Technology Options for the Collider Magnets

S.Mariotto[1,2], A. Bersani[3], B.Caiffi[3],
S. Farinon[3], D. Novelli[3,4], T. Salmi[5], L. Bottura[6]

IMCC Collaboration Meeting, Orsay
21 June2023

[1]Università degli Studi di Milano, [2]INFN – Milano LASA, [3]INFN – Genova
[4]Università la Sapieza Roma, [5]Tampere University, [6]CERN

Outline

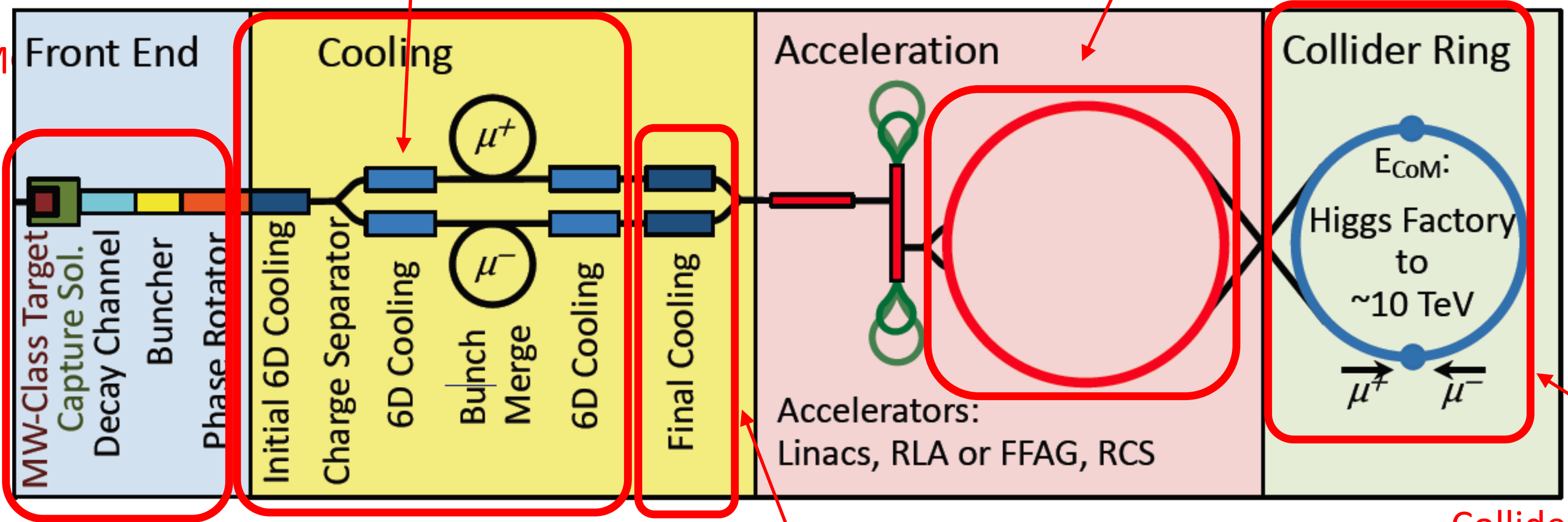
- Introduction
- Magnet requirements
- Technology options
- How to define technology limits
- Working plan
- Conclusion

Task 7.4

6D Cooling solenoids
Field: 4 T … 19 T
Bore: 90 mm … 600 mm
Length: 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

Accelerator magnets
Field: ±1.8 T (NC), < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m … 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD

Target solenoids
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1
Radiation dose: 80 M



Final Cooling solenoids
Field: > 40 T (ideally 60 T)
Bore: 50 mm
Length: ≈ 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD

Collider ring magnets
Field: 16 T peak (IR 20 T)
Bore: 150 mm
Length: 10 m … 15 m (x 700)
Radiation heat load: ≈ 5 W/m
Radiation dose: ≈ 20…40 MGy

Magnet Catalog

Courtesy of Luca Bottura

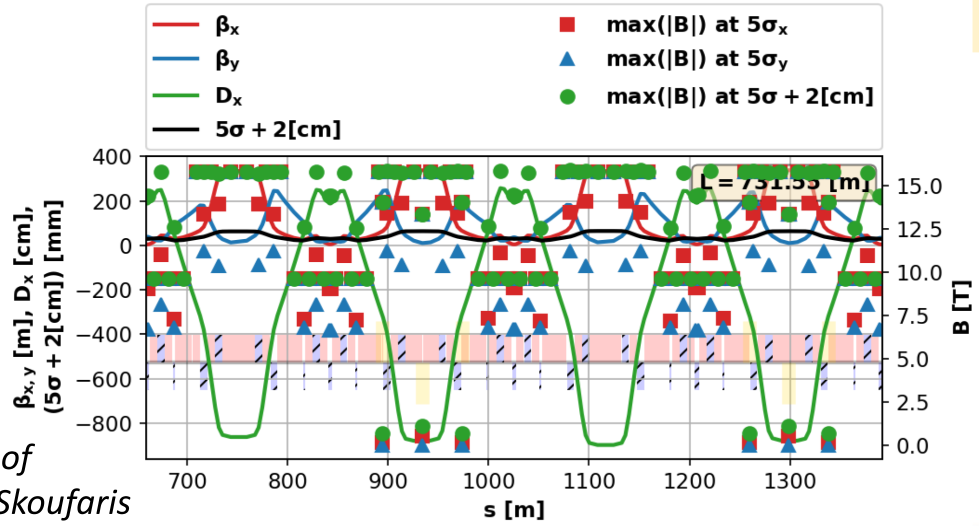
Assumptions for magnets scaling:

- **16 T** peak field CC/Arc
- **20 T** peak field at Final Focusing
- Required **flexibility of quadrupole/dipole** ratio
- space between magnets: 300 mm

Complex	Sector	Baseline	Magnet Type	Magnet technology	Field (T)	Gradient (T/m)	Aperture (mm)	Gap (mm)	Width (mm)	Length (m)	Number (-)	Ramp time (s)	Field rate (T/s) / (T/m/s)	Homogeneity (units)	Persistance (units/s)	Beam power deposition (kW/m)	Comments
Target and Capture	Target	baseline	solenoid	LTS	15		2400			2	1	21600	0.0007	100		1	baseline 15 T, 2.4 m bore design, assumes 6 hours ramp-up time and 5 kW deposited total power
		baseline	solenoid	NC	5		150			0.5	1	1	5.0000	100		100	baseline 5 T resistive insert
		option	solenoid	HTS	20		600			1.5	1	21600	0.0009	100	0.1	5	option based on a HTS cable, reduced bore and shielding, operating at 10…20 K
	Capture and decay channel		solenoid	TBD													
Cooling	Ionization Cooling	baseline	solenoid	TBD	2.2		600			2	66	21600	0.0001	100	0.1		cell A1
		baseline	solenoid	TBD	3.4		500			1.32	130	21600	0.0002	100	0.1		cell A2
		baseline	solenoid	TBD	4.8		380			1	107	21600	0.0002	100	0.1		cell A3
		baseline	solenoid	TBD	6		264			0.8	88	21600	0.0003	100	0.1		cell A4
		baseline	solenoid	TBD	2.2		560			2.75	20	21600	0.0001	100	0.1		call B1
		baseline	solenoid	TBD	3.4		480			2	32	21600	0.0002	100	0.1		call B2
		baseline	solenoid	TBD	4.8		360			1.5	54	21600	0.0002	100	0.1		call B3
		baseline	solenoid	TBD	6		280			1.27	50	21600	0.0003	100	0.1		call B4
		baseline	solenoid	TBD	9.8		180			0.806	91	21600	0.0005	100	0.1		call B5
		baseline	solenoid	TBD	10.5		144			0.806	77	21600	0.0005	100	0.1		call B6
		baseline	solenoid	TBD	12.5		98			0.806	50	21600	0.0006	100	0.1		call B7
		baseline	solenoid	TBD	13.6		90			0.806	61	21600	0.0006	100	0.1		call B8
	Final Cooling	baseline	solenoid	HTS	30		50			0.5	17	21600	0.0014			0	baseline design from US-MAP
		minimal option	solenoid	HTS	40		60			0.5	17	21600	0.0019	100	0.1	0	HTS NI option, including aperture margin
		target option	solenoid	HTS	60		60			0.5	17	21600	0.0028	100	0.1	0	HTS NI option, including aperture margin
Accelerator	RCS1		dipole	NC	1.8			30	100	8.08	432	7.35E-04	2448.980	10			
	RCS2		dipole	LTS	10		100			2.4	288	1000	0.010	10			
			dipole	NC	1.8			30	100	6.06	432	1.80E-03	1000.000	10			
	S3		dipole	LTS	10		100			2.6	288	1000	0.010	10			
			dipole	NC	1.8			30	100	5.05	432	1.80E-03	1000.000	10			
	S4		dipole	LTS	10		100			2.6	288	1000	0.010	10			
			dipole	NC	1.8			30	100	5.05	432	8.46E-03	212.716	10			
	:		dipole	HTS	10	300	150					1000	0.010	10		0.5	

Location	Function	Technology	Dipole Field [T]	Quadrupole [T/m]	Aperture [mm]
ARC	Dipole	HTS	10	[illegible]00	150
IR	Quadrupole	HTS		4[illegible]32	171.4
	Quadrupole	HT[illegible]		[illegible].93	212.2
	Quadrupole	[illegible]S		300.71	266
	Quadrupole	[illegible]S		191.41	417
	Quadrupole	HTS		214.03	411.2

OLD



Courtesy of Kyriacos Skoufaris

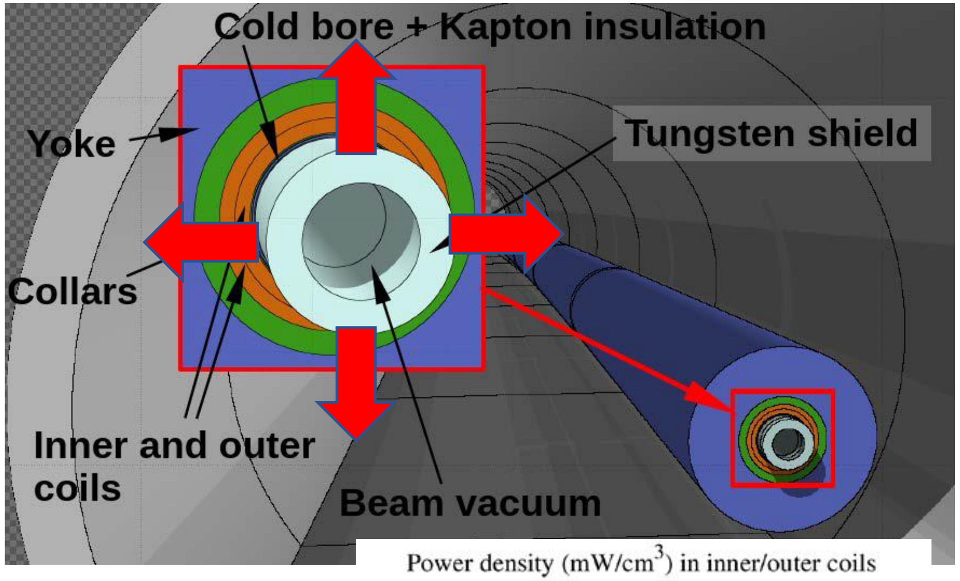
See “Beam dynamics requirements”
K. Skoufaris, https://indico.cern.ch/event/1183573

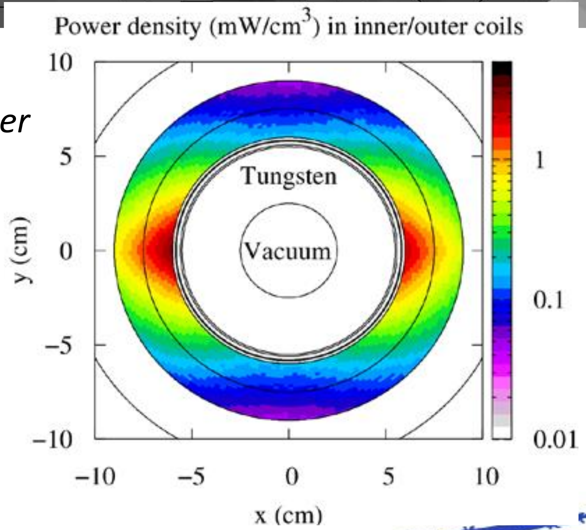
Heat Load and Radiation

Input by other studies:

Calculations of the heat load on magnet coils

- Use of a W shielding (**2-4 cm** thick)
- Considered 3 TeV and 10 TeV config





Courtesy of Anton Lechner

Results:

- Power penetrating shield: **5W/m**
- **Cumulative dose** equals to 20-40 MGy in 10 years of operation
- **DPA max 1.3E-4** after 10 years

Shield thickness → 4 cm to limit cumulative dose

See "Shielding design and requirements"
A. Lachner, https://indico.cern.ch/event/1183573

Radial Building

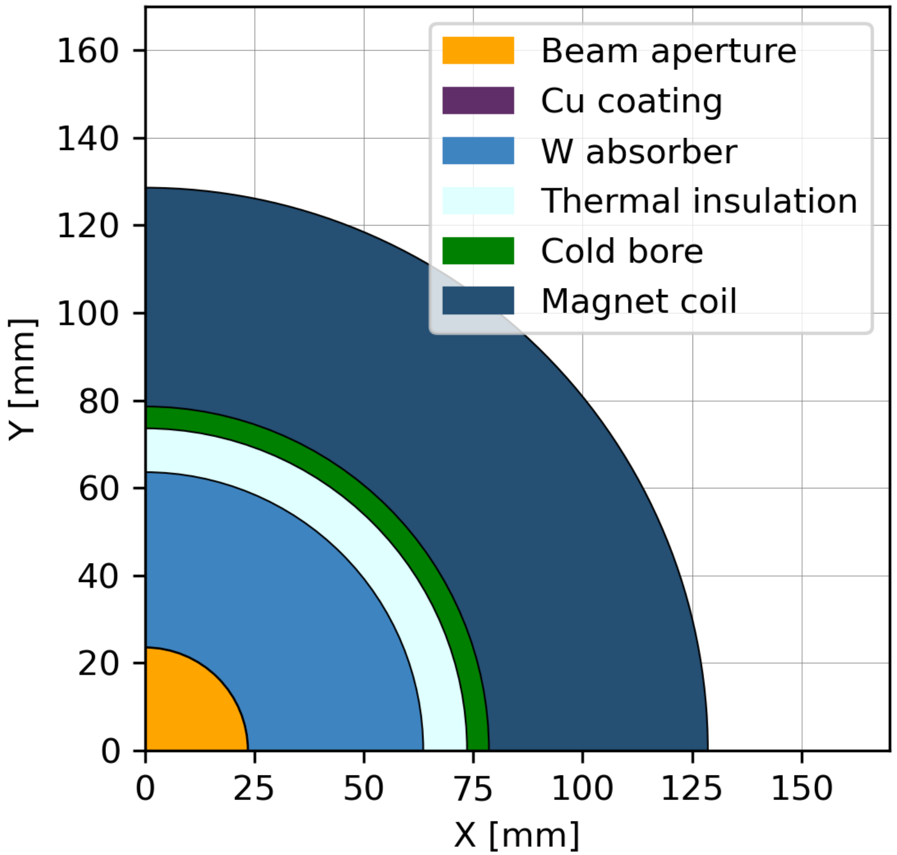
Cryogenic options calculated using same assumption of heat load calculations

- $T_{absorber} > 250\ K$
- $T_{coil} > 4.5\ K$
- $W_{elett} < 2.5\ kW/m$

→ Heavily **dependent** from **geometry** and heat loads

How to share last update designs?
Radial Building

• Beam aperture (5σ)	23.5 mm radius
• Cu layer beam screen	0.01 mm thick
• Tungsten absorber	40 mm thick
• Thermal insulation	11 mm thick
• Cold bore	3 mm thick
• Coil pack	50 mm thick



Courtesy of Patricia Borges De Sousa

See "Cryogenics options for future accelerators"
Patricia Borges De Sousa, https://indico.cern.ch/event/1240043

Material Options

<table>
<tr><th colspan="2">Technology</th><th>Pro’s</th><th>Con’s</th></tr>
<tr><td colspan="2">LTS (Nb-Ti)</td><td>• Known and well developed technology (TRL 8)</td><td>• Probably do not meet all magnet requirements</td></tr>
<tr><td colspan="2">LTS (Nb_3Sn)</td><td>• Known technology, reaching demonstration level in accelerators (TRL 6/7)</td><td>• Probably do not meet all magnet requirements
• Brittle/stress limited</td></tr>
<tr><td colspan="2">Hybrid
(LTS Nb_3Sn) + (HTS)</td><td>• Lower cost
• Exploit potential of both materials</td><td>• Low readiness level for HTS insert (TRL 3/4)
• LTS/HTS joints and integration to be developed
• Temperature limited by LTS</td></tr>
<tr><td rowspan="3">All-SC (HTS)</td><td>Insulated</td><td rowspan="3">• Most compact solution
• Allows operation at high temperature
• Profit from on-going R&D activities on insulation/no-insulation windings</td><td rowspan="3">• R&D at low readiness (TRL 3/4)
• Quench protection to be demonstrated
• Field delay and field stability in case of NI winding</td></tr>
<tr><td>Controlled Insulated</td></tr>
<tr><td>Non Insulated</td></tr>
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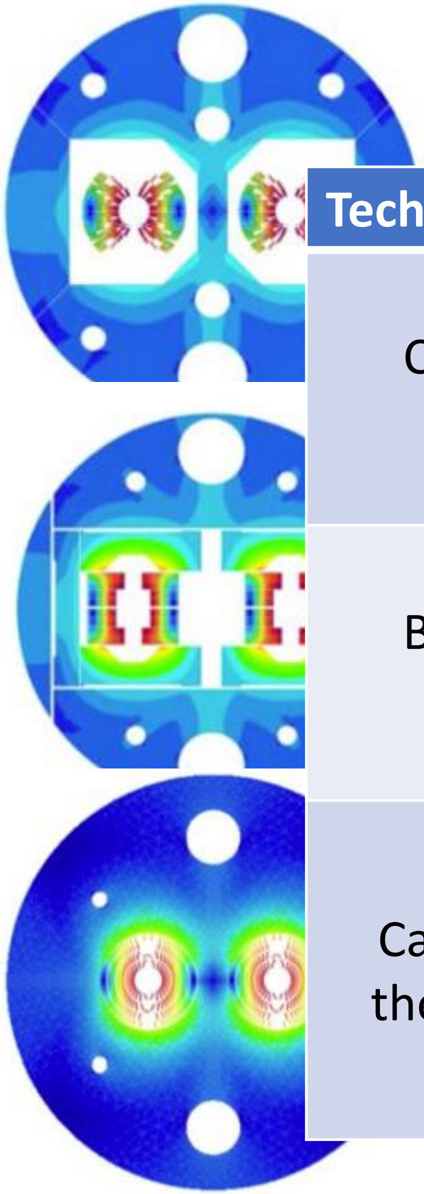
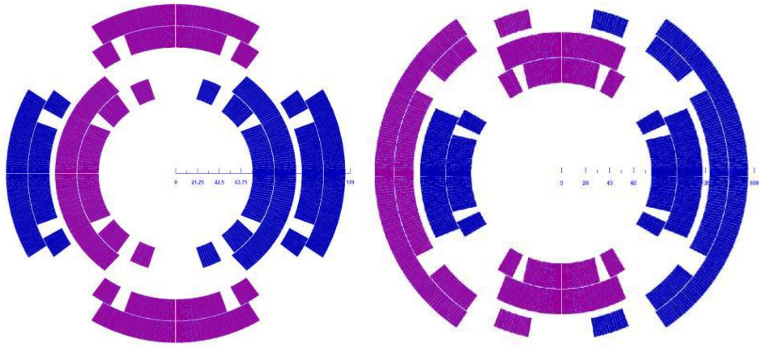
Design Options (1/2)

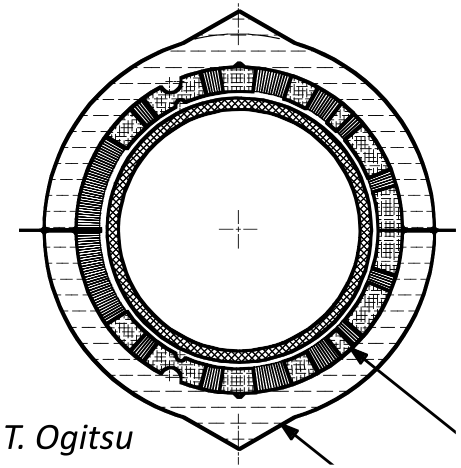

CCT

Technology	Pro’s	Con’s
Cos-theta Design	• Well known design • Wound around a cylindrical mandrel, end shape already suitable for beam tube insertion	• Mechanical structure can be complex • Not most easy winding geometry for HTS tapes
Block Coil Design	• Known design principles • Mechanical structure simplify stress management • Easier geometry for HTS-tapes	• Difficult stress management on coil ends • Higher ratio conductor length/produced field
Canted Cos-theta Design	• Intrinsic stress management • Low number of parts and tools • Easy winding procedure	• Requires more cable than the other layouts • Quench protection more difficult • R&D needed

Design Options (2/2)

A. Zlobin

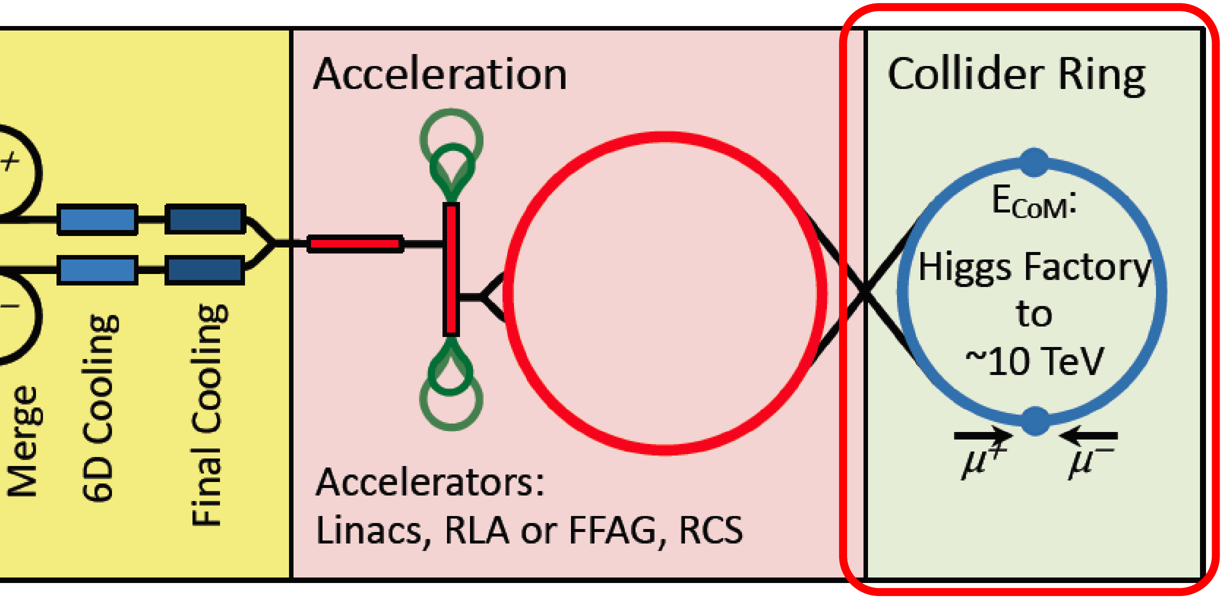




T. Ogitsu

Technology	Pro's	Con's
NESTED Configuration	• Separate Powering Dipole/Quadrupole • Inherit experience on Nb_3Sn magnets for HiLumi and LARP-US development program	• High Stress on Internal Coil • Alignment • Higher Costs
Asymmetric Coil Design	• Single type of coil • Optimized margin and field quality	• Fixed Dipole/Quadrupole ratio • Stress on the supporting structure is not balanced

Working Group



INFN Milano

S. Mariotto, M. Statera, M. Prioli, E. De Matteis, R. Valente, S. Sorti

INFN Genova

B. Caiffi, A. Bersani, S. Farinon, D. Novelli

CERN

L. Bottura, A. Lechner

Tampere University

T. Salmi

Synergies

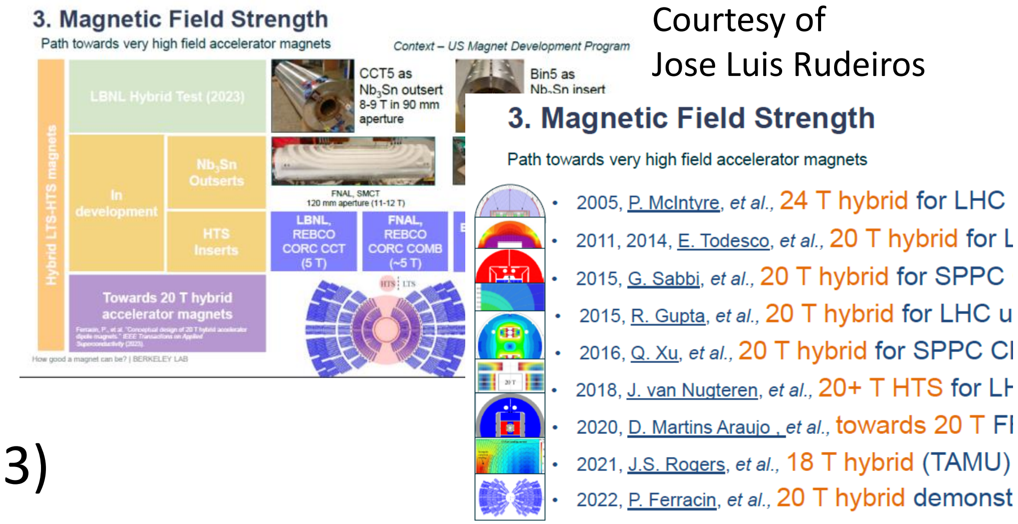
Huge help and feedback will come from:

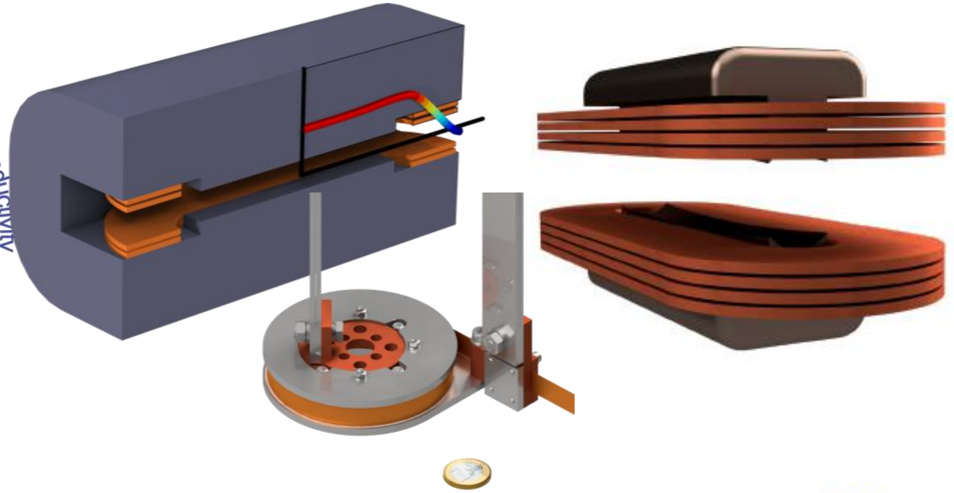
- 20T+ development program US
- CERN – HFM

Possible feedback loop also inside INFN
PNRR-IRIS project (see L. Balconi 20-05-2023)
ans small HTS coil pancake program

- 10 T of dipolar field
- Bore dimensions 80x50 mm^2
- Operating temperature 20 K
- Physical L < 1 m

Courtesy of
Jose Luis Rudeiros





Analytical Expressions

Presentation: "Collider magnets designs and limits"
D. Novelli, IMCC Collaboration Meeting, 20-06-2023

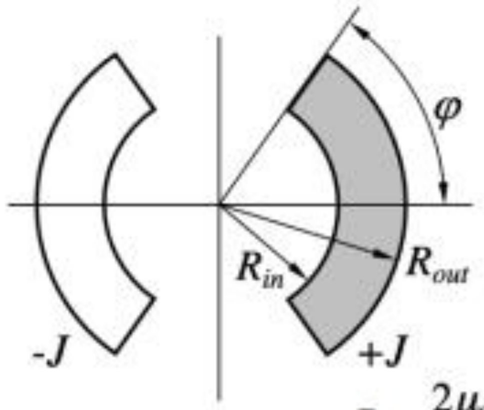
Use of analytical formulae for fast estimation of magnet scaling and limits

- Analysis of different materials:
  - NbTi (1.9 K)
  - Nb_3Sn (4.2 K)
  - HTS (*Re*BCO) (4.2 K and 20 K)

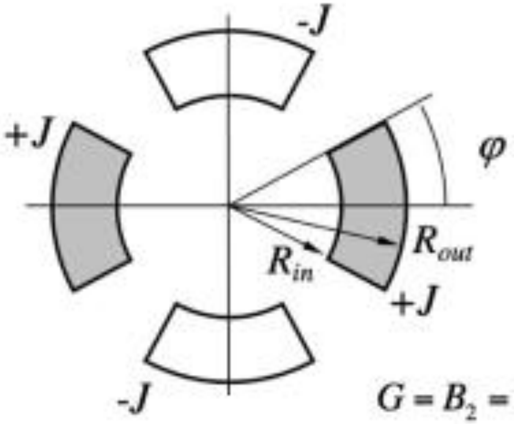
- Selection of scaling laws and fixed parameters
- Evaluation of peak field, forces, FQ…

→ (Aperture, BField) < LIMITS

1. Hot-Spot T_{MAX}
2. σ_{MAX}
3. \$ Cost



$$B_1 = \frac{2\mu_0}{\pi} J (R_{out} - R_{in}) \sin(\varphi)$$



$$G = B_2 = \frac{2\mu_0}{\pi} J \ln\left(\frac{R_{out}}{R_{in}}\right) \sin(2\varphi)$$

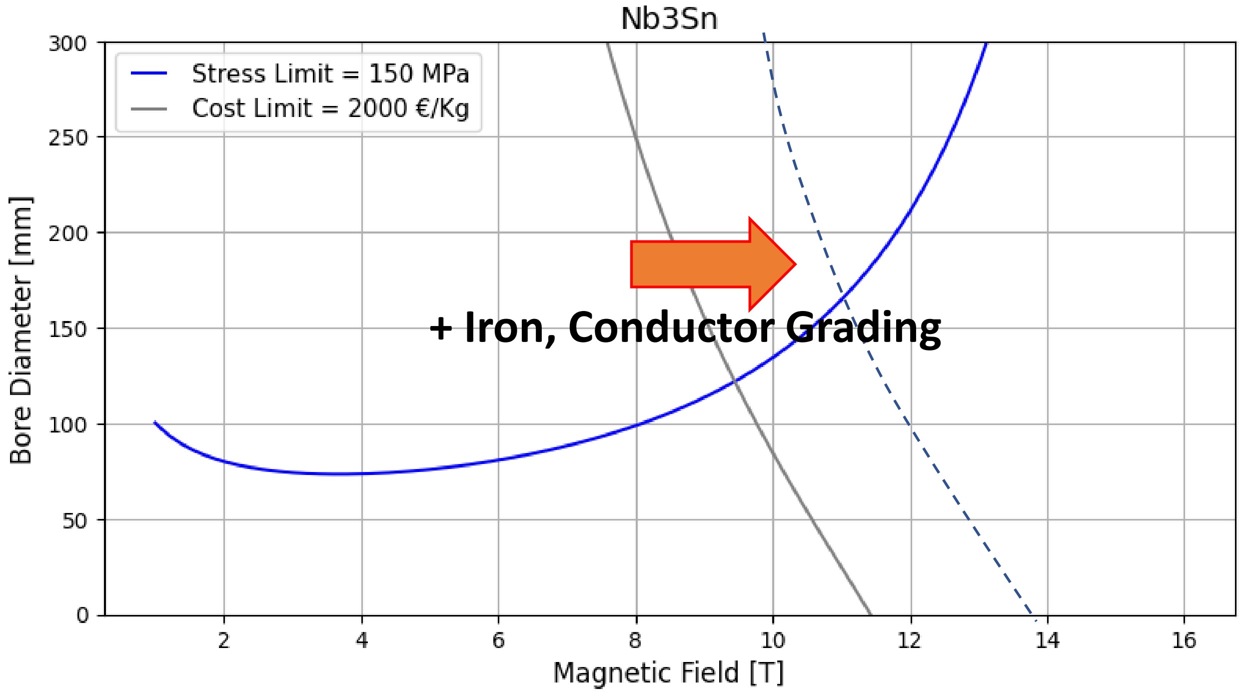
Analytical Expressions

How we start? Fixed paramater values which link all magnet configurations

→ Fixed Enthalpy Margin

ρC_p $T_1 = T_{op} + \Delta T$ Sector Coil Approx

$$\Delta H \rightarrow \Delta T \rightarrow J_{eng} = f_{sc} J_{sc}(B, T_1) \rightarrow w = f\left(B, J_{eng}\right) \rightarrow \sigma_{MAX} = g(w, B, J_{eng}, r)$$



PROBLEM:
Low B ↔ Very high J_{eng} and viceversa

Quench Protection:
Low field becomes IMPOSSIBLE
High field becomes EASY

Analytical Expressions

What about fixing the maximum engeneering current density?

Sector Coil Approx

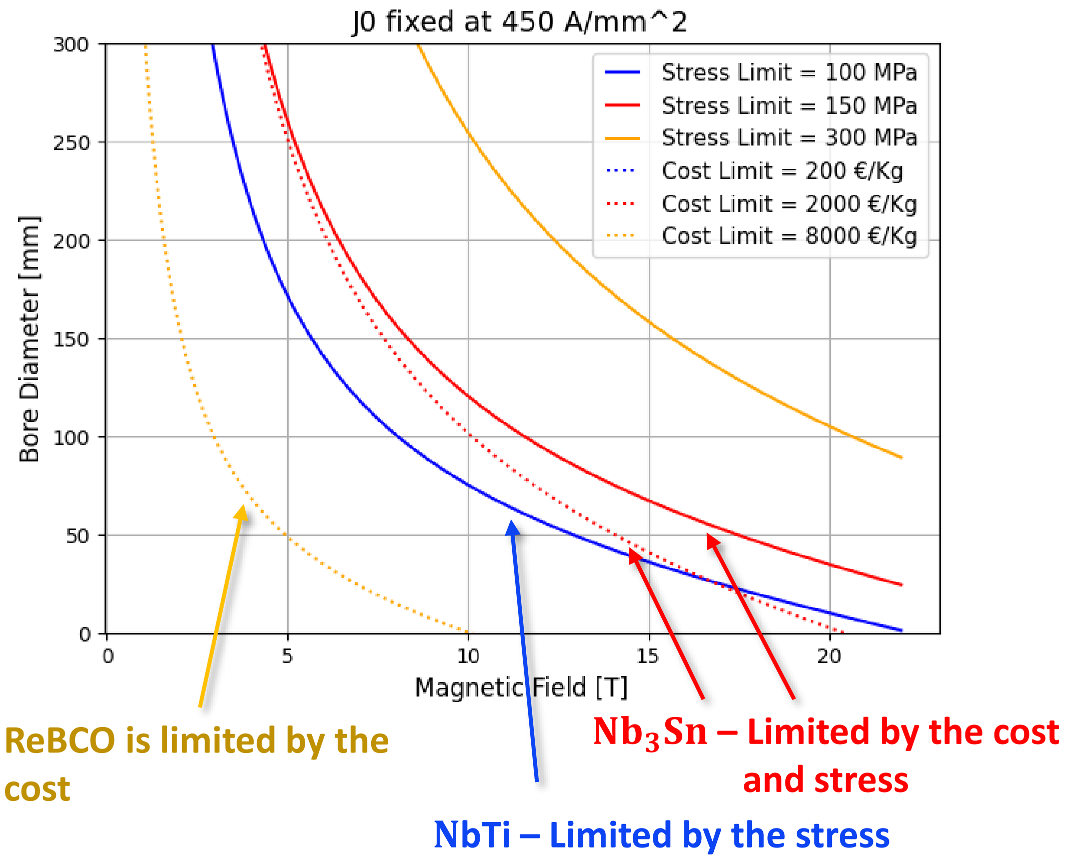
$$w = f(B, J_{eng}) \rightarrow \sigma_{MAX} = g(w, B, J_{eng}, r)$$

PROBLEM: Magnet are NOT OPTIMIZED

- High B values → Very Low Margin
  - NbTi (< 10T), Nb3Sn (< 12T), ReBCO @ LT (< 20 T)
- Low B values can be protected!!!!

Nb_3Sn and HTS best technologies

- **Nb_3Sn** limited by **stress on the conductor** (brittle)
- **All-HTS** solutions still limited by **cost limits**
  - ReBCO @ 20 K could work close to critical surface (high field and bore diameter)

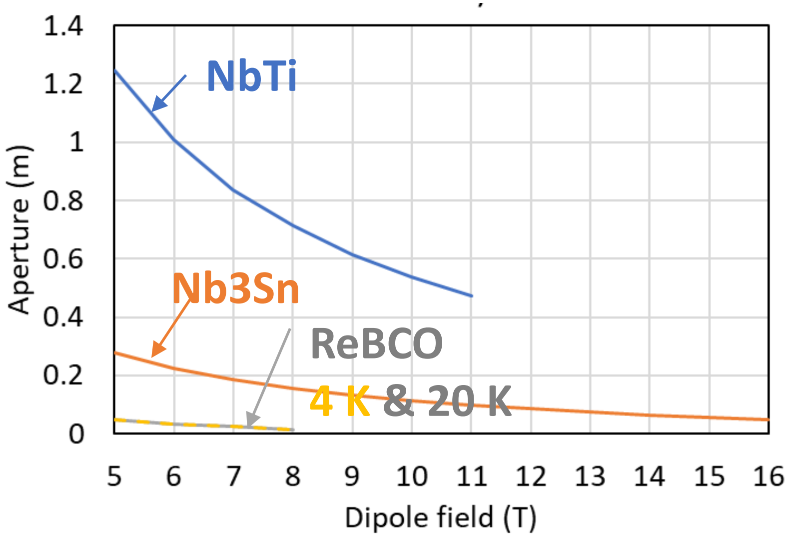


Analytical Expressions

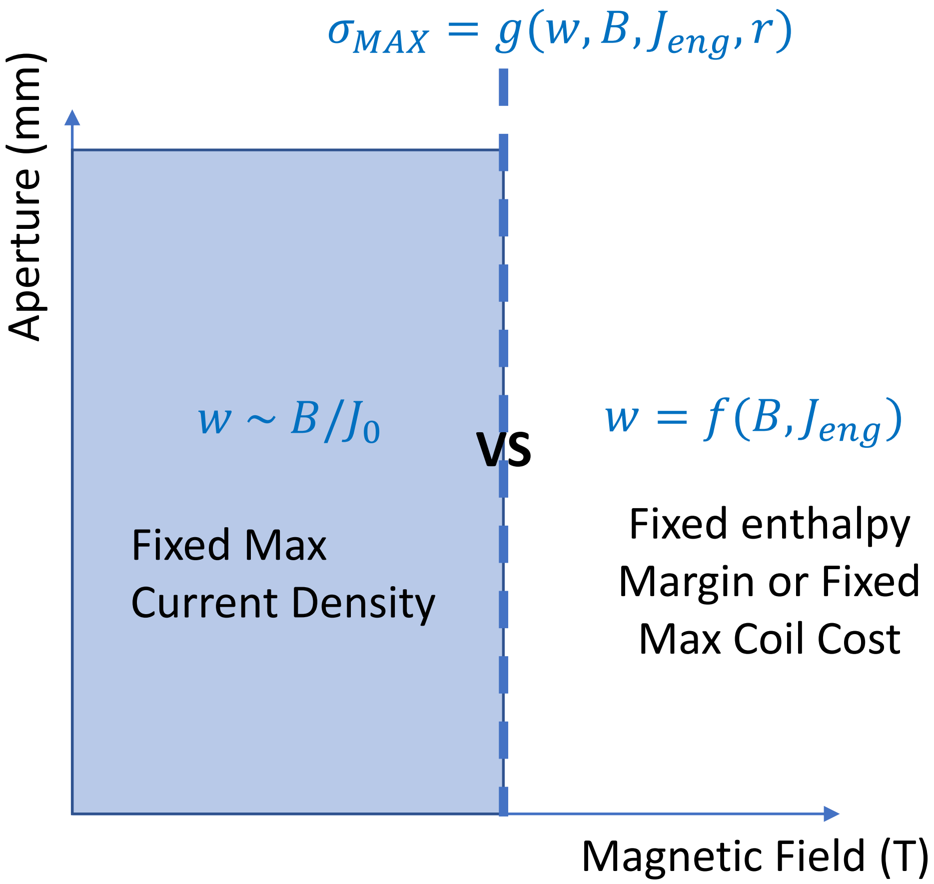
TO DO: Mixed approach using constant engeneering current density @ low B and maximum coil cost @ high B values

Observation:

- $\sigma_{MAX}(B, R)$ for a fixed enthalpy margin at high B field diverge because the coil $w \to \infty$
- Limited *w* only with the fixed max coil cost



Courtesy of T. Salmi



Project Plan (1/2)

Author: Siara Fabbri

Today: 15/6/2023

	2023				2024				2025				2026				2027			
	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1
	S	S	S	S	M	M	M	T	W	T	T	W	T	W	W	T	F	T	T	F

TASK		OBJECTIVES (can be in Parallel)	COLLABOR/	PROGRESS	MONTHS	START	END
	1	Initiate and maintain meetings with beam/shield/cryo/vacuum on magnet specifications and accelerator configuration	INFN		continuous		
	2	Collect first evaluation of the performance specifications required for the design (Physical Aperture, Dipole Field, Quadrupole Field,	INFN		12.0		
		First version		80%	6.0	1-Jan-23	#######
		Draft final version		0%	3.0	1-Jul-23	#######
		Final version		0%	3.0	1-Oct-23	#######
	3	Setup analytic expressions for fast evaluation of magnet parameters (Main Component, Peak Field, Field Errors, Forces). Analytic study of relative weight of a combined function magnet	INFN		18.0		
		First version		75%	6.0	1-Jan-23	#######
		Draft final version		0%	6.0	1-Jul-23	#######
		Final version		0%	6.0	1-Jan-24	#######

Courtesy of Siara Fabbri

First part of the Proposal:

- Summary of all **magnet requirements**
- Evaluation of **analytical formulae** to rapidly scale and evaluate D/Q and D/S config.
- Interaction with other workpackages and **iterate**

Project Plan (2/2)

Author: Siara Fabbri

Today: 15/6/2023

	2023				2024				2025				2026				2027			
	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1	gen 1	apr 1	lug 1	ott 1
	S	S	S	S	M	M	M	T	W	T	T	W	T	W	W	T	F	T	T	F

TASK		OBJECTIVES (can be in Parallel)	COLLABOR/	PROGRESS	MONTHS	START	END
TASK 4 Collider Complex		Final version		0%	6.0	1-Jan-24	######
	4	<u>Basic decisions on:</u> 1) Select the material of the conductor (Nb3Sn, HTS, Hybrid) for the ARC and IR magnets 2) Conductor configuration, margin and protection 3) Open midplane 4) Operating temperature 5) LTS/HTS	INFN		24.0		
		Tentative version			18.0	1-Jan-23	1-Jun-24
		Final version			6.0	1-Jul-24	######
	5	<u>Dipole magnet design - select layout of the coil (Block, CosTheta) for the ARC and IR magnets:</u> 1) Select Nested/Asymmetric Coil for the ARC Magnets	INFN		30.0	1-Jan-25	######
	6	<u>**Milestone (M7.5)**: Report on high-field collider magnet design - by Nov. 31 2025</u>				######	######
	7	<u>**Milestone (M7.8)**: Workshop on high-field collider magnets - by Nov. 1 2026</u>				1-Nov-26	1-Nov-26
	8	Cost and power estimate	INFN		54.0		
		First draft		0%	12.0	1-Jan-23	######
		Draft final version		0%	18.0	1-Jan-24	######
		Final version		0%	24.0	1-Jul-25	######

Courtesy of Siara Fabbri

- Basic desicions on materials (HTS/LTS, Hybrid), layout, T_{op}, protection
- Main combined function ARC dipole design and limits for IR magnets (**M7.5 – Dec 2025**)
- Estimation of costs and power (**M7.7 – Sep 2026**)

Conclusions

- Several **technological requirements** for the collider magnet design **identified** have been used to produce a **radial building method** to share design updates
- Analysis of the performance of available superconductors:
  - **Nb3SN and HTS** (insulated, controlled insulated, non insulated), Hybrid
- **3 different design options** are presently considered for the design study (costheta, block coil and canted)

- Requirements of **combined function magnets**: Nested vs Asymmetric Solutions

- Working plan divided in three main parts:
  - Development of **analytical formulae** to rapidly converge to final beam optic
  - Decision of **best promising design** to be fully analyzed and optimized
  - Production of conceptual design report focused on **main combined arc magnets** (most challenging)

Thank you
for your attention