Research on High Field Magnets

A. Ballarino, CERN

ICFA Seminar, DESY, 30/11/2023

Outline

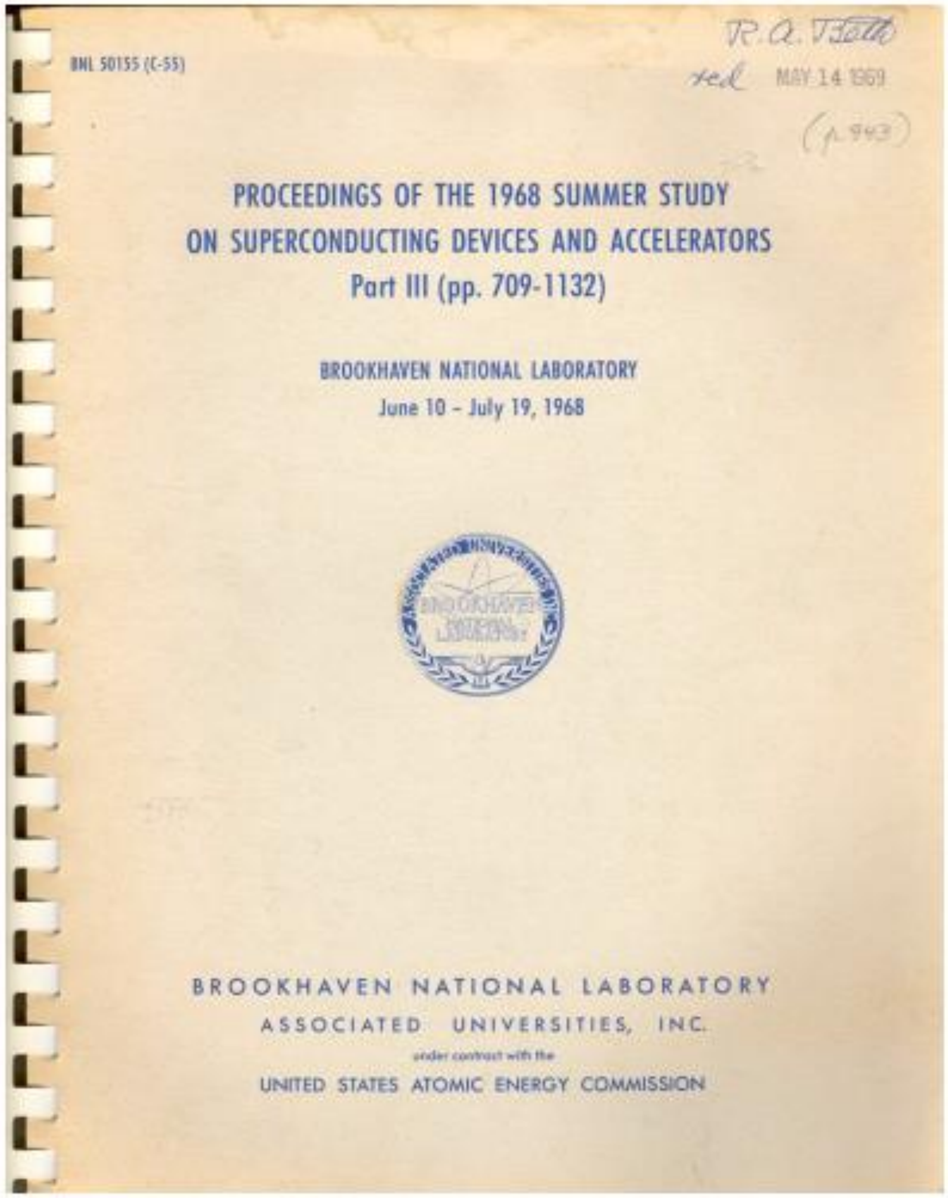
- Status of Nb_3Sn and HTS technology for high field magnets
- Lessons learnt from HL-LHC
- Key developments for future accelerators
- The HFM Program
- Roadmap and timeline
- Potential impact on society
- Conclusions

High Field Magnets

- **High Field Magnets** are among the key technologies that will enable **search for new physics at the energy frontier**
- **Future circular machines** (FCC h-h, SppC) require a **new magnet technology** able to achieve fields beyond the reach of Nb-Ti and beyond the fields produced via Nb_3Sn in HL-LHC (~ 12 T)
- The **path toward the next generation of magnets** for future colliders is complex and requires:
  - **R&D** on new concepts (superconductors, magnets and associated technology);
  - Validation of concepts in **short models**;
  - Production of **medium-size** robust magnets;
  - **Industrialization** of cost-effective design;
  - Collaboration among l**aboratories**, **university** and **industry**: a wide range of expertise is required
  - **LTS and HTS** do not have today the same level of maturity

Superconductivity for Accelerators

- **Superconducting magnets** first suggested by **mid-60s**
- **1968**: Brookhaven Summer Study
  - Most influential event where all important **topics related to Nb-Ti magnets** were discussed – including flux jumps and stability in superconductors
- **1971**: "compacted fully transformed cable" produced at Rutherford Lab: the Rutherford cable
- Technological progress slow and steady in the last half century. **Mainly Nb-Ti**, despite **early magnet pioneers on Nb_3Sn**



Superconductivity for Accelerators

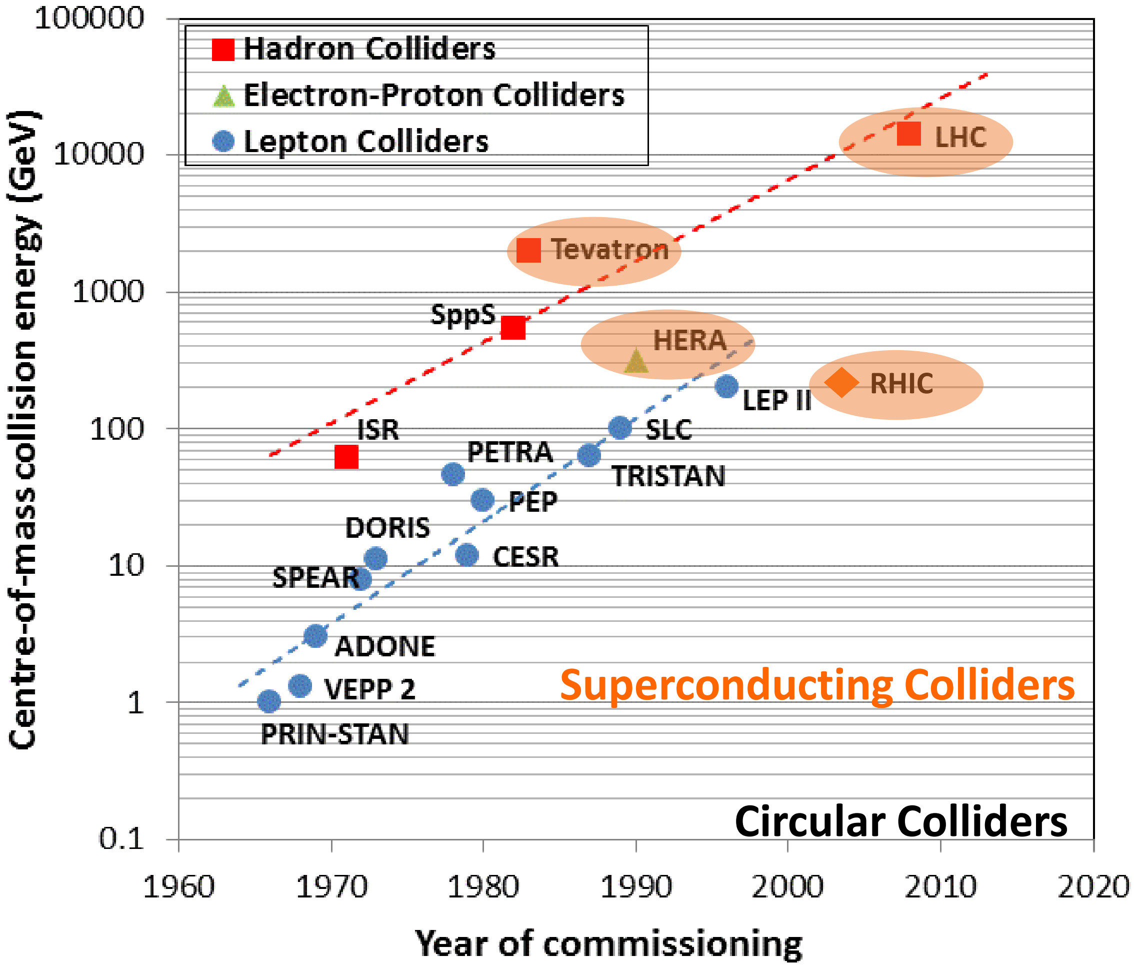
Event	Year	Who and Where
High Field Nb_3Sn	1961	Bell Telephone Labs
ANL 25 cm BC Magnet	1965	Argonne National Lab
Cryostatic Stability Concept	1965	Avco Everett Research Lab
12 inch MHD Dipole Magnet	1966	Avco Everett Research Lab
Intrinsic Stability Concept	1968	RAL, AVCO
12 ft & 7 ft H_2 Bubble Chambers	1968	Argonne & Brookhaven
High Quality M.F. NbTi	1970-80	Industry
Hollow Conductor	1972	CERN
Ramped Magnet Development	1972 to present	Tevatron, HERA, RHIC, SSC, LHC
M.F. Nb_3Sn	1976 to present	Industry
MRI	1982	Industry

U.S. DEPARTMENT OF ENERGY

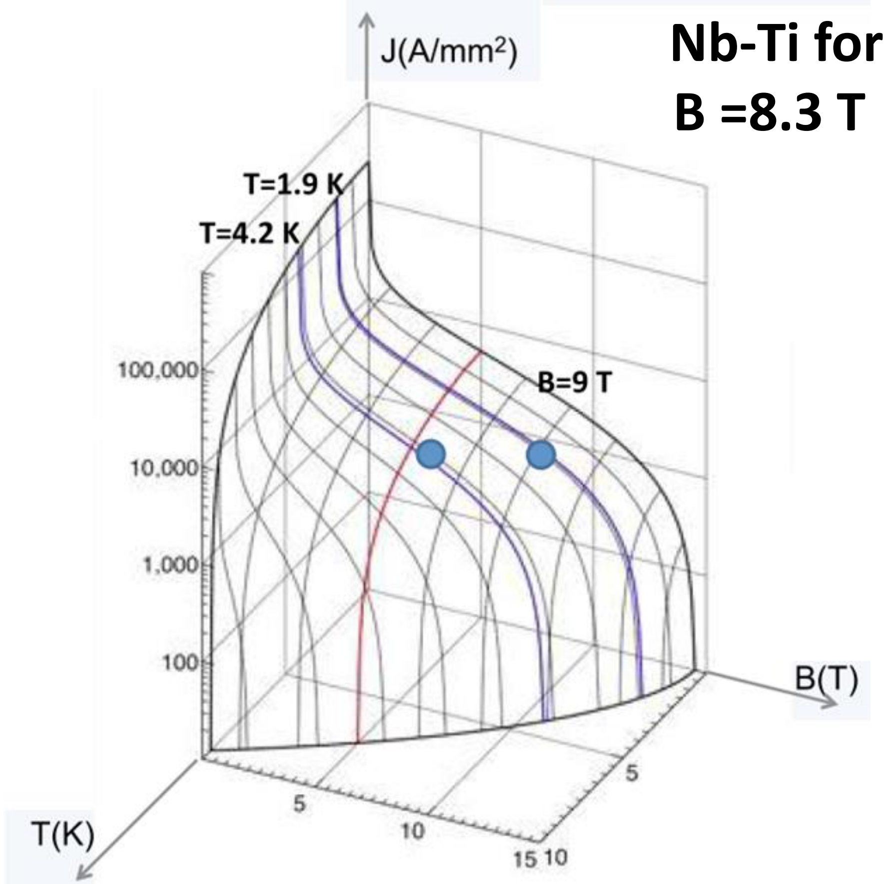
B. Strauss

Superconductivity for Accelerators

The quest for higher energies



Nb-Ti for LHC
B =8.3 T



Jc(4.2 K, 6 T)~2300 A/mm^2

Jc(1.9 K, 9 T)~2300 A/mm^2

~ 1265 tons of Nb-Ti cables

State-of-the-art Nb-Ti magnets: coordinated effort during about 30 years

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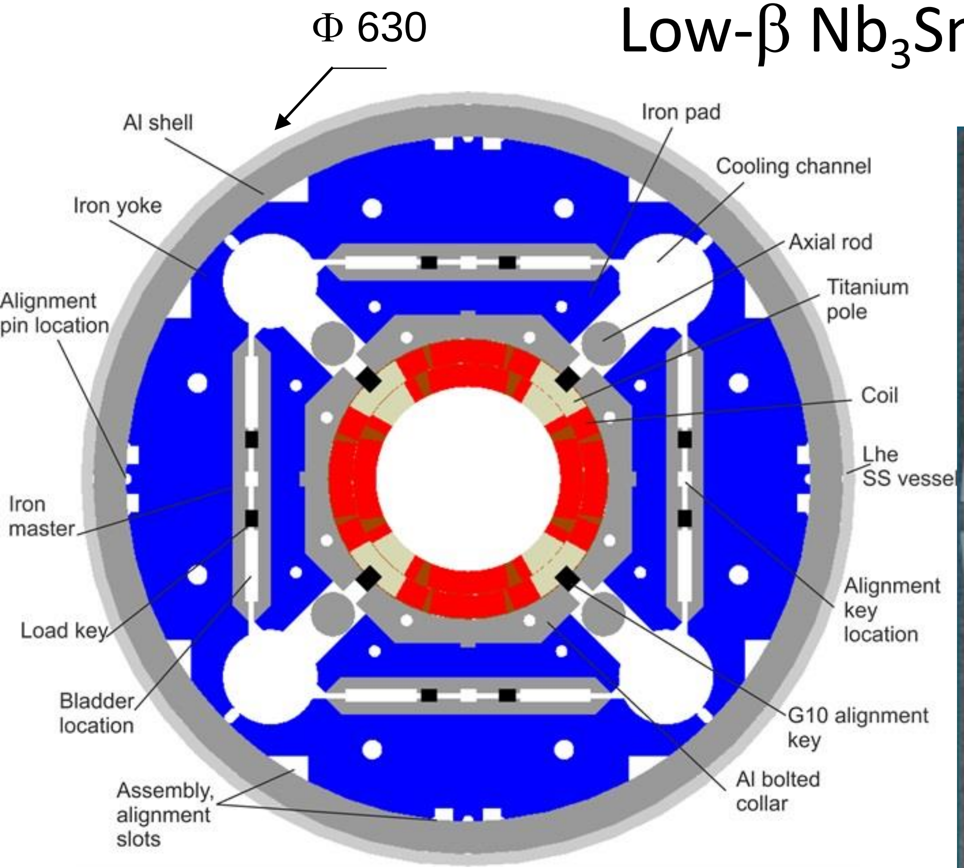
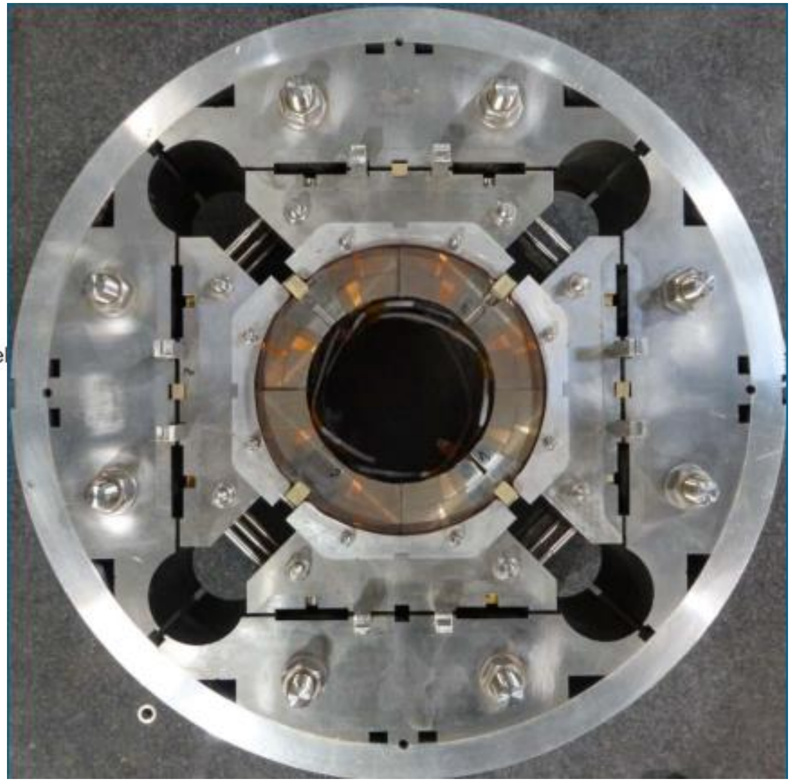
Nb$_3$Sn Quadrupoles for HL-LHC

Beyond ~ 10 T: Nb$_3$Sn Technology

Low-β Nb$_3$Sn Quadrupoles for HL-LHC Triplets





Large aperture:
150 mm (70 mm in LHC)

Bpeak:
11.4 T (8.6 T in LHC)
Nb$_3$Sn (Nb-Ti in LHC)

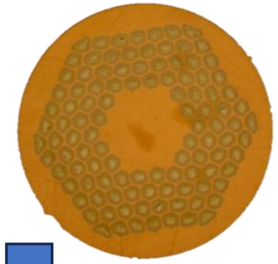
Number of magnets:
8 + 2 (7.2 m long)
16 + 4 (4.2m long)

Bladder and keys technology. Design developed by the USA-LARP program – initiated in 2003

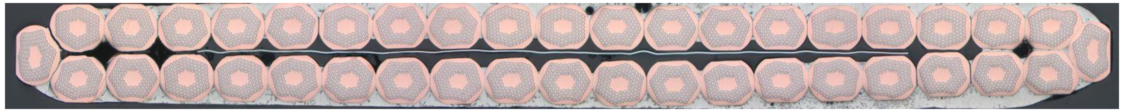
Installation in the LHC underground and commissioning: 2026 - 2028

State of the Art: Nb_3Sn for HL-LHC

RRP 108/127

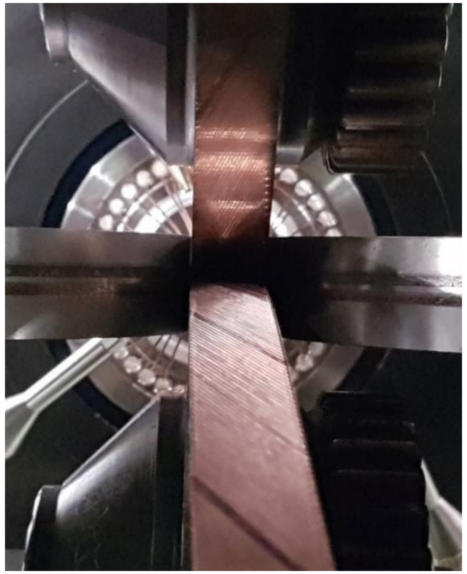


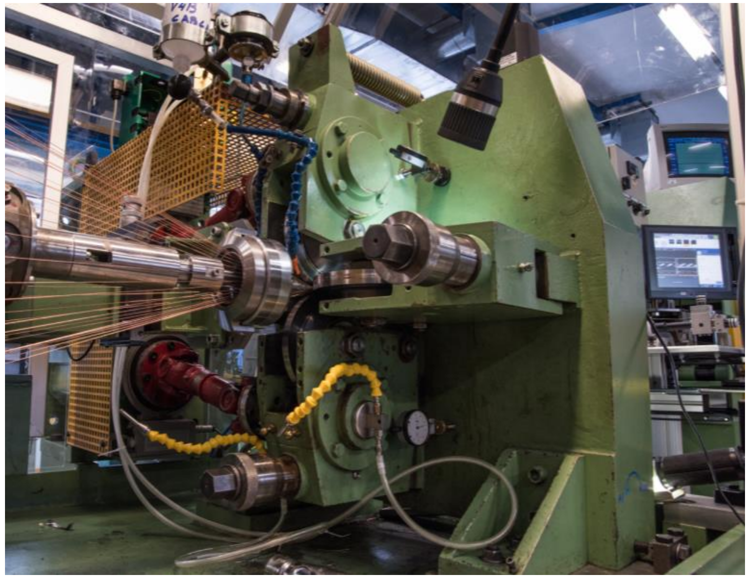
MQXF Cable, 40 Nb_3Sn wires (Φ = 0.85 mm)



width = 18.15 mm, mid-thickness = 1.525 mm

	Lay-out	Sub-El. size [μm]	J_c (12 T), σ [A/mm²]	J_c (15 T), σ [A/mm²]	B_{c2}, σ [T]	J_c (16 T), σ [A/mm²]	J_c (18 T), σ [A/mm²]
RRP 0.7 mm	108 / 127	46	**2637,** *82*	**1371,** *74*	**24.2,** *0.5*	**1064,** *70*	**581,** *61*
RRP 0.85 mm (75 hrs @ 665 ˚C)		55	**2797,** *53*	**1573,** *43*	**25.9,** *0.3*	**1266,** *41*	**769,** *36*
RRP 0.85 mm (50 hrs @ 665 ˚C)			**2725,** *61*	**1498,** *47*	**25.4,** *0.3*	**1194,** *44*	**704,** *38*
PIT 0.85 mm Bundle Barrier	192	39	**2267,** *46*	**1317,** *28*	**26.9,** *0.3*	**1075,** *25*	**681,** *19*





Total procurement for HL-LHC ~ **30 tons**

Jc(12 T, 4.2 K) > 2450 A/mm²

Cabling at CERN and at LBNL (via AUP: the Fermilab-headquartered USA contribution to HL-LHC)

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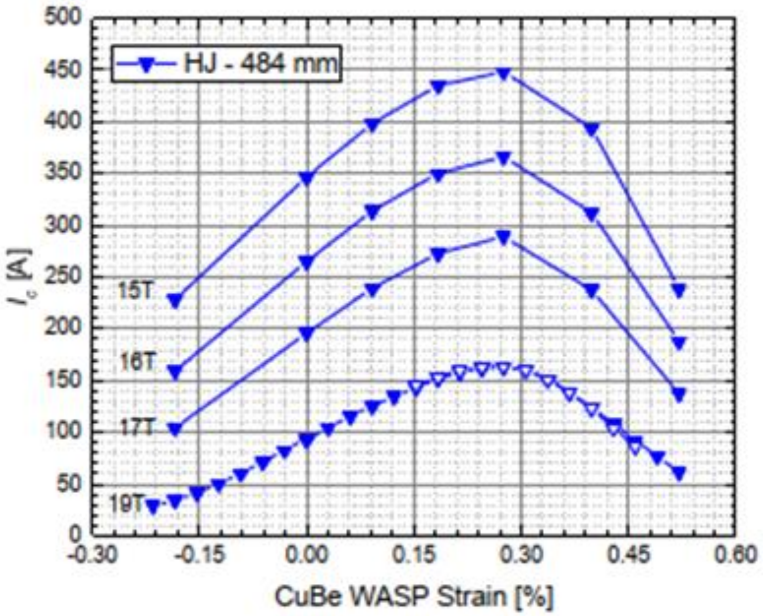
State of the Art: Nb_3Sn for HL-LHC

- **Wind & React technology**: winding of un-reacted cables and final heat treatment of coils
- Long **reaction heat treatment** (~ 7 days, with last plateau at 665°C for 50 h) of coils
- Coils assembled in the **final mechanical structure after reaction** and impregnation
- **Brittle material**, with strain dependent electrical performance

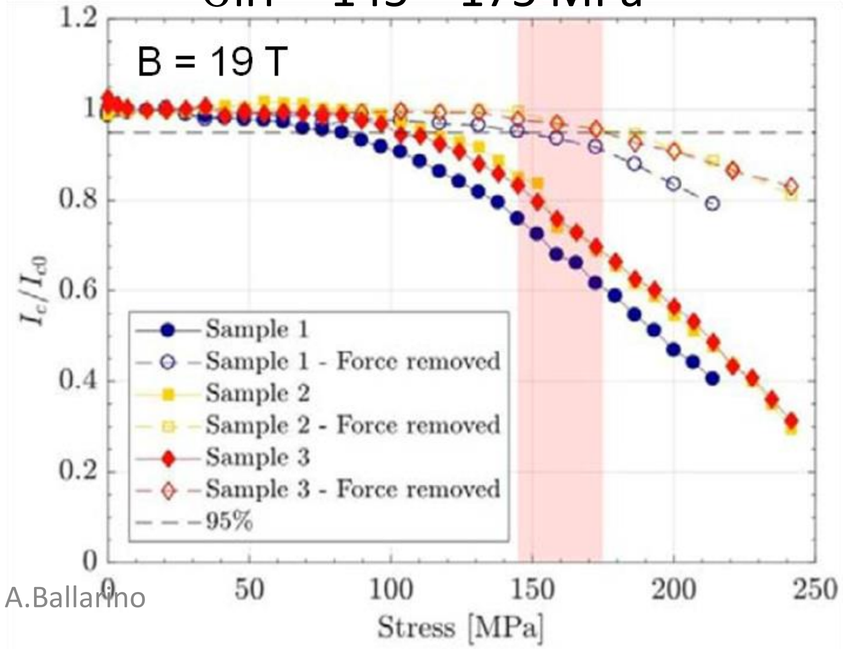
Axial strain at 4.2 K

ε_{irr} = 0.48 % -0.51 %



Transverse pressure at RT

σirr = 145 – 175 MPa



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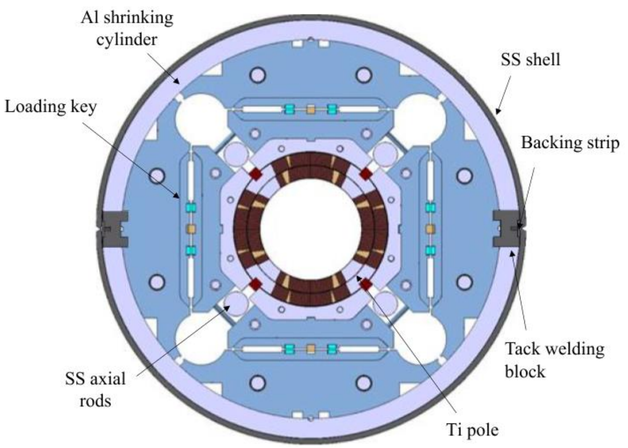
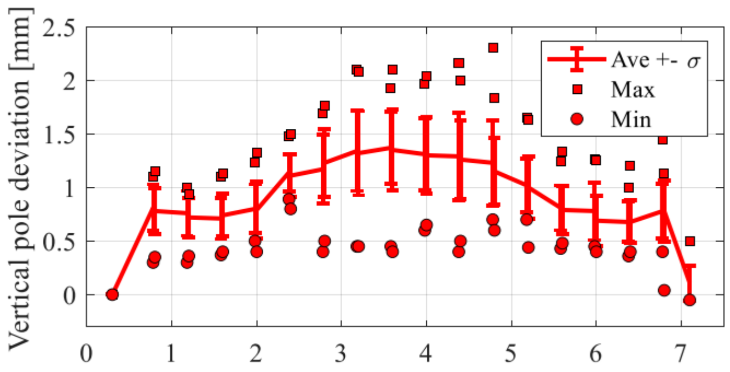
Challenges – Nb_3Sn : Mechanical

- **Challenges and performance limitations** of **HL-LHC prototype magnets** identified to be of **mechanical nature** (excessive stress on conductor) during:
    - **Cold mass assembly** (non optimum coupling between welded outer stainless steel and magnet stricture – aluminum rings)
    - **Magnet pre-loading** (unbalanced and/or local excessive pre-stress)
    - **Coil manufacturing** (deformation during handling and/or manufacturing, including heat treatment))

Weld of stainless steel shell



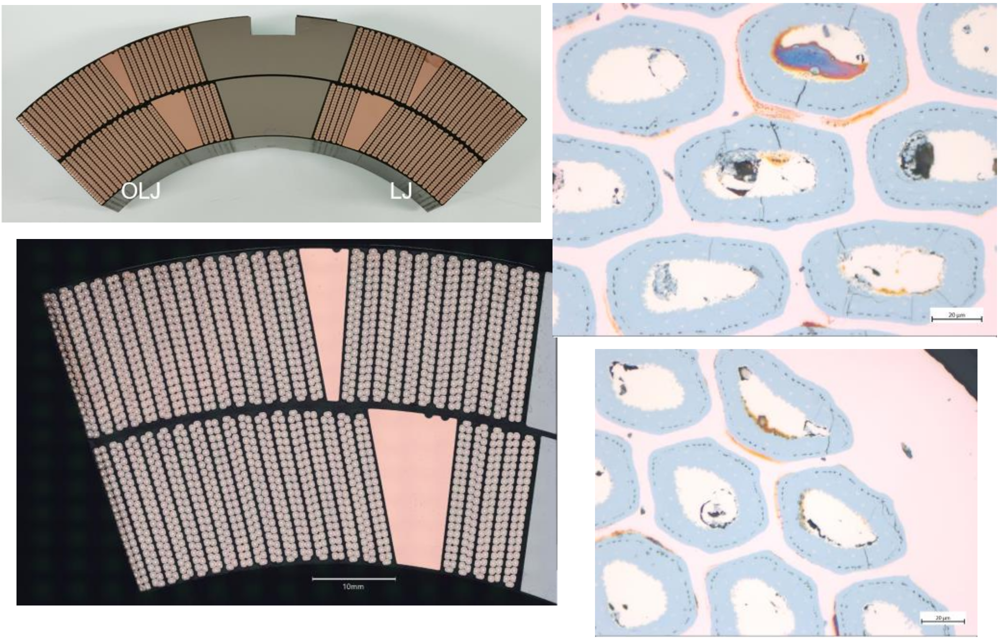
Vertical displacement of the coil after heat treatment



Challenges – Nb_3Sn : Mechanical

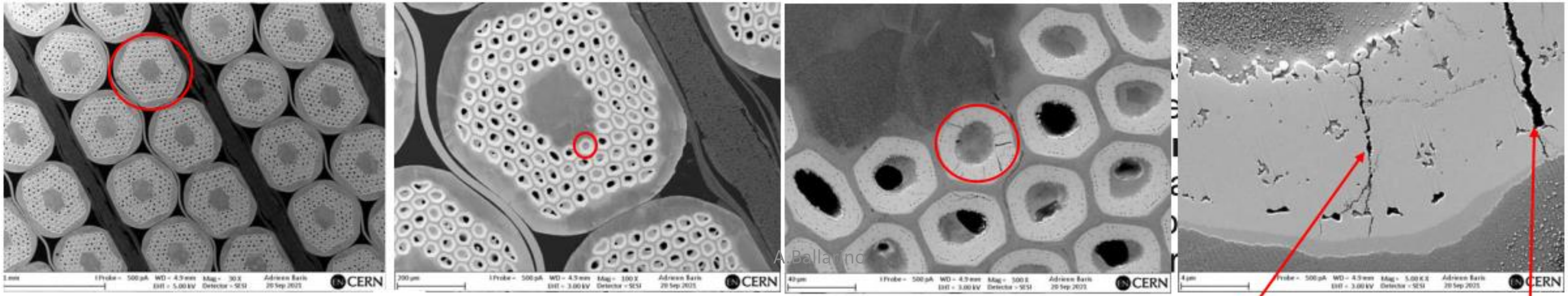
Problems identified via post-mortem analysis on HL-LHC Nb_3Sn coils

Filament cracks in MQXF Coil

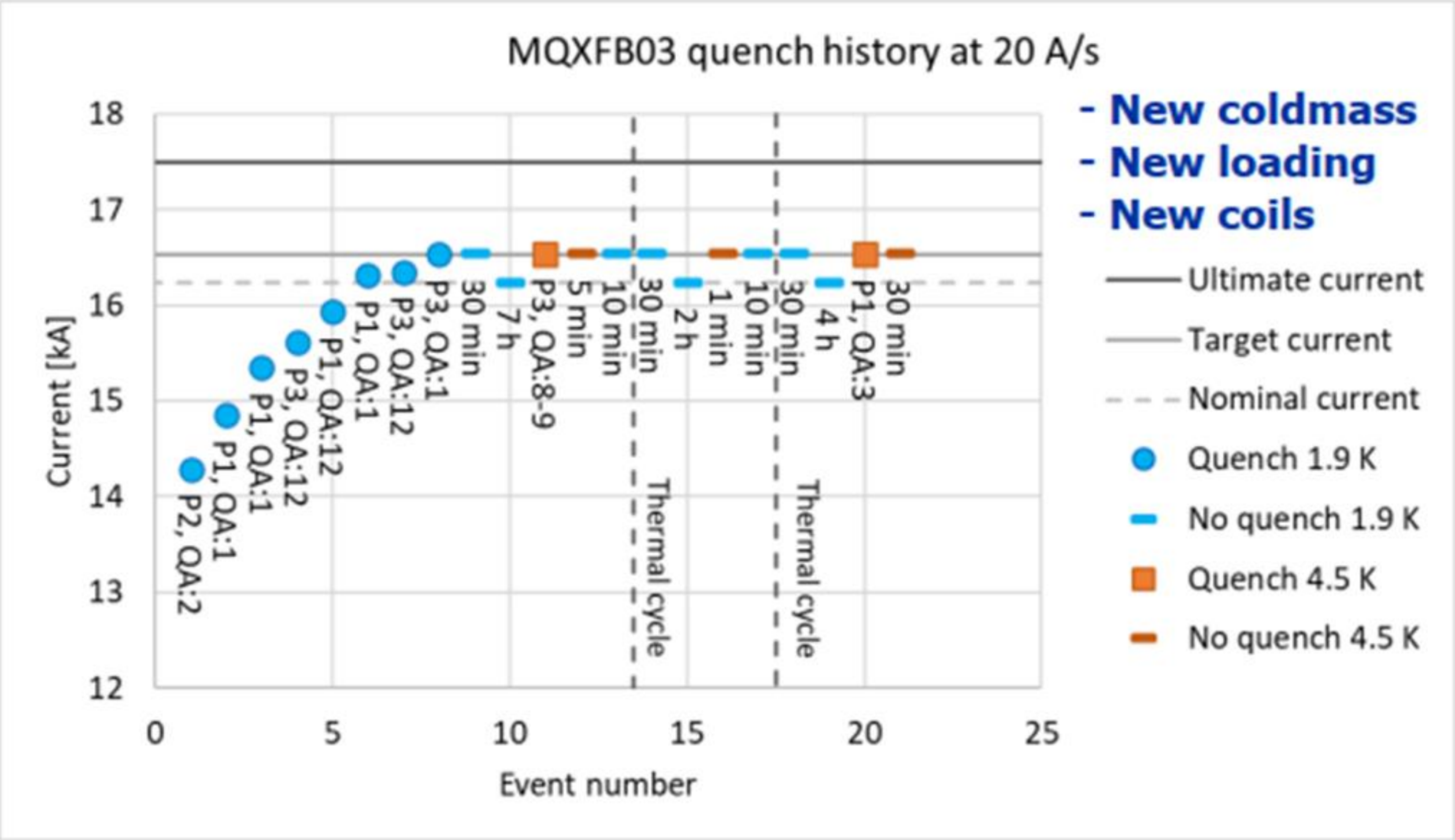


- **Performance degradation of coils** has been identified to be due to **defects of mechanical origin**
- **Excessive transverse stress** applied during loading at room temperature is one of the possible causes of mechanical degradation

S. Sgobba el al, CERN



Successful MQXFB03 Qualification

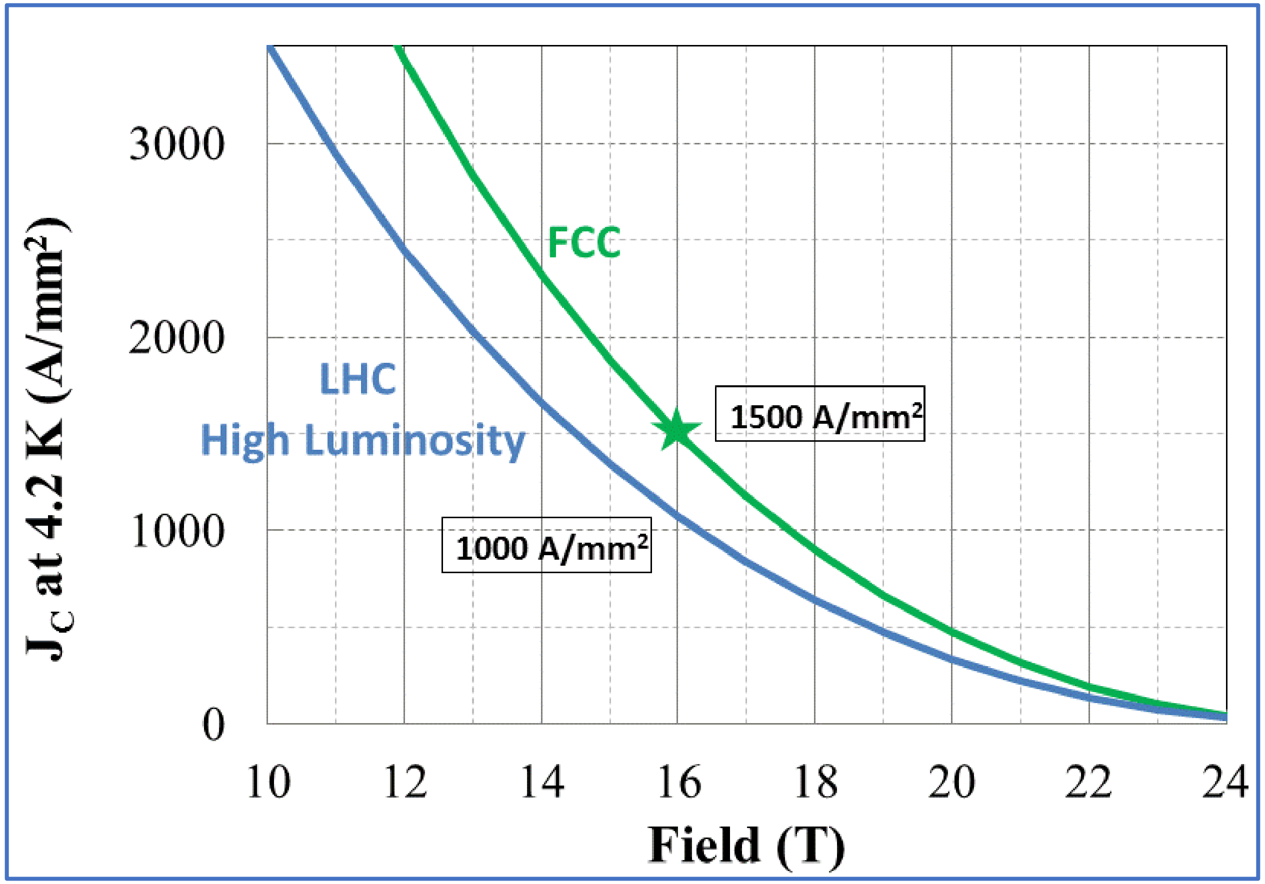


R&D on Nb_3Sn for Future Accelerators

- Jc of Nb_3Sn wire
- Deff of Nb_3Sn wire
- Stability
- Stress management of Nb_3Sn coils

Target for Jc of Nb_3Sn Wire – 16 T

FCC Jc target vs HL-LHC performance



Needed: 7000 tons - 9000 tons superconductors

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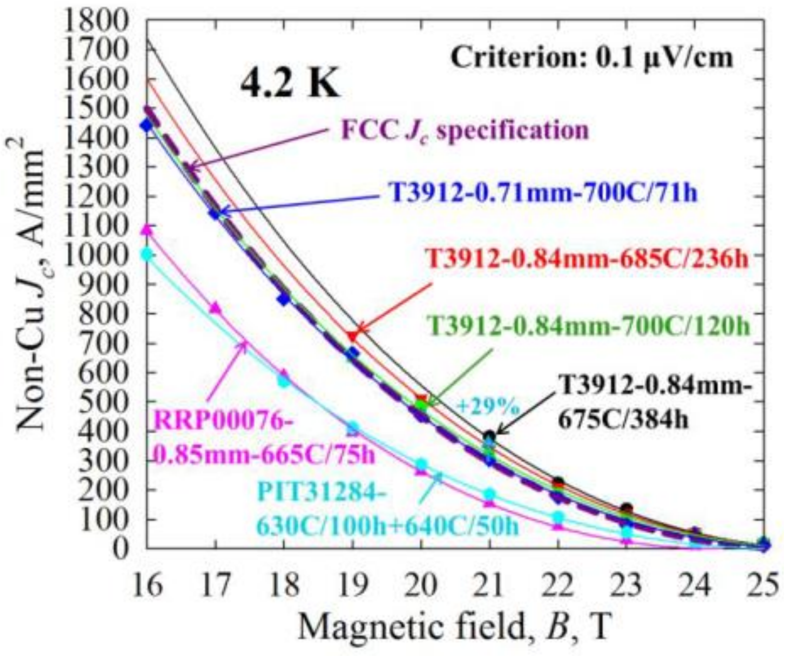
Jc on R&D Nb_3Sn wire

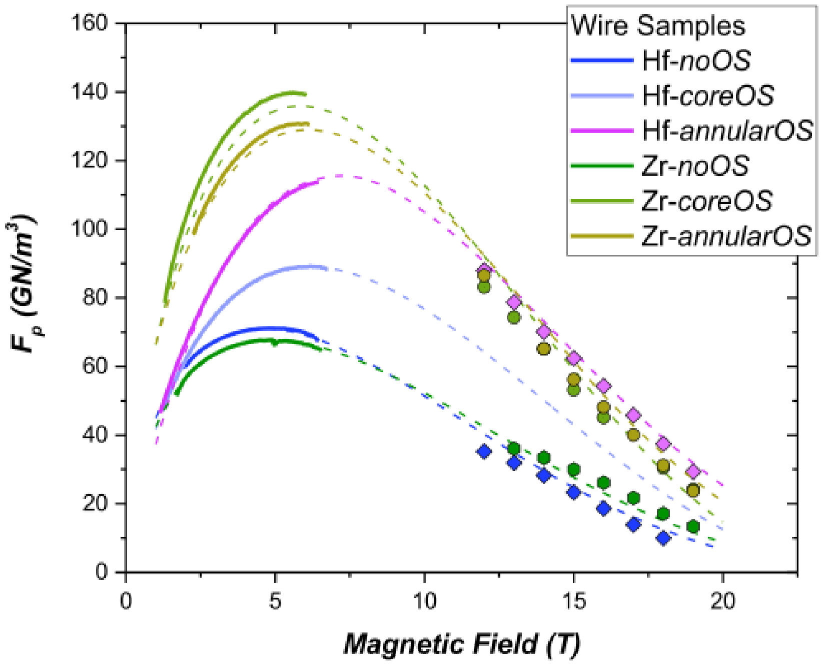
Internal Oxidation Process at Fermilab

Nb-1wt%Zr -7.5 wt% Ta



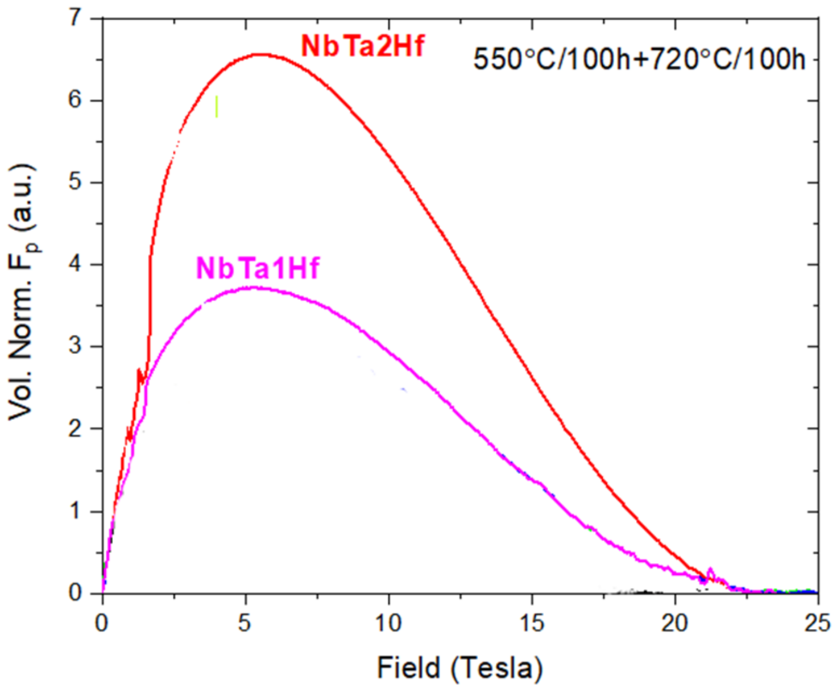
X. Xu et al, arXiv:1903.08121, 2019

Internal Oxidation Process at Unige



G. Bovone *et al.*
Supercond. Sci. Technol. 36 (2023) 095018

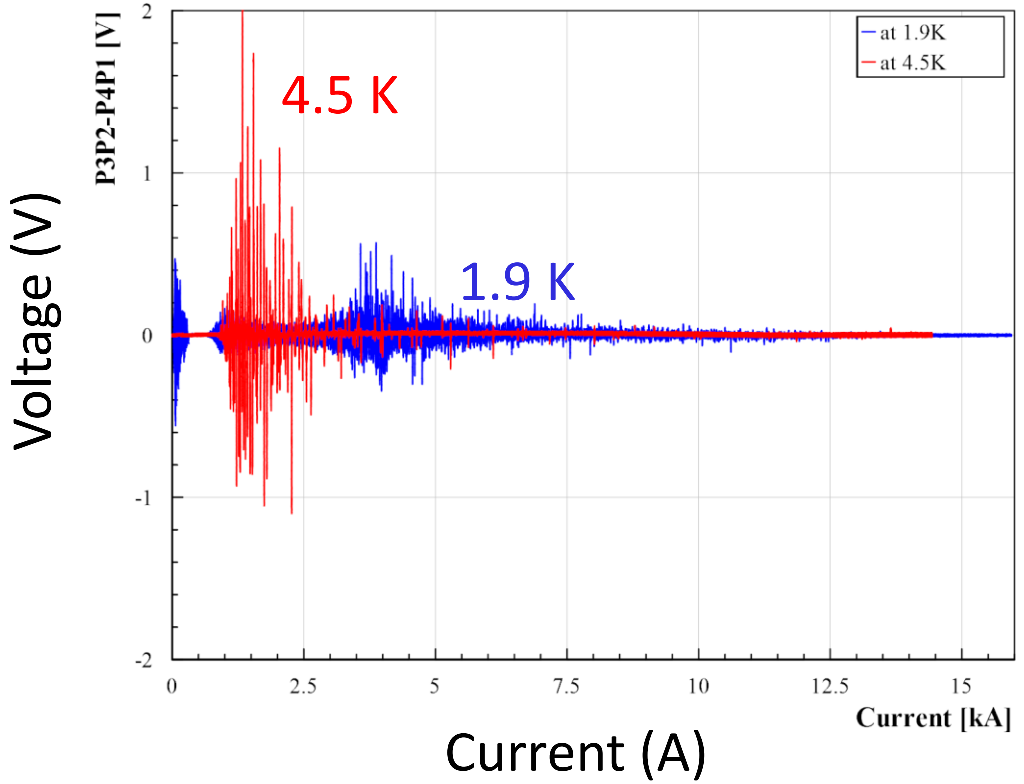
Alloying Nb-Ta with Hf at ASC

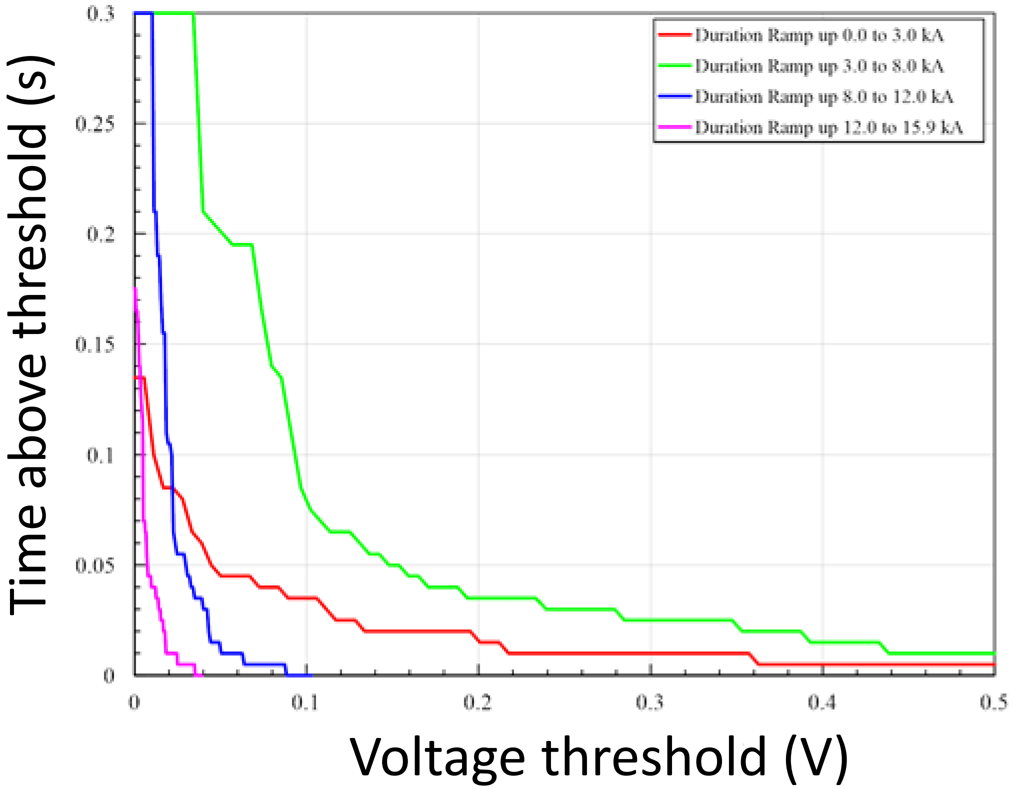


S. Balachandran *et al.*
Supercond. Sci. Technol. 32 (2019) 044006

Achieved > 1500 A/mm² at 12 T

Challenges – Nb_3Sn : Flux Jumps





MQXF Prototype - Quench detection settings

Main quench detection thresholds	Low threshold	Short validation time
I < 3 kA	400 mV, 200 ms	1000 mV, 70 ms
3 kA < I < 8 kA	300 mV, 50 ms	400 mV, 30 ms
8 kA < I < 12 kA	100 mV, 14 ms	150 mV, 8 ms
12 kA < I	100 mV, 5 ms	150 mV, 3 ms

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Challenges – Nb_3Sn : Field Quality

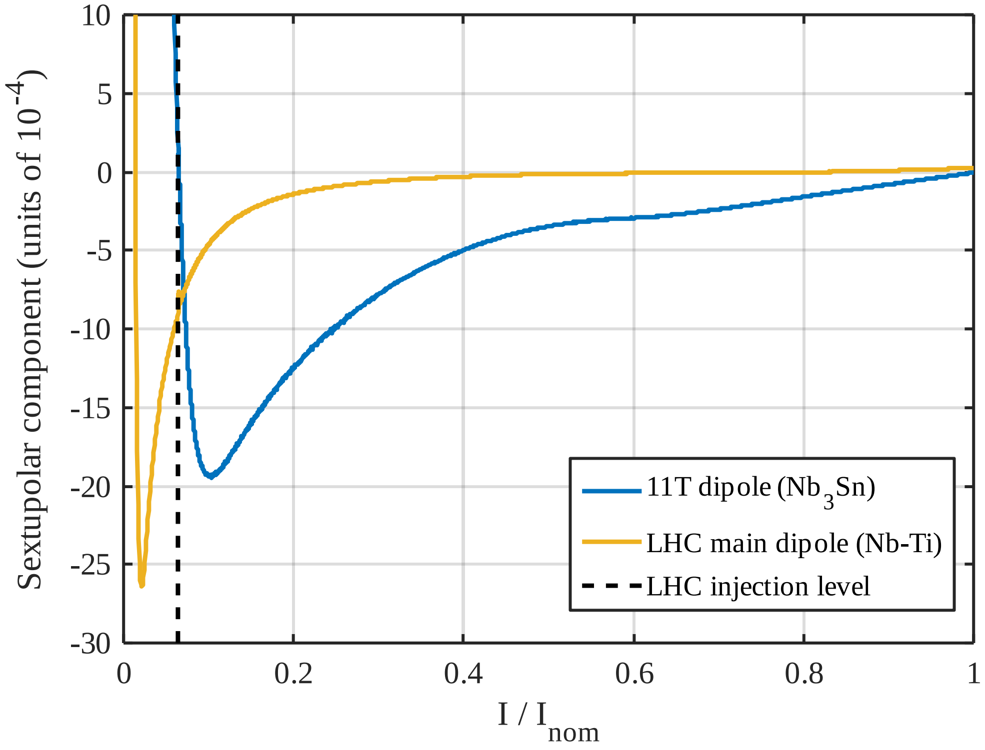
Sextupole field errors (b3) in dipole magnets induced by persistent currents: 11 T Nb_3Sn vs LHC Nb-Ti Main Dipole

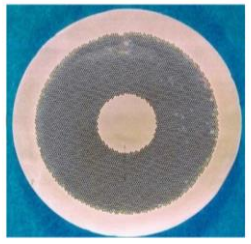
LHC Main Dipole aperture = 56 mm

Nb-Ti filaments ~ 5 µm

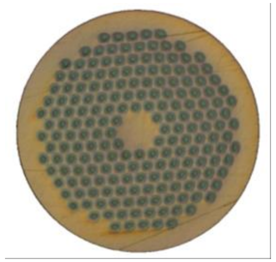
11 T Dipole aperture = 60 mm

Nb_3Sn sub-elements ~ 40 µm



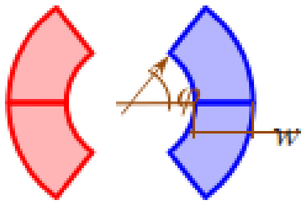


Nb_3Sn

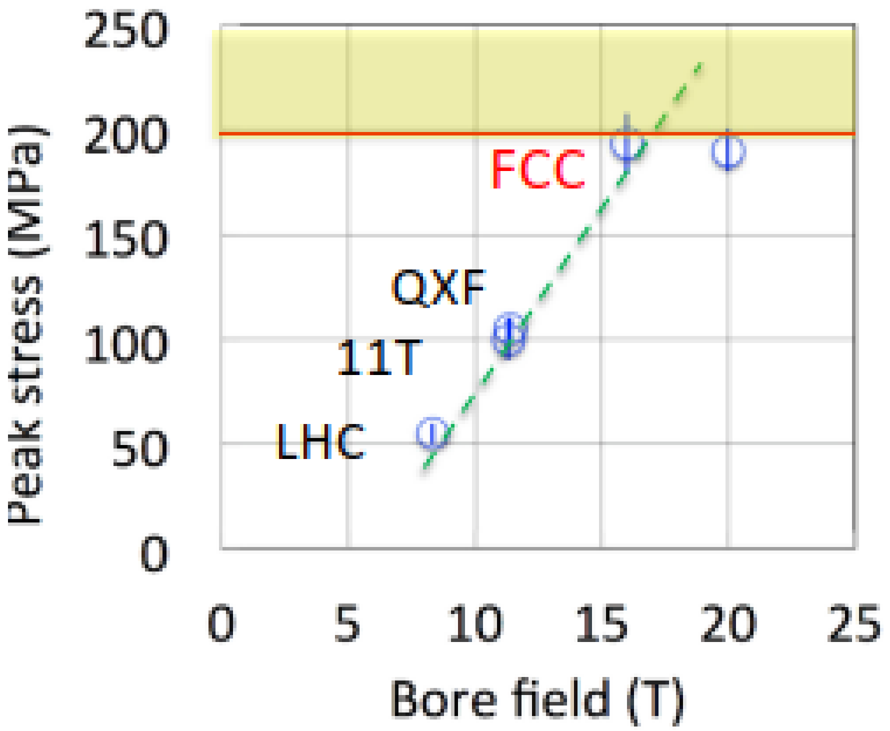


- Full penetration of Nb_3Sn after injection:
  peak of field distortion during the acceleration ramp
- **During the ramp**, **variation for Nb_3Sn three times larger than for Nb-Ti**
- Systematic effect that in principle **can be taken into account and corrected**

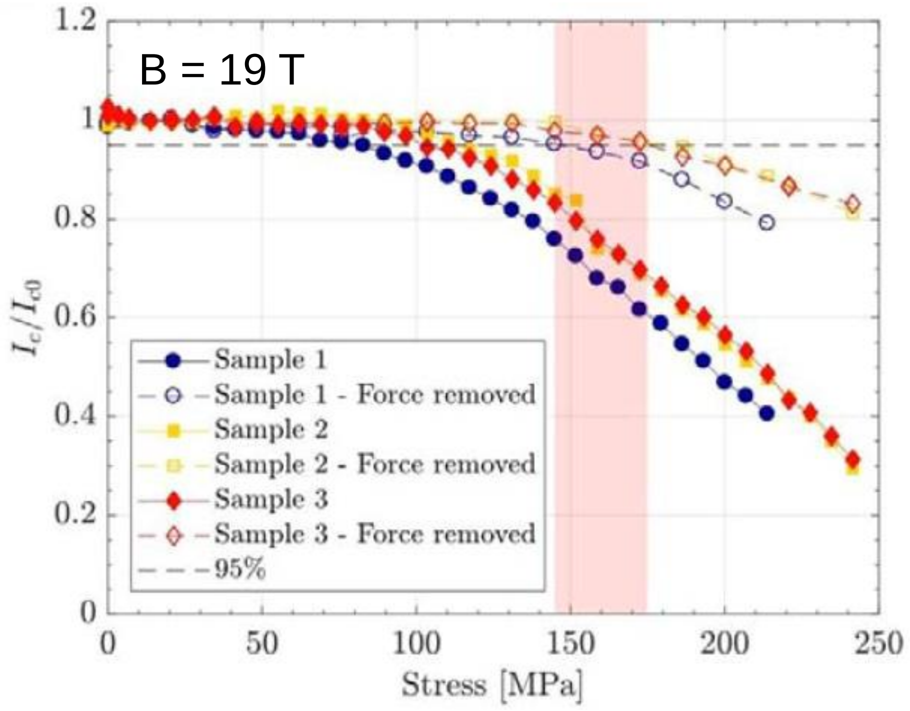
R&D on Nb_3Sn Magnets



$$\left.\begin{array}{l} F \propto B^2 \\ w \propto \dfrac{B}{J} \end{array}\right\} \longrightarrow \boxed{\sigma \approx \frac{F}{w} \propto JB}$$



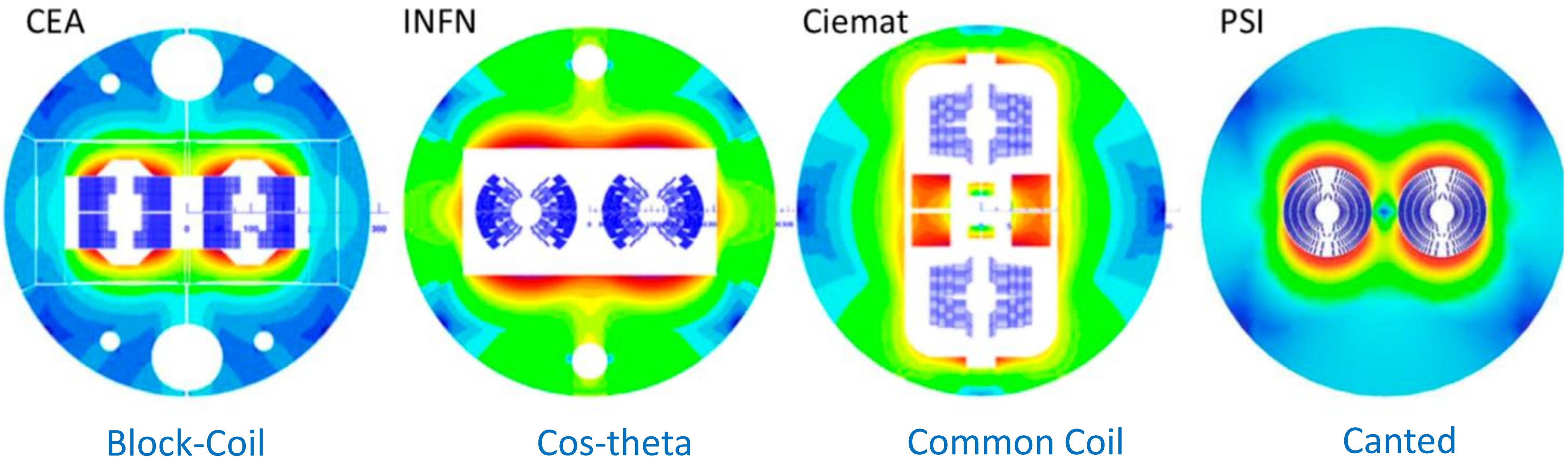
Measurements at UNIGE, Geneva



σirr = 145 – 175 MPa

Supercond. Sci. Technol. **34** (2021) 035008

R&D on Nb_3Sn Magnets



FCC Dipole conceptual designs - EuroCircol

Bbore = 16 T

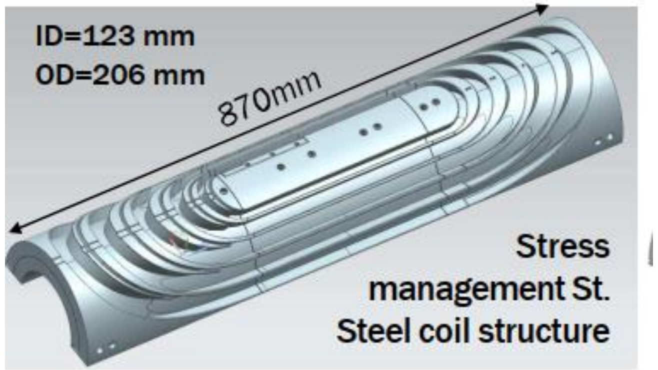
Bpeak = 18.6 T

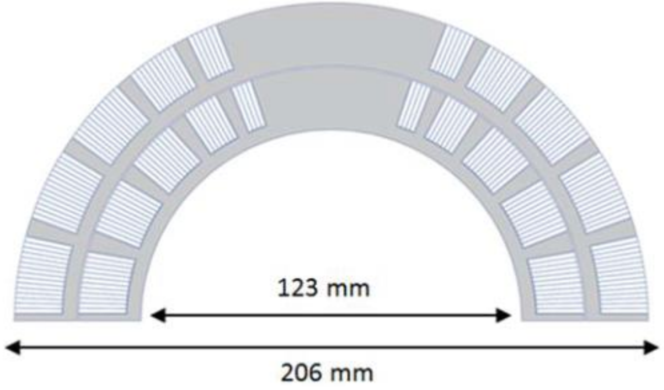
Jc = 1500 A/mm^2 at 16 T

R&D on Nb_3Sn Magnets

Stress management

Stress management concepts
Fermilab

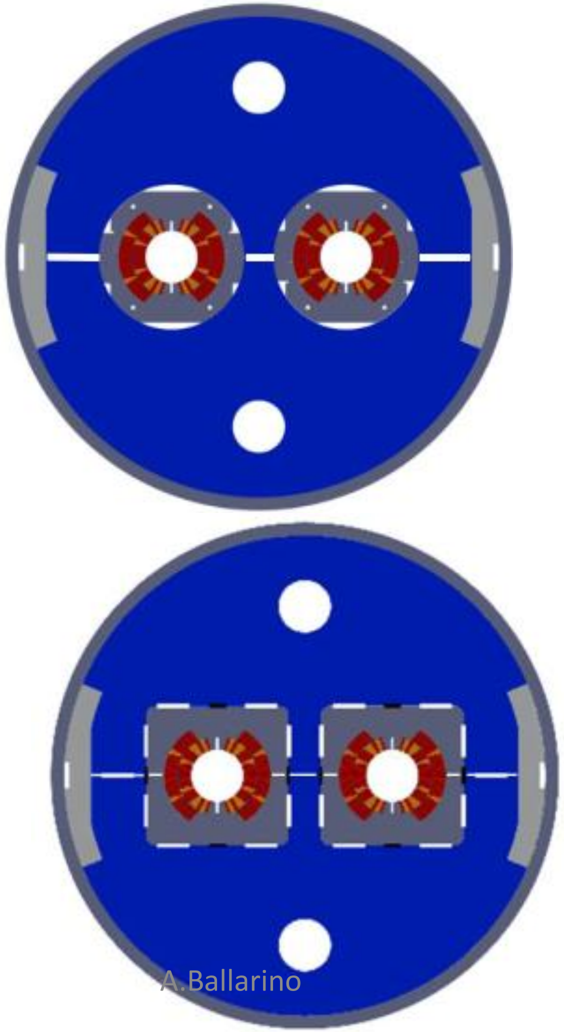




U.S. MAGNET DEVELOPMENT PROGRAM

Double aperture

12 T Collared vs Bladder & Key
CERN



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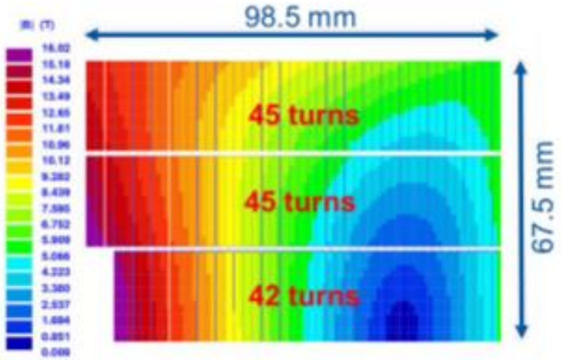
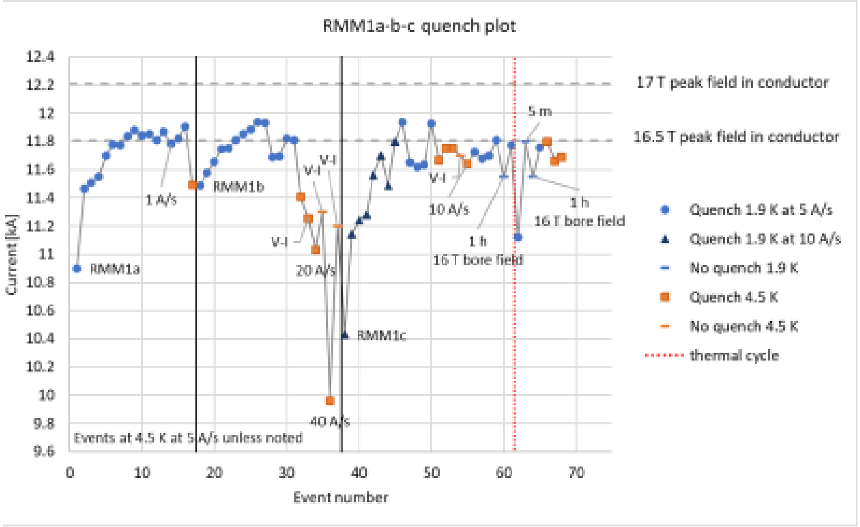
Demonstrators

Racetrack Magnet Model (RMM)
CERN





16.5 T in the closed bore

HTS and its Potentials

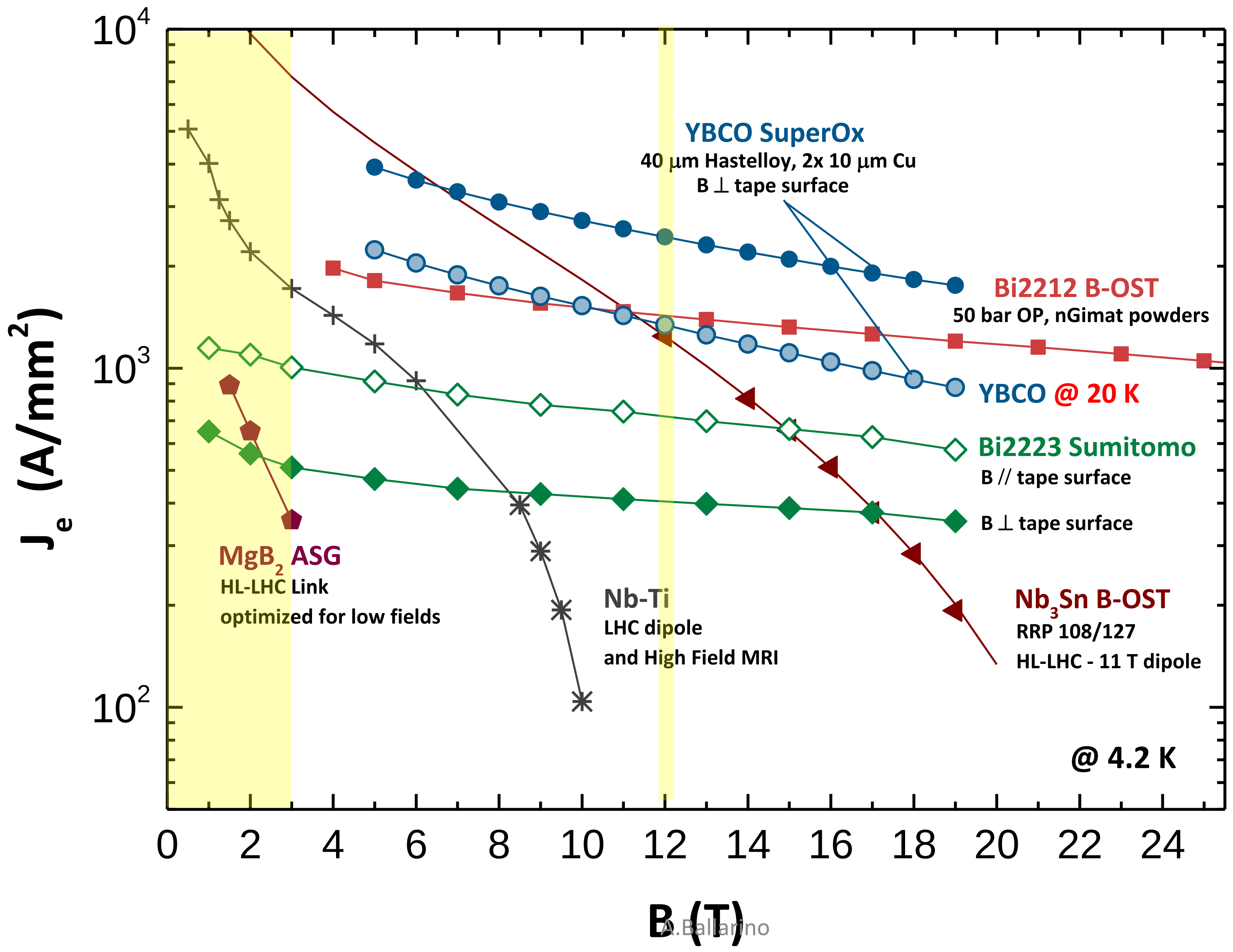
		Dipoles	Quadrupoles	Undulators/Wigglers	Detectors	Field (T)
Higgs Factories	FCC-ee		IR Quad		×	< 3 T
	CEPC		IR Quad		×	< 5 T
	ILC	×	×	×	×	< 2 T
	CLIC			×	×	< 2.5 T
Energy Frontier	FCC-pp	×	×			16 T -20 T
	SppC	×	×			12 T- 24 T
	Muon Colliders	×	×			Solenoids > 10 T-20 T

HTS and its Potentials

		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

HTS Enabling Technology

The Present HTS Landscape



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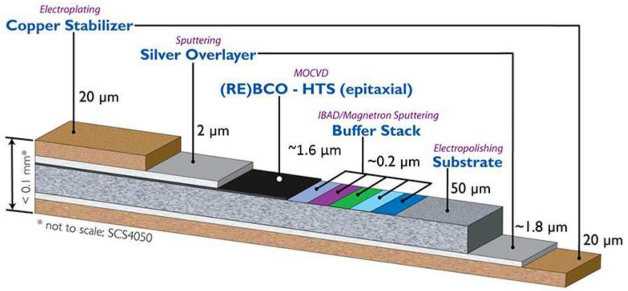
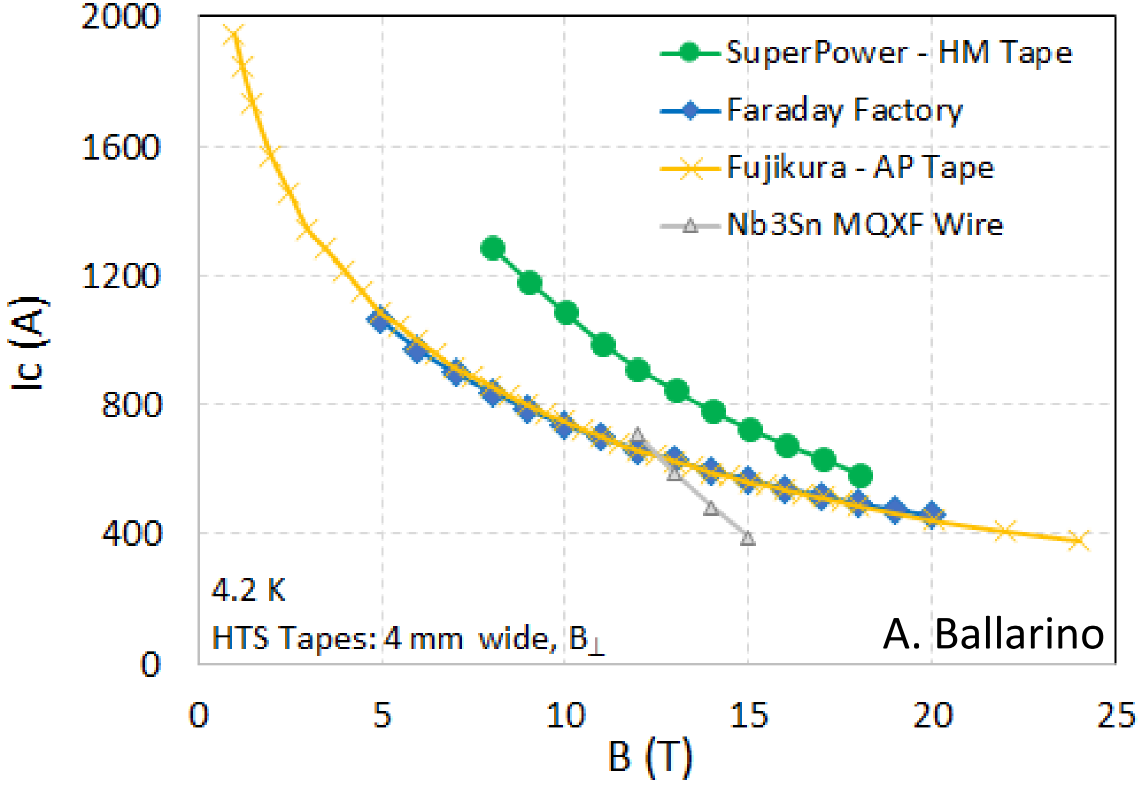
REBCO Tape

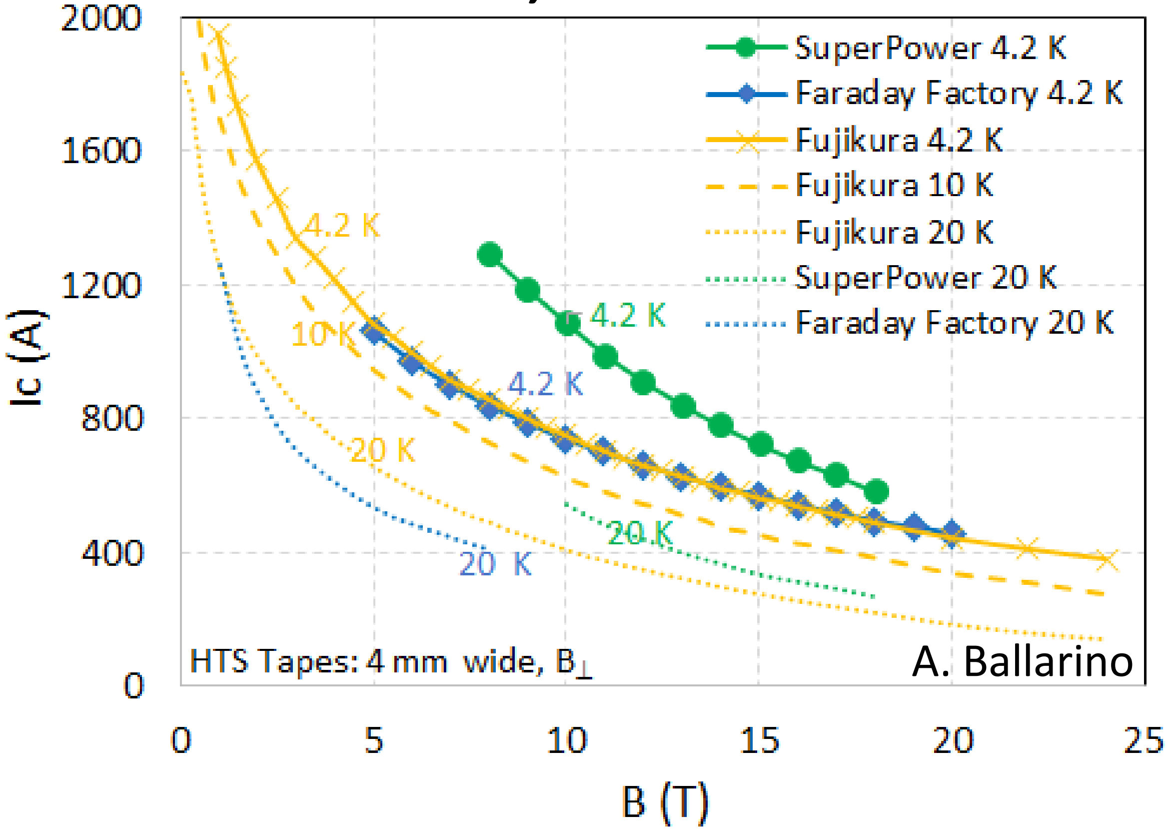
High current capability



4.2 K

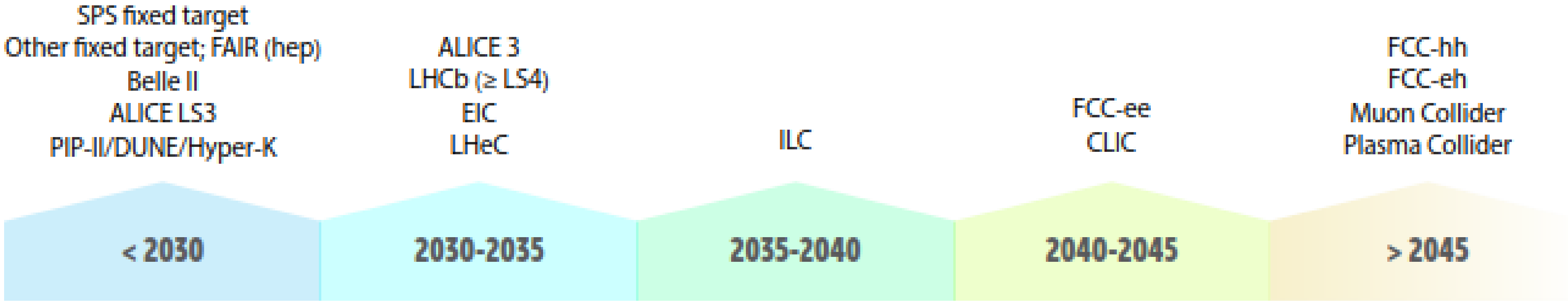


4.2 K, 10 K and 20 K



Plots based on data presented by tape manufacturers at the HiTAT Workshop, CERN, March 2023

LDG Report: HTS beyond the range of Nb_3Sn



- ❑ **LDG Roadmap**: "demonstrate the suitability of High-temperature superconductor (HTS) for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the range of Nb_3Sn, with a target in excess of 20 T"
- ❑ **LDG timeline** driven by technical readiness

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

HTS and its Potentials

Higgs Factories

Beneficial Technology

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

Energy Frontier

HTS Enabling Technology

HTS for Sustainability: operation at higher temperatures (> LHe) to minimize power consumption

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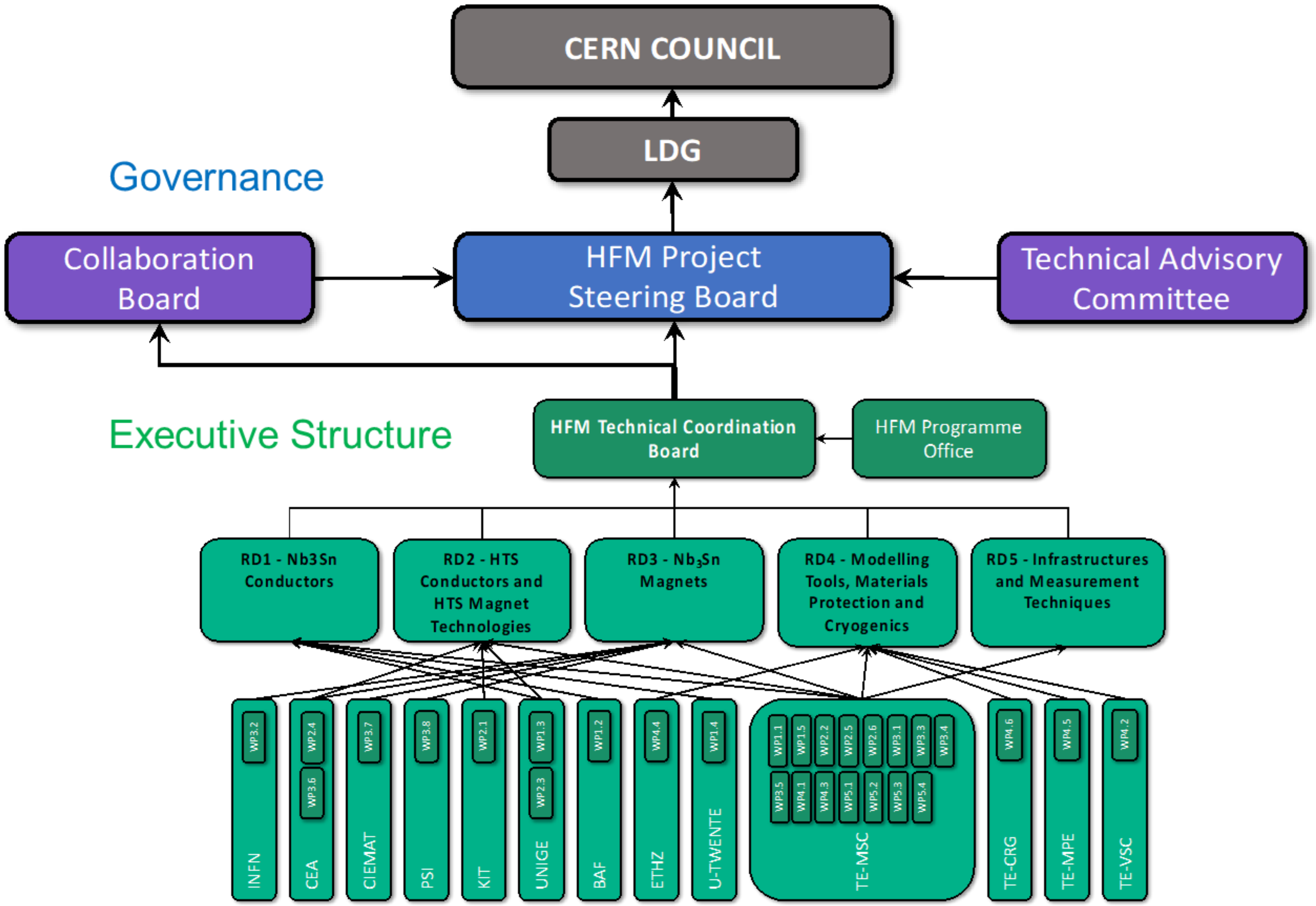
The HFM Program

- The 2020 update of the European Strategy for Particle Physics (CERN/3493/C/Rev) has identified a clear and immediate need for a **reinforced R&D on advanced accelerator technologies**, and in particular **high-field superconducting magnets**, including high-temperature superconductors

- The High Field Magnets R&D (HFM) Programme is the response that **CERN** has initiated, in collaboration with **National Laboratories from the Member States and Associate Member States** and linking possibly beyond to ongoing worldwide efforts, particularly in the US and Japan.

- The HFM Programme – broad goals are:
  - Explore the performance limits of LTS accelerator magnets with a focus on robust large-scale implementation
  - Explore the HTS magnet technologies for accelerator application beyond the limits of Nb3Sn
  - Develop the next generation of accelerator magnets for future colliders

The HFM Program



Conclusions