Introduction to Accelerators
Part 1

M W Poole
Director, ASTeC
Basic Acceleration Principle

A voltage drop accelerates charged particles

Electrostatic acceleration in cathode ray tubes:
- televisions
- computer monitors
- oscilloscopes
Birth of Particle Physics and Accelerators

- **1909** Geiger/Marsden MeV $\alpha$ backscattering - Manchester

- **1919** Rutherford disintegrates Nitrogen - Manchester

- **1927** Rutherford demands accelerator development
  Particle accelerator studies start - Cavendish

- **1929** Cockcroft and Walton start high voltage experiments

- **1932** The prize achieved: Cockcroft + Walton split Li !!!!

‘High’ voltage generation is UK achievement at this stage – brute force
UK grid initiated (132 kV) and industrial base started
Walton, Rutherford, Cockcroft - 1932

NOBEL PRIZE !

Start of the modern era – particle accelerators
Cockcroft-Walton Generator

ISIS  665 kV

Removed  2005

See our Atrium!

Greinacher 1921
Electrostatic Monster: the NSF

- 1936 van der Graaff pioneers electrostatic solution (2.5 MeV)
- 1961 6 MeV machine at Liverpool (Manchester collaboration)
- 1972 Design Study of 20-30 MV facility at Daresbury
- 1974 Civil construction starts
- 1983 NSF commissioned
- 1992 Closure

World’s highest voltage machine

No nuclear physics replacement
Daresbury Nuclear Structure Facility (NSF)

Van de Graaf
20+ MV

Last of the line!
Seriously high voltages!
Resonant Accelerator Concept

The acceleration occurs in the electric field between cylindrical *drift tubes*.

The RF power must be *synchronised* with the motion of the electrons, so that acceleration occurs in every cavity.

This naturally produces *bunches* of electrons.

**Linear Accelerator = LINAC**  
Wideroe - 1928
Recirculation Concept - Cyclotron

Radio frequency alternating voltage

Hollow metal drift tubes

D-shaped RF cavities

Lawrence:
4” – 80 keV
11” - 1.2 MeV

Synchronisation Necessary

Orbit radius increases with energy
Expensive/impractical for high energies (1 GeV)

\[ qvB = \frac{mv^2}{r} \]

\[ r = \frac{mv}{qB} \]

\[ T = \frac{2\pi m}{qB} \]
Phase Synchronism

Synchronous particle \((A)\) crosses cavity after one turn at same phase relative to RF peak

Particle \(B\) delayed behind \(A\) receives higher accelerating voltage and therefore after next turn returns nearer or even ahead of \(A\)

Particles undergo harmonic synchrotron oscillations about \(A\) as they orbit the accelerator

*NOTE*: This leads to **BUCHING** about \(A\)*
Accelerator Developments

• Cyclotrons have huge magnets - spiral orbits

• Also complicated by relativistic mass increase

• Solution:

  Raise magnetic field strength as particle energy increases
  Produces annular orbit geometry

  SYNCHROTRON
Synchrotron Ring Schematic

Bending and focusing often combined
Magnet Focusing

Quadrupole magnets are used to focus the beam.

FQUADs (shown above) focus the beam horizontally.

DQUADs (as above, rotated 90º) focus the beam vertically.
RF Accelerating Cavities

Single cell example
Klystrons
Simple Accelerator Lattice

F Quardrupole

Dipole

D Quardrupole

FODO Cell

finite dispersion
Betatron Oscillations

Transverse motion of particles in both planes is harmonic - as they deviate from the design orbit a restoring force increases with displacement.

The particles follow betatron oscillations as they orbit the accelerator.

The amplitude and wavelength of this motion is characterised by the beta functions of the accelerator.

Off-energy particles follow a dispersion function.
**Phase Space**

**Emittance** measures phase space area

**Beta function** gives transverse envelope
The Double Bend Achromat Cell

Dispersive Path

Dipole

Quadrupole

Sextupoles

Quadrupoles

Dipole

Non-Dispersive
Lattice Functions - DBA Example

Lattice Functions

Beta functions (m)

Dispersion (m)

Distance (m)
Sextupole Magnets

Chromatic Correction
(off energy particles)

In finite dispersion region focussing matches energy
Penalty: Collapse of Dynamic Stability

No sextupoles

Corrected to zero chromaticity
Recovery of Stability - Sextupoles in Patterns

Four families

Six families

Eight families
Early (UK) History

(Synchro)Cyclotrons

Berkeley (Lawrence) 60” (1939)
Liverpool 37” 20 MeV (1939)
Harwell 110” 175 MeV (1949)
Liverpool 156” 380 MeV (1954) (extraction)

Linacs

Harwell 3.5 MeV (1947)  15 (Mullard), 55 (Met Vickers), 136 MeV

Synchrotrons

Woolwich Arsenal - Goward & Barnes 8 MeV (1946) (Betatron 1943)
Malvern 30 MeV (1950)
Oxford 125 MeV (1952)
Birmingham 1 GeV p (1953)
Glasgow 350 MeV (1954)
NIMROD RAL 7 GeV p (1960)
NINA DL 5 GeV (1966)
Origins of Daresbury Laboratory

- 1957  Wilkinson proposes HE electron synchrotron

- 1960  Cockcroft + Cassels propose 4 GeV version

- 1961  Cockcroft proposes Cheshire site !!!!

- 1962  NINA approved - £3.5M

  Many local sites considered

- 1963  Daresbury selected

HEI driving force: Liverpool/Manchester/Glasgow/Sheffield/ (Lancaster)
Construction of NINA - 1964
A Bad Day at the Office!
Grand Opening of NINA - 1967
The NINA Synchrotron
Chadwick’s 75th Birthday – Daresbury Event
NINA Closure

• UK joined SPS at CERN on condition domestic programme terminated (NINA AND NIMROD)

• NINA switched off in 1977

• Alternative major facilities already sought - and found:
  • NSF (discussed)
  • ISIS and SRS (part 2 next week)
EM Radiation from Accelerating Charge

Non-relativistic charge source
Fundamentals of Radiation Emission

- Any charge that is accelerated emits radiation

- Properties calculated since 1897 (Larmor)

Lienard and Schott studied relativistic particles on circular trajectories:

\[ P \propto E^4/R^2 \]

- So this applies to accelerated beams of charged particles in a ring (synchrotron)

SYNCHROTRON RADIATION

\[ \text{eg NINA} \]

\[ \Rightarrow \text{Severe losses and energy restrictions} \]
Relativistic Emission Cone

Electron rest frame

Laboretical frame

Transforming between frames

\[ \tan \theta = \gamma^{-1} \sin \phi \left( 1 + \beta \cos \phi \right)^{-1} \]

if \( \phi = 90^0 \)

then:

\[ \theta = \gamma^{-1} \]
Emission from Bends

First observed 1947
GE Synchrotron

Electron

Cone angle = $1/\gamma$

$\gamma = E/m_0c^2$

Acceleration

Magnet

Synchrotron Light
Synchrotron Radiation Spectrum

Pulse Length

\[
\approx \frac{4R}{3c\gamma^3}
\]
(electron transit arc - photon transit chord)

Typical wavelength

\[
\approx \frac{4R}{3\gamma^3}
\]

For 2 GeV, 1.2 T:

R \sim 5.5 \text{ m}, \gamma \sim 4000

Wavelength \sim 0.1 \text{ nm}
Universal Synchrotron Radiation Curve

\[ N = 2.46 \times 10^{13} E I_b \left( \frac{\omega}{\omega_c} \right) \int_{\omega/\omega_c}^{\infty} K_{5/3}(u) du \]

In units of photons/s/mrad/0.1% bandwidth

Spectral Photon Flux (photons/s/mrad/0.1% bandwidth/GeV/100mA)
Accelerators in Space

Crab Nebula
Synchrotron Radiation – New Particle Accelerator Applications

Accelerating charged particles emit electromagnetic radiation
  – very inconvenient for circular electron accelerators!

• 1972     Scientific use started at Daresbury by Manchester group

• 1974     SRS Design Study       (NINA replacement – 2nd Generation)

• 1980     SRS commissioning      (world’s first dedicated x-ray source)

• 1987     High brightness upgrade

• Many pioneering additions:
  – superconducting wigglers       undulators       precision beam steering       high currents

• 2008     Project termination
Daresbury SRS

- Design studies completed 1975 – anticipate NINA end
- Based on an electron storage ring
- World’s first dedicated x-ray source
- First user programme 1981
- Major UK success story for 27 years
- Pioneering developments and upgrades
Daresbury SRS Concept

World’s first dedicated x-ray source

Linac

Booster

80 keV

12 MeV

600 MeV

2 GeV

Storage Ring

Beamlines

80 keV

12 MeV

600 MeV

2 GeV
## SRS Storage Ring Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy</td>
<td>2 GeV</td>
</tr>
<tr>
<td>Operating Current</td>
<td>300 mA</td>
</tr>
<tr>
<td>Total Circumference</td>
<td>96 m</td>
</tr>
<tr>
<td>Revolution Frequency</td>
<td>3.1 MHz</td>
</tr>
<tr>
<td>Pressure in Beam Tube</td>
<td>$10^{-12}$ atm</td>
</tr>
<tr>
<td>Number of Dipoles</td>
<td>16</td>
</tr>
<tr>
<td>Dipole Current at 2 GeV</td>
<td>1,420 A</td>
</tr>
<tr>
<td>Dipole Field</td>
<td>1.2 T</td>
</tr>
<tr>
<td>RF Power Input to Beam</td>
<td>250 kW</td>
</tr>
<tr>
<td>Stored Beam Lifetime</td>
<td>30 hours</td>
</tr>
</tbody>
</table>
SRS Components - High Technology
A Synchrotron as an Injector

SRS Booster

600 MeV
SRS Lifetime (Example)

Operating mode is fill storage ring every morning
24/7 running       (6000 hours annual)
Real Synchrotron Radiation

Beam port
Synchrotron Radiation Spectrum

Broad band source

Covers huge spectral range

Range set by electron energy and bending field strength

Flux/power far exceeds previous sources
From Source to Detector

- Light from source can be split for more than one experiment
- Light focused using mirrors
- Narrow range of wavelengths selected by monochromator
- Light illuminates crystal sample and is diffracted
- Diffraction pattern observed with detector
Wide Range of Applications

FMV Virus Structure (1990)
Protein Crystallography

Light Harvesting Complex (photosynthesis)

Materials science

LIGA
The Nobel Prize: F1 ATPase structure

- Sir John Walker shared **1997 Nobel Prize for Chemistry** - structure of the F1 ATPase enzyme, using the SRS
High Field Insertion Devices

Normal Straight

With Insertion Device

SRS
Superconducting Wavelength Shifter
6.0 Tesla
Alternative Compact Light Source

Designed at Daresbury
Sold by Oxford Instruments to IBM in 1990 - lithography
Operated successfully for 10 years

Helios Machine

700 MeV
4.5 T

HELIOS at JLab
Big Accelerators - CERN
Types of Accelerator

- **Linear Accelerators** (Linacs)
  - Multi-cell concepts  TW and SW

- **Cyclotrons**
  - Low energy limit

- **Synchrocyclotrons**
  - RF variation compensates mass change – extends energy reach

- **Betatrons**
  - Beam is ‘secondary’ of a transformer - magnetic field limit

- **Synchrotrons and Storage Rings**
  - Ramped magnetic field matches energy – annular design

- **Other variants**
  - Microtron  RFQ  FFAG  ???
Accelerator Physics Challenges

- Classical electrodynamics - Maxwell (mainly !)
  - Lorentz forces: Deflection and acceleration

- Single particle dynamics
  - transport, stability, nonlinear dynamics - tracking & differential algebra

- Multi-particle dynamics
  - collective effects, wake fields, space charge, coherent instabilities

Production    Transport    Injection    Acceleration    Extraction    Manipulation    Delivery

Analytic modelling    +    Computer simulation    (Start-to-End)
(Major code development)

Experimental verification    (Commissioning !)

fs          nm
Accelerator Technologies

**Sources**
- electron guns
- photoinjectors
- ion sources

**Magnets**
- EM / SCM / PM
- DC / AC / Pulsed
- Harmonic / Periodic
- Power supplies

**RF System**
- structures
- power sources

**Vacuum**
- UHV modelling
- diagnostics
- pumping

**Diagnostics**
- fast
- high precision
- non-interactive

**Geodesics**
- alignment
- feedback

**Radiation**
- losses
- shielding
- personnel safety

**Dumps**
- spallation targets
- collimators

**Engineering**
- mechanical
- electrical
- civil

**Controls**
- advanced process control

**NB**
- Multi-disciplinary teams.
- Resource issues - construction/operation.
Concluding Remarks

- Origins of particle accelerators discussed
- Reason for Daresbury Lab (and CI) existence explained
- Applications beyond particle physics highlighted
- Additional concepts mentioned
- Next week: surveys of various advanced applications