



# HTS materials & magnets R&D at Renaissance Fusion

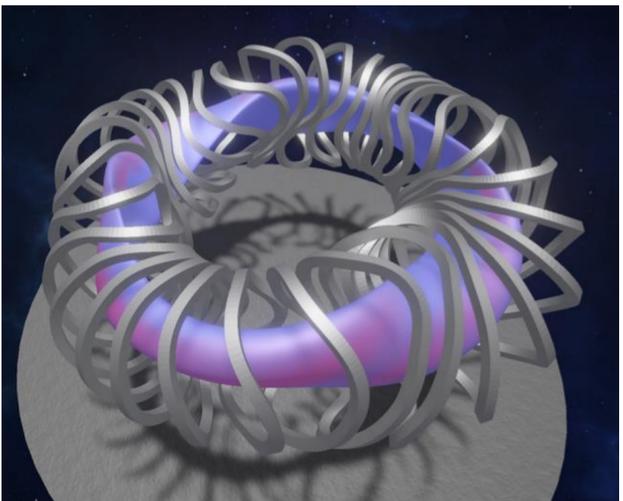
March 2025 / [francesco.volpe@renfusion.eu](mailto:francesco.volpe@renfusion.eu) (founder) / CCA Workshop at CERN / [renfusion.eu](http://renfusion.eu)

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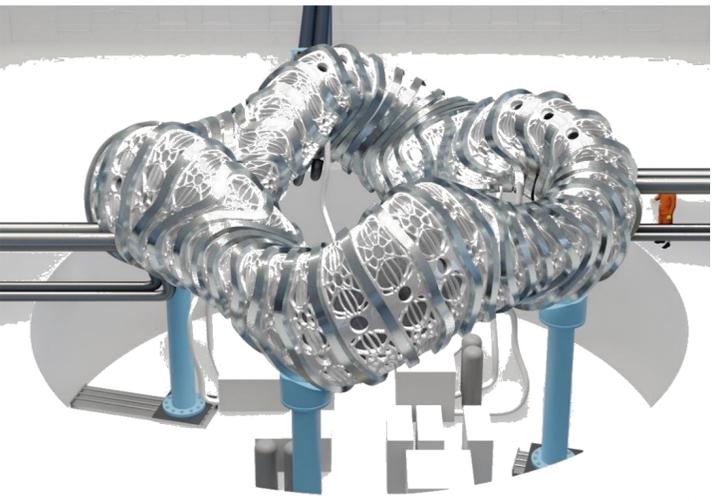
# Stellarators operate with d.c. coil-currents → good for fusion, good for HTS, but plasma (and coils?) are complicated

Two schools of thought

## 1) Build 3D coils

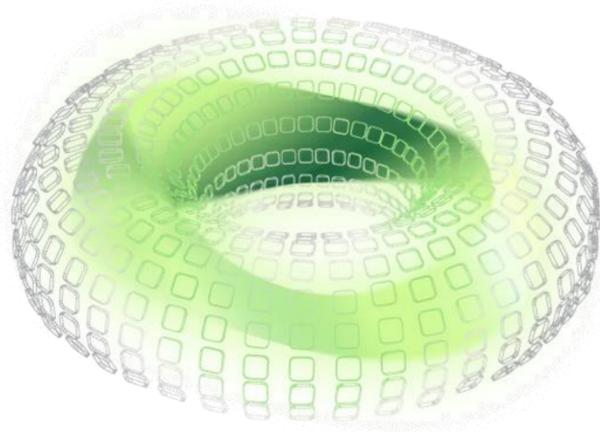


Credit: proximafusion.com

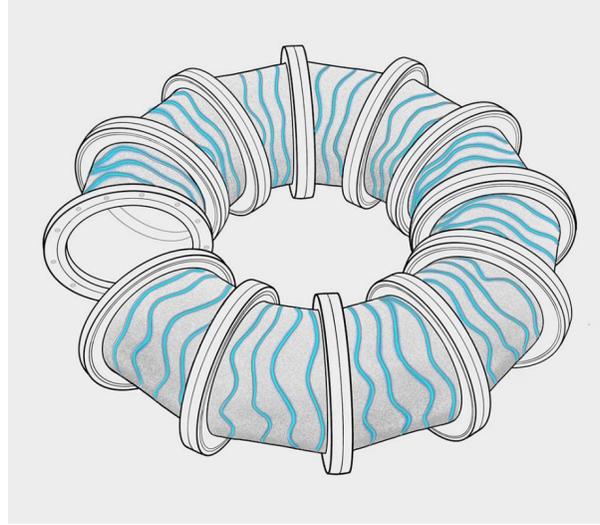


typoneenergy.com

## 2) Generate same field with simpler, 2D coils



Credit: thea.energy



renfusion.eu

What makes us unique

# Renaissance Fusion develops a simplified HTS stellarator with plasma-facing liquid walls, and of low aspect ratio

PROBLEMS

Low-field tokamak and stellarator reactors are **large and expensive**.



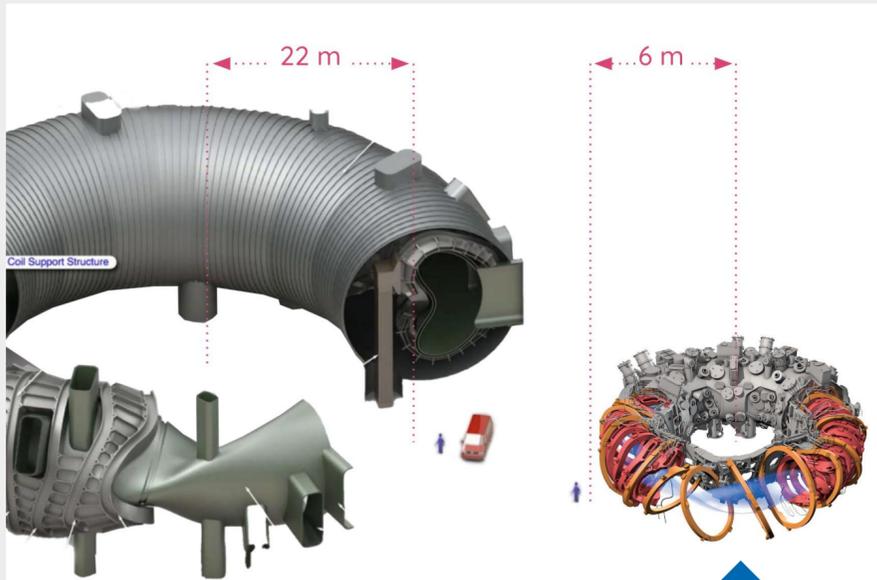
D-T fusion neutrons induce **radioactivity** and damage to solid parts.



Stellarator coils have **complex** 3D shapes.



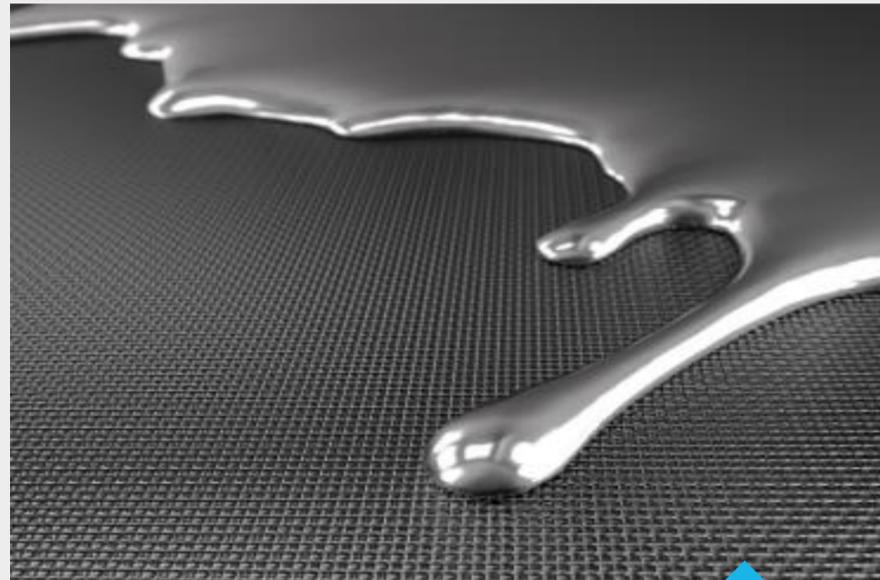
SOLUTIONS



## High Temperature Superconductors (HTS)



HTS generate stronger fields, unleashing the same power from smaller devices.



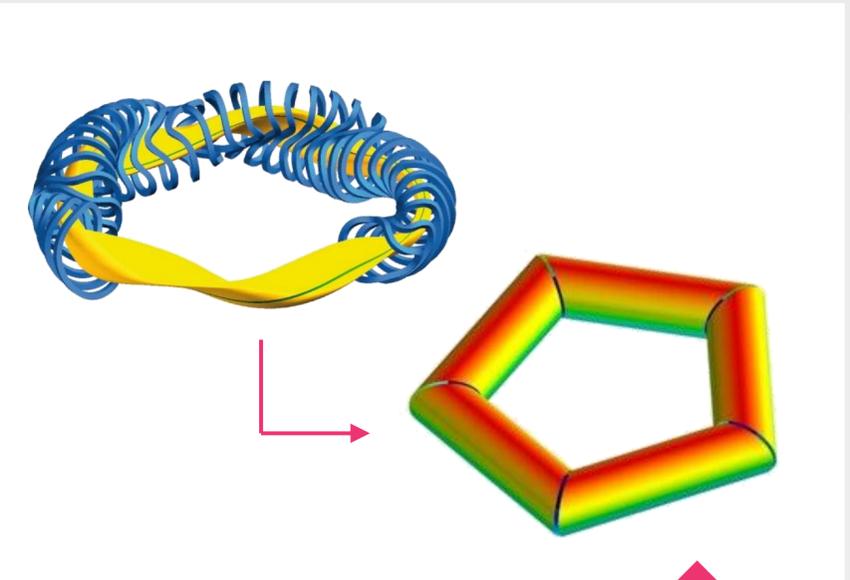
## Liquid Metals (LM)



Plasma-facing, thick Lithium-based walls absorb neutrons without getting activated, making reactors safer.

Bonus 1: resilient to non-uniform  $\alpha$  particle losses.

Bonus 2: low aspect ratio



## Simplified Stellarators



of simpler “coil winding surfaces” are easier to build, by wide HTS deposition & laser engraving.

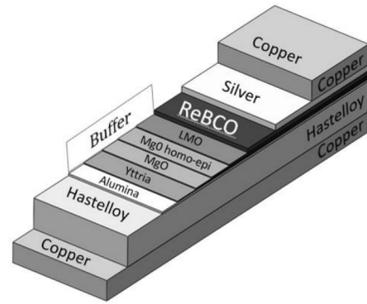


Old vs New

# HTS “canvases” do not exist → For Renaissance, becoming a producer of (wide) HTS was a necessity

TRADITIONAL PROCESS

Like sculptures



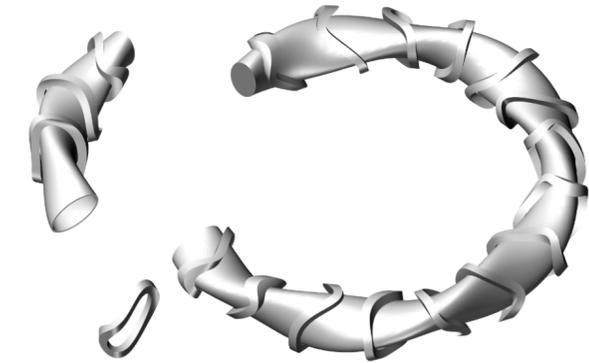
Narrow tape  
(cm wide, 10,000 Km long!)



Cable



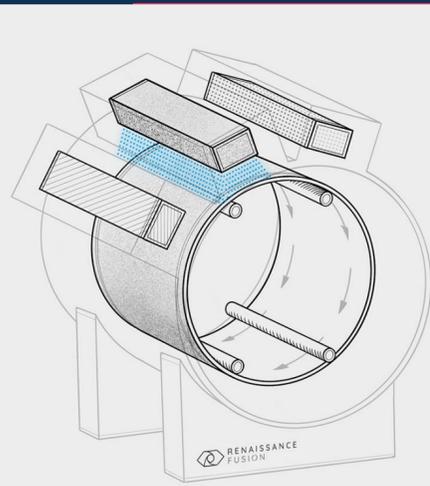
Coil  
(mm precision, difficult)



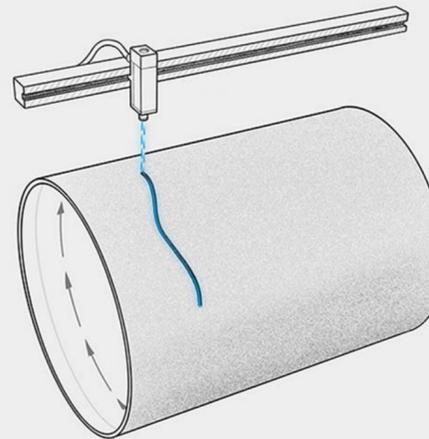
Positioning  
(mm precision, difficult)

Like laser-painting on an HTS canvas

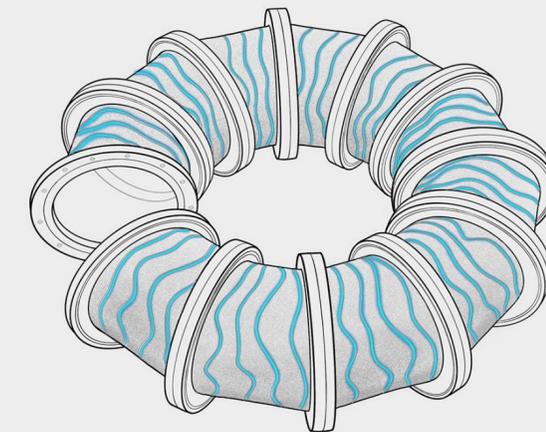
PROPRIETARY PROCESS



Wide HTS  
deposition  
(meters wide,  
meters long)



Engraving  
( $\mu\text{m}$   
precision,  
easy)



Assembly  
of modules  
shipped  
to site

# Taking a risk now for a better stellarator later

## Stellarator-optimized HTS

### 1. Internalized HTS production

Competitors buy scarce, pricey HTS tapes. RF makes & sells them.

### 2. Laser-precise HTS coils

Faster, simpler, cheaper. Commercial lasers attain micrometric precision in seconds; traditional winding, epoxying and positioning attains millimetric precision and takes days.

### 3. A more efficient HTS tape orientation

Only with our constructive approach is HTS everywhere parallel to the magnetic field. This enables higher performance (current, field), or 7x less material for the same performance.

### 4. No HTS crystal strain. More plasma shaping

Since engraving is responsible for most of the plasma shaping, our HTS is only bent in one direction, and only by a modest amount. In a future improvement (direct deposition on rigid, curved substrates), it won't be bent at all.

No twisting and little or no bending gives us an advantage over competitors: we don't need to worry on damaging or breaking the HTS, therefore we suffer not from their limitations in coil and plasma shaping.

## Versatility

### 5. At RF, different stellarator configurations just need different laser programming

There are 3 main configurations (quasi-isodynamic, quasi-axisymmetric, quasi-helical), but no consensus yet on the best [D. Gates *et al.*, *J. Fusion Energy* 2018]. RF is versatile and resilient to the tech risk of premature specialization. And since it's not a spin-off, it has no obligation to promote the mother institute and its configuration, and can be more agile in adopting the eventual winner, bearing in mind that:

- (i) there could be more than one winner, or a combination thereof (a QI-QH hybrid?),
- (ii) symmetries and concepts like quasi-isodynamicity are neither patented nor patentable and
- (iii) the differences in performance are much smaller than between a low-field and high-field stellarator, so probably we should all focus on that, instead of overselling a specific configuration 😊

## Better stellarator reactors

### 6. Only liquid walls can cope with the extreme conditions of compact HTS stellarators, and only RF's shielding is thin and inexpensive

The "extreme conditions" are high neutron flux and non-uniform alpha particle losses.

Competitors adopt solid walls that get activated and damaged. This calls for frequent, expensive replacements, and poses a nuclear waste problem. Massive, expensive shielding could protect the HTS and other parts, but would be a paradox in a compact, cost-effective HTS stellarator.

### 7. Low Aspect Ratio

Jargon aside, our doughnut resembles more a cored apple than a bicycle tire. This is the only way to reconcile physics, engineering and economics [V. Prost, F.A. Volpe, *Nucl. Fusion* 2024]. Everybody focuses on 2x higher magnetic field  $B$ , but 2x lower aspect ratio  $A$  is equally impactful, and the two can be combined thanks to our plasma shapes and patented materials (see point 6 above). Here are the relevant scalings: energy confinement time  $\sim B^2/A^2$ , "triple product"  $\sim B^4/A^2$ , fusion power  $\sim B^4/A^2$ .

### 8. Less heating power

High field and low aspect ratio (point 7) enhance confinement to the point that we can ignite the plasma with ultra-low amounts of heating power (less than half the power used by competitors). This dramatically simplifies and discounts a part of the power-plant receiving little attention but easily accounting for 1/3 of its cost (and that, ironically, must only be turned on for a minute at the beginning of operations).

# One technology, many applications

Any large-volume, high-field, high-precision application

MRI



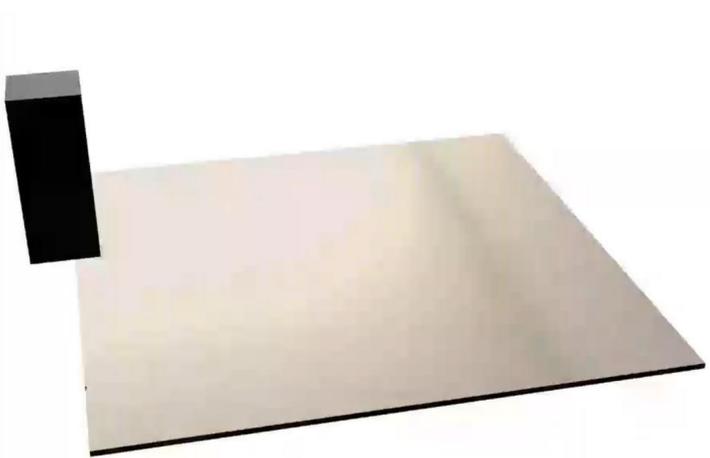
Energy Storage



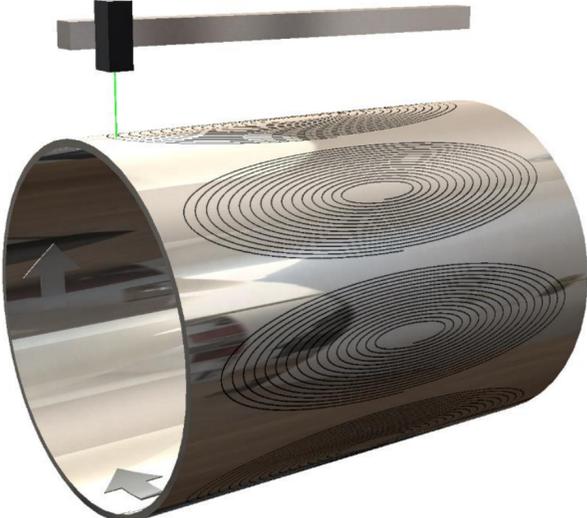
HTS tapes



Undulators

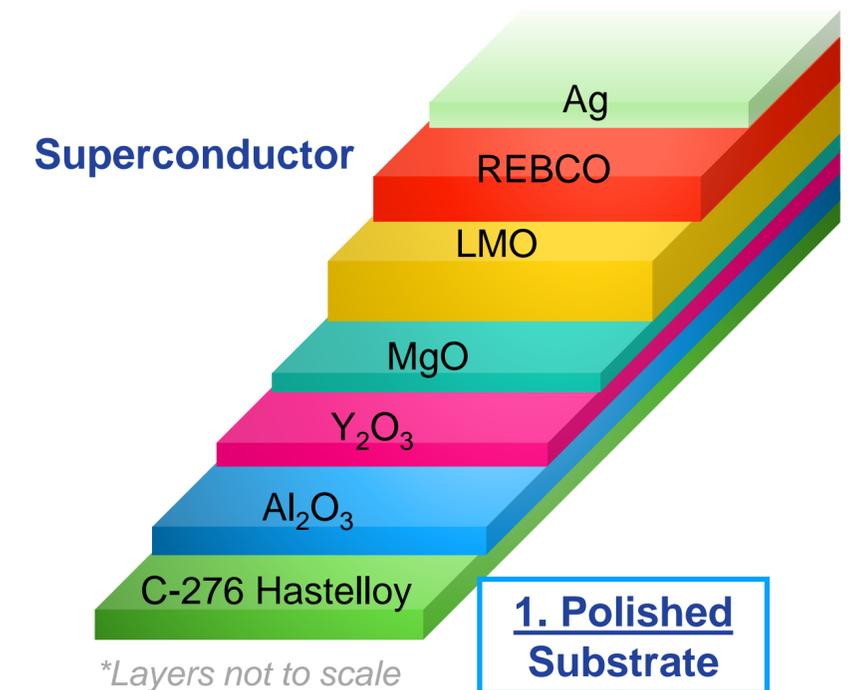


Electric Motors, Accelerator's Magnets



# Adapting the architecture and Advanced MOCVD of U. Houston to widths $w = 240 \rightarrow 670 \rightarrow 920$ mm

Layer	Deposition		Thickness ( $\pm 5\%$ )	Purpose	Machine
	Method	Conditions			
$\text{Al}_2\text{O}_3$	2. Magnetron	RT/ $10^{-2}$ torr	80 nm	Diffusion barrier to metal ions from Hastelloy substrate	PVD1
$\text{Y}_2\text{O}_3$	3. Magnetron	RT/ $10^{-2}$ torr	7 nm	Seed layer for MgO	
MgO	4. IBAD	RT/ $5 \times 10^{-4}$ torr	10 nm	Initiate MgO epitaxy	
	5. Magnetron	$\sim 750^\circ\text{C}$ $10^{-4}$ torr	20 nm	Template for the epitaxial deposition of REBCO	PVD2
LMO	6. Magnetron	$\sim 750^\circ\text{C}$ $10^{-4}$ torr	30 nm	Buffer layer (Lattice match)	MOCVD
REBCO	7. MOCVD	$\sim 900^\circ\text{C}$ 1-4 torr	2 $\mu\text{m}$	YBCO/BZO HTS layer	
Ag	8. Magnetron	$\sim 300^\circ\text{C}$ $10^{-1}$ torr	2 $\mu\text{m}$	Protection layer	PVD3
O <sub>2</sub>	9. Anneal	$\sim 300^\circ\text{C}$	N/A	Oxygenation of REBCO layer	O <sub>2</sub>



**PVD** = Physical Vapor Deposition  
**MOCVD** = Metal Organic Chemical Vapor Dep.

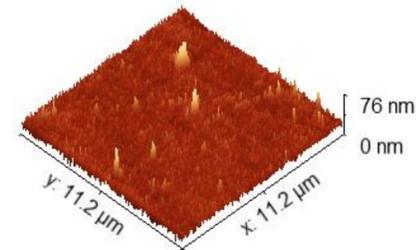
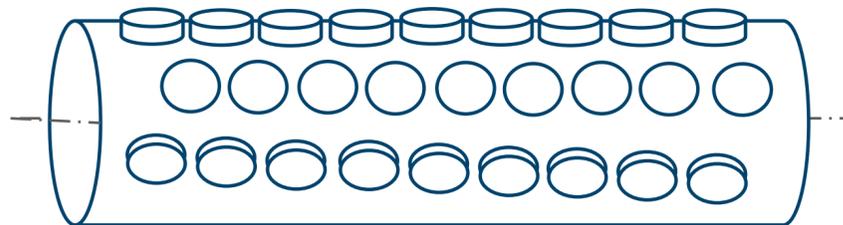
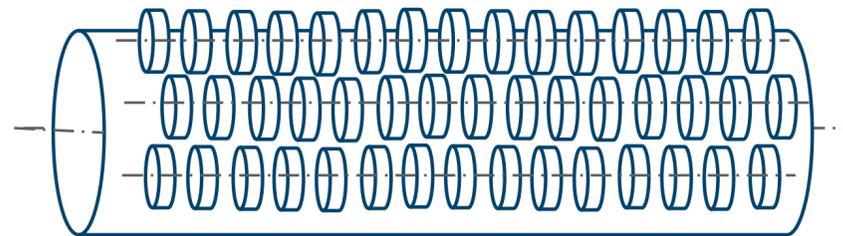
**Magnetron** = Atoms are sputtered (knocked off) a “target” and deposited on the tape

**IBAD** = Ion Beam Assisted Deposition similar to magnetron but uses ion beams to improve the film crystal orientation

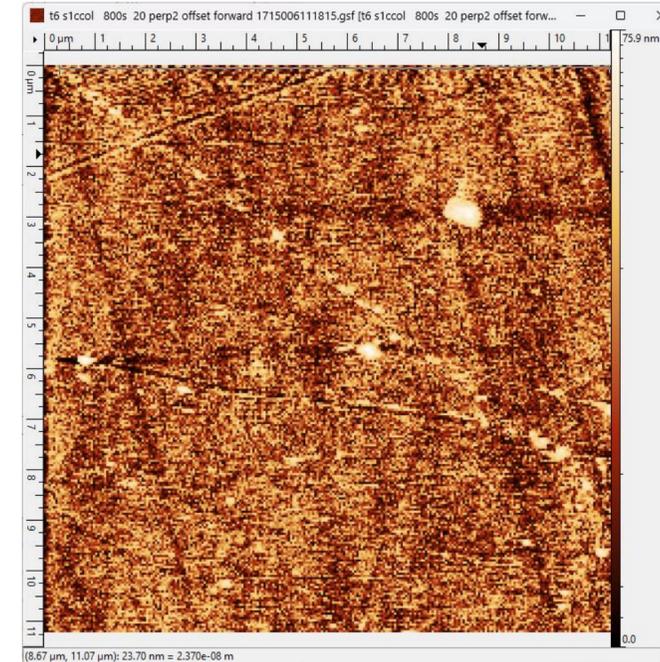
**RT** = Room Temperature (unheated)

# Wide Hastelloy was manually polished to <2nm roughness. Now being automated.

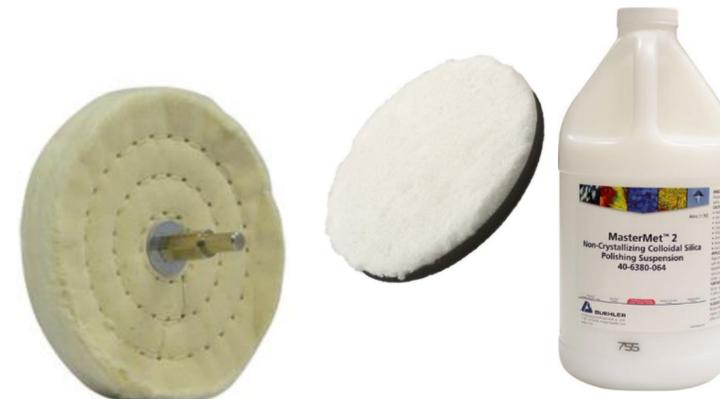
Perpendicular and parallel polishing pads  
Capable of meeting specification <2nm Ra



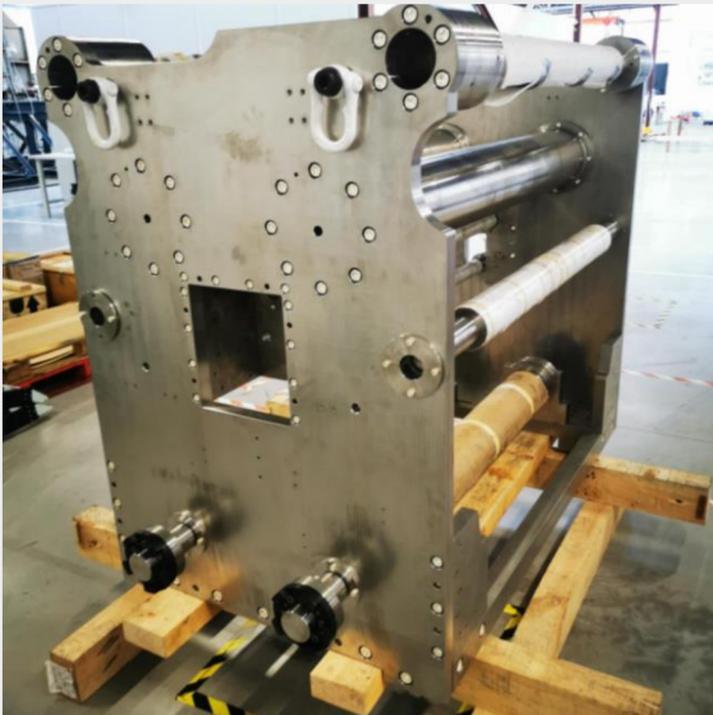
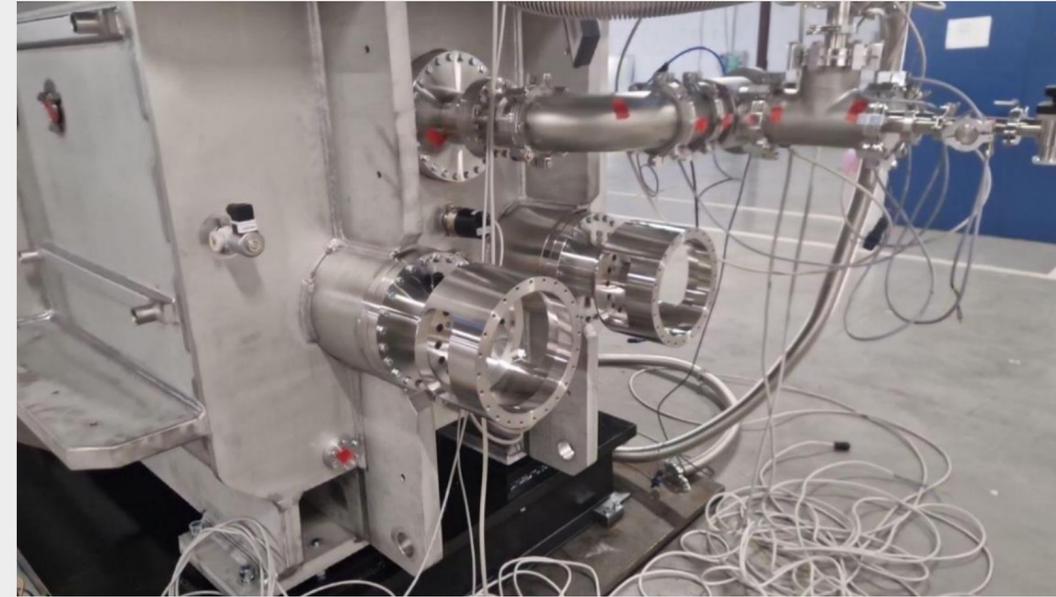
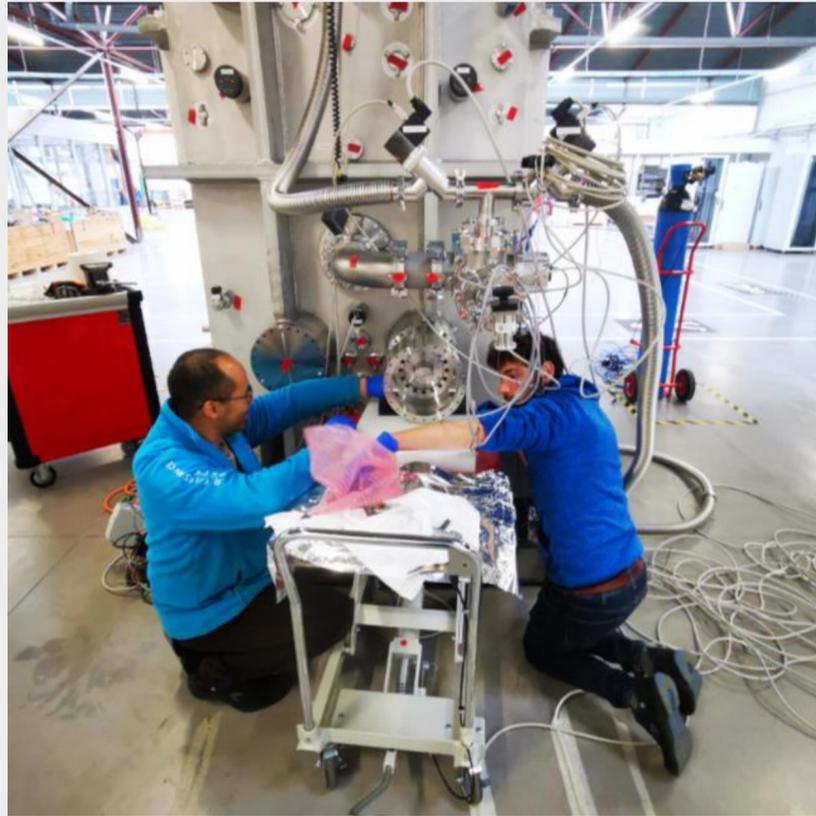
AFM Roughness  
Ra = 1.99 nm



Atomic Force Microscopy  
and Light Microscopy



PVD1 vacuum chamber received, vacuum tested. Now installing roll-to-roll.  
Next: Magnetrons, IBAD, diagnostics



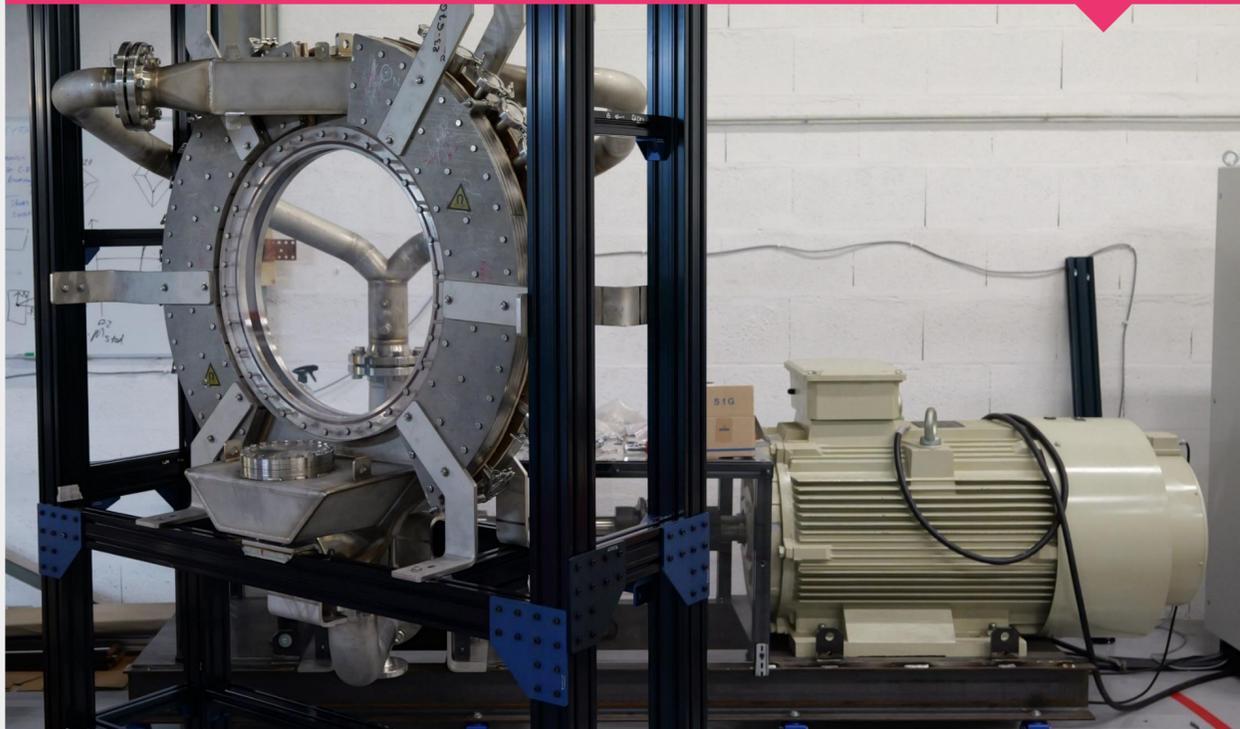
# MOCVD chamber & reactor received and vacuum-tested. Now installing uniform heating system. Next: chemEng.



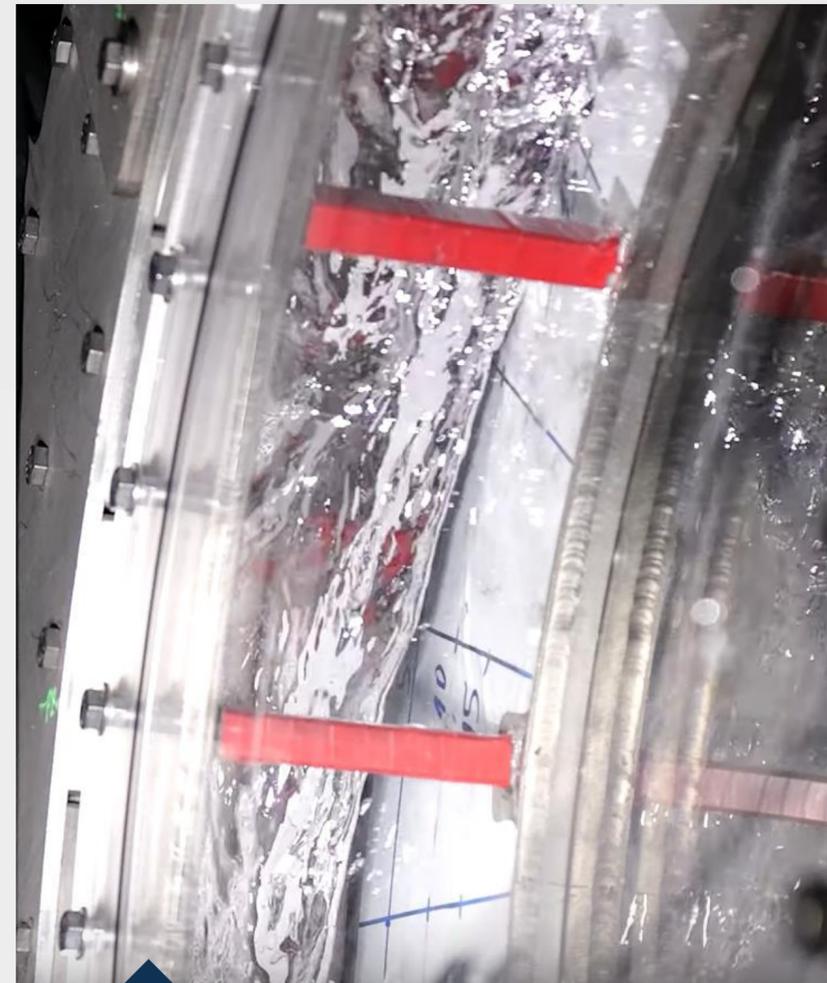
## Solving the neutron challenge

# Thick, flowing plasma-facing liquid metal walls stop neutrons, protect HTS, extract heat and breed T

Levitated, in 1 m diameter chamber, a 10 cm thick layer of liquid GaInSn. This was equivalent to levitating 120 cm of Li-LiH, with ample margins w.r.t. the 35 cm reactor target!



Thanks to e.m. forces, liquid metal walls fall along the solid walls, thus shielding them. They absorb 99.9% of the neutron energy, thus acting as the primary working fluid, entering at 700 C and exiting at 900 C.



We levitated liquid GaInSn, 10 cm thick, equivalent to 120 cm Li-LiH.

Next, Sn at 870 C by mid-2025.  
Then Li → Li, LiH → + Pb

## Advantages of our Liquid Walls:

MINIMAL

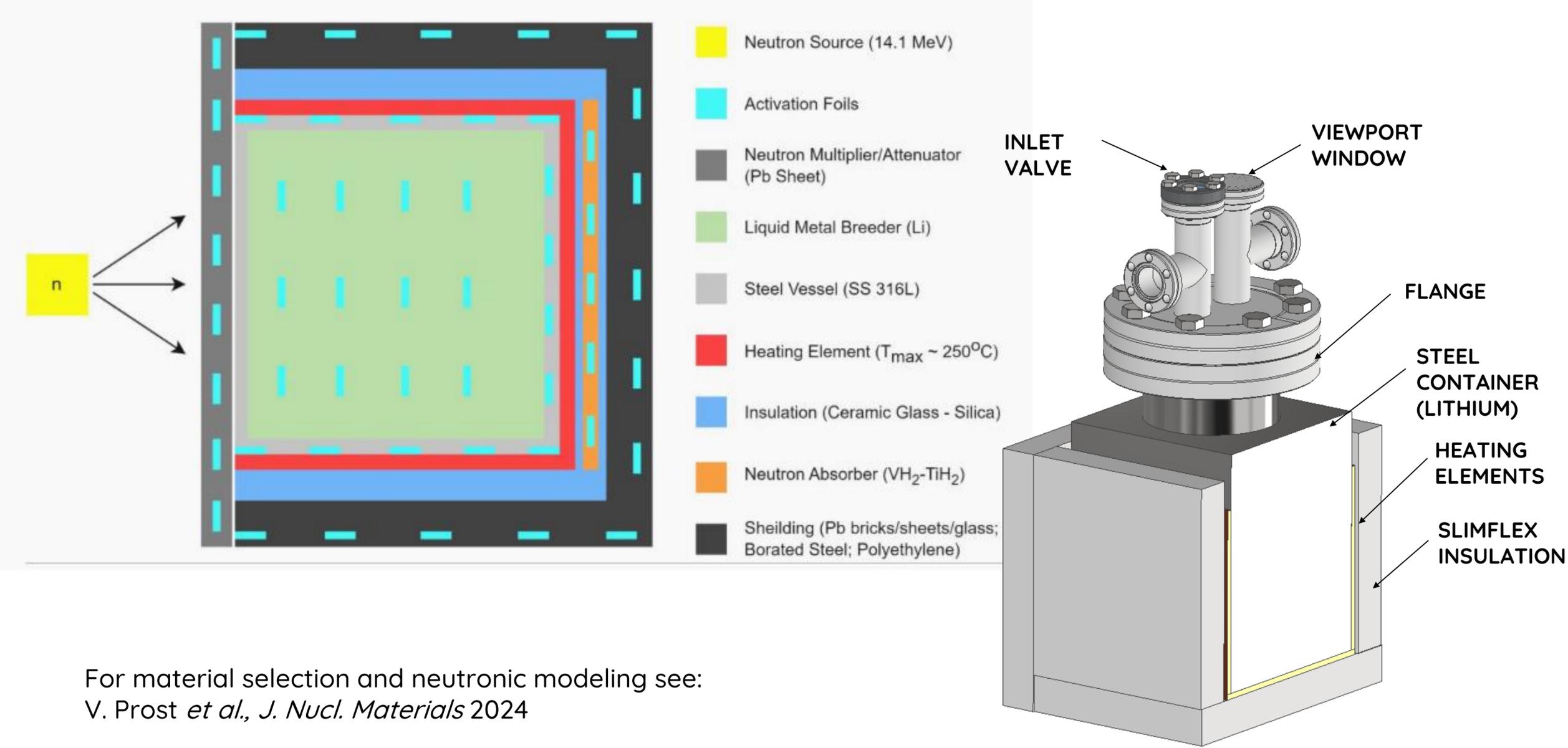
- radioactivity
- damage to delicate HTS
- maintenance, replacements
- cryogenics
- regulations
- reactor size
- cost of electricity

MAXIMAL

- Thermodynamic efficiency of the power plant (at high T)
- Crucially, public acceptance. activity

# Li-based shielding of HTS will be tested with 14 MeV neutron source in Grenoble

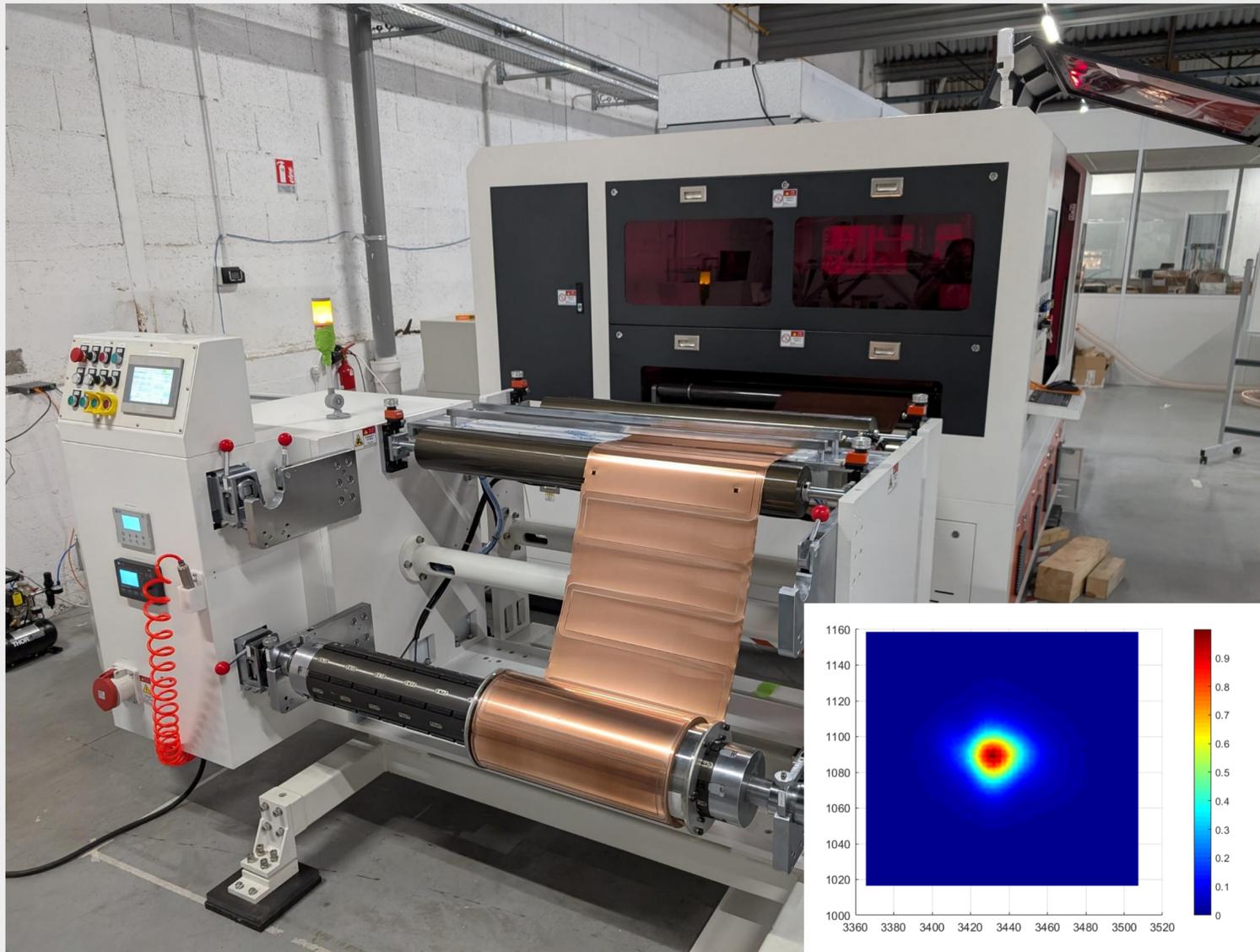
## LIGHT - Liquid metal Irradiation for Generation & Handling of Tritium



For material selection and neutronic modeling see:  
 V. Prost *et al.*, *J. Nucl. Materials* 2024

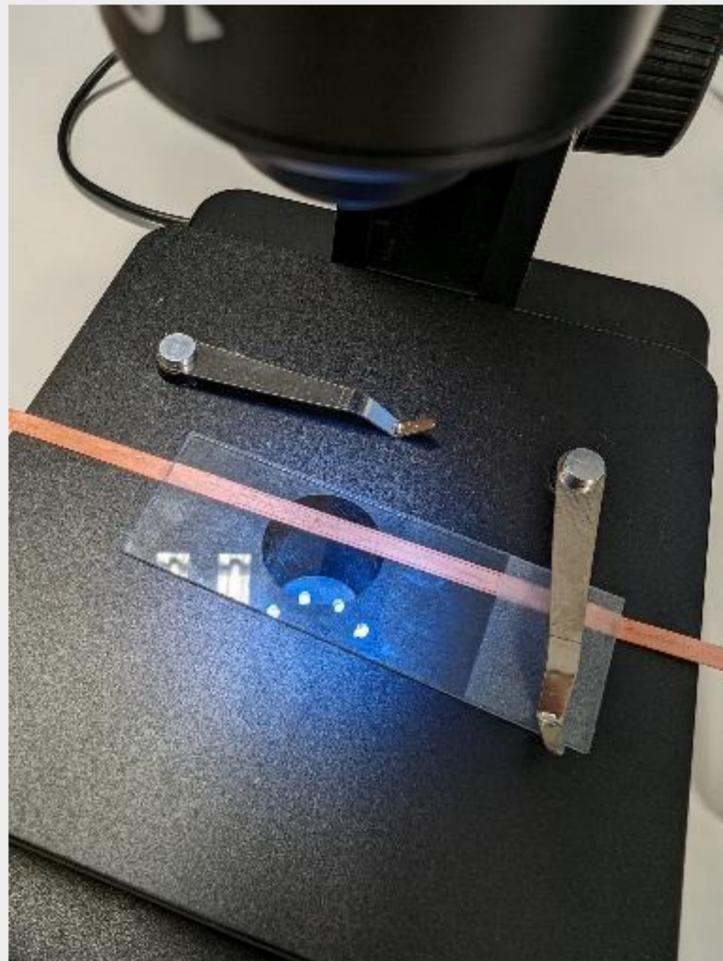
Laser engraving: check!

# Successfully laser-engraved meter-wide Cu and commercial HTS with ns and ps lasers, 40 $\mu\text{m}$ wide beams



Laser engraving: check!

Profilometry confirmed few  $\mu\text{m}$  in width and depth.  
 $I_c$  measurements in bottlenecks confirmed “clean” engraving.



Optical measurements of engraving sizes

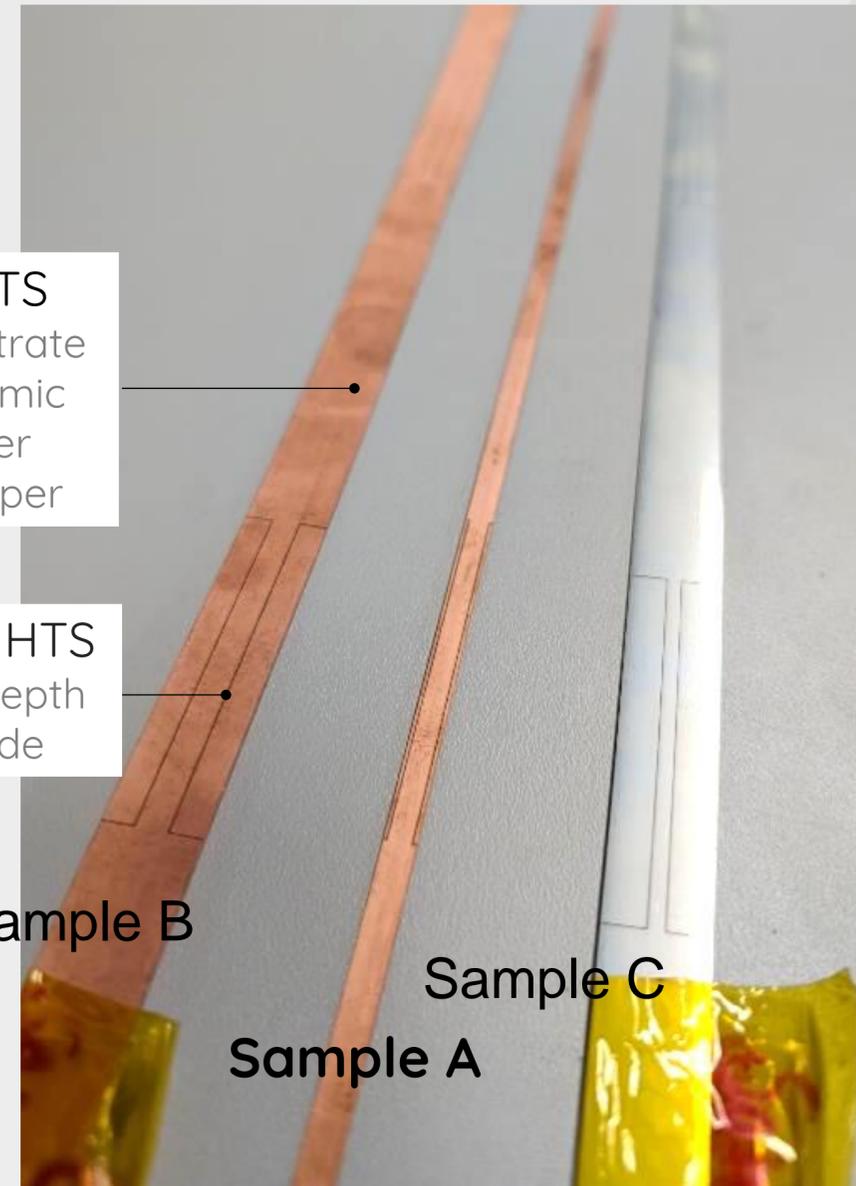
Clean HTS  
75  $\mu\text{m}$  substrate  
10  $\mu\text{m}$  ceramic  
5  $\mu\text{m}$  Silver  
20  $\mu\text{m}$  Copper

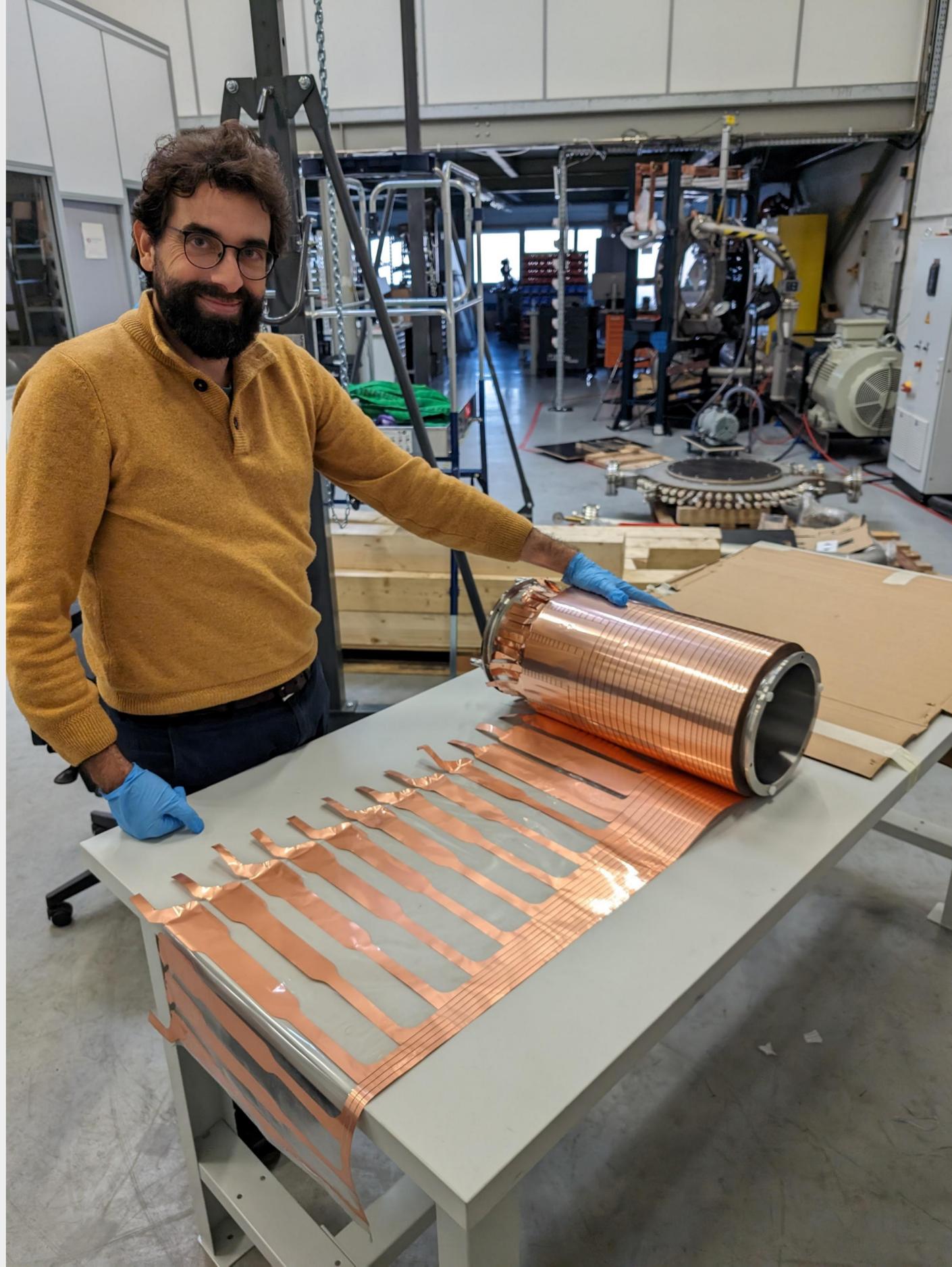
Engraved HTS  
35-40  $\mu\text{m}$  depth  
40  $\mu\text{m}$  wide

Sample B

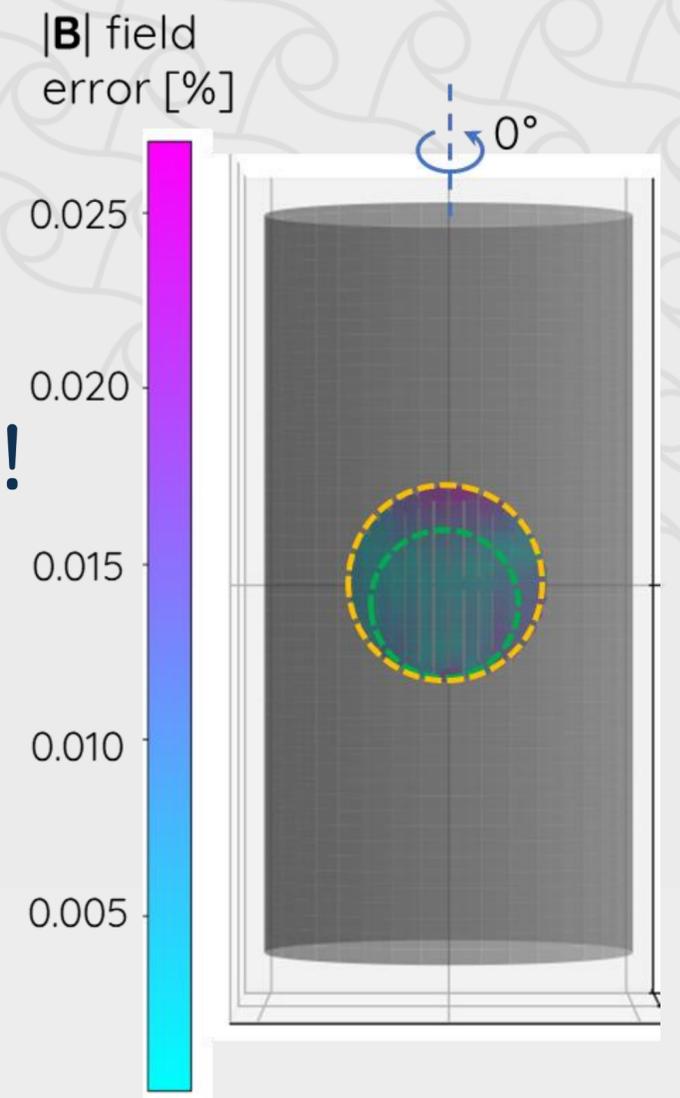
Sample C

Sample A



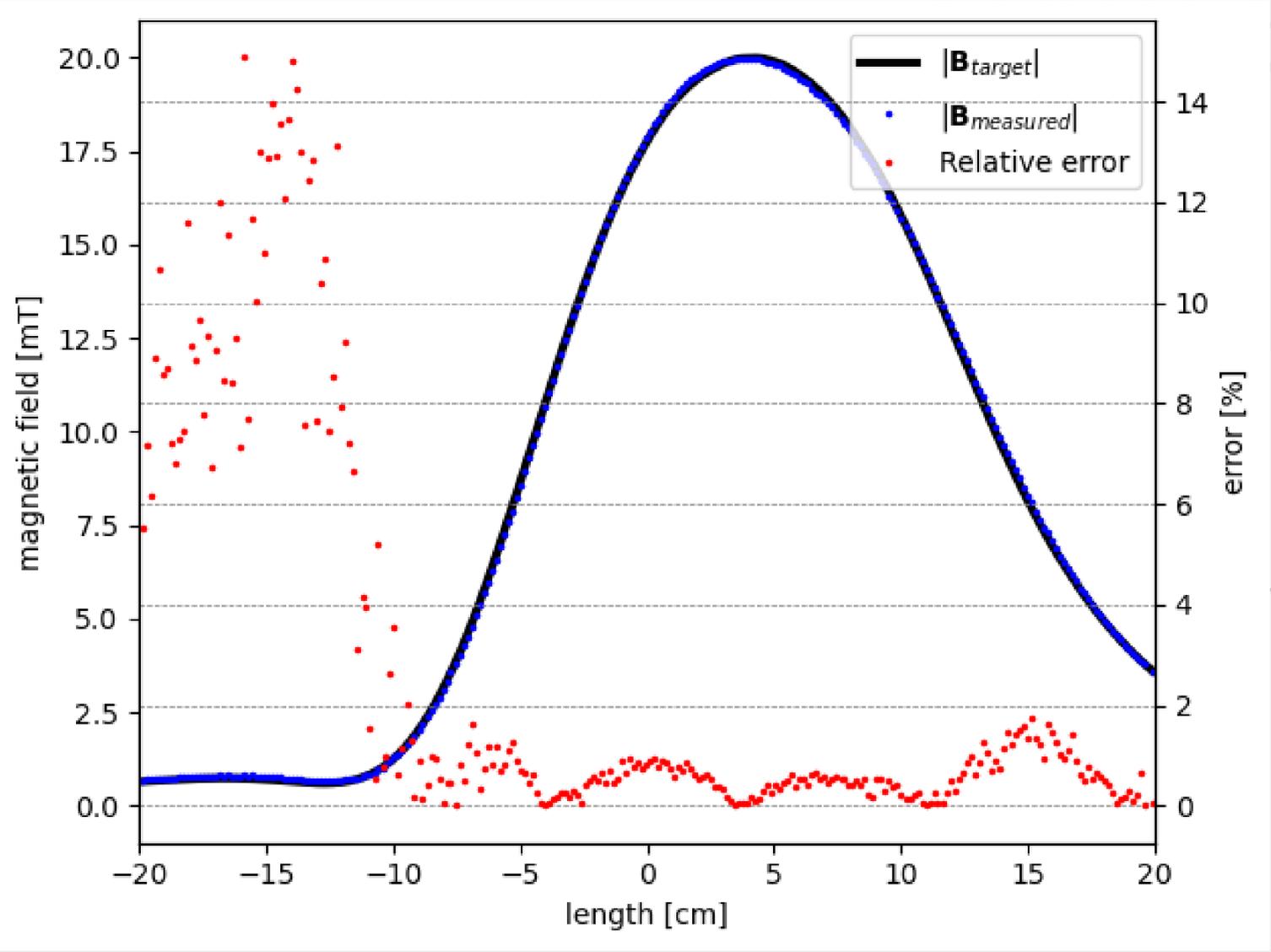
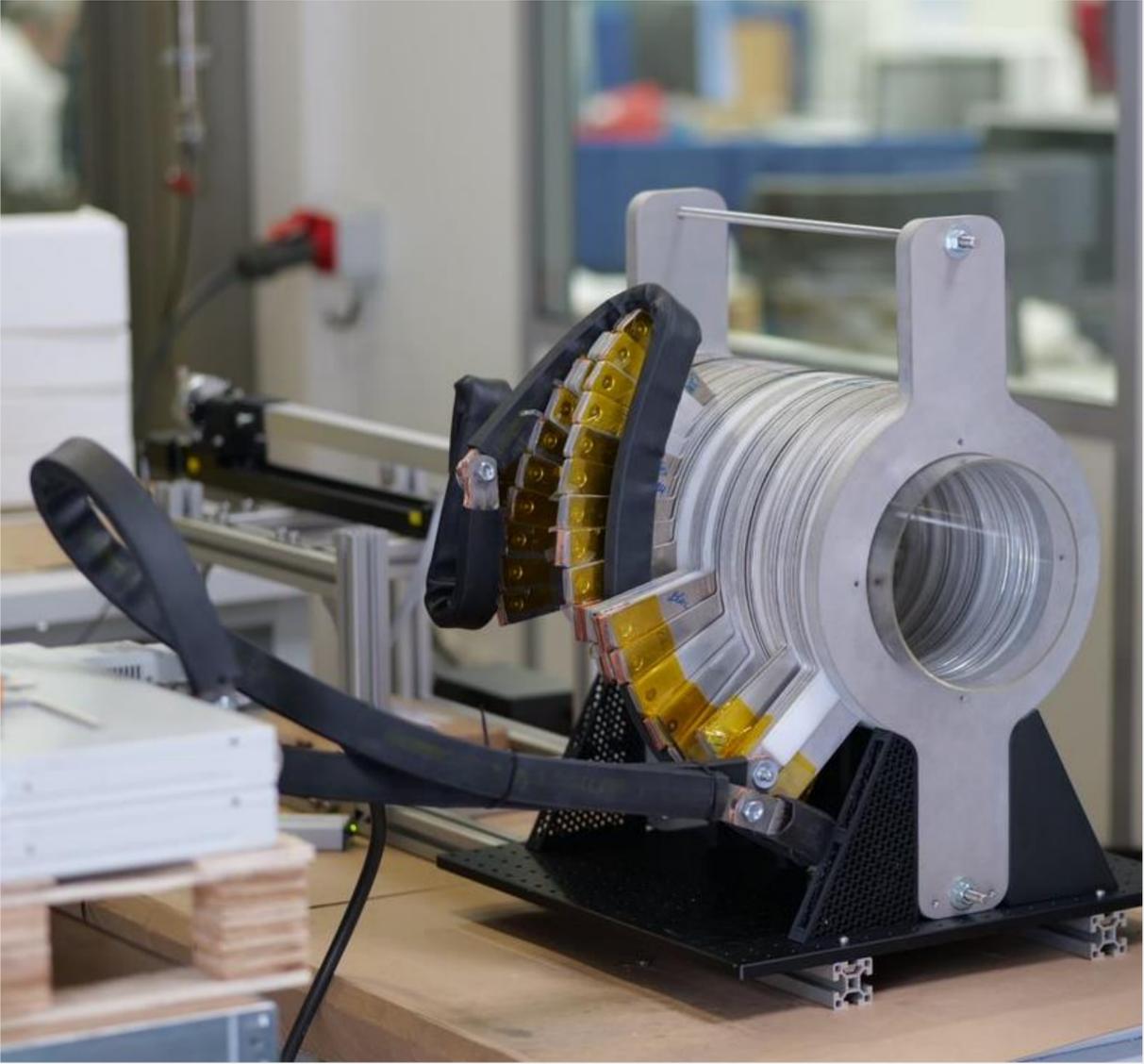


Wide corrugated Cu generates MRI fields with 40 ppm precision, even without shimming !



Field homogeneity @ 8 cm VOI			
	Model	As Built	Measured
$\epsilon_{max}$ [ppm]	40	80-220	<b>152</b>
$V_{RMS}$ [ppm]	12.3	29 - 54	<b>40.5</b>

# Machined Aluminium generates accurate B for microwave source (Gyrotron)



Thanks to a recent €32M investment and €10M grant, we have **many openings** in the HTS and Magnets Departments, including Heads, Group Leader and junior positions, and we welcome unsolicited applications. Apply at <https://renfusion.eu/jobs> !



**Thank you!**

[francesco.volpe@renfusion.eu](mailto:francesco.volpe@renfusion.eu)

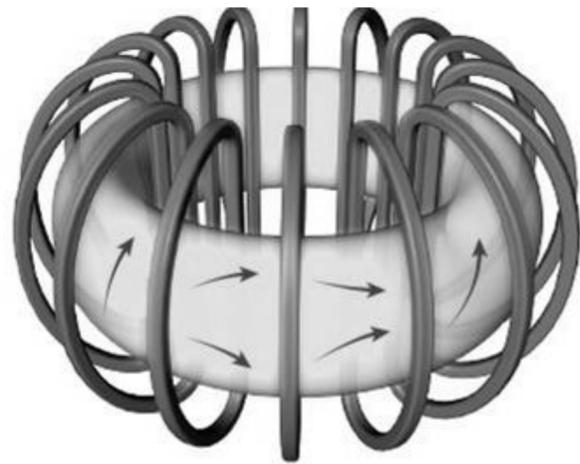
## The differences

# Simple to build, simple to operate

Both Tokamaks and Stellarators confine the plasma by doughnut-shaped, helically twisted magnetic fields. They differ by how they generate the twist.

## Tokamaks

generate the twist by a current in the plasma



### ✓ Simple to build

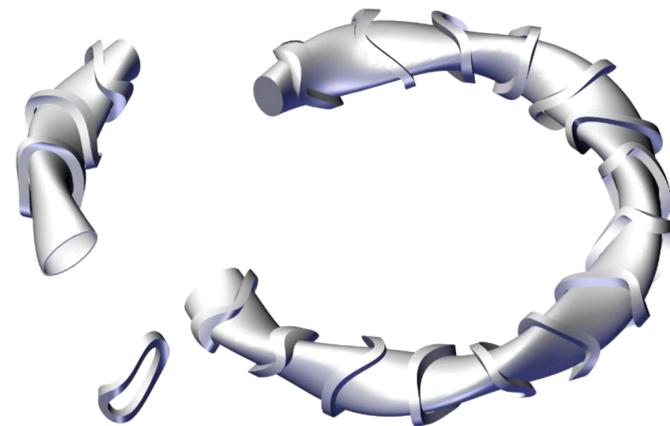
All coils are planar (2D)

### ✗ Difficult to operate

The plasma current is pulsed, unstable, subject to disruptions, and most coils are pulsed too. This introduces losses, operational and regulatory difficulties.

## Stellarators

generate the twist by twisted 3D coils



### ✗ Difficult to build

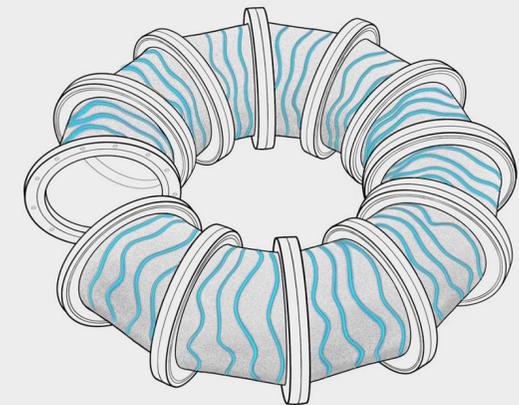
Intricate 3D coils are computed, built and positioned with mm precision.

### ✓ Simple to operate

Magnetize, evacuate, inject gas, ionize, heat. Leave it on.

## Renaissance Stellarators

generate the twist by 2D integrated coils



### ✓ Simple to build

Our coils are thin films directly deposited on cylindrical vessel-modules, then engraved. Over 560x faster than regular.

### ✓ Simple to operate

It's a stellarator