Target, decay and capture solenoid

L. Bottura, C. Accettura, B. Bordini, A. Kolehmainen,
R. Losito, J. Manczack, G. Lerner, A. Lechner, CERN
J. Lorenzo Gomez, A. Portone, P. Testoni, F4E

Seminar Series
for the National Lab Muon Accelerator Study Group
26 January 2026

Partly funded by the European Union under
Grant Agreement n. 101094300

Outline

- From US-MAP to IMCC
- Supporting analysis
- IMCC design evolution
- Issues and next steps
- A “20@20” model coil demonstrator
- Conclusions and perspectives

Outline

- From US-MAP to IMCC
- Supporting analysis
- IMCC design evolution
- Issues and next steps
- A “20@20” model coil demonstrator
- Conclusions and perspectives

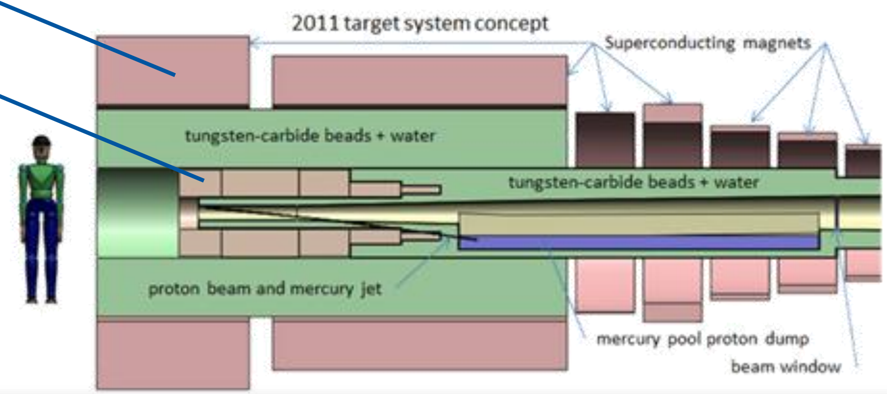
CERN

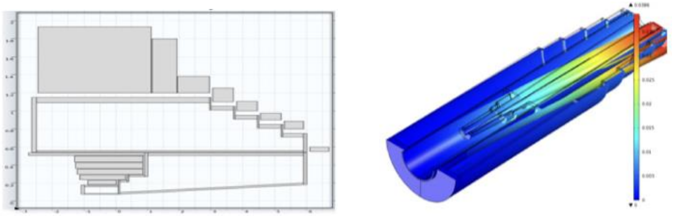
Target solenoid – The beginning with US-MAP

Superconducting (LTS) outsert

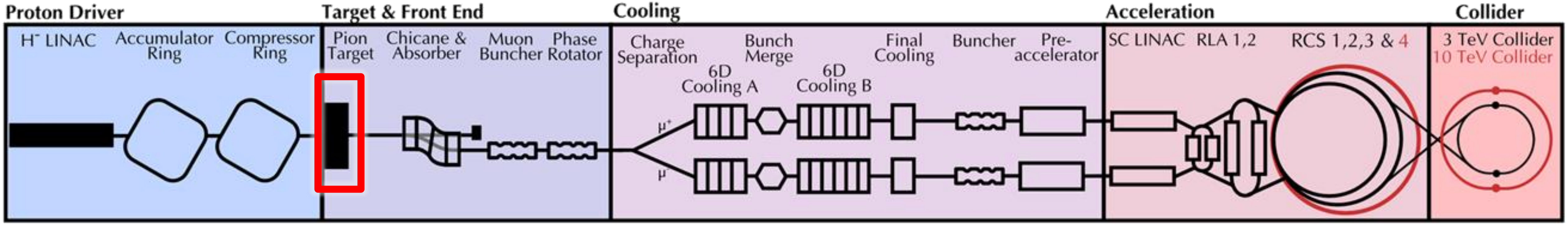
Rad-hard resistive insert

Field on target 20 T, 150 mm
Beam power on target: 1…2 MW





R.J. Weggel, et al., *A Target Magnet System for a Muon Collider and Neutrino Factory*, Proc. IPAC2011, pp. 1650-1652, 2011.
R.J. Weggel, et al., Design of the Magnets for the Target and Decay Region of a Muon Collider/Neutrino Factory,
Proc. IPAC2013, pp. 1514-1516, 2013.,

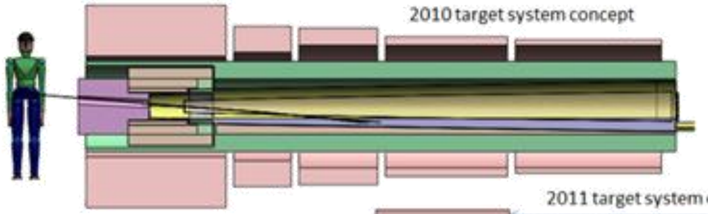


Large stored energy o(2) GJ, mass o(300) tons (cost o(100) M)

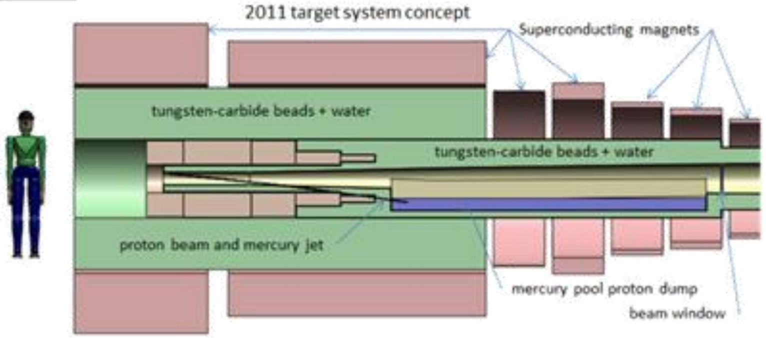
Target solenoid – Enter HTS

- Reduce the mass (CAPEX) of the system, and increase operating temperature to improve cryogenic CoP (OPEX)

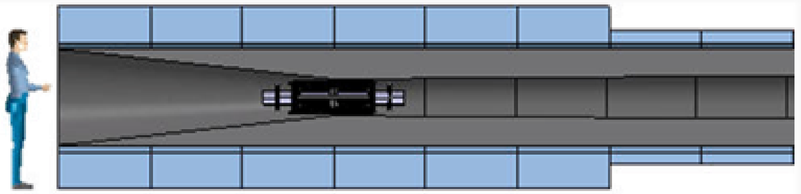
US-MAP **2010** design
LTS (14 T) + NC (6 T)



US-MAP **2011** design
LTS (14 T) + NC (6 T)



MuCol **2022** design
HTS (20 T, 20 K)



C. Accettura, et al., *Conceptual Design of a Target and Capture Channel for a Muon Collider*, IEEE TAS 34, 4101705, 2024

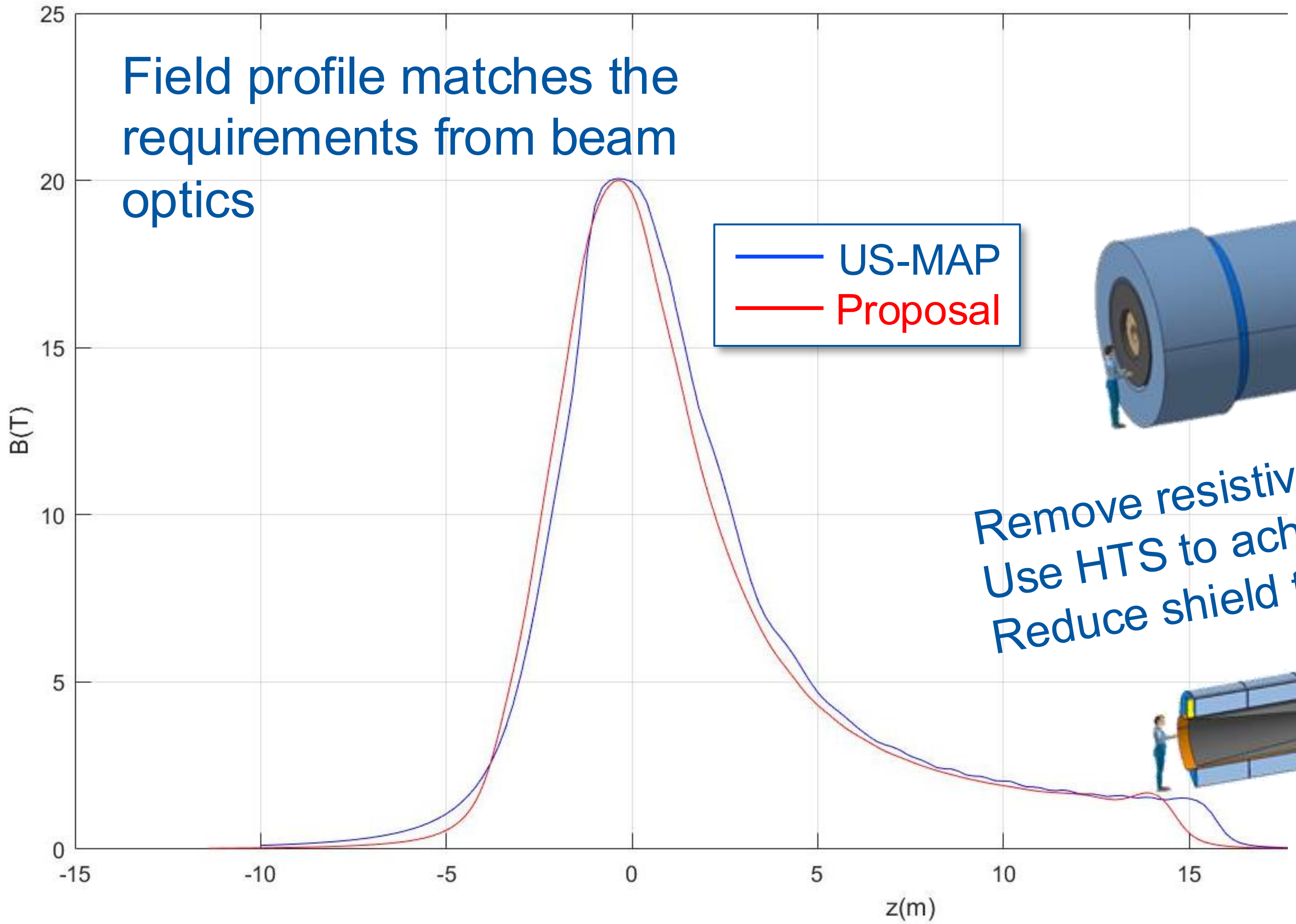
L. Bottura, et al., *Design and Analysis of a HTS Internally Cooled Cable for the Muon Collider Target and Capture Solenoid Magnets*, Cryogenics 144, 103972, 2024

Magnet	z_{min} (cm)	Δz (cm)	r_{min} (cm)	Δr (cm)	I (A/mm^2)
RC1	-131.3	47.3	17.8	30.24	16.56
RC2	-84	86.2	17.8	30.88	16.56
RC3	2.1	56.2	17.8	30.25	16.56
RC4	58.3	57	17.8	16.6	16.56
RC5	115.3	43.5	21.88	7.96	16.56
SC1	-222.6	169.4	120	75.85	23.22
SC2	-53.1	26.1	120	54	0
SC3	-27.1	327.1	120	54.07	23.1
SC4	310	65	110	1.16	29.96
SC5	385	65	100	20.76	33.31
SC6	460	65	90	6.4	35.85
SC7	535	65	80	8.71	38.21
SC8	610	65	70	5.61	40
SC9	685	65	60	6.06	40
SC10	760	65	50	4.72	40
SC11	835	65	45	4.6	40
SC12	910	65	45	4.42	40
SC13	985	65	45	4.31	40
SC14	1060	65	45	3.85	40
SC15	1135	65	45	3.83	40
SC16	1210	65	45	3.51	40
SC17	1285	65	45	3.53	40
SC18	1360	65	45	3.44	40
SC19	1435	140	45	3.24	40

Target solenoid – Comparison

E_M = 2.9 GJ
T_{op} = 4.2 K
M_{coils} = 200 tons
M_{shield} = 300 tons
P = 12 MW

Field profile matches the requirements from beam optics

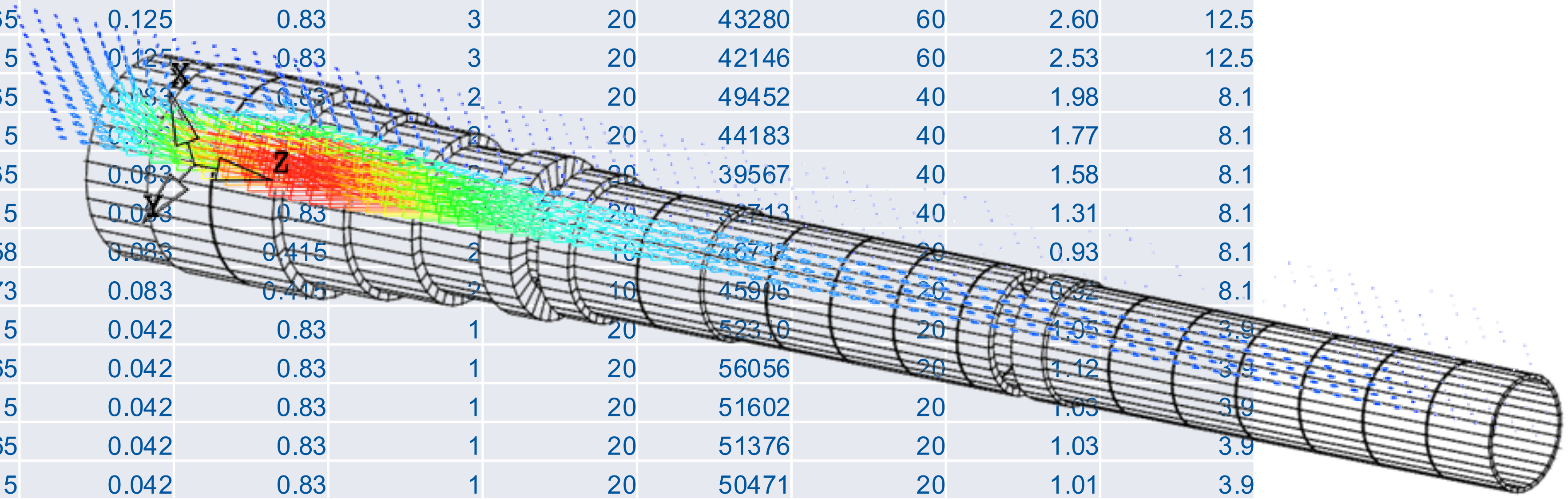


Remove resistive insert (10 MW)
Use HTS to achieve field of 20 T
Reduce shield thicknes, accept higher heat load at 20 K (4 kW)

E_M = 1 GJ
T_{op} = 10…20 K
M_{coils} = 110 tons
M_{shield} = 196 tons
P = 1MW

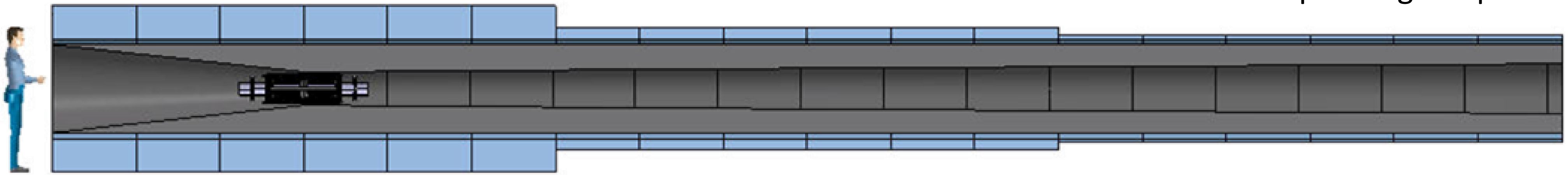
IMCC design – coils

Coil	Rc (m)	Zc (m)	dR (m)	dZ (m)	Layers (-)	Pancakes (-)	Iconductor (A)	Turns (-)	Icoil (MA-turn)	Lpancake (m)
1	0.849	-0.185	0.498	0.83	12	20	58905	240	14.14	64.0
2	0.87	0.665	0.54	0.83	13	20	60710	260	15.78	71.1
3	0.87	1.515	0.54	0.83	13	20	60392	260	15.70	71.1
4	0.808	2.365	0.415	0.83	10	20	51654	200	10.33	50.8
5	0.766	3.215	0.332	0.83	8	20	47469	160	7.60	38.5
6	0.704	4.065	0.208	0.83	5	20	46504	100	4.65	22.1
7	0.745	4.708	0.291	0.415	7	10	46293	70	3.24	32.8
8	0.704	5.423	0.208	0.415	5	10	53168	50	2.66	22.1
9	0.662	6.065	0.125	0.83	3	20	43280	60	2.60	12.5
10	0.662	6.915	0.125	0.83	3	20	42146	60	2.53	12.5
11	0.642	7.765	0.083	0.83	2	20	49452	40	1.98	8.1
12	0.642	8.615	[illegible]	[illegible]	2	20	44183	40	1.77	8.1
13	0.642	9.465	0.083	0.83	[illegible]	20	39567	40	1.58	8.1
14	0.642	10.315	0.083	0.83	[illegible]	20	32713	40	1.31	8.1
15	0.642	10.958	0.083	0.415	2	10	46717	20	0.93	8.1
16	0.642	11.673	0.083	0.415	2	10	45905	20	0.92	8.1
17	0.621	12.315	0.042	0.83	1	20	52310	20	1.05	3.9
18	0.621	13.165	0.042	0.83	1	20	56056	20	1.12	3.9
19	0.621	14.015	0.042	0.83	1	20	51602	20	1.03	3.9
20	0.621	14.865	0.042	0.83	1	20	51376	20	1.03	3.9
21	0.621	15.715	0.042	0.83	1	20	50471	20	1.01	3.9
22	0.621	16.565	0.042	0.83	1	20	52861	20	1.06	3.9
23	0.621	17.415	0.042	0.83	1	20	57438	20	1.15	3.9



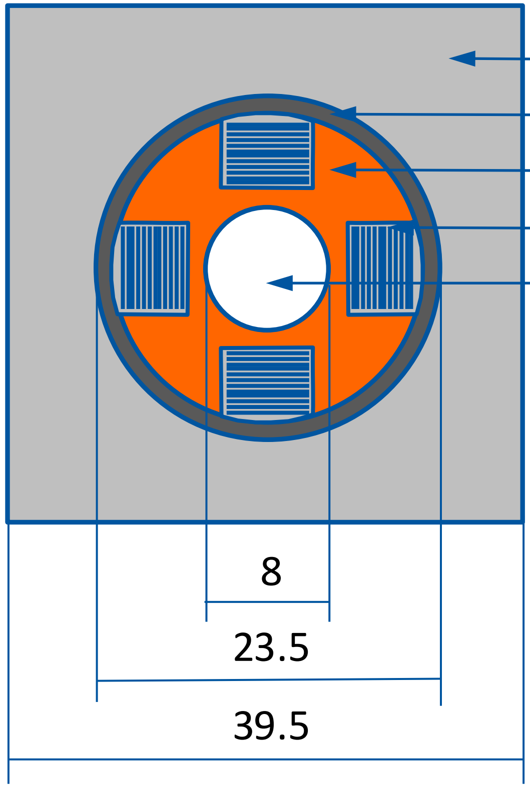
Solenoids design (2022)

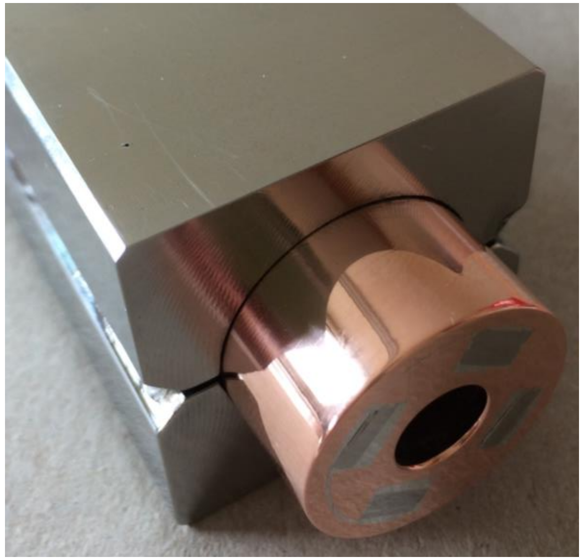
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K



MIT “VIPER” conductor

M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

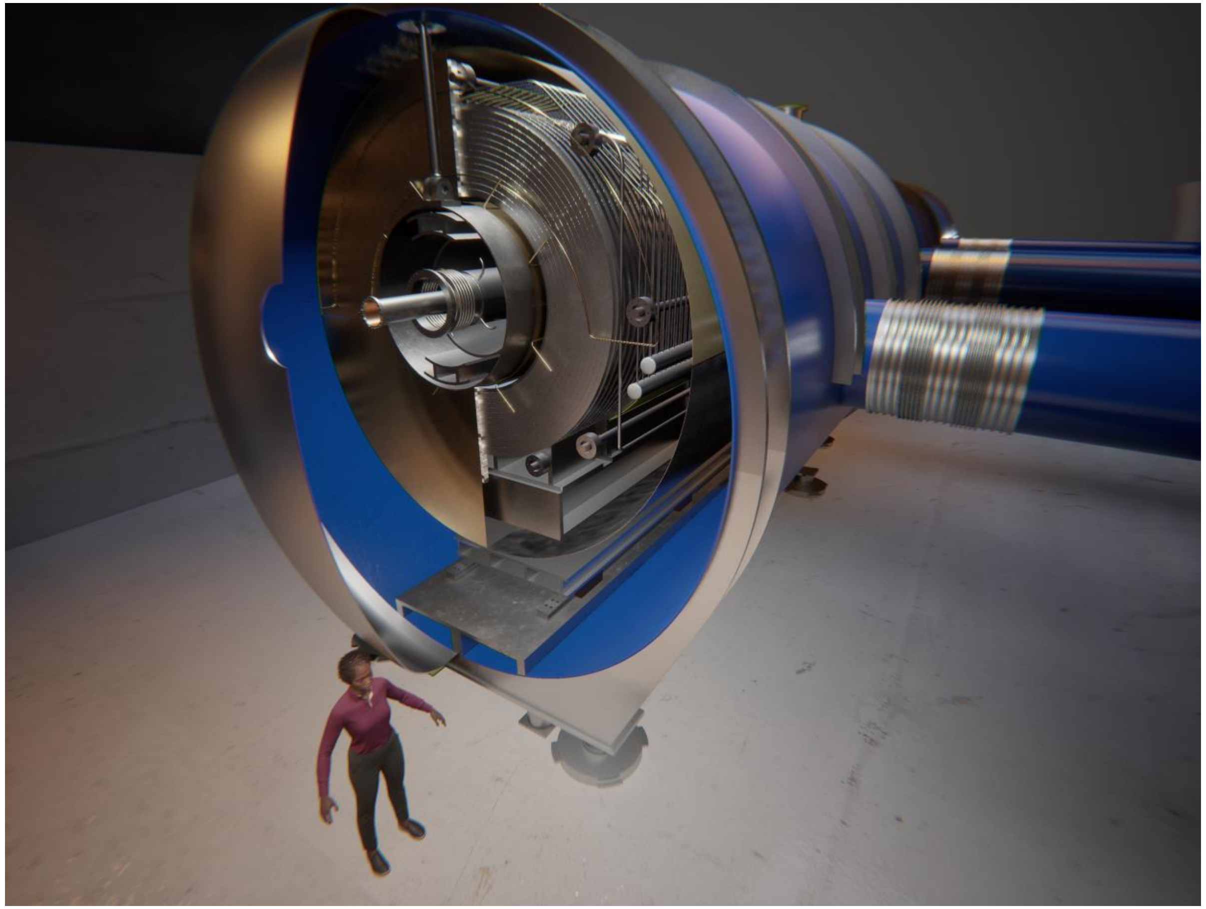


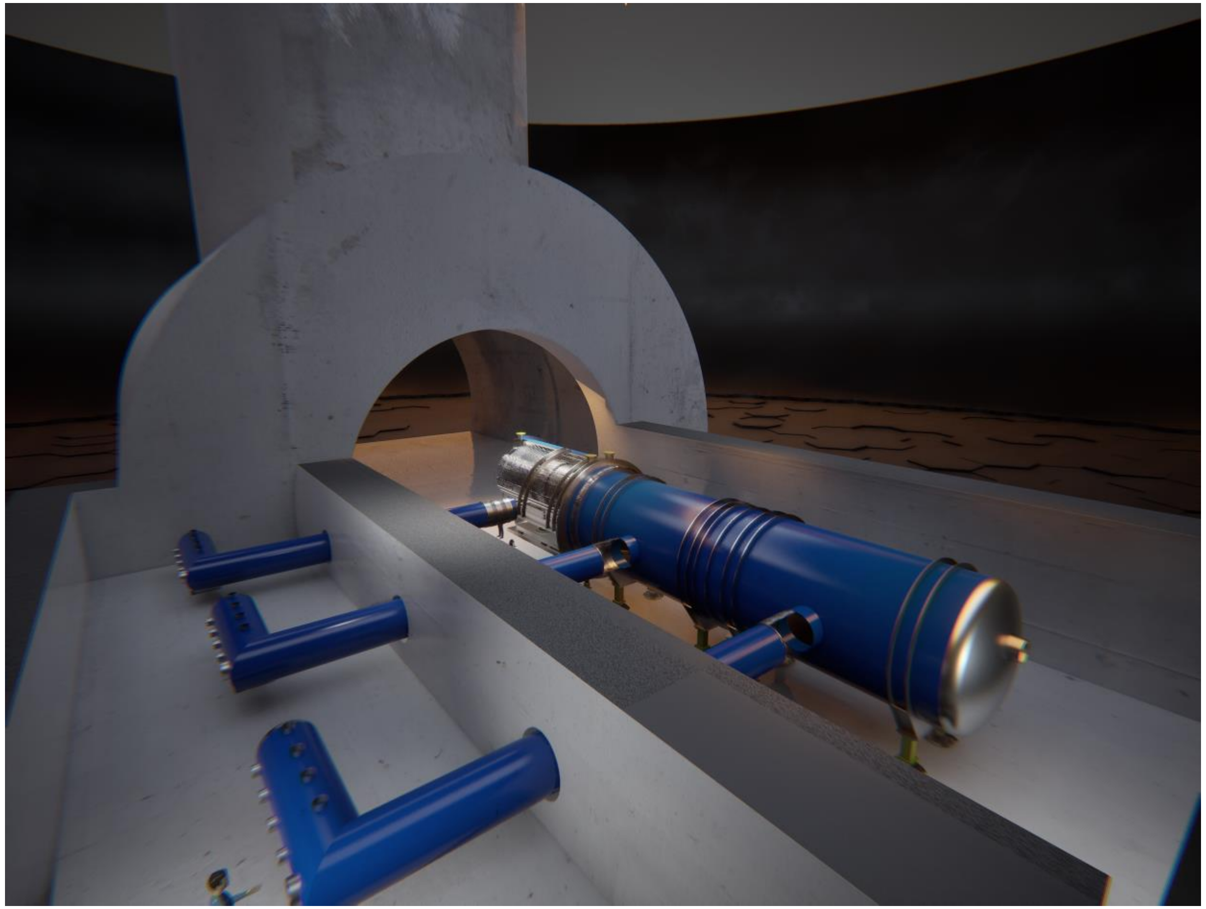


HTS conductor sample

Looks much like an HTS magnet for fusion !!!

Rendering impressions





M. Brice, CERN

Outline

- From US-MAP to IMCC
- Supporting analysis
- IMCC design evolution
- Issues and next steps
- A “20@20” model coil demonstrator
- Conclusions and perspectives

CERN

Conductor design

HTS tape thickness	(mm)	62
HTS tapes	(-)	80
HTS stack width	(mm)	6
HTS stack thickness	(mm)	5
HTS stack width	(mm)	6
HTS tapes	(-)	80
Number of HTS stacks	(-)	4
Copper diameter	(mm)	23
Hole diameter	(mm)	8
Wetted perimeter	(mm)	25
Wrap thickness	(mm)	0.25
Jacket outer dimension	(mm)	39.5

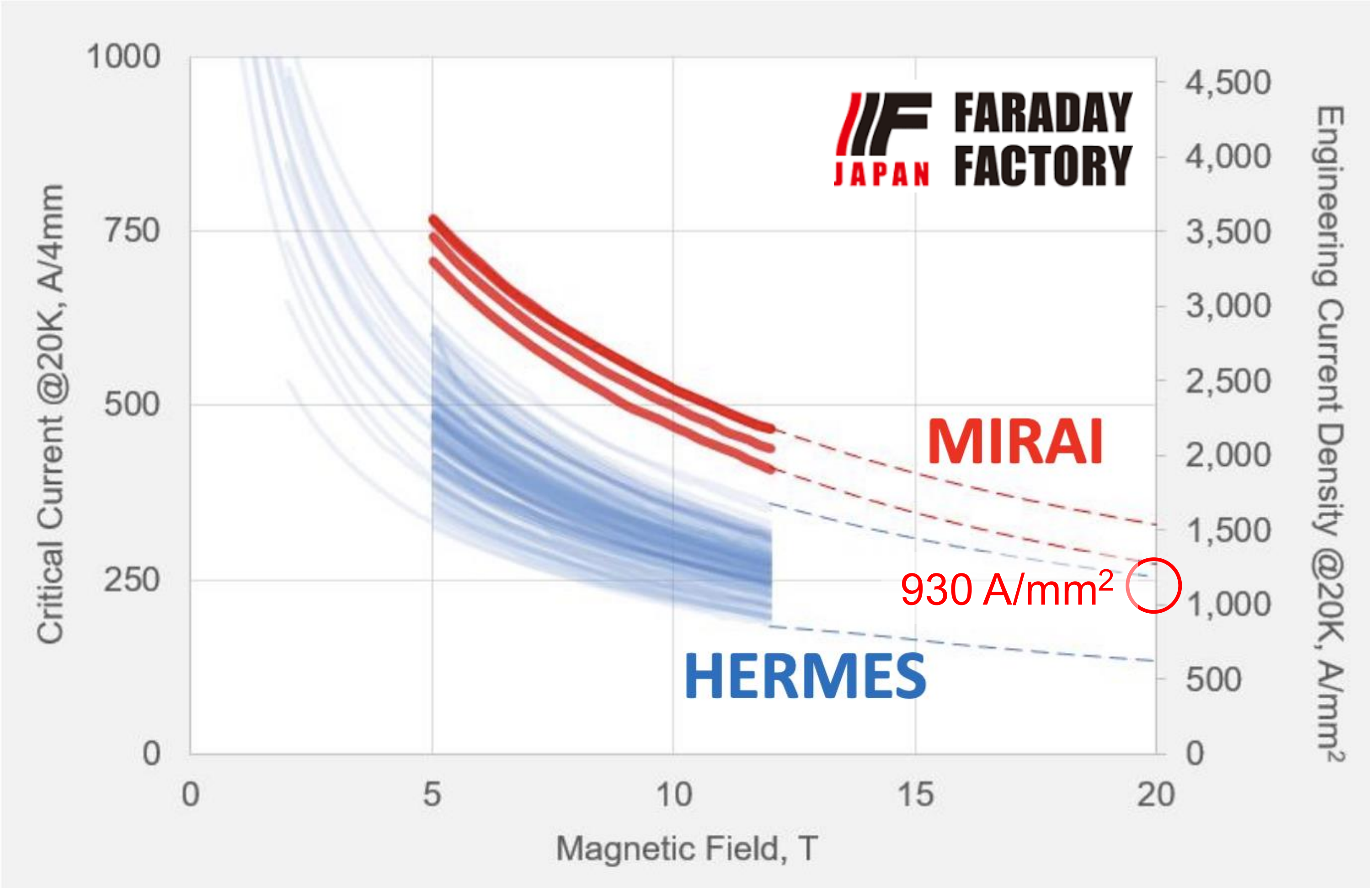
I_{op} = 61 kA

B_{op} = 20 T

T_{op} = 20 K

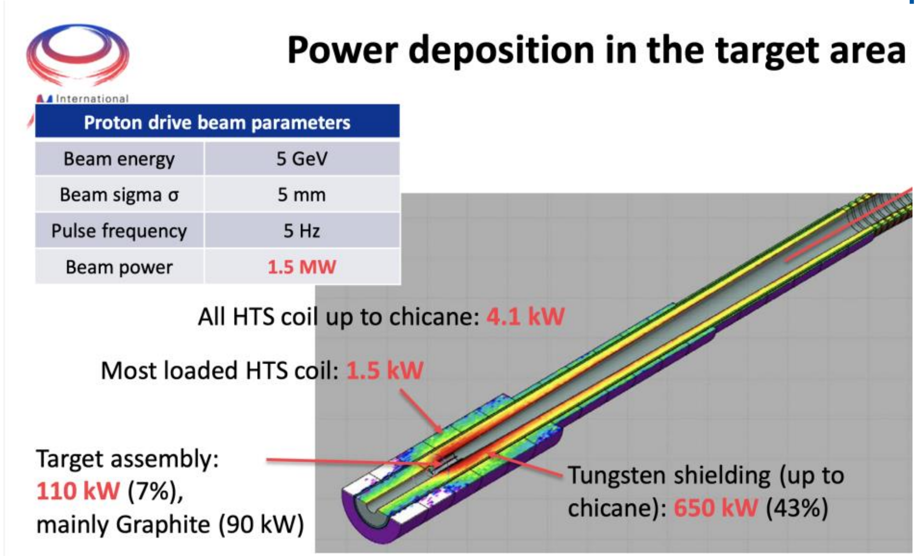
T_{cs} = 29.7 K

J_e = 930 A/mm^2

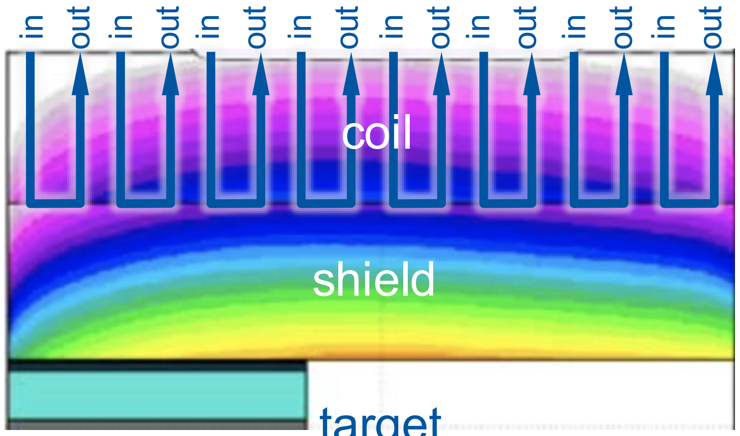


https://indico.cern.ch/event/1431972/contributions/6419983/

Cooling



Total heat in the coil 4.1 kW

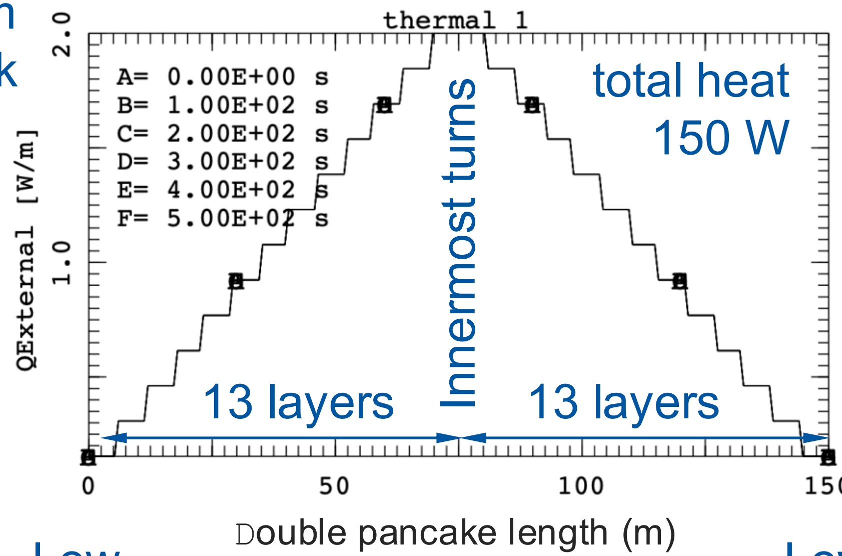


Proton beam

D. Calzolari and A. Lechner, CERN

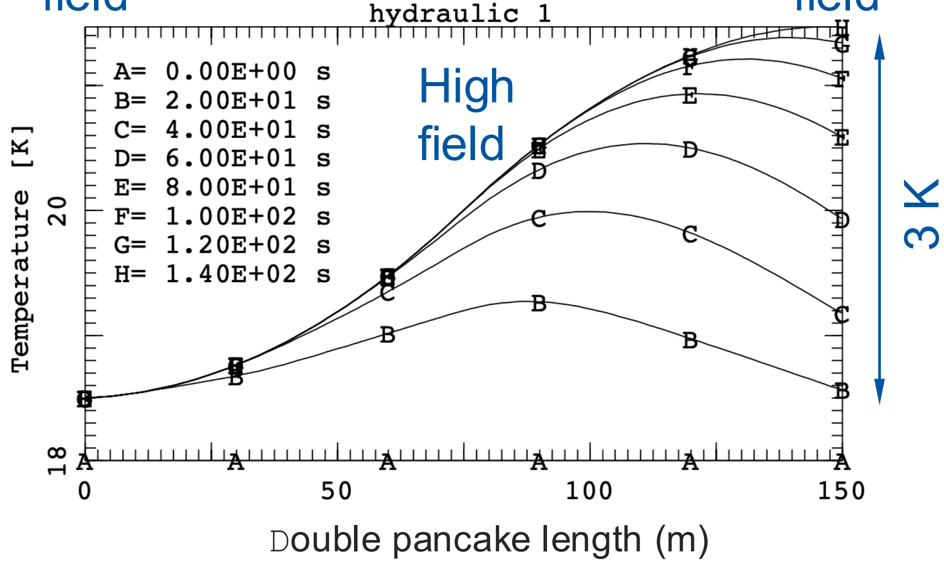
NOTE: time stucture ignored

2 W/m peak



Low field

Low field

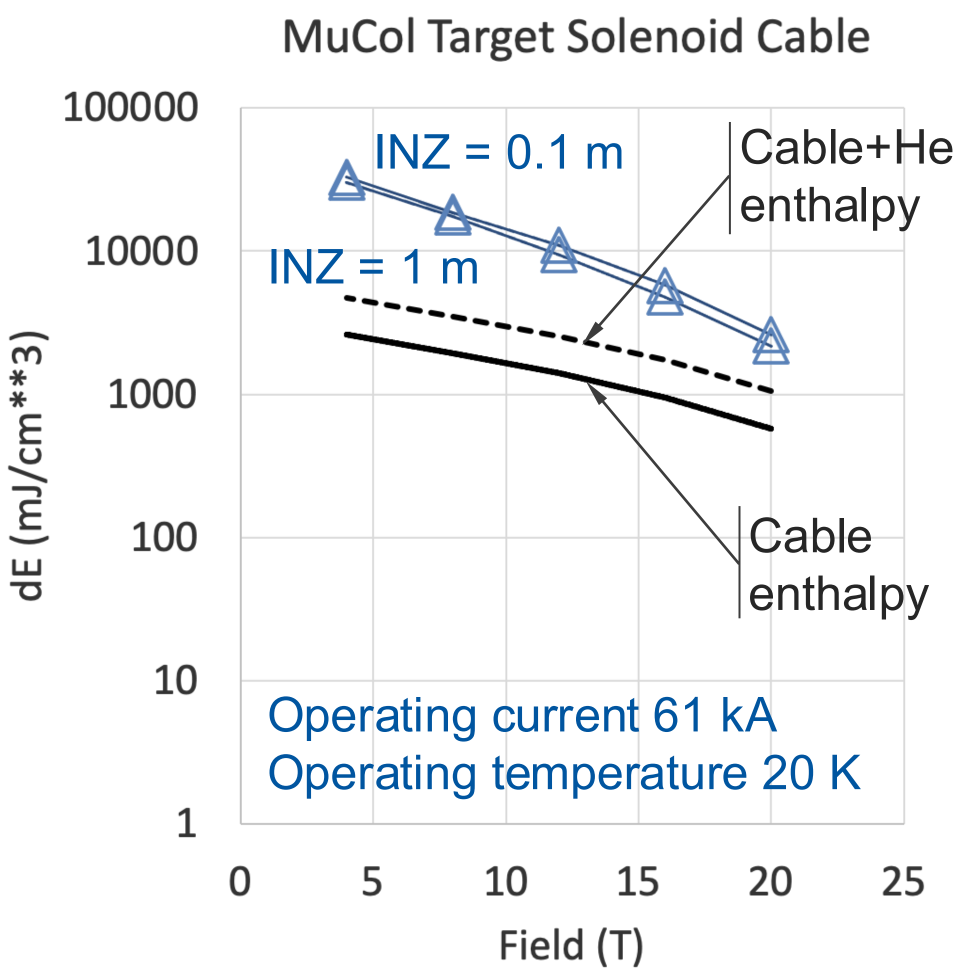


A flow dm/dt of approximately 8 g/s is required to remove a nuclear heat load of 150 W with a **temperature increase ΔT of 3 K**

With this flow the pumping loss is about 20 W (considering an adiabatic efficiency η_{pump} of 80 %)

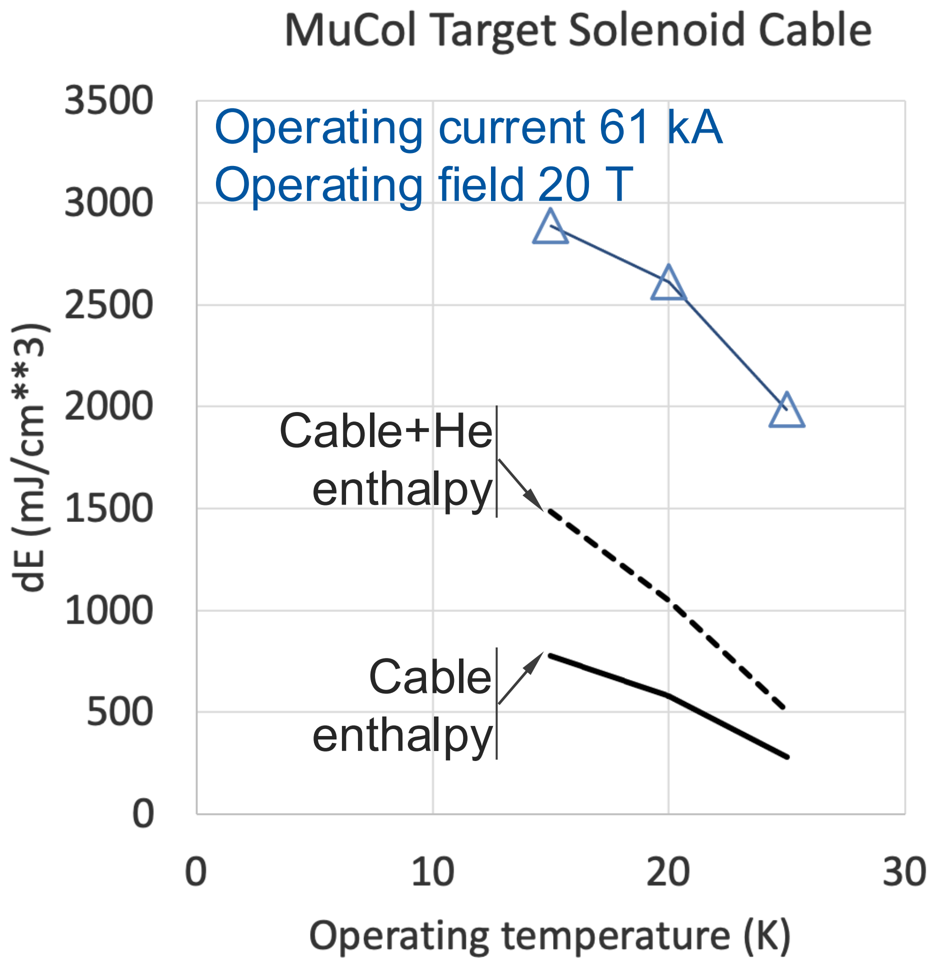
This is about 13 % of the nuclear heat load, and is an **acceptable overhead**

Margin and stability



Values of stability margin are (as expected) very high ! It is **very unlikely that the cable will quench** because of transient heat inputs

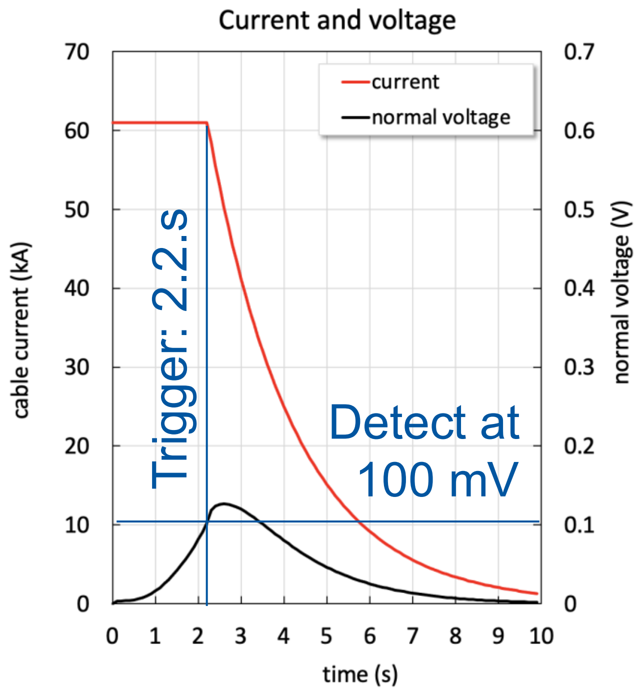
Operating at higher temperature than 20 K (e.g. 25 K) **may still be an option**, the energy margin is substantial

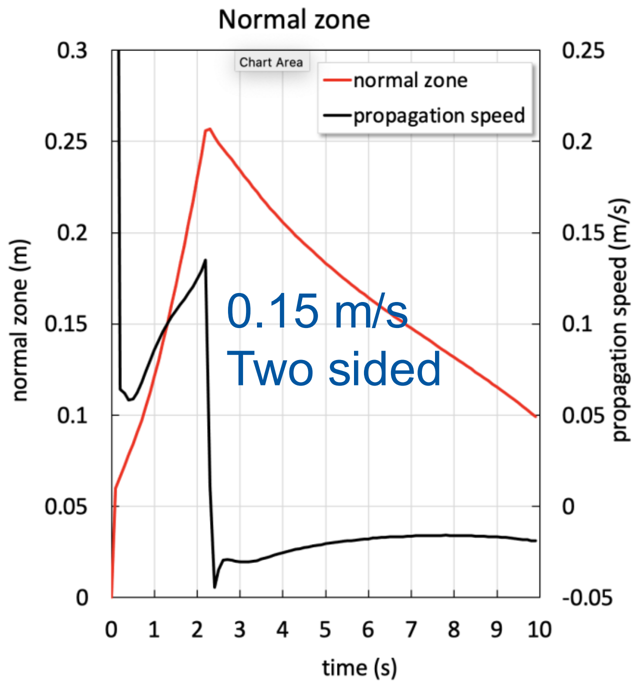


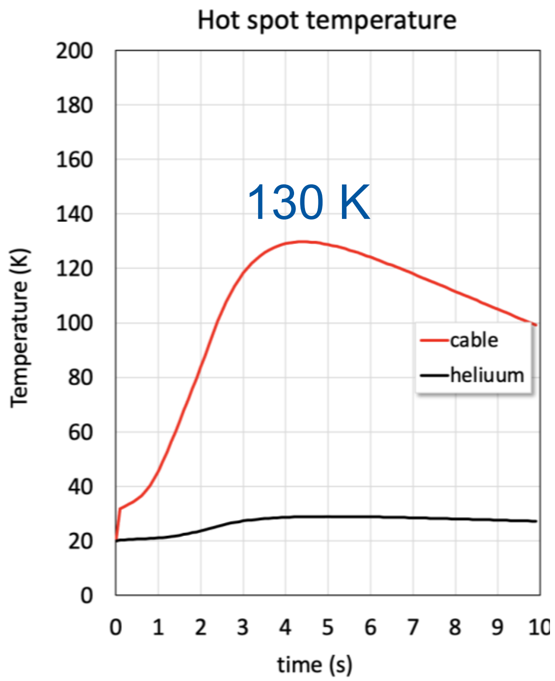
Detection and protection – 1/3

Coil Module 2 (high field and current)
- Single coil stored energy: 165 MJ
- Coulped stored energy: 299.7 MJ
- Dump voltage: 5 kV (2.5 kV to ground)

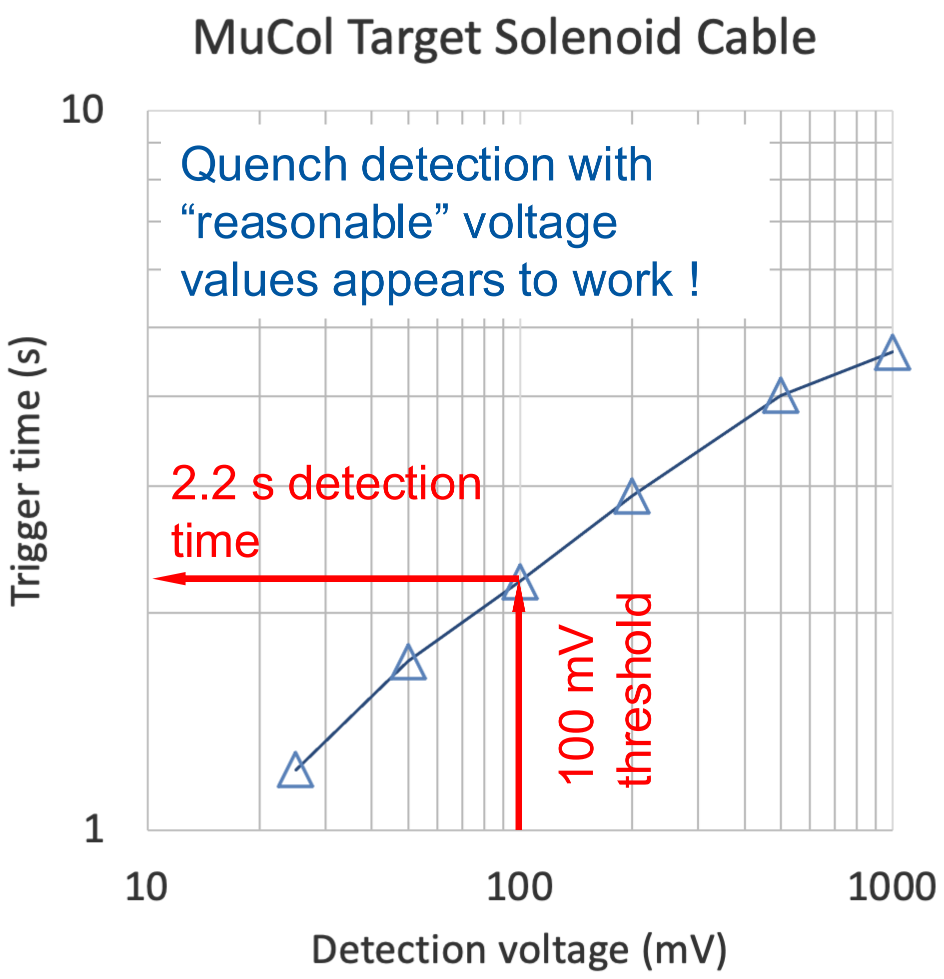
INZ in the center of the double pancake
10 cm length quenched
Exponential dump following trigger







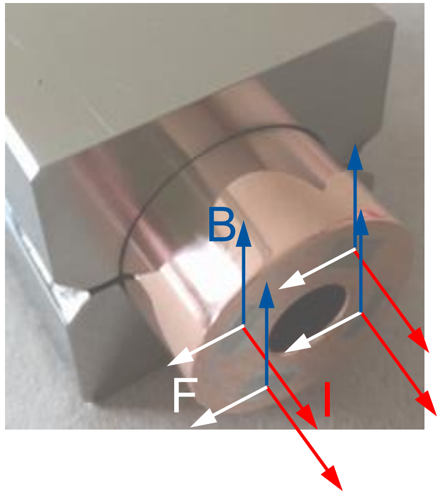
Detection and protection – 3/3

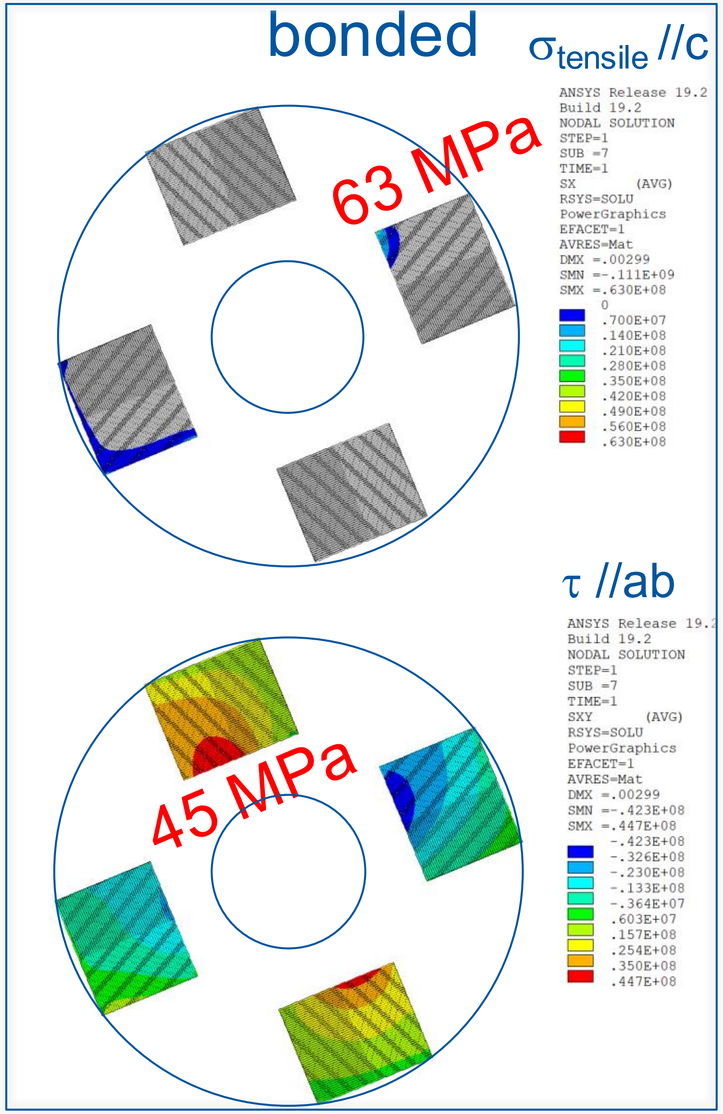


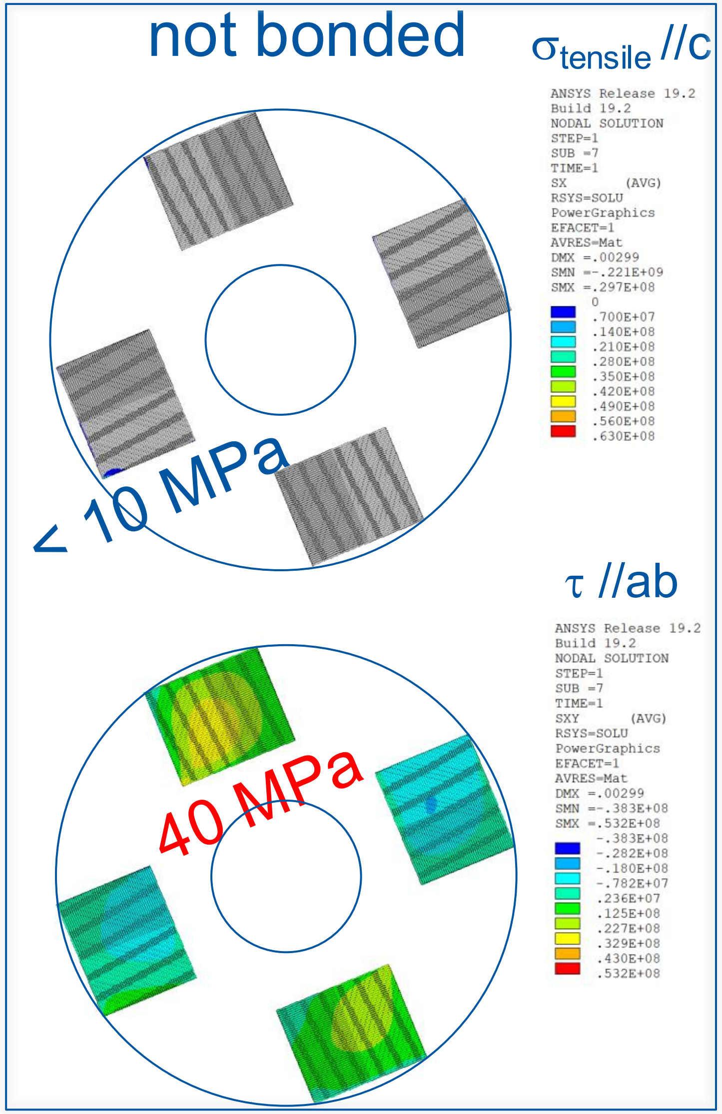
- Study of the detection and dump for quenches in the low field region or at low current/field
  - The low field region at nominal current seems to be most dangerous
  - Low current/low field (e.g. during ramp) implies long detection times, but this appears compatible with modest hot-spot limits

I_{op} (kA)	B_{op} (T)	$t_{Detection}$ (s)	T_{max} (K)
61	20	2.2	130
61	**4**	**2.8**	**172**
30	9.84	14.8	140

HTS cable mechanics







This could explain the degradation of high field and high current cables ?

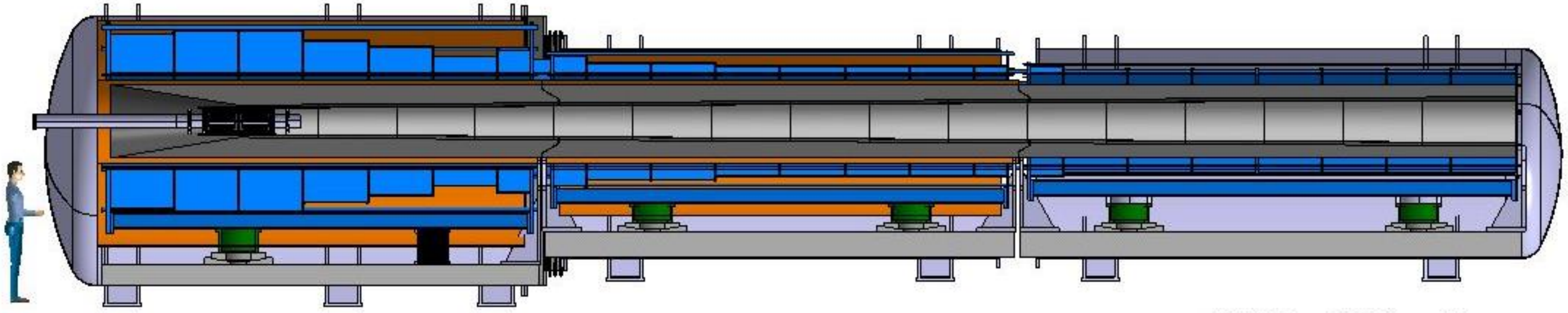
Outline

- From US-MAP to IMCC
- Supporting analysis
- IMCC design evolution
- Issues and next steps
- A “20@20” model coil demonstrator
- Conclusions and perspectives

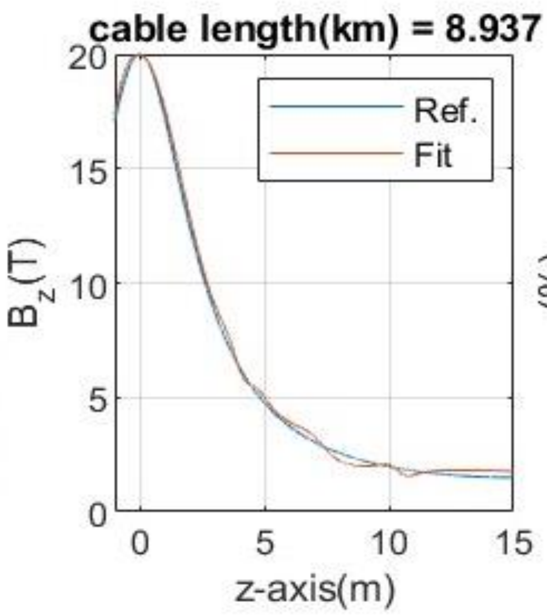
IMCC design – 2025 iteration motivation

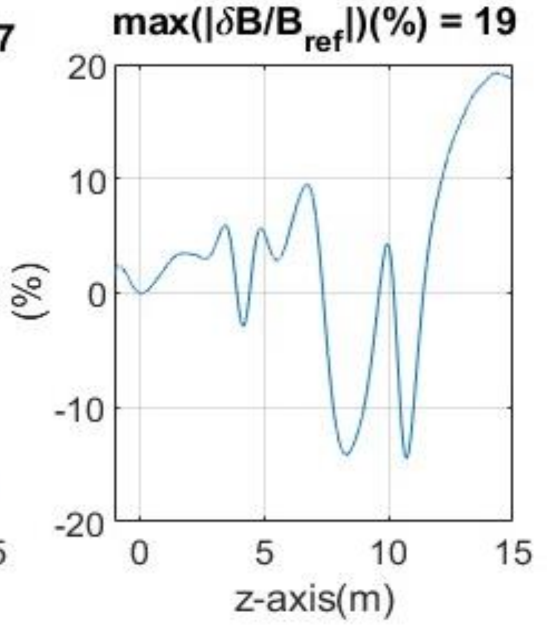
- Issues to be resolved:
  - Increase space between sections for mechanical structure (minimum gaps of 480 mm)
  - Increase coils shielding in the high field target region (bore diameter larger than 1.3 m)
  - Reduce coils power supply cost/complexity by making all coil currents approximately equal (I approximately 60 kA)
  - Assess impact on B_Z due to chicane coils
  - Define beam extraction path from target region channel

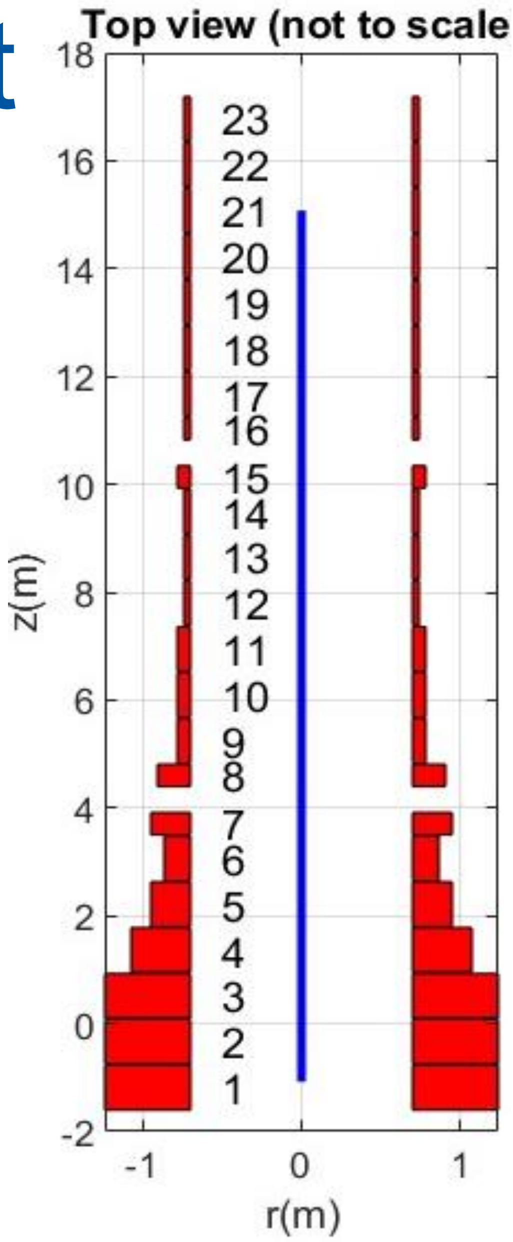
IMCC design – 2025 iteration result



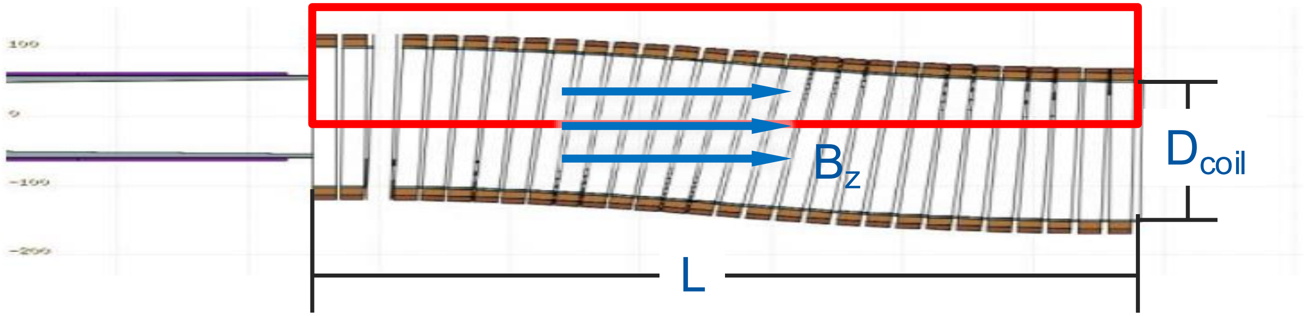
- All coil currents are equal 61.15 kA
- All coils inner bore 1.4 m and 0.48 m gaps between sections
- Magnetic energy ≈ 1.48 GJ,
- Cable length ≈ 9 km







Chicane power estimates



J_{cu}	$\approx$ 15 A/mm^2 (water-cooled magnets)
η	$\approx$ 1.88 10^{-8} Ω m (50 ºC)
D_{coil}	= 2.8 m
L	= 10 m
P	**≥ 29.6 MW**

- According to "Teorema del Portone", there is a relation between the minimum ampere-turns I_{tot} required to generate a given field integral $B_z dL$ in a solenoid:

  $$I_{tot} \geq BdL / \mu_0$$

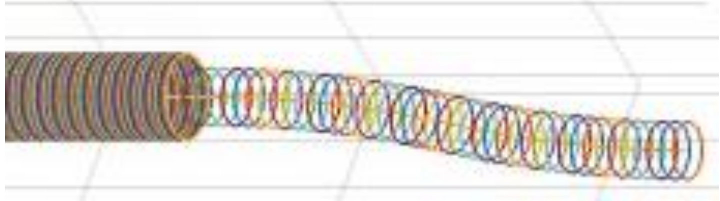
- From the copper current density J_{cu}, thje coil inner diameter D_{coil}, and the resistivity η, we can compute the Joule power:

  $$P \geq \eta\, p_{coil} / Acu\, I_{tot}^2 \quad \Rightarrow \quad P \geq \pi\, \eta / \mu_0\, D_{coil}\, J_{cu}\, B_z dL$$

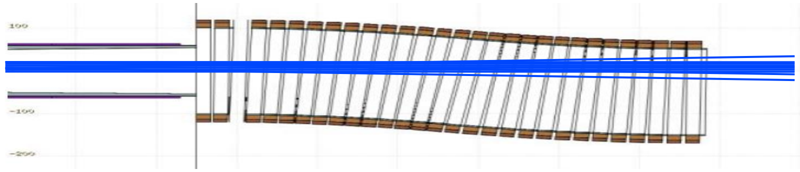
- The Joule power scales (at least) linearly with (i) the required $B_z dL$, (ii) the coil operating current density J_{cu}, and (iii) the coil inner diameter D_{coil}

Chicane

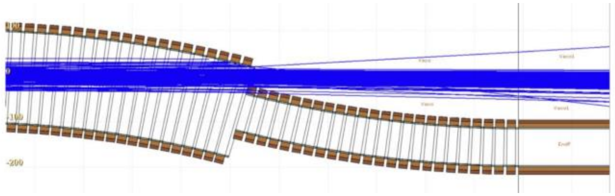
- Several options were evaluated, from the basic one of a "bare bone" copper twisted solenoid, to widening bore chicanes, in the attempt to locate the spent beam extraction in the first curved leg
- None of them seem to offer an "optimal" solution to beam extraction
- The main issue in these solutions is the **resistive power**
- The chicane should be best designed as **mainly (if not fully) superconducting**



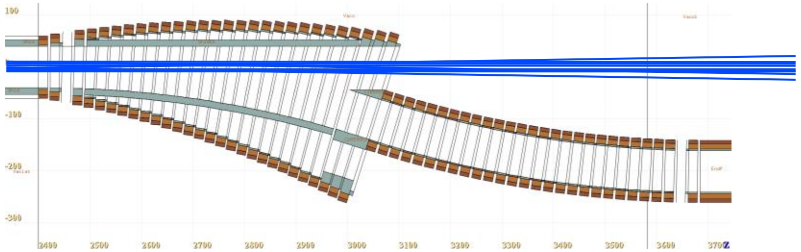
Minimum bore chicane ≈ 15 MW



Large bore chicane ≈ 30 MW



Bore-step chicane ≈ 23 MW



Trombone chicane ≈ 30 MW

Outline

- From US-MAP to IMCC
- Supporting analysis
- IMCC design evolution
- Issues and next steps
- A “20@20” model coil demonstrator
- Conclusions and perspectives

Open issues (besides making it)

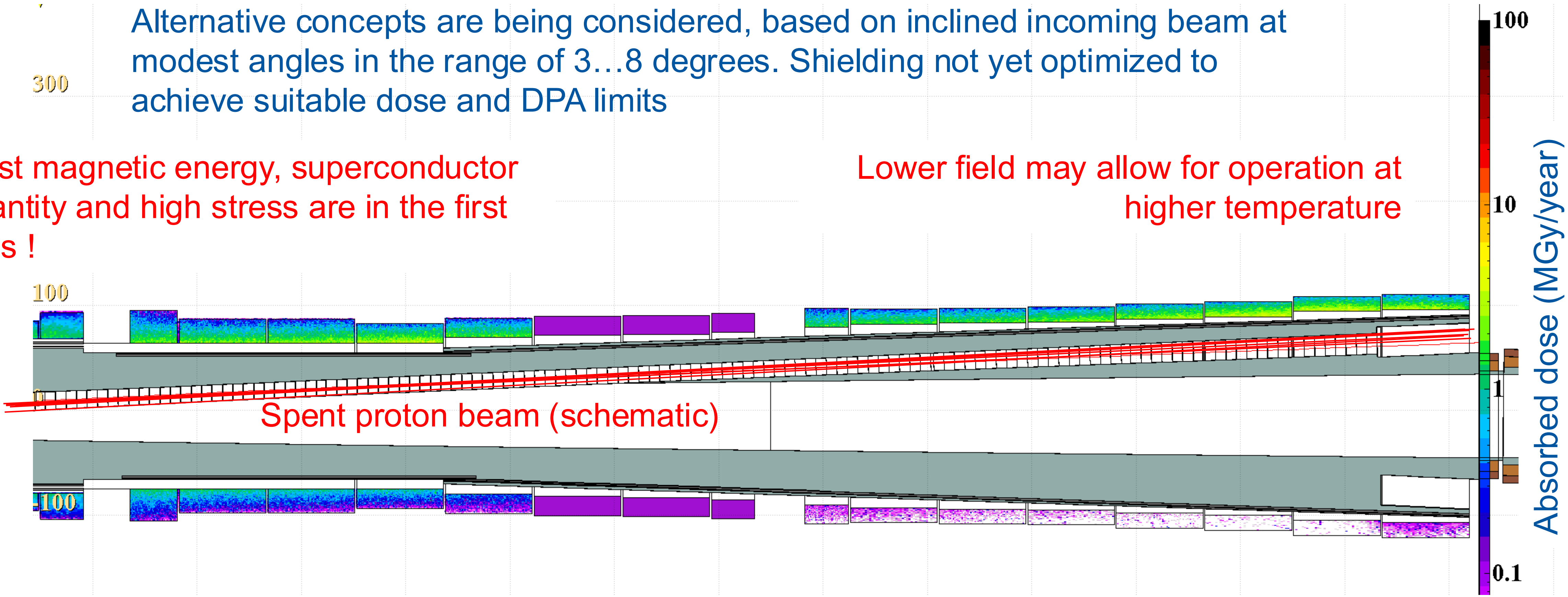
- We do not yet have a robust solution for the **spent beam extraction**
- We need to **design a superconducting chicane**
- We have been discussing a 4 MW primary beam to increase muon production. **New coil design required**, with more shielding, as the present configuration cannot accommodate it by simple “increase of performance”
  - Double cryogenic power
  - Roughly double radiation damage

Early spent beam extraction

Alternative concepts are being considered, based on inclined incoming beam at modest angles in the range of 3…8 degrees. Shielding not yet optimized to achieve suitable dose and DPA limits

Most magnetic energy, superconductor quantity and high stress are in the first coils !

Lower field may allow for operation at higher temperature



Low incoming beam angles are beneficial, moving the channel enlargement from regions of 5 T bore field (6…8 degrees) to downstream regions of 2 T bore field (≈ 3 degrees)

J. Manczack, G. Lerner and A. Lechner, CERN

Outline

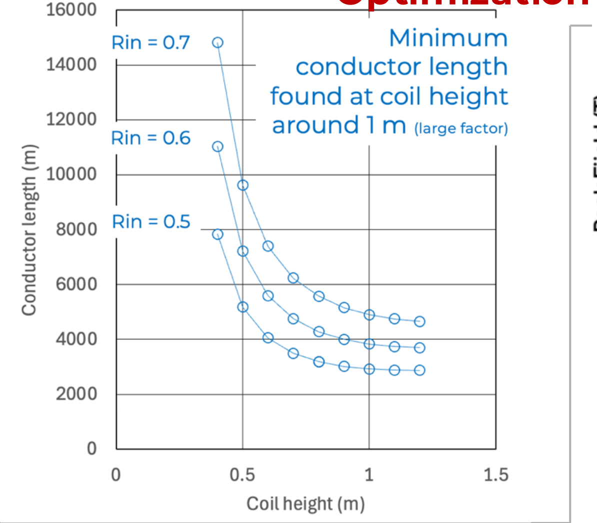
- From US-MAP to IMCC
- Supporting analysis
- IMCC design evolution
- Issues and next steps
- A “20@20” model coil demonstrator
- Conclusions and perspectives

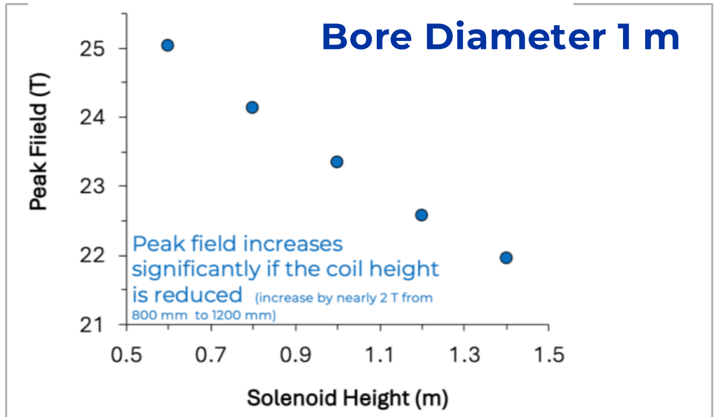
A 20@20 model coil demonstrator

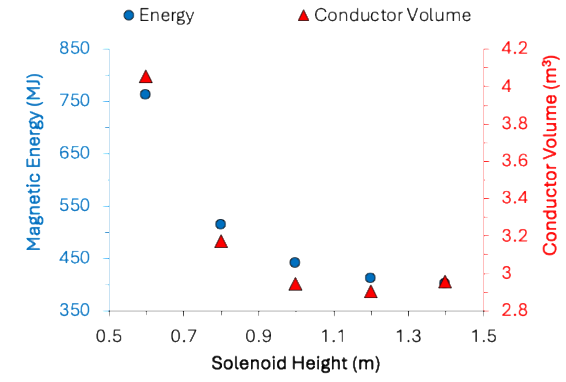
- The performance required of the Target Decay and Capture Solenoid goes **well beyond the current state of the art**. This is why we are proposing to build and test a **model coil achieving a field of 20 T at 20 K (20@20)**
  - Critical step to raise the technology readiness level
  - Provide confidence that the full system can indeed be built and operated.
- Besides the Muon Collider, this development is also aligned with the needs of other scientific domains, such as **high-field physics**, as well as societal applications, including **fusion energy**.
- Several major European players in HEP and fusion are associating in this effort (and others have expressed interest in joining), contributing to the definition of performance requirements and coil geometry, as well as to the development of a design that includes initial engineering & analysis of the 20 T @ 20 K model coil.

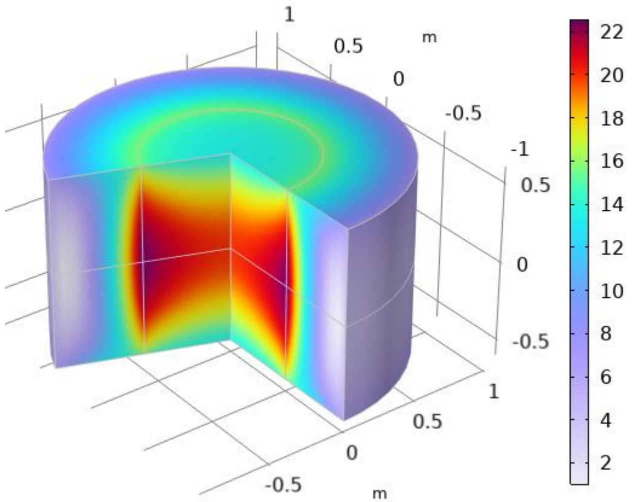
20@20 conceptual design

Optimization 1: Cost-Oriented — 20 T on the Bore

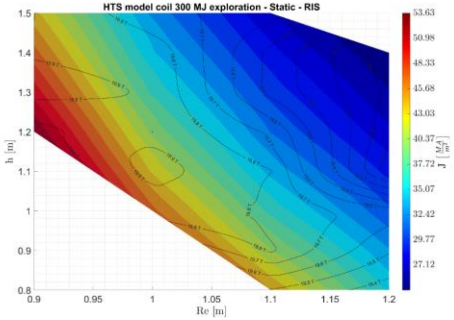


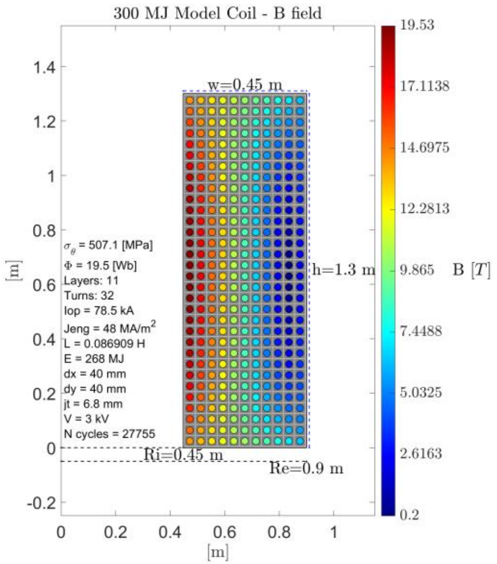




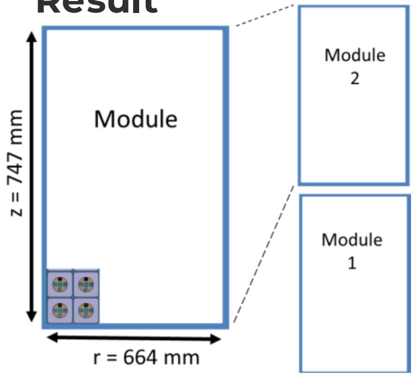


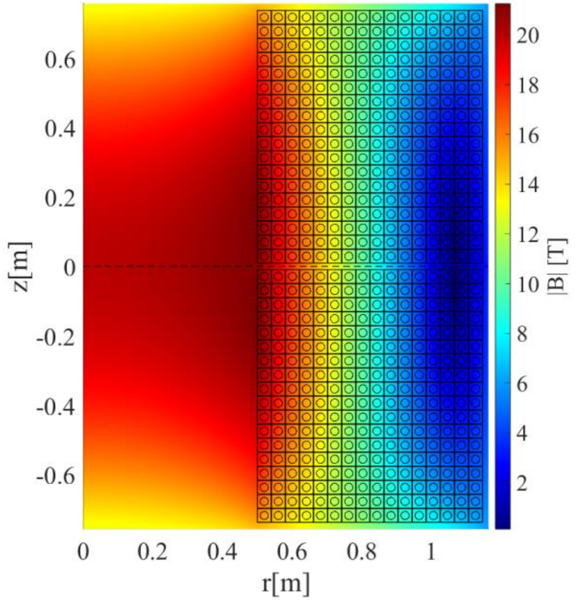
Optimization 2 : Robust 300 MJ Coil



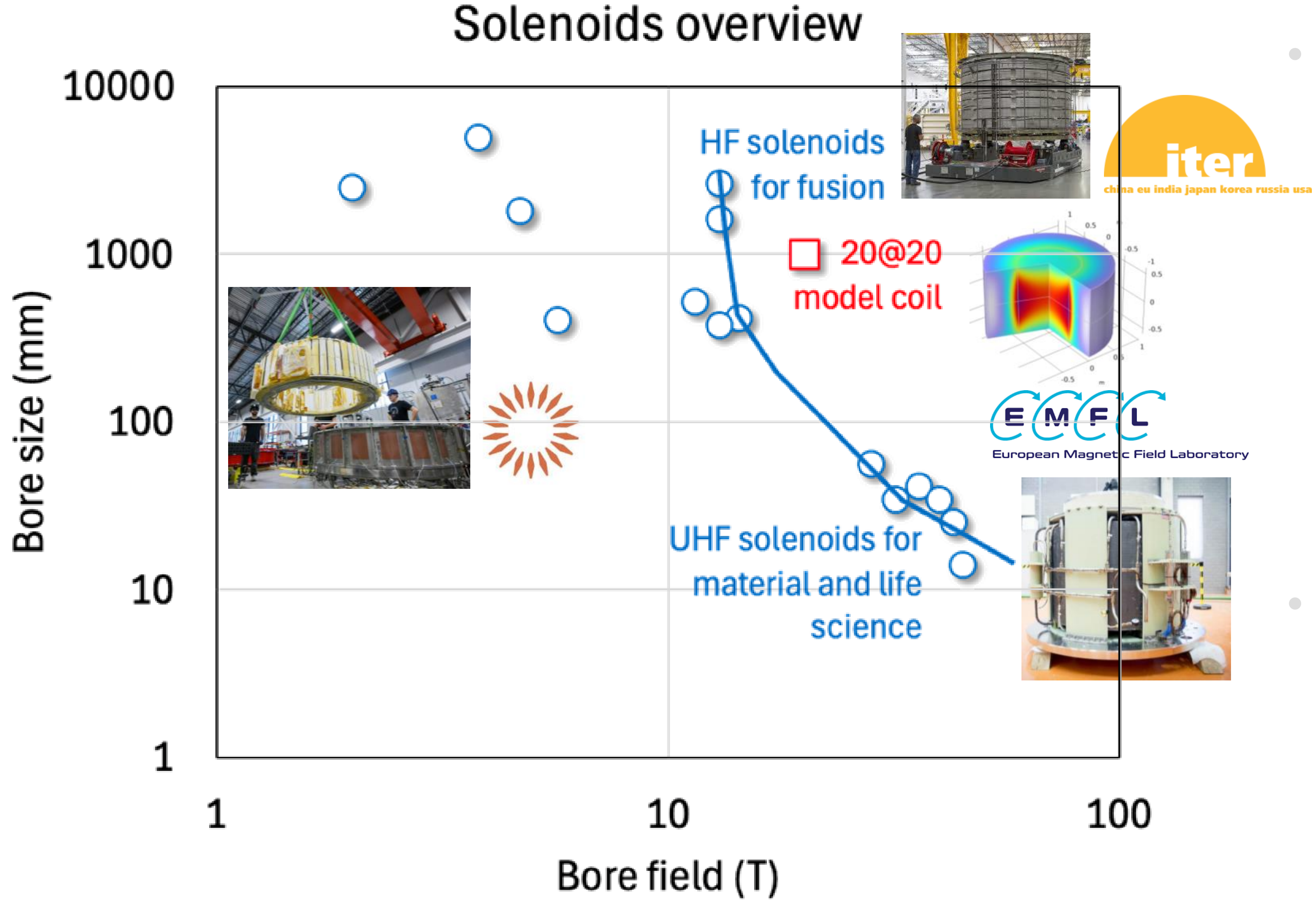


Result





20@20 in world perspective



- The 20@20 model coil **outperforms existing SC magnets** by over 50 % in field (at comparable bore dimension) and by one order of magnitude in bore dimension (at comparable field)
- No other project worldwide matches the proposed geometry and performance targets

CERN

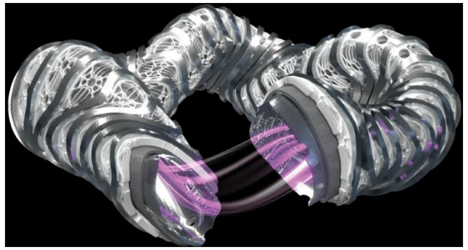
Outline

- From US-MAP to IMCC
- Supporting analysis
- IMCC design evolution
- Issues and next steps
- A “20@20” model coil demonstrator
- Conclusions and perspectives

Opportunities and perspective

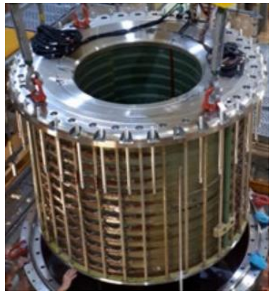
Commonwealth Fusion Systems

TYPE ONE ENERGY



Proxima Fusion

LNCMI



- We have developed a design of the target and capture channel of the Muon Collider, targeting a peak field of 20 T on axis, based on an HTS force-flow cooled cable operating at 20 K
  - Lower footprint, mass, stored energy and cost than an LTS/NC hybrid
  - Better energy efficiency than a 4.5 K system
- Though there is much work to do, **the design selected seems to be feasible !**
- Issues to be solved: (i) **spent beam extraction**, (ii) SC chicane design, (iii) higher beam power
- A **20@20 model coil**, part of the ESPPU R&D proposal, will be instrumental to demonstration and success
- This work is also important because of **implications for other societal and scientific applications !**