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 Accelerators
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

K.G. Steffen
High Energy Optics
(Interscience Publishers, J. Wiley & sons, 1965)

H. Bruck
Accelerateurs Circulaires de Particules
(PEF, 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 Publishers 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

A.D. Vlasov
Theory of Linear Accelerators
(Program for scientific translations, Jerusalem 1968)
...... and some "more recent" textbooks

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Publisher and Year</th>
</tr>
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<tbody>
<tr>
<td>P. J. Bryant and K. Johnsen</td>
<td>The Principles of Circular Accelerators and Storage Rings</td>
<td>Cambridge University Press, 1993</td>
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<tr>
<td>H. Wiedemann</td>
<td>Particle Accelerator Physics</td>
<td>Springer-Verlag, Berlin, 1993</td>
</tr>
<tr>
<td>M. Reiser</td>
<td>Theory and Design of Charged Particles Beams</td>
<td>J. Wiley &amp; sons, 1994</td>
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<tr>
<td>K. Wille</td>
<td>The Physics of Particle Accelerators: An Introduction</td>
<td>Oxford University Press, 2000</td>
</tr>
<tr>
<td>E.J.N. Wilson</td>
<td>An introduction to Particle Accelerators</td>
<td>Oxford University Press, 2001</td>
</tr>
</tbody>
</table>

... and of course also the lectures of the CERN accelerator schools: "CAS"
The cathode ray tube: a "complete accelerator at home"
Accelerating Particles (I)

- acceleration \( a \) of particle of mass \( m \) needs a force \( F \):
  \[
  F = m \cdot a
  \]
  (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 \( v \):
  \[
  F = q \left( E + v \times B \right)
  \]

- 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:
  \[
  W = q \ V
  \]

- (typically **used unit**: electron volt \([\text{eV}]\))
Accelerating Particles (II)

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 $p$):
  \[ \lambda = \frac{h}{p} \]  
  (de Broglie wavelength),
  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

\[ E = mc^2 \]

**Useful Dimensions or Distances**

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

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<th>Leptons</th>
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<tr>
<td>Flavor</td>
<td>Mass GeV/c²</td>
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<tr>
<td>e⁻</td>
<td>&lt;1×10⁻⁸</td>
</tr>
<tr>
<td>ν_e</td>
<td>0.000511</td>
</tr>
<tr>
<td>μ⁻</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>ν_μ</td>
<td>0.106</td>
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<tr>
<td>τ⁻</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>ν_τ</td>
<td>1.7771</td>
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<table>
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<th>Quarks</th>
<th>spin = 1/2</th>
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<td>Flavor</td>
<td>Mass GeV/c²</td>
</tr>
<tr>
<td>u</td>
<td>0.003</td>
</tr>
<tr>
<td>d</td>
<td>0.006</td>
</tr>
<tr>
<td>c</td>
<td>1.3</td>
</tr>
<tr>
<td>s</td>
<td>0.1</td>
</tr>
<tr>
<td>t</td>
<td>175</td>
</tr>
<tr>
<td>b</td>
<td>4.3</td>
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**Spin** is the intrinsic angular momentum of particles. Spin is given in units of ℏ, which is the quantum unit of angular momentum, where ℏ = ℏ/2π = 6.38×10⁻³⁵ GeV s = 1.03×10⁻³⁴ 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/c² (remember E = mc²), where 1 GeV = 1.60×10⁻⁹ eV = 1.60×10⁻¹⁶ joule. The mass of the proton is 0.938 GeV/c² = 1.67×10⁻²⁷ kg.

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**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!!
Towards Unification

Note in passing,

- that accelerators have been the prime instruments for providing the experimental proof for the Standard Model, containing 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 built at Pisa the VIRGO experiment, a 3 km long high-precision interferometer for observing gravitational waves.
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, biology, 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 builds 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 Christofilos’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 SpêS).
- **1970**
  - Kapchinski & Telyakov invent the radio-frequency quadrupole (RFQ).
- **early 80’s**
  - Superconducting magnets for cyclotrons 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.
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.
Ions are produced in a **ionized gas** (‘plasma’)

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

\[
\frac{n_i}{n_n} \approx 3 \times 10^{27} \left( \frac{k_B T}{e} \right)^{3/2} \frac{I_j}{k_B T}
\]

Ionization energy: \(I_j\) \((j: \text{charge state})\)

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

Magnetspulen (Spiegelfeld)

Mikrowelle
14,5 GHz

Isolator

Plasmakammer
6.6 x 16 cm

Gas ein

Pumpe (Vakuum)

Ionentransport

Eisenjoch (Hexapol)

‘hot plasma’

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

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

Der Sauerstoff dient als Hilfsgas

70 µA Pb^{26+}

O^{32+}

O^{24+}

O^{25+}

O^{26+}

O^{4+}

O^{5+}

H^{+}

Analyzing field

125

208 Pb

Afterglow Mode
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

- consider an element of an accelerating column of an electrostatic accelerator
- at any moment, the electric field is in the same direction, allowing continuous 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 length of the drift tubes has to increase.
Linacs, towards the next Lecture

- On the preceding 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

\[ m = \gamma \, m_0 \quad E_0 = m_0 \, c^2 \]

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

- \( \gamma \) = Lorentz factor
- \( m_0 \) = rest mass
- \( v \) = particle speed

Kinetic energy, \( T \), and momentum, \( p \), of a relativistic particle

\[ T = m \, c^2 \left( \gamma - 1 \right) = E - E_0 \]

\[ E^2/c^2 = p^2 + m_0^2 \, c^2 \]

\[ p = m \, v = m_0 \gamma \, v \approx m \, c \text{ if } v \approx c \]

Non relativistic approximation: \( v \ll c \)

\[ E \approx m_0 \, c^2 + \frac{1}{2} \, m_0 \, v^2 \]

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

Useful numbers:

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

- Electron rest energy: \( E_0 = 0.511 \text{ MeV} \)
- Proton rest energy: \( E_0 = 938 \text{ MeV} \)
Basic Concepts: Fields

- **Equation of motion and Lorentz force**
  \[ \vec{F}_{\text{Lorentz}} = \frac{d\vec{p}}{dt} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{\text{el}} + \vec{F}_{\text{mag}} \]

- Electric field can transfer energy to the particles
  \[ \Delta E = \Delta T = \int \vec{F}_{\text{Lor}} \cdot d\vec{s} = q \cdot \int \vec{E} \cdot \vec{v} \cdot dt \]

- 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 ...)

Electrostatic fields are used for the source
\[ \nabla \times \vec{E} = 0 \]

Time varying harmonic (RF) electric fields, via resonant cavities, transfer energy to the beam
\[ \nabla \times \vec{E} \neq 0 \]
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
  \[ E_{0,\text{proton}} \approx 2000 \ E_{0,\text{electron}} \]

- A proton varies its velocity on a much higher kinetic energy range

- "Synchronous" condition for a multicell cavity:
  \[ L = \frac{\lambda_{\text{RF}} \beta}{2} \]

- 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 \( \beta \).

- Below \( \beta \approx 0.5 \), special structures are required.
The resonant cavity

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

\[
\begin{align*}
\nabla \cdot \mathbf{E} &= 0 \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}
\end{align*}
\]

Maxwell equations can be solved only when the boundary conditions are given

For a perfect conductor:

\[
\begin{align*}
n \cdot \mathbf{B} &= 0 \\
n \times \mathbf{E} &= 0
\end{align*}
\]

Assuming a field of the form (uniform section):

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

The transverse components are functions of the derivatives of the longitudinal

\[
\begin{align*}
e_x &= -i/k_c^2 (\beta \partial e_z / \partial x + \omega \partial b_z / \partial y) \\
e_y &= i/k_c^2 (-\beta \partial e_z / \partial y + \omega \partial b_z / \partial x) \\
b_x &= i/k_c^2 (\omega / c^2 \partial e_z / \partial y - \beta \partial b_z / \partial x) \\
b_y &= -i/k_c^2 (\omega / c^2 \partial e_z / \partial y + \beta \partial b_z / \partial x)
\end{align*}
\]

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: \( \text{TM}_mnl \))
    - these are the **accelerating modes**
  - \( E_z = 0 \) (Transverse electric modes: \( \text{TE}_mnl \))
    - are the **deflecting modes**

Pattern of the E and B fields in the \( \text{TM}_{010} \) mode

\[
\begin{align*}
\omega &= \frac{2.405}{a} \\
E_z &= E_0 J_0 \left( \frac{2.405}{a} r \right) \\
b_\phi &= i \frac{E_0 J_1 \left( \frac{2.405}{a} r \right)}{c}
\end{align*}
\]
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.

\[ L = \frac{\Lambda_{RF} \beta}{2} \]
The energy gain of the particle depends on:
- The accelerating field
- The operating synchronous phase $\Phi_s$
- The velocity mismatch between the particle velocity and the synchronous velocity in the cavity

For protons $\Phi_s$ must be $-20^\circ$ to $30^\circ$ 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 to divide it into sections, each using a different cavity geometry in an energy range.

- If \( N \) is large, 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:
- \( S_1: 100 \beta 190 \text{ MeV} \) (\( \beta = 0.47 \), i.e. 145 MeV)
- \( S_2: 190 \beta 430 \text{ MeV} \) (\( \beta = 0.65 \), i.e. 296 MeV)
- \( S_3: 430 \beta 1600 \text{ MeV} \) (\( \beta = 0.85 \), i.e. 843 MeV)

Increasing \( \beta \):
- 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
  \[ V_0 \sin 2\pi \omega_{rf} t = V_0 \sin \phi(t) \]

  - 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 \( 0 < \phi_s < \pi \)
  \[ \Delta E = qV_0 \sin \phi_s \]

- 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

\[
\frac{1}{f} = \left( \frac{B'}{Bp} \right) L
\]

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:

\[
x_o = x_i + x_i'L
\]

\[
x_o' = x_i'
\]

F-O-D Transfer Matrix:

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

- 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

LEP quadrupole (CERN)
Circular accelerators: useful Definitions & Formulas (I)

- 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

![Cyclotron and Synchrotron](image)

**Lorentz force:**

\[ F = q \left( E + v \times B \right) = \frac{dp}{dt} \]

**(relativistic) Kinetic Energy**

\[ (pc)^2 = W_{\text{total}}^2 - W_0^2 \quad \text{with} \quad W_0^2 = m_0 c^2 \]

Examples: electron rest mass: \( m_0 = 511 \text{ KeV/c}^2 \), proton rest mass \( m_0 = 0.938 \text{ GeV/c}^2 \)

Neglecting the comparatively small accelerating term \( dp/dt = qE \) for a moment, a reference particle with mass \( m \) in a given orbit \( \rho \) will have \( |p| \approx \text{constant in each point} \). The Lorentz force will be in equilibrium with the centrifugal force:

\[ mv^2/\rho = dp/dt = qvB \]
The preceding formulas allow to write:

\[ p = q \, B \, \rho \quad \text{and} \quad W_{\text{total}}^2 = (q \, c \, B \, \rho)^2 + W_{0}^2 \]

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 \( B_{\text{m}} \rho \), 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 kinetic, hence total energy \( W_0 \ll W_{\text{total}} \), one gets the rule of thumb relation:

\[ W_{\text{total}} = 300 \, Q \, B_{\text{m}} \, \rho \]

in MeV \quad Q = q/e_0 \quad \text{in Tesla} \cdot \text{meters}
Energy Gain in Circular Accelerators

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

\[
2 \delta W = 2 q c \left( q c B_m \rho \right) \left( \rho \delta B_m + B_m \delta \rho \right)
\]

- which, after some "simple" operations gives

\[
\delta W = \left( 2\pi \rho / \delta t \right) q \left( \rho \delta B_m + B_m \delta \rho \right) = 2\pi \rho q \left( \rho \dot{B}_m + B_m \dot{\rho} \right)
\]

- 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 \( R \)
- \( \delta W = 2\pi \rho q \rho B_m \) 
  \[ \delta W = 2\pi R^2 q \dot{B}_m \]
  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 $B = 10\, T$) and radius of the machine, recall $W \,[\text{MeV}] = 300 \, Q \, B \, \rho \,[\text{Tm}]$, and it can be used as a collider.

- A synchrotron is a pulsed machine, typical repetition rates are about $1 \, \text{Hz}$.

- 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 $\mu\text{A}$ 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...

- 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
The Large Hadron Collider (LHC)

Collisions at LHC

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Energy (GeV)</th>
<th>Luminosity ($10^34$ cm$^{-2}$s$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>LEP</td>
<td>e+ e-</td>
<td>200</td>
</tr>
<tr>
<td>LHC</td>
<td>p p</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Pb Pb</td>
<td>1312</td>
</tr>
</tbody>
</table>

Proton-Proton
Protons/bunch: $10^{11}$
Beam energy: 7 TeV ($7 \times 10^{12}$ eV)
Luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
Crossing rate: 40 MHz
Collisions: $10^7 - 10^9$ Hz

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 Straight 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

Arrivée sur la position d’installation

Transport dans le tunnel par véhicule à guidage optique

Installation du toroïde d’ATLAS
Properties of Cyclotrons (I)

- Cyclotrons \((\delta B_m = 0)\) are intrinsically low-energy machines \((W_{\text{kin}} \ll W_{\text{total}})\), thus, from

\[
2 \delta W W = 2 q c (q c B_m \rho) (r \delta B_m + B_m \delta \rho)
\]

- one obtains

\[
\frac{\Delta W_{\text{kin}}}{W_{\text{kin}}} = 2 \frac{\Delta \rho}{\rho}
\]

- 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 \(|p| \approx \text{constant}\) for the derivation of the equations, but it also hints that efficient extraction of the beam is a major challenge

- With \(W_{\text{kin}} \ll W_{\text{total}}\) 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

\[
\frac{W_{\text{kin}}}{A} = 48 (B_m \rho)^2 (Q/A)
\]

or

\[
\frac{W_{\text{kin}}}{A} = K (Q/A)^2
\]
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. $\beta = c$)
- 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

\[
\nu = \frac{1}{T} = \frac{v}{2\pi \rho} = \frac{v m c^2}{2\pi \rho m c^2} = \frac{c}{2\pi \rho} \left( \frac{pc}{W_{total}} \right) = \frac{c q c B_m \rho}{2\pi \rho m_0 c^2} = \frac{q B_m}{2\pi m_0}
\]
the preceeding slide derived the expression for the **cyclotron frequency** $\nu$

$$\nu = \frac{qB_m}{2\pi m_0}$$

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 compensated by correspondingly increasing the magnetic field in order to maintain the frequency $\nu$ constant, this can be done by shaping the poles (see figure) and adding "trim coils", such an accelerator is called an **isochroneous cyclotron**, varying $\nu$, 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

- 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?**

- Cyclotrons are 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 prototyping 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
- H₂⁺ acceleration (followed by "stripping" = break-up into two protons) can be a solution (it doubles the external intensity) but, according to \( W_{\text{kin}}/A = K (Q/A)^2 \) 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

\[ \Delta E = \Delta T = \int \vec{F}_{\text{Lor}} \cdot d\vec{s} = q \int \vec{E} \cdot \vec{v} \cdot dt \]

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, \( R_s \)

- **Its shunt impedance,** \( r \)
  - function of the cavity geometry and of the surface resistance, \( R_s \)

\[ Q = \frac{\omega U}{P_{\text{diss}}} \]
\[ r = \frac{(\Delta V)^2}{P_{\text{diss}}} \]

- \( U \) is the energy stored in the cavity
- \( P_{\text{diss}} \) is the power dissipated on its surface
- \( \Delta V \) is the voltage seen by the beam
- \( \frac{r}{Q} \) 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 \( P_{\text{diss}} \))
- **Good design** for maximum \( r/Q \)
A cavity at the fundamental mode has an equivalent resonant lumped circuit:

\[ \omega_0 = \frac{1}{\sqrt{LC}} \quad Q = \omega_0 RC \]

- \( Q \) determines the frequency band \( \Delta f \)
  \[ \Delta f = \frac{f_0}{Q} \]
- \( R \) proportional to \( Q \) determines \( P_{\text{diss}} \)
- \( R \) depends inversely from the cavity \( R_s \) through a geometrical factor

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.

\[ P_{\text{diss}} = \frac{V^2}{2R} \]

\[ R_s \propto \frac{1}{R} \]

\[ R \propto Q \]

\[ \omega_0 = 2\pi f_0 \]
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

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

$0 K \approx -273.15^\circ C$
$c \approx 2,998 \times 10^8$ m/s

Beam tube  cell  iris  equator  Power port

Beam tube  cell  iris  equator  Power port

Superconducting cavity (IPN Orsay) – 5 cells, 700 MHz, $\beta=0.65$
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
An electric field is created on the beam axis, and is available to accelerate charged particles.

This electric field \( E \) is time and space dependant.

With \( f \) the cavity frequency, \( T = 1 / f \)

\[ Ex : f = 700 \text{ MHz} \rightarrow T = 1.43 \text{ ns} \]
SC Cavity: basics and recall of lecture 2 (II)

(2) The charged particle enters the cell: 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 $T_{RF}/2 \iff \frac{L_{cell}}{v} = \frac{1}{2f}$

The cell length should verify:

- $L_{cell} = \frac{v}{2f} \frac{\beta c}{2f}$
- $L_{cell} = \frac{\beta \lambda}{2}$
Proton case

\[ q > 0, v_{ih} \]

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

Energy gain:

\[ \Delta U = q \times \int_{t_{\text{entrée}}}^{t_{\text{sortie}}} E \cdot v \, dt \]

or

\[ \Delta U = q \times E_{\text{acc}} \times L_{\text{acc}} \times \cos(\phi) \]

- \( E_{\text{acc}} \): accelerating field of the cavity (for a given particle velocity)
- \( L_{\text{acc}} \): cavity accelerating length
- \( \phi \): particle phase with respect to the RF wave

Ex: \( f = 700\text{MHz} \); 5-cell proton cavity \( \beta = 0.65 \) (\( L_{\text{acc}} = 5 \times 14\text{cm} \)); \( E_{\text{acc}} = 10\text{MV/m} \); \( \phi = 0^\circ \)

\( \Rightarrow \) Energy gain: \( \Delta U = 1\text{eV} \times 10\text{MV/m} \times 0.7 \times 1 = 7 \text{ MeV} \)
**Beam acceleration**: particles should be bunched and synchronized with the electromagnetic wave.

$T_{beam} = n \times T_{RF}$ (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 ($T_{beam}$=2.86 ns), then the cavity should resonate at:

- $f = 350$ MHz ($T_{RF}$=2.86 ns), or
- $f = 700$ MHz ($T_{RF}$=1.43 ns), or
- $f = 1050$ MHz ($T_{RF}$=0.95 ns), etc.

**Cas du proton q > 0**

---

Alex C. MUELLER

IAEA school on ADS, Trieste, Italy, October 19-30 2007
"Cold" vs. "Warm": the winner takes it all (1)

RF power transmitted to the beam
\[ P_{\text{beam}} = \Delta U \times I_{\text{beam}} \]

Dissipated RF power on the cavity walls
\[ P_{\text{cavity}} \propto (E_{\text{acc}} L_{\text{acc}})^2 / Q_0 \]

Total RF power to give to the cavity
\[ P_{RF} = P_{\text{beam}} + P_{\text{cavity}} \]

Order of magnitude (700 MHz cavity - \( \beta = 0.65 \) - 5 cells - 10 MV/m - \( \varphi = -30^\circ \) - protons beam 10 mA)

- SC cavity \( (Q_0 \sim 10^{10}) \):
  - \( P_{\text{beam}} = 6 \text{ MeV} \times 10 \text{ mA} = 60 \text{ kW} \)
  - \( P_{\text{cavity}} \approx 16 \text{ W} \)

- "Warm" cavity \( (Q_0 \sim 3 \times 10^4) \):
  - \( P_{\text{beam}} = 60 \text{ kW} \) also
  - \( P_{\text{cavity}} \approx 5.5 \text{ MW} \) !!! \(< \text{not possible in CW!} \)
"Cold" vs. "Warm": the winner takes it all (II)

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

<table>
<thead>
<tr>
<th></th>
<th>Cavité niobium (2K)</th>
<th>Cavité Cuivre (300K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface resistance</strong> $R_s$ (ideal)</td>
<td>$20 , \Omega$ (3.2 nΩ)</td>
<td>$7 , \Omega$</td>
</tr>
<tr>
<td><strong>Quality factor</strong> $Q_0$ (ideal)</td>
<td>$10^{10}$ (6.10$^7$)</td>
<td>$3.10^4$</td>
</tr>
<tr>
<td><strong>Energy</strong> $E_{acc}$ (theoretical)</td>
<td>$10 , \text{MV/m}$ (44 MV/m)</td>
<td>$2 , \text{MV/m}$</td>
</tr>
<tr>
<td><strong>Beam power</strong> $P_{beam}$</td>
<td>$60 , \text{kW}$</td>
<td>$12 , \text{kW}$</td>
</tr>
<tr>
<td><strong>Dissipated power / cavity</strong> $P_{cav}$</td>
<td>$16 , \text{W @ 2K}$</td>
<td>$218 , \text{kW @ 300K}$</td>
</tr>
<tr>
<td><strong>RF power / cavity</strong> $P_{RF} = P_{beam} + P_{cav}$</td>
<td>$60 , \text{kW}$</td>
<td>$230 , \text{kW}$</td>
</tr>
<tr>
<td><strong>Power taken to the grid</strong> $P_{AC}$</td>
<td>$125 , \text{kW}$</td>
<td>$400 , \text{kW}$</td>
</tr>
<tr>
<td><strong>Accelerator efficiency</strong> $P_{beam} / P_{AC}$</td>
<td>48 %</td>
<td>3 %</td>
</tr>
<tr>
<td><strong>Number of cavity to gain 100 MeV</strong></td>
<td>17 (about 30m)</td>
<td>85 (about 80m)</td>
</tr>
</tbody>
</table>

Cavité 700 MHz β=0.65
5 cellules (protons 10mA)
**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:
\[
\begin{aligned}
\text{if } f < 500 \text{ MHz } &\rightarrow T \sim 4.2 \text{ K (Liquid Helium)} \\
\text{if } f > 500 \text{ MHz } &\rightarrow T \sim 2 \text{ K (Superfluid Helium)}
\end{aligned}
\]

**Niobium characteristics**
\[
\begin{align*}
T_c &= 9.2 \text{ K} \\
R_s (\Omega) &\approx 2 \times 10^{-4} \frac{1}{T} \left( \frac{f(\text{GHz})}{1.5} \right)^2 e^{-17.67/T} + R_{\text{res}}
\end{align*}
\]
When creating $E_{\text{acc}}$ inside the cavity, surface electromagnetic fields are also created, with maximum values referred as $B_{pk}$ et $E_{pk}$.

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

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

For elliptical cavities $\beta = 1$, we have

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

$$\Rightarrow @ T = 2 \text{ K}, E_{\text{accMAX}} = 220 \text{ mT} / 4 = 55 \text{ MV/m}$$

This theoretical maximum $E_{\text{acc}}$ varies with the cavity $\beta$:

- cavity $\beta = 0.65$, $B_{pk}/E_{\text{acc}} \approx 5 \text{ mT/(MV/m)}$ i.e. $E_{\text{accMAX}} = 44 \text{ MV/m} @ 2\text{K}$
- cavity $\beta = 0.5$, $B_{pk}/E_{\text{acc}} \approx 6 \text{ mT/(MV/m)}$ i.e. $E_{\text{accMAX}} = 37 \text{ MV/m} @ 2\text{K}$
Various SC cavities for different particle velocity

- $\beta = 0.01$
  - Structures inter-digitales (ATLAS, Argonne)
    - 48 et 72 MHz - $\beta = 0.009$ à 0.037
  - RFQs supra (Legnaro)
    - 80 MHz - $\beta = 0.009$ à 0.035
  - Résonateurs split-ring (ATLAS, Argonne)
    - 97 et 145 MHz - $\beta = 0.06$ à 0.16

- $\beta = 0.1$
  - Cavités ré-entraînantes (Legnaro)
    - 352 MHz - $\beta \geq 0.1$
  - Cavités quart d’onde (ALPI, Legnaro)
    - 80 à 352 MHz - $\beta = 0.047$ à 0.25
  - Résonateurs split-ring (ATLAS, Argonne)
    - 97 et 145 MHz - $\beta = 0.06$ à 0.16
  - Cavités spoke (CNRS Orsay)
    - 352 MHz - $\beta = 0.15$ et 0.35
  - Résonateurs demi-ondes (Argonne)
    - 355 MHz - $\beta = 0.12$

- $\beta = 1$
  - Cavités elliptiques
    - 350 MHz à 3 GHz - $\beta = 0.47$ à 1
  - Résonateurs demi-ondes (Argonne)
    - 355 MHz - $\beta = 0.12$
  - Cavité APT (Los Alamos)
    - 700 MHz - $\beta = 0.64$
  - Cavité TTF
    - 1.3 GHz - $\beta = 1$
SC cavity: fabrication

Niobium sheets 3 mm thick
Welding by electron beams

Spoke cavity

\[ \beta = 0.35 \]

\[ f = 352.2 \text{ MHz} \]
SC cavity technology: preparation and test

Chemistry

High pressure rinsing

Assembly in clean room

CryHoLab
SC Cavity : cold tuning system
Power couplers (I)

- Cavity coupling port
- Outer conductor cooling (LHe @ 4.5 K)
- Ceramic window cooling (Water)
- Doorknob: transition waveguide to coax
- Cavity (1st cell)
- Inner conductor (water cooled)
- Outer conductor
- Vacuum
- Ceramic window
- Air
- Waveguide
Power couplers (II)
Power couplers (III)

▲ Outer conductor: Helium cooling

▲ Inner conductor: Water cooling
One example: Performances of a spoke cavity

Test @ 2 K (may 2004)

Eacc max = 16.2 MV/m
No quench
RF power limitation

Helium processing

XADS Goal

Eacc = 16.2 MV/m means Epeak = 49.5 MV/m & Bpeak = 134 mT
2nd example: Performances of TESLA cavity

![Graph showing performance of TESLA cavity](image)

- Q₀ vs. Eₐcc (MV/m)
- C1 - before annealing @ 1400 °C
- I1 - before baking
- I2 - after baking @ 110 °C / 60 h

Quench, RF power limitation, Quench

B. Visentin et al. EPAC 2002