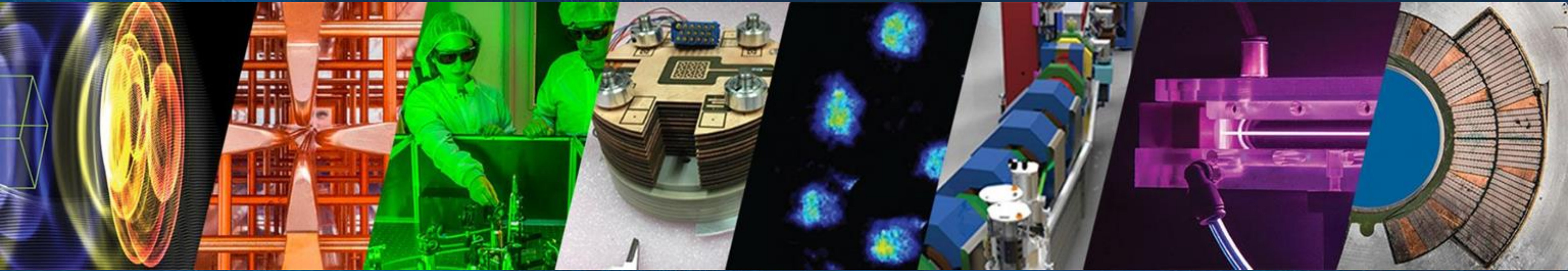
RF studies at LBNL and application to cooling

Tianhuan Luo, ATAP, LBNL



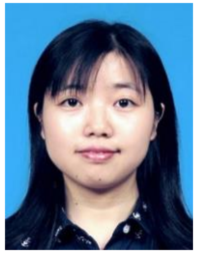
International Muon Collider Collaboration: Demonstrator Workshop
Oct 31, 2024

BERKELEY LAB
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP
U.S. DEPARTMENT OF ENERGY | Office of Science

Overview of the RF development for particle accelerators at LBNL

RF electromagnetic design


T. Luo

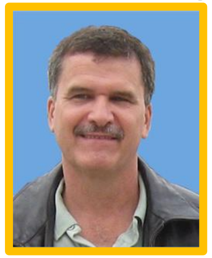

D. Wang


J. Staples


D. Merenich (incoming)

Mechanical design


A. Lambert


S. Virostek

Low Level RF control


G. Huang


Q. Du

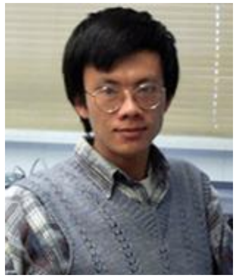

L. Doolittle

Fabrication

Comprehensive engineering shops and laboratories in LBNL Engineering Div.

RF related beam dynamics


C. Mitchell

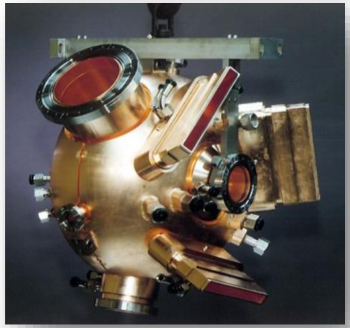

J. Qiang

Core R&D areas on RF:

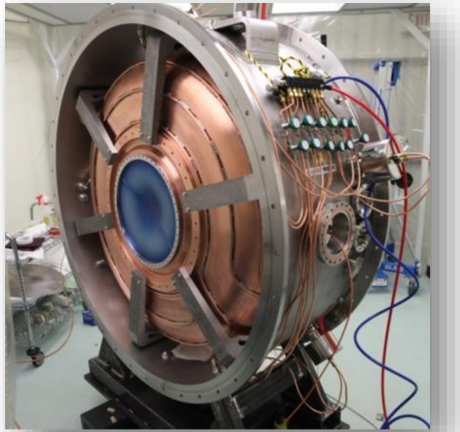
- Advanced RF design, engineering & fabrication
  - Specialized RFQ accelerator and CW **NCRF** design and engineering;
  - Innovative and HOM-damped RF cavities and beam impedance modeling;
  - Novel RF structure design.
- High precision Low Level RF control
  - developed FPGA-based MARBLE board;
  - contribution to LCLS-II, PIP-II, AWA, etc.
- Many of our RF projects are close collaborations across different programs and divisions.

Innovative NC RF design, engineering, fabrication and system integration have been one of Berkeley Lab's core strengths to serve DOE's accelerator projects in HEP, BES and NP

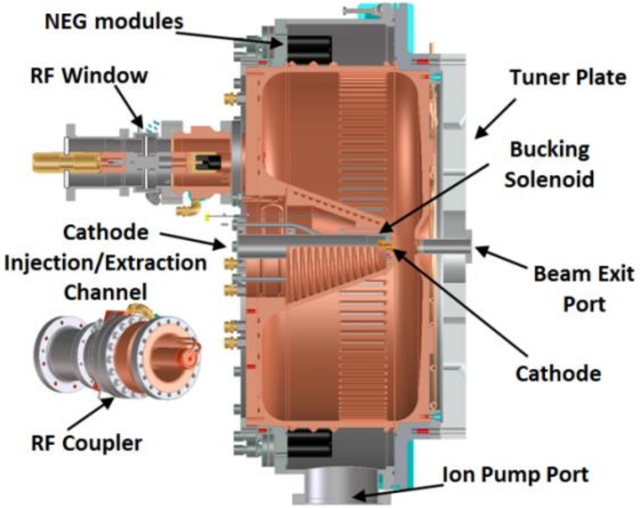
PEP-II HOM Damped Cavity



201 MHz MICE RF module

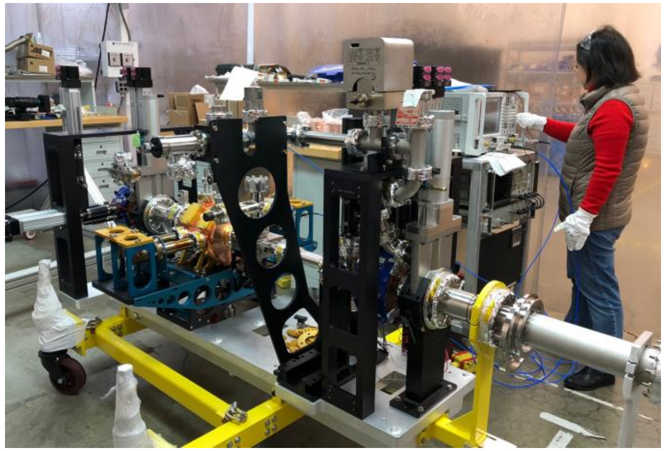


APEX 186 MHz CW Gun Cavity at HiRES UED Beamline, LBNL

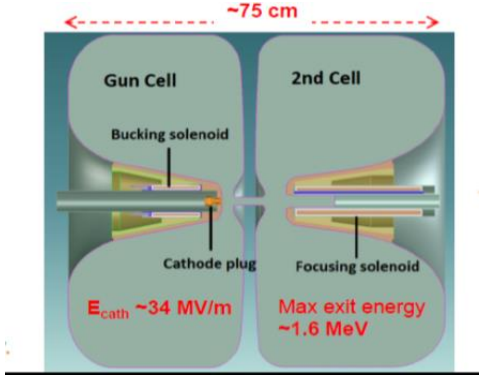


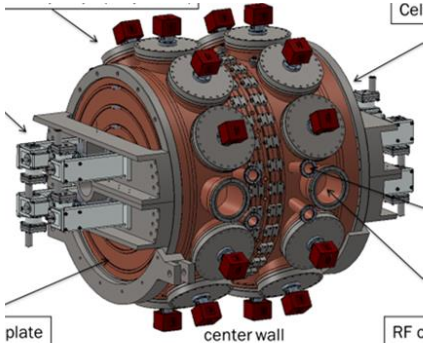
162.5 MHz CW RFQ for PIP-II

LCLS-II Injector (186 MHz Gun & 1.3 GHz buncher)

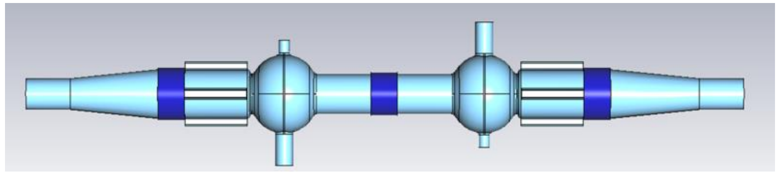


RF and conceptual mechanical design for 186 MHz APEX2 Gun for high energy XFEL and UED/UEM





RF design for an 1.5 GHz HOM-damped, low r/Q 3rd harmonic cavity for ALS-Upgrade



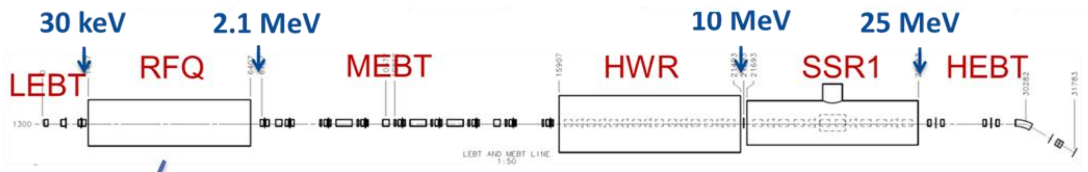
RF geometry design implementing multi-objective optimization computational tools:

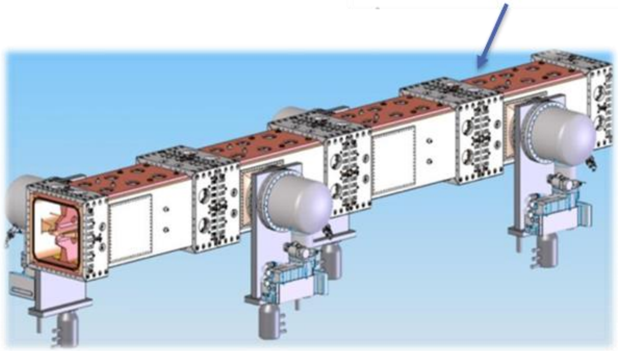
- APEX2 (design)
- ALS-U 3rd harmonic cavity

RFQ for PIP-II Injector: a CW RFQ Berkeley Lab built with high transmission and innovative RF designs

Beam dynamics

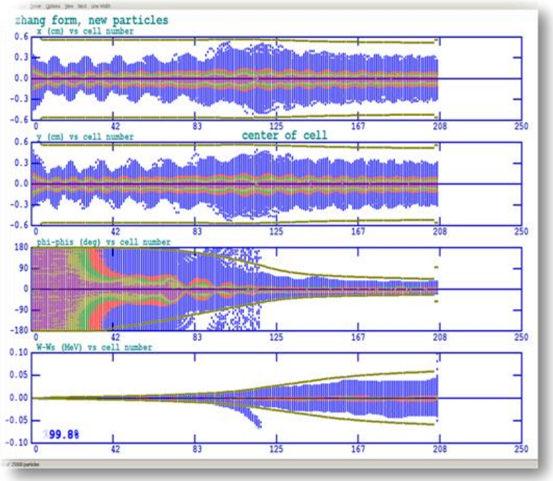
PIP-II Injector:





3D CAD model of PIP-II RFQ

Modulated Vane



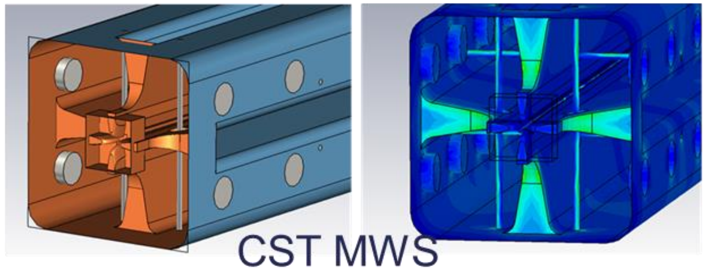
Beam Dynamics Tracking by PAMTEQ

- Meet the PIP-II RFQ beam dynamics requirements with over 99% transmission
- Large operational and dipole mode separation
- Low tip-to-tip vane voltage ➔ lower RF power

RFQ for PIP-II Injector: 3D RF Design with advanced *EM* simulation codes in collaboration with FNAL

Beam dynamics

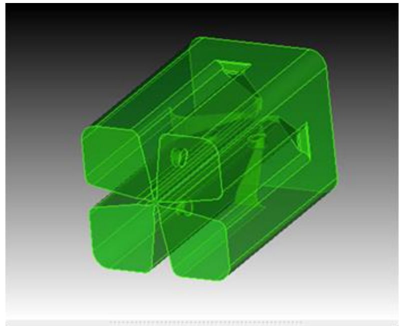
RF design



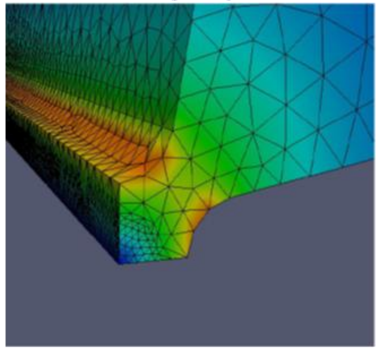
CST MWS

Parameters	PXIE-T
Frequency, MHz	162.493
Frequency of dipole mode, MHz	181.99
Q factor	14660
Q factor drop due to everything, %	-14.7
Power loss per cut-back, W (In/Out)	336/389
Max power loss density at cut-back, W/cm^2	7.9
Total power loss, kW	73.8
H, mm	172.73

Section	Power (kW)
Walls	29.5
Vanes	31
Input cut-backs	1.34
Output cut-backs	1.56
Pi-mode rods (32)	5.53
Tuners (80)	4.79
Sub-total	73.72
Beam power at 5 mA	10.5
Total	**84.22**



ACE3P



- We have developed an effective RF and engineering design method (procedures and tools) in RF structure designs starting from physics/beam dynamics ➔ RF ➔ thermal ➔ mechanical stress analysis
- We have successfully applied the method to the design of many RF structures.

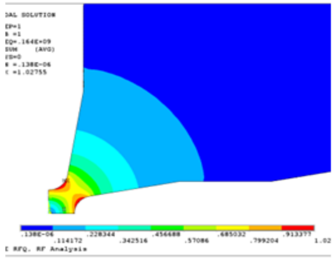
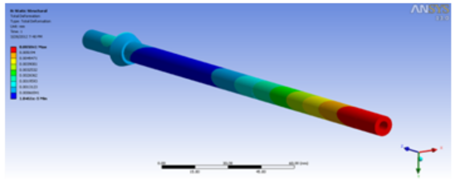
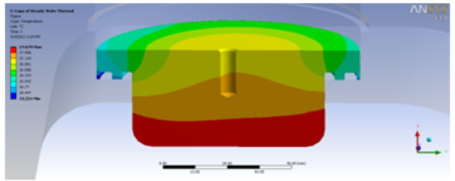
RFQ for PIP-II Injector: Thermal and stress management (cooling design) thru ANSYS analysis

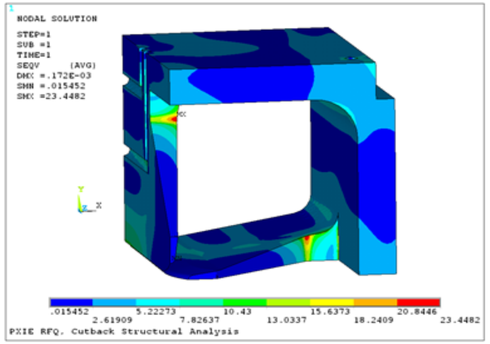
Beam dynamics

RF design

Mechanical design & analysis

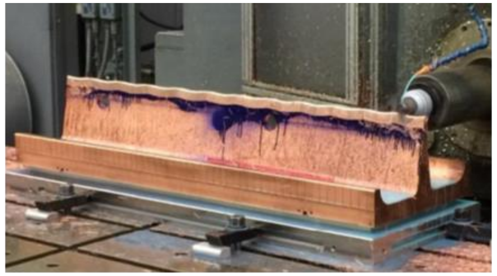
- **Numerous engineering analyses carried for design validation**
- **Cavity body and vane cutback thermo-mechanical analyses using an ANSYS RF/thermal/structural model**
- **Stress analysis using converted ANSYS thermal model**
- **Water temperature tuning analysis using a separate ANSYS model**
- **Calculation of area properties for body stiffness analysis**
- **Sub-model of the cutback region (RF, thermal, displacement)**

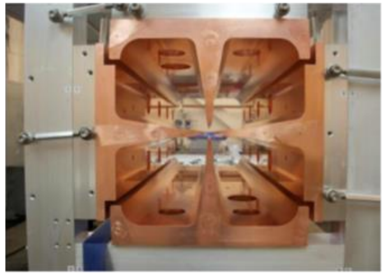


RFQ for PIP-II Injector: Fabrication, assembly, cooling & support system integration & RF tuning at Berkeley Lab

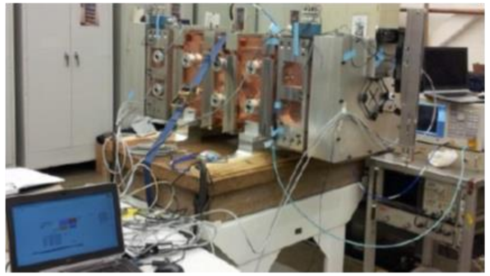
- Beam dynamics
- RF design
- Mechanical design & analysis
- Fabrication
- Low power RF test & calibration



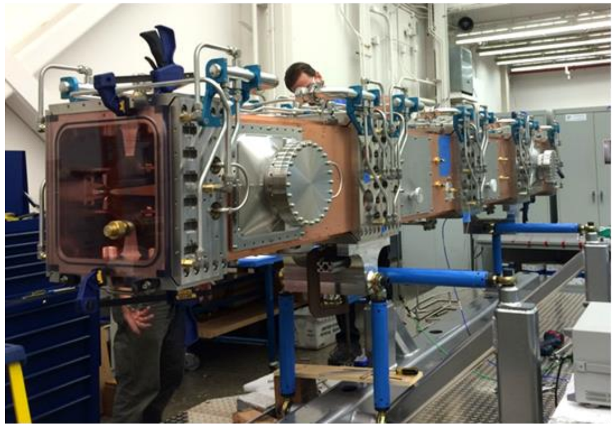
High precision machining



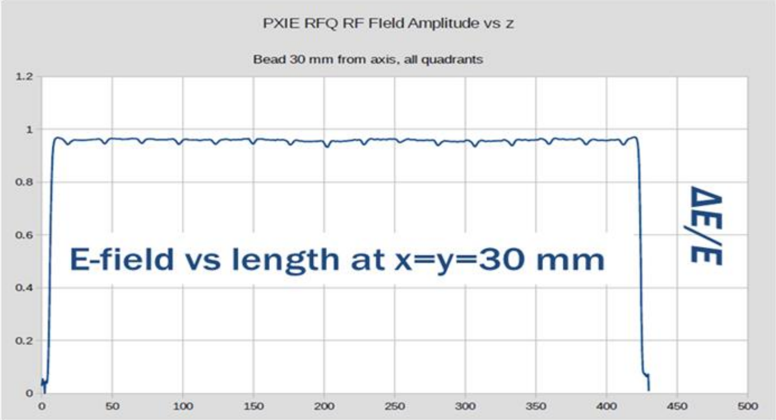
Cross-section of Test Module



Bead pull measurement



Water cooling system installation



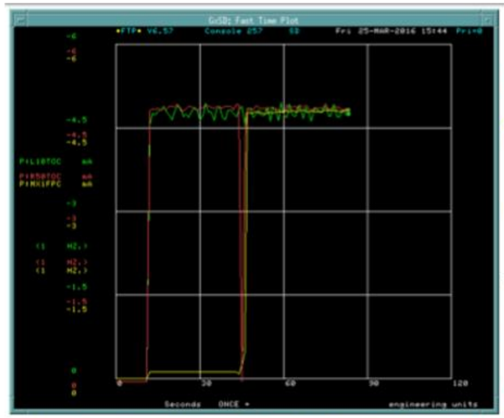
Field flatness ~ within ± 1%

RFQ for PIP-II Injector: Successfully commissioned at FNAL with nearly 100% beam transmission (pulsed) and full CW power

- Beam dynamics
- RF design
- Mechanical design & analysis
- Fabrication
- Low power RF test & calibration
- High power commissioning

- The RFQ beam commissioning started on March 23, 2016, and saw an accelerated beam within an hour with
  - Beam transmission of 98% ± 2%
  - Beam current 1-10 mA (pulsed)
  - Beam energy: 2.11 MeV ± 0.5%
- Switched to CW RF commissioning & reached full design power in 1.5 days

RFQ installed at FNAL



Red – beam current at the entrance of RFQ.
Green – beam current at the exit of the RFQ
Yellow – beam current measured in the Faraday Cup.
MEBT quadropoles turned on at t = 45 seconds

Vertical axis – beam current: 1.5 mA/div.
Horizontal axis – time: 30 sec/div.
(Pulsed results: 50-100 us at 10 Hz)

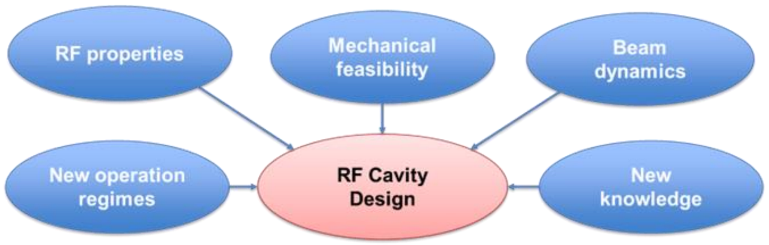
With quadrupoles and dipole correctors tuned, practically the entire beam goes into the Faraday Cup at the end of the beam line at the nominal current of 5 mA.

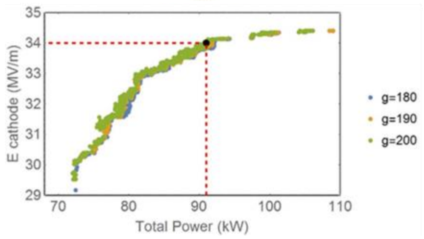
RFQ for PIP-II Injector: Team work among physicists, engineers and technicians; smooth collaboration between LBNL and FNAL.

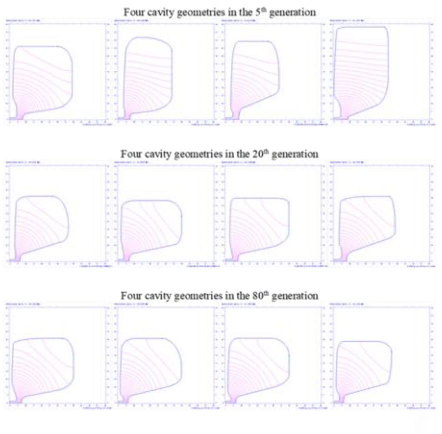
Developing advanced computational methods for general RF cavity geometry design

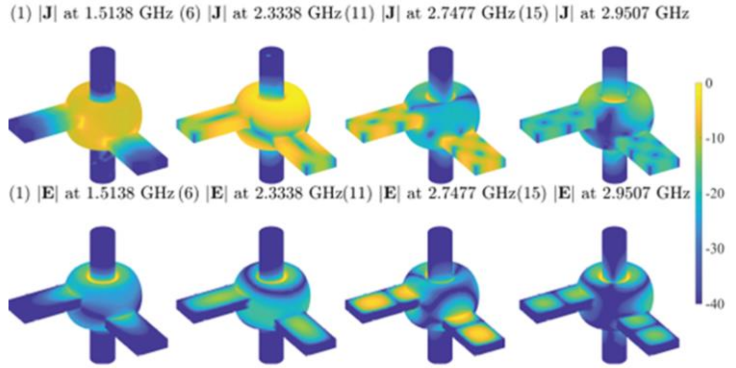
- A cavity design program based on Non-dominating Sorting Genetic Algorithm has been developed and applied to several cavity design projects.
- Future upgrade: implementing surrogate modeling for the multi-objective optimization and strengthening the HPC capabilities.
- With Computing Science Division, applied a Green’s function-based field solver to RF cavity eigenmode simulation: significant reduction of simulation time and memory.
- Extending from frequency domain to time domain for the beam-cavity interaction.
- Looking forward to applying them to the MuC cavity design.

RF cavity design: a complex Multi-objective optimization problem



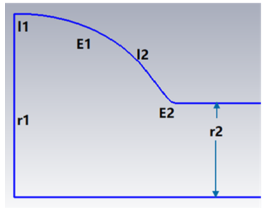


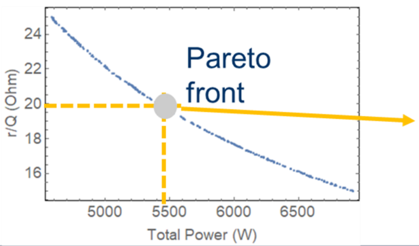


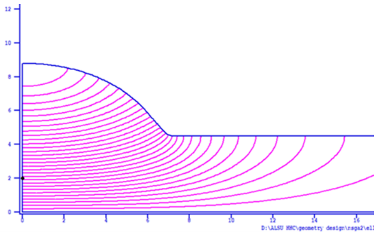


Novel RF design for specific beam dynamics requirements: a HOM heavily-damped NCRF cavity for ALS-U

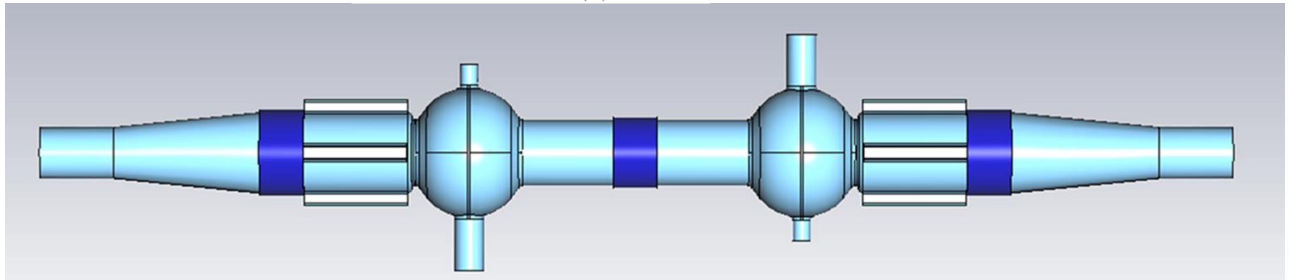
- ALS Upgrade (ALS-U): a soft X-ray diffraction limited synchrotron light source, a significant increase of the light brightness compared to today’s ALS, a major scientific facility upgrade at LBL.
- We designed the new 1.5 GHz 3rd harmonic cavity for ALS-U to lengthen the bunch to achieve the required beam lifetime.
  - Novel EM design of an elliptical cavity with enlarged and ridged waveguide for the unusual requirement of a high Q but low r/Q.
  - Supporting the mechanical design (in progress) and future hardware production and testing.





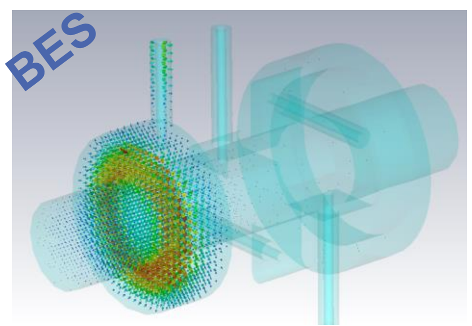


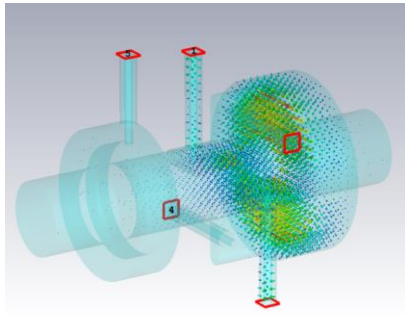
A direct application of our newly developed design program based on the genetic algorithm.



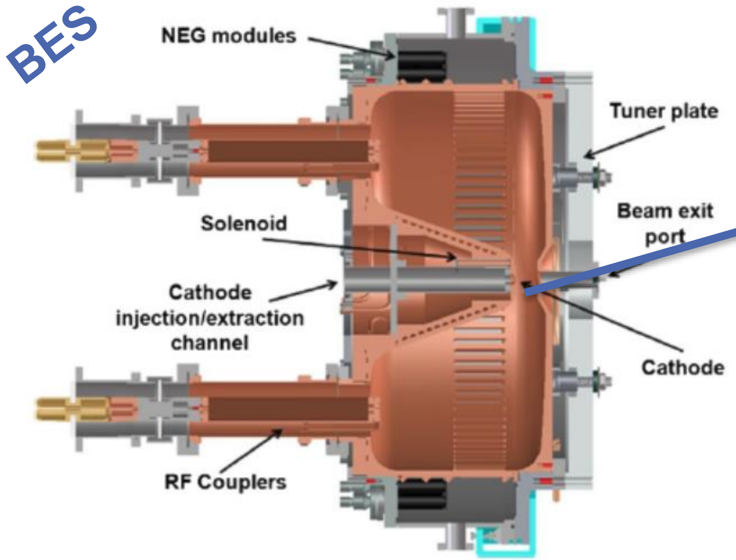
EM design focusing on higher-order-mode (HOM) damping and beamline absorbers (BLA),

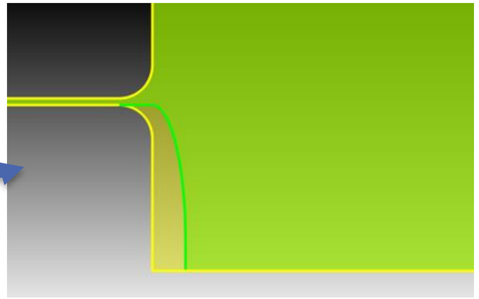
Collaborating within and outside LBNL to apply NCRF expertise to particle accelerators and beyond





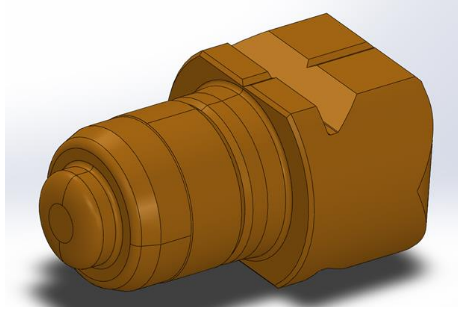
Cavity BPM for MeV Ultrafast Electron Microscopy **HIRES beamline at LBNL.**



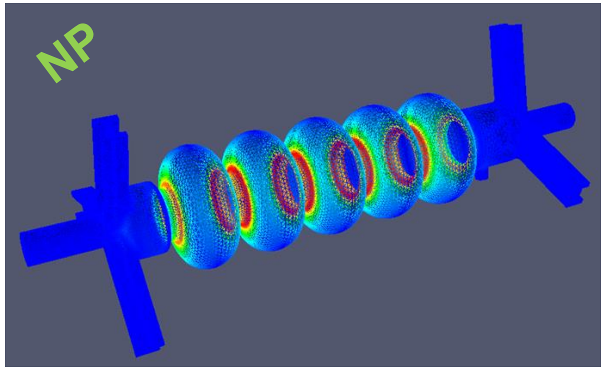


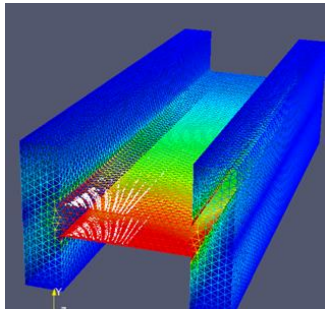
Yellow: APEX plug
Green: new plug for $E_{cathode}$~25 MV/m

A new cathode plug design to significantly increase the E field on the cathode for **LCLS-II HE** cathode testing program. Collaborating with **SLAC**.



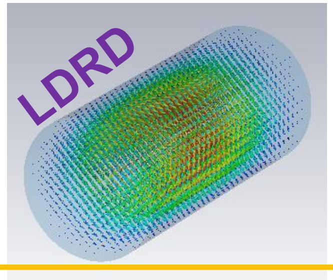
3D CAD model of the new plug



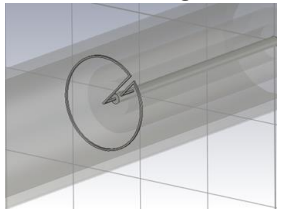


Multipacting and HOM damping analysis for the then proposed Energy Recovery Linac for **Electron Ion Collider**. Collaborating with **BNL**.

Cyclotron radiation resonant mode



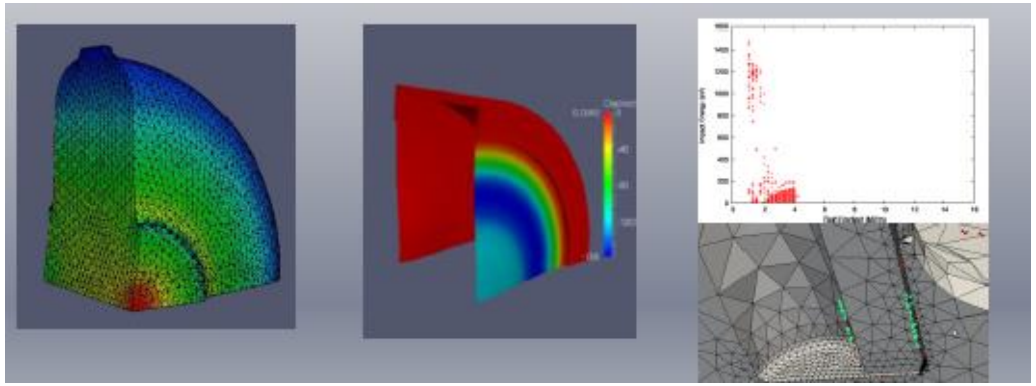
A novel antenna readout design

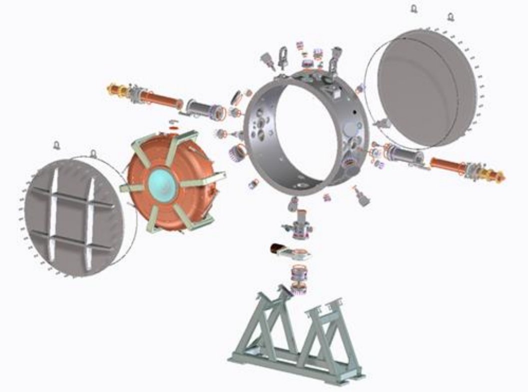


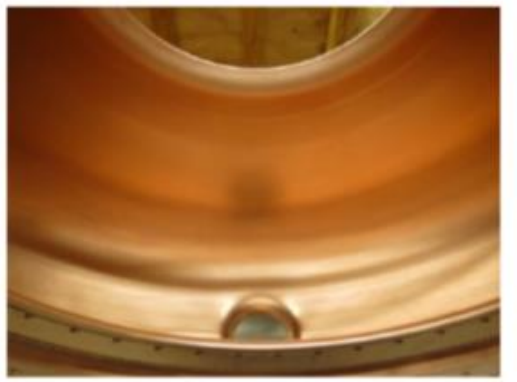
Designing a RF cavity to detect the frequency in the Cyclotron Radiation Emission Spectroscopy for **Project 8**, a nuclear experiment to measure the neutrino mass. Collaborating with **LBL Nuclear Science Division**.

201 MHz RF cavity module for Muon Ionization Cooling Experiment

- At LBNL, we designed, built and carried out the low-power test for the 201 MHz MICE cavity.
- RF design study:
  - Novel RF design.
  - High precision calculation of EM field.
  - Multipacting investigation.
  - RF cavity thermal and Lorentz force analysis.
- Engineering development:
  - Curved thin beryllium windows.
  - Electropolishing of a large irregular surface.
  - TiN coating by plasma deposition on irregular surface.
  - Frequency tuning arms with pressurized actuator.
  - Operation of two coupled vacuum volumes and vacuum burst protection for Be windows.
- High power commissioning of MICE cavity at Fermilab Mucool Test Area (MTA) has demonstrated the stable operation in the strong B field similar to the MICE environment. However, the cavities were not installed on the MICE beamline eventually, due to the time and resource limits.

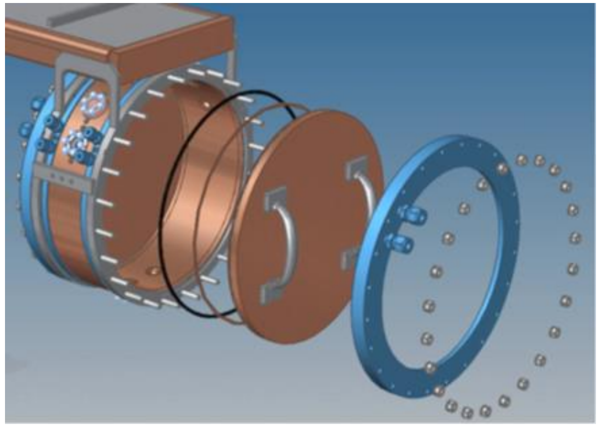


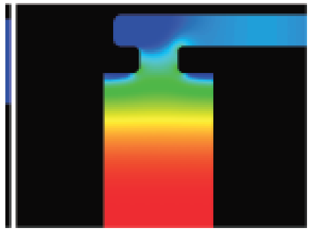


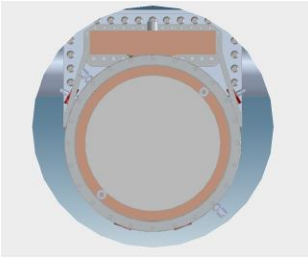


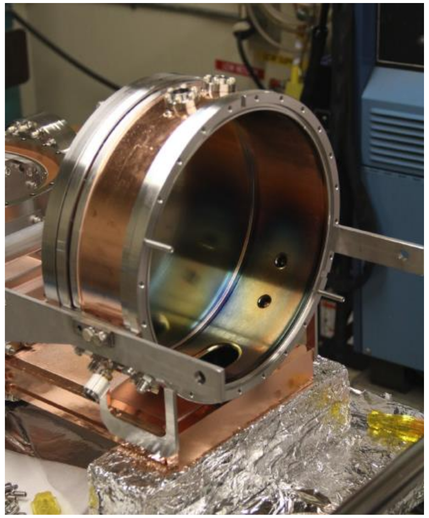
805 MHz modular cavity developed under Muon Accelerator Program (MAP)

- At LBNL, we have collaborated with SLAC and Fermilab on the design, production and low power RF test of an 805 MHz modular cavity, and actively participated the high-power test at Fermilab MTA.
- This cavity is the most recent iteration of a series of testing RF cavities for studying the RF breakdown in the strong B field for the muon ionization cooling, an integration of all previous experience and lessons-learned.
  - Moving the power coupling to the side wall to reduce the peak E field at the coupler.
  - Designing the cavity geometry to minimize the effects of dark current and pulsed heating.
  - Cleaning and polishing the interior cavity surfaces to reduce the density of field emission sites.
  - Investigating the role of material type, production, surface conditioning, etc. in the breakdown process.
- Achieving the steady operation at ~ 50 MV/m in B=3T environment with Be end plates, a significant milestone for the cavity R&D for the muon ionization cooling.







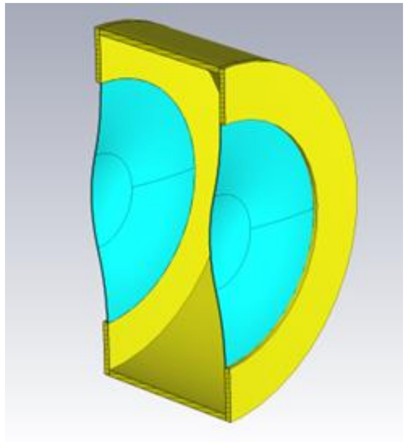


Stable Operation Gradients achieved with different end plate materials at MTA tests

Material	B-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

A recent conceptual design of an 805 MHz cavity with Be windows for cooling

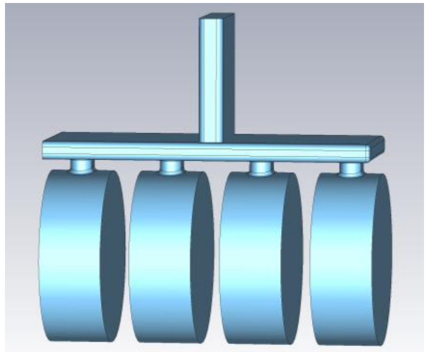
- The basic idea is to implement the RF design and engineering experience learnt from MICE and MAP cavities to design a new cavity.
  - E_cu_max < 13 MV/m & E_Be_max < 50 MV/m, as demonstrated by MAP modular cavity.
  - Coupling from the torus on the side to avoid high E field at the coupling iris, with the price of a larger solenoid bore size.
  - Curved B windows to mitigate the thermal stress.
  - Cavity length optimized for maximum shunt impedance per unit length.
- Relatively high technical readiness with moderate cavity gradient relevant to the cooling demo.
- Explore the novel distributed coupling for RF power feeding.
- Some features such as the large size (r~9.6cm) Be window needs further scrutiny.



Average E gradient w/o transient factor (MV/m)	27.4
E max on the Cu surface (MV/m)	13.0
E max on the Be surface (MV/m)	39.1
r/Q (Ω) w/o transient factor	259
Q_0	21320
RF power (MW)	1.36

The achievable gradient, which is calculated as the total voltage divided by the cavity length, is 27.4 MV/m, comparable to the desired gradient for the rectilinear cooling channel.

The required RF power 1.36MW is at a similar level of MAP modular cavity.



A summary of LBNL RF capabilities applicable to cooling demonstrator

- Novel NCRF structure designs
  - MICE and MAP cavity development experience.
  - MOGA-based design program
  - Software: SUPERFISH, CST, ACE3P, ANSYS
  - Hardware: BACI 512 GB 16-core server, NERSC.
- NCRF engineering, mechanical design, fabrication, assembly and system integration
  - MICE and MAP cavity development experience.
  - Comprehensive fabrication capabilities at LBNL Engineering Div., complemented by bay area local vendors.
- Training the next generation, both the physicists and engineers.
  - One NIU student supported by DOE SCGSR starts this Dec at LBNL working on cooling cavities' design.
- High precision LLRF.
- We still have 10 Be windows (curved, ID=42cm, thickness~0.38 mm) from MICE. If you see a good use for them for the cooling R&D, we are happy to share!