IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2019.
Invited presentation 1MOr2A-01 was given at ASC 2018, October 28-November 02, 2018, Seattle (USA).

REBCO coated conductor development in the ARIES program for HTS accelerator magnets

Lucio Rossi, Luca Bottura and Amalia Ballarino, CERN
Carmine Senatore, Univ. of Geneva,
Ulrich Betz and Alexander Usoskin, BHTS (De)

On behalf of the ARIES-WP14.5 collaboration

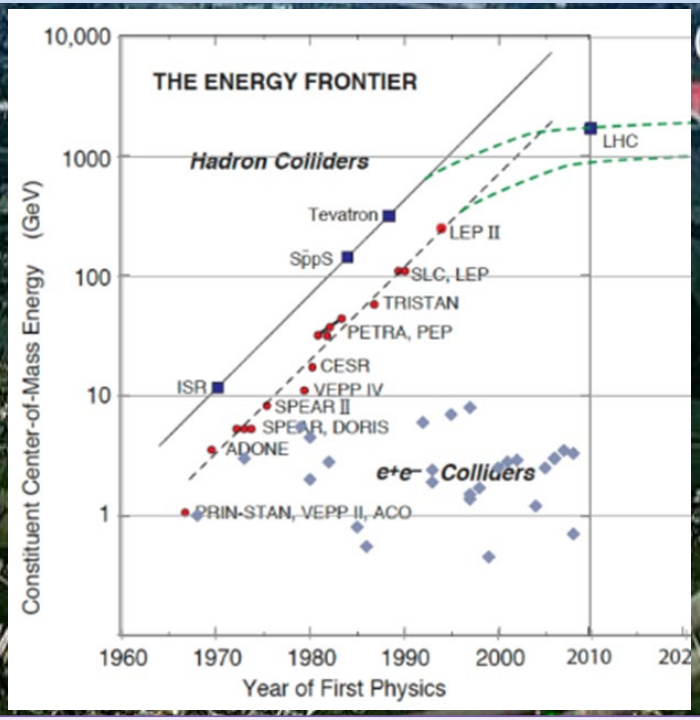
ARIES is co-funded by the European Commission Grant Agreement number 730871

Accelerator Science in the XXI Century

of all particle accelerators,

- <1% used for basic science
- 5% for applied science
- 35% for medicine
- ~ 60% in industry

Engines of discovery: 1/3 of all Nobel prizes in physics since 1939 are connected to particle accelerators.



Courtesy of M. Vretenar (CERN)
H2020-ARIES coordinator

Updated Livingstone-type chart (Wikipedia 2014, uploaded by J.Nash, Imperial College) Exponential growth of accelerator energy is slowing down. We need new technologies to sustain the discovery reach. ARIES collaborative effort partially funded by the H2020 – EC program supports new technogies

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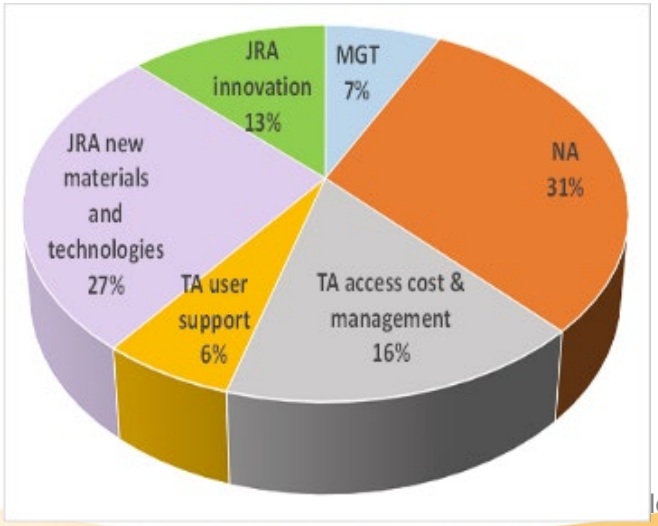
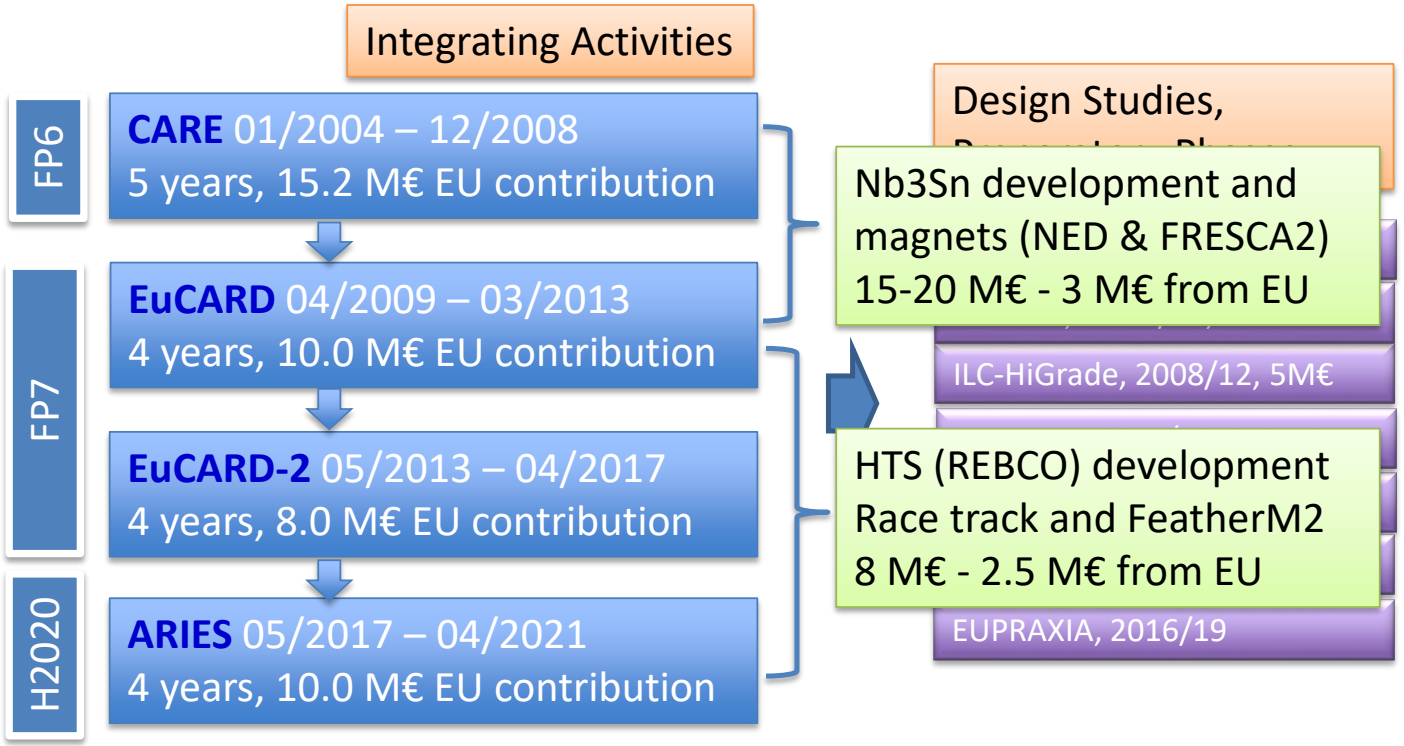
ARIES Key Figures

- 19 Workpackage Coordinators: 6 from CERN, 4 from UK, 4 from Germany, 3 from France, 1 from Switzerland, 1 from Sweden. 4 female (21%).
- EC contribution 10 M€, total cost 24.9 M€, funding rate 40%.
- Share of EC contribution: Management 7%, Networks 31%, TA 22%, JRAs 40%.
- 51 Deliverables and 67 Milestones
- 42 beneficiaries from 18 EU countries (+CERN, ESS)

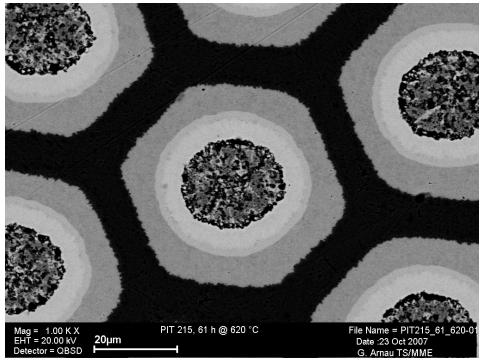


EU support to particle accelerator R&D



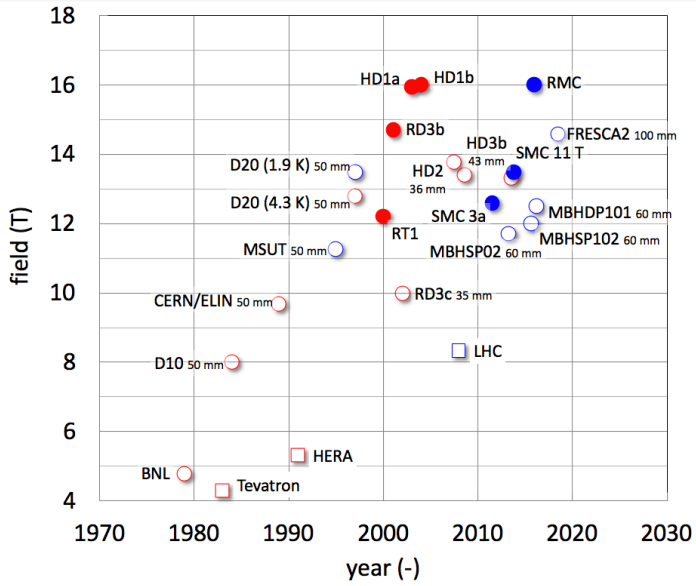
Low priority of long-term R&D for large laboratories focused on short-term projects, while small institutions lack critical mass and the experience to be effective → a joint collaborative effort with the EU support is the most effective way to push the limits of our technologies.

CARE – EuCARD: 15 y Nb_3Sn development in EU



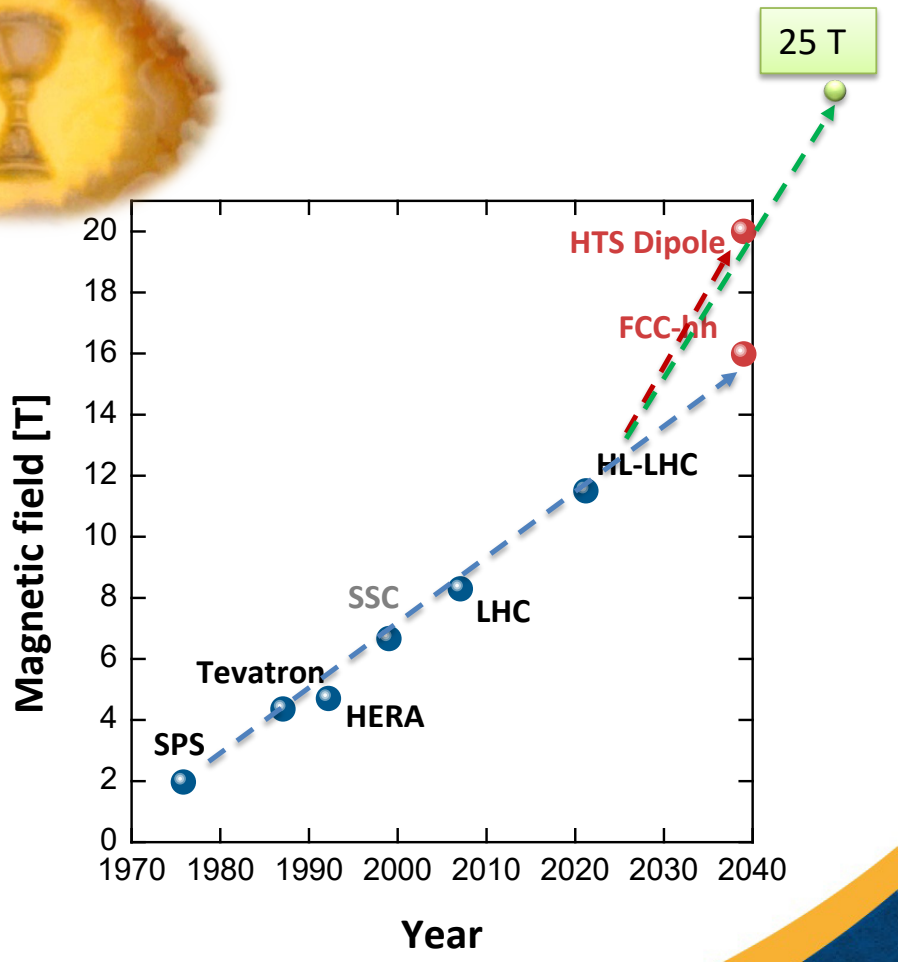
CARE-NED 2004-2008 then CERN + CEA
Development of PIT conductor and first HF dipole design
PIT of 1300-1500 J_c at 15T

Fresca 2 all Nb3sn (RRP+PIT) record field dipole: 14.6 T in 100 m free bore

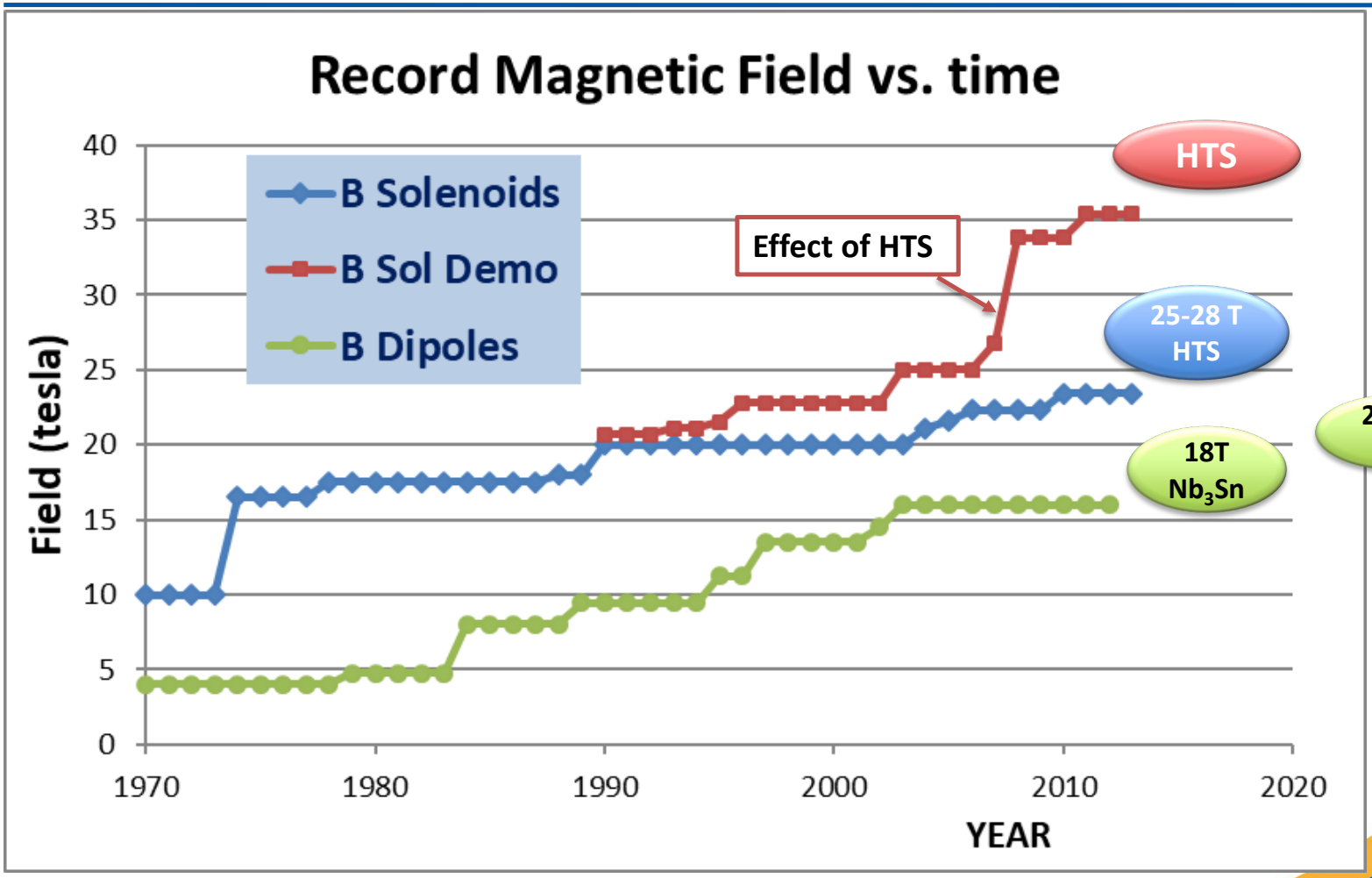


HTS in accelerators: not only highest field

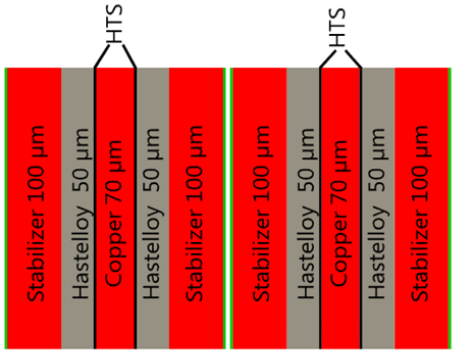
- **20+ T** dipole field is the ho grail for accelerator people
- High rad zone, B=15-16 T with high margin
- **Operation of full accelerator in 10-20 K gas**
- Pulsed magnets in the accelerator chain: **3-6 T at 20-80 K for low power consumption**
- Long SC links (s.f. 100-200 kA cable, 100-500 m long)



Field evolution: dipoles vs solenoids



EuCARD HTS (2008-13), CEA-CERN collab. (2014-17)



Cable: 0.92 mm thick

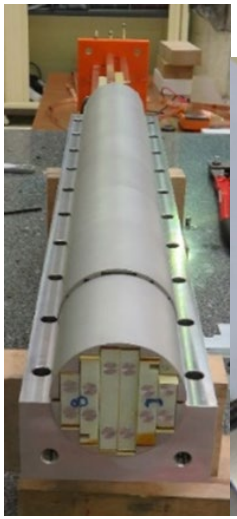
First attempt –in EU – to go for dipole-like coil. Stacked tapes, no transposition, with large amount Cu

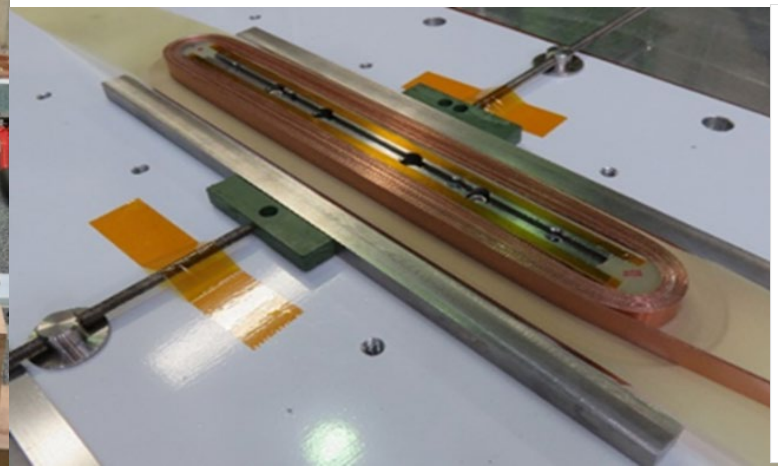
Simple racetrack.

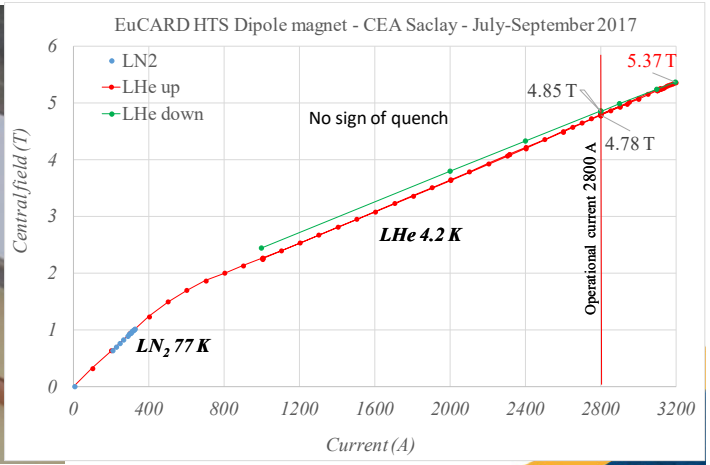
Transposition between the two sub-cables of top and bottom pole.

HTS conductor By SuperPower

Magnet design, construction,test. Technological support by INP Grenoble







M. Durante et al., CEA

Program of EuCARD2-WP10 *Future Magnets:* 2013-2017

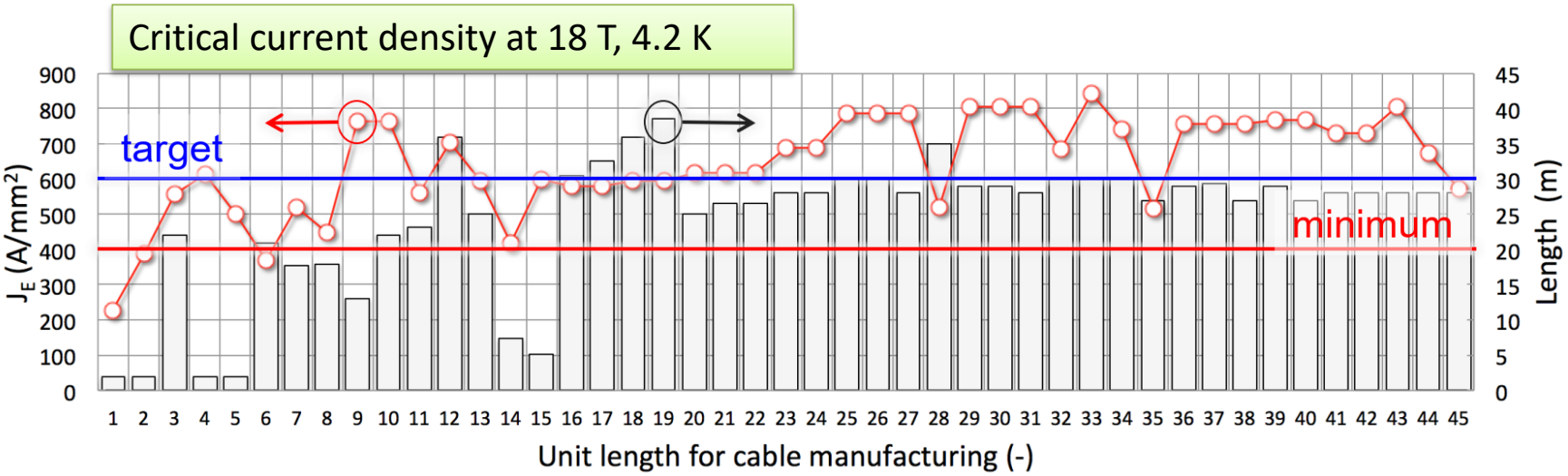
CONDUCTOR

- 5-20 kA cable @4.2K 5-20T **ten kAmps-class cable**
- For accelerator dipoles:
- $J_{overall} \geq 400$ A/mm^2
  - 80-85% filling factor
  - J_{eng} strand ≥ 400 A/mm^2 min.
  - **J_{eng} strand ≥ 600 A/mm^2 enhan.**
- Field Quality
  - transposed
- Not too many joints $\Rightarrow$ high current – 100 m long tape

MAGNET DEMO accelerator quality

- **Aperture ~ 40 mm** (R_{min} cable $\Rightarrow$ 20 mm!)
- 5 T standalone with 20% margin (> 6 T ss limit)
- Insertable in High Field $\Rightarrow$ outer Diam < 100 mm (including mech. structure)
- Length < 1m ($L_{straight} \geq$ 200mm)
- Must reach 17 T in 13 T background (Fresca2)

Results in EuCARD2 : tapes



- About 1 km of tape was produced above 400 A/mm^2
- Most of tapes are above 600 A/mm^2
- This with 100 μm thick substrate: very high J_{layer}
- Production length: typical 90 m (cut in 30 m unit for cabling)

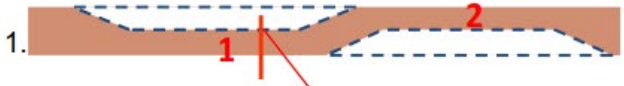
Results of EuCARD2: Roebel Cable (for test)

New improved punching tool: first tests

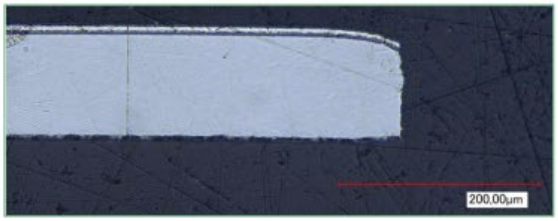
Punching in one-step:

- Within CERN collaboration agreement
- Reduced tape transport error
- Possibility of adjustment to the tape width
- Tooling clearance 5 µm +/-2 µm

One-step punching TL = 300 mm



Bruker punched tape – cross section



Roeble cable by KIT for the EuCARD2

- Large currents ~ 10 kA with **good FF ~ 85%** (same range Ruth. Cable)
- **Transposed** (good FQ also in ramping)
- **Good contact resistance despite impregnation: 10-30 μΩ (not low - not high)**

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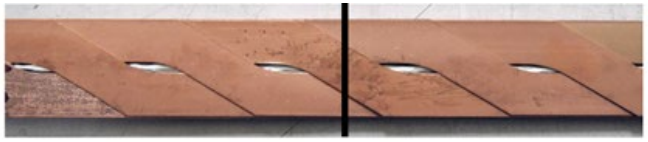
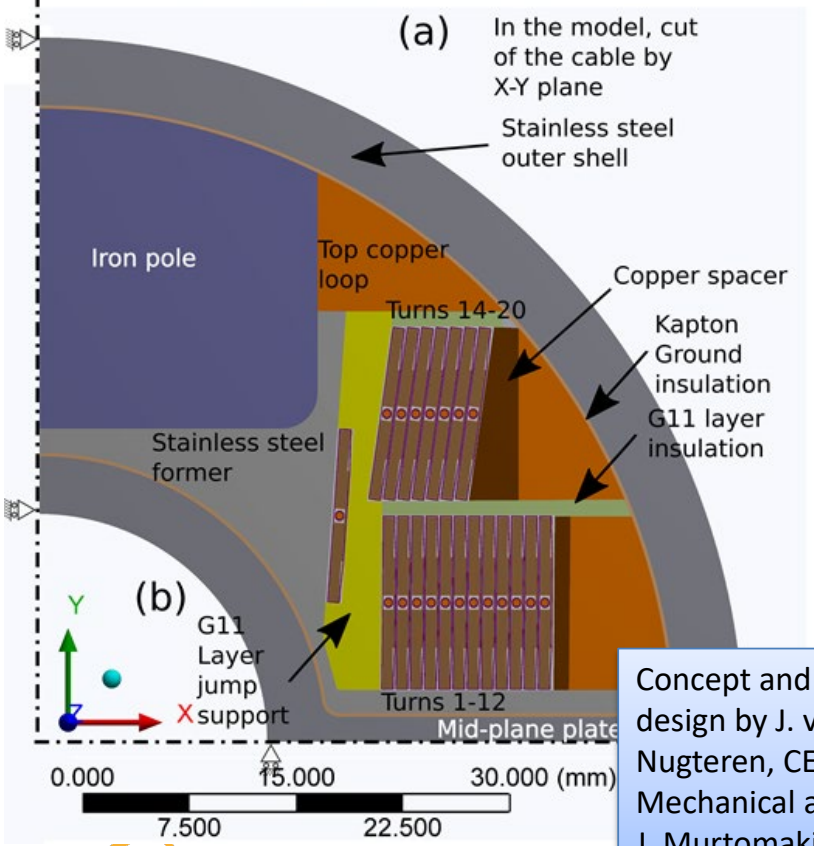
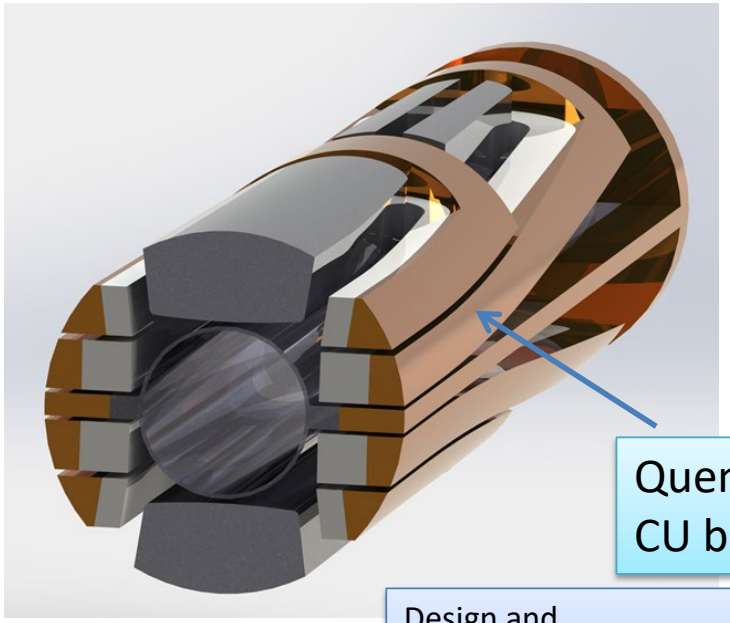
Results of Eucard2: demonstrator dipole





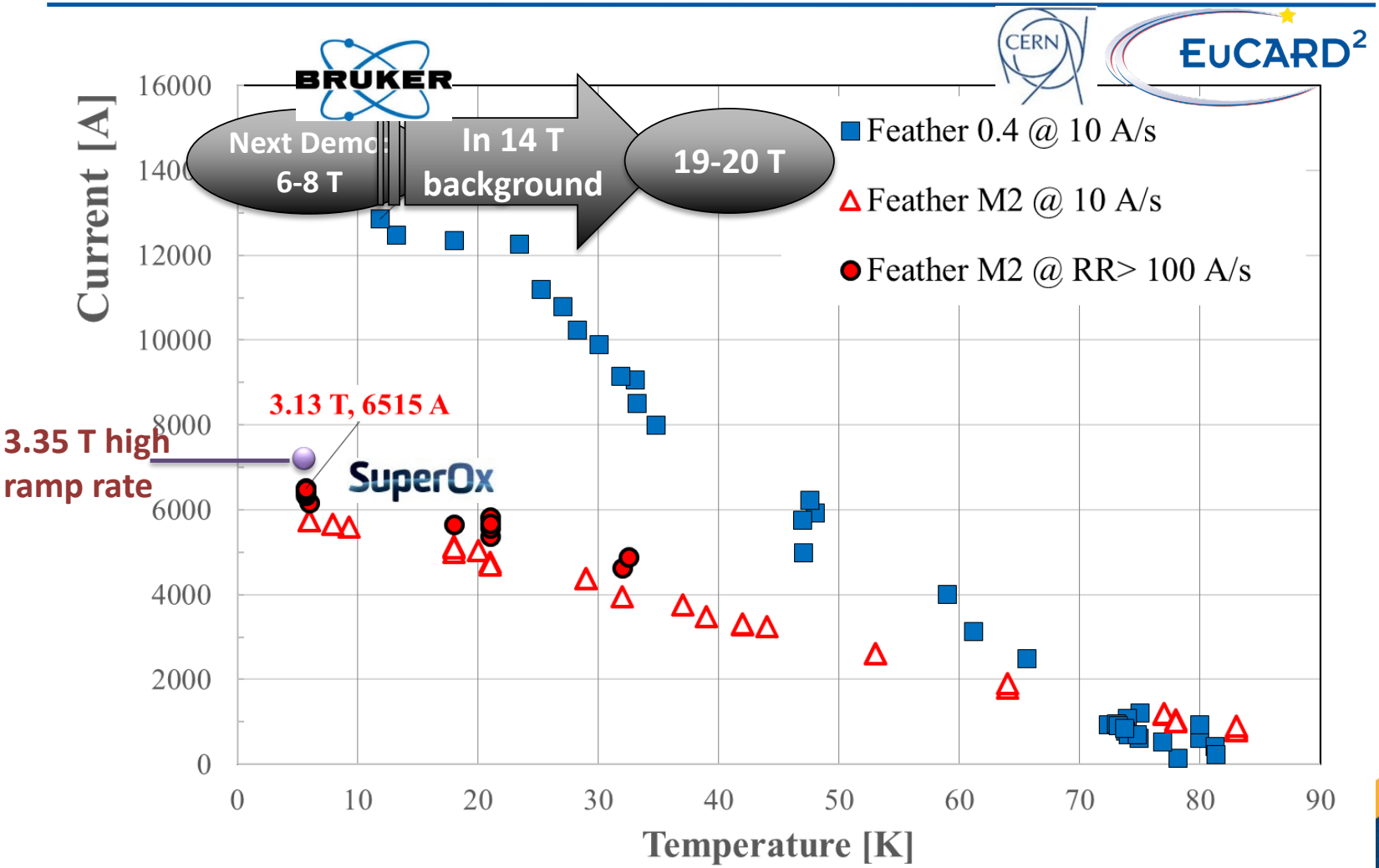


Quench CU bars

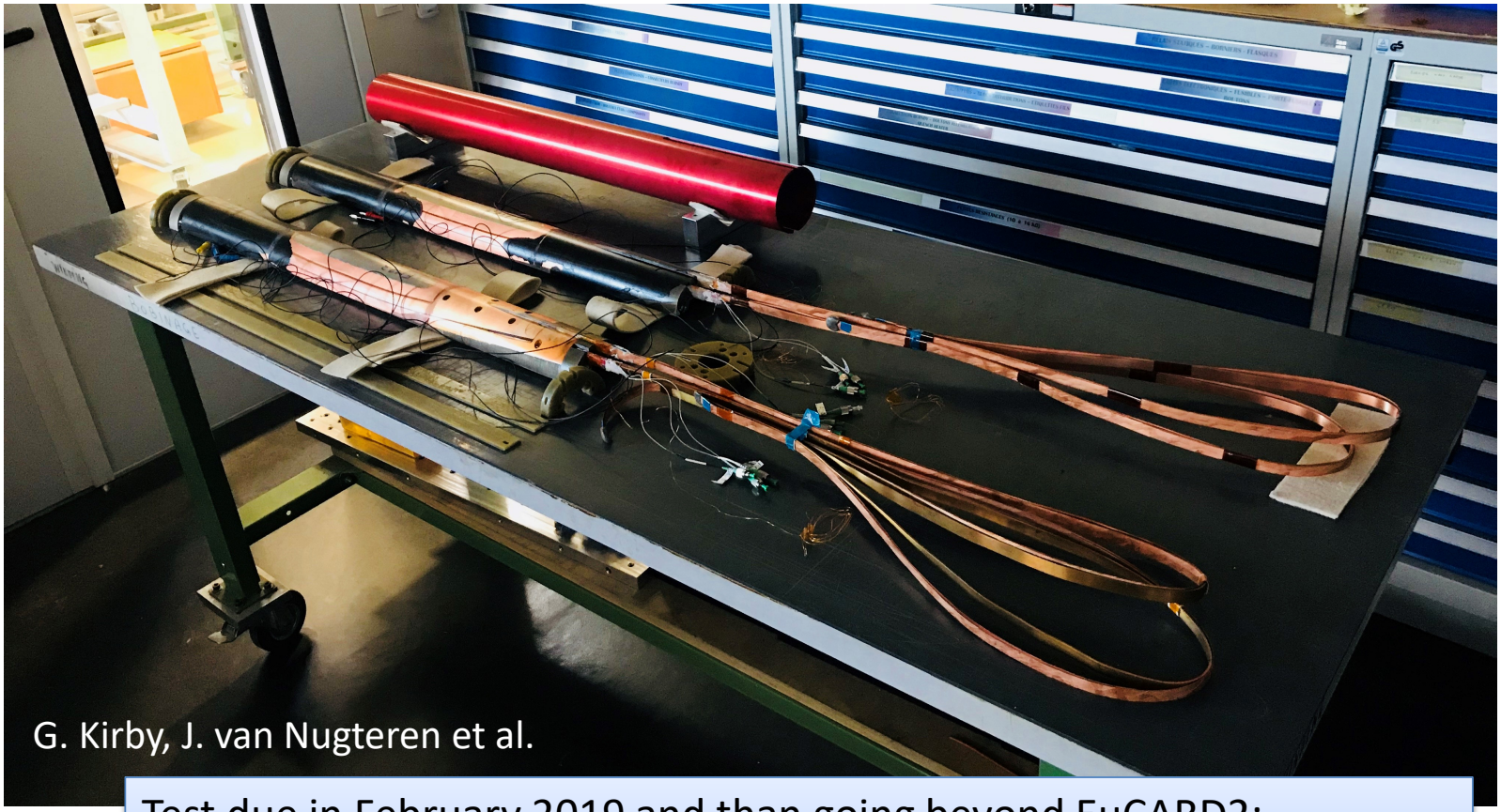
Design and technology innovation by G. Kirby, CERN

Concept and e.m. design by J. van Nugteren, CERN
Mechanical analysis by J. Murtomaki, CERN

EuCARD2 1st demonstrator test and more…



Next demo FeatherM2.3-4 is almost ready



Test due in February 2019 and than going beyond EuCARD2:
More coils wiht further Eucard2 quality BHTS tapes (CERN) procured)
and with SuperPower tapes and SuperOx tape (all to test Roebel)

ARIES - WP14 Promoting Innovation

WP14.5 High Temperature Superconducting (HTS) innovative process for accelerator magnet conductor

Lucio ROSSI – Task Leader

Thibault LECREVISSE – Deputy Task Leader

Alexander USOSKIN – Ulrich BETZ – Industrial Partner

Marc DHALLÉ

Carmine SENATORE

Contribution possibly also from

Scope of the work of WP14.5

- ***Set up a NEW process optimization in BRUKER to:***
  - ***Increase J_e by a factor 2 wrt EuCARD²***

    from J_e (4.2 K, 20 T) = 400-600 A/mm²

    to J_e (4.2 K, 20 T) = 800-1000 A/mm²
- ***Produce in BRUKER some 450 m of tapes***
- ***Use in a winding at CERN cea (very much like EuCARD²)***
- ***Reduce the cost by a factor 2 in the production (at BRUKER)***
- ***Electrical, magnetic, mechanical and thermal properties tested at UNIVERSITEIT TWENTE. and UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES***

ARIES

Task 14.5 – budget, deliverables and milestones

Budget: **1700 k€ total of which 550 k€ from EU**: 330 BHTS
115 Univ. of Twente
105 Univ. of Geneva

D14.1	Set-up of the Proof-of-Concept innovation-funding scheme	14.2	CERN	R	PU	M12
D14.2	Academia meets industry event 1	14.3	CERN	R	PU	M24
D14.3	Production of material samples of carbon-based composites and metal-diamond composites	14.4	CERN	DEM	PU	M24
D14.4	First long length industrial High Temperature Superconductor	14.5	CERN	DEM	PU	M30
D14.5	Real-time Event Distribution Network brought to openly accessible "product grade level"	14.6	COSYLAB	Other	PU	M46

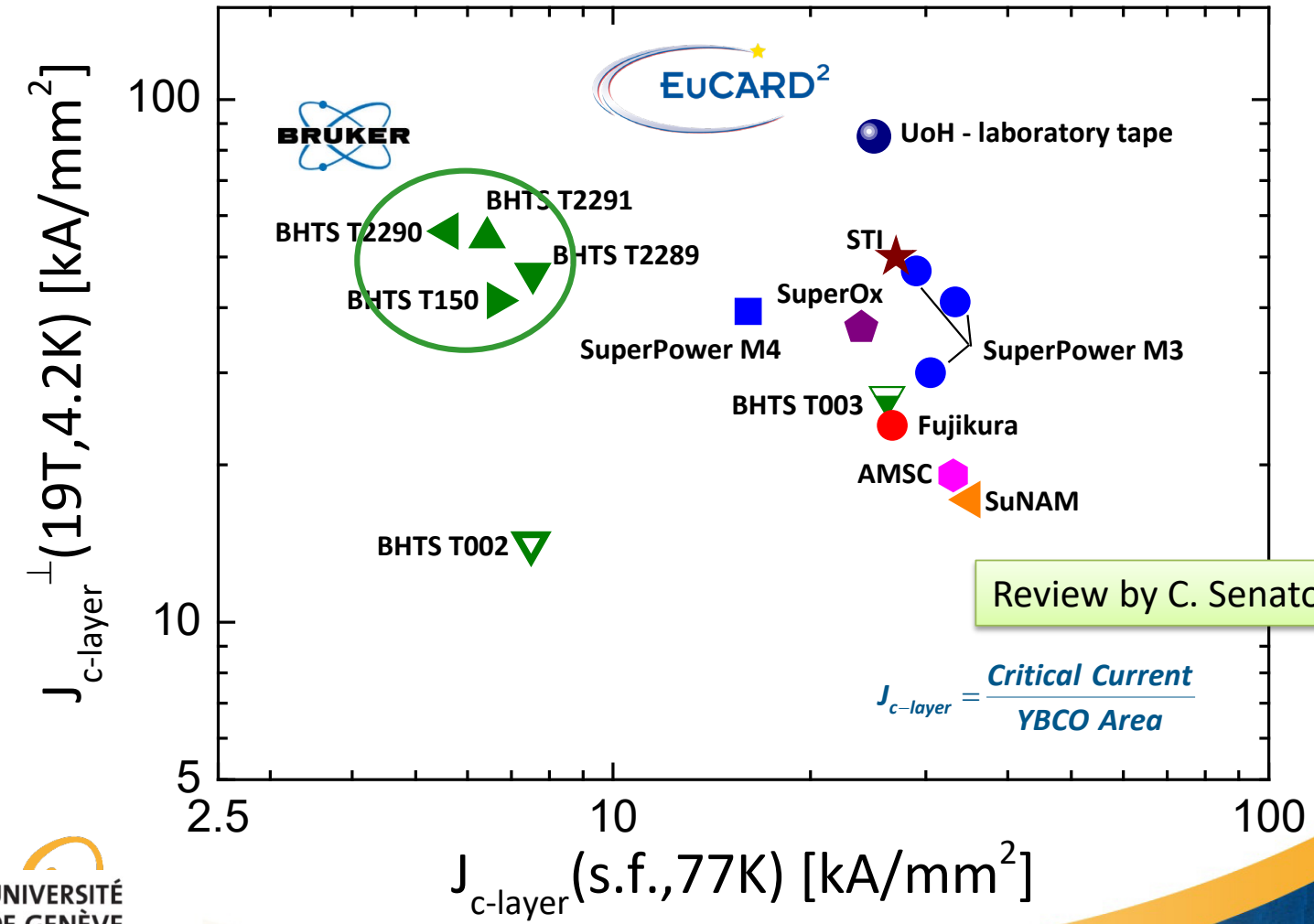
Oct 2019

MS42 → appointing IAB - M12
MS43 → 1st academia meets industry – M24
MS44 → 2nd academia meets industry – M36
MS45 → 1st HTS short length – M14
MS46 → characterization of 1st ~~short~~ **long** lenght – M36
MS47 → review requirements doc – M12
MS42 → review design and conf doc– M21

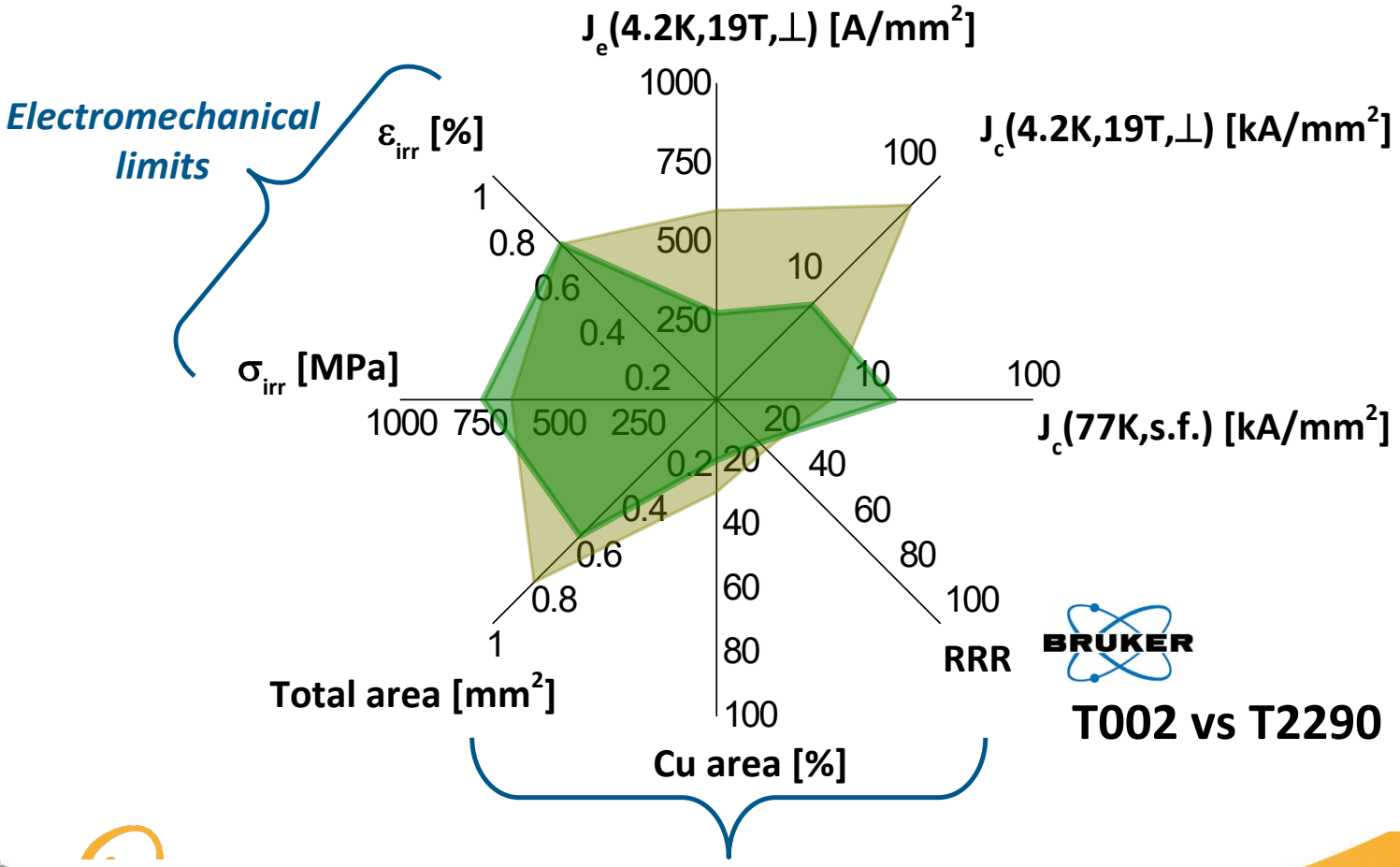
May 2018

Apr 2020

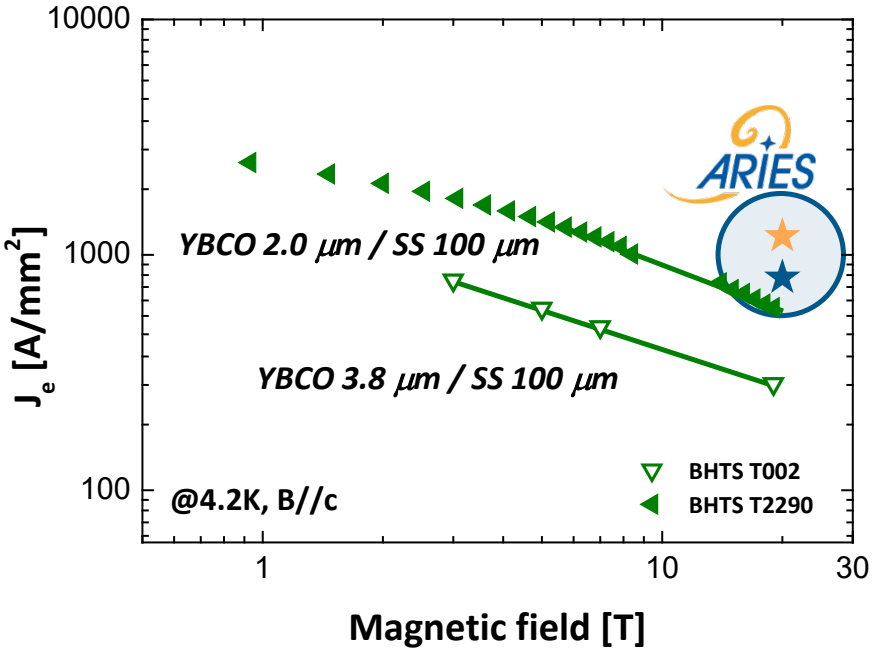
Overview: Jc(s.f.,77K) vs. $J_c^{\perp}$(19T,4.2K) (ca. 2016)

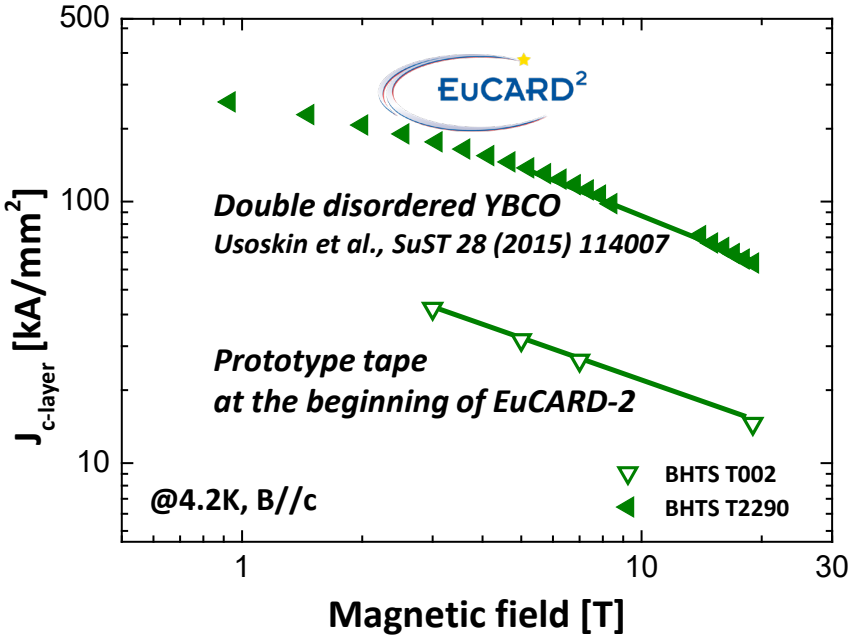


J_C not all: exploring the full parameter space



Performance target for ARIES

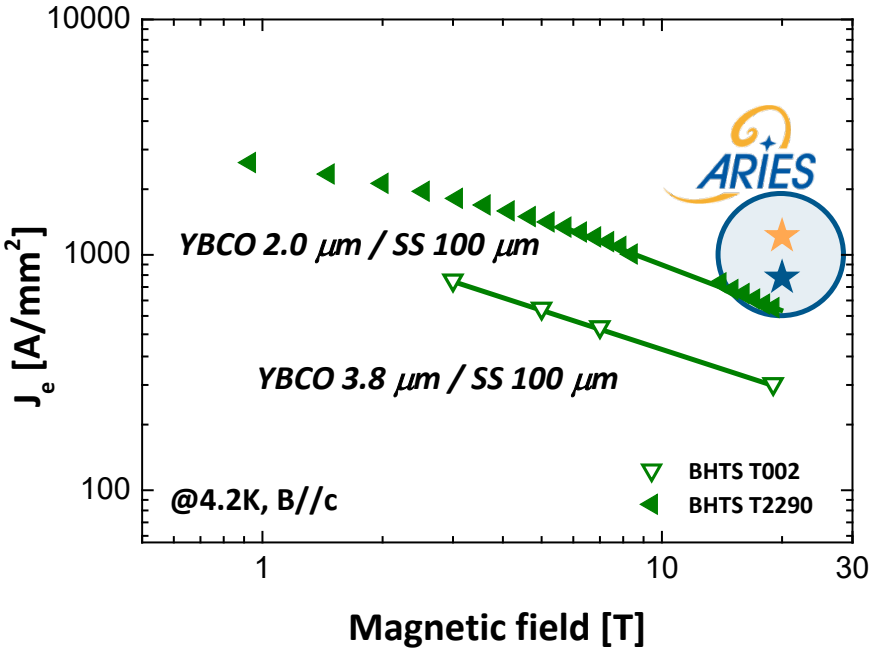




$$J_e = \frac{\text{Critical Current}}{\text{Total Area}}$$

$$J_{c-layer} = \frac{\text{Critical Current}}{\text{YBCO Area}}$$

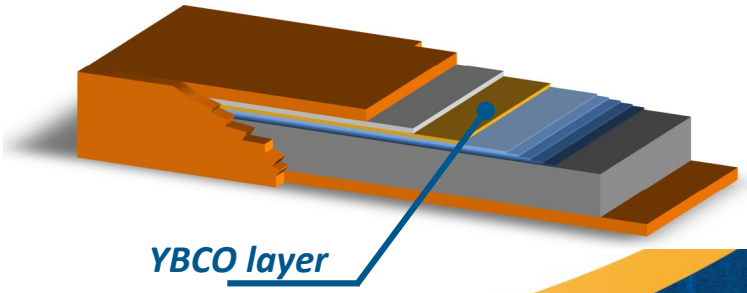
Main target for ARIES : increase J_e



How to get there?

- *Increase the layer J_c of YBCO*
- *Increase the thickness of YBCO*
- ***Reduce the thickness of the substrate 100 μm SS → 50 μm SS***

$$J_e = \frac{Critical\ Current}{Total\ Area}$$

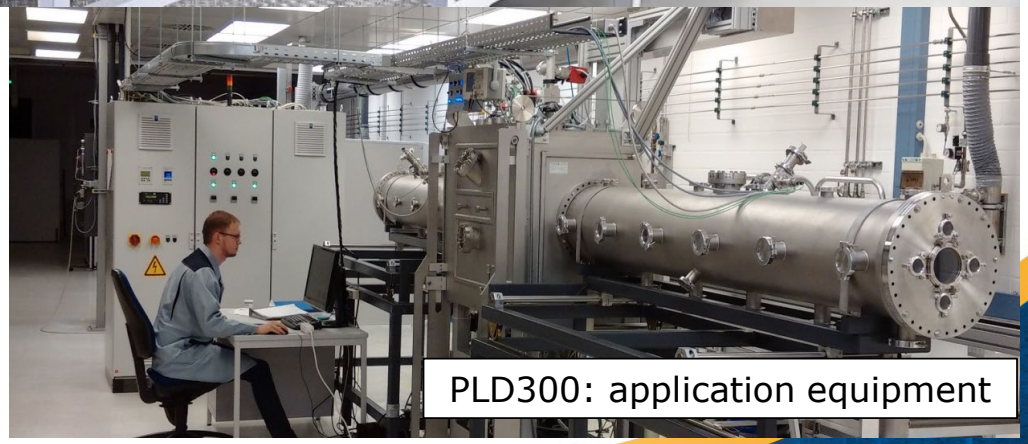


ARIES project @ Bruker HTS

The PLD300 system, used for ARIES, is co-owned by BHTS and CERN

Pulsed Laser Deposition PLD600: production equipment

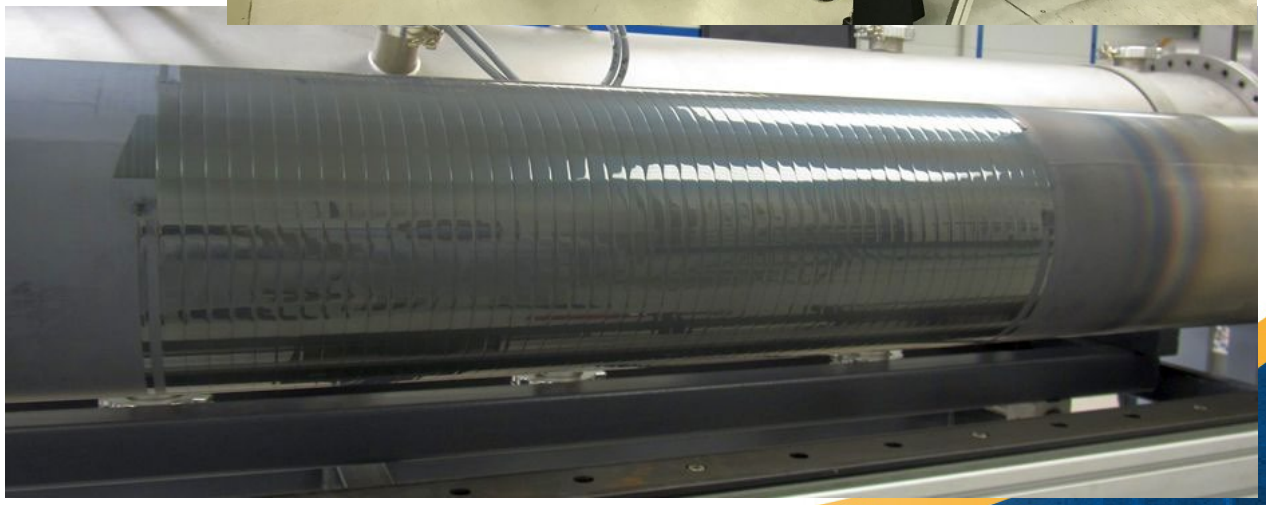
PROCESSING CHAIN OF HTS PILOT-LINE PRODUCTION
SUBSTRATE PREPARATION (SUB)
BUFFER LAYER COATING (ABAD)
HTS LAYER COATING (PLD)
METAL COATING (MET)
COPPER PLATING (PLA)
FINAL TAPE INSPECTION (INS)



PLD300: application equipment

PLD300 first year operation

12mm wide HTS tape coated in PLD300 for ARIES



Production tooling for ARIES 12 mm tape

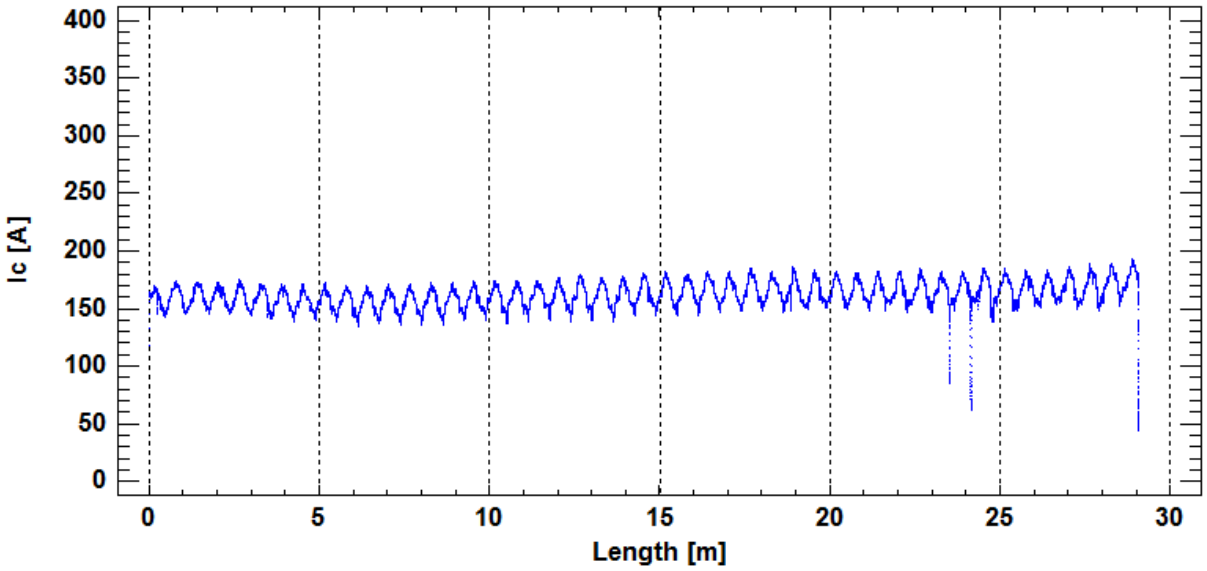
TACOMA M
Ag coater now ready for 12mm wide HTS tape processing with low thickness for 90 m. (St.Steel substrate is less strong than Hastelloy substrate)
Reel-to-Reel new system is under consideration

Modification of load lock for tape transfer into high vacuum

ARIES project @ Bruker HTS

PROCESSING 50 µm x 12 mm x 29 m HTS tape

- I_c measurement from tape sample (start position) I_c(77 K, s.f.) = 174 A
- Average I_c value from Hall-Probe-Measurement (TapeStar) of the 29 m long HTS tape I_c(77 K, s.f.) = 161 A
- 2 x I_c drops detected in the range 23-25 m



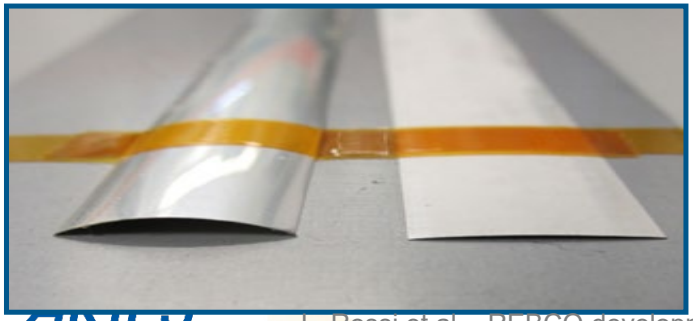
Courtesy of A. Usoskin, BHTS

ARIES project @ Bruker HTS

General appearance of HTS tapes with 50 µm SS substrates

The new tapes reveal a strong tape curvature (tape bow) due to intrinsic film stresses of the coatings

Curvature does not exceed the critical one: no deterioration of I_c is observed after flattening

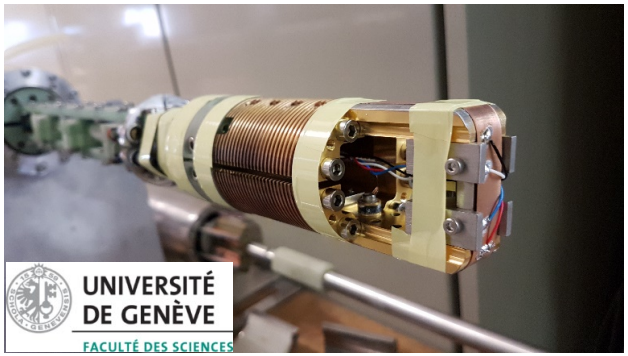


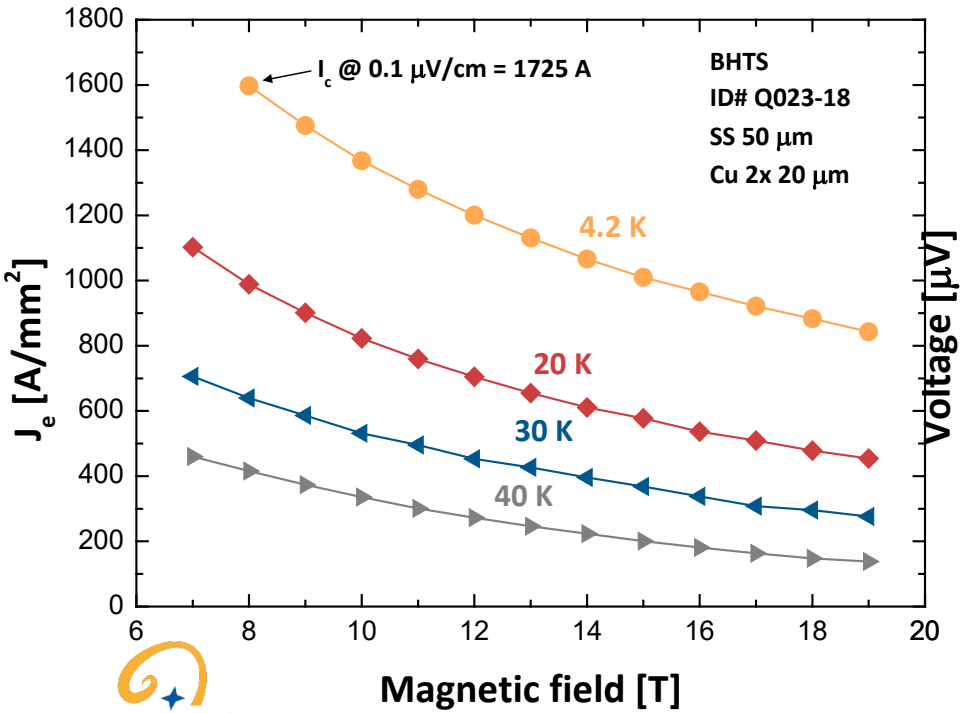
Optimization of the coating process is ongoing

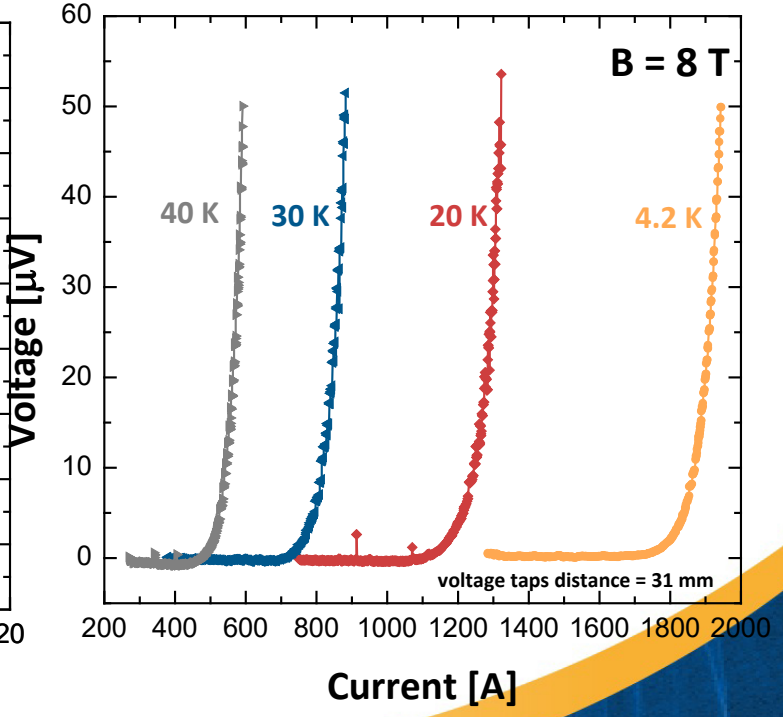
First results show a large reduction of the tape bow

U. Betz and A. Usoskin BHTS

12-mm ARIES tape: 50 µm SS + 2x 20 µm Cu



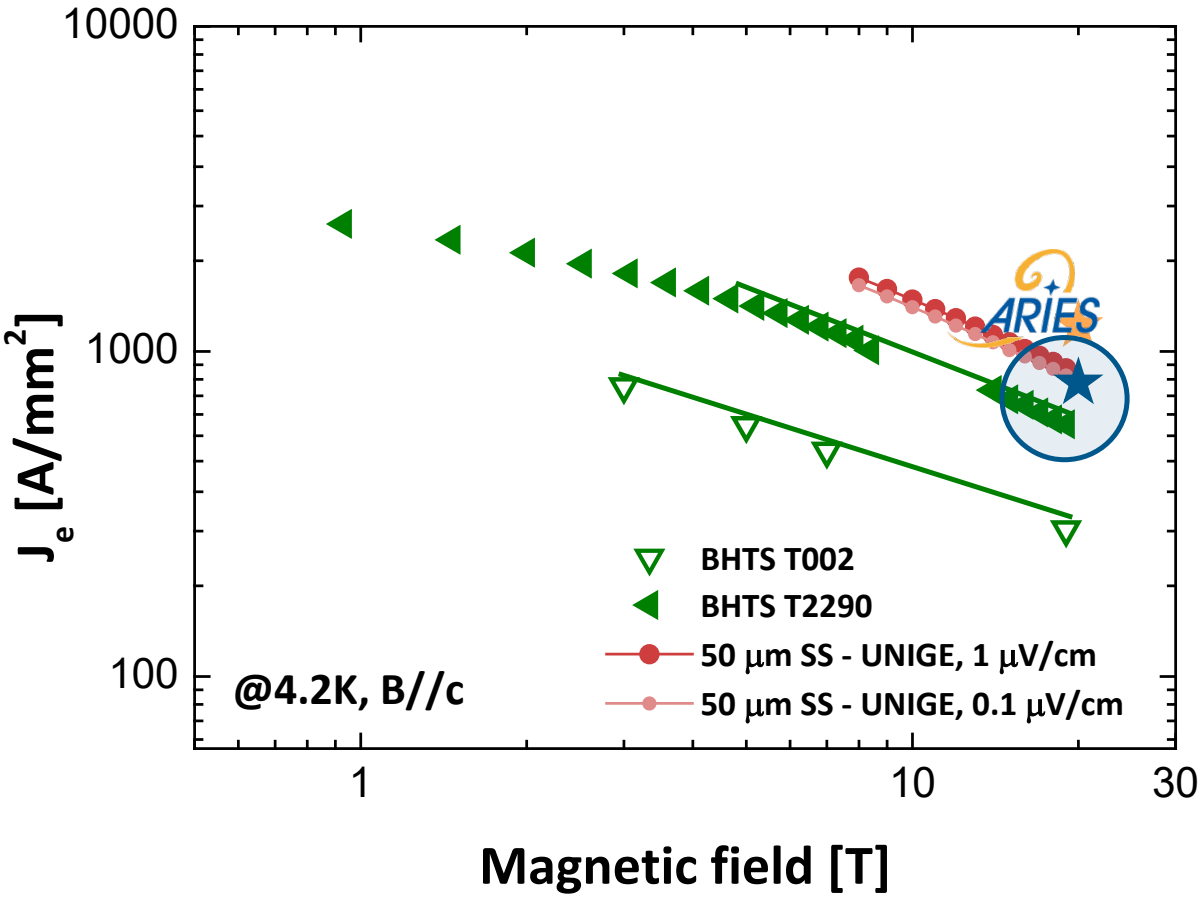




UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Ic performance of ARIES tape

BRUKER



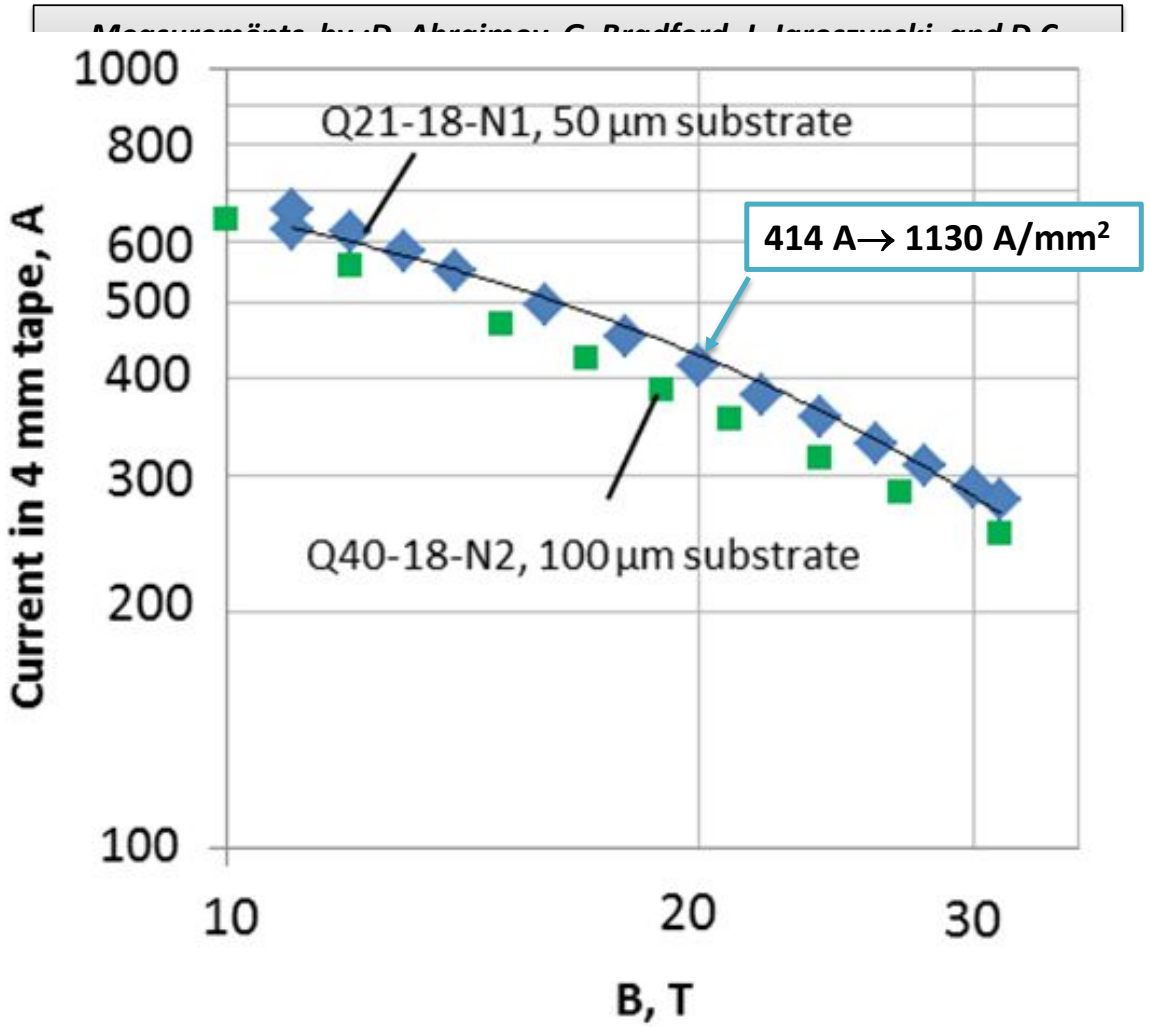
Jc over a while 12 mm @ 20 T 4.2 K: 954 A/mm²

First Milestone of ARIES is successfully achieved !!

ARIES

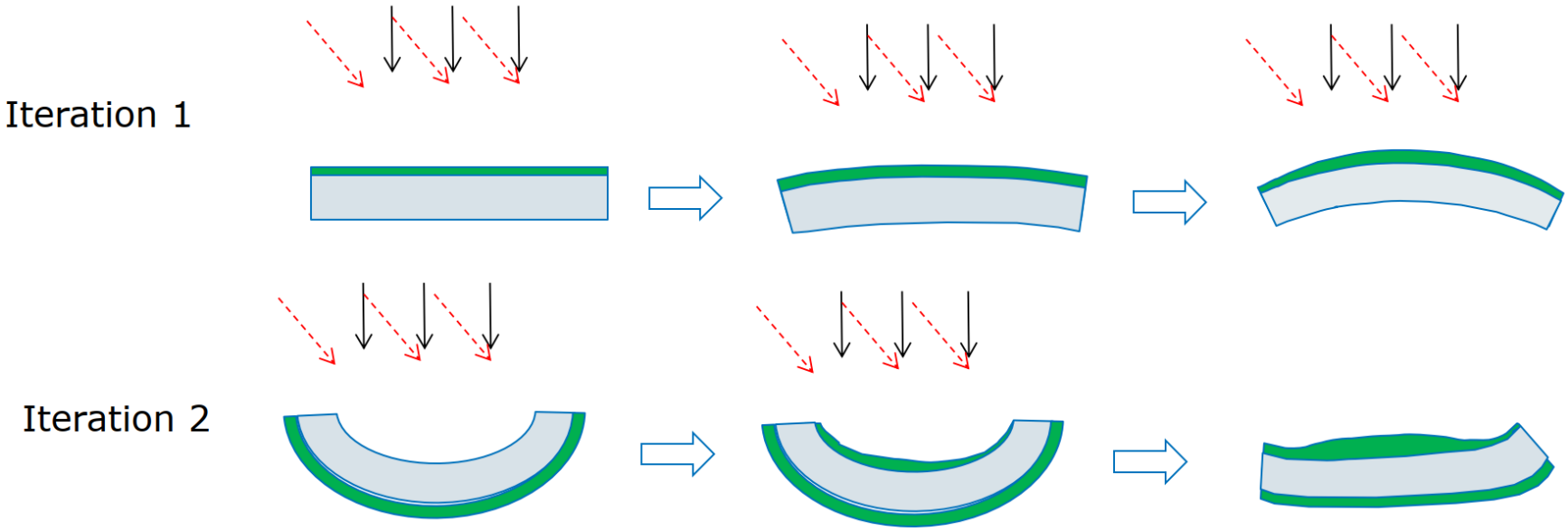
High current density confirmed in NHMFL-FL

- Q040: Ic in-field measurement of 4 mm wide HTS production tape from 2017 showing 250 A at 4.2 K, 30 T, B//c
- Q021: I_C in-field measurement of 12 mm wide ARIES HTS tape with 50 µm substrate thickness from 2017 revealing 290 A at 4.2 K, 30 T, B//c
- **Highest in-field engineering current density:**
  J_e >1100 A/mm² at 20 T, 4.2 K, B//c,
  50 µm thick substrate



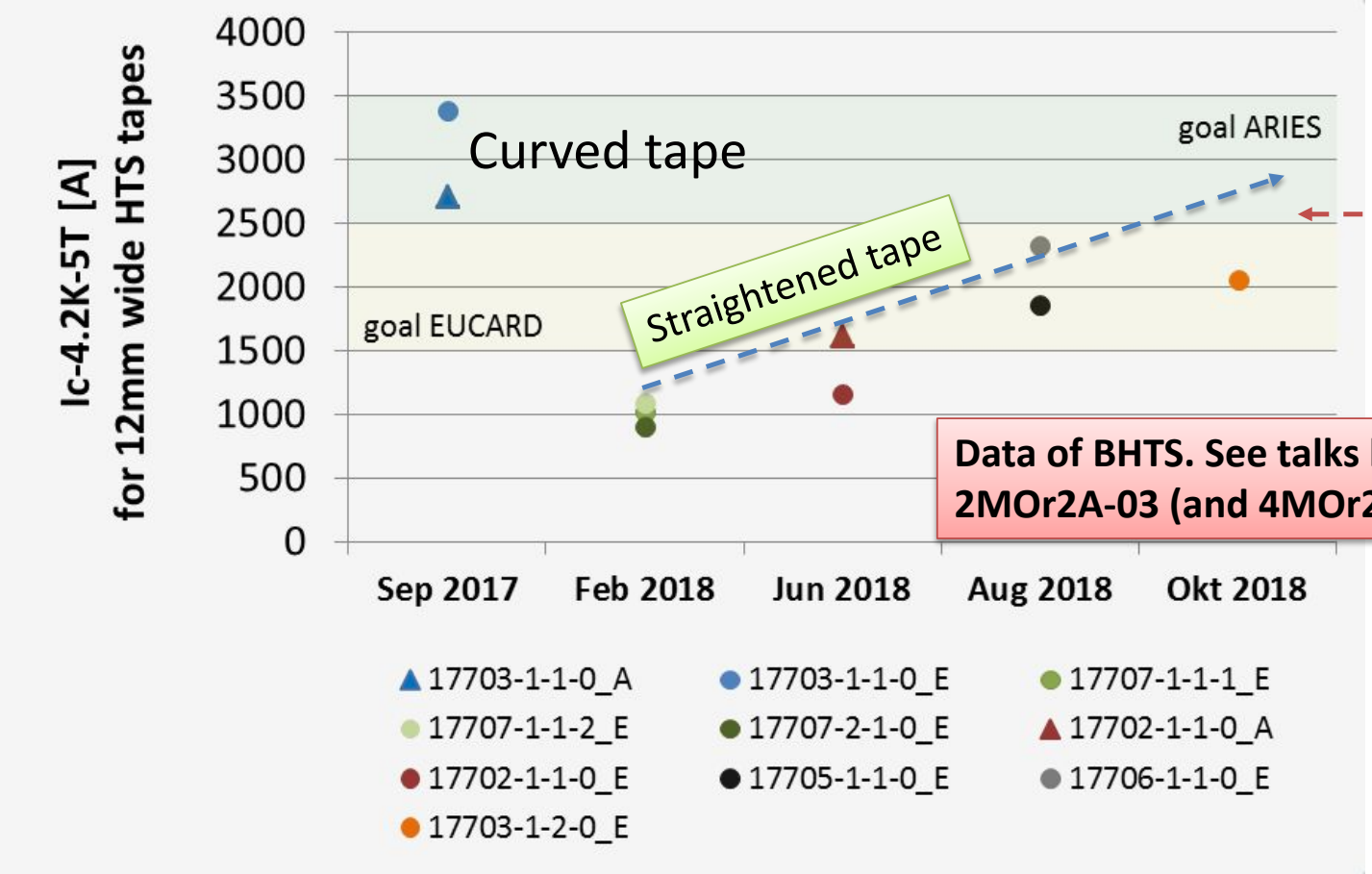
But bending is an issue for practical use…

At high temperature stainless substrate is soft. And YSZ is thick…
Using YSZ with ABAD to try to correct the curvature

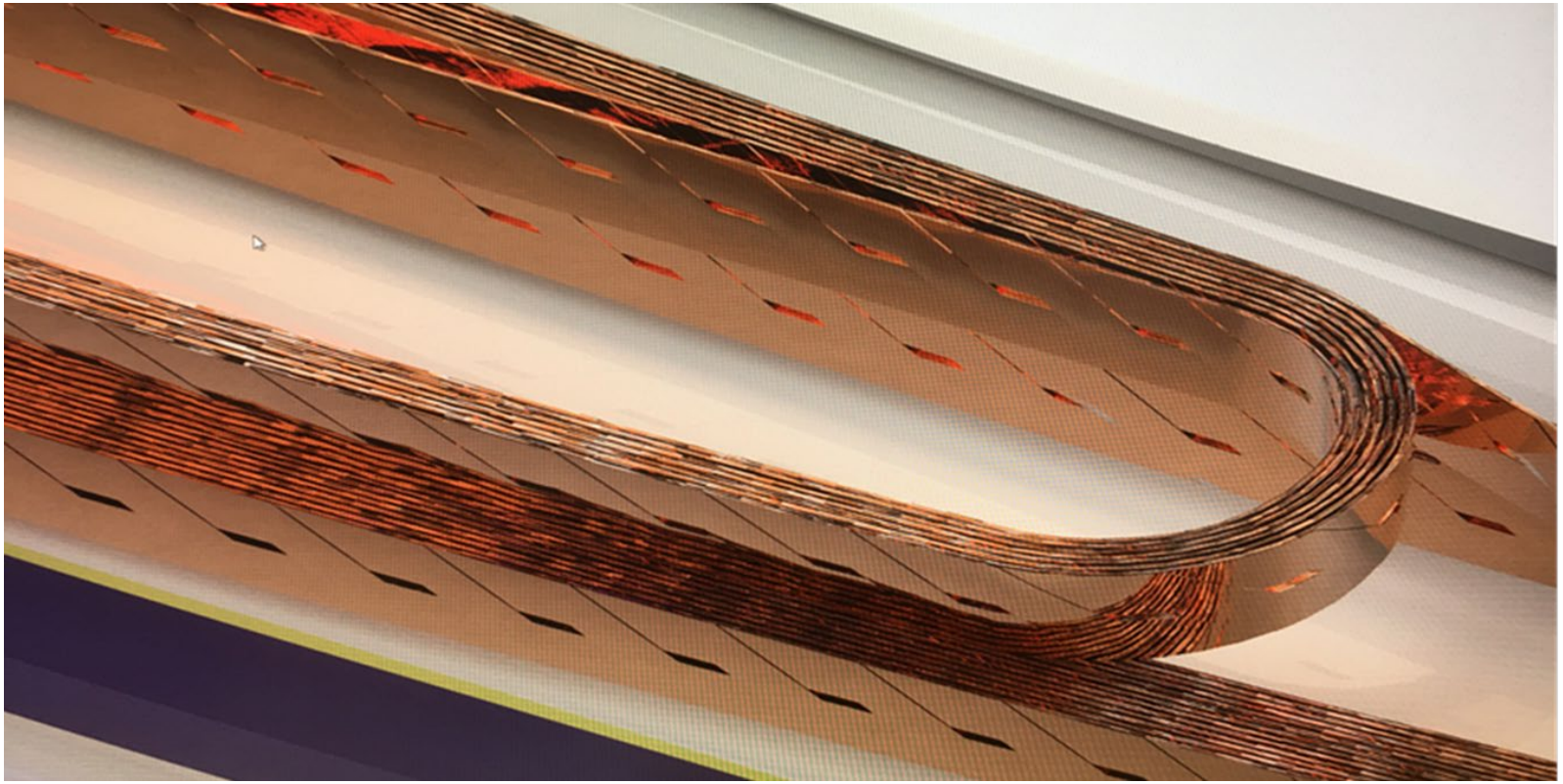


Now trying for more sphisticated attempts…

Results not fully succssful, yet…

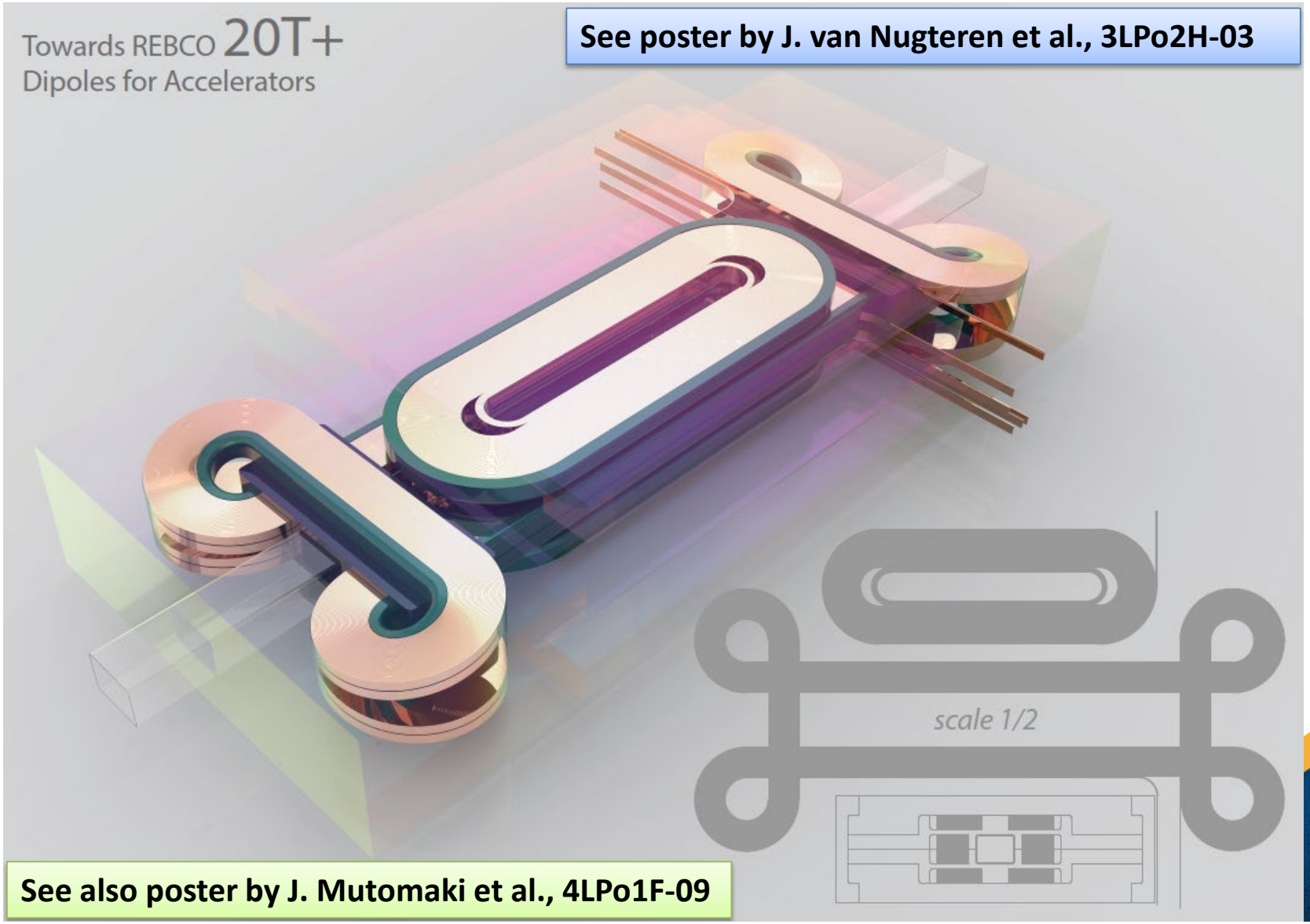


Will we continue to use Roeble cable?



ARIES tape with 50 µm stainless steel is delicate
Use of cable with two stacked tapes with low Cu, possibly with Cu strips is under consideration

New ideas for HTS dipole with cable or double tape



See poster by J. van Nugteren et al., 3LPo2H-03

See also poster by J. Mutomaki et al., 4LPo1F-09

Thank you for your attention

Question?

ARIES is co-funded by the European Commission Grant Agreement number 730871