SRF Activities at ANL

2011 HEP-DOE Review

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Overview of SRF Activities

I. ILC SRF Program
II. Argonne Tandem Linear Accelerator System Intensity Upgrade
    a) Prototype advanced quarter-cavity for low-β velocities ~8% the speed of light
    b) Install cryomodule of 7 quarter-wave cavities by end of 2012
III. Compact heavy-ion accelerator development
    a) Locate field limiting defects in complex low-β SRF cavities
    b) Develop techniques/procedures to eliminate defects and improve heavy-ion SRF cavity performance
    c) Develop compact accelerator lattice designed using the world's highest performance low-β (β < 0.8) cavities.
IV. Cavity and accelerator lattice development for MSU/FRIB
V. Support testing of ALD coated cavities
VI. Support testing of Advanced Photon Source SRF crab cavities

ILC Project SRF Program Motivation and Goals

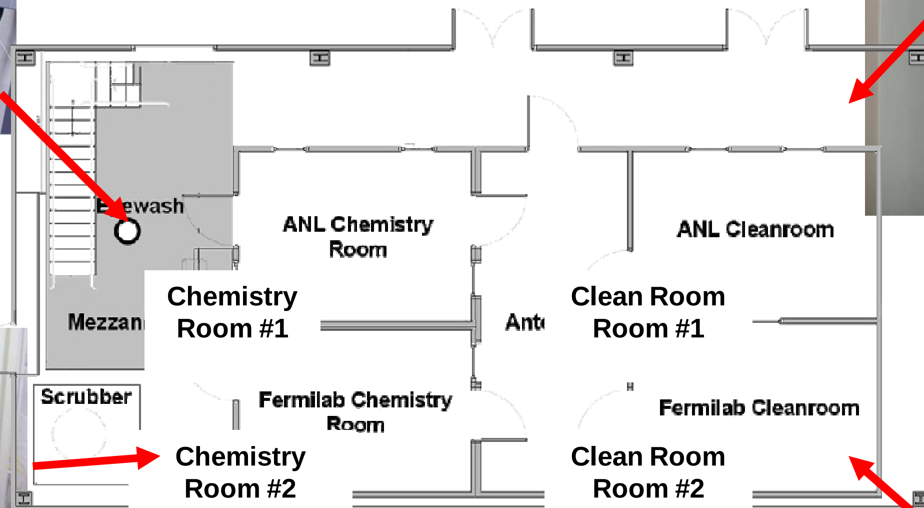
- To perform R&D that demonstrates a high yield (>80%) of cavities which after a single processing cycle perform at E_{acc} = 35 MV/m with a quality factor of 8 x 10^9

- Make technical choices which position the ANL SRF effort to design and build the next generation of high-intensity particle accelerators
  - Transfer techniques developed for ILC cavities to other SRF cavity projects
  - Generally useful solutions are much more appealing than single project applications

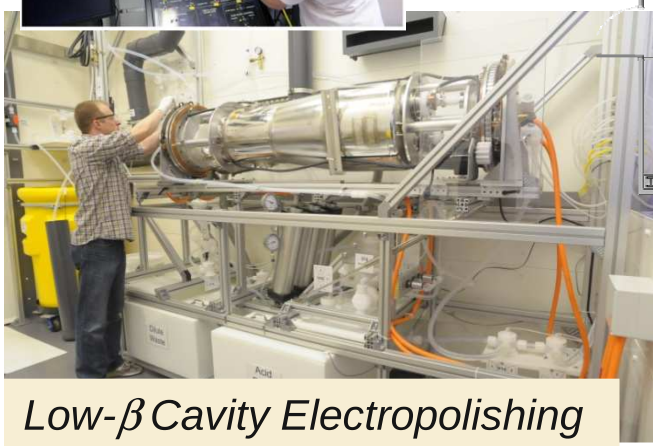
Joint ANL/FNAL Surface Processing Facility

ILC Electropolishing

Low-β Cavity Cleaning



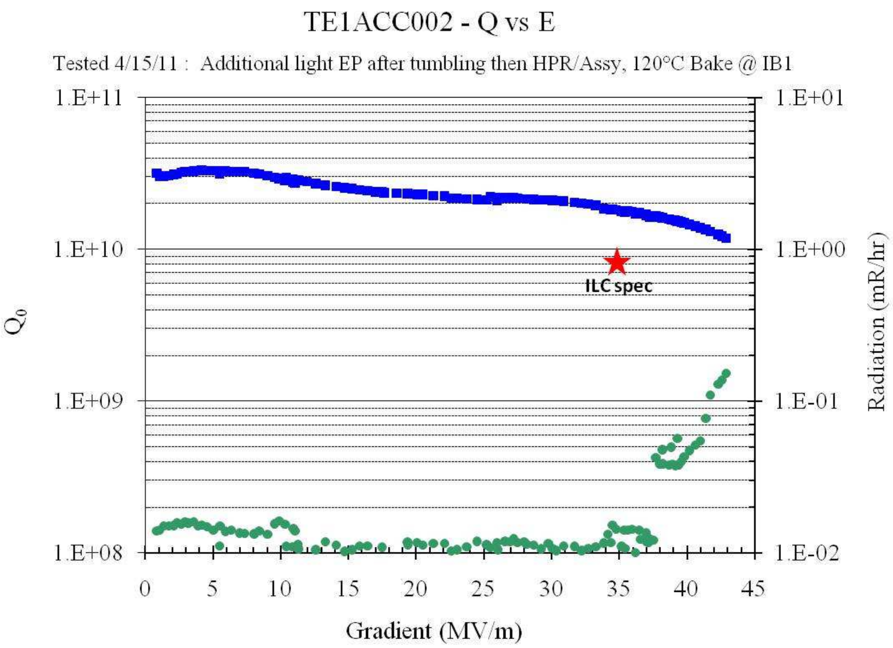
ILC Cleaning

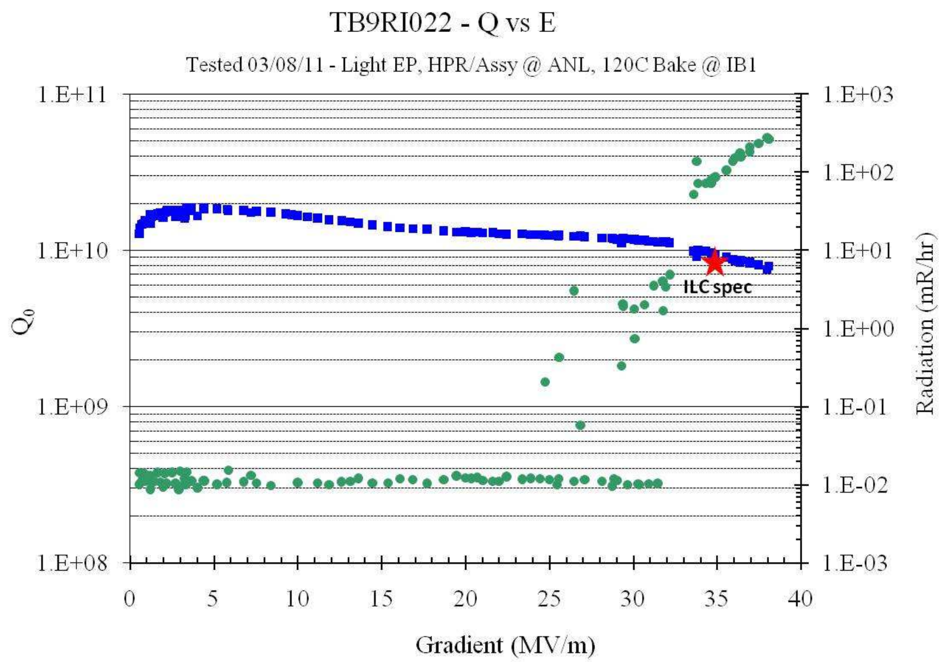


Low-β Cavity Electropolishing

- Highly skilled personnel and state-of-the art facilities cover the full range of SC cavity activities
- Collaboration of ANL- PHY, HEP and Fermilab enabled this work

ANL SRF R&D ILC Results





- Test results for the highest performing single (left) and nine (right) cell cavities processed at ANL.
- Cavities electropolished and cleaned at ANL are routinely meeting and exceeding the ILC vertical test acceptance criteria
  - E_{acc} > 35 MV/m
  - Q > 8 x 10^9

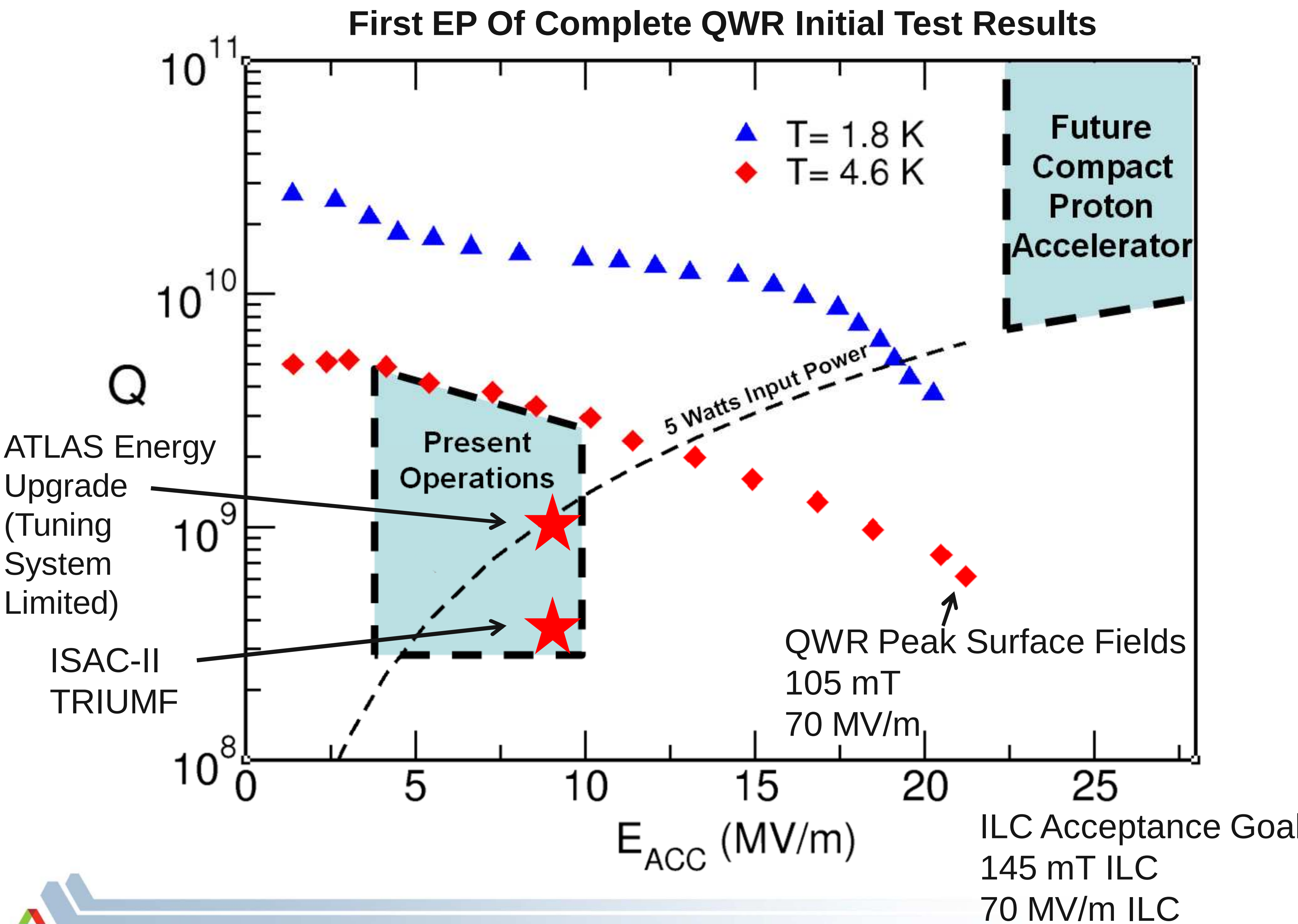
ANL ILC R&D Technology Transfer I

Before

After

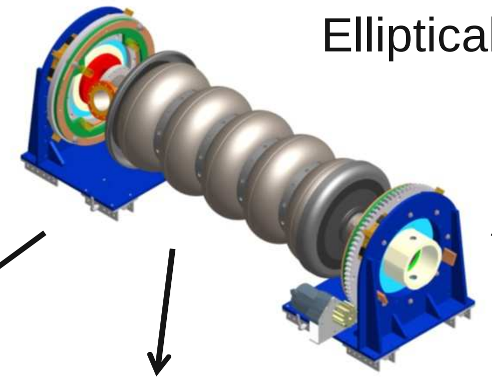
- Performed world's first horizontal electropolish of a finished quarter-wave cavity March 2011.
- This is the world's highest performing quarter-wave cavity after polishing only (no additional ILC-type treatments, e.g. baking)

ANL ILC R&D Technology Transfer I



ANL ILC R&D Technology Transfer II: FNAL Project-X

MSU/Project- X
Halfwave



Elliptical Cell EP

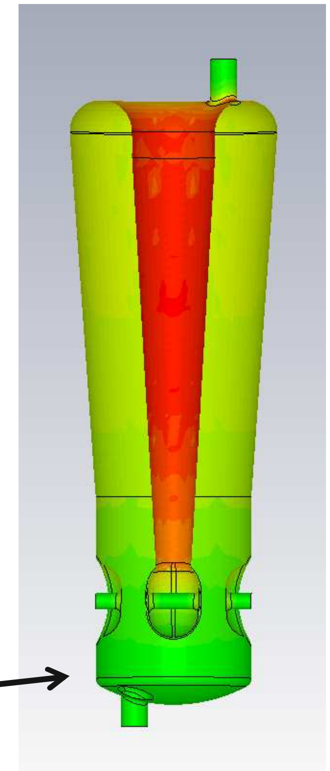
β=0.11	β=0.22	β=0.4	β=0.61	β=0.9	β=1.0

325 MHz 2.5-160 MeV	650 MHz 0.16-3 GeV	1.3 GHz 3-8 GeV

- ANL SRF is a world leader in low-beta cavity/cryomodule design, prototyping, and fabrication
- We have proven high performance processing and design techniques which are directly applicable to Project-X
- We have already developed similar SRF technology necessary for the low-beta sections of Project-X
- We are **still** in negotiations with FNAL to start work

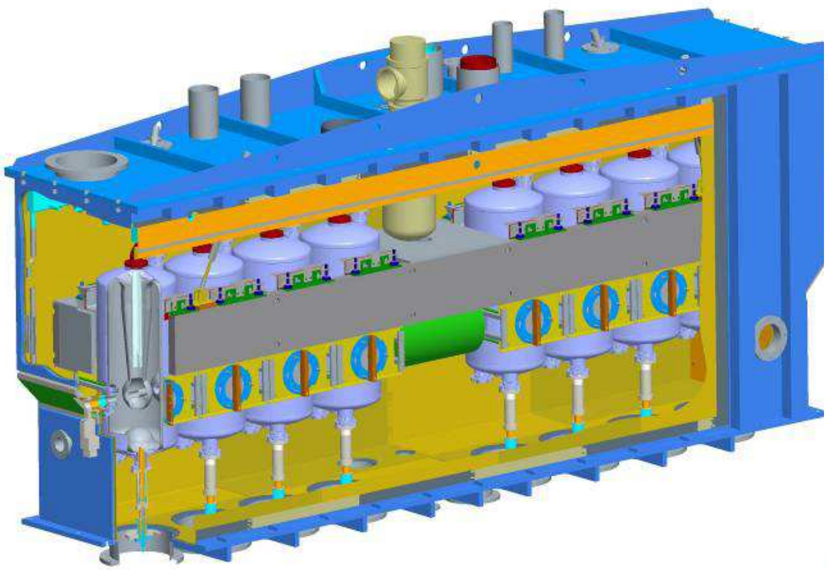
ATLAS Intensity Upgrade SRF

- A cryomodule containing 7 β=0.15 quarter-wave cavities was added to the ATLAS heavy ion linac in 2009, increasing heavy ion beam energy by 30-40% providing a 14.5 MV accelerating potential in a 4.6 m module
- Now the ATLAS user facility is being upgraded to increase the intensity of heavy-ion beams for nuclear physics experiments:
  - Old devices which were state-of-the-art in the early 1990's are now limiting the accelerator performance:
    - The acceptance is too small (accelerator transmission < 40%)
    - The current superconducting cavities have a smaller real-estate gradient that current state-of-the-art.
  - Increase available cryogenic system cool power
  - High efficiency transport of short lived isotopes from recently commissioned CARIBU fission source
- The ATLAS Intensity Upgrade SRF
  - Since 2009 an advanced design with tapered conductors was developed with twice the performance compared to straight cylinders
  - Since then maximum voltages of 4.4 MV per cavity have been achieved (E_{PEAK} = 70 MV/m, B_{PEAK} = 105 mT)
  - A new cryomodule for β = 0.077 is being built which provides and accelerating potential of 17.5 MV in a 5.2 meter length

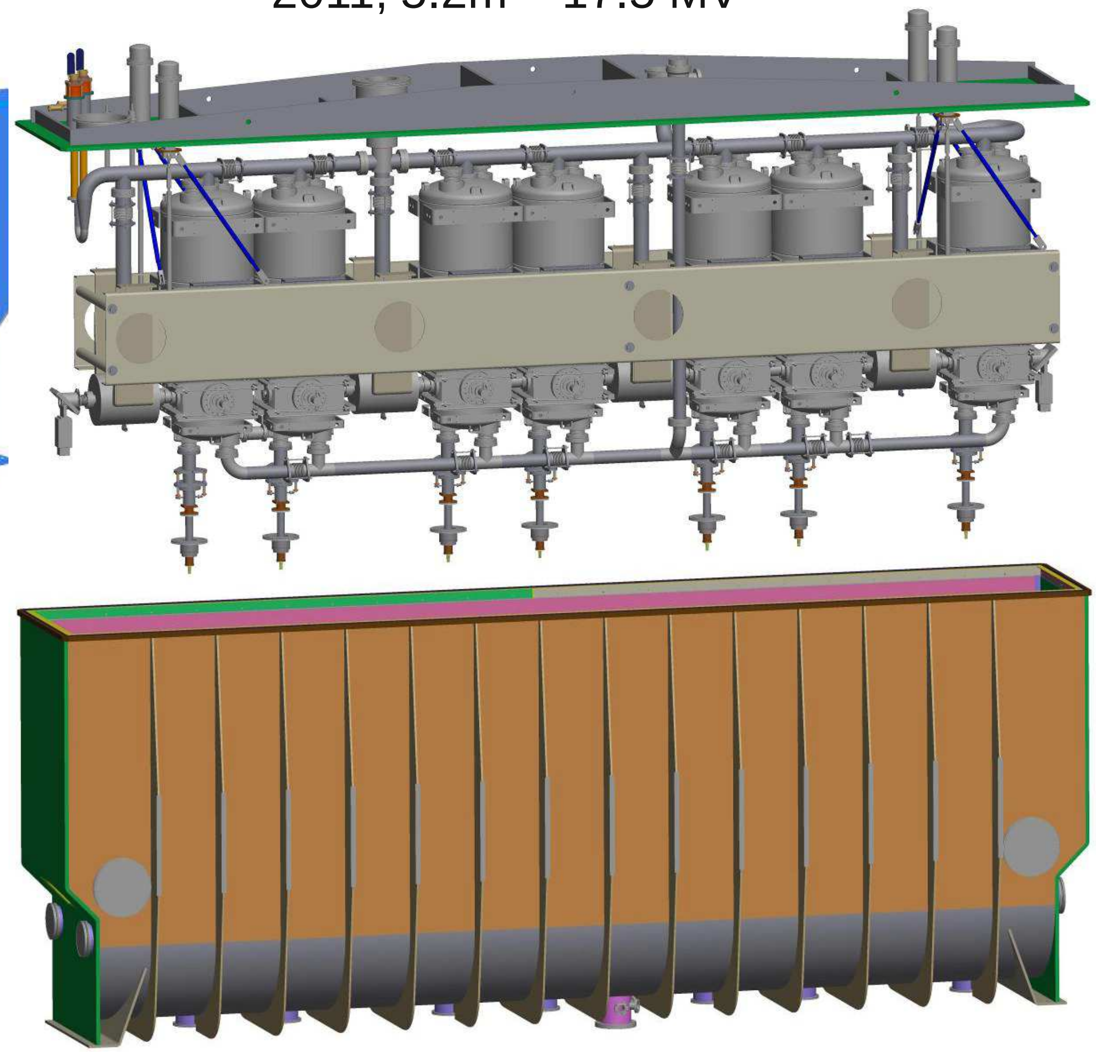


ANL SRF Cryomodules

2009, 5m = 14.6 MV



2011, 5.2m = 17.5 MV



- 7 cavities, 4 solenoids
- A box cryomodule for the front end of Project-X would be very similar with a few changes.

MSU/Project-X Resonator Development

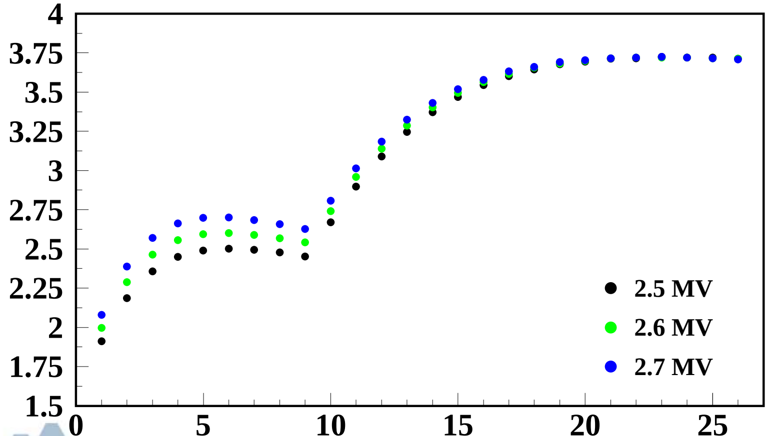
- At the current stage of the FRIB project we are providing support for the development and the construction of the 16 to 60 MeV/u section of the driver linac. This work is directly applicable to Project-X and all heavy-ion accelerator projects.
- We have developed an advanced β = 0.29 halfwave accelerator cavity with tapered inner and outer conductors to optimize the cavity performance and maximize the real-estate gradient. This work follows from our successful work with the 72.75 MHz quarter-wave cavity prototyped for our intensity upgrade project.
- We have optimized the β = 0.29 accelerator lattice section of FRIB to incorporate our advanced cavity design.
- By coupling the β = 0.29 and β = 0.54 lattice simulations and using our advanced β = 0.29 cavity design we reduced the cavity count by 23 and the cryomodule count by 5.
- We are ready to start fabrication of a prototype cavity.
- Results of this work are presented on the following slides: lattice development, cavity E&M Design, and cavity tuning system hardware characterization.

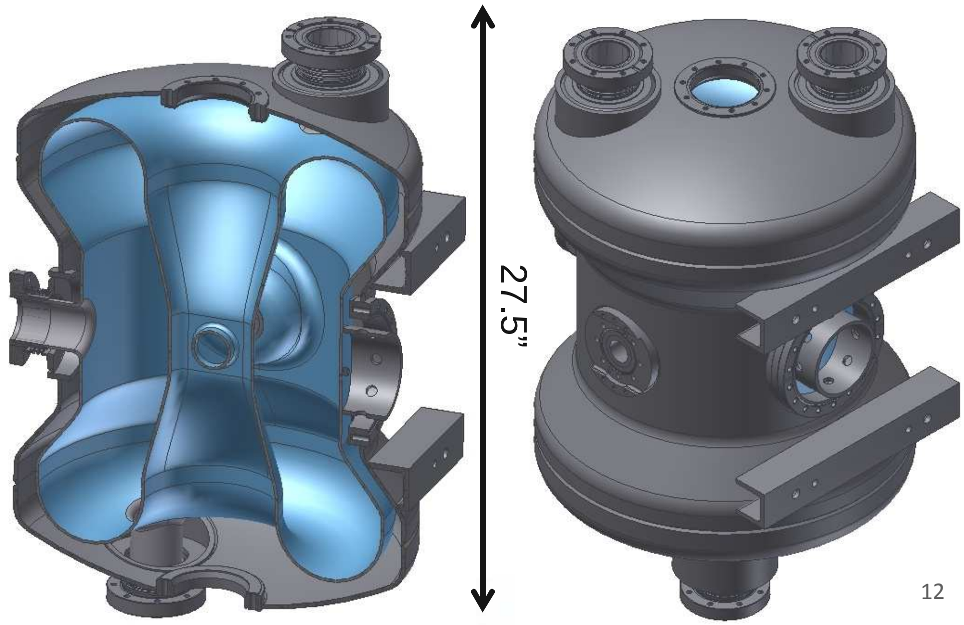
β = 0.29 Linac Development for FRIB

- We have optimized the β = 0.29 section of FRIB to incorporate our advanced cavity design and performance levels achieved with our state-of-the-art processing techniques.
- By coupling the β = 0.29 and β = 0.54 simulations and using our advanced β = 0.29 cavity design we reduced the cavity count by 23 and the cryomodule count by 5.

β ~ 0.29 (MV)	β ~ 0.29 # of Cryos	β ~ 0.54 # of Cryos	β ~ 0.29 # of Cav	β ~ 0.54 # of Cav	β ~ 0.29 W_{in} (MeV/u)	β ~ 0.29 W_{out} (MeV/u)	β ~ 0.54 W_{out} MeV/u)
1.9 (MSU)	13	18	78	144	16.3	54.6	201.0
2.6 (ANL-1)	8	18	56	144	16.3	57.2	204.9
2.6 (ANL-2)	9	17	63	136	16.3	62.4	205.0

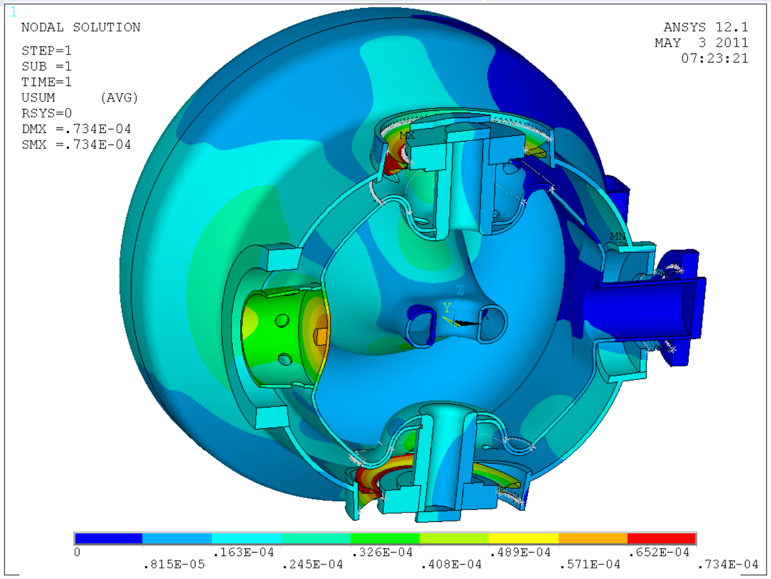
Average cavity voltage per cryomodule for 9 β ~ 0.29 cryos + 17 β ~ 0.54 cryos





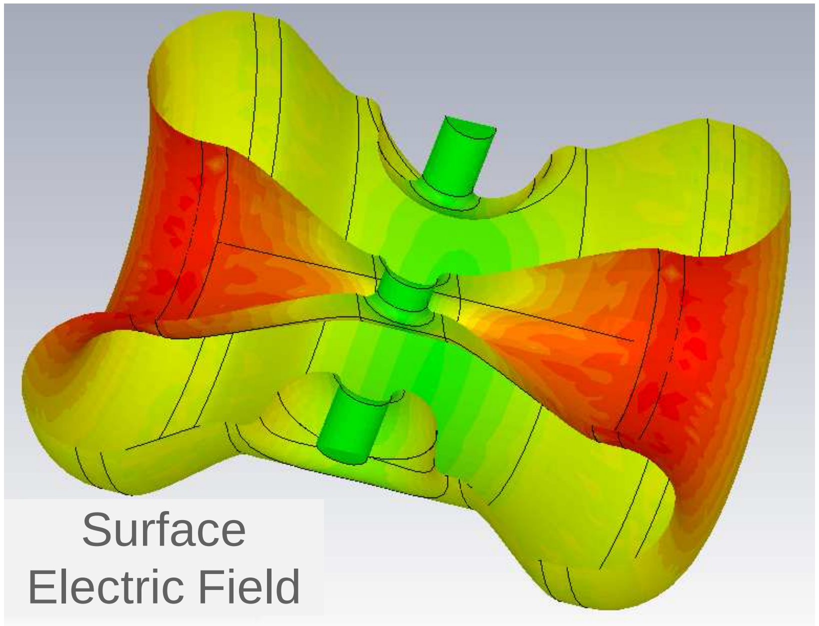
β = 0.29 322 MHz HWR

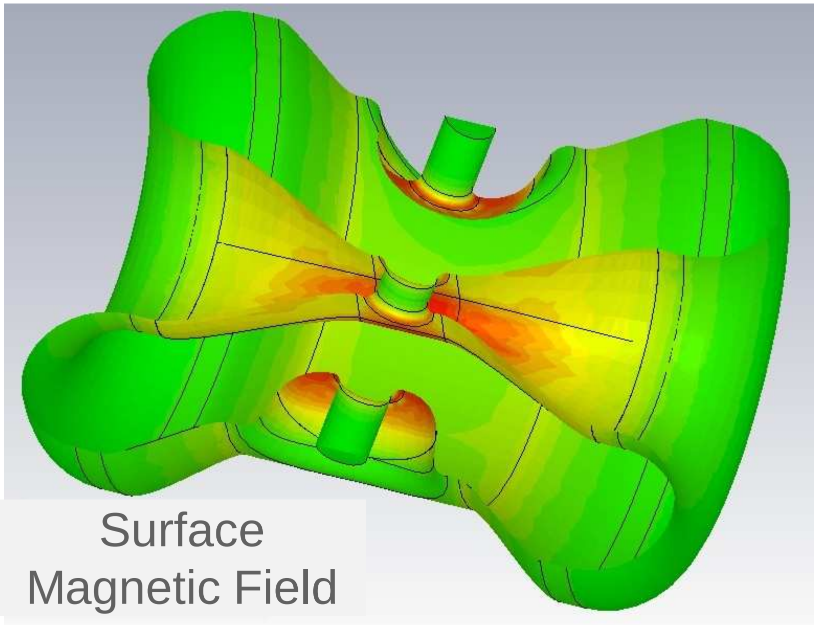
	Without Ports
Frequency (MHz)	322
β	0.285
L_{eff} (m, $\beta\lambda$)	0.28
E_{pk}/E_{acc}	4.2
B_{pk}/E_{acc} (mT/(MV/m))	7.3
G (Ω)	100.7
R/Q (Ω)	194.5



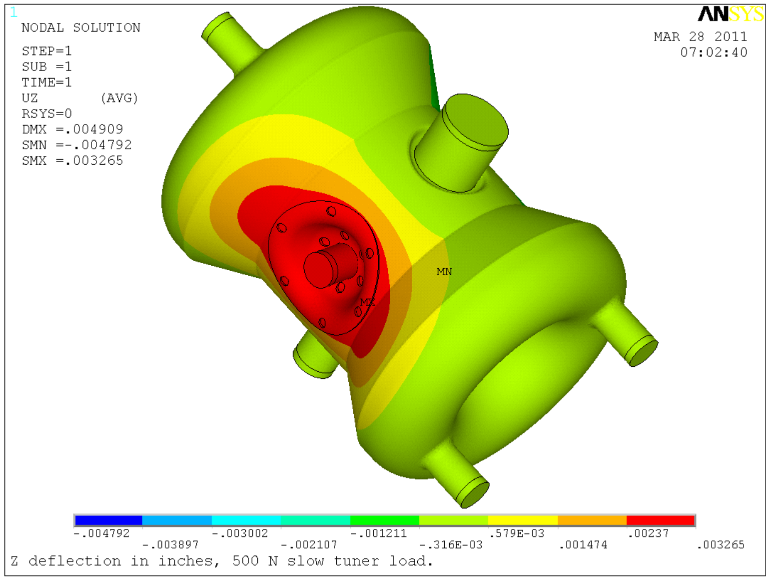
ANSYS Multiphysics Simulation

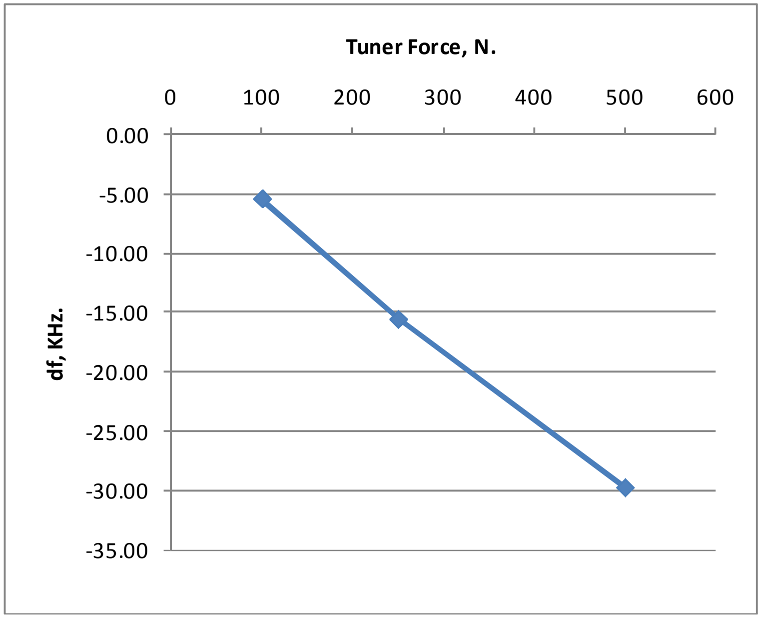
$\Delta f/\Delta p \sim \pm 2$ kHz/atm

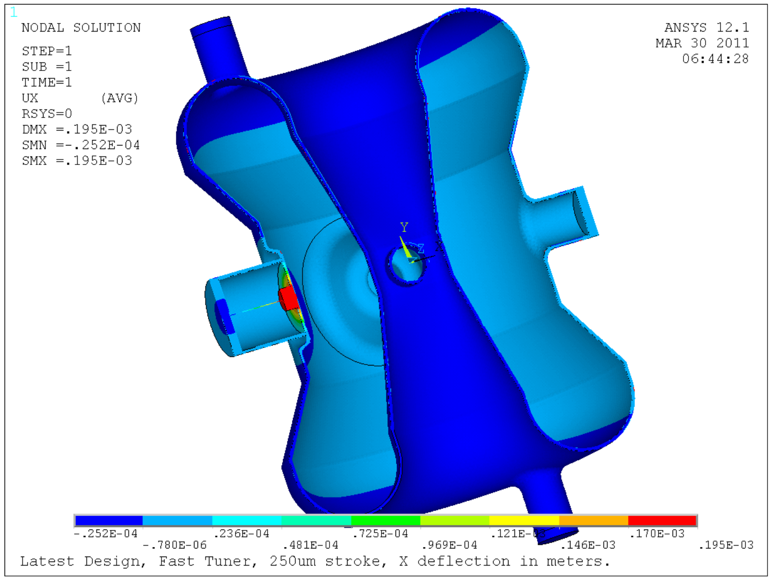


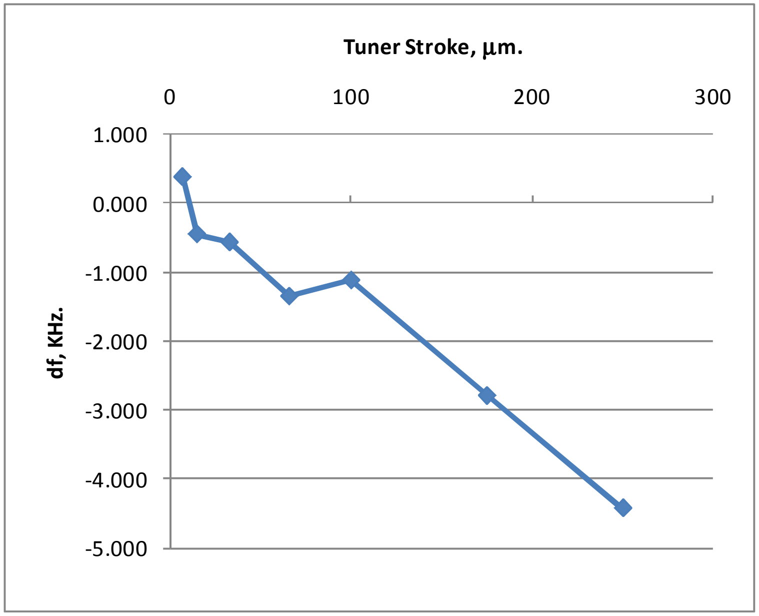


β = 0.29 322 MHz HWR Tuning Systems



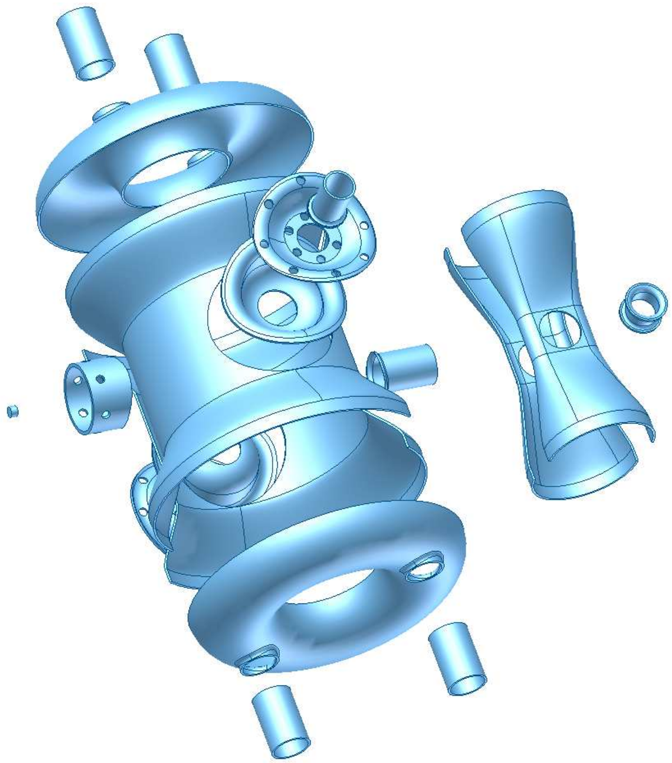






ANSYS Multiphysics Simulations of the ANL Slow (top) and Fast (bottom) tuners.

MSU/Project-X Cavity Ready To Prototype



Cavity Niobium Parting

Preliminary Cryomodule
Conceptual Design

Compact Heavy Ion Linac Development SRF Goals

- To perform R&D that increase the levels of SRF heavy-ion accelerator cavities to the performance levels attained for the ILC

- Develop highly optimized cavity geometries to minimize the required accelerator real-estate

- Perform detailed second sound measurements to determine what is making the highly complex heavy-ion cavities quench at levels below what prototype ILC cavities are performing at today

- Make the front end (<1 GeV) of heavy-ion accelerators affordable for 1-50 mA projects

- We have two funded projects here:
  - One to build and test cavities
  - One sponsored by LDRD to develop technique to locate defects via second sound

LDRD Funded SRF Work

- Develop techniques which are generally useful for locating quench in complicated heavy-ion accelerator applications.

- Focus of this work is on second sound measurements
  - Oscillating Superleak Transducers (Cornell 2008)
  - Germainum Thermometers (ANL 1977)

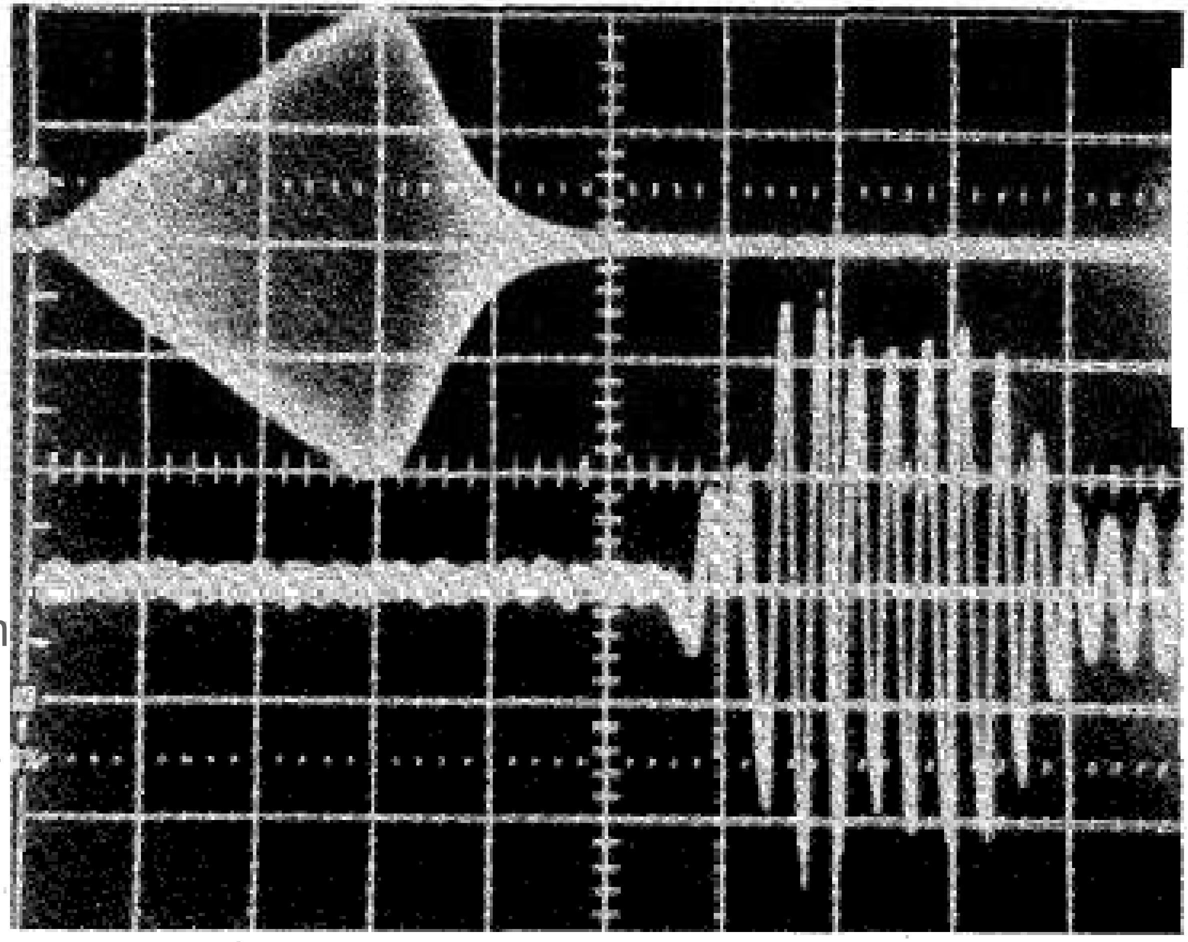
- **Thermometry**
  - Full temperature map of the cavity at various field levels
  - Required for a detailed understanding of the cavity performance
  - Requires thousands of transducers

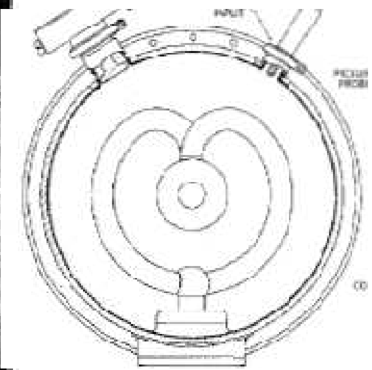
- **Second Sound**
  - Requires a few transducers (e.g. 8)
  - Simple
  - Fast
  - Accurate
  - Only locates the quench-spot
  - Convenient for the rapid testing/repair of poor performing cavities

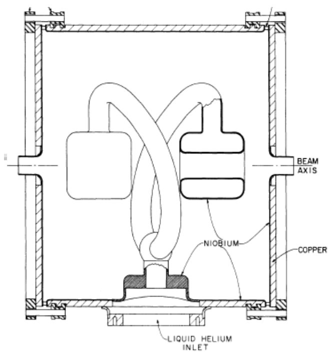
A brief history of second sound defect location

Cavity Field

Second-Sound
Wave Detection







16” (40.6 cm)

1.9 K (v_s = 18.8 m/s), Vertical Scale = 10 ms/div

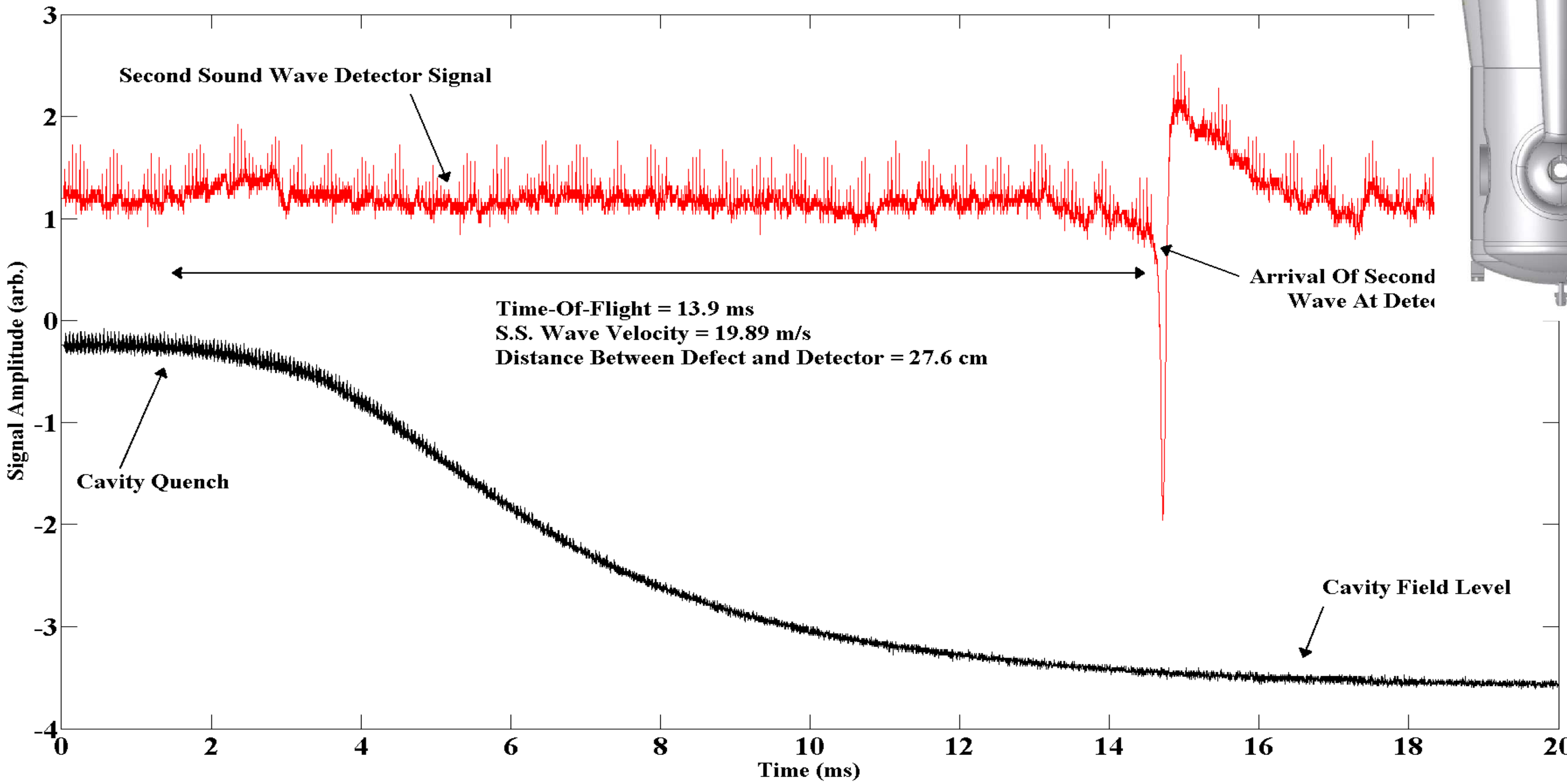
K.W. Shepard et. al, IEEE Trans. Mag, Vol. mag-15, no.1, January 1979, Pg. 666

Second Sound Defect Location

- Simple defect localization schemes can be implemented by exploiting the properties of superfluid He, e.g. second sound waves.
- When a cavity quenches, typically several joules of thermal energy are transferred to the helium bath in a few milliseconds.
- If the cavity is operated at $T < 2.17K$, the helium bath is a superfluid and a second sound wave propagates away from the heated region of the cavity.
- By locating several transducers in the superfluid helium bath, the second sound wave front can be observed. The time of arrival of the second sound wave at a given transducer is determined by the time of flight from the heated region, which is centered on the defect causing quench.
- Measuring the time of flight to 3 or more uniquely located transducers, unambiguously determines the defect location.
- We performed our first measurements with a quarter wave cavity 2 weeks ago details on next slide.
- The picture on the right shows the cavity and the locations of the detectors.

Second Sound Defect Location

- Using Oscillating Superleak Transducers designed at Cornell we have located a defect in the prototype 72.75 MHz quarter-wave cavity for the ATLAS Intensity Upgrade.
- The defect is on the center conductor of the cavity in a region with a surface magnetic field of 92 mT at quench.
- Future inspection of the defect location is planned.



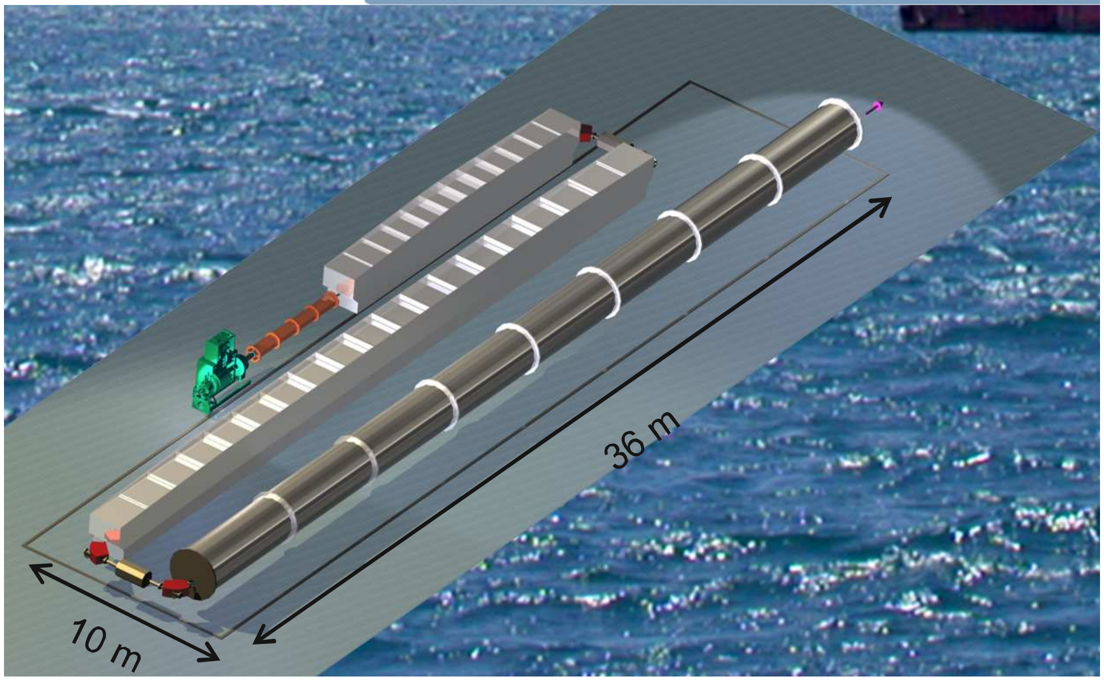
Defect Location

Goals of Compact Heavy-Ion Work

- We are working to:
  - Develop a very compact (10mx36m) 1 GeV, 1 mA, proton linac.
  - Build two prototype low-β cavities which will be used to locate and study the physical phenomena which limit the maximum achievable surface fields in TEM-class cavities, typically to levels below where the ILC cavities operate today in vertical acceptance tests (70 MV/m, 150 mT).
  - Develop techniques to mitigate field limiting phenomena which will increase the maximum achievable fields in future TEM-class cavities.
    - Locate field limiting defects via second sound measurements
    - Inspect defect locations
    - Try to repair the defect via improved fabrication techniques, repeat chemical polishing, local grinding, etc.
- We are currently fabricating the first of the two prototype cavities, a quarter wave cavity with an identical design to what we are building for the ATLAS Intensity Upgrade. We will begin testing this cavity in late summer 2011.
- We will start fabrication of the second prototype cavity, a half wave cavity, this summer and will begin testing this cavity in summer 2012.
- What we learn with these cavities will benefit all of our SRF cavity projects.
- The next three slides briefly highlight the work ongoing for this project.

Compact 1 GeV 1 mA Proton Linac

- Beam dynamics simulations for an extremely compact 1 mA 1 GeV proton linac have been performed to optimize the accelerator performance in a very small footprint
- The design uses low-beta cavities operating with peak surface magnetic fields of >120 mT

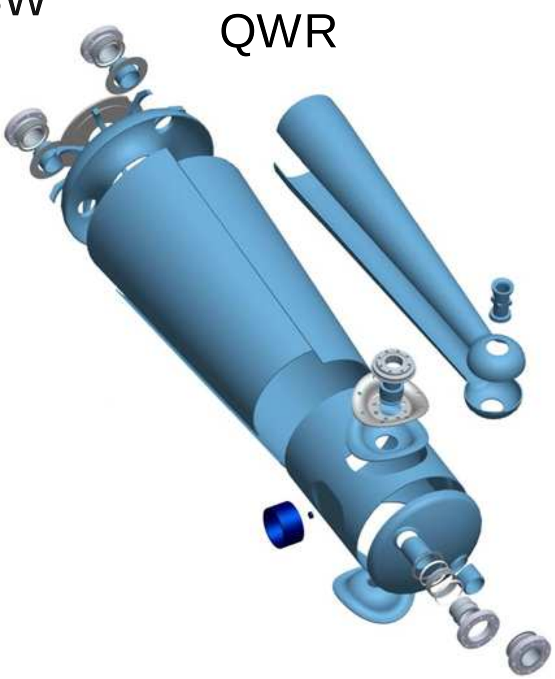


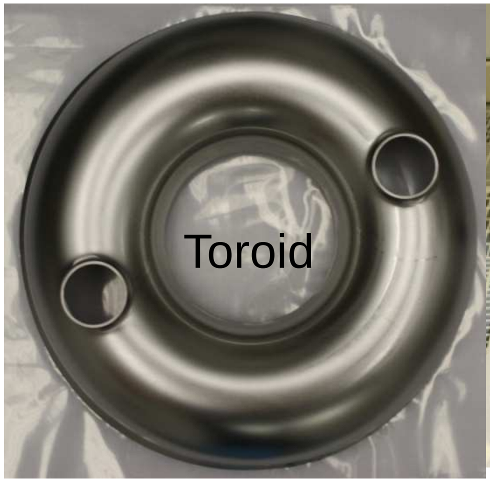
NN	Part of the linac	Content	Total length	Output beam energy
1	IS	ECR type ion source with electrostatic beam formation structure	1 m	25 keV
2	RFQ	Radio Frequency Quadrupole with coupling windows	4.0 m	1.5 MeV
3	Cryomodule I	Three QWRs + 20 HWR + seven SC solenoids	11.5 m	144 MeV
4	Bend 1	SC dipole magnet + two RT quadrupoles	1.2 m	144 MeV
5	Cryomodule II	21 TSR + six SC solenoids	27.1 m	461 MeV
6	Bend II	SC dipole magnet + two RT quadrupoles	1.2 m	461 MeV
7	Cryomodule III	24 elliptical cavities	32.9 m	1016 MeV

Quarter-Wave Resonator For Fundamental Studies

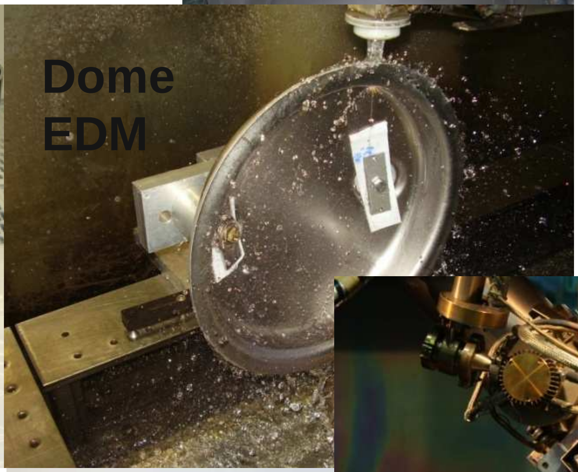
- This QWR is being fabricated to locate and study limits to the maximum achievable accelerating gradient in TEM-class cavities.
- Fabrication will be complete in late summer/early fall with advanced surface processing following soon after.

Tapered Housing EBW



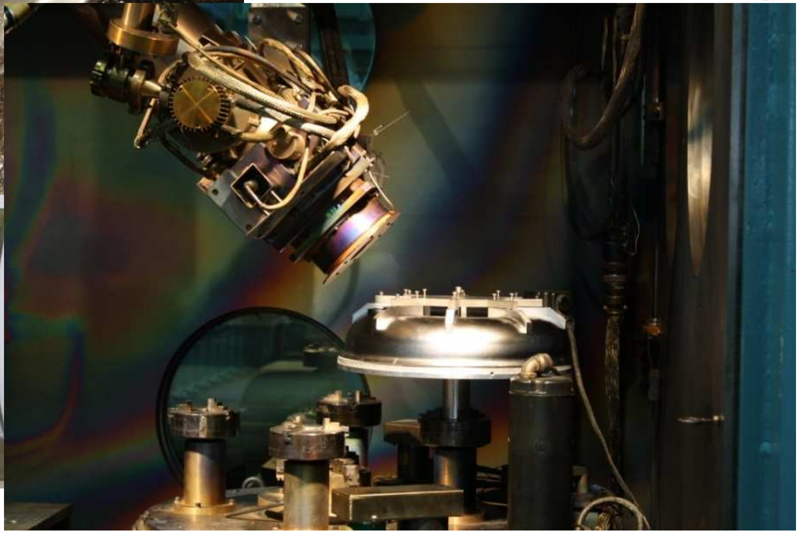


Cylindrical Housing



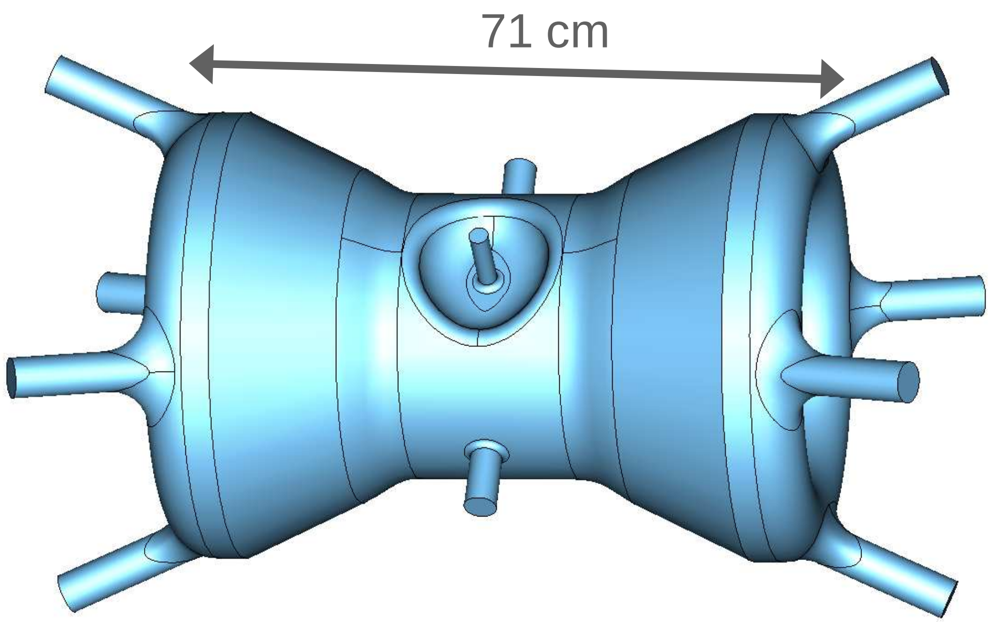
Coupling Ports

Reentrant Nose and Doubler



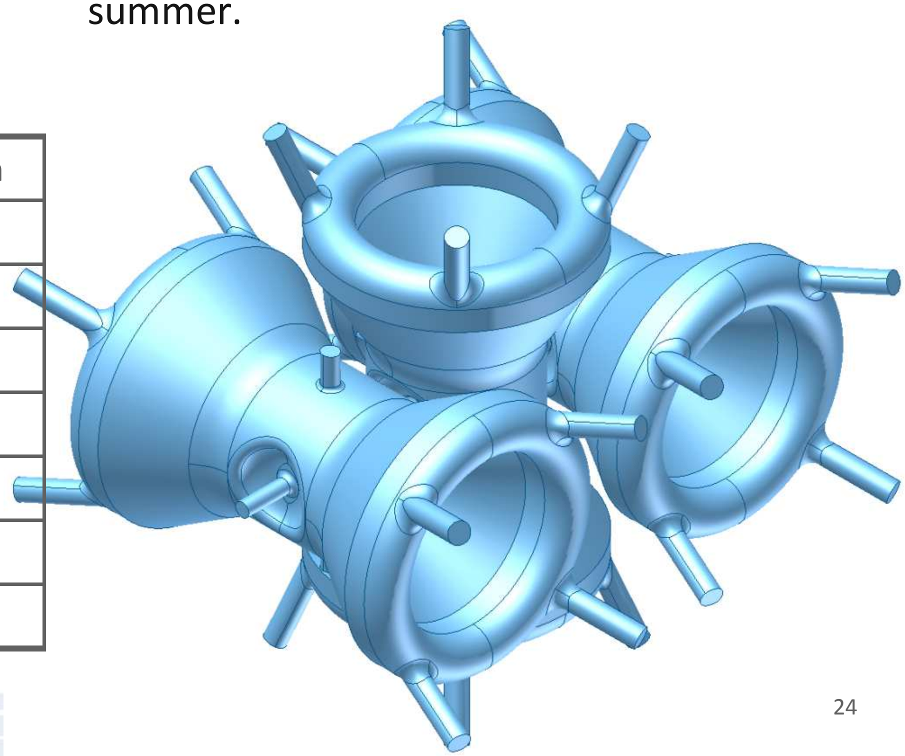
Advanced Electron Beam Welding

The worlds most advanced halfwave resonator design



- We have designed and will start construction of an advanced halfwave resonator.
- The resonator was designed to minimize the peak surface fields for a given accelerating voltage by using an hourglass shape.
- The hourglass shape also allows for the resonators to be tightly packed together to maximize real-estate gradient and minimize linac length
- Construction of a prototype will begin this summer.

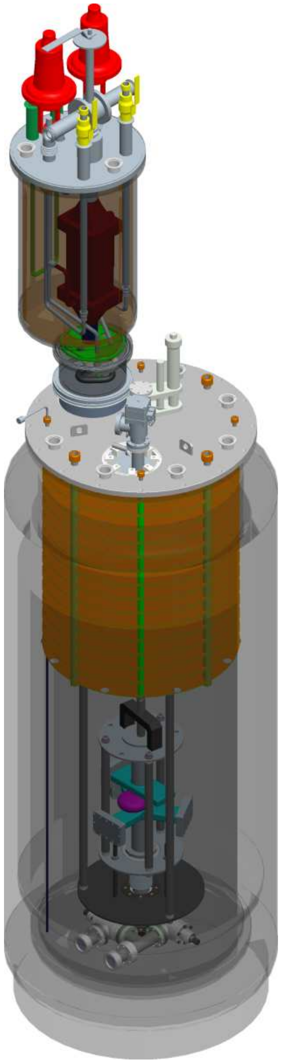
	ANL RIA Halfwave	DTRA Design
β	0.26	0.236
l_{eff} ($\beta\lambda$, cm)	45.9	30.3
Frequency (MHz)	170	233.5
B_{peak}/E_{acc} (mT/(MV/m))	11.9	6.1
E_{peak}/E_{acc}	4.4	4.1
G = Q*R_s (Ω)	57	73
R_{sh} / Q (Ω)	241	164



Support of Laboratory Wide SRF Activities

ILC Single Cell Cavity 2 K Test Preparation

Crab Cavity Test for APS SPX Project



- The 2 Kelvin test preparation shown above (left) was supported by LDRD (2009-2011)
- No new lab support for this type of work as of now

Summary

- SRF at ANL has extensive experience with low-β SRF cavities and cryomodules

- SRF at ANL is in a unique position to work on:
  - Project-X @ FNAL
  - ILC
  - FRIB @ MSU
  - Compact High-Intensity Proton Accelerators

- Besides ALD, no DOE or laboratory R&D support beyond FY11 for a compact SRF linac