The CERN Accelerator School

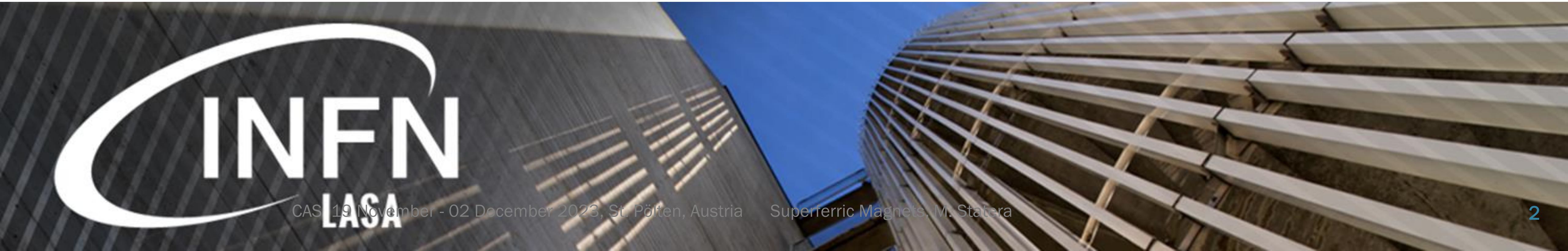
INFN
Istituto Nazionale di Fisica Nucleare

Superferric Magnets

Marco Statera, INFN Milano LASA

Outline

- Superferric magnets
  - What are they? Why use them?
- Selected examples
  - HE physics, precision experiments, light sources…
- High Order correctors, the first superferric magnets in LHC
  - Why superferric?
  - How they are designed and built
  - Do they perform?
- How can we use superferric magnets in future



Superferric magnet

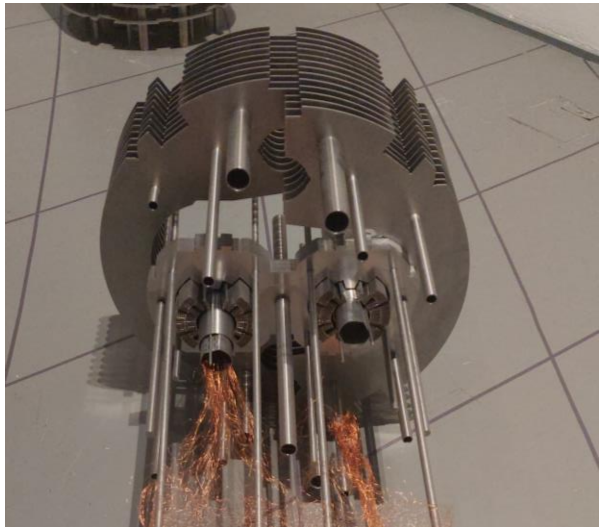
Magnet

- Magnetic field
- Shape
- Volume

Superferric

- Superconducting
- Iron geometry strongly affects the field shape

Smithsonian
www.si.edu



https://triennale.org/

The iron

ARMCO© is a trade mark by AK Steel International B.V.

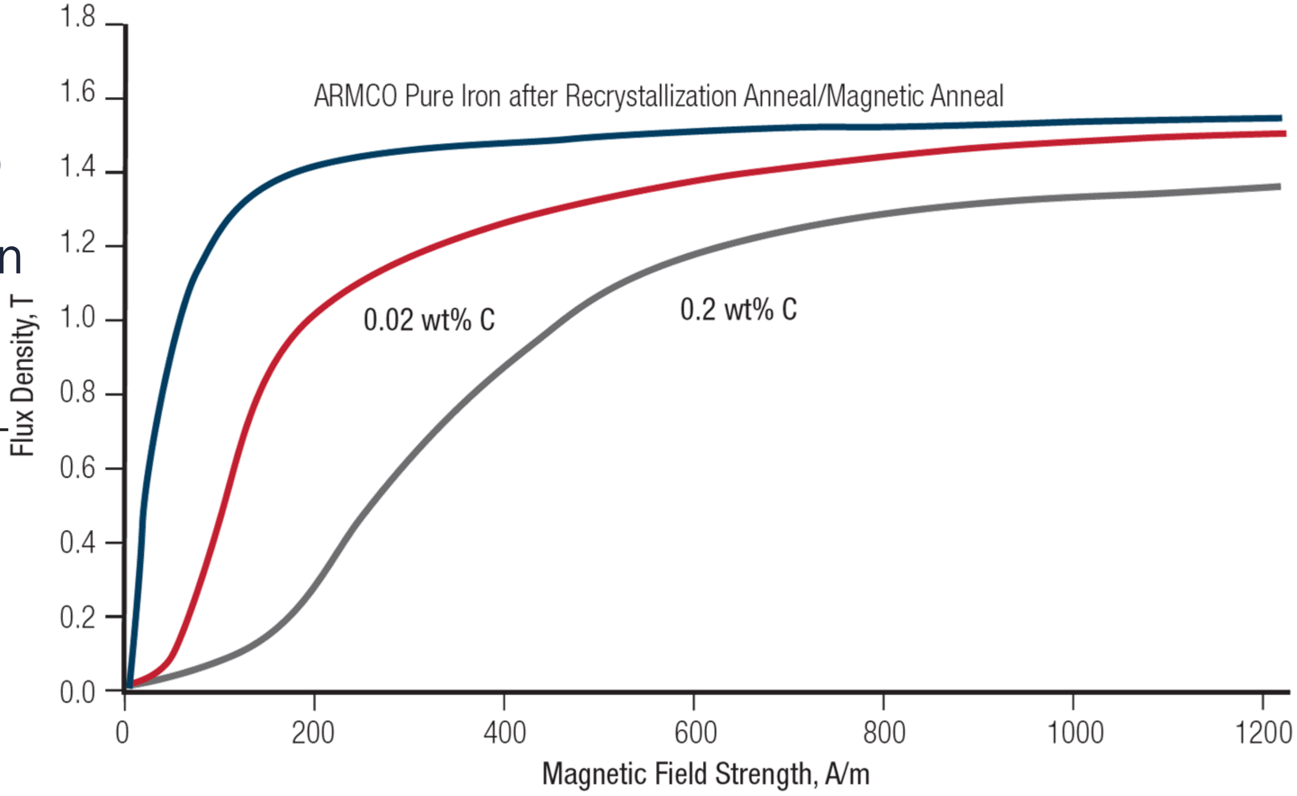
PURE IRON 99.85% low impourities

- Low mechanical properties wrt low carbon steel
- Excellent magnetic properties (zero crossing)
  - Sensitive to impurities and deformation (machining)
- Improved resistance against corrosion and oxidation in comparison to normal steels
- Good cold forming capability
- Ideally suitable for welding
- Small deformation with temperature

Oversimplification
Zero field crossing
Add one tesla to the pole field

GRADE 4

Composition		Max. Analysis %
Carbon	(C)	0.010
Manganese	(Mn)	0.060
Phosphorus	(P)	0.005
Sulfur	(S)	0.003
Nitrogen	(N)	0.005
Copper	(Cu)	0.030
Cobalt	(Co)	0.005
Tin	(Sn)	0.005

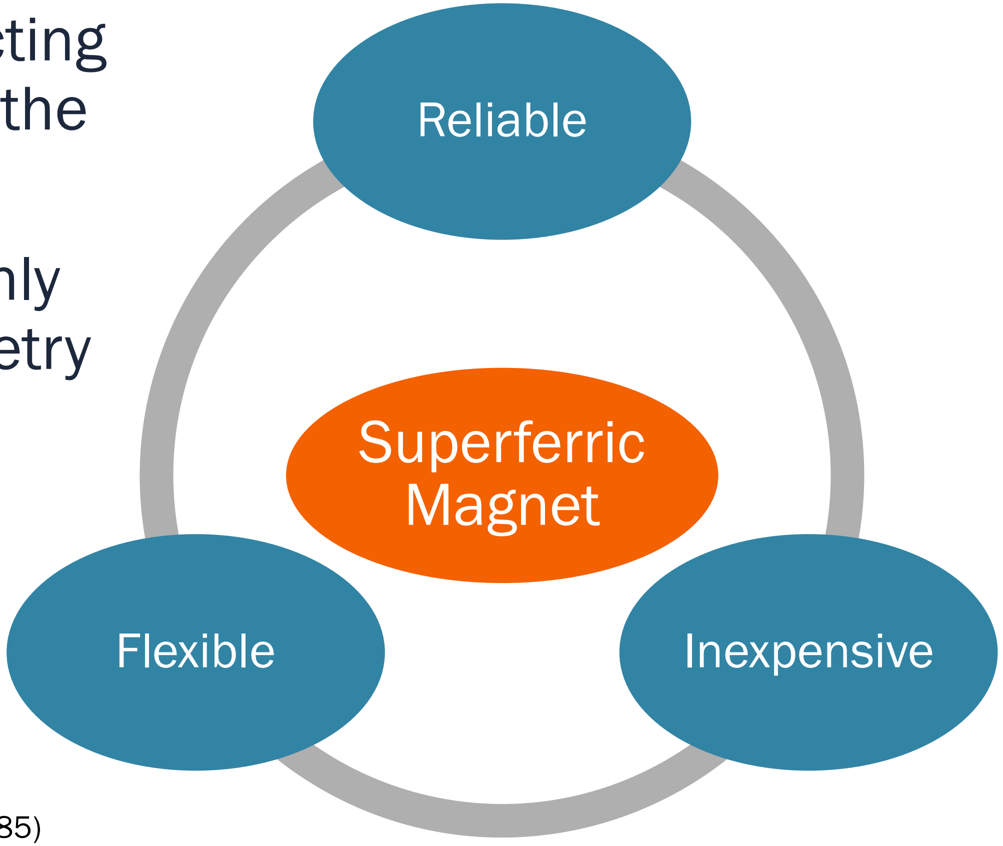


By AK Steel International B.V.

Why superferric magnets

Superferric design is characterized by a close coupling of the superconducting coil to the iron flux return of the manget.

The shape of the field is highly influenced by the iron geometry



Two regimes

Ferric B<M μ~∞

Superferric B>M μ=1

Two different optimizations

- Tradeoff for field quality at different fields
- Single regime use

F.R. Huson et al. IEEE tr. On Nuclear Science, 32-5 (1985)
F.R. Huson et al. Particle Accelerators, 28 pp213-218 (1990)

Superconducting Super Collider, USA

Superferric magnets for beamline and syncrotron

17’ - 44 cm

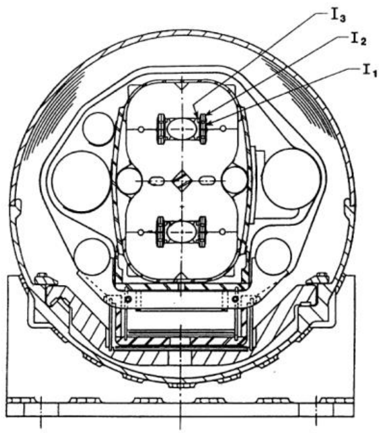
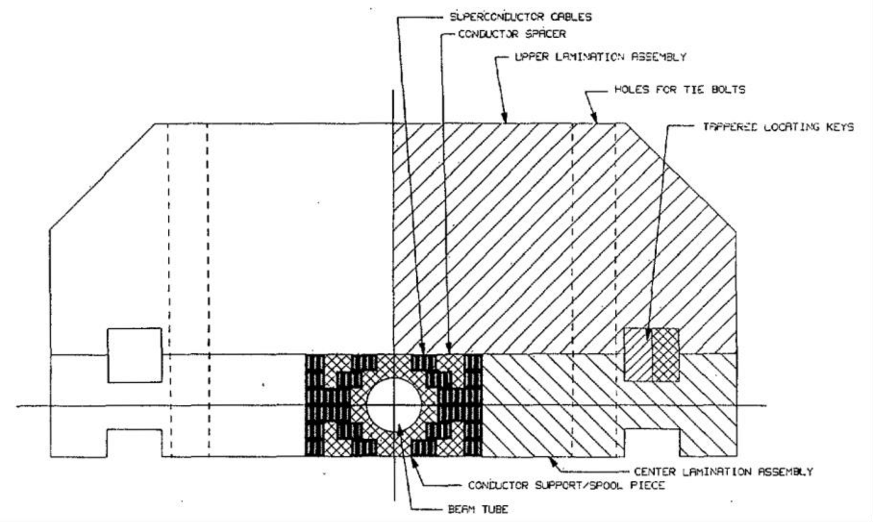


Figure 2: The 2-in-1 3 Tesla superferric magnet is enclosed in a vacuum chamber of 16 3/4'' O.D. The iron is 1/16'' laminations. The two magnet channels are magnetically independent. The gap of the magnet is 1 inch. The good field is greater than 2 cm diameter. The support in the figure is made of 2 concentric fiberglass cones, one between 10°K and 80°K and the other between 80°K and 300°K. There is a support every 24 feet. The small pipes are for liquid helium and nitrogen and the larger ones for helium gas. Sixty layers of superinsulation are between 80°K and 300°K.

3 T compact



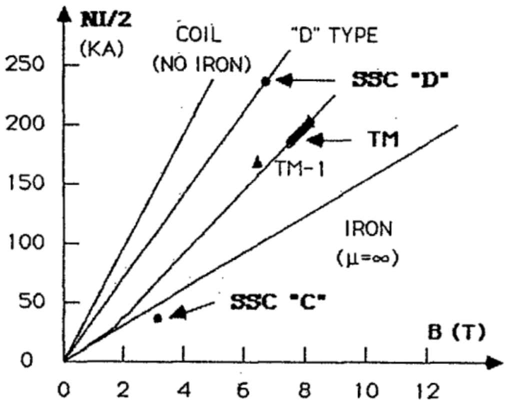


Fig. 4: Quadrant ampere-turns NI/2 for several types of magnets. SSC "D" has 2 cm inner coil radius. The gap in the iron for SSC "C" is 2.54 cm, TM is 4 cm and TM-1, 4.8 cm. The Ampere-turns for

6.5 T dual coils

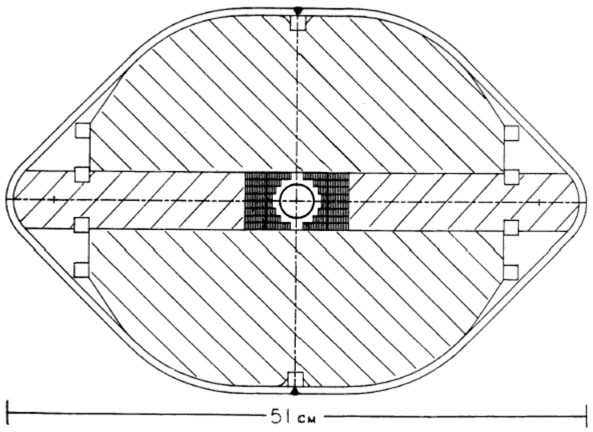


FIGURE 1 Cross-section of two-mode superferric magnet.

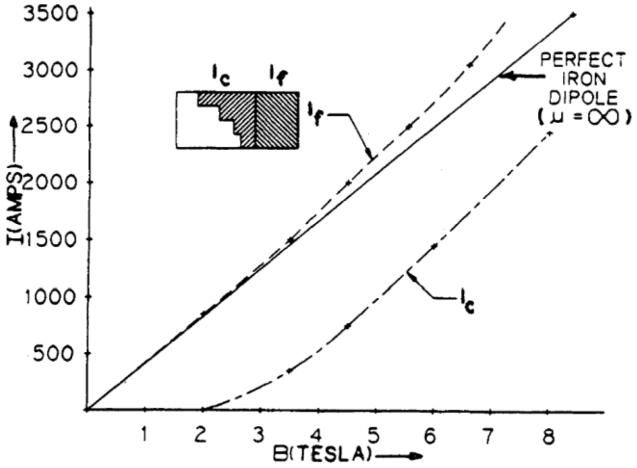
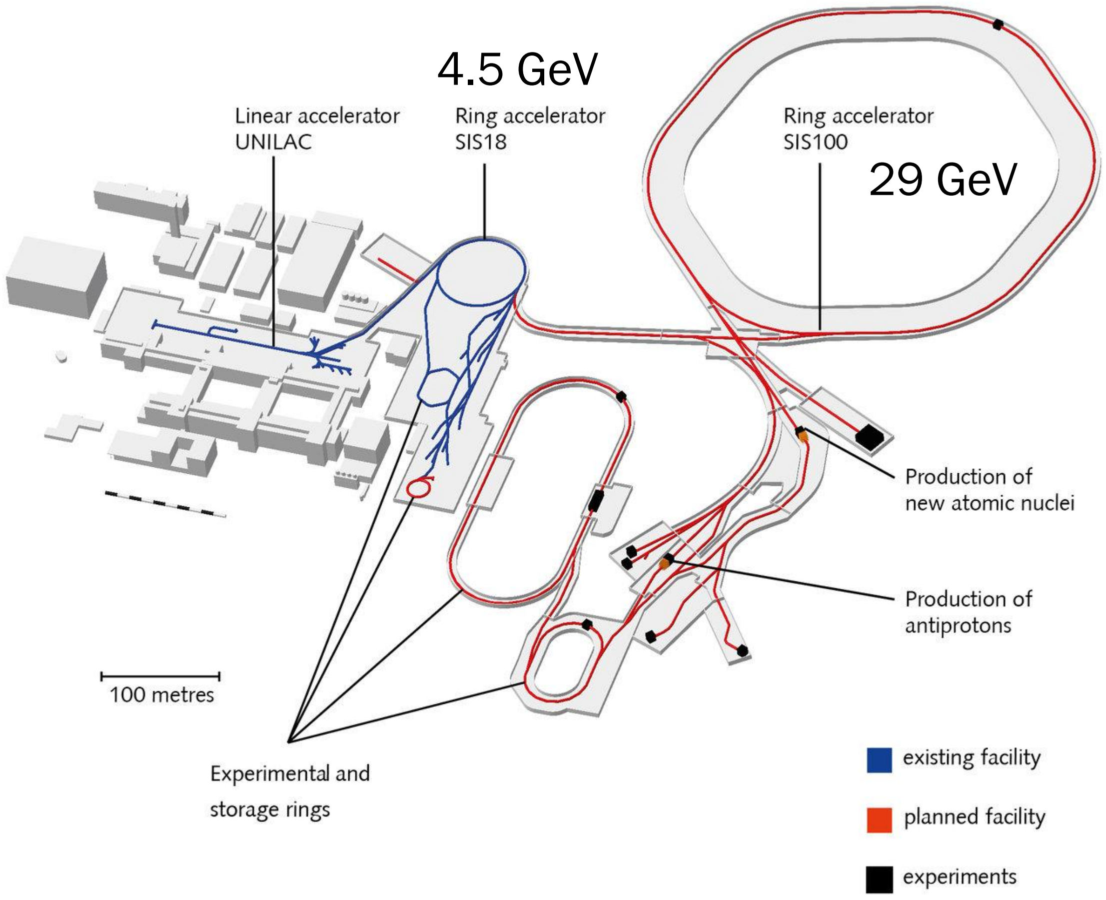


FIGURE 2 Calculated current programming of the two coil segments.

W. Xie et al., IEEE Tr. In Magnetics VOL. MAG-23, NO. 2 (1987)
F.R. Huson et al. Particle Accelerators, 28 pp213-218 (1990)

FAIR at GSI

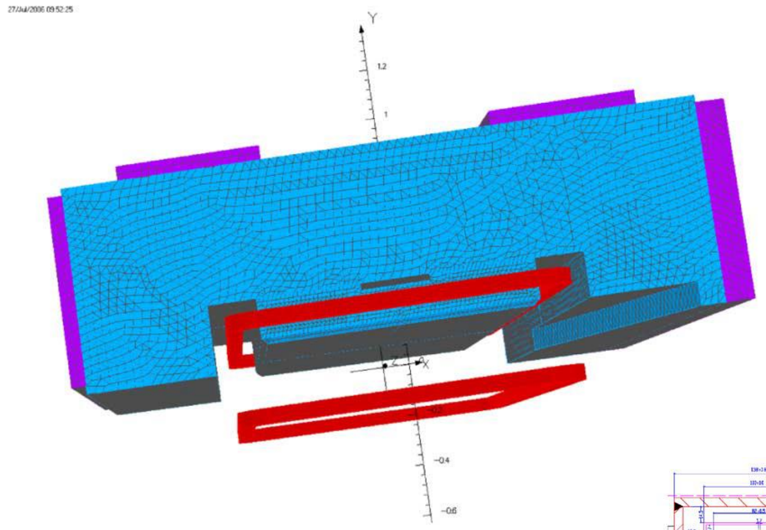


www.gsi.de

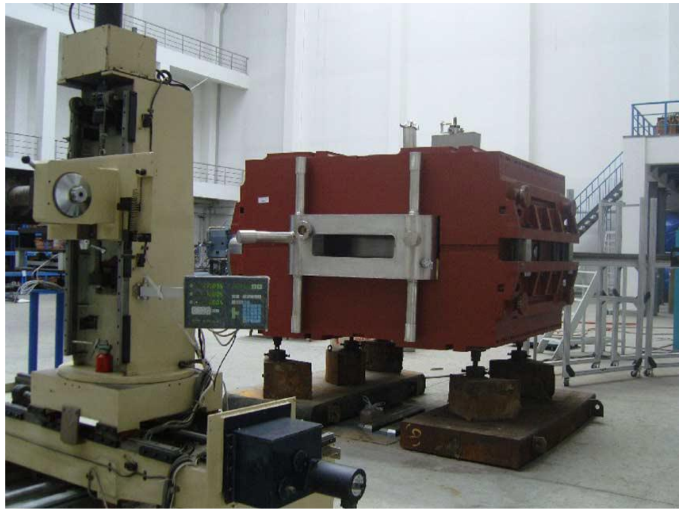
- SIS fast ramped Ring Accelerator (4 T/s)
- When the accelerated ions impact a material sample, antiprotons or special isotopes
- The Super-FRS is a two-stage fragment separators, that uses the Bρ-ΔE-Bρ method, in which the analysis of the magnetic rigidity (Bρ) is combined with the energy loss in a specially shaped degrader (ΔE)
- Extensive use of superferric magnets

Prototype of the Superferric Dipoles for Super-FRS

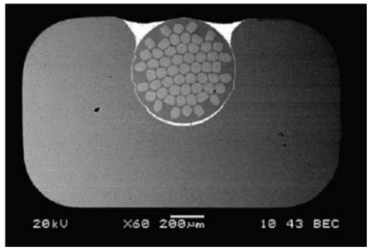
- In the target area resistive magnets due to high radiation dose
- For the dipoles also a normal conducting solution could come into consideration. Here the enormous **power consumption** of a conventional dipole leads to the decision of using superconducting coils.

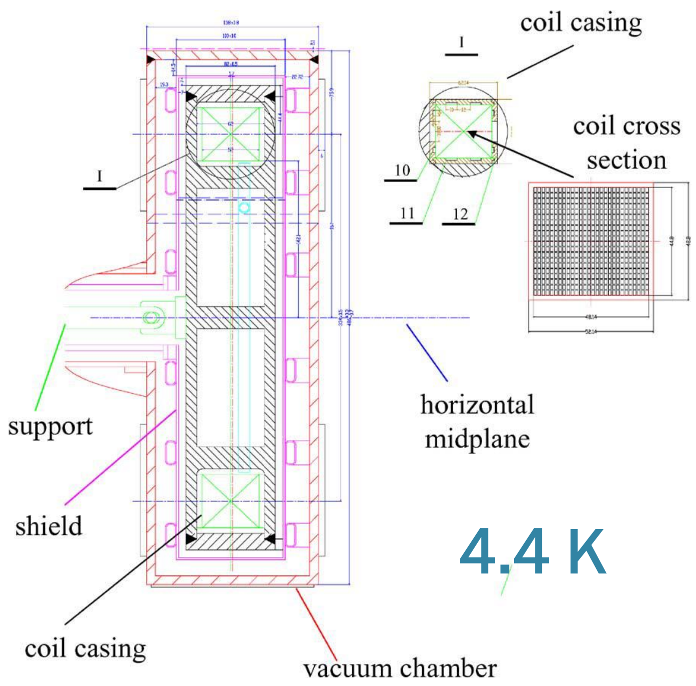


H-type iron yoke
Max field 1.6 T



Racetrack coils
NbTi conductor
Coils cooled by LHe





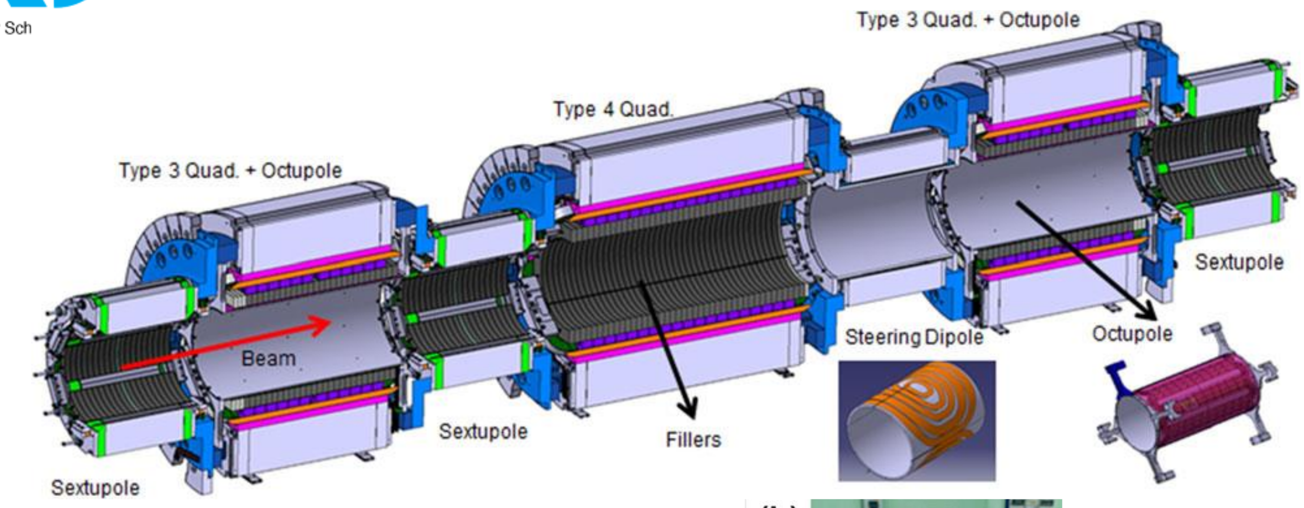
Integral field quality (relative)

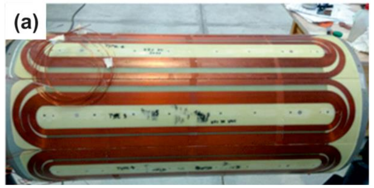
$$\frac{\Delta(\int Bdl)}{\int Bdl}$$

for B=0.15 to 1.2 T: $\pm 3\cdot 10^{-4}$
and for
B=1.2 T to 1.6 T: $\pm 1\cdot 10^{-4}$

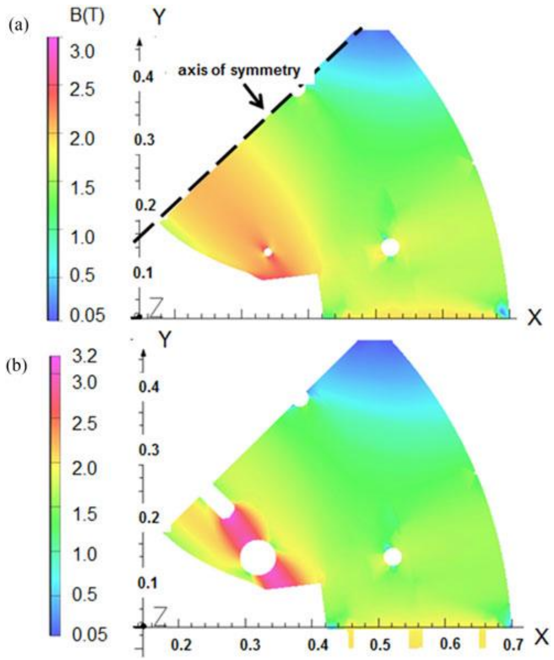
H. Leibrock et al., IEEE Tr. Appl. Sup, VOL. 20, NO. 3 (2010)
P. Szwarngruber et al., Physics Procedia 36 (2012) 872 – 877 (2012)
P. Szwarngruber et al., IEEE Tr. Appl. Sup, VOL. 23, NO. 3 (2013)

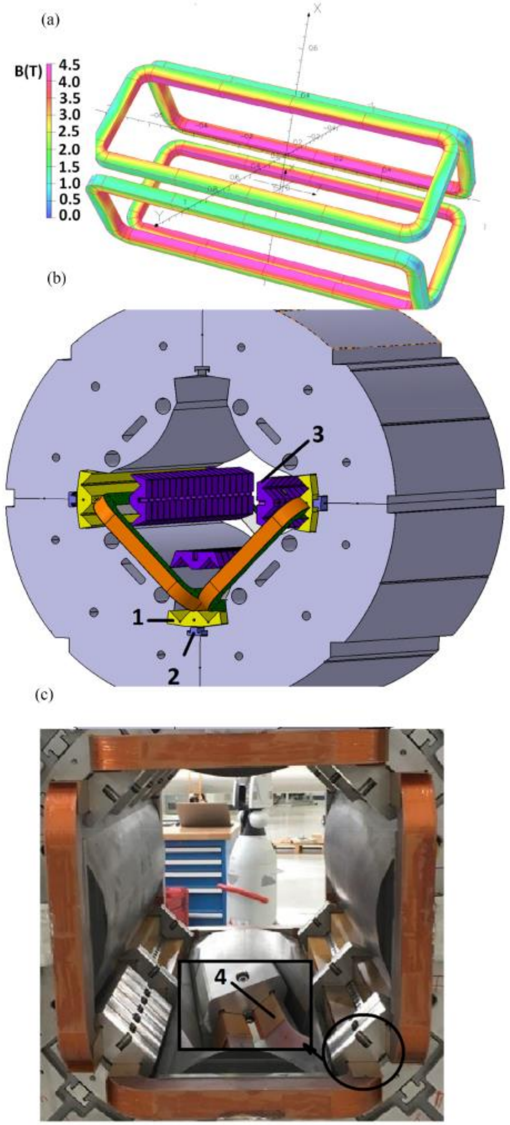
Super-FRS Multiplets





- 179 magnets
- Quadrupoles and sextupoles are superferric
- Octupole and steering dipole are cosin theta
- Good field region ϕ 380 mm

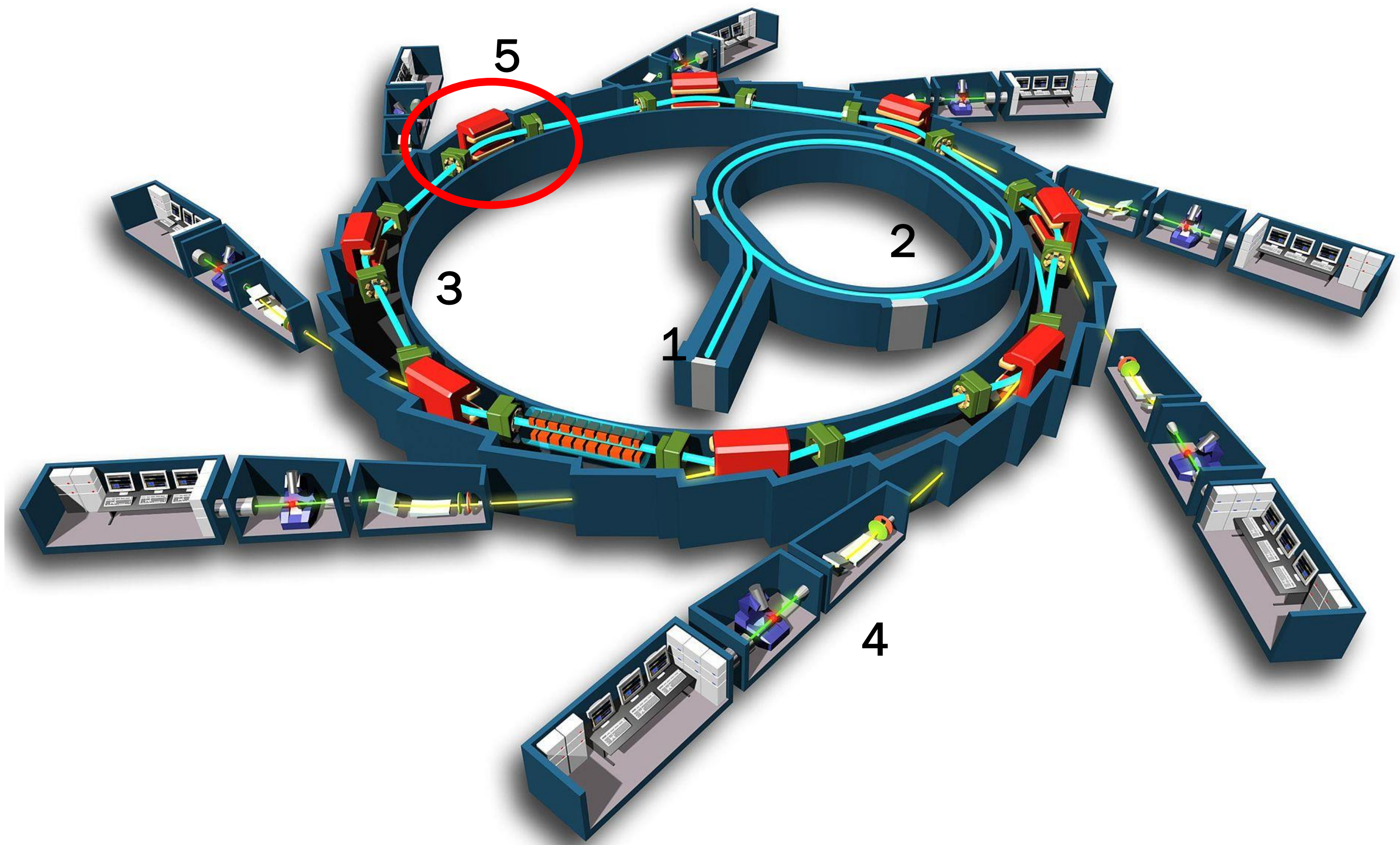




Pole geometry optimized to reduce the b6 contribution

E Cho et al., IEEE Tr. Appl. Sup, VOL. 28, NO. 4 (2018)
E Cho et al., IEEE Tr. Appl. Sup, VOL. 30, NO. 4 (2020)
E Cho et al., IEEE Tr. Appl. Sup, VOL. 32, NO. 4 (2022)

Synchrotron – Light Source



1 – Injector
2 – Booster Ring
3 – Storage Ring
4 – Beamline
5 – Bending Magnet

Bending Magnet

The bending magnets in the storage rings are the primary sources of radiations.

The BM source produces a beam of fixed vertical opening angle ψ ~ γ^{-1} (photon beam divergence), while the horizontal spam is determined by the length of the BM arc.

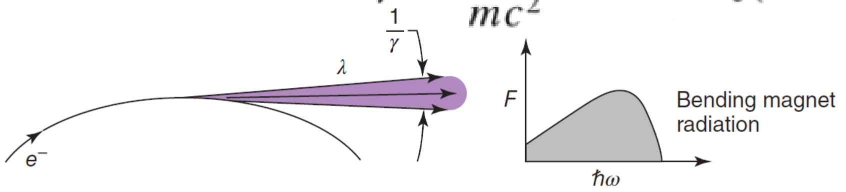
The critical energy of a synchrotron source depends upon the storage ring energy and the magnetic field of BM.

To be able to reach high photon energies (50keV and more) the solution is to use superconducting magnets to increase the magnetic field.

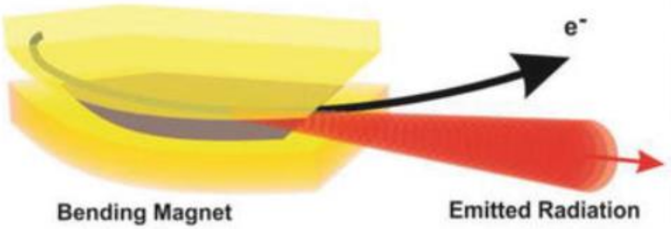
$$E_c = \hbar\omega_c = \frac{3e\hbar B\gamma^2}{2m}$$

$$E_c(\text{keV}) = 0.6650E_e^2(\text{GeV})B(\text{T})$$

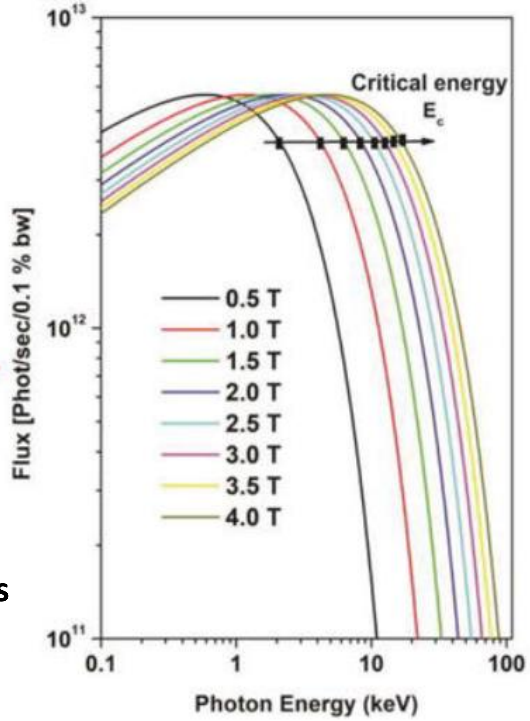
$$\gamma = \frac{E_e}{mc^2} = 1957E_e(\text{GeV})$$



Attwood, D. (2007)Soft X-rays and Extreme Ultraviolet Radiation: Principle and Applications, Cambridge University Press.



Fundamental of Synchrotron Radiations
Amardeep Bharti and Navdeep Goyal



Bending vs Superbending Magnets

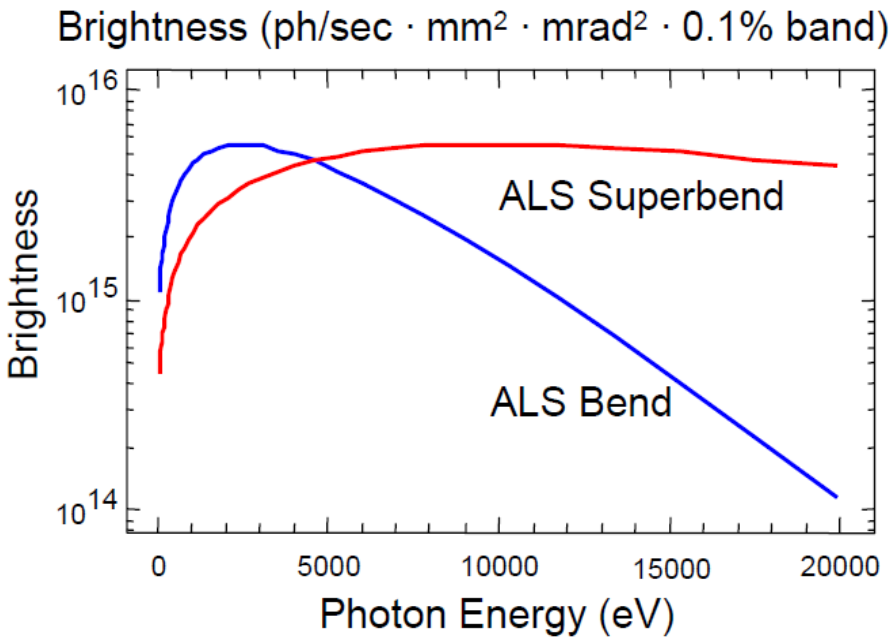


Figure 1: Brightness of a Superbend versus the normal conducting bend

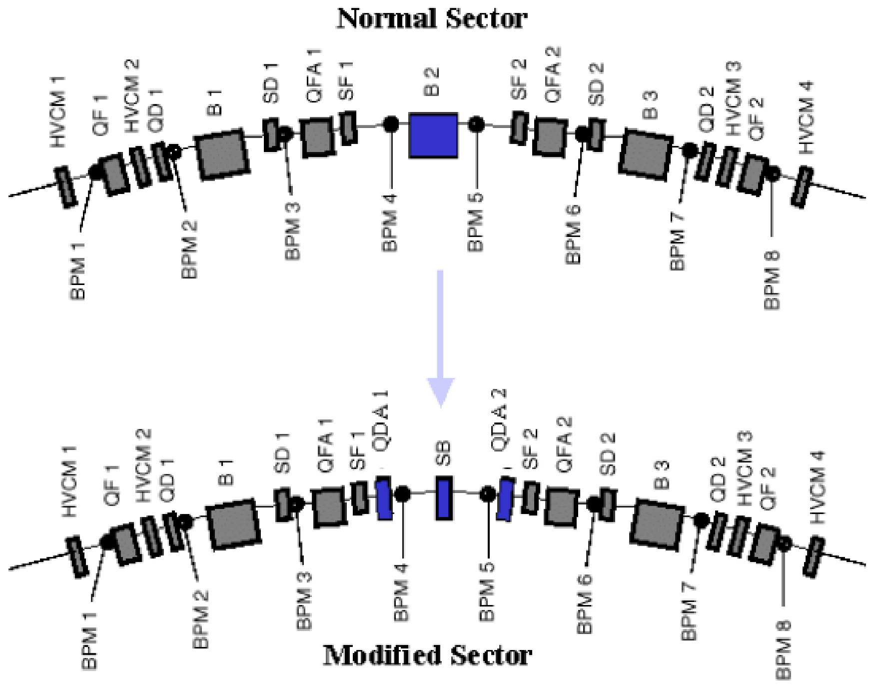
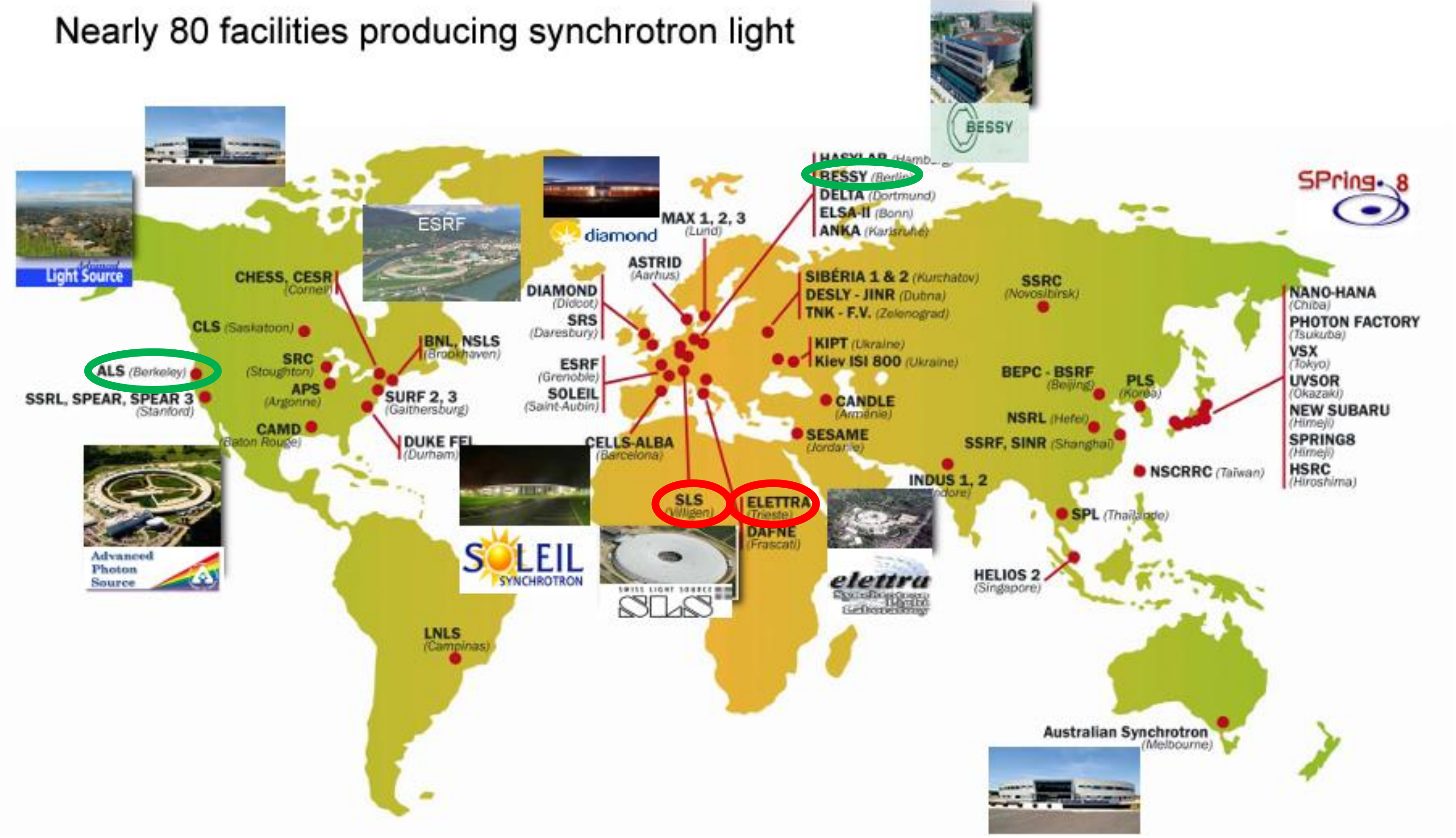


Figure 2: Magnetic layout of a normal (top) and modified (bottom) sector.

SUPERBEND UPGRADE AT THE ADVANCED LIGHT SOURCE D.Robin

Light Sources in the World



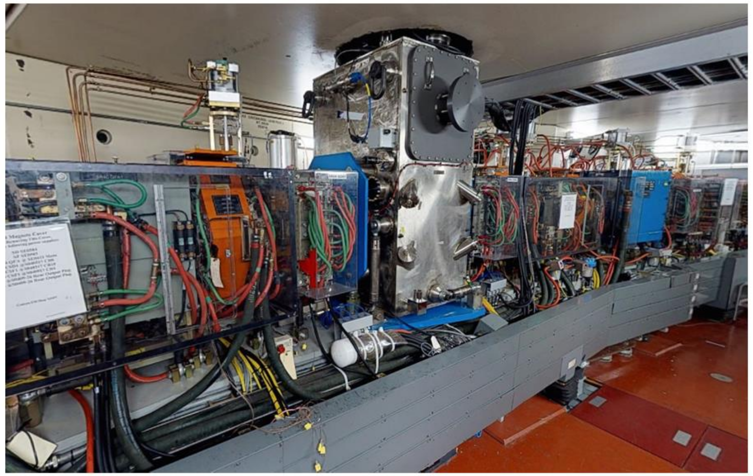
ALS (Berkeley) and BESSY (Berlin) have already installed Superconducting Bending magnets

Elettra (Trieste) and SLS (Villigen) are in the design/production phases for their Superconducting Bending magnets

Laurent S. Nadolski, 60 years of J. Laskar, April 28-30, 2015

LBNL – ASL SuperBend

ALS sector with superbend



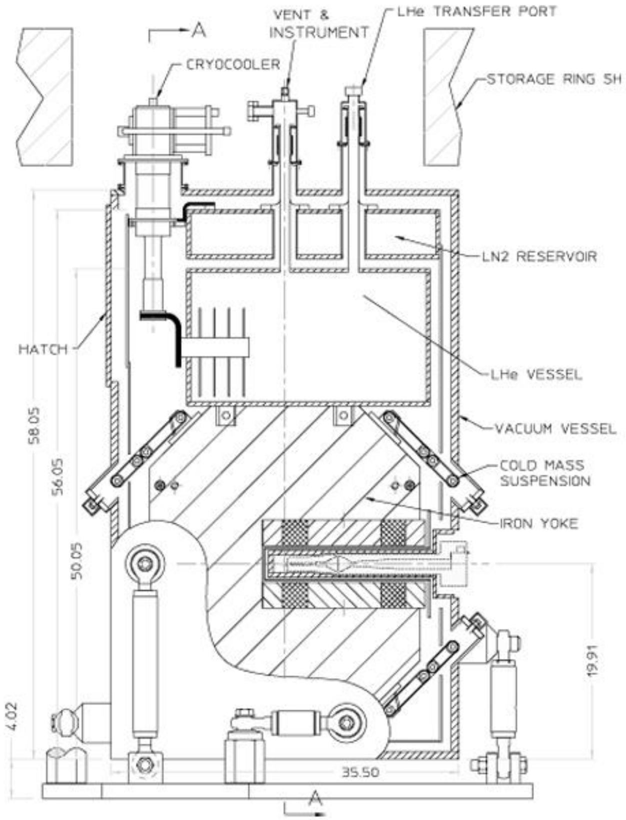


TABLE V
SUPERBEND MAGNET PARAMETERS

Quantity	Value
agnet type	Racetrack windings, iron poles
le length along beam	114 mm
le length transverse to beam	180 mm
rns per layer	33
umber of layers	70
nductor length per coil	1725 m
erating current	291 A at 1.9 GeV
ak field at conductor	6.8 T
action of critical current	0.44 at 4.3 K
ored energy	150 kJ
w-field inductance	11 H
gh-field inductance	3 H
tal cold mass	15 00 kg

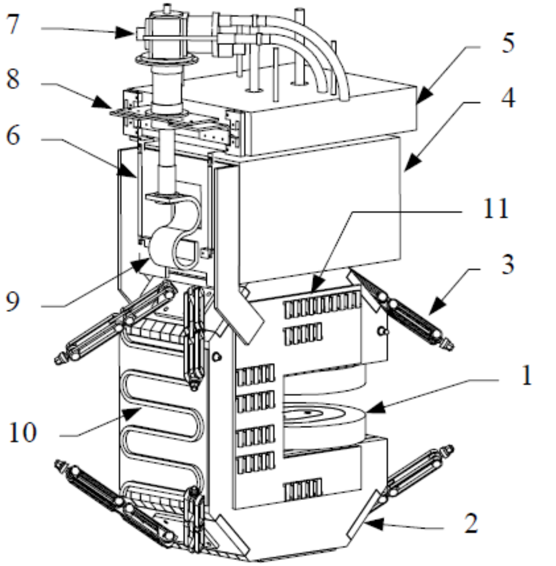


Fig. 1. Superbend cold mass assembly: 1 – superconducting coils with steel poles, 2 – laminated steel yoke, 3 – suspension straps, 4 – LHe vessel, 5 – LN_2 vessel, 6 – HTS leads, 7 – cryocooler, 8 – 50 K thermal connection, 9 – 4 K thermal connection, 10- cooldown tube, 11 – warmup heater.

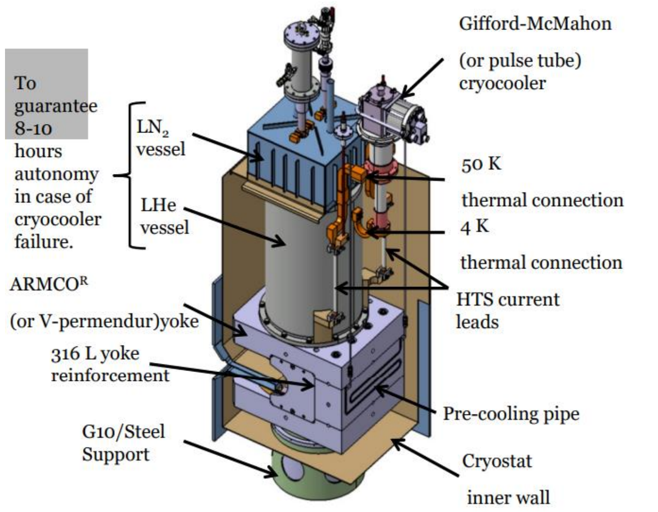
6.8 T on conductor

- Superferric
- Cooled by coldhead in the 4 K range
- Realibility in case of cold head failure

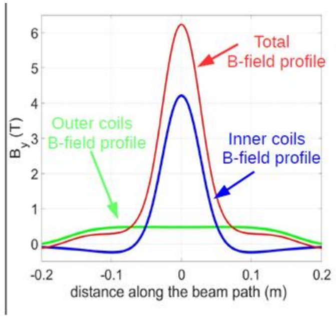
ALS Superbend Magnet System J. Zbasnik (2000)

PSI SLS-2 SuperBend

Superbend main components and parameters



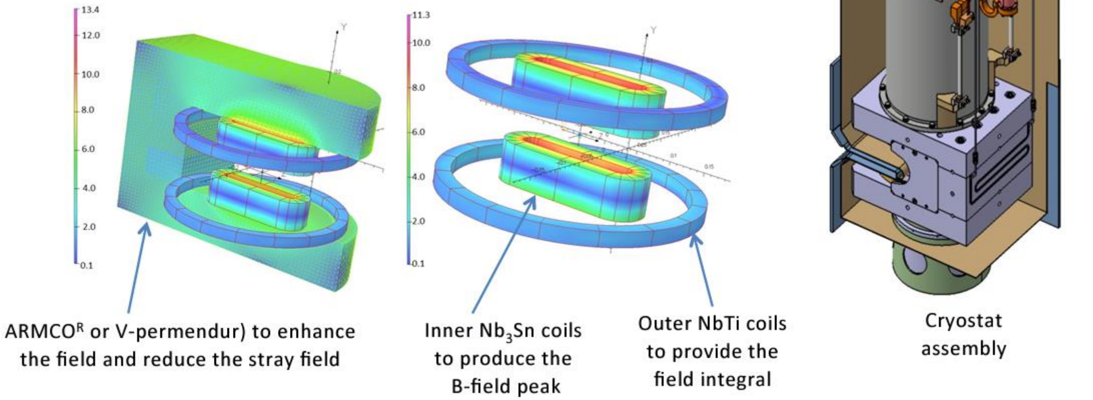
	Outer coils	Inner coils
Conductor type:	Nb-Ti	Nb_3Sn (RRP)
Insulation:	Formvar	S-glass
I_c @ 4.2 K (A)	752 @ 5T	810 @ 12T
Magnetic energy (kJ) (1 coil)	3.8	16.6
Inductance (mH) (1 coil)	50	210
Current per turn (A)	400	400
N. turns (1 coil)	200	1485
Extraction Voltage (V) (τ_{damp}=0.4s)	340	140
Horizontal aperture (mm)		53
Peak field at conductor (T)	2.8	11.3
Peak temperature (K)	4.2	4.3



C. Calzolaio, S. Sanfilippo, A. Anghel, S. Sidorov

Longitudinal gradient superbend

- split racetracks + solenoids
- B-field profile full width half maximum (FWHM): 40-70 mm.
- B-field peak: ≈ 6 T.



A. Streun, PSI   SLS-2: Upgrade of the Swiss Light Source   PHANGS workshop, Trieste, Dec. 4-5, 2017   32/36

Challenges for the magnet projects at the Paul Scherrer Institut – PHANGS workshop (2017)
Stephane Sanfilippo

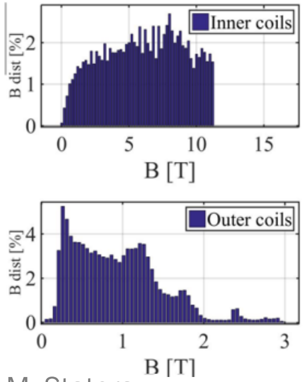
- Superferric
- Cooled by coldhead in the 4 K range
- Realibility in case of cold head failure

Inner coils

50% of the winding pack experiences a field above 6 T

10% of the winding pack experiences a field above 10 T.

Peak field: 11.3 T → Nb_3Sn



Outer coils

50% of the winding pack experiences a field above 0.8 T.

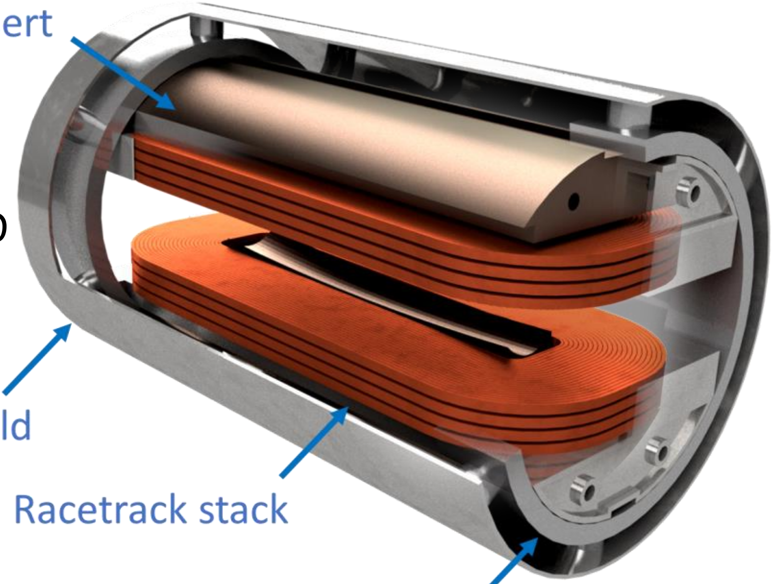
10% of the winding pack experiences a field above 1.7 T.

Peak field: 2.9 T → Nb-Ti

ESMA by IRIS

Energy Saving HTS Magnet for sustainable Accelerators (ESMA)

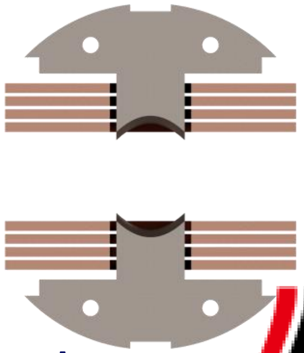
- Scope: superconducting cables test up to 10 T
- **Deliverale: 10 T – 70 mm aperture HTS conduction cooled dipole** operating @ 10-20 K conduction cooled by coldheads
- Goal: increase of the TRL for 15 T – 20 K magnets for FCC and Muon Collider



S. Sorti and L. Balconi
Univ. of Milano & INFN-LASA

Iron contribution about 1 T – Field quality to be optimized

Parameter	Unit	Value
Central field	tesla	10
Free bore dimensions	mm	H80 x V50
Magnet length	mm	1000
Good field region uniformity	N/A	1.5%
Good field region extension	mm	H50xV30xL400
Operating temperature Minimum op. temper. for test	K K	20 10
Maximum current	A	<1000



Innovative Research infrastructure on applied Superconductivity

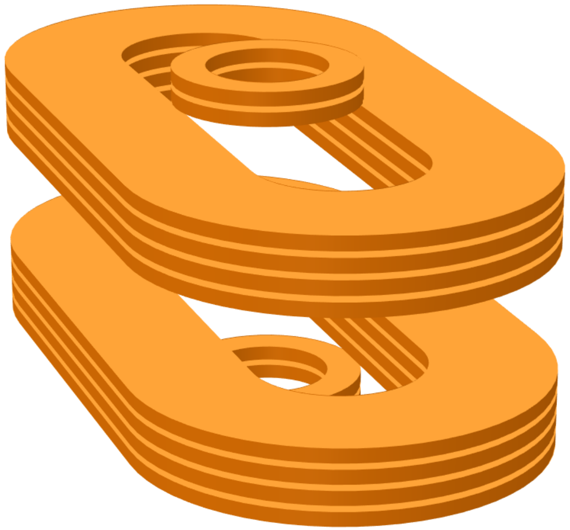
Procured by LASA
Installed in INFN Genova

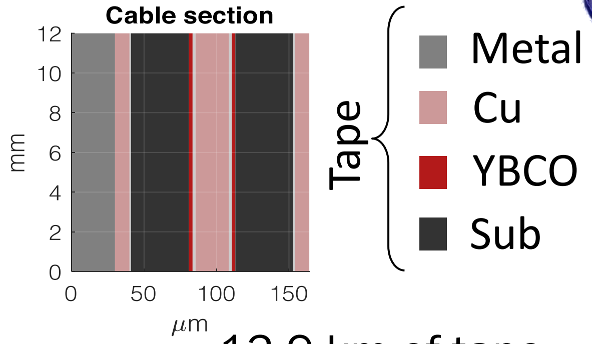
Dimensions	12 mm × 67 µm
Substrate	40 µm of Hastelloy C276
Copper stabilizer	2 × 10 µm, RRR>20
Easy-way minimum bend	10 mm
Allower longitudinal strain	-0.4 % to 0.3 %
I_c, 77 K, self-field Ic, 20 K, 15 T	Min. 400 A, average 470 A Min 500 A

Tape procured by LASA: 15 km of 12 mm by FARADAY

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

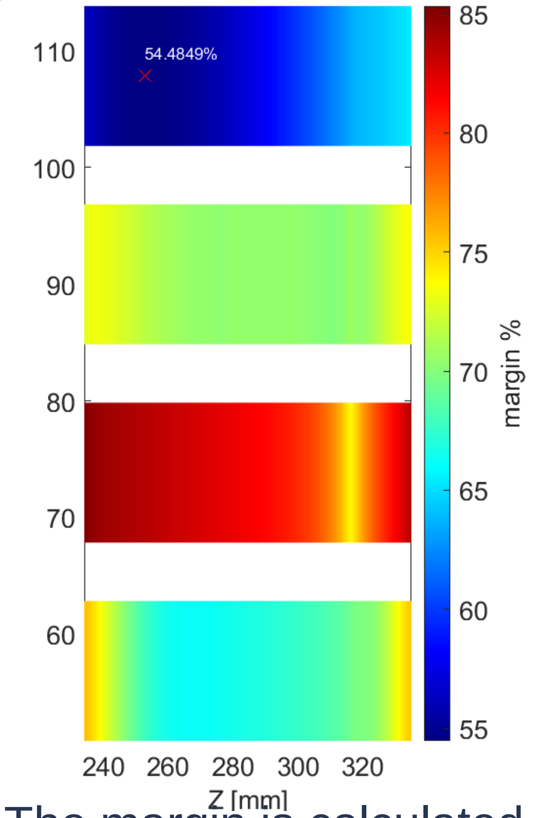
Actual design



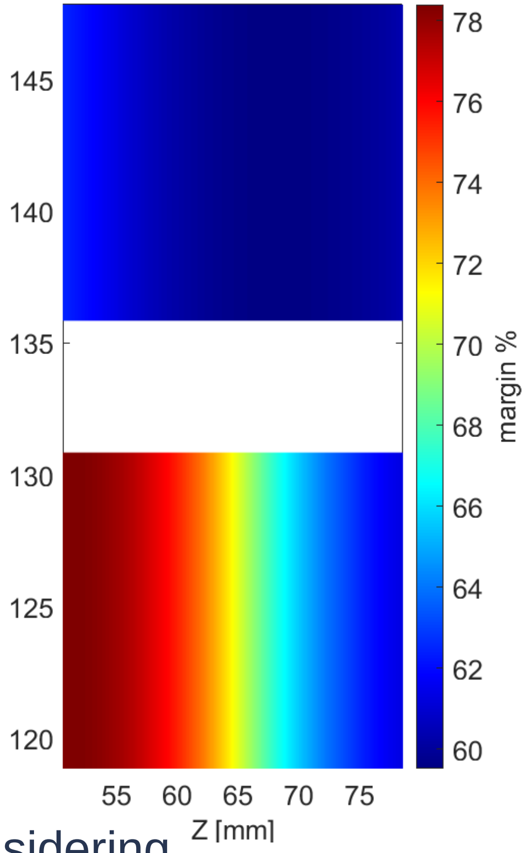


~13.9 km of tape

Racetrack coils margin



correction coils margin



Central field B_0	tesla	10
Minimum central field B_{0min}	tesla	8
Free aperture	mm	Ø70
Good field region uniformity	N/A	±1.5%
Good field region extension	mm	H50xV30xL350
Operating temperature	K	20
Operating Current	A	810

The margin is calculated considering Temperature and field angle
For safety this calculation includes the case of a 100% current sharing between the tapes.

HL-LHC

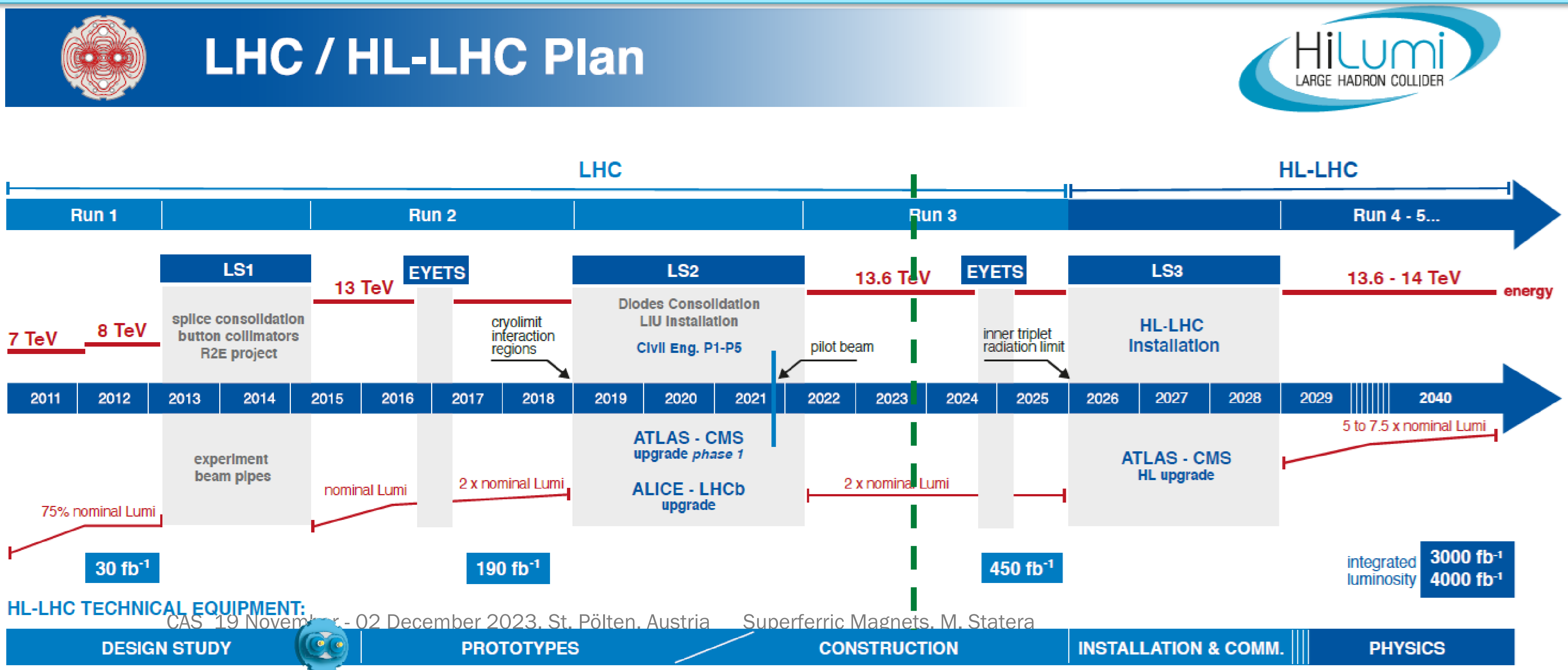
The main objective of HiLumi LHC Design Study is to extend the LHC lifetime by **another decade** and to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1} twelve years after the upgrade.**

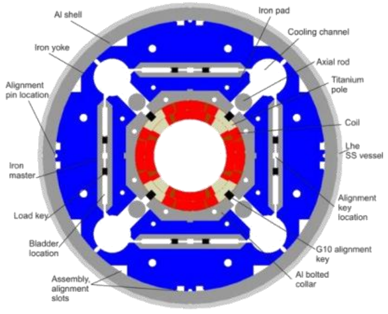
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Courtesy of O. Brüning –Project Leader

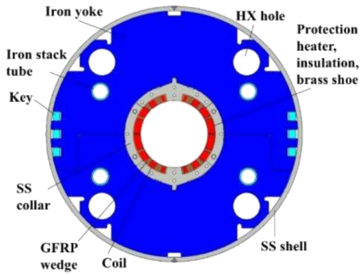


HO Corrector Magnets Zoo

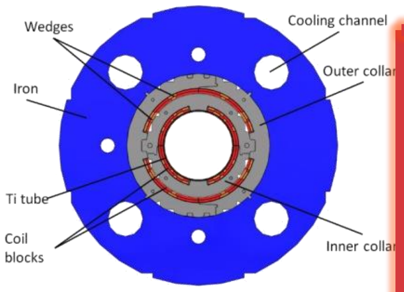
Courtesy of E. Todesco



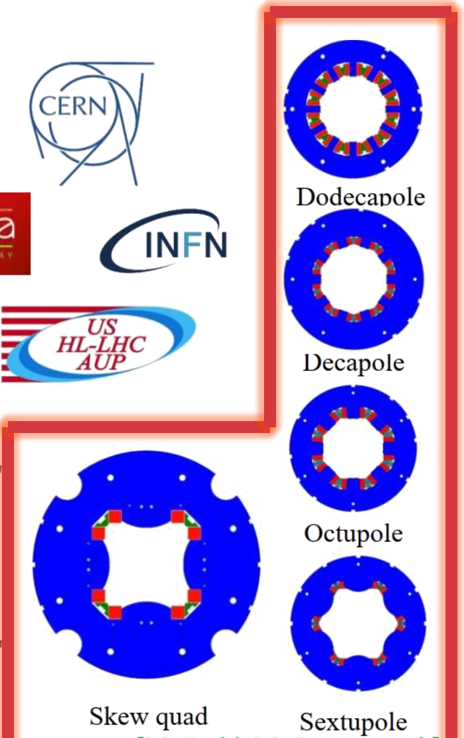
Triplet [G. Ambrosio, P. Ferracin et al.]



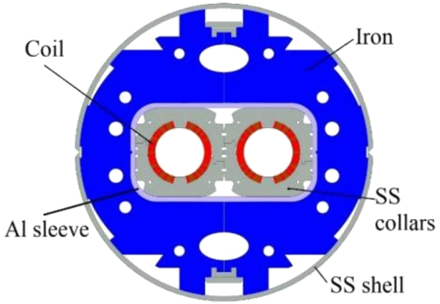
D1 [T. Nakamoto, et al.]



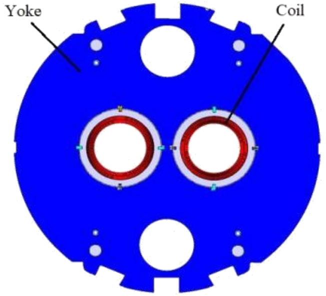
MCBXF [F. Toral, et al.]



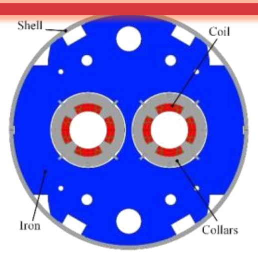
[M. Sorbi, M. Statera, et al.]



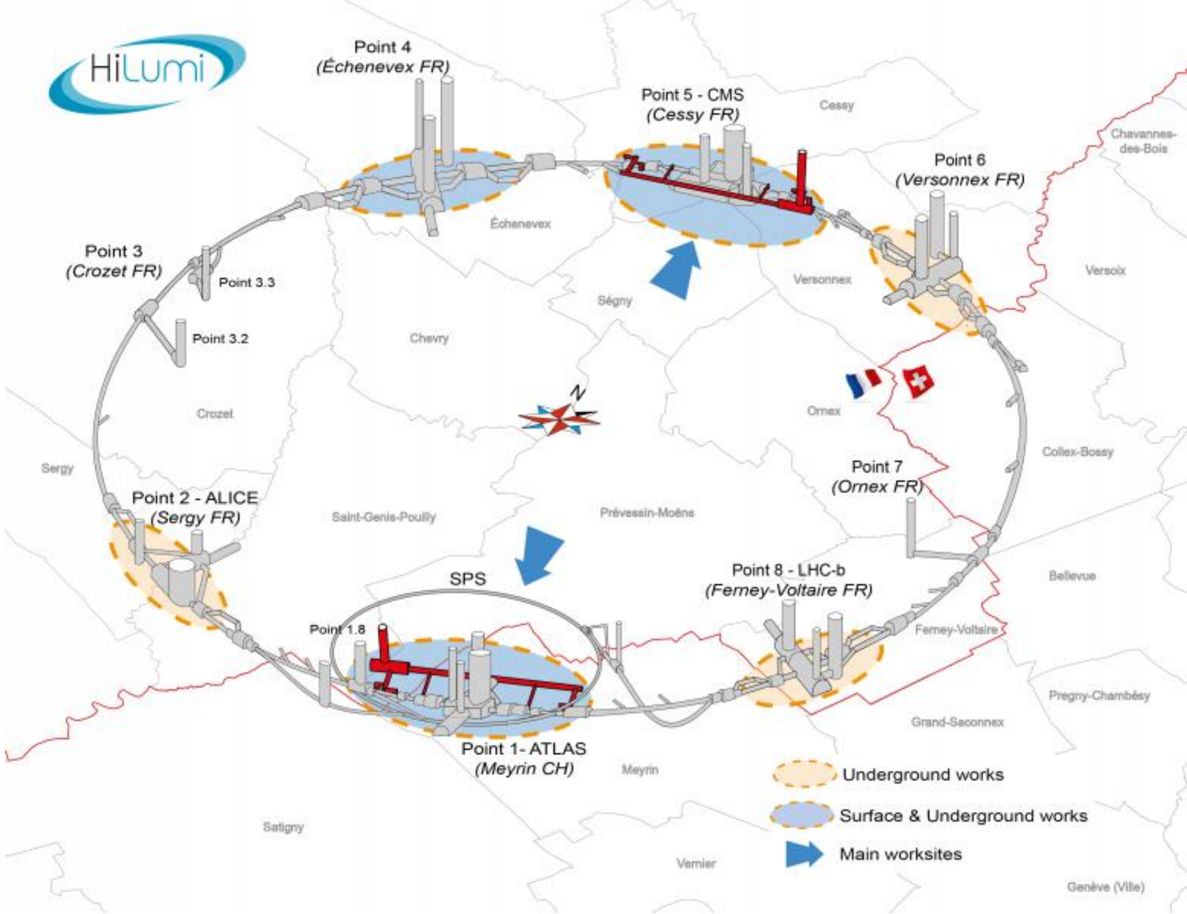
D2 [P. Fabbricatore, S. Farinon, et al.]



D2 correctors [G. Kirby, Q. Xu, et al.]

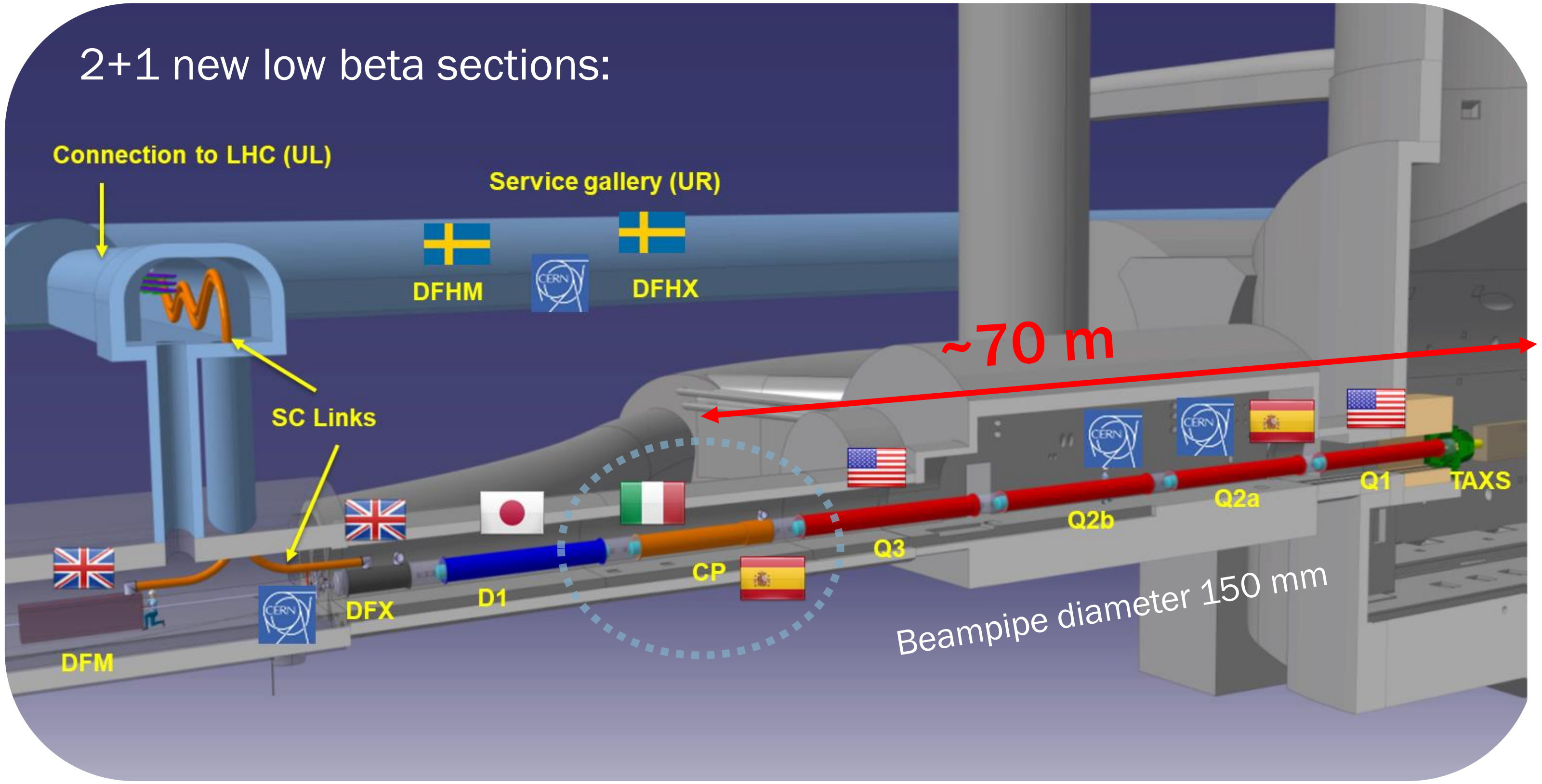


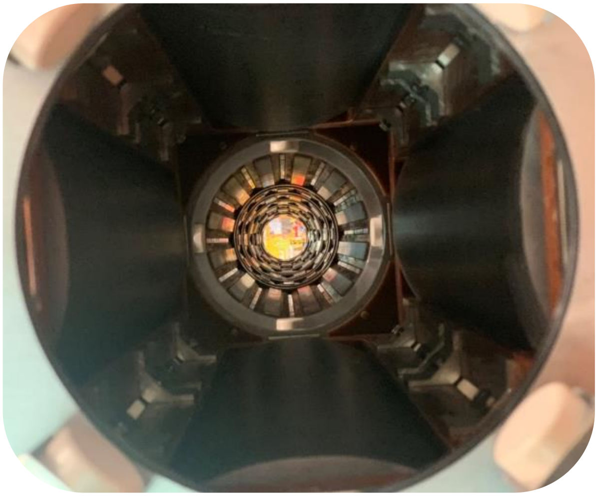
MQYY [H. Felice, et al.]



Courtesy of CERN

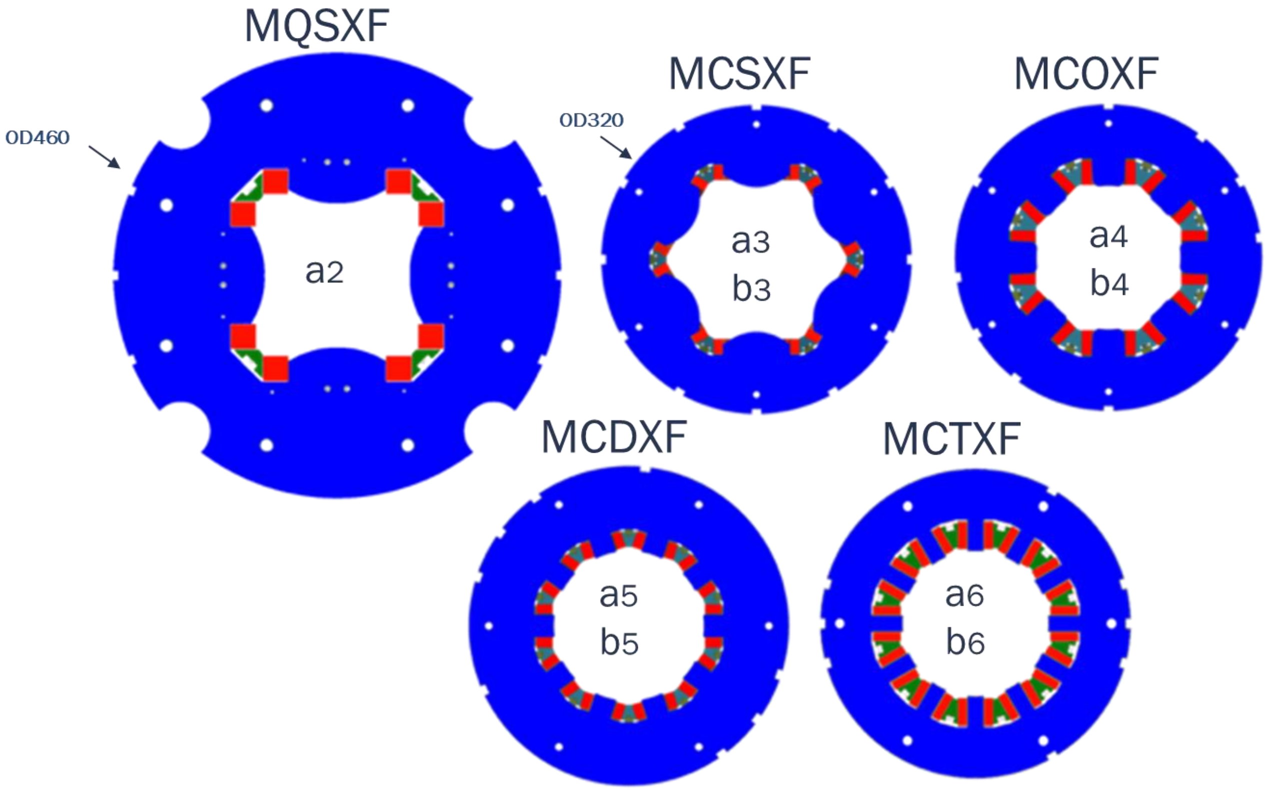
The low beta section

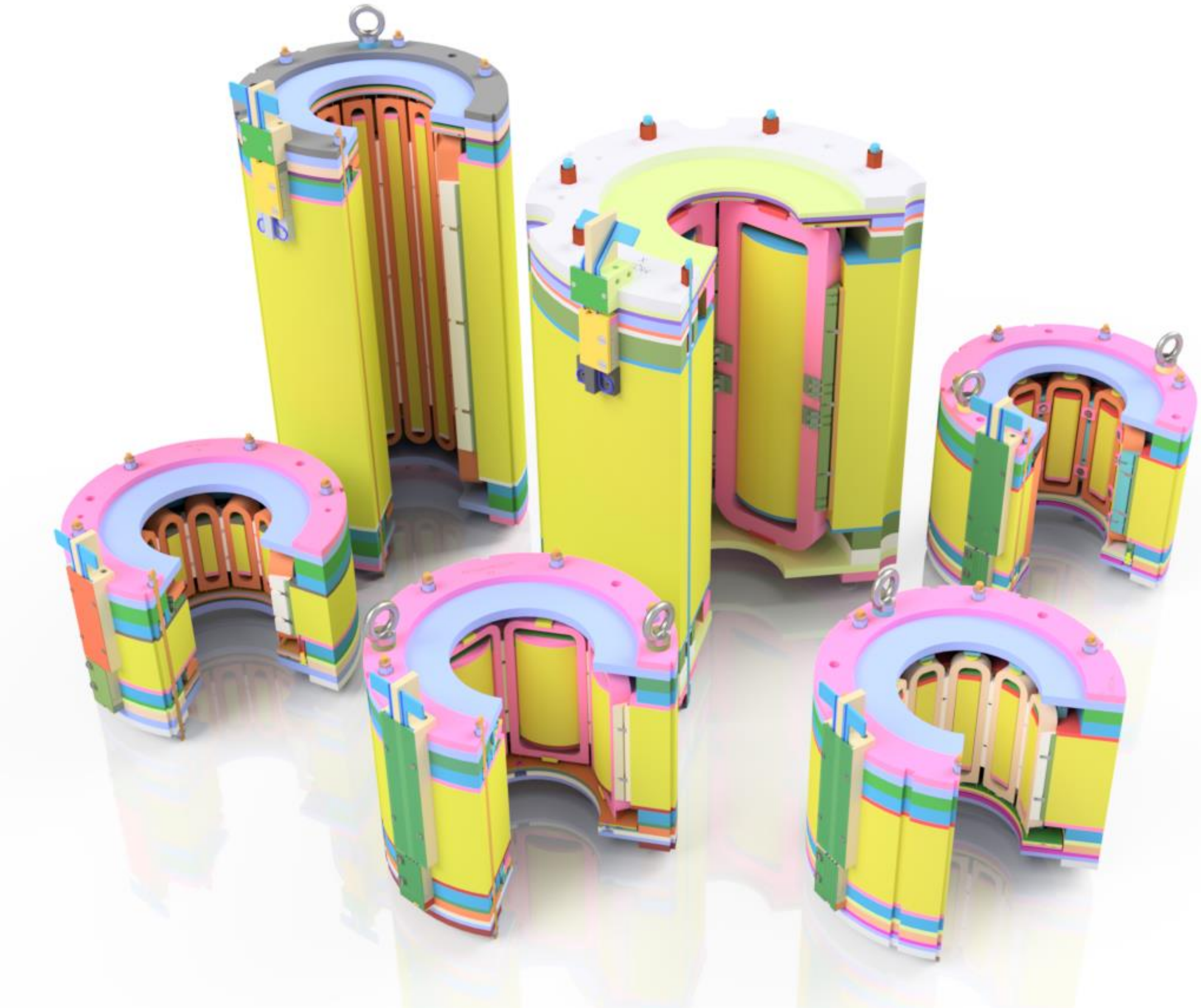




- The High Order Correctors have to provide integrated field and to be as compact as possible
- First superferric magnets in LHC
- In the actual configuration about 3.5 m

HO Corrector Magnets Zoo





NbTi SuperFerric design
Geometrical lengths: 200 mm - 580 mm
Quench protection: no energy extraction (but 4P)
60% margin @ 1.9 K

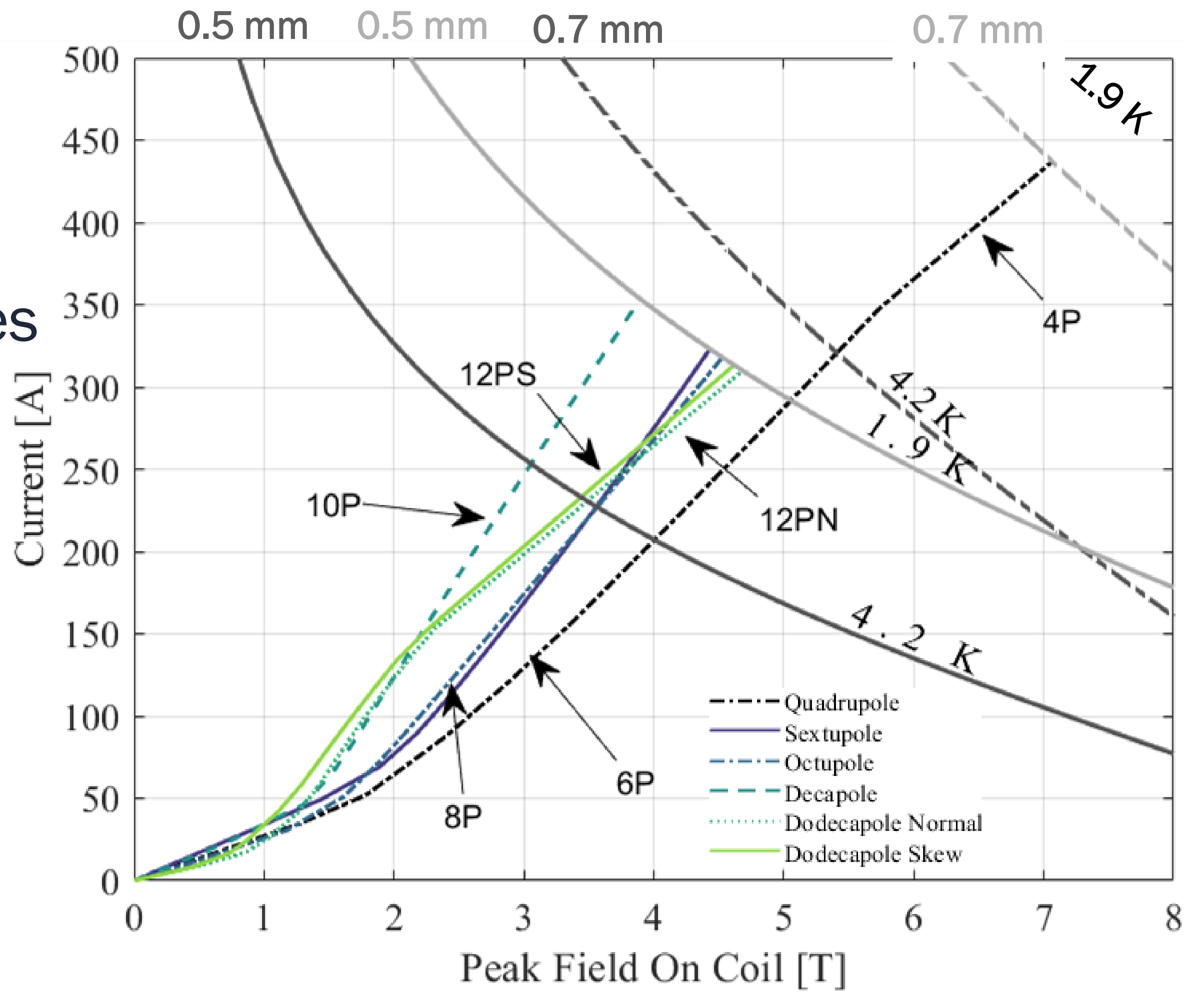
F. Toral et al., EPAC 2006 and CERN–2014–005 (CERN, Geneva, 2014)
G. Volpini et al., IEEE Tr. Appl. Sup, VOL. 26, NO. 4 (2016)

Loadlines

NbTi superconding coils
- Racetrack
- Insulation by S2 glass reinforced material

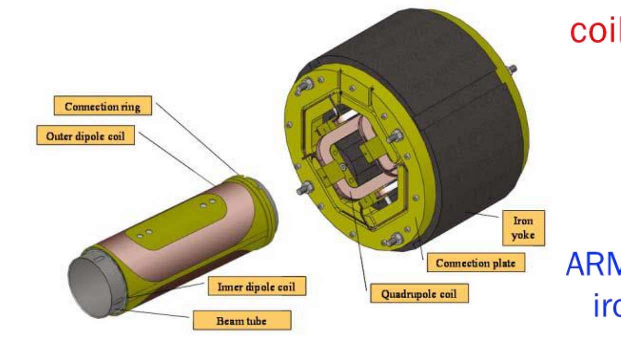
Superferric design
- Compact and modular
- Strong contribution of the iron poles
- Field quality influenced by the shape of the poles

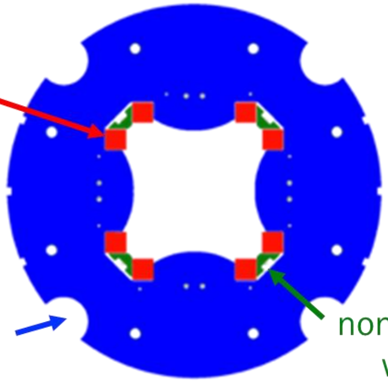
Magnet	Type (normal/skew)	Integral field at r=50 mm	Magnetic Length	Coil Peak Field	Magnetic stored energy @Iult	Operating Current	Ultimate current	Turns per coils	Ic @ 4.2 K	Margin @1.9K
		T·m	m	T	kJ	A	A	-	A	%
Quadrupole (4P)	S	0.700	0.401	3.53	36	174	197	754	315	57.1
Sextupole (6P)	N,S	0.064	0.168	2.14	1.2	99	112	280	225	>60
Octupole (8P)	N,S	0.046	0.145	2.06	1.1	102	115	372	230	>60
Decapole (10P)	N,S	0.026	0.145	1.73	0.5	92	106	228	256	>60
Dodecapole (12P)	N	0.086	0.469	1.44	7.8	85	97	436	233	>60
Dodecapole (12P)	S	0.017	0.099	1.44	~0.9	84	94	436	230	>60



pole shape

Relaxed field quality 100 U
Need for compact magnets
Inner diameter 150 mm

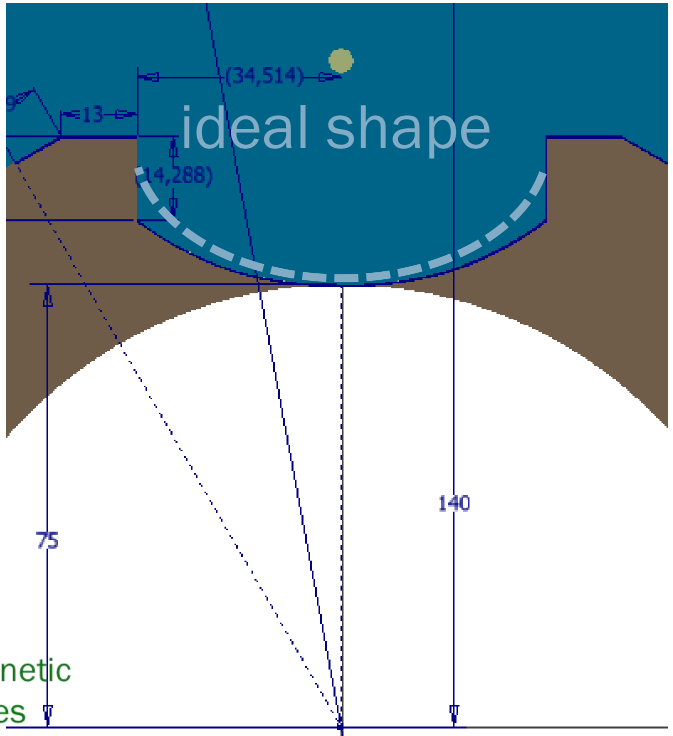




The design is based on the studies by Toral et. al on superferric magnets for Free Electron Lasers (XFEL)

Toral et al. EPAC 2006

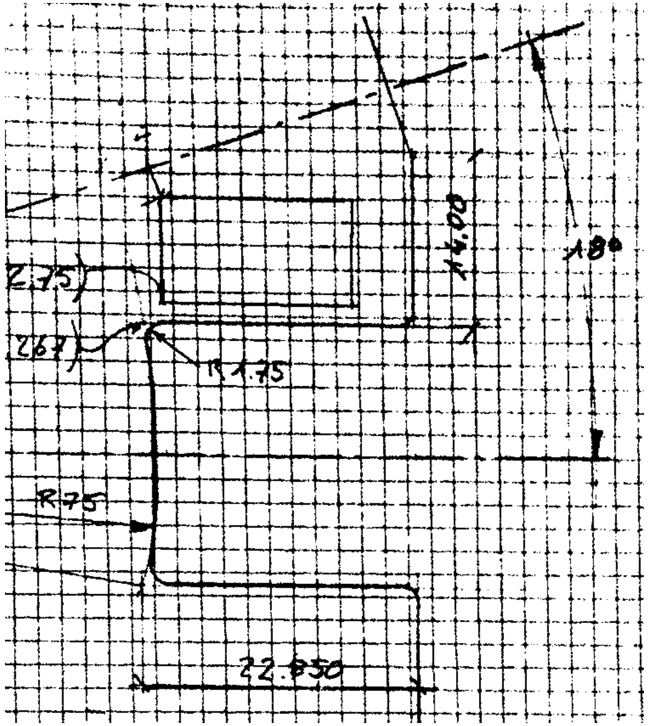
modifed ideal
n= 2; 3



Quadrupole simple increase of thickness at the sides of the pole

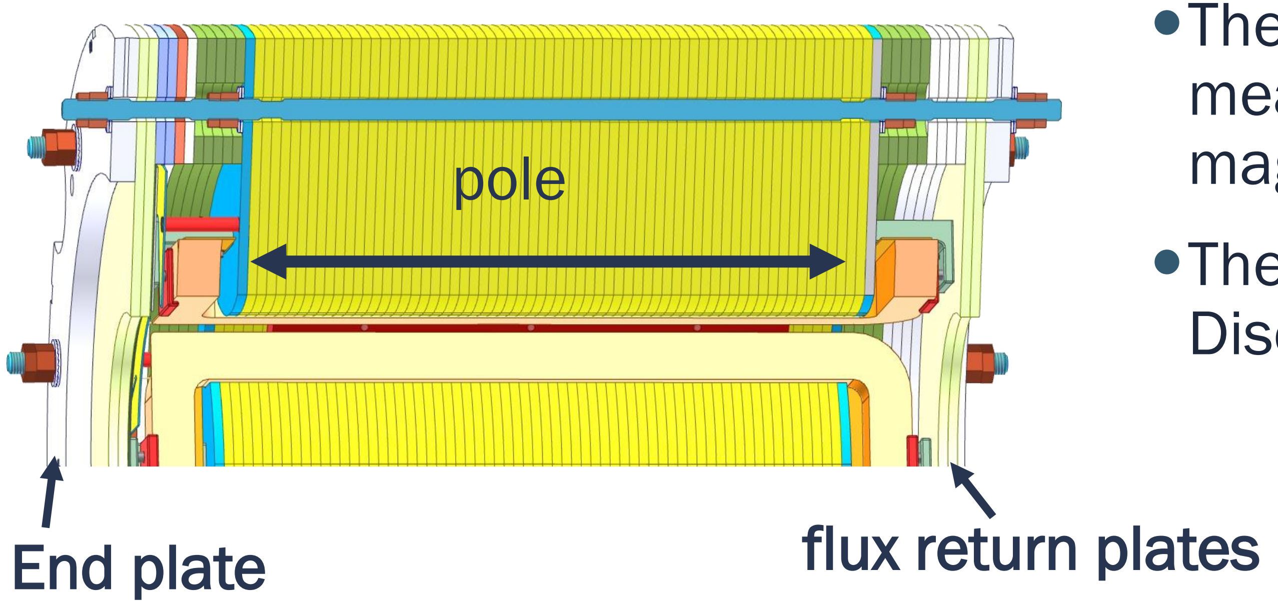
Sextupole ideal pole shape

maximum area
n > 3



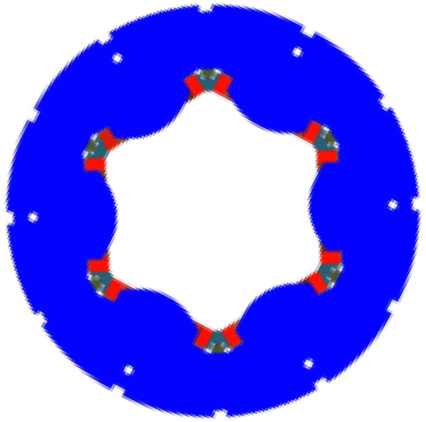
As much as possible iron area in the pole

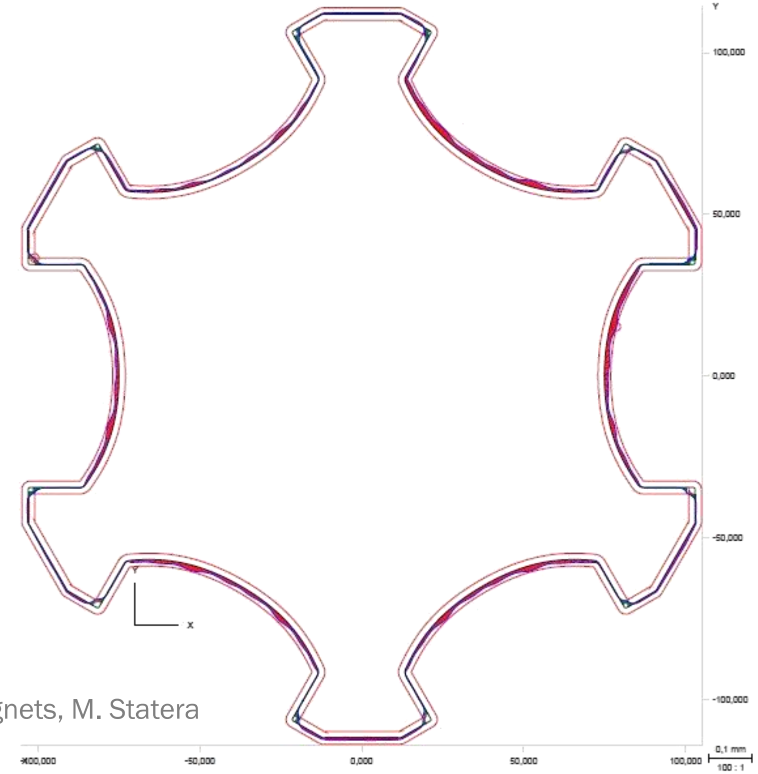
Mechanics



- The shape of the pole is extensively measured with high accuracy to quarantee magnetic performance
- The outer alignment slots are also Electrical Discharge Machined (EDM) and measured

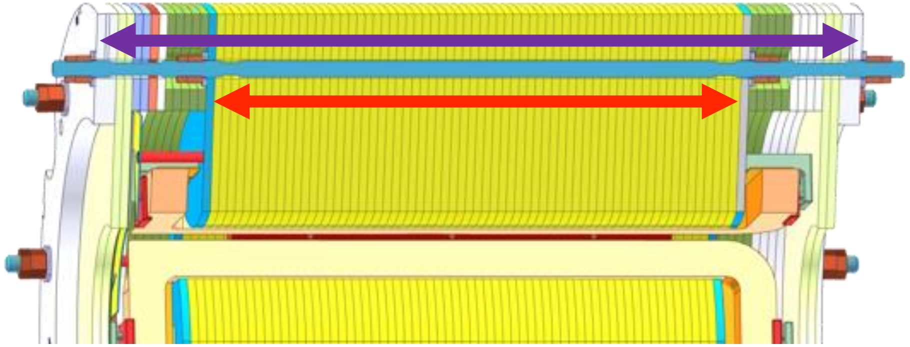
Fringe field is reduce by radial iron and flux return plates
Compactness of single magnets
Lower distance between magnets





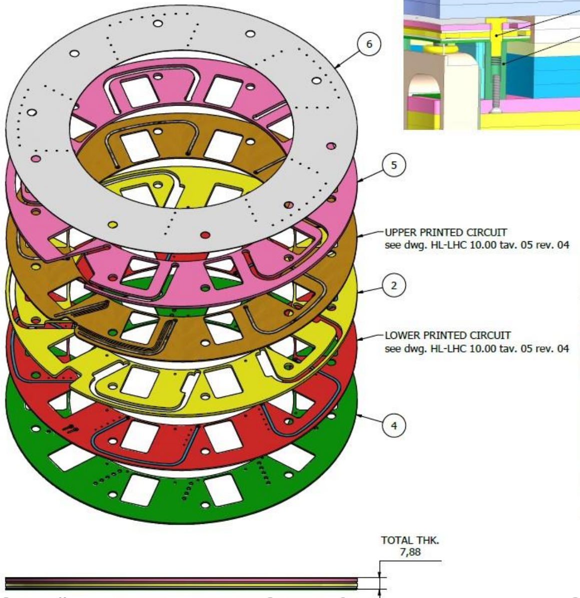
Preload

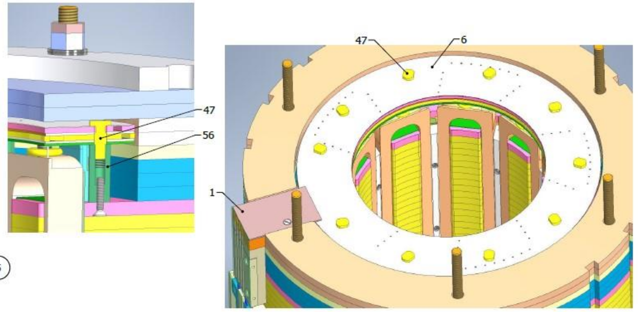
Handling at room temperature

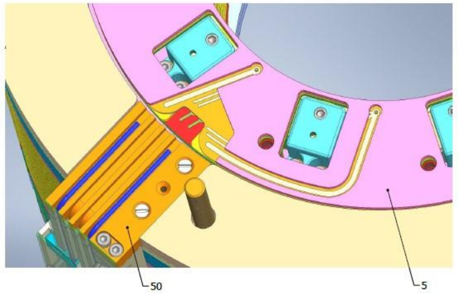


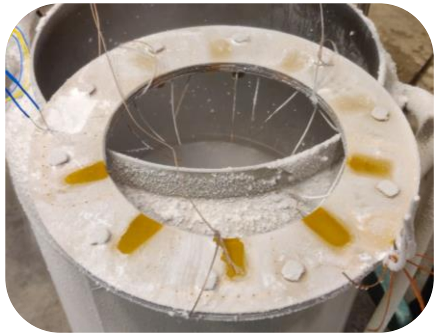
Longitudinal prestress on iron

- Avoid lamination movements during transportation (2.5 g MAX) handling and installation
- 1D model
- Two step prestress (pole and full magnet)
  - CuBe rods (high yeld stress) to increase preload at cold
  - A fix the pole
  - B pack the magnet









- Tolerances
  - Electrical connections mechanically protected
  - Several custom components
  - Mechanical tolerances may create interference at room temperature

Preload

Coils in place at cold

The coils are supported by wedges and longitudinal prestress on plates

The force on coils is a function of the order

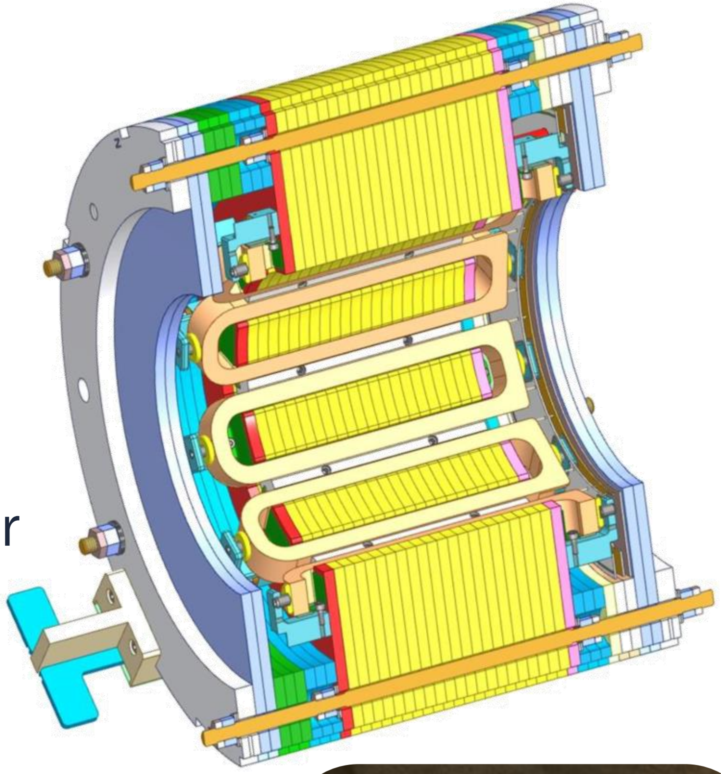
Simplified models and 2.5D simulations have been developed

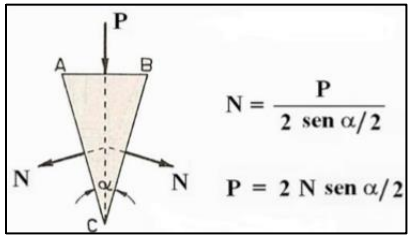
Prestress on coils

Aim guarantee contact at cold and low as possible stress on coils to avoid damages

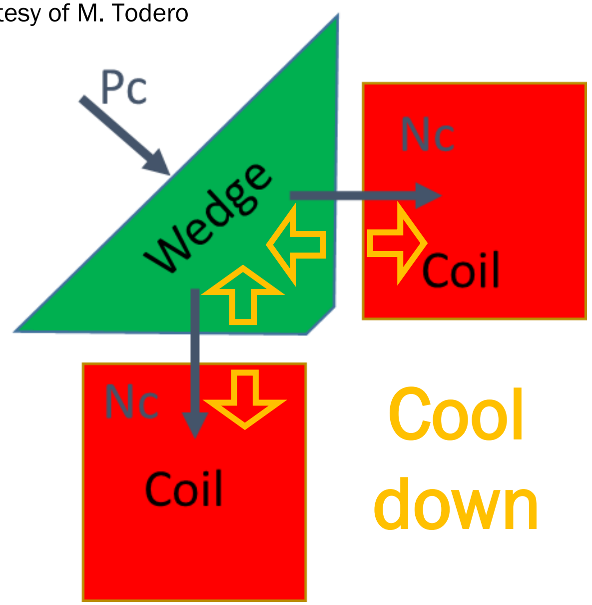
Beware of mechanical tolerances

Goal lower stress may reduce the training





Courtesy of M. Todero



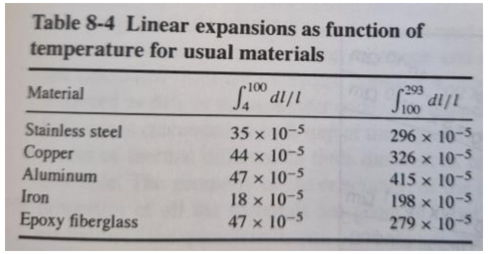


Table 8-4 Linear expansions as function of temperature for usual materials

Material	$\int_4^{100} dl/l$	$\int_{100}^{293} dl/l$
Stainless steel	35×10^{-5}	296×10^{-5}
Copper	44×10^{-5}	326×10^{-5}
Aluminum	47×10^{-5}	415×10^{-5}
Iron	18×10^{-5}	198×10^{-5}
Epoxy fiberglass	47×10^{-5}	279×10^{-5}

Handbook of cryogenic engineering, J.G. Weisend II

Preload

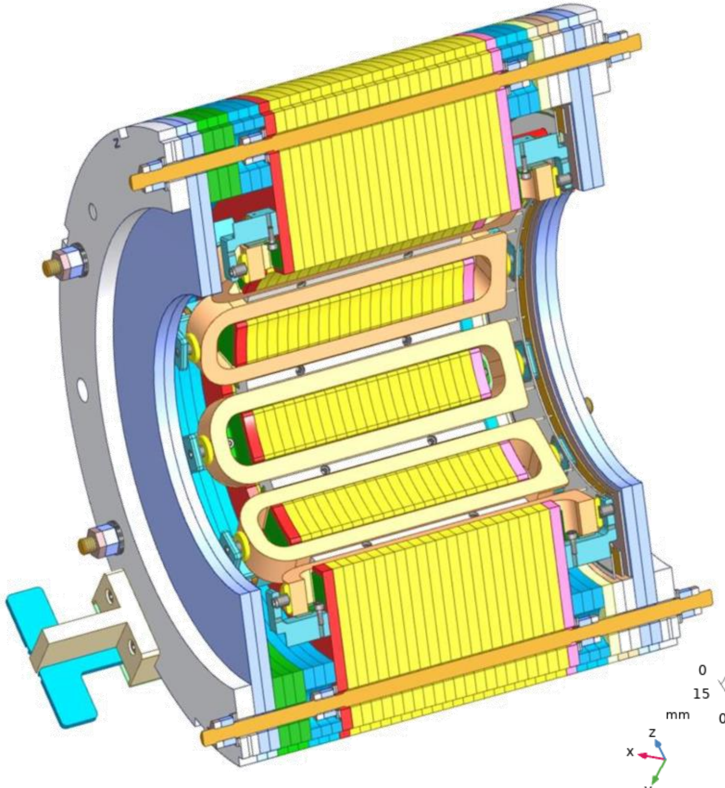
The output are the toques to be applied during assembly

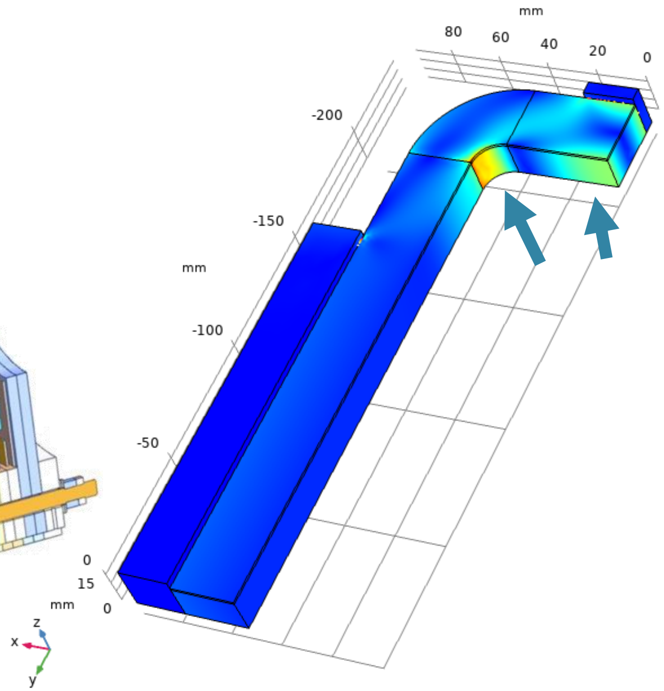
Longitudinal

- 1D model plus 2.5D model
- Differential contraction between Iron laminations and coil-supports-screws

Wedges prestress

- Avoid coils movements/falling
- Use the elasticity of each coil family
- 2D model
- 2.5 D model

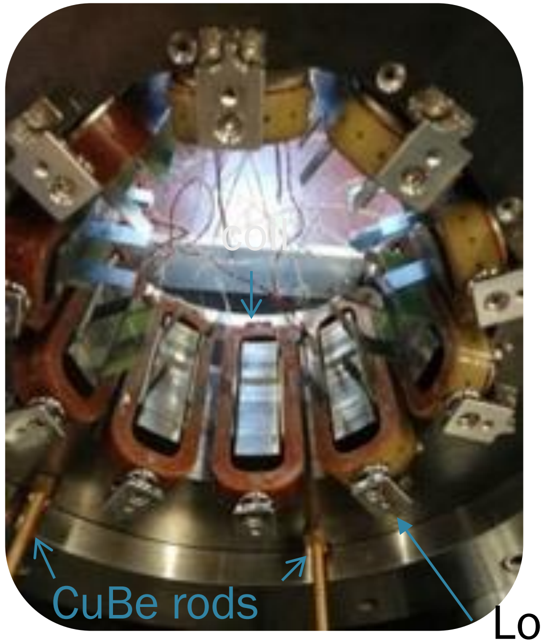




Magnet	torque [n. x Nm]	range [Nm]	Tools 1 range 0.20-0.50 Nm 2 range 0.50-2.00 Nm	Calculated Torques [n. x Nm]
4P	2 x 1.00	0.94-1.06	2	2 x 0.8
6P	2 x 0.44	0.40-0.48	1	2 x 0.2
8P	2 x 0.55	0.52-0.58	2	2 x 0.25
10P	2 x 0.35	0.32-0.39	1	2 x 0.20
12P S	2 x 0.49	0.45-0.53	1	2 x 0.35
12P N	2 x 0.31	0.28-0.34	1	2 x 0.20

HOC ASSEMBLY

alignment frame

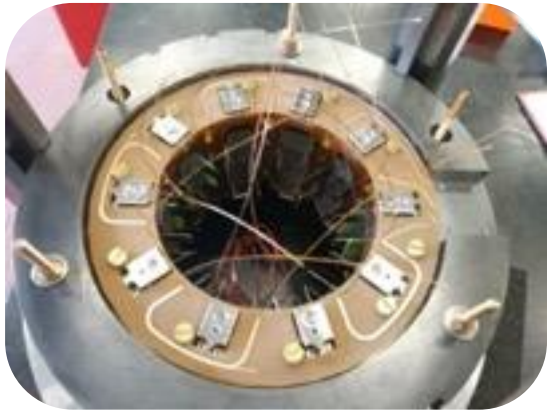


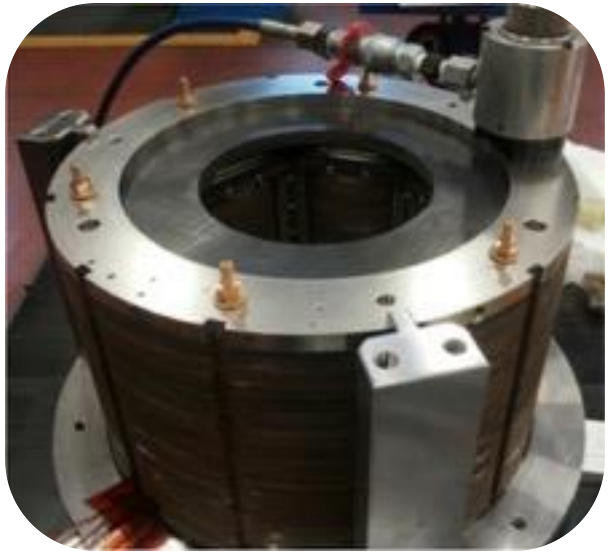
Longitudinal support

Coil technology and magnet assembly procedure have been developed at LASA
Developing and transfering and QA are key point to pursuit reproducible results

- Procedure developed at LASA on prototypes
- 6P, 8P, 10P assembled at LASA
- 12P and 4P assembled in industry

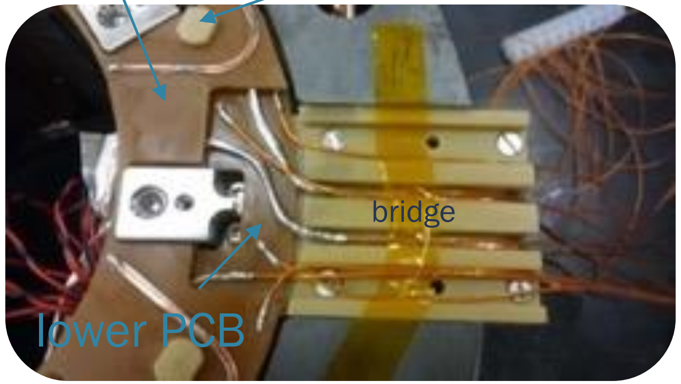
wedge





upper PCB

PCBs fixing



Quench Protecion

LASA Quench Protection

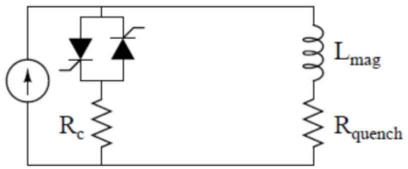
- ENERGY EXTRACTION by dump resistor
- Threshold 200 mV
- Validation time 20 ms

Protection in LHC – no energy extraction (except the quadrupole)

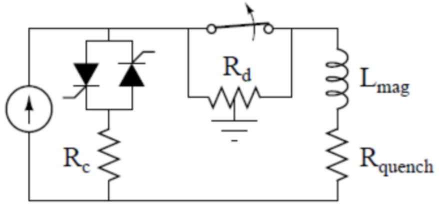
- Measuring current
- Time range 60-180 ms
- Max current: ultimate current (up to 114 A)

Tests at LASA – R dump = 0

- Quech induced by heater (and AlN insert)
- Increase validation time
  up to 180 ms at ultimate current

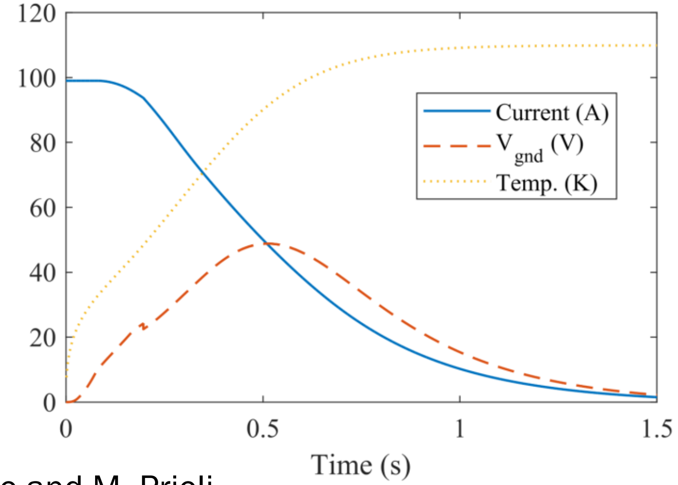


Simplified schematic of the protection circuit applied to the other corrector magnets (6p, 8p, 10p, 12p (N), 12p (S)). From left to right: power converter, crowbar, magnet.

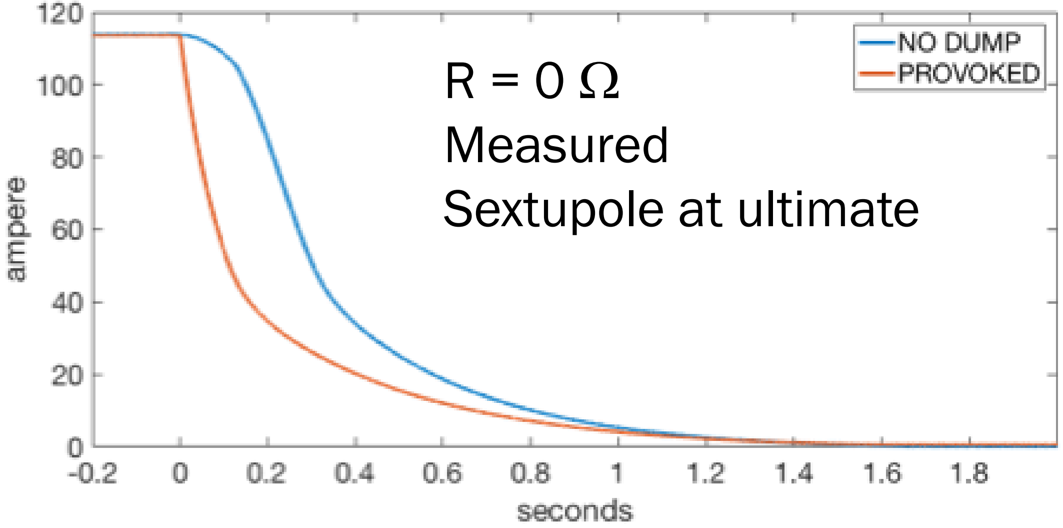


Simplified schematic of the protection circuit applied to the quadrupole magnet (4p), Dump resistor

Sextupole at nominal

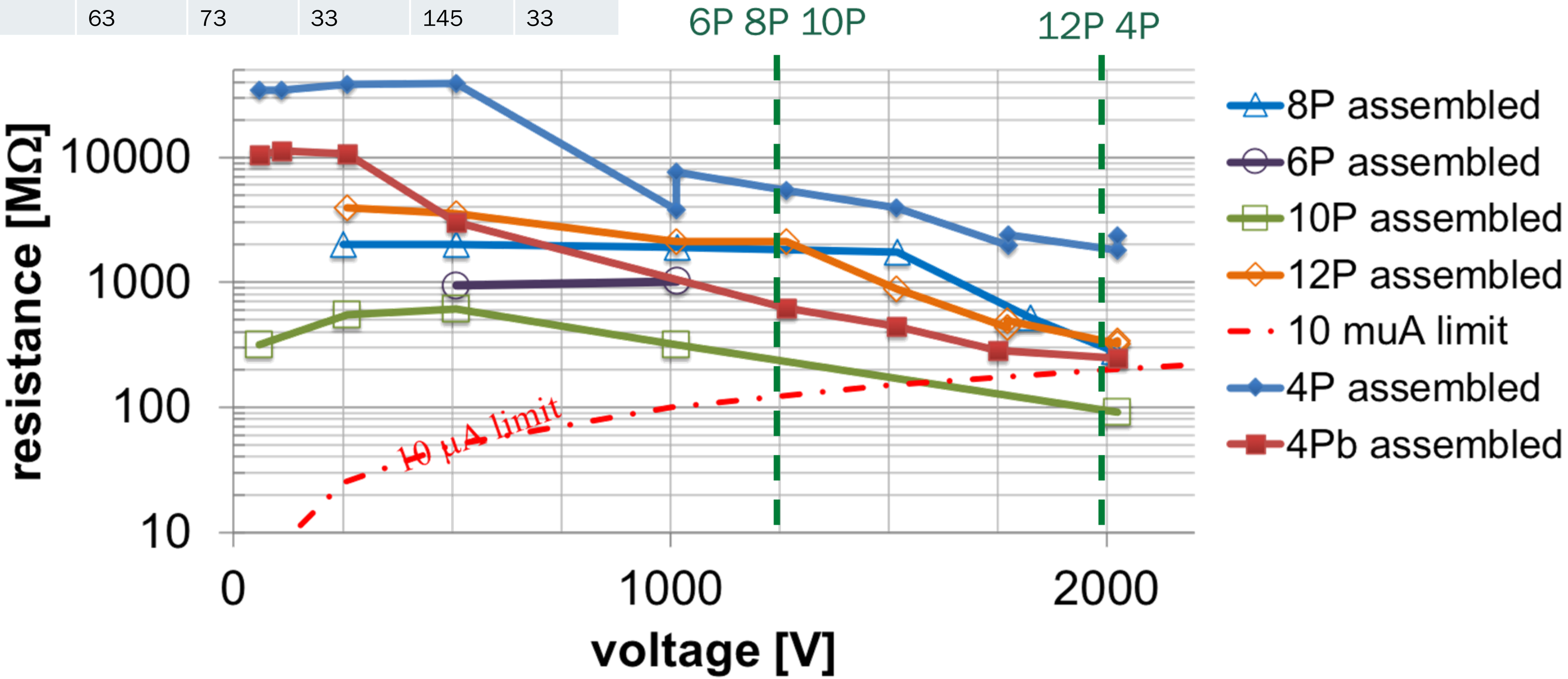


Courtesy of S. Mariotto and M. Prioli

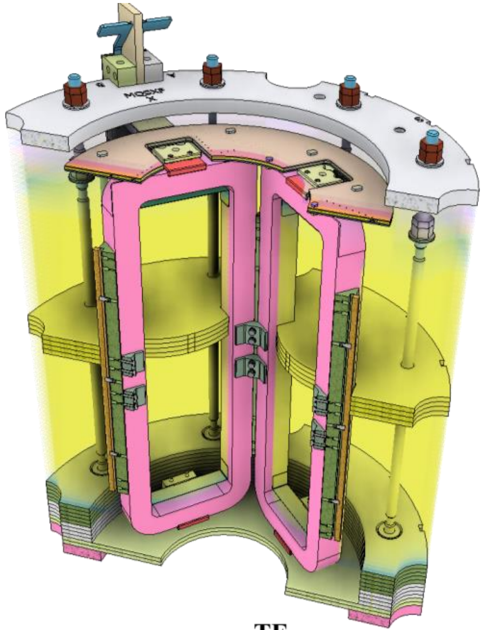


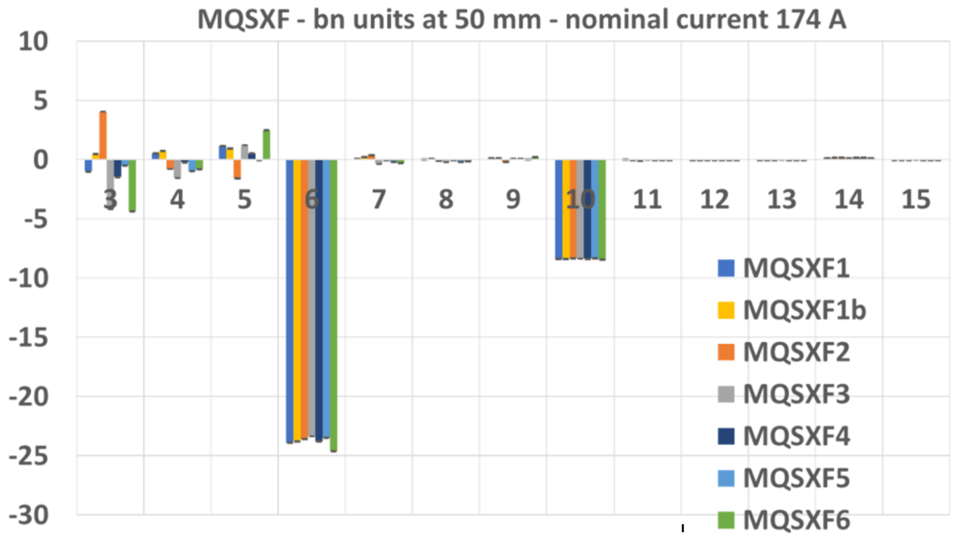
Protection

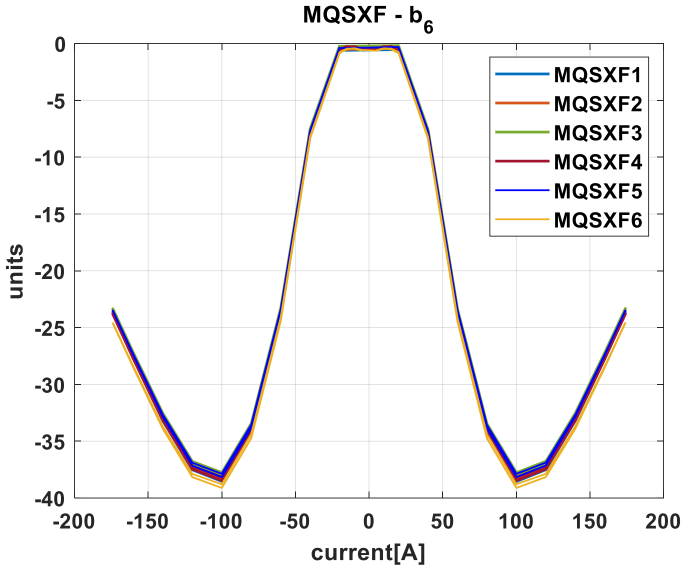
Magnet	MCSXF	MCOXF	MCDXF	MCTXF	MCTSX F
Magnet Order	6p	8p	10p	12p (N)	12p (S)
T_{max} (K)	122	121	99	112	98
$V_{gnd, max}$ (V)	63	73	33	145	33

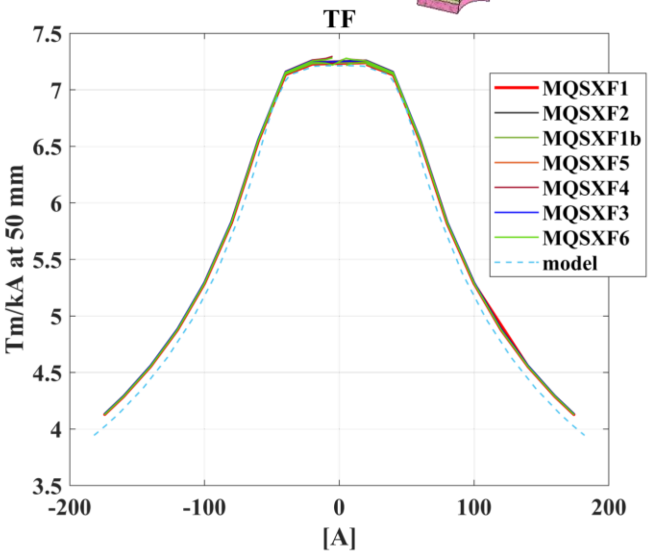


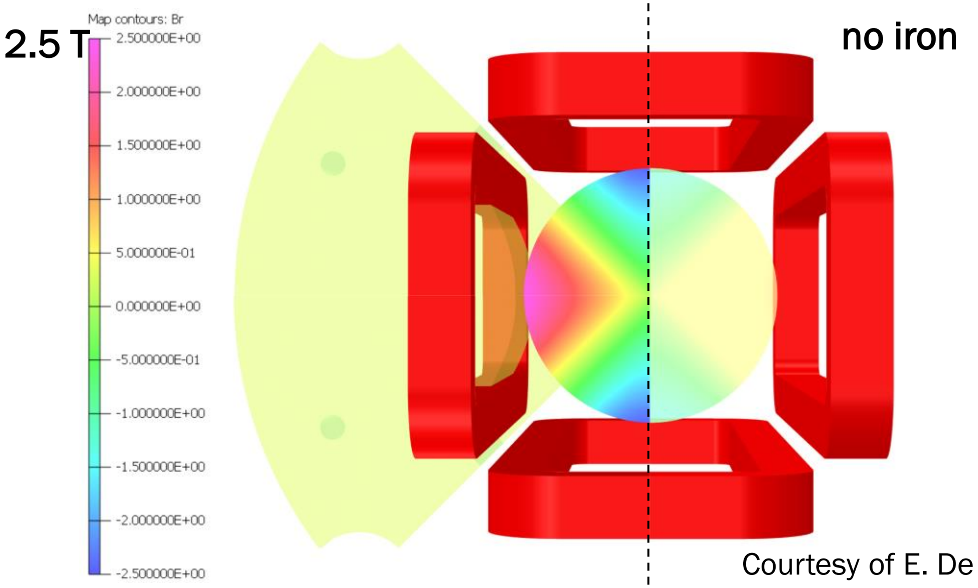
Skew Quadrupole Family Field Quality



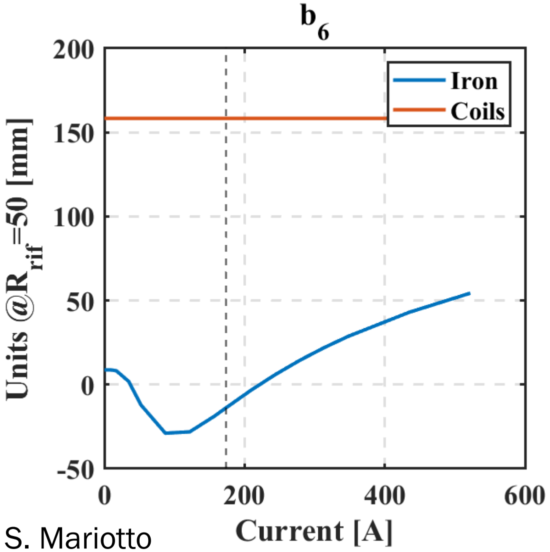






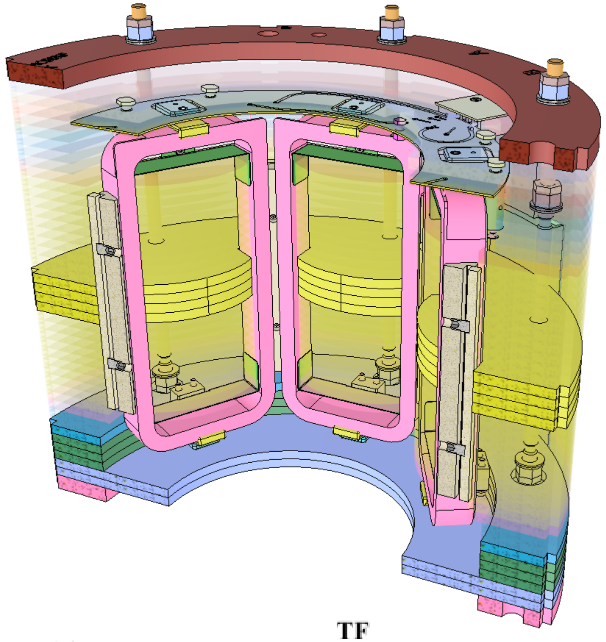


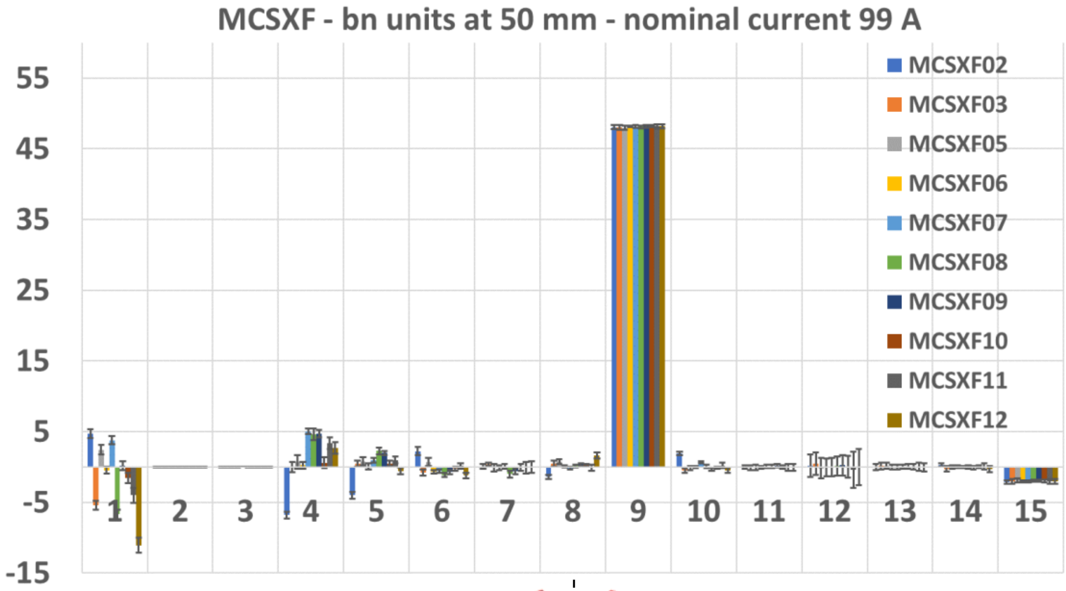
Simulation

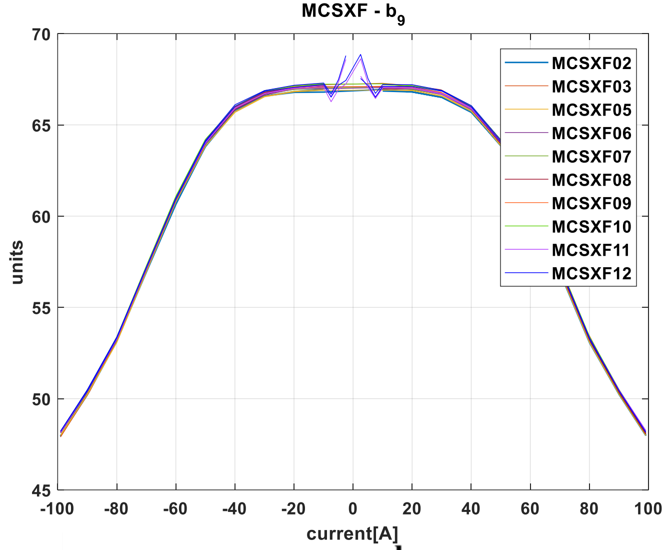


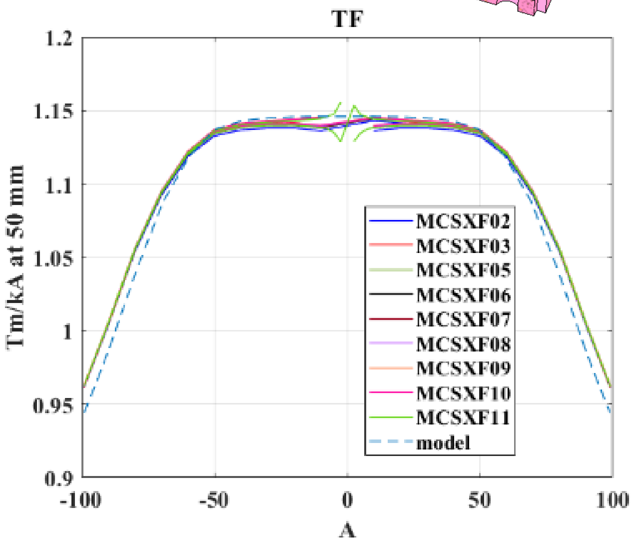
Courtesy of E. De Matteis and S. Mariotto

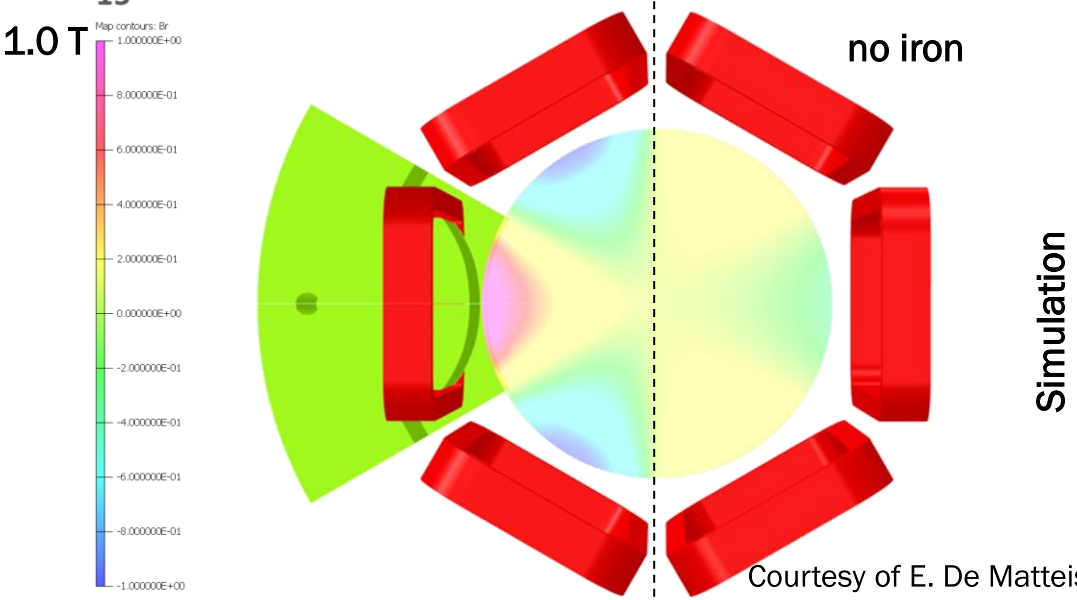
Sextupole Family Field Quality

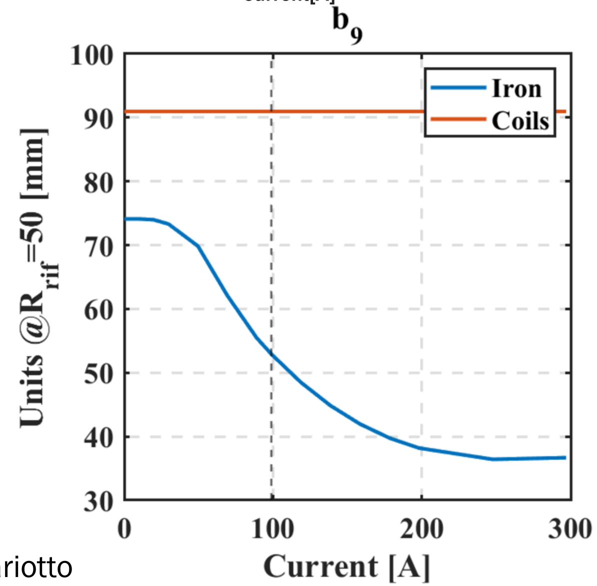






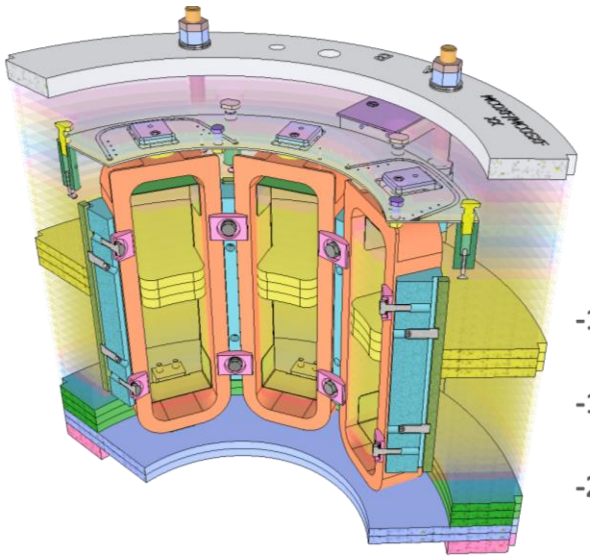


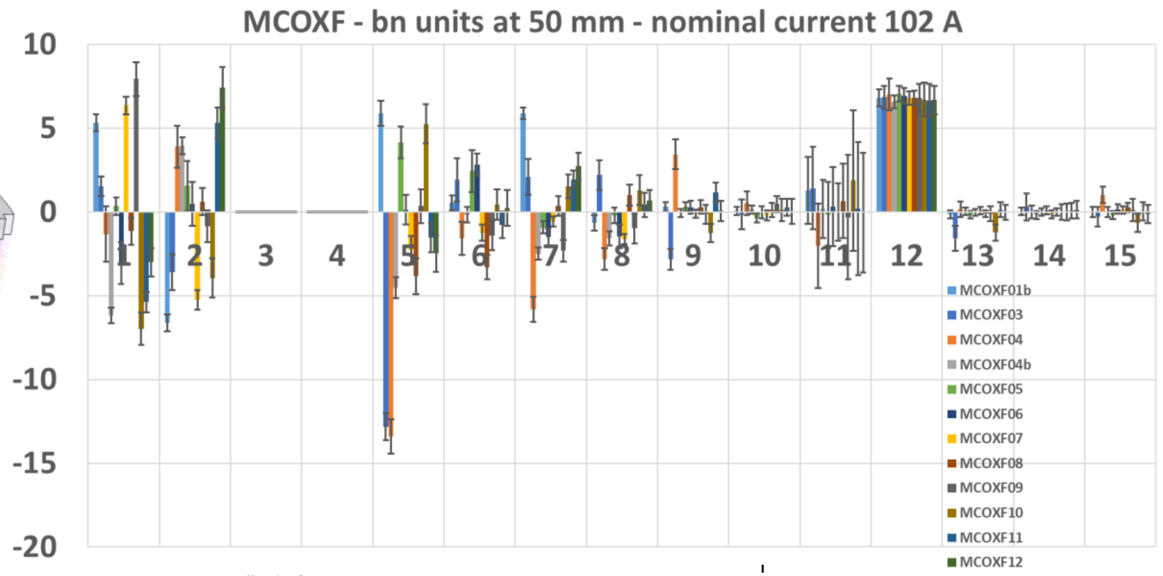


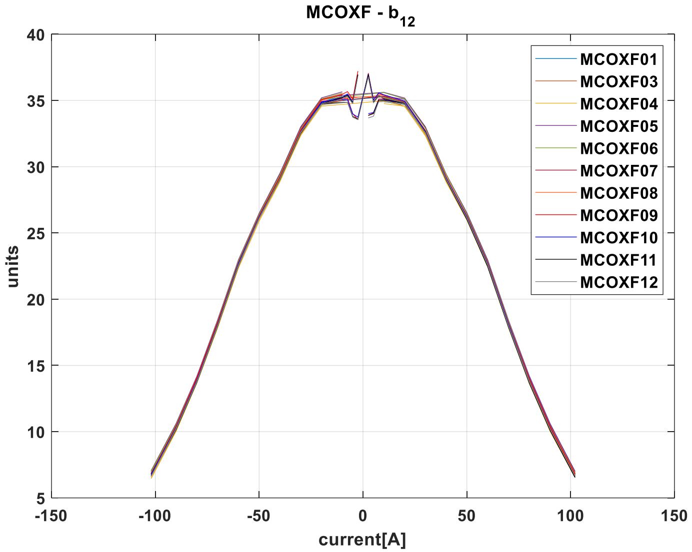


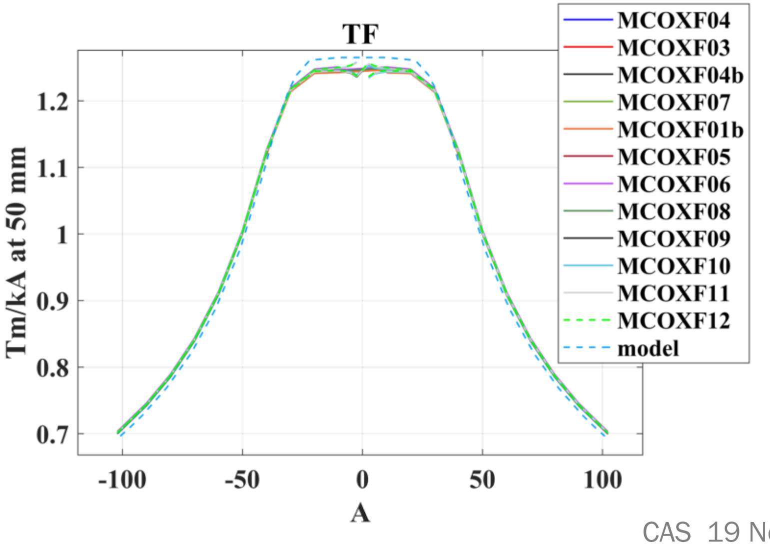
Courtesy of E. De Matteis and S. Mariotto

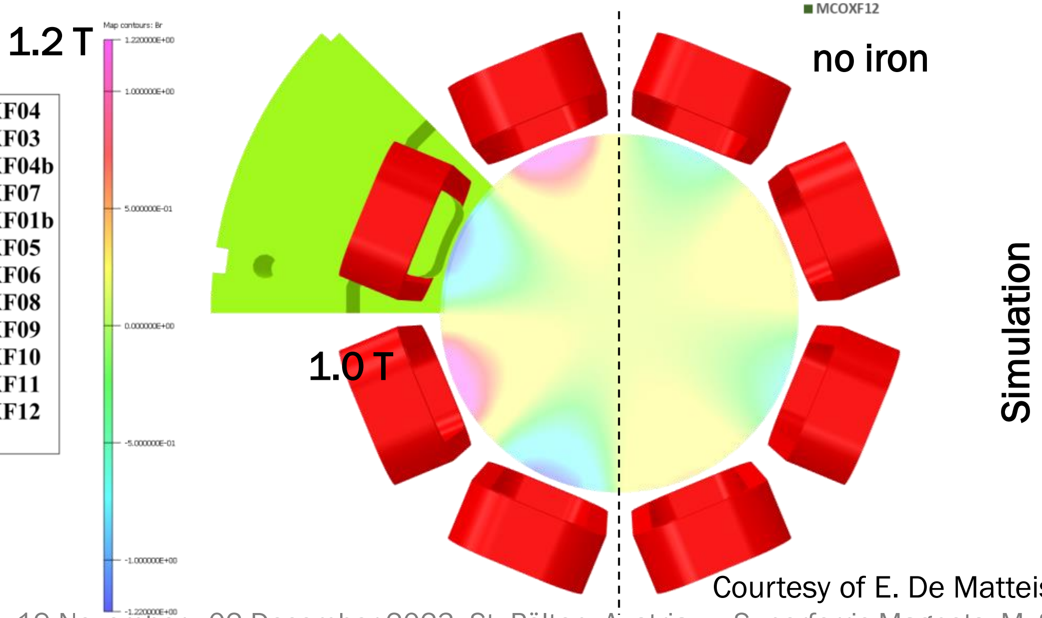
Octupole Family Field Quality

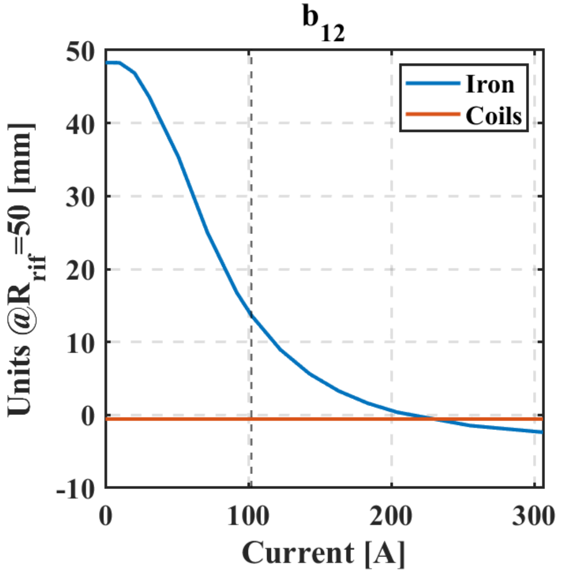






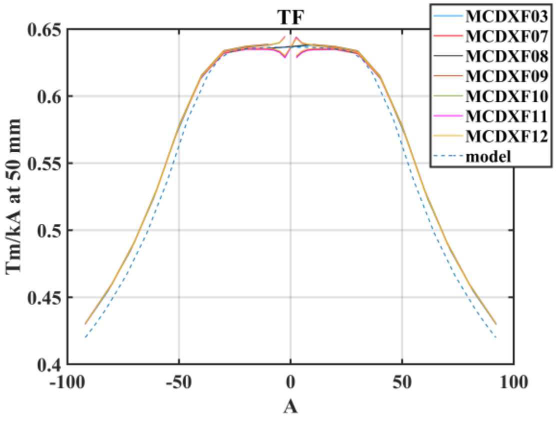


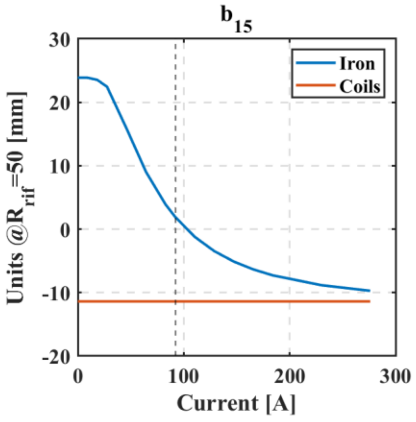


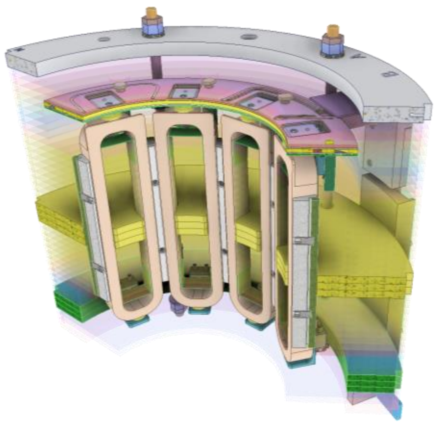


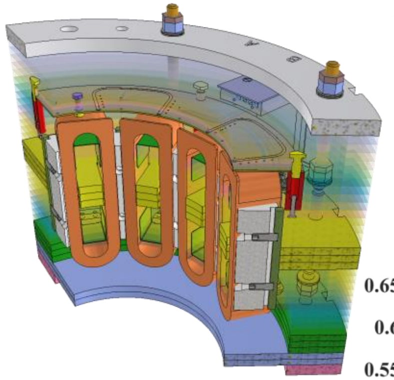
Courtesy of E. De Matteis and S. Mariotto

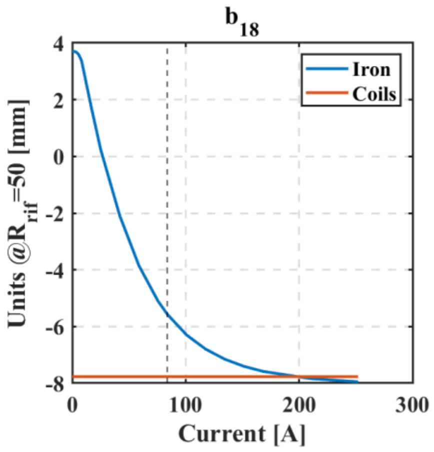
Decapole and Dodecapoles Transfer Functions

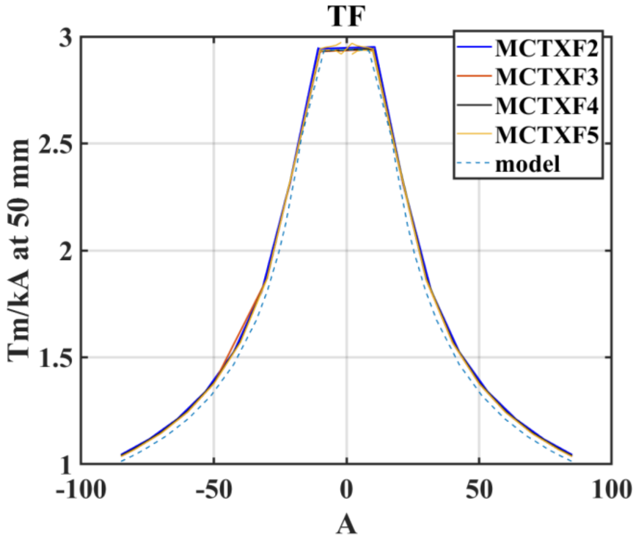


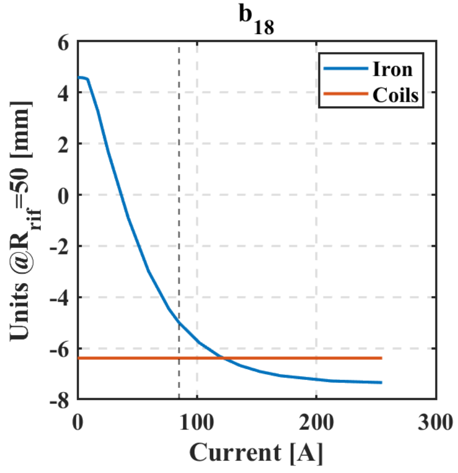


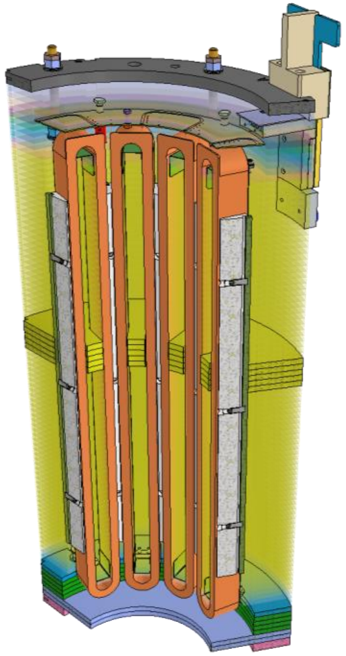


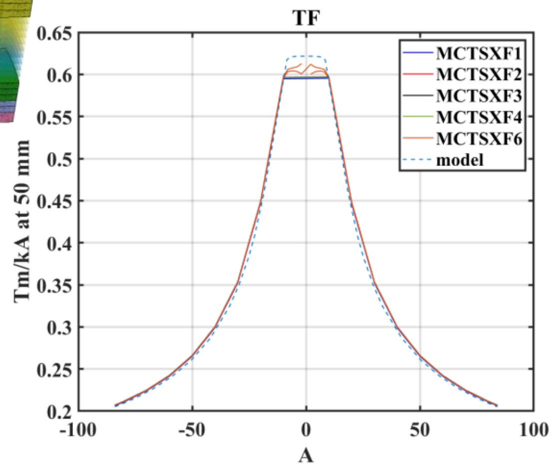




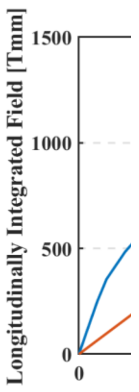


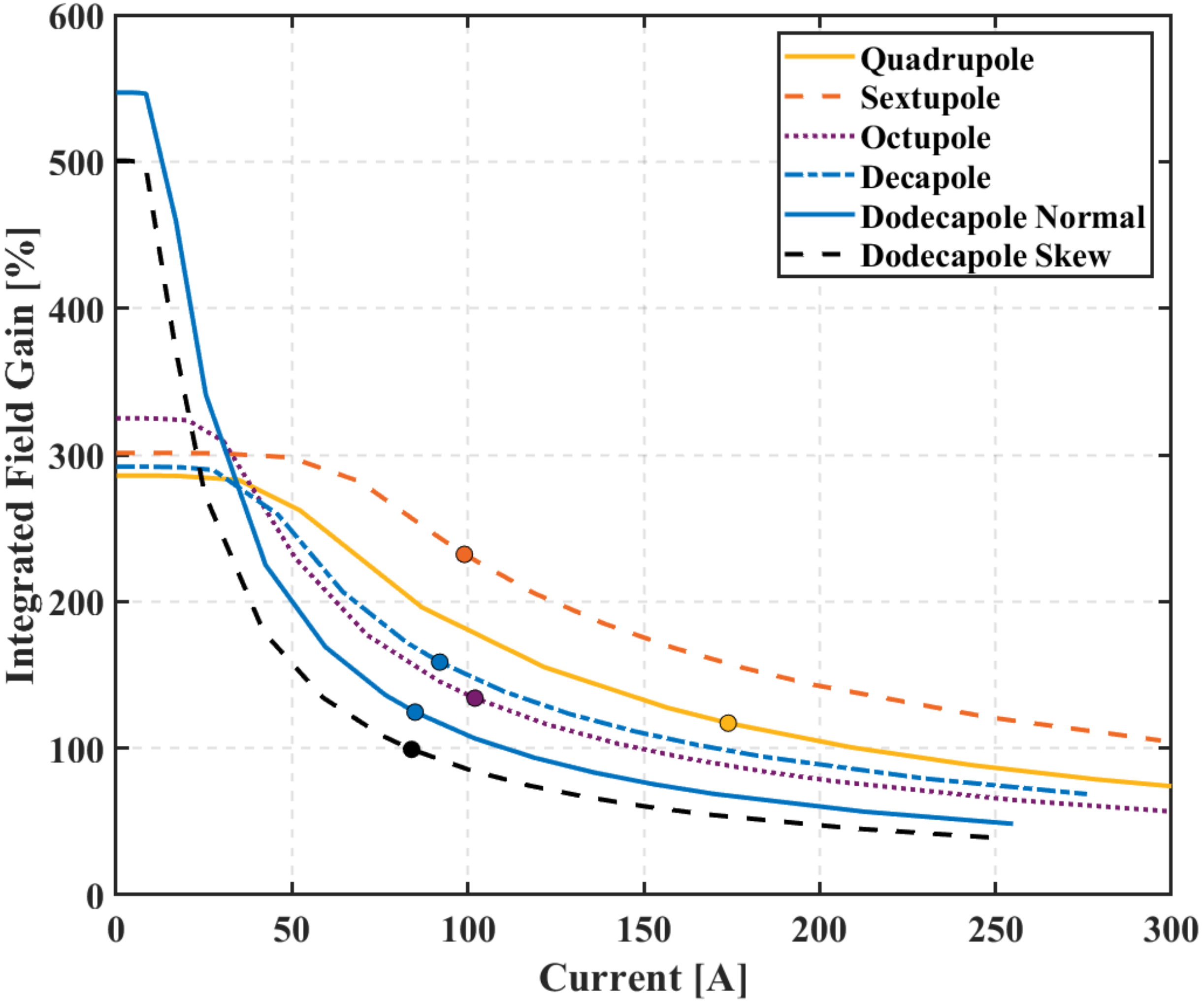




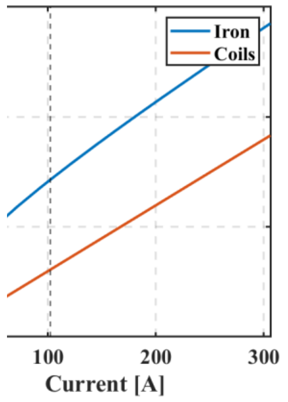


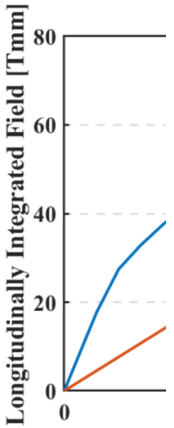
Effect of Iron in Superferric HOC



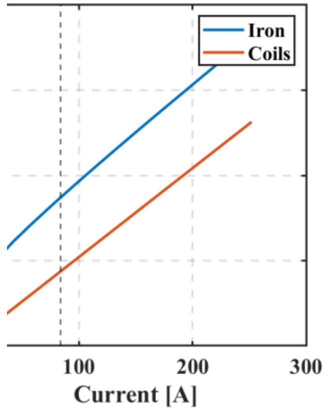


8P





12PS

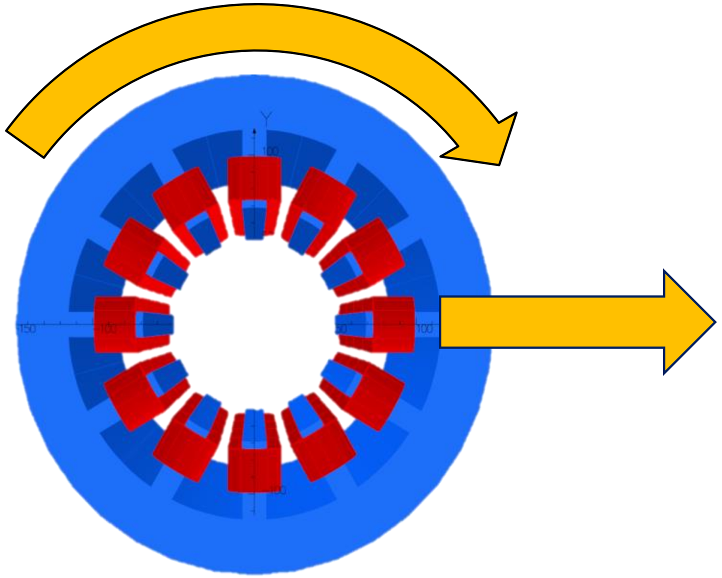


MECHANICAL TOLERANCES

Effect of assembly tolerances on field quality, analysis by S. Mariotto

The superferric design allows a release of assembly tolerances, thus reducing the cost

Allowed overall harmonic content 100 U

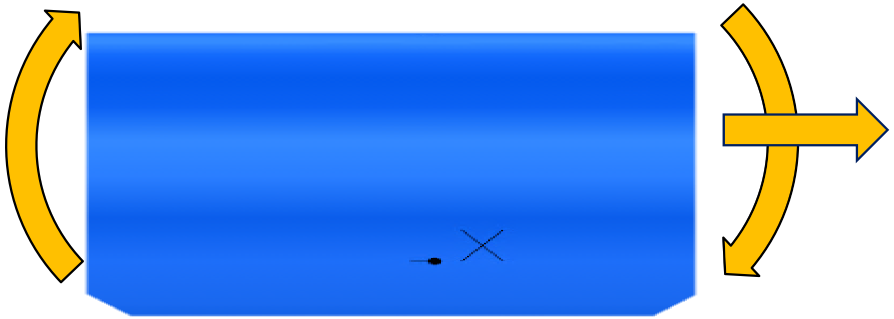


Displacement max 0.1 mm

$b_5 = -47.5$ units

$b_7 = -4.6$ units

$a_6 = 20.4$ units



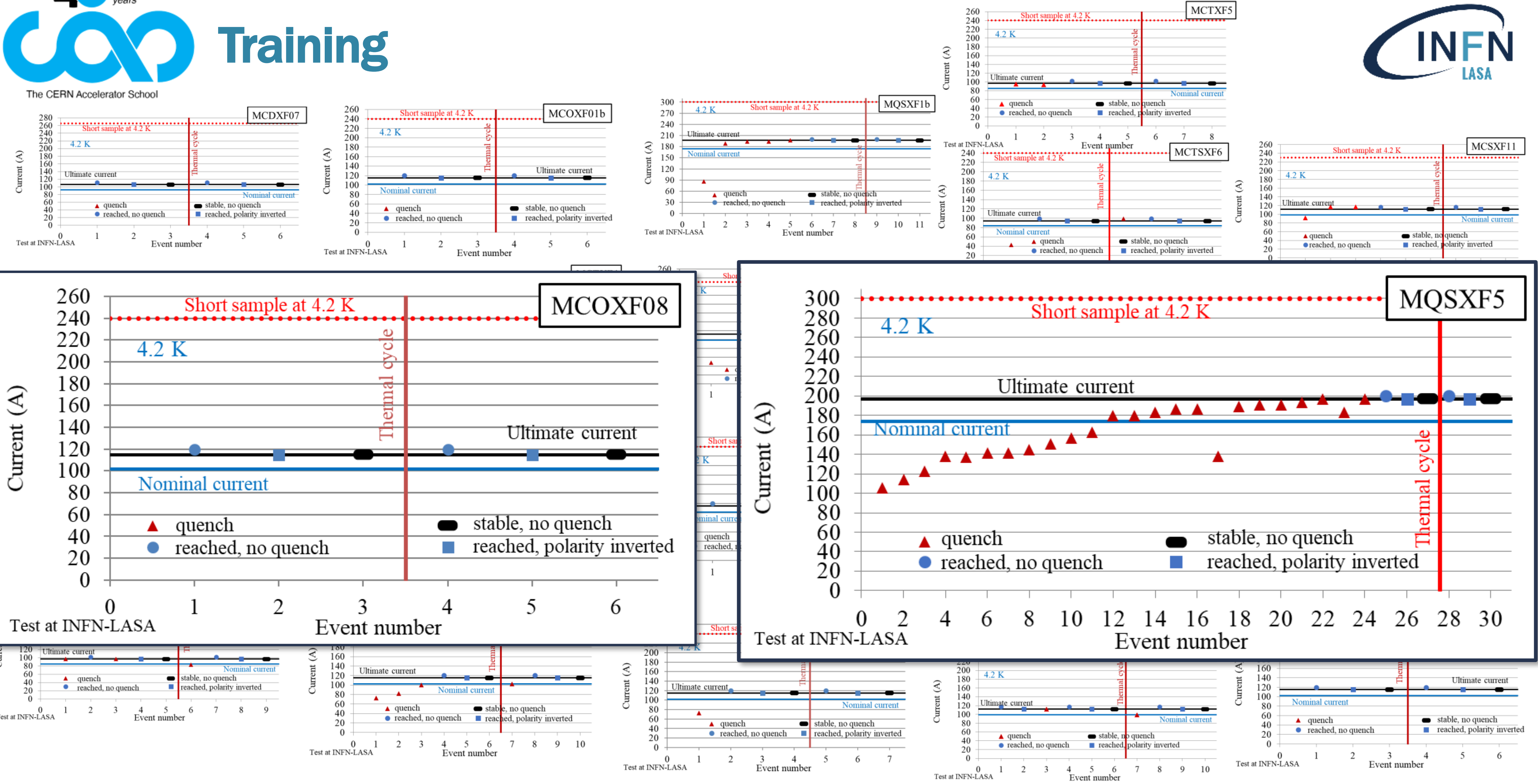
Horizontal displ. 0.3 mm

$a_4 = -1.1$ units

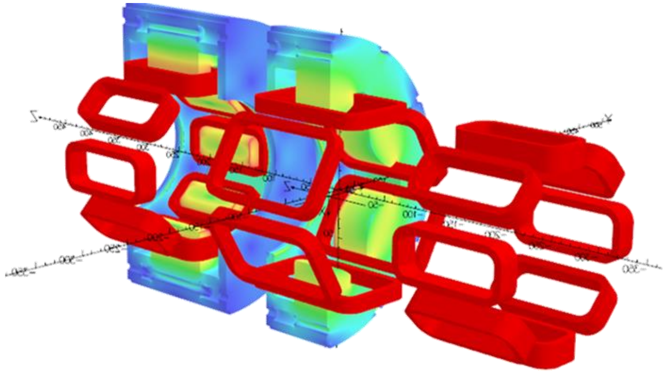
Displacement max 0.1 mm

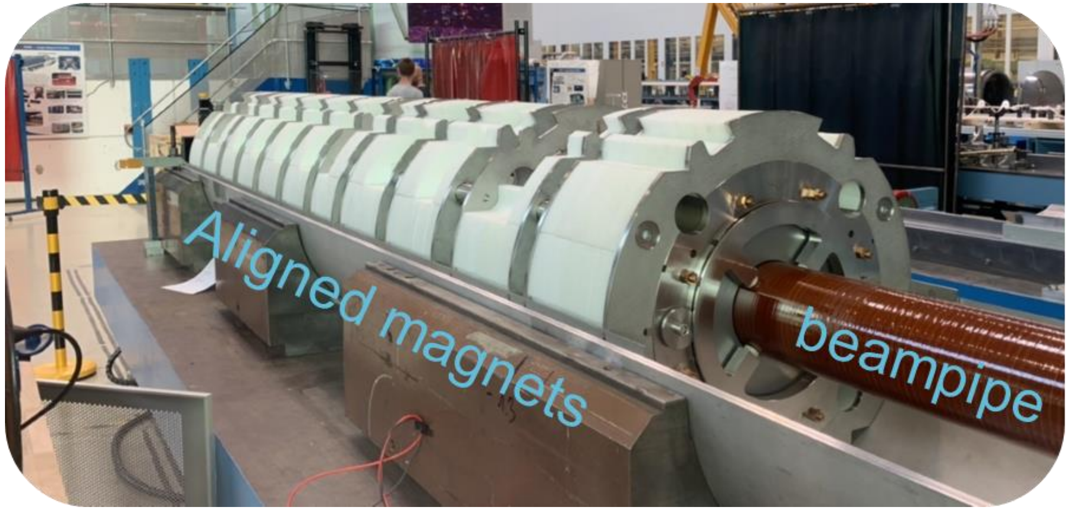
negligible

Training


MCOXF08
Short sample at 4.2 K
4.2 K
Thermal cycle
Ultimate current
Nominal current
Current (A)
Event number
Test at INFN-LASA
quench
reached, no quench
stable, no quench
reached, polarity inverted
MQSXF5
MCDXF07
MCOXF01b
MQSXF1b
MCTXF5
MCTSXF6
MCSXF11

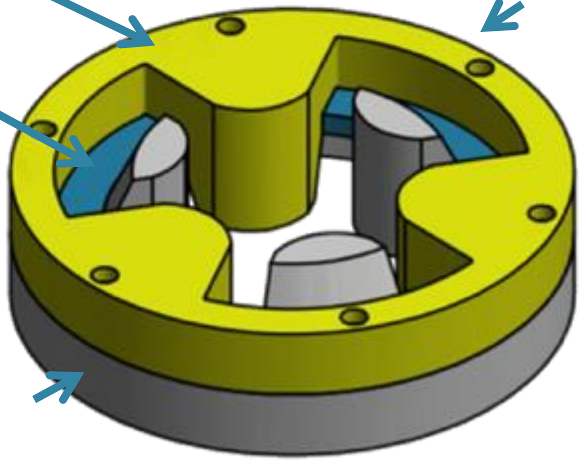
Integration





Courtesy of E. Prin

Exploring Different Designs Round Coil Magnet



Demonstrator: one module

alternating poles on each iron ring

Iron rings for the flux return

The special iron pole and return flux shaping generate a multipolar field (I. F. Malyshev and V. Kashikhin)

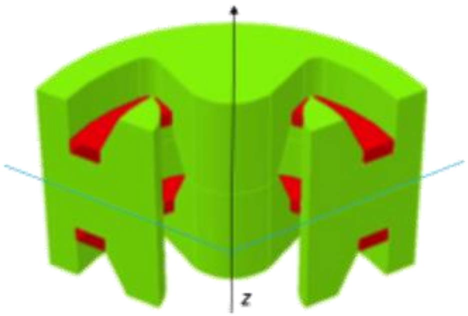
Iron dominated

Fits strain sensitive superconductors i.e. MgB2 and ReBCO

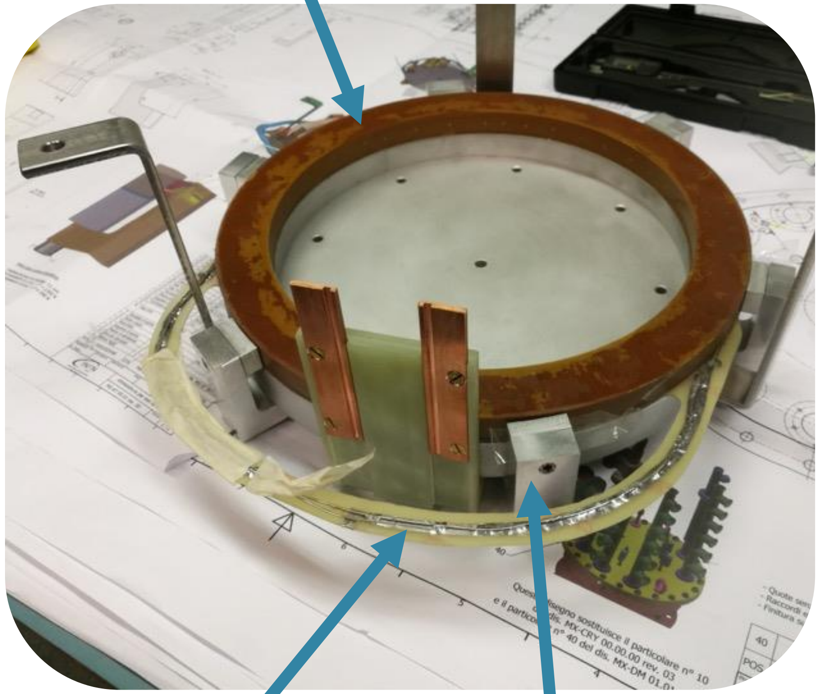
A full magnet has 2 coil to cancel solenoidal field

I. F. Malyshev, Patent 1 689 890/26-25, Oct. 12, 1973, Bulletin 41.
V. Kashikhin, IEEE Trans. Appl. Supercond., vol. 20 (2010)
V. Kashikhin et al., Proc. IPAC 2010

Full magnet

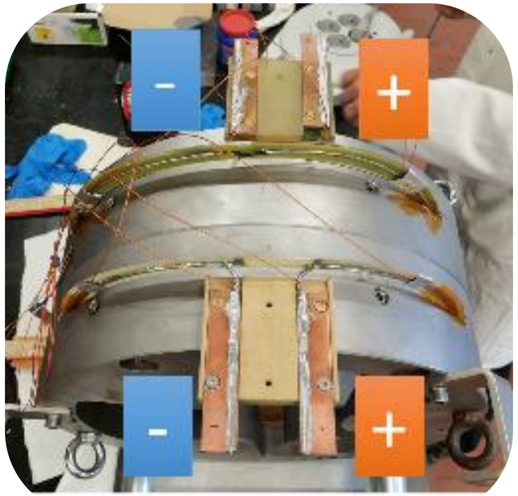


G. Volpini et al. Eletromagnetic Study of a Round Coil Superferric Magnet,IEEE Tr. App. Sup, 26, 4 (2016)

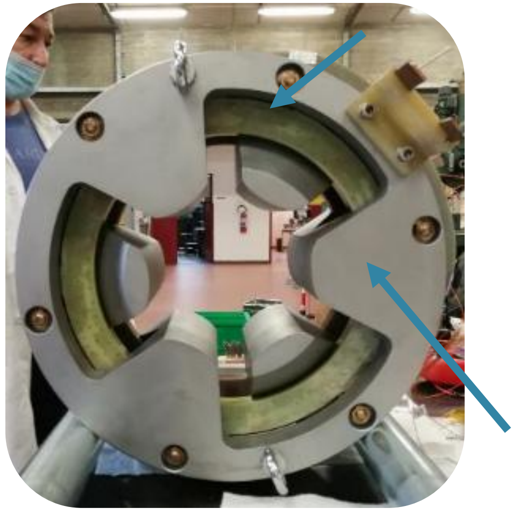


Exploring different designs

- The development of the round coil magnet idea is a way to introduce HTS superconductors in accelerators
- Not the best choice for HL but suitable for lower energy accelators and/or to operate at higher temperature
- One way toward higher **sustainability** of accelerators (10 K – 20 K operation)



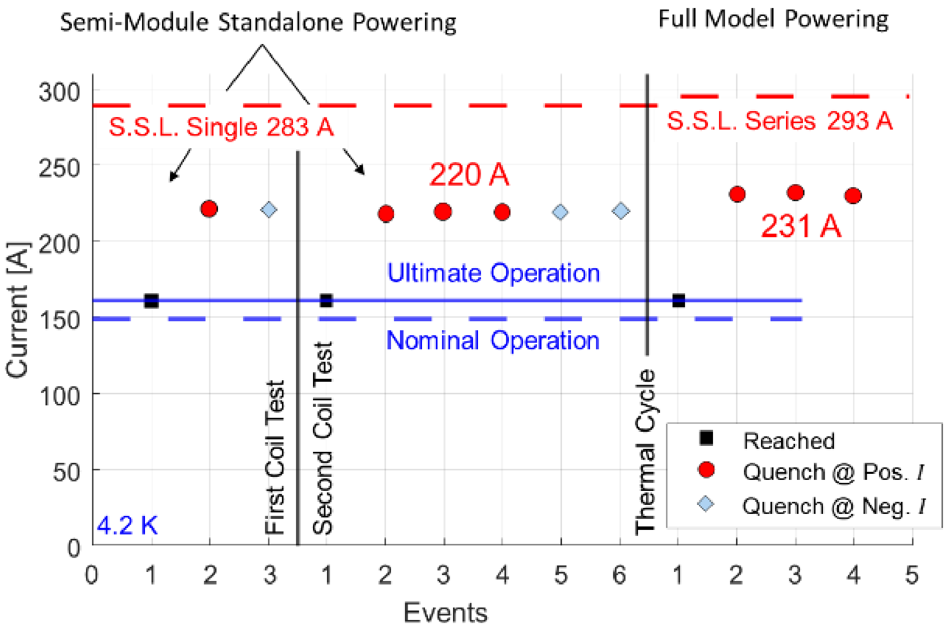
Full module



conductor

iron

Courtesy of R. Valente



ESABLiM

INFN LASA

Energy saving accelerator and beam line magnets

European Strategy for Particle Physics 2020

Energy consumption of particle accelerator facilities is expected to **increase** in the future: Need for «Improvement of energy efficiency»

«**Cryogen-free superconducting magnets** instead of common resistive magnet for **heavy particles beam lines**»

Objectives:

- Use of **MgB_2** or **HTS** conductors
- **Energy** consumption 5-20 lower
- Work @ **T=>20 K** with solid conduction cooling to reduce cryogenic power consumption

Courtesy D. Tommasini, CERN

MNP33-Dipole
NA62-CERN
7560 MWh/y

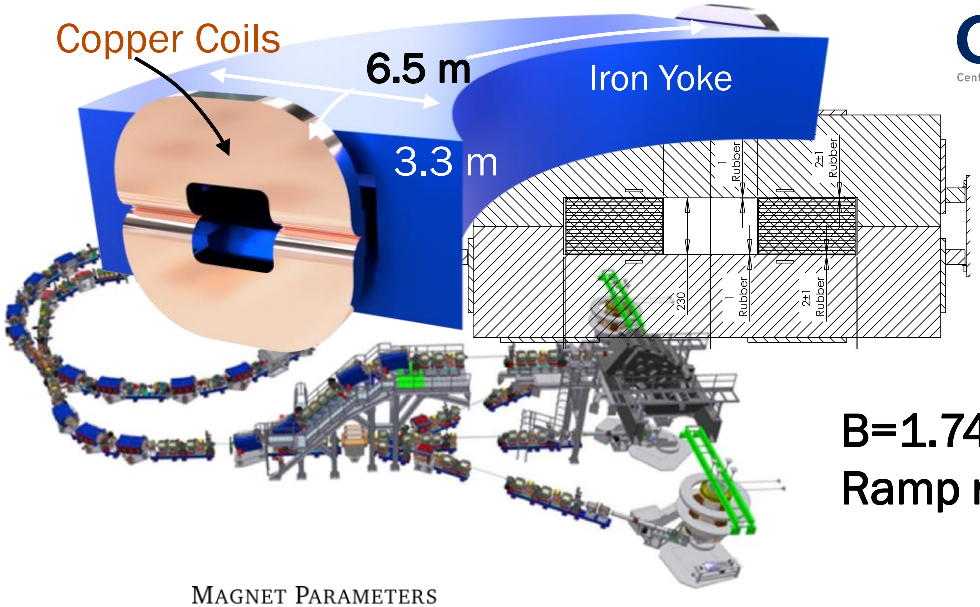
SM2-Dipole
Compass-CERN
6953 MWh/y

Revamping	Superferric	Coil dominated	Exotic
MgB_2 or HTS conductors **Cheapest** solution	Optimized **iron geometries** **Intermediate field**	**HTS conductors (high field)** Reduced Magnet Dimensions	**Combined function magnets** New beamline design

Courtesy of S. Mariotto

Magnet Case Studies

Ramped Bending Dipole «Window-Frame»



CNAO
Centro Nazionale di Adroterapia Oncologica

B=1.74 T
Ramp rate 0.2 T/s

MAGNET PARAMETERS

Nominal Current	2280 A
Min Current	380 A
Nominal Field	1.74 T
Magnetic Lenght	5740 mm
Entrance Angle	30°C
Exit Angle	21°C
Field Homogenity	2 units
Maximum Power	700 kW

Main Features:

Field quality: ± 2E-4 $\Delta B/B_0$ in 200x200 mm² aperture

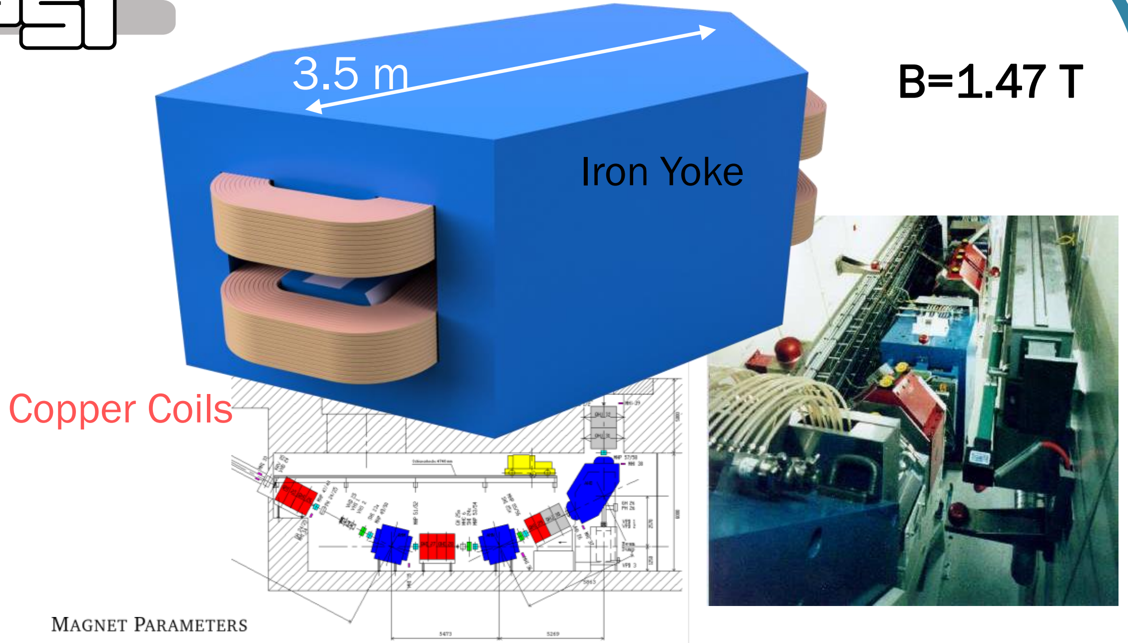
Duty cycle depends strongly from patient treatment

30 kW DC = 262 MWh/year

Courtesy of S. Mariotto

PAUL SCHERRER INSTITUT
PSI

Steady-state H-Type bending Dipole



B=1.47 T

MAGNET PARAMETERS

	AHO
Air Gap	100 mm
Max. Current	1000 A
Max. Voltage	95 V
Max. Power	95 kW
R @ 20°C	83 mΩ
Cond. Dimensions	18.5×18.5 mm
Cooling Channel Diam.	11.5 mm
Water Flow	60 l/min
Pressure drop	8 bar
T Rise	23°C
Turns	144

Main Features:

Weight of magnet: 50 tons

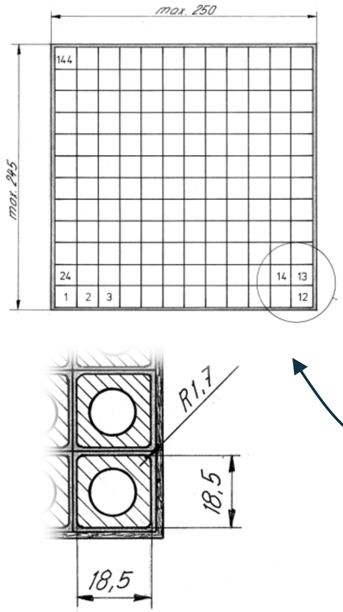
Copper coils cooling power **190 kW** continuously mid-May to mid-Dec.

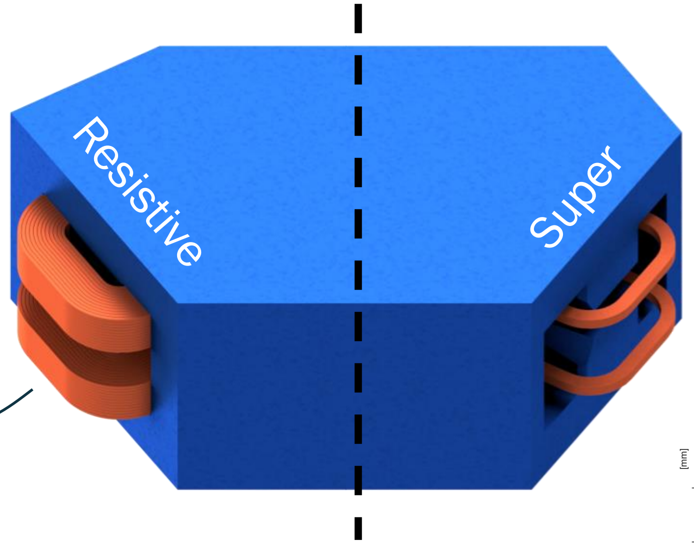
E_{tot} = 715 MWh/year

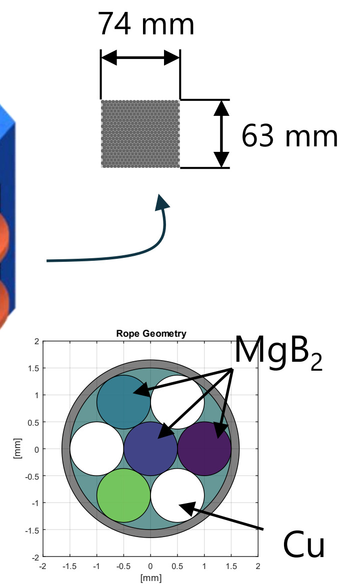
MgB_2 @ 20 K Electromagnetic Design

Target of the electromagnetic design optimization

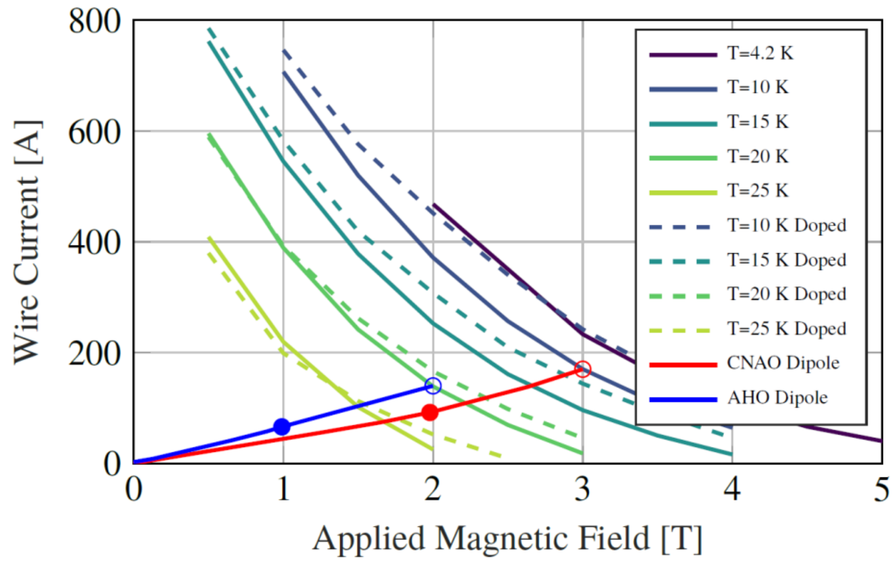
- Magnetic field of 1.45 T at center.
- Field quality given by the yoke poles (coil used to magnetize it). Same ampere-turns (144 x 1000 A)
- Use of a rope (4 MgB_2 conductors and 3 high-purity copper wires).
  - 484 ropes carrying 300 A @ 1.2 T (50% margin LL – 8 K temperature margin)







300 A

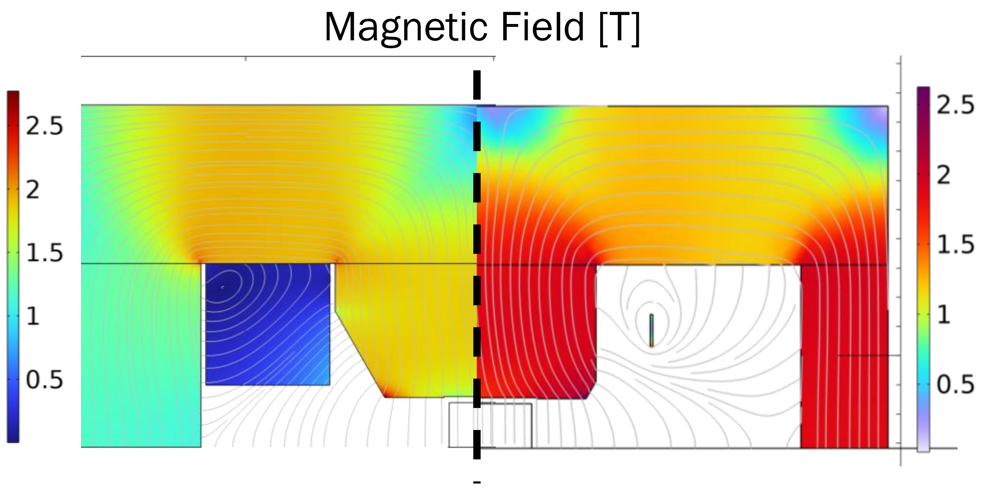


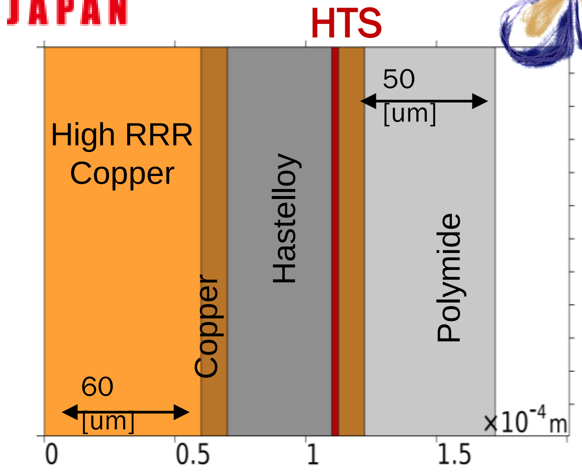
Courtesy of S. Mariotto

HTS @ T=50 K EM Design Optimization

Target of the electromagnetic design optimization

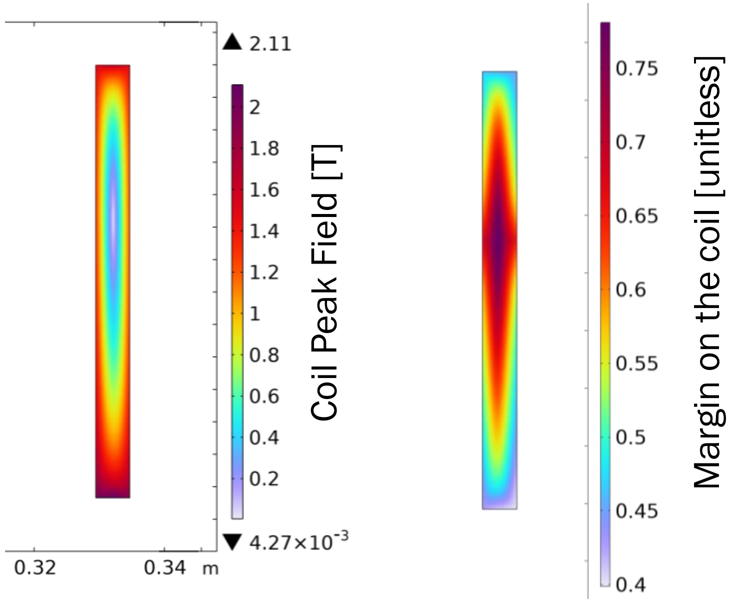
- Magnetic field of 1.45 T at center.
- 2D Field magnetic optimization of coil cross-section
- Minimize Peak Field on conductor while obtain the maximum margin on LL
    - Scaling of the old ampere-turns (144 A x 1000 turns)





Courtesy of S. Mariotto

Dimensions	4 mm × 67 µm
Substrate	40 µm of Hastelloy C276
Copper stabilizer	2 × 10 µm, RRR>20
Easy-way minimum bend	10 mm
Allower longitudinal strain	-0.4 % to 0.3 %
I_c, 50 K, 2 T	Min. 508 A with $B_\perp$ Max. 832 A with $B_\parallel$



Mechanical Design

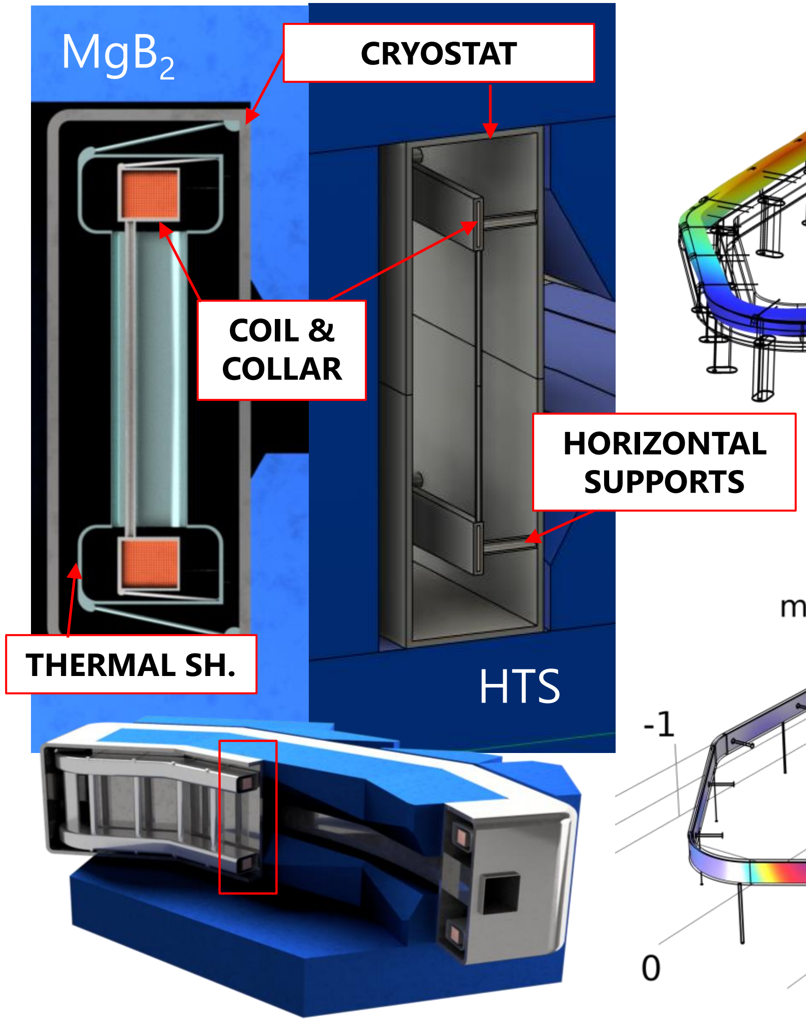
To limit coil displacement and deformation a **collar** can be used (SS 316LN)

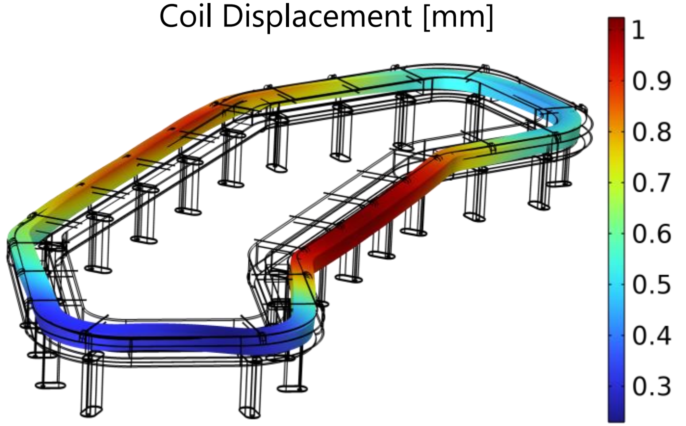
A distributed **set of SS 316LN tie-rods** or **cylindrical support** in **G10** is adopted to sustain mechanically the coil

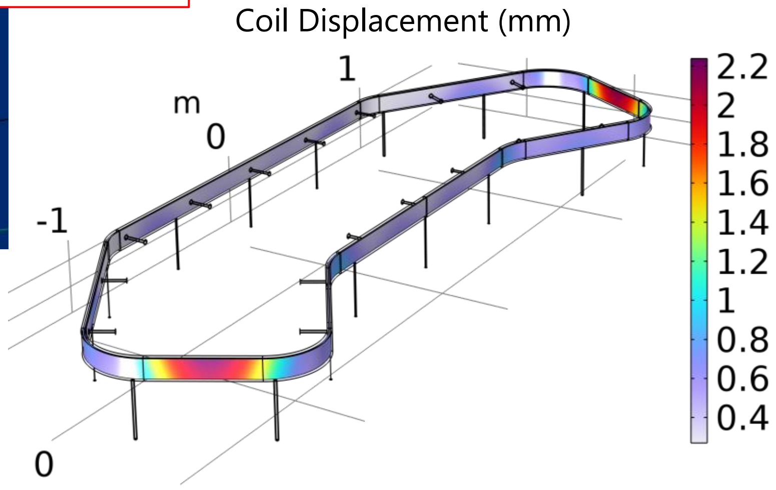
MgB_2 configuration requires active cooled aluminum **thermal shield** (cooled @ 70 K with coils @ 20 K). **HTS can work @ 50K**

	Supports	N	Length (mm)	Diam. (mm)
MgB_2	Coil-shield	48	130	4
	Shield-cryost.	48	180	6
HTS	Horizontal	16	130	20
	Vertical	16	198	10

Courtesy: Stefano Sorti, UNIMI



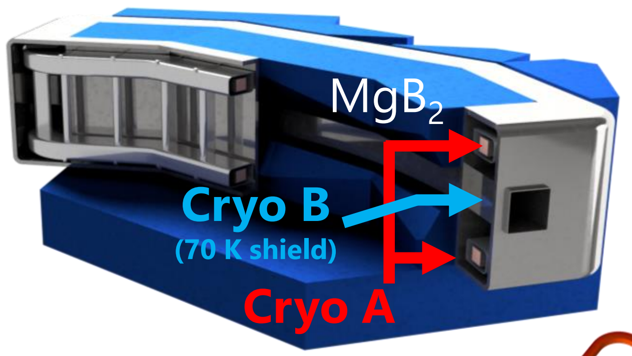


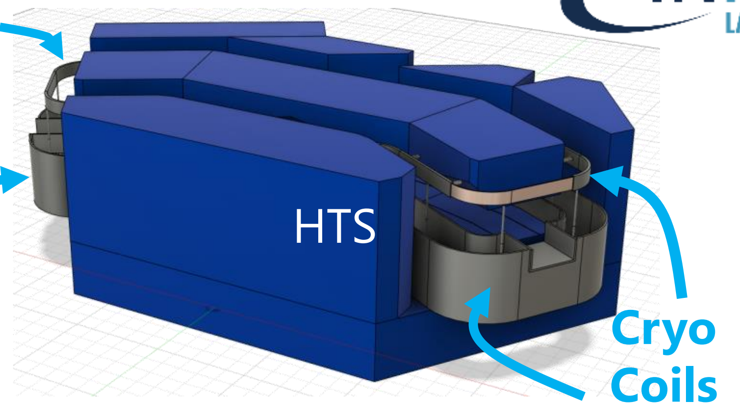


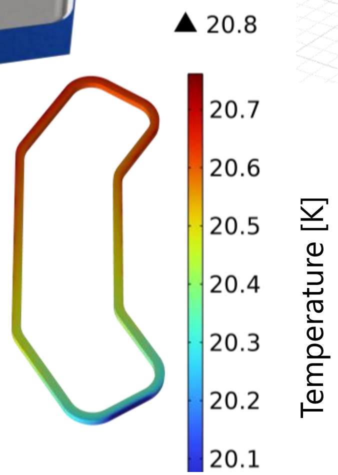
Thermal Design

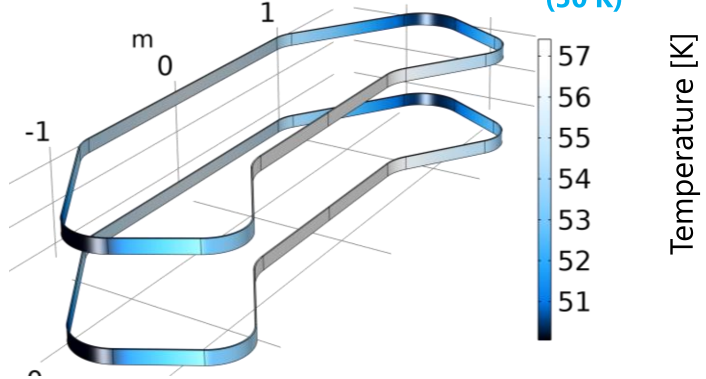
How to optimize the thermal loads:

- MLI (30 Layers) used to reduce the radiation power on thermal shield
- **Current leads** have to be carefully design to minimize heat load on coil. Choice of **operational current** is important (300 A)
- Cryocoolers installed on **one/both side** of the magnet









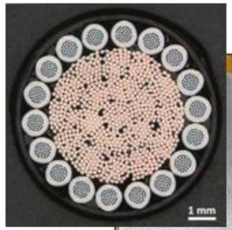
MAGNET	MgB_2		HTS
	Coils @ 20 K	**Shield @ 70 K**	**Coil @ 50 K**
Q support	1.35 W	12 W	4.6 W
Q Current Leads	0.2 W	24 W	28 W
Q radiation	0.45 W	11 W	11.7 W
Q tot	2 W	**47 W**	**44.3 W**

Energy Consumption		
Resistive Config.	**MgB2 @ 20K** Design	**HTS @ 50K Design**
190 kW 715 MWh/year	5 kW 18 MWh/year	3,4 kW 13 MWh/year
Reduction Factor	**40 Times**	**56 Times**

Courtesy of S. Mariotto

Energy Efficient Superferric Dipole

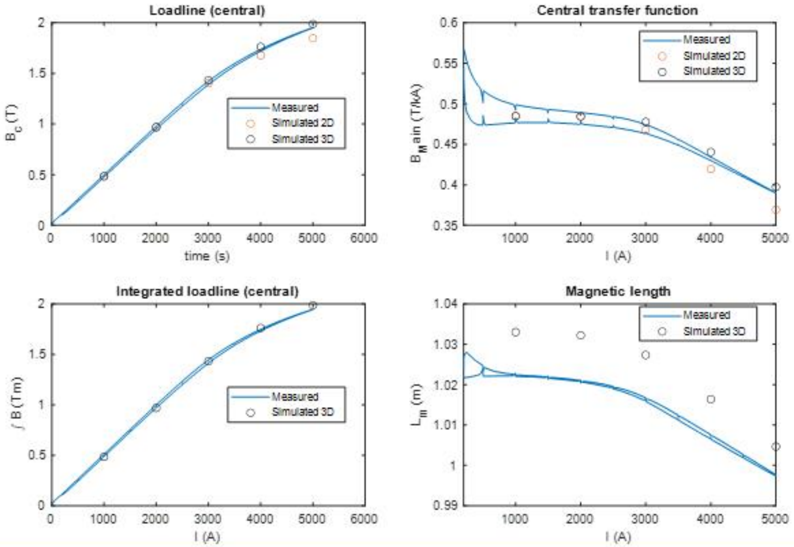
Test and Magnetic measurement of EESD magnet demonstrator



MgB_2 Cable (18 Strands Twisted Around Braided Copper Core)

EESD magnet demonstrator

- **Energy-Efficient Superferic Dipole (EESD)** is an innovative iron-dominated magnet design relying on **the 3-kA MgB_2 cable developed for sc link in WP6a.**
- **A demonstrator** was built and tested, which achieved **5 kA and 1.95 T dipole field at 4.5 K** wihtout quench.



- **Magnetic measurement date** confromed to expectations.
- **20 K test** under preparation.

Courtesy of A. Devred, A. Ballarino, N. Bourcey, F. Mangiarotti, A. Milanese, C. Petrone (CERN/TE-MSC)

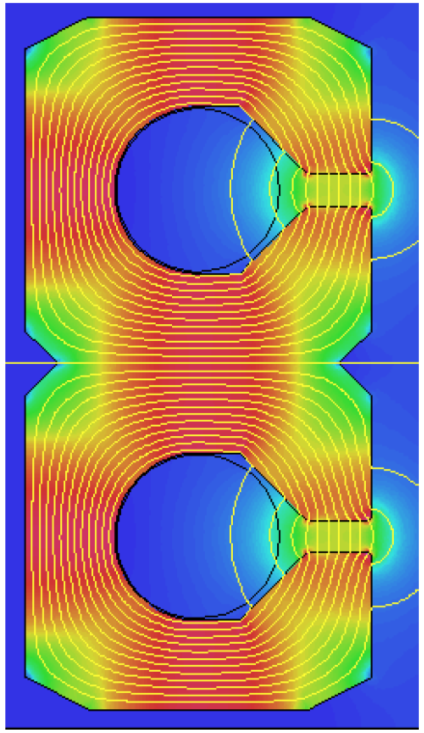
Solid design for the cable

Good performance at low temperature

High current to be evaluated in case of a conduction cooled test

Courtesy of A. Devred, A. Ballarino, N. Bourcey, F. Mangiarotti, A. Milanese, C. Petrone (CERN/TE-MSC)

Superferric option for FCC



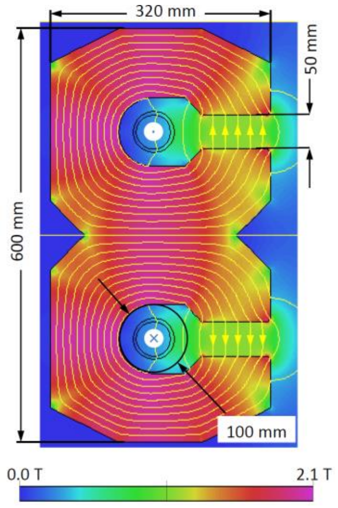
A. Milanese et al, IPAC 2014

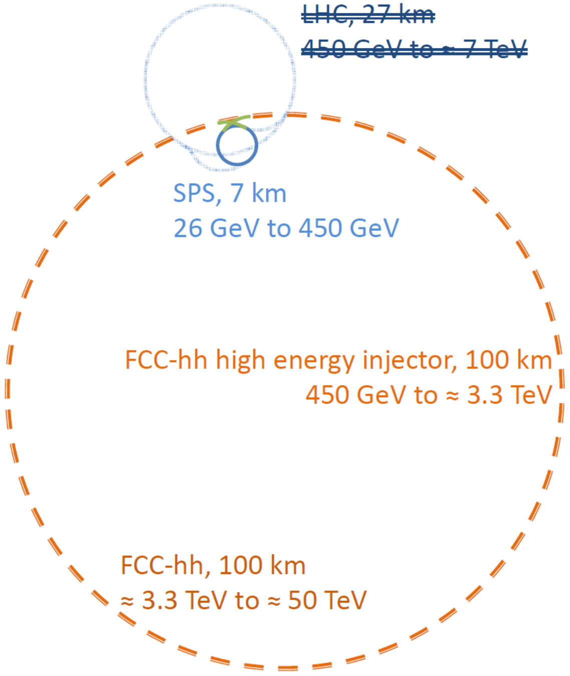
Resistive

- peak power (in magnets only) of 100 MW with coil operating at low current density (1 A/mm^2)
- overall size 54 x 108 cm
- 45 kA for 1.1 T in bore
- parallel physics?

Superconducting

- cryogenic power to be evaluated, function of cycle (ramp rate and frequency), superconducting material , operating temperature, cryostat design
- overall size 32 x 60 cm
- 50 kA for 1.1 T in bore





- An option for the FCC-hh higher energy injector
- Optimization by 2 apertures
- Manifacture potentially cheap
- High current, but one power converter
- Cryogenics to be optimized

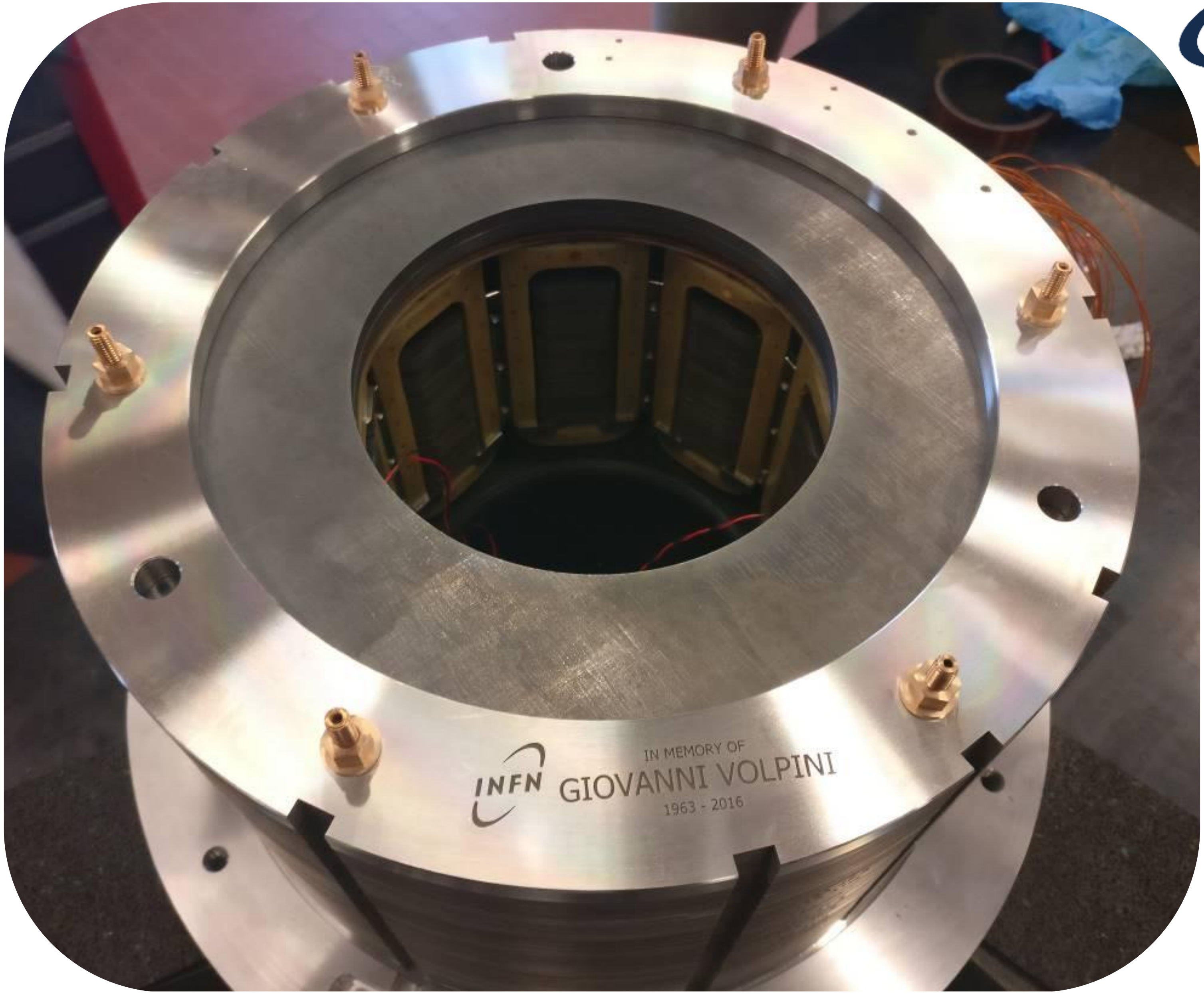
Conclusion

- Superferric magnets are
  - Flexible
  - Reliable
  - Inexpensive
- Not solving any possible technical problem
- Interesting for energy saving reserach and applications

LASA team
F. Broggi, E. De Matteis, S. Mariotto, A. Paccalini, A. Pasini, D. Pedrini, A. Leone, M. Quadrio, A. Palmisano, M. Prioli, M. Sorbi, S. Sorti, M. Statera, M. Todero, R.U. Valente, C. Uva

CERN
E. Gautheron, A. Musso, E. Todesco

SAES Getters and SAES Rial Vacuum
F. Gangini, P. Manini, M. Campaniello, C. Santini, A. Zanichelli



40 1983 —2023 years

The CERN Accelerator School

THANK YOU

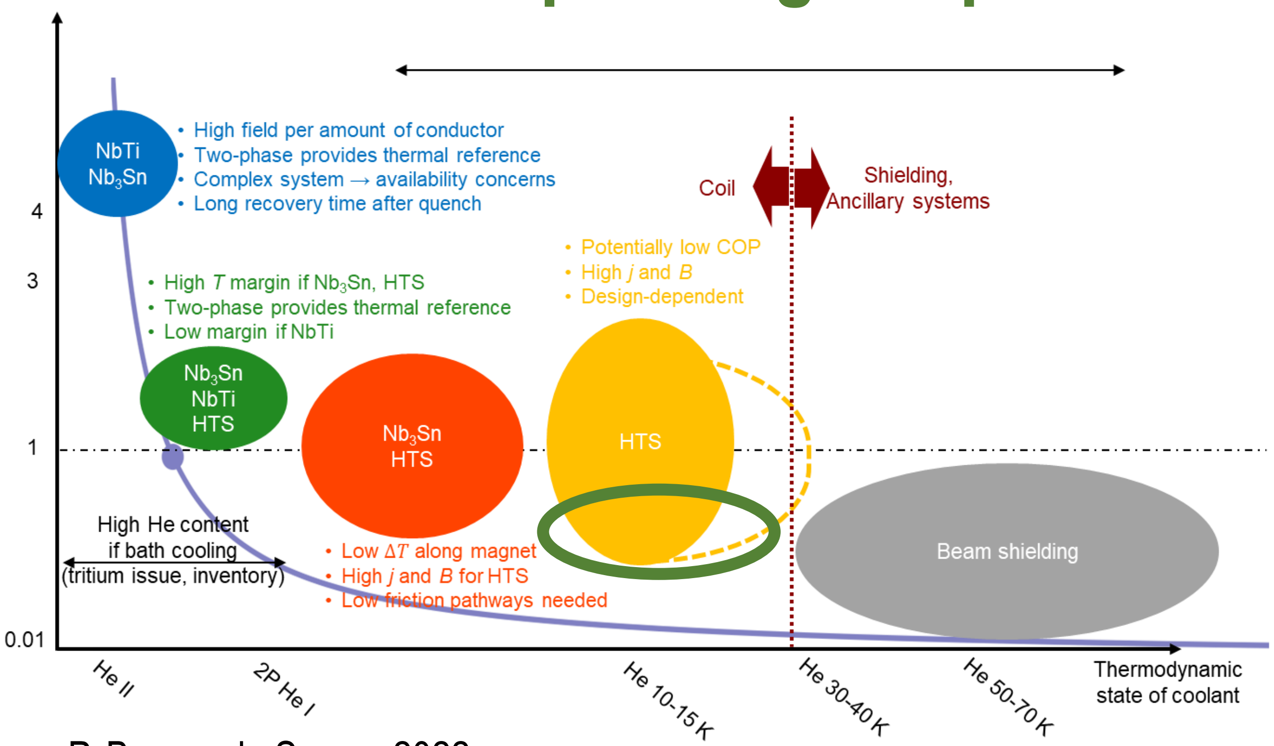
Ph. by G. Fornasier

Motivation and conductor characterization

3 pillas of design:

Performance (field and field quality), Cost and Sustainability

10 K to 20 K operating temperature

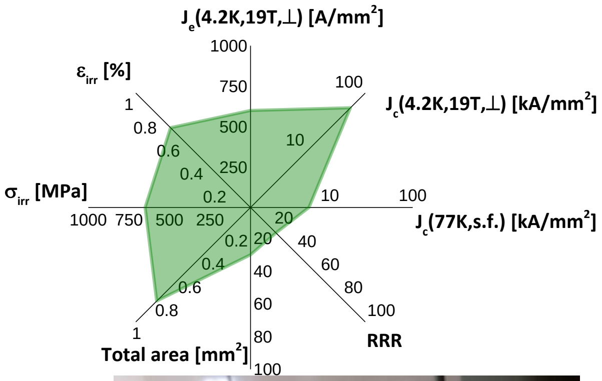


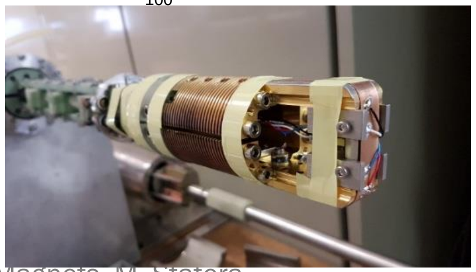
P. Borges de Sousa, 2022

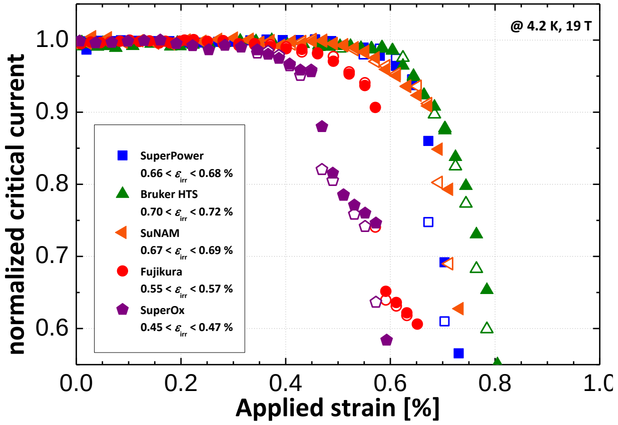
Ongoing conductor characterization and modeling

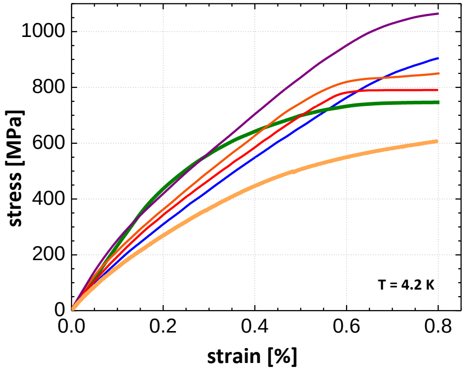
HTS inventory for IMCC

SuperPower Inc. · 上海超导 SHANGHAI SUPERCONDUCTOR · Fujikura · FARADAY FACTORY JAPAN









Electromechanical properties

Courtesy of C. Senatore, UniGE