Introduction to Accelerators

Lecture 1

Motivations

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When we talk about the energy or momentum of individual particles, the Joule is inconvenient.

Instead we use the eV, the energy that a unit charge

\[ e = 1.6 \times 10^{-19} \text{ Coulomb} \]

gains when it falls through a potential, \( \Delta \Phi = 1 \text{ volt} \).

\[ 1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joule} \]

For momentum we use the unit, eV/c, where c is the speed of light.
We can use Einstein’s relation,

\[ E_o = mc^2 \]

to convert rest mass to energy units (m is the rest mass)

For electrons,

\[ E_{o,e} = 9.1 \times 10^{-31} \text{ kg} \times (3 \times 10^8 \text{ m/sec})^2 = 81.9 \times 10^{-15} \text{ J} \]
\[ = 0.512 \text{ MeV} \]

For protons,

\[ E_{o,p} = 938 \text{ MeV} \]
Why do we build accelerators?
Accelerators in the world

Total number ~ 20'000
Growing at about 10% per year

- Research: 5%
- Medicine: 35%
- Industry: 60%

From L. Rivkin, CHIPP Lectures, 2008
**What are these machines used for?**

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion implanters and surface modification</td>
<td>7’000</td>
</tr>
<tr>
<td>Accelerators in industry</td>
<td>1’500</td>
</tr>
<tr>
<td>Accelerators in non-nuclear research</td>
<td>1’000</td>
</tr>
<tr>
<td>Radiotherapy</td>
<td>5’000</td>
</tr>
<tr>
<td>Medical isotopes production</td>
<td>200</td>
</tr>
<tr>
<td>Hadrontherapy</td>
<td>20</td>
</tr>
<tr>
<td>Synchrotron radiation sources</td>
<td>70</td>
</tr>
<tr>
<td>Research in nuclear and particle physics</td>
<td>110</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>15’000</strong></td>
</tr>
</tbody>
</table>

From L. Rivkin, CHIPP Lectures, 2008
Why do we need beams?

Collide beams

Figures of Merit (FOM):
Collision rate,
Energy stability,
Accelerating field

Examples: LHC, ILC, RHIC
What we know by direct observation
How can we understand the underlying structure of things?

Wilhelm Röntgen Discovered X-rays in 1895
Rutherford explains scattering of alpha particles on gold & urges … on to higher energy probes!
Why do we need high energy beams

 Resolution of "Matter" Microscopes
  ➔ Wavelength of Particles (\(\gamma, e, p, \ldots\)) (de Broglie, 1923)

  \[
  \lambda = \frac{h}{p} = 1.2 \text{ fm}/p [\text{GeV}/c]
  \]

  ➔ Higher momentum ➔ shorter wavelength ➔ better the resolution

 Energy to Matter
  ➔ Higher energy produces heavier particles

  \[
  E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma m_0 c^2
  \]

  ➔ Penetrate more deeply into matter
Examples: Where we are today - Heavy ion collisions

D - Au at RHIC

Next ALICE @ LHC
CERN Accelerator Complex

(not to scale)
Inside the LHC tunnel

This goes on for 28 km!
Figure of Merit 1: Beam Energy \( \Rightarrow \) Energy frontier of discovery

The Energy Frontier

(Discoveries)

- **Hadron colliders**
  - (top quark, W, Z bosons)
  - Tevatron
  - SppS

- **Lepton colliders**
  - SLC, LEP (Nv = 3)
  - PETRA, PEP (gluon)
  - ILC-U
  - ILC
  - VLHC

- **SLED**
- **μcoll**

**Wakefields, impedances**

**Stochastic cooling**

**Colliding beams**

**Strong focusing**

**“Livingston plot”**
Example from High Energy Physics: Discovery space for future accelerators

Log luminosity (cm$^{-2}$ s$^{-1}$)

SuperLHC
Linear Collider
LHC
Very Large Hadron Collider
Tevatron
LEP

Luminosity = \frac{\text{Energy} \times \text{Current}}{\text{Focal depth} \times \text{Beam quality}}
Figure of Merit 2: Number of events

Events = Cross-section \times \langle{\text{Collision Rate}}\rangle \times \text{Time}

Beam energy: sets scale of physics accessible

Luminosity = \frac{N_1 \times N_2 \times \text{frequency}}{\text{Overlap Area}} = \frac{N_1 \times N_2 \times f}{4\pi\sigma_x\sigma_y} \times \text{Correction factors}

We want large charge/bunch, high collision frequency & small spot size
How far can we go with this approach?

1 PeV?
Limits of accelerator-based HEP

E. Fermi
How big is a PeV collider?

1 PeV?

Romania
FoM 3: Resolution (Energy/ΔEnergy)

- Intertwined with detector & experiment design
  - In hadron colliders: production change, parton energy distribution
  - In lepton colliders: energy spread of beams (synchrotron radiation)
The future of HEP runs through CERN
“Après moi, le déluge”

- LHC upgrades rely on advances in magnet technology
  - Reliability upgrade (2013) - replace IR Quads & collimators
  - Luminosity upgrade - very high gradient, Nb$_3$Sn quads
  - Super LHC (energy upgrade) - very high field dipoles
Why do we need beams?

Secondary beams

FOM: Secondaries/primary
Examples: spallation neutrons for condensed matter physics, neutrino beams for high energy physics, rare isotopes
Example: The Spallation Neutron Source

1 GeV, 35 mA of protons, 6% duty factor

1 MW liquid Hg target

$>10^{17}$ n/sec
Figures of Merit: Spectrum & time structure

- **Liquid MH₄ Moderator**
- **O - LANCE Flight Path 4**
- **Moderator Area Viewed = 90.2 cm²**
- **Source-to-Sample = 6.95 m**
- **Current = 57 μA**

**Neutron flux from D-D tube**
- **(1.2 x 10¹¹ n/s)**
- **80 kV, 1 A, 100 % DF**

**Flux (neutron/(cm² s eV))**

- **Eₙ(eV)**

O The measured (circles) neutron flux v. neutron energy

1MW SNS (1 GeV, 60 Hz)

Protons per pulse $\approx 10^{14}$
Neutrons per pulse $\approx 20 \times 10^{14} = 2 \times 10^{15}$
Rate = 60 Hz $\implies$ yield $\approx 10^{17}$ n/s.

$E/\text{neutron} = 1 \text{ MW} / 10^{17} \text{ n/s} \approx 10^{-11} \text{ J/n}$

Overall efficiency for accelerator system $\approx 2\%$

$\implies \approx 5 \times 10^{-10} \text{ J/n}$

D-T neutron tube (120kV, 1 A $\implies 10^{14}$ n/s)

$E/\text{neutron} \approx 120 \text{ kW} / 10^{14} \text{ n/s} \approx 10^{-9} \text{ J/n}$

DC power supply efficiency $> 85\%$

$\implies \approx 10^{-9} \text{ J/n}$
Explore nuclear structure & reactions involving nuclei far from the valley of stability

These nuclei participate in explosive nucleo-synthesis in novae, x-ray bursts, and supernovae via rapid proton and neutron capture
Matter to energy: Synchrotron radiation science

Synchrotron light source

FOM: Brilliance v. λ

\[ B = \frac{ph/s/mm^2/mrad^2}{0.1\%BW} \]

Science with X-rays
- Microscopy
- Spectroscopy
Coherent Imaging: TwinMic on BACH-ELETTRA

Figure 3. Scanning mode

Figure 4. Full-field mode
Does the tracheal system limit the size of insects?

Research* at the Argonne Advanced Photon Source (APS) explains what limits size in beetles: the constriction of tracheal tubes leading to legs.

FOM 1 from condensed matter studies: Light source brilliance v. photon energy

Duty factor correction for pulsed linacs
Pump-probe experiment concept for ultra-fast science and/or imaging

- Pulses can be x-rays, VUV, electrons or ions
- Requires control/measurement of $\Delta t$ with a resolution $<<$ x-ray pulse duration (possibly as small as 100 attoseconds)
Synchrotron light source  
(pulsed incoherent X-ray emission)

Pulse rates – kHz => MHz  
X-ray pulse duration ~ 1 ps  
High average e-beam brilliance & e-beam duration ~ 1 ps  
⇒ One pass through ring  
⇒ Recover beam energy  
⇒ High efficiency

⇒ SC RF

Pulse duration limited by CSR
Even higher peak brightness requires coherent emission \( \Rightarrow \) FEL
FIRST FLASH DIFFRACTION IMAGE OF A LIVE PICOPLANKTON

March 2007
FLASH soft X-ray laser
Hamburg, Germany

FLASH pulse length: 10 fs
Wavelength: 13.5 nm

Thanks
J. Hajdu and H. Chapman

J. Hajdu, I. Andersson, F. Maia, M. Bogan, H. Chapman, and the imaging collaboration
FOM 2 from condensed matter studies: Ultra-fast light sources
Radiography

FOM: Signal/noise ==> Dose at 1 m & resolution (x,t)
Example: Flash radiography

Debris cloud produced by an Al sphere impacting a thin AL shield at hypervelocity.

Source: http://www.udri.udayton.edu/NR/exeres/9E82E5F2-AC29-4467-8F15-0E5A7FEA48F3.htm
Industrial uses of beams

Alter matter

FOM: process time
    process efficiency
Ions prepare Si wafers for further processing finally yielding integrated circuit chips

> > 1 B$/year business in semi-conductor “machine tools”

Emerging areas

- Flat-panel video displays
- Ultra-high density electronics
Example of ion beam lithography

in 180 nm Shipley DUV resist UViHS

Stencil Mask

Wafer

75 keV He⁺ ions
0.46 μC/cm²
exposure dose

W. Bruenger
FhG ISIT
Nov 1999

650 nm L/S → 8.7x reduction → 75 nm L/S
Therapy

FOM: treatment time
tumor control probability
precision beam control
Example: Conformal therapy

Challenge: Kill the tumor cells w/o killing healthy tissue

Gamma rays from electron linac
Control of glioblastoma multiformae with neutron capture therapy
What’s the difference between the beams?

Reactor-based (BNL) 3 MW

Accelerator-based production (LBNL)

Kill healthy cells in front of tumor

Ideal energy band
Hadron therapy allows for the best treatment of deep tumors with minimized dose to healthy tissue.
Ion beams to produce fusion energy
Matter in extreme conditions can be driven by intense heavy ion beams.
The inertial fusion power plant

1. Driver - accelerator to heat & compress the target to ignition

2. Targets (and a factory to produce about 5 per second)

3. Focusing system

4. Fusion chamber to recover the fusion energy pulses from the target

5. Steam plant to convert fusion heat into electricity
Example: neutral beams for TFTR at Princeton

ITER will require 60 MW of neutral beam heaters
How much do these things cost?

N.B., VERY ROUGH ESTIMATES

kilo Euros/"effective MeV"

Year

VLHC/ELN?
Just what are these beams?

That’s the next lecture