News on Detector Solenoids

Karsten Buesser
LCWS2024
09.07.2024

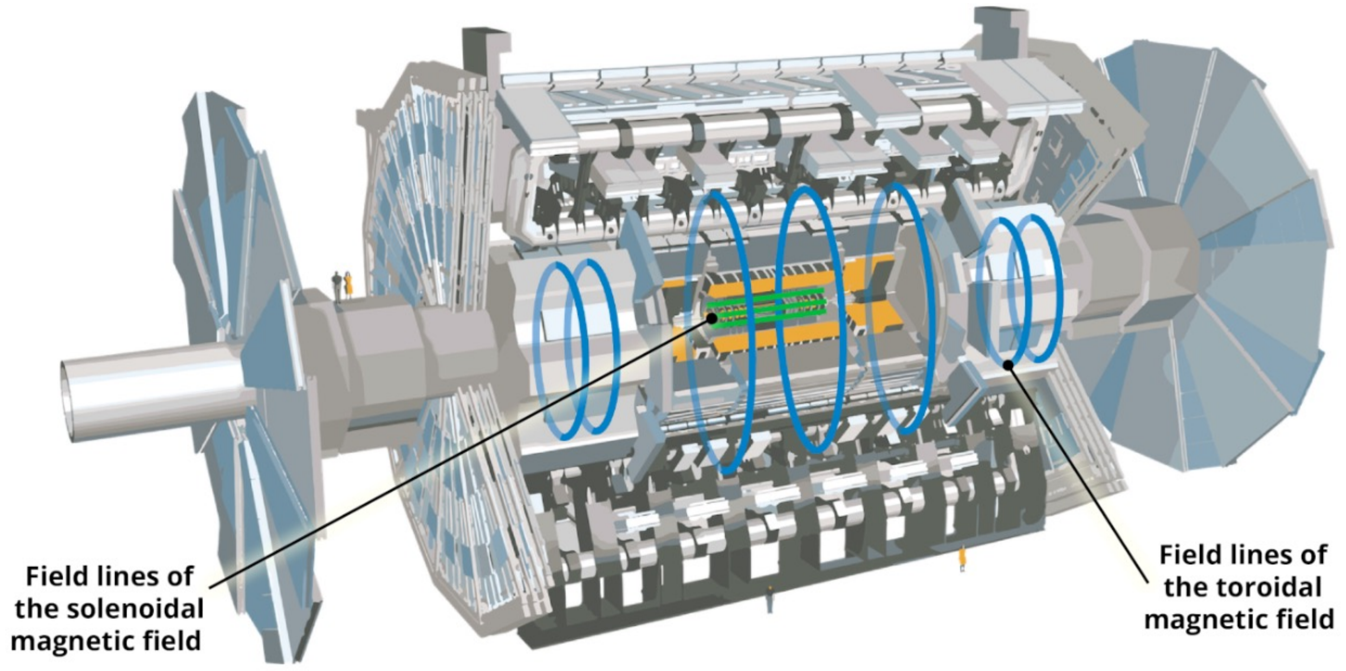
Historical experiences of the ATLAS and CMS magnet projects

Very large superconducting detector magnet projects!

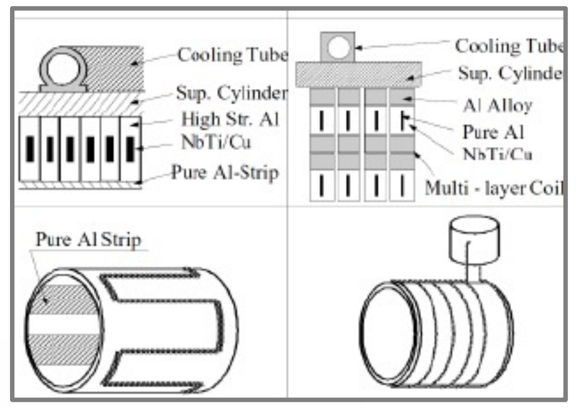
- Time-scale for engineering design and validation effort, the construction, and the commissioning: More than 15 years each
- Production of components (conductor, coils, support structure, etc) in industry, and subsequent assembly at CERN
- Designed, constructed, commissioned, and maintained with strong 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

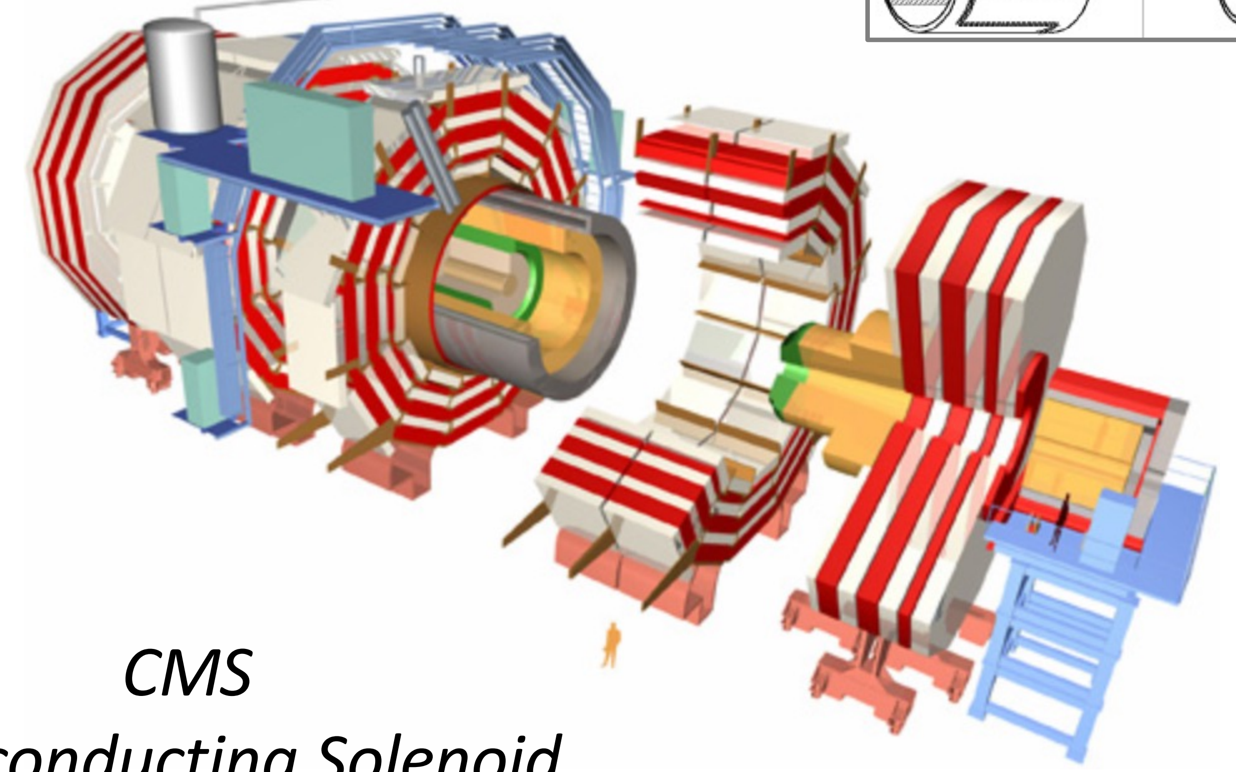
Important lessons:

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



ATLAS Superconducting magnets





CMS Superconducting Solenoid

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

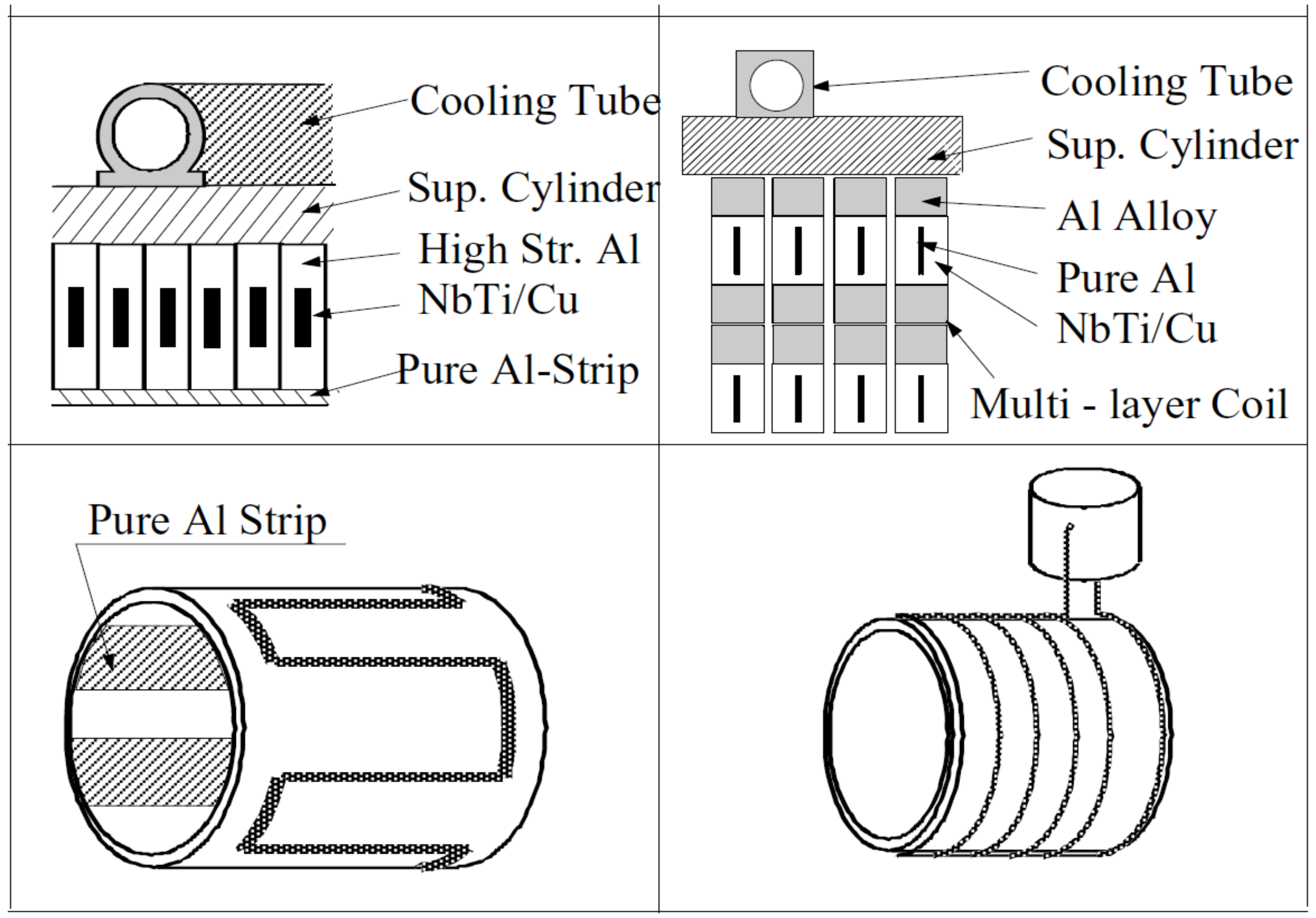
Challenges

- 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



M. Mentink et al 2023 JINST 18 T06013

Al-stabilized Conductors

Aluminum as stabilizer

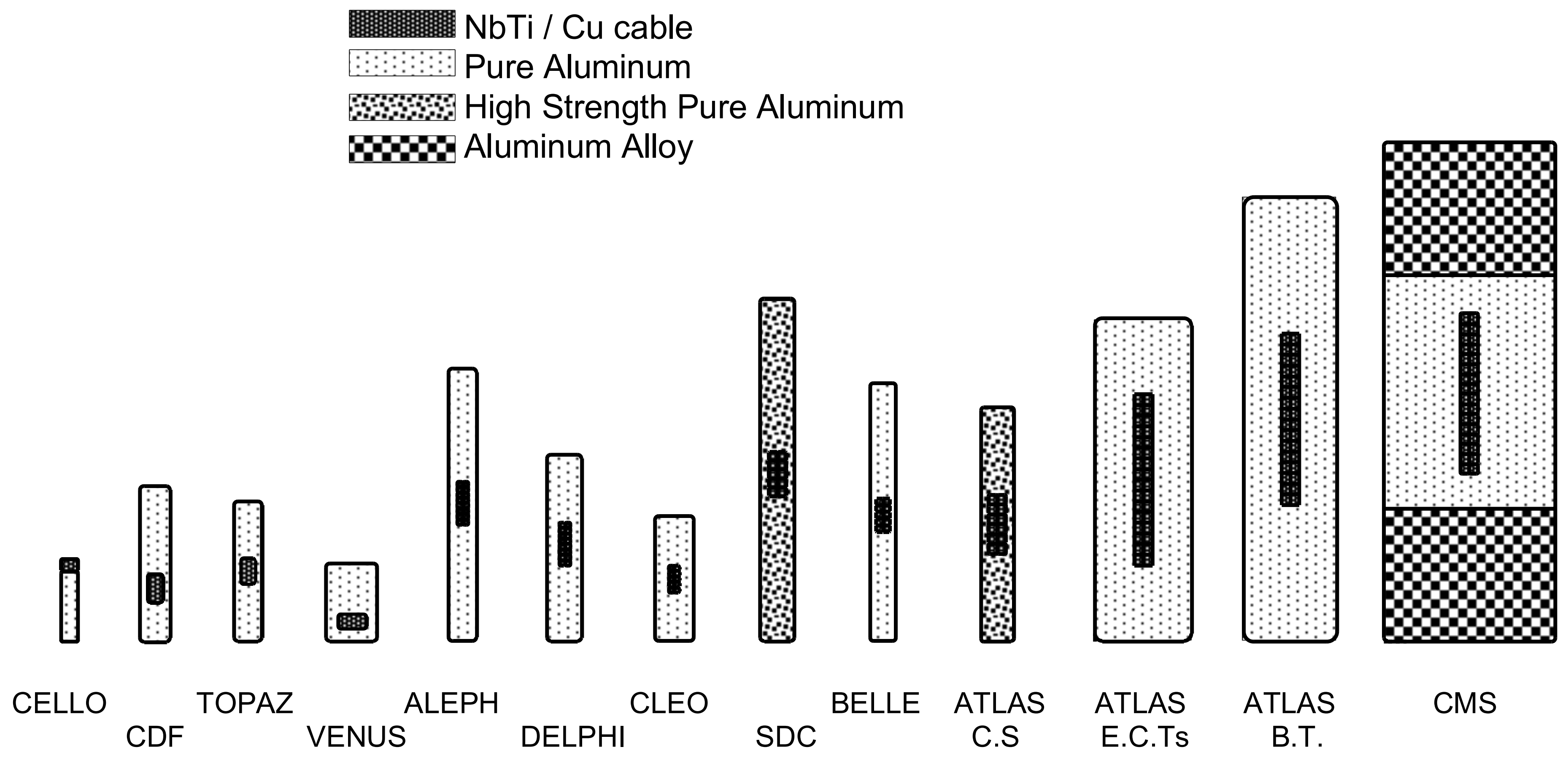
- has to absorb stored energy in case of a quench
  - compensate forces
  - protect superconductor
- good thermal and electrical conductor
- good mechanical strength
- minimum material and weight

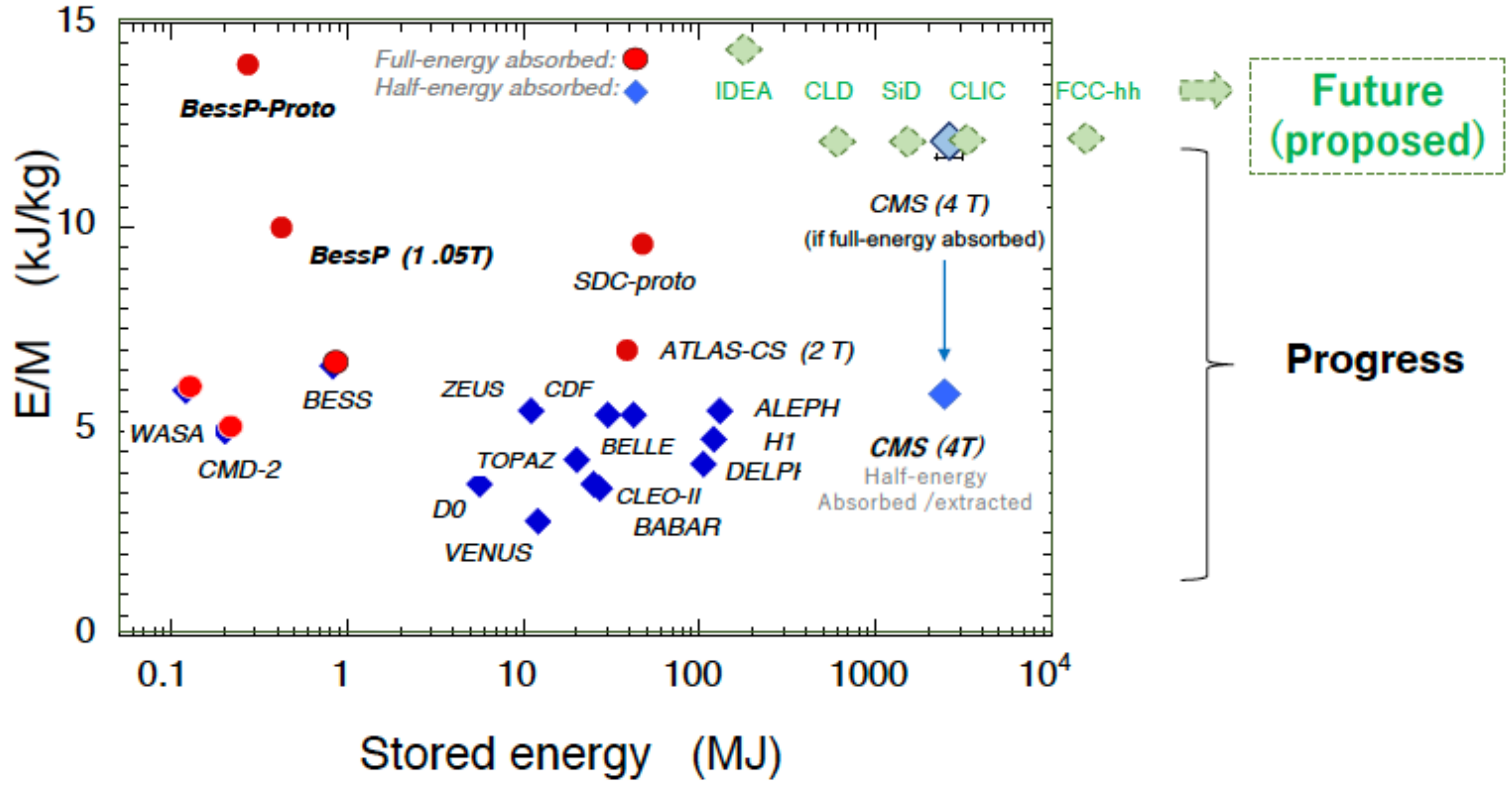
Pure high-conductivity Al is rather soft

- 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





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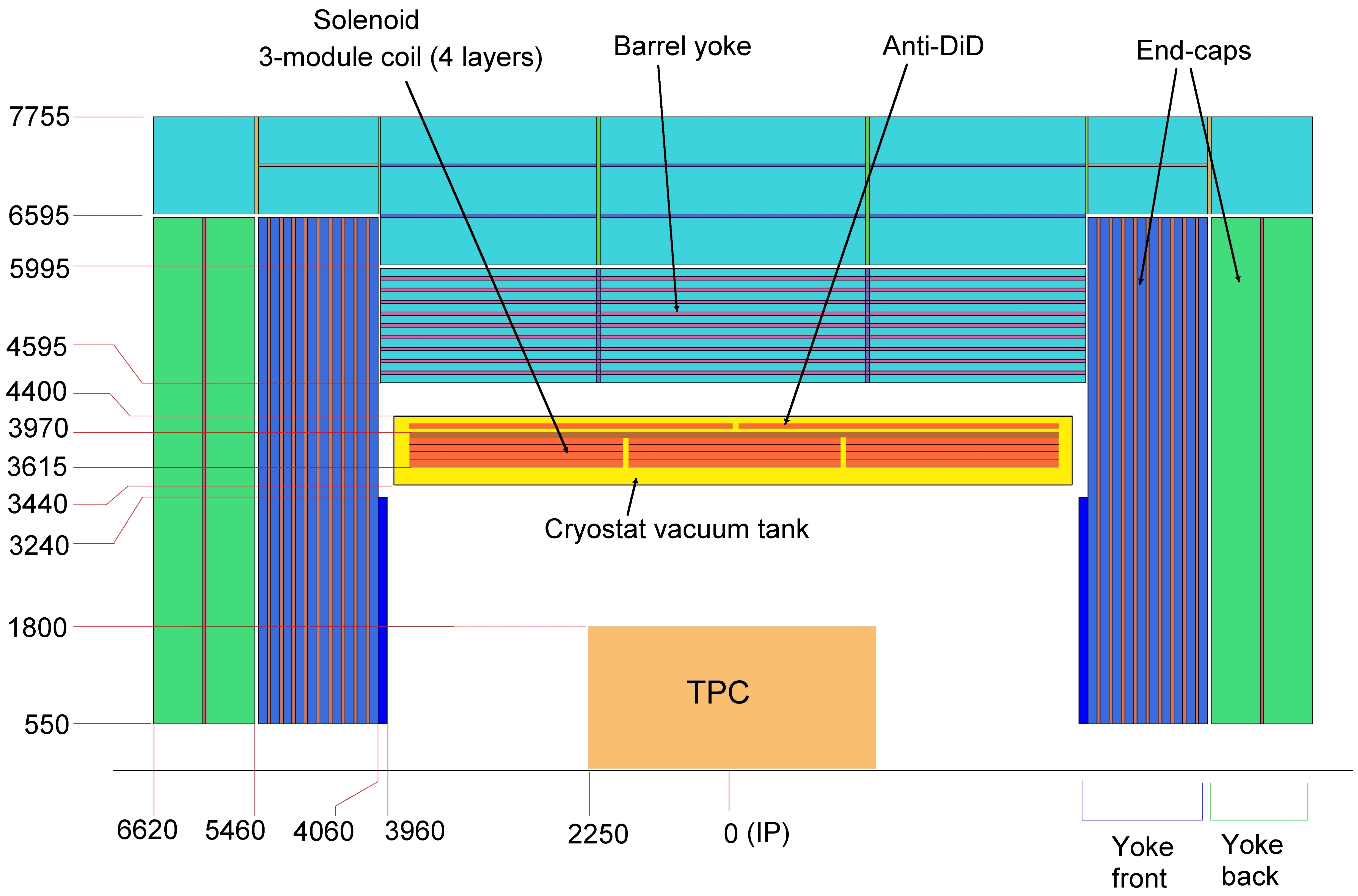
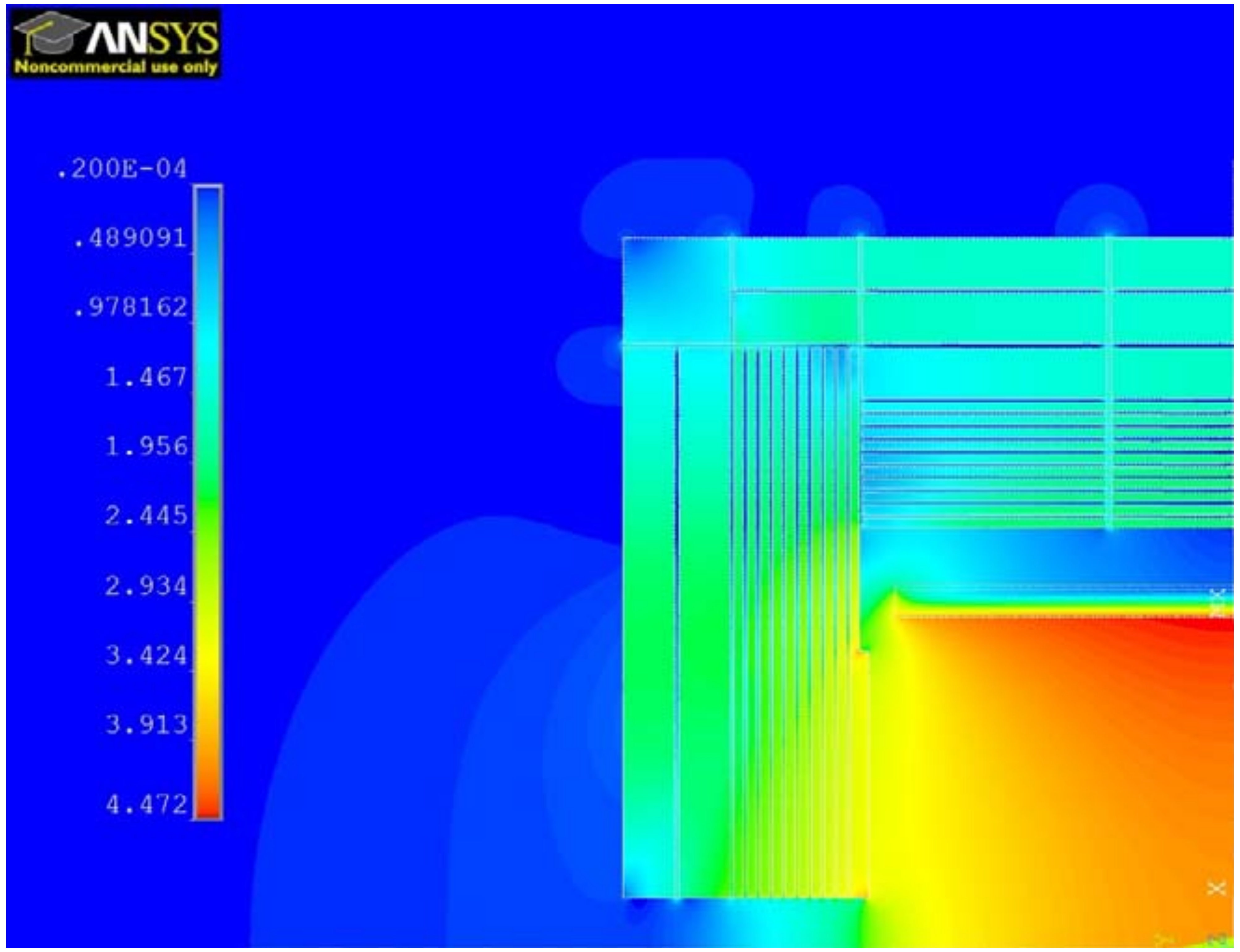
ILD Magnet

Modelled after CMS experience

- 4T central field, 2.3 GJ stored energy





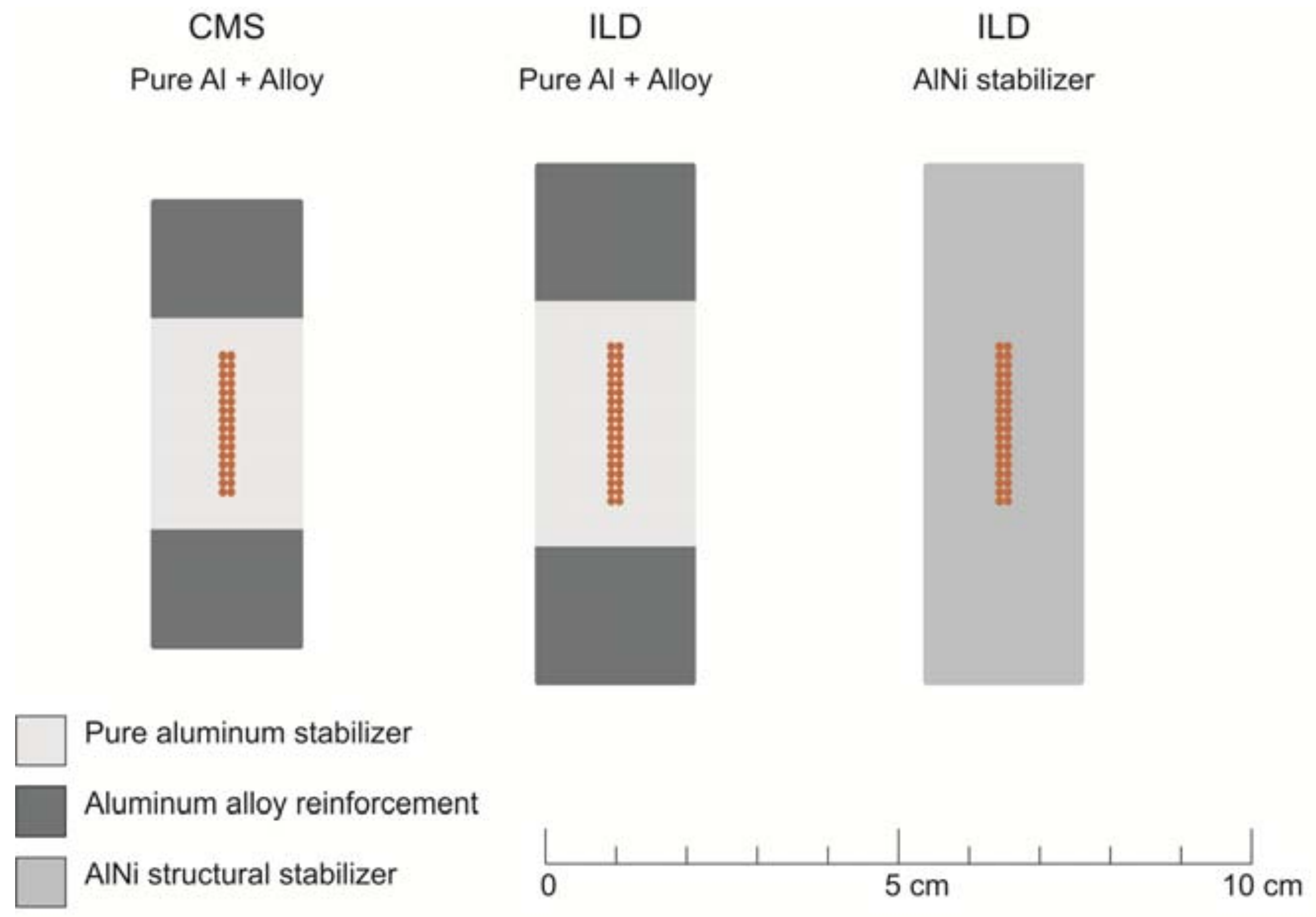
LC-DET-2021-081

ILD Magnet

Conductor

- Rutherford Cable
- Aluminum stabiler
  - Either CMS-like: Pure Al + Alloy
  - Or homogeneous AlNi

Design maximum solenoid central field (T)	4.0	Nominal current (kA)	22.4
Maximum field on conductor (T)	4.6	Total ampere-turns solenoid (MAt)	27.65
Field integral (T*m)	32.65	Inductance (H)	9.2
Coil inner radius (mm)	3615	Stored energy (GJ)	2.3
Coil outer radius (mm)	3970	Stored energy per unit of cold mass (kJ/kg)	13
Coil length (mm)	7350		



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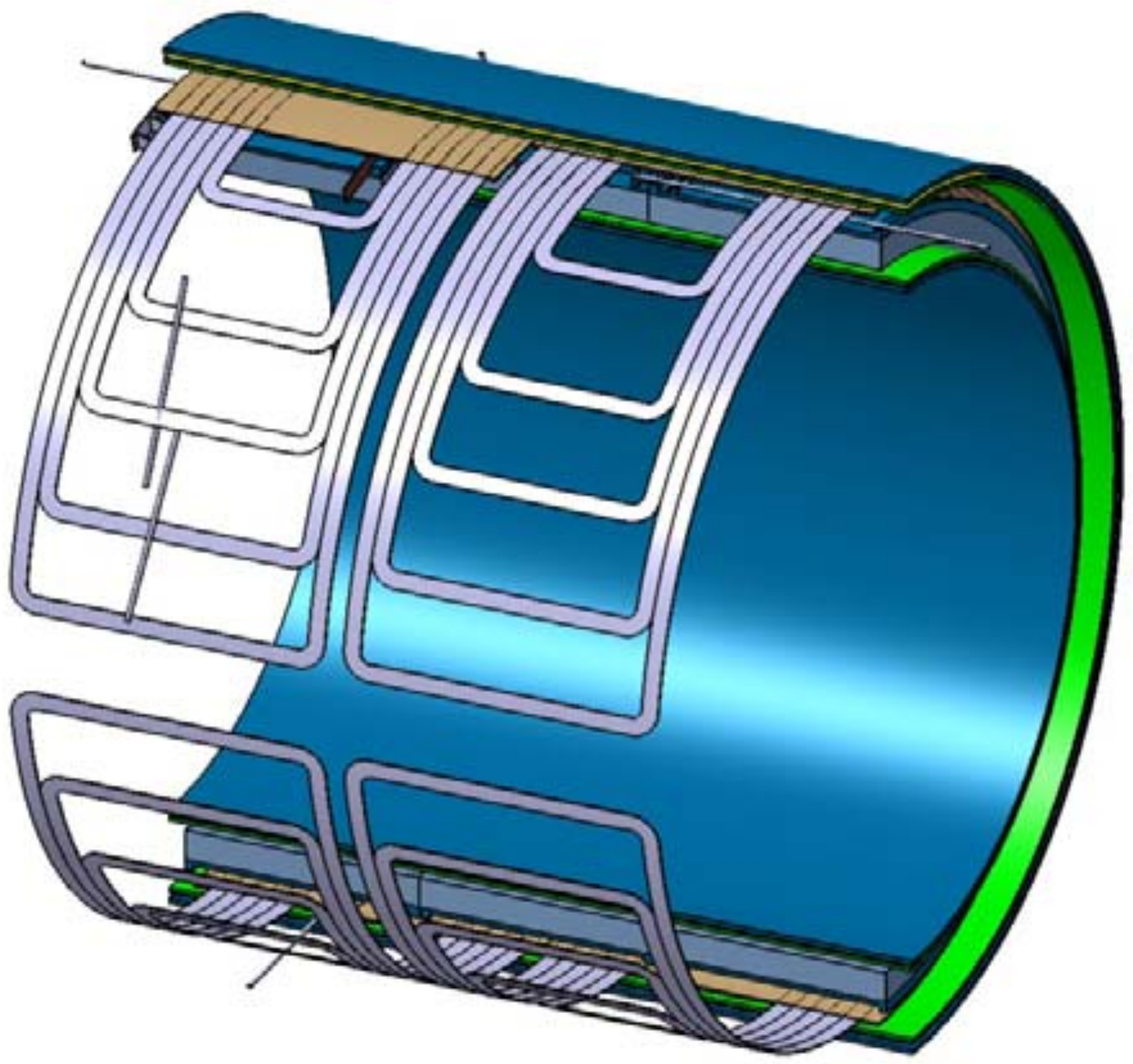
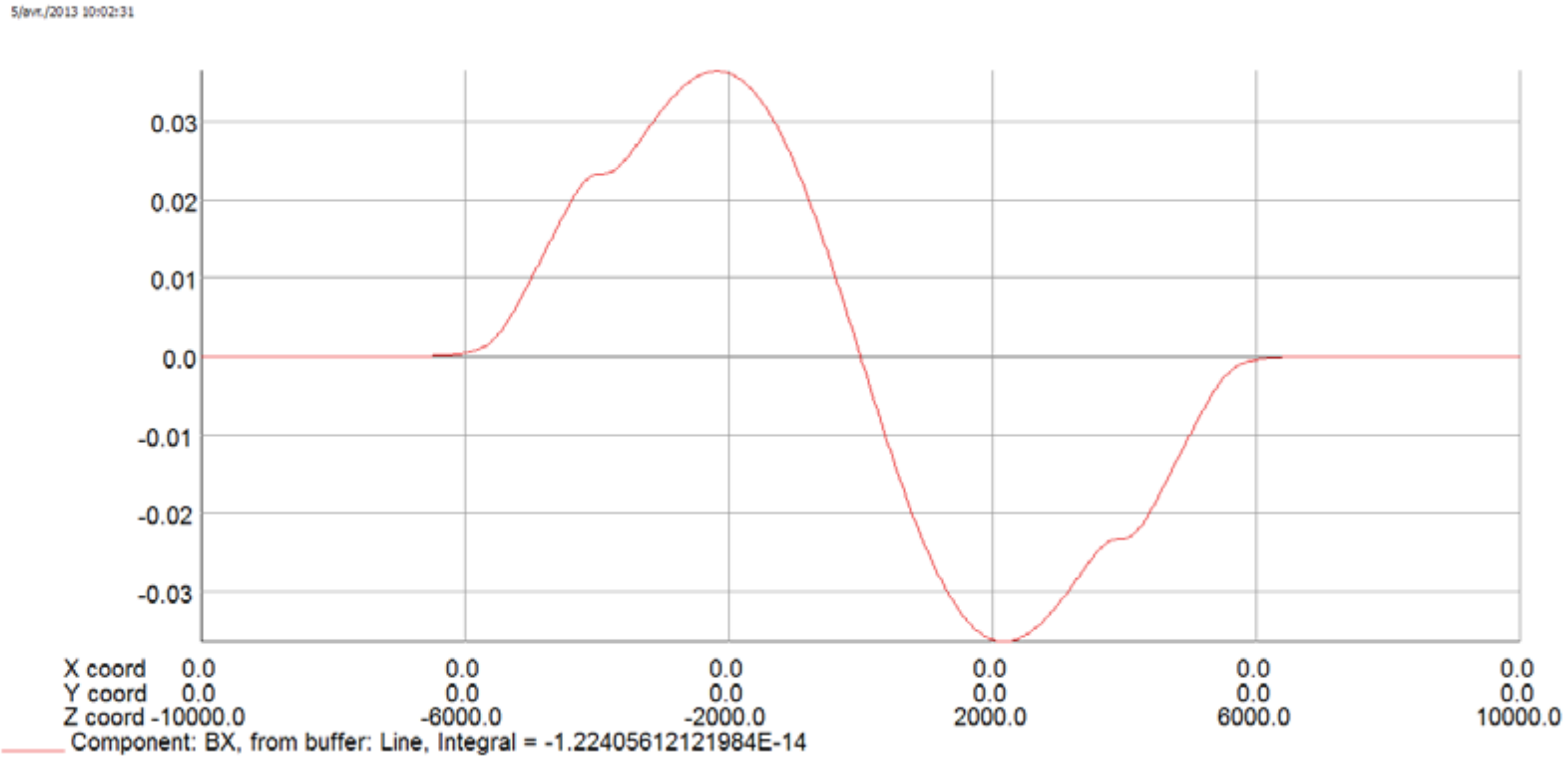
ILD Anti-DID

DID: Detector Integrated Dipole

- Added outer dipole coils to align magnetic field with ILC crossing angle (7 mad)
- Could help to reduce beam-induced background
- Adds complexity to the engineering design and assembly procedures (see talk from Y. Makida)

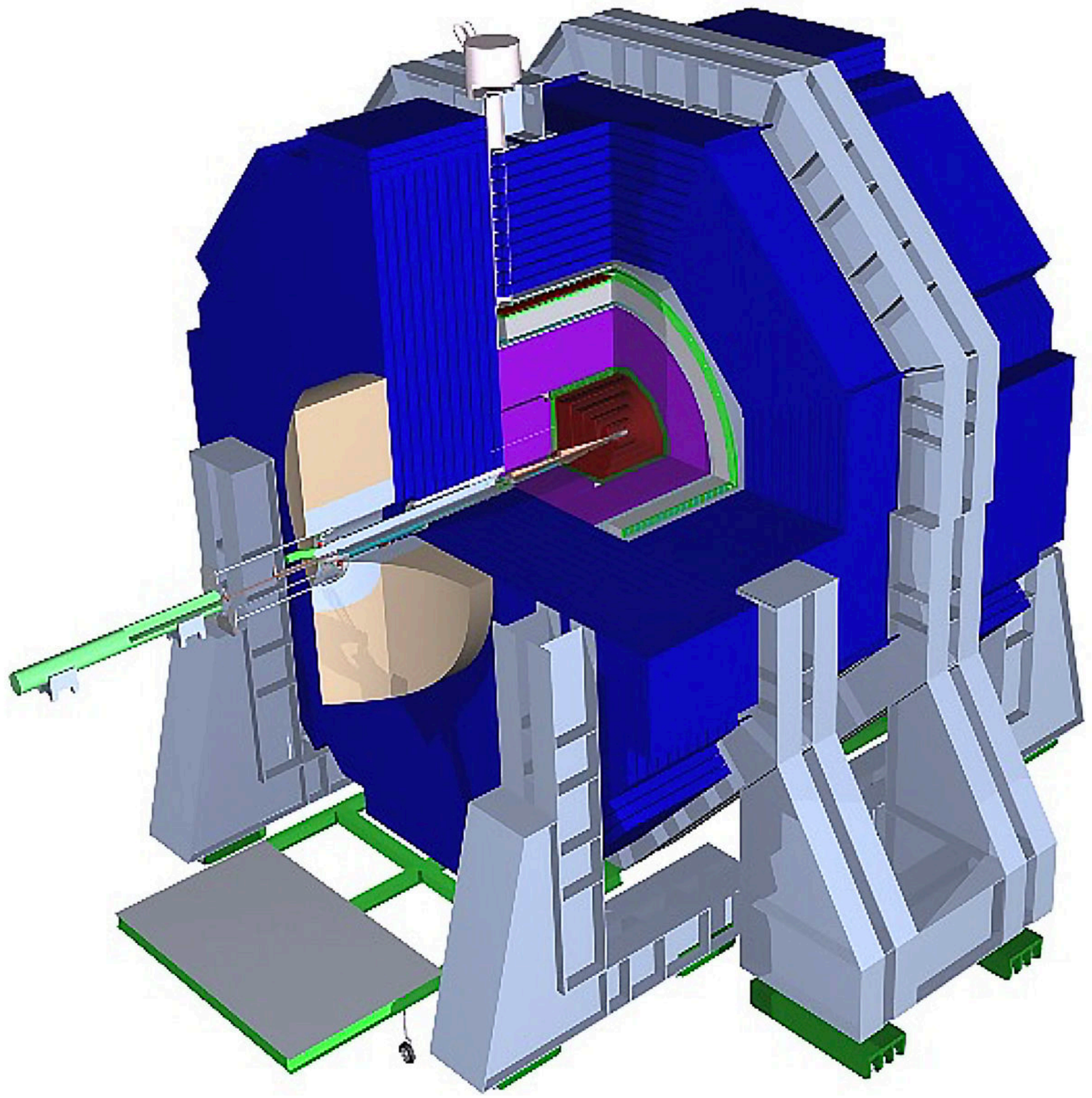


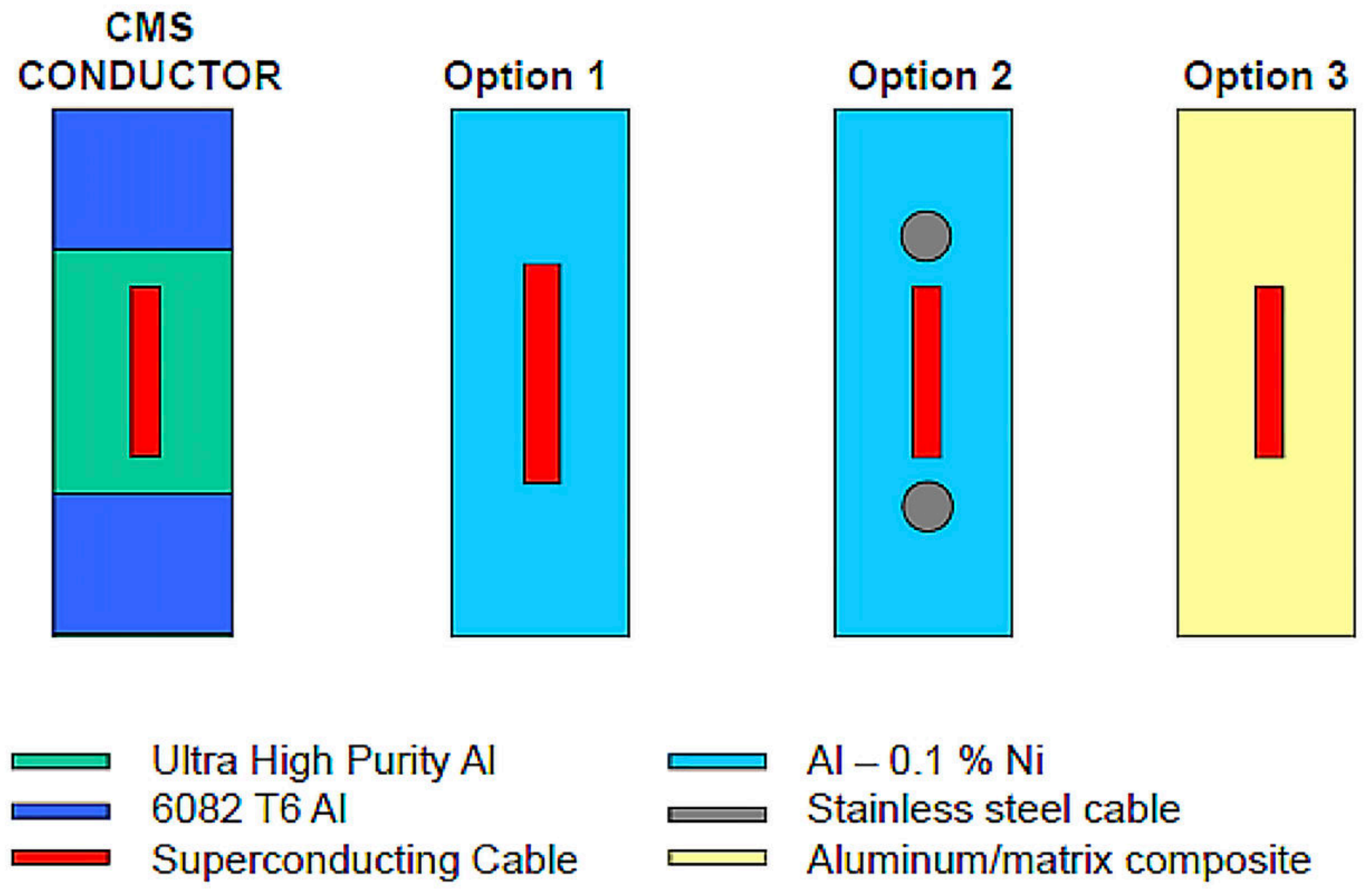


LC-DET-2021-081

SiD

- 5T maximum central field
- Smaller volume as ILD, less stored energy





ILC-REPORT-2013-040

Quantity	SiD	CMS	Units
Central Field	5.0	4.0	T
Stored Energy	1.59	2.69	GJ
Stored Energy Per Unit Cold Mass	12	11.6	kJ/kg
Operating Current	17.724	19.2	kA
Inductance	9.9	14.2	H
Fast Discharge Voltage to Ground	300	300	V
Number of Layers	6	4	
Total Number of Turns	1459	2168	
Peak Field on Superconductor	5.75	4.6	T
Number of CMS superconductor strands	40	32	
% of Short Sample	32	33	
Temperature Stability Margin	1.6	1.8	K
Total Cold Mass of Solenoid	130	220	tonne
Number of Winding Modules	2	5	
R_{min} Cryostat	2.591	2.97	m
R_{min} Coil	2.731	3.18	m
R_{max} Coil	3.112	3.49	m
R_{max} Cryostat	3.392	3.78	m
Z_{max} Cryostat	$\pm$ 3.033	$\pm$ 6.5	m
Z_{max} Coil	$\pm$ 2.793	$\pm$ 6.2	m
Operating Temperature	4.5	4.5	K
Cooling Method	Forced flow	Thermosiphon	

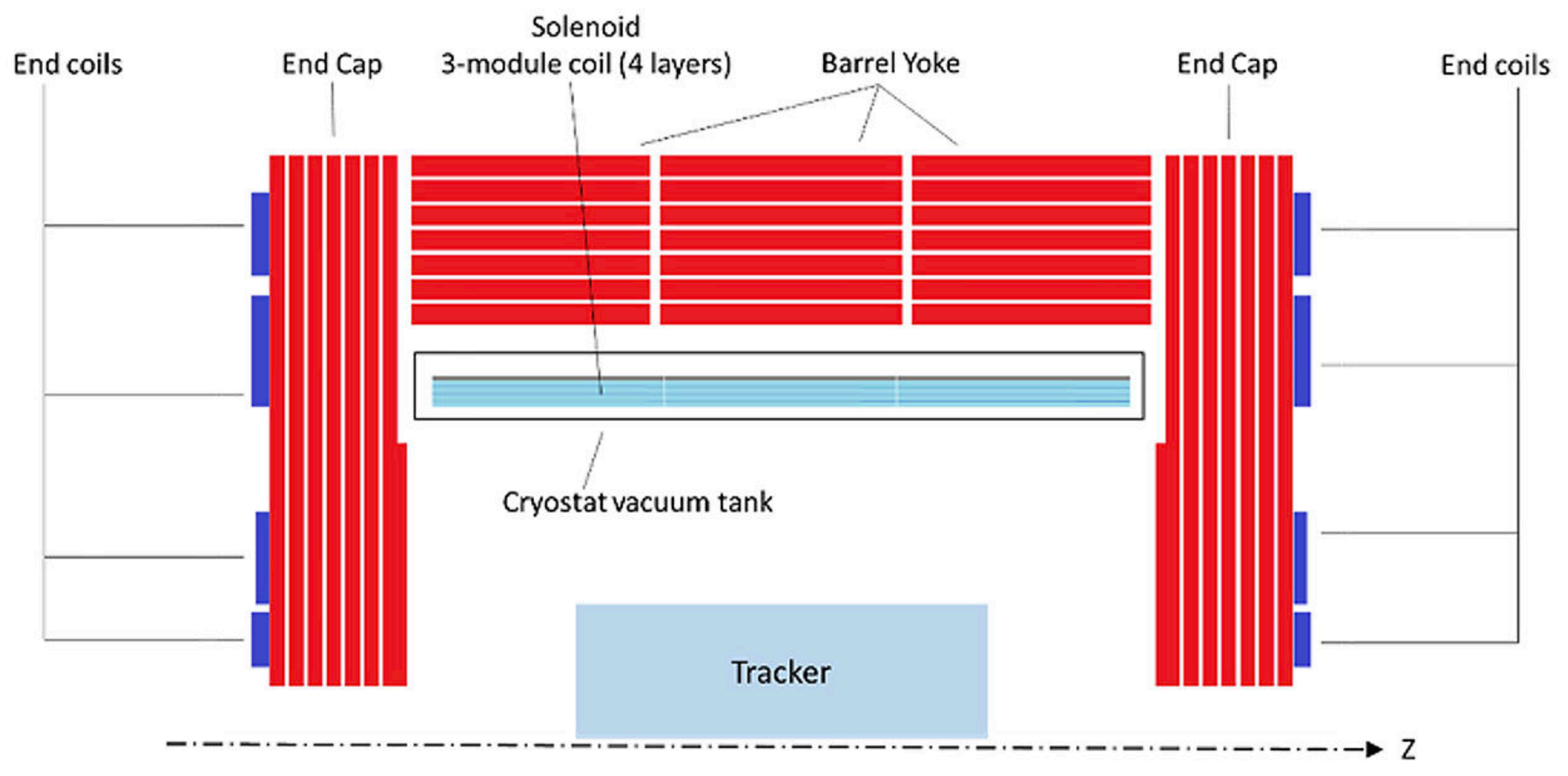
M. Mentink et al 2023 JINST 18 T06013

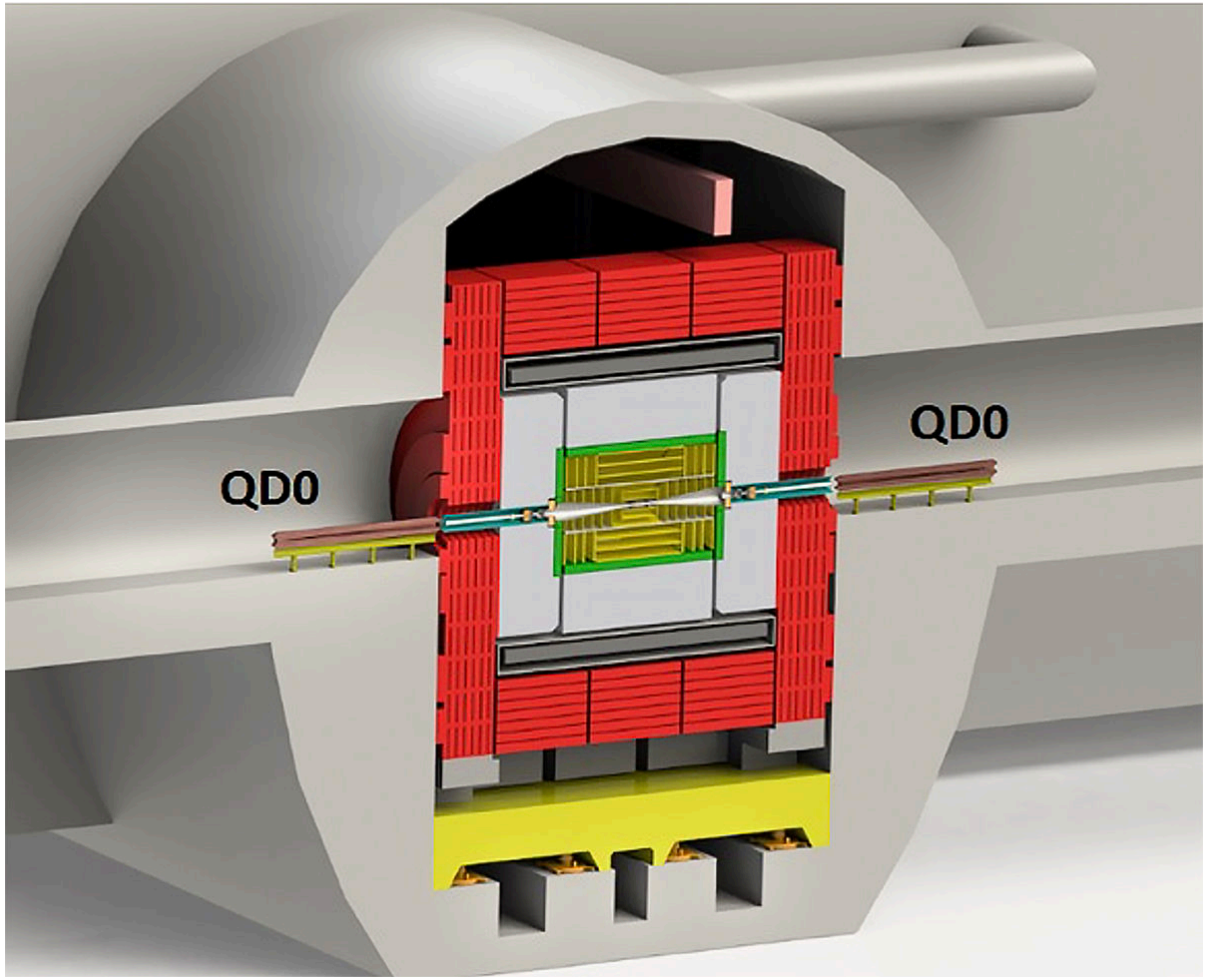
CLICd

Similar design as ILD/SiD

- With end-cap coils to reduce iron size

Property	Value
Magnetic field at IP (T)	4
Inductance (H)	12
Nominal current (kA)	20
Stored energy (GJ)	2.3
Average energy density (kJ/kg)	13
SC cable number of Nb-Ti strands	32
Conductor cross section (mm^2)	83×20
Coil inner radius (mm)	3650
Coil length (mm)	7800





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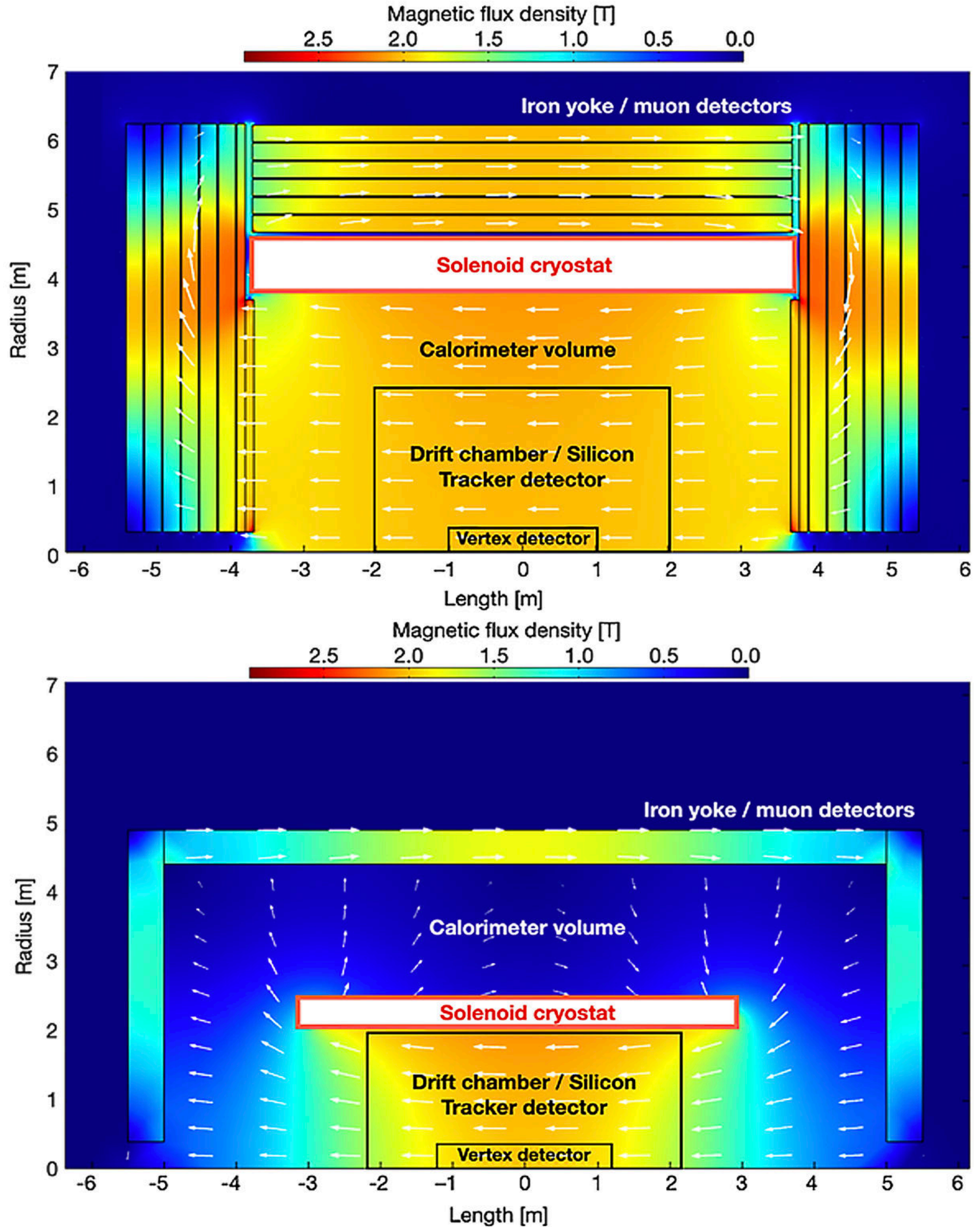
FCC-ee

Examples CLD and IDEA

- Both with 2T maximum field
- CLD: coil outside of the calorimeters
- IDEA: coil inside of the calorimeters

Property	IDEA	CLD	Unit
Conductor			
Conductor material	Nb-Ti/Cu in Al/Ni cladding		
Conductor height	36	36	mm
Conductor width	10	22	mm
Turn-to-turn insulation	1	1	mm
Number of strands	30	26	
Strand diameter	1.1		mm
Cu:SC ratio	1: 1		
Operating current	20		kA
Operating temperature	4.5		K
Coil			
Inner radius	2.235	4.02	m
Length	5.8	7.2	m
Weight	12.5	49.5	t
Number of turns x layers	530 x 1	300 x 1	
Support cylinder thickness	12	25	mm
Total coil thickness	53	102	mm
Central field	2		T
Stored energy	170	600	MJ
Energy density	14	12	kJ/kg



FCC-hh

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
- No return yoke
  - Would be too heavy for molasse-type rock

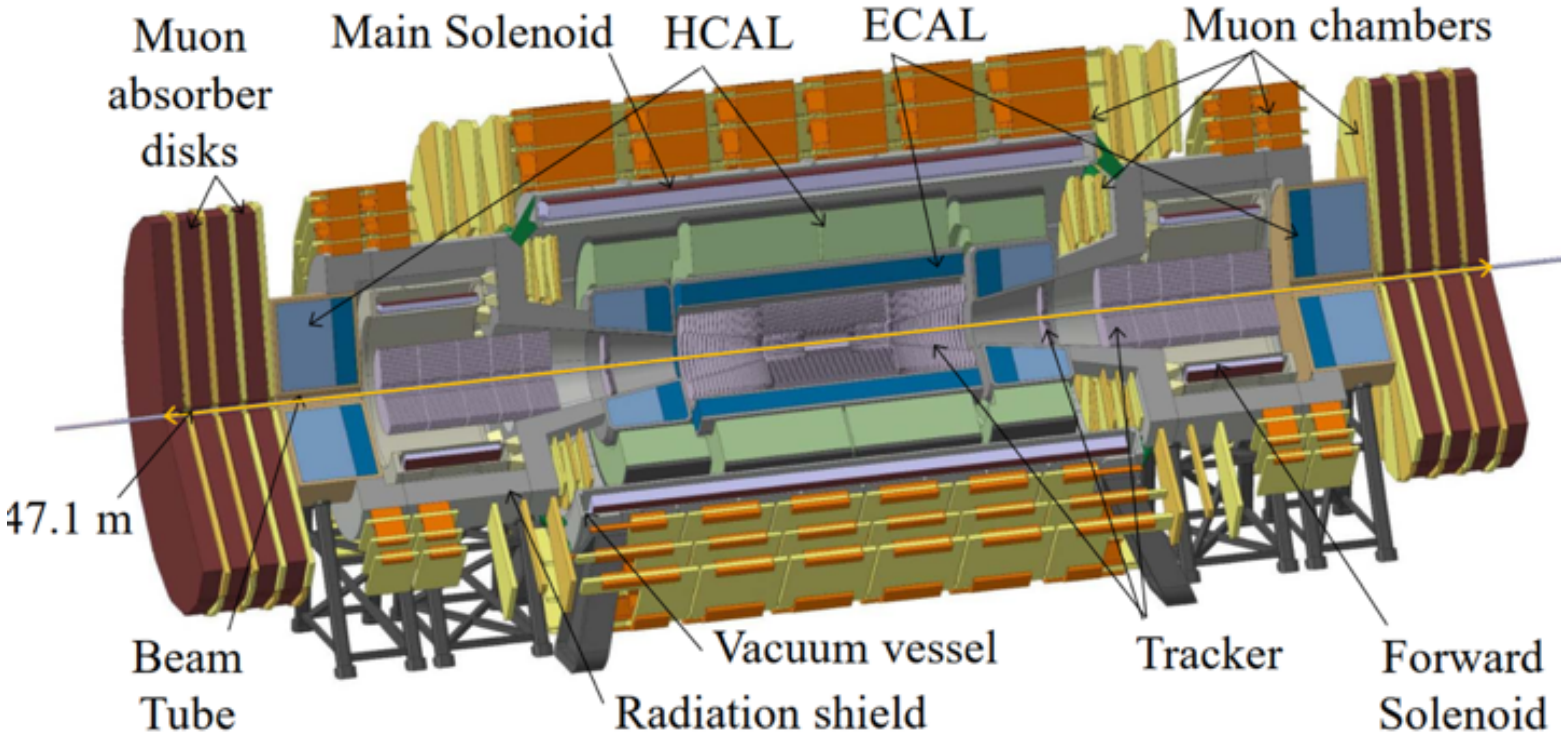
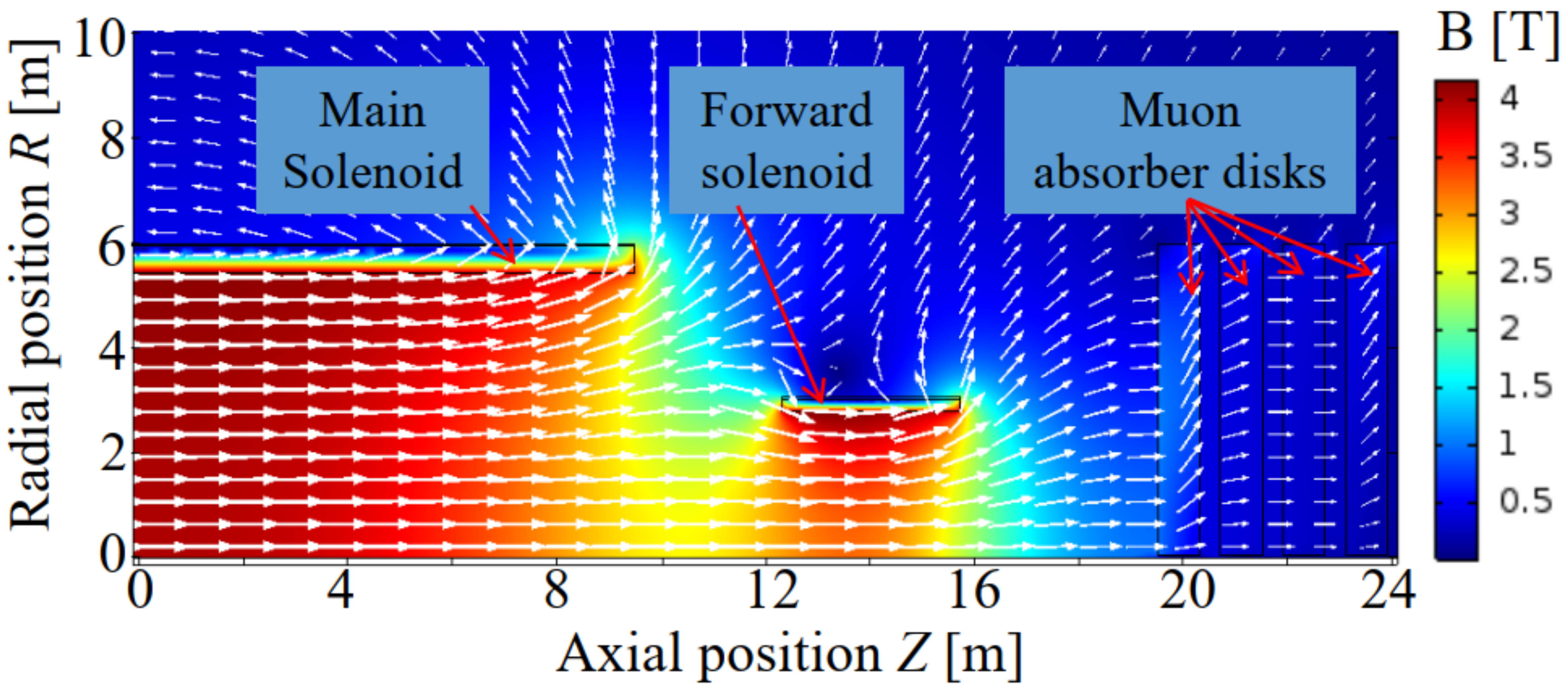


Fig. 4.4 Proposed FCC-hh detector base-line layout



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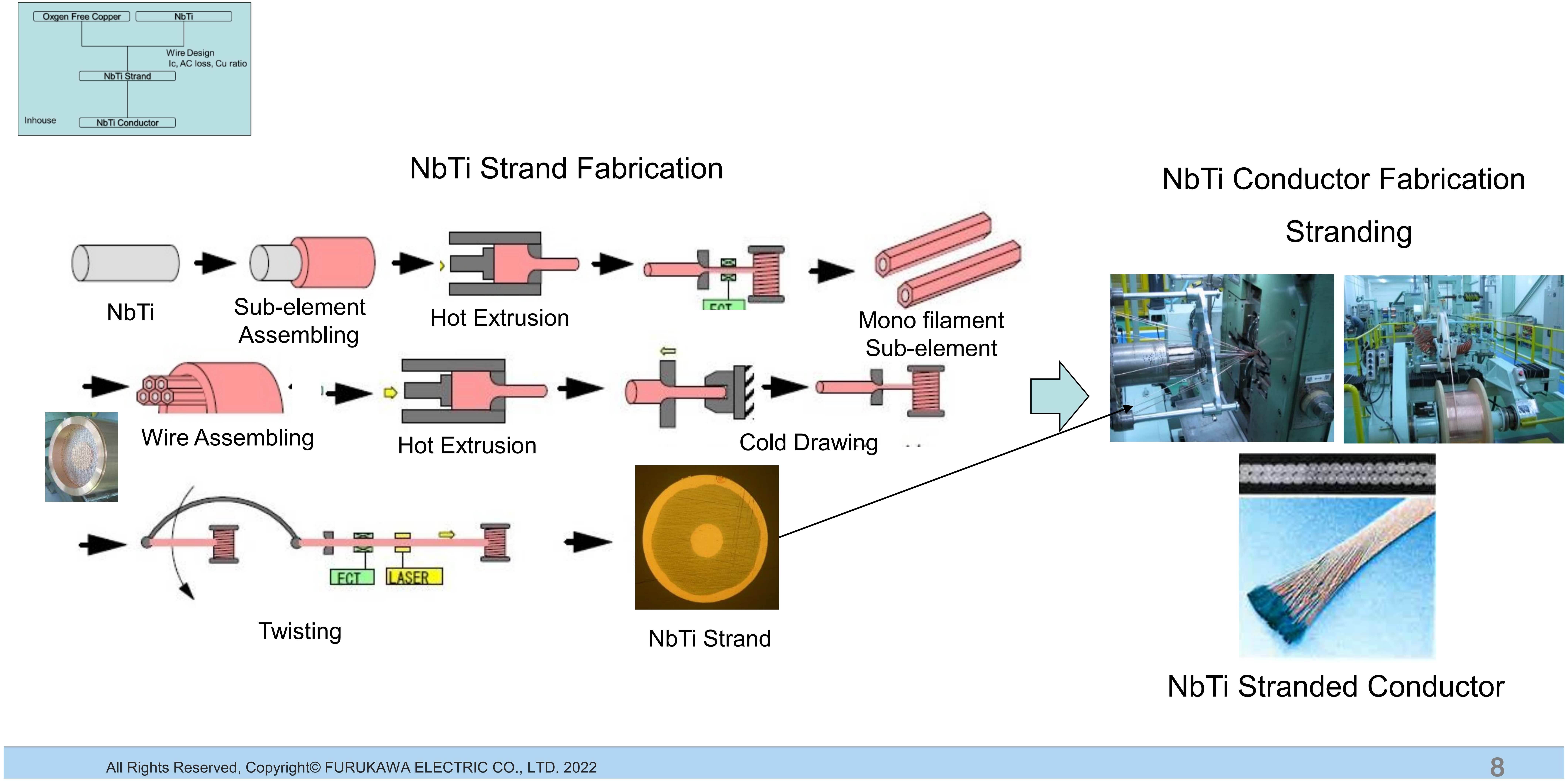
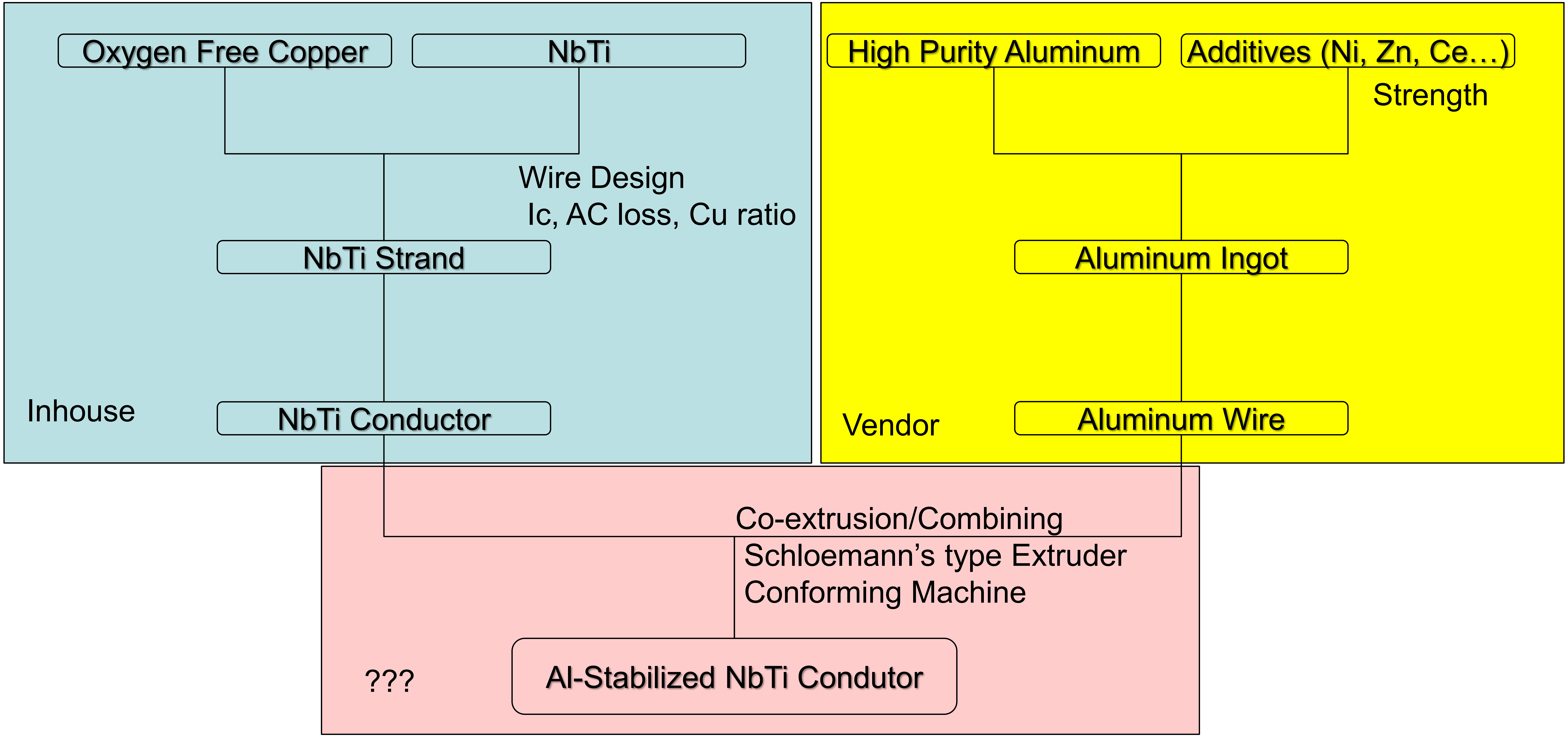
Nb/Ti Conductor Production

Established process in industry



Furukawa Electric, CERN Workshop on S/C Magnets, 09/2022

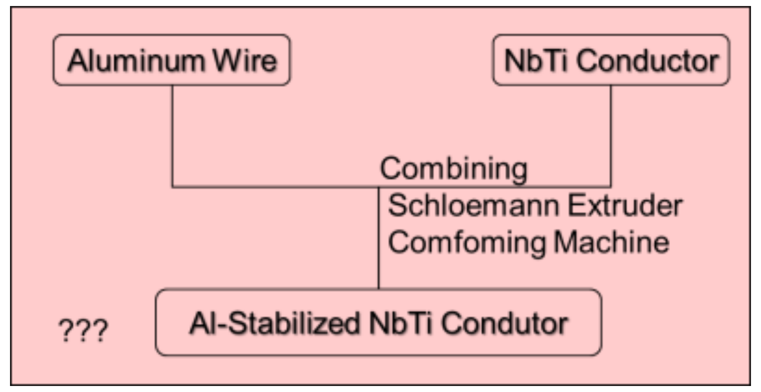
Bringing Al and Conductor together



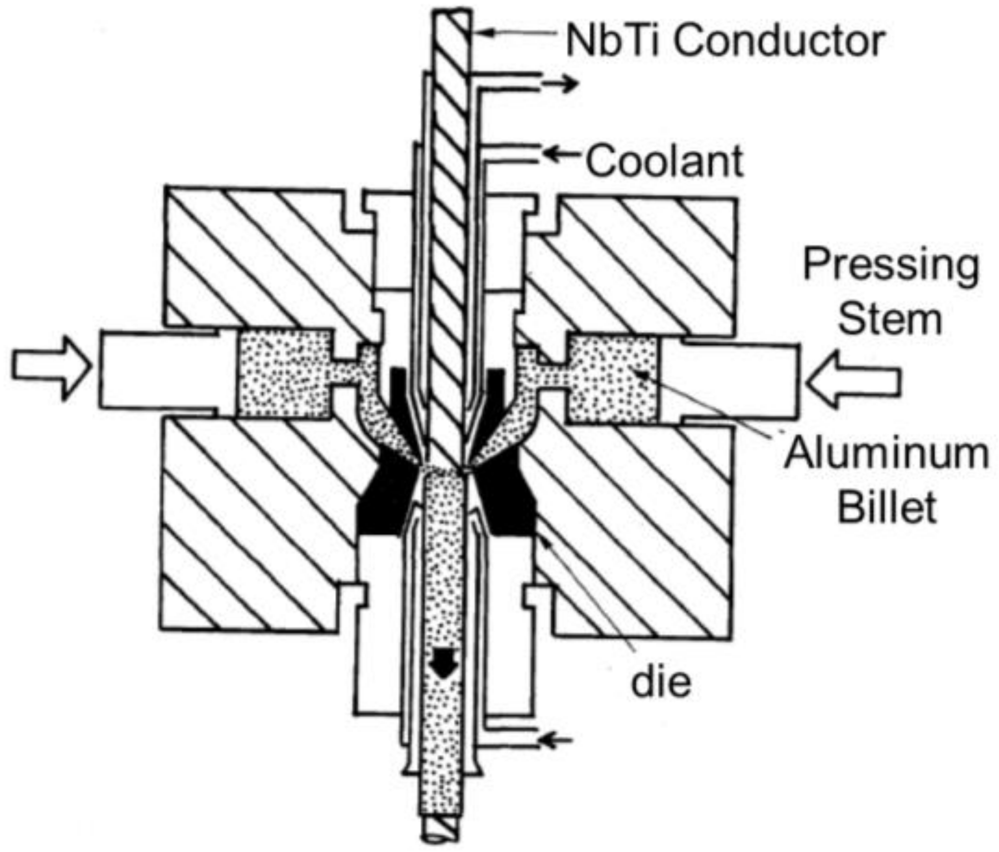
Furukawa Electric, CERN Workshop on S/C Magnets, 09/2022

Combining NbTi conductor and Al Stabilizer

FURUKAWA ELECTRIC



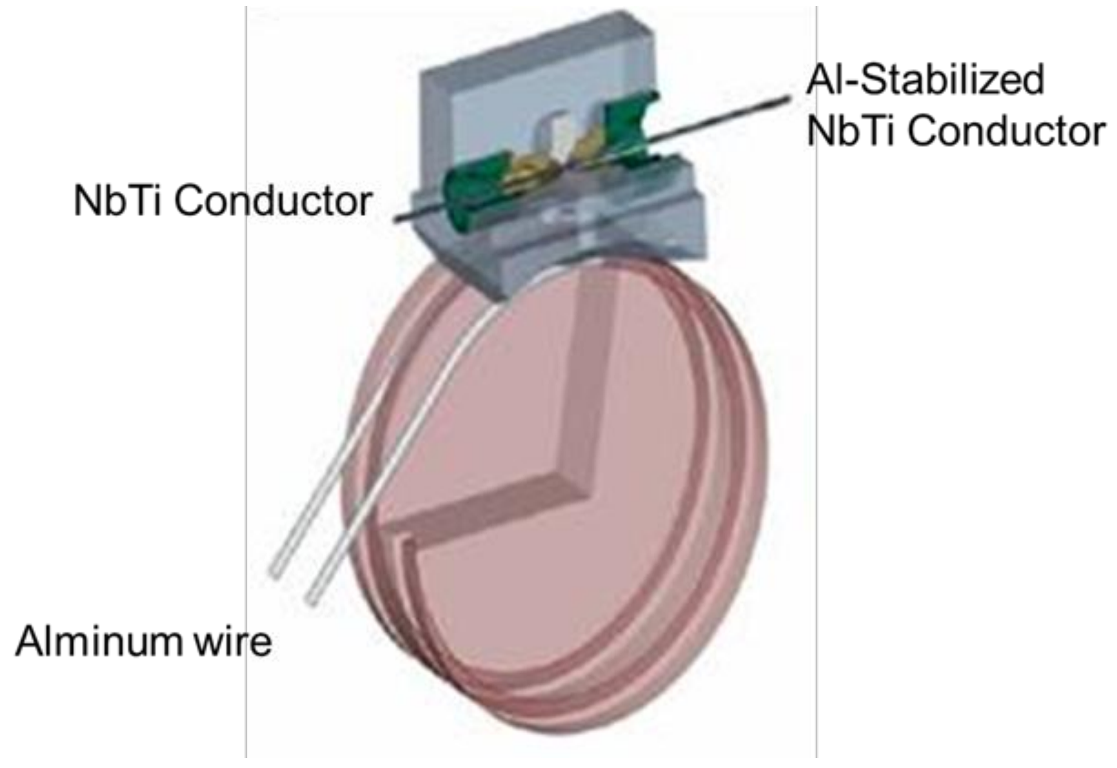
Historically, two types of machines are used for combining NbTi conductor and Al stabilizer. One is Schloemann's cable claddig press and the other is conforming (conklad) machine.



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/

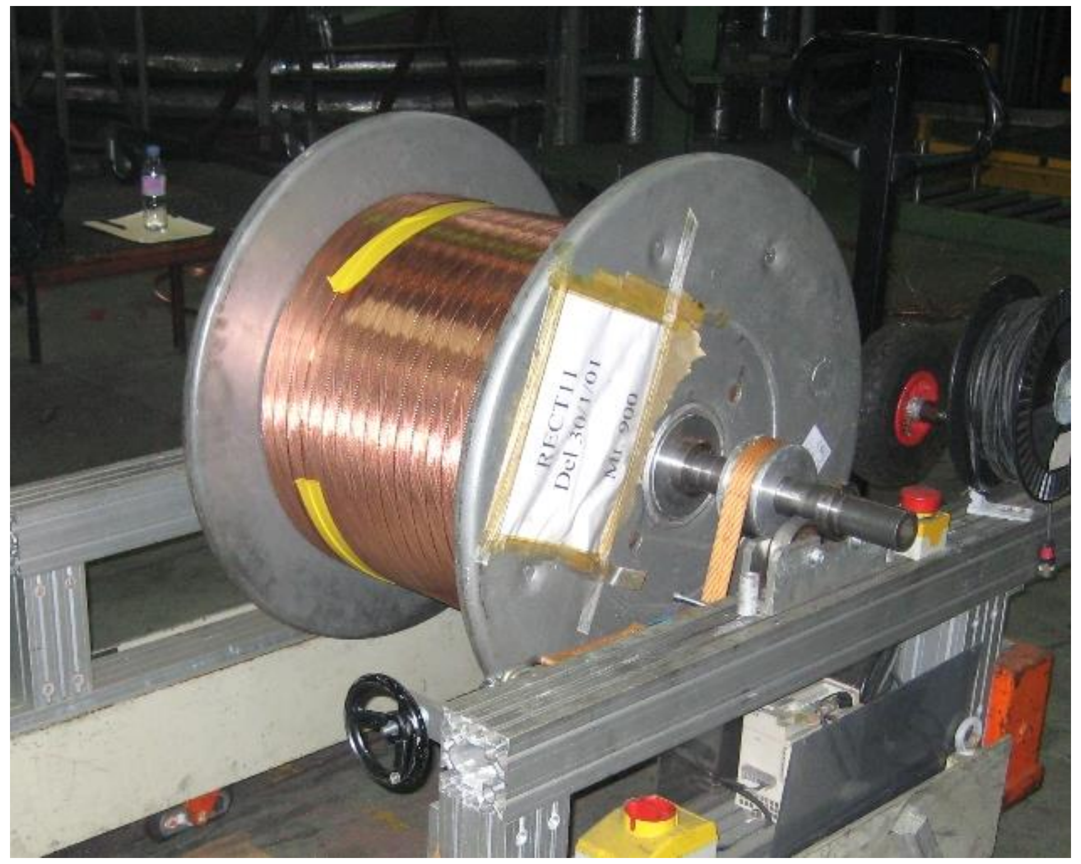
Furukawa Electric, CERN Workshop on S/C Magnets, 09/2022

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, CERN Workshop on S/C Magnets, 09/2022

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

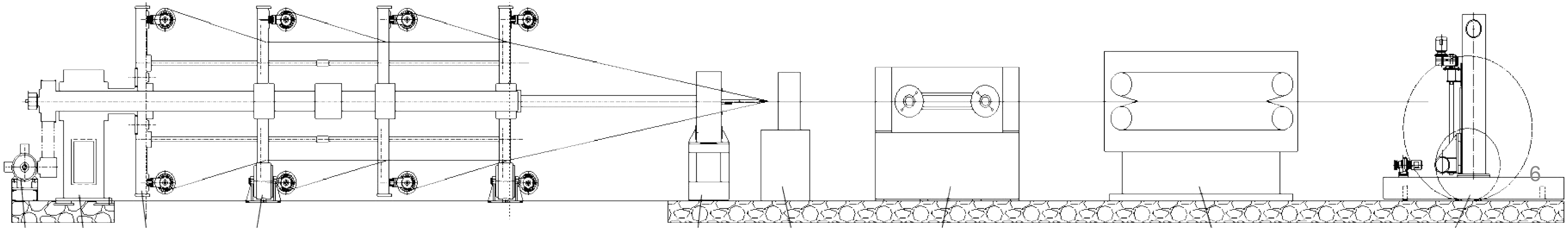
- PANDA is working with institutes in Russia
  - no alternative anymore

B. Curé, CERN Workshop on S/C Magnets, 09/2022

TOLY Electric - China

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, CERN Workshop on S/C Magnets, 09/2022

TOLY Electric - China

Al-stabilized superconductor

Al rods/cable releaser

Ultrasonic cleaning

Extrusion machine

Cooling system

Caterpillar tractor

Take-up machine

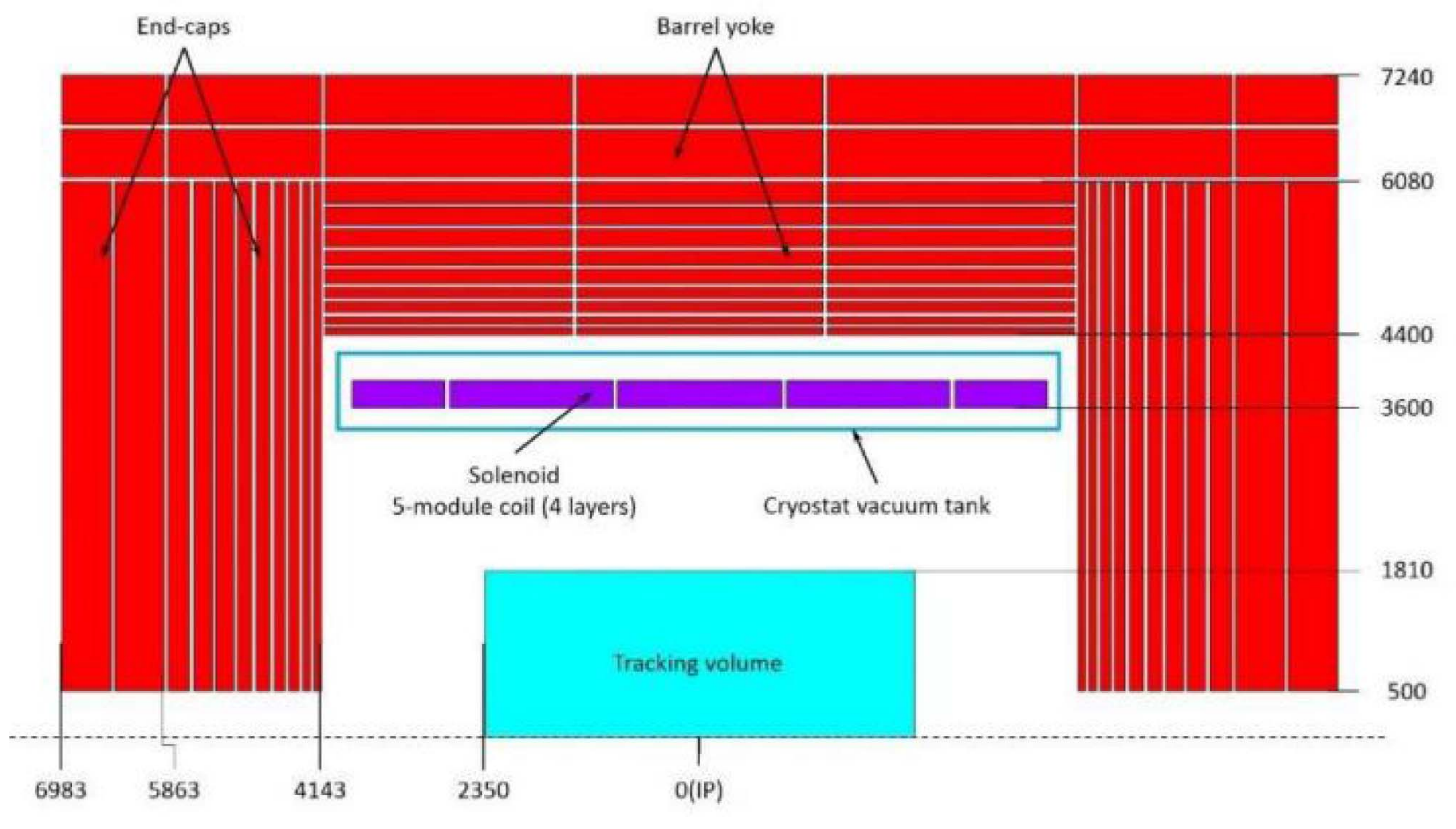
TOLY Electric, CERN Workshop on S/C Magnets, 09/2022

L. Zhao et al, IEEE Transact. o. Appl. Supercond., 34/5 (2024)

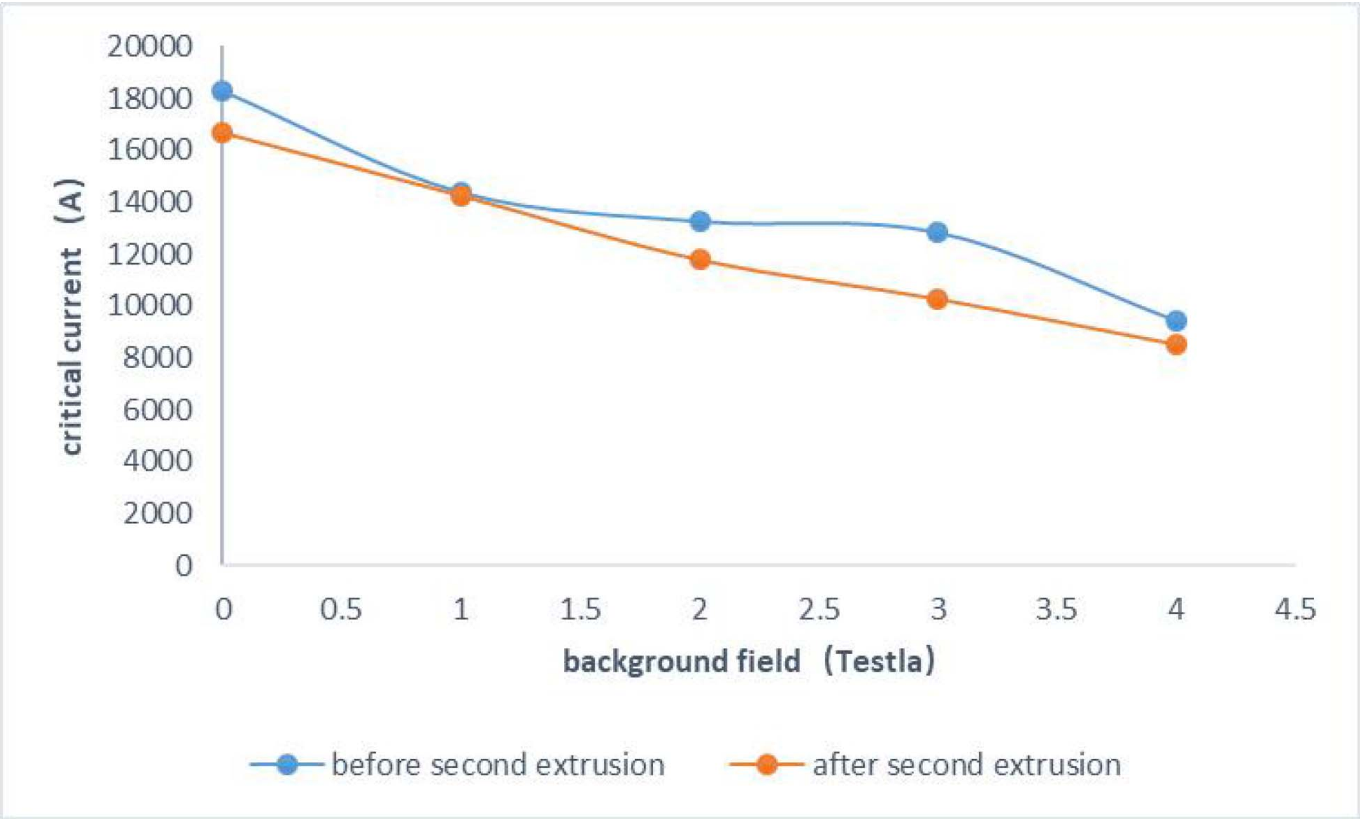
CEPC R&D

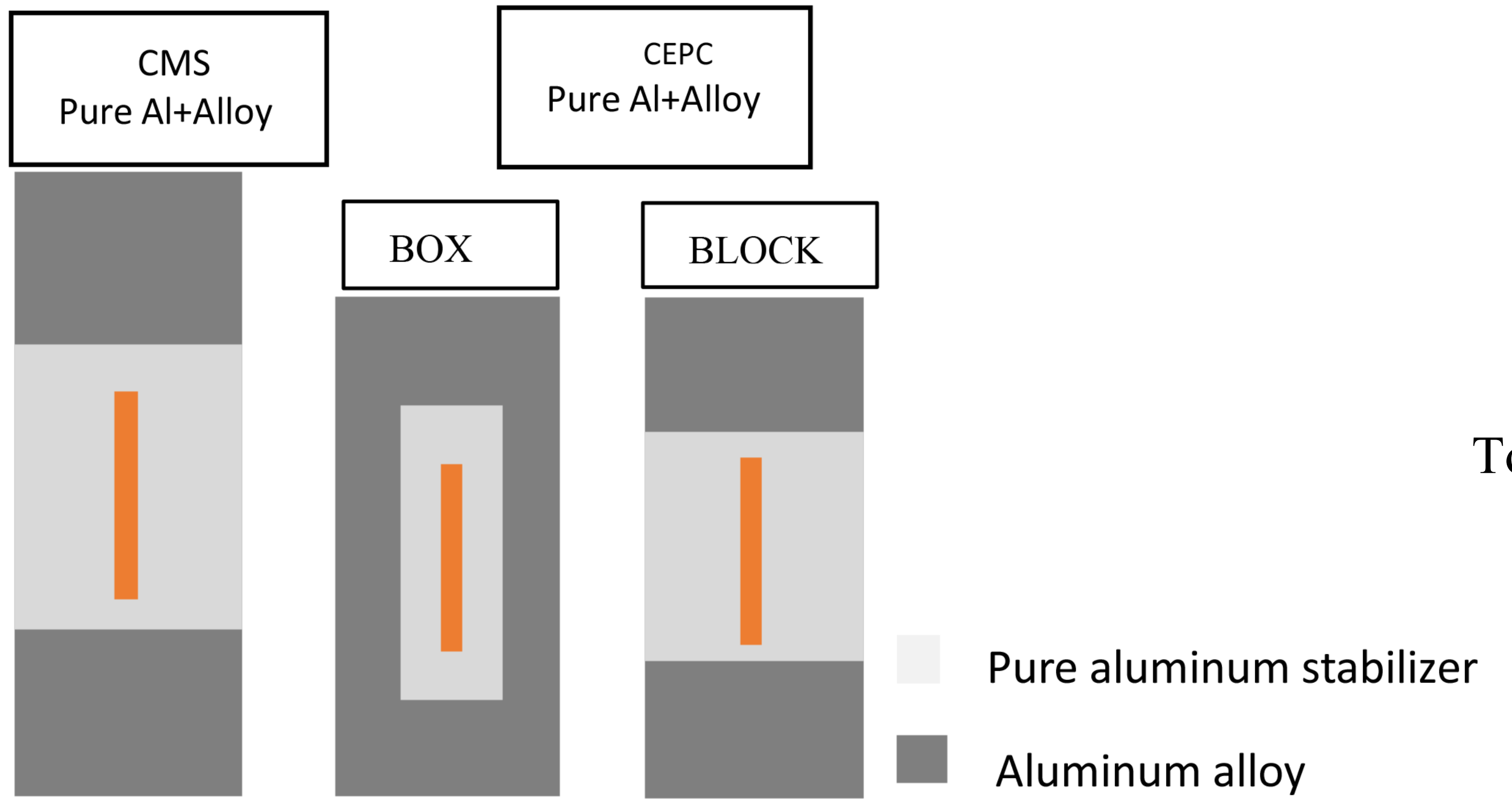
Cooperation with Wuxi Toly

- Rutherford cable manufactured
- 2 Al co-extrusion processes
  - Cable cladding
  - Box-conductor produced with pure Al stabiliser
- Test samples look promising
- Still work in progress



Parameter	Unit	Value
The solenoid central field	Tesla	3
Maximum field on conductor	Tesla	3.5
Coil inner radius	mm	3600
Coil outer radius	mm	3828
Coil length	mm	7445
Working current	A	15779
Total ampere-turns of the solenoid	MAt	20.3
Inductance	H	10.5
Stored energy	GJ	1.3
Conductor length	km	30.1



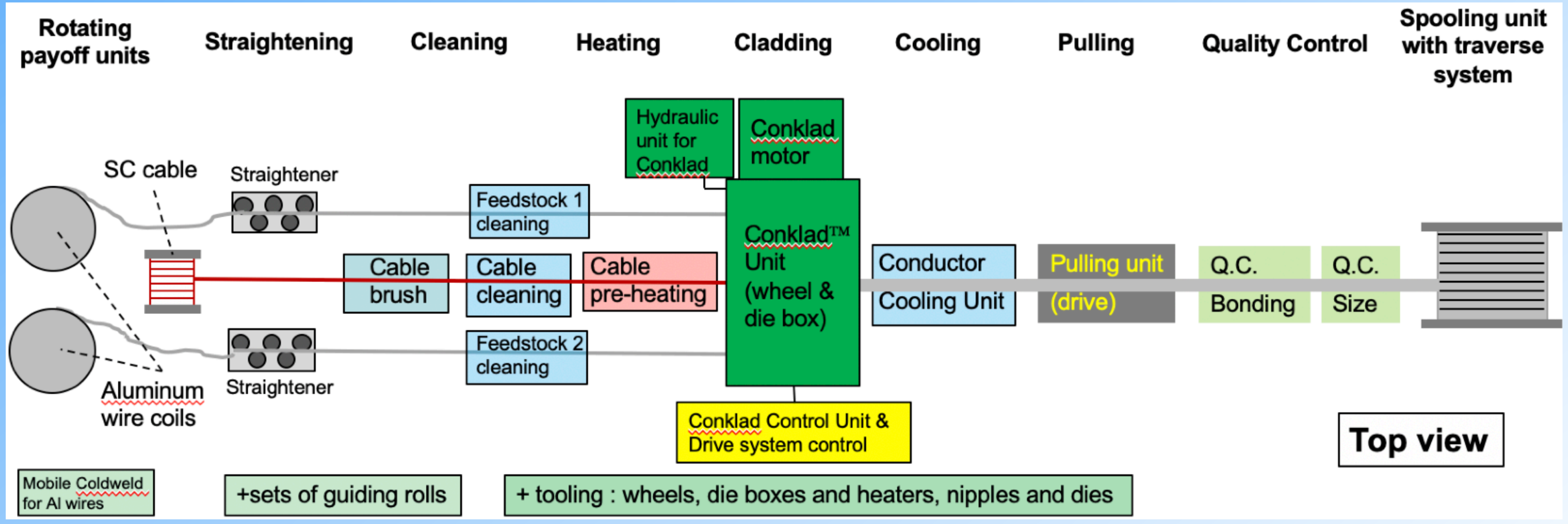


Co-extrusion R&D Facility at CERN?

C. Rembser, 09/2022

- Set up a development co-extrusion line, including cold working, either in industry (if availability) or at CERN, for:
  - R&D on aluminum-stabilized NbTi/Cu superconductors, future developments and applications of this technology.
- Project supported by CERN & KEK for setting up this co-extrusion R&D facility.
- Access to co-extrusion R&D facility for project and collaborations according to the priorities agreed in the HEP community;

- Sketch of a complete coextrusion line (with inputs from K. Miyashita @ KEK);
- About 25~30m x 10m minimum (not including: delivery, services and storage space areas);
- Infrastructure to be defined: electrical power, water, compressed air, N2 (or Ar) lines, crane.



Alternative Soldering?

C. Berriaud, CERN Workshop on S/C Magnets, 09/2022

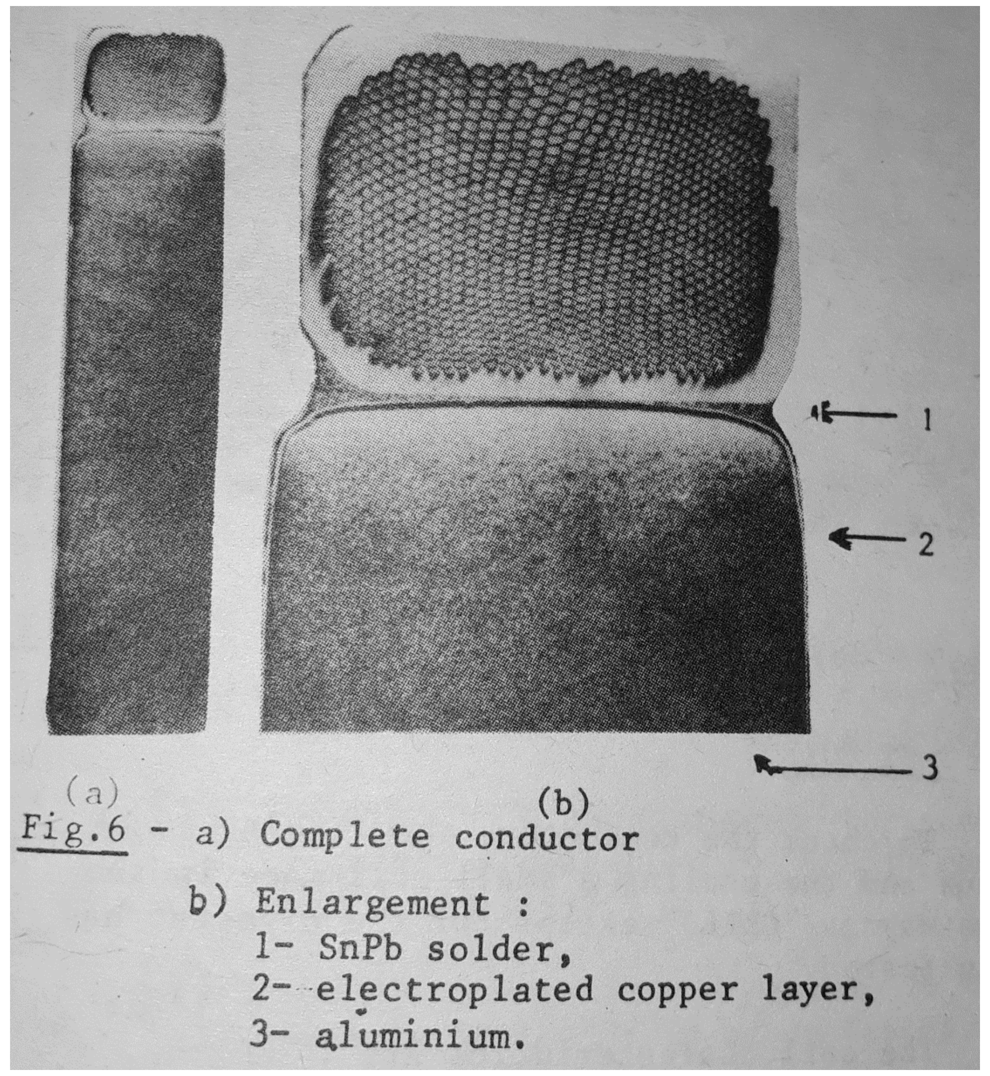
Has been done in the past

- 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

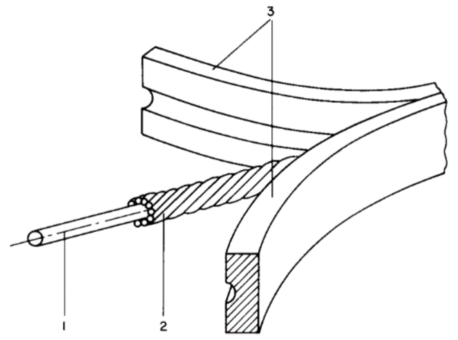
- requires R&D
- Electron-beam welding might be an option



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).

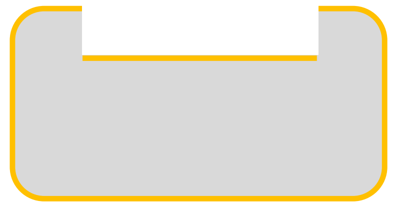
One year after Morpurgo magnet



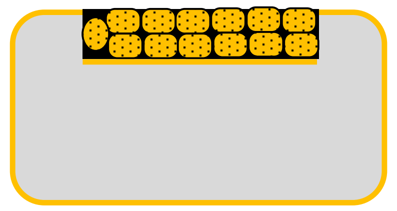
CERN workshop– 12-14/09/2022

CMS / ATLAS R&D FIRST MOCK UP

Existing Al. stabilizer with copper deposition

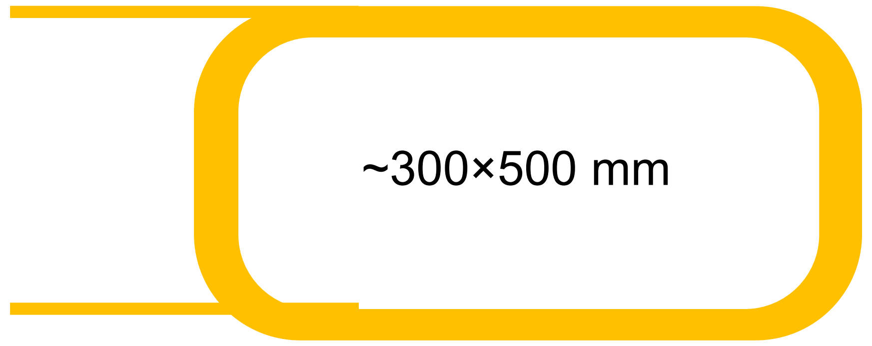


Groove machined by Turck head



Existing Rutherford & soldering by hand

~2×5 mm



Quench studies & inductive heater

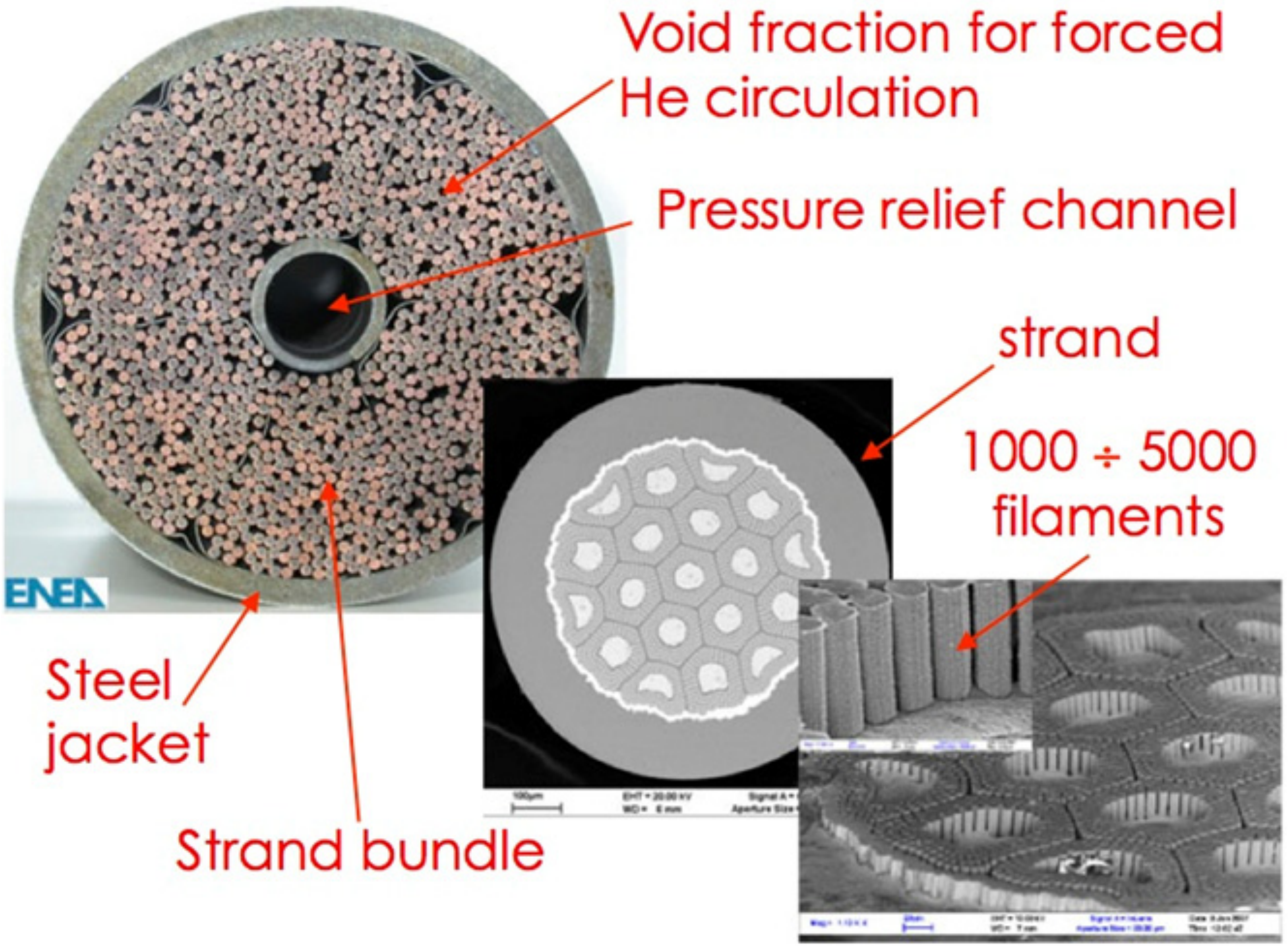
First ATLAS Ractrack (MicroB)

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
  - But is this really an issue for LC detectors?
  - Calorimeters are often inside the coil



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

The Future - HTS?

Only choice for

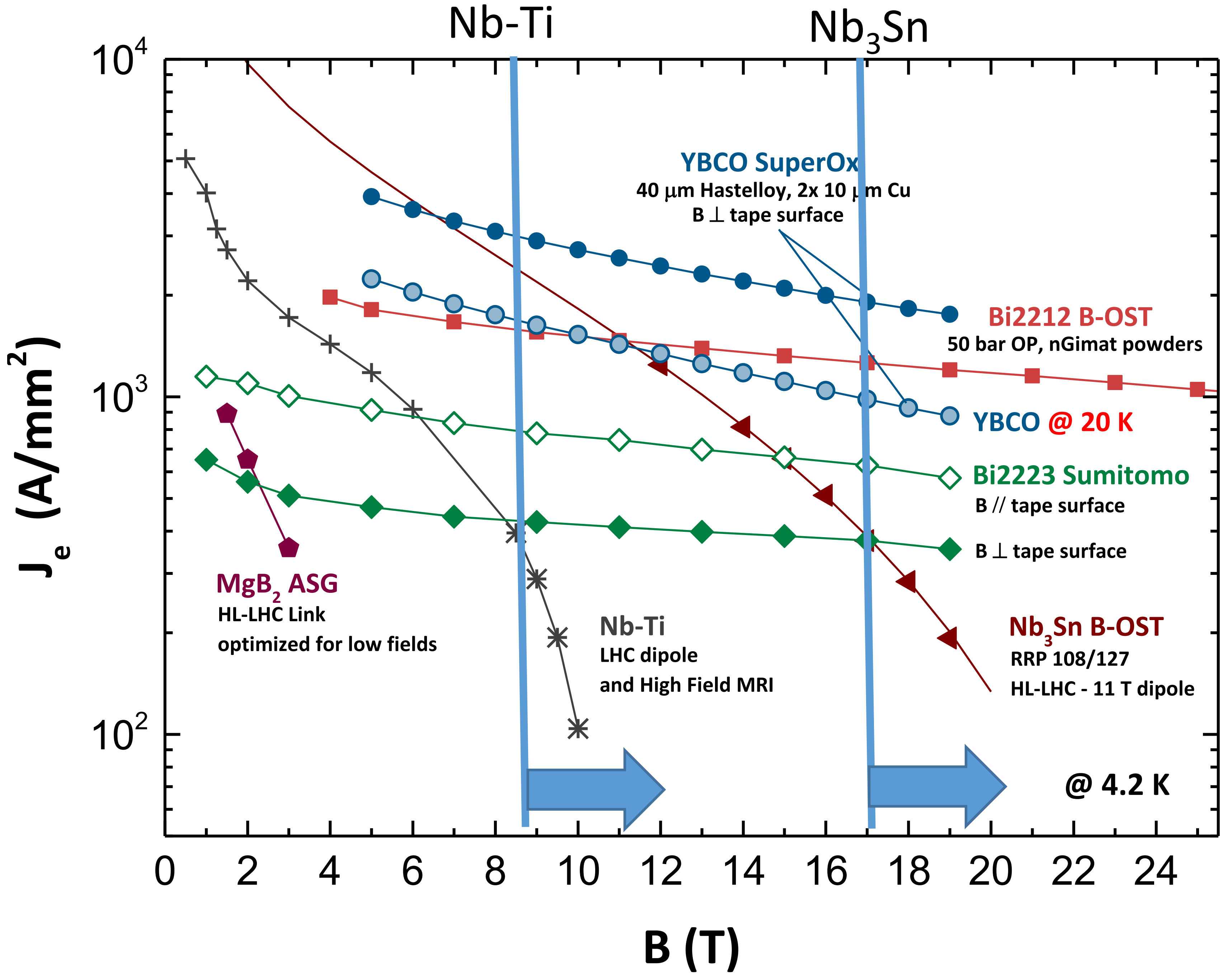
- >16T fields
- cooling temps ~30K
  - indirect cooling
  - gaseous He cooling
  - lower cryo cost

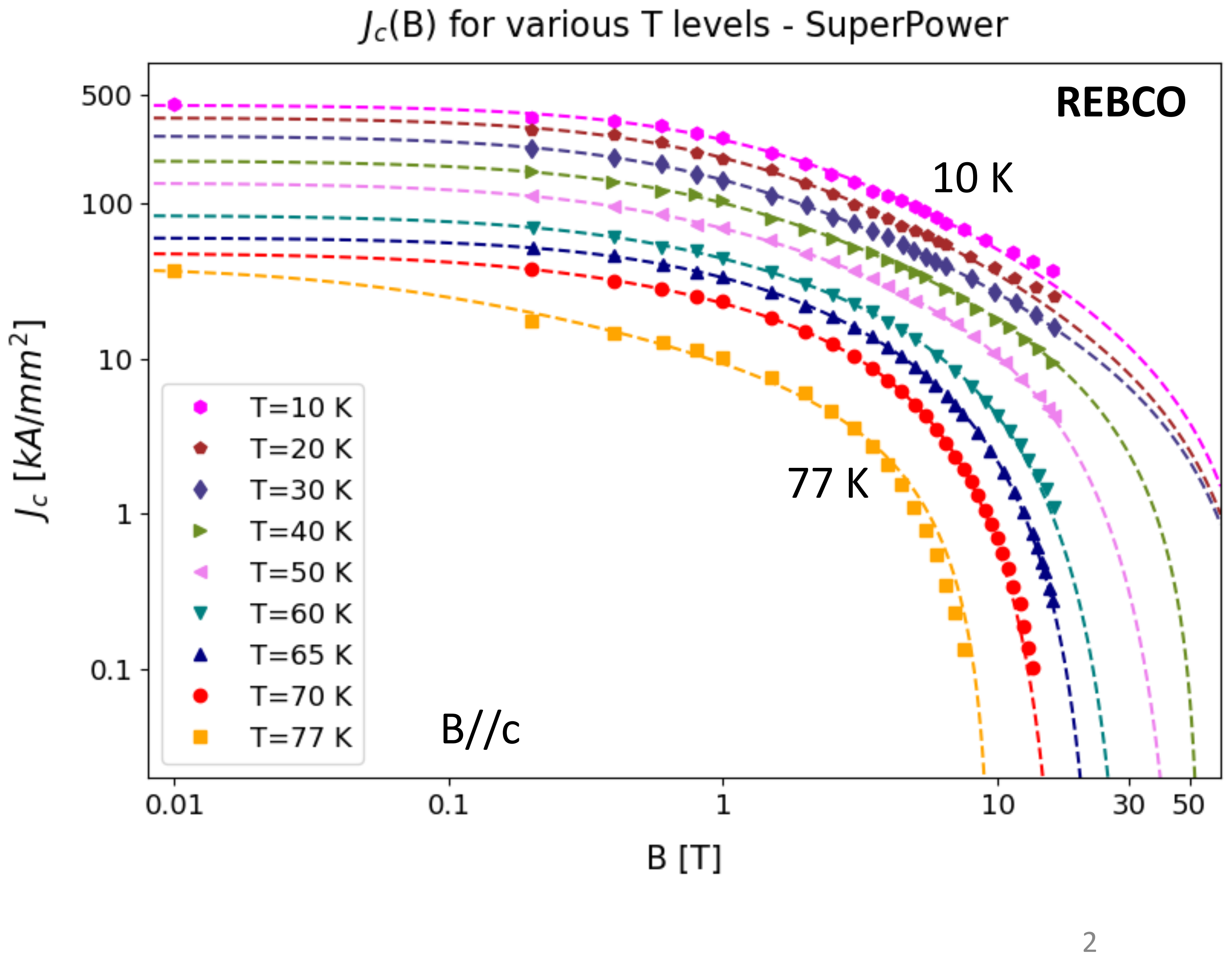
Active field of R&D

- Co-extrusion probably not the way to go here
- Soldering HTS on support could be a solution

HTS in magnets

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





A. Ballarino, CERN Workshop on S/C Magnets, 09/2022

Conclusions

All future collider experiments rely on large scale 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 not an option anymore
- A newcomer from China (TOLY) is doing R&D for CEPC
  - an on-going and promising process
- Ideas for R&D facility at CERN

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!