Introduction to Particle Accelerators: Part 1

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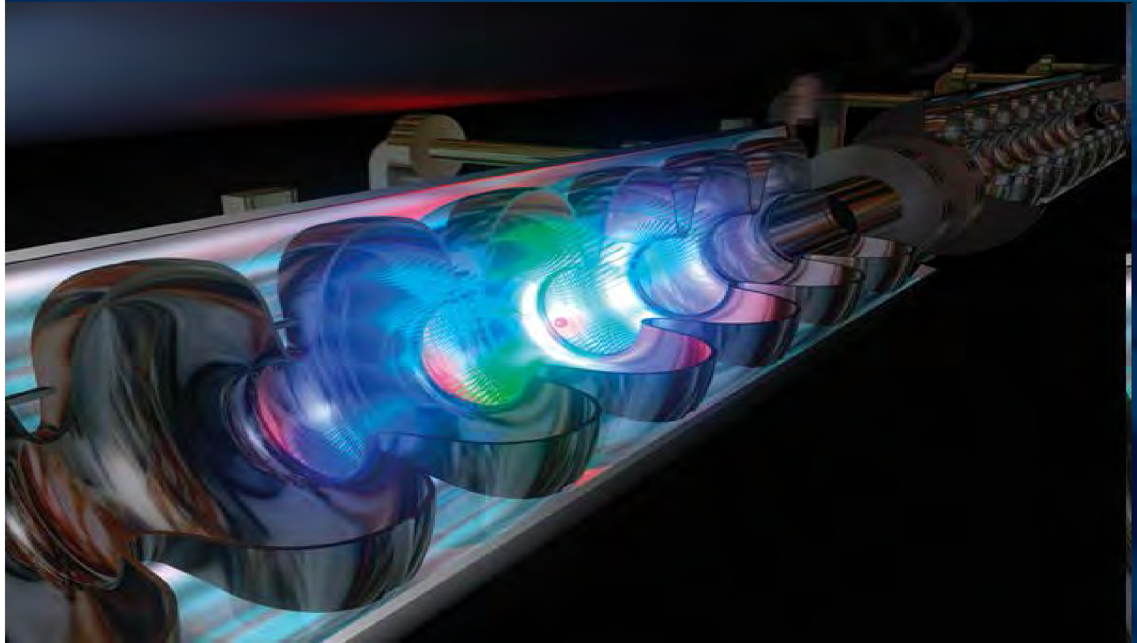
Accelerators for Particle Physics

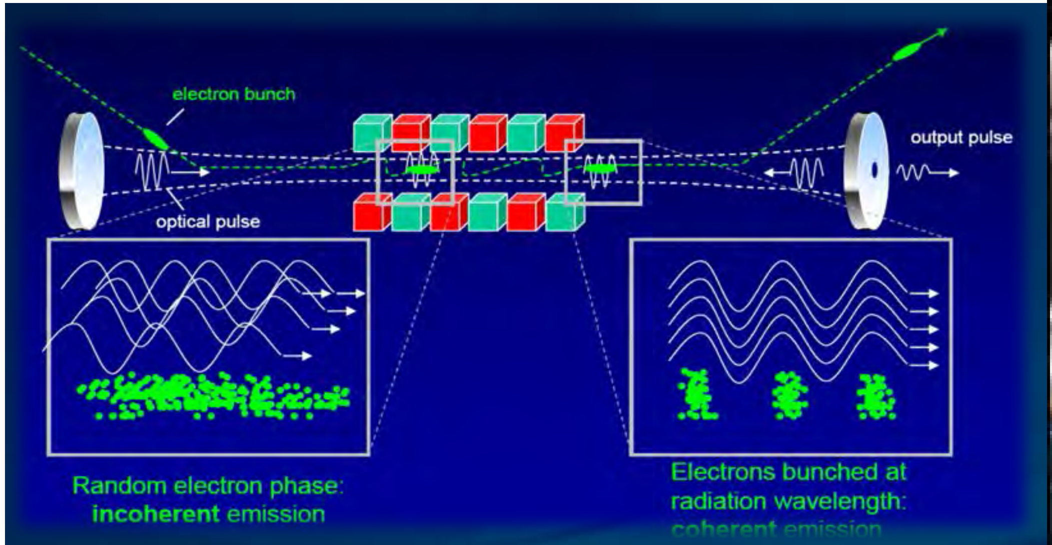
In order to study the Higgs boson and new physics at the Terascale exciting new accelerators with higher energy and more luminosity are required.

The UK is playing a lead role in

- Upgrading the LHC
- Designing the next linear collider
- Neutrino factories



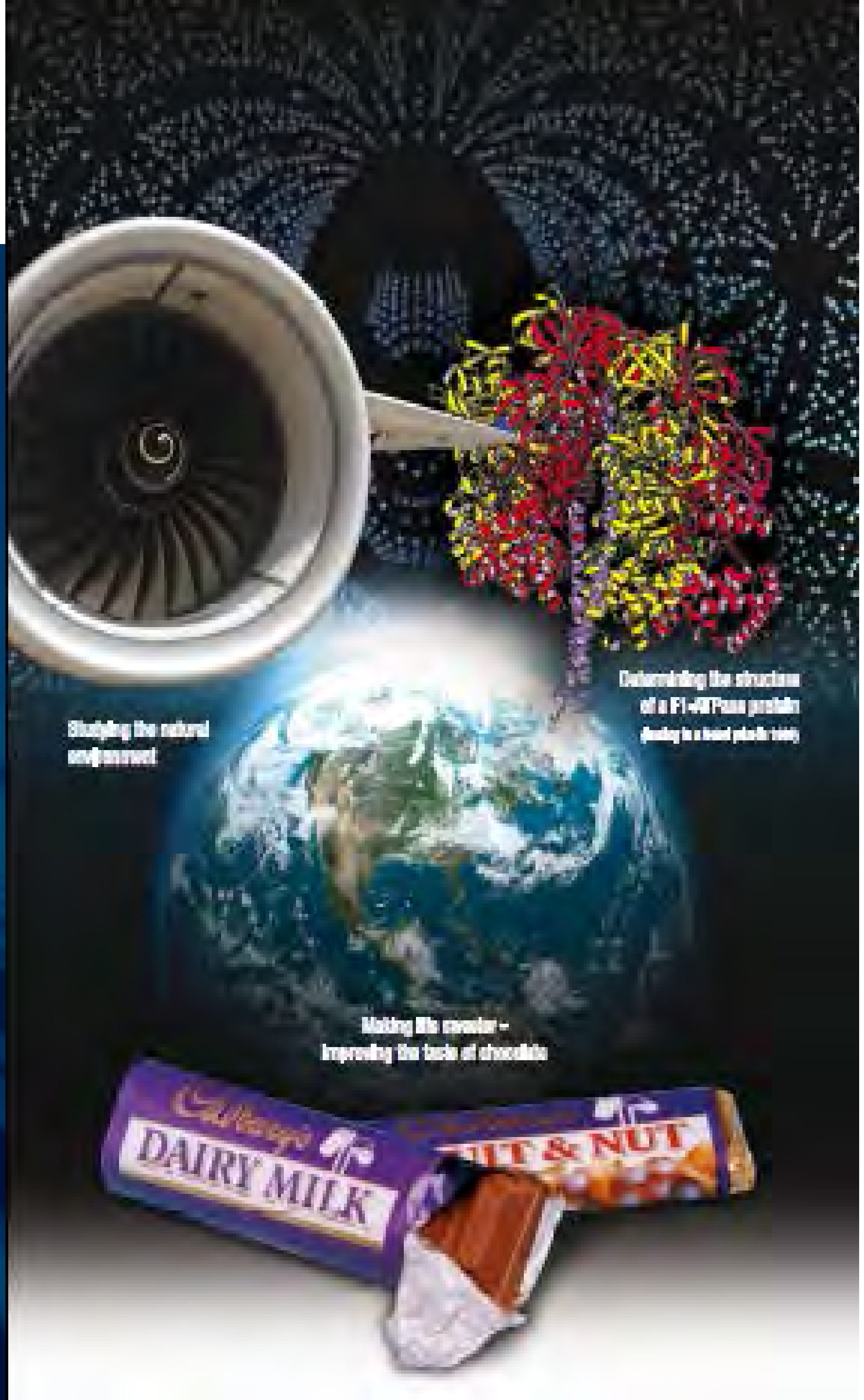
Accelerators for probing matter



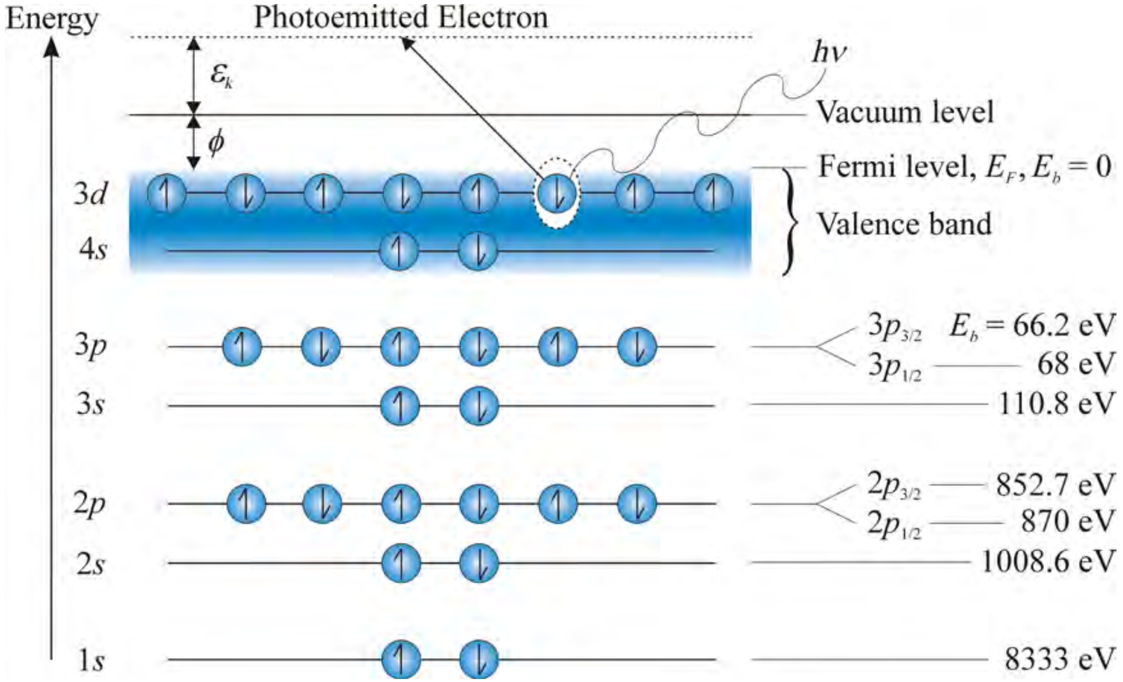
New X-ray and neutron sources are needed to study biology, chemistry and new materials

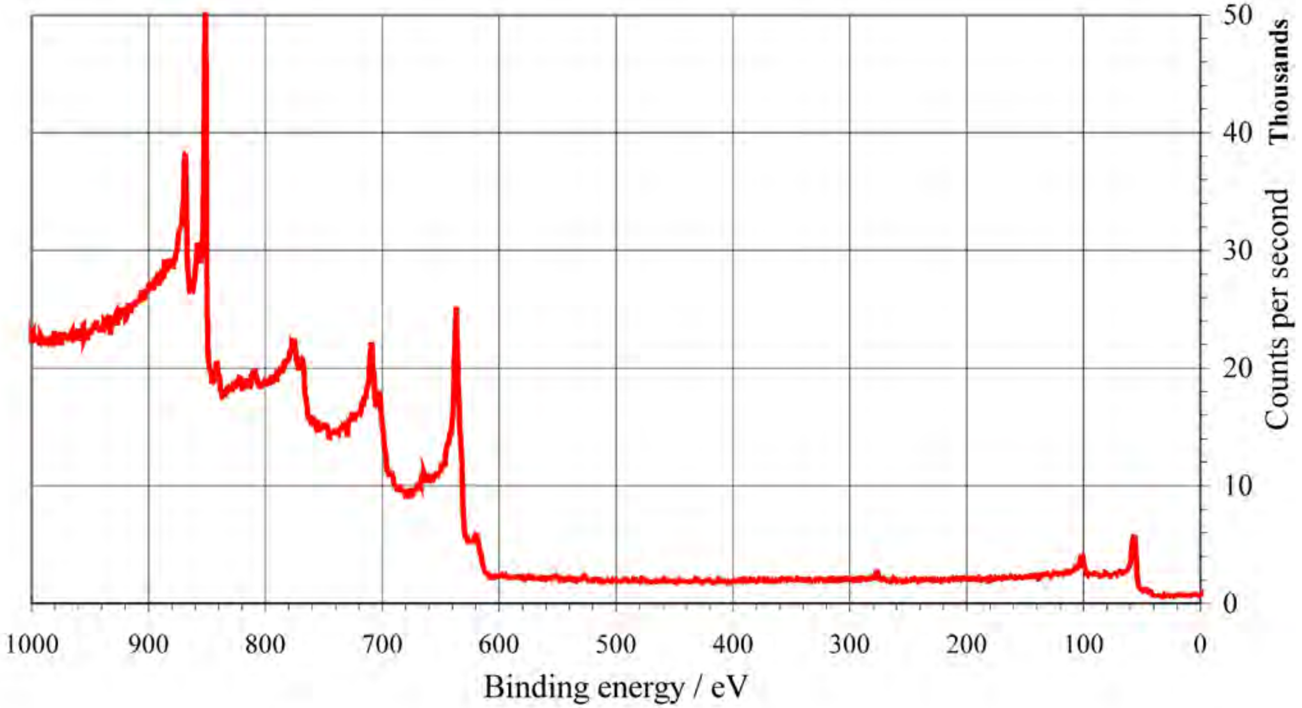
The UK is playing a lead role in

- ISIS Spallation source
- CLARA – UK FEL test facility
- ALICE – THz and IR source
- DIAMOND – The UK's light source

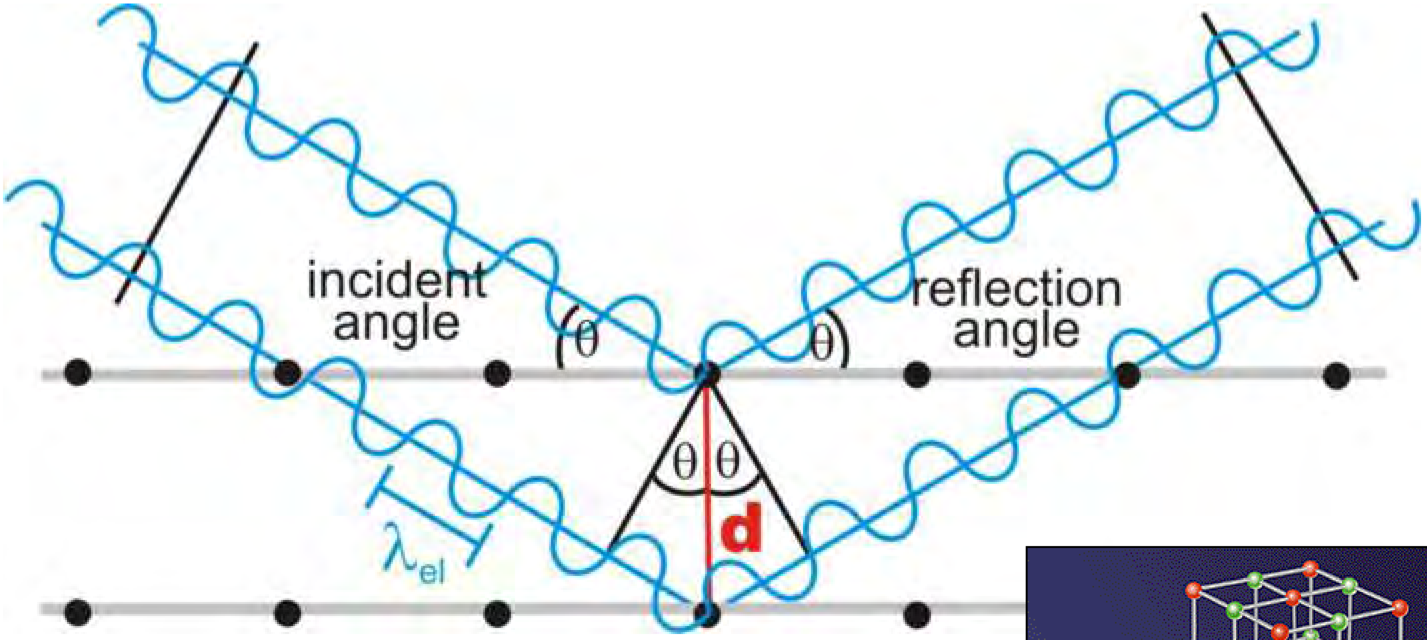


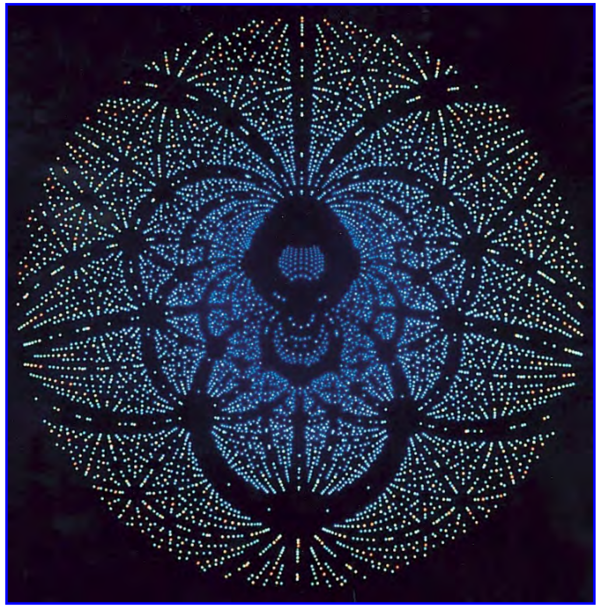
X-ray Photoelectron Spectroscopy (XPS):

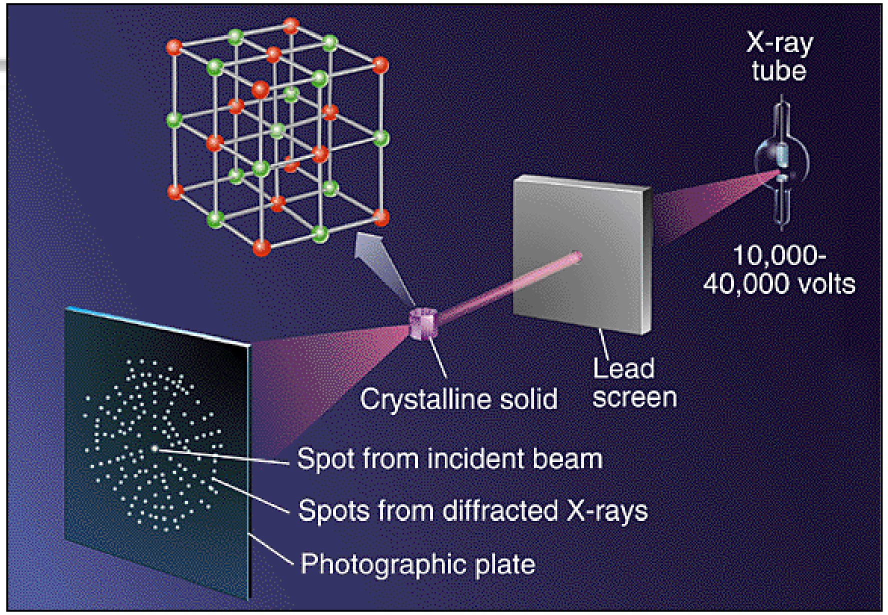




X-ray Diffraction (XRD):

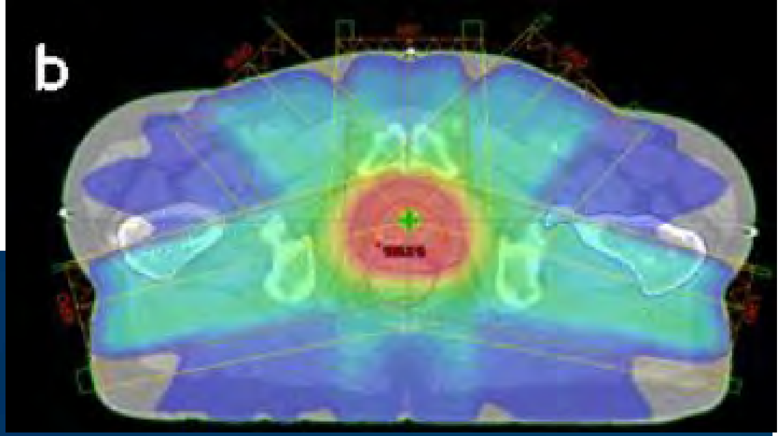






X-rays scatter of the crystal structure. They scatter at certain angles where the waves are in phase, dependant on the position of atoms.

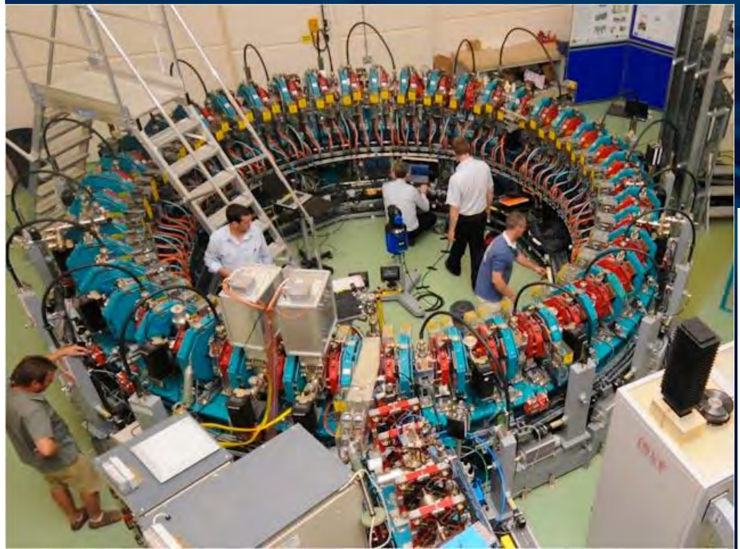
Accelerators for Medical, Energy and Security

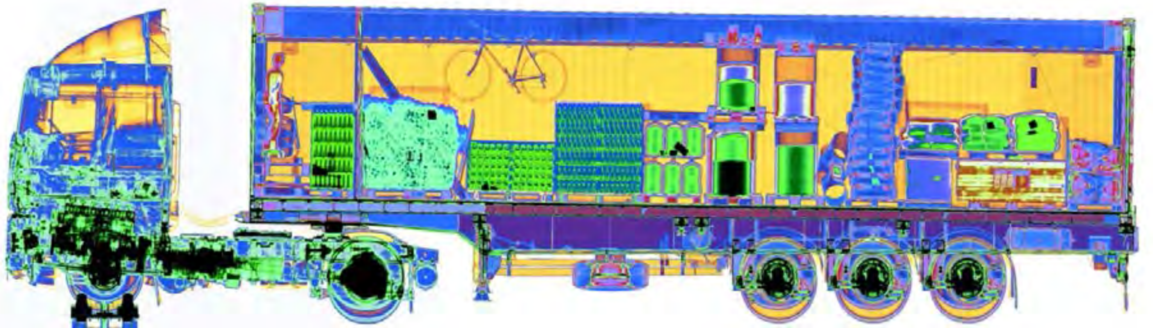


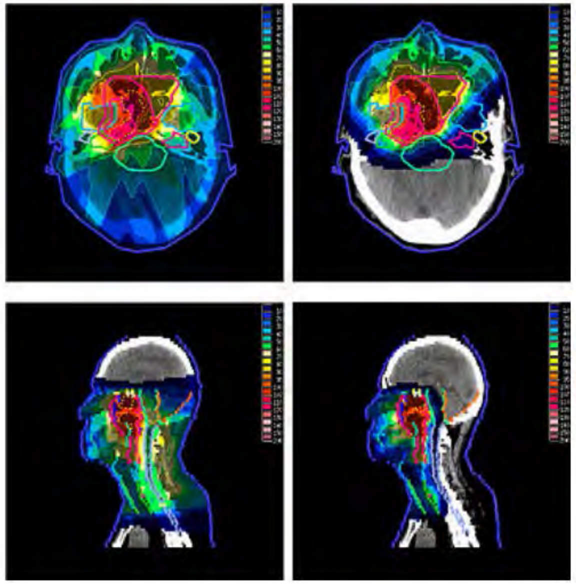
Accelerators can be used to produce X-rays, electrons and hadrons for

- Treatment of cancer with hadrons
- Radiotherapy
- Sub-critical nuclear reactors
- Scanning of cargo

The UK is developing a new generation of particle accelerators to meet the needs of these applications

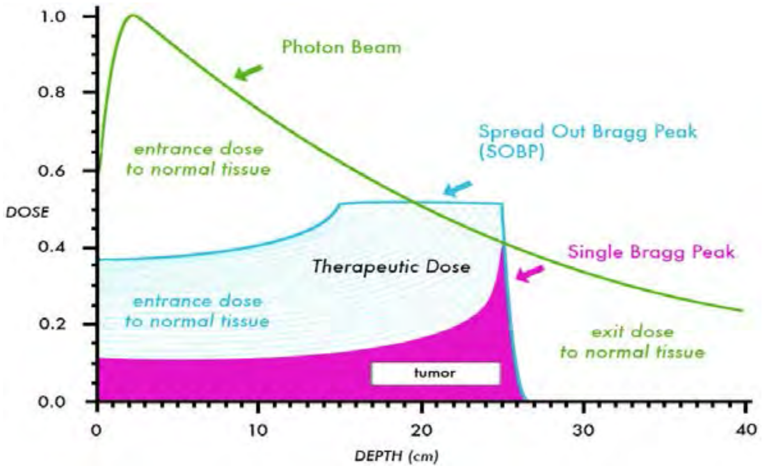




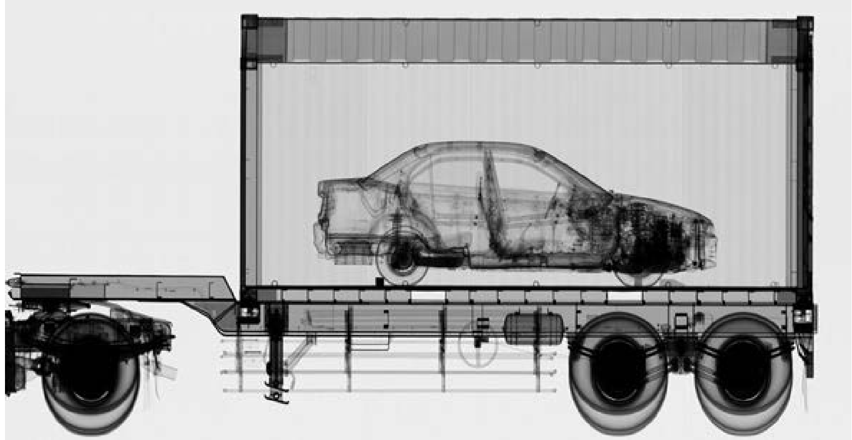


Proton therapy

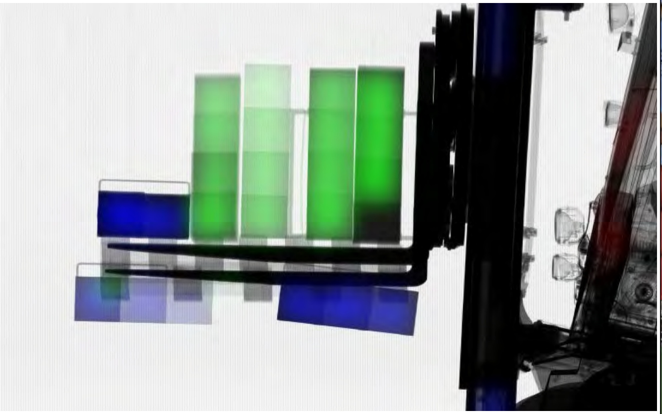
- Christie hospital in Manchester are building a new UK proton therapy centre.
- Maximum energy is deposited within the tumour site with minimal energy deposited in healthy tissue.



Cargo screening

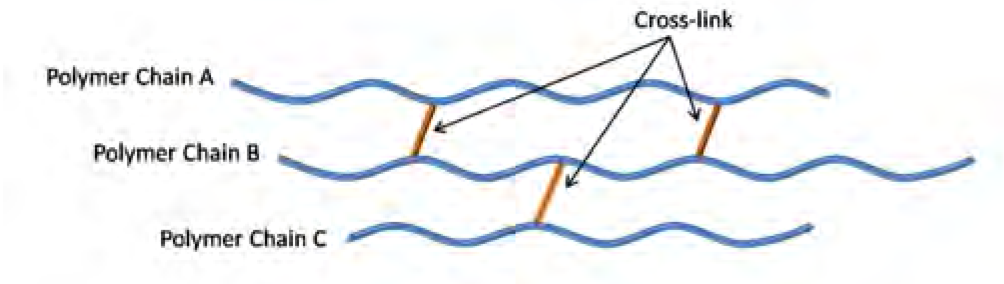


- A major use is in cargo screening to ensure that what is in a shipping container is what is in the manifest and not cash, drugs, gold, uranium, cigarettes or cars.



Cross-linking

- Cross-linking is the process of bonding polymer strings together.
- They can be covalent bonds or ionic bonds. "Polymer chains" can refer to synthetic polymers or natural polymers (such as proteins).
- The effect of this is to make the polymer stronger and heat resistant. This is often used to make cable insulation that doesn't melt.
- It can also make them insoluble.
- It can also be used to make the polymer shrink when heat is applied. This process is used to wrap most chickens, turkeys, pizza etc as well as lots of electronics and tamper proof packaging.



Curing

- In EB curing chemical are added to cure inks and coatings.
- The ink is made of monomers and short chain polymers that are cross-linked by the beam to solidify them instantly.
- This uses 100 times less energy that water-borne drying and as no material is evaporated there are no volatile organic compounds (VOCs)
- In addition as it isn't a thermal mean of drying it can take place at ambient temperatures which is required for most plastics and heat sensitive films.
- It is similar to UV curing but has the ability to penetrate pigments.
- A typical use is in printing cereal boxes.

Electric Fields and Particles

The rate of change of the potential (voltage) between two plates is known as the electric field.

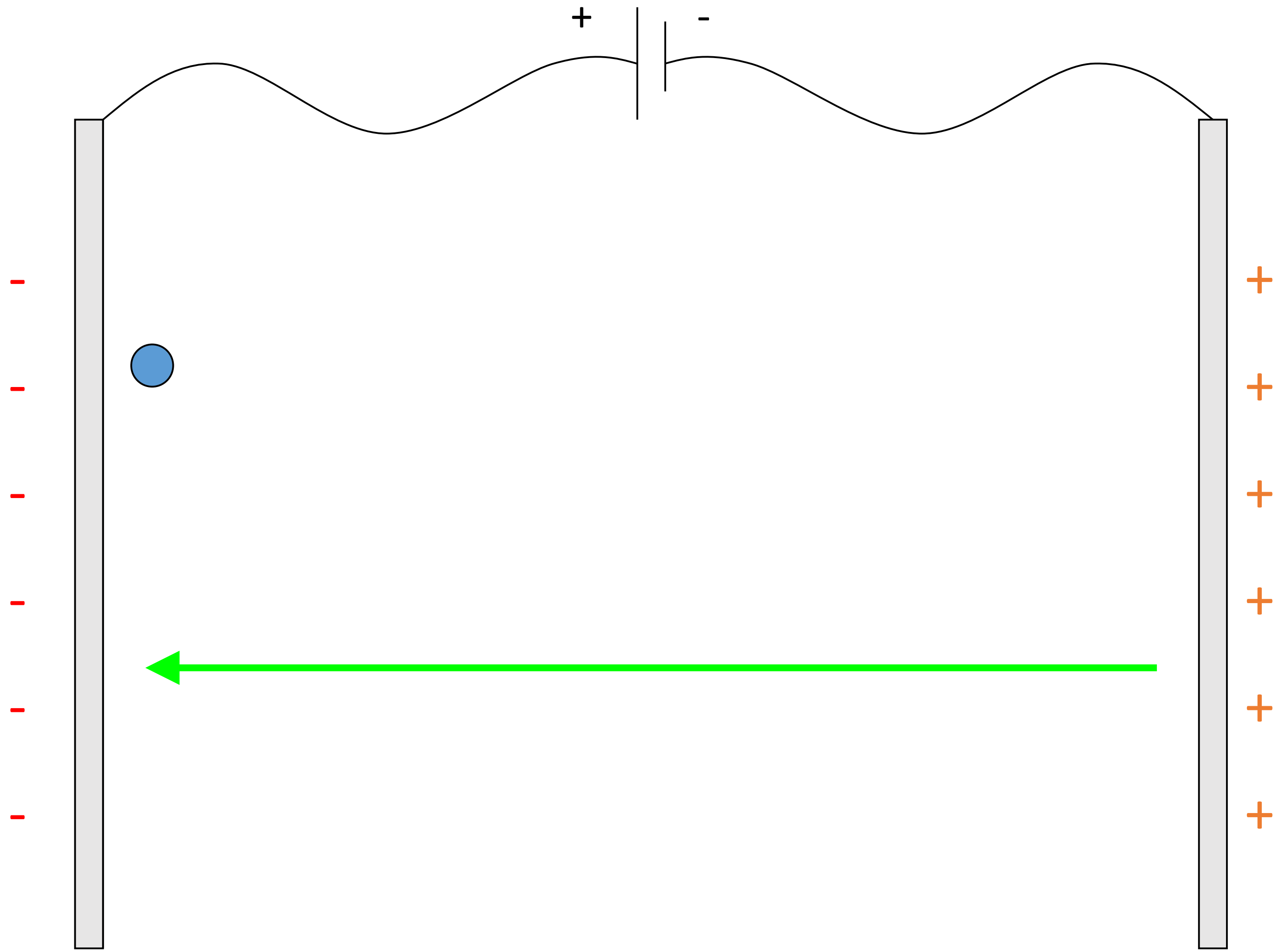
An electron in an electric field created by applying a voltage across two plates will experience a force

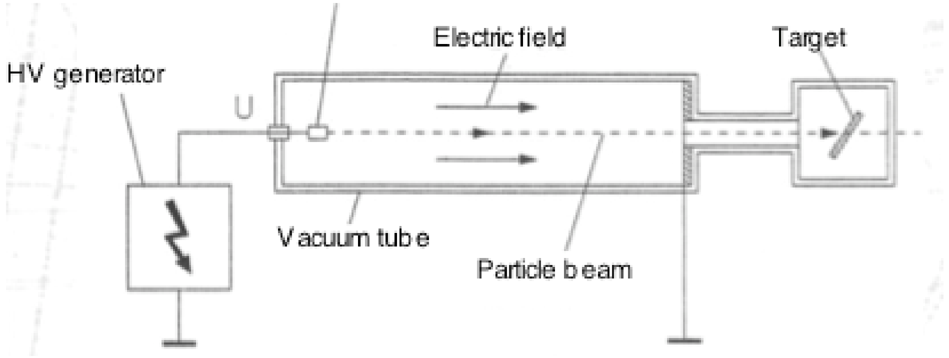
$$F=eE$$

This force will accelerate the particle to faster velocities and higher energies.

The energy change of an electron leaving the accelerating region (in eV), will be the equal voltage between the plates (times the charge of the electron)

Electrostatic Acceleration





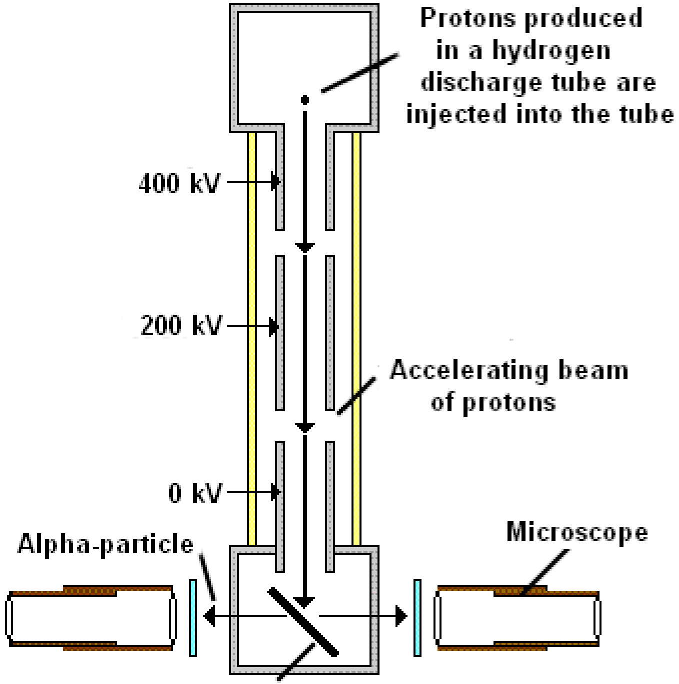
Just like the electron guns used in RF sources.

Fields limited by electrical breakdown effect to few MV -> few MeV electrons

Walton, Rutherford, Cockcroft - 1932

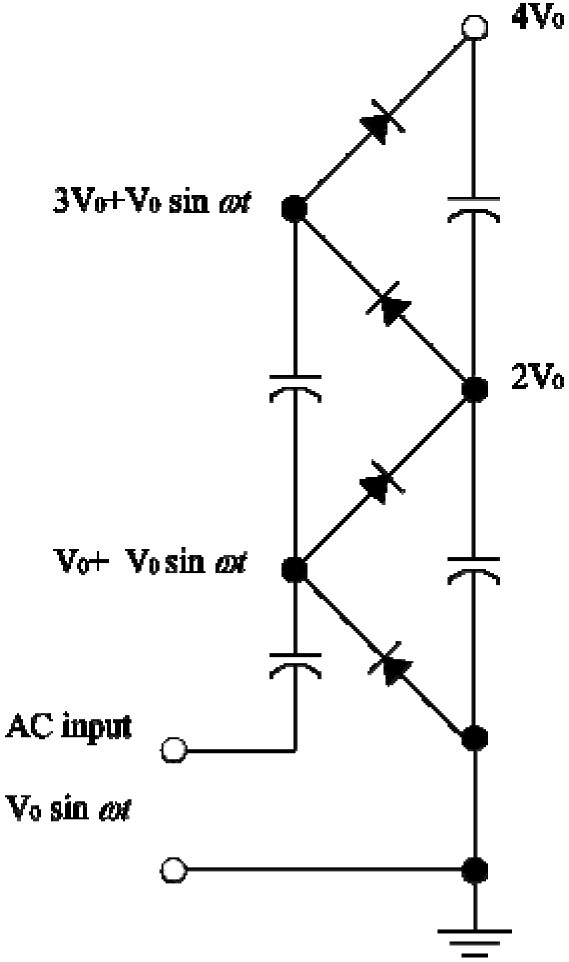
Start of the modern era – particle accelerators

NOBEL PRIZE !



Cockcroft-Walton

- Since we are in the Cockcroft Institute Walton Rooms no review of DC accelerators would be complete without mentioning the Cockcroft-Walton.
- This is a simple voltage multiplier where a AC voltage charges capacitors in parallel so each stage provides a potential of $2V_{0.}$
- The first capacitor charges on an anti-clockwise current and on a clockwise loop the 2nd capacitor is charged by both the source and the discharging first capacitor
- Adding more stages increases the voltage until the breakdown voltage is reached.



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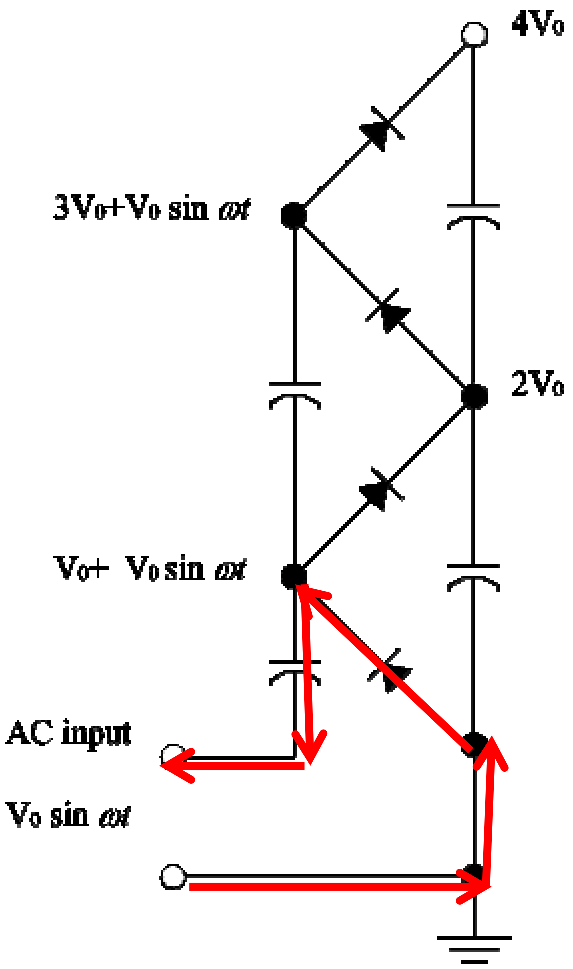

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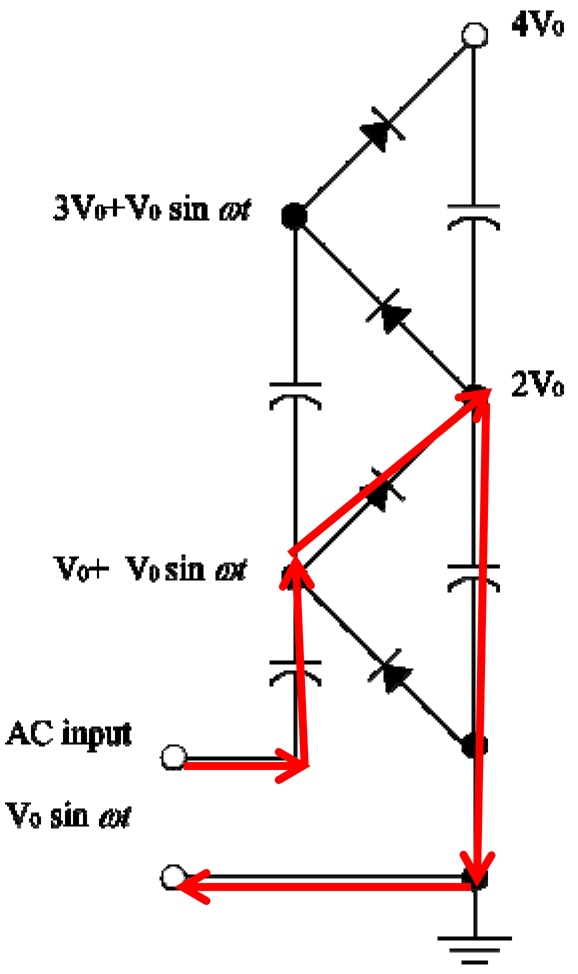
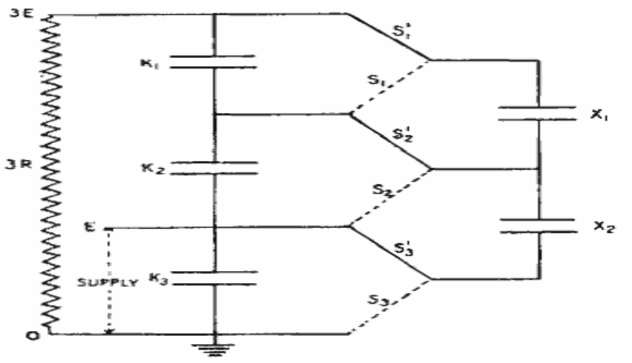


Cockcroft-Walton Generator

ISIS **665 kV**

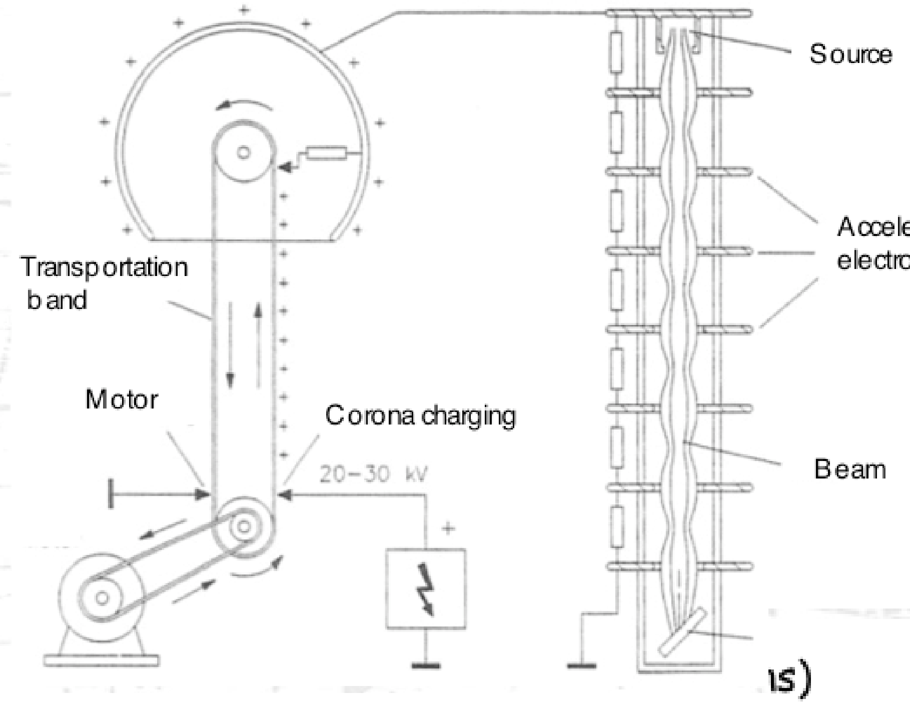
Removed 2005

See our Atrium !



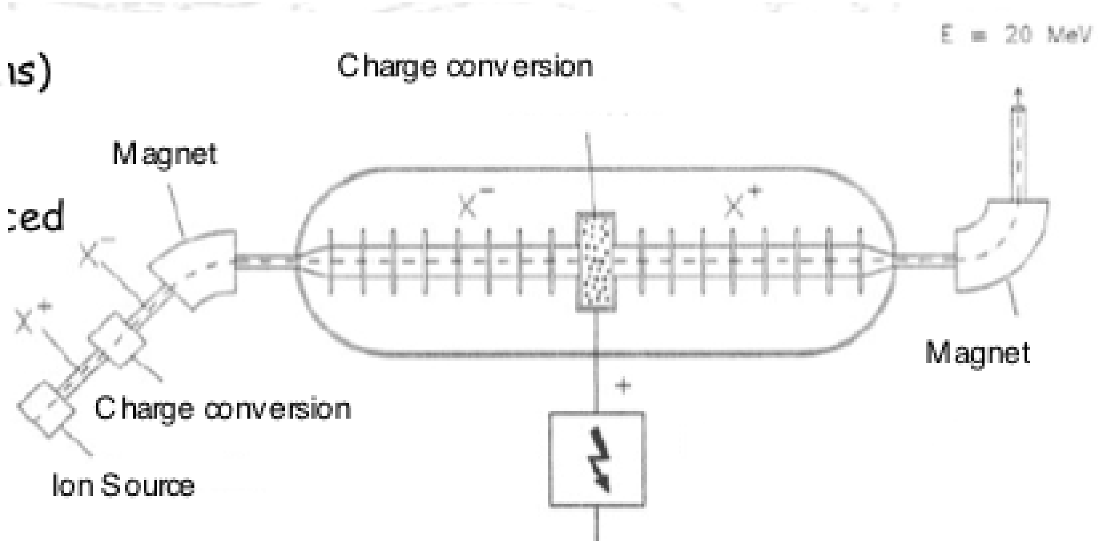
Greinacher 1921

Van-de Graaff - 1930s

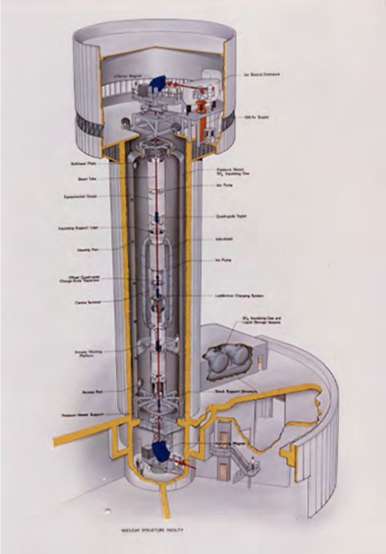


A standard electrostatic accelerator is a Van de Graaf

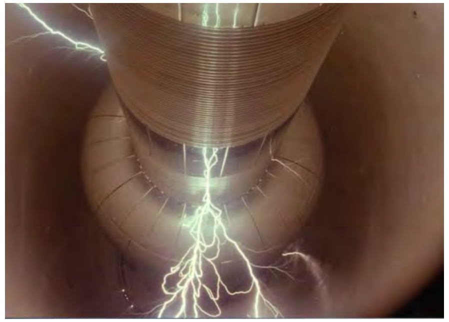
These devices are limited to about 30 MV by the voltage hold off across ceramic insulators used to generate the high voltages (dielectric breakdown).

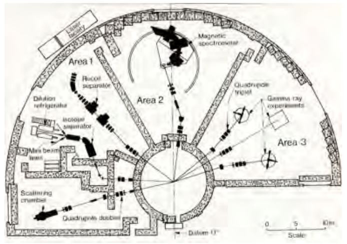


Daresbury Nuclear Structure Facility (NSF)



20+ MV **world record**





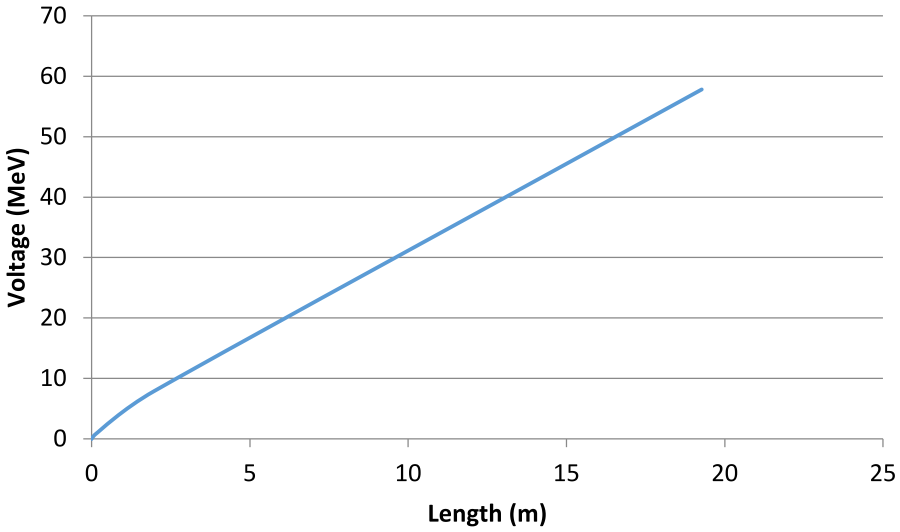
Operational 1983 - 1992

Note: Liverpool 6 MeV machine in 1961 (+ Manchester)

Kilpatrick Criterion

- The breakdown (max) voltage for electrostatic accelerators is given by the Kilpatrick criterion. Above this voltage a plasma forms

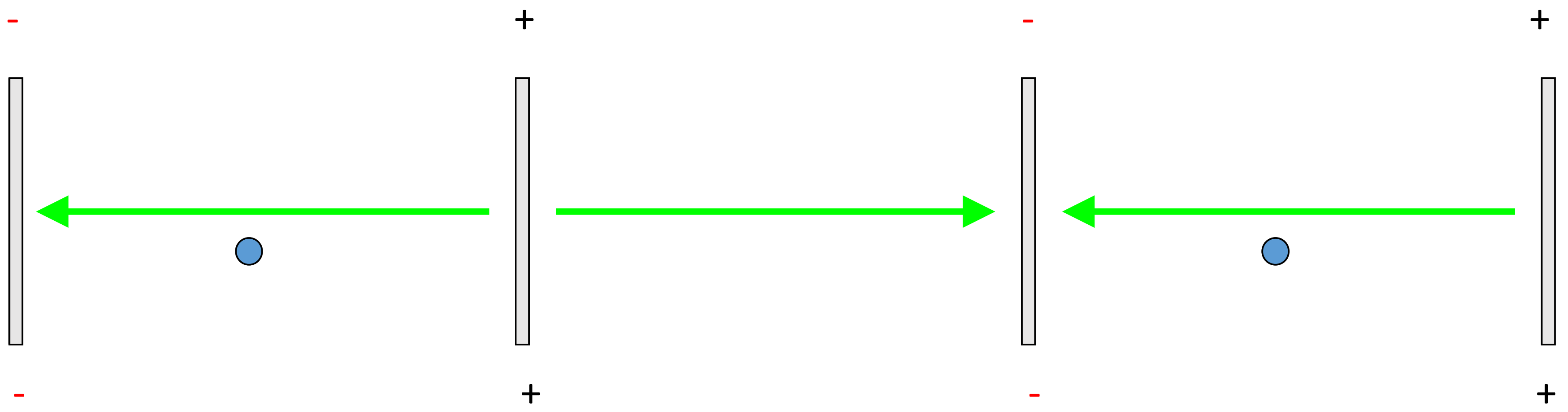
$$VE^2 \exp\left(-\frac{1.7\times10^7}{E}\right) \le 1.8\times10^{18}$$



DC accelerators are very simple but the achievable gradient is very low for voltages above 10 MeV (around 3 MV/m).
Higher gradients are possible for smaller gaps and hence lower voltages.
In addition it is difficult to generate the high voltage in the first place.

RF Acceleration

By switching the charge on the plates in phase with the particle motion we can cause the particles to always see an acceleration

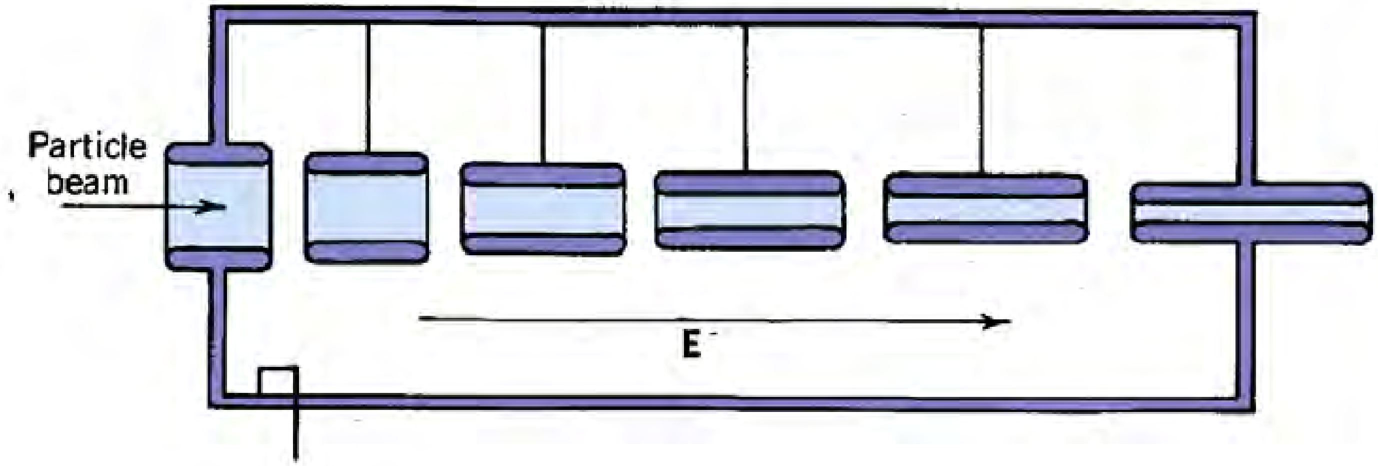


You only need to hold off the voltage between two plates not the full accelerating voltage of the accelerator. Gradients of 20-100 MV/m are possible.

Early Linear Accelerators (Drift Tube)

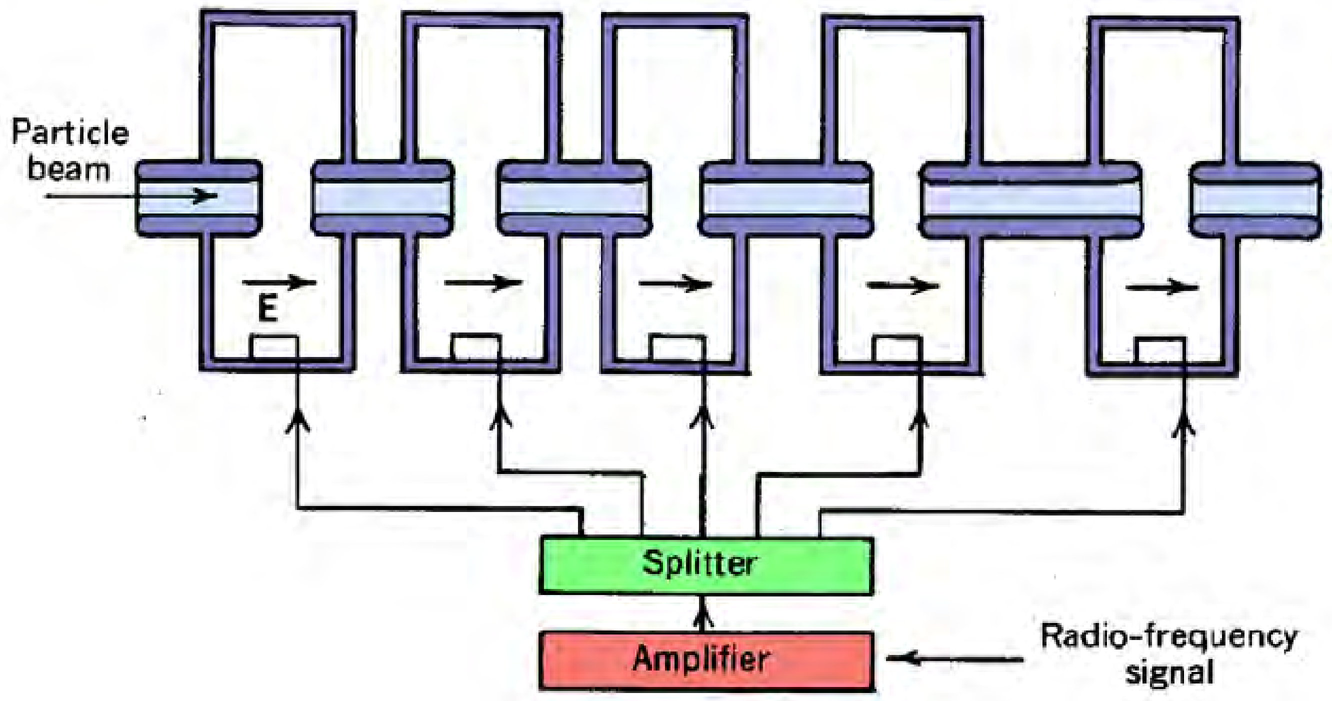
- Proposed by Ising (1925)
- First built by Wideröe (1928)
- Alvarez version (1955)

Replace static fields by time-varying fields by only exposing the bunch to the wave at certain selected points. Long drift tubes shield the electric field for at least half the RF cycle. The gaps increase length with distance.
More on these later.



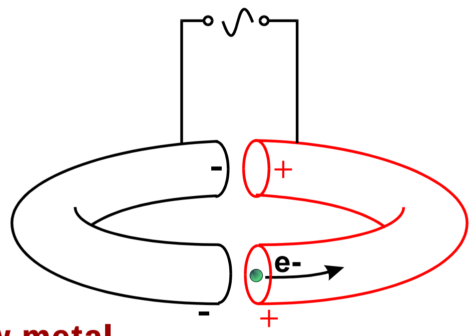
Cavity Linacs

- At high β it is more efficient to use cavities so that you do not need to waste space with long drift tubes.
- If individually powered the phase can be individually set for each cavity.



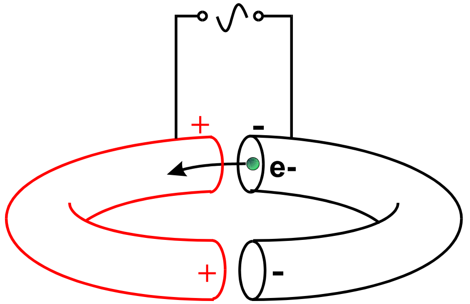
Recirculation Concept - Cyclotron

Radio frequency alternating voltage

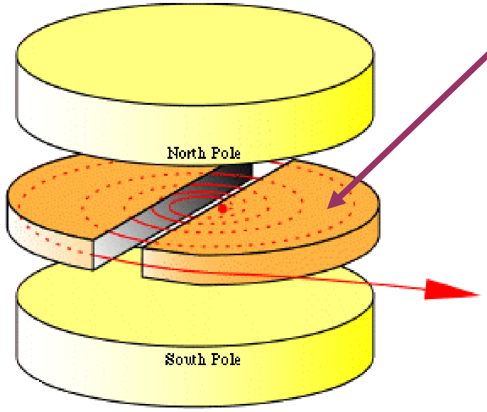


time t =0

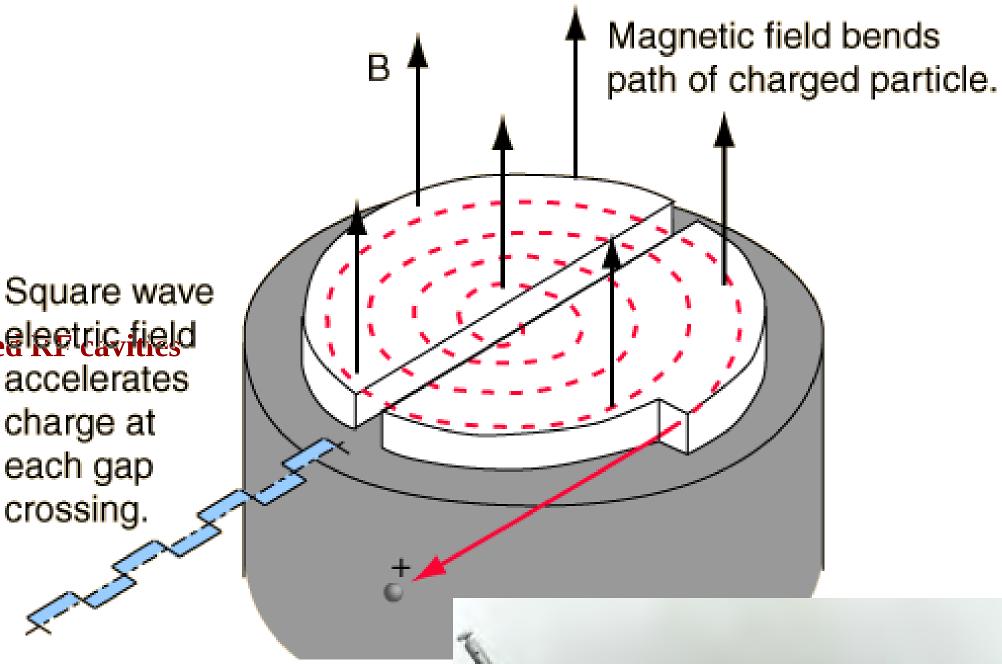
Hollow metal drift tubes



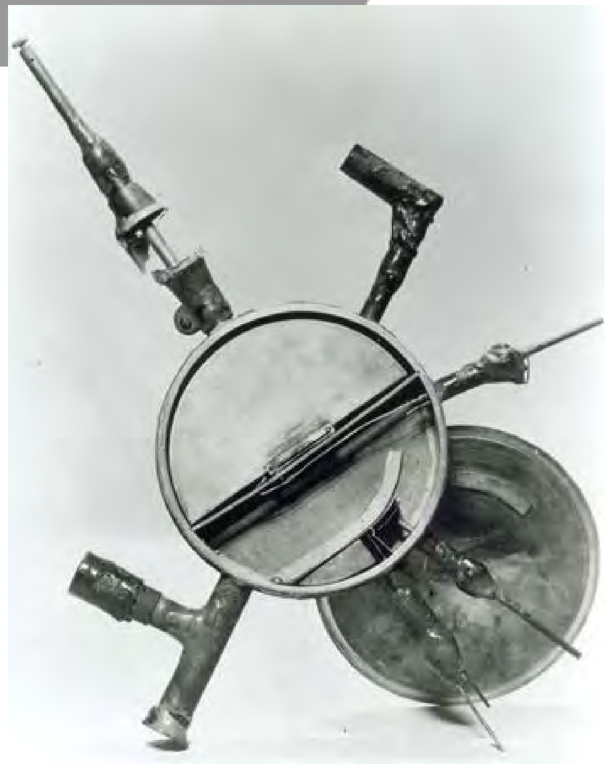
time t =½ RF period



D-shaped RF cavities



Lawrence:
4" – 80 keV
11" - 1.2 MeV



$$q\,v\,B = mv^2 / r$$

$$r = mv / qB$$
$$T = 2\pi m / qB$$

Automatic Synchronisation

Orbit radius increases with energy

Expensive/impractical for high energies (1 GeV)

Accelerator Developments

- High energy Cyclotrons have huge magnets - spiral orbits
- Also problem of relativistic mass increase: desynchronises

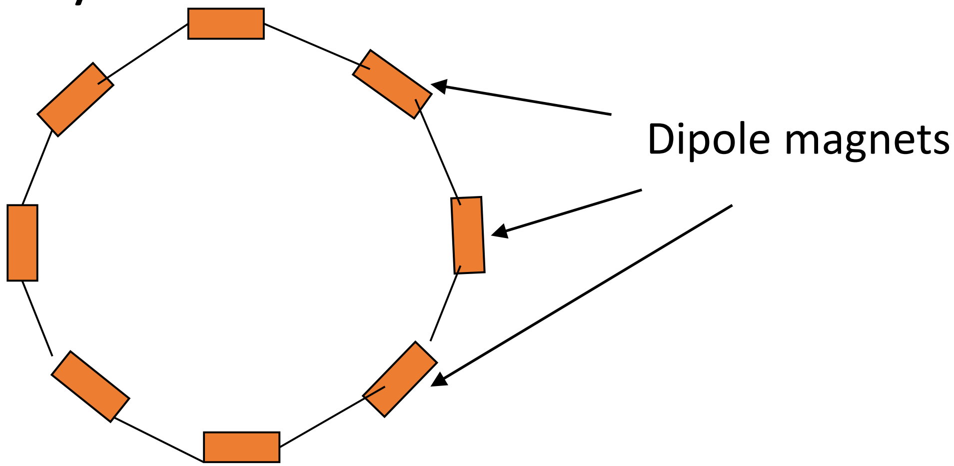
  (some help from FM synchrocyclotron)

- Solution:

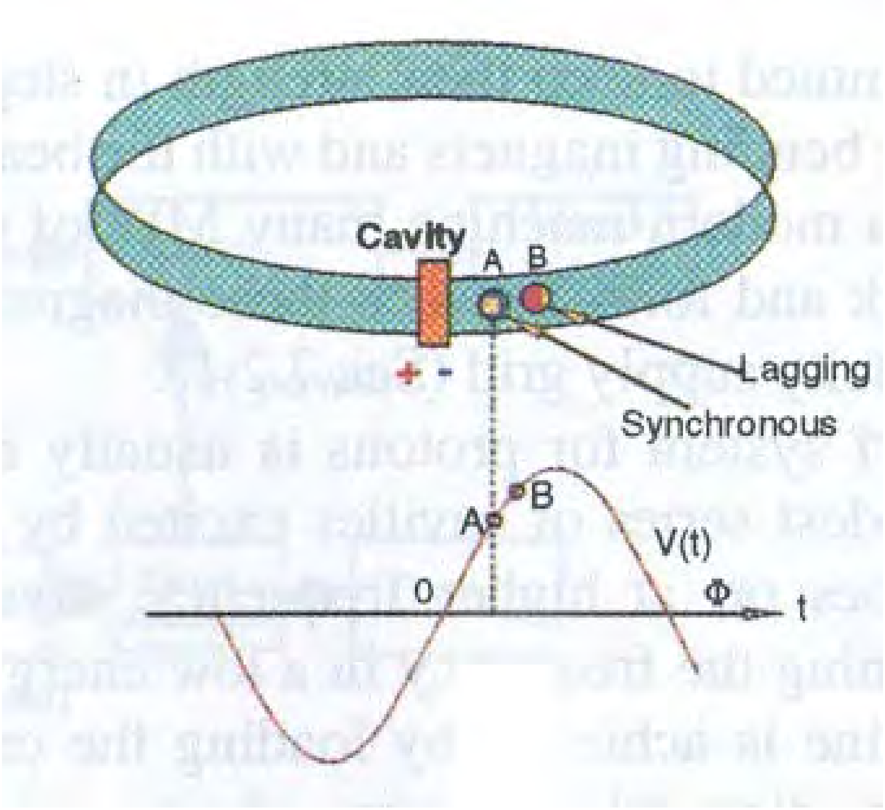
  Raise magnetic field strength as particle energy increases by using separate small magnets so that beam takes a single trajectory

  Produces annular orbit geometry

SYNCHROTRON



Phase Synchronism



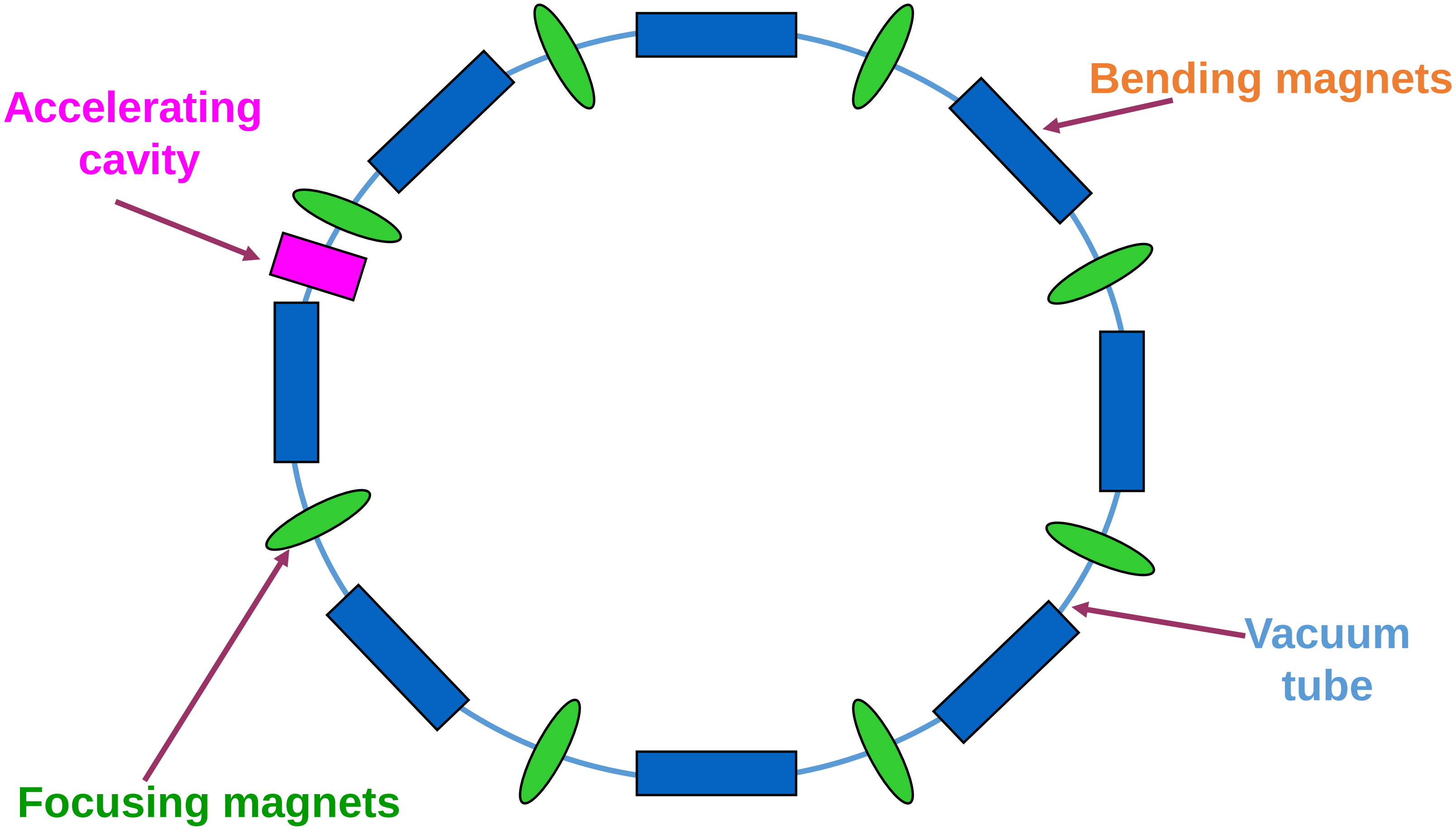
Synchronous particle (A) crosses cavity after one turn at same phase relative to RF peak

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 BUNCHING about A**

Synchrotron Ring Schematic

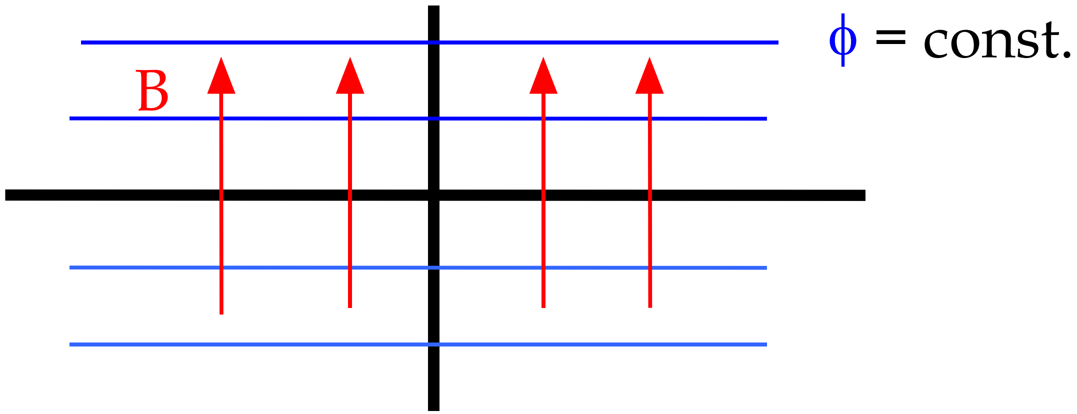


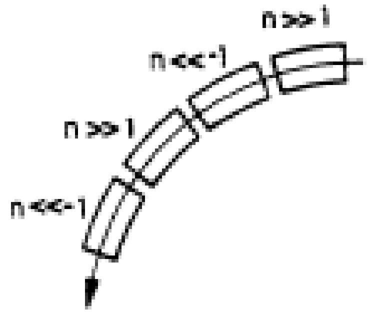
Bending and focussing often combined

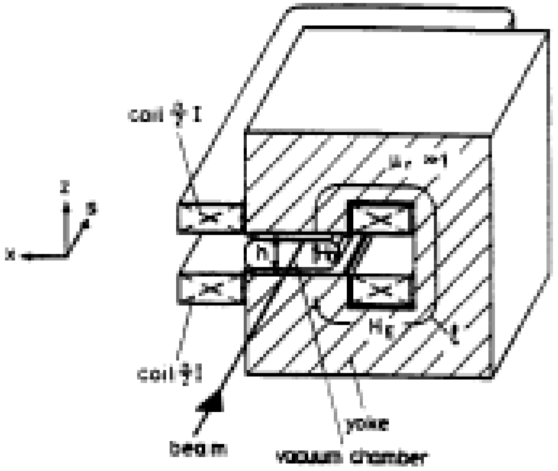
Dipole field: n = 1

Dipole magnets have a constant vertical B field causing the beam trajectory to bend in the horizontal plane.

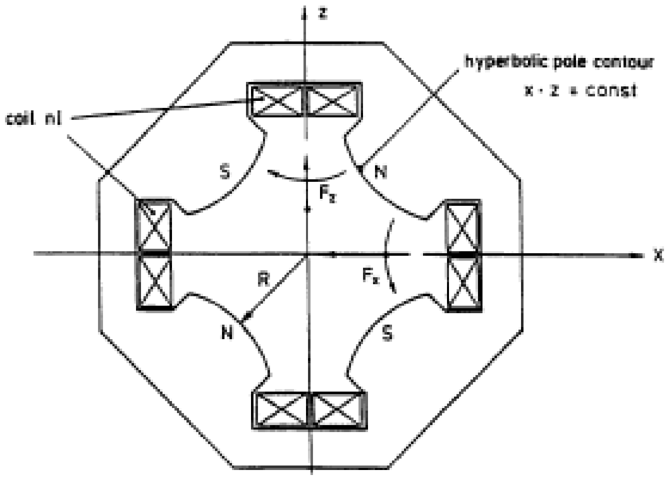
$$F = e\left(E + v \times B\right)$$







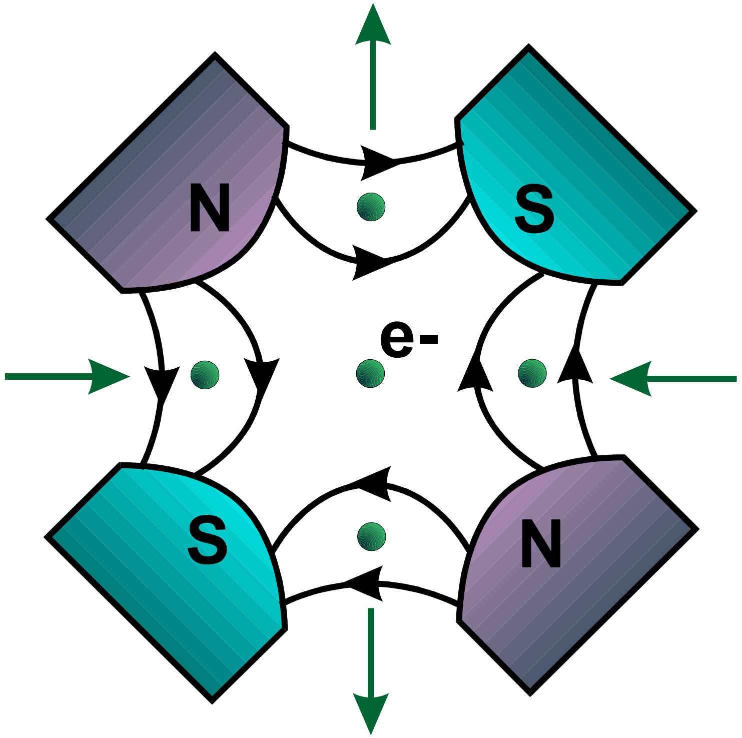
Quadrupole field: n = 2

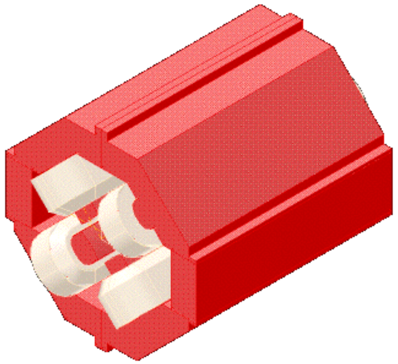


A Quadrupole magnet is focussing in one plane and defocussing in the other.

The force experiences is proportional to the particle offset.

Quadrupole magnets are used to focus the beam. Solenoids are not used as they would couple the x and y planes.





FoDo Lattice

- As the quadrupoles are only focussing in one plane we must alternate the magnets. One popular configuration is the FoDo lattice. This gives an overall focussing because the beam on average has a larger offset in the focussing magnets.

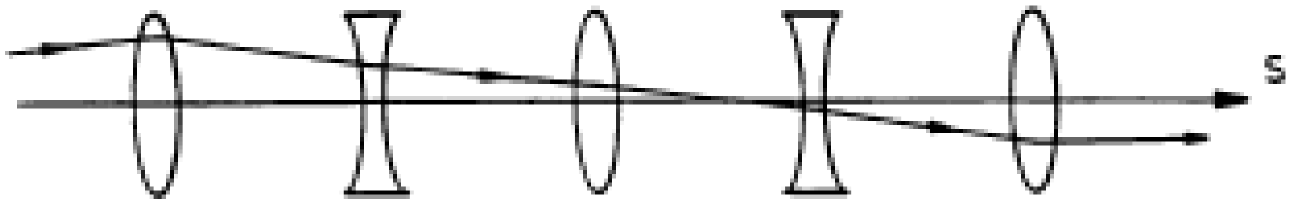
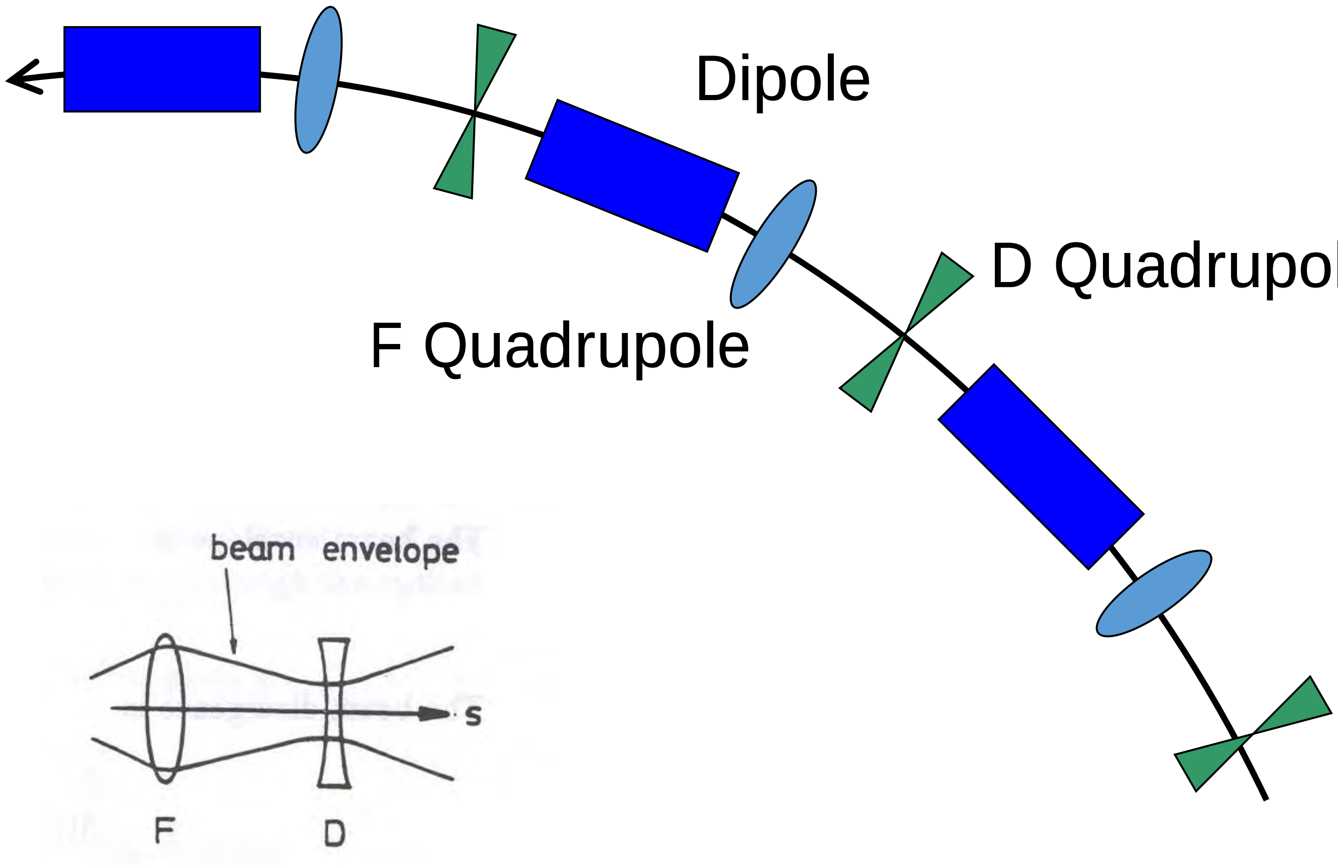


Figure 6: An alternating series of focusing and defocusing lenses leads to overall focusing if the distances between the lenses are not too large.

Simple Accelerator Lattice

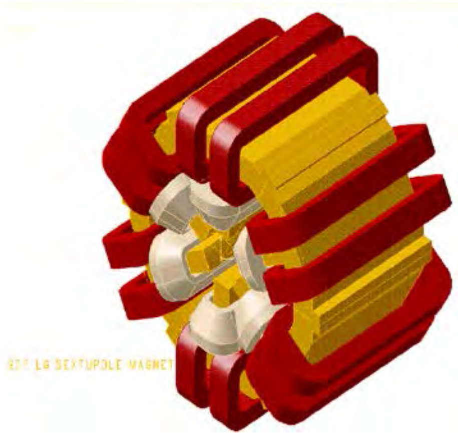


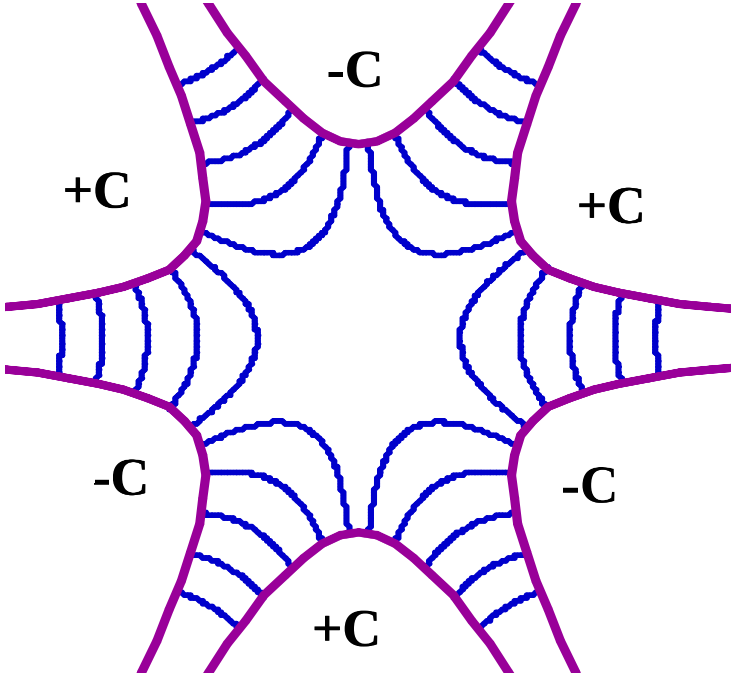
FODO Cell

Challenge: finite dispersion

Sextupole field: n = 3

Sextupole magnets are used to correct for chromaticity. This is when the path taken by each particle varies with its energy. Mostly affects offset (hence off momentum) particles





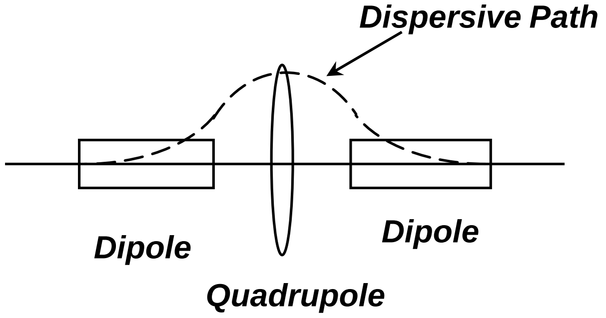
The sextupole magnet gives the lattice a constant focal length as a function of energy over a finite energy range.

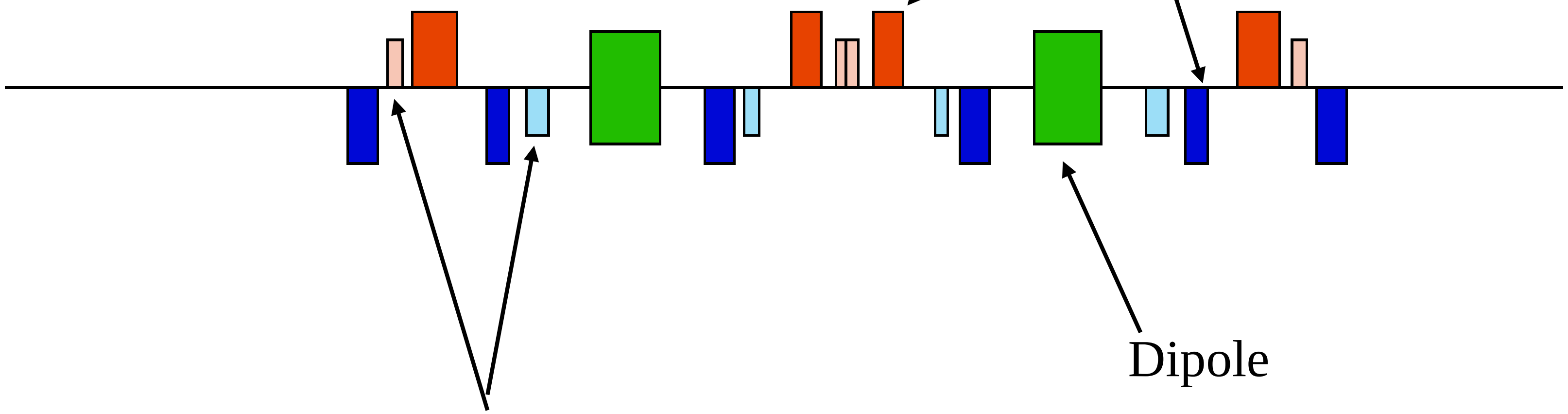
Line of constant scalar potential

Lines of flux density

$$B \sim x^2$$

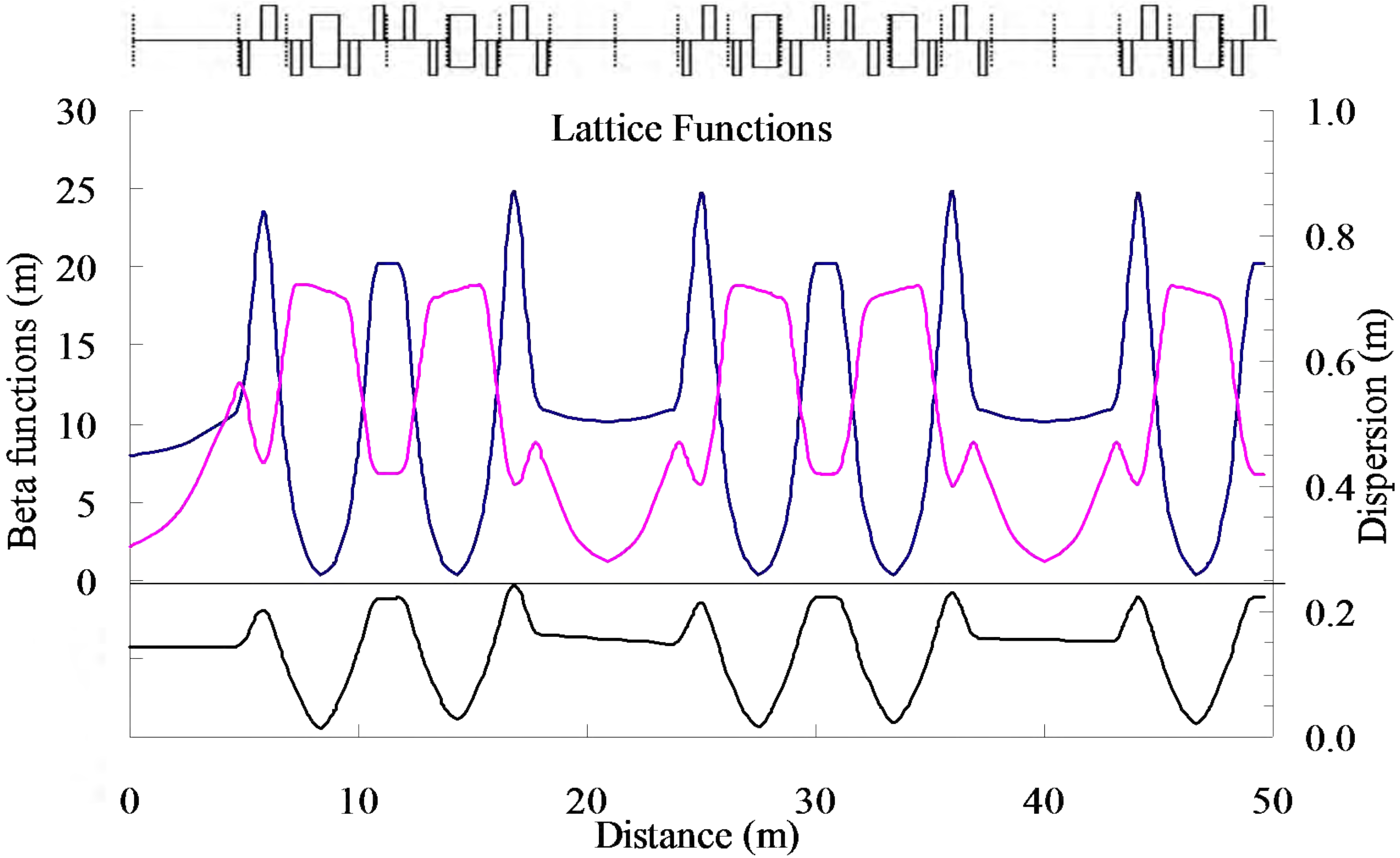
The Double Bend Achromat Cell





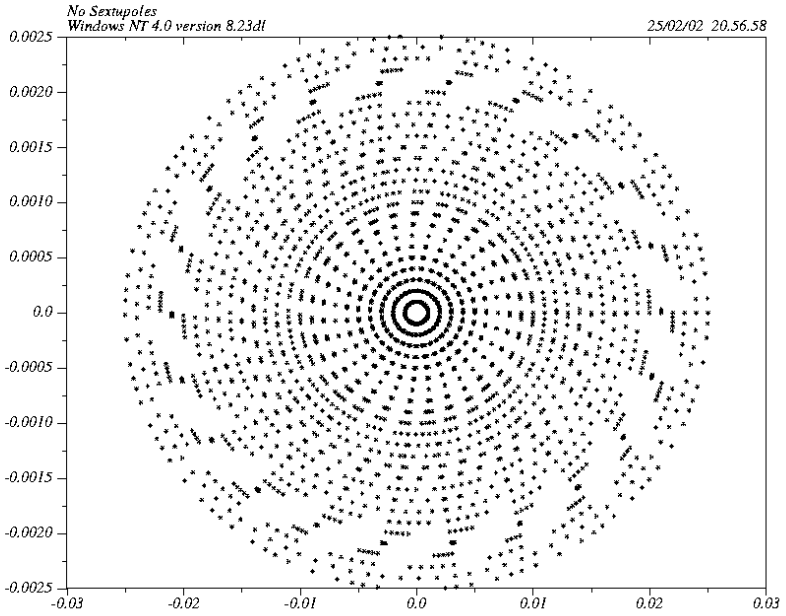
Non - Dispersive

Lattice Functions - DBA Example

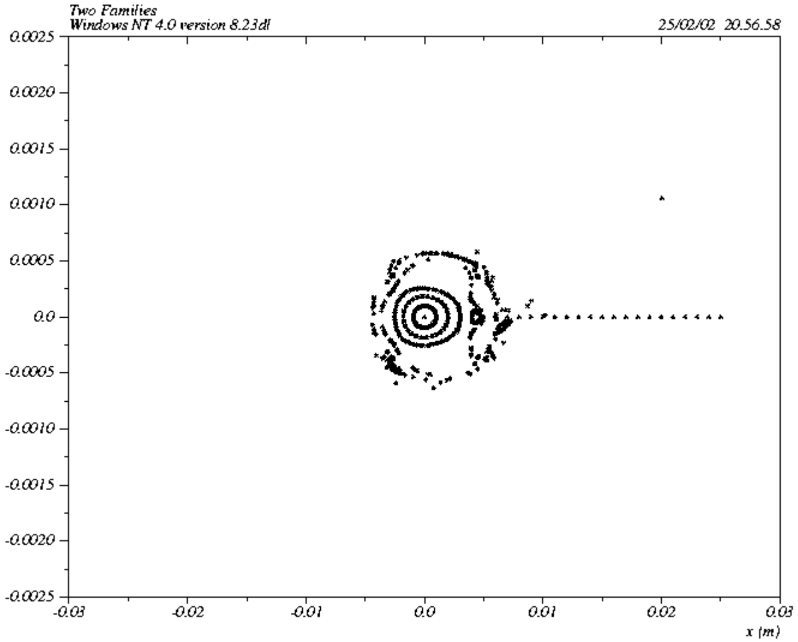


Penalty: Collapse of Dynamic Stability

Available aperture for beam

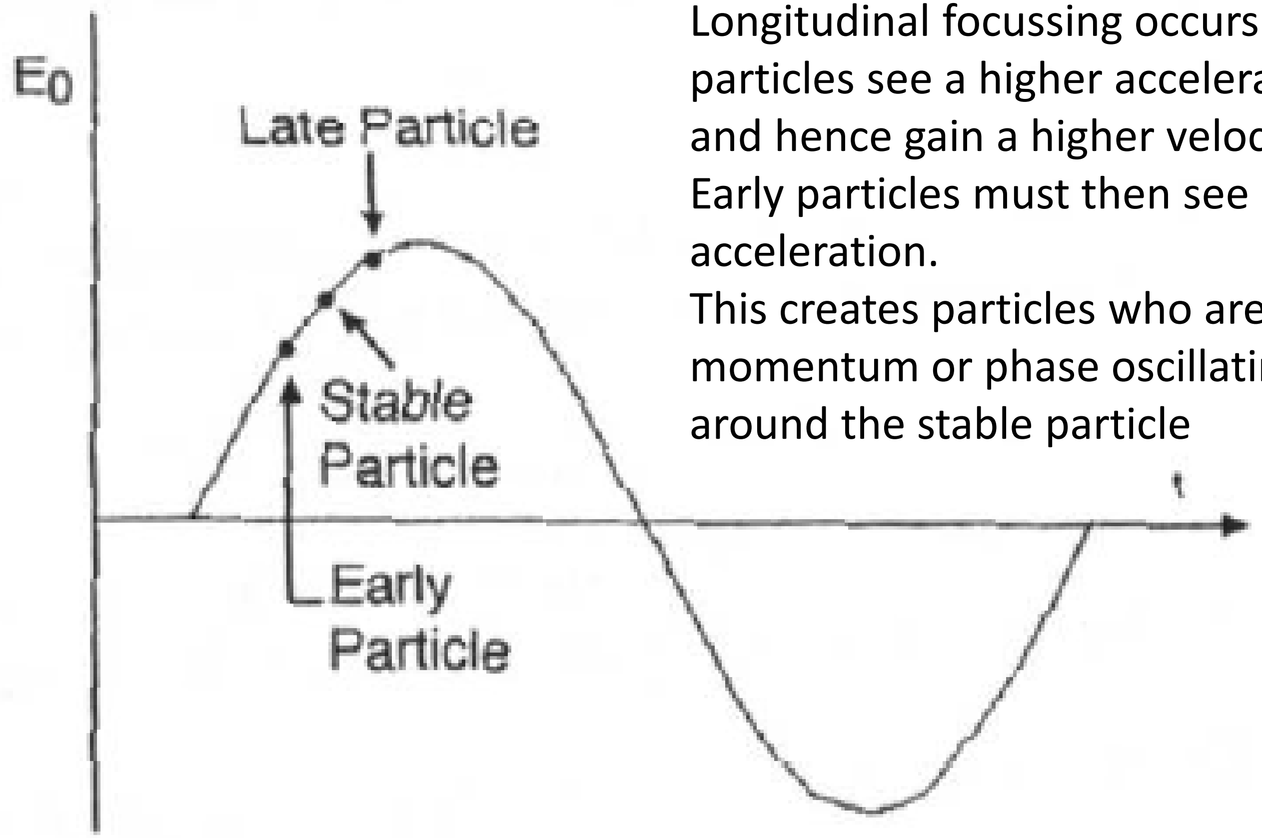


No sextupoles

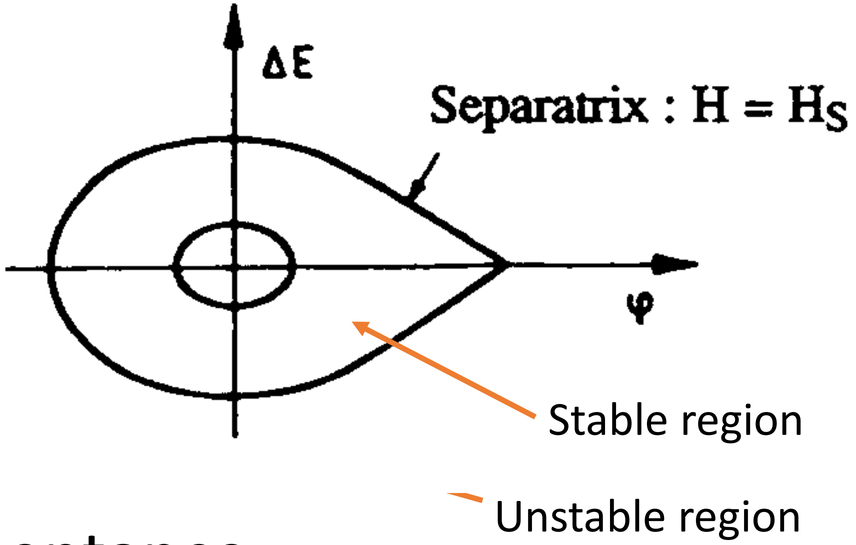


Corrected to zero chromaticity by single magnet family

Longitudinal Focussing



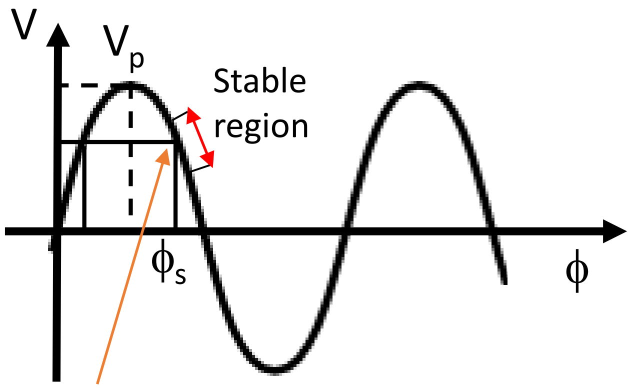
Longitudinal focussing occurs if late particles see a higher acceleration, and hence gain a higher velocity. Early particles must then see less acceleration.
This creates particles who are off momentum or phase oscillating around the stable particle



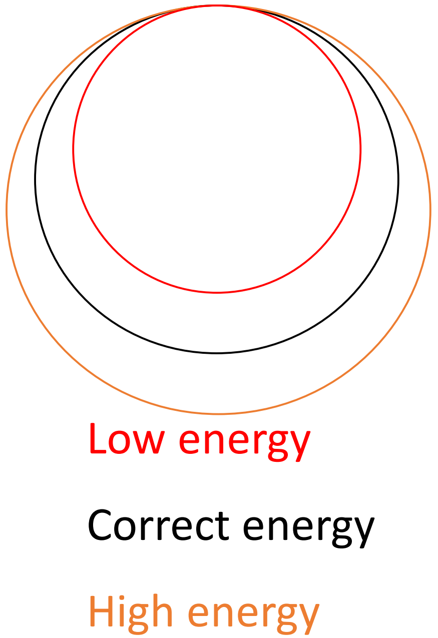
- Particles with energies outside the energy acceptance ΔE drop out of the RF bucket.

Momentum Compaction

- A particle which arrives early/late will receive a different acceleration than a synchronous particle.
- At low energies, the more energy a particle has the faster it travels.
- At high energies the speed is constant but the path around the ring will be longer as the larmour radius increases.



Phase stability is given by off-crest acceleration



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:

$$P \quad \alpha \quad E^4/R^2$$

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

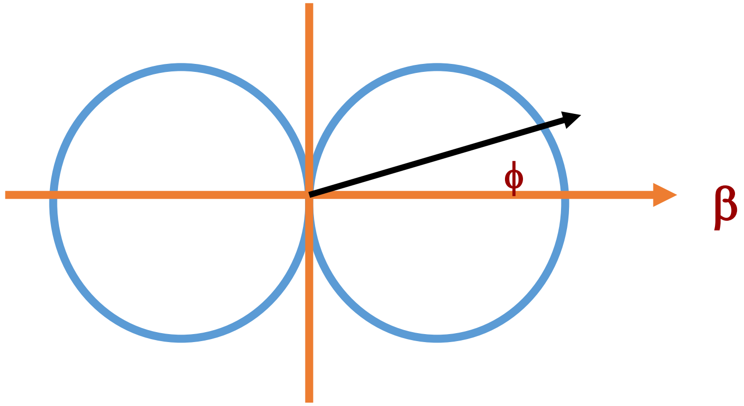
SYNCHROTRON RADIATION

=> Severe losses and energy restrictions

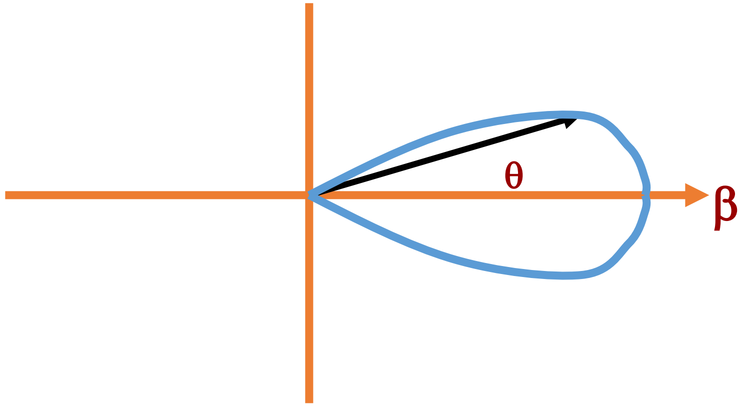
eg NINA

Relativistic Emission

Electron rest frame



Laboratory frame



Transforming between frames

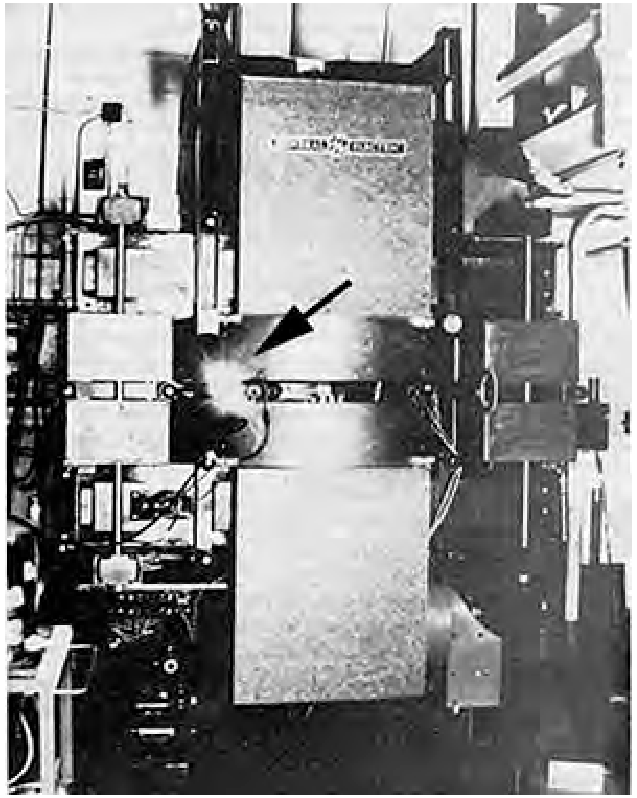
$\tan\theta = \gamma^{-1}\sin\phi\,(1 + \beta\cos\phi)^{-1}$

Relativistic Emission Cone

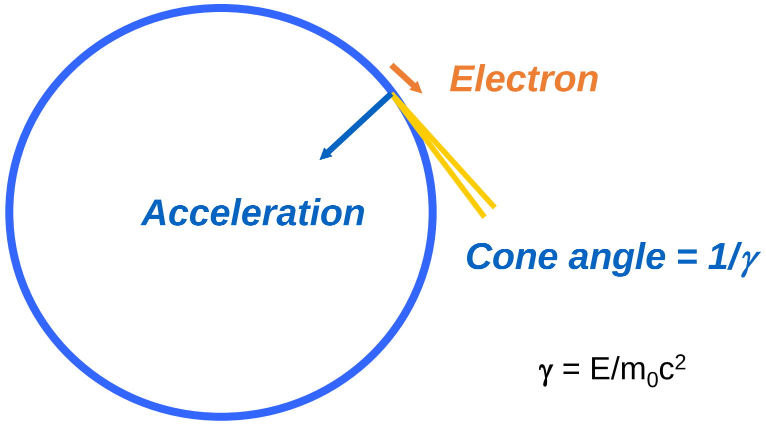
if $\phi = 90^0$

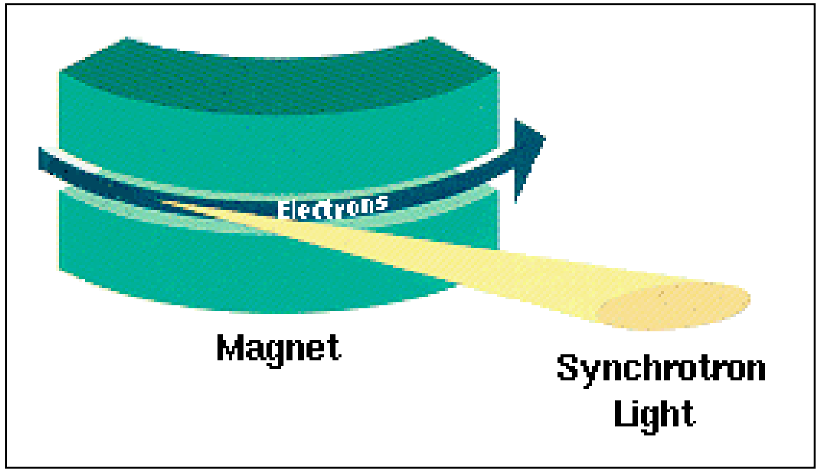
then: $\theta = \gamma^{-1}$

Emission from Bends

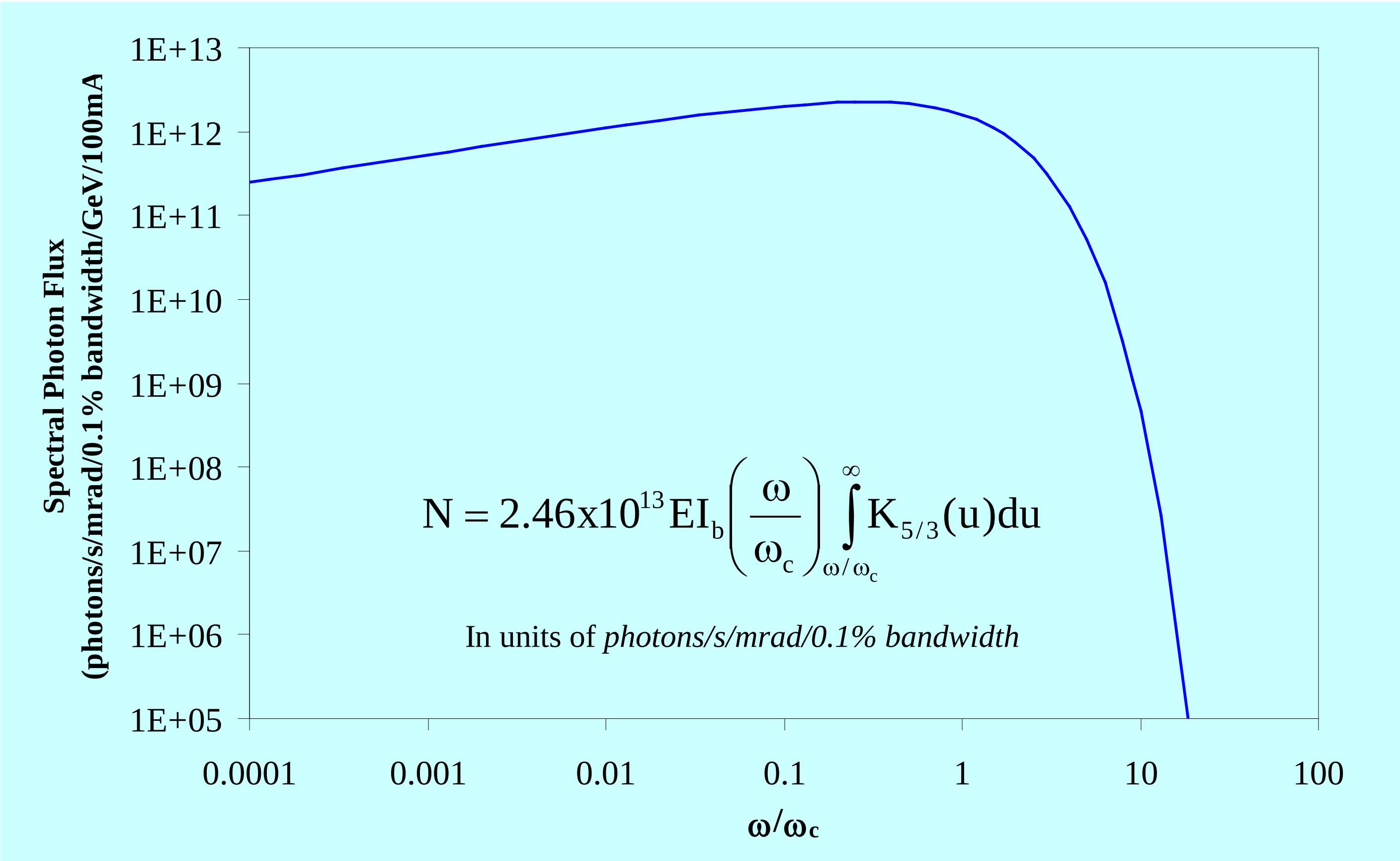


First observed 1947
GE Synchrotron





Universal Synchrotron Radiation Curve



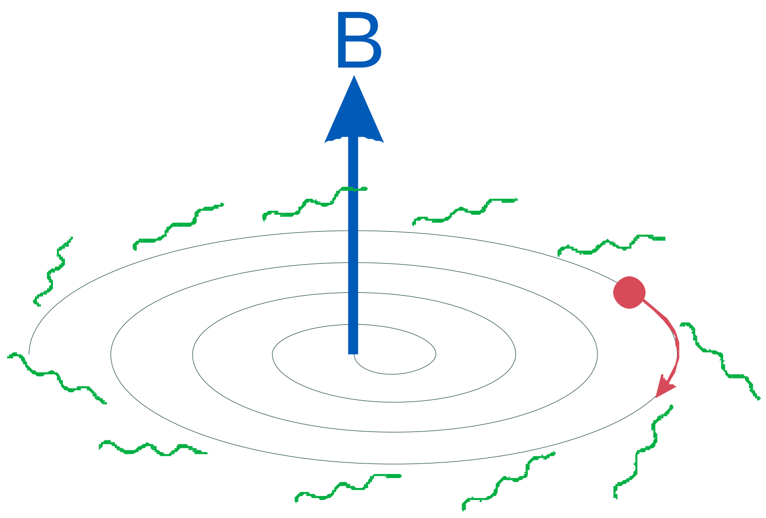
- Synchrotron radiation is a quantum process, but is averaged over a great number of electrons (N^o e^- per bunch~10^{10}).
- The synchrotron radiation spectrum typically ranges from IR to X-rays
- Synchrotron radiation is emitted as a pencil of light in the direction of the beam trajectory.

Accelerators in Space

Crab Nebula

Circular Acceleration

<u>Synchrotron Radiation</u> from an electron in a magnetic field:



$$\boxed{P_\gamma = \frac{e^2 c^2}{2\pi} C_\gamma E^2 B^2}$$

<u>Energy loss</u> per turn of a machine with an average <u>bending radius</u> ρ:

$$\boxed{\Delta E / rev = \frac{C_\gamma E^4}{\rho}}$$

Energy loss must be replaced by RF system

cost scaling \$ $\propto E_{cm}{}^2$

Insertion devices

- Wigglers

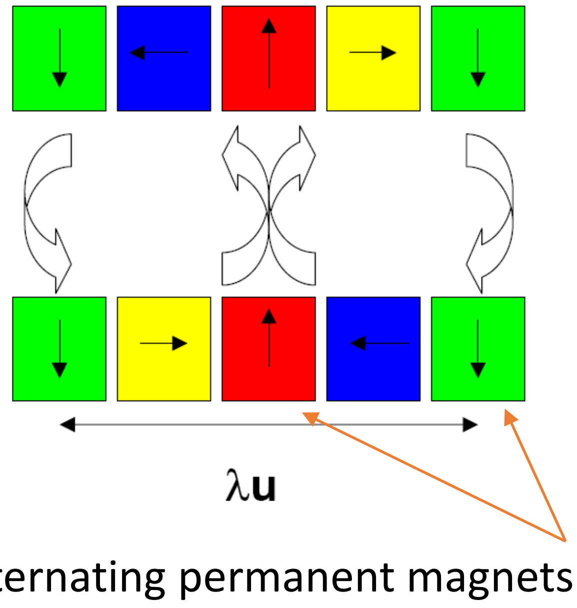
  Large oscillations of the beam creating a fan of broad-band incoherent radiation

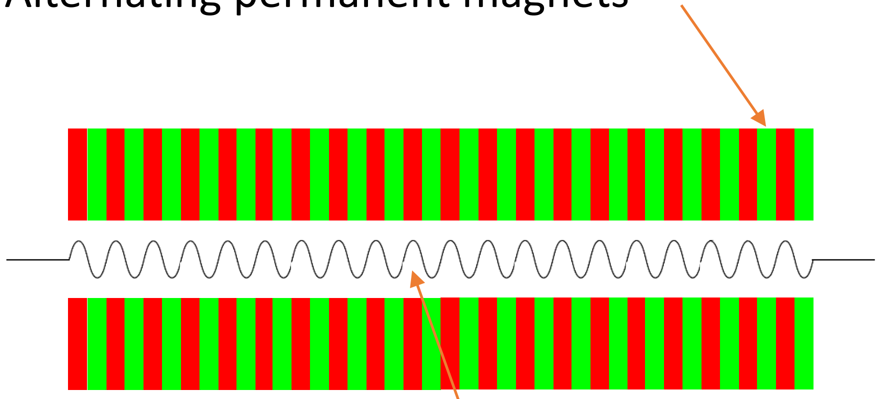
- Undulators

  Smaller deflections of the beam creating a thin pencil of coherent light

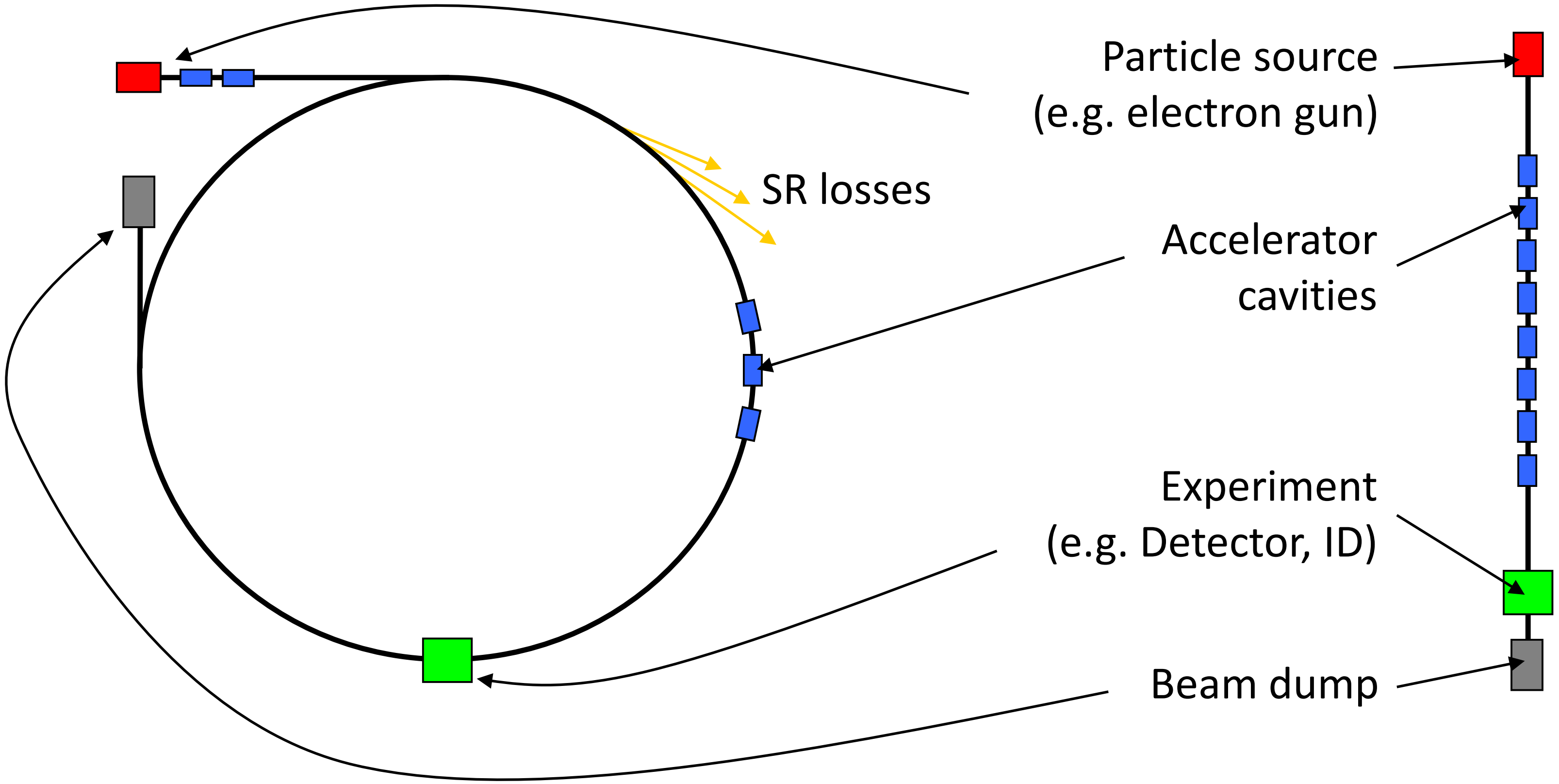
- Free electron laser

  Synchrotron radiation, contained by mirrors, creating intense coherent light





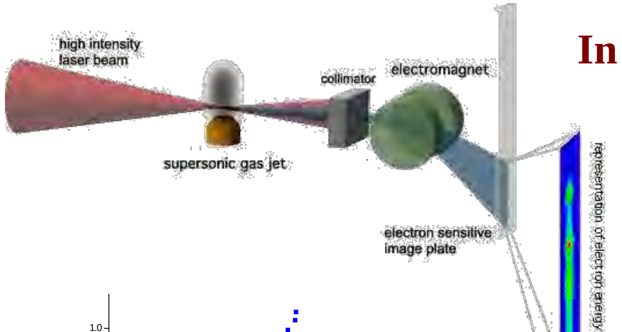
Accelerating in a line or a circle



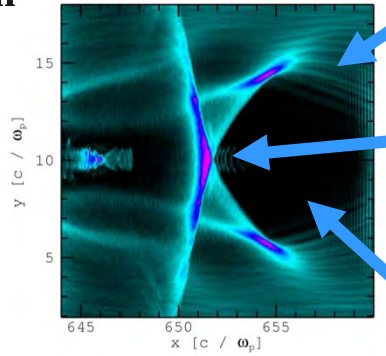
- Heavy SR losses (leptons)
- Size of ring determines max energy (hadrons)

- All acceleration from single pass
- Length of accelerating section determines max energy

Plasma Wake Accelerators ?



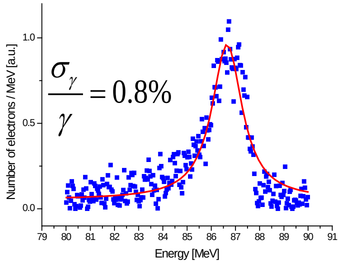
In principle 100 GeV/m



laser

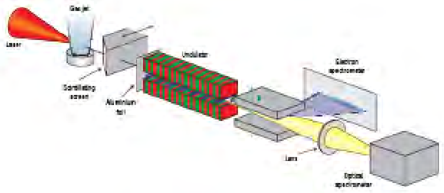
self-injected electron bunch undergoing betatron oscillations

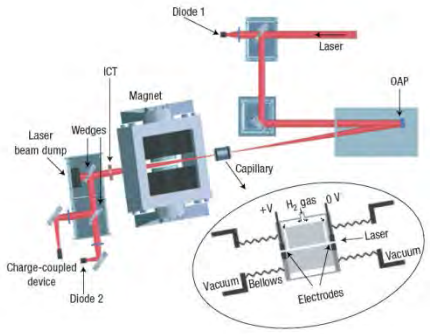
ion bubble



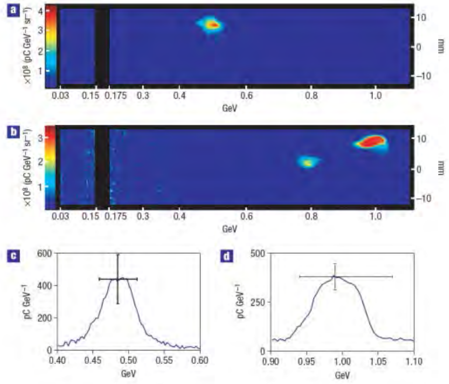
Strathclyde

Radiation source demonstrations





33 mm plasma channels



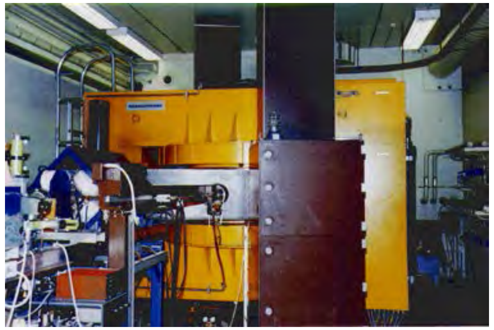
Big Lasers !!

Berkeley: 1 GeV achieved

Early (UK) History

(Synchro)Cyclotrons

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



Clatterbridge Oncology Centre
65 MeV

Linacs

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

Synchrotrons

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

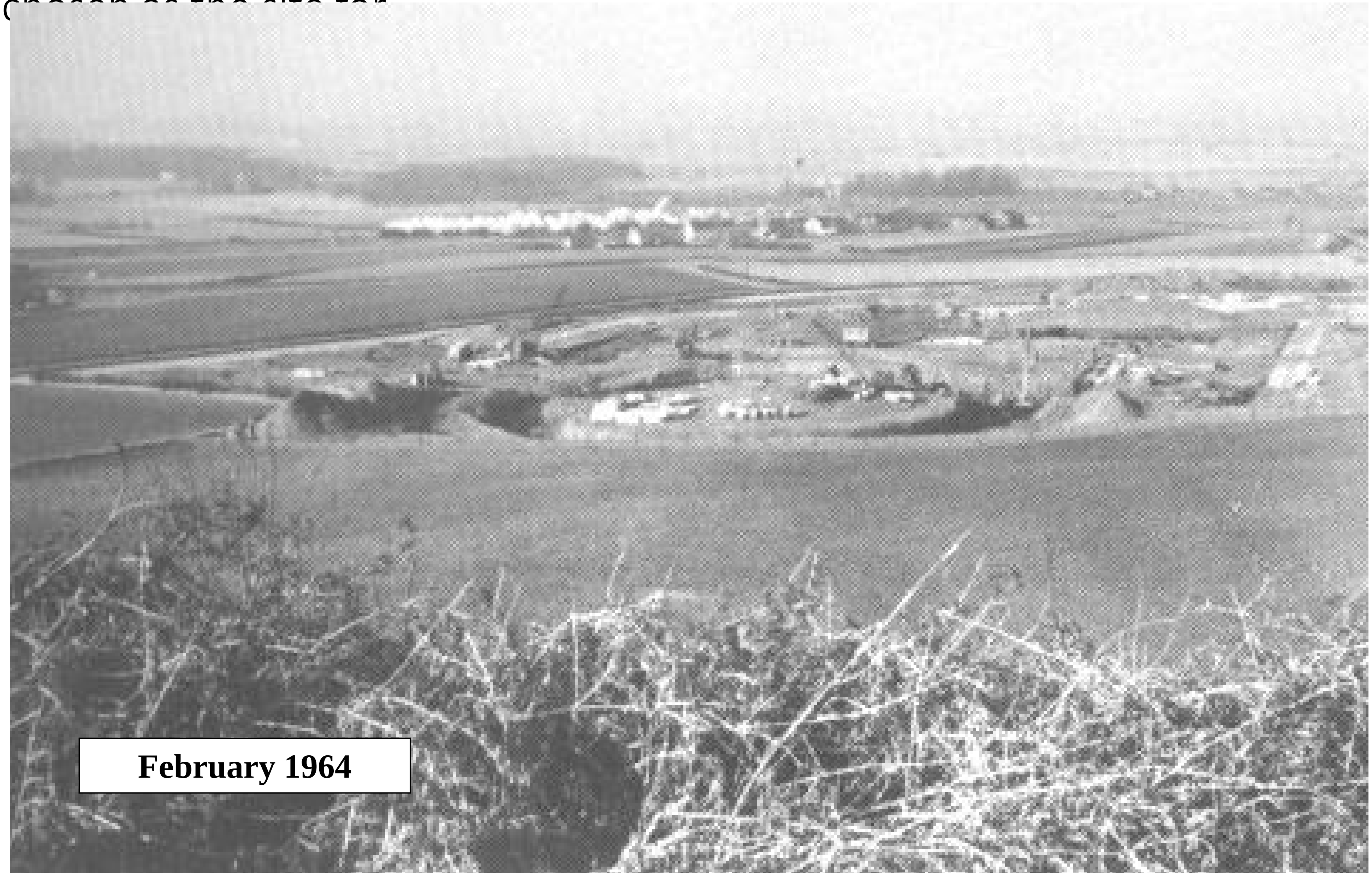
HEI driving force: Liverpool/Manchester/Glasgow/Sheffield/ (Lancaster)

The *Daresbury Laboratory* site, circa 1962

a quiet, fertile field in Cheshire

Construction of the *Daresbury Nuclear Laboratory*

was chosen as the site for



February 1964

NINA: The *Northern Institutes Nuclear Accelerator*

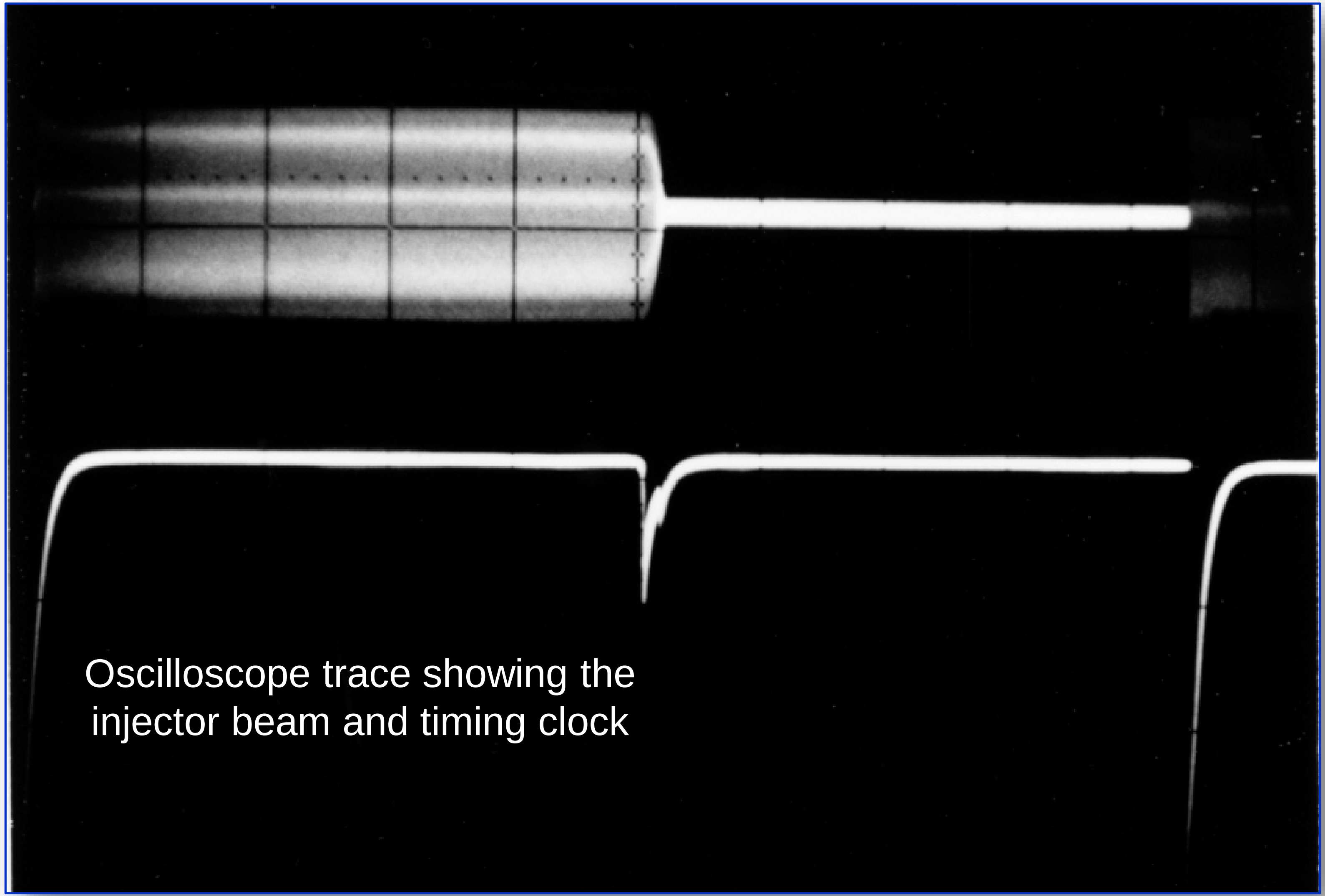
NINA: The *Northern Institutes Nuclear Accelerator*

Before shielding was complete

-

NINA beam on 2nd December 1966

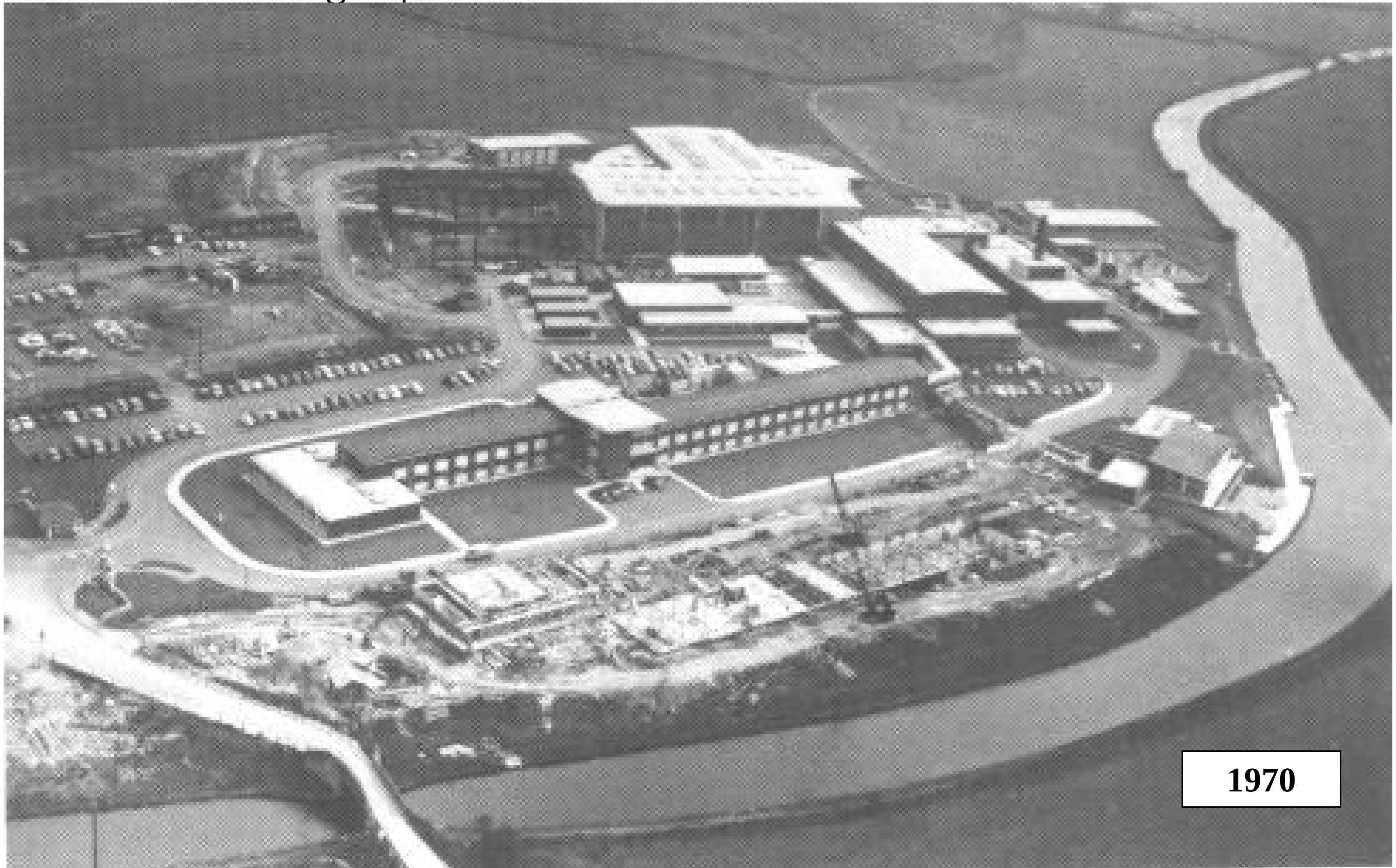
NINA's Heartbeat .....



Oscilloscope trace showing the injector beam and timing clock

The construction of the NINA experimental halls

Experimental hall being expanded



The completed *Daresbury Nuclear Laboratory*

NINA

The NINA machine parameters

- Type: fast-cycling e^- synchrotron
- Circumference: 220 m
- Rep. frequency: 53 Hz
- Injection energy: 43 MeV
- Normal peak energy: 4.0 GeV
- Maximum peak energy: 5.4 GeV
- Max. circ. current: 35 mA
- Max. extract. current: 1 μ A
- Number of dipoles: 40
- Peak dipole field (5.4 GeV): 0.9 T
- Radiation loss at 5 GeV: 2.7 MeV

THE UNIVERSITY of LIVERPOOL

TELEPHONE: ARDWICK 3333.

Atomic & Molecular Physics Group,
THE PHYSICAL LABORATORIES,
THE UNIVERSITY,
MANCHESTER, 13.

5th January, 1966.

MANCHESTER 1824

The University of Manchester

Professor A. W. Merrison,
Department of Physics,
University of Liverpool,
LIVERPOOL.

Dear Professor Merrison,

I am writing on behalf of our Branch Committee, to ask you whether it would be possible for the Manchester Branch to hold their 1966 Summer visit at the Daresbury accelerator laboratories. Several of our Branch members have expressed interest in the accelerator and the work being carried out in the laboratories.

We have normally held our visits in July, but, of course, we would come at any time convenient for the laboratory staff. It has been suggested that there might be more to see if the visit were to be held on a day when the machine is shut down for maintenance. Would this be possible?

If you feel our visit will not cause much inconvenience, perhaps you could let me know what day, or days, would be suitable for the visit.

On a topic quite unconnected with the Institute of Physics:– in the Molecular Physics Group here, we are hoping to extend our studies into the vacuum ultraviolet (from 2000 Å to 100 Å) and have some money available for equipment. One problem is to obtain an intense continuous source of radiation for excitation in this region.

Dr. Kanaris (from our Department) told me of some work he had come across when in Hamburg, concerned with the properties of the emission from centripetally accelerated electrons in a synchrotron. It sounds as though such emission might provide an ideal source of excitation for our experiments.

I am still waiting for more details from Dr. Kanaris, and have at present little idea of the experimental problems involved in extracting such emitted radiation from a large accelerator.

However, I thought I would like to write to you now to let you know what we are thinking about, and to ask what you feel about making use of the Daresbury accelerator in this way, if the project should prove feasible. Has anybody else considered a project of this nature?

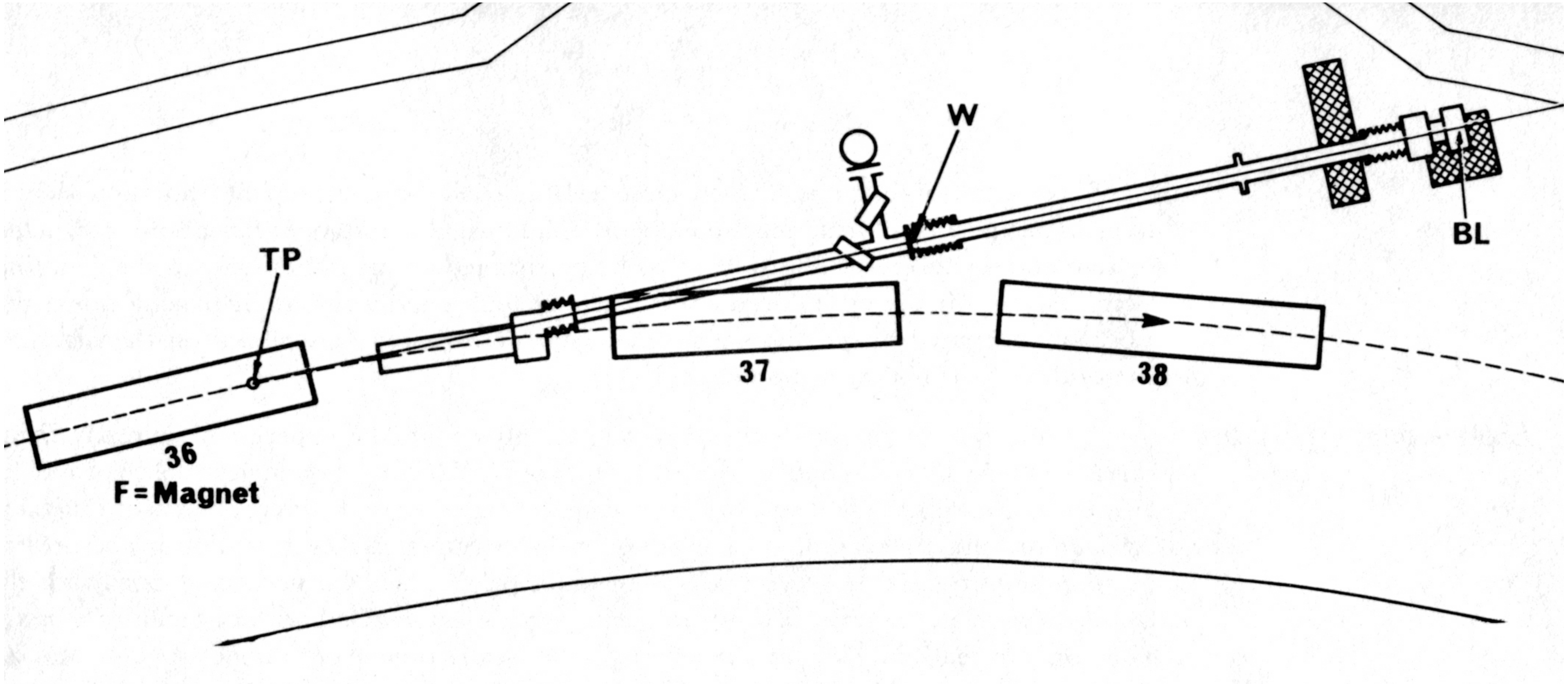
Yours sincerely,

I. H. Munro

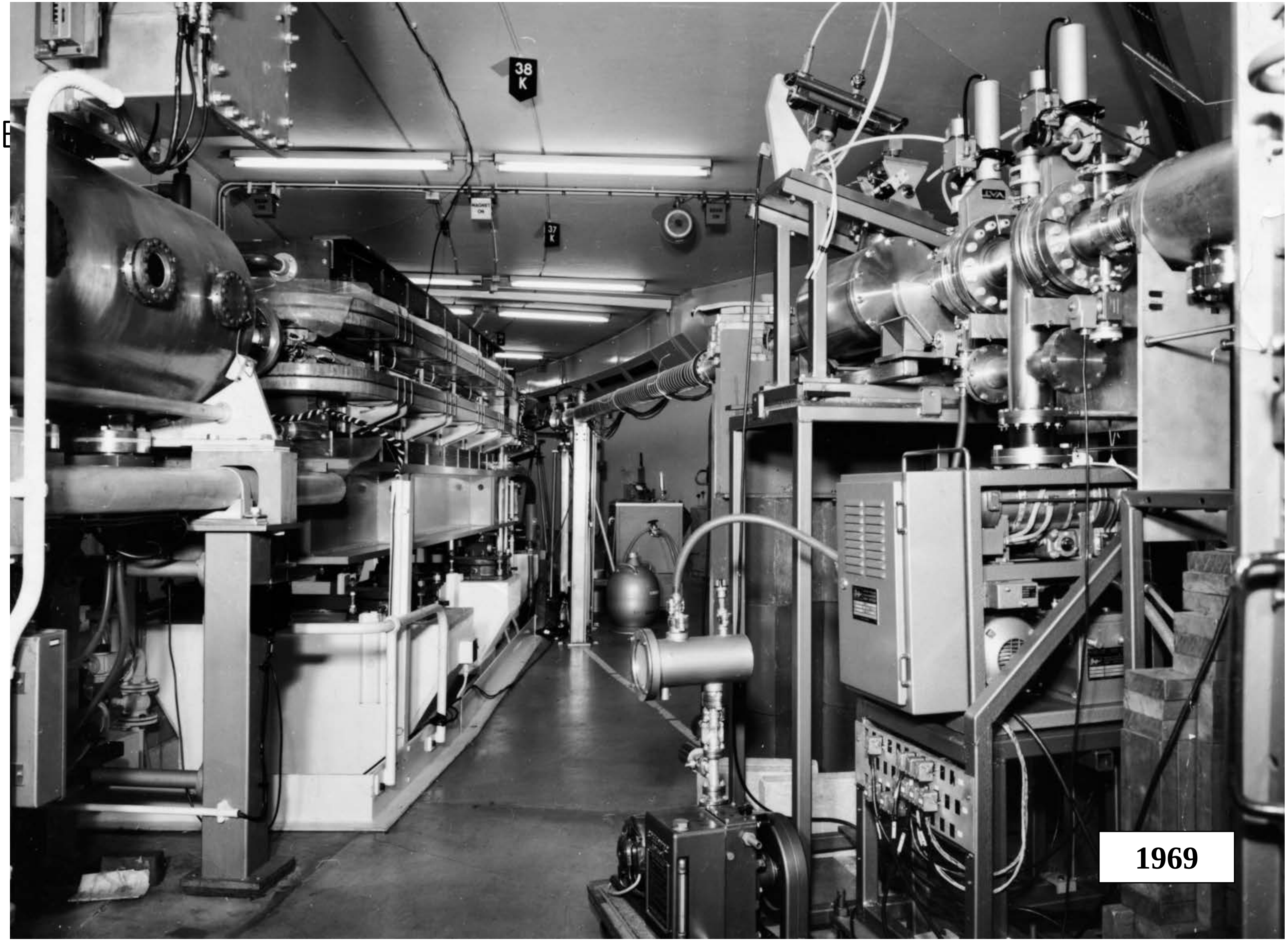
I. H. MUNRO.

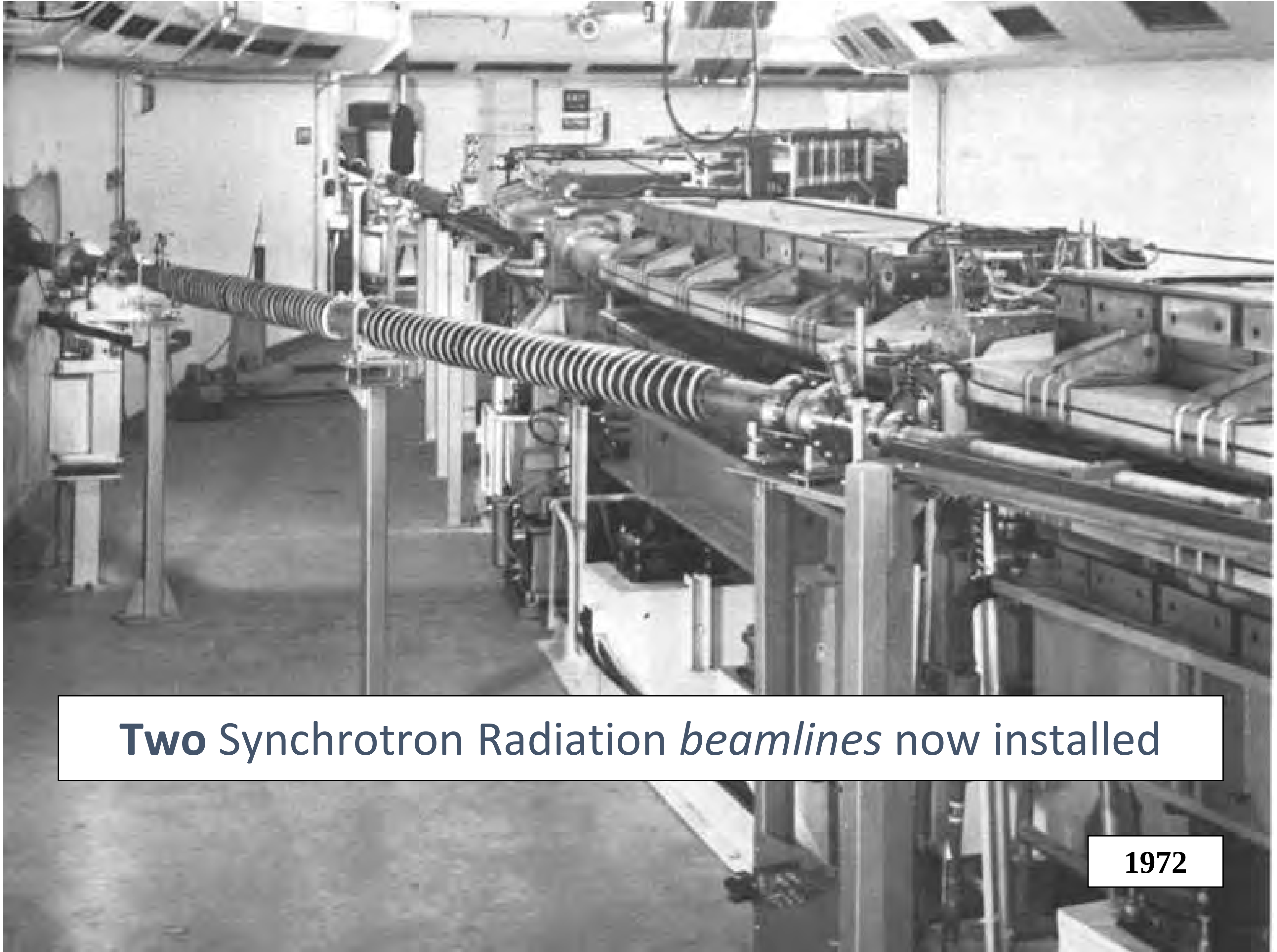
January 1966

Munro proposed a **Synchrotron Radiation** experiment *inside* the NINA ring tunnel

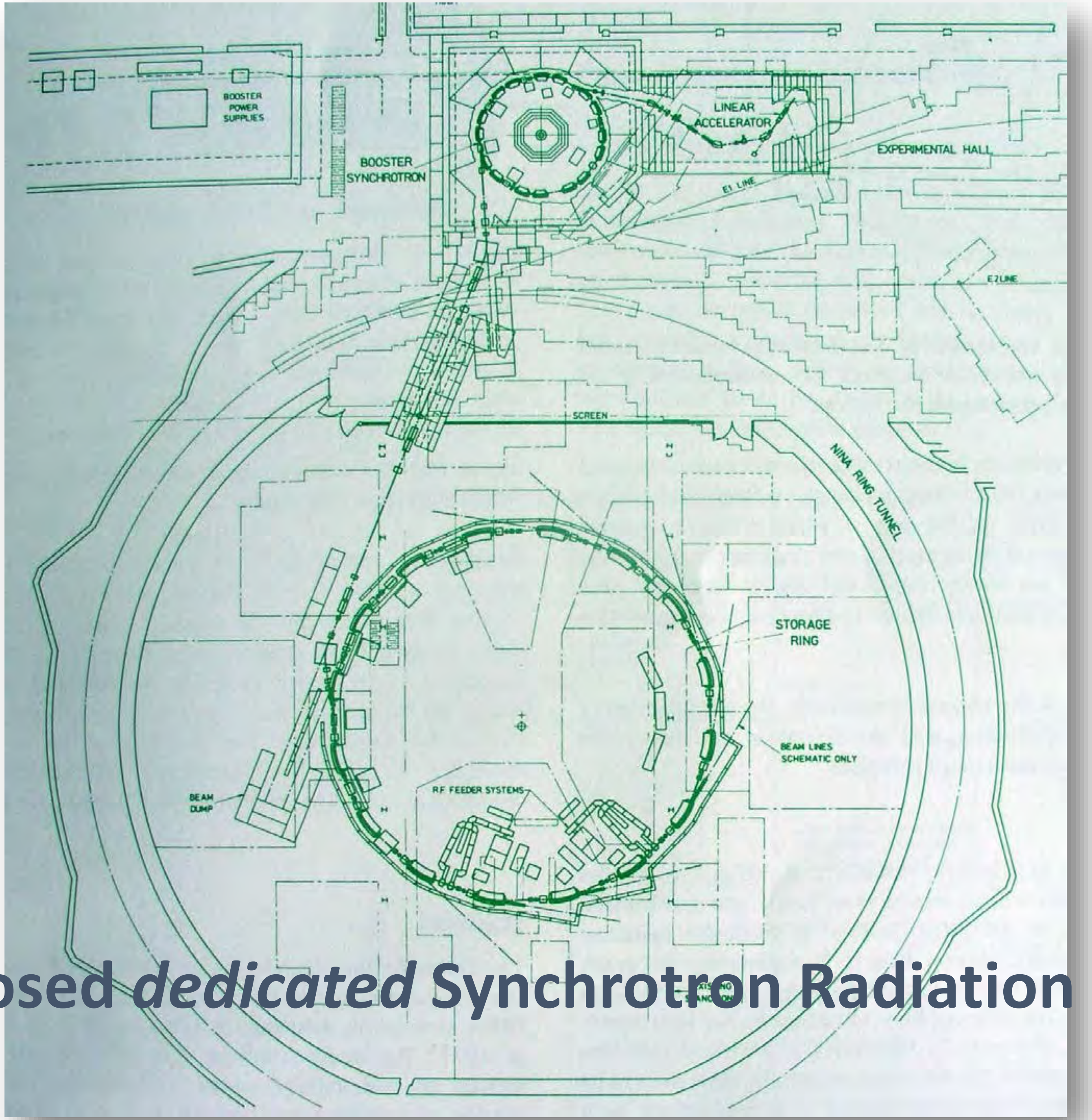


S.R. E




Two Synchrotron Radiation *beamlines* now installed
1972

1974
Annual
Report



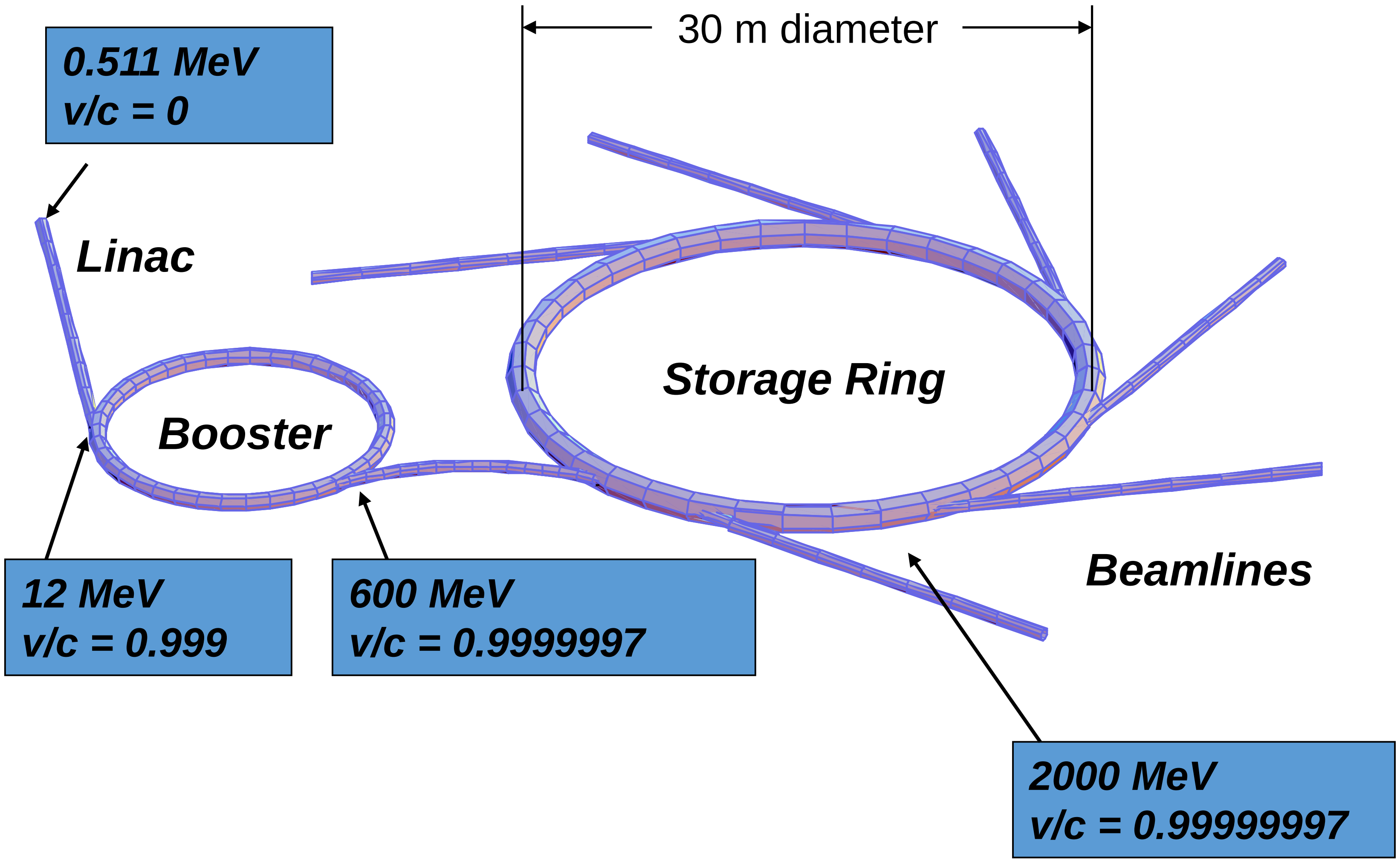
A proposed *dedicated* Synchrotron Radiation Source

NINA is gone - the way is clear for the *SRS*

The Inner Hall showing the proposed layout of the SRS

late 1977

The SRS Synchrotron Radiation Source



August 4^{th}, 2008:

Ceremonial switch-off of the SRS

Ian Munro ‘dumps’ the last stored beam from the SRS storage ring while staff raise a glass in a toast to the machine’s achievements

- 28 years of operation
- 2 million hours of science
- >5,000 publications

The SRS pioneered the way for the development of more than 60 similar machines worldwide

Particle Accelerators in the UK

Particle accelerators can have different sizes and shapes. Some are very big and require their own building, like Diamond, ISIS or ALICE but others are much smaller, small enough to fit in an hospital.

In total there are more than 150 particle accelerators in the UK. Every major city, every major hospital has at least a few.

The map on the left shows most locations in the UK where there is a particle accelerator.

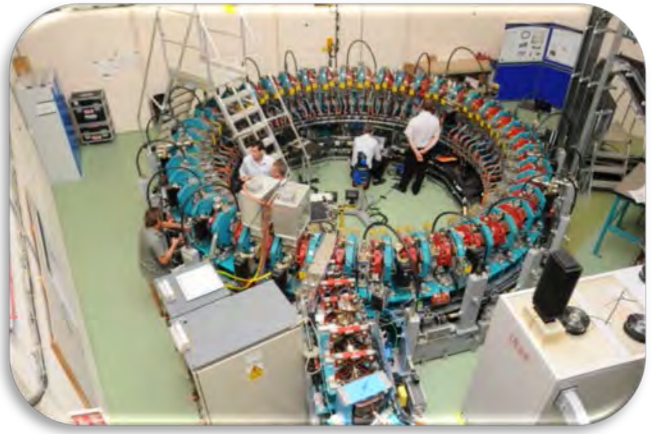
UK accelerators (Past and Present)

- NIMROD - 1st major UK accelerator at RAL, proton synchrotron
- NINA – 1st accelerator at DL, electron synchrotron, 1st light source
- SRS - Daresbury Light source, electron synchrotron, 1st dedicated light source
- ISIS - RAL neutron source, proton synchrotron
- DIAMOND – UKs first 3rd Generation Light source, electron synchrotron
- ALICE – Energy Recovery Prototype, electrons
- EMMA- Electron Machine of Many Applications, 1st ns-FFAG electrons
- CLARA – UK FEL Test bed, electron linac
- VELA- Small industrial accelerator, electron linac
- ALPHA-X – Plasma Wakefield Accelerator, electrons
- SCAPA - Plasma Wakefield Accelerator, electrons
- Most accelerators in the UK are medical Linacs

ALICE, EMMA, VELA & CLARA

ALICE

VELA



EMMA

Daresbury is home to four prototype accelerators/ test facilities.
We are currently working on a next generation light source test facility named CLARA.