Performance Analysis of Spoke Resonators, Statistics from Cavity Fabrication to Cryomodule Testing

CNRS/IN2P3/IJCLab Université Paris-Saclay

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Spoke cavities and their challenges

- Technology choice in a medium-β section of proton drivers
- Rich R&D programs since the late 1980s
- Matured technology for deployment in accelerators

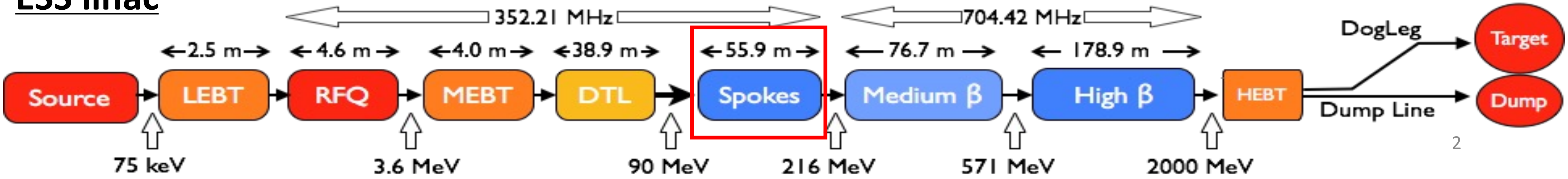
<u>Challenges and questions answered in this talk</u>

1. Tuning strategy during manufacturing and processing
2. Standard heat treatments
3. First series production and cryomodules

<u>Work in progress</u>

- Full Industrialization
- Optimum multipacting vs HPR

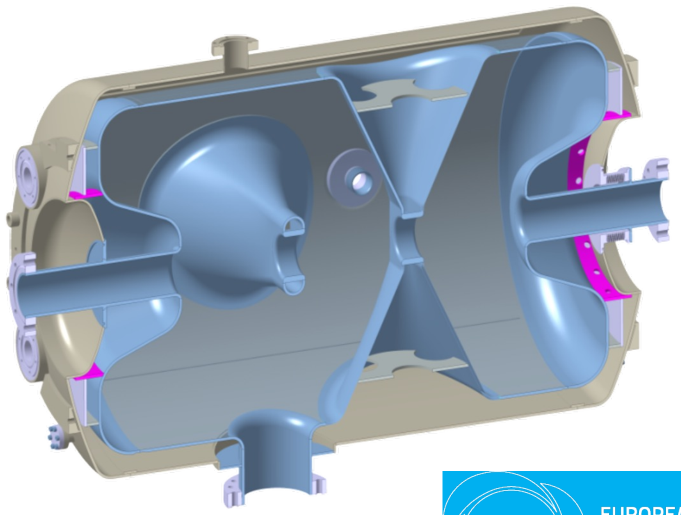
<u>ESS linac</u>



Spoke cavities @ IJCLab (summer 2023)

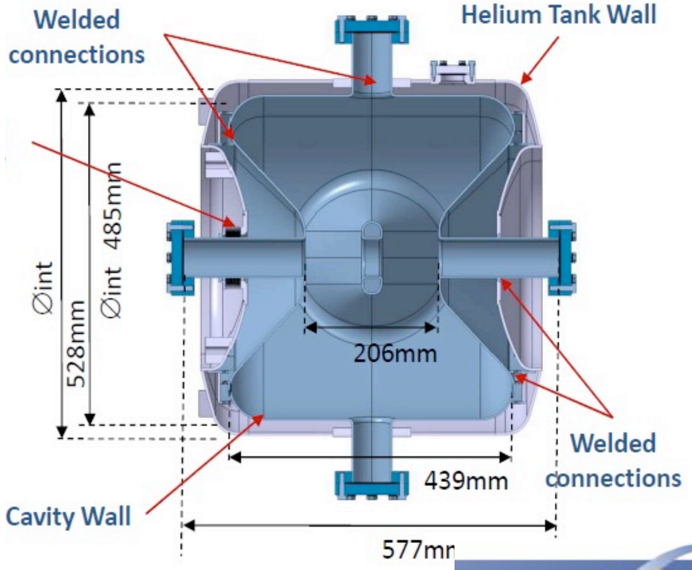
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

ESS DSR β=0.5, 3**52** MHz



- ✓ Prototyping (3)
- ✓ Series production (14x2+1)
- ✓ Series cryomodule (13x2)
- ➢ Deployment to the machine

MYRRHA β=0.37, 3**52** MHz

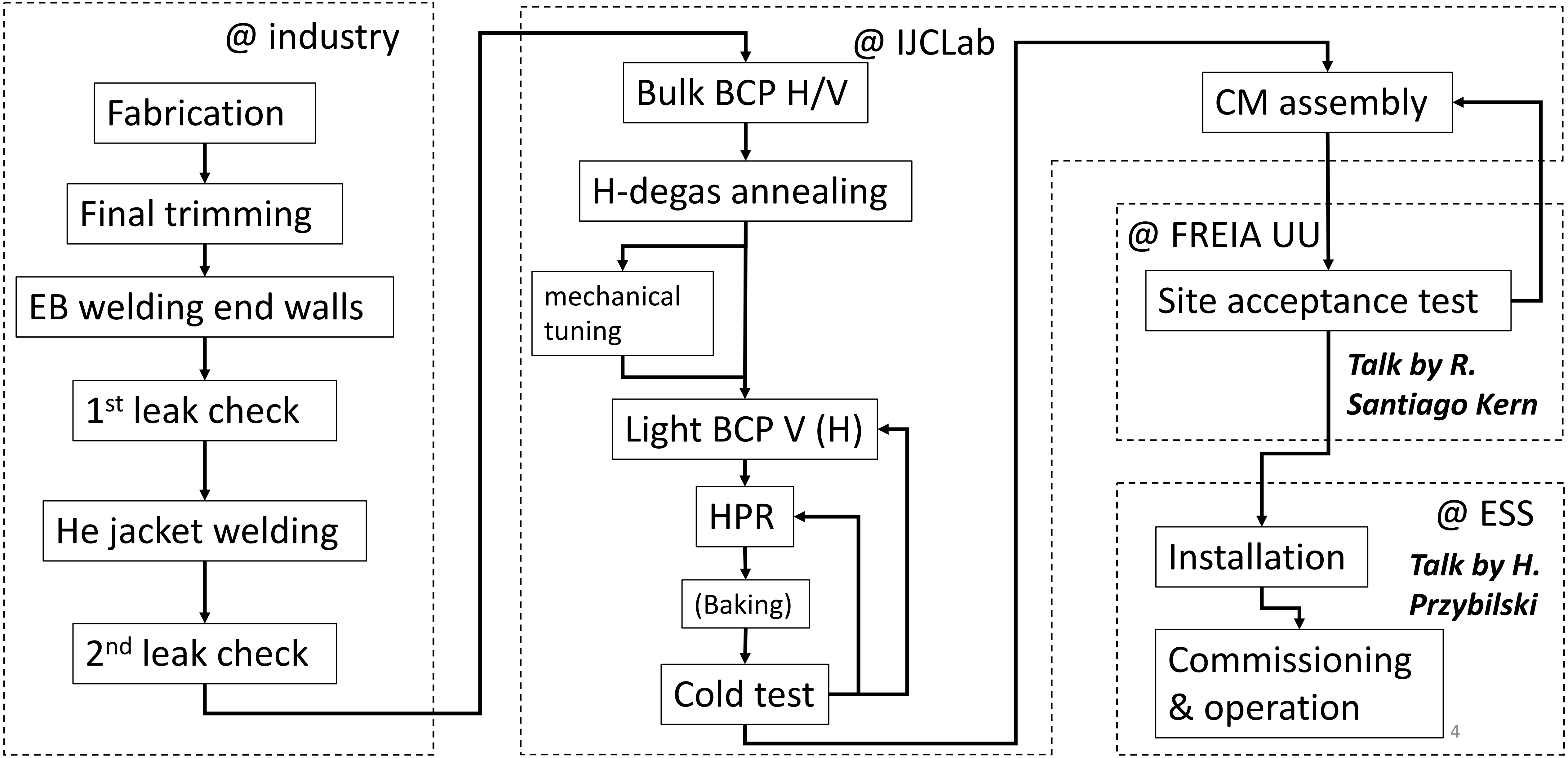


- ✓ Prototyping (4)
- ➢ Pre-series cavities (6)

PIPII SSR2 β=0.47, 3**25** MHz

- ➢ Prototyping (3)

Series ESS double spoke life cycle



Series ESS double spoke life cycle

@ IJCLab

? H/V

nealing

E

1st leak

He jacket

2nd leak

CM assembly

@ FREIA UU

Site acceptance test

Talk by R. Santiago Kern

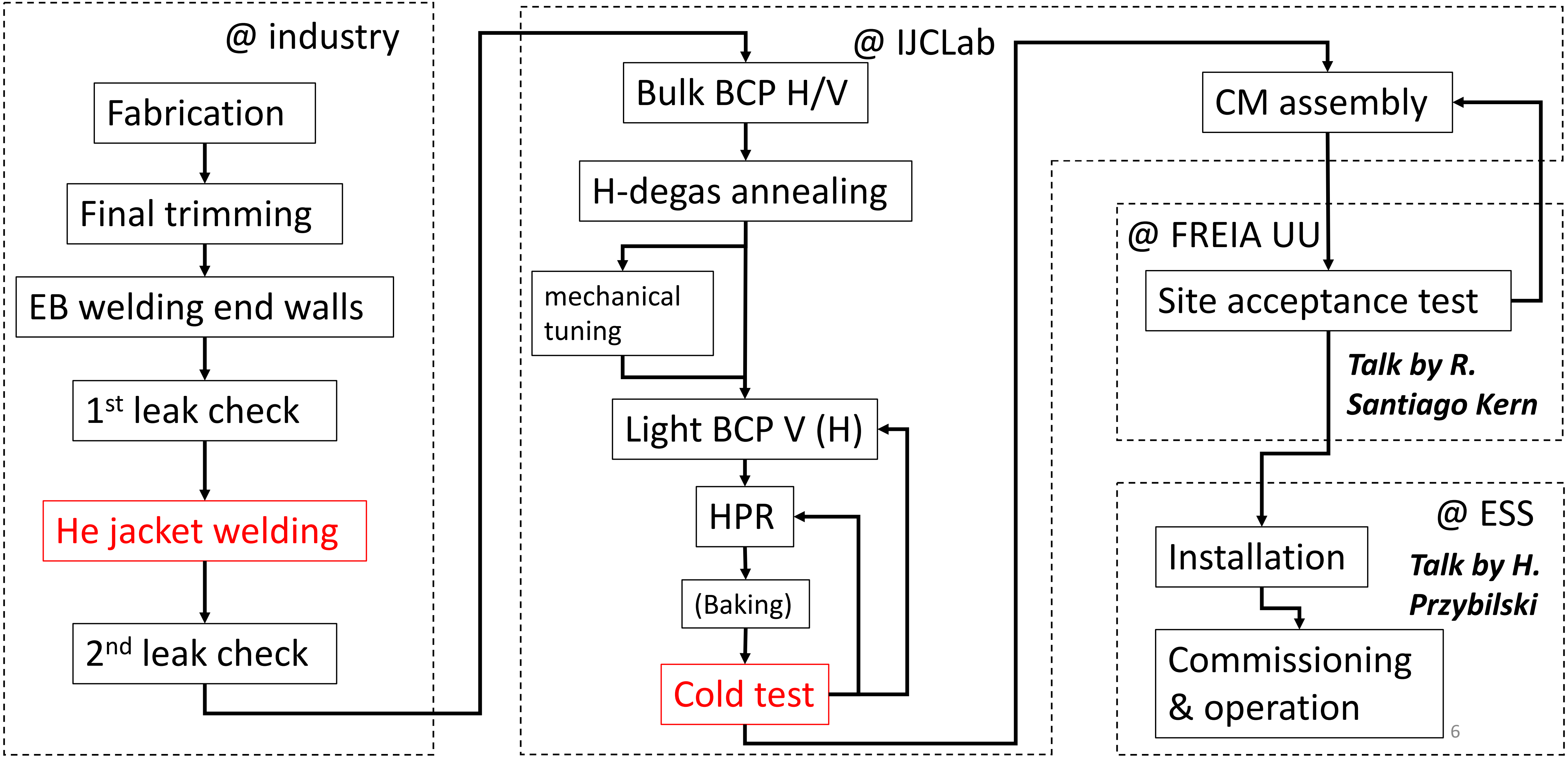
@ ESS

Installation

Talk by H. Przybilski

Commissioning & operation

Series ESS double spoke life cycle



Vacuum insert + Vertical cryostat @ IJCLab

Merits of vacuum inserts

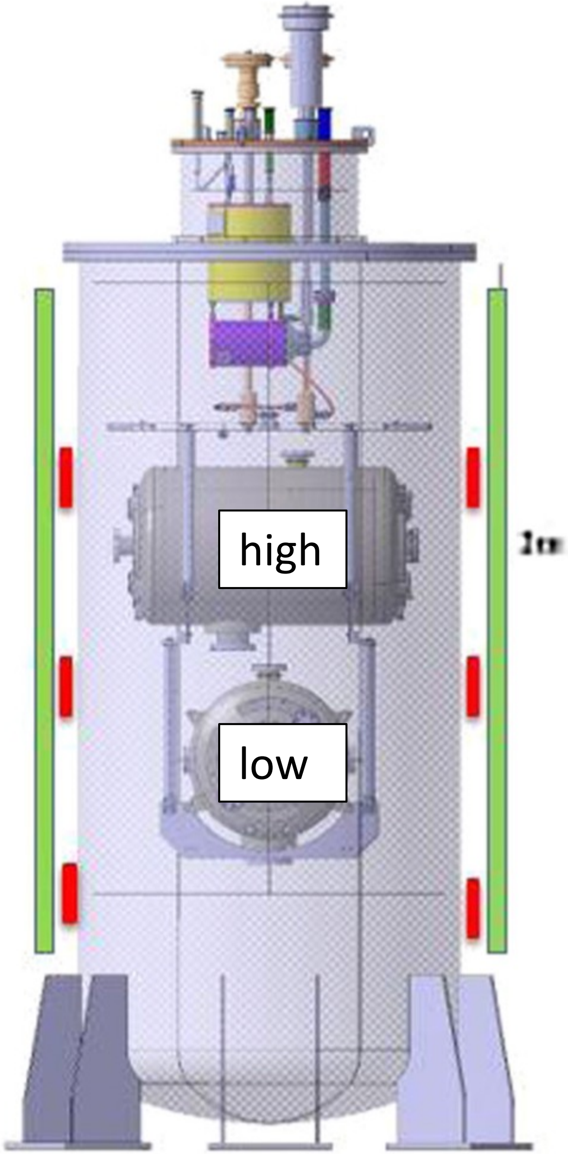
- IJCLab tests only jacketed cavities
- Less liquid helium is needed compared to conventional liquid inserts
- Faster cooling down and warming up

Challenge

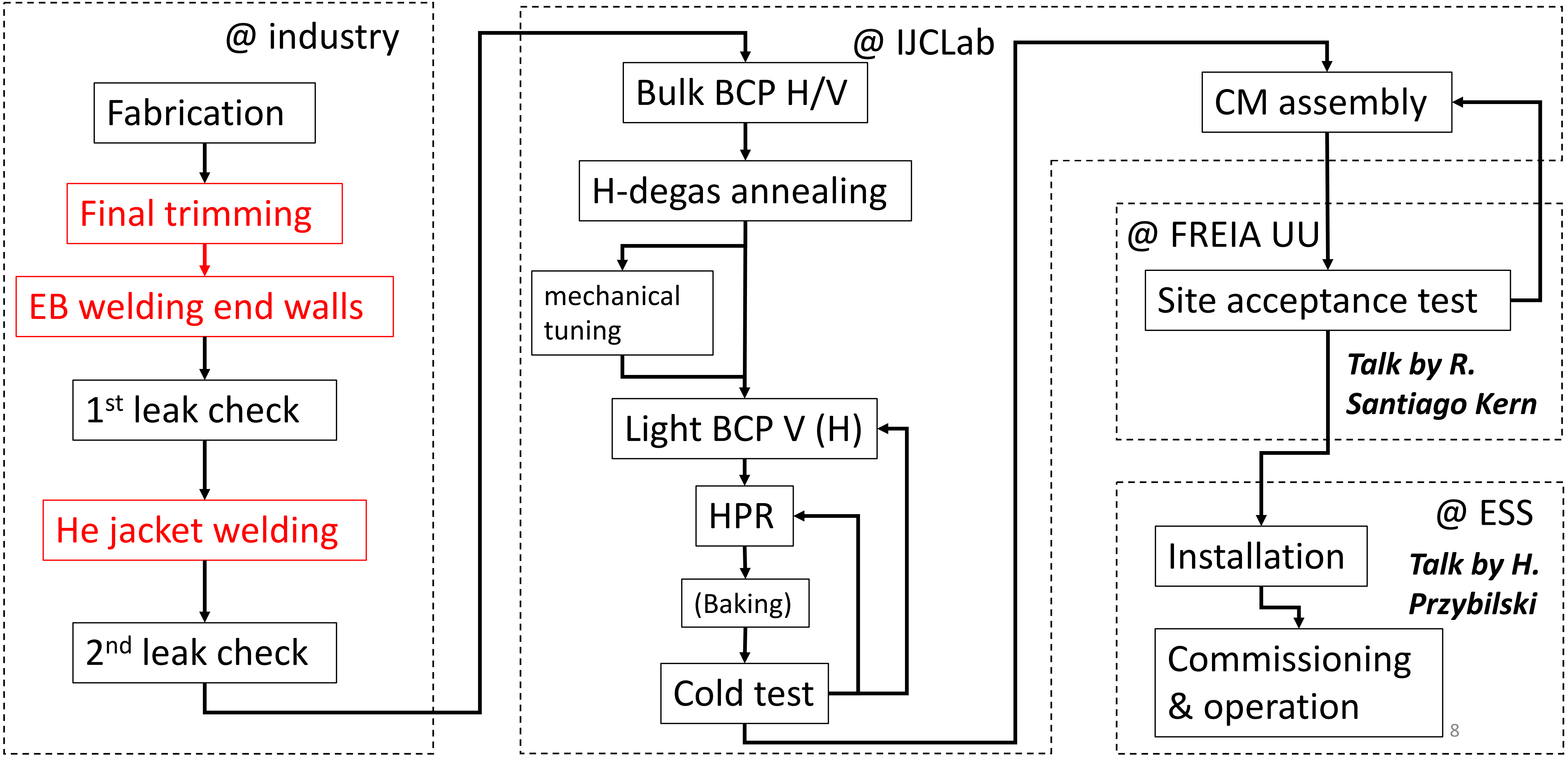
- We need to tune the frequency without testing a bare cavity at cold
- Quality control of manufacturing and processing are key

Other points

- The cavity at lower position gets colder way earlier (cryo-pumping?)
- μ-metal + coils for field compensation



Series ESS double spoke life cycle

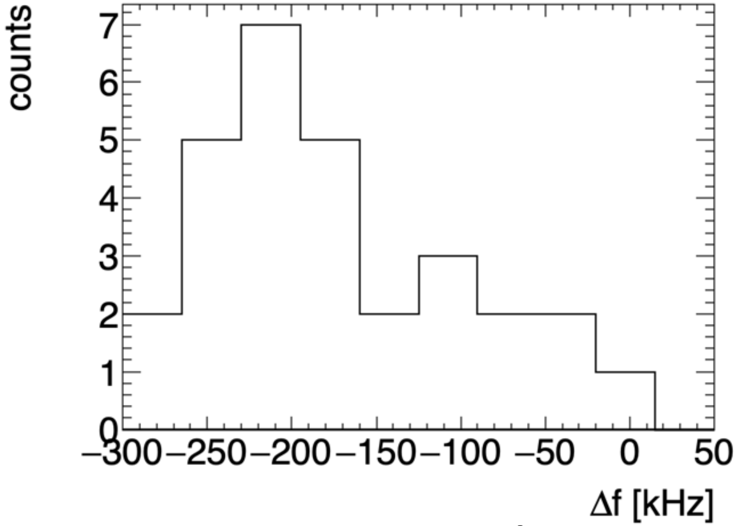


Tuning at the fabrication process (goal ±150 kHz)

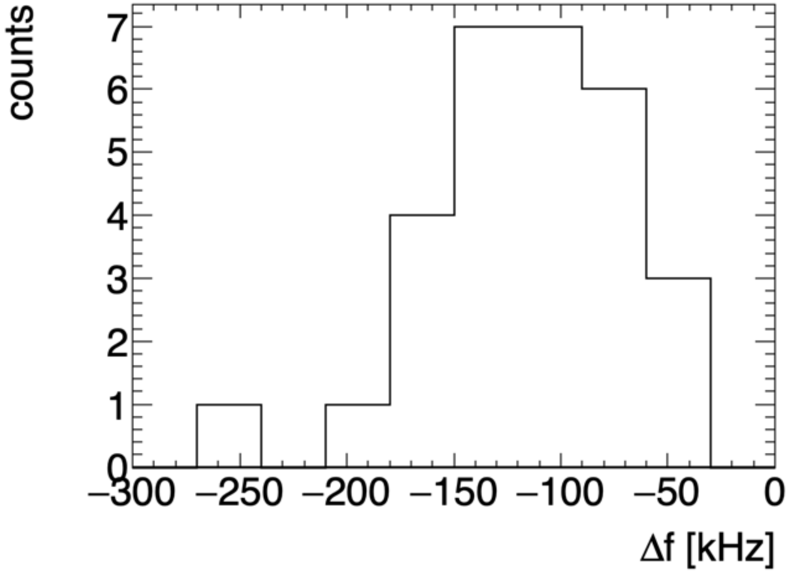
Final trimming of the cavity

- 5 mm trimming margin for both sides
- Trimming based on frequency measurement (parts clamped)

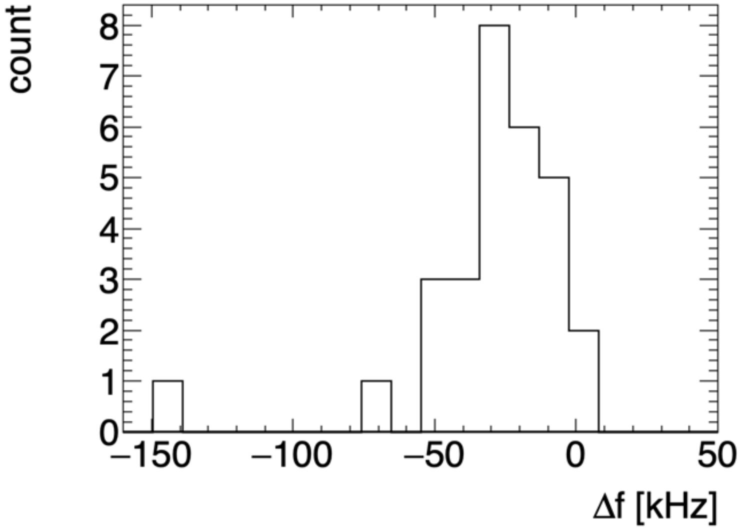
He Jacket TIG welding



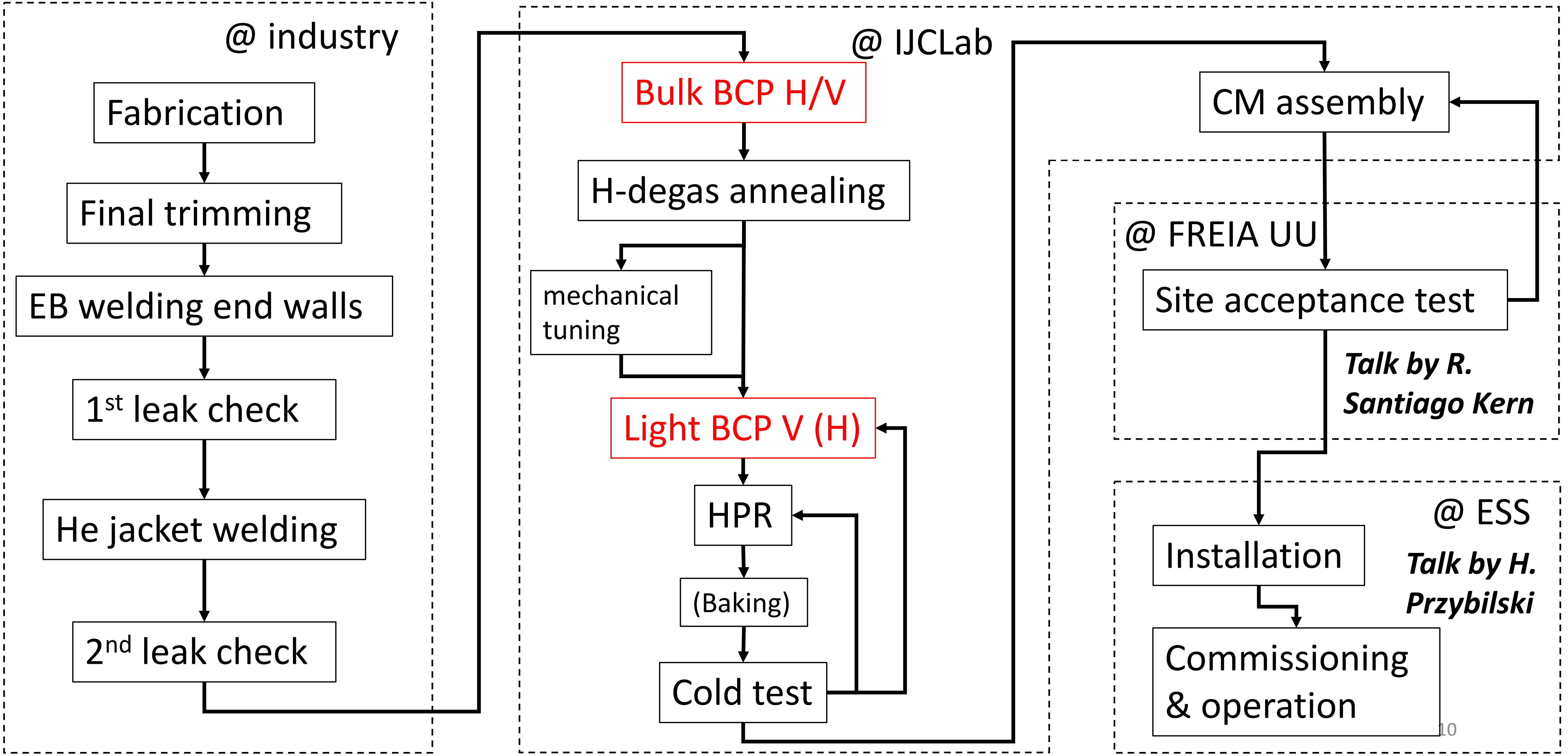
Final EB welding



Final machining (for tuner)



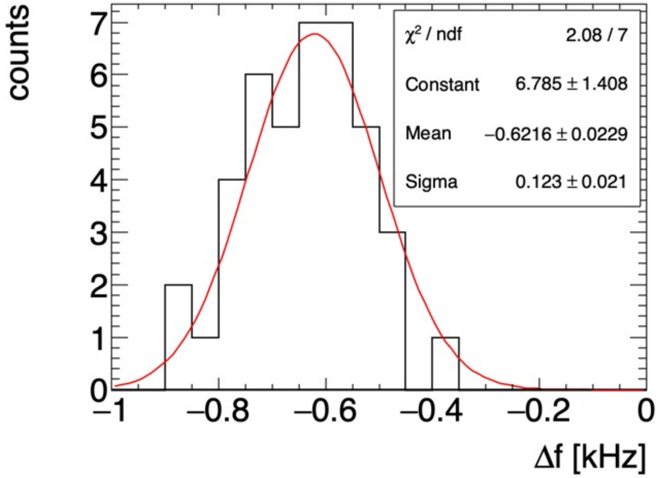
Series ESS double spoke life cycle

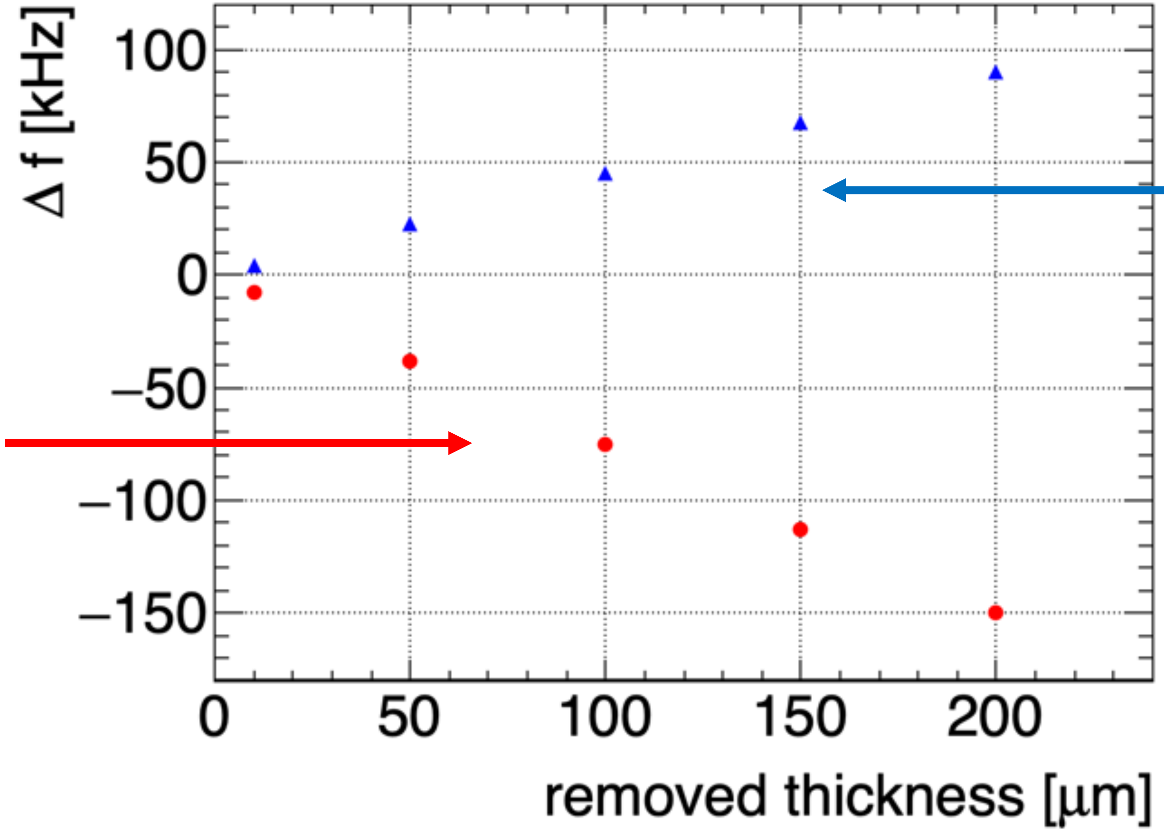


Vertical and horizontal BCP: main tuning tool

Horizontal

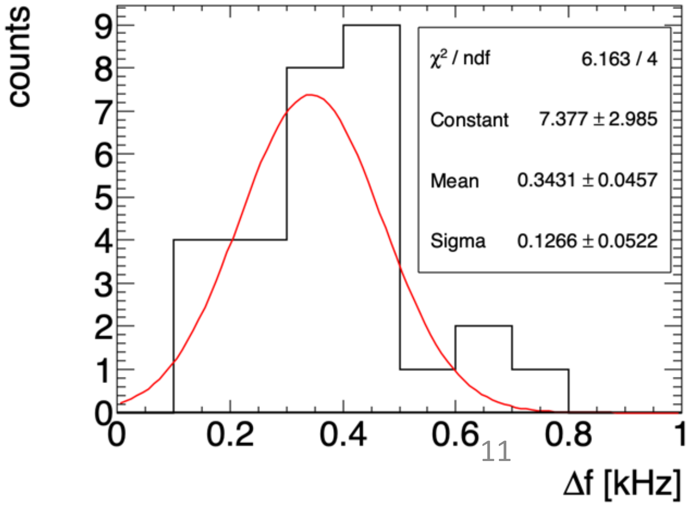
0.40 µm/min





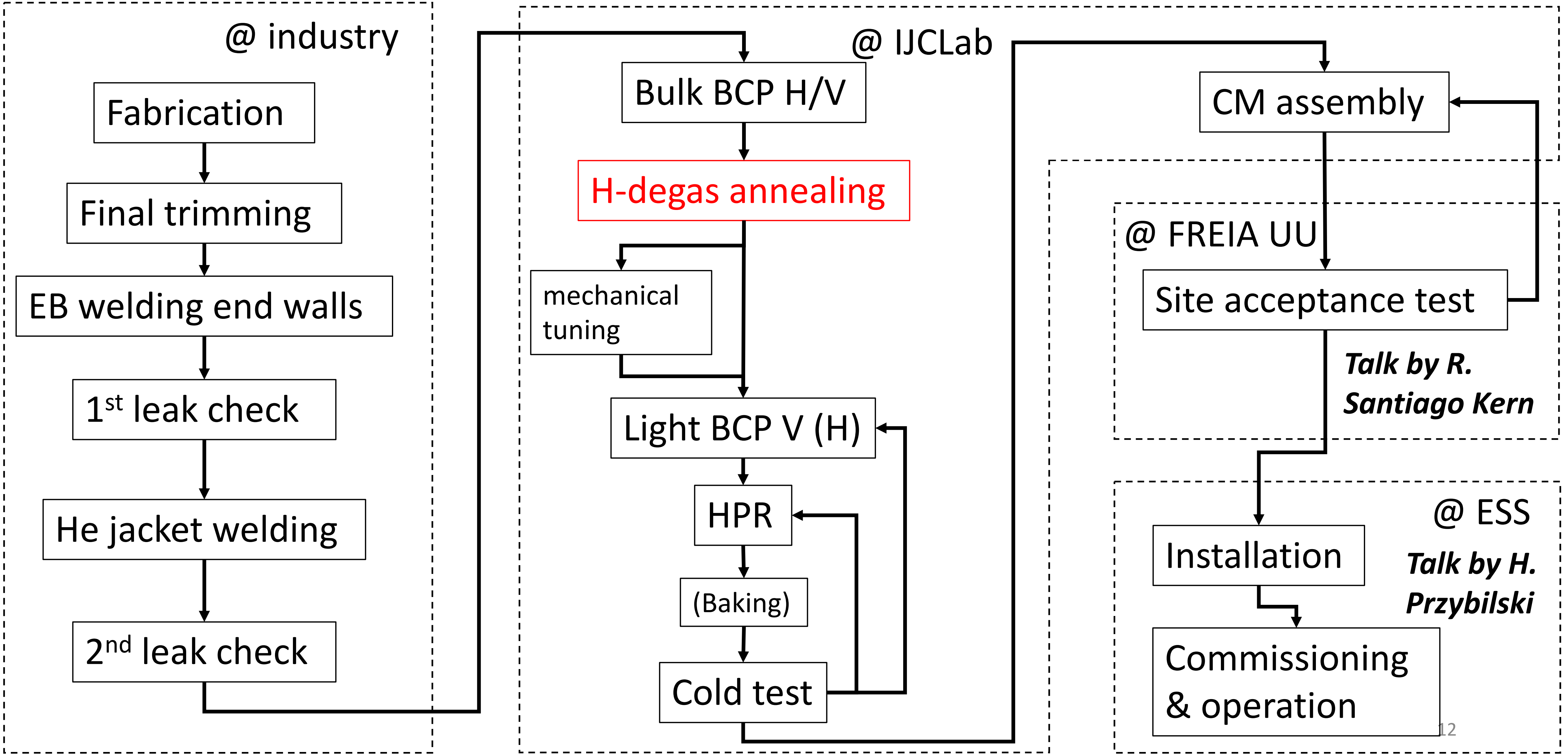
Vertical

0.39 µm/min

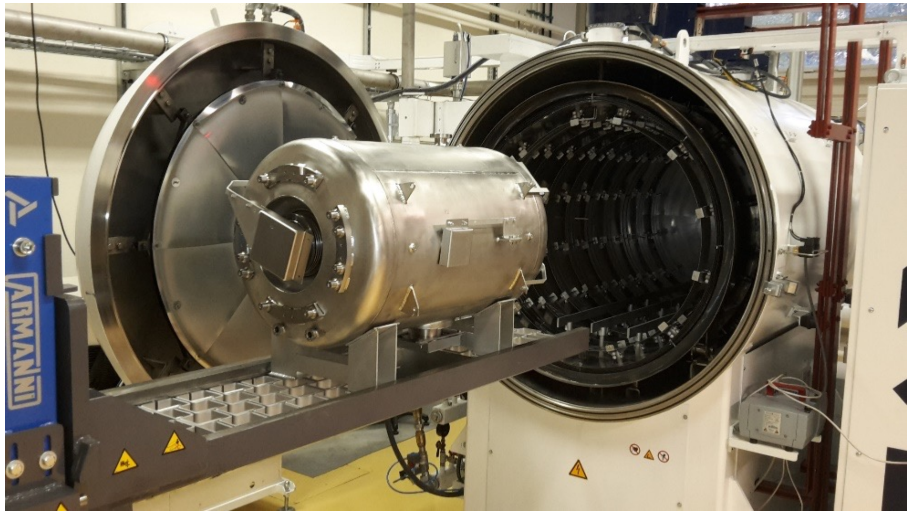


- Combination of vertical and horizontal BCP can precisely tune the cavity frequency
- Benefit of having HPR port for vertical BPC
  - Compromise to RF performance

Series ESS double spoke life cycle



H-degassing: temperature and tuning (goal ±40 kHz)



H-degassing: expected

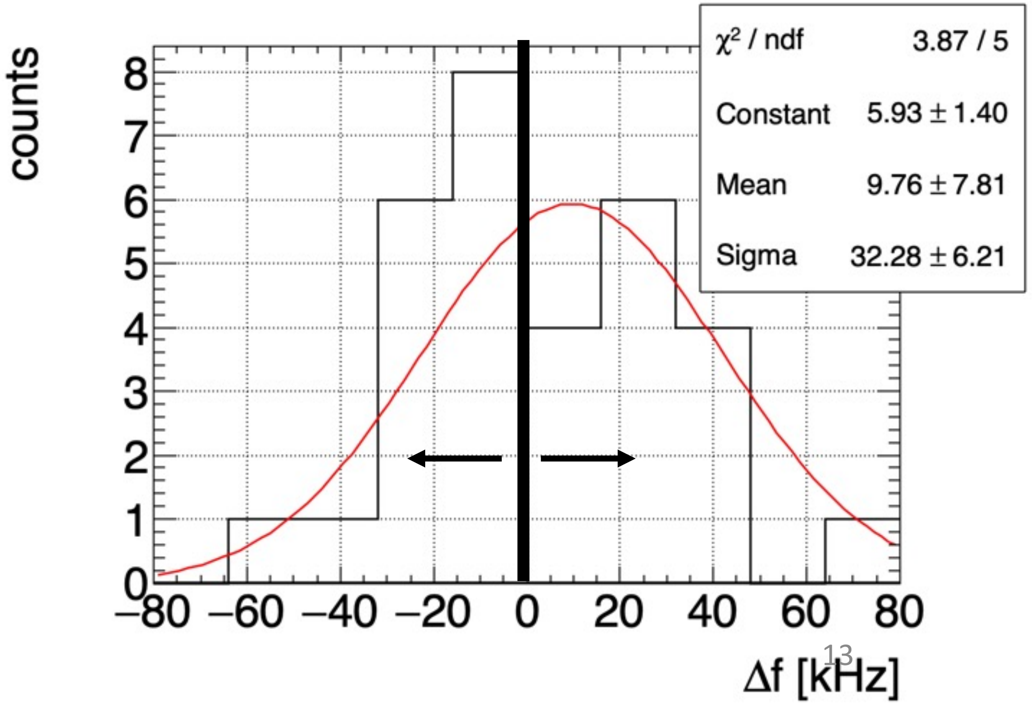
- Flux sensitivity is small (small gain by flux expulsion)
  - Low frequency and geometrical effect

→ **650C for 10 hours** is sufficient and safe

- Some flanges are copper brazed

H-degassing: ***unexpected***

- Frequency shifts to either positive or negative directions **randomly**
- H/V (light) BCP to compensate the unexpected change
- Mechanical tuning for a few cases



Open questions

- Is it due to the **Ti jacket** around annealed altogether?
  - Mechanical stress released by annealing
- Can the Ti act as a getter as well?

H-degassing: temperature and tuning (goal $\pm$40 kHz)

H-degassing: expect

- Flux sensitivity is
  - Low frequenc

→ **650C for 10 hour**

- Some flanges ar

H-degassing: ***unexp***

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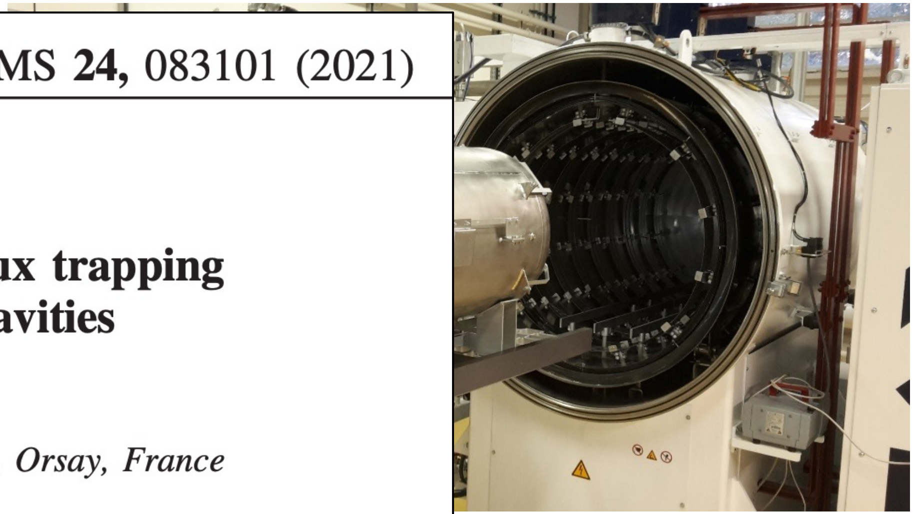

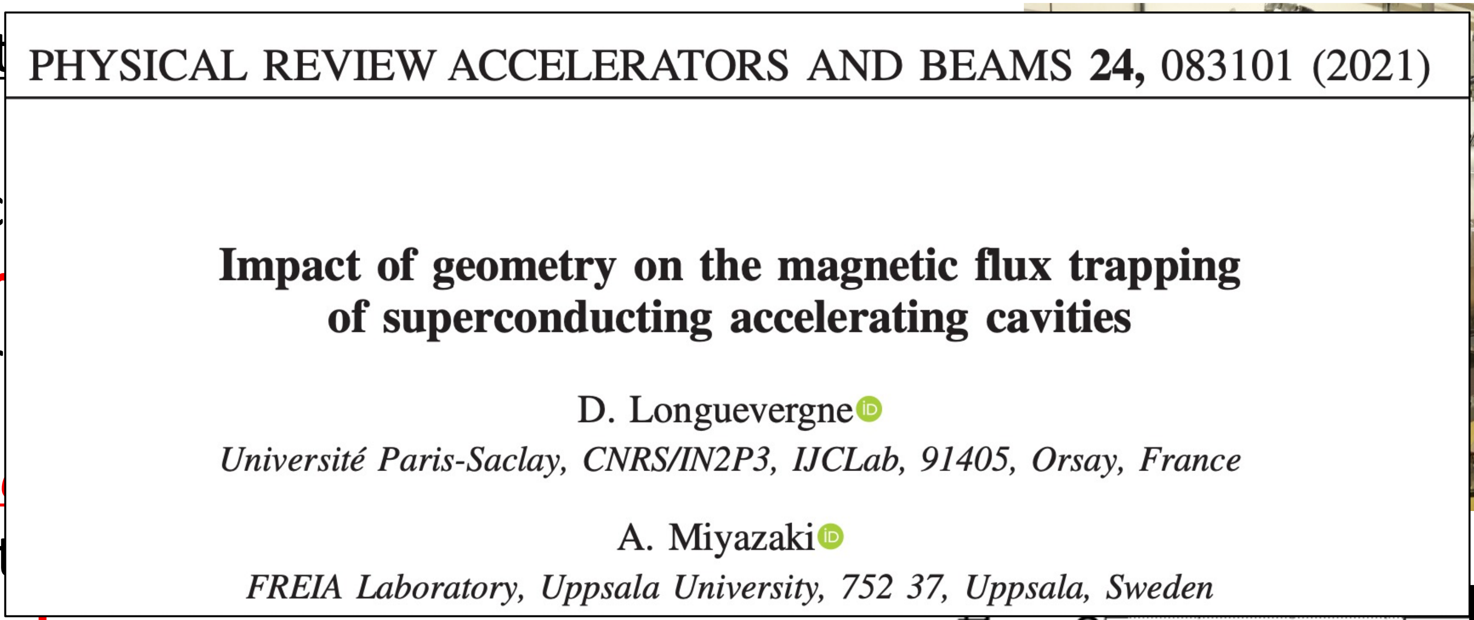
PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 083101 (2021)

Impact of geometry on the magnetic flux trapping of superconducting accelerating cavities

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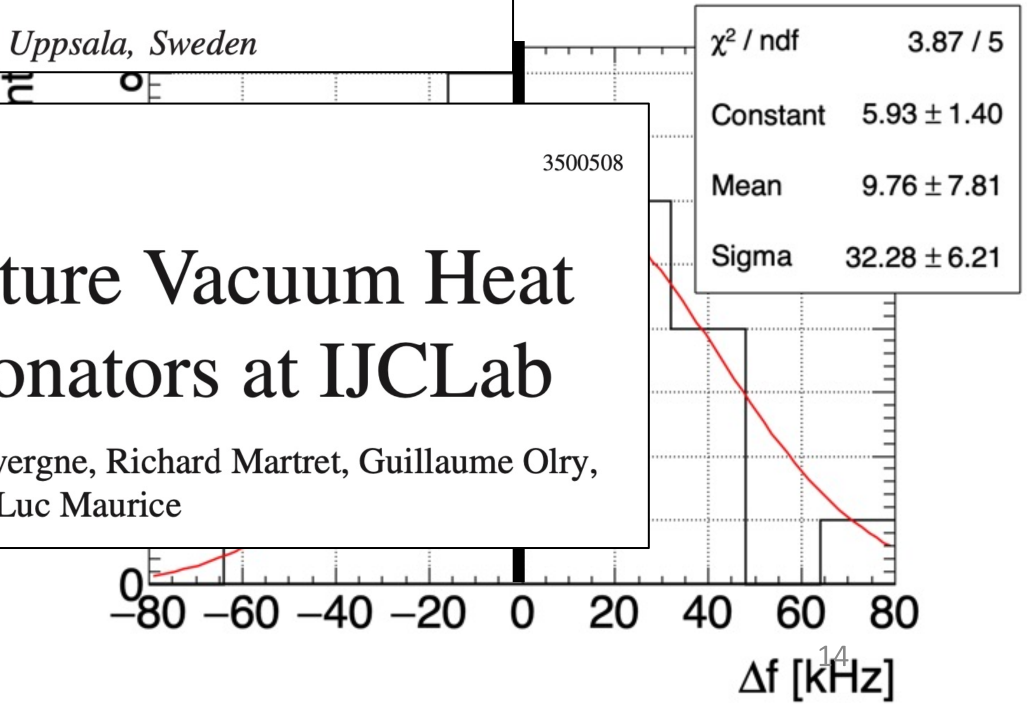
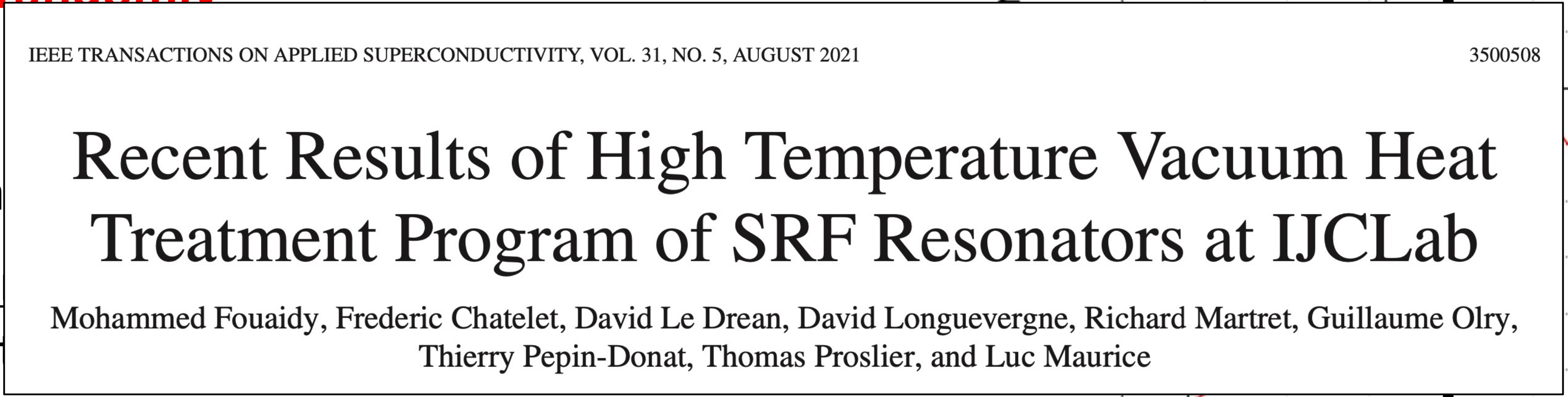
A. Miyazaki

FREIA Laboratory, Uppsala University, 752 37, Uppsala, Sweden

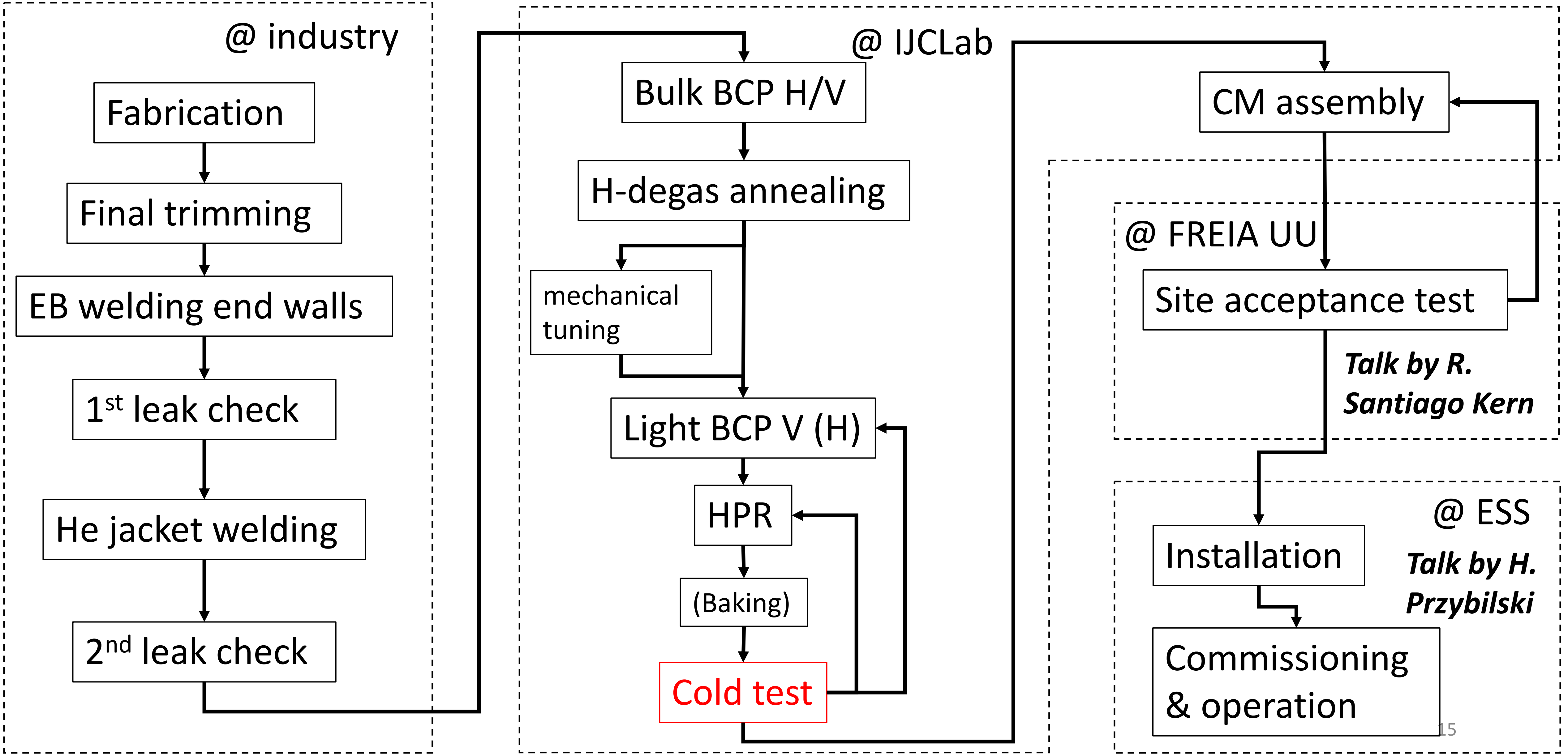



IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 31, NO. 5, AUGUST 2021 3500508

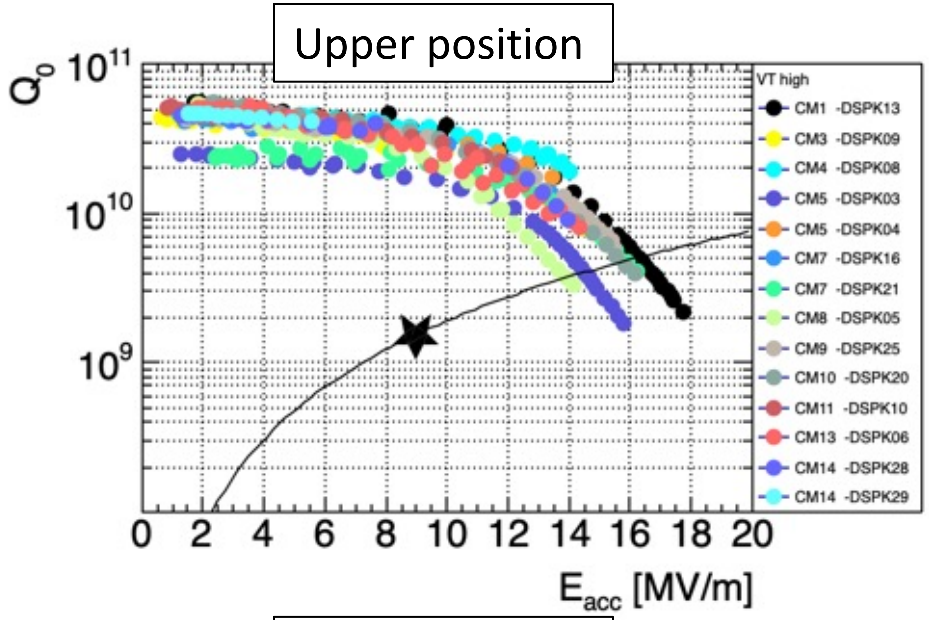
Recent Results of High Temperature Vacuum Heat Treatment Program of SRF Resonators at IJCLab

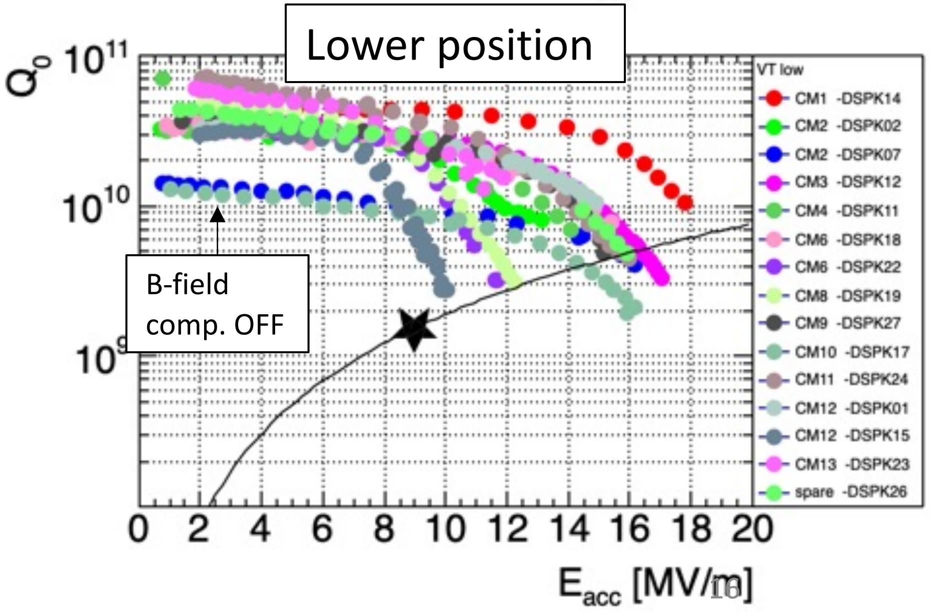
Mohammed Fouaidy, Frederic Chatelet, David Le Drean, David Longuevergne, Richard Martret, Guillaume Olry, Thierry Pepin-Donat, Thomas Proslier, and Luc Maurice

Series ESS double spoke life cycle



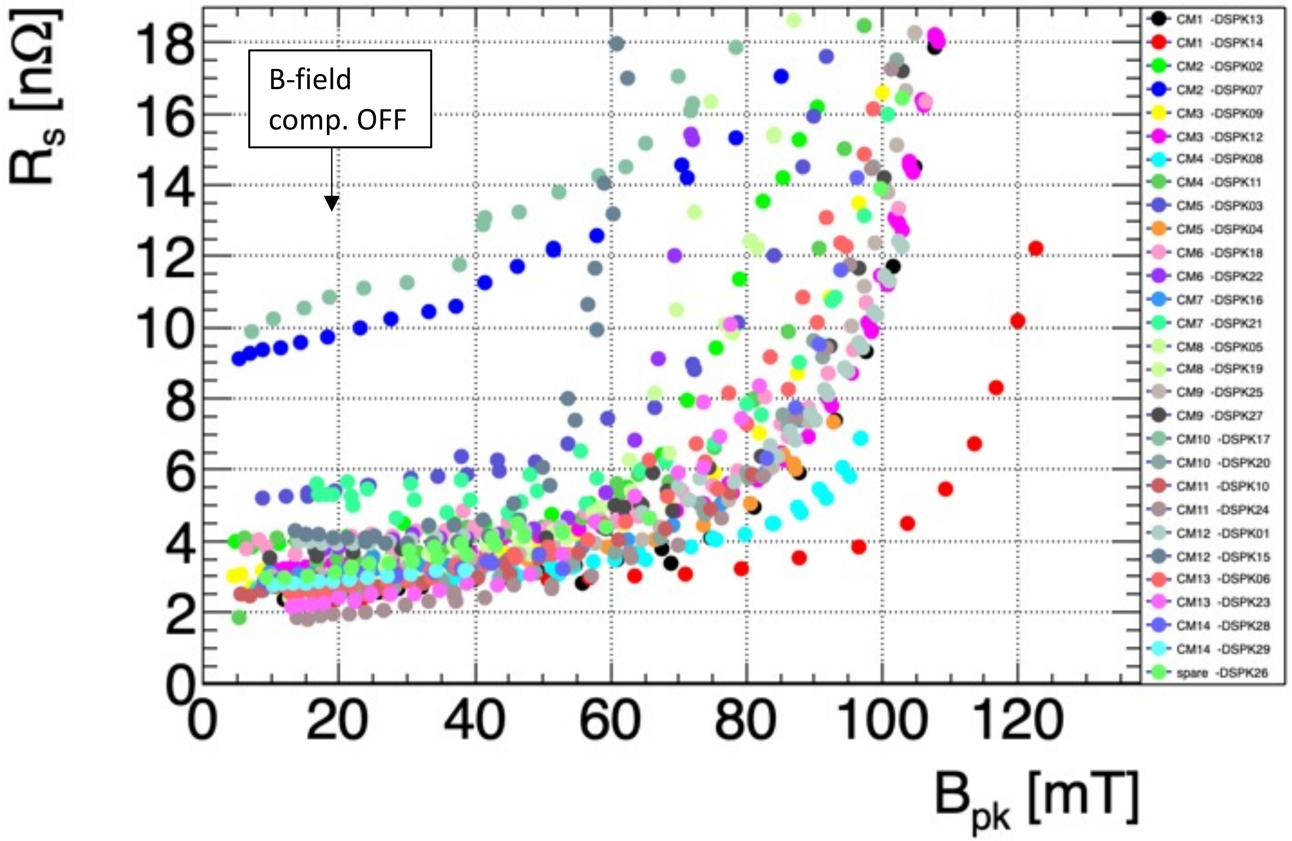
Series ESS cavities: cold tests





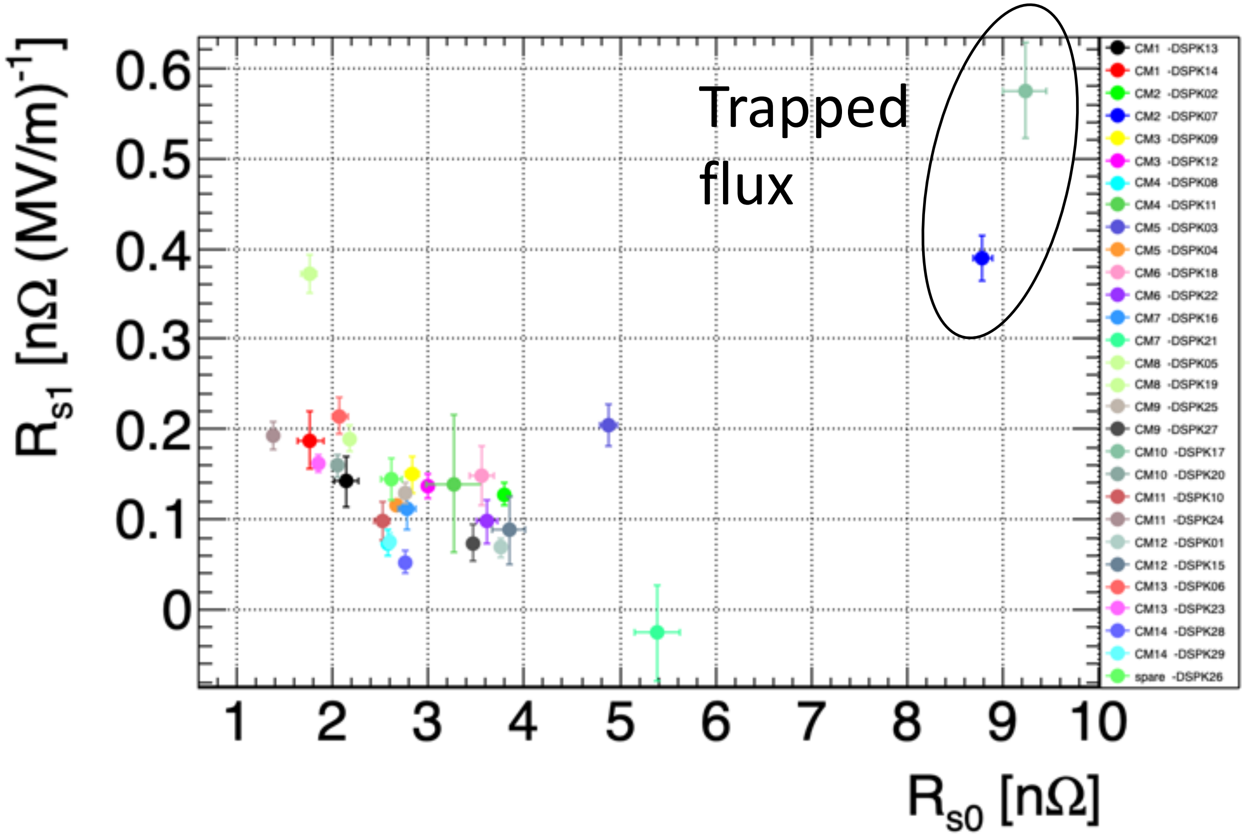
✓ **Excellent performance was achieved at 2K**

- $2\ \mathrm{n}\Omega < R_s < 7\ \mathrm{n}\Omega$ at low field
- Field emission onset >> 8 MV/m for most cavities
- No major difference due to position in the VT



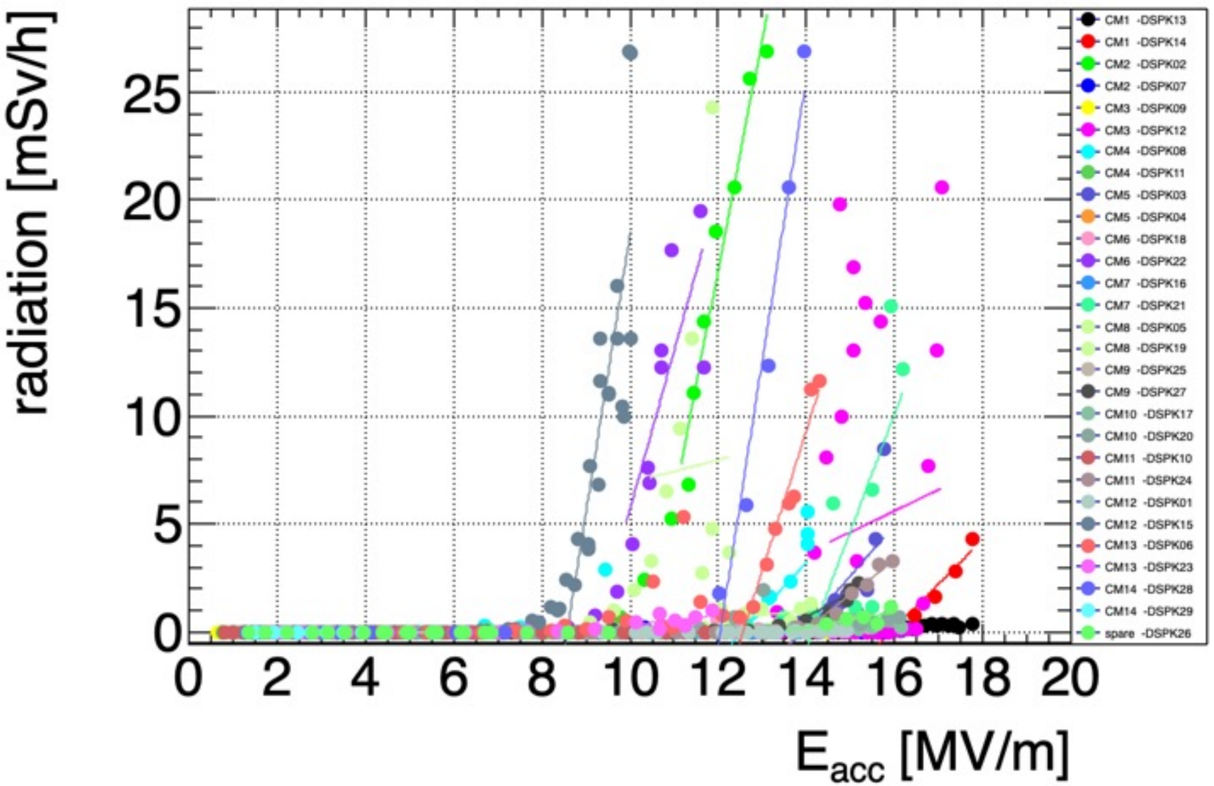
Cavity performance: some statistics at 2K

Nonlinear Rs vs low-field Rs



- Trapped flux increases both R_{s0} and R_{s1}
  - Support some theoretical models
- Intrinsic R_{s0} and R_{s1} might be anti-correlated
  - Higher R_{s0} may hide nonlinear R_{s1}

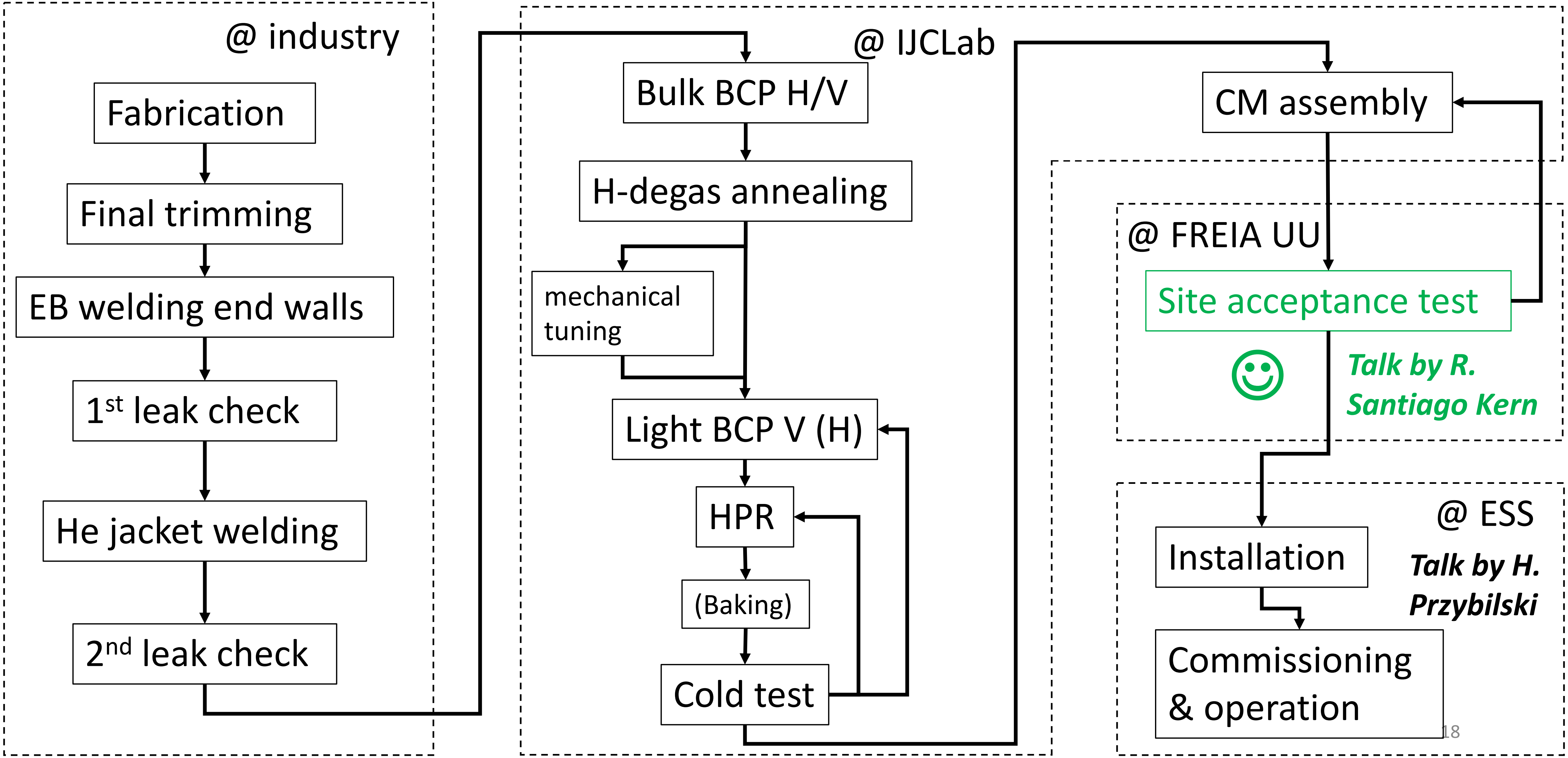
Field emission onset with X--ray



- FE onset is above nominal field for most cavities
- No HPR between VT and CM assembly

→ How is in CM after assembly?

Series ESS double spoke life cycle



MYRRHA prototype cavities

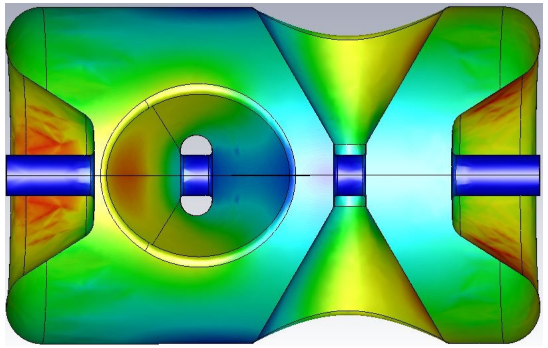
- Similar shape to ESS cavities
- Vertical BCP is impossible due to lack of a HPR port

✓ Excellent performance was achieved at 2K

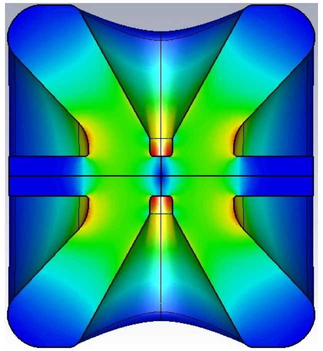
  - Comparable to ESS series cavities

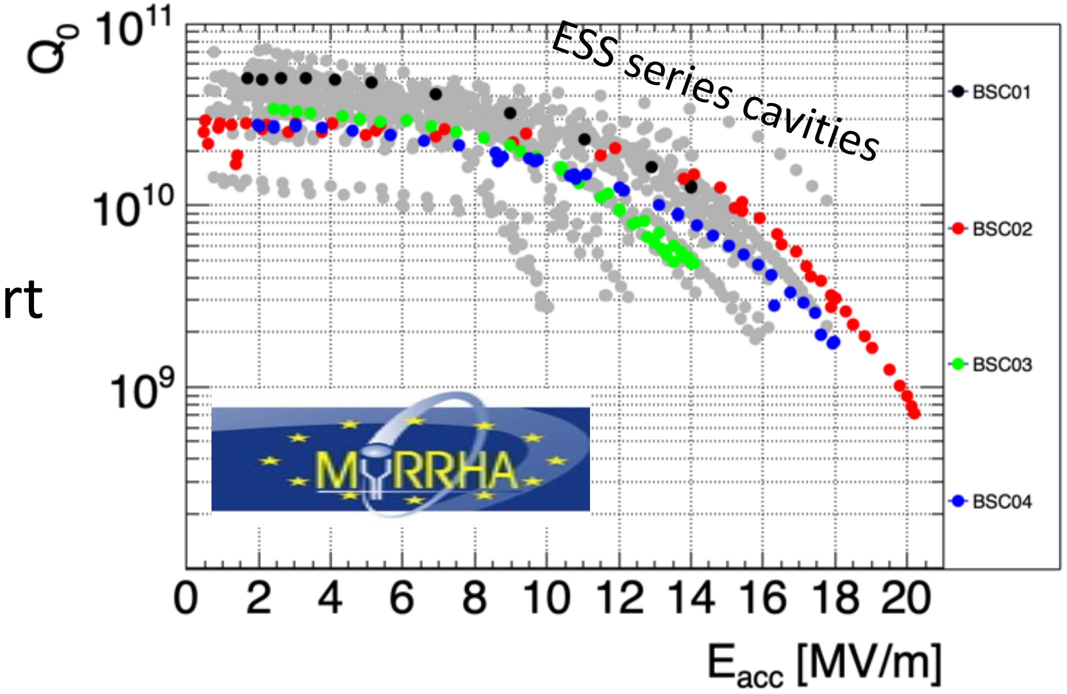
	ESS	MYRRHA
Frequency [MHz]	352	352
G [Ω]	130	109
B_{pk}/E_{acc} [mT/(MV/m)]	6.9	7.3
β_{opt}	0.5	0.37

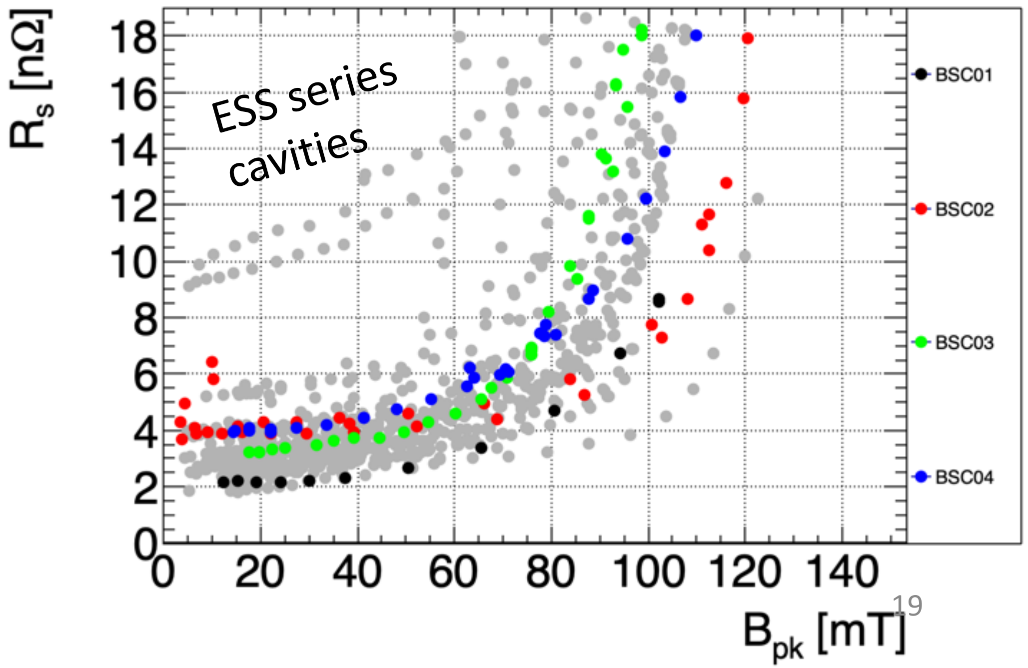
ESS



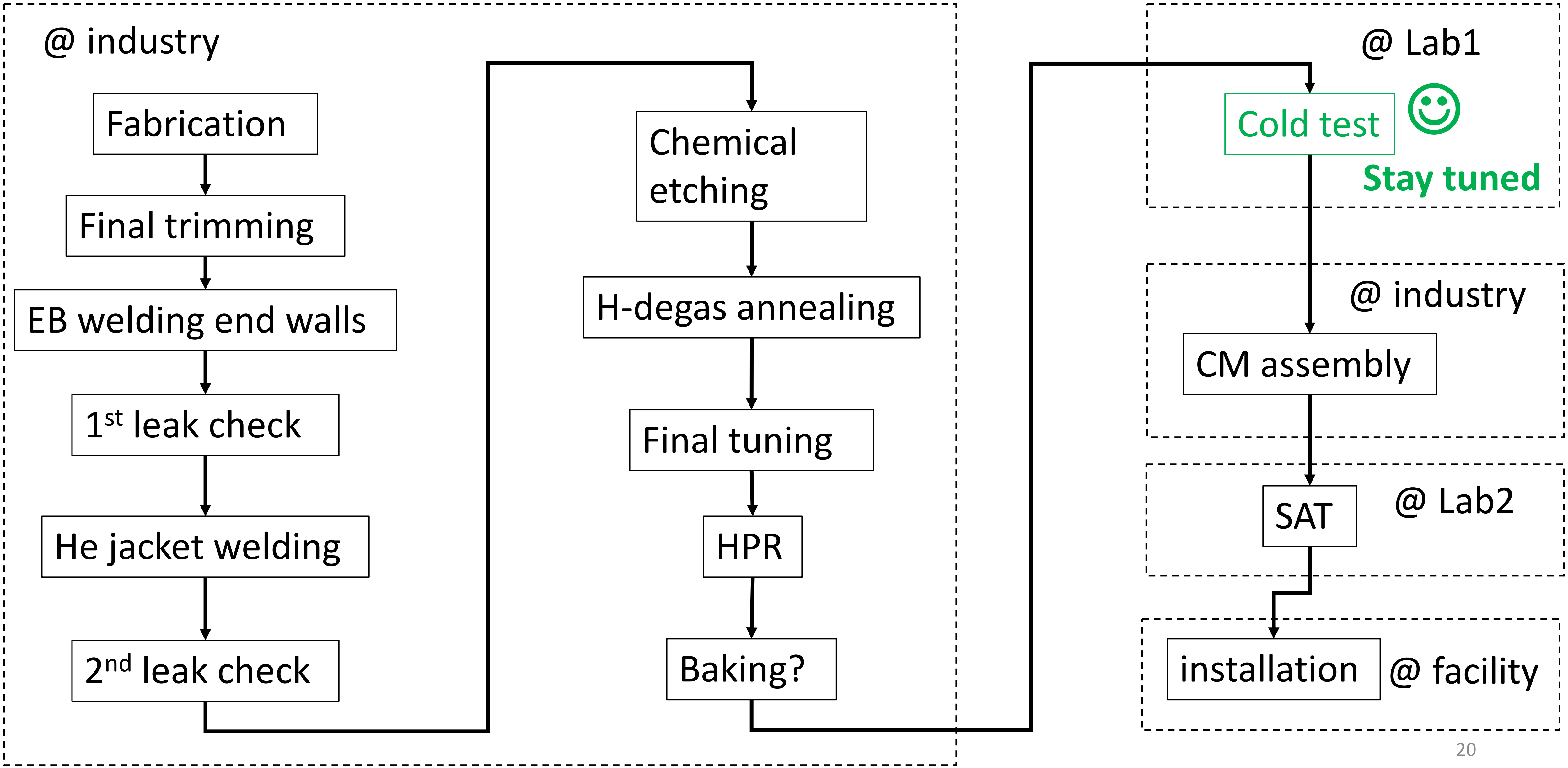
MYRRHA



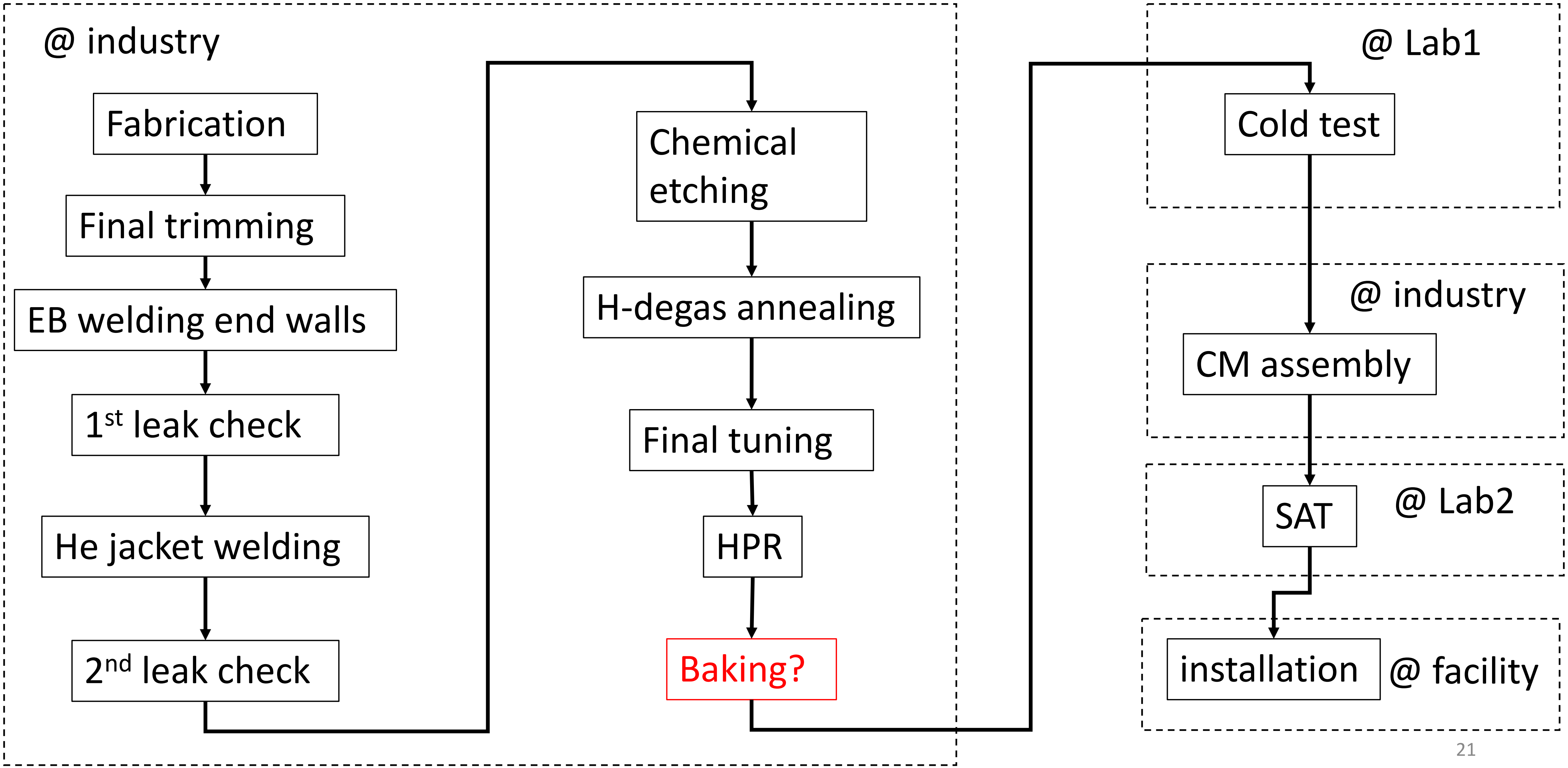




New challenge → more industrialization with **pre-series** cavities



New challenge → more industrialization with pre-series cavities



Do we need baking for spoke cavities (325-352 MHz)?

<u>Standard arguments</u>

- BCS resistance $R_{\mathrm{BCS}} \sim 0.8\ \mathrm{n\Omega} < R_{\mathrm{res}}$ **at 2K becaue of low frequency < 400 MHz**
  - Baking (usually) decreases R_{BCS} and increases R_{res}
- Peak field at nominal gradient $B_{\mathrm{pk}} = 62\ \mathrm{mT}$
  - Far away from high-field Q-slope

→**Low-T baking (120C/48h) is high risk no gain (higher R_{res})**

✓ Very gentle baking (3h) for drying water to reduce MP

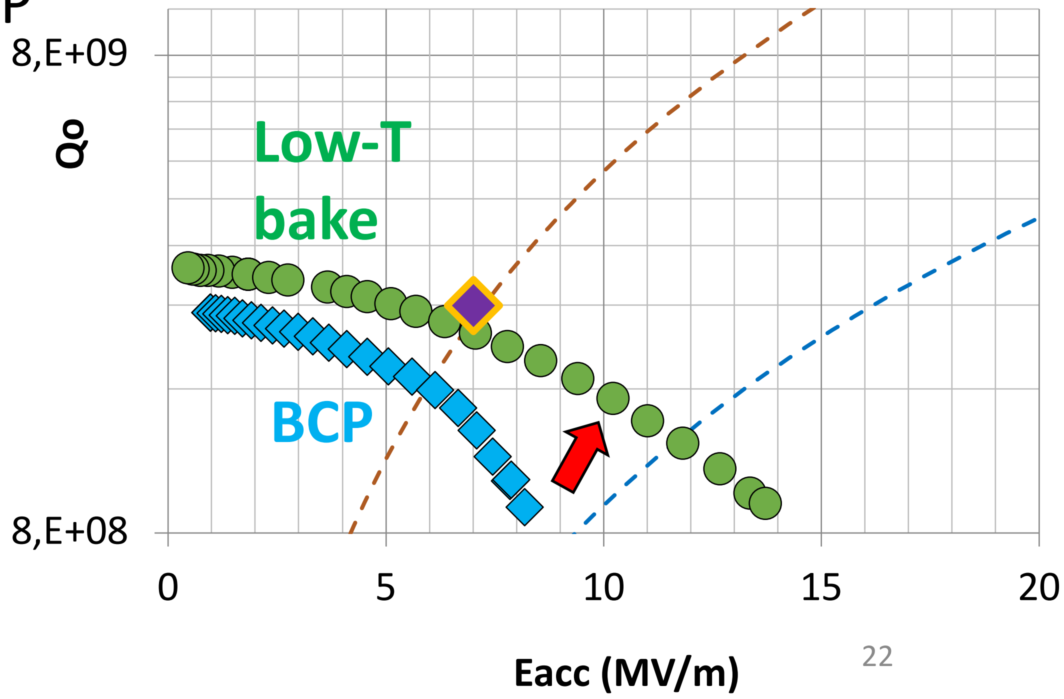
<u>However</u>

- BCS resistance $R_{\mathrm{BCS}} \sim 39\ \mathrm{n\Omega} \gg R_{\mathrm{res}}$ **at 4.2K**

→ Baking paves the way to the proton drivers at 4 K

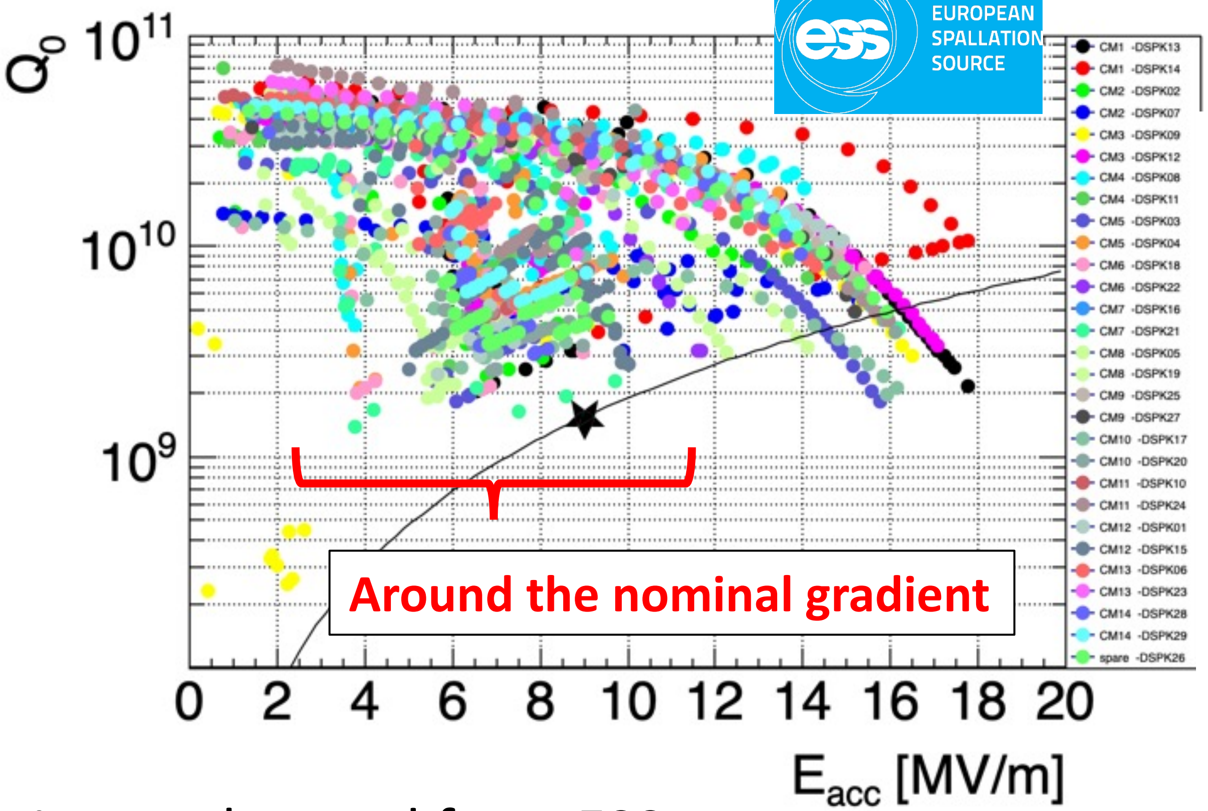
- A MYRRHA prototype met the specification for 2 K even at 4.2 K after low-T baking (but lost Q_0 at 2K)
- Mid-T baking may be the way to go

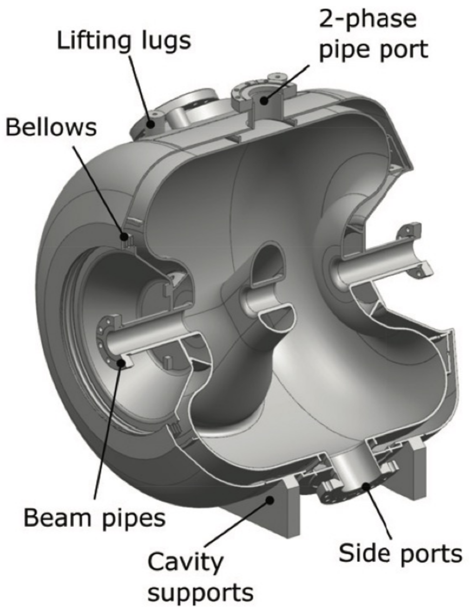
MYRRHA prototype 4K



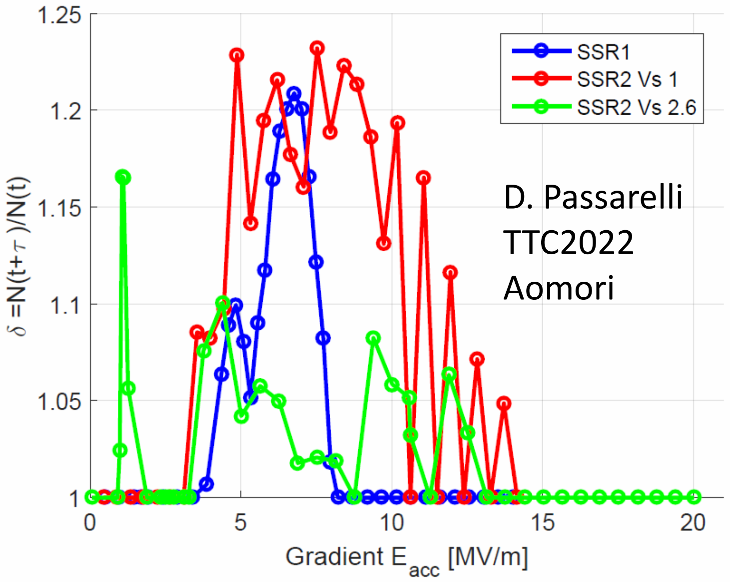
future R&D: mid-T of spoke cavities

MP barriers may be a potential problem of ESS/MYRRHA

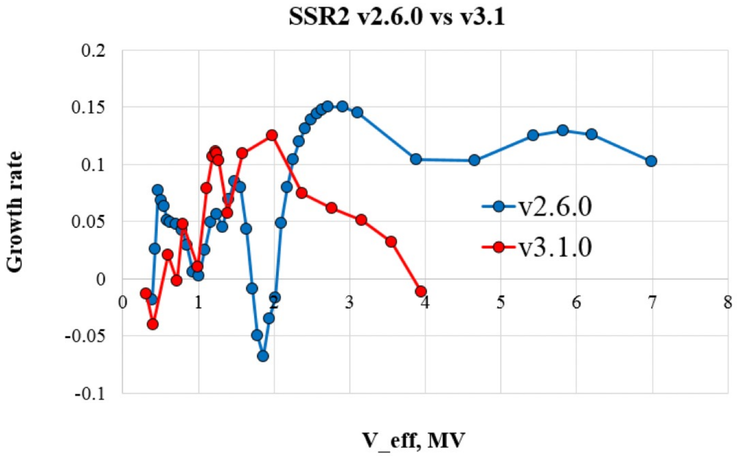




P. Berrutti, et al, TUP066 SRF2019
M. Parise, et al, TUP014 SRF2019



D. Passarelli
TTC2022
Aomori

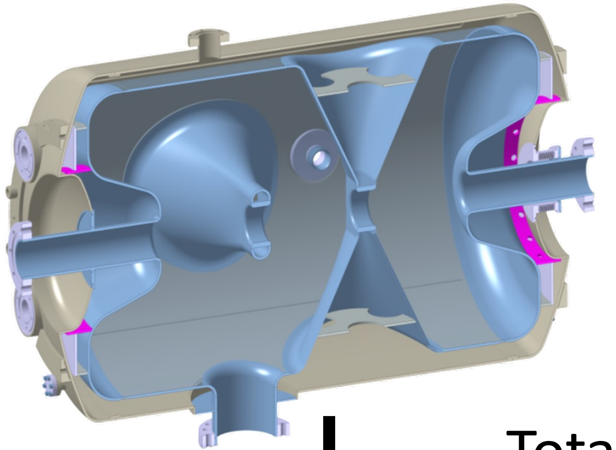


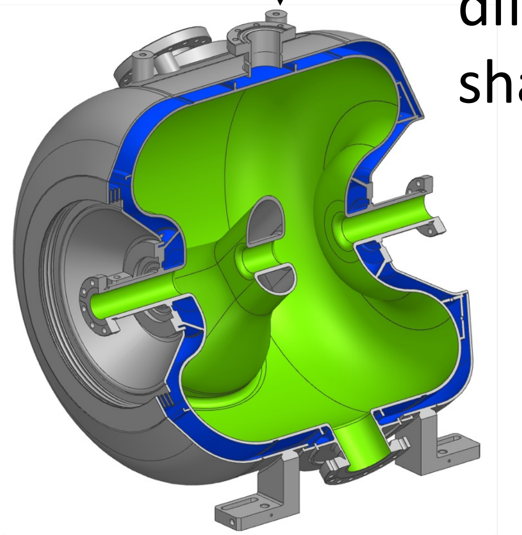
<u>Lesson learned from ESS</u>

- MP barriers are around the nominal field
  - Possible to condition within half an hour
  - Potential issue during beam operation (?)

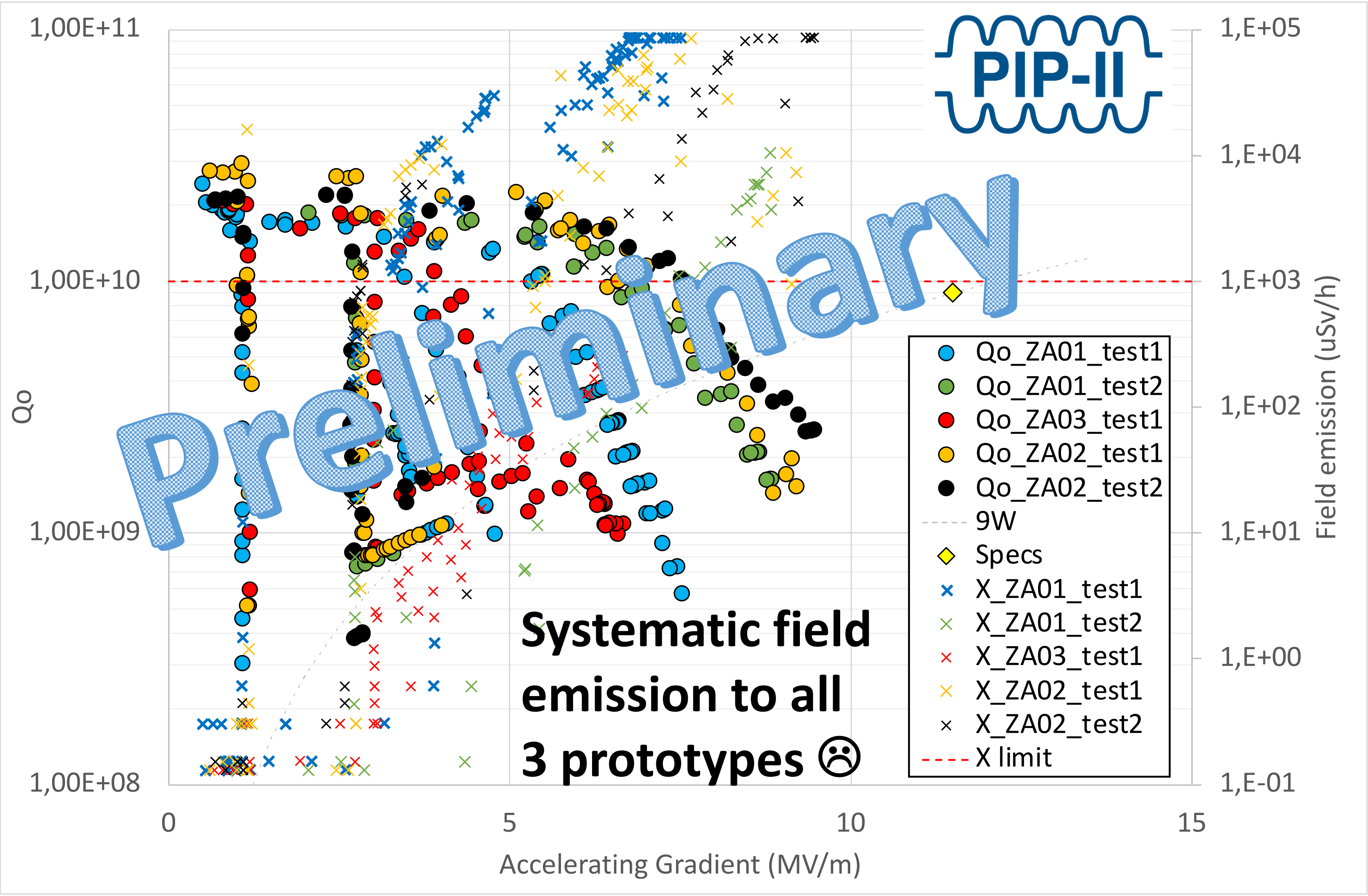
→ PIPII SSR2 cavities were designed to include features of Balloon Cavities to reduce MP

Preliminary results of PIPII SSR2 prototype



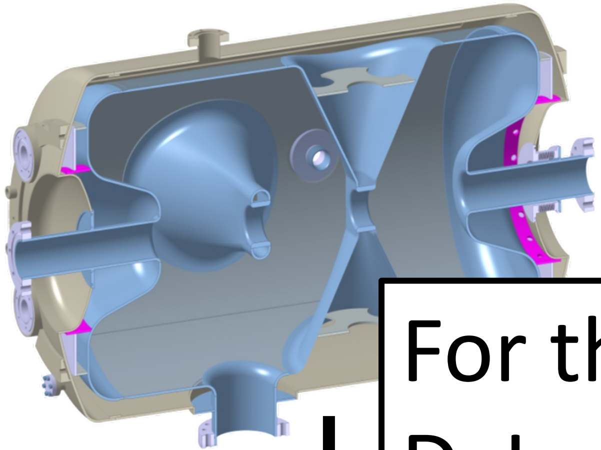


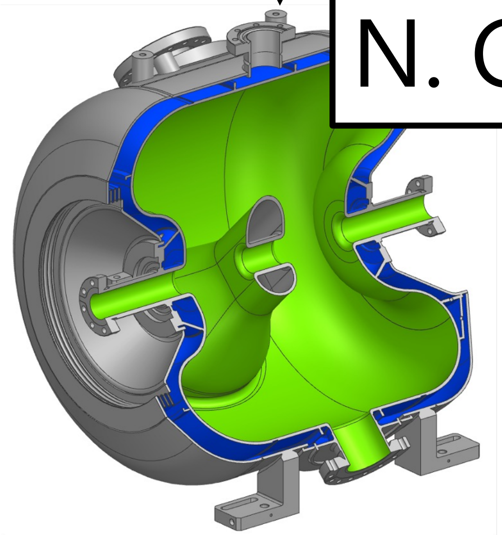
Totally different shape!

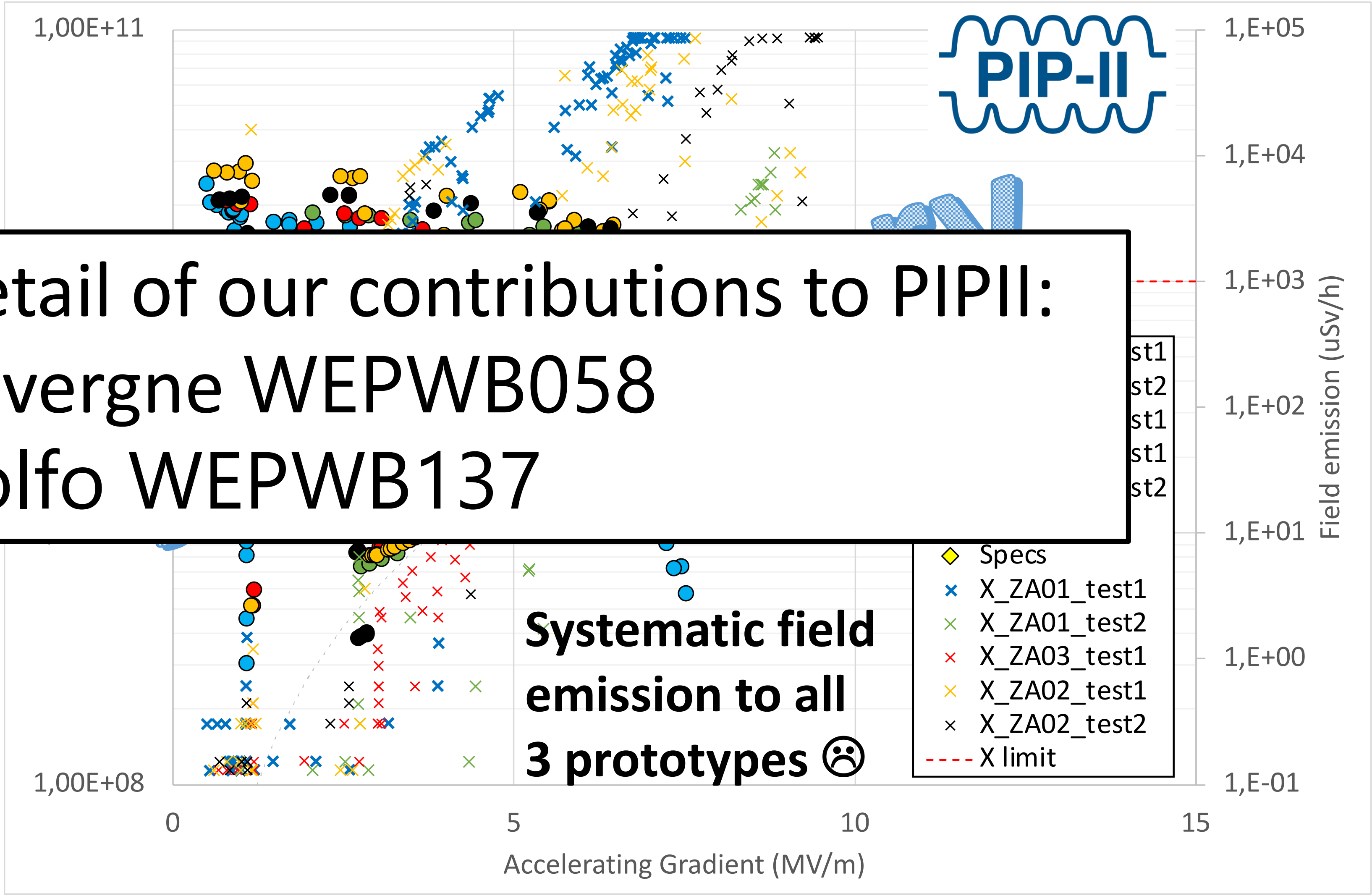


We cannot reuse the same HPR tools → optimizing new HPR

Preliminary results of PIPII SSR2 prototype







For the detail of our contributions to PIPII:
D. Longuevergne WEPWB058
N. Gandolfo WEPWB137

We cannot reuse the same HPR tools → optimizing new HPR

Conclusion and outlook

- IJCLab has been leading development and deployment of various spoke cavities
- Challenges in manufacturing and processing were overcome
  - Skipping bare cavity testing and directly welding helium jacket in industry
  - Frequency tuning with vertical/horizontal BCP (+ mechanical tuning)
  - H-degassing at 650C was successful with the titanium jacket
- ESS series production is completed with excellent performance and will start accelerating protons soon
  - **CM testing results? → See next presentation by Rocio Santiago Kern!**
- MYRRHA prototype cavities showed as excellent performance as ESS series
- Industrialization of chemical process, annealing, and baking is on-going
  - Goal: as much as industry can → similar to 1.3 GHz TESLA type cavities
- MP barriers were identified as a potential issue of ESS-type spoke cavities
  - Prototype PIP-II SSR2 was designed to avoid MP inspired by the balloon cavity
  - As a side-effect, existing HPR tooling is not sufficient → optimization is on-going
- On-going R&D
  - Baking of spoke cavities (325-352 MHz) toward 4 K operation
  - Plasma processing of TEM cavities