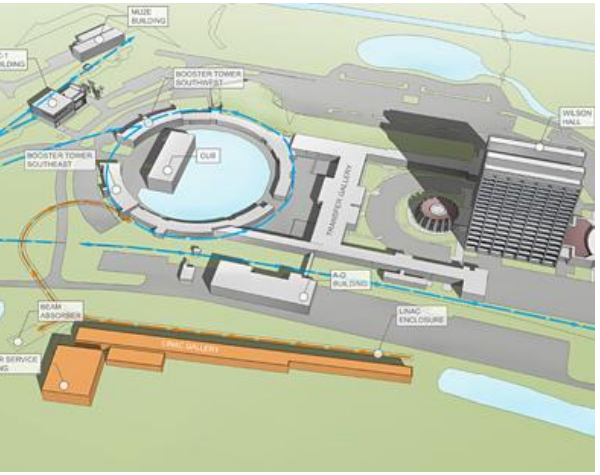
Towards megawatts beam power accelerator

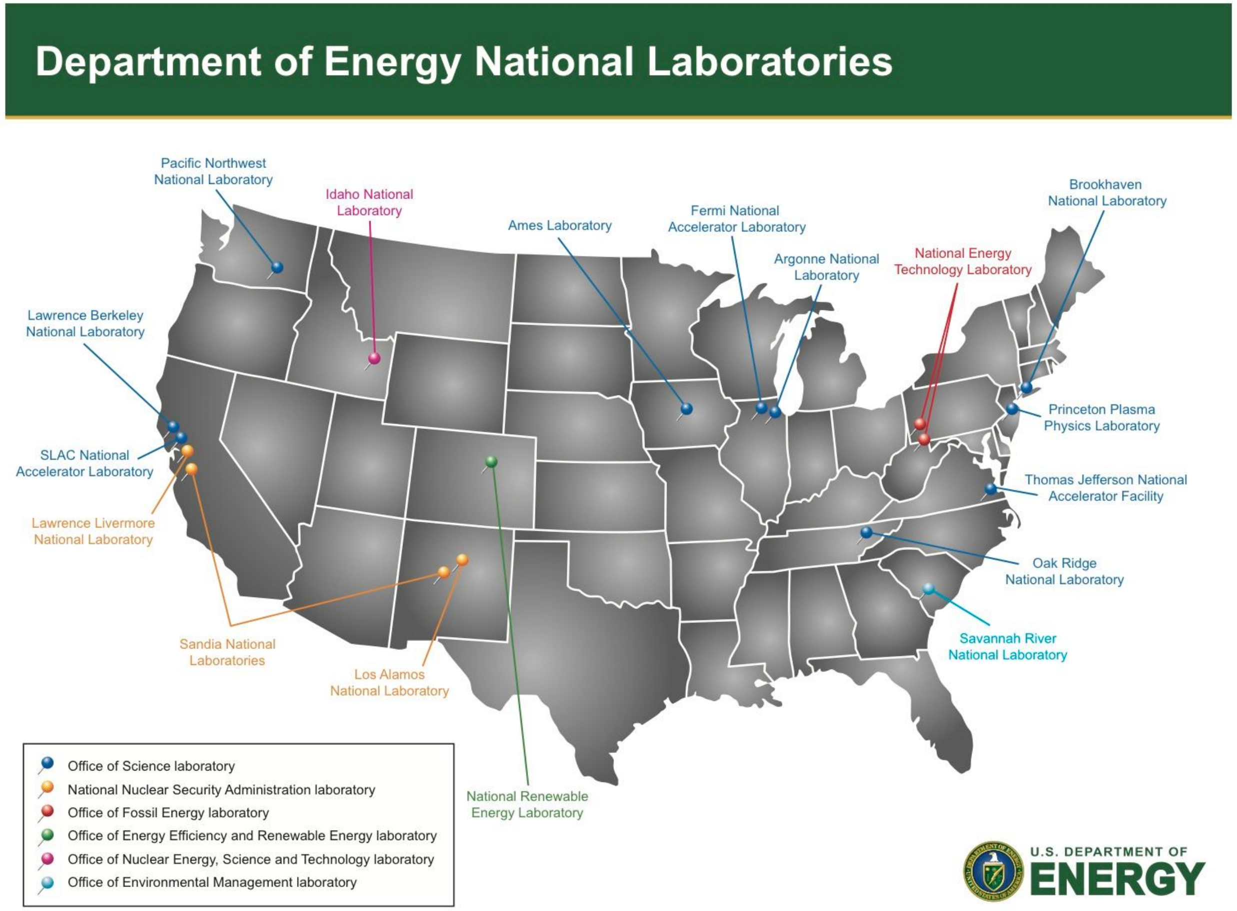
Dr. Chen Xu
Brookhaven National Laboratory
May 18th 2017

Selected major SRF accelerator facilities in USA

PIP-II@FNAL

eRHIC@BNL





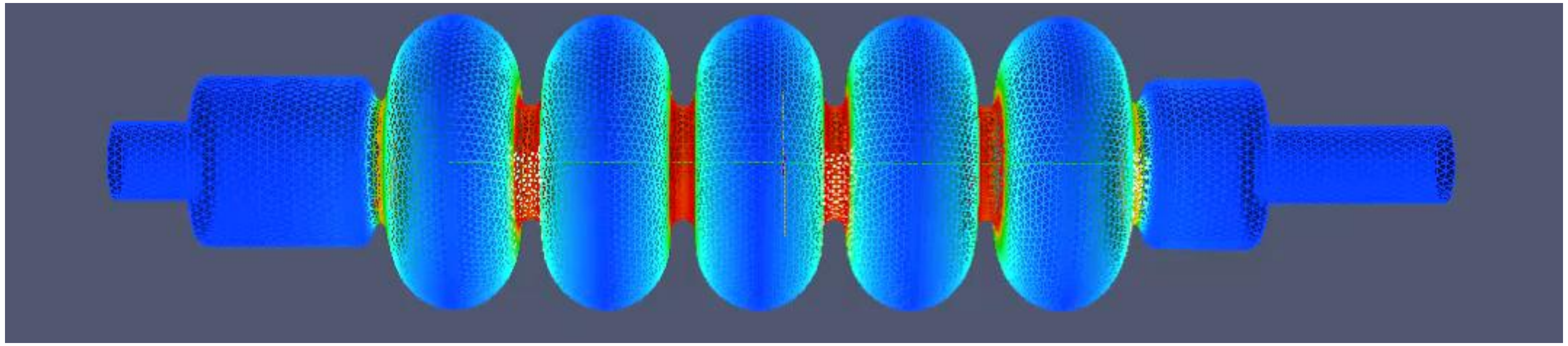
LCLS-II@SLAC

Accelerators: Nuclear Physics (NP), High Energy Physics (HEP), Basic Energy Science (BES).
Superconducting Radiofrequency (SRF) is a maturing technology .

CEBAF@JLAB

High efficiency and high beam power accelerators

- SRF is the solution for the future intensity frontier.
  - High quality factor on high accelerating gradient.
    - Surface treatments: BCP/EP, doping, infusions.
    - New SRF materials: Thin film, SIS and high H_c materials.
    - Integrations: Magnet expulsion, LLRF control.
  - High RF structure and components for high current beam.
    - Accelerating structure optimization, high power systems, RF sources.
- Synergies between SRF and RF technologies.



Dark current simulation from **"C. Xu**. et.al. Proceedings of NAPAC 2016"

Outline

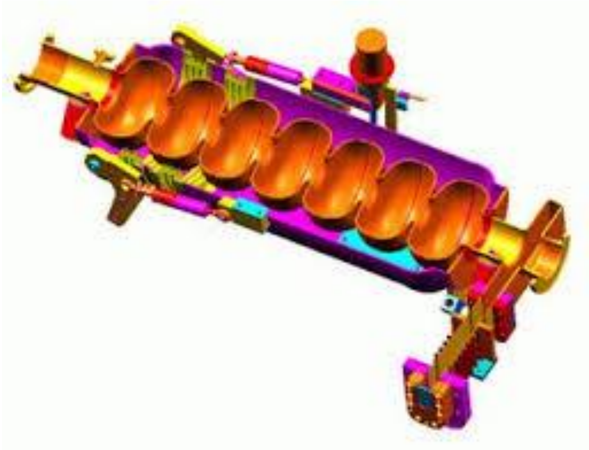
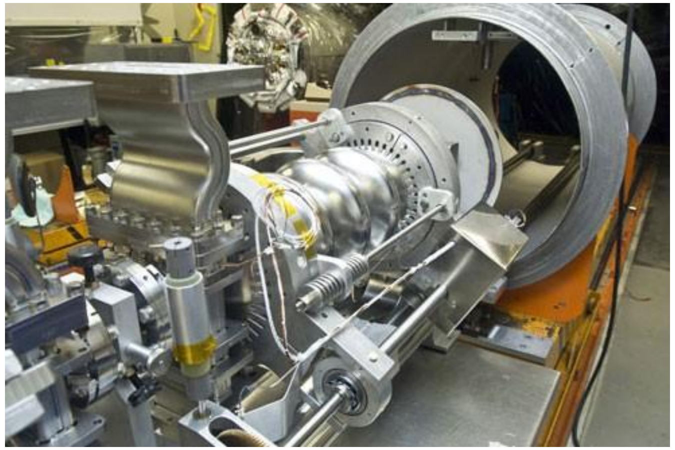
- **SRF systems and SRF surface resistance**
- **Some of my research topics in accelerator physics**
    1. Research on SRF materials and processing at CEBAF.
    2. SRF cavities design to minimize Higher Order Modes (HOM) for eRHIC.
    3. High power SRF components design for eRHIC.
    4. Dark current radiation in LCLS-II SRF linac.
    5. High power X band RF compressor system for LCLS.
    6. Electron Medical accelerator target.

- **Selected future opportunities**
    1. SRF frontier studies for PIP-II/III.
    2. High intensity accelerating component studies.
    3. Innovations for HEP in Fermi Test Beam Facility.

SRF systems assembly procedure

- Designs: Computer-aid multi-physics design and optimization.
- Fabrication and surface treatments: polishing, doping, infusion.
- RF components tests: Cryogenic test, high power couplers.
- System integrations: Lorent force detune, microphonic tuner and LLRF.
- Post-processing: Helium process and plasma cleaning.



C. Xu, et.al. Phys. Rev. Accel. Beams 19, 033501 (2016)
C. Xu, et.al. Applied Surface Science. V 274, I 1 (2013).
C. Xu, et.al. Phys. Rev. ST Accel. Beams 15.043502. (2012)
C. Xu, et.al. Phys. Rev. ST Accel. Beams 14, 123501. (2011)

SRF surface resistance

- The properties of top ~30nm surface determine the SRF performance.

$$Q_0 = G/R_s$$

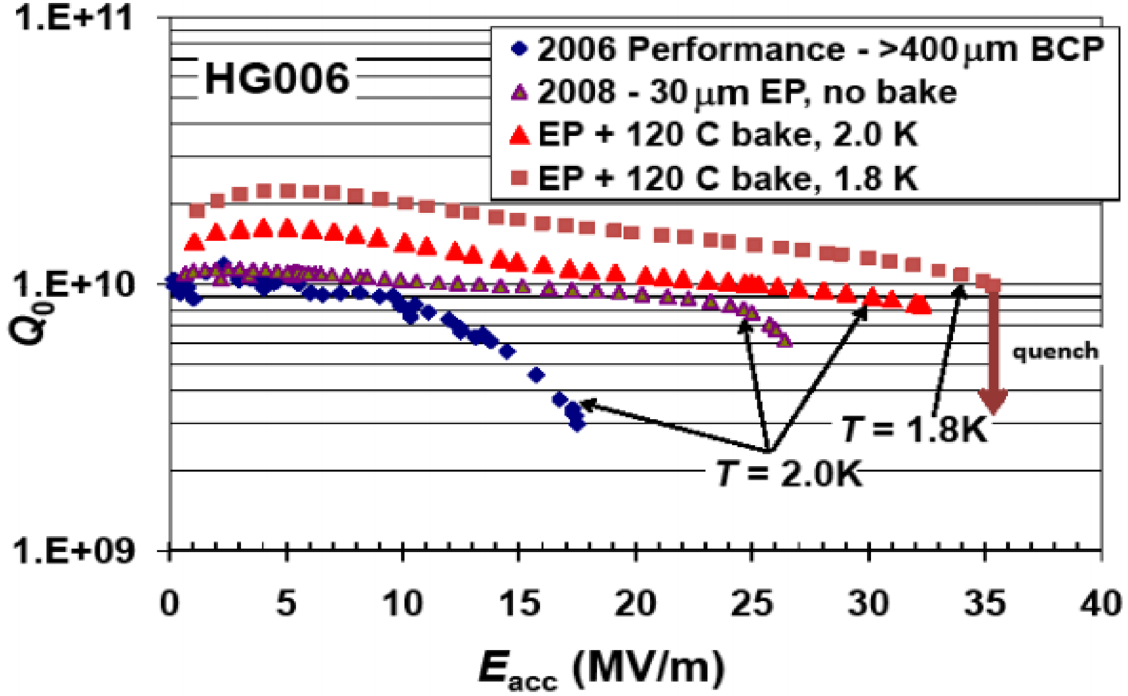
$$R_s(T,B) = R_{BCS}(F,T) + R_{residual} + R_{magnet}(B)$$

1. The BCS resistance is defined at zero external field.
   - Energy gap (T_c), mean free path(foreign materials), London penetration depth(coherent length) and frequency.
2. Residual resistance is a fitting parameter.
3. The magnetic resistance from residual DC magnetic field.

- Other unknown mechanisms:
  - Magnet vortex pinning, surface roughness, other unknown defects scattering contributions.

Topic 1: Research on SRF materials and processing at CEBAF

CEBAF upgrade recipes results



BCP: Buffered Chemical Polishing.
EP: Electropolishing.

Why EP improves the SRF performance?

Motivations:

- Understanding how surface topography affects the SRF cavity performances.
- Establish models to understand, predict and improve the cavity performance from different recipes.

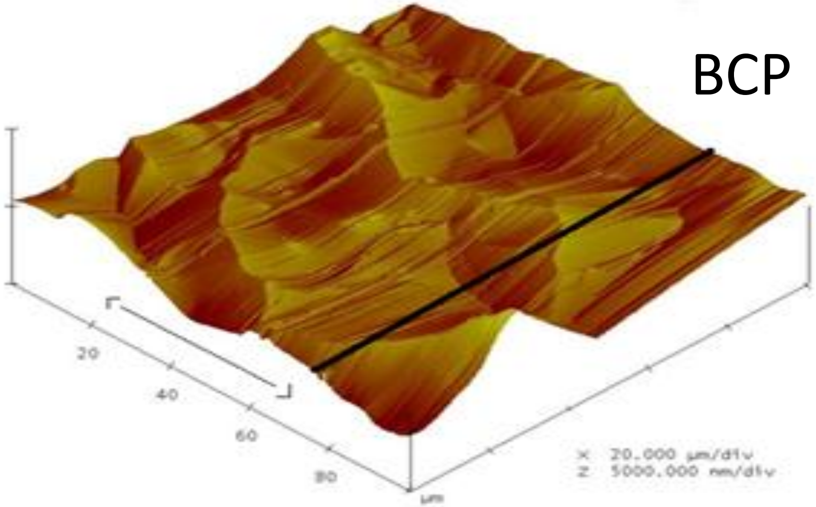
Solutions:

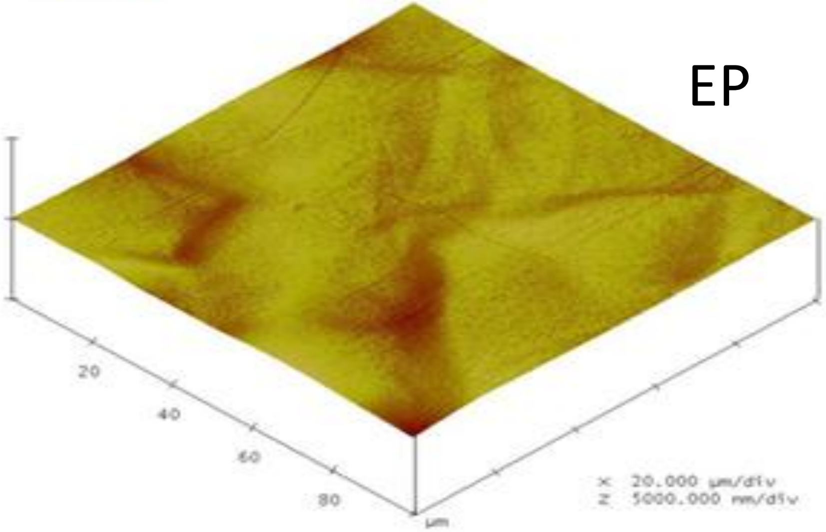
- Charactering the surface topography and developing a material model.
- Understanding the process can facilitate the new recipe development.

Best student poster award. **IPAC 2012**

C. Xu, et. al. Analysis of high field non-linear losses on SRF surfaces. Phys. Rev. Accel. Beams 19, 033501 (2016)

Internal surface acquisition and characterization

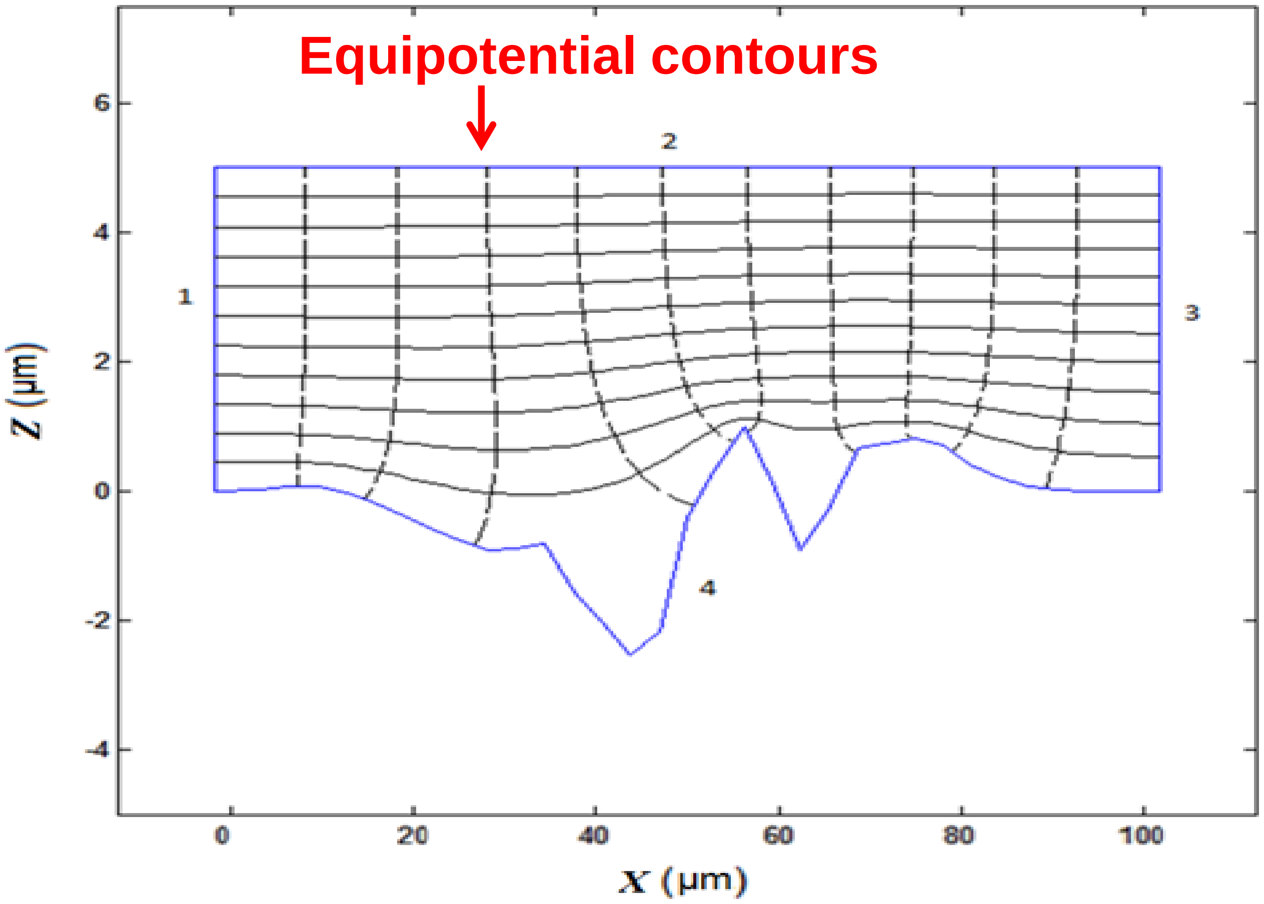


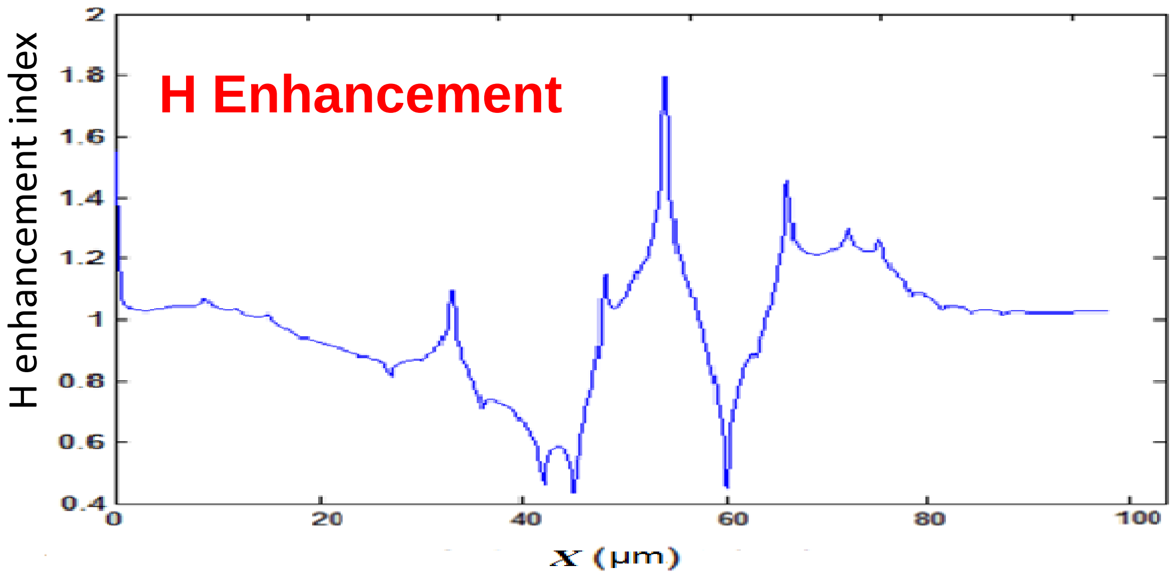


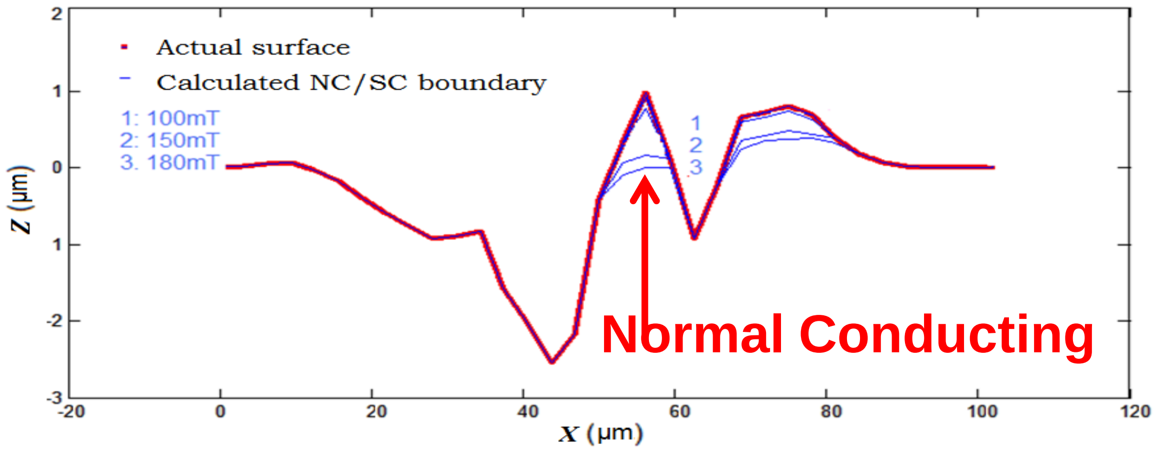
C. Xu, et. al. Characterization of Nb SRF cavity materials by white light interferometry and replica. Applied Surface Science. V 274, I 1 (2013).

Modeling and explanations of the excessive RF loss

- Commercial Finite Element Analysis(FEA) could not resolve the surface roughness in the computation.
- I implement a simulation and materials modeling by C++ and Matlab.

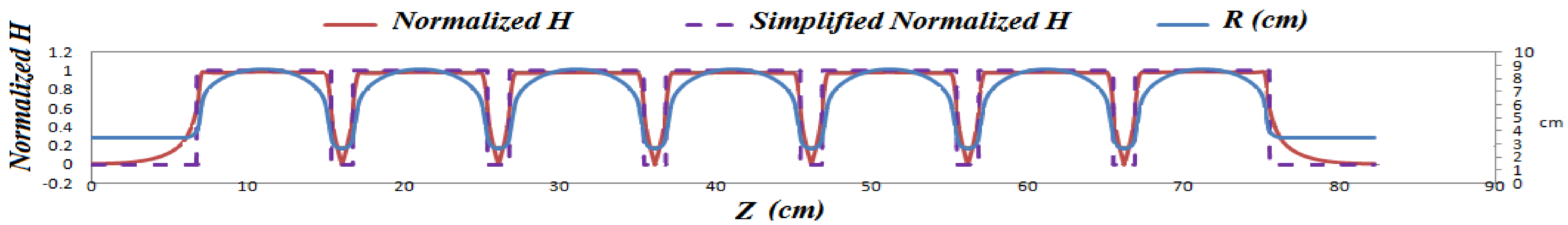


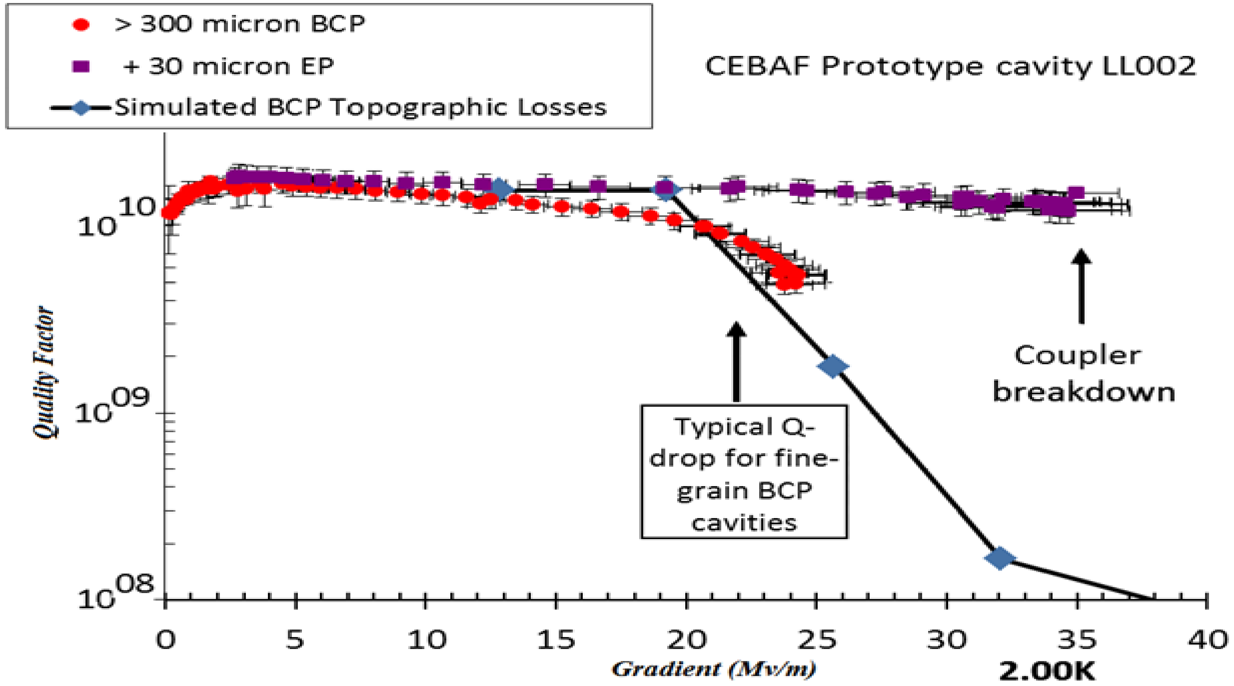




Magnetic Field enhancement model

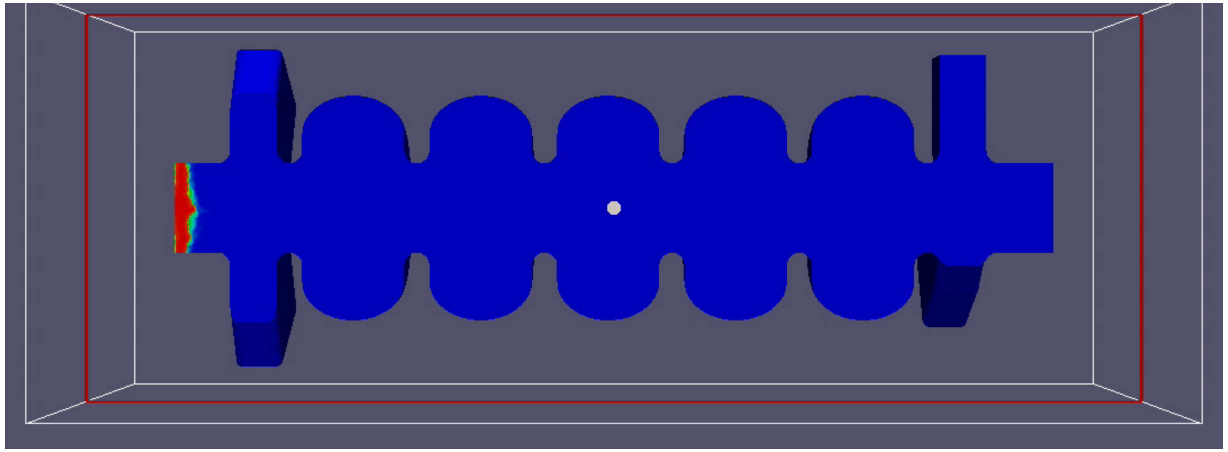
Linkage to the Cavity RF loss

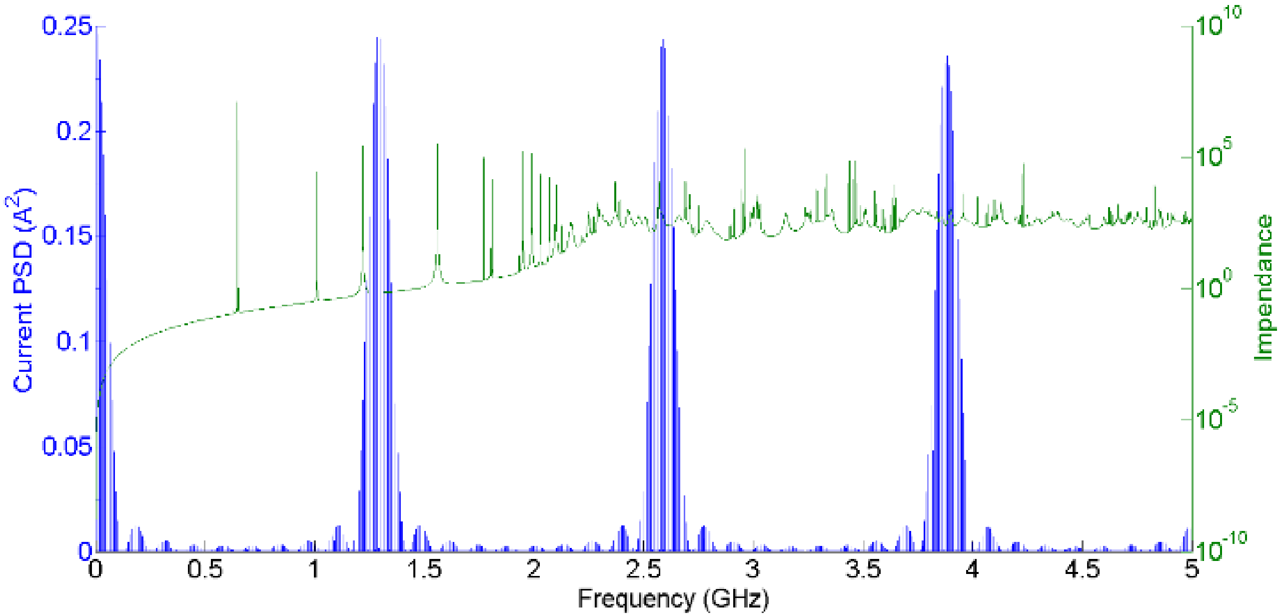




- The RF loss comes from two parts: Super and Normal conducting.
- The Simulation agrees with measurements, also could explain Q switch.
- This model can successfully explain the improvement from the topography modifications.

Topic 2: SRF cavities design to minimize HOM for eRHIC ERL.





current spectrum (blue) , impedance spectrum (green)

Higher Order Modes (HOM) have harmful effects, including kicking successive particles and causing extra surface loss.

Motivations:

- HOM power reduction is a critical design consideration for high current SRF accelerators.

Solutions:

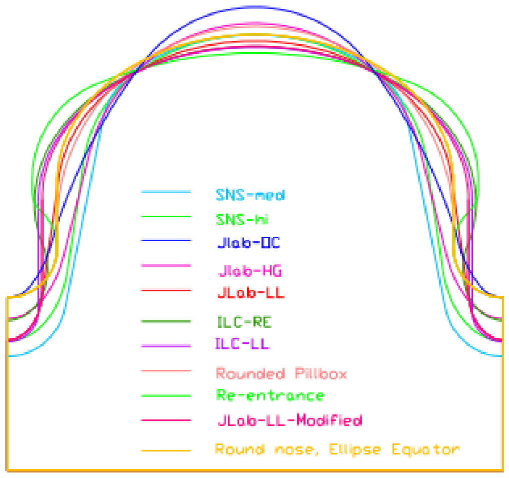
- Design multi-cell cavities to minimize HOM loss.

C Xu, Ilan Ben-Zvi. Invited talk. CERN ERL conference 2017
C Xu et al. In preparation, 2017

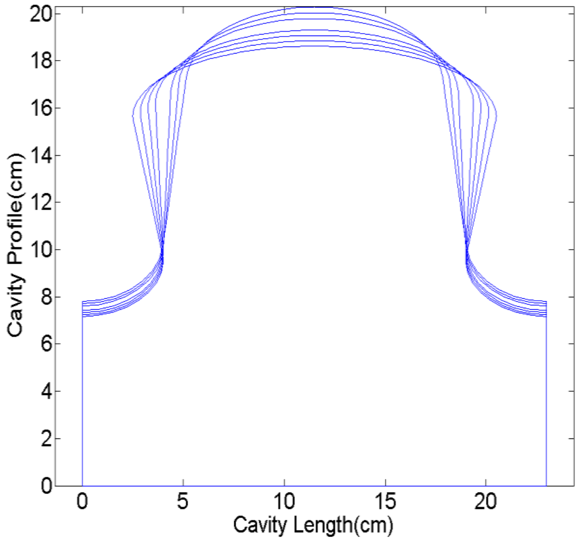
The resonant frequencies and dispersion relations

- A “dispersion relation” describes the relationship between the resonant frequencies and the phase delay.

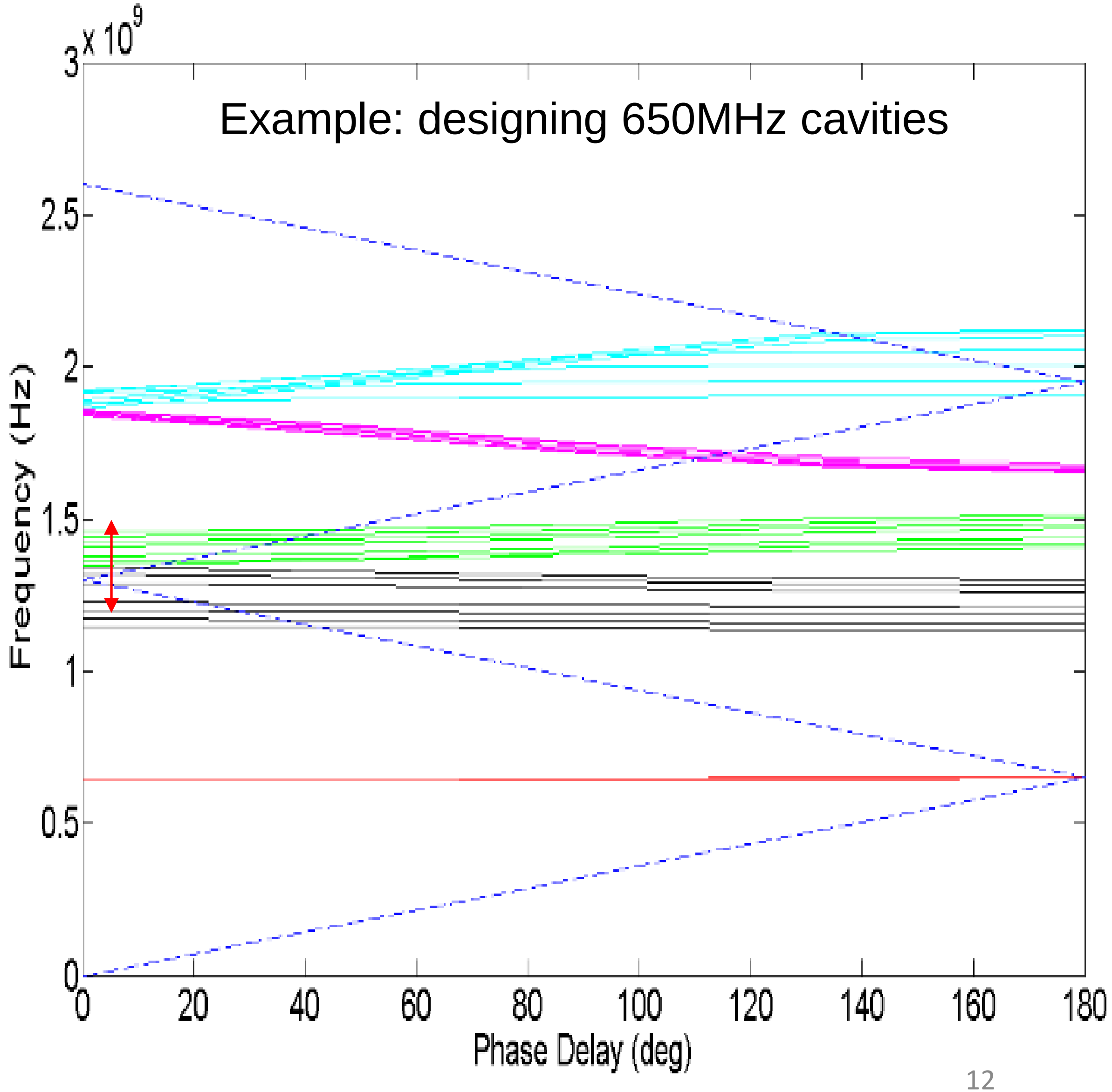
- The fundamental frequency has to be fixed, the cavity shape will tune the frequencies of HOMs.



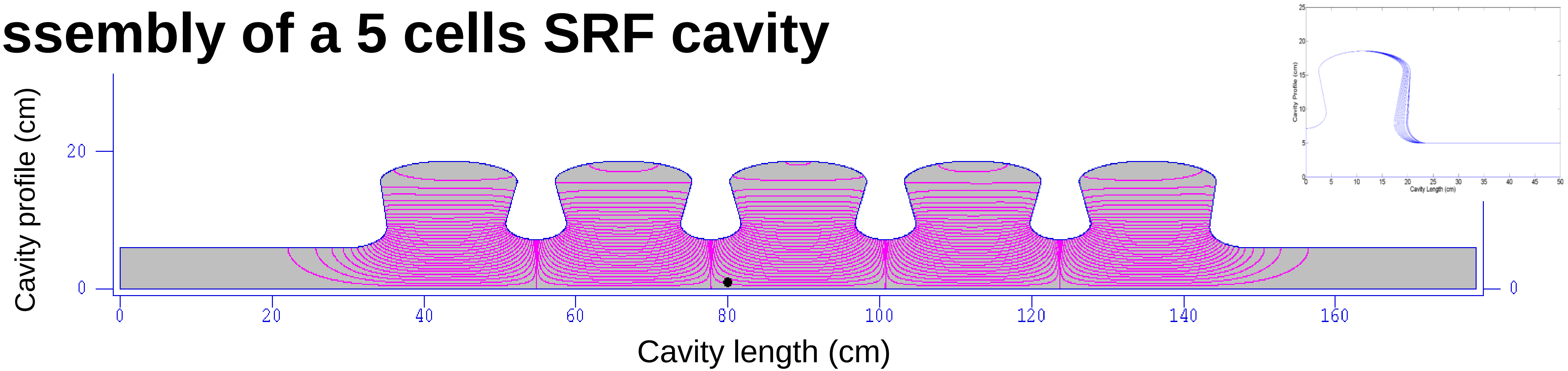
Existing cavity design



My cavity designs

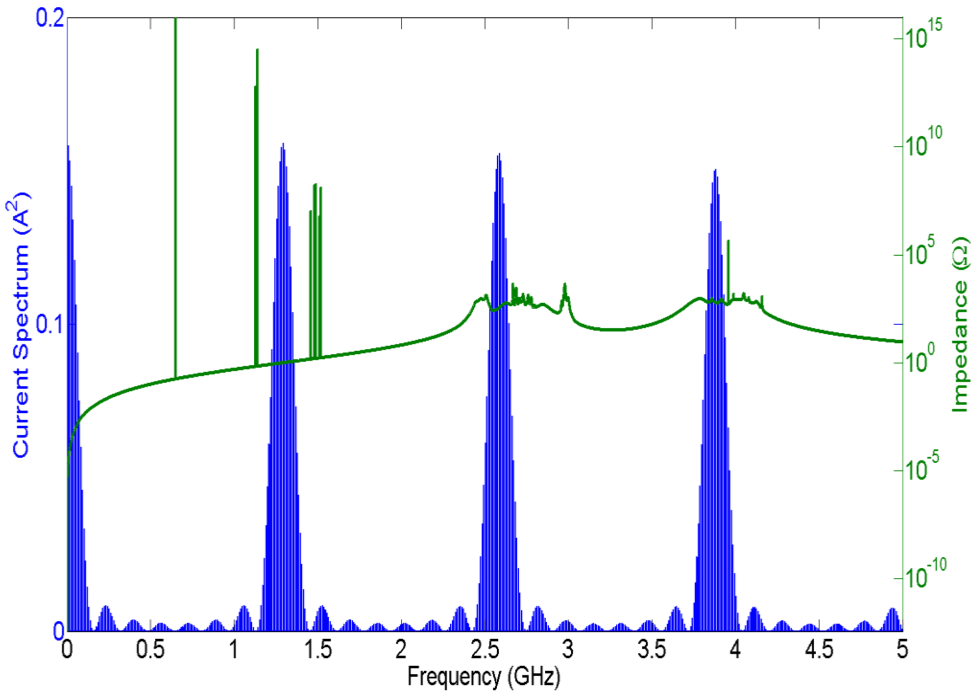


Assembly of a 5 cells SRF cavity



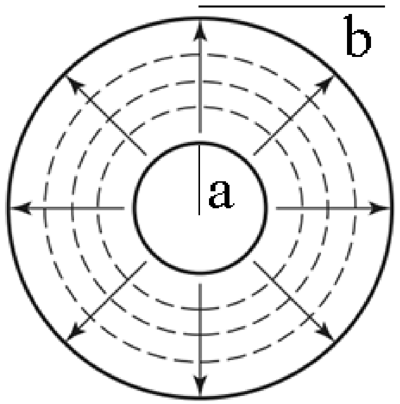
After multiple parameters optimization processes in FEA, we successfully achieved:

- The impedance (green) is misaligned with the current spectrum (blue).
- The generated RF power is minimized by this novel cavity design (<4kW).
- This cavity is optimized for high current accelerators.

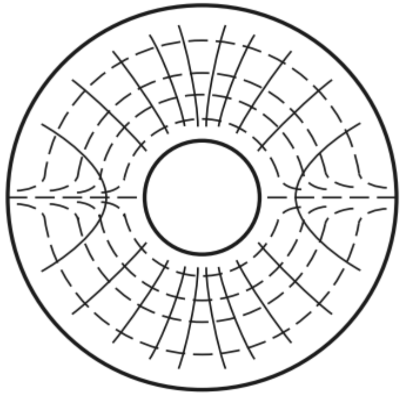


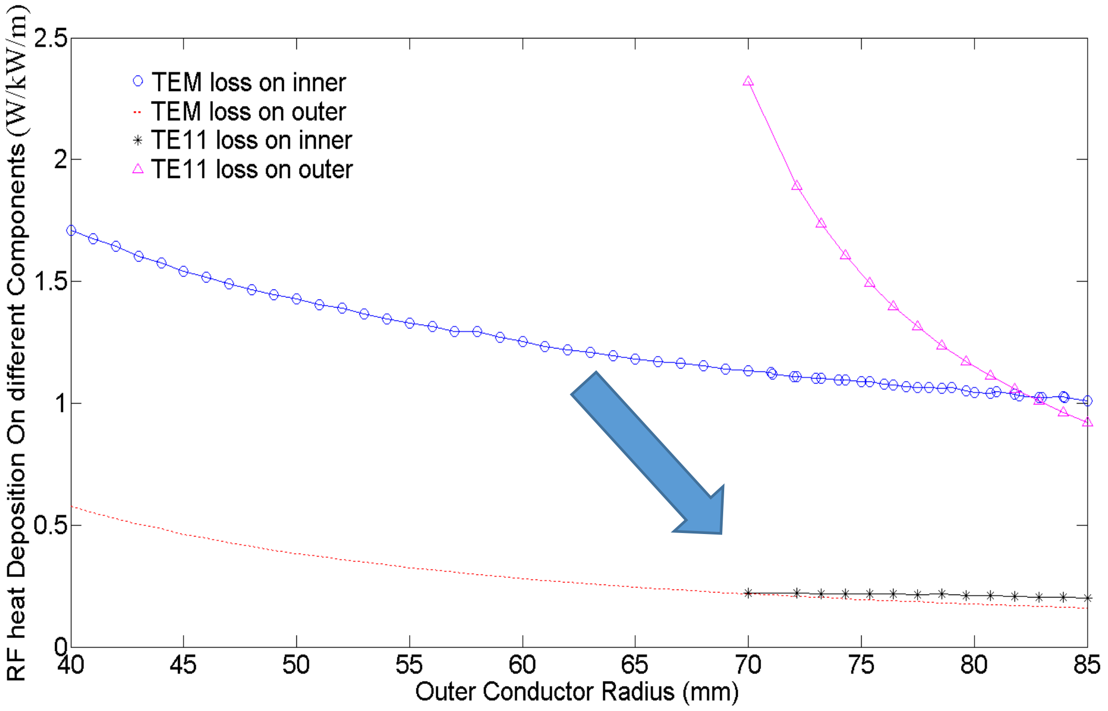
Topic 3: High power SRF components design for eRHIC.

TEM



TE11





Motivations:

- High current SRF accelerators requires strong and high power RF couplers.
- Conventional TEM coaxial couplers limit the high power operation (<200kW CW@ 1.3GHz), because of the inner conductor loss.

Solutions:

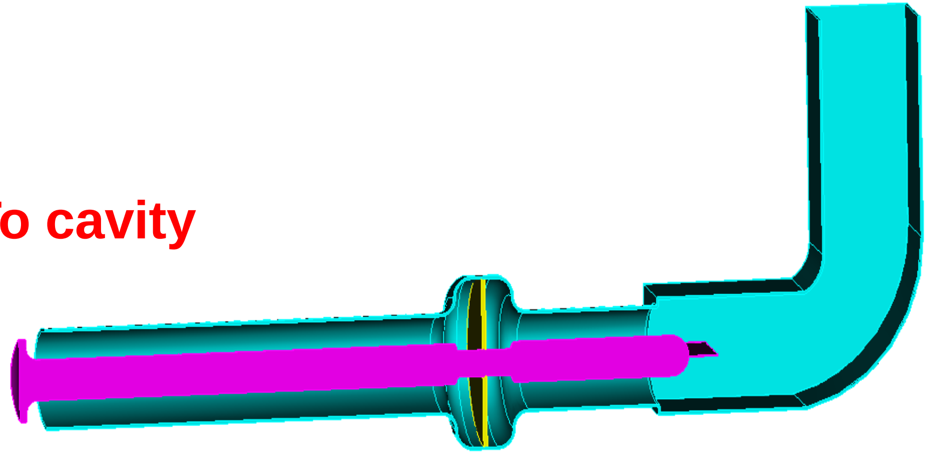
- A novel TE11 mode with reduced RF loss on the inner conductor could be used for the high power applications.
- A new detailed design with high power operation of >200kW CW at 1.3GHz without water cooling is proposed.

C. Xu, Invited talk. FRIB TTC Conference 2017

C. Xu, et. al. Progress in Electromagnetics Research B. Vol. 75, page 59-77. (2017)

RF design of the coupler assembly

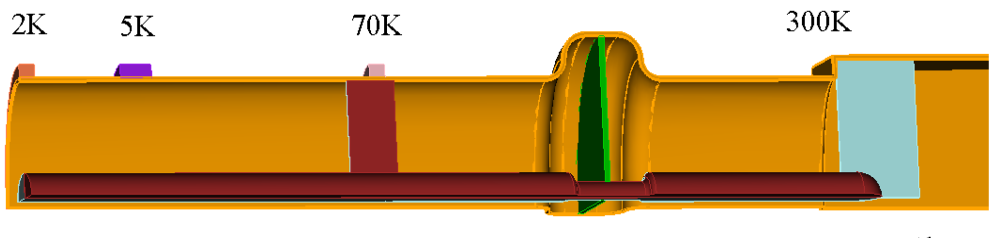
- The TEM mode utilizes the bulky door knob converter, while the TE11 mode utilizes the simple converter.
- I used an E-bend rectangular waveguide which is commercially available.

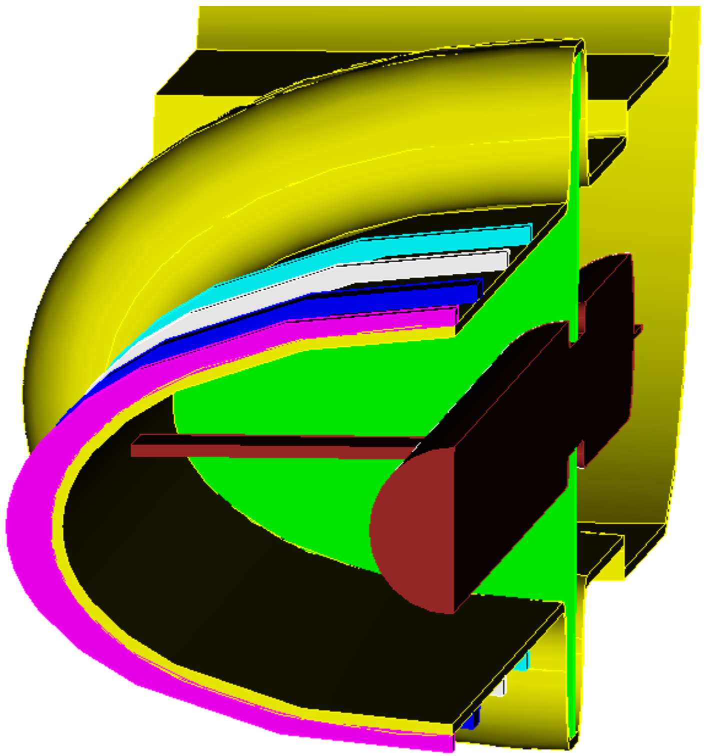


Frequency: 1.3 GHz (db)	S:1:1 (TE10)	S:2:1 (TEM)	S:2:2 (TE11_V)	S:2:3 (TE11_H)
S:1:1 (TE10)	-24.9	-38.3	-0.0244	-62
S:2:1 (TEM)	-38.3	-0.0134	-38.3	-86.7
S:2:2 (TE11_V)	-0.0244	-38.3	-24.9	-62.3
S:2:3 (TE11_H)	-62	-86.7	-62.3	-57.2

Thermal cooling scheme

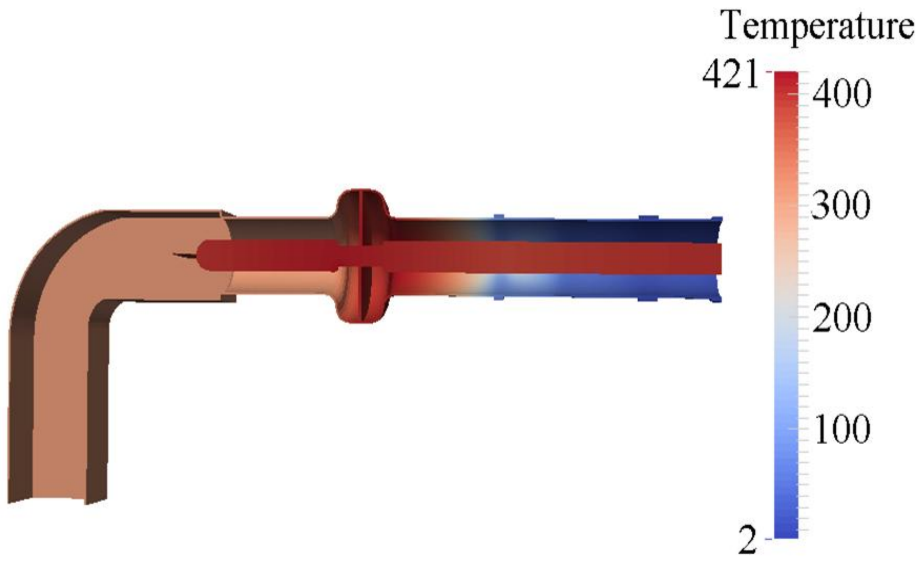
- In the new design, a metal plate can be added to cool the inner conductor without compromising the RF fields.
- The temperature of inner conductor will be reduced to a low level, and can further reduce the dynamic loss.
- Such feature is not available on TEM couplers, i.e, inserting a flat plate will destroy the TEM field pattern.





Dynamic loss comparison of TEM/TE11 couplers

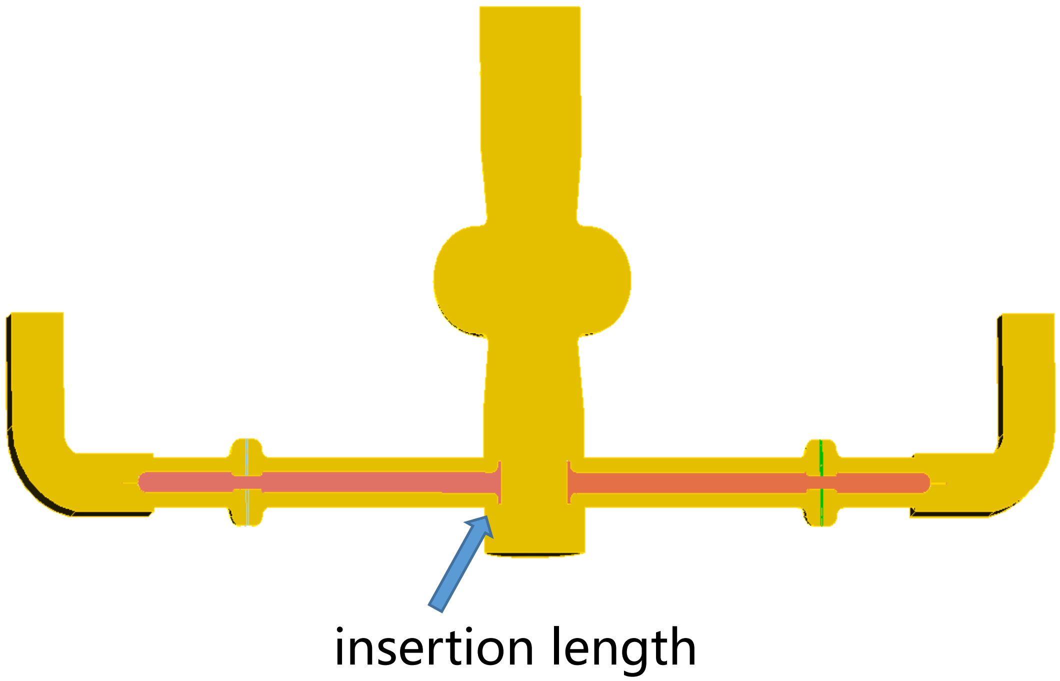
- The outer conductor is well cooled by thermal anchors and chill water.
- The total RF loss on TE11 couplers is around >40% of the TEM couplers.
- The new design could deliver >200kW power.

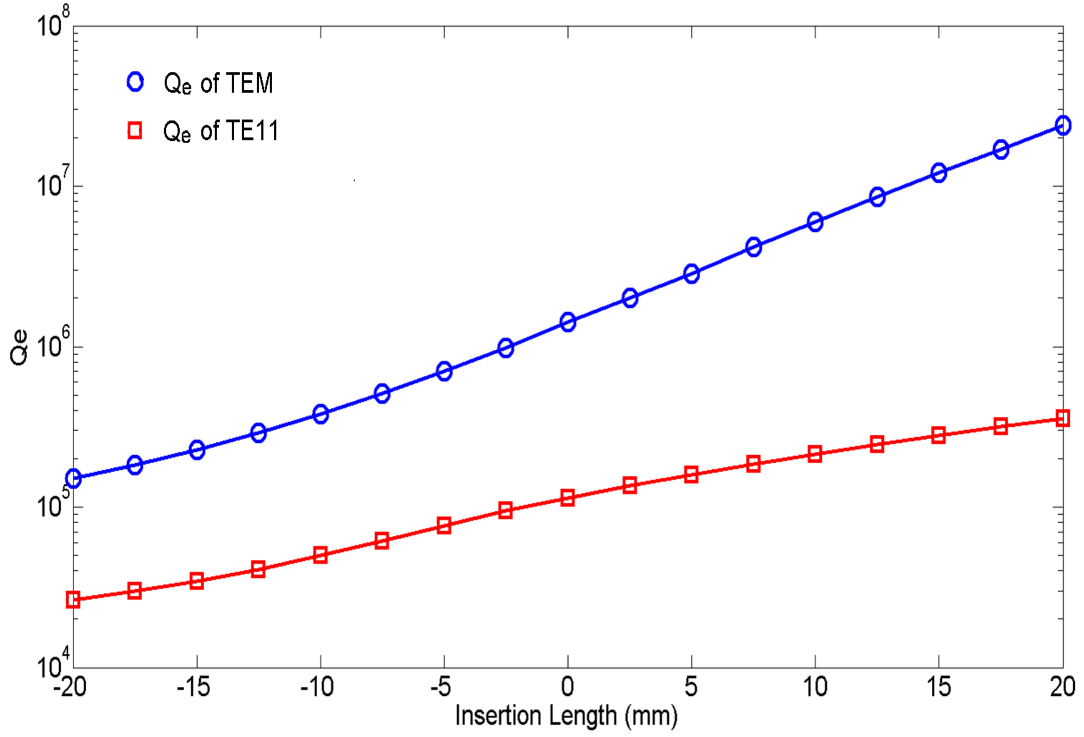


Dynamic loss (W)	TEM (115kW)	TEM (200kW)	TE11 (115kW)	TE11 (200kW)
2K	0.656	0.871	0.772	1.024
5K	3.025	3.943	5.877	8.338
80K	15.994	22.376	111.932	166.615
300K	165.685	314.692	116.484	228.806
Water Cooling	293.496	488.436	N/A	N/A
Total Loss	478.856	830.317	235.064	404.783

Coupling to a cavity

- When the beam loading is high, the strong coupler is needed : external Q is around $10^4 \sim 10^5$.
- The TE11 couplers have 10 times higher coupling capability than TEM couplers at the same insertion length.





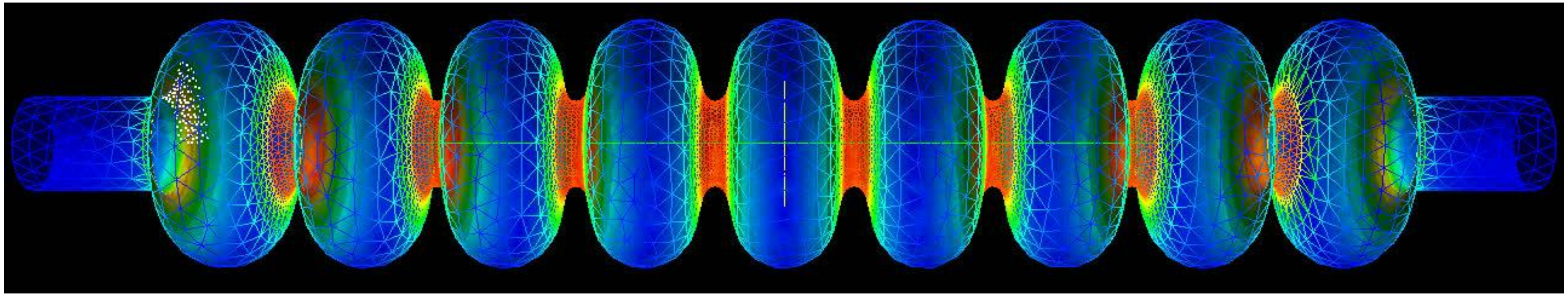
Topic 4: Dark current radiation in LCLS-II SRF linac

Motivations:

- LCLS-II accelerating gradient is 16MV/m. The high E field will facilitate the surface electron field emission.
- The field emitted electron damage the SRF surfaces and electronics and cause beam cryogenic loss.

Methods and solutions:

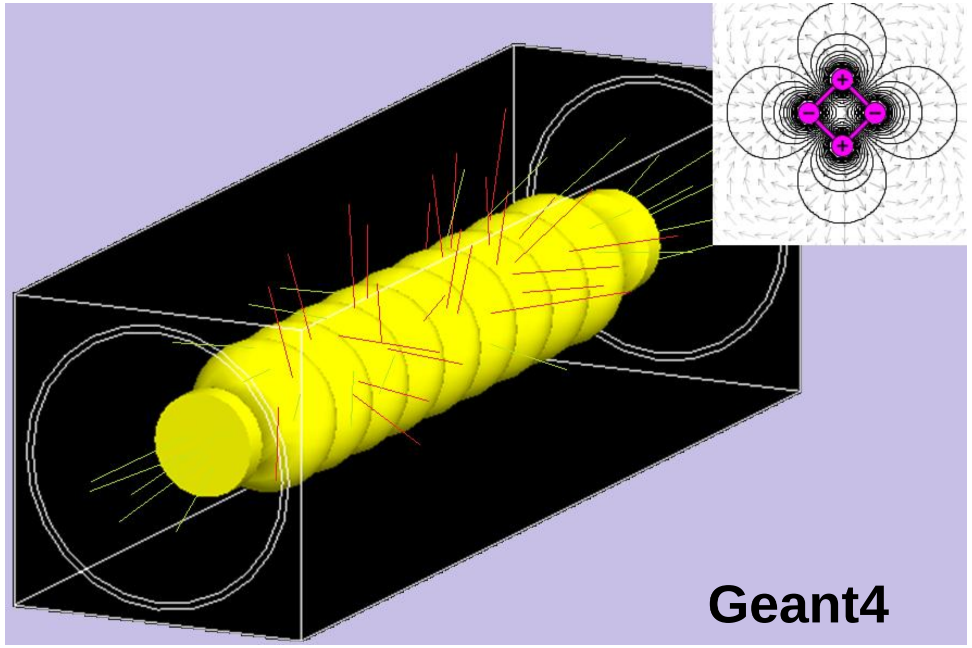
- Track the emission particles with finite element analysis.
- Estimate the radiation and loss by Monte Carlo model.



M. Santana Leitner, L. Ge, Z. Li, **C. Xu**, et al.. Studies of Radiation Fields of LCLS-II Super Conducting Radio Frequency Cavities. International Journal of Modern Physics. 44. (2016)

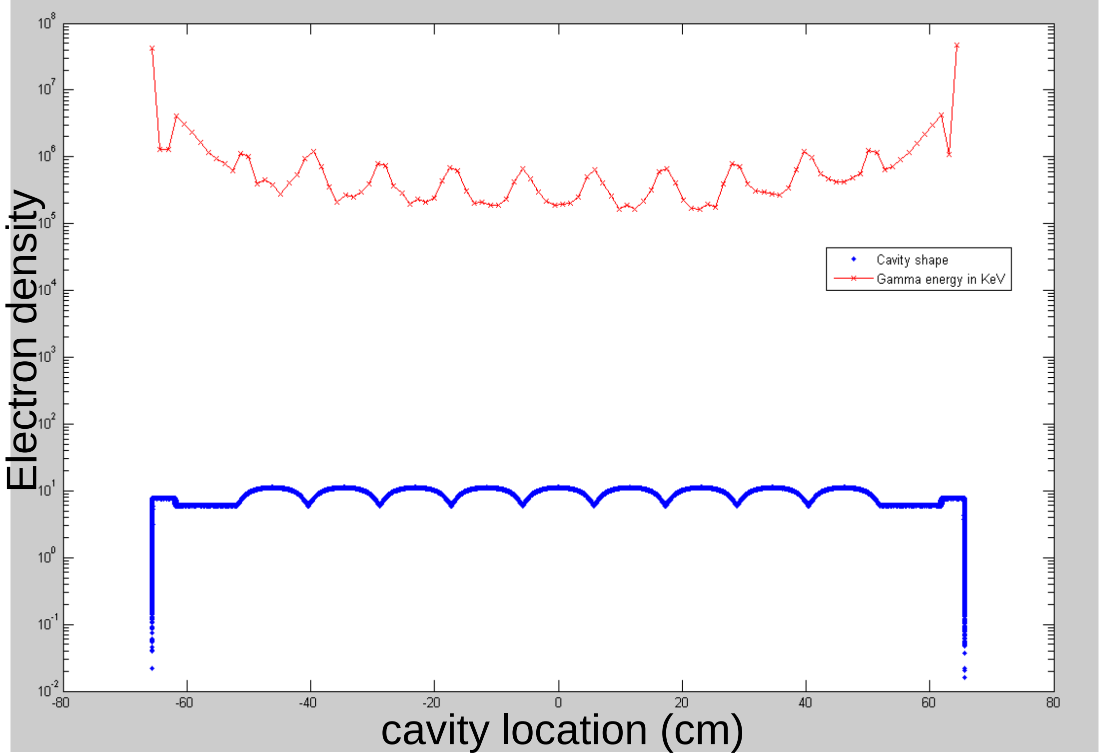
Radiation protection simulation and instrumentation

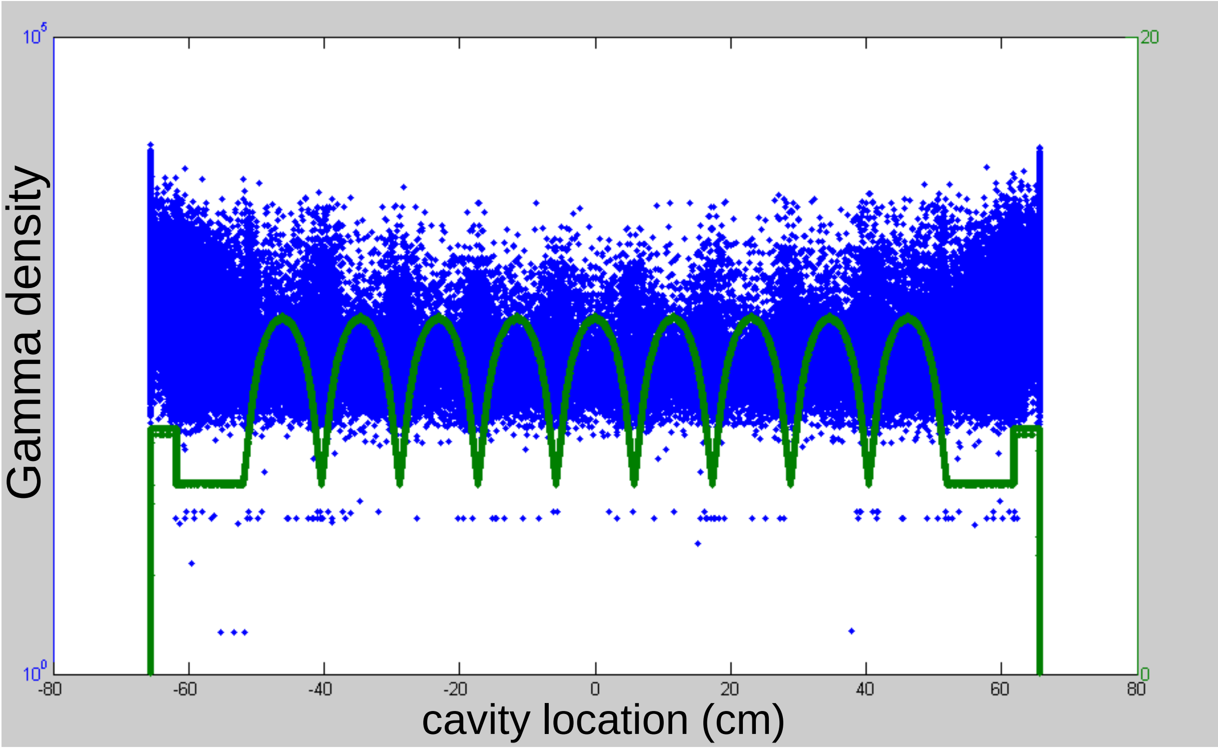
- The escaped electrons are captured by the Faraday cups and dispersed by quadrupole magnets.
- Dark current beam loading reduces accelerating gradient and develops into halo.
- The trapped electrons hit SRF walls and generate gamma radiation.



Electron and gamma distributions

Geant 4 simulation uses (Livermore + Penelope) low energy lepton physics models





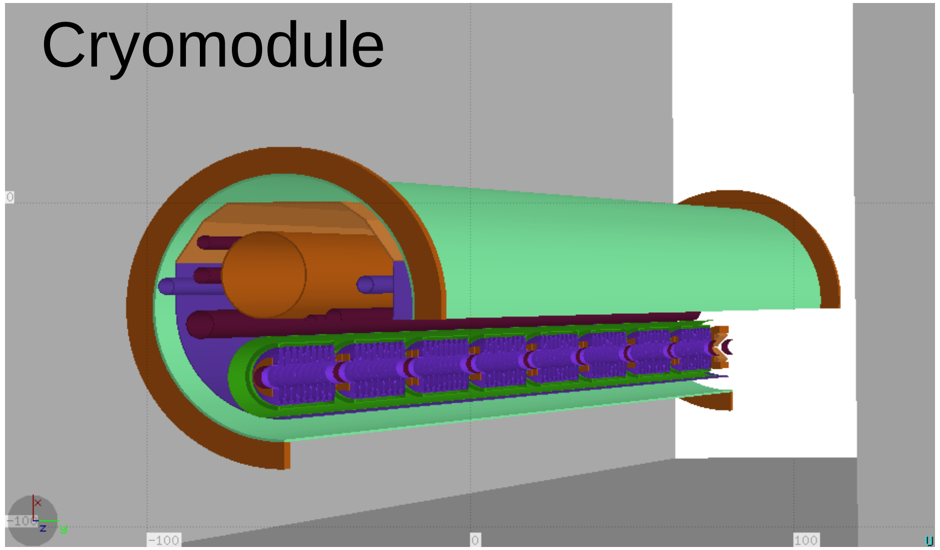
Within 5 RF cycles : 3.84×10^{-9}s

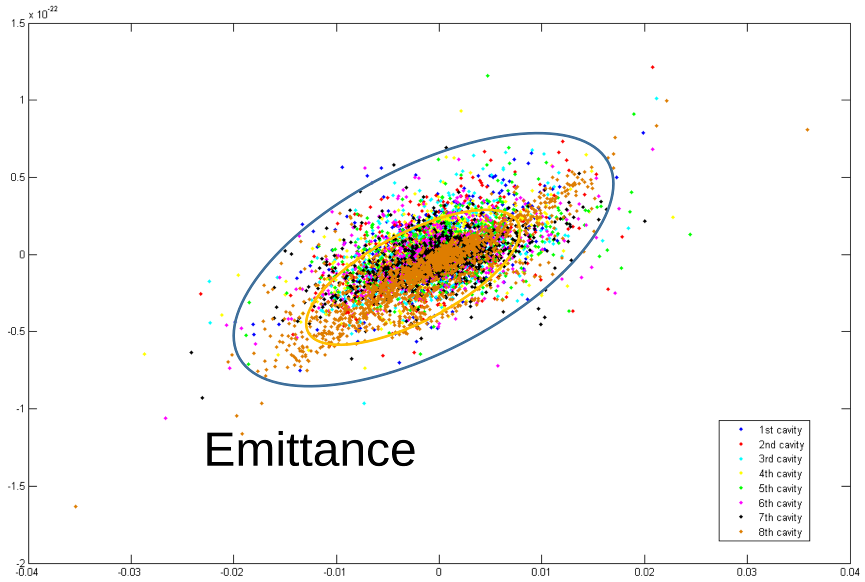
Gamma: $=2.51 \times 10^{-11}$J

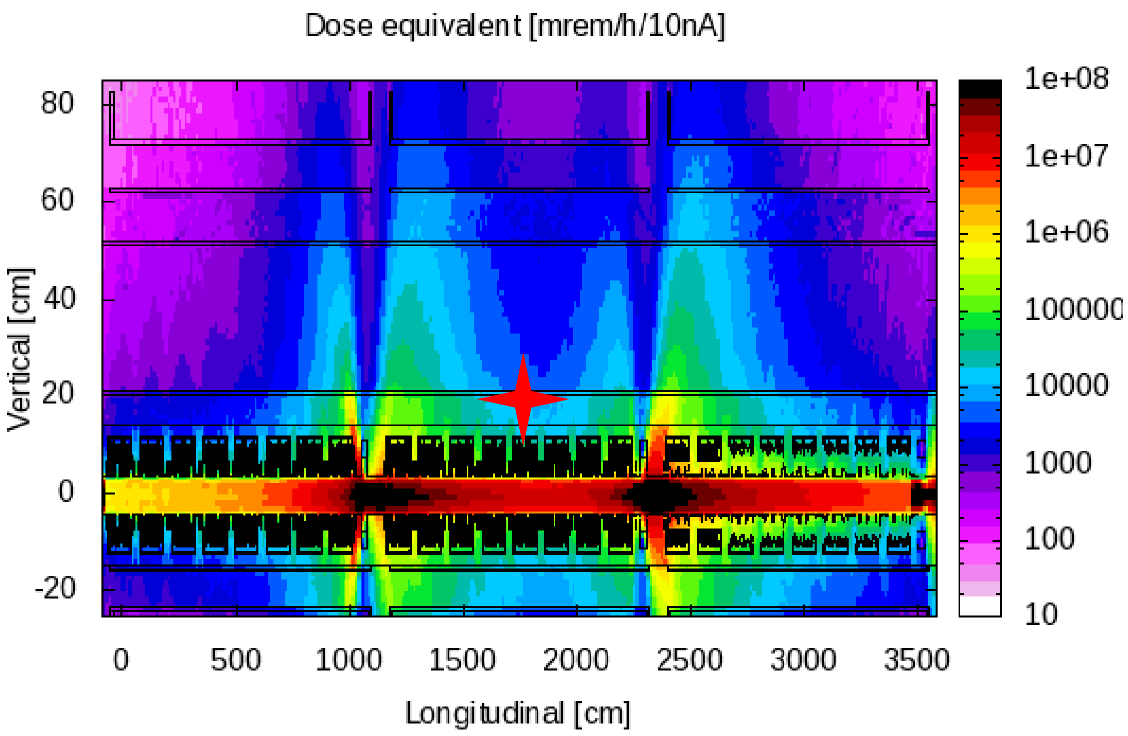
Electron: $=1.24 \times 10^{-12}$J -> Escape current: 3.2×10^{-9}A

Cryogenics Loss: <0.1W.

Radiation in the tunnel and emission tracking

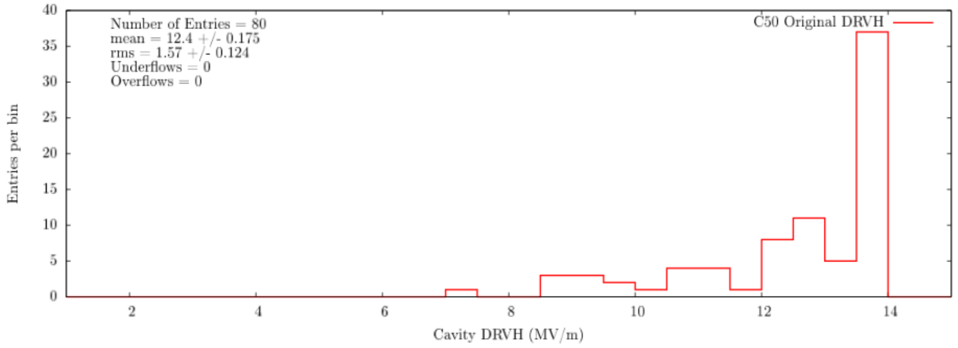




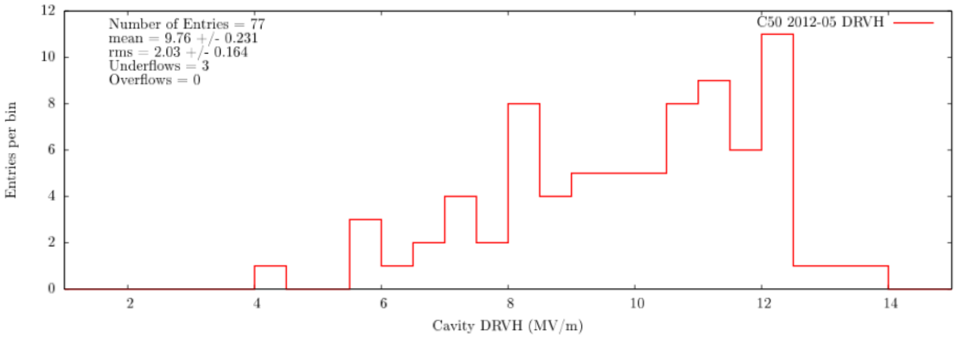


- Radiation pattern and quadrupole magnets strength are given and optimized.
- The area of X emittance is reduced with distances. Helo track can be followed.

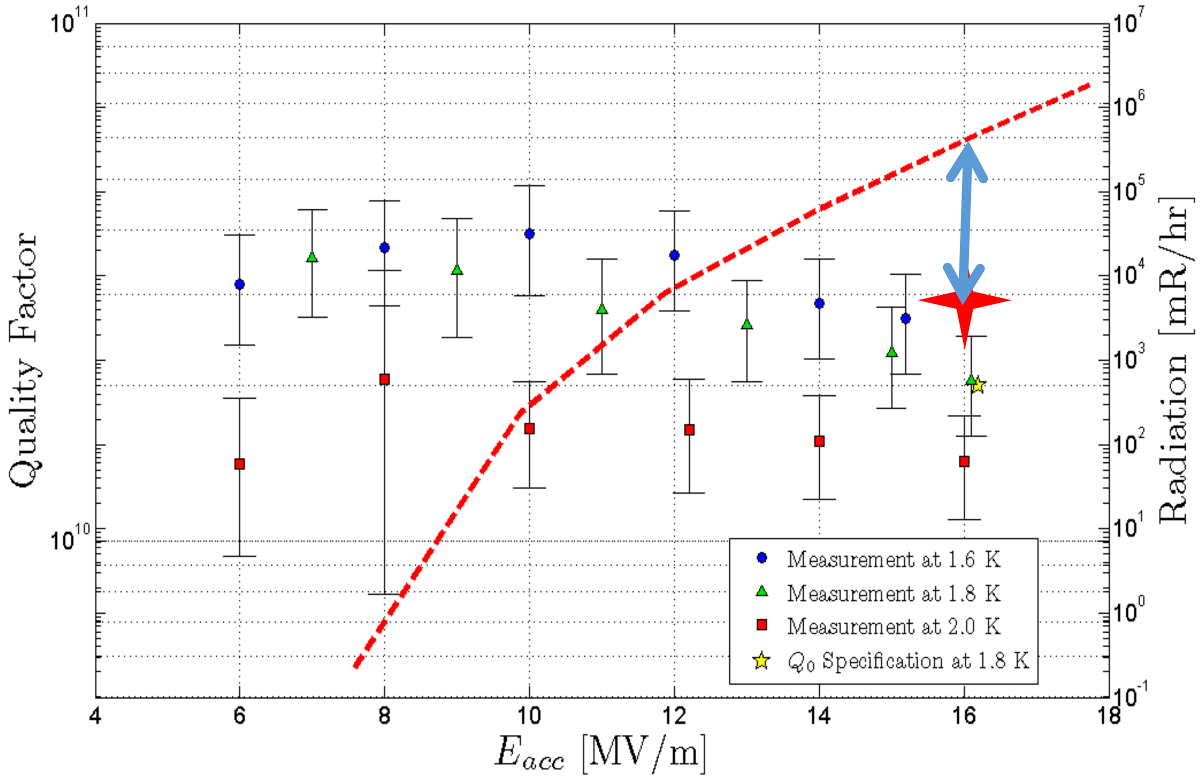
Cavity radiation criteria and operation degradation



Initial distribution of gradients of C50 cavities



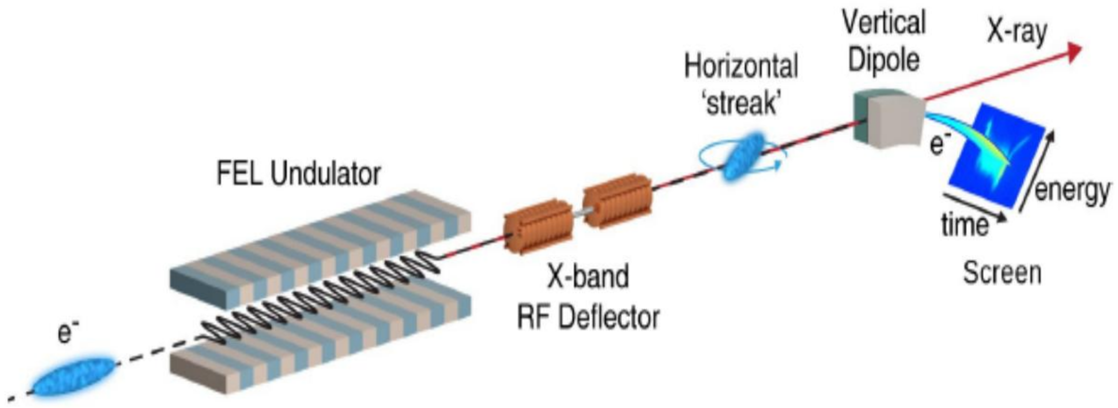
Distribution of gradients of the same C50 cavities (~ 4 years later)



Measurements of Q_0 and X-rays from Cornell and JLab operation experience

- A radiation standard specification should be considered for future operation concerns.
- Once the field emission turn-on gradient is less than 8MV/m, and cavities should be clean again.

Topic 5: High power X band RF compressor system for LCLS

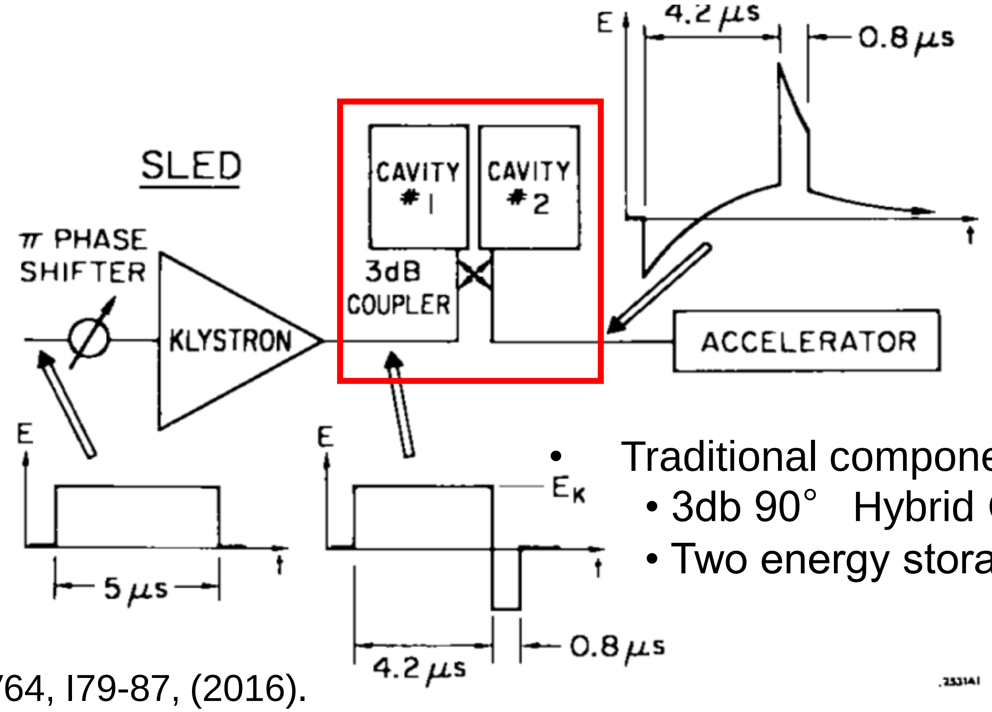


Solutions:

- Feeding normal-conducting RF deflecting cavities.
- Compressing High power RF pulses.
- Compact RF compressor
  - Over-moded cavity
  - Mode converter and combiner.

Motivations:

- Characterize the temporal resolution of the beam after FEL at LCLS.
- X-Band deflector for beam diagnostics.
- High RF power needed for Improvement of resolution. > 50MV/m.



- Traditional components:
  - 3db 90° Hybrid Coupler
  - Two energy storage cavities

C. Xu, S. Tantawi, and J. Wang. Phys. Rev. Accel. Beams 19, 062003. (2016)

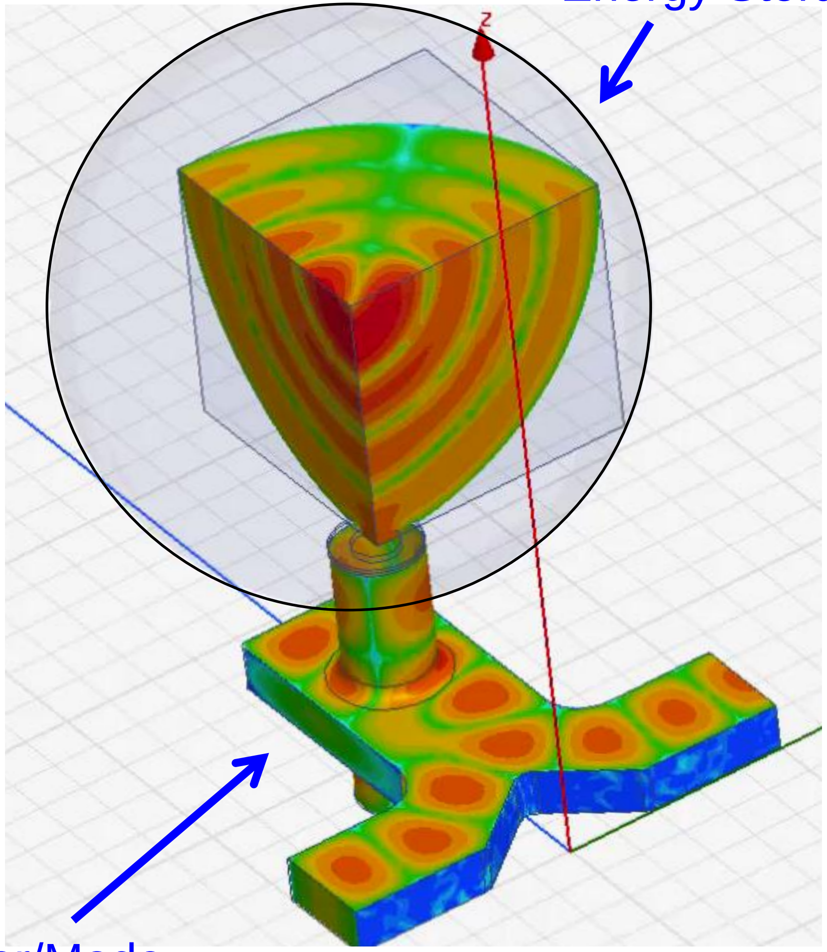
C. Xu, S. Tantawi, and J. Wang. Progress in Electromagnetics Research C, V64, I79-87, (2016).

J. Wang, **C. Xu**, S. Tantawi. Proceedings of IPAC2016, Busan, Korea

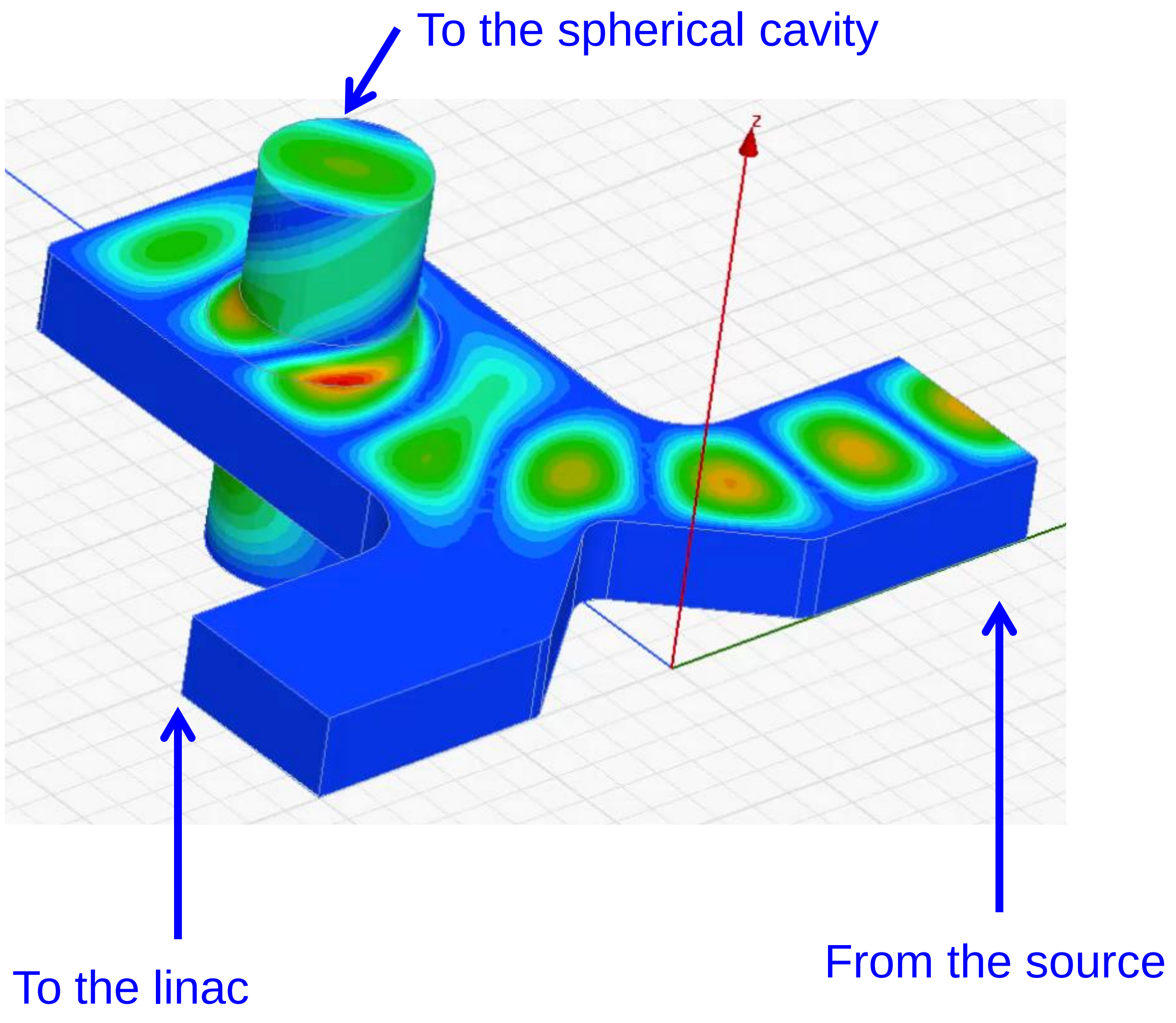
Our new compact RF compression system

ACE3P code is used in NERSC supercomputers to design and optimize the RF structures.

- **RF storage cavity**
  - Stores energy in two resonant modes in a single cavity instead of two cavities.
  - The spherical cavity reduces RF losses.
- **Mode converter**
  - Guides the RF power into and out of the cavity.



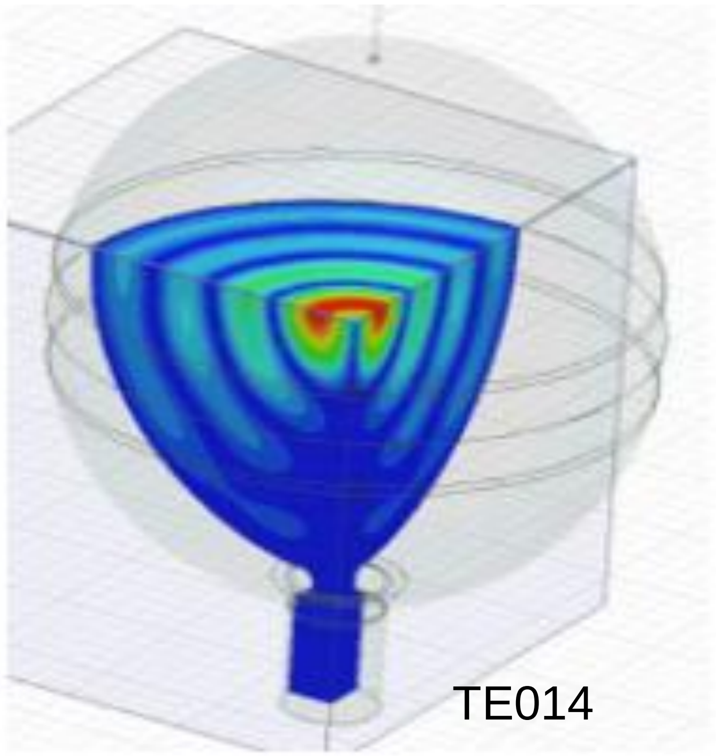
RF Mode converter

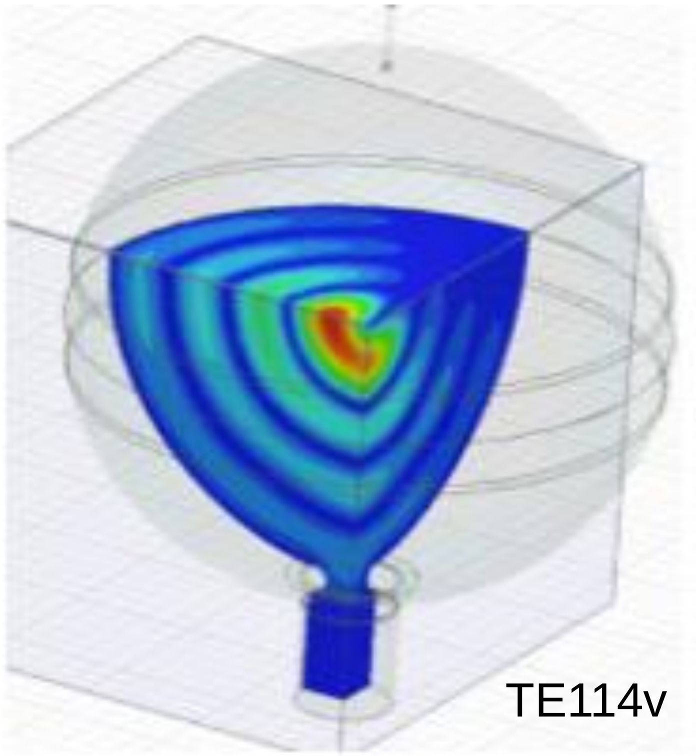


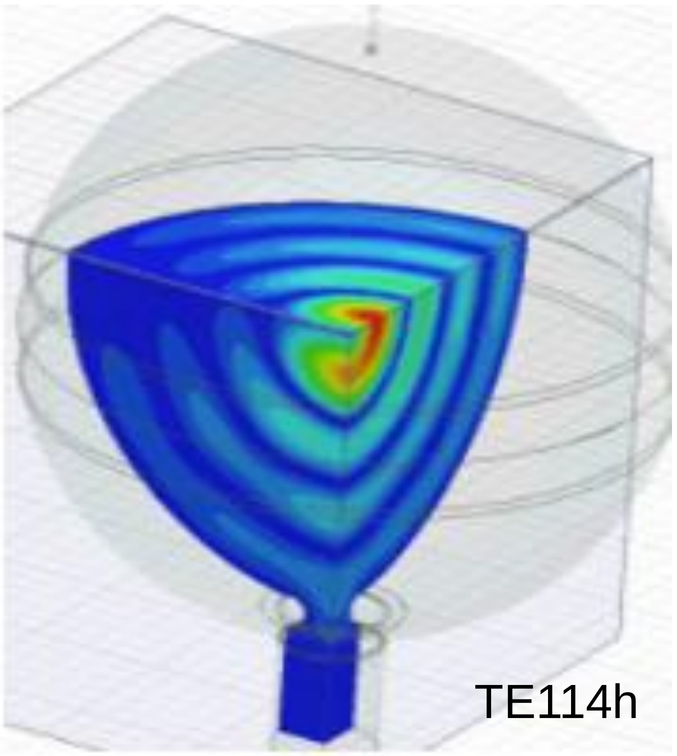
Key features:

1. Mode conversion of the TE10 rectangular waveguide mode into the two TE11 polarizations.
2. The two TE11 modes are ±90° apart, which define the Right/Left Hand Circular Polarization (RHCP/LHCP).
3. The RHCP mode transfers into the right hand arm waveguide, while the LHCP mode would transfer to the left arm: Directional coupling.
4. Full match without reflection.

Over-moded resonant cavity and the orientations

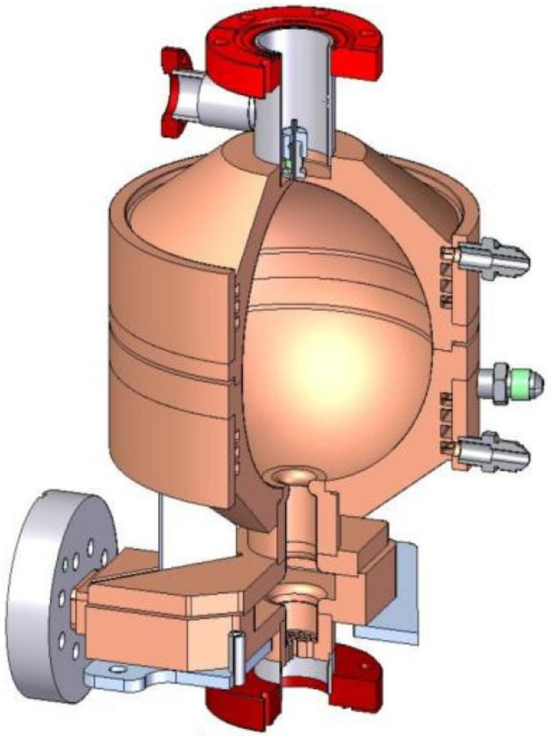






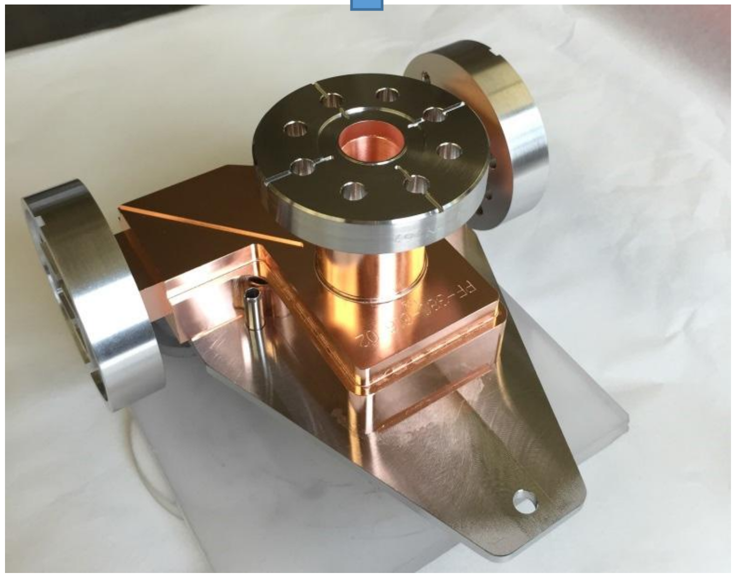
1. TE modes in a spherical cavity have very high quality factor.
2. Each mode has three polarizations but we need only two modes. Two modes from the circular waveguide are independently fed to the two TE_{mnp} modes.

Fabrication: Two pieces



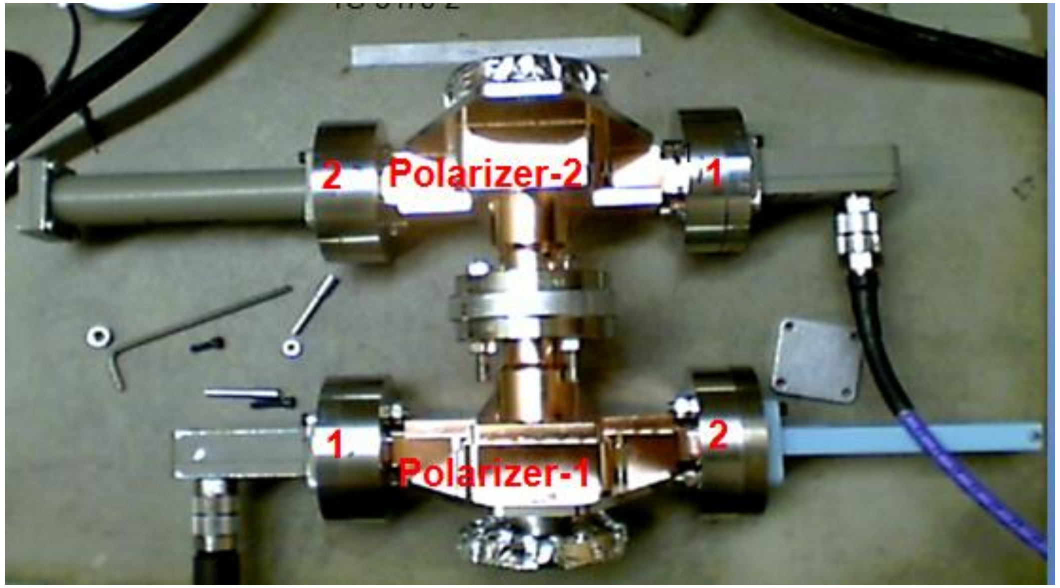
Mechanical Design

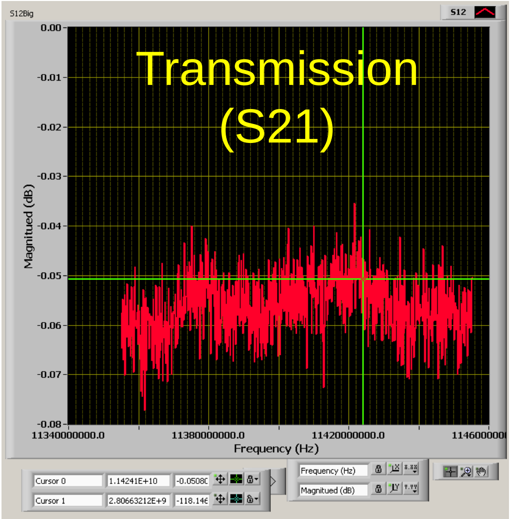
Fabricated Assembly

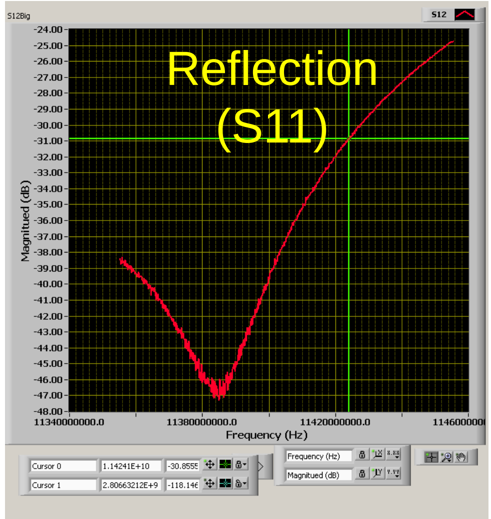


Thermal and mechanical simulation included

Low power RF Measurements

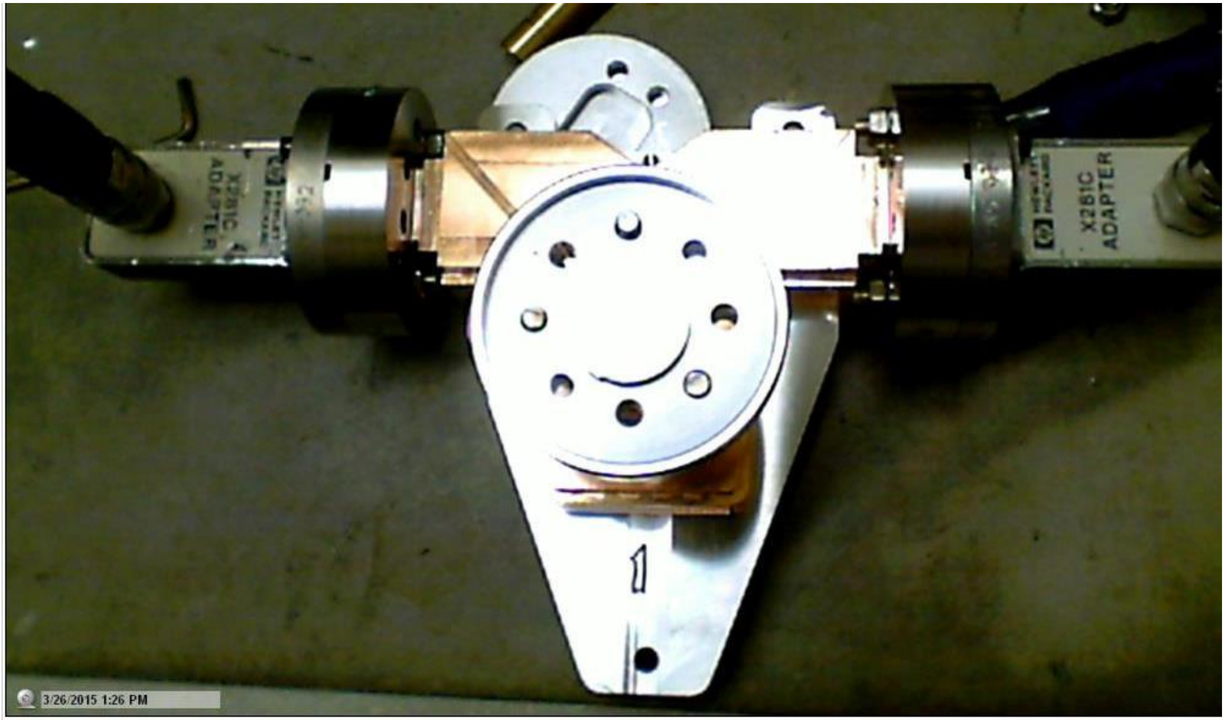




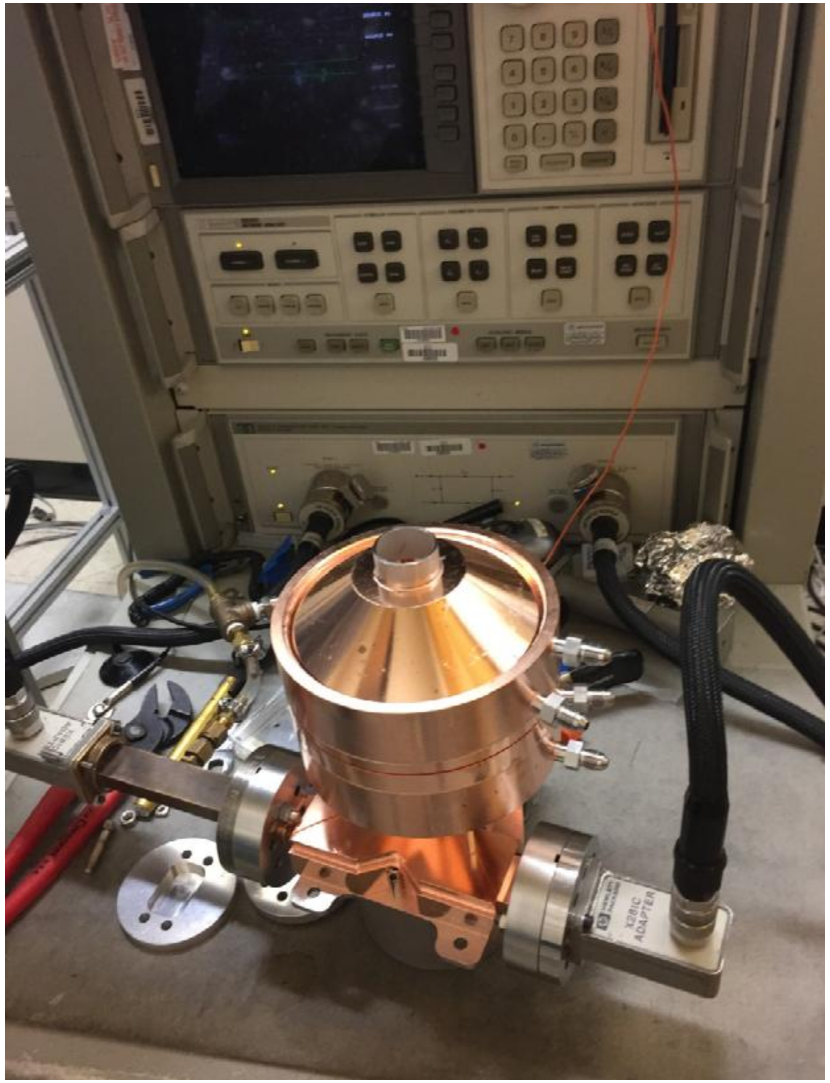


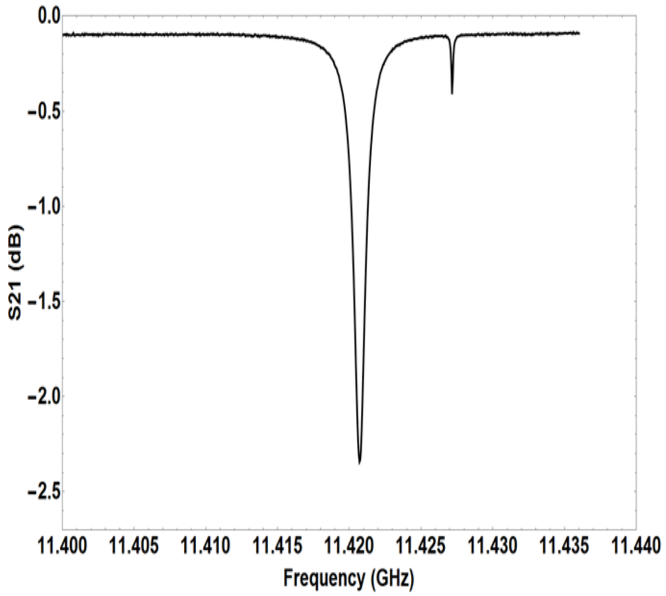
Measurements achieved:

1. >100 MHz Broad pass band to insure stable operation.
2. Less than -30.8 dB reflections.

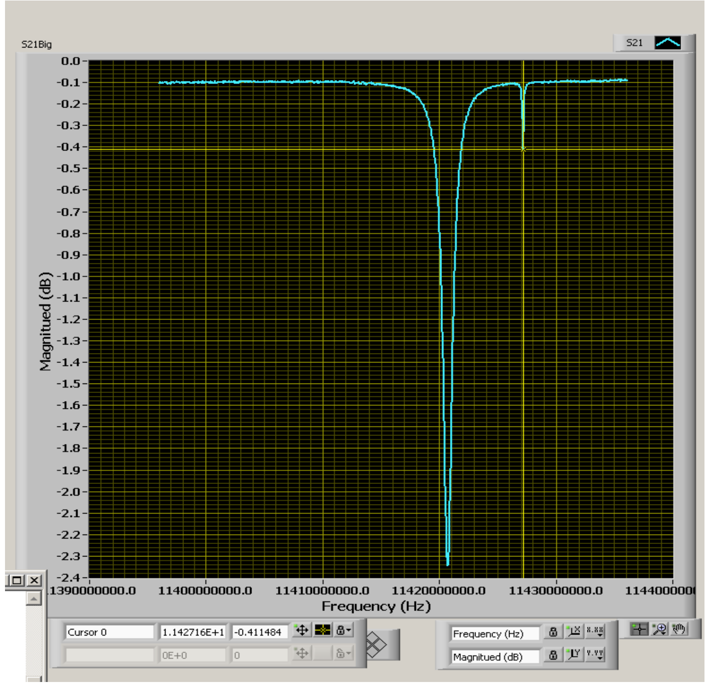


System assembly: Measurements agrees with simulations.



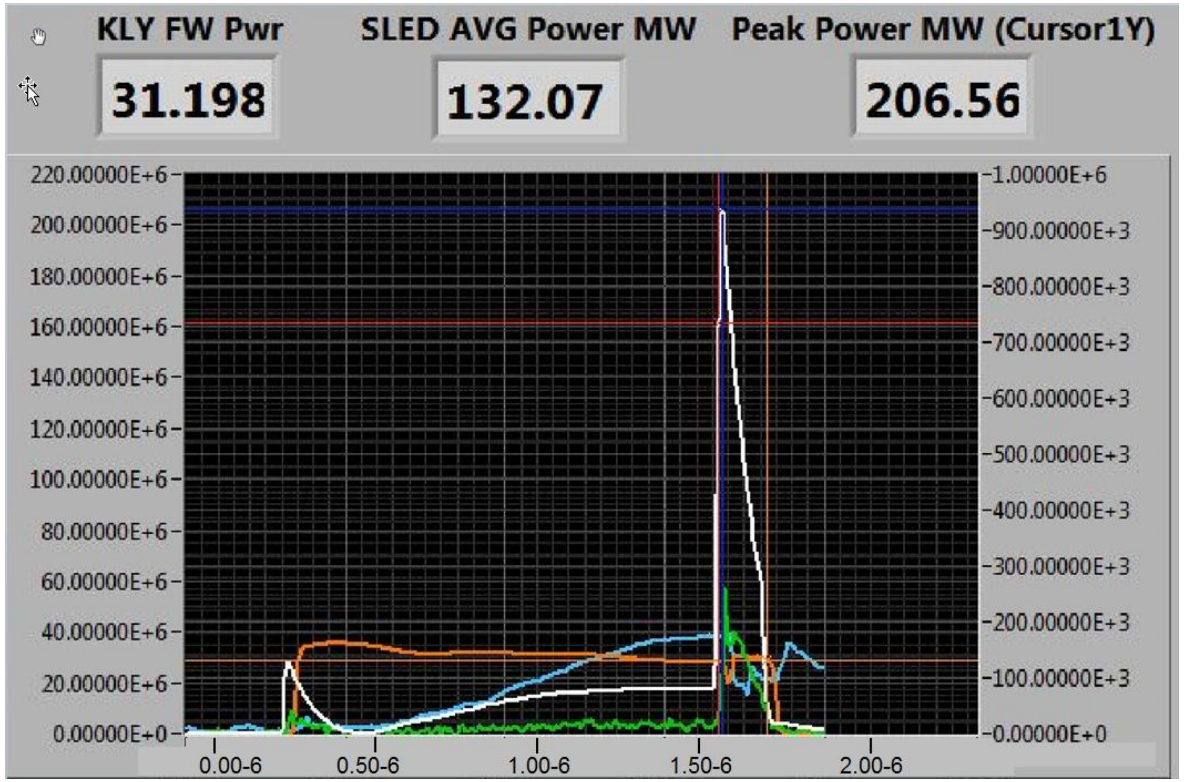


Theoretical design simulation.



Measured SLED working modes:
Q_0 94000 and β 7.8

High power testing with an X band klystron



Compression achieved at 4.2X.
RF pulse width 1.5 μs, flip phase in last 165 ns
Average klystron output power 31.2 MW
SLEDed average power 132 MW
Peak SLEDed power 206.6 MW

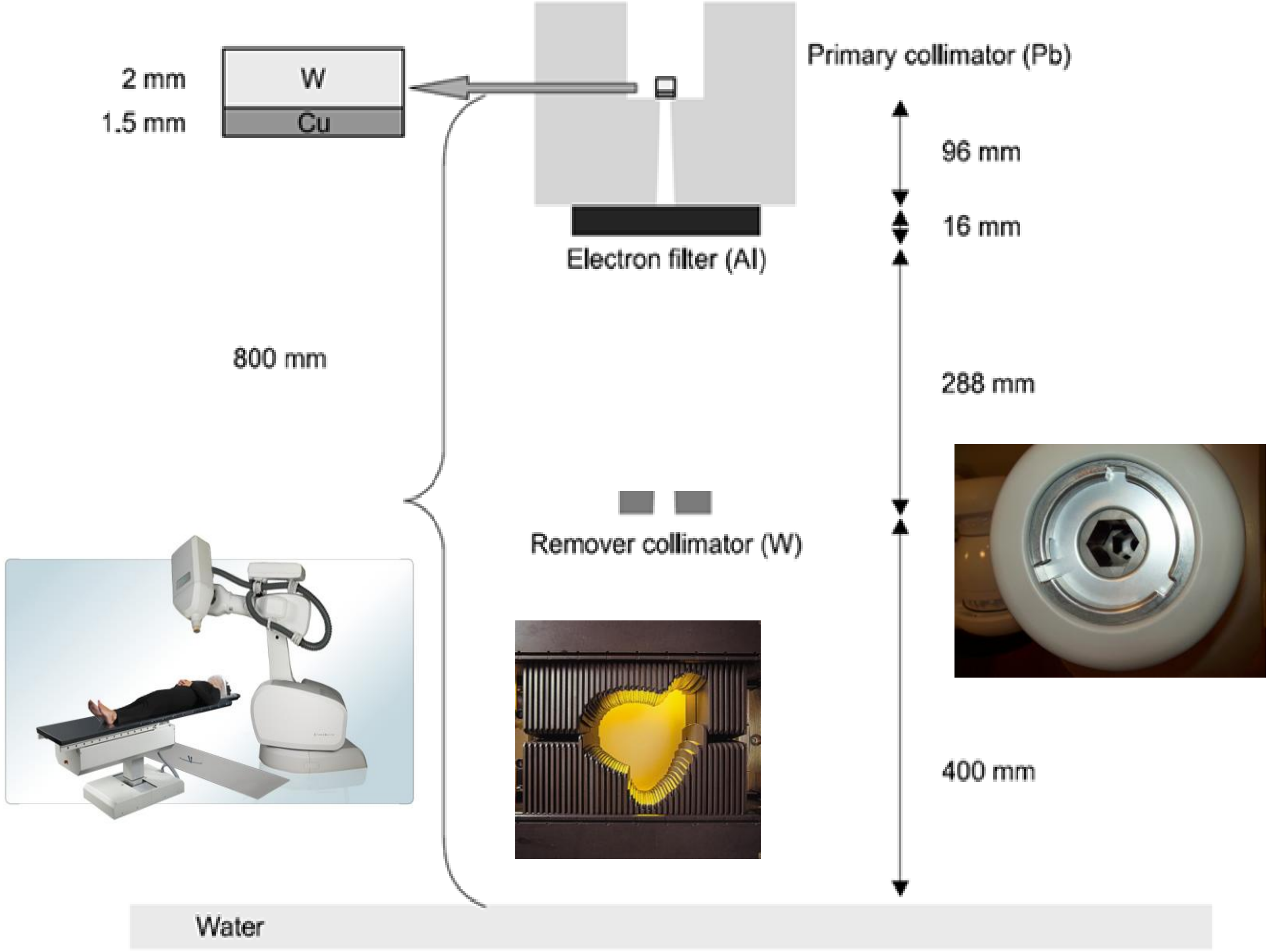
Topic 6: Electron Medical accelerator target

Motivations:

- The linac accelerates electrons which smash the target and generate the X-ray beam.
- Improve the X-ray production rate.

Solutions:

- The target shape design defines the gamma ray energy and beam size.
- Guiding the gamma ray, collimators system are required.
- Parallel linac solutions.

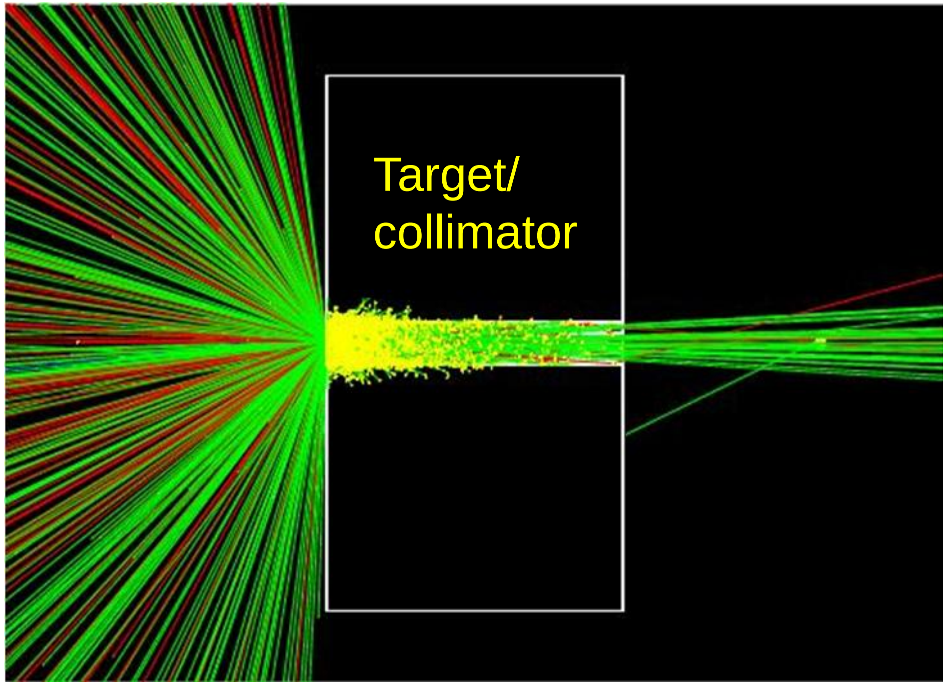


Limitation and future collimation challenges

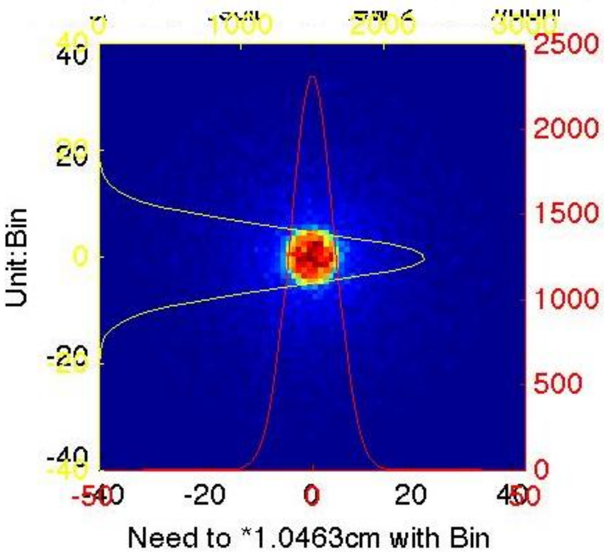
- Currently, low dosage is obtained by Cyberknife.

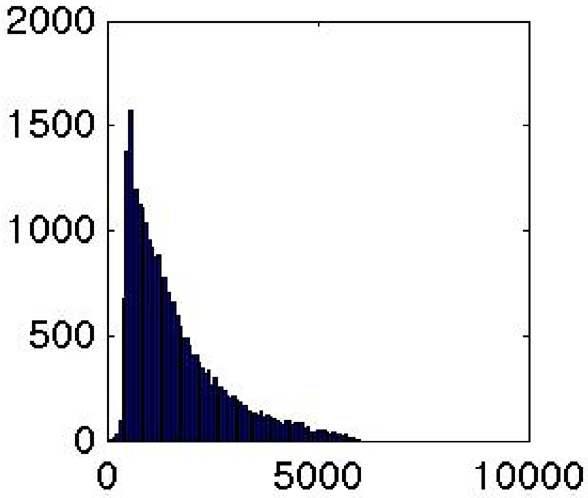
Backscatter electrons/gamma.

Forward gamma.



Intensive Monte Carlo Simulation.
Green: gamma; Red: electron



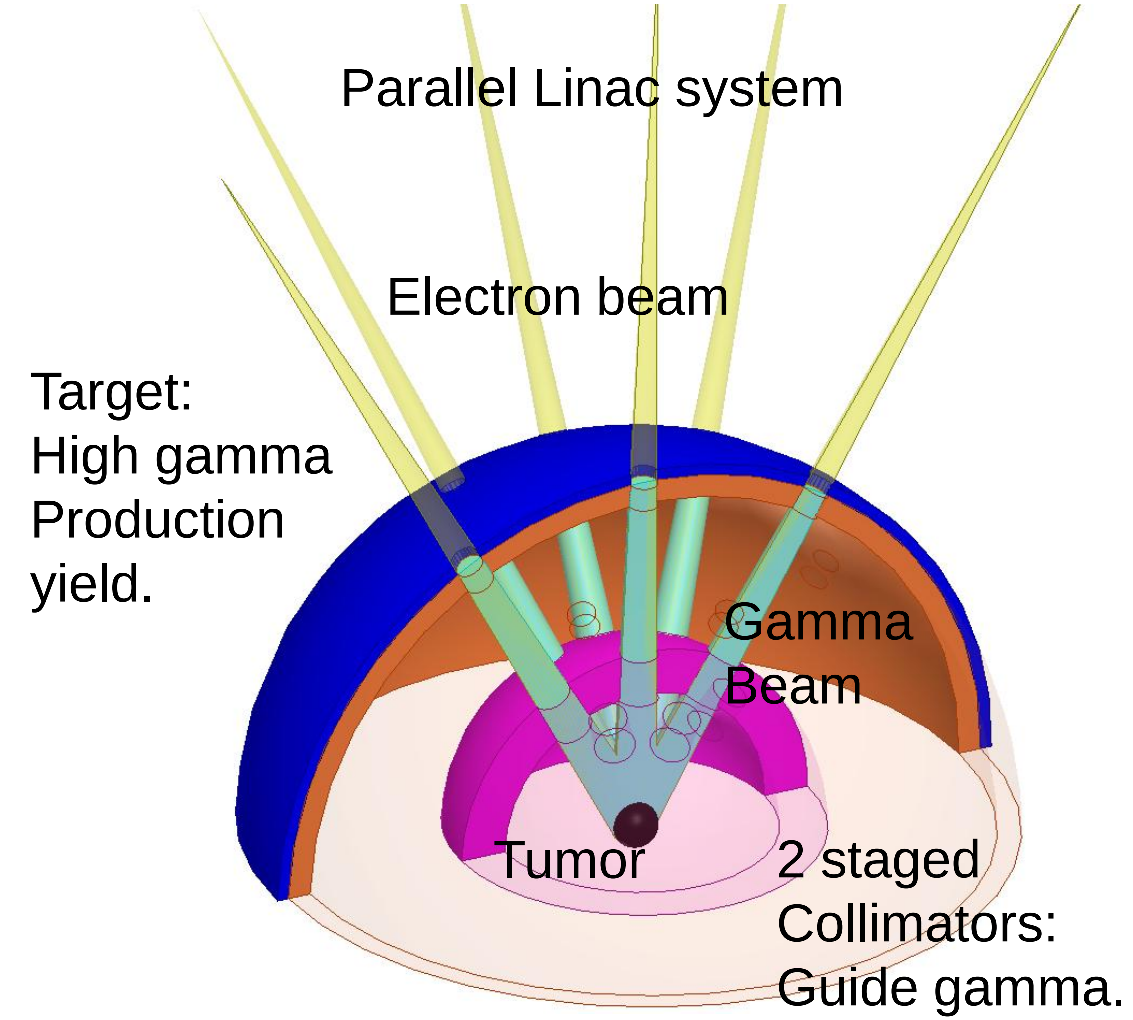


Forward gamma energy spectrum

Typical Cyberknife dosage:

- 10 Gy/min=10 Joule/kg/min
- > 30mins treatment time.

Optimization: production rate, penumbra, spectrum dosage



SLAC is planning to build a parallel accelerator system for the higher dosage, using 9 parallel linac systems with a shared target / collimator.

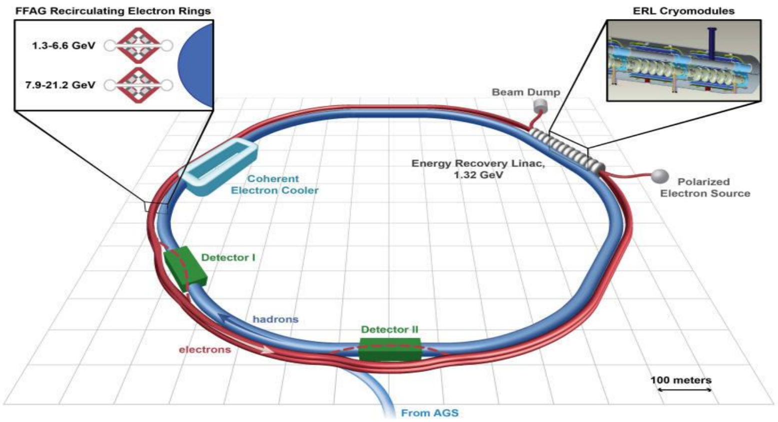
Courtesy of Accuray.

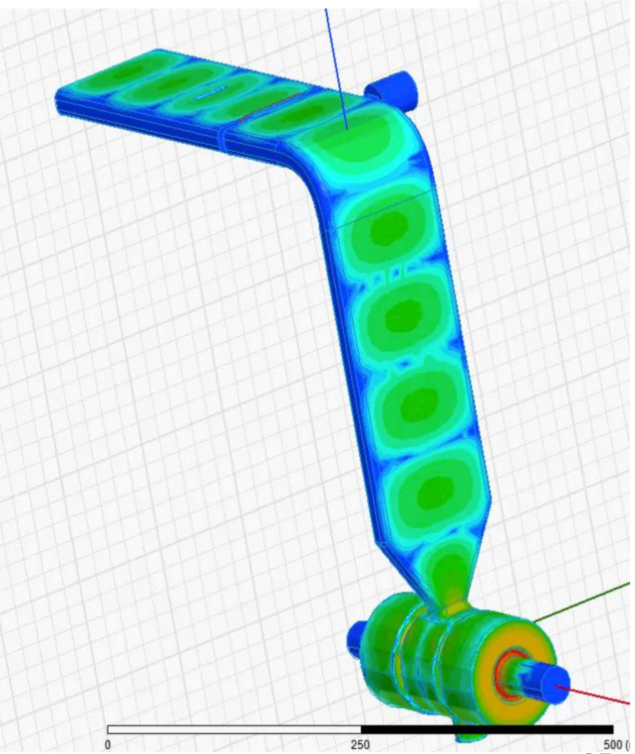
The new target can achieve:

- ~80 Gy/min=80 Joule/kg/min
- < 5 mins treatment time
- Same penumbra size

Other accelerator physics and selected publications

- High power RF coupler antennas and standing/traveling wave cavities.
  - **C. Xu**, et.al. Accepted to Nuclear inst. and method, A in Mar (2017).
  - **C. Xu**, et.al. Progress in Electromagnetics Research B. Vol. 75, page 59-77. (2017)
  - **C. Xu**, et.al. Physics Review Accel. Beams 19. 022002. (2016)
- Free Electron Laser (FEL),
  Energy Recovery Linac (ERL),
  Cosmic Background Microwave (CBM) research.
  - **C. Xu**, et.al. Submitted to Phys. Rev. Accel. Beams in Jul (2016)
  - **C. Xu**, et.al. Progress in Electromagnetics Research C, V64, I79-87, (2016).





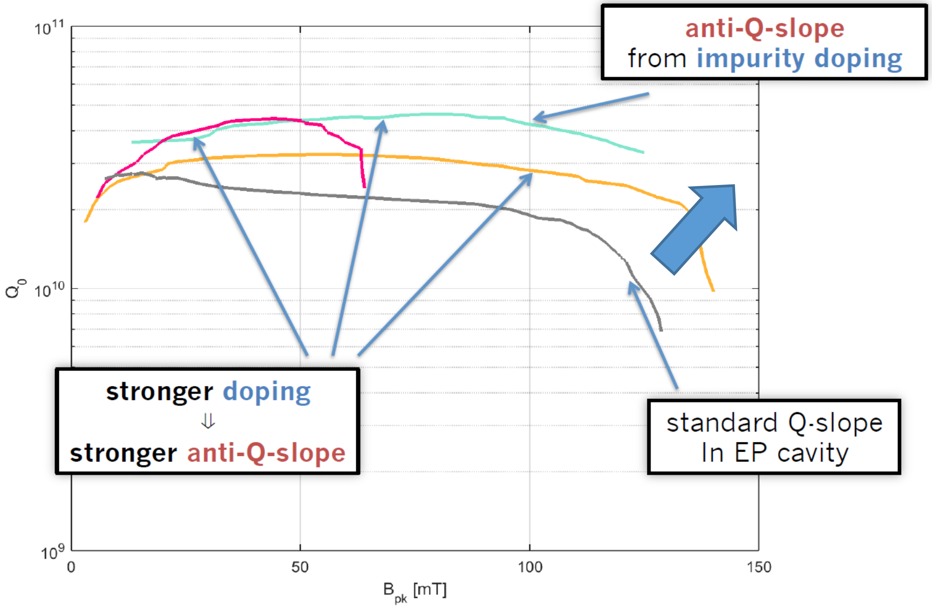
Selected future opportunities

1. **SRF frontier studies for PIP-II/III.**
    a. Achieving high quality factor and High accelerating gradient simultaneously for SRF cavities.
    b. Development of thin film technology and SRF materials science.
    c. Studies of SRF operational degradation and remedy schemes.
2. **High intensity accelerating component damage.**
3. **Innovations for Fermi Test Beam Facility.**

1.SRF frontier studies for PIP-II/III

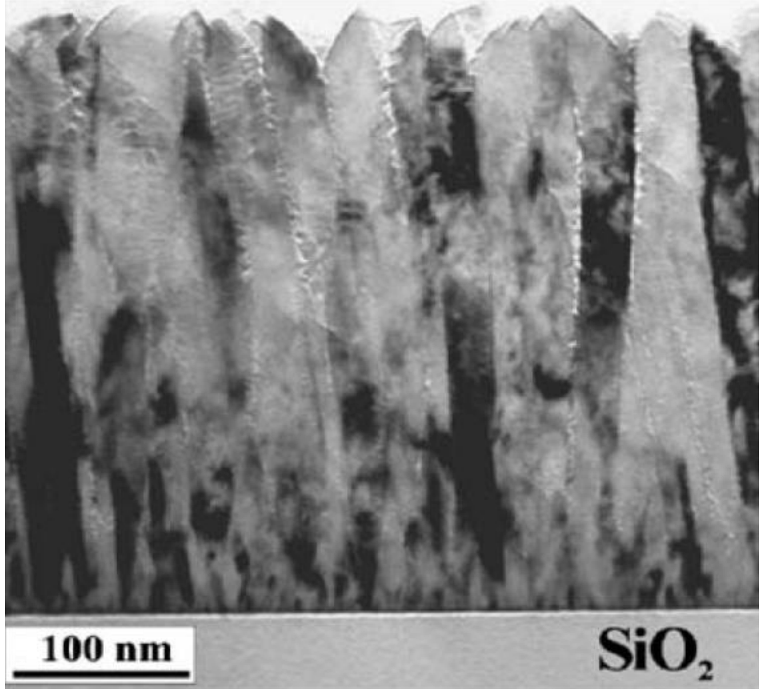
a. High Quality factor and High accelerating gradient SRF cavities

- **Motivations:**
  - Improvement on bulk Nb material performance.
  - High Q_0 at high gradient(>30MV/m) simultaneously.
  - Other type SRF cavities recipe.
- **Solutions:**
  - Understand how nitrogen doping/infusion improves Q_0 with a material model.
  - Origin of anti-Q slope: mean free path or trapped flux.
  - Grain Boundary effect on trapping flux and scattering of Cooper pairs by characterizations. (EBSD)
  - Optimize doping level.



b. Development of thin film technology for future SRF accelerators

- **Motivations:**
  - Improvement on thick film materials.
  - A rough sputtering thin film is obtained even though the substrate is smooth enough.
  - Columnar structure with a changing grain orientation and small macroparticles can cause additional RF loss.
  - Accelerating gradient is limited by high field Q slope.
- **Solutions:**
  - Understand how the defects contribute to the Q slope at high field.
  - Optimize the new recipe.
  - Implement the recipe on single cell cavity with cryo-test.



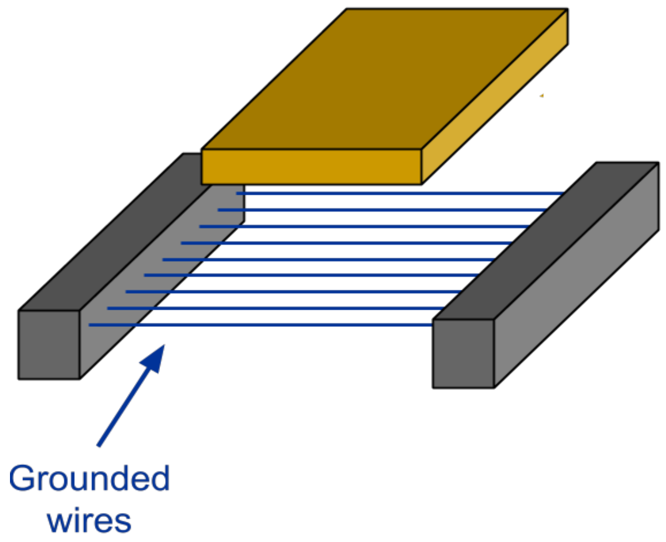
Cross sectional TEM images of Nb films deposited by Sputtering.

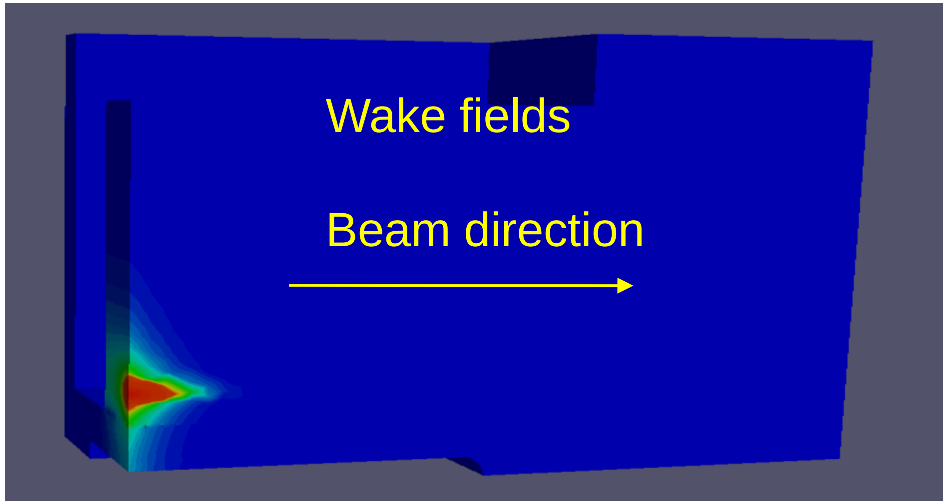
c. Studies of SRF operational degradation and remedy schemes

- **Motivations:**
  - Degradation of the usable accelerating gradient and Q_0 are observed in existing SRF accelerators.
  - High power RF processing and helium processing are found to be ineffective.
- **Solutions:**
  - Plasma processing research
    - Understand the plasma cleaning mechanism.
    - Test various gas combined with different RF modes.
    - Optimize the plasma process recipe.

2. High intensity accelerating component studies (MI52 Extraction Septum)

- **The high current R&D for future accelerators.**
- **Grounded anode wires breaking from radiation and/or mechanical damage:**
  - Investigate the following mechanisms:
    - Hypothesis 1: Strong wake fields, RF heating, thermal cycle material fatigue (RF+ Transient heating)
    - Hypothesis 2: Particle showers damage (Geant 4 simulation, X-ray survey measurements empirical evidence)
    - Hypothesis 3: Thermal gradients and shock waves via energy deposition (1D thermal static simulations and measurements)
- **Confirmation/Solutions:**
  - Conduct verifying experiments: Wakefield measurement, X-Ray survey, calorimetric methods…
  - Investigate remedial solutions: critical for increased intensity and fast vs. slow-spill extraction.

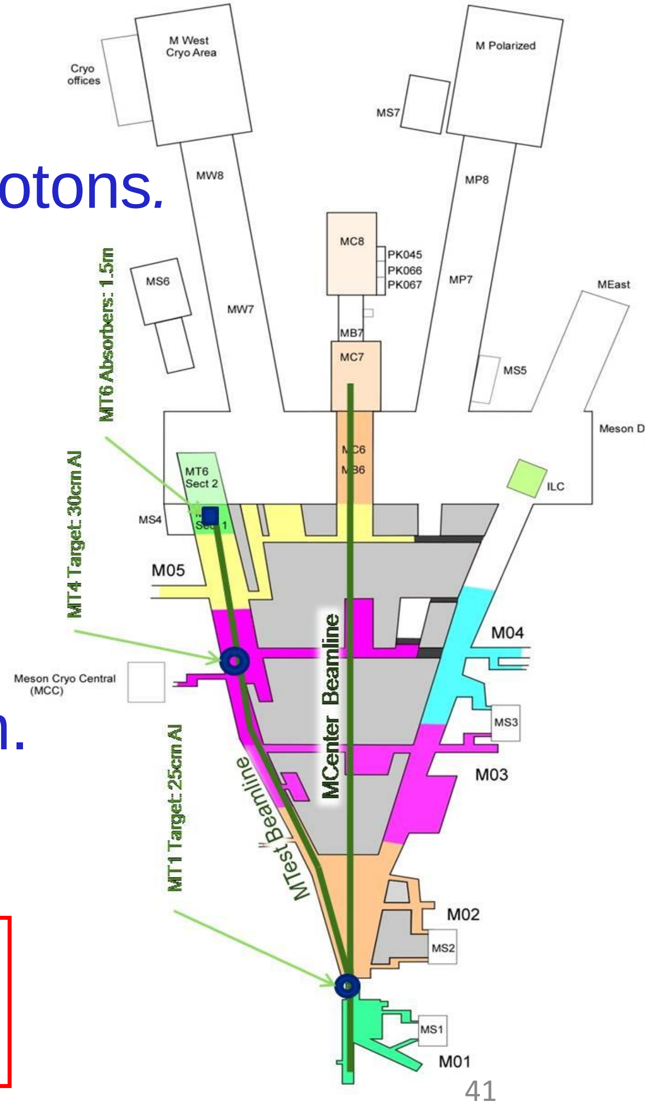




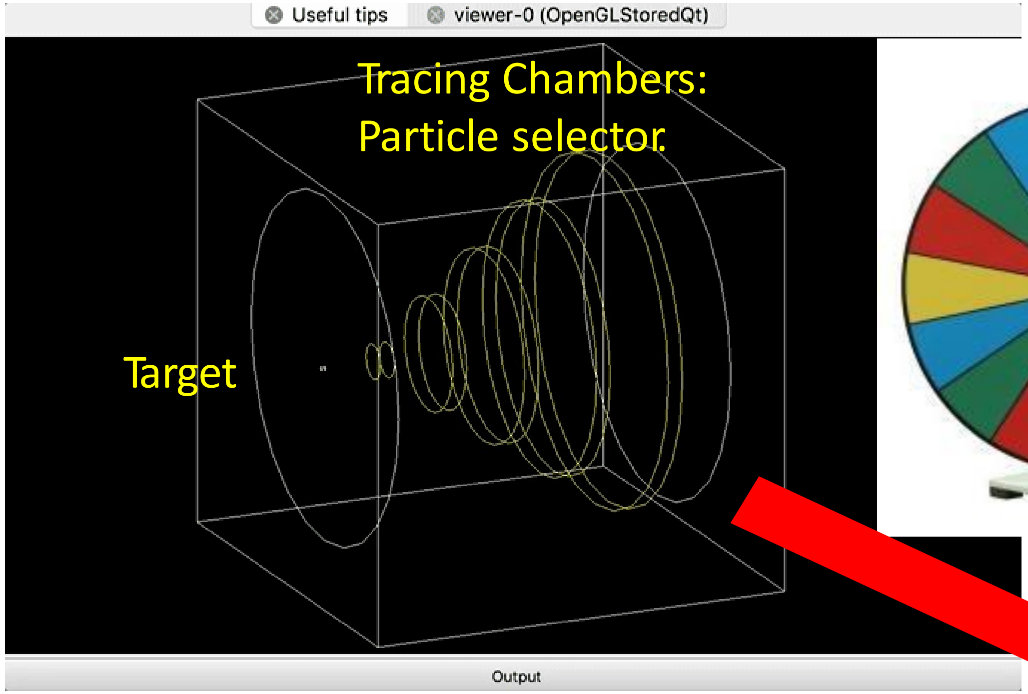
3. Innovations for HEP in Fermi Test Beam Facility

- **Motivations:**
  - 30-80GeV high-purity $\mu/K/\pi$ /e/e^+ beams from 120GeV MI protons.
  - Exploit rare production processes by increasing intensity.
  - Optimized target designs. (Geant4 and FEA)
- Innovations:
  - Secondary beamline designed to select momentum.
  - Tertiary beamline for species selection and high purity beam.
  - A promising production rate is observed.

Be ready in time for two-year CERN test beam shutdown 2019-2020

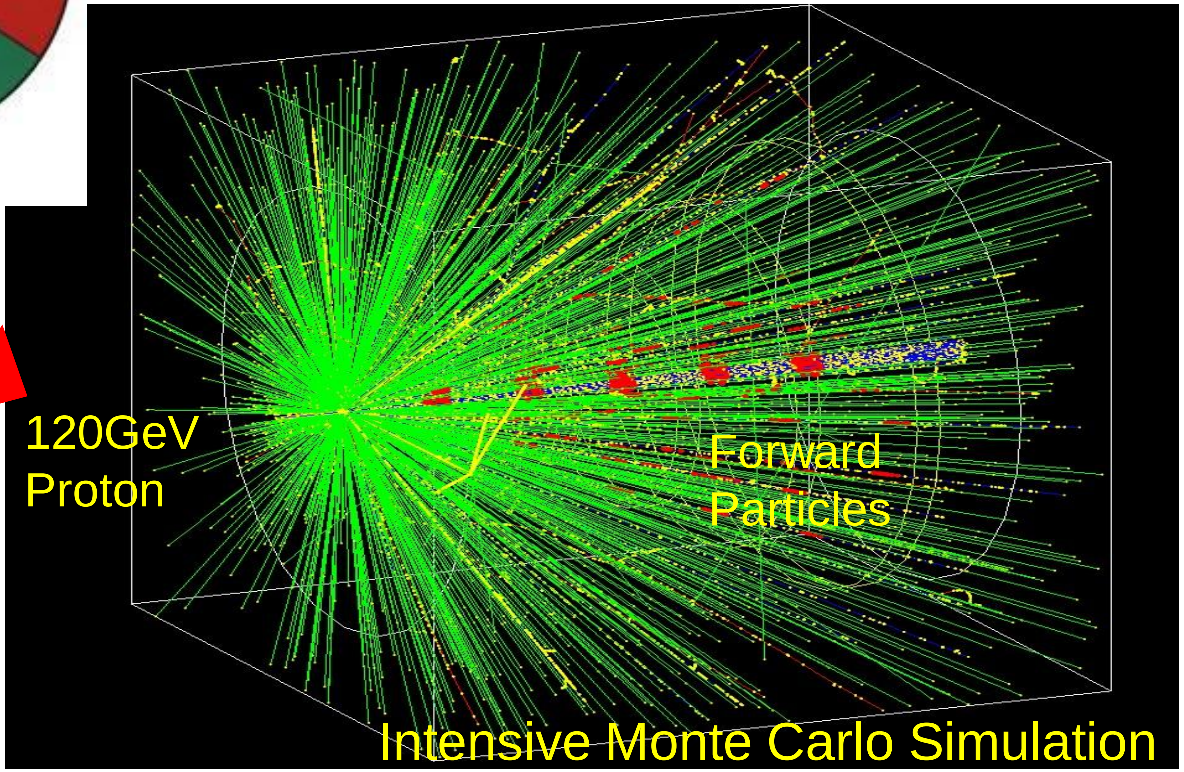


Monte Carlo simulations for particle production



Current example shows the 120GeV proton interacts with 33cm Be target.

Forward Particles.



Green: gamma; Red: electron

Design concepts:

1. 120 GeV proton production yields @ 10^{13} /spill.
2. Materials selections and Target geometry designs.
3. Selectable energy and particle species.
4. Collimator optimization.
5. Systematic Multiphysics optimizations.

Summary

1. High power and high efficiency are important factors for future accelerator projects. SRF is an enabling technology for large scale accelerators.

2. Previous projects convey my experience and achievements in the accelerator R&D, including: intense parallel multi-physics simulations, design, prototyping and commissioning of RF, SRF and other accelerator systems.

3. My research interests are: 1) SRF frontier studies, 2) High power beam SRF and RF accelerator systems, 3) Intensity Frontier R&D and 4) Accelerator applications.

4. There are challenging but exciting future projects at Fermi National Accelerator Laboratory.

Thank you for your attention

Acknowledgements:

- Prof Ilan Ben-Zvi,
  - Associate Chair, Collider-Accelerator Department, Brookhaven National Laboratory.
  - BNL Professor of Physics, Stony Brook University.
  - Fellows of American physics society, IEEE.

- Dr Juwen Wang,
  - Senior Scientist, Accelerator Division, SLAC National Accelerator Laboratory.
  - Fellow of American physics society.

- Dr Charles Reece,
  - Senior Scientist, Accelerator Division, Thomas Jefferson National Accelerator Facility.
  - Deputy director of SRF institute, Thomas Jefferson National Accelerator Facility.

- Colleagues in Thomas Jefferson National Accelerator Facility, SLAC National Accelerator Laboratory and Brookhaven National Laboratory.