Hadron Accelerators

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Accelerator Beam Physics Group

Beams Department - CERN
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• W. Fischer (RHIC)
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Contents – Lecture 1

• Introduction
  – Scope of lecture. What is an accelerator? Tevatron, RHIC, LHC. Limits and high tech solutions

• What are beams?
• Collider goals: Energy, event rate and luminosity
• Generating beams
• Proton bending
• Beam acceleration
• Collimation
• Beam dump
• Colliding beams
LHC Latest News: 1 fb$^{-1}$ Produced

Goal for year 2011

Delivered Luminosity for All Experiments = 2322.0 pb$^{-1}$
LHC Latest News: 1 fb\(^{-1}\) Produced

Goal for year 2011

Delivered Luminosity for All Experiments = 2322.0 pb\(^{-1}\)

LHC performance discussed in lecture 2!

First: Let’s get an idea of hadron accelerators!
There are many hadron accelerators around the world:

- Hadron synchrotron colliders (Tevatron, RHIC, LHC)
- Hadron synchrotrons without collisions (SIS, …)
- Hadron linacs (SNS, UNILAC, medical applications, …)
- Hadron cyclotrons (PSI, medical applications, …)

Very broad field. Here focus on hadron colliders.

As we are at CERN: Particular focus on LHC, including latest news from the control room.
What is an Accelerator?

The **accelerator** ("atom smasher")

A **scientific instrument** that **increases the kinetic energy** of charged particles!
Particle beams find many usages

• Use particle beams:
  – for scattering experiments (Transmission Electron Microscopy)
  – to destroy cancer (medical accelerators).
  – to produce high temperature, high density plasmas (plasma physics).
  – to produce diamonds (high temperature – high pressure).
  – to build a fusion reactor (high temperature – high pressure)
  – to initiate a nuclear chain reaction or to get rid of nuclear waste (transmutation).
  – to produce neutrons (neutron spallation sources – material science).
  – to produce neutrinos (neutrino physics).
  – to produce new particles in colliding beam experiments (high energy physics).

• Use emitted light:
  – for applied research (synchrotron light facilities).
  – for lithography (microchip production).
Accelerators

• Beams of charged particles are a very powerful tool for science.
• Many applications exist with new ideas coming up regularly.
• Different types of accelerators: Protons, anti-protons, electrons, positrons, ions!
• Hundreds of accelerators support scientific advance around the globe.
• The future of accelerators will be very active and diverse.
• RHIC – Collider for ion physics and polarized protons.
• Tevatron – Discovery of the top. To be switched off in 2011.
• LHC is the new flagship accelerator for high energy physics!
Technology as Base for Innovation
or: The Connection Between a Washing Machine and an iPhone

- **Steve Jobs:**
  - “We ended up opting for these Miele appliances, made in Germany... These guys really thought the process through. They did such a great job designing these washers and dryers. I got more thrill out of them than I have out of any piece of high tech in years.” (1996)
  - “We're both busy and we both don't have a lot of time to learn how to use a washing machine or to use a phone - you get one of the phones now and you're never going to learn more than 5 per cent of the features.” (Oct 2005)

- Let’s look at the washing machines (accelerators) to make an iPhone (new territory in physics)!
Tevatron

Proton source

Antiproton source

CDF

DØ

Main Injector\ Recycler

R. Assmann
Tevatron Collider Timeline

Jul 1983  Tevatron SC synchrotron commissioned, reached world record 512 GeV (protons)
1982-1985 Antiproton source construction & commissioning, installation of the B0 low beta insertion magnets
Oct 1985  First 1.6 TeV c.o.m. p-pbar collisions in CDF
1987-1989 Collider Run at 1.8 TeV c.o.m., magnet leads fix
1990 -1992 HV separators installed, new low beta insertions at D0 and B0 interaction regions
1992 -1993 Collider Run Ia at 1.8 TeV c.o.m., both CDF & D0
1992 -1993 400 MeV Linac construction and commissioning
1994 -1996 Collider Run Ib, top quark discovery
1993 -1999 Main Injector construction and commissioning
Mar 2001-(?) Collider Run II, 1.96 TeV c.o.m.
RHIC – a High Luminosity (Polarized) Hadron Collider

Operated modes (beam energies):

- **Au–Au** 3.8, 4.6, 5.8, 10, 32, 65, **100 GeV/n**
- **d–Au** 100 GeV/n
- **Cu–Cu** 11, 31, **100 GeV/n**
- **p↑–p↑** 11, 31, **100**, 250 GeV

Planned or possible future modes:

- **U – U** 100 GeV/n
- **Au – Au** 2.5 GeV/n (~ SPS cm energy)
- **p↑ – Au** 100 GeV/n (*asymmetric rigidity*)

Achieved peak luminosities (100 GeV, nucl.-pair):

- **Au–Au** $155 \times 10^{30}$ cm$^{-2}$ s$^{-1}$
- **p↑–p↑** $50 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

Other large hadron colliders (scaled to 100 GeV):

- **Tevatron** (p – pbar) $35 \times 10^{30}$ cm$^{-2}$ s$^{-1}$
- **LHC** (p – p, design) $140 \times 10^{30}$ cm$^{-2}$ s$^{-1}$
LHC: The Biggest Machine on Earth

Diameter: 27 km
Depth: ~100 m below ground surface
LHC: “collider”
Limit: The Dipole Magnets

Hadron (p) circular collider

Limited by available bending field strength (even SC):

\[ p = e R B_y \]  

(increase momentum by increasing radius times bending field)

LHC: 8.3 T bending field from 1232 magnets!

56 mm holes for beams.
At less than 1% of nominal intensity LHC enters new territory. Collimators must survive expected beam loss…

Entry and exit holes of an electron beam impacting on a spoiler (courtesy P. Tenenbaum)
High Tech Solutions

- These and other challenges are addressed with high tech solutions.
- Fundamental research as a driver for technology…
RHIC: Siberian Snakes
Tevatron: Electron Beam Lens

V. Shiltsev, et al., FNAL 1997
LHC: SC Magnets
LHC: Super-Conducting RF Cavities
What Are Beams?
The Charged Particle Beam

• The accelerator generates, accelerates, transports and delivers beams to the user (e.g. HEP exp).

• Beam are transported in ultra-high vacuum.

• A beam can consist of individual bunches.

• Each “bunch” is an ensemble of charged particles that are grouped together in space and carry the same (very similar) energy.

• Radio-frequency fields are used to accelerate particles coherently and to group them together longitudinally.

• Magnetic fields are used to guide the beam particles on well defined paths and to focus them into a small transverse area.
Purpose of accelerators

- Increase kinetic energy of particles
- More particles per bunch
- Smaller transverse areas
- Shorter bunches
- More bunches
The choice of particle type

Hadron colliders
(p-pbar or pp or ions)

“Discovery” machines

LHC 2009
p-p: 2 × 7 TeV
Pb-Pb: 2 × 2.76 TeV

VLHC study
p-p: 2 × 20 TeV
2 × 100 TeV

Lepton colliders
(e-e+ or γγ)

“Precision” studies

B factory upgrade studies

Linear collider study
e+e-: 0.5-1.5 TeV
(eγ, γγ, e-e- options)

μμ collider study
2 × 0.15/4.0 TeV

Plasma accelerators
Tevatron: Anti-Proton Beam

Antiproton Production Rate

- Wider Bandwidth 2-8 GHz
- Main Injector and SlipStacking Recycler as Storage Ring
- Electron Cooling in RR
- Apertures opened
- 75kG/cm Li lens

Hourly Antiproton Production Rate $(10^{10}/\text{hr})$

2000
2002
2004
2006
2008
2010

1994
1996
1998

28.5 x $10^{10}$ /hr
The LHC Beam

- **Increase kinetic energy** of particles (3.5 – 7 TeV)
- **More protons** per bunch (150,000 – 300,000 billion)
- **Smaller transverse areas** (~ 30 μm – width of hair)
- **Shorter bunches** (~ 7 cm)
- **More bunches** (~ 400 – 2808)
Goal: Fully polarized beam, e.g. all spins UP.
Manipulation of polarization vector needed!
Collider Goals
High & well-defined beam energies

Einstein’s famous formula:

Mass can be converted into energy!

Collide electrons (matter) and positrons (anti-matter):

\[ e^+ + e^- \rightarrow (2E) \rightarrow \text{particles} \]

If energy is high enough new particles can be produced…

Maximum beam energy for highest discovery potential!
Example: Producing the Z-boson

The Z boson:

\[ e^+ + e^- \rightarrow f + \bar{f} \]

Discovered in the SppS with proton and anti-protons (nobel prize C. Rubbia and S. van de Meer 1984) \(\rightarrow\) accelerator innovation!

Detailed studies at the LEP collider with electrons and positrons.

\[ M_{Z_0} = \left( \frac{E_{e^+} + E_{e^-}}{c^2} \right) = 91.2 \text{ GeV} \]

\(E = \text{Beam energy}\)
The need for high event rate

Event rate \( = \frac{N_{e^+} + N_{e^-}}{A_{beam}} \cdot f_{coll} \cdot \sigma_{p^+p^- \rightarrow X} \)

Luminosity \( L \)

\( A_{beam} = \) Transverse beam area
\( N = \) Particles per bunch
\( f_{coll} = \) Collision rate
\( \sigma_{p^+p^- \rightarrow X} = \) Cross section physics process

\( \Rightarrow \) Determines how long the PhD student has to wait for his data…
Gaussian transverse distributions (neglecting effect of self-focusing of beams):

\[
L = \frac{f_{\text{rep}} N_{\text{bunch}} N_{e^+} N_{e^-}}{4\pi \sigma_x \sigma_y}
\]

- \(f_{\text{rep}}\) = Repetition or revolution frequency
- \(N_{\text{bunch}}\) = Number of bunches per beam
- \(N_{e^+/e^-}\) = Number of particles per bunch
- \(\sigma_x/\sigma_y\) = Transverse beam sizes

Neglecting geometric factor \(F\)…
Generating Beams
Producing the LHC beams

- p (protons)
- e⁺ (positrons)
- e⁻ (electrons)
- ions

H gas

Linacs: LEP’s Linac Injector
EPA: Electrons-positrons Accumulator
PS: Proton Synchrotron
SPS: Super Proton Synchrotron
LEAR: Low Energy Accumulator Ring
LEP: Large Electron-Positron Collider
LHC: Large Hadron Collider
Proton bending (circular)
Governed by Maxwell’s Equations

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \]

\[ \nabla \cdot \mathbf{B} = 0 \]

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} \]

Very few acceleration issues require quantum mechanics (e.g. spin polarization).

\[ \begin{align*}
\mathbf{E} & = \text{Electrical field intensity} \\
\mathbf{B} & = \text{Magnetic flux density} \\
\mathbf{J} & = \text{Total current density} \\
\rho & = \text{Total charge density} \\
\mu_0 & = \text{Permeability of free space} \\
\varepsilon_0 & = \text{Permittivity of free space}
\end{align*} \]
Lorentz Force $F$

$$F = q (E + v \times B)$$

$q$ = Charge

$v$ = Velocity

Longitudinal electrical field to accelerate a particle

Transverse magnetic field to guide a particle
The electron accelerator in your (past) living room

CATHODE RAY TUBES

For Television and Other Uses

This series of articles will fill a long-felt need for practical construction data on cathode ray equipment. Complete details for making a cathode ray oscilloscope and television equipment will be given and the manifold applications of this equipment discussed.

By John M. Hollywood and Marshall P. Wilder

Cathode Tubes in Television

The cathode-ray tube has been hailed and feared much about the merits of the cathode-ray tube, and particularly its recent connection to television experiments, which have revolutionized the field of television. Cathode-ray tubes are basically the heart of all television apparatus. Their function is to convert electrical impulses into visible light images. The improvements made in recent years have made cathode-ray tubes more sensitive and reliable than before, and have resulted in improved performance of television systems. These improvements have made cathode-ray tubes indispensable for television work. The cathode-ray tube has been hailed and feared much about its merits. Its ability to convert electrical impulses into visible light images makes it indispensable for television work. The improvements made in recent years have resulted in improved performance of television systems.

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Cathode Ray Tube (CRT) has the basic ingredients of a scientific accelerator:

- **Particle source**
- **Acceleration scheme**
- **Focusing scheme**
- **Beam steering**
- **Beam observation**

Particle momentum \( \mathbf{p} \) given by Lorentz Force:

\[
\frac{d\mathbf{p}}{dt} = \mathbf{F} = q \left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right)
\]
Transverse deflections:

Transverse magnetic fields are used for beam deflections!

\[ F_x = q \nu_z B_y \]
\[ F_y = q \nu_z B_x \]

Transverse fields used for:

- Focusing lattice
- Bending (esp. circular)
- De-magnifying
- Steering

Proton

Depends on particle energy and transverse field
The PSI Cyclotron

590 MeV protons, 1.3 MW
Fixed target physics
neutrons, muons
Cyclotron Principle

Square wave electric field accelerates charge at each gap crossing.

Magnetic field bends path of charged particle.
Limited in Energy Reach

• Constant bending field $B$ with time $\rightarrow$ Radius $R$ will change during acceleration (increase of momentum $p$):

$$ p = R e B $$

• Solution: Increase bending field synchronous with momentum gain $\rightarrow$ constant radius $\rightarrow$ large rings with a vacuum pipe become possible.

• See also: Large accelerators (big $R$) are required to reach high momentum if bend fields are limited!

• Large synchrotrons (LHC, …).
Dipolmagnet Coils in Synchrotrons
Strong focusing lattice → Quadrupoles

\[ B_x = B'y \quad B_y = B'x \]

\[ F_x = q v_z B'x \quad F_y = -q v_z B'z \]

Force is restoring in one, anti-restoring in the other plane.

More focusing (beam size larger) than defocusing!

Equation of particle motion:

\[ \frac{d^2 x}{ds^2} + K(s) x = 0 \]

\[ K(s) = \frac{qB'}{p} \quad \text{with} \quad p = \gamma m v \]
LHC

Fit the LHC ring into the LEP tunnel

8.3 T bending field from 1232 magnets!

56 mm holes for beams.
Tevatron Magnet Technology

Two colliding beams in the same vacuum pipe!
Tevatron Ring

Tevatron Magnets

This is not Tevatron! -remnants of Main Ring

This is the Tevatron!

C=6.28km, ~800 SC magnets (4d+q) @ 4.2 K, E_max/inj=980/150GeV, small size, quench protection
Tevatron Cooling System

Technology: Cryoplant

INTERNATIONAL HISTORIC
MECHANICAL ENGINEERING LANDMARK
CRYOGENIC COOLING SYSTEM
OF THE
FERMILAB TEVATRON ACCELERATOR
1983

WHEN PLACED IN SERVICE, THIS WAS THE LARGEST VERY-LOW-TEMPERATURE
(CRYOGENIC) COOLING SYSTEM EVER BUILT, WITH A CAPACITY OF 23.2 kW AT 5K
(-268 °C, -450 °F) PLUS 1,000 LITERS (264 GALLONS) PER HOUR OF LIQUID HELIUM.
IT MAINTAINS THE COILS OF THE MAGNETS, WHICH BEND AND FOCUS THE PARTICLE
BEAM, IN A SUPERCONDUCTING STATE (ZERO ELECTRICAL RESISTANCE). POWER
CONSUMPTION IS ONE-THIRD WHAT IT WOULD BE AT NORMAL TEMPERATURES.
MANY INNOVATIONS ARE INCLUDED IN THE SYSTEM, WHICH HAS BEEN A MODEL FOR
SIMILAR SYSTEMS WORLDWIDE.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS--1993
Why Super-Conducting?

- For LHC we need **12,000 A current** to generate the bending fields required for 7 TeV protons!
- A resistive magnet would just over-heat and melt.
- We need to build **super-conducting magnets**: no resistance $\rightarrow$ high currents and fields are possible.
- Magnets cooled to **1.9 K** and some to **4.5 K** $\rightarrow$ biggest refrigerator on earth (Helium).
- CERN is the coldest place on earth (inside the magnets).
High Beam Energy with Super-Conducting Magnets: Handle High Currents and Large Stored Energy

Each beam in a separate vacuum pipe!

The 15-m long LHC cryodipole
Regular arc:
Magnets

392 main quadrupoles + 2500 corrector magnets

1232 main dipoles + 3700 multipole corrector magnets

R. Schmidt
Supply and recovery of helium with 26 km long cryogenic distribution line

Connection via service module and jumper

Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length

Regular arc: Cryogenics
Insulation vacuum for the cryogenic distribution line

Beam vacuum for Beam 1 + Beam 2

Insulation vacuum for the magnet cryostats

Regular arc: Vacuum
Quench Limit of LHC Super- Conducting Magnets

Beam 362 MJ

SC Coil: quench limit 12 - 41 mJ/cm³
If Resistance Develops...
Electrical arc between C24 and Q24

Resistance → current cannot flow as foreseen → electrical arc!

Local material is destroyed by electrical arc.

Liquid Helium escapes and inflates.

What is not taken out by safety valves runs as pressure wave along the accelerator!

Pressure waves hit the vacuum barriers that are located every two cells.
Consequences

Magnet supports cannot handle pressure wave and buckle...
Beam Acceleration: RF System

Wideroe accelerator

Cylindrical cavity

E.g. \( d = \frac{\lambda_{RF}}{2} \): \( \lambda_{RF} \) is the RF wavelength

\[ l = \frac{v}{f_{RF}} = \frac{c}{f_{RF}} = 2pc / v_{RF} \]

\( f_{RF} = 400 \text{ MHz} \)
Smooth waveguide: \( V_{ph} > C \)

Obstacles (irises) to slow down accelerating wave for synchronous acceleration:

Bunch length shorter than \( \lambda_{RF} \)
400 MHz system:
16 sc cavities (copper sputtered with niobium) for 16 MV/beam were built and assembled in four modules.
Fitting Beam in RF Buckets

RF bucket

2.5 ns

<table>
<thead>
<tr>
<th>Energy Level</th>
<th>RMS Bunch Length</th>
<th>RMS Energy Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td>11.2 cm</td>
<td>0.031%</td>
</tr>
<tr>
<td>7 TeV</td>
<td>7.6 cm</td>
<td>0.011%</td>
</tr>
</tbody>
</table>
To get to 7 TeV: Synchrotron – circular accelerator and many passages in RF cavities

LINAC (planned for several hundred GeV - but not above 1 TeV, e.g ILC)

LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV takes about 20 minutes

....requires deflecting magnets (dipoles)
Collimation

- **Shock beam impact:** 2 MJ/mm² in 200 ns (0.5 kg TNT)

- **Maximum beam loss at 7 TeV:** 0.1% of beam (360 MJ) per second

  *(assumed lower than Tevatron/HERA)*

- **Quench limit** of SC LHC magnet:

  ~ 5 mW/cm³ ➔ proportional to stored energy

R. Assmann, 12JUN09
At less than 1% of nominal intensity LHC enters new territory.
Collimators must survive expected beam loss…
Examples of damage from beams

Entry and exit holes of an electron beam impacting on a spoiler
(courtesy P. Tenenbaum)

Tungsten collimator in the SPS

Lead block accidentally put into a p beam

Damage of coating of a SLC collimator
(courtesy G. Stevenson)
Examples of damage from beams

TEVATRON Dec 2003
Photographs courtesy D. Still
Hearing Proton Beam...

Proton beam...

450 GeV
3 \(10^{13}\) p in the beam
2 MJ
0.7 x 1.2 mm\(^2\)

~ Tevatron beam
~ \(\frac{1}{2}\) kg TNT

Collimator
Beam Dump
LHC Collimators: Dilute and Stop

Quench limit: \( \sim 5 \text{ mJ/mm}^2 \) (any SC magnet)

Incoming: up to \( \sim 50 \text{ MJ/mm}^2 \) (primary collimator)

Required “filter” factor:

\[
1 \times 10^{-10} = \frac{\text{Leakage}}{\text{Dilution}}
\]

Leakage factor (inefficiency): \( 10^{-4} \)

Dilution factor: \( 10^6 \)

Cannot be achieved with single collimator \( \Rightarrow \) therefore multi-stage collimation for betatron cleaning (x, y, skew) and momentum cleaning.
Multi-Stage Cleaning & Protection

3-4 Stages

Beam propagation

Unavoidable losses

Impact parameter ≤ 1 μm

Primary halo (p)

Secondary halo

Secondary collimator

CFC

Shower

p

π

e

e

CFC

High Z coll

W/Cu

Superconducting magnets

SC magnets and particle physics exp.

Tertiary halo

R. Assmann, 12JUN09
108 collimators and absorbers in phase I (only movable shown in sketch)

Gaps: \( \pm \frac{6}{7} \sigma \)

2-3 mm

R. Assmann, 12JUN09
Beam Dump: Disposing the Beam

Ø 0.7m × 7.7 m C cylinder
Dilution with spiral sweep

- Dilution kicker

- At 7 TeV would allow currents of ~4 A in distributed bunches
Colliding the Beams
Crossing Angles

Long-range

Head-on
To be continued tomorrow…