CM Workshop: SRF Cavity Processing Tutorial

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3 September 2018

In partnership with:
India/DAE
Italy/INFN
UK/STFC
France/CEA/Irfu, CNRS/IN2P3

Outline

- Intro/Bio
- What is SRF cavity processing?
- Processing steps and functions

Introduction/Biography

- Current – PIP-II Project Engineer
- Past
  - L2 Manager for PIP-II SRF Systems
  - L3 Manager for PIP-II 650 MHz Sub-system
  - Deputy Dept. Head of SRF Department
  - **Group Leader for SRF Cavity Processing and Facilities**
  - ….

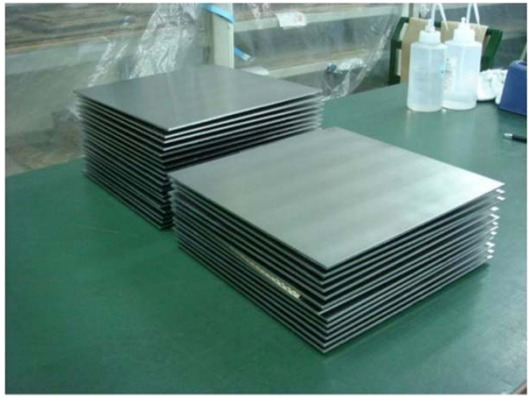
What is SRF cavity processing?

- Steps required to prepare the inner conductive layer of a Superconducting radio frequency (SRF) resonator to enable very high electric and magnetic surface fields while achieving very low surface resistance and minimal field emission.

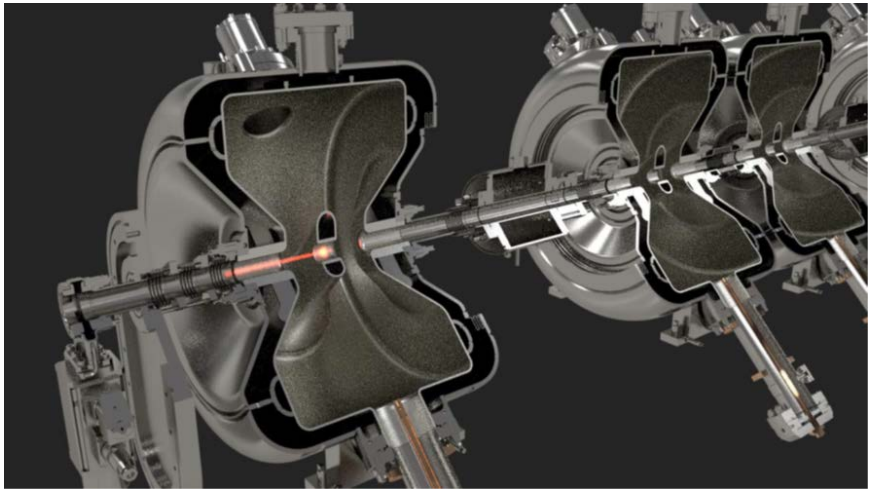
Main processing requirements:

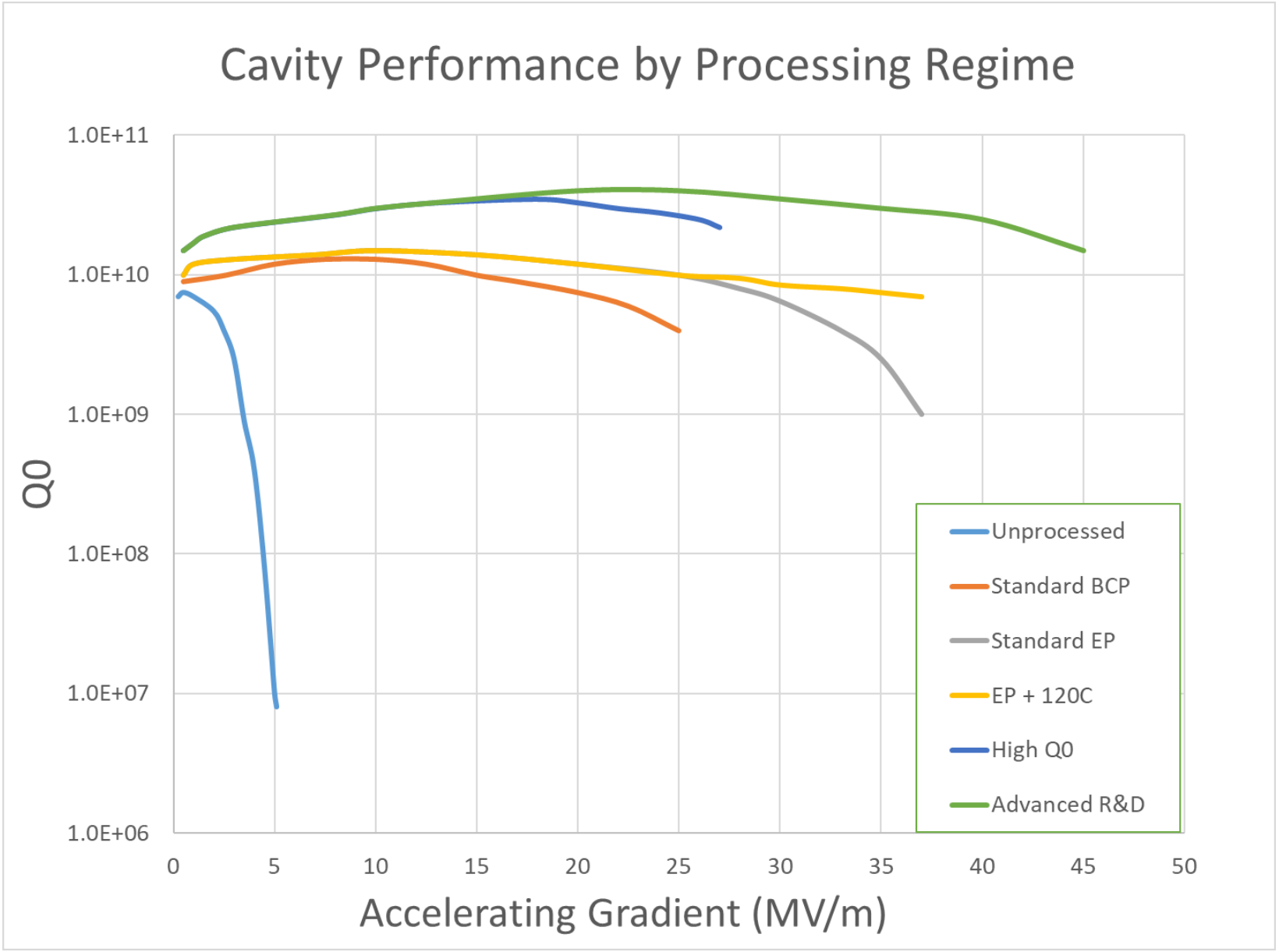
- Damaged layer removal via chemical etching or polishing.
- Hydrogen degasification via high-temperature vacuum heat treatment.
- Particulate and surface residue removal via ultra-clean high-pressure water rinsing.
- Evacuation.
- Surface water removal and surface oxide modification via low-temperature vacuum heat treatment.

From sheet metal to SC particle accelerator.

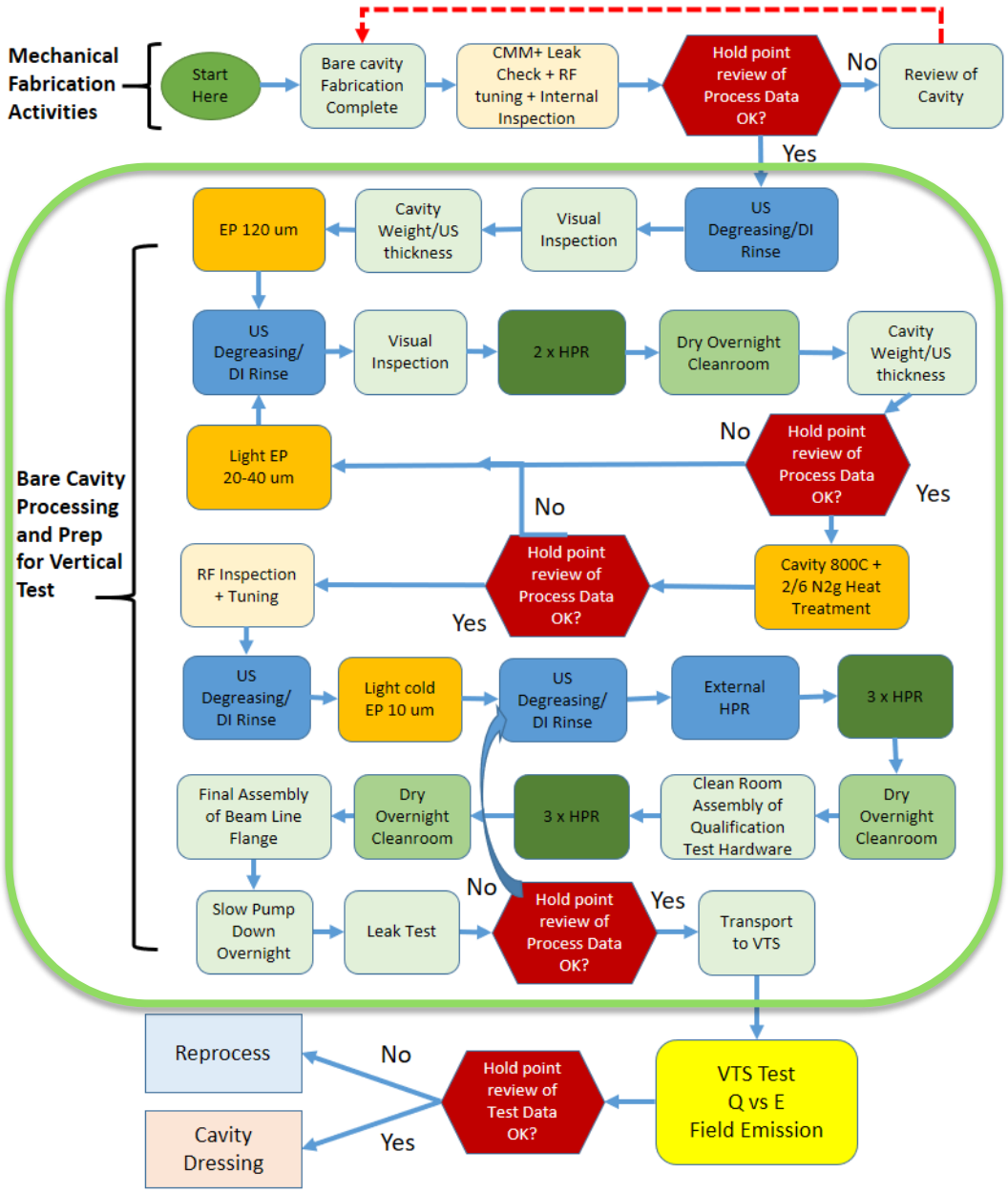


Cavity Processing & Qualification




Cavity Performance by Processing Regime
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
Q0
0
5
10
15
20
25
30
35
40
45
50
Accelerating Gradient (MV/m)
Unprocessed
Standard BCP
Standard EP
EP + 120C
High Q0
Advanced R&D

PIP-II 650 MHz Cavity Processing Flow Chart



Bulk Chemistry – Buffered Chemical Polishing

- Damaged layer removal caused by manufacturing
  - Requires 120-200 *um* material removal from the RF carrying surface
- Two primary techniques: BCP and EP
  - Buffered Chemical Polishing (BCP) – an etching process
    - Oxidation – Reduction cycle
    - 1:1:2 Ratio - 48.5% HF : 70% HNO_3 : 85% H_3PO_4

$$2\,Nb + 10\,HNO_3 = Nb_2O_5 + 10\,NO_2 + 5H_2O$$

and

$$Nb_2O_5 + 10\,HF = 2\,NbF_5 + 5\,H_2O;$$

hence

$$Nb + 5\,HNO_3 + 5\,HF = NbF_5 + 5\,NO_2 + 5\,H_2O$$

    - Reaction surface temperature controlled: 12-15C
    - Best for asymmetrical/complex cavity geometry + lower gradient and quality factor requirements
    - Relatively simple process setup
    - Extremely hazardous due to HF and noxious fumes

BCP – Bare cavity setup

- Exterior surface temp control
- BCP solution is chilled to < 5C
- Gravity filled and dumped
- Pneumatic pumps slowly circulate solution
- Agitation via flows tailored to resonator geometry
- Ultrapure water rinsing following etching to remove residual salts
- Transfer to cleanroom while surfaces are still wet

Jacketed SSR1 BCP Setup

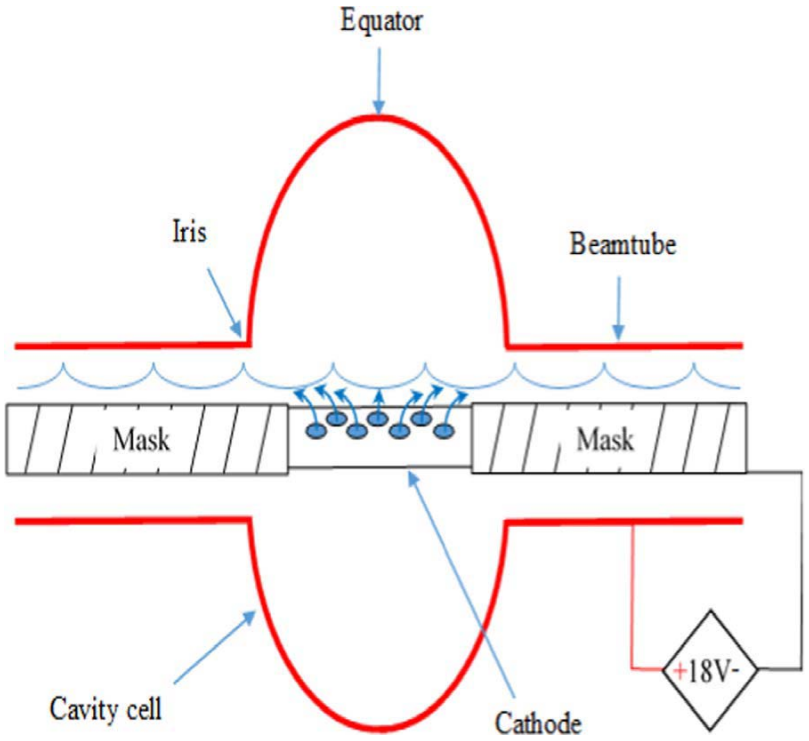
- Reaction temperature and fluid flows are carefully controlled

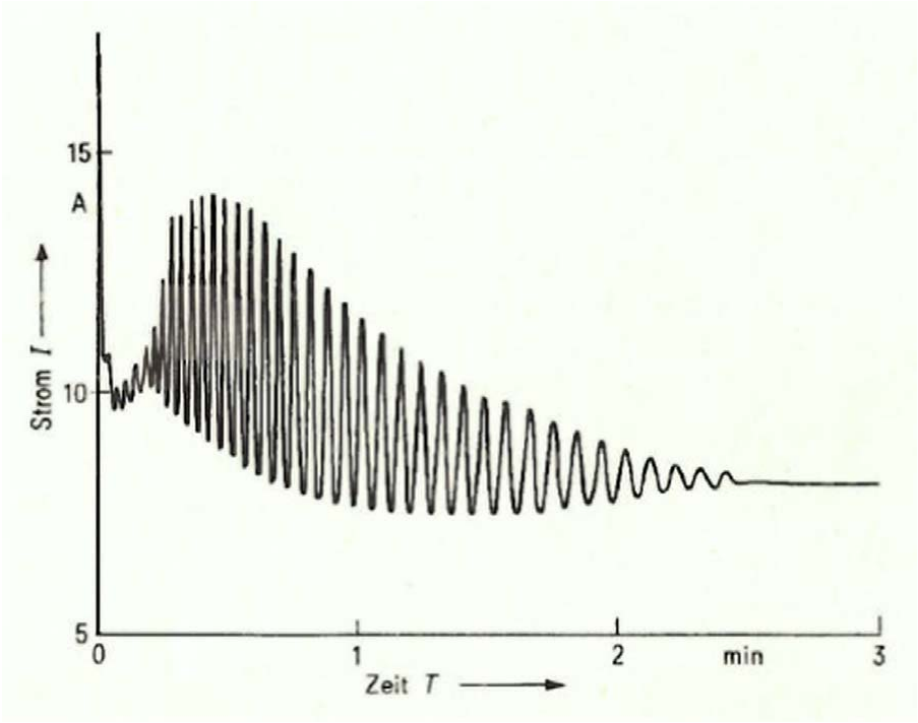
Bulk and Fine Chemistry: Electropolishing

- Damaged layer removal + light polishing for surface optimization.
- Much more complex than BCP.
- Ideal for azimuthally symmetrical resonators like elliptical structures.
- Can be implemented if considered during the cavity design phase.
- Generally required for gradients > 25 MV/m.
- Required for very high Q0 applications (N2 doping recipes).
- Tight process controls essential to achieving high quality surface polishing results.
- Process extremely hazardous due to HF

Electropolishing Principals

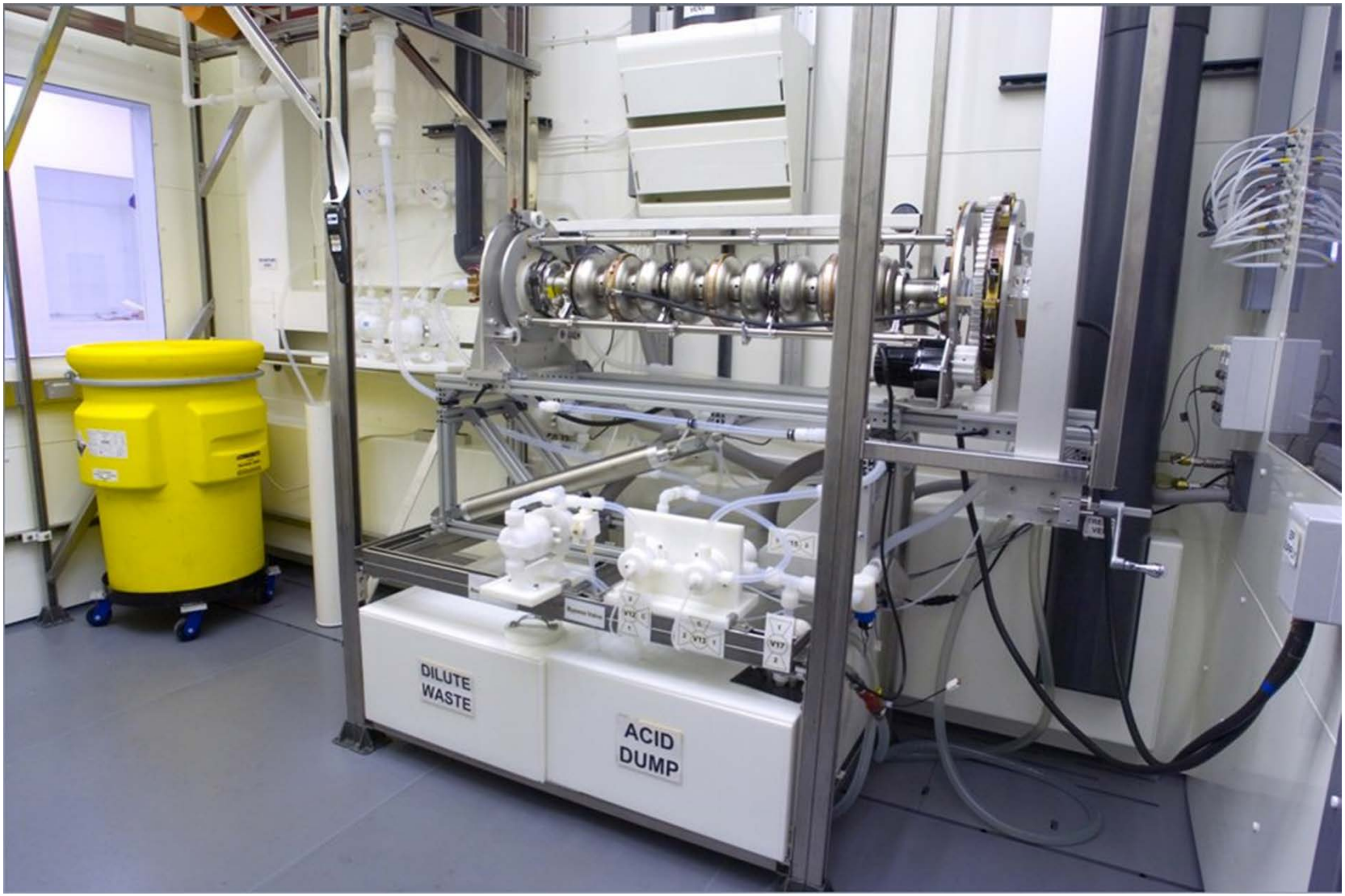
- 10:1 Volumetric Ratio of 96% H2SO4 : 49% HF (other ratios exist)



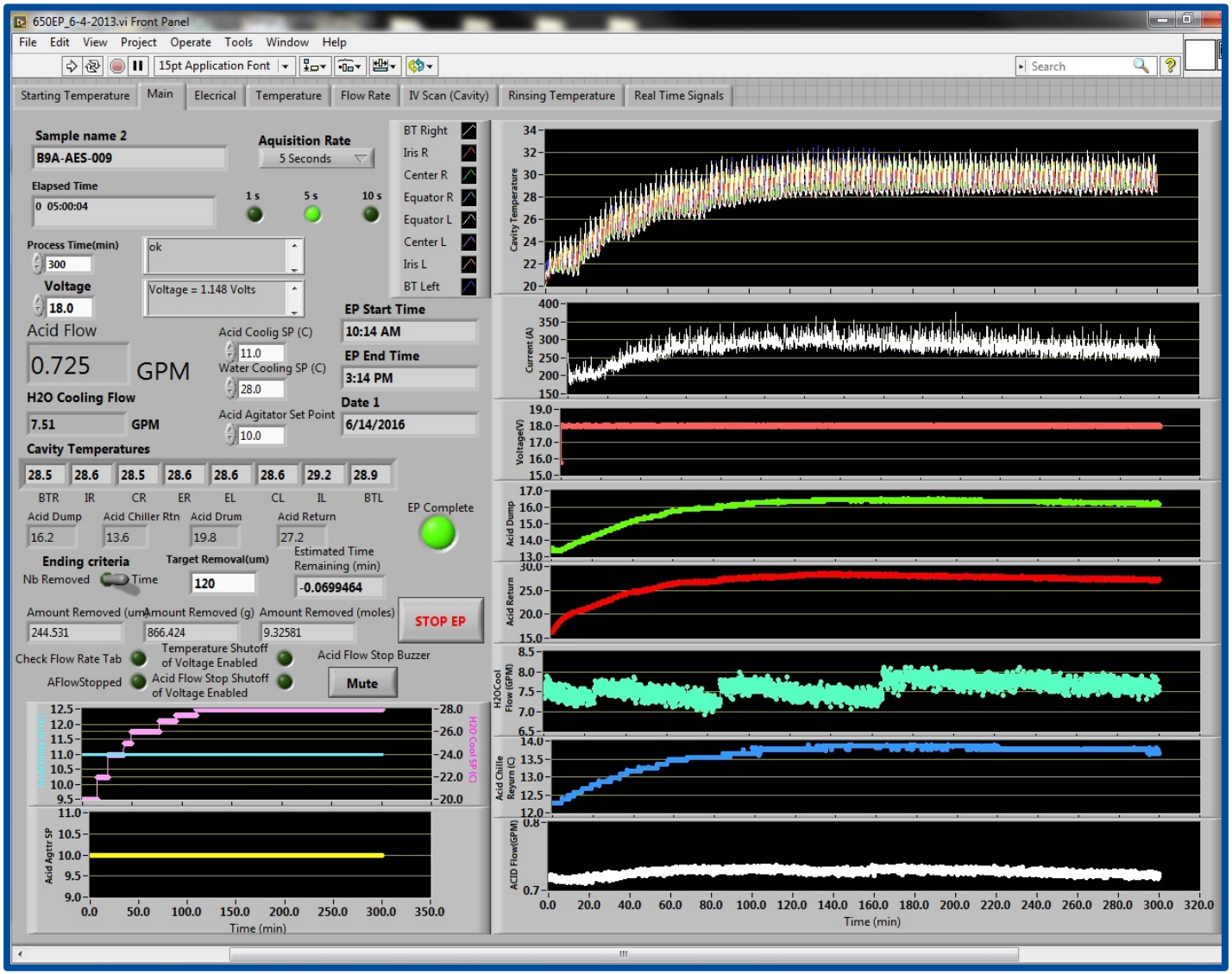


Anthony C. Crawford https://www.sciencedirect.com/science/article/pii/S0168900217300086
H. Diepers, O. Schmidt, H. Martens, F. Sun, A new method of electropolishing niobium, Phys. Lett. 37A (2) (1971) 139

Electropolishing Facility at Argonne Nat'l Lab

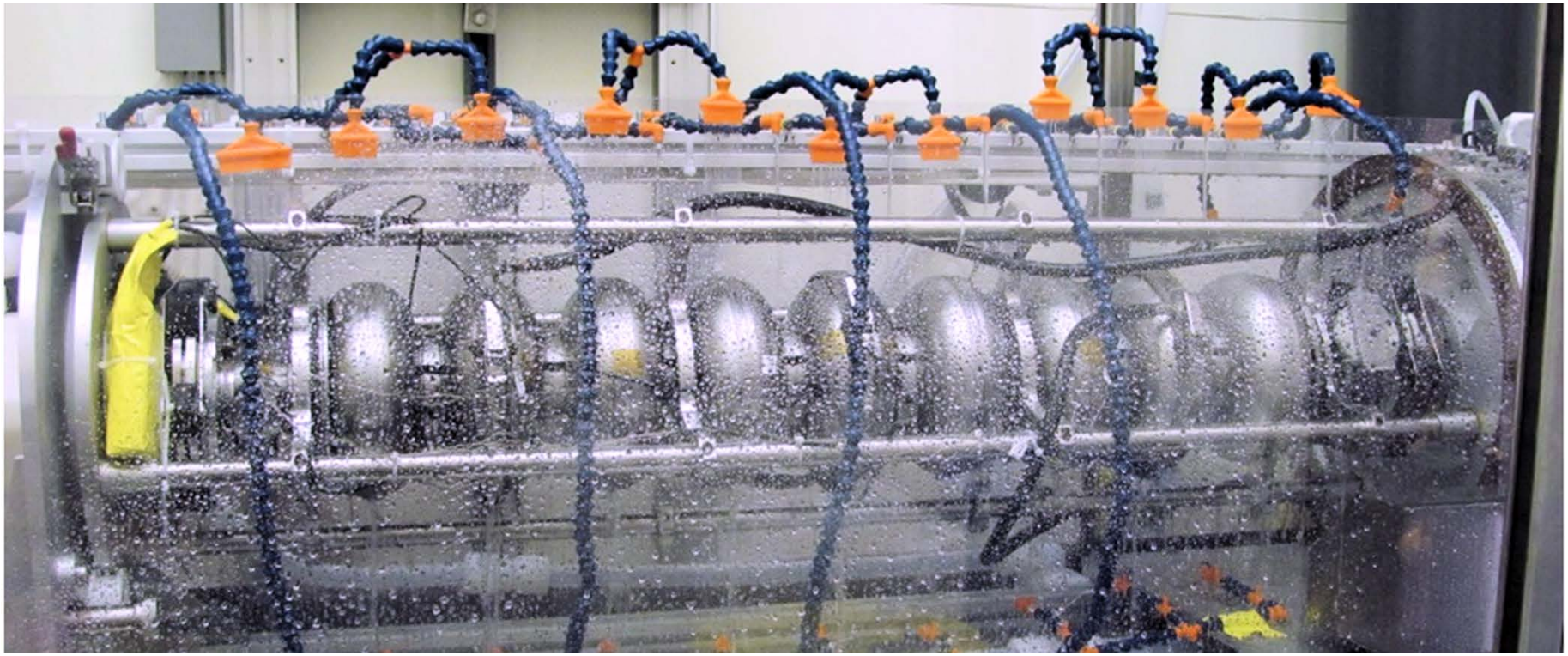


Electropolishing Tool Interface



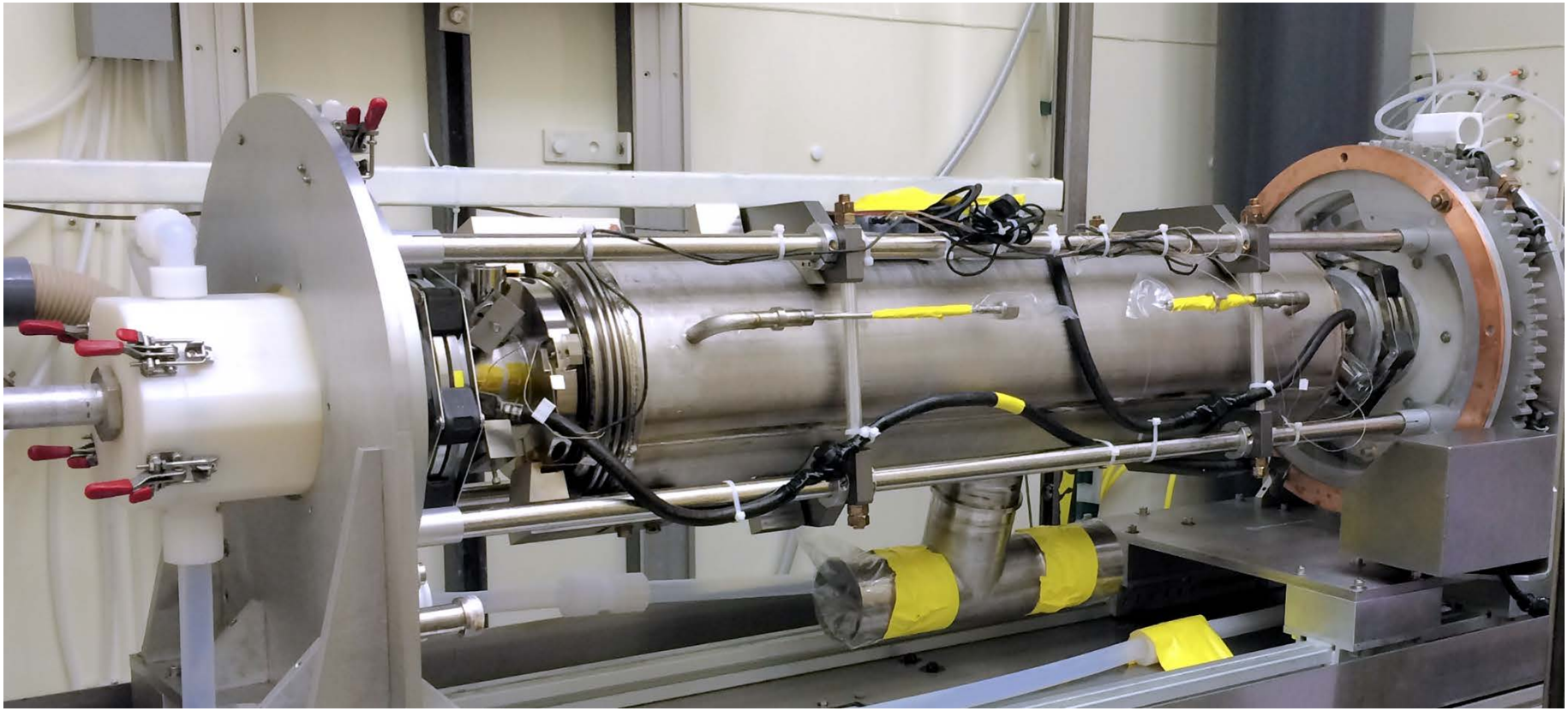
Commercial-style Electropolishing Facility

ILC/XFEL/LCLS-II Bare Cavity Electropolishing



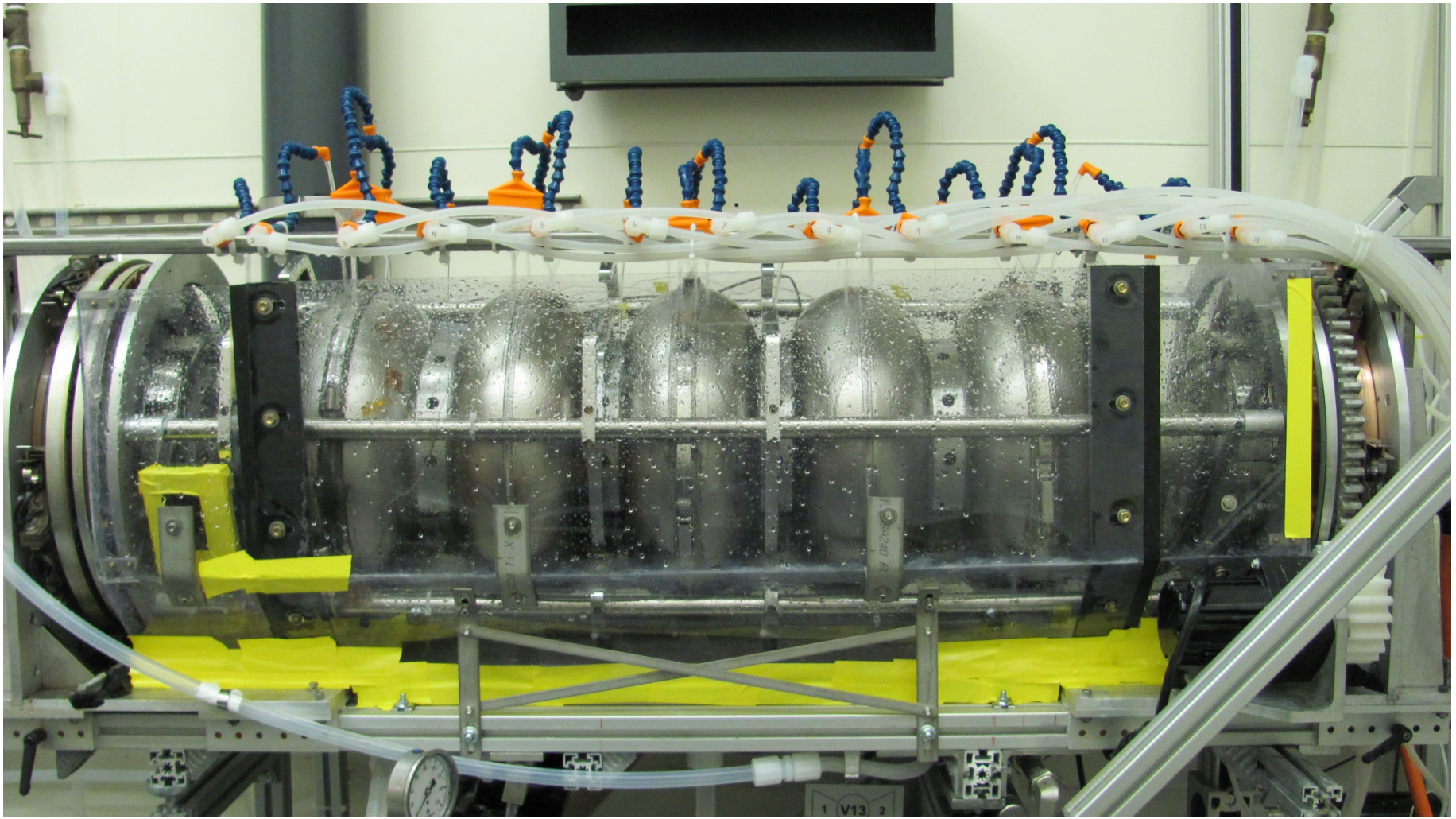
External water cooling, in particular at the irises, is used to control material removal rates and reduce polishing depth ratios between the irises and equators.

ILC/XFEL/LCLS-II Jacketed Cavity Electropolishing



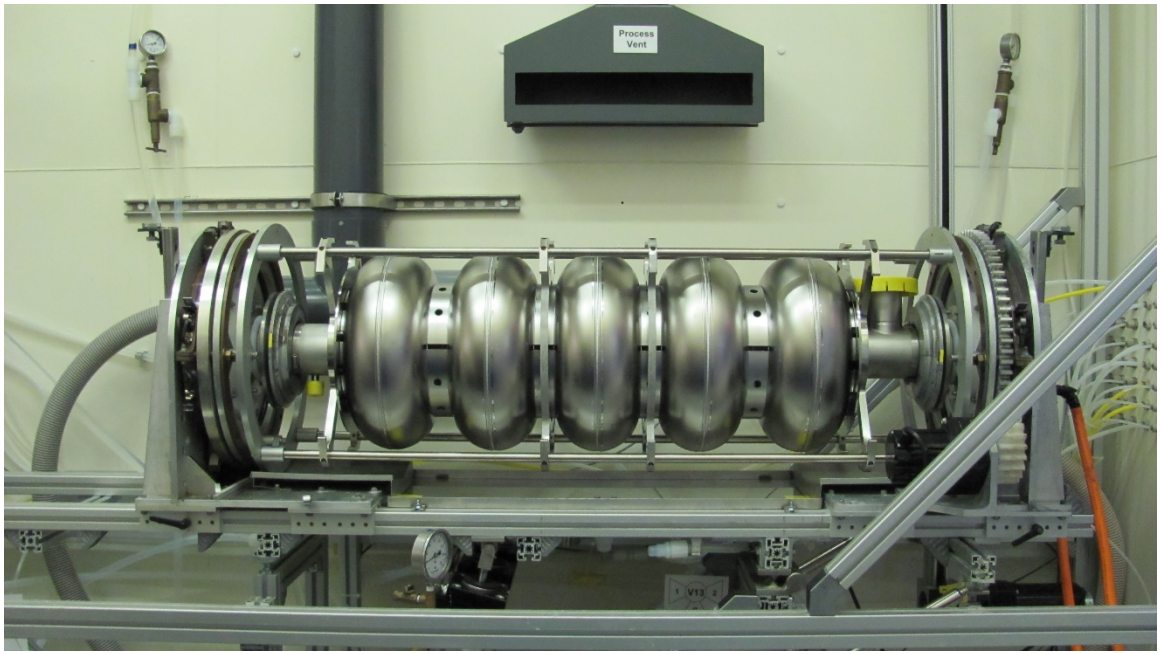
- Helium vessel used as cooling jacket.
- Modest removal amounts (5-15 um) acceptable up to the field flatness requirement limits.

650 MHz Electropolishing



Draining electrolyte + rinsing

- After EP, the cavity is rinsed several times with ultra-pure water to remove chemical salts.



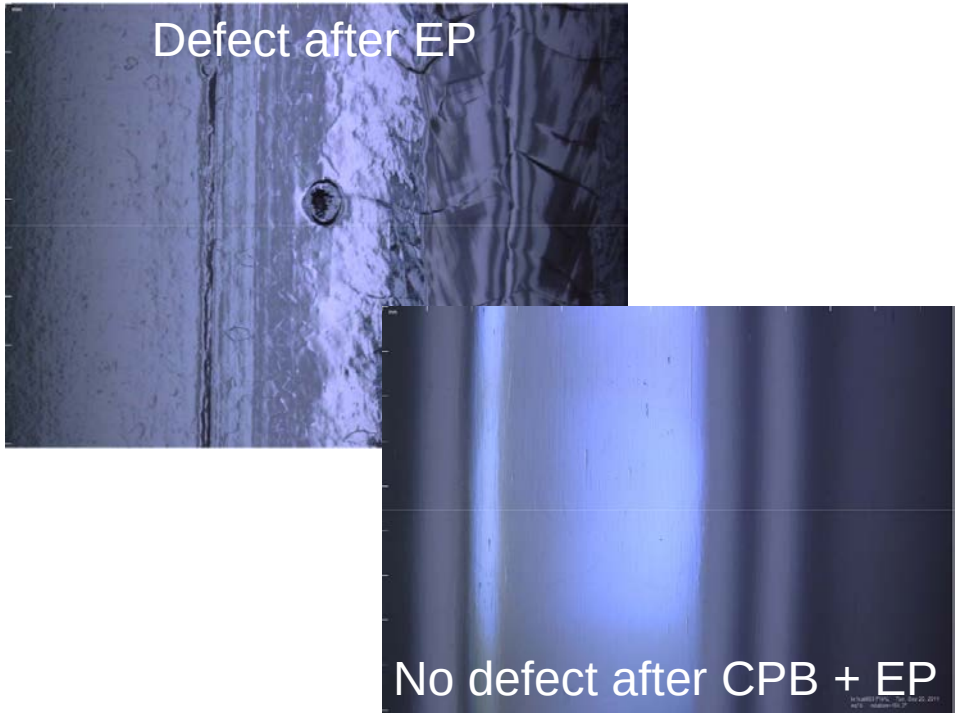
Centrifugal Barrel Polishing

IB4 High centrifugal barrel polishing tool repairs 1.3 GHz inner surfaces when defects appear. Two 9-cell 1.3 GHz cavities can be tumbled simultaneously.

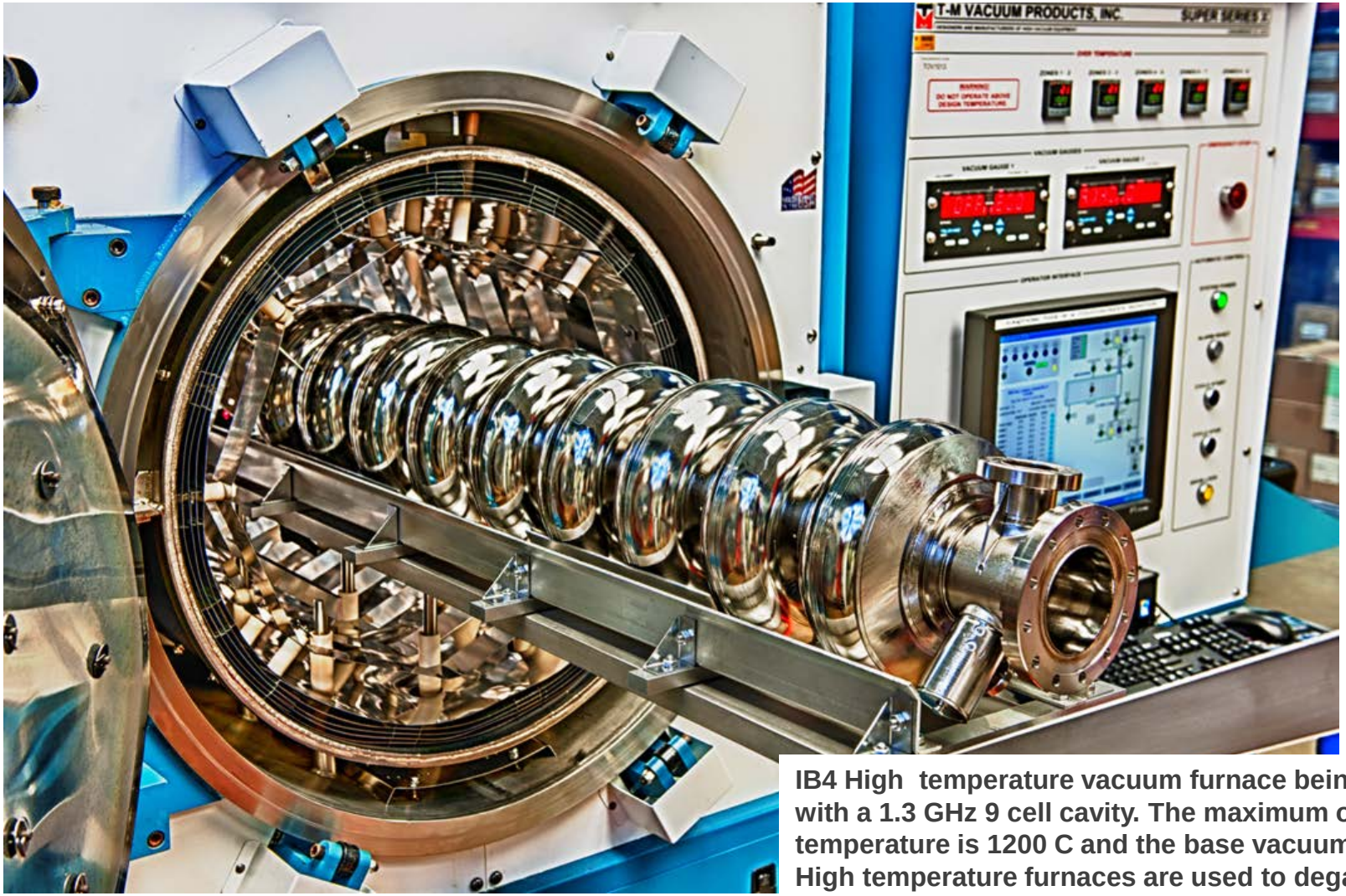
Centrifugal Barrel Polishing

- Implemented for Elliptical cavities
- Primarily used to repair large defects in welds/HAZ
- Can be used as a bulk chemistry replacement
- Requires EP to remove residual contamination left by CBP media

Cutting and Polishing Media

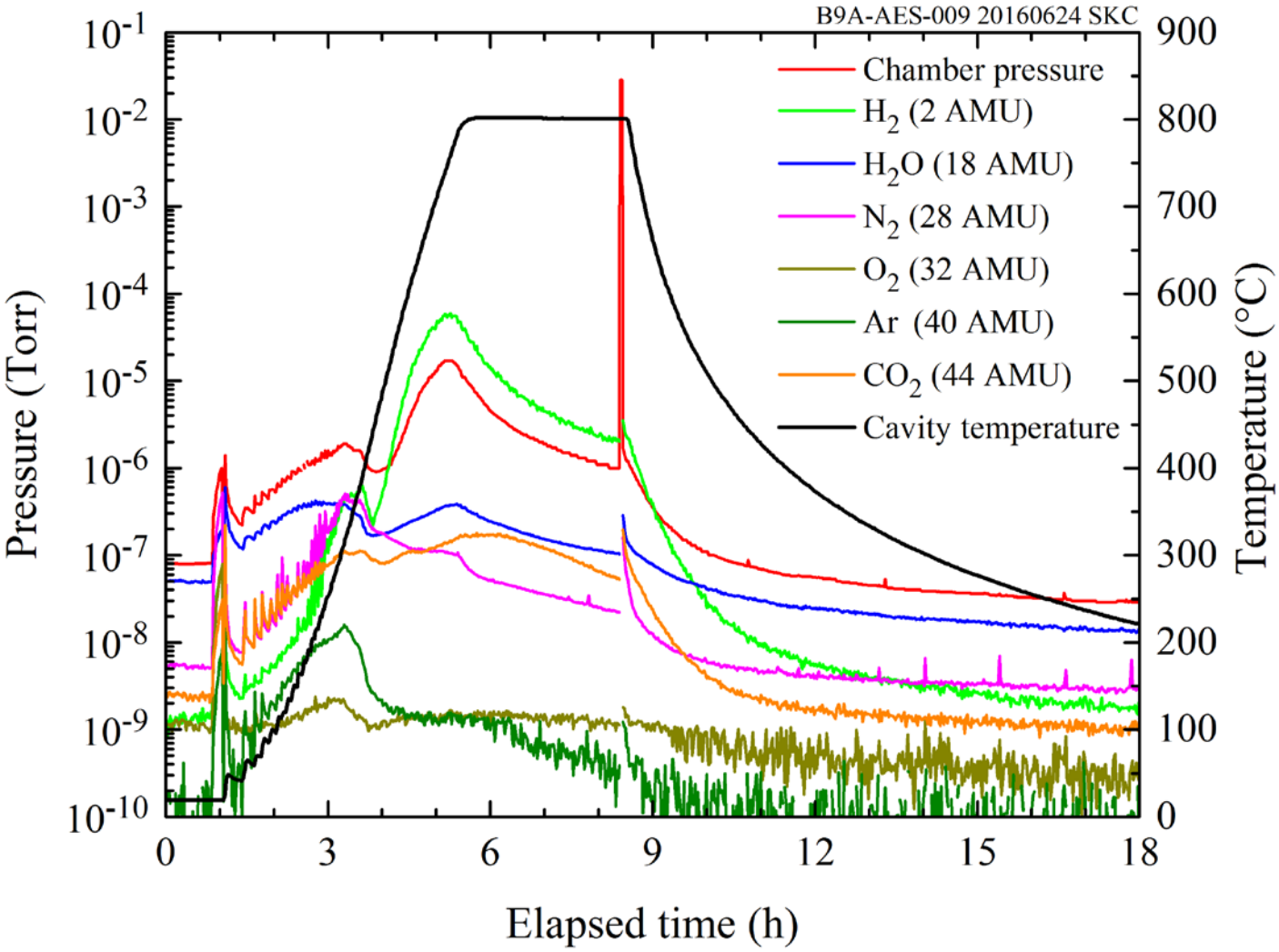


Hydrogen Degasification



IB4 High temperature vacuum furnace being loaded with a 1.3 GHz 9 cell cavity. The maximum operating temperature is 1200 C and the base vacuum is 10^{-8} Torr. High temperature furnaces are used to degas and dope cavities.

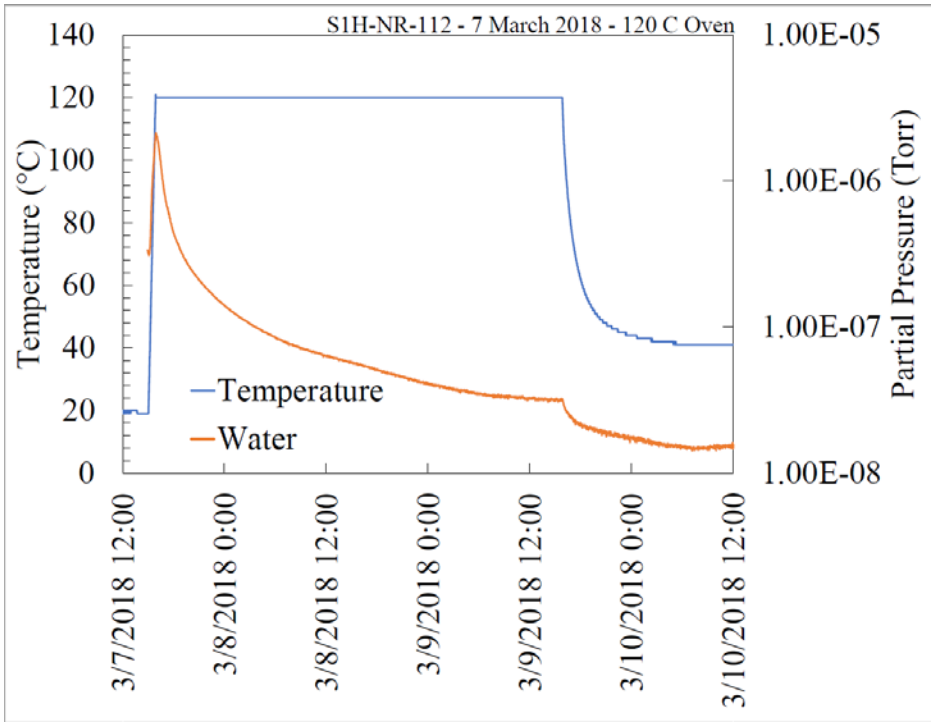
Hydrogen Degas and N2 Doping Cycle



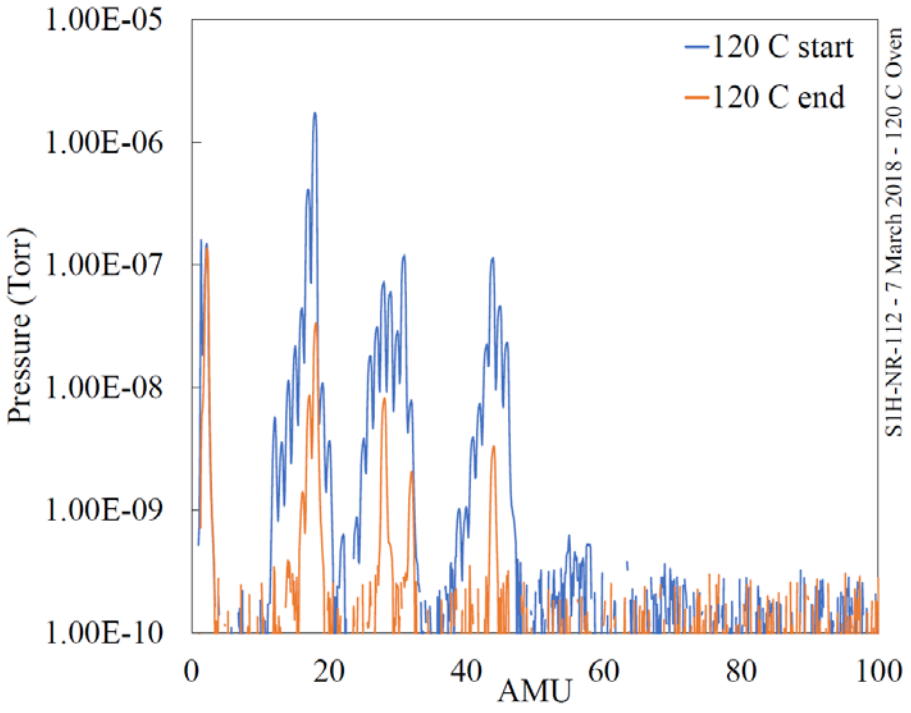
Low Temperature Baking

- Low temperature (<300C) ovens use hot-air circulation to heat cavities.
- UHV system maintains cavity vacuum and prevents particle migration.
- Used to mitigate multipacting and correct high-field Q-slope.

48 hour 120C Bake Cycle



Residual water removal

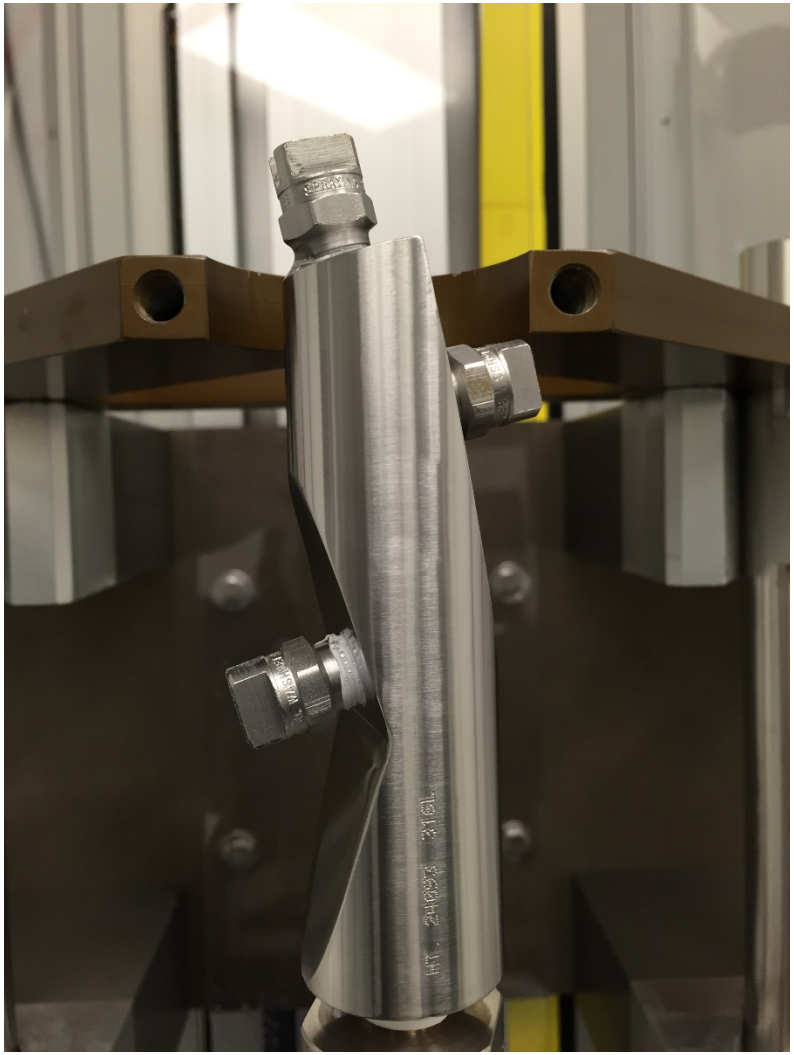


Before/after 120C RGA spectrum

High-pressure Rinsing (HPR)

Basic Parameters

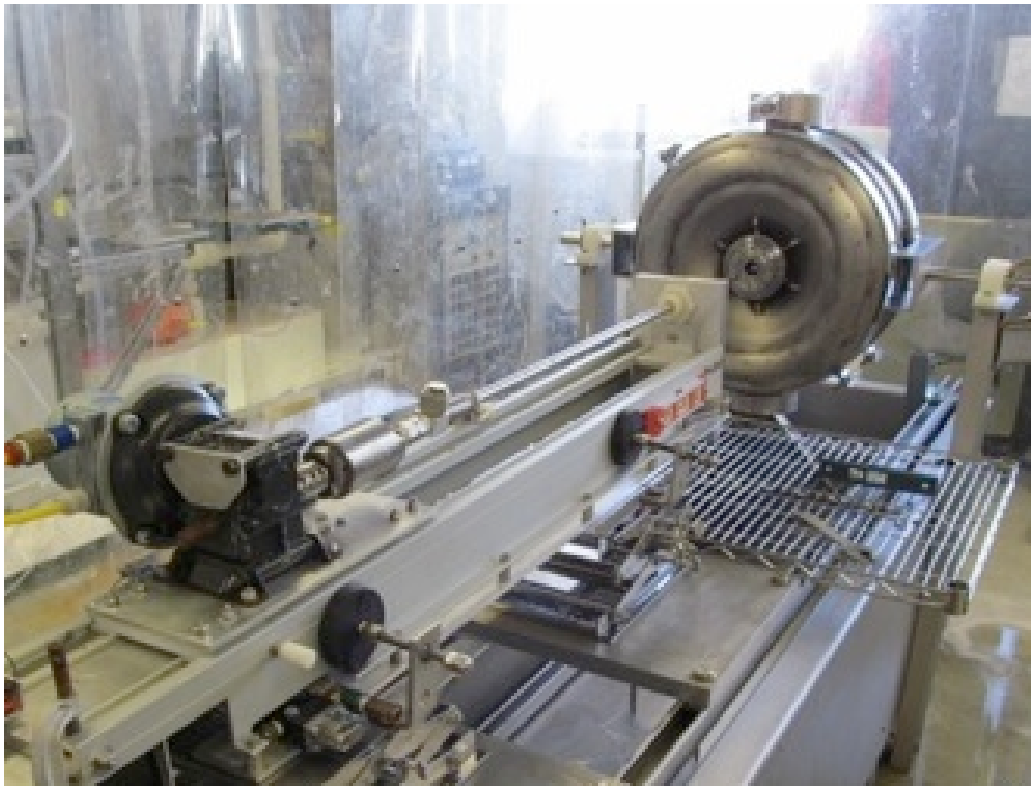
- ISO Class 4 Cleanroom
- 100 ATM Pressure
- 8-20 L/min
- Ultrapure water
  - Semi-conductor quality
  - >18 MOhm
  - 0.05 *um* filtration
  - < 10 ppb TOC
- 8-24 hour rinse cycles
- 10-30 sec. integrated dwell times
- Fan-jet or circular orifice nozzles
- All wetted materials SRF compatible.



650 MHz HPR nozzle

Spoke Cavity High Pressure Rinsing

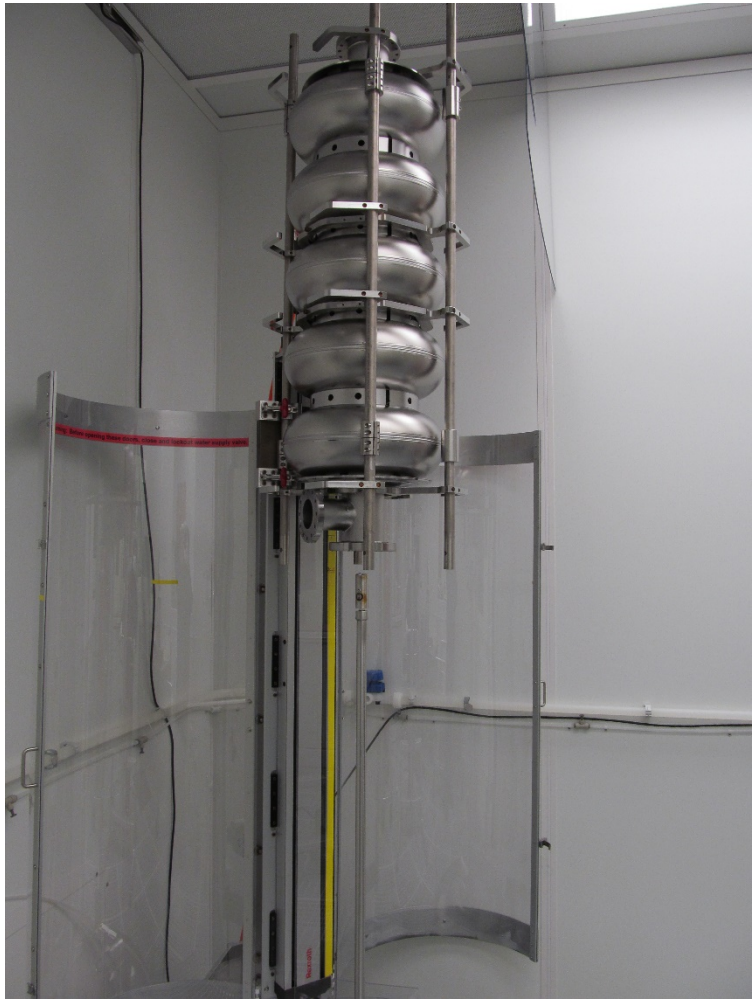
- Multiple rinse passes and orientations
- Complex geometry requires caution



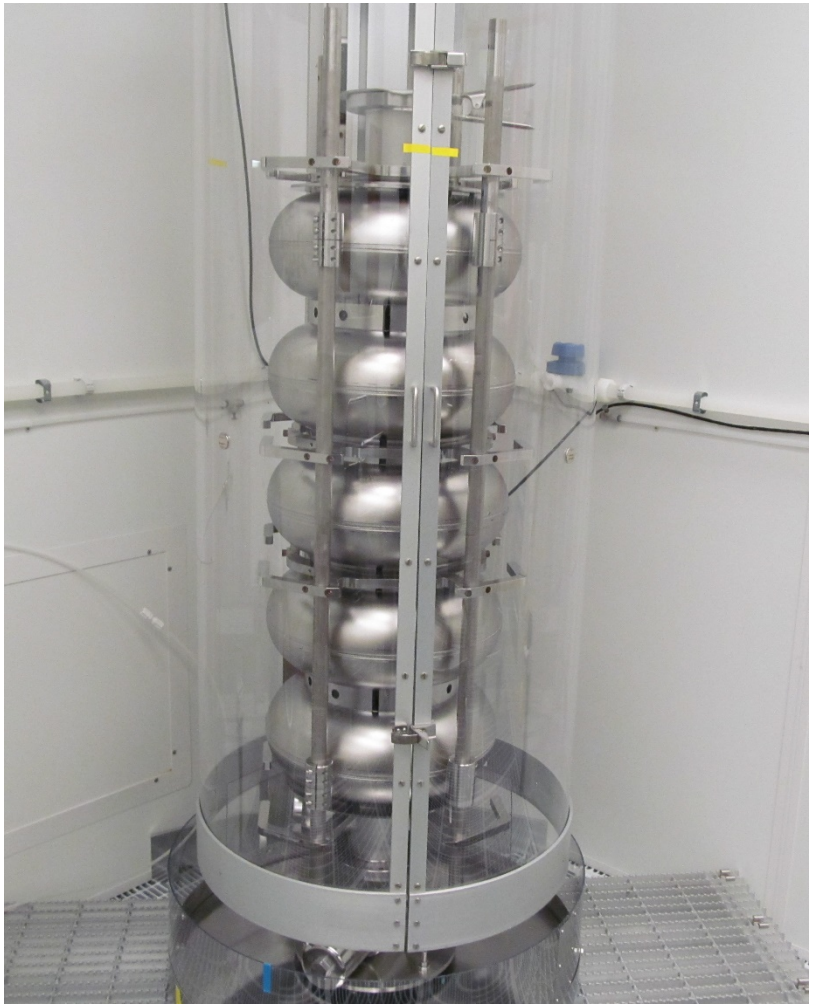
Horizontal orientation

Vertical orientation

650 MHz Elliptical Cavity High Pressure Rinsing



Cavity in top position



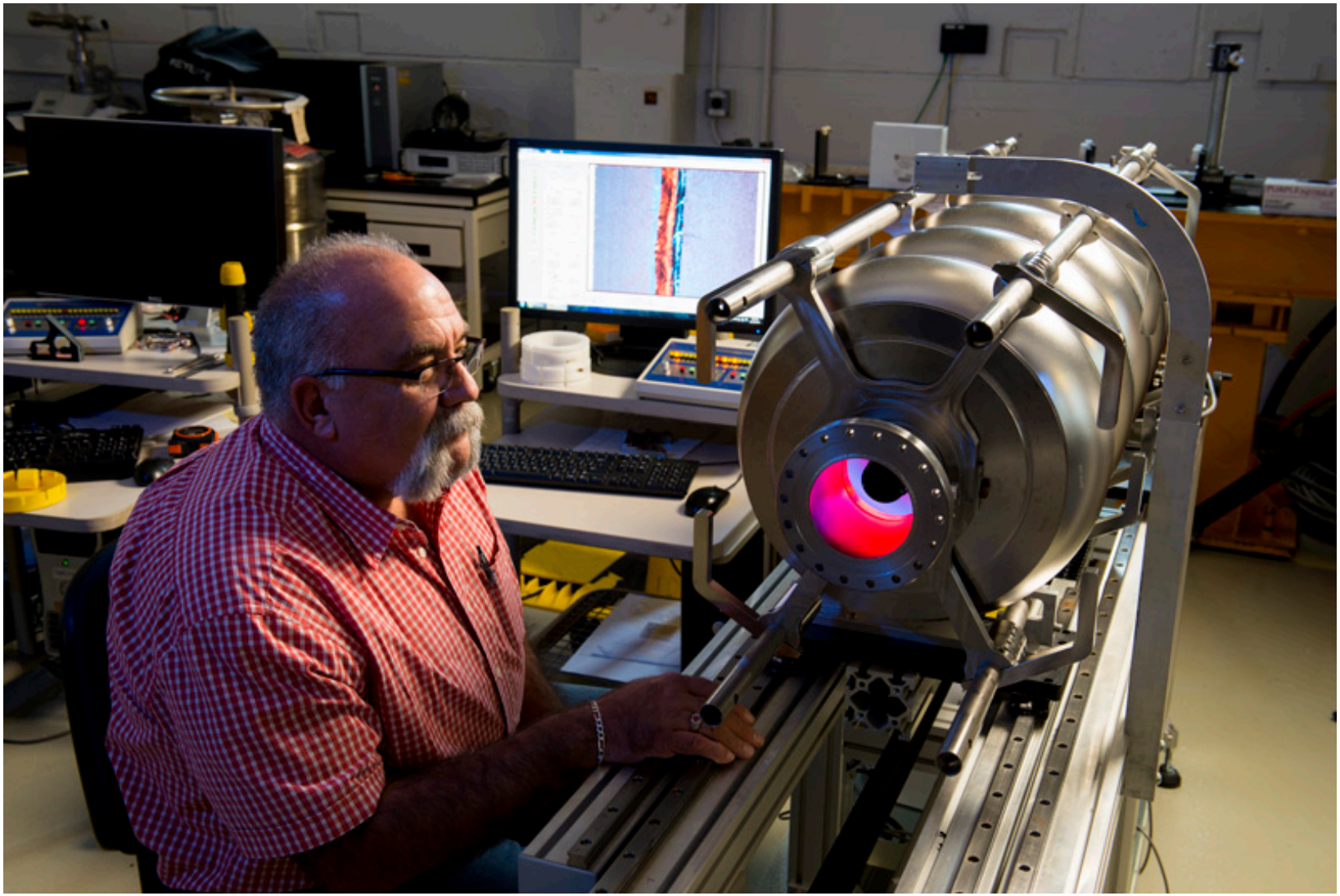
Cavity in bottom position

Cleanroom Assembly

Requirements

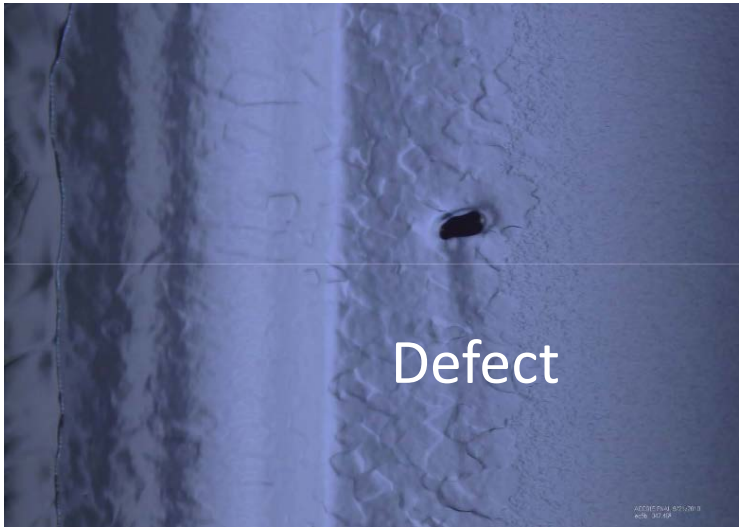
- ISO Class 4 or better environment
- High-level technical skills
- Patience
- Precise process controls
  - Component preparation
  - Assembly planning
  - Clear rejection criteria
  - Work-location monitoring
- Component compatibility
  - CR environment
  - SRF use
  - Ease of assembly
- Slow evacuation
- **Culture of SRF Technology**

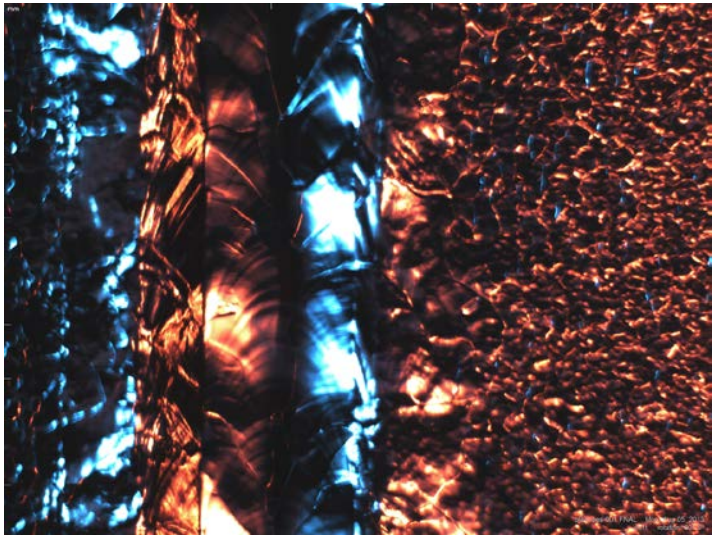
Optical Inspection Setup



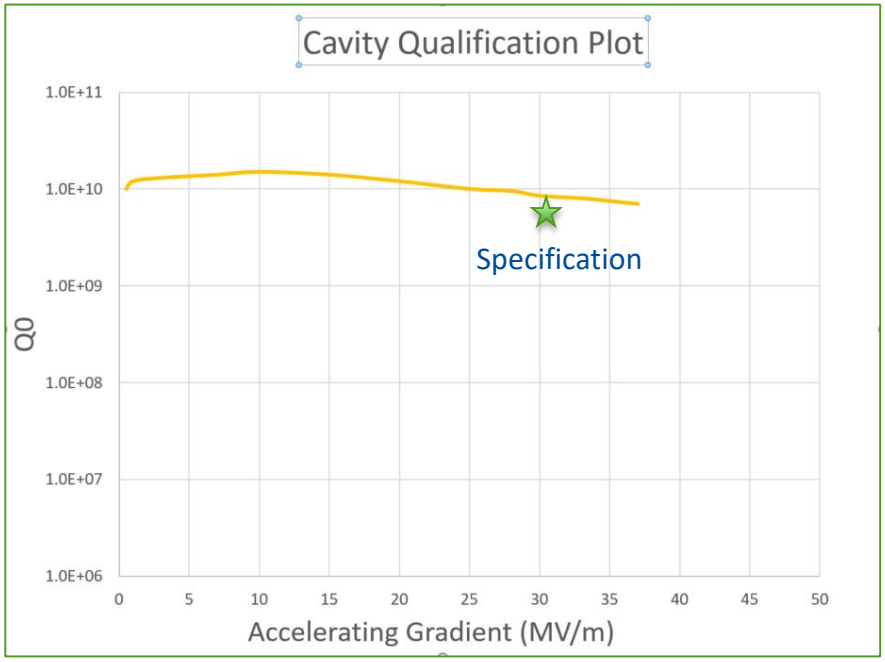
Optical Inspection Purpose

- Used as diagnostic
- Defect identification
- Repair technique guide
- Surface feature historical tracking
- Optimized for elliptical cavities

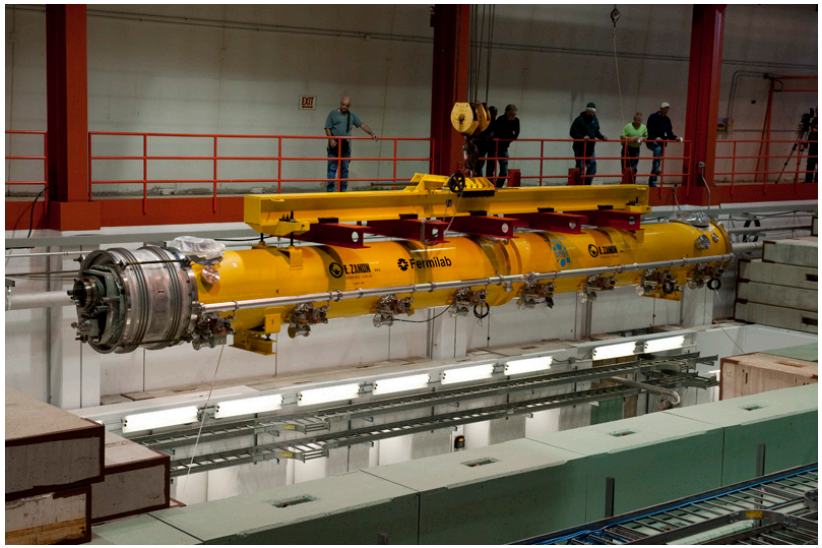




End Game



* n_{string} Cavities



The Reward – A high-performance cryomodule!