HTS Developments

A. Ballarino, CERN

FCC Week 2023

June 5 – 9, 2023

Millennium Gloucester Hotel London Kensington

Outline

- **Introduction**
  - Potentials of HTS technology
- **HTS Materials and cables**
  - REBCO, BSCCO 2212, Iron Based Superconductors, MgB_2
- **HTS magnet developments**
- **HTS in the High Field Magnet Program**
- **Test facilities for HTS technology**
- **HTS for fusion**
- **Conclusions**

The physics landscape

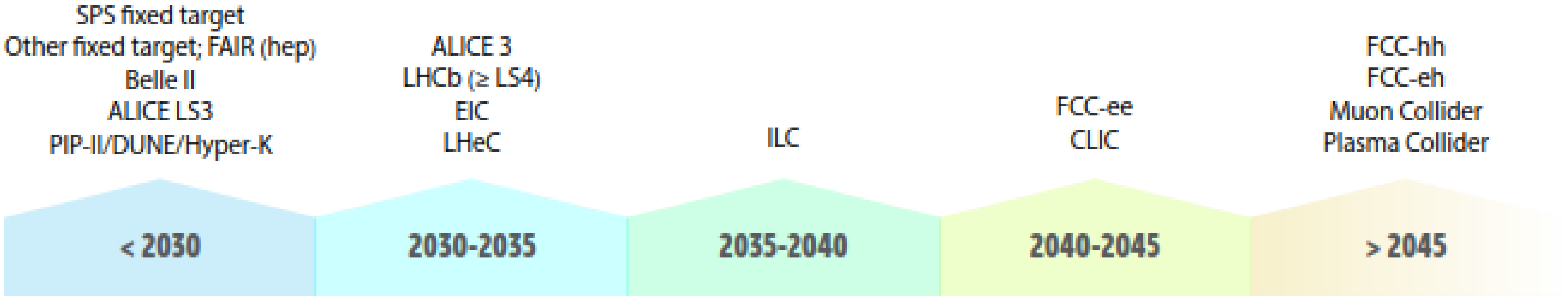
		Dipoles	Quadrupoles	Undulators/Wigglers	Detectors	Field (T)
Higgs Factories	FCC-ee		IR Quad		×	< 3 T
Higgs Factories	CEPC		IR Quad		×	< 5 T
Higgs Factories	ILC	×	×	×	×	< 2 T
Higgs Factories	CLIC			×	×	< 2.5 T
Energy Frontier	FCC-pp	×	×			16 T -20 T
Energy Frontier	SppC	×	×			12 T- 24 T
Energy Frontier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

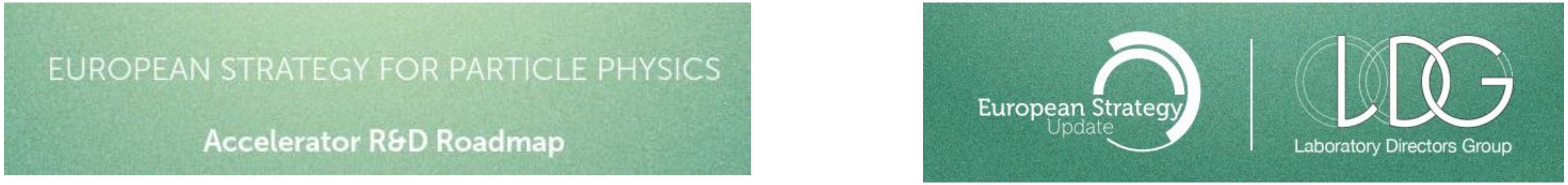
The physics landscape

		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

HTS Enabling Technology

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

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

Beneficial Technology

HTS Enabling Technology

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

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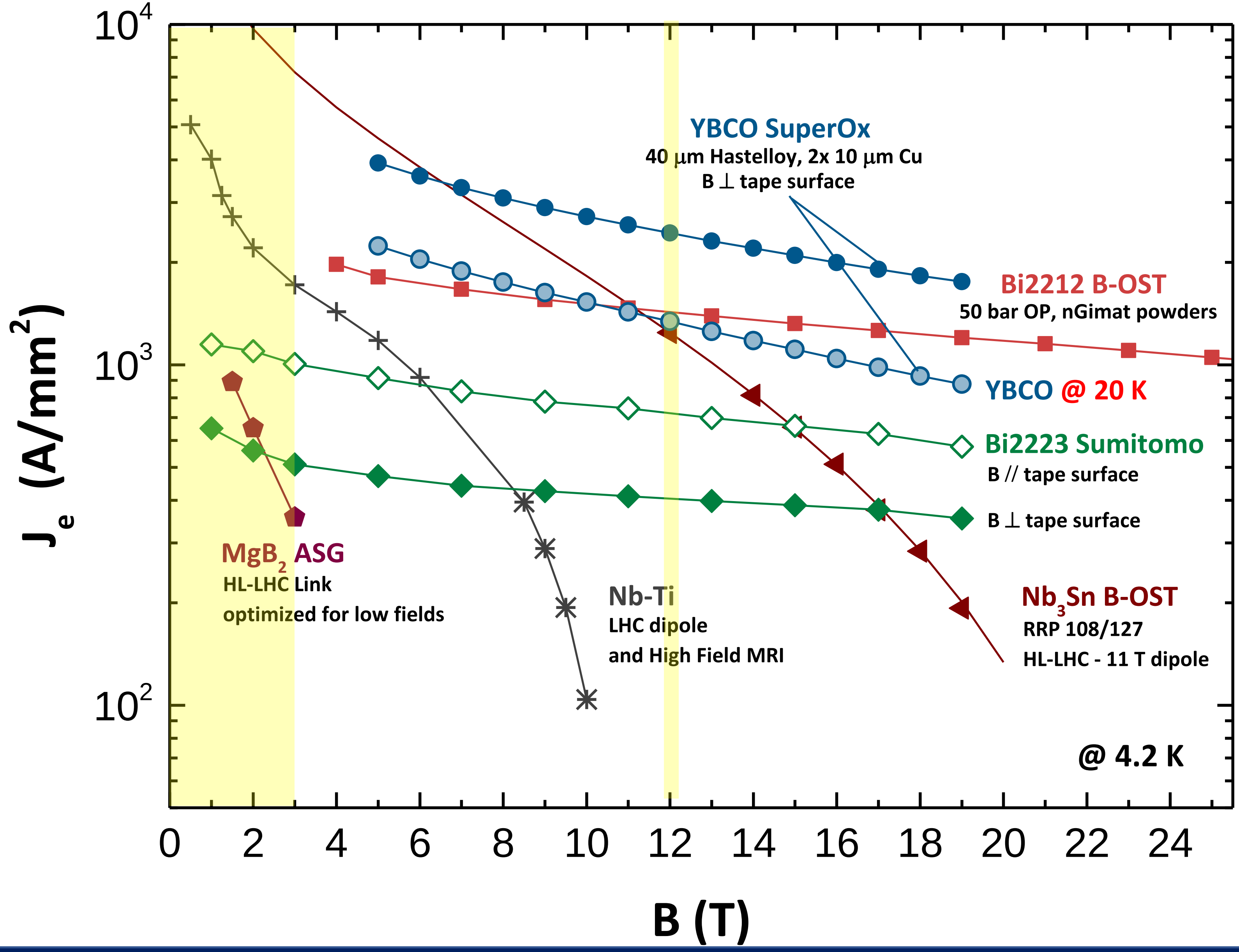
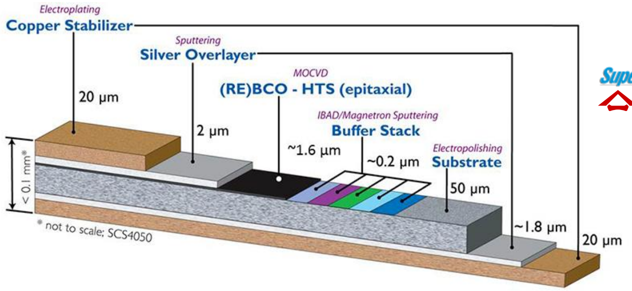
- Conclusions

The present HTS landscape



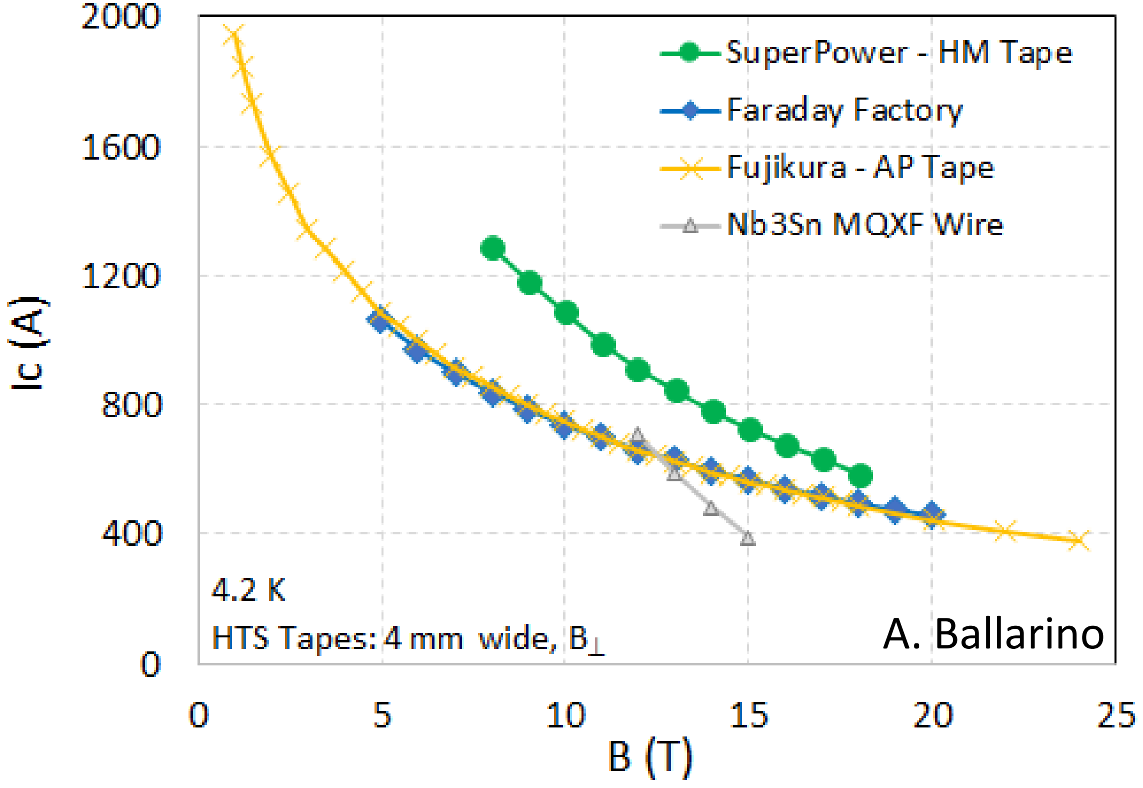
REBCO – Tape

High current capability

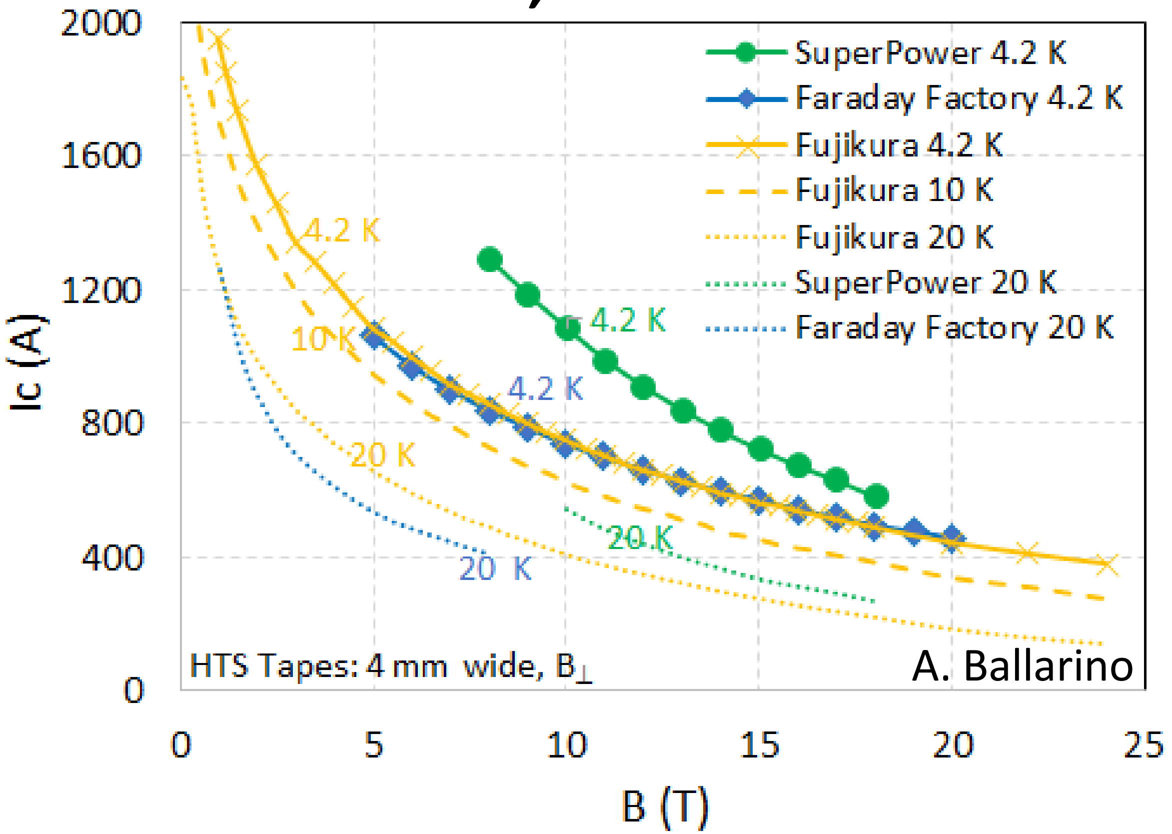


SuperPower FURUKAWA ELECTRIC GROUP

4.2 K



4.2 K, 10 K and 20 K



Data presented by tape manufacturers at the HiTAT Workshop, CERN, March 2023

REBCO

Development on magnets requires having solved all issues on superconductors !

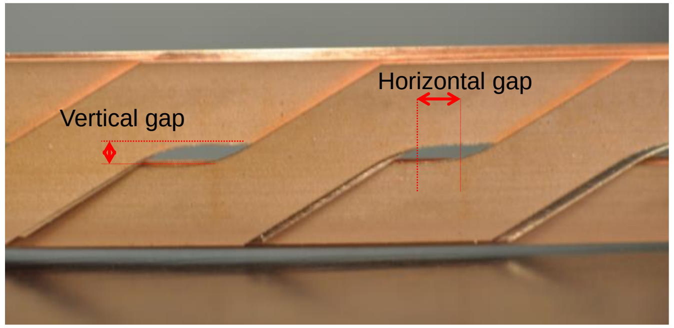
- **Very high current capability**
- **React & Wind technology**
- **Several manufacturers word-wide** (unit lengths ~ 300 m)

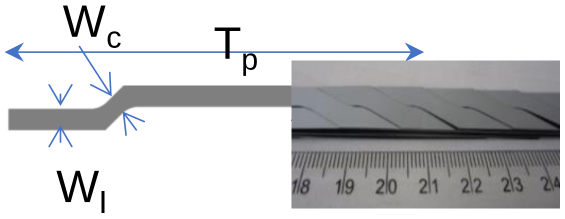
Development to be done on:

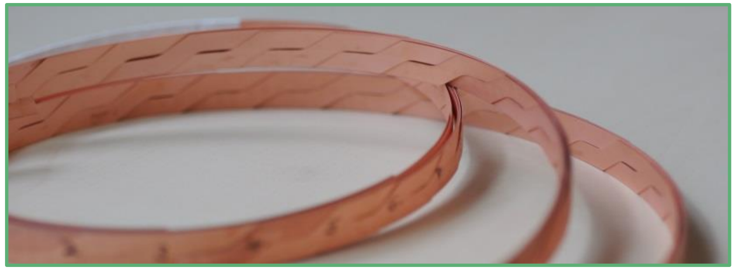
- **QA** of **conductor**
- Longer (> 1 km) conductor **unit lengths**
- **Field quality** issues (effect of persistent currents in wide tapes)
- Effect of **screening currents** on stress/strain distribution
- High current **cables** (twisted and transposed ?)
- **Modelling**
- **Quench detection**, **quench protection**
- **Impregnation** and **insulation** techniques (no insulation, metal insulation, high voltage insulation)
- High current **splices**
- **Magnet** geometry/design – taking into account also tape **anisotropy**
- ….

REBCO – Cables (1/2)

Roebel flat cables for EU Eucard 2







Unit length ~ 54 m

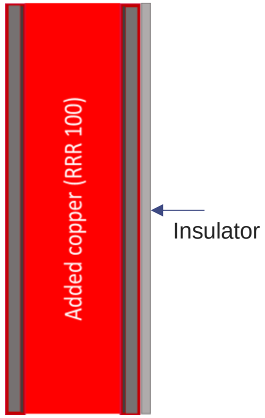
KIT

CORC® round cables

Advanced Conductor Technologies

Stack of tapes

Twisted + insulated, CERN

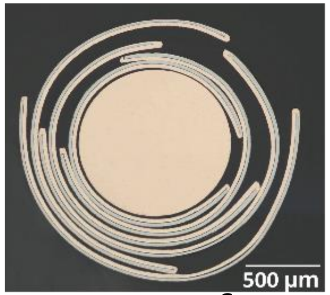


MI, IFAST, CEA

Twisted, MIT

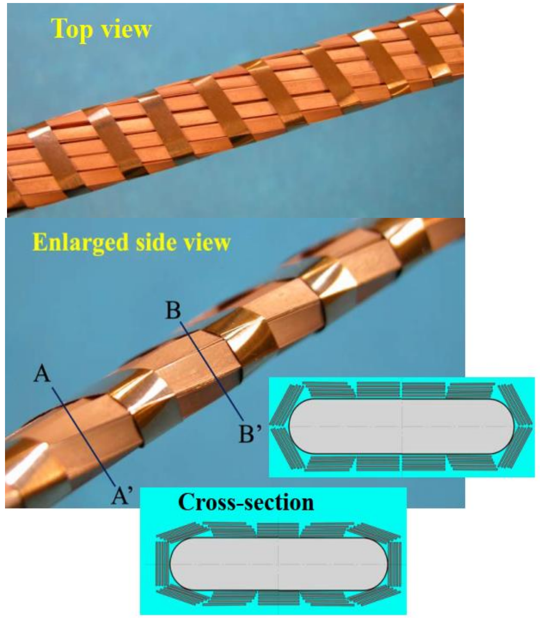
STAR® REBCO Wire

(Φ~0.8 mm)



University of Houston

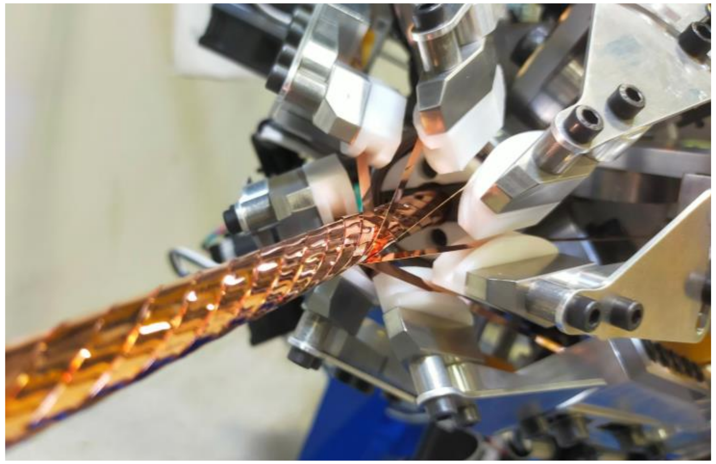
Staked tapes on a flat former

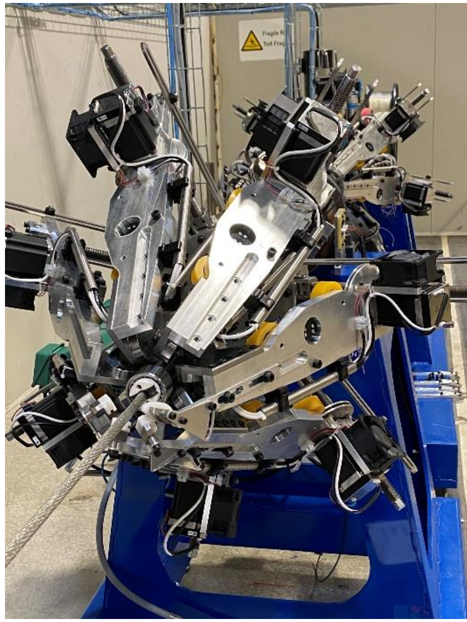


MIT

REBCO Cables for HL-LHC (2/2)

- **Round, flexible, electrically insulated** REBCO cables
- **No** measurable **critical current degradation** of tapes after cabling
- Current rating of REBCO cables: **600 A, 3000 A, 7000 A** and **18000 A @ 60 K** (~ 0.7 T)
- **Cabling machine** designed and constructed at CERN
- **Two layers of tape**
- **On-line** Polyimide **insulation**

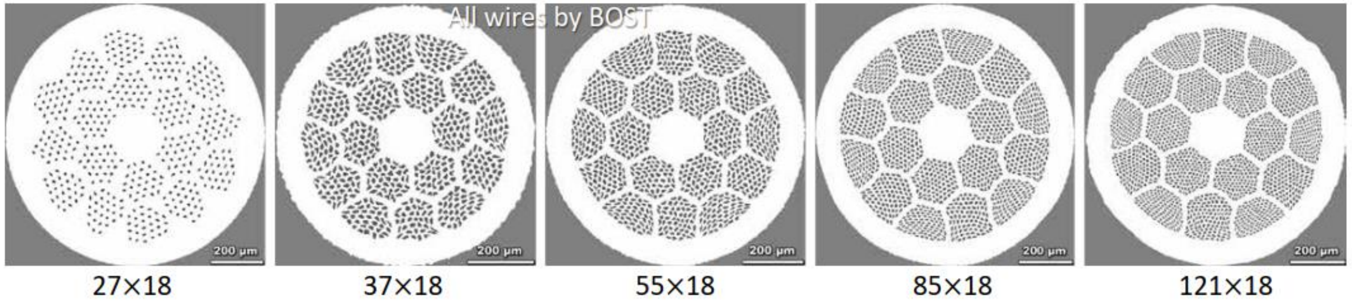




3 kA @ 60 K (B = 0.7 T)

BSCCO 2212 Wire

- Bi-2212 has become a magnet conductor after more than 10 years of coordinated university-lab-industry support through DOE-OHEP and the CDRP
  - It has great advantages – genuinely multifilament with low AC loss, macroscopically isotropic, round and available in single pieces now > 1 km length in multiple architectures and variable diameters
  - It has major disadvantages too – it requires a Wind and React route for HEP and lab magnets at almost 900 C and now optimized Jc requires ~50 bar overpressure (1 bar O_2 and balance Ar)
  - Wires have a breaking strength of ~170 MPa, well below the stresses foreseen for many magnets



D. Larbalestrier, HiTAT Workshop, CERN, March 2023

Iron Based Superconductors

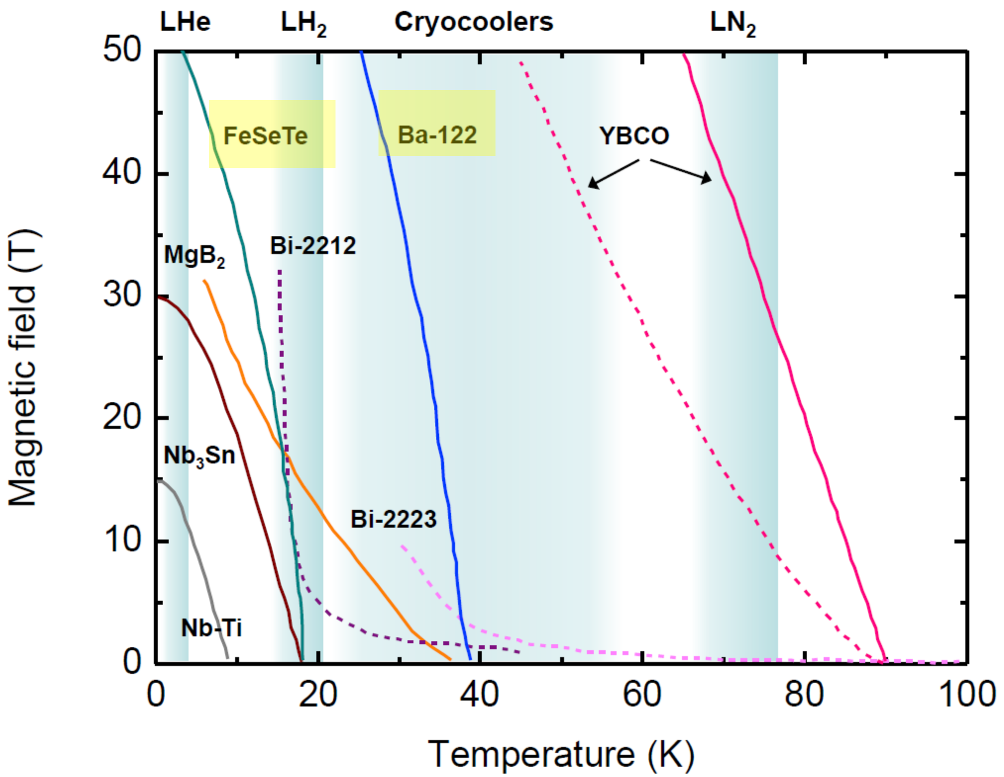
Ba-122:

Tc ~ 38 K

Hc2(20 K) > 70 T

- **High** upper critical **field** (H_{c2})
- **Hirr close to H_{c2}**
- **Small anisotropy**
- Transition to **weak link: θc ~ 9°**

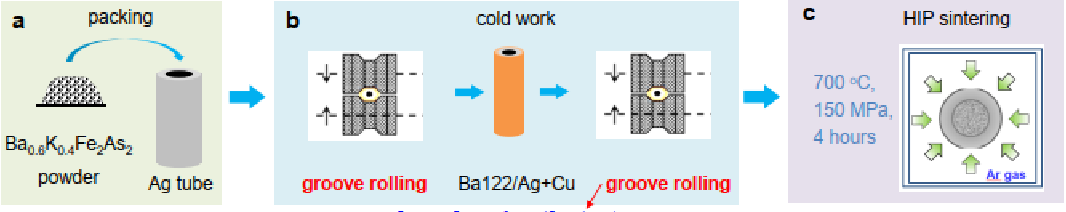
  → **suitable for wires**
- Wires can be produced with the **known scalable Powder In Tube** process at potentially **low cost**



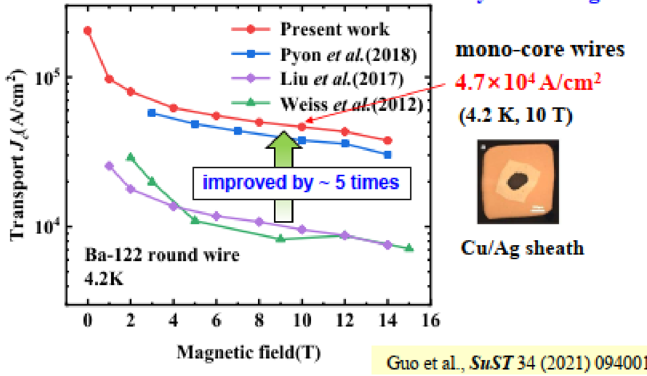
- *A Gurevich, Ann. Rev. Cond. Matt. Phys* **5** *(2014) 35*
- *C Yao and Y Ma, iScience* **24** *(2021) 102541*

Iron Based Superconductors in China

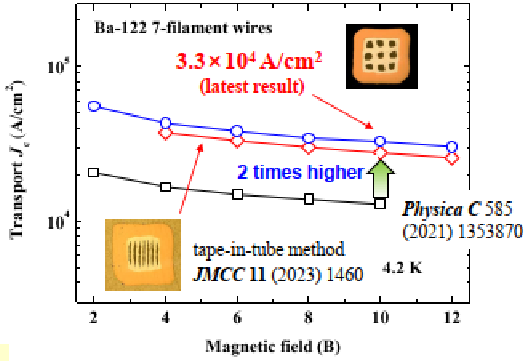
High-J_c Ba-122 HIP wires improved by GR+HIP



by enhancing the texture

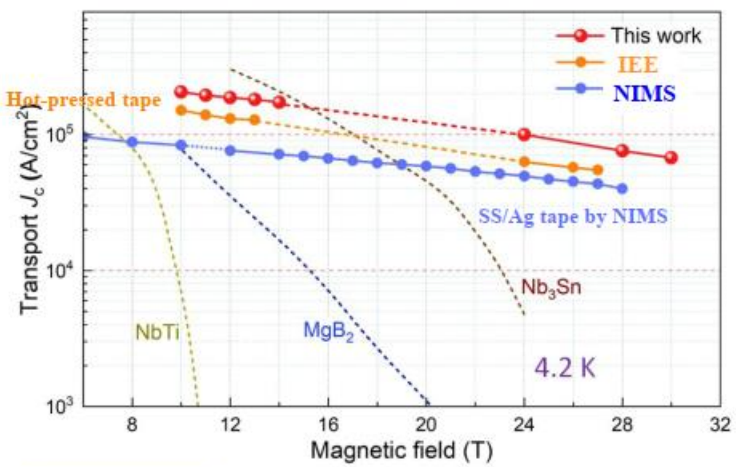


Guo et al., *SuST* 34 (2021) 094001



New record high J_c in PIT SS/Ag Ba122 tapes

Special technique to remove FeAs wetting phase, details will be published soon.

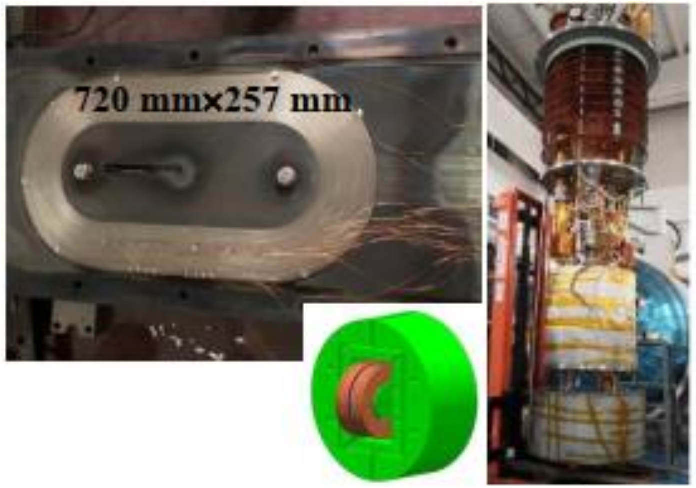


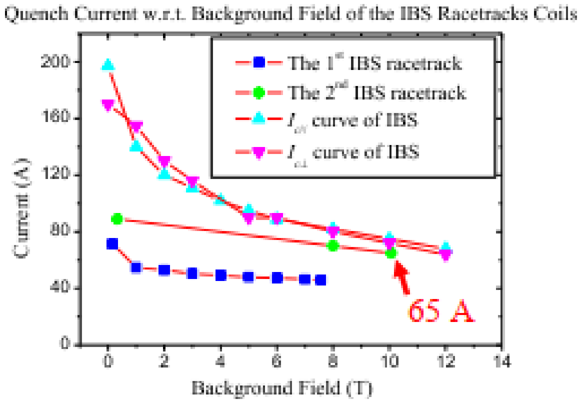
New record!

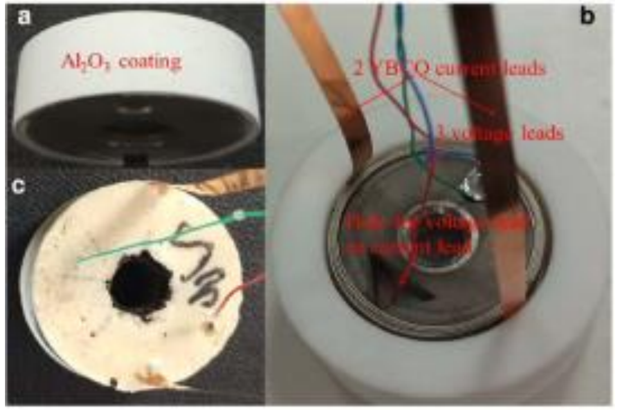
- High J_c @ 4.2 K :
  - J_c~2.2×10^5 A/cm² @ 10 T
  - J_c>10^5 A/cm² even @ 24 T
- High mechanical strength
- Low material cost
- Easy fabrication process scalable to long length tapes

Very promising to be used in high field magnets!

No published data







D. Wang and Y. Ma, HiTAT Workshop, March 2023, CERN

Platform for kilometer-scale IBS wire

D. Wang and Y. Ma, HiTAT Workshop, March 2023, CERN

Plant layout, ~3000 square meters

Currently, a platform for the preparation of kilometer-scale long IBS wire is constructing in China.

Equipment in place

Wire drawing machine

Tape rolling machine

HIP furnace

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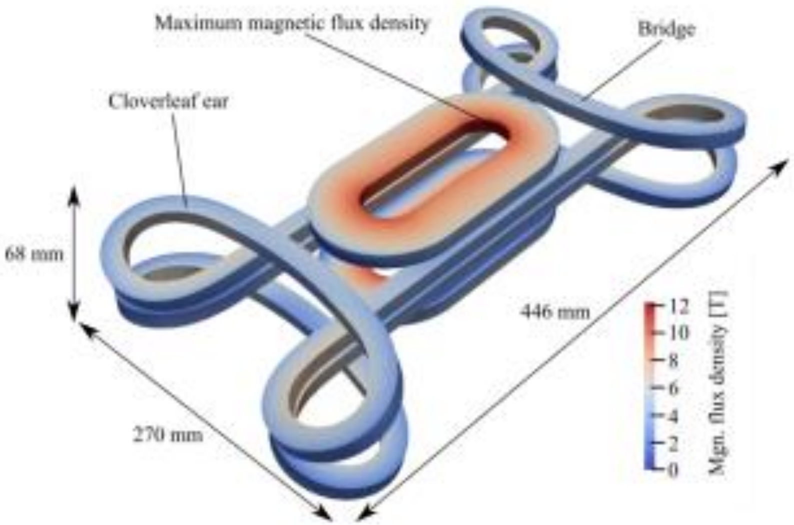
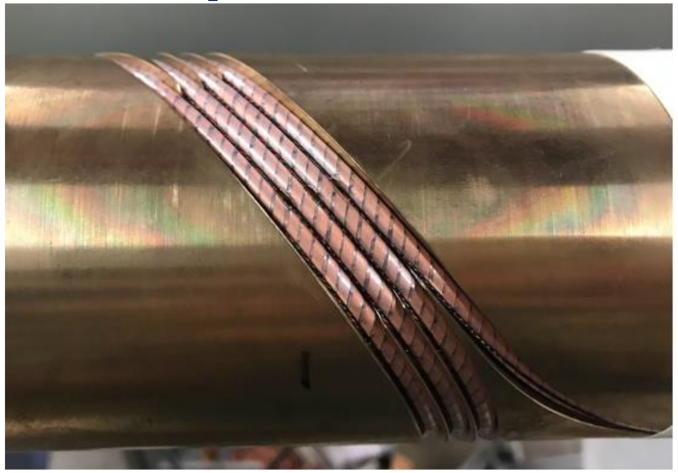
Recent magnet developments

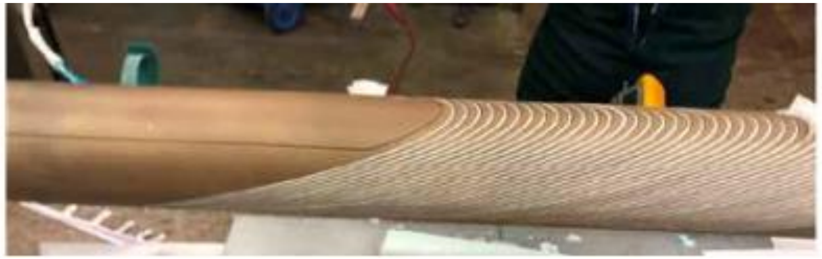
Top the *Re*BCO coil, bottom the Cu tape dummy coil

REBCO Cloverleaf, CERN and KIT
PhD Thesis of Th. Nes

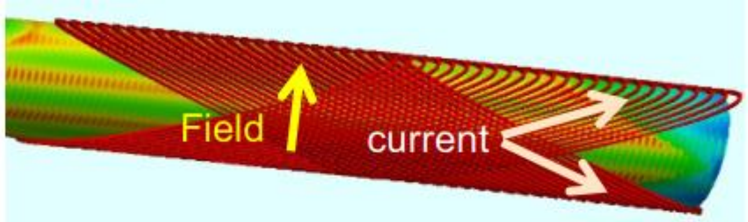


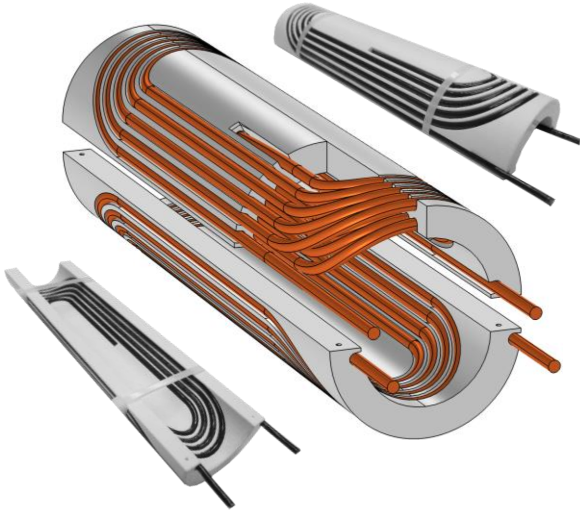


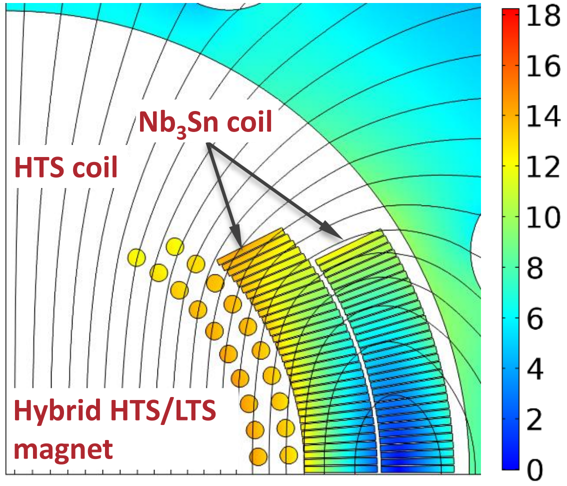
REBCO CORC® CCT,
LBNL



BSCCO 2212 CCT, LBNL and ASC
Rutherford cable







REBCO Conductor **O**n **M**olded **B**arrel (COMB)
Fermilab, STAR Wires

HTS Undulators

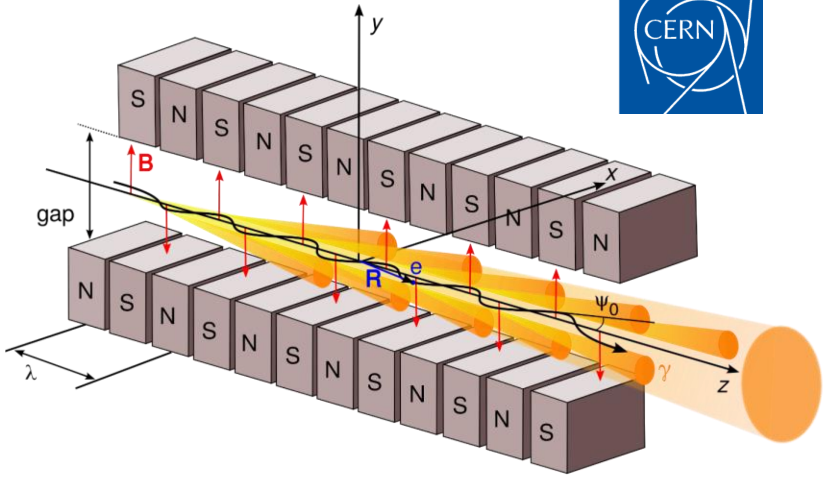
HTS undulators

High field, **short-period**, **compact** undulators operated at **higher temperatures**

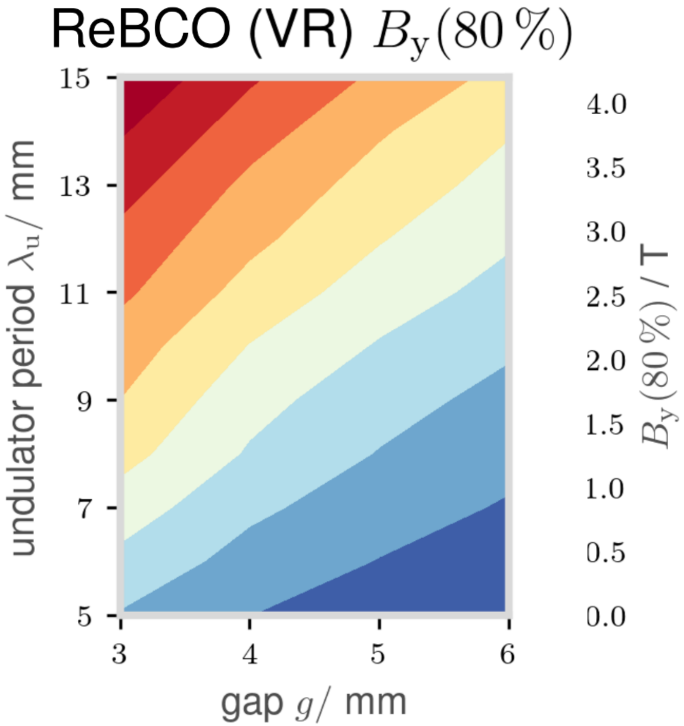
Vertical (VR) and Helical (HL) prototype coils manufactured and tested

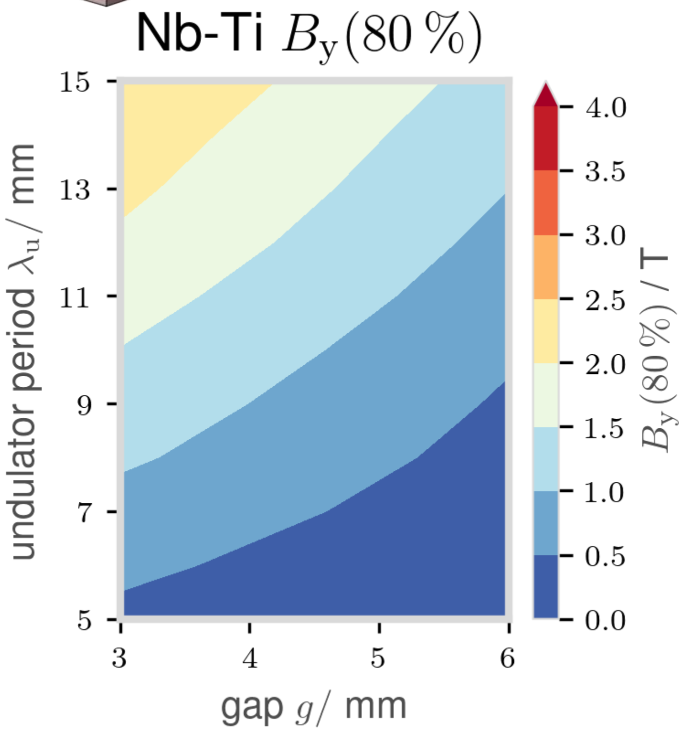
Challenges

- Bending radius < 5 mm
- Quench protection
- Field quality (during ramping)



Planar Undulator





S. Richter, PhD Dissertation at KIT in May 2023

F. Nguyen *et al.* “XLS - D5.1: Technologies for the CompactLight Undulator” (2019), doi: 10.5281/zenodo.3024409

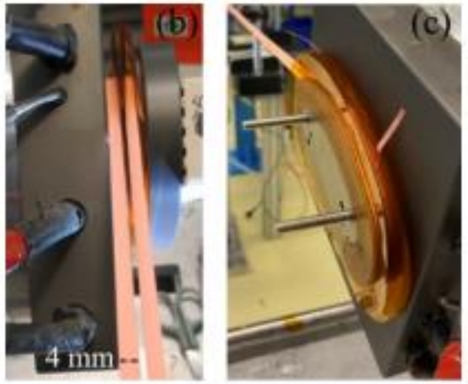
HTS Undulators

No-insulated coils for quench protection

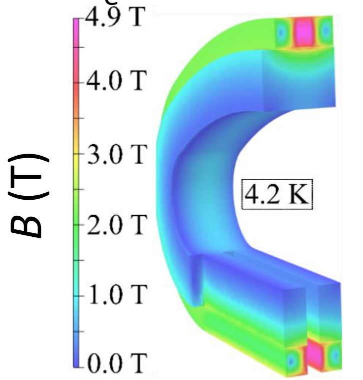
Cu-stabilized for transverse current bypassing

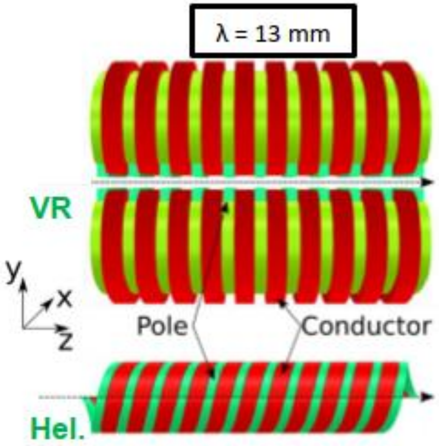
4 mm wide REBCO tape

Vertical



J_e = 2 kA/mm^2





One-period coil

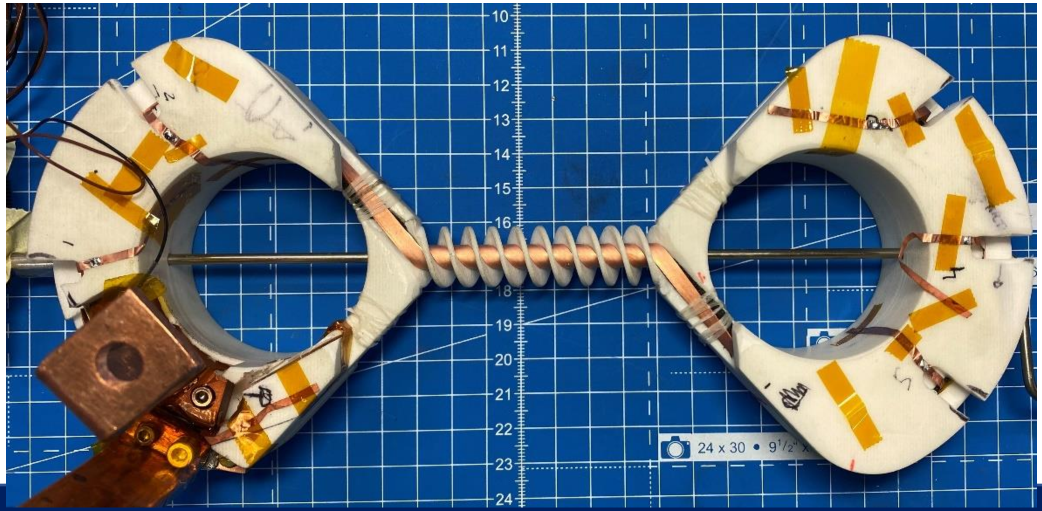
λ_u = 13 mm

Tested at **4.2 K**:

B ≈ 1.5 T, Je=2.3 kA/mm^2

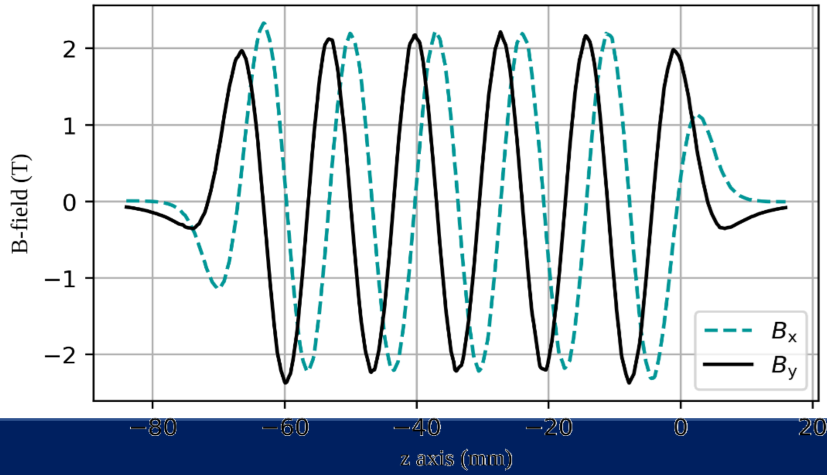
B ≈ 2 T, Je=3.6 kA/mm^2

Helical



Courtesy of S. Richter

Short model simulations at 4.2 K



Very compact design !

12 turns, 2-tape stack

Goal:

λu = 13 mm

Gap 5 mm, 2 T @ 4.2 K

120 turns

The HFM programme

HFM R&D consortium (present main contributors)

PAUL SCHERRER INSTITUT PSI

cea

CNR

SPIN

KIT Karlsruher Institut für Technologie

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

INFN Istituto Nazionale di Fisica Nucleare

ETH zürich

University of Twente The Netherlands

TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG Die Ressourcenuniversität. Seit 1765.

UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES

CERN

- **OBJECTIVE 3:**

  Explore the capabilities and limitations of state-of-the-art HTS and magnet technology based on these superconductors. Demonstrate the suitability of HTS

A. Siemko

HFM Program – KIT/CERN collaboration agreement (1/2)

HTS Coated Conductor synthesis Laboratory

- **Scope**: laboratory for testing at a small scale new scientific ideas, both on REBCO tape and REBCO cables
- **Phase 1**: installation of machine, **setting-up the laboratory**
  Commissioning by end 2023
- **Phase 2** / **Phase 3**: **production of coated conductor** –`lengths of up to 100 m

Laboratory at KIT

HFM Program – KIT/CERN collaboration agreement (2/2)

To be transferred to KIT....

- Tape processing equipment with different substrate handling concepts (batch and reel-to-reel R2R processes) including stabilization

PLD600
Batch vacuum coating

R2R electroplating

ABAD vacuum coater

PLD600
substrate drum

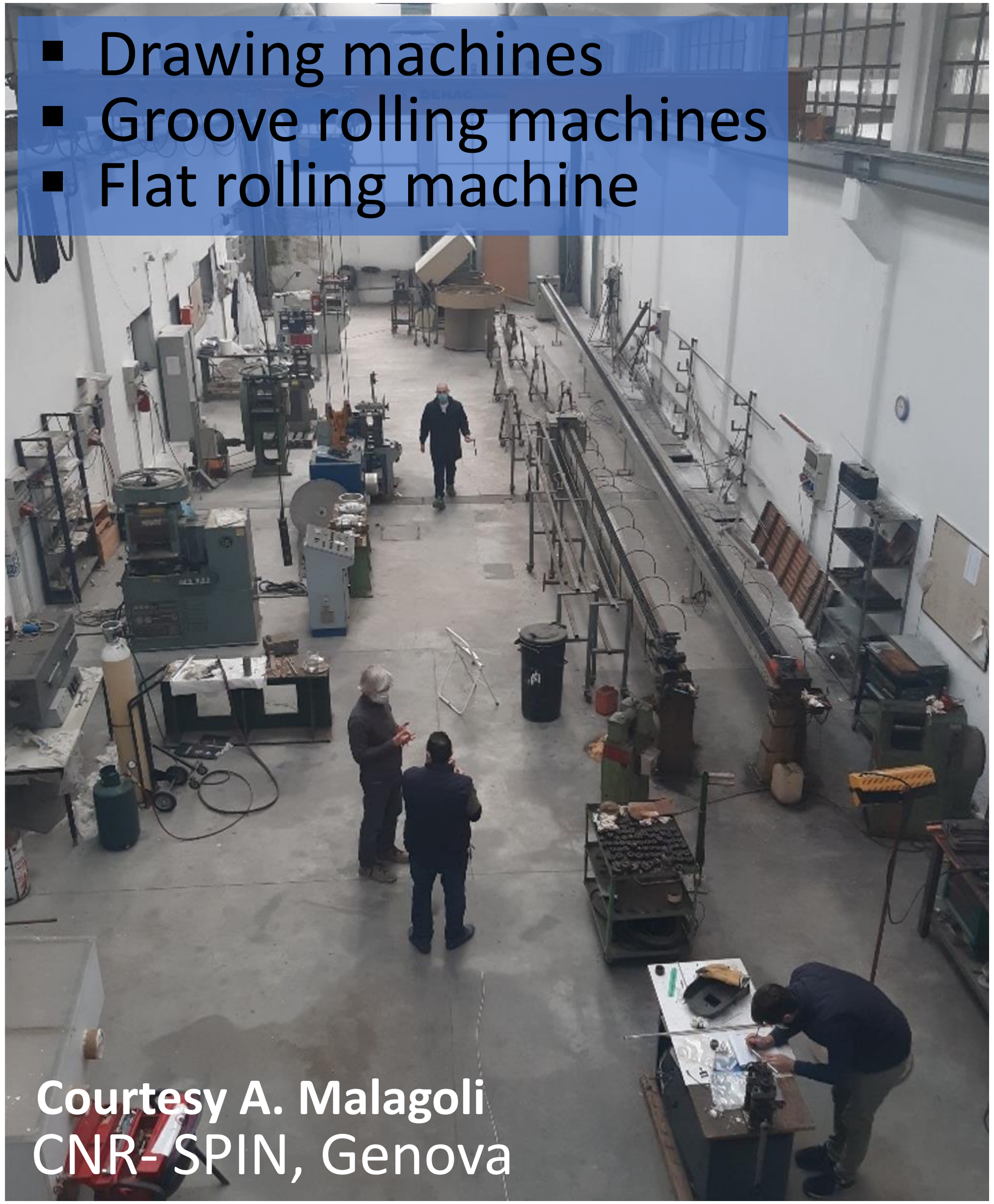
PLD

B. Holzapfel
HiTAT Workshop

HFM Program - CERN/SPIN collaboration agreement

Iron Based Superconductors Laboratory

- R&D on Iron Based 122 PIT wires
- Critical current density (J_c) through reliable, simple and scalable techniques that could enable industrialization
- **Target Jc ≥ 10^3 A/mm^2 at 16 T**
- From mono to multi-filamentary wire
- Target unit length ~ 100 m



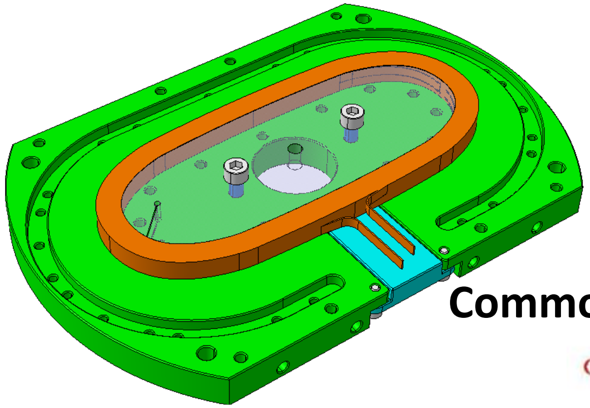
HFM HTS CERN programme

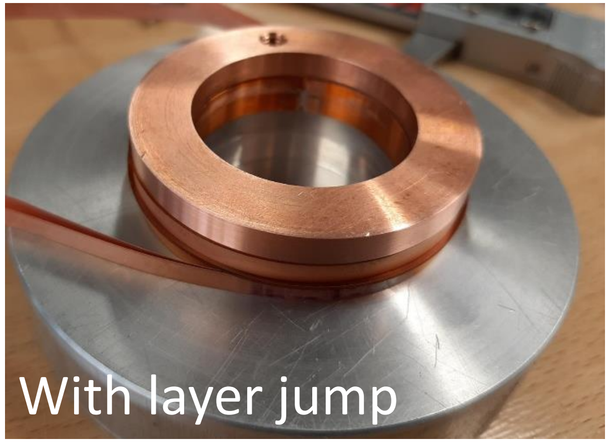
- **Objective**: demonstrator of **5 T in** a background field **of 15 T**
- Development of electrically insulated cables. **Target**: 10 kA @ 20 T, 5 kV
- Model racetrack coils
- Common coil design

Electrically insulated stacks of REBCO tapes

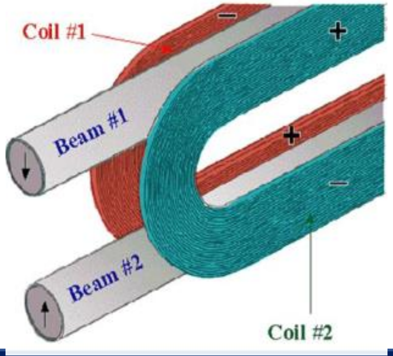
Ø int 37 mm
Ø ext 57 mm

Winding machine - up to 14 tapes



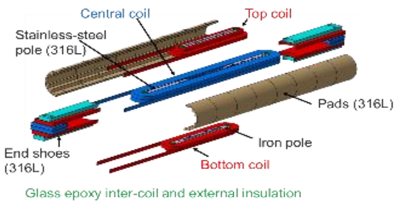


Common-coil design, R. Gupta

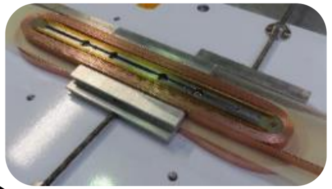


HFM HTS CEA Programme –CERN/CEA Collaboration Agreement

Racetrack EUCARD (insert)



2017
→ 5.4 T ☺



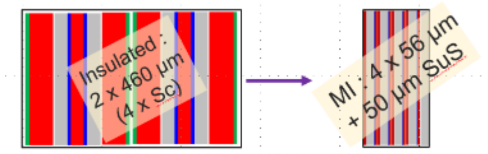
BUT ☹

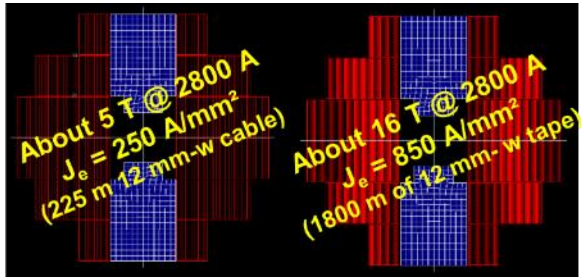
NOUGAT MI REBCO insert

2018 → **32.5 T** (in 18 T)
Still working ☺

MI : high j_e, self-protected

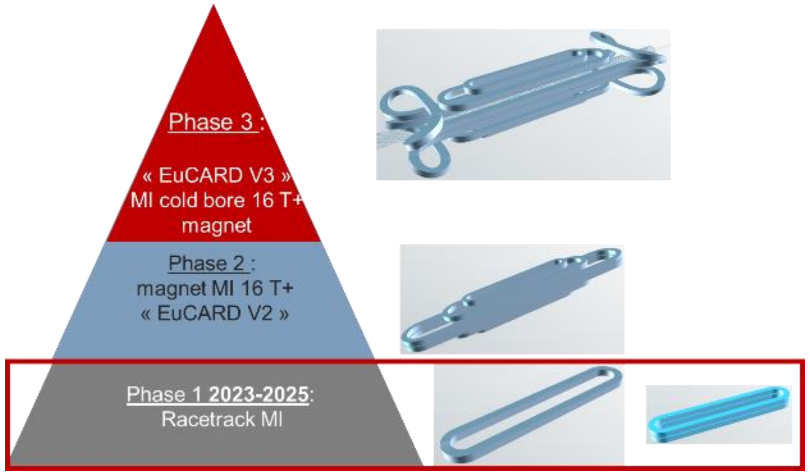
Consider MI technology for helping HFM HTS dipole





With same margin (ROXIE)

3 main phases program « step by step »



Phase 1 : HFM KE 5647/TE CERN/CEA Agreement

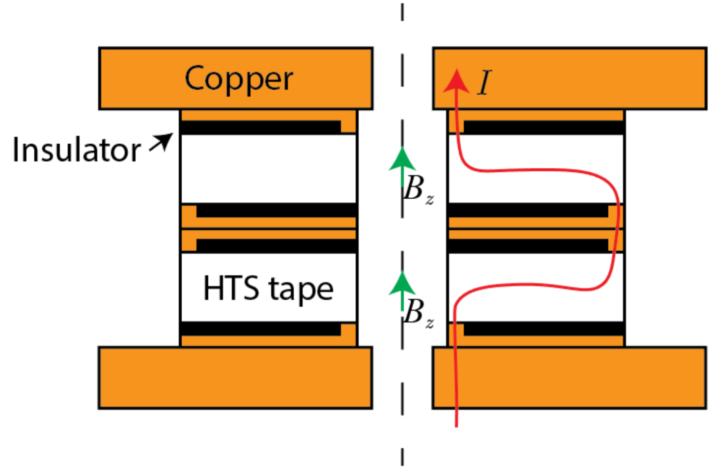
- **Use «Metal-insulated (MI)» winding:**
  - No need for insulation nor Cu stabilizer
  - **Considerable increase of the current density** in the coil to reach very high fields
- **Concepts:**
  - **20 T @ 4.2K**
  - Or **16 T @ 20 K** → opportunity to lower exploitation costs or simplify cryogenics
- **Use reduced model coils:**
  - **Lower risks and costs**
  - **Lower** development times
  - Possibility to change the central coil to add aperture

Th. Lecrevisse

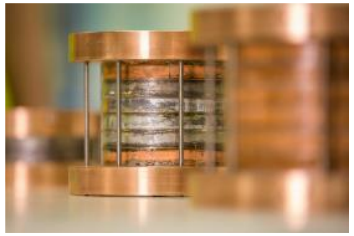
HFM programme at PSI

Swiss Accelerator Research and Technology

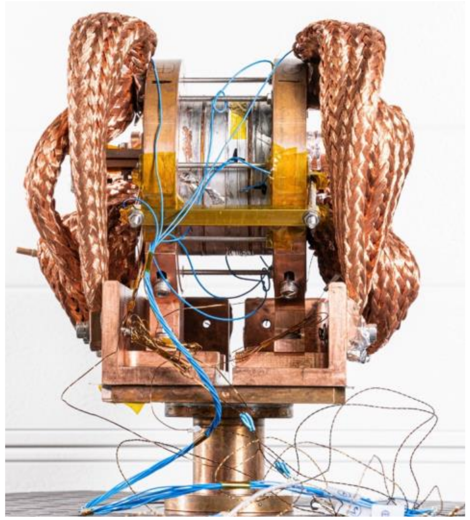
NI coil technology license agreement with Tokamak Energy



Tokamak Energy



Greg Brittles



REBCO, 2 tapes

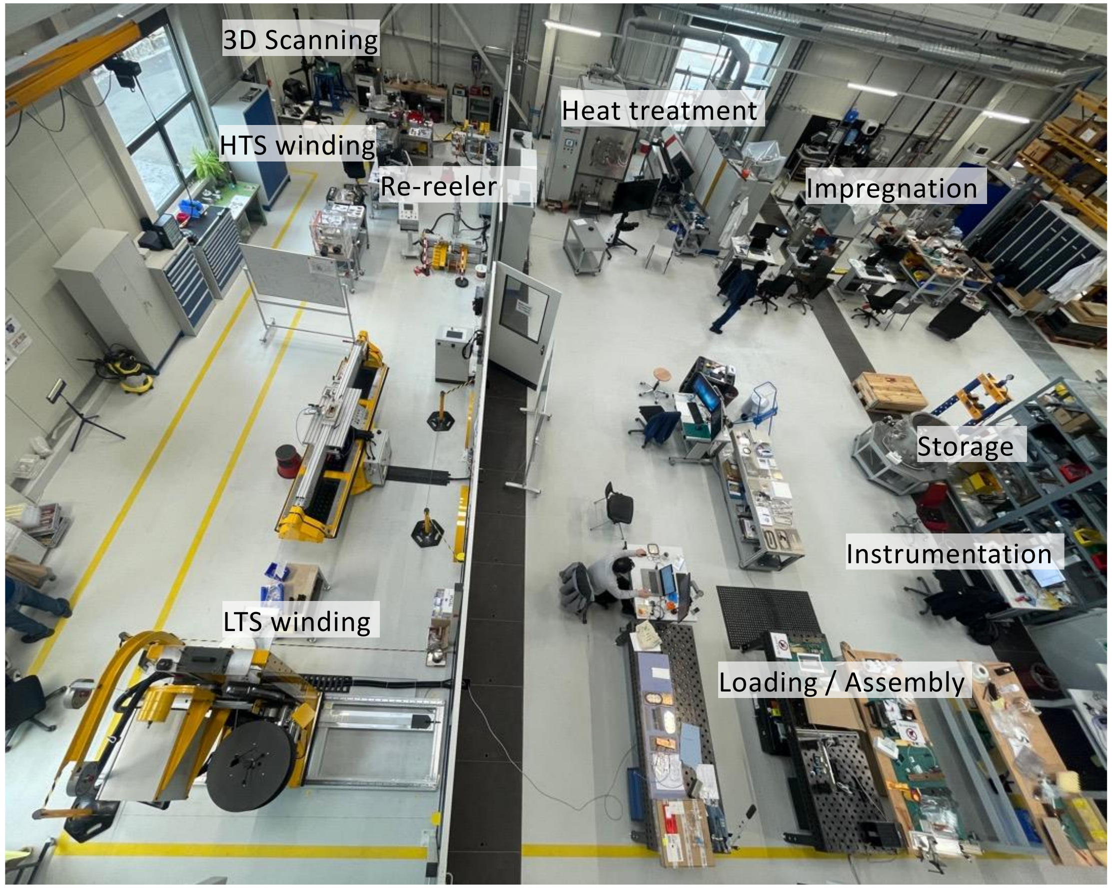
18.2 T in the center,

20.3 T on the conductor

2 kA and 12 K

Aperture: 50 mm

MagDev Laboratory



B. Auchmann, HiTAT Workshop at CERN, March 2023

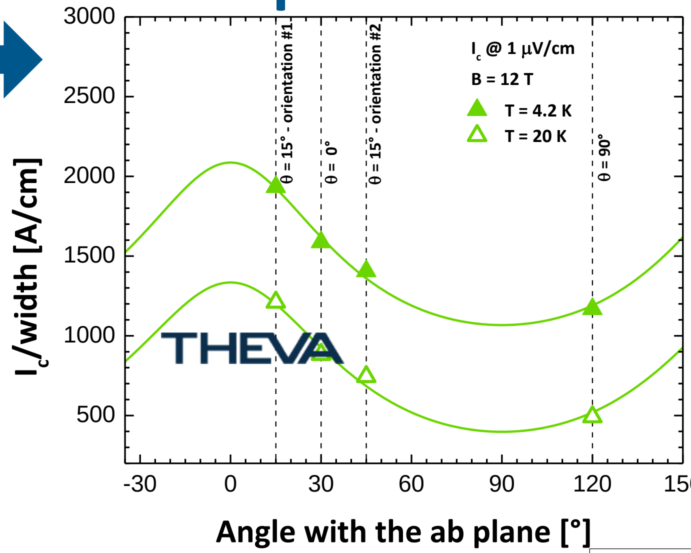
HFM HTS UNIGE Programme –UNIGE

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

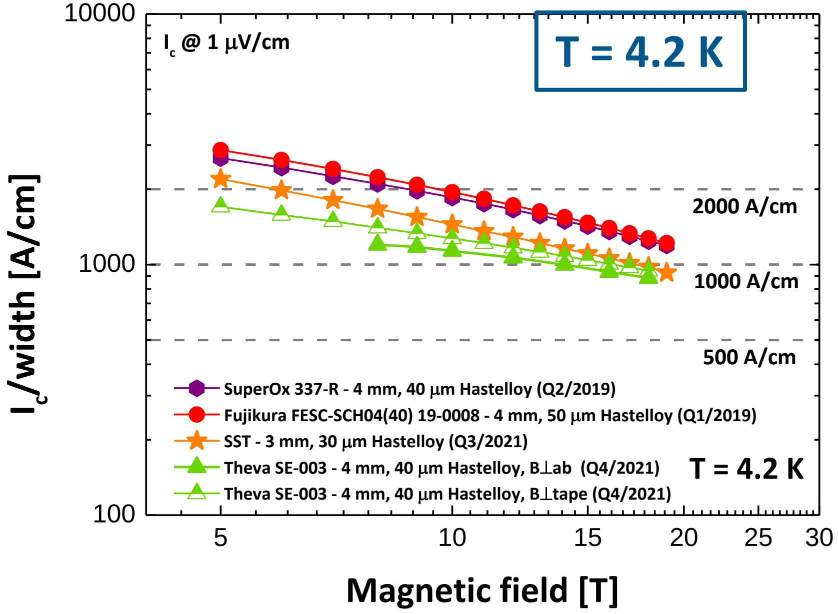
Transport critical current tests up to 2 kA

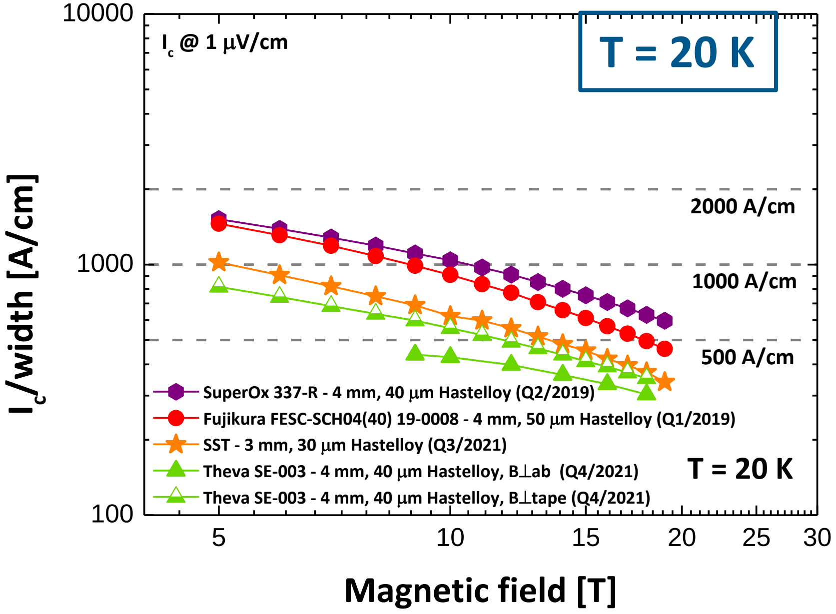
Various orientations in magnetic fields up to 19 T/21 T and variable temperatures

Angular dependence of I_c

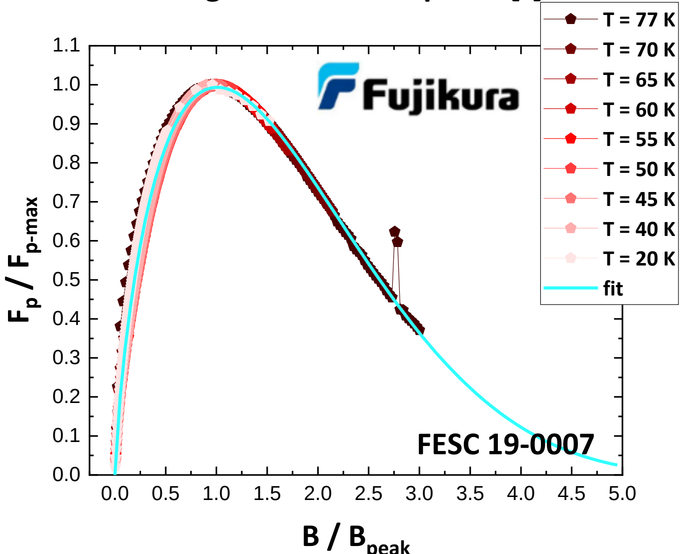


Comparison of I_c / width – high performance tapes





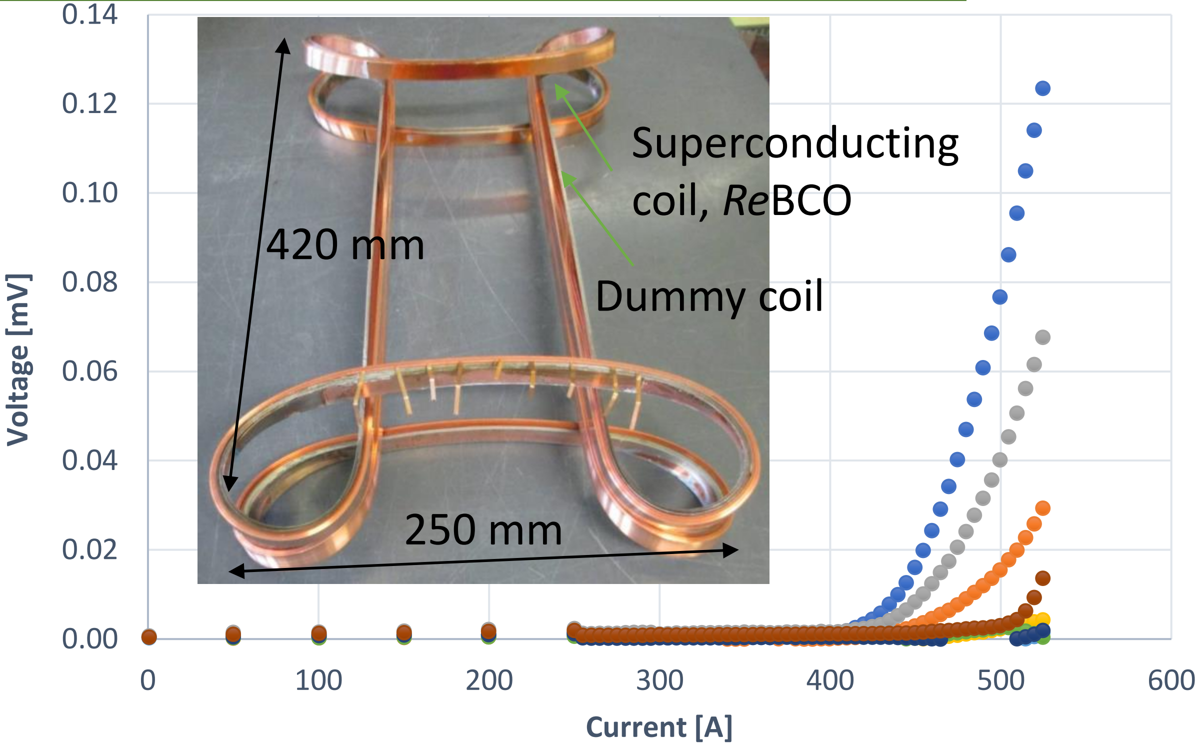
Pinning force scaling



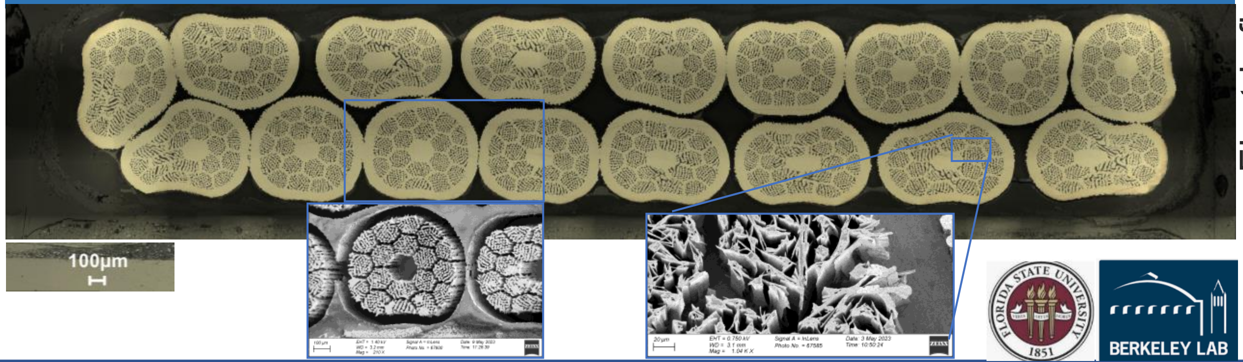
C. Senatore

Twente University

Cloverleaf measurement in 77 K and self-field



Transverse stress of BSCCO-2212 Rutherford cable

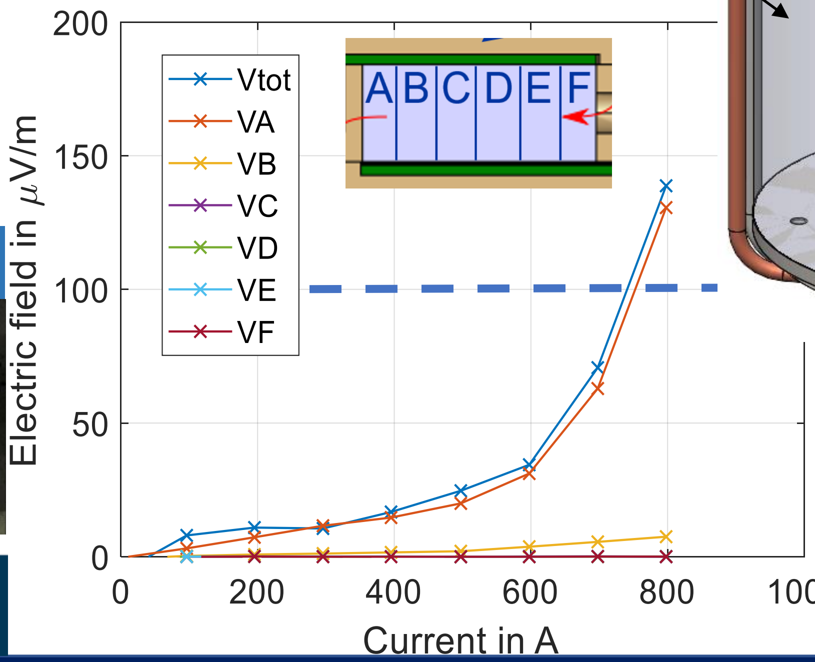


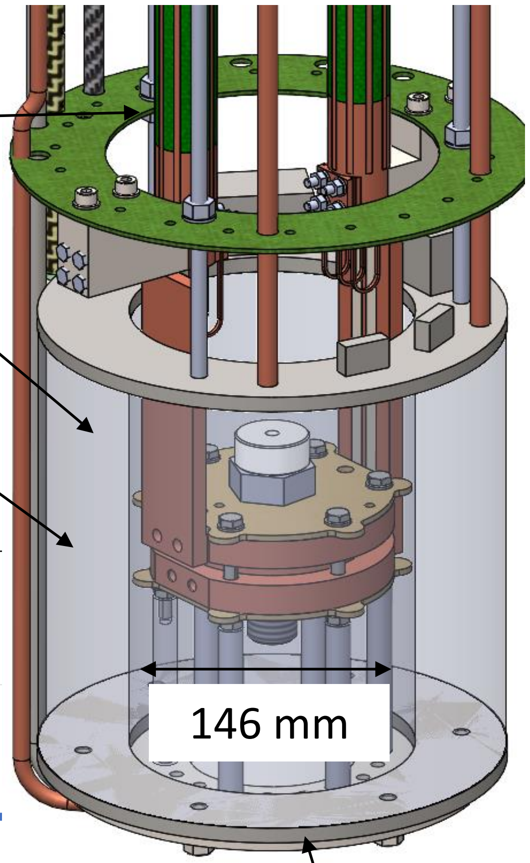
Measurement of ReBCO pancake in background field

HTS/vapor cooled current leads

Solenoid magnet 7 T

NI dry wound double *Re*BCO pancake coil





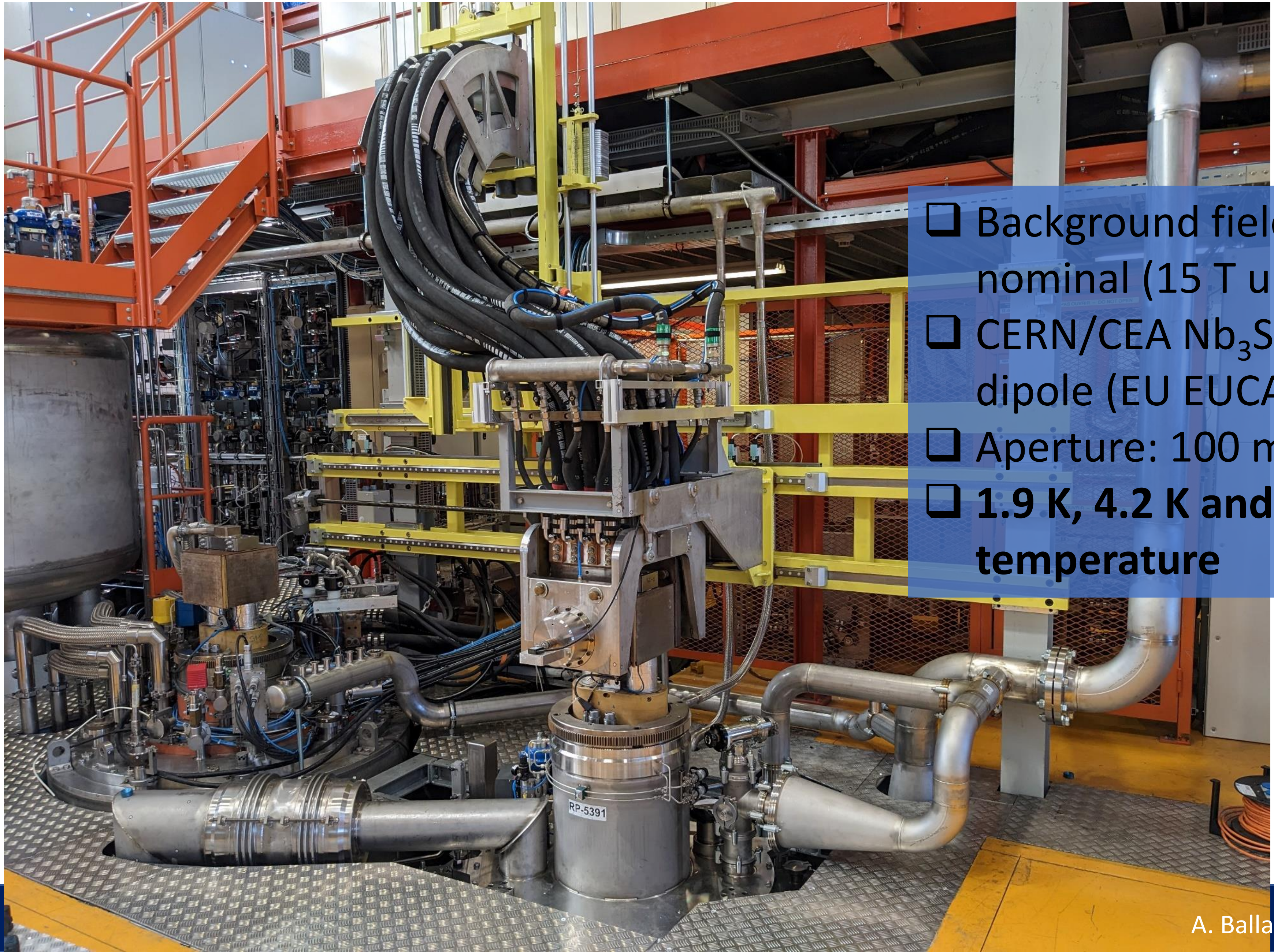
*Re*BCO coil mechanical support

A. Kario

Outline

- Introduction
  - Potentials of HTS technology
- HTS Materials and cables
  - REBCO, BSCCO 2212, Iron Based Superconductors, MgB_2
- HTS magnet developments
- HTS in the High Field Magnet Program
- **Test facilities for HTS technology**
- HTS for fusion
- Conclusions

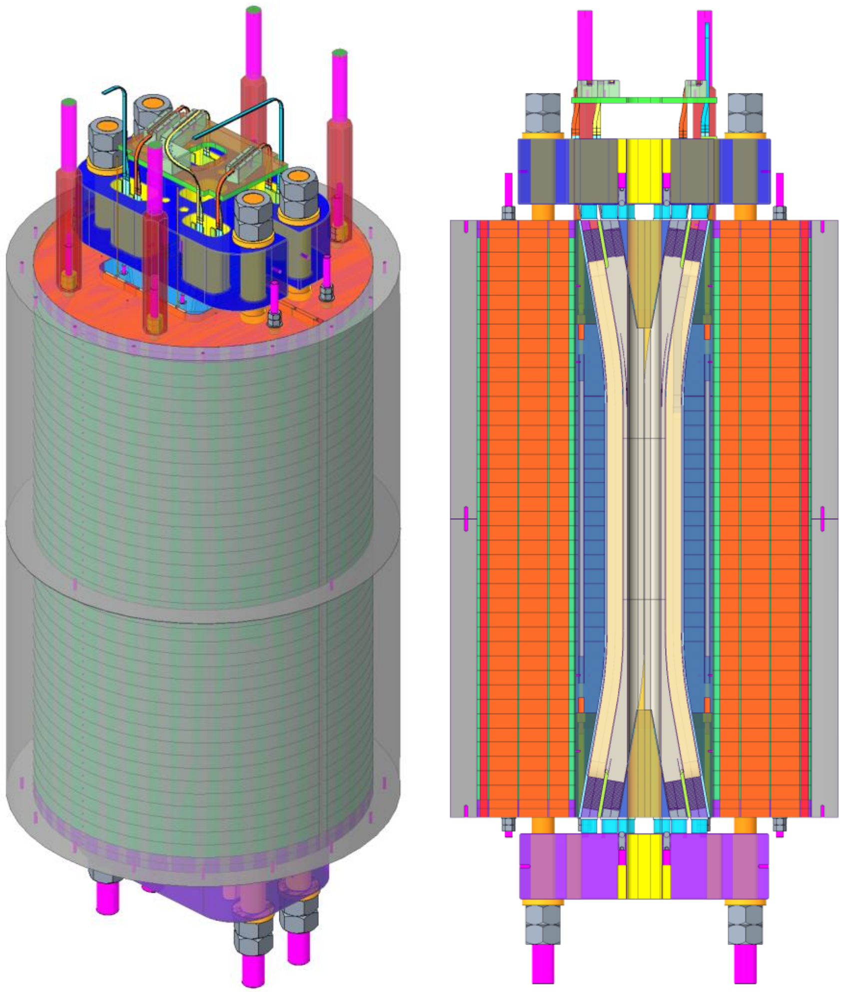
Fresca 2 at CERN – The superconductors laboratory



- Background field: **13 T** nominal (15 T ultimate)
- CERN/CEA Nb_3Sn block-coil dipole (EU EUCARD project)
- Aperture: 100 mm
- **1.9 K, 4.2 K and variable temperature**

HTS Cable Test Facility – a DOE sponsored FES + HEP Effort, FNAL + LBNL Collaboration

- Leveraging work by the HEPDipo collaboration and experience from the FRESCA-II team
- **Nb_3Sn** Magnet with an operation target of **15 T at 1.9 K** (design target 16 T at 1.9 K)
- Bladder-and-key + Al shell, block coil design
- Straight section (<1% variation) >750 mm
- 150 x 102 mm rectangular aperture with superimposed 114 mm diameter
- Conductor: Ti-doped Nb_3Sn RRP® 162/169 at 1.1 mm diameter, 44-strand Rutherford cable
- **Started in 2019**, **expected operation in 2026**



Courtesy of Yan Pong

Dipole Magnet Design in USA, Fabrication & Test – LBNL Facility Host & Operator – FNAL

HTS Cable Test Facility Project
LBNL PI: Soren Prestemon . FNAL PI: Giorge Velev

Magnet Advisor
Paolo Ferracin

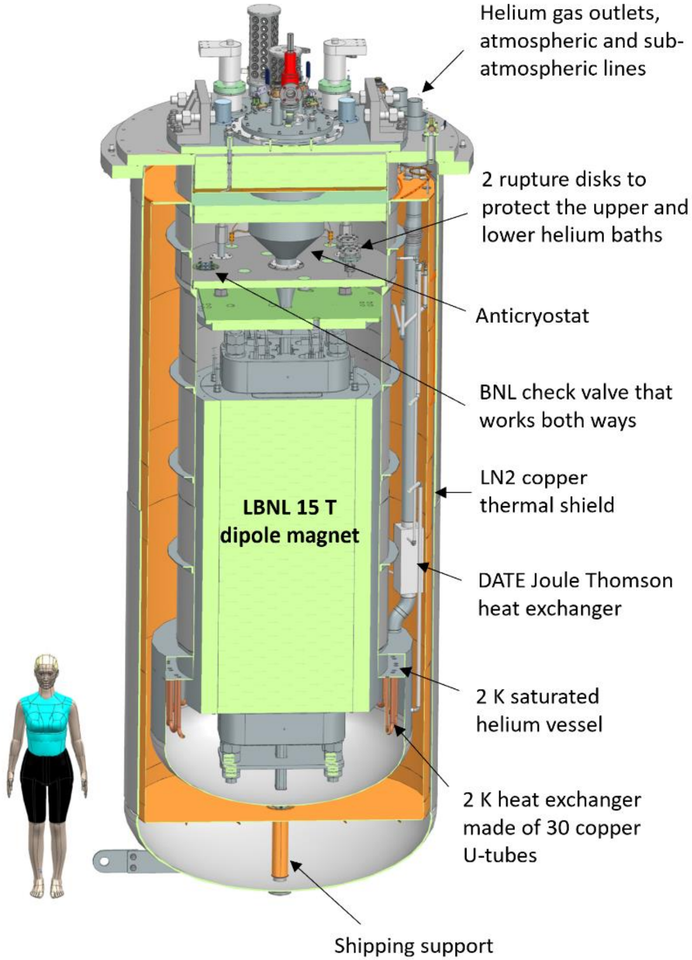
Test Facility Dipole
PI: Soren Prestemon
Project Manager: GianLuca Sabbi

- Conductor & Cable: Ian Pong
- Magnet Design & Fab: Diego Arbelaez
  - Magnet analysis Giorgio Vallone
  - Magnet construction Jose-Luis Rudeiros Fernandez

HTS Cable Test Facility
Pi/Project Director George Velev
Project Manager: V. Nikolic

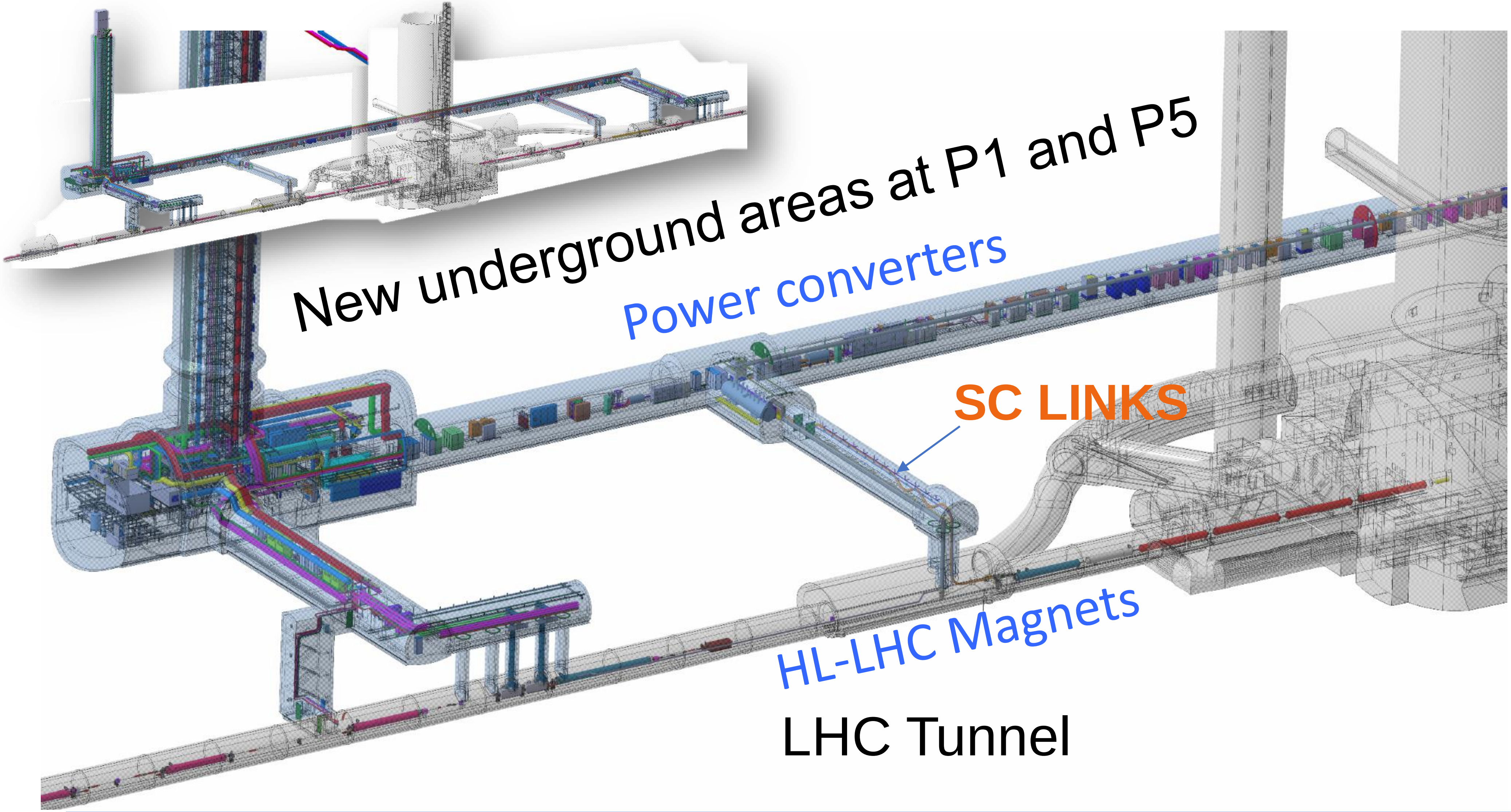
- Mechanical V. Nikolic
- Cryostat R. Bruce
- QP/QC system C. Arcola
- Power supplies X. Yuan
- Integration G. Velev (interim)

Parameter	Value
Background Dipole Field	15 T
Minimum Operational Temperature	1.9 K
Maximum Magnet Diameter	1.3 m
Maximum Magnet Length	3.0 m
Maximum Stored Energy	20 MJ
Maximum Weight	20 t
Test Sample Temperature	4.5-50.0 K
Max. Test Sample Current (direct)	16 kA
Max. Test Sample Current (transformer)	100 kA



G. Velev et al., "*Status of the High Field Cable Test Facility at Fermilab*", ASC 2022

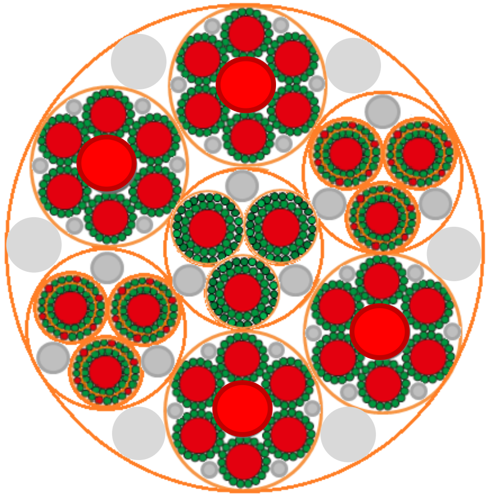
HTS for accelerators – Electrical transmission for HL-LHC



Ten Systems for HL-LHC : 5 for the Triplets and 5 for the Matching Sections

HTS for accelerators – Electrical transmission for HL-LHC

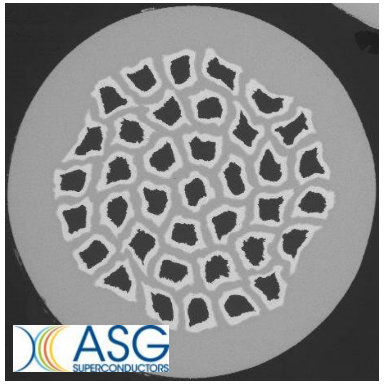
- Procured in total **1430 km** of **MgB_2 wire (Φ = 1 mm).** Delivered by ASG in **unit lengths** of up to ~ **4 km**
- **Industrialized cabling**: 70 % of the production completed

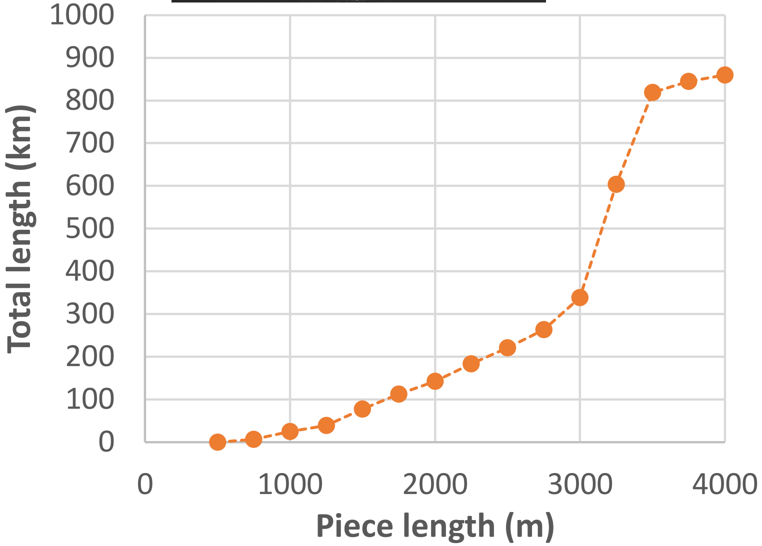


120 kA @ 25 K and 1 T
Φ~90 mm

HTS for accelerators – Electrical transmission for HL-LHC

MgB_2 wire, Φ = 1 mm





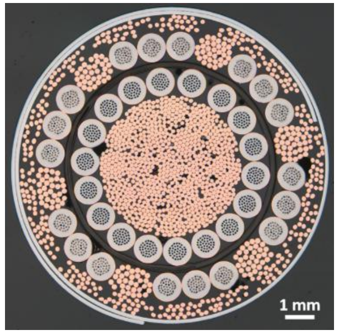
Distribution of piece lengths (by length)

Wire diameter	mm	1	± 0.2
Wire ovality	mm	≤ 0.015	
Cu fraction	%	≥ 12	
Cu coating	µm	≥ 30	
Filaments eq. diameter	µm	≤ 60	
Filaments Twist Pitch	mm	≤ 100	± 5
Tensile strain at RT *	%	≥ 0.26	
Bending radius after HT *	mm	≤ 100	
Unit Length	m	≥ 500	
RRR (Cu)	-	> 100	
Ic(25 K, 0.9 T)	A	≥ 186	
Ic(25 K, 0.5 T)	A	≥ 320	
Ic(20 K, 0.5 T)	A	≥ 480	
n-value@ 25 K and 0.9 T	-	> 20	

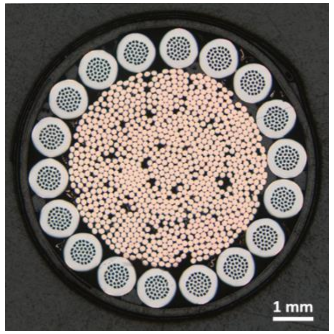
Cabling made with reacted wire

Series cabling at TRATOS/ICAS

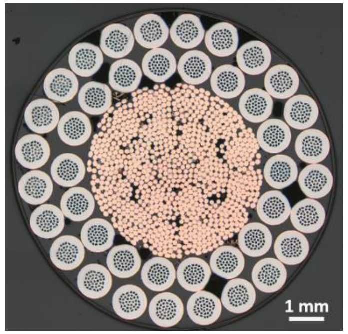
3 kA coaxial @ 25 K



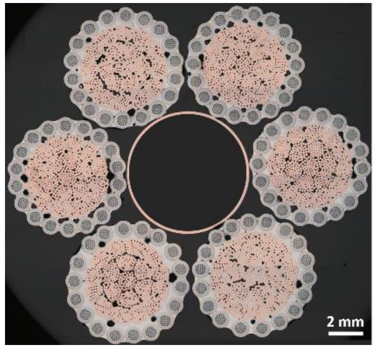
3 kA @ 25 K



7 kA @ 25 K



18 kA @ 25 K



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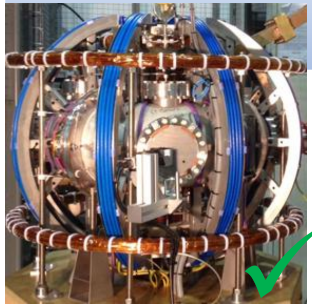
- **Test facilities for HTS technology**
- **HTS for fusion**
- **Conclusions**

HTS for fusion (1/2)

Development Roadmap

Tokamak Energy

2014



ST25

ST25 Achievements

- ST Concept
- Plasma heating and current drive development

2015

ST25-HTS

ST25-HTS Achievements

- First HTS TF coils
- H plasma held for 29 hours

2016 – on-going

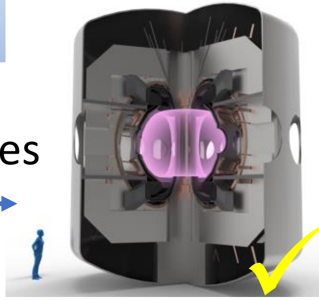
ST40

ST40 Achievements

- Highest field ST worldwide at 2.1 T on-axis.
- 100M °C D-H plasma temperature
- On-going development programme

- TF and PF REBCO Coils
- Stacks of tapes

Build completion 2026



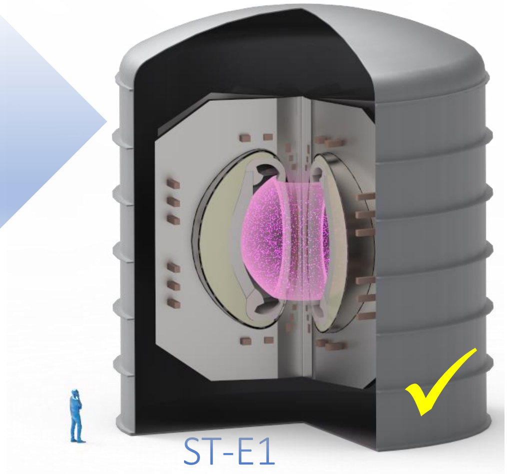
ST80-HTS

ST80-HTS Objectives

- Demonstrate long pulse operation
- Control and protection of mid-scale HTS magnets

Up to 20 T in the TF coils (~ 30 kA)

Early 2030s

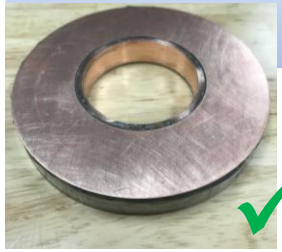


ST-E1

ST-E1 Objectives

- Up to 200MW of net electrical power
- Prototype energy generating ST
- Full scale HTS magnets
- Demonstrate plasma control and fault condition recovery at scale

2018



QA NI coils

QA NI Coils Achievements

- Tape QA
- Defect tolerant coils
- Robust jointing & ETI plates
- Modular magnet build

2019

Demo3

Demo3 Achievements

- First, conduction-cooled all REBCO magnet to exceed 22T (field on tape) at 20K

2020

Demo2

Demo2 Achievements

- PI development
- Validation of bespoke transient modelling tools (Racoon)
- Quench resistant
- Magnet dynamics very closely correlated to model predictions

2020 -2022

AMR WP4

AMR Achievements

- Demonstrated cryogenic PSU technology
- Developed EFC coil design code
- Coil scale-up study
- Coil Cryogenic Compression System designed and built
- Quench modelling code developed and validated

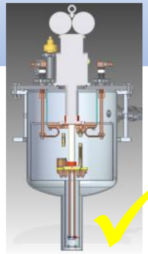
2019 - 2023

Demo4

Demo4 Objectives

- Demonstrate PI for TF coils
- Operation of balanced set of TF coils
- Explore transient control and losses in PF coils
- Explore PF field shine on TF coils
- Quench protection and energy dumping trials

2023



Gamma

Gamma Objectives

- Irradiate small test coils wound from selected REBCO tapes
- Co60 irradiation up to 10MGy dose.
- Coils are cooled to 20K and energised to Ic
- Ic degradation measured in real time

2022 - 2026

BB01

BB01 Objectives

- Developing prototype coils for ST80
- Developing coil manufacturing processes and tooling
- Developing magnet assembly processes and tooling

Rod Bateman, presented at HiTAT Workshop – March 2023

HTS for fusion (2/2)

Conclusions

- **HTS is the enabling technology for high field magnets**. It also offers solutions for magnets operated at lower fields – and higher temperature

- **A vigorous and focused R&D** is needed in order to make of HTS a robust technology for future accelerator magnets. A **major re-thinking of the existing technology and mode of operation** is required

- **Cost** of today industrially available HTS conductor is a challenge. A **large application** is **required to boost production and reduce the cost**

Thank you for your attention !

HiTAT Workshop at CERN

https://indico.cern.ch/event/1220254/

iFAST CERN

1st High Temperature superconductors for Accelerator Technology (HiTAT) workshop

Mar 9 – 10, 2023
CERN
Europe/Zurich timezone

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- CERN Shuttle
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- How to upload a presentation

Contact

Valerie.Brunner@cern.ch

We are pleased to announce the **1st High Temperature superconductor Accelerator Technology (HiTAT) workshop**. HiTAT, on this occasion organised in the framework of the H2020-I.FAST project – WP8: Innovative Magnets, follows the WAMHTS-5 event, organised in the framework of the H2020-Aries project, WAMHTS-5 (Budapest, 11-April 13, 2019)).

HiTAT will be held on 9-10 March 2023 at CERN in Building 30/7-018

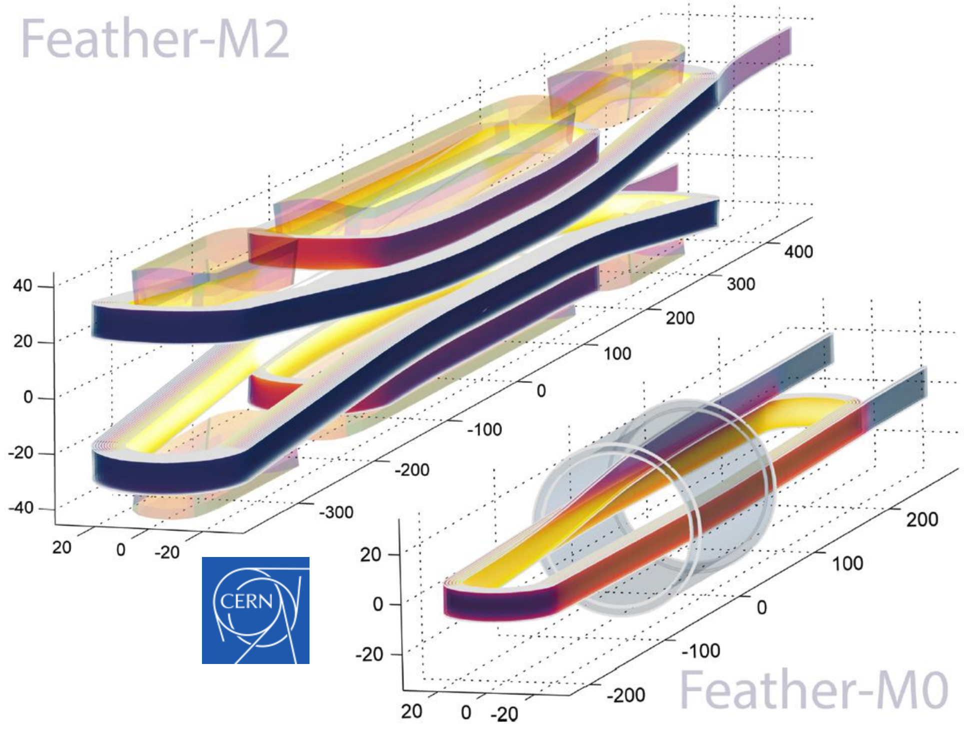
The focus of the program is on REBCO coated conductor for use in Hadron Therapy accelerator magnets, including post HL-LHC high energy colliders and beam lines.

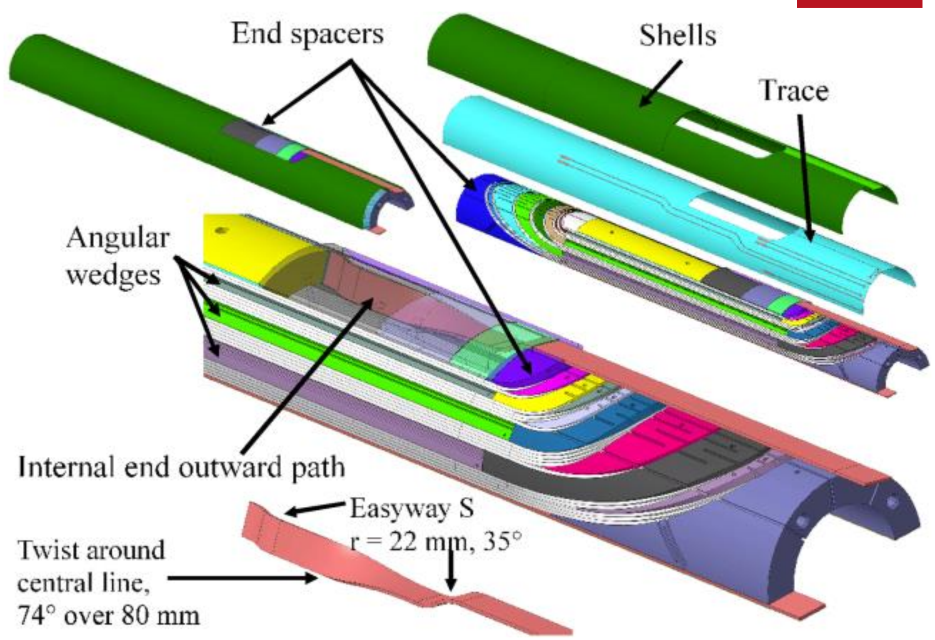
A preliminary draft programme, along with practical information regarding venue and accommodation (hotels and booking form), is available at the workshop website. The main topics that will be discussed are: conductor progress and availability (with the presence of producers); characterisation of tapes and cables; magnet technology and R&D in the on-going main R&D programs. A more refined program will be communicated by the beginning of 2023 with the second announcement of the workshop.

Participation in the workshop is by invitation only and is free of charge. Participants should cover the cost of their travel and accommodation.

We look forward to meeting you at CERN.

EuCARD2 HTS magnets





Feather M2	9 kA – 4.5 T (4.5 K)	Degradation: after thermal cycle and during powering with Fresca2	Probably stress in the Roebel cable, or caused by the induction copper rings
Cos-theta	3 kA – ~1.5 T (4.5-6 K)	Yes, but stable and distributed	Known: overheating during manufacturing

F. Mangiarotti