Magnets for accelerator, an accelerated view

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TE-MSC-MNC

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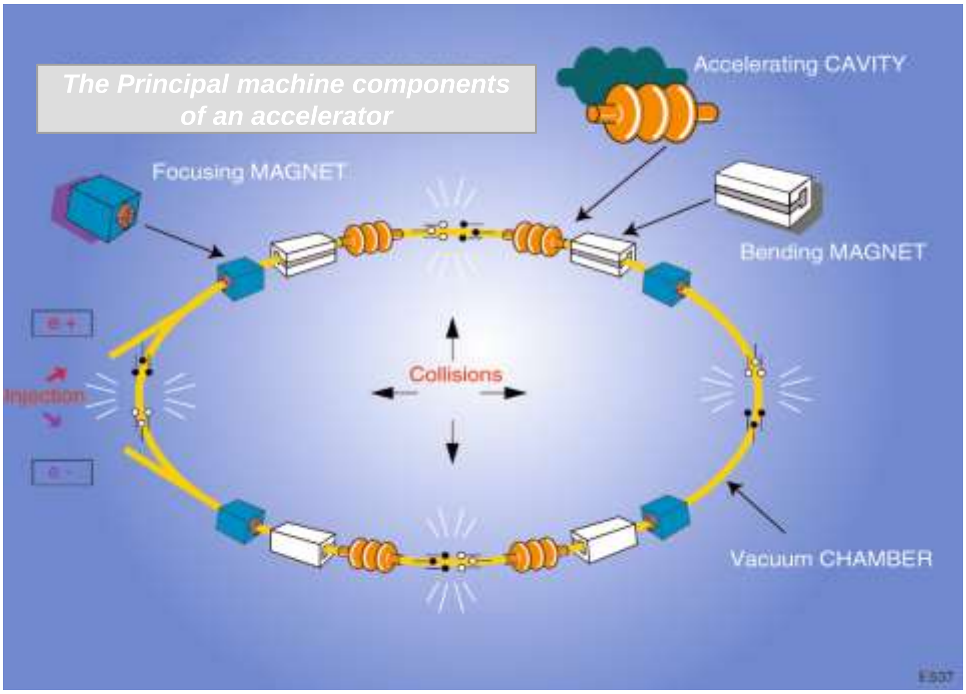
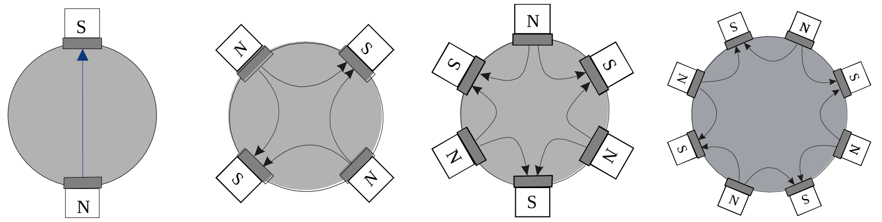
Outline

- Introduction to magnets for accelerators
- Normal conducting magnets or iron dominated magnets
  - Field
  - Forces
  - Cooling
  - Construction
  - An example of technological issue: the insulation radiation resistance
- Superconducting materials
- Superconducting magnets
  - Field, forces and structures
  - An example of technological issue: the insulation
  - Superconducting magnet construction

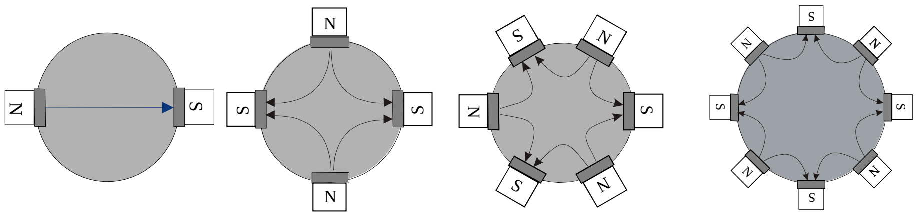
INTRODUCTION



Magnet types : field harmonics

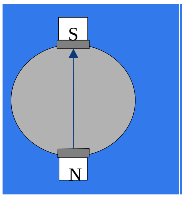
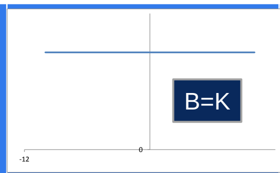
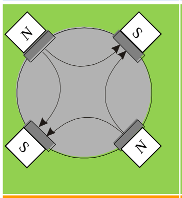
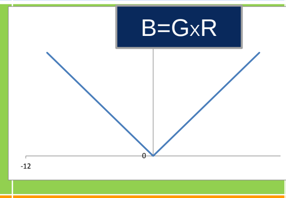
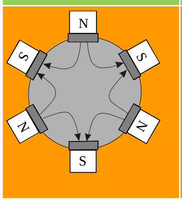
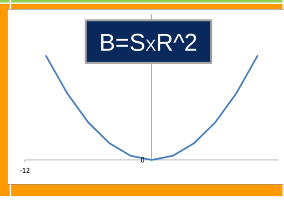


NORMAL : vertical field on mid-plane



SKEW : horizontal field on mid-plane

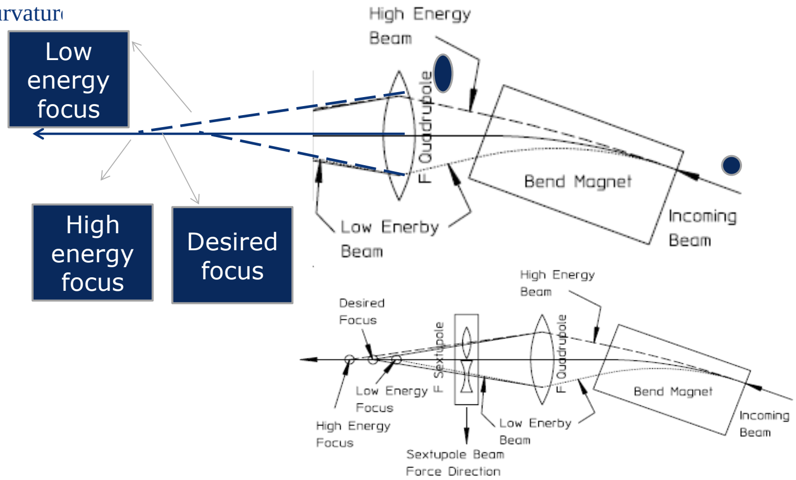
Field type: shape and function I

	**Dipoles=Bending magnets: bend the beam along the set path**		
	**Quadrupoles=Focussing magnets: move the particles back to the centre of the aperture**		
			

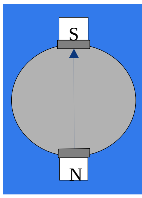
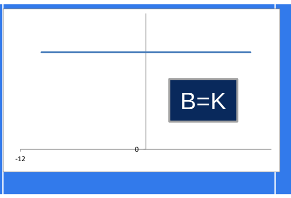
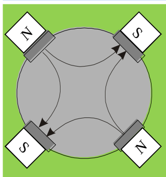
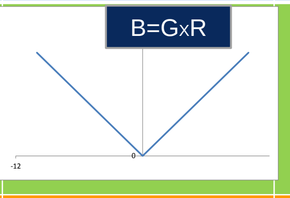
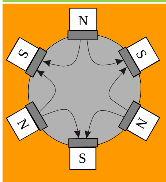
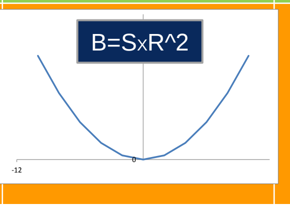
Why sextupole ?

$$B\rho = \frac{1}{qc}\sqrt{T^2 + 2TE_0},$$

q = charge in Coulombs
c = the speed of light in m/sec
T = beam energy
E0 = the particle rest mass energy
ρ= radius of curvatur

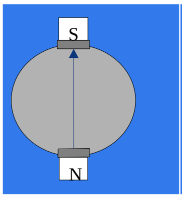


Field type: shape and function II

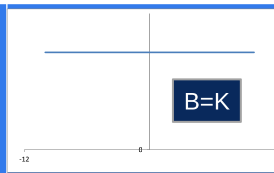
	Dipoles=Bending magnets: bend the beam along the set path		
	Quadrupoles=Focussing magnets: move the particles back to the centre of the aperture		
	Sextupole=correct for the chromatic aberration due to dispersion in a dipole caused by the momentum spread in the beam.		

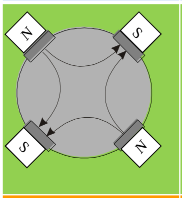
NORMAL CONDUCTING MAGNET OR IRON DOMINATED MAGNETS

Field type: shape and function III

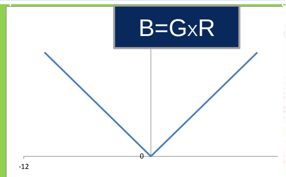


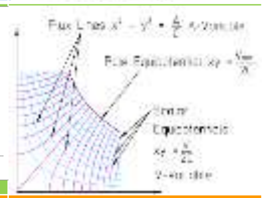
Dipoles=Bending magnets: bend the beam along the set path

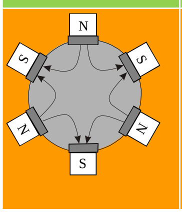




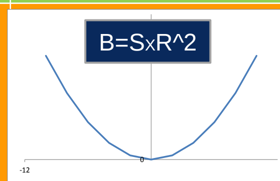
Quadrupoles=Focussing magnets: move the particles back to the centre of the aperture

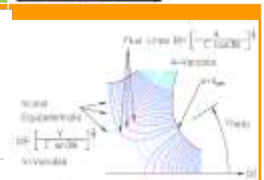






Sextupole=correct for the chromatic aberration due to dispersion in a dipole caused by the momentum spread in the beam.





Shaping the field

$$(\overrightarrow{B_2} - \overrightarrow{B_1}) \cdot \vec{n} = 0$$

$$(\overrightarrow{H_2} - \overrightarrow{H_1}) \times \vec{n} = \frac{4\pi}{c} \vec{K}$$

$$\overrightarrow{B_2} \cdot \vec{n} = \overrightarrow{B_1} \cdot \vec{n}$$

$$\frac{\overrightarrow{B_2}}{\mu_2} \times \vec{n} = \frac{\overrightarrow{B_1}}{\mu_1} \times \vec{n} \;\; \rightarrow \overrightarrow{B_2} \times \vec{n} = \frac{\mu_2}{\mu_1} \overrightarrow{B_1} \times \vec{n}$$

$$B_2 \cos\alpha_2 = B_1 \cos\alpha_1$$

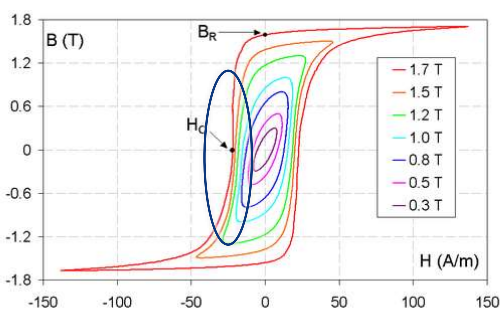
$$B_2 \sin\alpha_2 = \frac{\mu_2}{\mu_1} B_1 \sin\alpha_1$$

$$\tan\alpha_2 = \frac{\mu_2}{\mu_1} \tan\alpha_1$$

$$\tan\alpha_2 = \frac{\mu_{r2}\mu_0}{\mu_{r1}\mu_0} \tan\alpha_1$$

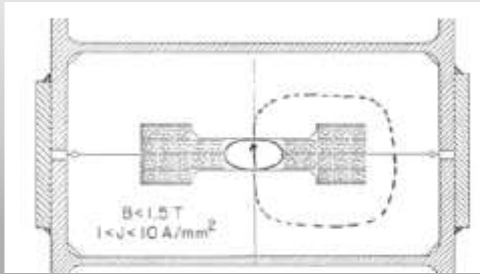
$$\tan\alpha_2 = \frac{1}{\mu_{r1}} \tan\alpha_1$$

$$\mu_{r1} \gg 1 \;\; \rightarrow \alpha_2 \sim \frac{\pi}{2}$$



Therefore the flux line (to which the $\overrightarrow{B}$ is tangent point by point) is perpendicular to the shape of the interface between a material with high μ_r and the air independently of the shape of the flux lines in that materials

Creating the field->you need coil



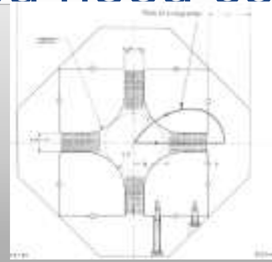
$$\oint H \cdot dl = NI$$

$$NI(\text{ampere turns}) = \oint \frac{B}{\mu} \cdot dl = \frac{Bg^{air}}{\mu_0} + \frac{B\ell^{iron}}{\mu_o}\left(\frac{\mu_o}{\mu_{iron}}\right)$$

$$\left(\frac{\mu_o}{\mu_{iron}}\right)\frac{g}{\ell} \gg 1$$

$NI \propto gap$
$P \propto Ni^2 \propto gap^2$

$$NI(\text{ampere turns}) = \frac{B\left(\text{weber/m}^2\right) g(\text{meter})}{\mu_o = 4\pi \times 10^7(\text{meter/ampmeter})}$$



$$\oint H \cdot dl = NI$$

$$NI = \oint H \cdot dl = \int_0^a \frac{B(r)}{\mu^o} dr + [\text{iron path}] + [\text{path} \perp \text{to the field}]$$

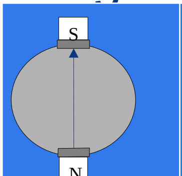
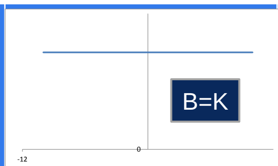
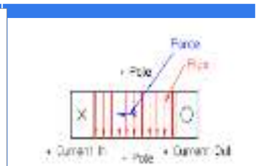
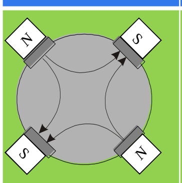
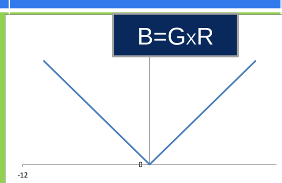
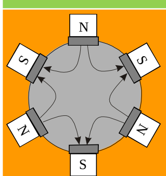
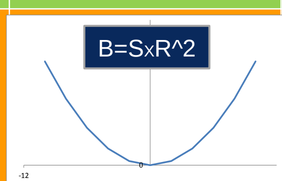
$$= \int_0^a Kr\,dr = \frac{Ka^2}{2} \ .$$

$NI \propto gap^2$
$P \propto Ni^2 \propto gap^4$

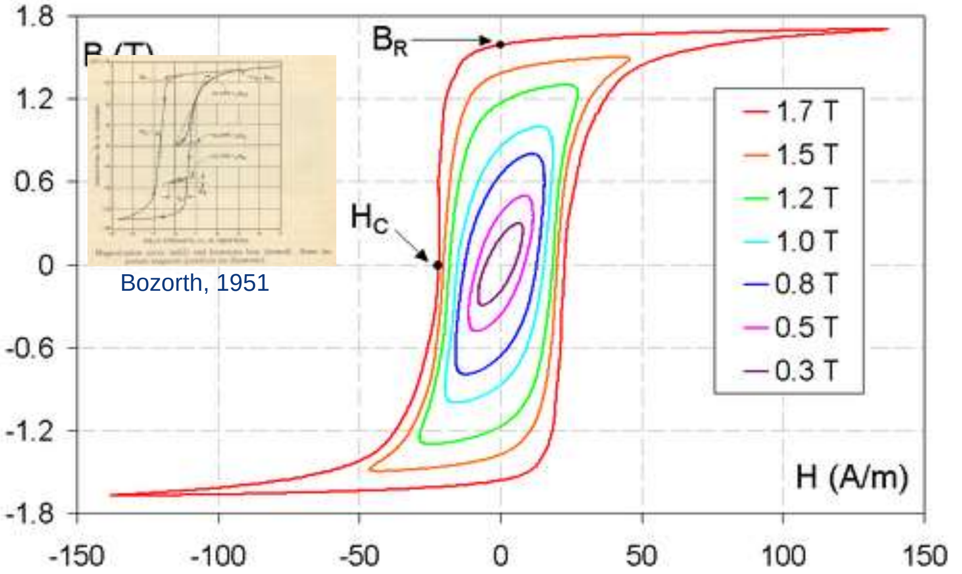
But, since $Ka = B_{\text{pole tip}}$,

$$\frac{NI}{\text{pole}} = \frac{B_{\text{pole tip}}(\text{weber/m}^2) \times a^2(\text{m})}{2\mu_o = 2(4\pi \times 10^{-7})}$$

Field type: shape and function, real magnet

	**Dipoles=Bending magnets: bend the beam along the set path**		
	**Quadrupoles=Focussing magnets: move the particles back to the centre of the aperture**		
	**Sextupole=correct for the chromatic aberration due to dispersion in a dipole caused by the momentum spread in the beam.**		

But iron saturates ,…..

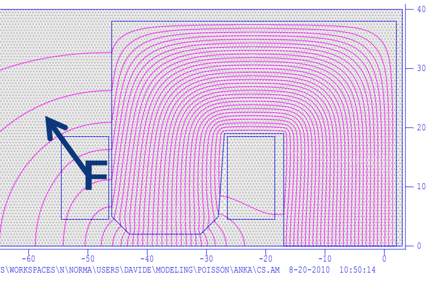


For iron, above 1.5-2 T any increase of magnetic field costs a lot of magnetomotive force

Effect of interaction field with the coil current:

On a conductor immerged in magnetic field

$$\mathbf{F} = I\cdot \boldsymbol{L}\times\mathbf{B}$$



Example for the Anka dipole:
On a the external coil side with N=40 turns, I= 700A, L~2.2 m
in an average field of B= 0.25 T

F= 40·700 · 2.2·0.25 = 15400 N =0.015MN~ 1.5 $tons_f$

0.007MN/m

Losses and heat removal

In a coil of cross section *S*, total current *I*, per unit of length *l*,

$$P/l\,[W/m] = \frac{\rho}{S}\cdot I^2$$

$$\rho_{cu} = 1.72\cdot(1+0.0039\cdot(T-20))\cdot 10^{-8}\,\Omega\cdot m$$

In the yoke we have losses due to:

- hysteresis: up to 1.5 T we can use the Steinmetz law

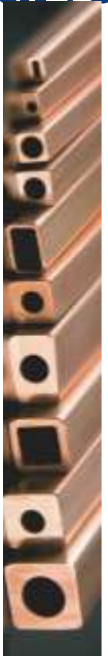
$$P[W/kg] = \eta\cdot f\cdot B^{1.6}$$

with $\eta = 0.01 \div 0.1$, about 0.02 for silicon steel

- eddy currents: for silicon iron, an approximate formula is

$$P[W/kg] = 0.05\cdot(d_{lam}\cdot\frac{f}{10}\cdot B_{av})^2$$

where d_{lam} is the lamination thickness in mm



To increase the temperature of 1 kg of water by 1 degree C we need 1 kcal=1/4.186 kJ

$$Q[l/\min] = 14.3\cdot\frac{P[kW]}{\Delta T}$$

To efficiently cool a pipe you need the fluid velocity be greater than zero on the wall, i.e. the flow being moderately turbulent (Reynolds > 2000):

$$R_e = \frac{d\cdot v}{\upsilon} \sim 1400\cdot d[mm]\cdot v[m/s] \text{ for water at} \sim 40°\text{C}$$

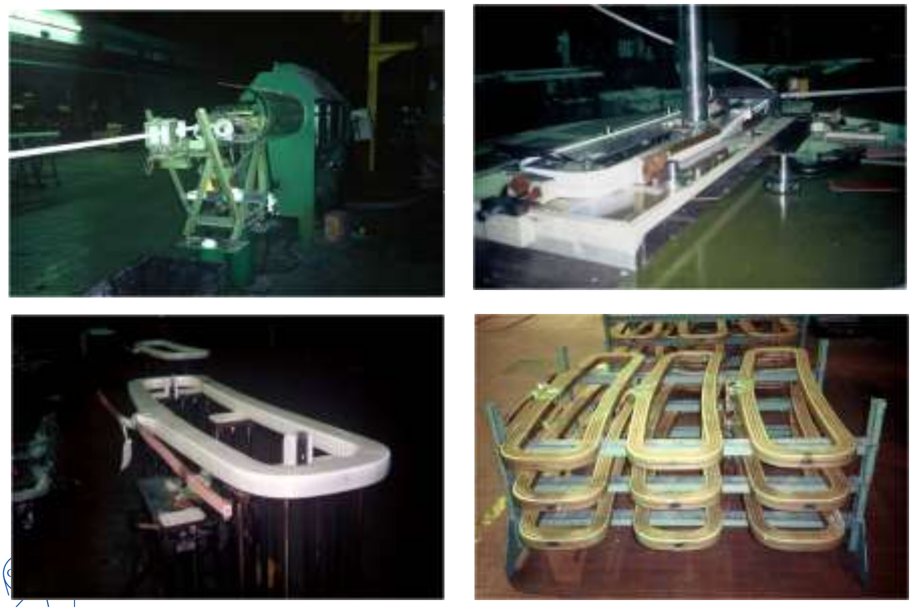
Small pipes need high velocity, however attention to erosion (v>3m/s)!

As cooling pipes in magnets can be considered smooth, a good approximation of the pressure drop ΔP as a function of the cooling pipe length *L*, the cooling flow *Q* and the pipe hole diameter *d* is derived from the Blasius law, giving:

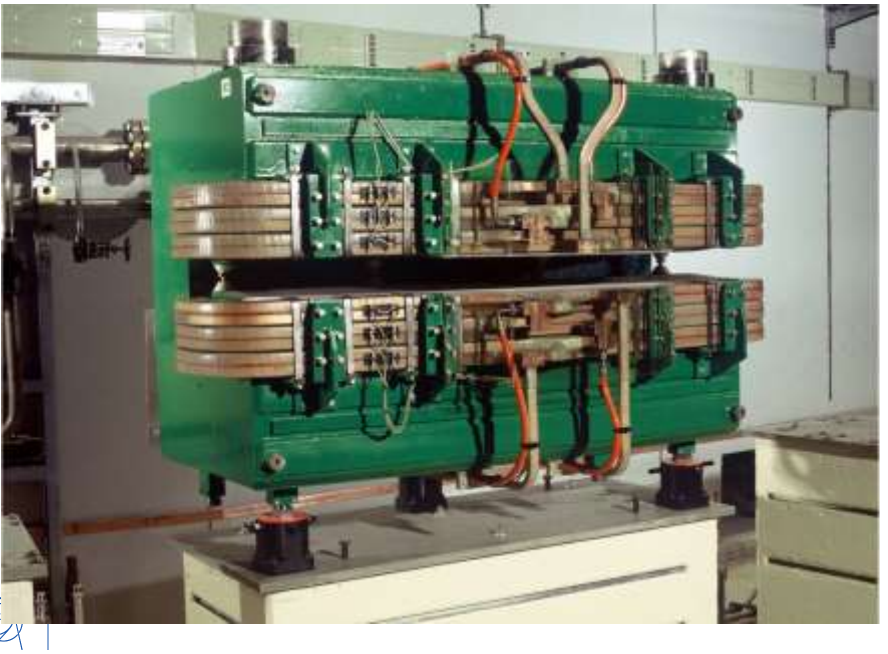
$$\Delta P[bar] = 60\cdot L[m]\cdot\frac{Q[l/\min]^{1.75}}{d[mm]^{4.75}}$$

Normal conducting magnet construction

Coil production

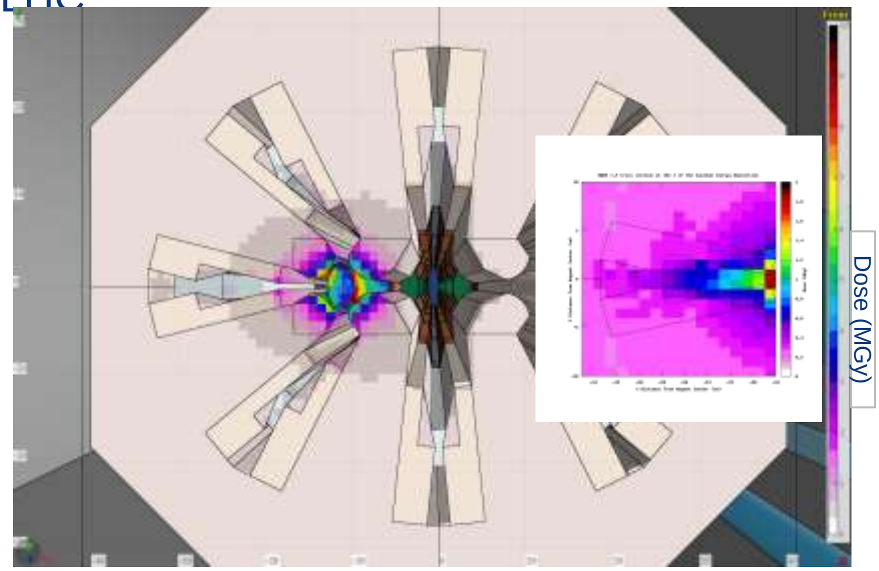


Iron yoke production



An example of technological issue:
the insulation radiation resistance

Dose on a normal conducting magnet in the LHC



Normalization: 1.15 10^{16} p (30-50 fb^{-1}).

Computations with E 6.5 TeV relaxed collimator settings

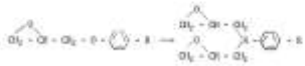
Different epoxy

Resins	Hardeners	Additives	Composition (p.p.)	Mix Temp (°C)	Viscosity (cPs)	Service life (mn)	Fig	Dose for 50% flex. (MGy)	Dose Range (MGy)
EDBAH	MA						5.4	1.4	1 - 3
EDBAH	MA	BDMA	100-105-0.2	80	45	>180	5.1	1.6	
BECP	MA						5.4	2.5	
BECP	MA	BDMA	100-110-0.2	80	40	>180	5.1	2.3	
ECC	MA		100-72	80	20	>240	5.5	1.8	1 - 6
VCD	MA	BDMA	100-160-05	60	20	>180	5.4	3.7	
DADD	MA		100-65	80	180	>240	5.4	5.5	
DGEBA + EDGDP	TETA		100-20-12	25			5.21	1.3	1 - 2
DGEBA	TETA	DBP	83-9-17	50	500	few	5.22	1.2	
DGEBA	DADPS		100-35	130	60	180	4.2	5.1	5 - 15
DGEBA + EDGDP	MDA		100-20-30	80			5.21	8.2	
DGEBA	MDA		100-27	80	100	50	5.9	13.0	
DGEBA	MPDA		100-14.5	65	200	30	5.7	23.5	**23**
DGEBA	AF		100-40	100	150	30	5.26	45.2	**45**
DGEBA	DDSA	BDMA	100-130-1	80	70	120	5.2	4.2	5 - 15
DGEBA	NMA	BDMA	100-80-1	80	80	120	5.2	5.9	
DGEBA	MA		100-100	60	69	>1440	5.23	7.1	
DGEBA	MA	BDMA					5.1	12.0	
DGEBA	MA	BDMA + Po. Gl.	100-100-0.1-10	60	65	300	5.23	12.1	
DGEBA	AP		100-70	120	26	180	5.2	13.0	
DGPP	DADPS		100-28	130			5.6	8.2	5 - 15
DGPP	MA		100-135	120			5.3	13.0	
EDTC	MDA		100-20	80		40	5.9	10.0	
TGTPE	DADPS		100-34	125	>20000		5.6	12.1	
TGTPE	MA	BDMA	100-100-0.2	125	>15000		5.3	10.6	
EPN	DADPS		100-35	100		30	5.6	23.5	**20 - 40**
EPN	MDA		100-29	100		35	5.10	37.2	
EPN	HPA	BDMA	100-76-1	80		40	5.10	13.0	**10 - 20**
EPN	MA	BDMA	100-105-0.5	80		100	5.3+5.25	15.0	
EPN	NMA	BDMA	100-85-1	100		80	5.10	20.6	
TGMD	DADPS		100-40	80		50	5.6	20.6	**10 - 25**
TGMD	MA	BDMA	100-136-0.5	60		30	5.3	11.4	
TGMD	NMA	BDMA	100-110-1	80	500	20	5.8	18.0	
TGPAP	NMA		100-137	80	<20		5.8	23.5	
DGA	MPDA		100-20	25		120-420	5.7	23.5	**20 - 30**
DGA	NMA		100-115	25	5 - 20	30-5760	5.8	28.6	

Legend

Resin
- Linear aliphatic
- Cycloaliphatic
- Aromatic

Hardener
- Aliphatic Amine
- Aromatic Amine
- Alicyclic Anhydride
- Aromatic Anhydride



Aromatic >
Cycloaliphatic >
Linear Aliphatic

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Aliphatic amine harderner
→ poor radio-resistance

Aromatic amine hardener
>
Anhydride hardener

H: Too high local concentration of benzene may induce steric hin disturbation

Good radio-resistance even if Cl (tendence to capture n_{th})

Novolac: HIGH Radio-resistance
- Large nb of epoxy groups
→ Density + rigidity

Glycidyl-amine: HIGH R.-resistance
- ~~Quaternary carbon → weakness~~
- ~~Ether group (R–O–R')~~ → Repl. by amina
→ weakness

Filler contribution

Resins	Hardeners	Additives	Filler	Composition (p.p.)	Fig	Dose for 50% flex. (MGy)	Dose Range (MGy)
DGEBA	MDA		Papier	100-27-200	5.14	1.3	1 - 2
DGEBA	MDA		Silice	100-27-200	5.14	10	10 - 15
DGEBA	MDA		Silice	100-27-200	5.18	11.4	
DGEBA	MDA		Silice (5 micron)	100-27-20	5.16	14.8	
DGEBA	MDA		Silice (20 micron)	100-27-20	5.16	14.8	
DGEBA	MDA		Silice (40 micron)	100-27-20	5.16	14.6	
DGEBA	MDA		Silice (40 micron)	100-27-200	5.17	12.1	
DGEBA	HPA	BDMA	Silice (40 micron)	100-80-2-200	5.17	<10	<10
DGEBA	MDA		Aérosil + Sulphate de Barium	100-27-2-150	5.14	15.8	15
DGEBA	MDA		Magnésie	100-27-120	5.14	18	18
DGEBA	MDA		Graphite	100-27-60	4.6	26.8	25 - 30
DGEBA	MDA		Graphite	100-27-60	5.14	30.5	
(DGEBA	MDA		Alumine	100-27-220	4.7	23.5)	20 - 50
DGEBA	MDA		Alumine	100-27-220	5.14	51.7	
DGEBA	MDA		Alumine	100-27-100	5.15	20.6	
DGEBA	MDA		Alumine	100-27-220	5.15	42.5	
DGEBA	**MDA**		**Fibre de verre**	**100-27-50**	**5.19**	**82**	**80 - 100**
DGEBA	**MDA**		**Fibre de verre**	**100-27-60**	**5.18**	**100**	
EPN	**MDA**		**Fibre de verre**	**100-29-50**	**5.19**	**>100**	**>100**
TGMD	**MDA**		**Fibre de silice**	**100-41-50**	**5.20**	**>100**	**>100**
TGMD	**DADPS**		**Fibre de silice**	**100-40-50**	**5.20**	**>100**	

Legend

Resin: Linear aliphatic; Cycloaliphatic; Aromatic

Hardener: Aliphatic Amine; Aromatic Amine; Alicyclic Anhydride; Aromatic Anhydride

2 Categories of fillers:
1. Powder fillers
2. Glass/Silice fibers

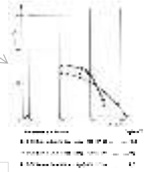
Paper [cellulose $(C_6H_{10}O_5)_n$]
→ Strong decrease of radio-resistance

The bigger the powder, the more radio-resistant

Hardener choice not influenced by filler

High r.-resistance for Graphite and Alumina

The more fillers, the more radio-resistant



Best Radio-Resistant materials are obtain with Glass/**Silice** (influence of boron) fibers and aromatic resins (**Novolac** and **glycidyl-amine**)

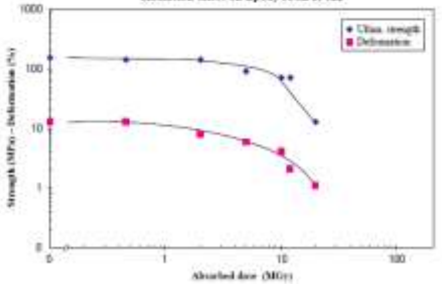
CERN 98-01/AI/E

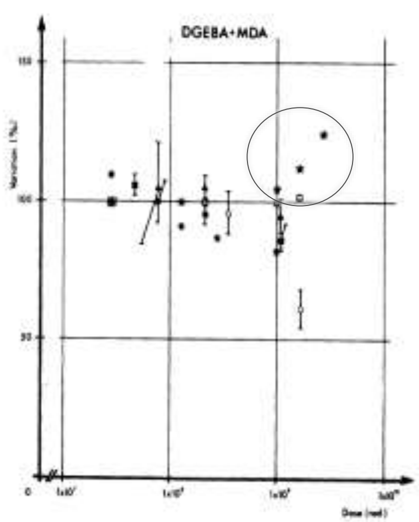
Material	Epoxy resin	TIS No. R 422
Type	MY 745 (50) + EPN 1138 (50) + CY 221 (20) + HY 905 (120) + DY 073 (0.5)	
Supplier	Ciba-Geigy	UL 94: n.m.
Remarks:	used for the ISR dipoles	LOI:

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose rate (kGy/h)	Dose (MGy)	Ultim. strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	0	153±1	13.1±1.5	3.80±0.03
0.2	0.5	142±1	12.9±0.3	3.50±0.02
0.2	2.0	140±1	7.0±0.3	3.50±0.02
180	5	93±2	6.1±0.3	4.00±0.03
180	10	73±1	4.2±0.2	4.10±0.04
0.5	12	71±6	2.1±0.2	3.7±0.1
180	20	13±1	1.1±0.1	3.40±0.04

Radiation index (RI) = 6.9 if strength is the critical property
Radiation index (RI) = 6.6 if deformation is the critical property

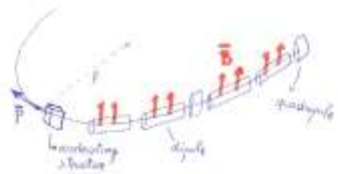


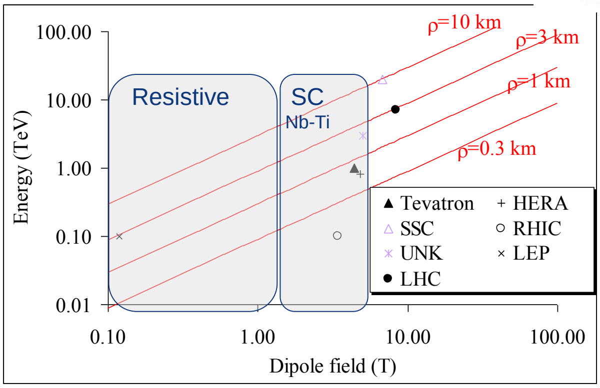


Modifications des propriétés mécaniques du DGEBA+MDA en fonction des doses absorbées

The limits of NC magnet application

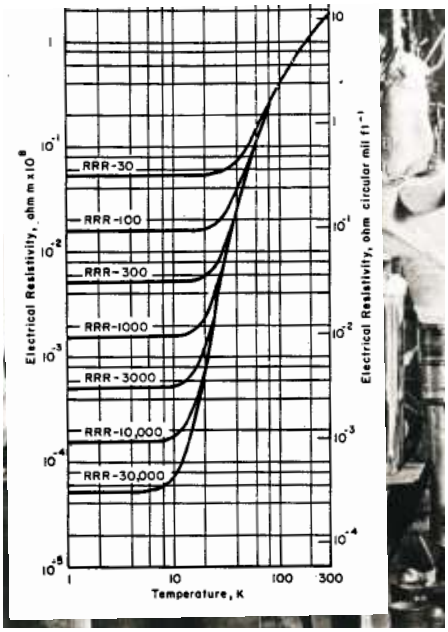
$$B\rho = \frac{1}{qc}\sqrt{T^2 + 2TE_0}$$

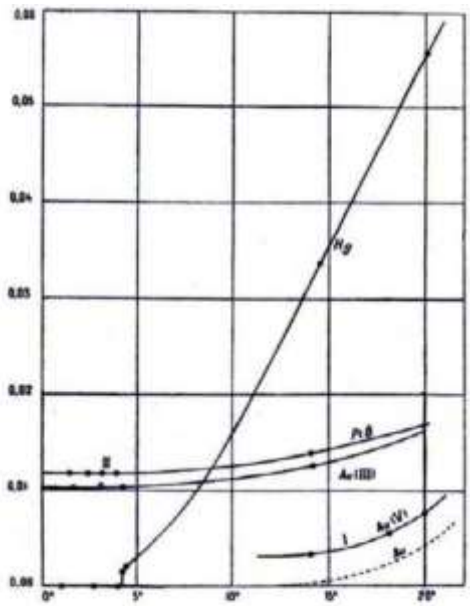


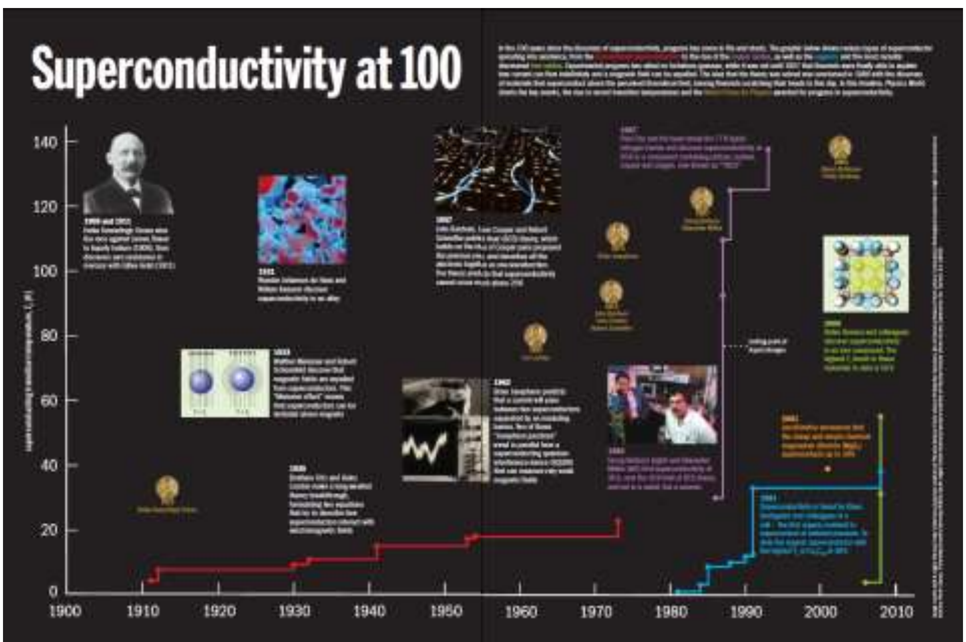


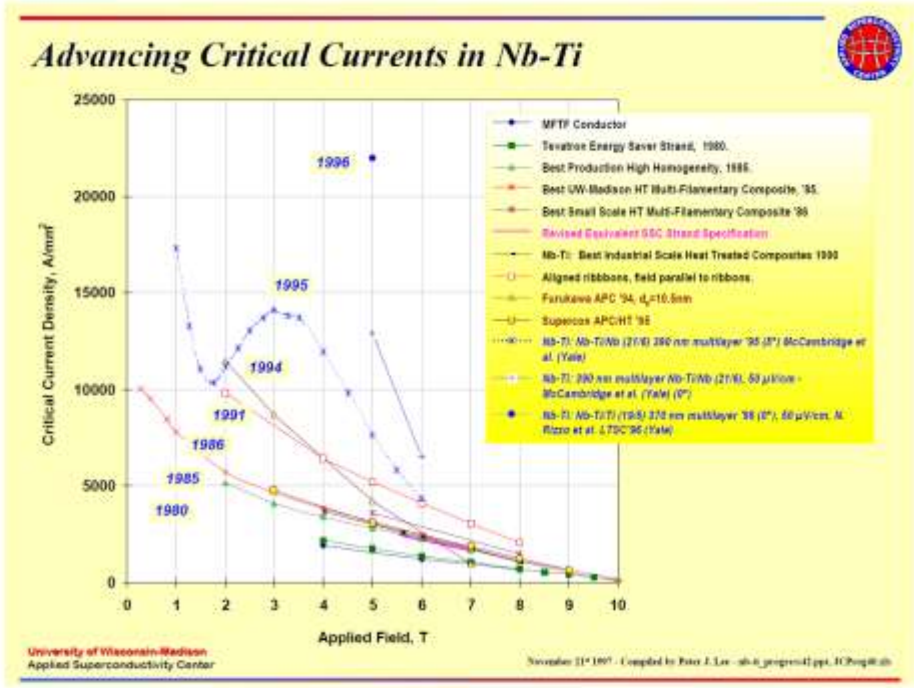
SUPERCONDUCTING MATERIALS

Superconductivity

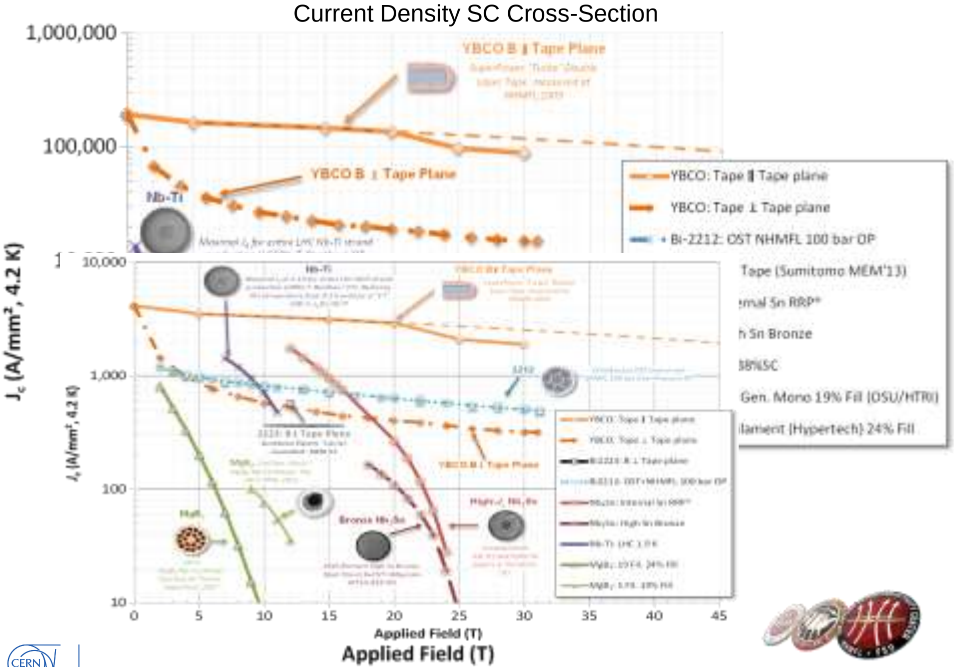






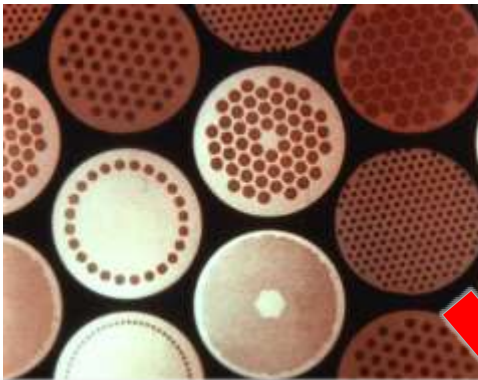


Current Density SC Cross-Section



Superconductor material, but under which conductor shape

for 5 to 10kA, we need 20 to 40 wires in parallel



•a single 5μm filament of Nb-Ti in 6T carries 50mA

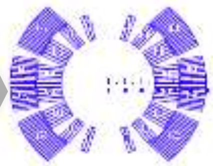
•a composite wire of fine filaments typically has 5,000 to 10,000 filaments, so it carries 250A to 500A

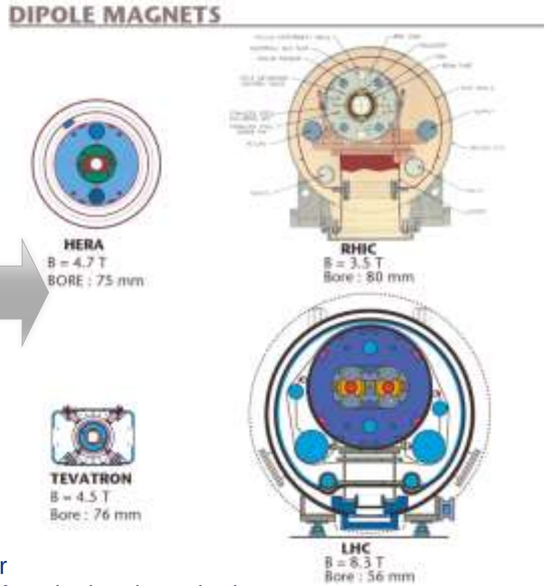
$$V = \frac{L\,I}{t} = \frac{2E}{I\,t}$$

- The main reason why Rutherford cable succeeded where others failed was that it could be compacted to a high density (88 - 94%) without damaging the wires. Furthermore it can be rolled to a good dimensional accuracy (~ 10mm).
- Note the 'keystone angle', which enables the cables to be stacked closely round a circular aperture

SUPERCONDUCTING MAGNETS

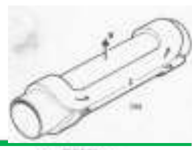
How we can use the SC cable ?

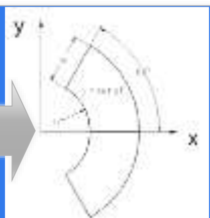


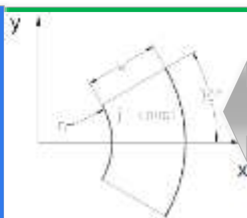


Remark: the field here is higher
of ferromagnetic material therefore the iron is pushed out
where the field is lower and closes the flux lines

GENERATION OF MAGNETIC FIELDS: FIELD OF A WINDING







$$|B| = \frac{I\mu_0}{2\pi\rho}$$

$$I \rightarrow j\rho d\rho d\theta$$

$$B = -4\frac{j\mu_0}{2\pi}\int_0^{\alpha}\int_r^{r+w}\frac{\cos\theta}{\rho}\rho d\rho d\theta = -\frac{2j\mu_0}{\pi} w\sin\alpha$$

B **∝ current density**
B **∝ coil width *w***
B **is independent of the aperture *r***

$$|B| = \frac{I\mu_0}{2\pi\rho}$$

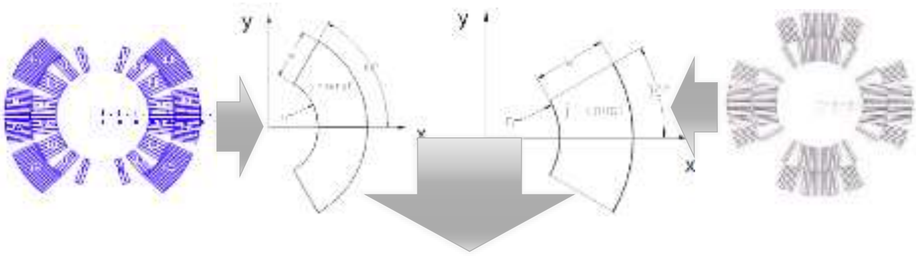
$$I \rightarrow j\rho d\rho d\theta$$

$$G \propto \int_r^{r+w}\int_0^{\alpha}\frac{\rho d\rho d\theta}{\rho^2 e^{-2i\theta}} \propto \sin(2\alpha)\log\left(1+\frac{w}{r}\right)$$

$$G = j\gamma_0 \log\left(1+\frac{w}{r}\right)$$

G ∝ current density
G∝ coil width w
G is inversely proportional of the aperture r

Approximate expression of the field



In the aperture

$$\begin{Bmatrix}B_r\\B_\varphi\end{Bmatrix} = -\frac{j\,\mu_0}{\pi}\left\{((r_i+w)-r_i)2\sin\alpha_0\begin{Bmatrix}\sin\varphi\\\cos\varphi\end{Bmatrix}\right\}$$

Outside the coil

$$\begin{Bmatrix}B_r\\B_\varphi\end{Bmatrix} = -\frac{j\,\mu_0}{\pi}\left\{\frac{((r_i+w)^3-r_i^3)}{3\,r^2}2\sin\alpha_0\begin{Bmatrix}\sin\varphi\\\cos\varphi\end{Bmatrix}\right\}$$

In the coil

$$\begin{Bmatrix}B_r\\B_\varphi\end{Bmatrix} = -\frac{j\,\mu_0}{\pi}\left\{((r_i+w)-r_i)+\frac{(r_i^3-r_i^3)}{3\,r^2}2\sin\alpha_0\begin{Bmatrix}\sin\varphi\\\cos\varphi\end{Bmatrix}\right\}$$

In the aperture

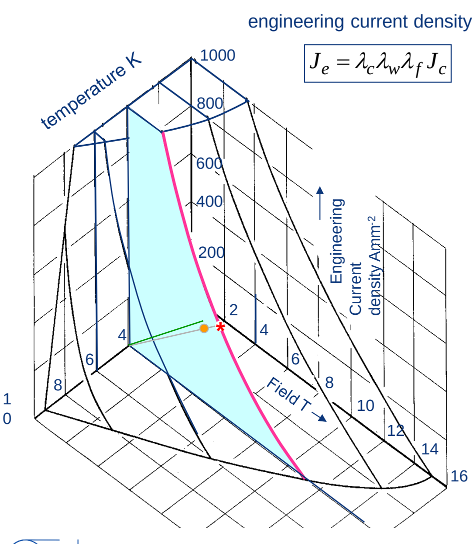
$$\begin{Bmatrix}B_r\\B_\varphi\end{Bmatrix} = -\frac{j\,\mu_0}{\pi}\left\{4r\ln\left(\frac{(r_i+w)}{r_i}\right)2\sin(2\alpha_0)\begin{Bmatrix}\sin 2\varphi\\\cos 2\varphi\end{Bmatrix}\right\}$$

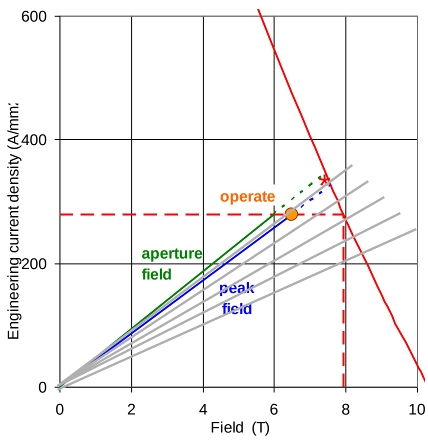
Outside the coil

$$\begin{Bmatrix}B_r\\B_\varphi\end{Bmatrix} = -\frac{j\,\mu_0}{\pi}\left\{\frac{((r_i+w)^4-r_i^4)}{r^3}2\sin(2\alpha_0)\begin{Bmatrix}\sin 2\varphi\\\cos 2\varphi\end{Bmatrix}\right\}$$

In the coil

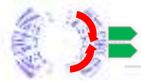
$$\begin{Bmatrix}B_r\\B_\varphi\end{Bmatrix} = -\frac{j\,\mu_0}{\pi}\left\{\left[4r\ln\left(\frac{(r_i+w)}{r_i}\right)+\frac{(r^4-r_i^4)}{r^3}\right]2\sin(2\alpha_0)\begin{Bmatrix}\sin 2\varphi\\\cos 2\varphi\end{Bmatrix}\right\}$$

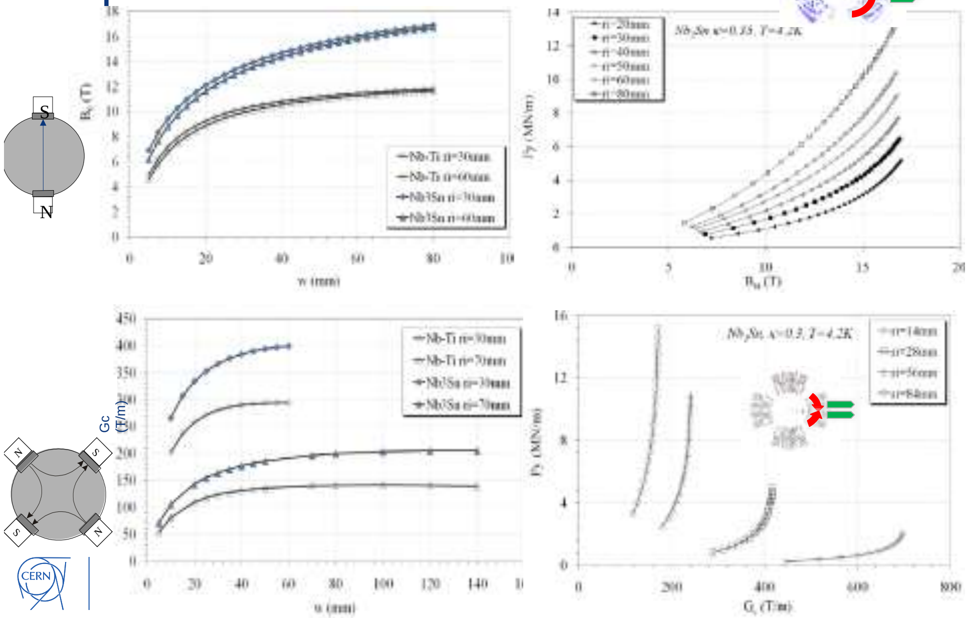




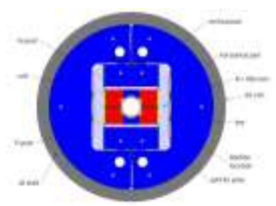
we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *
usually back off from this extreme point and operate at ●

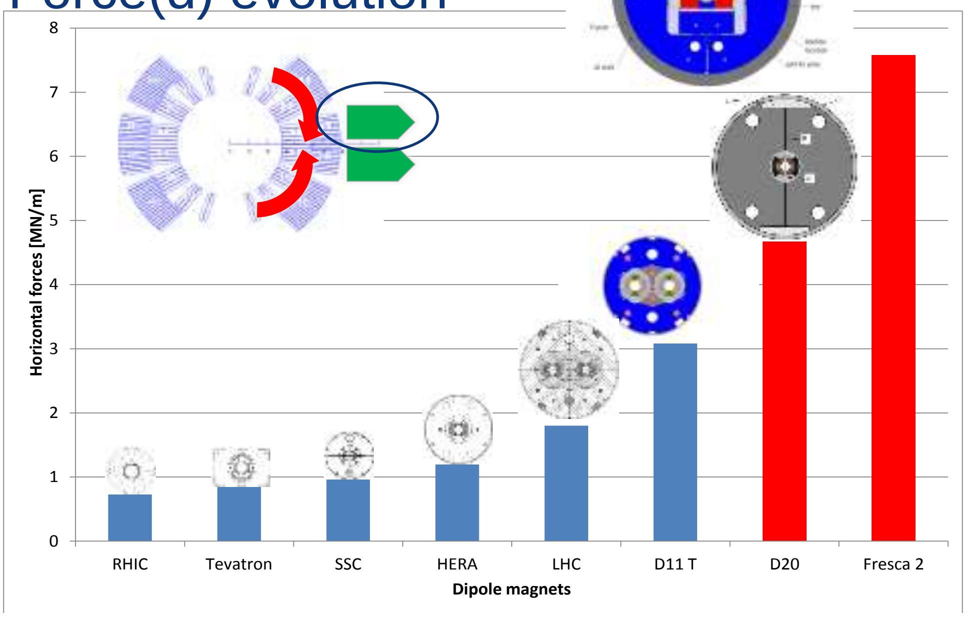
Creating field: limited by the critical surface and paid in term of forces



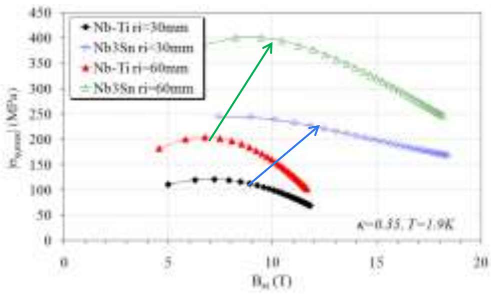


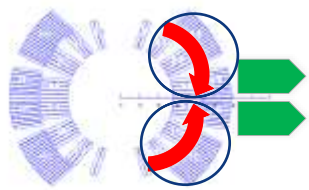
Bending magnets: the Force(d) evolution

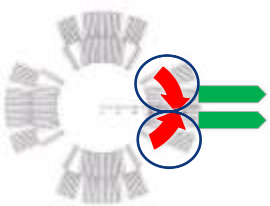


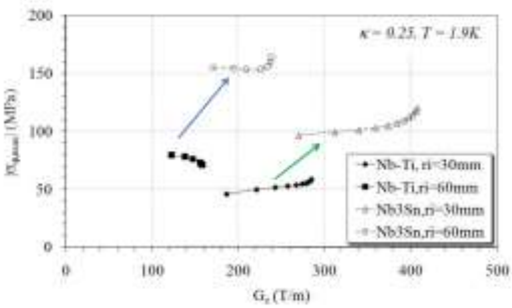


And what about stresses ?

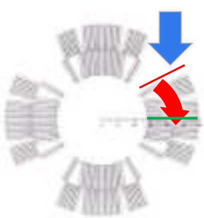


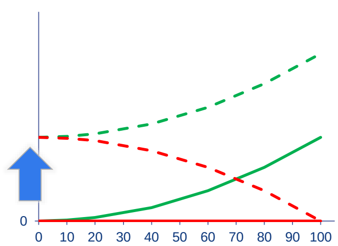


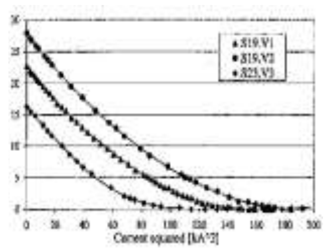




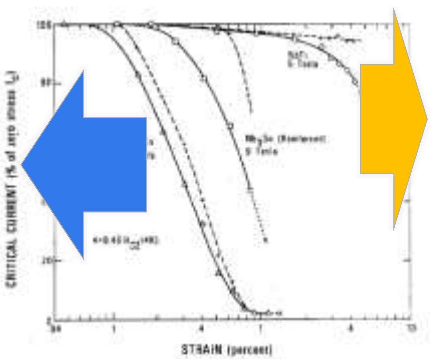
Preventing coil movement: preload



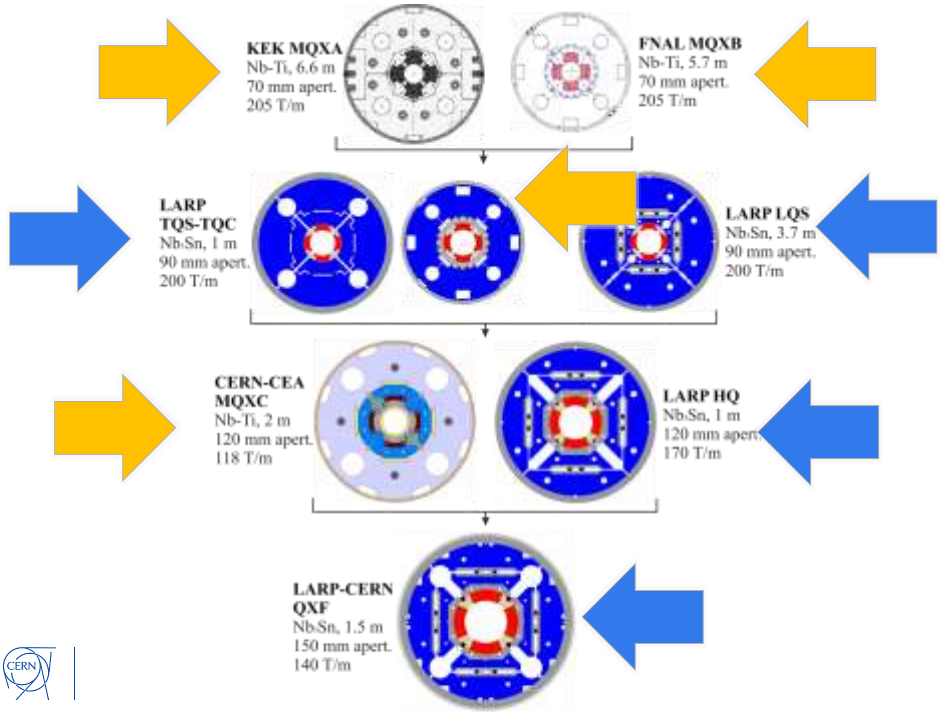




Adding pre-compression during cool down due to differential thermal contraction of components. Mechanical structure and assembly controlled by force



Adding pre-compression at warm during mechanical assembly. Mechanical structure and assembly controlled by displacement



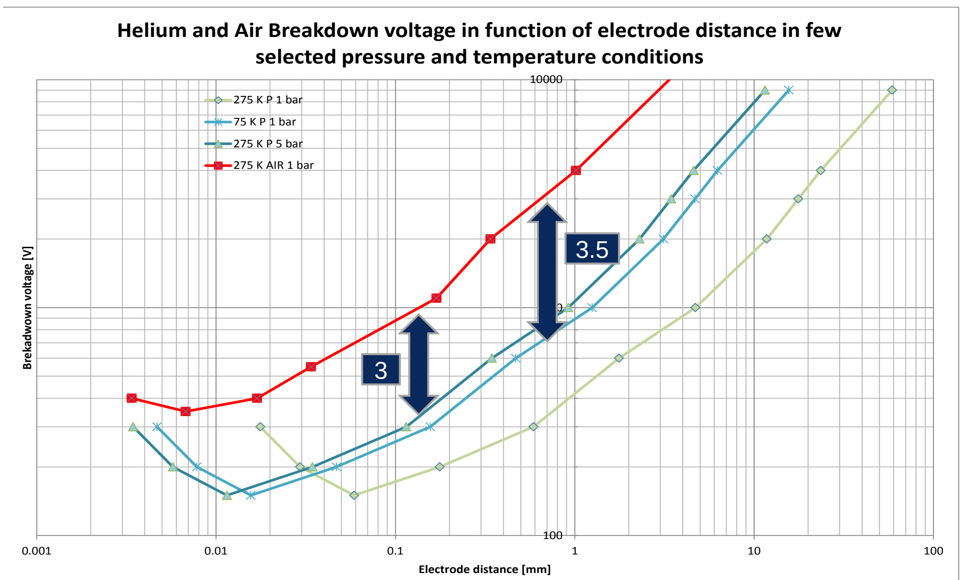
Superconducting magnets an example of technological issue: the insulation

Stress sensitivity, different materials, new problems, new technological approaches to coil production

Nb-Ti	Nb3Sn
The Superconductor is ductile and therefore the finished cable with the SC phase existing can be used for coil production	The Superconductor is fragile therefore cable with the SC phase precursors are used and the SC phase is formed only after winding (in the past react and wind was also tested)
insulate → i.e. Polyimide	insulate → Fibre glass
wind	wind
cure → 190º C time linked to coil dimension	react → 650º C for about 2 weeks
	impregnate → Epoxy or other resin providing dielectric and mechanically protecting the superconductor

ASSEMBLY

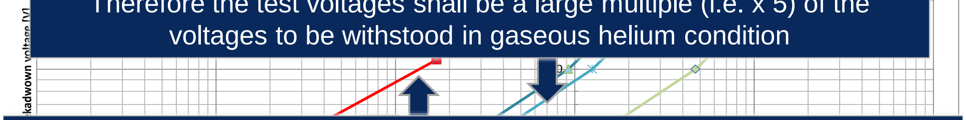
The environment as dielectric



The environment as dielectric

The liquid helium is a very good insulator,
but the largest voltages in Sc devices appear during quench
Quench normally create local heating and therefore vaporization of He.
Insulation design shall be performed therefore taking as reference gaseous helium

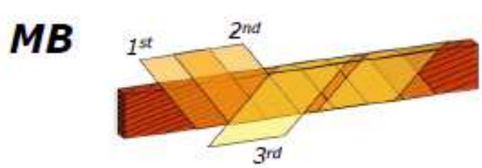
During component fabrication tests are performed in air.
Therefore the test voltages shall be a large multiple (i.e. x 5) of the voltages to be withstood in gaseous helium condition

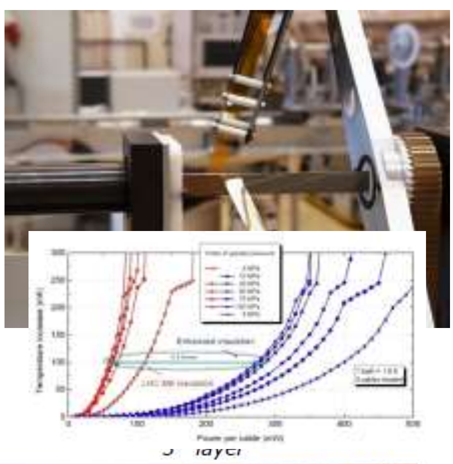


Sc magnet insulation shall be

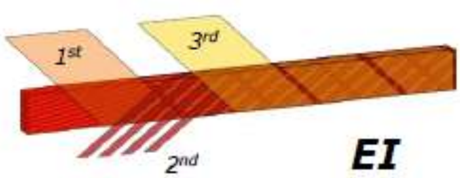
1) Capable of withstanding few thousands volts in gaseous helium
2) Withstand high stress
3) Working at cryogenic temperature
4) As thin as possible to dilute as low as possible J
5) Provide good heat transfer

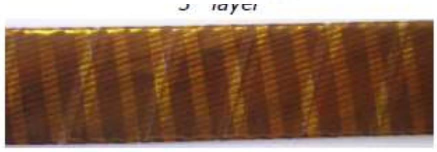
Insulation for Nb-Ti





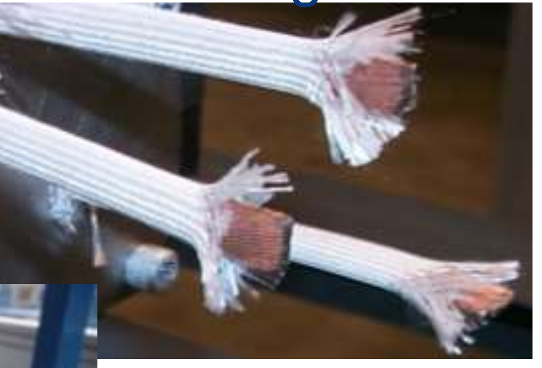
Enhanced insulation for improved heat transfer

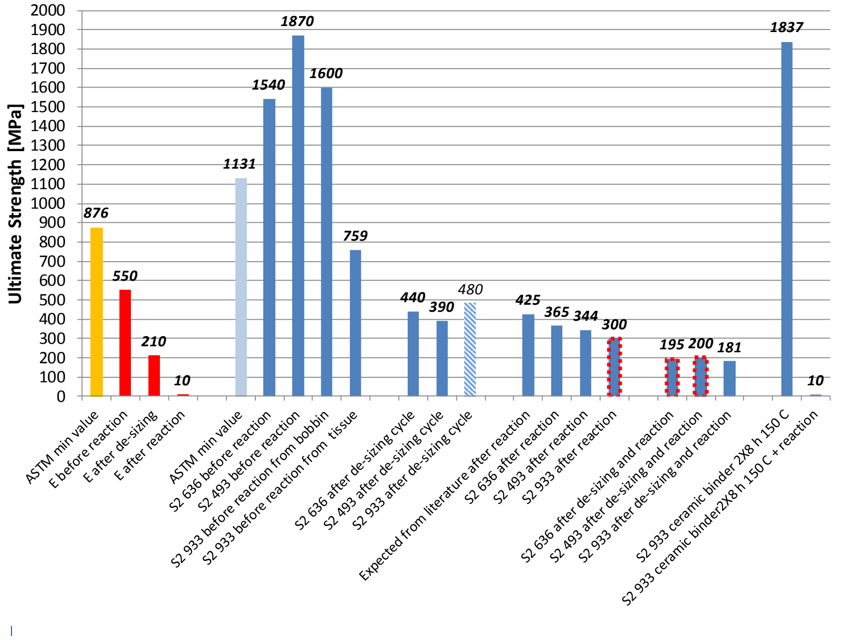




Insulation for Nb3Sn magnets

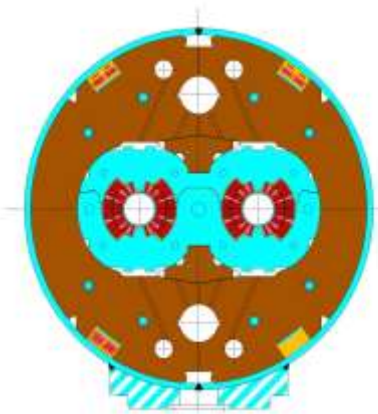
- In Nb_3Sn magnets, where cable are reacted at 600-700 °C, the most common insulation is a tape or sleeve of fiber-glass.
- Typically the insulation thickness varies between 70 and 200 μm.





Superconducting magnets construction

Example of assembly process: the LHC Nb-Ti main dipole



Coil production I

Cable insulation

Coil winding I

Coil winding II

Preparation for curing

Coil production and collaring

Curing press

Ready for collaring

Collaring press

Collared coils ready for cold mass assembly

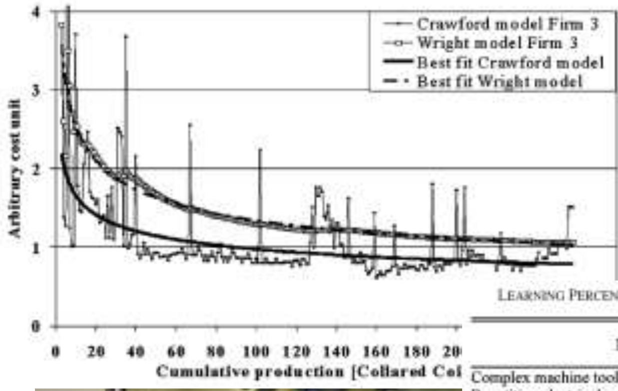
Cold mass assembly

Introducing collared coils in cold masses

Shell welding

Feet and alignment

Instrumentation completion



LEARNING PERCENTAGE OF SELECTED REFERENCE INDUSTRIES

Industry	l.p.
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
Shipbuilding	80%-85%
Aerospace	85%
Purchased Parts	85%-88%
Repetitive welding operations	90%
Repetitive electronics manufacturing	90%-95%
Repetitive machining or punch-press operations	90%-95%
Raw materials	93%-96%

TABLE I
LEARNING PERCENTAGE ACCORDING TO CRAWFORD AND WRIGHT MODELS
COLLARED COILS PRODUCTION

Firm	Crawford Model	Wright Model
Firm 1	88%	88%
Firm 2	90%	86%
Firm 3	89%	88%

TABLE II
LEARNING PERCENTAGE ACCORDING TO CRAWFORD AND WRIGHT MODELS
COLD MASS PRODUCTION

Firm	Crawford Model	Wright Model
Firm 1	83%	81%
Firm 2	82%	81%
Firm 3	88%	82%

Thanks you for your attention

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