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UNIVERSITÀ DI ROMA

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Innovative Research Infrastructure on applied Superconductivity
IRIS

Flat racetrack HTS design option for the lattice combined function MQ/MS of the FCC-ee collider ring

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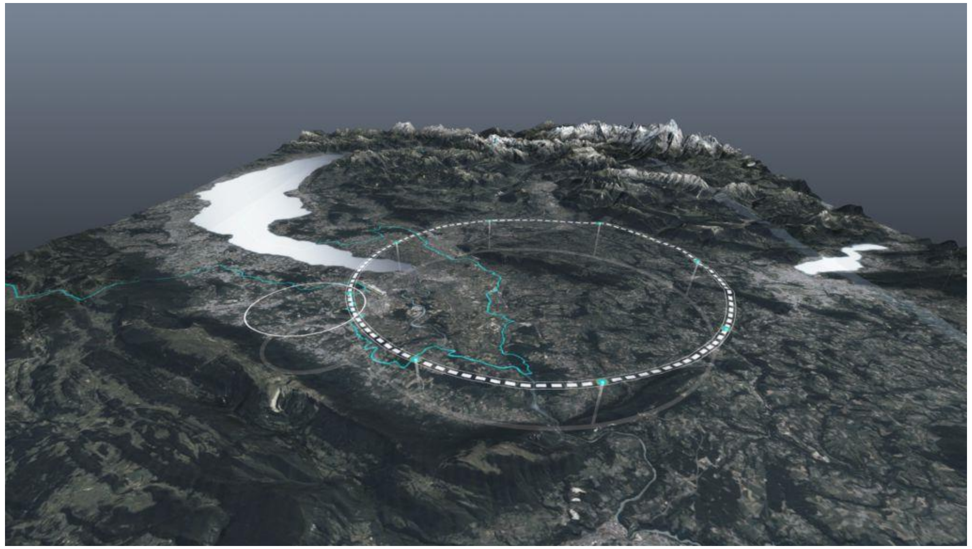
Introduction



Motivation of the contribution:

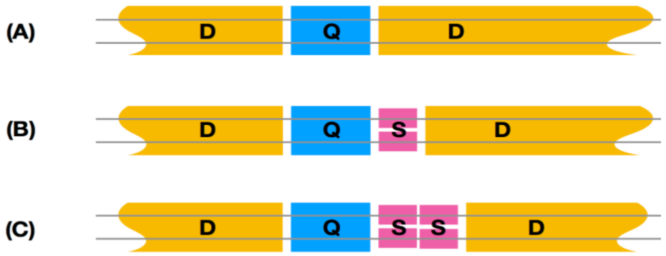
- FCC-ee energy consumption 20 TWh (14 y)
  DC collider operation (high power consumption)
- **90+ km ring tunnel**: thousands of resistive magnets
- *European Strategy for Particle Physics 2020*
  Need for «Improvement of energy efficiency»

PROPOSAL:

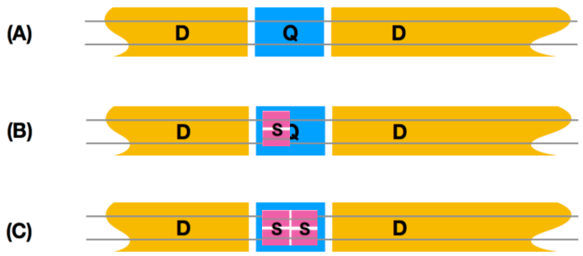
“Replacement of 2900 quadrupoles and 4700 sextupoles in the 80 km ARC cells”

1. **HTS** Superferric Magnets
2. Combined Magnets (**reduced length**)
3. High operating temperature (up to **50 K**)

CDR arc lattice

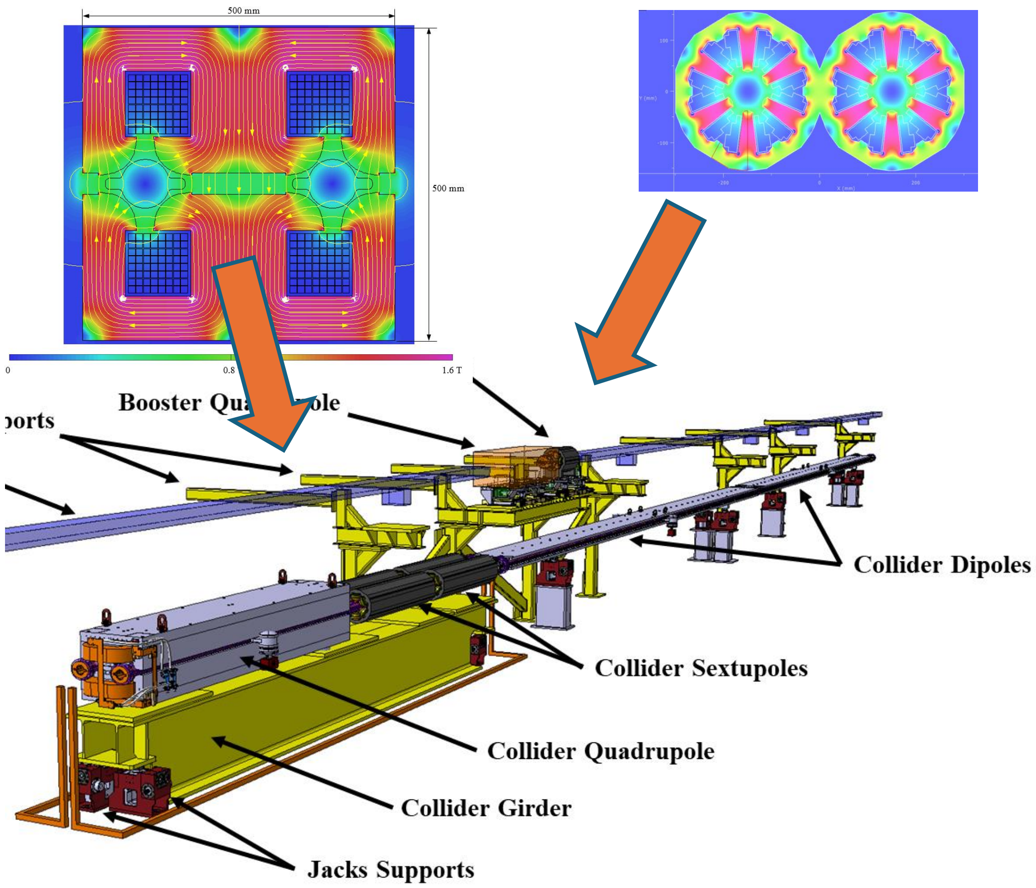


Superconducting



Starting Point

Twin F/D arc quad design **Twin Sextupoles**



MAIN IDEA:

Superconducting 4P+6P can save energy, $E_{sync} \propto \frac{1}{\rho}$

- **Synchrotron Energy Radiation scaling: 10%**
- **Comparable scaling for the RF cavities consumption**

Different F/D Quadrupoles in **Z-mode and tt-mode**

- **Independent** tunable quadrupole and sextupoles

Need of light-distributed cryogenic/Single cryocoolers

Experience from HL-LHC corrector magnet:

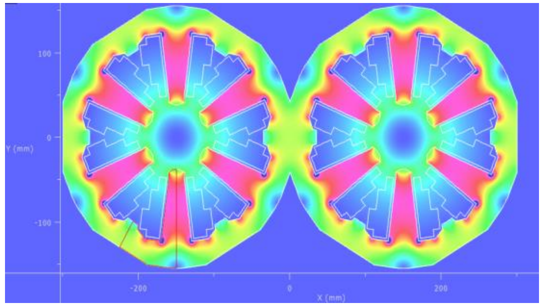
Several families of magnets from 4P up to 12P

- Racetrack coils suitable for HTS
- Modular design
- Easy mechanical assembly
- Optimal Field Quality
- Very good reproducibility (several magnets)

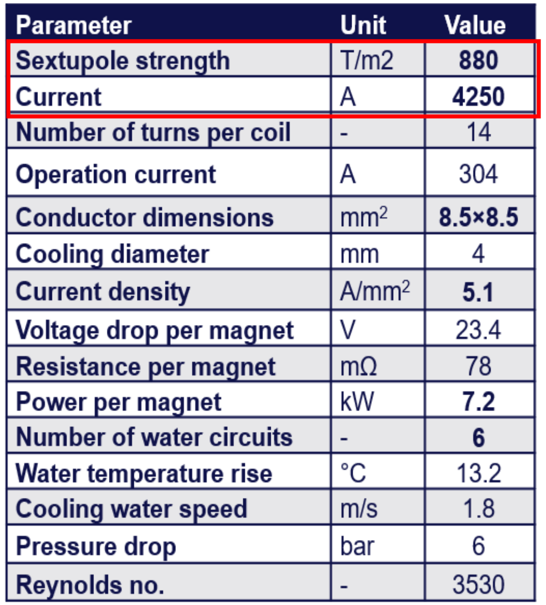
*Still to consider Cryogenic Consumption

Requirements for the magnet

Sextupole

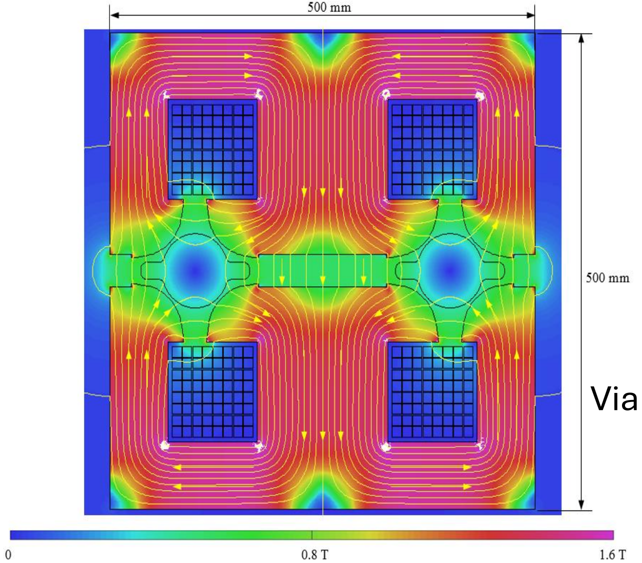


Magnets for FCC-ee, J. Bauche et al.



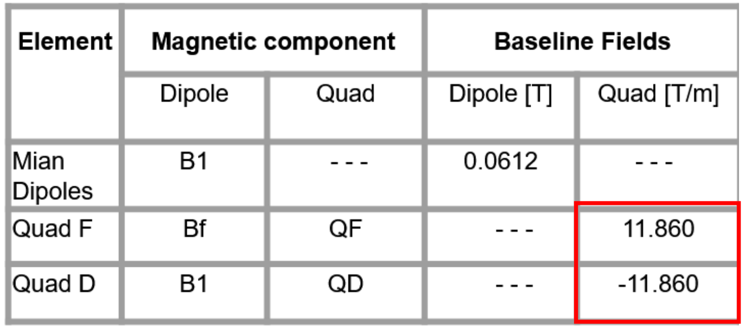
Parameter	Unit	Value
Sextupole strength	T/m2	**880**
Current	A	**4250**
Number of turns per coil	-	14
Operation current	A	304
Conductor dimensions	mm^2	**8.5×8.5**
Cooling diameter	mm	4
Current density	A/mm^2	**5.1**
Voltage drop per magnet	V	23.4
Resistance per magnet	mΩ	78
Power per magnet	kW	**7.2**
Number of water circuits	-	**6**
Water temperature rise	°C	13.2
Cooling water speed	m/s	1.8
Pressure drop	bar	6
Reynolds no.	-	3530

Quadrupole



10 T/m design (CDR)

$t\bar{t}$



Element	Magnetic component		Baseline Fields	
	Dipole	Quad	Dipole [T]	Quad [T/m]
Mian Dipoles	B1	- - -	0.0612	- - -
Quad F	Bf	QF	- - -	11.860
Quad D	B1	QD	- - -	-11.860

Via EPFL (Leon Van Riesen-Haupt , Cristobal Garcia) through PSI

Property	CDR	LASA - HTS
Magnetic Length	2.9 + 1.5	2.9
Max Quadrupole Gradient [T/m]	11.86	11.86
Max Sextupole Strength [T/m^2]	880	455
Integrated Sextupole Field [T m]	0.132	0.13195

WHY HTS Magnet?

Superconducting Magnet

- Increase Dipole Filling Factor, lower energy dispersion hence reducing the RF power consumption, can lead to an increased beam intensity
- Optics Flexibility

Higher Operating temperatures (20-50 K)

- Reduction of power consumption wtr LTS
- No need of LHe (cost reduction)

Parallel Synergies

- Detector Magnets
- Nuclear Fusion
- Medical Facilities

WHY Superferric Magnet?

Iron Dominated Magnet

- Well Know design, like a resistive magnet
- No need of complicated geometries for the coils, HTS materials are fragile.
- Small amount of HTS (lower material costs)

Combined Magnet

- Low number of power supplier
- Reduce total number of magnets
- Increase of dipole filling factor

MAIN GOAL of the proposal:

Combined Sextupole and Quadrupole Superferric HTS magnet

LASA-proposal:

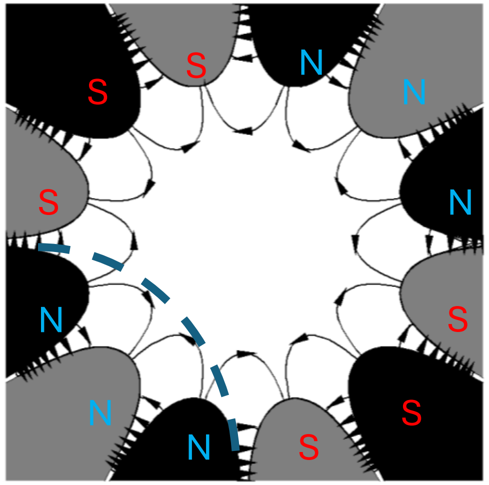
Requirements:

- **Independent** Quadrupole and Sextupole, have to work only as either a quadrupole or sextupole
- **Minimum** number of power supplier to lower energy consumption
- **High field quality** in the bore @Rref = 10mm
- Bore Dimension : 35 mm
- Quadrupole can not be shorter due to **quadrupole synchrotron radiation** (Open Challenge)

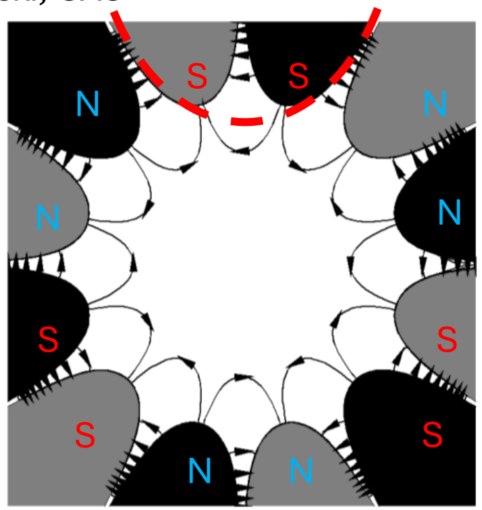
Solution:

- Dodecapole iron structure
- Two Independent power supplier

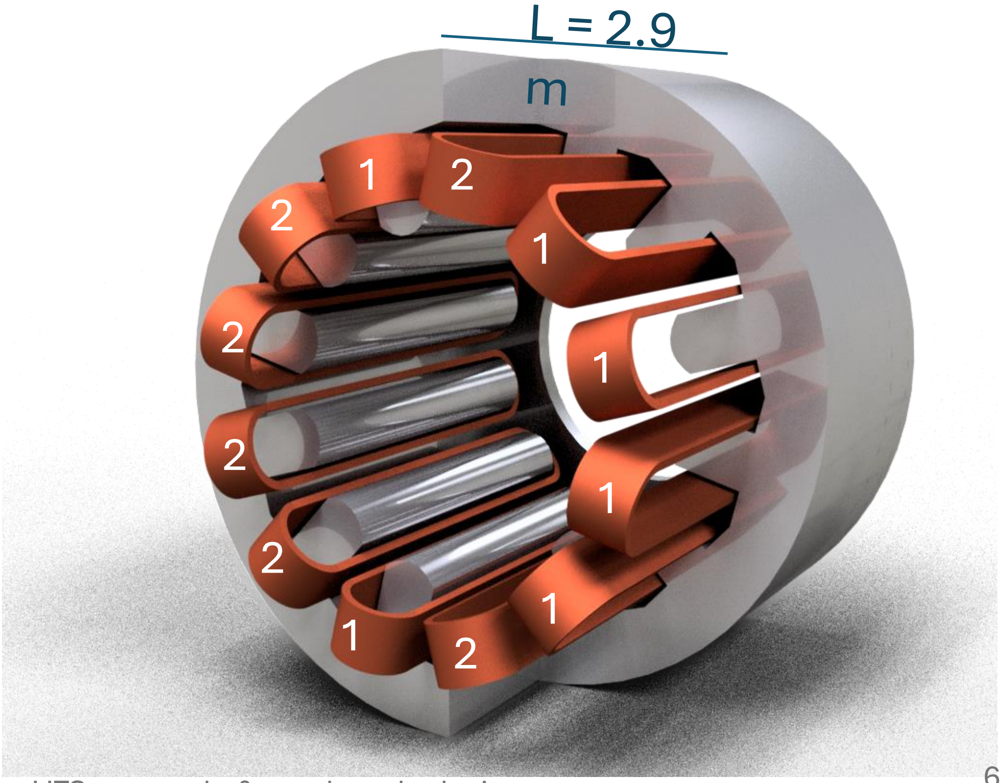
From Andrzej Wolski, CAS



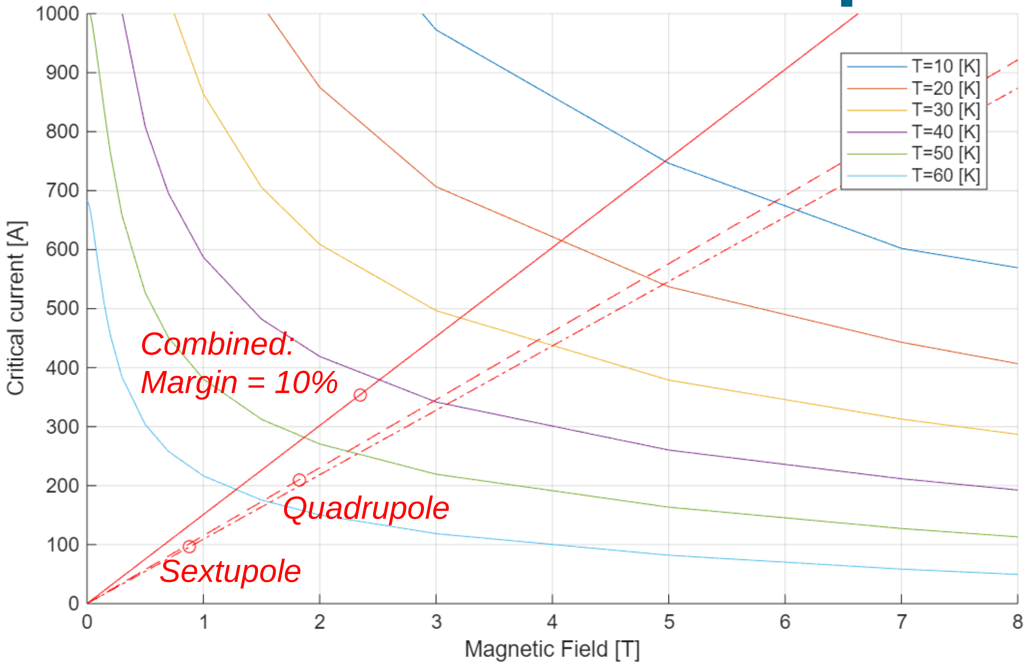
Quadrupole configuration



Sextupole configuration



Combined HTS Superferric Design



Working @ 40K

Peak Field on the tape: 2.35 T

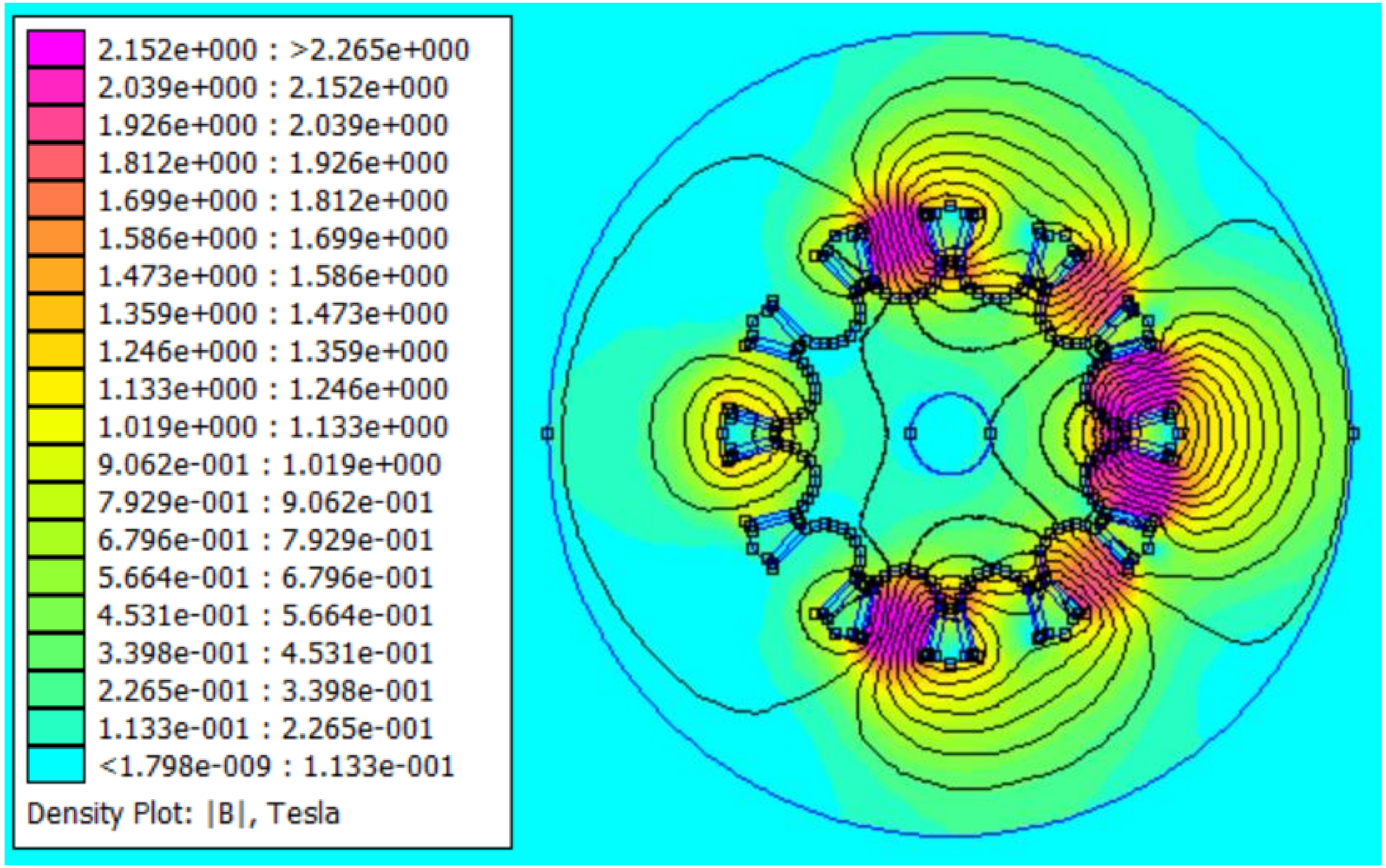
Current in each 4 mm tape:
- power supplier 1: 354.6 A
- power supplier 2: 103.1 A

Inductance: 0.0227 mH

Tape Used: FFJ - SuperOx YBCO 2G HTS

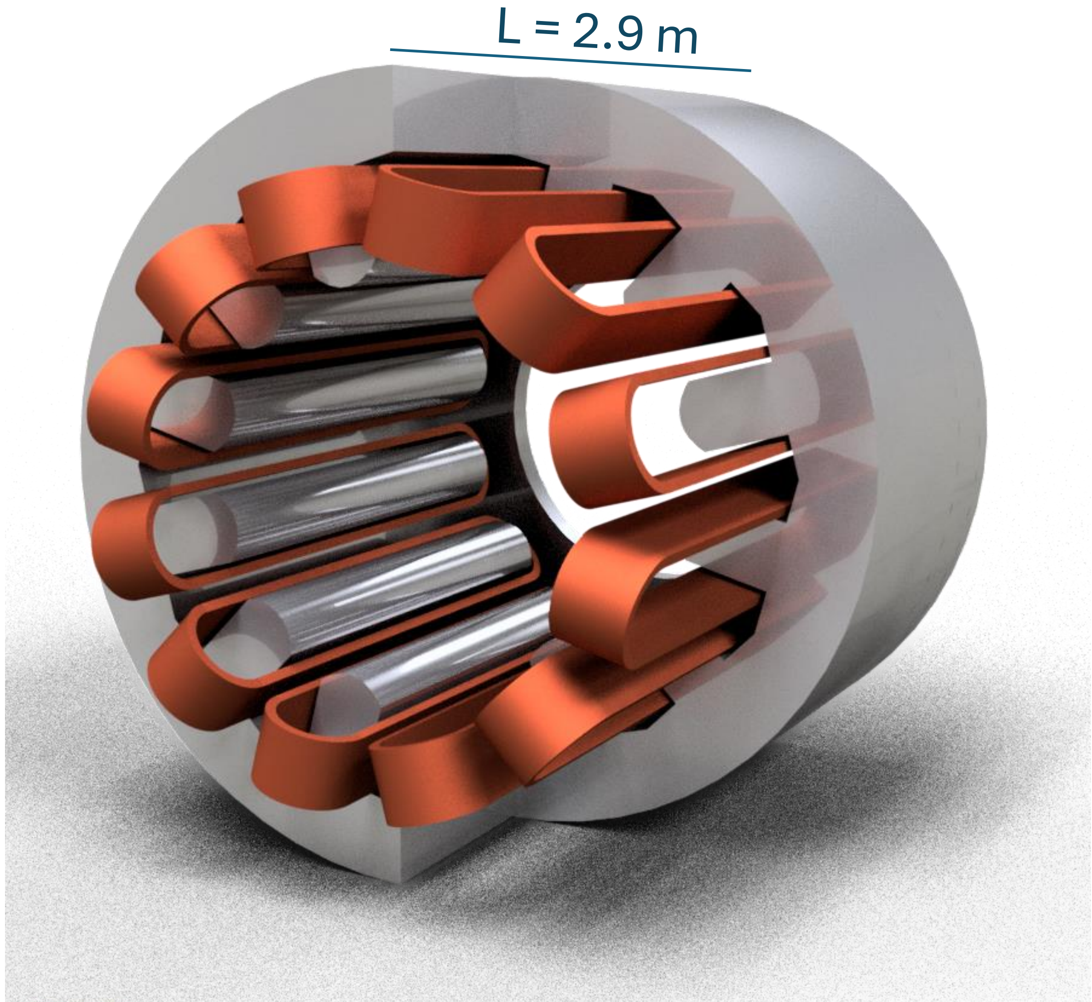
Mode	Target Value	NI group 1 [Aturn]	NI group 2 [Aturn]	Dipole Field [T]	G [T/m]	S [T/m^2]	b4 [units]
Combined	11.8 T/m 455 T/m^2	8510	2474	-0.019	11.83	454.9	30.65
Quadrupole	11.8 T/m	5060	5060	1*10^-5	11.86	0.05	1.04
Sextupole	455 T/m^2	2325	-2325	-2*10^- 6	-5*10^- 4	455	0.84

Combined HTS Superferric Design



Parameter	Value
Radius of the bore (r0) [mm]	35
Radius of cut for the iron pole (rc) [mm]	40.8
N° of 12 mm tapes turns per coil	8
Tape bending radius [mm]	9

Design Considerations

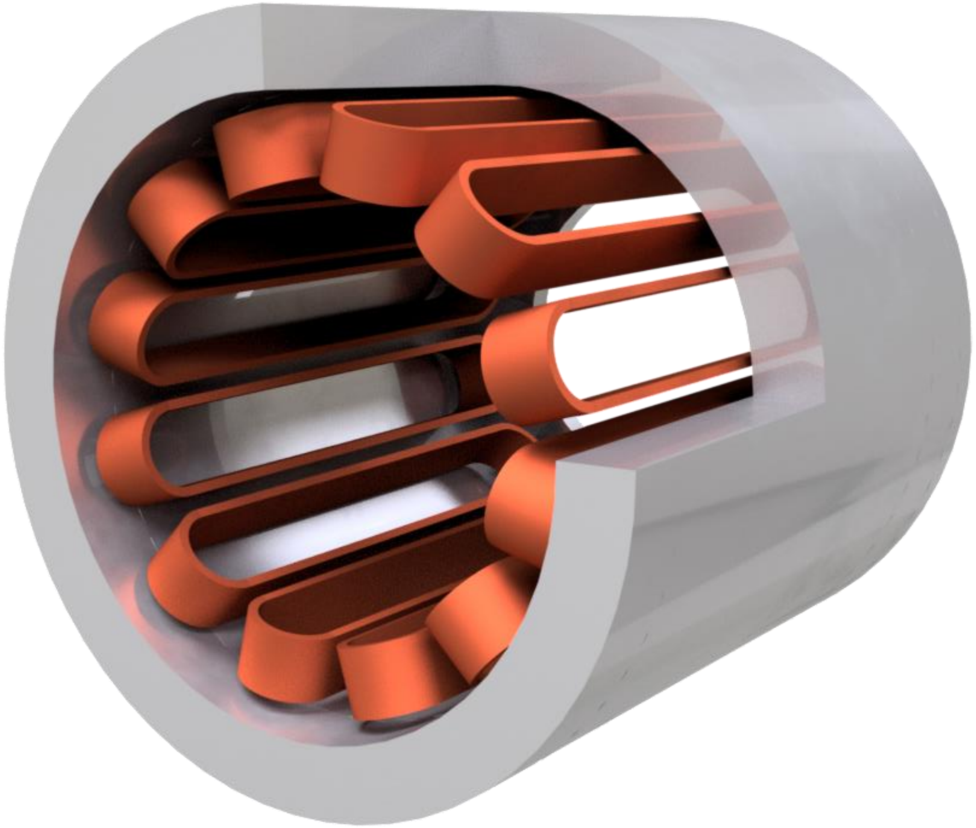


Open Points:
Not tunable Dipole component comparable with the main dipole of the ring.

Possible Solutions:

- In air coils to remove the iron pole, that is the main cause of non linearity -> high field quality and zero dipole field
- Modify the power supplier introducing an asimmetry in the coils or introduce an external coil -> control the dipole field

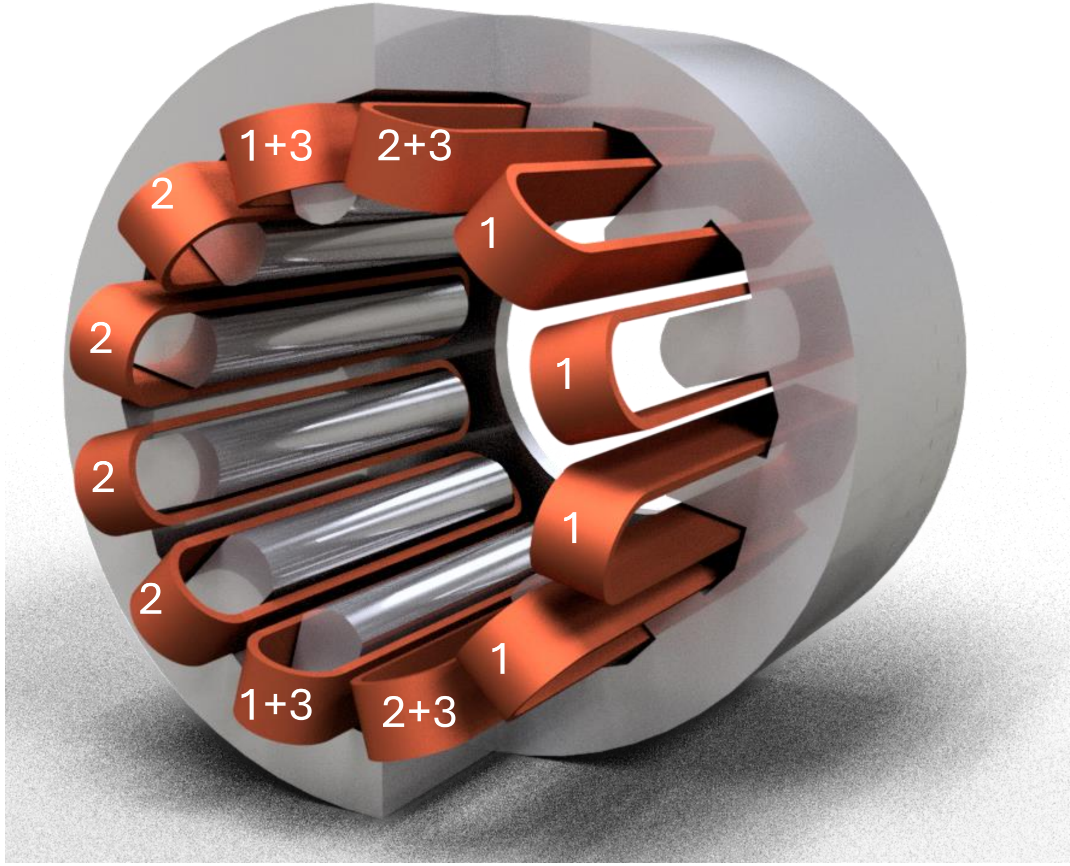
Design Proposal 1: In Air Coils



Main Features:

- Field generated mainly by coils
- High HTS use, up to 3 times the previews design
- Low dipole component compared to the main dipole field, down to a fraction of percentage
- Good Field Quality
- Easy assembly and manufacturing of the coil, larger bending radius

Design Proposal 2: Three Power Supplier



Main Features:

- Three power supplier, two main and a lower one to regulate
- Slight increase on the HTS use wtr the two power supplier design
- Able to cancel the dipole component

Future Developments:

- How to control the dipole field
- Analyze the full effect on the other high order harmonics

Open Points and Next Steps

Open exchange of ideas with PSI:
Compare our study with their proposals

Open Points

Field Quality and Magnet optimization
- Use of the combined magnet also as a dipole, to increase the filling factor
- Update with the new main ring optics
- Possible coupling between the two beam lines

Coil Construction
- Is it possible to have such a narrow coil?
- Insulated or Non insulated
- Junction and winding

ESMA project @ LASA plans to answer this questions

Next Steps

Energy Losses and Cryogenics
- Quench Analysis
- Cryocooling, Cryogen line?
- Cooling methods and thermal isolation, Iron mass is cold?

Mechanical structure and Assembly
- Supports, position of the walls and how to assemble it
- Lorentz forces analysis ad effect on the HTS material

Demostrator @ LASA
~ 0.5 m 2025-2026

Thank You For Your Attention!

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LASA

Energy Saving with HTS Magnet

Resistive filling factor	0.797802773	-
HTS filling factor	0.890007847	-
Resistive Synch. rad	50	MW turn
HTS Synch. rad	44-46	MW turn

$$P_{sync} \propto filling\ factor^{-2} \Longrightarrow \int over\ the\ dipoles \Longrightarrow E_{sync} \propto filling\ factor^{-1}$$