International MUON Collider Collaboration

HTS for the *Muon Collider*

Challenges and Perspective

Presented by L. Bottura, CERN

CCA2023

International Workshop on Coated Conductors for Applications

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and the Muon Magnets Working Group

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Outline

- The HEP landscape
  - The muon collider as a viable option
- The magnet challenges of the muon collider
  - The HEP push towards HTS
- Challenges and perspective

This is work in progress !

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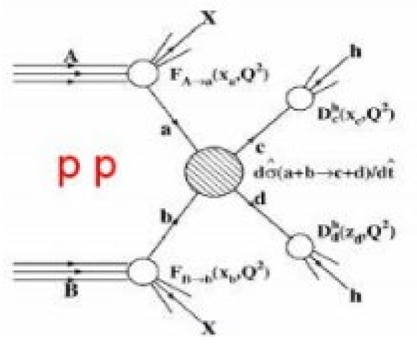
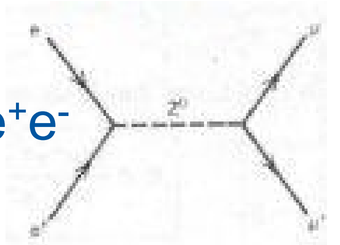
Collider Choices

- Hadron collisions: compound particles
  - LHC collides 13.6 TeV protons
  - Protons are mix of quarks, anti-quarks and gluons
  - **Very complex to extract physics**
  - **But can reach high energies**
- Lepton collisions: elementary particles
  - LEP reached 0.205 TeV with electron-positron collisions
  - Clean events, easy to extract physics
  - **Lepton collisions $\Rightarrow$ precision measurements**
  - **Hard to reach high energies**



e^+e^-



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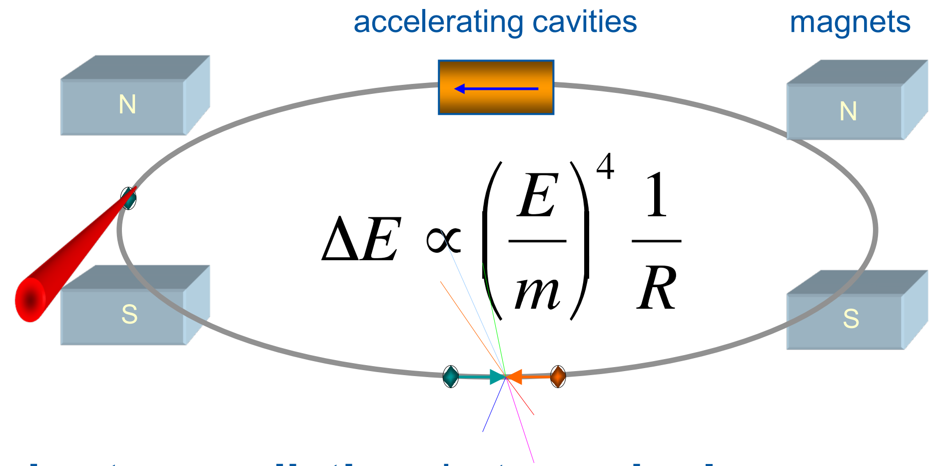
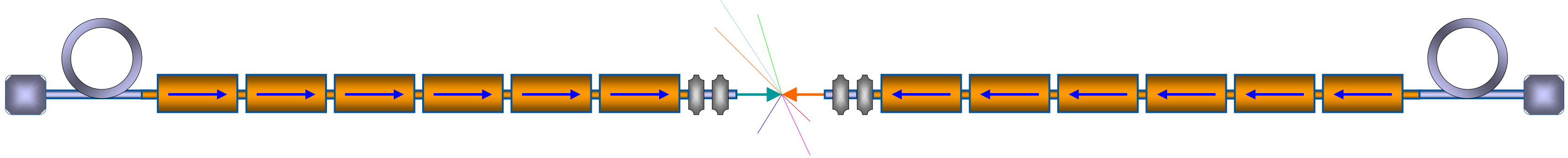
Energy Limit



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron rings (*multi-pass colliders*) are **limited by synchrotron radiation**

Electron-positron linear colliders **avoid synchrotron radiation**, but are **single pass**
Typically cost proportional to energy and power proportional to luminosity,



Hence present energy frontier is probed by proton rings

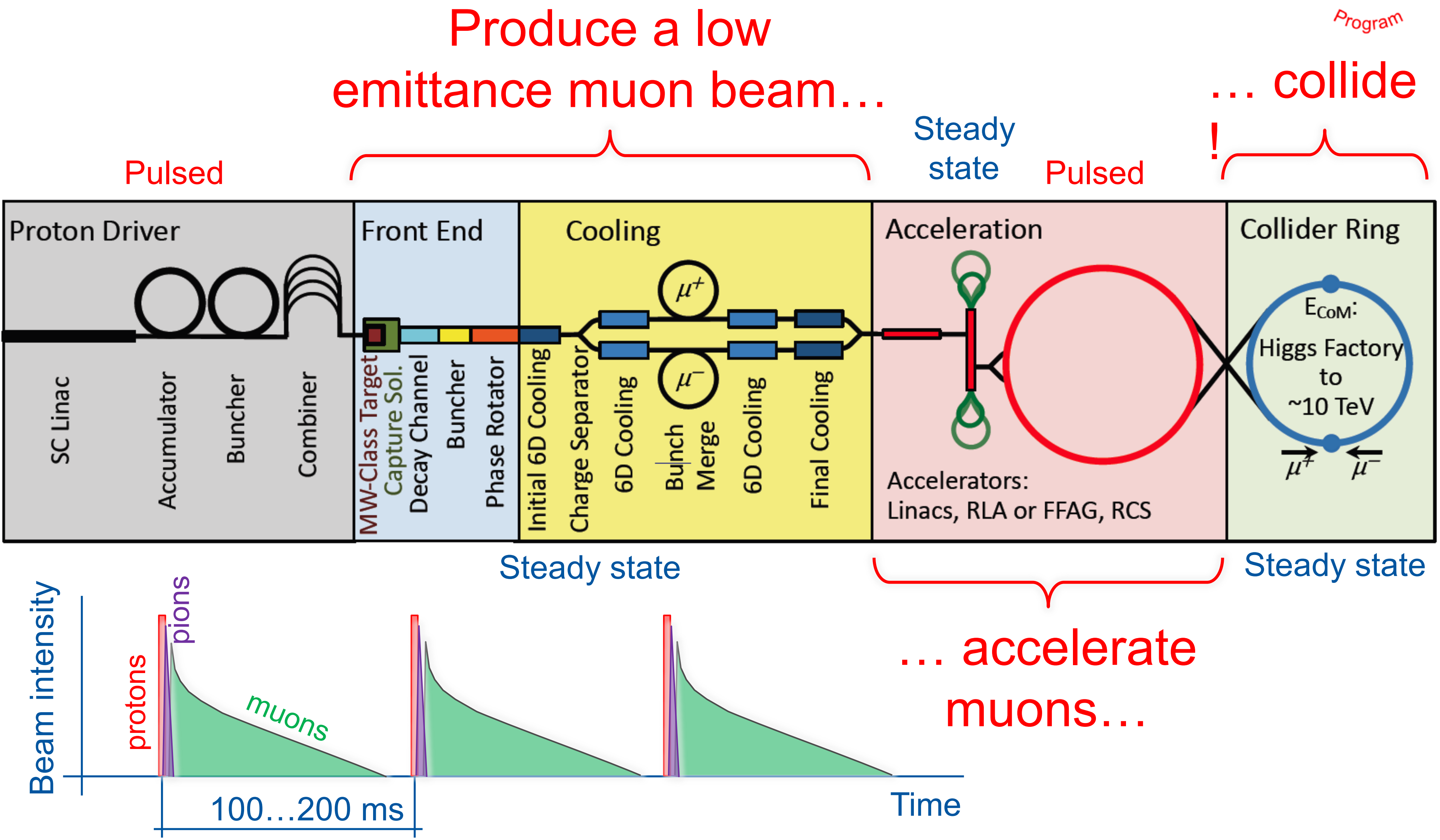
Novel approach: the **muon collider**
Large mass suppresses synchrotron radiation => circular collider, **multi-pass**
Fundamental particle yields clean collisions => **less beam energy** than protons
But lifetime at rest only 2.2 μs (increases with energy)

The muon collider is part of the European Accelerator R&D Roadmap

Courtesy of D. Schulte

e^-: 0.511 MeV
μ: 106 MeV
p^+: 938 MeV

Proton-driven Muon Collider Concept



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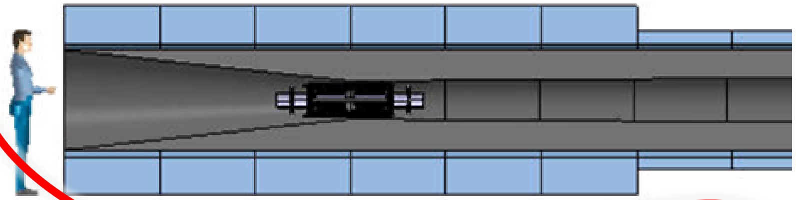
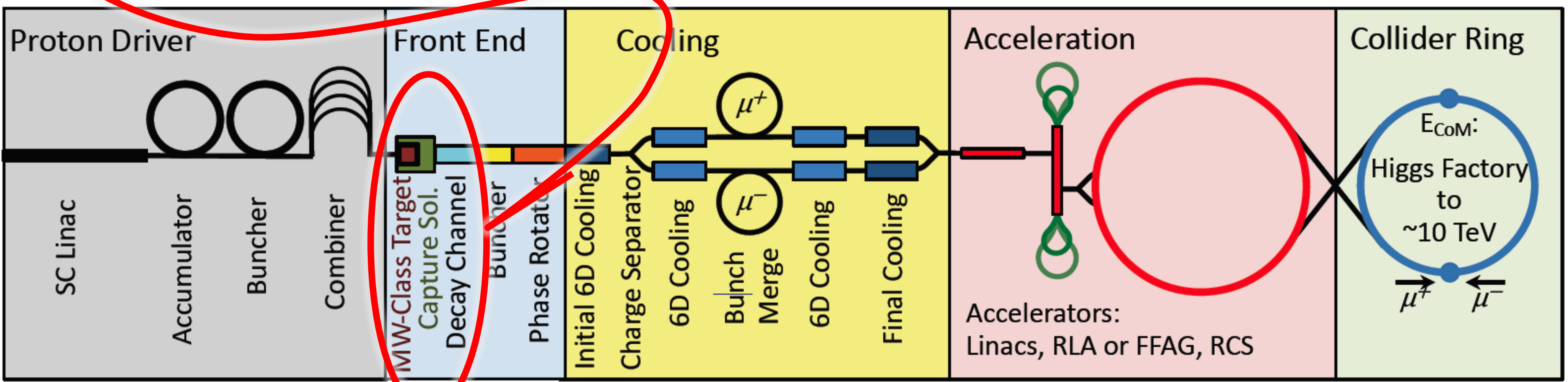
Target and capture – 1/2

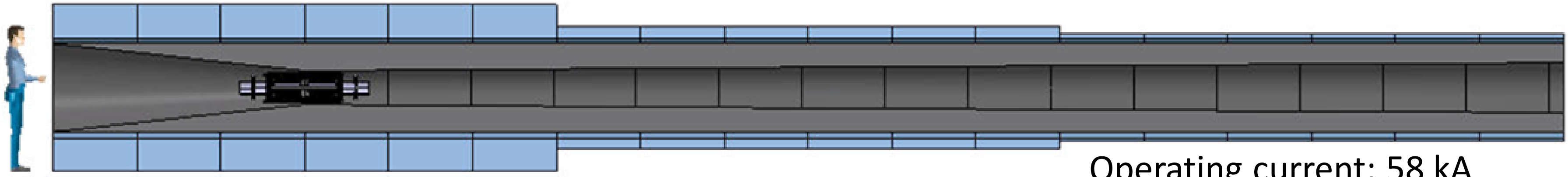
20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy





- **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**

Target and capture – 2/2

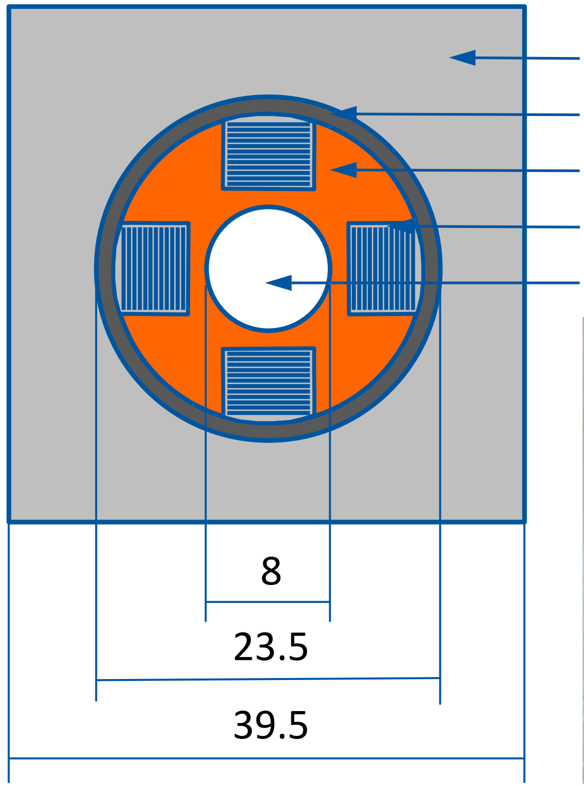


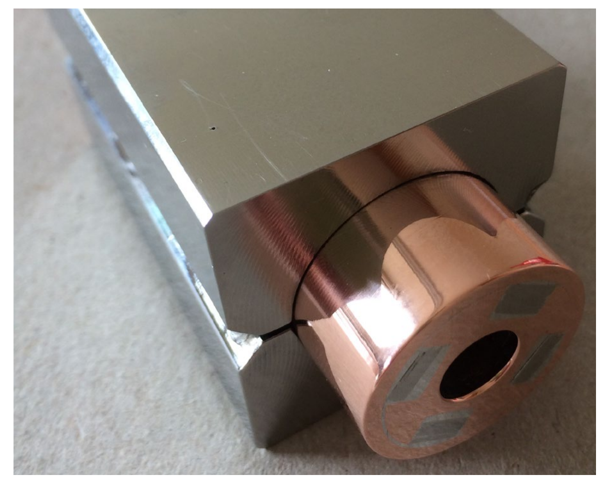
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K

MIT “VIPER” conductor

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

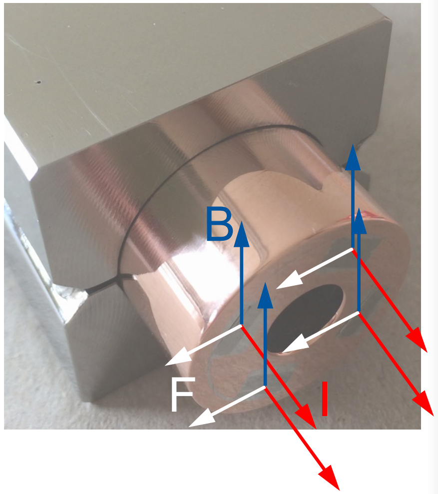
HTS conductor design

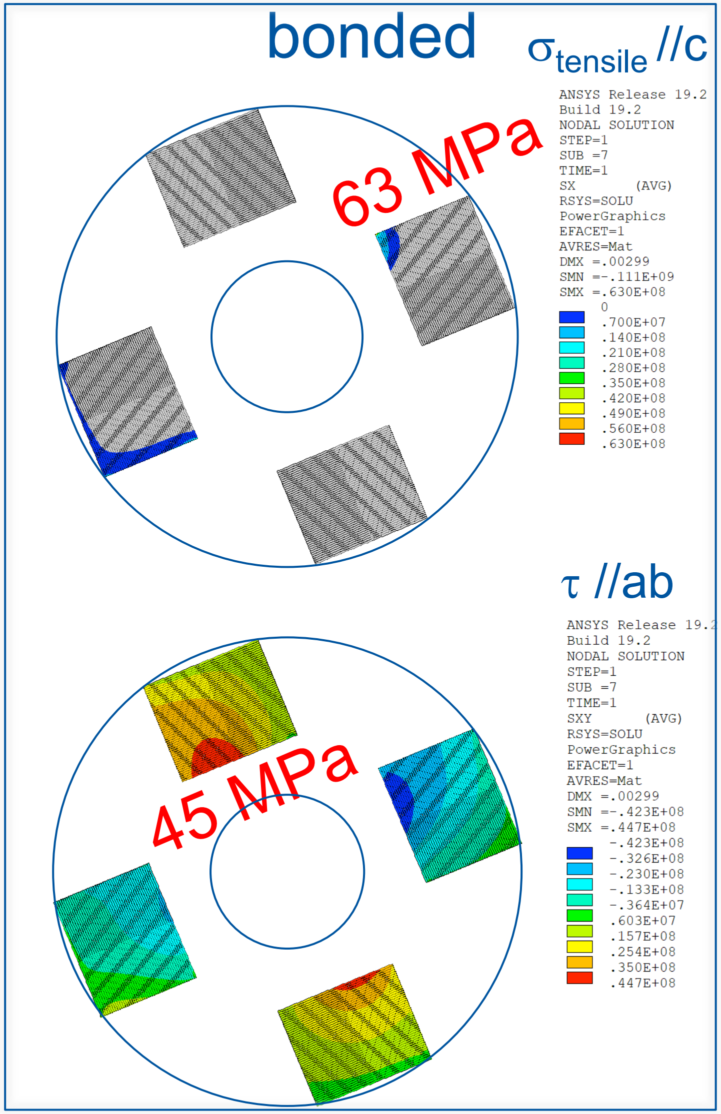


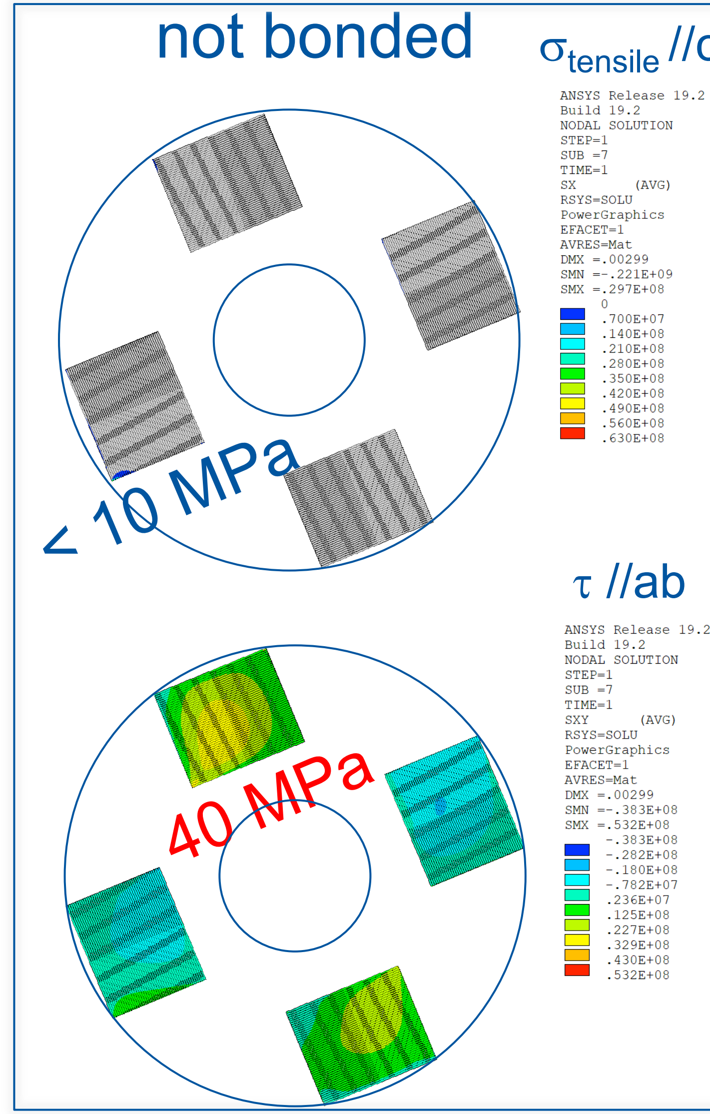


Strong connection to HTS magnets for fusion

HTS cable mechanics



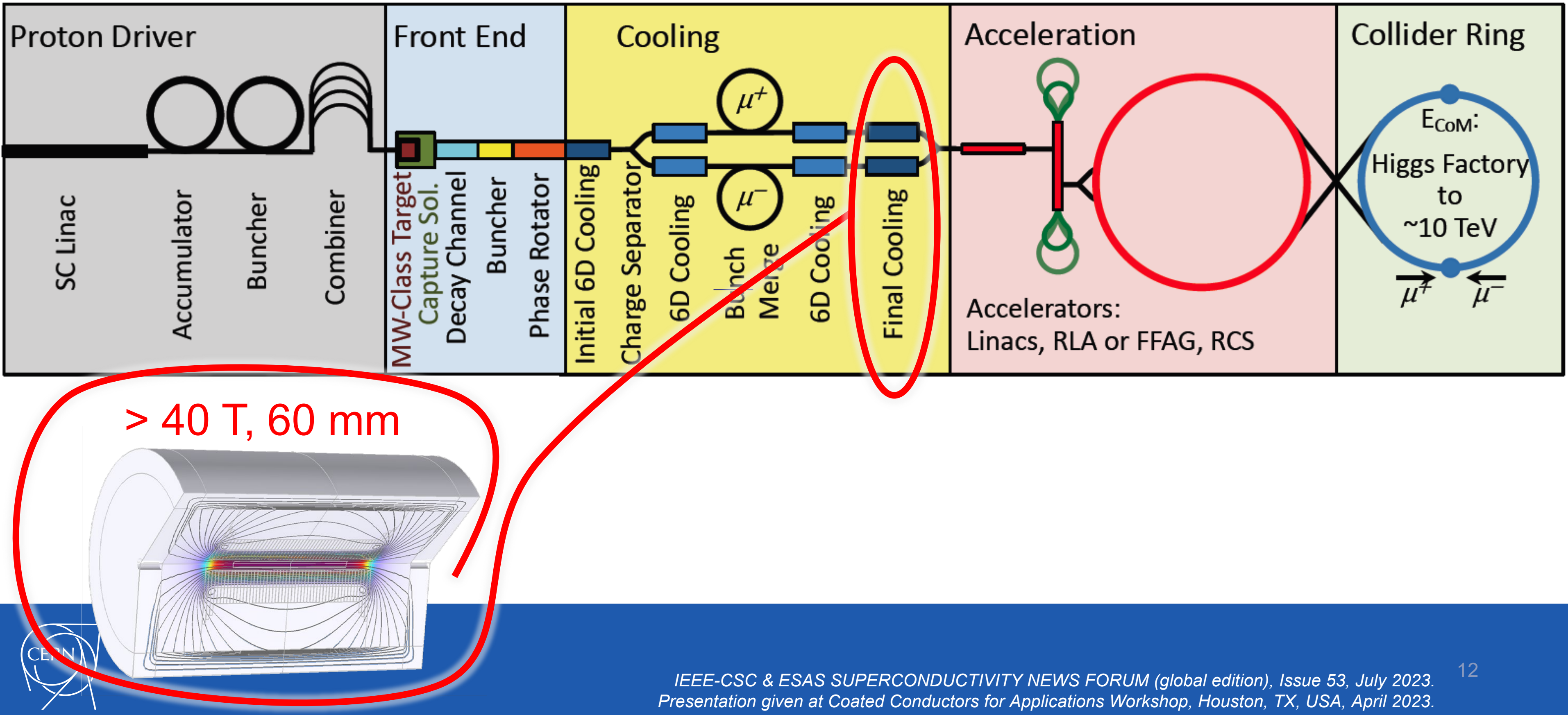




May this be the reason why soldered and twisted high field and high current cables are also subject to degradation ?

Final cooling – 1/2

- **Total 1 km, o(1600) units of solenoid magnets, from 4 T to 18 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**



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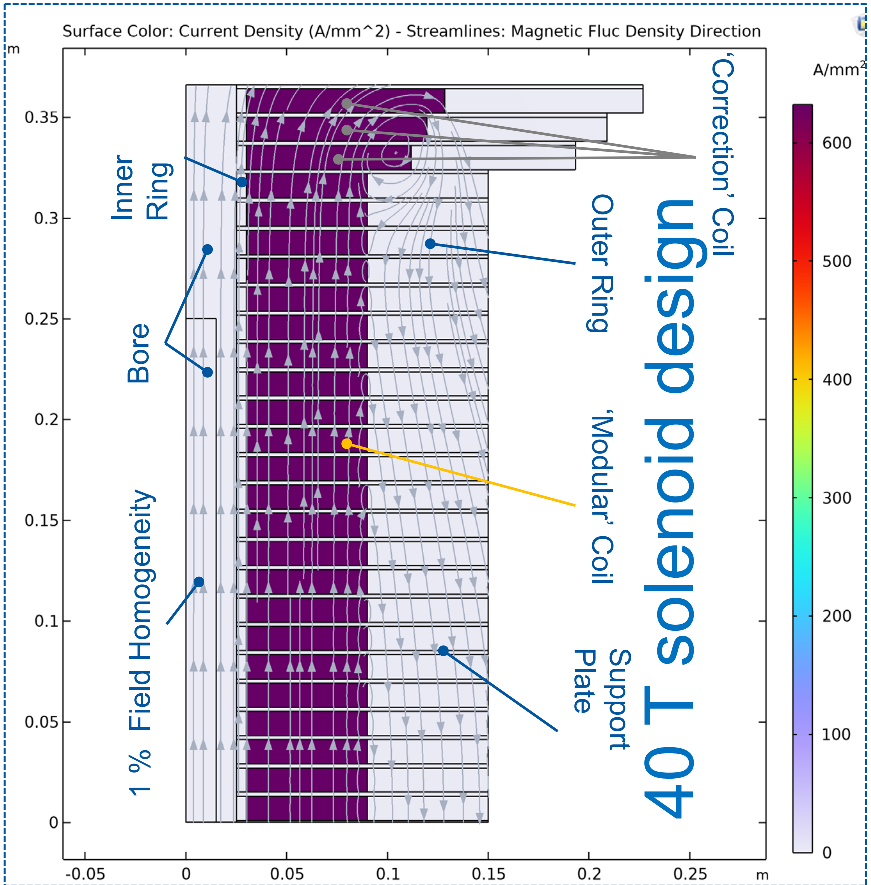
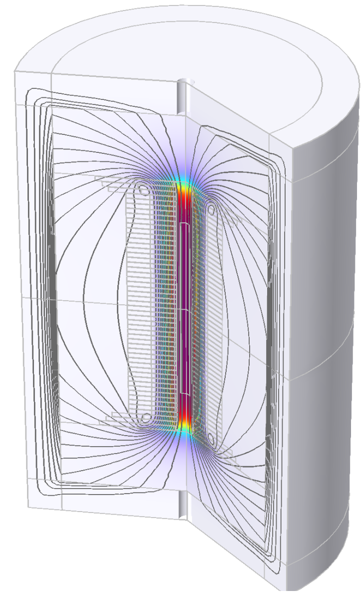
Final cooling (40 T) – 2/2

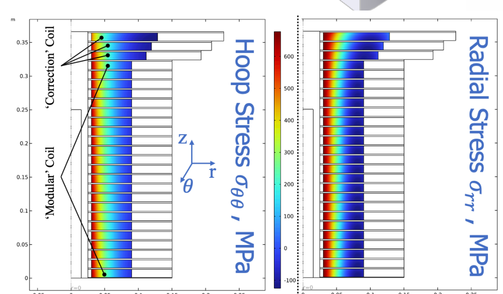
Poster 5PO17

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

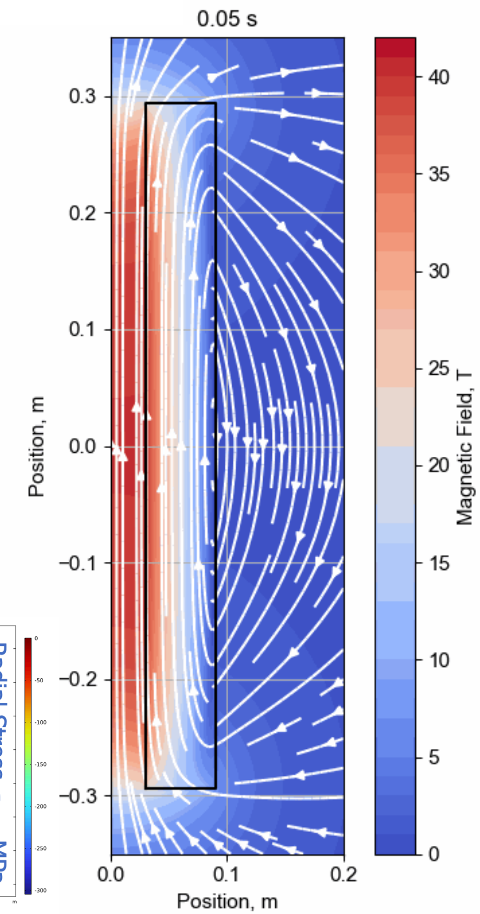
A. Dudarev, CERN







B. Bordini, CERN

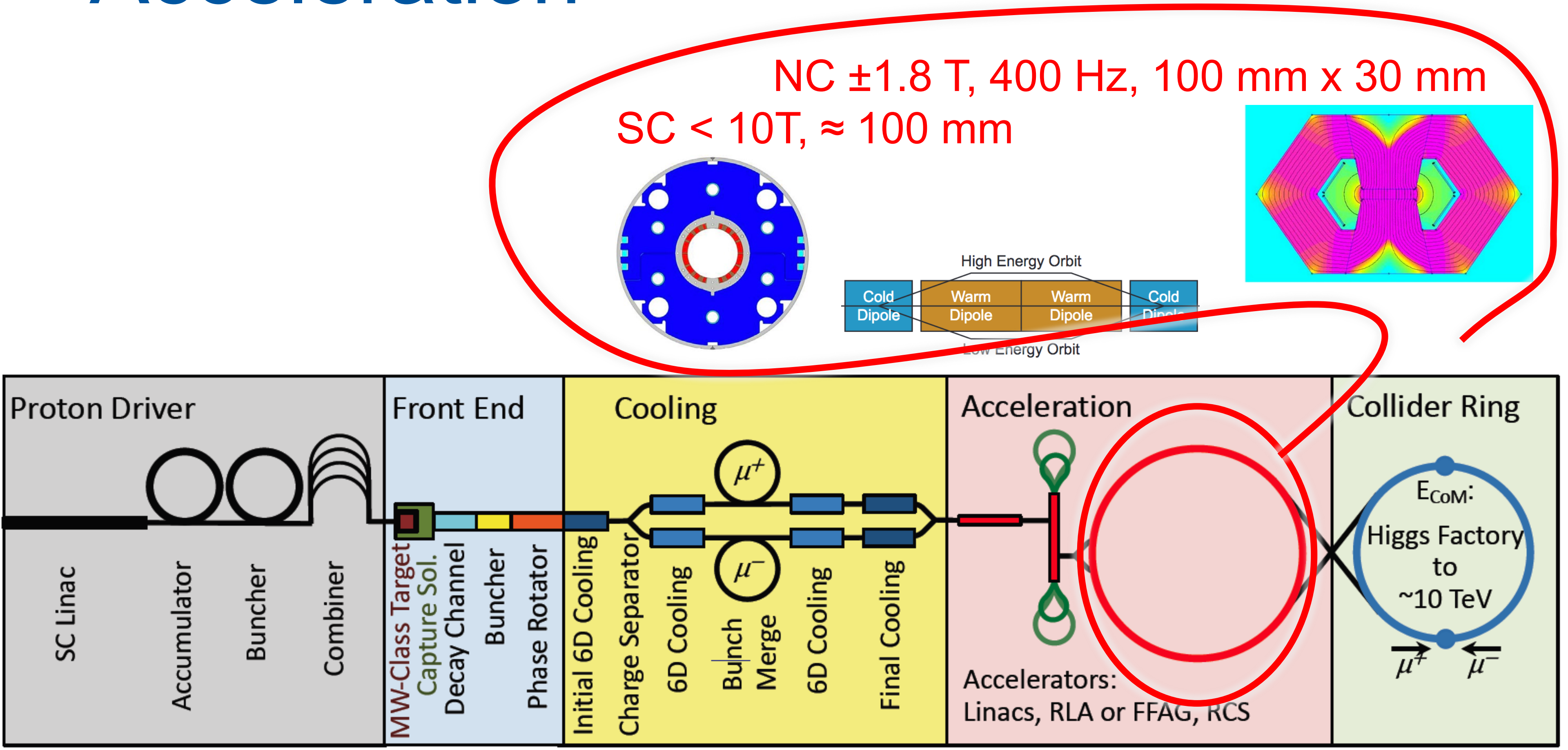


T. Mulder, CERN

B. Bordini, CERN

Strong connection to HTS magnets for science

Acceleration



- **Energy storage and power management o(50) GW**
- **Ramp linearity control, requirement (TBD)**
- **Medium field o(10 T) SC dipoles subjected to radiation load**

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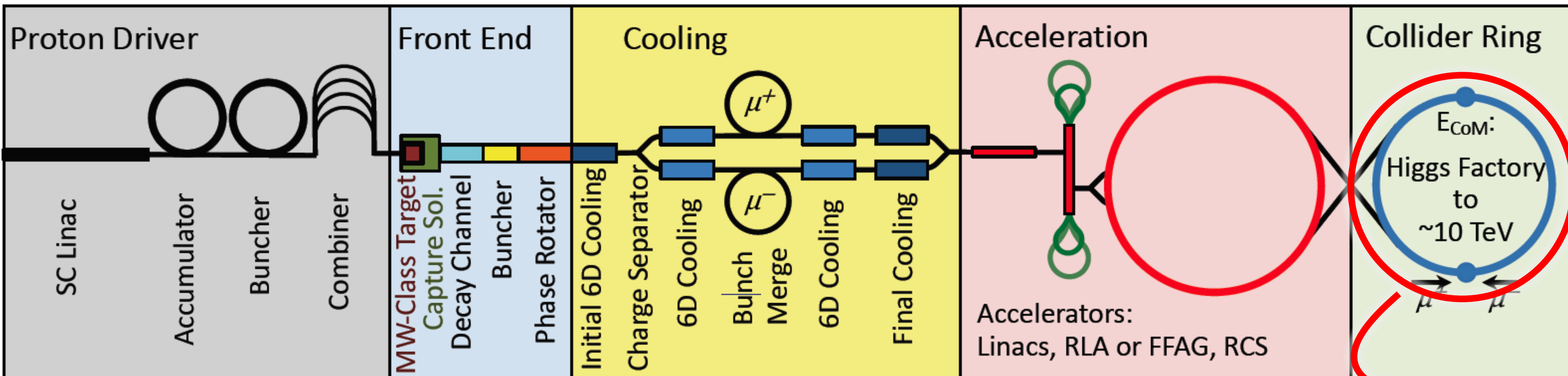
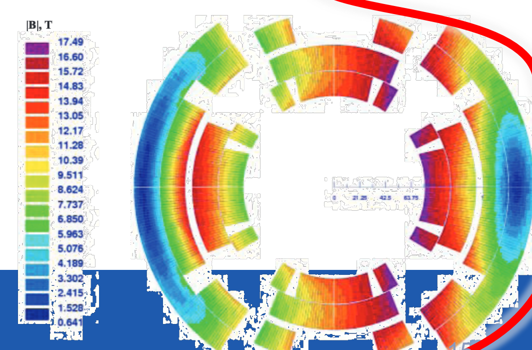
Collision

- **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



The HEP push towards HTS

Reduce energy consumption
(FCC-ee 350 MW, FCC-hh 580 MW)

Operate SC magnets at *higher* cryogenic temperature (gas)

Increase energy efficiency
(COP at 1.9 K is about 1000)

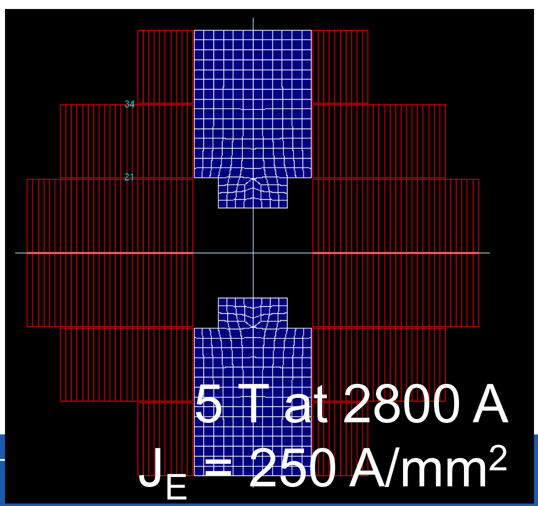
Risk with helium supply chain
(FCC-hh would require 900 tons of lHe)

Avoid large liquid helium bath and operate with gas (lower density)

Infrastructure (magnet) cost
(FCC-hh quoted at 9 BCHF)

Reduce SC cost per unit length and current

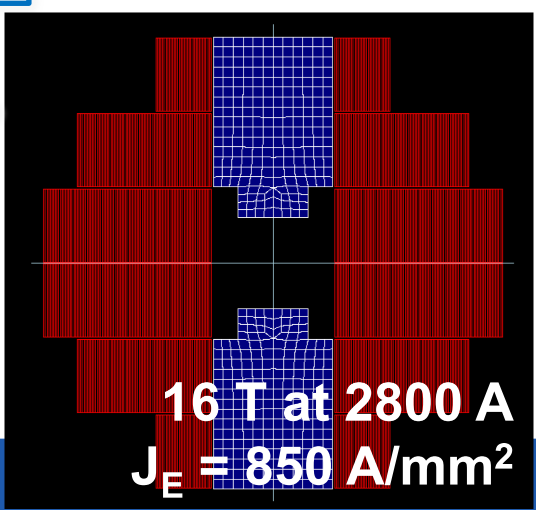
Increase coil current density to decrease conductor inventory



Calculation example
(T. Lecrevisse, CEA)

Compact HTS windings
- **Target J_E 1000 A/mm^2**

Operation in gaseous He
- **Range of 15…25 K**



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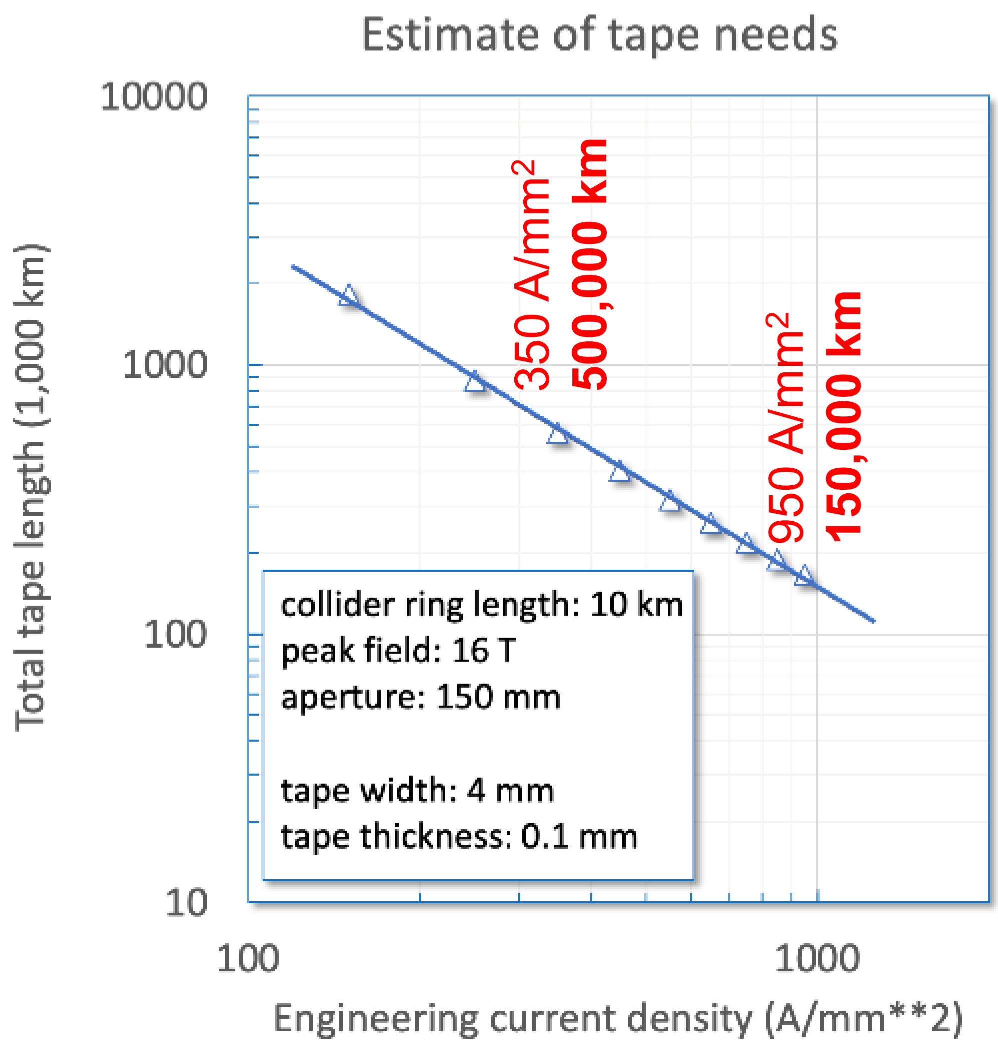
Compact windings



- We need to increase the winding current density to fall in a *reasonable* range of tape length (the same applis to **conductor mass** for LTS)

- Unresolved issues:
  - Winding geometry for tapes and stacks (ends, alignment, transposition possibly superfluous ?)
  - Mechanics of coils under the exceptional electromagnetic loads (longitudinal stress in the range of 600 MPa, transverse stress in the range of 400 MPa)
  - Quench management at high current and energy density (above 100 MJ/m^3)
  - Radiation hardness of materials and coils (40…80 MGy and 10^{22} n/m^2)

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HTS for accelerators

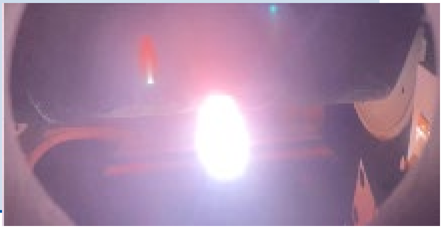
		Specification	Target
Minimum $J_{non\text{-}Cu}$ (4.2 K, 20 T)	(A/mm^2)	1500	3000
Minimum $J_{non\text{-}Cu}$ (20 K, 20 T)	(A/mm^2)	600	1250
$\sigma(I_C)$	(%)	10	5
Minimum copper RRR	(-)		20
Minimum Unit Length (UL)	(m)	200	500
Minimum bending radius	(mm)	15	10
Allowable $\sigma_{longitudinal\ non\text{-}Cu}$	(MPa)	800	1000
Allowable compressive $\sigma_{transverse}$	(MPa)		400
Allowable tensile $\sigma_{transverse}$	(MPa)		25
Allowable shear $\tau_{transverse}$	(MPa)		20
Allowable peel σ_{peel}	(MPa)		TBD
Allowable cleavage $\sigma_{cleavage}$	(MPa)		TBD
Range of allowable $\varepsilon_{longitudinal}$	(%)	-0.1…0.4	-0.1…+0.5
Internal specific resistance $\rho_{transverse}$	($n\Omega/cm^2$)		20

Width:	4…12 mm
Substrate (non-magnetic alloy):	40…60 μm
Copper stabilizer (total):	20…40 μm
Total tape thickness:	60…100 μm

The questions and the answers

Gaps in technology	Coil technology for high J_E (1000 A/mm^2) Winding geometry for tapes Mechanics at high stress (600 MPa longitudinal, 400 MPa compressive) Quench management (up to 300 MJ/m^3) Radiation hardness (up to 80 MGy, 10^{22} n/m^2) AC loss and/or field quality for accelerators
Conductor specifications	See table
Prioritized list of improvements	Mechanical properties (internal adhesion > 25 MPa) Resistive properties (internal resistance < TBD) Cost per UL (further factor 2 reduction)
Supply chain issues	Concerns on sustainability of supply chain
Potential areas of collaboration with other applications	Magnetically confined fusion NMR (future MRI ?) High Field Science Power generation KC^4 as a **collaborative R&D hub**

1st deposition run 1 March 2023



Two more challenges

- We are in dire need of robust scaling of the critical surface
  - More extensive data is required to enlarge the available database: ultra-high field, intermediate cryogenic temperatures, angle, …
  - Practical scaling to be used for magnet design and construction (see experience of NHMFL)
- What to do about AC loss and magnetization ? Increased AC loss can frustrate the gain of efficiency from operating at higher temperature
  - Ramped accelerators
  - Fusion magnets (flux and controls)

Summary

- The next step at the energy frontier of high energy physics (the muon collider, but not only) needs
  - High fields (dipoles and quadrupoles from 16 T up to 20 T, solenoids from 20 T up to 40 T and more)
  - Energy efficiency (increase operating temperature to profit from Carnot, *minimal cryogen* usage)
  - Economics (high J_E, compact magnets, to reduce construction costs, sustainable Maintenance and Operation)
- **HTS may offer it all, provided…**
  - **We develop a new magnet technology palette**, higher current density, higher operating temperature (large degree of innovation required), using present conductor: do not wait for better
  - **Deploy rapidly for users**: they get to know the features of the new devices, cope and (may) adapt demands
  - **Profit from cost reduction**: one more "factor two reduction" possible ? That would be disruptive (HTS/LTS cross over)

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Abstract

HTS is a game changer for many applications of superconductivity, not last particle accelerators and detectors. This talk relates the potential of HTS, and in particular REBCO coated conductors, to the needs and evolution of superconducting magnets for accelerators. HTS already have a spectacular current carrying ability at high field, demonstrated and available on relevant lengths. The main perceived challenges are rather associated with magnet mechanics and quench management. HTS may offer solutions to both, relying on innovative winding technology. Furthermore, the extended range of operating temperature of HTS will benefit energy efficiency and sustainability. This potential is of very high interest towards sustainable large scale research infrastructures such as particle accelerators.