Muon Collider WP7 - Magnets

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on behalf of the Muons Magnets Working Group
12/12/2022

Scope of the talk

- Guidelines for the upcoming (magnet) work
- The four challenges
  - Technical advances
- Work organization
- AOB
- Summary and plans

This is still work in progress

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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**

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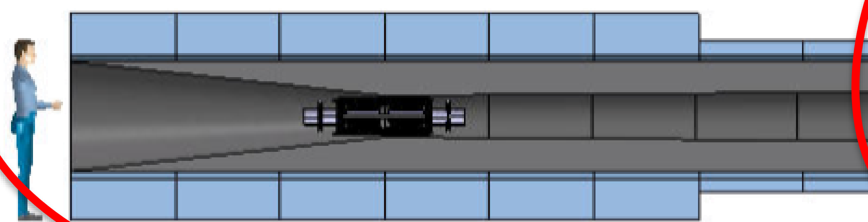
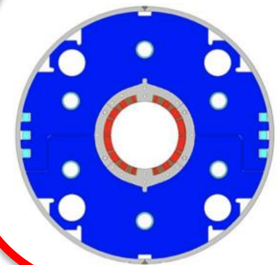
Magnet *specifications*

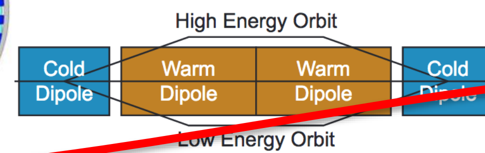
International MUON Collider Collaboration

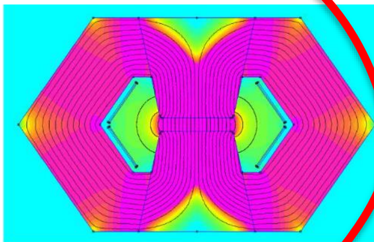
20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: >> 20 MGy

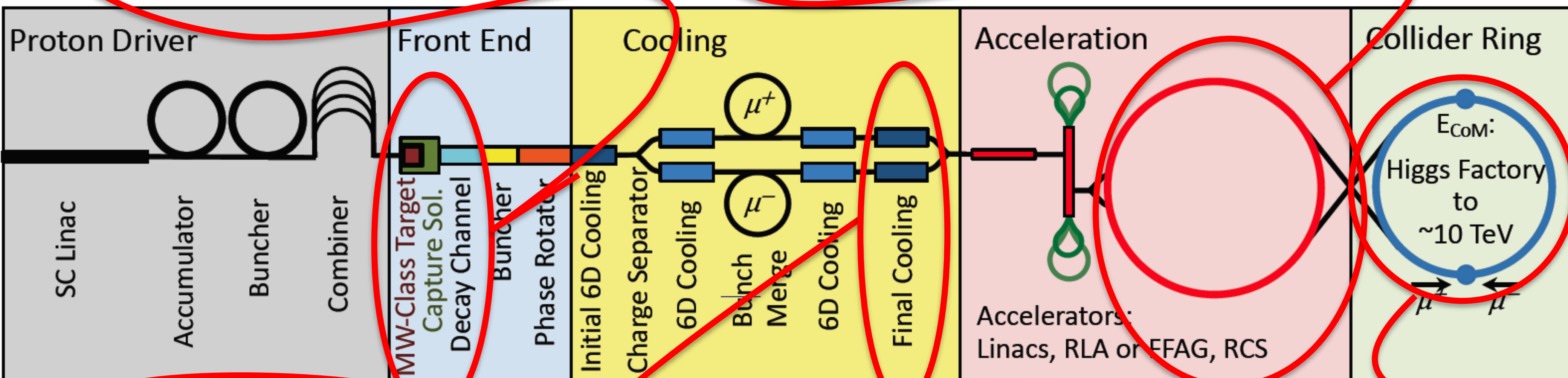


NC ±1.8 T, 400 Hz, 100 mm x 30 mm
SC < 10T, ≈ 100 mm

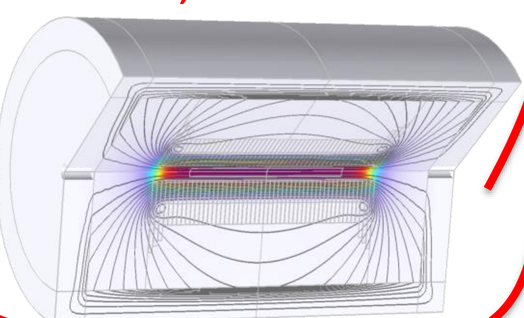




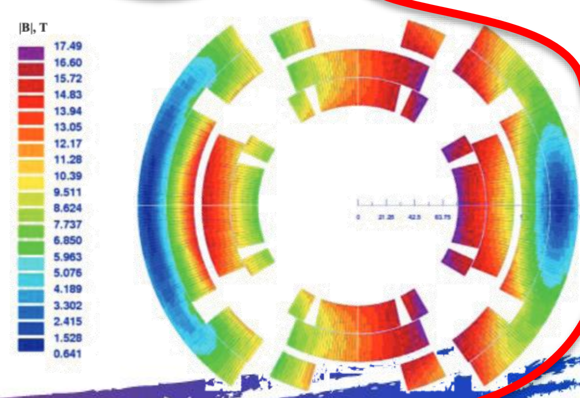




> 40 T, 60 mm

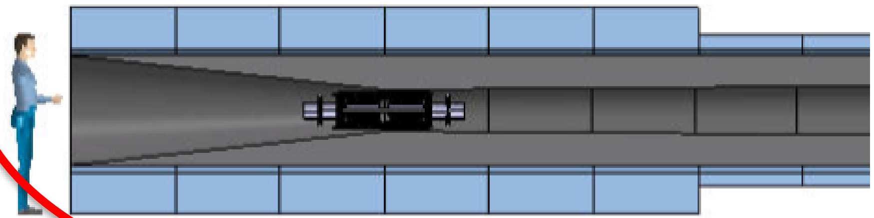


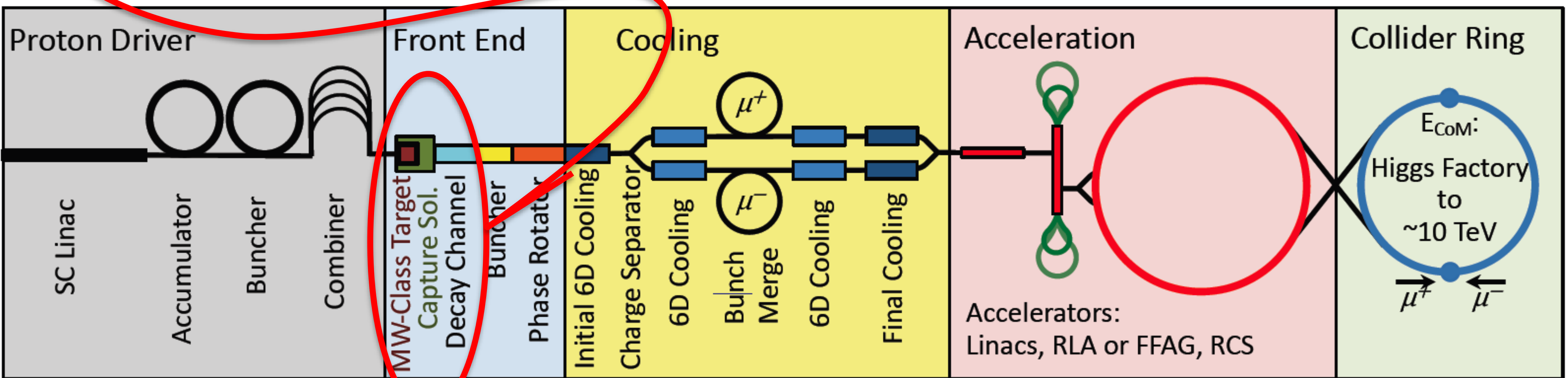
16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 Mgy



The four challenges – 1/4

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

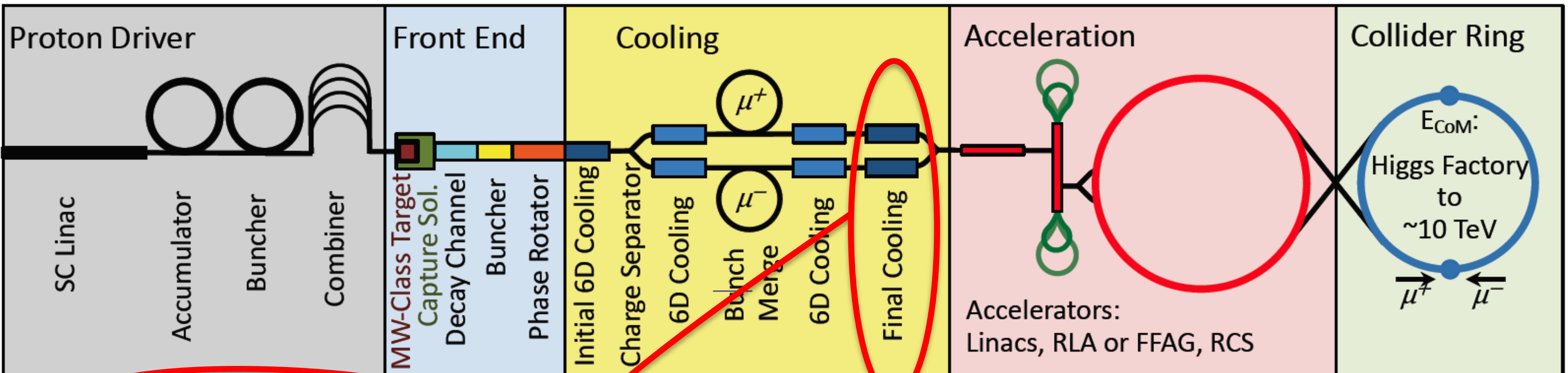


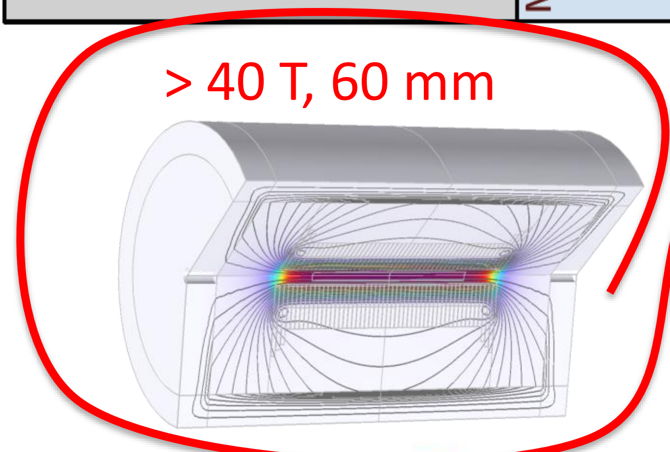


- **Large stored energy o(1) GJ, mass o(300) tons, cost o(100) M**
- **Considerable RT and cryogenic heat load: RT power o(1) MW**
- **Radiation dose o(80) MGy and radiation damage o(10^{-2}) DPA**

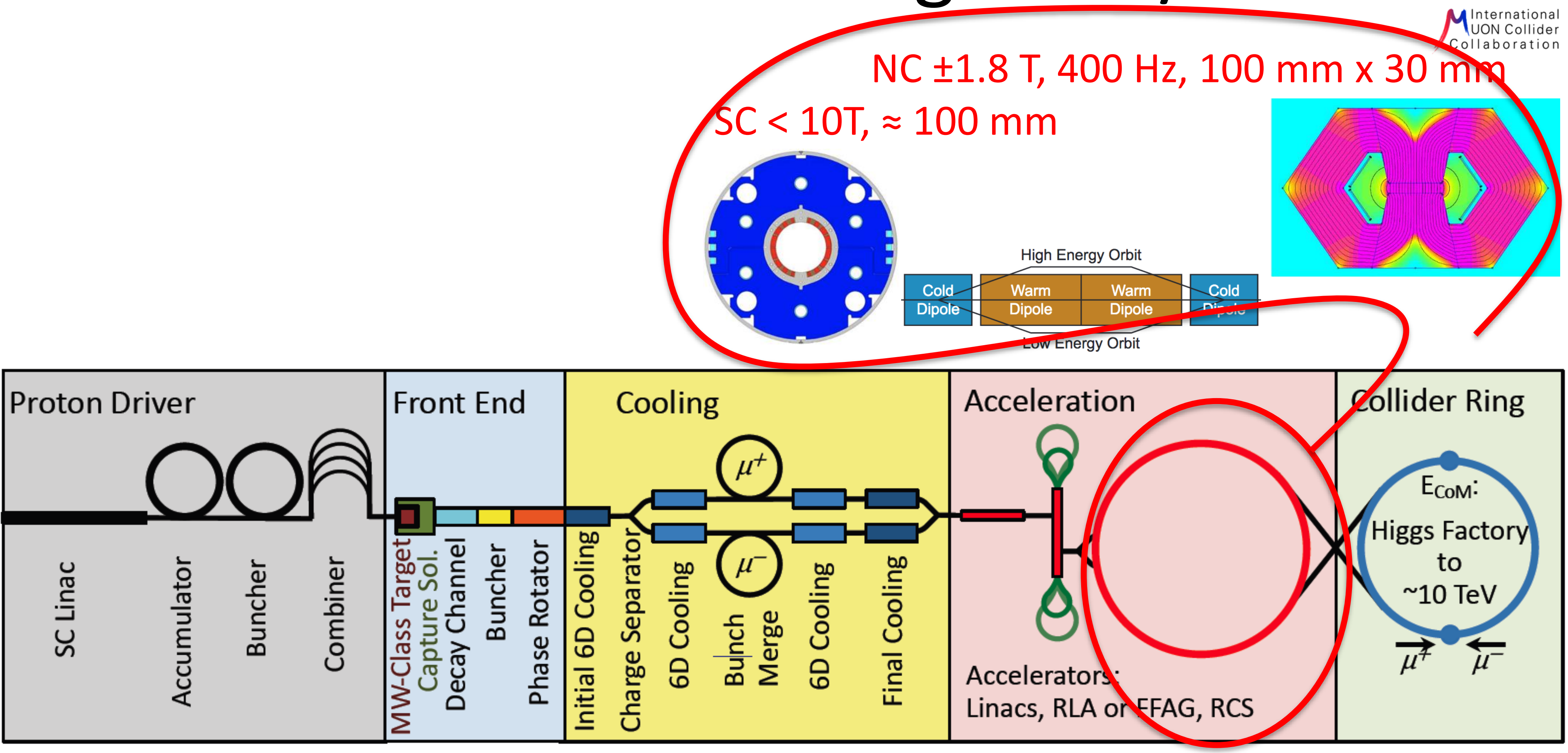
The four challenges – 2/4

- **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**





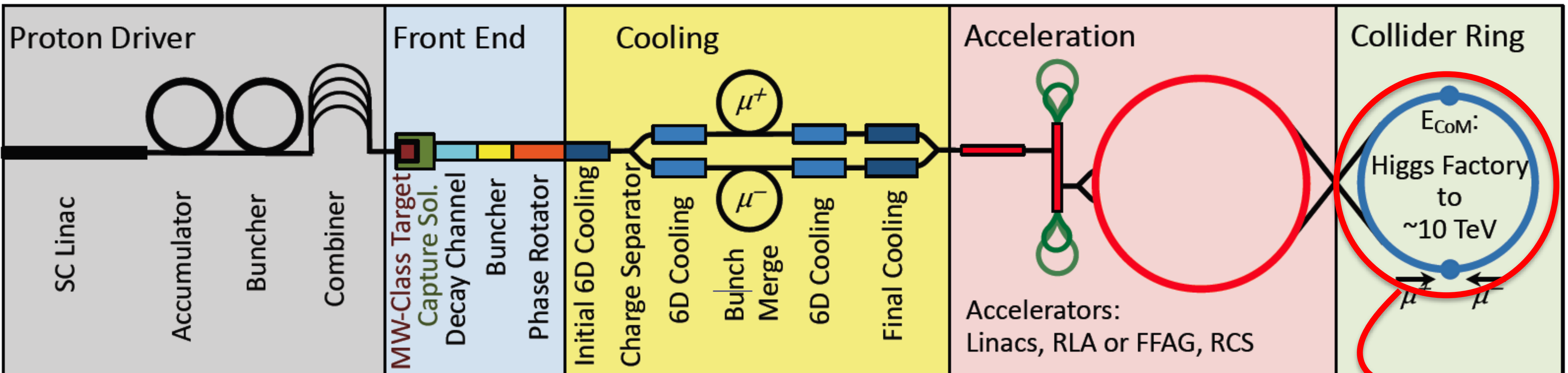
The four challenges – 3/4



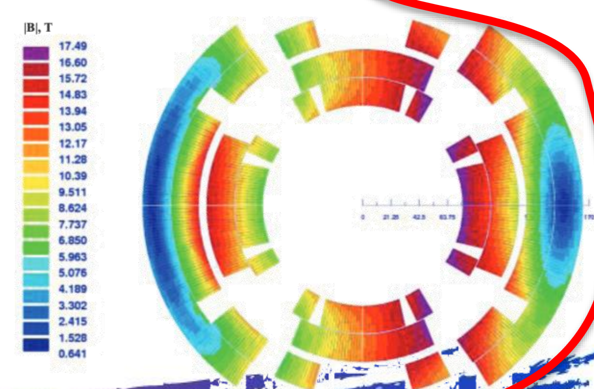
- **Energy storage and power management o(50) GW**
- **Ramp linearity control, requirement (TBD)**

The four challenges – 4/4

- **Large bore o(150mm), high field o(10…20T) arc and IR magnets result in large e.m. stress o(300…400MPa) and require novel stress management concepts**
- **Significant Energy deposition o(5 W/m) and dose o(40 MGy)**



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



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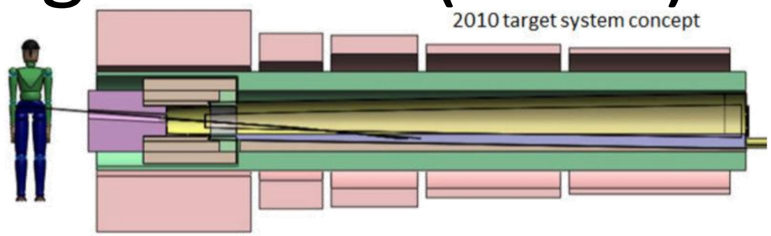
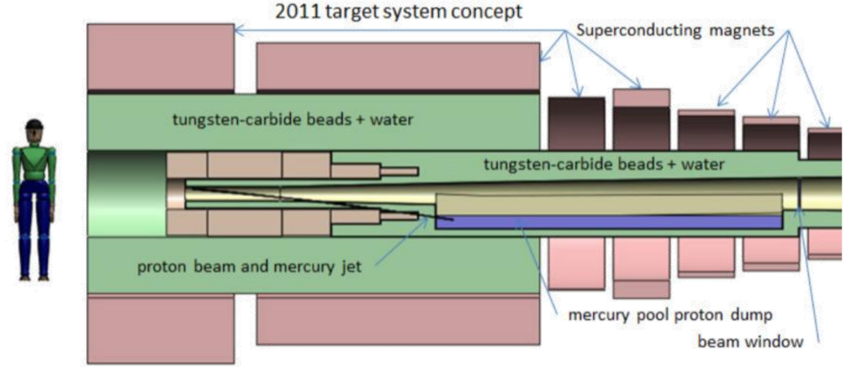
Target and capture – 1/4

- 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)



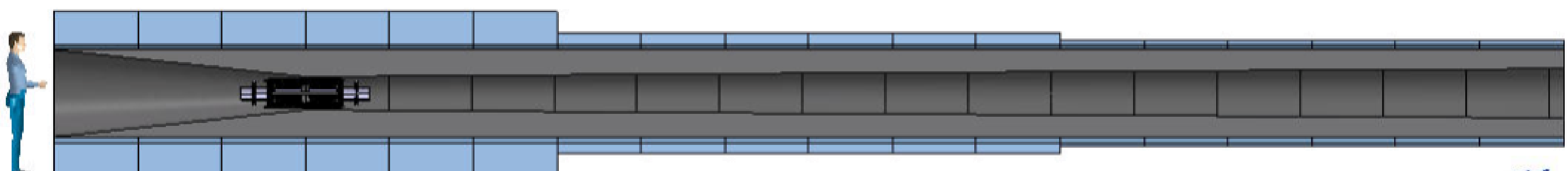
US-MAP **2011** design
LTS (14 T) + NC (6 T)



H.G. Kirk, PAC 2011

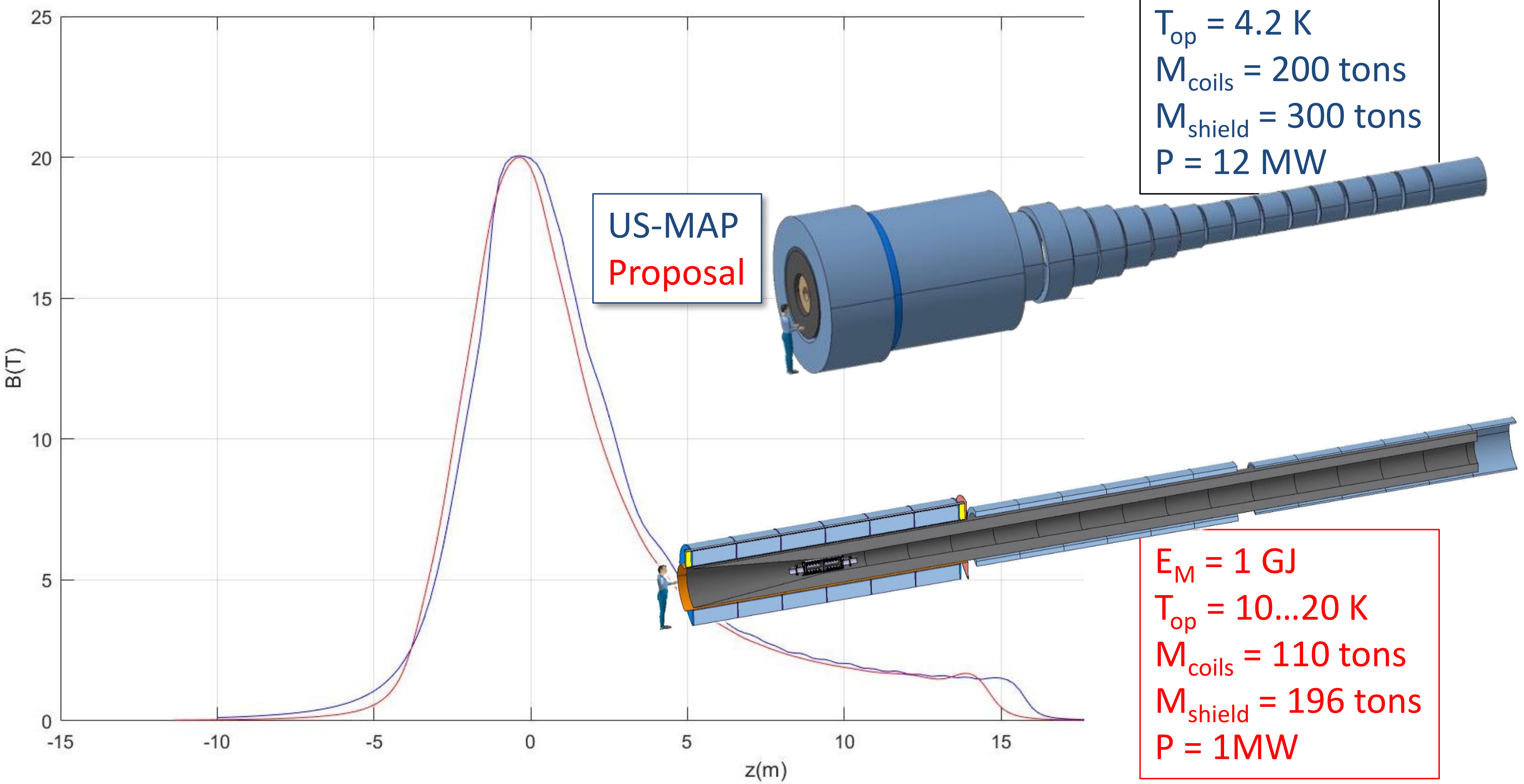
Magnet	z_{min} (cm)	Δz (cm)	r_{min} (cm)	Δr (cm)	I (A/mm^2)
RC1	-131.3	47.3	17.8	30.24	16.56
RC2	-84	86.2	17.8	30.88	16.56
RC3	2.1	56.2	17.8	30.25	16.56
RC4	58.3	57	17.8	16.6	16.56
RC5	115.3	43.5	21.88	7.96	16.56
SC1	-222.6	169.4	120	75.85	23.22
SC2	-53.1	26.1	120	54	0
SC3	-27.1	327.1	120	54.07	23.1
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



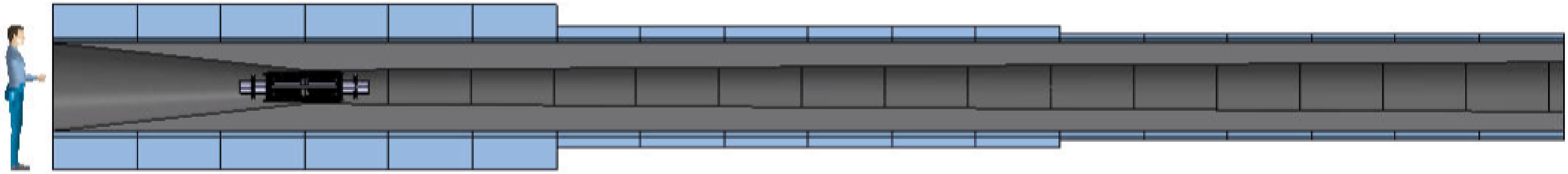
US-MAP
Proposal

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

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

A. Portone, P. Testoni, F4E

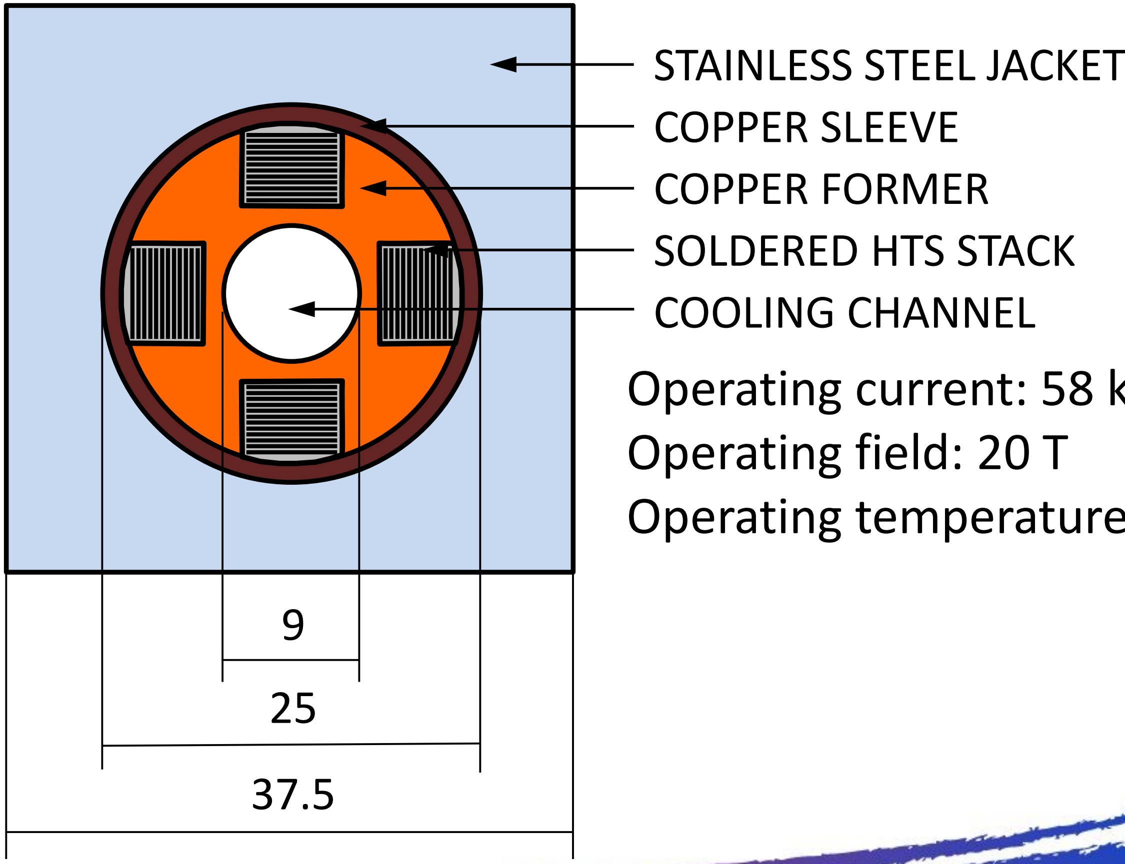
Target and capture – 3/4



MIT "VIPER" conductor

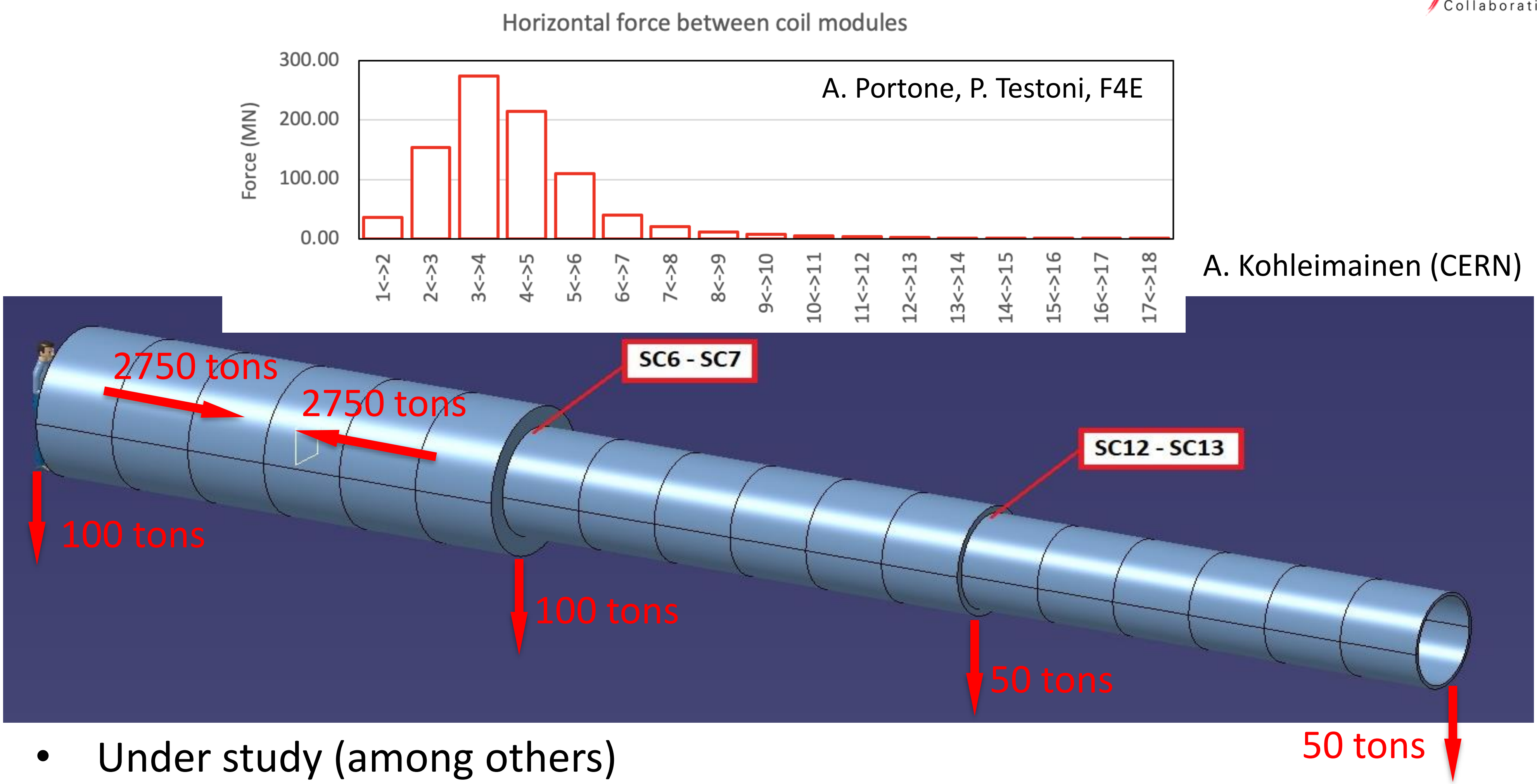
M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

HTS conductor design



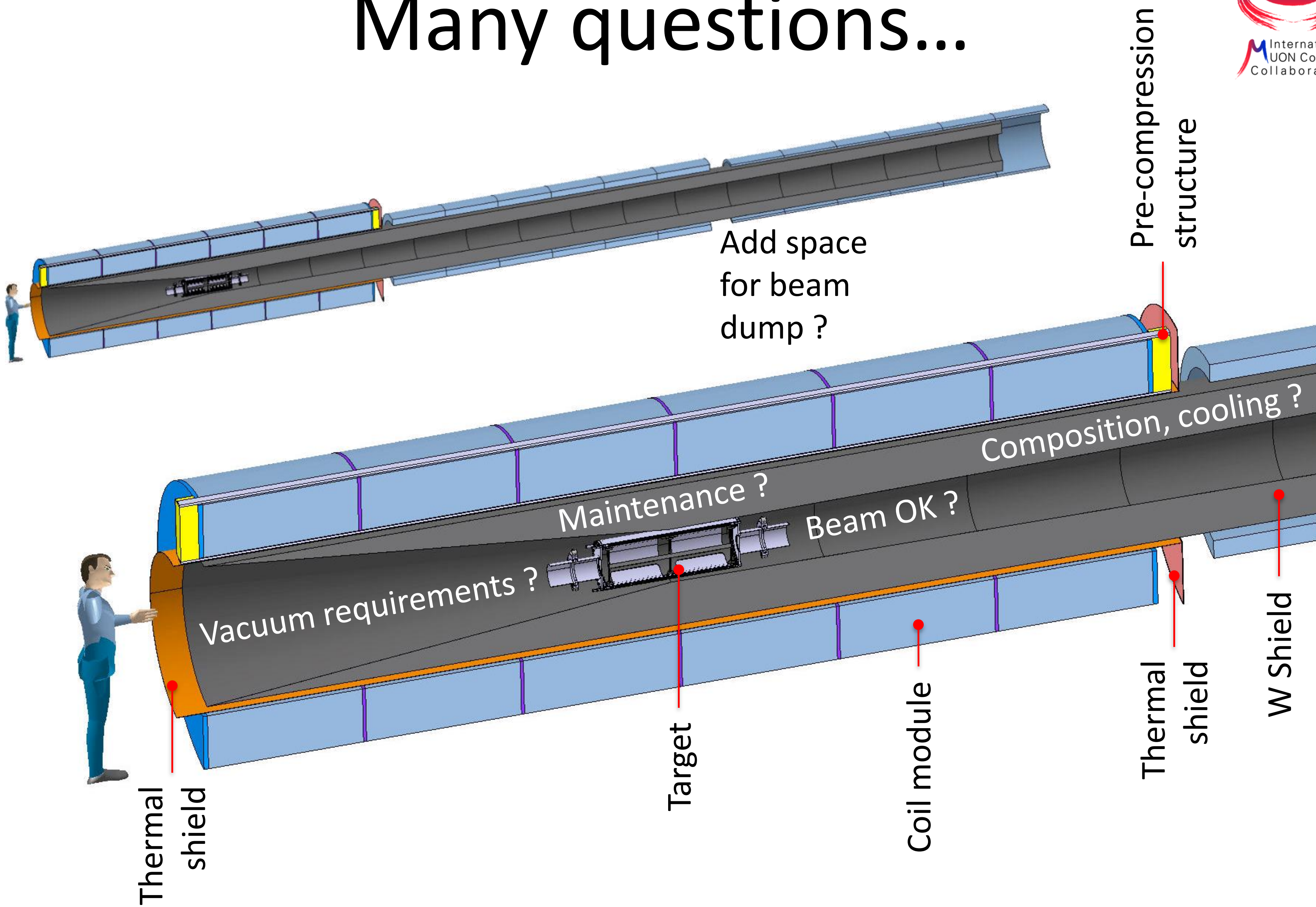
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K

Target and capture – 4/4



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

Many questions…



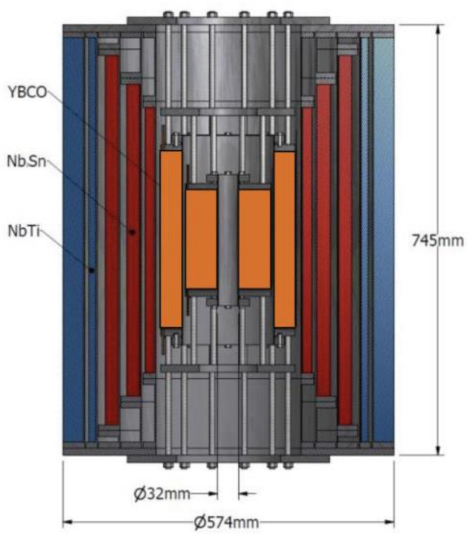
A. Kohleimainen (CERN)

Final cooling – 1/3

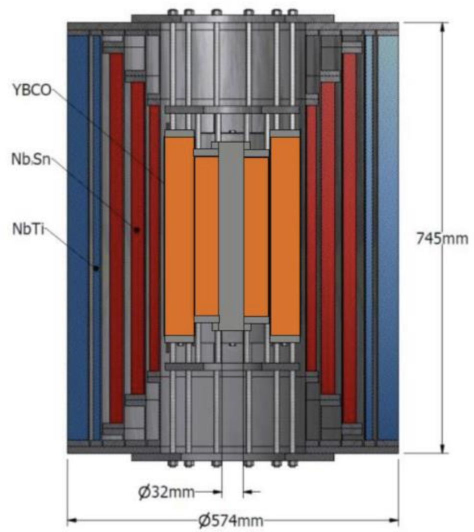
- Probe the limits of UHF solenoid magnets for the final cooling (performance)
- Make windings compact to reduce mass (CAPEX)

LTS/HTS hybrids

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

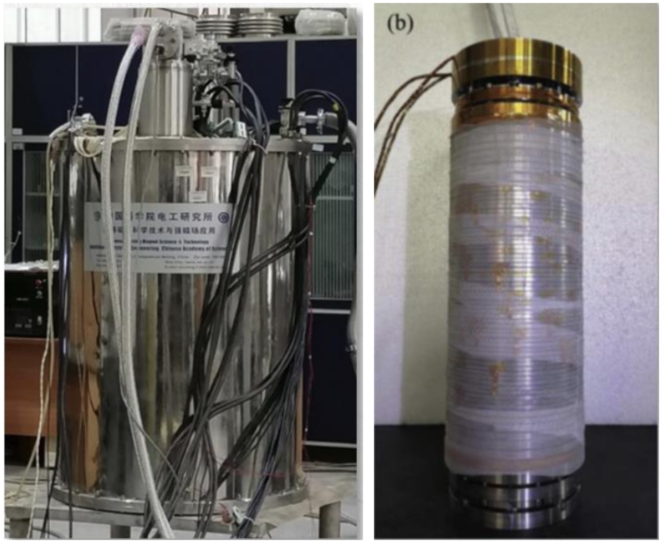


Cartoon design of 40 T, 32 mm user facility solenoid (developmental)



R&D test achieved 25.4 T At NHMFL

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



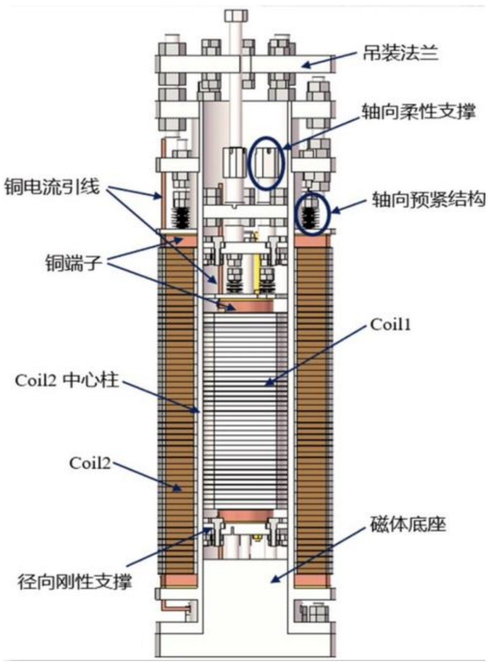
I. Dixon, NHMFL

Final cooling – 2/3

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

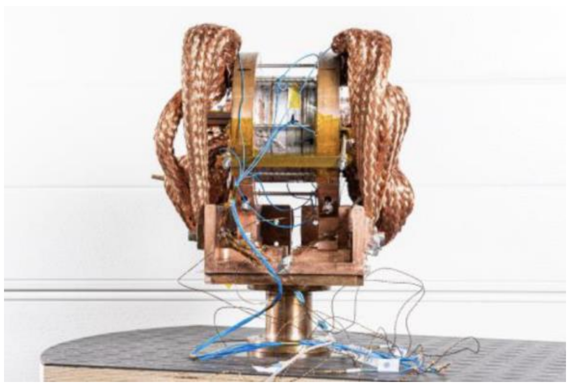
All-HTS

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

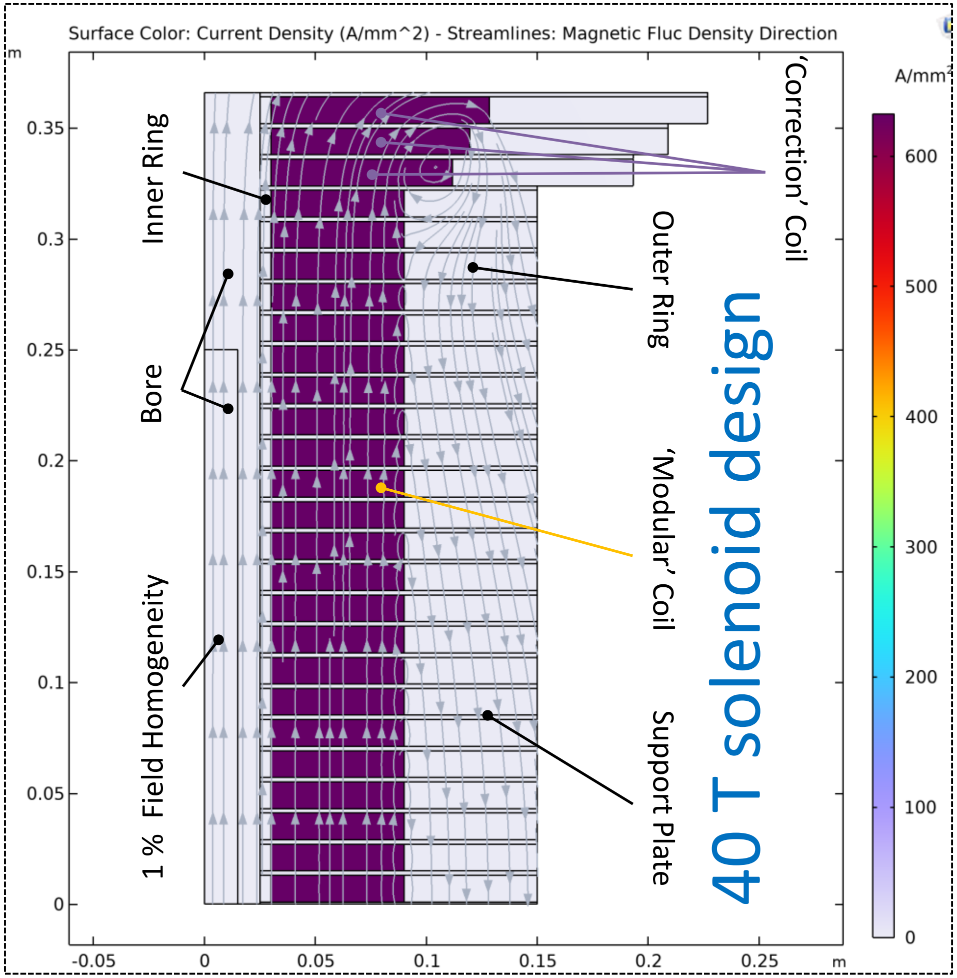
R&D NI *insert coil*
achieved 32.5 T
at LNCMI

J.-B. Song, LNCMI

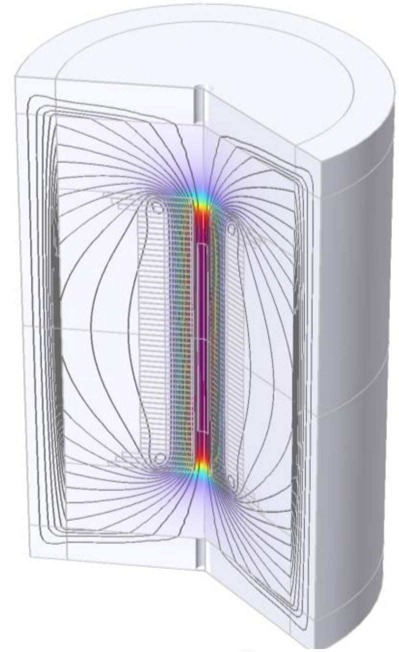
Final cooling (40 T) – 3/3

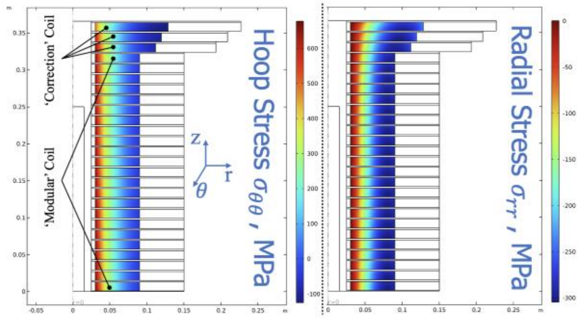
$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0} \xrightarrow{\sigma_{max} = 600\ \text{MPa}} B_{max} \approx 55\ \text{T}$$

A. Dudarev, CERN

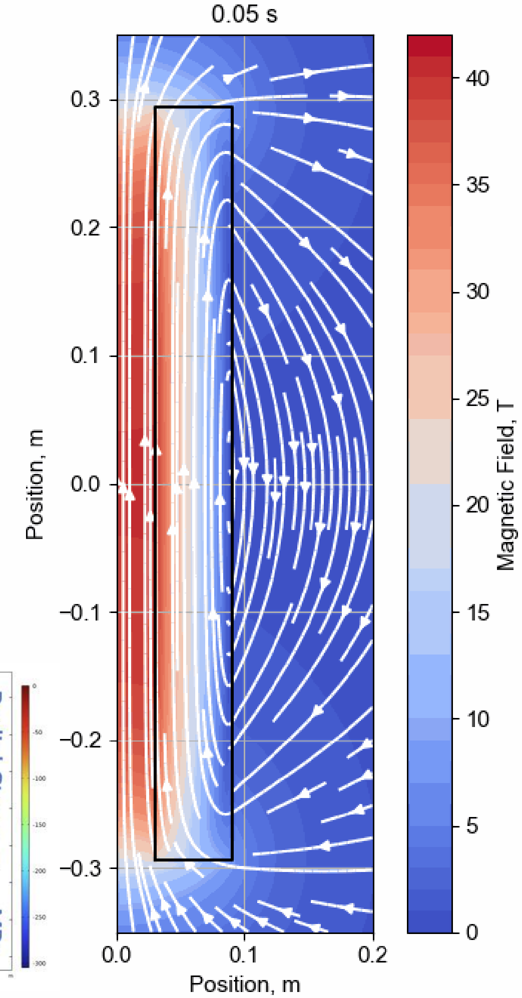


B. Bordini, CERN





B. Bordini, CERN

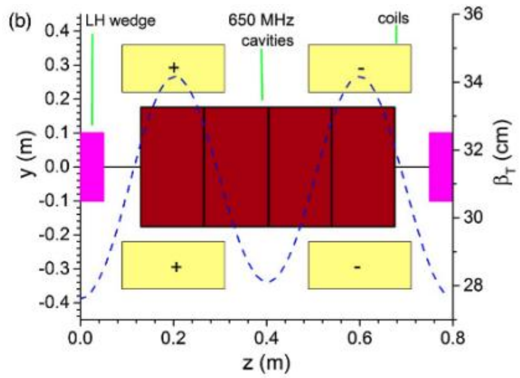


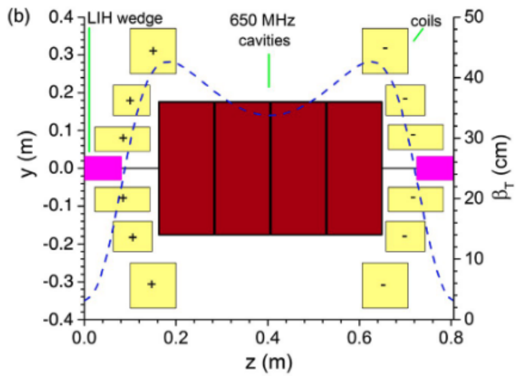
T. Mulder, CERN

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

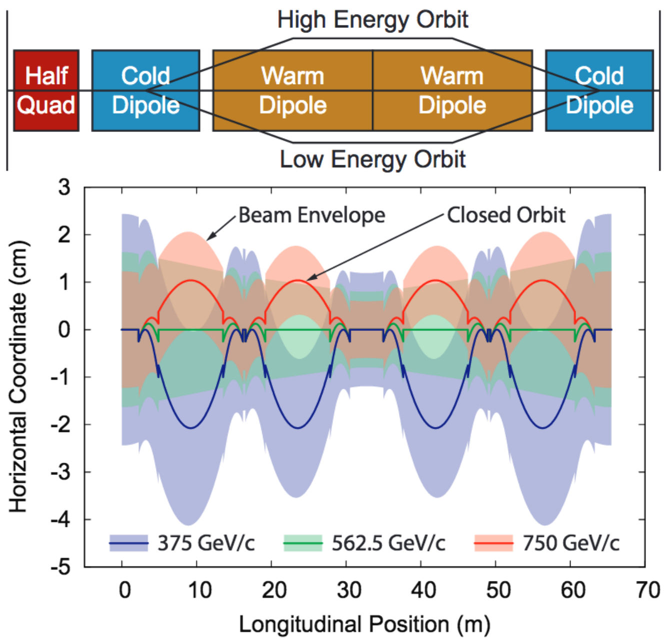


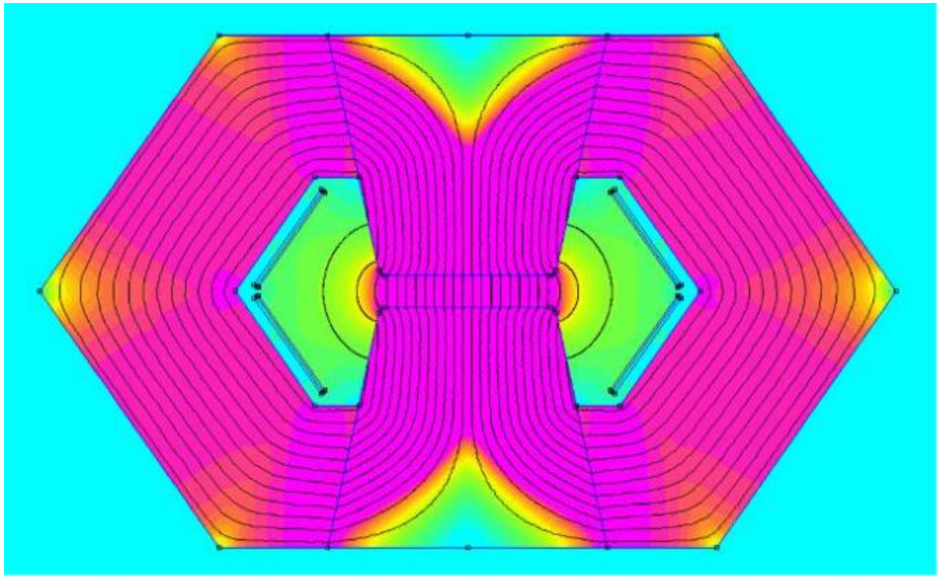


Good starting point, **magnet work will start in 2023**

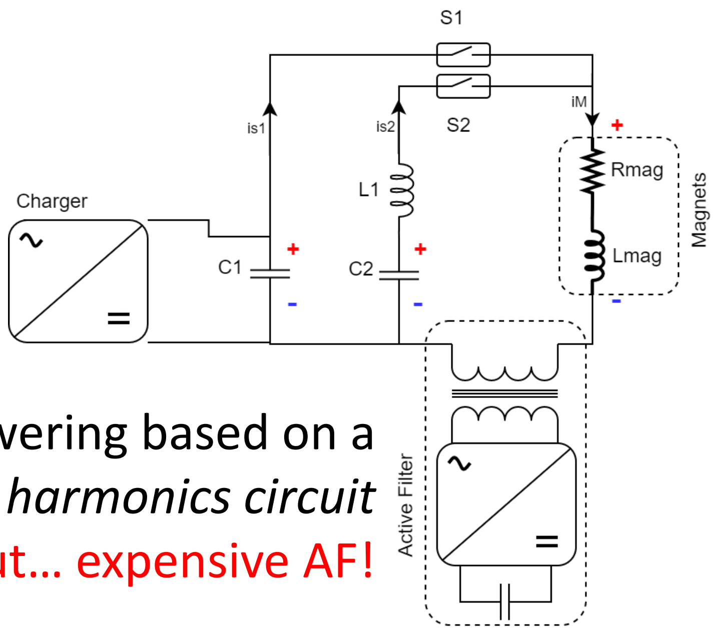
https://indico.cern.ch/event/1147941/contributions/4851978

Accelerator magnets – 1/4

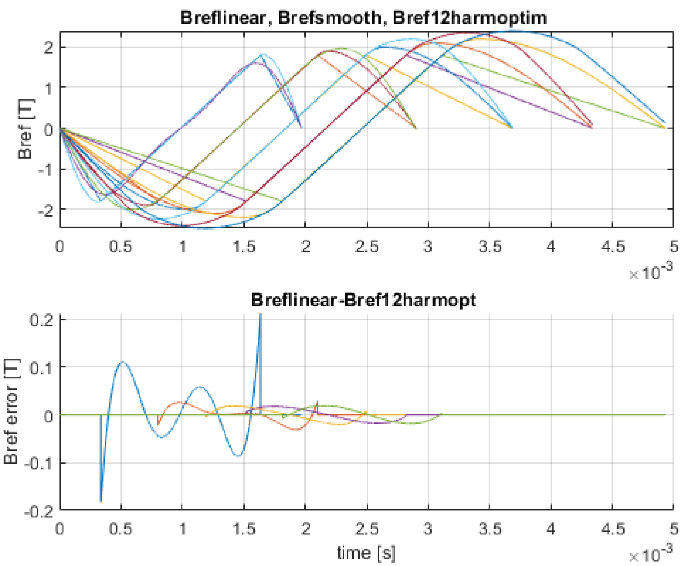




US-MAP



Powering based on a *two harmonics circuit* but… expensive AF!



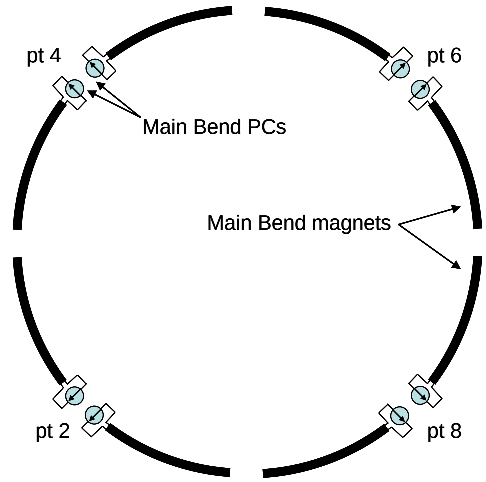
F. Boattini, CERN

Field ramp linearity can be obtained driving the magnets into saturation (≈ 0.1 T)

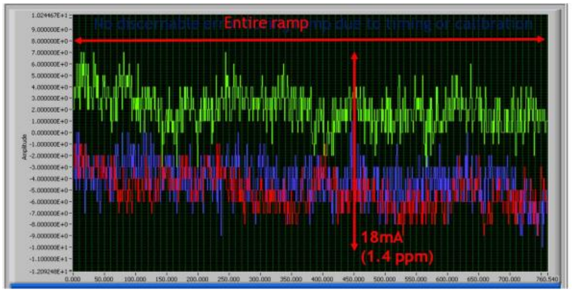
- Field quality ?
- Losses ?
- Reproducibility ?

Accelerator magnets – 2/4

- To limit the stored energy, power, and voltage the string of NC dipoles will be "broken" in many individually powered circuits
- A capacitor discharge is largely influenced by
  - Capacitor temperature
  - Ageing
  - Any other changes in R-L-C characteristics
- Active control will be necessary (active filter)
- The **specification on the field tracking** can have a significant impact on the design and cost of the active filter in the power converter



Tracking on the 24 main circuits of the LHC achieved control accuracy of ppm's of nominal current



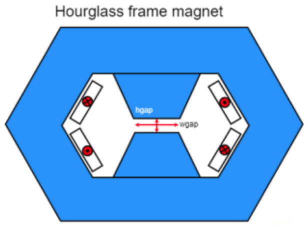
Accelerator magnets – 3/4

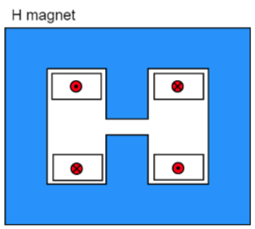
M. Breschi, R. Micelli, P. Ribani (UniBo), F. Boattini (CERN)

	Active power (MW/m)	Reactive power (MVA/m)	Energy in gap (J/m)	Energy in air (no gap) (J/m)	Energy in coils (J/m)
***Hourglass* magnet**	**0.15**	**15.7**	3.8	1.2	0.07
H-magnet (3 coils)	0.36	16.3	3.8	1.3	0.55
H-magnet (2 coils)	0.18	19.9	3.9	3.1	0.14
Windowframe magnet	**1.24(*)**	**14**	3.7	0.7	1.49

(*) mainly due to skin effect, can be limited by subdividing the copper conductors

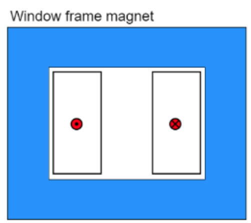
Highly optimized cross section

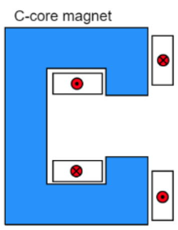




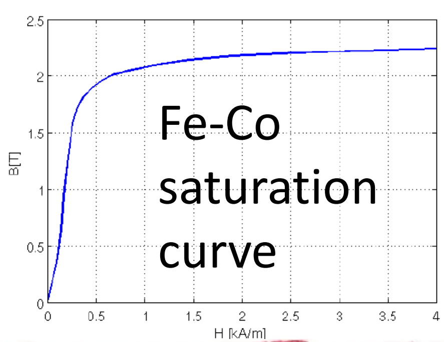
Does not seem interesting

Higher loss but marginally lower stored energy





Configuration to be studied



- The magnet stored energy is directly proportional to iron gap and pole width: **keep them as small as possible**
- **Fe-Co** seems the only practical way to reach fields in the range of 1.8 T, but **may pose RP issues** (to be quantified)

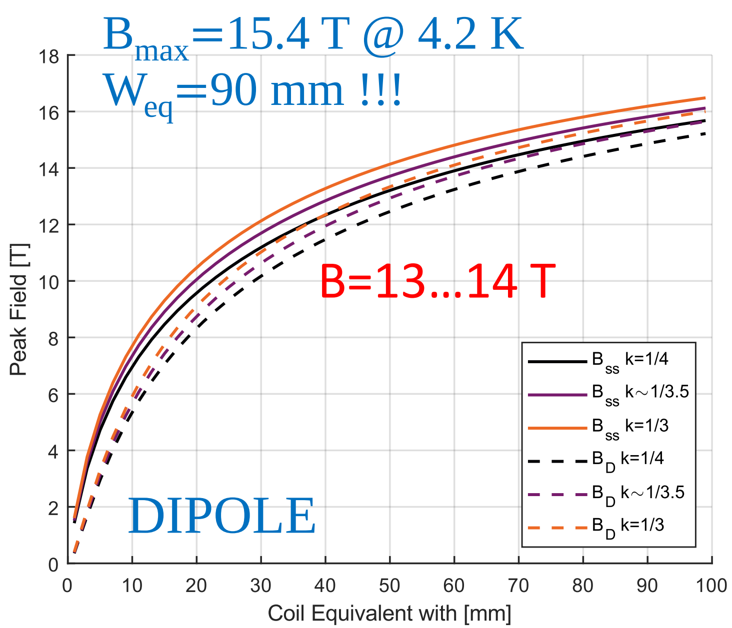
Accelerator magnets – 4/4

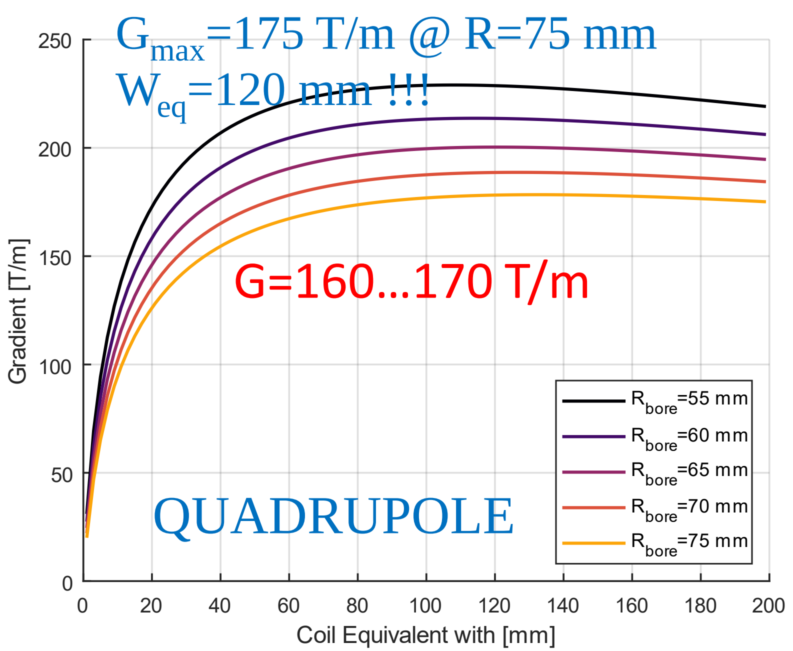
- SC magnets
  - 10 T is an "unfortunate" number for Nb-Ti
    - LHC heritage, resulting from the years if competition with the SSC. Only a couple of models (MFISC, FRESCA) and 10m prototypes made it to (or close to) 10 T
    - LHC ultimate field (magnet design) is set at 9 T. This field level was reached in a large part of the series production
    - For practical reasons the LHC dipoles operate at 8 T
    - **Set the Nb-Ti design dipole field to 8…9 T** (see later)
  - NOTE: 16 T is similarly un "unfortunate" number for Nb_3Sn
    - **Set the Nb_3Sn design dipole field to 13…14 T** (see later)

Collider magnets – 1/3

On-axis peak field	10 T
On-axis peak gradient	300 T/m
Bore diameter	150 mm
Magnetic length	15 m
Field Quality	10 units
Technology	LTS/HTS
Temperature range	1.9/4.2 K (LTS) or 10 to 20 K (HTS)

The combination of these three is not possible





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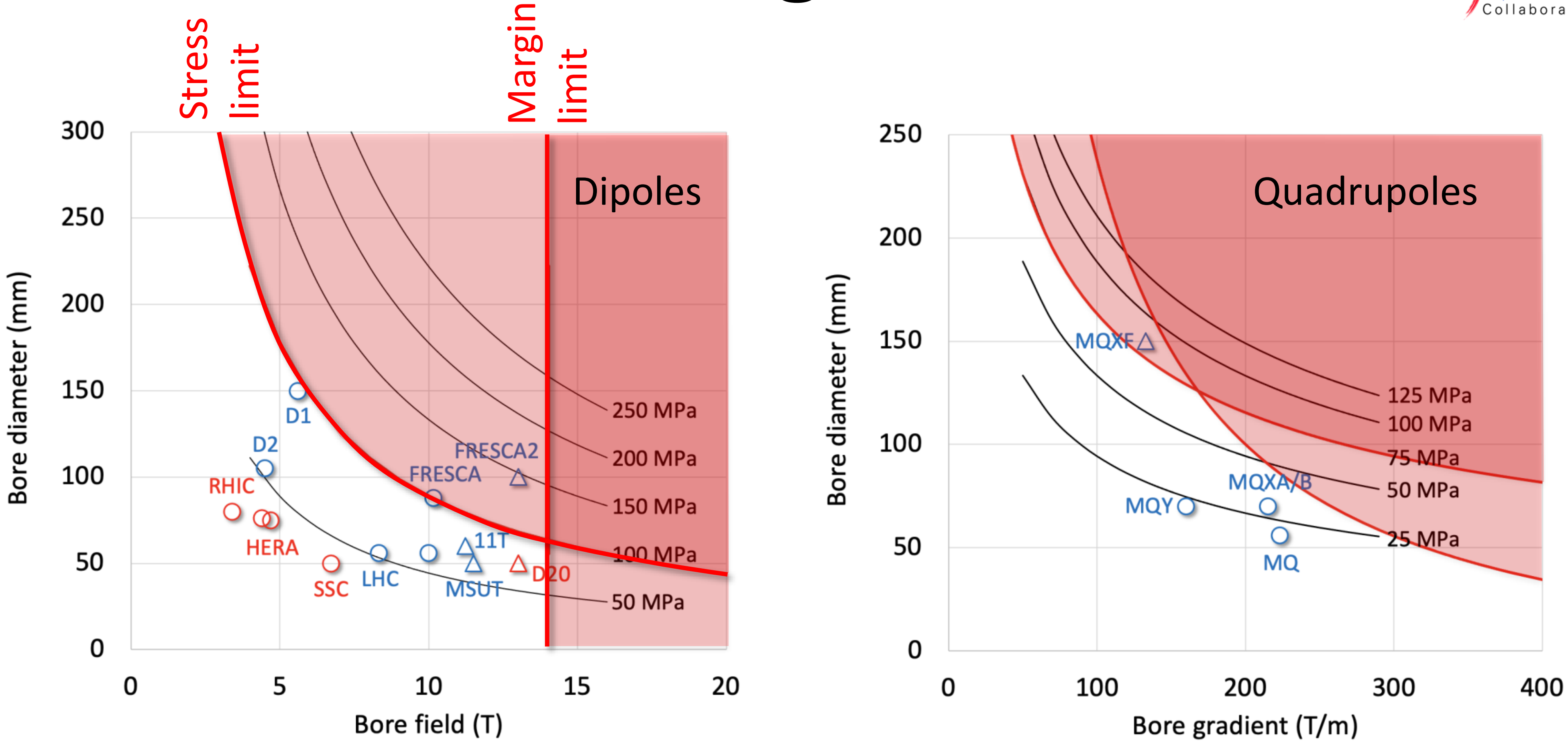
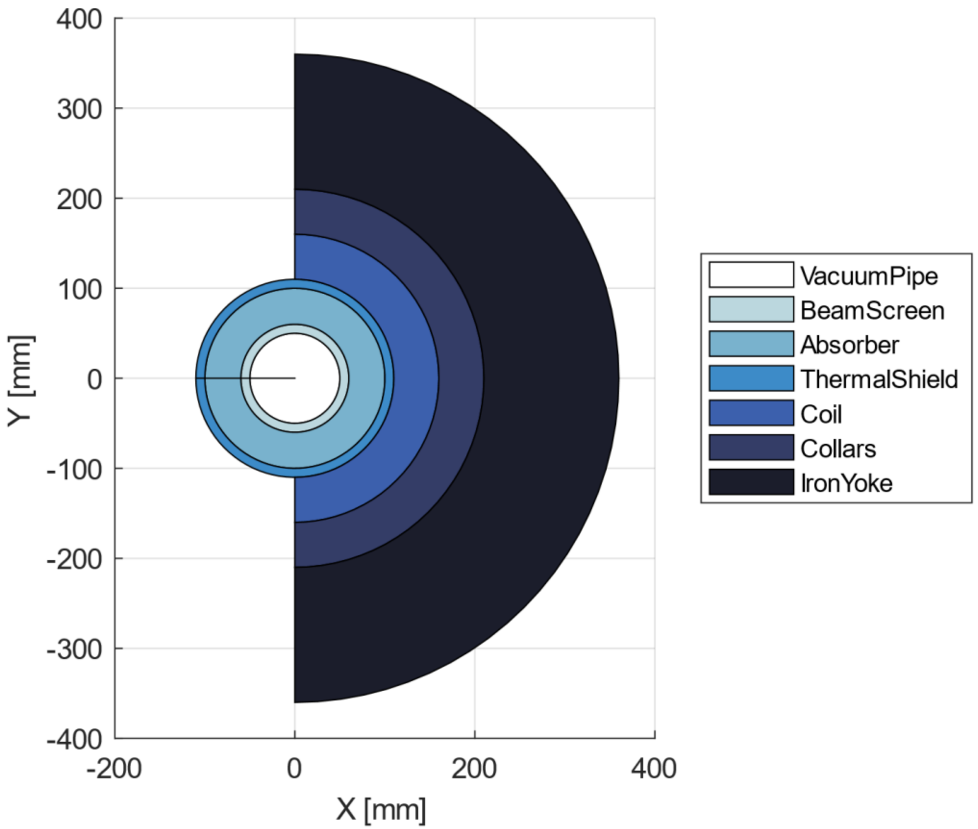
Collider magnets – 2/3



- Work in progress to provide analytical expression for the magnet design limits
  - Maximum field and gradient vs. magnet aperture in LTS and HTS
  - Combined function limits B+G and B/G
- **Proposal: take provisionally 9 T for NbTi and 14 T for Nb_3Sn**

Collider magnets – 3/3

	Rad Thickness [mm]	R int [mm]	R ext [mm]
VacuumPipe	50	0	50
BeamScreen	10	50	60
Absorber	40	60	100
ThermalSh	10	100	110
Coil	50	110	160
Collars	50	160	210
IronYoke	150	210	360



- A first attempt to compile a physical radial build for the various components in the collider bore and magnet, **to be continued**

S.Mariotto, B.Caiffi, D. Novellini, INFN

Scope of the talk

- Guidelines for the upcoming (magnet) work
- The four challenges
  - Technical advances
- Work organization
- AOB
- 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 – 1/4

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 – 2/4

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

The Team and the work – 3/4

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** (FB, LB, TECH)
  - UNIBO (MB, PR, RM)
  - LNCMI (JB)
  - TWENTE (HTK, AK)
  - TUDa (HVG, post-doc)
- Activities (≈ 12 months)
  - Power converter conceptual design and optimization, including energy storage
  - Components tests (capacitors)
  - Conceptual design and 2D optimization of resistive magnets for RCS
  - Initiate detailed 2D/3D analysis of resistive magnets for RCS, including saturation, end effects, anomalous loss
  - Conceptual design of SC magnets for RCS
  - Study of HTS options for pulsed magnets

The Team and the work – 4/4

International MUON Collider Collaboration

Magnet Systems

Task 1
Technical Coordination and Integration

Task 2
Target, Capture and Cooling Magnets

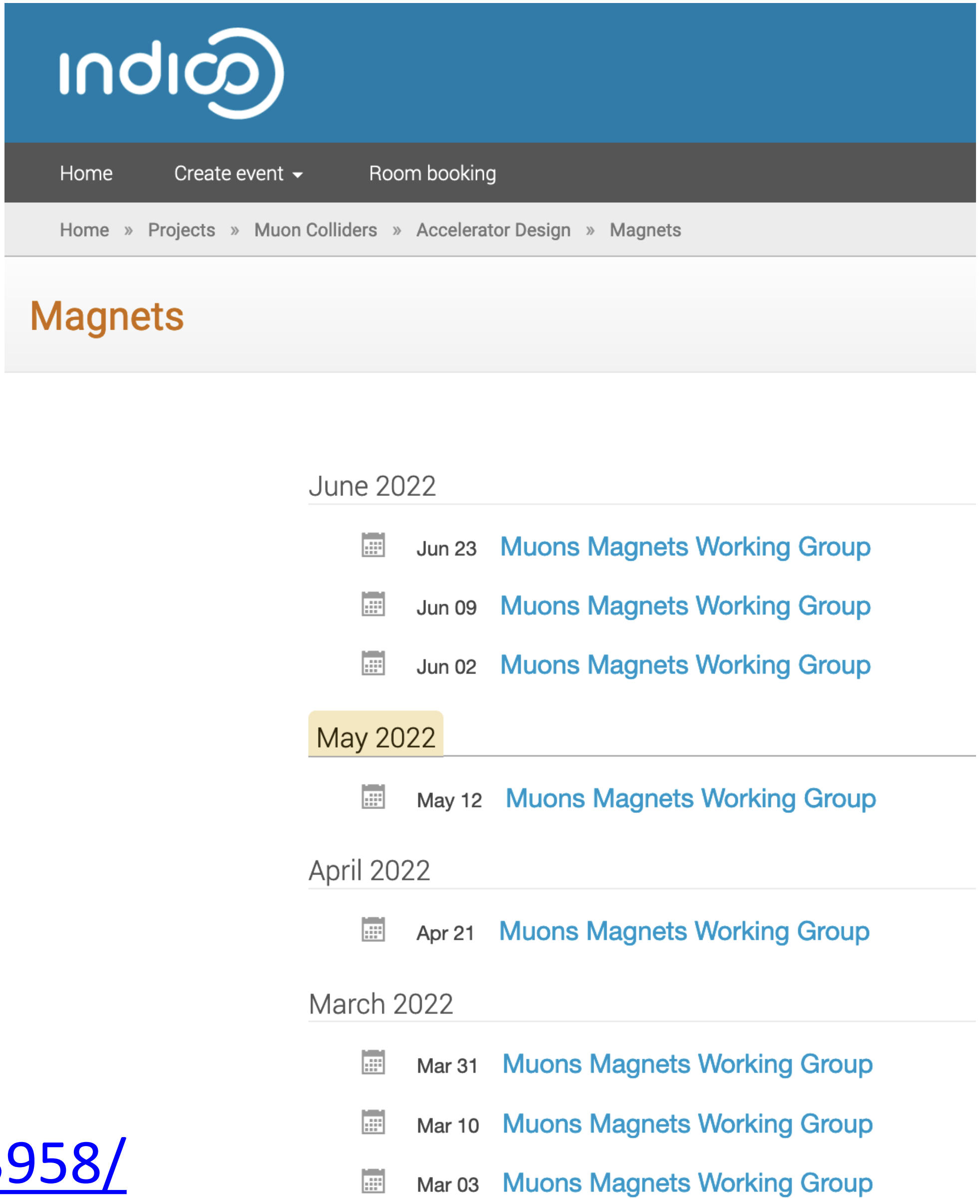
Task 3
Fast Cycled Accelerator Magnets

Task 4
Collider Ring Magnets

- Participants
  - **INFN** (SM, BC, DN)
  - CERN (LB)
  - UNIMI (SM)
- Activities (≈ 12 months)
  - Establish limits of SC dipoles and quadrupoles, considering LTS and HTS as well as combined function options
  - Agree on arc dipole specification
    - Field and gradient
    - Aperture
    - Nested/asymmetric windings
    - Operating conditions
  - Initiate conceptual design of main arc magnet

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

Scope of the talk

- Guidelines for the upcoming (magnet) work
- The four challenges
  - Technical advances
- Work organization
- AOB
- Summary and plans

AOB

- **Papers**
  - Submitted to IPAC-2023 (Magnets for a Muon Collider)
  - Plan to submit specific contributions to MT-28 and EUCAS-2023
- **First material order issued**, 414 m of 4 mm REBCO tape for initial tests on high-J solenoids
- In preparation (collaboration with INFN) a **HTS tape performance specification** for muon collider magnets

Magnets for a Muon Collider

L. Bottura, F. Boattini, B. Caiffi, S. Mariotto, L. Quettier, M. Statera
and the Muon Magnets Working Group (author list to be completed)

The new interest for a muon collider has motivated a renewed and thorough analysis of the accelerator technology required for this collider option at the energy frontier. Magnets, both normal- and super-conducting, are among the crucial technologies throughout the accelerator complex, from production, through acceleration and collision. In this paper we initiate a catalog of magnet specifications for a muon collider at 10 TeV center-of-mass. We take the wealth of work performed within the scope of the US-DOE Muon Accelerator Program as a starting point, update it with present demands for the increased energy reach, and focus on the magnet types and variants with most demanding performance. These represent well the envelope of issues and challenges to be addressed by future design and development. We finally give a first and indicative selection of suitable magnet technology, taking into account both established practices as well as the perspective evolution in the field of accelerator magnets.

Order Lines

Item	Quantity	Description
1	1	**4mm HTS tape** Theva Pro-Line 4421 Length: 414 m Width: 4 mm Metallization: 10 μm Cu surround Ic,min (77K, self field): 90 A Ic,av (77K, self field): 230 A QS220037 Country of origin: **GERMANY (DE)**, Delivery: **30-6-018 BUREAU MEYRIN**, Procurement Code: **02250502 - Superconducting wires and tapes [Material]**, Goods already delivered: **No**, Date: **20.12.2022** Budget Codes: **61980 - Muon Collider Study - Project Management & Personnel**

Table I. Range of geometry and composition characteristics for the REBCO coated conductor.

		Specified	Range
Coated conductor width	(mm)	12	4…12
Substrate material			Non-magnetic stainless steel or equivalent high resistance alloy
Substrate thickness	(μm)	40	40…60
Copper RRR	(-)		30…100
Total copper thickness	(μm)	20 (2x10)	20 (2x10)…40 (2x20)
Coated conductor thickness	(mm)		60…100

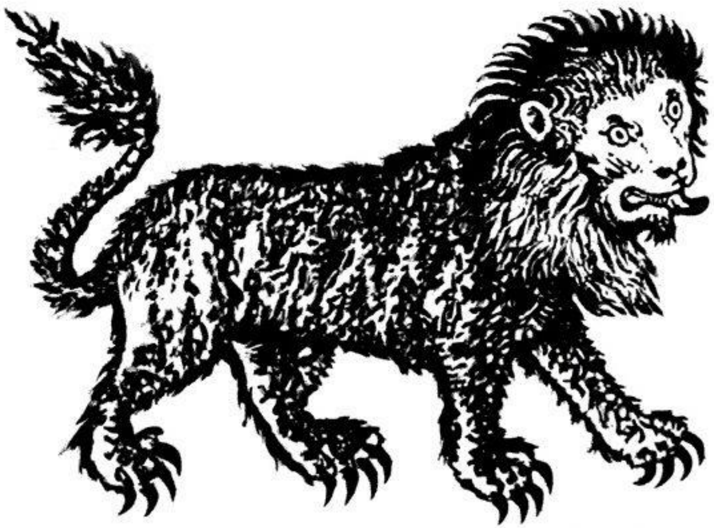
Scope of the talk

- Guidelines for the upcoming (magnet) work
- The four challenges
  - Technical advances
- Work organization
- AOB
- Summary and plans

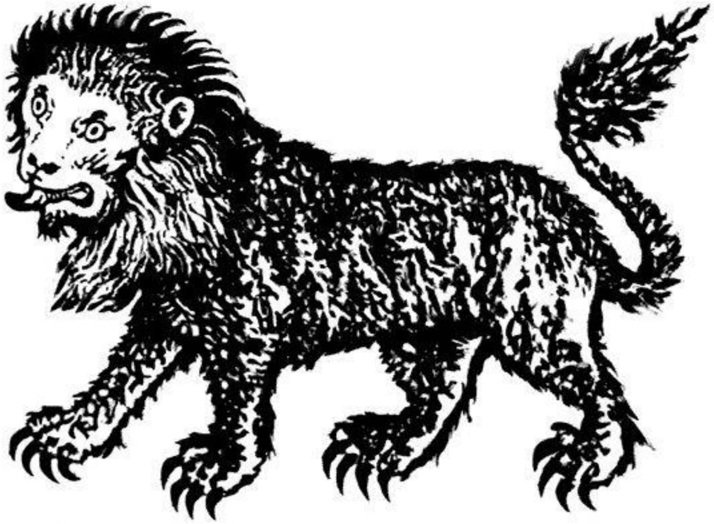
Summary and Plans

- **Four 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
- This is largely integration/configuration work, and would probably **deserve its own life** at the level of the project

- 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



HIC SUNT LEONES



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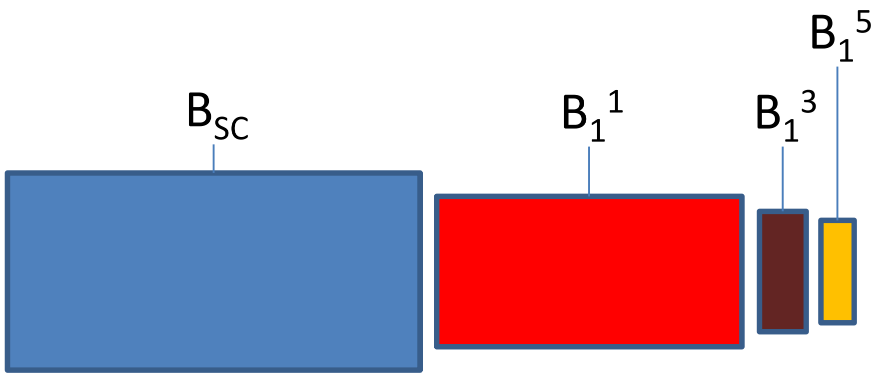
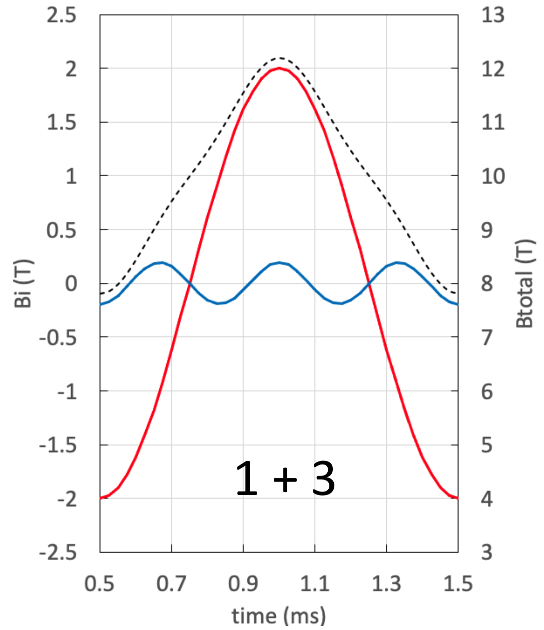
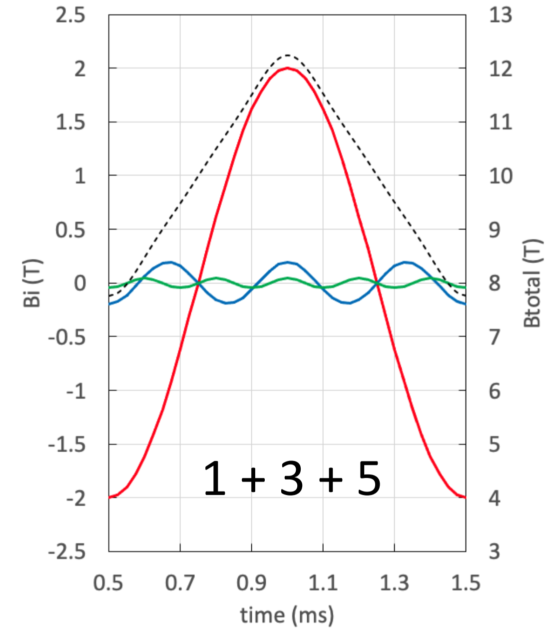
Magnet powering alternatives

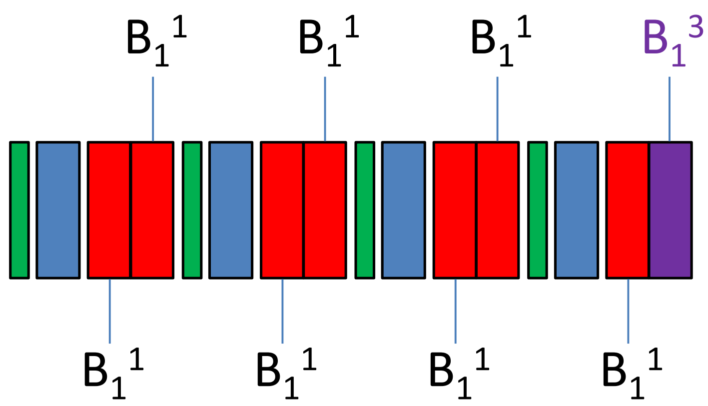
Local correction

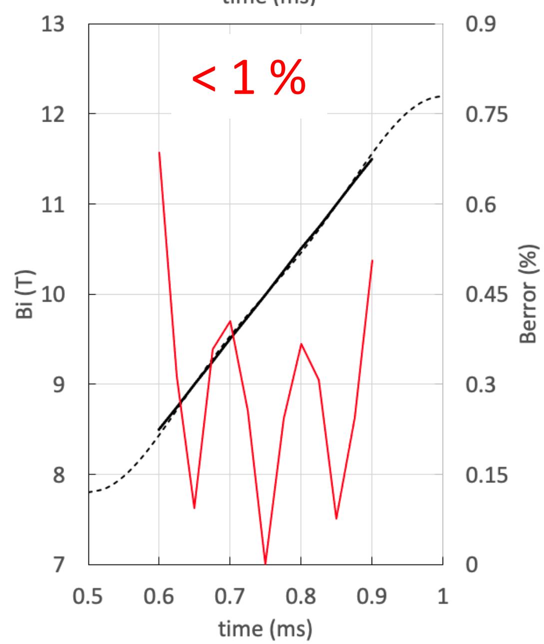


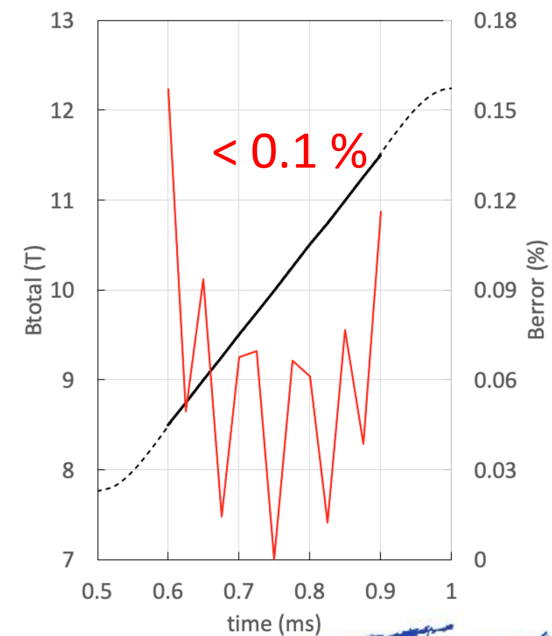




Global correction

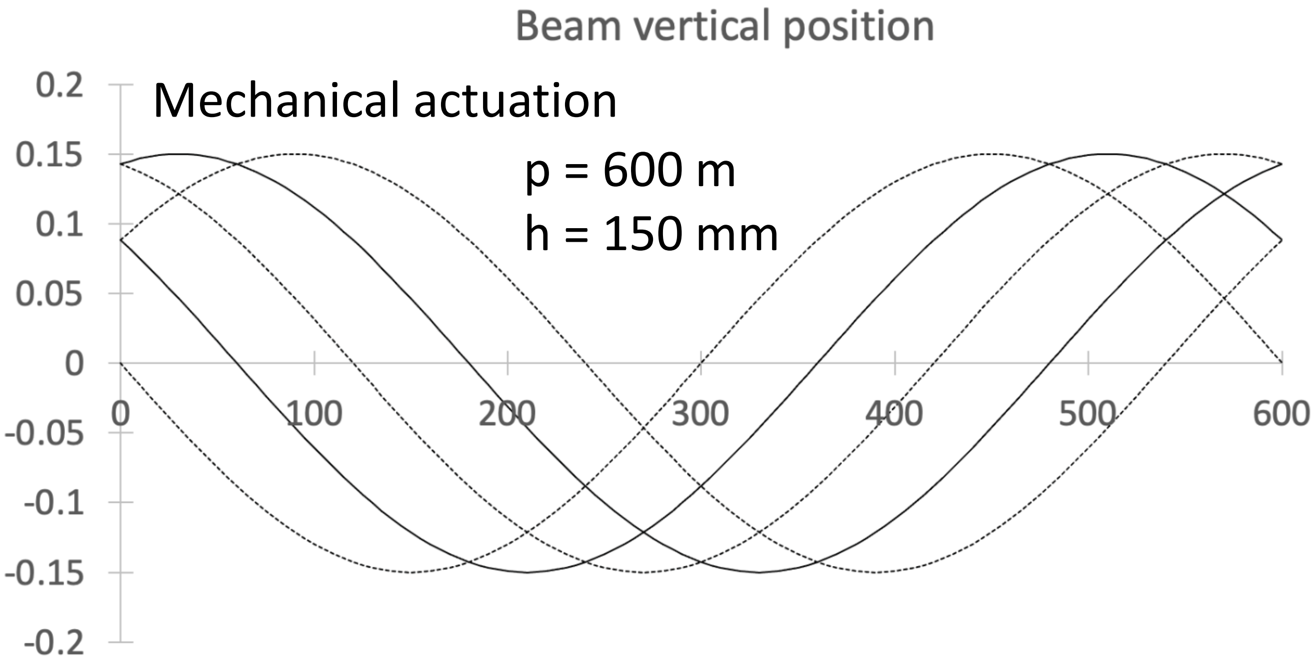






Compatible with beam specs ?

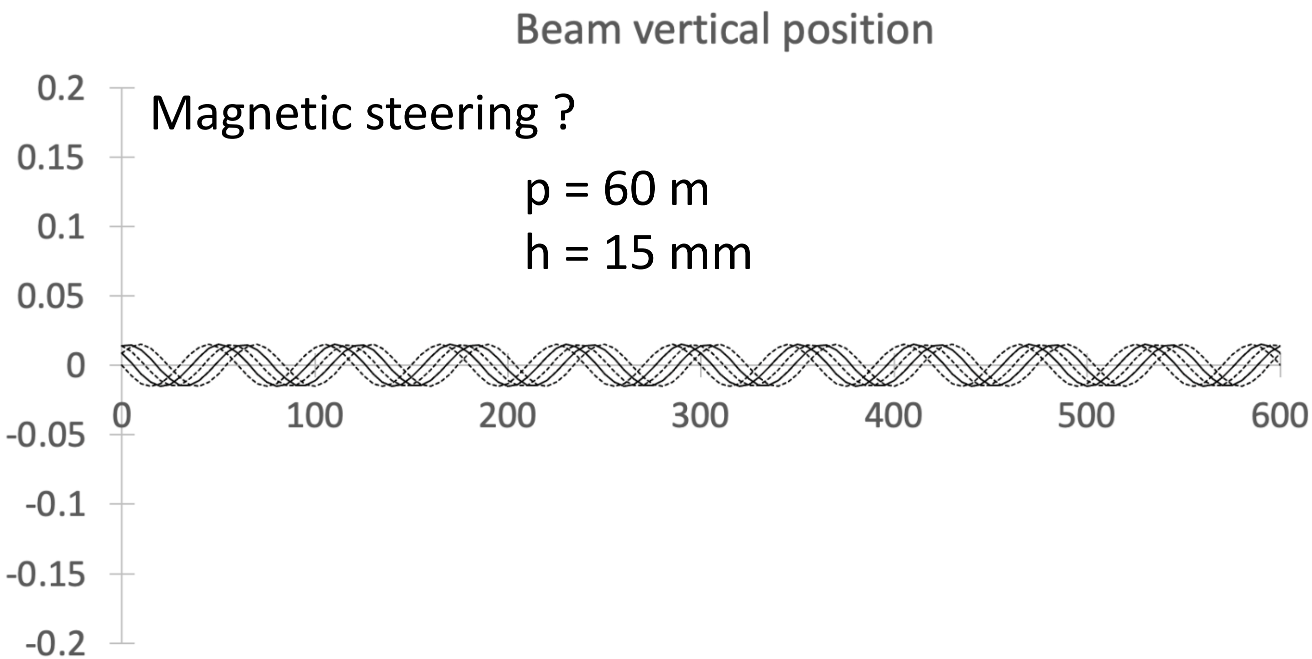
Collider wobbles

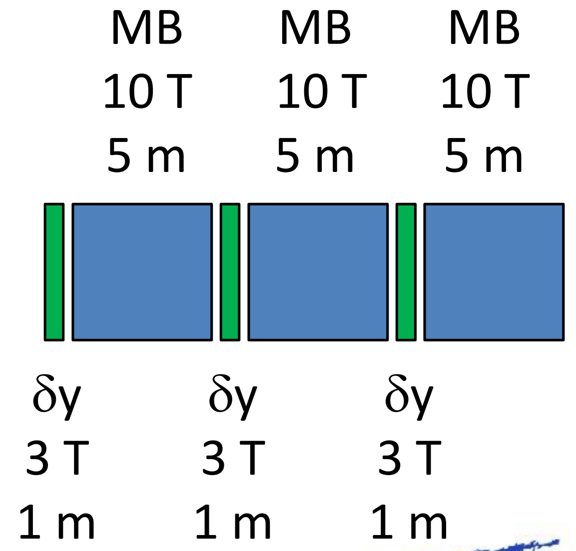


h: beam height
p: wave period

Neutrino emission angle ≈ h/p

The same angle can be obtained changing p and h by the same ratio

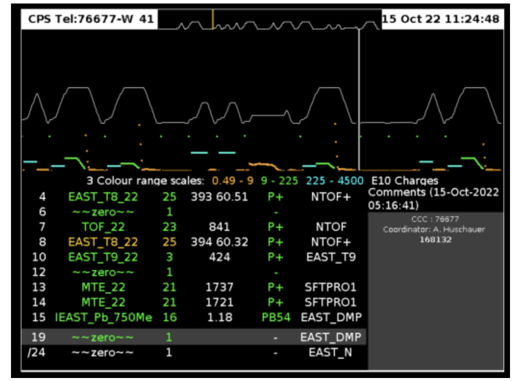


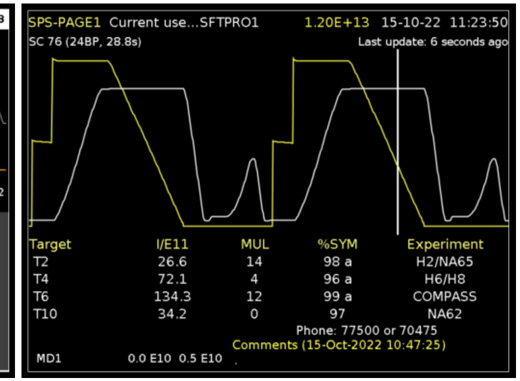


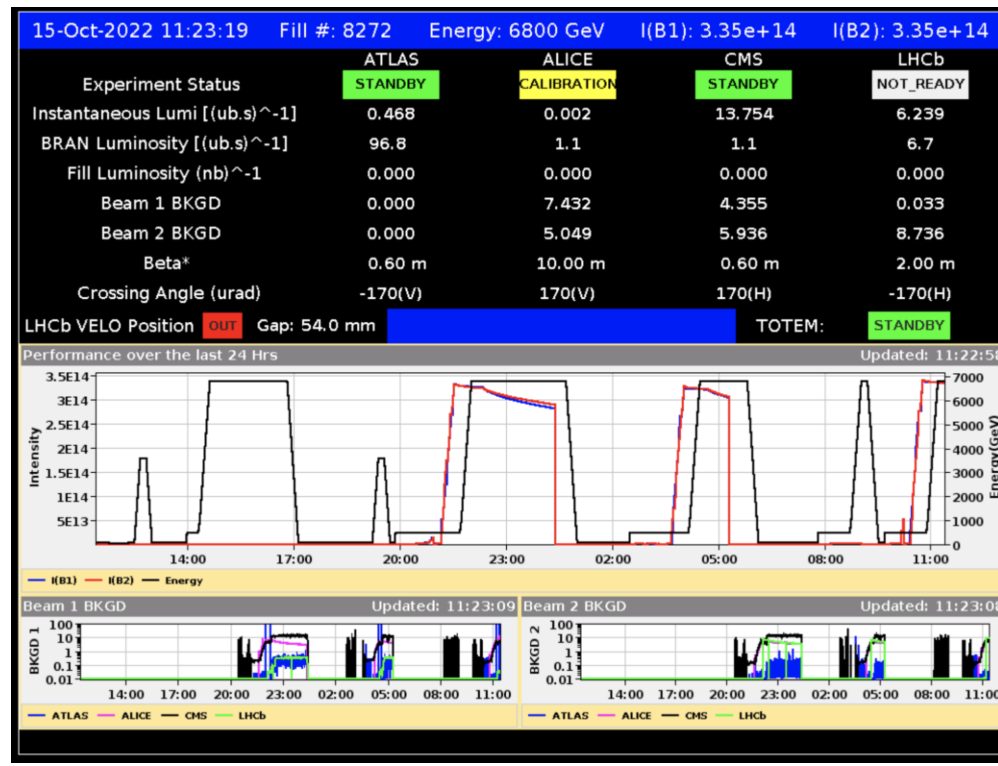
The need for energy

International MUON Collider Collaboration

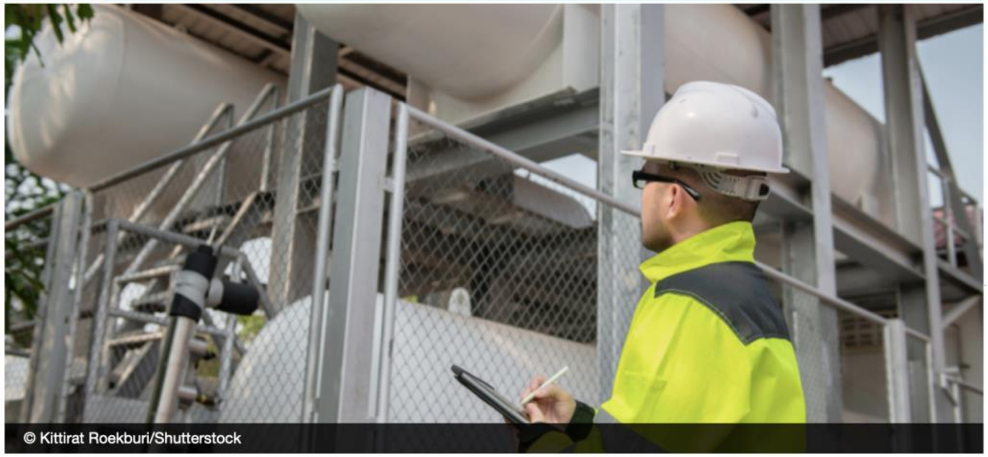
- CERN uses today **1.3 TWh** per year of operation, with peak power consumption of **200 MW** (running accelerators and experiments), dropping to **80 MW** in winter (technical stop period)
- Electric power is drawn directly from the French 400 kV distribution, and presently supplied under agreed conditions and cost
- **Supply cost, chain and risk** are obvious concerns for the present and future of the laboratory







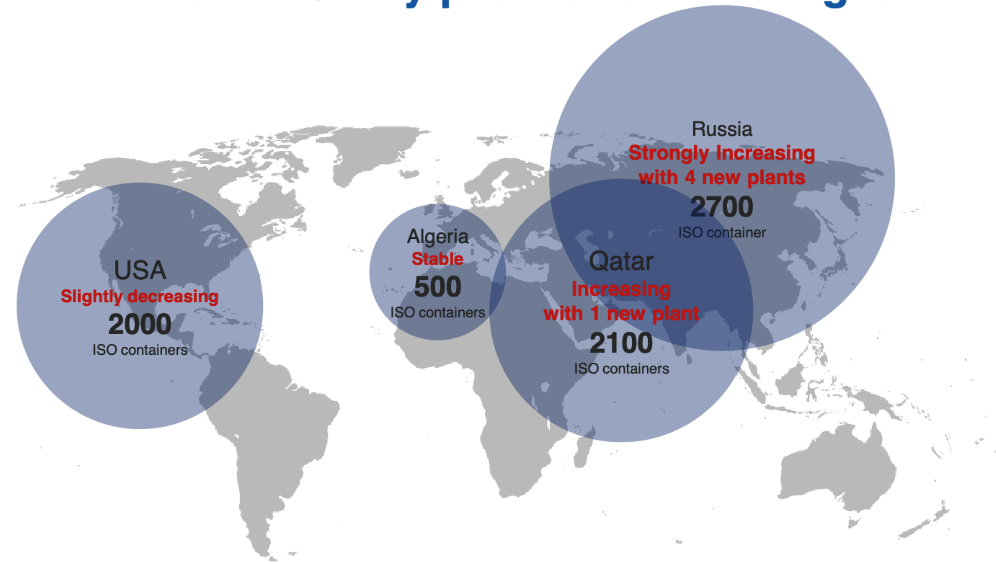
16 JUIN 2022 **Publications** Briefings de l'Ifri



Aurélien REYS, Vincent BOS

Hélium : les nouvelles géographies d'une ressource critique
Briefings de l'Ifri, 16 juin 2022

Helium is a **by-product of natural gas**



Tentative forecast in 2026 based on public announcements of new capacities available in quantity of Iso container of 4.5 tonnes

Future helium **supply is limited** and entails a substantial economical and availability **risk**

F. Ferrand, CERN

Consequences

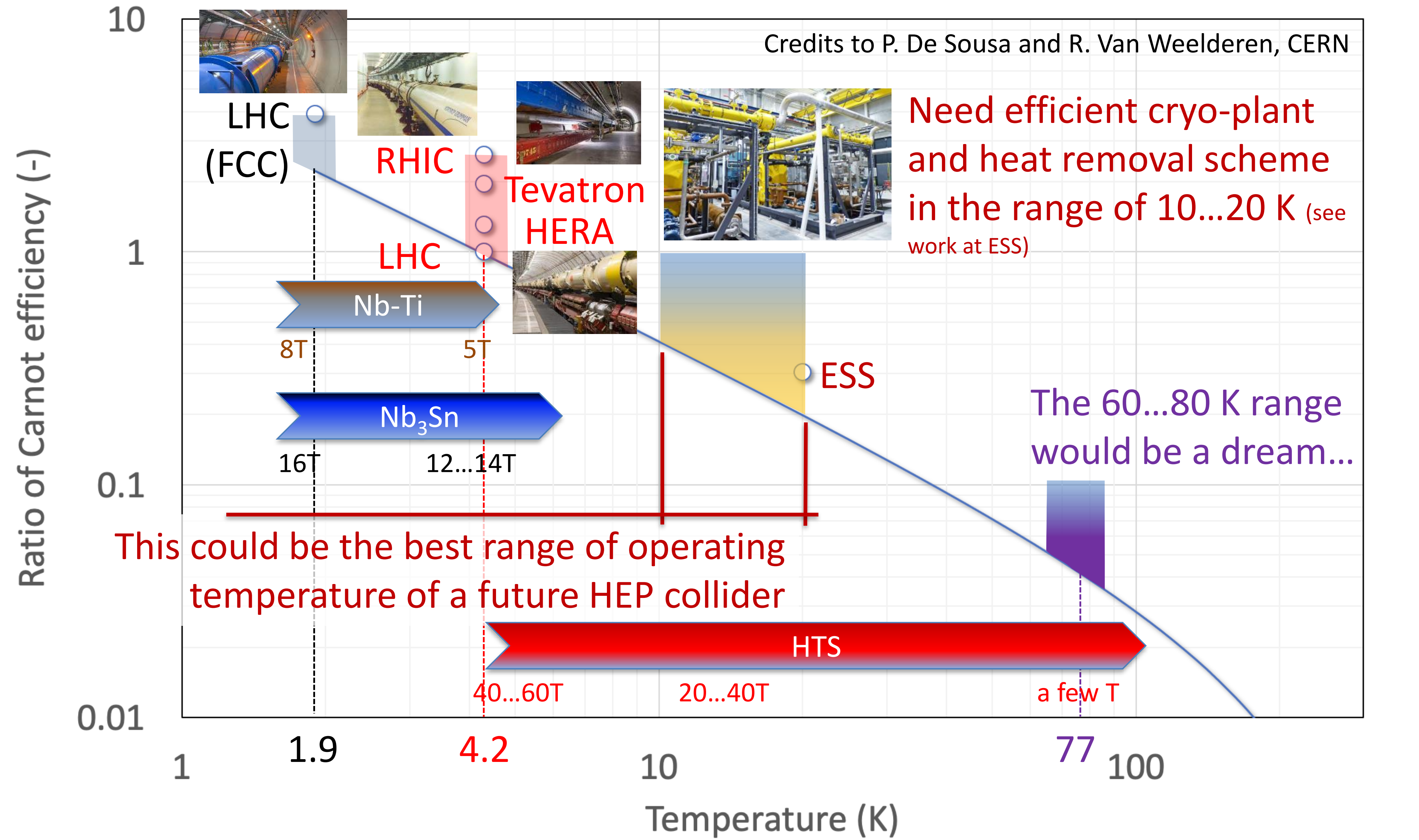
Current situation

- Market shortage is affecting industrial and scientific customers
- Manufacturing industry contracts are impacted with volume limitations
- Large scientific instrument cannot do so & rely on established industrial partnership

Helium market still at risk in 2023 and for the coming years

- Uncertainty on the effective Russian production capacity and market access
- Algerian gas production transferred using pipeline instead of LNG
- No more back-up from the US federal authorities, Cliffside for sale ! (C&en News)

Energy efficient cryogenics



HTS may be the only path towards a future collider

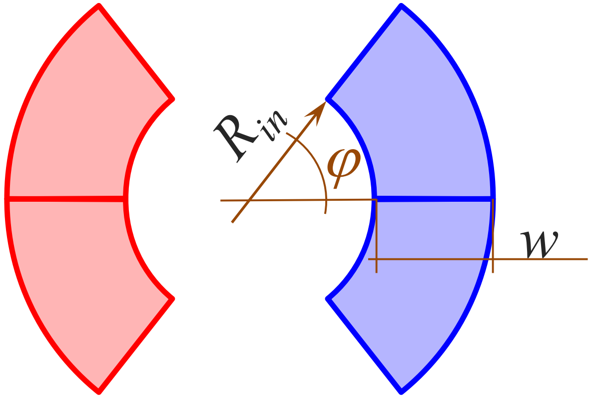
The need for economics

International MUON Collider Collaboration

- A large component in the magnet cost is the **amount of superconductor** (coil cross section)
- High-field superconductors are (significantly) more expensive than *good-old* Nb-Ti
- Need to work in two directions:
  - **Reduce the coil cross section (increase J !)**

$$B = \frac{2\mu_0}{\pi} J w \sin(\varphi)$$

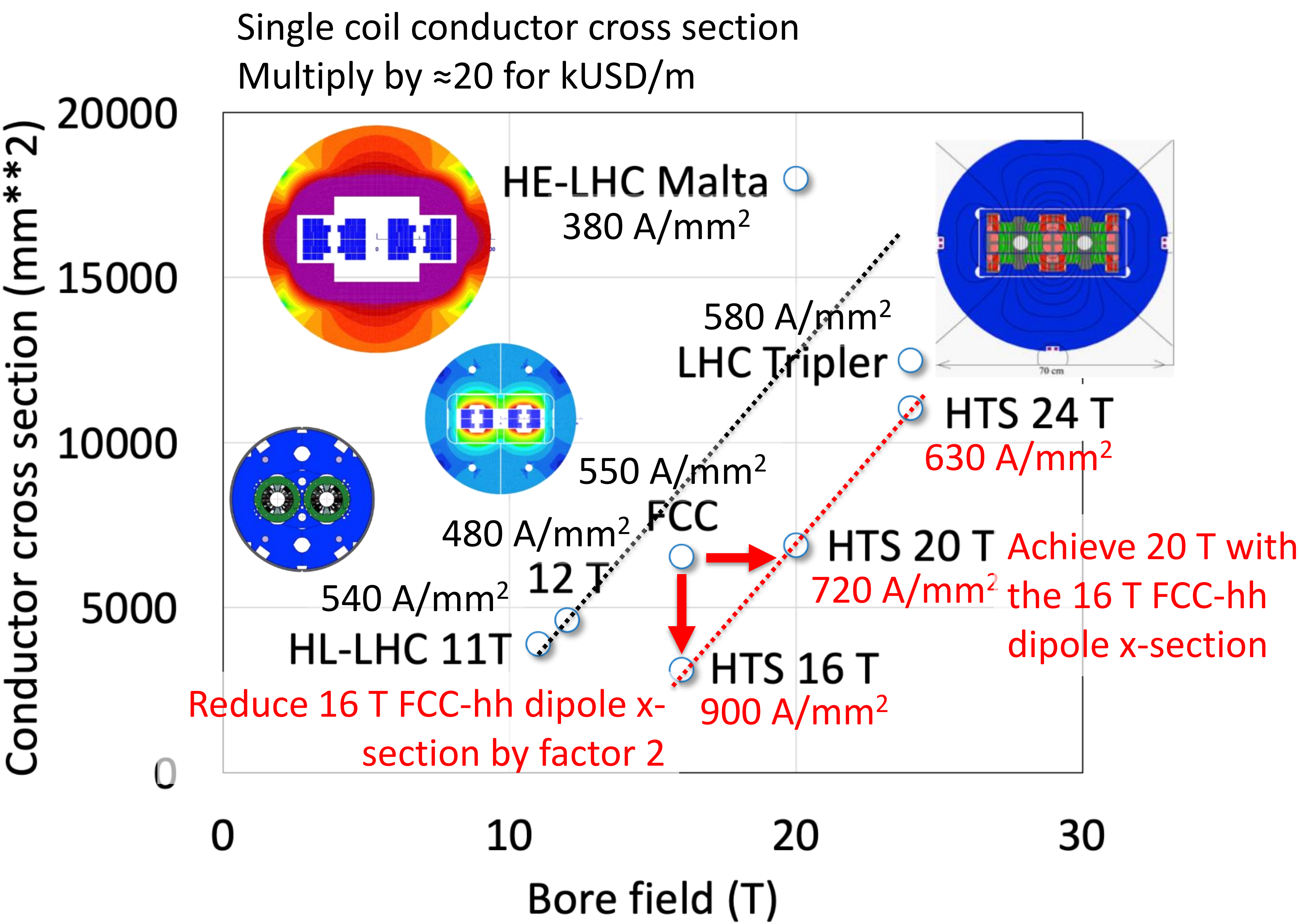
$$A_{coil} = 2\varphi(w^2 + 2R_{in}w) \sim \frac{1}{J^{1.5}}$$



  - **Reduce unit conductor cost**

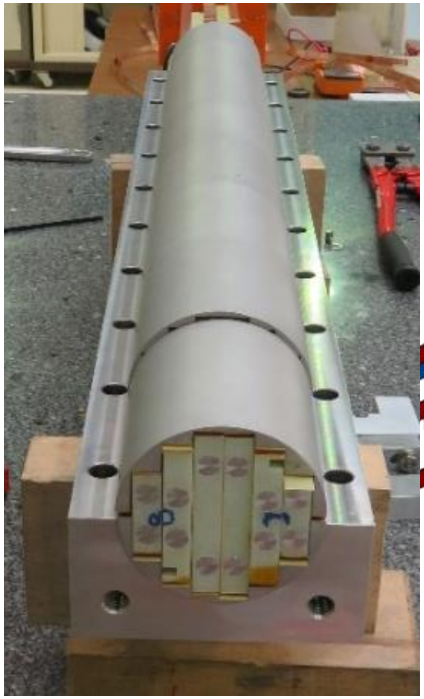
HTS may offer both

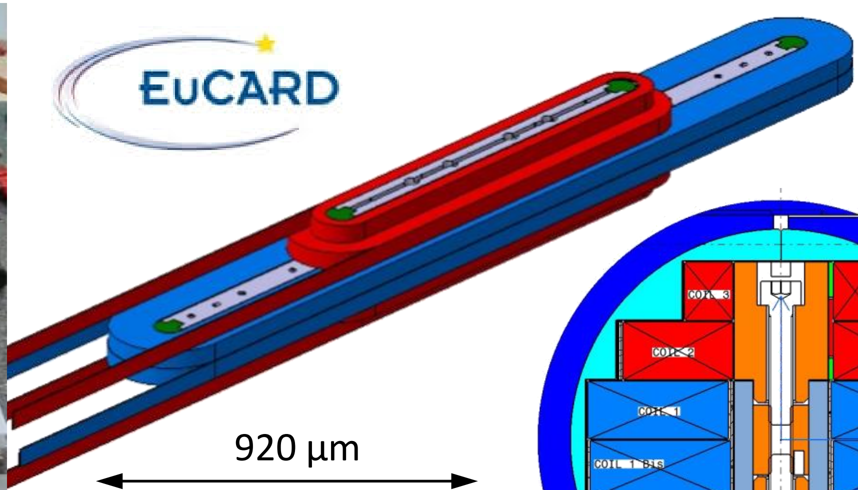
On a slimming diet !

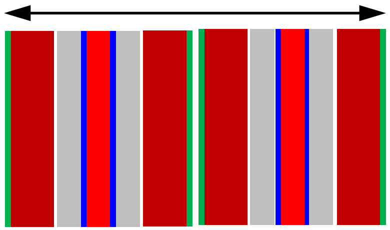


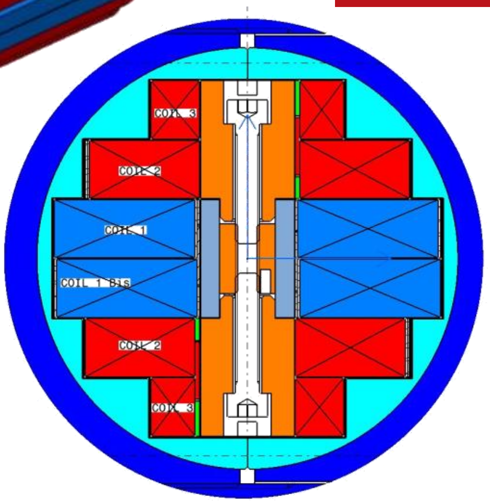
New winding technology needed

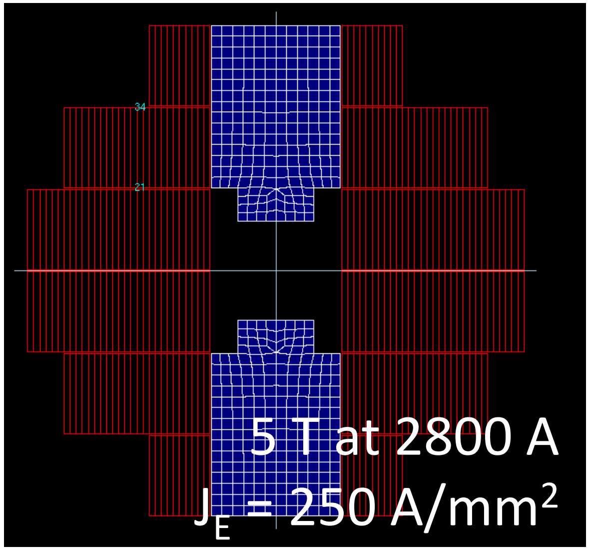
T. Lecrevisse, CEA

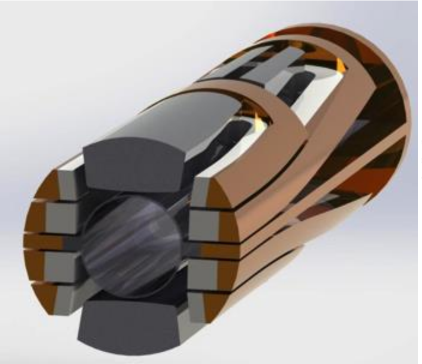


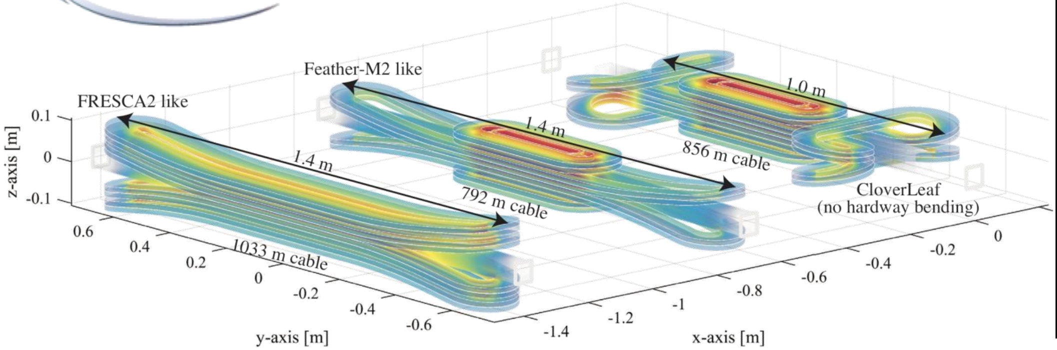


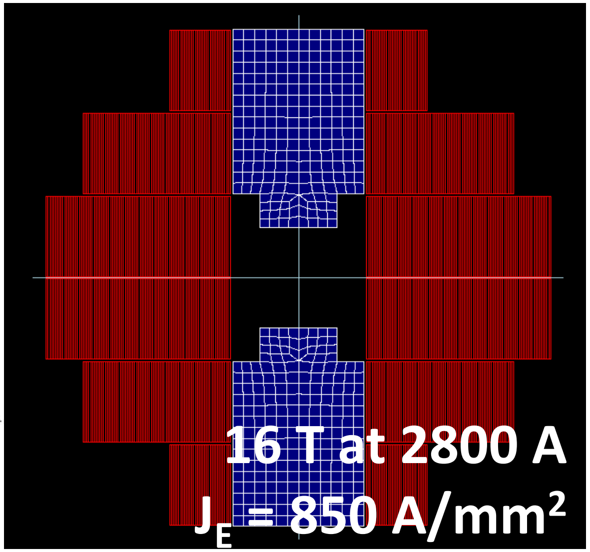












HTS windings can profit from “NI” technology

Conductor cost

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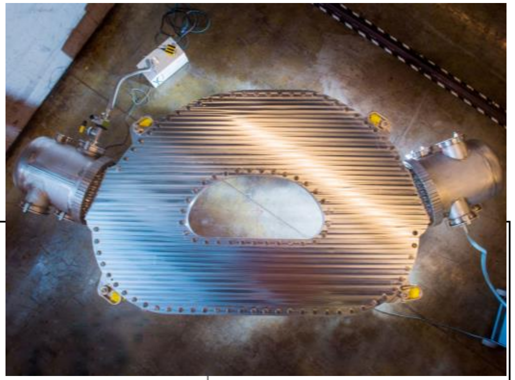
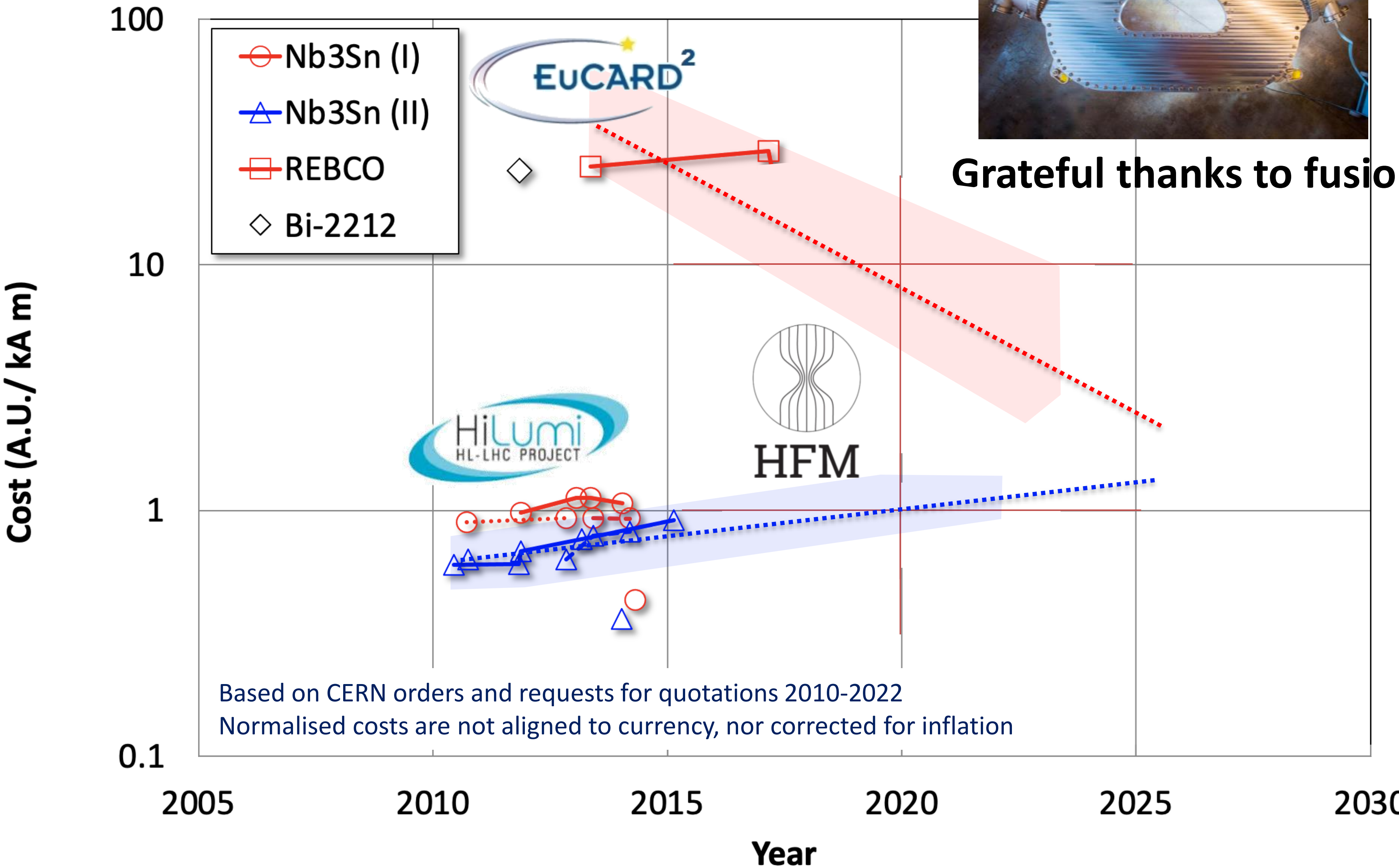


Grateful thanks to fusion !



Impressive cost reduction in HTS !

HTS for accelerators – an attempt

		Specification	Target
Minimum J_{non-Cu} (4.2 K, 20 T)			3000
Minimum J_{non-Cu} (20 K, 20 T)			1250
$\sigma(I_C)$			5
Unit length UL	(m)		500
Minimum bending radius	(mm)		
Allowable $\sigma_{longitudinal\ non-Cu}$	(MPa)		
Allowable compressive $\sigma_{transverse}$	(MPa)		
Allowable tensile $\sigma_{transverse}$	(MPa)		25
Allowable shear $\tau_{transverse}$			20
Allowable peel σ_{peel}			
Allowable cleavage $\sigma_{cleavage}$			
Range of allowable $\varepsilon_{longitudinal}$			-0.1…+0.5
Internal specific resistance $\rho_{transverse}$	$(n\Omega/cm^2)$		

Use non-Cu as basis of comparison independent of the amount of stabilizer added

J_E targets are within reach, comparable to fusion specificartions

Main attention on mechanics, which is the true challenge of high fields. Need to understand and characterize systematically

Other parameters may be important, but we do not know yet

Substrate (non-magnetic alloy): 40…60 μm
Copper stabilizer (total): 20…40 μm

For discussion