Muon Collider
(solenoid) Magnets Studies

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on behalf of the Muons Magnets Working Group
KIT 25/1/2023

Scope of the talk

- The solenoid challenges for a muon collider
- Technical advances
- Work organization
- Summary and plans

This is work in progress

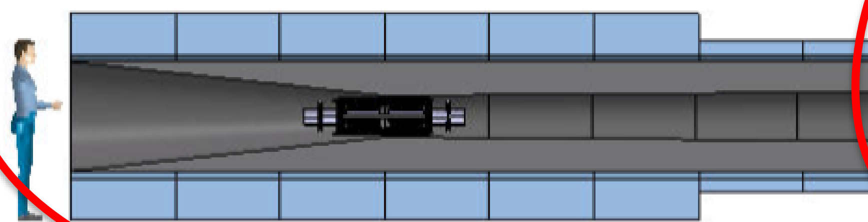
General guidelines

- Magnets are relatively **power hungry**
  - The main power consumption for superconducting magnets is for the **cryogenic** system
  - The main power consumption for resistive magnets is to overcome **resistive losses** (active power, needs to be cooled away) **and inductive voltages** (reactive power, can be partly retrieved)
- Magnets are relatively **expensive infrastructure**
  - Unit cost is large due to the combination of **costly materials**, **complex technology**, **large mass**
  - Magnets tend to ***pave* extensively** the whole accelerator complex

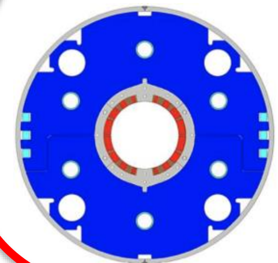
- Seek for practical solutions to minimize capital investment (CAPEX) and operation costs (OPEX). It is unlikely that simple extrapolation of known technology will work, so we still require a **large dose of innovation**
- Produce a credible and affordable accelerator complex design: **technology is a mean, not the end of this work**

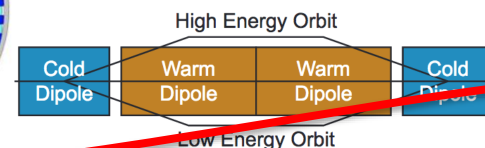
Magnet *specifications*

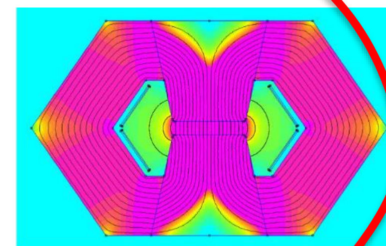
20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: >> 20 MGy

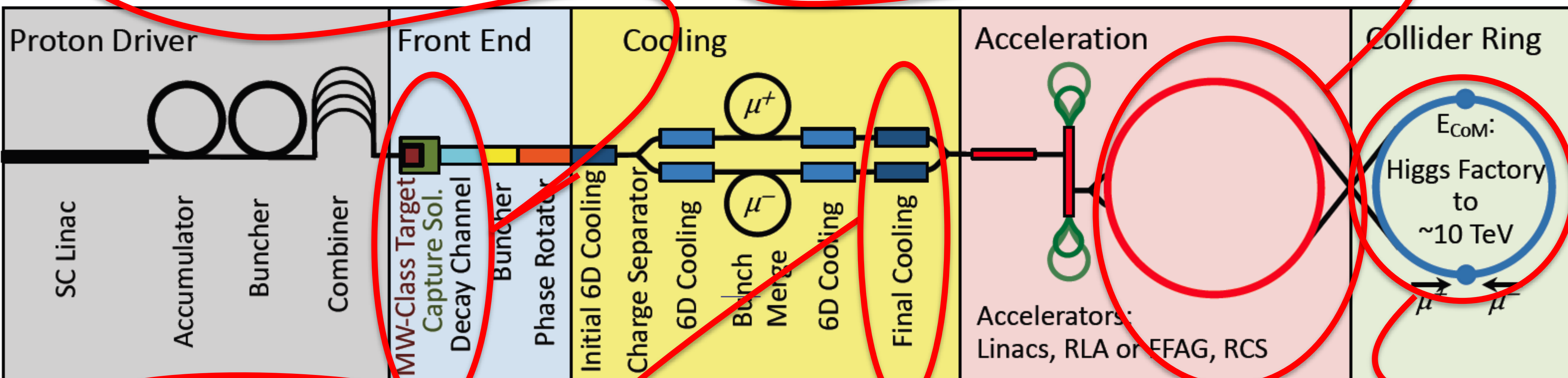


NC ±1.8 T, 400 Hz, 100 mm x 30 mm
SC < 10T, ≈ 100 mm

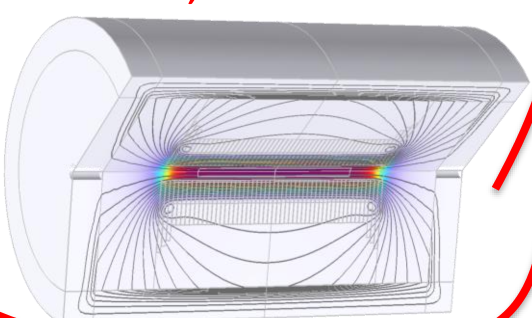




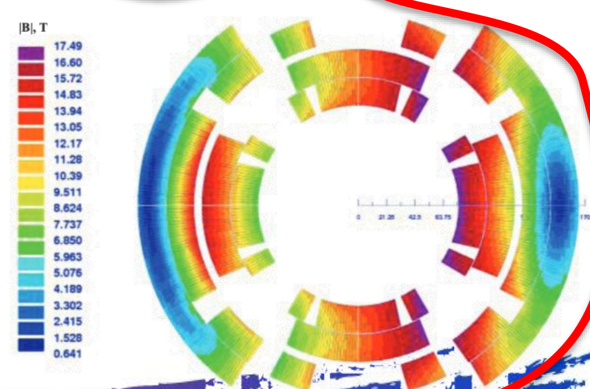




> 40 T, 60 mm

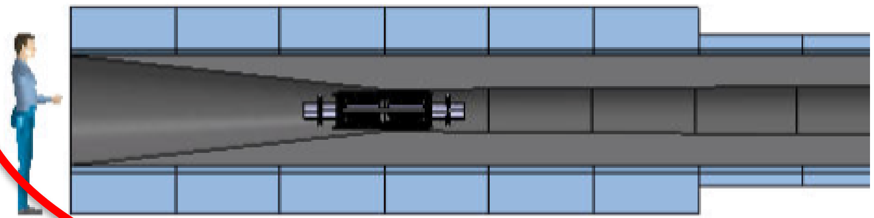


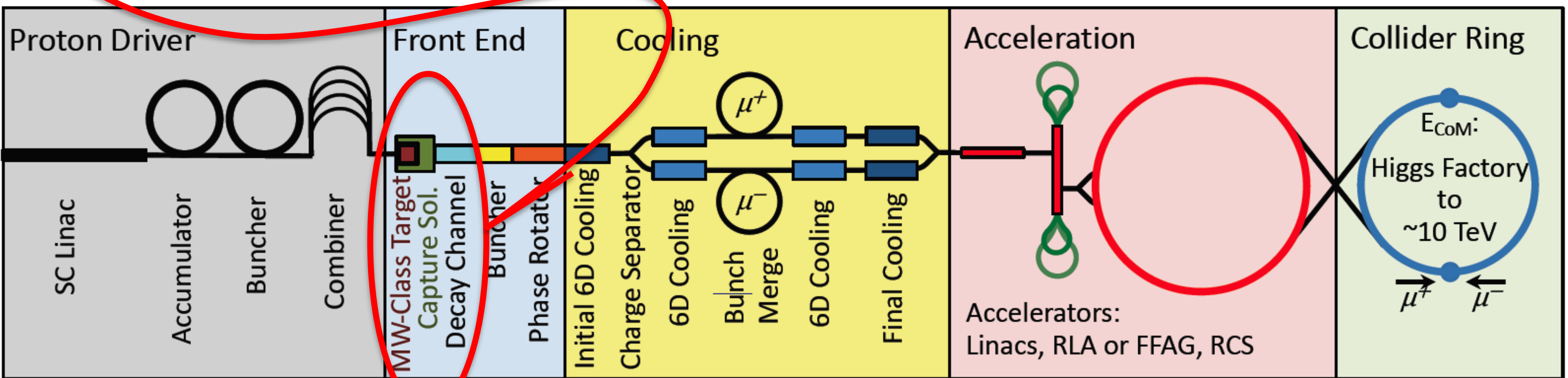
16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 Mgy



The solenoid challenges – 1/2

20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

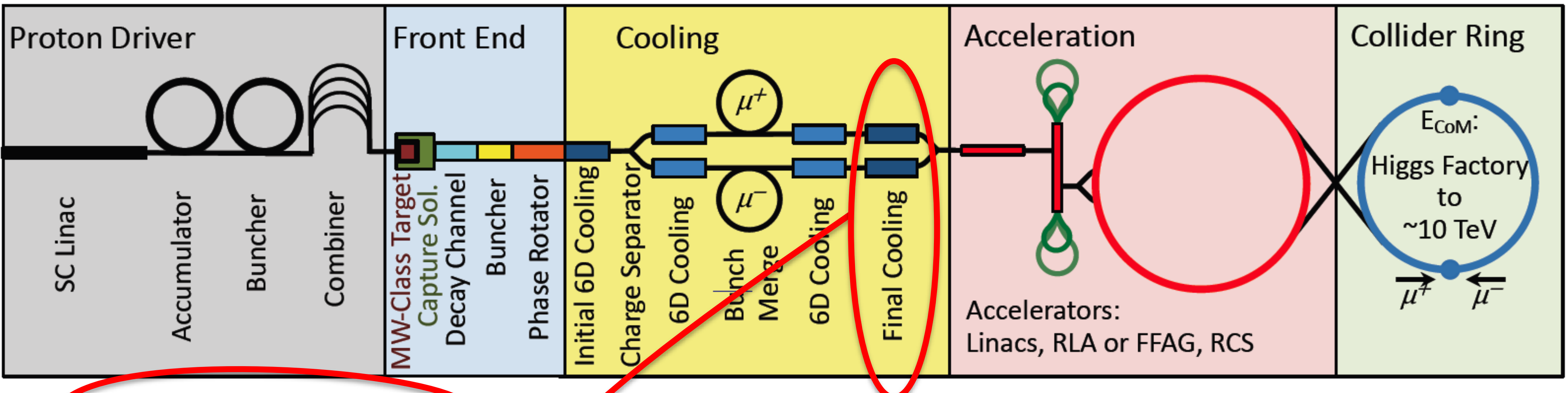


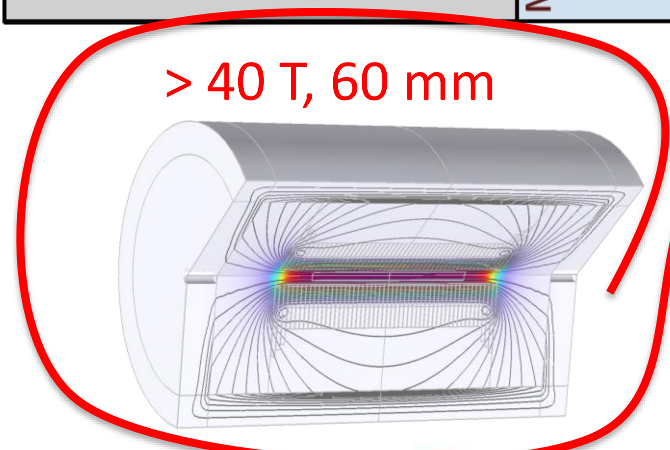


- **Large stored energy o(1) GJ, mass o(300) tons, cost o(100) M**
- **Considerable RT and cryogenic heat load: RT power o(1) MW**
- **Radiation dose o(80) MGy and radiation damage o(10^{-2}) DPA**

The solenoid challenges – 2/2

- **Total 1 km, o(1600) units of solenoid magnets up to o(20) T requires compact windings and careful cost optimization**
- **UHF solenoids, with field beyond state-of-the-art o(40…60) T, calls for novel HTS technology**

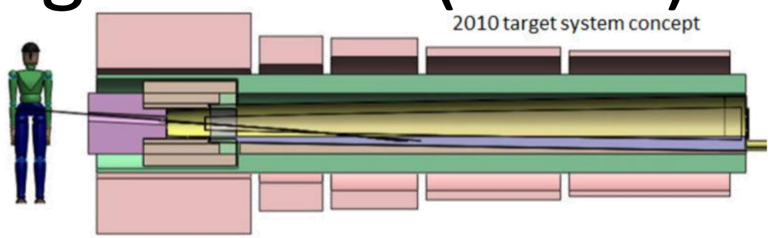




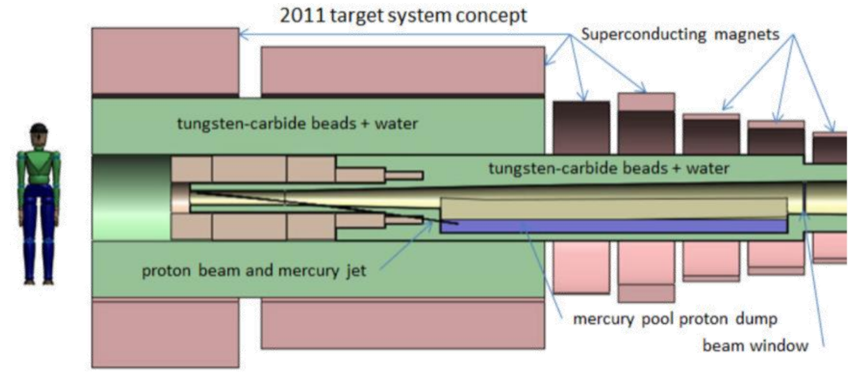
Target and capture – 1/4

- Attempt to 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)



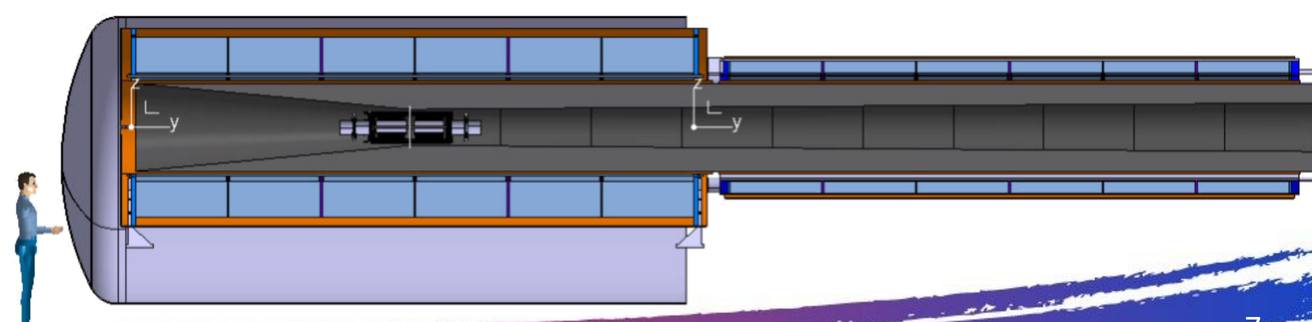
US-MAP **2011** design
LTS (14 T) + NC (6 T)



H.G. Kirk, PAC 2011

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

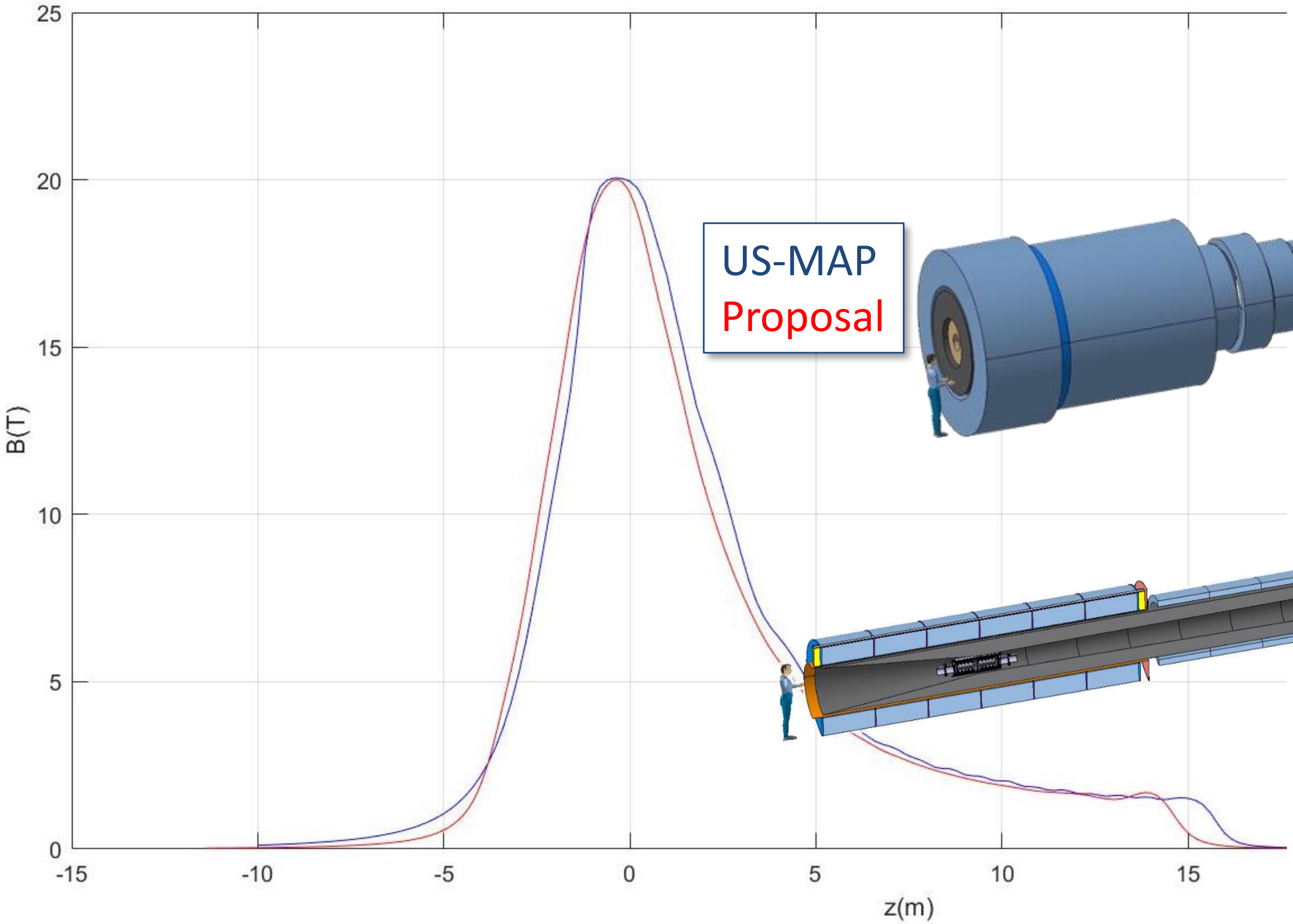
MuCol **2022** design
HTS (20 T, 20 K)



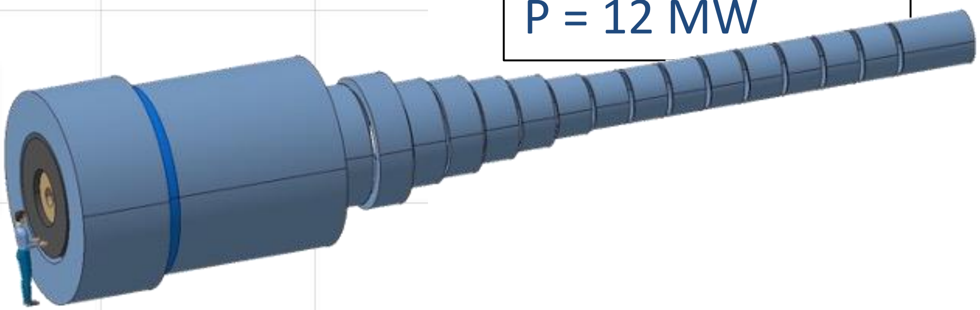
A. Portone, P. Testoni (F4E)
L. Bottura, A. Kohleimainen (CERN)

Target and capture – 2/4

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



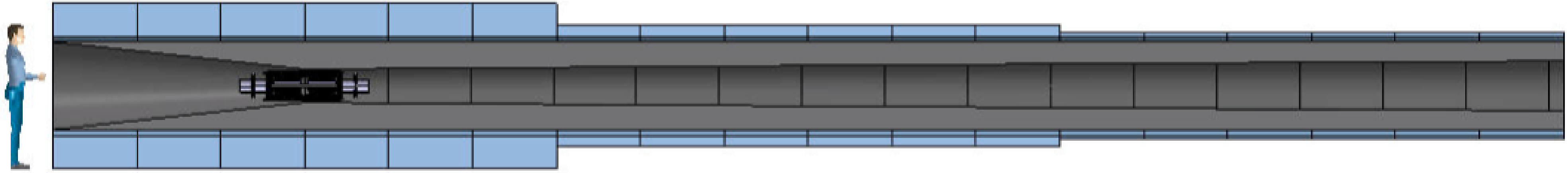
US-MAP
Proposal



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

A. Portone, P. Testoni, F4E

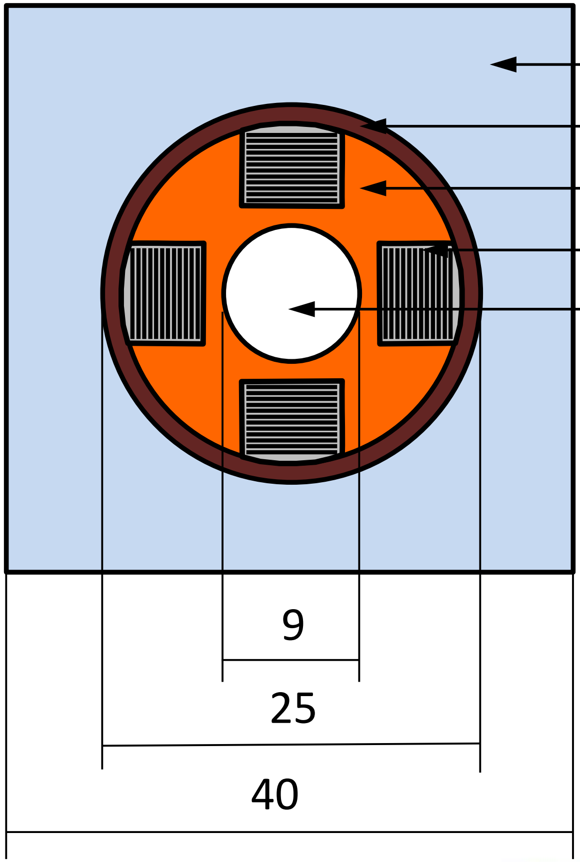
Target and capture – 3/4



MIT "VIPER" conductor

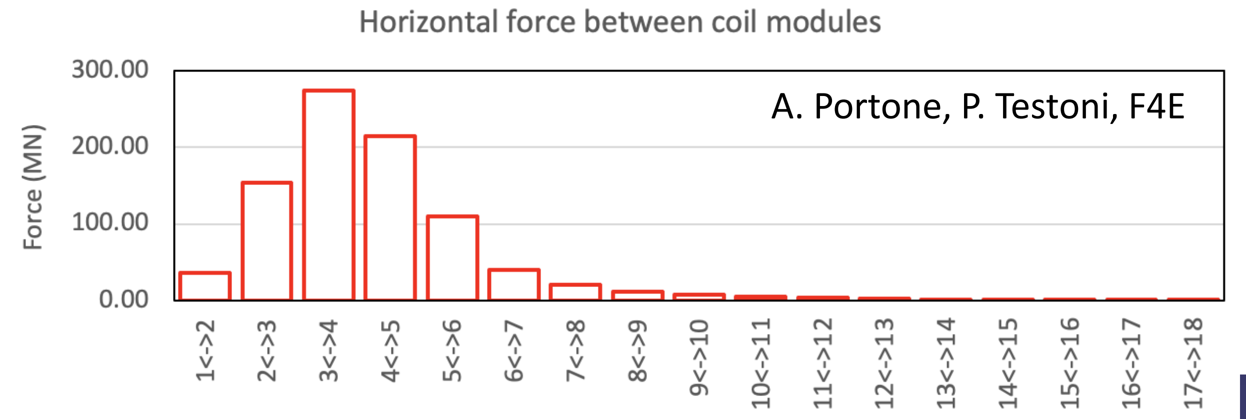
M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

HTS conductor design

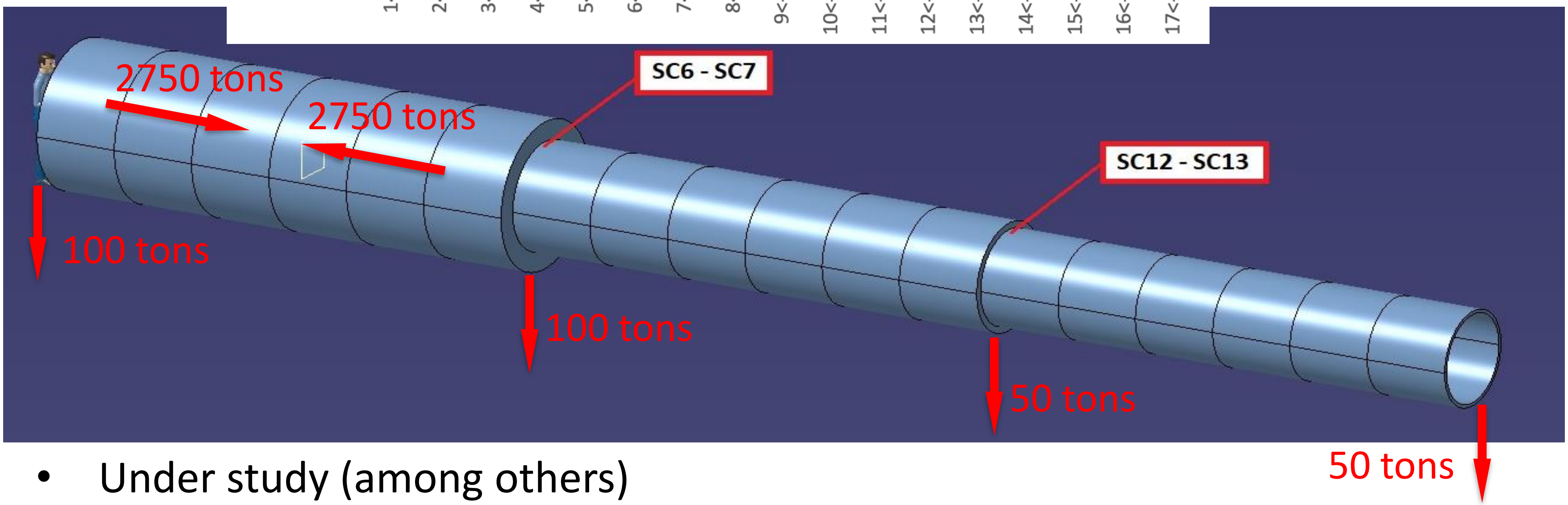


Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K

Target and capture – 4/4



A. Kohleimainen (CERN)

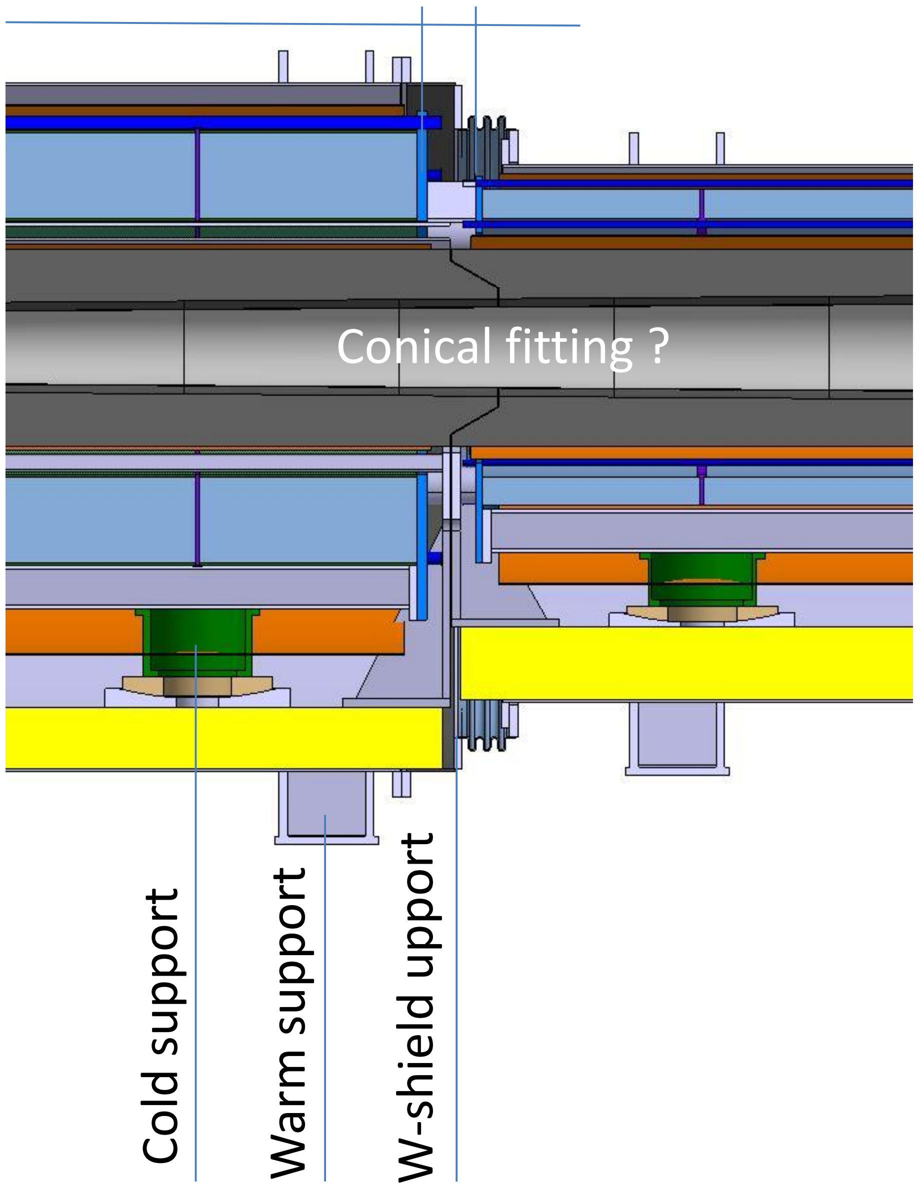


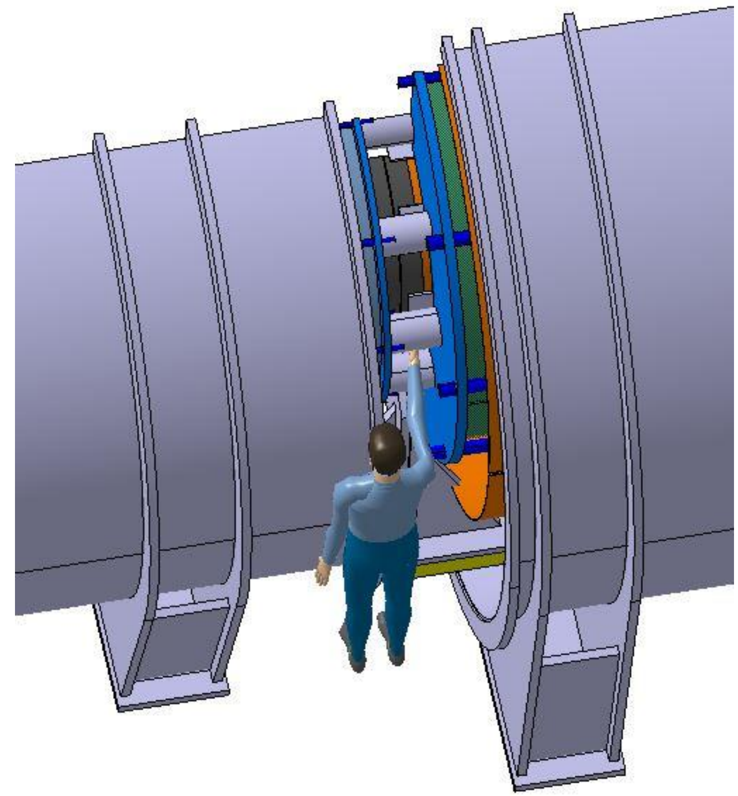
- Under study (among others)
  - Magnetic configuration
  - Mechanical support of coils and W-shield (195 tons)
  - Integration in a cryostat
  - Cooling and cryogenics
  - ....

Integration work – 1/2

A. Kohleimainen (CERN)

300 mm coil gap for supports and thermal shield





Difficult access to inter-coil space

Limit operations to:

- intercoil support installation,
- hydraulic connection, and
- thermal shield closure

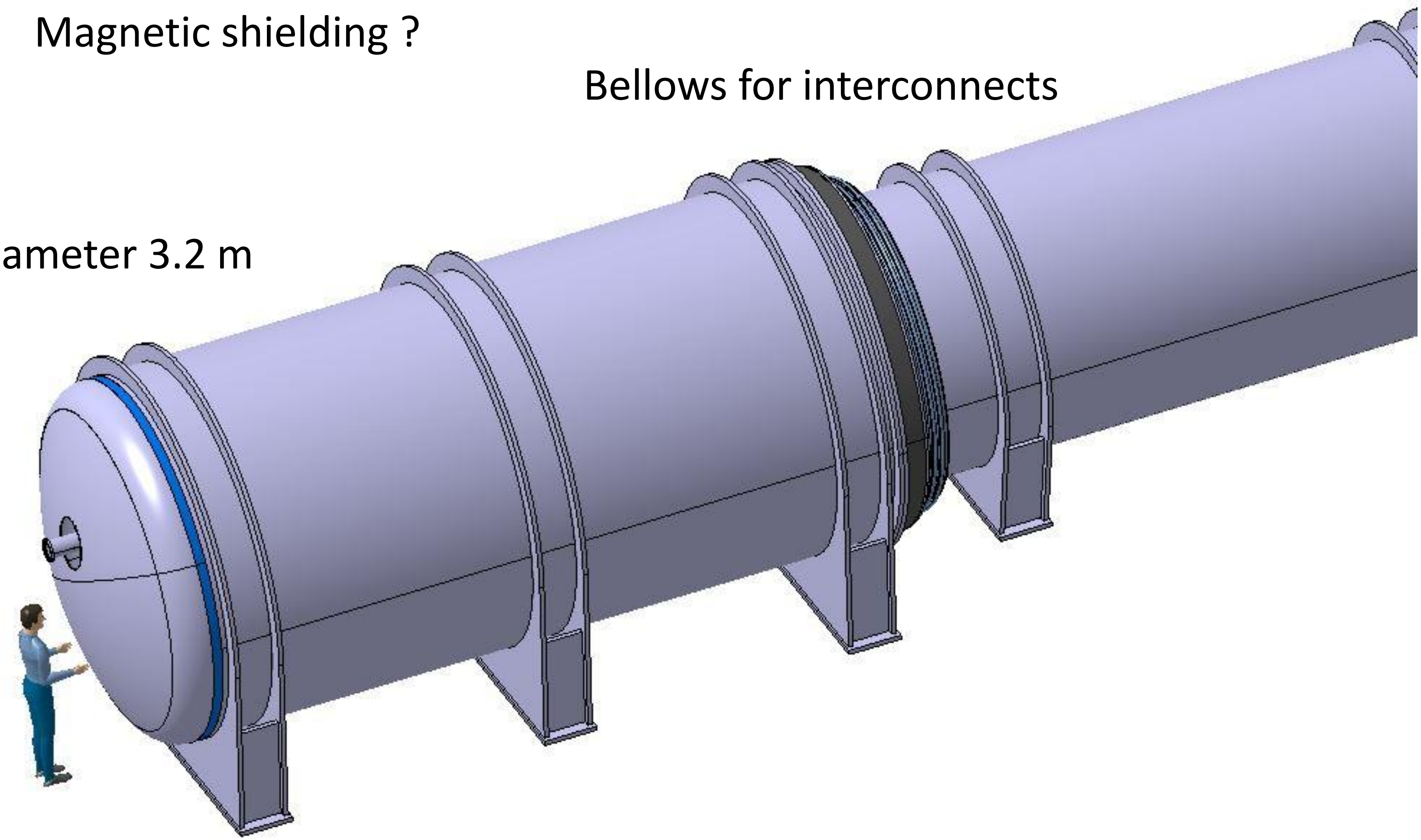
Integration work – 2/2

A. Kohleimainen (CERN)

Stray fields ?
Magnetic shielding ?

Bellows for interconnects

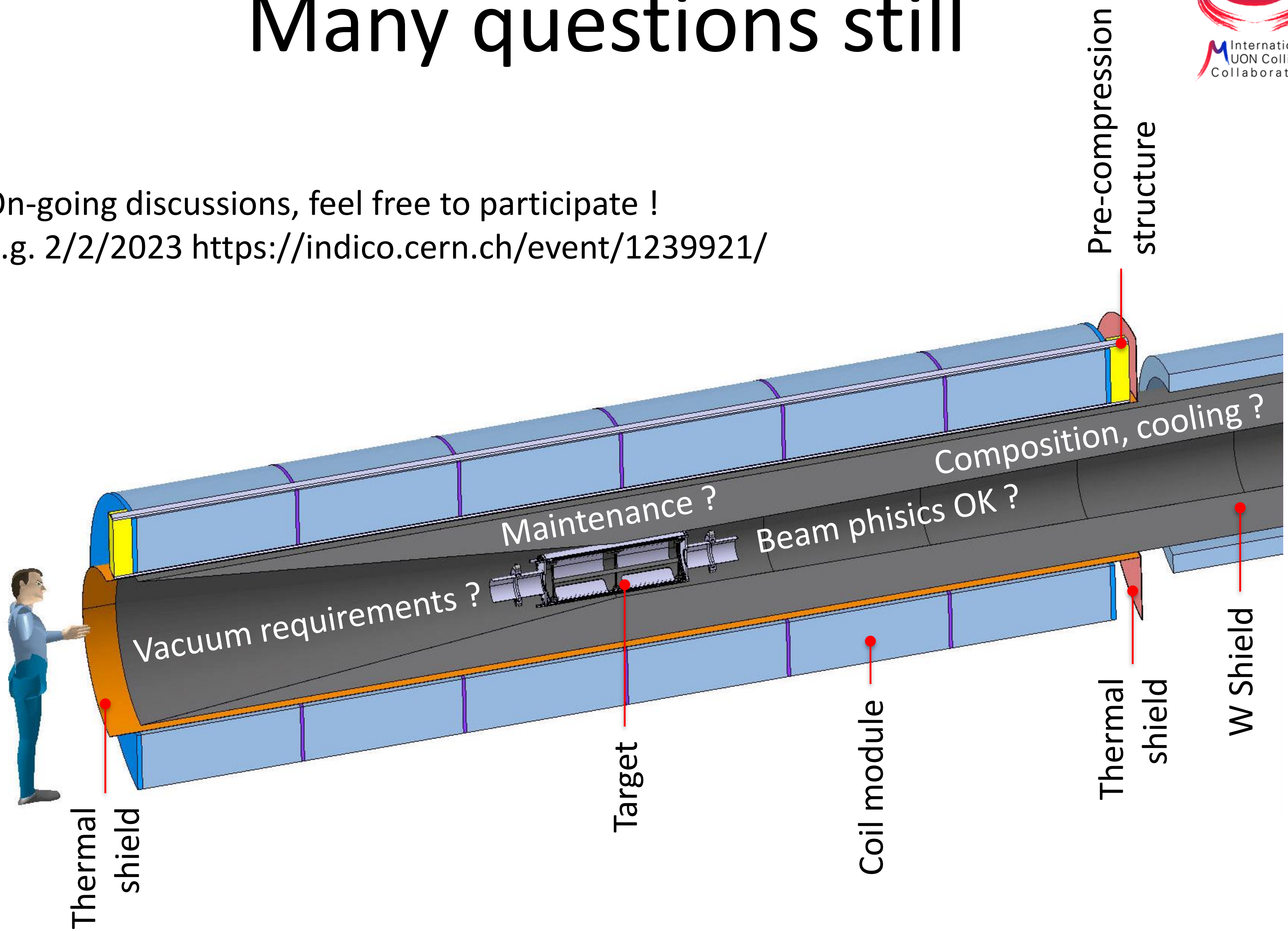
Max diameter 3.2 m



Vacuum loads support (70 tons)

Many questions still

On-going discussions, feel free to participate !
e.g. 2/2/2023 https://indico.cern.ch/event/1239921/



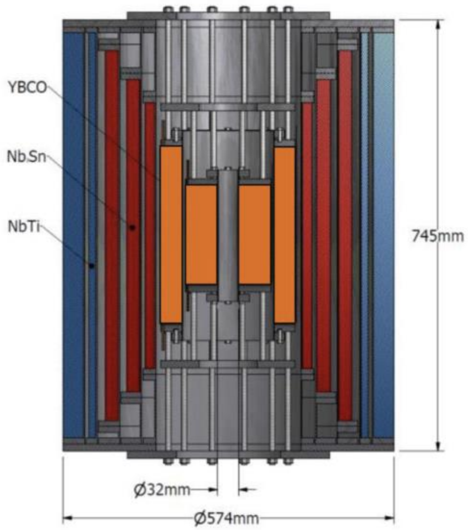
A. Kohleimainen (CERN)

Final cooling – 1/3

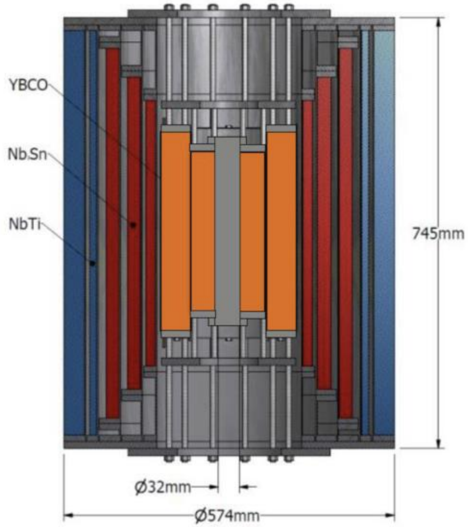
- Probe the limits of UHF solenoid magnets for the final cooling (performance)
- Make windings compact to reduce mass (CAPEX)

LTS/HTS hybrids

Cross section of 32 T, 32 mm user facility solenoid at NHMFL



Cartoon design of 40 T, 32 mm user facility solenoid (developmental)



R&D test achieved 25.4 T At NHMFL

Images of 32.35 T, 21 mm user facility solenoid at CAS-IEE

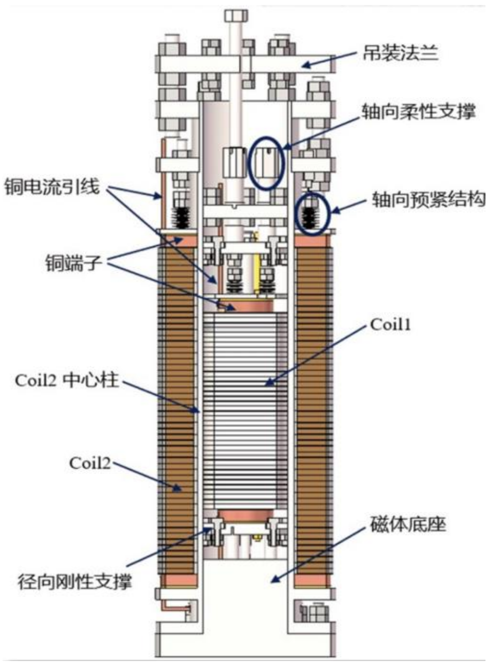
I. Dixon, NHMFL

Final cooling – 2/3

- Probe the limits of UHF solenoid magnets for the final cooling (performance)
- Make windings compact to reduce mass (CAPEX)

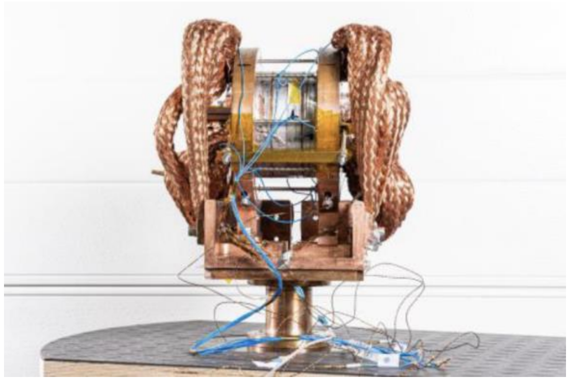
All-HTS

REBCO insulated coil
achieved 24.1 T
at CAS-IPP



B. Song, SST

R&D NI *coil*
achieved 18 T
at PSI



J. Kosse, PSI

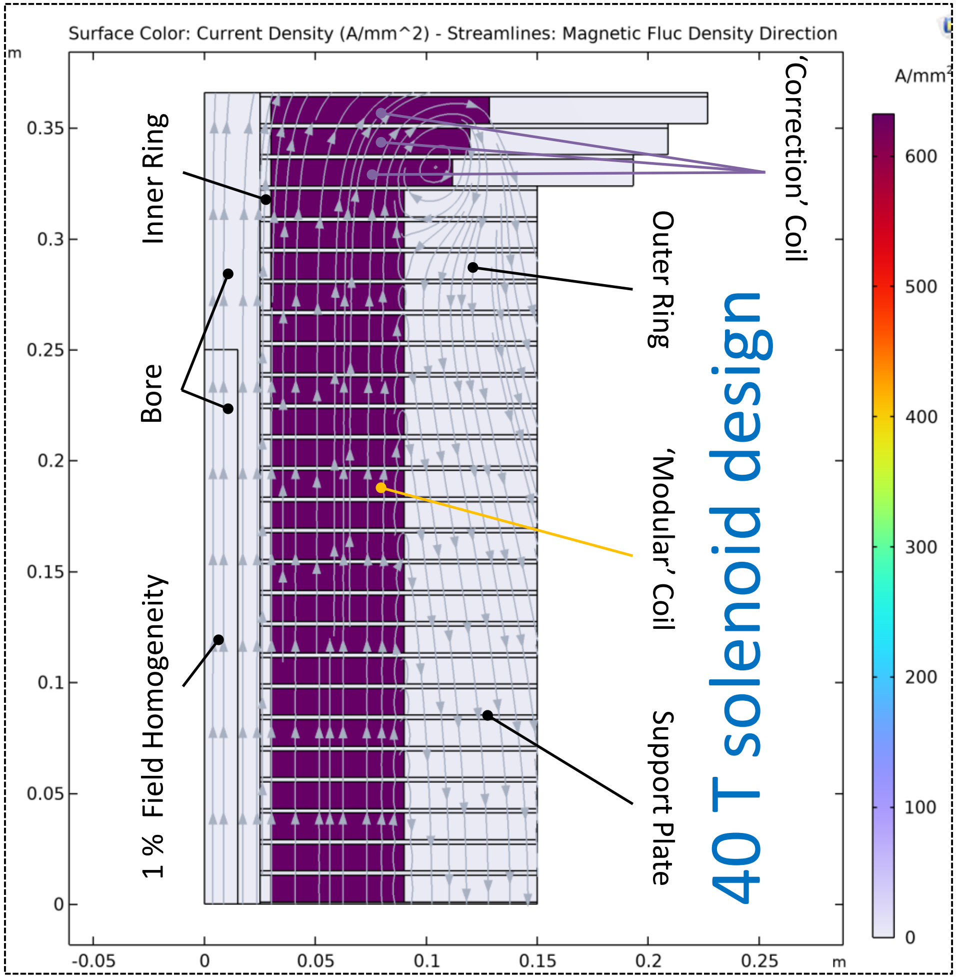
R&D NI *insert coil*
achieved 32.5 T
at LNCMI

J.-B. Song, LNCMI

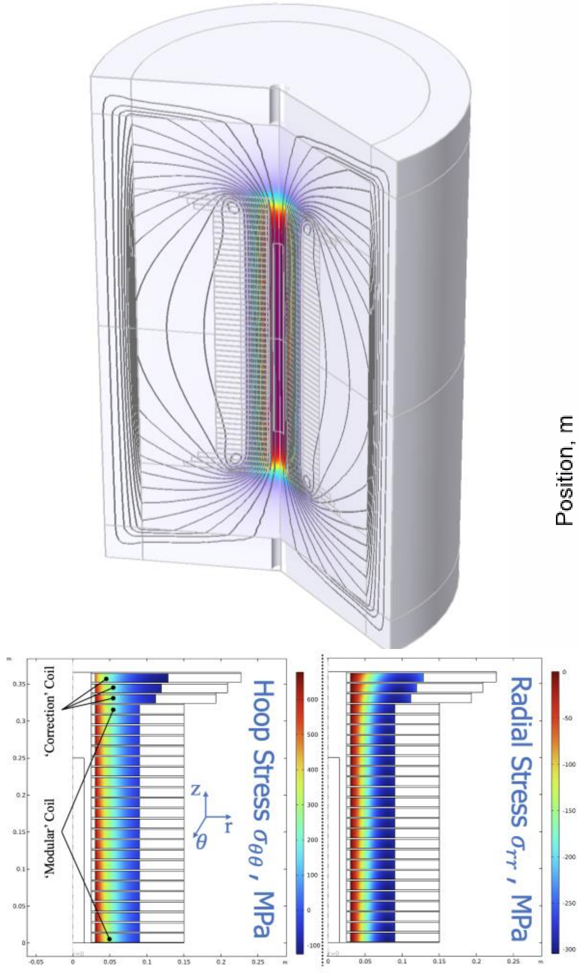
Final cooling (40 T) – 3/3

$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0} \xrightarrow{\sigma_{max} = 600\ \text{MPa}} B_{max} \approx 55\ \text{T}$$

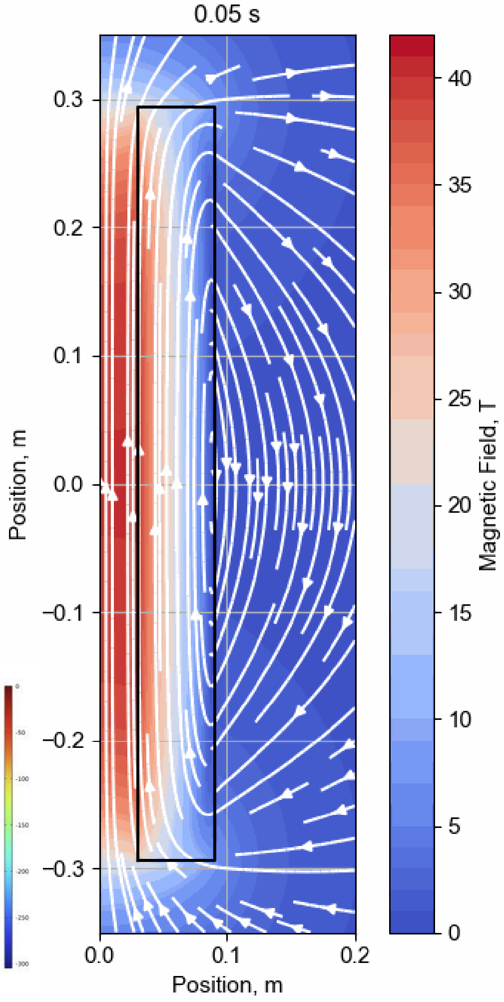
A. Dudarev, CERN



B. Bordini, CERN



B. Bordini, CERN

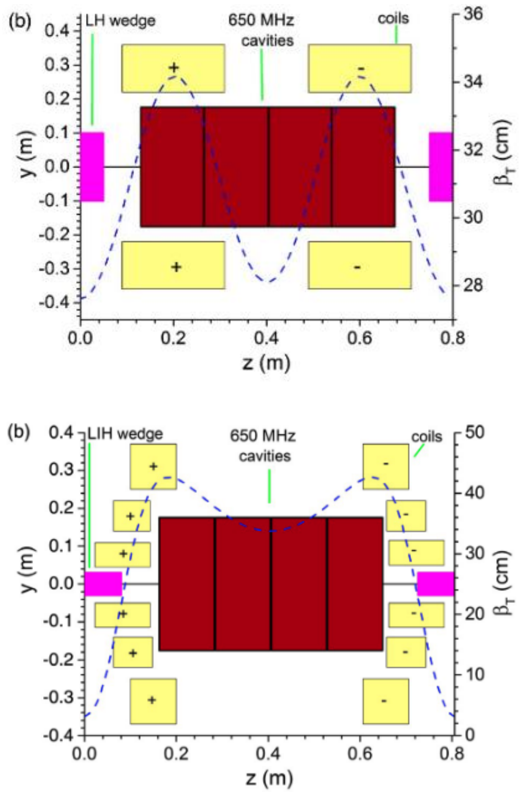


T. Mulder, CERN

6D cooling

- On-axis field and field profile B(s)
- Aperture and clearances
- Energy deposition, radiation dose, DPA's

Stage	Beam pipe radius [mm]	Solenoid peak on-axis field [T]	Dipole peak field [T]	Cell Length [m]	Total Length [m]
HfoFo	400	4	0.02		
A1	300	2.2	0.12	2	132
A2	250	3.4	0.11	1.32	171.6
A3	190	4.8	0.13	1	107
A4	132	6	0.07	0.8	70.4
B1	280	2.2	0.03	2.75	55
B2	240	3.4	0.08	2	64
B3	180	4.8	0.09	1.5	81
B4	140	6	0.12	1.27	63.5
B5	90	9.8	0.12	0.806	73.35
B6	72	10.5	0.13	0.806	62.06
B7	49	12.5	0.17	0.806	40.3
B8	45	13.6	0.14	0.806	49.16



Good starting point, **magnet work is starting**

https://indico.cern.ch/event/1147941/contributions/4851978

Scope of the talk

- The four main magnet challenges for a muon collider
- Technical advances
- A digression on HTS
- Work organization
- Summary and plans

Tasks

Magnet Systems

Task 1
Technical Coordination and Integration

Task 2
Target, Capture and Cooling Magnets

Task 3
Fast Cycled Accelerator Magnets

Task 4
Collider Ring Magnets

- The organization of the tasks overlaps with the EU MuCol study
- The scope of the work in most tasks, however, **extends beyond the EU proposal** (e.g. target solenoid study, HTS tape procurement and measurements, test of HTS pancakes, …)
- Most tasks activities also rely on advances and synergy with other projects and programs (e.g. HFM, UHF solenoid R&D, HTS fusion magnets R&D, HTS generators R&D, …)

The Team and the work – 1/2

Magnet Systems

Task 1
Technical Coordination and Integration

Task 2
Target, Capture and Cooling Magnets

Task 3
Fast Cycled Accelerator Magnets

Task 4
Collider Ring Magnets

- Participants
  - **CERN** (LB, SF)
  - CEA (LQ)
- Activities
  - Periodic meeting of the “muons magnets Working Group”
  - Machine configuration (“magnet catalogue”)
  - Interface to physics, radiation, vacuum, cryogenics, safety and RP
  - Review of radiation hardness of superconductors and insulation systems (joint activity with radiation studies)
  - Documentation and reporting

The Team and the work – 2/2

Magnet Systems

Task 1
Technical Coordination and Integration

**Task 2
Target, Capture and Cooling Magnets**

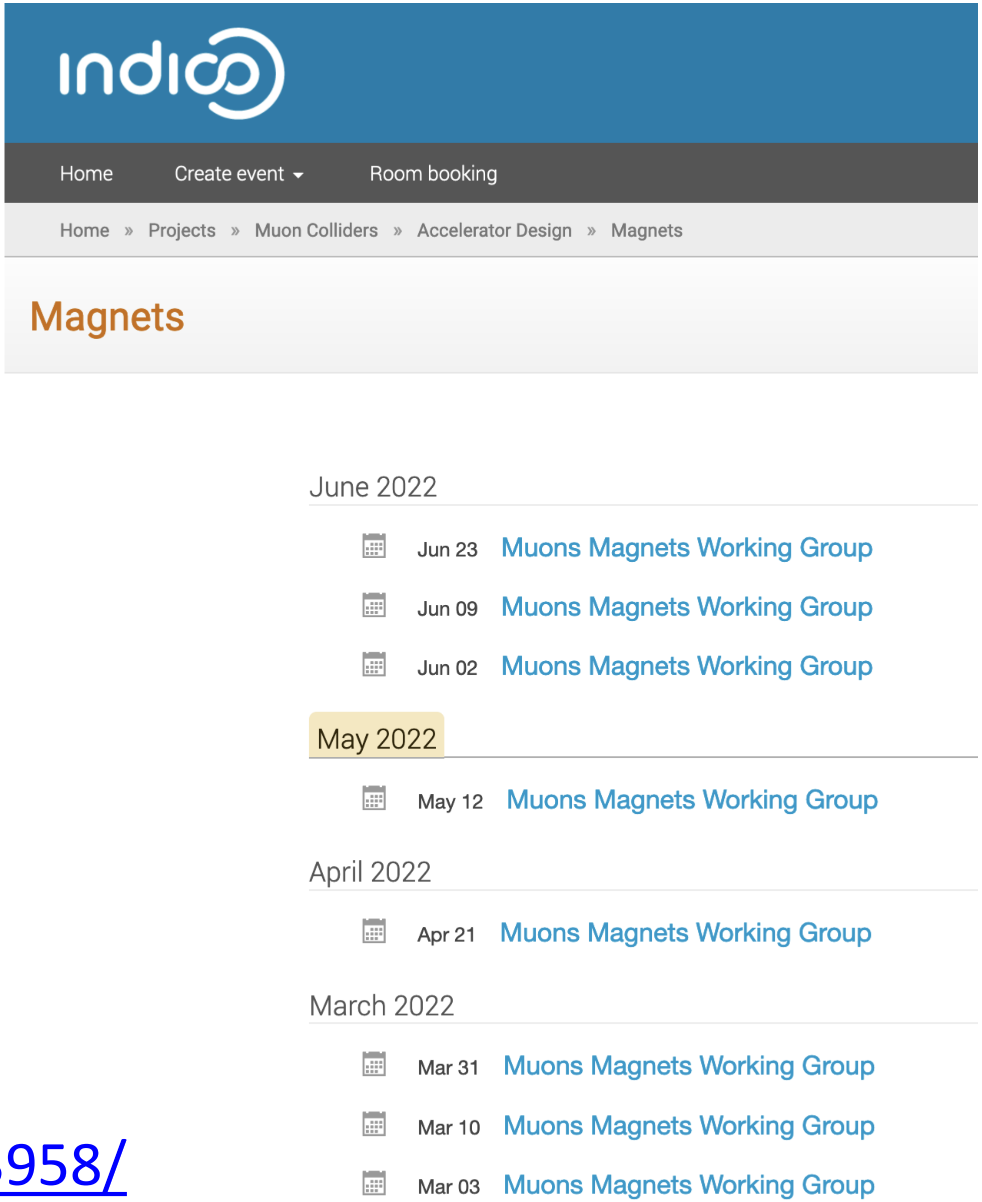
Task 3
Fast Cycled Accelerator Magnets

Task 4
Collider Ring Magnets

- Participants
  - **INFN** (MS)
  - CEA (LQ, PhD)
  - CERN (AD, BB, TM, LB, AK, CA, AB)
  - *CNRS (XC)*
  - *F4E (AP, PT)*
  - *KIT (TA)*
  - *PSI (JK)*
  - *SOTON (YY, post-doc)*
  - *UNIGE (CS)*
  - TWENTE (HTK, AK, post-doc)
- Activities (≈ 12 months)
  - Conductor review and specification
  - Design of target and capture channel solenoids
  - Design of final cooling solenoid
  - Procurement and electro-mechanical characterization (UHF) of test HTS material
  - Pancake model coils, engineering design, manufacturing solutions, mechanical and powering tests

Muons Magnets WG

- Twenty-one meetings to date, with participants from m ost collaborating institutes and universities
- Since April we meet:
  - to “learn” about the previous work (MAP) and advances in relevant fields,
  - to discuss in an informal setting initial ideas and options, and
  - in preparation of upcoming activities, in particular the EU MuCol



Site: https://indico.cern.ch/category/13958/
Mailing list: muoncollider-magnets@cern.ch

Summary and Plans

- **The grand challenges have been identified**, they represent well the envelope of design and performance issues. Work has started to see what are the limits, propose technical solutions and associated R&D
- The challenges are aligned with the structure of MuCol (Tasks 7.2, 7.3 and 7.4). This simplifies the forming and coordination work with the team. **We plan to continue along these lines**
- The interaction with the other ”specialties” has started, to discuss specifications, give and receive feedback on feasibility:
  – Beam optics
  – Impedance limitations
  – Radiation heat loads, dose and damage
  – Vacuum and cryogenics
- It looks like **HTS can make a huge difference** towards a compact, energy efficient and sustainable collider. Priority will be devoted to this R&D