ALICE

Accelerators and Lasers In Combined Experiments

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Synchrotron Light Sources
Formal opening of NINA by Harold Wilson

Dec 1966
High Energy Physics Experiments
Producing Light 1

In a radio transmitter mast, electrons are forced to oscillate up and down an antenna.
As the electrons accelerate, they emit electromagnetic waves.
Electromagnetic waves are always given out when charged particles accelerate.
The frequency of the waves depends on the acceleration of the particles.
In a synchrotron, magnetic fields cause the electrons to change direction. Since a change in direction is an acceleration, this makes them emit electromagnetic radiation. The electrons lose energy, which is replaced by the RF power.
Synchrotron Radiation Emission

The Electromagnetic Spectrum

- Size:
  - House
  - Baseball
  - Cell
  - Protein
  - Atom

- Wavelength (m):
  - $10^3$ to $10^5$
  - $10^{-1}$ to $10^{-3}$
  - $10^{-5}$ to $10^{-7}$
  - $10^{-9}$ to $10^{-11}$
  - $10^{-13}$ to $10^{-15}$

- Energy (eV):
  - $10^{-9}$ to $10^{-7}$
  - $10^{-3}$ to $10^{-1}$
  - $10^1$ to $10^5$
  - $10^7$ to $10^9$
  - $10^{10}$ to $10^{12}$

- Sources:
  - Radio
  - Microwave Tubes
  - Light Bulbs
  - Synchrotron Radiation
  - Radioactive Elements
Synchrotron radiation on NINA

A first generation source

1968
Real synchrotron radiation

Beam port
Synchrotron radiation in space

Crab Nebula
Daresbury SRS Concept

A second generation source

Synchrotron becomes a storage ring

World’s first dedicated x-ray source

- 600 MeV
  - $v/c = 99.99997\%$

- 12 MeV
  - $v/c = 99.9\%$

- 0.051 MeV
  - $v/c = 0\%$

- 2000 MeV
  - $v/c = 99.9999997$
We can increase the amount of radiation produced by using arrays of magnets.
Wiggler magnet at the SRS
The UK built the world's first dedicated accelerator to produce light for scientists to use in a wide range of experiments.

The SRS at Daresbury in Cheshire ran successfully for 28 years and gave two million hours of science, including:

- structure of Foot & Mouth virus
- memory for iPods
- better-tasting chocolate
- more effective washing powder
Solid cocoa butter fat can exist in six different forms. The taste and texture of the chocolate depends on the relative quantities of each form.

Work on the SRS has helped identify the best conditions for making the chocolate, to give the best taste and texture.
The Nobel Prize: F1 ATPase structure

• Sir John Walker won a share of the 1997 Nobel Prize for Chemistry for solving the structure of the F1 ATPase enzyme using the SRS
• The enzyme F1-ATPase plays a crucial role in the synthesis of ATP, the ‘fuel cell’ for all animals.
• Developed an important new technique; opens the way for new insights into metabolic and degenerative disease
A 3rd Generation Light Source
DIAMOND

24 Sections 550 m Circumference

Long 5m straights
undulators & wigglers

Insertion Device

Beam sizes ~1/100th that of the SRS
X-rays from Diamond is 1,000,000,000,000 times brighter than from an X-ray tube!
Diamond

Built at the Harwell Site In Oxfordshire
7 things we could not have done without synchrotrons

- The development of the ‘anti-Flu’ drug, Relenza.
- Work on non-nucleoside inhibitors, which it is hoped will form the basis for the next generation of anti-HIV RT non-nucleoside drugs.
- Help the fight against malaria by studying the life cycle of the deadly malaria parasite in living red blood cells.
- The detection and analysis of arsenic in the Asian wetlands – vital work for environmental control.
- Use intense X-ray beams to penetrate large, complex engineering structures such as aircraft wings to increase our knowledge of residual stresses.
- Work towards having a laptop computer that’s ready to use as soon as you turn it on.
- Find answers to important forensic & historical questions such as “Was Beethoven poisoned?” by studying cultural heritage samples (in Beethoven’s case a hair sample).
Linac Versus Storage Ring

Linacs electrons pass through once, the source size and duration are determined by the electron source.

Storage rings electrons stay in for many hours, the source size and duration are determined by equilibrium conditions.
Linac Based Light Sources - Beyond the 3rd

- Storage Ring
- Linac
- Diffraction limited @ 8keV

Source: Ivan Bazarov
Ultra short pulses
Stanford: the galloping question

The negatives of these photographs were made at intervals of twenty-seven inches of distance, and about the twenty-fifth part of a second of time; they illustrate consecutive positions assumed in such twenty-seven inches of progress during a single stride of the mare. The vertical lines were twenty-seven inches apart; the horizontal lines represent elevations of four inches each. The exposure of each negative was less than the two-thousandth part of a second.
Science case

Molecular & atomic ‘flash photography’
Science case

Bio-molecular structures
4th Generation Light Sources
Free Electron Lasers
Free Electron Lasers

Peak Brilliance [phot/sec mm² mrad² mm² 0.1% bandwidth]

Energy [eV]
Free Electron Lasers
X-Ray Diffraction from a Single Protein Molecule

LCLS applications:

Avoids radiation damage problem by taking diffraction data before damage occurs

Would allow much broader range of biological structures to be determined
X-Rays have opened the Ultra-Small World
X-FELs open the Ultra-Small and Ultra-Fast Worlds

Ultra-Small

Nature
- Flea
- Human hair ~30 µm wide
- Red blood cells & white cell ~5 µm
- Virus ~200 nm
- DNA helix ~3 nm width
- Water molecule
- Atom

Technology
- Micro gears 10-100 µm diameter
- DVD track
- 1 µm Electrodes connected with nanotubes
- Carbon nanotube ~2 nm diameter
- Atomic corral ~14 nm diameter

Ultra-Fast

Nature
- Hydrogen transfer time in molecules is ~1 ns
- Spin processes in 1 Tesla field is 10 ps
- Shock wave propagates by 1 atom in ~100 fs
- Water dissociates in ~10 fs

Technology
- Computing time per bit is ~1 ns
- Optical network switching time per bit is ~100 ps
- Shortest laser pulse is ~1 fs
- Oscillation period of visible light is ~1 fs

4th Gen Operating Ranges

Courtesy of John N. Galayda
300 mA x 3,000 MeV = 900 MW
ALICE
Accelerators and Lasers in Combined Experiments

Europe's first energy recovery accelerator
Photoinjector

Copper brazed joint 350 kV

First electrons August 2006

Gun ceramic – major source of delay – at Daresbury (~1 year late)
Injector upgrade

- Improved vacuum conditions
- Reduction of contamination from caesium ions
  - Improved gun stability under high voltage
- Reduced time for photocathode changeover, from weeks to hours
- Higher quantum efficiency
  - Allows practical experiments with photocathodes activated to different electron affinity levels

ALICE photocathode gun equipped with a photocathode preparation & exchange facility

Lab based test facility achieved 15% Qe
LC1 - Radiation
Linac Low Level Controls

Pre He Processing
Post He Processing
Cryomodule Collaboration

- 2 x 9-cell 1.3 GHz cavity
- 10 kW CW fixed coupling FPC

Current Module

Saclay II Tuner

7-cell 1.3 GHz Cavity

Beam-pipe HOM Absorbers

25 kW CW Adjustable Coupling FPC
ALICE

Arc

FEL

Compresso

IR-FEL

Photoinjector Laser

Laser

Energy Recovery Linac

High brightness electron source

Linac

Deceleration

Acceleration

Acceleraton

LINAC

Deceleraton
ALICE Energy Recovery

Cavity Power Signals for Full energy recovery (December 2008)

Power demand signals without (left) and with (right) energy recovery
Photon applications
ALICE - not just an energy recovery linac
Terahertz for security
Accelerator sources of terahertz radiation

Power of laboratory instruments

At 1 THz ~ 100 µ watts

Short electron bunches

When bunch length < wavelength

Coherent emission ---> massive output power

ALICE
THz programme & tissue culture facility on ALICE

A world-unique facility allowing the effect of high peak power / high rep rate THz on living cells to be investigated.

Weightman et al
University of Liverpool
University of Nottingham

THz has important role in security
Understanding the origins of life?

Life has evolved at room temperature. Energy available = \( kT \approx 6 \text{ THz} \)

**Free Energy** from capturing sunlight in photosynthesis and oxidation of molecules

These processes involve interactions between molecules

The molecules show remarkable organisation and activity

**Example: DNA**

Human genome 3 billion base pairs. Double helix 2m long folded into \( \sim 2 \mu m \)

Unwound, read and rewound on a daily basis

Weightman et al

University of Liverpool
The mechanisms of molecular organisation

Do THz modes distribute and use of free energy released by molecular interactions?
Do they live long enough to organise processes important to life?
Is quantum coherence important at the molecular level in cells?

Theory

YES H. Frohlich Int. J. Quantum Chem. 2 641 (1968)
Metabolic processes could stimulate coherent excitations in biological systems
Natural frequency of DNA sequences and membranes ~ 1012 hz (THz)
Interaction with H2O is important


THz modes dissipate energy into “adjacent” modes in ~ 10-12 sec (p sec)

Experimental results: sparse and controversial
Some evidence for long lived coherent modes that mediate biological processes

“Non-linear THz excitations can induce and drive conformational change”

We need experiments with intense sources of THz
The solar energy problem

- Global power requirements set to double by 2050, currently 13 TW
- Most optimistic estimates of capabilities:
  - renewables exc. solar 2-4 TW (currently <1 TW)
  - nuclear fission 3-5 TW (currently ca. 1 TW)
- Power reaching Earth from Sun 100 000 TW
- Urgent need to improve solar cell efficiency
- Require a step-change in the cost of photovoltaic power

www.in.gov/energy/technologies/solar.html
Hybrid solar cells for micro-generation

- How are carriers transported through these cells?

- Need to measure initial charge injection and transport on ultra-fast timescales

O’Brien, Saunders, Turner, Binks, Flavell, Kirschen, Mutale, Durrant, Nelson
UK EPSRC ‘Materials for Energy Supply’ initiative
Laser-THz pump-probe measurements

- Initial charge injection can occur on fs timescales, transport is slower
- fs laser pump pulse, THz probes excitonic energy levels directly
- Variable time delay, $\Delta t$, between pump and probe
- Time evolution of carrier transients
ALICE - not just an Energy Recovery Linac
Compton Backscattering

**Electron beam**
- ~40pC/bunch
- 29.6 MeV
- RMS beams size 30 x 40 um
- Bunch length < 1ps?

**Laser**
- Ti:sapphire multi-teraWatt
- 800 nm pulses
- *circa* 70 fs duration
- 500 mJ pulse power
- repetition rate 10 Hz
Successful Detection of Short-pulsed X-rays

15th Nov 2009

Scan through the electron beam using laser timing

Number of X-rays estimated to be $3 \times 10^6$
ALICE - not just an Energy Recovery Linac
IR FEL Commissioning 2010

Installed 18th Nov 2009

Spontaneous radiation signal detected Feb 2010
ALICE - not just an Energy Recovery Linac
Electro-optic sampling of Coulomb field

probe laser co-propagates with bunch (with transverse offset)

Coulomb field of relativistic bunch

probe laser

encoding of bunch information into laser

decoding of information from laser pulse

thanks to S. Jamison
EMMA

the World's First Non-Scaling FFAG Accelerator
Proton & Carbon Therapy
Tumour irradiation

Craniospinal Irradiation: Medulloblastoma
Aim:- build a hadron therapy facility using a novel accelerator technology called a Non-Scaling Fixed Field Alternating Gradient synchrotron (NS-FFAG)

These combine many of the important features of the two types of accelerator currently used, the cyclotron and the synchrotron
Hadron Therapy Accelerators

An IBA Proteus 235 cyclotron. About half of the world's proton therapy centres use these machines.

The synchrotron used for proton therapy at the Loma Linda Medical Centre.
### Comparison of Accelerator Types

<table>
<thead>
<tr>
<th></th>
<th>Cyclotron</th>
<th>Synchrotron</th>
<th>FFAG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field</strong></td>
<td>fixed</td>
<td>varied</td>
<td>fixed</td>
</tr>
<tr>
<td><strong>Repetition</strong></td>
<td>continuous</td>
<td>slow pulse</td>
<td>fast pulse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;50Hz</td>
<td>~1kHz</td>
</tr>
<tr>
<td><strong>Focusing in</strong></td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>longitudinal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Focusing in</strong></td>
<td>weak</td>
<td>strong</td>
<td>strong</td>
</tr>
<tr>
<td><strong>transverse</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>medium</td>
<td>low</td>
<td>high? (not proven)</td>
</tr>
<tr>
<td><strong>current</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Acceptance</strong></td>
<td>large? in H</td>
<td>small in H</td>
<td>large in H</td>
</tr>
<tr>
<td></td>
<td>small in V</td>
<td>small in V</td>
<td>large in V</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>fixed</td>
<td>variable</td>
<td>variable</td>
</tr>
</tbody>
</table>
FFAGs have Ancient History

Bohr

20 to 400 keV

Operated at MURA in 1956
KEK POP

50-500 keV

1 kHz

June 2000
Scaling and Non-scaling FFAG

Pioneered in Japan - Scaling Type

Magnets are large, complex & expensive

Orbit excursion ~0.9m

\[ B = B_0 \left( \frac{r}{r_0} \right)^k \]

where \( k = 7.5 \)

Scaling

Non-scaling
• Much smaller orbit excursion
• Linear fields possible

Orbit Comparison

Cheaper magnets
Conform

BASROC (The British Accelerator Science and Radiation Oncology Consortium)

- CONFORM project (Construction of a Non-scaling FFAG for Oncology, Research, and Medicine)
- 4 year project April 2007 – March 2011
- 3 parts to the project
  - EMMA design and construction ~ £6.5m
  - Electron Model for Many Applications (EMMA)
  - PAMELA design study
  - Applications study
EMMA

Electron Model for Many Applications
Applications of NS-FFAGs

Proton & Carbon Therapy

- Relative dose (%)
- Depth (mm)
- Electrons (21 MeV)
- Carbon (270 MeV/u)
- Photons

Neutrino Factory

- International Design Study for Neutrino Factory
- Proton Driver
- Hg Target
- Buncher
- Bunch Rotation
- Cooling
- Linac to 0.9 GeV
- 0.9–3.6 GeV RLA
- 12.6–25 GeV FFAG
- Neutrino Beam
- Muon Storage Ring

Sub-critical Thorium Reactor

- Accelerator
- Spallation Target
- Reactor Core
- Neutron multiplication factor typically $k = 0.98$
EMMA International Collaboration

- EMMA design is an international effort and we recognise and appreciate the active collaboration from:
  - Brookhaven National Laboratory (USA)
  - Cockcroft Institute UK
  - Fermi National Accelerator Laboratory (USA)
  - John Adams Institute UK
  - LPSC, Grenoble (France)
  - Science & Technology Facilities Council UK
  - TRIUMF (Canada)
  - ............
A 6 Cell Girder Assembly

- F Magnet
- D Magnet
- Cavity
- Location for diagnostics
- Girder
- Ion Pump
- Beam direction
Off Line Assembly

Injection Line Modules

6 Cell Ring Module
1/7th of Circumference
EMMA in the ALICE Area 6th Dec 09
Many thanks for the efforts of all the team.

4 Sector Commissioning

Beam image on screen
At the end of 4 sectors
22 cells
22:37 on 22.6.2010
Realisation of EMMA August 2010
Complete Ring

16th Aug 2010
Coasting beam no RF

Without rf, beam circulates more than 1000 turns
Betatron oscillation

tunes & dispersion

Beam position at 7 BPMs

Tunes from fit

Dispersion from average position

At 100% effective momentum (15.5 MeV/c)
Horz disp = 82mm
Vert. disp. = 3mm
Consistent to predicted values

Horz disp = 82mm
Vert. disp. = 3mm
EMMA Summary

- NS-FFAGs are a novel untested concept
- EMMA is a model for that concept
- The EMMA experiment will test that concept
- The technical design is complete
- All major subsystems have been defined and designed to meet the requirements of the experiment

A key aim is to:–

Show non scaling FFAG acceleration works, compare results with the theoretical studies and gain real experience of operating such accelerators

The next step will be to apply the lessons learnt to new applications!
ALICE † Future Vision

5 year vision—aim to have this vision in place by Nov 2010

ALICE has an unusually diverse set of sub-projects
- FEL physics – THz studies and exploitation
- EMMA – ERL-based accelerator physics
- Electro-Optic diagnostic development – Laser induced microbunching & acceleration
- RF and SC linac developments – Photoinjector developments
- Photon exploitation – Compton Back Scattering

Have to solicit proposals for future e-beam test facility activities

Develop consistent, realistic scenarios which address future R&D requirements

Stakeholder & STFC engagement

EMMA is developing its own plan for a future 2.5 year programme

†ALICE in this context is shorthand for electron test accelerators at Daresbury and all associated experimental programs!
Acknowledgements

- All the team
  - STFC staff
  - University collaborators
  - All the international collaborators

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