Manufacturing and Technology Developments in ReBCO High Temperature Superconductors for Compact Tokamak Reactor

Furukawa Electric Co.Ltd. / SuperPower Inc.

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Key Topics

Recent initiatives to bring the fusion-energy to commercial

ReBCO (Rare-earth Barium Copper Oxide) conductor enables:

- Strong magnetic field excitation by artificial pinning structure
- Next-gen reactors of compact in Helium-less cryogenic system

On-going assessment to:

- Feasible business cases in volume scale
- Steps from new pilot-plant to scale, referring optical-fibre mfg.

Corporate Vision & SDGs

Furukawa Electric Group, Vision 2030

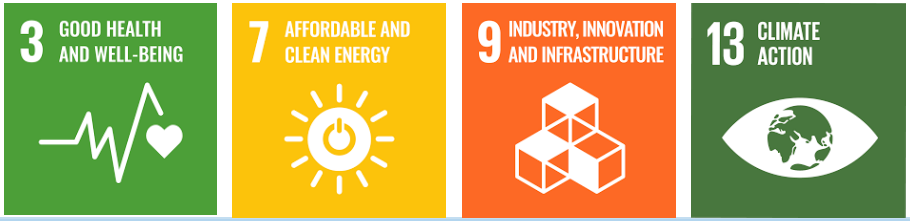
In order to build a sustainable world and make people's life safe, peaceful and rewarding, Furukawa Electric Group will create solutions for the new generation of global infrastructure combining information, energy and mobility.

Superconductor (LTS & HTS) is in line with our SDGs.

Energy Breakthrough: Fusion Power & Carbone Neutral

Life, Nature, Universe: NMR, MRI, Accelerator

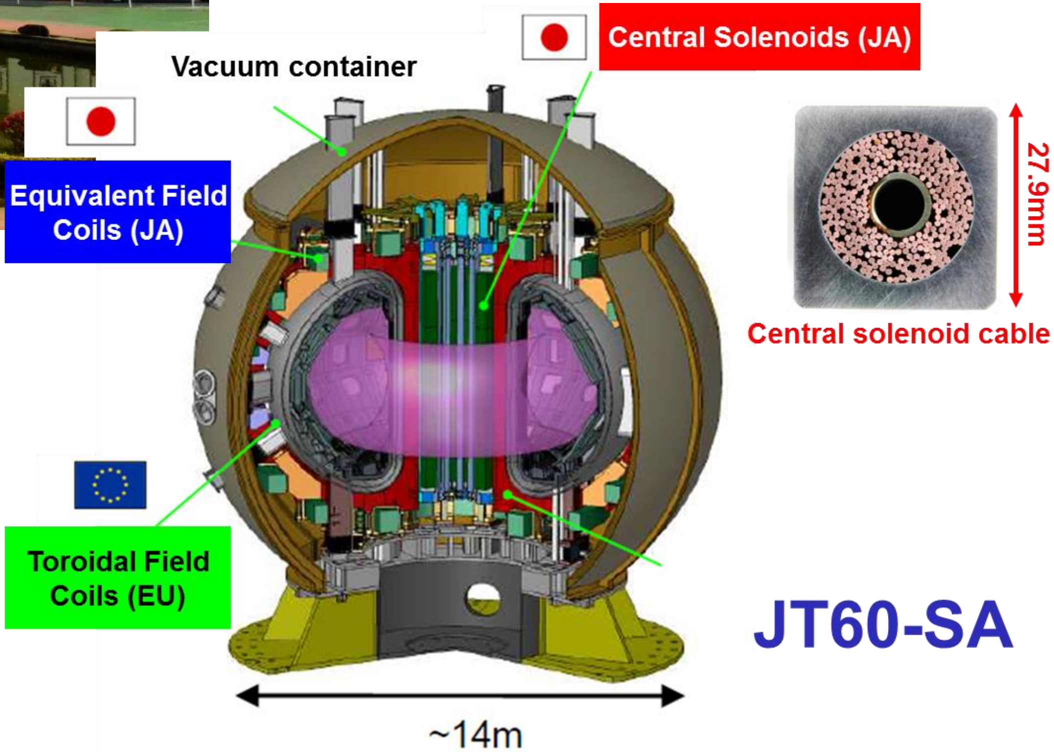
Sympathy beyond distance: Next-gen. Electric Mobilities



FEC contributes to ITER & JT-60

NbTi/Nb3Sn Cable Assembly:

Produced & contributed by Furukawa Electric for JT-60 & ITER collaborative projects.



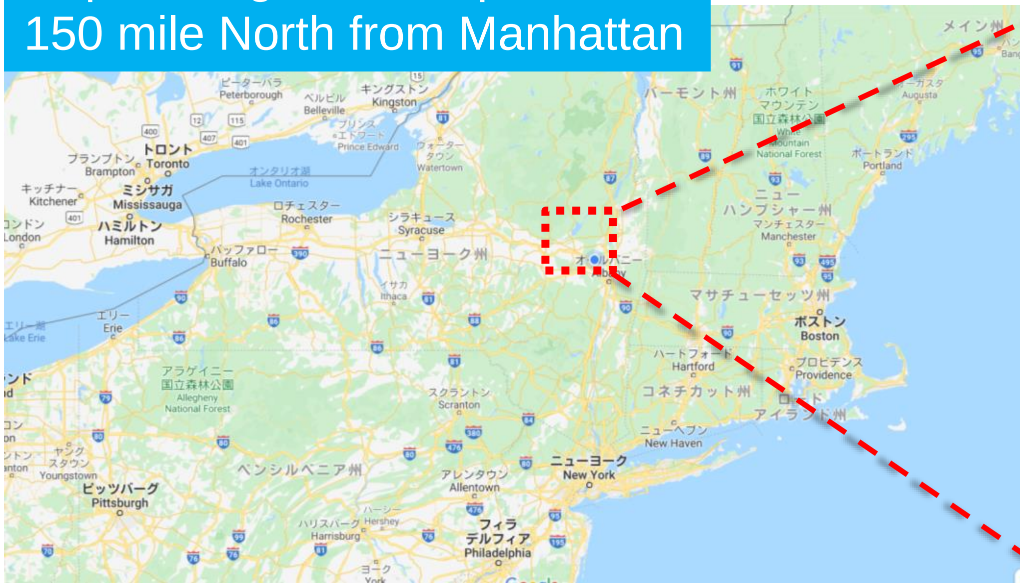
Our Nikko Works continue to play a key role in the community of technology-development for nuclear fusion.

Leverage & synergies to HTS-compact fusion development.

New Facility: Glenville, NY

Capital Region of Empire State
150 mile North from Manhattan

- - since Feb. 2020



SPI serves HTS manufacturing since 2000

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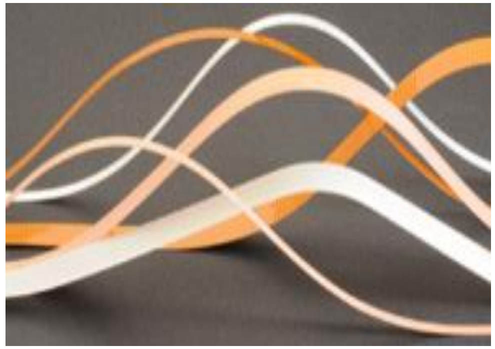
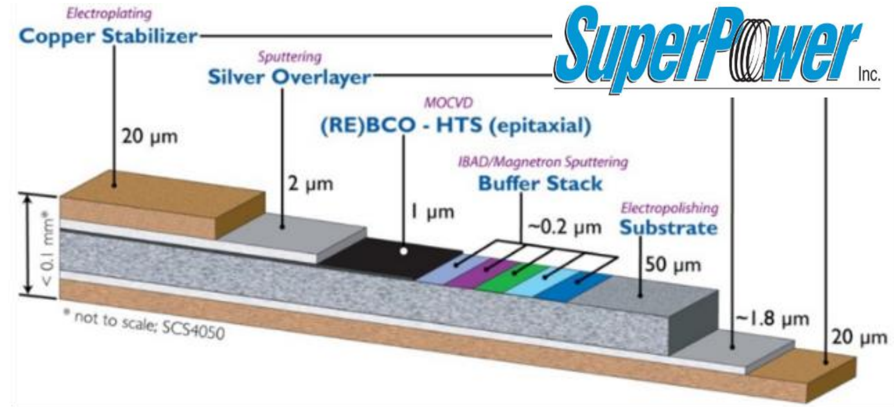




Electro-polishing → Buffer layer-stack → YBCO-coating MOCVD-growth → Characteri-zation → Slitting, Ag/Cu contact → Final inspection

SuperPower Inc., a member of Furukawa Electric since 2012

- Continuous manufacturing efforts in USA
- Aiming future applications in line with corporate SDGs

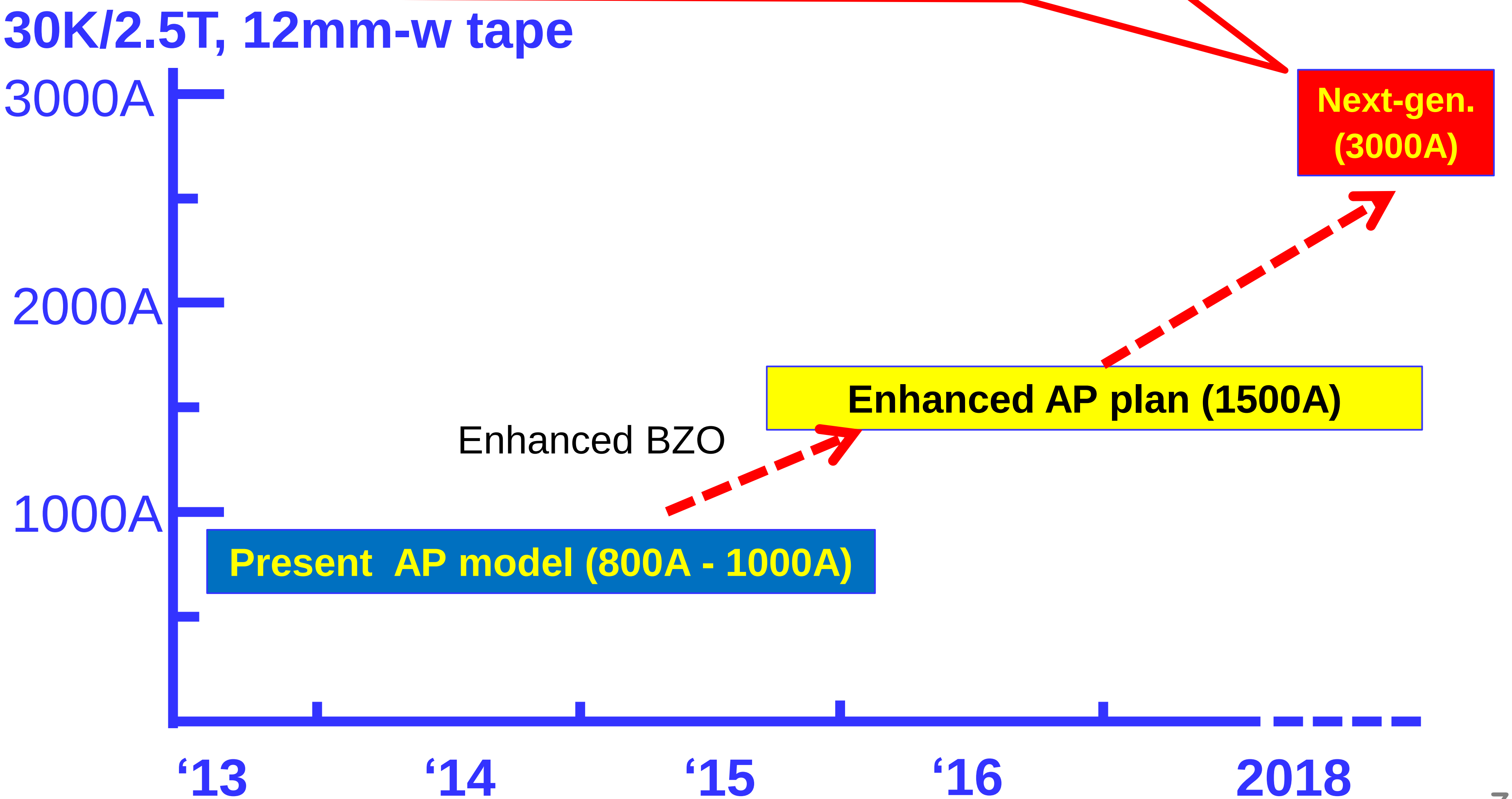
Topics Today:

- Reinforced technology & business for coated conductor
- Targeting the enterprise application of Compact Fusion Reactors.

Roadmap (presented in MT2013)

2013: Design-target = HTS-motor & generators

2021: SPI achieved the design goal for 3000A (30K/2.5T);
… following with modification & optimization.



Did pandemic impact our scope?

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SDGs?
Longer scope?

Scope at present, after pandemic:

1) Science ***"Non"*** Fiction
NMRs, Micro-fusions, Accelerators, etc.
→ V.H.F. (4.2-20K/ 20T+)

2) Practical & Industrial
E-Airplanes, E-Vehicles, Motors/Gen,
→ M.F. (20-50K/ 2-5T)

3) Clean power-grid infrastructure
Future replacement for copper devices
→ L.F. (65-77K/ self)

Scenario 2012~2013:

1) Clean power-grid infrastructure
HTS-Cables, FCL, SMES

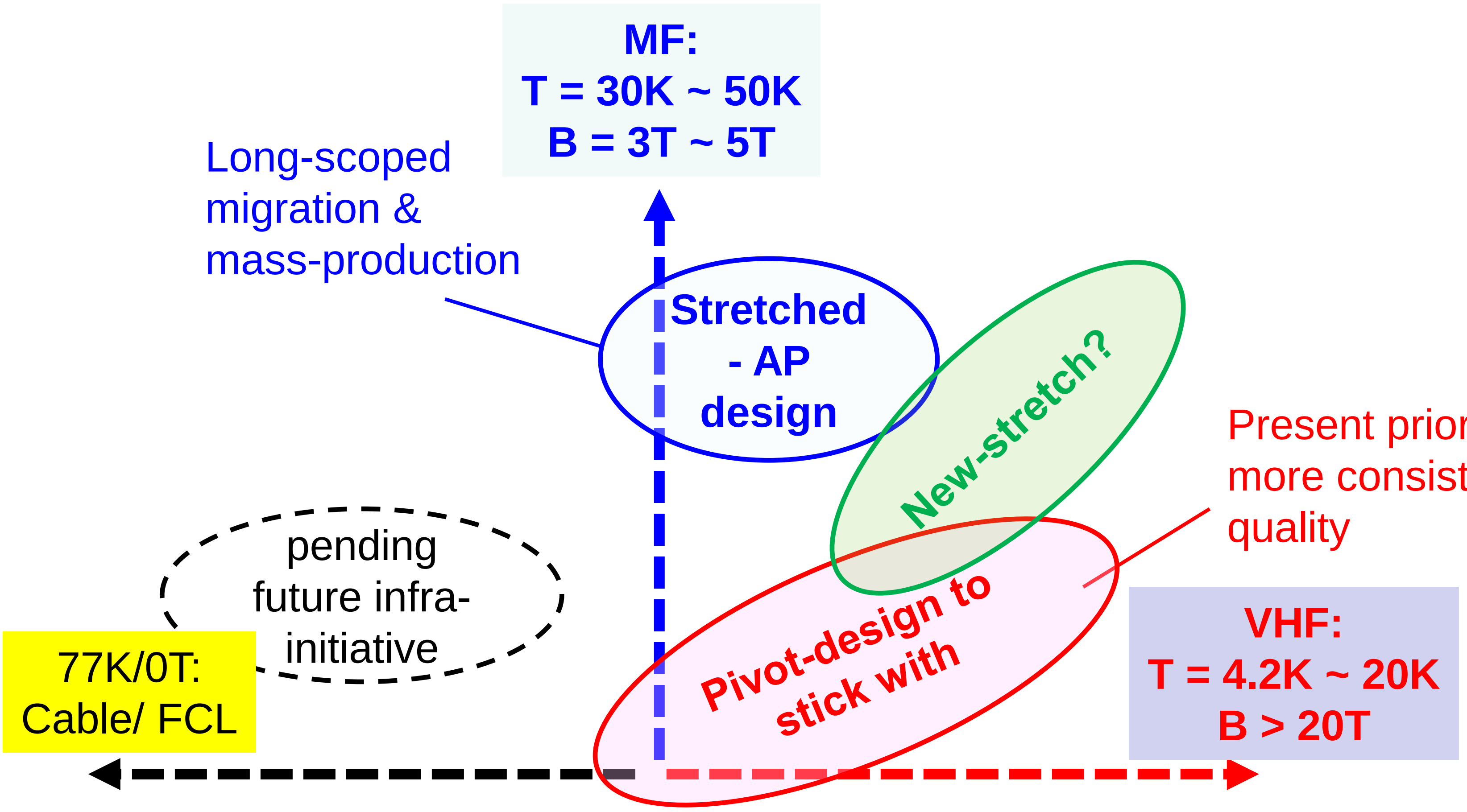
2) Practical & Industrial
Motors/ Generators

3) Science Fictions
??????

Compact fusion initiatives even more accelerate the requirements for in-field performances…

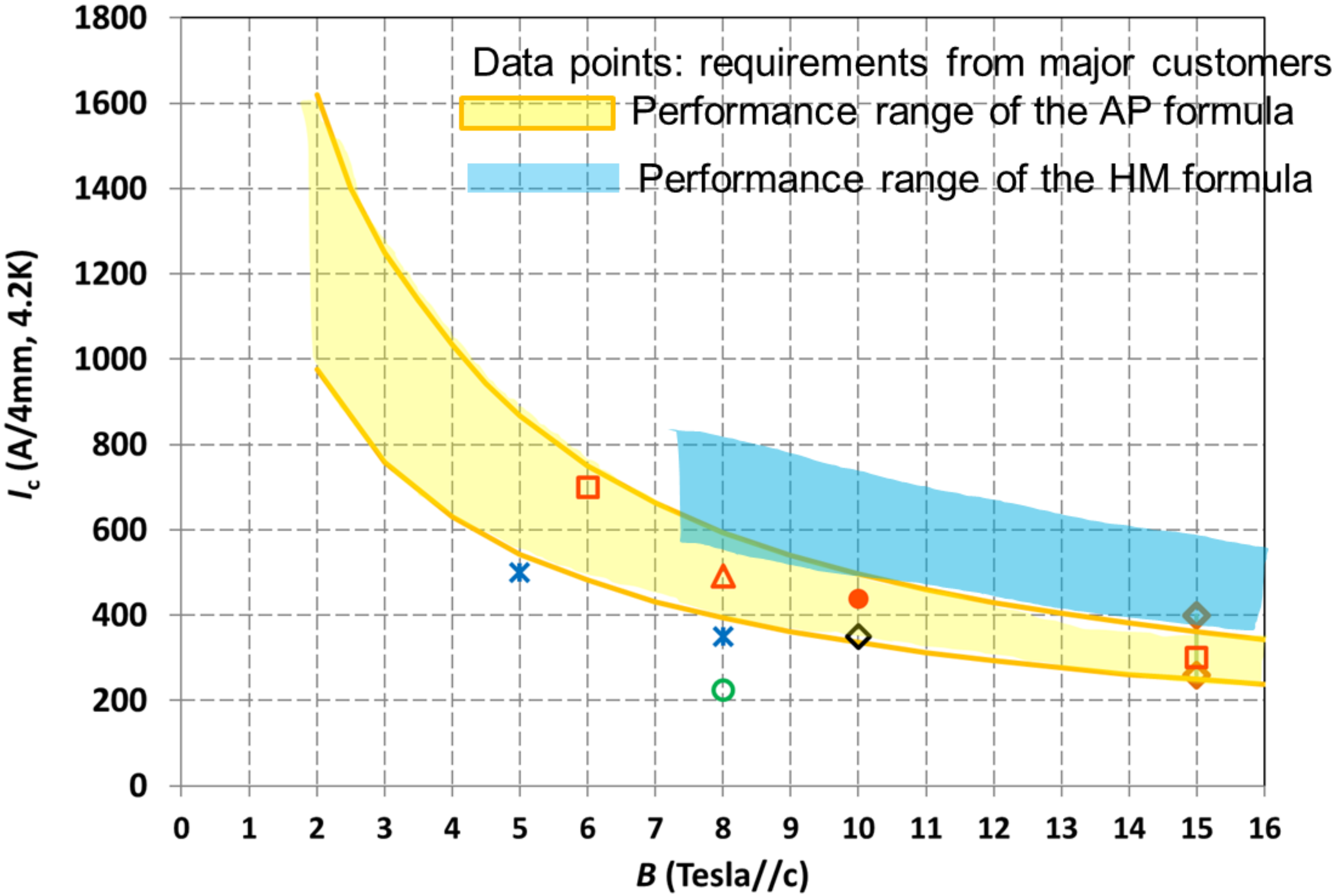
ReBCO design aligned to applications

Most demanding volume zone will dictate our manufacturing goals.
Present focus is to align ReBCO HTS formula toward fusion reactors in scale.

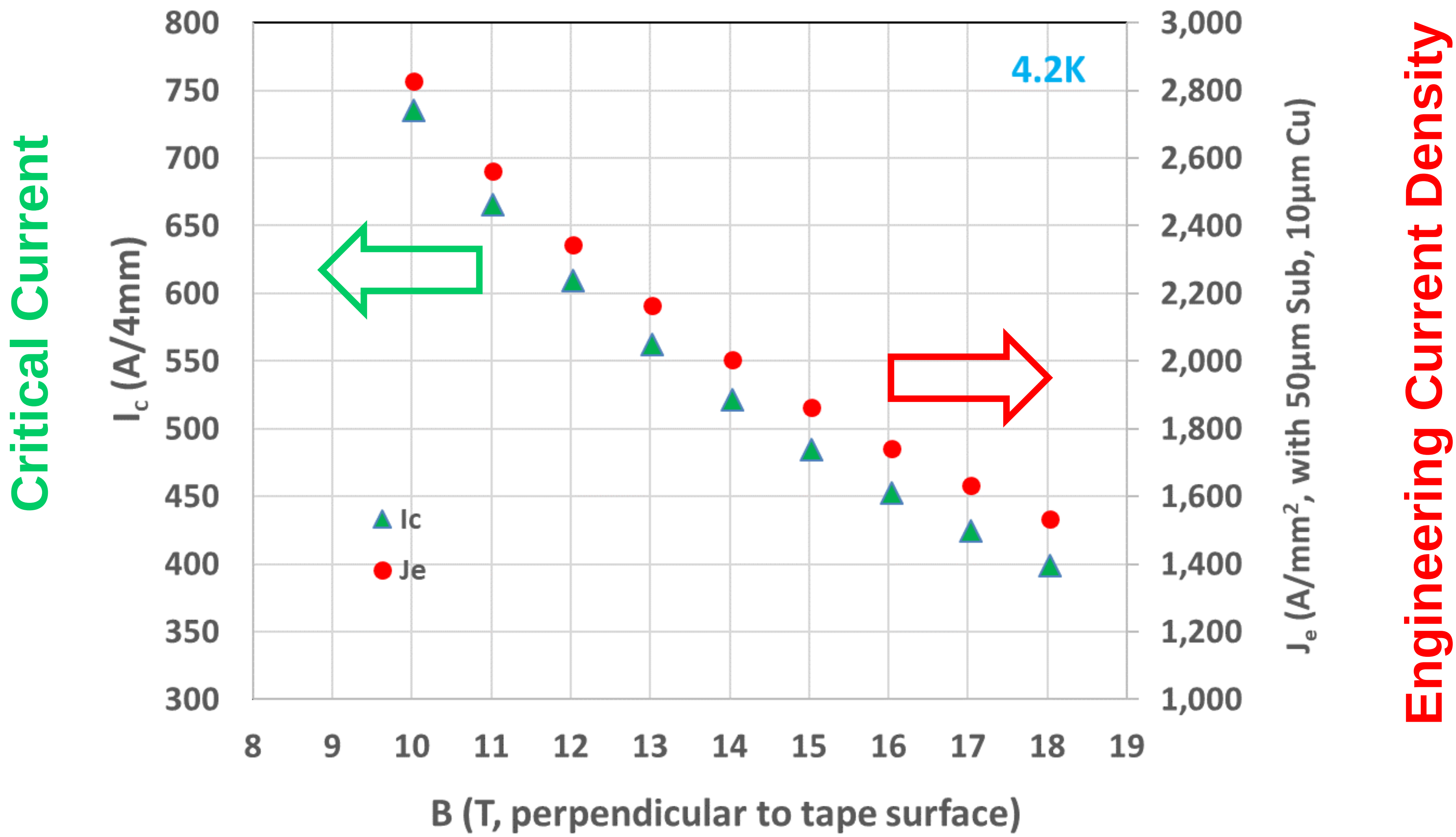


Improvement in in-field performance

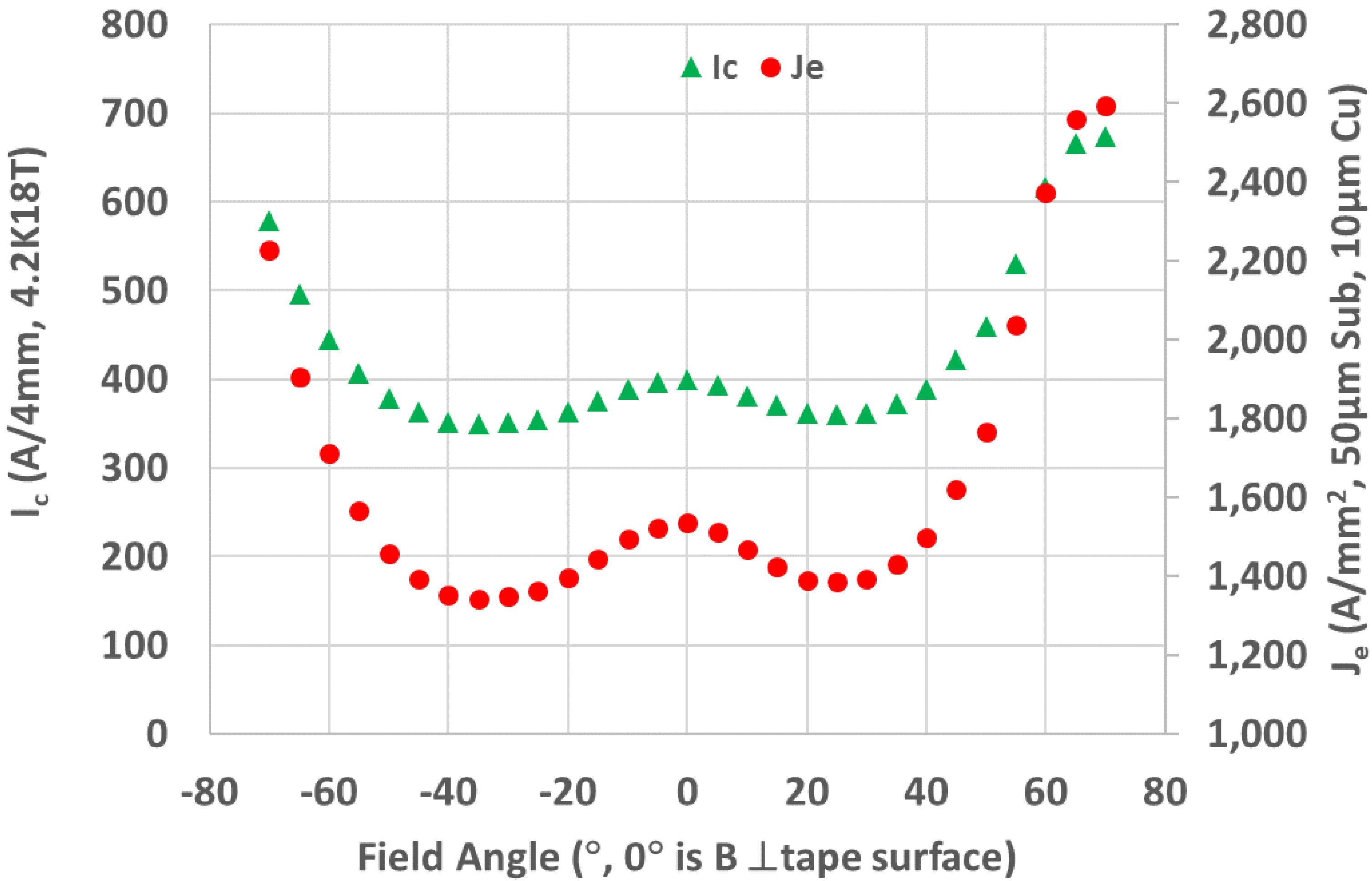
- In-field I_c requirements are mostly defined with a minimum I_c, meaning “the higher the better”
- In-field I_c requirements are evolving to higher levels, calling for continuous improvement



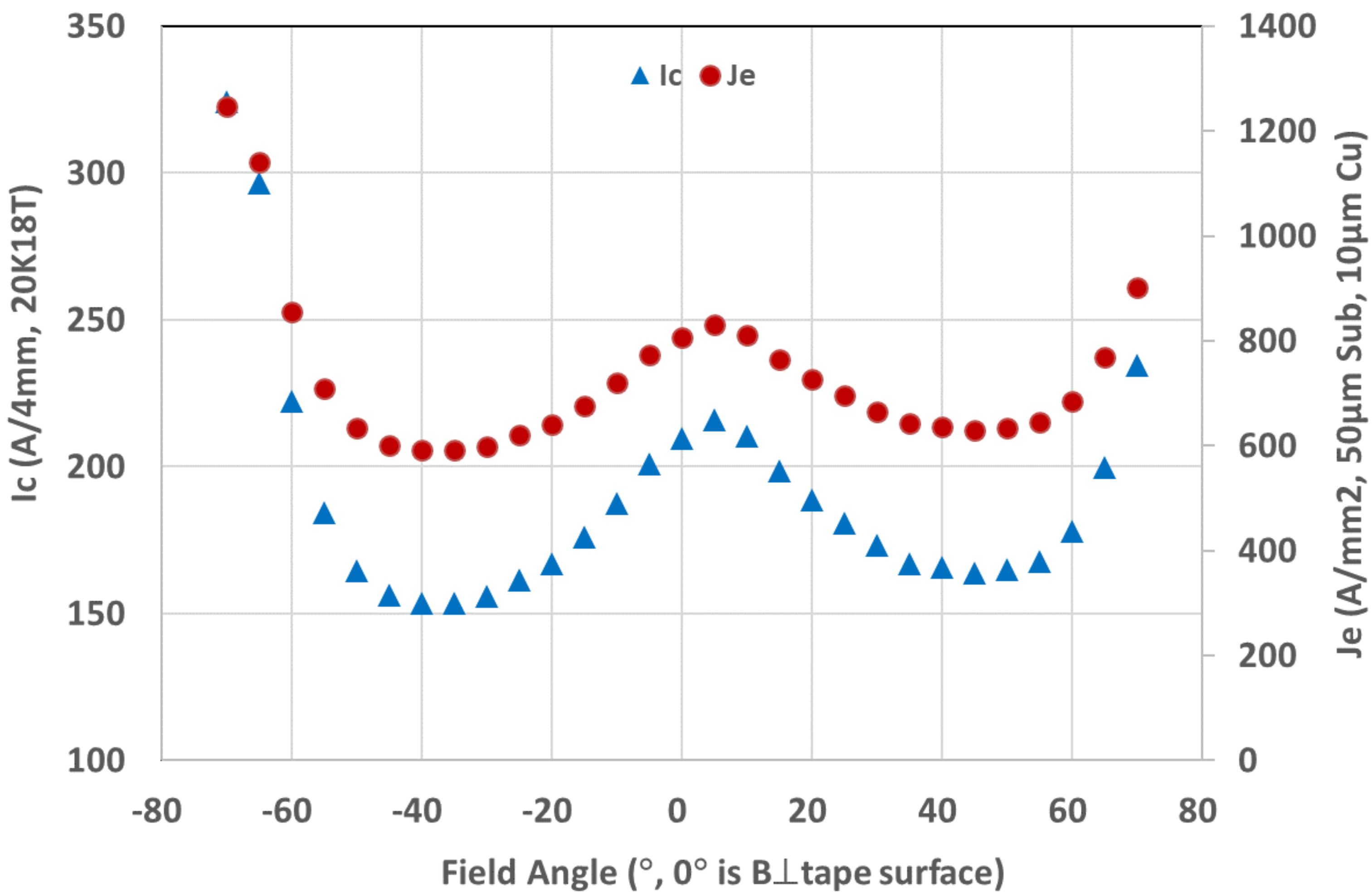
Field dependence of HM tape at **4.2K**



Field angle dependence at 4.2K and 18T

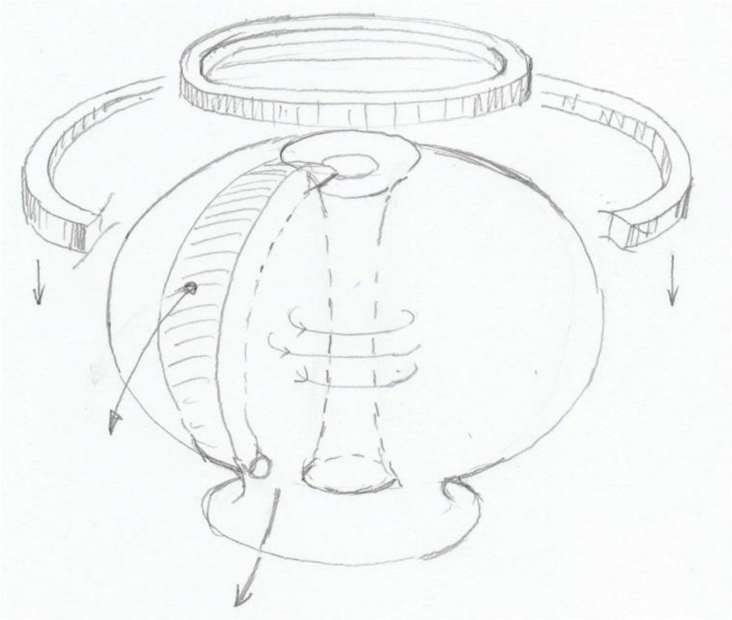


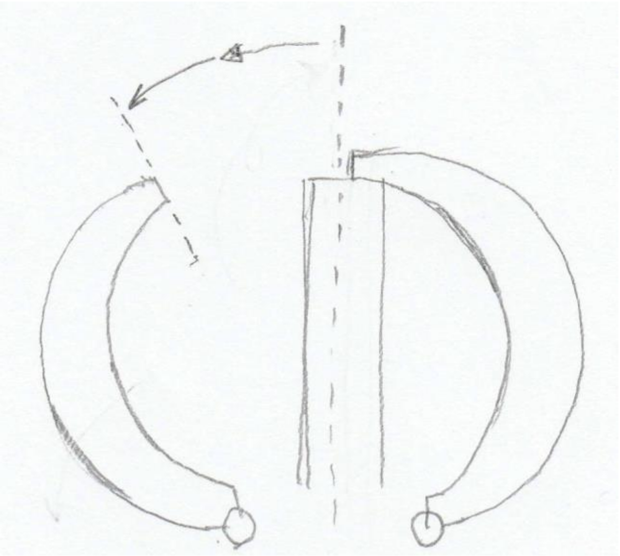
Field angle dependence at 20K and 18T



Consideration in Fusion Reactors:

- 10T~20T high-field operation is the “must”, and conductor Je is required for packing density for Toroidal Field Coils (TF) or Center Solenoids (CS).
- Mechanical stress to be assessed, also, neutron, proton, other irradiation-resistivity should matter to conductor-design.
- The TF magnet may not be of simple D-shape design, but could be separatable for blanket material to be replaced/repaired.
- Need diverting port operatable, poloidal field band (PF) to be also required to positioning the plasma, so various other magnets should associate.





Keys to Compact Fusion

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Keys	Requirements	Status
Magnetic & Electrical	20T, as an example. Some specific current density.	Customer gave us a target. It is clear, got it. Leave it to HTS. AC-loss, screening current…?
Mechanical	Twist, curve, hoop, contraction.	Unknown. Or, being evaluated as of cable-form at present. Magnet cycle-stress will be next.
form/ fit/ functional variety	Surface finish (Cu, etc.) Width, thickness, length	Vary from one customer to the other, or by the type of magnets (TF, PF, Center, etc.).
Fundamental	Neutron irradiation.	Shielded, of course, but how much HTS can be exposed or dosed?
Volumes	Huge. Multi 1000km/ system.	Worldwide total capacity： 1000km/ annum
Time	Originally noted to begin 2020. Now, 2022, so to speak.	Mr. Bezos, Mr. Gates,,,,

Our approaches

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Item	Issues	Approaches	Thoughts/Status
In-field Ic	Uniformities, margins, yields	APC, with modified composition	New model is in evaluation, as of Oct, 2021.
Mechanical	Edge-damages	Modified slitting	Conceptual design phase
f/ f/ f	Longer wires Surface finish	Large spool, bulk-supply Cu, or PbSn	Process lot-size over 1km Plating option is ready
Irradiation	Impact analysis	Collaboration with fusion community	To be initiated
Volume	Capital investment	Buffer-process, IBAD, MOCVD	Equipment is on track Space/ facility prepared
Time	Corporate initiatives	LTS/HTS combined business cases	2 years delay, dependent on customers' VC funding

Last key for the manufacturing = man; human resources

- Engineers in USA: Please, GAFA is not the only place to work….
- Worldwide: Semiconductors first, Superconductors next?

FEC's scale experience in fiberoptics

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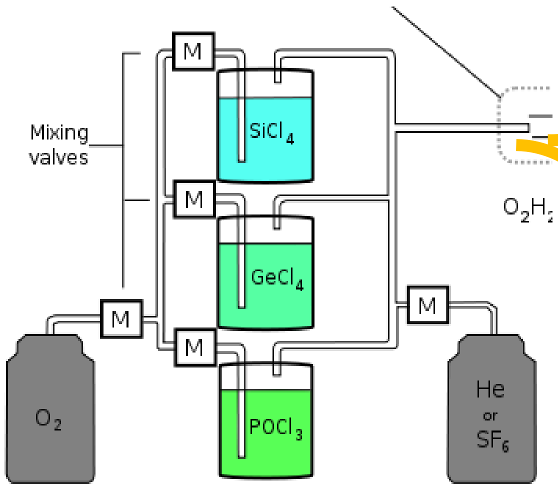

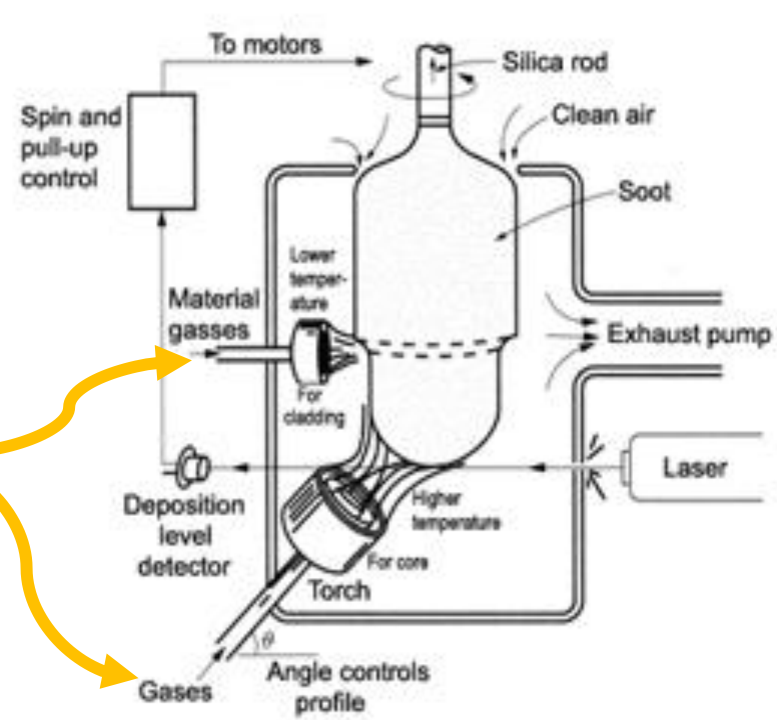

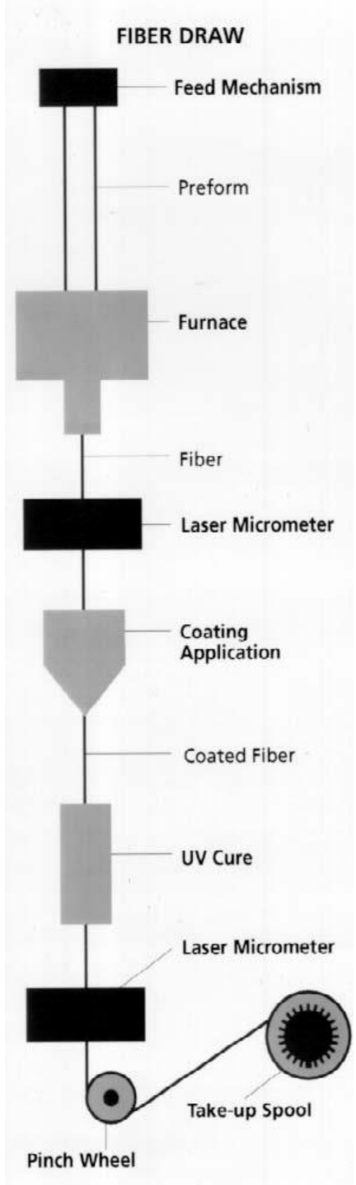

- Glass-preform synthesis by VAD (vapor-phase axial deposition), followed by drawing, and final plastic coating.
- Transmission core-diameter is 10um, 125um-dia cladding, and finished plastic coating up to 250um-dia.
- Flexible, bend radius is less than 10mm, when glass surface is completely clean, or free from scratch/ damages.

Thoughts for scale enhancement

Issues	Optical Fiber	HTS
Uniformity	Industry-grade, over 40 years.	MOCVD system is being modified in thermal & flow dynamics.
Robustness	No physical contact until very end of processes, up to final coating.	Mechanical slitting has worked fine, but need next-level improvements.
Piece-length	Preform size increased over years in 3D-directions, to be drawn 125um-d, 1000km-long piece.	1D-way: next target is over 1km 2D-way: ????? … tape cannot be drawn longer…
Capital-equipment & efficiency	SiO2 core & clad preform synthesized by number of CVD-chambers, with established and repeated design. Turn-around time between lots continue to be minimized by Kaizen-approach.	Precursor delivery to MOCVDs can be applied plant-wide, and automated. MOCVD chambers are composed of commodity piece parts, which is feasible for capital investment.

Analogy to optical fiber production will be leveraged and enhanced.
Differences and disadvantages should be modified, which is challenging but worth trying.

Things addressed in this session:

Building compact magnets for next-gen. fusion reactor is very much dependent on HTS coated conductor performances, robustness, and potential capability of scale-manufacturing.

The growth technology and machines are also essential, however, the real challenge is the feasibility of business cases. Not only for the capacity, but also for the value-chains including material supply, human resources, or manufacturing experiences.

Other steps to be taken, for instance, long-term reliability in unique operating conditions in the fusion reactor, or design-flexibility to various requirements in form, fit, and functions.

Our hope is that new-business inventors could bring up different ideas of applications for compact fusion, than conventional power-grid, which might even motivate the fund-owners at venture capitals.

It could be a long & winding road to real commercialization of fusion-reactors, but coated conductors will strive for the future to it.

Thanks to fusion-community and friends.

Viva! Reel to Reel!