Cornell's ERL Main Linac Cryomodule: Design, Construction and Results

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on behalf of
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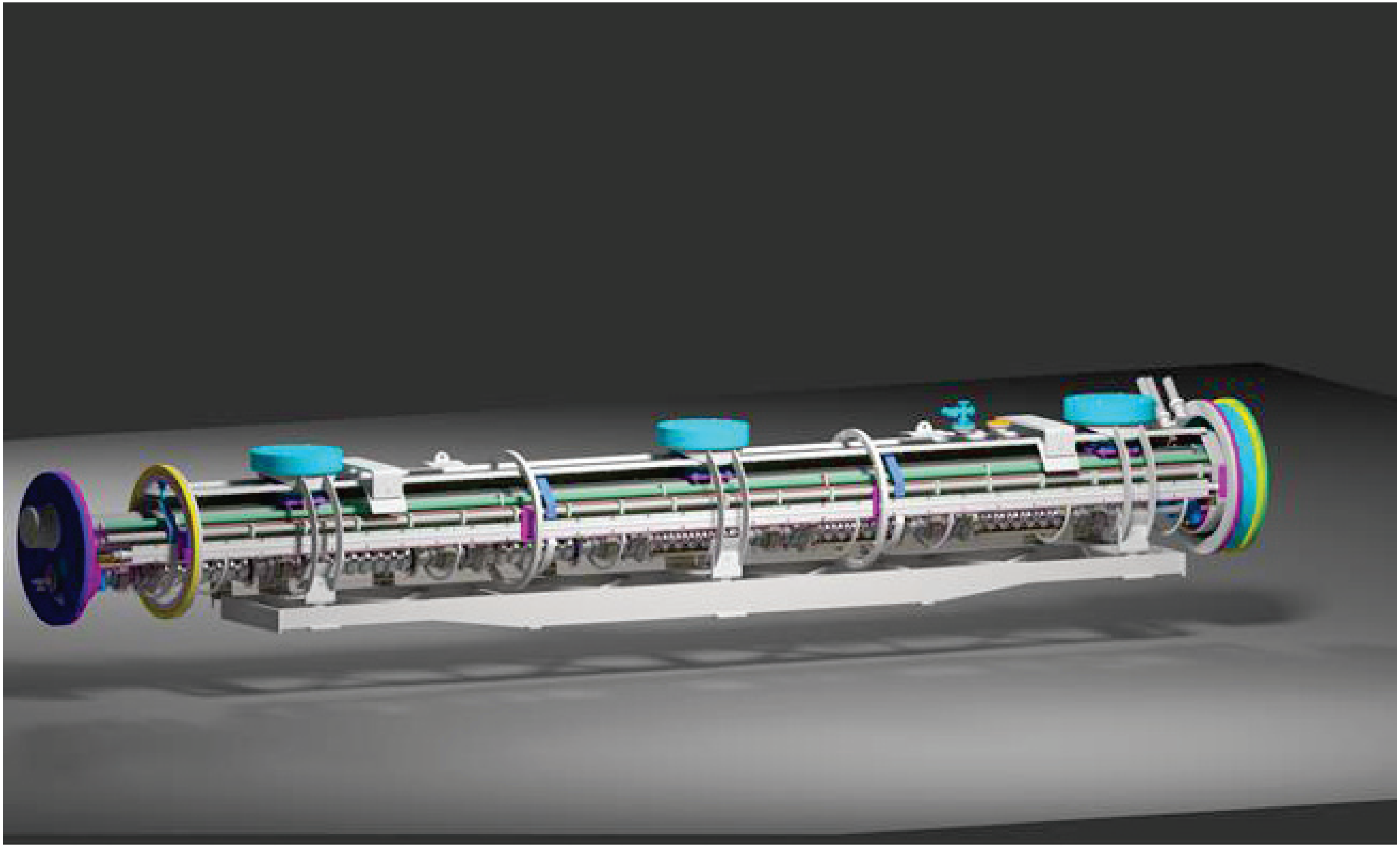
Cornell's ERL Main Linac Cryomodule



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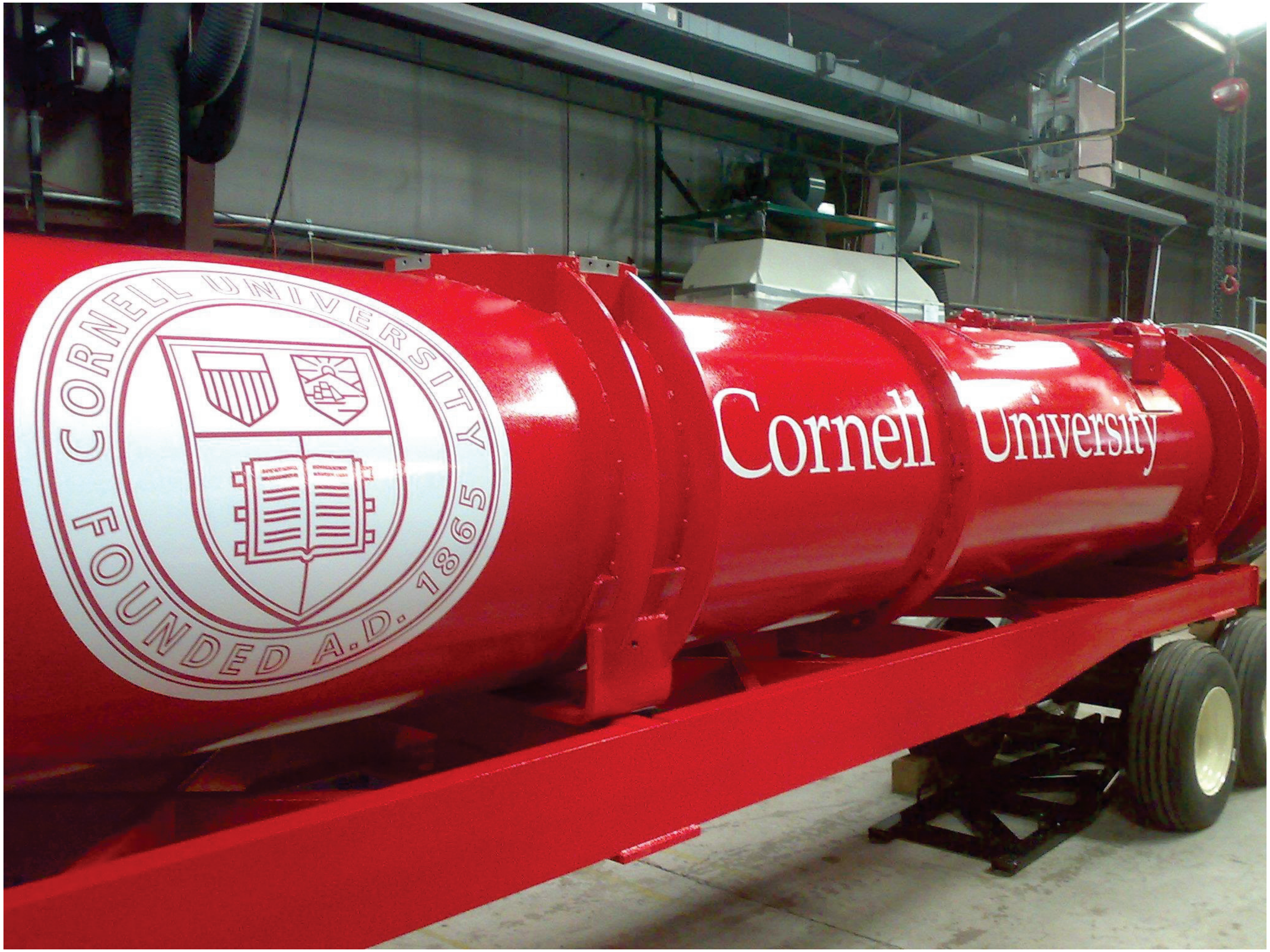
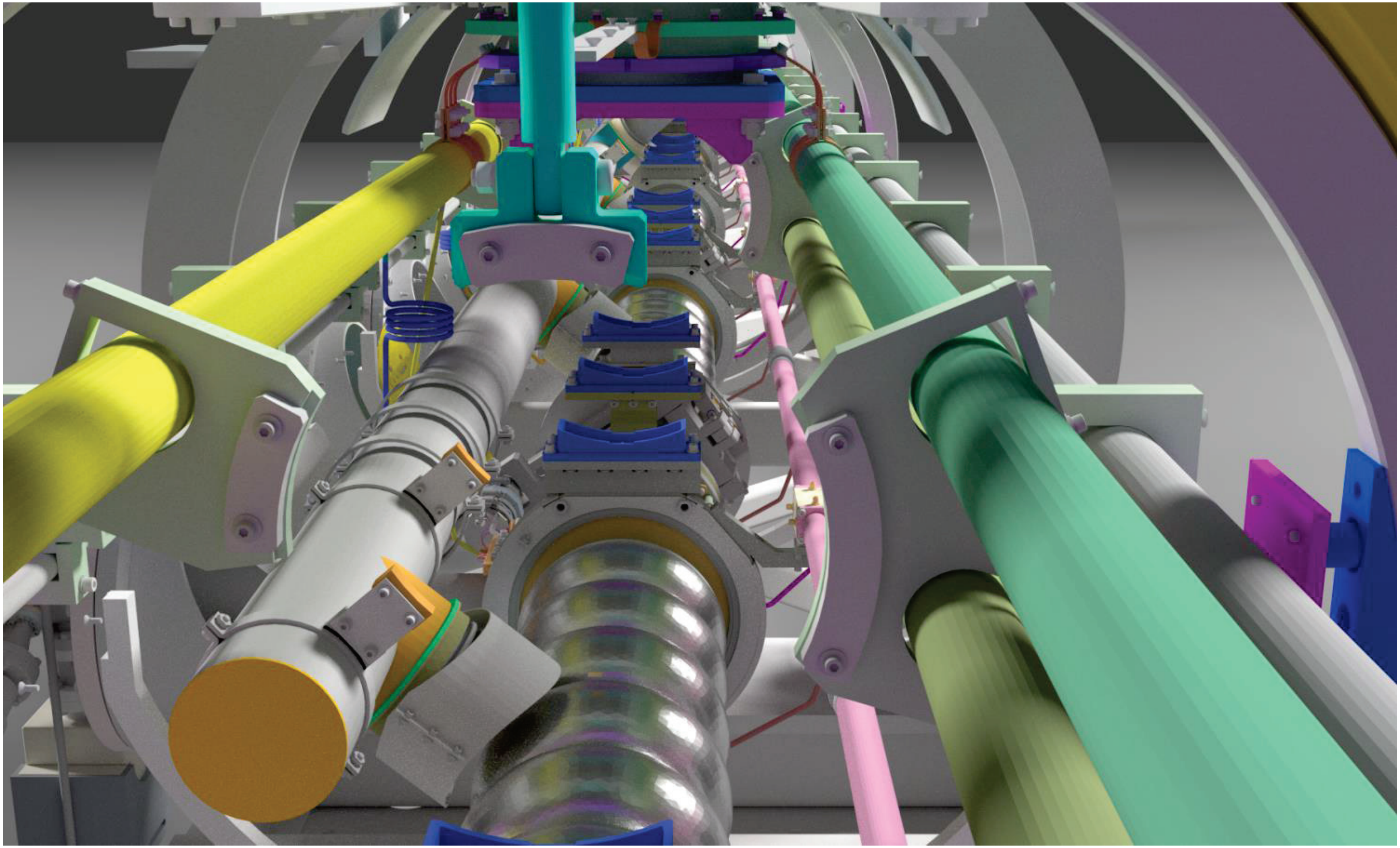
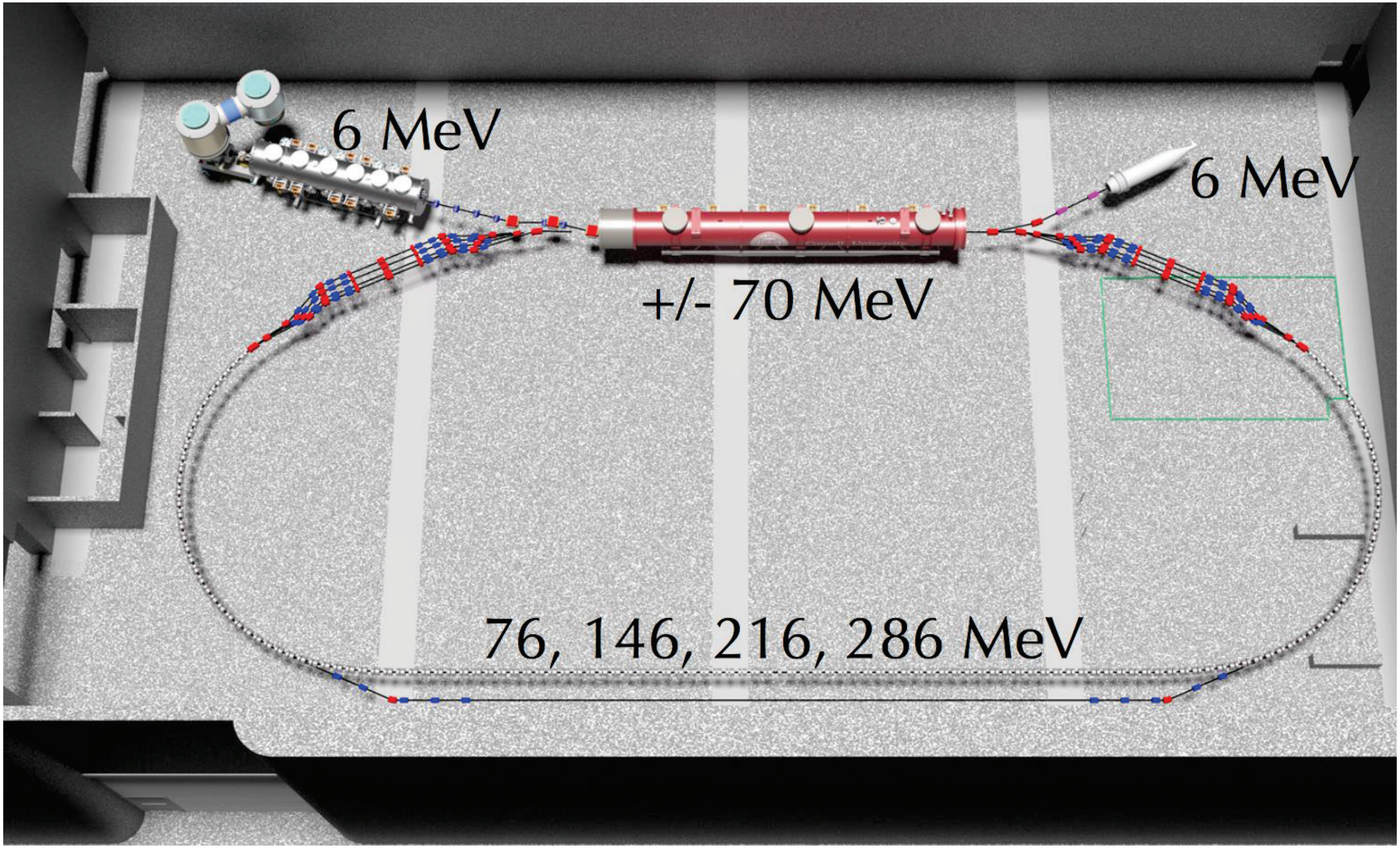


Cornell's ERL Main Linac Cryomodule

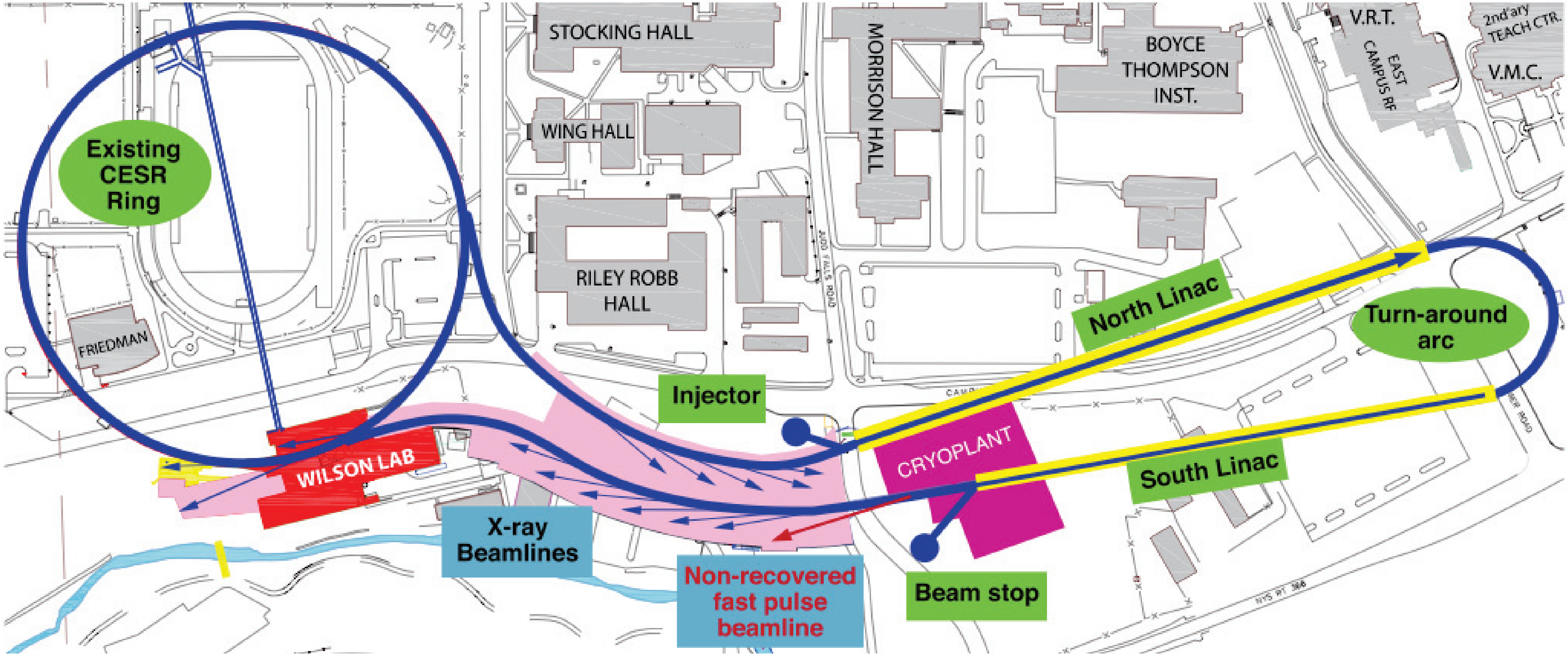


Cornell's ERL Main Linac Cryomodule



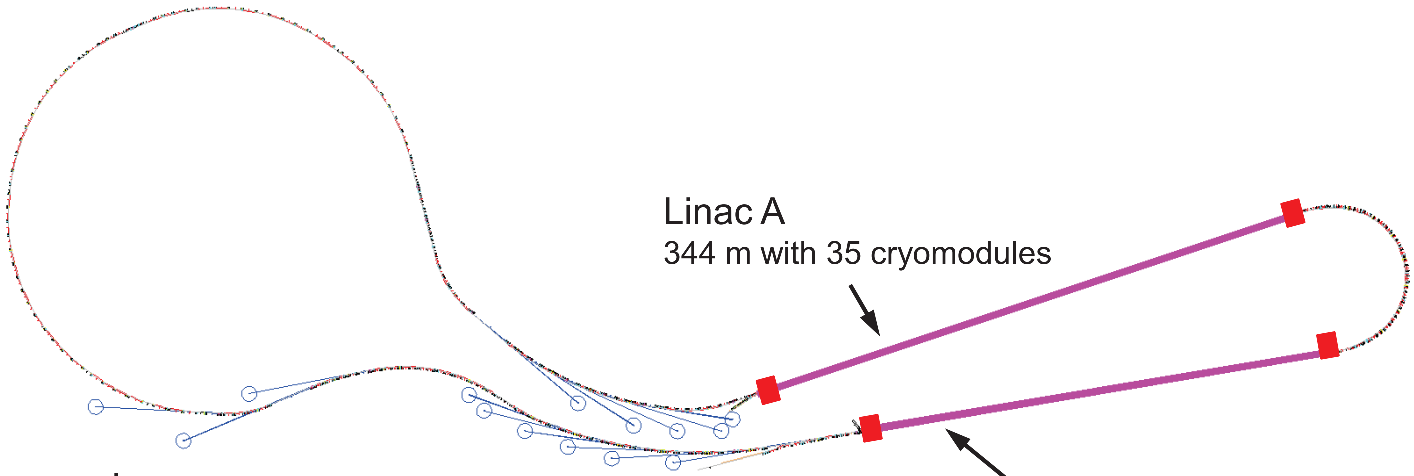
Cornell ERL parameters

5 GeV, 100 mA, 8 pm emittances, 2 ps bunch length,
16 M/m cw , Q > $2*10^{10}$, 200 W HOM power per cavity,



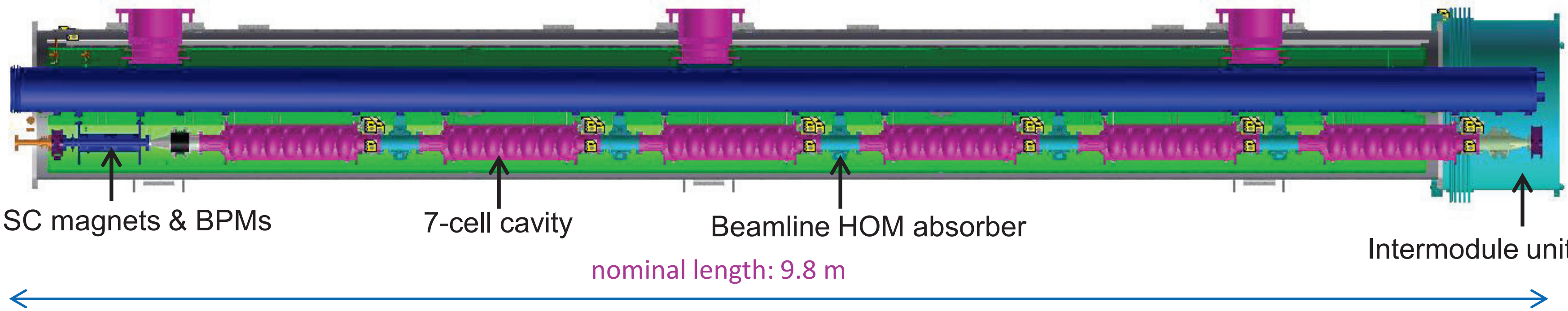
PDDR: https://www.classe.cornell.edu/Research/ERL/PDDR.html

Linac cryomodule for the ERL (MLC)

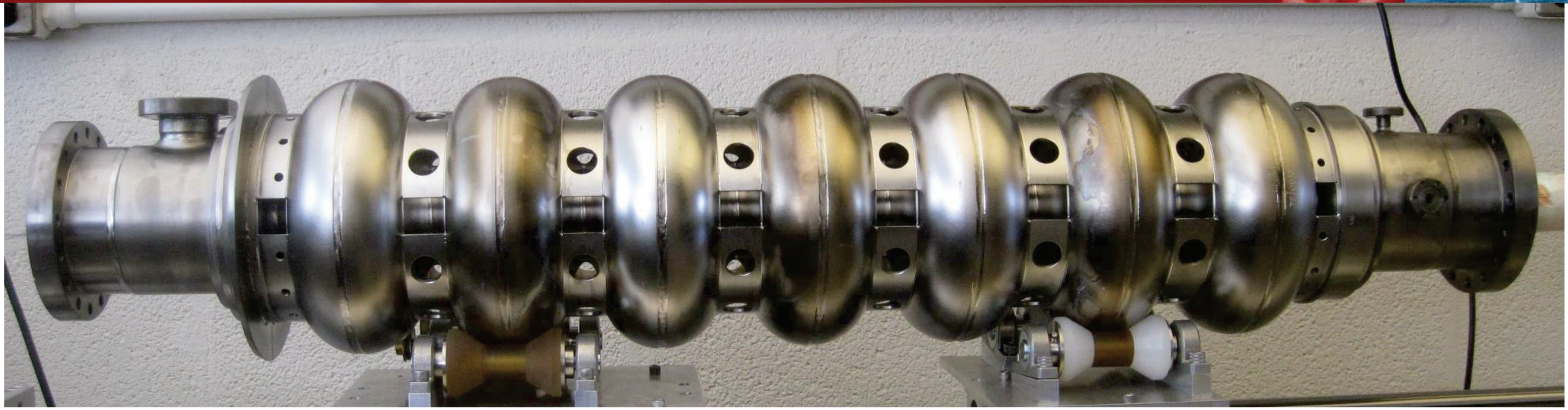


Total 64 cryomodules, each:

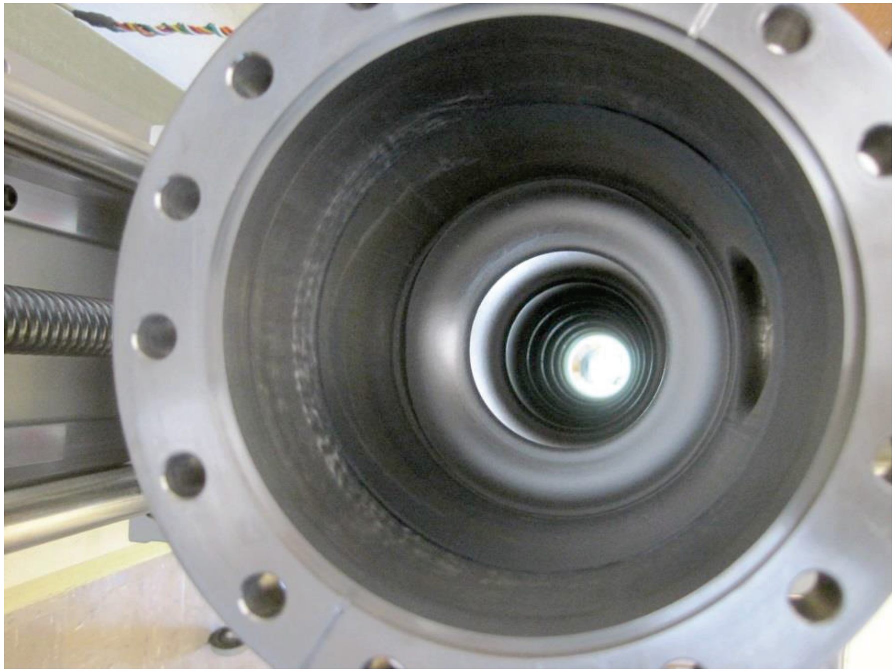
- six packages of 7-cell cavity/Coupler/tuner
- a SC magnets/BPMs package
- five regular HOMs/two taper HOMs



Cornell ERL Cavity



- 7 cell cavity
- 1.3 GHz
- optimized for high BBU limit
- no HOM antenna
- fully built in house



ERL Cavity: accuracy matters

Stringent Length & Frequency Tolerance: **L=1160 mm +/- 0.5 mm**

1st Series Production: Un-Stiffened Cavities

- ***Initial series production after single HTC prototype***

- After welding, ***cavities were too long***
- Cavities were also ***too low in frequency*** (requires stretching of cavity to tune to correct frequency), compounding length issues
- **After tuning, cavities were over the length tolerance by a large amount**

	Target Frequency (MHz)	Frequency as Built (MHz)	Target Length (mm)	Length as Built (mm)	Length Post-Tune (mm)
ERL7-002	1298.985	1298.460	1160	1161.04	1165.95
ERL7-003	1298.985	1298.460	1160	1161.54	1163.56
ERL7-004	1298.985	1298.498	1160	1160.66	1162.09

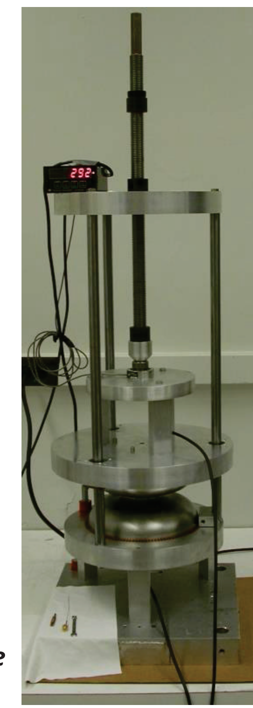
Frequency & Length of ERL Cavities After Welding

Root Cause of Production Cavity Frequency and Length Discrepancy

- **There were several reasons the 1st series cavities did not meet production standards:**
  - Insufficient tracking of salient production variables
  - Lack of a protocol for length and frequency control of cavities during production
    - We assumed that by cutting the dumbbells to the **target frequency**, they would be the **right length**
  - **Inaccurate RF Measurement Fixture for Dumbbells!**
    - **The measurement fixture deformed the dumbbells during measurements**
    - **Root cause for dumbbells being the wrong frequency (~500 kHz offset)**
    - **When combined with the erroneous trimming protocol, this leads to an unfixable length error**

    - **RF Measurement Fixture redesigned**

Improved RF Fixture



Inaccurate RF Measurement Fixture

2nd batch cavity accuracy

2nd Series Prototyping

- **Six Dumbbell were selected to form the cavity ERL7-005**
- After measuring the dumbbells, it was discovered that if trimmed to the "ideal" frequency, they would all be much too short!
- So, the protocol was employed:
  - The dumbbells were trimmed slightly too long (lower frequency)
  - The entire cavity would be tuned to the correct frequency (by stretching) resulting in the correct length and frequency!
- ***Result:***
  - ERL7-005 was ***too short and too low in frequency***, as built.
  - The amount of etching was adjusted to compensate for the discrepancy in frequency.
  - After some investigation, it was determined that ***the estimated weld shrinkage for each equator was to small.***
  - After adjusting this value, the following cavities came out much better.

	Target Frequency (MHz)	Frequency as Built (MHz)	Target Length (mm)	Length as Built (mm)	Length Post-Tune (mm)	ΔLength
ERL7-005	1298.600	1298.259	1157.9	1157.1	1158.4	-0.6

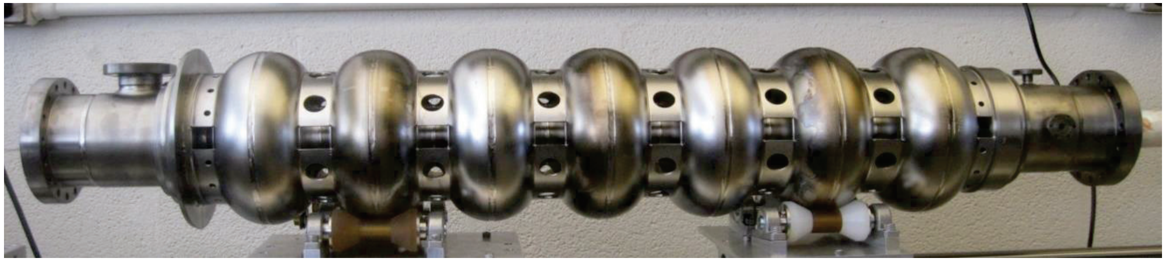
ERL7-005

	Target Frequency (MHz)	Frequency as Built (MHz)	Target Length (mm)	Length as Built (mm)	Length Post-Tune (mm)	ΔLength
ERL7-006	1298.85	1298.486	1157.84	1157.85	1159.09	**0.09**
ERL7-007	1298.75	1298.386	1157.39	1157.99	1159.3	**0.3**
ERL7-002a	1299	1298.578	1161.66	1161.36	1160.08	**0.08**

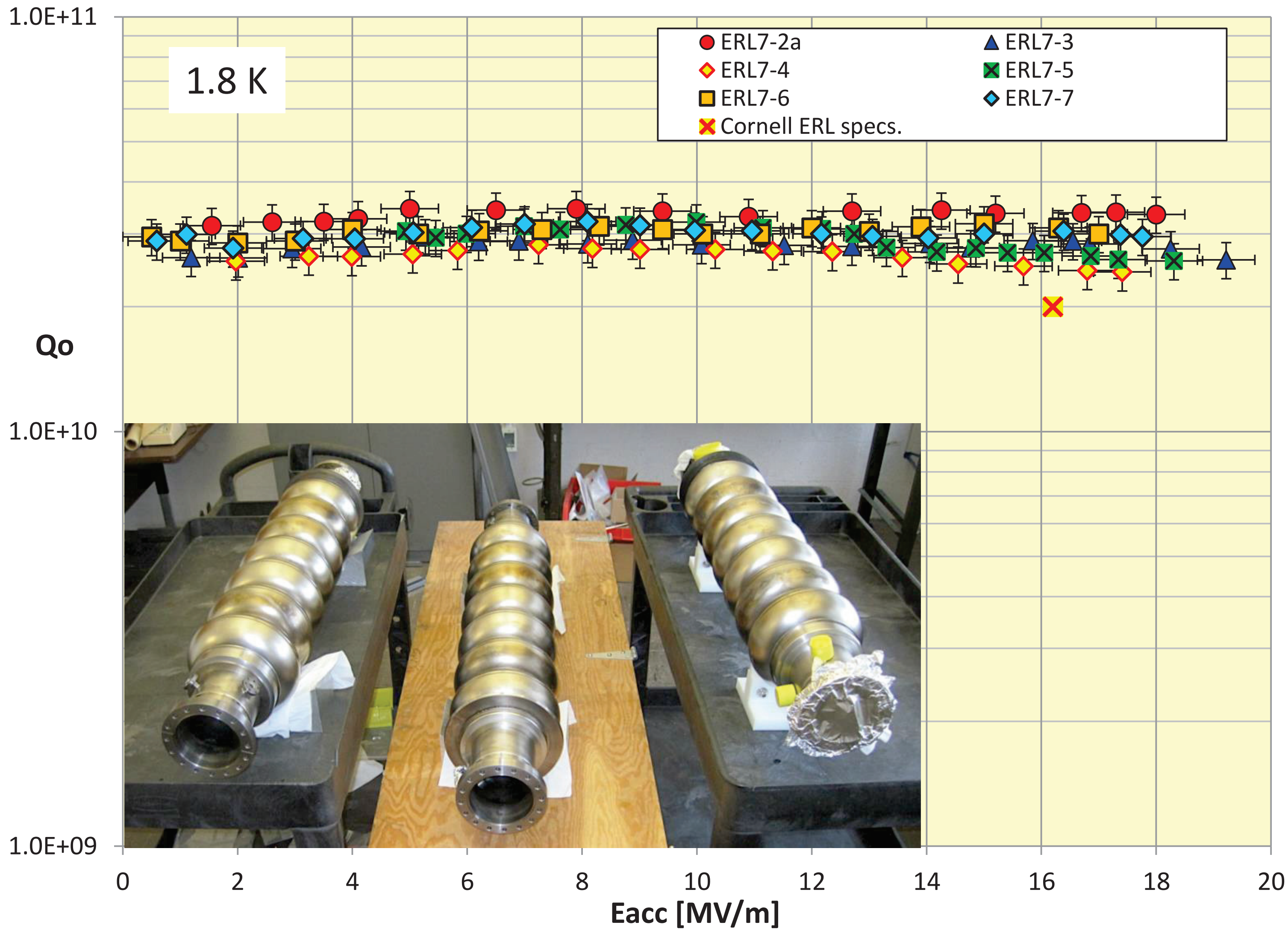
2nd Series Production Cavities

2nd Series Production

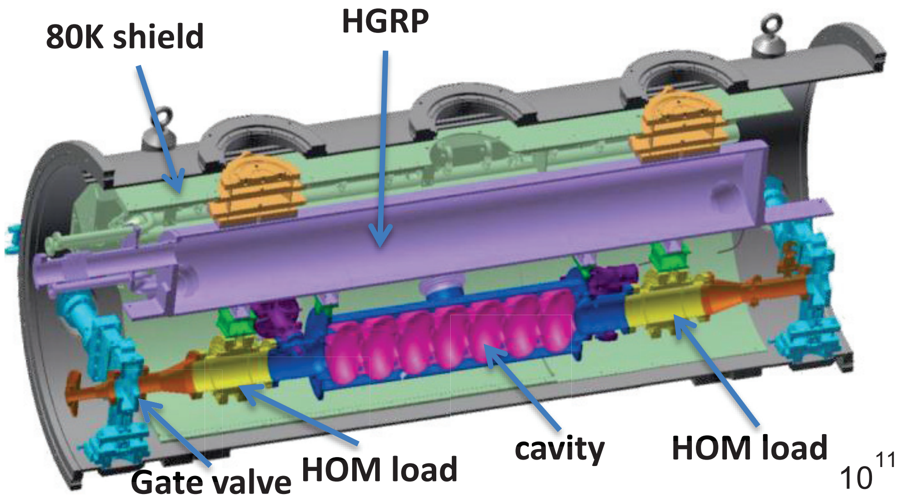
- ***Using the above experience, the next three cavities were produced.***
- ***All three met the frequency and length requirements set forth.***
- ***All six cavities have been tested with a 100% yield.***



Vertical Cavity Test Results



Horizontal Cavity Test Results

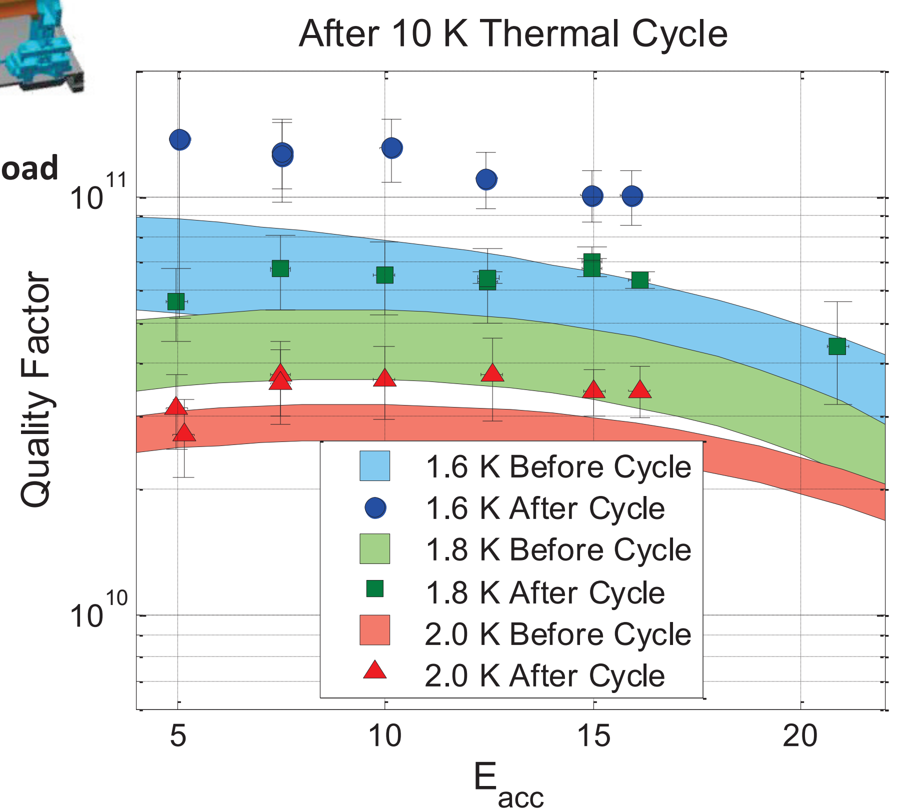


Horizontal Test Cryostat:

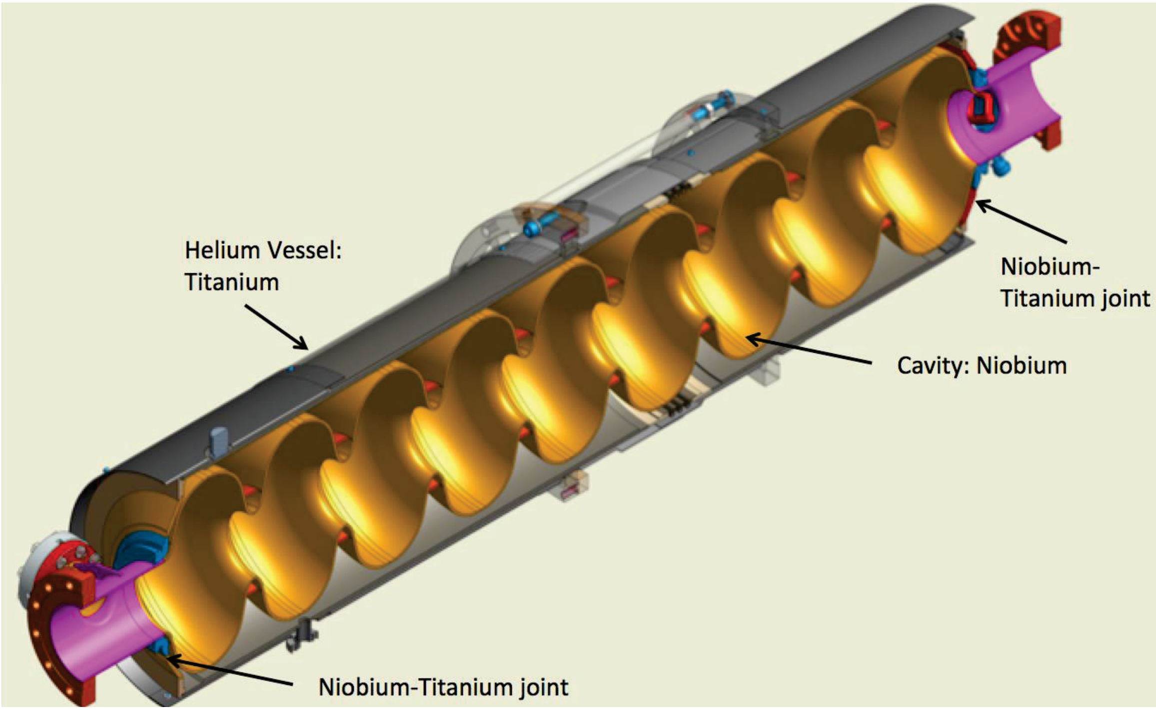
16MV/m, 1.8K: Q_0 = 2.E10 (reached with coupler)

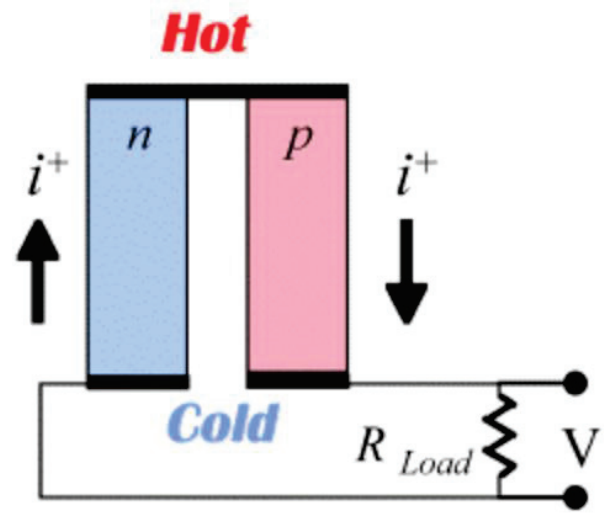
Q_0 = 3.5E10 without coupler

Q_0 = 6E10 with coupler and HOM absorbers



Cool-Down Effects: Thermocurrents





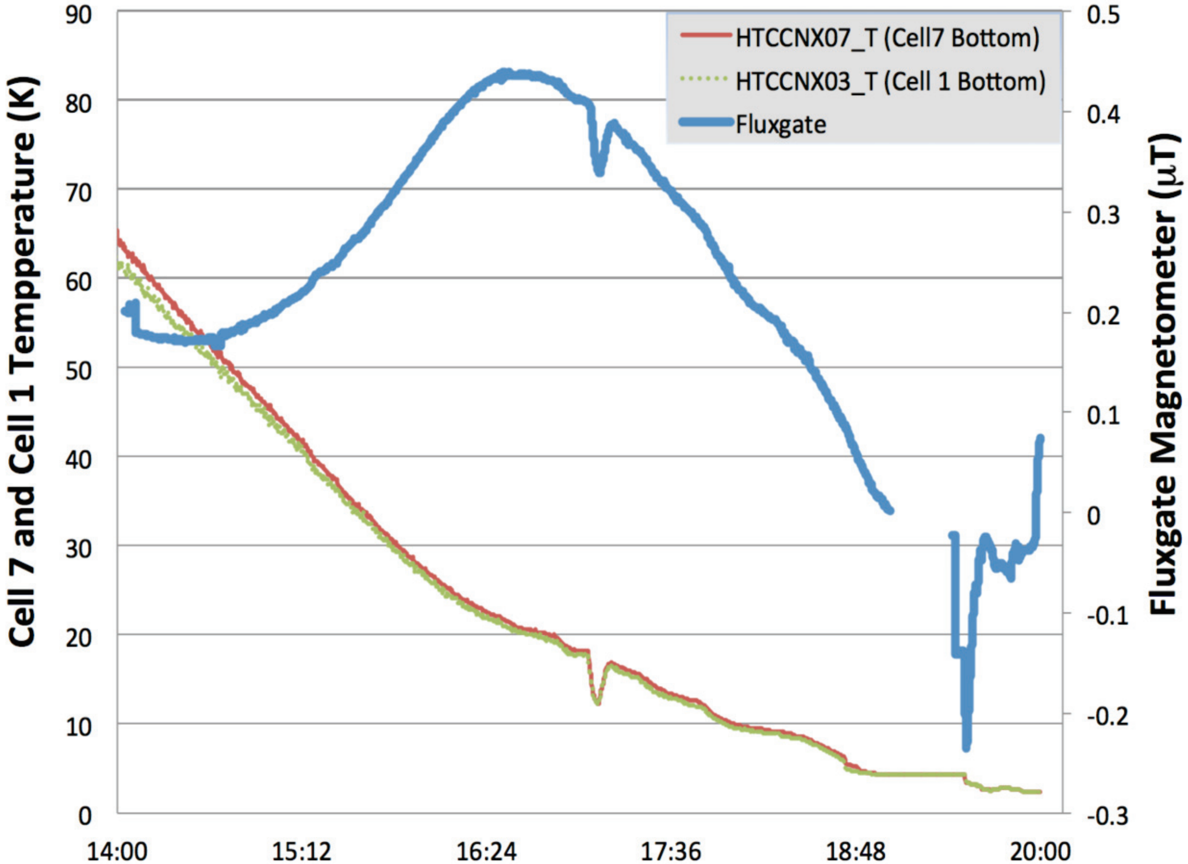
	10 K	20 K	50 K	80 K	100 K
Nb	0.31	0.98	2.73	3.09	3.13
Ti	N/D	N/D	-3.00	-3.00	-2.60

$$U_{th} = \int_{T_1}^{T_2} \left(S_{Nb}(T) - S_{Ti}(T) \right) dT$$

Seebeck Voltages can be some 10 μV, currents can reach 10 A

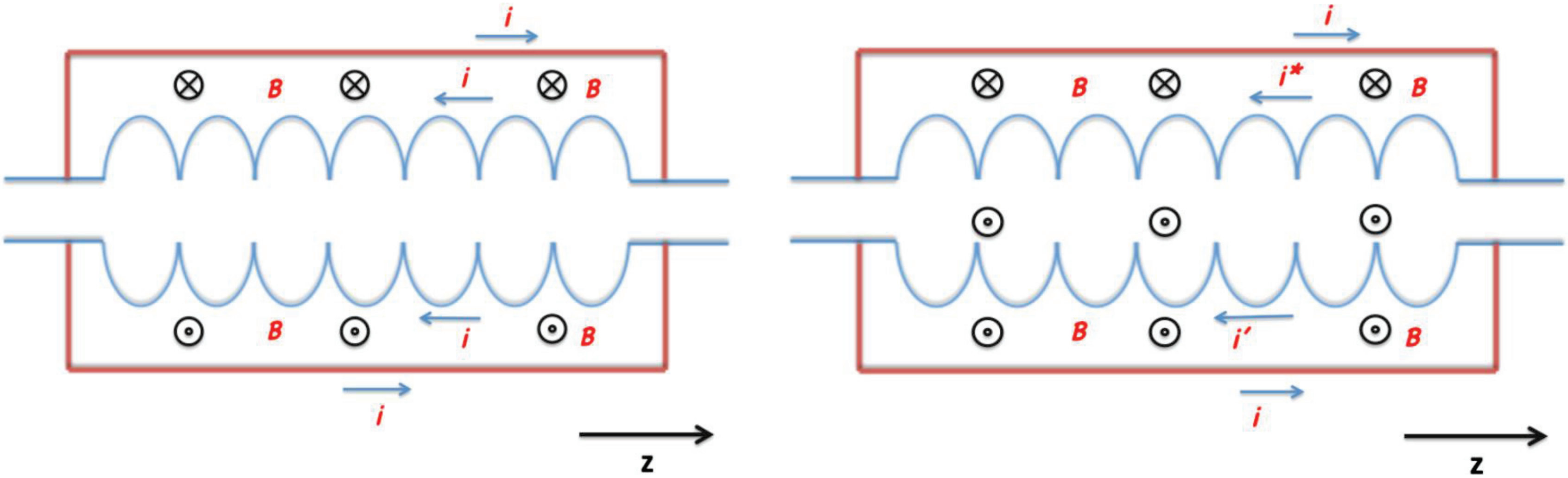
Cool-Down Effects: Thermocurrents

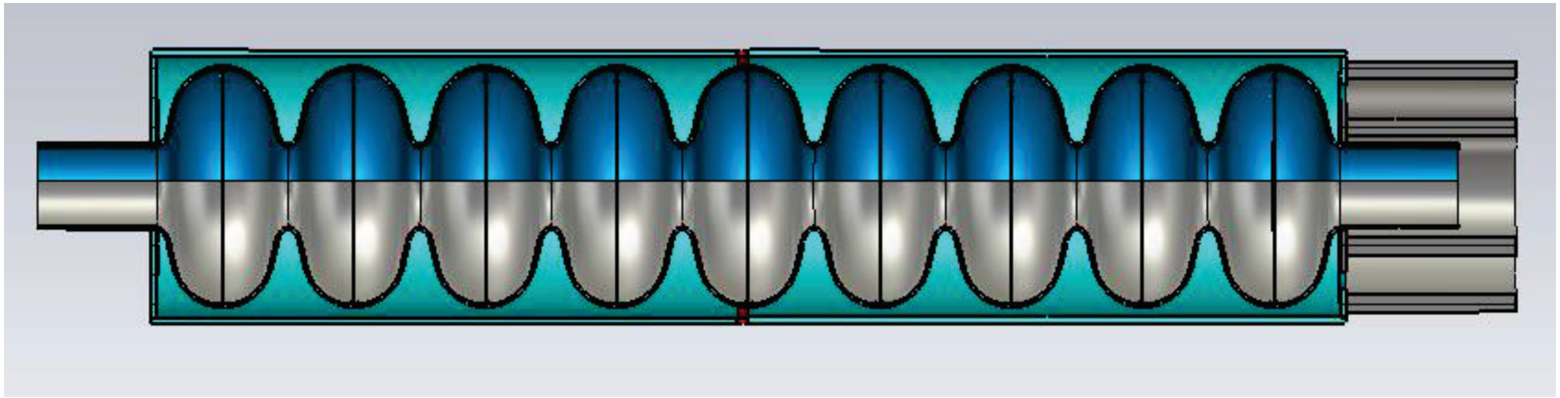
- Is it real?
- Magnetometer data from a horizontal test, with probe placed next to the cavity



Cool-Down Effects: Thermocurrents

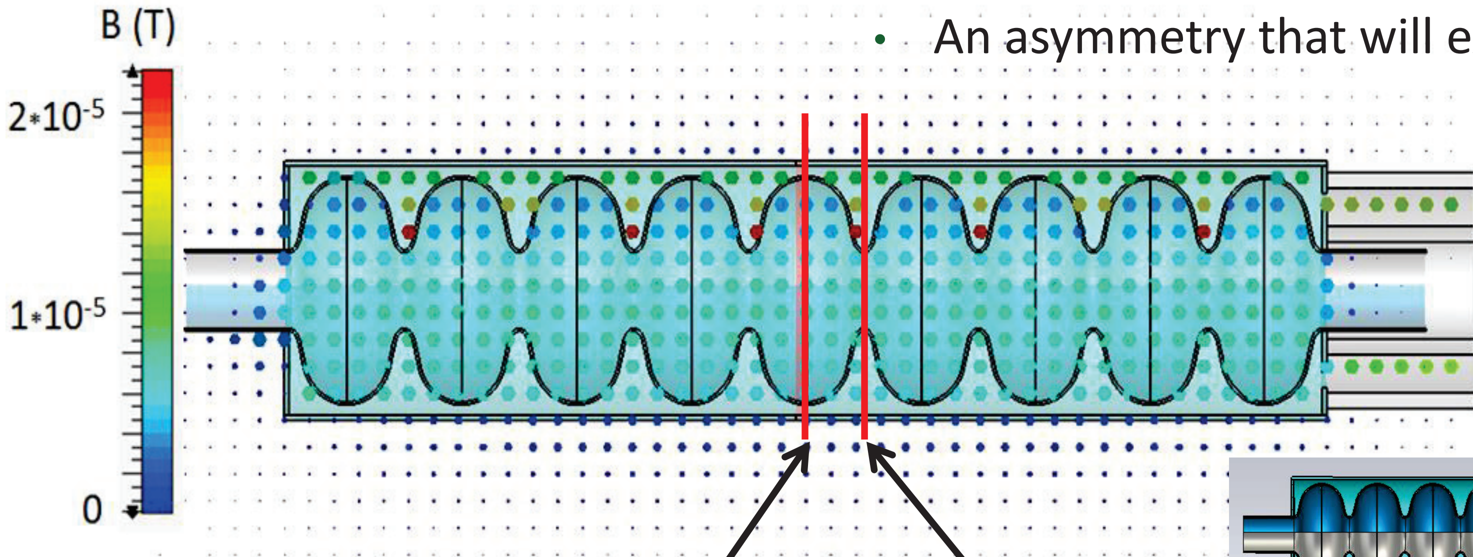
- Does it hurt?
- In a symmetric situation: no

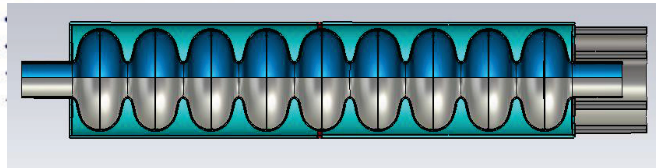


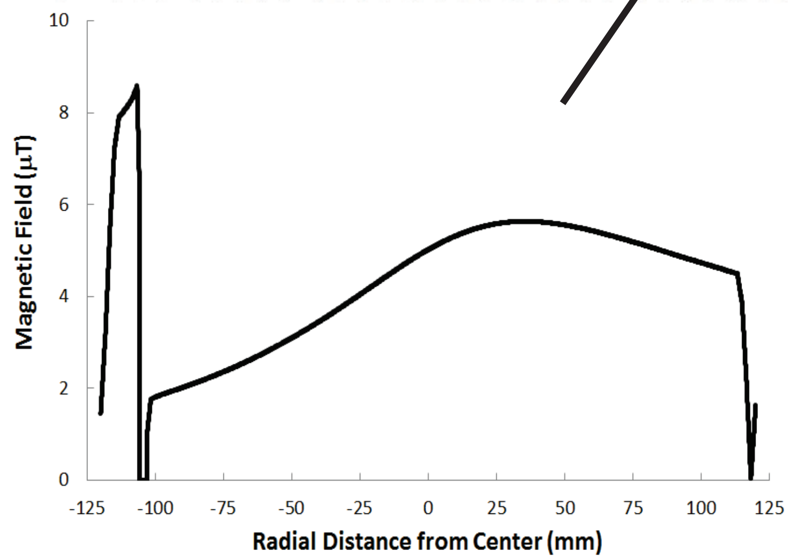


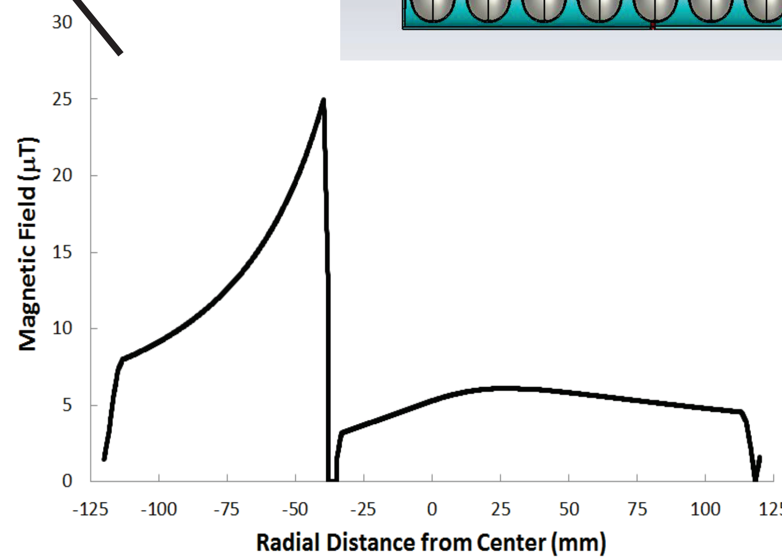
Cool-Down Effects: Thermocurrents

- An asymmetry that will exist:



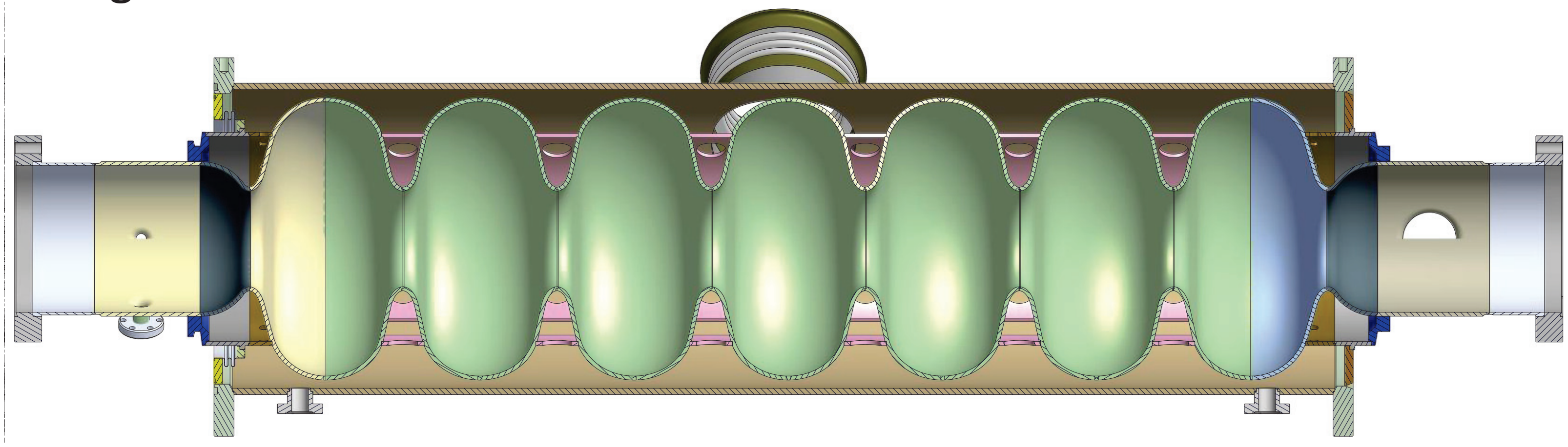




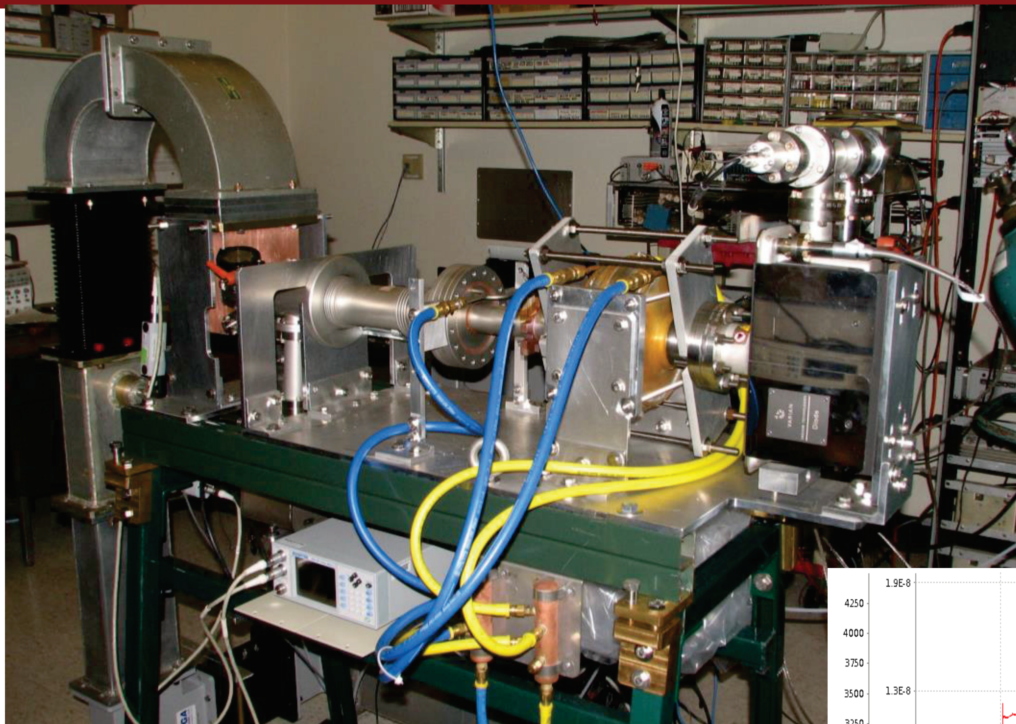


Cool-Down Effects: Thermocurrents

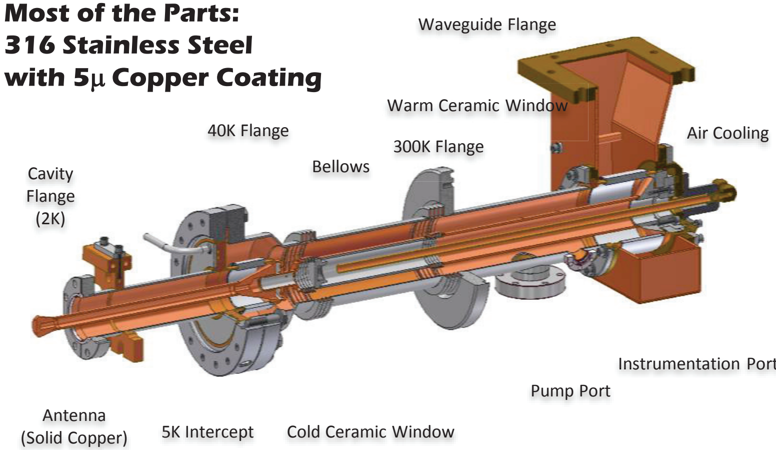
- Horizontal cool-down breaks symmetry
- Longitudinal gradients produce thermo-currents
- Transversal gradients define the asymmetry and the amount of thermocurrent induced magnetic field hitting the RF surface
- => single gradients are acceptable, combinations degrade cavity performance
- But: Temperature gradients may be necessary to expel residual magnetic field



Main Linac Input Coupler Testing



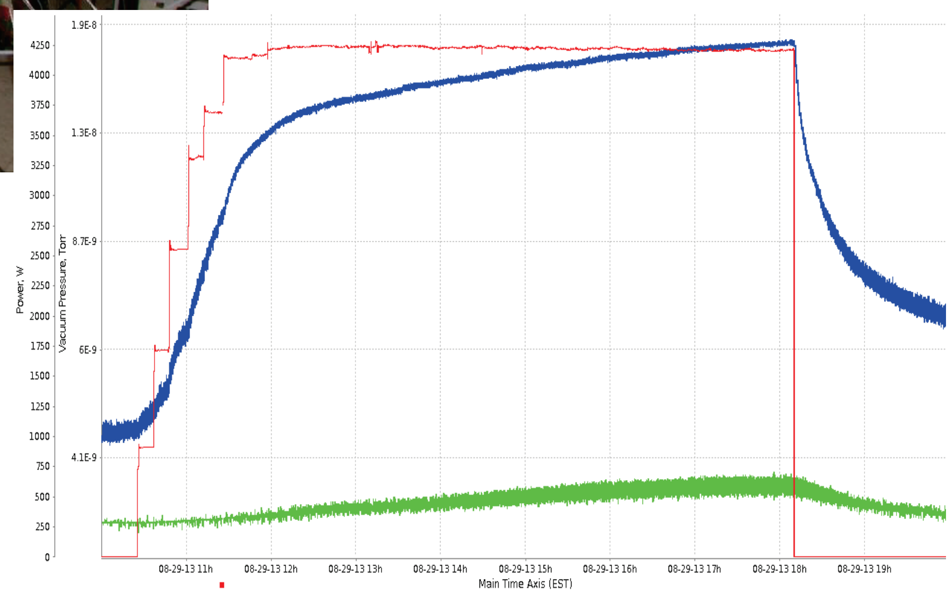
Most of the Parts:
316 Stainless Steel
with 5μ Copper Coating



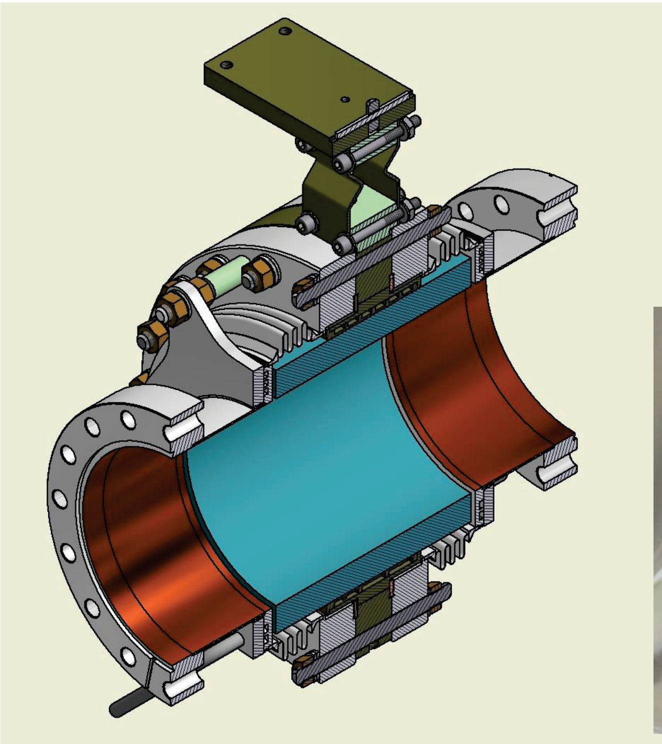
Power rating: 5 kW CW

Designed by Cornell

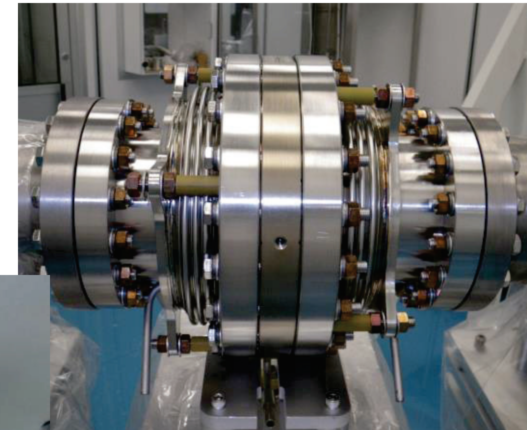
Built by CPI

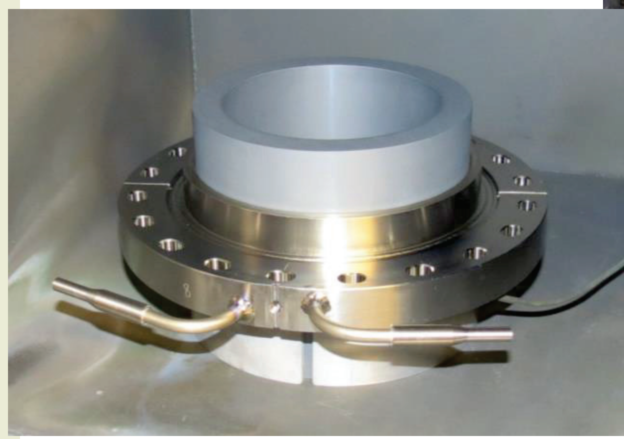


Cornell HOM Beamline Absorbers



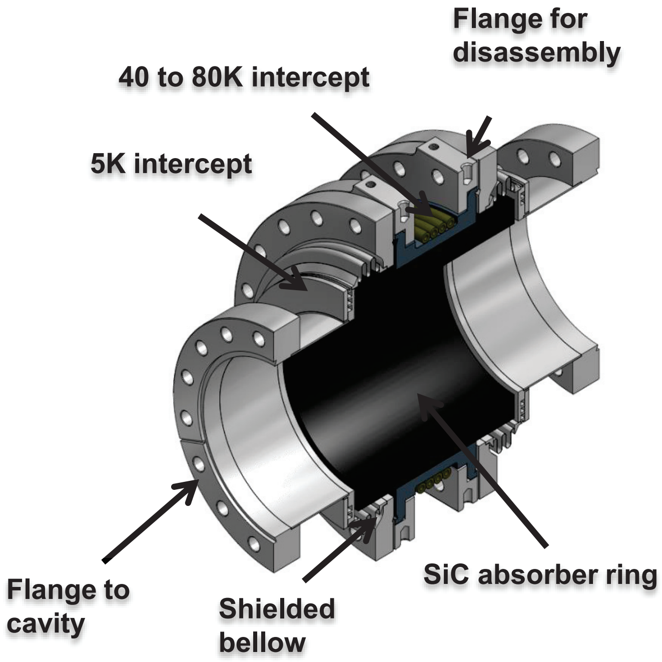
Absorbing Material:
Doped SiC





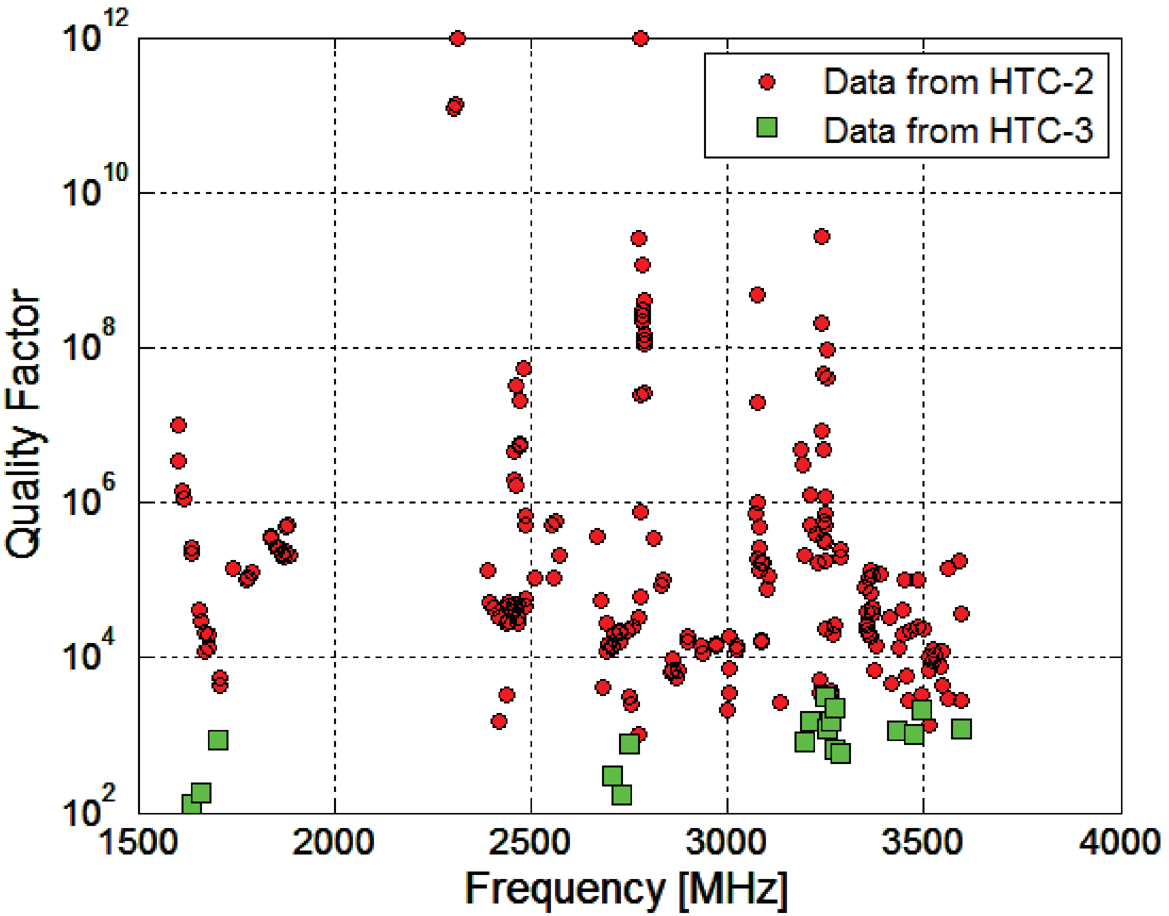
Cooling Passage
Configuration of 80K
Cooling Jacket

HOM Absorbers



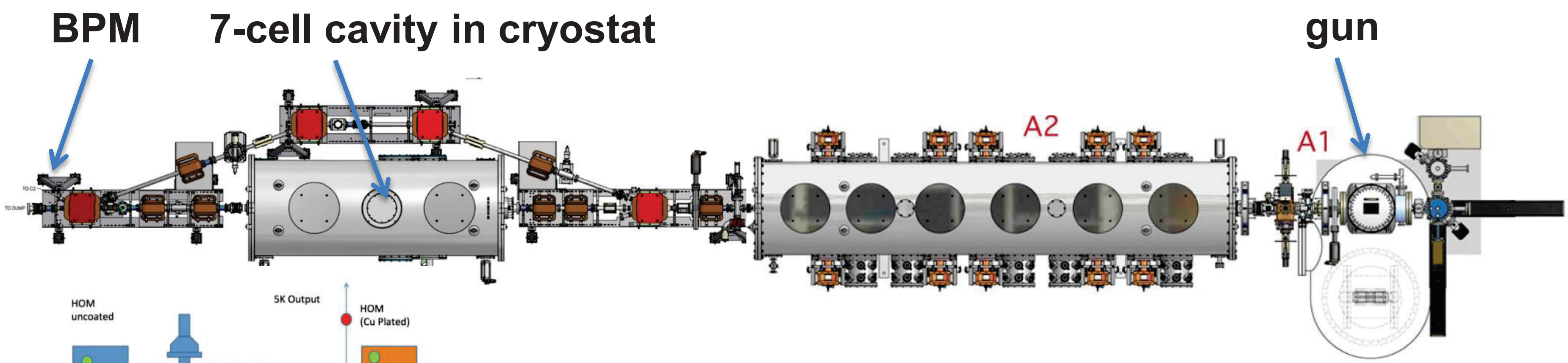
HTC-2: No HOM Absorbers

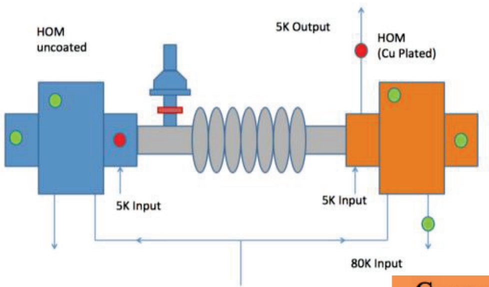
HTC-3: With HOM Absorbers



Beamline HOM absorbers strongly damp dipole HOMs to under Q ~ 10^4

HOM Absorbers Beam Test



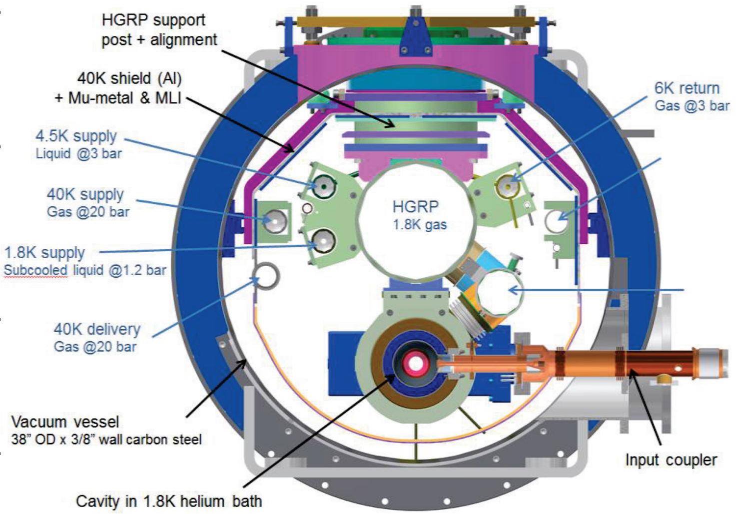


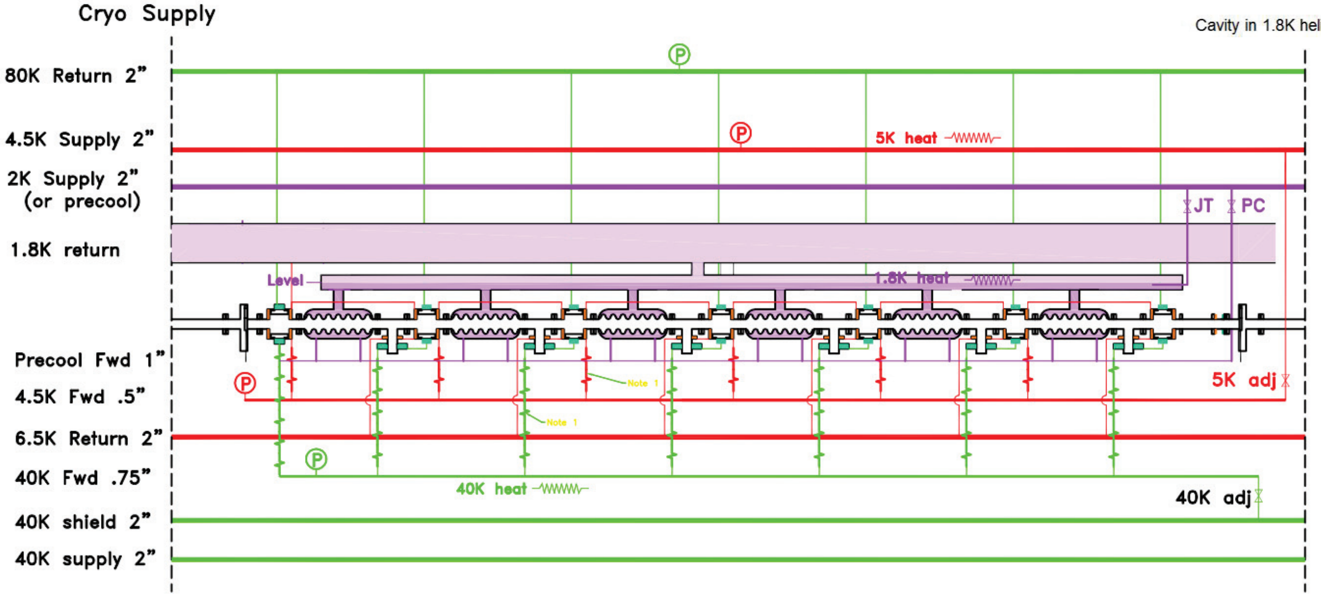
Current, bunch length	ΔT (beam pipe behind Abs.) coated/uncoated	ΔT (80K gas temp) coated/uncoated	ΔT (80K absorber temp) coated/uncoated	ΔT (5K flange next to cavity) coated	ΔT, beam pipe to cavity coated/uncoated
25 mA, 3.0 ps	0.075/0.075	1.14/0.82	1.02/0.975	0.007	0.076/-.005
40 mA, 3.4 ps	0.2475/0.335	2.95/2.16	2.72/2.53	0.021	0.179/0.009
40 mA, 2.7 ps	0.2975/0.425	3.00/2.22	2.772/2.63	0.027	0.203/0.014

- No charge-up of the HOM ceramics observed
- HOM heating was less than expected

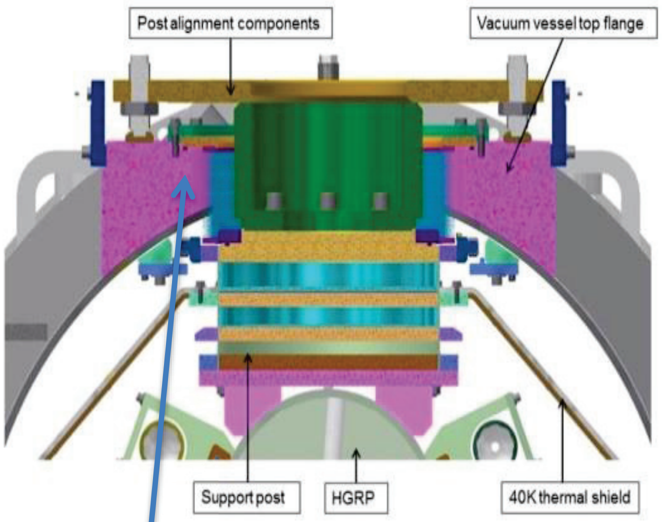
Cryogenic sketch of one Module

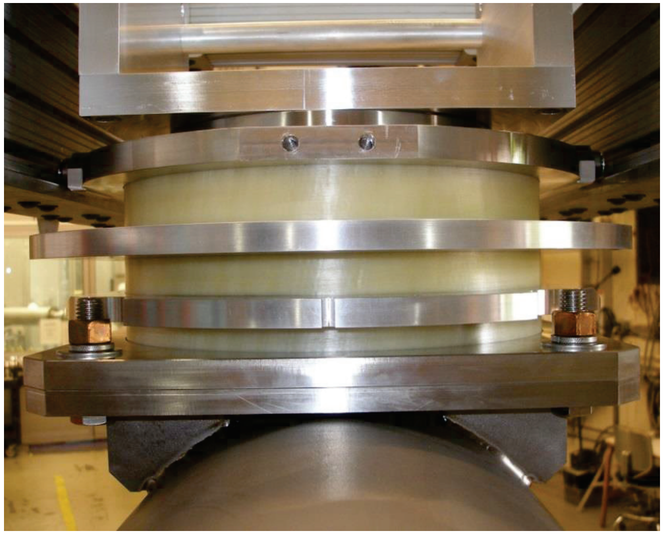
1 line for 2K supply	subcooled liquid @1.2 bar	• 2K helium bath for cavities via 2K-2 phase line • pre-cool gas for cool-down • 90% heat load from RF losses in the cavities
2 lines for 4.5-6K	3.0 bar He liquid Single phase flow	• Thermal intercept for HOM absorbers and couplers • 2/3 dynamic heat load
3 lines for 40-80K	20 bar He gas	• Thermal intercept for HOM absorbers and couplers • 40K thermal shield • 90% heat load from HOM





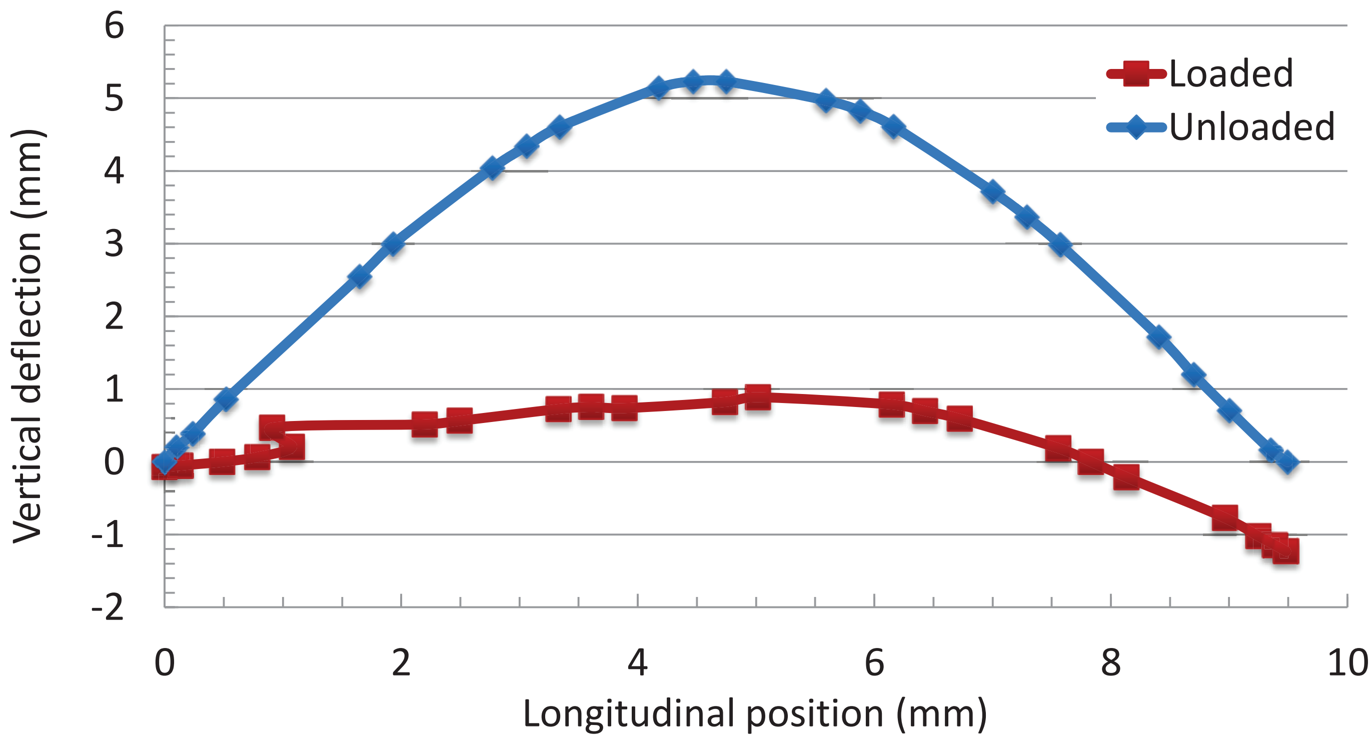
Support Structure/ Alignment





Support Structure/ Alignment

Expected to be less than .5 mm max

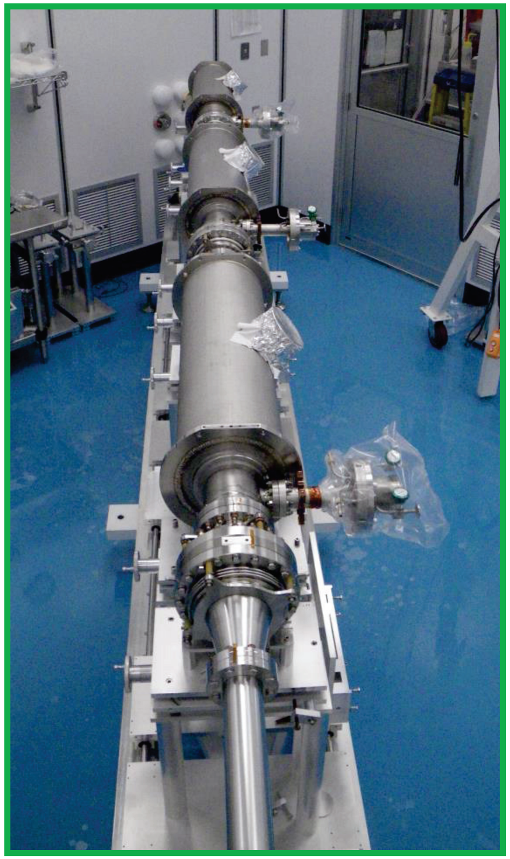


MLC Milestones
(as of Fall 2013)

- Dec ‘12 – Design completed
- Jan ‘12 – Order 6 remaining input couplers (6 month fab)
- Feb ‘12 – 3 unstiffened cavity built, testing started
- Apr ‘13 – Award vacuum vessel PO (6 month fab) & HGRP (6 month)
- July ‘13 – Production of 3 stiffened cavities started
- Sept. ‘13 – In-house fabrication of string components complete (tuners, HOMs, tapers…)
- Jan. ‘14 – Begin string assembly in clean room
- May ‘14 – Begin cold mass assembly and instrumentation (outside clean room)
- End of ‘14 – MLC ready for testing

MLC string assembly

Feb. 2014



MLC string assembly (2nd half)

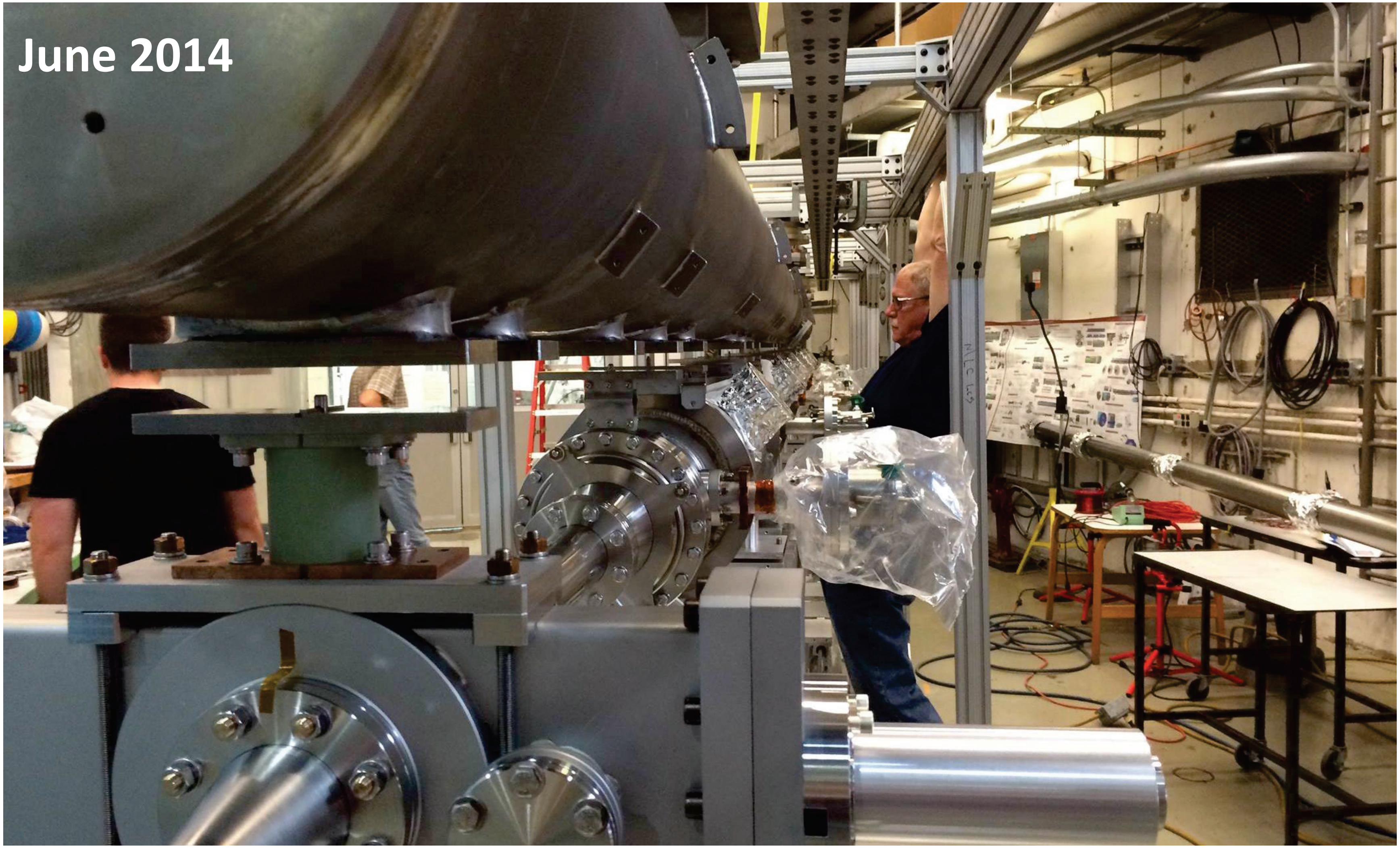
MLC magnetic/ thermal shield

Apr. 2014

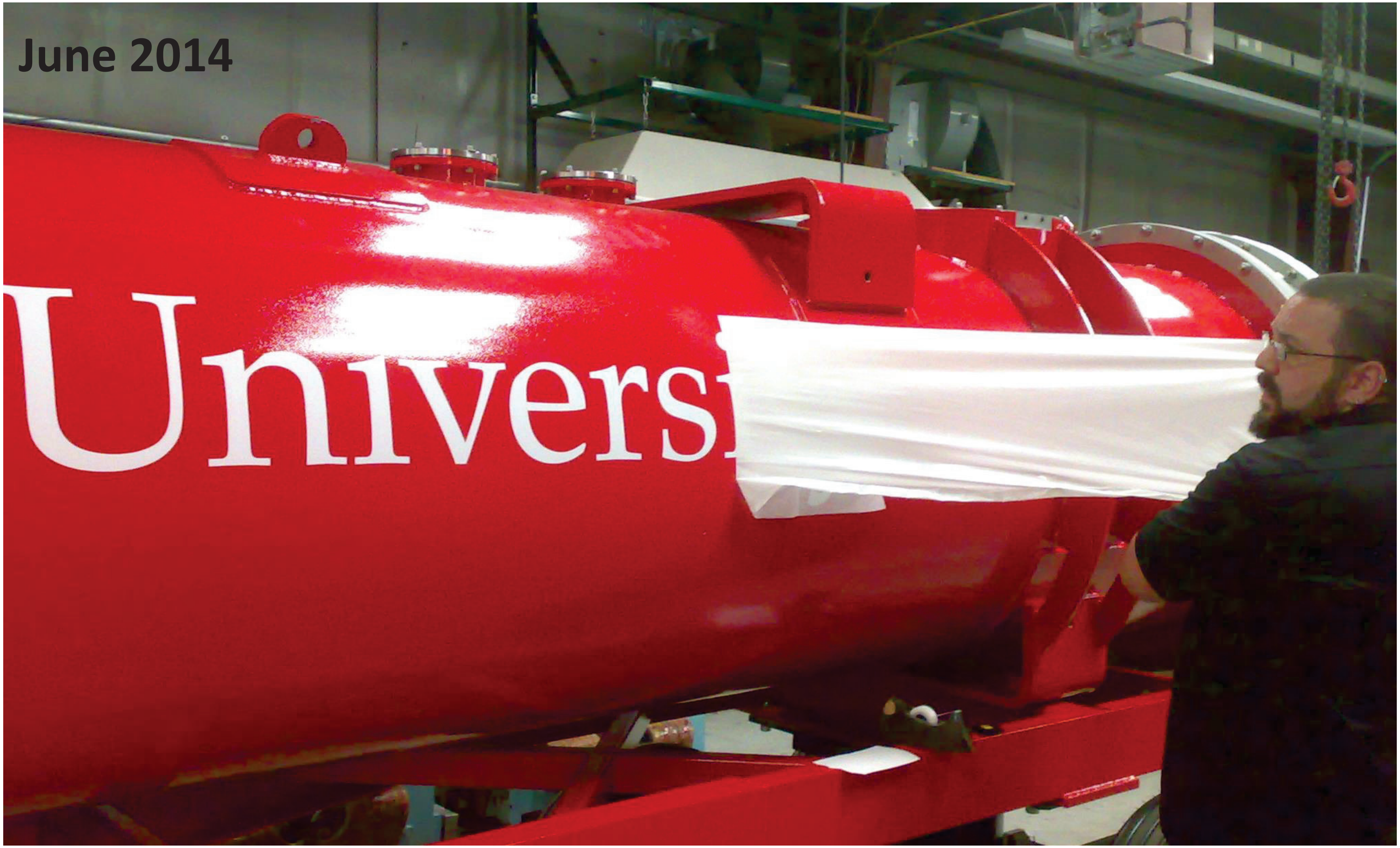
HGRP line

May 2014

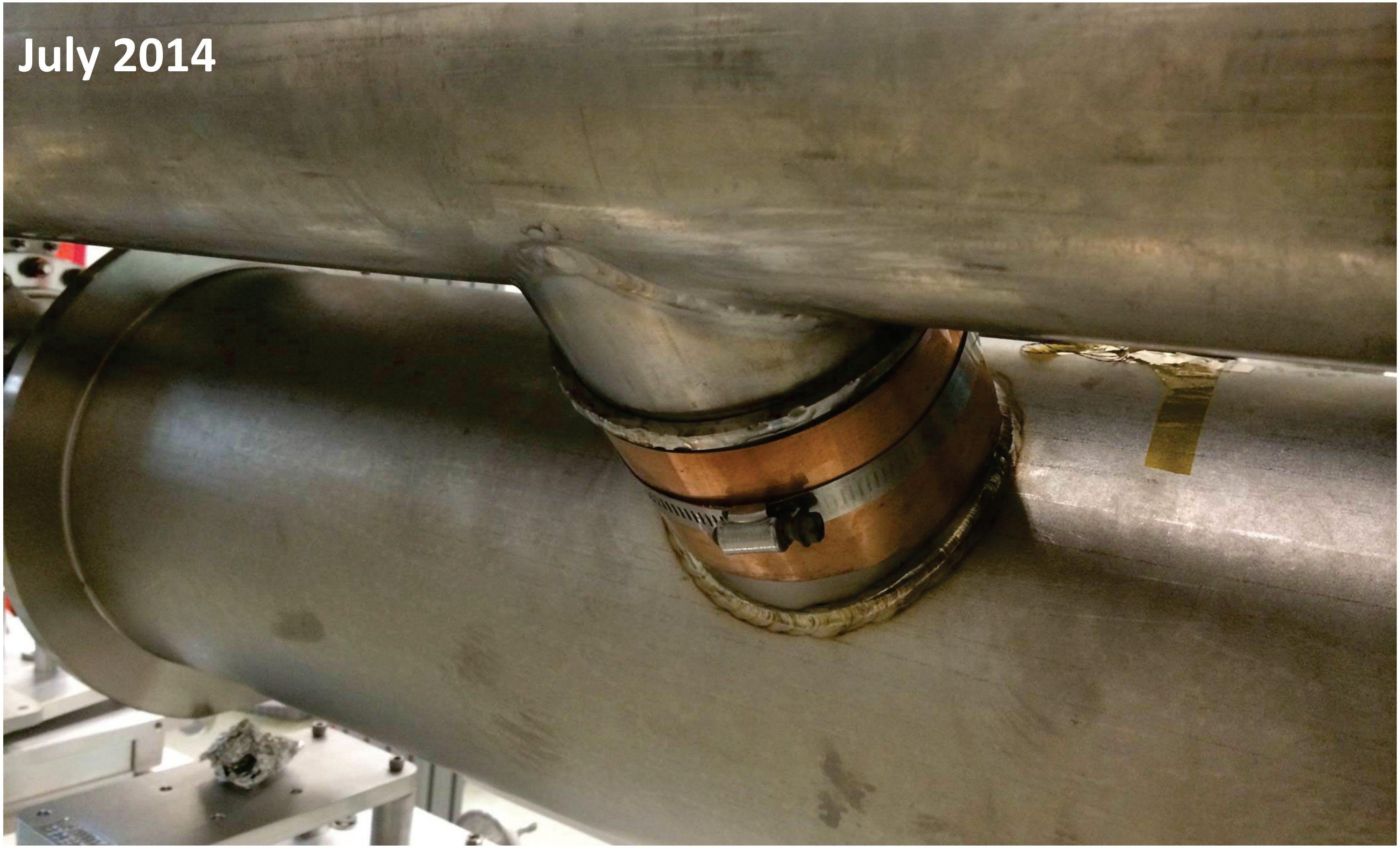
String HGRP mating



Vacuum Vessel

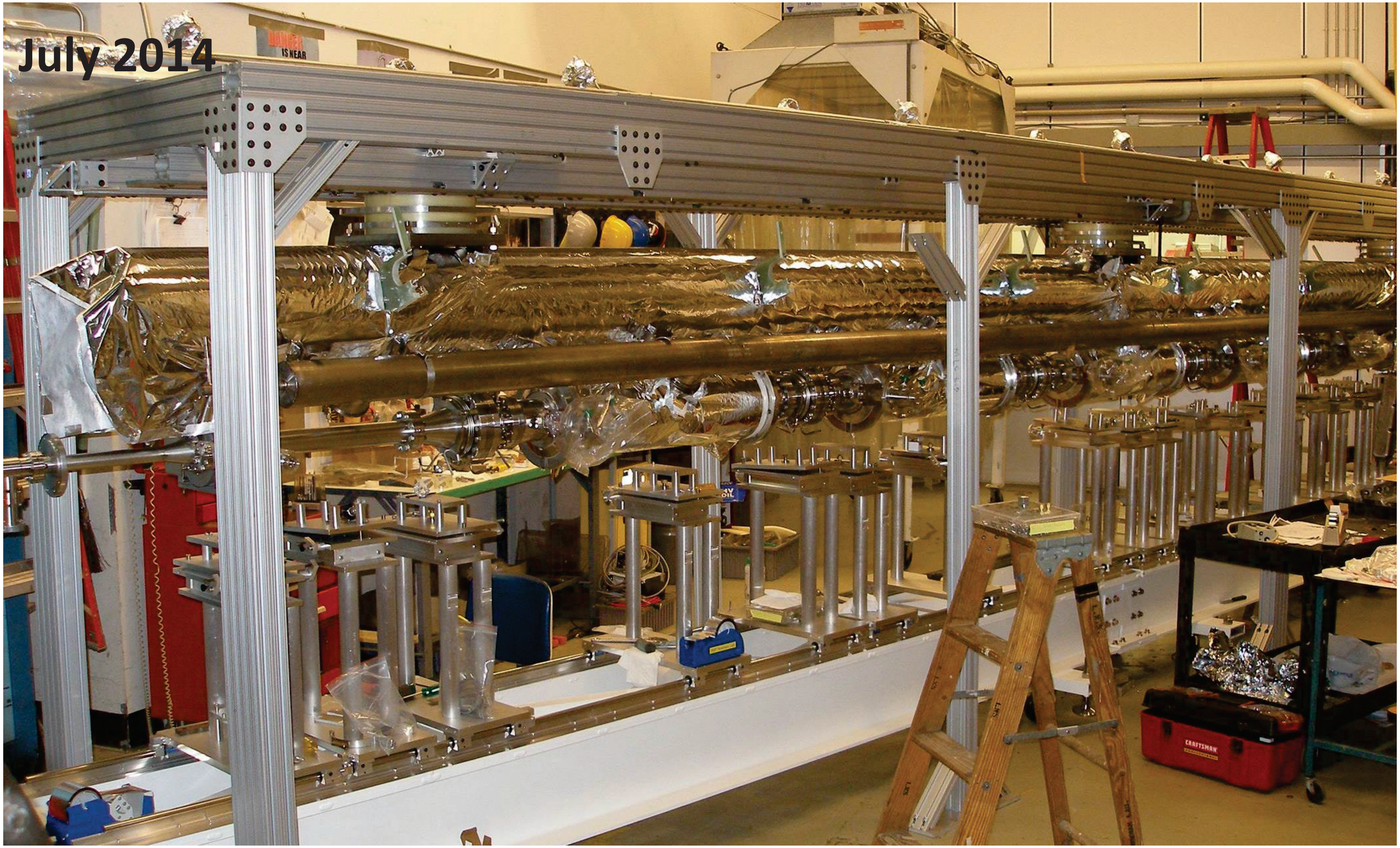


2K 2Phase line welding



Cryo-Manifold Installation

Cold mass assembly

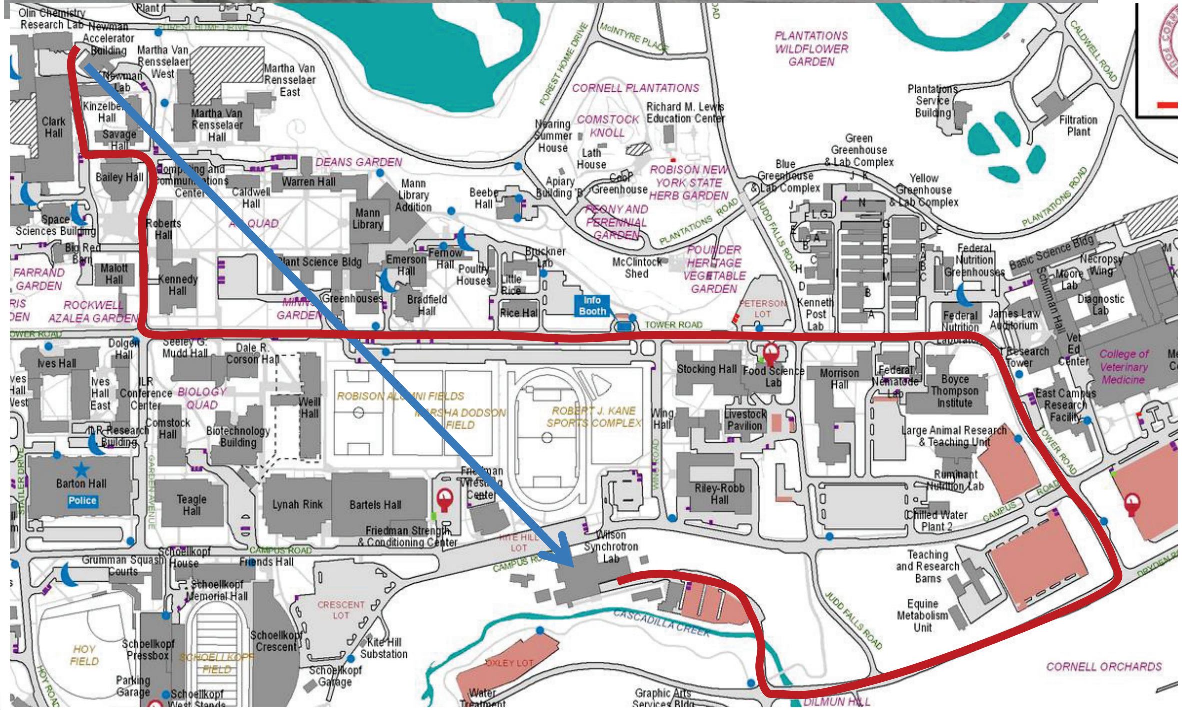


Finishing the MLC

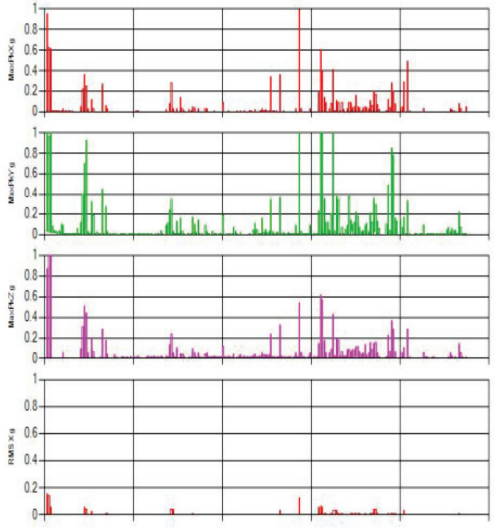
Nov. 2014

Moving MLC to Wilson Lab

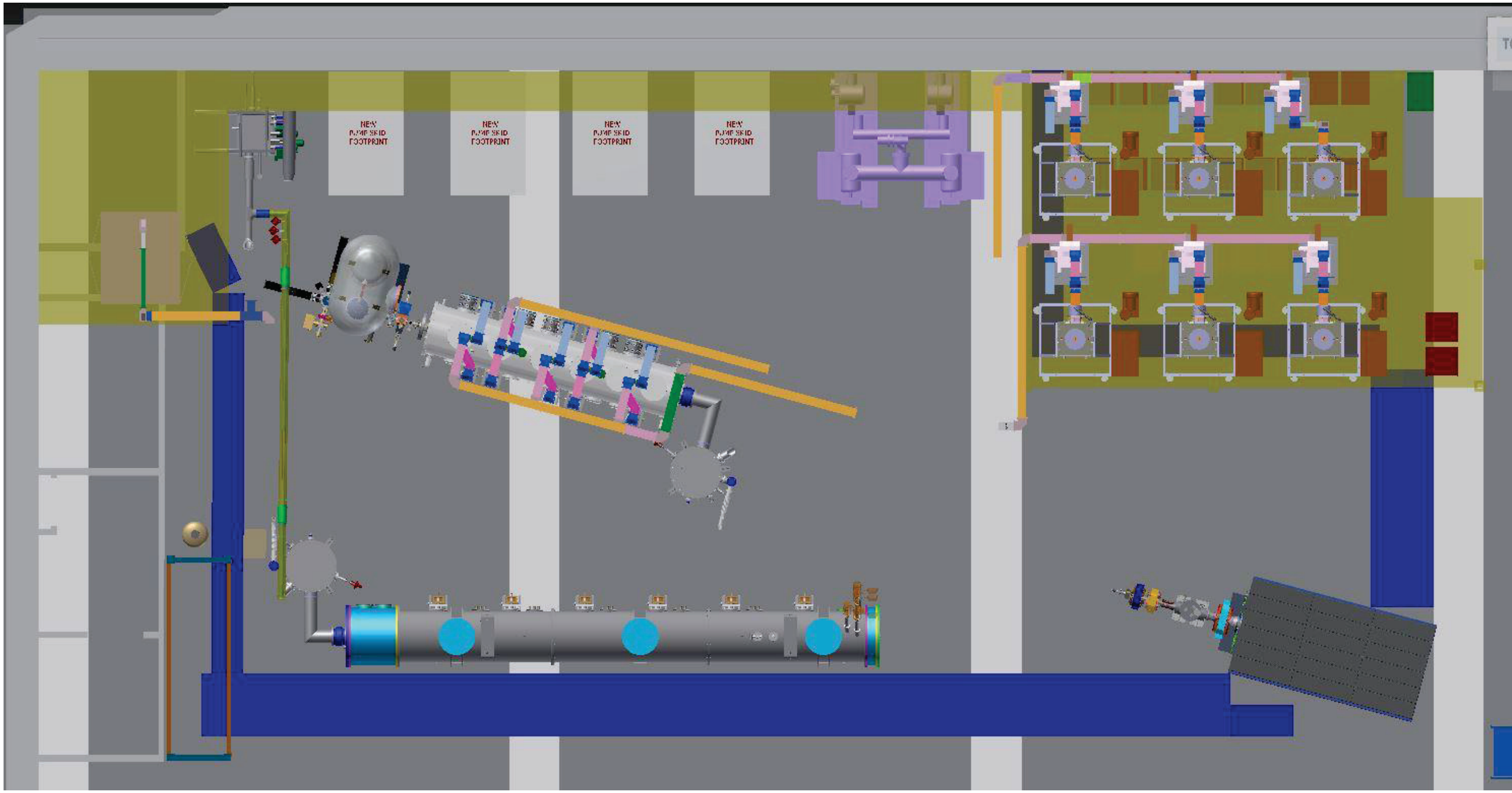
Mar. 2015



Model:	298	Firmware Version:	28
Journey Start:	3/10/2015 8:10:29 AM	Download Date	3/10/2015 1:01:19 PM
Journey End:	3/10/2015 12:48:29 PM	Recorded Duration	4Hours 38Min's
Report Start:	3/10/2015 8:10:29 AM	Serial No.	47812
Report End:	3/10/2015 12:48:29 PM	Slot Alarms:	0



Cool-Down and Testing at Wilson Lab



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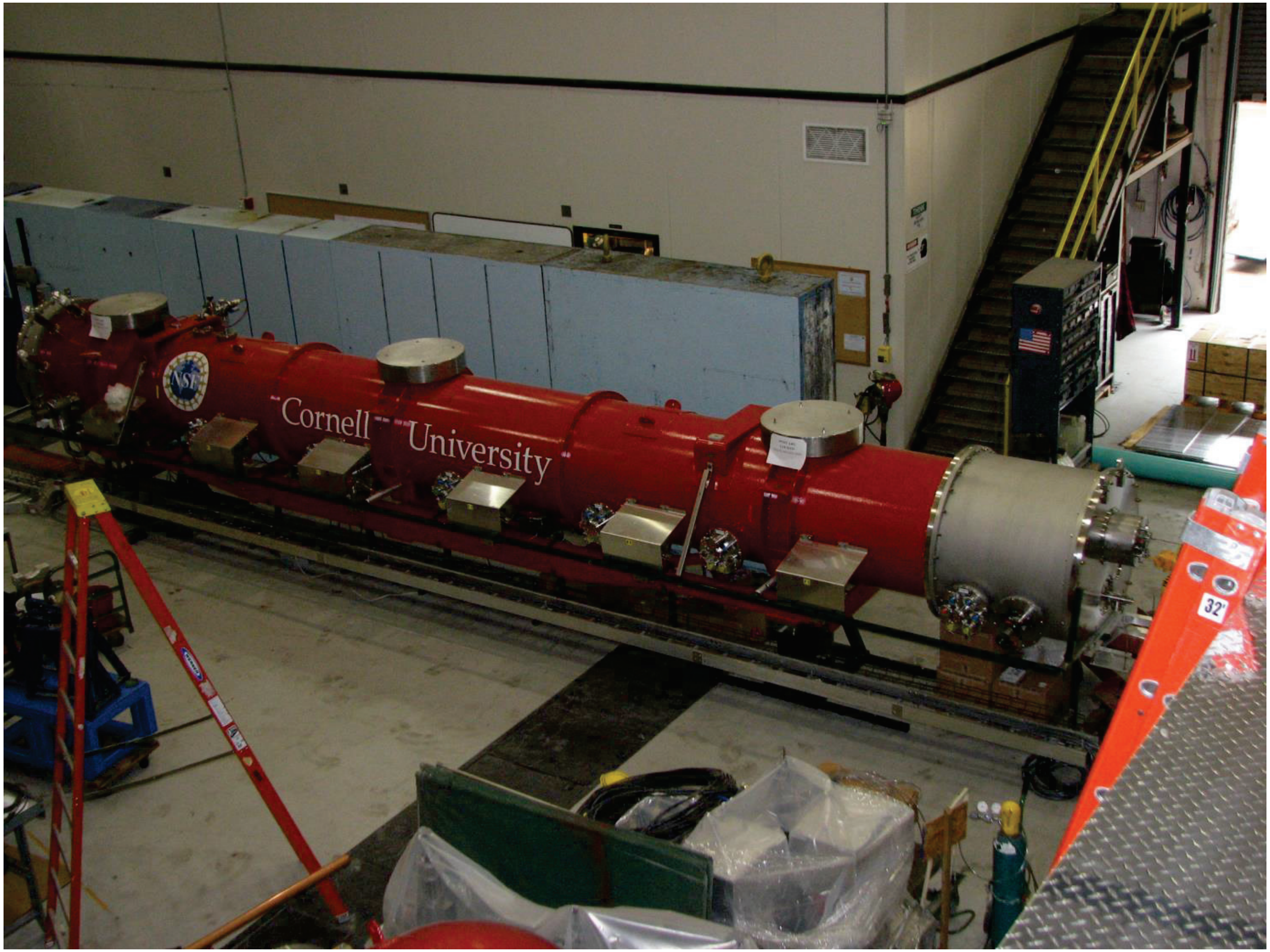
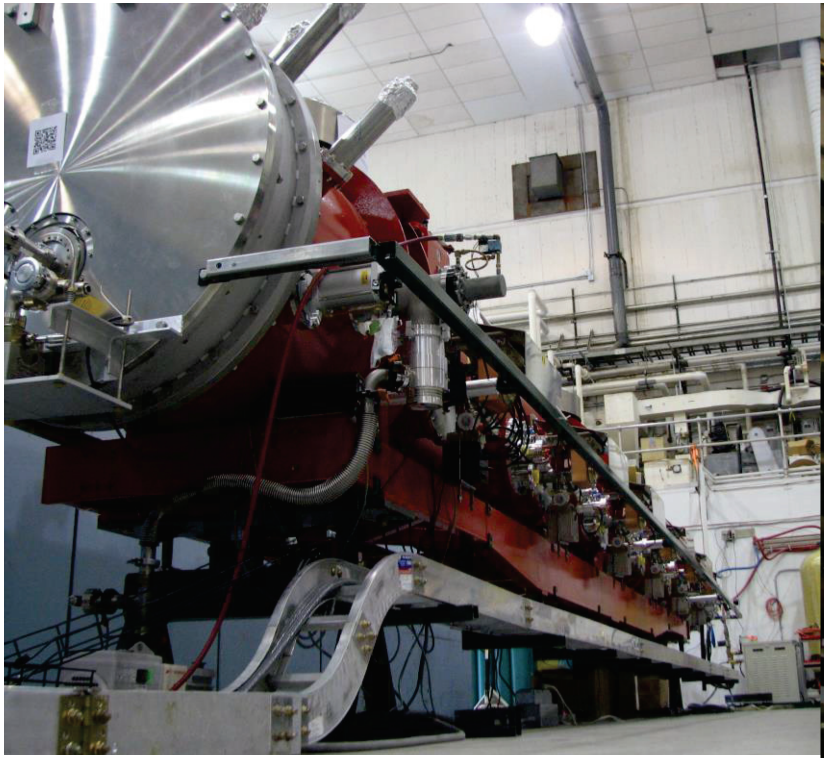
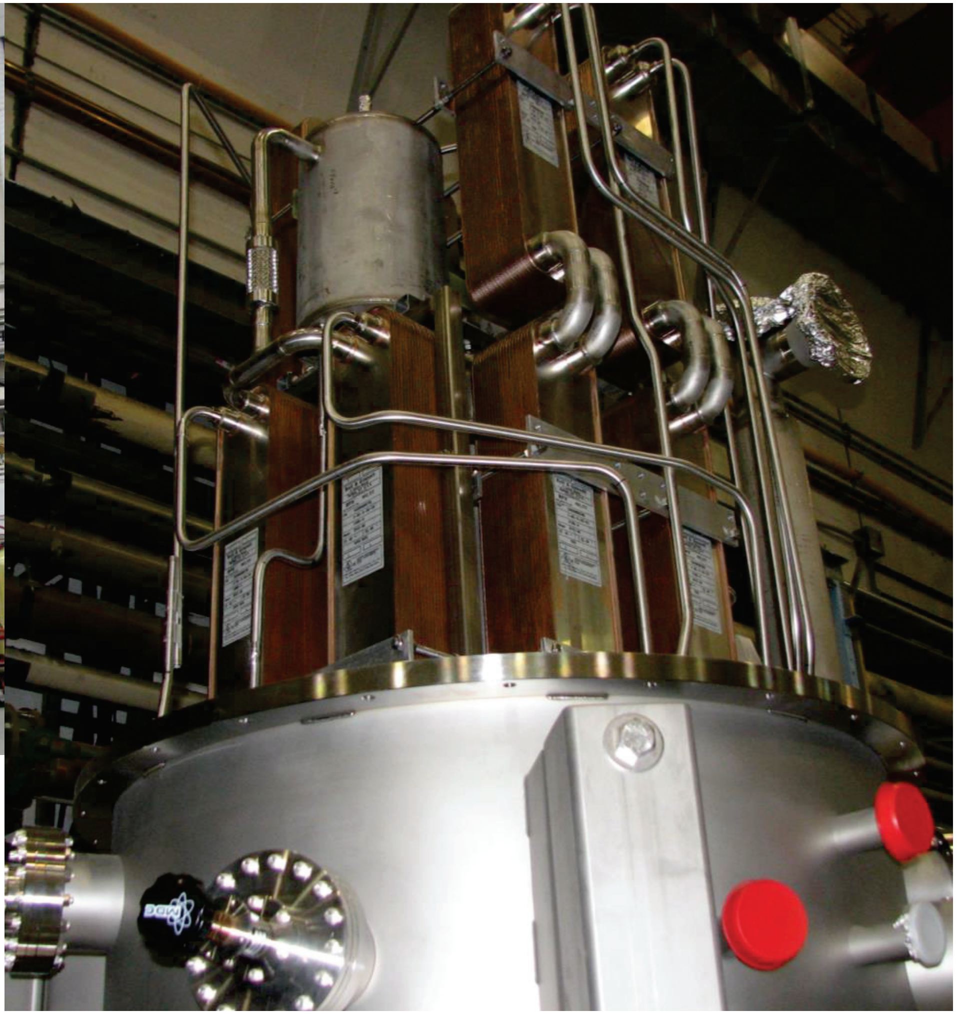


June 2015

Cool-Down and Testing at Wilson Lab





June 2015

Summary and Outlook

Summary:

- Finished a 40,000 h effort on designing, prototyping and building a next generation high Q cw cryomodule (in time and budget)
- Resolved many interesting scientific questions in SRF and cryogenics

Outlook:

- To be pessimistic: cool-down starts in July
- Q data taking will start August (2 weeks per cavity)
- Ramp up to all cavity operation early 2016
- Use this module inside an accelerator

Thanks!