Dynamic effects on superconducting dipoles used for an ion beam cancer therapy gantry

P.Fabbricatore

INFN-Genova, Italy

The magnets involved in superconducting gantries for ion beam cancer theraphy suffers the problem of dynamic effects during magnetic field changes. Mainly ac losses could limit the performances by increasing the time of the field changes (more prolonged tratments). The field quality is also affected by dynamic effects. In this talk I review the dynamic effects and give some examples of computation on different possible conductors.

Three sources of ac losses

In a superconducting magnet there are three main sources of ac losses:

1) Losses in conductor
2) Losses (eddy + magnetic) in the magnetic yoke (if cold yoke is present)
3) Ac losses in the metallic structures

Our experience shows that losses in conductor could be relevant (50%) and this talk is focussed on this aspect. Eddy current losses of points 2 and 3 can be computed with commercial codes (e.g. ELECTRA). Magnetic losses requires a dedicated approach.

Ac losses in sc conductor

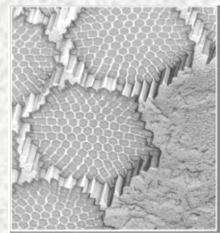
Within superconducting filaments (Hysteretic)

Between filaments (Coupling)

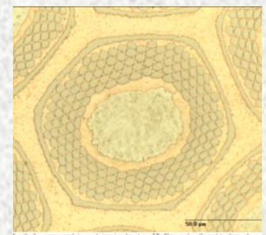
Eddy current in the matrix

Between strands (Coupling)

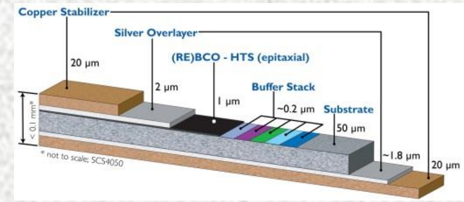
Eddy currents in the stabiliser



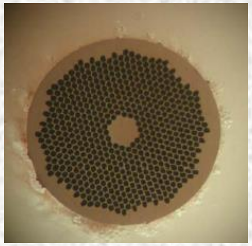
NbTi

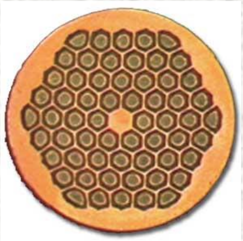


Nb_3Sn

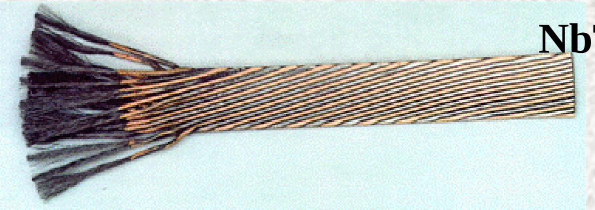


2G Rebco



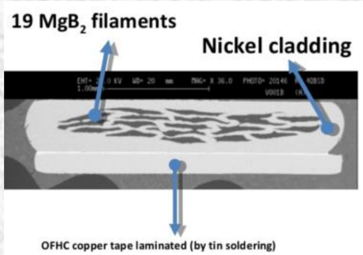


1G BSCCO

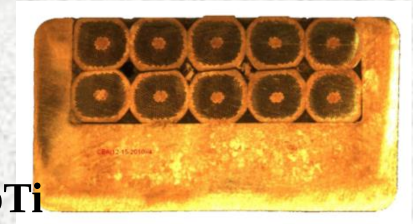


NbTi

MgB$_2$

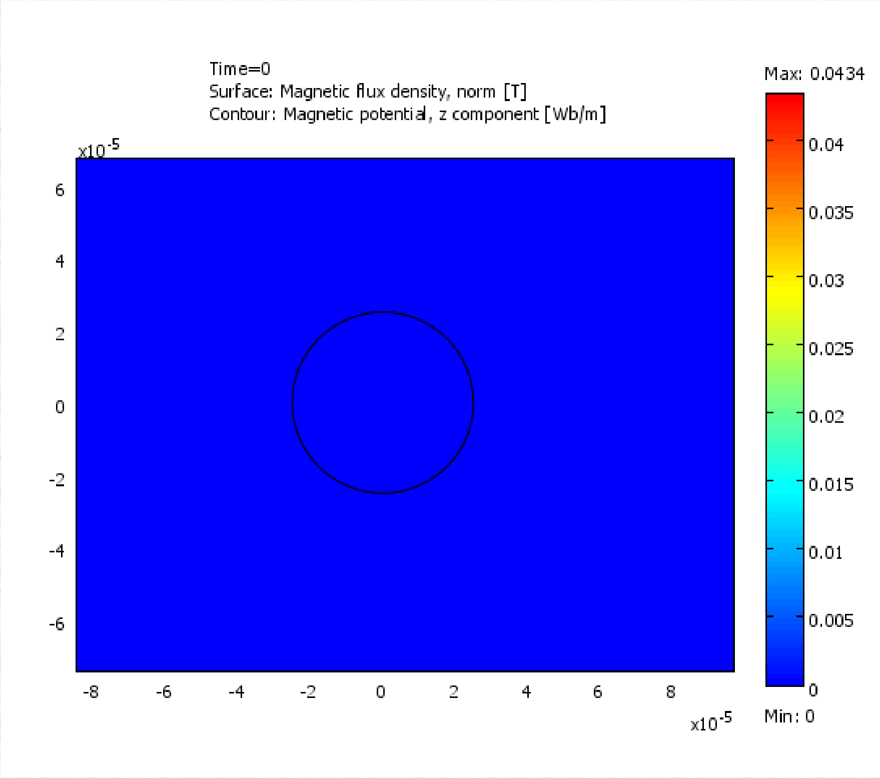


NbTi

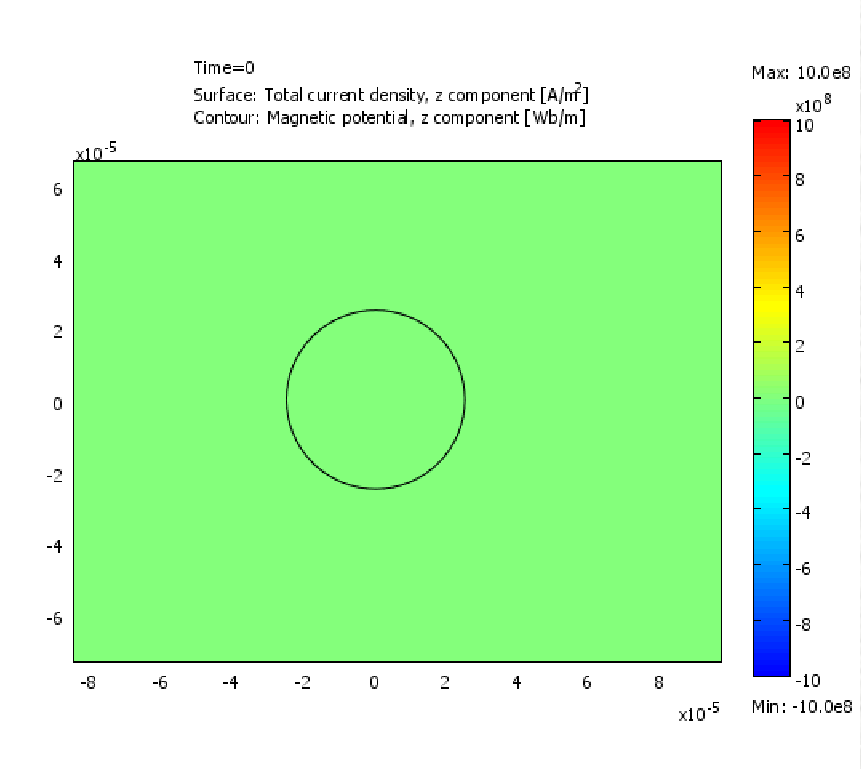


The causes of hysteretic losses

A superconducting filament in raising transverse magnetic field (according to the Critical State Model $\vec{\nabla}\times\vec{B}=\mu_0\vec{J}_c$)

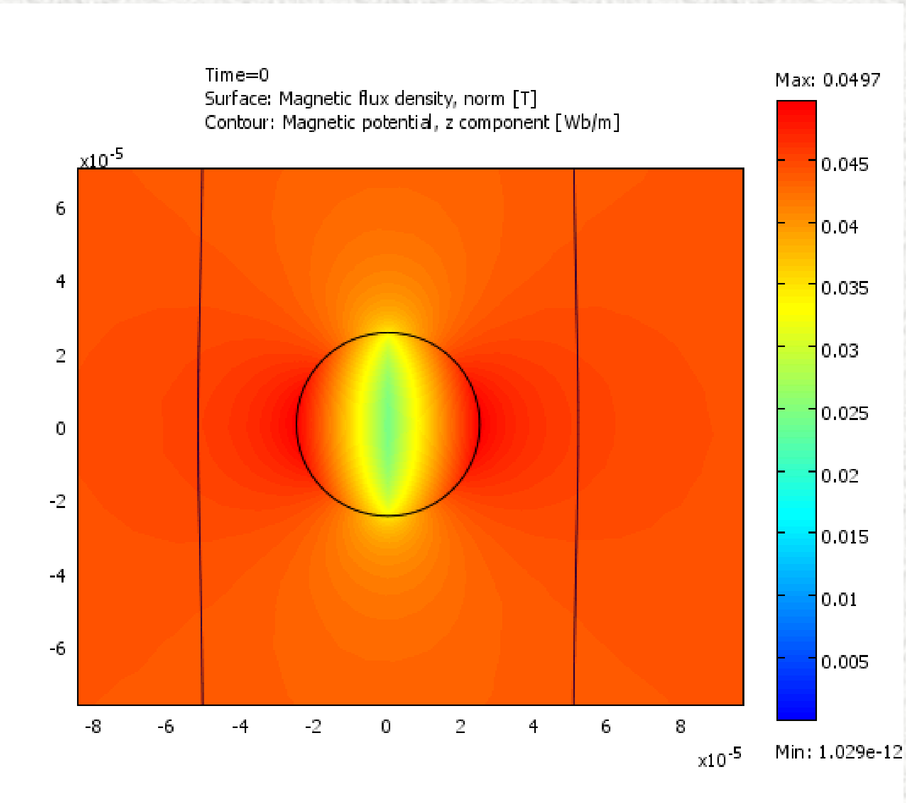


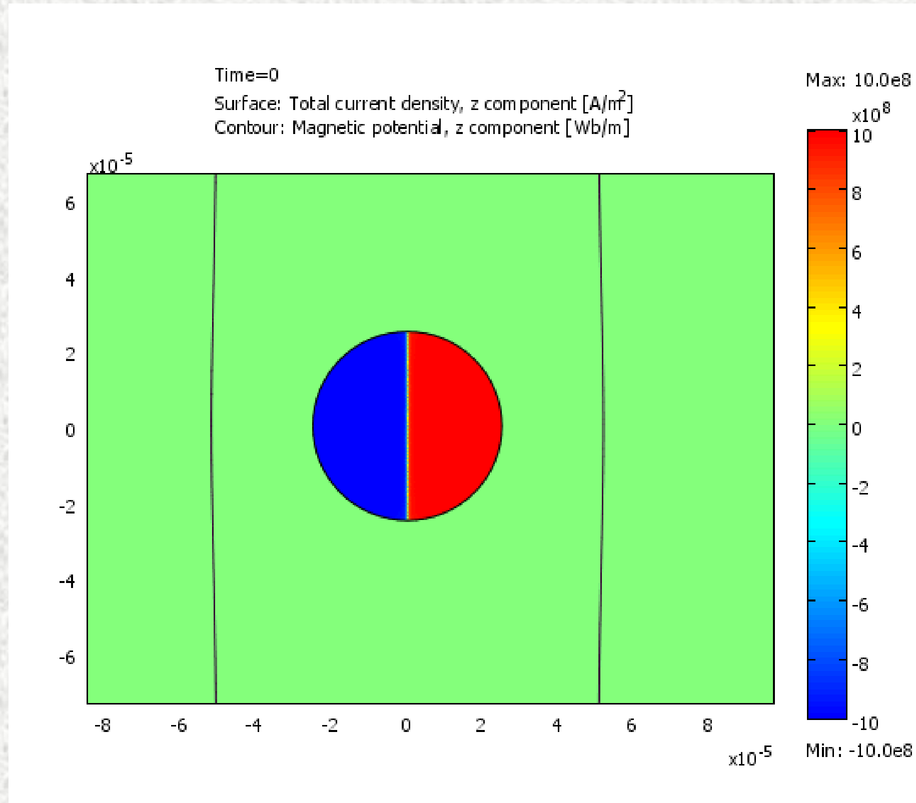
Magnetic field penetration



Bulk shielding current

Deacreasing the external field some magnetic flux remains trapped. The cross section is saturated by bulk shielding currents

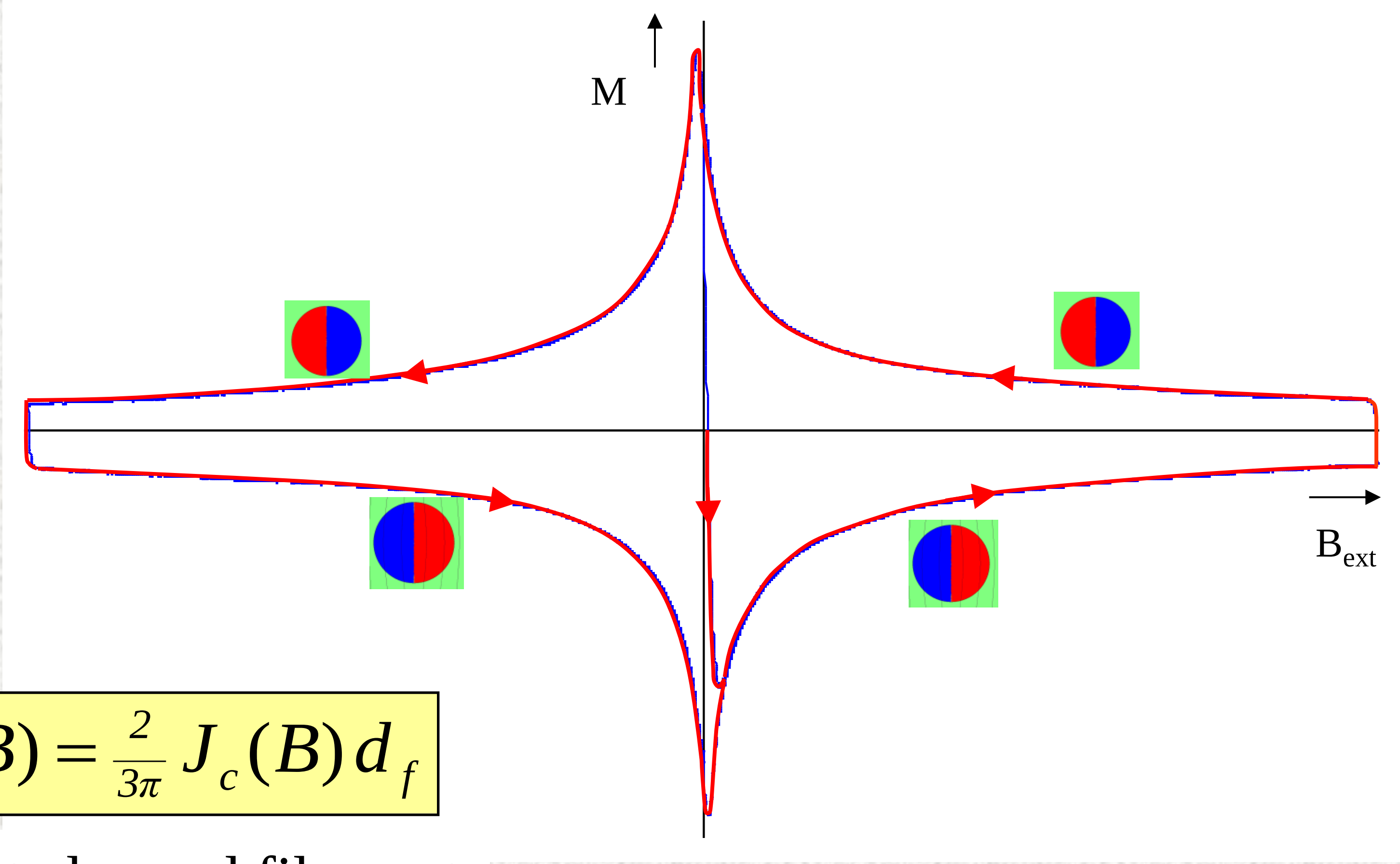




Magnetic field penetration

Bulk shielding current

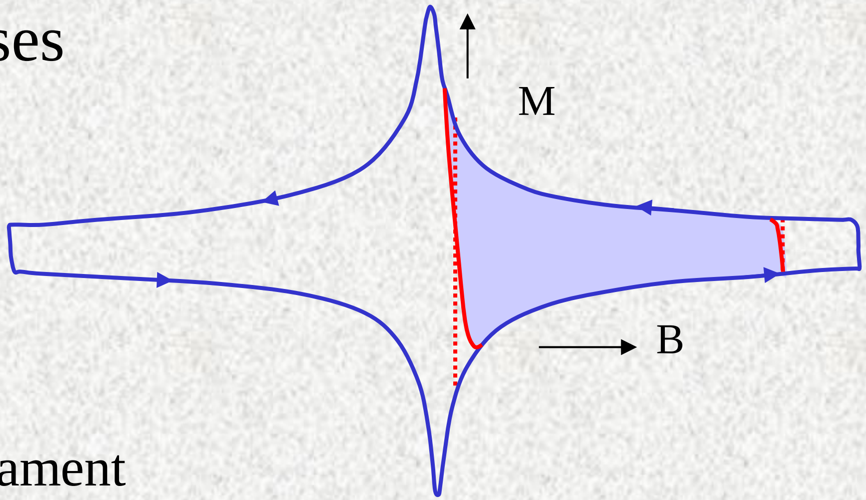
The persistent bulk currents causes an irreversibility in the magnetization cycle



$$M(B) = \frac{2}{3\pi} J_c(B)\, d_f$$

Saturated round filament

The irreversibility of M(B) → ac losses



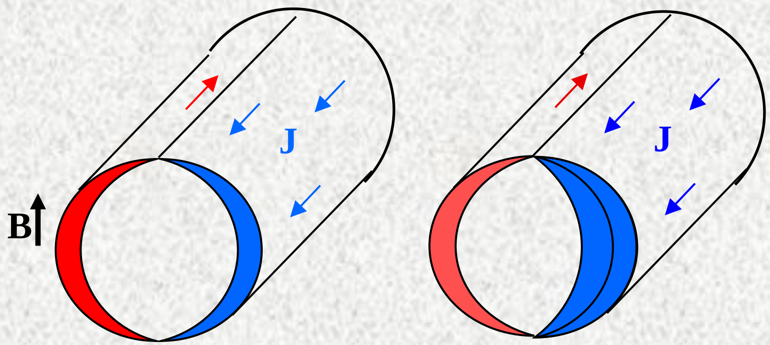
$$Q = \int \mu_o H dM = \int \mu_o M dH$$

If the magnetic field is normal to the round filament

$$P[W/m^3] = M\dot{B} = \frac{2}{3\pi} J_c(B) d_f \dot{B}$$

This is an important relation: the local contribution to the power losses in a position (x,y,z) inside a winding can be numerically computed starting from the knowledge of the time derivative of B(x,y,x). However we are not yet considering that the wire carries a current ....

The transport currents increase the losses as previously computed

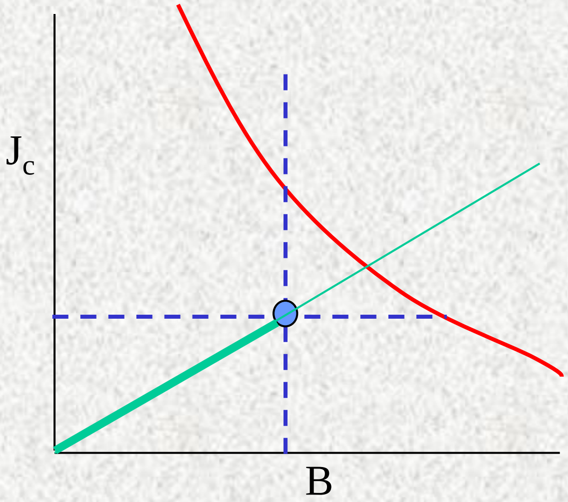


The increase factor is $(1+\boldsymbol{i}^2)$

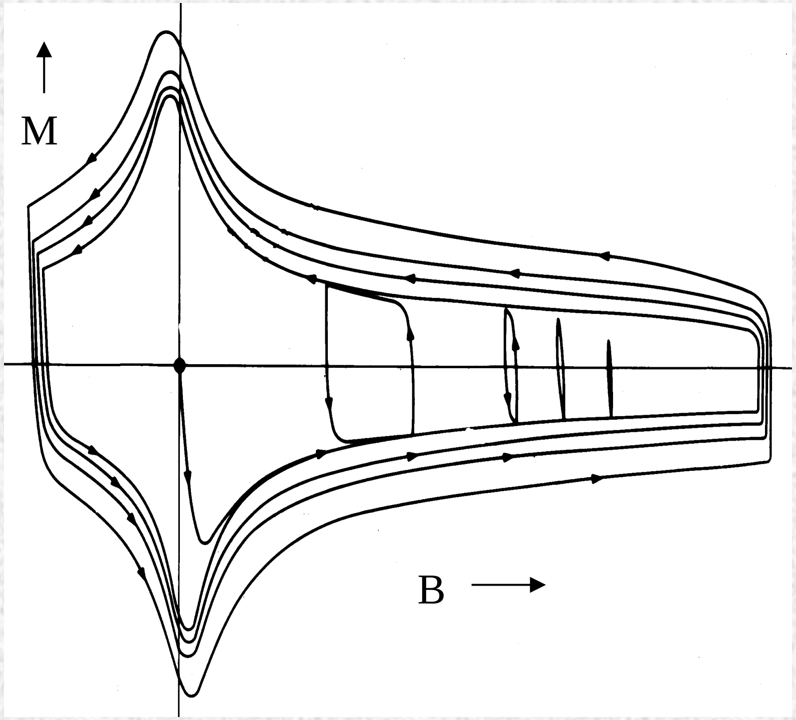
where $\boldsymbol{i} = \boldsymbol{I}_{max} / \boldsymbol{I}_c$

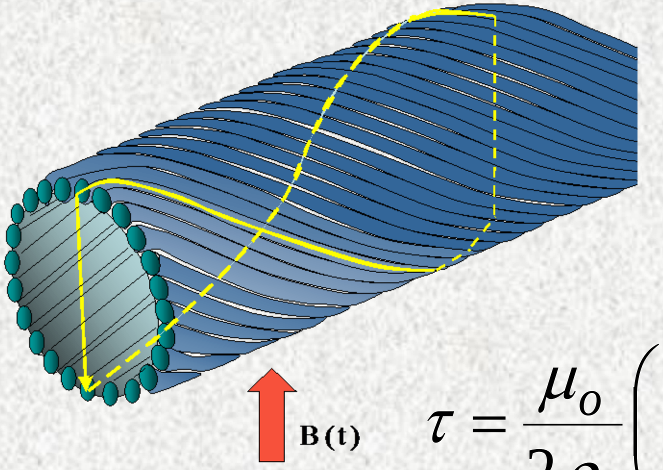
Due to the quadratic dependence, when operating with some margin (>30% for a gantry magnet) the factor could be quite low

Other corrections should be introduced due to the demagnetizing fields. However these corrections are mostly negligible



Inter-filaments coupling currents





$$\tau = \frac{\mu_o}{2\rho_t}\left(\frac{p}{2\pi}\right)^2$$

This a completely dynamic effect contributing to both ac losses and perturbation of the field quality.

$$P = M\dot{B}_i \approx \frac{2}{\mu_o}\dot{B}_e^2\,\tau$$

(Low frequency approximation)

It can be kept as low as possible by reducing the twist pitch (p) or increasing the transverse resistivity

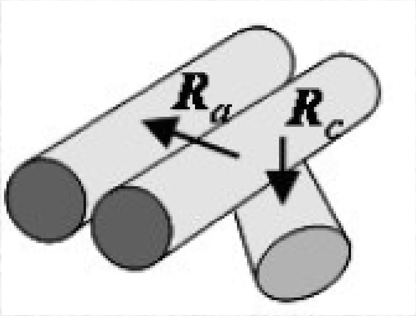
Still again the these losses can be computed through the knowledge of the amplitude of the magnetic field $B_e(x,y,z)$.

Inter-strand coupling currents

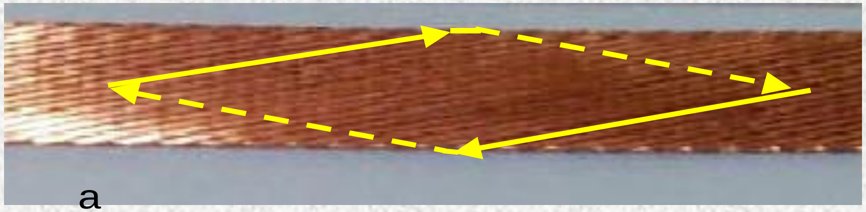
A ss core cuts down this term

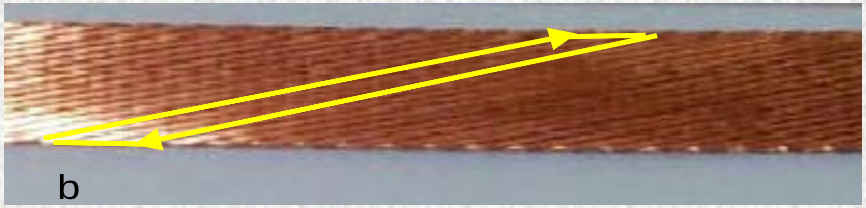
$$\dot{Q}_{tc} = \frac{1}{60}\frac{\dot{B}_t^2}{r_c}p^2\frac{c^2}{b} = \frac{1}{120}\frac{\dot{B}_t^2}{R_c}N(N-1)p\frac{c}{b},$$

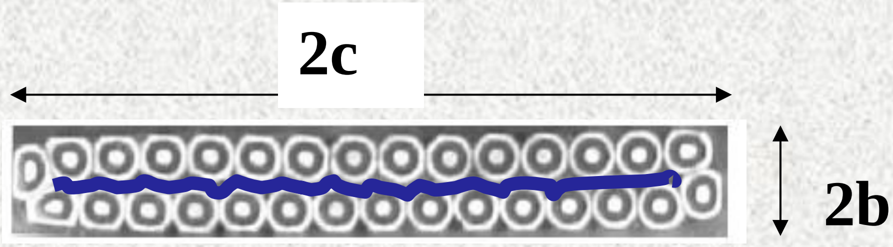
$$\dot{Q}_{ta} = \frac{1}{12}\frac{\dot{B}_t^2}{r_a}p^2\frac{c}{N\cos\theta} = \frac{1}{6}\frac{\dot{B}_t^2}{R_a}p\frac{c}{b},$$



Two kinds of coupling: a) opposite strands; b) adjacent strands

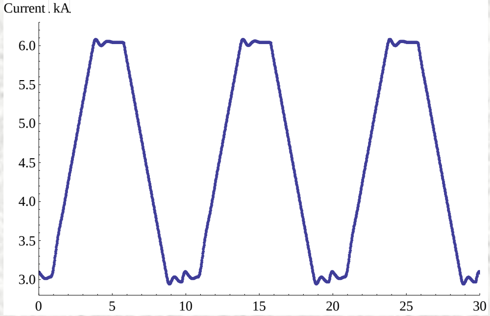






Check of computations- Test of FAIR SIS300 prototype dipole

Ac losses in the magnet body (no end coils contribution)	**SIS300 4.5T 100mm bore** Total loss when ramping from 1.5T to 4.5T at 1 T/s: **7.7 [W/m]**	
Hysteresis	30 %	$D_{fil\ effect}$ =3.5 μm (2.5 μm geom. 3 μm eff.)
Coupling Strand	9 %	CuMn $\rho_t = 0.43$ nΩ·m (0.3 nΩ·m) lp 5 mm (7 mm)
Interstrand Ra+Rc	6 %	Cored cable
Total conductor	**(45 %)**	
Collars + Yoke eddy + Prot. sheets	6 %	Collar 3 mm tick Iron 1 mm tick
Yoke magn	24%	H_c (A/m)=35
Beam pipe	14 %	$\frac{\pi}{\rho_0} \cdot \dot{B}_0^2 \cdot r_{av}^3 \cdot \Delta r$
Collar-Keys-Pins	8 %	
Yoke-Keys-Pins	3 %	



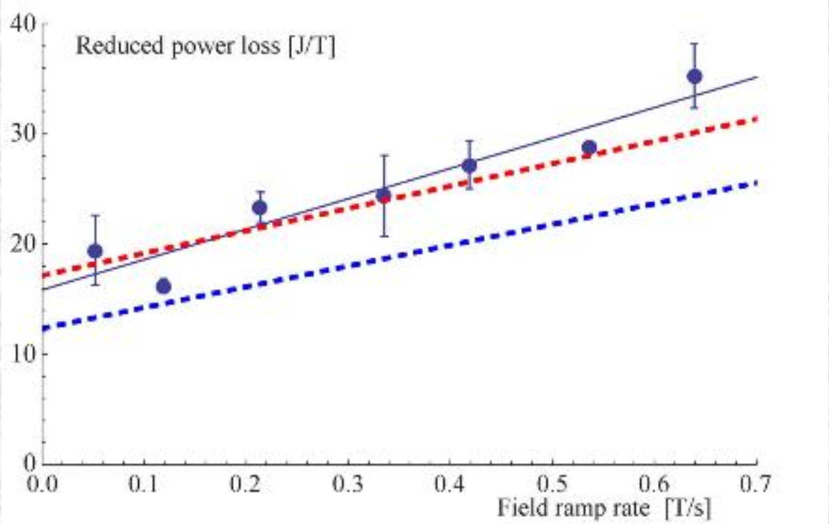
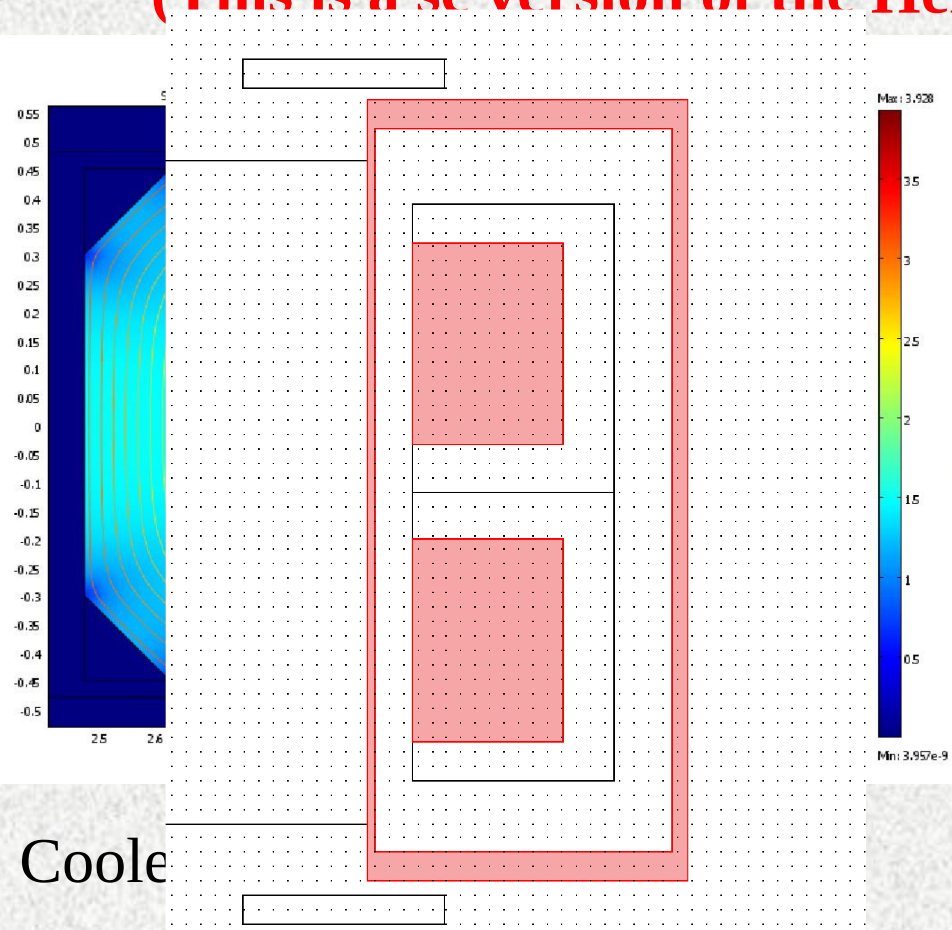


Fig. 6. Reduced power loss results summary. The blue line represents the best fit (not weighted) of the experimental points, and the blue and red dashed lines the minimum and the maximum expected reduced loss, respectively (from Table II).

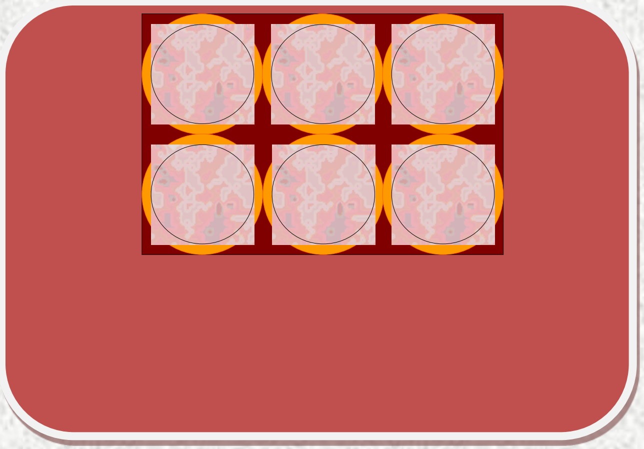
An example of ac losses in sc dipoles for gantries in hadrontheraphy. Superferric 90 degree dipole. Warm iron (This is a sc version of the Heidelberg 90 degree dipole)



Coole

Central field (T)	2.03
Curvature radius (m)	3.31
Over all current density (A/mm^2)	52
Current (A)	1000
Turns	189
Inductance (H)	1.8
Stored Energy (MJ)	0.9
Weigh Total/Cold mass (t)	41/1.5
GFR (mm × mm)	(200 × 200)
Field uniformity in the GFR	$< 5\ 10^{-4}$
Iron yoke	Laminated (1mm) warm
Cooling	Indirect (cryo-cooler)
Coil supporting structure	Al alloy

The conductor is a NbTi Rutherford in a copper matrix



Conductor dimensions (non-insulated)	3.2×4.7 mm^2
Conductor overall dimensions (insulated)	3.7 × 5.2 mm^2
Stabilizer	Copper
Strand diameter	0.825 mm
Filament diameter	< 3 μm
Cable dimensions	1.6×2.4 mm^2
Number of strands	6
Strand twist pitch	6 mm
Cable twist pitch	30 mm
Cu/SC ratio	1.7
Critical current at 4.2 K and 5 T	3100 A

Treatment time and ac losses

dB/dt (T/s)	$P_{hysteretic}$	P_{is}	P_{Ra}	P_{eddy}	$P_{structure}$	P_{total}
0.1	1.5	0.2	1.1	1	0.4	4.2
0.2	3.0	0.6	4.5	3.8	1.5	13.4
0.3	4.5	1.3	10.1	8.5	3.4	27.8
0.4	6.0	2.3	18.0	15.2	6.0	47.5

2.8 mJ/kg

a) The field is ramped in 5 seconds from 0 T (or almost 0) to 2 T in one go;

b) The field is decreased to 0.3 T in 20 steps (20 treatment planes) each one lasting the time for scanning, changing the field plus 1 second in total for a total time of 24.25 seconds if the field rate is 0.4 T/s (field variation in 4.25 s).

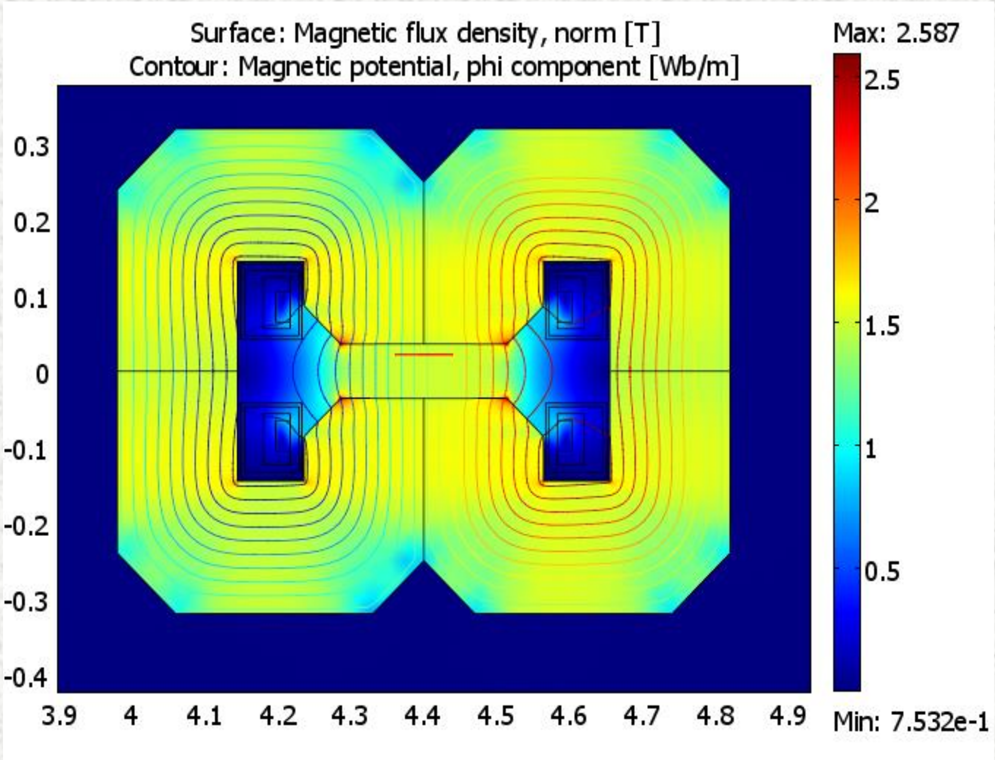
c) The field is decreased to 0 in 0.75 s.

Total time 30.25 s

At max speed for a treatment we calculated in total a loss of 475 J in 30s giving 15.83 W of average power.
This value is too high for being removed in steady state condition by cryo-coolers. <u>One should count on the enthalpy margin (coil warm-up depending on material Tc) .</u>

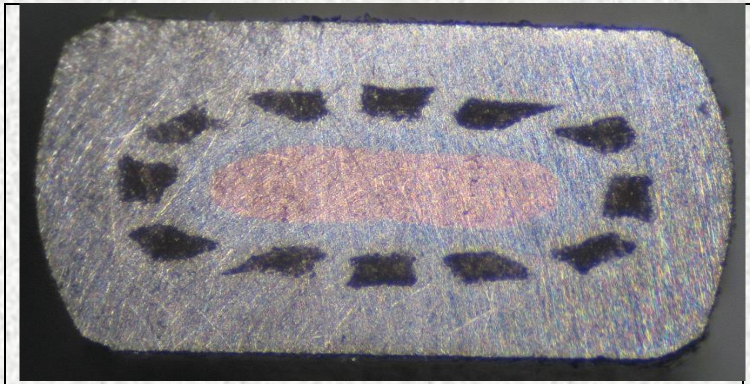
At min. speed the needed time increases to 1 minute and average power is 2.8 W

A second example: 45 degree iron dominated SC dipole. Warm iron

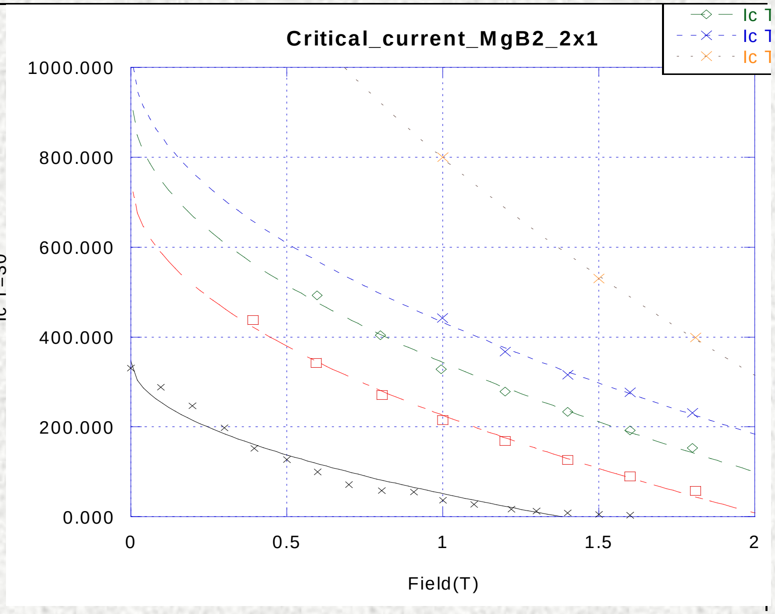


Central field (T)	1.50
Curvature radius (m)	4.4
Over all current density (A/mm^2)	55
Current (A)	155
Turns	284
Inductance (H)	6.7
Stored Energy (kJ)	81
Weigh (t) Tot/C.M,	15/.15
GFR (mm × mm)	(44×80)
Field uniformity in the GFR	< 2 10^{-4}
Iron yoke	Laminated
Operating temperature and cooling syst.	16 K; indirect
Coil supporting structure	Al alloy

Cooled by cryo-coolers



MbB_2 conductors developed by Columbus (Genova)



The peak field in the winding is 1T. Operating at 16 K the temperature margin is about 9K. The magnet works at 1/3 of the critical current at fixed field.

As for the 90 degree dipole, the AC losses in ramping conditions were calculated at 0.075 T/s equivalent to 0.1 T/s of the 90 degree dipole (17 s ramping time).

8.7 mJ/kg

B rate (T/s)	$P_{hysteretic}$	$P_{intrastrand}$	$P_{interstrand}$	P_{eddy}	$P_{structure}$	P_{total} (W)
0.075	1.00	0.07	-	negligible	0.15	1.3

Many methods for calculating the effects on field quality of permanent and induced coupling currents

- Perform a FE computation with an average magnetization of the winding

For p.c. $$M(B) = \frac{2}{3\pi} J_c(B) d_f \lambda_f$$

λ_f is the fraction of the superconductor in the winding

For coupling currents $$M = \frac{2}{\mu_o} \dot{B}_e \tau \lambda_s$$

λ_s is the fraction of the strand in the winding

- **Use the code ROXIE (CERN)**

Our experience with calculation of field quality of SIS300 dipole

TABLE V
SEXSTUPOLE AND DECAPOLE FIELD HARMONICS DUE TO PERSISTENT CURRENTS (REF. RADIUS 35 mm, Units $\times 10^{-4}$)

Bo (T)	0.5	1.5	3.0	4.5
	δb3 / δb5	δb3 / δb5	δb3 / δb5	δb3 / δb5
Fortran code	-3.65/-0.44	-0.72/-0.09	-0.25/-0.03	-0.13/-0.02
Ansys dipole	-3.41/-0.55	-0.70/-0.08	-0.24/-0.05	-0.12/-0.03
Opera	-3.67/-0.45	-0.72/-0.09	-0.25/-0.04	-0.13/-0.02
Ansys	-3.54/-0.38	-0.74/-0.09	-0.26/-0.04	-0.14/-0.02
Roxie	-3.49/-0.37	-0.72/-0.09	-0.25/-0.04	-0.13/-0.02

TABLE VI
SEXSTUPOLE AND DECAPOLE FIELD HARMONICS DUE TO INTER-FILAMENT COUPLING CURR. (REF. RADIUS 35 mm, Units $\times 10^{-4}$)

Bo (T)	0.5	1.5	3.0	4.5
	δb3 / δb5	δb3 / δb5	δb3 / δb5	δb3 / δb5
Fortran code	-0.63 / 0.10	-0.16 / 0.02	-0.06 / 0.01	-0.04 / 0.00
Opera	-0.63 / 0.08	-0.17 / 0.02	-0.06 / 0.01	-0.03 / 0.00
Roxie	-0.63 / 0.09	-0.17 / 0.02	-0.06 / 0.01	-0.03 / 0.00

M.Sorbi et al. IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008

An intensive R&D activities has been performed for developing fine NbTi filaments immersed in a Cu-Mn matrix

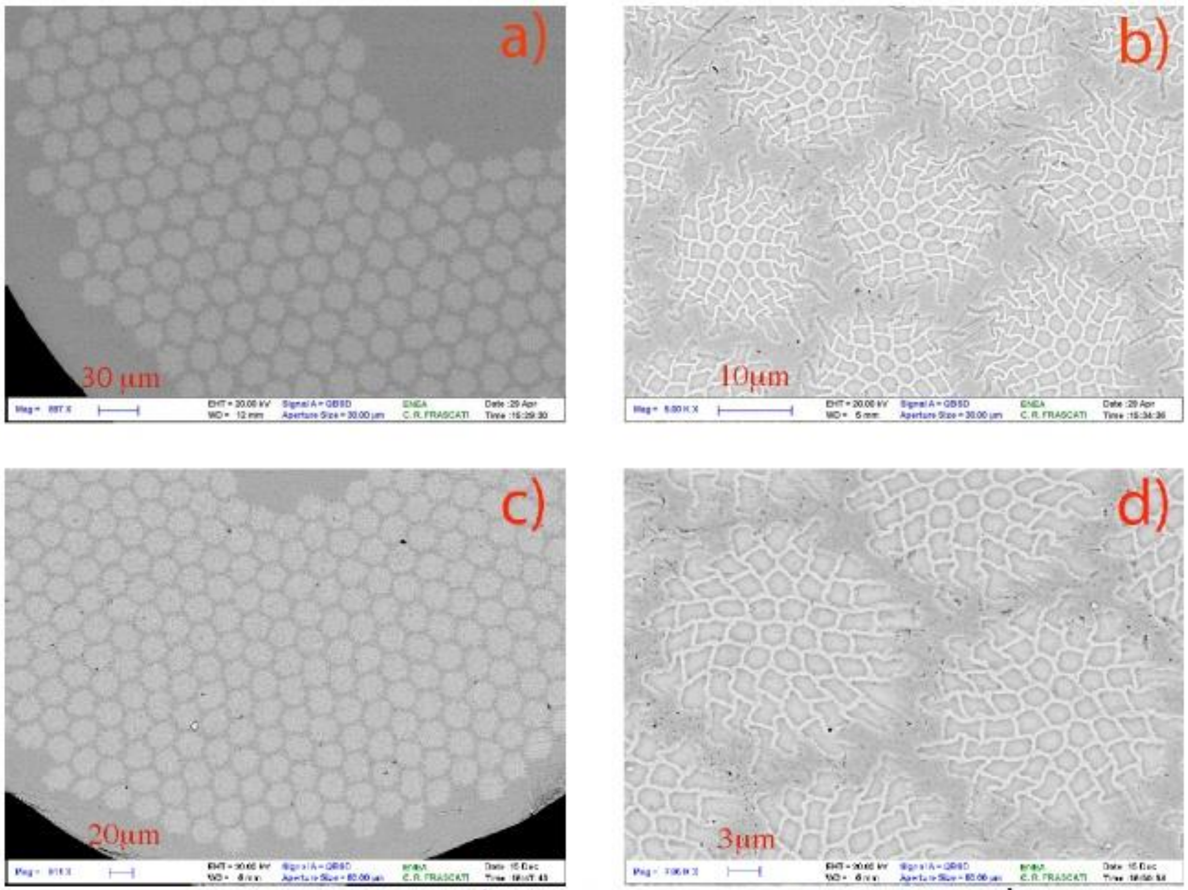
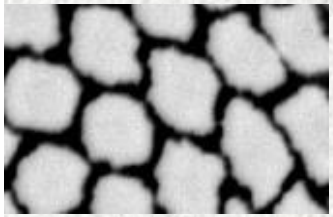
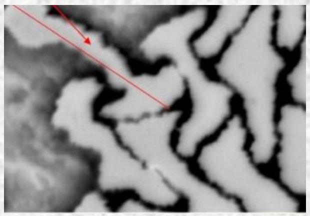


Fig. 1. SEM pictures of the 1st generation wire (a, b) and the 2nd generation wire (c, d).





- Investmement of the order of 700 k€ with results only partially satisfactory, because we had many breakages during wire production. In the end few available length.
- **<u>A low loss wire will be one of the main issues for future developments with NbTi.</u>**

CONCLUSIONS

Gantries involving superconducting magnets have limitations due to ac losses in sc conductors affecting the treatment time.

The losses and field quality can be predicted with a good approximation through the knowledge of the wire magnetization in static and dynamic conditions (computation or experimental results on wires/cables) and the magnetic field distribution (through a FE computation).

Magnets involving NbTi still require conductor R&D
MgB_2 looks promising for the temperature margin
Nb_3Sn (High Jc and large filaments are detrimental for losses!!)