3rd Lecture

Circular Accelerators

By Alex C. Mueller

- Some Generalities on Circular Accelerators
- Synchrotrons
- Cyclotrons
- High Power Cyclotrons, the PSI machine
- Transition to the final lecture (from TWG to PDS-XADS)
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

Lorentz force: 
\[ F = q (E + v \times B) = \frac{dp}{dt} \]

(relativistic) Kinetic Energy: 
\[ (pc)^2 = W_{\text{total}}^2 - W_0^2 \text{ with } W_0^2 = m_0 c^2 \]

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

\[ \frac{mv^2}{\rho} = \frac{dp}{dt} = qvB \]
Useful Definitions & Formulas (II)

- the preceding formulas allow to write

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

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 kinetic, hence total energy \((W_0 << W_{\text{total}})\), one gets the rule of thumb relation

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

\( W_{\text{total}} \) in MeV, \( Q = q/e_0 \) in Tesla \( \cdot \) meters
Energy Gain in Circular Accelerators

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

\[
2 \delta W W = 2 q c (q c B_m \rho) (\rho B_m' + B_m \frac{\delta \rho}{\delta t})
\]

- which, after some "simple" operations gives

\[
\delta W = (2\pi \rho / \delta t) q (\rho B_m' + B_m \rho)
\]

\[
= 2\pi \rho q (\rho B_m' + B_m \rho)
\]

- a **synchrotron** is a machine with $B_m \rho = 0$

- a **cyclotron** is a machine with $\rho B_m = 0$
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 \( R \)

- Energy gain per turn
  \[ \delta W = 2\pi \rho q \rho B_m \]
  \[ \delta W = 2\pi R^2 q B_m \]
  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 $W \ [\text{MeV}] = 300 \ Q \ B \ \rho \ [\text{Tm}]$, 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 $\mu A$ 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

- 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 is a $2 \times 100$ GeV electron-positron collider
LHC, CERN's future Accelerator

The Large Hadron Collider (LHC)

Collisions at LHC

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<th>Beams</th>
<th>Energy</th>
<th>Luminosity</th>
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<td>LEP</td>
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<td>LHC</td>
<td>p p</td>
<td>14 TeV</td>
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<td>Pb Pb</td>
<td>1312 TeV</td>
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</table>

(2835 x 2835 bunches)

Protons/bunch

Beam energy: 7 TeV (7x10^{12} eV)

Luminosity: \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\)

Crossing rate: 40 MHz

Collisions: \(10^7 - 10^8 \text{Hz}\)

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

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FJOH School 2002

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Construction of Main LHC Components

- Presently, the construction of LHC is strongly advancing (notwithstanding budgetary problems)
- 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 Straignt Short Sections contain the superconducting focusing quadrupoles

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

\[
\delta W_{\text{kin}} / W_{\text{kin}} = 2 \delta \rho / \rho
\]

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

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

or

\[
W_{\text{kin}} / A = K (Q/A)^2
\]
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 \((W_{\text{total}} \approx W_0 = m_0c^2)\) it can be expressed as

\[
\nu = \frac{1}{T} = \frac{\nu}{2\pi \rho} = \frac{\nu m c^2}{2\pi \rho m c^2} = \frac{c}{2\pi \rho} \left( \frac{pc}{W_{\text{total}}} \right) = \frac{c q c B_m \rho}{2\pi \rho m_0 c^2} = q B_m / 2\pi m_0
\]

...
Properties of Cyclotrons (III)

- The preceding slide derived the expression for the cyclotron frequency $\nu$
  \[ \nu = \frac{qB}{2\pi m_0} \]
  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 isochronous cyclotron, varying $\nu$, however, is technically challenging, and the corresponding accelerator, the synchrocyclotron, is necessarily a pulsed, weak current machine.

- Unfortunately, a cyclotron cannot 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 New 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 protootypical (e.g. for an ADS) **molten metal target MEGAPIE** (see left).
Cyclotrons for ADS?

- 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

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
TWG: a European ADS Roadmap

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

April 2001

The European Technical Working Group on ADS

The European Technical Working Group (members see below, left) issued in 2001 a Roadmap for Developing ADS (see above), with the proposal for a 100 MWth demonstrator. A TWG subgroup elaborated the project PDS-XADS (see next slide) which was funded by the EU.

Table 2. Estimated costs (M€) for the development of a 100 MWth accelerator driven system

<table>
<thead>
<tr>
<th>Year 2000+</th>
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* Estimated cost to 2012 for development of dedicated fuel & fuel processing

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

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The European Technical Working Group for Nuclear Waste Incineration (TWG) meeting in Brussels, Belgium, 16-17 October 2002

Carlo Pagani

FJOH School 2002

Alex C. Mueller
PDS-XADS plays a central rôle in the development of transmutation in Europe (left).

The right figure shows the organisation of PDS-XADS in Working Packages to which a total of 25 partners (national Institutes, Firms, Universities) participate.

Alex C. Mueller coordinates the WP3 and is the scientific responsible for CNRS, Carlo Pagani is the scientific responsible for INFN.