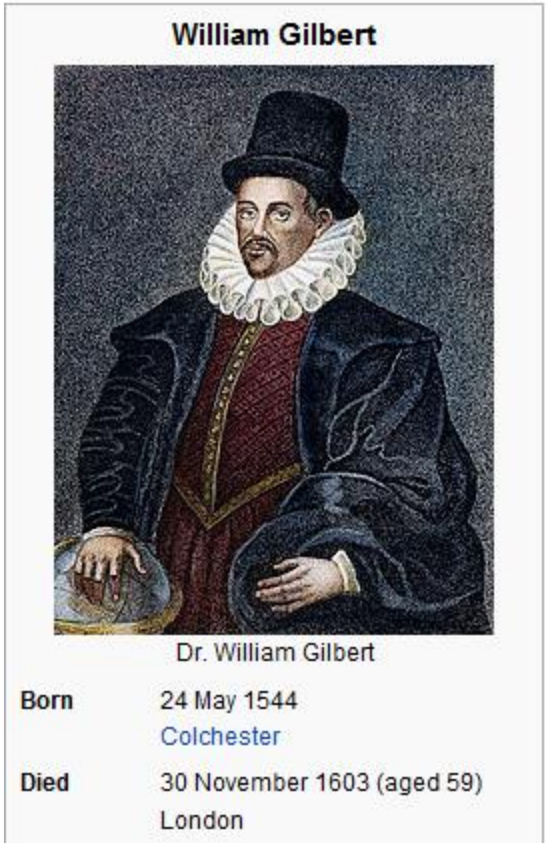
oPAC Advanced School on Accelerator Optimization; Royal Holloway College, U. of London; July 2014.

Accelerator

MAGNETS



William Gilbert

Dr. William Gilbert

Born	24 May 1544 Colchester
Died	30 November 1603 (aged 59) London

The father of magnetism.

Neil Marks; Cockcroft Institute, STFC ASTeC; University of Liverpool.

‘Optimization’(?)

‘Optimist’ – One disposed, under all circumstances, to expect the best; (18th c.)’;

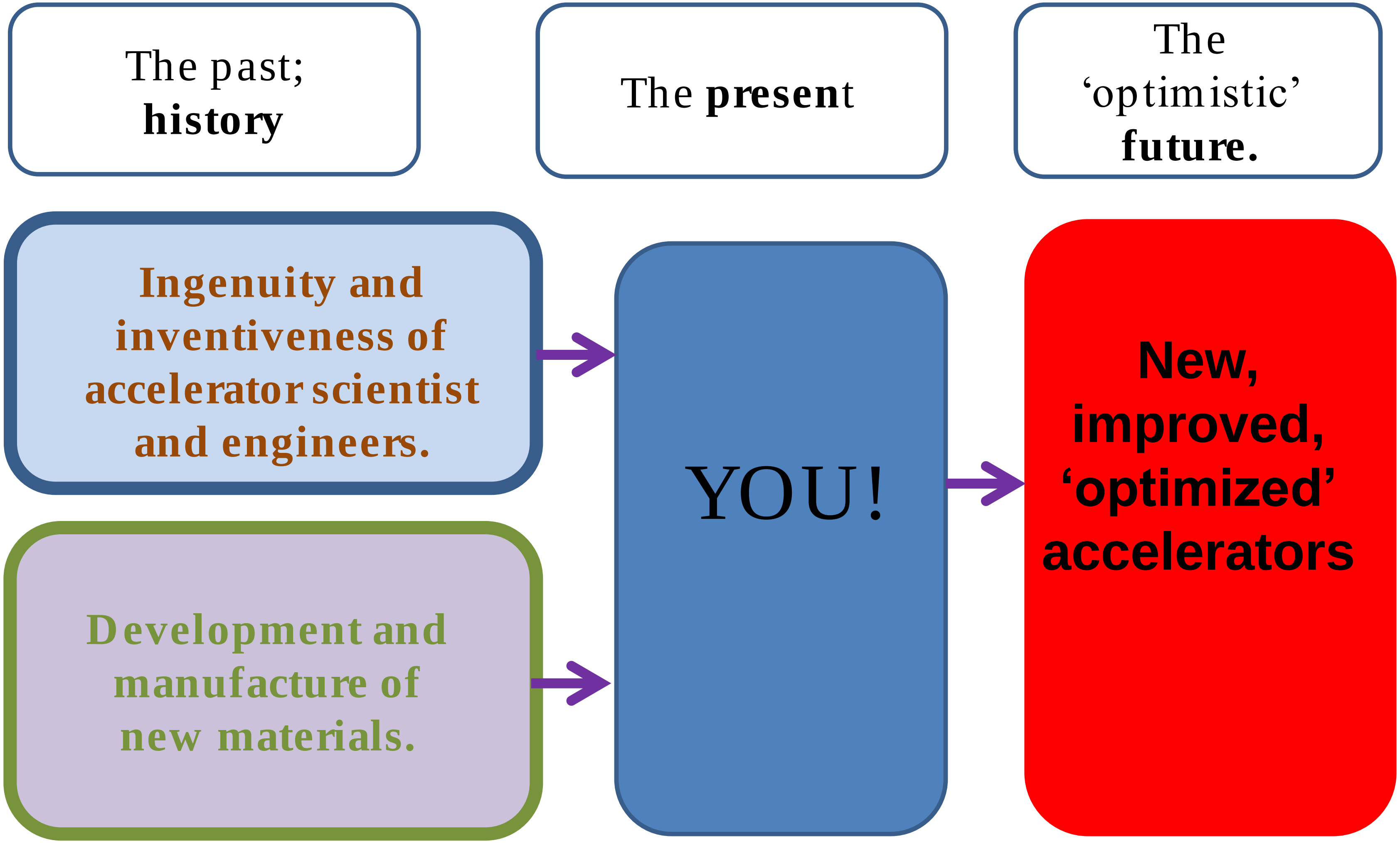
***so* ‘Optimize’ – *v*.**

Oxford English Dictionary.

The whole history of the development of particle accelerators revolves around successive **problem solving** to improve the effectiveness of the accelerators –

‘to expect the best’!

Development, past, present and future.



The past; **history**

The **present**

The 'optimistic' **future.**

Ingenuity and inventiveness of accelerator scientist and engineers.

Development and manufacture of new materials.

YOU!

New, improved, 'optimized' accelerators

Innovative Engineering.

The model T Ford – top speed c 40 mph; acceleration – 0 to 35 mph in 48 seconds!

The Hennessey Venom GT – top speed 270.5 mph, 0-200 mph 14.5 seconds.

Particle accelerators - 600 KeV to 5 TeV over 80 years!

a factor of 10^7 !

The first accelerator **needed to improve** nuclear physics investigation.

At the Cavendish Lab Cockcroft and Walton invented the high voltage generator which is named after them.

This would allow the acceleration of charged particles – but across a single gap – in a straight line – so no magnets needed!

The 665 kV Cockcroft Walton set, built to accelerate H^- for injection into ISIS at Rutherford - Appleton Lab.
This is now located in the entrance hall of the Cockcroft Institute at Daresbury.

The first 'C-W' generator used for acceleration.

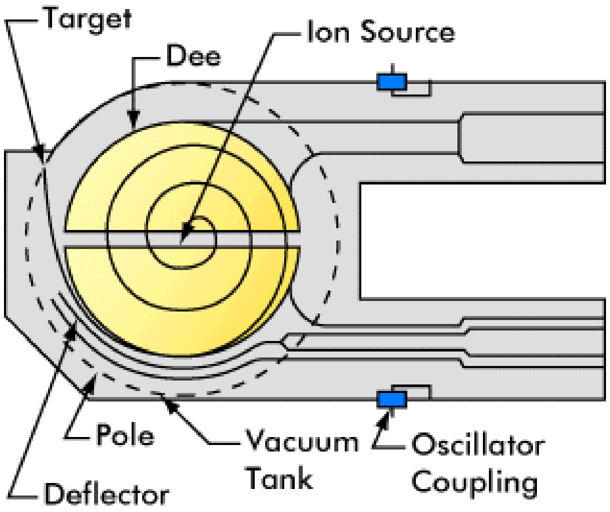
1932: John Cockcroft and Ernest Walton focused a proton beam, accelerated to 600 keV, onto lithium, splitting its nucleus to produce 2 helium atoms. **The era of accelerator-based experimental nuclear physics was born.**

$${}_3Li^7 + {}_1H^1 \longrightarrow 2\ {}_2He^4$$

John Cockcroft (left) and Ernest Walton flank their boss, Ernest Rutherford, soon after their successful experiment.

But:

Much higher energy particles were needed. In 1930, Earnest Lawrence invented the cyclotron:



A cyclotron uses a strong vertical **magnetic field** to produce a circular particle orbit. In the vacuum vessel are two semi-circular ‘D’s, with **an oscillating radio frequency voltage** applied between them. This oscillates at **the ‘cyclotron frequency**’, so that bunches of particles are accelerated each time they cross the gap.

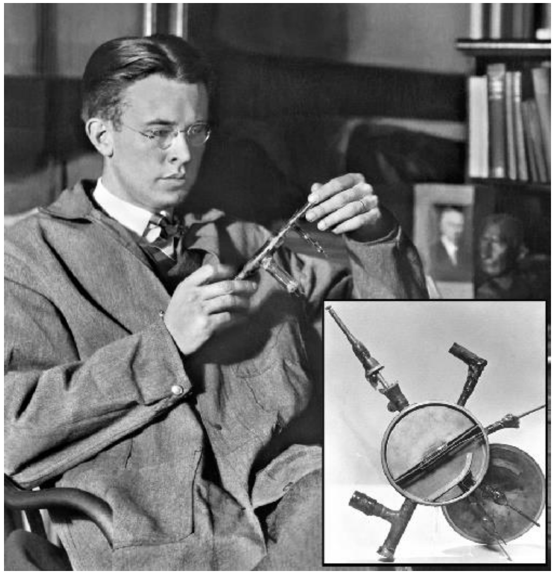
Force on moving charge = Bev;
Centripetal force = v²/ r;
So r is proportional to v;
Cyclotron frequency:

$$f = (1/2\pi)(Be/m);$$

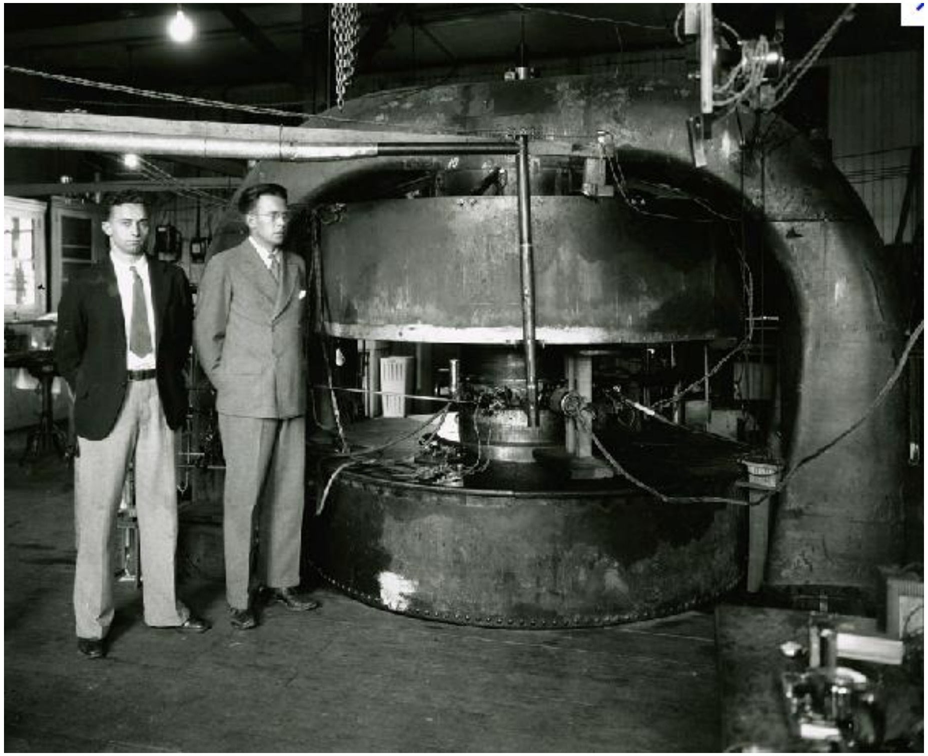
constant if B/m is constant.

B: magnetic flux density;
e: charge on particle;
v: velocity of particle;
r: radius of orbit;
f: cyclotron frequency.

Lawrence and his first cyclotron



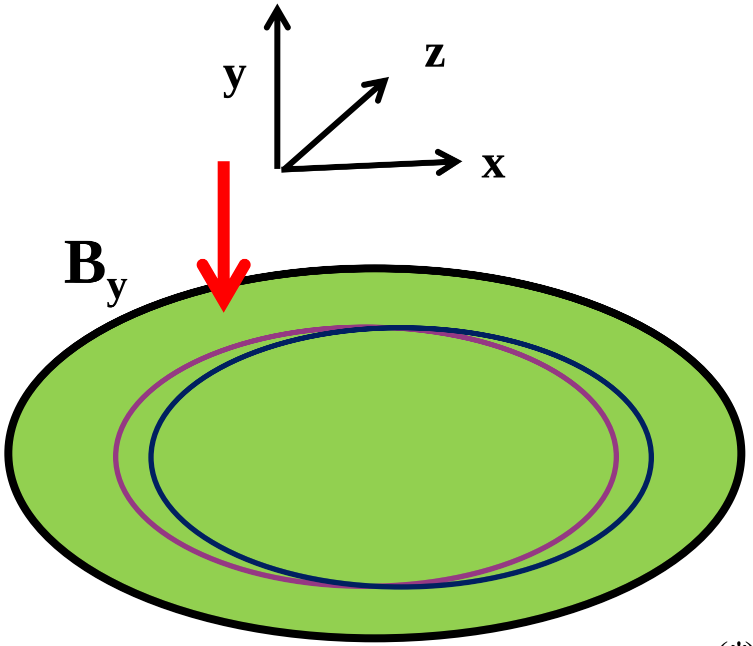
NOBEL PRIZE!



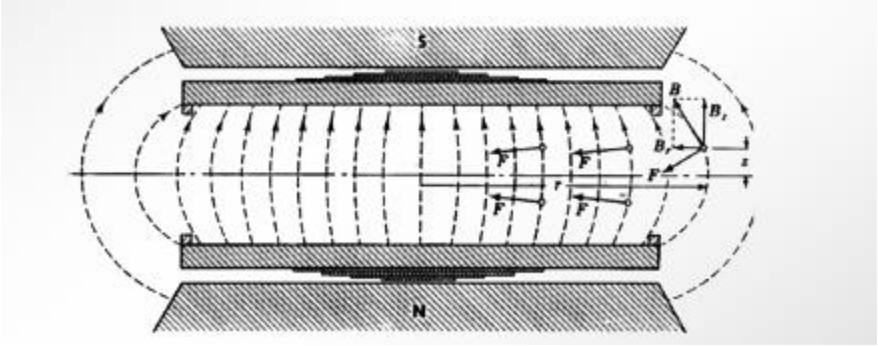
The1932 Lawrence cyclotron;
27 inch, 3.6 MeV;

Focusing in the cyclotron

Horizontal focusing provided by (nearly) constant vertical bending field By:



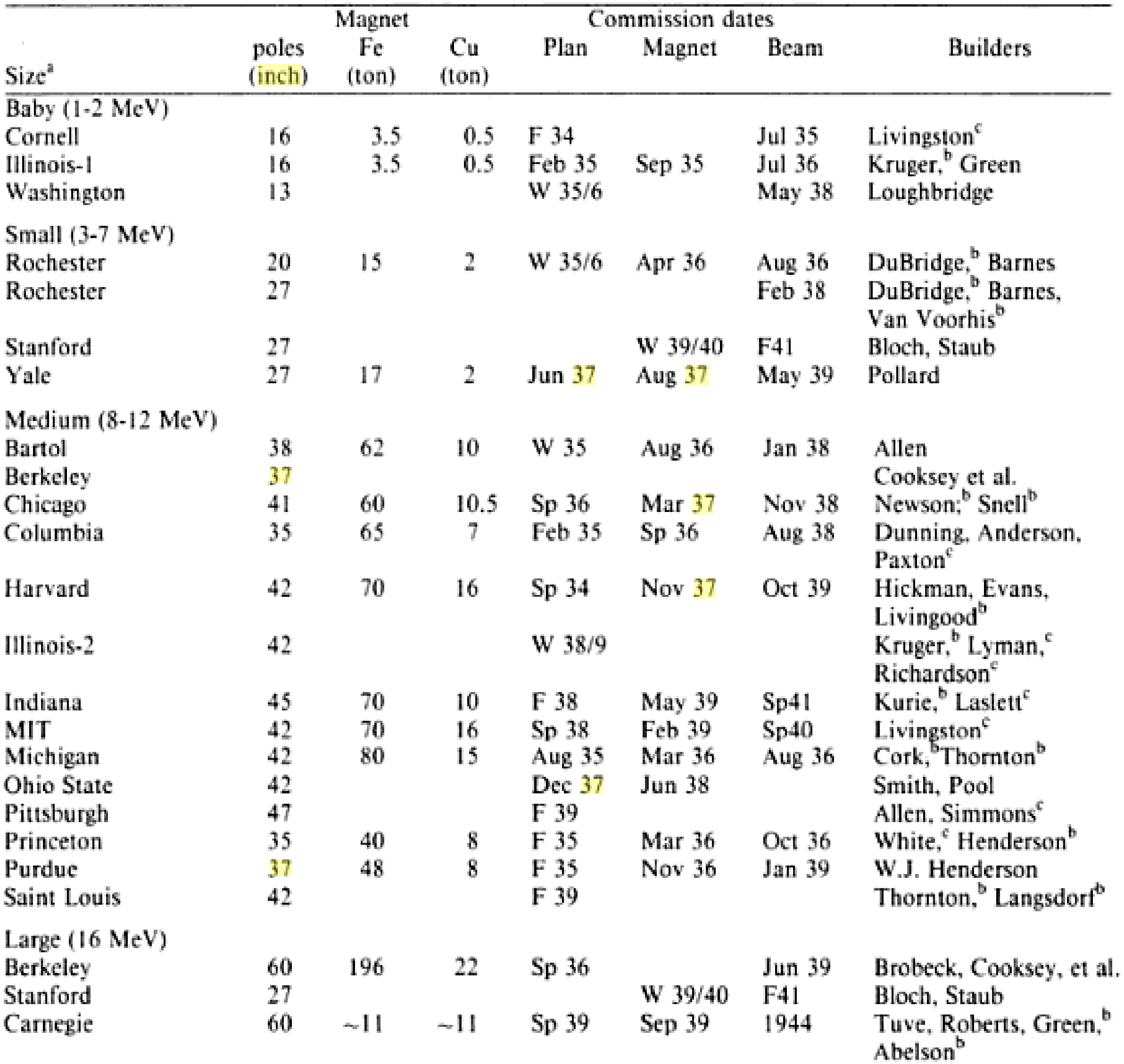
Vertical focusing provided by radially **decreasing** field(*):



Within limits of dB_y/dr, focusing can be provided in both planes – **'weak focusing'.**

(*) From USPAS 'Cyclotrons Old but Still New' -with permission from William Barletta.

USA Cyclotrons pre 1940



Size[a]	Magnet poles (inch)	Fe (ton)	Cu (ton)	Commission dates Plan	Magnet	Beam	Builders
Baby (1-2 MeV)							
Cornell	16	3.5	0.5	F 34		Jul 35	Livingston[c]
Illinois-1	16	3.5	0.5	Feb 35	Sep 35	Jul 36	Kruger,[b] Green
Washington	13			W 35/6		May 38	Loughbridge
Small (3-7 MeV)							
Rochester	20	15	2	W 35/6	Apr 36	Aug 36	DuBridge,[b] Barnes
Rochester	27					Feb 38	DuBridge,[b] Barnes, Van Voorhis[b]
Stanford	27				W 39/40	F41	Bloch, Staub
Yale	27	17	2	Jun 37	Aug 37	May 39	Pollard
Medium (8-12 MeV)							
Bartol	38	62	10	W 35	Aug 36	Jan 38	Allen
Berkeley	37						Cooksey et al.
Chicago	41	60	10.5	Sp 36	Mar 37	Nov 38	Newson;[b] Snell[b]
Columbia	35	65	7	Feb 35	Sp 36	Aug 38	Dunning, Anderson, Paxton[c]
Harvard	42	70	16	Sp 34	Nov 37	Oct 39	Hickman, Evans, Livingood[b]
Illinois-2	42			W 38/9			Kruger,[b] Lyman,[c] Richardson[c]
Indiana	45	70	10	F 38	May 39	Sp41	Kurie,[b] Laslett[c]
MIT	42	70	16	Sp 38	Feb 39	Sp40	Livingston[c]
Michigan	42	80	15	Aug 35	Mar 36	Aug 36	Cork,[b] Thornton[b]
Ohio State	42			Dec 37	Jun 38		Smith, Pool
Pittsburgh	47			F 39			Allen, Simmons[c]
Princeton	35	40	8	F 35	Mar 36	Oct 36	White,[c] Henderson[b]
Purdue	37	48	8	F 35	Nov 36	Jan 39	W.J. Henderson
Saint Louis	42			F 39			Thornton,[b] Langsdorf[b]
Large (16 MeV)							
Berkeley	60	196	22	Sp 36		Jun 39	Brobeck, Cooksey, et al.
Stanford	27				W 39/40	F41	Bloch, Staub
Carnegie	60	~11	~11	Sp 39	Sep 39	1944	Tuve, Roberts, Green,[b] Abelson[b]

Cyclotron **Problem 1.**

Problem:

- **at energies c 25 MeV and higher (for p+) mass begins to increase with energy;** $m' = m_0 / \sqrt{1 - (v/c)^2}$;
- **so to stay in synchronism, B must increase with radius;**
- **BUT THAT IS VERTICALLY DEFOCUSING!**

Solution (at the time!):

the synchro-cyclotron: frequency modulation of the r.f. voltage kept a short bunch of beam in synchronism;

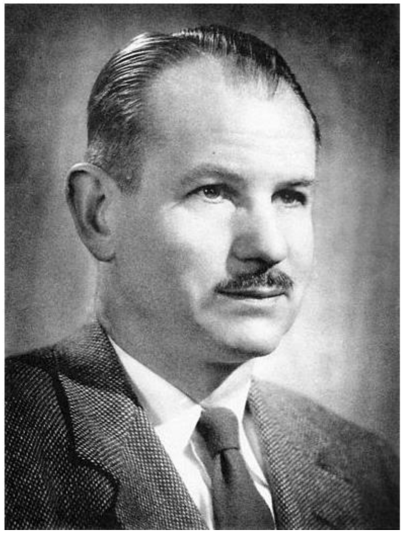
BUT:

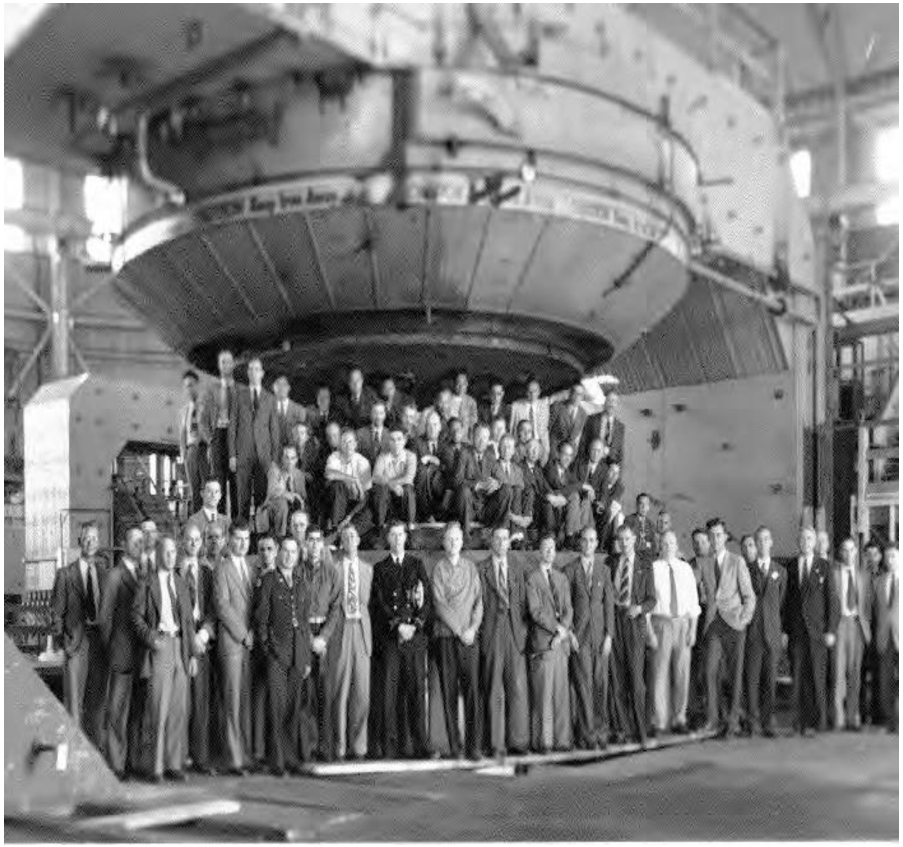
- **beam current no longer a continuous stream but a short pulse at the modulation cycle frequency;**
- **big technical problems with frequency modulation.**

Problem solved? The Synchrocyclotron

Invented in 1945 by Ed McMillan, a member of Lawrence's staff at Berkley Lab; (see next but one slide);

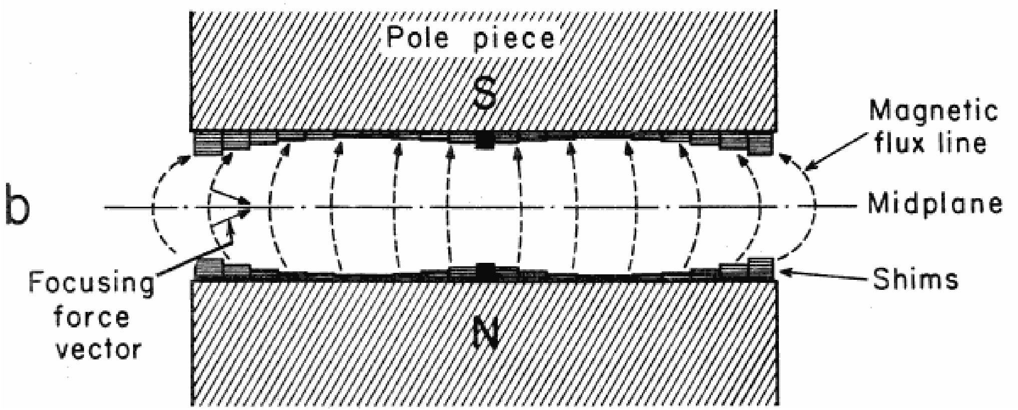
NOBEL PRIZE!





Lawrence's 184 inch accelerator; commenced 1939 as a cyclotron, completed in 1946 as a 100 MeV synchrocyclotron

The 184 inch synchrocyclotron



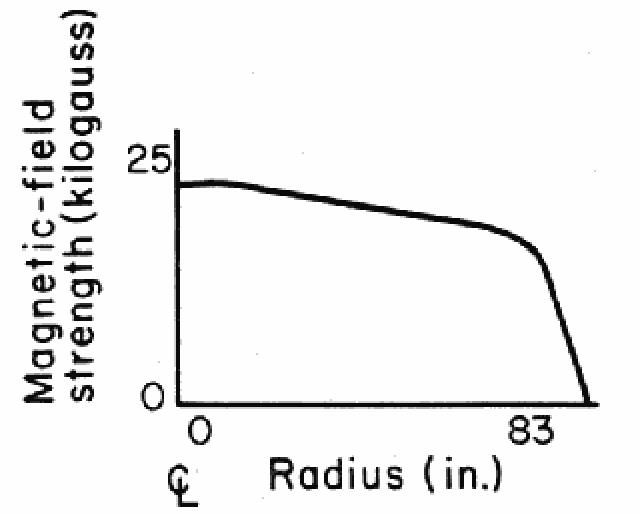


Fig. 4. (a) Plot of magnetic-field strength vs radius. The field strength decreases gradually out to a radius of about 83-in., after which it falls off sharply. This point marks the maximum usable radius for particle orbits. Further out they are unstable. (b) Magnetic flux lines are represented as broken arrows, and focusing forces as solid arrows. An ion above the midplane is directed downward, while an ion below the midplane is directed upward.

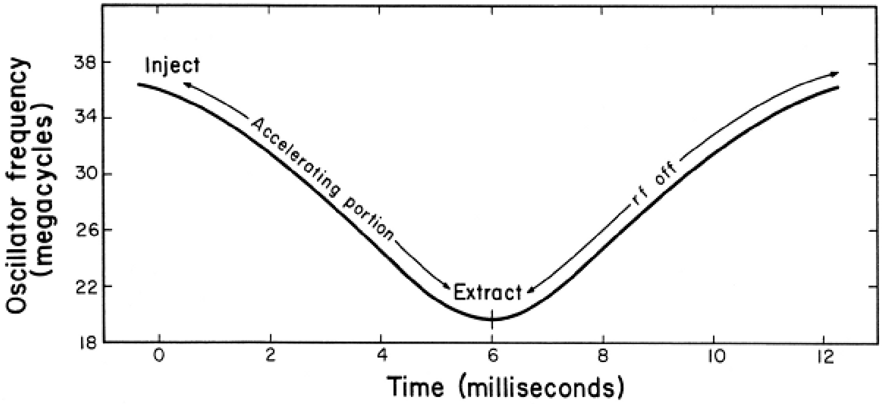


Fig. 5. Radiofrequency cycle for accelerating protons. Sixty-four such cycles are repeated each second.

The CERN Synchrocyclotron

CERN's first accelerator; build 1957; Energy 600 MeV.

Cyclotron **Problem 2**

- **for higher energy the magnet has to be very big;**
- **solution: take the middle out of the magnet, use just a thin line of magnets round the circumference (but the magnetic field has to increase with the momentum of the particles).**

And the synchrotron is born!

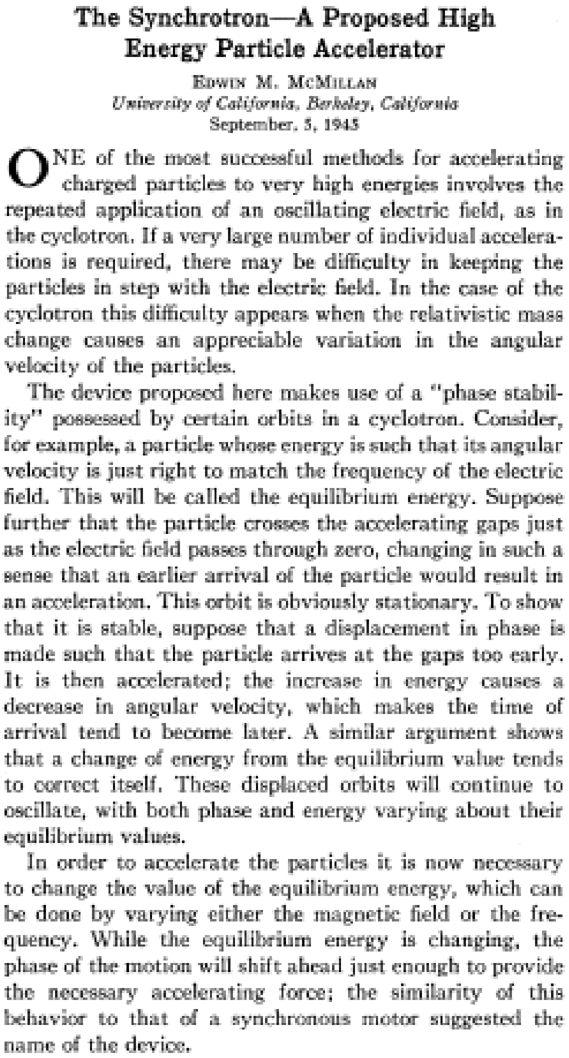
Ed McMillan's 'High Energy Accelerator'

The Synchrotron – A proposed High Energy Particle Accelerator;

Letter to 'Phys Rev 68,143 – 1 September 1945;

Edwin M.McMillan.
Included:

- **'variable frequency' – the synchrocyclotron;**
- **'variable field' – the synchrotron;**
- **'phase stability' – the principle that keeps it all together!**



The Synchrotron—A Proposed High Energy Particle Accelerator

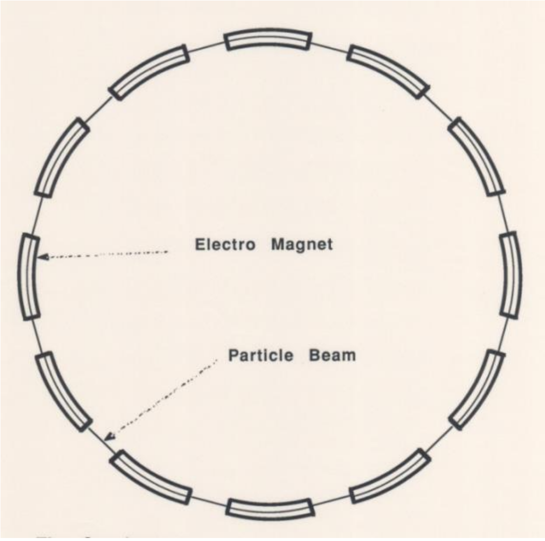
Edwin M. McMillan
University of California, Berkeley, California
September. 5, 1945

ONE of the most successful methods for accelerating charged particles to very high energies involves the repeated application of an oscillating electric field, as in the cyclotron. If a very large number of individual accelerations is required, there may be difficulty in keeping the particles in step with the electric field. In the case of the cyclotron this difficulty appears when the relativistic mass change causes an appreciable variation in the angular velocity of the particles.

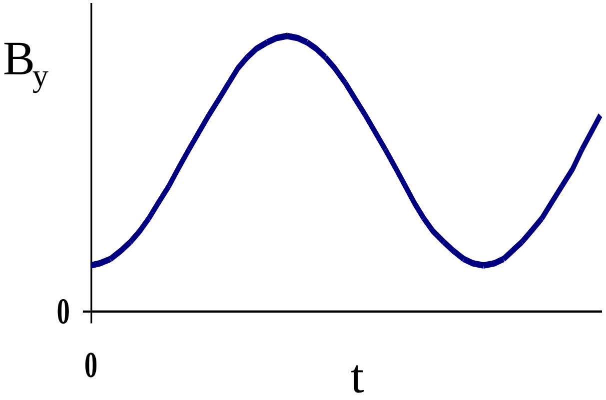
The device proposed here makes use of a "phase stability" possessed by certain orbits in a cyclotron. Consider, for example, a particle whose energy is such that its angular velocity is just right to match the frequency of the electric field. This will be called the equilibrium energy. Suppose further that the particle crosses the accelerating gaps just as the electric field passes through zero, changing in such a sense that an earlier arrival of the particle would result in an acceleration. This orbit is obviously stationary. To show that it is stable, suppose that a displacement in phase is made such that the particle arrives at the gaps too early. It is then accelerated; the increase in energy causes a decrease in angular velocity, which makes the time of arrival tend to become later. A similar argument shows that a change of energy from the equilibrium value tends to correct itself. These displaced orbits will continue to oscillate, with both phase and energy varying about their equilibrium values.

In order to accelerate the particles it is now necessary to change the value of the equilibrium energy, which can be done by varying either the magnetic field or the frequency. While the equilibrium energy is changing, the phase of the motion will shift ahead just enough to provide the necessary accelerating force; the similarity of this behavior to that of a synchronous motor suggested the name of the device.

The synchrotron (including storage rings).



The beam is maintained at a constant orbit radius by a ring of electro-magnets - the ‘**bending magnets**’; their strength is varied to be proportional to particle momentum;



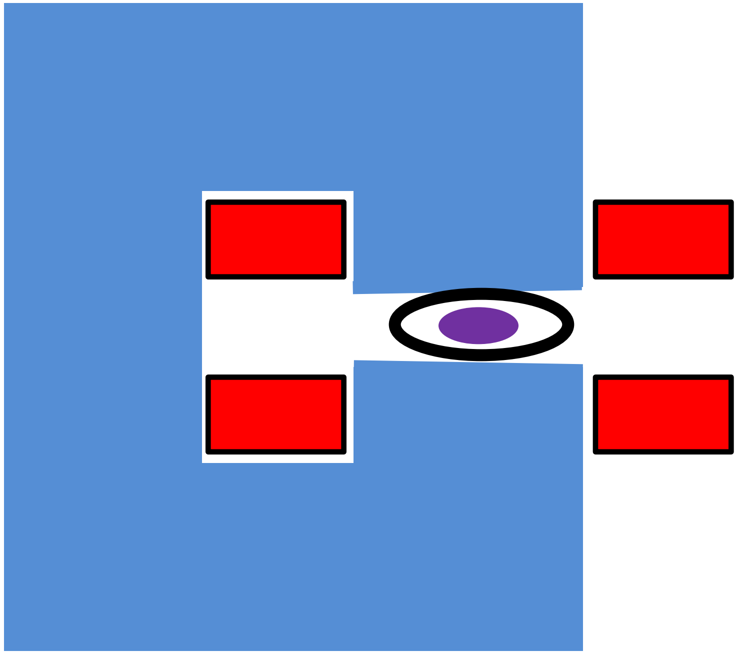
In a storage ring, the field is constant in time – ie d.c.

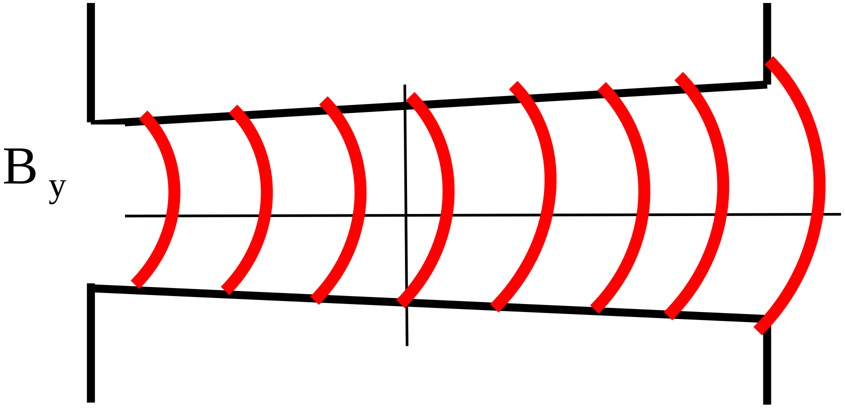
It then becomes economically possible to build rings with much larger radii.

The bending magnets in a synchrotron

These generate a vertical magnetic field across the beam.

This is done by DIPOLE (ie, 2 pole) electro-magnets. In earlier synchrotron they also provided the '**weak focusing**' by a small decrease in B_y with radius.





Field quality ~ 1 : 10^4 of reference; typical B_y between 1.2 and 1.5 T

Weak focusing magnets in p+ synchrotrons

Brookhaven cosmotron; 3.3 GeV; 1952 .

Weakly focused beams are large in both transverse planes – so, therefore, are the bending magnets!

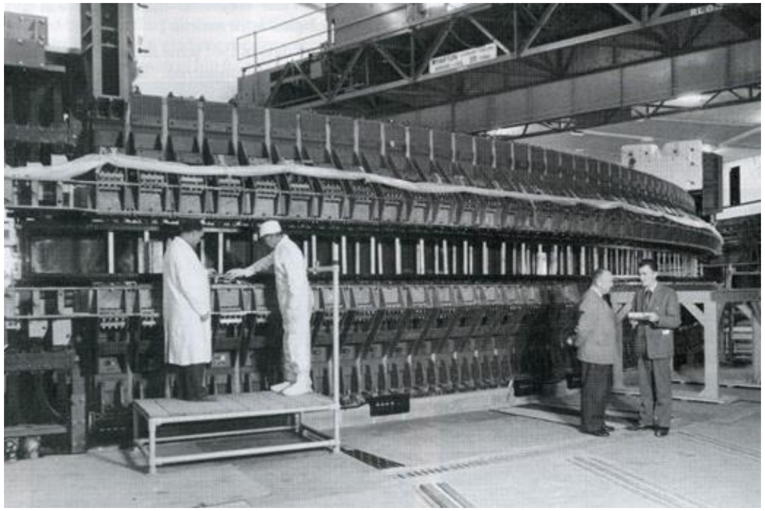
The Berkley Bevatron; 6.2 GeV; 1958.

At that time, BeV was used in USA for 10^9 eV.

Problem – massive size, high capital and running costs.

NIMROD Magnets

NIMROD was a 7 GeV weak-focusing p+ synchrotron built at the Rutherford Laboratory in early 1960s.



Magnet steel : 7,000 tons;
Stored magnetic energy: 20 MJ
Useful aperture for beam:
1.2 m x 0.3m.

Problem solved?

Strong, alternating gradient (A.G.) focusing

In 1949 a Greek lift engineer, Nicholas Christofilos, invented strong alternating gradient focusing and patented it Greece and USA.

In 1952, Ernest Courant and colleague H.S. Snyder at Brookhaven national Lab. independently discovered the same concept but later acknowledged Christofilos' priority.

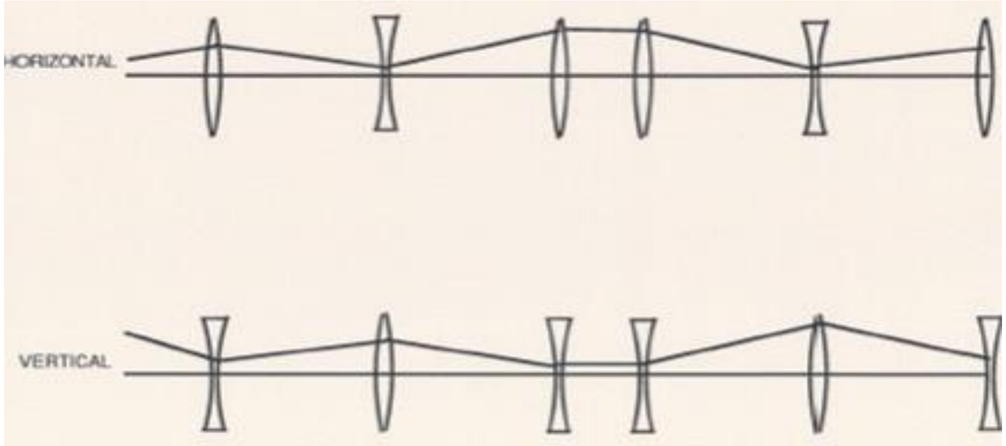
This new strong-focusing reduced the beam dimensions in both transverse planes by substantial factors – with corresponding reduction in the weight and stored energy of the bending magnets by circa an order of magnitude.

A.G. (Strong) Focusing

Two types of bending magnet with very strong gradients were used:

- positive dB_y/dr gives strong horizontal focusing, defocusing vertically;
- negative dB_y/dr gives strong vertical focusing, defocusing horizontally.

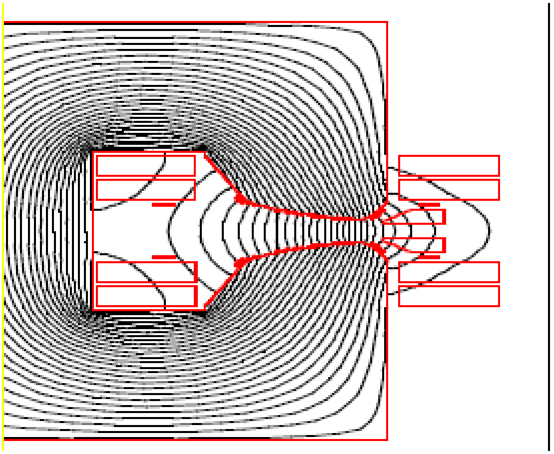
The focusing in both planes is far stronger than weak focusing.



The addition of a gradient, a 'Quadrupole Field', into a dipole bending magnet gives a 'Combined Function' magnet.

The CERN P.S.

A.G., combined function magnets of the CERN proton synchrotron.
First operation November 1959; still operating 2014!
Peak energy 26 GeV.



Combined function A.G. magnets.

The 5 GeV electron synchrotron alternating gradient combined function magnet ring at Daresbury Lab in 1966.
(before shielding had been installed)

‘**F**’ type- horizontally **f**ocusing – field increases with radius

‘**D** ’ type – horizontally **d**efocusing, vertically focusing - field decreases with radius.

NINA combined function 'D' magnet.

NINA magnets: dipole + quadrupole + (a bit of) sextupole.

Note size of magnet compared to the weak focusing magnets.

Peak stored magnetic energy
NINA: 1 MJ

Peak stored magnetic energy
NIMROD: 20 MJ.

Both were cycling accelerators – so stored energy is a **critical parameter.**

Problems with combined function magnets!

The C.F. magnets have focusing built into the pole (steel!).

Focusing (tune) is **critical** (radial and vertical **'Q' values**);

How can the tune be varied?

Solutions:

'Separated function' magnets to make a 'lattice'.

The lattice will contain:

Dipoles ☺;

quadrupoles ?;

sextupoles........?

Separately powered!

The lattice of the Fermi Lab Tevatron (courtesy Fermilab).

What are these new magnets?

WE NEED SOME THEORY!

A bit of theory!

In the vacuum - static Maxwell equations ie no steel:

$$\underline{\nabla} . \underline{\mathbf{B}} = 0 \;;$$

$$\underline{\nabla} \wedge \underline{\mathbf{H}} = \underline{\mathbf{j}} \;;$$

No currents ie $\underline{\mathbf{j}} = 0$;

Then we can put: $\underline{\mathbf{B}} = - \underline{\nabla} \phi$ (ϕ is the magnetic scalar potential)

So that: $\underline{\nabla}^2 \phi = 0$ (Laplace's equation).

The scalar potential in two dimensions cylindrical coordinates:

$$\phi = \Sigma_n \left(J_n \, r^{\,n} \cos n\theta + K_n \, r^{\,n} \sin n\theta\right),$$

with n integral and J_n,K_n are functions of external geometry (remote steel and currents).

This is an infinite series of harmonics; they define the allowed distributions of <u>B</u> in 2 dimensions <u>in the absence of currents</u> within the domain of (r,θ).

Into Cartesian coordinates for **n = 1**

$\phi = J_1 r \cos\theta + K_1 r \sin\theta.$

$B_r = J_1 \cos\theta + K_1 \sin\theta;$

$B_\theta = -J_1 \sin\theta + K_1 \cos\theta;$

$\phi = J_1 x + K_1 y$

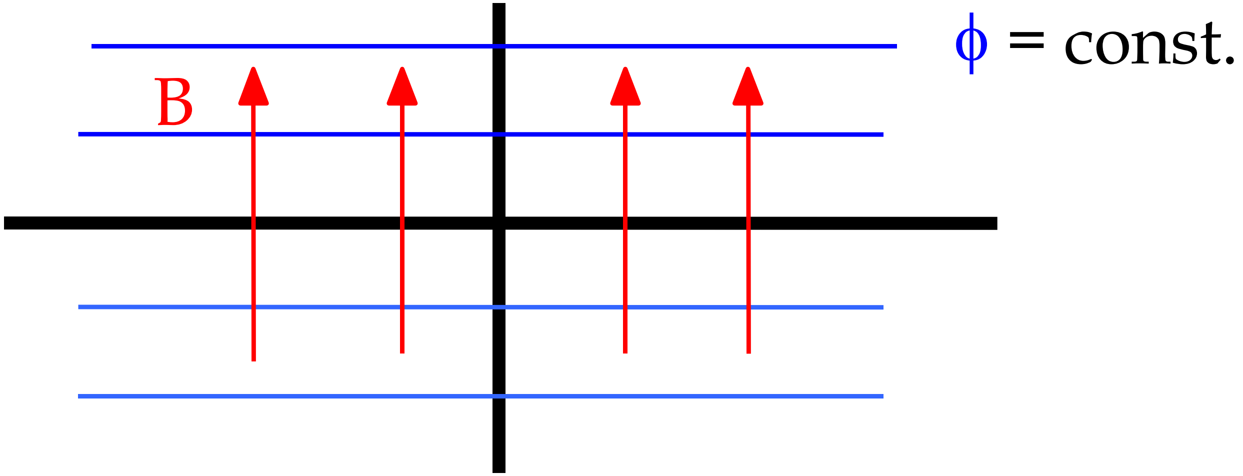
$B_x = J_1$

$B_y = K_1$

This is a dipole field!

$J_1 = 0$ gives vertical field:

$K_1 = 0$ gives horizontal field.



Next harmonic **n = 2.**

$\phi \;=\; J_2\, r\; 2 \cos 2\theta + K_2\, r\; 2 \sin 2\theta;$

$B_r = 2\, J_2\, r\;\; \cos 2\theta + 2K_2\, r\;\; \sin 2\theta;$

$B_\theta = -2J_2\, r\;\; \sin 2\theta + 2K_2\, r\;\; \cos 2\theta;$

$\phi = J_2\,(x^2 - y^2) + 2K_2\, xy$

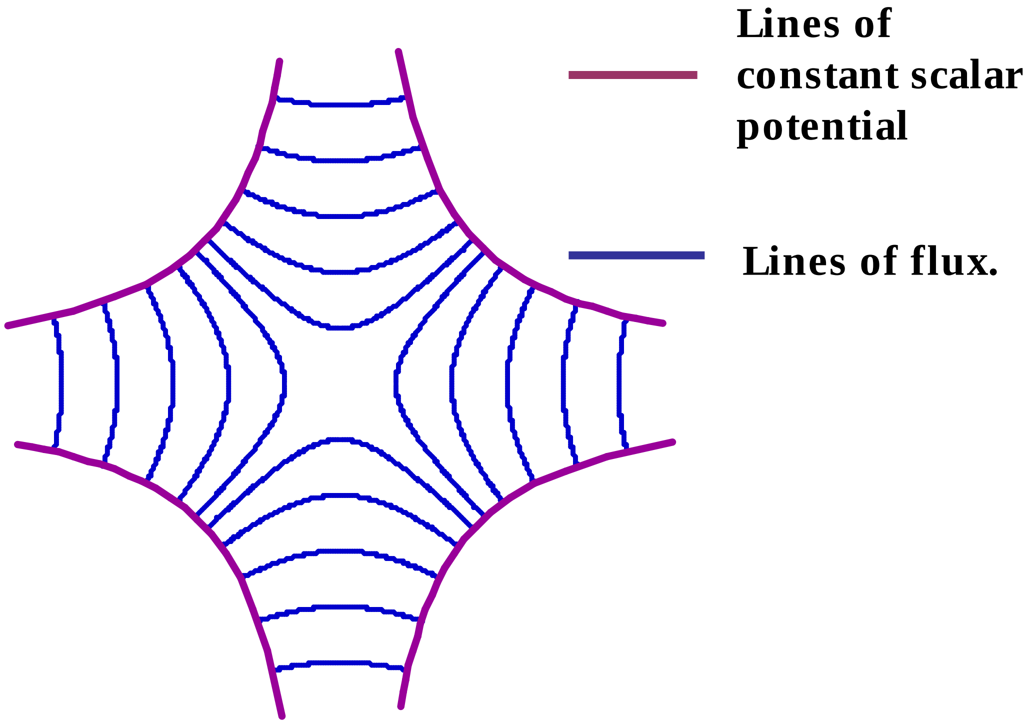
$B_x = 2\,(J_2\, x + K_2\, y)$

$B_y = 2\,(-J_2\, y + K_2\, x)$

Quadrupole field!

$J_2 = 0$ gives 'normal' or ‘upright’ quadrupole field.

$K_2 = 0$ gives 'skew' quad fields (above rotated by $\pi/4$).



Next harmonic n = 3

$\phi = J_2 r 2 \cos 2\theta + K_2 r 2 \sin 2\theta;$

$B_r = 2 J_2 r \cos 2\theta + 2K_2 r \sin 2\theta;$

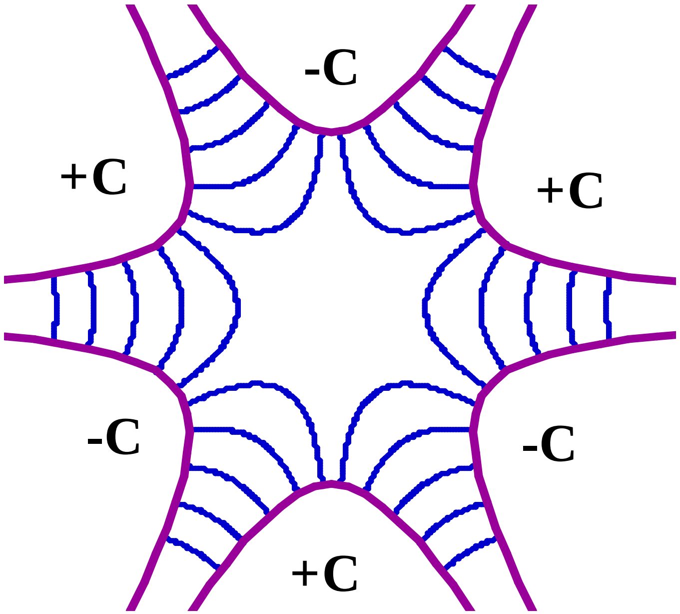
$B_\theta = -2J_2 r \sin 2\theta + 2K_2 r \cos 2\theta;$

$\phi = J_2 (x^2 - y^2) + 2K_2 xy$

$B_x = 2 (J_2 x + K_2 y)$

$B_y = 2 (-J_2 y + K_2 x)$

Sextupole Field.



$J_3 = 0$ giving 'normal' or 'upright' sextupole field.

▬ **Line of constant scalar potential**

▬ **Lines of flux density**

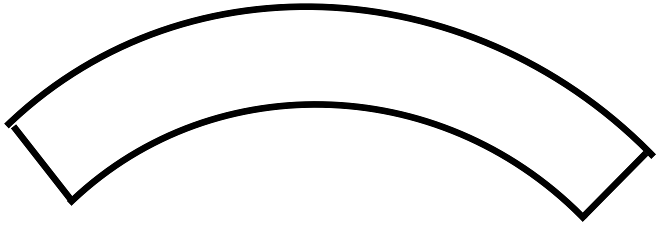
What have we learned?

- all the harmonics are mathematically orthogonal; **multiple harmonics can be created in our combined function magnets**;
- all harmonics have a sin and a cosine term – so full 360° rotation of flux density distributions is available – **'upright' and 'skew' fields can be generated**;
- these issues are determined by the external steel and coil geometry – defining **the task for the magnet designer**;
- by definition, $\underline{B}$ is normal to the contours of ϕ; also $\underline{B}$ is normal to any vacuum/ high permeability ferromagnetic interface; so **the equations for ϕ define the ideal pole shape**.

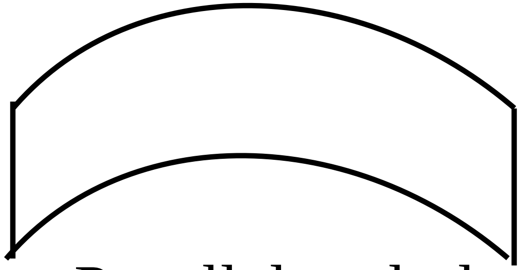
Magnets – pure dipoles

To bend the beam uniformly, dipoles need to produce a field that is constant across the aperture.

But at the ends they can be either:



Sector dipole

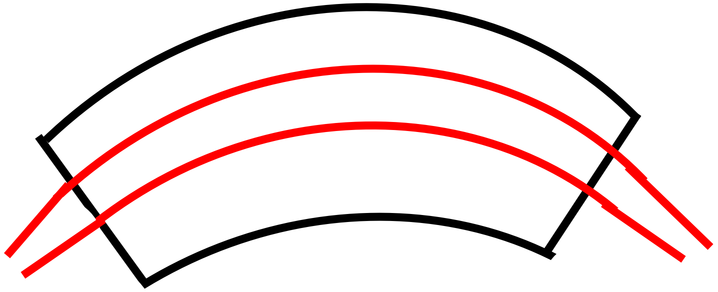


Parallel ended dipole.

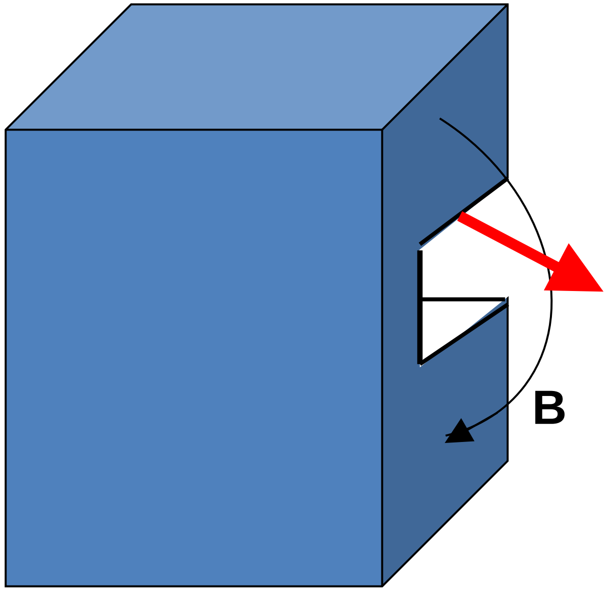
They have different focusing effect on the beam; (their curved nature is to save material and has no effect on beam focusing).

Dipole edge focusing

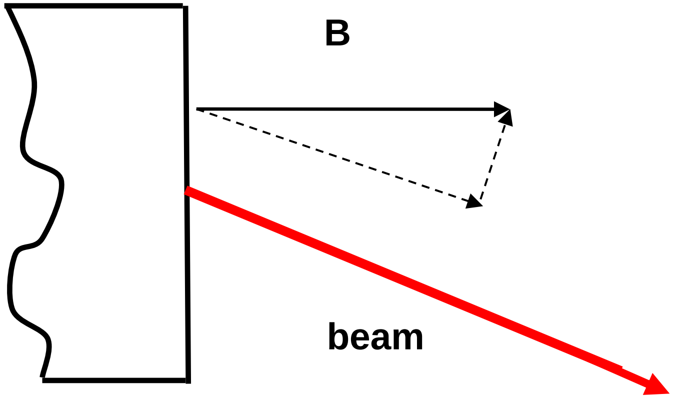
Sector dipoles focus **horizontally**



The end field in a **parallel ended dipole** focuses **vertically**

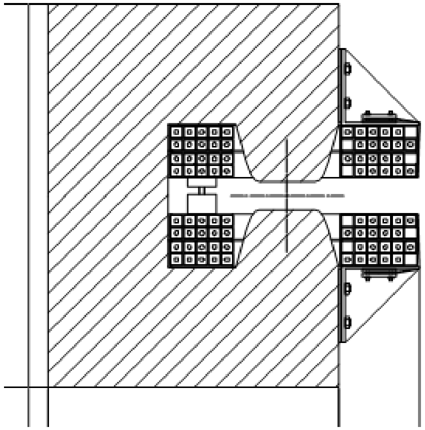


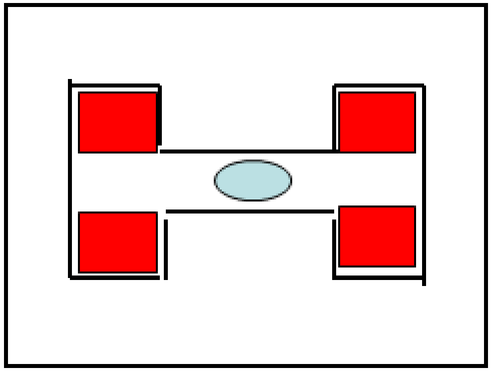
Off the vertical centre line, the field component normal to the beam direction produces a vertical focusing force.



Conventional dipoles.

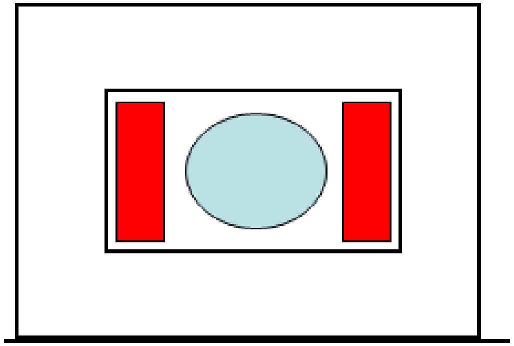
‘C type’





‘H type’

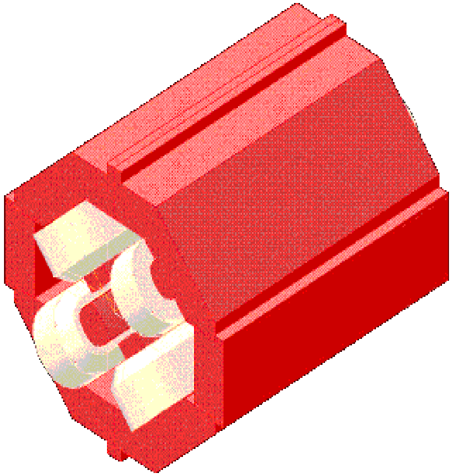
‘Room-temperature’ magnets; field amplitude and distribution are determined by ferrous poles and yokes.

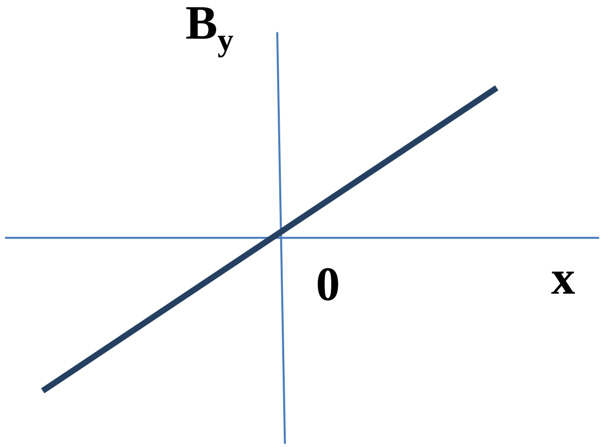


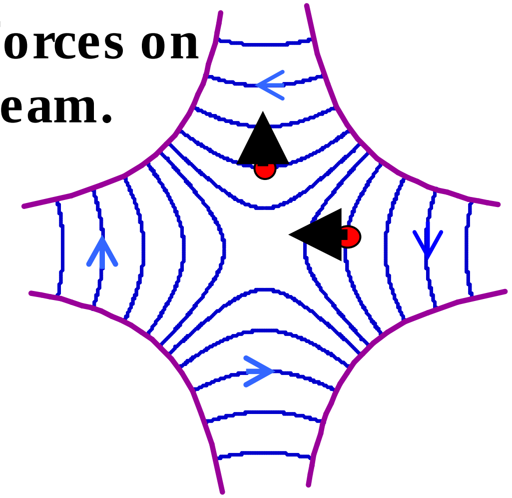
‘Window frame’

Behaviour of quadrupoles

Quads will only focus in one plane – defocus in the other – '**F**' and '**D**' quads (just as when they were built into a C.F. dipole)



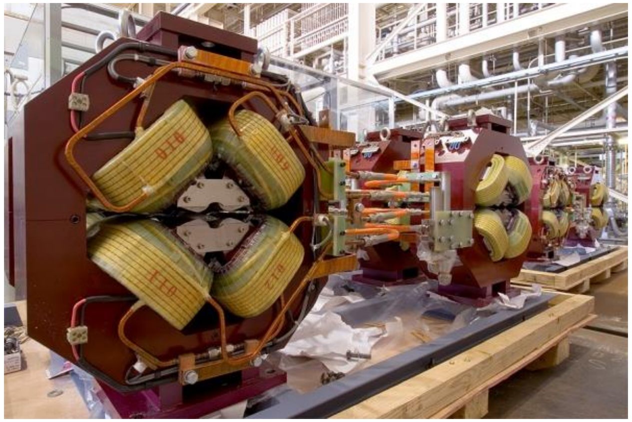




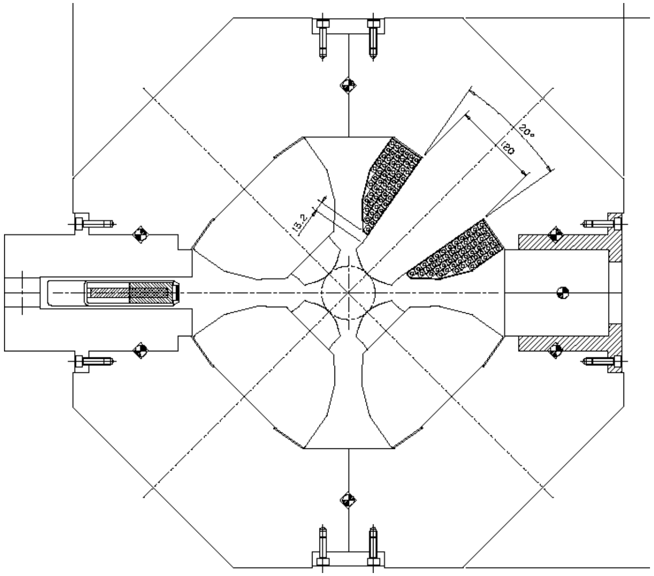
Field lines and forces on the beam.

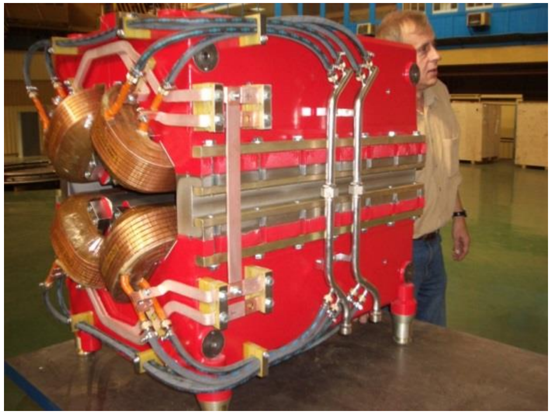
The quadrupoles determine the transverse 'tune' in the horizontal and vertical planes. These are expressed as the ratio of the transverse 'betatron' oscillations to the beam revolution frequency – Q_R, Q_V. In 'strong focusing' rings they are >> 1; and are **crucial** parameters.

‘Room temperature’ quadrupoles.



‘Conventional’

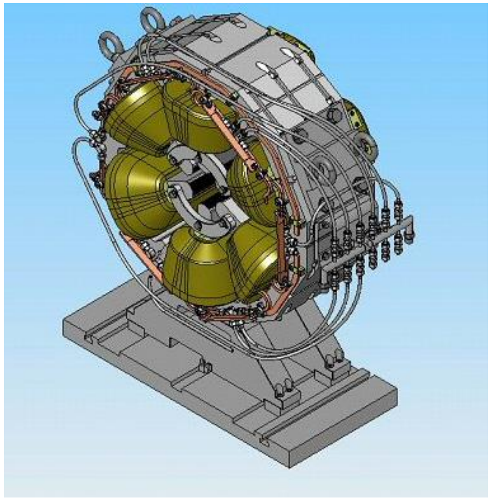


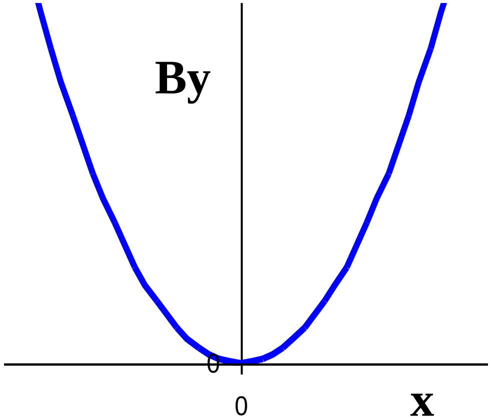


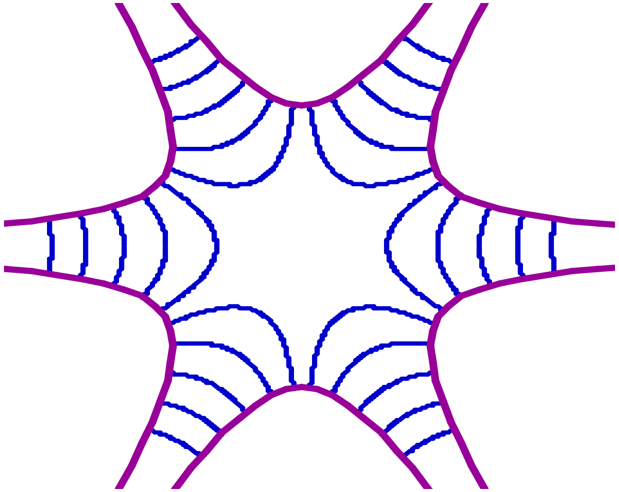
Open sided
–for s.r. sources.

Sextupole magnets.

The beam has 'off-momentum' particles that get the wrong focusing from the quads. In sections of the lattice where there is 'dispersion', the different energy particles are at different horizontal positions in the aperture; corrected by **SEXTUPOLE** magnets, controlling '**chromaticity**'.



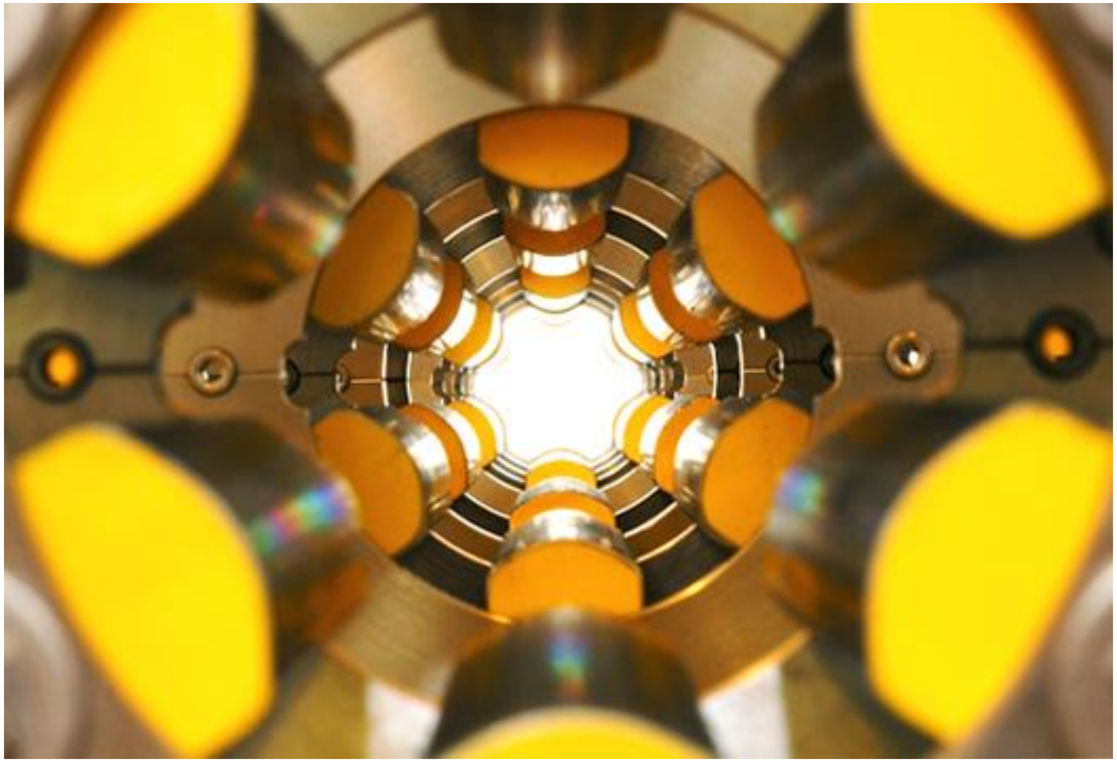




Sextupoles produce a parabolic field distribution across the beam. Field and field gradient is zero at the 'magnetic centre' so that 'on-axis' beam is not deflected, neither focused nor defocused.

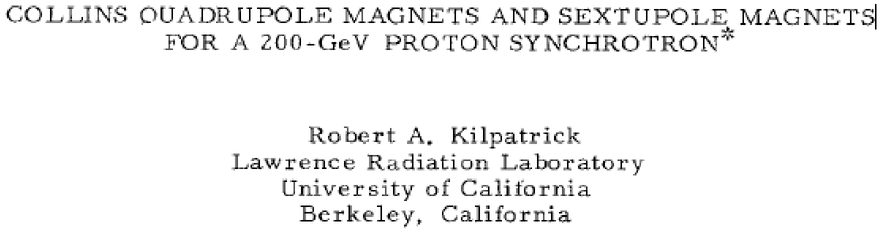
Conventional sextupoles.

Skew sextupole



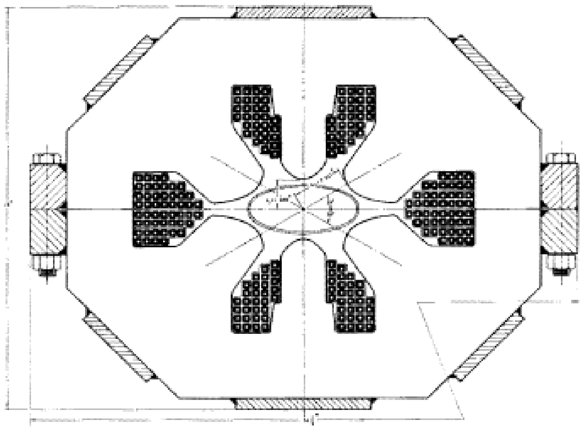
Plans for S.F. accelerator in 1965

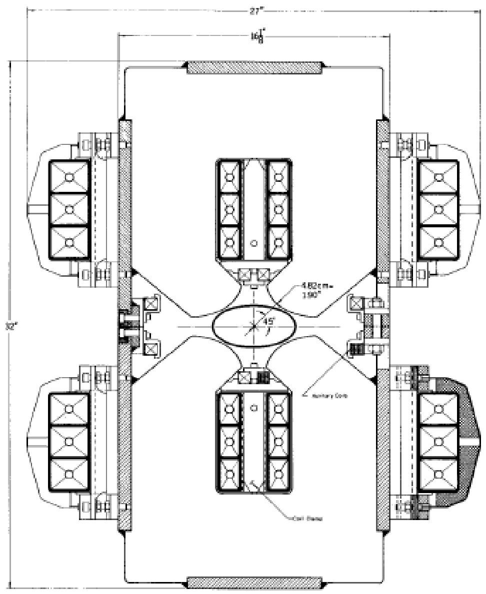
Proc. of 1st International Conference on Accelerator Technology, Stanford, 1965.



COLLINS QUADRUPOLE MAGNETS AND SEXTUPOLE MAGNETS
FOR A 200-GeV PROTON SYNCHROTRON*

Robert A. Kilpatrick
Lawrence Radiation Laboratory
University of California
Berkeley, California





The SPS (CERN) S.F. Lattice

Synchrotron radiation sources:

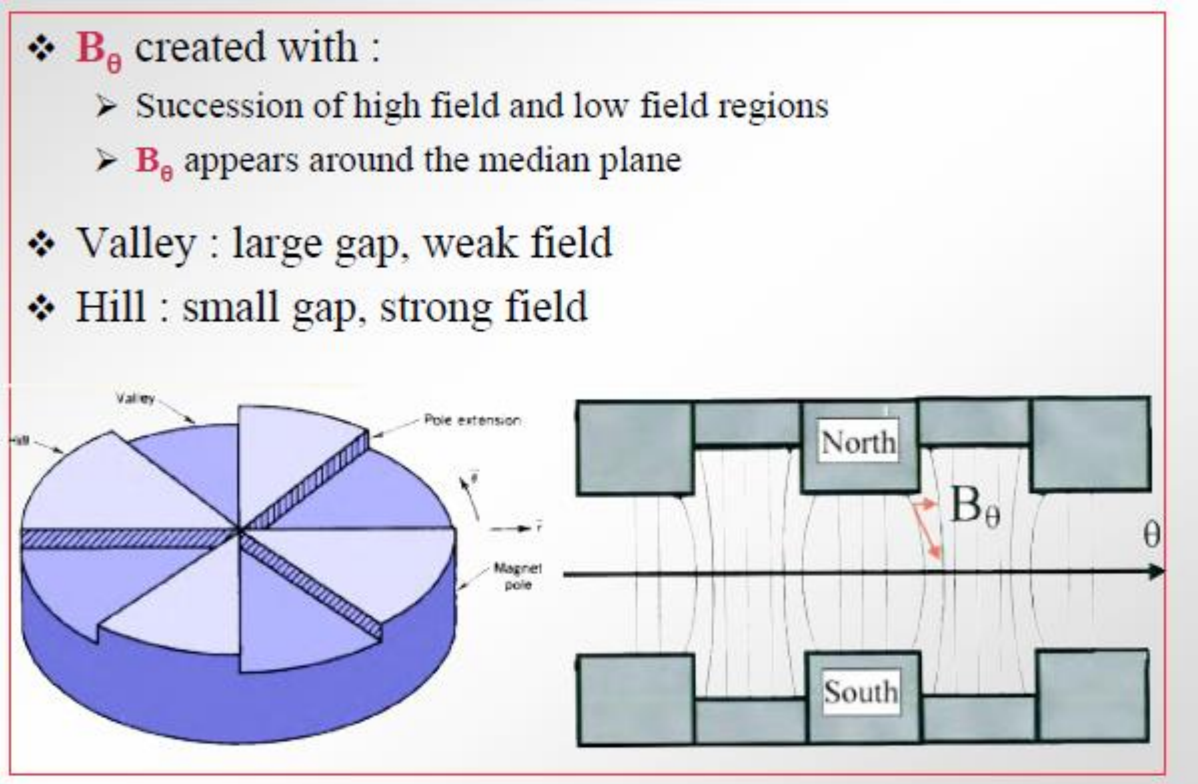
Require complex s.f. lattice; see Diamond – UK’s new(ish) 3 GeV synchrotron radiation source:

48 dipoles, 240 quadrupoles, 168 sextupoles, **provide the flexibility to adjust beam size for each experimental beam-line.**

Each quadrupole and sextupole are independently controlled by a separate power supply.

Back to cyclotrons again

Using edge focusing, it is now possible to increase B_y with radius to still focus the beam in both planes; high energy isochronous cyclotrons are now possible.



- B_θ created with :
  - Succession of high field and low field regions
  - B_θ appears around the median plane
- Valley : large gap, weak field
- Hill : small gap, strong field

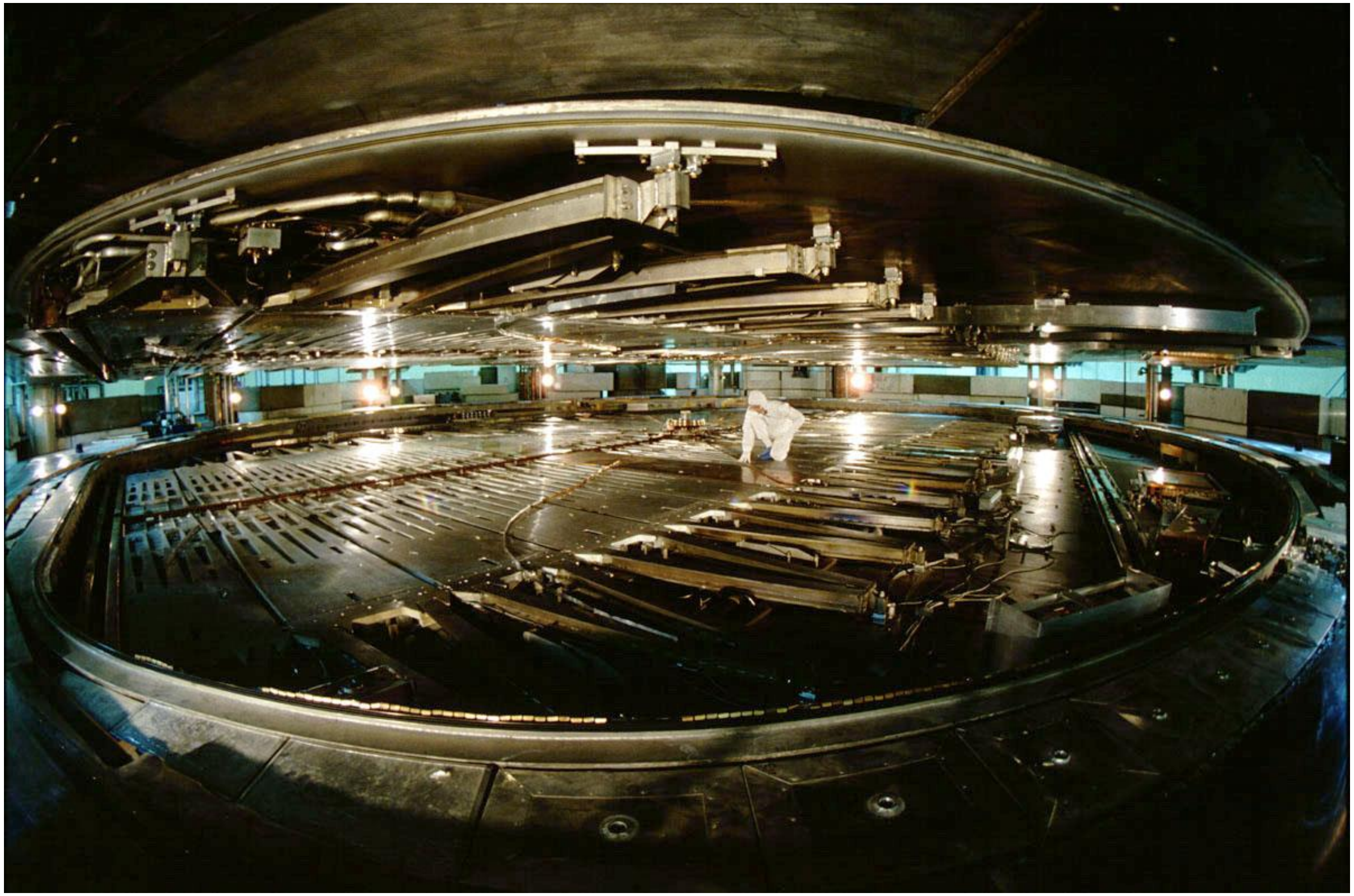
From USPAS 'Cyclotrons Old but Still New' -with permission from William Barletta.

The world's biggest cyclotrons 'isochronous':

P.S.I., Switzerland: 590 MeV

'Triumf' lab, B.C., Canada: 520 MeV

The TRIUMF Cyclotron



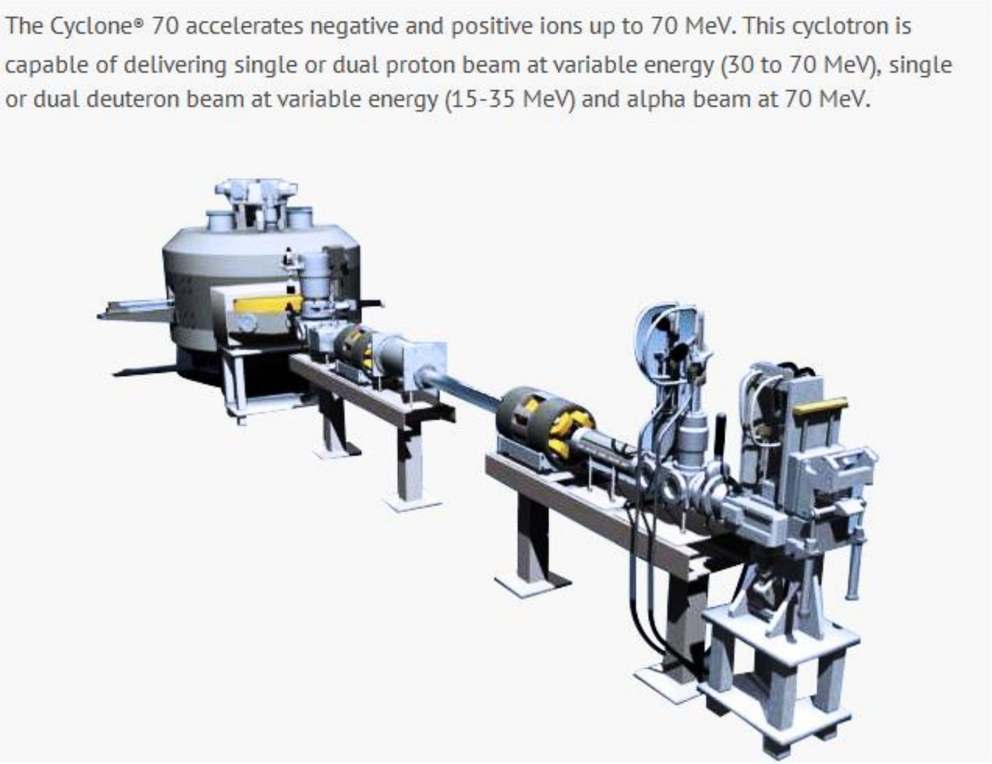
Diameter = 18m; Magnet weight = 4,000 tonnes.

Medical cyclotrons for oncology

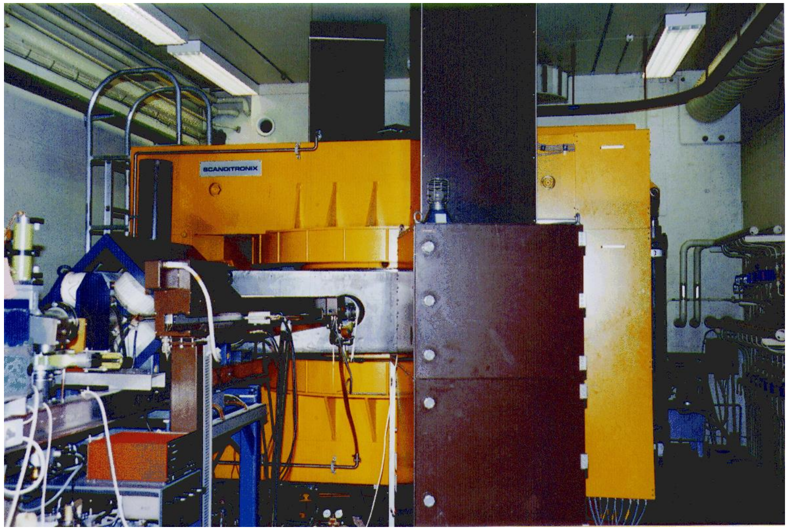
RADIOPHARMA
SOLUTIONS

GMP RADIOPHARMACY

There are about 650 cyclotrons now operational in the world – many for medical applications.



The Cyclone® 70 accelerates negative and positive ions up to 70 MeV. This cyclotron is capable of delivering single or dual proton beam at variable energy (30 to 70 MeV), single or dual deuteron beam at variable energy (15-35 MeV) and alpha beam at 70 MeV.



The Claterbridge oncology centre's 85 MeV cyclotron.

Problem with the synchrotron

- Synchrotron magnet strengths must increase in proportion with the particle momentum;
- energy has to be cycled between the magnets and an enegy store
- for the dipoles in a large machine this is many MJ.
- Three 'time frames':
  - Slow cycling: accel time c 3 s; cycle frequency (0.25 to 0.5 Hz)
  - Medium cycling: accel time c 0.3 s; cycle frequency (2 to 5 Hz);
  - Fast cycling; accel time 10 ms; cycle frequency (50 Hz);

To accelerate unstable particles (eg muons $\tau = 2.2\ \mu s$) ???

Solution: a 'Fixed field alternating gradient' accelerator (the FFAG);

Combining the advantages of the cyclotron and the synchrotron;

Reducing or eliminating their disadvantages!

FFAGs?

In a synchrotron:

- beam keeps the same orbit radius in the dipoles;
- magnetic field varies;

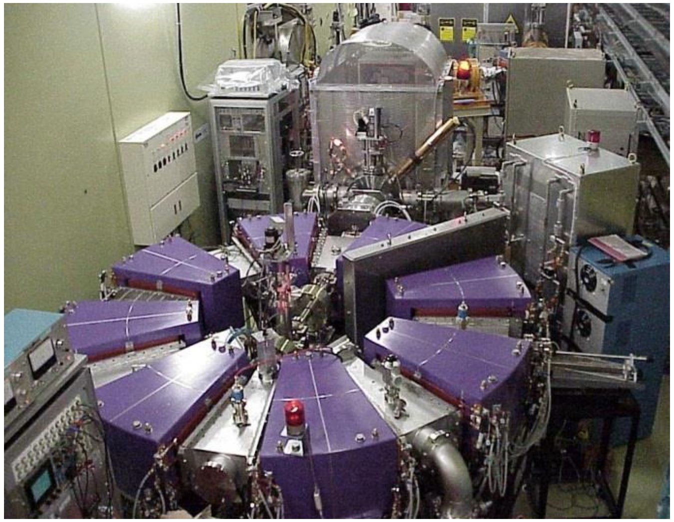
In a cyclotron:

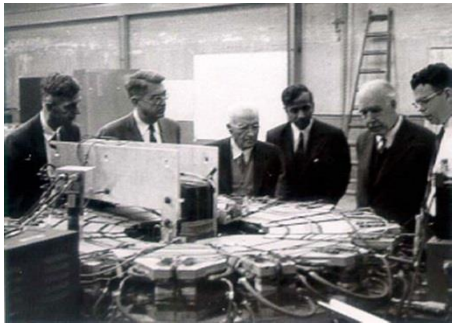
- magnets are d.c;
- beam moves from the centre to the outer radius when accelerating;

The ‘fixed field alternating gradient’ (FFAG) accelerator:

- magnets are d.c.;
- acceleration time is <<< acceleration time in a synchrotron;
- beam moves in the aperture during acceleration;
- but the aperture and magnets is << the size of a cyclotron;
- the momentum range is < the possible range in a synchrotron.

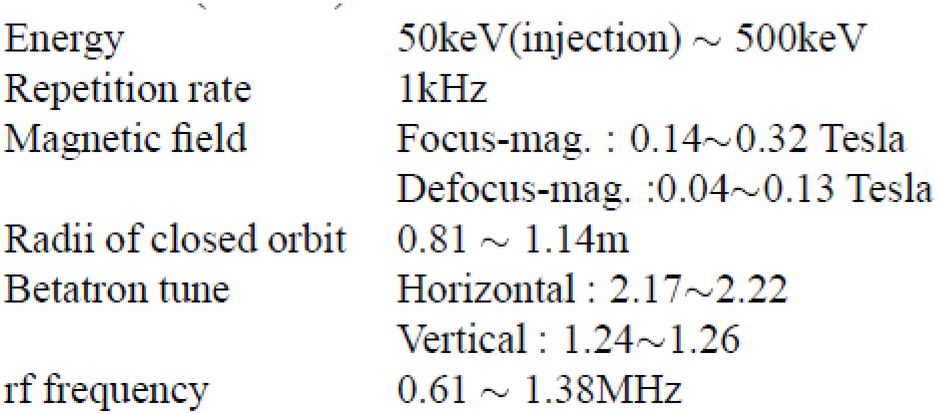
FFAGs –old and recent!





The first FFAG ever built, a 400 keV electron machine first operated at MURA in 1956.

The first proton FFAG ever built, the Proof-of-Principle machine first operated at the KEK Laboratory in Japan in 2000.



Energy	50keV(injection) ~ 500keV
Repetition rate	1kHz
Magnetic field	Focus-mag. : 0.14~0.32 Tesla Defocus-mag. :0.04~0.13 Tesla
Radii of closed orbit	0.81 ~ 1.14m
Betatron tune	Horizontal : 2.17~2.22 Vertical : 1.24~1.26
rf frequency	0.61 ~ 1.38MHz

Note – acceleration x10; radius x 1.4; asynchronous!

Magnets for **scaling** FFAGs

In a scaling FFAG, the beam orbits change diameter, but have the same shape. The magnets generate the following field configuration:

$$B_r = 0, \quad B_\theta = 0, \quad B_z = ar^k \, f(\psi),$$

where

- $\psi = N \, [\tan \zeta \; \ln(r/r_0) \; - \; \theta],$
- k is the field index,
- N is the periodicity,
- ζ is the spiral angle (which equals zero for a radial machine),
- r the average radius, and
- $f(\psi)$ is an arbitrary function that enables a stable orbit.

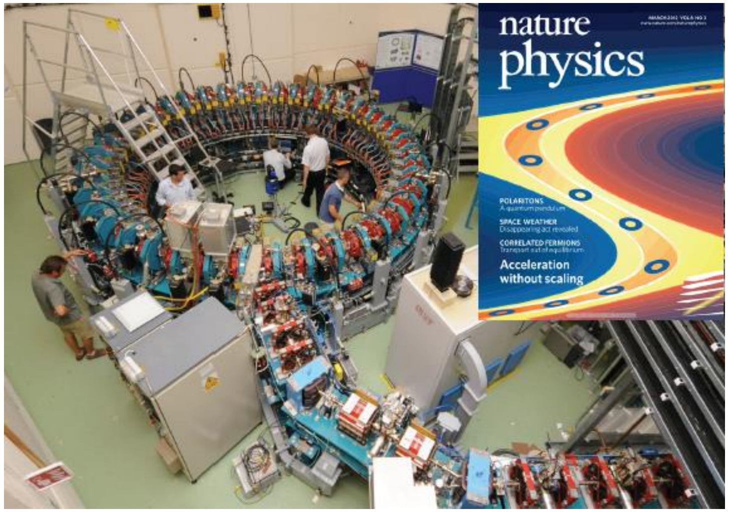
For k >>1, the FFAG is much smaller than a cyclotron of the same energy, but is highly non-linear.

EMMA at Daresbury Lab.

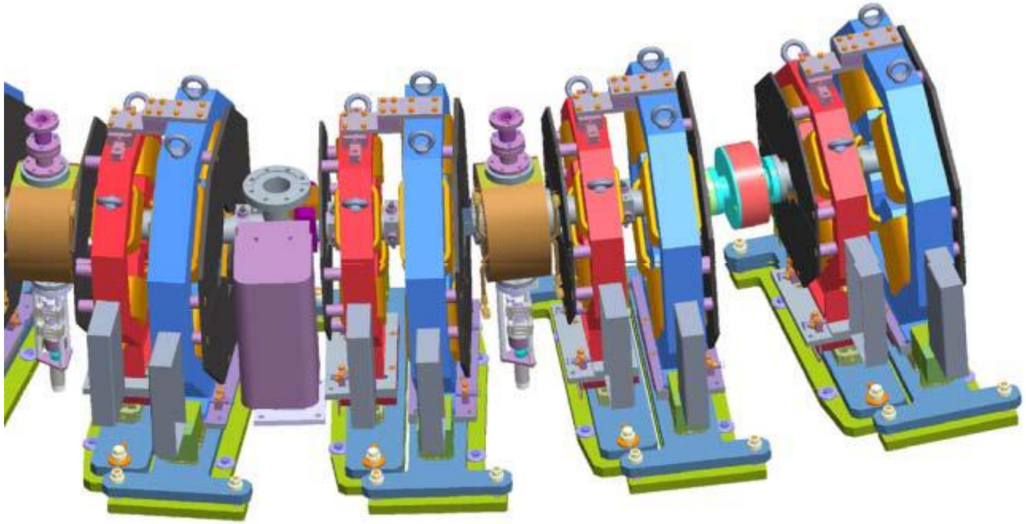
EMMA (Electron Machine with Many Applications) is a **non-scaling**, **linear** FFAG with a lattice of 42 cells, each containing an **F and a D quadrupole.**

It accelerates electrons from **10 to 20 MeV in 10 turns - c 550 ns**.

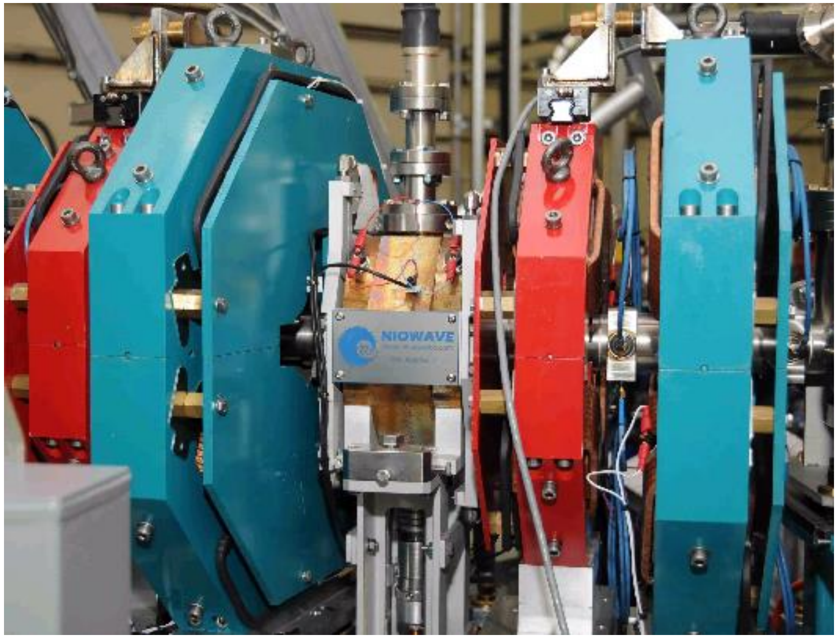
Tune and beam trajectory vary during acceleration.



No dipoles! The beam is off centre in the quads which therefore provide a dipole field to give the necessary bending.



Thin, thin quadrupoles in EMMA



Quadrupole magnet parameters:

F quad:

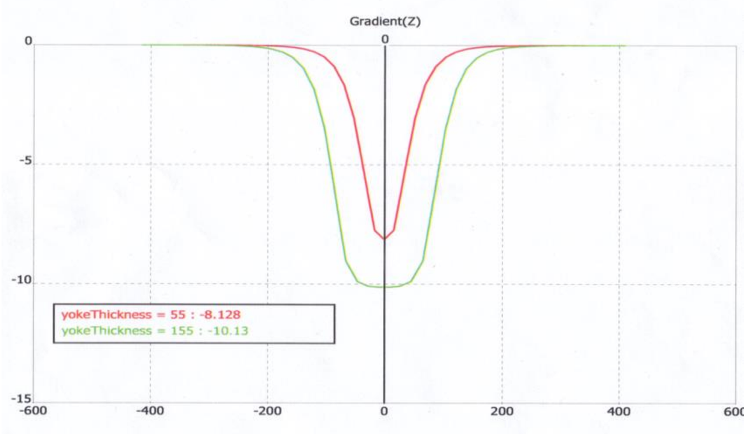
length:	55 mm;
Inscribed diameter:	74 mm:

D quad:

length:	65 mm;
inscribed diameter:	106 mm.

So the magnets are all ends and no middle!

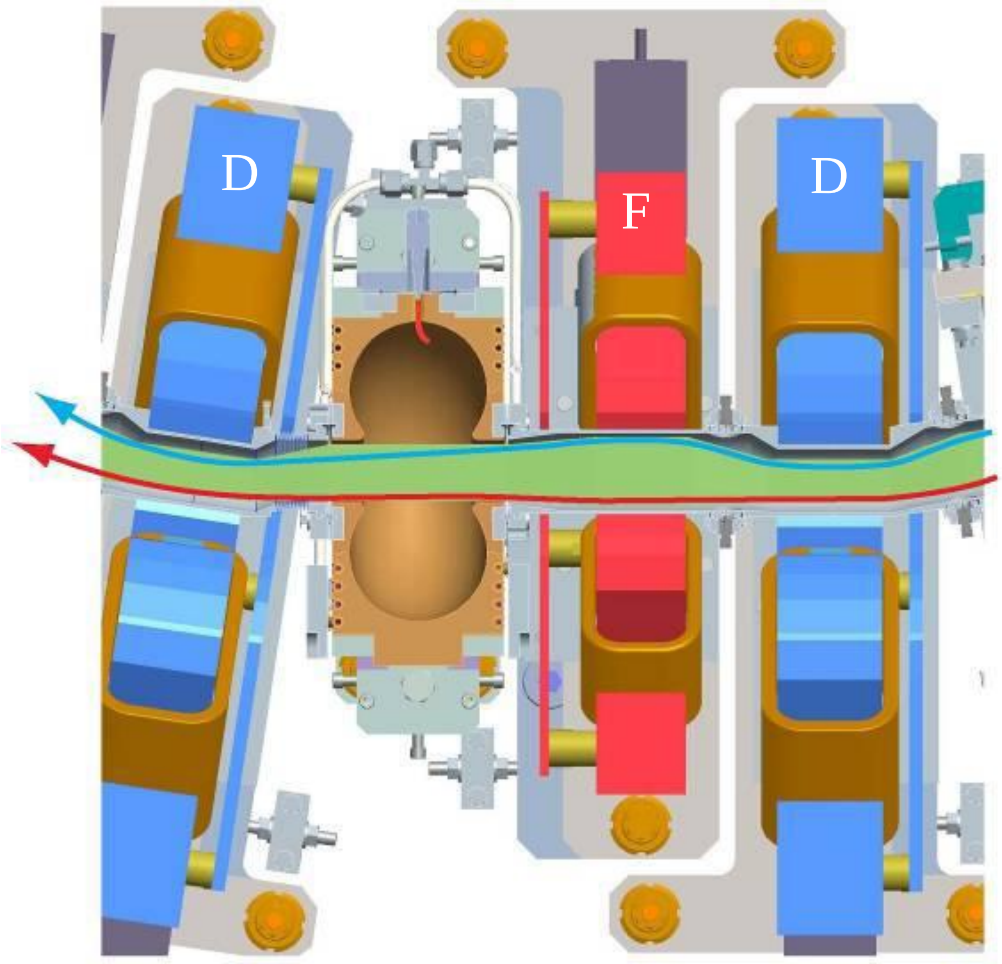
See graph of field gradient (dB/ dx) vs azimuthal position (z) for F — and D —



Beam trajectories in EMMA

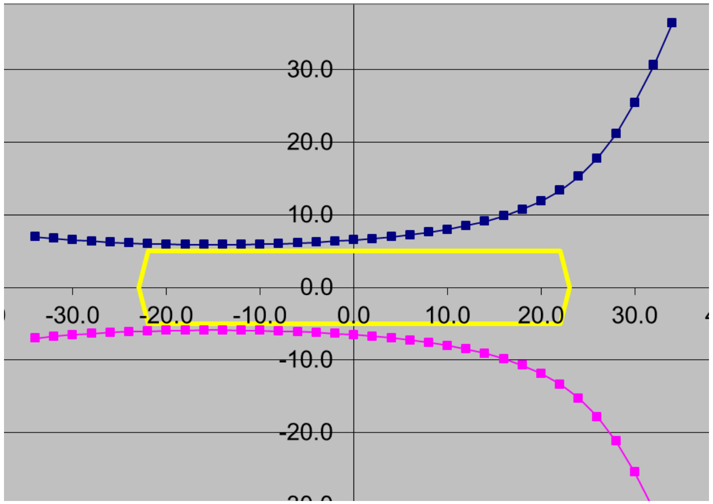
Low energy beam

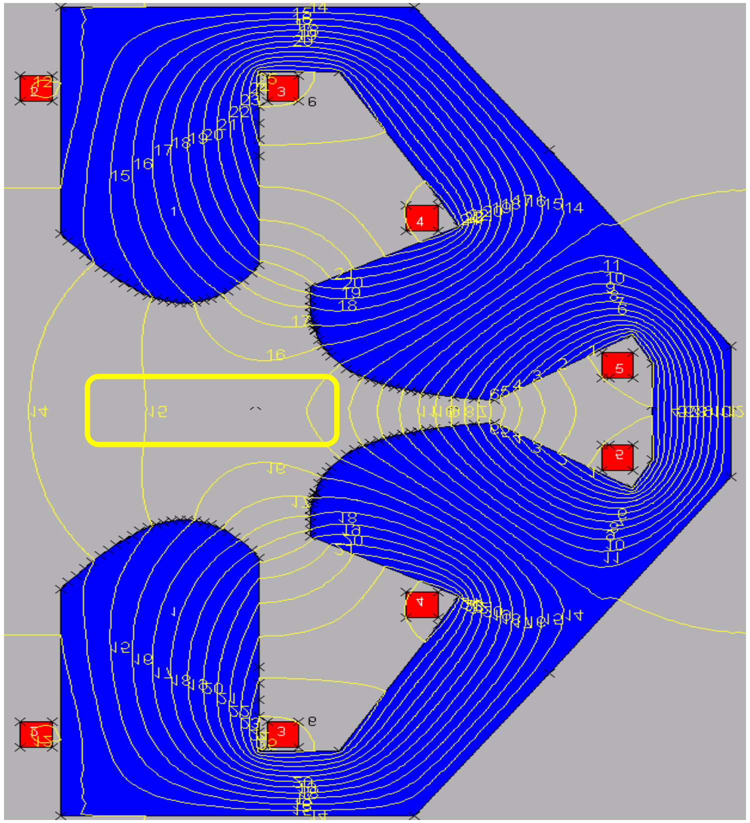
High energy beam

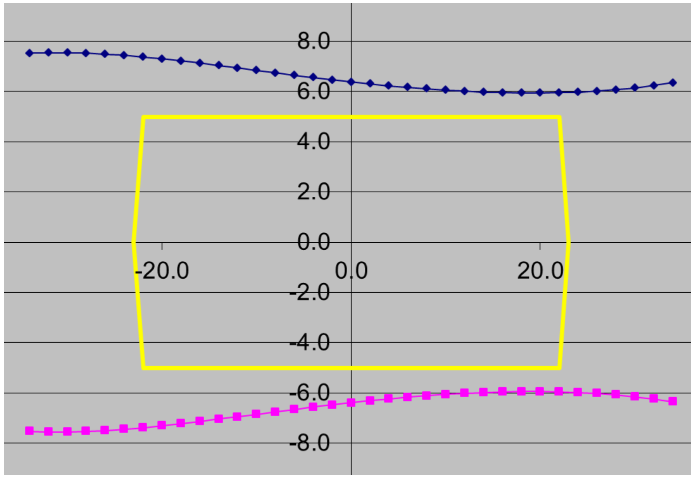


Horizontal section through vertical centre line; the beam moves ~ 10 mm during a factor of 2 increase in momentum.

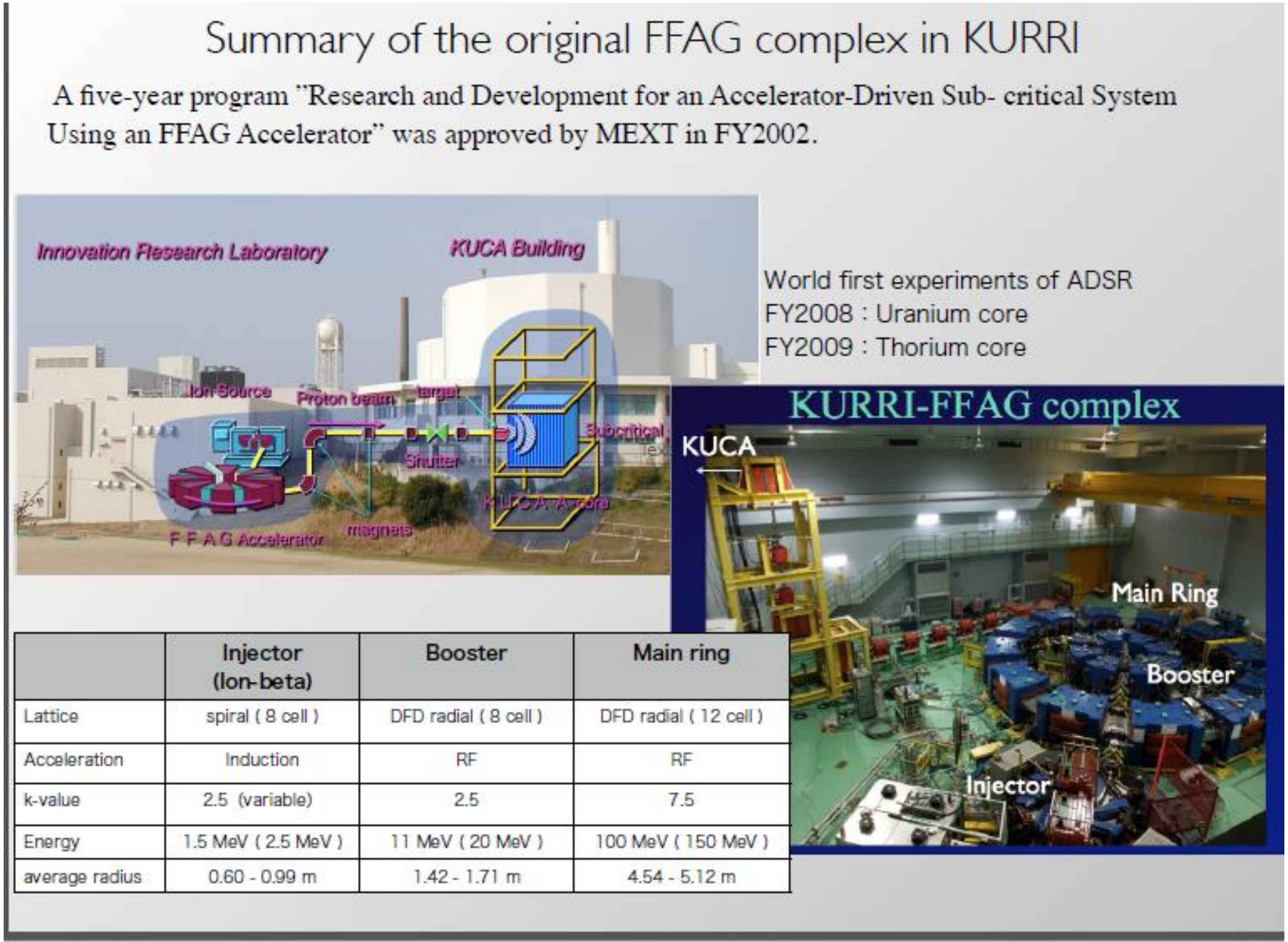
Poles of three types of magnet for a non-scaling, non-linear FFAG







KURRI explores Accelerator Driven Sub-critical Reactor using FFAGs



Summary of the original FFAG complex in KURRI

A five-year program "Research and Development for an Accelerator-Driven Sub- critical System Using an FFAG Accelerator" was approved by MEXT in FY2002.

World first experiments of ADSR
FY2008 : Uranium core
FY2009 : Thorium core

KURRI-FFAG complex

	Injector (Ion-beta)	Booster	Main ring
Lattice	spiral (8 cell)	DFD radial (8 cell)	DFD radial (12 cell)
Acceleration	Induction	RF	RF
k-value	2.5 (variable)	2.5	7.5
Energy	1.5 MeV (2.5 MeV)	11 MeV (20 MeV)	100 MeV (150 MeV)
average radius	0.60 - 0.99 m	1.42 - 1.71 m	4.54 - 5.12 m

The FUTURE

FFAGs are being investigated for:

- accelerating short-lived particles;
- seeding sub-critical Uranium/ Thorium reactor cores;
- proving low cost hadron therapy facilities;

Possibilities; **scaling/non-scaling**; **linear/non-linear**; **isochronous /asynchronous** ?

Challenges need to be met and development made to meet these applications!

Ingenuity of materials inventors.

THE ALCHEMIST.

1. GOLD? – NO!

2. HIGH ENERGY DENSITY PERMANENT MAGNET MATERIALS – YES

3. SUPERCONDUCTORS – YES, YES, YES!

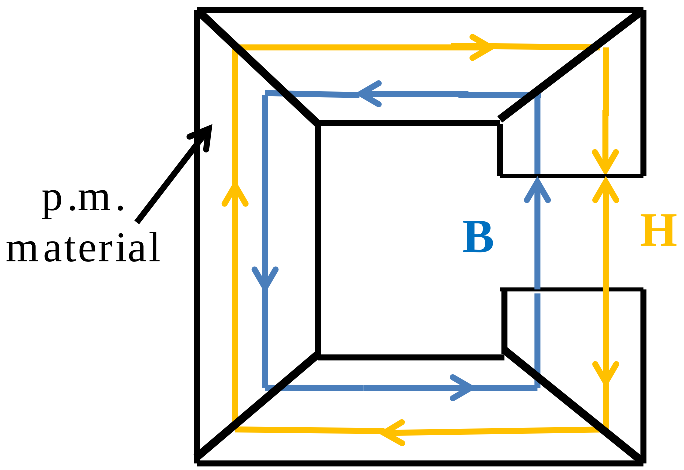
Use of permanent magnet (p.m) materials.

In p.m. external currents = 0;

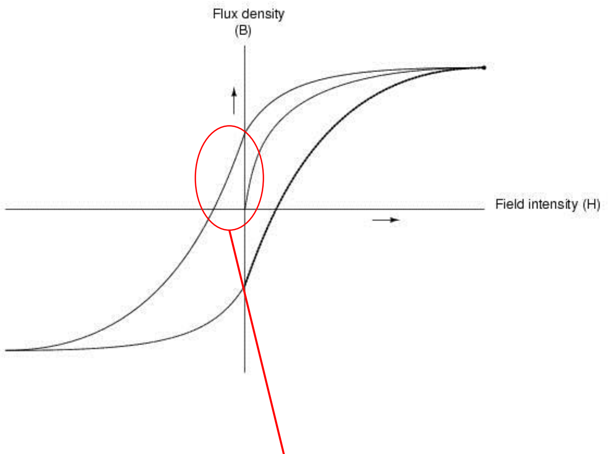
so: $\text{curl } H = 0$;

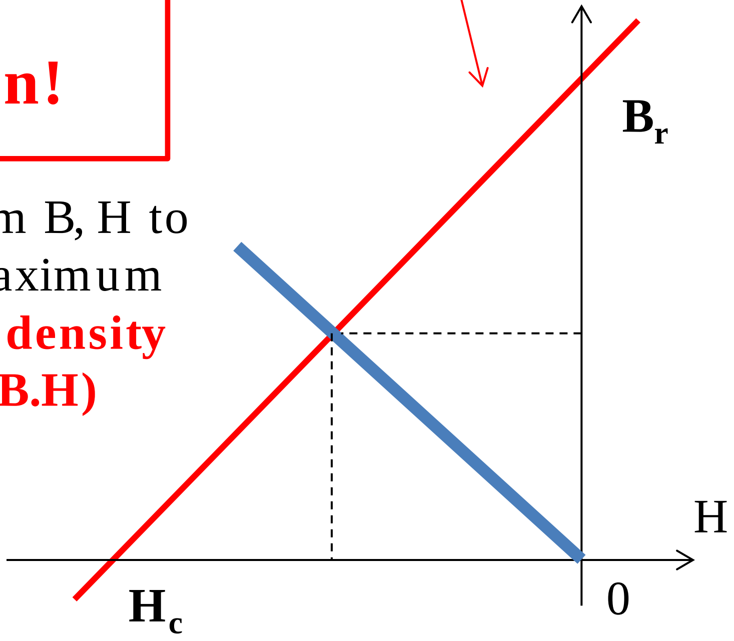
around any closed loop:

$$\int H.ds = 0;$$



p.m. is polarised! magnetised only in the 'easy' direction!

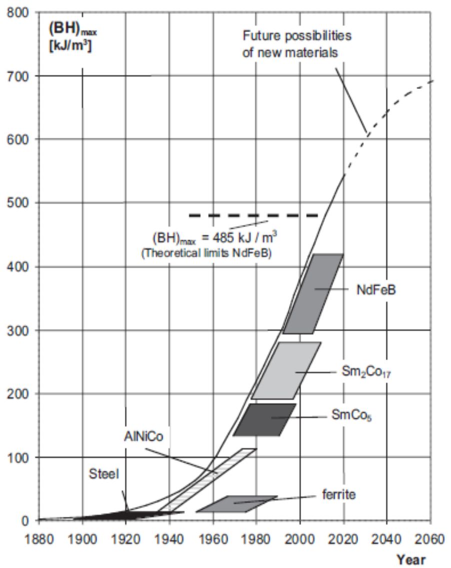


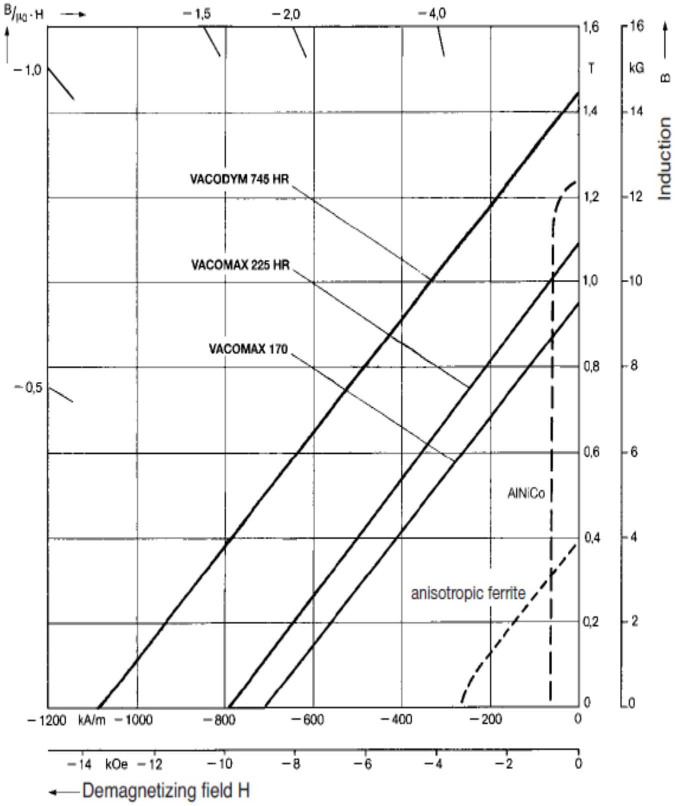


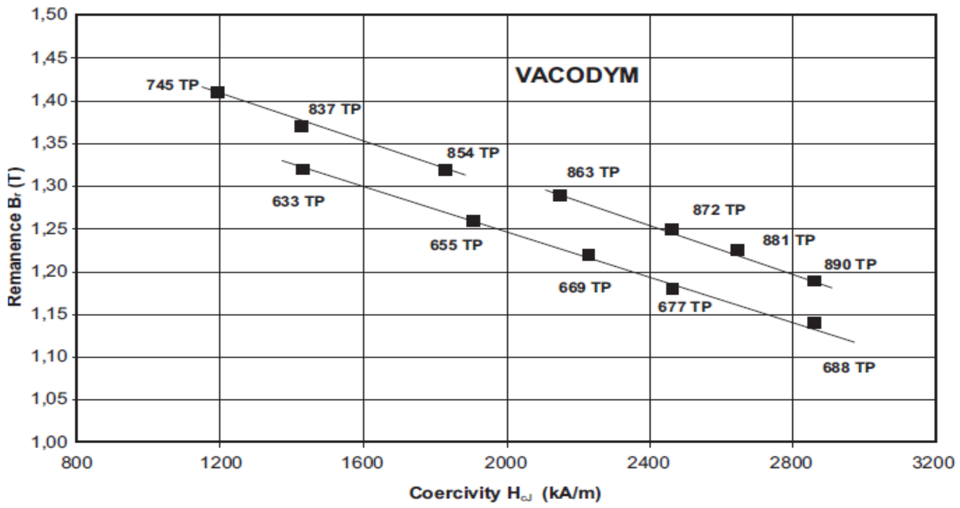
Optimum B, H to give maximum **energy density = (B.H)**

so if: $B_{air} > 0$, then: $H_{pm} < 0$;
but B is continuous, so $B_{pm} > 0$;
the material operates in the 2nd quadrant of the hysteresis loop.

Vacuumschmelze data



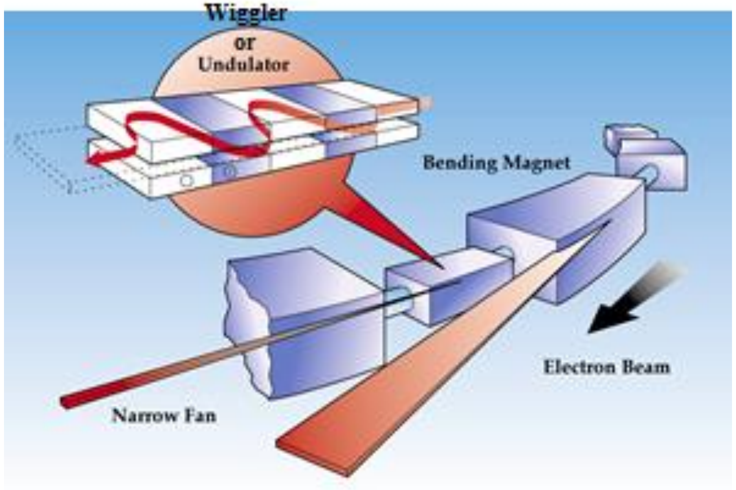




Synchrotron Radiation

Relativistic electrons passing through a magnetic field emit:

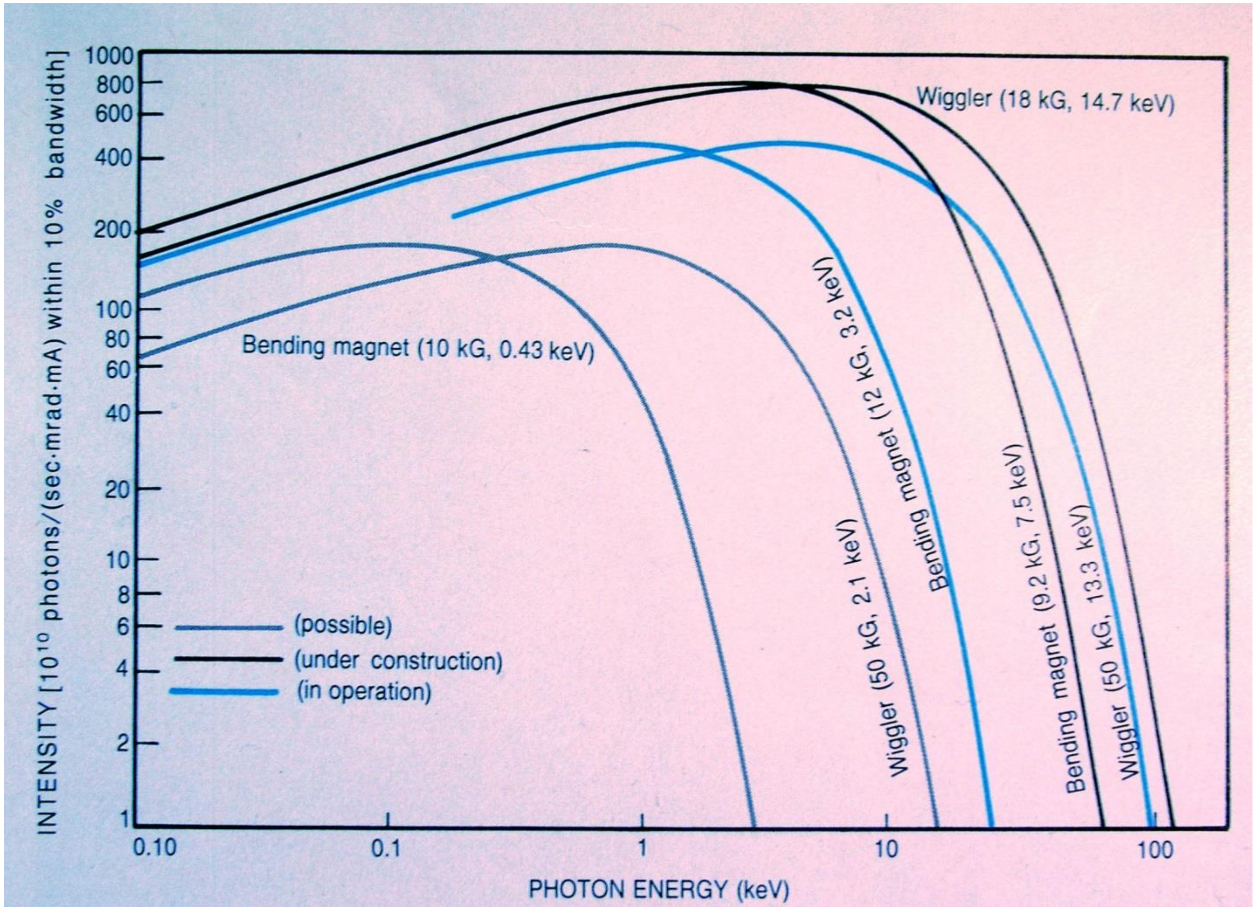
'**synchrotron radiation**' – broad band electro-magnetic radiation that is widely used for materials research.



In an s.r. facility storage ring, the radiation from the dipole bending magnets is useful, but considerable advantage is gained by using '**insertion devices**' which generate **spatially alternating vertical field** as the principle source of s.r:

- **undulators**: relatively low field producing narrow intense spectral lines of highly collimated s.r.; **usually using permanent magnets**;
- **wigglers**: high field devices generating intense broad band radiation shifted to lower wavelengths – higher photon energy; **permanent magnets/warm current carrying coils/super-conducting coils**.

Typical spectra for bending dipoles and wigglers for various energy e^-.



SPEAR (SSRL):

—

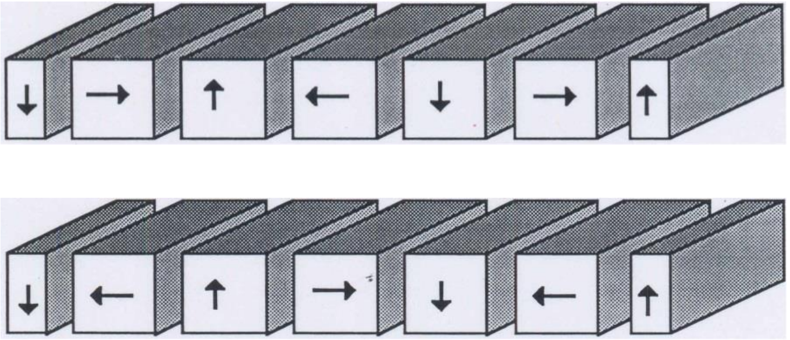
3.5 GeV e-;
0.9 T dipoles;
1.8 T wiggler:

SRS (Daresbury):

—

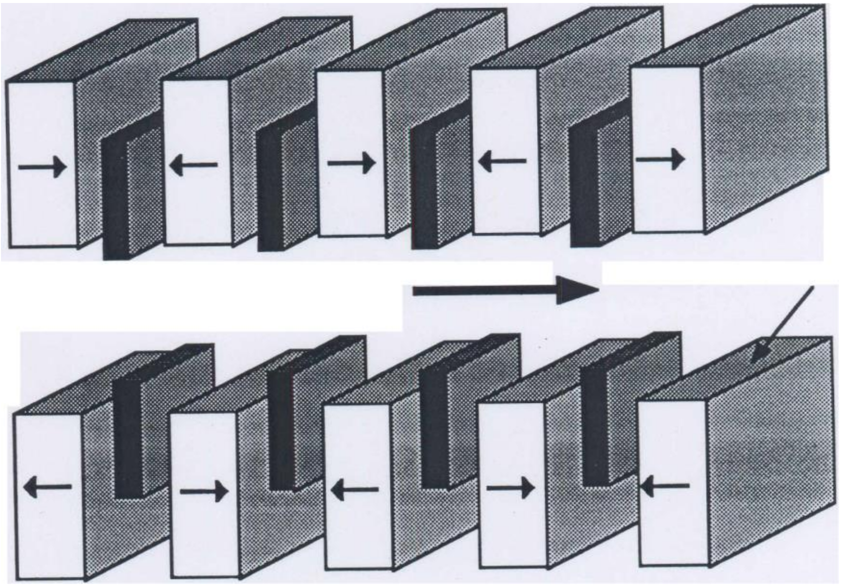
2.0 GeV e-;
1.2 T dipoles;
5.0 T wiggler:

P.M. structures for insertion devices.



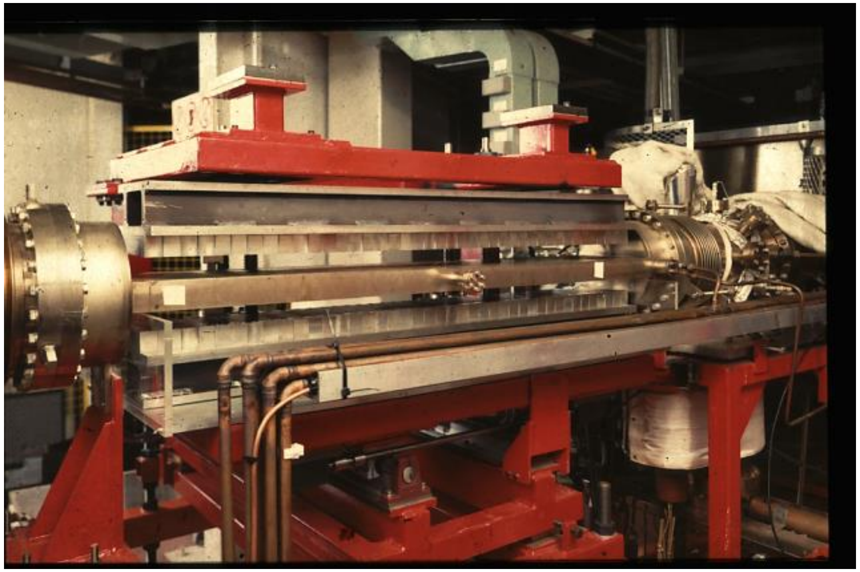
Assembly for low field **undulators**. Arrows indicate direction of polarisation in p.m. **Field at the beam has similar magnitude to that in the p.m.**

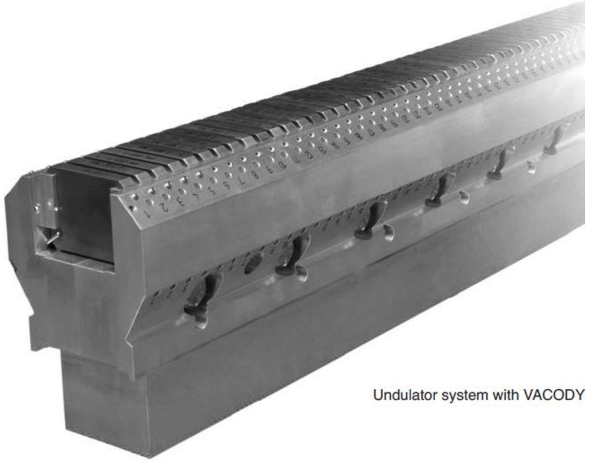
Assembly for high field**, hybrid wigglers**; high permeability steel interleaved with p.m. has large cross section at steel/ p.m. interface; low cross section at pole (beam interface).



Field in pm << field at beam.

Undulator assemblies



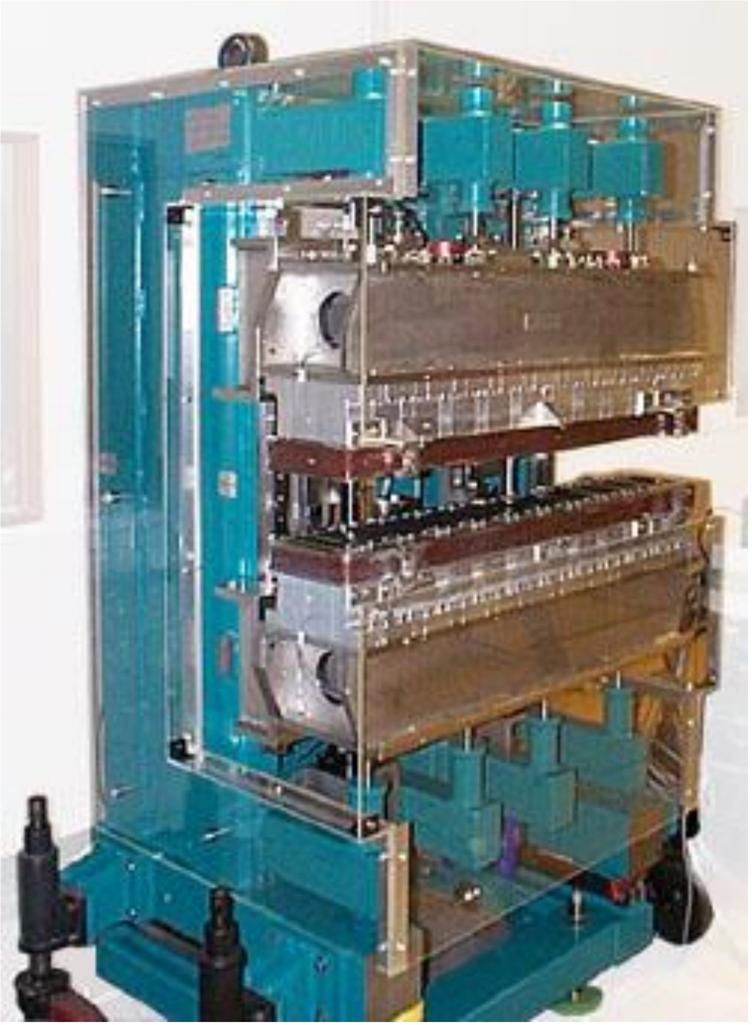


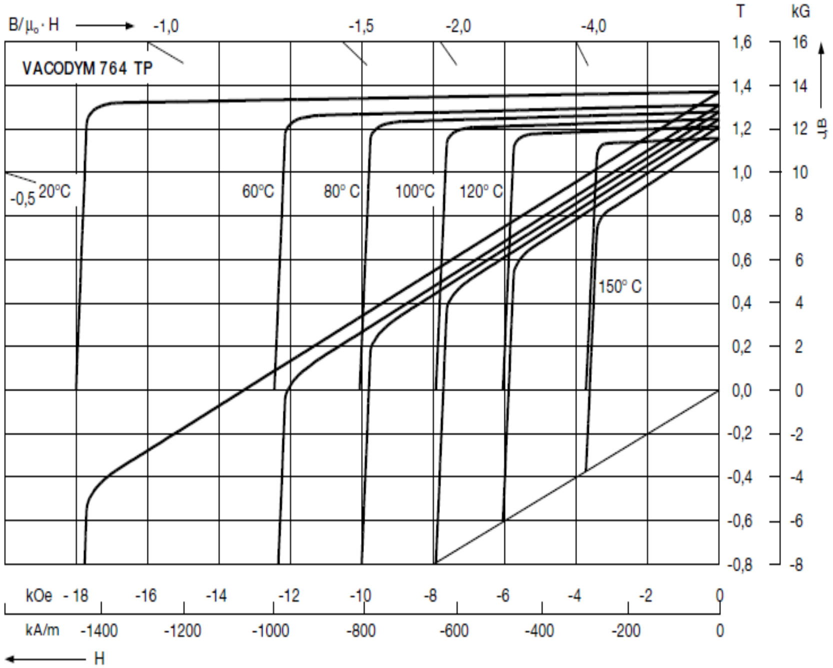
Undulator system with VACODY

'Massive mechanical assembly needed to restrain attractive force between top and bottom assemblies. (Tonnes!).

Jaws can be opened or closed to vary field.

Wiggler on the SRS





Field at beam **2.4 T (world record?);**

Field in **VACODYM 764 TP c 0.8 T;**

P.M. used in lattice magnets?

STFC ASTeC has been working with CERN on quadrupoles for the drive beam-line in CLIC:

- **The power consumption for the EM version will be ~8 MW;**
- **Total power load limit to air within the tunnel is only 150 W/m;**
- **A PM quad would potentially have many advantages:**
  - **Vastly reduced electrical power;**
  - **Ecologically 'green';**
  - **Very low operating costs**
  - **No cooling water needs**
  - **Very low power to air.**

Problem: how to vary the strength of the quadrupole by a factor of 1.7;

Solution: mechanical change to the p.m. geometry;

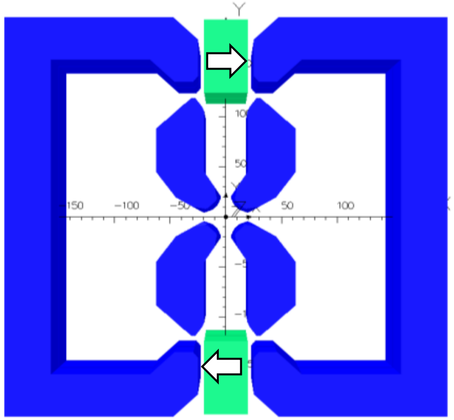
Problem: pole position **is fixed** and must be **stable to c 20 μm**.

Solution.

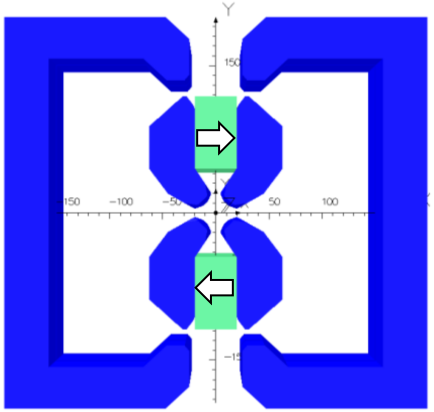
Pole ands yoke fixed;
p.m. moves;

Lab prototype (*) meets spec.

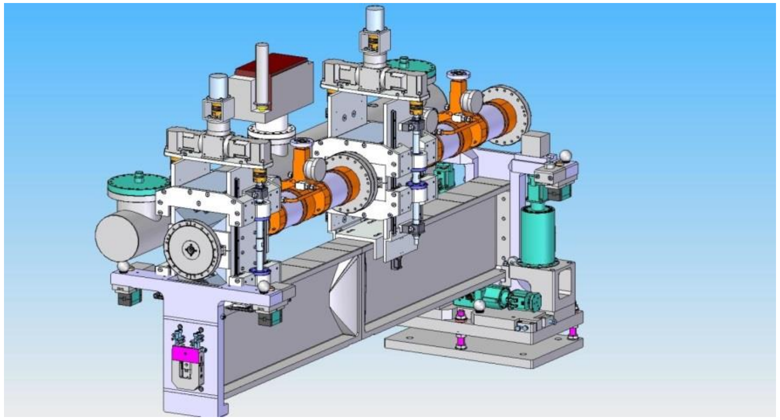
(*) Acknowledging Ben Shepherd and
Norbert Collomb, Daresbury Lab.



At 58 % strength

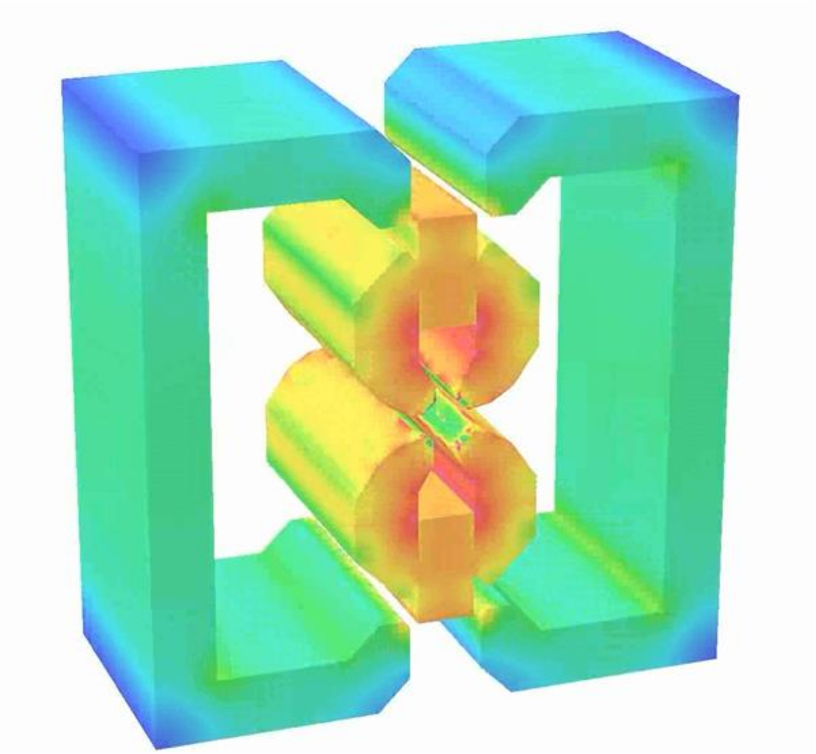


At 100 % strength

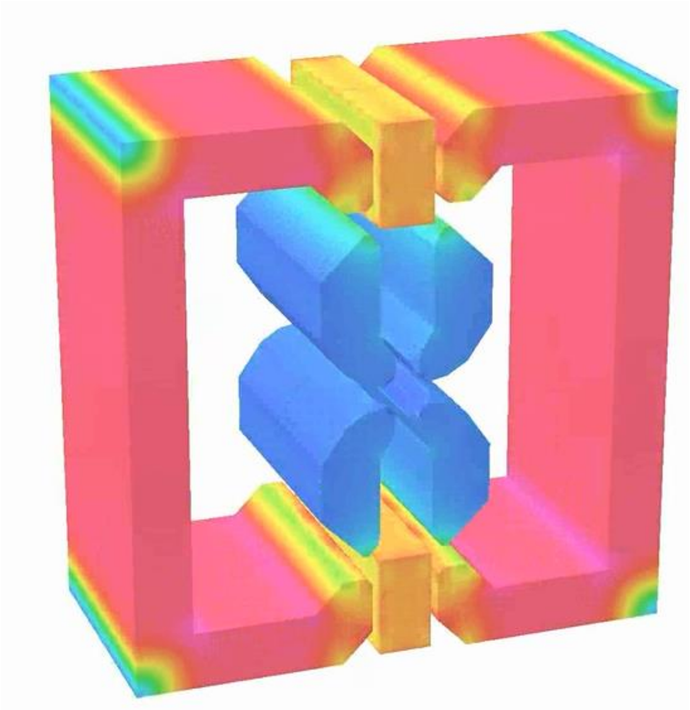


Design (*) for mounting in CLIC drive beam.

Dynamic model.



100%



58%

Colour code: red-high field; blue-low field.

TimeLapseUpDownavi

The **FUTURE** - p.m. lattice magnets?

Advantages:

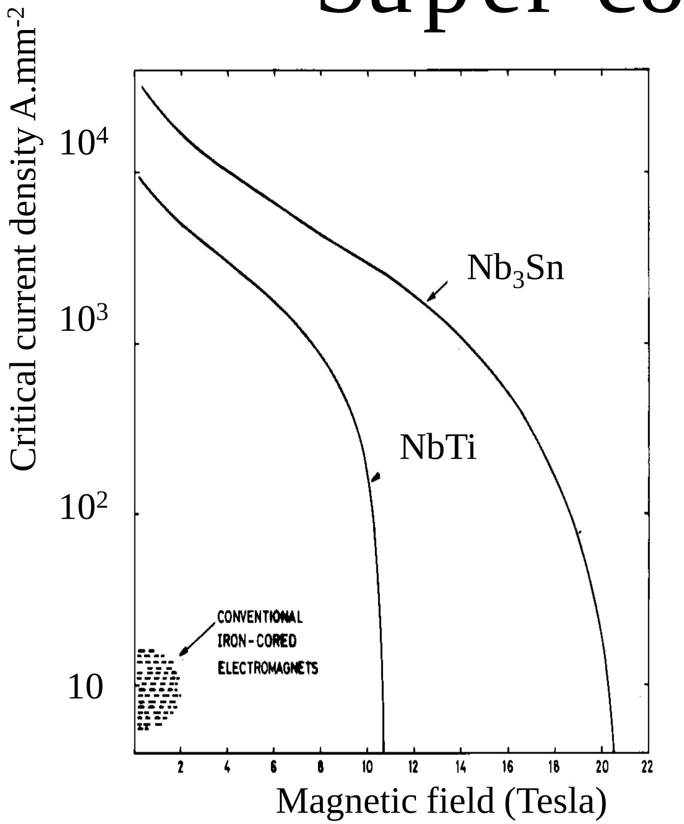
- no high current power supplies;
- much reduced power consumption;
- lower operating costs;
- politically acceptable in an ecology friendly world.

Disadvantages:

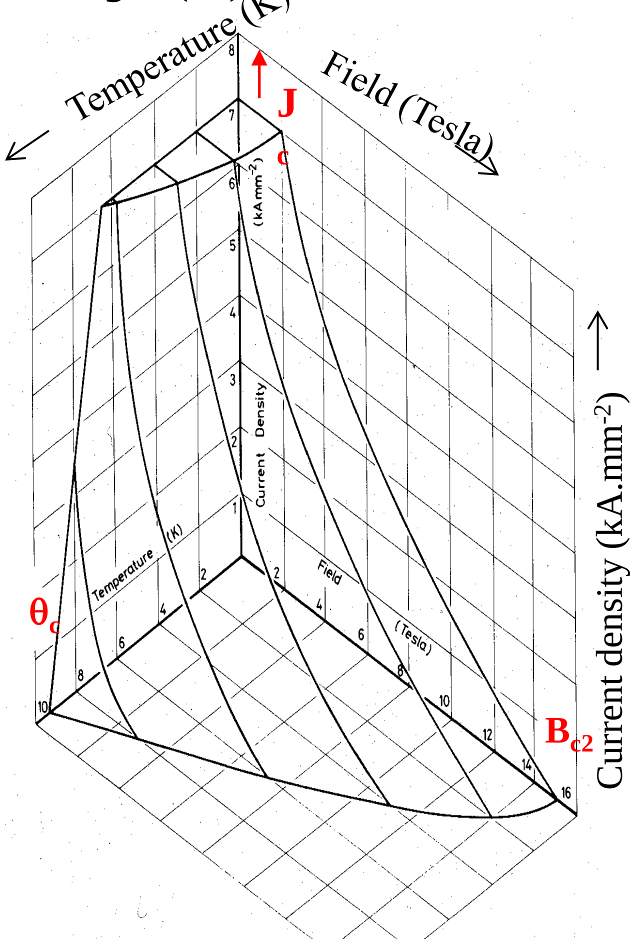
- higher capital cost;
- much more difficult to assemble;
- performance affected by radiation and temperature.

Are p.m. powered lattice magnets used in the accelerators of the future?

Super-conductivity(*)



Performance depends on field and current density; curves for NbTi and Nb_3 Sn

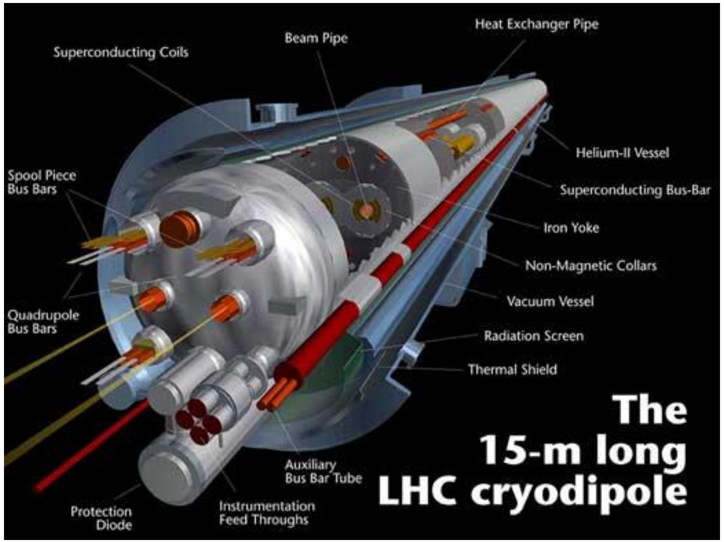


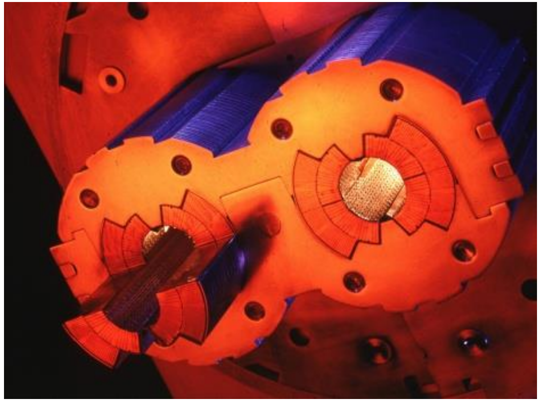
and also temperature!

(*) With thanks to Martin Wilson, ex Oxford Instruments and CERN;
See sessions 1 to 4 in 'course material – Dr Martin Wilson' at:
http://www.cockcroft.ac.uk/education/academic0506.html

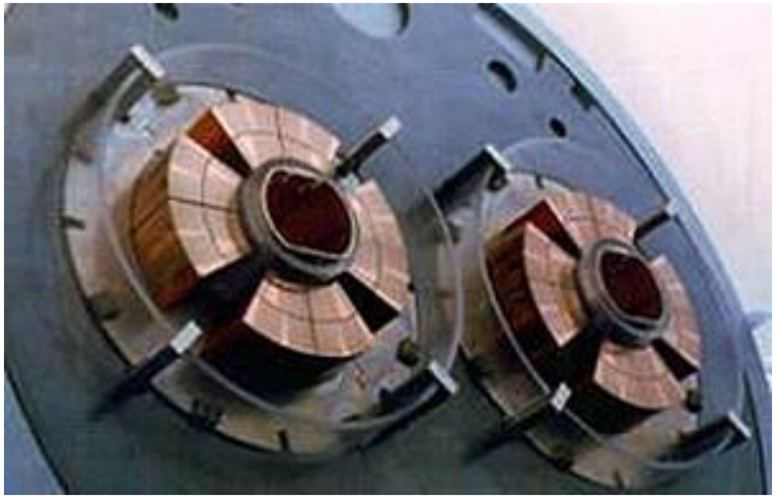
LHC superconducting magnets

To obtain the required performance, the LHC magnets operate in liquid helium at 1.9 K:





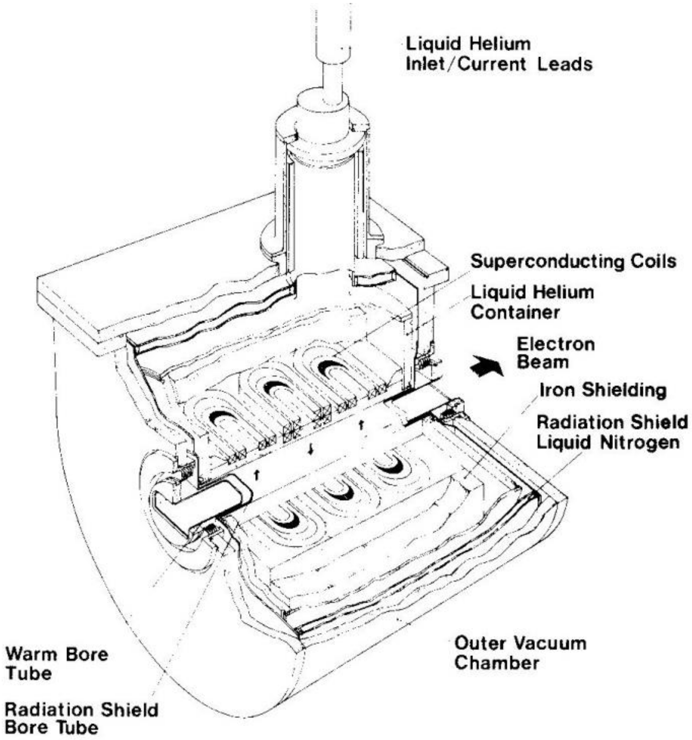
The LHC dipole; ultimate field >8T.

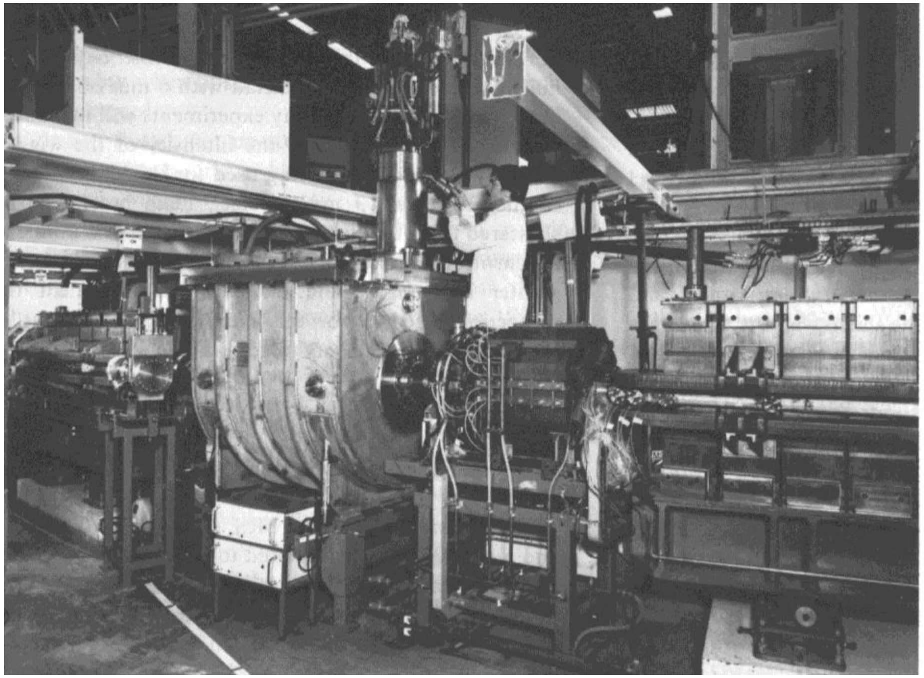


The superconducting quadrupoles.

Unlike 'room-temperature' magnets, where the field distribution and amplitude is dominated by ferrous yokes, s.c. magnets are coil current dominated; steel provides external screening.

S.C. Wigglers used in s.r. sources





The thee pole-pair, 5 T 'wavelength shifter' on the Daresbury SRS, serving 7 beam-lines with high energy photons.

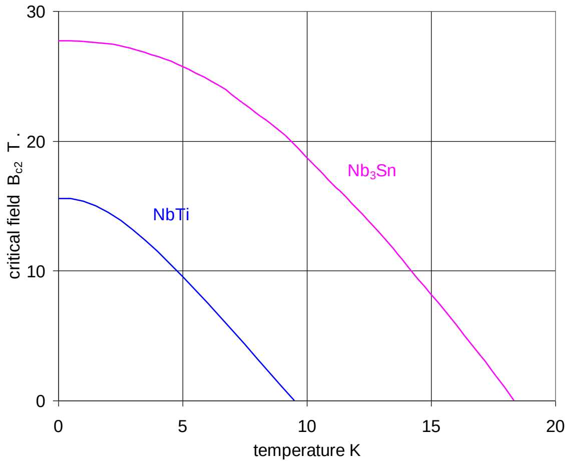
A complete s.c. synchrotron source.

‘HELIUS’ – built by Oxford Instruments in 1980s.

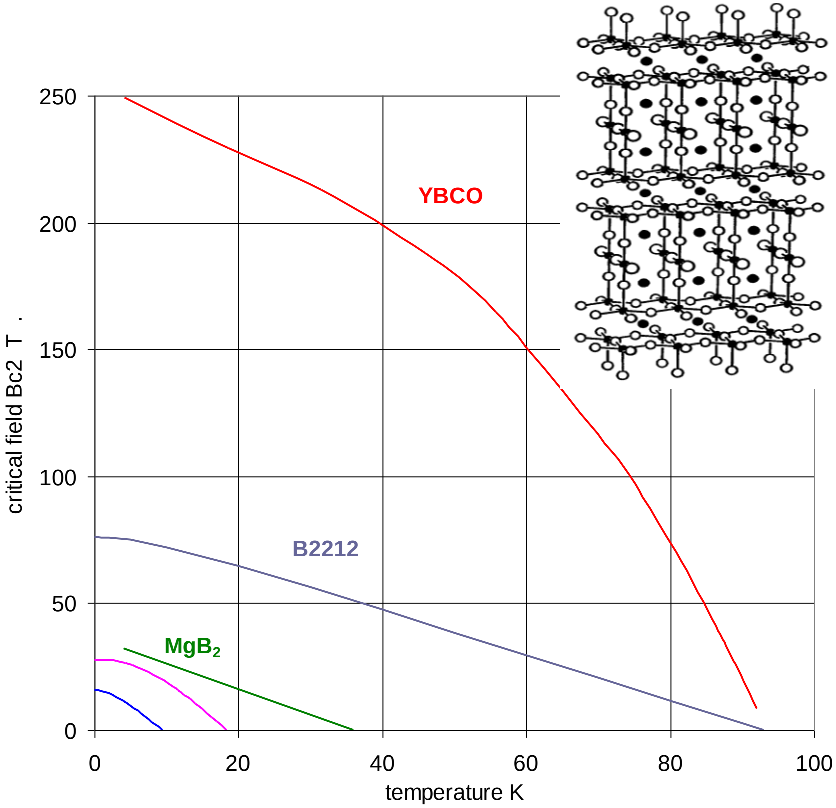
e^- energy	700	MeV;
dipole bending field	4.5	T;
max. beam current	600	mA;
beam lifetime	c 10	hours;
photon critical energy	1.5	keV;
beam ports	20.	

Ordered by IBM; small enough to travel in the cargo hold of a Boeing 747!

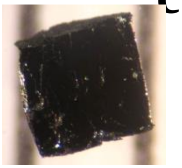
High T_c s.c.-critical field (T) vs. temperature



For comparison: 'classical' metallic 'type 2' s.c.



All high T_c materials are ceramic- not ductile!:



BI2223

Magnesium Di-Boride MgB_2

Barium Strontium calcium Copper Oxide BSCCO

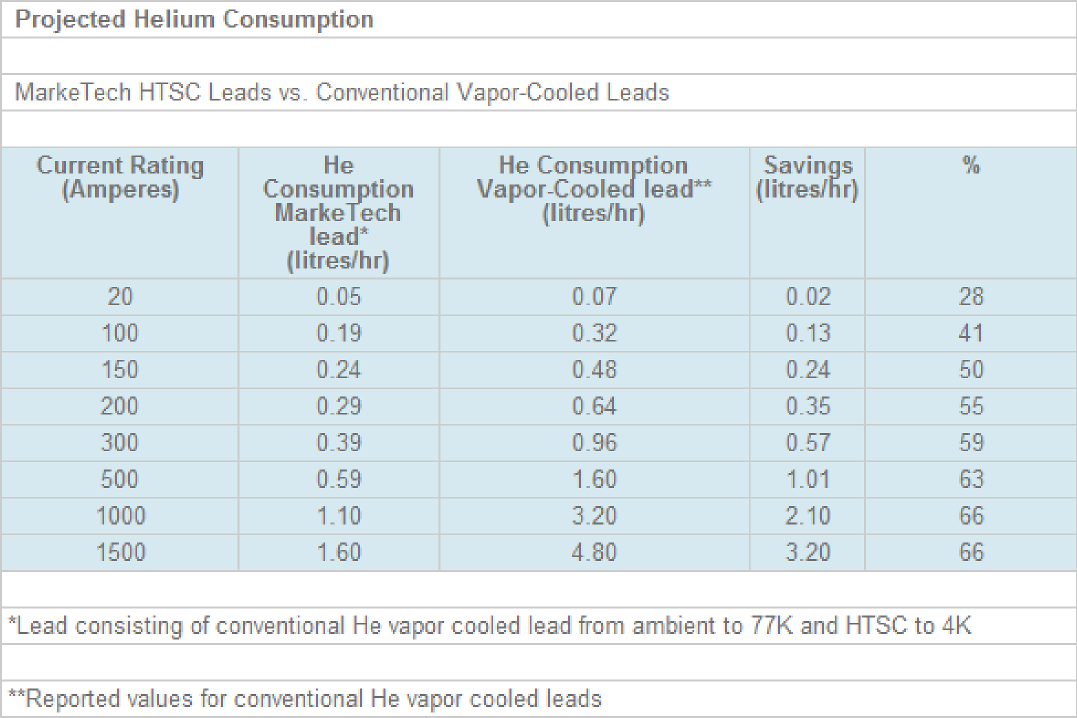
Yttrium Barium Copper Oxide $YBa_2Cu_3O_7$

Unlike metallic superconductors, HTsc do not have a sharply defined critical J.

Use of HTSC conductors

HTC are ideal for high current leads to s.c. magnets in cryostats; they have low thermal conductivity hence strongly limit heat ingress and the resulting loss of cryo-liquids.

MarkeTech (*) data on LHe savings:



Projected Helium Consumption

MarkeTech HTSC Leads vs. Conventional Vapor-Cooled Leads

Current Rating (Amperes)	He Consumption MarkeTech lead* (litres/hr)	He Consumption Vapor-Cooled lead** (litres/hr)	Savings (litres/hr)	%
20	0.05	0.07	0.02	28
100	0.19	0.32	0.13	41
150	0.24	0.48	0.24	50
200	0.29	0.64	0.35	55
300	0.39	0.96	0.57	59
500	0.59	1.60	1.01	63
1000	1.10	3.20	2.10	66
1500	1.60	4.80	3.20	66

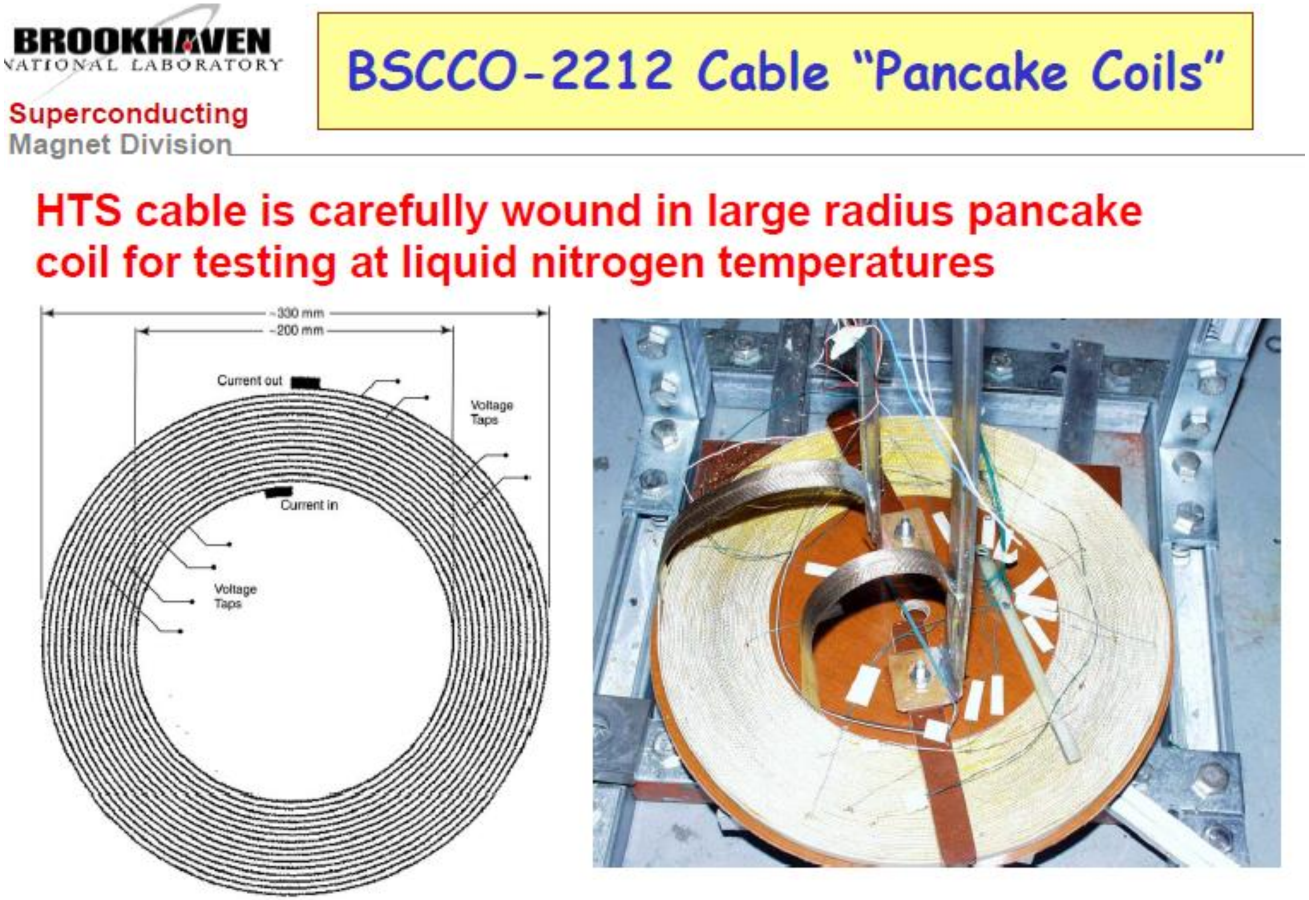
*Lead consisting of conventional He vapor cooled lead from ambient to 77K and HTSC to 4K

**Reported values for conventional He vapor cooled leads

(*) http://mkt-intl.com/products/superconductors/high-temperature-superconducting/.

HTSC for accelerator magnets?

Brookhaven Lab investigate coil winding using HTSC cable (*):



BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

BSCCO-2212 Cable "Pancake Coils"

HTS cable is carefully wound in large radius pancake coil for testing at liquid nitrogen temperatures

(*) http://www.bnl.gov/magnets/staff/gupta/scmagcourse/uspas03/RG03/lecture11.pdf

The **FUTURE** of s.c. magnets?

Looked for (hoped for) developments with classical s.c.:

- Further improvements in **B_c, J_c, θ_c ?**
- Accelerator magnets operating routinely at **B>10 T**?
- New **metallic s.c**.?

And for HTSC:

- Further **enhanced parameters**?
- More **ductile** material?
- Accelerator **dipoles** and **quadrupoles** using s.c.?
- **Room temperature** s.c. materials ???

New **PEOPLE** for the **FUTURE**

So we look for new, optimistic, accelerator scientists and engineers to ‘optimise’ and develop:

- Novel accelerators, inc. FFAGs;
- Routine use of permanent magnet materials to power lattice magnets;
- Advanced, innovative use of new super con. materials;.

And many many more things!

OVER TO YOU!