Magnets for accelerator, an accelerated view

Presented by P. Fessia
TE-MSC-MNC

Acknowledgments

Thanks to the colleagues that have provided support and material to prepare this seminar. In particular, A. Ballarino, F. Cerutti, P. Ferracin, M. Karppinen, E. Todesco, D. Tommasini, T. Zickler and many others.

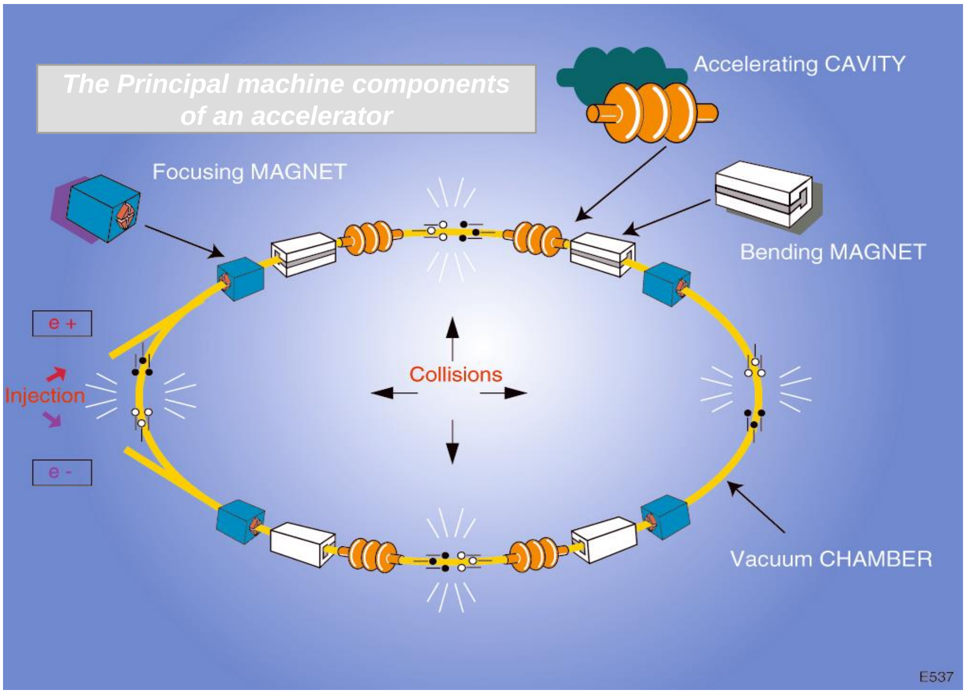
References

- Fifth General Accelerator Physics Course, CAS proceedings, University of Jyväskylä, Finland, September 1992, CERN Yellow Report 94-01
- •International Conference on Magnet Technology, Conference proceedings
- •Iron Dominated Electromagnets, J. T. Tanabe, World Scientific Publishing, 2005
- •Magnetic Field for Transporting Charged Beams, G. Parzen, BNL publication, 1976
- •Magnete, G Schnell, Thiemig Verlag, 1973 (German)
- •Electromagnetic Design and mathematical Optimization Methods in Magnet Technology, S. Russenschuck, e-book, 2005
- •CAS proceedings, Magnetic measurements and alignment, Montreux, Switzerland, March 1992, CERN Yellow Report 92-05
- •CAS proceedings, Measurement and alignment of accelerator and detector magnets, Anacapri, Italy, April 1997, CERN Yellow Report 98-05
- •Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen, K. Wille, Teubner Verlag, 1996
- •CAS proceedings, Magnets, Bruges, Belgium, June 2009, CERN Yellow Report 2010-004

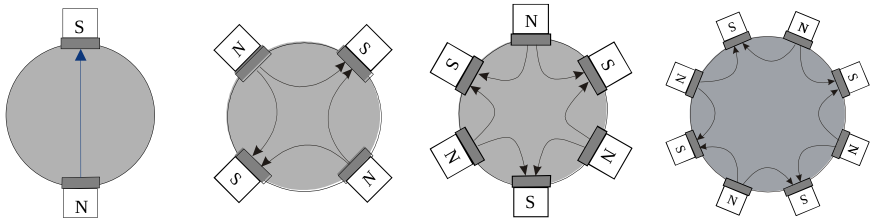
Outline

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

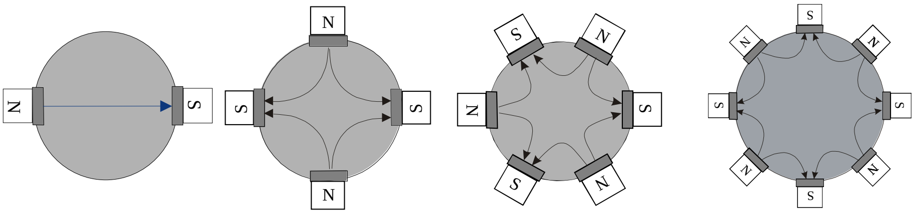
INTRODUCTION



Magnet types : field harmonics

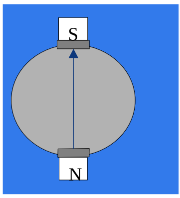
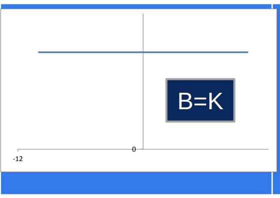
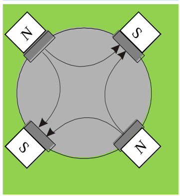
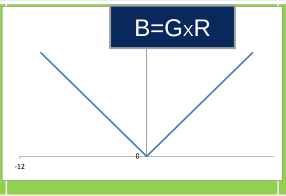
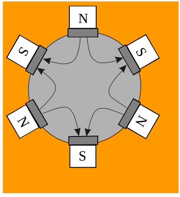
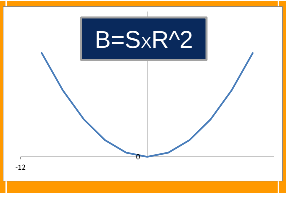


NORMAL : vertical field on mid-plane



SKEW : horizontal field on mid-plane

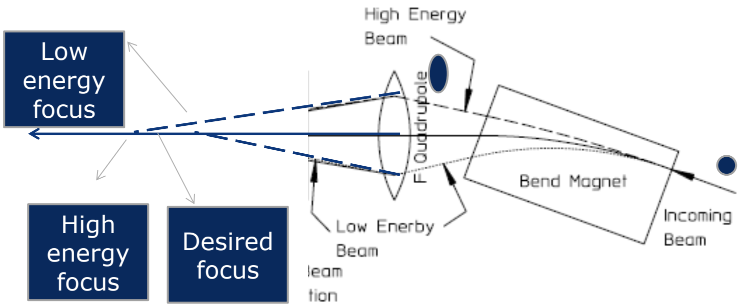
Field type: shape and function I

	**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 curvature in m

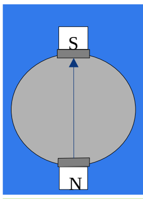
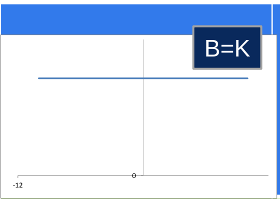
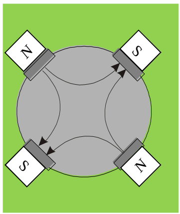
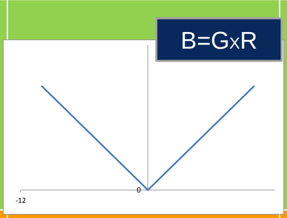
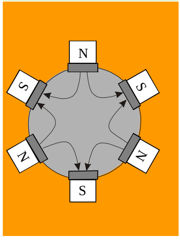
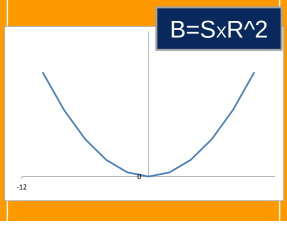


Low energy focus

High energy focus

Desired focus

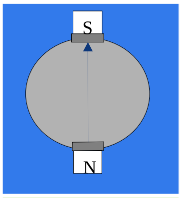
Field type: shape and function II

	**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.**		

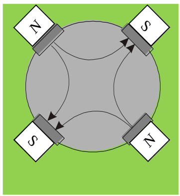
NORMAL CONDUCTING MAGNET OR IRON DOMINATED MAGNETS

Field type: shape and function III

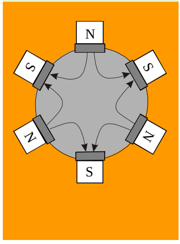
satisfying LaPlace’s equation with the function $F = C_n z^n$



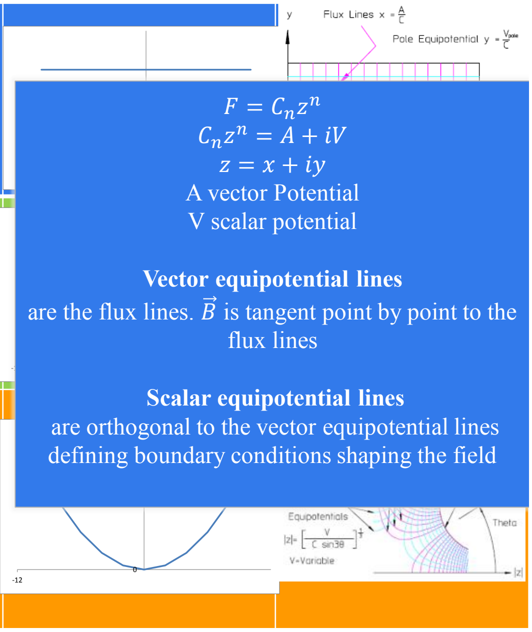
Dipoles:
Bending magnets:
bend the beam along the set path
n=1



Quadrupoles:
Focussing magnets: move the particles back to the centre of the aperture
n=2



Sextupole:correct for the chromatic aberration due to dispersion in a dipole caused by the momentum spread in the beam.
n=3



$$F = C_n z^n$$
$$C_n z^n = A + iV$$
$$z = x + iy$$
A vector Potential
V scalar potential

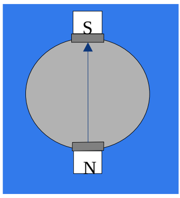
Vector equipotential lines
are the flux lines. $\vec{B}$ is tangent point by point to the flux lines

Scalar equipotential lines
are orthogonal to the vector equipotential lines defining boundary conditions shaping the field

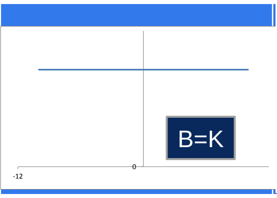
---

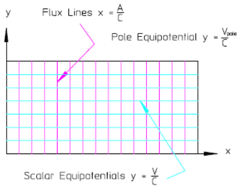
Field type: shape and function III

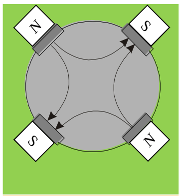
satisfying LaPlace’s equation with the function $F = C_n z^n$



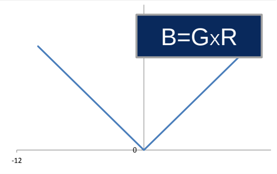
Dipoles:
Bending magnets:
bend the beam along the set path
n=1

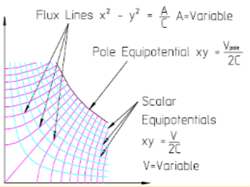


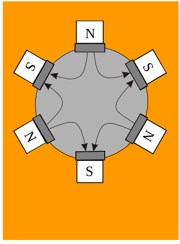




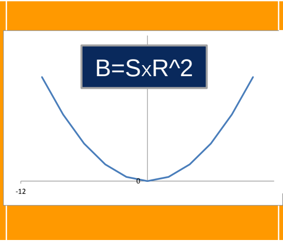
Quadrupoles:
Focussing magnets: move the particles back to the centre of the aperture
n=2

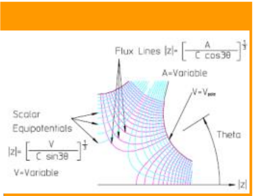




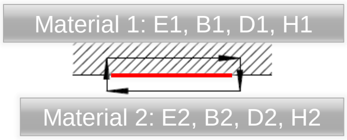


Sextupole:correct for the chromatic aberration due to dispersion in a dipole caused by the momentum spread in the beam.
n=3





Shaping the field: making material the boundary conditions I

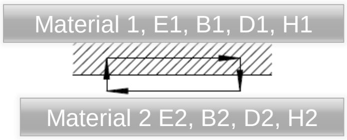


Material 1: E1, B1, D1, H1

Material 2: E2, B2, D2, H2

- $$\begin{cases} \nabla\cdot\boldsymbol{D} = 4\pi\rho \\ \nabla\times\boldsymbol{H} - \frac{1}{c}\frac{\partial\boldsymbol{D}}{\partial t} = \frac{4\pi}{c}\boldsymbol{J} \\ \nabla\times E + \frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t} = 0 \\ \nabla\cdot\mathbf{B} = 0 \end{cases}$$
- ***From 2***
- $\oint_c \boldsymbol{H}\cdot\boldsymbol{dl} = (\boldsymbol{t}\times\boldsymbol{n})\cdot(\boldsymbol{H_2}-\boldsymbol{H_1})\,\Delta\boldsymbol{l}$
- $\oint_c \left[\frac{1}{c}\frac{\partial\boldsymbol{D}}{\partial t} + \frac{4\pi}{c}\boldsymbol{J}\right]\cdot\boldsymbol{t}\,da = \frac{4\pi}{c}\boldsymbol{K}\cdot\boldsymbol{t}\Delta\boldsymbol{l}$
- $\boldsymbol{n}\times(\boldsymbol{H_2}-\boldsymbol{H_1}) = \frac{4\pi}{c}\boldsymbol{K}$
- ***From 4***
- $\oint_s \mathbf{B}\cdot\boldsymbol{n}\,da = 0 \xrightarrow{\textbf{yields}} (\boldsymbol{B_2}-\boldsymbol{B_1})\cdot\boldsymbol{n} = \boldsymbol{0}$

Shaping the field: making material the boundary conditions II



Material 1, E1, B1, D1, H1

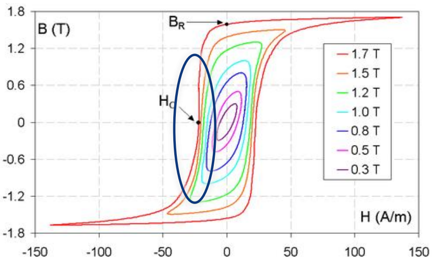
Material 2 E2, B2, D2, H2

$$(\overrightarrow{B_2}-\overrightarrow{B_1})\cdot\vec{n} = 0$$
$$(\overrightarrow{H_2}-\overrightarrow{H_1})\times\vec{n} = 0$$

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

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

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



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

If material 2 air

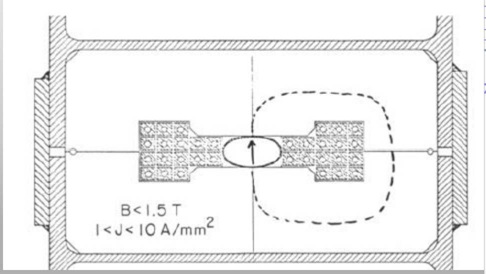
$$\tan\alpha_2 = \frac{1}{\mu_{r1}}\tan\alpha_1$$

If material 1 iron

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

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 material

Creating the field->you need coil

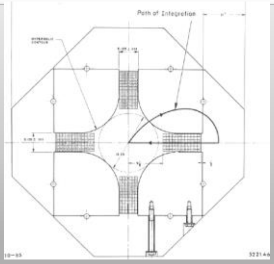


$$\oint H \cdot dl = NI$$

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

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

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



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

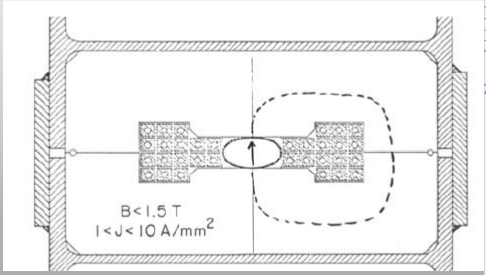
$$NI = \oint H \cdot dl = \int_o \frac{B(r)}{\mu^o} dr + [\text{iron path}] + [\text{path} \perp \text{to the field}$$

$$= \int_o^a Krdr = \frac{Ka^2}{2} \quad ,$$

But, since $Ka = B_{\text{poletip}}$,

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

Creating the field->you need coil



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

$NI(\text{ampere tu}$ … Bg^{air} … $B\ell^{\text{iron}}$ $\left(\frac{\mu_o}{\mu_{\text{iron}}}\right)$

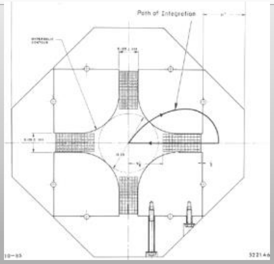
$P = R \times i^{\,2} = N \times R_t \times i^{\,2}$

Fixed B

$Ni \propto gap$

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

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



Fixed K

(Gradient)

$Ni \propto gap^2$

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

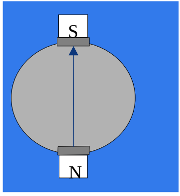
$NI =$ … $\perp$ to the field

$$= \int_o^a Krdr = \frac{Ka^2}{2} \quad ,$$

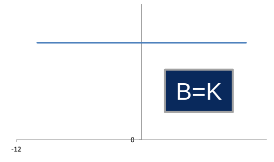
But, since $Ka = B_{\text{poletip}}$,

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

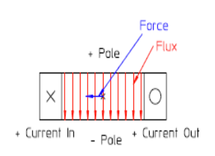
Field type: shape and function, real magnet

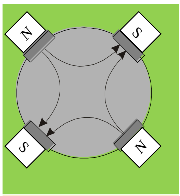


Dipoles=Bending magnets: bend the beam along the set path

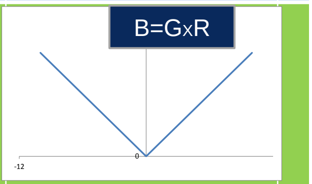


B=K

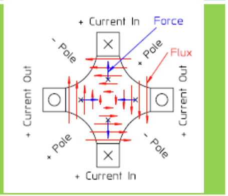


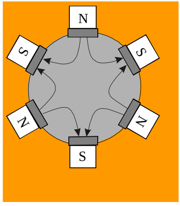


Quadrupoles=Focusing magnets: move the particles back to the centre of the aperture

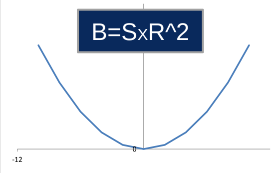


B=GxR

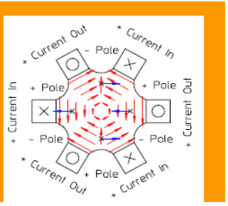




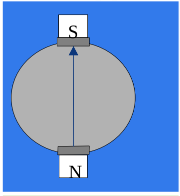
Sextupole=correct for the chromatic aberration due to dispersion in a dipole caused by the momentum spread in the beam.



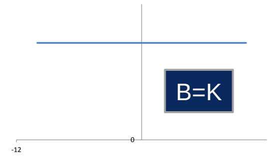
B=SxR^2



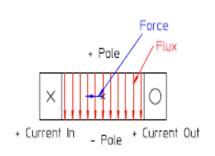
Field type: shape and function, real magnet

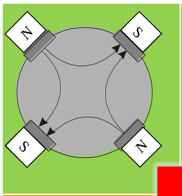


Dipoles=Bending magnets: bend the beam along the set path

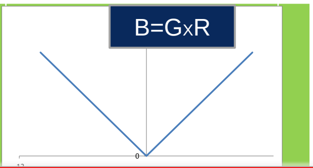


B=K

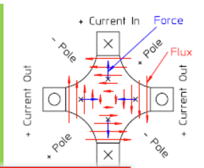


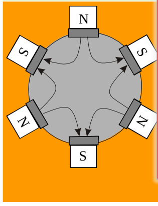


Quadrupoles=Focusing magnets: move the particles back to the centre of the aperture

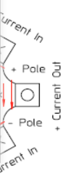


B=GxR



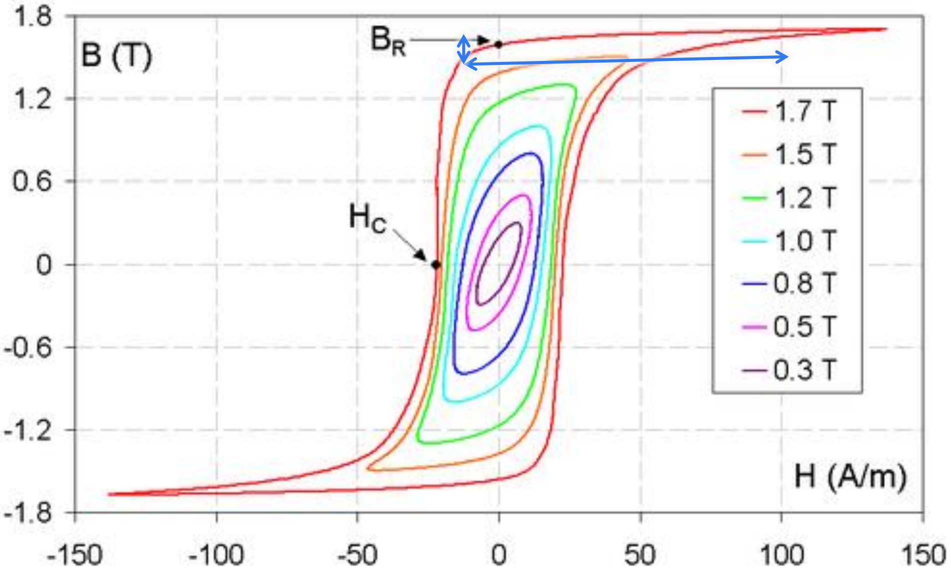


In normal conducting magnet the iron yoke provides the field quality therefore the yoke shape shall be extremely precise



spread in the beam.

But iron saturates ,…..

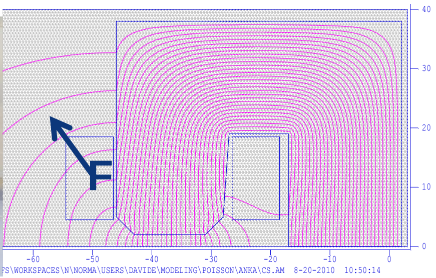


For iron, above 1.5-2 T any increase of magnetic field costs a lot of magnetomotive force

Effect of interaction field with the coil current:

On a conductor immerged in magnetic field

$$F = I \cdot L \times B$$



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

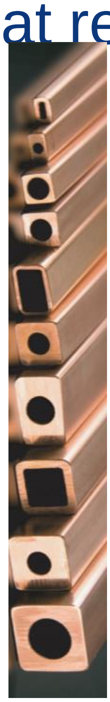
$$P[W/kg] = \eta\cdot f\cdot B^{1.6}$$

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

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

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

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):

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

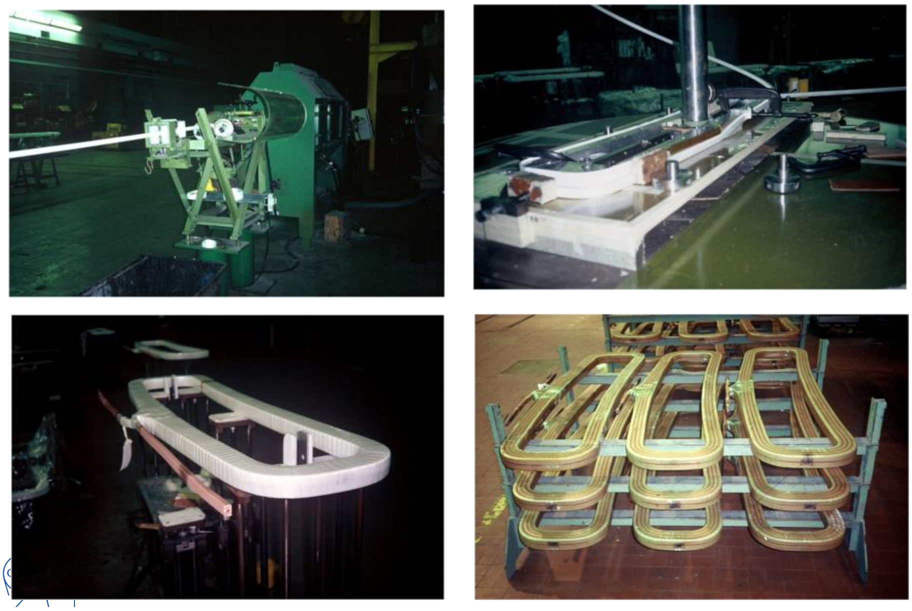
Small pipes need high velocity, however attention to erosion (v>3m/s)!

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:

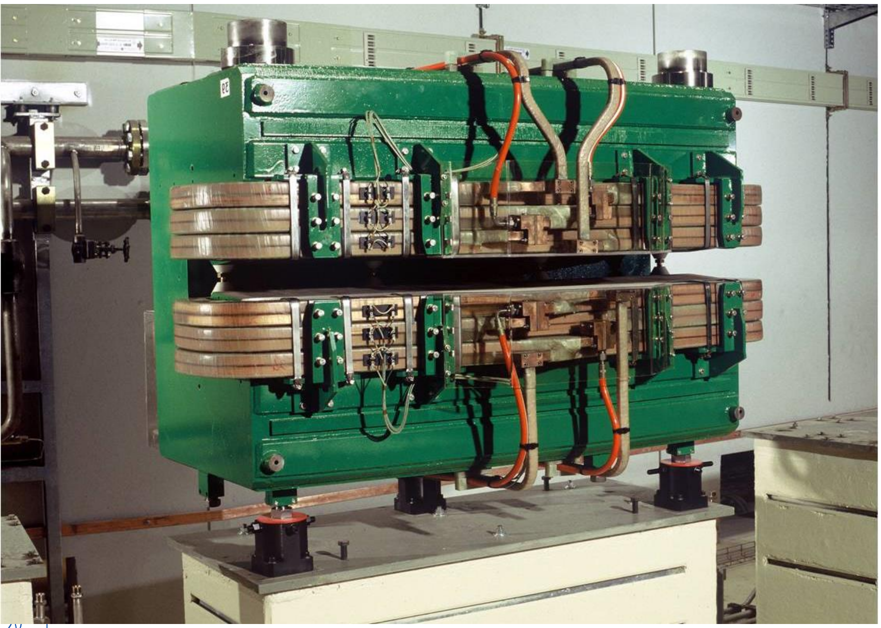
$$\Delta P[bar] = 60\cdot L[m]\cdot\frac{Q[l/\min]^{1.75}}{d[mm]^{4.75}}$$

Normal conducting magnet construction

Coil production

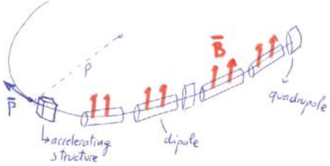


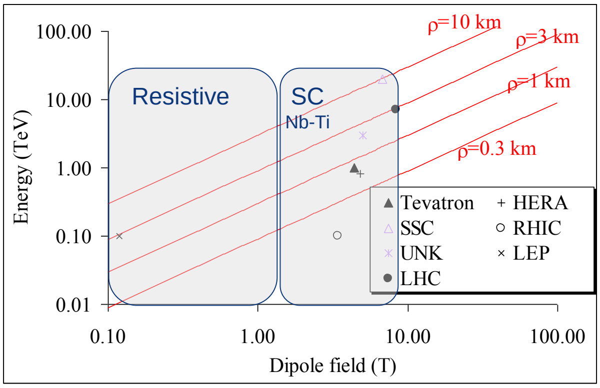
Iron yoke production



The limits of NC magnet application

- Relation momentum-magnetic field-orbit radius
  - Having 8 T magnets, we need 3 Km curvature radius to have 7 TeV
  - If we would have 800 T magnets, 30 m would be enough …

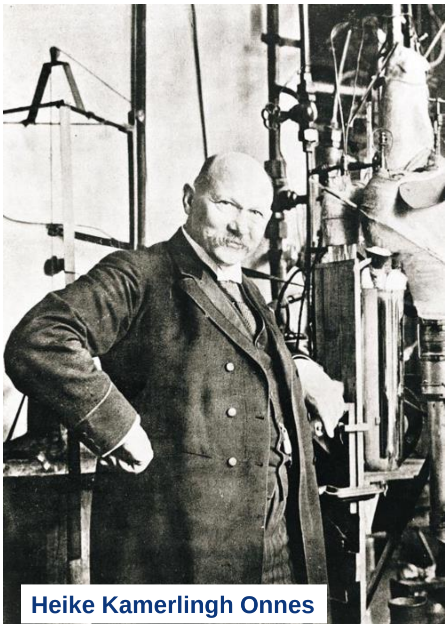




$$B\rho = \frac{1}{qc}\sqrt{T^2 + 2TE_0}$$

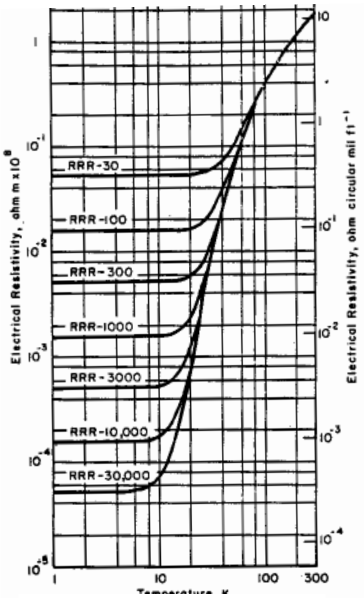
SUPERCONDUCTING MATERIALS

Superconductivity

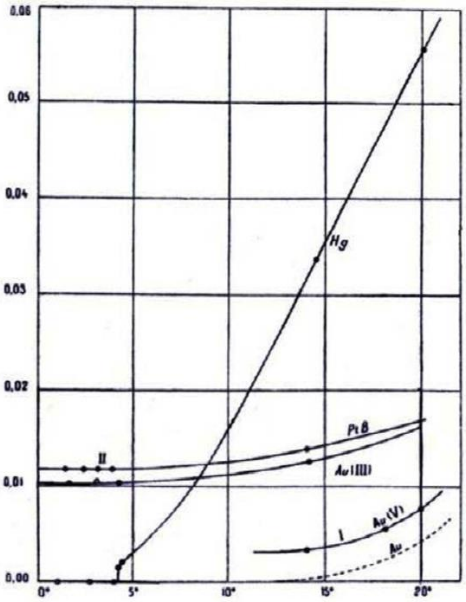


Heike Kamerlingh Onnes

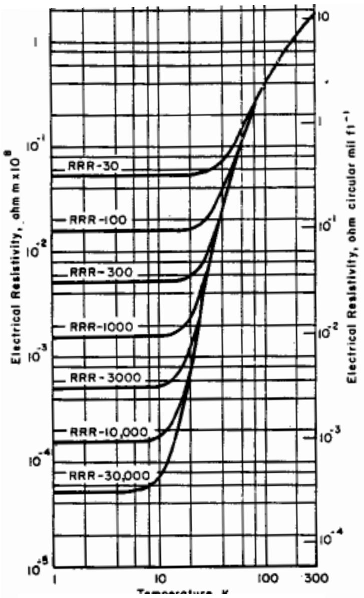
Superconductivity



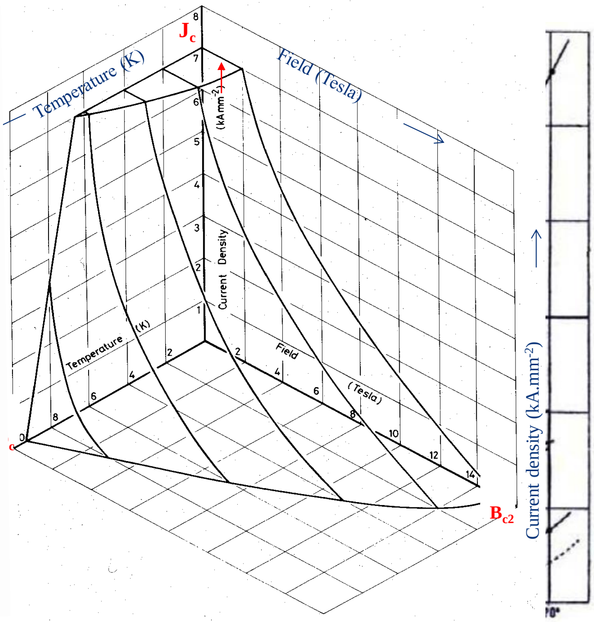
Heike Kamerlingh Onnes

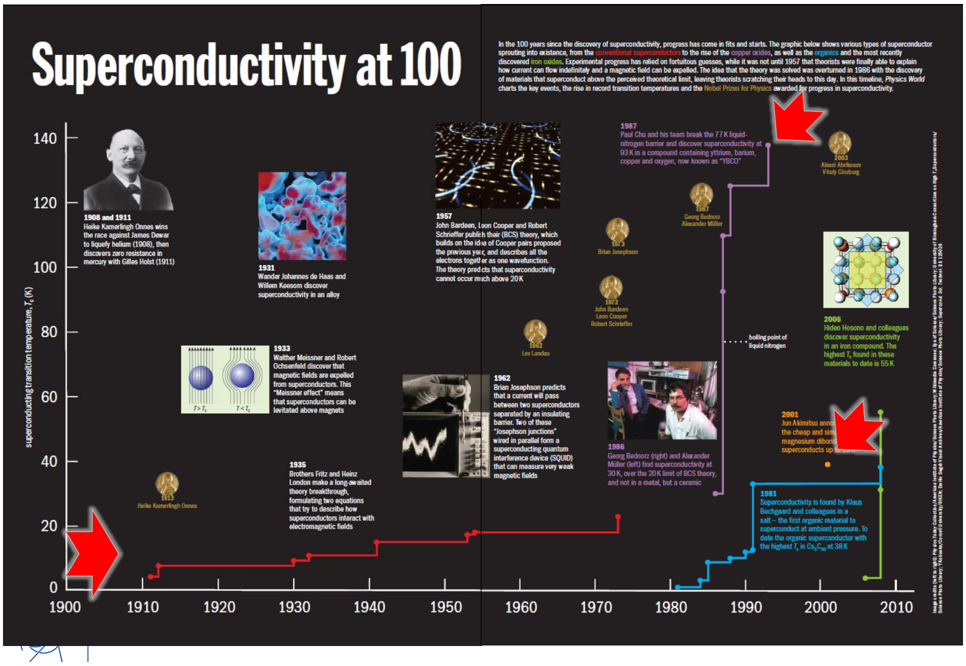


Superconductivity



Heike Kamerlingh Onnes





Superconductivity at 100

In the 100 years since the discovery of superconductivity, progress has come in fits and starts. The graphic below shows various types of superconductor sprouting into existence, from the conventional superconductors to the rise of the copper oxides, as well as the organics and the most recently discovered iron oxides. Experimental progress has relied on fortuitous guesses, while it was not until 1957 that theorists were finally able to explain how current can flow indefinitely and a magnetic field can be expelled. The idea that the theory was solved was overturned in 1986 with the discovery of materials that superconduct above the perceived theoretical limit, leaving theorists scratching their heads to this day. In this timeline, *Physics World* charts the key events, the rise in record transition temperatures and the Nobel Prizes for Physics awarded for progress in superconductivity.

1908 and 1911
Heike Kamerlingh Onnes wins the race against James Dewar to liquefy helium (1908), then discovers zero resistance in mercury with Gilles Holst (1911)

1931
Wander Johannes de Haas and Willem Keesom discover superconductivity in an alloy

1933
Walther Meissner and Robert Ochsenfeld discover that magnetic fields are expelled from superconductors. This "Meissner effect" means that superconductors can be levitated above magnets

1935
Brothers Fritz and Heinz London make a long-awaited theory breakthrough, formulating two equations that try to describe how superconductors interact with electromagnetic fields

1957
John Bardeen, Leon Cooper and Robert Schrieffer publish their (BCS) theory, which builds on the idea of Cooper pairs proposed the previous year, and describes all the electrons together as one wavefunction. The theory predicts that superconductivity cannot occur much above 20 K

1962
Brian Josephson predicts that a current will pass between two superconductors separated by an insulating barrier. Two of these "Josephson junctions" wired in parallel form a superconducting quantum interference device (SQUID) that can measure very weak magnetic fields

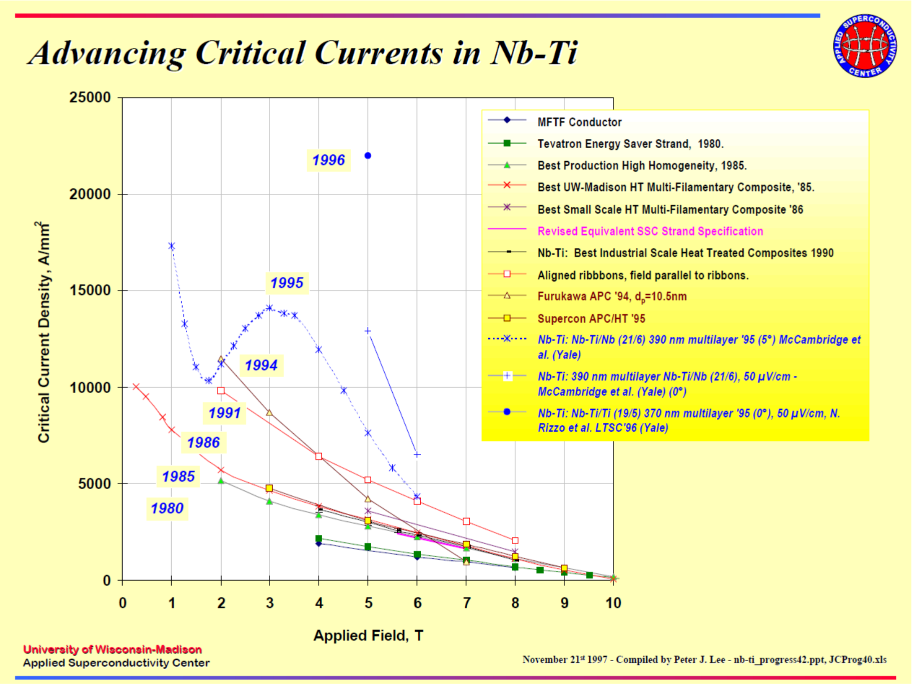
1986
Georg Bednorz (right) and Alexander Müller (left) find superconductivity at 30 K, over the 20 K limit of BCS theory, and not in a metal, but a ceramic

1987
Paul Chu and his team break the 77 K liquid-nitrogen barrier and discover superconductivity at 93 K in a compound containing yttrium, barium, copper and oxygen, now known as "YBCO"

1981
Superconductivity is found by Klaus Bechgaard and colleagues in a salt – the first organic material to superconduct at ambient pressure. To date the organic superconductor with the highest T_c is Cs_3C_{60} at 38 K

2001
Jun Akimitsu anno
the cheap and sim
magnesium diborid
superconducts up

2006
Hideo Hosono and colleagues discover superconductivity in an iron compound. The highest T_c found in these materials to date is 55 K

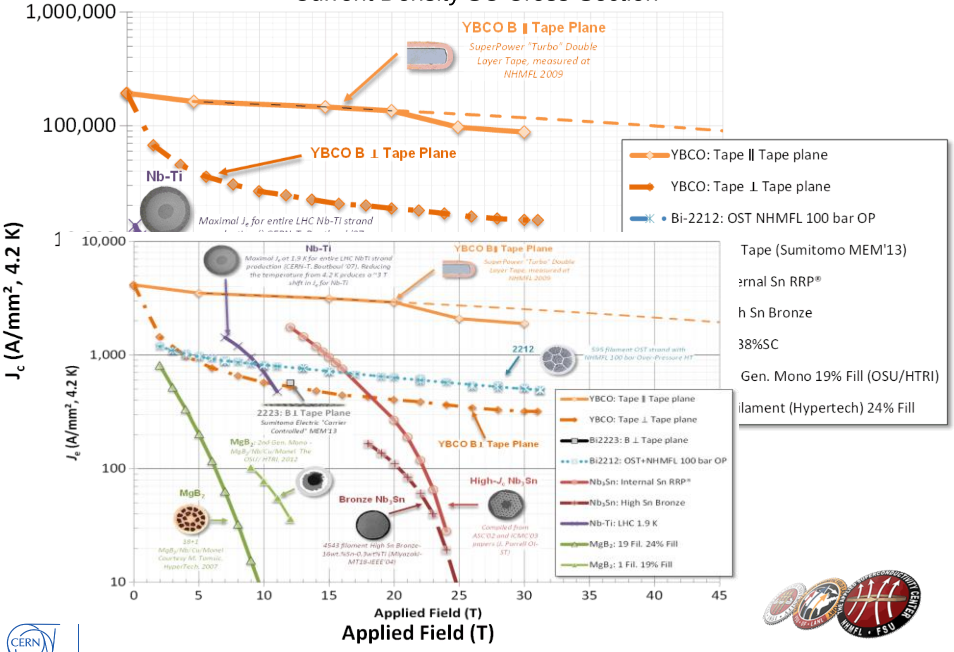


Advancing Critical Currents in Nb-Ti

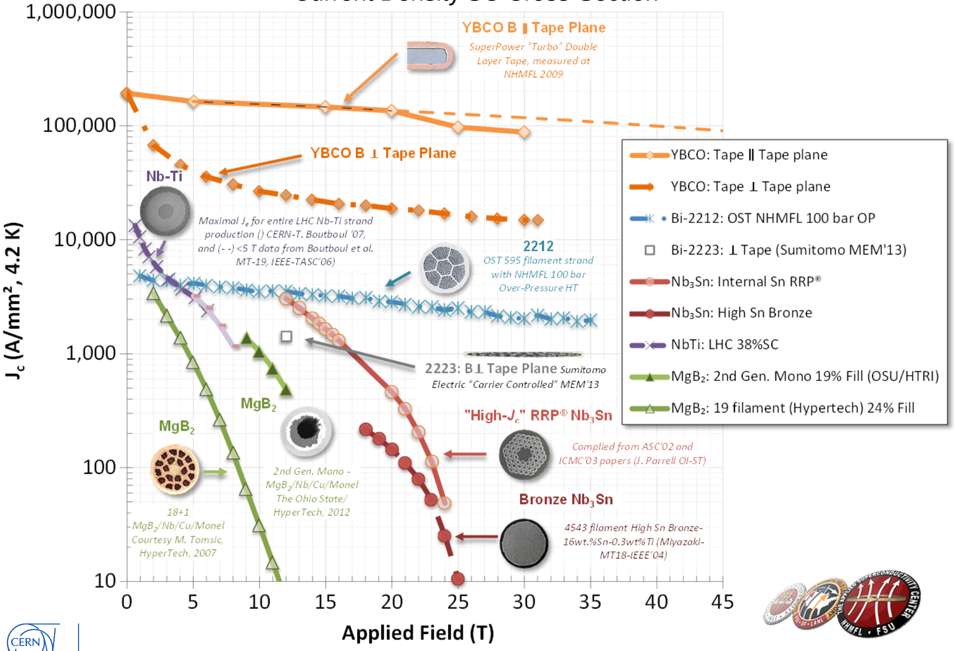
University of Wisconsin-Madison
Applied Superconductivity Center

November 21st 1997 - Compiled by Peter J. Lee - nb-ti_progress42.ppt, JCProg40.xls

Current Density SC Cross-Section



Current Density SC Cross-Section

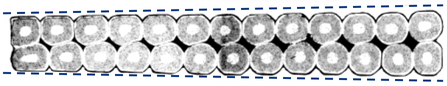


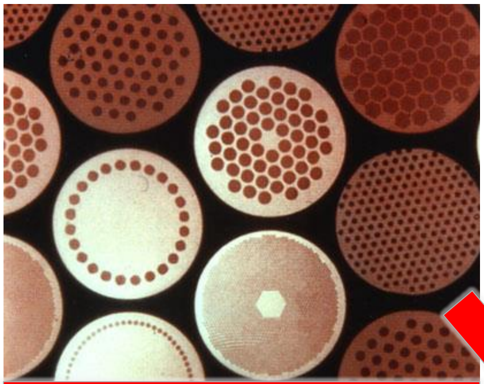
Superconductor material, but under which conductor shape

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

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

To limit the voltage long charging time or high current





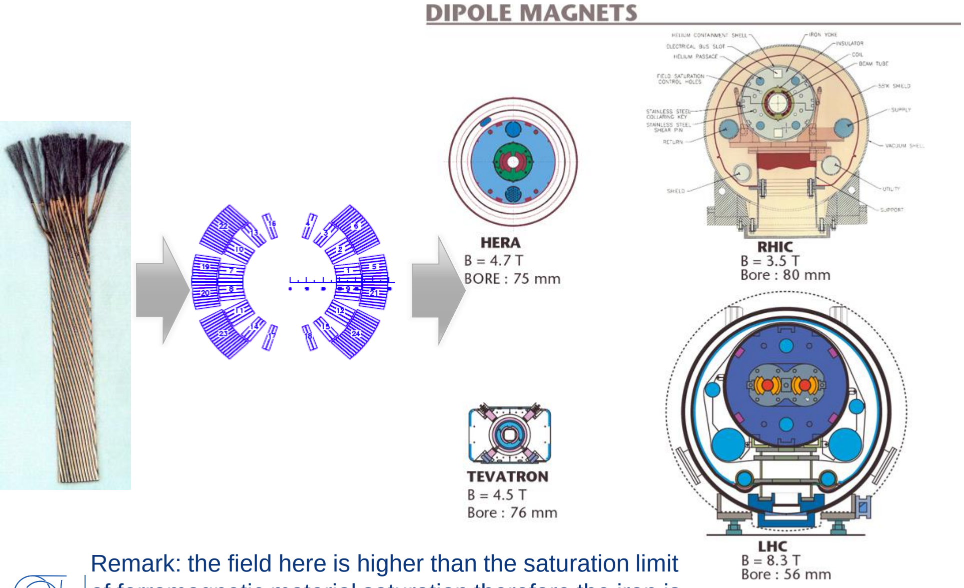
- a single 5μm filament of Nb-Ti in 6T carries 50mA
- a composite wire of fine filaments typically has 5,000 to 10,000 filaments, so it carries 250A to 500A

- 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

$$\boxed{J_e = \lambda_c \lambda_w \lambda_f J_c}$$

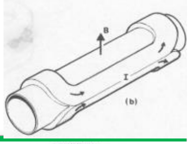
SUPERCONDUCTING MAGNETS

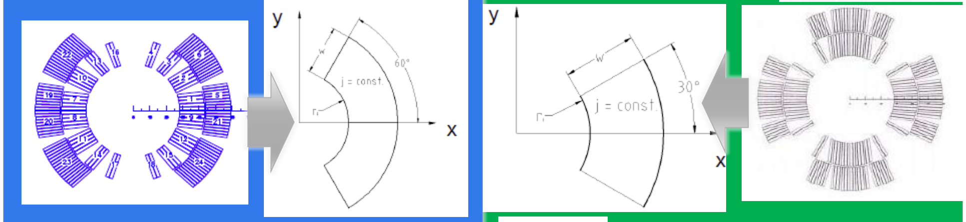
How we can use the SC cable ?



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

GENERATION OF MAGNETIC FIELDS: FIELD OF A WINDING





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

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

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

$B \propto$ current density
$B \propto$ coil width *w*
B is independent of the aperture *r*

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

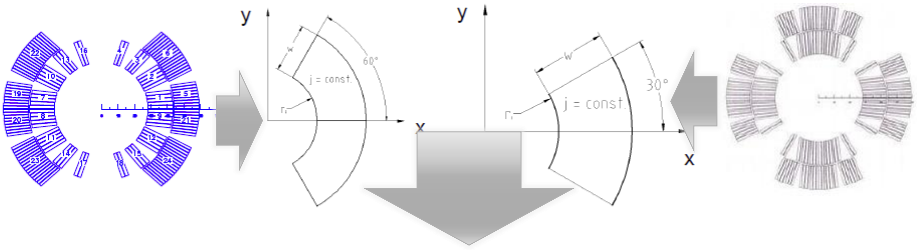
$$I \rightarrow j\rho d\rho d\theta$$

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

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

G $\propto$ current density
G$\propto$ coil width w
G is inversely proportional of the aperture r

Approximate expression of the field



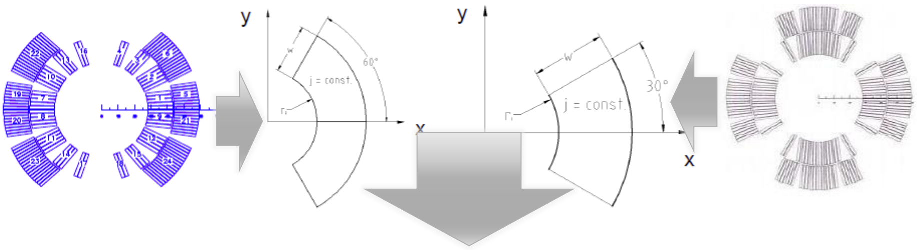
In the aperture

In the aperture

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

In superconducting magnet the conductor distribution provides the field quality therefore the conductor position and their deformations shall be kept under tight control

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

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

In the coil

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

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

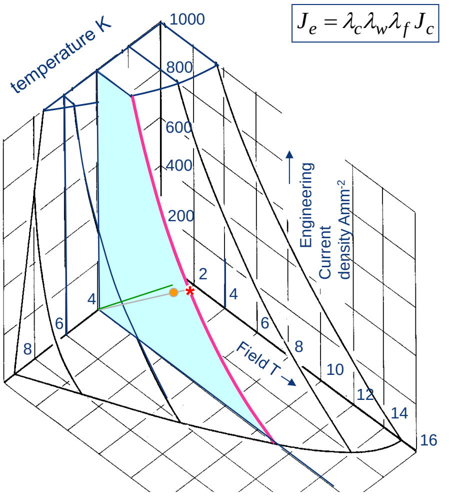
$$\begin{Bmatrix} B_r \\ B_\varphi \end{Bmatrix} = -\frac{j\,\mu_0}{\pi}\left\{\frac{\left((r_i+w)^4-{r_i}^4\right)}{r^3}2\sin(2\alpha_0)\begin{Bmatrix}\sin 2\varphi \\ \cos 2\varphi\end{Bmatrix}\right\}$$

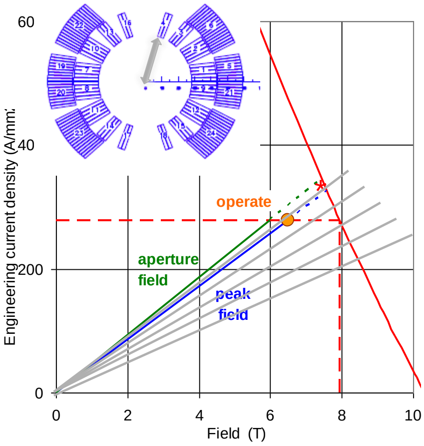
In the coil

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

engineering current density

$J_e = \lambda_c \lambda_w \lambda_f J_c$

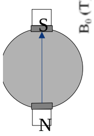


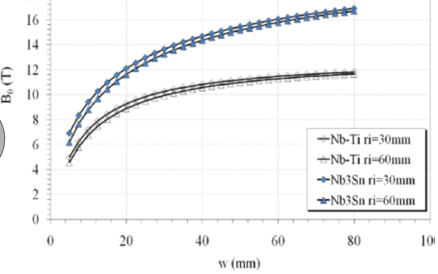


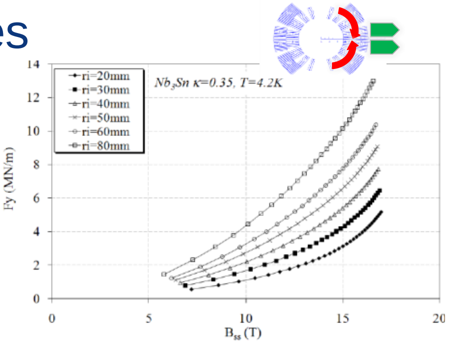
we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *

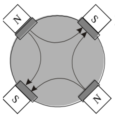
usually back off from this extreme point and operate at ●

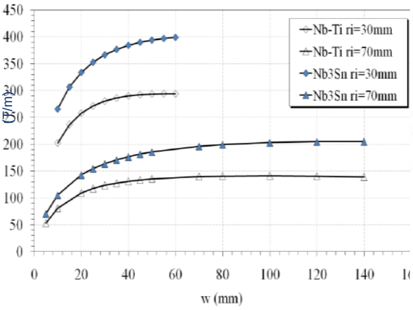
Creating field: limited by the critical surface and paid in term of forces

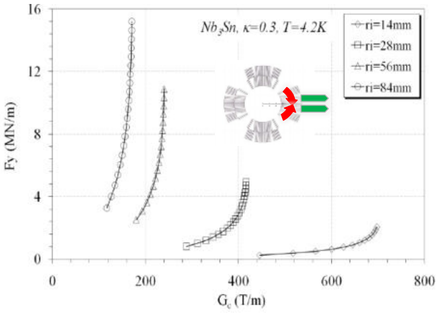




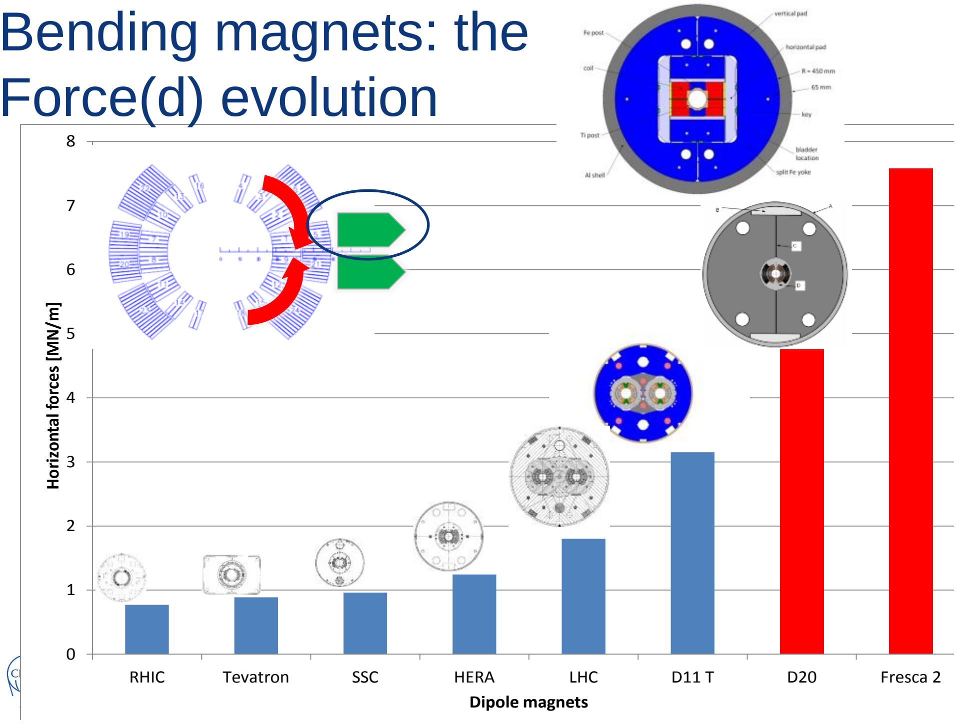




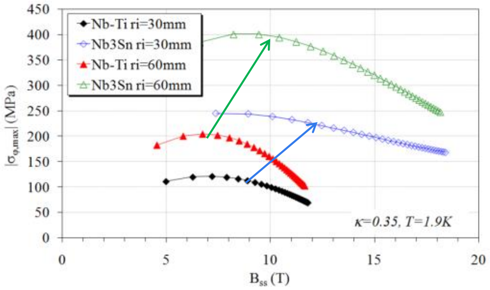


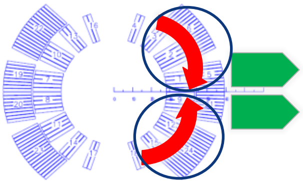


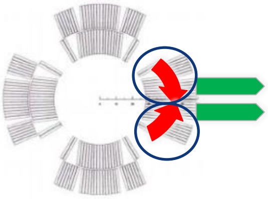
Bending magnets: the Force(d) evolution

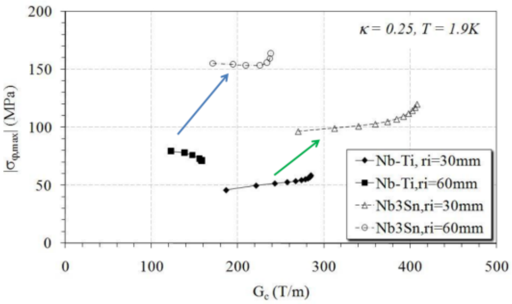


And what about stresses ?

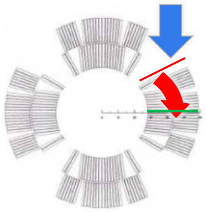


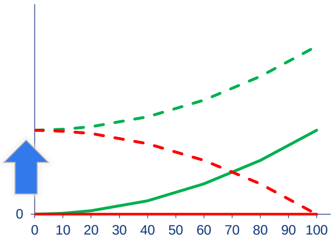


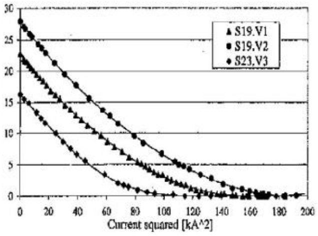




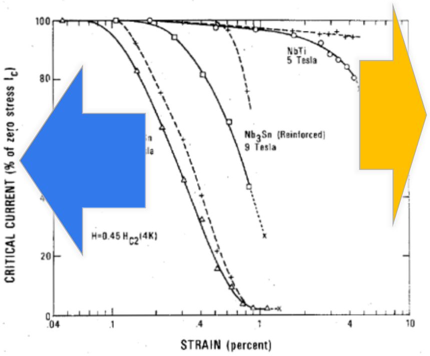
Preventing coil movement: preload



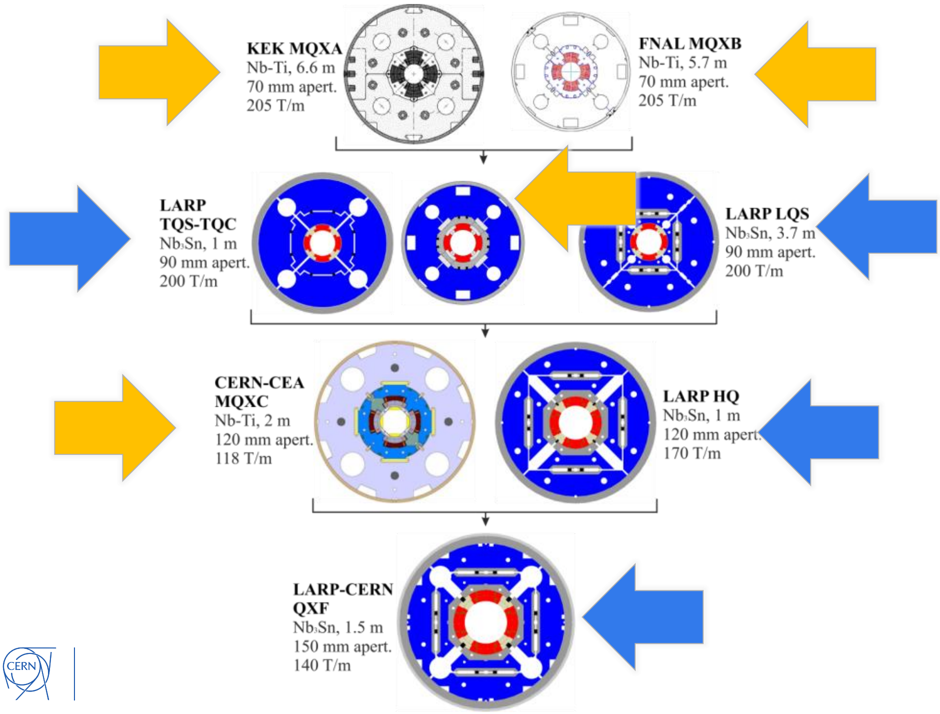




Adding pre-compression during cool down due to differential thermal contraction of components. Mechanical structure and assembly controlled by force



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



KEK MQXA
Nb-Ti, 6.6 m
70 mm apert.
205 T/m

FNAL MQXB
Nb-Ti, 5.7 m
70 mm apert.
205 T/m

LARP TQS-TQC
Nb_3Sn, 1 m
90 mm apert.
200 T/m

LARP LQS
Nb_3Sn, 3.7 m
90 mm apert.
200 T/m

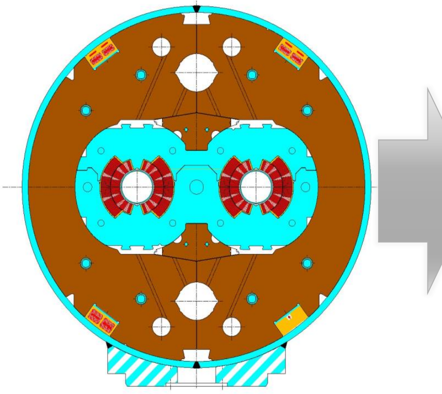
CERN-CEA MQXC
Nb-Ti, 2 m
120 mm apert.
118 T/m

LARP HQ
Nb_3Sn, 1 m
120 mm apert.
170 T/m

LARP-CERN QXF
Nb_3Sn, 1.5 m
150 mm apert.
140 T/m

Superconducting magnets construction

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

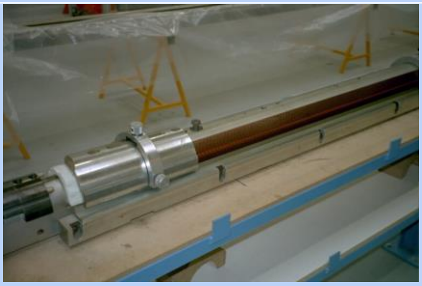


Coil production I

Cable insulation

Coil winding I

Coil winding II



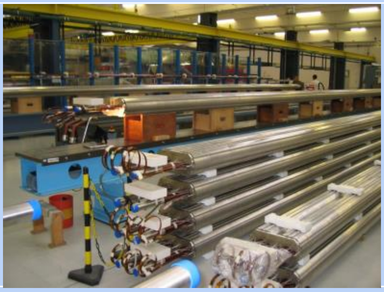
Preparation for curing

Coil production and collaring

Curing press

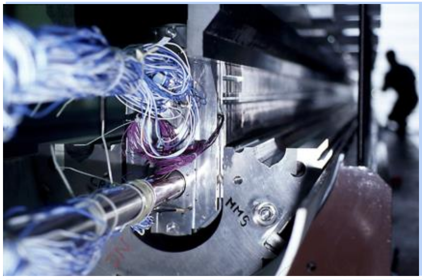
Ready for collaring

Collaring press



Collared coils ready for cold mass assembly

Cold mass assembly

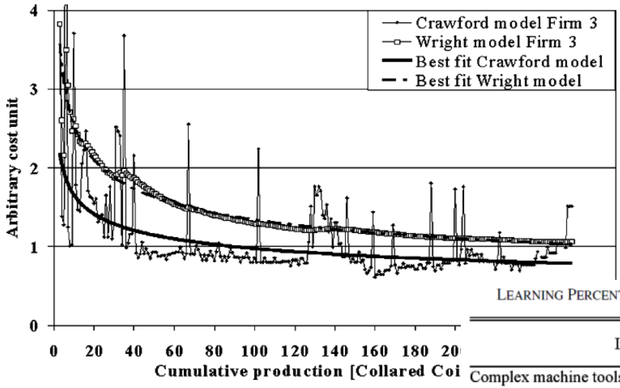


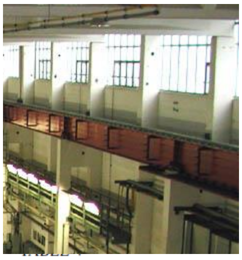
Introducing collared coils in cold masses

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%

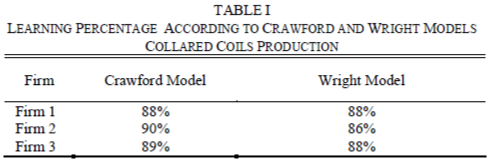


TABLE I
LEARNING PERCENTAGE ACCORDING TO CRAWFORD AND WRIGHT MODELS
COLLARED COILS PRODUCTION

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

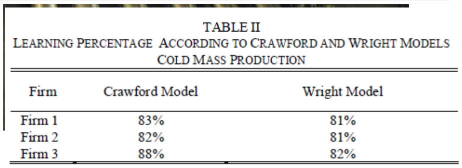


TABLE II
LEARNING PERCENTAGE ACCORDING TO CRAWFORD AND WRIGHT MODELS
COLD MASS PRODUCTION

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

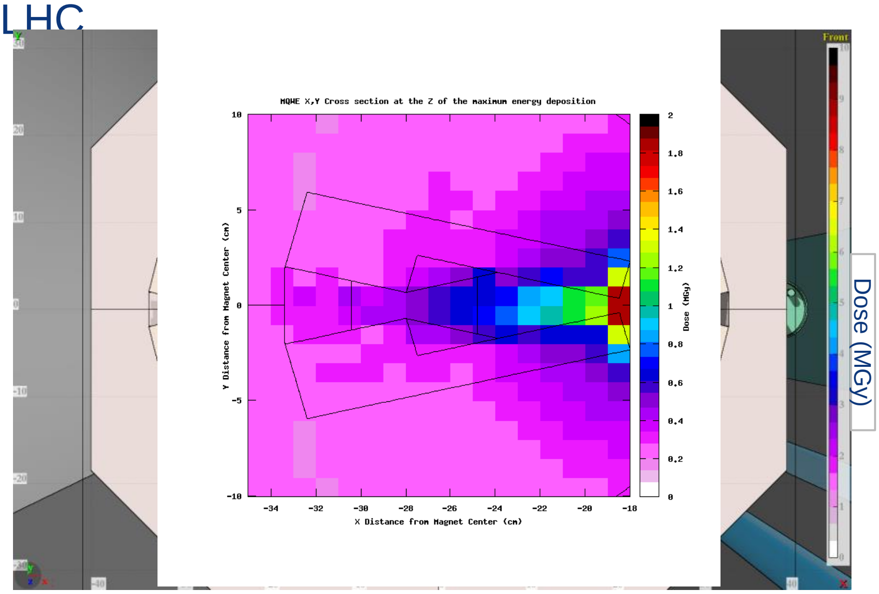
Thanks you for your attention

www.cern.ch

extras

An example of technological issue: the insulation radiation resistance

Dose on a normal conducting magnet in the LHC



Dose (MGy)

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	

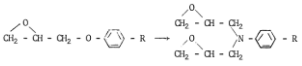
Legend

Resin

🟥	Linear aliphatic
🟧	Cycloaliphatic
🟨	Aromatic

Hardener

🟩	Aliphatic Amine
🟩	Aromatic Amine
🟦	Alicyclic Anhydride
🟦	Aromatic Anhydride

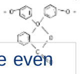


Aromatic >
Cycloaliphatic >
Linear Aliphatic

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

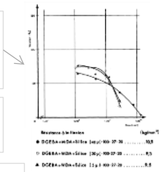
Resin
- 🟥 Linear aliphatic
- 🟧 Cycloaliphatic
- 🟨 Aromatic

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

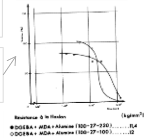
The bigger the powder, the more radio-resistant



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/A3/E

Material: **Epoxy resin** TIS No. **R 422**
Type MY 745 (50) + EPN 1138 (50) + CY 221

DGEBA+MDA

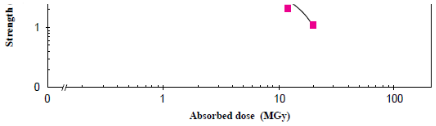
Table III.1e

Effect of nuclear radiation on the dielectric strength of epoxy resins

Resin composition	Dielectric strength (kV/mm) versus dose (rad)						
	0	2.3 × 10^8	5.6 × 10^8	6.8 × 10^8	1.2 × 10^9	1.2 × 10^9	2.7 × 10^9
1) Araldite F + MDA	21.2 ± 0.8				17.7 ± 0.8(83.5)		16.1 ± 0.8(76)
2) Araldite F + DADPS	21.4 "				18.5 " (86.5)		17.5 " (82)
3) Araldite F + MA	19.0 "				18.2 " (96)		17.8 " (93.5)
4) Araldite B + AP	18.1 "				17.4 " (96)		14.5 " (80)
5) Araldite F + DPA + TETA	19.6 "	19.5 ± 0.8(100)		16.5 ± 0.8(84)	0		
6) EPN + MA + BDMA	22.5 "		21.0 ± 0.8(93.5)			20.0 ± 0.8(89)	
7) EPN + MDA	19.1 "		20.0 " (105)			18.5 " (97)	
8) TGMD + MA + BDMA	20.1 "		18.7 " (93.5)			18.0 " (90)	
9) TGMD + MDA	23.4 "		23.3 " (100)			25.2 " (108)	

The values in brackets represent the percentage of the initial value.

- 95 -

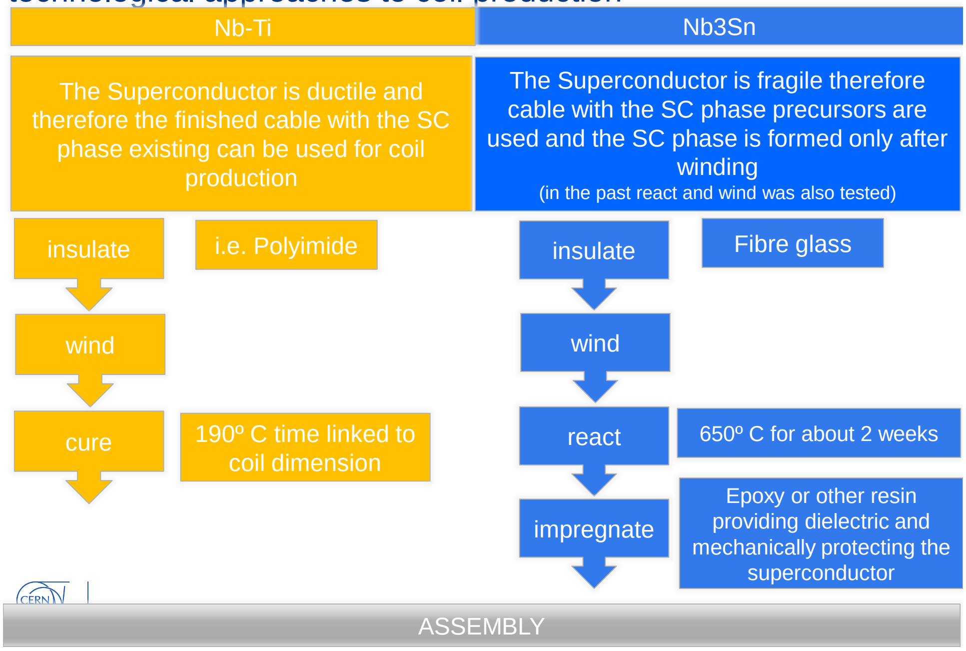


● 1 - Résistance à la flexion	17	kg/mm²
○ 2 - Résistance à la traction	7,2	kg/mm²
▲ 3 - Module d'élasticité	325	kg/mm²
△ 4 - Allongement à la rupture		mm
■ 5 - Résistance au choc	25	kg-m/cm²
□ 6 - Dureté	86	Shore D
★ 7 - Absorption d'eau - 25 °C , 4 jours	0,6	%
✱ 8 - Point de flèchissement à la chaleur	158	°C

Superconducting magnets an example of technological issue: the insulation

---

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



Nb-Ti

The Superconductor is ductile and therefore the finished cable with the SC phase existing can be used for coil production

- insulate – i.e. Polyimide
- wind
- cure – 190º C time linked to coil dimension

Nb3Sn

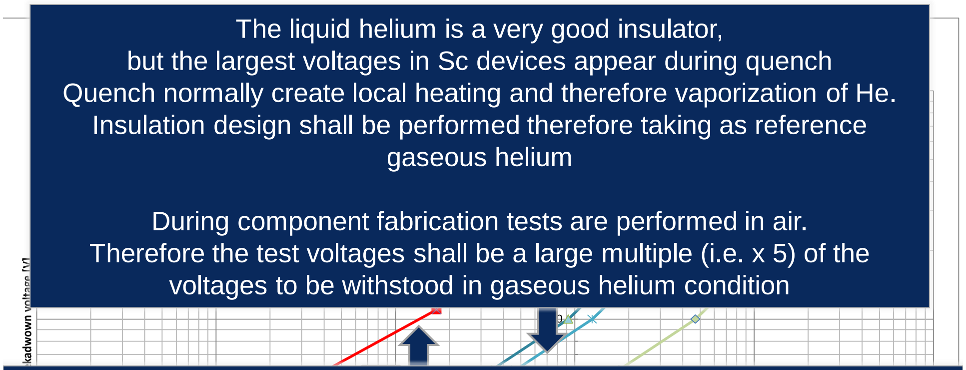
The Superconductor is fragile therefore cable with the SC phase precursors are used and the SC phase is formed only after winding

(in the past react and wind was also tested)

- insulate – Fibre glass
- wind
- react – 650º C for about 2 weeks
- impregnate – Epoxy or other resin providing dielectric and mechanically protecting the superconductor

ASSEMBLY

The environment as dielectric



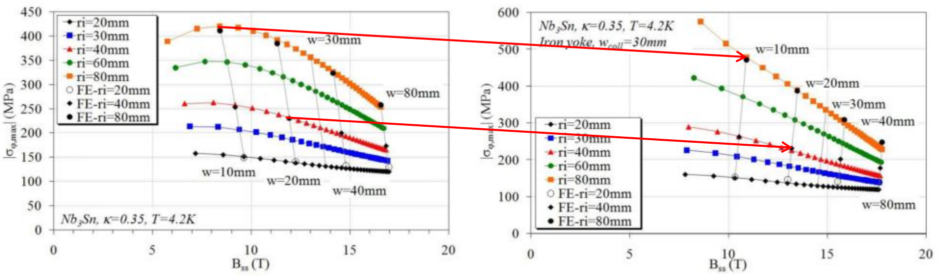
The liquid helium is a very good insulator,
but the largest voltages in Sc devices appear during quench
Quench normally create local heating and therefore vaporization of He.
Insulation design shall be performed therefore taking as reference gaseous helium

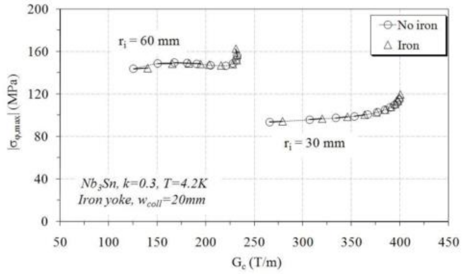
During component fabrication tests are performed in air.
Therefore the test voltages shall be a large multiple (i.e. x 5) of the voltages to be withstood in gaseous helium condition

Sc magnet insulation shall be

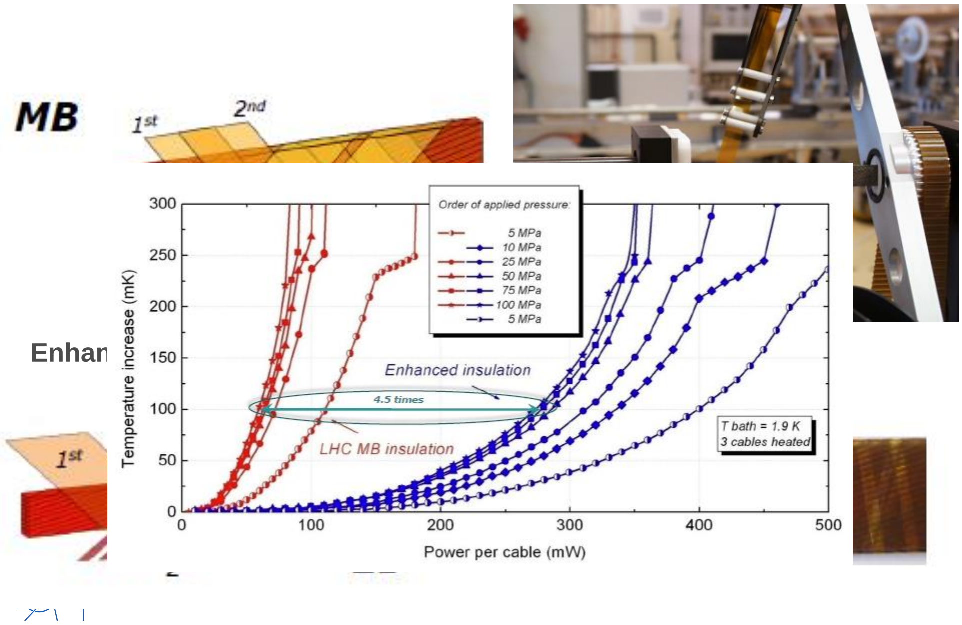
1) Capable of withstanding few thousands volts in gaseous helium
2) Withstand high stress
3) Working at cryogenic temperature
4) As thin as possible to dilute as low as possible J
5) Provide good heat transfer

And the iron contribution ?





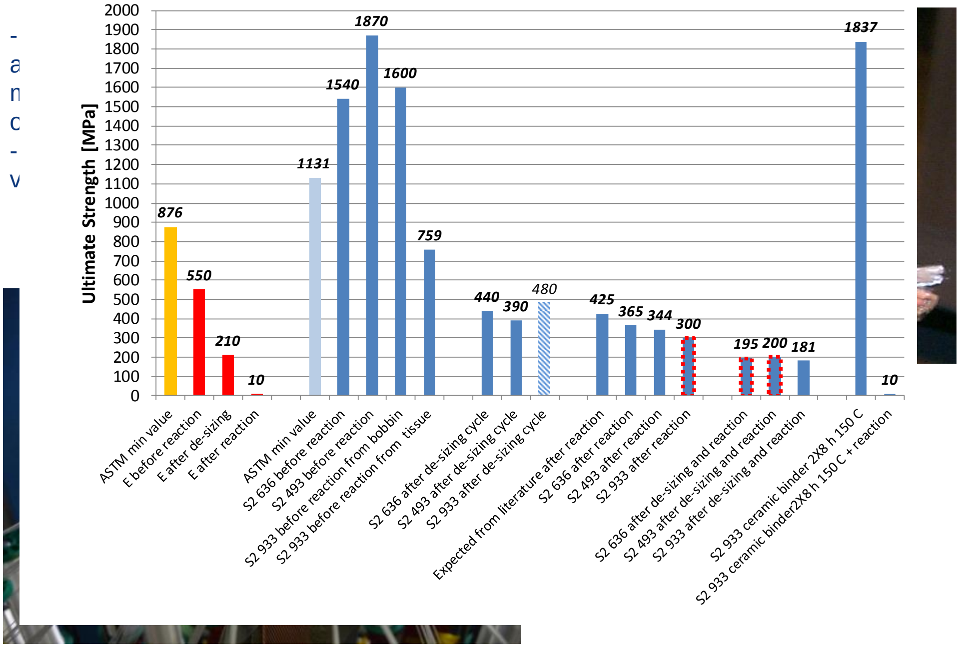
Insulation for Nb-Ti

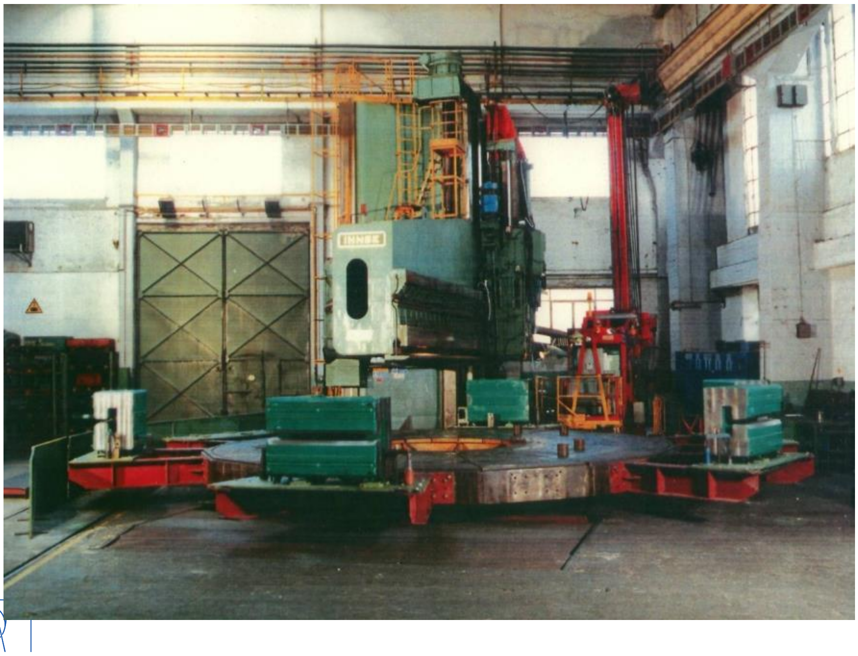


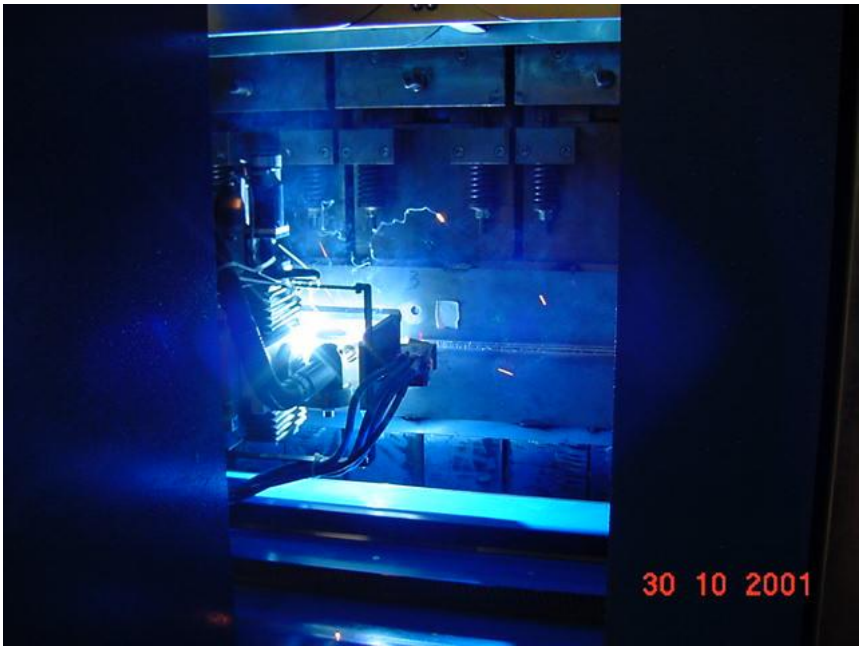
Enhan

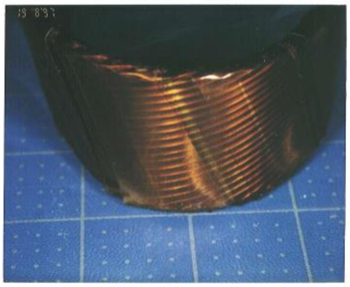
Insulation for Nb3Sn magnets

-
a
n
c
-
v

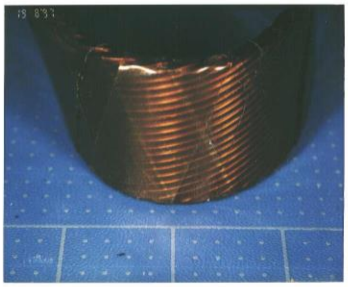



INNSE

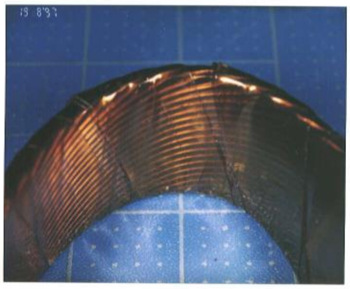

30 10 2001

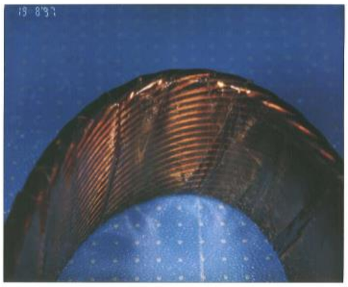


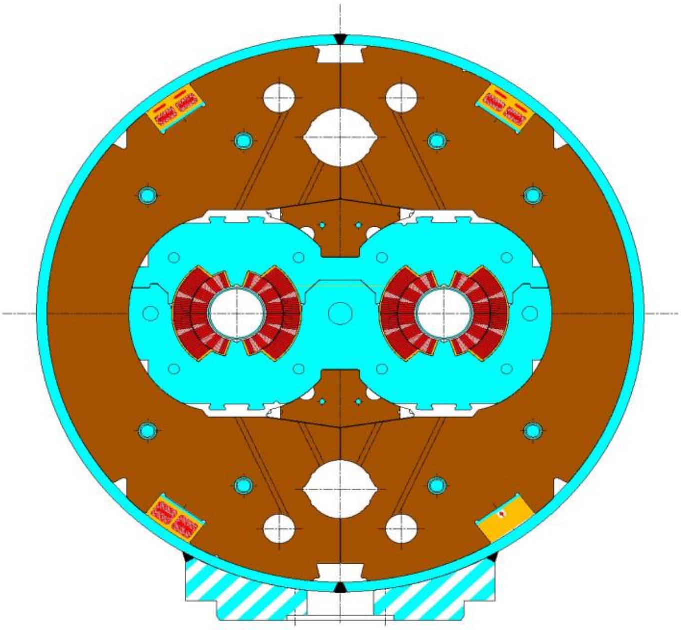
N° 4 ext



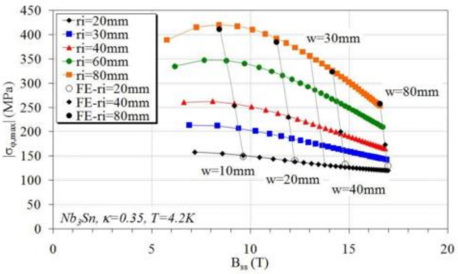
N° 3 ext

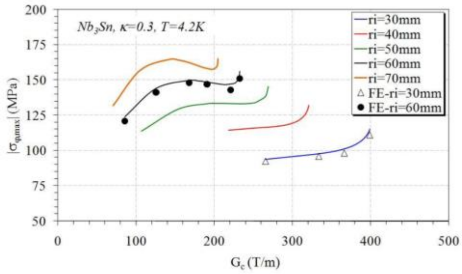




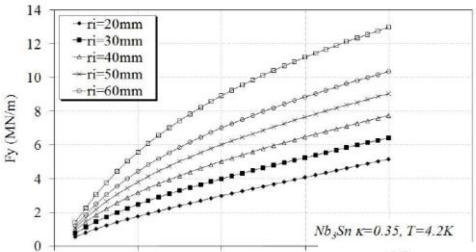


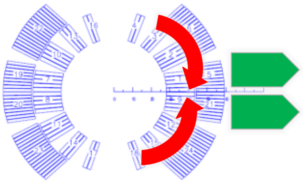
And what about stresses ?

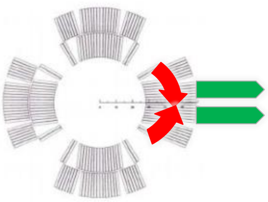


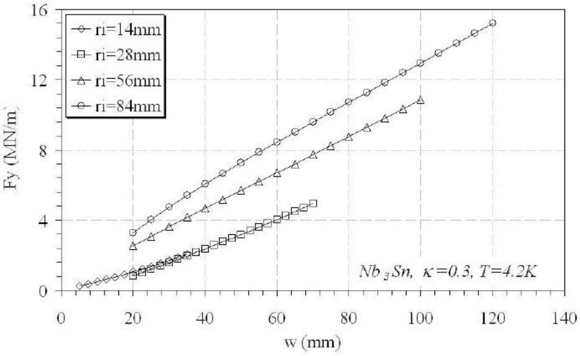


Or forces respect to the coil width









And if you have a defect in the insulation ?