PAUL SCHERRER INSTITUT

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CHART
Swiss Accelerator Research and Technology

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ReBCO High-Temperature Superconductors for Application in High Field Accelerator Magnets

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Swiss Accelerator Research and Technology (CHART) program (www.chart.ch).

FCC-hh Main Machine Parameters

From F. Gianotti, “Introductory Remarks”, FCC Week 2023, London, UK.

Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	1020-4250		7.3	3.6
SR power / length [W/m/ap.]	13-54		0.33	0.17
long. emit. damping time [h]	0.77-0.26		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	6.1-8.9		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300

If FCC-hh after FCC-ee: significantly more time for high-field magnet R&D

aiming at highest possible energies

[emphasis added]

HTS in the LDG Accelerator R&D Roadmap

- LDG Roadmap on High-Field Magnets, p. 33
  - "Consideration of only engineering current density would suggest that magnetic fields in the range of 25 T could be generated by HTS"
  - "… performance of HTS in the range 10 to 20K has reached values of Je well in excess of 500 to 800A/mm2, i.e., the level that is required for compact accelerator coils. […] it would open a pathway towards a reduction of cryogenic power, [and] a reduction of helium inventory (e.g., dry magnets)"

Aspirational Goals

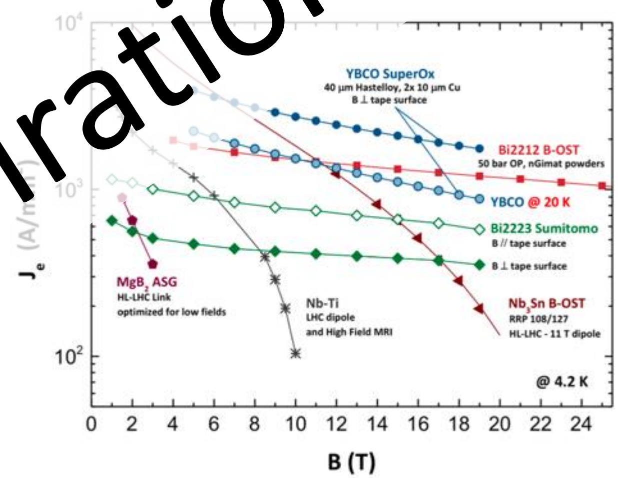


Fig. 2.3: Engineering current density J_e vs. magnetic field for several LTS and HTS conductors at 4.2 K. Latest results for REBCO tapes are reported both at 4.2 K as well as 20 K.

[LDG Accelerator R&D Roadmap, High-Field Magnets, https://arxiv.org/abs/2201.07895]

Main Challenges with ReBCO

- Ramp losses and field quality
  - LTS wires have filament sizes of few microns (Nb-Ti) to 50 µm (Nb_3Sn).
  - ReBCO tapes are 2-12 mm wide. Screening currents and associated ramp losses are substantially increased.
  - Tape orientation matters!

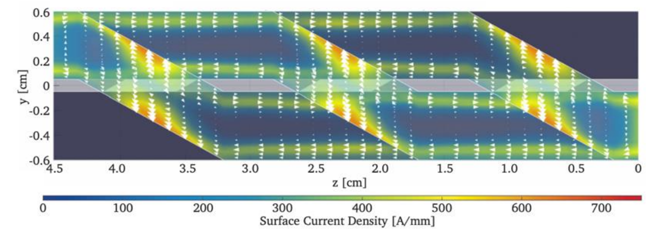


Figure 4.1. *Calculated vector field, which indicates the overall current direction for a Roebel cable, shown for an perpendicular uniform applied magnetic field of 0.7 T, which was ramped over the virgin curve using a frequency of 0.1 Hz. The operating temperature is set at 4.5 K. The engineering current density of the conductor is scaled to 527 A/mm² at 20 T ⊥ 4.5 K and 4.4 kA/mm² at 20 T ∥ 4.5 K in the 100 µm thick tape.*

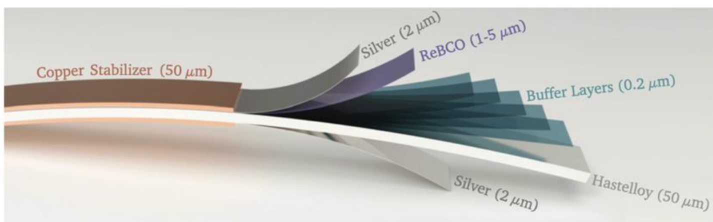


Figure 1.7. *Material composition of ReBCO coated conductor. For visual clearness the tape is cut in half along its length such that the inside becomes visible. In reality the copper and the silver layers fully surround the hastelloy substrate carrier.*

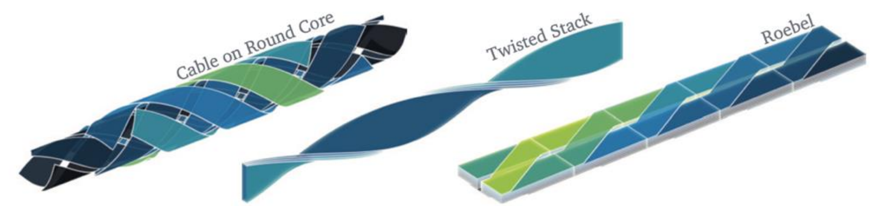
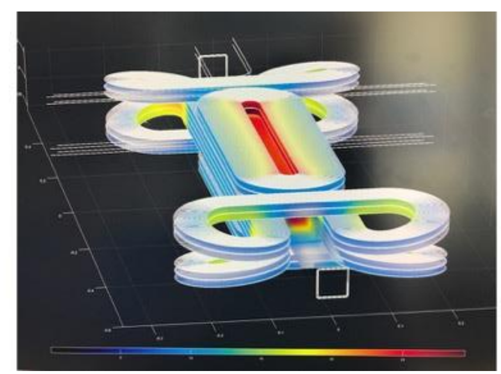


Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*

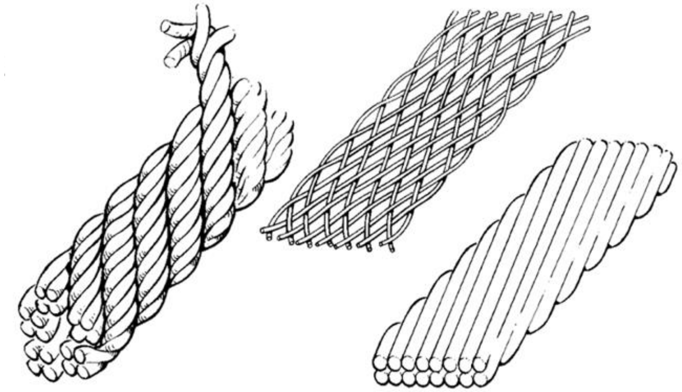
[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]

- High-current, low-loss cables and their windability
  - Do we need full transposition (every tape in a cable ”sees” the same field, inductive loops are shortened)?
  - Can we pre-fabricate a cable, or do we need to assemble and insulate it “on the fly” during winding?
  - Can the cable withstand pressure of 400+ MPa?



[Courtesy G. Kirby, J. v. Nugteren, J. S. Murtomäki, et al.]

HTS technology for HEP is at the level of LTS technology in the late 1970s



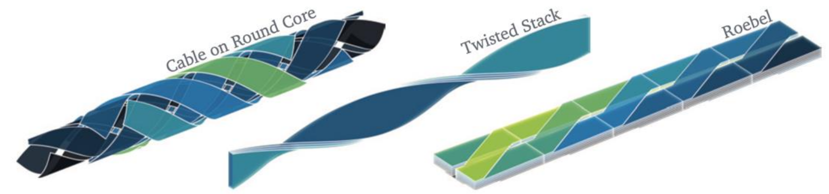
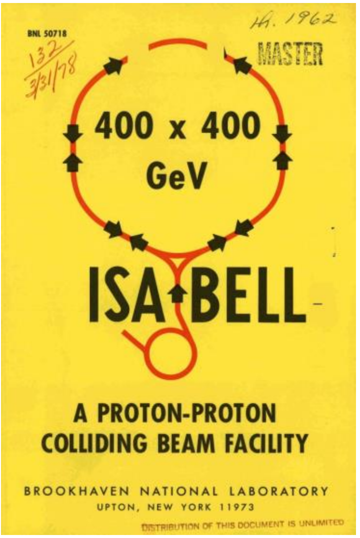


Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*

Early options of cables for main dipoles in Isabelle accelerator at BNL:

Braided cable failed in series manufacturing.
Rutherford-cable development arrived too late, but underpinned Nb-Ti accelerators:
Tevatron, RHIC, Hera, (SSC), LHC



[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]
[M. Wilson, Pulsed Superconducting Magnets' CERN Academic Training May 2006]

Main Challenges with ReBCO

J. v. Nugteren, et al., A Fast Quench Protection System for HTS Magnets, IEEE Trans. On Appl. SC, Vol 29, 2018.

- Protection:
  - HTS conductors are intrinsically more thermo-electrically stable than LTS conductors.
  - The same margins make detection of quenches and protection from
    quench-induced damage more challenging.
  - Disruptive innovation is required, if we are to account also for
    - quadratic scaling of stored magnetic energy with field,
    - and the fact that cost considerations push magnet engineers towards higher engineering current-densities with lower stabilizing copper fraction.
- Mechanics:
  - Due to the quadratic scaling with field, mechanics of 20 T magnets is expected to be a formidable challenge.
  - The robust operation of novel conductors and cablesin high-stress/strain conditions is yet to be studied.
  - New mechanical concepts and novel materials may need to be explored.

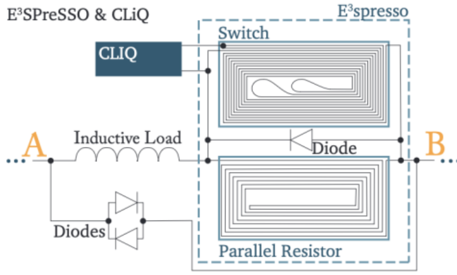


Fig. 4. Schematic showing the electrical connection of the E³SPreSSO unit to the CLIQ box, consisting of a quadrifilar switch and bifilar parallel resistor, and the main inductive load it is protecting.

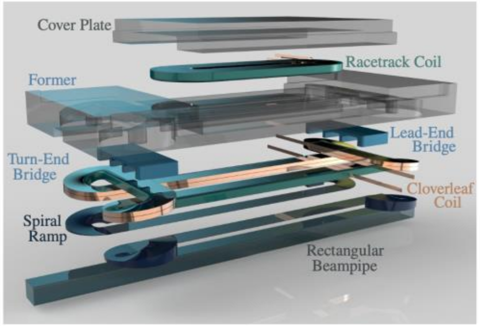
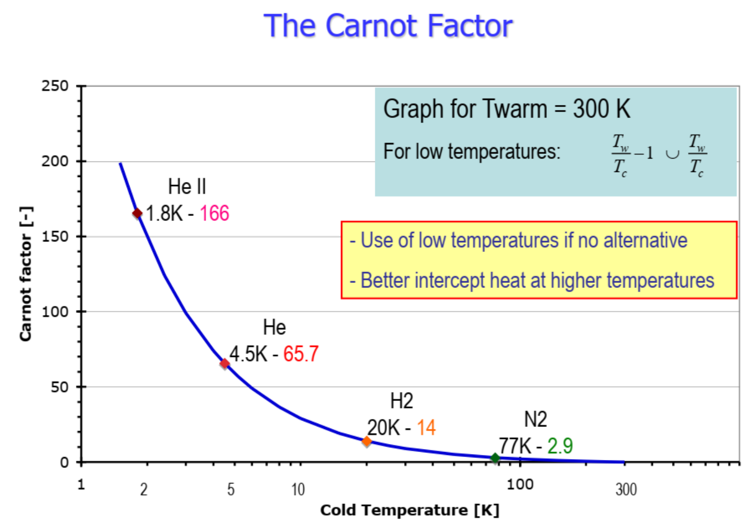


Fig. 11. Exploded view of the conceptual design of the REBCO 20 T+ magnet under development by CERN.

J. v. Nugteren, et al., Towards REBCO 20 T+ Dipoles for Accelerators, IEEE Trans. On Appl. SC, Vol 29, 2018.

Main Challenges with ReBCO

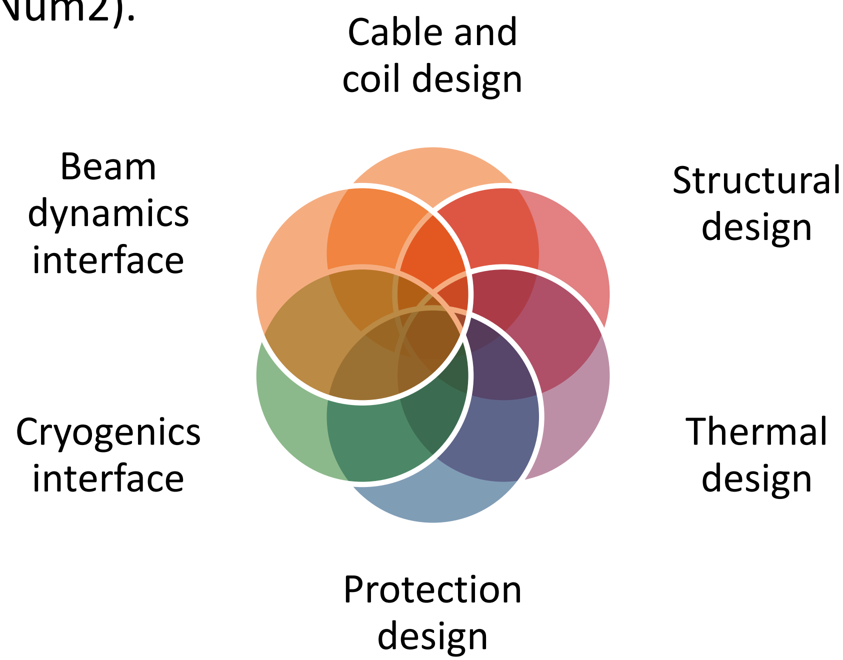
- Cryogenics
  - Improved Carnot factor can offset increased ramp losses.
    - Only if ramp losses can be reduced sufficiently will this lead to a net saving in cooling power!
  - FCC-hh has short turnaround time: 6h nominal, 2h for HL-FCC-hh.
    - Ramp losses must be extracted quickly from SC coils.
  - Increased temperatures (10-20 K) and reduced cryogen inventory will lead to increased temperature gradients within magnets and along cryogenic circuits.
  - Co-development of magnet and cryogenic technologies are essential.



[Serge Claudet, Introduction to Cryogenics for accelerators, CAS on Vacuum for Particule Accelerators Glumslöv-ESS, SE 7-15 June 2017]

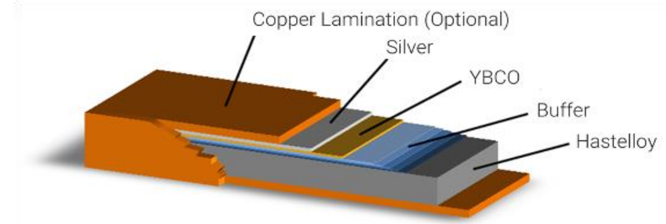
Systems Engineering Challenge

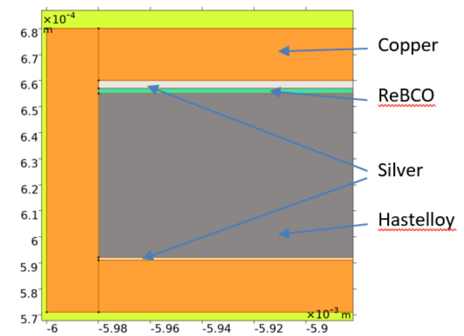
- Any future accelerator-magnet system will be strongly coupled to other accelerator subsystems such as cryogenics, beam optics, powering, etc.
- Novel conductors and cryogenics concepts will mean that this coupling is far more consequential and bi-directional than in past accelerators, HL-LHC included.
- New systems-engineering methods of cooperation and negotiation of specifications across subsystem boundaries will be required.
- CHART is developing tools for Model-based systems engineering (MagNum/MagNum2).



Numerical Challenges and Alternative Conductors

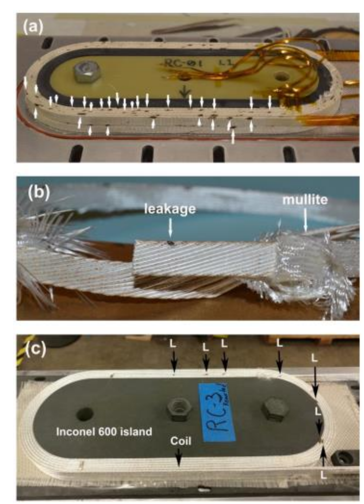
- Numerics Challenge
  - Aspect-ratio of physically relevant layers in ReBCO tape make modeling and homogenization in all physical domains difficult.
    - Shielding current calculation
    - Thermal modeling
    - Mechanical behavior
  - The community lacks a commonly agreed design approach/tool for HTS magnets.





Courtesy D. Sotnikov

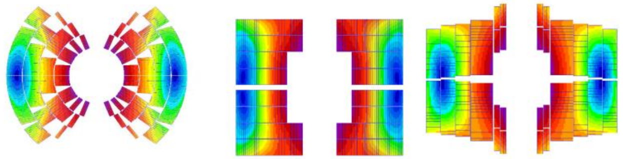
- Alternative conductors:
  - Bi-2212: studied in US-MDP program.
    - Today not a commercial product.
    - Fragile conductor.
    - Heat treatment > 1000º C.
  - Iron-based superconductors: in the earliest stages of R&D. European program is only now being set up. Whether it can be ready in time for FCC-hh is not known.



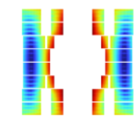
Courtesy T. Shen, LBNL

Ramp-Loss Studies

- An HTS 16-T block coil at 20 K has simulated AC losses of 224 kJ/m*.
- LTS magnets feature about 20 kJ/m and powering cycle (that is 2 times higher the CDR target of 10 kJ/m).



Coil geometry		Cos-theta	Block	Common Coil
Deff	µm	50	50	50
AC-loss (2 Ap)	J/m	18330	19603	23489



4-mm width
224680

Courtesy D. Sotnikov

- Carnot efficiency increases 10-fold from 1.9 to 20 K, and 4-fold from 4.2 to 20 K.

- Total Cost = CAPEX (tape) + OPEX (cryo power)
- CAPEX is reduced and OPEX increased at lower temperatures.
- Affordable 20-T magnets with reduced cryo power are still beyond the horizon.

*** Caveat: models need to be validated!**

[S. I. Bermudez, et al., AC loss for EuroCirCol 16 T designs, CERN 01-11-2017]

HTS Innovation Funnel for HFM

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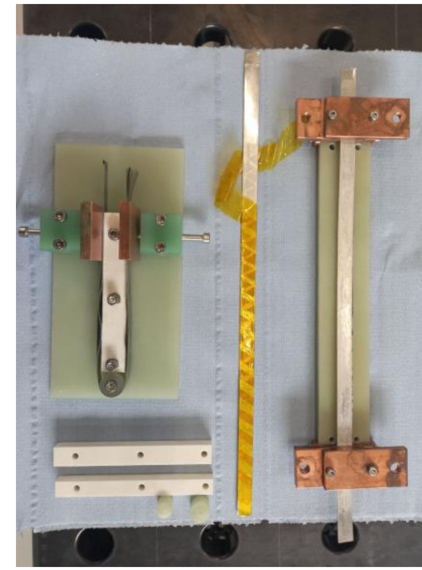
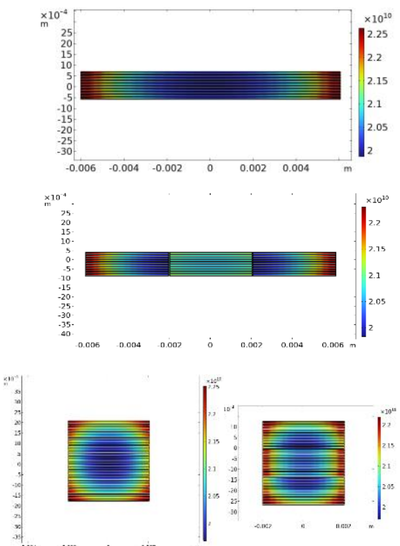
First deliverable		*#Deliverables / year*
2023	***Materials*** and ***Numerical Design Studies***	100s
2023	***Powered Cable Samples***	10
2024	***Technology Racetrack Coils***	2
2025	***Short Hybrid HTS/LTS*** Sub-Scale and Ultimate-Field *Magnets* (7…17 T)	1
	Short All-HTS Magnets (16…20 T) (4.2…20 K)	



Courtesy H. G. Rodrigues



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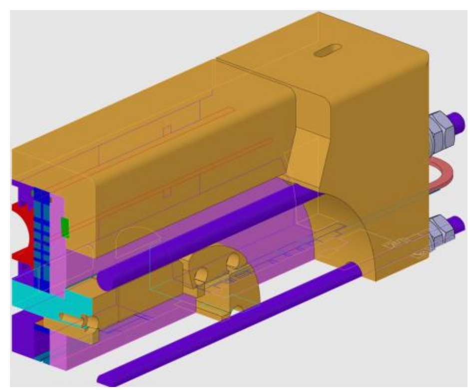
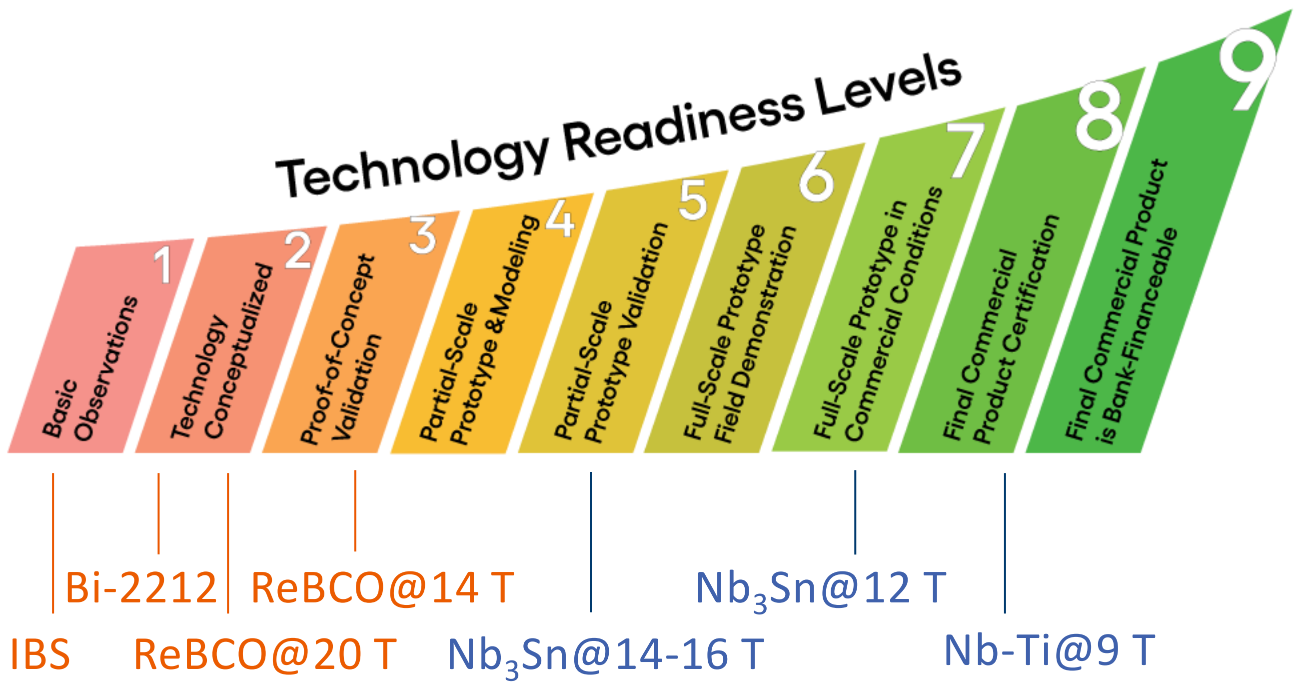


Courtesy D. Araujo, T. Michlmayr

Magnet Technology Readiness Gap



Rough estimates; bottom line is:

HTS technology must catch up to LTS over the coming 10 years in TRL to LTS.