# High-Performance SC Cryomodules for CW Ion Accelerators

## LINAC 2010

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Physics Division

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# Contributors and Outline

## Outline

1. A few of the significant developments worldwide
2. ANL approach to CW SC Cryomodule

## Thank you

- Bob Laxdal – TRIUMF
- Amichay Perry – SARAF
- Alberto Facco – INFN Legnaro
- Thomas Nicol, Ivan Gonin – FNAL
- Evgeny Zaplatin – Jülich/IFMIF
- Walter Hartung - MSU

# SC Ion Accelerators Around the Globe

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| Location | Cavity Type | Frequency (MHz) | Beta (v/c) | # Cavities |
|---|---|---|---|---|
| Spiral-2/Ganil | QWR | 88 | 0.07,0.12 | 26 |
| MSU/ReA3 | QWR | 80.5 | 0.04, 0.085 | 15 |
| SARAF/Soreq | HWR | 176 | 0.09 | 6 |
| Triumf | QWR | 80 | 0.06-0.07 | 40 |
| New Delhi | QWR | 97 | 0.08 | 14 |
| Canberra | Split-ring, QWR | 150.4 | 0.09-0.11 | 14 |
| INFN Legnaro | QWR | 80, 160 | 0.05-0.13 | 74 |
| Kansas State | Split-ring | 96, 97 | 0.06-0.1 | 14 |
| JAERI | QWR | 130, 260 | 0.1 | 46 |
| U. Washington | QWR | 150 | 0.1-0.2 | 36 |
| Florida State | Split-ring | 97 | 0.07-0.1 | 15 |
| Stony Brook | Split-ring, QWR | 150.4 | 0.07-0.1 | 40 |
| Argonne | Split-ring, QWR | 48, 72, 97 | 0.01-0.10 | 64 |

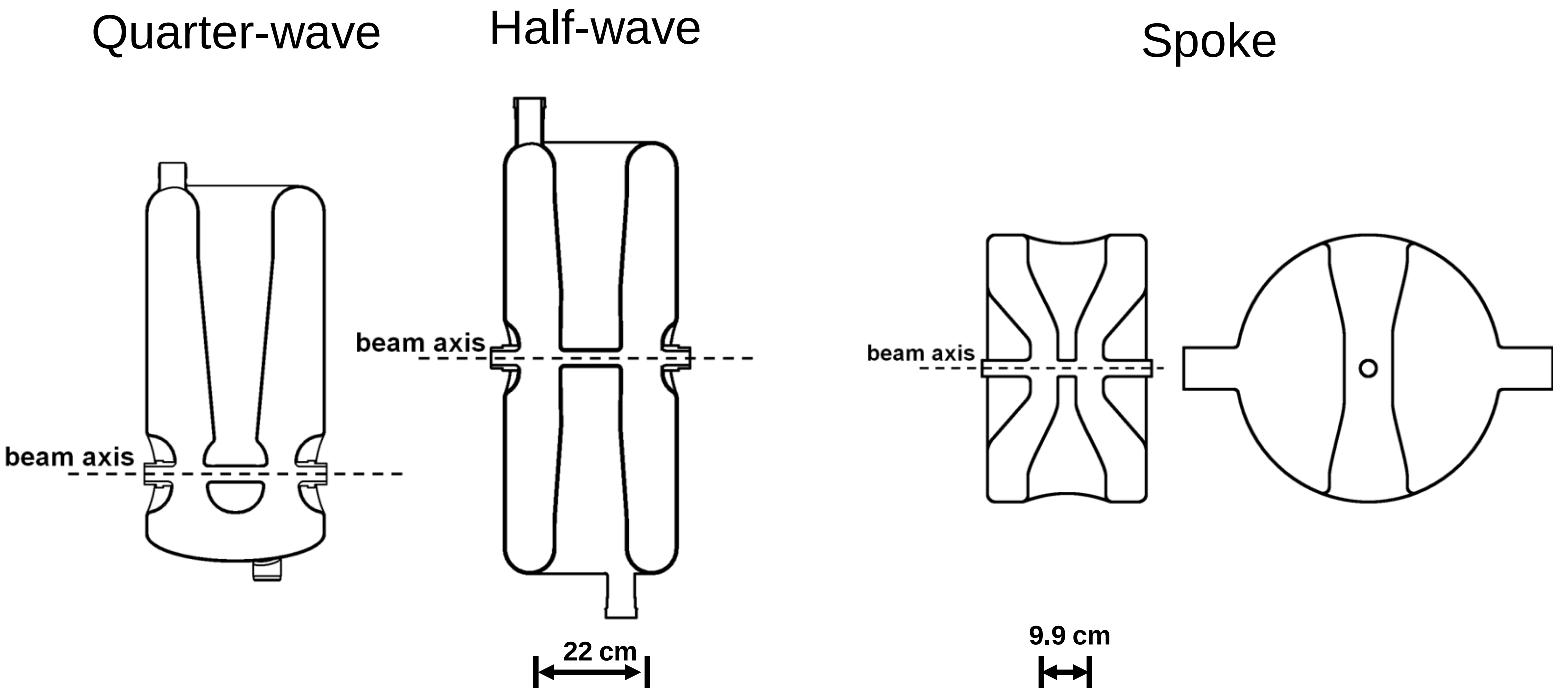
| Operations & Upgrades | Under construction | No longer operating |
|---|---|---|

# SC Ion Accelerators Around the Globe

| Applications | Frequency (MHz) | Beta (v/c) | Particle type | # Cavities (total cavities) | Duty Factor |
|---|---|---|---|---|---|
| CERN Rex-Isolde | 101 | 0.063, 0.103 | Heavy-ion | 32 | CW |
| MSU FRIB | 322 (HWR) | 0.285, 0.52 | Proton to Heavy-Ion | 336 | CW |
| Project X | 325 (Spoke) | 0.2-0.6 | Proton | 88 | CW |
| ESS | 352 (Spoke) | 0.45 | Proton | 42 | Pulsed |
| EURISOL | 176, 352 | 0.09-0.36 | Proton, Light ion | 108 | CW |
| IFMIF | 175 (HWR) | 0.094, 0.17 | Deuteron | 42 | CW |

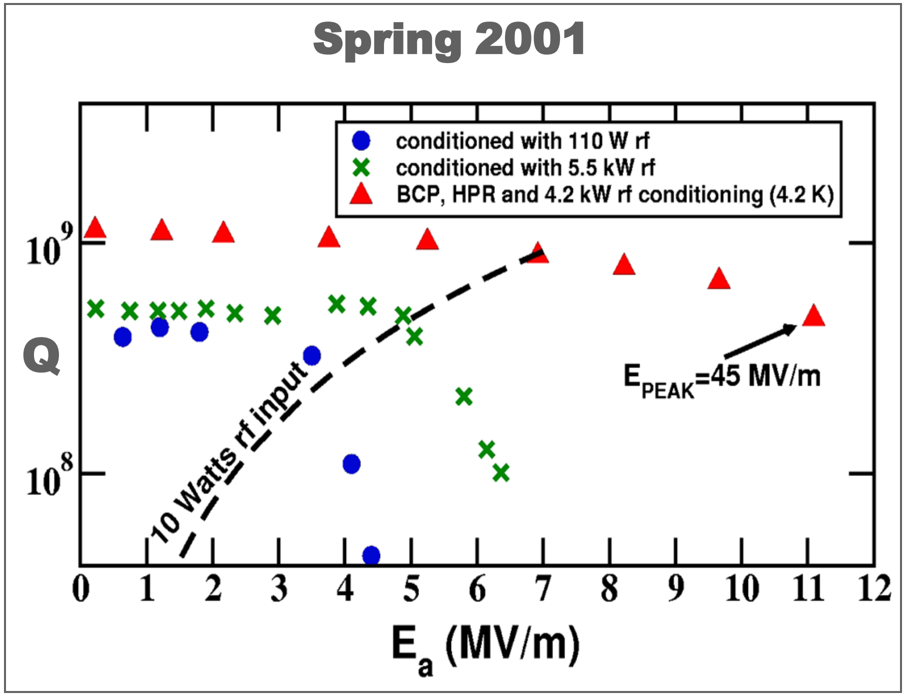
Planned

# Modern low-beta TEM, a.k.a "drift-tube", cavities




- Operated in lowest TEM-like mode
- $\lambda/4$ or $\lambda/2$ structures
- Physical dimensions $0.1<\ell<1$ meter
- Frequencies 50-800 MHz
- 4 Kelvin operation (Future 2 K @ f~325 MHz and above?)

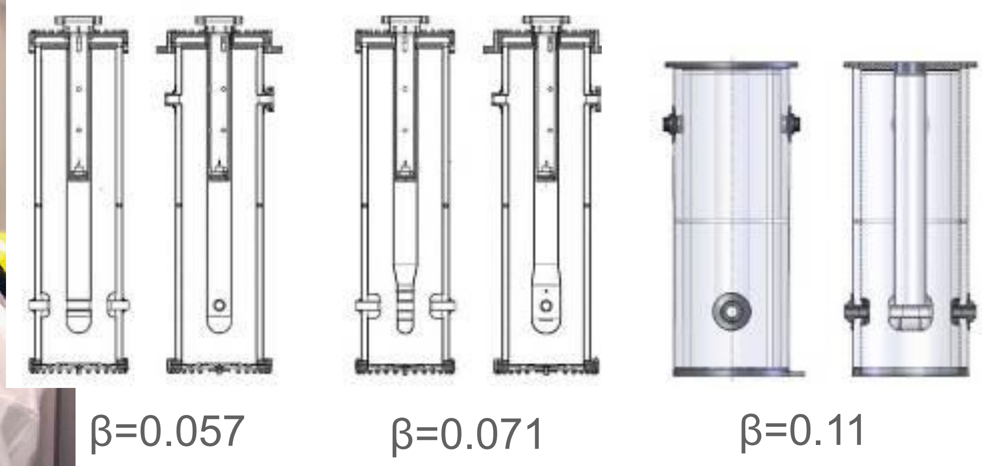
# Clean techniques for low-β SRF cavity 10 years ago

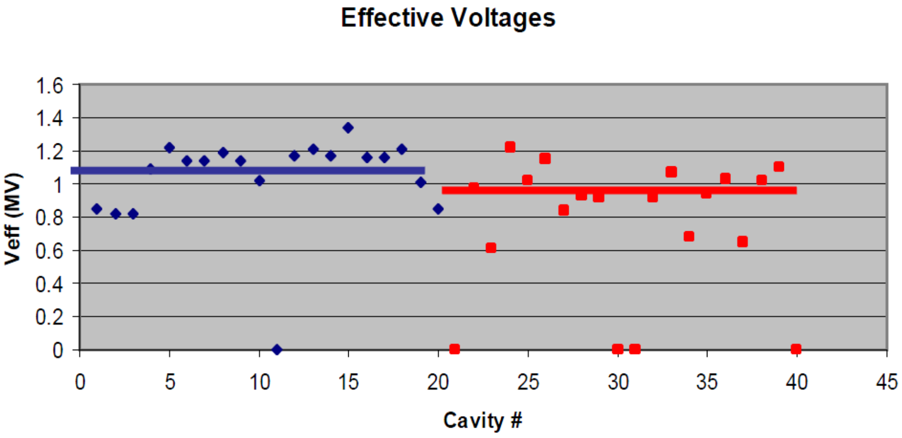



**Dramatic performance increase from HPR consistent and repeatable if cavity kept clean**

# ISAC-II Phase II SC-Linac Upgrade and Status

MO202

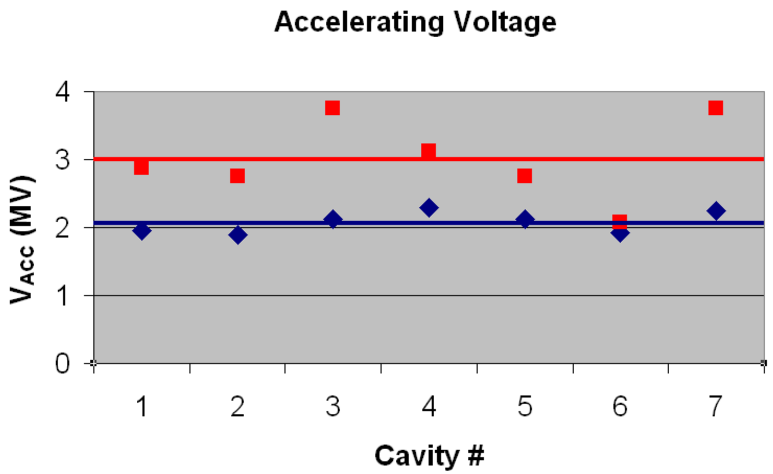



- Eight cryomodules containing **40 quarter-wave cavities** providing $V_{ACC}$~1 MV/cavity
- Clean room assembly of the complete cryomodule

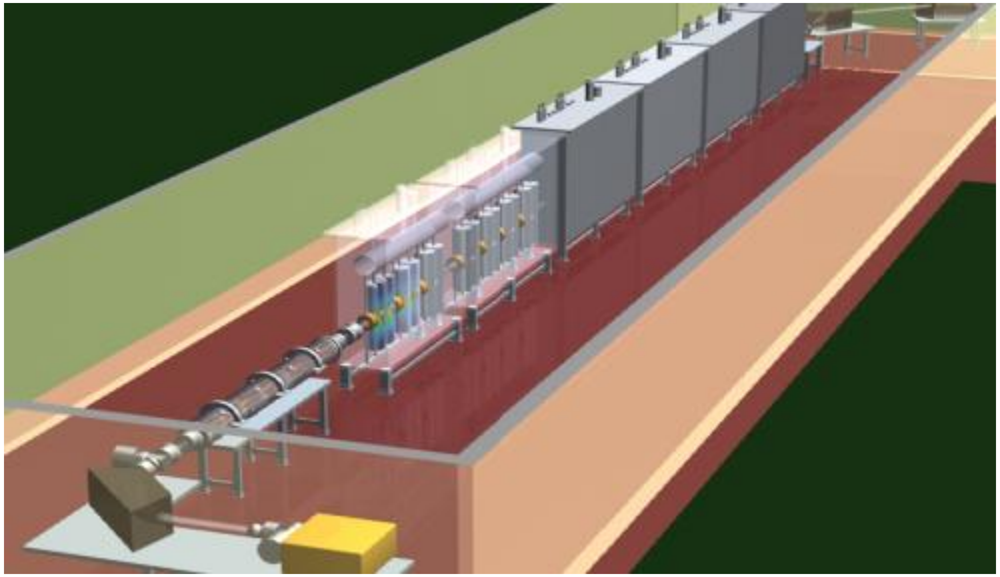
# ATLAS SC Ion Linac at ANL: Upgrade and Status

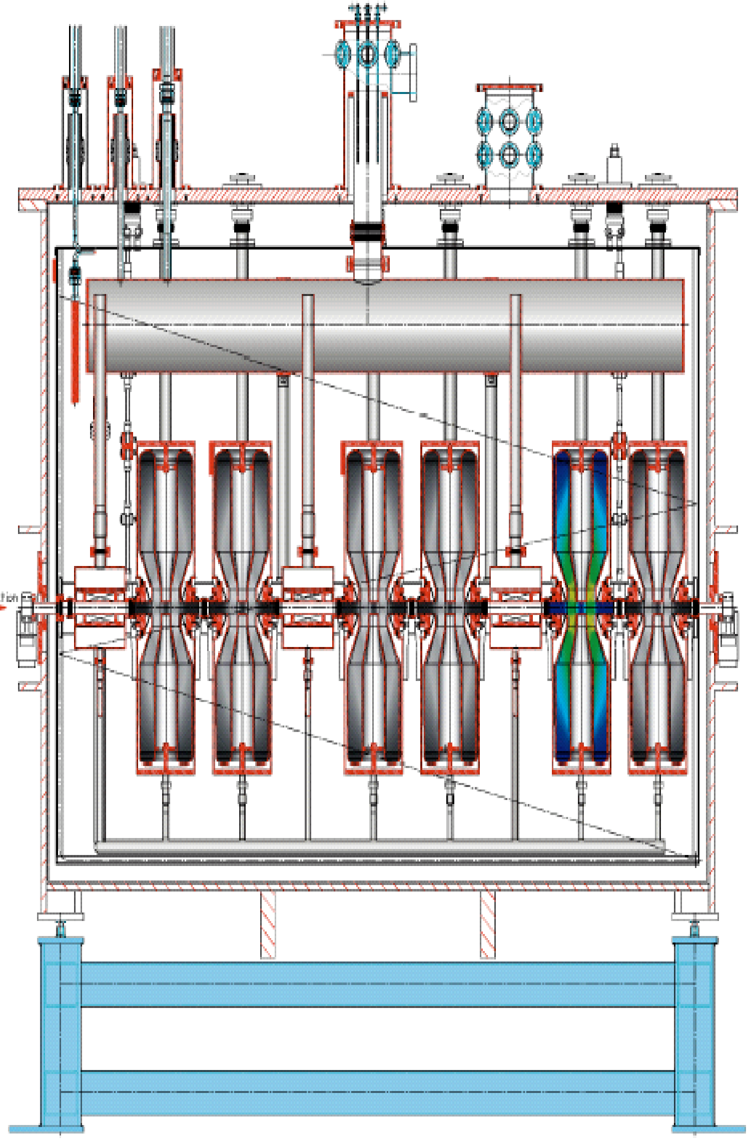
- 1 Cryomodule, seven **β=0.15 quarter-wave cavities** added to the ATLAS heavy ion linac
- Separate cavity vacuum space
- Maximum voltages of **3.75 MV per cavity** have been achieved ($E_{PEAK}$ = 48 MV/m, $B_{PEAK}$ = 88 mT)
- Real gradient for operational cavities of **14.5 MV in 4.6 m module length**; new standard for low-beta SC linacs



# SARAF at Soreq

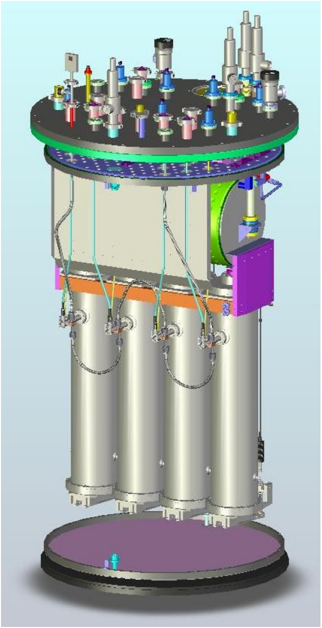
- Six 176 MHz β=0.09 **half-wave cavities** fabricated in industry by Accel (now RI); first TEM λ/2 structures for beam acceleration
- **CW 1 mA proton beams** accelerated to 3.7 MeV

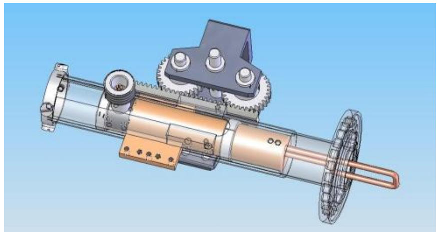


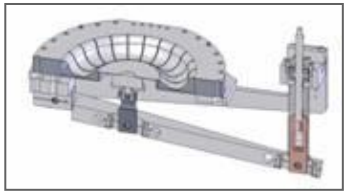


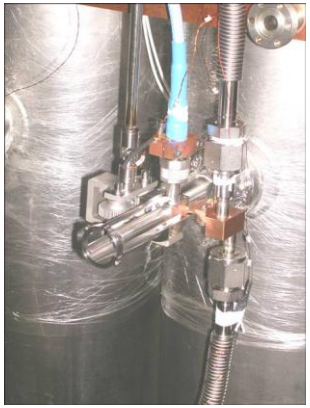
# INFN Legnaro: ALPI-PIAVE low-beta section upgrade

- Aim: Double energy gain at minimum cost by cooling rf couplers
- Status: 1 cryostat successfully upgraded and operated at 6 MV/m
- Before: $V_{ACC}$=11 MV, 20 QWR's,
- After (goal): $V_{ACC}$=21-25 MV, 24 QWR's



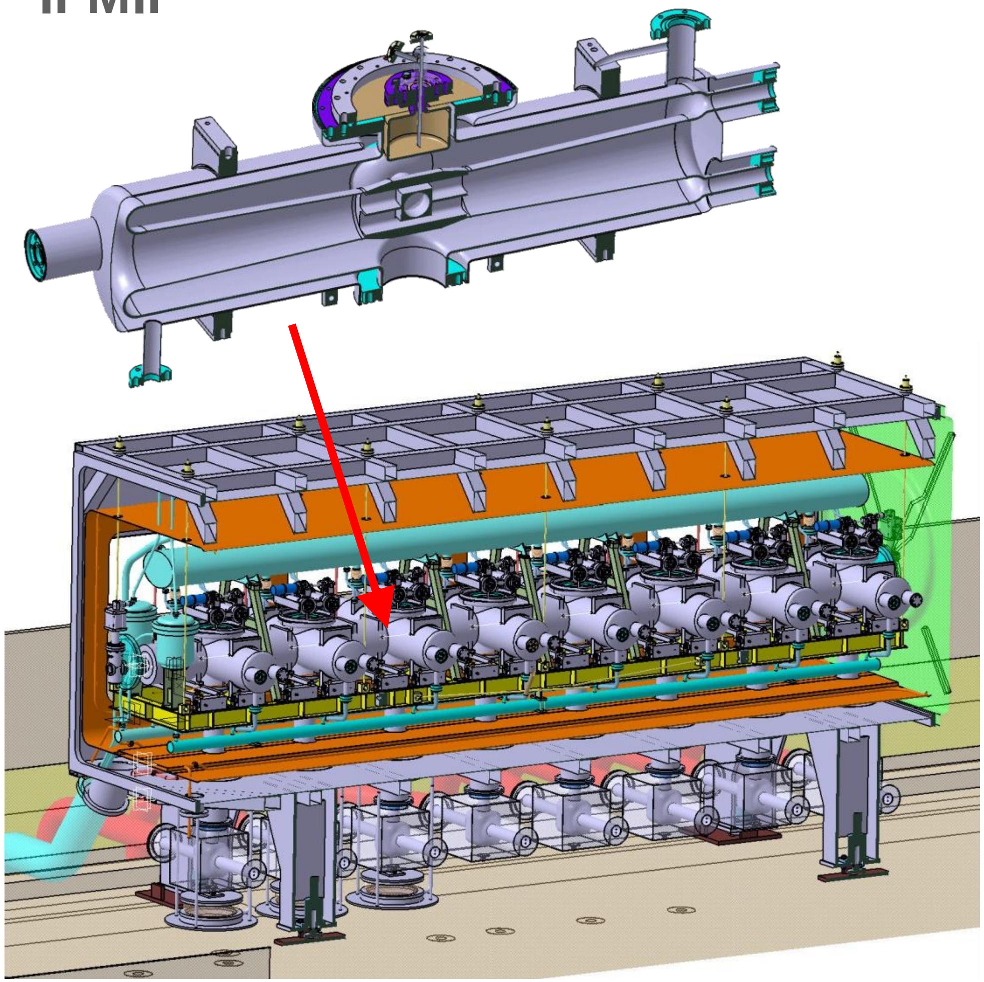






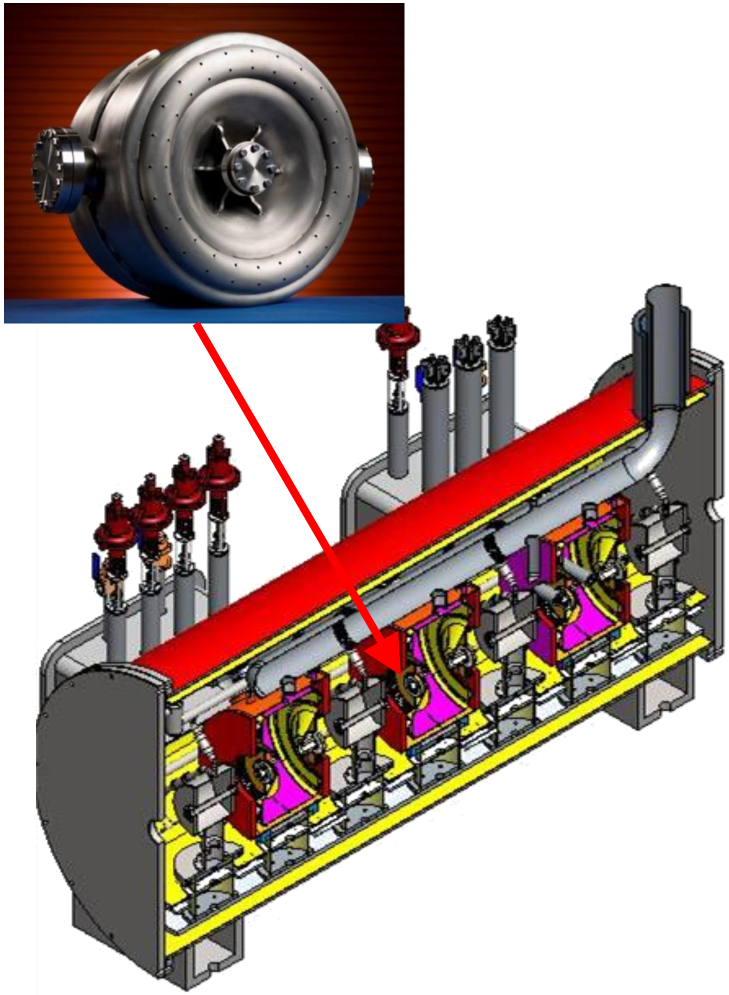
# Prototypes under design/construction

## IFMIF



- 8 HWR‘s 175 MHz β=0.094
- ~70 kW RF power per cavity!

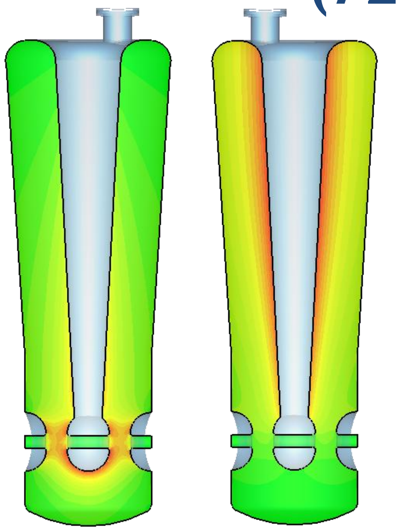
## Project X



- 3 single-spoke 325 MHz β=0.2 cavities/4 SC solenoids

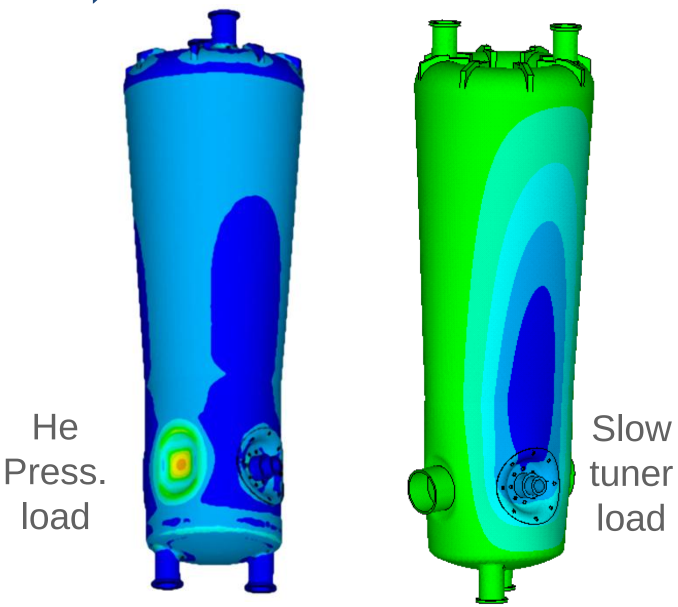
# Part II. ANL approach to CW SC Cryomodule

# ANL Design for a Low-Beta SC Cavity (72.75 MHz, $\beta$=0.077)



$E_p/E_{acc}$=3.25
$L_{eff}$=20 cm

$\frac{B_p}{E_{acc}} = 4.8 \frac{mT}{MV/m}$

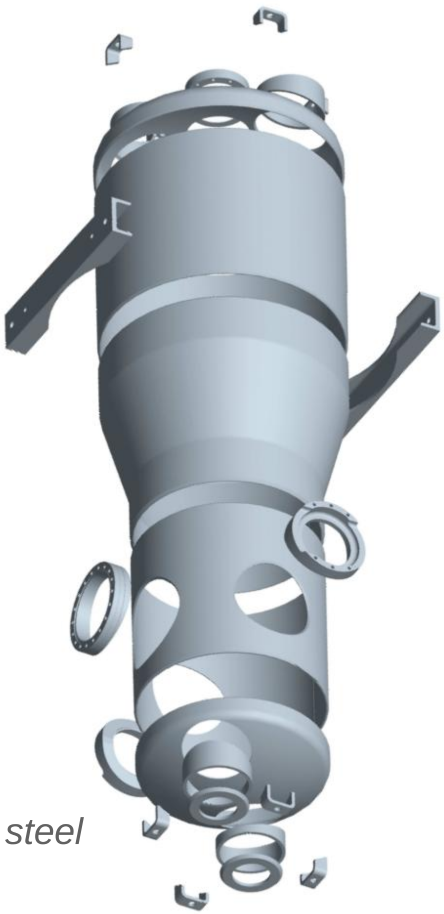



$\Delta f/\Delta p$~1.6 Hz/Torr

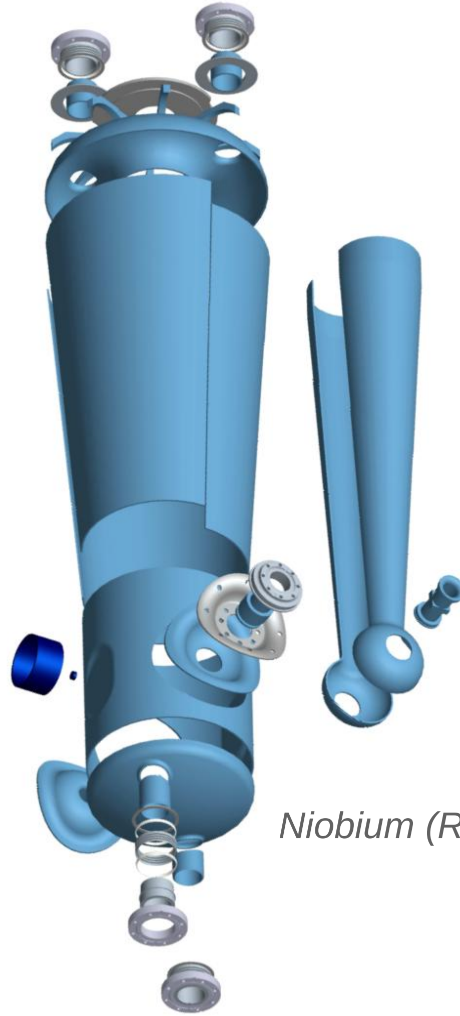
AES/ANL

- Electromagnetic Design
  - Minimize surface fields consistent with fabrication/processing/cleaning
  - Steering corrected drift-tube face to eliminate beam steering
- Mechanical Design
  - Below niobium yield cold for all normal conditions
  - 4 K system, moderate beam loading
    - ***Null helium pressure sensitivity***
    - Increase pendulum mode frequency with modest stiffening

# ANL Design for a Low-Beta SC Cavity



*Stainless steel*



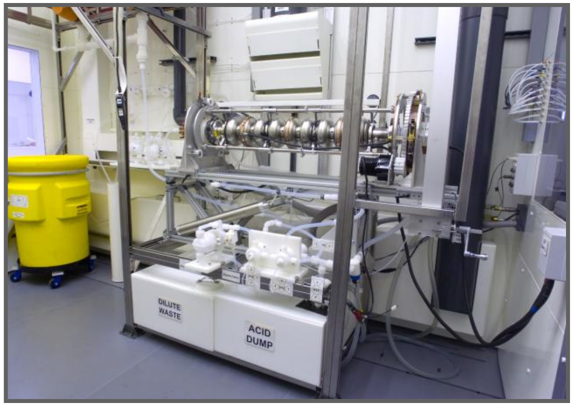
*Niobium (RRR250)*

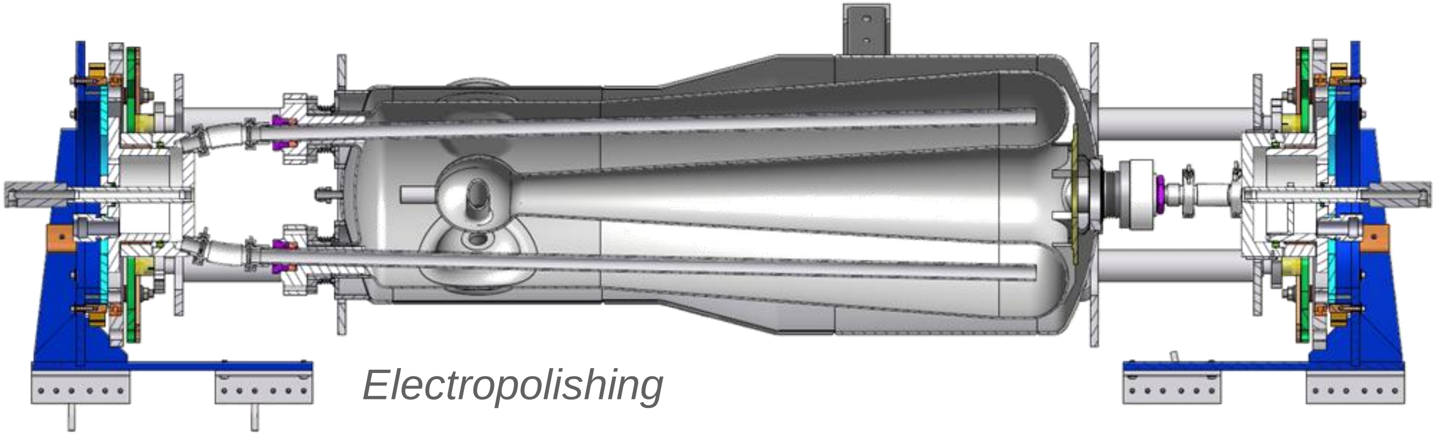
*Complete Assembly*

- Niobium is hydroformed or deep drawn all with blended transitions
- Stainless steel helium vessel assembled around the e-beam welded niobium cavity

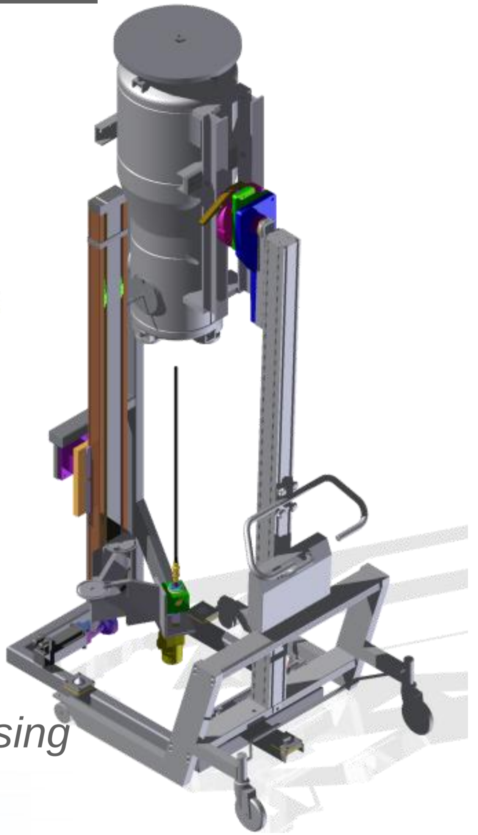
# ANL Processing for a Low-Beta SC Cavity

- Final electropolishing on complete jacketed cavity
  - Similar to ILC 9-cell EP
  - Direct water cooling built in
- Why not BCP?
  - EP demonstrated statistically better for niobium approaching rf limits
  - EP can be repeated without making surface progressively rougher



*Electropolishing*

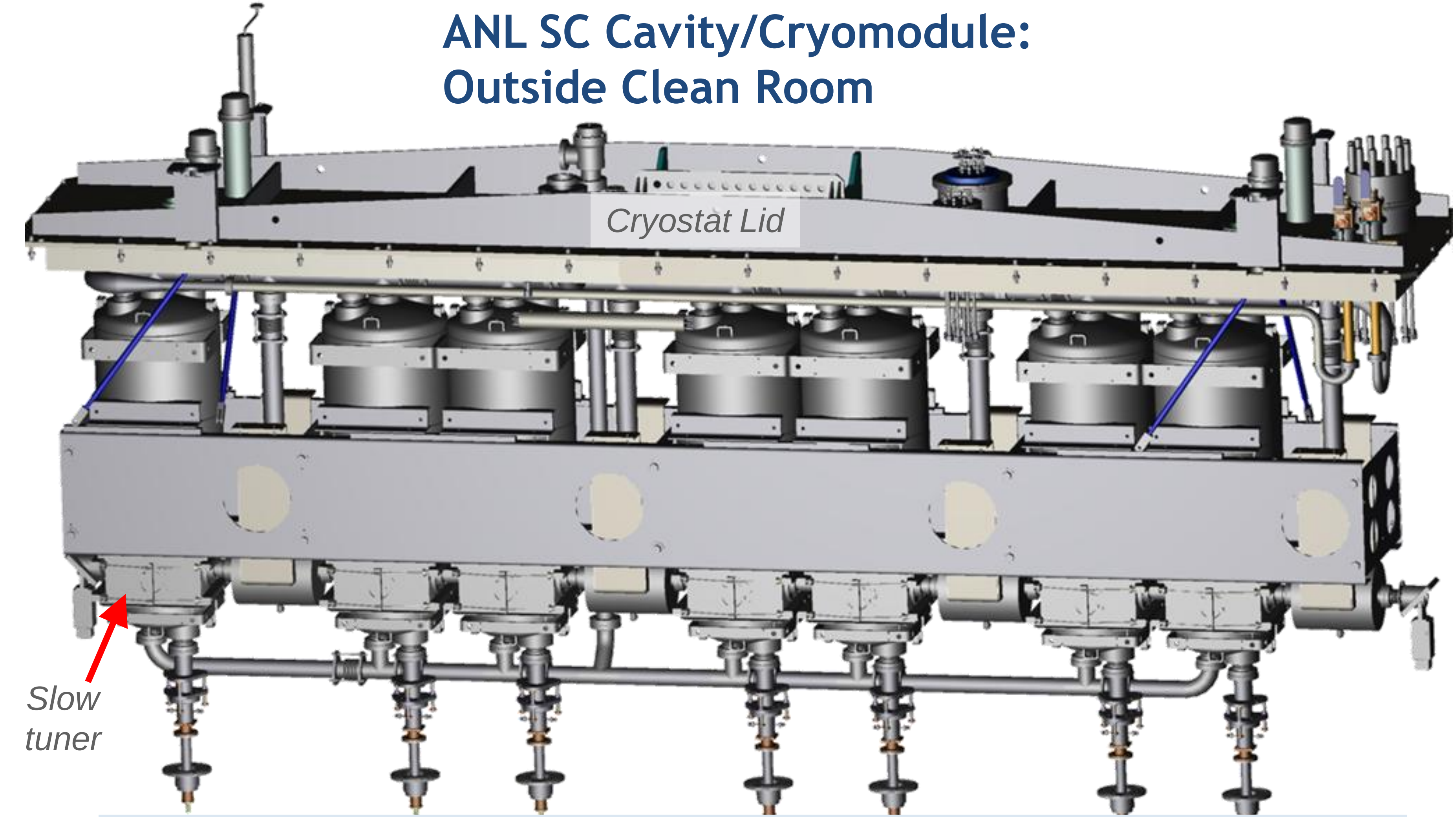


*High-pressure rinsing*

# ANL SC Cavity/Cryomodule: Clean Room Assembly

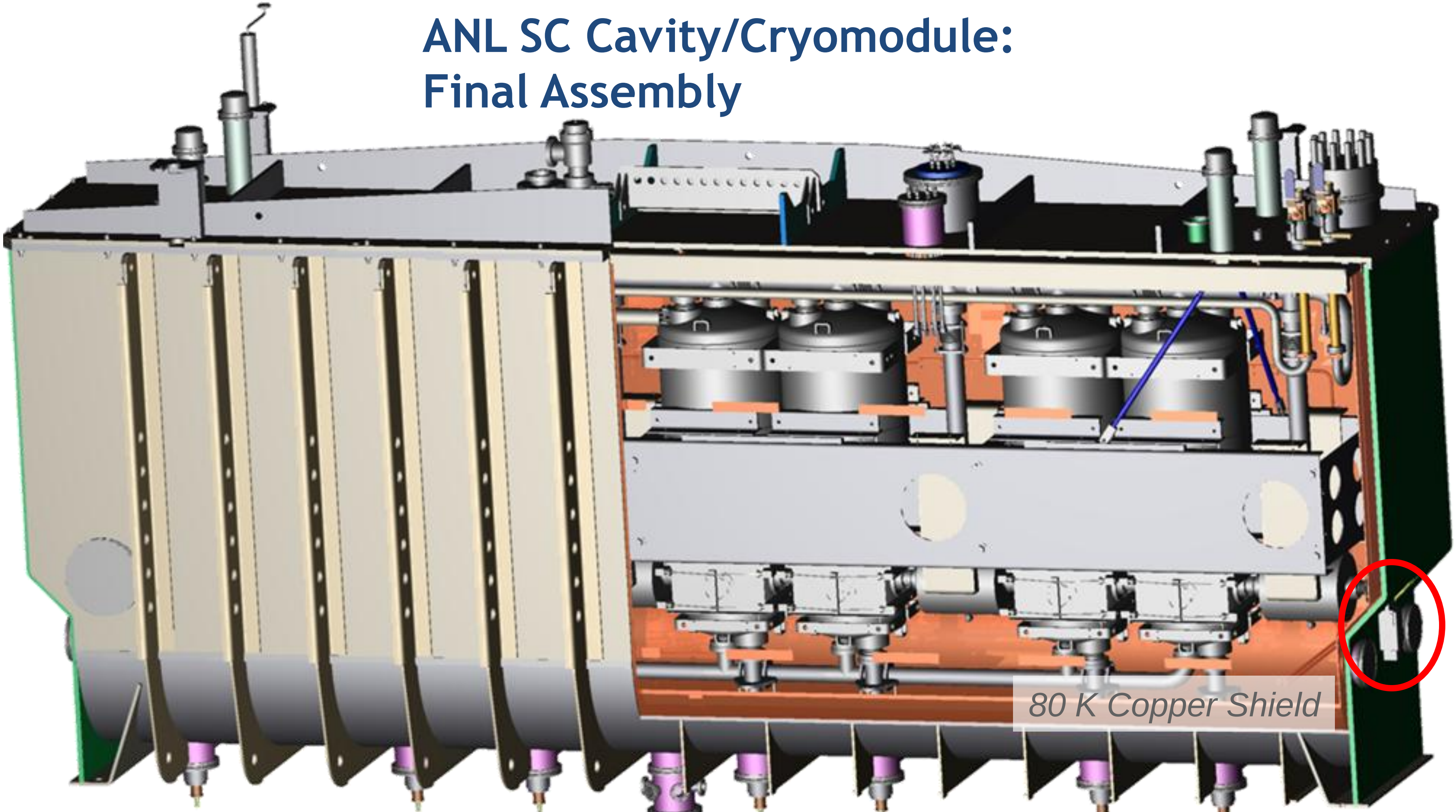

- Minimize parts required inside the clean room:
  - Cavities
  - Solenoids
  - Cold Section of Coupler (4 kW E-field)
  - Vacuum lines and valves

# ANL SC Cavity/Cryomodule: Outside Clean Room




- Assemble remaining components outside clean room:
  - Cryogenics (4.5 K helium, 150 Watts, 15 W static load)
  - Tuners (30 kHz pneumatic slow tuner, fast piezo electric)
  - Cryostat lid

# ANL SC Cavity/Cryomodule: Final Assembly



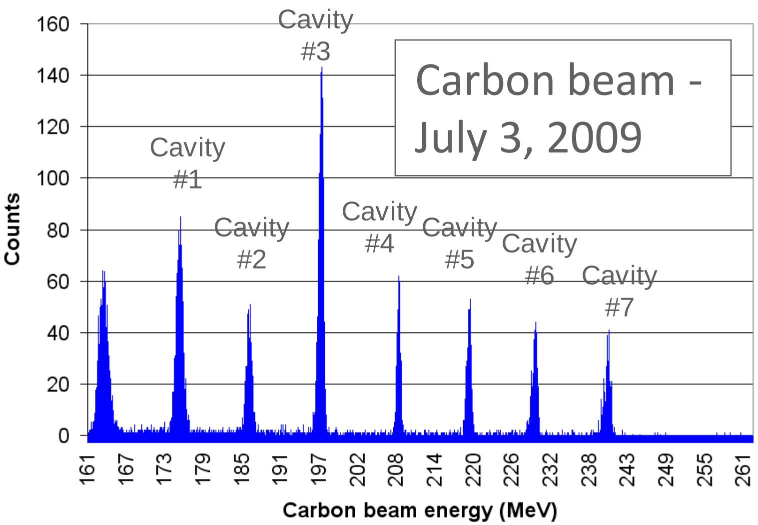

- Angled end walls for beam valves; also used for FRIB, Rex-Isolde
- Main features
  - Long (5 m) cryomodule, high packing factor
  - Top loading; easy access to cavities
  - 80 K Copper, magnetic shields, multi-layer insulation permanent in lower section of cryomodule
  - *Goal: 2.5 MV/cavity, 17.5 MV in 5 meters*

# Into the tunnel…

Mock Assembly - January 23, 2009

Into the tunnel - June 1, 2009

Final Assembly - March 13, 2009




Carbon beam - July 3, 2009

# Summary

- Major improvements in SRF technology for ion linacs in the last decade
  - Sophisticated designs
  - Clean room techniques
  - Improved cavity performance

- New directions for SC ion linacs
  - **Upgrades and new machines for basic science**
  - **Very high intensity CW light ion drivers for medicine, national security, and accelerator driven systems**

- The ANL approach
  - Low frequency optimized cavities
  - Large voltage gain per cavity, high quality factor (Q)
  - High real estate gradient for cryomodules

- New high performance SC cryomodules well positioned for next generation of high-current CW ion linacs