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and Cultural Organization

International Atomic
Energy Agency

Workshop on
"Technology and Applications of Accelerator Driven Systems (ADS)"

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Design Acceleator for ADS

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DESIGN OF ACCELERATORS FOR ADS

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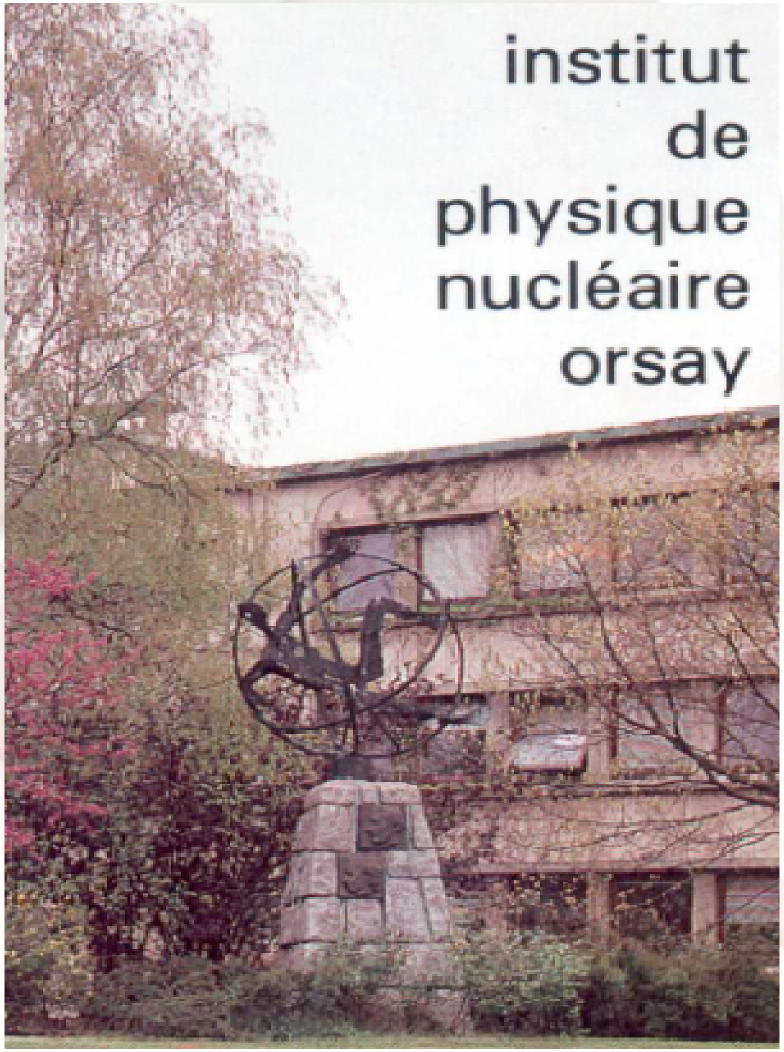


Chapter 1

Introduction to the Accelerator World

- Introductory Remarks & Literature
- Acceleration of charged particles
- Why we need particle accelerators
- History and Livingston chart
- Example of a charged particle source
- Electrostatic Accelerators
- From Electrostatic to RF Acelerators

Introductory Remark

My lecture series *"DESIGN OF ACCELERATORS FOR ADS"* aims at providing:

1) an introduction to the field of particle accelerators
2) some more insight into linear accelerators, chosen by PDS-XADS as reference solution for ADS applications
3) a discussion of the principles of "overdesign, redundancy and fault-tolerance required for "ADS-class" accelerators
4) an overview on the R&D presently under way in the context of technological validation (IPHI, warm and SCRF cavities) within 6FP project EUROTRANS
5) information on Radioprotection, Budget and Roadmap towards XT-ADS

My thanks for help go to many colleagues of the Accelerator Division at IPN Orsay, the colleagues of the European Projects PDS-XADS and EUROTRANS, and Prof. Carlo Pagani (INFN and U Milano), together with whom I gave a lecture a few years ago, and reused some material.

useful literature: some "older" textbooks……

M. Stanley Livingston	**High Energy Accelerators** (Interscience Publishers, 1954)
J.J. Livingood	**Principles of Cyclic Particle Accelerators** (D. Van Nostrand Co Ltd , 1961)
M. Stanley Livingston and J. B. Blewett	**Particle Accelerators** (Mc Graw Hill Book Company, Inc 1962)
K.G. Steffen	**High Energy Optics** (Interscience Publishers, J. Wiley & sons, 1965)
H. Bruck	**Accelerateurs Circulaires de Particules** (PUF, Paris, 1966)
M. Stanley Livingston (editor)	**The Development of High Energy Accelerators** (Dover Publications, Inc, N. Y. 1966)
A.A. Kolomensky & A.W. Lebedev	**Theory of Cyclic Accelerators** (North Holland Publihers Company, Amst. 1966)
E. Persico, E. Ferrari, S.E. Segre	**Principles of Particles Accelerators** (W.A. Benjamin, Inc., 1968)
P.M. Lapostolle & A.L. Septier	**Linear Accelerators** (North Holland Publihers Company, Amst. 1970)
A.D. Vlasov	**Theory of Linear Accelerators** (Program for scientific translations, Jerusalem 1968)

…… and some "more recent" textbooks

M. Conte, W.W. Mac Kay — **An Introduction to the Physics of Particle Accelerators** (World Scientific, 1991)

P. J. Bryant and K. Johnsen — **The Principles of Circular Accelerators and Storage Rings** (Cambridge University Press, 1993)

D. A. Edwards, M. J. Syphers — **An Introduction to the Physics of High Energy Accelerators** (J. Wiley & sons, Inc, 1993)

H. Wiedemann — **Particle Accelerator Physics** (Springer-Verlag, Berlin, 1993)

M. Reiser — **Theory and Design of Charged Particles Beams** (J. Wiley & sons, 1994)

A. Chao, M. Tigner — **Handbook of Accelerator Physics and Engineering** (World Scientific, 1998)

K. Wille — **The Physics of Particle Accelerators: An Introduction** (Oxford University Press, 2000)

E.J.N. Wilson — **An introduction to Particle Accelerators** (Oxford University Press, 2001)

… and of course also the lectures
of the CERN accelerator schools CAS

The cathode ray tube: a "complete accelerator at home"

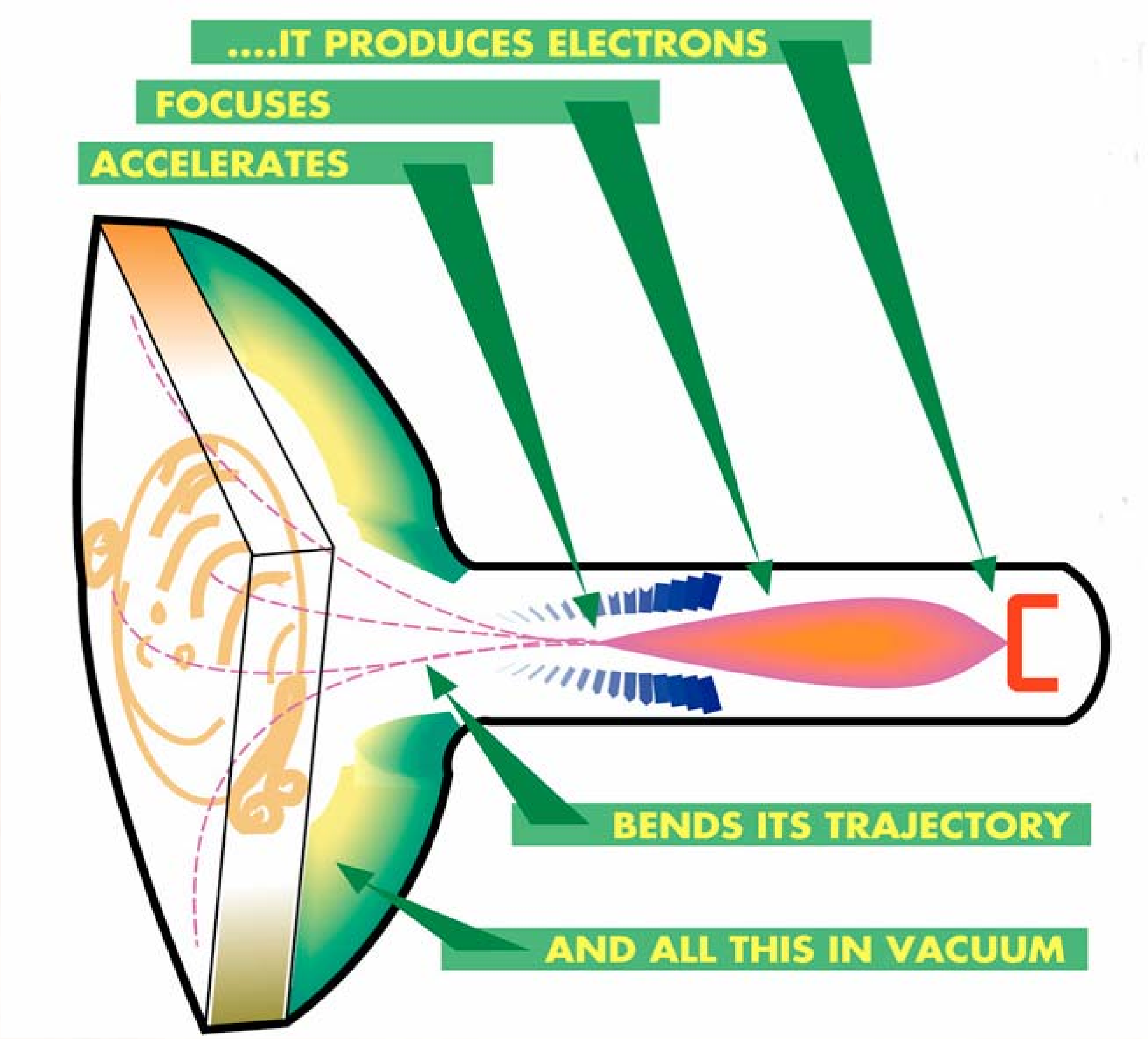


Figure from a CERN Website

Accelerating Particles (I)

- acceleration **a** of particle of mass m needs a force **F** :

$$\boxed{F = m \bullet a} \qquad \text{(Newton)}$$

- of the 4 fundamental forces, the only one we can control by technological means is the **electromagnetic force**

- from Maxwell's 4 equations describing electromagnetic fields (electric: **E**, magnetic: **B**), one obtains the **Lorentz force** which acts on a charge q evolving with speed **v** :

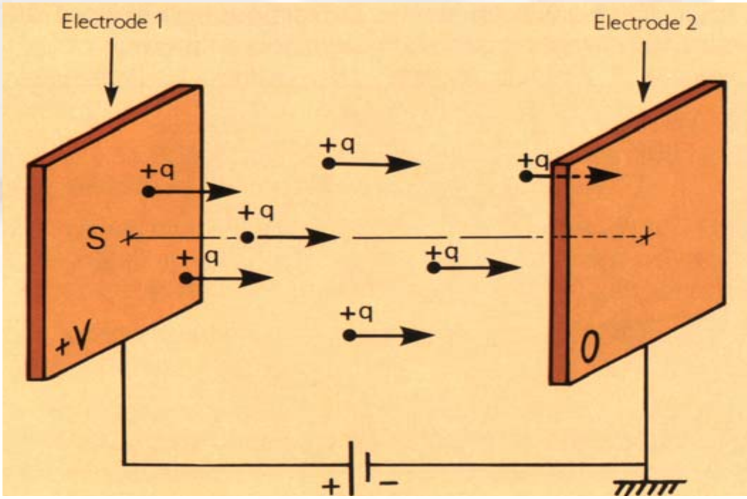
$$\boxed{F = q\,(E + v \times B)}$$

- note: we can only accelerate **charged particles**

- the **energy gain** W of a charge q in an **electric field** generated by a **potential** V is:

$$\boxed{W = q\,V}$$

- (typically **used unit:** electron volt [**eV**])



Accelerating Particles (II)

schematic view

An accelerator has the following principal components

- a **source** of charged particles

  electrons, protons, heavy ions, special case: positrons & anti-protons

- **accelerating elements**

  electrostatic columns or radiofrequency cavities which provide the electric fields giving the energy to the particle (beam)

- beam **guiding elements**

  mainly magnetic, in order to maintain (focus) the beam on the wanted trajectory and to provide the orbit (closed for a synchrotron) in the case of a circular machine

- as most important ancillary systems **vacuum and beam diagnostics**

  high vacuum is needed to avoid perturbation of the beam by collisions with residual gas, and beam diagnostics assure the monitoring of the beam trajectories

- the **user installation**

  (often complex) experimental set-ups including targets, spectrometers, detectors
  special case: secondary beams produced by a nuclear reaction (e.g.: neutrons) or an electromagnetic process (e.g.: photons by Bremsstrahlung / Synchrotron Radiation)

Accelerators & Fundamental Physics

- Accelerators have become the most powerful tool to study the physics of elementary matter: its Constituents and their Interactions.
  An important interdisciplinary aspect is the history of the Universe (Big-Bang, Nucleosynthesis)

- The scales probed correlate with the beam energy (or its momentum p):

$\boxed{\lambda = h/p}$ (de Broglie wavelenght),

a simultaneous aspect being the binding energies and masses of the subatomic and subnuclear particles which require more and more energetic particle beams according to Einstein's $\boxed{E = m c^2}$

Useful Dimensions or Distances

• Quark	10^{-19} m	• Earth	10^{7} m
• Proton & Neutron	10^{-15} m	• Sun	10^{9} m
• Atom	10^{-10} m	• Solar System	10^{13} m
• Cell	10^{-8} - 10^{-3} m	• Milky Way	10^{21} m
• Man	10^{0} m	• Univers	10^{26} m

Elementary Constituents of Matter

- discovery and measurement of their properties by the high-energy accelerators, allowing the establishment of the "Standard Model"
- prominent example from LEP, CERN:
  there are exactly 3 families of neutrinos,
  this has important cosmological consequences

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

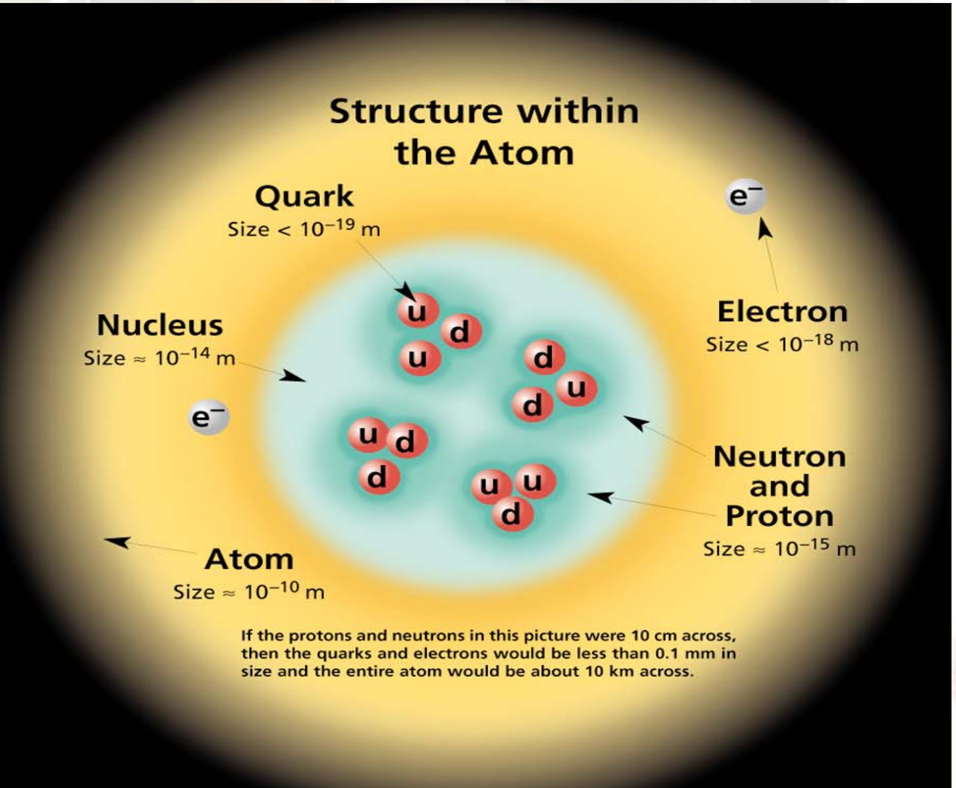


Figure from: http://www.particleadventure.org

Bosons, the Carriers of Forces

- famous experiments with the CERN accelerators, for which Carlo Rubbia and Simon van der Meer received the Nobel prize, discovered in 1983 the $W^{+/-}$, Z^0 Bosons, mediators of the weak force, which makes a nuclear reactor working
- note, part of the award was for stochastic cooling = accelerator physics!!

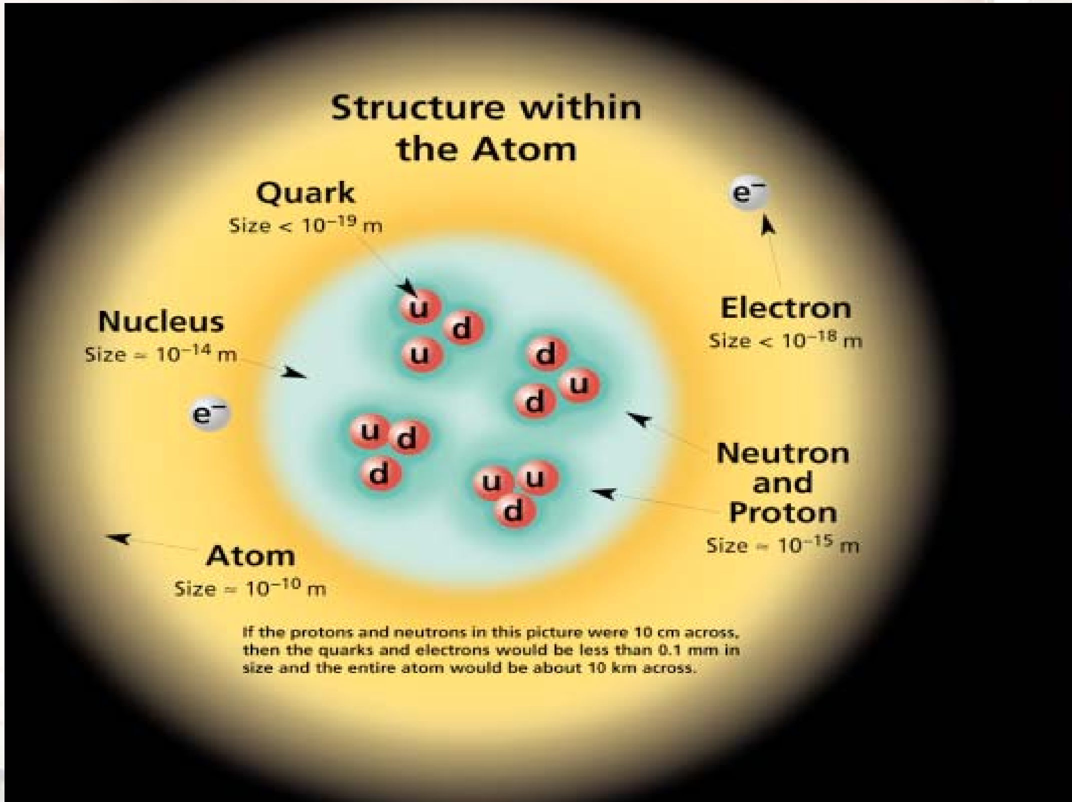


Figure from: http://www.particleadventure.org

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electri-cally-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the ener-gy in the color-force field between them increases. This energy eventually is converted into addi-tional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

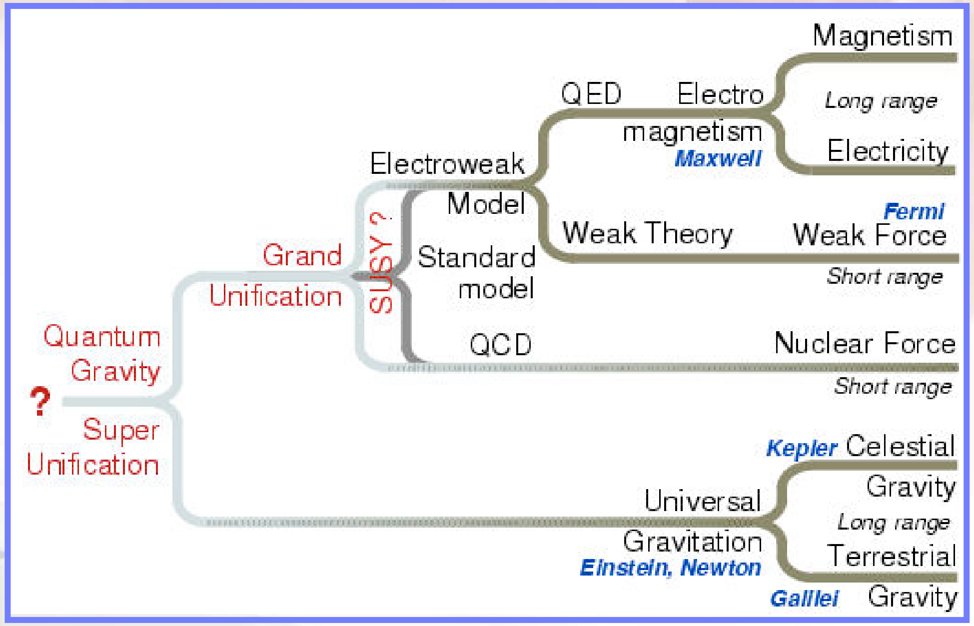
Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual elec-trical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

Towards Unification……?

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

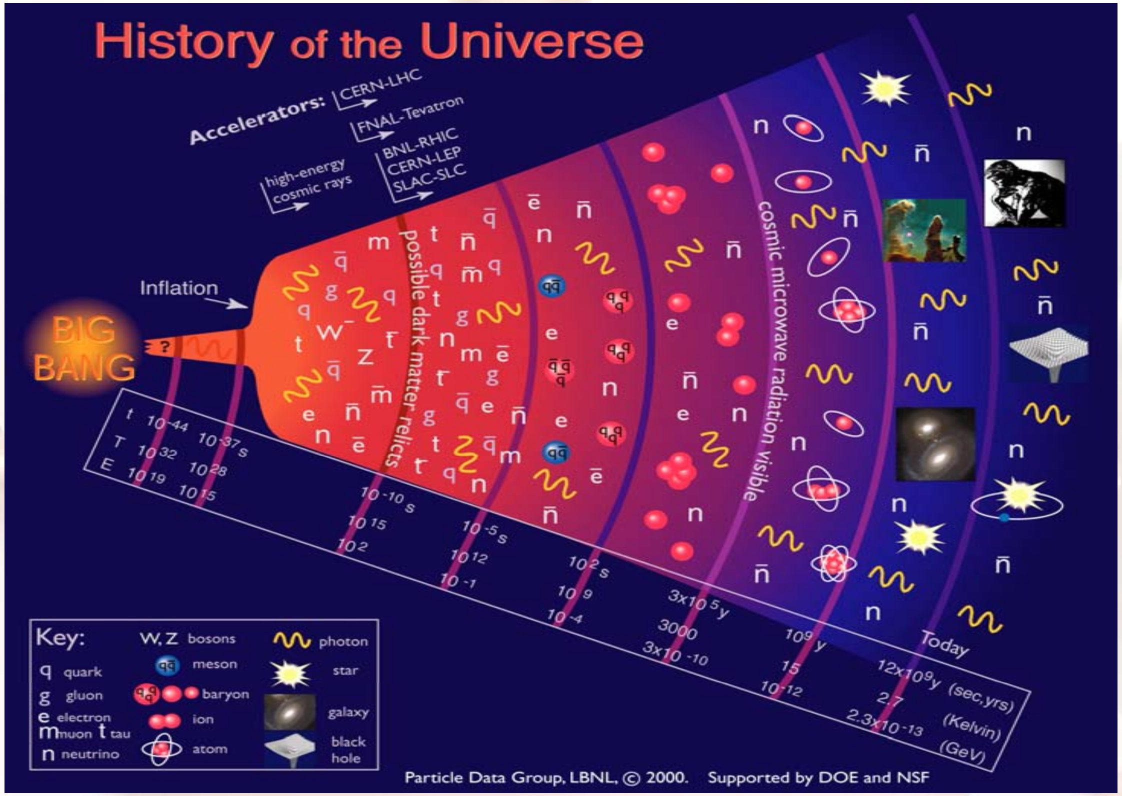
Figure from: http://www.particleadventure.org

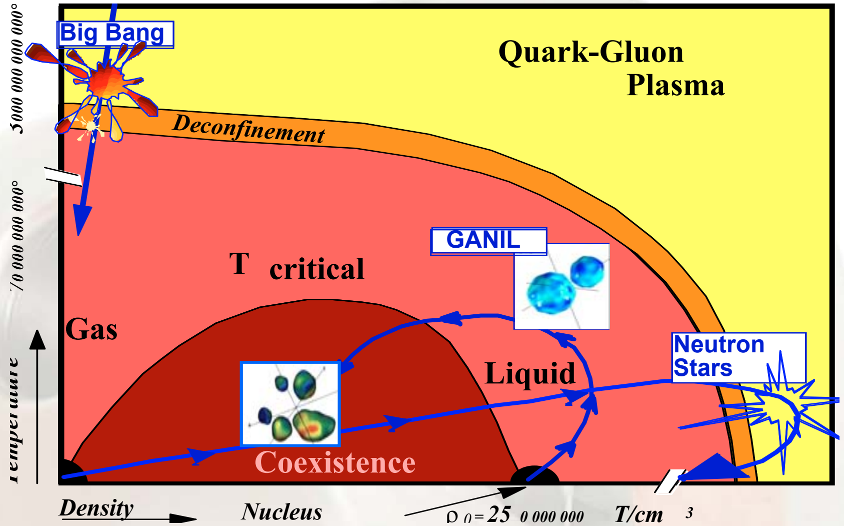


Note in passing,

- that accelerators have have been the prime instruments for providing the experimental proof for the Standard Model, containing the the weak, electromagnetic and strong force
- that among the next milestones might be the observation of supersymmetric particles at LHC, and the observation of proton decay in underground laboratories
- that experiments at nuclear reactors also play a very important rôle, a typical example has been the precise measurement of the neutron decay time at ILL
- that the mediator of Gravitation is not yet observed, and that e.g. INFN and CNRS have just buildt at Pisa the VIRGO experiment, a 3 km long high-precision interferometer for observing gravitational waves.

Accelerators & the Universe (I)

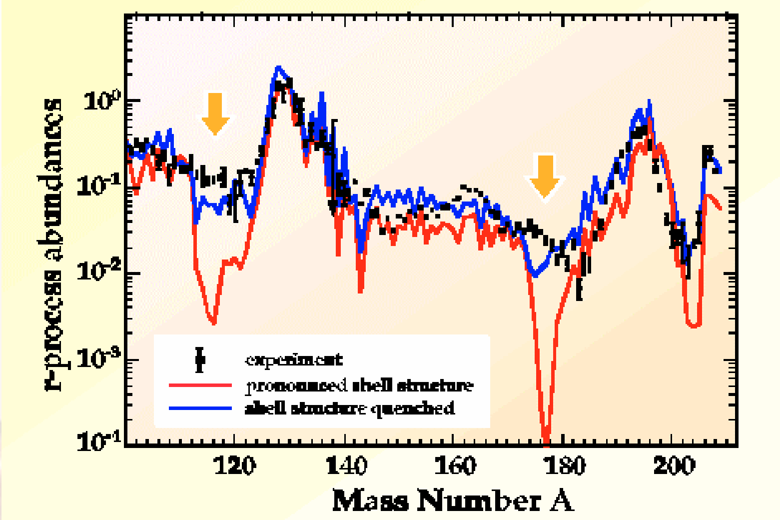




- We believe that today's world emerged from the Big Bang
- At the beginning, when the universe was small enough to hold it in the hand!

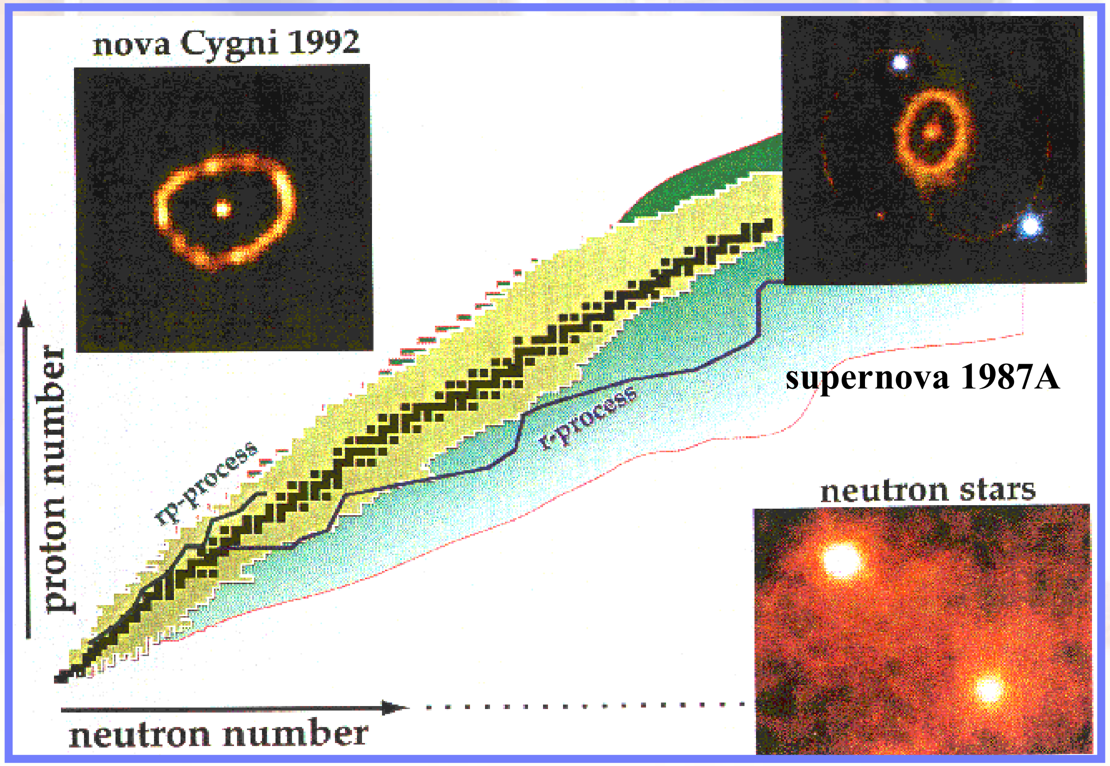
- All the particles which make up every day matter had yet to form, but presently, the universe has expanded to billions of light years.
- The Quarks and Gluons, today locked up inside the protons and neutrons, were then to hot to stick together. Matter in this state is called the Quark Gluon plasma, QGP.
- To create the Quark Gluon Plasma in the laboratory, scientists must collide ions, atoms stripped of electrons, into each other at very high energy, squeezing the protons and neutrons together to make them melt.
- It is the aim of the future LHC experiment ALICE to create these conditions and study them.

Accelerators & the Universe (II)



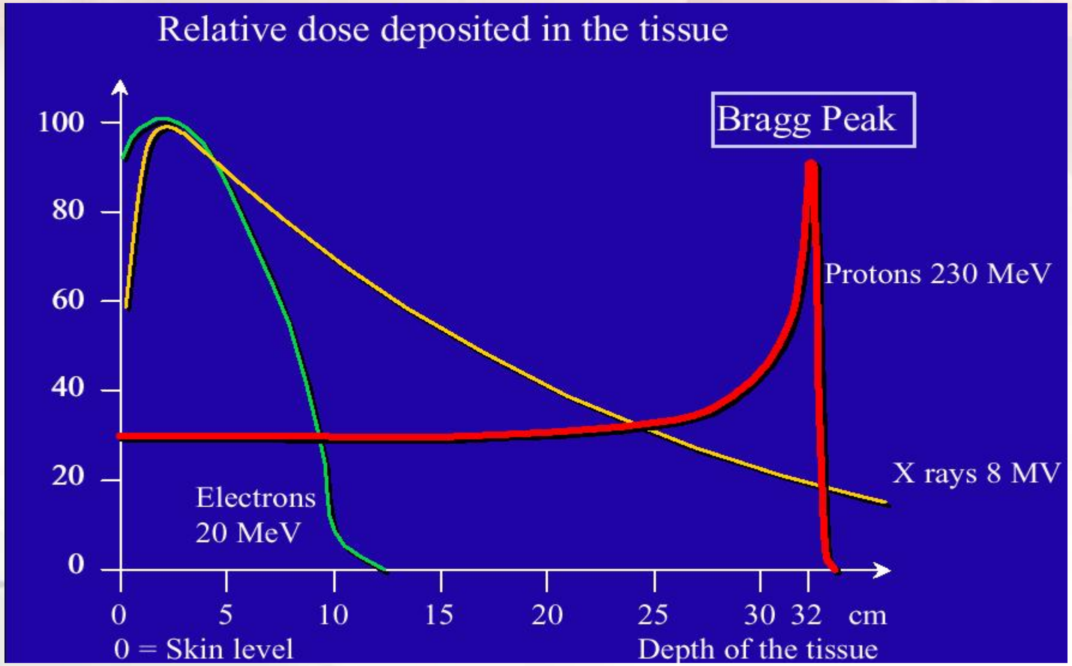
- the rapid proton (rp) and neutron (r) capture generate very short-lived nuclei
- the nuclear structure properties of these nuclei are often unknown.
- yet their masses, decay-properties, reaction cross sections critically determine the isotopic abundance (in the figure, note the difference between normal and quenched shell structure)
- this is a very important physics goal for present & future accelerators like GANIL, GSI, SPIRAL-II, FAIR, EURISOL
- the high-intensity EURISOL accelerator has remarkably similar specifications to the one for the ADS!

- nuclear astrophysics studies the nuclear reactions which happen in stars
- the reactions give rise to the energy production and make the chemical elements, "isotopic abundance", our world is made of
- the left figure shows, e.g. the abundance produced in the r-process, believed to happen when supernovae explode (black = measured abundance)



Some Accelerator Applications

- a microscope of supreme resolving power
  - ➔ photons and neutrons for research in solid state and atomic physics, novel materials, chemistry, biologie, etc.
  - ➔ ultra-sensitive trace analysis by accelerator mass-spectrometry, dating, environment surveillance
- a radiation source for
  - ➔ micro-lithography, sterilisation of food and other materials, inducing chemical reactions



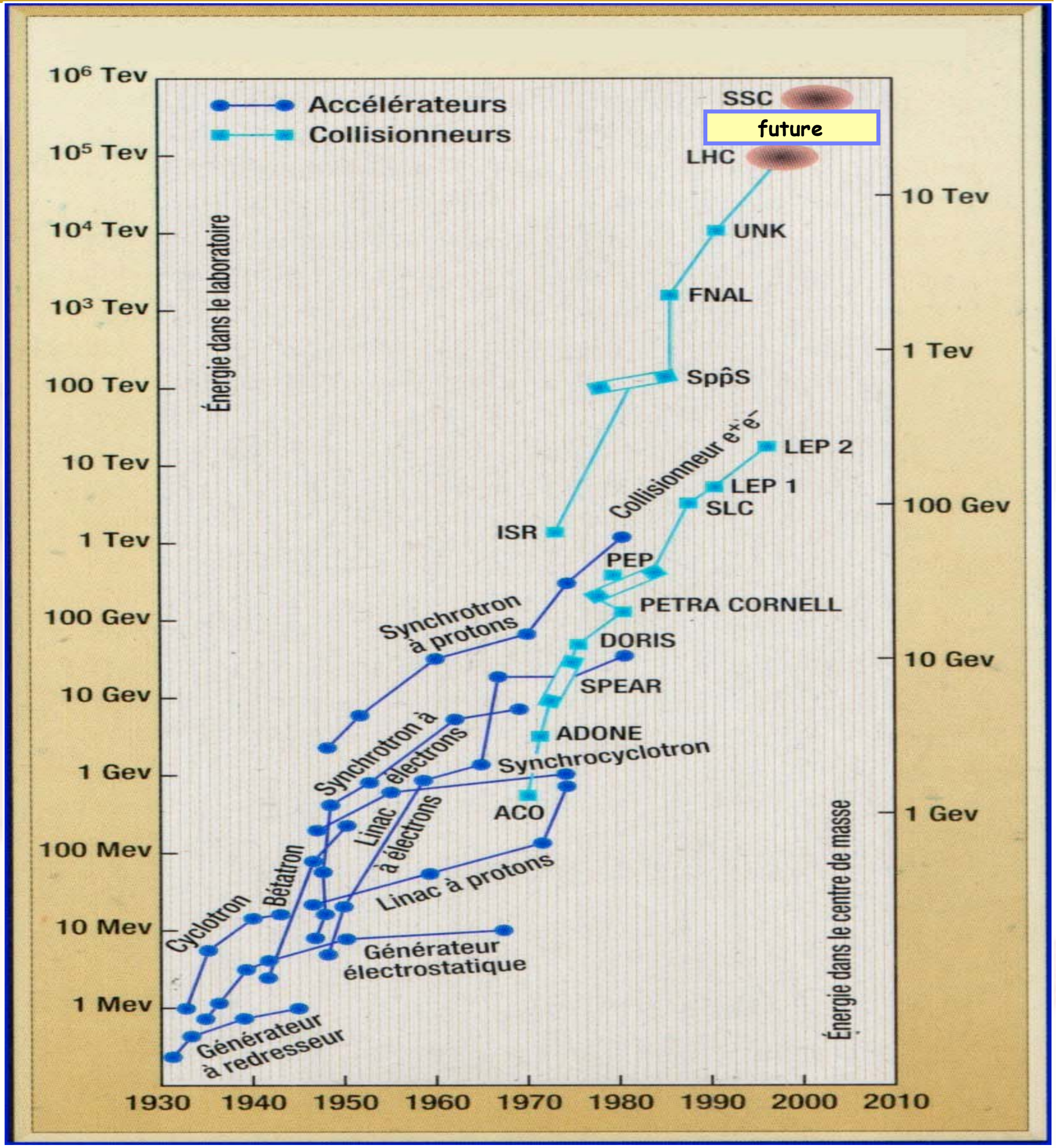
- nuclear medicine
  - ➔ production of radioisotopes
  - ➔ cancer treatment, thousands of x-ray & electron sources and are installed at hospitals but note the promise, see figure, of proton- and heavy-ion therapy more than 20000 patients so far (e.g. CPO Orsay, GSI)
- and also nuclear power, the topic of our IAEA school !

Some Milestones for Accelerators

- 20th century, first 25 years — Prehistory: fundamental discoveries made with "beams" from radioactive sources (Rutherford!) trigger the demand for higher energies
- from 1928 to 1932 — Cockcroft&Walton develop a 700kV electrostatic accelerator based on a voltage multiplier, Van de Graaff uses a charge conveyor to reach 1.2MV.
- 1928 — first Linac by Wideroe based on Ising's concept of resonant acceleration.
- 1929 — Lawrence invents the cyclotron.
- 1944 — MacMillan, Oliphant & Veksler develop the synchrotron
- 1946 — Alvarez builts a proton linac with Alvarez structures (2π mode)
- 1950 — Christofilos patents the concept of strong focusing
- 1951 — Alvarez conceives the tandem
- 1954 — Courant, Livingston and Snyder implant strong focusing at the Brookhaven Cosmotron Synchrotron (and learn with disappointment about Christrofilos's patent)
- 1956 — Kerst stresses in a paper the concept of a collider, but physics with useful event-rates was much later (e.g. in the 80's with the $Sp\bar{p}S$)
- 1970 — Kapchinski & Telyakov invent the radio-frequency quadrupole (RFQ).
- early 80's — superconducting magnets for cylotrons and synchrotrons considerably boost the performance (energy for size), in particular for colliders
- from mid 80's — Geller's ECR sources are implanted at many heavy ion accelerators and greatly improve reliability and energy range (they deliver high q)
- the last years — the development of superconducting accelerating cavities provides very high power conversion efficiency, and CW operation for high luminosity

The Livingston Chart

- Around 1950, Livingston made a quite remarkable observation:
- Plotting the energy of an accelerator as a function of its year of construction, on a semi-log scale, the energy gain has a linear dependence.
- 50 years later, that still holds true.
- In other words, so far, builders of accelerators have managed exponential growth, every ten years, roughly a factor of 33 is won.
- Note that for a given "family" of accelerators, generally, saturation of maximum energy sets in after some time.



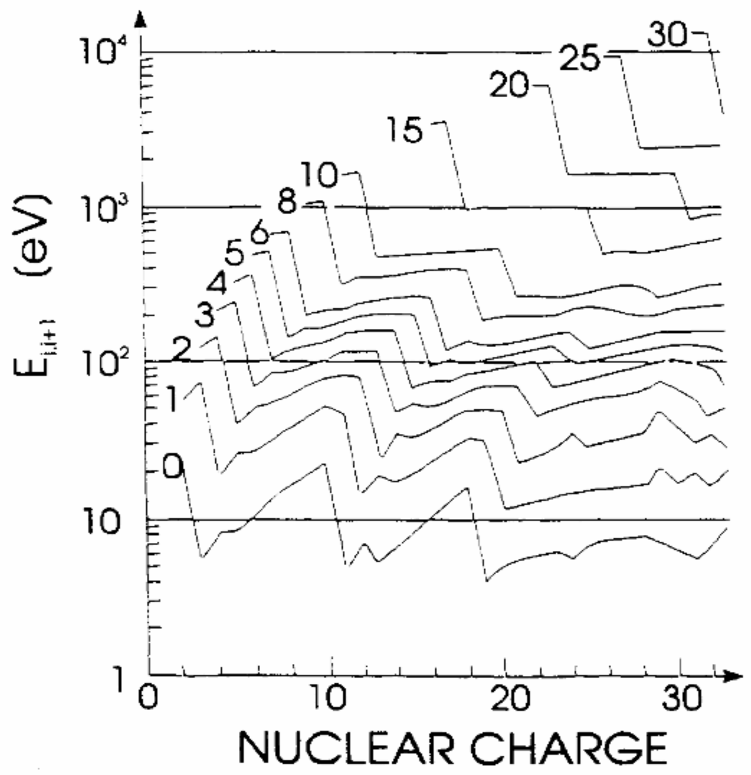
How to make charged particles (here ions)

Ions are produced in a ionized gas ('plasma')

In thermal equilibrium the Saha equation describes the amount of ionization in a gas

$$\frac{n_i}{n_n} \approx 3 \times 10^{27} \frac{(k_B T)^{3/2}}{n_i} e^{-\frac{I_j}{k_B T}}$$

Ionization energy: I_j (j: charge state)



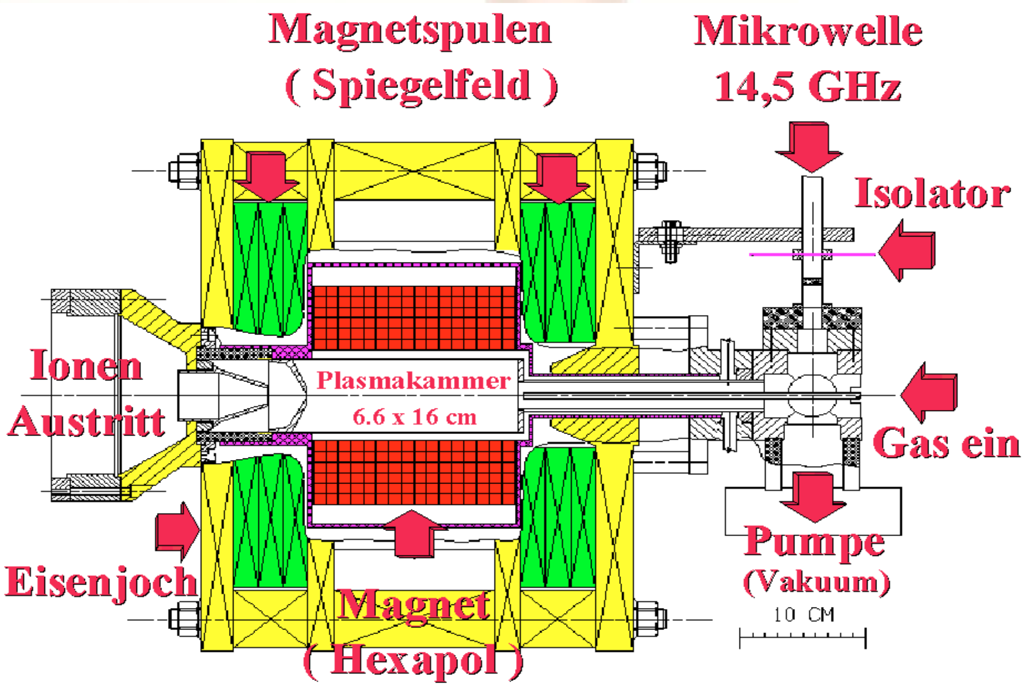
Transparency from a lecture by O. Boine-Frankenheim, GSI

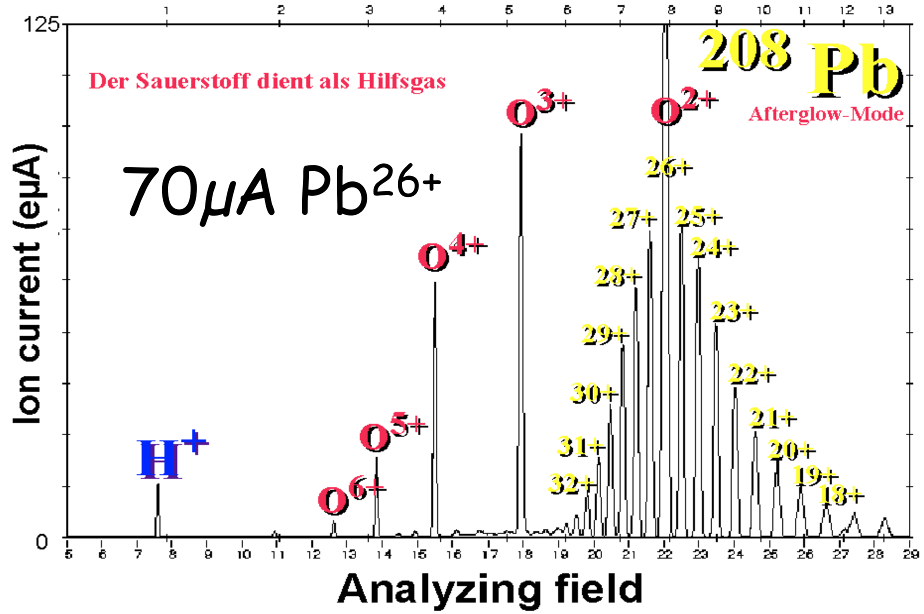
Highly stripped ions require high plasma temperatures and good plasma confinement.

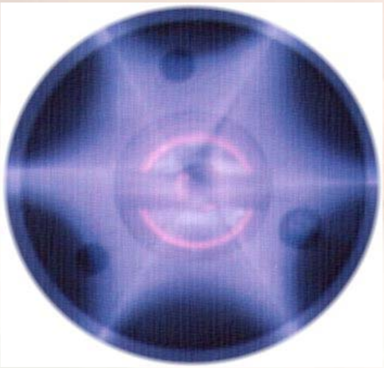
High ion currents are achieved for lower charge states ions.

Charged Particle Sources: Example of the ECR source

Transparency from a lecture by O. Boine-Frankenheim, GSI



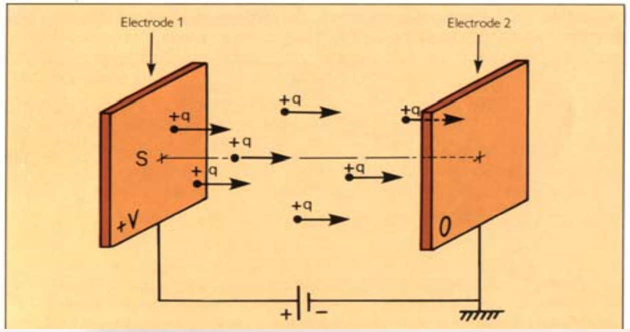




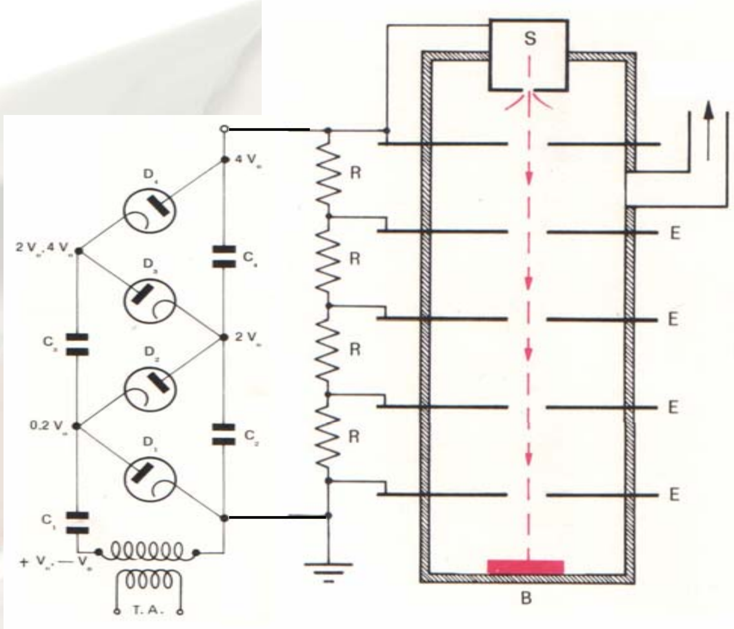
'hot plasma'

High current sources: e.g. > 10 mA U^{4+}
and also > 100 mA p
(see later, IPHI R&D for ADS)

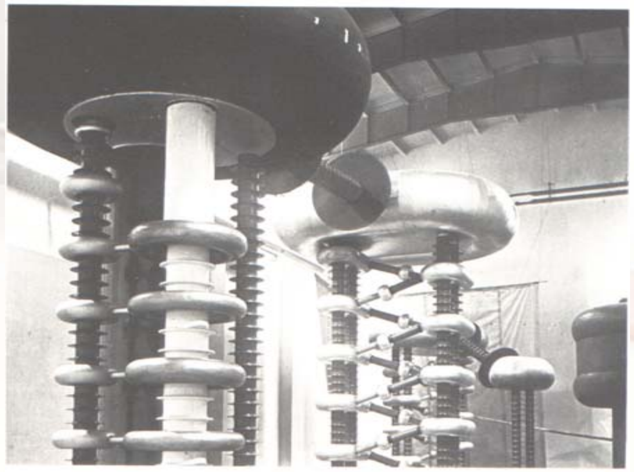
Electrostatic Accelerators (I)



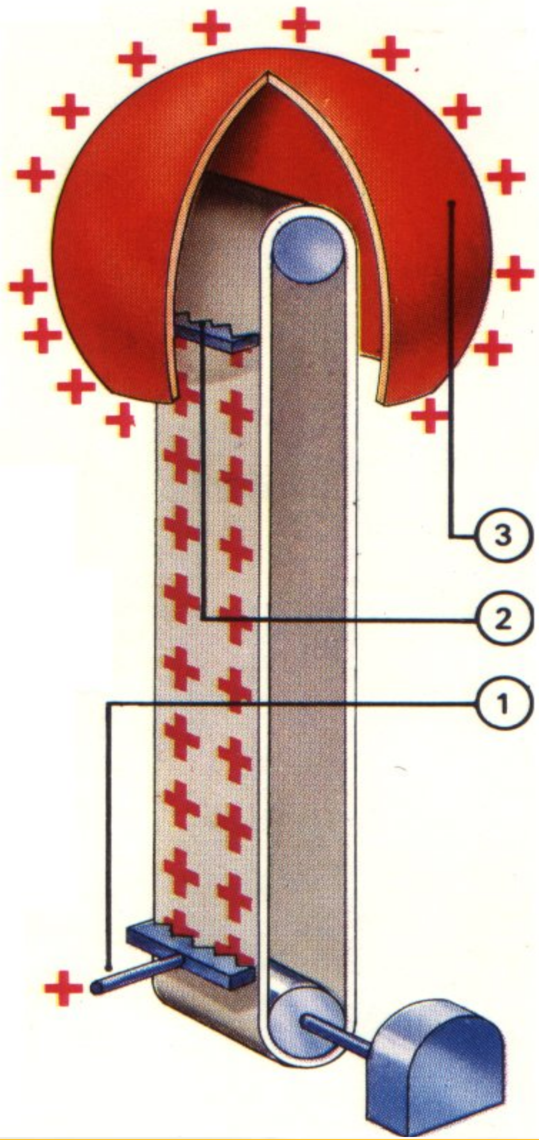
- Starting from the "elementary cell" of acceleration, (recalled left), an electrostatic accelerator is an insulating column



- At its entry side, an ion source injects the charged particles
- Between the entry and the exit, (here target B) a continuous high voltage is applied, mediated by intermediate electrodes for a smooth and regular increase of the electric field
- In a Cockroft&Walton Accelerator, a rectifier-multiplier produces the high-voltage applied to the column, see upper right figure.
- This allows to reach high beam currents, of interest for many applications, but the voltage is practically limited to somewhat above 1 MV, because of breakdown of insulation. Such high voltage is quite a matter of technology knowledge, see lower right figure



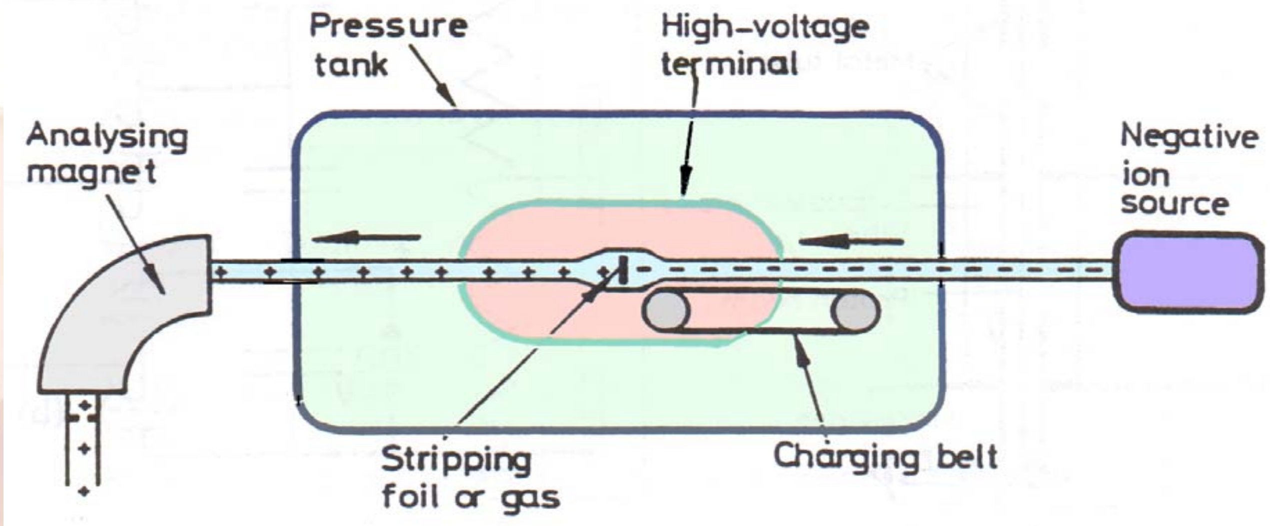
Electrostatic Accelerators (II)



- how to increase the voltage for electro-static acceleration?
- the concept of charge transport (see left) has been introduced by R. J. van de Graaff
- a comb-like electrode (1) sprays charges on an insulating conveyor belt (the high-voltage generator typically being again a rectifier multiplier)
- The conveyor transports the charges inside the sphere-shaped terminal (3), which forms in fact a Faraday cage
- The charges are collected by a second, comb-like, electrode (2) which is connected to the sphere
- consequently, the charges accumulate on the outside of the sphere and the inside get charge free, ready to accept further charging
- In practice, one can reach up to 25 MV, provided one uses (expensive) SF_6 gas for limiting breakdowns

Electrostatic Accelerators (III) : the Tandem

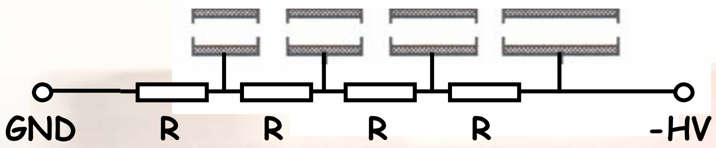
- consecutive to the HV terminal, a second accelerator column is installed leading back to ground potential
- a stripper is installed at the terminal through which the beam particles have to pass
- this principle works only for the injection of negative ions because of the stripping process

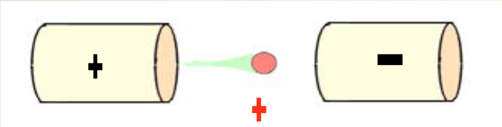


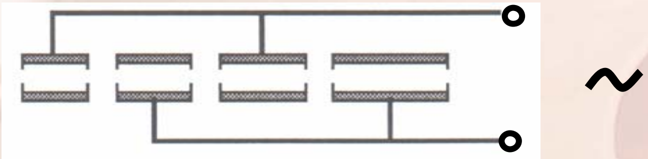
- however, at typical terminal voltages, several electrons can be stripped off, considerably augmenting the energy gain of the second section
- Such a Tandem (see right the SF_6 pressure vessel of the machine at IPN Orsay containing conveyor and accelerating column), can continuously accelerate any charge-to-mass ratio with an excellent beam energy spread, but it is limited in intensity.

- The Orsay Tandem is presently much used for measuring fission and capture cross sections of actinides for Reactor Physics in the context of GEDEPEON activities.

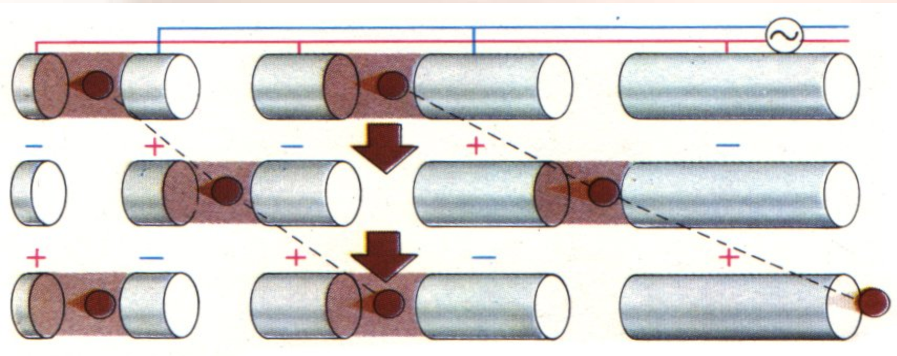
From Electrostatic to RF acceleration





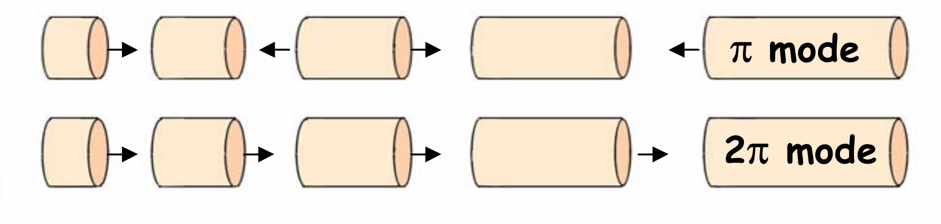


π mode



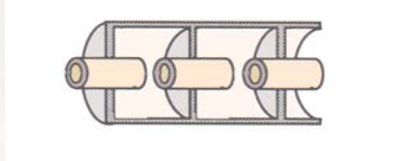
- consider an element of an accelerating co-lumn of an electrostatic accelerator
- at any moment, the electric field is in the same direction, allowing continuos acceleration
- consider now such a column, but driven with an alternating voltage, in such way that con-secutive electrodes are connected to opposite polarity of the RF generator
- suppose now, that the RF frequency is such that it accelerates the particle between electrodes 1&2 (and also 3&4), whereas the field is opposite, at that moment, between accelerating gaps, 2&3 and 4&5, respectively
- if this particle arrives now at the gap bet-ween 2&3, precisely, when the RF has chan-ged to opposite phase, acceleration occurs again, and so on.
- note, that while the polarity change occurs, the particle is in the field-free space of the drift tube of such a Wideroe linac. Further, to stay in phase with the RF, as the speed of the particle increases, the lenght of the drift tubes has to increase

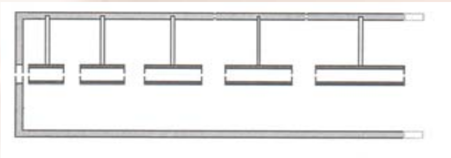
Linacs, towards the next Lecture



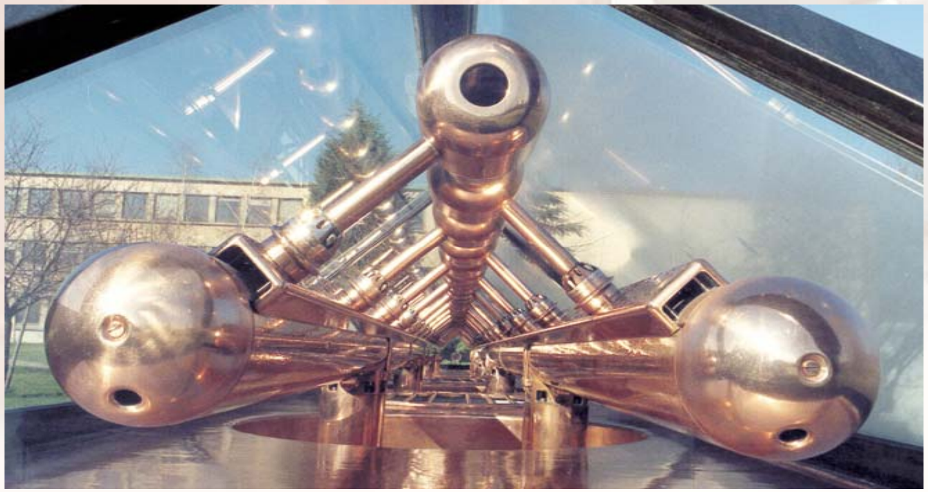
- on the preceeding slide, the Wideroe linac operating in the π mode was introduced, but it is also possible to run at higher harmonic, e.g. in the 2π mode

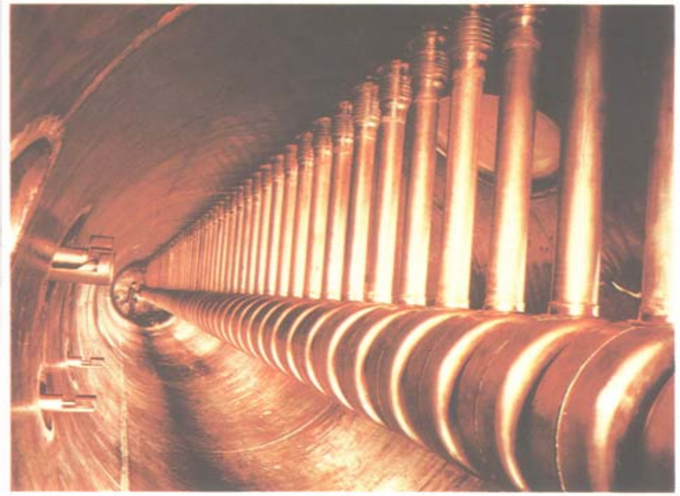
- in order to minimise the RF power deposited in the structures, the gaps and drift tubes form cavities resonant to the RF frequency





- in the 2π mode, the currents circulating in the wall separating two subsequent cavities cancel, hence one can suppress this wall. This gives the Alvarez-structure of the classical DTL





Historical examples: a Wideroe type structure (ALICE heavy ion injector, IPN Orsay) — a drift tube linac (DTL) (Saturne, Saclay)

Chapter 2
RF Accelerators

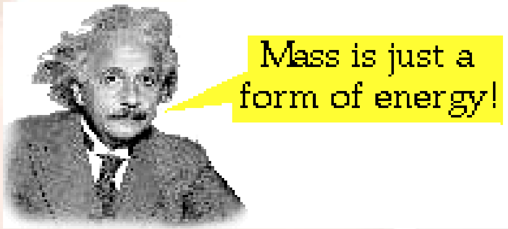
- Basic Concepts
- RF Linacs: Protons and Electrons
- The Resonant Cavity
- Longitudinal and transverse focusing
- Generalities on Circular Accelerators
- Synchrotrons
- Cyclotrons
- Intrinsic Limits of Cyclotrons (for ADS)

Basic Concepts: Energy

- Energy of a relativistic particle

$$E = m\,c^2$$

E = total energy
m = relativistic mass
c = speed of light



$$m = \gamma\, m_0 \qquad E_0 = m_0\, c^2$$

$$\gamma = (1-\beta^2)^{-1/2} \qquad \beta = v/c$$

m_0 = rest mass
v = particle speed

- Kinetic energy, T, and momentum, p, of a relativistic particle

$$T = m\,c^2\,(\gamma - 1) = E - E_0$$

$$\mathbf{p} = m\,\mathbf{v} = m_0\,\gamma\,\mathbf{v}$$

$$E^2/\,c^2 = p^2 + m_0^{\,2}\,c^2$$

$$p \approx m\,c \quad \text{if} \quad v \approx c$$

- Non relativistic approximation: $v \ll c$

$$E \approx m_0\,c^2 + \tfrac{1}{2}\,m_0\,v^2$$

$m_0\,c^2$ = rest energy
$\frac{1}{2}\,m_0\,v^2$ = classical kinetic energy

- Useful numbers:

Speed of light: $c = 2.9979 \cdot 10^{8}\ \mathrm{ms^{-1}}$
Energy unit: $1\mathrm{eV} = 1.6021 \cdot 10^{-19}$ joule

Electron rest energy: E_0 = 0.511 MeV
Proton rest energy: E_0 = 938 MeV

Basic Concepts: Fields

- Equation of motion and Lorentz force

$$\vec{F}_{Lorentz} = \frac{d\vec{p}}{dt} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{el} + \vec{F}_{mag}$$

  - Electric field can transfer energy to the particles

$$\Delta E = \Delta T = \int \vec{F}_{Lor} \bullet d\vec{s} = q \cdot \int \vec{E} \bullet \vec{v} \cdot dt$$

  - Magnetic field can guide the beam in a stable path
- All Particle Accelerators are based on these rules
  - The beam moves inside a vacuum chamber
  - Electromagnetic objects placed on the beam path perform the tasks
    - Magnets guide the beam on the chosen trajectory and produce focusing
    - Resonant RF cavities are used to apply the electric accelerating field
    - The few exceptions are: Betatron, RFQ and Electrostatic Accelerators

Block diagram of an RF Linac

Particle Source

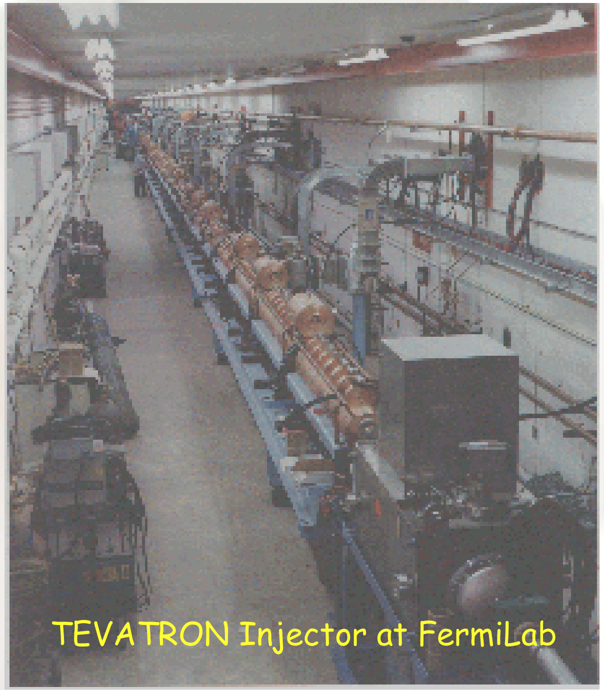
Linac structure:

Acceleration (cavities)
Transverse focusing (magnets)

Output beam
(experiments, users, applications ...)

Subsystems

- Electric power
- Vacuum
- Cooling
- RF power and controls



TEVATRON Injector at FermiLab

- Electrostatic fields are used for the source

$$\vec{\nabla} \times \vec{E} = 0$$

- Time varying harmonic (RF) electric fields, via resonant cavities, transfer energy to the beam

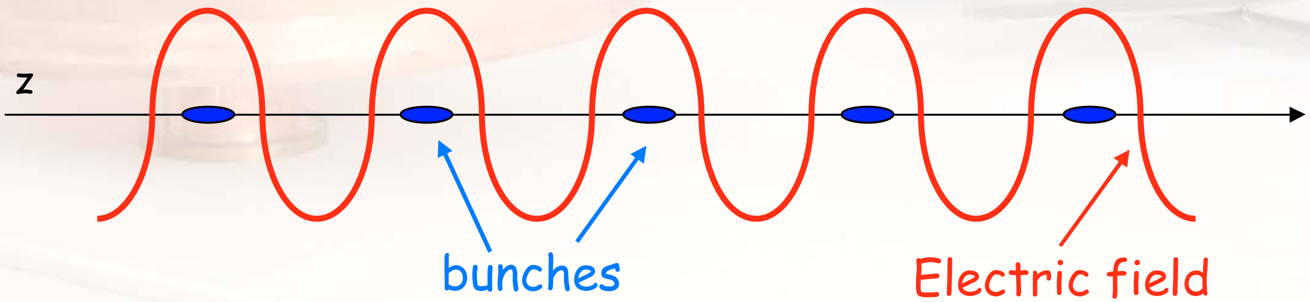
$$\vec{\nabla} \times \vec{E} \neq 0$$

The linac is a resonance accelerator

- An RF source is used to generate an electric field in a region of a resonant metallic structure
- The particles of the beam need to be localized in *bunches* and properly phased with respect to the field so that the beam is accelerated

$$\frac{d(\gamma m_0 c^2)}{ds} = qE_z(s,t)$$

- In order to keep acceleration along the linac this synchronism condition needs to be maintained.



Electrons and Protons

- electron and proton masses

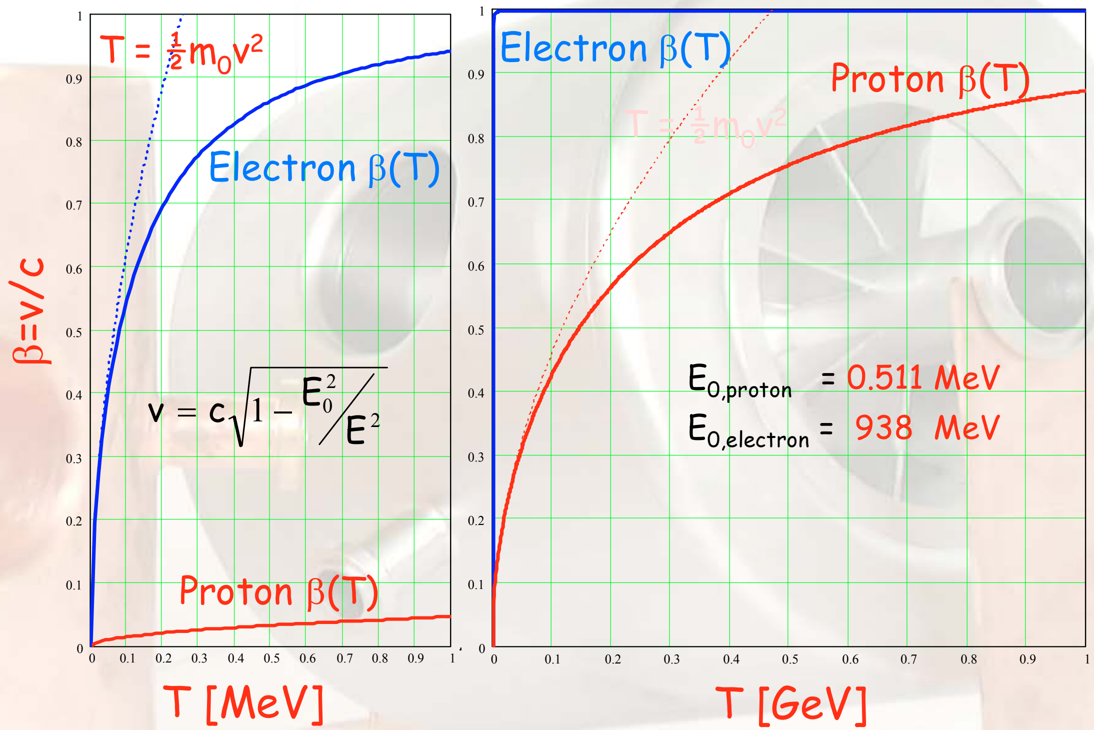
$$E_{0,proton} \approx 2000\ E_{0,electron}$$

- A proton varies its velocity on a much higher kinetic energy range
- "Synchronous" condition for a multicell cavity:

$$L = \frac{\lambda_{RF}\beta}{2}$$

- The cell length depends on the particle velocity.
- Synchronism is exact only for a given velocity value.

  Cavities operated in a velocity range.



- For electrons all RF cavities are identical
- For protons, cavity geometries follow the particle velocity, that is the particle β.
- **Below $\beta \approx 0.5$, special structures are required**

The resonant cavity

- An ideal cavity is a vacuum region surrounded by infinitely conducting walls

$$\begin{cases} \nabla \cdot \mathbf{E} = 0 \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \dfrac{\partial \mathbf{E}}{\partial t} \end{cases}$$

$$\nabla^2 \begin{Bmatrix} \mathbf{E} \\ \mathbf{B} \end{Bmatrix} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \begin{Bmatrix} \mathbf{E} \\ \mathbf{B} \end{Bmatrix} = 0$$

Assuming a field of the form (uniform section):

$$\begin{Bmatrix} \mathbf{E} \\ \mathbf{B} \end{Bmatrix} = \begin{Bmatrix} \mathbf{e}(x,y) \\ \mathbf{b}(x,y) \end{Bmatrix} \exp[i(\omega t - \beta z)]$$

The transverse components are functions of the derivatives of the longitudinal

$$\begin{cases} e_x = -i/k_c^2 (\beta \partial e_z / \partial x + \omega \partial b_z / \partial y) \\ e_y = i/k_c^2 (-\beta \partial e_z / \partial y + \omega \partial b_z / \partial x) \\ b_x = i/k_c^2 (\omega / c^2 \partial e_z / \partial y - \beta \partial b_z / \partial x) \\ b_y = -i/k_c^2 (\omega / c^2 \partial e_z / \partial y + \beta \partial b_z / \partial x) \end{cases}$$

Maxwell equations can be solved only when the boundary conditions are given
For a perfect conductor:

$$\begin{cases} \mathbf{n} \cdot \mathbf{B} = 0 \\ \mathbf{n} \times \mathbf{E} = 0 \end{cases}$$

$$\nabla_\perp^2 \begin{Bmatrix} e_z \\ b_z \end{Bmatrix} + k_c^2 \begin{Bmatrix} e_z \\ b_z \end{Bmatrix} = 0$$

$$k_c^2 = \frac{\omega^2}{c^2} - \beta^2$$

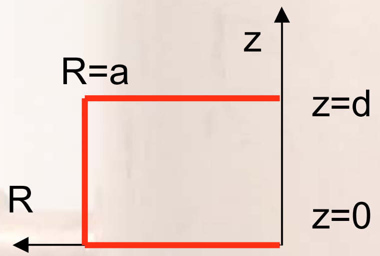
+ boundary conditions

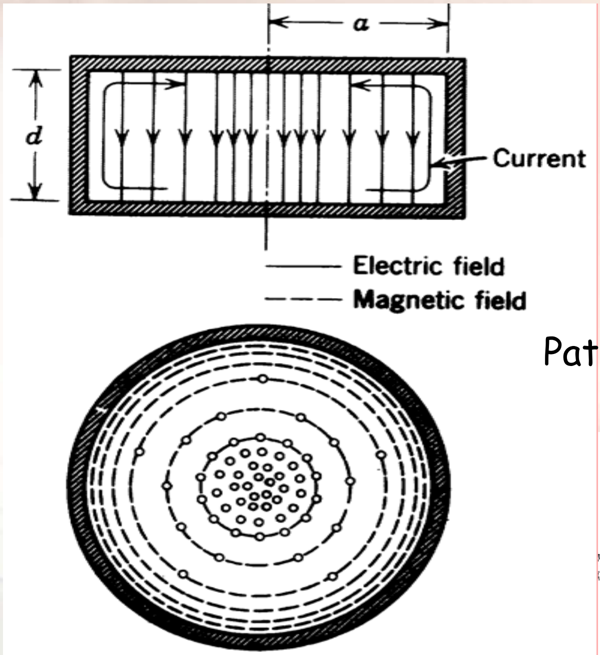
↓

Cavity Eigenmodes

A simple resonator: the pillbox

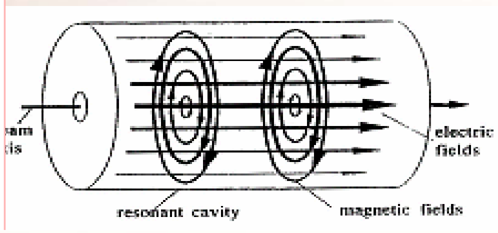
- Simplest geometry: Axysimmetrical cilindrical cavity
- Neglecting the beam holes for particle transmission the wave equations can be solved exactly





- Two families of solutions are possible (Zoology of cavity modes)
  - In fact, all the possible cylindrical circular waveguide modes propagating in the axial direction with an integer number of half guide wavelength between the plates
- $B_z=0$ (Transverse magnetic modes: TM_{mnl}) these are the accelerating modes
- $E_z=0$ (Transverse electric modes: TE_{mnl}) are the deflecting modes

Pattern of the E and B fields in the TM_{010} mode

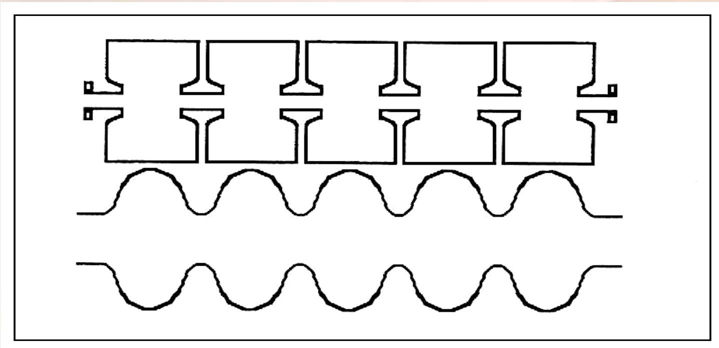


$$\omega = c\frac{2.405}{a}$$

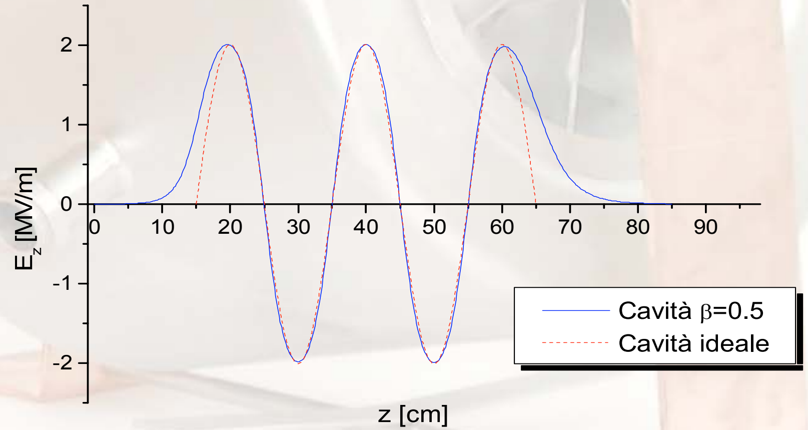
$$\begin{cases} e_z = E_0 J_0\left(\frac{2.405}{a} r\right) \\ b_\varphi = \frac{i}{c} E_0 J_1\left(\frac{2.405}{a} r\right) \end{cases}$$

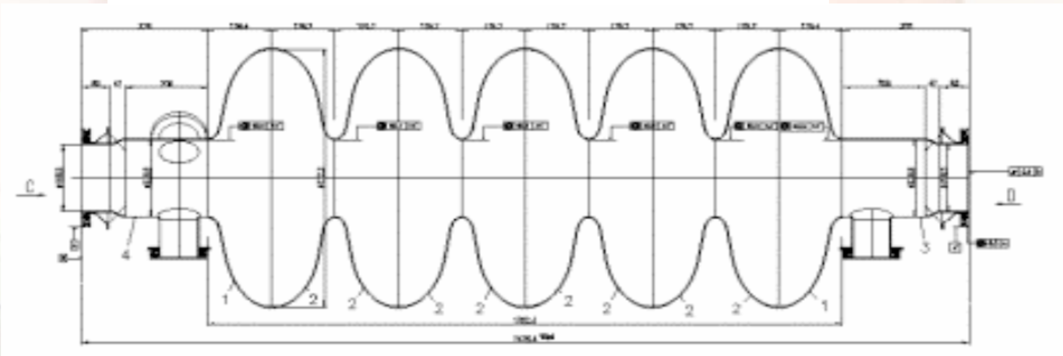
Realistic multicell cavities

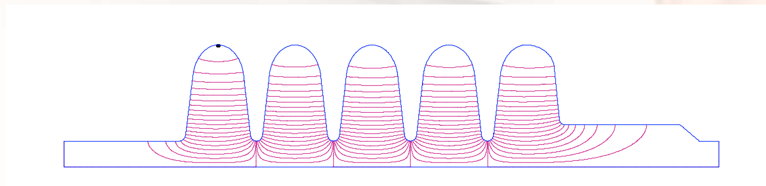
- In order to efficiently accelerate the beam, *multicell resonators are used*, by periodically repeating the resonant structure and providing coupling between the different cells. Any geometry can be computed with existing numerical codes
  - The simplest coupling is represented by the **E** field through the beam hole (capacitive coupling)
- The beam needs to keep the relative phase with the field



$$L = \frac{\lambda_{RF}\beta}{2}$$







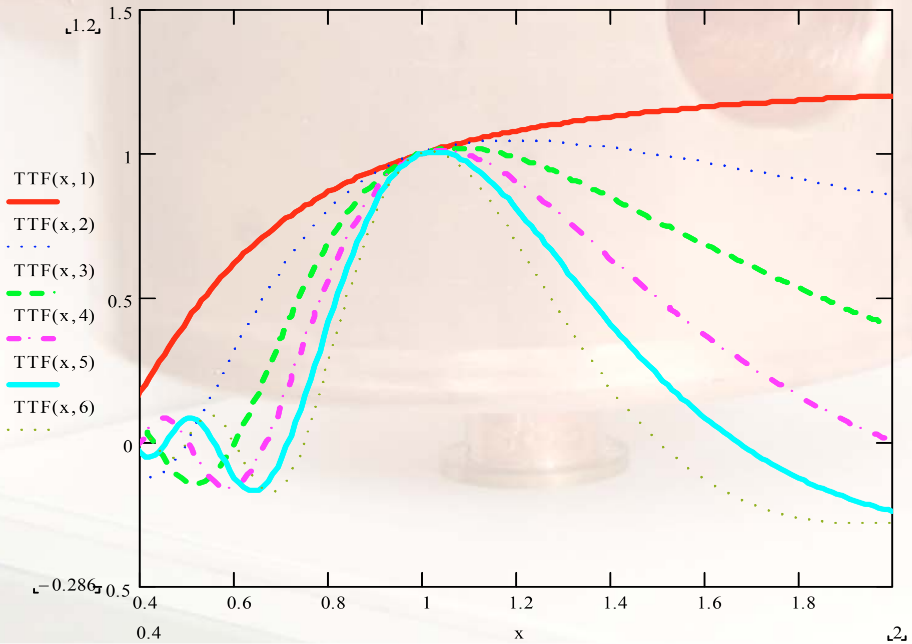
Transit Time Factor

- Proton Case:

$$\Delta W_{kin} = qE_{acc} L_{cav} T_N(\beta_c, \beta_p) \cos \Phi_s$$

$$T_N(\beta_c, \beta_p) = \frac{4}{\pi N} \frac{\sin\left(N \frac{\pi}{2}\left(1 - \frac{\beta_c}{\beta_p}\right)\right)}{1 - \left(\frac{\beta_c}{\beta_p}\right)^2}$$

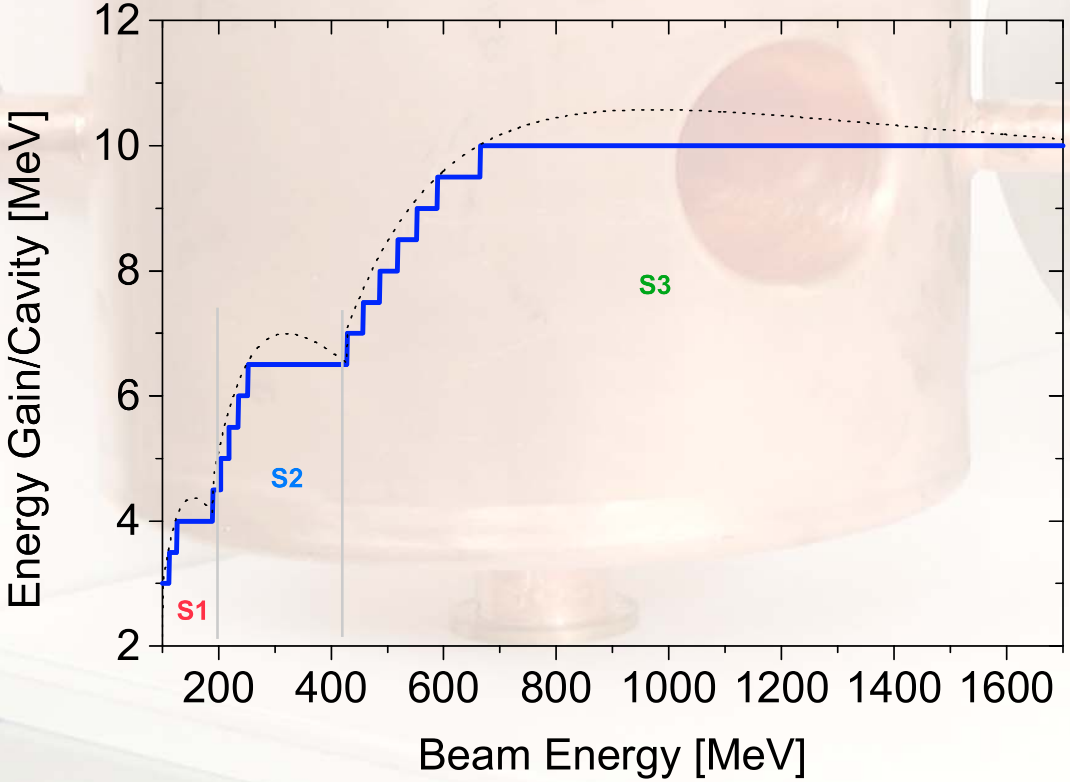
Transit Time Factor vs number of cells



- **The energy gain of the particle depends on:**
  - The accelerating field
  - The operating synchronous phase Φ_s
  - The velocity mismatch between the particle velocity and the synchronous velocity in the cavity
- **For protons Φ_s must be – 20÷30° for phase stability**
- **For high N values the Transit Time Factor is too narrow, i.e. The cavity works efficiently in a small velocity range: N = 5 or 6 is the good choice**
- **Filling Factor improves with N**
  - Compromise between space efficiency and velocity acceptance
- **E_{acc} is limited by peak fields!**

Efficient use of the cavities

- In order to efficiently design a linac it is necessary divide it in sections, each using a different cavity geometry in an energy range
- If N is big, too many sections are needed (low velocity acceptance). Conversely if N is too small the filling factor is penalized



Example for a LINAC with order of magnitude energy of 1 GeV (i.e. ADS,…)

Transition energies at 190 MeV and 430 MeV:

S1: 100 Þ 190 MeV (β =0.47, i.e. 145 MeV)
S2: 190 Þ 430 MeV (β =0.65, i.e. 296 MeV)
S3: 430 Þ 1600 MeV (β =0.85, i.e. 843 MeV)

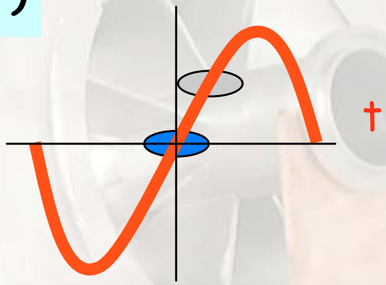
Increasing β :

- Higher accelerating field
- Longer cavities

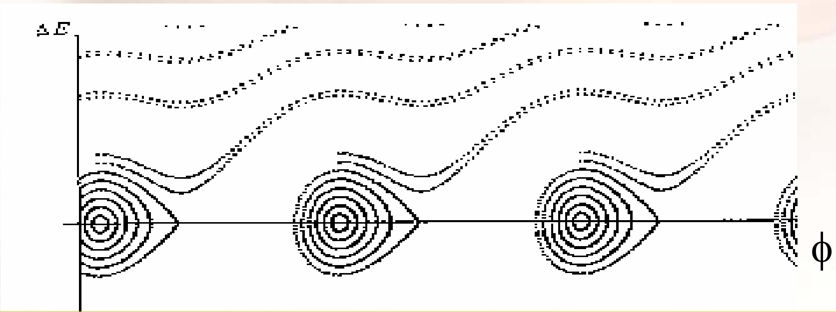
Greater energy gain!

Longitudinal stability

- Bunch passing cavity:
  centre of bunch called the **"synchronous particle"**
- Particles "see" a voltage of $V_0 \sin 2\pi\omega_{rf} t = V_0 \sin \varphi(t)$
  - For synchronous particle $\phi_s = 0$ (no acceleration)
  - Particles arriving early see $\phi < 0$
  - Particles arriving late see $\phi > 0$



- energy of those in advance is decreased and vice versa: **"Bunching"**
- To accelerate, make $0 < \phi_s < \pi$ $\Delta E = qV_0 \sin \varphi_s$
- For longitudinal (phase) stability, make $-\pi/2 < \phi_s < +\pi/2$

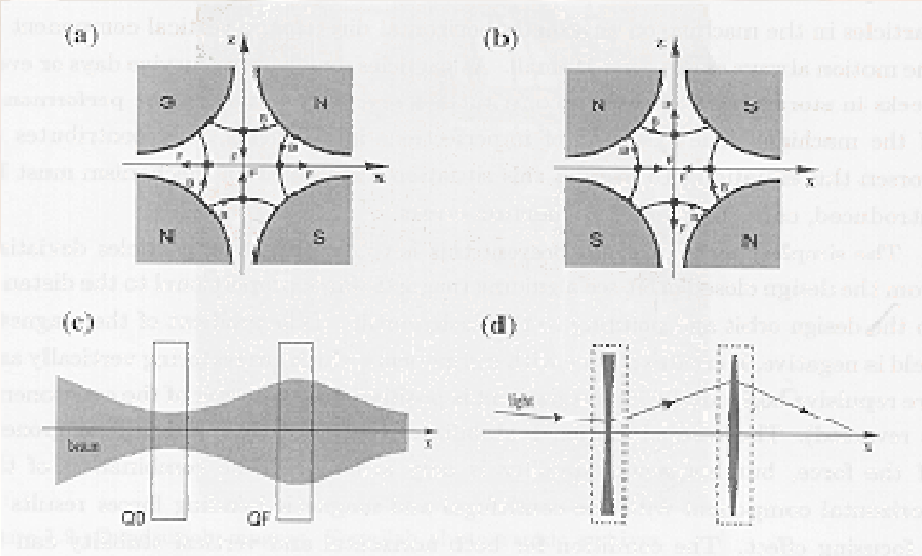


Not all particles are stable. There is a limit to the stable region (the separatrix or "bucket") and, at high intensity, it is important to design the machine so that all particles are confined within this region and are "trapped".

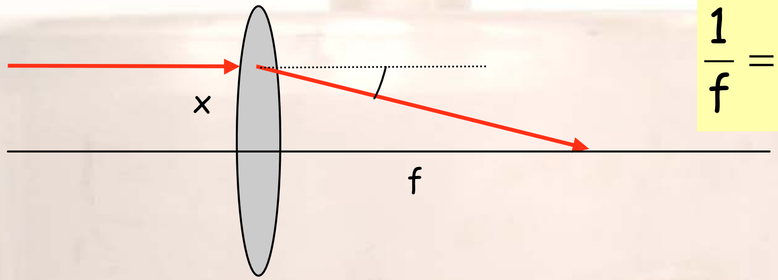
Transverse "Strong Focusing"

- Alternating gradient (AG) principle (1950's)
- A sequence of focusing-defocusing fields provides a stronger net focusing force.
- Quadrupoles focus horizontally, defocus vertically or vice versa. Forces are proportional to displacement from axis.
- A succession of opposed elements enable particles to follow stable trajectories, making small oscillations about the design orbit.

- Technological limits on magnets are high: iron saturation and dissipated power for high current
- Superconducting magnets are required for high field
- Solenoids are preferred at low energy, with high space charge forces: continuous focusing



Thin lens analogy of AG focusing



$$\frac{1}{f} = \left(\frac{B'}{B\rho}\right)L$$

Focusing: $F = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$

Defocusing: $D = \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix}$

Drift: $O = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$

Drift space effect

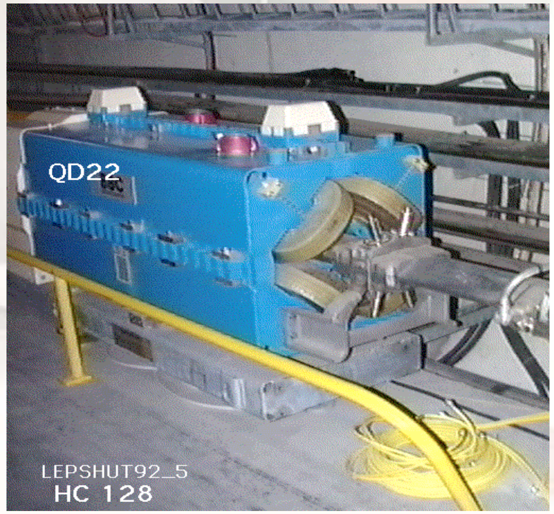
- $x_o = x_i + x_i'L$
- $x_o' = x_i'$

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{out} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_{in}$$

F-O-D
Transfer Matrix

$$\begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} = \begin{pmatrix} 1 + \frac{L}{f} & L \\ -\frac{L}{f^2} & 1 - \frac{L}{f} \end{pmatrix}$$

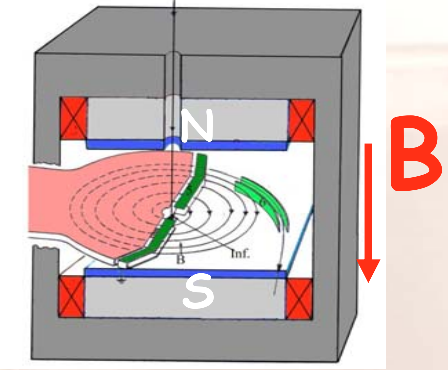
- Thin lens of focal length f^2/L, focusing if $L \ll f$
- Same for D-O-F ($f \to -f$)
- A system of AG lenses can focus in both planes



LEP quadrupole (CERN)

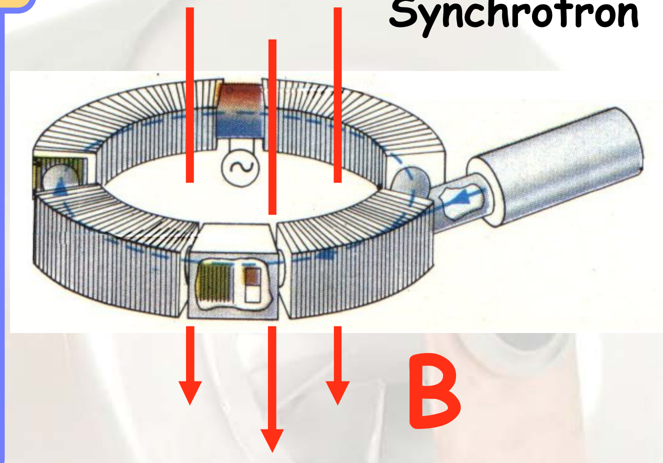
Circular accelerators: useful Definitions & Formulas (I)

Cyclotron



- a circular accelerator is a machine which has a median plane
- the median plane is a plane in which the magnetic field is perpendicular in all points
- the so-called reference particle evolves in this plane

Synchrotron



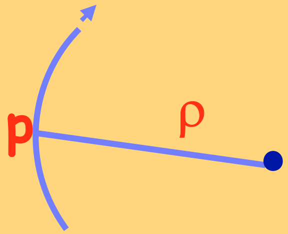
Lorentz force:

$$F = q\,(E + v \times B) = dp/dt$$

(relativistic) Kinetic Energy $W_{kin} = (pc)^2$

$$(pc)^2 = W^2_{total} - W^2_0 \quad \text{with} \quad W^2_0 = m_0\, c^2$$

Examples: electron rest mass: m_0 = 511 KeV/c^2, proton rest mass m_0 = 0.938 GeV/c^2



Neglecting the comparatively small accelerating term dp/dt = qE for a moment, a reference particle with mass m in a given orbit ρ will have |p| ≈ constant in each point. The Lorentz force will be in equilibrium with the centrifugal force:

$$mv^2/\rho = dp/dt = qvB$$

Useful Definitions & Formulas (II)

- the preceding formulas allow to write

$$p = q\,B\,\rho \quad \text{and} \quad W^2_{total} = (q\,c\,B\,\rho)^2 + W^2_0$$

thus, the final energy obtainable in a circular machine is essentially depending on the $B\rho$, called the magnetic rigidity, one, in fact, often uses the average magnetic rigidity $B_m\,\rho$, integrated over the orbit and which takes into account that one may have, for technological (or other!) reasons locally a different (in particular no) magnetic field.

- if the rest mass is very small compared to the kinectic, hence total energy ($W_0 << W_{total}$), one gets the rule of thumb relation

$$W_{total} = 300\ Q\ B_m\ \rho$$

in MeV

$Q = q/e_0$

in Tesla • meters

Energy Gain in Circular Accelerators

- from the formula for the total energy one obtains, by differentiation, an expression a change in energy $\delta W = \delta W_{total} = \delta W_{kin}$

$$\boxed{2\,\delta W\ W = 2\,q\,c\,(q\,c\,B_m\,\rho)\,(\rho\,\delta B_m + B_m\,\delta\rho)}$$

- which, after some "simple" operations gives

$$\delta W = (2\pi\,\rho/\delta t)\,q\,(\rho\,\delta B_m + B_m\,\delta\rho)$$

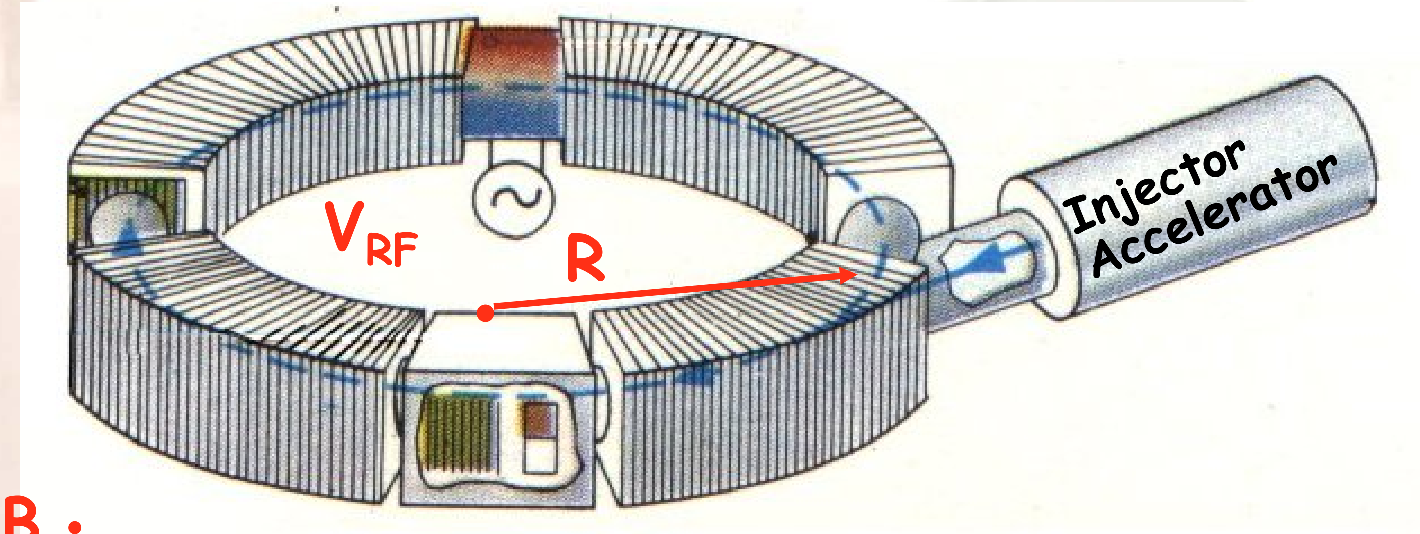
$$= 2\pi\,\rho\,q\,(\rho\,\dot{B}_m + B_m\,\dot{\rho})$$

- a synchrotron is a machine with $B_m\,\dot{\rho} = 0$
- a cyclotron is a machine with $\rho\,\dot{B}_m = 0$

Properties of Synchrotrons (I)

- the accelerating RF is applied to one (or more) cavities

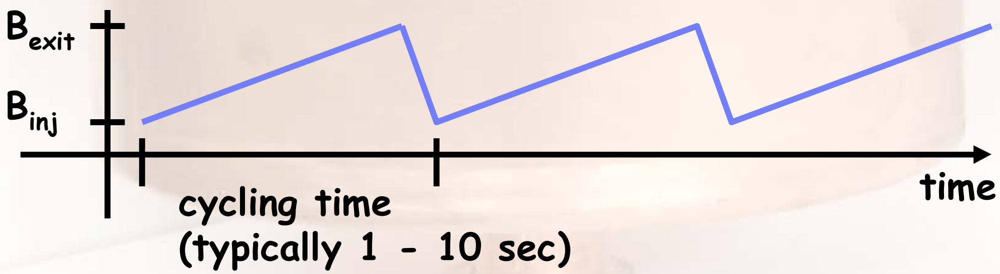
$$V_{RF} = V_0 \sin \omega t$$



- <u>Synchrotron =</u> "Ring"-Accelerator with radius R

- $\delta W = 2\pi \rho\, q\, \rho\, \dot{B}_m$

$$\Rightarrow \quad \delta W = 2\pi R^2 q \dot{B}_m$$



that means, that we have a constant energy gain per turn, which is equivalent to a linear increase, in time, of the average magnetic field B_m

- that means also, that this energy has to be provided by the accelerating radiofrequency cavities, hence

$$\delta W = q\, V_{RF} \sin \Phi_S$$

Properties of Synchrotrons (II)

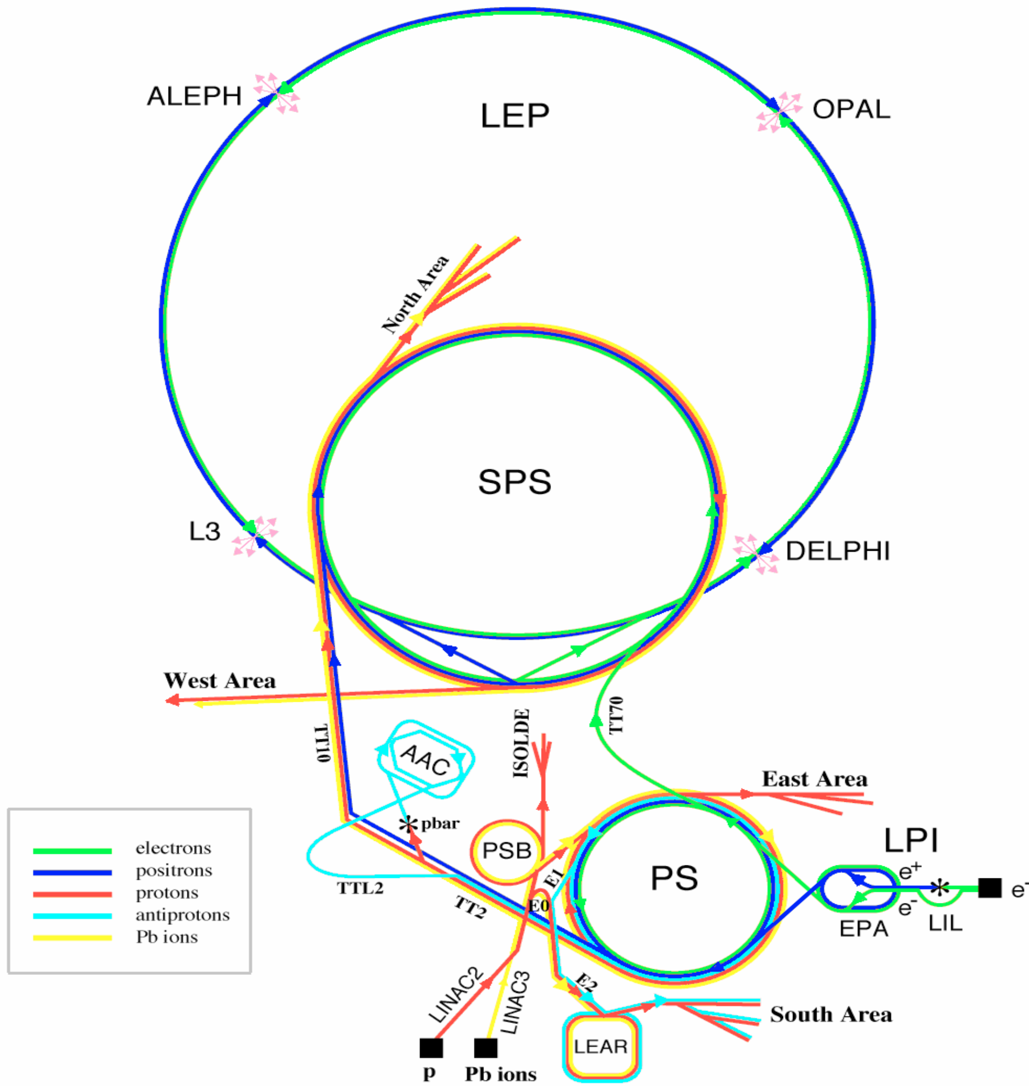
- synchrotrons accelerate up to the highest energies, determined by the bending fields (today, superconducting magnets approach B = 10T) and radius of the machine, recall W [MeV] = 300 Q B ρ [Tm], and it can be used as a collider
- a synchrotron is a pulsed machine, typical repetition rates are about 1 Hz
- the implantation of the principle of strong focusing (see preceding lecture) in synchrotrons allows the acceleration of quite strong beams, in fact, up to about 10^{14} charges can be extracted, corresponding to internal beams circulating in the Ampère-regime.
- The low-duty factor, however, makes that the time averaged intensities are in the μA range, and therefore, a synchrotron is not considered for ADS

- the major components of a synchrotron (photo: MIMAS, SATURNE)
- the bending elements, magnetic dipoles
- the focusing elements, magnetic quadrupoles
- the accelerating elements, RF cavities

The CERN Synchrotrons, until recently…

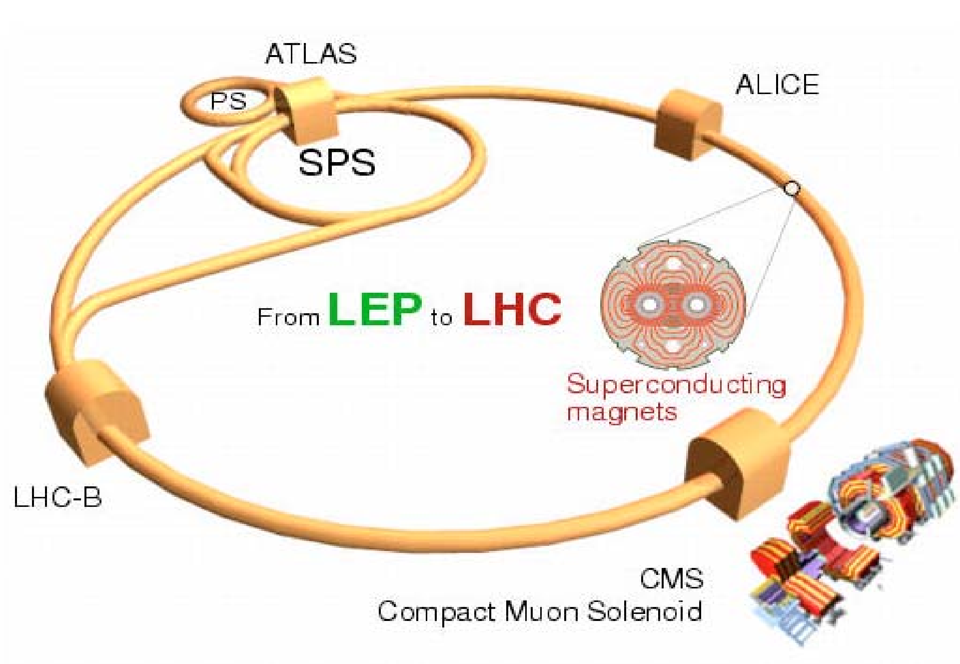
Aerial view of the CERN site with an indication of the circular LEP tunnel

- starting with the "historic" PS, operating since the sixties, CERN constitutes the world's largest com-plex of interconnected synchrotrons
- CERN's synchrotrons accelerate very different type of particles: electrons, positrons, protons, antiprotons and heavy ions
- LEP "was" a 2 x 100 GeV electron-positron collider



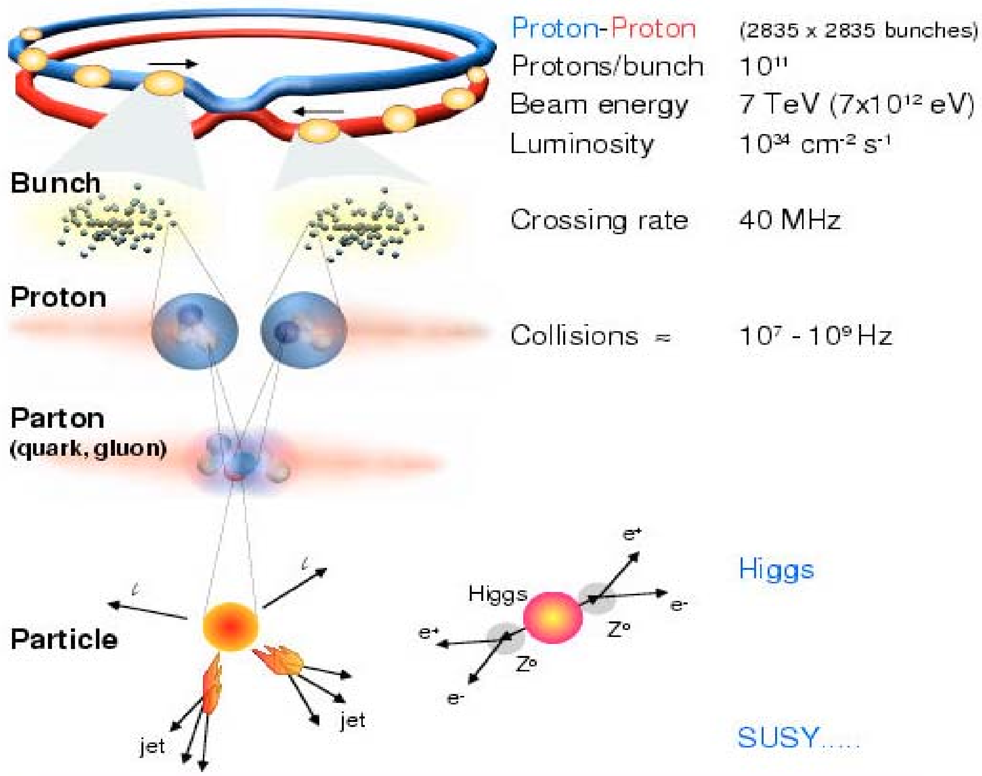
LHC, CERN's future Accelerator

The Large Hadron Collider (LHC)



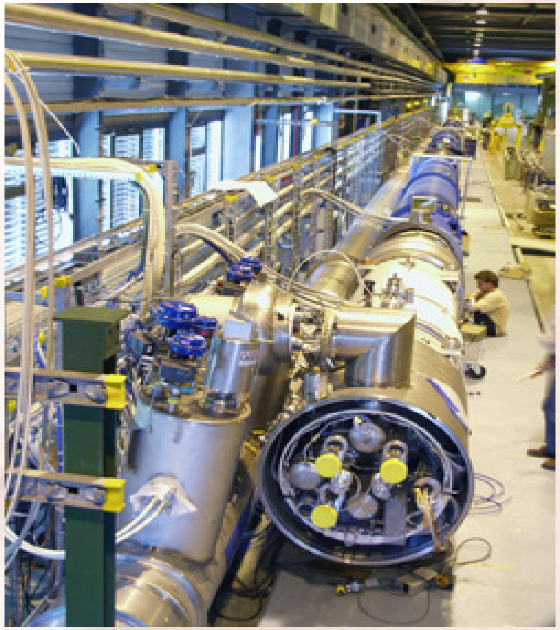
	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

Collisions at LHC



Selection of 1 in 10,000,000,000,000

Construction of Main LHC Components



- Presently, LHC is in the phase of mounting all the components in the tunnel
- First beam is expected in 2007
- Shown photos are related to the French "exceptional contribution" (contracts CEA-CERN-CNRS)
- many other countries, including non-member states make also very important contributions

⊲ "String 2", prototype section containing the superconducting dipole magnets

⊲ "SSS 3" the Straigt Short Sections contain the superconducting focusing quadrupoles

Prototype Cryogenic plant (compressors and pumps) for the superfluid helium ➢

LHC: some recent photos

Descente de la première SSS le 19 avril 2005

Transport dans le tunnel par véhicule à guidage optique

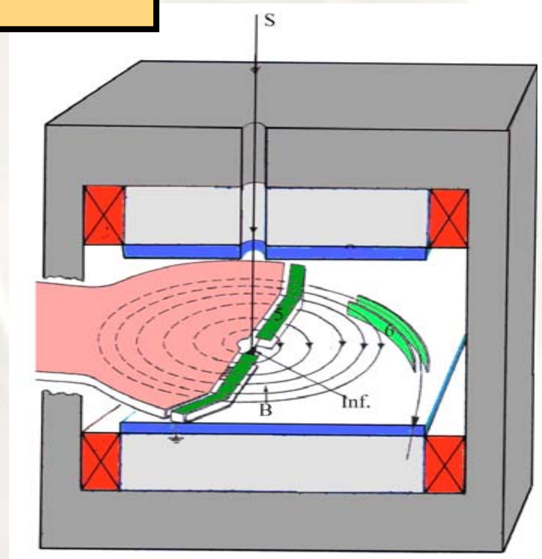
Arrivée sur la position d'installation

Installation du toroïde d'ATLAS

Properties of Cyclotrons (I)

- Cyclotrons ($\delta B_m = 0$) are intrinsically low-energy machines ($W_{kin} \ll W_{total}$), thus, from $2\,\delta W\; W = 2\, q\, c\, (\, q\, c\, B_m\, \rho\,)\; (\, r\, \delta B_m + B_m\, \delta\rho)$
- one obtains

$$\delta W_{kin} / W_{kin} = 2\, \delta\rho/\rho$$



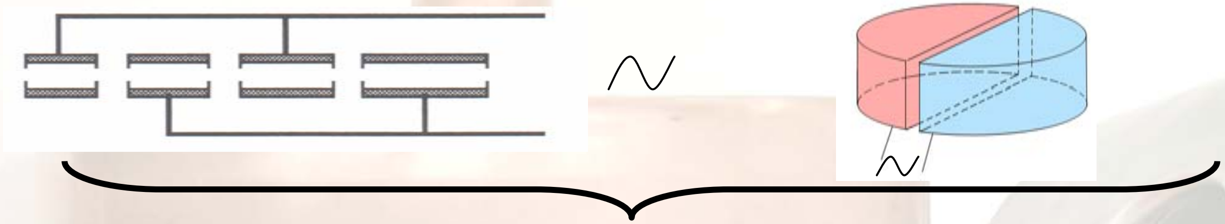
- which shows that the pitch of the spiral formed by the beam in the cyclotron is indeed small, just twice the ratio of the energy change
- a cyclotron typically has 1-4 accelerating cavities, with an energy gain of up to a few hundred keV
- thus the beam typically makes hundreds of turns in the accelerator, and the turn separation is rather small
- this actually confirms our initial assumptions of a "closed turn" with $|p| \approx$ constant for the derivation of the equations, but it also hints that efficient extraction of the beam is a major challenge
- With $W_{kin} \ll W_{total}$ one also derives the formulas where the energy is in MeV, and A the mass-number of the accelerated particle, e.g. A=1 for the proton. The factor K is often used to describe a cyclotron's characteristics

$$W_{kin}/A = 48\, (B_m\, \rho)^2\, (Q/A)$$

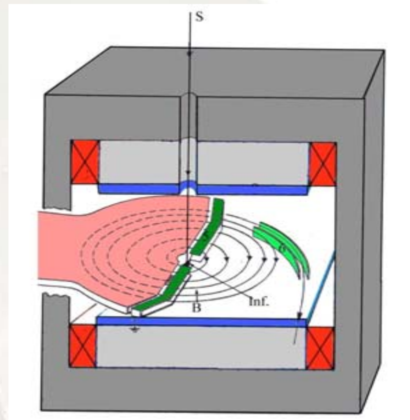
or

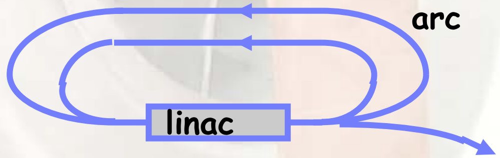
$$W_{kin}/A = K\, (Q/A)^2$$

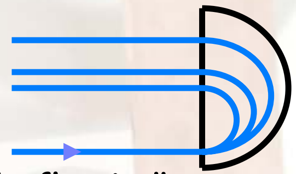
Properties of Cyclotrons (II)



- (Intrinsically), linacs and cyclotrons both are CW machines
- The classical "2 Dee" cyclotron can be imagined by analogy as a linac with 2 drift-tubes (hence two accelerating gaps), leaving the second gap, the beam being bend back into the first drift tube by the overlying magnetic field
- Note that there actually exist "recirculating linacs", where one actually does exactly that, e.g. the 6 GeV electron accelerator of the Jefferson Laboratory (USA) has 4 arcs, in smaller versions the 180° arc may be within the same magnet (microtron). Recirculating machines work with the condition that the velocity does stay constant (i.e. β = c)
- The frequency of revolution, the so-called cyclotron frequency has to be constant, so that the particle always "sees" the same RF phase, with ($W_{total} \approx W_0 = m_0c^2$) it can be expressed as



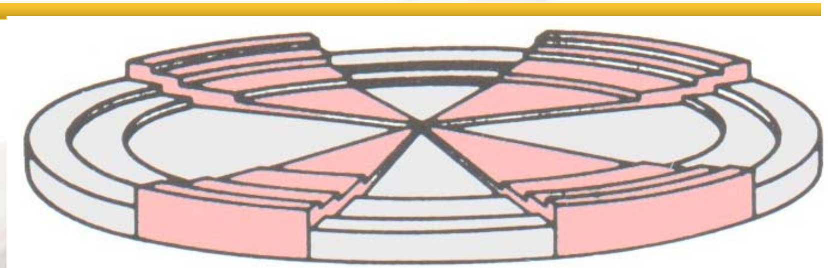




"reflecting" magnet (Microtron)

$$\nu = 1/T = v/2\pi\rho = vmc^2/2\pi\rho mc^2 = (c/2\pi\rho)\,(pc/W_{total})$$
$$= cqcB_m\rho/2\pi\rho m_0c^2 = qB_m/2\pi m_0$$

Properties of Cyclotrons (III)

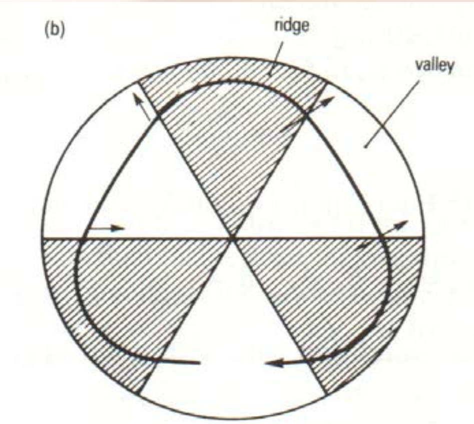


- the preceeding slide derived the expression for the cyclotron frequency ν

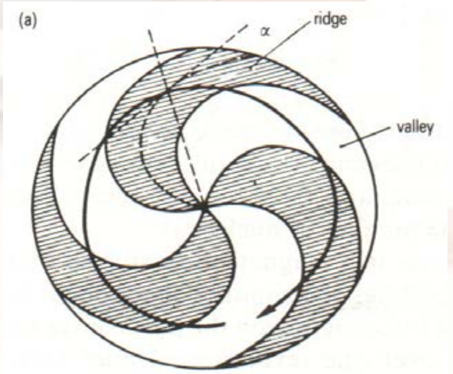
$$\boxed{\nu = qB_m / 2\pi m_0}$$

showing the link between mass, field and frequency, note, that this can be used for high-precision nuclear mass measurements

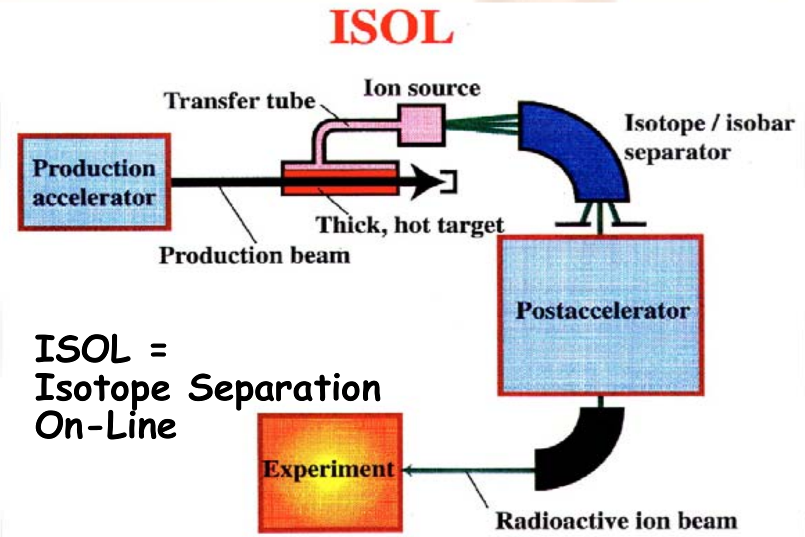
- but the formula, even more importantly, also suggests how to overcome the initial relativistic effects in a cyclotron (starting around 20 MeV for a proton): the relativistic mass increase with increasing $\beta = v/c$ of $m = \gamma \cdot m_0$, $\gamma = (1-\beta^2)^{-1/2}$ can be compensatedby correspondingly increasing the magnetic field in order to maintain the frequency ν constant, this can be done by shaping the poles (see figure) and adding "trim coils", such an accelerator is called an isochroneous cyclotron, varying ν, however, is technically challenging, and the corresponding accelerator, the synchrocyclotron, is necessarily a pulsed, weak current machine



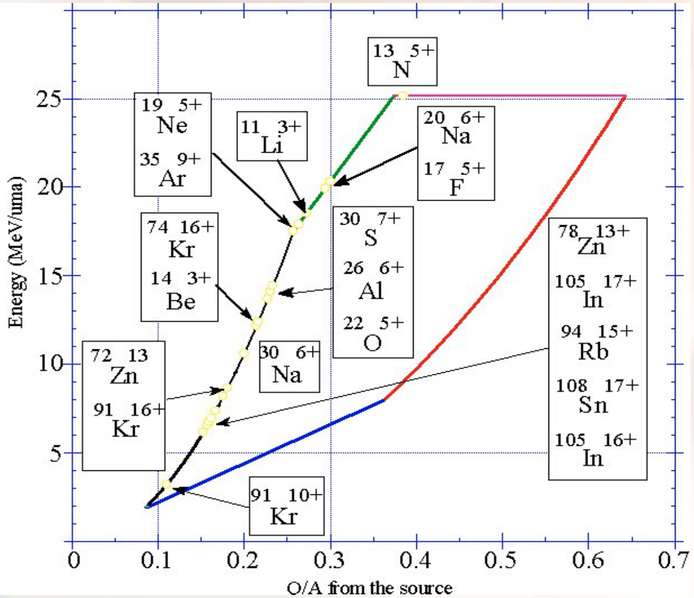
- unfortunately, a cyclotron can not have any direct focusing elements inside and that for flight paths which exceed kilometers
- The way to overcome partially the absence of vertical focusing, is to use alternate gradient focusing (see 2nd lecture), by passing in successively in sectors of strong and weak (or zero fields. A radially decreasing field has also been shown to work, but of course this is in contradiction to the relativistic effect correction



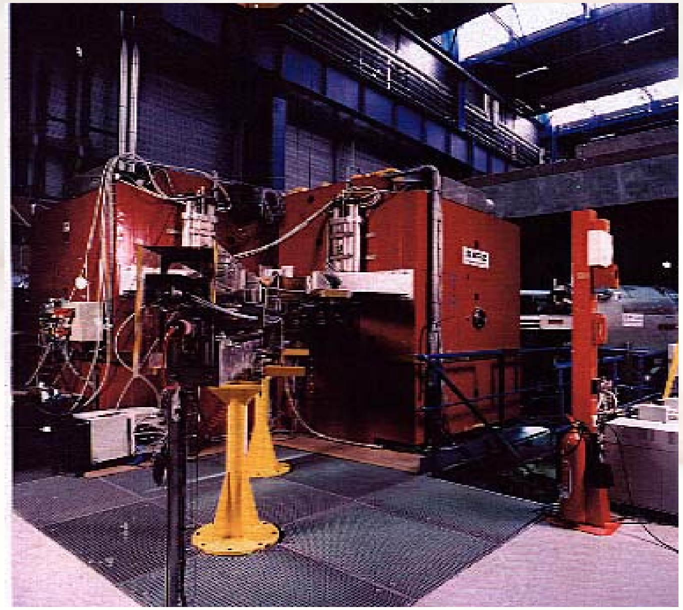
A Recent Cyclotron: SPIRAL @ GANIL



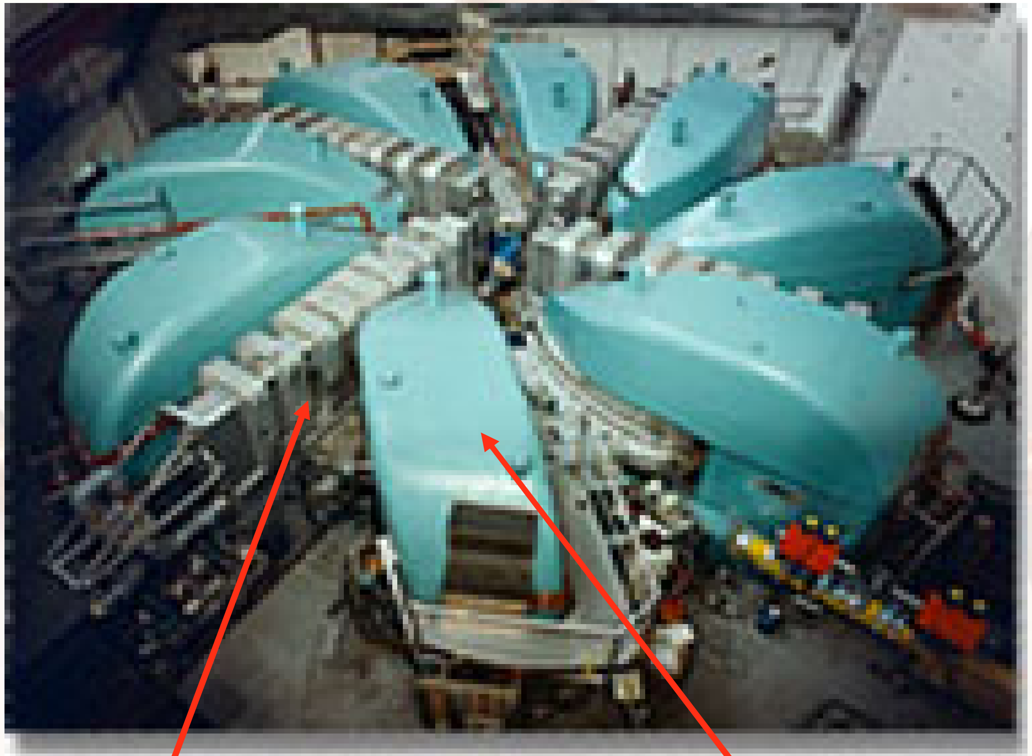
ISOL =
Isotope Separation
On-Line



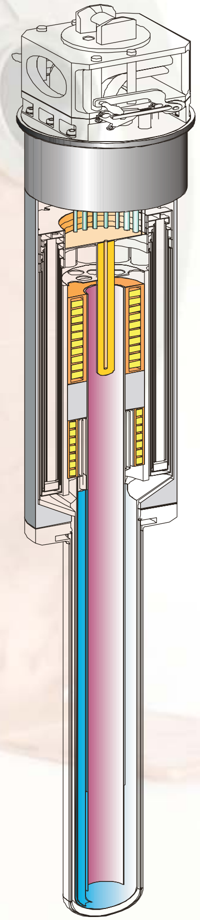
- the SPIRAL facility (collaboration: IN2P3 CEN-Bordeaux, CEA Bruyères, IN2P3 LPC-Caen, GANIL, IN2P3 IPN Orsay, CEA Saclay, LNS SATURNE), uses the GANIL facility, (coupled cyclotrons, K=380, 100 MeV/A) as "driver"
- from a target-ion source system radioactive ions are produced and extracted by the ISOL method (see left)
- the ions are the post-accelerated by the most recently built large (K=265) research cyclotron CIME (collaboration GANIL, IPN Orsay), see below right, its operational range is shown left
- transmission optimised (up to 50%), secondary beam intensities can reach up to 10^9 pps in a mass range up to A=100
- the SPIRAL facility has come into operation for physics since 2001



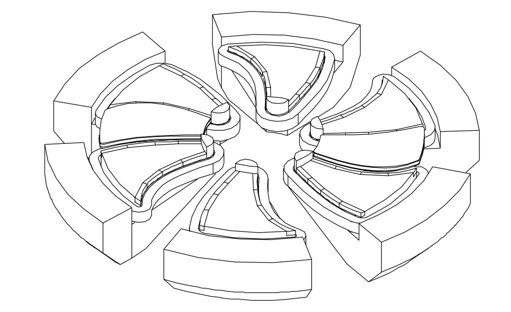
The PSI cyclotron facility



- The K=590 cyclotron of the PSI facility is a 8 separated sector machine with 4 accelerating cavities
- The injection energy of 70 MeV is provided by another cyclotron
- The accelerator is in operation since the 1970's, and has been very carefully optimised for this long period
- The exceptional experience gained at PSI allows now to approach an intensity of almost 2 mA
- These high current 590 MeV proton beams feed the SINQ spallation neutron source
- The SINQ solid metal target will be temporarily replaced by the protoypical (e.g. for an ADS) molten metal target MEGAPIE (see left)



Cyclotrons for ADS ?



lower half of the six sector magnets of the 350 MeV cyclotron proposed for the MYRRHA project by the accelerator building firm IBA

- cyclotrons more compact and "cheaper"
- cyclotrons are limited in max. energy
- cyclotrons, because of weak focusing are intrinsically limited to much lower beam intensities than linacs
- cyclotrons have much less potential for "ADS-class" operation than linacs, it is difficult to build a machine according to the principles of overdesign, redundancy, "spare-on-line" and maintainability
- PSI is today accelerating 1MW and makes important efforts to log, analyse and cure its beam trips
- Based on a PSI extrapolation feasibility of 4-5 MW (Calabretta), even 10 MW (Stammbach) at 1 GeV are claimed, the so-called "dream-machine", however critics have expressed concern that this is pushing beyond the limit, in particular since (for ADS) contradictory requirements need to be fulfilled (e.g. the large increase of energy gain per turn is opposite to increased reliability, the extraction losses pose a problem of maintainability, the compactness makes protoyping difficult….)
- Certain experts feel, that for reliability, electrostatic elements are to be avoided, but the solution of H^- extraction by stripping has to high losses according to experience from TRIUMF
- H_2^+ acceleration (followed by "stripping" = break-up into two protons) can be a so-lution (it doubles the external intensity) but, according to $W_{kin}/A = K\,(Q/A)^2$ the prize to pay is a 4 times larger accelerator
- Funneling of several cyclotrons poses the problem of the funnel, and is costly

DESIGN OF ACCELERATORS FOR ADS

Chapter 3

Acceleration of High Intensities: SCRF Cavities

- Energy gain and dissipated power
- Superconducting Cavities, Basics
- "Colds" vs. "Warm"
- SC Cavities, Technology, Fabrication & Tests
- ADS: the TWG
- From TWG to the 5PCRD PDS-XADS

Energy gain and dissipated power

- To accelerate particles efficiently, very high electric field is required

$$\Delta E = \Delta T = \int \vec{F}_{Lor} \bullet d\vec{s} = q \cdot \int \vec{E} \bullet \vec{v} \cdot dt$$

- In any structure (cavity) holding an electromagnetic field, both dissipated power and stored energy scale quadratically with the fields
- The efficiency of a cavity depends from:
  - Its quality factor, Q
    driven by the surface resistance, R_s

    $$Q = \frac{\omega U}{P_{diss}}$$

    - U is the energy stored in the cavity
    - P_{diss} is the power dissipated on its surface
  - Its shunt impedance, r
    function of the cavity geometry
    and of the surface resistance, R_s

    $$r = \frac{(\Delta V)^2}{P_{diss}}$$

    - ΔV is the voltage seen by the beam

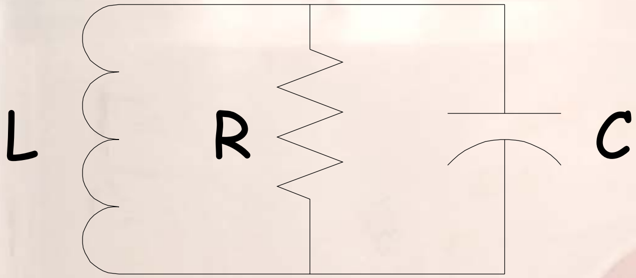
    $$\frac{r}{Q} = \frac{(\Delta V)^2}{\omega U}$$

    "r over Q" is purely a geometrical factor
- For efficient acceleration Q, r and r/Q must all be as high as possible

→
- Good material for maximum Q and r (that is minimum P_{diss})
- Good design for maximum r/Q

Cavity lumped circuit model and R_S

- A cavity at the fundamental mode has an equivalent resonant lumped circuit



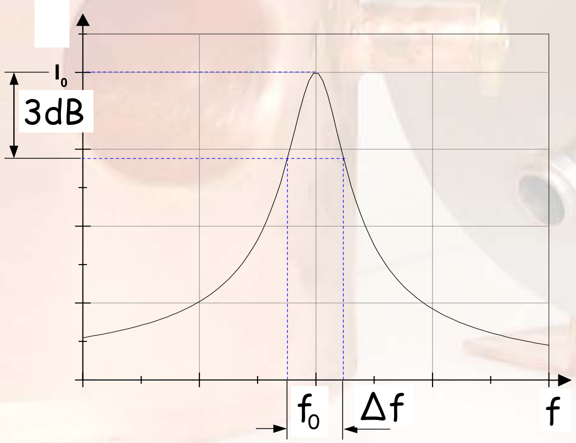
$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad Q = \omega_0 RC$$

$$\omega_0 = 2\pi f_0$$

$$P_{diss} = \frac{V^2}{2R}$$

- Q determines the frequency band Δf

$$\Delta f = \frac{f_0}{Q}$$



- R proportional to Q determines P_{diss}

$$R \propto Q$$

- R depends inversely from the cavity R_s through a geometrical factor

$$R \propto \frac{1}{R_s}$$

- In practice, for a given geometry and a given accelerating field the surface resistance R_s plays the crucial role of determining the dissipated power, that is the power required to sustain the field

$$\boxed{R_S}$$

Superconducting cavities

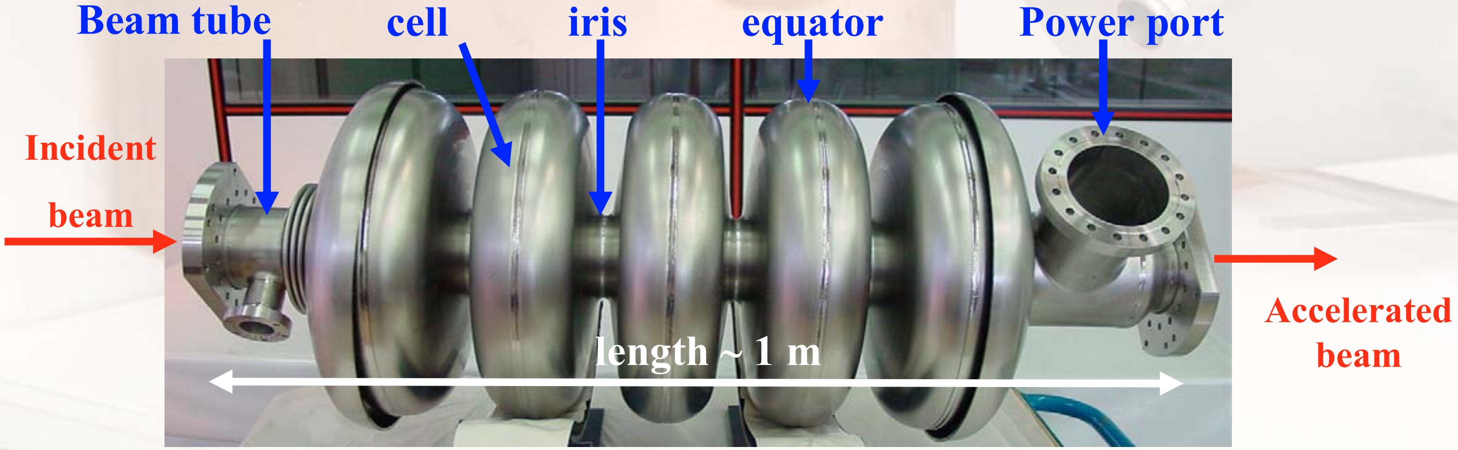
- « **CAVITY** » = Electromagnetic resonant cavity

  ⇒ RF fields (electric and magnetic)

  ⇒ To accelerate charged particles

- « **SUPERCONDUCTING** » : very low operating temperature (Liquid Helium)

  ⇒ Superconducting state of the matter



Superconducting cavity (IPN Orsay) – 5 cells, 700 MHz, β=0,65

Frequency f

50 MHz to 3 GHz

Size

Proportional to 1/f

Temperature T

1,5 K to 4,5 K

Accelerated particle velocity

$\beta = v/c$ from 0,01 to 1

0 K ≈ - 273,15 °C

$c \approx 2{,}998 \cdot 10^8$ m/s

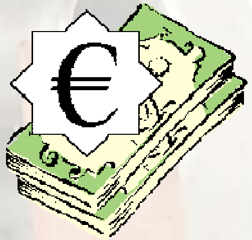
Why superconducting cavities ?

<u>Intrinsic advantage of cold cavities</u>

Almost no losses on the cavity wall (thanks to superconductivity)

⇒ ~100% of the injected RF power goes to the beam : very high efficiency !!!

- **<u>Operating cost gain</u>** as compared to warm structures (which dissipate ~10^5 times higher)



- **Possibility to accelerate CW beams or beams with a high duty cycle (> 1 %) with high accelerating gradients** (impossible with warm structures)

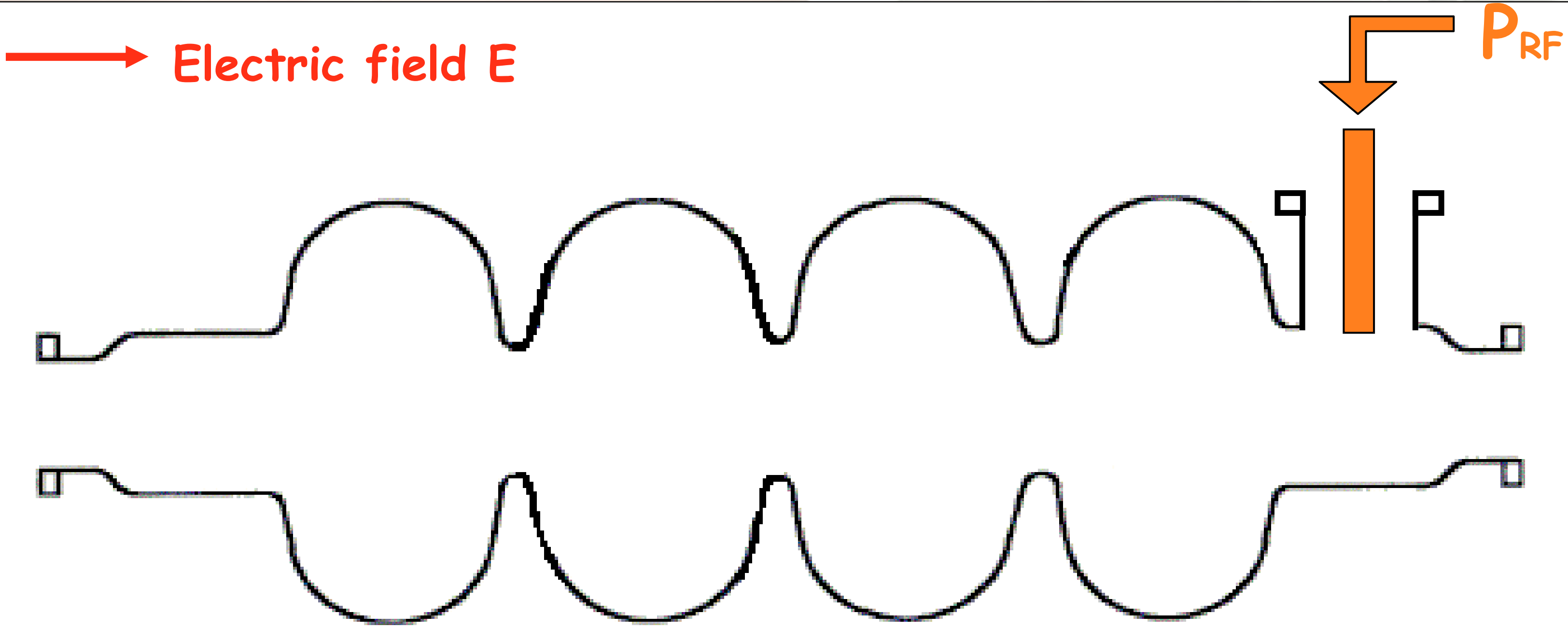
- Possibility to relax the constraints on the cavity RF design: choosing larger beam port aperture is possible ⇒ reduction of the activation hazard = <u>security gain</u>

- **High potential for reliability and flexibility**

- **Main drawback** : need to be operated at cryogenic temperature

SC Cavity : basics and recall of lecture 2 (I)

(1) An electric field is created on the beam axis , and is available to accelerate charged particles



This E field is time and space dependant

With f the cavity frequency, T = 1 / f

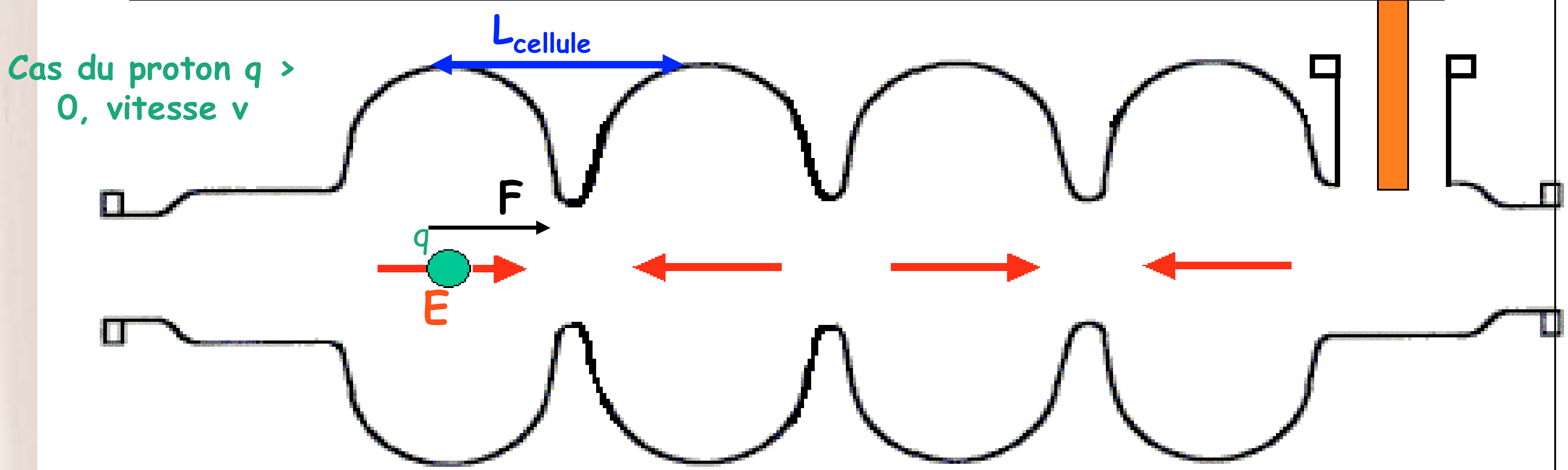
Ex : f = 700 MHz → T = 1,43 ns

SC Cavity : basics and recall of lecture 2 (II)

(2) **The charged particle enter the : for an efficient acceleration, the particle should be synchronized with the RF wave**

→ The particle should arrive at the right time in the cell

The cell length should be adjusted to the particle velocity

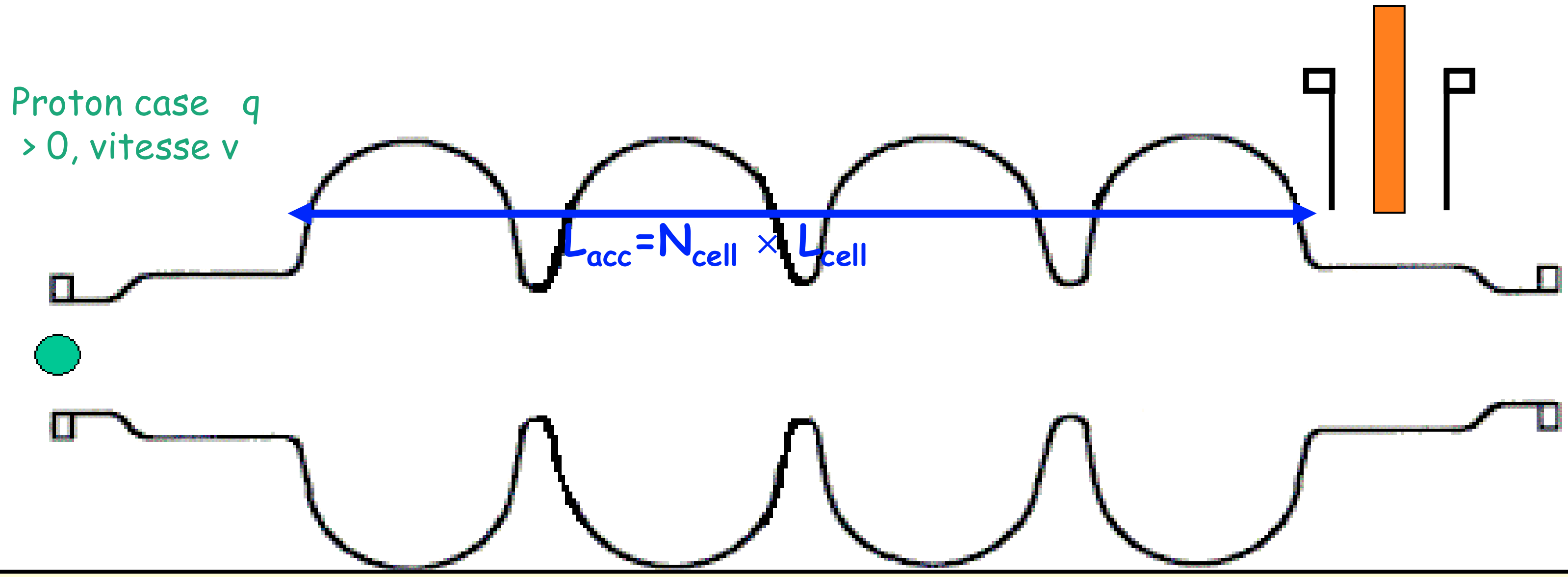


Synchronism condition :

The time for the particle to cross one cell should be $T_{RF}/2$ ⇔ $\frac{L_{cell}}{v} = \frac{1}{2f}$

The cell length should verify: $\boxed{L_{cell} = \frac{v}{2f} = \frac{\beta c}{2f}}$, $L_{cell} = \frac{\beta\lambda}{2}$

SC Cavity : basics and recall of lecture 2 (III)



Energy gain :

$$\Delta U = q \times \int_{t_{entrée}}^{t_{sortie}} \vec{E}.\vec{v}\, dt \quad \text{or} \qquad \boxed{\Delta U = q \times E_{acc} \times L_{acc} \times \cos(\varphi)}$$

E_{acc}: accelerating field of the cavity (for a given particle velocity)

L_{acc}: cavity accelerating length

φ : particule phase with respect to the RF wave

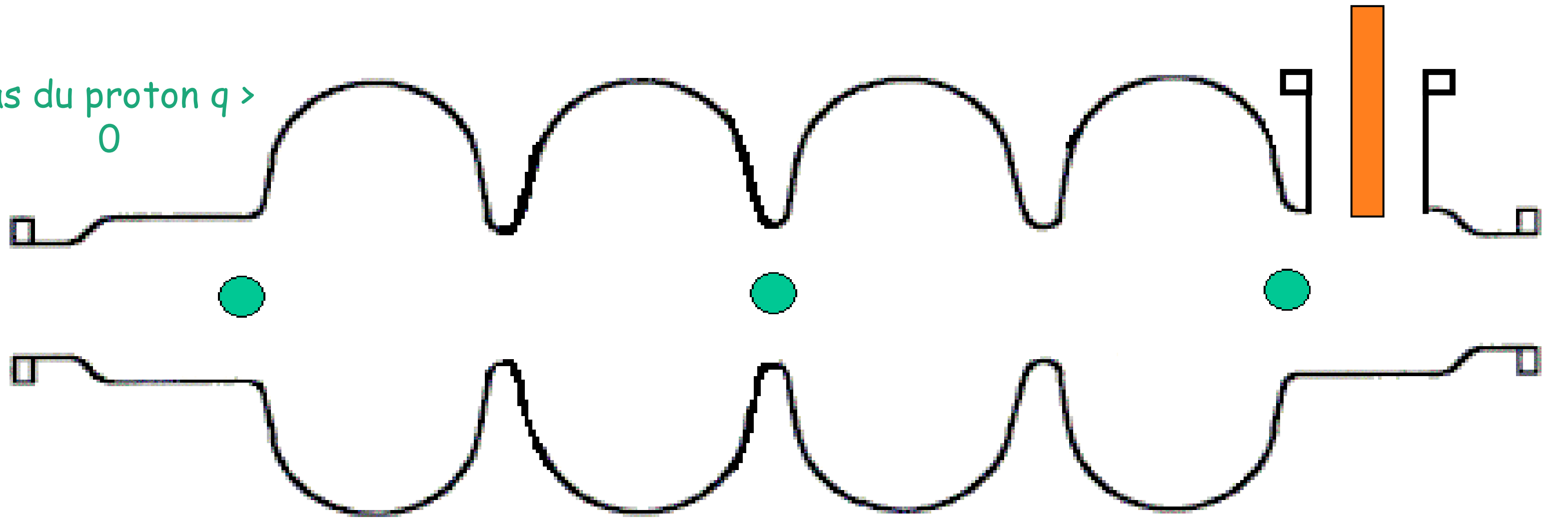
Ex : f = 700MHz ; 5-cell proton cavity β = 0,65 (L_{acc}=5×14cm); E_{acc}= 10MV/m ; φ = 0°

*⇒ Energy gain : ΔU = 1eV × 10MV/m × 0,7m × 1 = **7 MeV***

SC Cavity : basics and recall of lecture 2 (IV)

(3) Beam acceleration : particles should be bunched and synchronized with the electromagnetic wave

Cas du proton q > 0



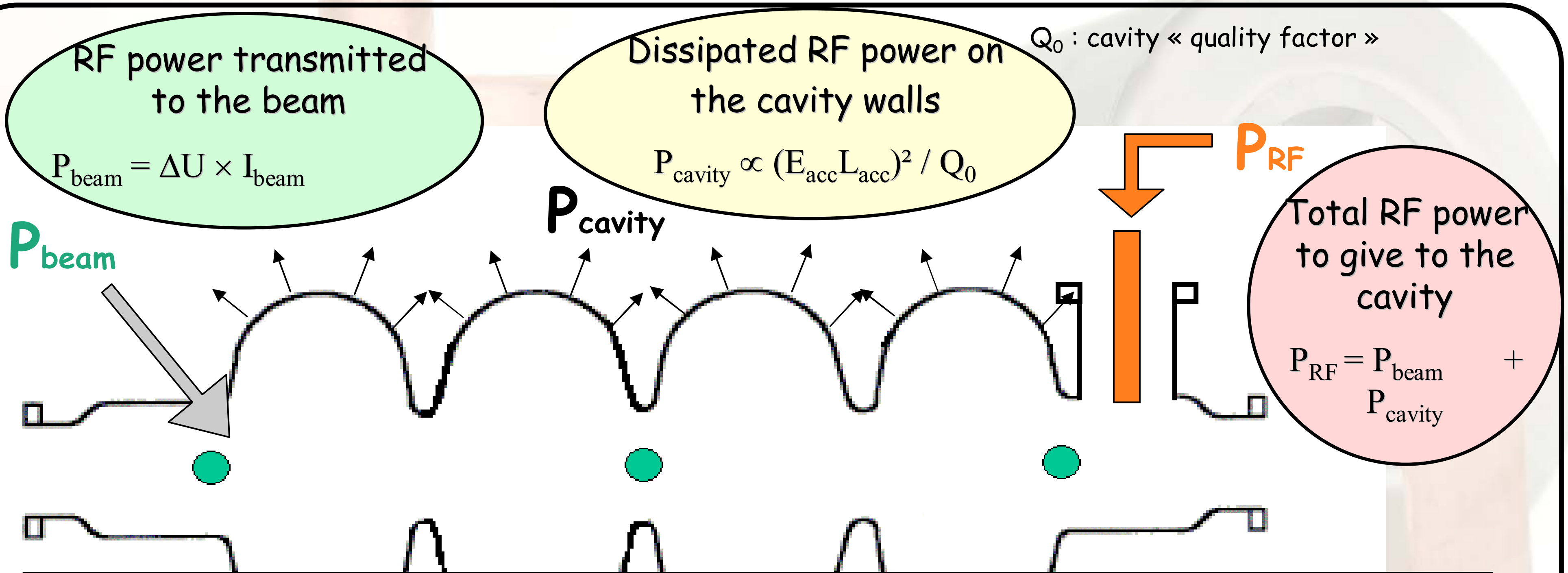
$T_{beam} = n\ T_{RF}$ (n=1,2,3…)

« the cavity resonant frequency should be a multiple of the beam frequency that it wants to accelerate»

Ex: if f_{beam}=350 MHz (T_{beam}=2,86ns), then the cavity should resonate at :

f = 350 MHz (T_{RF}=2,86ns), or f = 700 MHz (T_{RF}=1,43ns), or f = 1050 MHz (T_{RF}=0,95ns), etc.

"Cold" vs. "Warm": the winner takes it all (1)



<u>Order of magnitude</u> *(700 MHz cavity - β = 0,65 - 5 cells- 10MV/m - φ=-30° - protons beam 10 mA)*

SC cavity (Q_0 ~ 10^{10}) : P_{beam} = 6 MeV × 10 mA = **60 kW**

P_{cavity} ≈ **16 W**

"Warm" cavity (Q_0 ~ 3.10^4) : P_{beam} = 60 kW also

P_{cavity} ≈ **5,5 MW !!!** ← *not possible in CW !*

"Cold" vs. "Warm": the winner takes it all (II)

Comparison between a "warm" and "cold" solution for a high intensity proton linac

Cavité 700 MHz β=0,65 5 cellules (protons 10mA)	Cavité niobium (2K)	Cavité Cuivre (300K)
Surface resistance R_S *(ideal)*	20 nΩ *(3,2 nΩ)*	7 mΩ
Quality factor Q_0 *(ideal)*	10^{10} *(6.10^{10})*	3.10^4
E_{acc} *(theoretical)*	10 MV/m *(44 MV/m)*	2 MV/m
Beam power P_{beam}	60 kW	12 kW
Dissipated power / cavity P_{cav}	16 W @ 2K	218 kW @ 300K
RF power / cavity $P_{RF} = P_{beam} + P_{cav}$	60 kW	230 kW
Power taken to the grid P_{AC}	125 kW	400 kW
Accelerator efficiency P_{beam} / P_{AC}	48 %	3 %
Number of cavity to gain 100 MeV	17 (about 30m)	85 (about 80m)

SC Cavities: Technological Considerations

Material choice → **niobium** = compromise between :

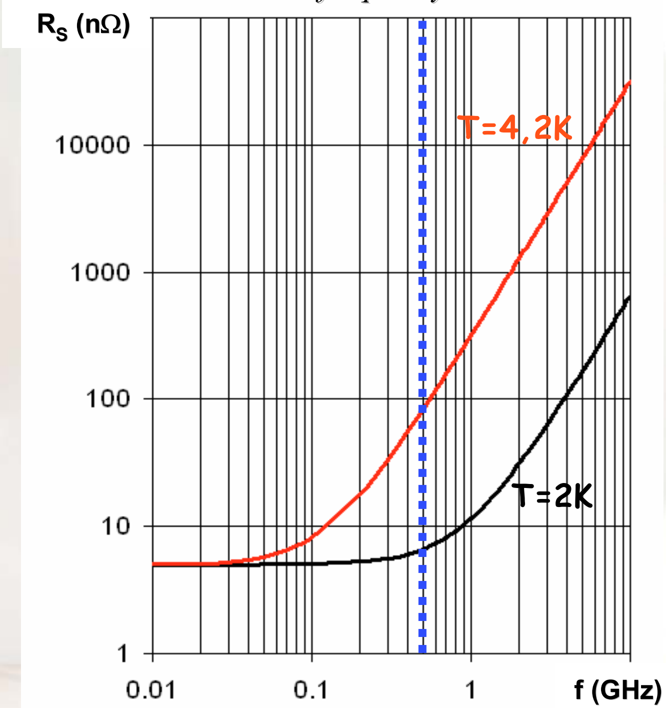
- High Tc and Bc
- Low surface resistance (in order to minimize the losses)
- Quite good mechanical (easy to shape) and thermal properties

Operating temperature → compromise between :

- Low surface resistance (means T not to high)
- Cooling system not too expensive (means T not too low)

Conclusion : $\begin{cases} \text{if f < 500 MHz} \rightarrow \text{T} \sim 4{,}2\text{ K (Liquid Helium)} \\ \text{if f > 500 MHz} \rightarrow \text{T} \sim 2\text{ K (Superfluid Helium)} \end{cases}$

Surface resistance as a function of frequency



Niobium characteristics

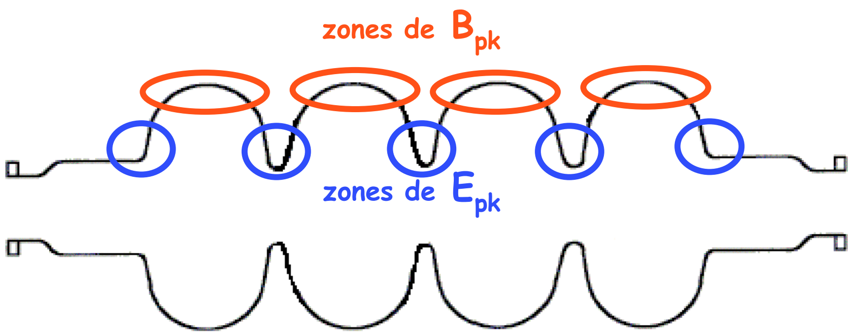
$$\begin{cases} T_c = 9{,}2\text{ K} \\ R_S(\Omega) \approx 2\times10^{-4}\dfrac{1}{T}\left(\dfrac{f(\text{GHz})}{1{,}5}\right)^2 e^{-17{,}67/T} + R_{res} \end{cases}$$

SC Cavities: Limits

→ **What achievable accelerating field ?**

When creating E_{acc} inside the cavity, surface electromagnetic fields are also created, with maximum values refered as B_{pk} et E_{pk}

In order to stay in the superconducting state, the niobium should not see a field $\mathbf{B_{pk} < Bc_{RF}}$



The ratio B_{pk}/E_{acc} (and also E_{pk}/E_{acc}) only depends on the cavity geometrical shape

For elliptical cavities β = 1 , we have

$B_{pk}/E_{acc} \approx$ 4 mT / (MV/m)

⇒ @ T = 2 K, $\mathbf{E_{accMAX}}$ = 220 mT / 4 = **55 MV/m**

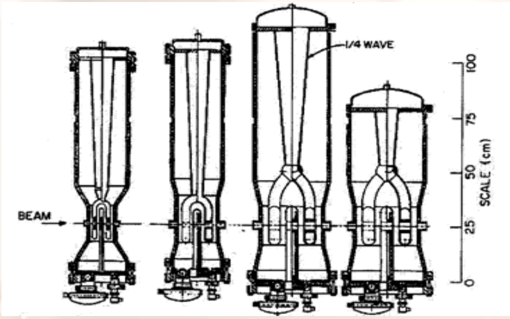
This theoretical maximum Eacc varies with the cavity β:

- cavity β = 0.65, $B_{pk}/E_{acc} \approx$ 5 mT/(MV/m) i.e. $\mathbf{E_{accMAX}}$ = **44 MV/m** @ 2K

- cavity β = 0.5, $B_{pk}/E_{acc} \approx$ 6 mT/(MV/m) i.e. $\mathbf{E_{accMAX}}$ = **37 MV/m** @ 2K

Various SC cavities for different particle velocity

β= 0,01 β= 0,1 β= 1



Structures inter-digitales (ATLAS, Argonne)

48 et 72 MHz - β = 0,009 à 0,037

Résonateurs quart d'onde (ALPI, Legnaro)

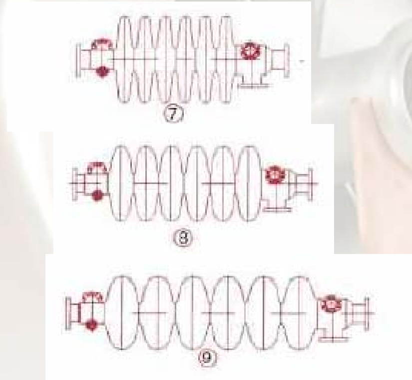
80 à 352 MHz - β = 0,047 à 0,25

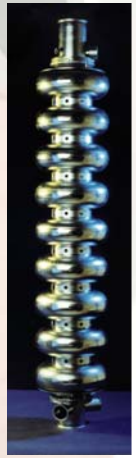
Cavité ré-entrante (Legnaro)

352 MHz - β ≥ 0,1

Cavités elliptiques

350 MHz à 3 GHz - β = 0,47 à 1



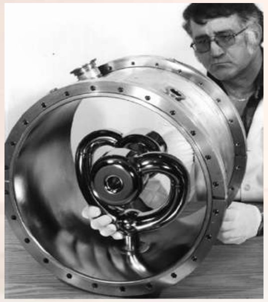


Cavité TTF

1,3 GHz - β = 1

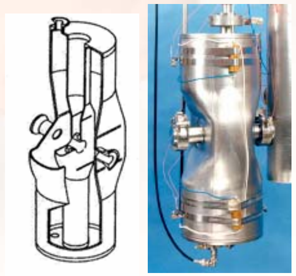
RFQs supra (Legnaro)

80 MHz - β = 0,009 à 0,035



Résonateurs split-ring (ATLAS, Argonne)

97 et 145 MHz - β = 0,06 à 0,16



Résonateur demi-onde (Argonne)

355 MHz - β = 0,12

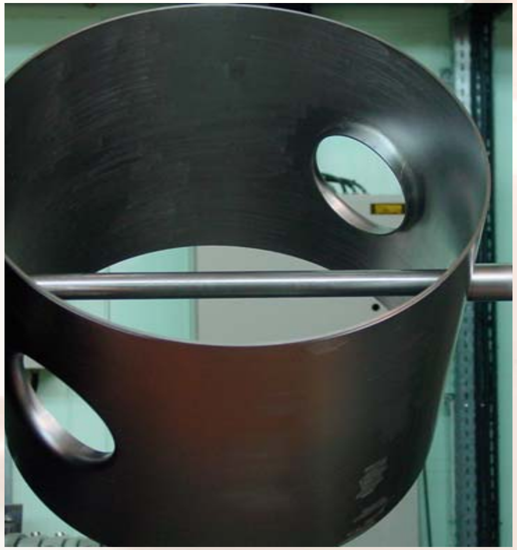
Cavités spoke (CNRS Orsay)

352 MHz - β = 0,15 et 0,35

Cavité APT (Los Alamos)

700 MHz - β = 0,64

SC cavity : fabrication

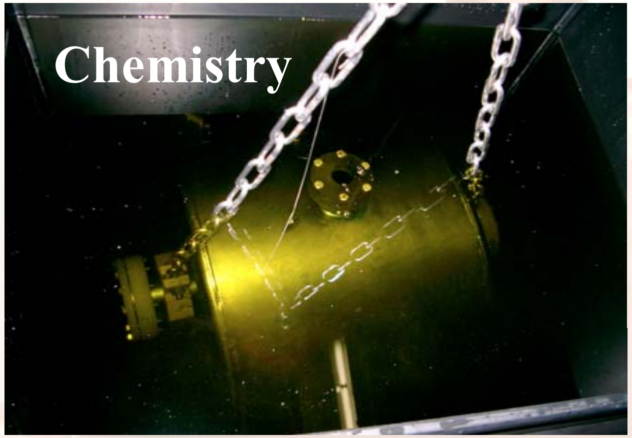


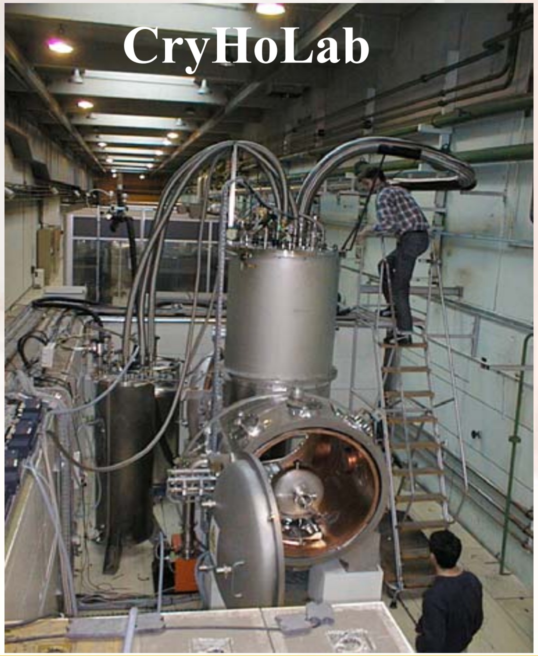
Niobium sheets 3 mm thick
Welding by electron beams

Spoke cavity

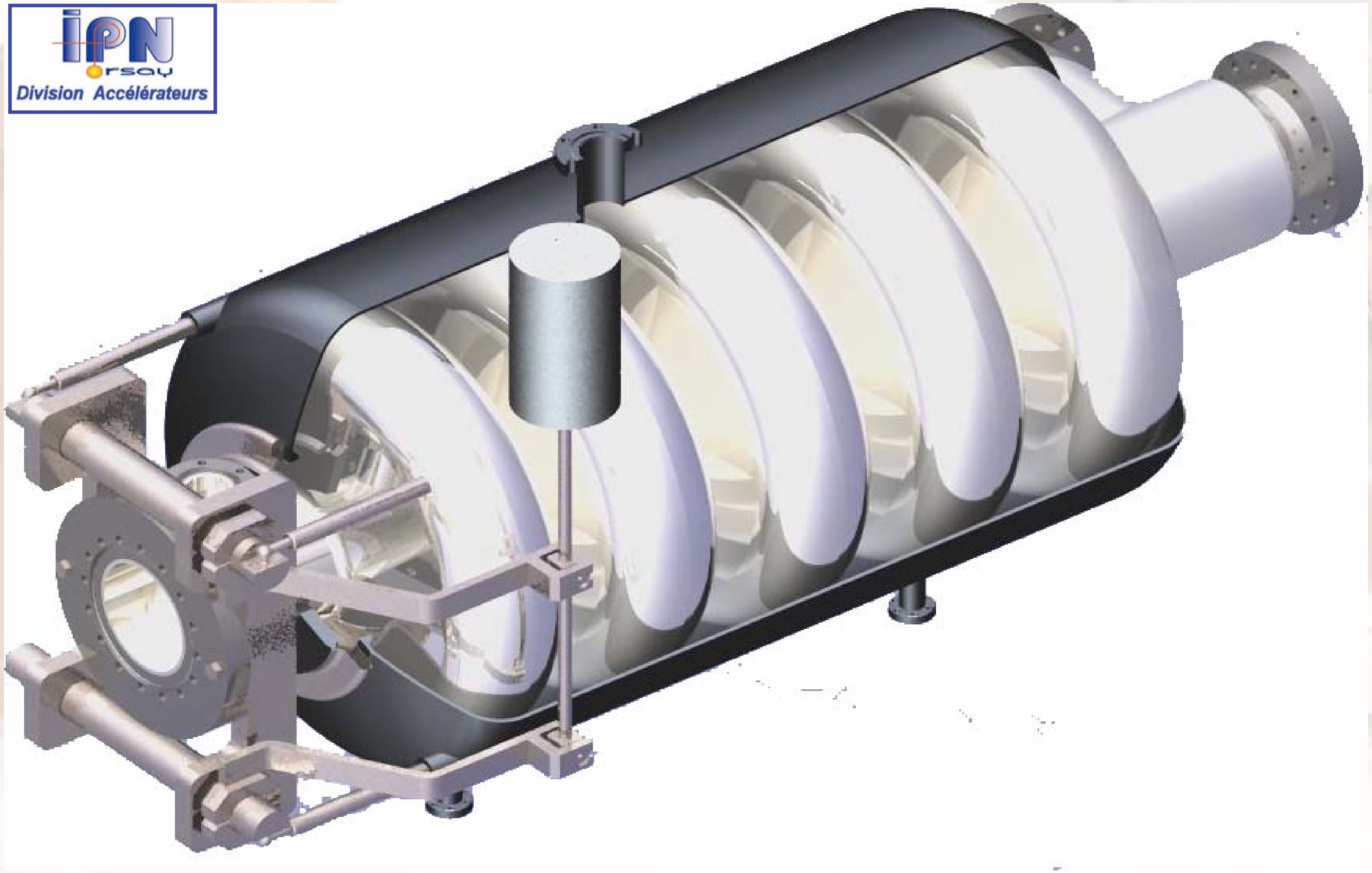
$\beta = 0.35$
$f = 352.2$ MHz

SC cavity technology: preparation and test

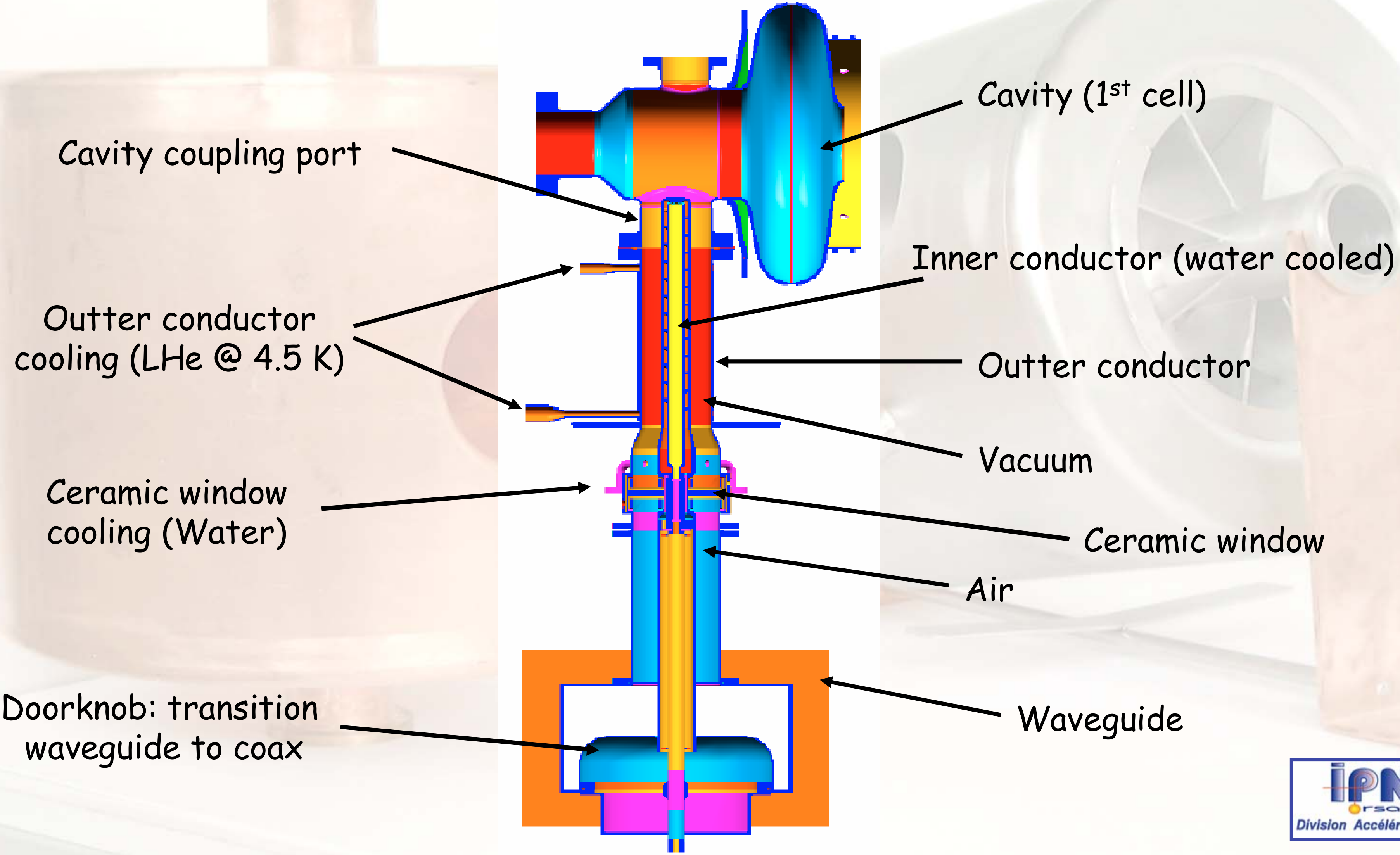




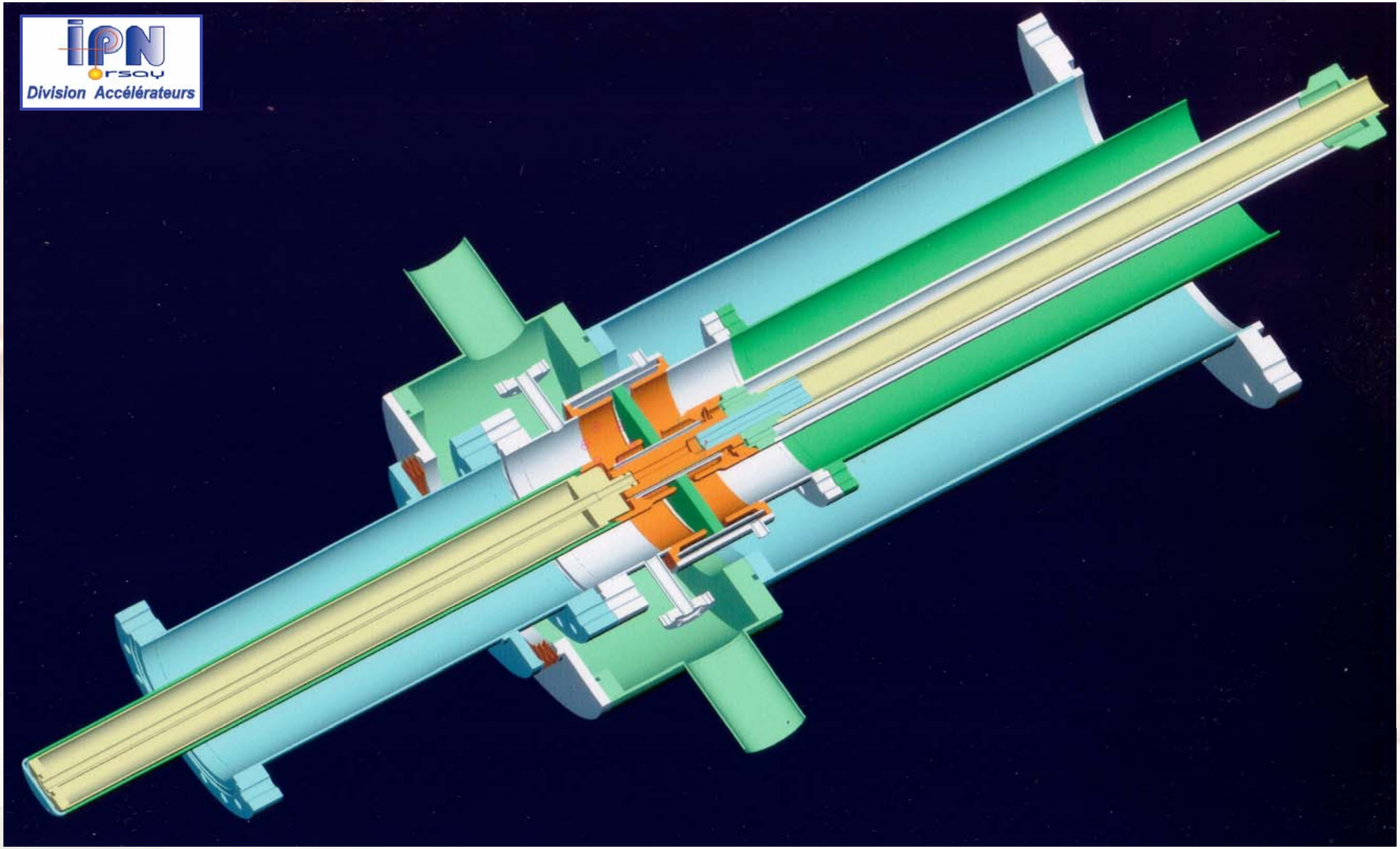
SC Cavity : cold tuning system



Power couplers (I)

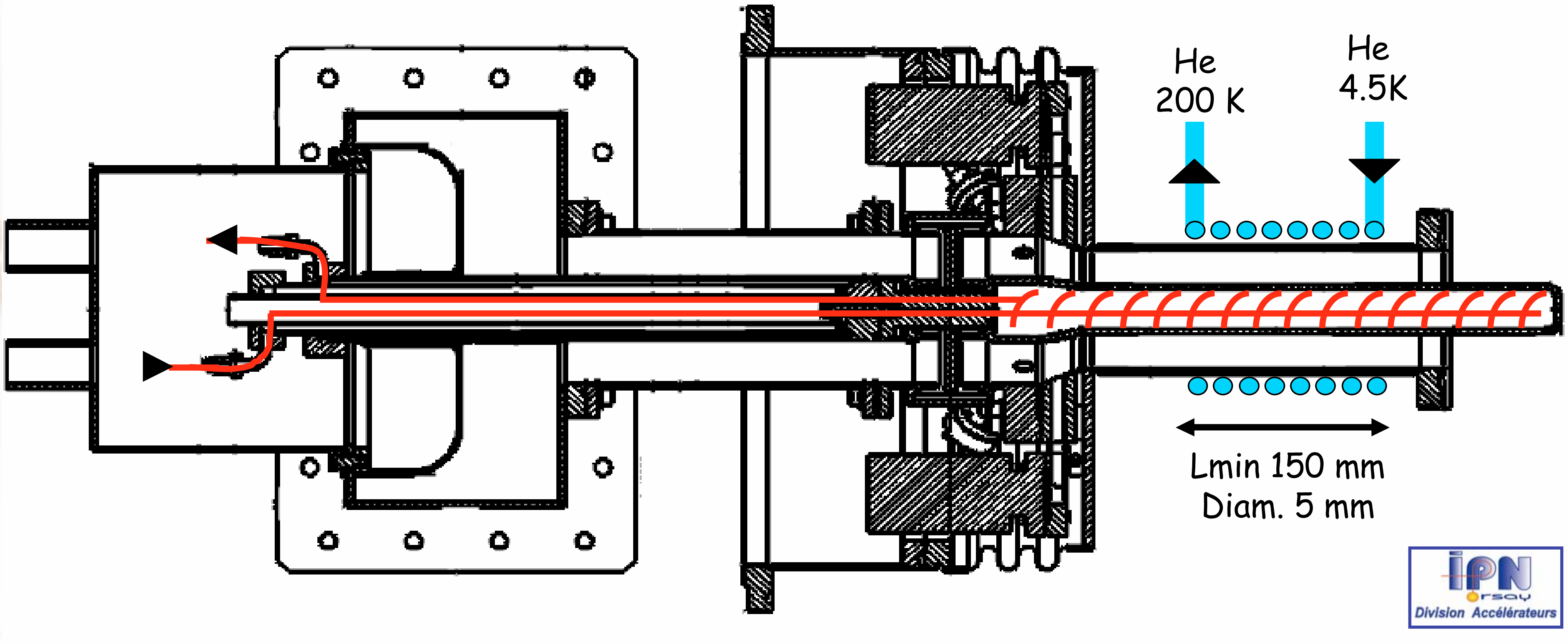


Power couplers (II)



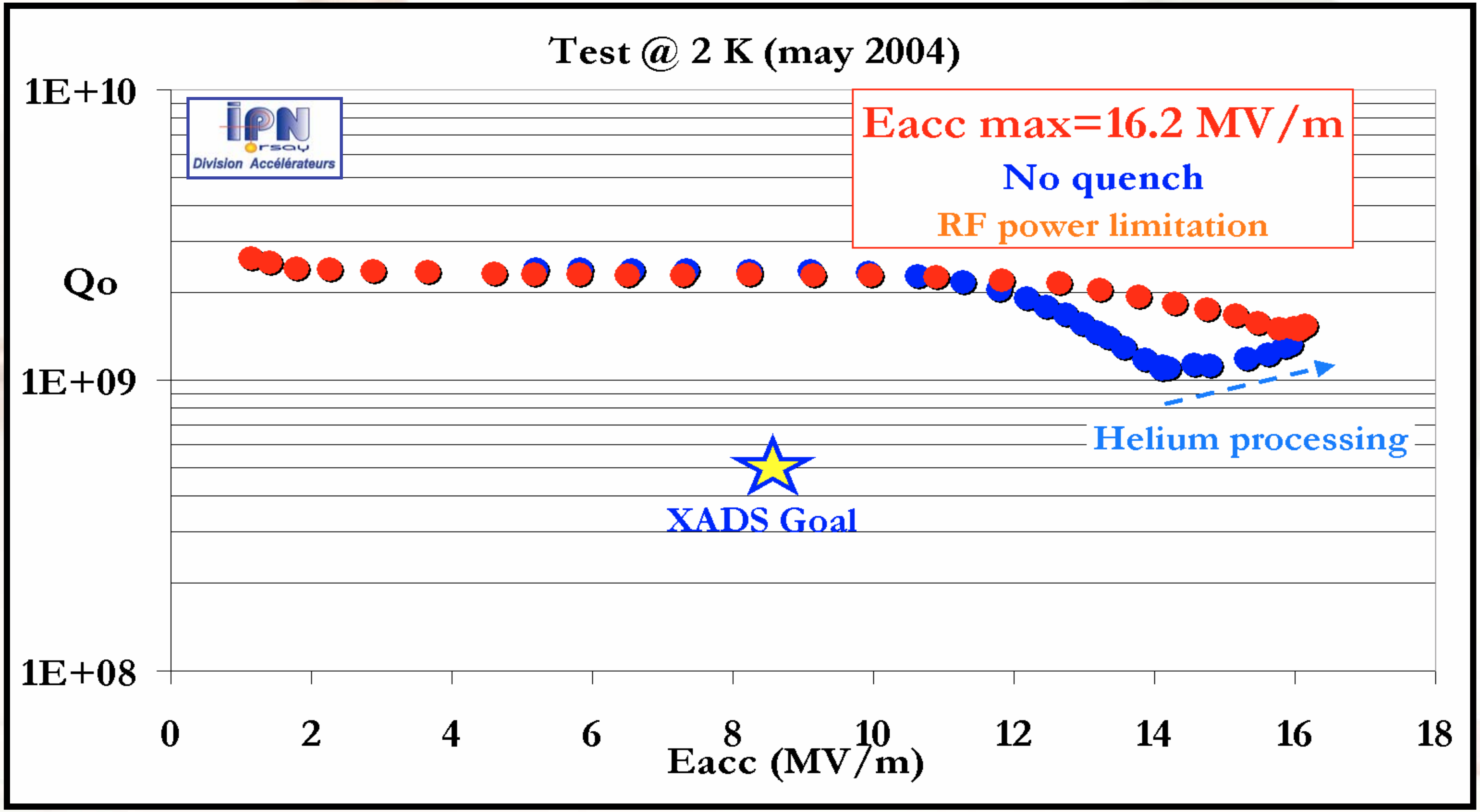
Power couplers (III)

- **Outer conductor:** Helium cooling



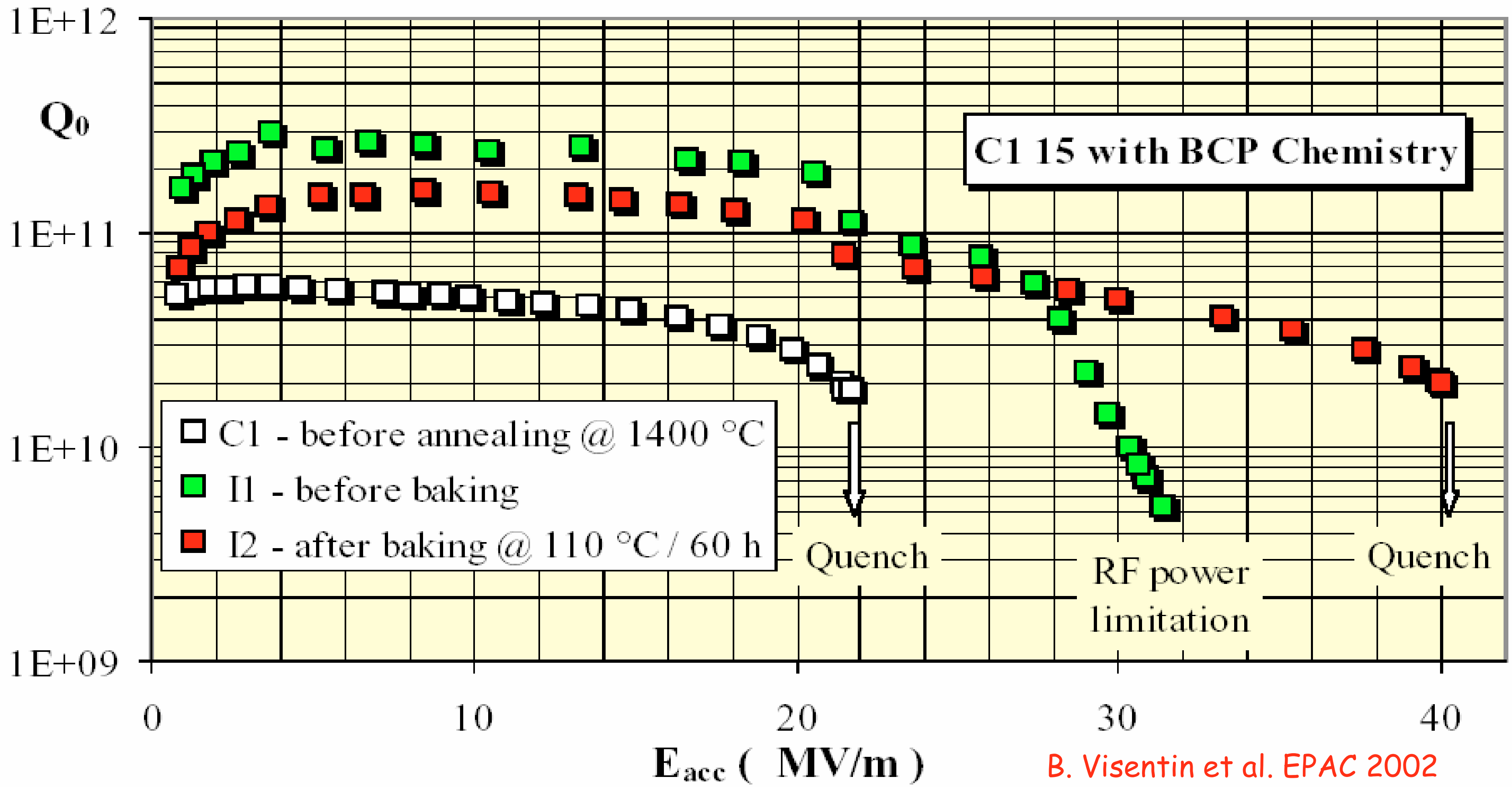
- **Inner conductor:** Water cooling

One example : Performances of a spoke cavity



Eacc = 16.2 MV/m means Epeak=49.5 MV/m & Bpeak=134 mT

2nd example : Performances of TESLA cavity



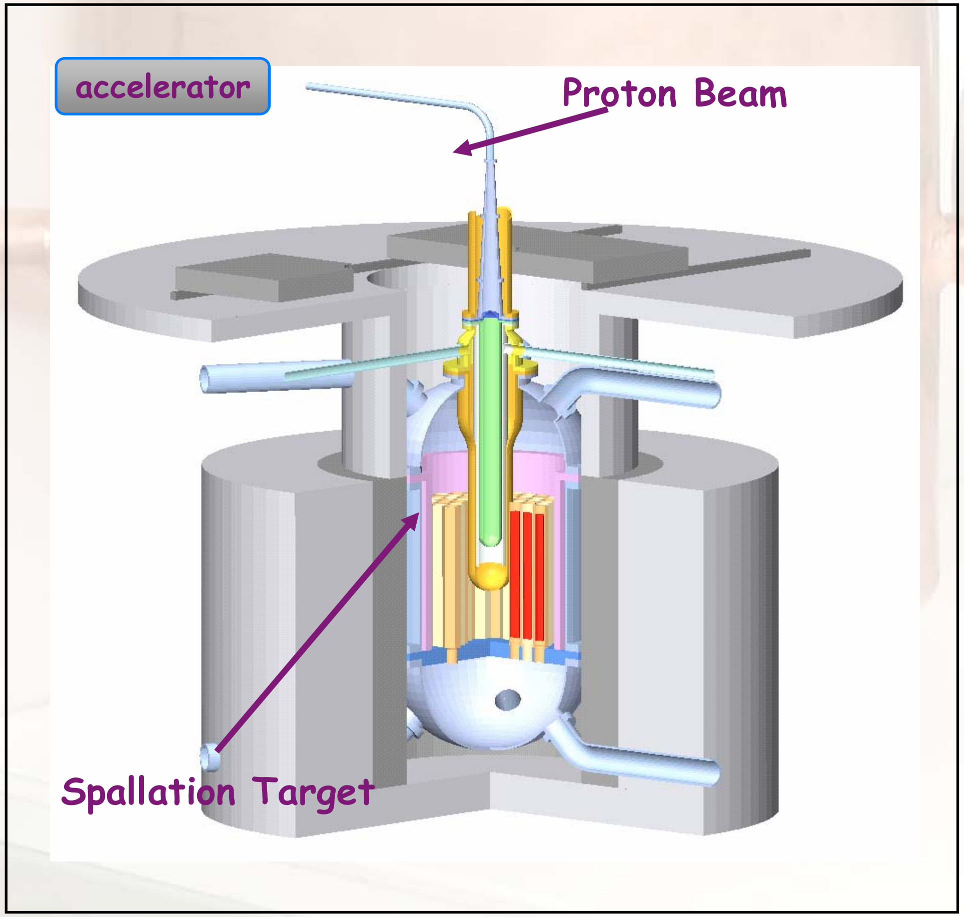
B. Visentin et al. EPAC 2002

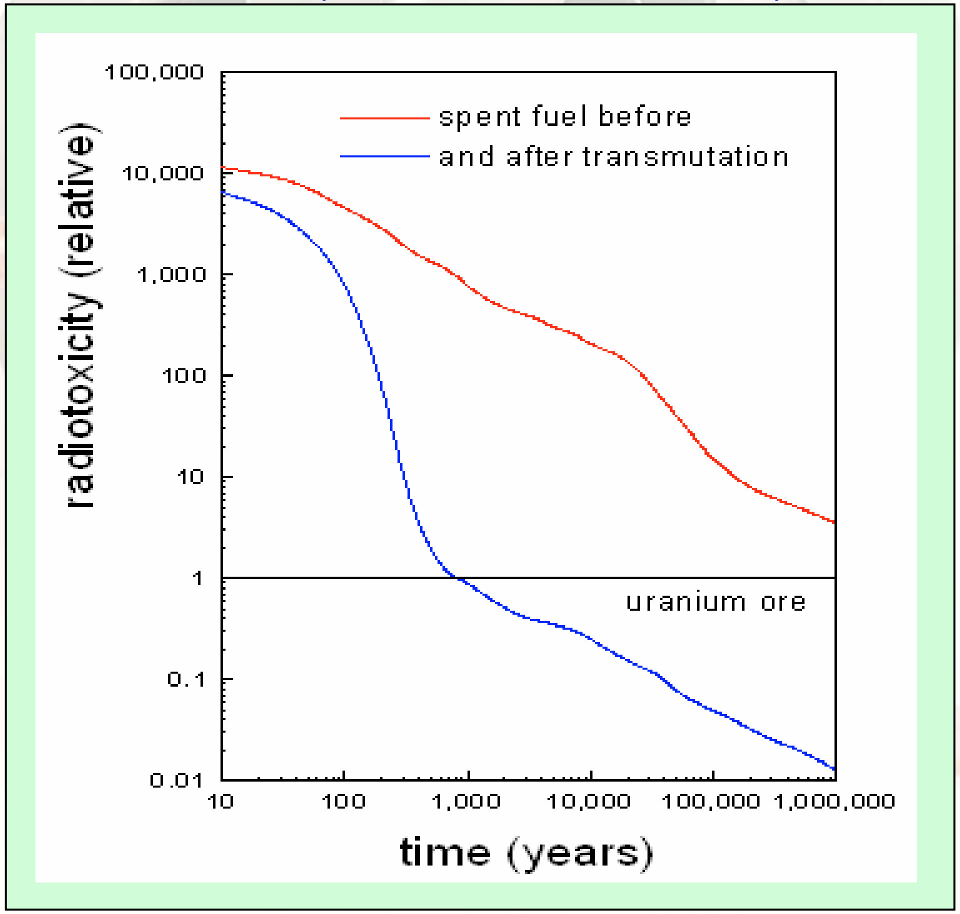
ADS: Accelerator Driven (subcritical) System for transmutation of nuclear waste

Both critical reactors and sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems.

Critical reactors, however, loaded with fuel containing large amounts of MA pose safety problems caused by unfavourable reactivity coefficients and small delayed neutron fraction.

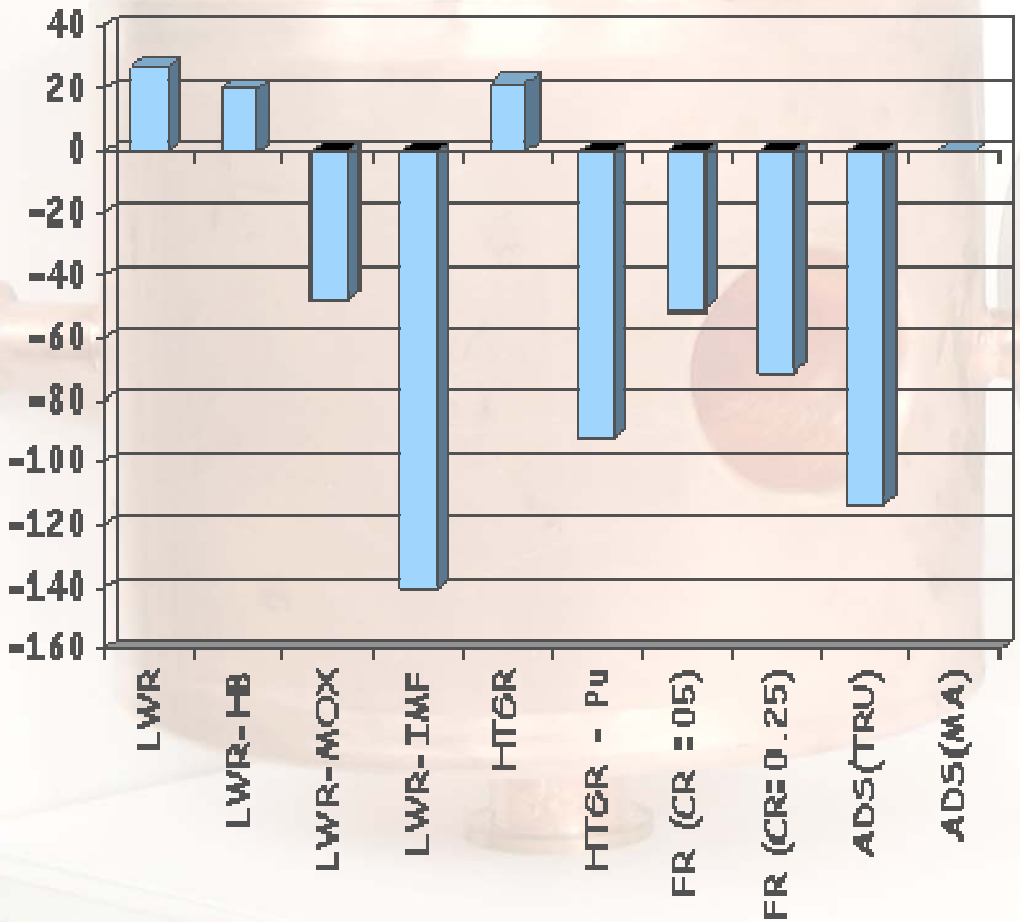
ADS operates flexible and safe at high transmutation rate (sub-criticality not virtue but necessity!)



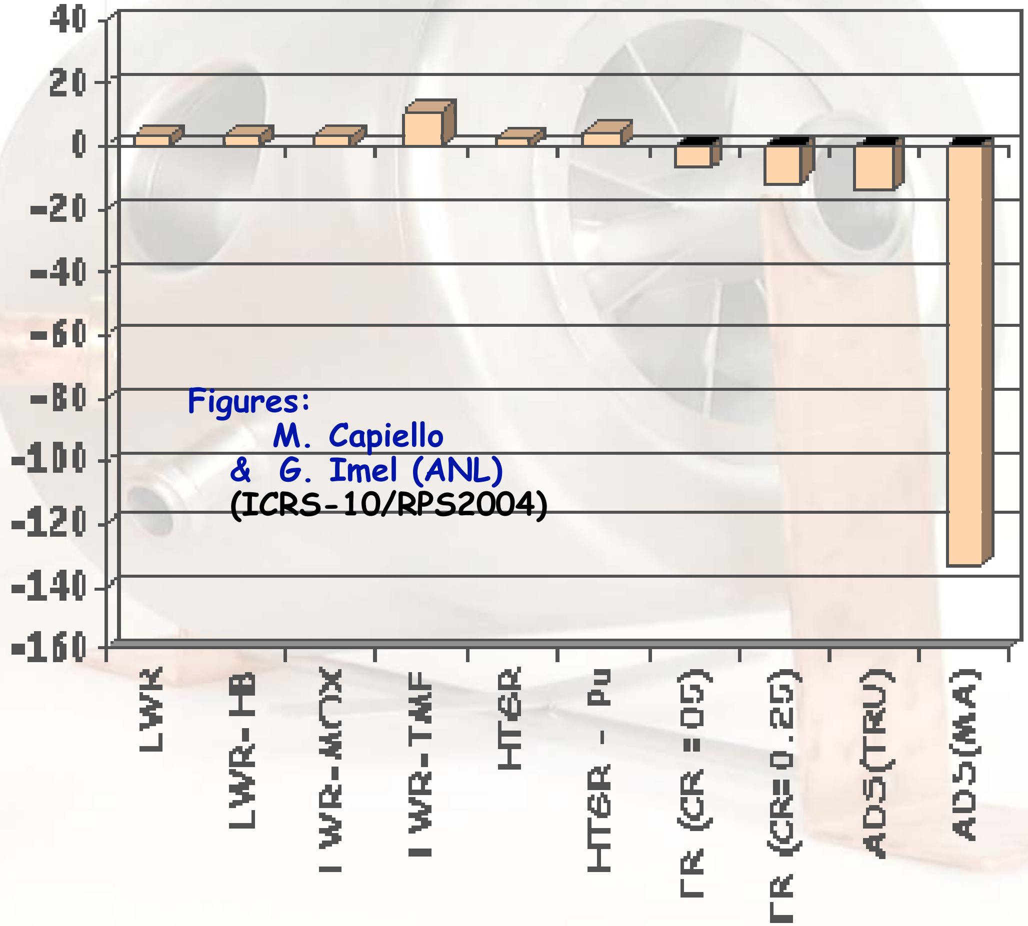


Burning (Breeding) Efficiency of different reactor types

- **The ADS is most efficient at Minor Actinide Transmutation**

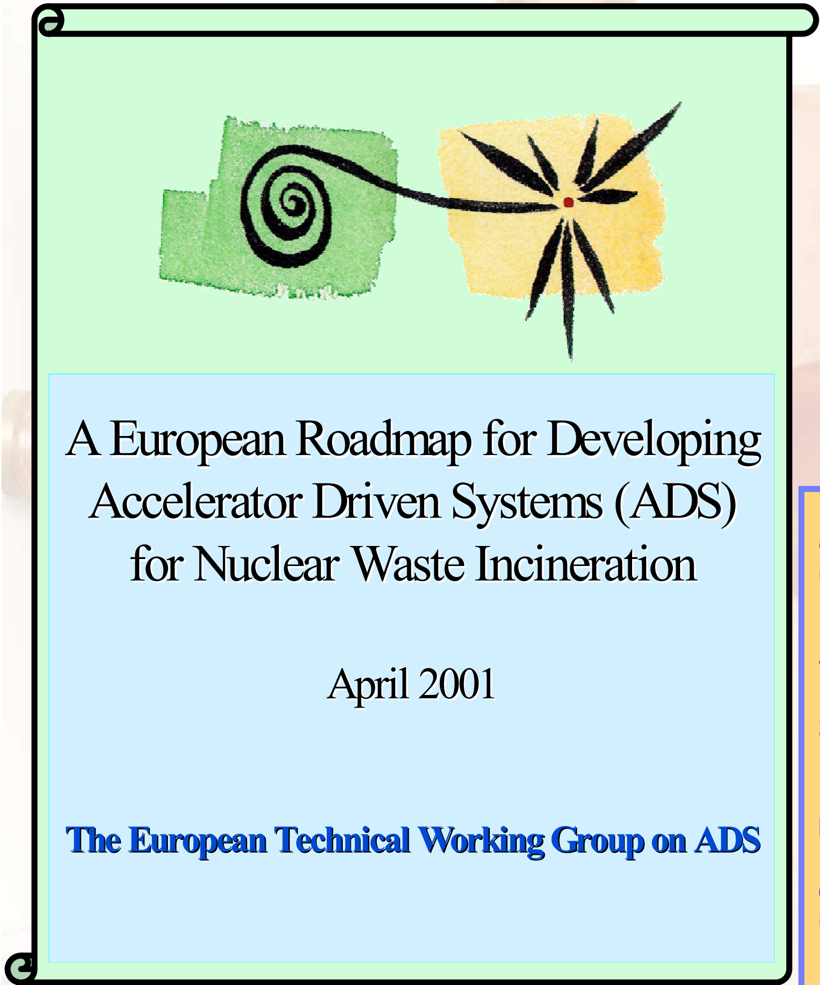


Pu Production Rate (grams / GWh)



MA Production Rate (grams / GWh)

TWG: a European ADS Roadmap


A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration

April 2001

The European Technical Working Group on ADS

The European Technical Working Group (members see below) issued in 2001 a Roadmap for Developing ADS (see left), with the propasal for a 100 MWth demonstrator.

Carlo Rubbia
ENEA, Italy, Chair

Hamid Ait Abderrahim
SCK-CEN, Belgium

Mikael Börnberg
VTT, Finland

Bernard Carluec
Framatome ANP, France

Guiseppe Gherardi,
ENEA, Italy

Enrique Gonzalez Romero
CIEMAT, Spain

Waclaw Gudowski
Royal Institute, Sweden

Gerhard Heusener
FZK, Germany

Helmut Leeb
Atominstitut, Austria

Werner von Lensa
FZJ, Germany

Joseph Magill
JRC, European Union

José Martinez-Val
Madrid Polytech, Spain

Stefano Monti,
ENEA, Italy

Alex C. Mueller
CNRS-IN2P3, France

Marco Napolitano
INFN, Italy

Angel Pérez-Navarro
LAESA, Spain

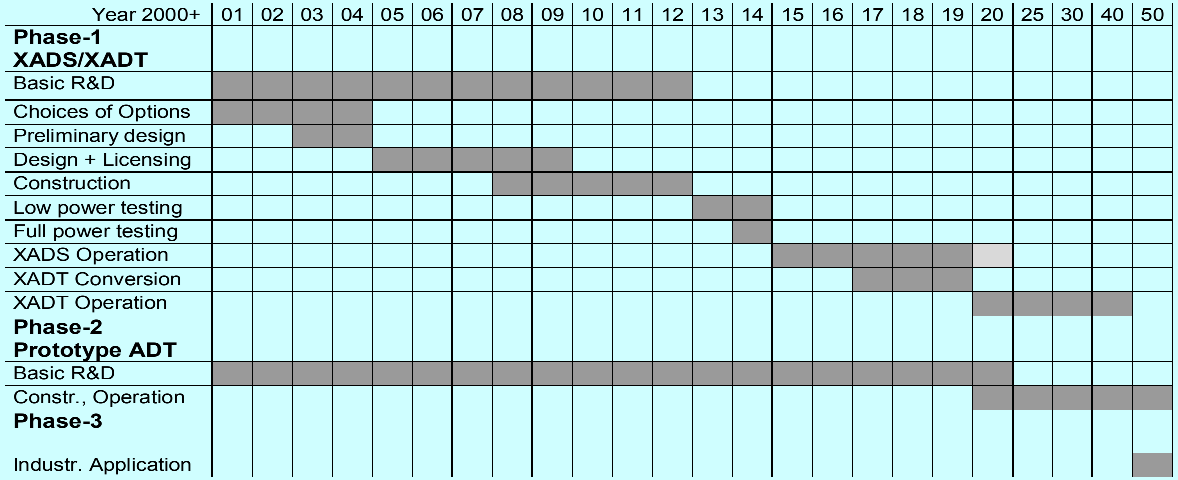
Massimo Salvatores
CEA, France

José Carvalho Soares
ITN Lisboa, Portugal

Jean-Baptiste Thomas
CEA, France

TWG Report: Roadmap & Cost estimate

Table 2.3. Time schedule and milestones for the development of ADS technology in Europe



Roadmap for the 100 MW_{th} demonstrator (left) and budget estimates (below).

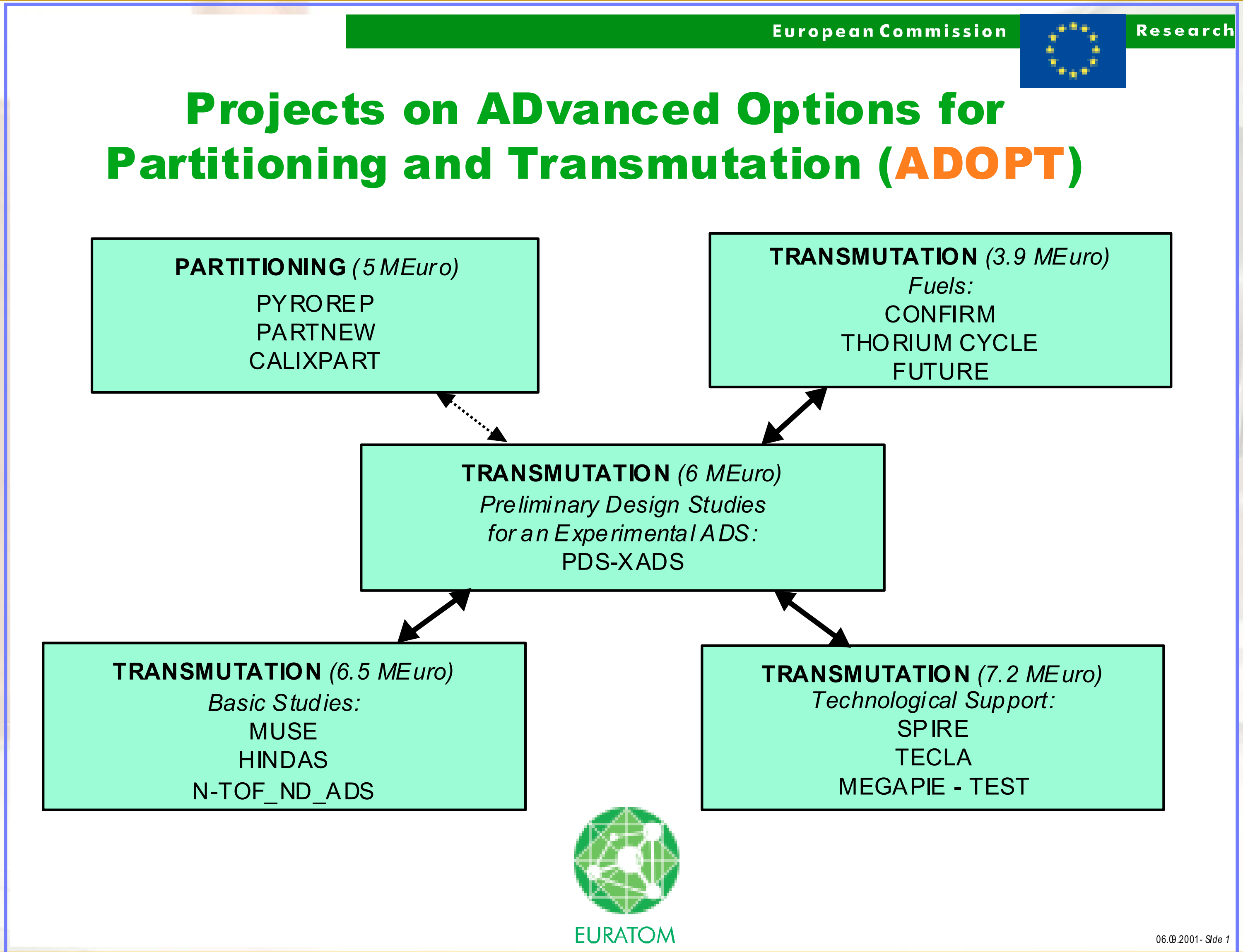
A TWG subgroup elaborated the project PDS-XADS (see next slide) which was funded by the EU.

Table 2. Estimated costs (M€) for the development of a 100 MW_{th} accelerator driven system

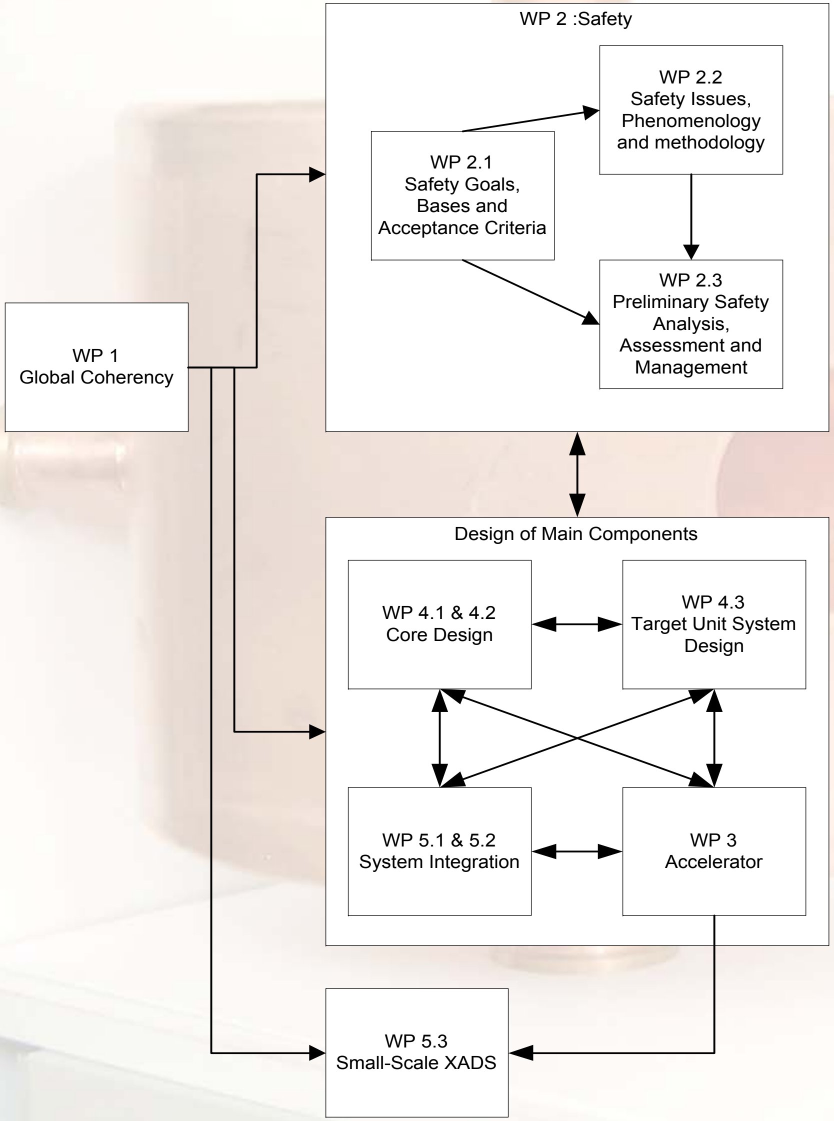
Year 2000+	1	2	3	4	5	6	7	8	9	10	11	12	**Total**
	5th FP		6th FP				7th FP						
Basic & Support R&D	30		90				70				10		200
Engineering Design	5		75				60				10		150
Construction	0		80				300				70		450
Fuel	0		10				120				50		180
Total	**35**		**255**				**550**				**140**		**980**
R&D for Dedicated Fuel	5		70				70				35		180*

* Estimated cost to 2012 for development of dedicated fuel & fuel processing

2001-2004: PDS-XADS as central P&T project



FP5 PDS-XADS*: Working Packages



*Contract N° FIKW-CT-2001-00179 (2001-2004)

A collaboration between Industrial Partners and Research Organisations

F: Framatome-F CNRS CEA
I: Ansaldo INFN ENEA CRS4
RFA: Framatome-D FZK FZJ UFra
Esp: CIEMAT Empresarios UPM
B: SCK IBA Tractebel
UK: NNC BNFL
Pt: ITN
S: KTH
Sui: PSI
Pl: UMM
NL: NRJ
Eur: JRC

coordinateur général : Framatome (B.Carluec, B.Giraud)
coordinateur accélérateurs: CNRS-IN2P3 (A.C. Mueller)

4th Lecture

The ADS Accelerator

- Specifications for the XADS, a HPPA
- High-power proton accel. presently under construction
- The reference linac developed within PDS-XADS
  - R&D efforts
  - Maintenance & radioprotection
  - Costing & roadmap
- The reliability issue
- EUROTRANS
- The accelerator WP within EUROTRANS

The PDS-XADS Accelerator Group (WP3)

- **WP3 partners**
  - Coordinator: CNRS-IN2P3 (F)
  - Participants: Ansaldo (I), CEA (F), ENEA (I), FANP (F), F GmbH (D), IBA (B), INFN (D), ITN (Pt), U. Frankfurt (D)

- **Main WP3 objectives**
  - Investigation of linac and cyclotron types with the main emphasis on the XADS requirements
  - Examination of the XADS accelerator characteristics: reliability, availability, stability, power control & maintainability
  - Definition of the R&D needs
  - Choice of the reference accelerator type for XADS and for a long-term extrapolated industrial transmuter
  - Definition of the road mapping of the ADS-class accelerators

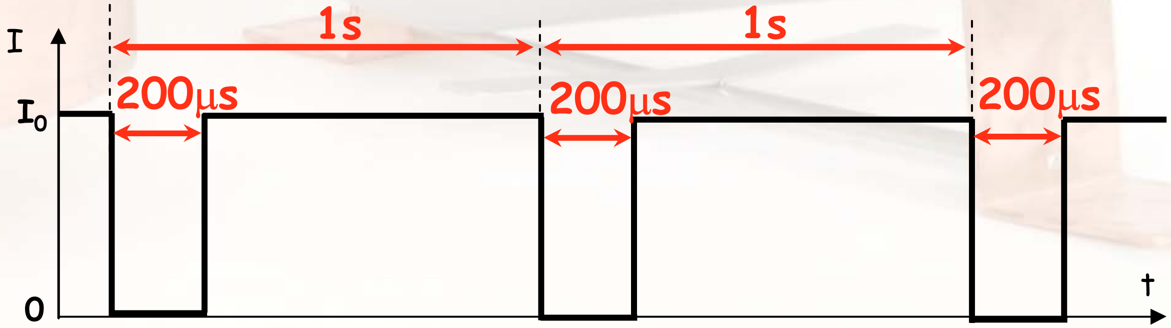
- **6 Deliverables**
  - D9 – D47 – D48 – D57 – D63 – D80

XADS Accelerator Requirements

- **Proton Beam Specifications**
  - Defined by WP1
  - 600 MeV, 6 mA max. for operation
  - 10 mA for the demonstration of concept
  - 350 MeV for the smaller scale XADS MYRRHA
  - High reliability requirement: less than 5 beam trips > 1 sec per year

Accelerator requirements	
Max. Beam Intensity	6 mA
Proton Energy	600 MeV
Beam entry	To be defined
Beam trip number	Less than 5 per year for the accelerator design Less than 50 per year for the reactor design
Beam type	CW, best solution Pulsed, back-up solution
Beam power stability	± 2 %;
Beam energy stability	± 1 %;
Beam intensity stability	± 2 %;
Beam footprint dimensions	± 10 %.

- **Additional requirements**
  - 200 μs beam « holes » for on-line sub-criticality measurements
  - Safety grade shutdown



Specifications for different HPPA

HPPA = High Power Proton Accelerator

>1

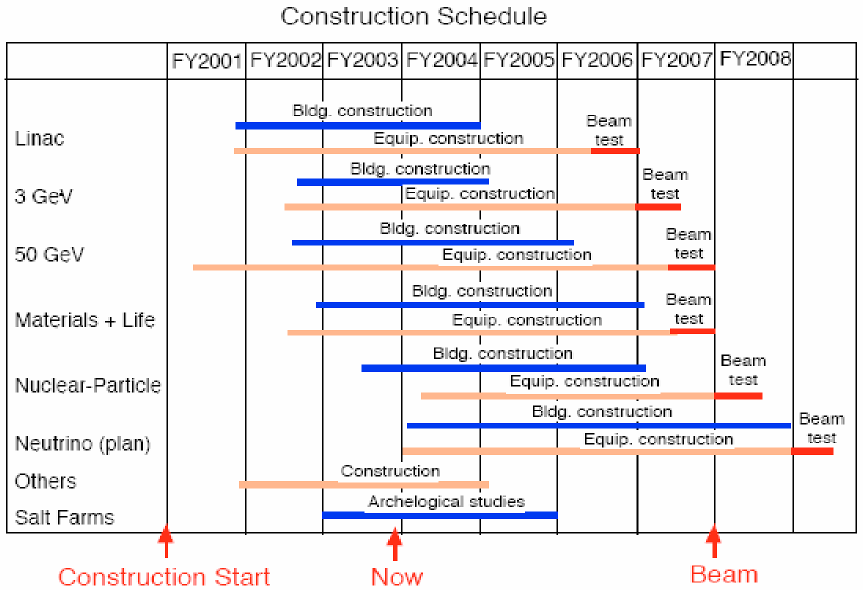
		Puissance [MW]	Énergie [GeV]
Faisceaux secondaires	Neutrinos, muons	4	2
Ions radioactifs	avec des protons avec des neutrons	.2 5	>.2 1
Irradiation des matériaux	par spallation par break-up ("IFMIF")	10 2 × 5.4	1 .04
Matière condensée	avec des neutrons	5	1.3
Transmutation	Démo 100 MW thermique Système industriel	5 10 à 20	.6 .8 à 1

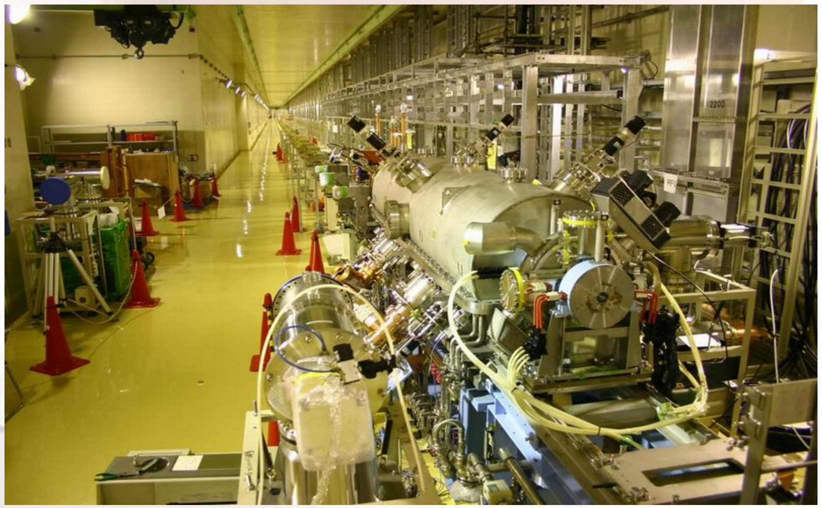
≈ 1

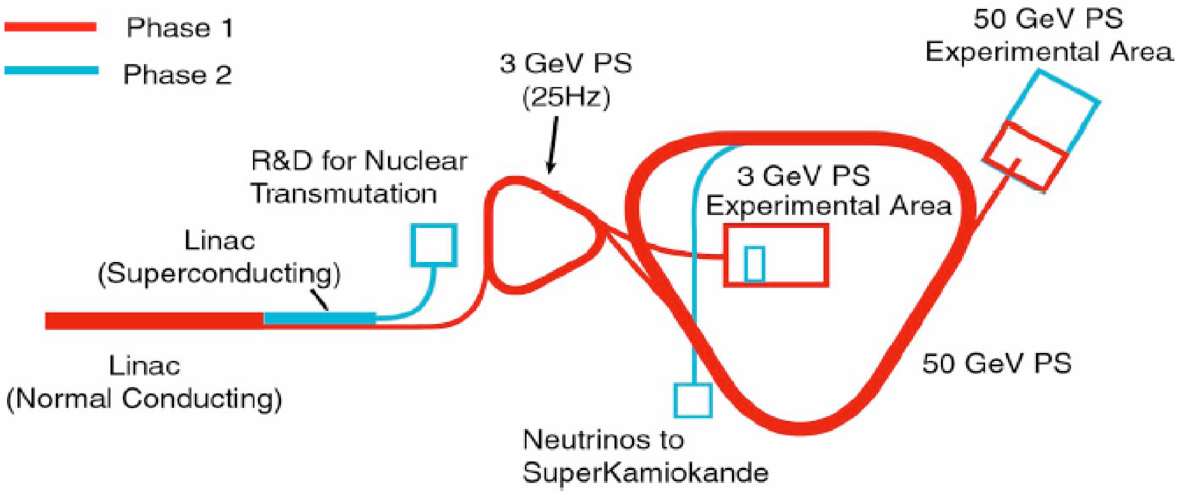
HPPA: Machines en Construction (J-PARC)

une "multi-purpose" Facility

HPPA: Machines en Construction (J-PARC)





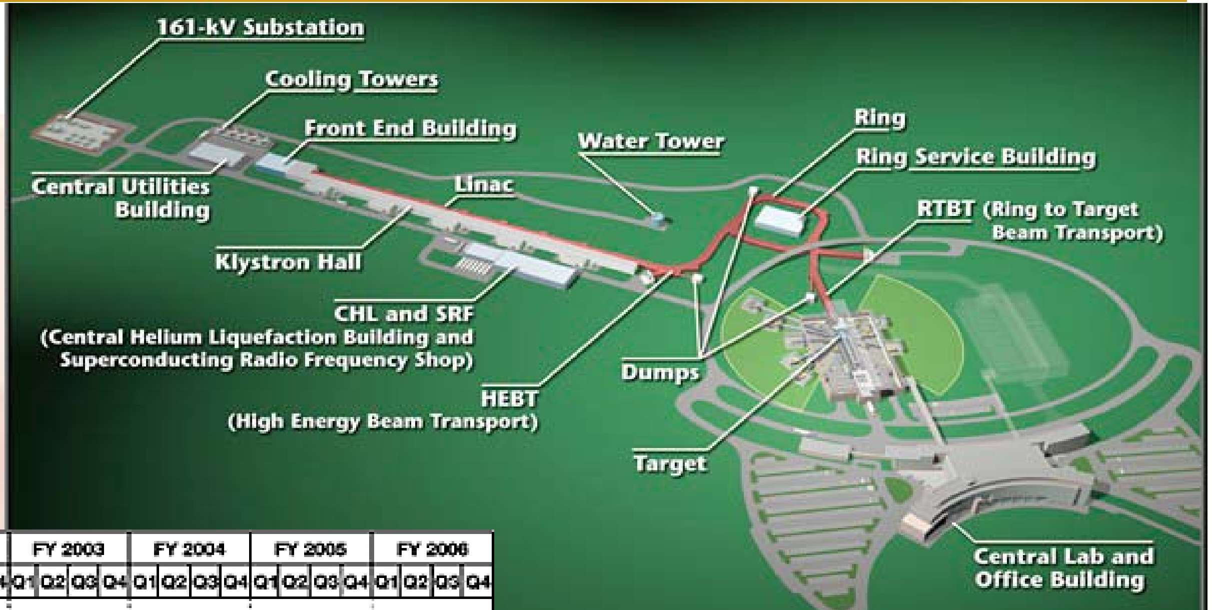


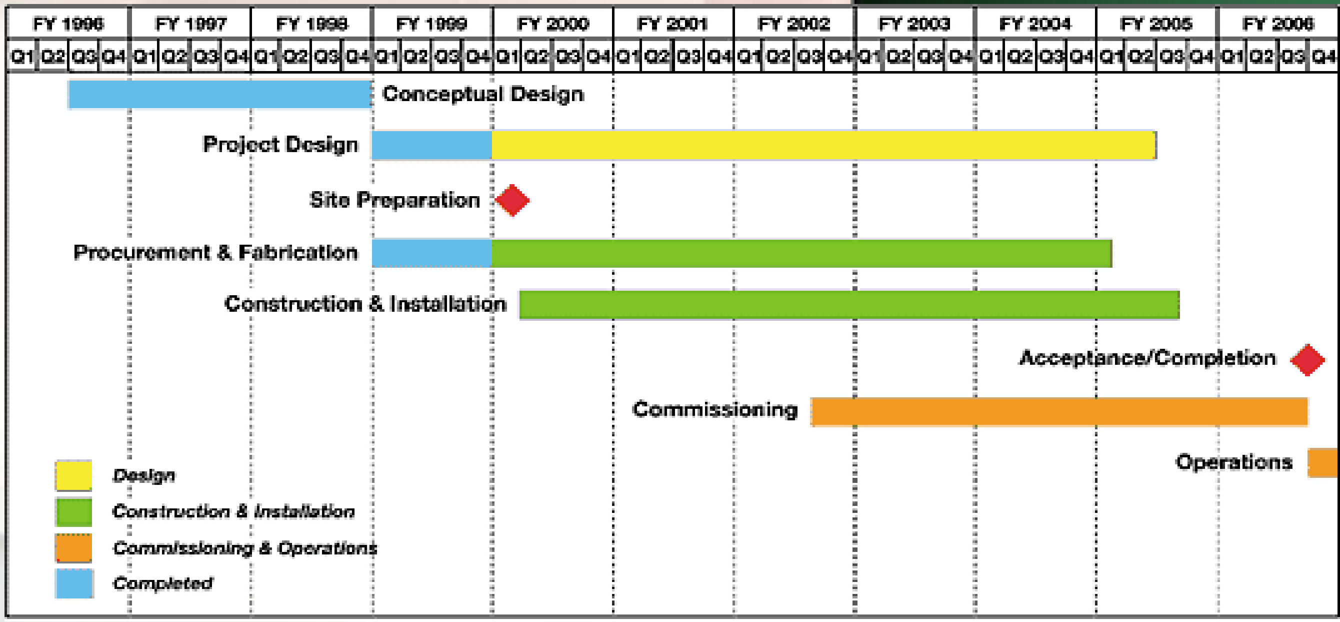
– Phase 1 + Phase 2 = 189 billion Yen (= $1.89 billion if $1 = 100 Yen).
– Phase 1 = 133.5 billion Yen for 6 years (= 2/3 of 189 billion Yen).
– Construction budget does not include salaries.

HPPA: Machines en Construction (SNS)

SNS à Oak-Ridge, prévu opérationel en 2006

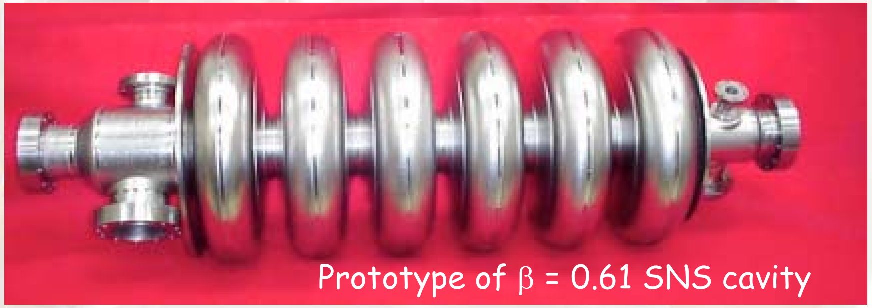
HPPA: Machines en Construction (2: SNS)

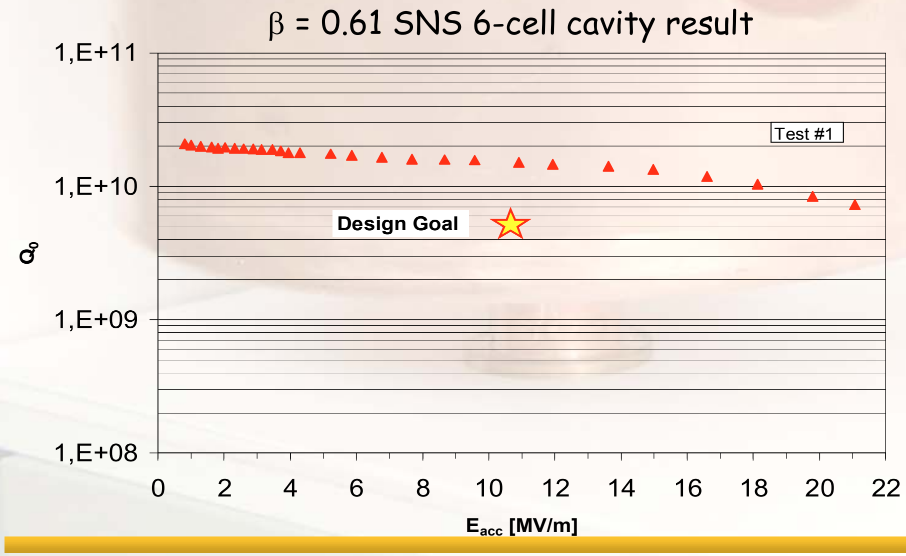


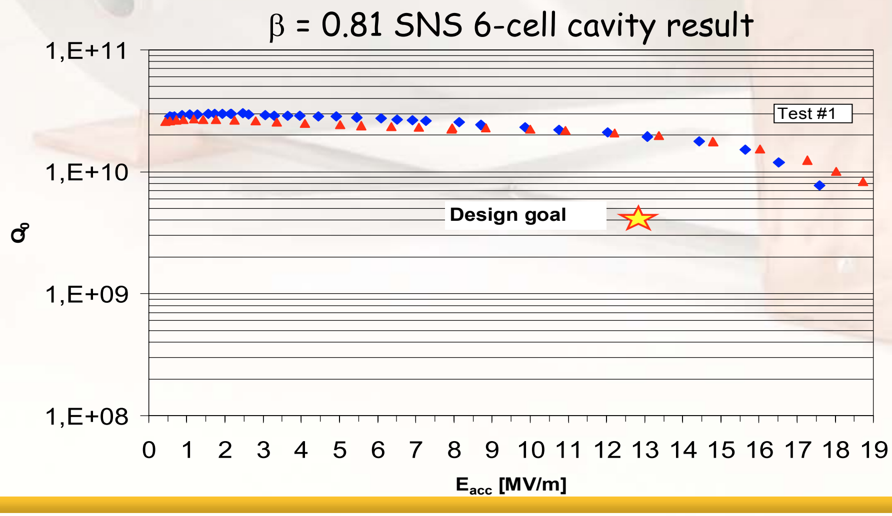


The SNS Example

- **Multicell structures have been built for the SNS project, for both the β=0.61 and the β=0.81 cavities**
  - All tests reached the design goals with good margins
  - Industrial fabrication for all the SNS cavities is in progess
  - The actual RIA linac proposed design uses the SNS cavities adding a β=0.47 6-cell cavity section, as in the European scheme



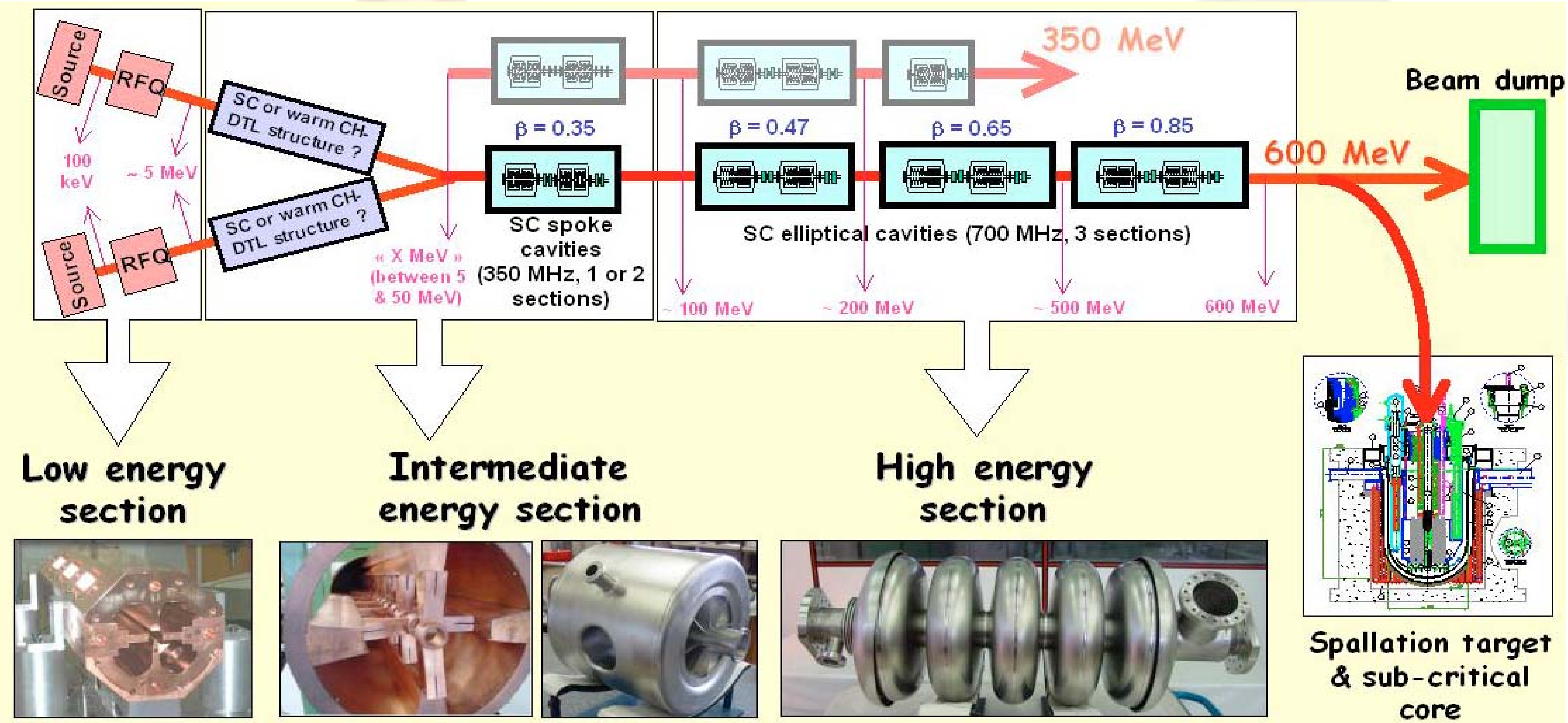




Choice of the Generic Accelerator Type

- **Main technical answers**
  - Superconducting linac
    - No limitation in energy & in intensity
    - Highly modular and upgradeable (industrial transmuter)
    - Excellent potential for reliability (fault-tolerance)
    - High efficiency (optimized operation cost)
  - Cyclotron
    - Attractive (construction) cost (?)
    - Required parameters at limits of feasibility ("dream machine")
    - Compact, but therefore not modular
- **In complete agreement with findings of the NEA report:**
  - **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice **for preliminary low power experiments**, where availability and reliability requirements are less stringent.
  - **CW linear accelerators must be chosen for demonstrators and full scale plants**, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.

PDS-XADS Reference Accelerator Layout



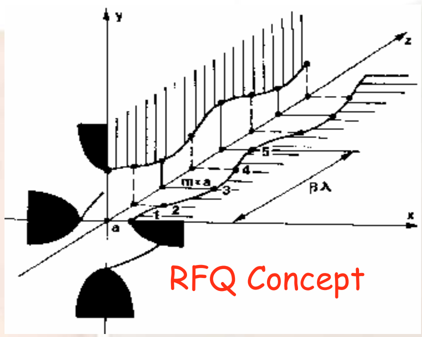
Strong R&D & construction programs for LINACs underway worldwide for many applications

(Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)

Injector: LEDA at LANL

Source & RFQ were operational in 1999 !

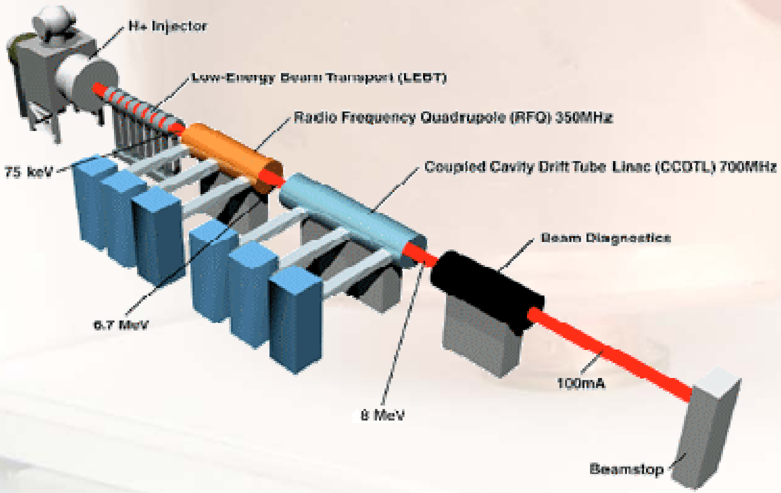
LEDA Source:	
Proton Beam current	110 mA
Total Beam current	130 mA
Beam emittance	0.2 π mm mrad
Operating voltage	75 kV

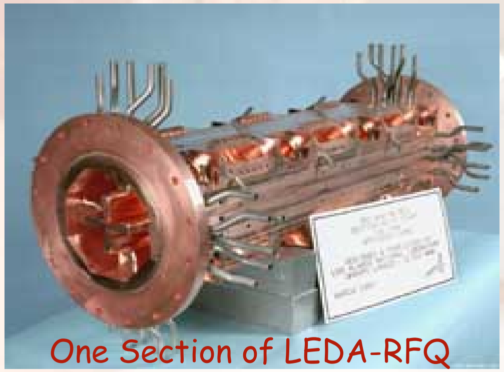


RFQ Concept

$$\vec{F}_{Lorentz} = \frac{d\vec{p}}{dt} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{el} + \vec{F}_{mag}$$

LEDA RFQ:	
Beam current	100 mA (95 %)
Beam emittance	0.22 π mm mrad
	0.17 π deg MeV
Final Energy	6.7 MeV
Length	8 m (4 sections)
RF Power	670 kW (beam)
	1.2 MW (structure)
Peak Field	1.8 Kilpatrick





One Section of LEDA-RFQ

Beam halo tests have been performed on the LEDA HEBT to compare simulation codes with experimental results

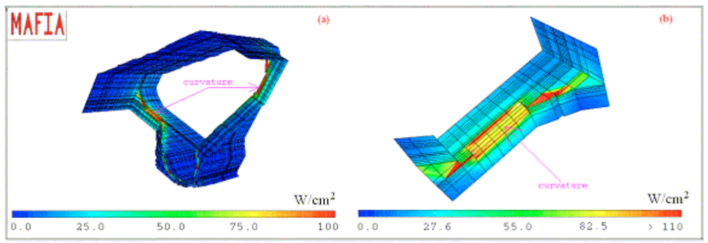
The LEDA-RFQ fully installed

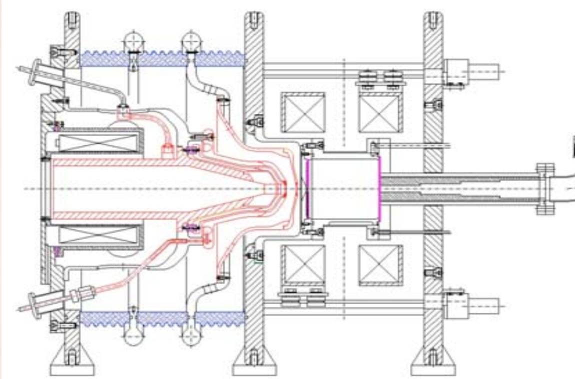
Linac Injector: TRASCO at INFN

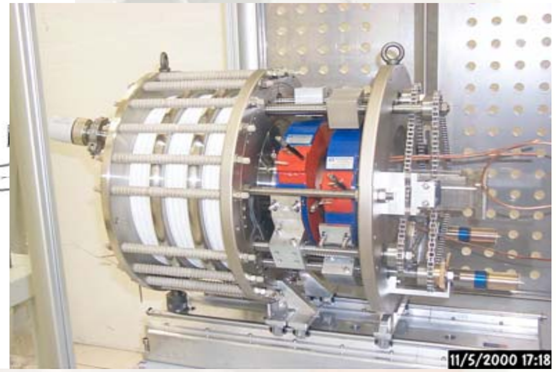
- Different optimization w/respect to LEDA
  - Limit to 1 klystron (1.3 MW CERN)
  - Lower design current: 30 mA
  - Peak field limited to 33 MV/m
  - Lower power dissipation: ~ 600 kW

- TRIPS, similar to SILHI with some extraction improvement and overdesign for reliability
- ECR source: 35 mA, 80 keV (operating)

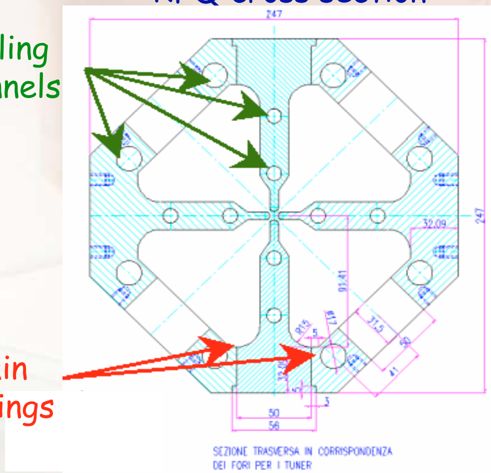
RFQ e.m. simulations



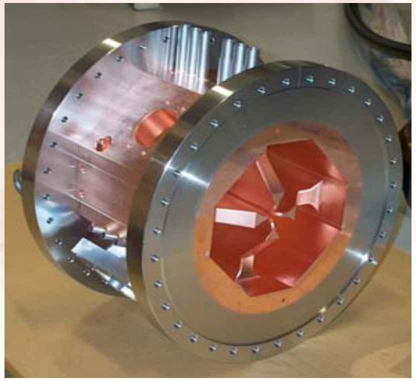


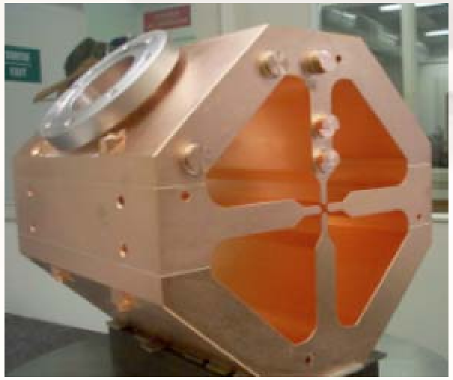


RFQ cross section

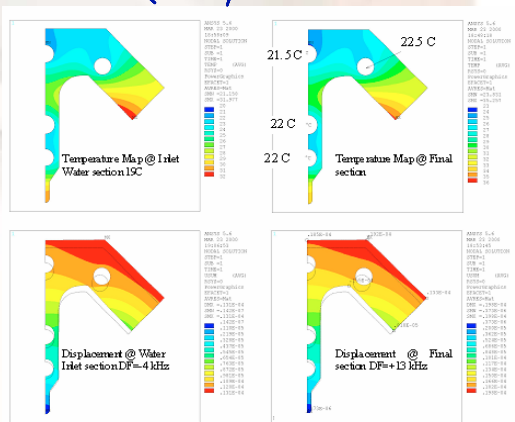


RFQ short models to set technology





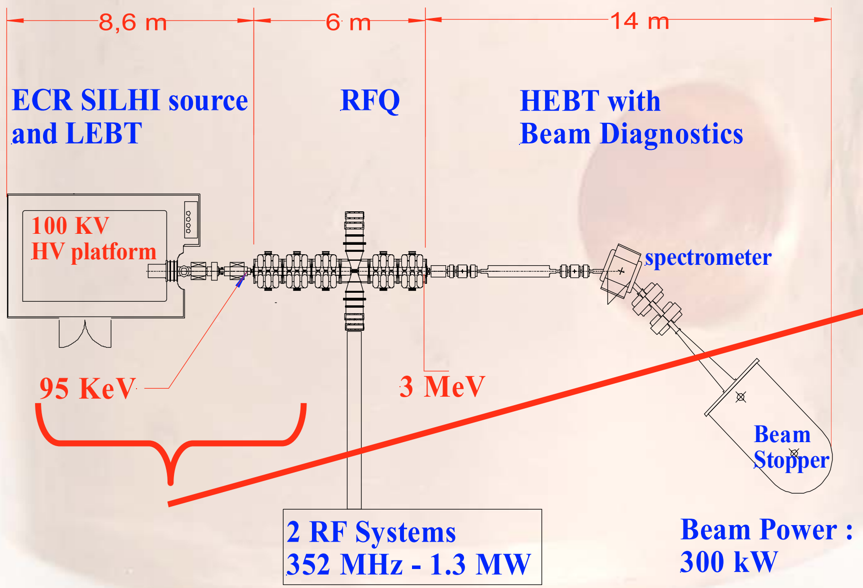
RFQ Ansys simulations



Injector: SILHI at Saclay

SILHI Goals:		Achievements
Beam current	110 mA (90 % p.f.)	157 mA (~83 % p.f.)
Beam emittance	0.2 π mm mrad	0.11 π mm mrad
Operating voltage	95 kV	95 kV
Beam noise (rms)	2 %	1.2 %

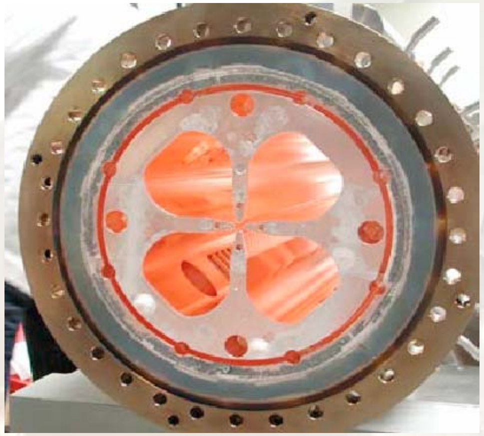
- The SILHI source is fully operationl
- ECR type: 110 mA, 95 keV



- Several reliability tests were performed on the source
  - 3 before extraction system changes: 99.96% availability (1 stop in 104 hours of operation)
  - 2 with new extraction system:
    99.8% availability (8 stops in 162 hours, automatic restarting in 2.5 min, MTBF=23.1 hours)

Injector: IPHI RFQ at Saclay

- IPHI RFQ under fabrication
- Two 1.3 Mw klystrons required
- First RFQ beam expected in 2007

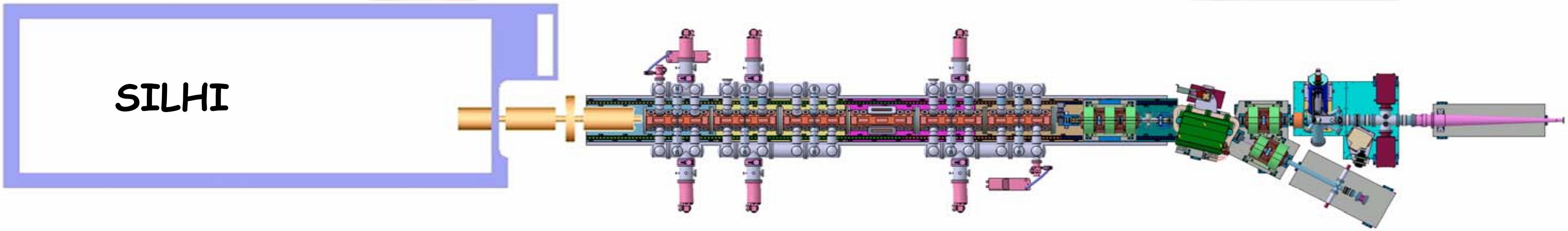


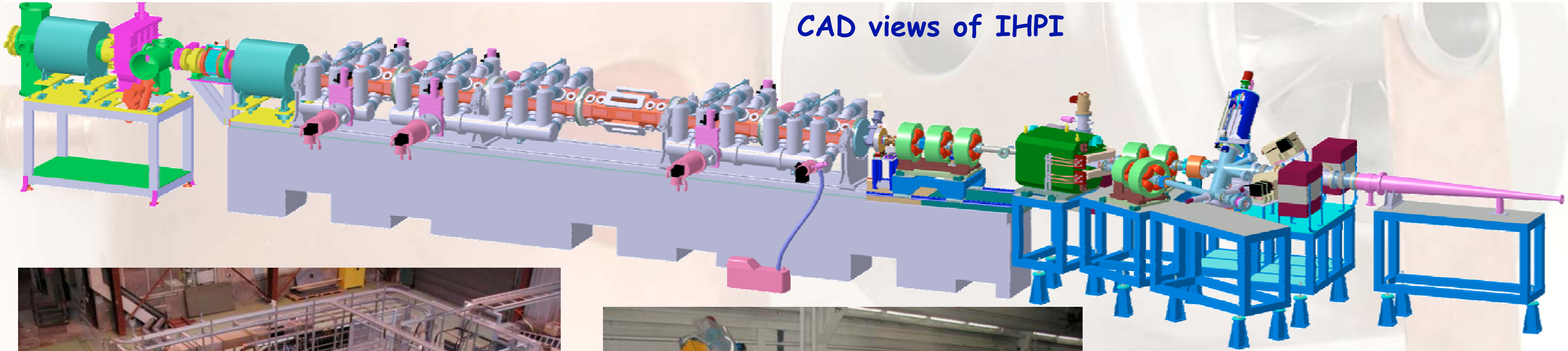
Picture of the first IPHI RFQ section ready for brasing

View of the vanes from the low energy side

IPHI RFQ parameters:	
Beam current	100 mA (99.2%)
Beam emittance	0.2 π mm mrad T
	0.2 π deg MeV L
Final Energ	5 MeV
Length	8 m (3 sections)
RF Power	500 kW (beam)
	1.2 MW (structure)
Peak field	1.7 Kilpatrick

IPHI (collaboration CEA-CNRS-CERN)





CAD views of IHPI

IPHI RF installation (left)

IPHI Diagnostics:
Wire Scanner (center)

Reference Accelerator: Low Energy Section

Reliability tests

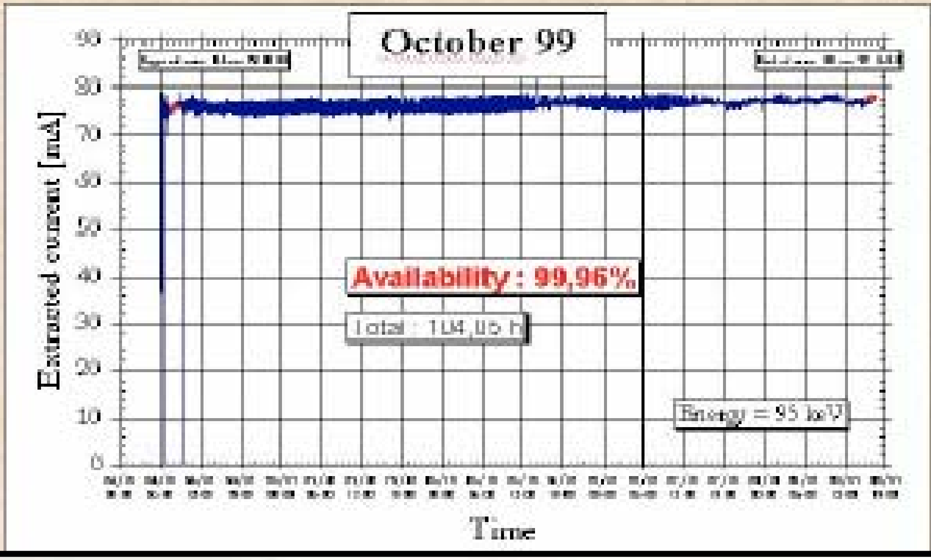
Parameters	Déc. 97	Mai 99	Oct. 99	March 01	June 01
Energy (keV)	80	95	95	95	95
Intensity (mA)	100	75	75	118	114
Duration (h)	103	106	104	336	162
Beam off number	53	24	1	53	7
MTBF (h)	1.75	4	n. appl.	≈ 6	23.1
MTTR (mn)	6	5.3	2.5	≈ 18	2.5
Uninterrupted beam (h)	17	27.5	103	25	36
Availability (%)	94.5	97.9	99.96	95.2	99.8

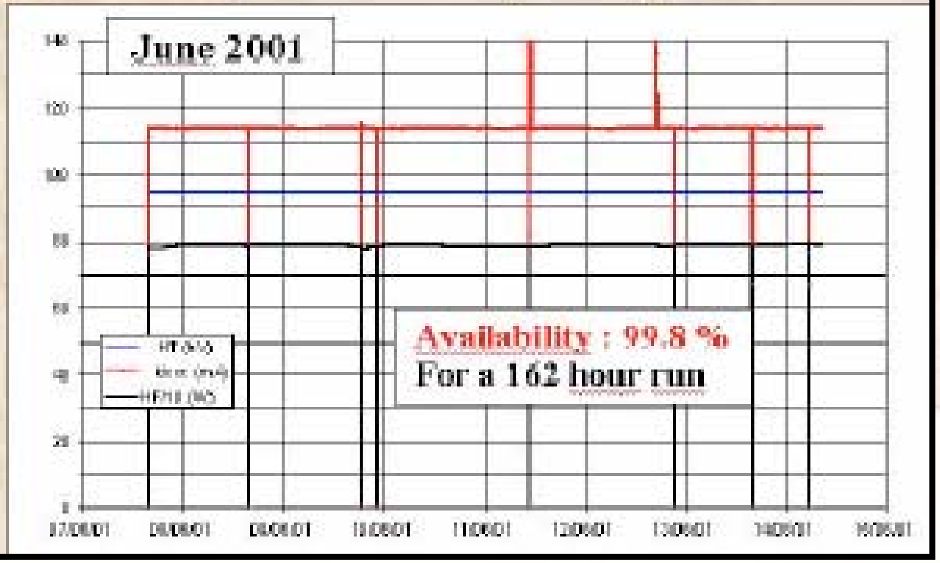
5 reliability tests have been performed :

3 with a limited extracted beam (old extraction system)

and the 2 last ones with the new system which limits beam losses on the electrodes.

Future test within EUROTRANS within the complete IPHI system (SILHI + RFQ) at 10 & 40 mA

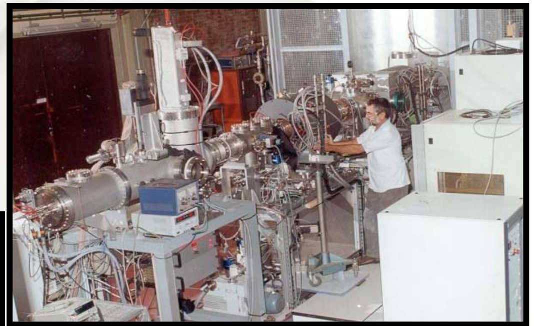


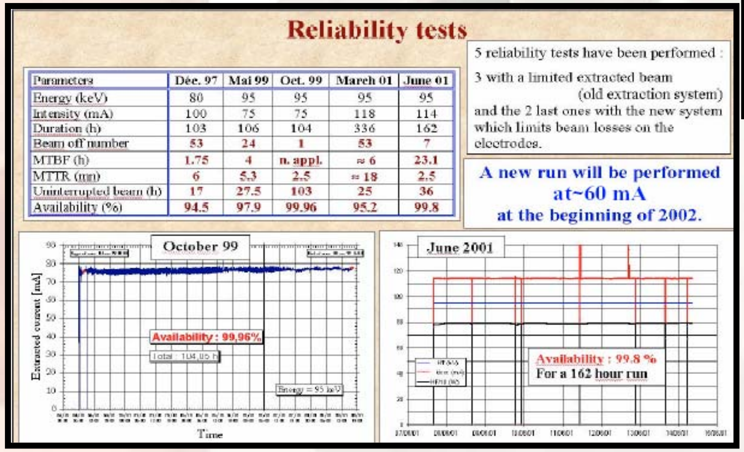


Reference Accelerator: Low Energy Section

- R&D on the injector part by the WP3 partners

  - « IPHI » ECR Source & Normal Conducting RFQ (CEA-CNRS)
  - « TRASCO » ECR Source & Normal Conducting RFQ (INFN)
  - Normal Conducting IH-DTL Structure (IBA)
  - Superconducting CH-DTL Structure (U. Frankfurt)



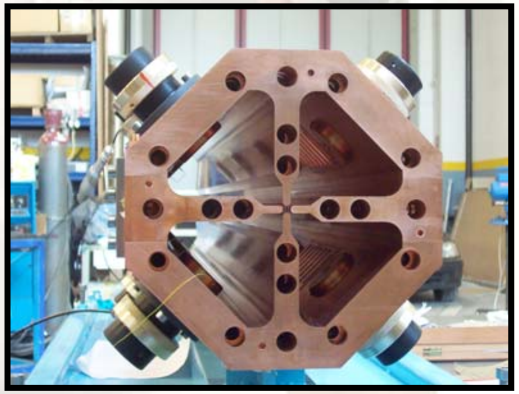


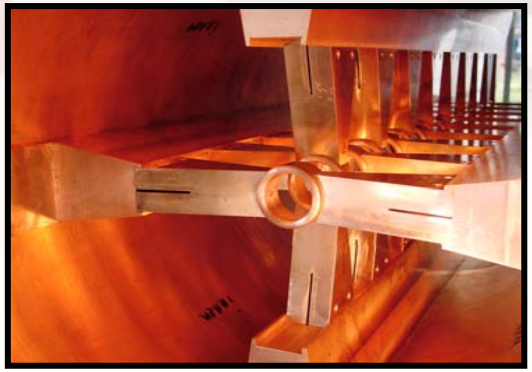
Reliability tests

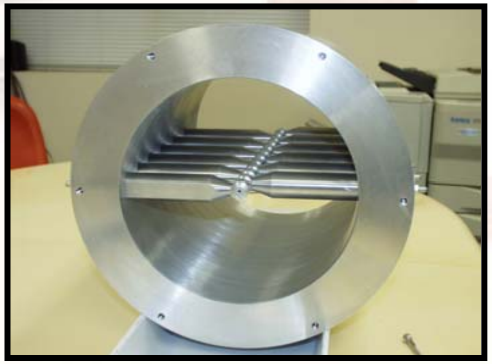
Parameters	Déc. 97	Mai 99	Oct. 99	March 01	June 01
Energy (keV)	80	95	95	95	95
Intensity (mA)	100	75	75	118	114
Duration (h)	103	106	104	336	162
Beam off number	53	24	1	53	7
MTBF (h)	1.75	4	n. appl.	≈ 6	23.1
MTTR (mn)	6	5.3	2.5	≈ 18	2.5
Uninterrupted beam (h)	17	27.5	103	25	36
Availability (%)	94.5	97.9	99.96	95.2	99.8

5 reliability tests have been performed :
3 with a limited extracted beam (old extraction system) and the 2 last ones with the new system which limits beam losses on the electrodes.

A new run will be performed at~60 mA at the beginning of 2002.





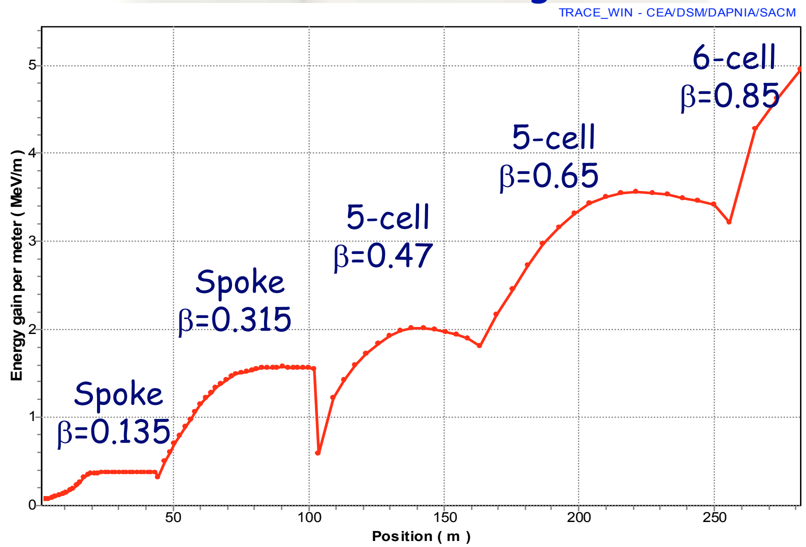


The 0-order Design for PDS-XADS

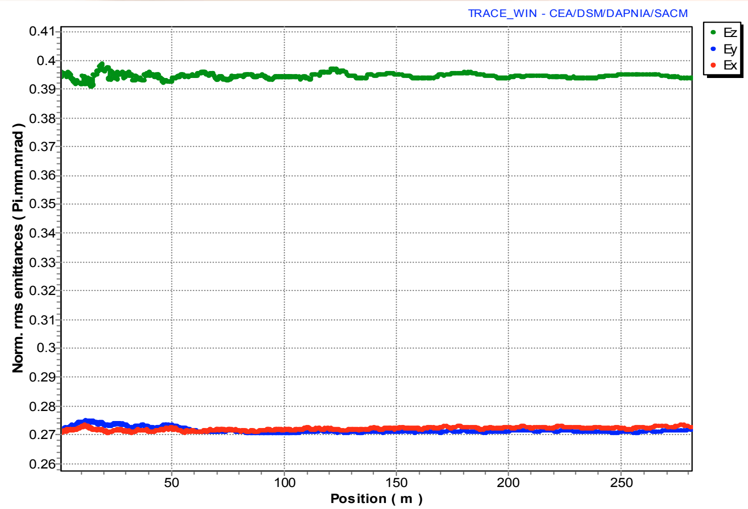
SC Linac Section Parameters

	Section number				
	1	2	3	4	5
Input Energy [MeV]	5	17	95	200	490
Output Energy [MeV]	17	95	200	490	600
Cavity Technology	Spoke		Elliptical		
Structure β_g	0.135	0.314	0.47	0.65	0.85
Number of cavity cells	2	2	5	5	6
Number of cavities	34	64	28	48	12
Focusing type	SC quad doublet		NC quad doublet		
Cavities/Lattice	1	2	2	3	4
Synch Phase [deg]	-65 to -30	-30	-25		
Lattice length [m]	1.3	1.9	4.2	5.8	8.5
Number of lattices	34	31	14	16	3
Section Length [m]	44.2	59.9	60.8	92.8	25.5
<gradient> [MV/m]	0.3	1.3	1.8	3.1	4.3

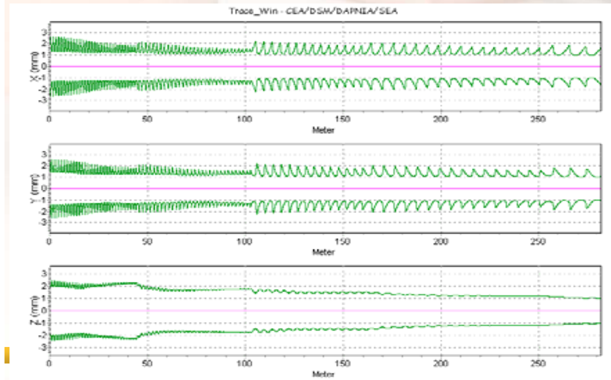
Real Estate ΔE/m along the linac



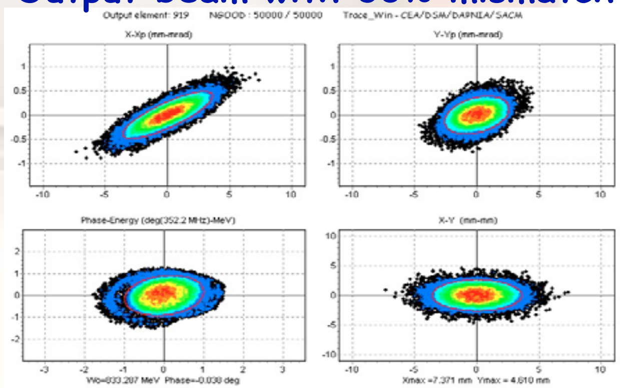
rms emittances in the whole linac



rms beam size along the linac



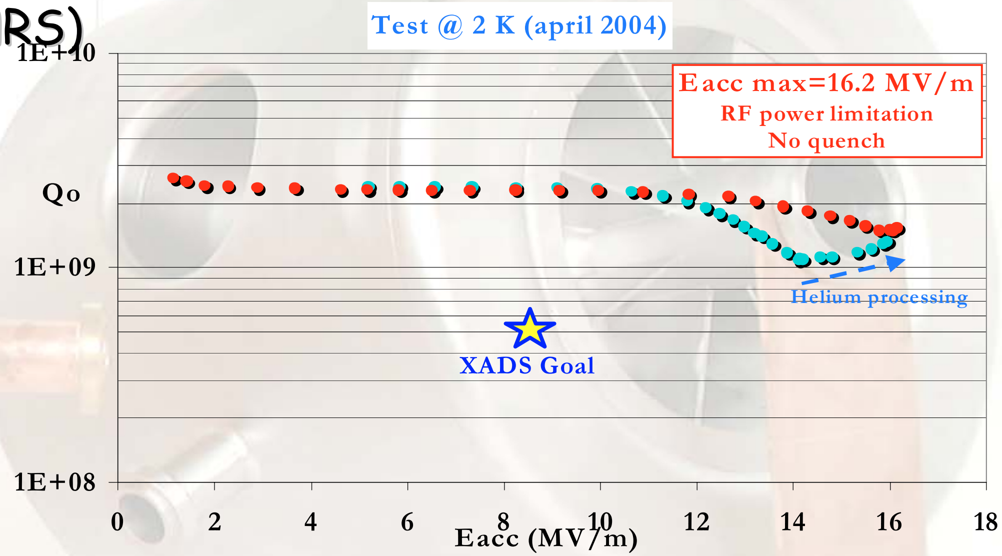
Output beam with 30% mismatch



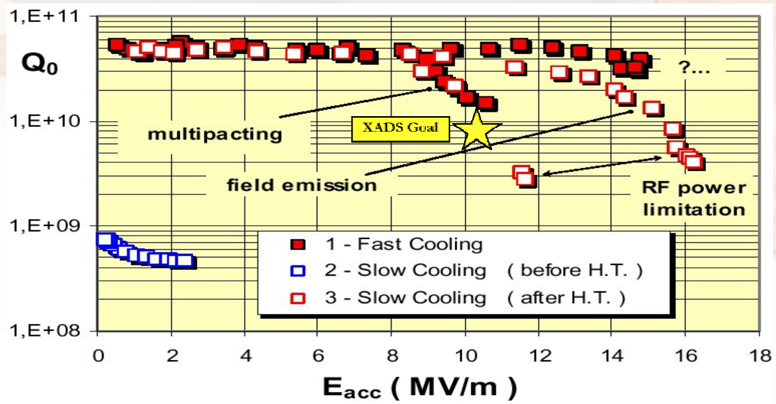
Reference Accelerator: High Energy Section

- R&D on SC prototypical cavities by the WP3 partners

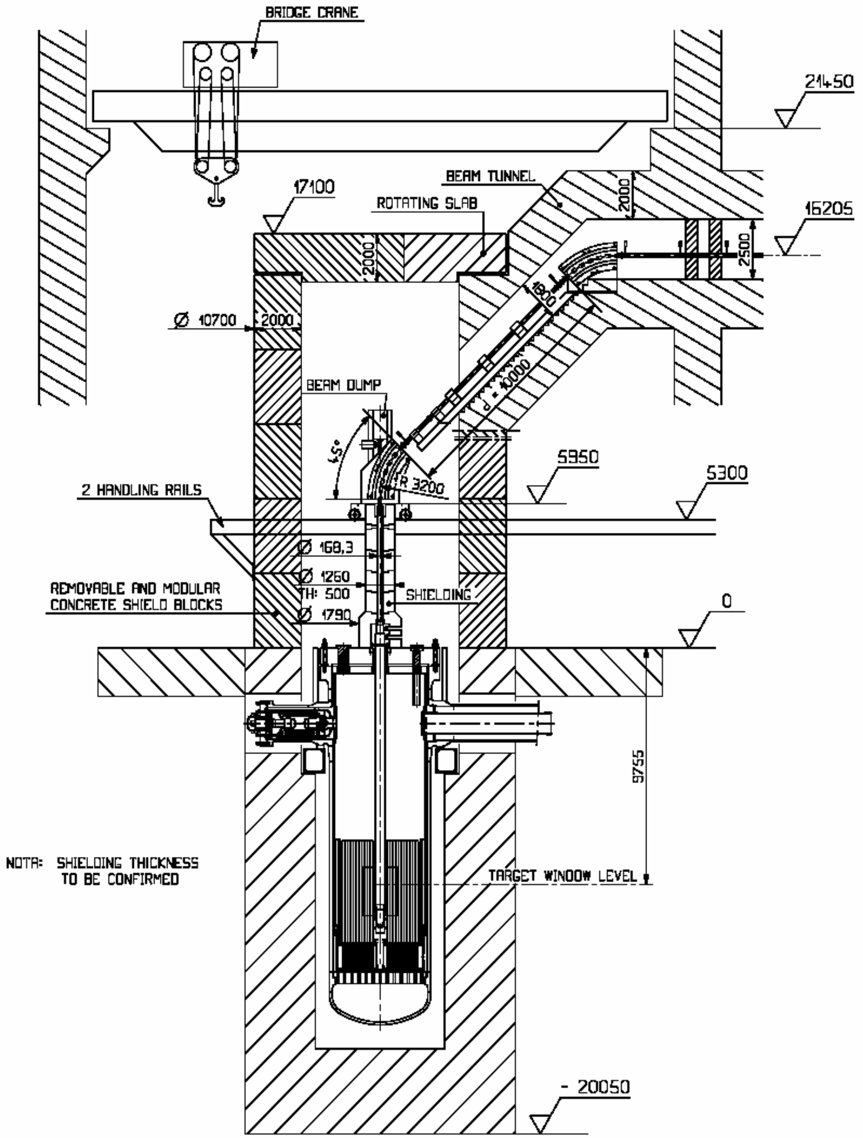
  - Spoke cavities β = 0.15 & β = 0.35 (CNRS)



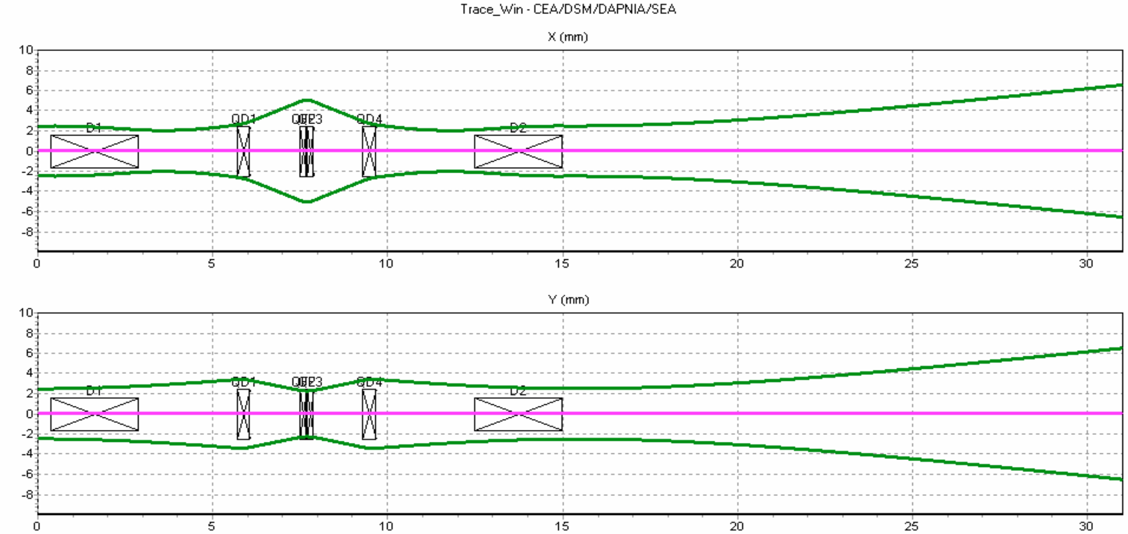
  - Elliptical cavities β = 0.5 & β = 0.65 (CEA-CNRS-INFN)



Reference Accelerator: Beam Line Transport

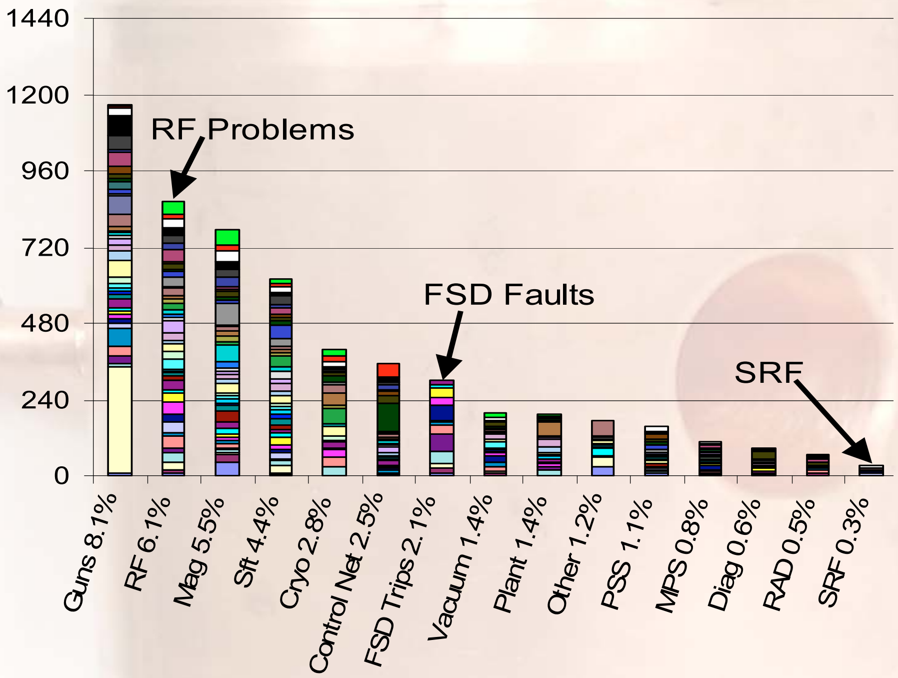


- The doubly achromatic beam line concept + beam scanning method meets the specifications:
  - of the Gas-cooled XADS
    (circular footprint, ∅160)
  - of the LBE-cooled XADS
    (rectangular footprint, 10×80)
  - of MYRRHA
    (quasi-circular footprint, ∅72)

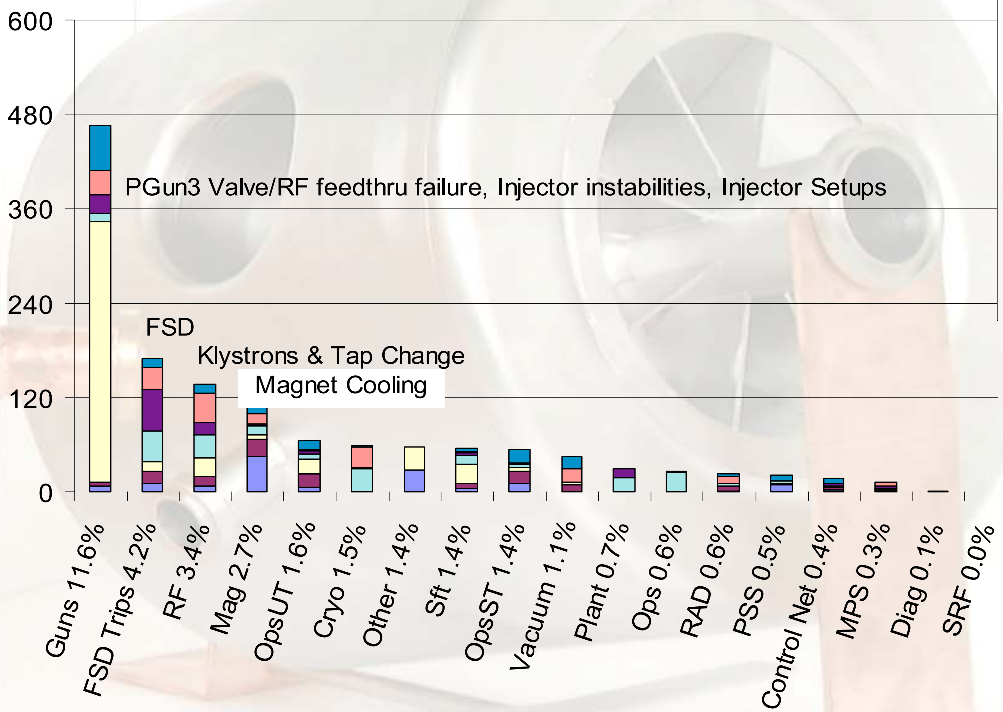


Reliability Example - CEBAF

Lost Time Totals June'97-May'01



Lost Time Totals FY 2001



- Reliability must be improved for ADS applications
- The SC linac is modular and allows: overdesign, redundancy and “spare-on-line”
- Fast dedicated control electronics is crucial
- Beam can stay “on” when the linac is resetting itself to use spere-on line
- SC cavity technology proved to be the minor concern

Reliability Analysis

FP5

CONTRACT N°: FIKW-CT-2001-00179

ISSUE CERTIFICATE

PDS-XADS
Preliminary Design Studies of an Experimental Accelerator-Driven System

Workpackage N° 3

Identification: N° DEL/03/057 **Revision: 0**

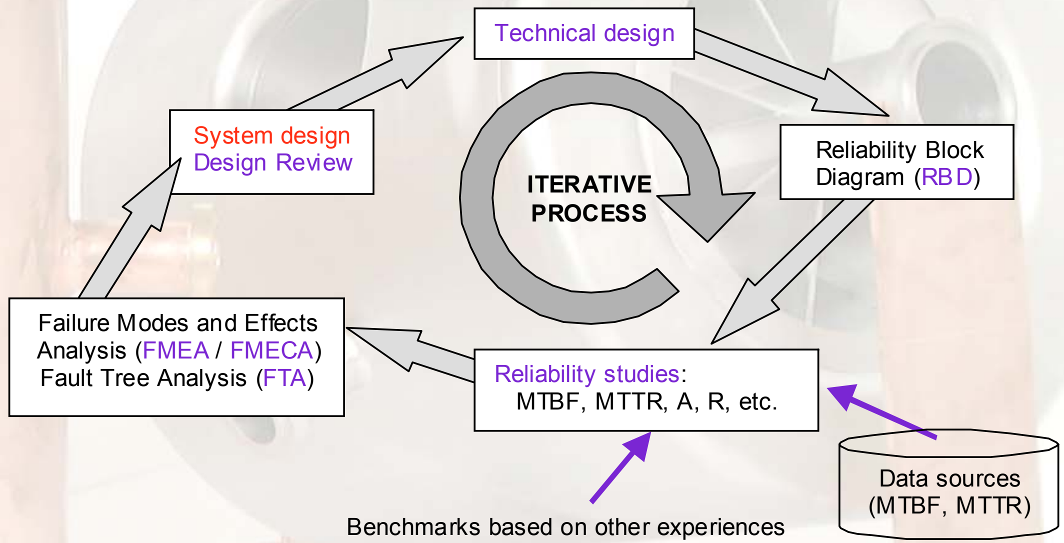
Potential for Reliability Improvement and Cost Optimization of Linac and Cyclotron Accelerators

Dissemination level: *RE*
Issued by: *INFN*
Reference: INFN/TC_03/9 (July, 23rd, 2003)
Status: *Final*

Summary:
This document identifies the suitable design strategies that have been followed in order to meet the reliability and availability specifications for the XADS accelerator outlined in Deliverable 1. The document describes also how these strategies can be applied in the different components of the XADS accelerator design, and how design iterations can lead to reliability improvements. The Failure Mode and Effect Analysis (FMEA) methodology has been used on the suggested design for highlighting the reliability critical areas. Finally, a first rough cost estimation of the XADS accelerator is also provided.

23/07/2003	Paolo Pierini, INFN	Alex C. Mueller, CNRS	Bernard Carluec Framatome ANP SAS
	[signature]	[signature]	[signature]
DATE	RESPONSIBLE Name/Company Signature	WP LEADER Name/Company Signature	COORDINATOR Name/Company Signature

- **Assessments using the « Failure Modes and Effects Analysis » (FMEA) method**



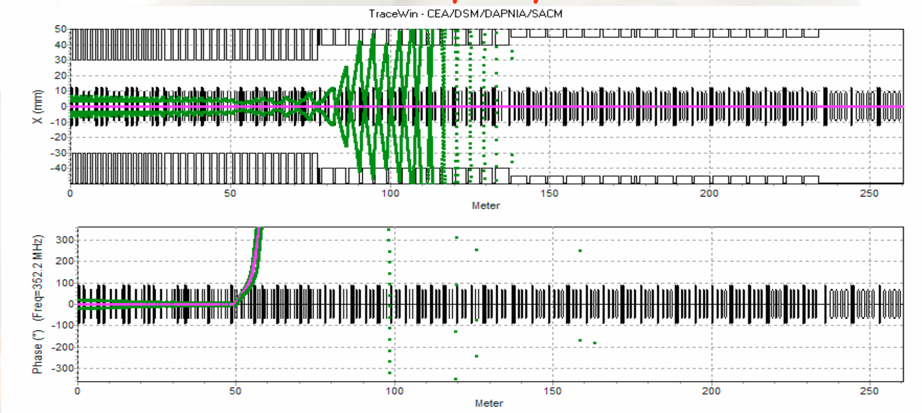
- **Reliability engineering is a discipline for estimating, predicting and controlling the probability of occurrence of system faults**

Main Conclusions on Reliability

- The cyclotron option for PDS-XADS does not seem to offer a sufficient perspective of reaching the requested reliability level
- No showstopper to reach high availability & high reliability with the XADS reference linac if over-design & redundancy are used
- Fault tolerance has been identified as key element in order to guarantee reliability by design and operation
  - Identification of the main component faults & estimate of their effect on the beam (not always straightforward)
  - Identification of strategies (and proper hardware systems) to deal with faults
  - Plans for the accelerator commissioning and maintenance
  - Reliability/availability allocation need to be examined with the constraints of legislation (safety aspects) & radioprotection

Fault Tolerance, a new concept uniquely applicable in a modular super conducting Linac

Fault tolerance in the independently phased SC sections is a crucial point
because a few tens of RF systems failures are foreseen per year.



1. Consequences of the failure of a superconducting RF cavity

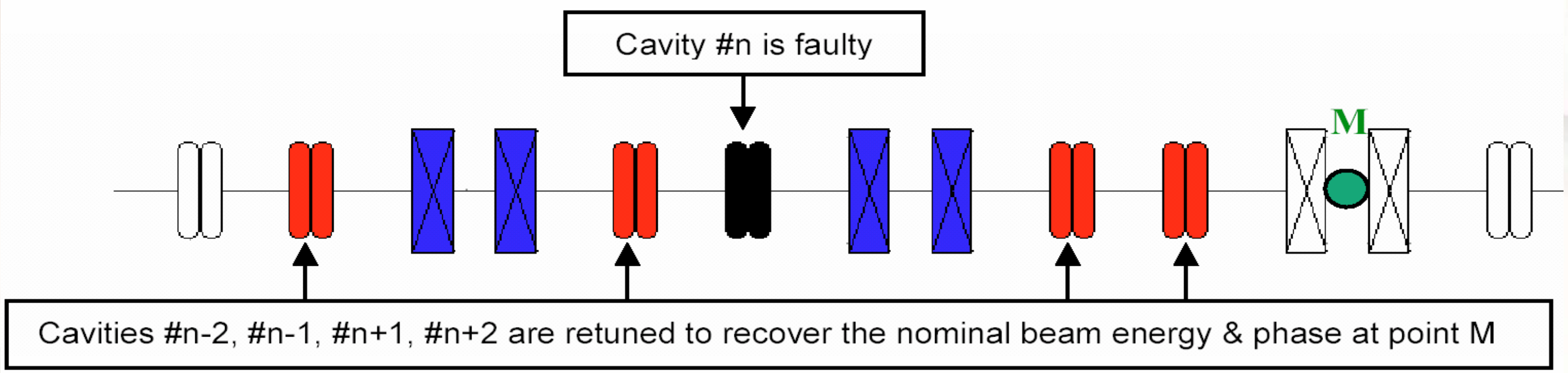
→An RF system failure induces phase slip (non relativistic beam)

→ If nothing is done, the beam is always LOST

2. Linac retuning after the failure of a RF cavity or of a quadrupole

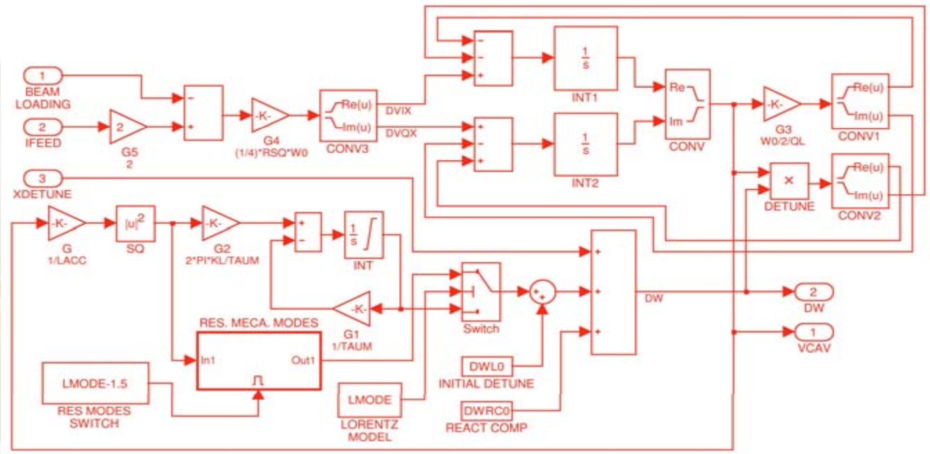
→ Local compensation philosophy is used

→ In every case, the beam can be transported up to the high energy end without beam loss



Reliability, Feedback Systems & Maintenance

- **The feedback systems has to provide the necessary energy stability, dealing with faults in order to reach the project goals** *(less than 5 beam trips per year)*
  - **Fast digital RF system** can implement fault tolerance with respect to cavity fault by dealing fault set tables
  - **Beam diagnostics** is also an area of prime importance



- **The maintenance strategy has to guarantee the reliability of the machine for more than 20 years**
  - It should guarantee the long-term validity of the linac prime criteria:
    - Over-Design / Redundancy / Fault Tolerance
  - Need for an expert system :
    - Detecting faulty or out-of-order equipment
    - Planning of subsequent maintenance & management of the intervention time according to radioprotection

Optimisation of Accelerator Reliability for ADS

The next slides will present the conclusions of PDS-XADS related to maintenance and radioprotection of the accelerator, as well costing aspects and a proposed roadmap which contains a 4 year on experimental reliability qualification of key components.

Then we come back to the discussion reliability/fault tolerance in some more detail.

In the hope that this is a wise decision as far as pedagogic is concerned……….

Reliability & Maintenance

- The maintenance strategy is presently under investigation, assuming 3 months of operation / 1 month of maintenance

PDS-XADS-WP3
Deliverable 48
Chapter 4
4.3.1 H+ source

Severity Ranking Tables	
Local effect	**Effect on beam**
0: No effect	0: Beam with nominal parameters on targ
1: Functionning with reduc	1: Beam with wrong parameters on target
2: Loss of function	2: No beam on target

Main Items	Function	Failure Mode	verity rank		Preventive action			Curative action		Rem.
			local	beam	action	freq.	time of int.	action	time of int.	
Boron nitride discs		Wear	1	1	Replace	6 months	24 H	Replace	24H	
Vacuum pumps		Wear	1	2	Regenerate	24 months				
		Out of order	2	2	-			Replace	8H	
Power supply filters		Get dirty	0	0	Clean	3 months	few min			
Power supply		Aging	0	0	Overhaul	24 months	few weeks			Use spare while overhauling
Cooling (water): filters, pumps...		Wear / dirty	0	0	Clean					
Plasma electrode		Aging	1	1	Replace	12 months	24H			
Magnetron		Out of order	2	2	Replace	24 months	2H	Replace	2H	Replace "before MTBF"
HV power supply		Out of order	2	2	Oil changing	24 months	8H	Replace	8H	
Extraction electrodes		Aging	1	1	Replace	24 months	48H			
Security devices :										
Water flow controller		get dirty			cleaning	12 months	30 min	Replace	2H	
Temperature controller		Out of order			Systematic tests	12 months	few min	Replace	8H	could be doubled
Emergency stop		Out of order			Systematic tests	12 months	1 H	Replace	1 H	
DGPT		Out of order			Systematic tests	12 months	1 H	Replace	8 H	

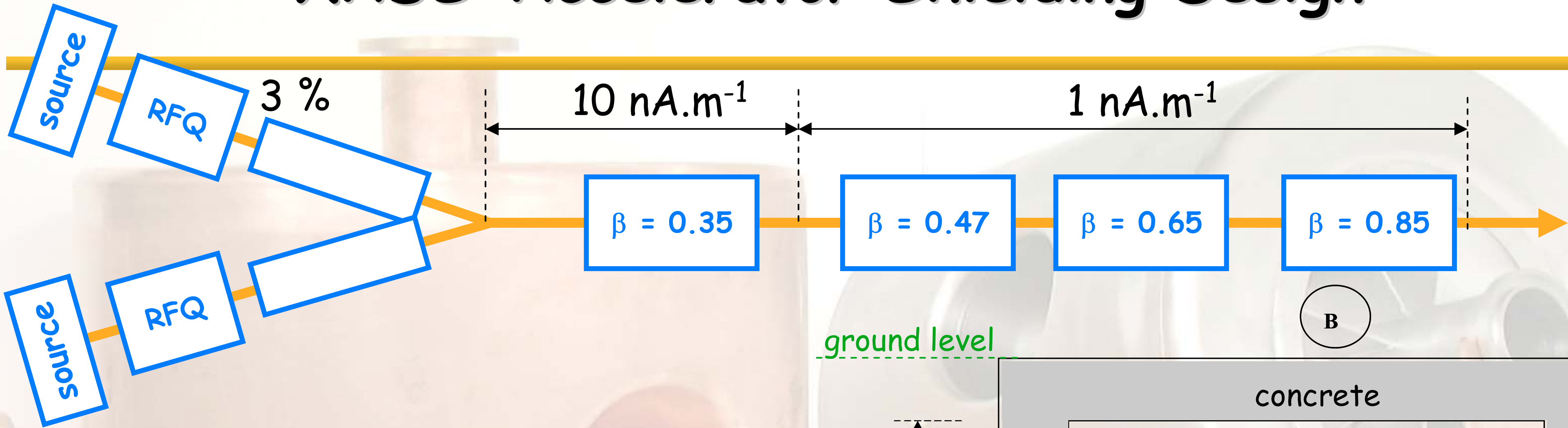
XADS: Safety Aspects & Radioprotection*

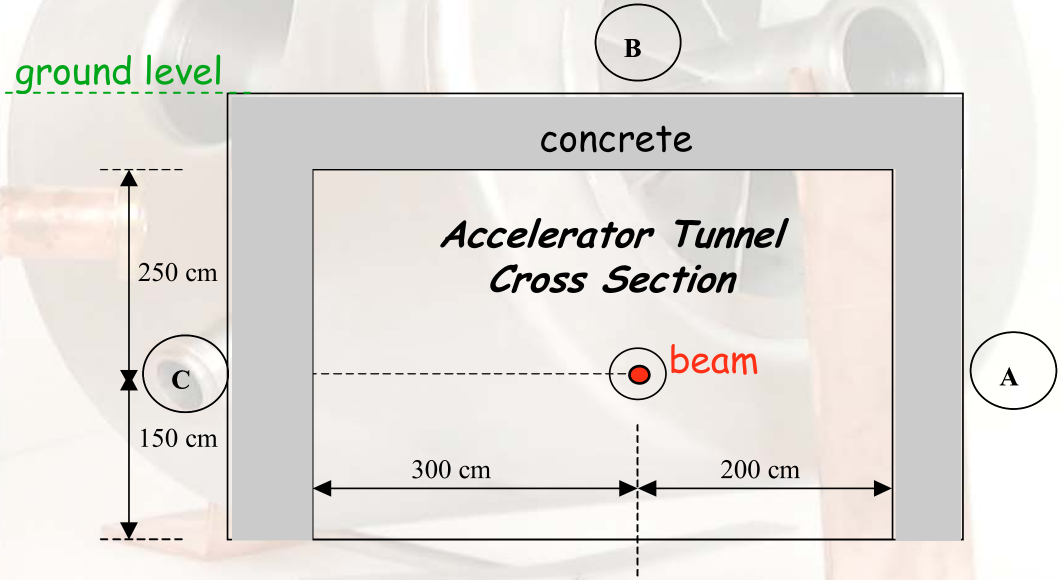
- **Legal framework**
  - Recommendations: ICRP publication 60
  - European Directive 96/29/Euratom
  - European Union: analysis of national legislations
    - Belgium
    - France
    - Germany
  - Very similar requirements from national legislations for an XADS facility, in particular:
    - Public enquiry
    - Decommissioning plan
  - Belgium: more restrictive definition of « radiation worker »

- **Accelerator shielding philosophy based on the ALARA principle**
  - <u>A</u>s <u>L</u>ow <u>A</u>s <u>R</u>easonably <u>A</u>chievable

**study performed within "Deliverable D48" by Paul Berkvens and S.Palanque relying on Moyer's model*

XADS-Accelerator Shielding Design





- **Conservative beam losses assumptions**
  - Normal beam losses
    - RFQ: 3%
    - Intermediate energy: 10 nA/m
    - High energy: 1 nA/m
  - Unwanted beam trips
    - P > 1. 10^{-2} $year^{-1}$ → included in the normal beam losses
    - P < 1. 10^{-2} $year^{-1}$ → "accidental beam losses" case

- **ALARA shielding design criteria**
  - < 1 mSv/year
  - I.e. **< 0.5 µSv/h** (2000 h/year)
  - Occupancy factor = 1

600 MeV XADS:
Shielding for Normal Operation and for Commissioning

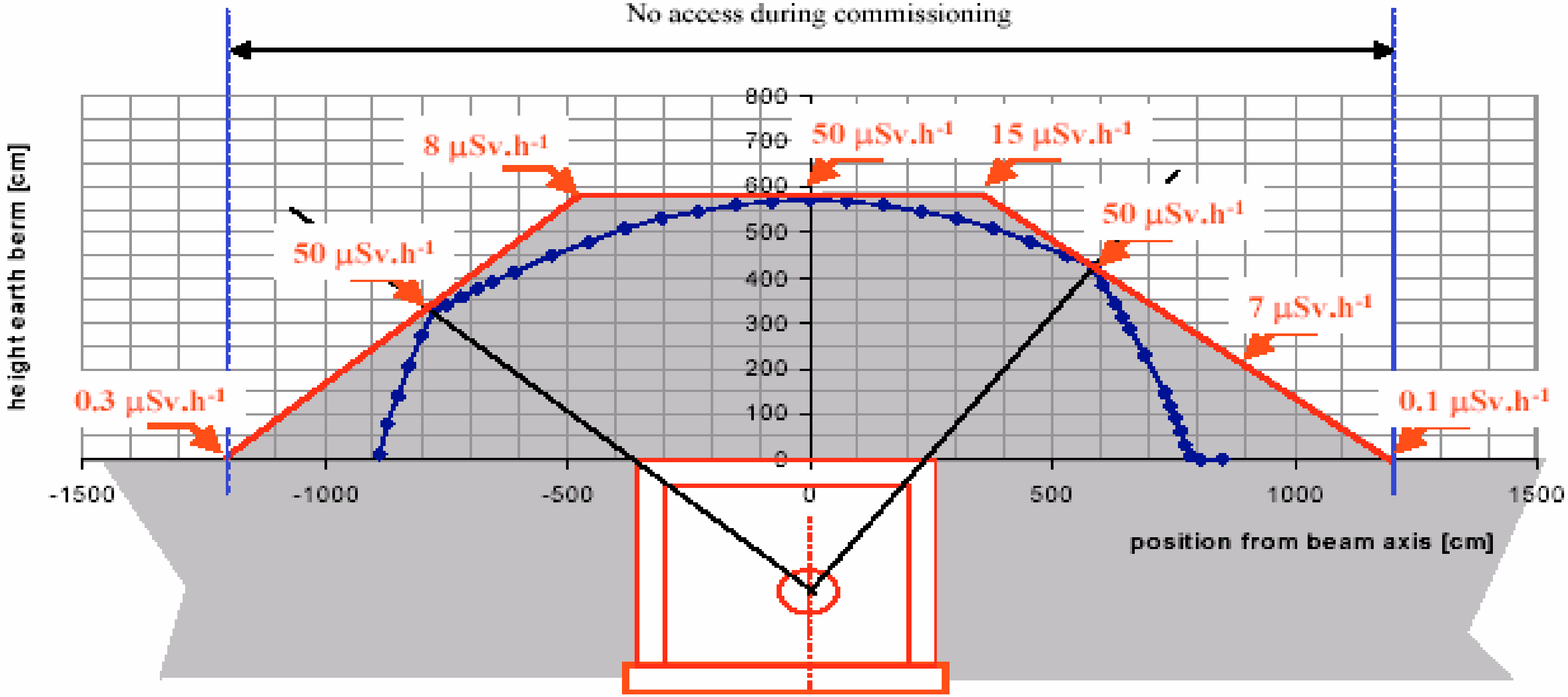
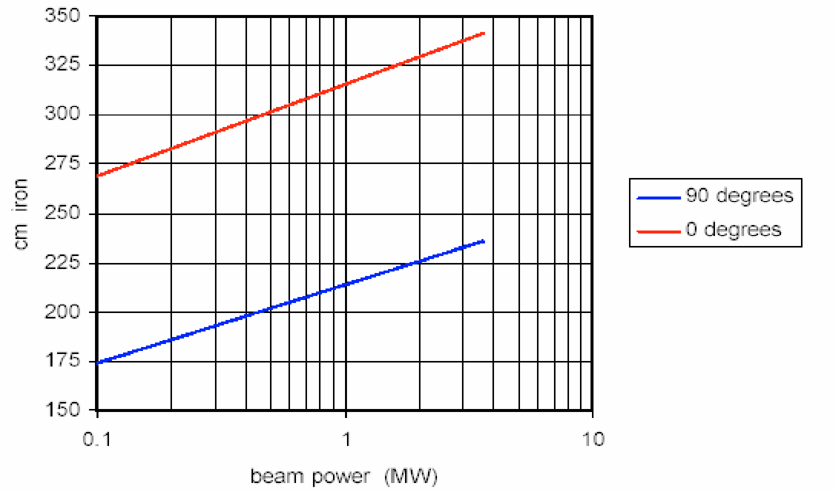
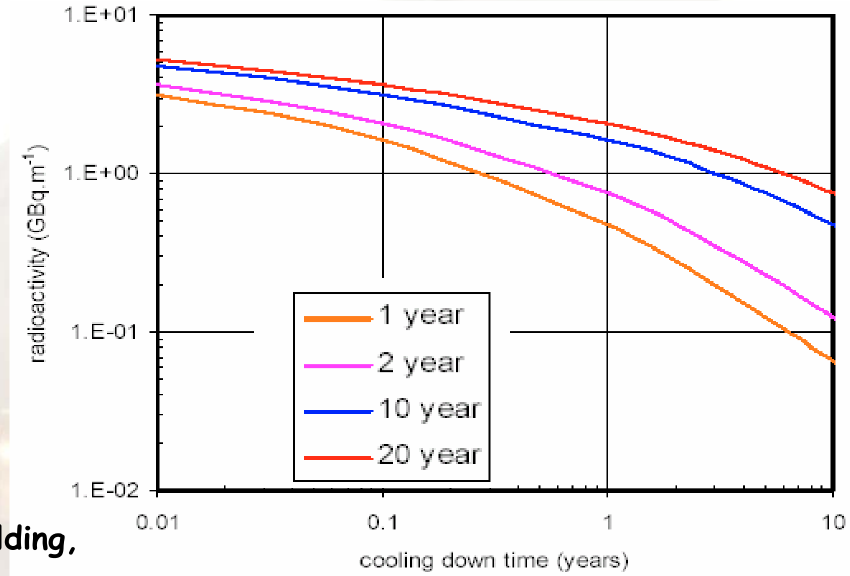


Figure 6.1 – Minimum earth profile above a 60 cm concrete tunnel (blue curve) corresponding to a beam loss rate of 1 nA.m^{-1} at 600 MeV for a residual dose rate of 0.5 □Sv.h^{-1}. Red curve: corresponding realistic earth profile. Dose rates are calculated for a beam loss rate of 100 nA.m^{-1} at 600 MeV.

600 MeV Beam Stop and Accelerator Activation

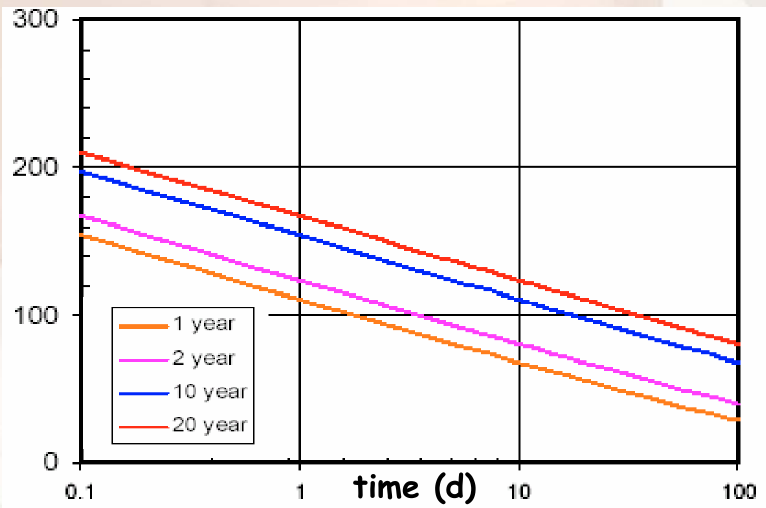


Iron shielding for a 600 MeV beam dump as a function of the beam power,required to reduce the dose rate outside a 60 cm concrete building, covered with 550cm of earth, below 0.5 $\mu Sv.h^{-1}$.



Radioactivity produced per meter along the high-energy part of the accelerator for a 1 $nA.m^{-1}$ beam loss, as a function of the decay time, for 4 different values of the irradiation time.

Dose Rate (μSv/h)



Dose rates at 50 cm from the beam axis, along the high-energy part of the accelerator for a 1 $nA.m^{-1}$ beam loss, as a function of the decay time, for 4 different values of the irradiation time.

Extrapolation to a 1 GeV industrial transmuter

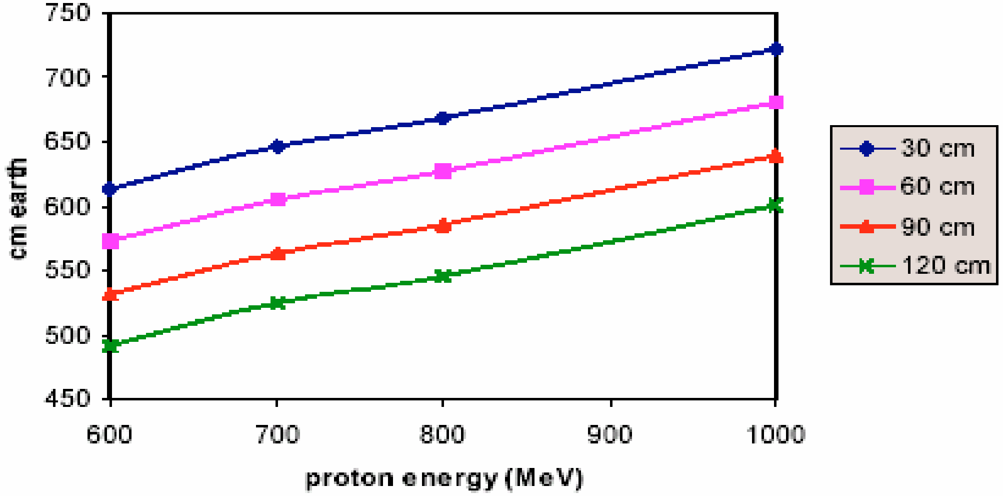


Figure 10.1 - Required earth thickness between 600 MeV and 1 GeV for four different values of the concrete shield wall thickness (30 cm, 60 cm, 90 cm and 120 cm respectively), for a linear beam power loss of 1 nA.m^{-1}.

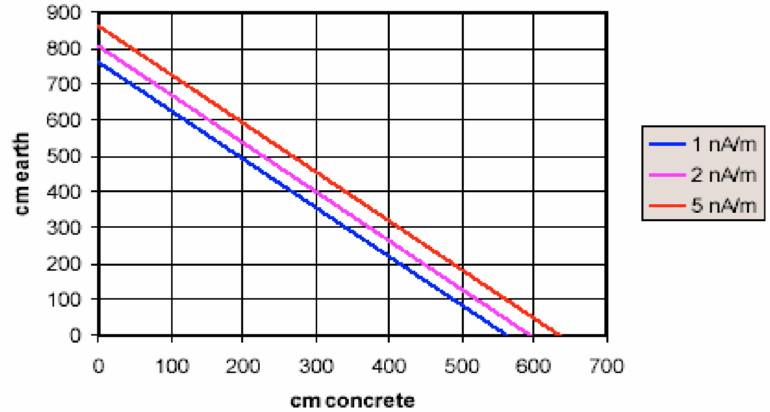


Figure 10.4 - Required concrete / earth combined thickness at 1 GeV, for a distance between the beam axis and the inner shield wall of 200 cm, for three values of the linear beam power loss: 1 nA.m^{-1}, 2 nA.m^{-1} and 5 nA.m^{-1}.

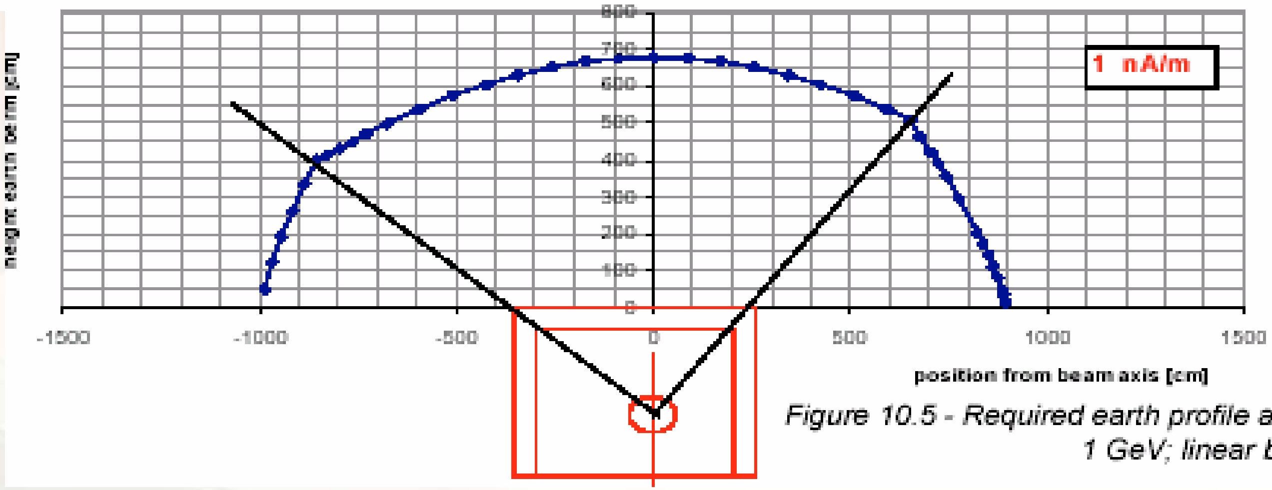
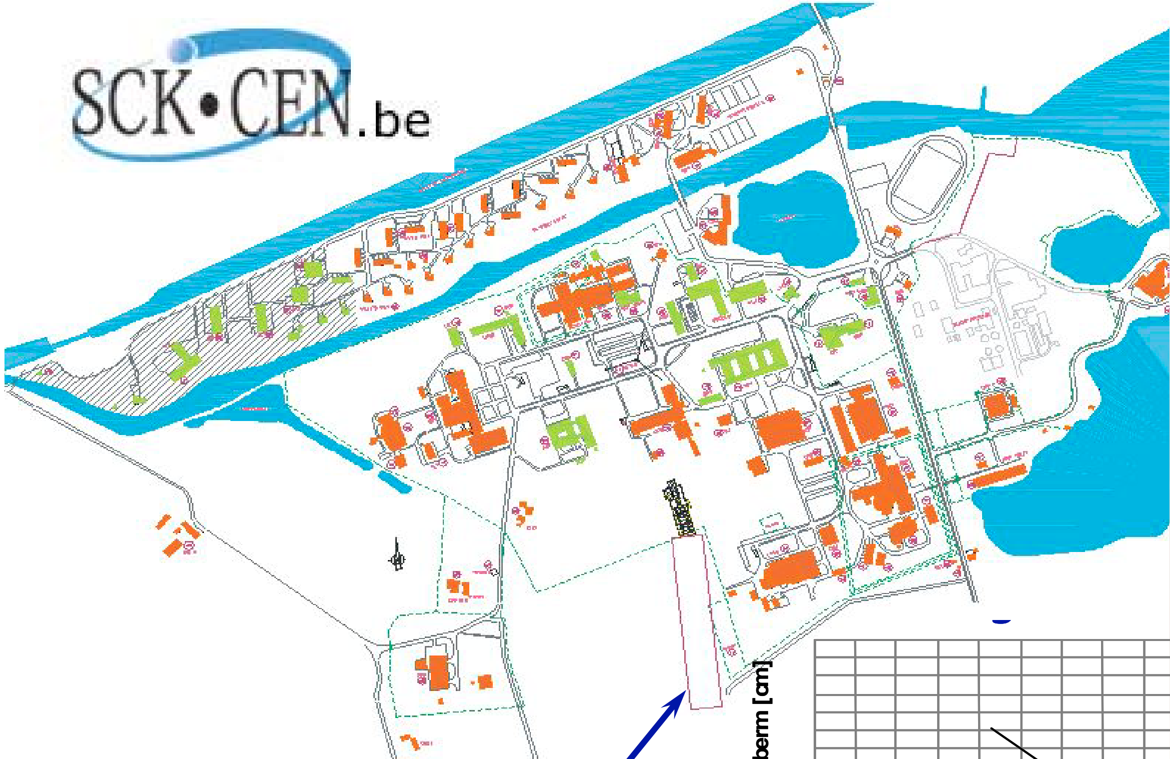


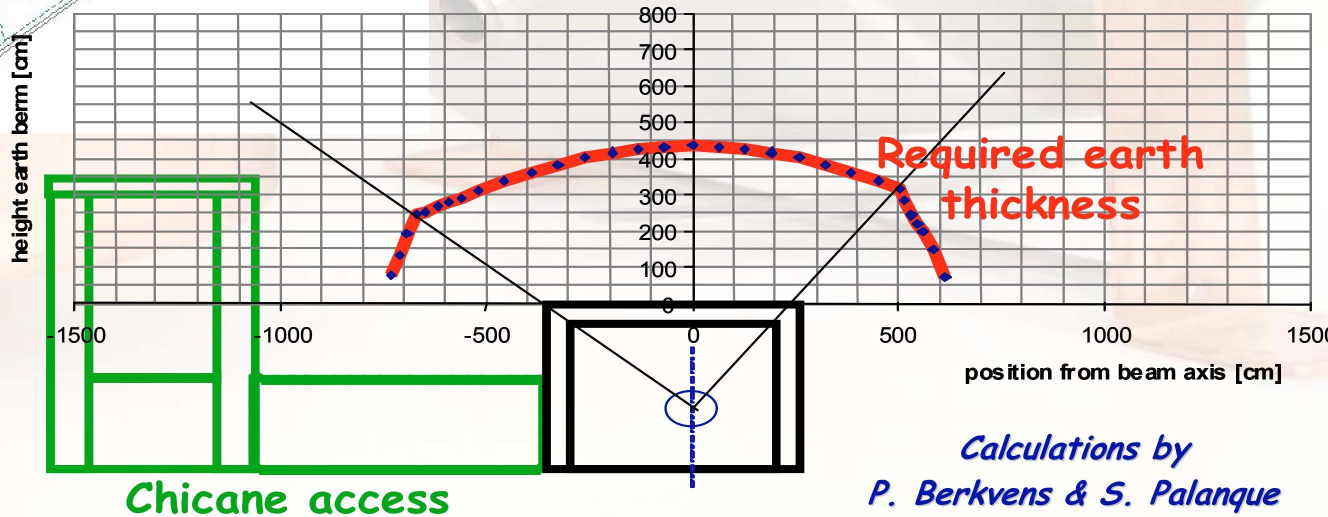
Figure 10.5 - Required earth profile above 60 cm concrete linac tunnel; proton energy: 1 GeV; linear beam loss power: 1 nA.m^{-1}.

Safety Aspects: Application to MYRRHA @ Mol



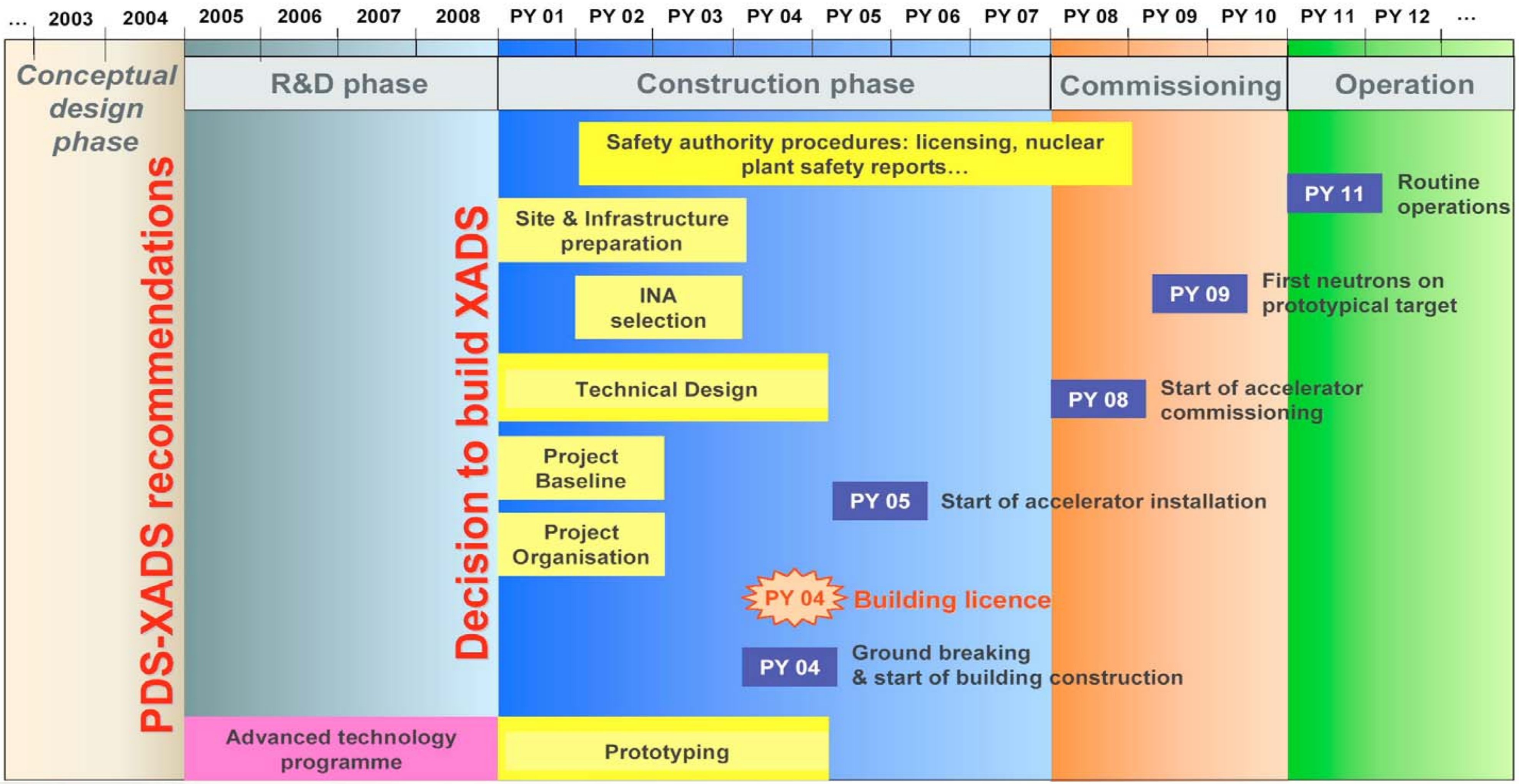
- **The 350 MeV MYRRHA machine**
  - Location on the SCK•CEN site, Mol, Belgium

- **Tunnel design for a 350 MeV XADS linac**
  - **Shielding calculations @ 350 MeV**, 1 nA/m, 0.5 µSv/h
  - Chicane access design
  - Shielding for normal losses also copes with « accidental losses »



Calculations by P. Berkvens & S. Palanque

Roadmap for the XADS-Accelerator (D63)



Cost Estimates for the Accelerator

Major sub-systems	Costs (M€)
Low Energy *	46
Intermediate Energy	18
High Energy	57
RF Power System	45
HEBT + Beam dump (500 kW)	21
Diagnostics + Vacuum + Control System	54
Cryogenic plant	20
Production assembly Hall of cavities	12
Total Estimated Costs (M€)	**273**

* including 2 Injector lines

- Includes internal and external man-power
- does not include purchase of land, basic infrastructures (roads, office buildings, cantine, water and electricity to the boundary of the site……)

Remarks:

1) 350 MeV cheaper
2) does an XT-ADS need double injector?
3) Possible savings from a well suited site

Buildings	Civil Engineering	Electricity & HVAC distrib.	Total
Front - End	7 000	3 000	**10 000**
Linac tunnel	4 500	1 500	**6 000**
Klystron Hall	3 000	7 000	**10 000**
Central Liquifier	600	900	**1 500**
Production assembly Hall	1 250	1 250	**2 500**
Total (k€)	**16 350**	**13 650**	**30 000**

Optimisation of Accelerator Reliability for ADS

RF systems have been identified as one of the critical areas*:

- Uncertainties on MTBF (most by engineering judgement)
- Not enough operation of 700 MHz CW RF sources
- Several subcomponents with low MTBF
- High "parts count"

1 RF system each cavity.
Redundancy (at expenses of operational cost and complexity)

If all are in series $MTBF_{series} = MTBF_{comp}/N$

Need to achieve fault tolerance to RF faults

*nb: this is true for all RF accelerators

Optimisation of Accelerator Reliability for ADS

Critical area: the RF system

Group	Components	Typical MTBF
Tubes (power amplifier)	Klystrons, IOT, Solid State	~ 50 000 h
RF power components	Windows, waveguides, circulators, loads	50 000…150 000 h
Low Level RF	Pre-amps, VCO, mixers, phase shifters	100 000 h
Transmitters	Auxiliary PS, interlocks, monitoring	5 000 … 10 000 h
HVPS	Oil tanks, HV passive components	20 000…50 000 h

Component **SNS**	Number	MTBF, khr	Failures year	MTTR, hr	Down Time/ year, hr
Klystron	81	50	9.72	4.5	43.7
Wave Guide	81	150	3.24	3.0	9.72
Load	81	75	6.48	3.0	19.4
Circulator	81	50	9.72	3.0	29.2
Converter/ Modulator	7	22.6	1.86	4.0	7.43
Transmitter	14	5.6	15	3.0	45.0
Window	81	100	4.68	24.0	116.6
LLRF	81	100	4.68	2.0	9.73
Totals			55.7		280.8

Table 4. Down time allocation for the 805 MHz, Super Conducting (SRF) RF System.

Optimisation of Accelerator Reliability for ADS

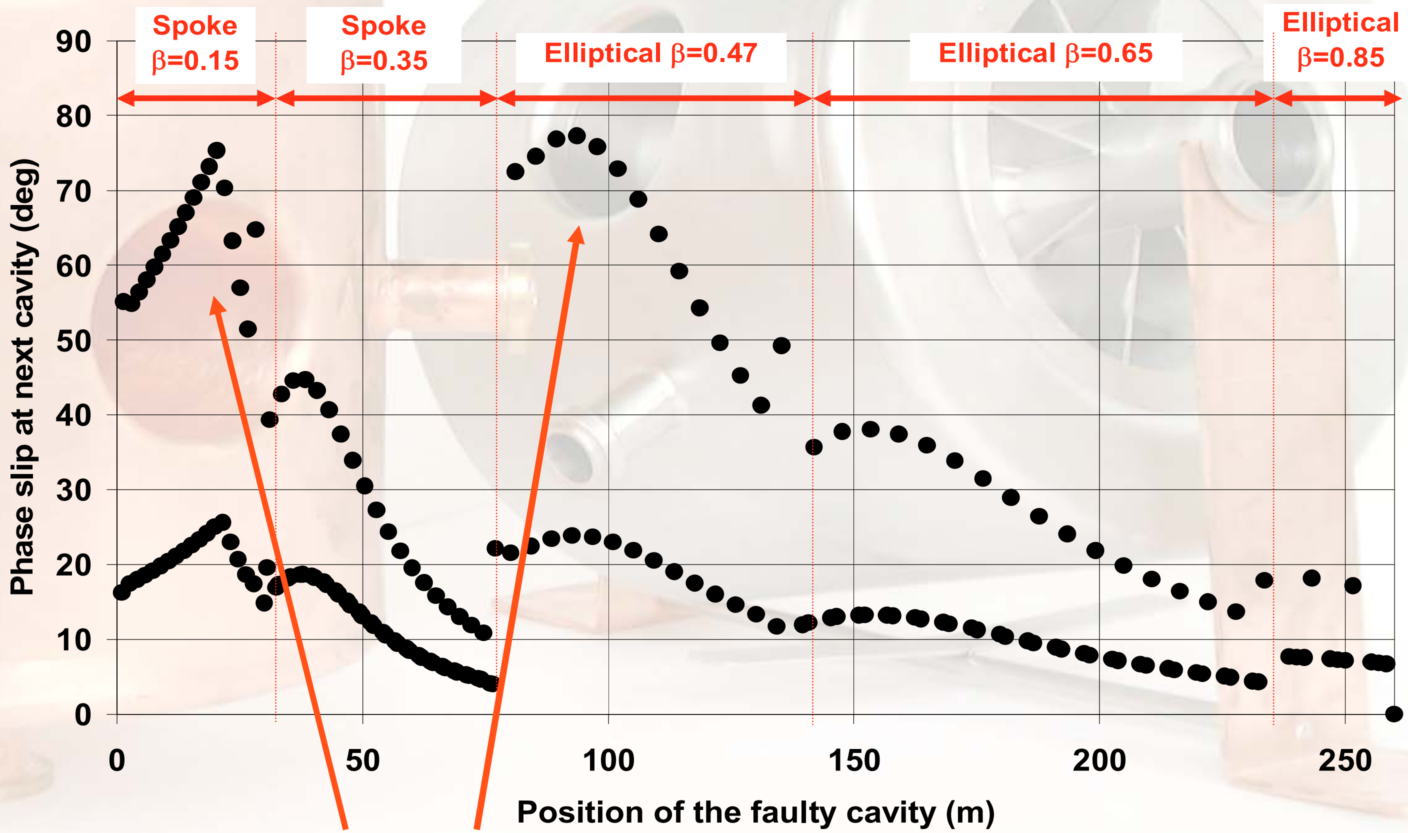
Consequences of cavity failure

We have a non-relativistic proton beam

Any energy loss will imply a phase slip along the linac increasing with the distance, beam can get out of stability region

$$\delta\varphi = 2\pi\left(\frac{\delta z}{\lambda}\right)\left(\frac{\delta\beta}{\beta^2}\right)$$

β is the beam velocity
λ the RF wavelength
$\delta\beta$ the velocity loss at δz

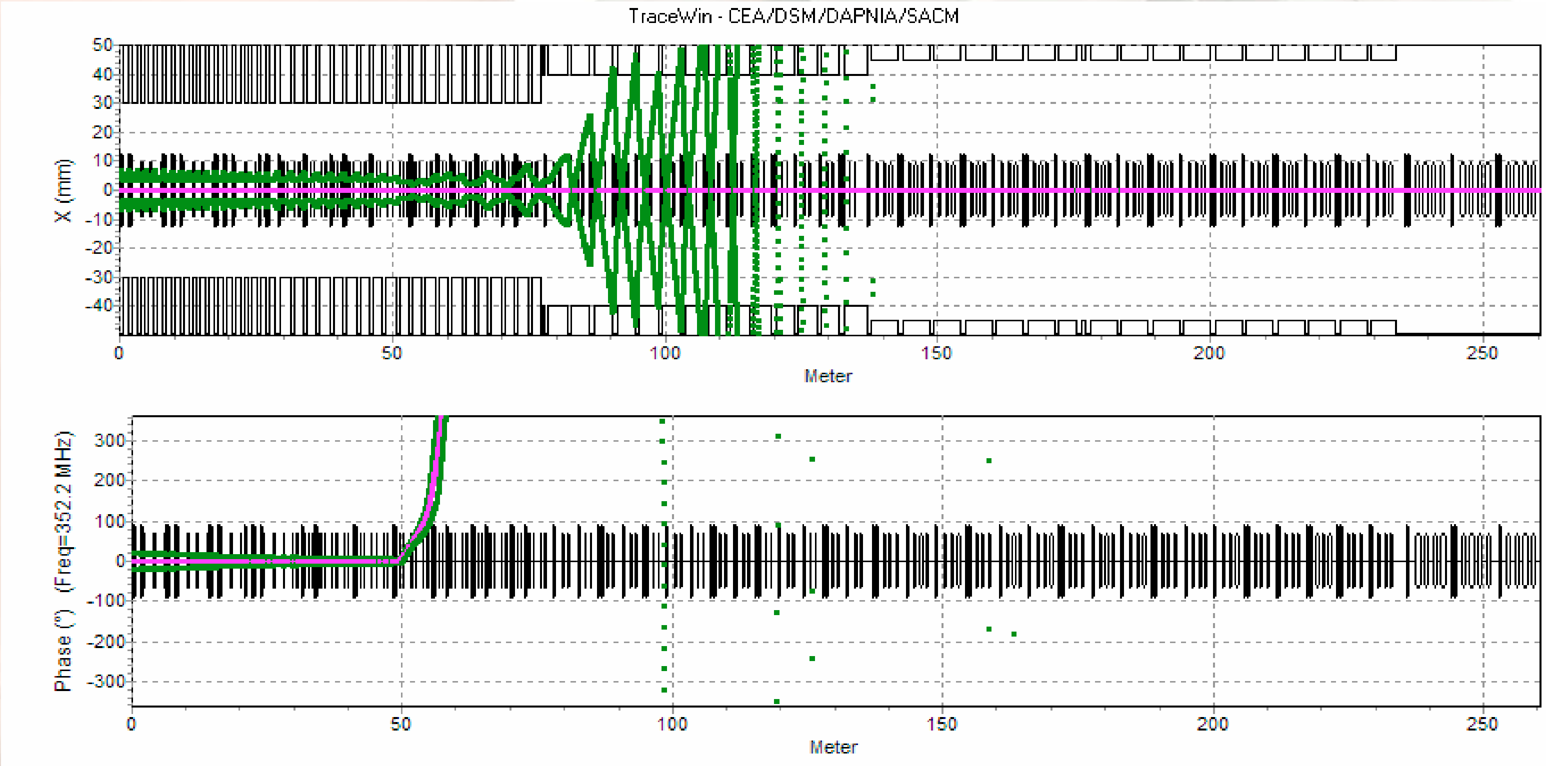


most critical sections

Optimisation of Accelerator Reliability for ADS

Consequences of cavity failure

If the synchronous phase or/and the accelerating field is too high, the beam is TOO LATE & leaves the stability region: the beam is lost



Beam dynamics simulation with TraceWin

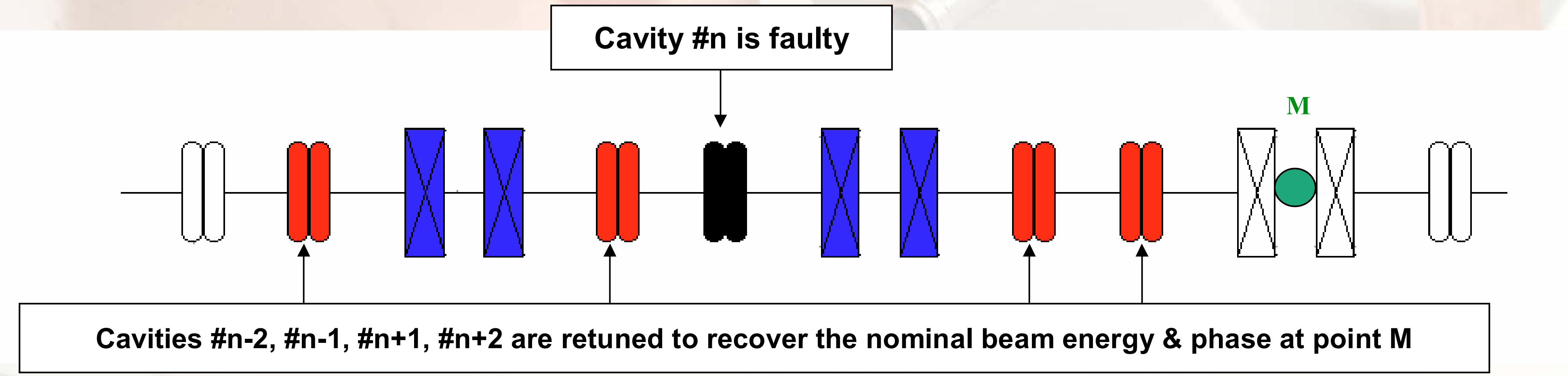
Optimisation of Accelerator Reliability for ADS

Need to have linac design that can handle the loss of one or several cavities

The modularity of our LINAC makes this possible because we have INDEPENDENTLY PHASED structures

We need to find procedure that use the neighbouring cavities to compensate phase/energy beam offset

These procedures should then be integrated in RF control system

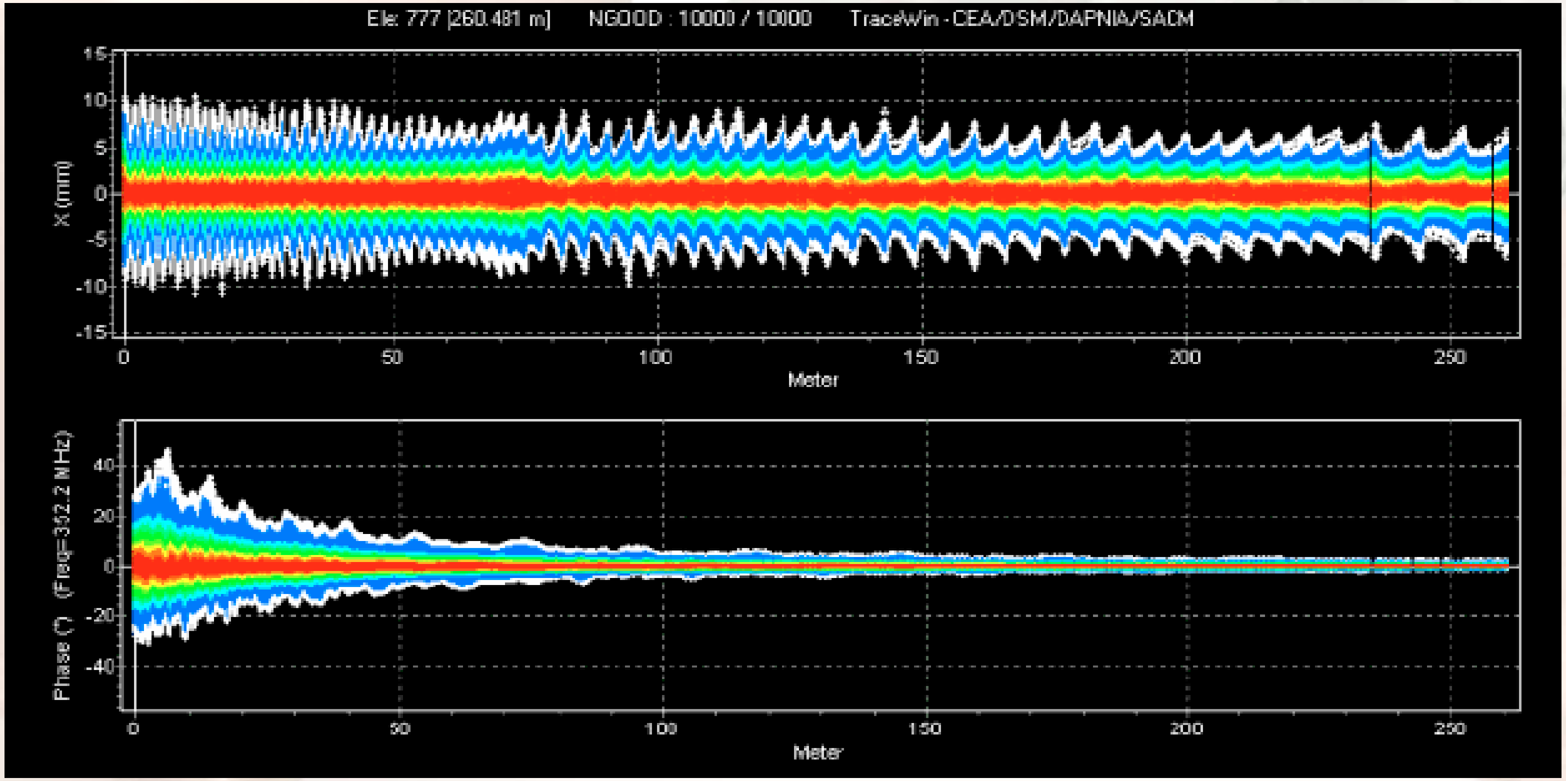


Optimisation of Accelerator Reliability for ADS

After retuning correct number of neighboring cavities

Amplitude

Phase



Fault-tolerance: Cavity retuning (Biarrotte & thesis Lukovac)

Study has been applied to **most representative cavities in all in all sections** (beginning, half and end of each section)

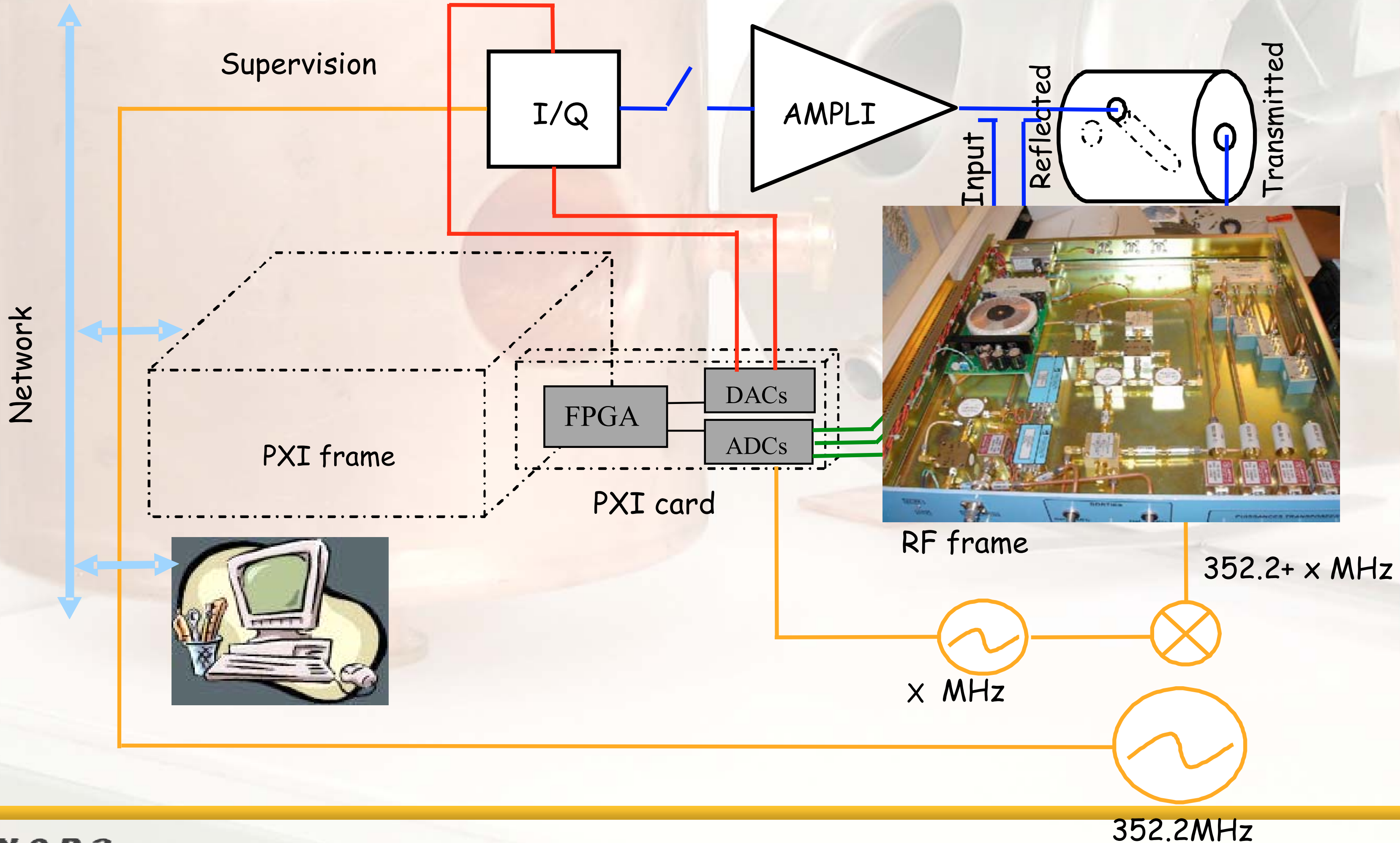
In every case, the beam can be transported up to high energy with 100% transmission, small emittance growths, nominal parameters

Only for E < 10 MeV increase above 30% is necessary

# faulty cavity	section	Final energy	Emittance growth (%) Transv.	Emittance growth (%) Long.	# of retuned cavities (bef + aft)	Max ΔEacc (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max ΔPower (%)	# retuned quads (bef + aft)
0	-	Nominal	+ 5 %	0 %	-	-	-	-	-
1	SP 0.15	Nominal	+ 7 %	+ 4 %	0 + 4	+ 67 %	19 MV/m	+ 67 %	0 + 4
2	SP 0.15	Nominal	+ 9 %	+ 12%	1 + 3	+ 90 %	19 MV/m	+ 68 %	0 + 4
3	SP 0.15	Nominal	+ 10%	+ 12%	2 + 3	+ 94 %	21 MV/m	+ 56 %	4 + 2
4	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 3	+ 46 %	15 MV/m	+ 35 %	2 + 4
19	SP 0.15	Nominal	+ 6 %	+ 6 %	2 + 3	+ 38 %	24 MV/m	+ 48 %	2 + 2
20	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 2	+ 37 %	26 MV/m	+ 58 %	2 + 2
35	SP 0.15	Nominal	+ 6 %	0 %	2 + 3	+ 20 %	32 MV/m	+ 27 %	2 + 2
36	SP 0.15	Nominal	+ 7 %	+ 4 %	3 + 3	+ 22 %	34 MV/m*	+ 32 %	2 + 2
37	SP 0.35	Nominal	+ 6 %	0 %	3 + 2	+ 22 %	35 MV/m*	+ 34 %	2 + 2
38	SP 0.35	Nominal	+ 7 %	+ 6 %	3 + 4	+ 29 %	31 MV/m	+ 26 %	2 + 2
39	SP 0.35	Nominal	+ 5 %	+ 5 %	4 + 2	+ 24 %	36 MV/m*	+ 35 %	4 + 2
61	SP 0.35	Nominal	+ 6 %	+ 2 %	2 + 3	+ 25 %	31 MV/m	+ 26 %	2 + 2
62	SP 0.35	Nominal	+ 6 %	0 %	2 + 2	+ 26 %	31 MV/m	+ 28 %	2 + 2
63	SP 0.35	Nominal	+ 5 %	+ 1 %	3 + 2	+ 25 %	31 MV/m	+ 27 %	2 + 2
94	SP 0.35	Nominal	+ 6 %	+ 2 %	3 + 3	+ 16 %	29 MV/m	+ 18 %	4 + 2
95	SP 0.35	Nominal	+ 7 %	- 1 %	3 + 3	+ 22 %	31 MV/m	+ 29 %	4 + 2
96	SP 0.35	Nominal	+ 5 %	+ 1 %	4 + 2	+ 21 %	30 MV/m	+ 25 %	4 + 2
97	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 18 %	59 mT	+27 %	4 + 2
98	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 23 %	62 mT	+ 31 %	4 + 2
109	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 20 %	60 mT	+ 28 %	4 + 2
110	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 20 %	60 mT	+ 29 %	2 + 2
123	EL 0.47	Nominal	+ 6 %	0 %	2 + 4	+ 20 %	60 mT	+ 26 %	4 + 2
124	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 19 %	60 mT	+ 28 %	4 + 2
125	EL 0.65	Nominal	+ 5 %	0 %	2 + 3	+ 18 %	59 mT	+ 27 %	4 + 2
126	EL 0.65	Nominal	+ 5 %	0 %	3 + 4	+ 21 %	61 mT	+ 20 %	4 + 2
127	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 21 %	61 mT	+ 25 %	4 + 2
146	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
147	EL 0.65	Nominal	+ 6 %	- 1 %	3 + 4	+ 19 %	60 mT	+ 22 %	4 + 2
148	EL 0.65	Nominal	+ 6 %	- 1 %	3 + 3	+ 20 %	60 mT	+ 22 %	4 + 2
173	EL 0.65	Nominal	+ 5 %	0 %	3 + 4	+ 17 %	59 mT	+ 19 %	4 + 2
174	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
175	EL 0.65	Nominal	+ 5 %	0 %	4 + 4	+ 17 %	59 mT	+ 18 %	4 + 2
176	EL 0.85	Nominal	+ 5 %	0 %	3 + 5	+ 18 %	59 mT	+ 22 %	4 + 2
177	EL 0.85	Nominal	+ 5 %	0 %	4 + 4	+ 18 %	59 mT	+ 20 %	4 + 2
178	EL 0.85	Nominal	+ 5 %	0 %	5 + 4	+ 18 %	59 mT	+ 19 %	4 + 2
179	EL 0.85	Nominal	+ 5 %	0 %	6 + 4	+ 17 %	59 mT	+ 16 %	4 + 2
184	EL 0.85	Nominal	+ 5 %	0 %	4 + 3	+ 17 %	59 mT	+ 29 %	2 + 2
185	EL 0.85	Nominal	+ 6 %	0 %	5 + 2	+ 19 %	60 mT	+ 30 %	2 + 2
186	EL 0.85	Nominal	+ 7 %	0 %	6 + 1	+ 21 %	61 mT	+ 33 %	2 + 2
187	EL 0.85	Nominal	+ 6 %	0 %	7 + 0	+ 25 %	63 mT	+ 37 %	2 + 2

Fault tolerance: Low Level RF Fast Feedback System

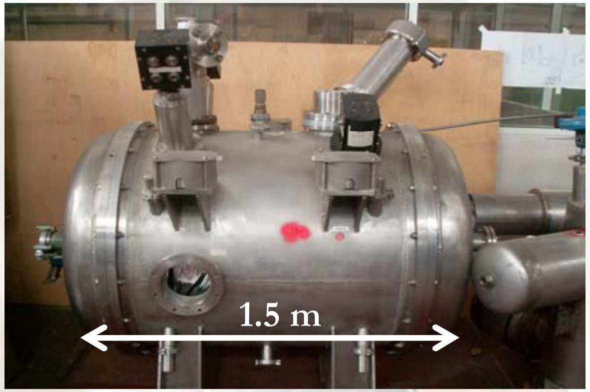
Collaboration IPN Orsay and LPNHE Paris

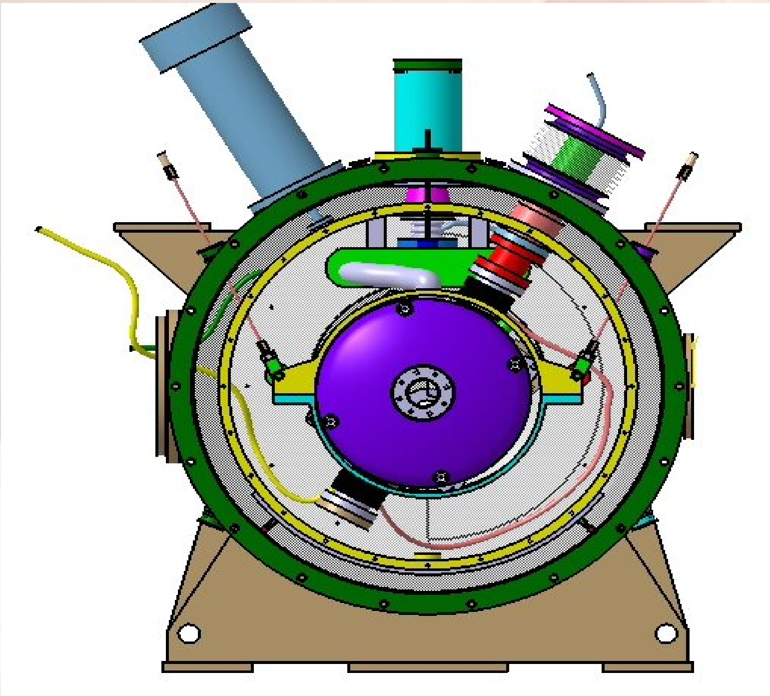


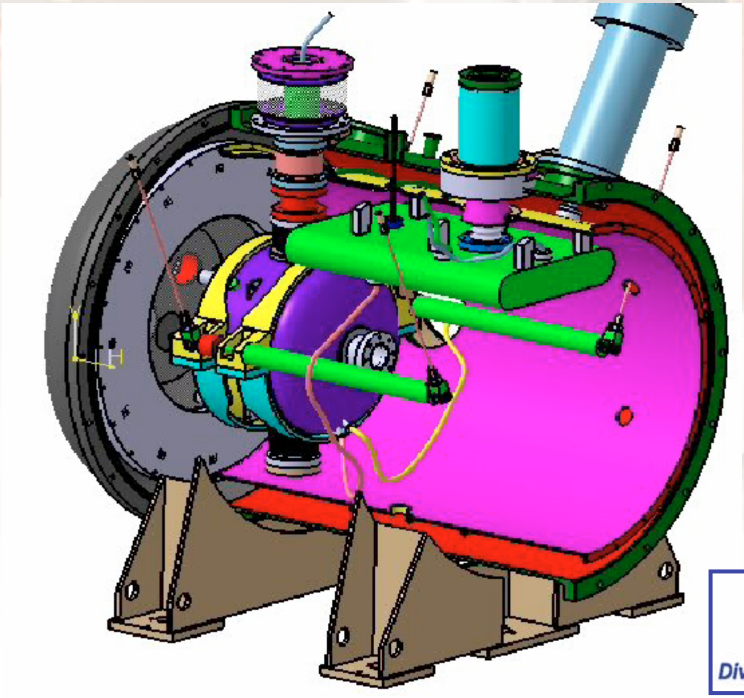
Optimisation of Accelerator Reliability for ADS

one selected example:

Tests of all components for a cryomodule :
LLRF digital system + RF power coupler + SPOKE cavity in horizontal cryostat foreseen for beginning 2007

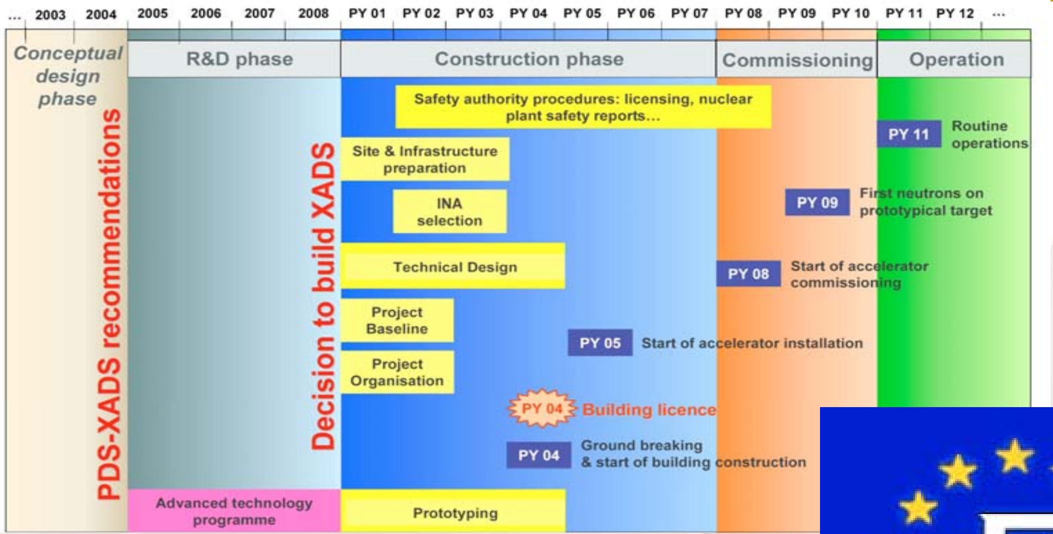






IPN Orsay Division Accélérateurs

From FP5 PDS-XADS to FP6 EUROTRANS



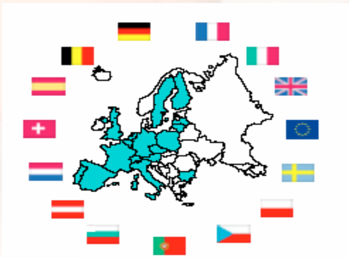
done within

FI6W-CT-2004-516520
Integrated Project
On European Transmutation
(EUROTRANS)

EUROTRANS

- EUROPEAN RESEARCH PROGRAMME FOR THE TRANSMUTATION OF HIGH LEVEL - NUCLEAR WASTE IN AN ACCELARATOR DRIVEN SYSTEM

FZK
AAA
ANSALDO
Nexia Solutions
CEA
CIEMAT
CNRS
CRS4
CSIC
EA
ENEA
ENEN
FANP SAS
FZJ
FZR



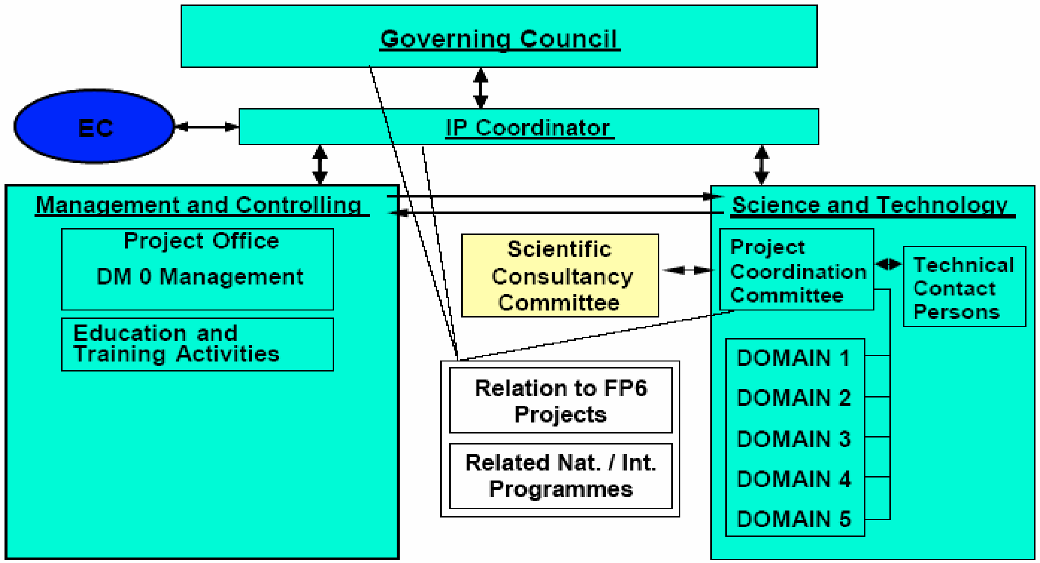
GSI
IBA
INFN
INRNE
ITN
JRC
NRG
NRI
OTL
PSI
SCK-CEN
Suez-Tractebel
FANP GmbH
NNC

From FP5 PDS-XADS to FP6 EUROTRANS

FP	Design Concepts			Objectives
FP5	**XADS (Pb-Bi)** 80 MW(th) 110 W/cm single batch loading	**XADS (Gas)** 80 MW(th) 250 W/cm single batch loading	**MYRRHA (Pb-Bi)** 50 MW(th) 500 W/cm multi batch loading	**XADS** Demonstration of technological feasibility of an ADS system
FP6	**European Transmutation Demonstration (ETD)** advanced design conceptual design, economics, scalability	**XT-ADS** < 100 MW(th) 250 - 300 W/cm multi batch loading		**XT-ADS** Short-term demonstration of transmutation on a sizable scale and of the ADS behaviour
		EFIT Several 100 MW(th) 250 - 300 W/cm multi batch loading		**EFIT** Long-term transmutation on an industrial scale

EUROTRANS-PCC: Tasks & Members

J.U. Knebel (FZK), coordinator
H.A. Abderrahim (SCK), DM1 Design
S. Monti (ENEA), DM2 ECATS
S. Pillon (CEA), DM3 AFTRA
C. Fazio (FZK), DM4 DEMETTRA
E. Gonzalez (CIEMAT), DM5 NUDATRA
B. Giraud (FANP), Industry
L. Cinotti (ANSALDO), Industry
A.C. Mueller (CNRS), Accelerator
M. Giot (ENEN), Universities



- Technical co-ordination of the project work programme,
- Preparation, where necessary, of revisions to the detailed work programmes,
- Approval of the IP Instruction Book and the QA Guidelines,
- Preparation of the updated Implementation Plan and associated financial plan for the EC,
- Identification of technical and scientific problems and/or issues,
- Identification of technical developments, which are related to patents and the development of design, component or process issues,
- Review and approve the contractually required interim and progress reports,
- Proposing technical workshops, technical meetings, etc.

The accelerator within EUROTRANS-DM1

WP1.3: ACCELERATOR

GOAL:

HPPA development, and in particular, qualification of the reliability of the prototypical components

CO-ORDINATING CONTRACTOR:

CNRS (F) – *Alex C. Mueller*

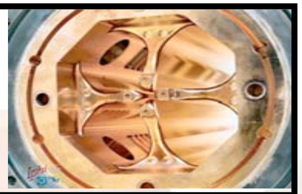
DM1 DESIGN WP1.3 - Accelerator	**TOTAL WP1.3**			
	Cons. k€	PM	Total k€	*EU request k€*
P5-CEA (F)	170	67	**840**	*420.0*
P8-CNRS (F)	180	138	**1560**	*780.0*
P13.4-IAP-FU (D)	75	27	**345**	*172.5*
P13.12-UPM (SP)	3	4	**43**	*21.5*
P18-IBA (B)	182	20	**382**	*191.0*
P19-INFN (I)	480	65	**1130**	*565.0*
P21-ITN (P)	10	10	**110**	*55.0*
P31-FANP GmbH (D)	3	2	**23**	*11.5*
Total WP1.3	**1103**	**333**	**4433**	*2216.5*

1 PM = 10k€

RED: *Leading Organization in this Work Package*

Injector Reliability

TASK 1.3.1



DM1 DESIGN WP1.3 - Accelerator	Task 1.3.1 Experimental evaluation of the proton injector reliability		
	Cons. k€	PM	Total k€
P5-CEA (F)	140	38	520
P8-CNRS (F)	0	15	150
P13.4-IAP-FU (D)	0	0	0
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	0	0	0
P19-INFN (I)	0	0	0
P21-ITN (P)	0	0	0
P31-FANP GmbH (D)	0	0	0
Total WP1.3	140	53	670

GOAL:

The injector IPHI, developed by CEA and CNRS, will be used for a long run test to demonstrate on a real scale the reliability of the injector part.

CO-ORDINATING CONTRACTOR:

CEA (F) – *Raphaël Gobin*

MILESTONES:

M1.3.1: Specifications for the long test run (+9)

M1.3.2: Injector operational for test (+18)

M1.3.3: Experimental tests accomplished (+36)

M1.3.4: Final report: results and analysis (+39)

DELIVERABLES:

D1.3.1: Preliminary short report. Specifications of the long test runs (CEA, +9)

D1.3.2: Intermediate progress report on injector status and proposed test schedule (CEA, +18)

D1.3.3: Final report on results and analysis (CEA, +39)

Intermediate-energy Section

TASK 1.3.2

GOAL:

Evaluation of room-temperature cavities and superconducting cavities performances, reliability and cost. Determination of the energy transition from where on doubling of the injector is no longer required for reliability.

CO-ORDINATING CONTRACTOR:

CNRS (F) – *Tomas Junquera*

MILESTONES:

M1.3.5: Specifications for prototypes (+6)

M1.3.6: Prototypes ready for test (+27)

M1.3.7: Experimental results of prototypes performances (+39)

M1.3.8: Final report: synthesis and design proposals (+42)

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.2 Assessment of the reliability performances of the intermediate energy accelerating components		
	Cons. k€	PM	Total k€
P5-CEA (F)	0	1	10
P8-CNRS (F)	50	24	290
P13.4-IAP-FU (D)	70	24	310
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	170	15	320
P19-INFN (I)	0	0	0
P21-ITN (P)	0	0	0
P31-FANP GmbH (D)	0	0	0
Total WP1.3	**290**	**64**	**930**

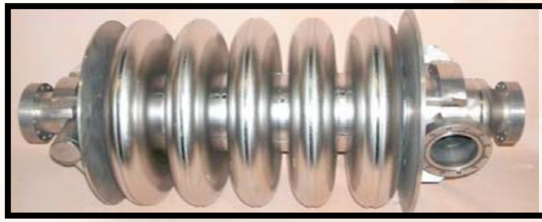
DELIVERABLES:

D1.3.4: Preliminary report. Specifications of the prototypes (IAP_FU, +6)

D1.3.5: Intermediate report on prototype test schedules (IBA, +18)

D1.3.6: Final report: tests results, synthesis and design proposals (CNRS, +42)

High-energy Section



TASK 1.3.3

GOAL:

Design, construction and test of a full prototypical cryomodule of the high energy section of the proton linac.

CO-ORDINATING CONTRACTOR:

INFN (I) – *Paolo Pierini*

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.3 Qualification of the reliability performances of a high energy cryomodule at full power and nominal temperature		
	Cons. k€	PM	Total k€
P5-CEA (F)	0	1	10
P8-CNRS (F)	100	80	900
P13.4-IAP-FU (D)	0	0	0
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	0	0	0
P19-INFN (I)	440	60	1040
P21-ITN (P)	0	5	50
P31-FANP GmbH (D)	0	0	0
Total WP1.3	540	146	2000

MILESTONES:

M1.3.9: Preliminary cryomodule specifications (+9)

M1.3.10: Cryomodule design finalized (+15)

M1.3.11: Cryomodule is ready for test (+30)

M1.3.12: Exptl. results of cryomodule performances (+39)

M1.3.13: Final report: synthesis and design proposals (+42)

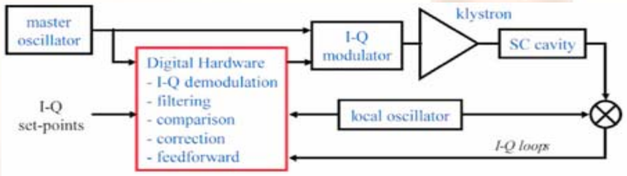
DELIVERABLES:

D1.3.7: Preliminary report: specifications for the cryomodule (INFN, +9)

D1.3.8: Report on cryomodule design and schedule (CNRS, +15)

D1.3.9: Final report: test results, synthesis and design proposals (INFN, +42)

Digital RF Control



TASK 1.3.4

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.4 Conceptual design of an RF control system for fault tolerant operation of the linear accelerator		
	Cons. k€	PM	Total k€
P5-CEA (F)	10	15	160
P8-CNRS (F)	0	5	50
P13.4-IAP-FU (D)	0	0	0
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	0	1	10
P19-INFN (I)	10	0	10
P21-ITN (P)	0	0	0
P31-FANP GmbH (D)	0	0	0
Total WP1.3	20	21	230

GOAL:

Modelling and VHDL analysis of a digital RF control system fault tolerant operation of the linear accelerator. *(Prototyping an RF control unit is strongly recommended)*

CO-ORDINATING CONTRACTOR:

CEA (F) – *Michel Luong*

MILESTONES:

M1.3.14: Preliminary RF control system specifications (+6)

M1.3.15: RF control system modelling (+24)

M1.3.16: Final report: VHDL architecture and synthesis (+42)

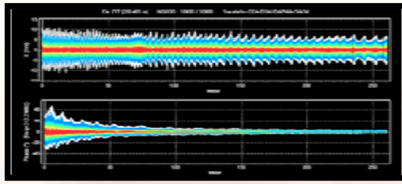
DELIVERABLES:

D1.3.10: Preliminary specifications of the RF control system (CEA, +6)

D1.3.11: Report on RF control system modelling (CEA, +24)

D1.3.12: Final report: VHDL architectures and synthesis (CEA, +42)

Beam Dynamics and Overall Coherence



TASK 1.3.5

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.5 Overall coherence of the accelerator design, final reliability analysis, cost estimation of XT-ADS and EFIT		
	Cons. k€	PM	Total k€
P5-CEA (F)	20	12	140
P8-CNRS (F)	30	14	170
P13.4-IAP-FU (D)	5	3	35
P13.12-UPM (SP)	3	4	43
P18-IBA (B)	12	4	52
P19-INFN (I)	30	5	80
P21-ITN (P)	10	5	60
P31-FANP GmbH (D)	3	2	23
Total WP1.3	**113**	**49**	**603**

GOAL:

Overall coherence of the accelerator design, including beam dynamics simulations, integrated reliability analysis, and cost estimation.

CO-ORDINATING CONTRACTOR:

CNRS (F) – *Jean-Luc Biarrotte*

MILESTONES:

M1.3.17: General specifications (+6)
M1.3.18: WP1.3 overall task review (+18)
M1.3.19: Results of beam dynamic simulations (+30)
M1.3.20: Reliability study experimental results (+39)
M1.3.21: Integrated reliability analysis (+45)
M1.3.22: Cost Analysis (+45)
M1.3.23: Final report (+48)

DELIVERABLES:

D1.3.13: General specifications for all the tasks (CNRS, +6)

D1.3.14: Beam dynamics simulations for fault tolerance (CNRS, +30)

D1.3.15: Report on integrated reliability analysis of the accelerator (INFN, +48)

D1.3.16: Final report: accelerator design, performances, costs for XT-ADS and EFIT and associated road map (CNRS, +48)