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# *Commissioning of the ATLAS Energy Upgrade Cryomodule*

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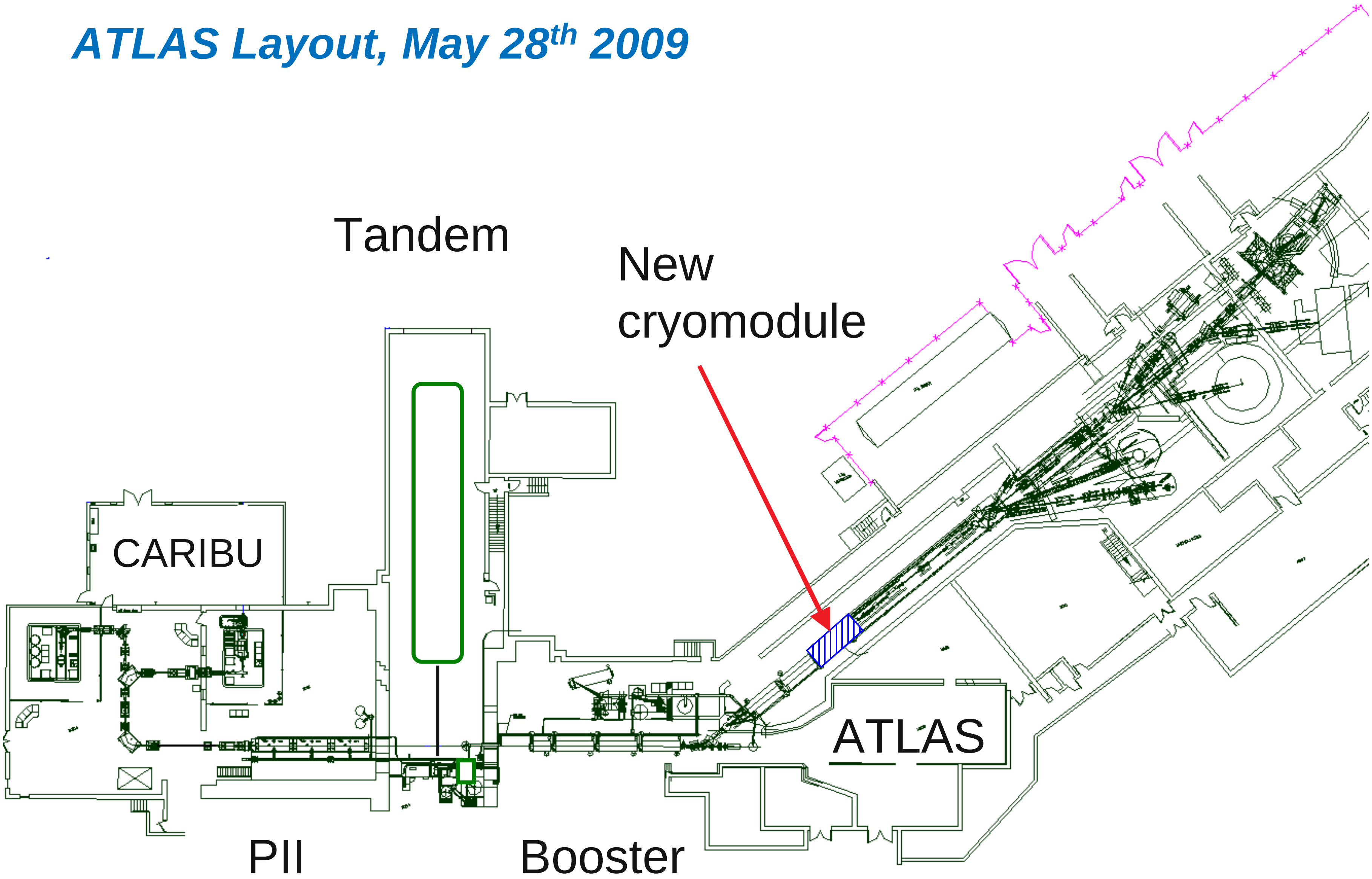
## *Content*

- Goal of the project
  - New design of a low-beta cryomodule
  - ATLAS energy upgrade
- Cavity parameters
  - Steering compensation
  - EM properties are well optimized
- Cryomodule assembly
  - Surface processing
  - Clean-room assembly
- Off-line commissioning
  - Pumping out, leak check, cool-down
  - Cold tests
- RF system
- Installation
  - New solenoid, cold trap
  - Alignment

## *The goal*

- QWRs are extended vertically: box cryomodules
- Originally developed for large scale production, FRIB
- Separation of the cavity vacuum space from the insulating vacuum
  - Similar to $\beta_G$=1 cavities in electron linacs: JLAB, ILC
- High performance
  - Optimized design of the cavities, EM, structural, Cancel the beam steering effect due to the RF field in the QWR
  - Surface processing, clean-room assembly, low-particulate pumping and venting system
- Top loaded cryomodule: minimize clean-room procedures
- Minimize distance between the cryomodules and provide space for beam diagnostics box
- Demonstrate average 27.5 MV/m peak surface field: design goal for ANL/FRIB
- Upgrade ATLAS beam energies
  - CARIBU beams, $q/A \approx 1/7$, W = 10 MeV/u

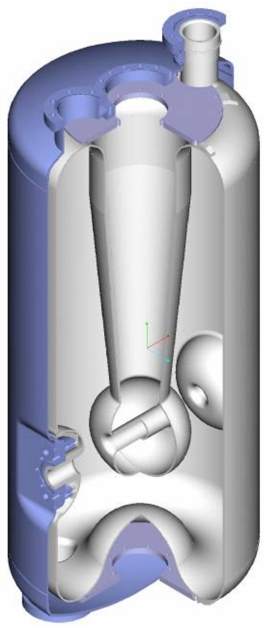
# *ATLAS Layout, May 28th 2009*

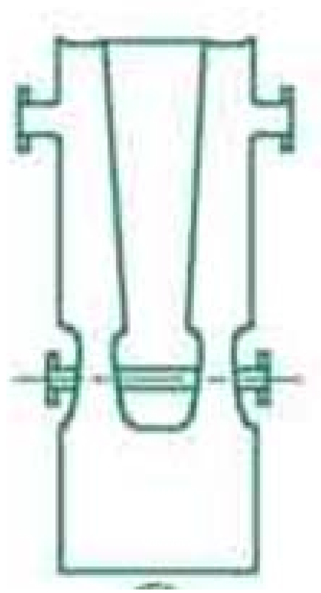


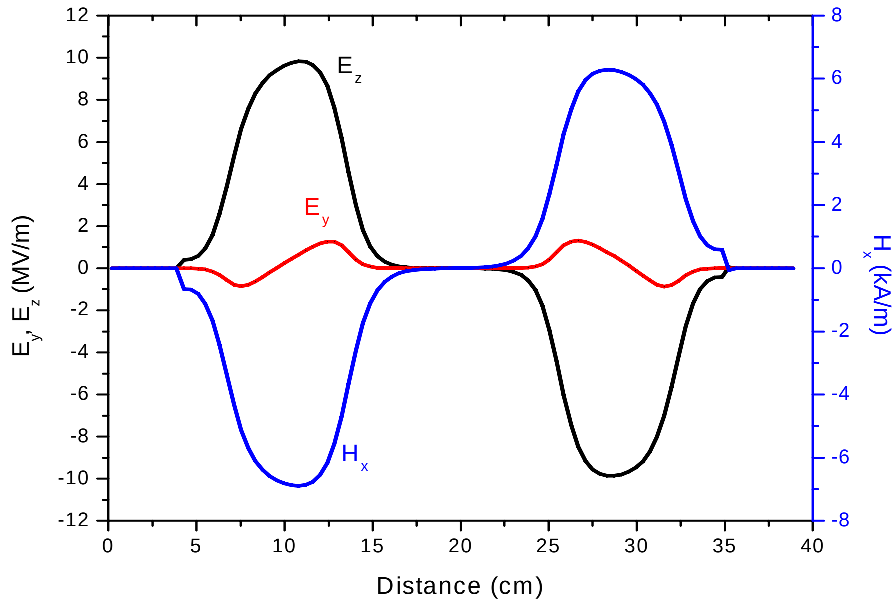
## *Compensation of the beam-steering effect*

(1) By cavity displacement in vertical plane: useful for heavy ions
(2) By reshaping of the drift tubes: universal for all regimes

Beam tests will be available in 1-2 weeks from now



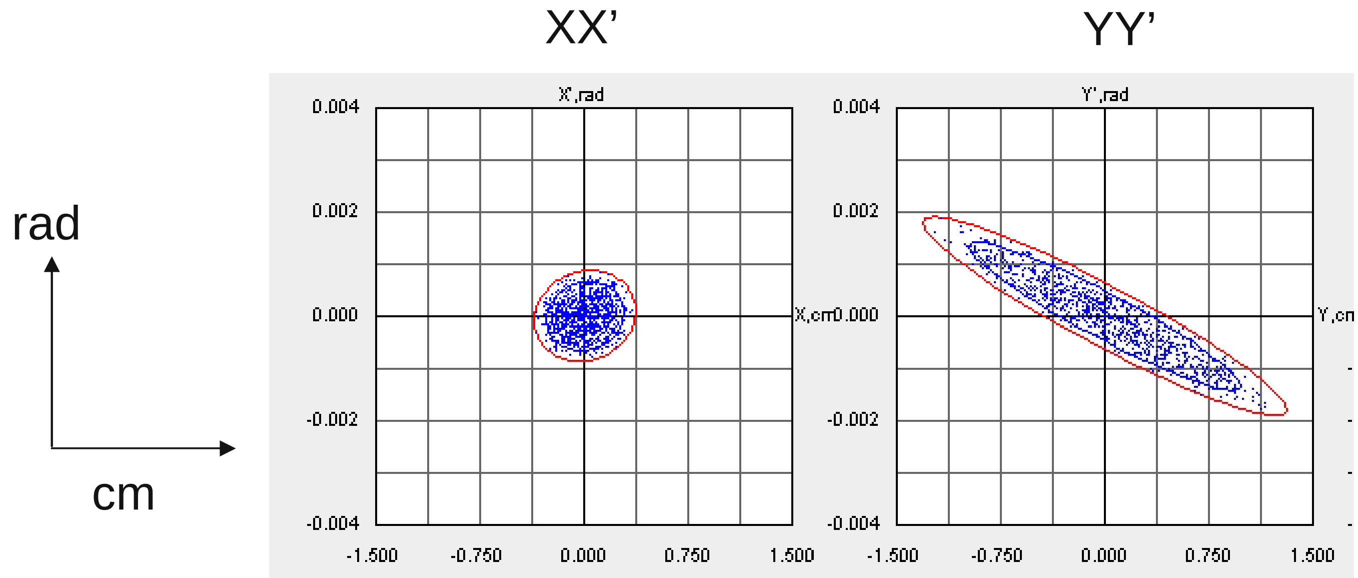




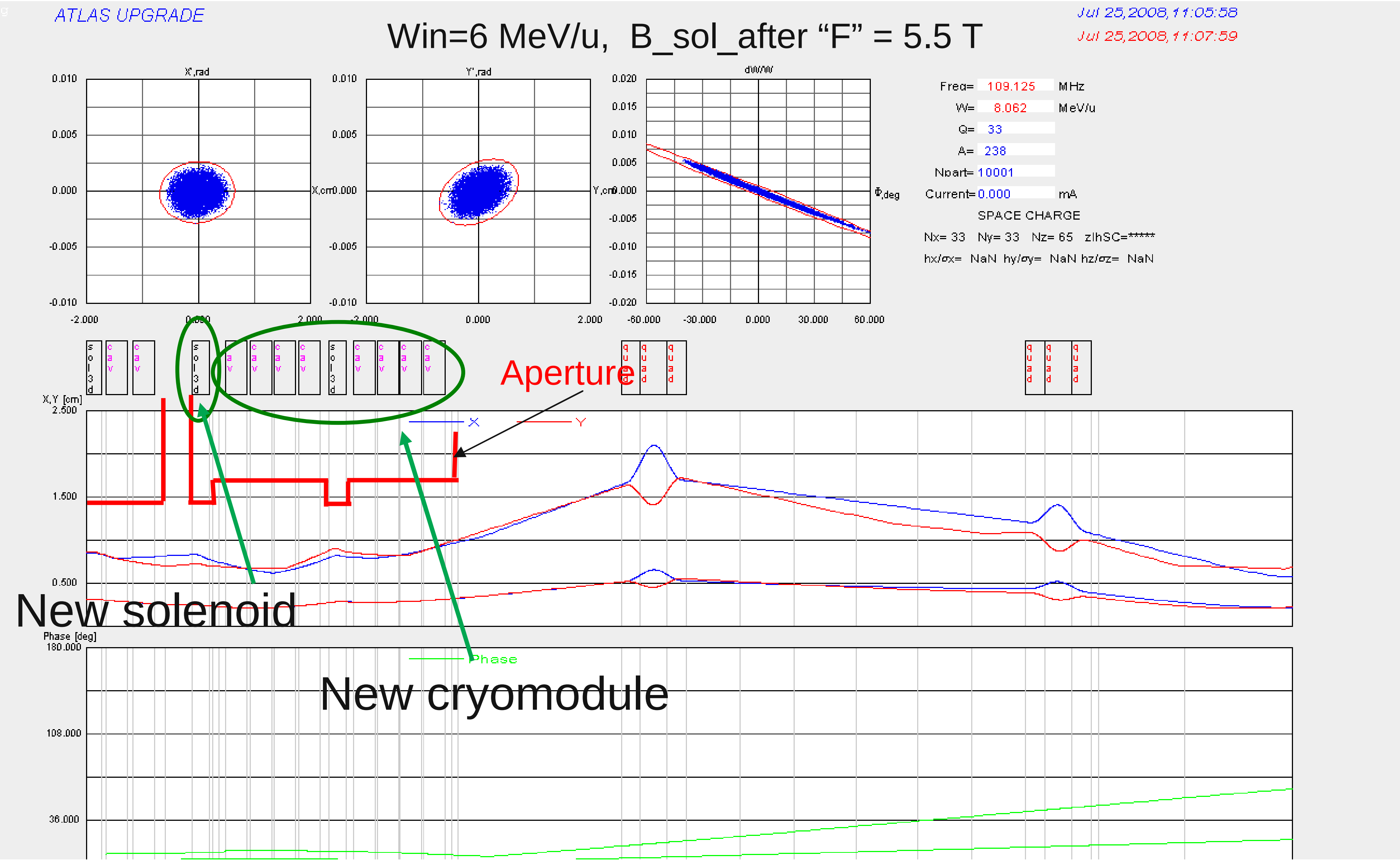
## $^{58}Ni^{14+}$ beam parameters at the entrance of the last solenoid in the F-cryostat as measured recently

| Emittance (π mm mrad) | X | Y |
|---|---|---|
| Normalized 1 rms | 0.065 | 0.11 |
| Normalized 90% | 0.2 | 0.47 |
| Un-normalized 90% | 2.1 | 4.8 |

| Twiss parameters | X | Y |
|---|---|---|
| Alpha | 0.06 | 2.79 |
| Beta | 0.53 | 2.04 |



# Uranium beam dynamics in the upgraded cryomodule

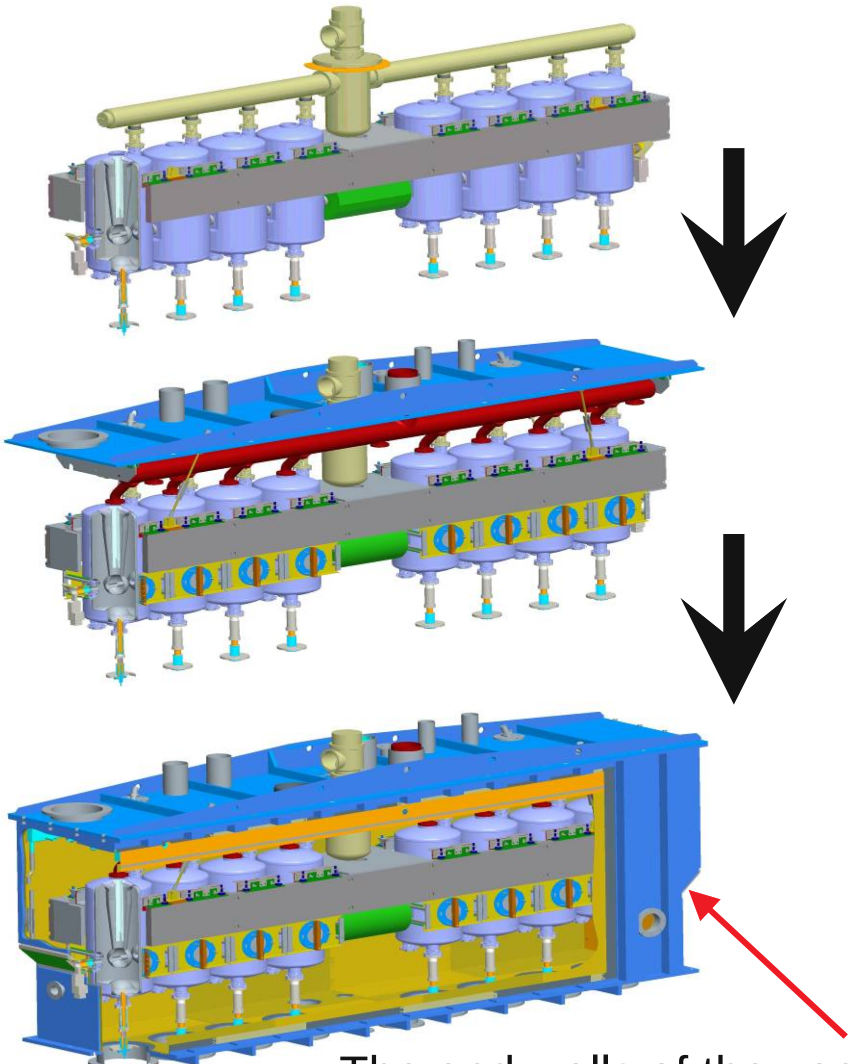


## *ATLAS beam energies with the upgrade cryomodule*

- Average accelerating gradient, 9.4 MV/m, demonstrated with the VCX, routine operation is recommended at 8.45 MV/m, provides 14.8 MV, this is 27.0 MV/m peak surface field

| Ion | Q1 | W (MeV/u) | Q1/Q2 | W (MeV/u) |
|---|---|---|---|---|
| $^{12}C$ | 4 | 19.3 | 4/6 | 23.9 |
| $^{16}O$ | 6 | 20.9 | 6/8 | 24.3 |
| $^{28}Si$ | 9 | 18.8 | 7/14 | 23.1 |
| $^{50}Ti$ | 13 | 16.2 | 12/21 | 20.8 |
| $^{64}Ni$ | 14 | 14.3 | 14/25 | 19.7 |
| $^{84}Kr$ | 15 | 12.2 | 15/31 | 18.5 |
| $^{92}Mo$ | 21 | 14.7 | 21/34 | 19.2 |
| $^{127}Xe$ | 25 | 13.2 | 25/40 | 17.1 |
| $^{178}Hf$ | 31 | 12.0 | 31/50 | 15.7 |
| $^{208}Pb$ | 36 | 11.9 | 36/55 | 15.1 |
| $^{238}U$ | 34 | 10.0 | | |

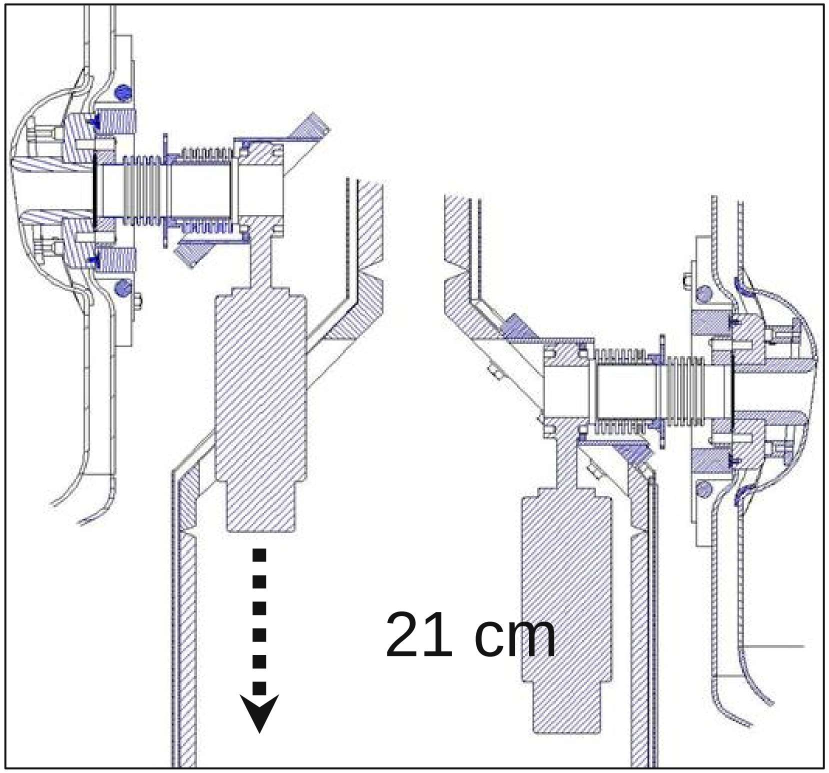
## *Top-loaded cryostat*



a) Space-efficient

b) Consistent with the requirements for high performance SRF surfaces.

Module-to-module spacing

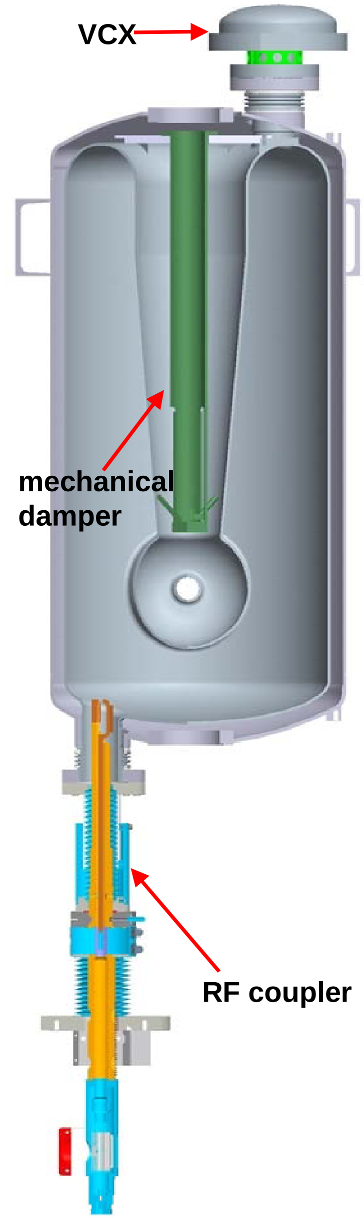



The end walls of the vacuum vessel are chamfered in the middle

# *Main design parameters of the SC cavities*

**Cavity Parameters**

| | | 1 MV/m | 15 MV/m | |
|---|---|---|---|---|
| **Frequency** | **109.125** | | | **MHz** |
| **beta** | **0.14** | | | |
| $\mathbf{U_0}$ | | **0.17** | **37.40** | **J** |
| **length** | **25.00** | | | **cm** |
| **βλ/2** | **39.05** | | | **cm** |
| $\mathbf{E_{PEAK}}$ | | **3.20** | **48.00** | **MV/m** |
| $\mathbf{B_{PEAK}}$ | | **58.30** | **874.50** | **G** |
| **G** | **39.90** | | | **Ohm** |
| $\mathbf{R_{sh}/Q}$ | **547.49** | | | **Ohm** |



# *Cavity surface processing*

- Electropolishing of fully assembled cavities
- Light BCP after final welding of the end plate
- HPWR

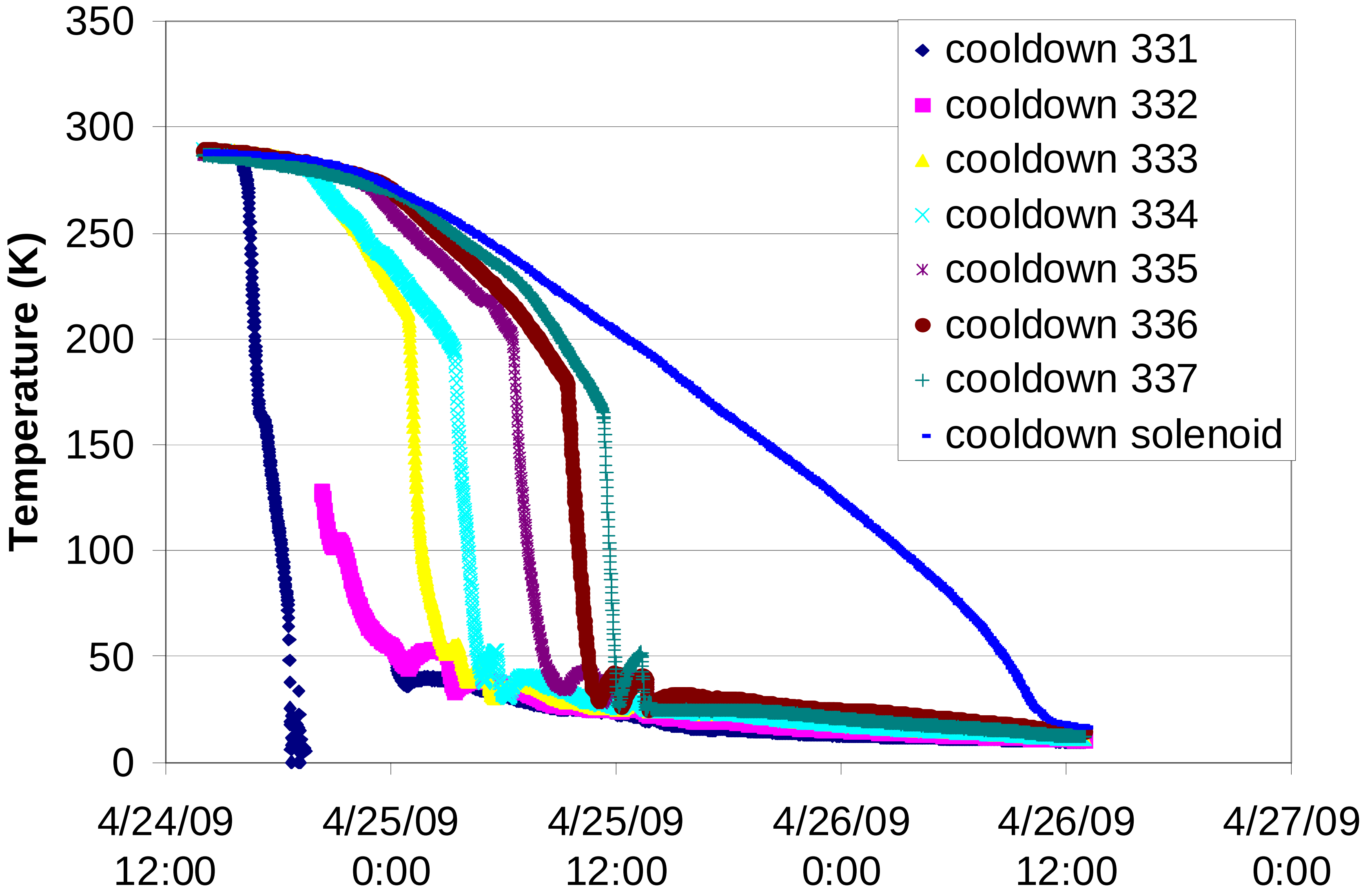
## *Cavity and its sub-systems*

- Designed for negligible beam loading: requires ~60 W RF amplifier to operate, critically coupled to ~$2\times10^8$ which is an intrinsic $Q_0$ with VCX
- Requires fast tuner which is VCX

## *The cavity string assembly in the clean area (between class 10 and 100) is complete, including complete, sealed cavity vacuum system*

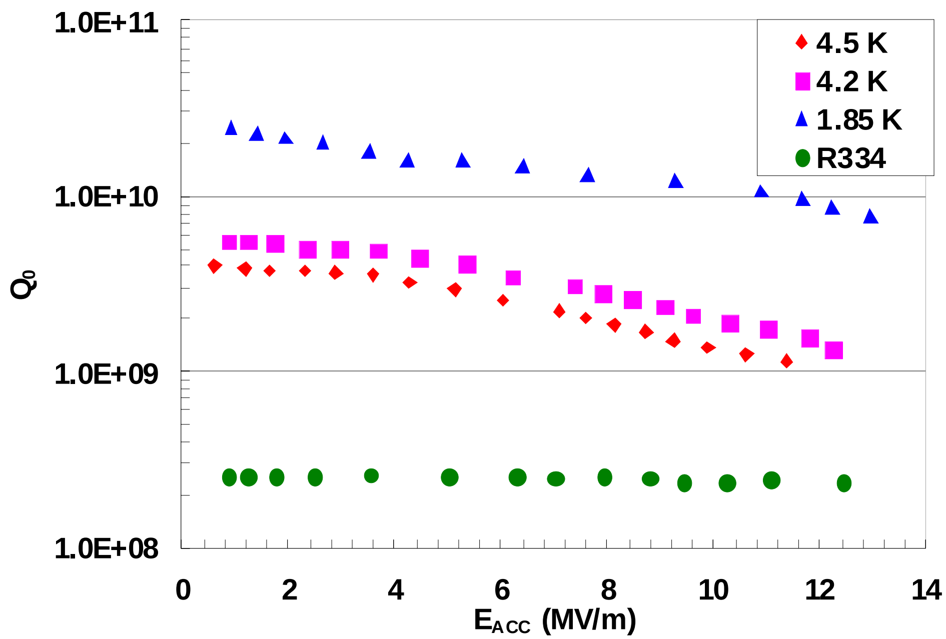
## *Cavity string suspended from the lid, with all cryogenic plumbing assembled and leak-checked, ready to drop into the box vacuum vessel*

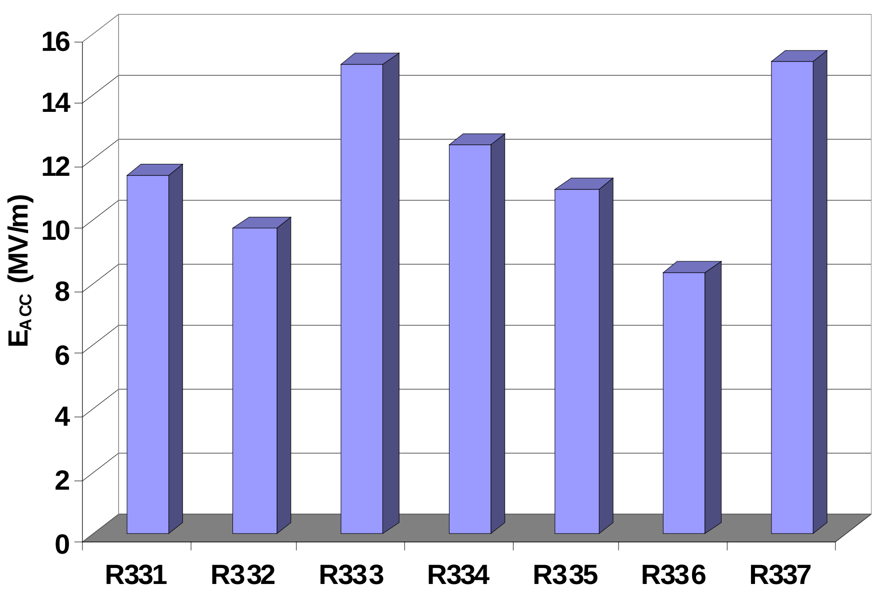
## *Cryomodule cool-down (total 38 temperature sensor)*



## *Accelerating fields*

- Maximum in 2 cavities = 15 MV/m
  - $V_{MAX}$=3.75 MV, $E_{PEAK}$= 48 MV/m $B_{PEAK}$= 875 Gauss
- Limited by VCX = 9.4 MV/m, averaged over 7 cavities
  - Large stored energy, tuning window is fixed, reactive power ~27 KVA
- Recommended for routine operation = 8.4 MV/m

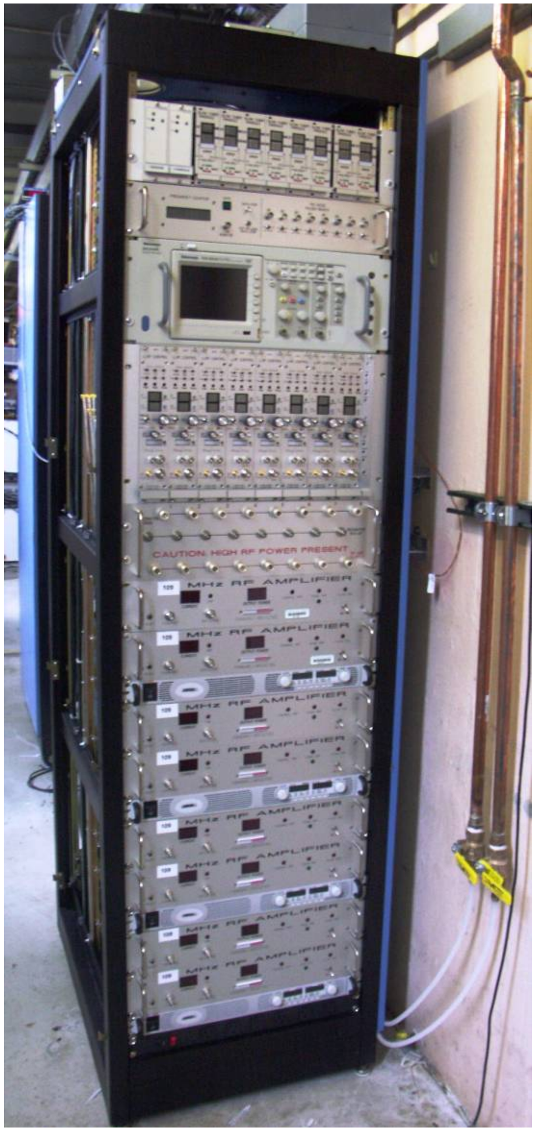


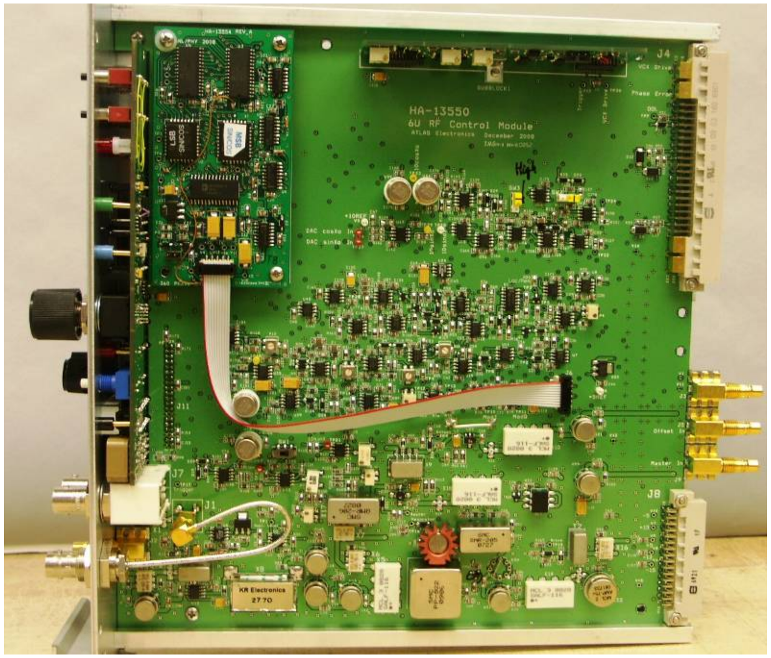
## *RF system*

- 250 W solid-state water-cooled amplifiers
- I&Q type LLRF controller has the following feedback loops
  - Frequency – use slow tuner
  - Amplitude – adjust input drive power
  - Phase  - use VCX
- Slow and Fast tuner controllers
- In addition, voltage pulsers are used to open-close VCX diodes

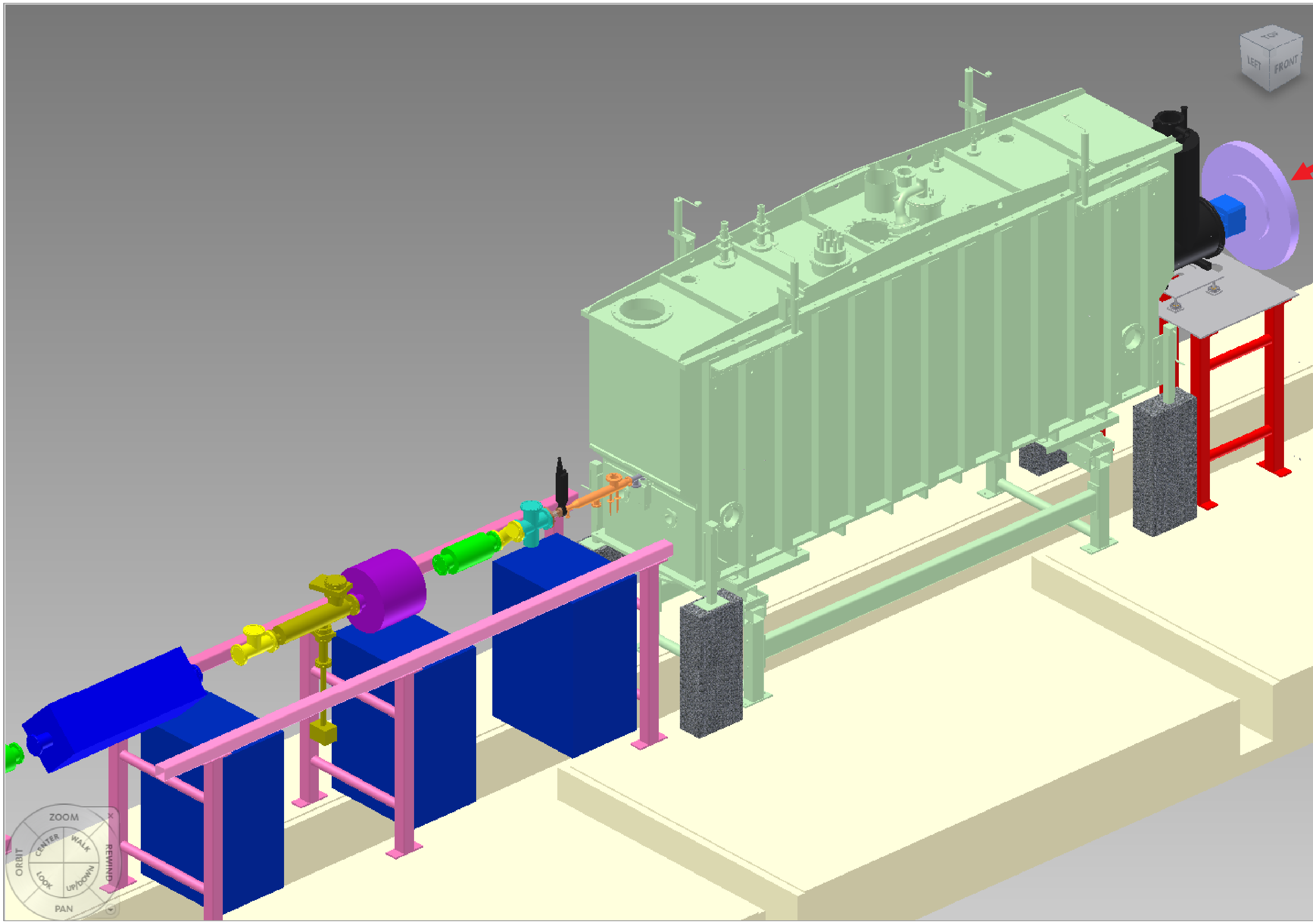
# RF system




LLRF CONTROL
Gain Adjust
Phase Error

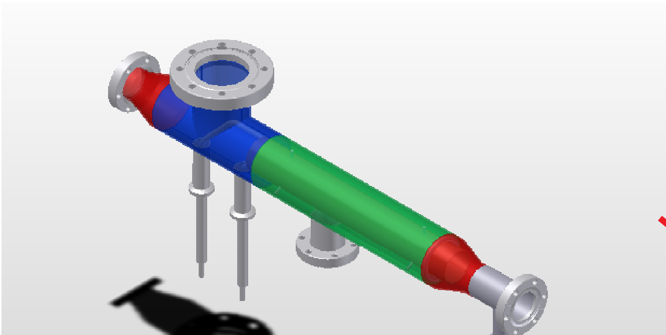

HA-13550
6U RF Control Module

# ATLAS Energy Upgrade Cryomodule in the tunnel



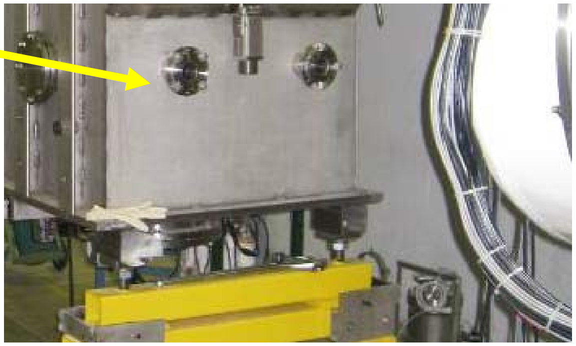

BEAM

# *Installation: cryomodule, 9-Tesla solenoid, LN trap*



## *Alignment*

- Box, lid and strongback have been fiducialized
- Special fixtures are used to transfer aperture centers to the resonator fiducial points
- Optical tooling instruments are used outside the clean room
- Initial alignment: ±0.1 mm
- Vertical movement of the targets in the cryostat due to cool-down: 1.5 mm
- Overall installation alignment in the tunnel: ±0.5 mm
- Viewing ports
- Limited time for alignment work due to the schedule
- Check with beam



## *Summary*

- All R&D design concepts were successfully demonstrated
- After short RF conditioning average performance of 7 cavities is better than in the test cryostat
- Routine operation of cavities
  - $V_0$=2.11 MV per cavity, or $E_{PEAK}$= 27.0 MV/m $B_{PEAK}$= 492 Gauss
- Without VCX could provide (different type of fast tuners are required)
  - Maximum $V_{MAX}$=3.75 MV, $E_{PEAK}$= 48 MV/m $B_{PEAK}$= 875 Gauss
  - Average $V_{MAX}$= 2.35 MV, $E_{PEAK}$= 30 MV/m $B_{PEAK}$= 547 Gauss
- New developments are necessary to use all potential of QWRs which are built with the available SRF technology:
  - Advanced optimal EM and mechanical design
  - Fast piezoelectric or magnetostrictive tuners for low intensity beams
  - High power RF couplers for high current beams
  - Operation at $E_{PEAK}$= 50 MV/m $B_{PEAK}$= 900 Gauss is visible
  - Very high voltages – 4 MV per cavity are realistic even for lower beta ~0.075