US activities and contributions in RF for MuC

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IMCC and Mucol Annual Meeting 2025, 05/15/2025 DESY, Hamburg, Germany

US RF activities in community planning

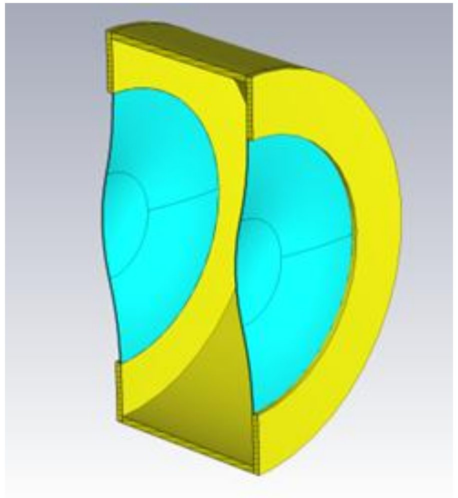
- MuC RF inputs to US Snowmass 2021
  - Muon Collider Forum report
  - Accelerator Frontier RF topical group report
- MuC RF inputs to US P5 2023
  - MuC study summary and documents submitted to P5
    - Many enthusiastic and well-thought feedbacks from MAP/Mucool RF veterans.
  - P5 townhall meeting contribute talk on NCRF from ionization cooling.
- RF inputs to Princeton Muon Collider Organizational Workshop, Feb 2024
  - A tentative near-term R&D plan "NCRF and SRF needs and priorities for the next 3-5 years"
- RF inputs to International Muon Collider Collaboration: Demonstrator workshop, Nov 2024
  - RF capabilities and application to cooling demonstrator or MuC in general presented by several DOE labs: Fermilab, SLAC, LBL, JLab, LANL and SNS.
- RF inputs to IMCC
  - IMCC Interim report
  - IMCC report to ESPPU

US RF activities in R&D

- So far no dedicated DOE direct funding for MuC RF R&D yet.
- DOE staffs' traveling for MuC conference/workshop can be supported by Lab general research funding.
- Leveraging other indirect funding: Laboratory Directed Research and Development (LDRD), Office of Science Graduate Student Research (SCGSR) Program, etc.
- Synergies with other funded RF R&D projects in US.
- Following up the IMCC RF R&D, building up collaborations.

Preliminary cooling cavity design study: a conceptual design of an 805 MHz cavity with Be windows

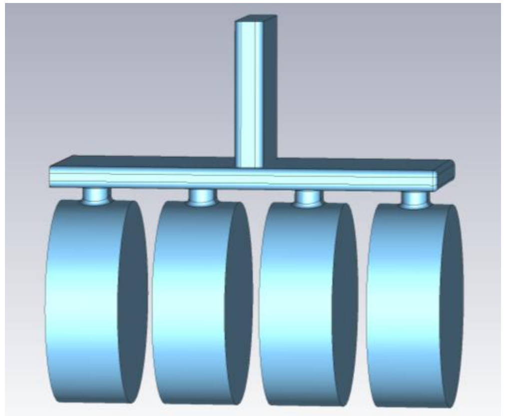
- A straightforward extrapolation of MICE and MAP cavities
  - E_cu_max < 13 MV/m & E_Be_max < 50 MV/m, as demonstrated by MAP modular cavity.
  - Power coupling from the torus to avoid high E field at the coupling iris, with the price of a larger solenoid bore size.
  - Curved B windows to mitigate the thermal stress.
- Relatively high technical readiness with moderate cavity gradient relevant to the cooling demo.
- Distributed coupling for RF power feeding.
- Some features such as the large size (r~9.6cm) Be window needs further examination.



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.

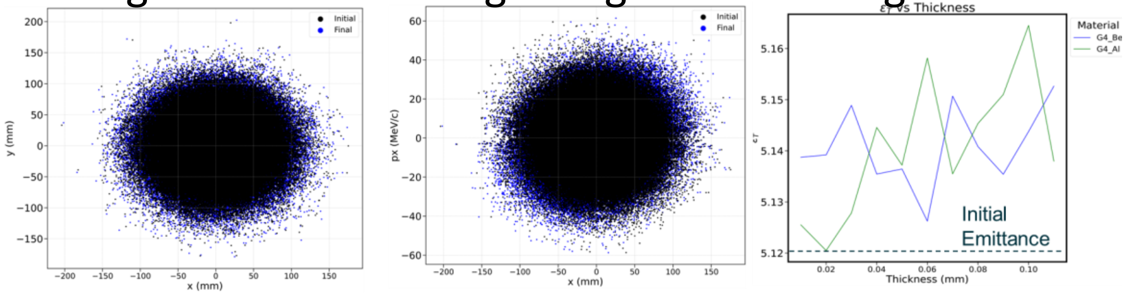


Preliminary cooling cavity design study: features of beam windows

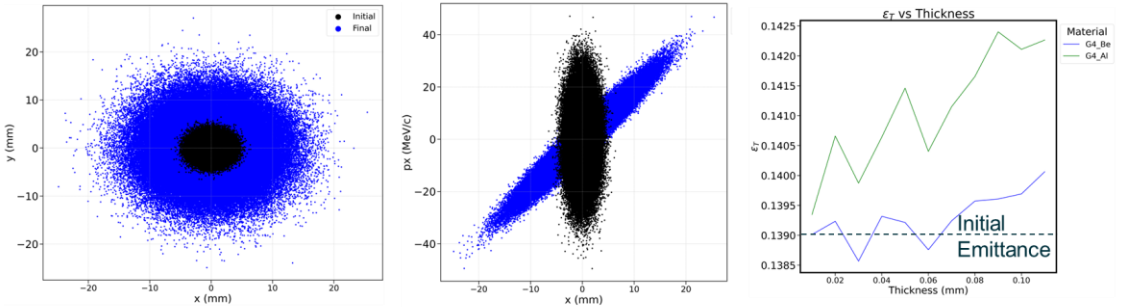
- Beam window: increase shunt impedance; mitigate the RF breakdown

Emittance dilution due to beam windows: Be vs Al

Stage A1: near the beginning of the cooling channel



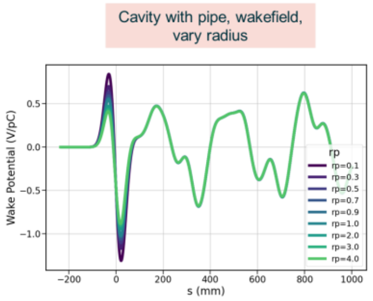
Stage B10: near the end of the cooling channel

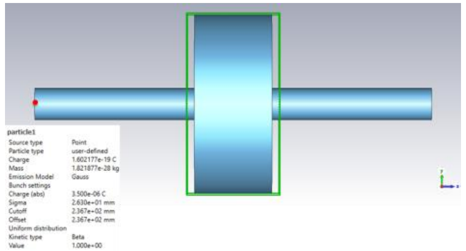


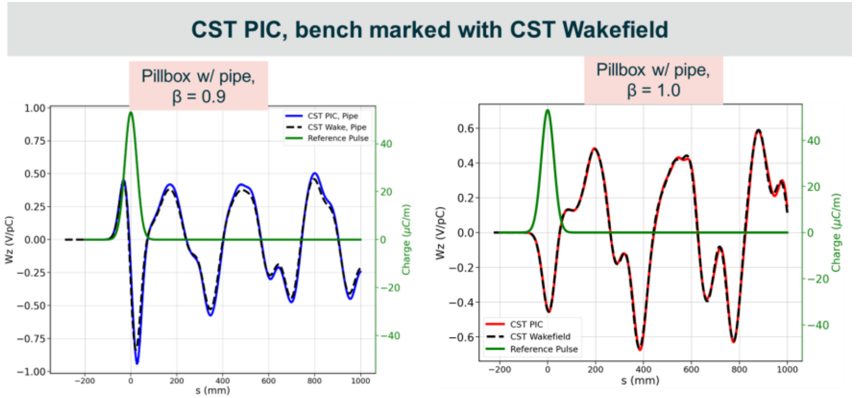
No noticeable difference at early cooling stage, noticeable more emittance dilution from Al than Be at late stage

Wakefield simulation for an enclosed cavity

CST wakefield solver is limited when simulating such an enclosed cavity. Exploring CST PIC solver





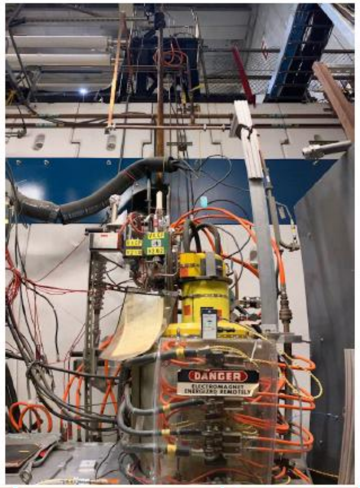


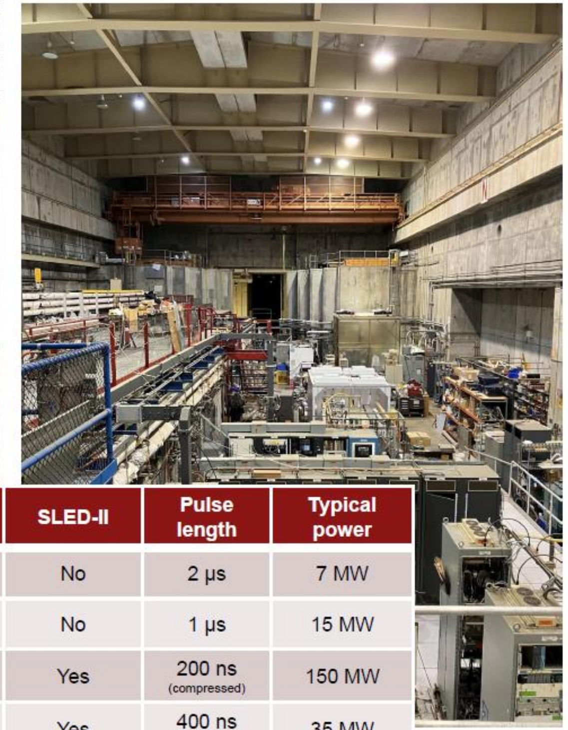
D. Merenich et al., Tue’s poster session

Testing opportunity at SLAC NLCTA for high power RF in strong B field

NLCTA Facility Infrastructure

- Bunker was designed for a 1.066 GeV beam energy with 1.45 kW of beam power
- Multiple high power RF klystrons: 3 X-band, 1 S-band under current Accelerator Safety Envelope (ASE)
- Ti:Sapph laser system for XTA beamline
- Housed in the End Station B building with access to laser room, clean room, and machine shop, as well as experiment staging areas





Test Stand	Klystron	Frequency (GHz)	SLED-II	Pulse length	Typical power
S	S-band 5045	2.856	No	2 μs	7 MW
X0	X-band XL-4	11.424	No	1 μs	15 MW
X2	X-band XL-4	11.424	Yes	200 ns (compressed)	150 MW
X3	X-band XL-4	11.424	Yes	400 ns (compressed)	35 MW

SLAC

High power L-band source (1.3 GHz) available but needs to be resurrected

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E. Nanni, Demonstrator workshop 2024

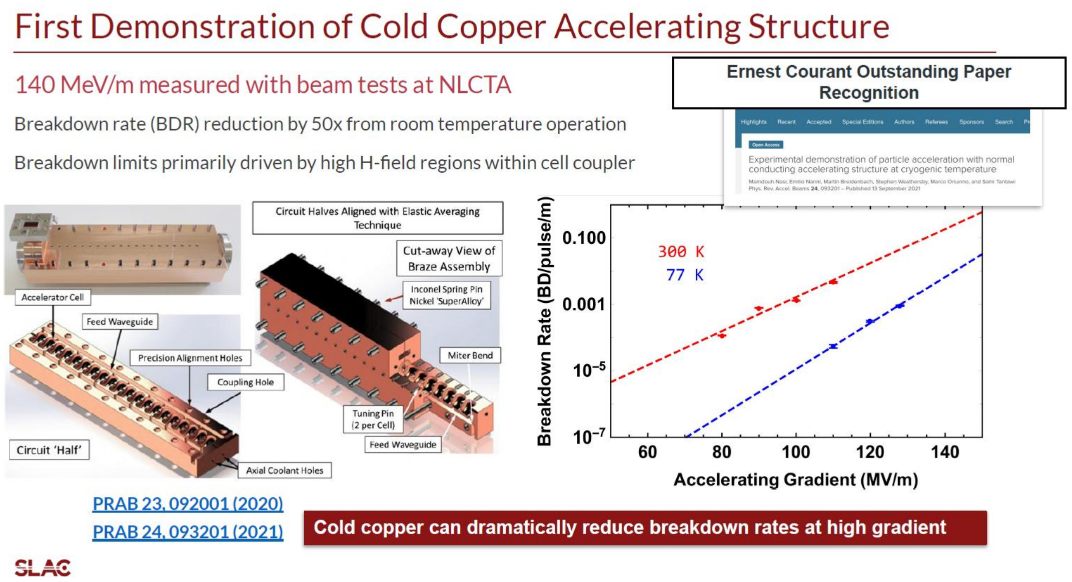
Testing facility with well-equipped infrastructure.

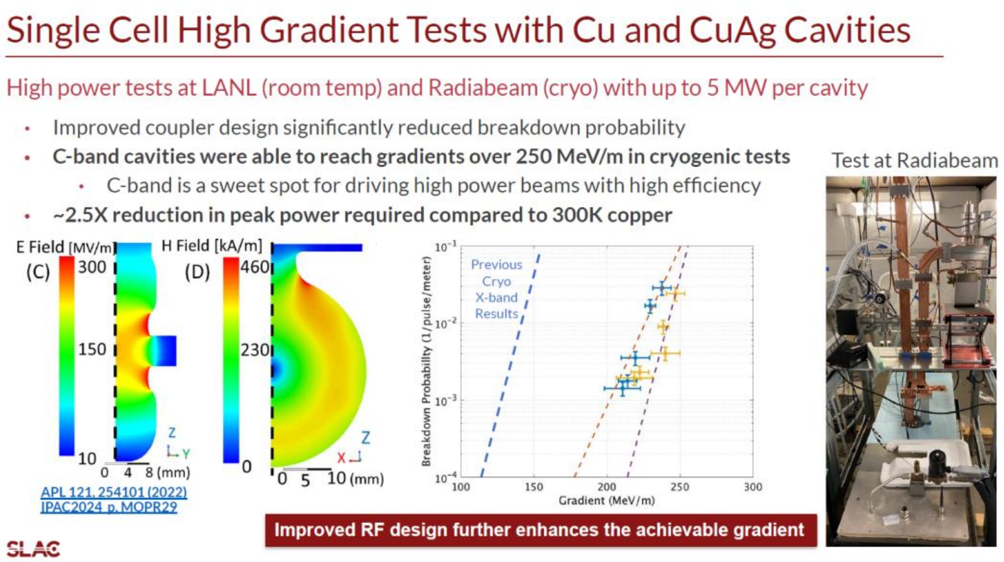
Currently providing 2.8 GHz and 11.4 GHz RF power, 1.3 GHz available but needs resurrecting.

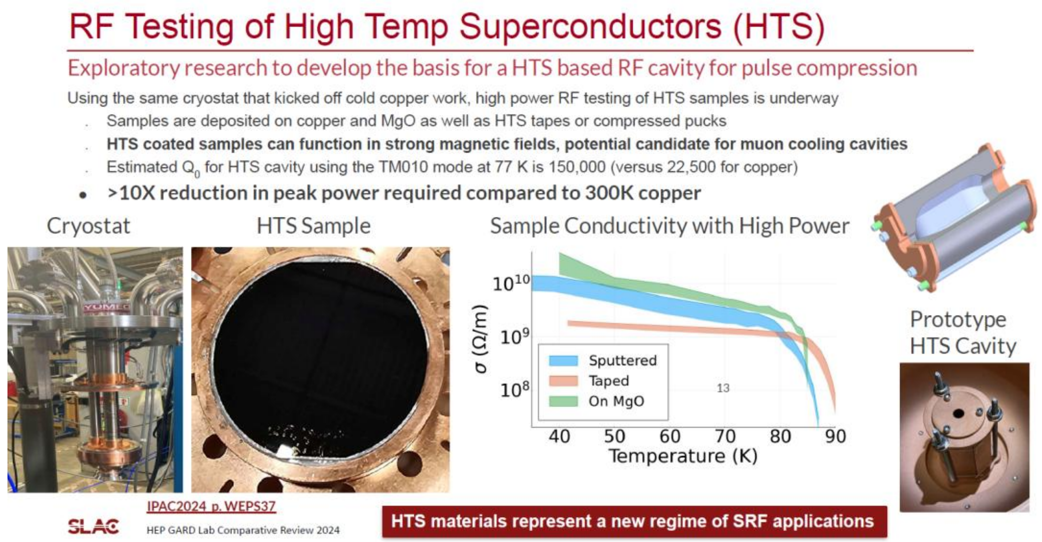
Purchasing a commercial SC solenoid with 5+T on-axis field and bore large enough to house a 1.3/2.8 GHz cavity.

E. Snively, C3 workshop 2025

High gradient and RF breakdown R&D at SLAC







E. Nanni, Demonstrator workshop 2024

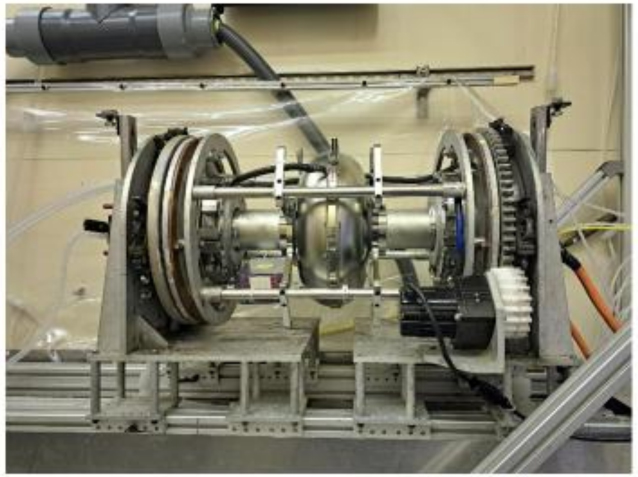
- Cold copper cavity shows significant increase of the achievable gradient than room temperature copper cavity.
- Copper alloy such as CuAg, with proper alloy composition, shows better RF breakdown resilience than copper at both room temperature and cryogenic temperature.
- Can these advantages be extended to lower frequency and high B field regime?
- HTS RF cavity: inherently more compatible with strong B field than nominal SRF cavity, low power RF test shows promising results, high power test undergoing.

High Q high gradient SRF R&D at Fermilab

SRF for muon acceleration: recent result

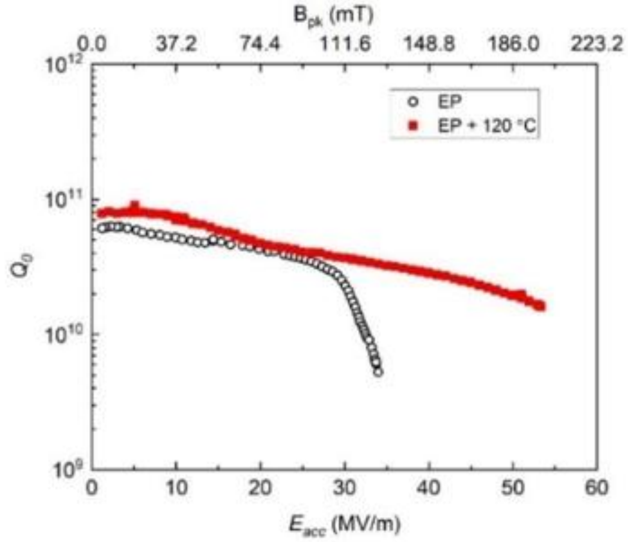
- As part of the R&D on improving SRF cavity Q and accelerating gradient, a single-cell HB650 (PIP-II shape) 650 MHz cavity was subjected to modified EP recipe and low-temperature bake and has reached 53.3 MV/m
- It is the highest performance to date for 650 MHz cavities
- The gradient was reached w/o field emission
- Very promising result for MC acceleration

53.3 MV/m



EP tool with the cavity B9AS-AES-003

Cathode structure used for cavity EP



Q versus E_{acc} curves for B9AS-AES-003 after optimal EP and 120°C bake

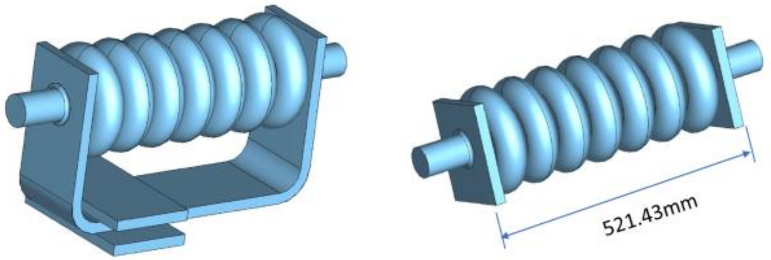
(from V. Chouhan, et al., LINAC'24)

For high gradient: SRF traveling wave cavity development at Fermilab

w/ R. Kostin, F. Furuta et al

Developing a half-meter scale TW cavity to advance TW technologies

- RF design process began with the development of plans for a 0.5~1 meter prototype TW cavity at Fermilab. By applying "lessons-learned" from the 3-cell to a longer TW structure and considering the physical dimensions of existing SRF facilities, a preliminary RF design of a half-meter scale (7-cell) TW cavity was proposed [4]. The inner cells of the 7-cell structure is identical to that of the 3-cell TW cavity.



Preliminary RF design of prototype TW 7-cell cavity by Sergey Kazakov

Objectives

- Conduct proof-of-principle demonstration for new RF configurations (next slide), necessary for scaling up to a full-size (1m) cavity
- Demonstrate 70 MV/m with scalable ancillary systems at cryogenic temperatures. Two separated goals are set as the 1st approaches toward a 7-cell TW cavity (slide #8)

70 MV/m

- TW: bunch always accelerated by a constant field at a fixed RF phase
- SW: bunch seeing a time varying RF field, overall acceleration compromised by the transient time factor.

- TW has lower peak surface E than SW with the same gradient on axis, thus can achieve higher gradient with the same surface peak E limit.

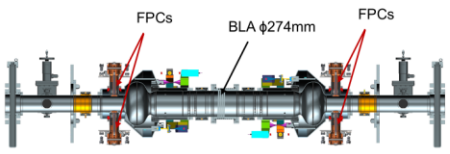
- Proposed for compact linear collider, synergies with MuC acceleration.

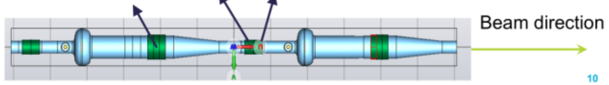
High power HOM damper R&D for EIC

- The high luminosity of EIC requires the RF systems to handle electron beam up to 2.5 A current, or 28 nC/bunch.
- Tight total impedance budget for long-range and short-range wake due to high beam current and bunch charge.
- Cavity string and beamline components especially BLAs need to be able to handle the very high HOM power.
- BLA is designed to minimize self-induced impedance.
- The high power testing has achieved **103 kW or 0.44 W/mm²**.

EIC ESR BLA requirements

- The previous design iteration has one cavity per CM, one ϕ150mm BLA and one ϕ274mm BLA, both are 240 mm long
  - With strong HOM self heating, especially in the ϕ150mm BLA, the heating in the ϕ150mm BLA is 41 kW, and 32 kW in the ϕ274mm BLA.
  - Heat density in the left half of the ϕ150mm BLA reaches 0.39 W/mm², and 0.36 W/mm² for the whole ϕ150mm BLA
- The latest design iteration adopted the 2-cavities CM with one ϕ274mm BLA, 240 mm in length. Total HOM power 57 kW for two cavities, and heat density 0.28 W/mm²





Electron-Ion Collider

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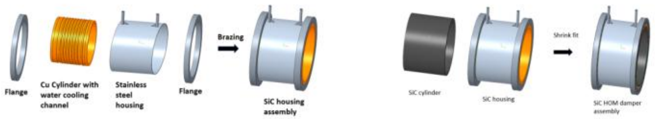
EIC BLA fabrication

- Shrink-fit SiC cylinder BLA design (APS-U style)
  - APS-U designed at 0.2 W/mm²
- An ϕ308mm mm prototype developed at BNL under LDRD program using Coorstek SC-35 with two articles fabricated, one tested, testing of the second BLA still under preparation
- Recently switched to Kyocera SC1000, under fabrication

R154mm BLA fabrication



BLA fabrication procedure

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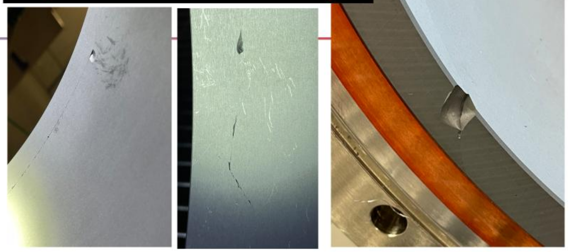
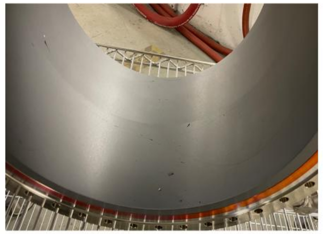
BLA testing results

- Visual inspection after tested to 103 kW or 0.44 W/mm² absorbed without damage found
- Visual inspection found damages after two arcing detected with 150 kW or 0.64 W/mm² absorbed
- The current cryomodule design requires 0.28 W/mm². The cooling will also improve with cooling channels extended to the edges of the BLA

Inspection observation after arcing





Electron-Ion Collider

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J. Guo, TTC2025 Meeting, High Current Cryomodules for Ampere Class Electron Storage Rings

RF cavity design and simulation tools for comprehensive cavity studies: ACE3P by SLAC

ACE3P for Multi-Physics Accelerator Modeling

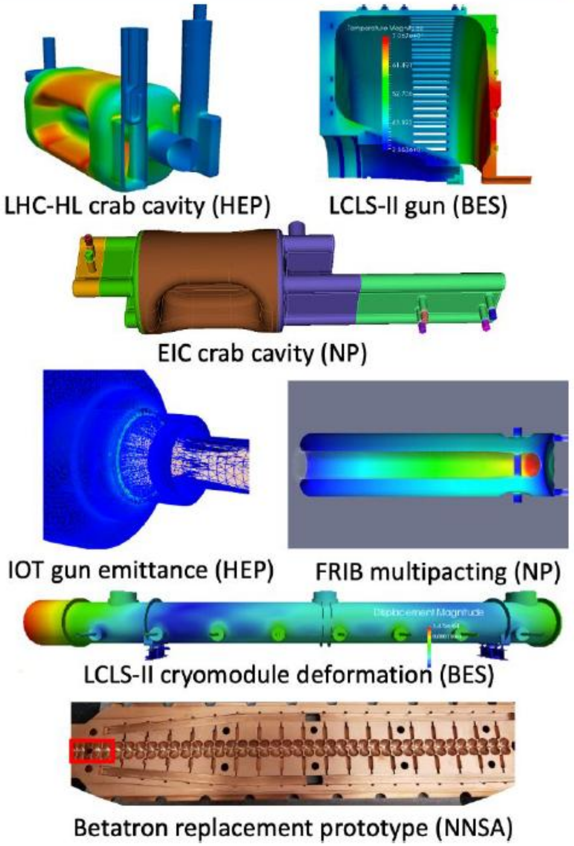
- **ACE3P**, developed at SLAC, is a comprehensive suite of *conformal, high-order, C++/MPI based parallel finite-element (FE) multi-physics codes* including electromagnetic (EM), thermal and mechanical capabilities.
  - Based on *curved high-order finite elements* for high-fidelity modeling
  - Implemented on *massively parallel computers* for increased memory (problem size) and speed

ACE3P (Advanced Computational Electromagnetics 3P)

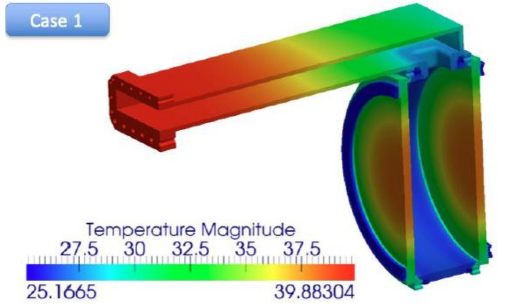
Frequency Domain:	**Omega3P**	**– Eigensolver (damping)**
	S3P	**– S-Parameter**
Time Domain:	**T3P**	**– Wakefields and Transients**
Particle Tracking:	**Track3P**	**– Multipacting and Dark Current**
EM Particle-in-cell:	**Pic3P**	**– RF guns & space charge effects**
Multi-physics:	**TEM3P**	**– EM, Thermal & Mechanical analysis**
Static Particle-in-cell:	**Gun3P**	**– DC guns & space charge effects**

High-fidelity, high-accuracy simulation for virtual prototyping of accelerator components at large scale

SLAC

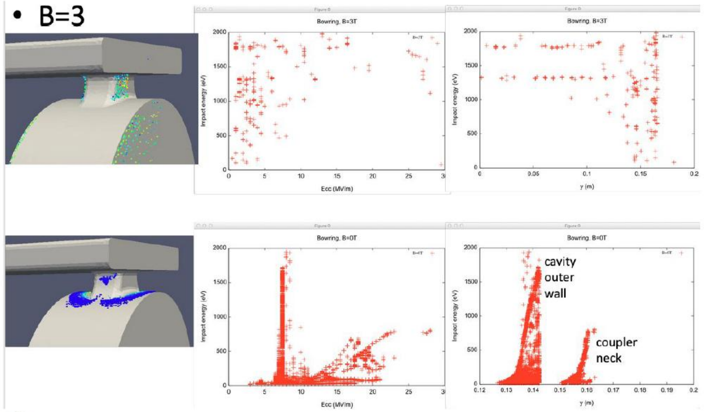


MAP modular cavity



	E_{max}	σ for Beryllium	Duty Factor
Case 1	25 MV/m	2.33e7 S/m	0.001

Thermal and mechanical stress analysis, Z. Li



Multipacting analysis, L. Ge

Outlook

- No dedicated DOE funding for MuC RF yet…
  - Experimental testing and hardware development are critical for both "near term" cooling demonstrator and the eventual MC. They need dedicated resources.
  - New approaches for RF breakdown mitigation have been developed in the last decade. Testing their effectiveness in the MC cooling RF regime can significantly impact the cooling performance and the cost.
- Keep on the modest R&D efforts with indirect resources. Engage more early career scientists.
- Coordinate with IMCC RF studies.
- Coordinate with beam physics, magnets and other subsystems for the cooling demonstrator development.
- Synergies with other US RF works.

Outlook