# Accelerator R&D for Future Colliders

T. Pieloni

With material from: L. Bottura, L. Rivkin, B. Auchmann, M. Seidel,  M. Calvi, M. Koratzinos, A. Ballarino, C. Senatore

Swiss Accelerator Research and Technology

www.chart.ch

# Outlook

- Landscape
- Magnets R&D:
  - Low Temperature Superconductors LTM
    - Limits of Nb3SN
    - Global effort, Cross-cutting activities
    - Epoxy Example
  - High Temperature Superconductors HTS
    - HTS developments for HFM
    - Material studies
    - Ondulators
    - Hybrid Magnets program 17 T
- Beam dynamics: importance of modelling and design
  - SuperKEKB → modelling and understanding
  - Power efficiency during design and smart choices for operational scenarious
- Summary

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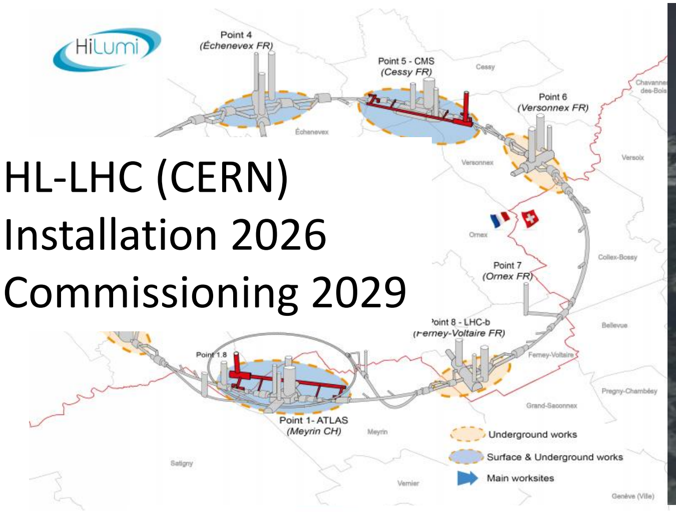
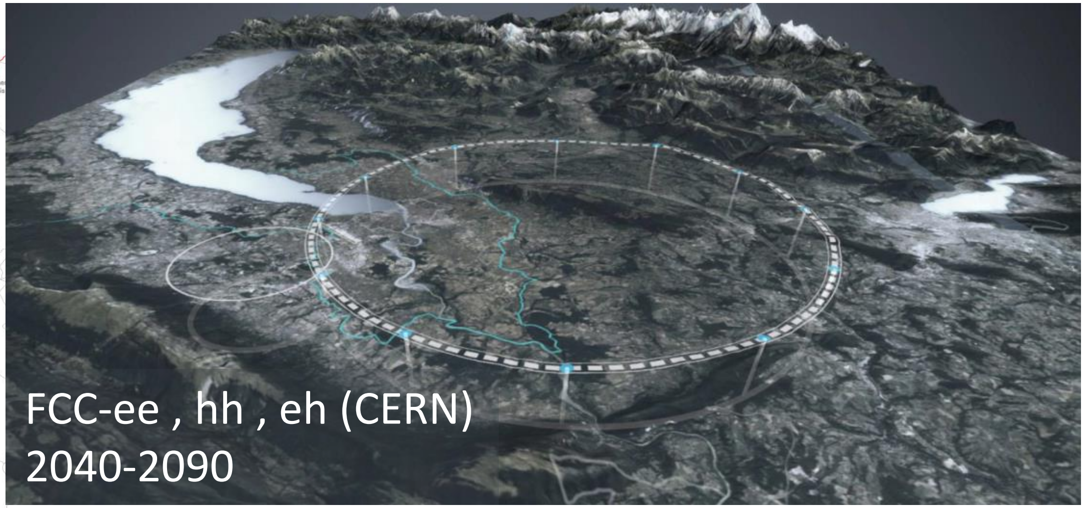
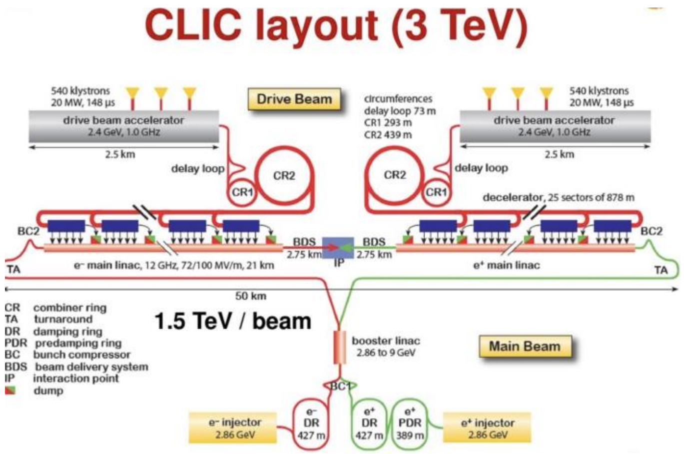
# HEP Landscape - Colliders

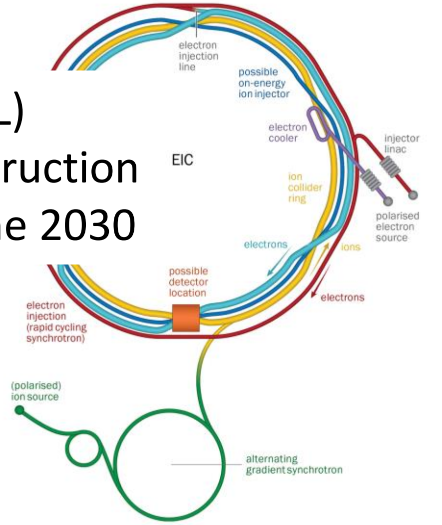



HL-LHC (CERN)
Installation 2026
Commissioning 2029



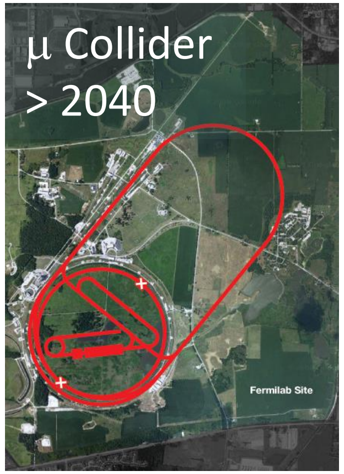
FCC-ee , hh , eh (CERN)
2040-2090



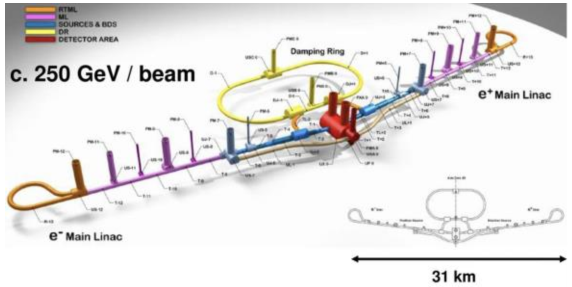

EIC (BNL)
In construction
CD4 June 2030

SppC (IHEP)
> 2040




µ Collider
> 2040

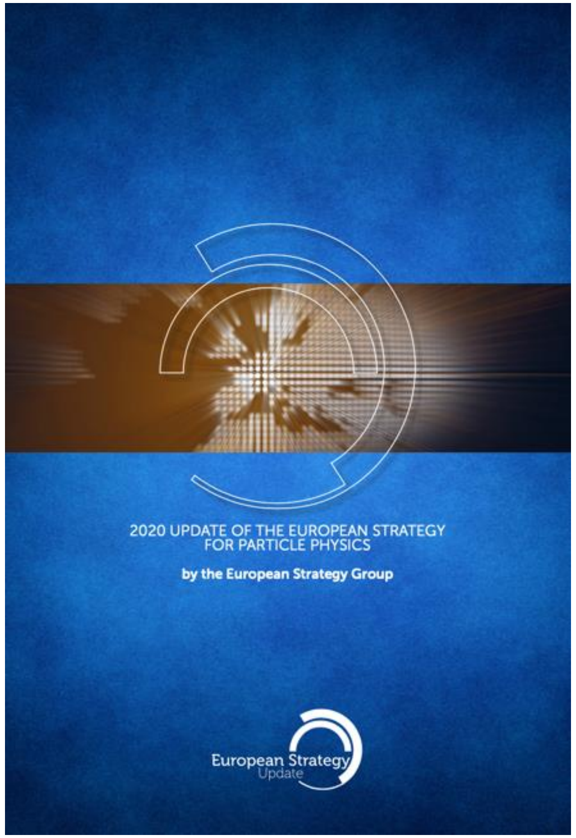
ILC



# 2020 Update of the European Strategy for Particle Physics

- ***"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV*** and with an electron-positron Higgs and electroweak factory as a possible first stage. "
- ***"The technologies under consideration include high-field magnets, high-temperature superconductors***, plasma wakefield acceleration and other high-gradient accelerating structures, **bright muon beams**, energy recovery linacs.

  The European particle physics community must intensify accelerator R&D and sustain it with adequate resources.




http://cds.cern.ch/record/2721370

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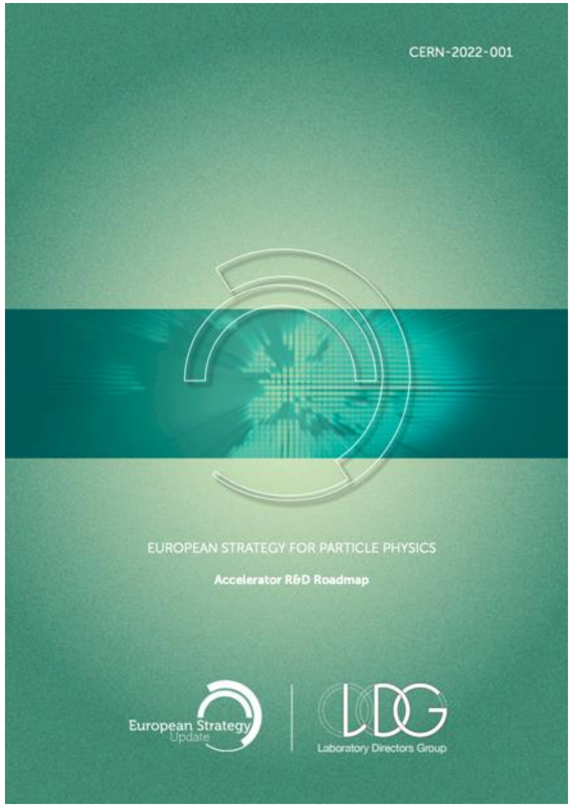
- ***A roadmap should prioritise the technology,*** taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry.
- ***Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes."***




https://arxiv.org/abs/2201.07895

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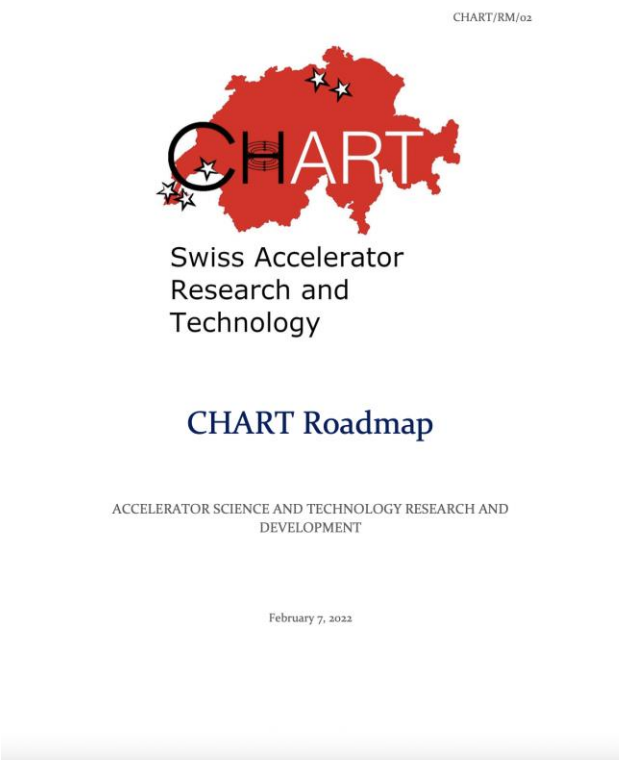
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CHART

Swiss Accelerator Research and Technology

CHART Roadmap

ACCELERATOR SCIENCE AND TECHNOLOGY RESEARCH AND DEVELOPMENT

February 7, 2022

https://chart.ch/wp-content/uploads/2022/09/220207_CHART-Roadmap.pdf

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# The physics landscape

| | | Dipoles | Quadrupoles | Undulators/Wigglers | Detectors | Field (T) |
|---|---|---|---|---|---|---|
| Higgs Factories | FCC-ee | | IR Quad | | × | < 3 T |
| | CEPC | | IR Quad | | × | < 5 T |
| | ILC | × | × | × | × | < 2 T |
| | CLIC | | | × | × | < 2.5 T |
| Energy Frontier | FCC-pp | × | × | | | 16 T -20 T |
| | SppC | × | × | | | 12 T- 24 T |
| | Muon Colliders | × | × | | | Solenoids > 10 T-20 T |

Magnets represent ~70% of a collider cost



Cortesy of A. Ballarino

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Higgs Factories

Energy Frontier

High Field Magnet Technology: Low Temp and High Temp Superconductors



Cortesy of A. Ballarino

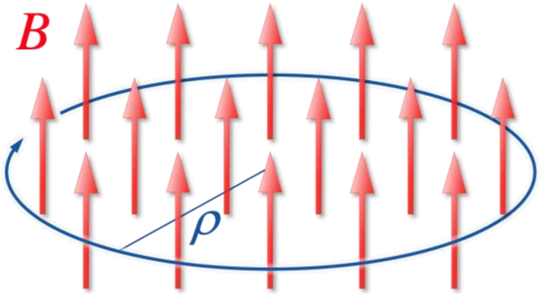
# High field magnets: dipoles

Beam energy

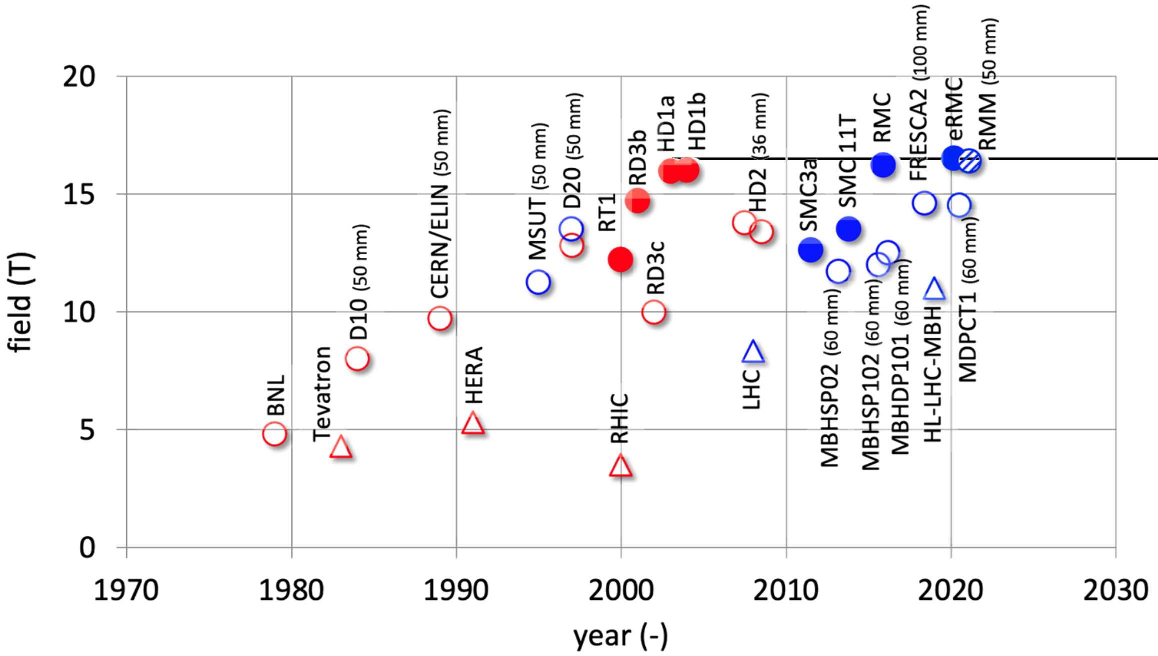
Bending radius

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

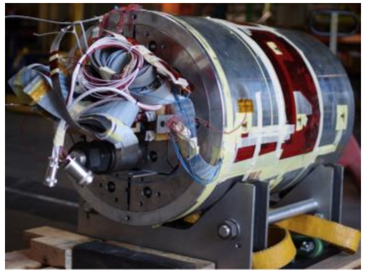
Dipole field

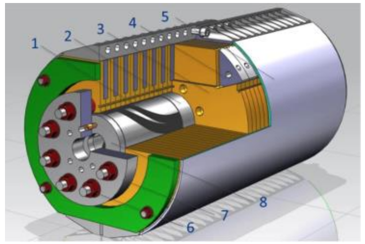



This is the reason for the steady call for **higher fields** in accelerator magnets

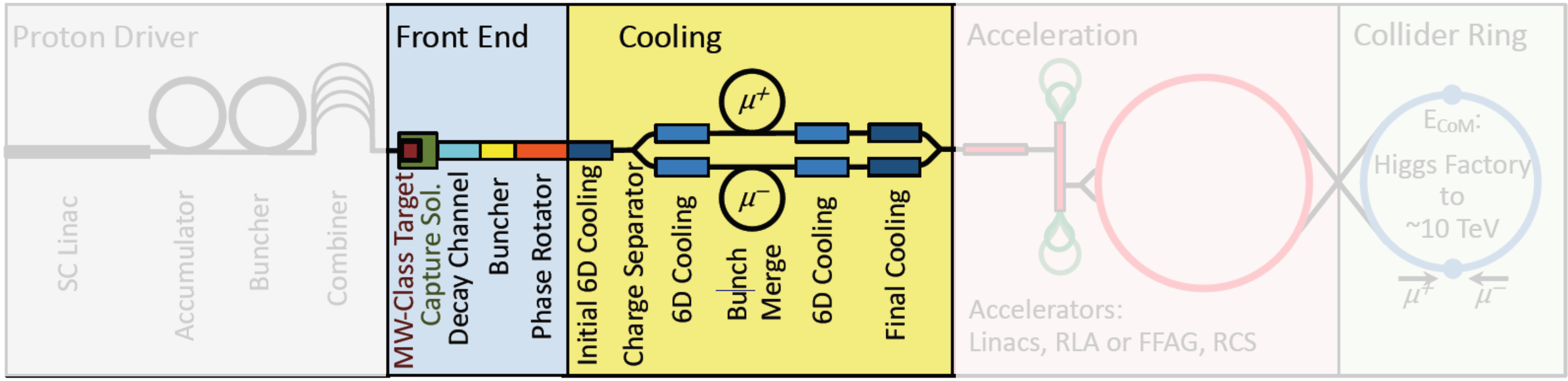


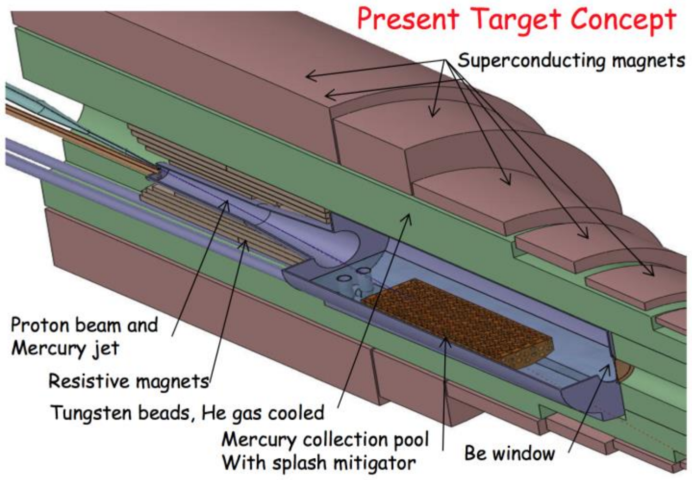

Upper limit of LTS ($Nb_3Sn$)



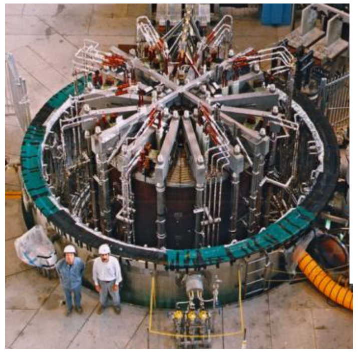


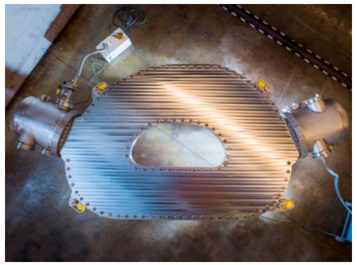

# High field magnets: solenoids (Muon Collider)

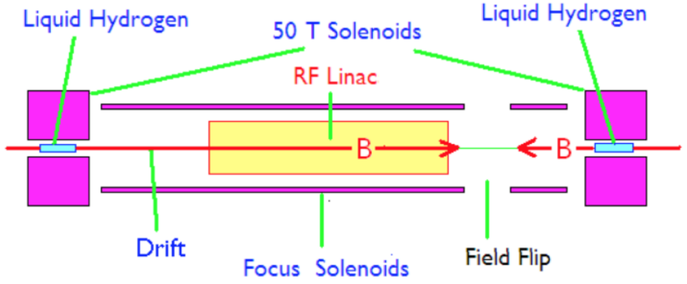


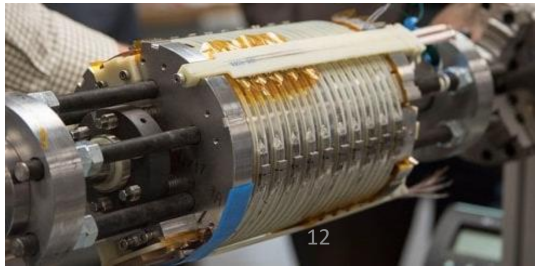

20 T, 150 mm, 100 kW

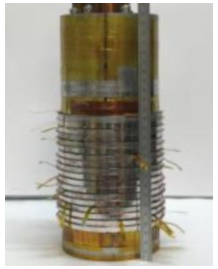






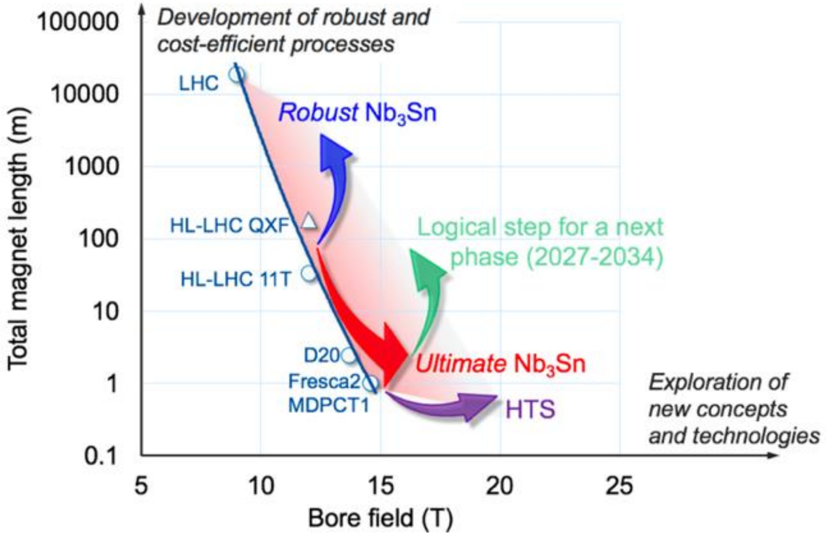

30…50 T, 50 mm





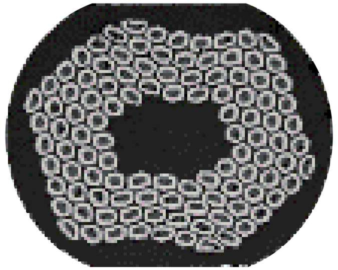
# Goals of Magnets developments

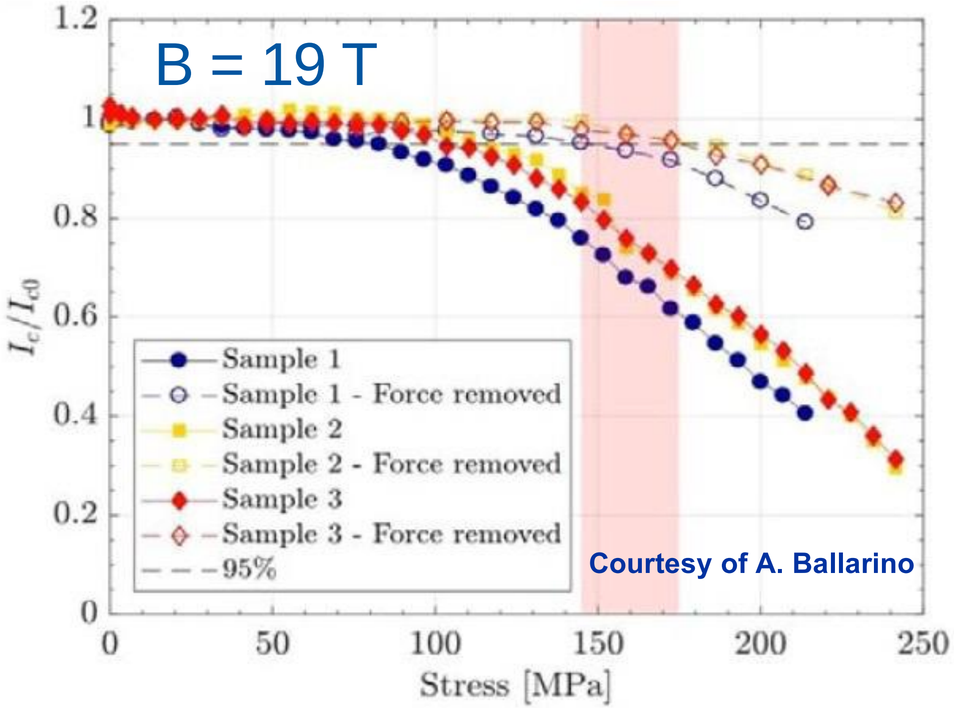
1. Demonstrate Nb3Sn magnet technology for large scale deployment, pushing it to its limits in terms of maximum field and production scale.
   - The effort to quantify and demonstrate Nb3Sn ultimate field comprises the development of conductor and magnet technology towards the ultimate Nb3Sn performance.
   - Develop Nb3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing and cost reduction.
2. Demonstrate the suitability of HTS for accelerator magnets, providing a proof-of-principle of HTS magnet technology beyond the reach of Nb3Sn.



# $Nb_3Sn$ Conductor Challenge

- Nb3Sn critical current $I_c(B,T,\varepsilon)$ is strain dependent.
- Stresses above 150 MPa lead to:
  - copper plasticization that 'freezes' strain permanently.
  - filment breakage that further degrades performance

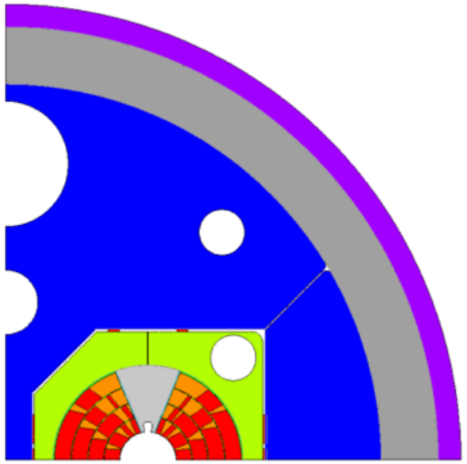





- $\sigma_{irr}$ = 145–175 MPa

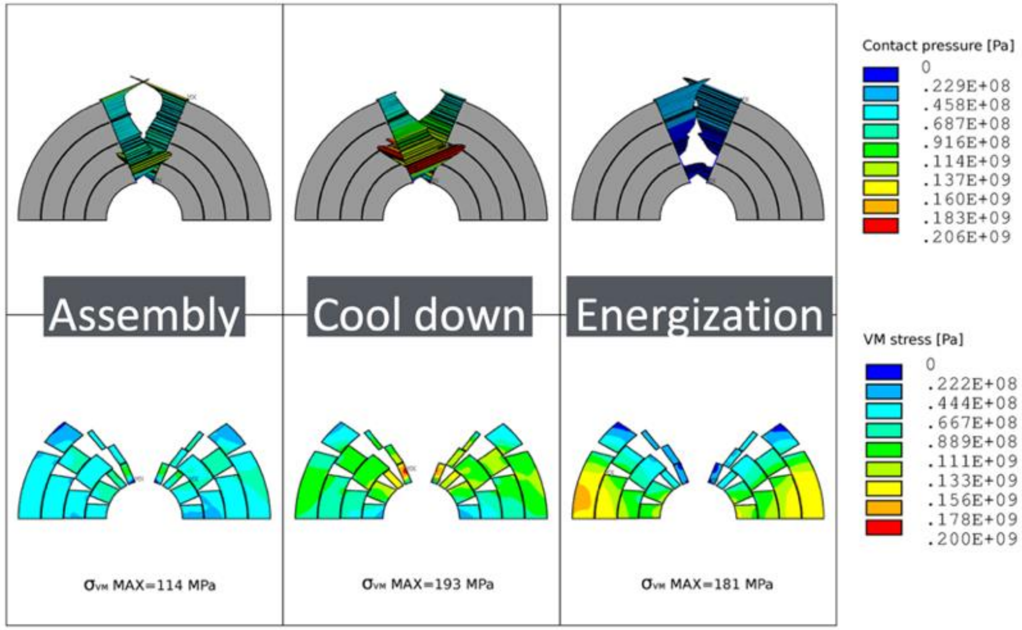
- $I_c/I_{c0}$ @ 150 MPa
  → 16 % - 28 %

# $Nb_3Sn$ High Field Magnet Mechanics Challenge



Full pre-stress: a lesson learned from the Nb-Ti era:

- Keep coils under compression at all stages of operation
  → avoid stick-slip motion.
  - Forces scale quadratically with field. For 16 T dipole,
    forces equivalent of 1.5 kt/m pull coil-halves apart.
  - 10 μm abrupt movement is enough to cause quench.
- Need to limit stress on $Nb_3Sn$!






[S. Farinon et al., in M. Benedikt et al., *FCC Conceptual Design Report,* 2019.]

# Focus Area $Nb_3Sn$ Conductors and Magnets

Reaching ultimate $Nb_3Sn$ performance (towards 16 T) is aided by innovation and new approaches in:

## Conductor Technology

- New $Nb_3Sn$ wire structures with enhanced mechanical strength
- Higher $J_c$ (increased margins)
- Industrialization of improved superconductors.

**$Nb_3Sn$ Conductor R&D**

**Novel Design Concepts**

## Magnet Technology

- Coil designs and structures with minimal stress in high-field regions.
- Low-prestress designs, allowing for some moderated movement.
- Reinforced coils; Stress-management eliminates pre-stress.

# Ongoing projects:
# $Nb_3Sn$ Conductor

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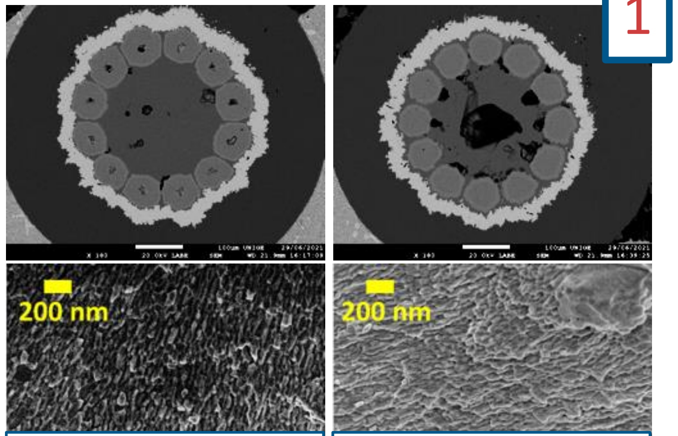
## Internal Oxidation in prototype multifilamentary wires

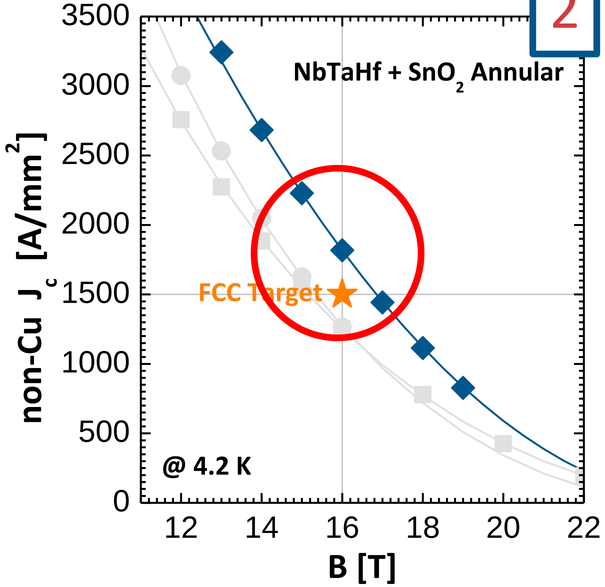
1



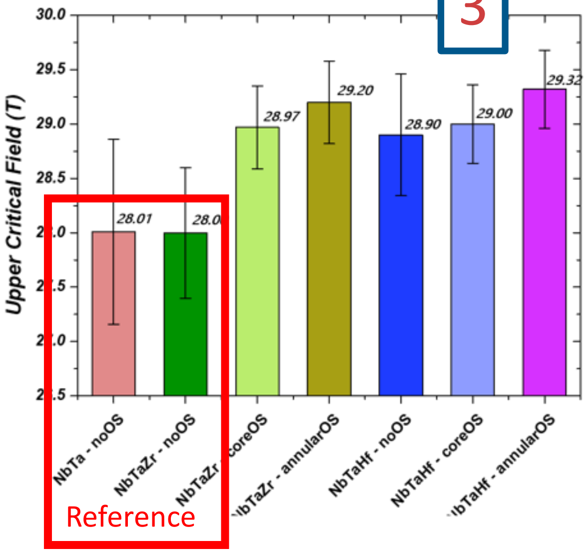

Average grain size ~ 47 nm

Average grain size ~ 45 nm

2




3




Larger billets under development

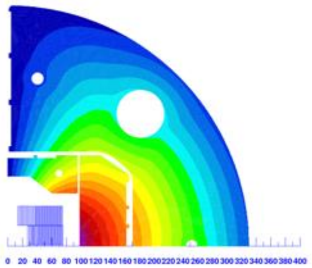
## Pushing $Nb_3Sn$ towards its ultimate performance

| | |
|---|---|
| 1 | Refinement of the grain size: 100 nm → 50 nm |
| 2 | Large increase of the layer $J_c$ → exceeding the FCC target |
| 3 | Enhancement of $B_{c2}$ by > 1 T → improved in-field performance |

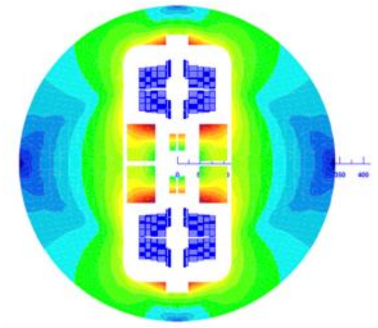
Courtesy of C. Senatore

# $Nb_3Sn$ Magnet Projects Ramping Up

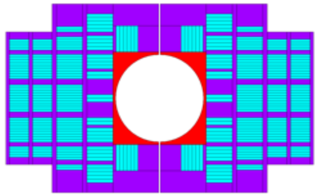
Development of technological steps towards 16-T block coil $Nb_3Sn$ magnets with stress management: conceptual design has started.



Collaboration agreement for the development of technological steps towards 16-T $Nb_3Sn$ magnets with low-prestress common coil structure: preparation of workshops for the implementation phase.



Collaboration agreement for the development of technological steps towards 16 T common coil $Nb_3Sn$ magnets with stress management: collaboration agreement is finalized. First test 14.5-15 T in 2025/26.



# Cross-Cutting Activities

- Numerical models, materials, protection techniques, cryogenics, diagnostics, magnetic measurements, etc. are all challenging applications of their respective engineering sciences.
- Involving more labs as well as academic and industrial partners promises enhanced efforts, competency and cross-pollination.
- Only a steady technical exchange can ensure that a magnet engineer's challenges motivate research into possible solutions, and that new developments inspire magnet designs.
- Open R&D Line Fora have started – HFM a dynamic research network!
- HFM R&D has suffered from slow turnaround and late feedback on technological choices.
- Magnet R&D developed as a [~~succession~~ funnel] of meaningful fast-turnaround demonstrations, ranging from non-powered material […] samples […] towards ultimate specifications. In this way, new technologies can be tested under realistic conditions at the earliest possible stage, the smallest relevant scale and cost, and the fastest pace."

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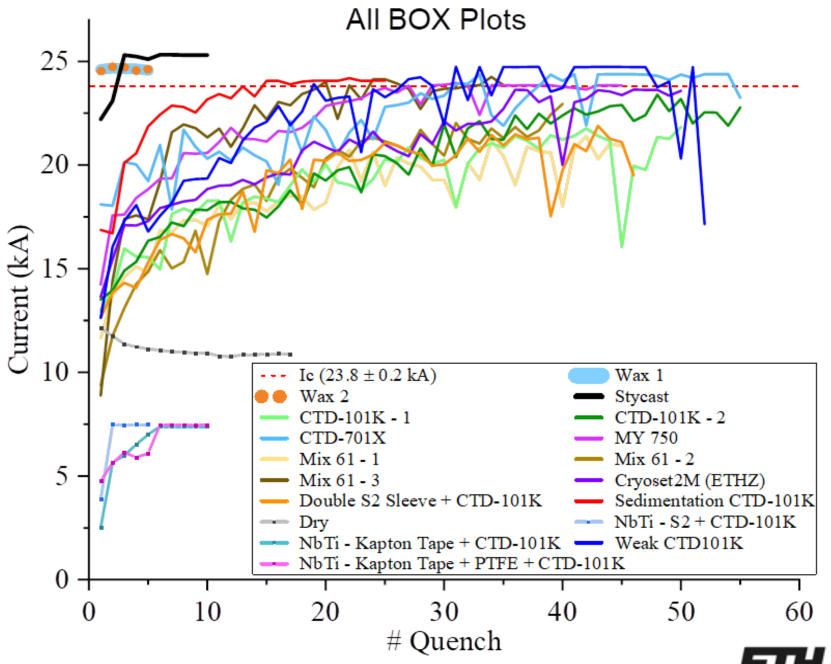
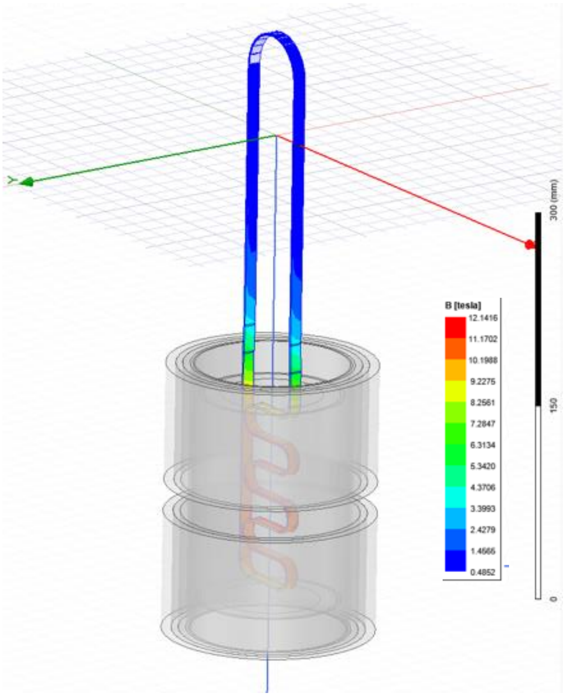
# BOX Program example

Traditional superconducting **magnet design ensures magnet can survive quenches** (transition between normal and the superconducting state)




Pictures by M. Daly, S. Sidorov, S. Otten

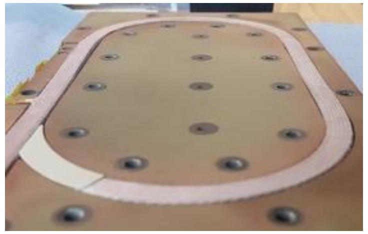
***BOX*** (BOnding eXperiment) program with university of Twente has shown a wide variety of results, from complete conductor ***degradation (no impregnation)*** to substantial ***training (epoxy)*** to ***no-training (wax, Stycast),*** with ***18 BOX samples*** successfully manufactured and tested in 2 years.

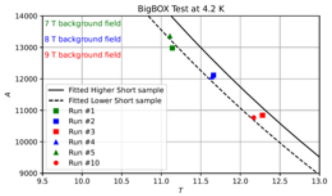
**Clear evidence of different training quench behaviours depending on impregnants (epoxy used to guarantee helium flow in cables). Multi disciplinary effort (material, magnet design, cryogenics and engineering)**

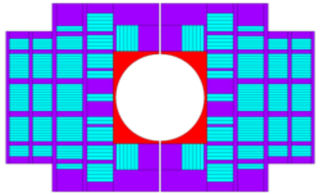
# Feedback to Magnet Programs

PSI's BigBOX: a 13-turn stress-managed racetrack.

- No training with 12.3 T coil field, 150 MPa coil stress at BNL's DCC17 facility.





[Courtesy D. Araujo et al]

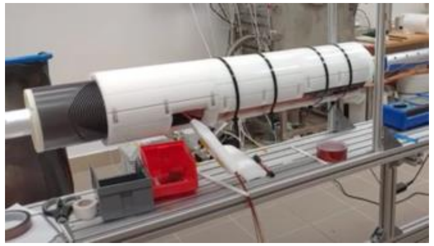
LBNL's wax impregnated sub-scale (5 T) CCT.

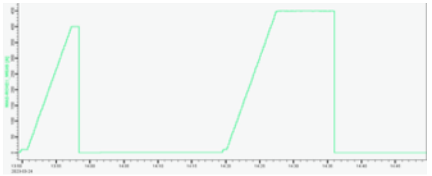
- First $Nb_3Sn$ CCT without training.
- Follow-up magnet and test planned.

[Courtesy J.L. Rudeiros Fernandez, LBNL]

Wigner Inst. / CERN collaboration on SuShi septum for FCC-hh

- Wax impregnated CCT required no training to nominal current.

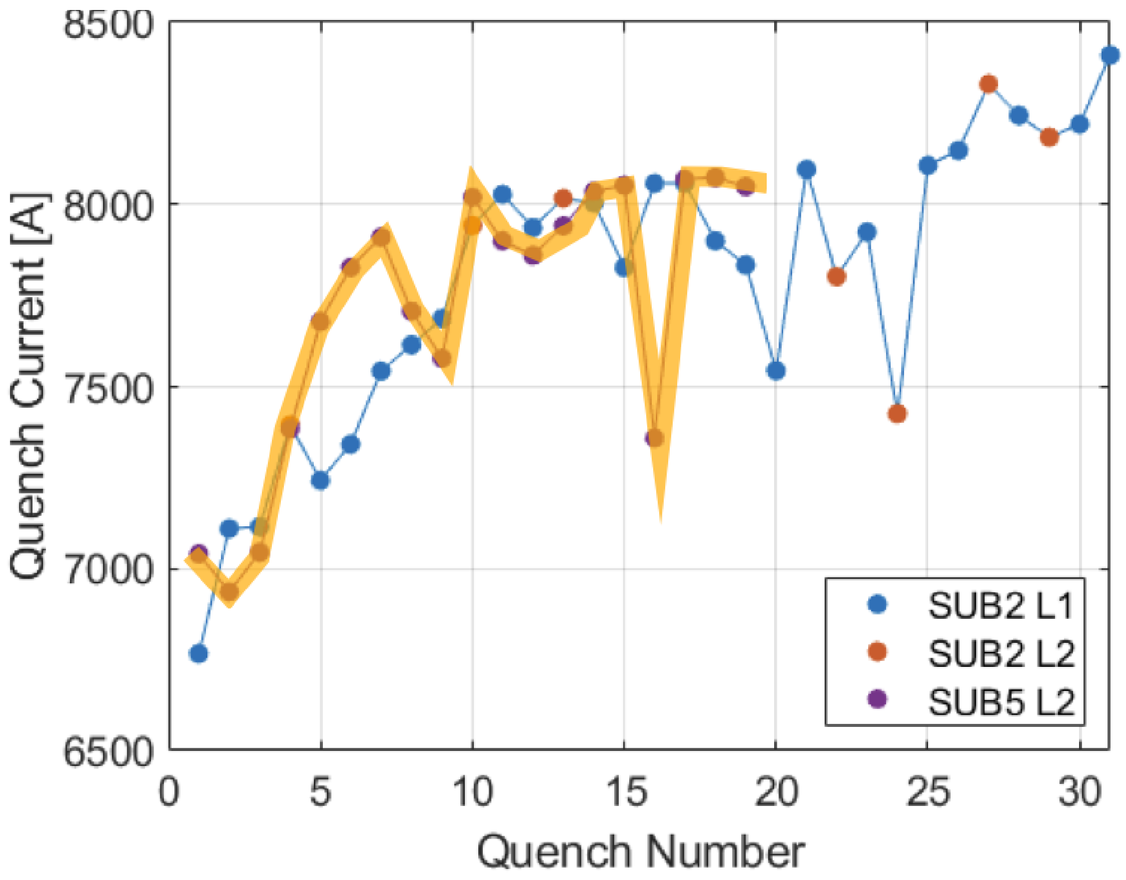




[Courtesy D. Barna et al., Wigner Institute]

# US Magnet development

**1st $Nb_3Sn$ CCT coil impregnated with wax**




⇒ ***no quench of inner wax coil!***
***All quenches were in outer coil***

*Curtesy of Soren Prestemon*
*US Magnet Development Program LBNL FCC week Presentation*

*Motivated by "Box" results: Daly et al 2022 SUST **35** 055014*

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LTS and HTS Enabling Technology

High field beyond Nb3Sn

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| CLIC | | | × | × | < 2.5 T |
| FCC-pp | × | × | | × | 16 T -20 T |
| SppC | × | × | | × | 12 T- 24 T |
| Muon Colliders | × | × | | × | Solenoids > 10 T-20 T |

Higgs Factories: HTS Beneficial Technology

Energy Frontier: LTS and HTS Enabling Technology

Exploration at lower fields: possible reduction of cryo power, lighter magnets, more efficient optics design…?

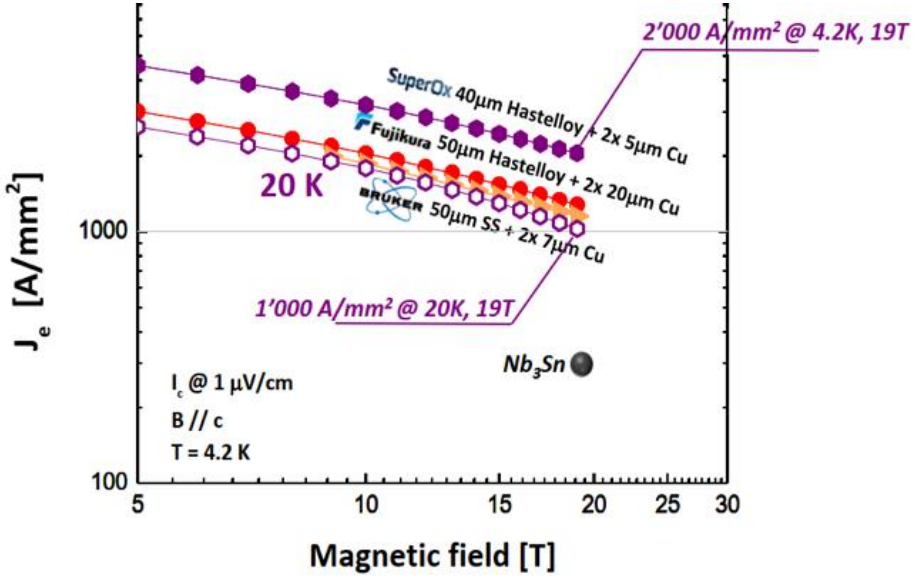
# Advantages of HTS

- **Very high in-field current density at low temperature**
  - **Enabling technology** for magnets with fields **> 16 T**
  - **No magneto thermal-thermal instability**, e.g. no flux jump (an issue to be treated for future high-field $Nb_3Sn$ accelerator magnets);
  - **Higher temperature margin,** e.g. capability of tolerating a rise of temperature due, for instance, to decay particles

- **Operation at higher temperature**
  - **Low(er) field magnets** operated at temperatures higher than liquid helium (dry-cooling, He gas cooling, $LH_2$, $LN_2$): operational **energy saving**
  - High specific heat, i.e. **high thermal stability** (MQE) – the issue comes once the quench has generated (detection and protection)
  - Higher **temperature margin** to the benefit of an easier cryogenic control

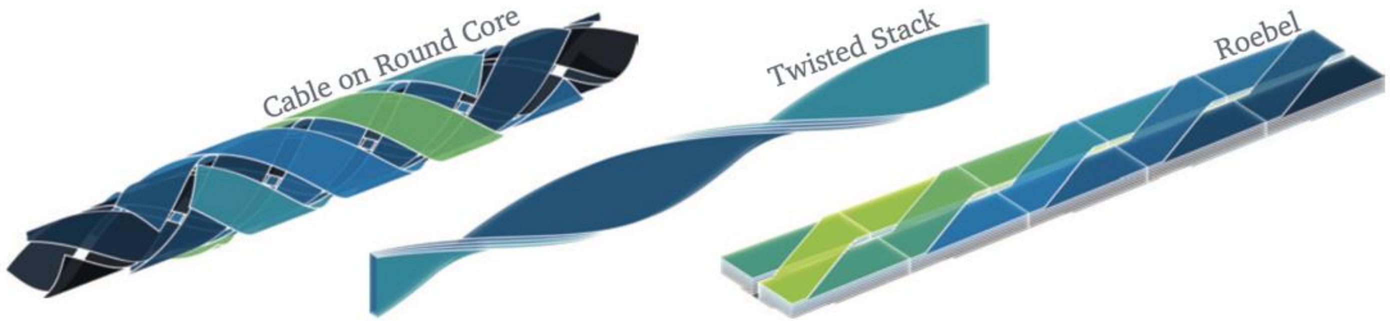
# Focus Area HTS Conductors and HFMs

- In Europe, we focus mainly on ReBCO tape, due to its availability from multiple suppliers and excellent performance.
- Drawbacks are related to
  - limited shear-strength,
  - large magnetization effects that impact ramp losses and field quality,
  - large anisotropy,
  - unit lengths, uniformity, bending radius, etc.
- Other HTS-related challenges pertain to magnet protection (slow-rising voltage signal, large temperature margins).

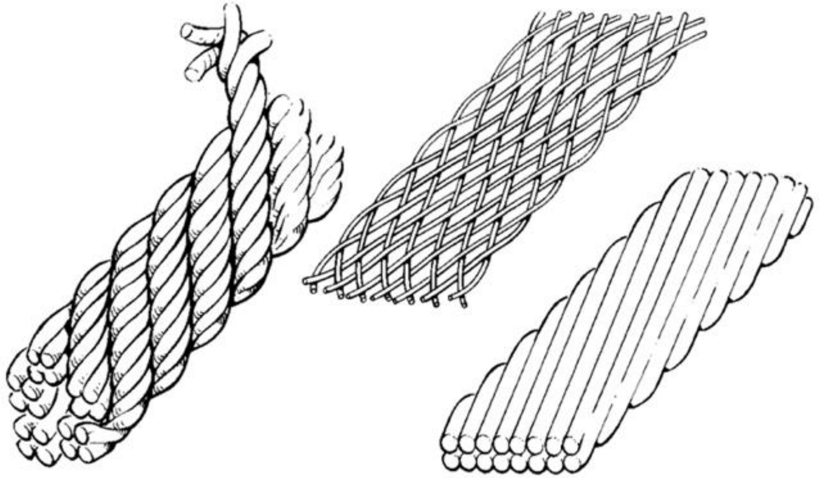



Engineering current density ($J_e$) in magnetic field perpendicular to substrate for selected conductors (C. Senatore, UNIGE)

# Back to the Future …




ReBCO magnet technology is at the stage of LTS in the 1970ies.



[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. UTwente, 2016.]
[M. Wilson, Pulsed Superconducting Magnets' CERN Academic Training May 2006]

# Focus Area HTS Conductor and HFMs

- “Consideration of only engineering current density would suggest that magnetic fields in the range of 25 T could be generated by HTS“
- “… performance of HTS in the range 10 to 20K has reached values of Jc well in excess of 500 to 800A/mm2, i.e., the level that is required for compact accelerator coils. […] it would open a pathway towards a reduction of cryogenic power, [and] a reduction of helium inventory (e.g., dry magnets)” [LDG Roadmap on High-Field Magnets, p. 33]
- We are building a new body of knowledge; today we do not know whether we can keep all of the above promises.
- Cryogenics, magnetics, mechanics, protection will be ever more tightly integrated – collaboration and communication, i.e., systems thinking and systems engineering will be mandatory.

**HTS Conductors**

- Improvement of ReBCO for low magnetisation, mechanical robustness, and reduced anisotropy
- Development of practical HTS cables
- Development of alternative HTS superconductors such as IBS

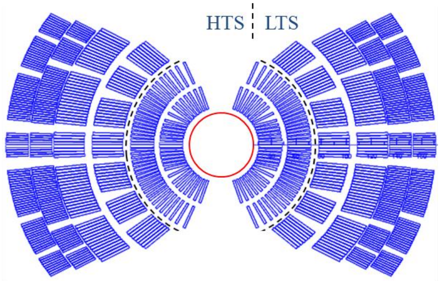
**HTS Magnets**

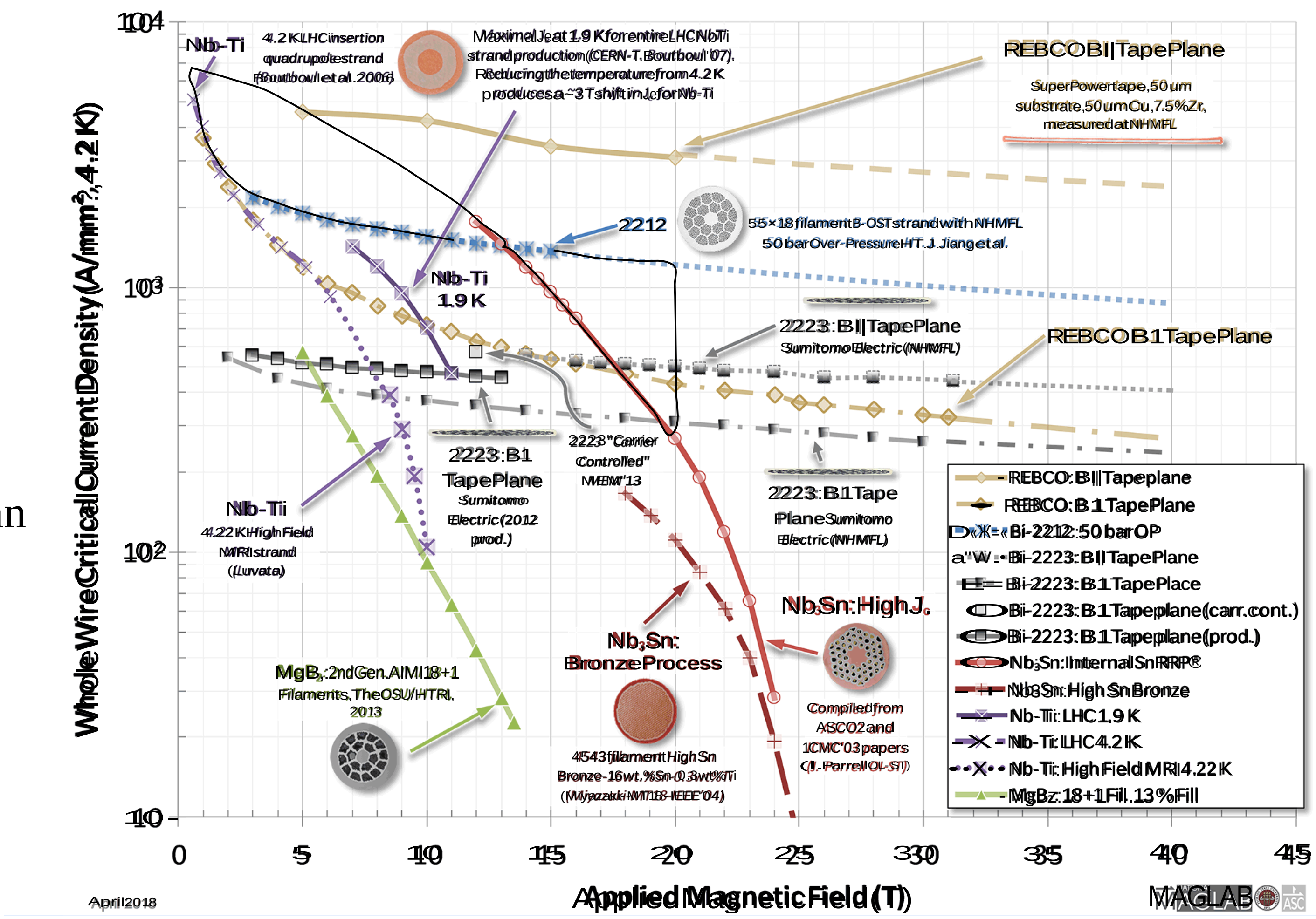
- Development of stand-alone HTS demonstrator magnets
- Subscale tests in background field and development of hybrid LTS/HTS magnets

# Hybrid Magnets: HTS + LTS superconductors & magnets

- HTS materials outperform LTS at higher field, but under-perform at low field

=> hybrid magnets are most efficient



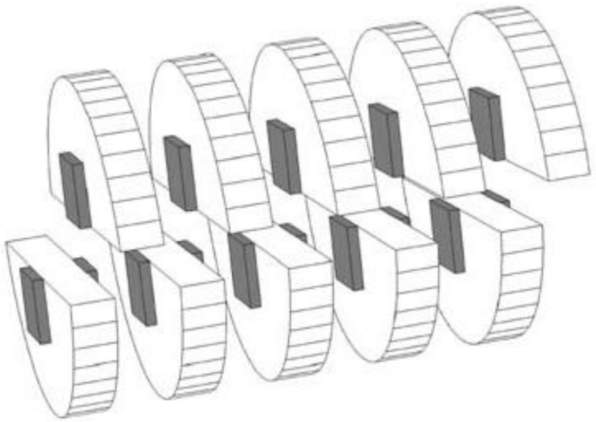



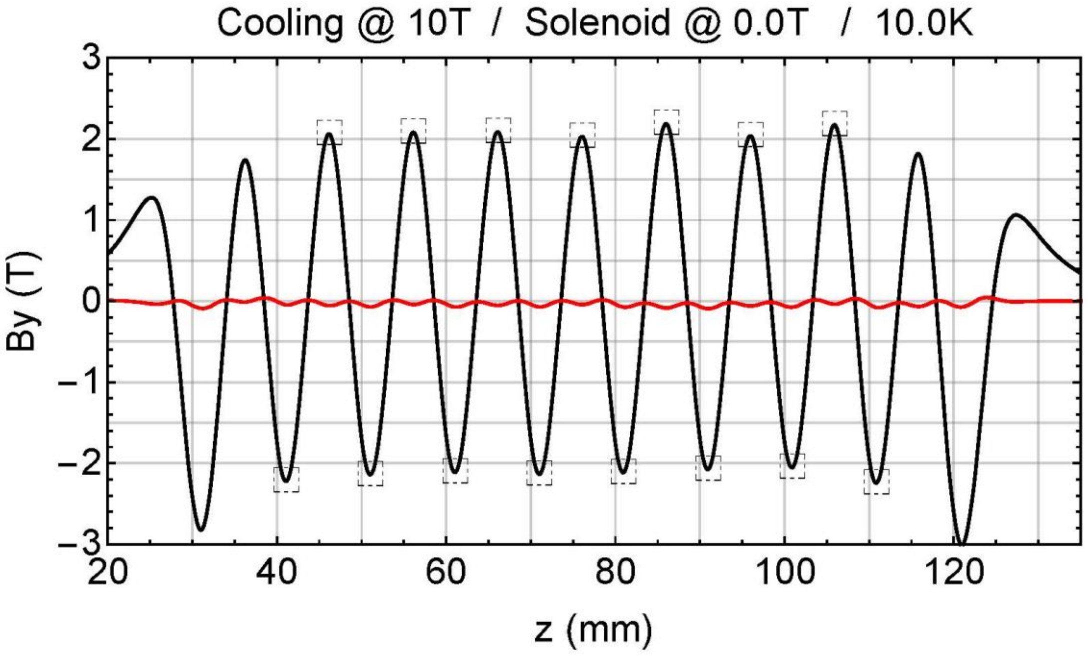

***Magnet Development Program seeks to address questions such as:***

- What is the nature of accelerator magnet training? Can we reduce or eliminate it?
- What are the drivers and required operation margin for $Nb_3Sn$ and HTS accelerator magnets?
- What are the mechanical limits and possible stress management approaches for $Nb_3Sn$ and 20 T LTS/HTS magnets?

# HTS superconducting magnet technology undulators synergy

Using bulk HTS material: has reached 2 Tesla for very short period magnets
Put the structure into a solenoid magnet, cool it and trap the field





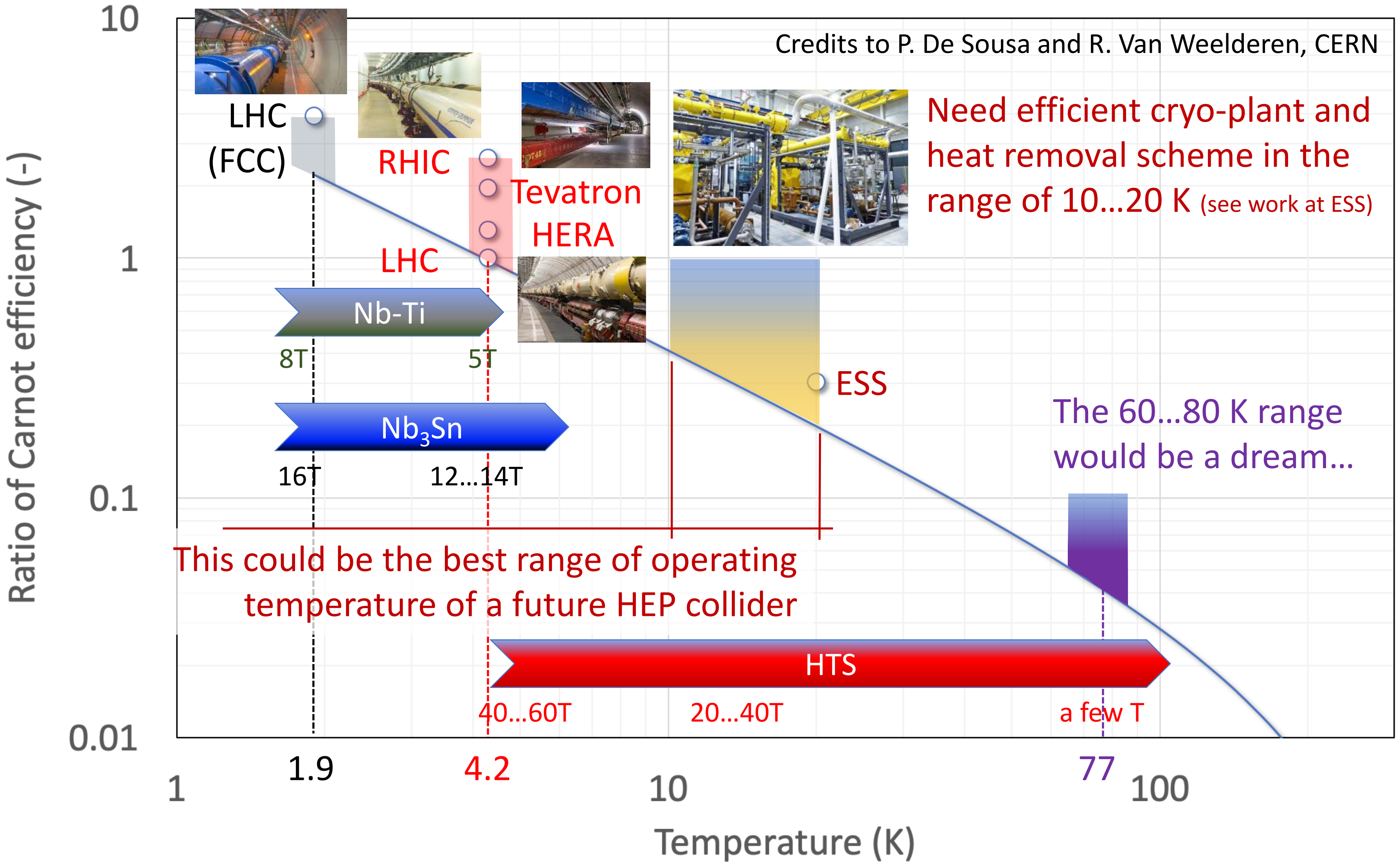


Use of HTS material in different sectors increases our knowmledge

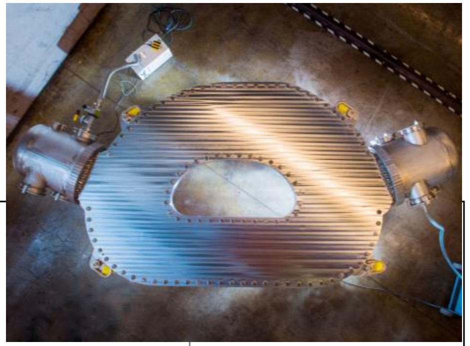


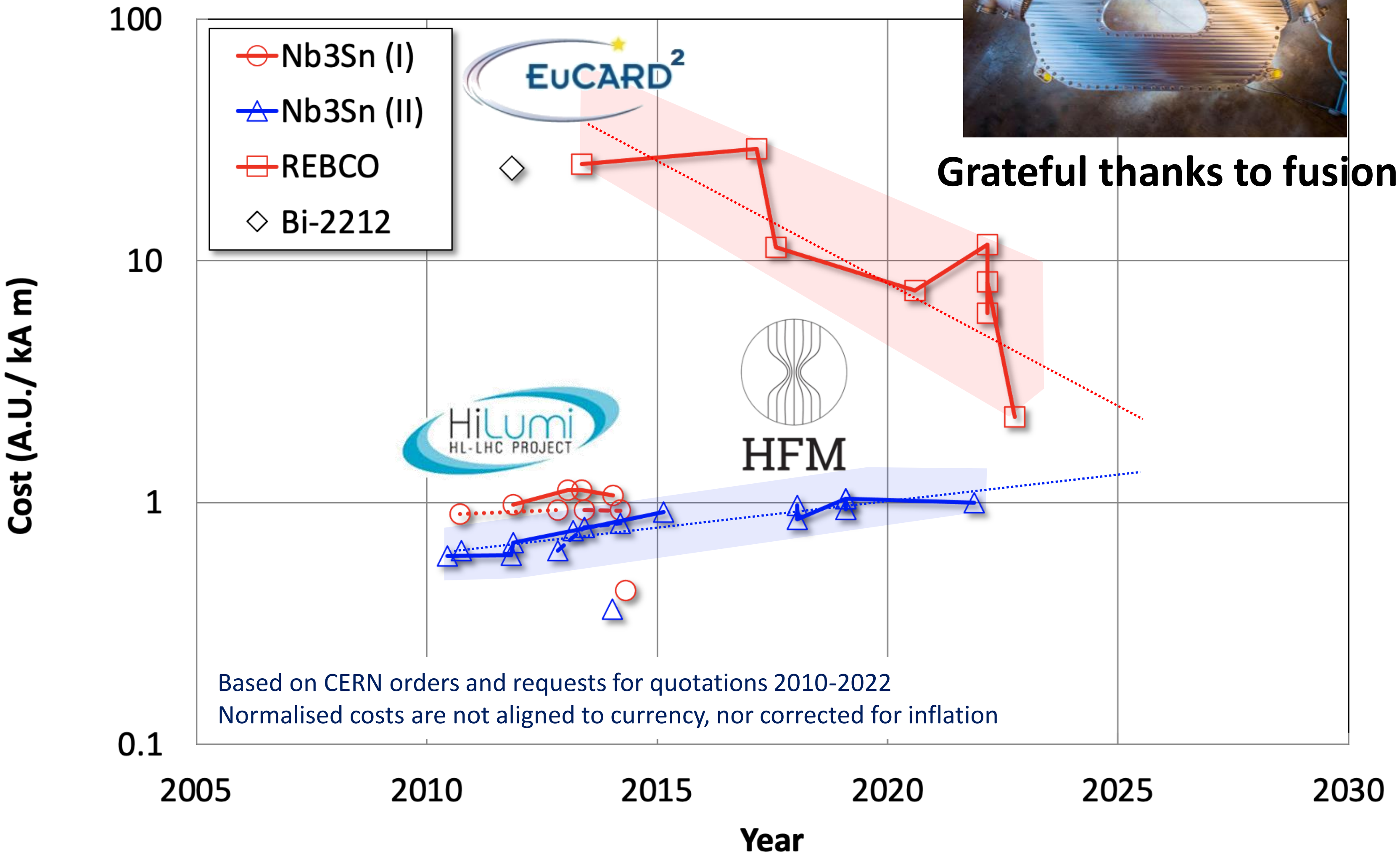
**Curtesy of M. Calvi PSI**

# Energy efficient cryogenics



# Conductor cost






**Grateful thanks to fusion !**

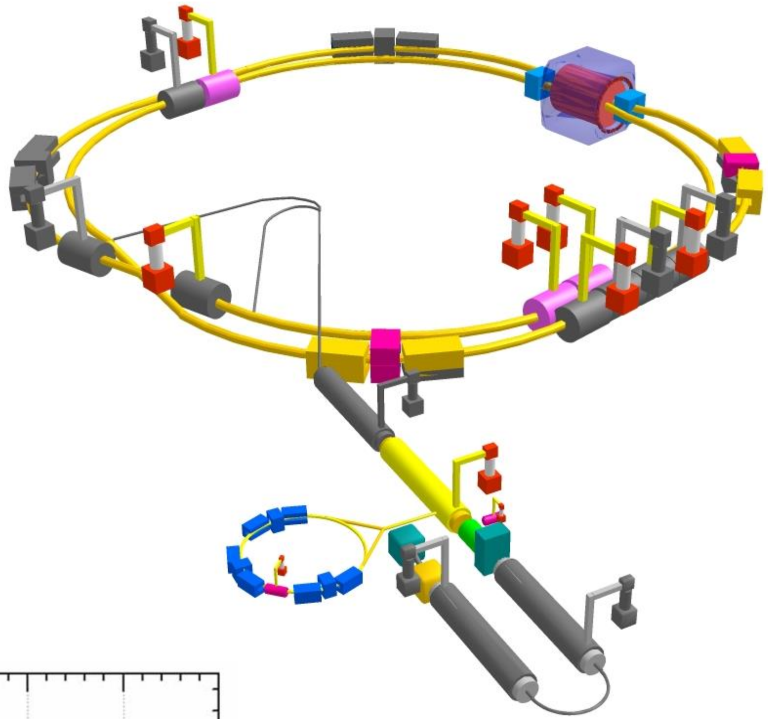
Mangnets represents ~70% of collider cost

# Outlook

- Landscape
- Magnets R&D:
  - Low Temperature Superconductors LTM
    - Limits of Nb3SN
    - Global effort, Cross-cutting activities
    - Epoxy Example
  - High Temperature Superconductors HTS
    - HTS developments for HFM
    - Material studies
    - Ondulators
    - Hybrid Magnets program 17 T
- Beam dynamics: importance of modelling and design
  - SuperKEKB → modelling and understanding
  - Power efficiency during design and smart choices for operational scenarious
- Summary

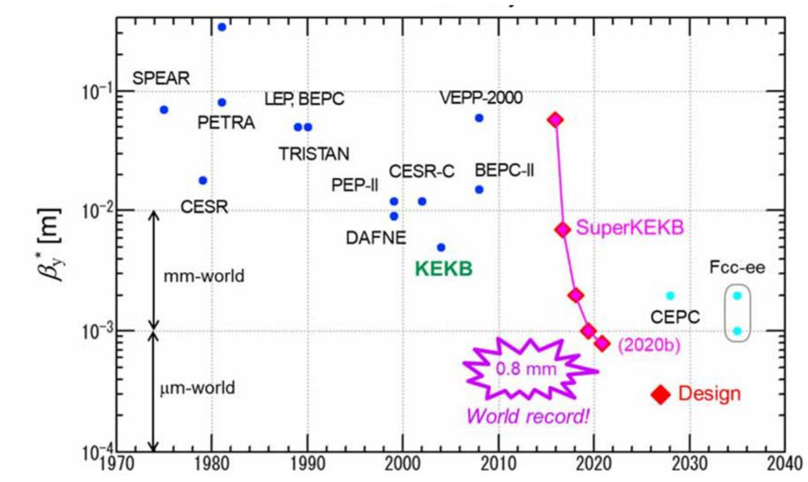
# Smarter Design and new paths

SuperKEKB*



Accelerator design defines the requirements, tollerances and possibly can give important input to the design of future magnets

- **Improve models to increase beam dynamics understandings** reproducing observations from existing machines (i.e. input models of material degradation SEY after huge beam losses)



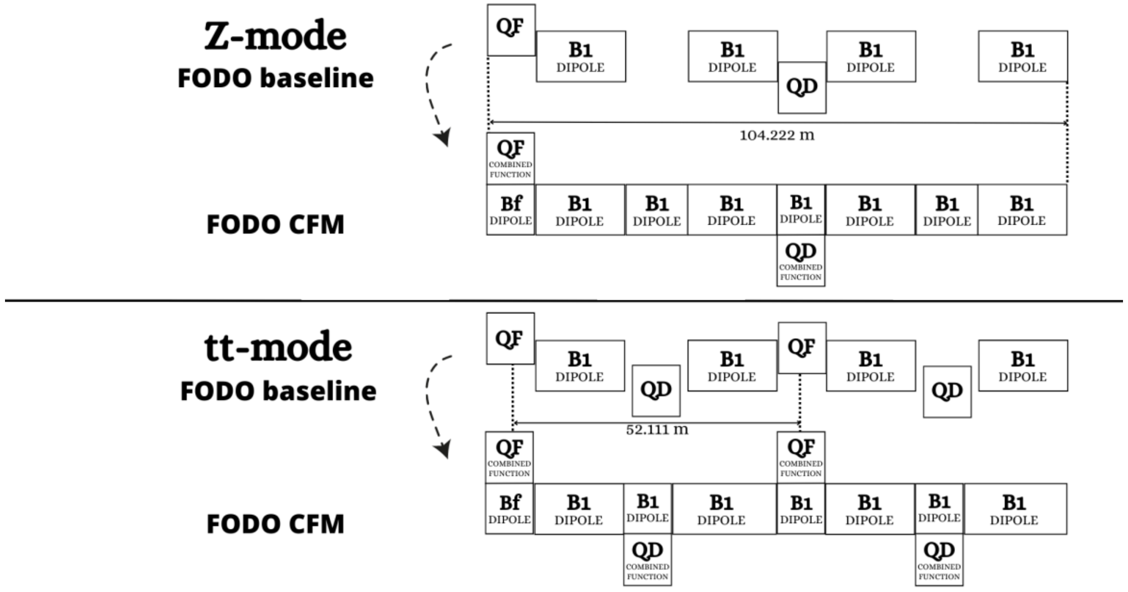

Critical to understand (not necessarily fix) Super KEKB luminosity versus current and 'fast beam loss' challenges!

# Smarter Design and new paths

Accelerator design defines the requirements, tollerances and possibly can give important input to the design of future magnets

- **Improve models to increase beam dynamics understandings** reproducing observations from existing machines (i.e. input models of material degradation SEY after huge beam losses)
- Study **alternative options** (i.e. HTS combined function magnets for colliders by C. Garcia talk yesterday)

**HTS combined function magnets lattice FCC-ee**




Cortesy Cristobal Garcia

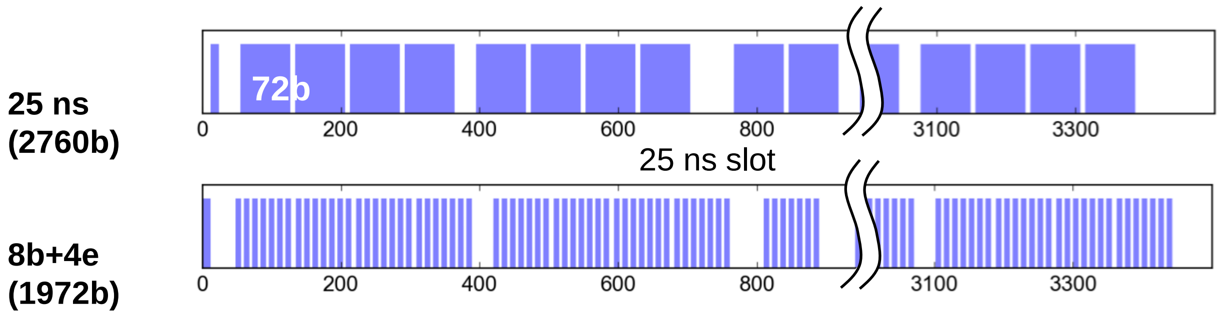
# Smarter Design and new paths

Accelerator design defines the requirements, tollerances and possibly can give important input to the design of future magnets

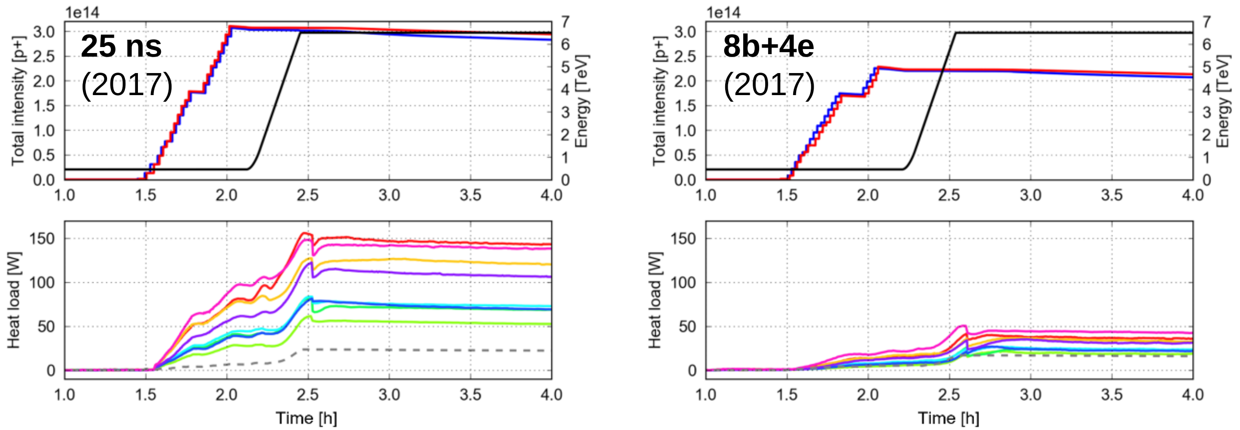
- **Improve models to increase beam dynamics understandings** reproducing observations from existing machines (i.e. input models of material degradation SEY after huge beam losses)
- Study **alternative options** (i.e. HTS combined function magnets for colliders by C. Garcia talk yesterday)
- Study **different operational scenarious** (i.e. electron cloud induced heat load reduction)

→Design to reach the goals but with a close contact to technology developments!

Electron Cloud heat-load studies




→ Successfully **tested** in the LHC in **2015** and **used in operation** in 2017




Cortesy of G. Iadarola, L. Mether

# Summary

- **The HEP landscape is very reach and now a clear goal is defined → High Field Magnets**
- **LTS→ fast and positive advancements 16 Tesla magnets seems more and more in reach!**
    - Re-thinking from material Nb3Sn, design, models, fast-turnaround of developments
    - Demonstrators testing in coming years
    - Scalability to large scale and robustness still needs to be proved
- **HTS → New technology advancing very fast but still with many un-knowns**
    - Material experience still very little
    - Magnets design has to be redefined
    - Very useful also for lower fields → more energy efficient
    - Cost and prove of principle still far
- **Collider design:**
    - We need to understand the present before moving to the future→ SuperKEKB
    - Close work with magnet people to define together the future magnet design and operational scenarious
    - A major re-thinking of the optics design and mode of operation is required

# Summary

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Fundamental ingredients: Interdisciplinary research, techinical exchange and coordinated network for fast turnaround of knowledge

# Material from FCC week

- Andrzej Siemko and Bernard Auchmann  High Field Magnets
- Soren Preston The US Magnet Development Program
- Amalia Ballarino HTS Developments
- Luca Bottura HTS for Accelerators Status, Needs and Perspective at the Applied Superconductivity Conference
- Marco Calvi

# BOX Program example

*A major factor in the design of large superconducting magnets is the problem of premature quenching, notably the 'training' effect, associated with the use of epoxy resin impregnants.*

*This paper draws attention to the existence of a simple but neglected solution to this problem. A review is given of a series of tests carried out in 1968–71 which showed that such effects were considerably reduced in the case of solenoid and quadrupole coils impregnated with wax or oil, allowing currents at least 85–90% of the critical value to be achieved consistently and reliably. The tests included a full scale prototype quadrupole (9 cm bore, 40 kG maximum field).*

*A discussion of the mechanical and thermal properties of such coils indicates no reason to doubt their long term reliability, and the adoption of this solution for operational magnets is recommended.*

**A solution to the 'training' problem in superconducting magnets**

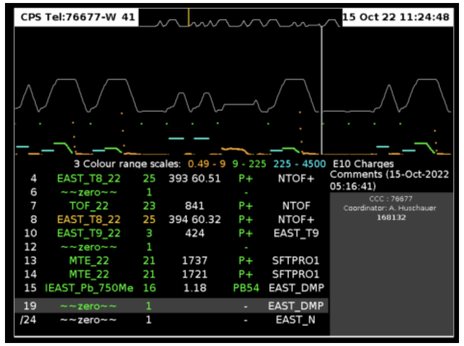
**P. F. Smith and B. Colyer**

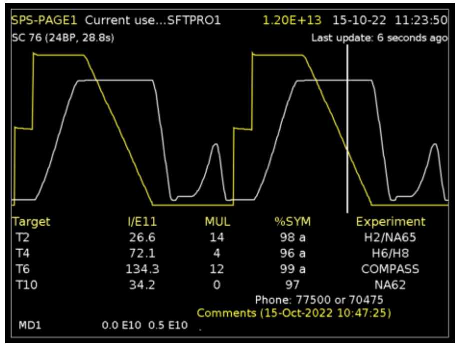
1975 review paper of 1968-71 results recommends wax or oil impregnation

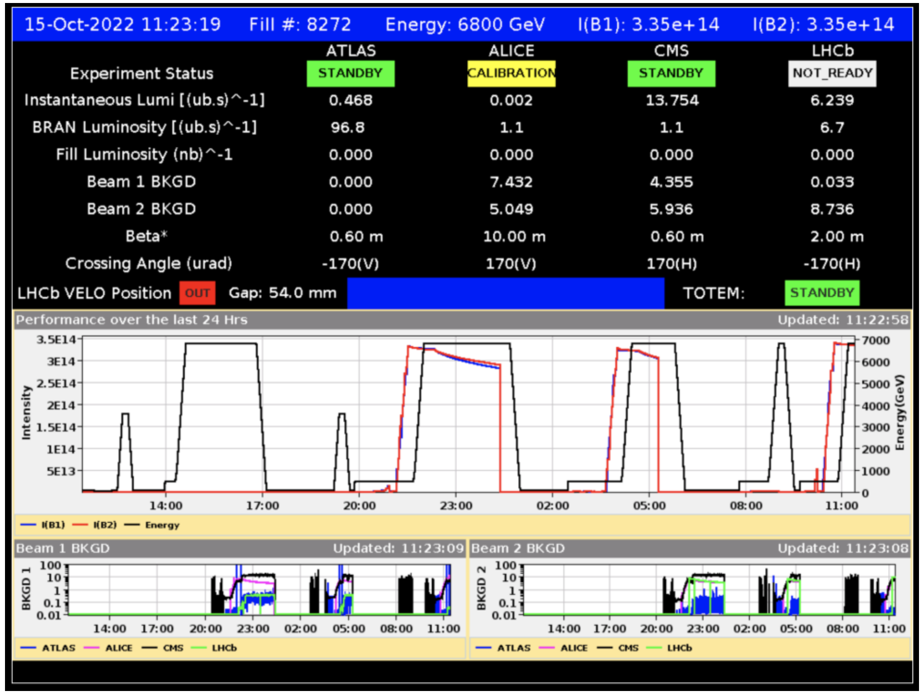
Modern take on wax: combination with stress-management extends the validitity of the approach.

# 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



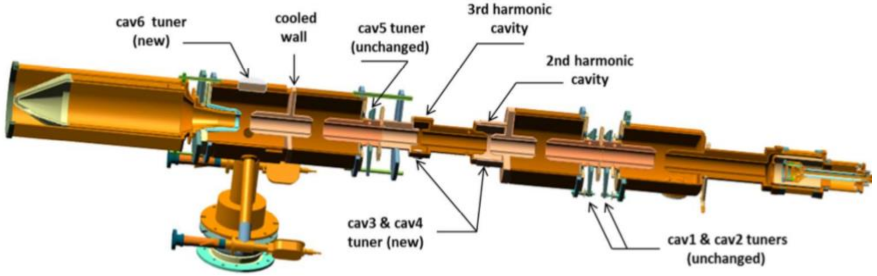



# FCC-ee R&D Examples

## efficient RF power sources
(400 & 800 MHz)

I. Syratchev

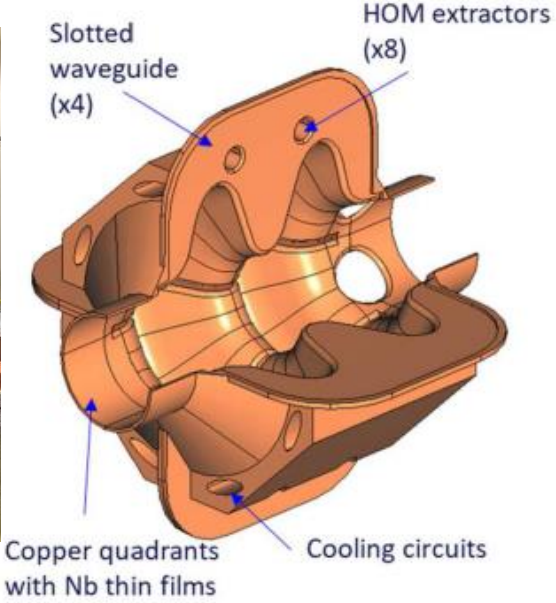



high efficiency klystrons
& scalable solid-state amplifiers

FPC & HOM coupler, cryomodule, thin-film coatings

## efficient high-Q SC cavities

**400 MHz 1- & 2-cell Nb/Cu, 4.5 K**



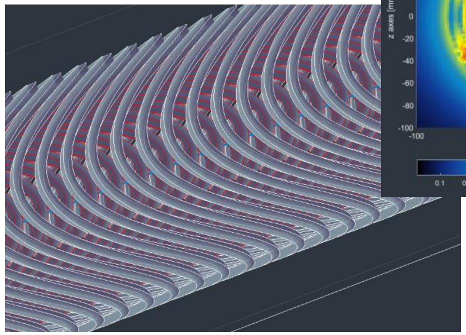

**Slotted Waveguide Elliptical cavity (SWELL)** for high beam current & for high gradient, seamless by nature – links to past work at ANL (Liu & Nassiri, PRAB 13, 012001)

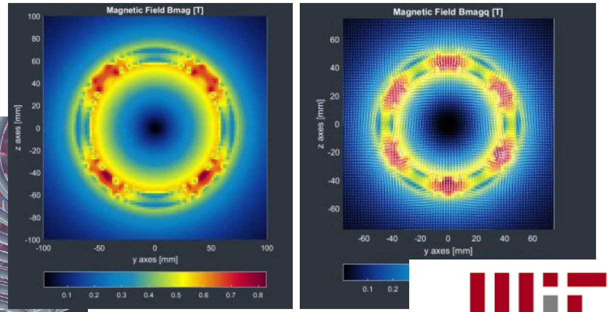
I. Syratchev

## under study: **CCT HTS quad's & sext's for arcs**

- **reduce energy consumption** by O(50 MW)

PAUL SCHERRER INSTITUT PSI

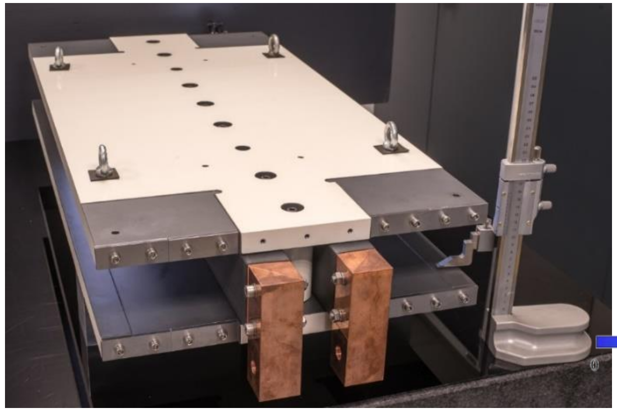


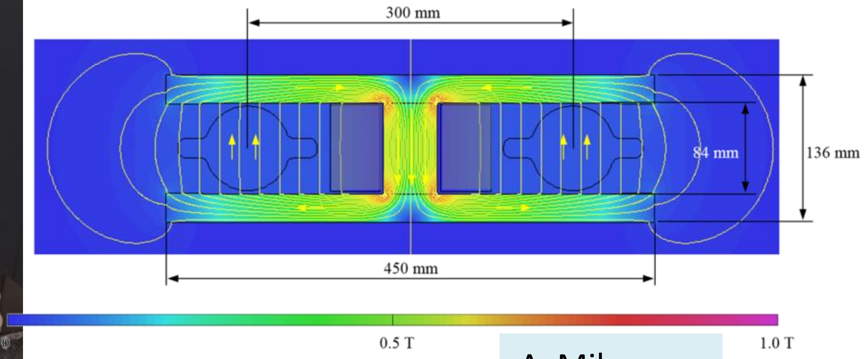



M. Koratzinos, B. Auchmann

Massachusetts Institute of Technology

## energy **efficient** twin aperture **arc dipoles**






A. Milanese