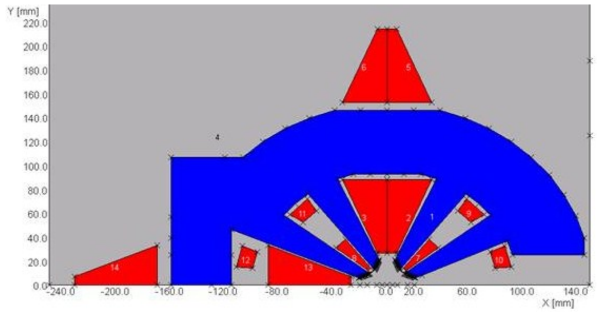
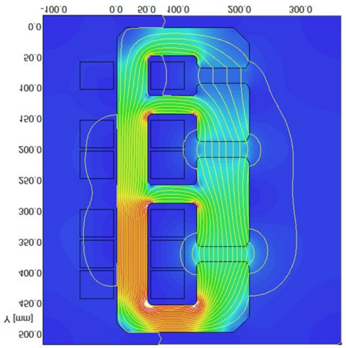
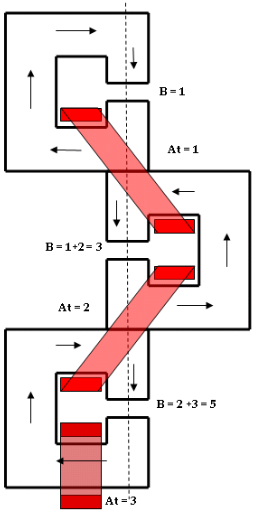
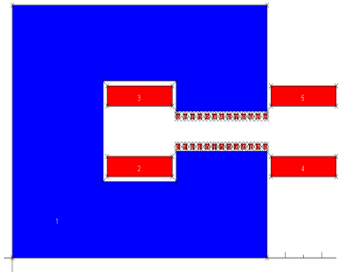
Weird





MAGNETS





that I have known

Neil Marks; ASTeC, STFC;
University of Liverpool.

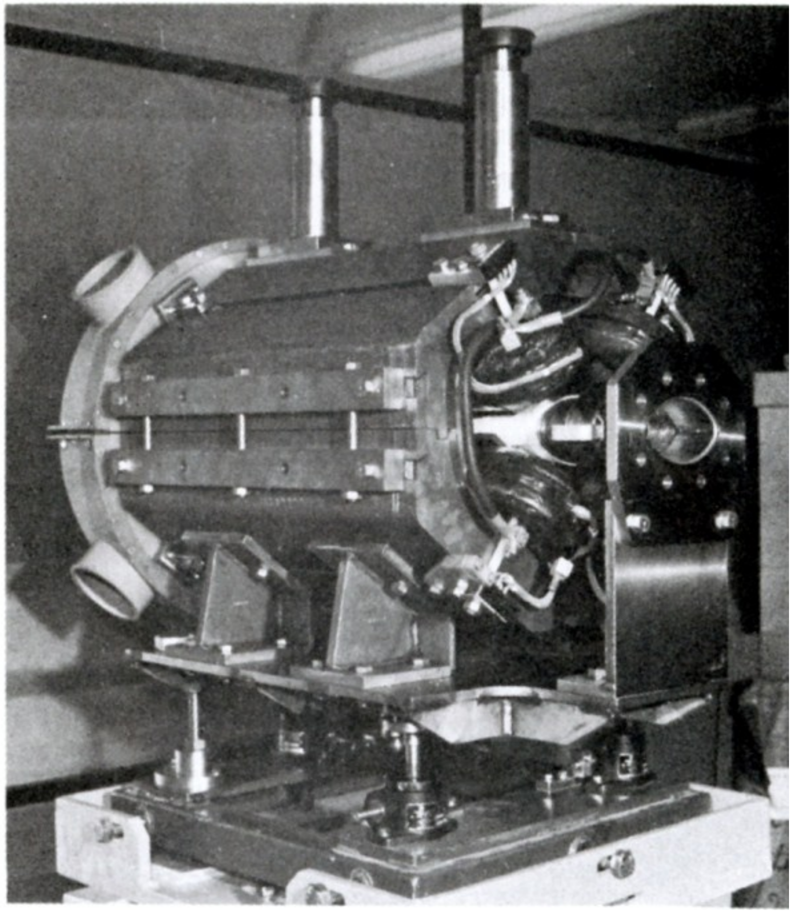
A brief survey of the more 'unusual' magnets that I have worked on in the last 50 years.

And acknowledging the many colleagues, without whom the projects would not have been possible.

Tuning up!

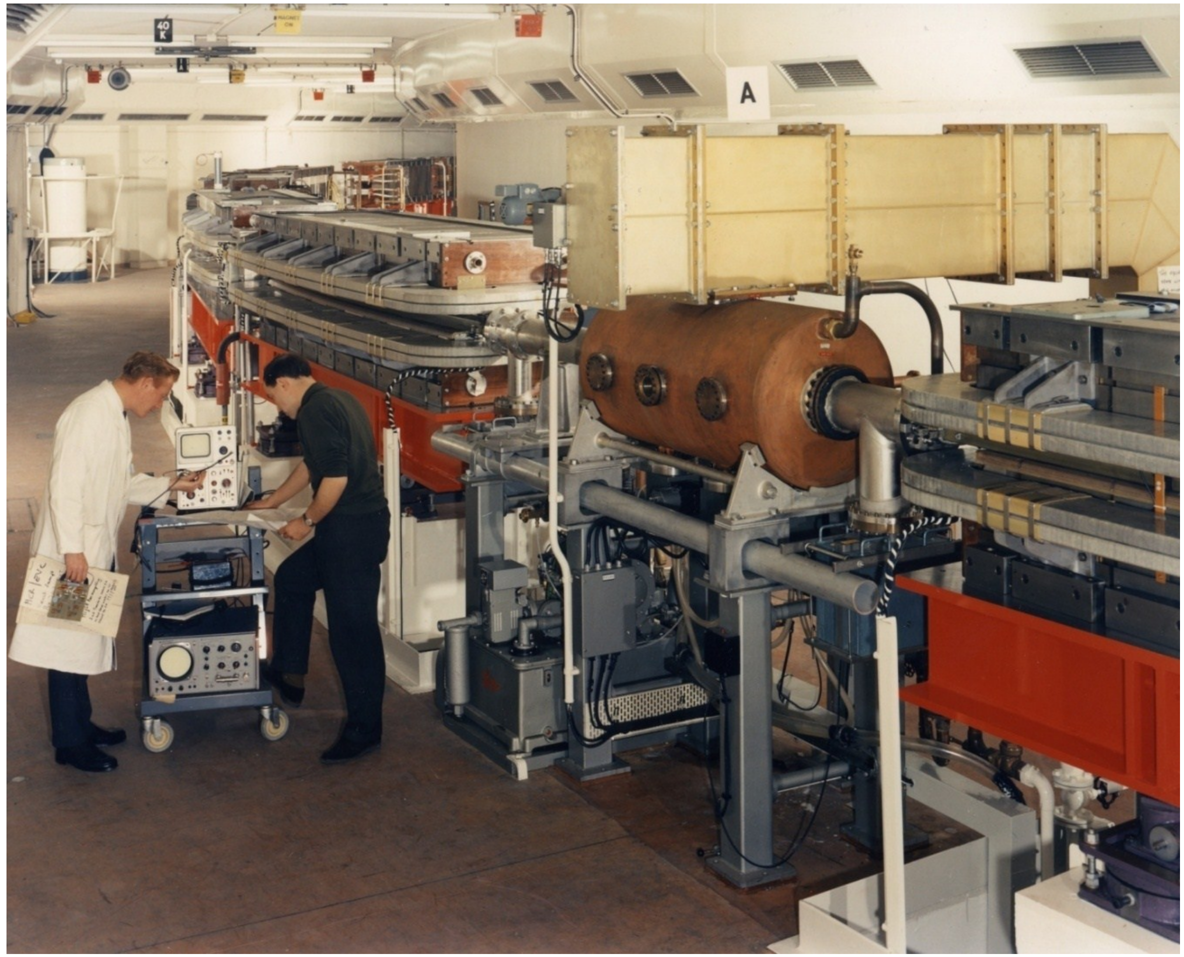
Royal Liverpool Philharmonic Orchestra

The NINA Programmed Quadrupoles



NINA – the first accelerator at DL

NINA was a 5 GeV electron synchrotron, built c 1964 and initially dedicated to particle physics.



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The NINA Main Magnets

The 50 Hz magnets were ‘combined function’– with a gradient built into the pole faces; so focusing was defined by the pole profile.

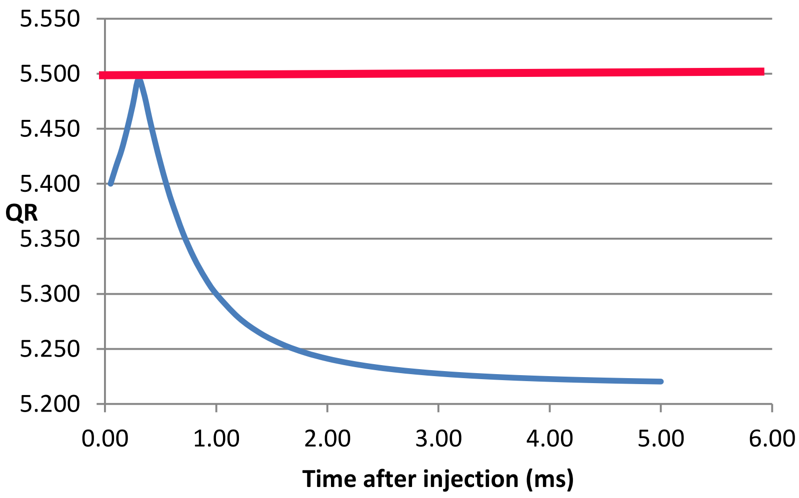
BUT – pole-face windings were fitted to control the injection Q values – **but not at high energy or even during acceleration.**

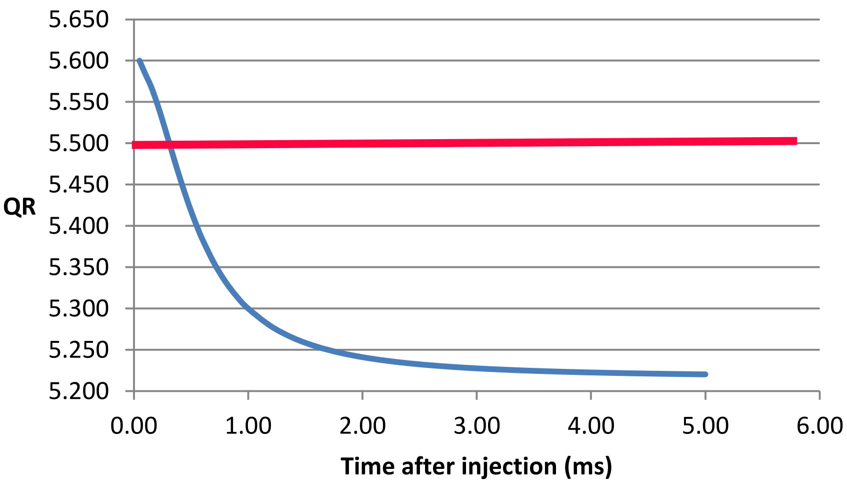
The ‘tune problem’ in NINA

Tunes at high energy after 9 ms acceleration were: **Q_R = 5.218**
Q_V = 5.265

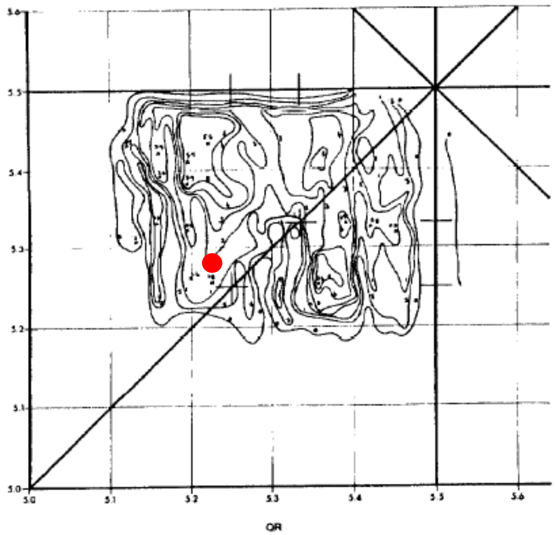
Injection was at 6.4 mT (**very low**); injection tunes were set by direct currents in the F and D pole face windings. Q_R measurements, using the ‘resonant disturbance’ method, usually showed this **strang**e variation with time. **Heavy beam loss occurred c 400 µs after injection – no surprise!**

Eventually shown that the measurement method gave reflections in major resonances; the actual tune variation was:

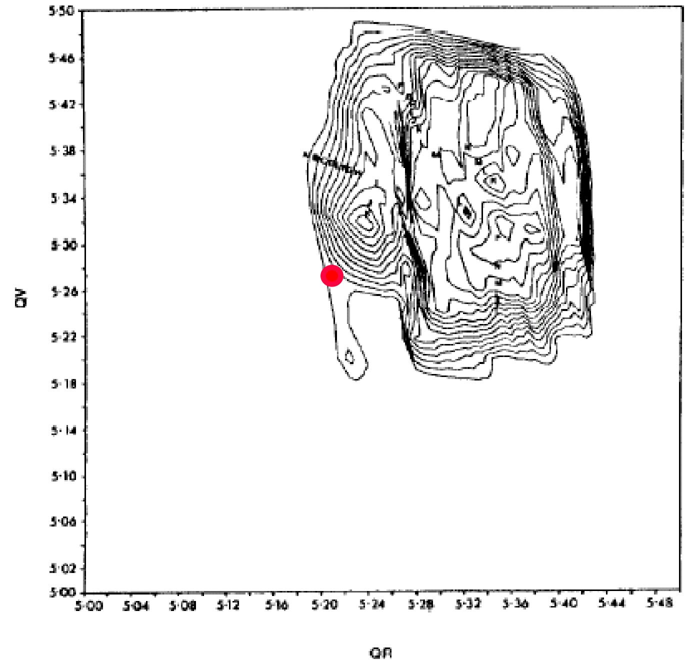




Plotting accelerated beam variation with Q_R and Q_V (*)



High energy tune: ●



Contours of beam current at **high energy** as a function of Q_R and Q_V **at injection**; note that the tunes at high energy were invariable!

Tunes varied and beam current noted manually; contours plotted by hand.

Automated plotting, using IBM 1800 (32K core) and Honeywell 316 (8K core). Data analysed and printed out on IBM 370/165 (70 K dedicated to 'NINALINK').

(*) N.Marks, E.A.Hughes, Proc of 5th PAC, San Francisco, 1973.

The NINA programmed quadrupoles (*)

Four quadrupole pairs (F and D) were introduced into the NINA lattice, to give:

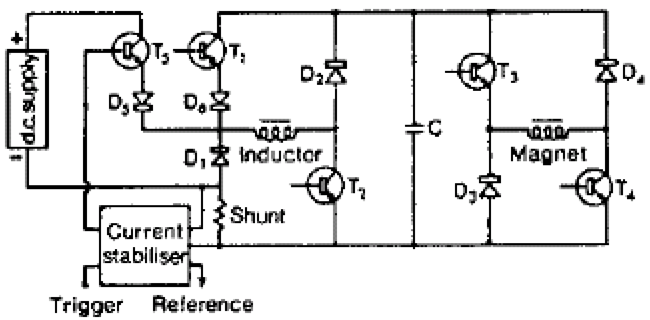
- a controllable tune shift of ± 0.2 in Q_R and Q_V at 5 GeV;
- to allow the 3 Q_R = 16 resonance to be engaged at high energy to give more efficient electron extraction (a single sextupole was built by Vic Suller);
- to provide control of the loci of Q_R &Q_V throughout the acceleration process to avoid major resonances.

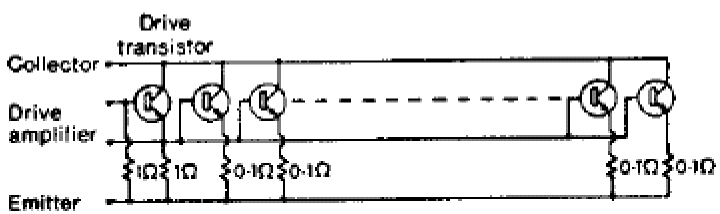
The success of the project depended on the design and construction of 50 Hz pulsed power supplies that could drive the quadrupoles according to a arbitrary waveform defined (within rating limits) by the machine operator.

(*) N.Marks, J.B.Lyall, M.W.Poole, IEEE Trans Nuc Sci, Vol NS-22, No3, 1975.

Power supply(*).

Jim Lyall produced a design for a 50 Hz pulsed power supply that provided the required ratings and flexibility:





A single switch, rated at 300 V, 100A, was assembled from fourteen silicon transistors.

This was a voltage bi-polar, pulsed, 'switch mode' system (**as used in the SLS - 25 years later!).**

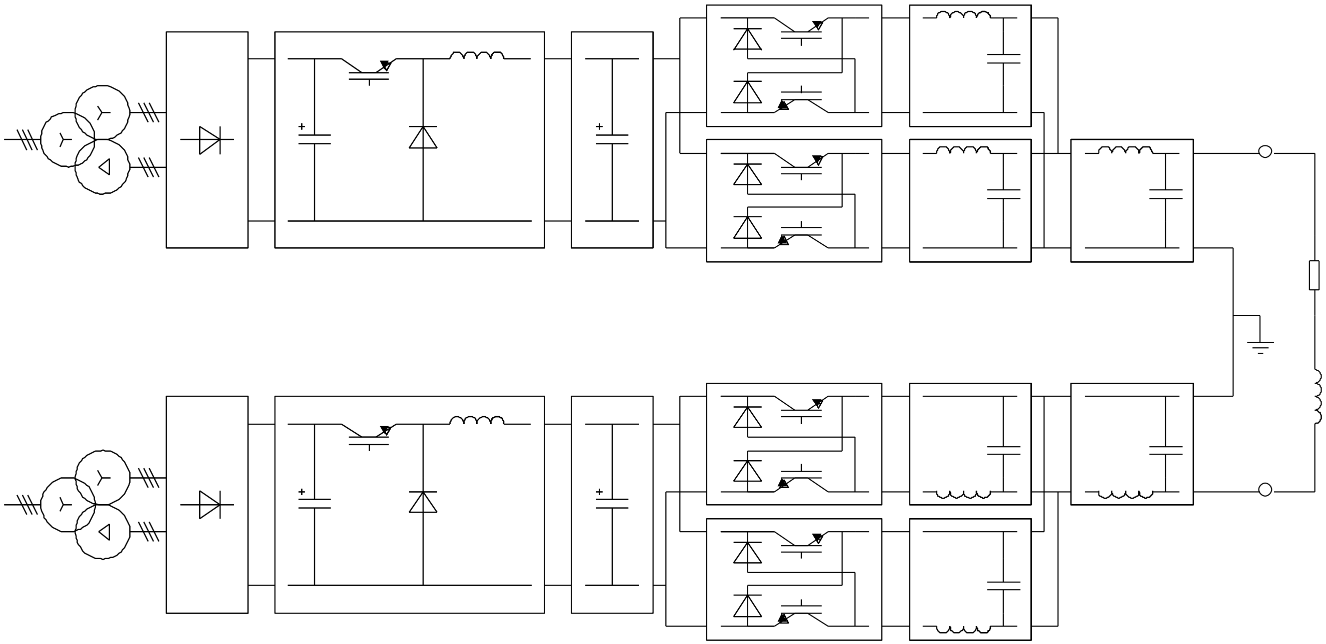
The 'switches' were assemblies of fourteen IC32 silicon transistors controlling in class C; the assembly operated at 300 V, 100 A, switching in c 1 μs.

The magnets were **voltage controlled** with the flux reset to zero before every cycle.

(*) J.B.Lyall, Proc 5th Int. Conf. Mag. Tech, Frascati, 1975.

The SLS booster supply (*)

Built 1997 – 2000; runs at 3 Hz, maximum energy 2.7 GeV



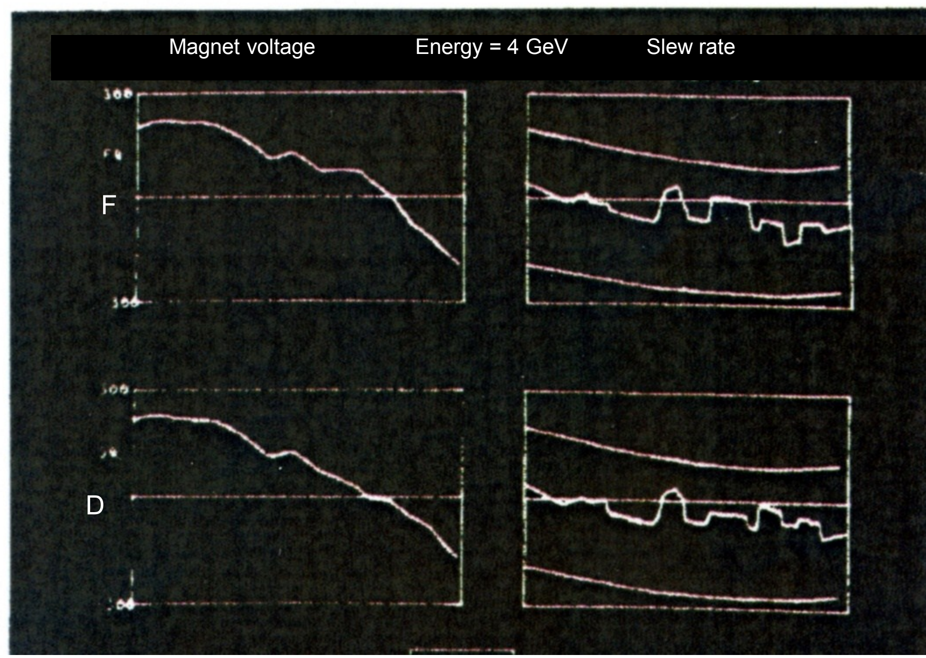
(*) SLS-PRE- TA-1998-0110. G. Iminger, M.Horvat, F.Jenni, H.U.Boksberger

Digital control and monitoring system.

The control room machine operator defined the required Q_R and Q_V waveforms. The magnet voltage waveforms were then calculated on the 370 main frame.

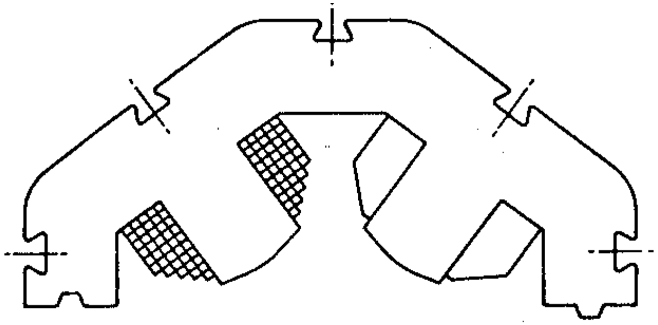
The resulting voltages and voltage slew rates (dV/dt was limited) were referred back to the operator for checking against maximum possible ratings.

The waveforms were then sent to a PDP 1 which, cycling in synchronism with NINA served analogue waveforms to the eight power supplies (4 Fs and 4Ds).



Work not published but participants included Ted Hughes, David Poole, David Gough, Tony Peatfield and Diana Dainton.

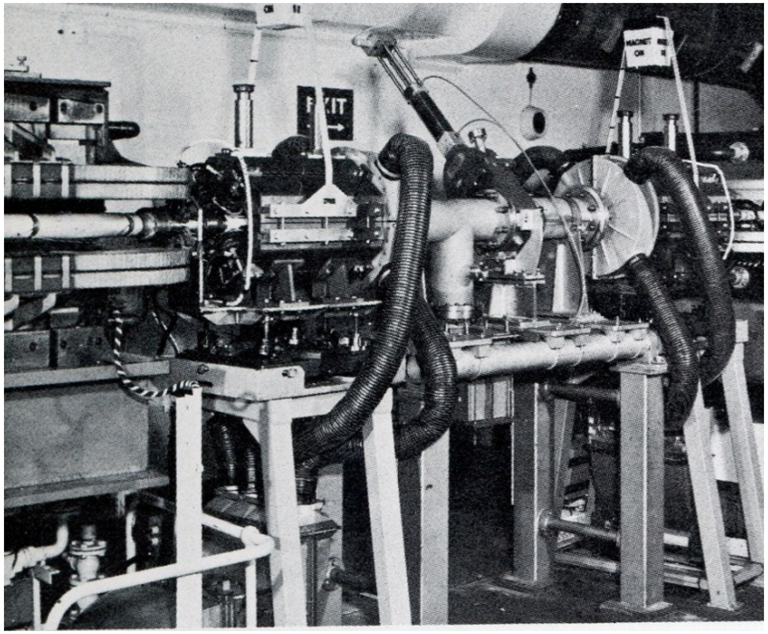
The 'bizarre' magnet (*).



The programmed quads:

- to limit stored energy, the poles were asymmetric about their 45° axes;

- because the coils operated at 50 Hz, they were made of stranded conductor, cooling water channels were not possible, so the coils were air blast cooled.



(*) M.W. Poole, Proc of 5th Magnet Tech Conf, Frascati, 1975.
With acknowledgement also to George Wright who performed all the thermal calculations.

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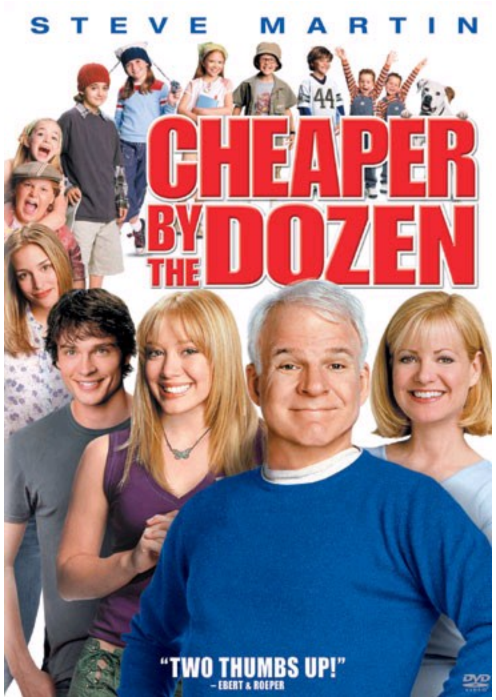
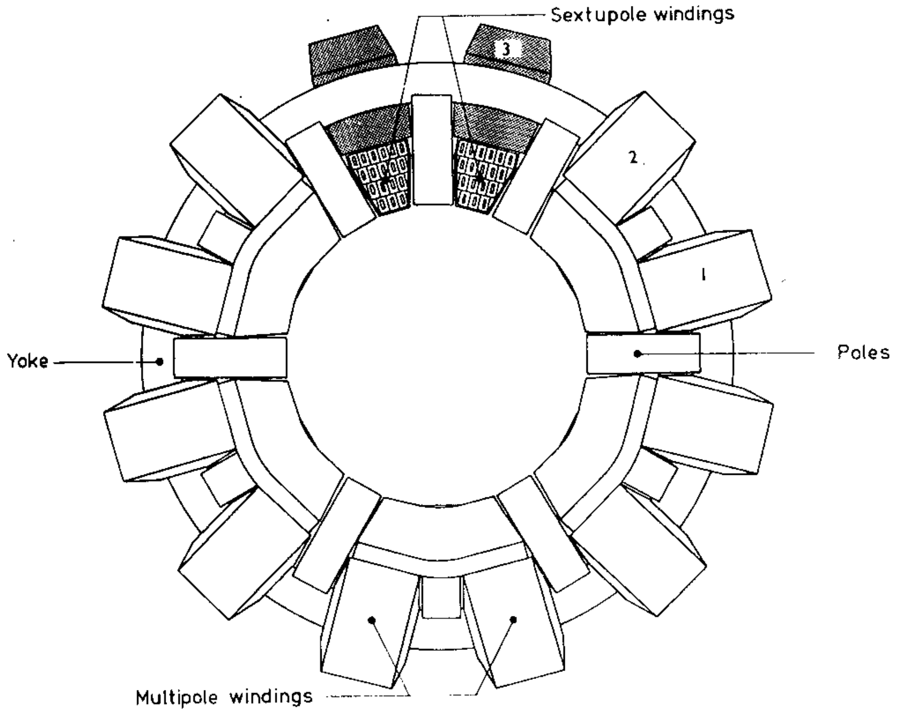
Cheaper by the Dozen?





The SRS 12 Pole 'MAD MULTIPOLES'

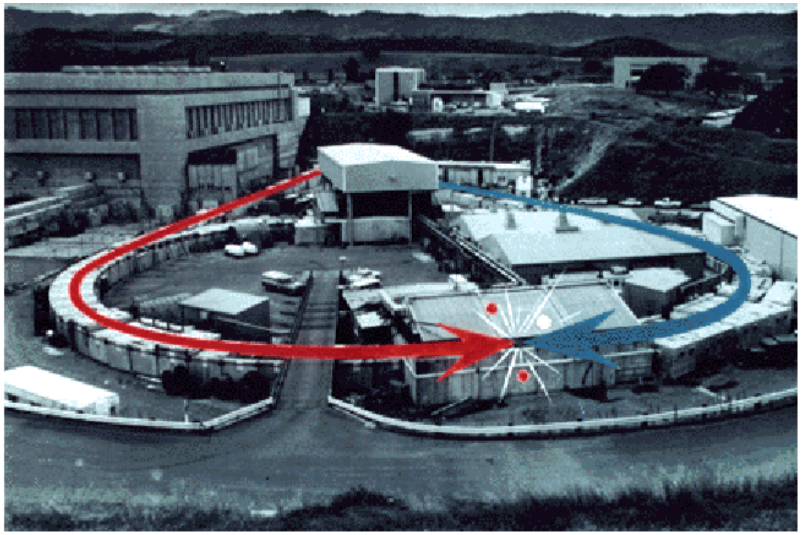
It all started at SPEAR

Visited in the mid 70s and found:

i) four pairs of octupoles installed for landau damping;

ii) low amplitude excitation – stacked current increased;

iii) higher amplitudes - complete beam loss - superperiodicity driving resonances.



SPEAR and SSRL

e+ e- collider at 4 GeV/ beam

BUT- SRS straights full with quads & sextupoles (and H & V steerers needed!).

Conclusion:

i) SRS needed octupoles;

ii) They needed to have full lattice periodicity.

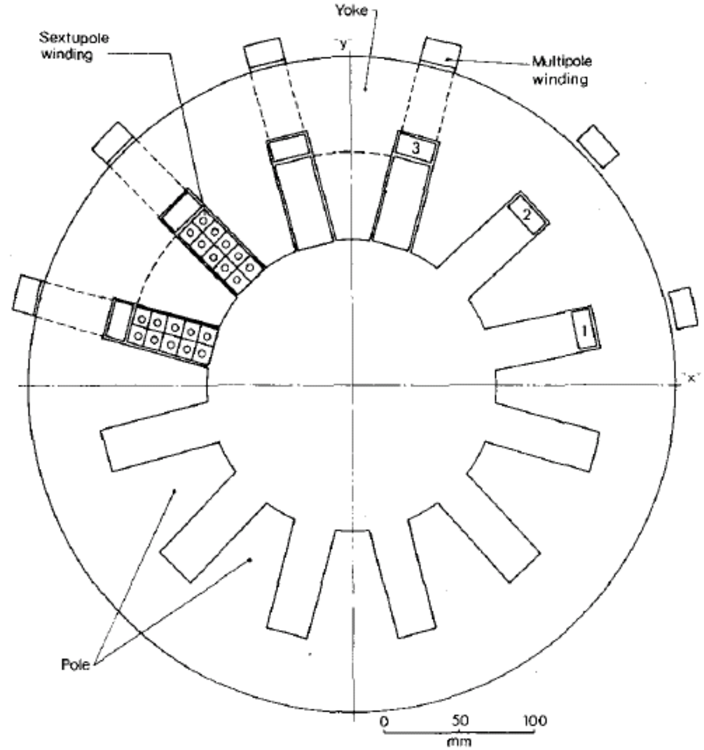
Solution – first concept (*)

A 12 pole magnet with:

- sextupole coils hard wound around 6 poles;
- 12 multipole coils on the back-leg, individually powered;
- backleg currents vary as cos nθ for 'upright' components – sin nθ for skew.

This would provide (simultaneously):

- H and V dipole correction;
- Upright and skew quad;
- Sextupole for full chromaticity correction.



NOTE- It is essential that:

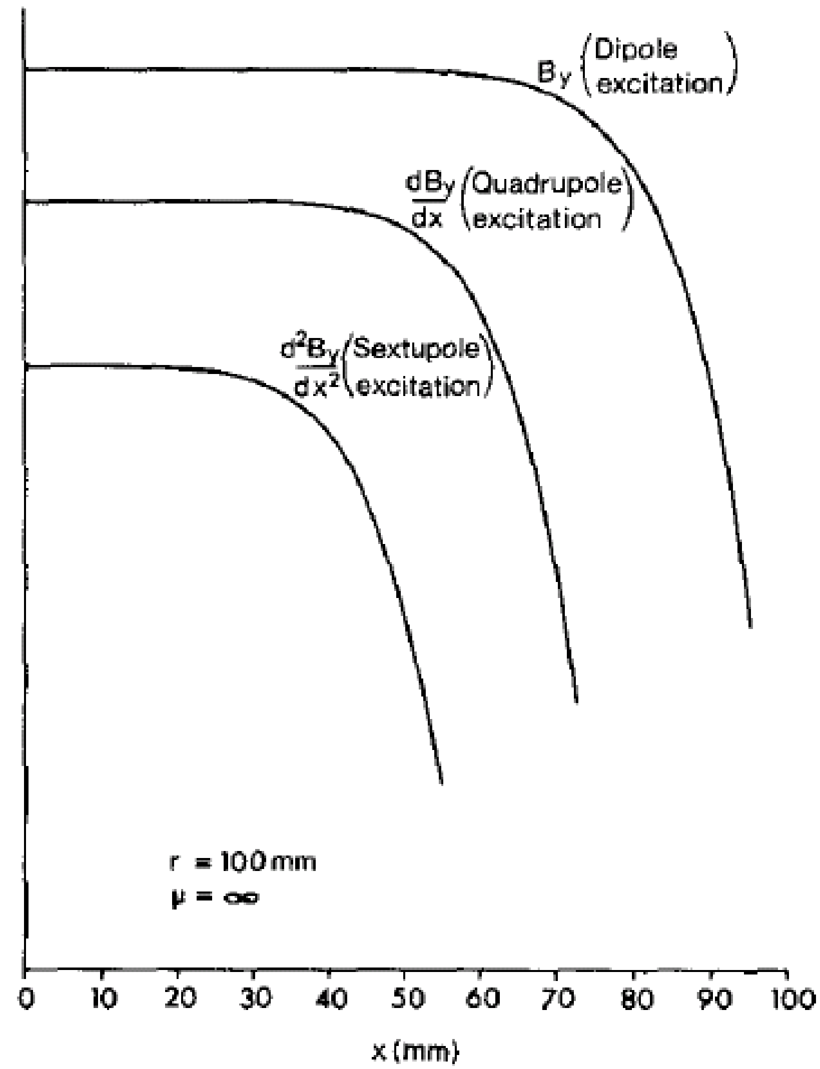
Σ back-leg currents = 0

(*) N.Marks; Proc of 5th Magnet Tech Conf, Frascati, 1975.

Model results

The early codes ‘Magnet’(*) and GFUN(†) were used to model the magnet and confirm the expected fields.

These could be orthogonally applied provided high permeability was maintained.

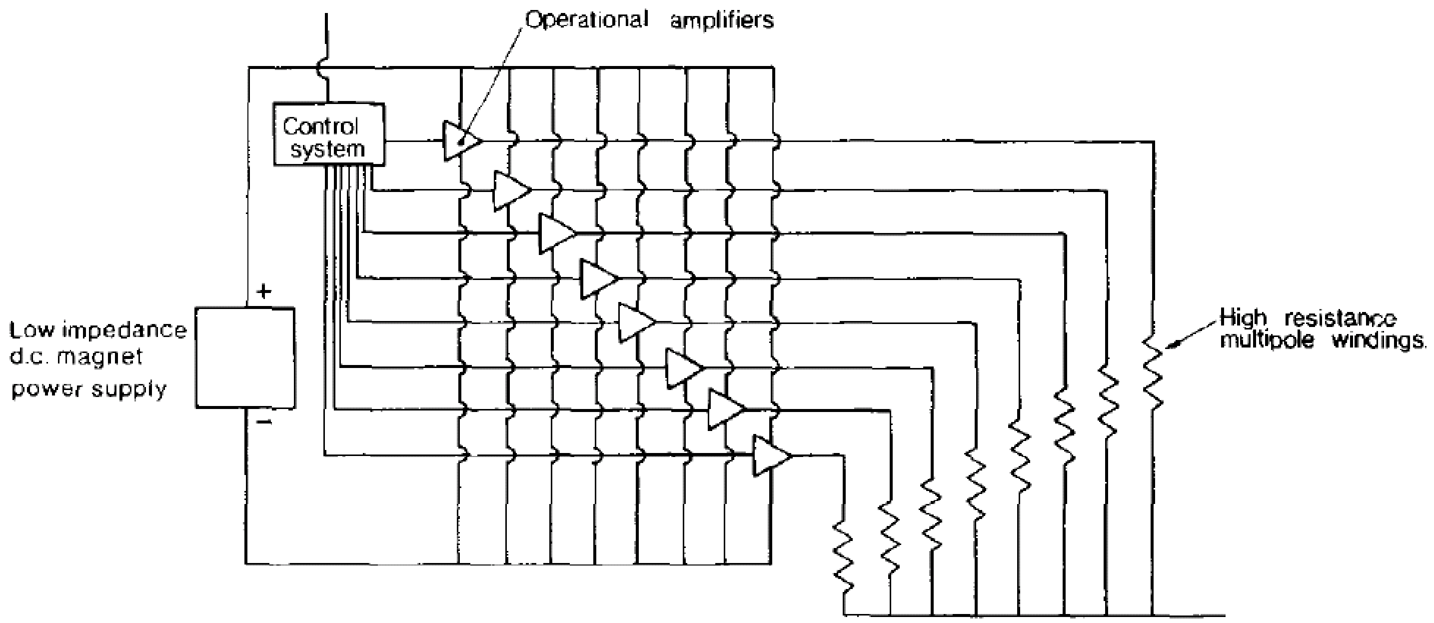


(*) **FEA Code, Ch. Iselin. CERN Program Library;**
(†) **Integral code, Vector fields, Kidlington, Oxon.**

Power supply

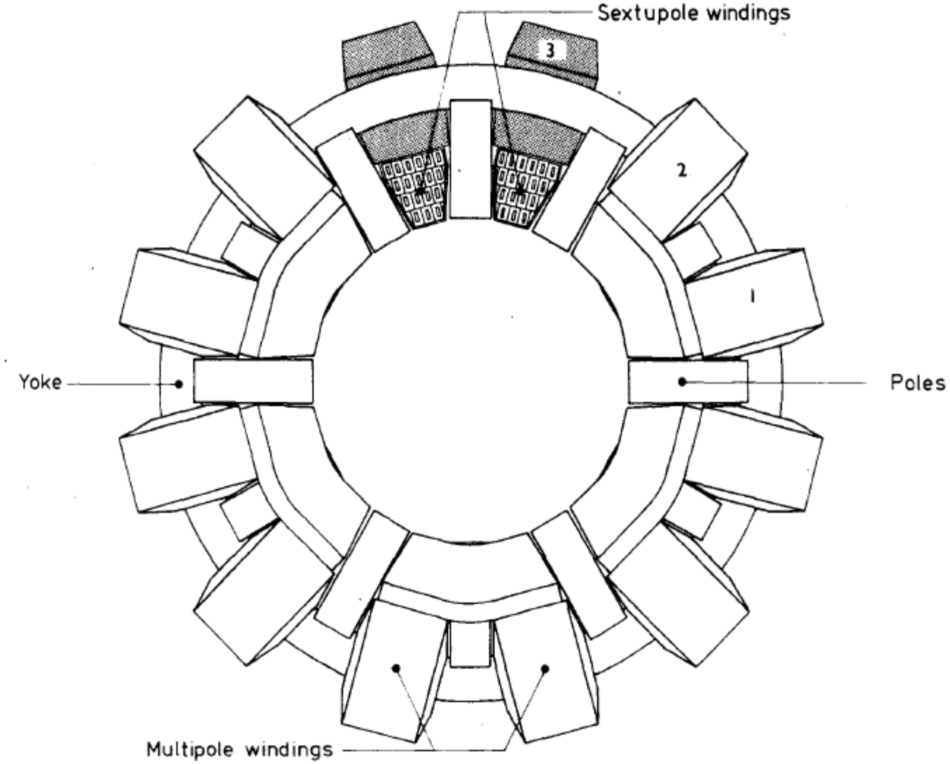
The concept was **made feasible** by the design of the power system, to independently power 12 separate coils on 16 magnets.

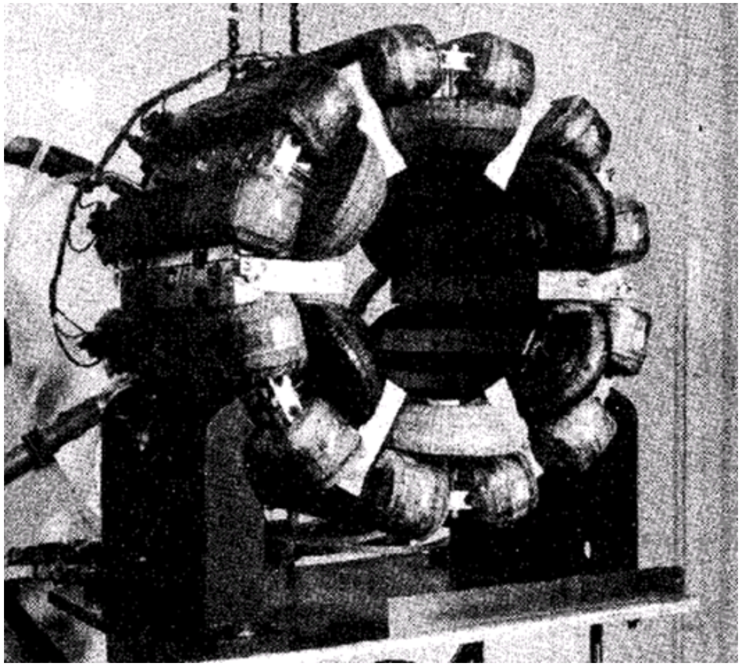
It used bi-directional op.amps, rated at 4 A at 20 V.



Designed and constructed by David Poole, Jim Lyall and Brian Tyson.

As finally engineered (*)



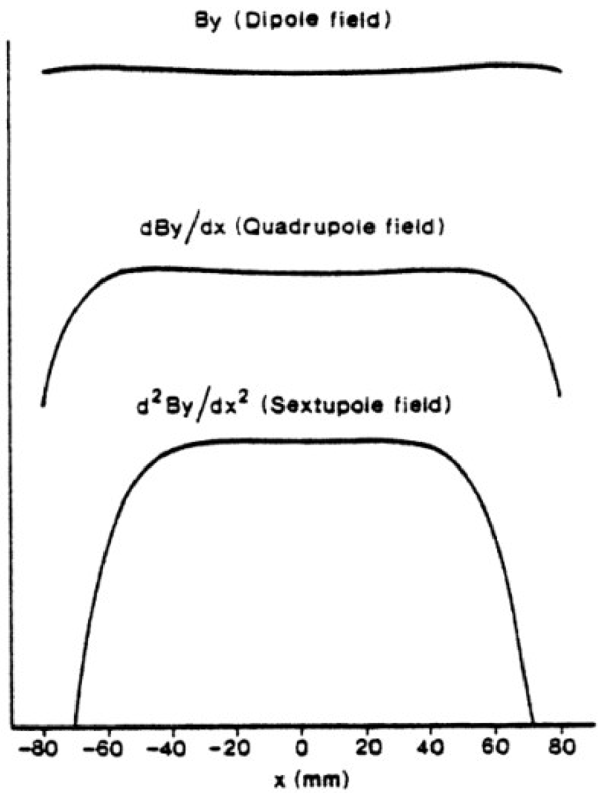


Prototype magnet

Sextupole coils: 18 turns at 500 A;
Multipole coils: 392 turns at 4 A maximum.

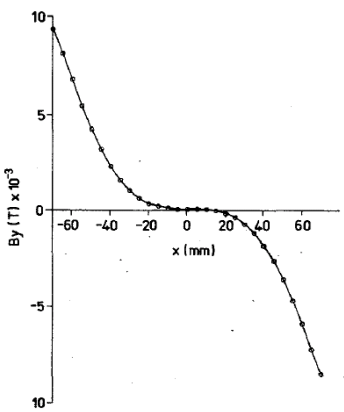
(*) N.Marks; Proc of 6th Magnet Tech Conf, Bratislava 1977.

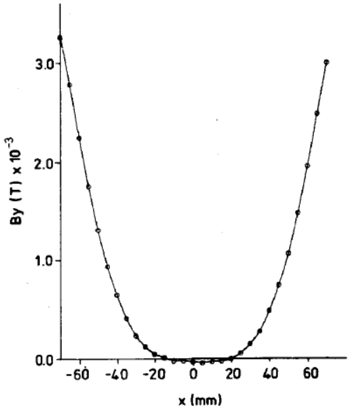
Measurements (*) on the multi-pole prototype



Radial field distribution for dipole, quadrupo and sextupole fields.

Field Type	Strength at Maximum Current		Magnetic Length
Main sextupole (500 A)	17.78	T/m^2	257.3
Dipole	30.67	mT	363.6
Quadrupole	0.2822	T/m	300.6
Sextupole	2.823	T/m^2	264.7
Octupole	16.12	T/m^3	246.6
Decapole	139.3	T/m^4	246.4
Skew-quadrupole	0.2162	T/m	-





$B_y(x)$: Octupole; Decapole

(*) R.P.Walker, proc. of MT7 Karlsruhe 1981; also acknowledging G.T.Wright, D.E. Gough, E. S.Walker.

Control and operation

The 16 multi-pole magnets were very demanding of the SRS control system(*):

- used ‘virtual parameters’, which seized control of several real parameters and adjusted them according to a defined algorithm;
- they performed exactly the same as a normal parameter; so the operator adjusted and monitored fields not individual currents;
- multiple orthogonal fields were simultaneously controlled;
- the control system, in ‘real time’, ensured that multiple incremental current steps did not destabilise the stored beam;
- the system continuously checked current amplitudes to ensure that multiple field demands never saturated a particular op. amp.

(*) D.E.Poole, W.R.Rawlinson, V.R.Aitkins, Proc. Europhysics Conf. Computing in Accelerator Design and Operation, Berlin, 1983.

Use in the SRS (*)

Throughout the life the life of the SRS, the multipole magnets were used;

During routine operation:

- sextupole field for chromaticity correction (augmented in SRS2);
- horizontal and vertical dipole for orbit control;
- octupole field for Landau damping;
- skew quadrupole filed for h/v decoupling.

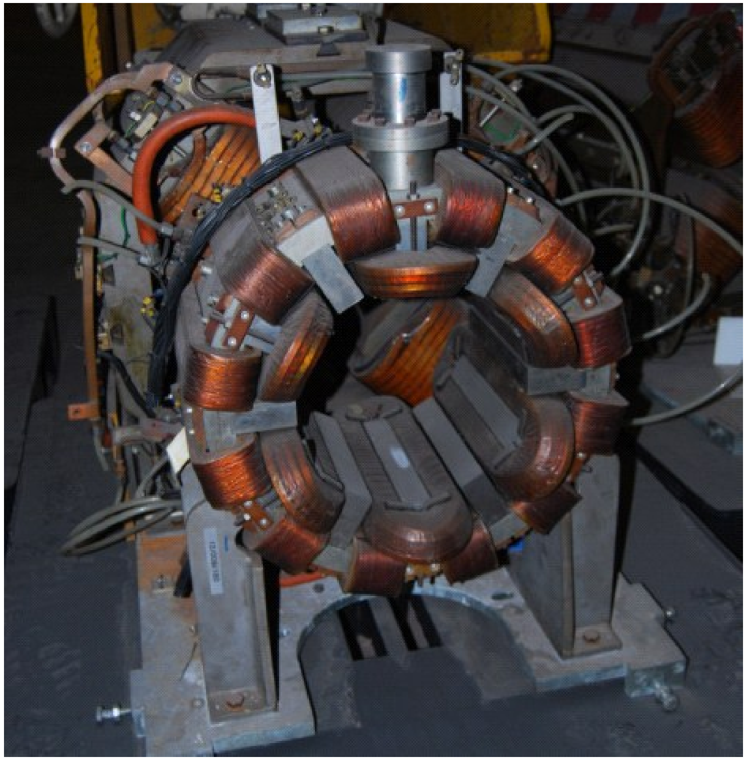
During accelerator diagnosis:

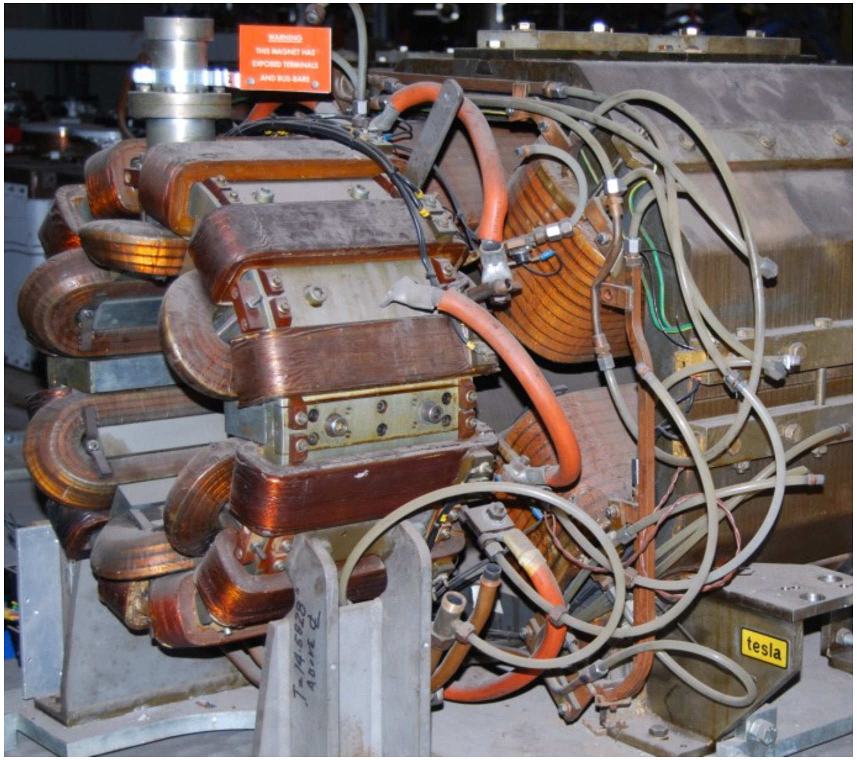
- localised individual quadrupole perturbation (for measurement of beta values).

(*) R.P.Walker; IEEE Trans. Nuc. Sci., Vol 28, No3.

Their final resting place

In the SRS magnet grave-yard:

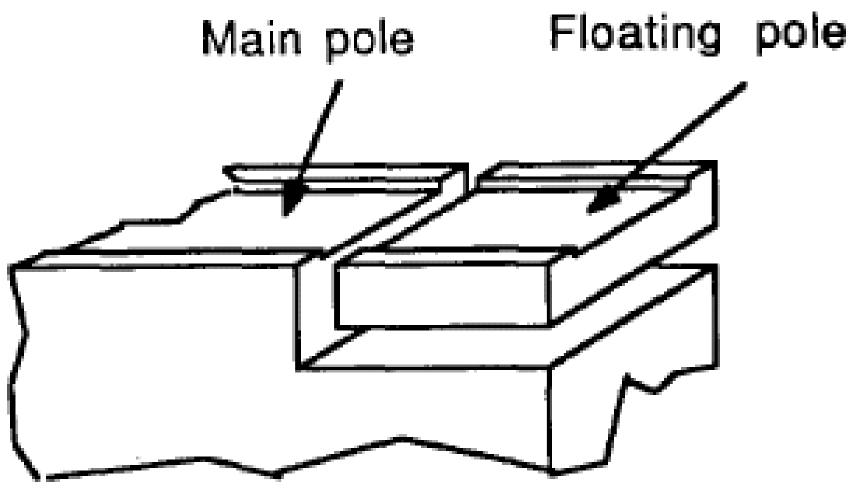




And some at Soileil for future possible use.

‘Isle Flottant’

A floating *island* is a French dessert consisting of meringue, floating on crème anglaise.

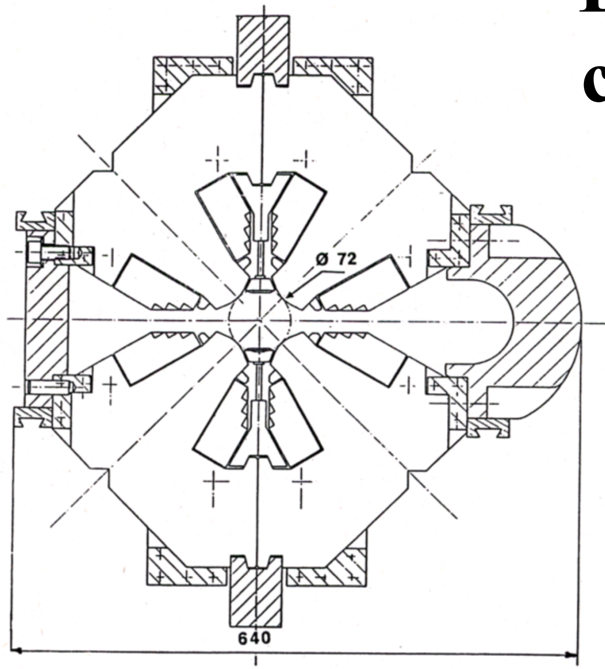


At ESRF (Grenoble) we invented ‘**Floating Poles**’ as a result of some Anglo-French engineering (*).

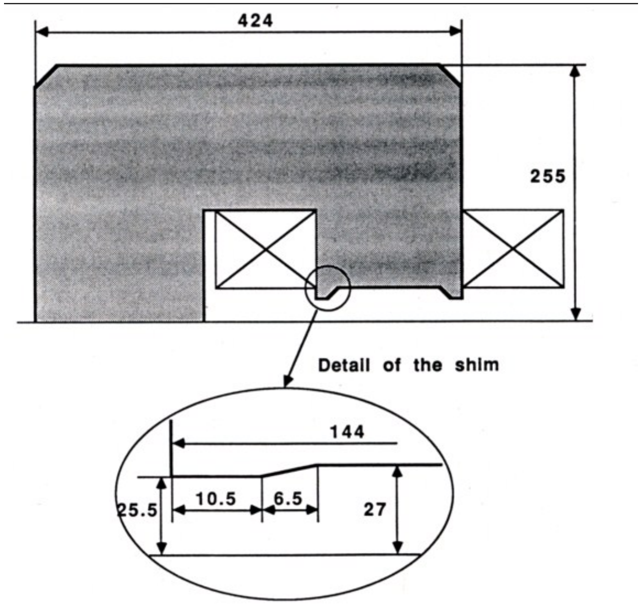
(*) N.Marks and M.Lieuvin, Proc. MT 10, Boston, 87; IEEE Trans on Magnetics, Vol 24, No 2, 1988.

ESRF Magnet cross sections.

At the beginning of the 'foundation phase' the magnet specifications were conventional:

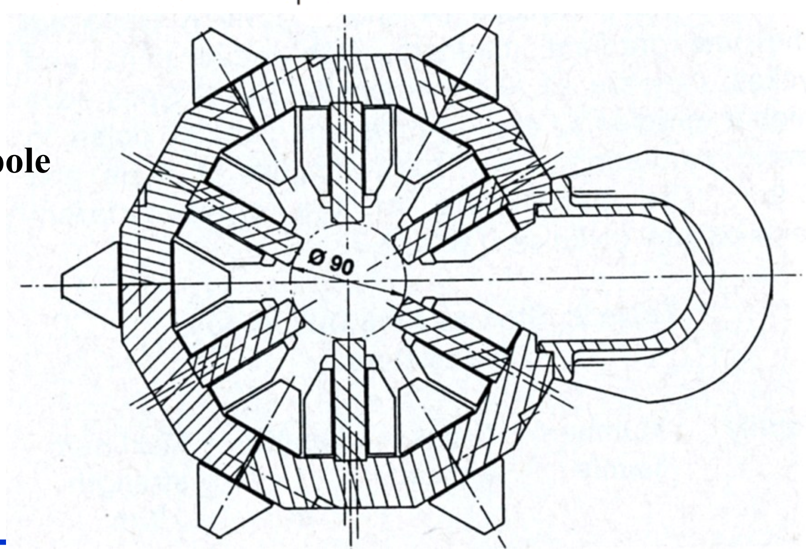


Quadrupole



Dipole

Sextupole



However …

Prof. Michael Hart (U. of Manchester), member of the ESRF SAC made a strong case for the dipole magnets to have a 'soft end'

– a short region of reduced field to give s.r. with lower critical wavelength.

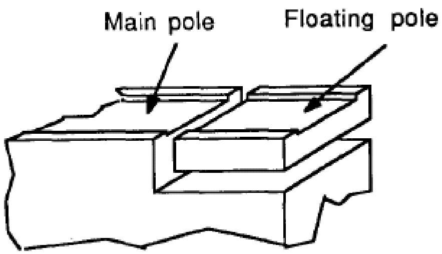
Original design:	B_y	= 0.802 T;
'Soft end' field:	B_y	= 0.402 T;
Over:		= 4 m rad;
Giving:	Ec	= 9.4 kV;

To maintain the dipole length, field in the rest of the magnet had to be increased to: B_y = 0.856 T;

Solution (*)

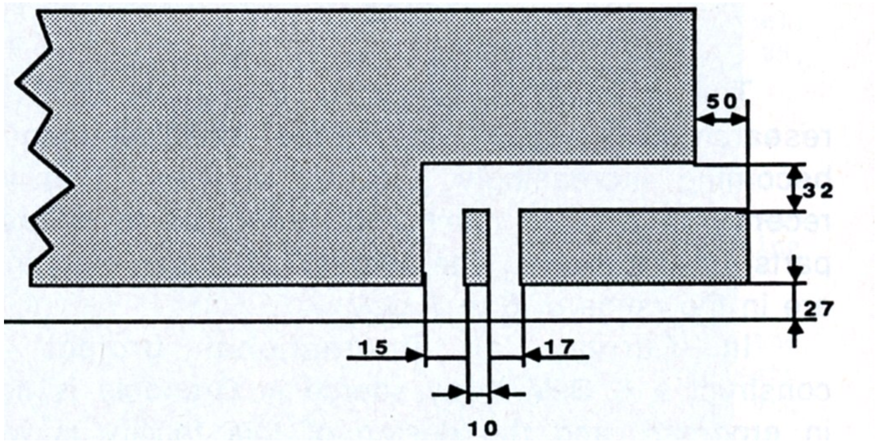
A short end section with double the gap.

Initial pole face concept:



But to provide the necessary longitudinal gap without loss of transverse field quality at the beam, an intermediate section was necessary.

As engineered:



(*) N.Marks and M.Lieuvin, Proc. MT 10, Boston, 87; IEEE Trans on Magnetics, Vol 24, No 2, 1988.

The floating poles in ESRF dipoles.

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As currently used in the ESRF (*)

Bending magnet beam-lines:

Application	Location	Module 1 M1 start	alignment [mrad] M1 fixed absorber	Fixed absorber Aperture [mrad]	Module 2 [mrad]	FE M2 defined apertures [mrad]	
Swiss Norvegian CRG	BM1	-6	-9	6	-9		
D2AM CRG	BM2	-6	-9	6	-9		Polished window
BM5 Optics	BM5	-6	-6.5	6	-6.5		Polished window, 2 absorbers
Gilda CRG	BM8	-6	-9	6	-9		
UK CRG	BM14	-6	-9	6	-9		
Spanish CRG	BM16	-6	-9	6	-9		
ROBL CRG	BM20	-6	-9	6	-9		M1 slit 3mrad+ M2 polished Be window & 1.5mrad hor. aperture summer 2011
XAS Beamline	BM23	-6	-9	6	-9		rad tests done 08 June 2010
Spanish SPLINE CRG	BM25	-6	-7	10	-7	2.5 to 4.5 -7* - 9.5 to 11.5	M2 treble absorber 85.91.1250/beamslit replaced October 2007
Dubble CRG	BM26	-6	-7	10	-7	2 to 12	M2 absorber 85.91.1159/beamslit replaced summer 2008
Xmas CRG	BM28	-6	-3.5	3	-3.5		0.250mm Be window 3mrad aperture - winter 2009-10
BM29	BM29	-6	-9	6	-9		
FIP CRG	BM30	-6	-7	10	-7	2.5 to 4.5 - 9.5 to 11.5	M2 double absorber 85.91.1238
Vacgroup cond. Bench	BM31	-6	-6	6	-	-	special setup
IF CRG	BM32	-6	-9	6	-9		

* BM25 3mm aperture @ -7mrad

Low energy (0.4T Field) ~ 0 to -5.8 mrad

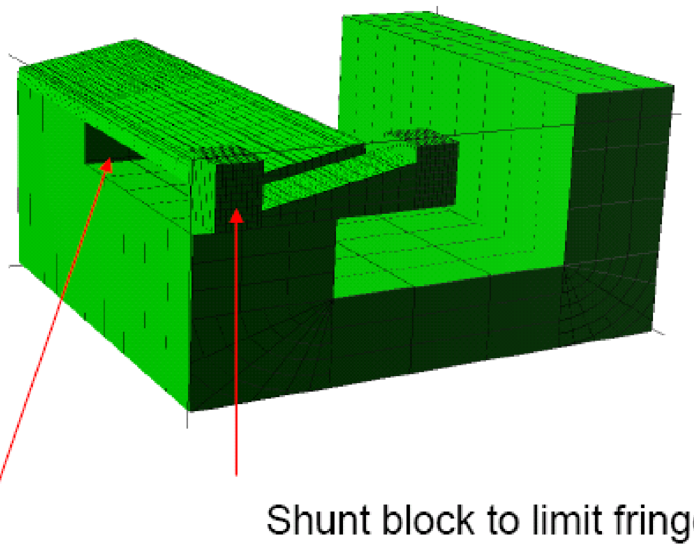
BL using Low Field (0.4T) [red]

(*) Private communication: Jean-Claude Biasci, (head of the Front-Ends group, Accelerator and Source Division, ESRF).

Later at Max-lab.

A similar concept in a design study for 3 GeV MAX IV(*):

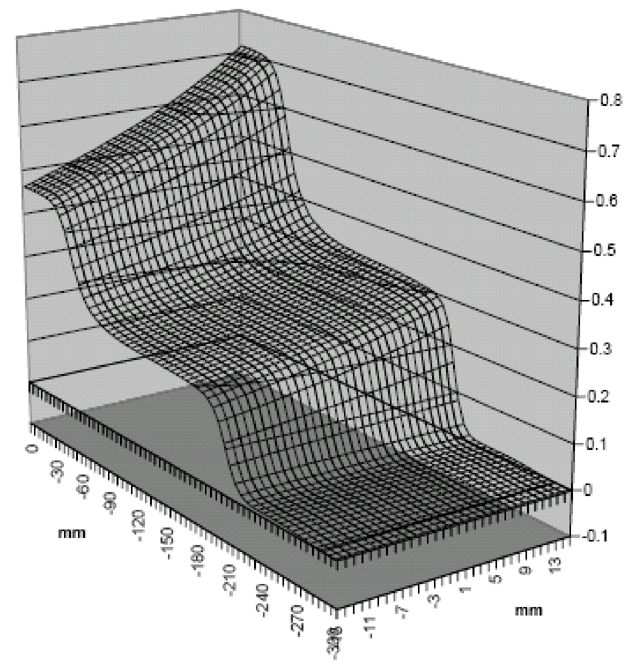
Iron yoke of the dipole magnet



Shunt block to limit fringe fields

Floating pole face for low field region

Magnetic field distribution (20 cell)



(*) Erik Wallén et al; non linear beam dynamics workshop, Grenoble May 26, 2008.

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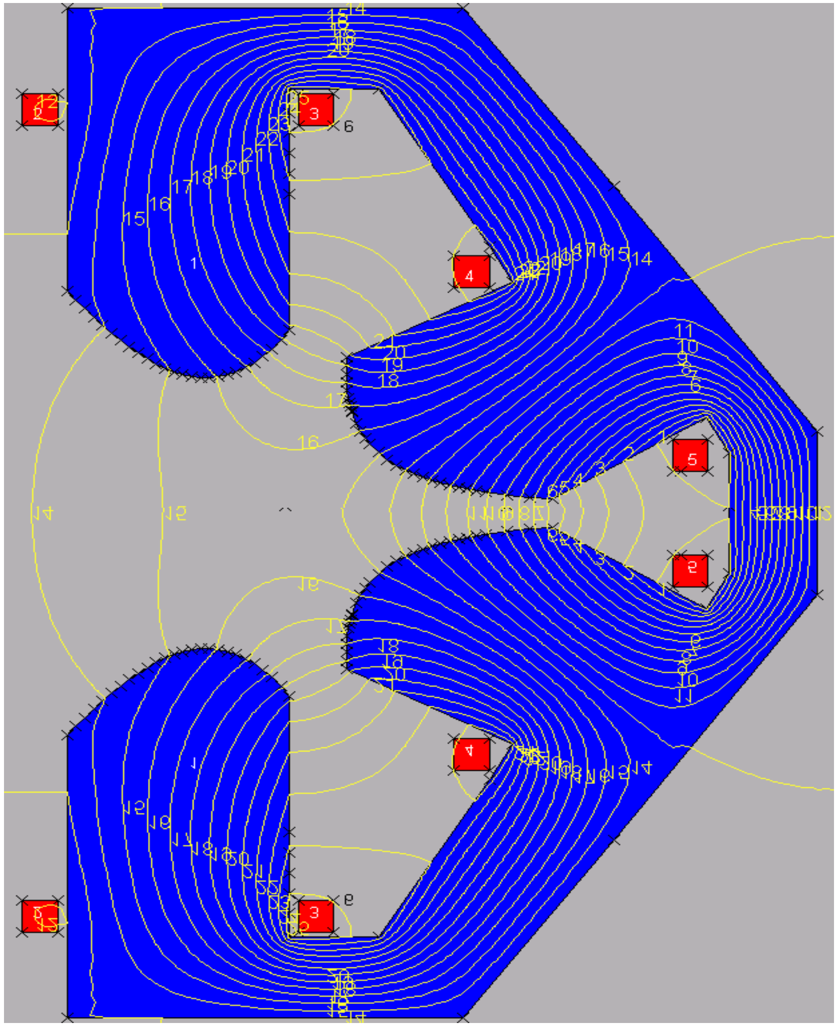
Losing poles!

‘To lose one pole is unfortunate – to lose two, smacks of carelessness.’ (*)

The **4 pole sextupole** and other bizarre magnets in ‘Pumplet’ – a non-linear, non-scaling FFAG lattice design by Grahame Rees.



(*) Lady Bracknell; ‘Importance of Being Earnest’; Oscar Wild, Penguin Popular Classics, £2.00 at Amazon.

Pumplet (*)

Details of a five (‘pump’ in Welsh) magnet cell:

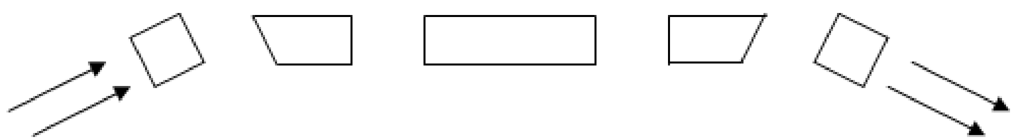
27 Cell, Electron Model for a 3 to 10 GeV, NFFAG, Proton Driver

Orbit circumference = 27 x (0.88067033 to 0.88000) m = 23.778098 to 23.7600 m

Energy and γ range = 3.00000 to 5.446315 MeV; γ = 6.8707725 to 11.658028

Betatron tunes (h,v) = 27 x (4/13, 3/13) = (8 4/13, 6 3/13) = 8.30769 to 6.230769

O bd(-) o BF(+) o BD(+) o BF(+) o bd(-) O



17.5 5.5 5.0 5.5 5.0 11.0 (cm) 5.0 5.5 5.0 5.5 17.5

-8.0° 7.5° 14.33333° 7.5° -8.0°

Figure 1. Cell Parameters for the 5.4463 MeV Closed Orbit.

(*) Grahame Rees, ASTeC, RAL, STFC; private communication.

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Magnet specifications:

T(MeV	−bd(gauss)	BF(gauss)	BD(gauss)	$K_v(m^{-2})$ bd	X(mm)	$-K_v(m^{-2})$ BF	X(mm)	$K_v(m^{-2})$ BD	X(mm)
5.4463	502.61014	471.19703	450.25492	0.25	17.984403	76.346784	14.587926	60.835520	8.4826225
5.270	502.07071	448.66274	460.62734	2.67	16.065935	78.355600	13.093898	60.188660	7.6037669
5.100	500.66550	425.95657	470.66254	5.07	14.138198	80.235645	11.579084	59.408088	6.7170154
4.950	498.59188	404.89207	479.60411	7.69	12.365652	82.175093	10.169445	58.542845	5.8925272
4.800	495.64991	382.83608	488.61128	10.15	10.517979	83.865580	8.6837834	57.513771	5.0247381
4.650	491.87125	359.83102	497.63974	12.45	8.5913580	85.314328	7.1189881	56.318225	4.1124628
4.500	487.29235	335.94282	506.63590	14.57	6.5810794	86.512030	5.4695276	54.953655.	3.1544761
4.350	482.02073	311.29840	515.61337	16.49	4.4828050	87.447889	3.7365221	53.416830.	2.1501785
4.200	475.93152	285.87404	524.32281	18.20	2.2911316	88.114074	1.9145014	51.699838	1.0988121
4.050 i	469.26794	259.89203	532.89601	19.67	0.0000000	88.487316	0.0000000	49.796092	0.0000000
3.900 i	462.04515	233.43397	541.20674	20.88	−2.3975051	88.544675	−2.0106491	47.692107	−1.1464574
3.750 i	454.35053	206.63685	549.18928	21.79	−4.9095333	88.245813	−4.1212940	45.373991	−2.3403381
3.600 i	446.28753	179.65751	556.77548	22.36	−7.5457418	87.539848	−6.3360636	42.818705	−3.5810667
3.450 i	437.97707	152.67488	563.89485	22.54	−10.317906	86.354699	−8.6596111	39.992161	−4.8677926
3.300 i	429.50293	125.79372	570.51425	22.56	−13.242444	84.684963	−11.105317	36.706618	−6.2099523
3.150 i	420.84710	99.000552	576.61410	22.58	−16.349105	82.420989	−13.702231	32.732805	−7.6314832
3.000 i	411.92391	72.234761	582.16910	22.60	−19.685474	79.272406	−16.497373	27.898608	−9.1732244

Note:

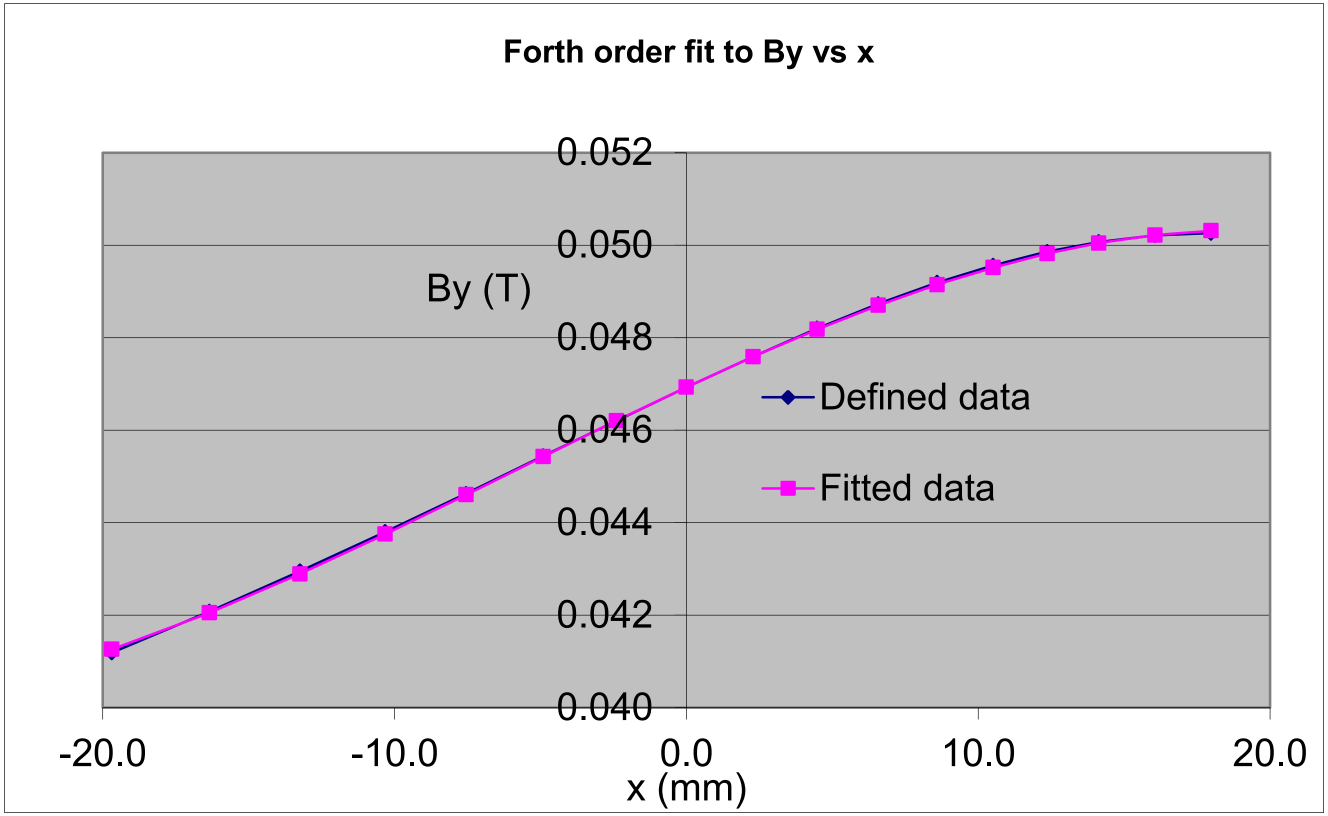
i) FFAG, so no central closed orbit; X = 0 defined for T = 4.050 MeV;

ii) What types of magnet are bd, BF, BD ? ‘Tis mystery all’ (C. Wesley);

iii) How do we find out?

Start by fitting $B_y(x)$ to a Taylor series

eg – fourth order fit (dipole to octupole) for magnet bd:



Series: $b_0 + b_1x + b_2\,x^2 + b_3\,x^3$;

Coefficients: $b_0 = 0.04693$; $b_1 = 2.9562$ E-4; $b_2 = -2.9366$ E-6; $b_3 = -1.6920$ E-7;

RMS fitting error: 3.67 E-5; 8:10^4 of mean (need to be better for actual project).

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We now obtain the pole equations

We know:

i) The ideal pole is a line of constant scalar potential Φ, because $B = \text{grad}\ \Phi$;

ii) Equations for scalar potential from first principles:

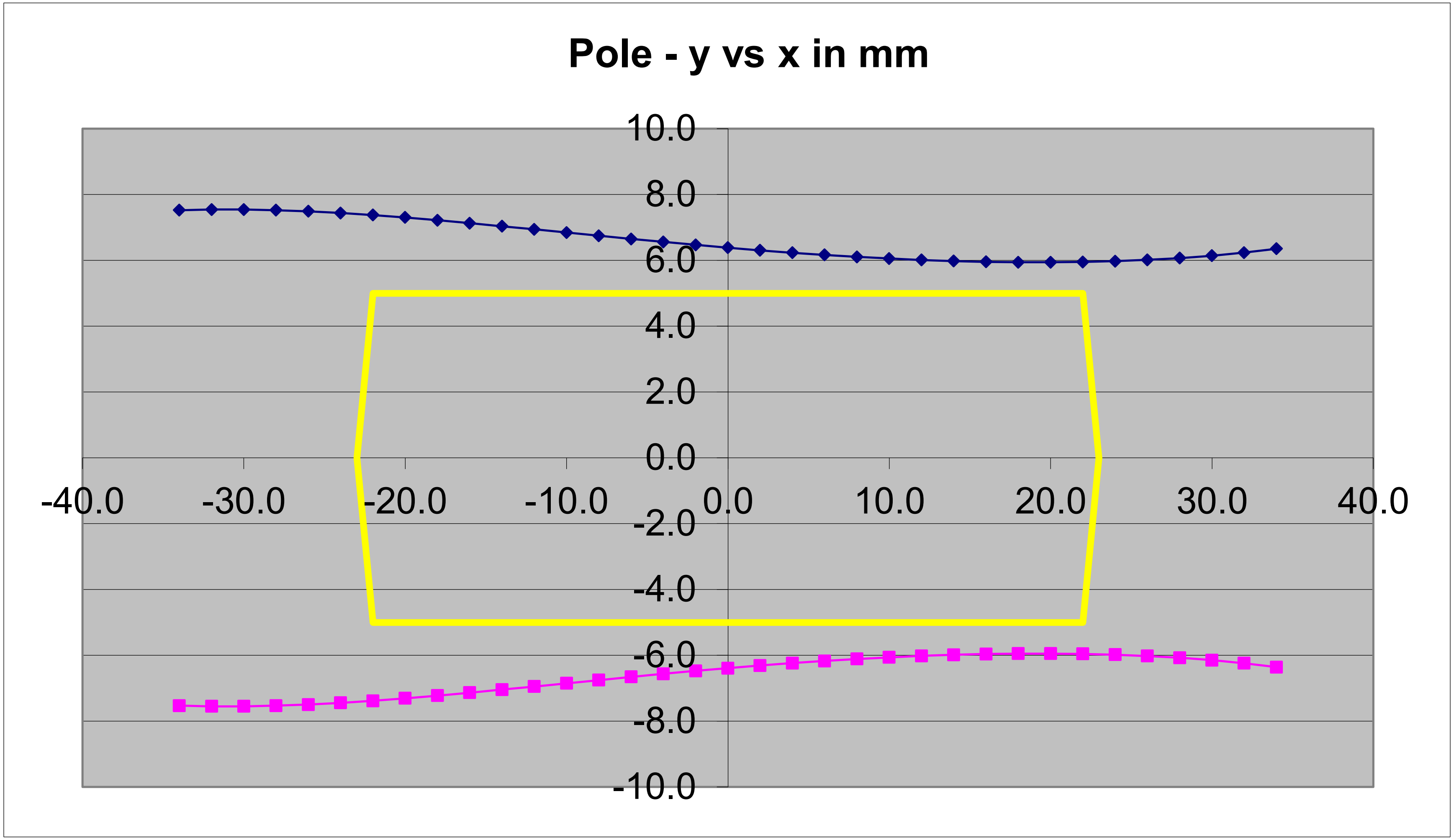
dipole	Φ_0	=	$b_0\ y$;
quad	Φ_1	=	$b_1\ 2xy$;
sext	Φ_2	=	$b_2\ (3yx^2 - y^3)$;
oct	Φ_3	=	$b_3\ 4(yx^3 - y^3x)$;

iii) Pole equations given by:

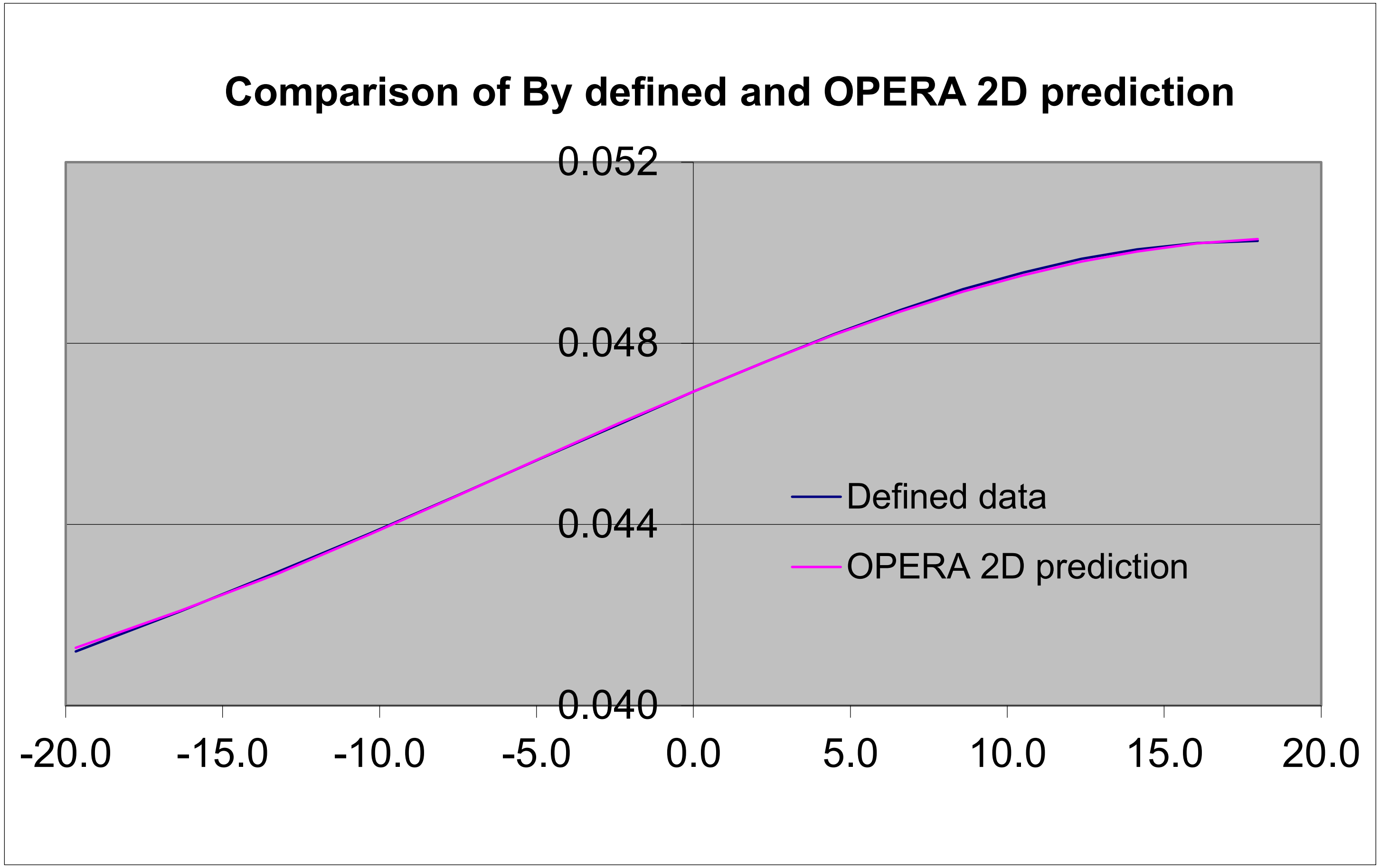
$$\sum_{n=0}^{3} \Phi_n = K$$

where K is a constant determined by gap or inscribed radius.

bd pole shapes and vac vessel

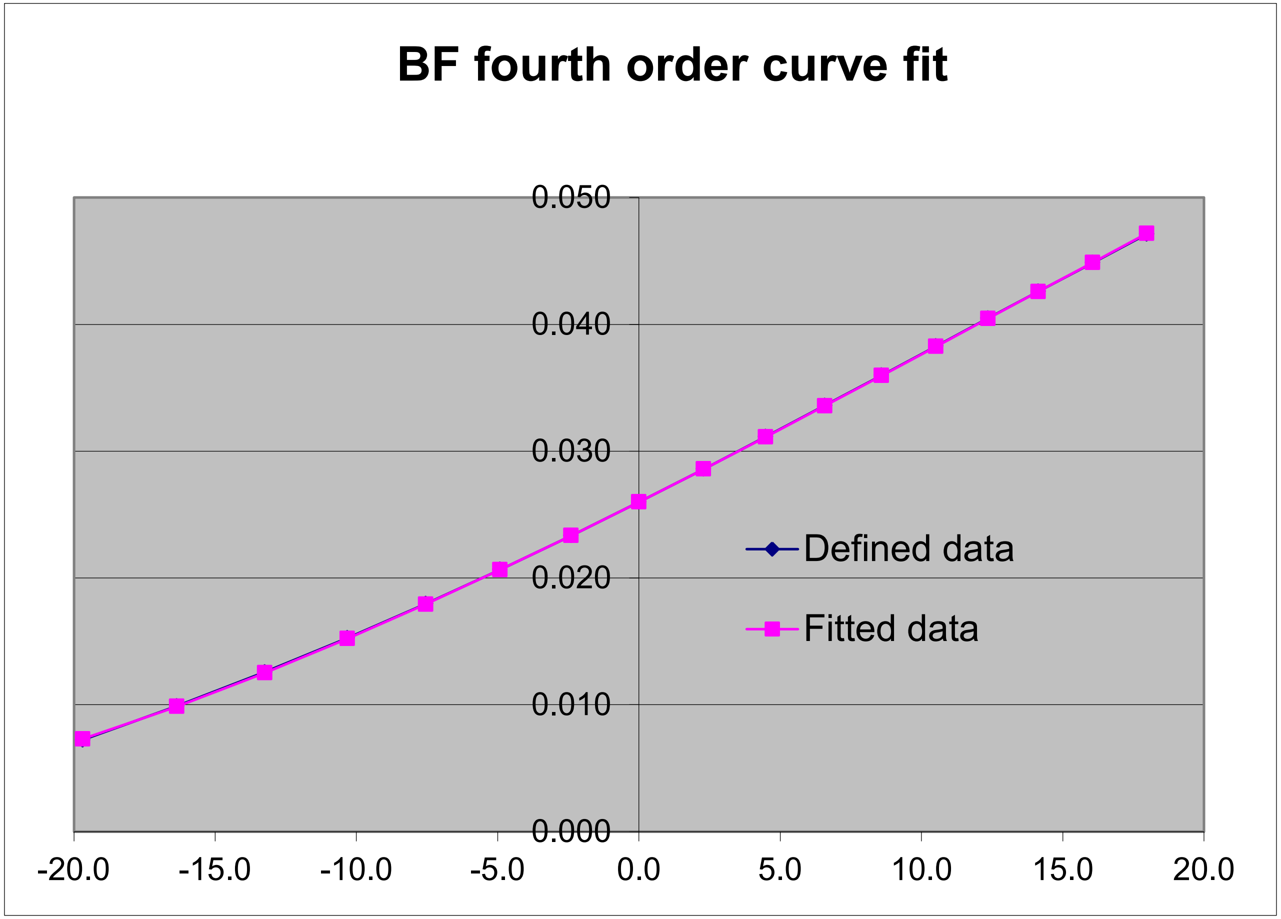


Comparison with specified field



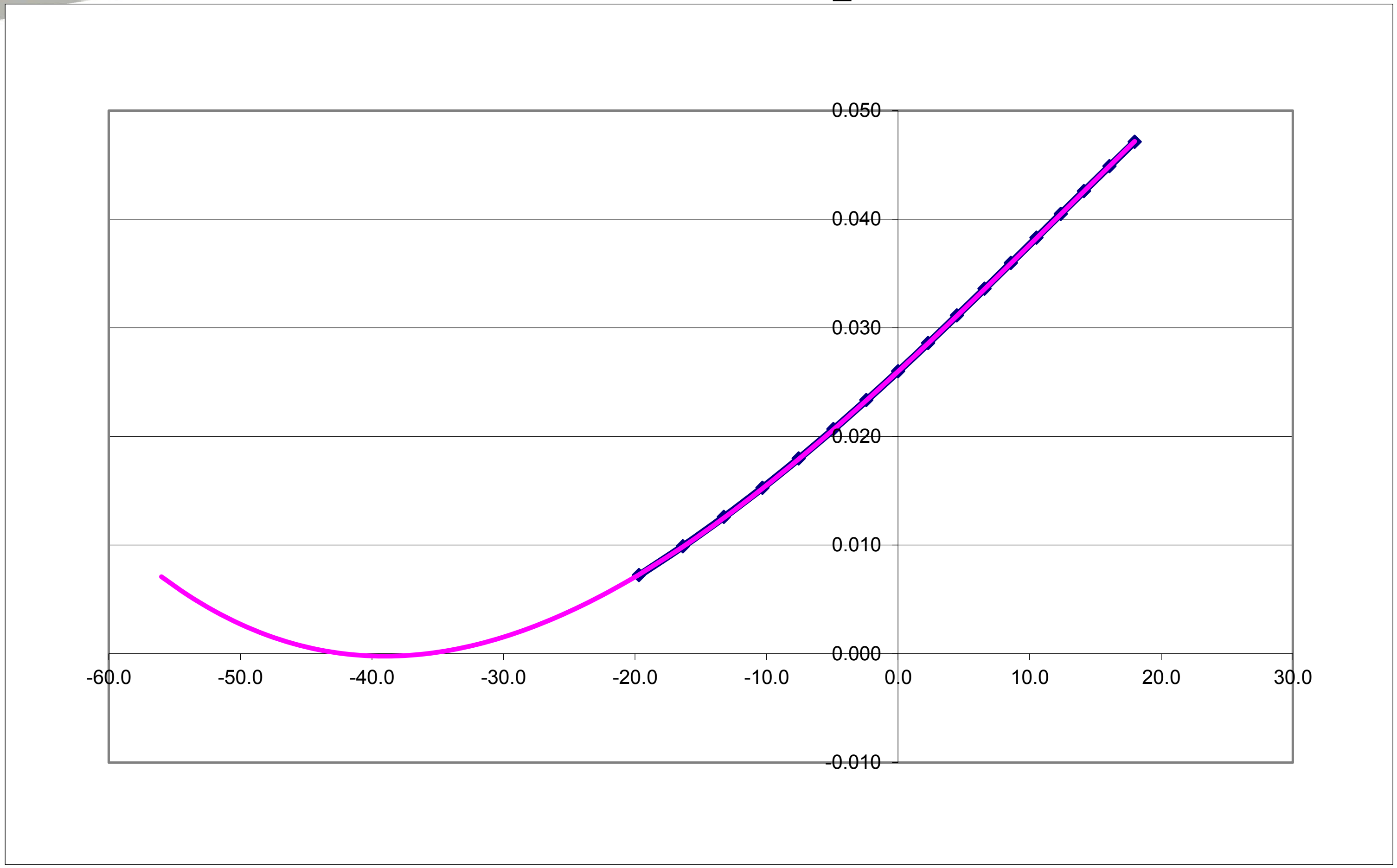
RMS error (fitting + determining potentials + OPERA) : 3.75 E-5

Now magnet BF !



What sort of magnet is this? dipole/quadrupole/sextupole?

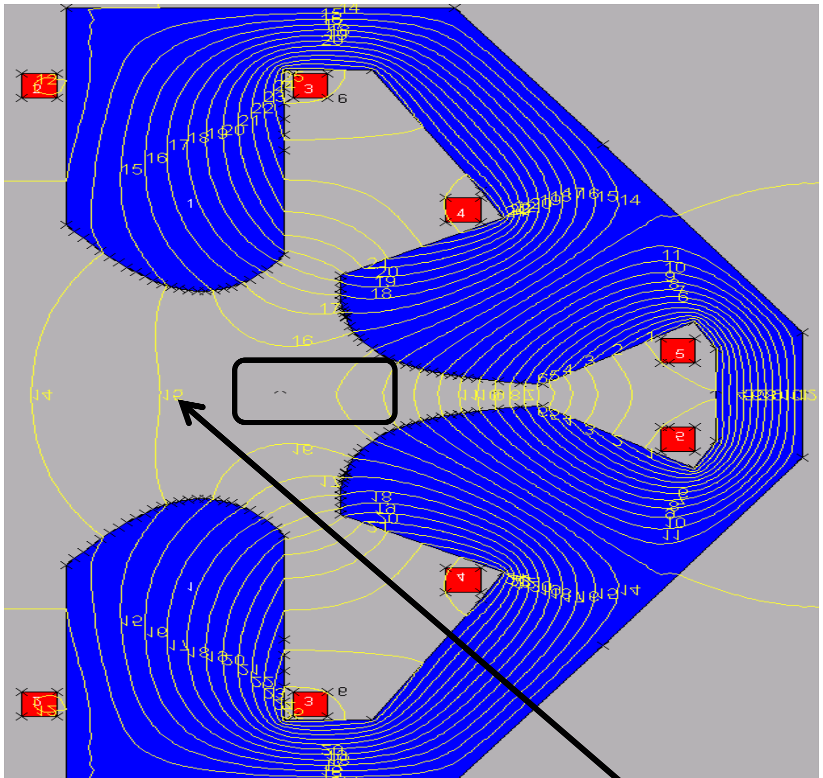
Curve fit extrapolated to -55 mm



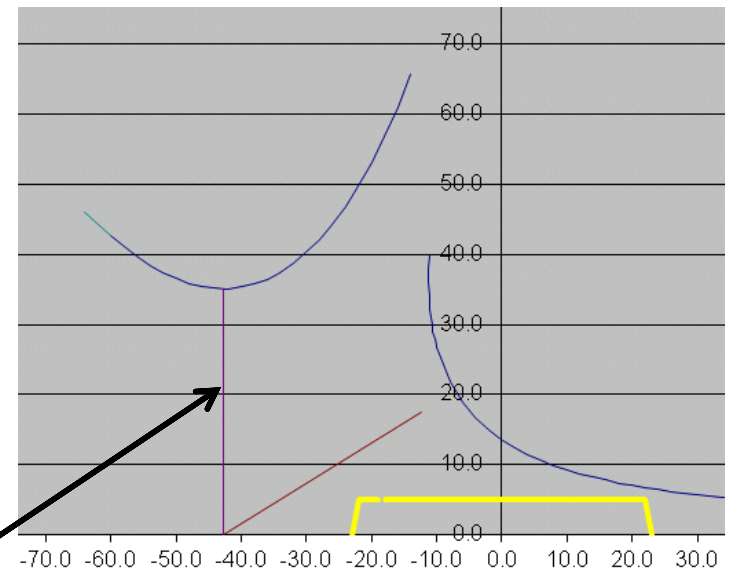
It's a sextupole (with dipole, quadrupole and octupole components).
Magnetic centre: X= - 40 mm; beam centre: X=0. We don't need the region < -20 mm.

So this is the magnet BF:

OPERA 2D model



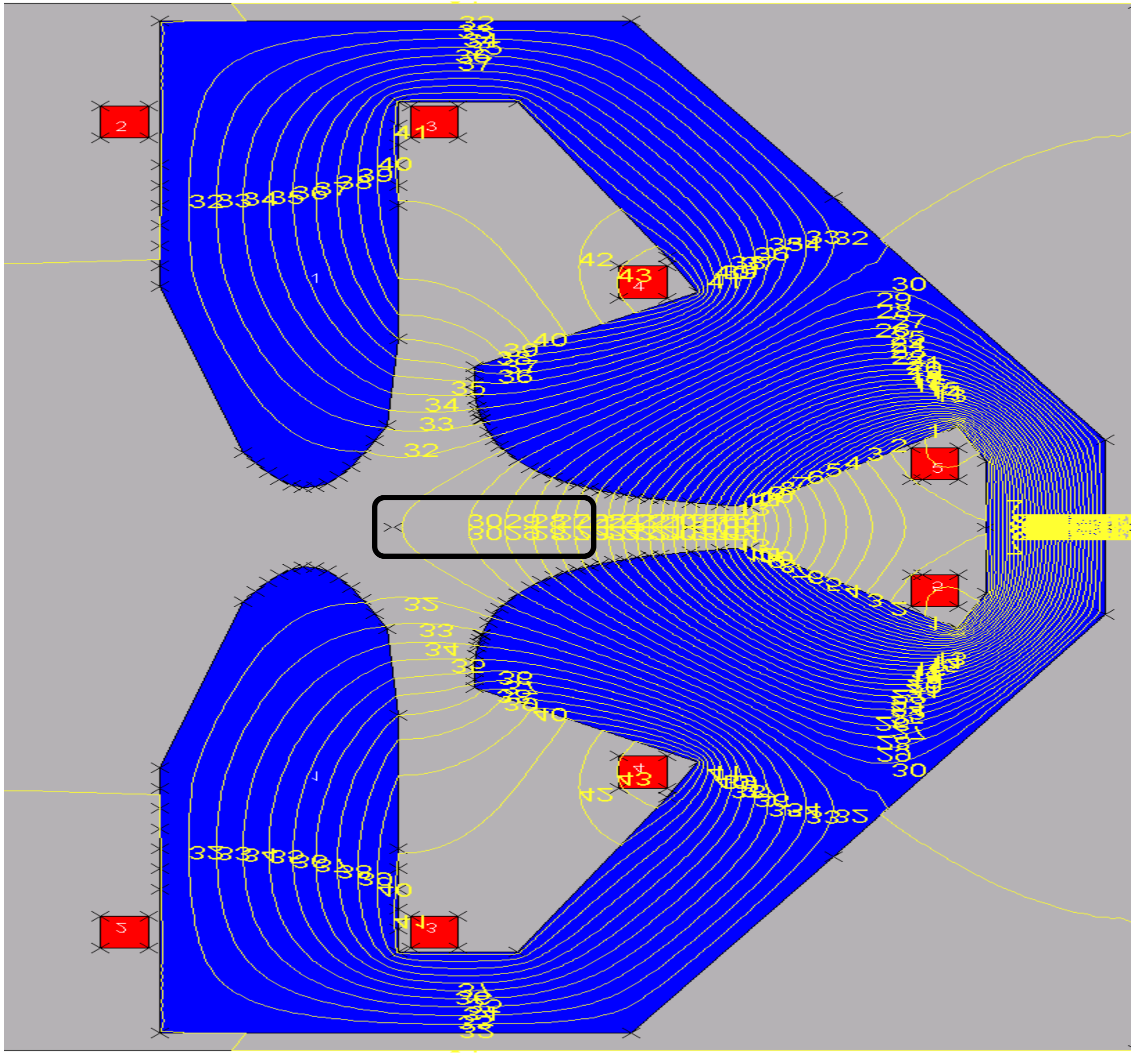
EXCEL plot of the top half of the central and right hand poles, with vessel in place;
poles have $\Phi = \pm\ 0.35$ T mm



As the beam is off-centre, this space between the two top poles is not needed!

The two top poles..

follow a line of reduced scalar potential – so require less coil current:

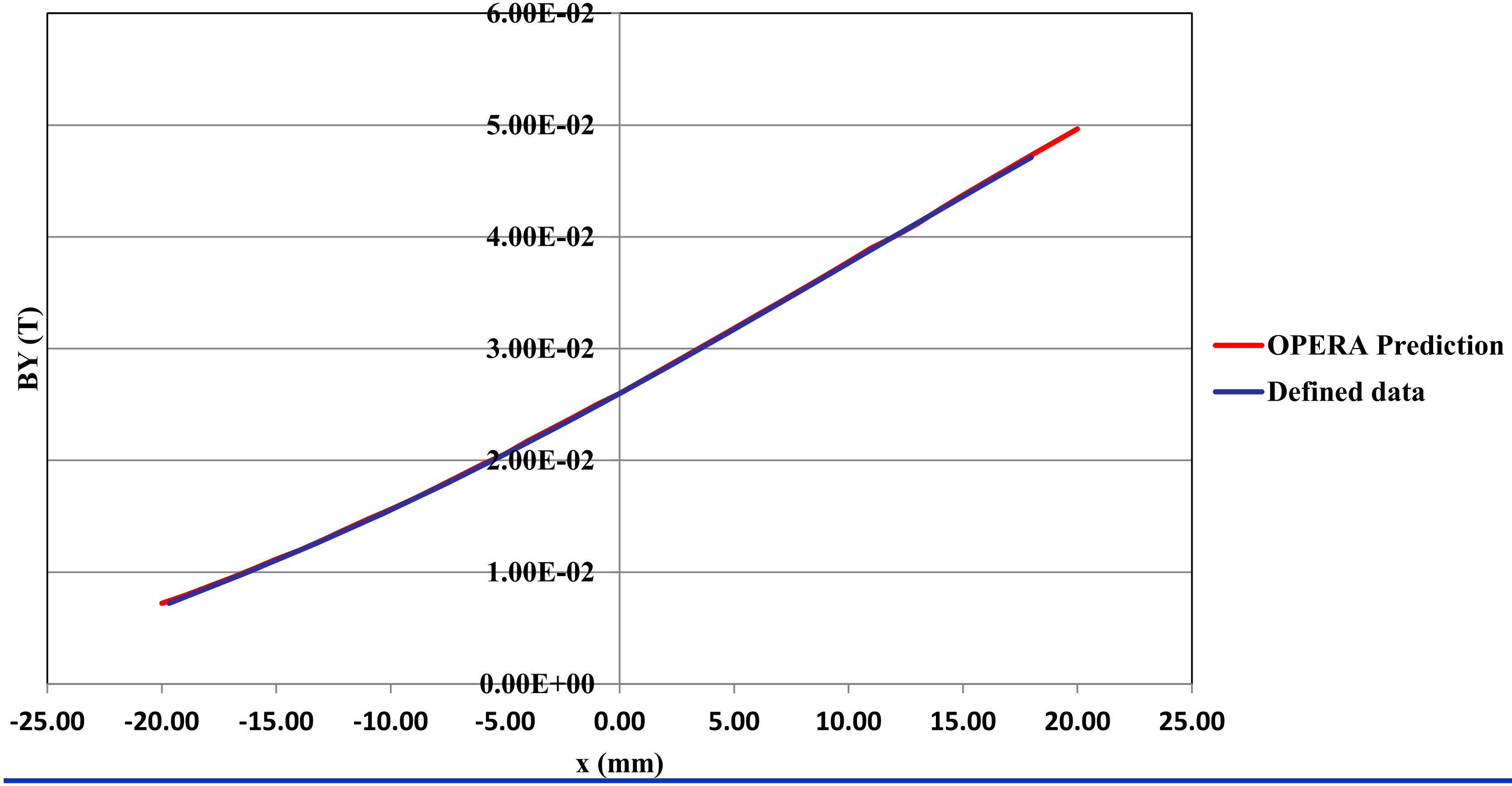


Side poles:
$\phi = \pm\ 0.35$ T mm;

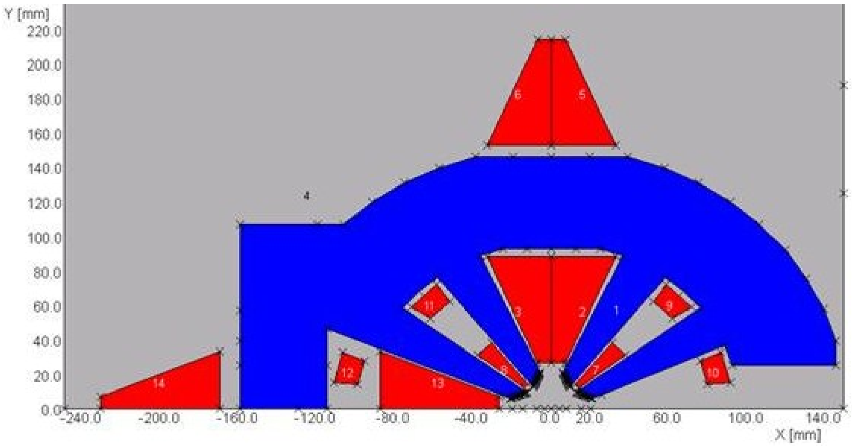
Central poles:
$\phi = \pm\ 0.01$ T mm;

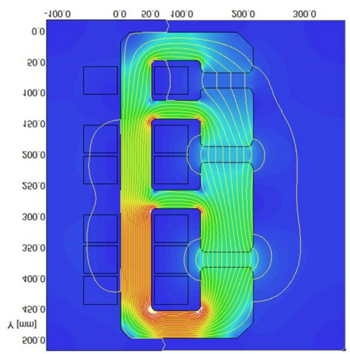
Therefore central poles require:
1/35 of the coil excitation current.

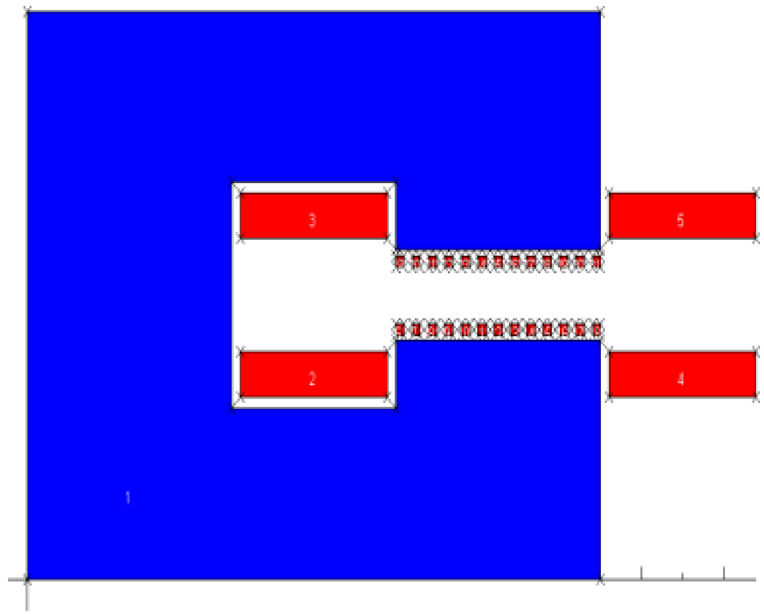
Tested with OPERA 2D model

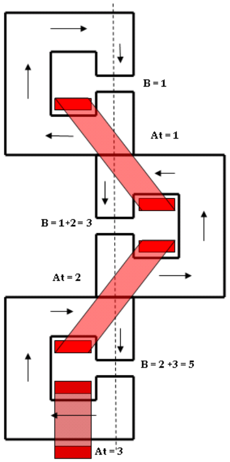


And the others from the title page ?



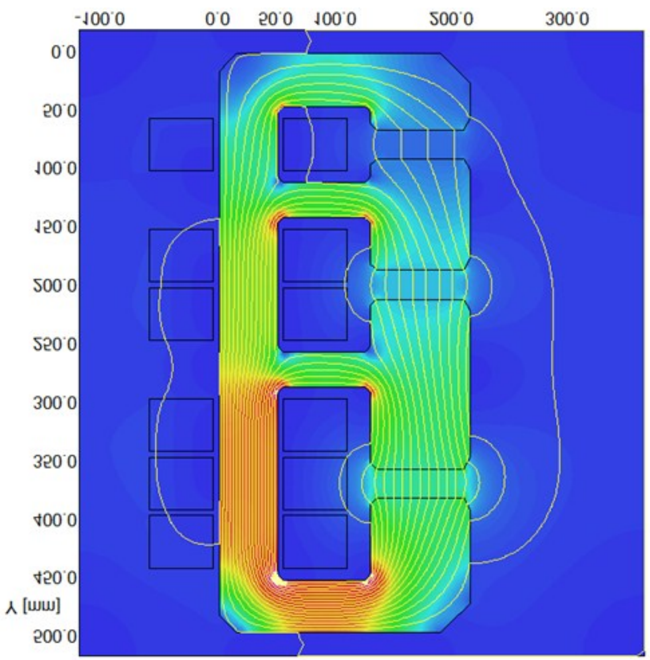




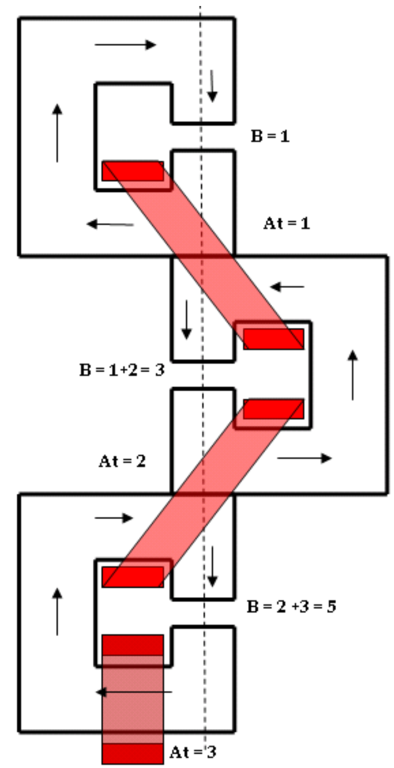


For the LHeC?

Stack of 3 dipoles for the return arcs of the linac/ring option of the proposed LHeC; the magnets are all separately powered.

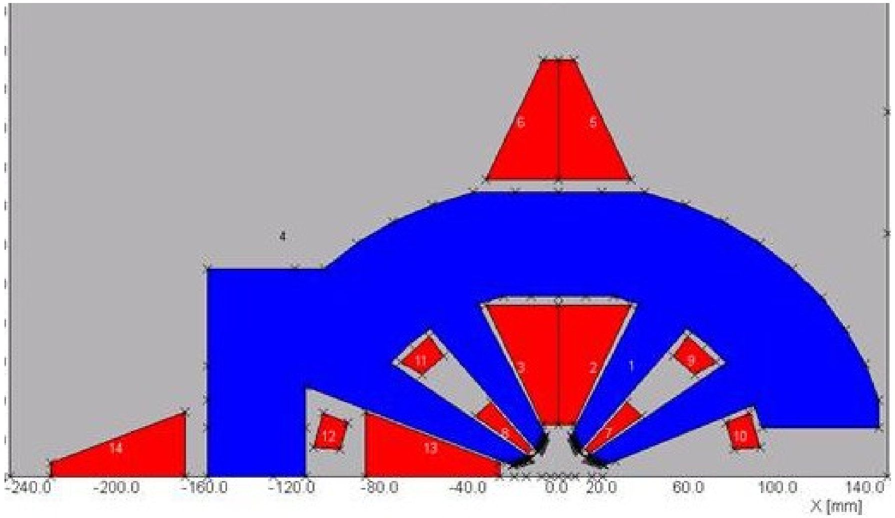


Alternative arrangement using shared coils to save 1/3 in coil volume and excitation power.

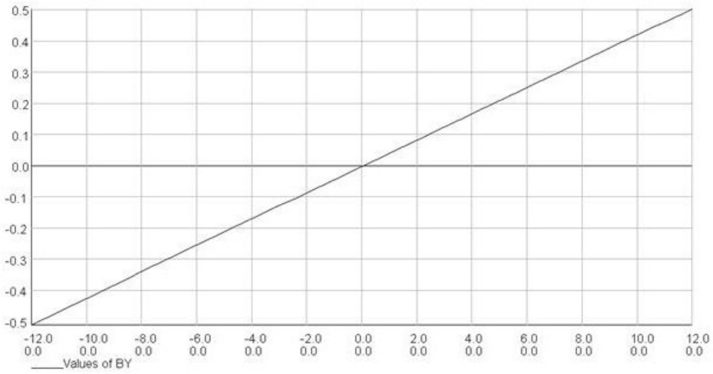


Investigation of a combined quadrupole/sextupole

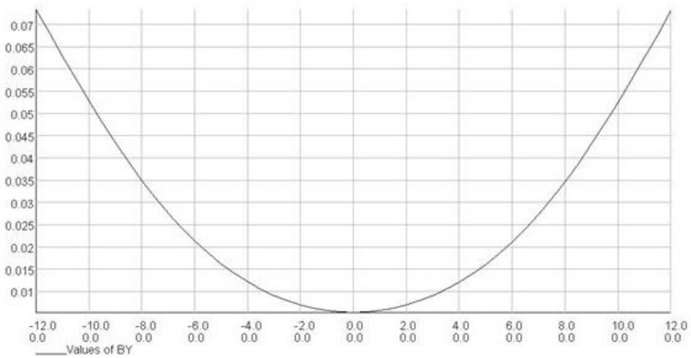
For possible lattice modifications on Diamond, to provide 2 new insertion straights.



Half of 8 pole magnet, with coils (in red).

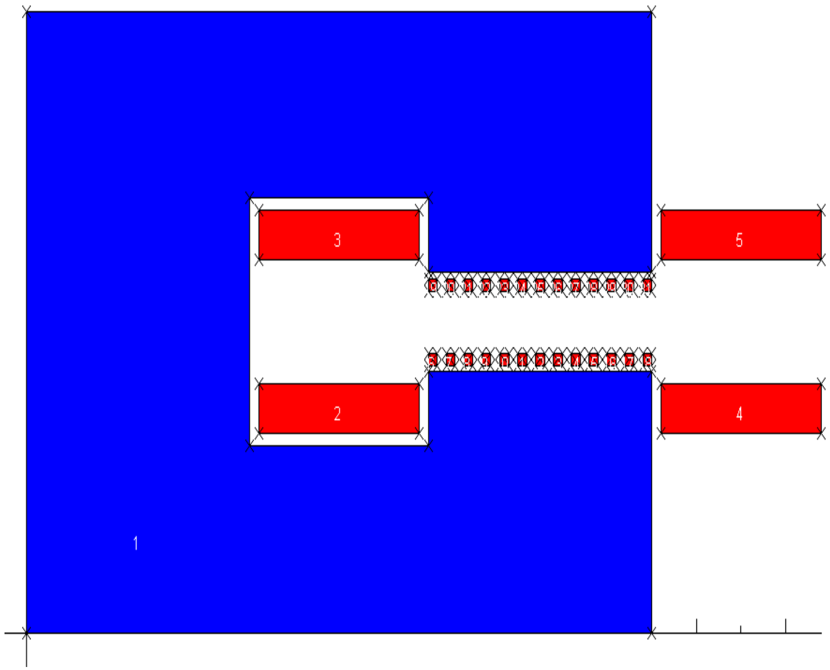


With quadrupole excitation



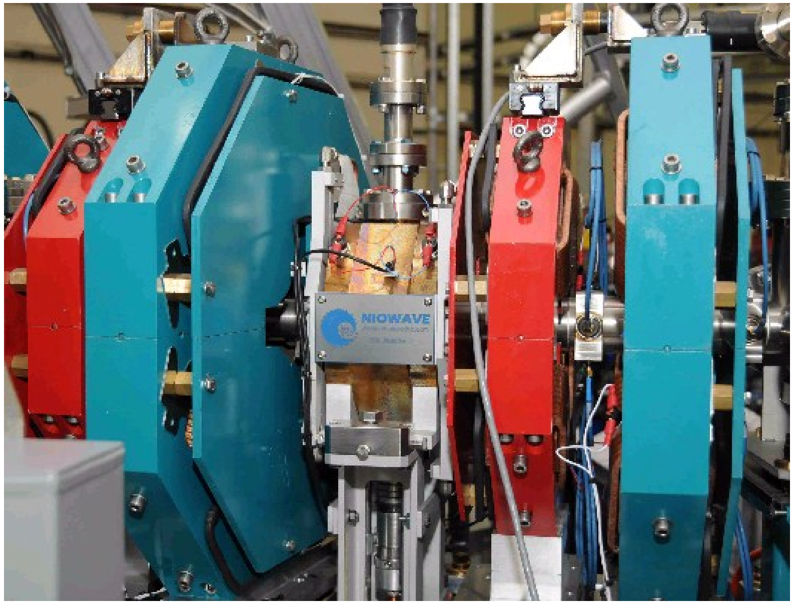
With sextupole excitation.

What EMMA could have been like!



Dipole with added quadrupole pole-face windings.

Quadrupoles with dipole component, provided by variable horizontal displacement.



But

Definitely NOT that!

That's all folks!

Thanks for listening.