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School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

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Accelerators for ADS: Science, Technology and Design.
Part I

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Accelerators for ADS:
Science, Technology and Design

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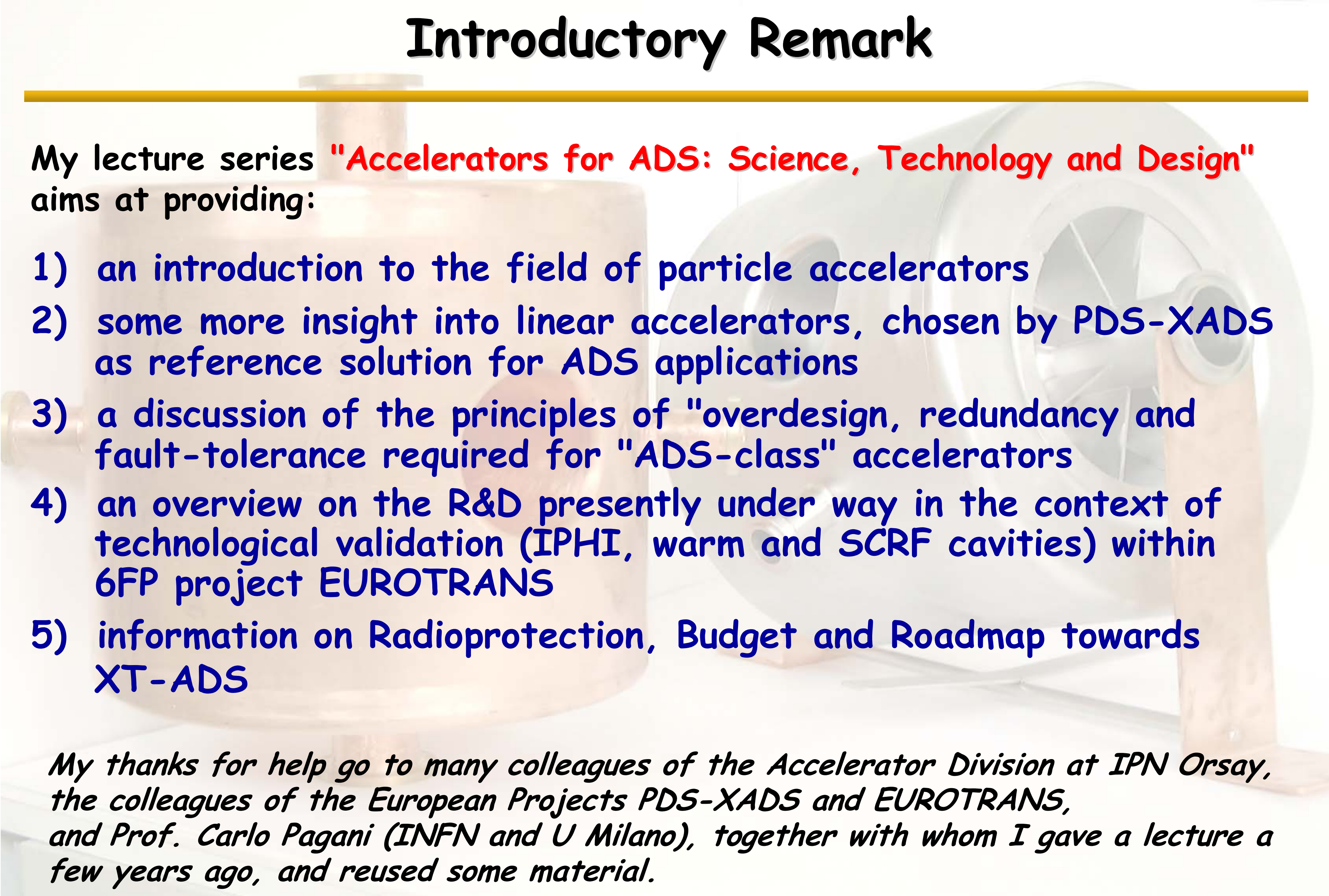
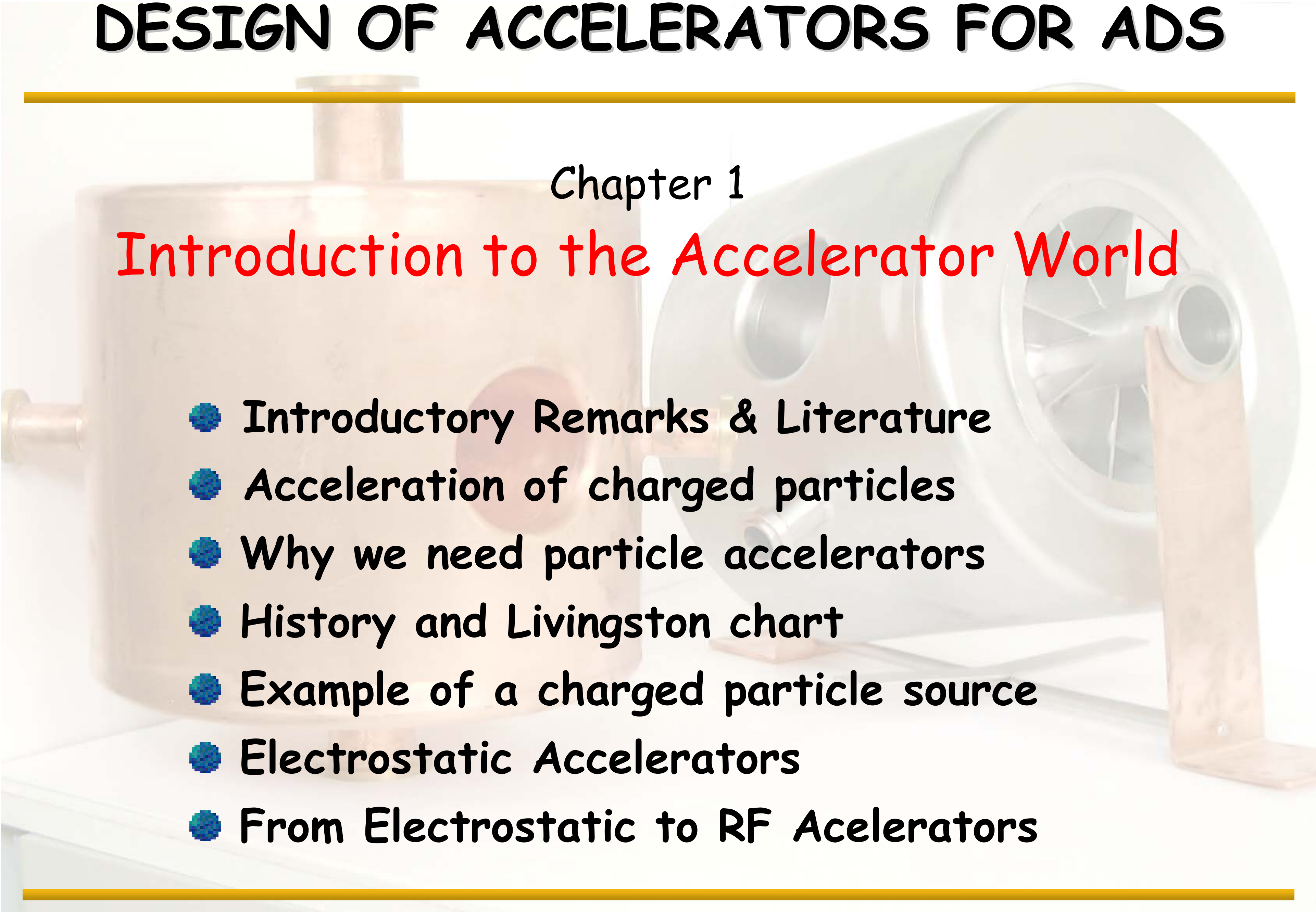


Introductory Remark

My lecture series "Accelerators for ADS: Science, Technology and Design" 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.

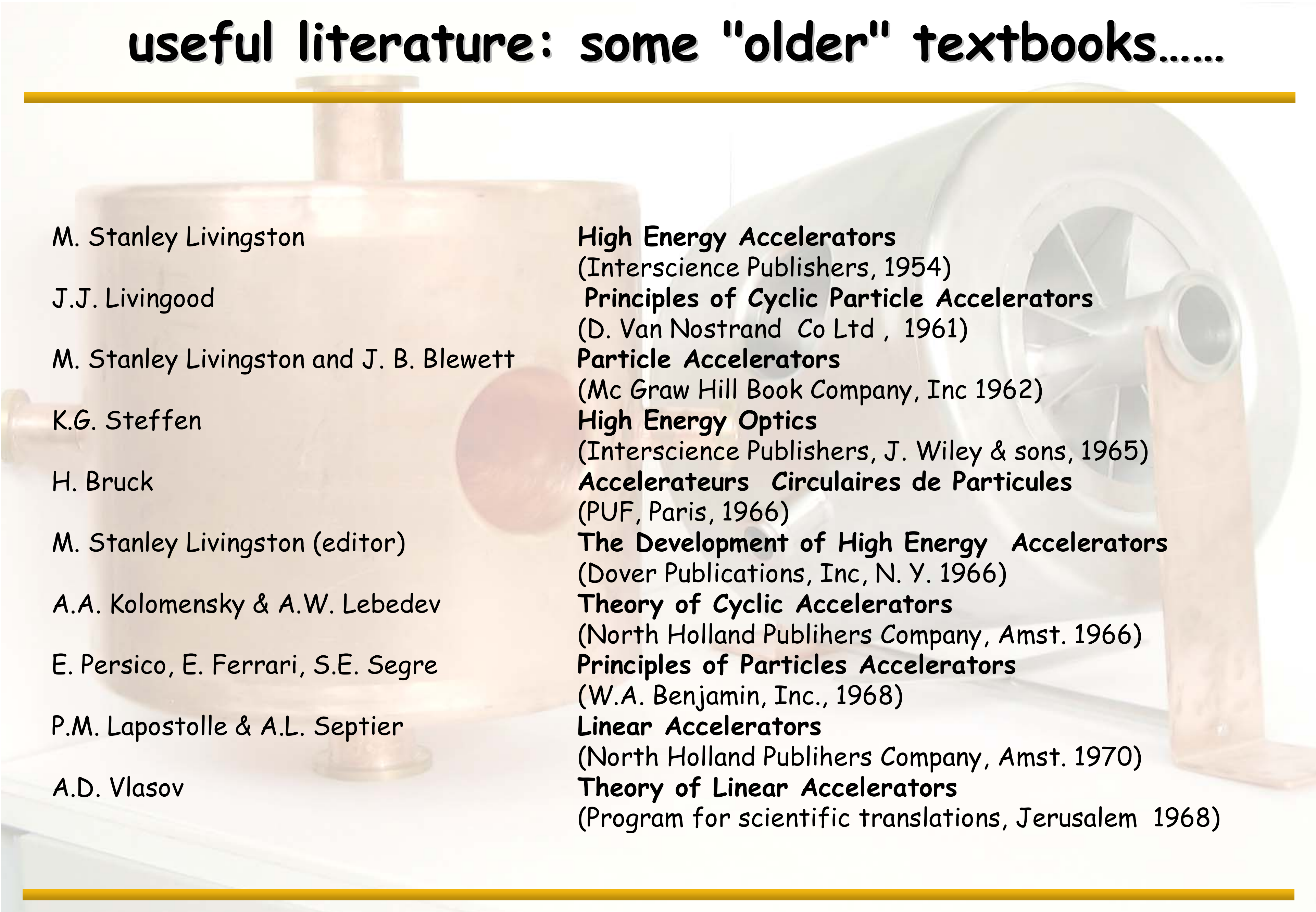


Chapter 1

Introduction to the Accelerator World

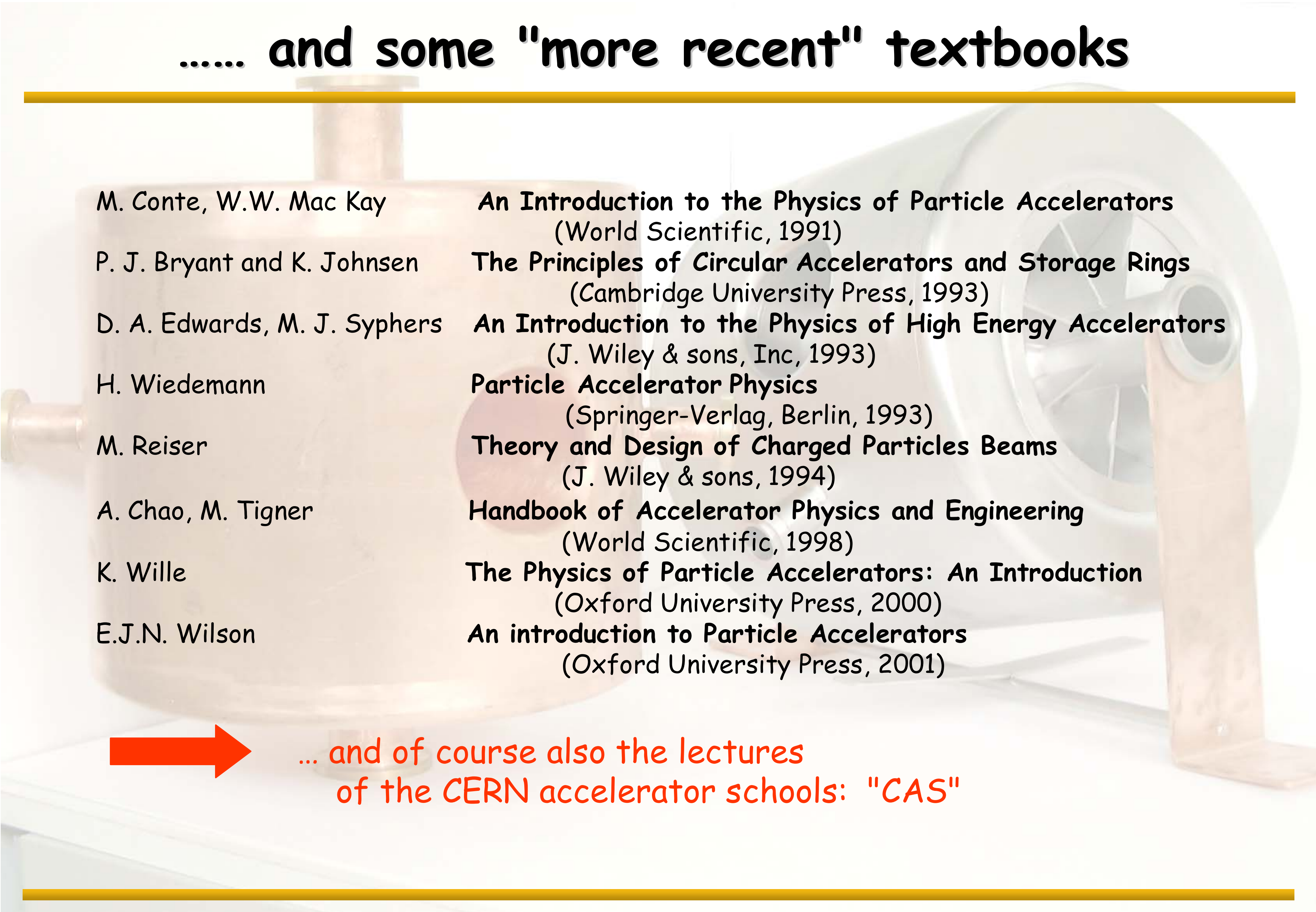
- Introductory Remarks & Literature
- Acceleration of charged particles
- Why we need particle accelerators
- History and Livingston chart
- Example of a charged particle source
- Electrostatic Accelerators
- From Electrostatic to RF Acelerators

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)

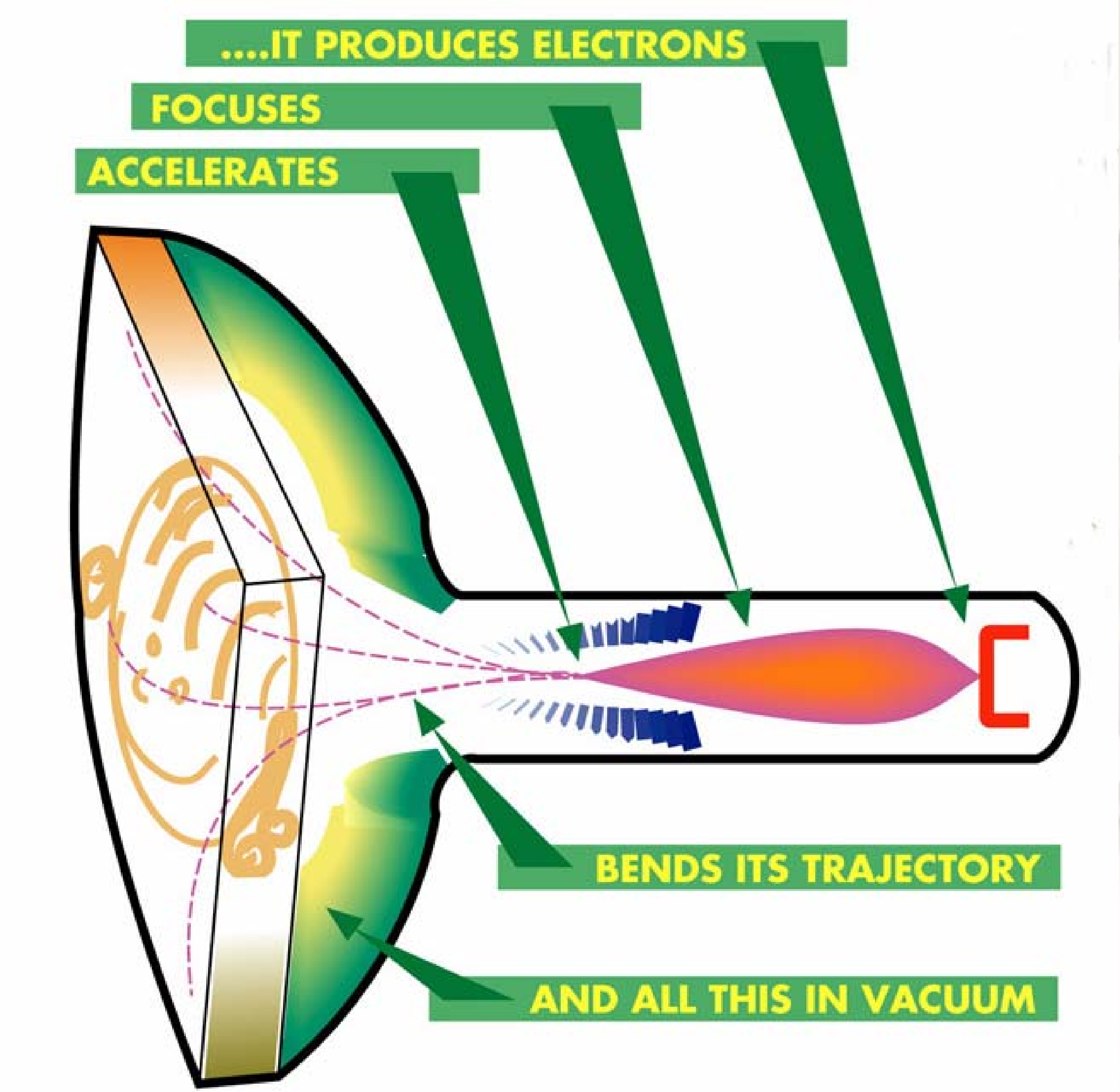
…… and some "more recent" textbooks



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"



....IT PRODUCES ELECTRONS

FOCUSES

ACCELERATES

BENDS ITS TRAJECTORY

AND ALL THIS IN VACUUM

Figure from a
CERN Website

Accelerating Particles (I)

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

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

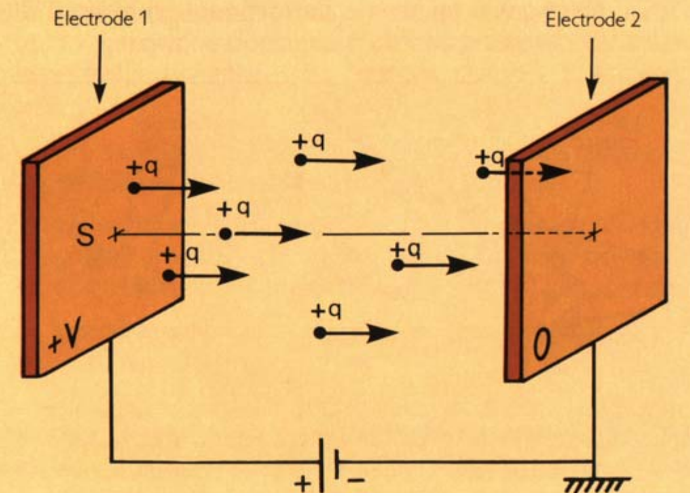
- of the 4 fundamental forces, the only one we can control by technological means is the electromagnetic force
- from Maxwell's 4 equations describing electromagnetic fields (electric: **E**, magnetic: **B**), one obtains the **Lorentz force** which acts on a charge q evolving with speed **v** :

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

- 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

Source → **Accelerator** → **User**

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**

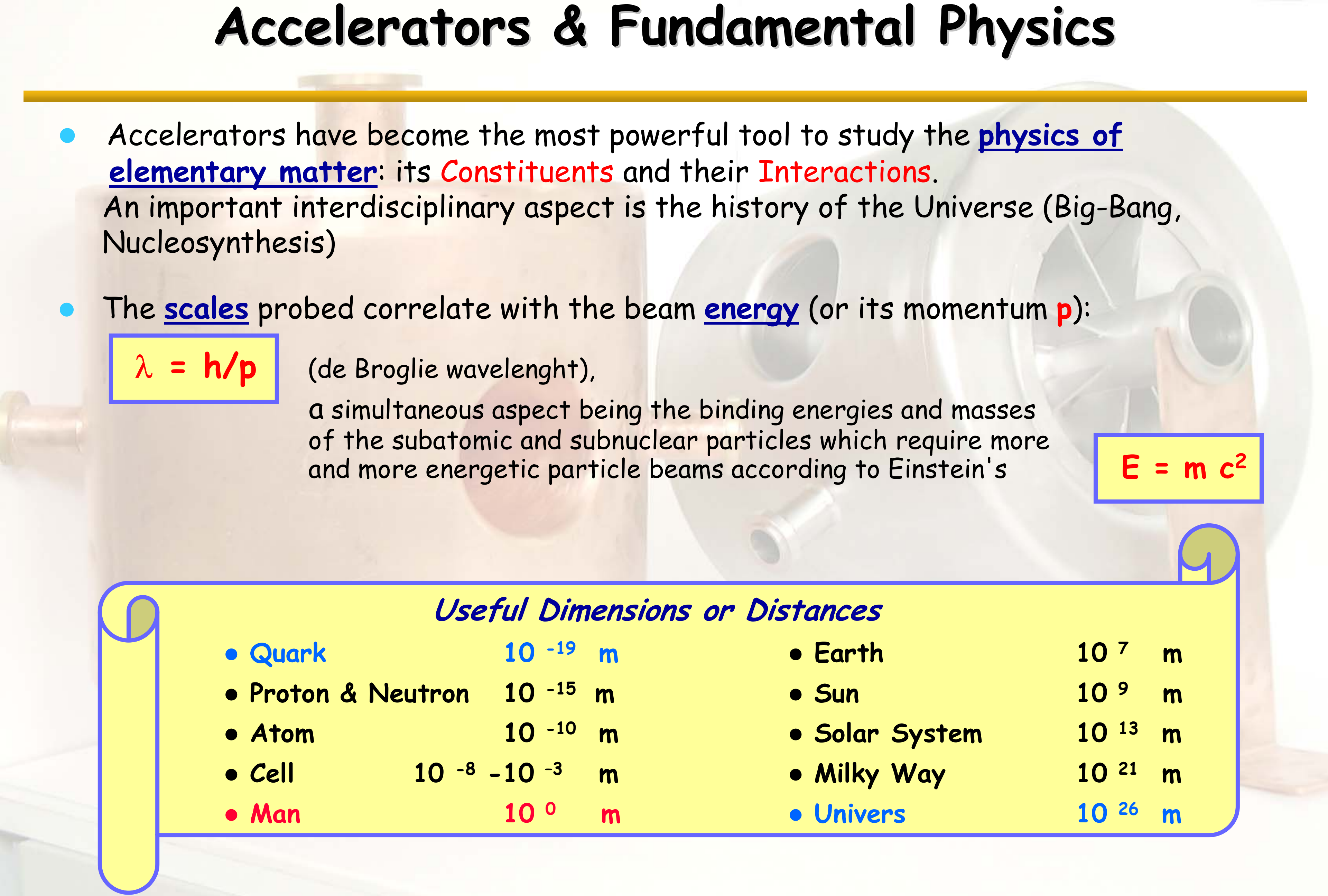
  mainly magnetic, in order to maintain (focus) the beam on the wanted trajectory and to provide the orbit (closed for a synchrotron) in the case of a circular machine

- 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

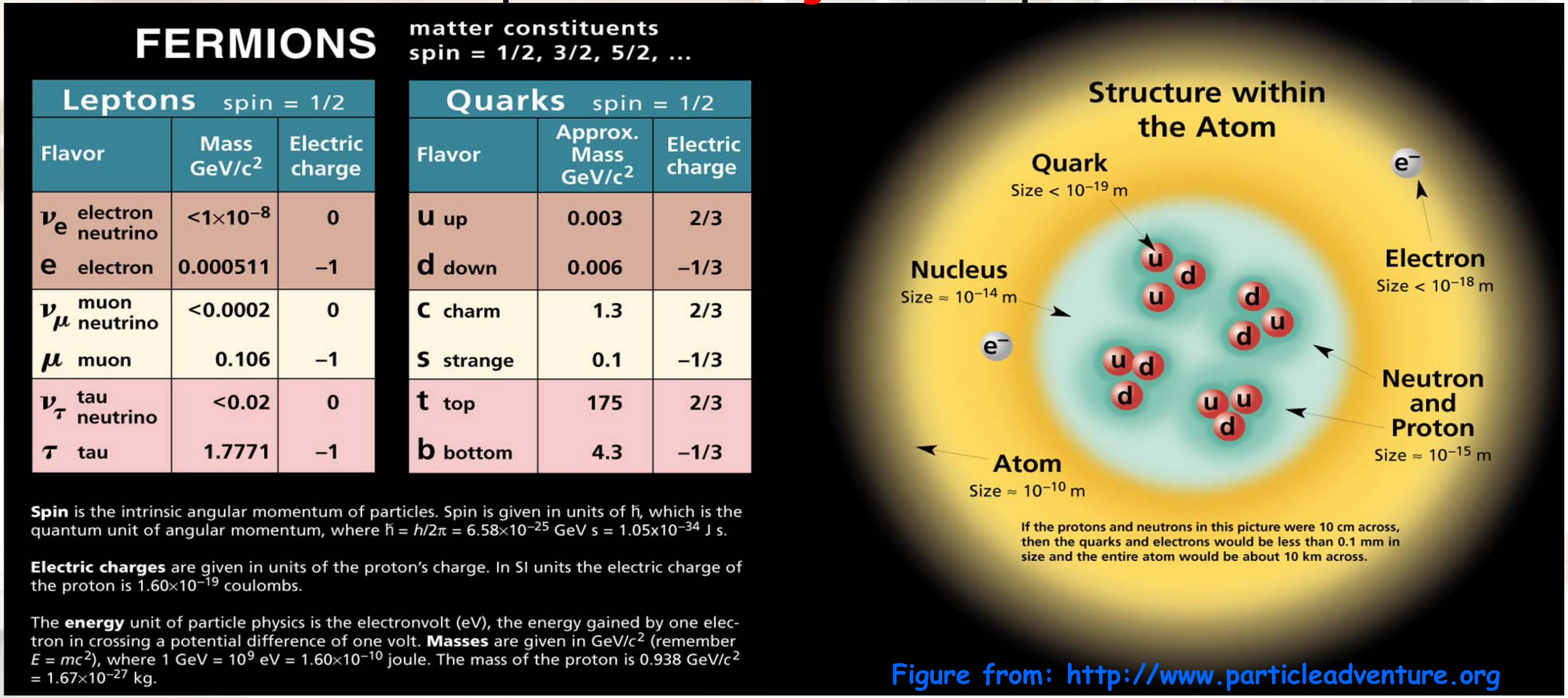
$$\boxed{E = m\,c^2}$$

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 $\hbar$, 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.

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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!!

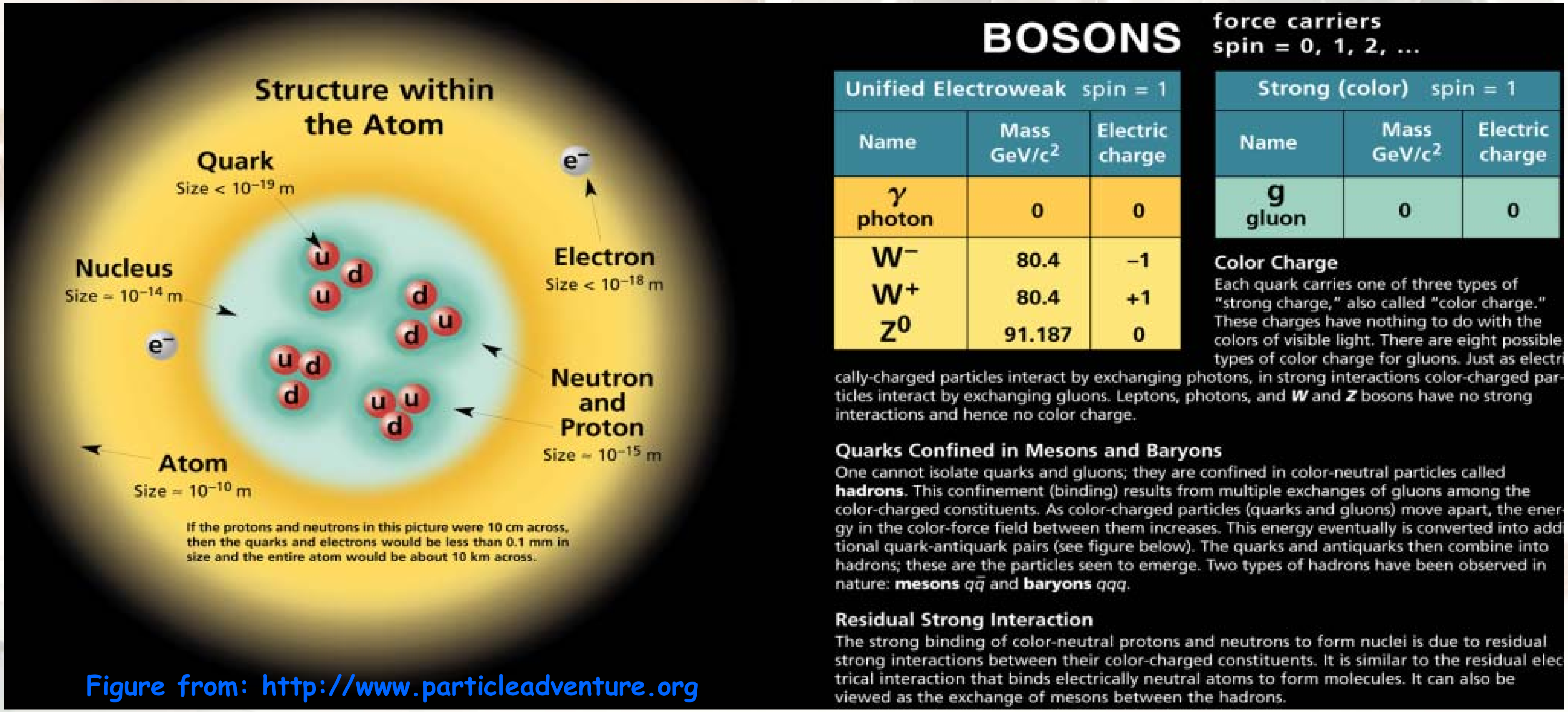


Figure from: http://www.particleadventure.org

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.

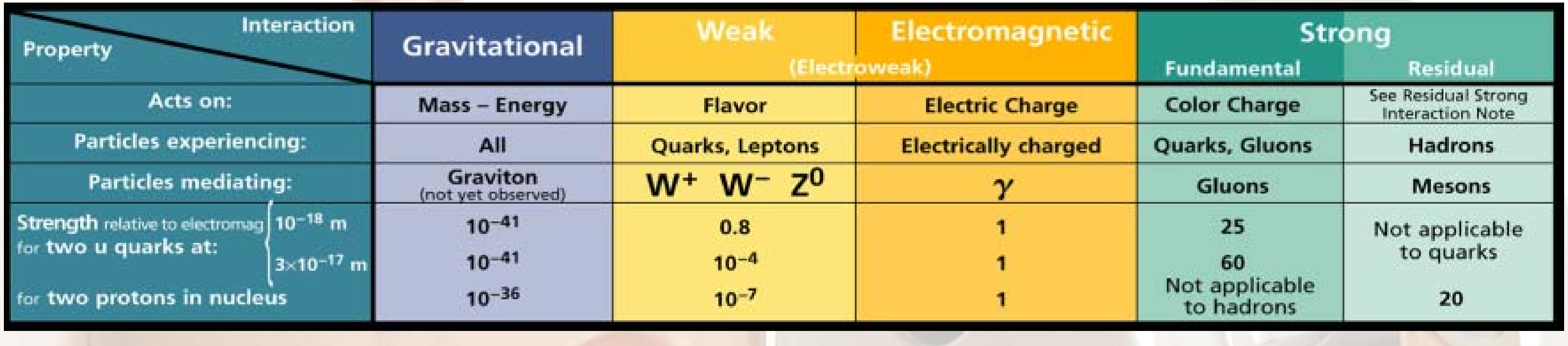
Quarks Confined in Mesons and Baryons

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 energy 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

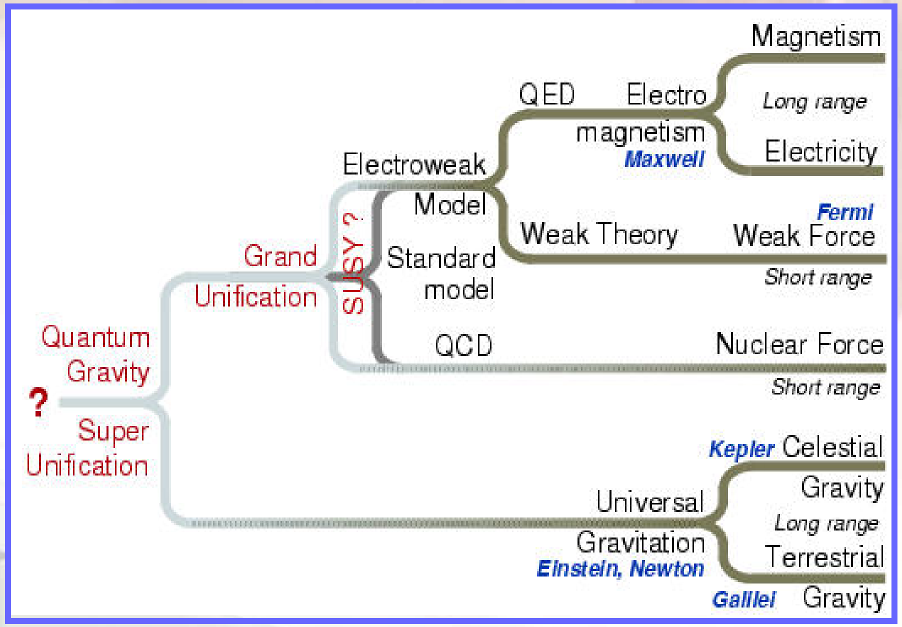
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual elec trical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange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

Towards Unification……?



Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	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

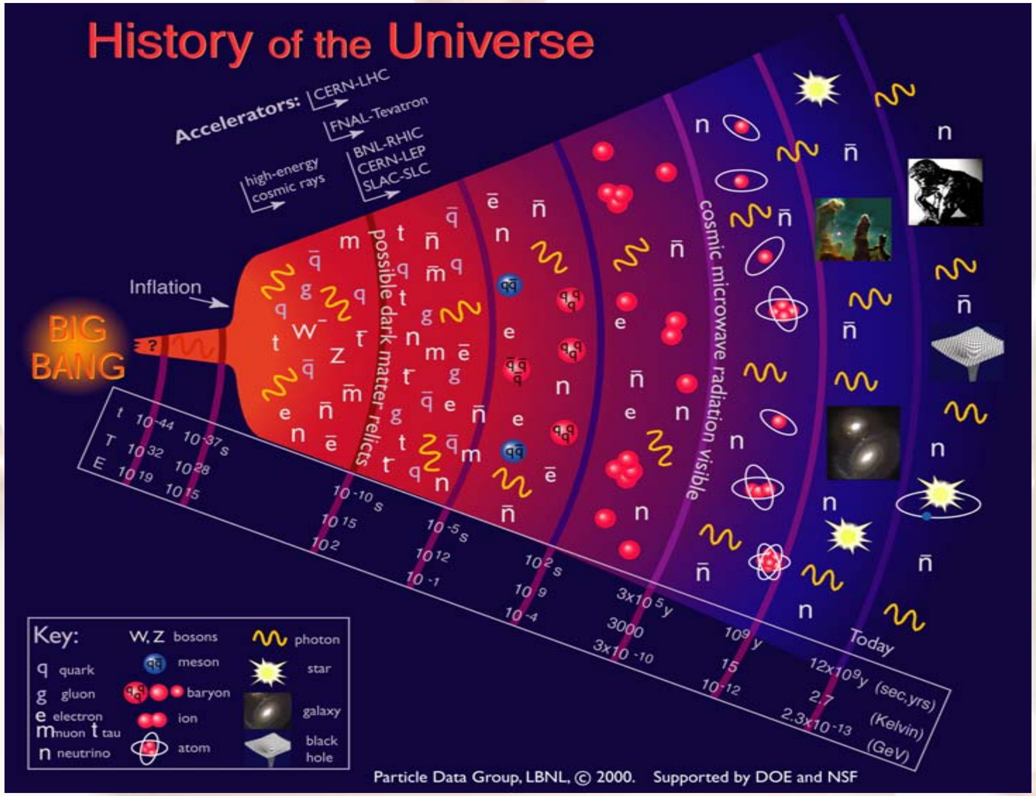
Figure from: http://www.particleadventure.org



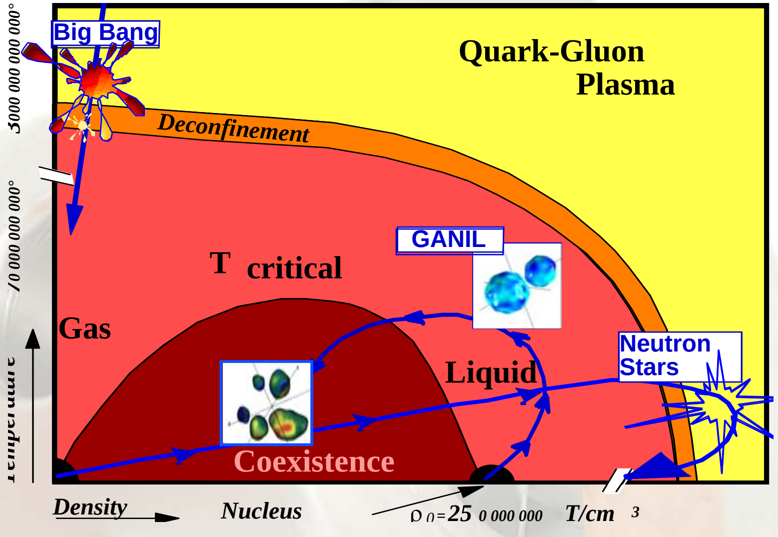
Note in passing,

- 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 build at Pisa the VIRGO experiment, a 3 km long high-precision interferometer for observing gravitational waves.

Accelerators & the Universe (I)



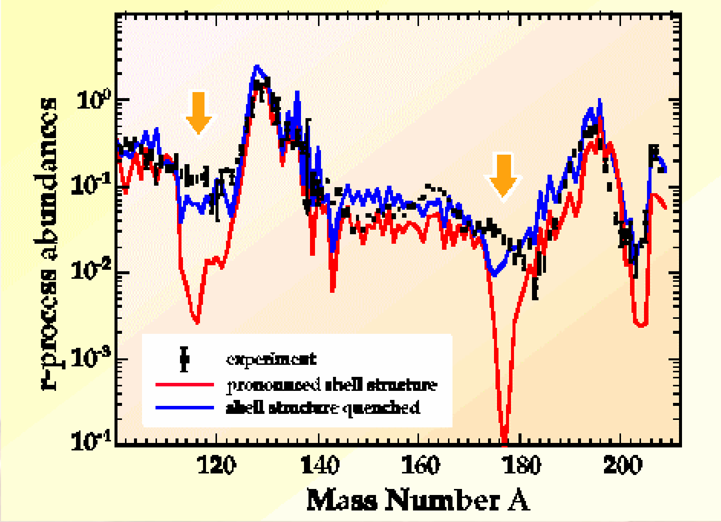
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



- 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!

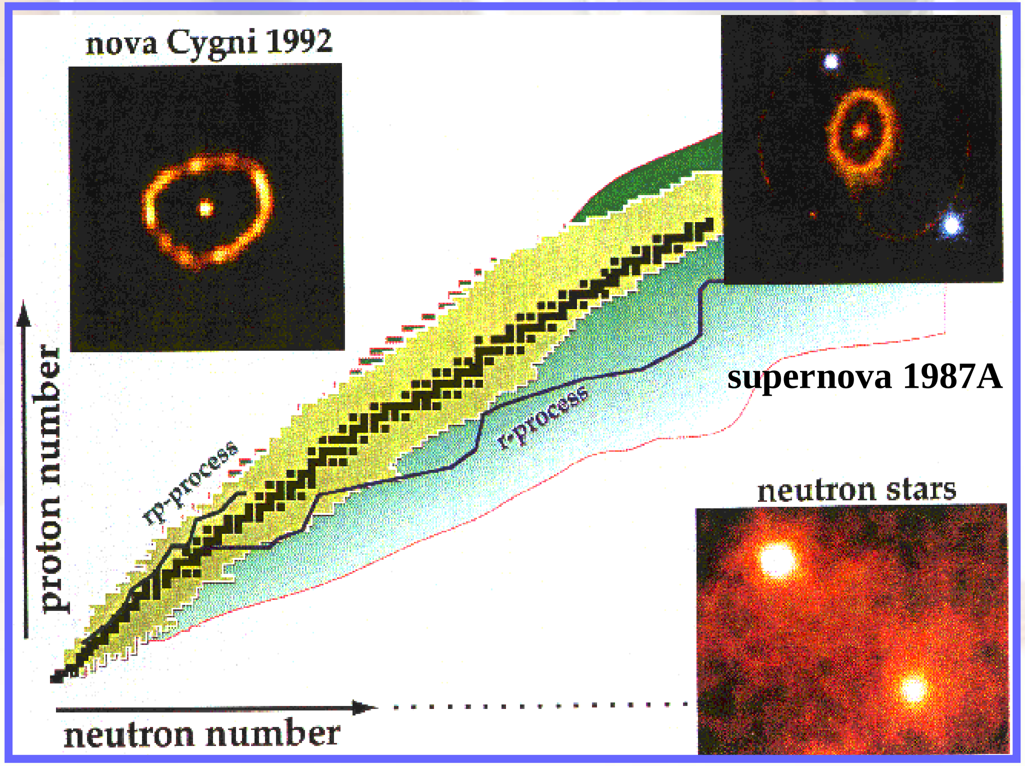
- All the particles which make up every day matter had yet to form, but presently, the universe has expanded to billions of light years.
- The Quarks and Gluons, today locked up inside the protons and neutrons, were then to hot to stick together. Matter in this state is called the Quark Gluon plasma, 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)



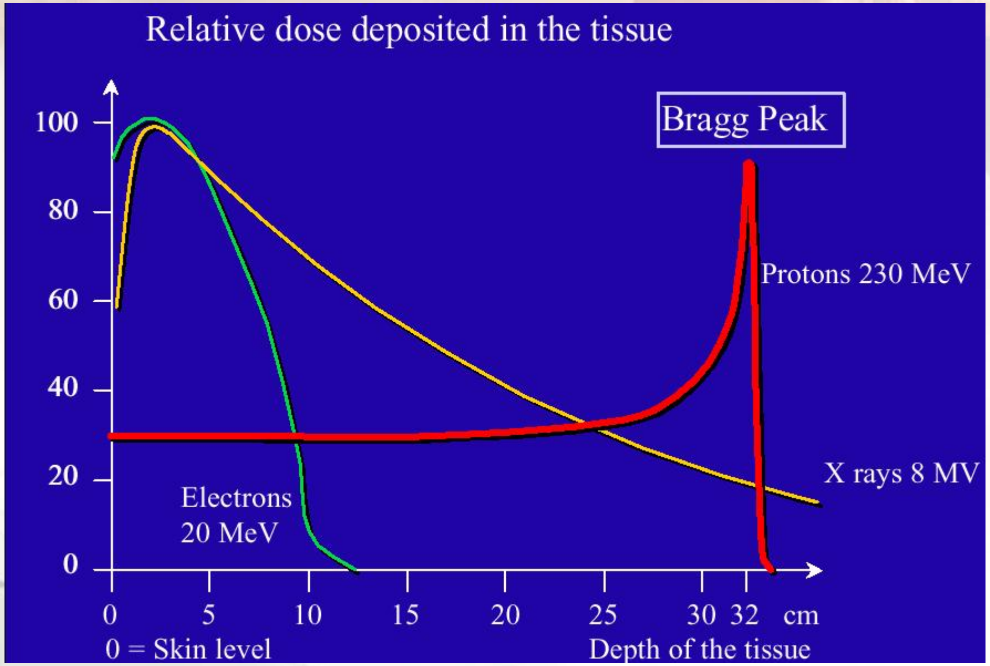
- nuclear astrophysics studies the nuclear reactions which happen in stars
- the reactions give rise to the energy production and make the chemical elements, "isotopic abundance", our world is made of
- the left figure shows, e.g. the abundance produced in the r-process, believed to happen when supernovae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

- 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!



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



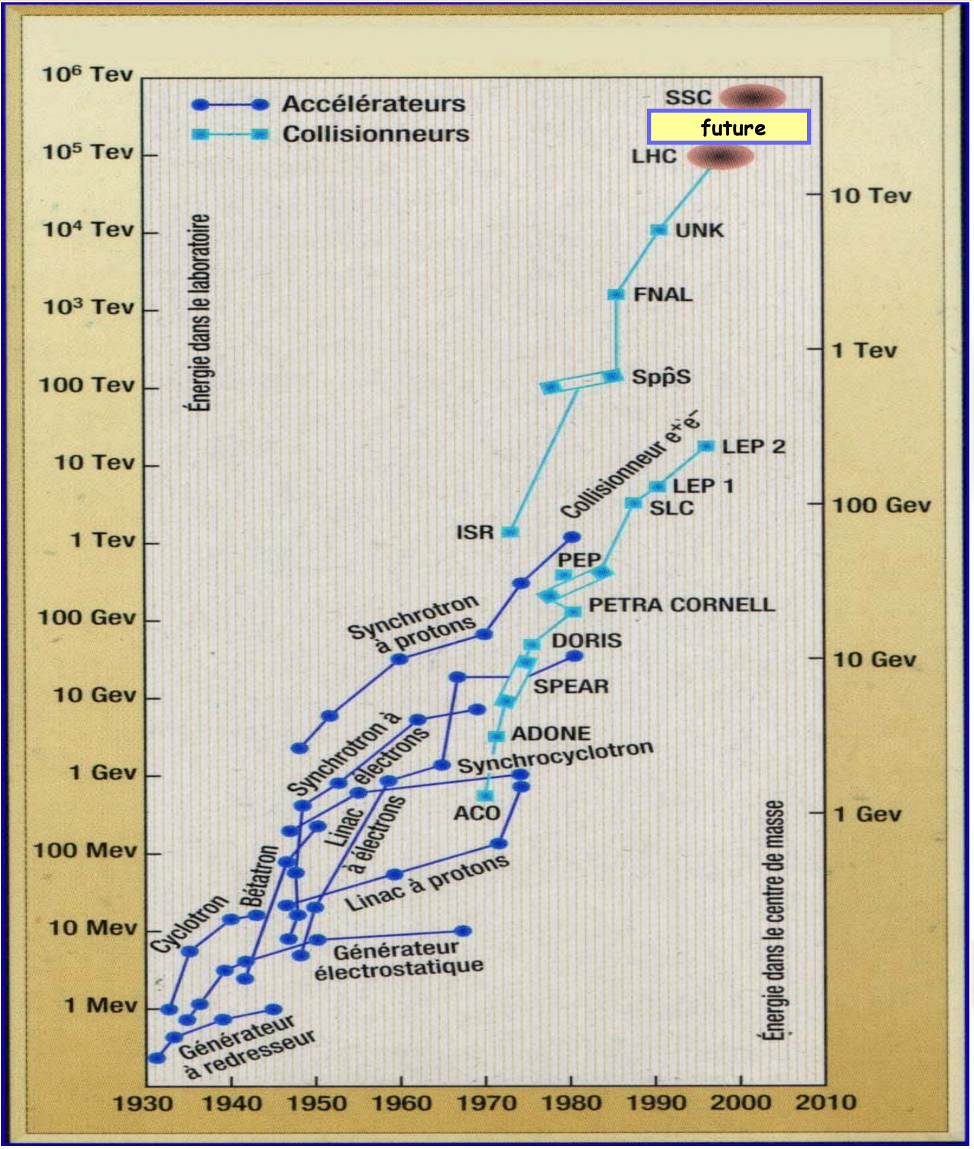
- nuclear medicine
  - ➔ production of radioisotopes
  - ➔ cancer treatment, thousands of x-ray & electron sources and are installed at hospitals but note the promise, see figure, of proton- and heavy-ion therapy more than 20000 patients so far (e.g. CPO Orsay, GSI)
- and also nuclear power, the topic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

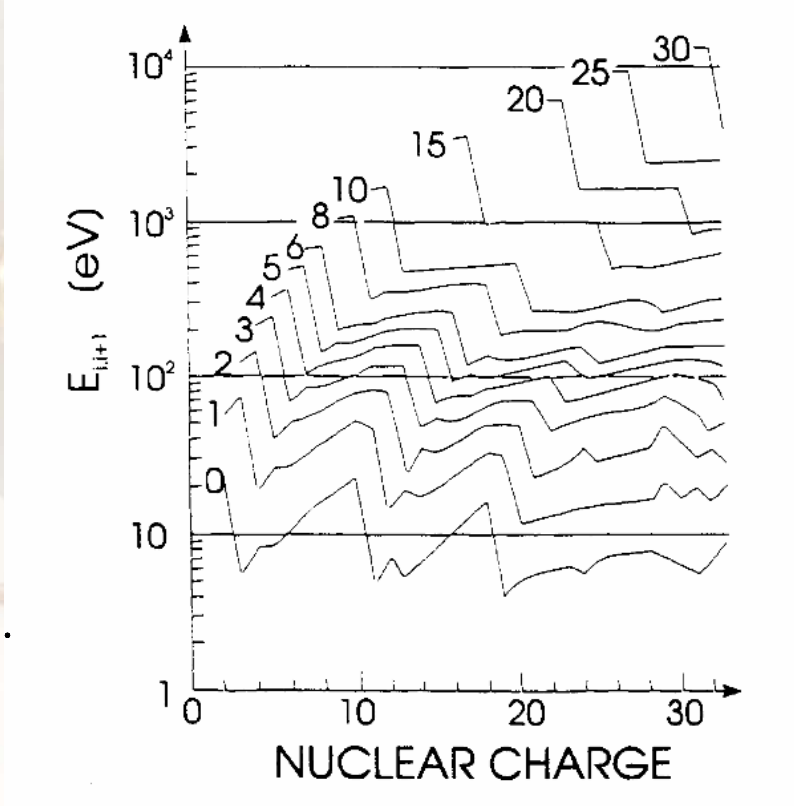
In thermal equilibrium the Saha equation describes the amount of ionization in a gas

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

Ionization energy: I_j (j: charge state)

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

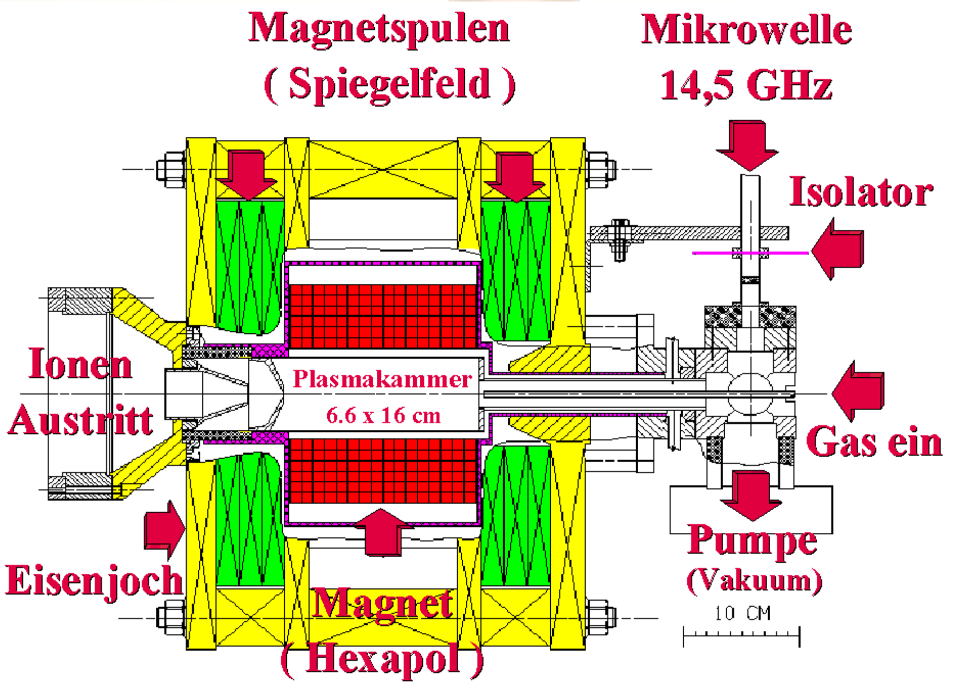
High ion currents are achieved for lower charge states ions.

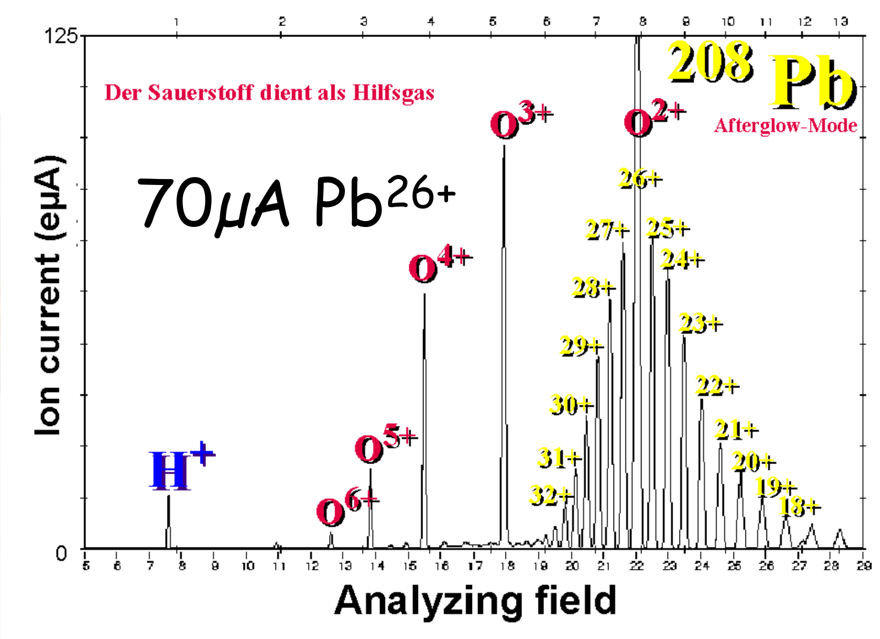


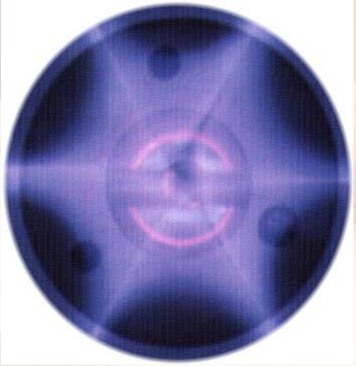
Transparency from a lecture by O. Boine-Frankenheim, GSI

Charged Particle Sources: Example of the ECR source

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







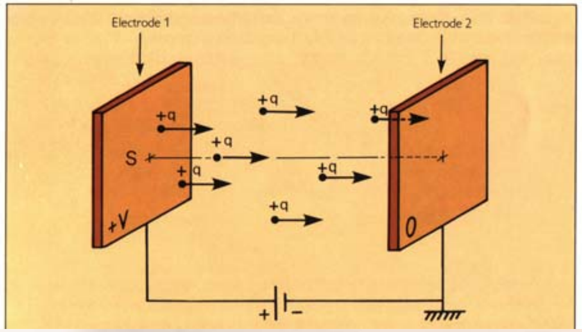
'hot plasma'

High current sources: e.g. > 10 mA U^{4+}

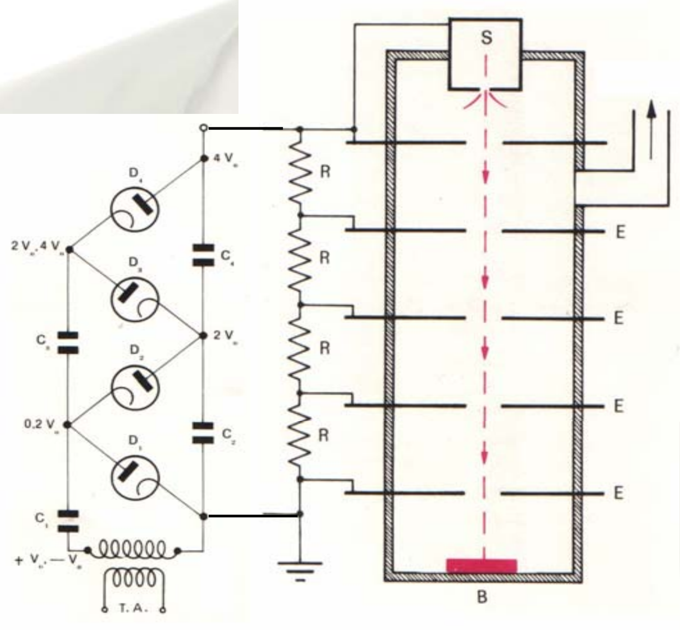
and also > 100 mA p

(see later, IPHI R&D for ADS)

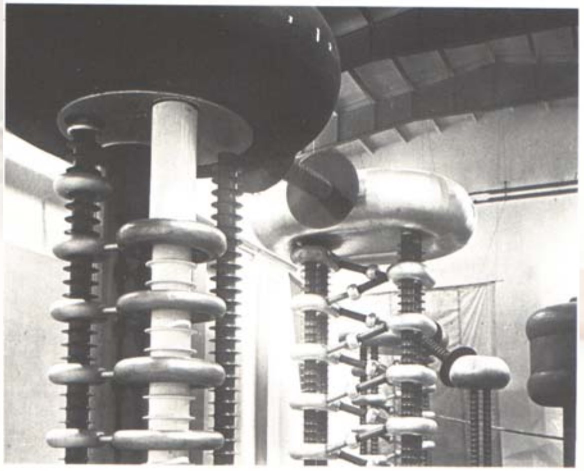
Electrostatic Accelerators (I)



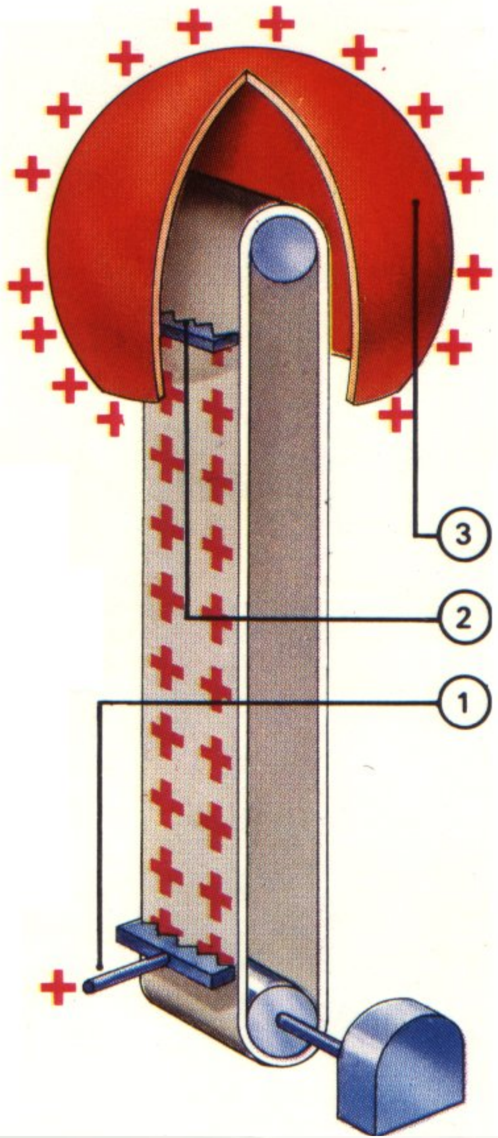
- Starting from the "elementary cell" of acceleration, (recalled left), an electrostatic accelerator is an insulating column



- 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



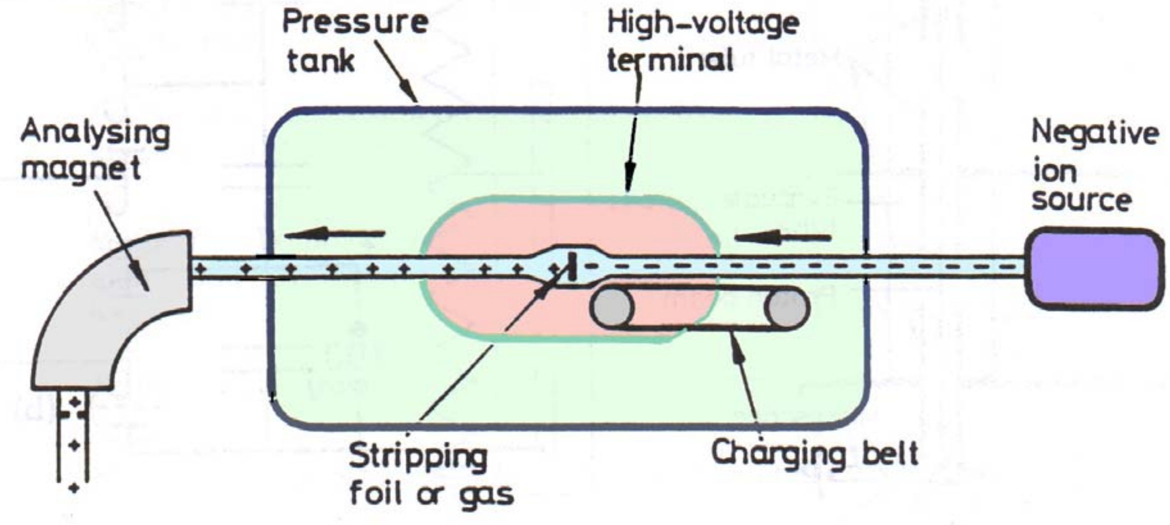
Electrostatic Accelerators (II)



- how to increase the voltage for electrostatic 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

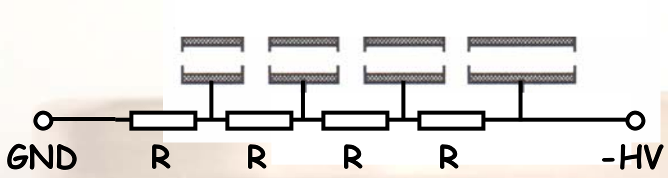
- consecutive to the HV terminal, a second accelerator column is installed leading back to ground potential
- a stripper is installed at the terminal through which the beam particles have to pass
- this principle works only for the injection of negative ions because of the stripping process

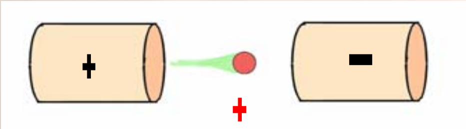


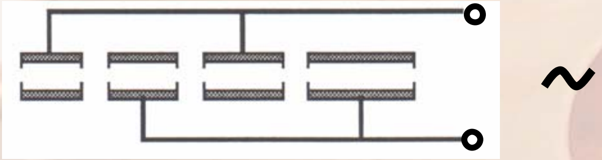
- however, at typical terminal voltages, several electrons can be stripped off, considerably augmenting the energy gain of the second section
- Such a Tandem (see right the SF_6 pressure vessel of the machine at IPN Orsay containing conveyor and accelerating column), can continuously accelerate any charge-to-mass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

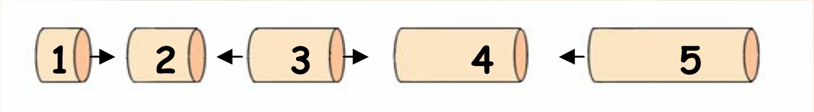
- The Orsay Tandem is presently much used for measuring fission and capture cross sections of actinides for Reactor Physics in the context of GEDEPEON activities.

From Electrostatic to RF acceleration

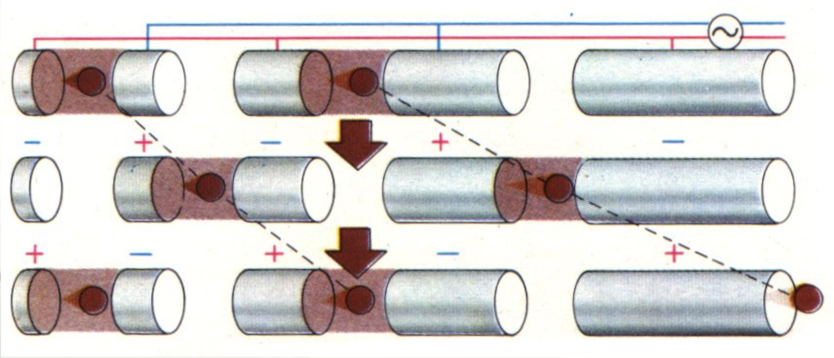






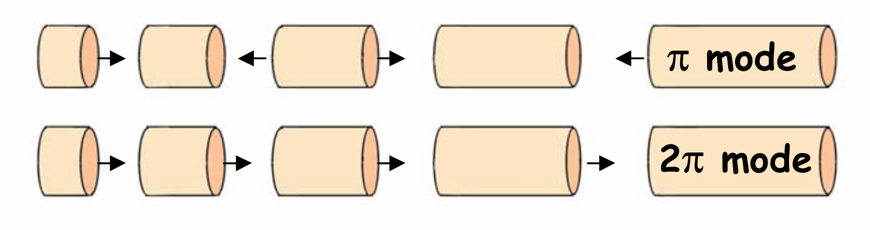


π *mode*

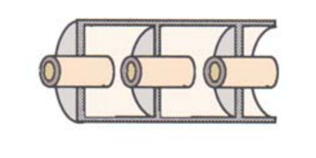


- consider an element of an accelerating column of an electrostatic accelerator
- at any moment, the electric field is in the same direction, allowing continuos acceleration
- consider now such a column, but driven with an alternating voltage, in such way that consecutive electrodes are connected to 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 between 2&3, precisely, when the RF has changed 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

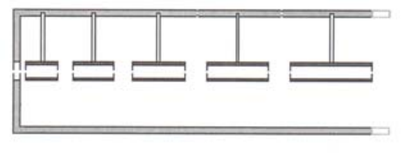
Linacs, towards the next Lecture



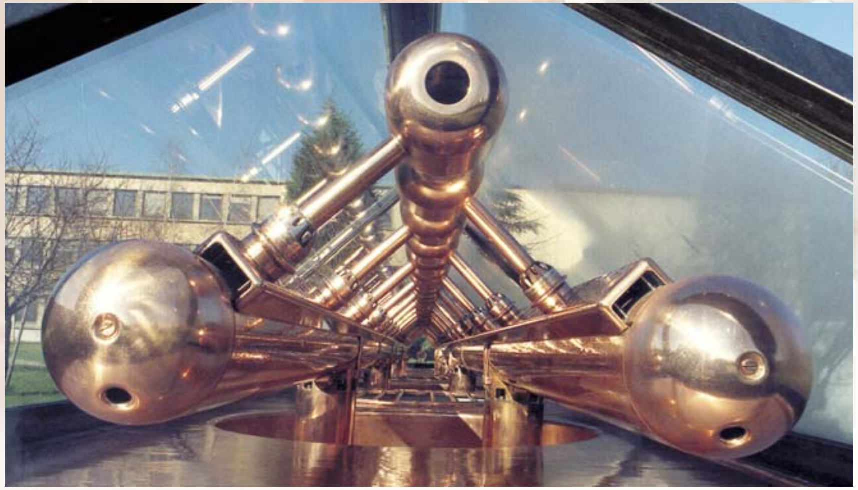
- on the preceeding slide, the Wideroe linac operating in the π mode was introduced, but it is also possible to run at higher harmonic, e.g. in the 2π mode



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



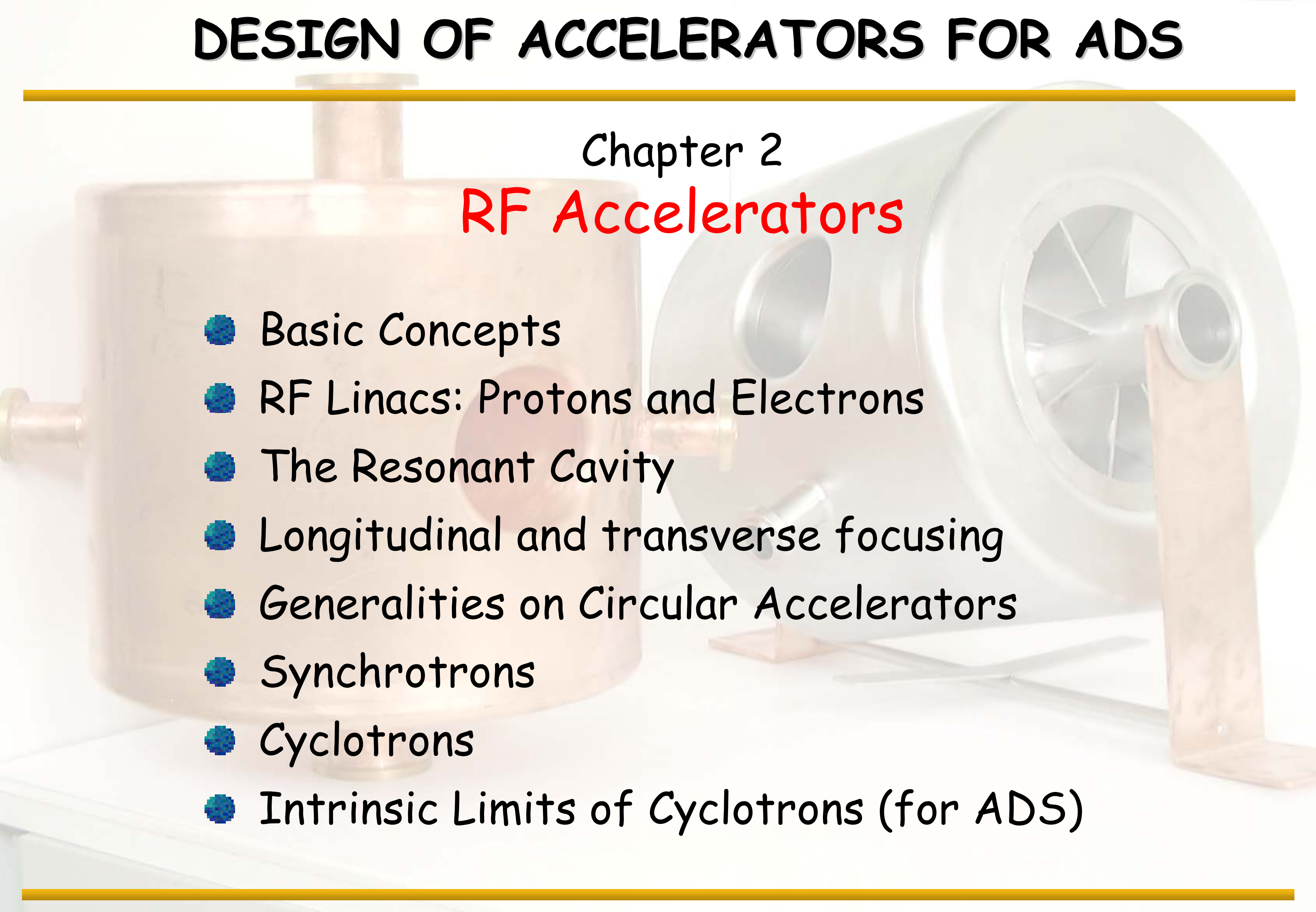
- in the 2π mode, the currents circulating in the wall separating two subsequent cavities cancel, hence one can suppress this wall. This gives the Alvarez-structure of the classical DTL



Historical examples: a Wideroe type structure (ALICE heavy ion injector, IPN Orsay)

a drift tube linac (DTL) (Saturne, Saclay)

DESIGN OF ACCELERATORS FOR ADS



Chapter 2

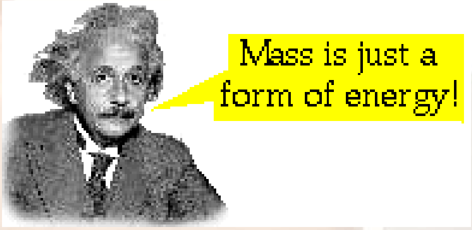
RF Accelerators

- 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

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

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

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 << c

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

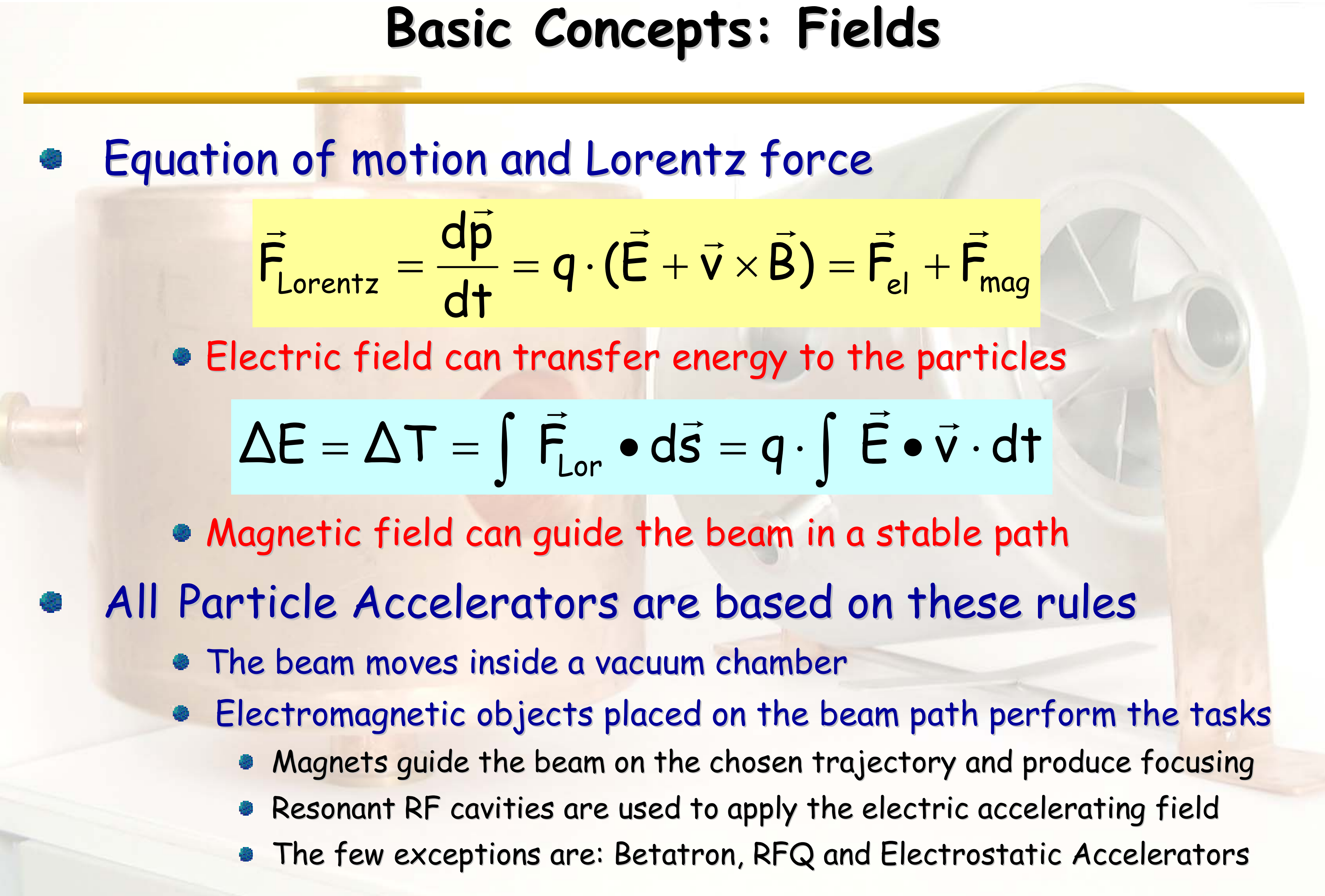
$m_0\,c^2$ = rest energy
$\tfrac{1}{2}\,m_0\,v^2$ = classical kinetic energy

- 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

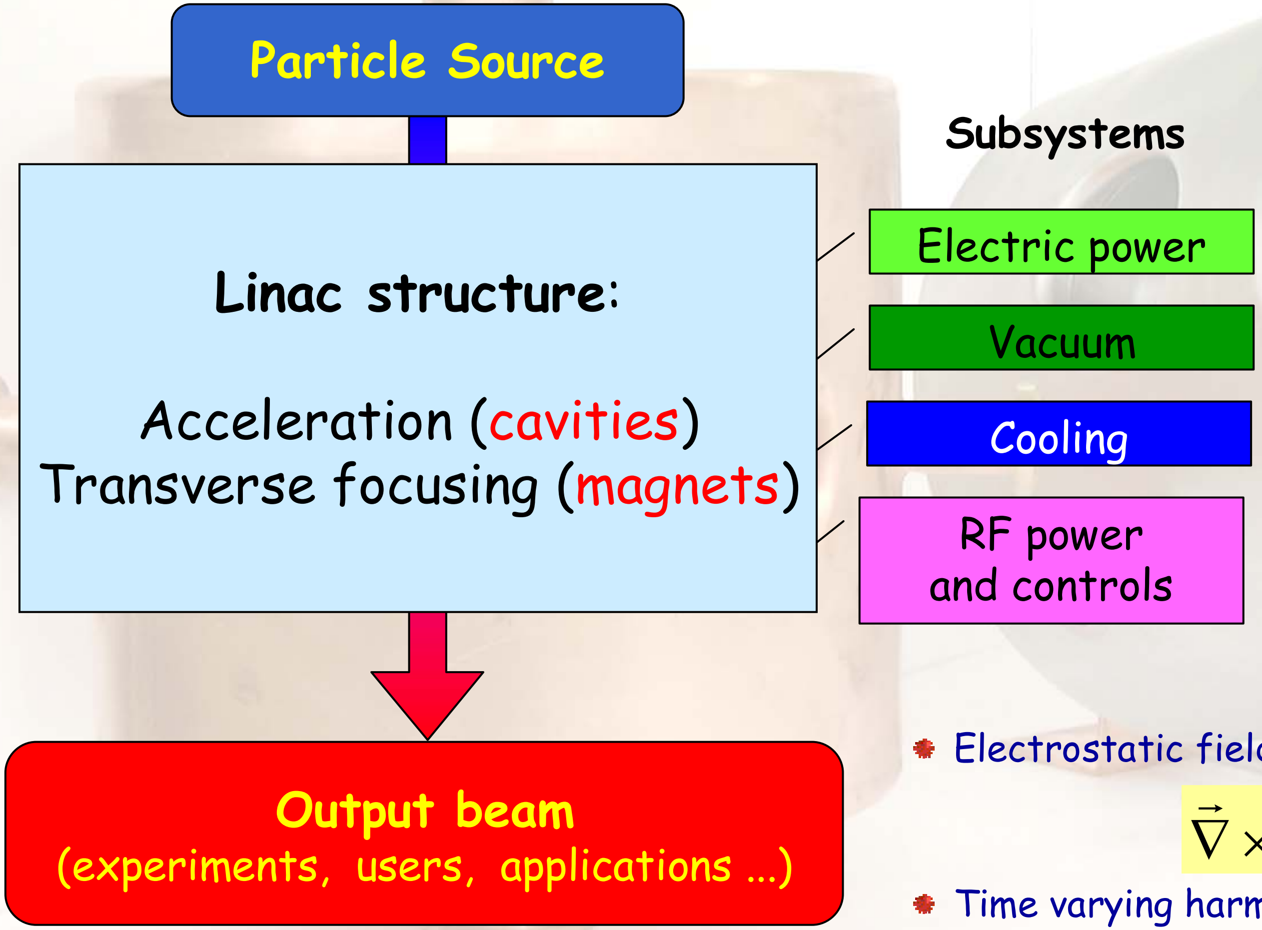
$$\vec{F}_{Lorentz} = \frac{d\vec{p}}{dt} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{el} + \vec{F}_{mag}$$

  - 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)

Subsystems

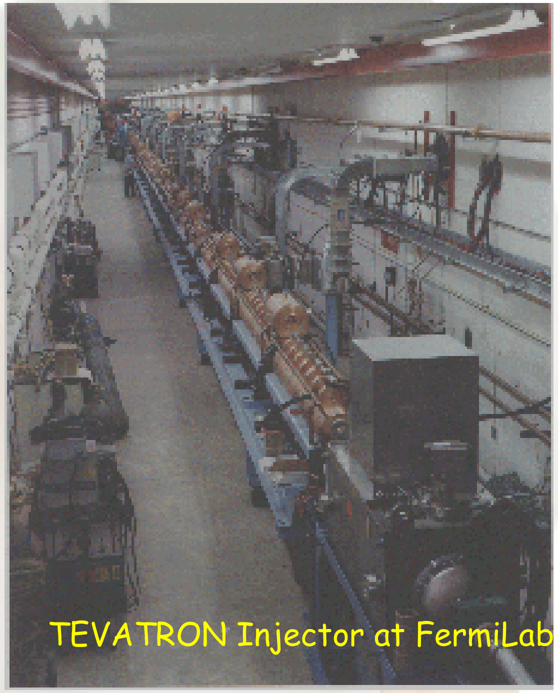
Electric power

Vacuum

Cooling

RF power
and controls

Output beam
(experiments, users, applications …)



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

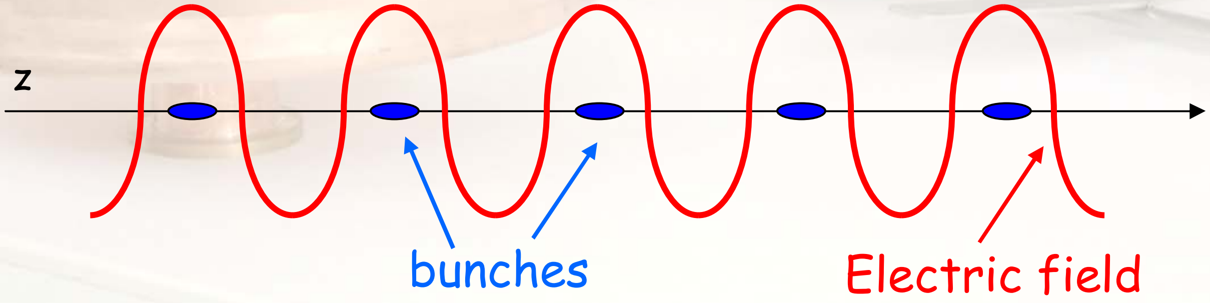
$$\vec{\nabla} \times \vec{E} \neq 0$$

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**

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

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



Electrons and Protons

- electron and proton masses

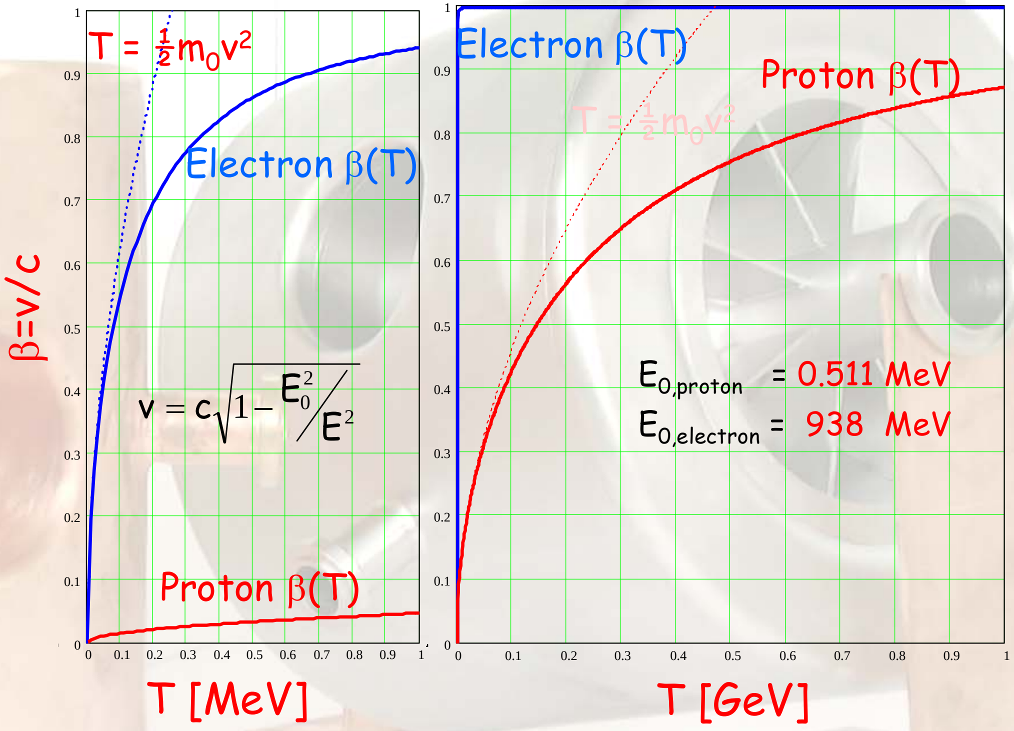
$$E_{0,proton} \approx 2000\ E_{0,electron}$$

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

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

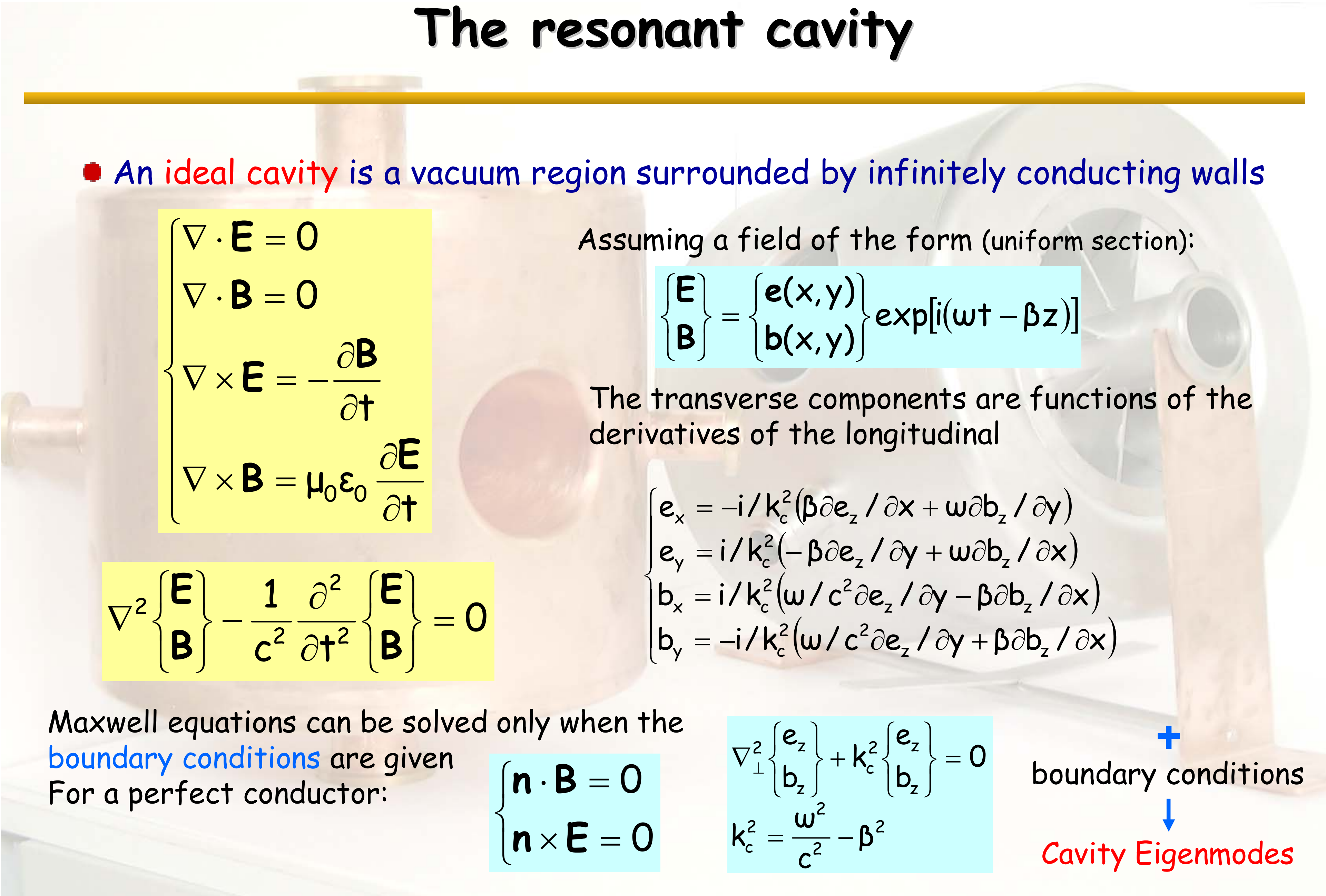
- The cell length depends on the particle velocity.
- Synchronism is exact only for a given velocity value.

→ 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 β ≈ 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:

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

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

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

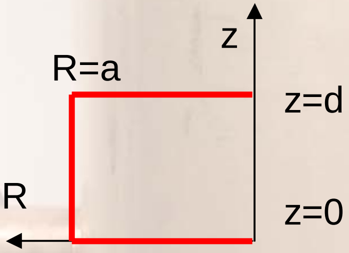
+ boundary conditions

↓

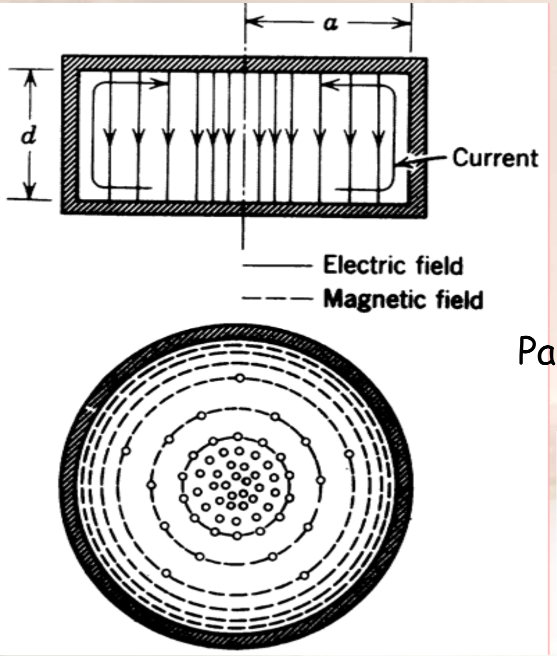
Cavity Eigenmodes

A simple resonator: the pillbox

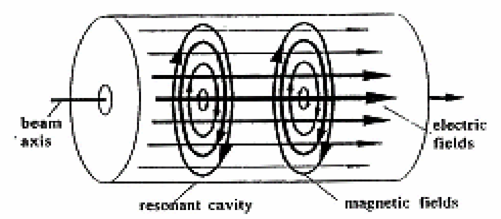
- Simplest geometry: Axisymmetrical cylindrical cavity
- Neglecting the beam holes for particle transmission the wave equations can be solved exactly



- 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

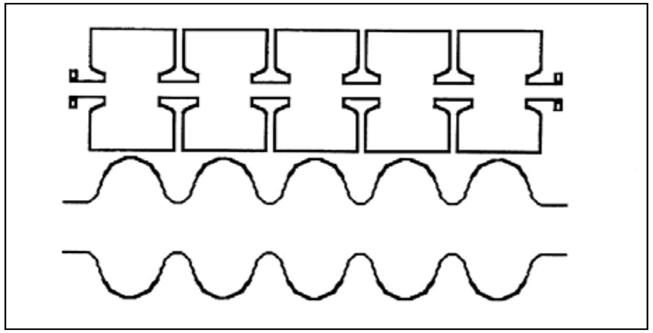


$$\omega = c\frac{2.405}{a}$$

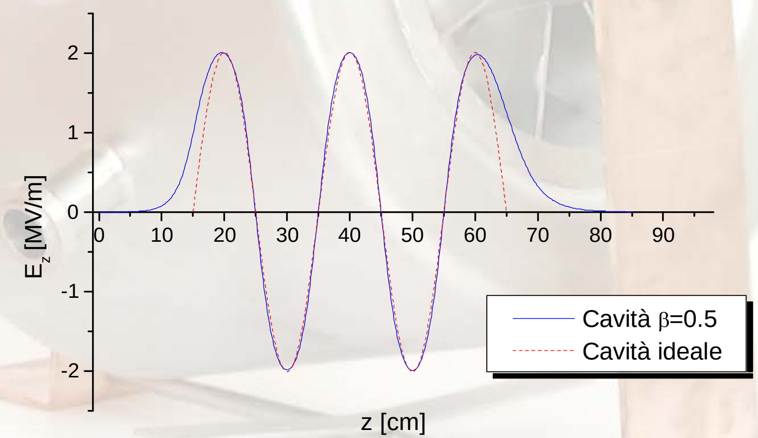
$$\begin{cases} e_z = E_0 J_0\left(\frac{2.405}{a} r\right) \\ b_\varphi = \frac{i}{c} E_0 J_1\left(\frac{2.405}{a} r\right) \end{cases}$$

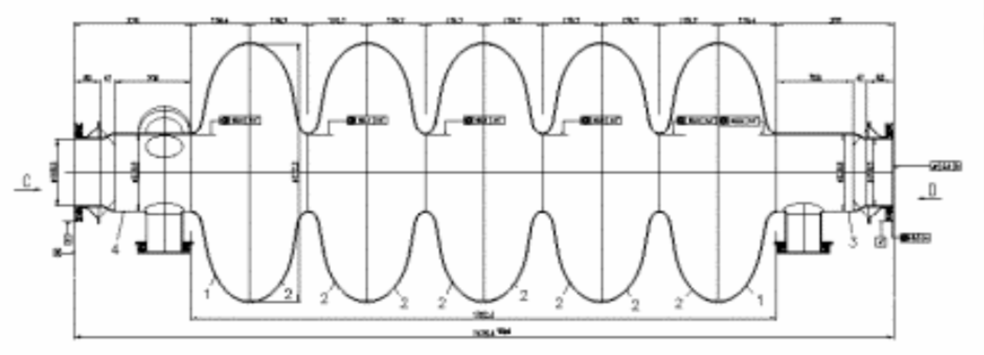
Realistic multicell cavities

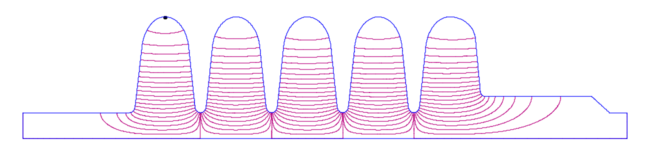
- In order to efficiently accelerate the beam, *multicell resonators are used*, by periodically repeating the resonant structure and providing coupling between the different cells. Any geometry can be computed with existing numerical codes
  - The simplest coupling is represented by the **E** field through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



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







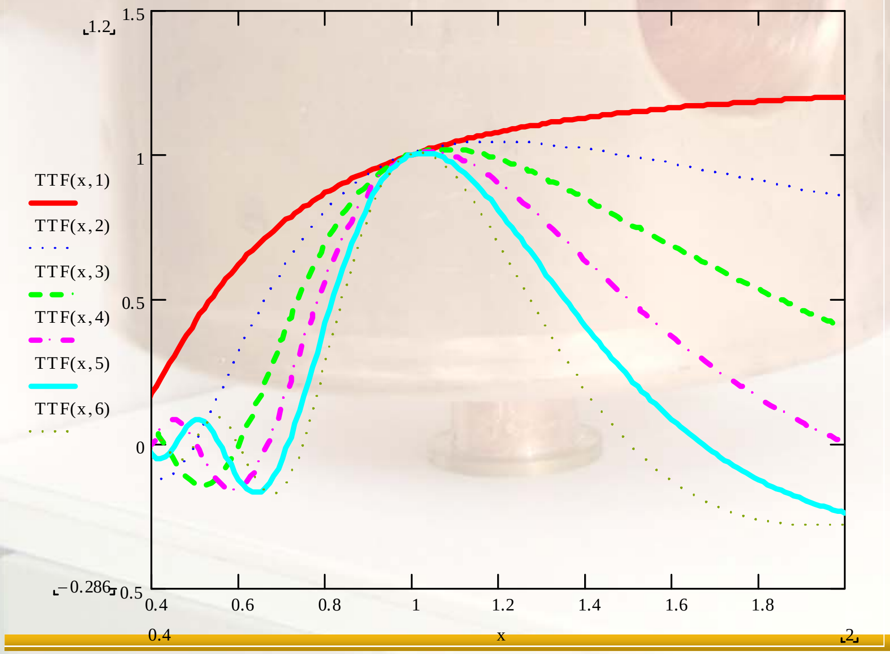
Transit Time Factor

- Proton Case:

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

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

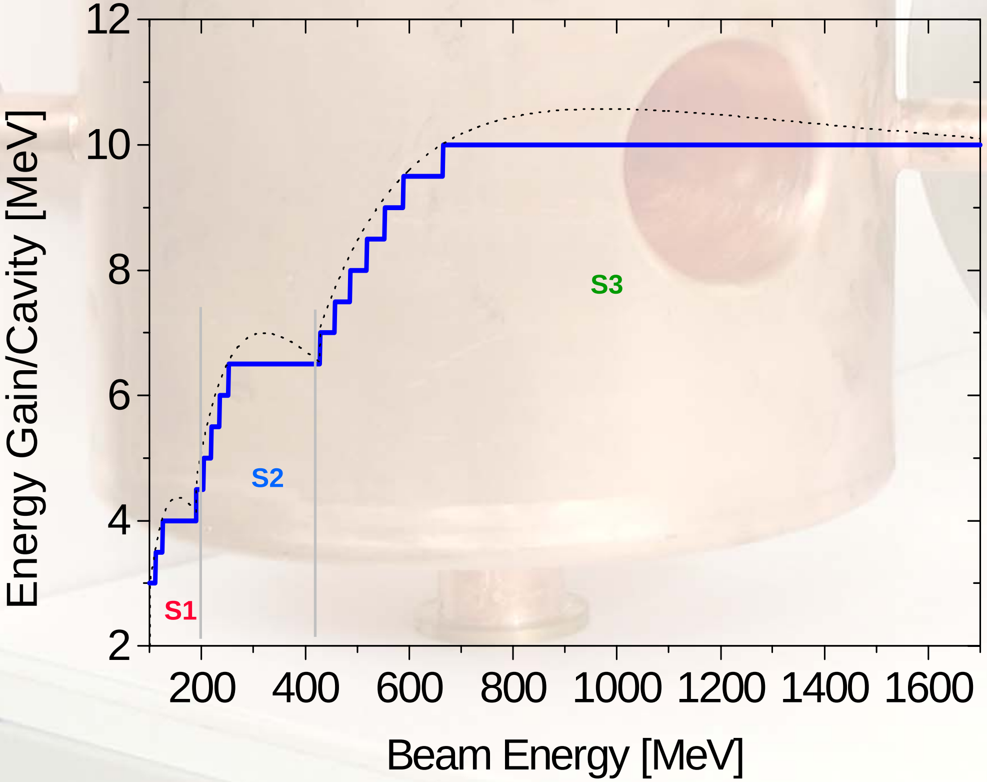
Transit Time Factor vs number of cells



- **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)

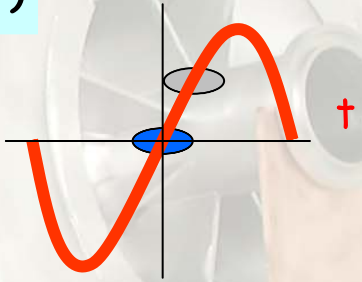
Increasing β :

- Higher accelerating field
- Longer cavities

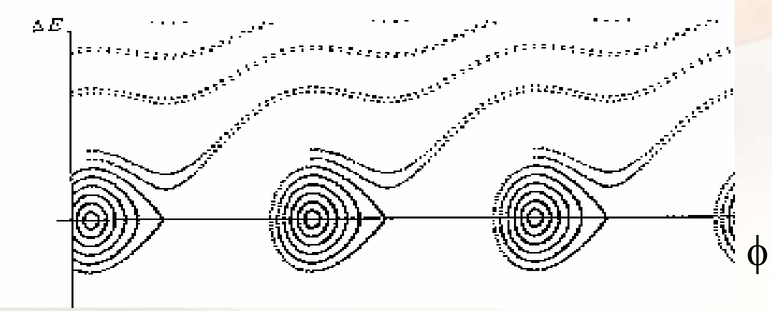
Greater energy gain!

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 $-\pi/2 < \phi_s < +\pi/2$

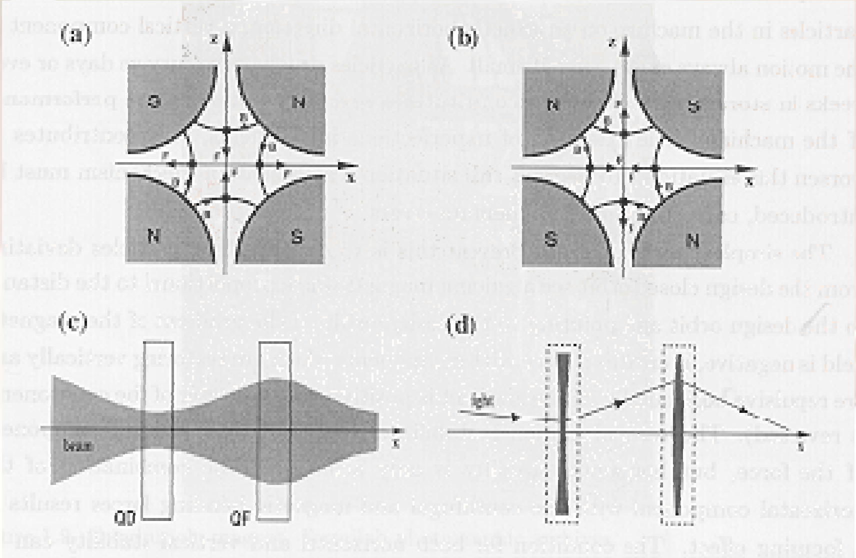


Not all particles are stable. There is a limit to the stable region (the separatrix or "bucket") and, at high intensity, it is important to design the machine so that all particles are confined within this region and are "trapped".

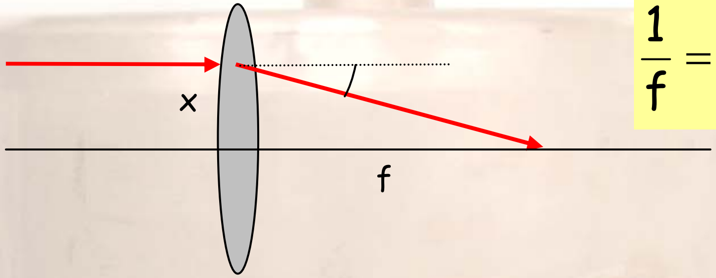
Transverse "Strong Focusing"

- 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

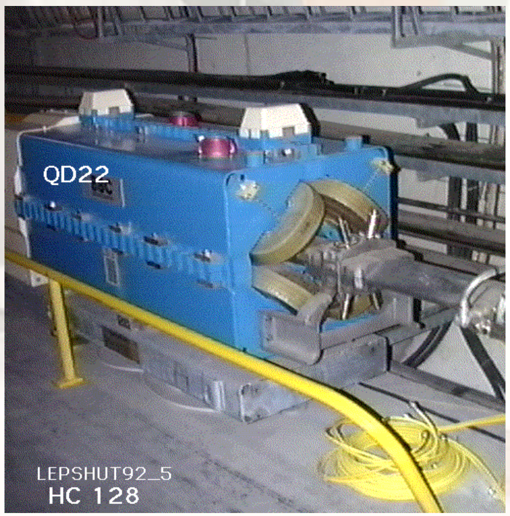
- $x_o = x_i + x_i' L$
- $x_o' = x_i'$

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

F-O-D

Transfer Matrix

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

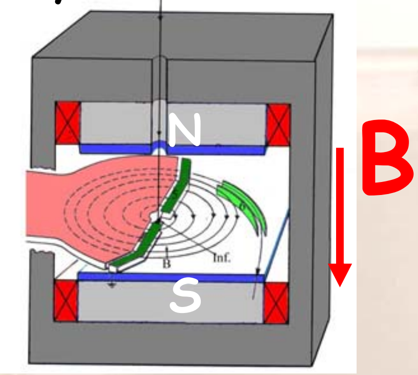


LEP quadrupole (CERN)

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

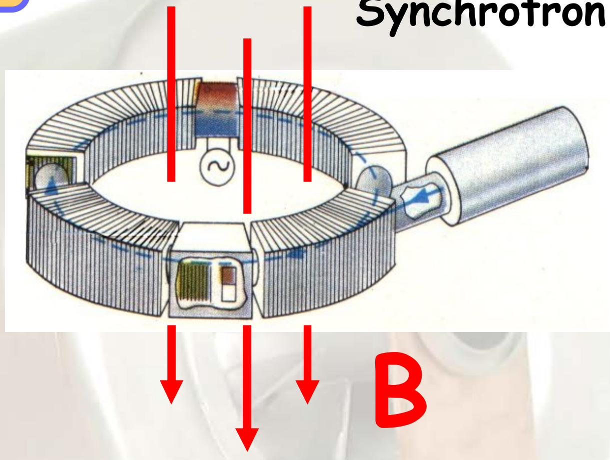
Circular accelerators: useful Definitions & Formulas (I)

Cyclotron



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

Synchrotron



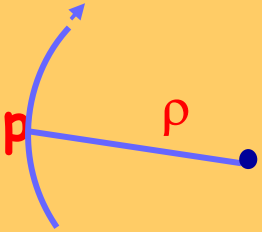
Lorentz force:

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

(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

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

W_{total} in MeV

$Q = q/e_0$

$B_m\,\rho$ 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 $\delta W = \delta W_{total} = \delta W_{kin}$

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

- which, after some "simple" operations gives

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

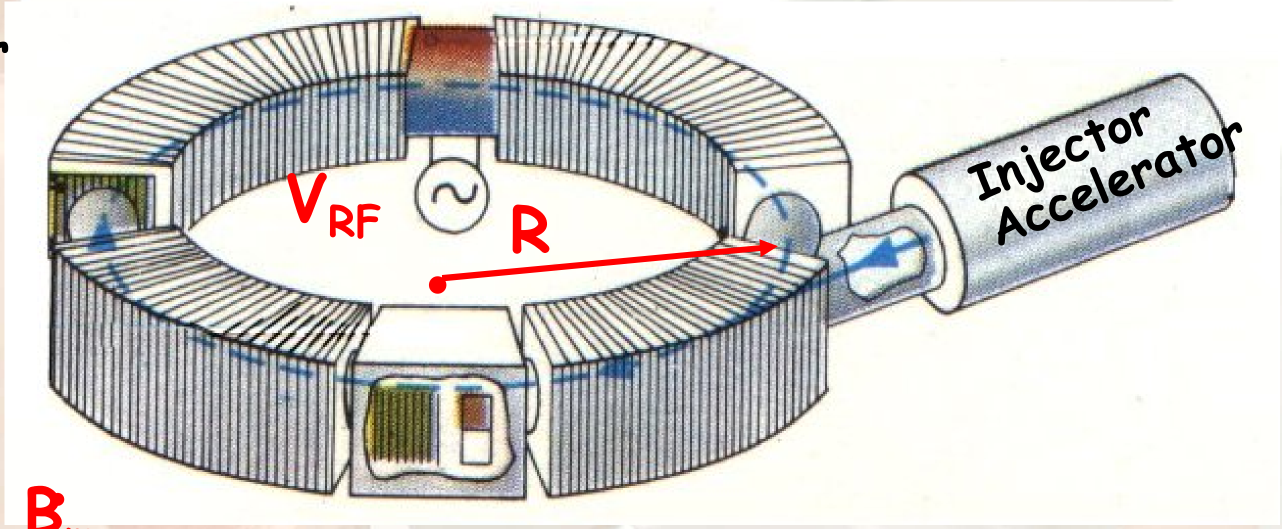
$$= 2\pi\,\rho\,q\,(\,\rho\,\dot{B}_m + B_m\,\dot{\rho})$$

- 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

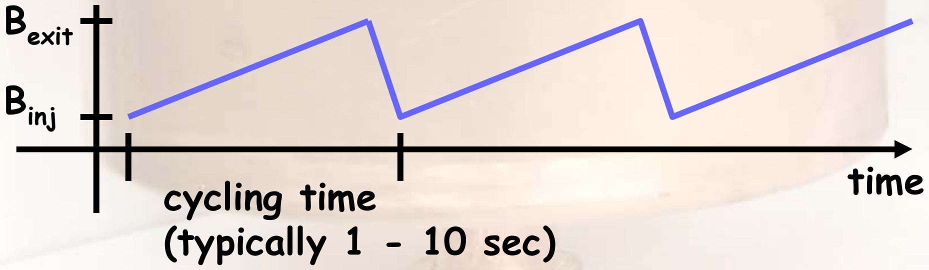
$$V_{RF} = V_0 \sin \omega t$$



- Synchrotron = "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)

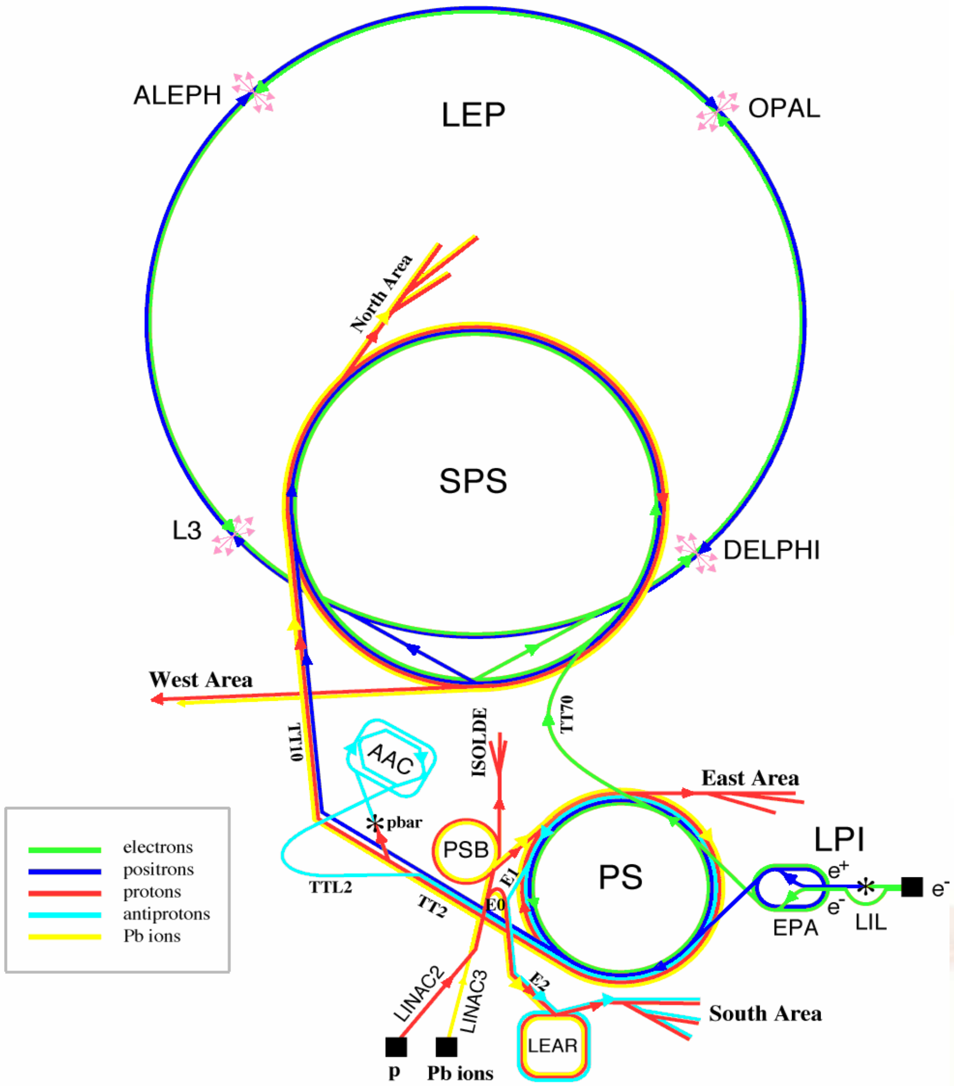
- synchrotrons accelerate up to the highest energies, determined by the bending fields (today, superconducting magnets approach B = 10T) and radius of the machine, recall W [MeV] = 300 Q B ρ [Tm], and it can be used as a collider
- a synchrotron is a pulsed machine, typical repetition rates are about 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…

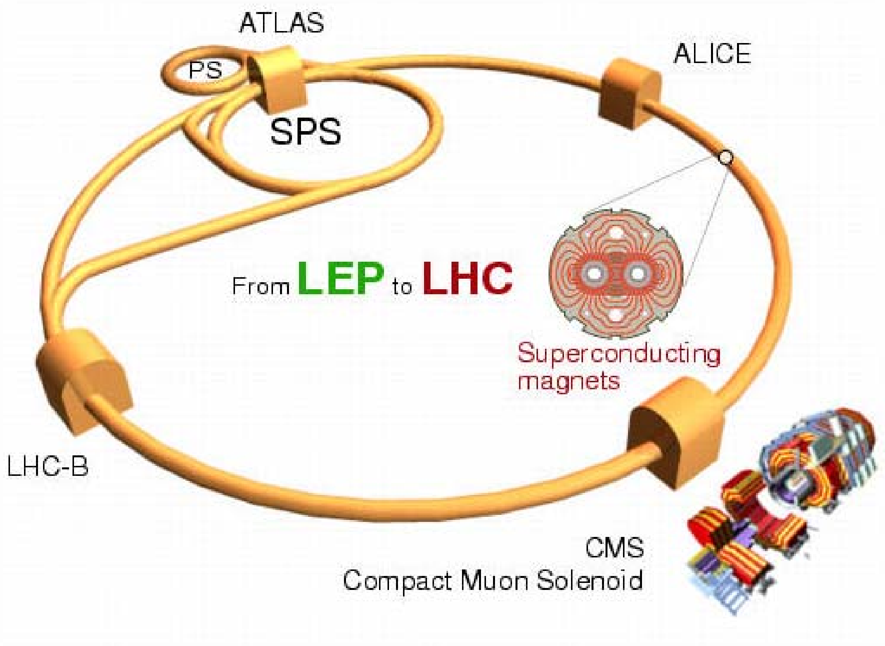
Aerial view of the CERN site with an indication of the circular LEP tunnel

- starting with the "historic" PS, operating since the sixties, CERN constitutes the world's largest complex 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



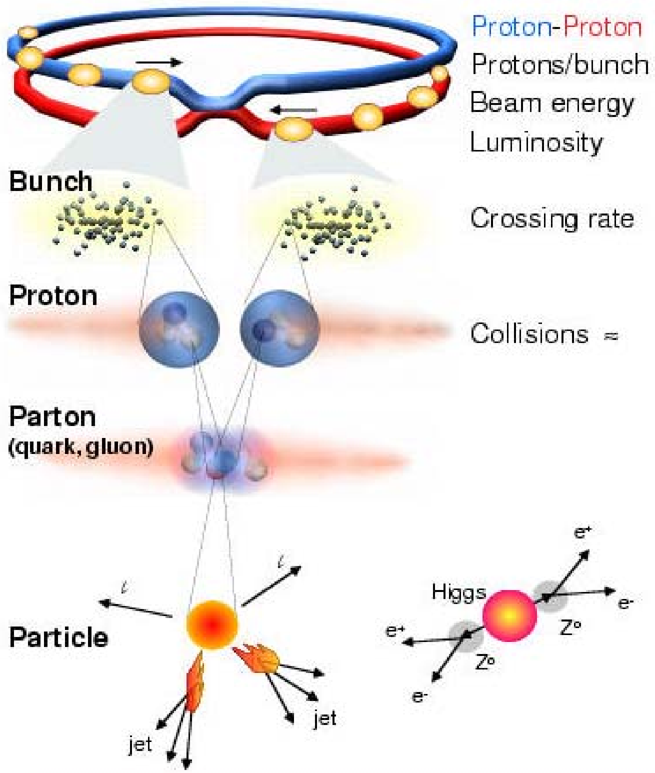
LHC, CERN's future Accelerator

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



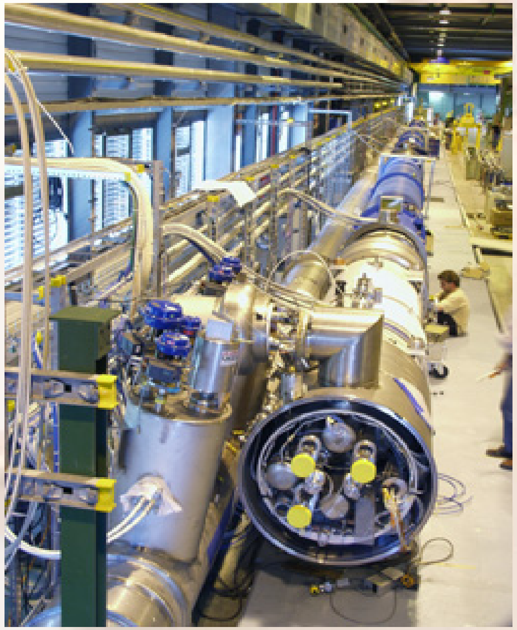
Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV (7x10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Higgs

SUSY.....

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

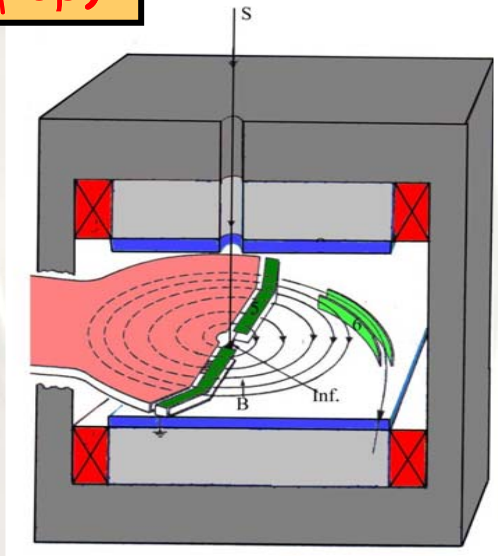
Properties of Cyclotrons (I)

- 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

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



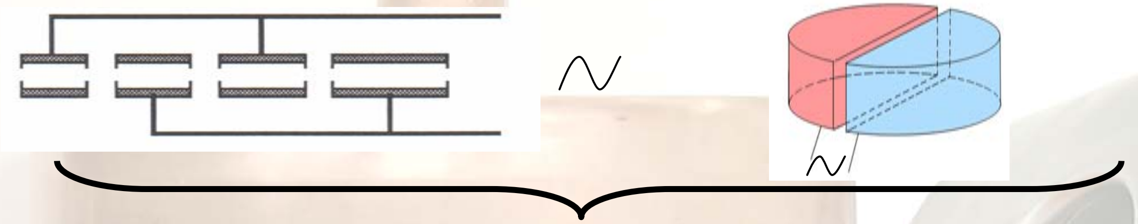
- which shows that the pitch of the spiral formed by the beam in the cyclotron is indeed small, just twice the ratio of the energy change
- a cyclotron typically has 1-4 accelerating cavities, with an energy gain of up to a few hundred keV
- thus the beam typically makes hundreds of turns in the accelerator, 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

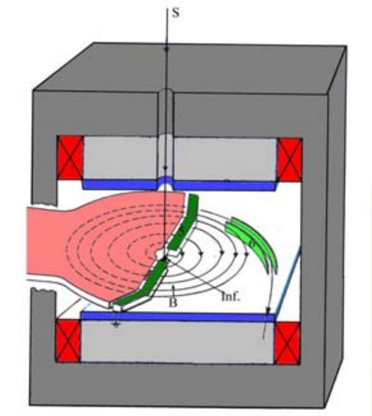
$$W_{kin}/A = 48\ (B_m\ \rho)^2\ (Q/A)$$

or

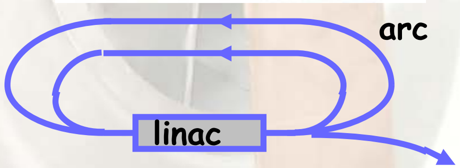
$$W_{kin}/A = K\ (Q/A)^2$$

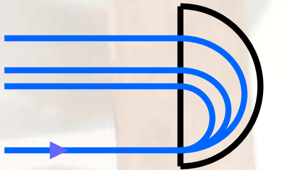
Properties of Cyclotrons (II)





- (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

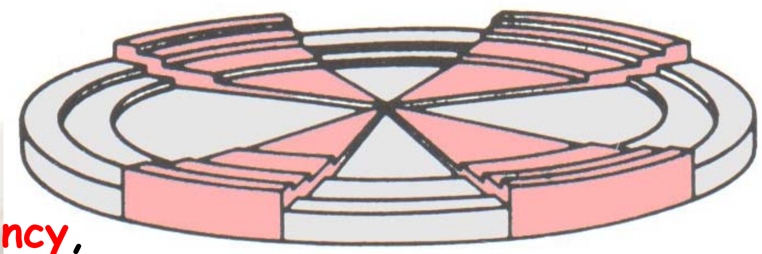




"reflecting" magnet (Microtron)

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

Properties of Cyclotrons (III)

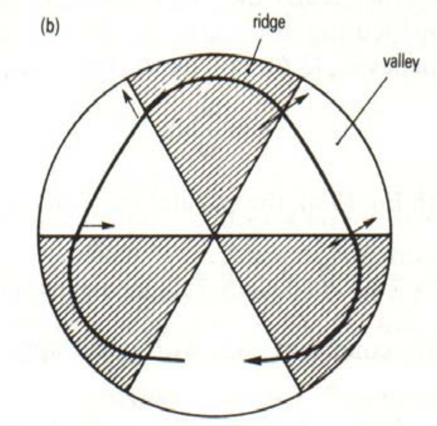


- the preceeding slide derived the expression for the cyclotron frequency ν

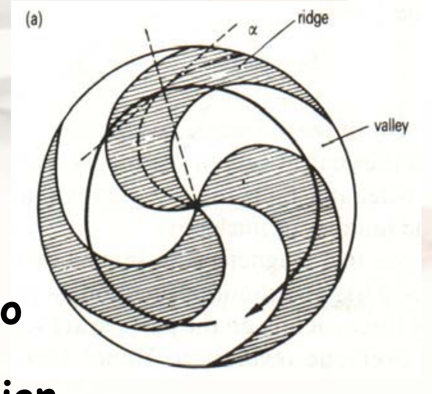
$$\nu = qB_m / 2\pi m_0$$

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

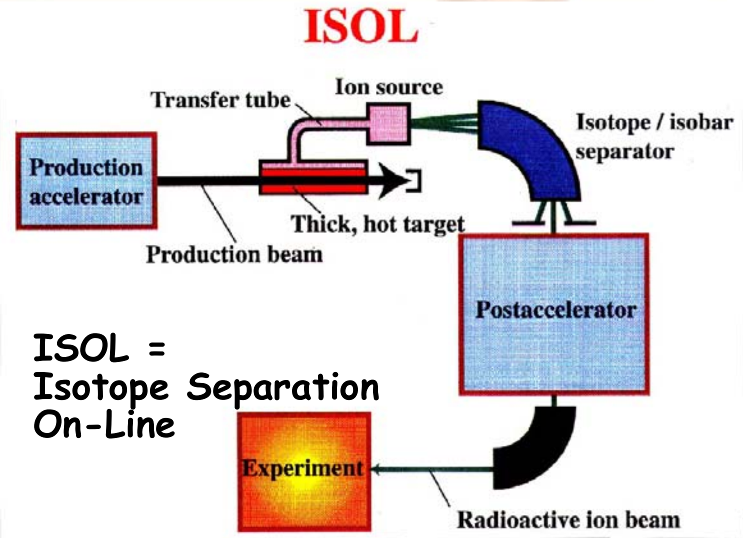
- but the formula, even more importantly, also suggests how to overcome the initial relativistic effects in a cyclotron (starting around 20 MeV for a proton): the relativistic mass increase with increasing $\beta=v/c$ of $m=\gamma \cdot m_0$, $\gamma=(1-\beta^2)^{-1/2}$ can be compensatedby correspondingly 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



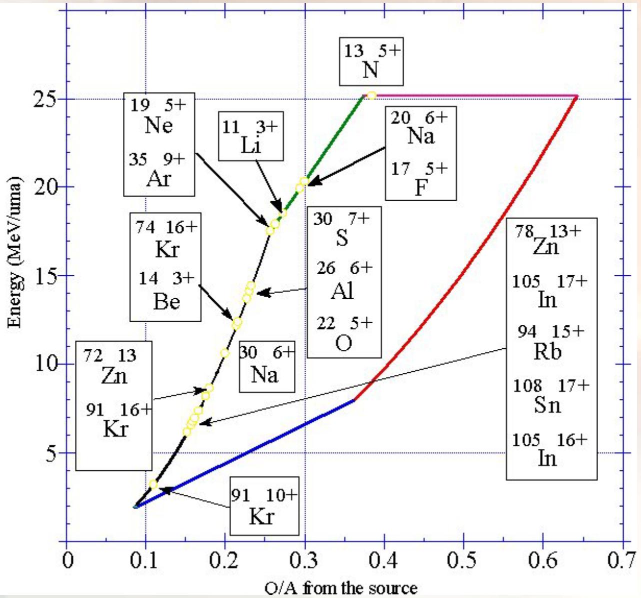
- unfortunately, a cyclotron can not have any direct focusing elements inside and that for flight paths which exceed kilometers
- The way to overcome partially the absence of vertical focusing, is to use alternate gradient focusing (see 2nd lecture), by passing in successively in sectors of strong and 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



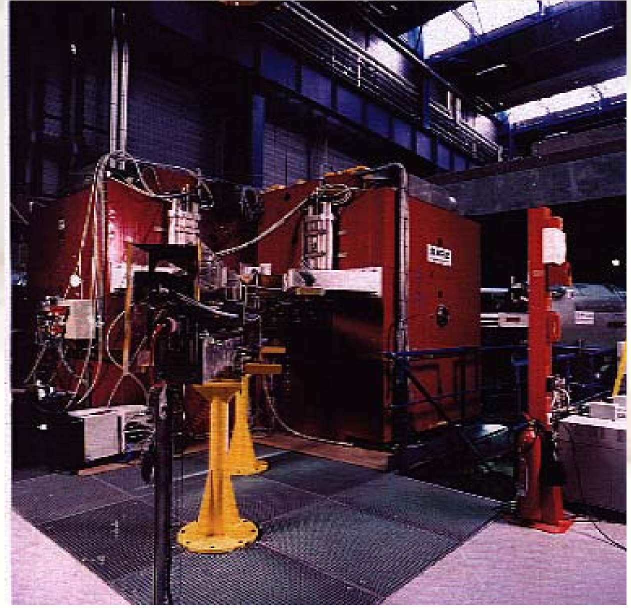
A Recent Cyclotron: SPIRAL @ GANIL



ISOL =
Isotope Separation
On-Line

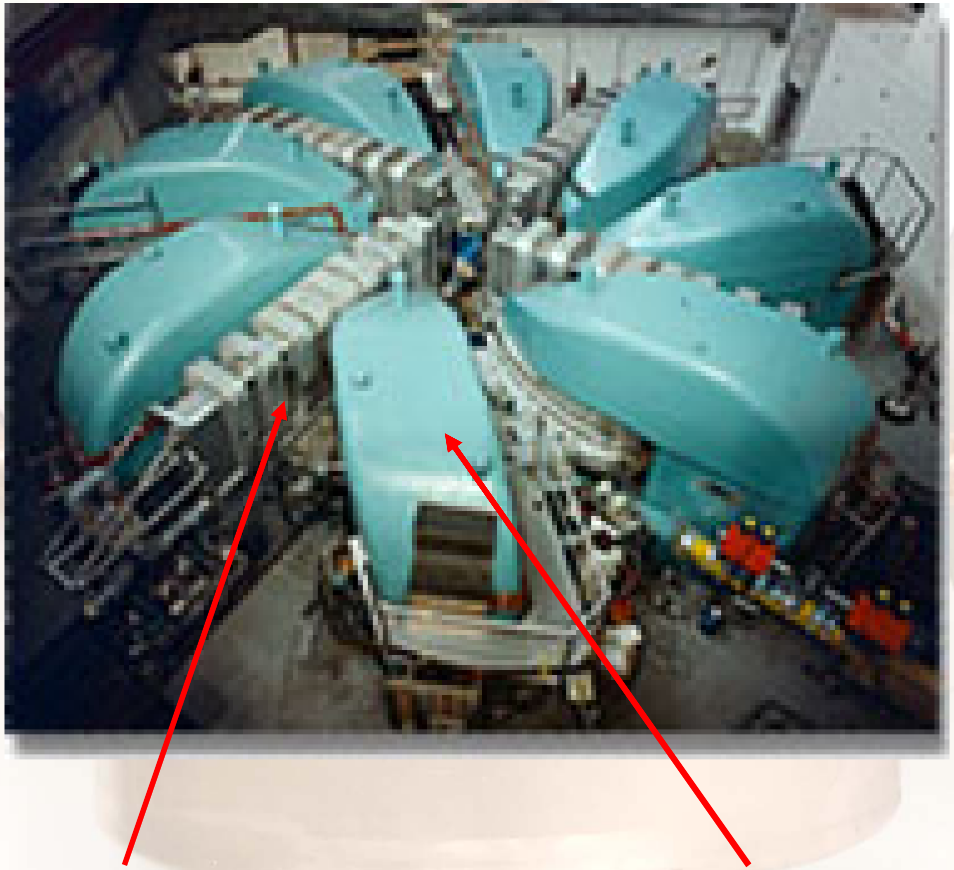


- the SPIRAL facility (collaboration: IN2P3 CEN-Bordeaux, CEA Bruyères, IN2P3 LPC-Caen, GANIL, IN2P3 IPN Orsay, CEA Saclay, LNS SATURNE), uses the GANIL facility, (coupled cyclotrons, K=380, 100 MeV/A) as "driver"
- from a target-ion source system radioactive ions are produced and extracted by the ISOL 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

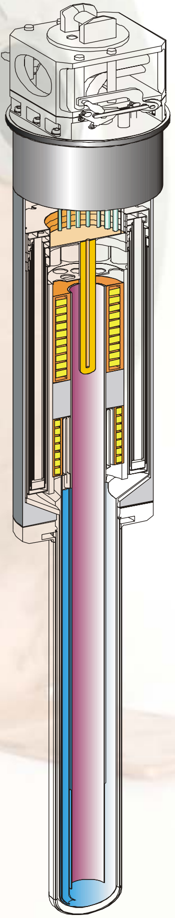


- transmission optimised (up to 50%), secondary beam intensities can reach up to 10^9 pps in a mass range up to A=100
- the SPIRAL facility has come into operation for physics since 2001

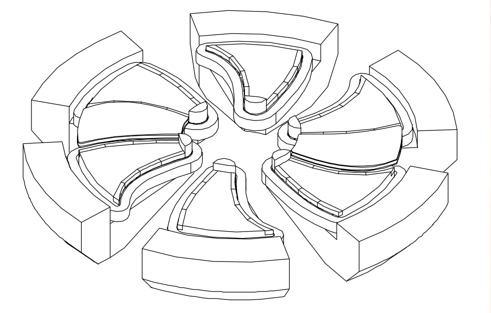
The PSI cyclotron facility



- 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)

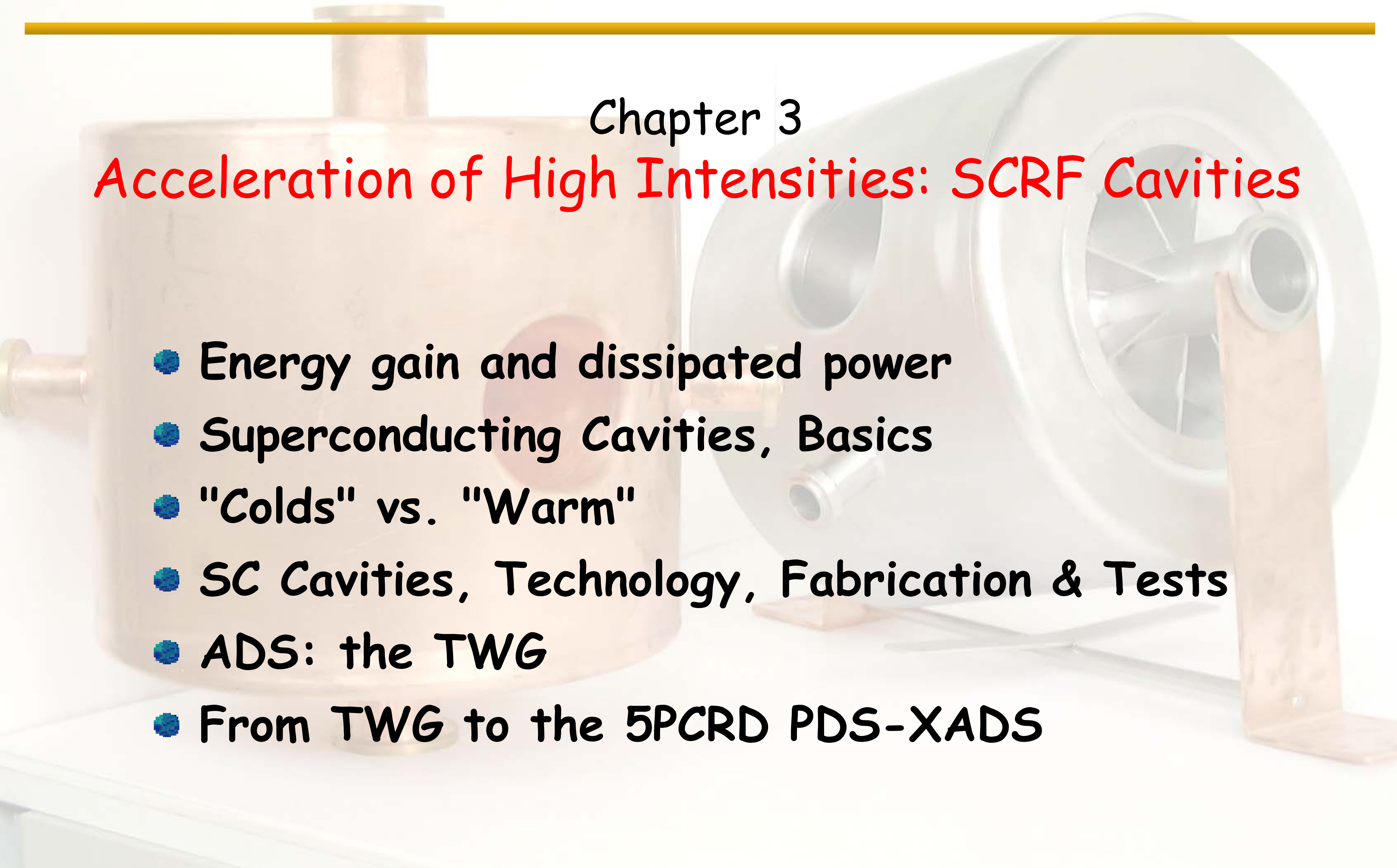


Cyclotrons for ADS ?



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 solution (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



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

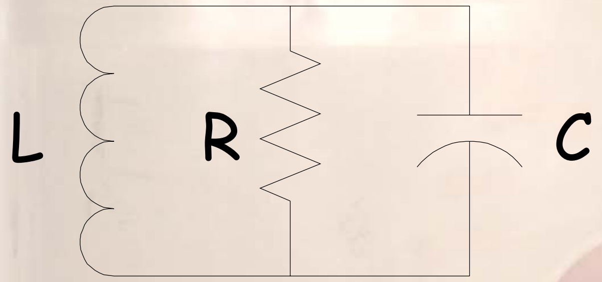
- For efficient acceleration Q, r and r/Q must all be as high as possible

→

  - 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



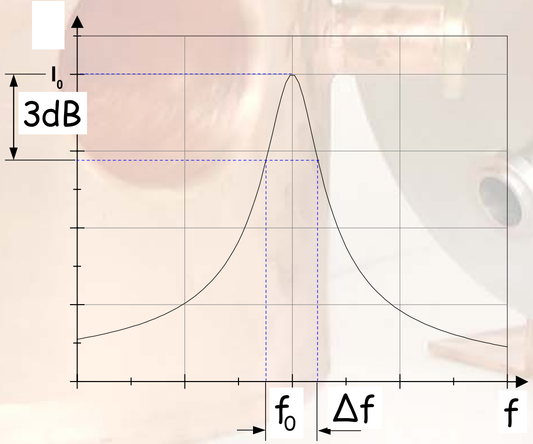
$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad Q = \omega_0 RC$$

$$\omega_0 = 2\pi f_0$$

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

- 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

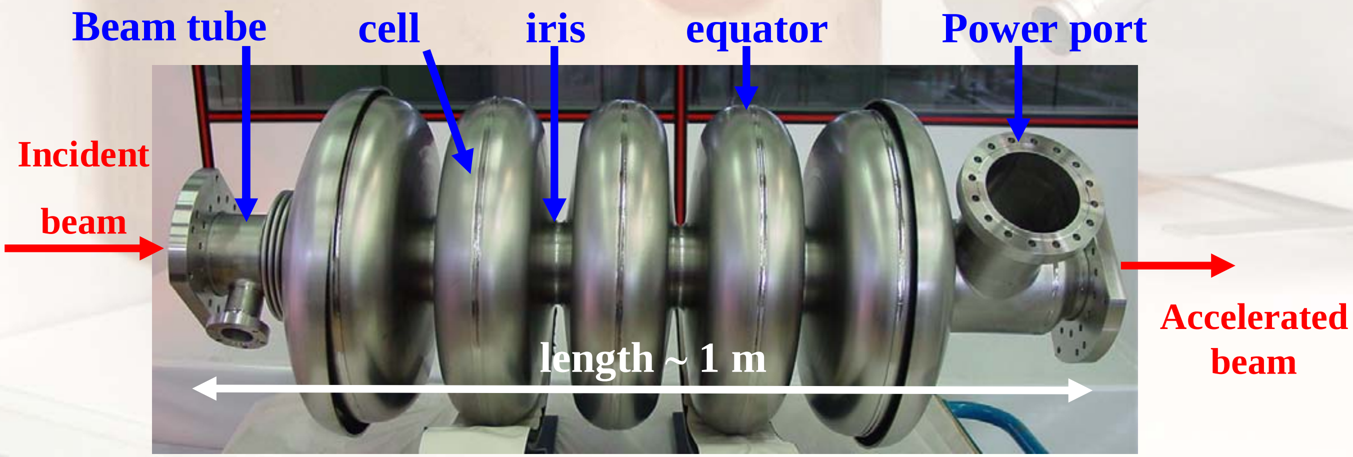
- « **CAVITY** » = Electromagnetic resonant cavity

  ⇒ 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

β=v/c from 0,01 to 1

0 K ≈ - 273,15 °C

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

Why superconducting cavities ?

Intrinsic advantage of cold cavities

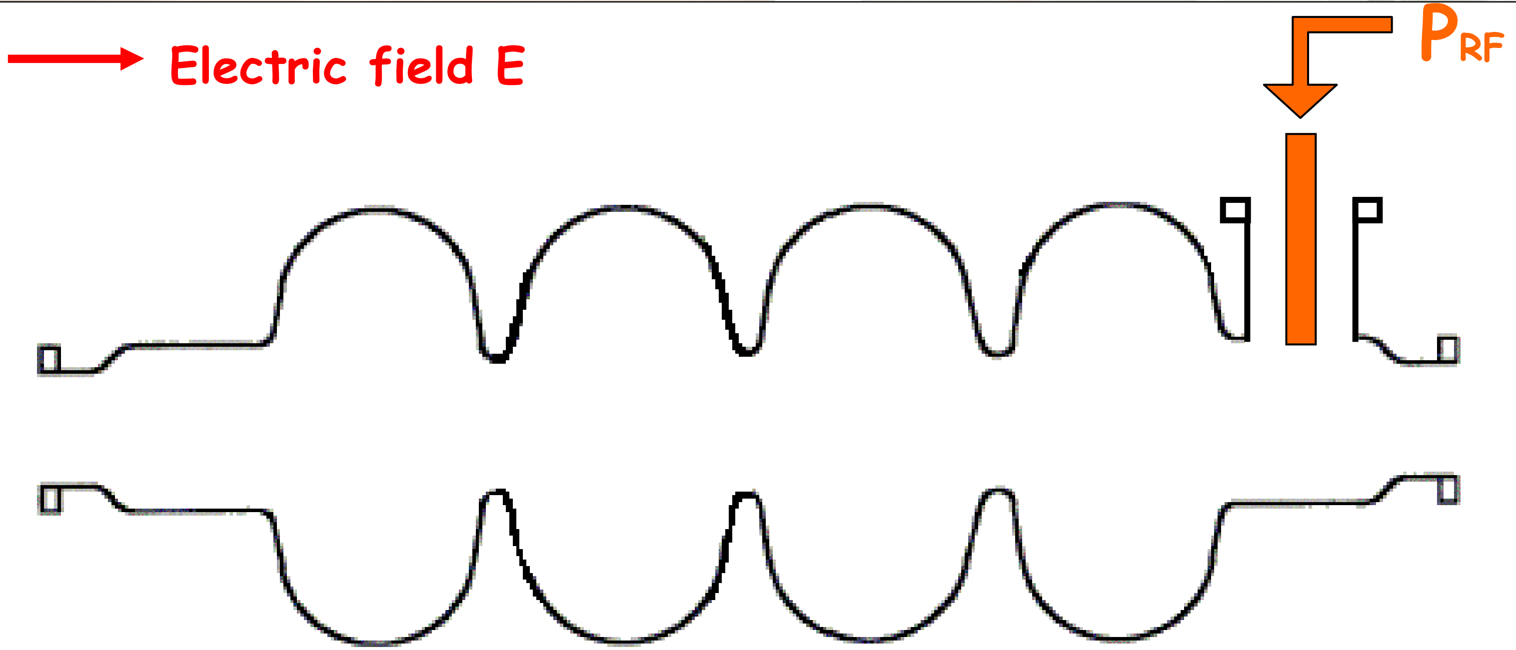
Almost no losses on the cavity wall (thanks to superconductivity)

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

- Operating cost gain 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 = security gain
- **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



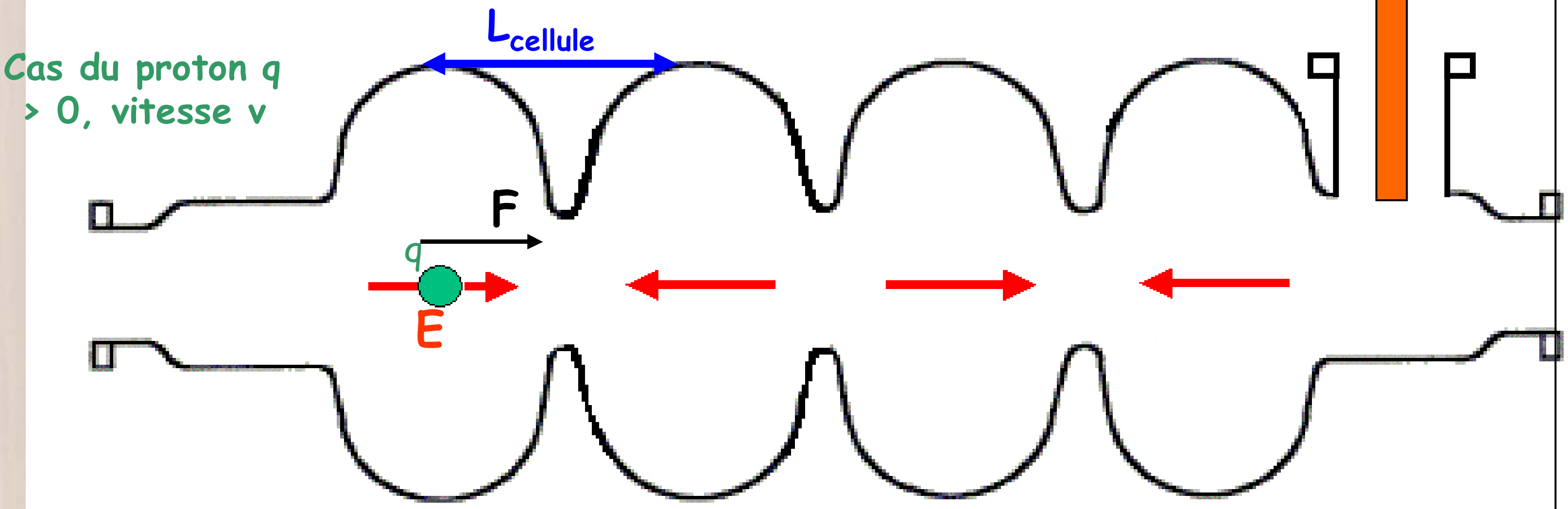
This E field is time and space dependant
With f the cavity frequency, T = 1 / f
Ex : f = 700 MHz → T = 1,43 ns

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

(2) <u>The charged particle enter the</u> : **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

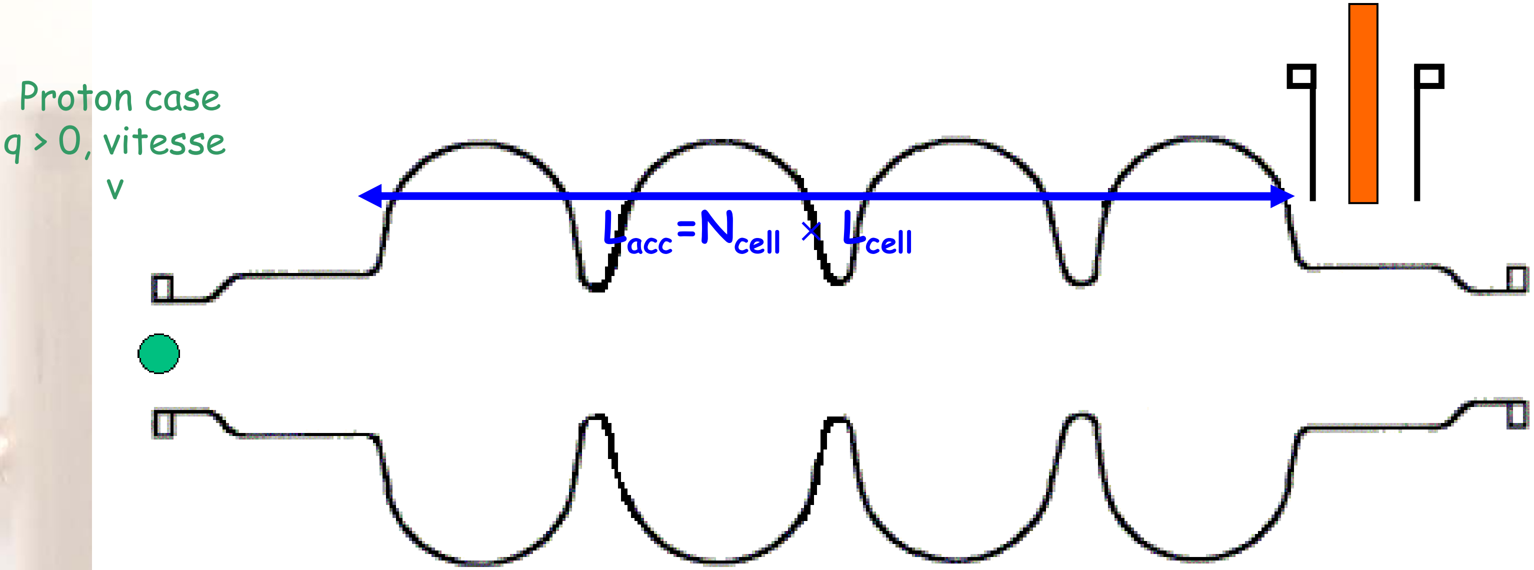


<u>Synchronism condition</u> :

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

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

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



Energy gain :

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

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

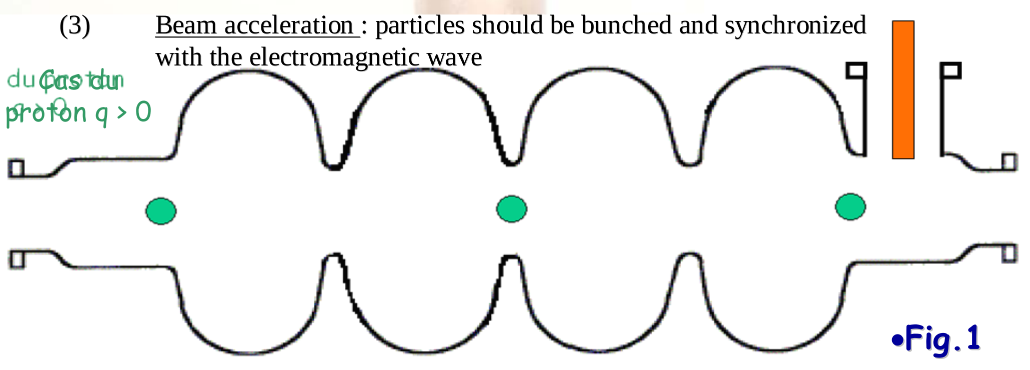
L_{acc}: cavity accelerating length

φ : particule phase with respect to the RF wave

Ex : f = 700MHz ; 5-cell proton cavity $\beta = 0{,}65$ ($L_{acc}=5\times14$cm); E_{acc}= 10MV/m ; $\varphi = 0°$

*⇒ 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

•Fig.1

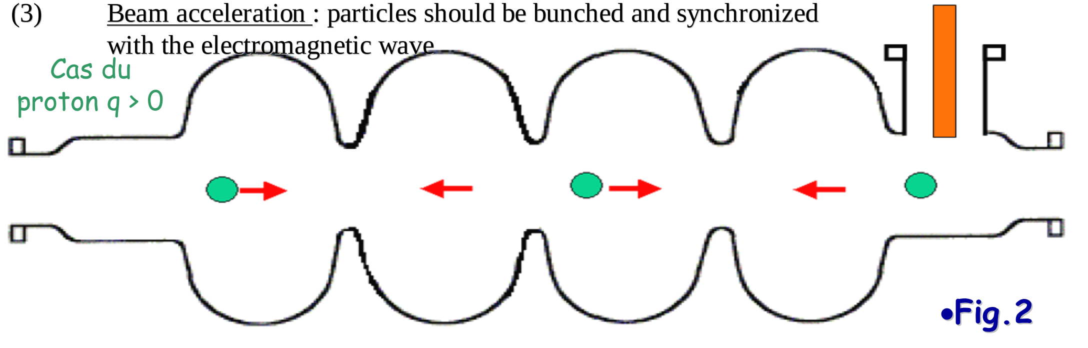
$T_{beam} = n\ T_{RF}$ (n=1,2,3…)

« the cavity resonant frequency should be a multiple of the beam frequency that

it wants to accelerate»

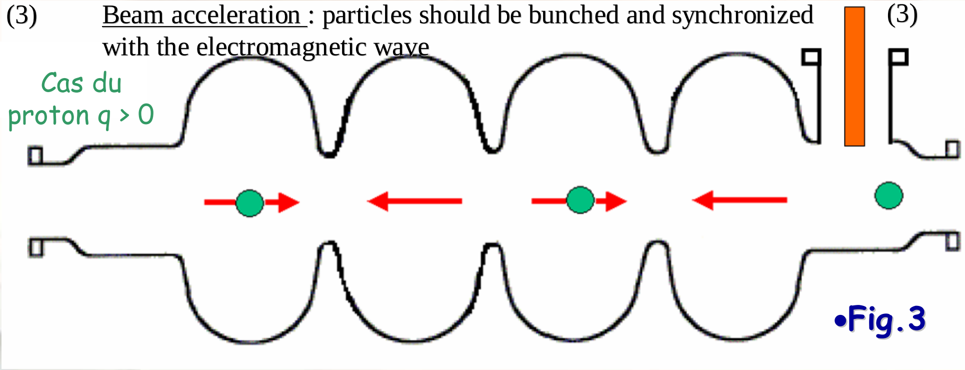
Ex: if f_{beam}=350 MHz (T_{beam}=2,86ns), then the cavity should resonate at :

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



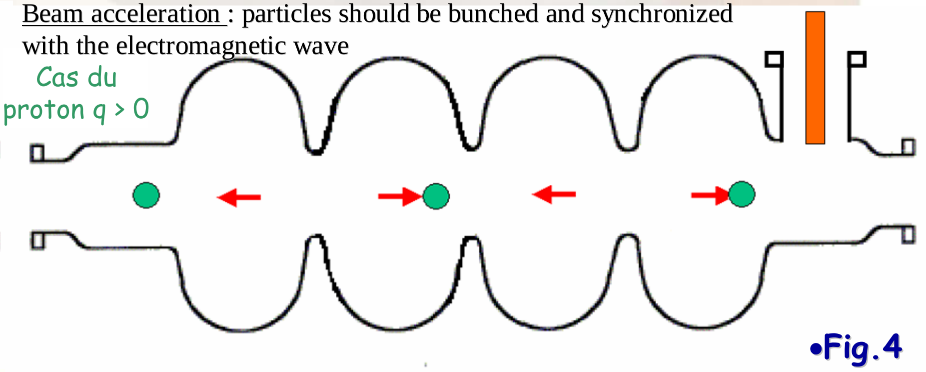
(3) Beam acceleration : particles should be bunched and synchronized with the electromagnetic wave

•Fig.2



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

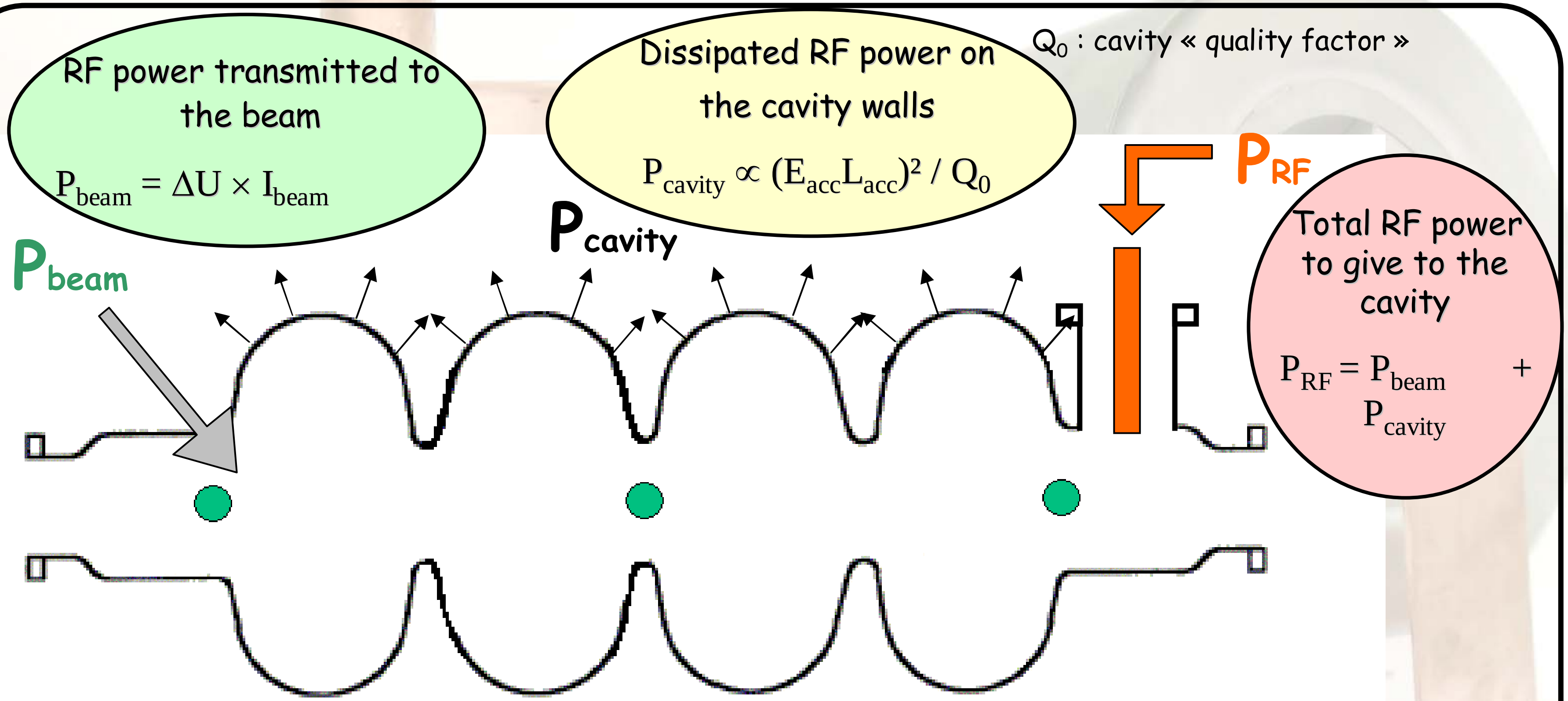
•Fig.3



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

•Fig.4

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



RF power transmitted to the beam

$P_{beam} = \Delta U \times I_{beam}$

Dissipated RF power on the cavity walls

$P_{cavity} \propto (E_{acc}L_{acc})^2 / Q_0$

Q_0 : cavity « quality factor »

P_{RF}

Total RF power to give to the cavity

$P_{RF} = P_{beam} + P_{cavity}$

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

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

$P_{cavity} \approx$ **16 W**

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

$P_{cavity} \approx$ **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 :

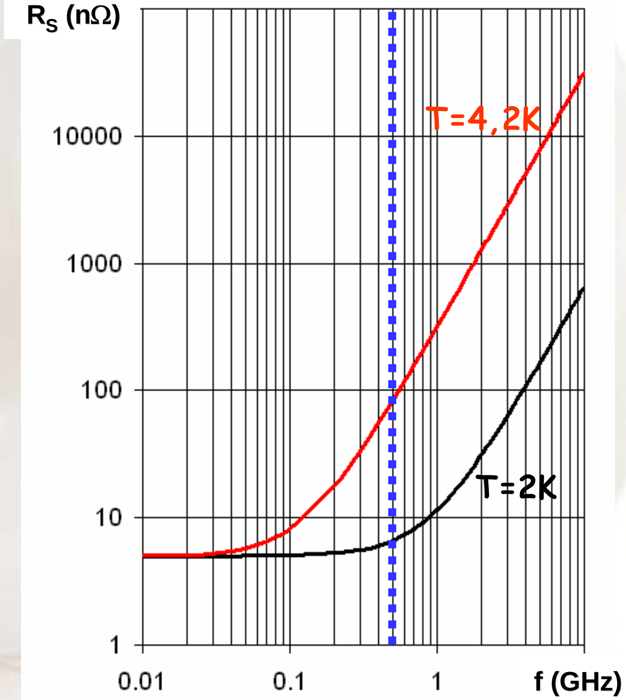
- High Tc and Bc
- Low surface resistance (in order to minimize the losses)
- Quite good mechanical (easy to shape) and thermal properties

Operating temperature → compromise between :

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

Conclusion $\left\{ \begin{array}{l} \text{if } f < 500 \text{ MHz} \rightarrow T \sim 4{,}2 \text{ K (Liquid Helium)} \\ \text{if } f > 500 \text{ MHz} \rightarrow T \sim 2 \text{ K (Superfluid Helium)} \end{array} \right.$

Surface resistance as a function of frequency



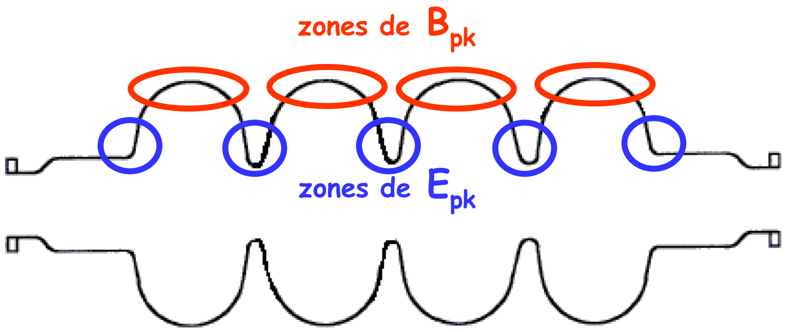
Niobium characteristics
$$\left\{ \begin{array}{l} T_c = 9{,}2 \text{ K} \\ R_S(\Omega) \approx 2\times10^{-4}\,\frac{1}{T}\left(\frac{f(\text{GHz})}{1{,}5}\right)^2 e^{-17{,}67/T} + R_{res} \end{array} \right.$$

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:

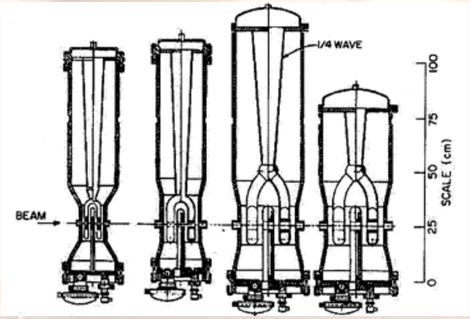
- cavity β = 0.65, $B_{pk}/E_{acc} \approx 5$ mT/(MV/m) i.e. $\mathbf{E_{accMAX}}$ = **44 MV/m** @ 2K
- cavity β = 0.5, $B_{pk}/E_{acc} \approx 6$ mT/(MV/m) i.e. $\mathbf{E_{accMAX}}$ = **37 MV/m** @ 2K

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)

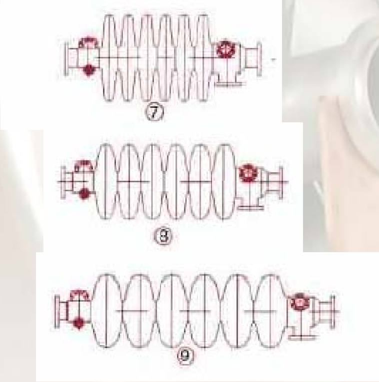
80 à 352 MHz - β = 0,047 à 0,25

Cavité ré-entrante (Legnaro)

352 MHz - β ≥ 0,1

Cavités elliptiques

350 MHz à 3 GHz - β = 0,47 à 1

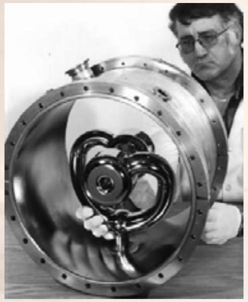


Cavité TTF

1,3 GHz - β = 1

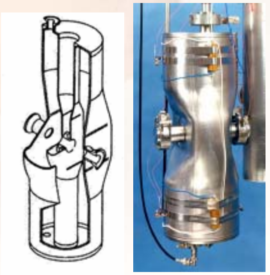
RFQs supra (Legnaro)

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

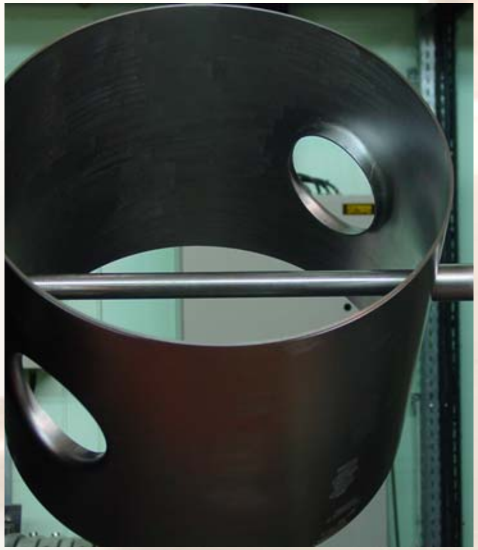
Cavités spoke (CNRS Orsay)

352 MHz - β = 0,15 et 0,35

Cavité APT (Los Alamos)

700 MHz - β = 0,64

SC cavity : fabrication

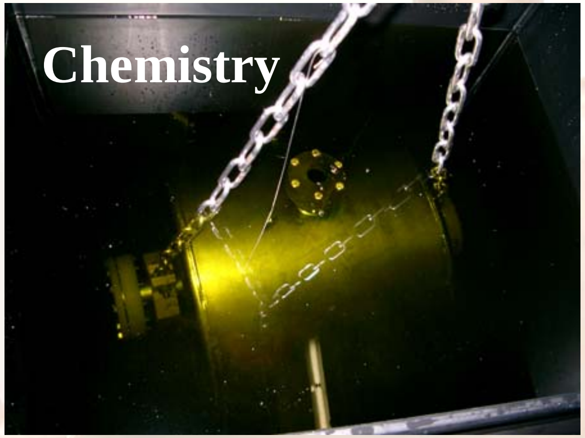


Niobium sheets 3 mm thick
Welding by electron beams

Spoke cavity

$\beta = 0.35$
f = 352.2 MHz

SC cavity technology: preparation and test

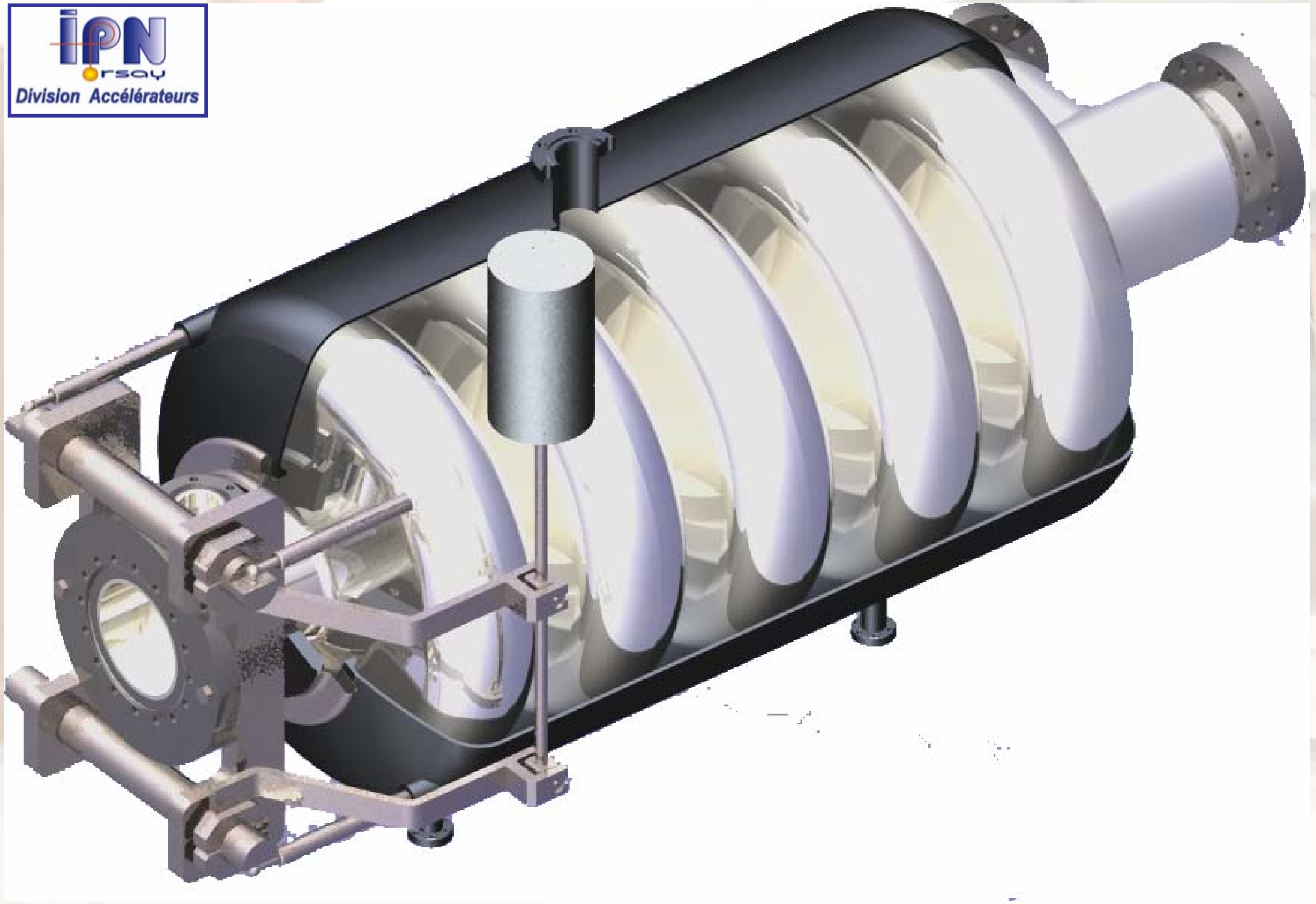

Chemistry


High pressure rinsing

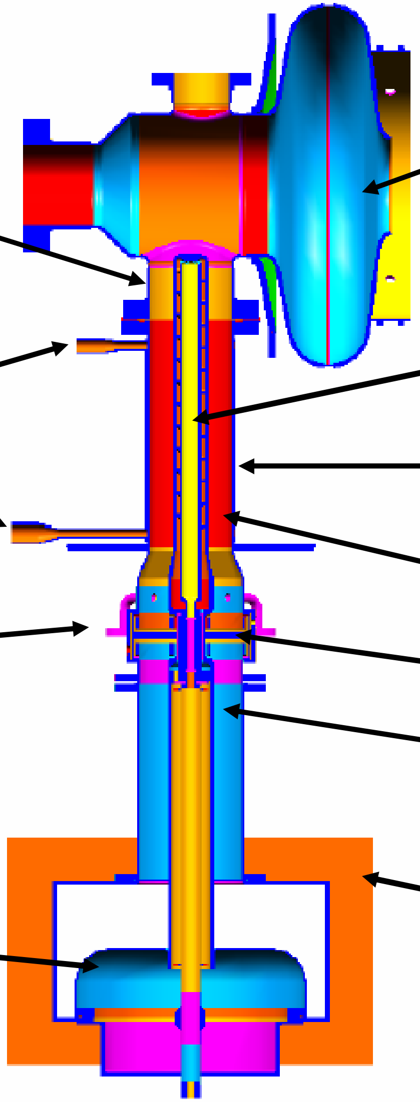

Assembly in clean room


CryHoLab

SC Cavity : cold tuning system



Power couplers (I)



Cavity (1st cell)

Cavity coupling port

Inner conductor (water cooled)

Outter conductor cooling (LHe @ 4.5 K)

Outter conductor

Vacuum

Ceramic window cooling (Water)

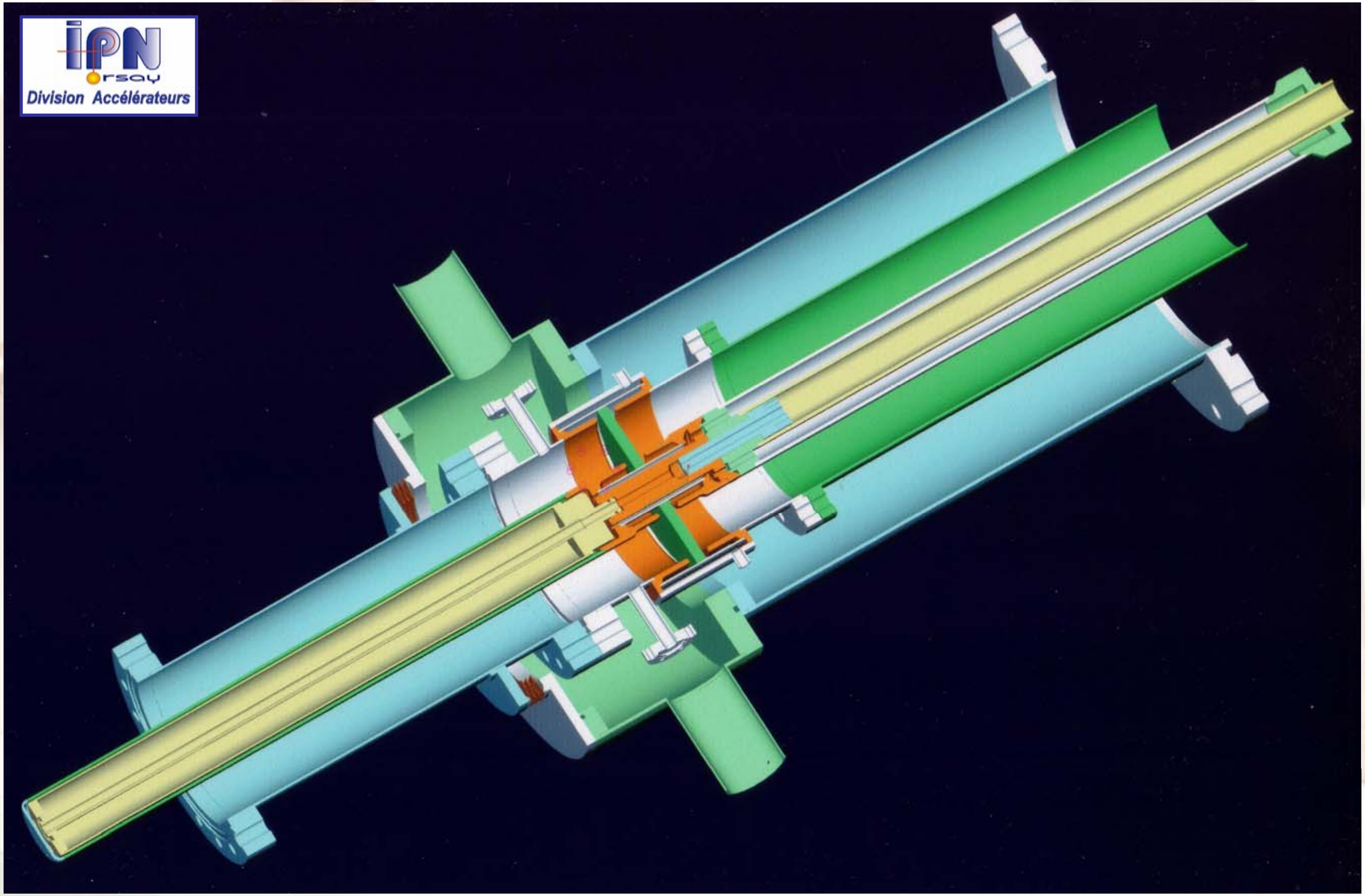
Ceramic window

Air

Waveguide

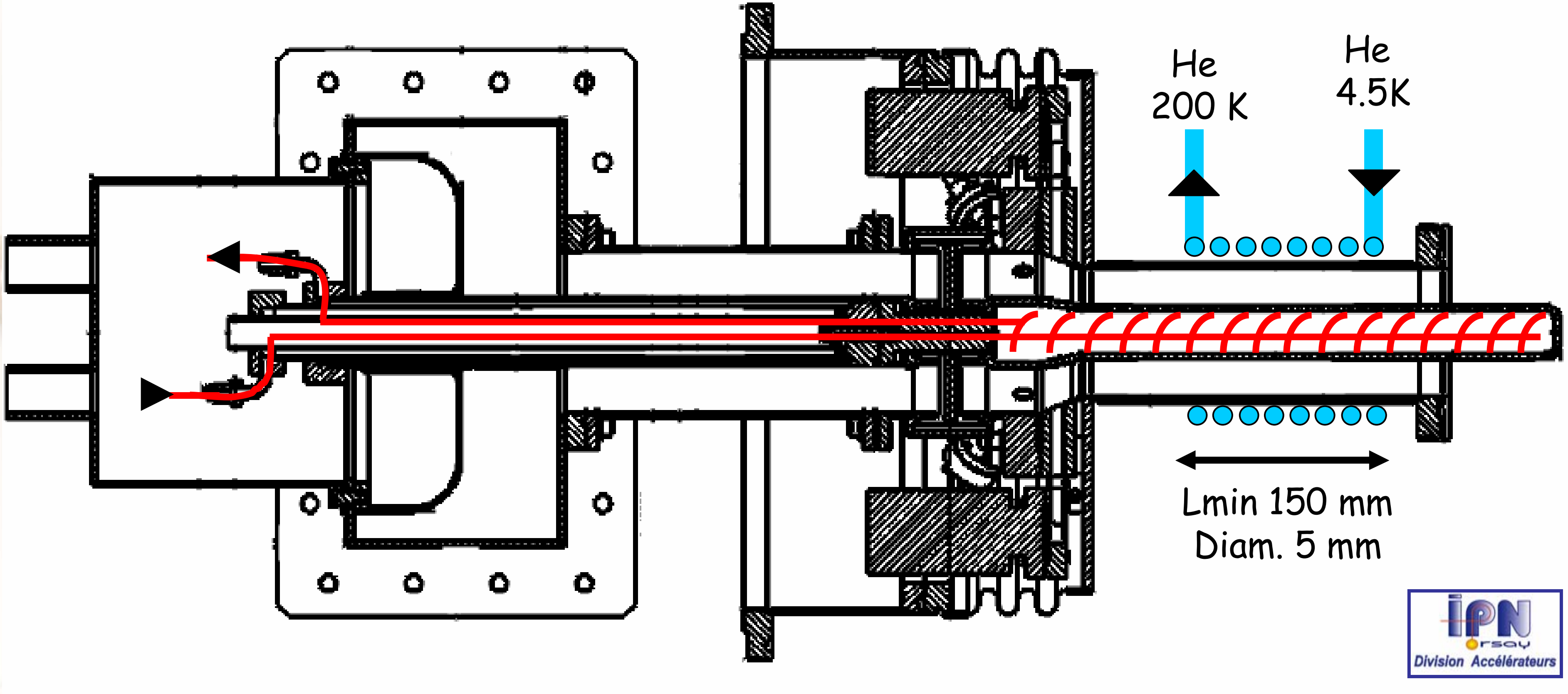
Doorknob: transition waveguide to coax

Power couplers (II)



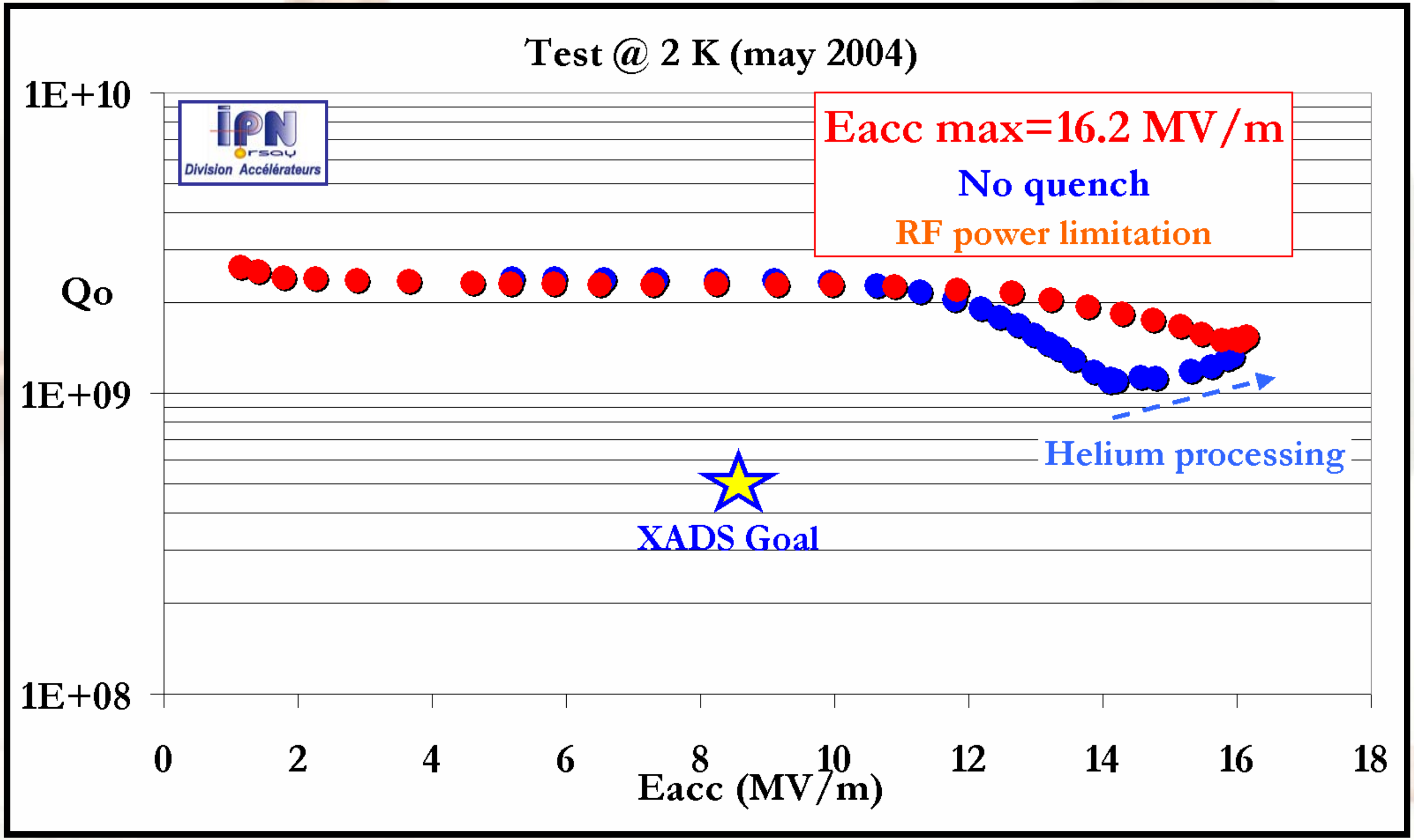
Power couplers (III)

- **Outer conductor:** Helium cooling



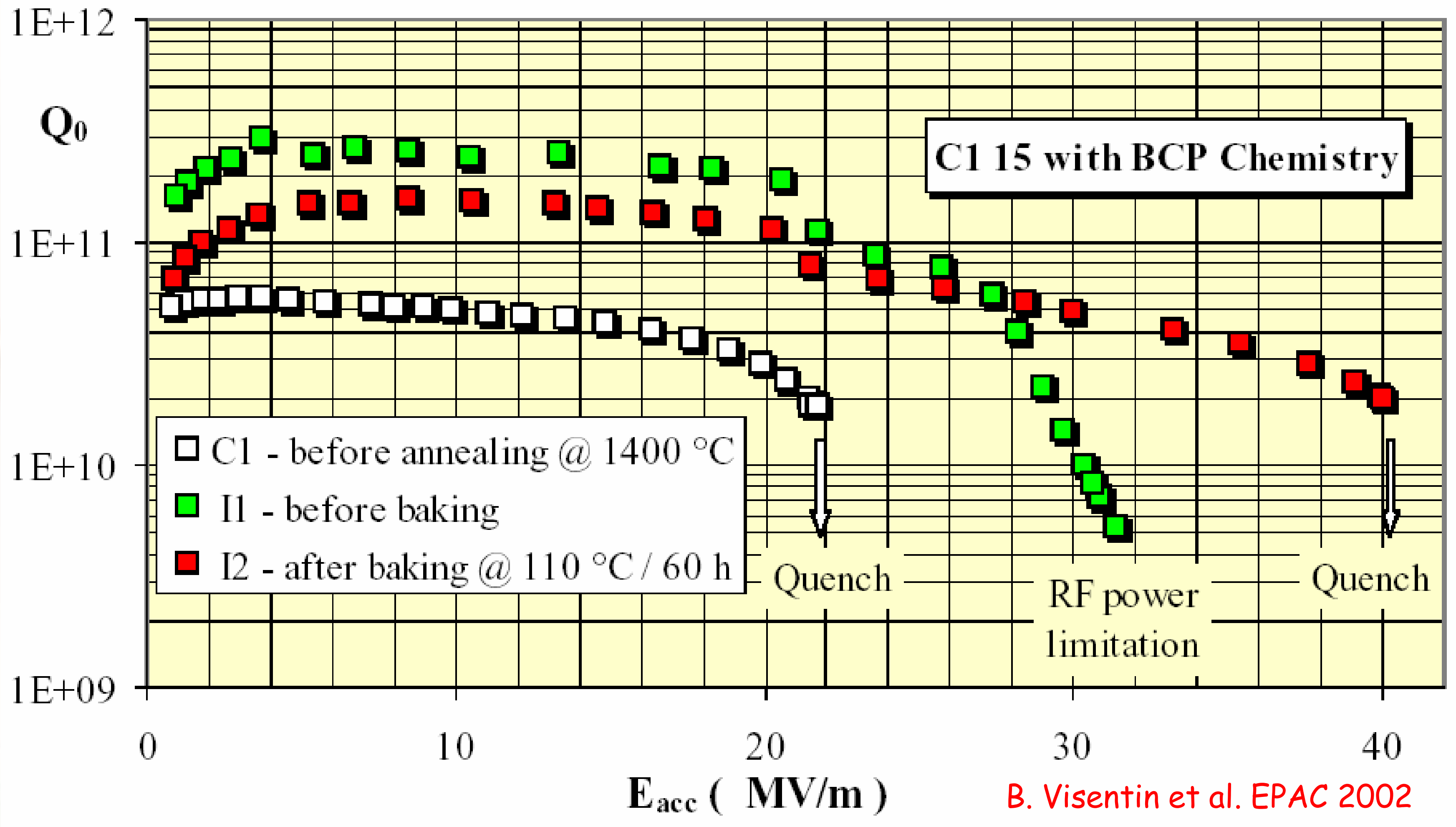
- **Inner conductor:** Water cooling

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