Applications of Accelerators

Prof Rob Edgecock
Rutherford Appleton Laboratory and
University of Huddersfield
• Introduction to particle accelerators
  - at CERN
  - used for applications

• Summary of accelerator applications outside research

• Energy applications

• Medical applications:
  - cancer therapy
  - radioisotope production

• Industrial applications

• Environmental applications
Particle Accelerators

- For research, e.g. CERN, main requirements
  - energy
  - beam control (for luminosity, etc)

- Main accelerators used for protons:
  - linear accelerators at low energy
  - synchrotrons to get to higher energy
Fermilab's Accelerator Chain

Main Injector

Target Hall

Antiproton Source

Booster Linac

Cockcroft-Walton

Proton

Neutrino

Meson

DZero

CDF

Tevatron
Two questions:
- why is that?
- what about everybody else?
Need to look at how they work
Linacs: how do they work?

160 MeV
102 MeV
50 MeV
50 MeV

LINAC 4

~76m

Source
3MeV

JP Corso le 29.05.2012
Linacs: how do they work?

Linac4 DTL

Photo credits: CERN
Linear Accelerators

Acceleration via electric fields
AC frequency in the RF range

ISIS 70 MeV linac at RAL
Linear Accelerators
Linac4 chopper (3 MeV) line
Linear Accelerators

Linac4 H- ion source

From Moehs et al, FERMILAB-PUB-05-094-AD
Linear Accelerators

Linac4 Radio Frequency Quadrupole
Electron Linacs

- e- commonly produced by emission from heated cathode
- “Brighter” beam than for ions
- Higher frequency (smaller wavelength) RF possible:
  - higher accelerating gradients
  - smaller structures
- e- relativistic at low energy
- Electron linacs (for applications) smaller and simpler than ions
Varian Medical Linac
• Advantages:
  - fixed RF frequency
  - fixed magnetic fields
  - easy to operate
  - reliable
  - good for non-relativistic particles

• Disadvantages:
  - each component used once per pass
  - long for high energies
  - expensive at higher energies
  - continuous operation has complications unless SC
Circular accelerators:

In 1949, a more powerful accelerator known as the synchrotron was introduced.
Strong Focussing

Quadrupole (LEP)

Sextupole (LEP)
Correction of chromatic spread.

Alternating Gradient or Strong Focussing Beam alternately focussed in horiz and vert planes.
Strong Focussing

NIMROD: 7 GeV weak focussing synchrotron

Bevatron: 6.2 GeV LBNL
### Strong Focussing

<table>
<thead>
<tr>
<th>Category</th>
<th>Type</th>
<th>Code</th>
<th>Quantity</th>
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<tr>
<td><strong>Main Dipoles</strong></td>
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<td><strong>Lattice quadrupoles</strong></td>
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<td><strong>Twin aperture Separation dipole in IR (188mm), D2</strong></td>
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<td><strong>Single Aperture Separation dipole, 1 MBRS magnet on each beam - one cryostat (D3 in IR4)</strong></td>
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<td><strong>Single aperture separation dipole, D1 in IR2 and IR8</strong></td>
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<td><strong>Quadrupole in the insertions (4.8 m)</strong></td>
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<td><strong>Wide aperture quadrupole in the insertions, twin aperture</strong></td>
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<td><strong>Quadrupole in the insertions (2.4 m)</strong></td>
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<td><strong>Twin aperture warm quadrupole in IR3 and IR7,</strong></td>
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<td><strong>Inner triplet quadrupole, single aperture (Q1, Q3)</strong></td>
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<td><strong>Inner triplet quadrupole, single aperture (Q2)</strong></td>
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<td><strong>Sextupole spool-piece (b3) associated to MCBXA</strong></td>
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<td><strong>Skew quadrupole (a2) in MQSXA</strong></td>
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</table>
Synchrotrons

Circular accelerators
• Advantages:
  - very high energies possible
  - very good beam control
  - small machine aperture

• Disadvantages:
  - big
  - expensive
  - pulsed
  - variable frequency RF
  - not so easy to operate
• Nearly 40000 accelerators in use
• About half < 5 MeV
• Nearly all of rest < 20 MeV
• About \( \frac{2}{3} \)rd electrons, \( \frac{1}{3} \)rd ion
• Used for a variety of applications
• Requirements different from HEP:
  - cost effective
  - reliable
  - easy to operate
  - current is usually more important than energy
• Three types of accelerator
  - electrostatic
  - linacs
  - cyclotrons
**Electrostatic Accelerators**

- Use a DC electric field for acceleration
- Various types
- Main limitation: electrical breakdown

1897 – J.J. Thomson
Cathode ray tube

- Cockcroft Walton ~voltage multiplier
- Van der Graaff
- Tandem
John Cockcroft & Ernest Walton
Voltage Multiplier
Cavendish Laboratory, 1932.
Dynamitron
Electrostatic Accelerators

- Van der Graaff generator

Diagram showing the components of a Van der Graaff generator:
- Metal sphere
- Collecting comb
- Conveyor belt
- Charged comb
- Voltage
Electrostatic Accelerators

• Advantages:
  - DC
  - large beam currents possible
  - easy to operate
  - very efficient
  - reliable

• Disadvantages:
  - limited beam energy
  - high voltages
First circular particle accelerator built by Ernest O. Lawrence & Stanley Livingston at Berkeley in 1930.
Energy = 80 keV, Diameter = 13cm

Simple cyclotron: isochronous to 12 MeV
Above that, the magnetic field must be shaped
Three things to worry about:

- **Isochronous:**
  where
  \[ B_{av}(r) \sim \gamma(r) \]
  \[ B_{av} = \langle B(\theta) \rangle \]

- **Horizontal control/focussing:**
  To 1st order, horizontal tune
  \[ \nu_x^2 \approx 1 + k \]
  where average field index \( k \)

- **Vertical control/focussing:**
  To 1st order, vertical tune
  \[ \nu_y^2 \approx -k + F(1 + 2\tan^2 \varepsilon) \]
  where flutter
  \[ F \equiv \left\langle \left( \frac{B(\theta)}{B_{av}} - 1 \right)^2 \right\rangle \]

→ Azimuthally Varying Field cyclotrons by L.H. Thomas in 1938
Images courtesy
GE and IBA

230 MeV IBA
Cyclotrons

PSI cyclotron
600MeV
Cyclotrons

• Advantages:
  - CW
  - fairly large beam currents possible
  - easy to operate
  - fairly efficient
  - reliable

• Disadvantages:
  - fixed beam energy
  - highish beam losses
Accelerator Applications

- Accelerators created for Particle Physics
- Many developments driven by PP
- Now used for other applications
  - ~40000 accelerators already in use around the World
  - Annual sales: >$3.5B
  - Annual product, etc, sales: >$0.5T
  - Fit into a few broad categories:
    - Energy
    - Environment
    - Healthcare
    - Industry
    - Security and defence
    - Research
Energy Applications

- All at an early stage

Fission:
- waste burners
- thorium energy amplifiers

Fusion:
- plasma heating
- materials studies
- heavy ion inertial fusion
(Almost) all fission reactors employ uranium-235 as fuel

Related problems

- only 0.7% of natural uranium → enrichment
- proliferation: plutonium production
- safety
- uranium supply is not infinite
- waste

Main waste issue:

Minor Actinides $^{237}\text{Np}$, $^{241}\text{Am}$, $^{244}\text{Cm}$
- long lived >1000 years
- very radiotoxic ($\alpha$, high energy $\gamma$)
- very hot
MAs are fissile

Fast neutron spectrum is essential
Requirements for ADS

• Sufficient beam energy for neutron spallation
• Sufficient beam current

Beam power: \( \geq 4 \text{ MW} \)

Requirements for ADS

• Sufficient beam reliability
**Example Projects**

- **MYRRHA in Belgium:**
  - 600 MeV, 1.5 MW
  - SC proton linac
  - lead-bismuth eutectic target

- **Timescale:**
  - 100 MeV accelerator in 2024
  - decision on next steps
Chinese ADS

- **China:** largest energy consumer in world; 79% coal in 2011

- **Nuclear power:**
  - Now: 22 reactors working (18GWe), 27 construction (27GWe)
  - 2020: 58 GWe (with 30 GWe under construction)
  - 2050: 350-400 GWe (~ total world production in 2014)

- **ADS project:**
  - 250 to 600 MeV
  - 2.5 mA
  - CW superconducting proton linac
  - Flowing granular target
Chinese ADS

Granular target

CIADS layout

Proton linac

Sub-critical core:
LBE coolant
<10 MWt

1. Ion source+LEBT+RFQ+MEBT
2. HWR009 section
3. HWR019 section
4. Spoke042 section
5. Elliptical062 section
6. Elliptical082 section
7. Coupling section
8. Reactor
Chinese ADS

- **Aim:** initial facility (>250 MeV, 10 mA, <10 MWt) - 2022
demo facility (1 GeV, <15mA, >500 MWt - 2030)

- **Currently prototyping**

10 MeV beam being commissioned
• $^{235}$U problems
  - only 0.7% of natural uranium → enrichment
  - proliferation: plutonium production
  - uranium supply is not infinite
  - waste
• Alternative fuel: thorium
  - 3*uranium in the Earth’s crust, all burnt as fuel:
    1 ton Th ~ 200 tons U ~ 3500000 tons coal [Carlo Rubbia]
    about same amount in crust as lead
    - proliferation resistant (no Pu)
    - 50% of waste for storage
    - but.........sub-critical
Known Resources (ktonnes)

- Canada: 172 ktonnes
- USA: 434 ktonnes
- Venezuela: 300 ktonnes
- Brazil: 1300 ktonnes
- Greenland: 93 ktonnes
- Norway: 320 ktonnes
- Finland: 60 ktonnes
- Sweden: 50 ktonnes
- Turkey: 890 ktonnes
- Egypt: 380 ktonnes
- India: 846.5 ktonnes
- South Africa: 140 ktonnes
- Kazakhstan: >50 ktonnes
- Russia: >155 ktonnes
- China: >100 ktonnes
- Australia: 521 ktonnes
- Rest of the World: 1781 ktonnes
Thorium Fuel Cycle

Sub-criticality – must make more neutrons.
One method: an accelerator ~ 10 MW

But, currently, there is only really talk about this, little actual activity
Fusion

JET Tokamak at Culham, UK.

- Create plasma of D and T
- Heat it to $1 \times 10^6$ °C
- Compress it magnetic
- Cause fusion
JET Tokamak at Culham, UK.

- Create plasma of D and T
- Heat it to $1 \times 10^6 \, ^\circ C$
- Compress it magnetic
- Cause fusion
Neutral ions can produce 35 MW of heating for JET
Single biggest source
ITER Neutral Beam Test Facility (PRIMA)

Mission of PRIMA MITICA SPIDER:
- Optimize NBI operation
- Maximize reliability of injectors
- Develop technologies for injectors
- Test key remote handling tools and procedures
- Achieve nominal parameters:

**SPIDER**
- $I_{spd} = 40$ A
- $V_{spd} = 100$ kV
- $t_{pulse} = 3000$ s

**MITICA**
- $I_{mit} = 40$ A ($D_2$)
- $V_{mit} = 1$ MV
- $t_{pulse} = 3000$ s

A. Masiello et al., Fusion Eng. Des. 86 (2011) 860
P. Sonato et al., AIP Conf. Proc. 1515 (2013) 549
P. Sonato et al., Fusion Eng. Des. 84 (2009) 269
**Fusion:**
Materials research

**DEMO:** $10^{18}$ neutrons m$^{-2}$s$^{-1}$ at 14.1 MeV

30 dpa/year

**IFMIF:**
Create ~14 MeV neutrons using Li(d,xn) reaction

2 x 40 MeV, 125 mA linear accelerators

20 dpa/year

5MW/beam
Heavy Ion Inertial Fusion

- Use heavy ions to compress fuel for fusion
- Idea has been around since 1970s
- Being studied mainly in the US

Multiple Beam Ion Source & Injector

- ~2-3 MeV
- ~1 A/beam
- ~20 μs

Acceleration with quadrupole focusing

- ~3 GeV
- ~200 A/beam
- ~200 ns

Target

Chamber Transport

focusing

Longitudinal compression

- ~3 GeV
- ~4000 A/beam
- ~10 ns

Bending

a few kilometers

12TW!

Courtesy: C.M.Celata
Heavy Ion Inertial Fusion

Ion Sources & Injector
Acceleration with electric focusing
Acceleration with magnetic focusing
Longitudinal compression
Chamber Transport
Bending

Courtesy: C.M. Celata
Heavy Ion Inertial Fusion

Proposed Integrated Beam eXperiment (IBX) in US. Next step towards demonstration of technique.

Injector
2 m
250 ns
1.7 MeV

Accelerator
40 m (10 MeV)

15 m
250 ⇒ 25 ns

5 - 10 MeV
Drift Compression

7 m
25 ns
Neutralization

Final Focus

Courtesy: C.M. Celata
Muon Catalysed Fusion

• Principle:
  - muonic atoms ~200 times smaller than standard
  - coulomb barrier thinner
  - fusion easier
  - muon released after fusion, hence catalyst

• Studied in various labs, e.g. Dubna, TRIUMF, PSI, KEK, RAL

• Works, but muons needs to be 10x cheaper
• Accelerators being studied for fission and fusion use
• Still under development
• Pushing (or well beyond!) the boundaries:
  - beam current
  - beam power
• ADS linac studies have built on:
  - CERN work on Superconducting Proton Linac (SPL)
  - European Spallation Source