HTS for the future of HEP

Accelerator Opportunities and Infrastructures Required

Presented by L. Bottura, CERN

I-FAST Industry Workshop
on HTS Development,
18 April 2023, Trieste, Italy

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

Outline

- The HEP landscape – a recap
- Why HTS ?
- Infrastructures & Co.
- Summary

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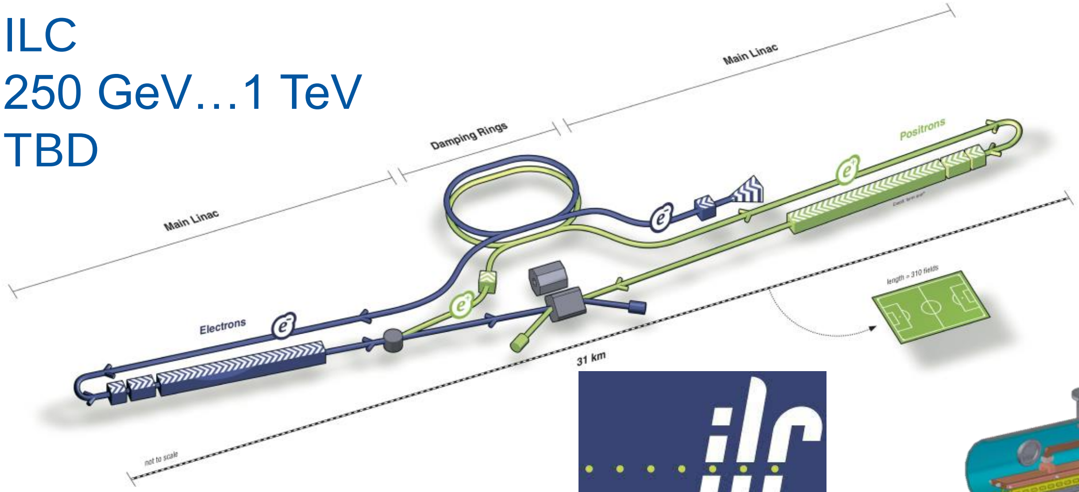
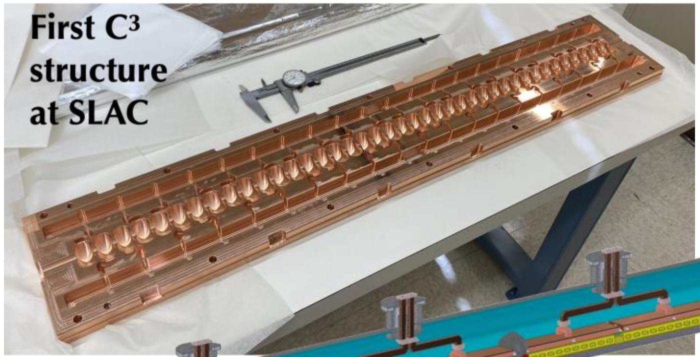
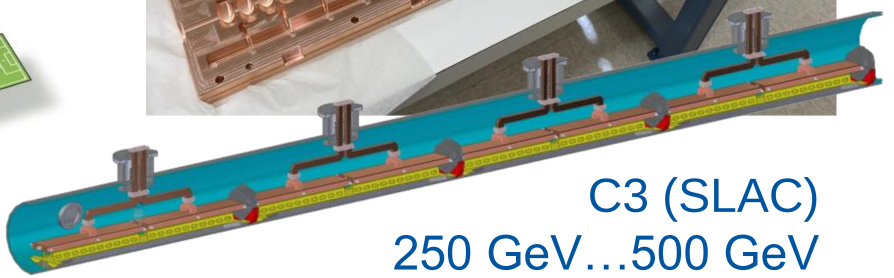
HEP Landscape - Linear Colliders

ILC
250 GeV…1 TeV
TBD



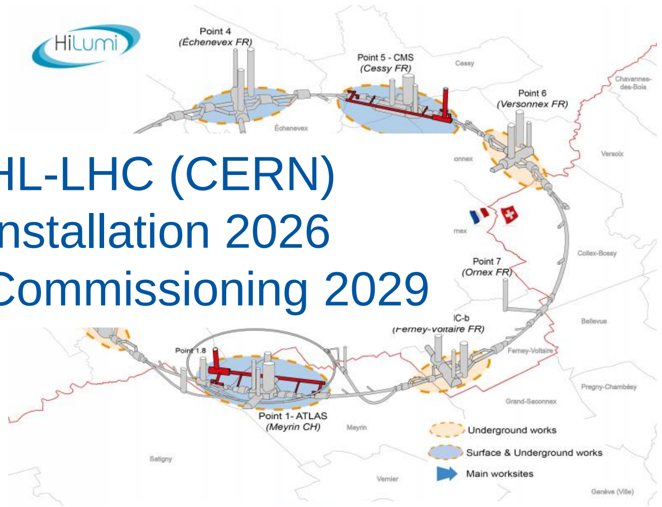




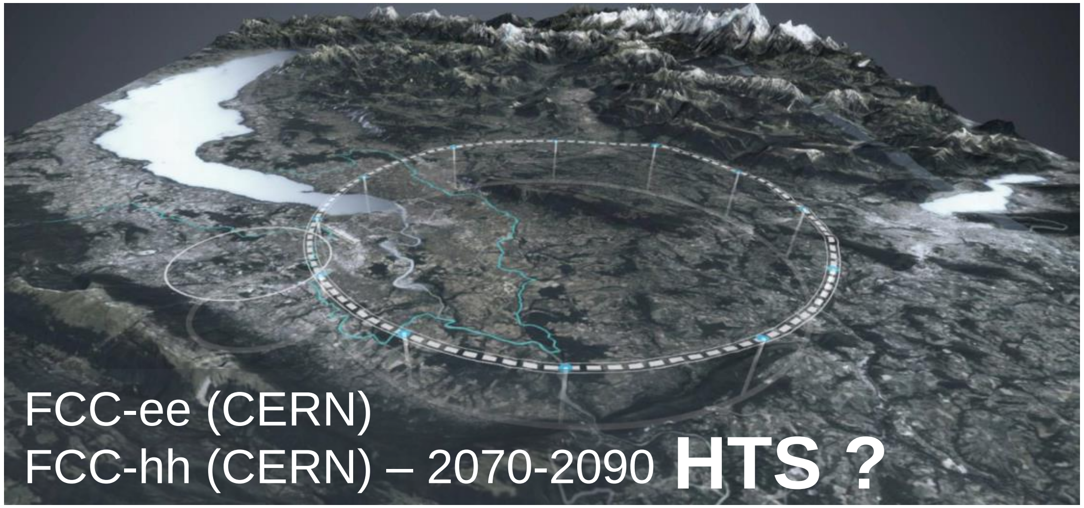
C3 (SLAC)
250 GeV…500 GeV
TBD

CLIC (CERN)
500 GeV…3TeV
TBD

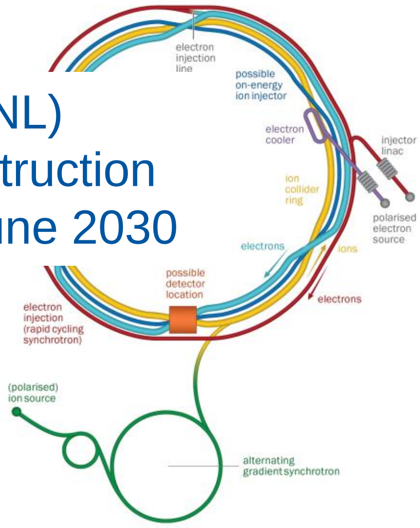
HEP Landscape - Circular Colliders



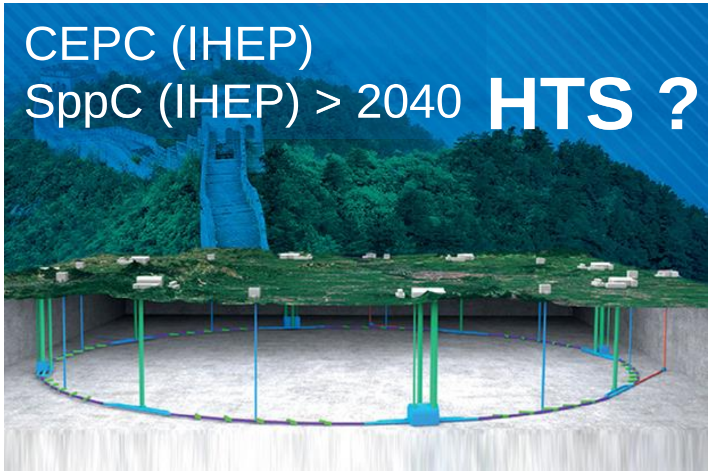
HL-LHC (CERN)
Installation 2026
Commissioning 2029



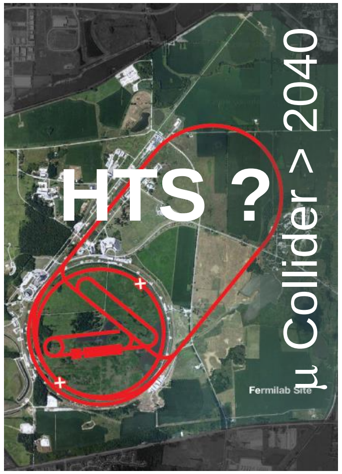
FCC-ee (CERN)
FCC-hh (CERN) – 2070-2090 **HTS ?**



EIC (BNL)
In construction
CD4 June 2030



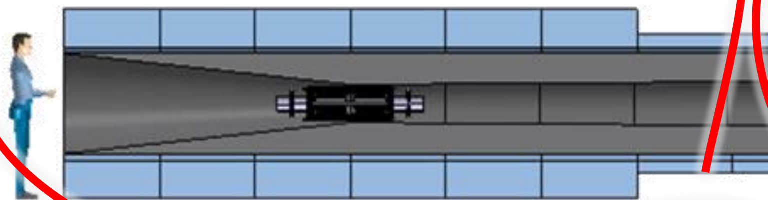
CEPC (IHEP)
SppC (IHEP) > 2040 **HTS ?**



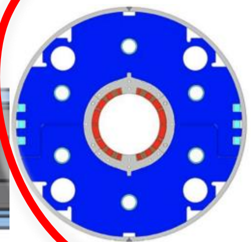
HTS ?
μ Collider > 2040

Muon Collider magnets

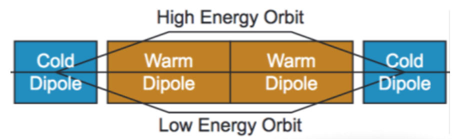
20 T, 200 mm **HTS !**
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

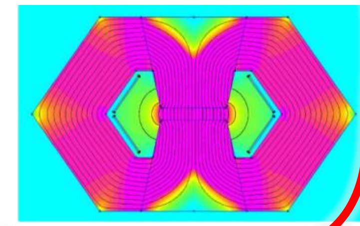


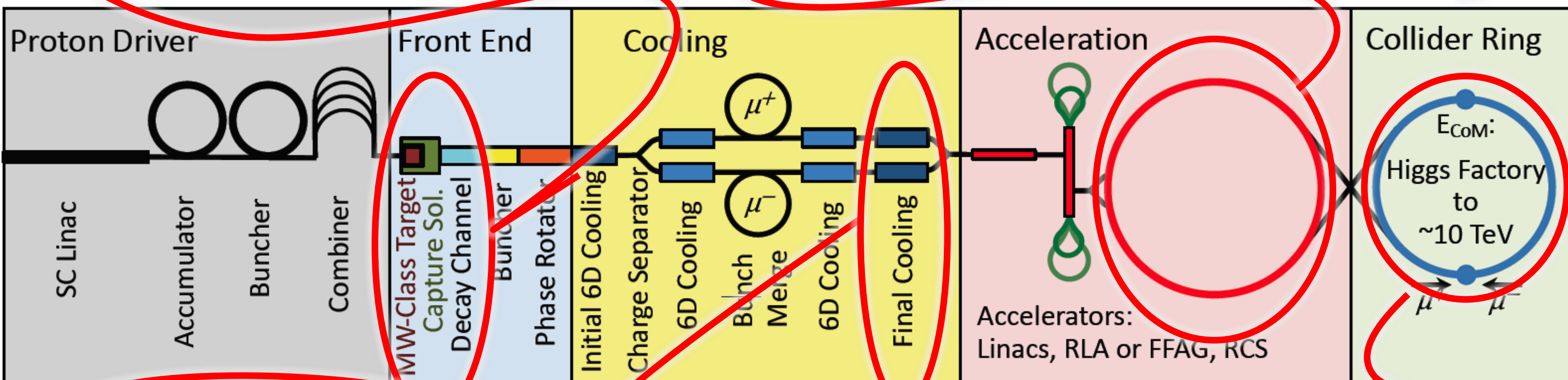
NC ±1.8 T, 400 Hz, 100 mm x 30 mm
SC < 10T, ≈ 100 mm



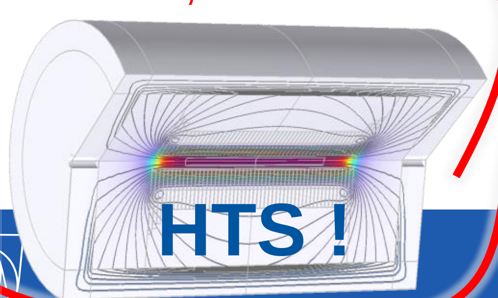
HTS ?







> 40 T, 60 mm



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

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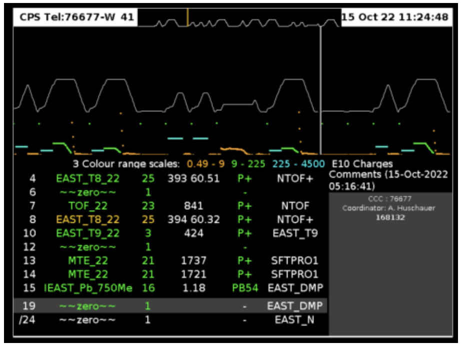
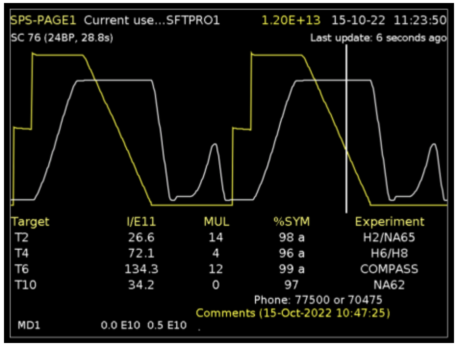
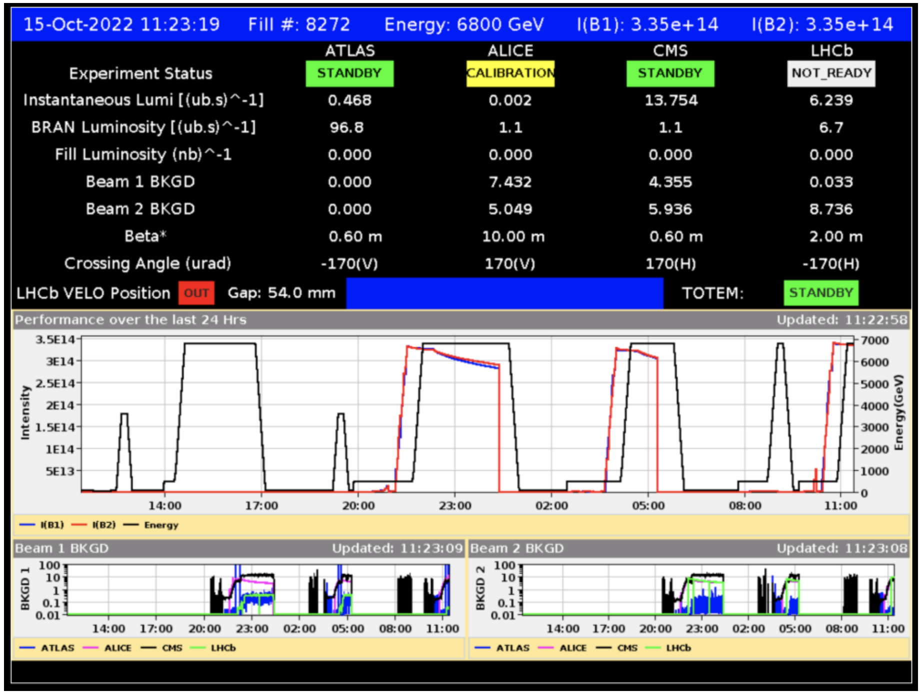
The need for energy

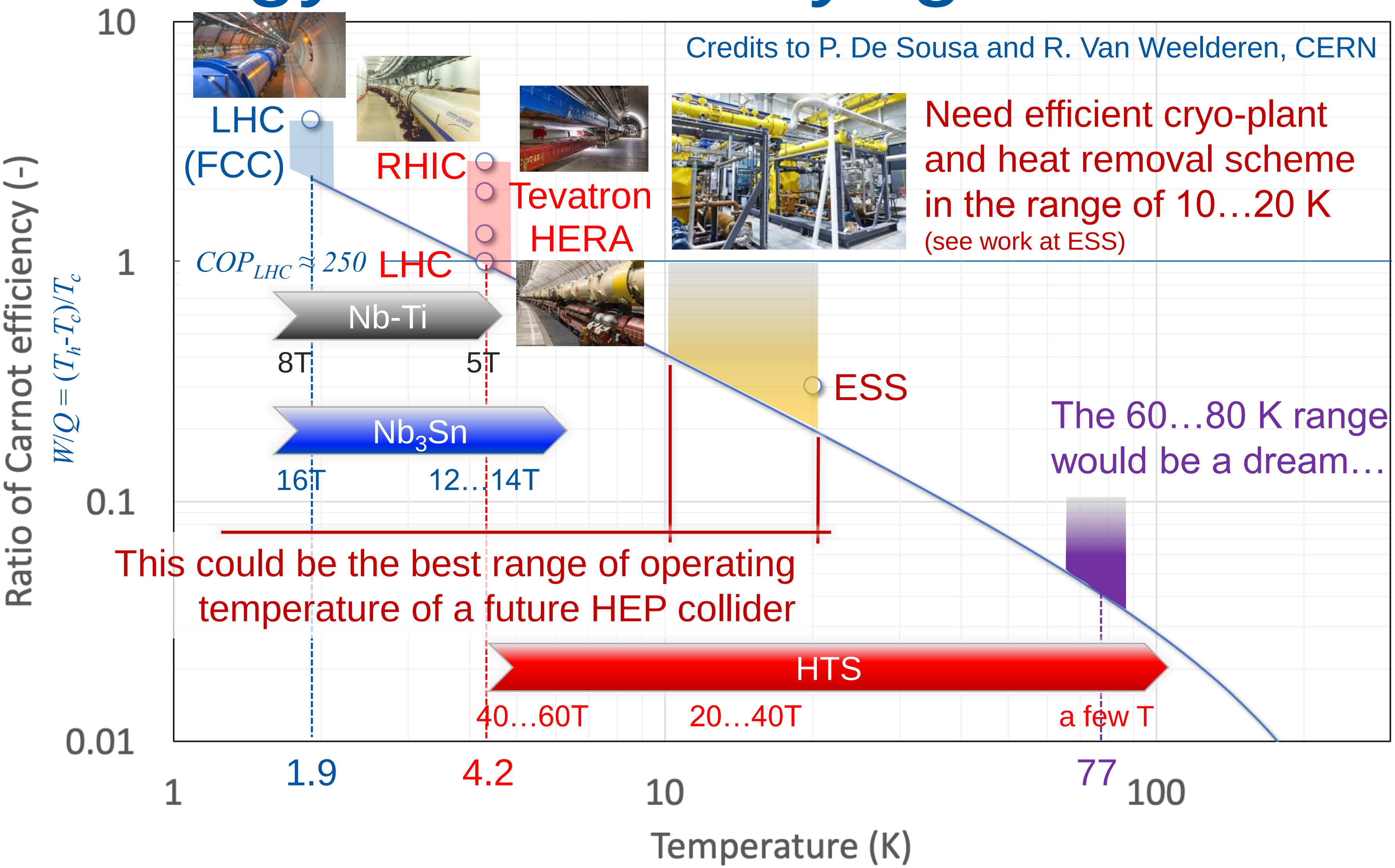
- CERN uses today **1.3 TWh** per year of operation, with peak power consumption of **200 MW** (running accelerators and experiments), dropping to **80 MW** in winter (technical stop period)
- Electric power is drawn directly from the French 400 kV distribution, and presently supplied under agreed conditions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



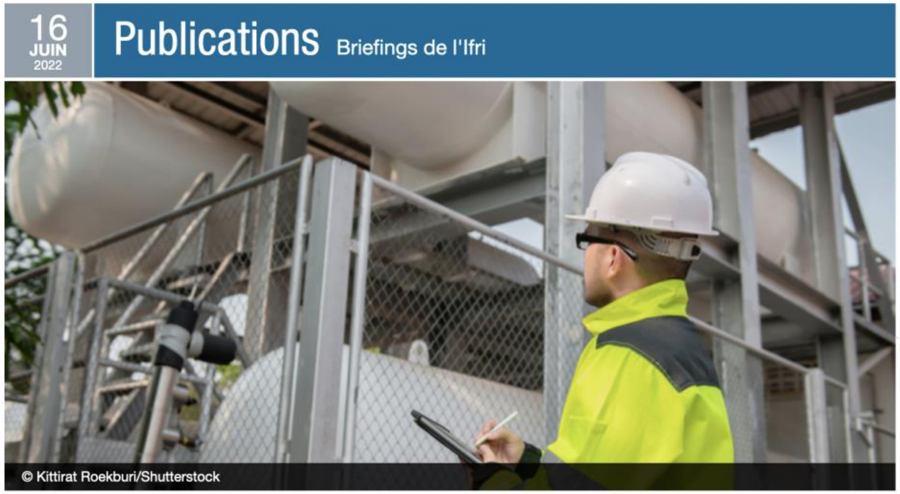




Energy efficient cryogenics



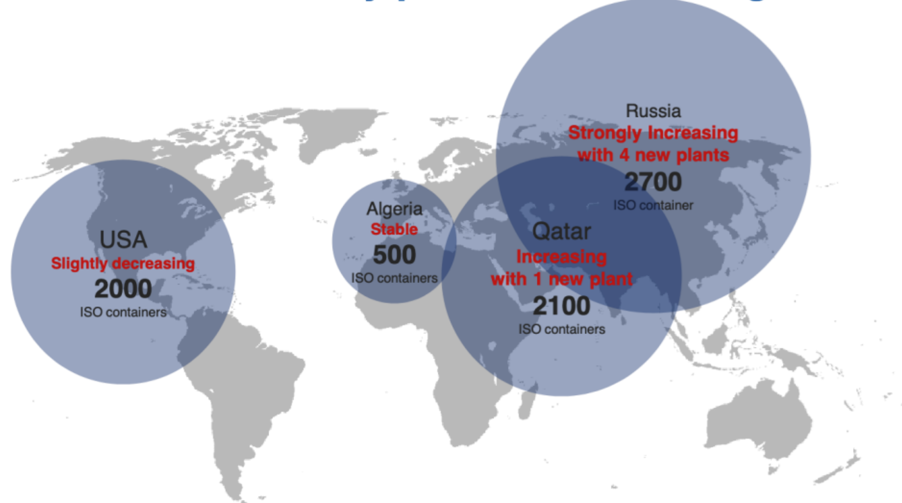
HTS may be the only path towards a future collider



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

TE CRG

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

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)

CERN

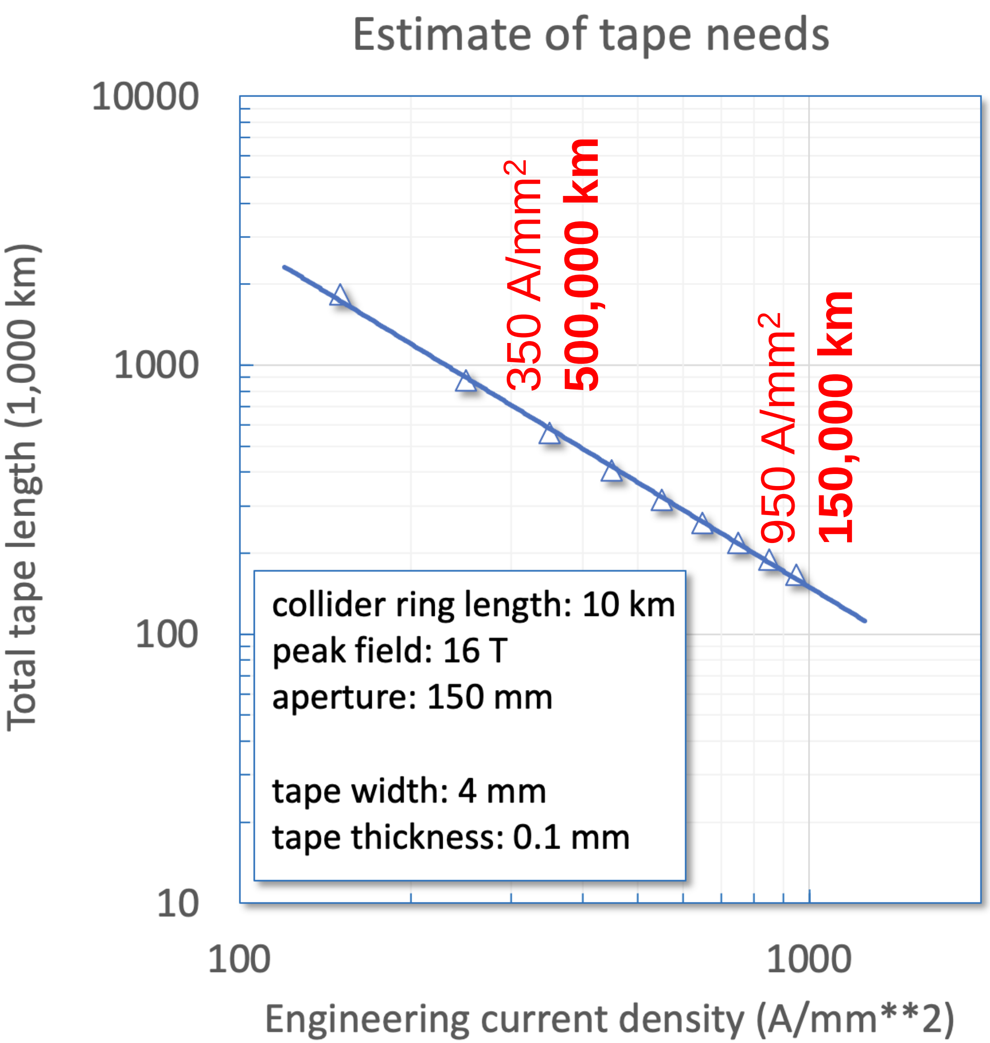
Courtesy of F. Ferrand, CERN

The need for economics

- 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* !**)
  - Reduce unit conductor cost

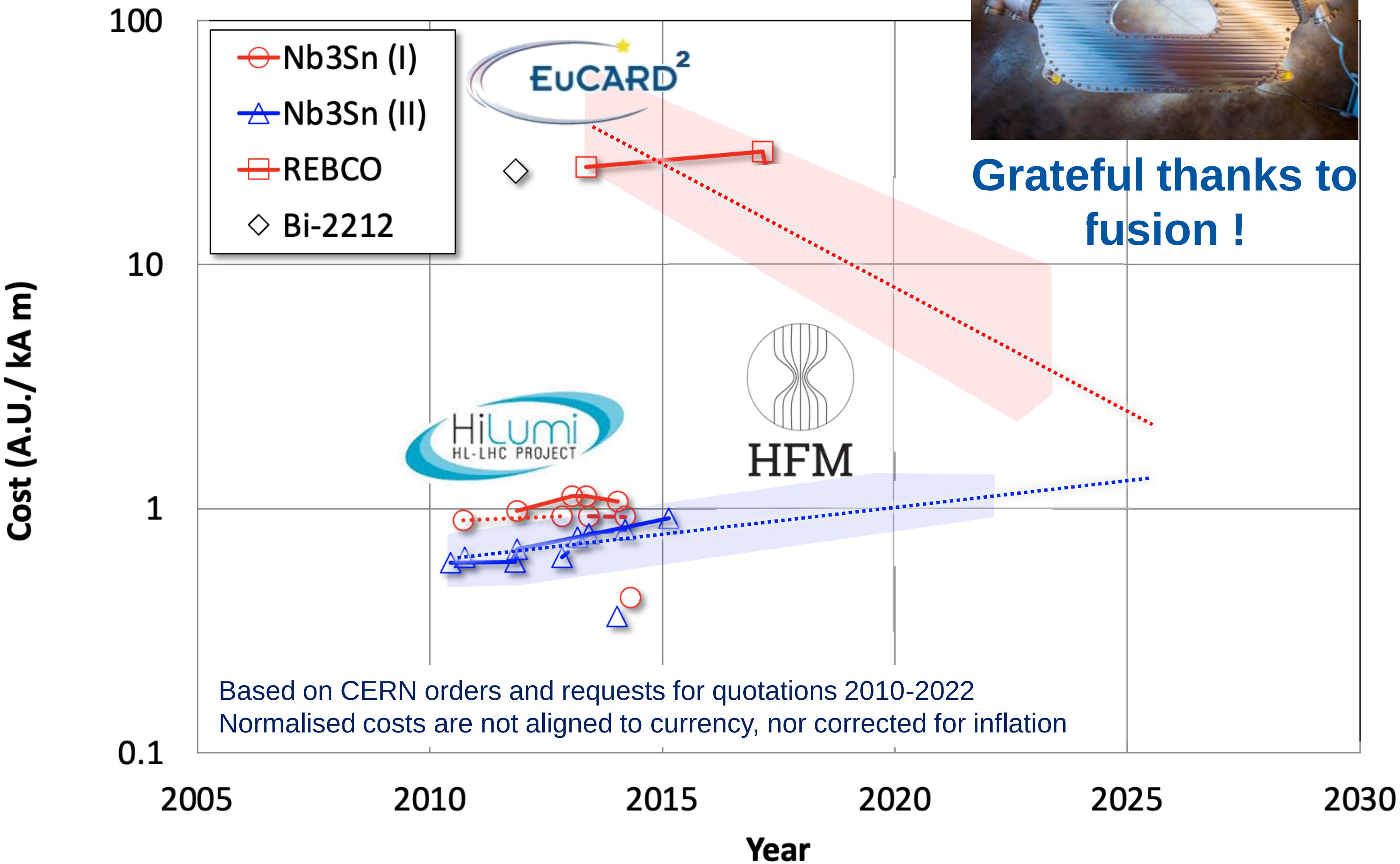
HTS may offer both

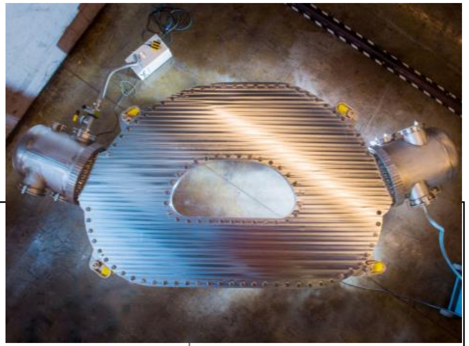
Compact windings



- We need to increase the winding current density to fall in a *reasonable* range of tape length (the same applies 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)

Conductor cost





Grateful thanks to fusion !

Impressive cost reduction in HTS !

The HEP push towards HTS

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

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

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

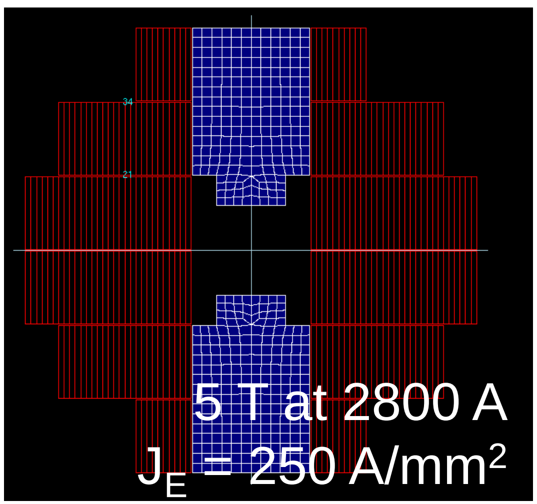
Operate SC magnets at *higher* cryogenic temperature (gas)

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

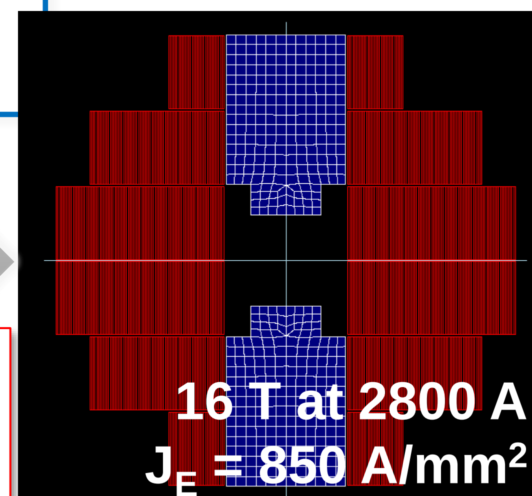
Reduce SC cost per unit length and current

Increase coil current density to decrease conductor inventory

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



Calculation example
(T. Lecrevisse, CEA)



Compact HTS windings
- **Target J_E 1000 A/mm²**

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

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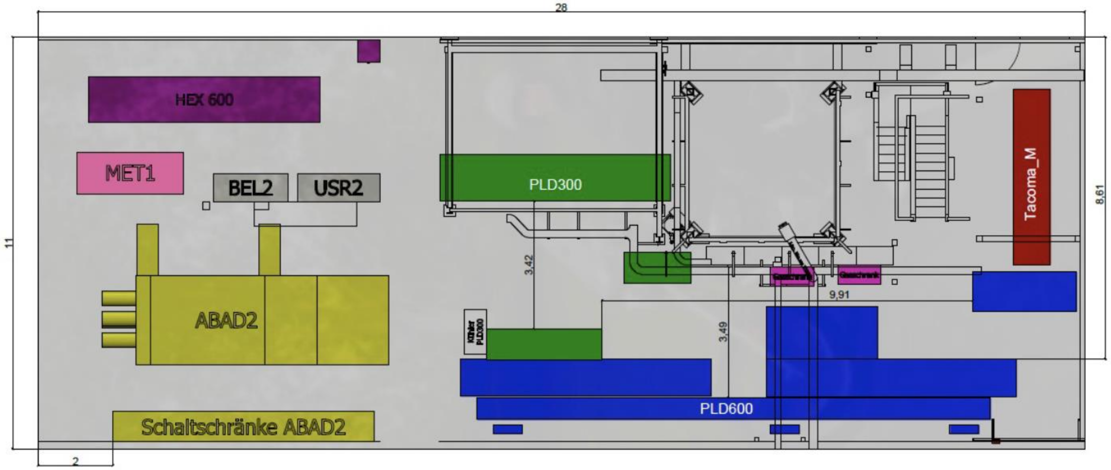
DISCLAIMER: next is a **personal and biassed** opinion based on the perceived risks and potential, setting a horizon of five years, and intended as motivator for guided discussion

Superconductor infrastructure

- Compared to LTS (Nb-Ti) HTS are still **novel materials**, and there is scope for:
  - **Material and wire/tape research** (e.g. composition, pinning, basic properties and specific characterization such as electro-mechanics and radiation effects)
  - **R&D on production routes and their optimization/simplification** (e.g. increase volume, improve yield, reduce cost)
  - **Not yet clear whether ”cables” require dedicated infrastructure** (NI winding technology ? Transposition ? AC loss ?)

HTS R&D – Example

KC^4: KIT-CERN Collaboration on Coated Conductor



1st deposition run 1 March 2023

Unique playground, also for industry !

Magnet infrastructure

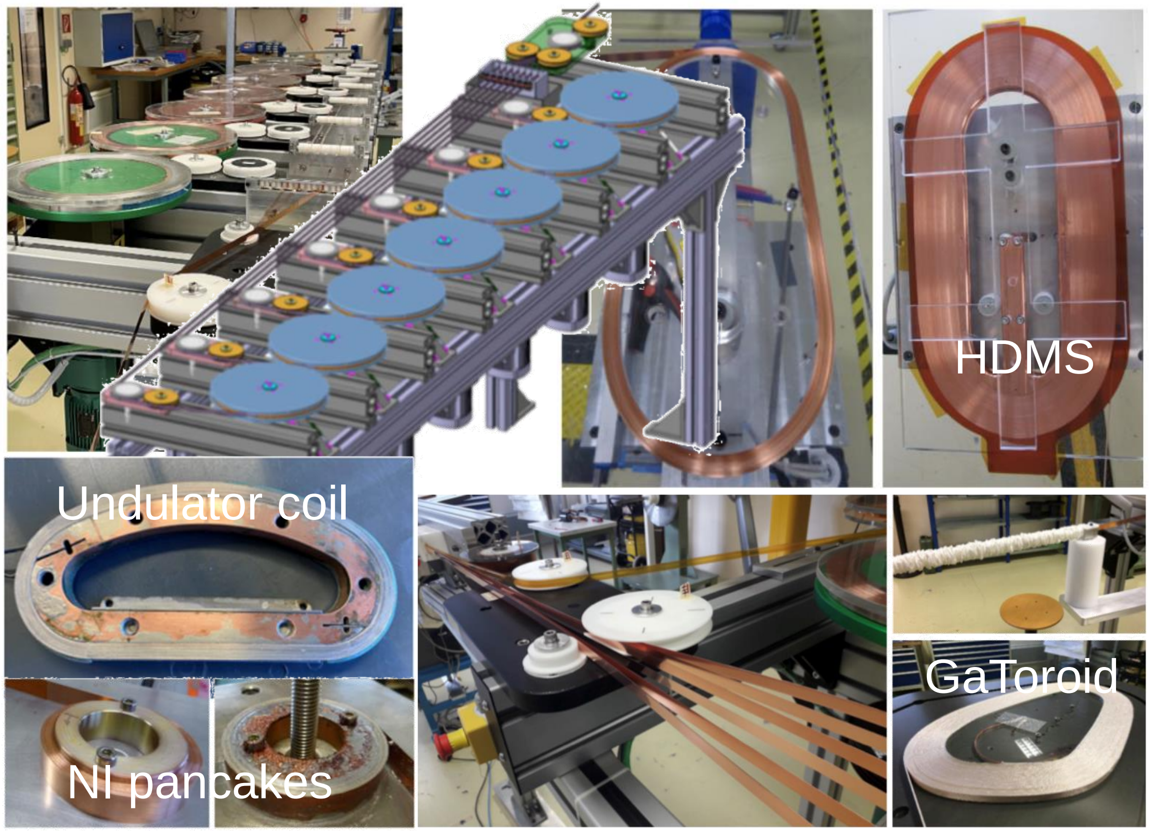
- Even more so than conductors, HTS magnets are only in the early infancy, and there is need of:
  - **Flexible winding tooling** (e.g. from simple to complex winding shapes, single to multiple wires/tapes) with good controls but modest dimension
  - **Flexible process tooling** (e.g. impregnation with alternative polymers, soldering, HT if required) of modest dimensions
  - **Upscaling not yet necessary** (e.g. long coils, series production), use *tailored solutions* if and when required

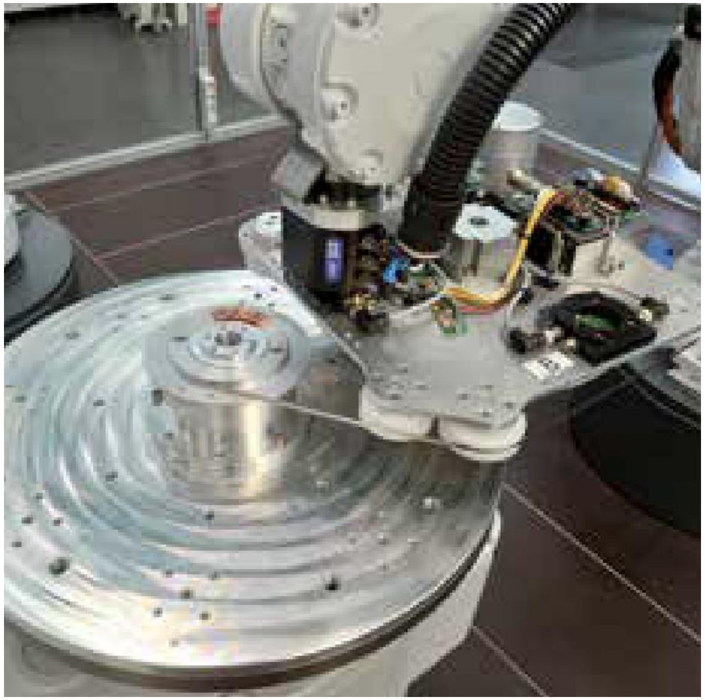
Magnet R&D – Examples

18th Int. Conf. on Acc. and Large Exp. Physics Control Systems ICALEPCS2021, Shanghai, China JACoW Publishing
ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-TUPV034

DEVELOPMENT OF AN AUTOMATED HIGH TEMPERATURE SUPER-CONDUCTOR COIL WINDING MACHINE AT CERN

H. Reymond, M. Dam, H. Felice, A. Haziot, P. Jankowski, P. Koziol, T.H. Nes, F.O. Pincot, S.C. Richter, CERN, Geneva, Switzerland





Flexible is the keyword !

Test infrastructure

- **We are in dire need of more:**
  - **UHF testing of materials and conductors**: higher field, and more facilities in the range of 20 T…40 T

HTS !

  - **HF testing of cables**: high field (B≈20 T), high current (I≈100 kA) and cryogenic temperature above lHe (T≈4 K to 100 K)

HTS !

  - **Background field test facilities**: test of small scale windings (OD≈150 mm x L≈0.1 m to 1 m) in relevant conditions of field (B≈20 T) and force (limiting factor, this is not a cable test facility !)

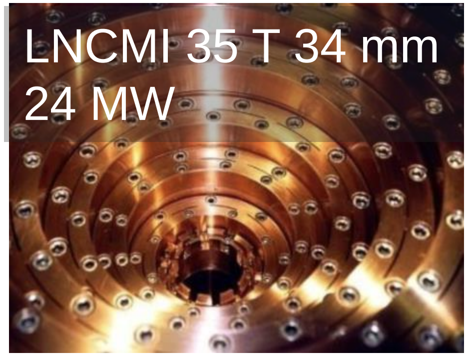
HTS !

  - **Variable temperature test facilities**: coils and magnets tests at cryogenic temperature above lHe (T≈4 K to 100 K)

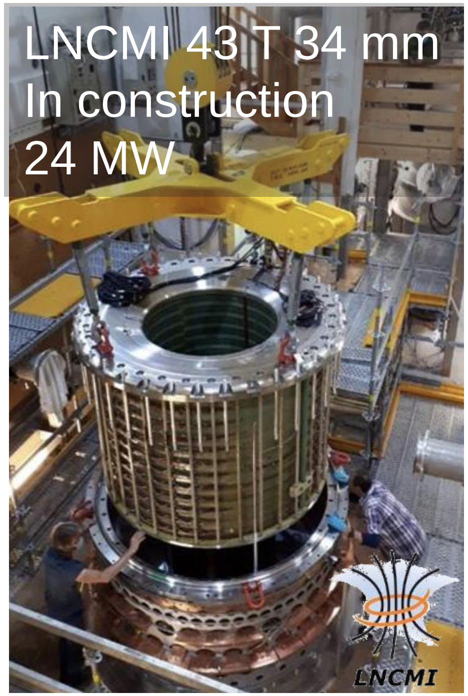
CERN

Test facilities - Examples

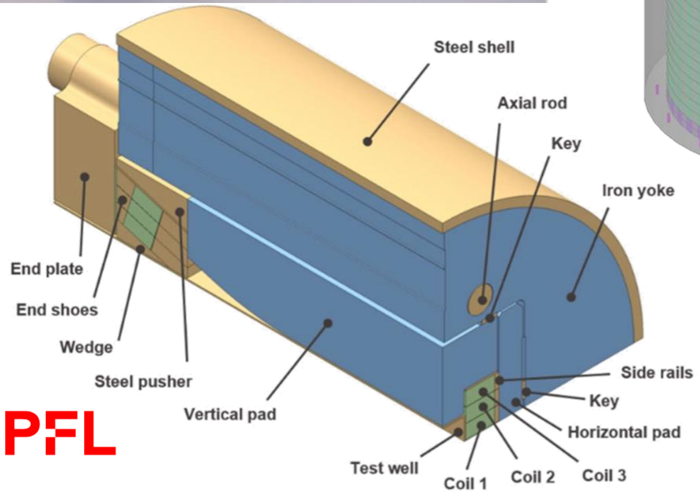
LNCMI 35 T 34 mm
24 MW



LNCMI 43 T 34 mm
In construction
24 MW



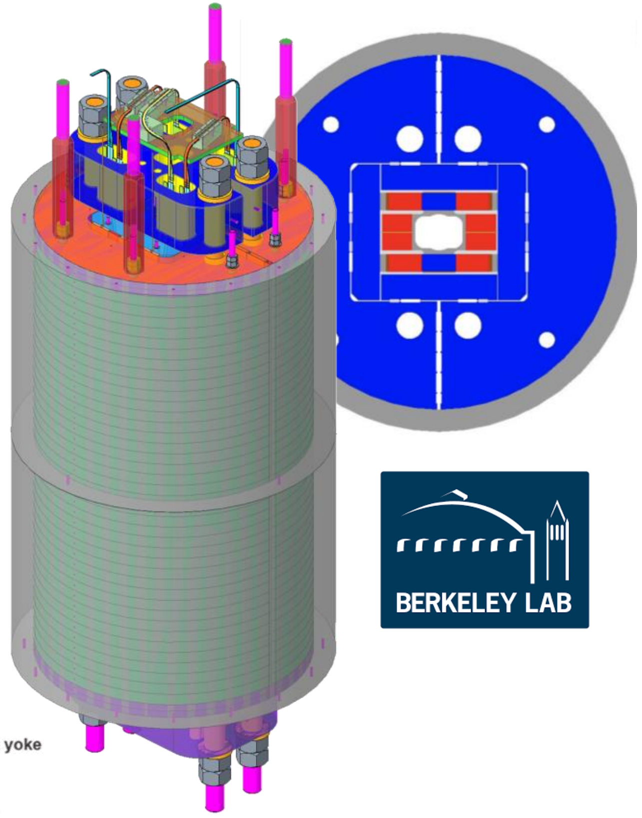
UNIVERSITÉ DE GENÈVE
21 T 50 mm



EPFL

EDIPO2 EPFL/SPC
15 T 144 mm x 144 mm

TFD LBNL
16 T 100 mm x 140 mm



BERKELEY LAB

Expand, increase and improve capability !

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Summary – 1/2

- The next step at the energy frontier of high energy physics 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)

Summary – 2/2

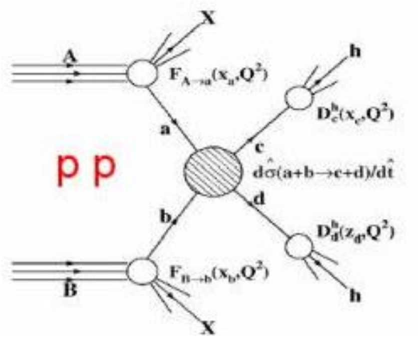
- Yes, there is arguably a lot of work to do, but
  - The HEP interest is **directly shared** with:
    - Fusion and other power applications
    - NMR and High Magnetic Field science
    - …
  - We are likely at a technology hinge, i.e. **there may not be another way**, we might as well embrace it
  - **Expanding the support infrastructure for HTS conductor and magnet R&D, and in particular the test facilities, can provide the technology bootstrapping needed**

www.cern.ch

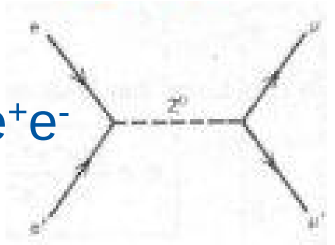
Collider Choices

- 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**

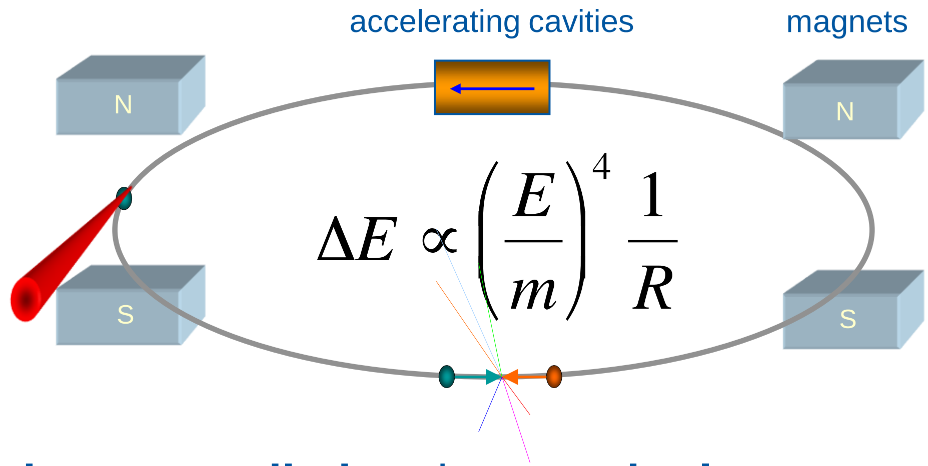
- Lepton collisions: elementary particles
  - LEP reached 0.205 TeV with electron-positron collisions
  - Clean events, easy to extract physics
  - **Lepton collisions $\Rightarrow$ precision measurements**
  - **Hard to reach high energies**



e^+e^-



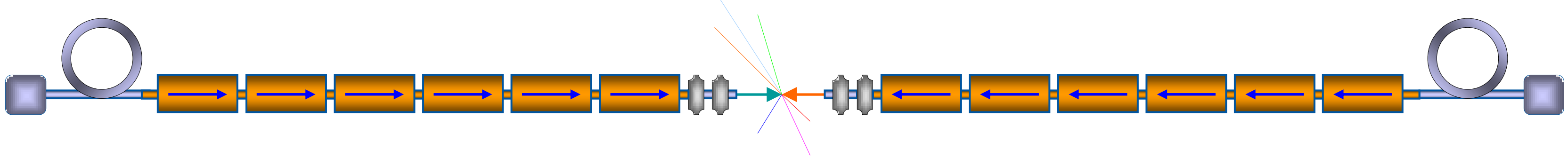
Energy Limit



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

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

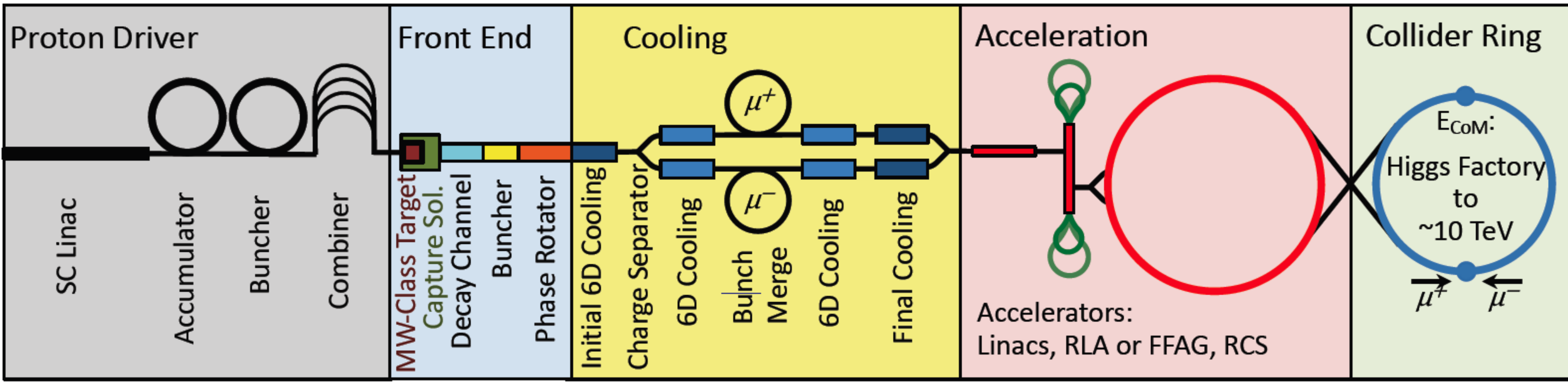
Courtesy of D. Schulte

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

Proton-driven Muon Collider Concept

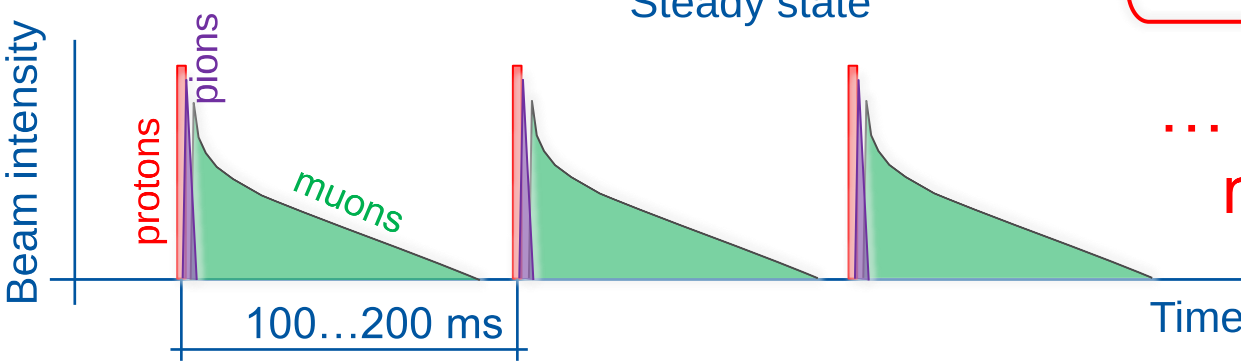
Produce a low emittance muon beam… … collide !

Pulsed | Steady state | Pulsed



Steady state | Steady state

… accelerate muons…



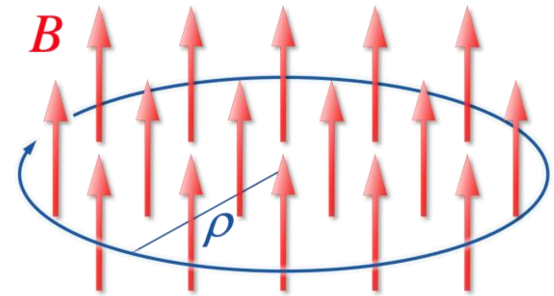
The need for high field

Beam energy

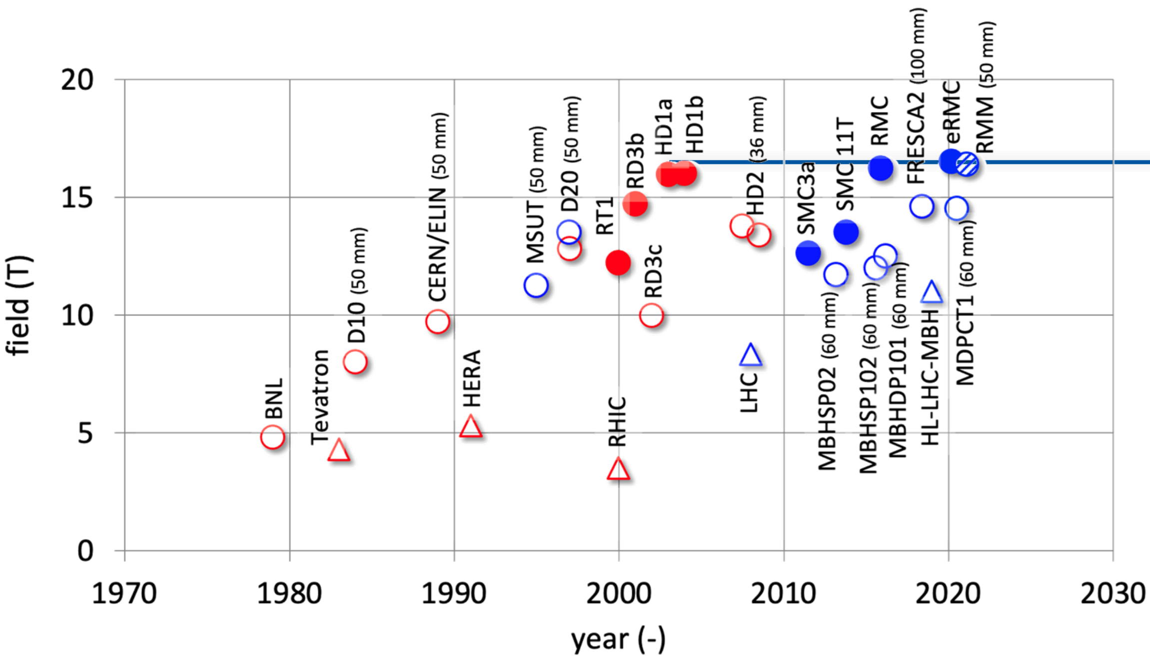
Bending radius

$$E[GeV] = 0.3\,B[T]\,r[m]$$

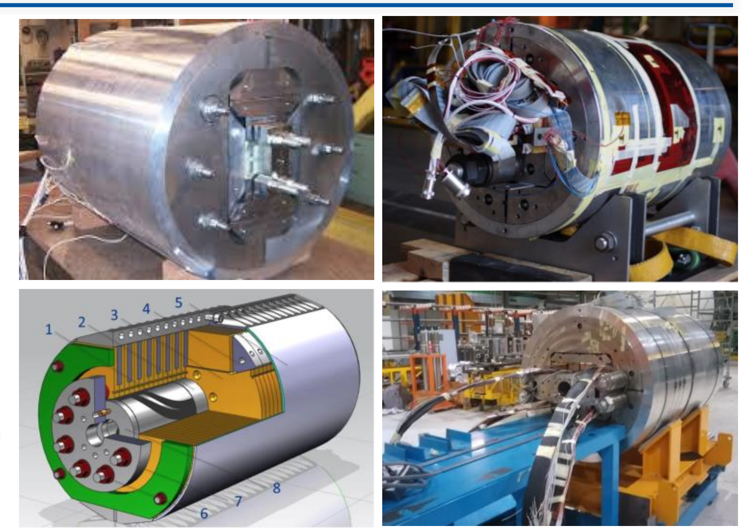
Dipole field



This is the reason for the steady call for **higher fields** in accelerator magnets

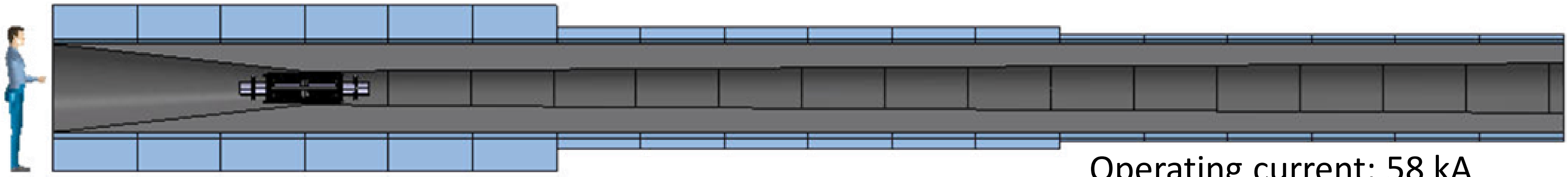


Upper limit of LTS (Nb_3Sn)



HTS is the only path beyond 16 T

Target and capture – 2/2

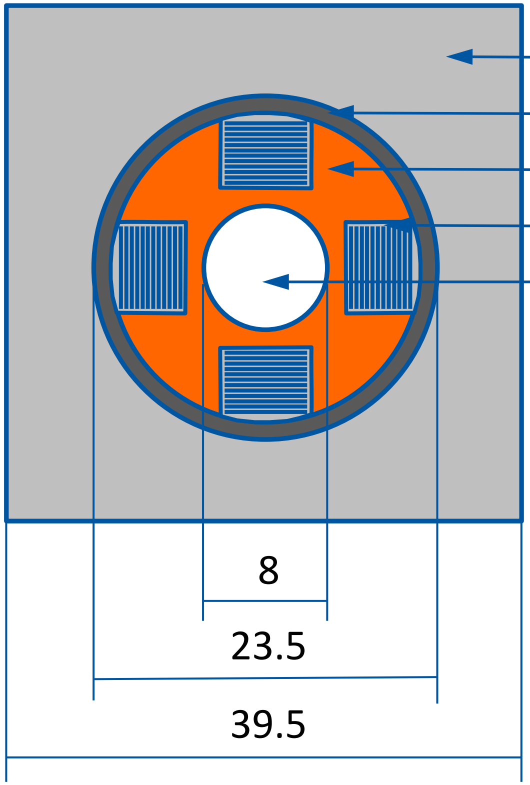


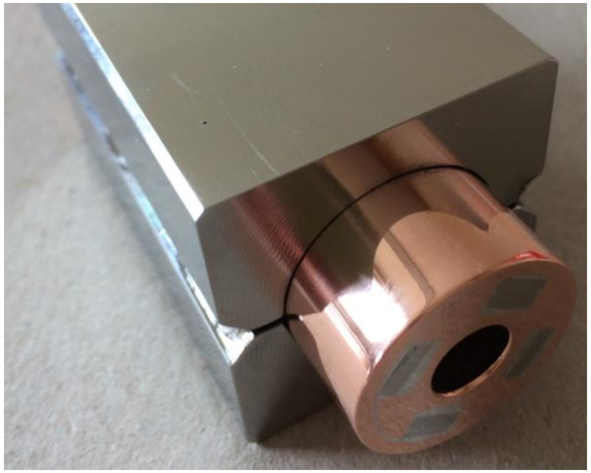
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K

MIT "VIPER" conductor

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

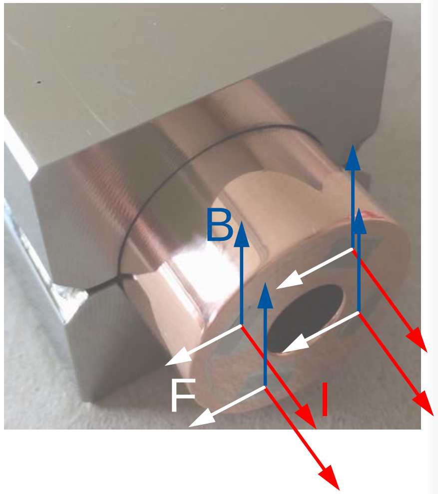
HTS conductor design

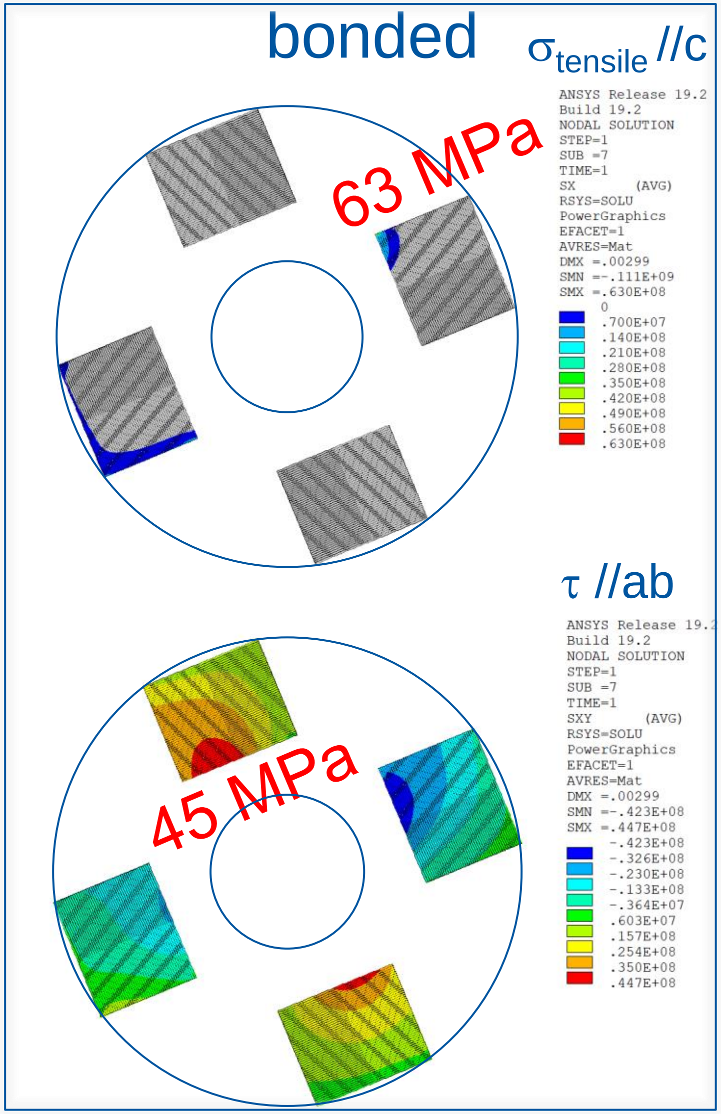


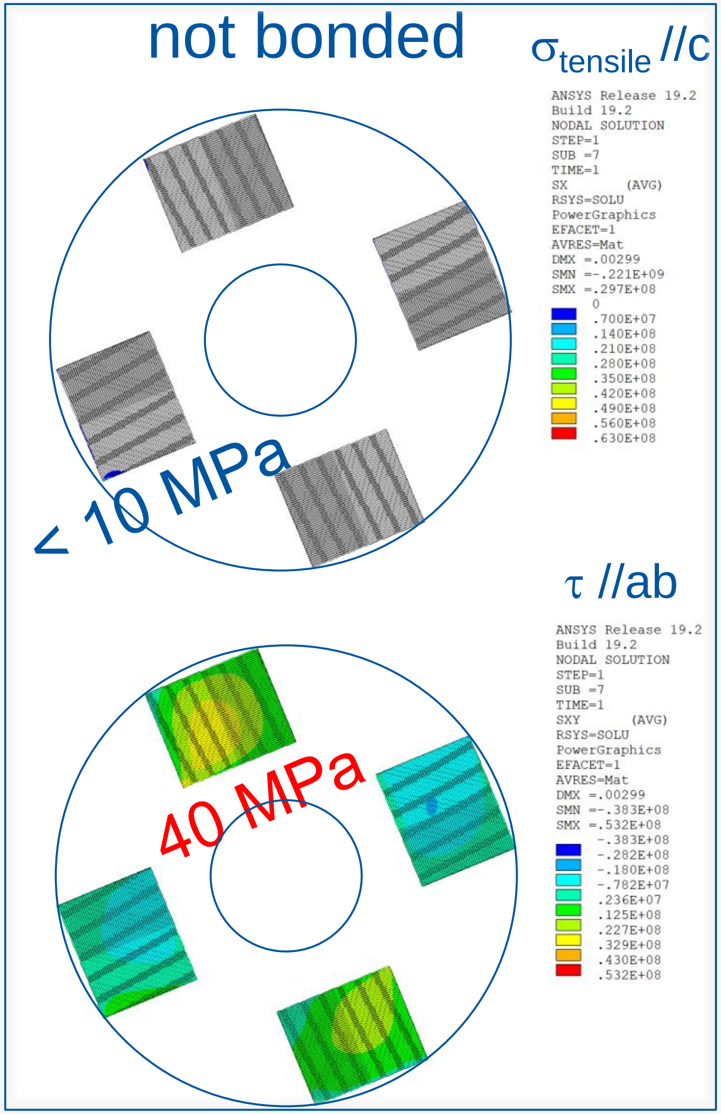


Strong connection to HTS magnets for fusion

HTS cable mechanics







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

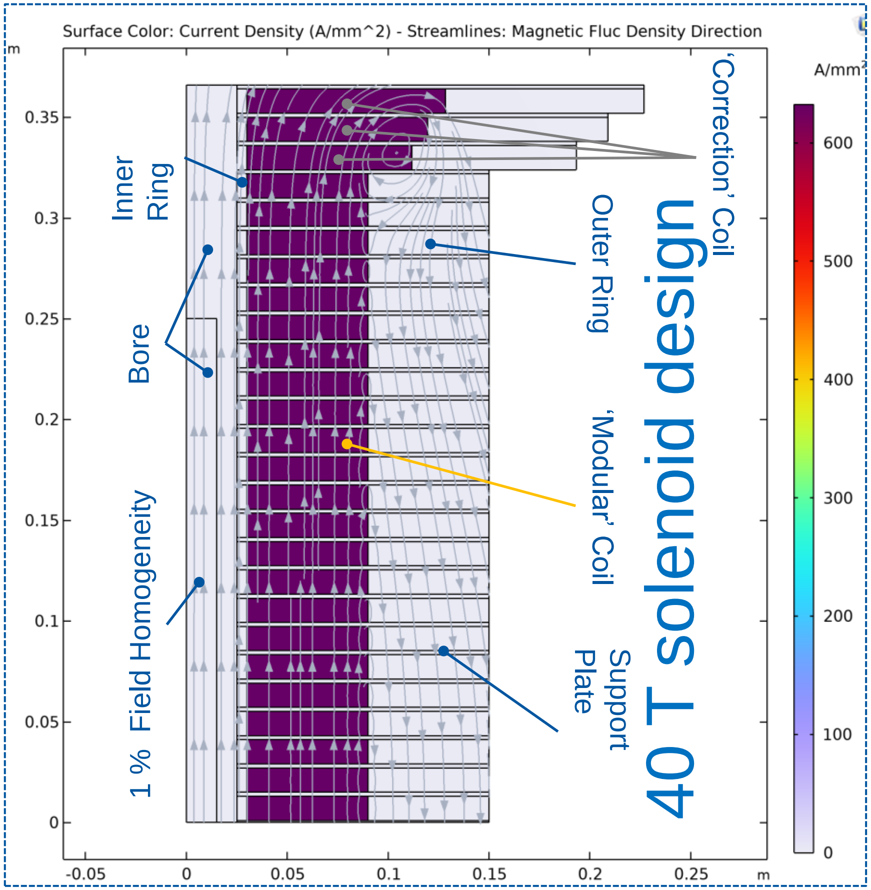
Courtesy of J. Lorenzo Gomez, F4E, Barcelona (Spain)

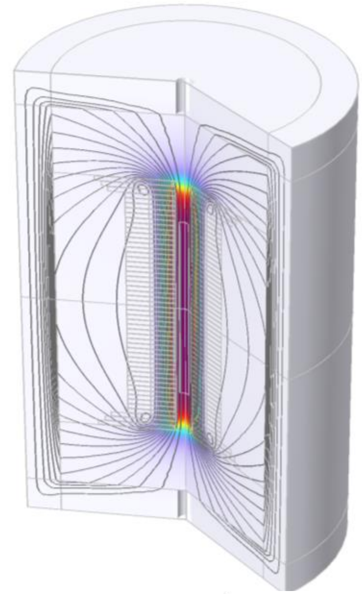
Final cooling (40 T) – 2/2

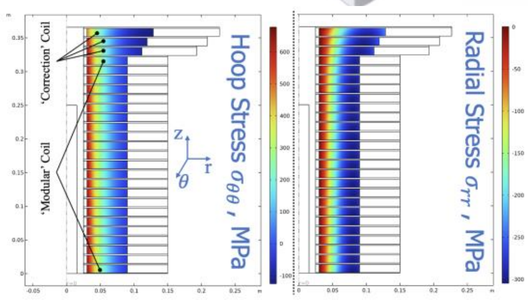
Poster 5PO17

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

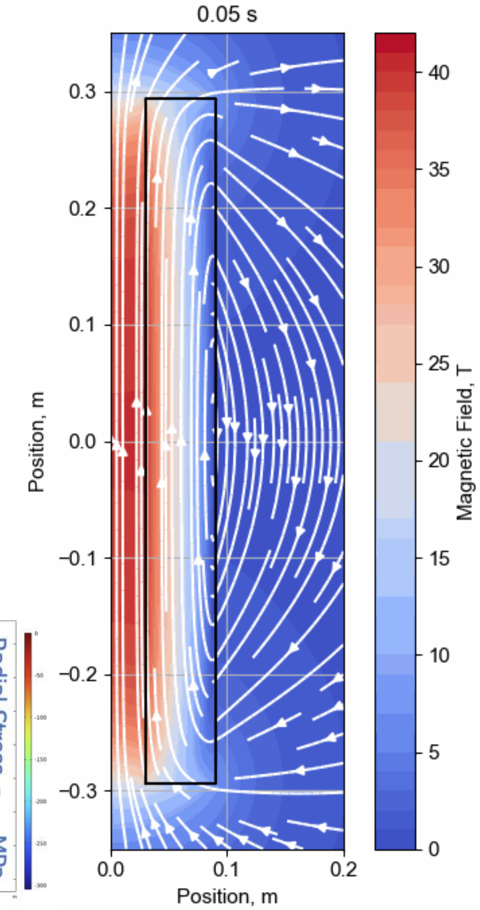
A. Dudarev, CERN







B. Bordini, CERN



T. Mulder, CERN

B. Bordini, CERN

Strong connection to HTS magnets for science

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

CERN