Highlights from Workshop on S/C Detector Magnets

12.-14. 09. 2022

CERN/Hybrid

Karsten Buesser
FC@DESY Meeting
28.10.2022

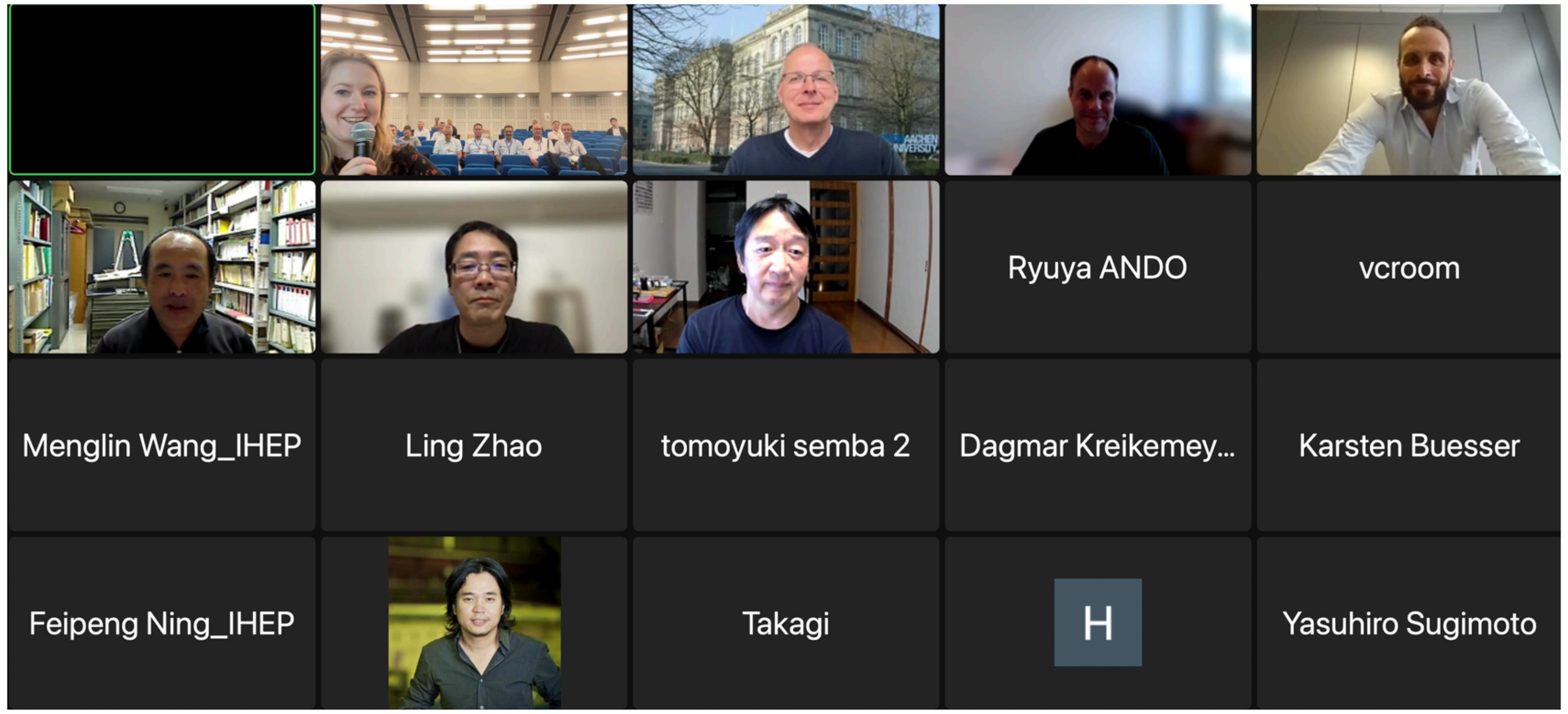
The Workshop

Organized jointly by CERN and KEK, hosted at CERN

- 90 participants, 57 on-site, 33 remote

Main Topics

- Addressing the issue of commercially available Al-stabilized superconductor technology for future detector magnets
- Assemble overview of planned detector magnets for future experiments
- Bring together physics/detector community with magnet designers and industry
- Understand status of industrial capacities and availabilities w.r.t. timelines of future experiments



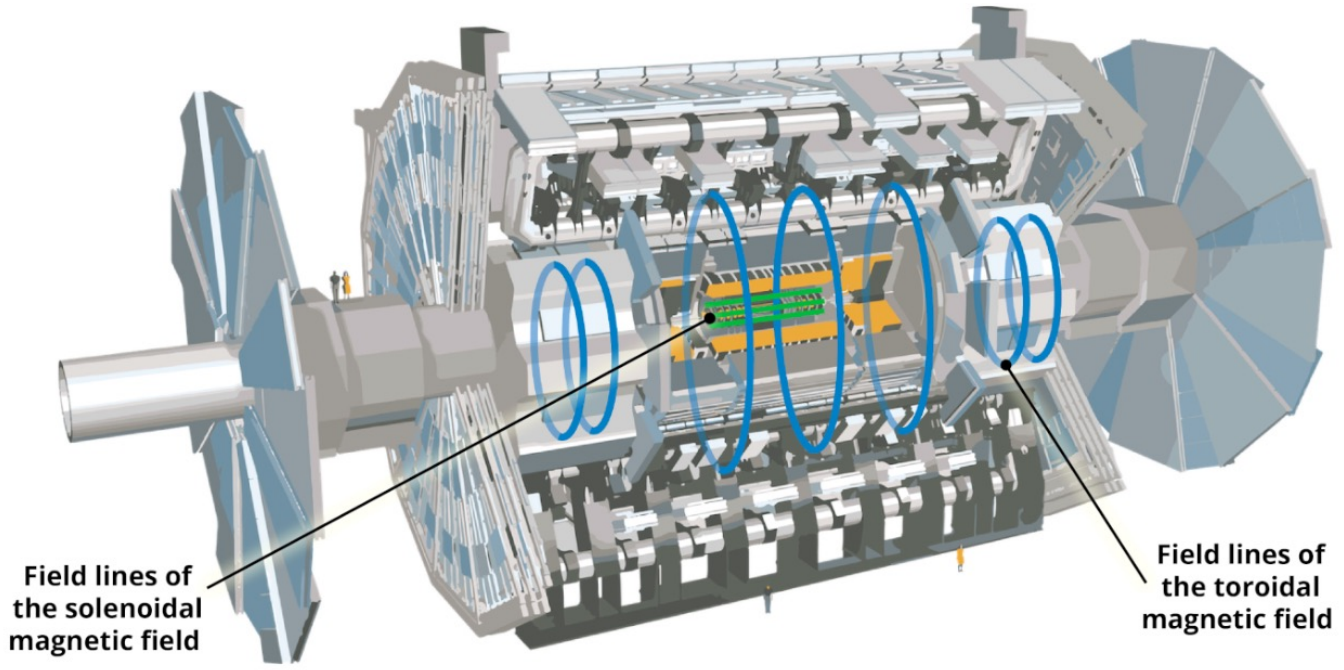
Historical experiences of the ATLAS and CMS magnet projects

Very large superconducting detector magnet projects!

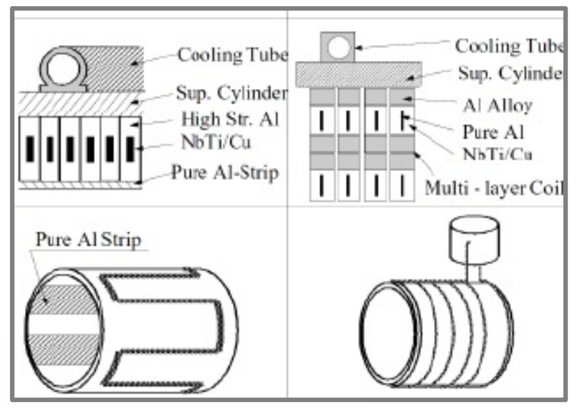
- Time-scale for engineering design and validation effort, the construction, and the commissioning: More than 15 years each
- Production of components (conductor, coils, support structure, etc) in industry, and subsequent assembly at CERN
- Designed, constructed, commissioned, and maintained with strong support from multiple institutes:
  - ATLAS: CEA-Irfu, KEK, INFN-LASA, RAL, NIKHEF, JINR-Dubna, IHEP-Protvino, ITAM Novosibirsk, CERN
  - CMS: CEA-Irfu, ETH Zurich, INFN Genoa, University of Wisconsin, Fermilab, ITEP Moscow, CERN

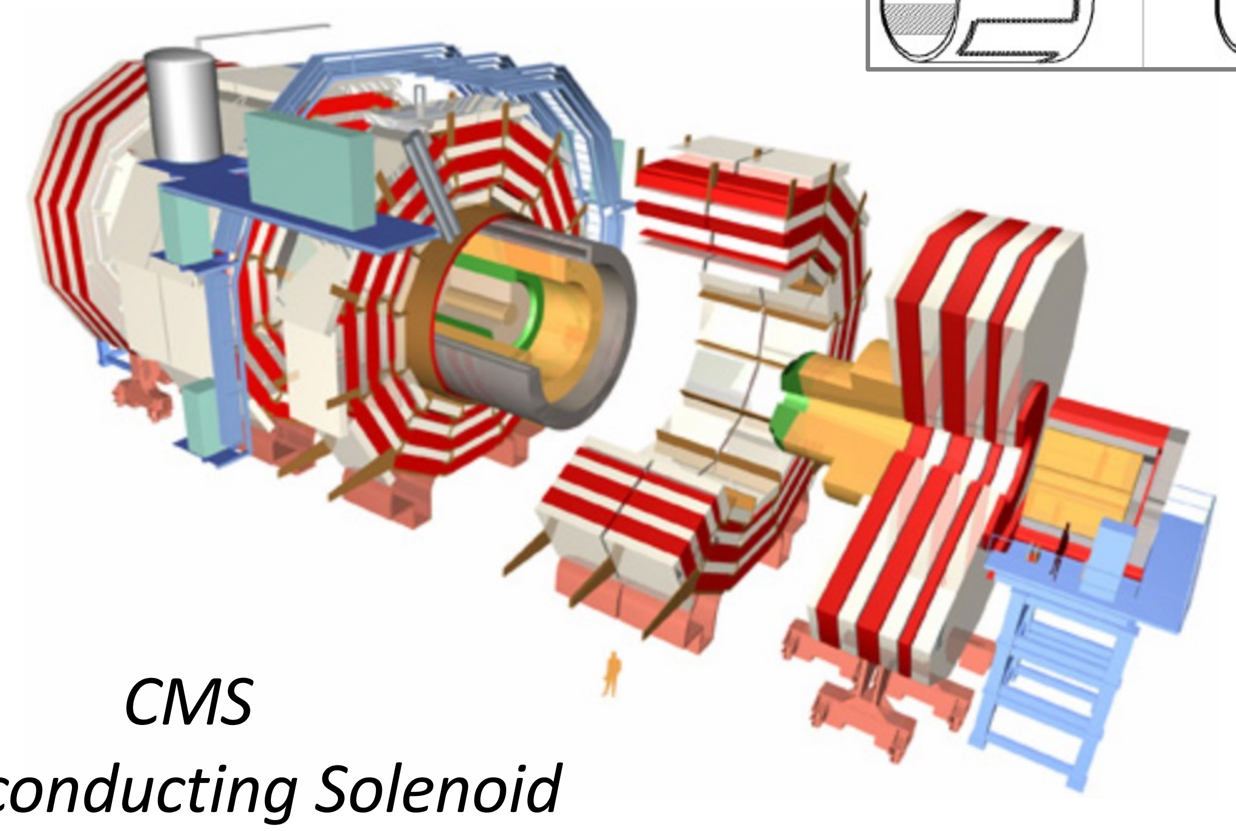
Important lessons:

- For large superconducting detector magnets a long-term strategy is needed
- **The historical importance of collaboration is evident**



ATLAS
Superconducting magnets





CMS
Superconducting Solenoid

A. Yamamoto

Detector Solenoid Challenges

Typical requirements for collider detectors

- Large volumes, length and radii O(few m)
- High central fields O(few T)
- As low mass as possible

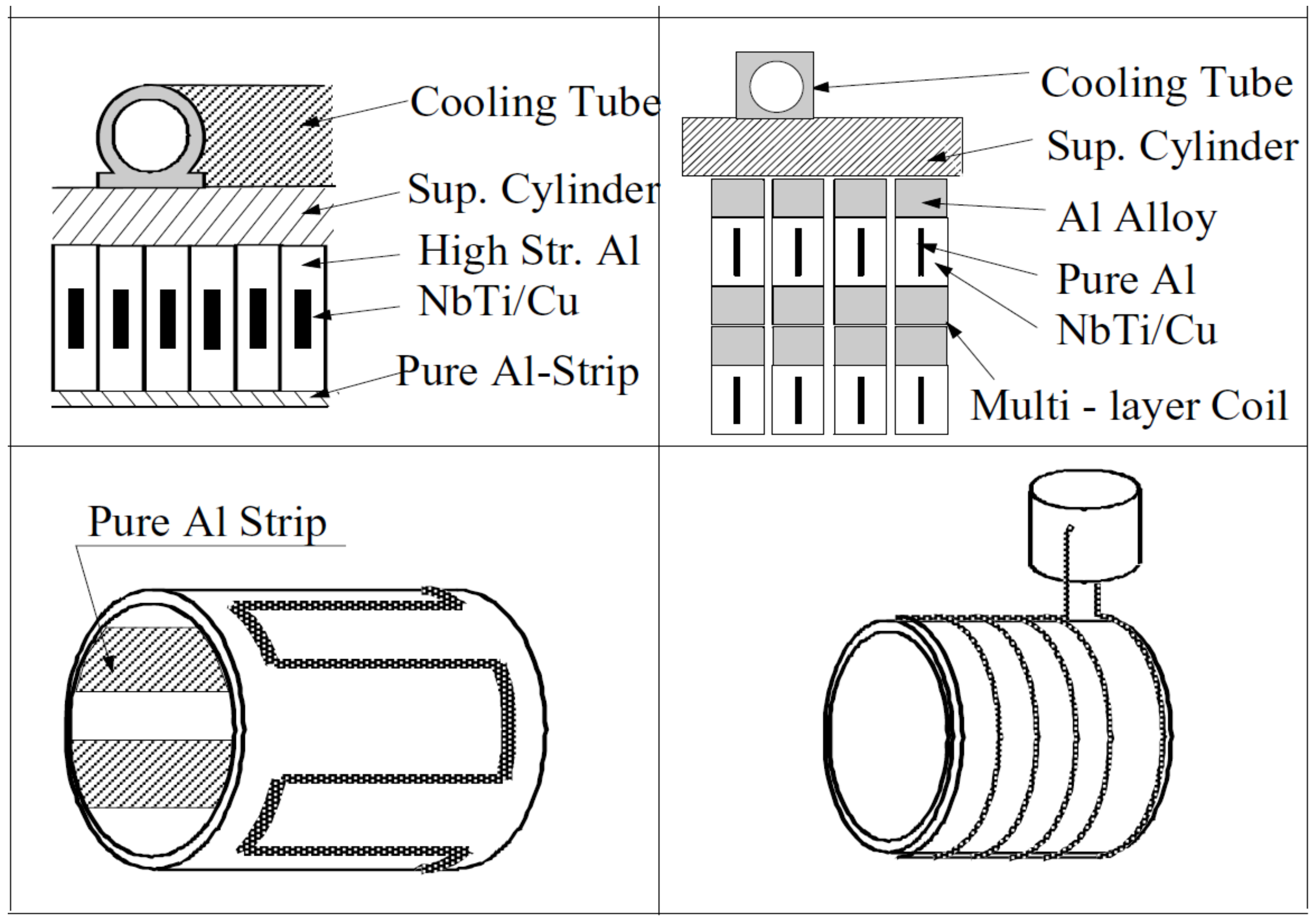
Challenges

- stored energy is large O (GJ)
- large forces on conductor and support structures
- high stresses

„Standard“ technologies

- Al-stabilized Nb-Ti superconductors
- Cooling via L-He in cooling pipes on outer support cylinder exploiting thermoconductivity
- Coil windings and support structure integrated by epoxy based resin
- Support vessel / cryostat provides mechanical strength and carries the mass

	A-CS	CMS
Requirement:		
Clear bore rad. (m)	1.18	2.95
Central field (T)	2	4
Design parameters:		
Coil inner rad. (m)	1.23	3.25
– half-length (m)	2.7	6.25
No. of coil layers	1	4
Full thickness (m)	0.045	~0.3
Max. field (coil) (T)	2.6	4.6
Nom. current (kA)	7.73	20
Stored energy (GJ)	0.04	2.6
Cold mass (t)	5.7	220
E/M (kJ/kg)	7	12.3



Snowmass-Paper, arXiv 2203.07799

Al-stabilized Conductors

Aluminum as stabilizer

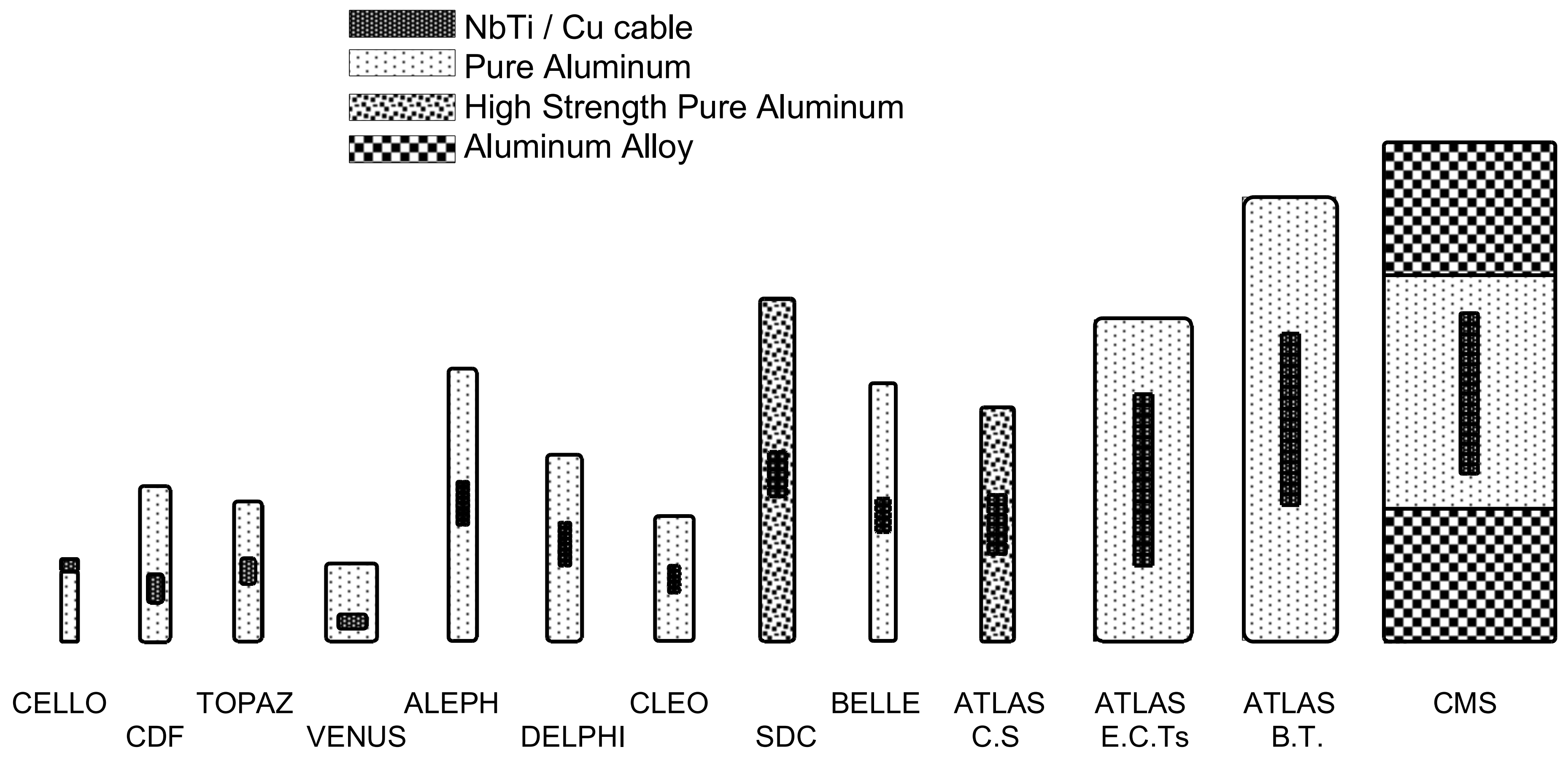
- has to absorb stored energy in case of a quench
  - compensate forces
  - protect superconductor
- good thermal and electrical conductor
- good mechanical strength
- minimum material and weight

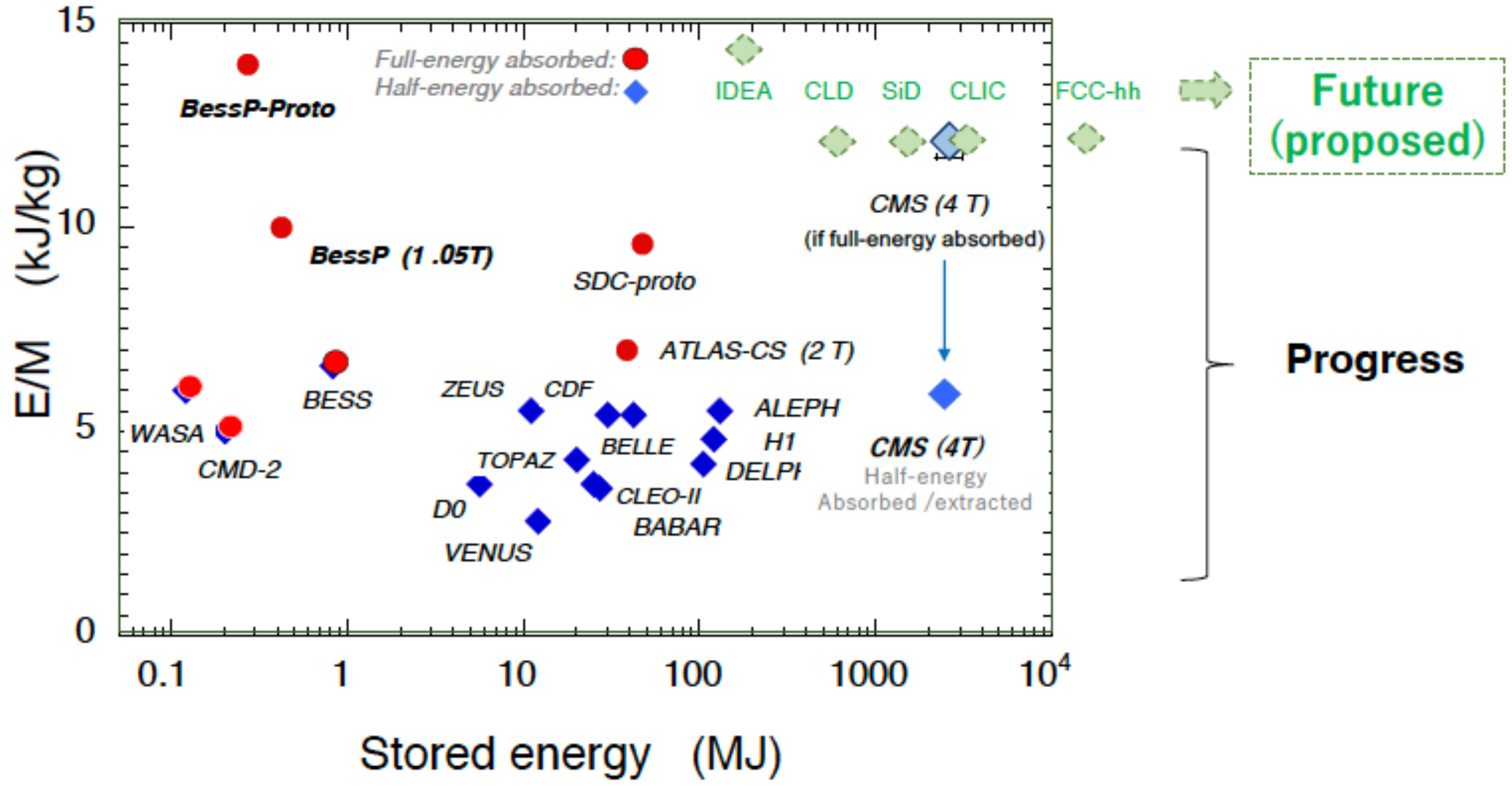
Pure high-conductivity Al is rather soft

- High-strength pure Al: refined with metallurgical methods
- Hybrid structures using Al-Alloys

E/M ratio as figure of merit

- keep mass small (transparency)
- bring stored energy up
  - large volumes, high fields





Snowmass-Paper, arXiv 2203.07799

Future Challenges

Study for FCC-hh detector

- Main solenoid
  - 4T, 5m radius, 19m length
  - 13.8 GJ of stored energy
- Forward solenoids
  - 4T, 2.5m radius, 3.4 m length

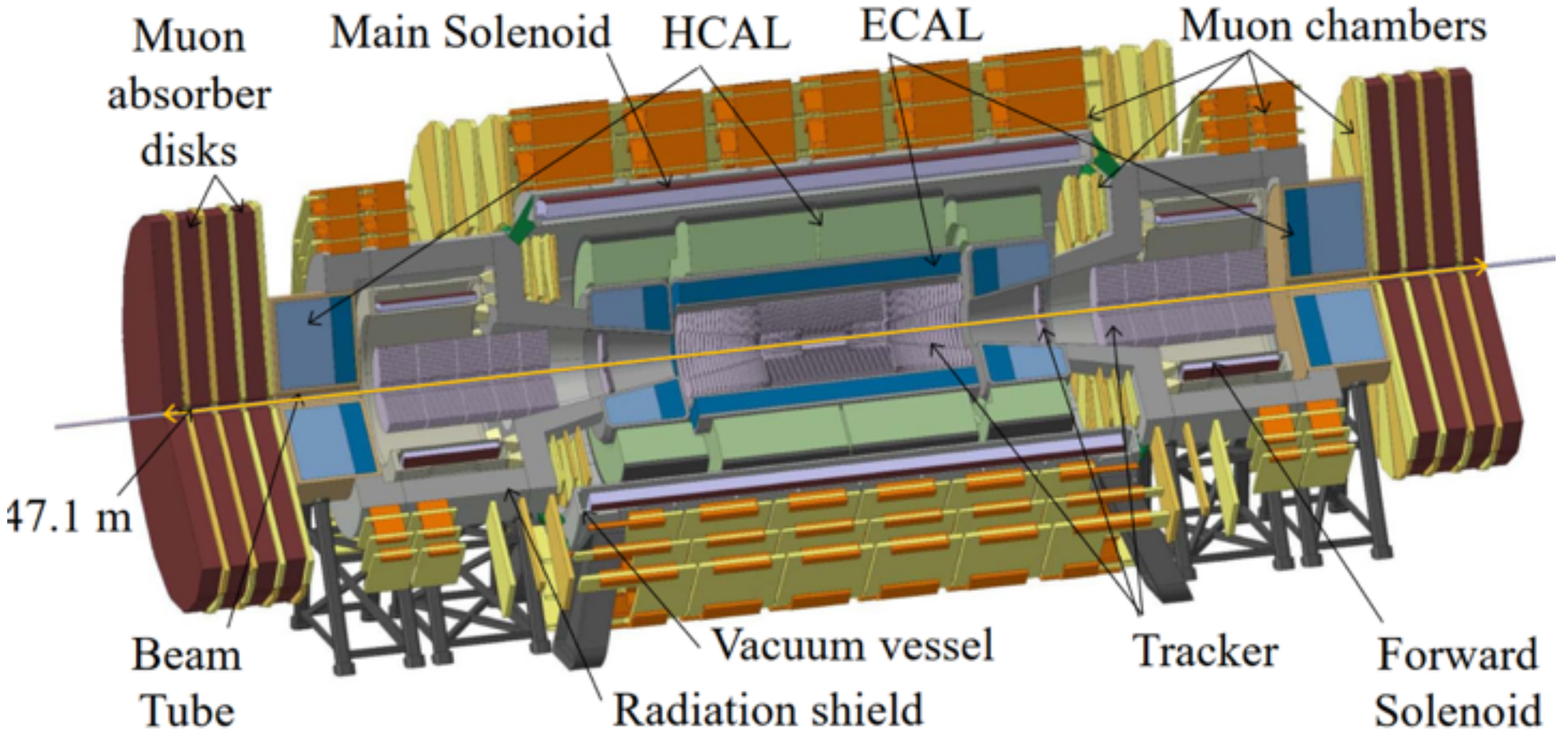
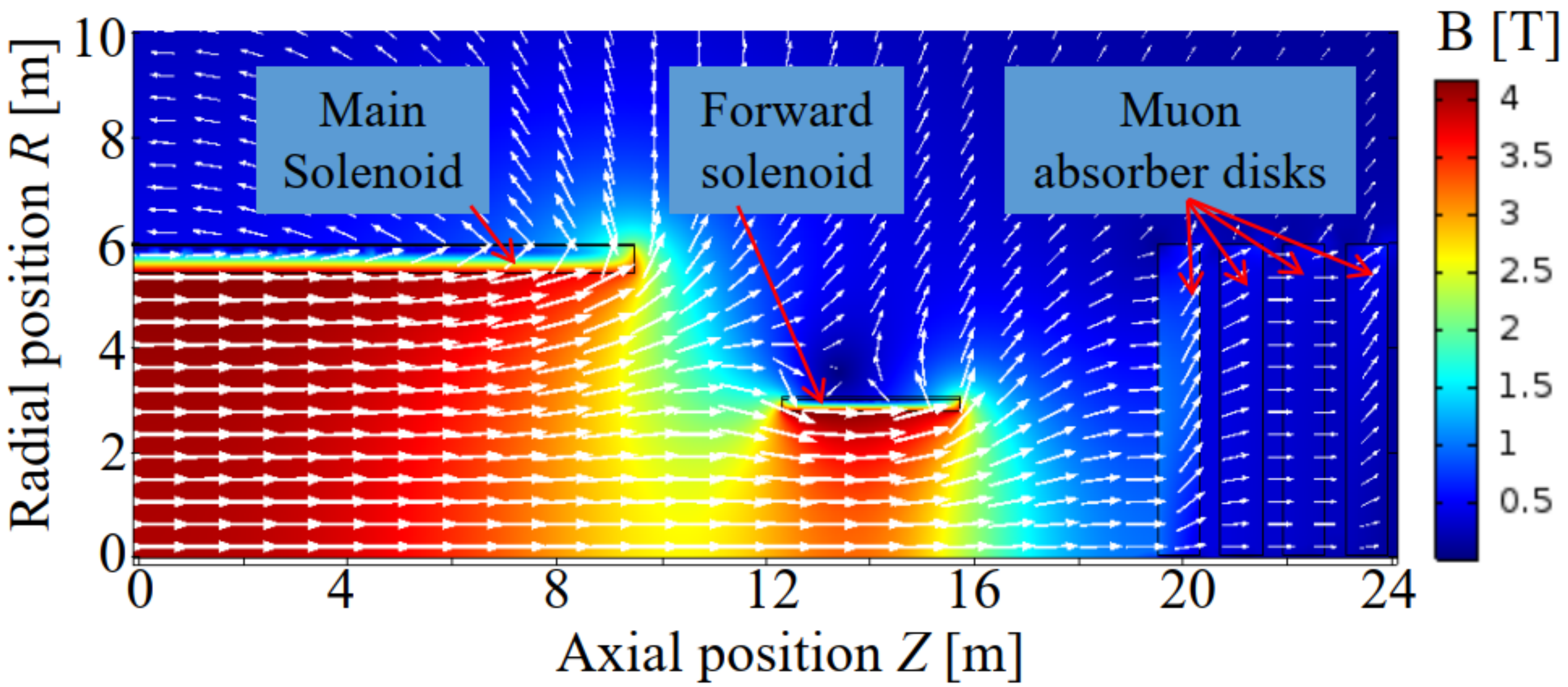


Fig. 4.4 Proposed FCC-hh detector base-line layout

ILD@ILC

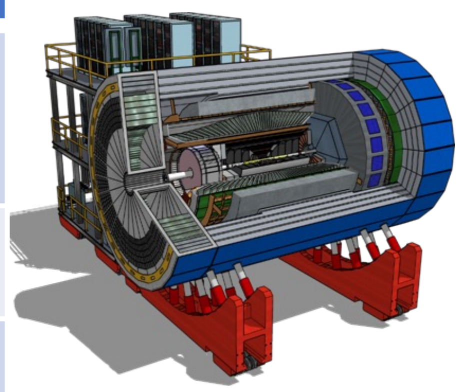
- Main solenoid
  - 4T max, 3.6m radius, 7.3m length
  - 2.3 GJ stored energy

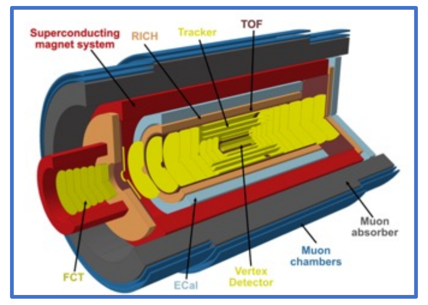


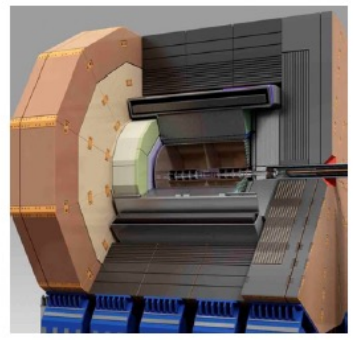
Snowmass-Paper, arXiv 2203.07799

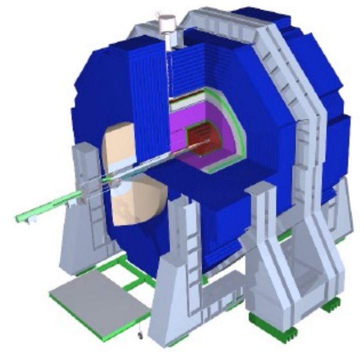
Day 1: Reports from Project Plans and Requirements

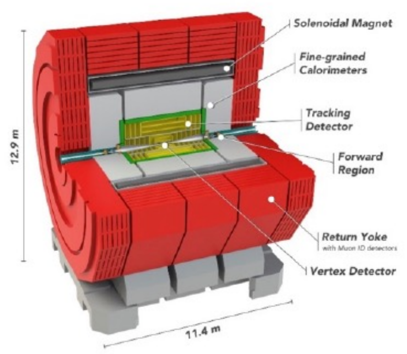
Subject / Project	Presented by
Welcome Address	**J. J. Mnich, (CERN Director for Physics and Computing)**
Opening Address	M. Mentink (CERN), T. Ogitsu (KEK)
Program Overview	A. Yamamoto (KEK-CERN)
The Electron-Ion Collider (EIC)	R. Rajput-Ghoshal (JLab)
International Linear Collider –ILD (ILC-ILD)	K. Buesser (DESY), Y. Makida (KEK)
International Linear Collider - SiD (ILC-SiD)	T. Markiewicz (SLAC)
Compact Linear Collider (CLiC)	B. Cure (CERN)
Leptron Future Circular Collider (FCC-ee)	N. Deelen (CERN)
Hadron Future Circular Collider (FCC-hh)	M. Mentink (CERN)
Circular Electron Positron Collider (CEPC)	F. Ning (IHEP)
A Large Ion Collider Experiment 3 (ALICE-3)	W. Riegler (CERN)
Muon to Electron (Mu2e)	M. Lamm (Fermilab)
Muon Experiments in Japan	K. Sasaki and M. Yoshida (KEK)
antiProton ANihilation at DArmstadt (PANDA)	L. Schmitt (GSI-Helmholtzzenter)
Baby International Axion Observatory (BabyIAXO)	U. Schneekloth (DESY)
MAgnetized Disc & Mirror Axion eXp. (MADMAX)	W. A. Maksoud (CEA)
Alpha Magnetic Spectrometer 100 (AMS-100)	T. Mulder (CERN), S. Schael (Rheinish Westfaeli…)

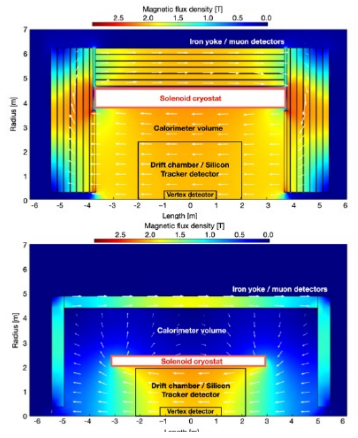

EIC

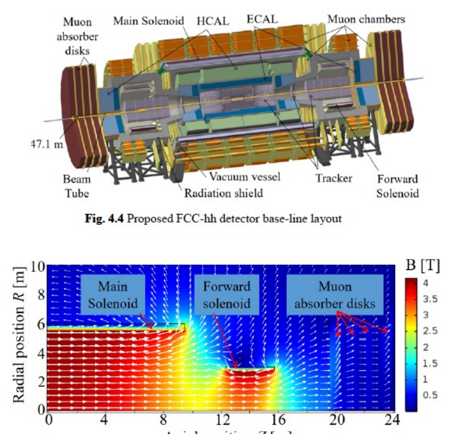

ALICE-3

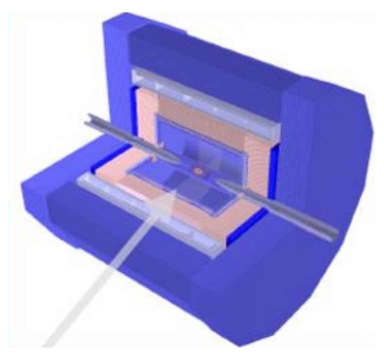

ILC-ILD

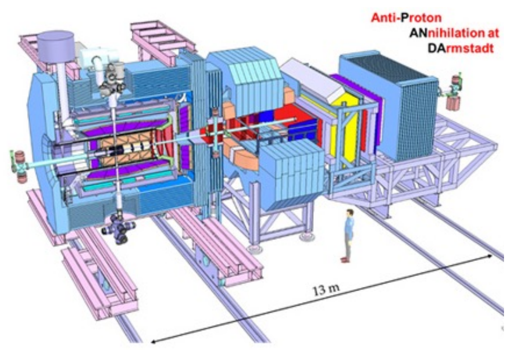

-SiD

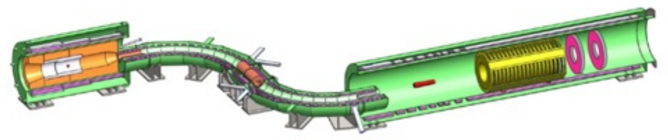

CLIC

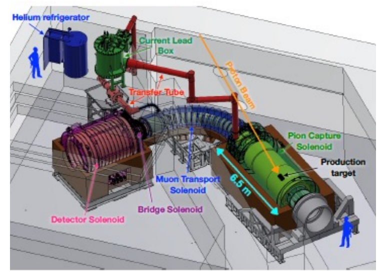

FCC-ee

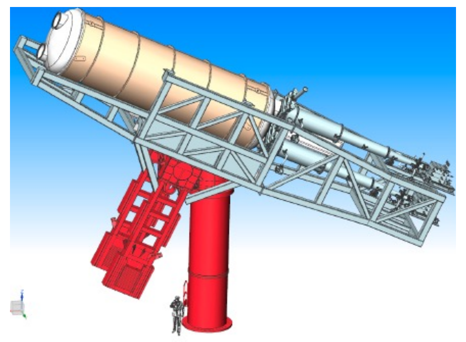

FCC-hh

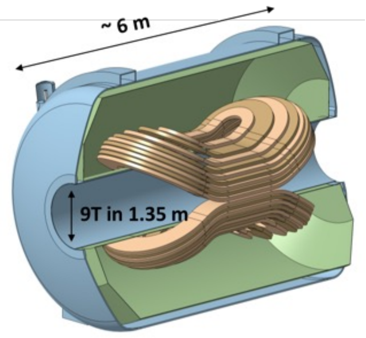

CEPC

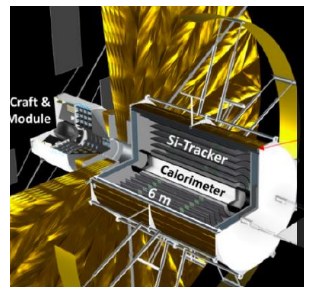

PANDA


Mu2e


Comet

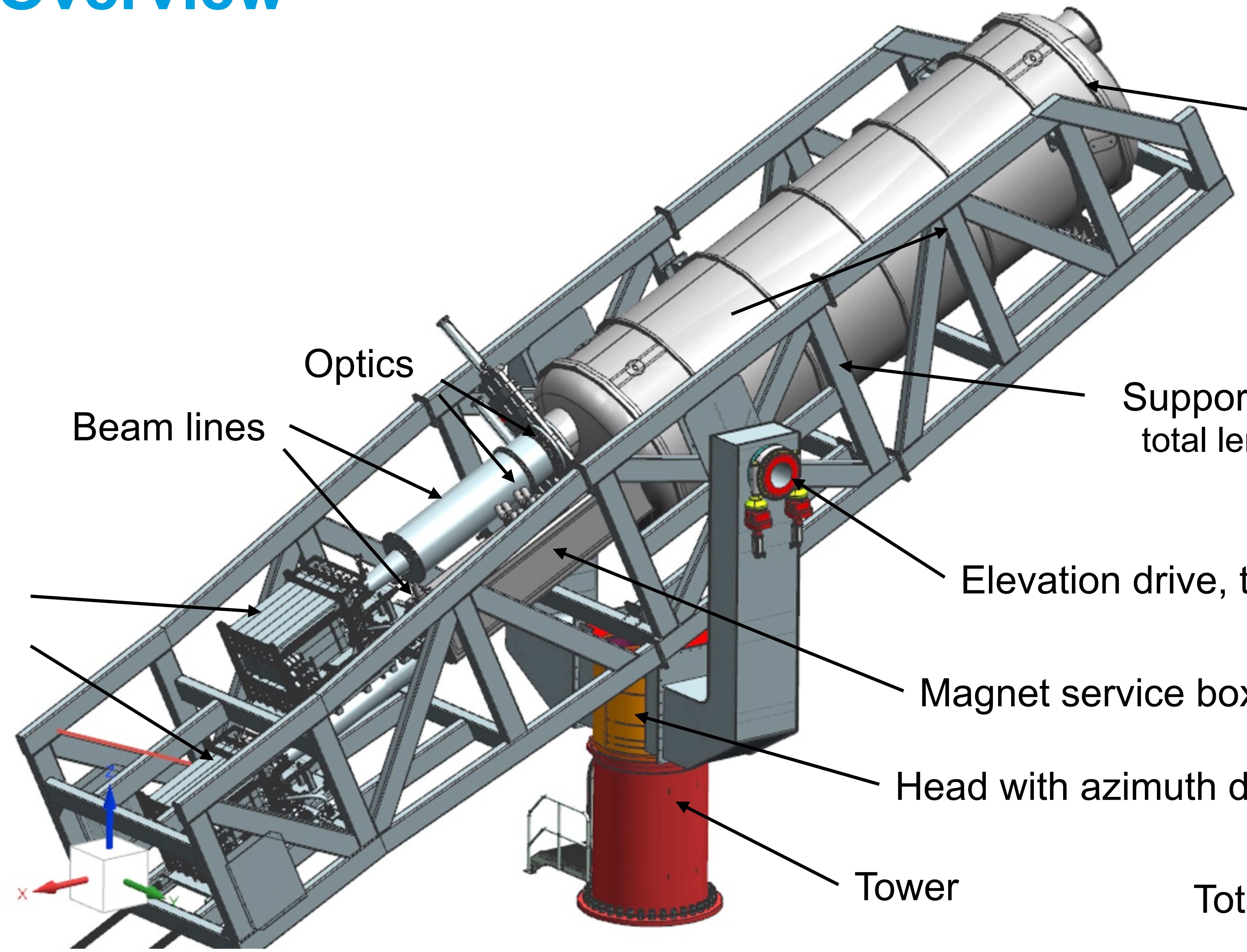

BabyIAX0,


MadMax


AMS100

A. Yamamoto

BabyIAXO Overview



U. Schneekloth

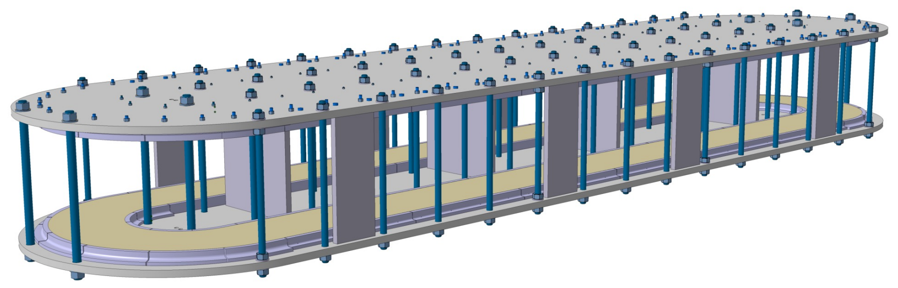
BabyIAXO

Challenging magnet desig

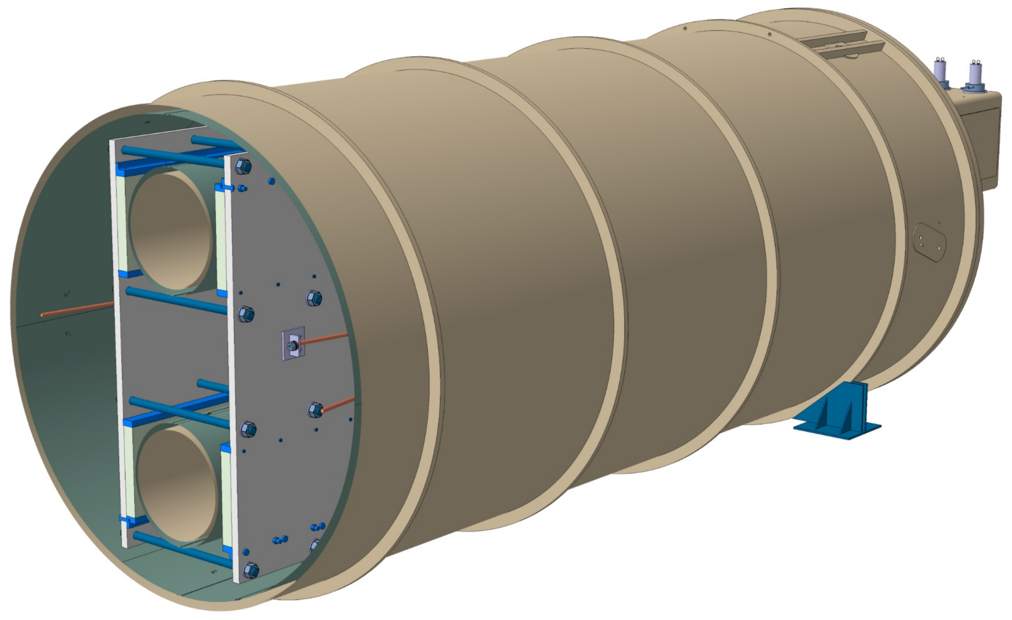
- no connection to central DESY cryo plant
- cooling with local cryo coolers

Al-stabilized superconductor

- PANDA-type
- existing conductor from INR did not work

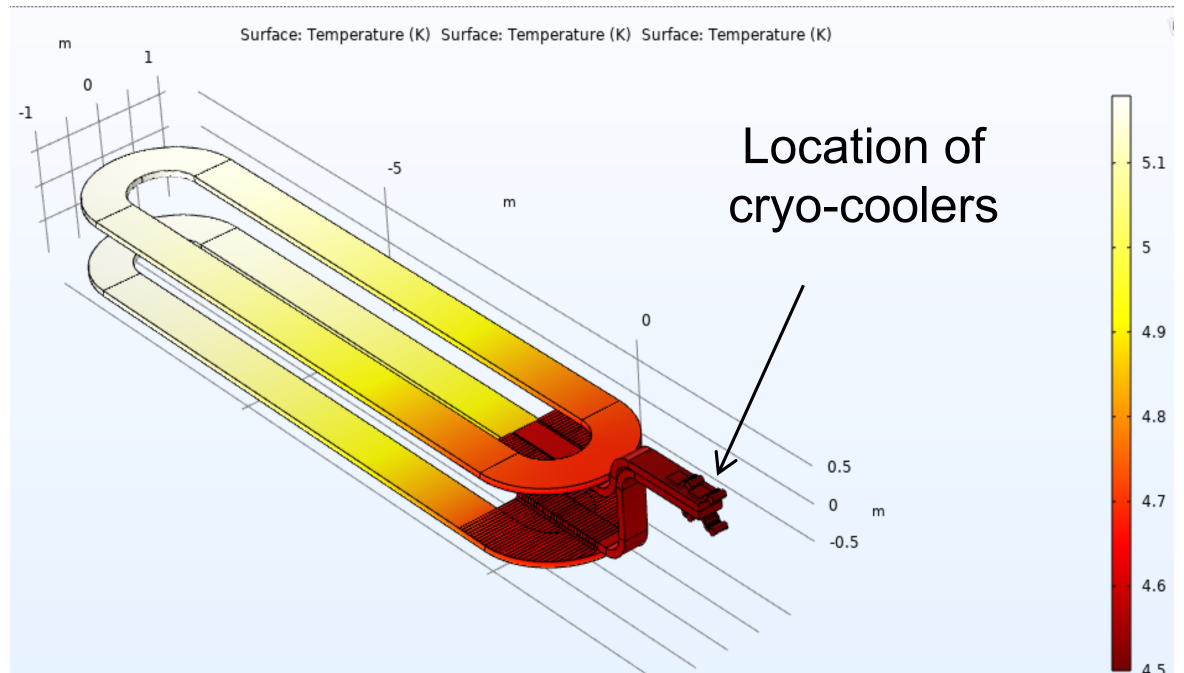


Aluminum-based cold mass support structure



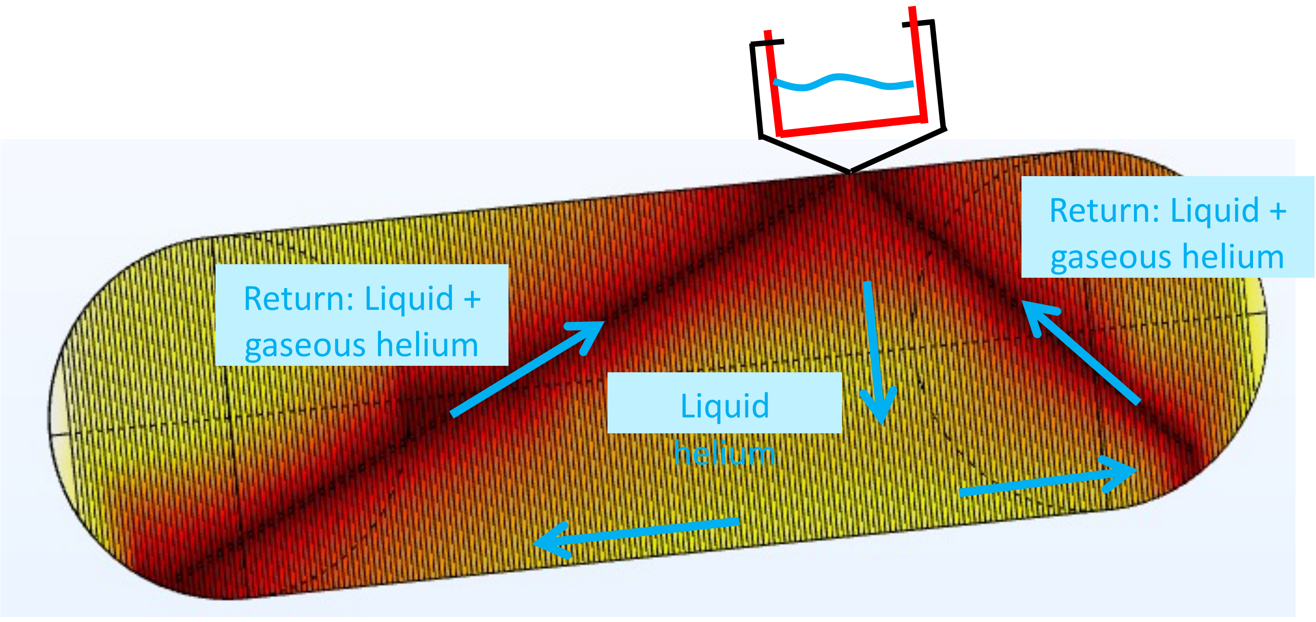
Vacuum vessel, coil suspension, cold mass, and bore tubes

Temperature gradient over the coils, interfaces, etc, dependent on the heat load

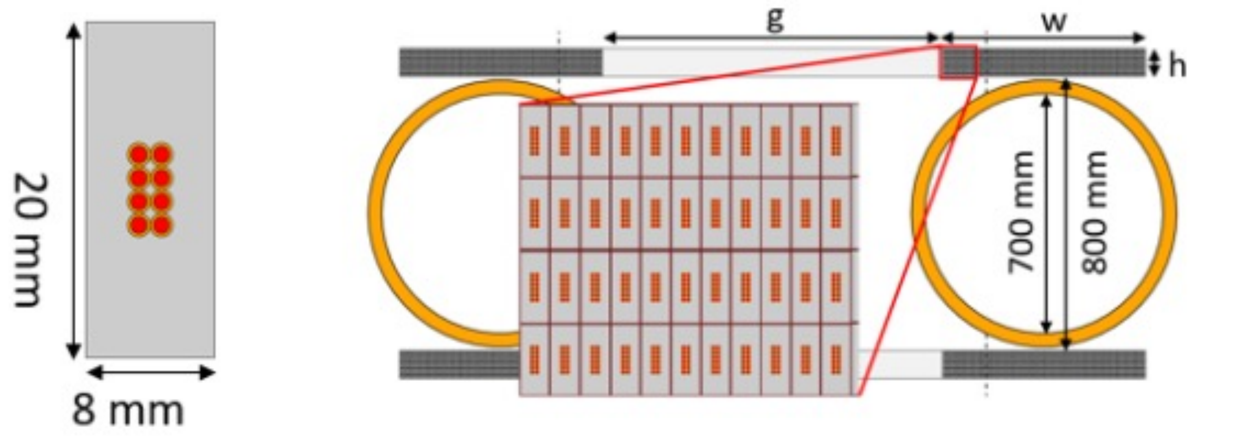


Thermal link concept

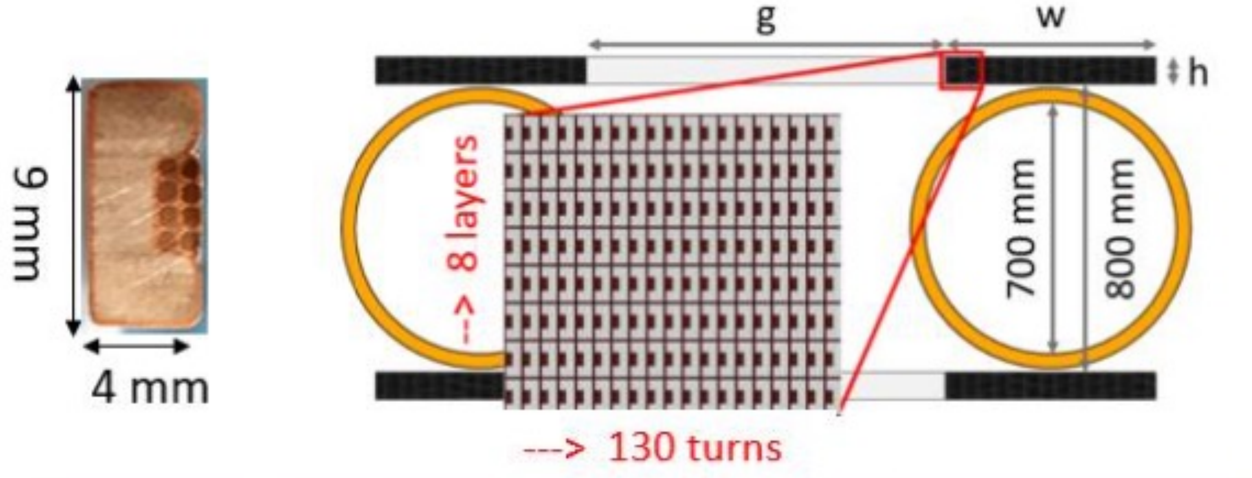
Liquid helium, provided by local cryo-cooler helium condensation (or external cryogenics)



Thermal siphon concept



10 kA type coextruded conductor
(production trials in Russia)
MFOM 3D-2D = 230-330 (based on today's Ic)



3 kA type cable-in-channel conductor
(available at INR, made medio 1990)
MFOM 3D-2D = 230-330 (based on "promised" Ic)

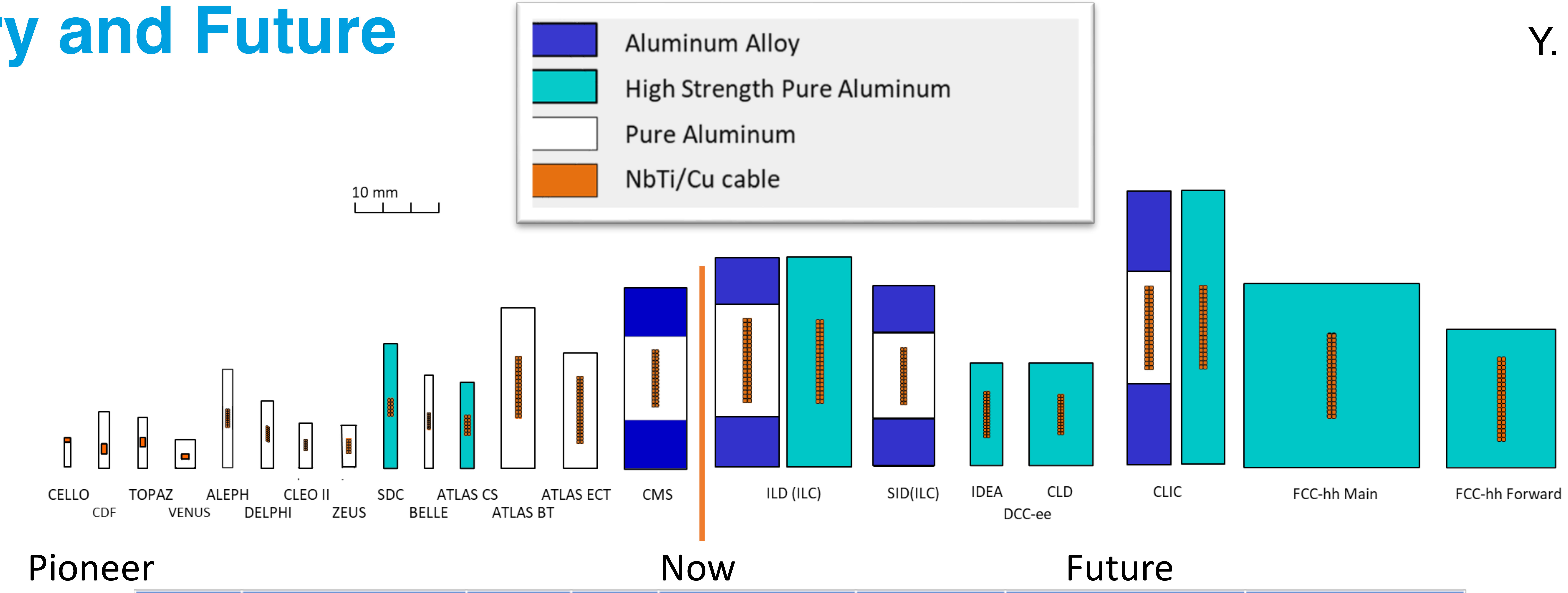
Cryogenics of the BabyIAXO magnet is very challenging, due to absence of external liquid He plant

- Baseline cooling concept: Cooling with cryo-coolers, which give very limited cooling power at 4 K, so **minimizing the losses and heat loads onto the cold mass and thermal shield is critical** and achieving thermal homogeneity in the magnet is a significant technological challenge
- Two options under consideration: Thermal link and thermal siphon concept

U. Schneekloth

History and Future

Y. Makida



	Experiments	Site	B	Size ID x L	Energy (MJ)	Note	Fabrication Expected
Collider	EIC-Detector	BNL	1.5~3	2.5~3.2 x 8.5	45.7	Cu only	2025 ~
	ILC-ILD	Japan	4	6.88 X 7.35	2300		2030 ~
	ILC-SiD	Japan	5	5 X 5	1400		2030 ~
	CLICdet	CERN	4	7 X 8.3	2320		2035 ~
	FCC-ee IDEA	CERN	2	4.2 X 6.0	170		2035 ~
	FCC-ee CLD	CERN	2	7.4 X 7.4	600		2035 ~
	FCC-hh	CERN	4	10 X 20	13800		2040 ~
Others	BabyAXIO	DESY	2	0.7 X 10	38	Racetrack	~2024
	AXIO	DESY	5 - 6	5 X 25	500	Toroid (Racetrack)	2024~

Day 2: Reports from Industry, Experience and Prospect

Reports from 10 (+3) leading companies (according to agenda order):

- ○ **Furukawa Electric**, Japan: ……………………………*Al-Stabilized NbTi Conductor for Detector Solenoid at Furukawa*
- ○ **European Industrial Status** on superconductor manufacturing ……………. *introduced by A. Ballarino (CERN)*
- ○ **Wuxi Toly Electric Works Co.,Ltd.**, China: ………………………………*Development of Al-stabilized superconductor*
- ○ **Techmeta**, France: ……………………*Continuous EB-Welding of the reinforcements of the CMS Superconductor*
- ○ **Status Report on Co-extrusion Facilities in Europe** for Detector Magnet SC …. *Introduced by B. Cure (CERN)*
- **Hitachi, Ltd.**, Japan: ………………………..*Development of Superconducting Magnets for Accelerators in Hitachi*
- **Toshiba Energy Systems & Solutions Corporation**, Japan: …………….*Superconducting Technology in Toshiba*
- **Mitsubishi Electric corporation**, Japan: ……………………………………*Manufacturing of Superconducting Magnet*
- **Bilfinger Noell**, Germany: ……………………….……………….*Presentation of the activity in the field of SC magnets*
- **ASG Superconductors**, Italy: …………………………..*Superconducting detector magnets at ASG Superconductors*
- **SAES Group**, Italy: …………………………………..*Fabrication of the High Order Corrector Magnets for Hi-Lumi LHC*
- **Sigmaphi**, France: ……………………………………………………………………………*Sigmaphi presentation*

○ ← Highlighted

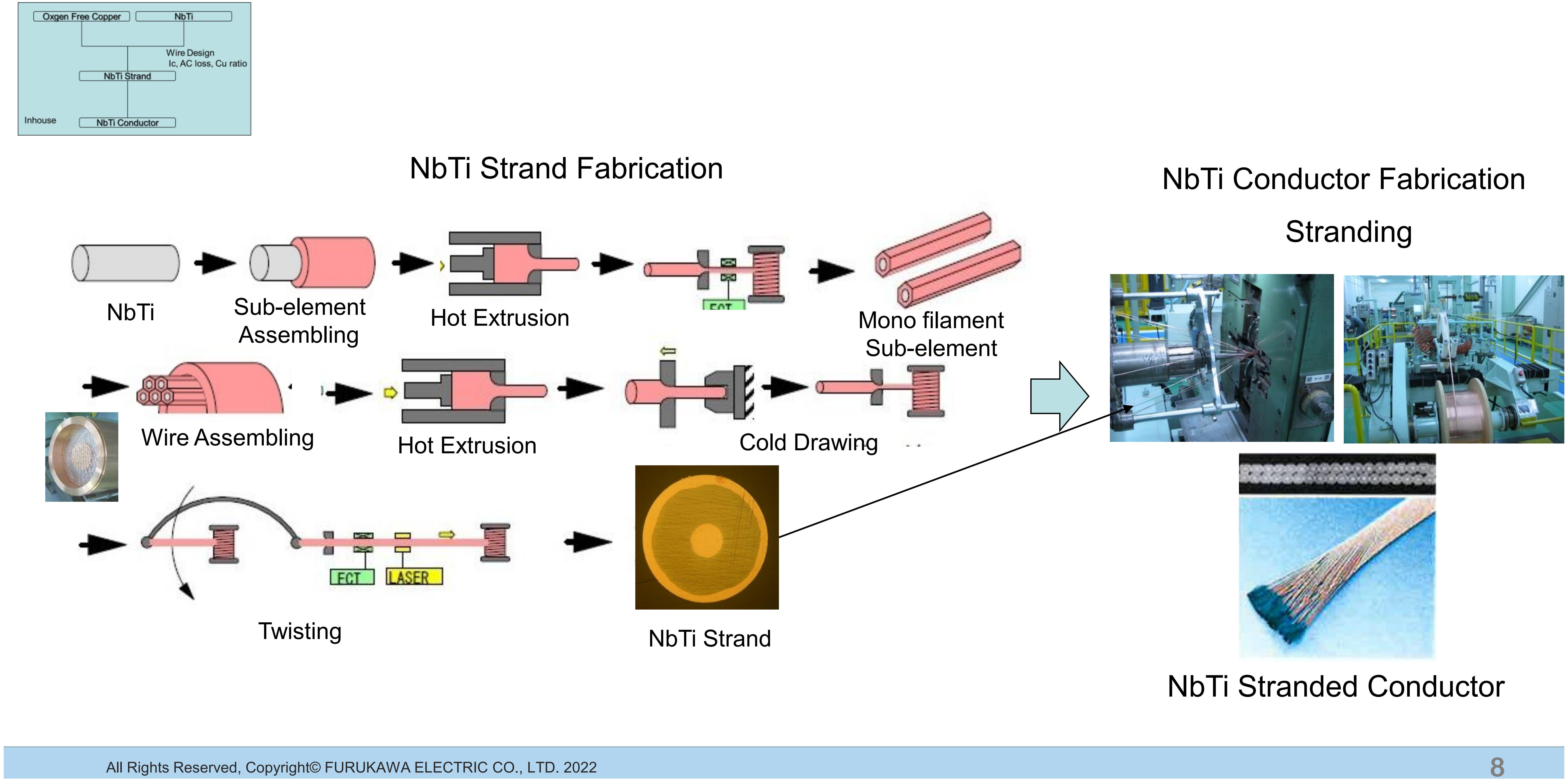
Presenting past or on-going development and manufacturing capacities :

- Superconductor (with Al or Cu stabilizer),
- Coil winding and magnet assembly, including cryostating,
- Specific technology.

A. Yamamoto

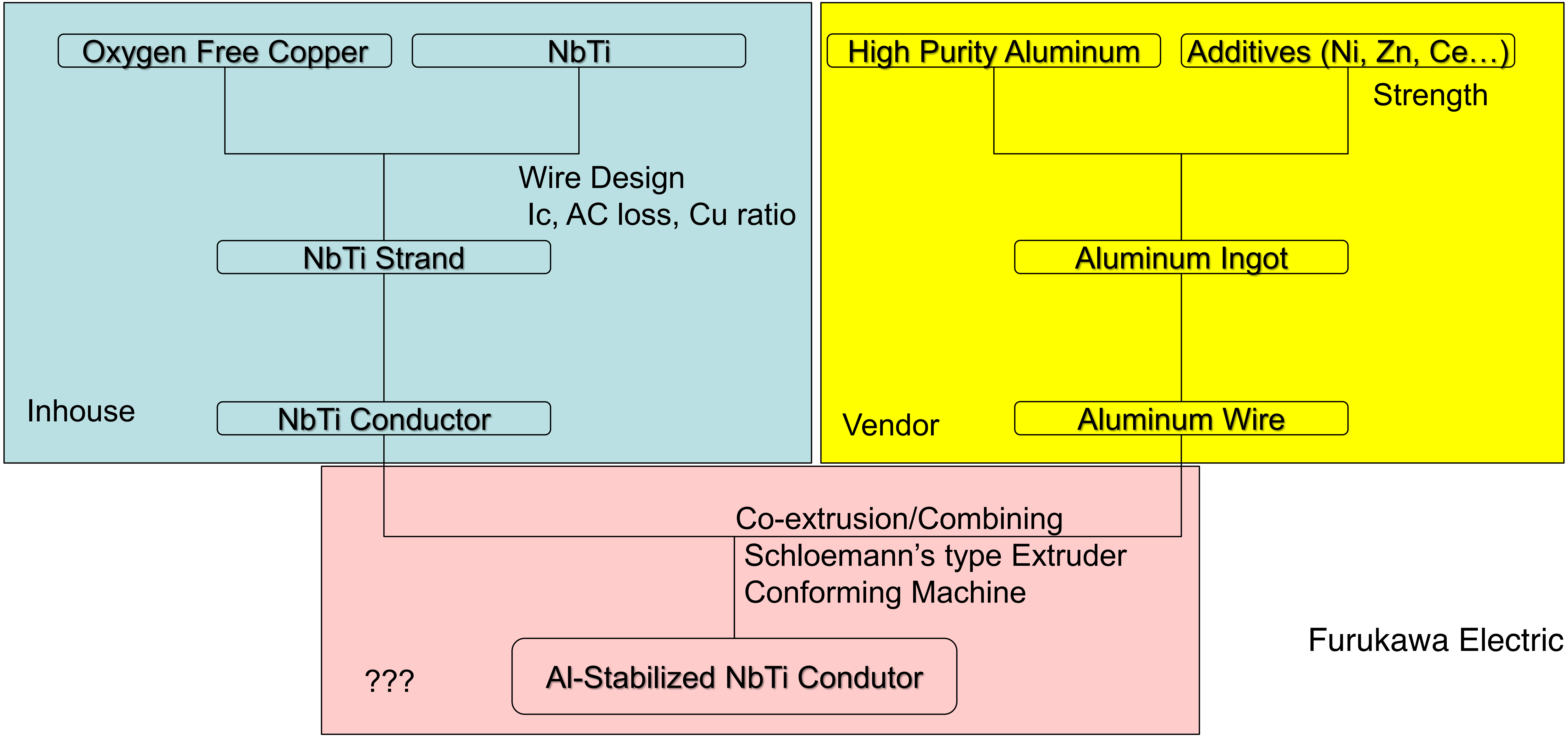
Nb/Ti Conductor Production

Established process in industry



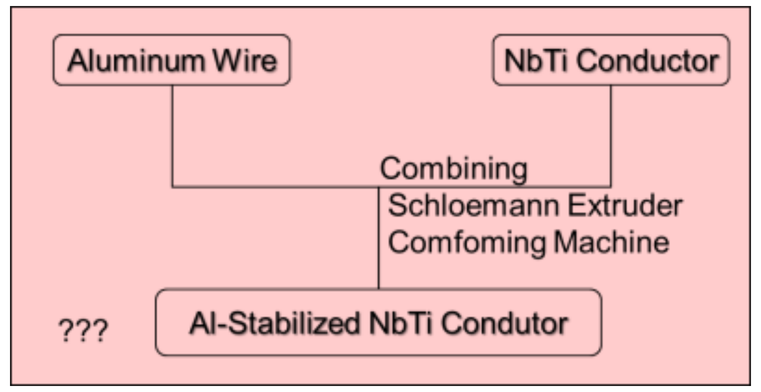
Furukawa Electric

Bringing Al and Conductor together

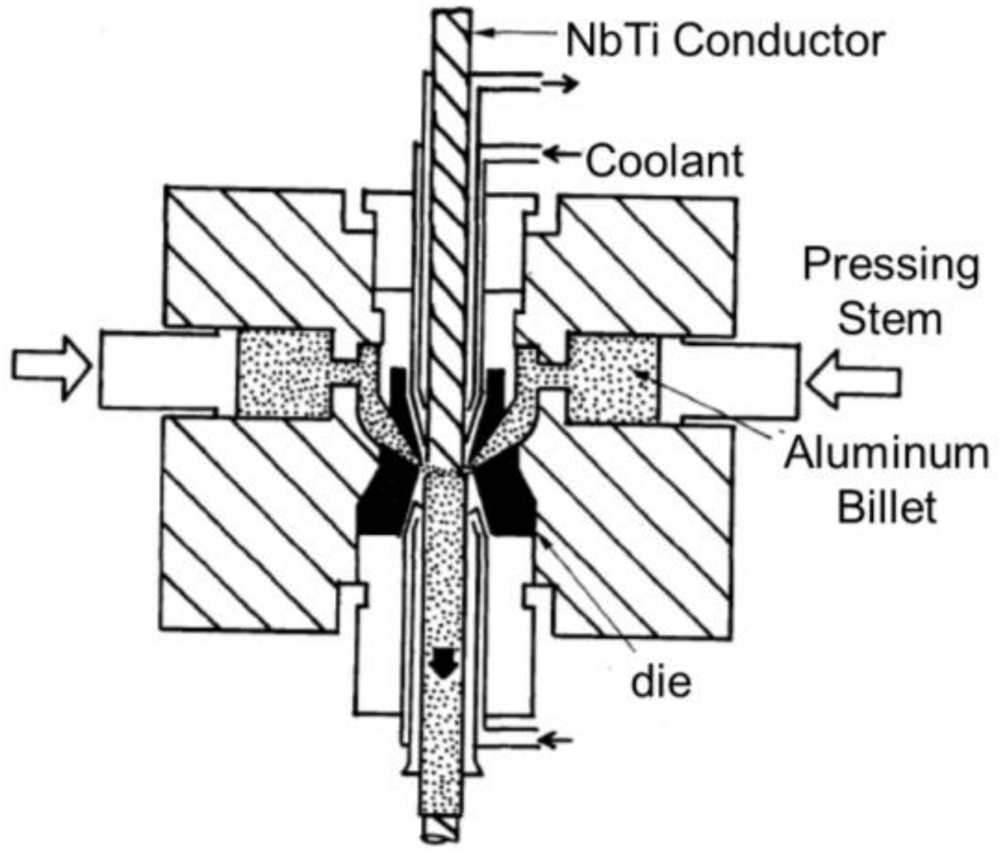


Combining NbTi conductor and Al Stabilizer

FURUKAWA ELECTRIC



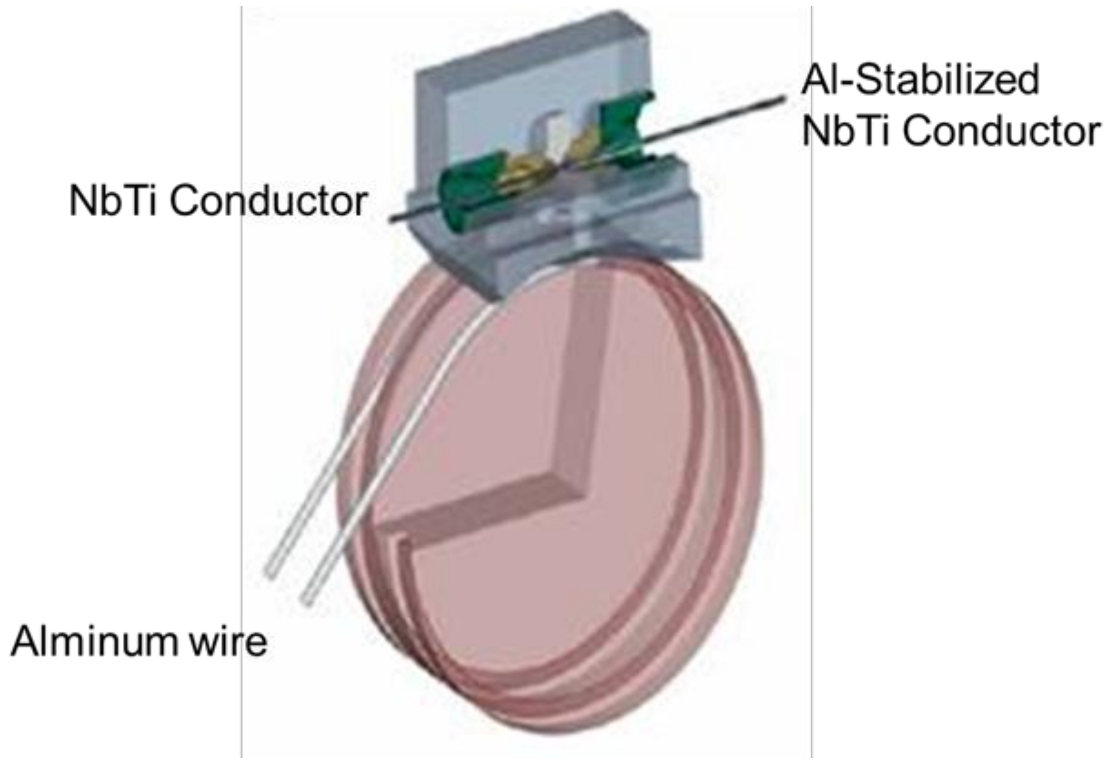
Historically, two types of machines are used for combining NbTi conductor and Al stabilizer. One is Schloemann's cable claddig press and the other is conforming (conklad) machine.



Schematic view of Schloemann's cable cladding press

K.Saito et al.,
J. JILM, Vol. 35, No. 5 (2020), 297-303
in Japanese

Item	Schloemann	Conforming
Al Source	Billet	Wire
Machine Size	Large	Small
Application	Clad wires	OPGW, AS
Al-stabilized NbTi conductor		
Cross Section of Al	Large	Small -170mm^2 (Max 300mm^2)
Length	Limited by Billet	Continuous



Schematic view of conforming machine
https://bwe.co.uk/conklad/

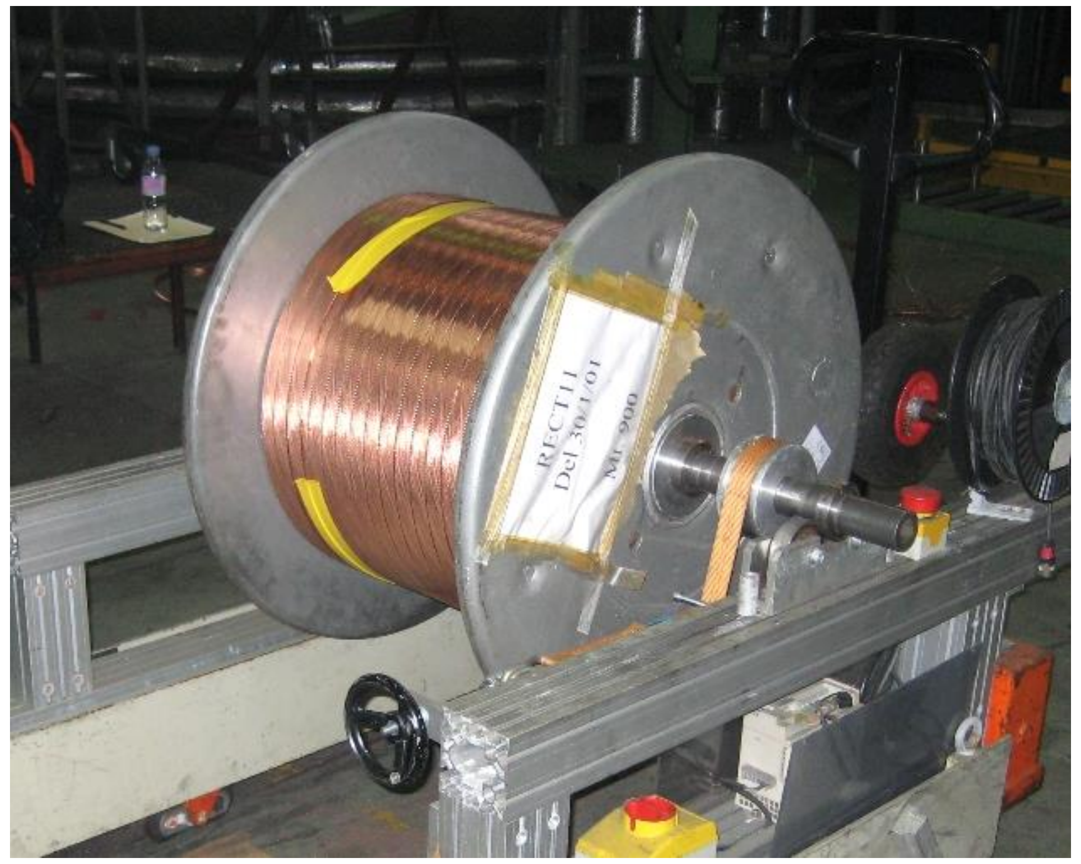
Furukawa Electric

Co-Extrusion Process is Heavy Metal

Manufacturing process

Co-extrusion

- done at **Nexans, Cortaillod, CH** (same press as CMS and ATLAS BT conductor coextrusion),
- Billet-on-billet co-extrusion process
- Double piston system, top and bottom, no stop,
- Atlas BT conductor die re-used,
- Rutherford cable from Atlas BT production used ~100-m of good leftover cable,
- 5N8 Al billets leftover from CMS production used.



Atlas BT conductor :

- 57 x 12 mm^2
- 40 strands
- Strand Cu/SC~1.2
- Strand ∅1.3mm

B. Curé

Status of co-extrusion in industry

Companies that performed coextrusion for the LHC detector magnets

ATLAS Conductors:

Barrel and End cap toroids:
- VAC Vacuumschmelze , Hydro aluminium (Seneffe, B) (later EAS). *Facility closed in 2014.*
- Alcatel Cable Suisse (later Nexans). *Facility dismantled (2022). Expert left company in 2016.*

No more contact or information available.

Central Solenoid: (Japan)
- Furukawa Electric Co. Ltd,
- Hitachi Cable Co. Ltd.

Ref: H. H. J. Kate, "ATLAS superconducting toroids and solenoid," in IEEE Transactions on Applied Superconductivity, vol. 15, no. 2, pp. 1267-1270, June 2005, doi: 10.1109/TASC.2005.849560.

CMS Conductor:

- Alcatel Cable Suisse (later Nexans). *Facility dismantled (2022). Expert left company in 2016.*

Ref: B. Blau et al., "The CMS conductor," in IEEE Transactions on Applied Superconductivity, vol. 12, no. 1, pp. 345-348, March 2002, doi: 10.1109/TASC.2002.1018416.

No new company identified yet.

Looking for manufacturer with coextrusion capacities:
- Continuous process,
- Semi-continuous process (short stop)
- With Rutherford cable exposed to max temperature < ~350°C for short time.
- Using typically extrusion press or Conform process.

We expect to find such companies in the high power cable market.

→ These are mostly **global corporations**, or subcontractors of them, inside international groups.

→ The **compatibility** of the production plans of these companies with our needs (and our schedules) should be considered, once potential companies are identified.

Currently no manufacturer in Europe, Japan or US available
- PANDA is working with institutes in Russia
  - no alternative anymore

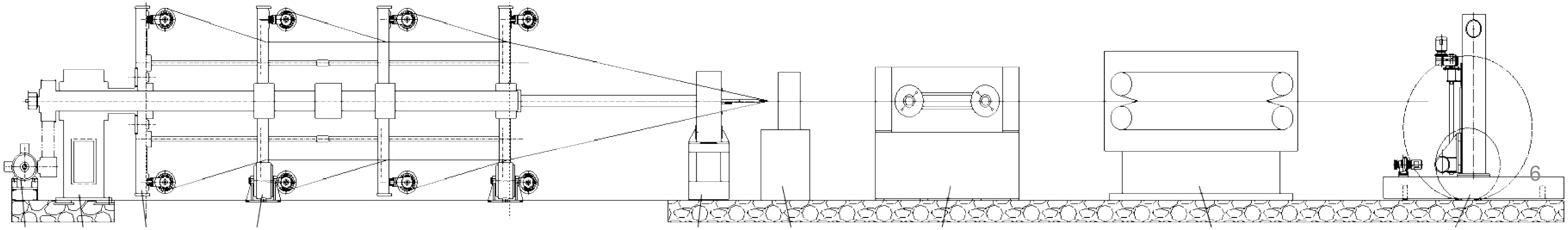
B. Curé

TOLY Electric - China

统力电工 TOLY ELECTRIC

Rutherford cable

Items	Value
Wire numbers	12×4=48
Diameter	φ0.5~1.5mm
Wire tension	0~40N
The speed of rotary movement	12.5rpm
The speed of production	0~10m/min



TOLY Electric - China

统力电工
TOLY ELECTRIC

Al-stabilized superconductor

Al rods/cable releaser

Ultrasonic cleaning

Extrusion machine

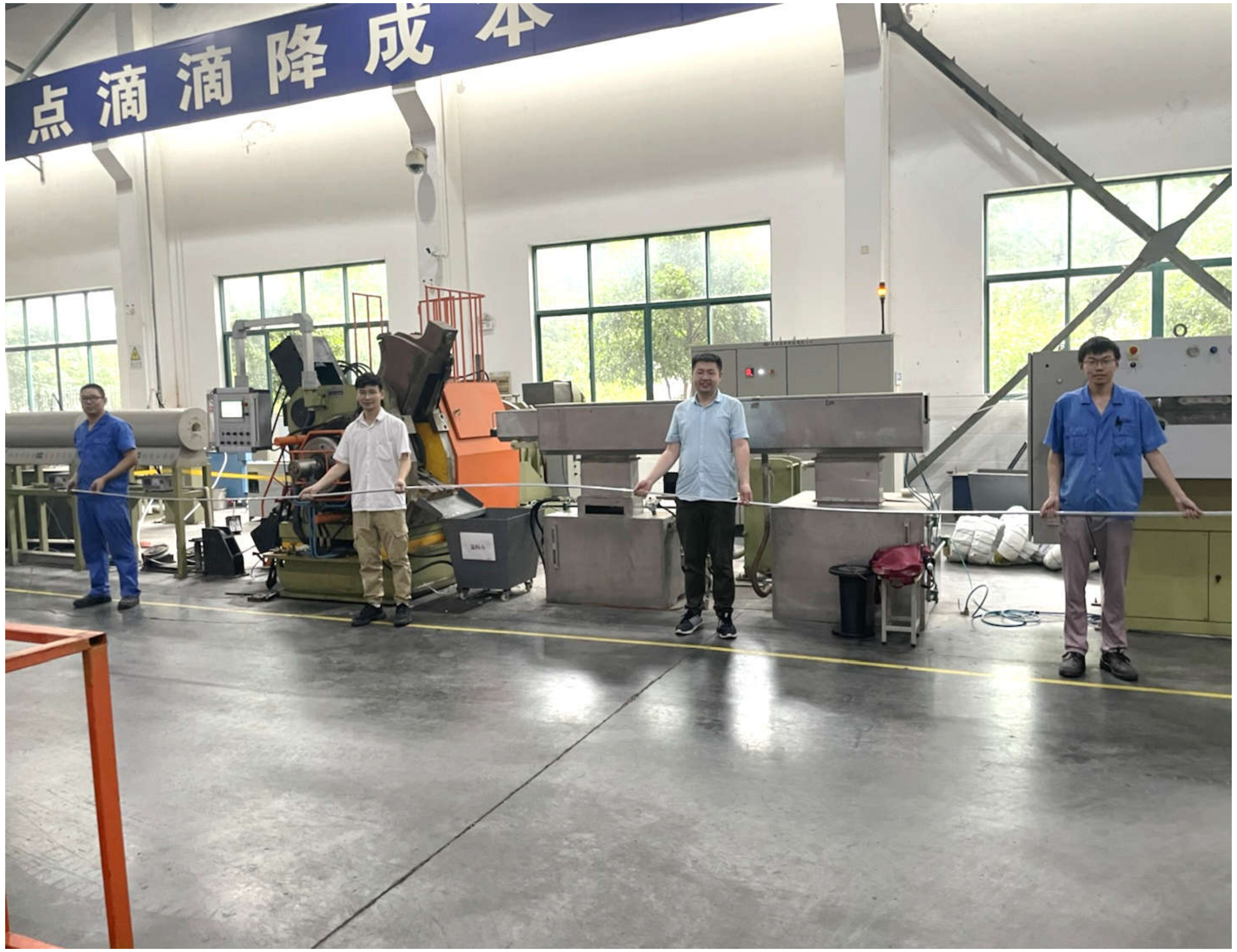
Cooling system

Caterpillar tractor

Take-up machine

TOLY Electric - China

Al-stabilized superconductor for CEPC detector magnet （HTS）



- **Short Al-stabilized ReBCO Stacked tape cable**

➢ Tensile strength of aluminum rod： 60MPa
➢ Temperature of the cavity mold： 500℃

Problems： the core cable is not centered, and the contact time during high temperature procedure is too long

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TOLY Electric - China

Al-stabilized superconductor for CEPC detector magnet （HTS）

- Toly Electric is participating in several pre-research projects of CEPC, mainly responsible for the fabrication of superconducting cables.
- We have found some difficulties and problems in the R&D .We are working hard to find new solutions.
- In the future, the group will increase budget for the R&D of Al-stabilized superconductor.

□ Short Al-stabilized ReBCO Stacked

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Alternative Soldering?

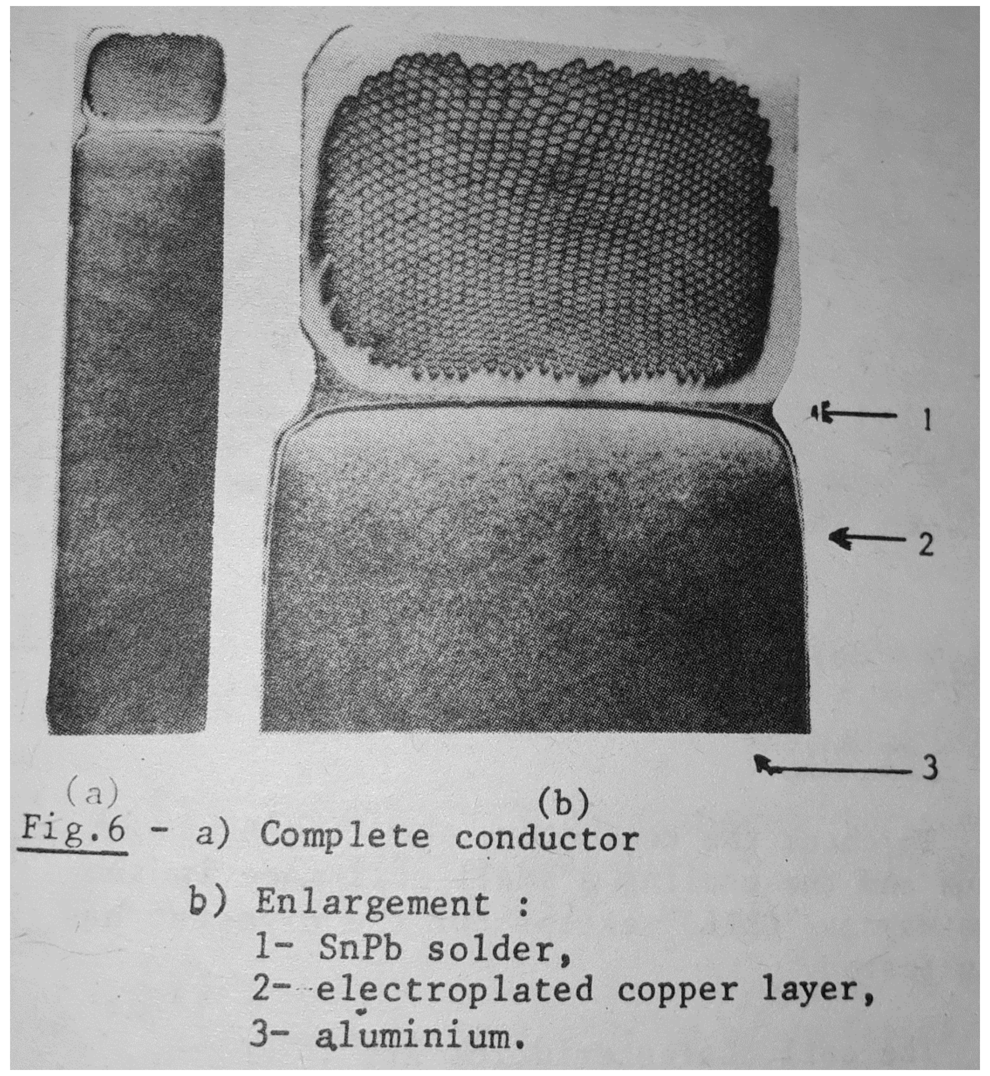
Has been done in the past

- CELLO@PETRA magnet was the first large scale s/c magnet using Al-stabilized conductor
- Conductor was soldered to Al body
  - Cu plating was required

Prototype tests also done for LHC detectors

Could be revived

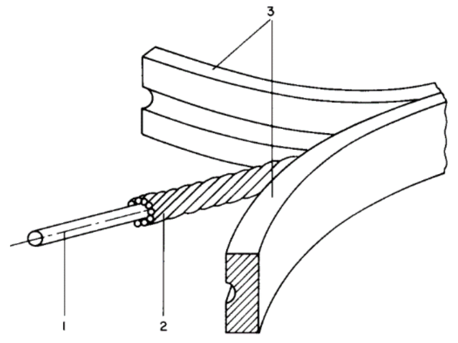
- requires R&D
- Electron-beam welding might be an option



Cello Conductor

One of the first aluminum soldered conductor 1979 for a solenoid of 1.5 T ($Ø_i$= 1.6 m, length 4 m).

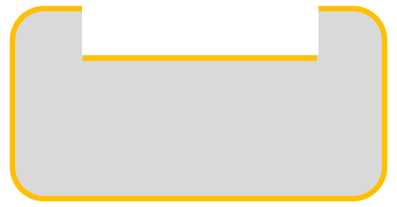
One year after Morpurgo magnet



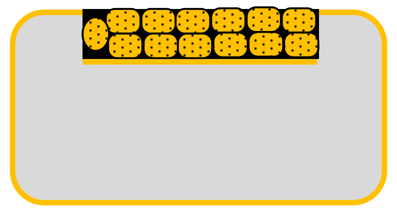
CERN workshop– 12-14/09/2022

CMS / ATLAS R&D FIRST MOCK UP

Existing Al. stabilizer with copper deposition

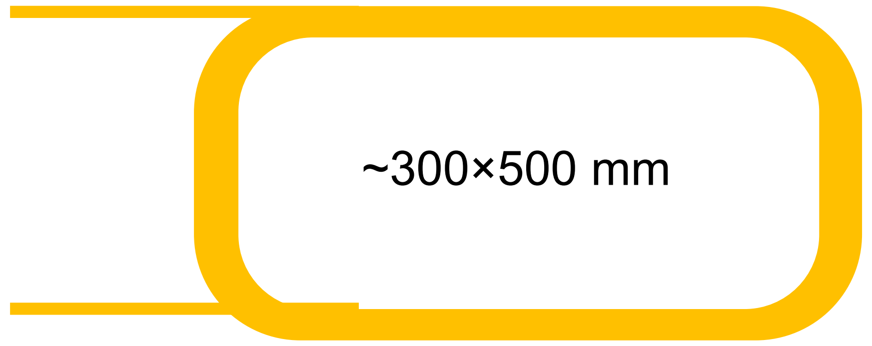


Groove machined by Turck head



Existing Rutherford & soldering by hand

~2×5 mm



Quench studies & inductive heater

First ATLAS Ractrack (MicroB)

C. Berriaud

Alternative CICC?

Cable-in-Conduit Conductors

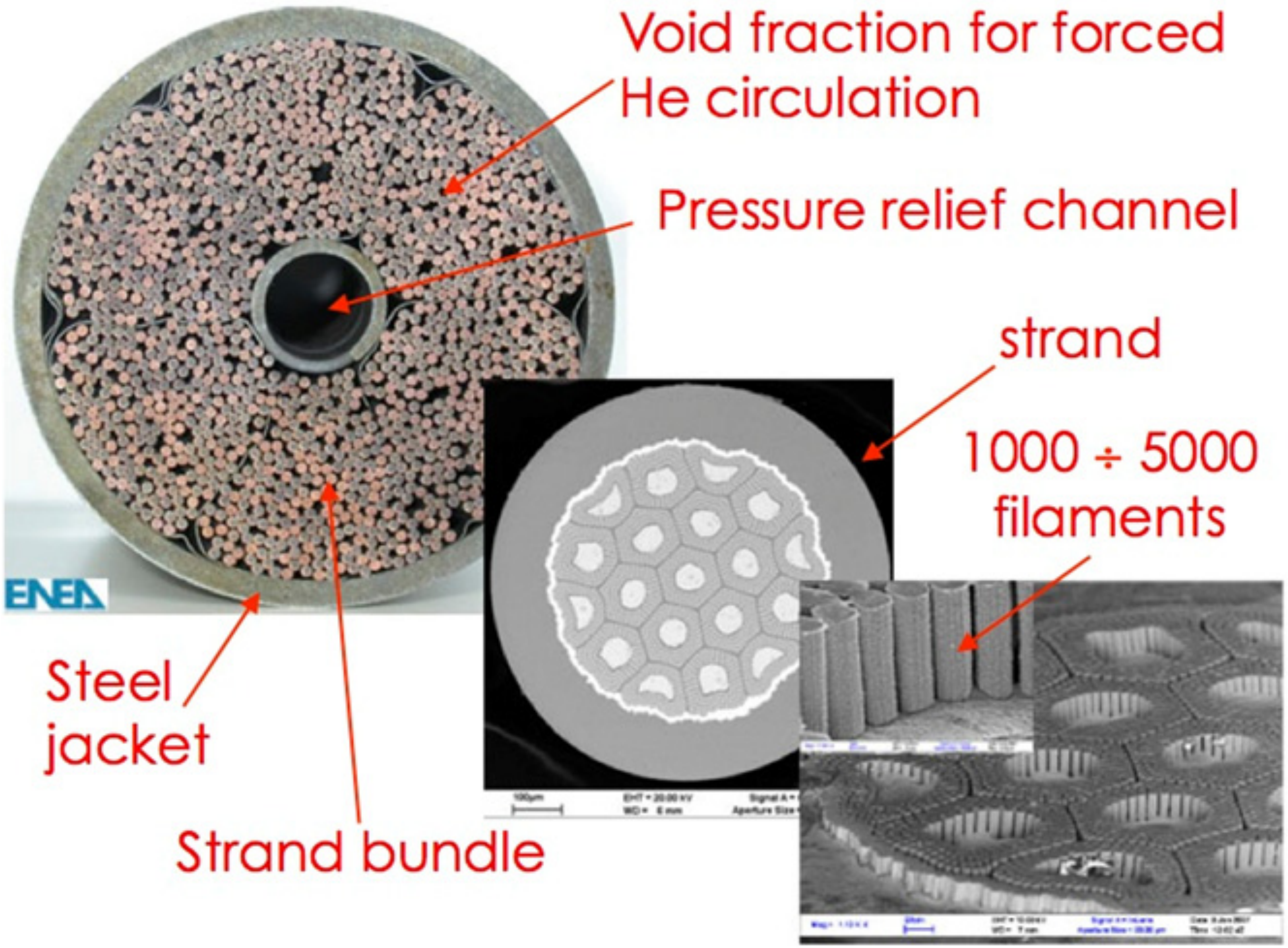
- S/C strands in conduits
- cooled by superfluid He

Advantages

- stable direct cooling situation
- established technology, e.g., in ITER

Challenges for detector magnets

- complicated cooling system
- pre-cooling requirements
- difficult to keep the material budget low



L. Muzzi et al, Supercond. Sci. Techn. 28 (2015) 053002

The Future - HTS?

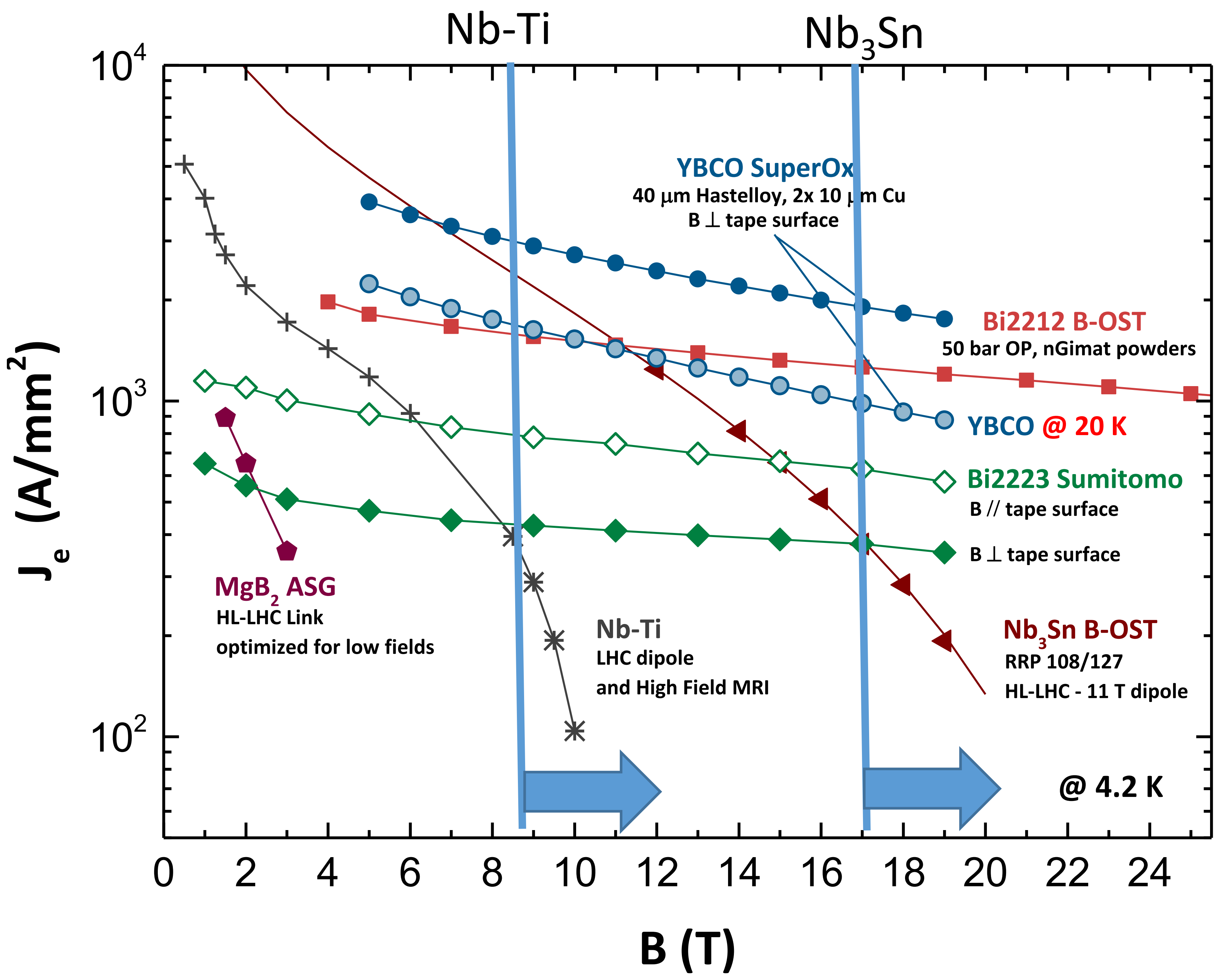
Only choice for

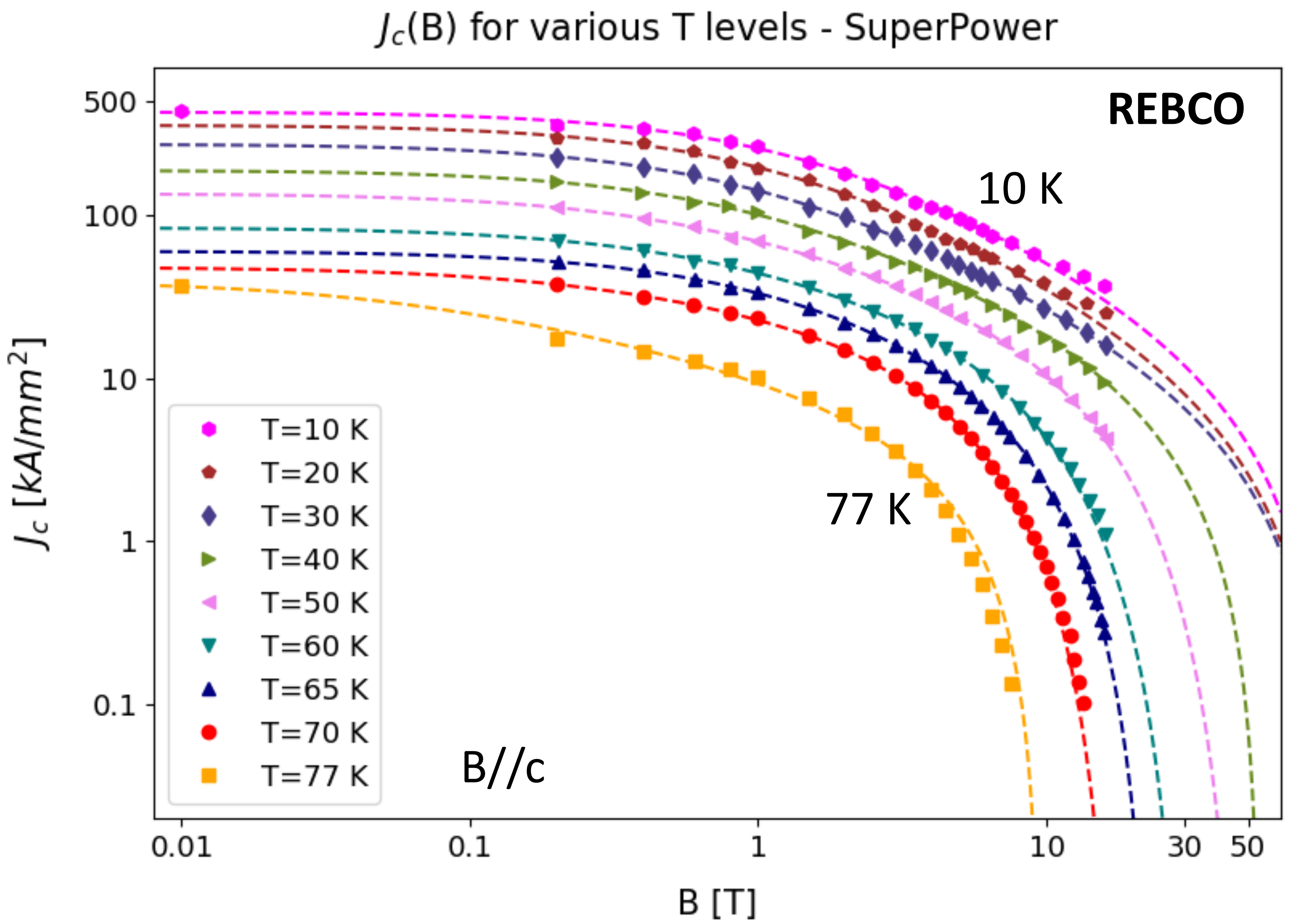
- >16T fields
- cooling temps ~30K
    - indirect cooling
    - gaseous He cooling
    - lower cryo cost

Active field of R&D

HTS in magnets

High Jc at 4.2 K **and/OR** **Higher temperatures**





Conclusions

There is a problem with the bread-and-butter technology of particle detector magnets

- Al-stabilized conductors are an established technology, best adapted to our requirements
  - high fields, large volumes, low material budget
- Unfortunately, industry in large parts of the world has abandoned the technology
  - there are no available production sites with a proven track record (e.g. from LHC detectors)
- Russian institutes and industry are still in the business and are (were?) involved in R&D for PANDA
- A newcomer from China (TOLY) is doing R&D for CEPC
  - an on-going R&D process

Soldering/EB-Welding might be an alternative

- was used in the past, but has not being followed up for large detector magnets since decades

CICC might be worth to look into in more detail

- requires different magnet system design

HTS are attractive

- but the Al-stabilization is also a good idea for them

Need to push for R&D in labs together with industry to keep the timelines of future projects!