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# NCRF and SRF R&D needs and priorities for the next 3-5 years

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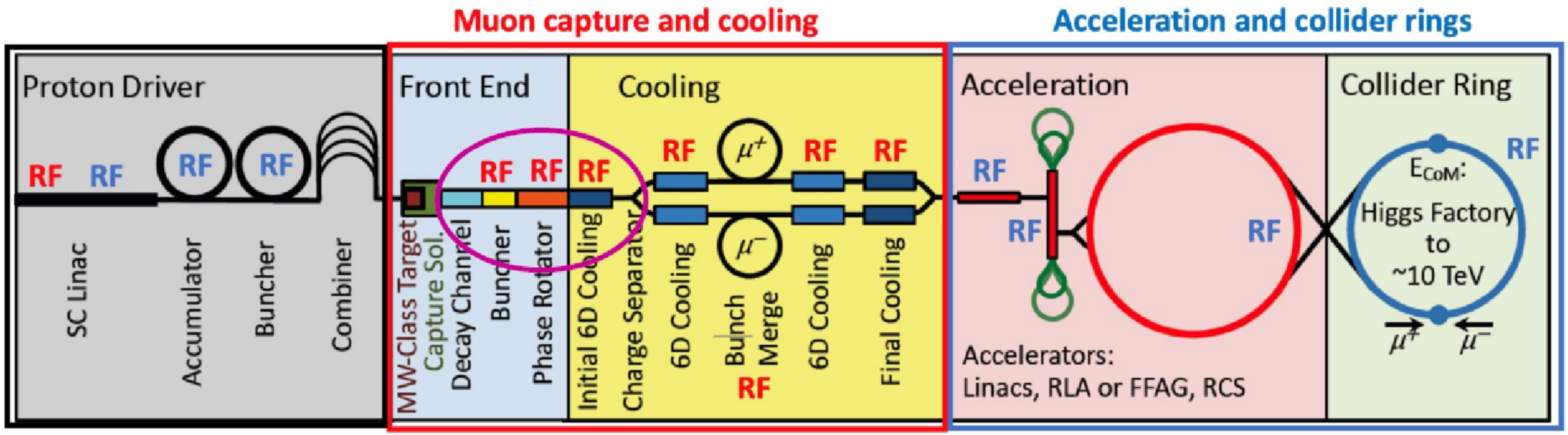
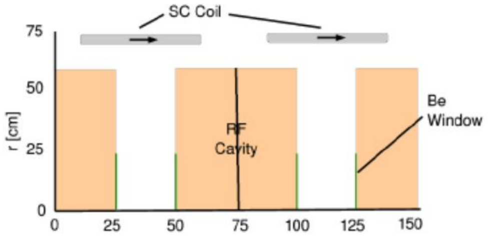
# Muon collider RF system overview



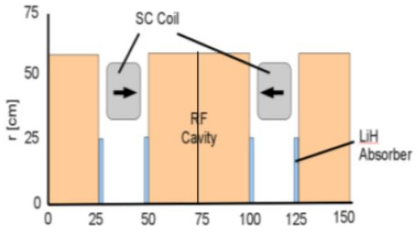

- Complex and prevailing in the Muon collider, from the start of the proton driver to the final collider ring.
- Versatile functions: acceleration, ionization cooling, longitudinal beam manipulation, etc.
- Broad range of operation conditions: NCRF and SRF, frequency from dozens of MHz to a few GHz, gradients up to 30+ MV/m, etc.
- Unique features: strong magnetic field background, enclosed cavity apertures, gas-filled, muon decays, very high bunch intensity etc.

# NCRF cavities in MC: mainly for muon capture and cooling

## Front end



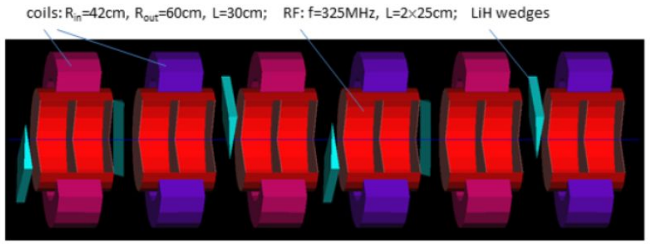

Buncher and rotator




4D initial cooler

Frequency: 499 ~ 325 MHz, gradient: 0 ~ 25 MV/m

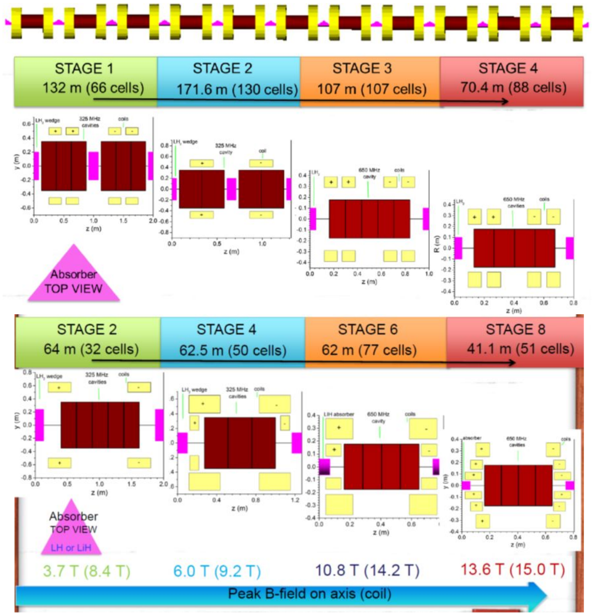
*B* field: 2 T continuous solenoid field in Buncher and Rotator, alternation focusing solenoid field up to 2.8 T on-axis in cooler




Gradient 25 MV/m
Peak $B_z$ on axis up to 4 T
Vacuum or gas-filled

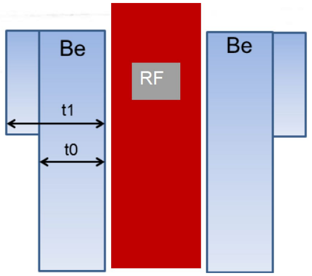
**Alternative: helical FOFO 6D initial cooler**

## Rectilinear 6D cooling



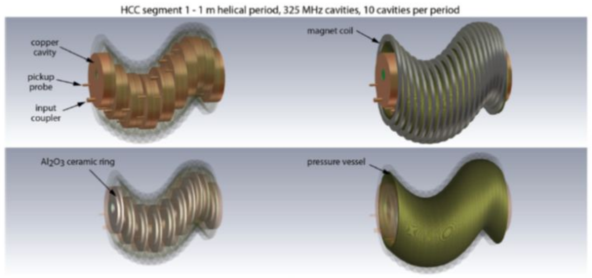

Frequency: 325 and 650MHz
Gradient: ~ 20 to 30 MV/m
Peak $B_z$ on axis: ~ 2 to 13 T

Stepped Be window




For first 4 stages,
t0: from 0.3mm to 0.125mm

## Helical Cooling Channel for 6D cooling



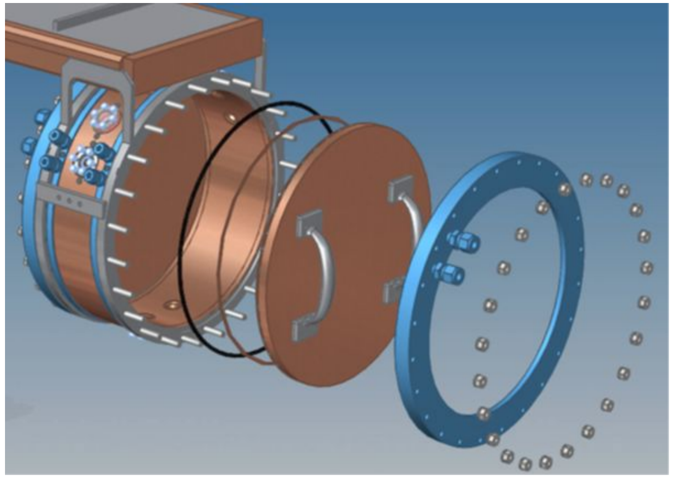

Peak RF gradient in the gas-filled RF cavities is 20 MV/m. Hydrogen gas pressure is 160 atm at room temperature. 30 um-thick Be RF windows are located at both ends of the RF cavity.

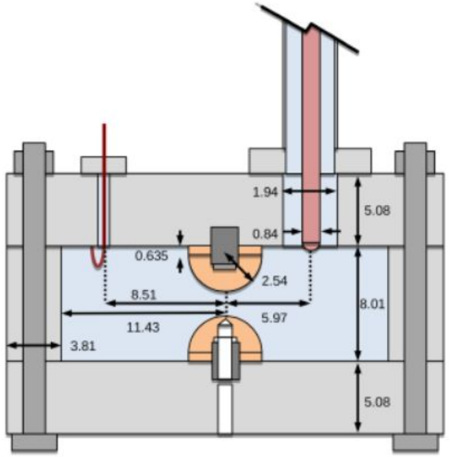
# Challenges for MC NCRF cavities

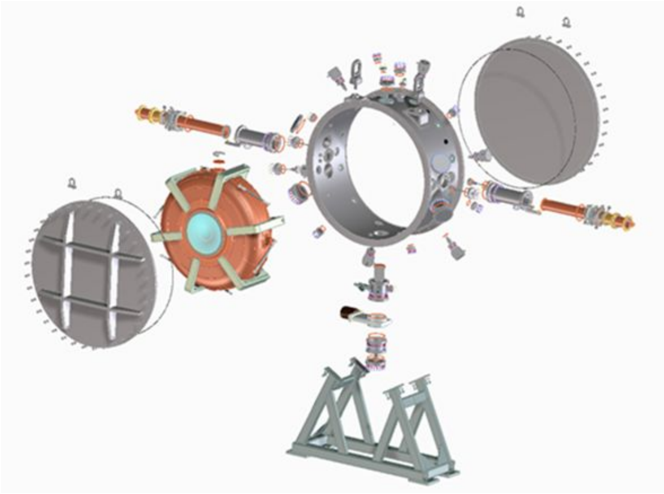
- High acceleration gradient $E_{acc}$ in multi-Tesla *B* field.
- Compact integration with other subsystems in the cooling channel such as SC solenoid, absorber, cryogenics, etc.
- High peak power, short pulse length RF power source.
- Large variety of cavity parameters: gradient, frequency, surrounding *B* field, beam window thickness, etc.

# Current state-of-art

- Considerable cavity R&Ds have been carried out in MAP and pre-MAP era to understand the RF breakdown in strong *B* field and how to mitigate it.
- For the field gradient demonstration: a 805 MHz MAP vacuum modular cavity and a 805 MHz high pressure hydrogen-filled cavity have achieved ~50 MV/m in a 3 T *B* field.
- For the engineering/production demonstration: the MICE 201 MHz cavity is a fully operational single cell cavity that has achieved the design gradient (~11 MV/m) in a ~0.2 T *B* field.
- Experience has been learnt on how to achieve high gradient and how to make such cavities, which should be applied to future cavities.





# Key R&D priorities for the next 3-5 years

***Task 1: design and build a RF cavity for the 1.5 cooling cell demonstrator.***

- Based on our current knowledge, a room temperature vacuum copper cavity with thin Be beam windows are the most readied path to achieve 25 MV/m in multi-Tesla *B* field and be fully operational, within ~5 year time frame.
- Apply the best cavity RF design and production practices we've learned to maximize the chance to achieve > 25 MV/m.
- Apply the demonstrated engineering design features to make a fully operational cavity.
- Work on the integration with other subsystems, which will affect rf power coupling, rf tuning, vacuum, cooling, etc.
- The cavity module can be either one-cell or multi-cell.

## *Task 2: Vacuum RF cavity breakdown in strong B field study*

- Look for solutions to significantly increase the breakdown threshold.
  - This is particularly important for the cavities in the later cooling stage, when beam windows become extremely thin and hard to implement.
  - Higher surface peak field threshold enables more flexibility in cavity geometry design, thus to maintain a high acceleration efficiency (shunt impedance) without the beam windows.
- Explore other cavity body materials: aluminum, Cu alloy (for example CuAg), Be-coated copper, etc.
- Explore beam window materials alternative to Be.
- Explore the cryogenic copper.
- Study the effect of pulse length, will a short pulse length reduce the breakdown?
- Analysis, multi-physics simulation, test planning.

- RF Testing opportunities:
  - The testing facility should have: high power RF, strong *B* field, comprehensive diagnostics to measure and characterize breakdown.
  - A dedicated testing facility:
    - Possibly re-use ILC positron source testing stand at SLAC. L-band (1.3 GHz) LINAC in a 0.5 T solenoid.
    - IMCC testing facility
  - Adding strong *B* field (SC or pulsed NC magnets) to existing RF cavity testing facilities:
    - Save cost and time, but the testing parameters might not be in the range for MC cooling, need careful experiment design and results interpretation/extrapolation.
    - Synergies with NCRF high gradient RF breakdown study for linear collider. (SLAC, LANL, etc.)
    - Synergies with cryogenic copper cavity development. (SLAC, UCLA, LANL, Radiabeam, etc.)
    - Synergies with RF electron source development, testing on an e-gun with a replaceable cathode. (AWA@ANL, etc.)

## *Task 3: Hydrogen gas filled RF cavity*

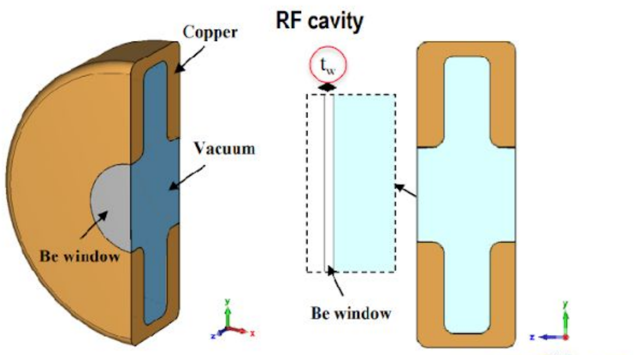
- Analysis and simulation on the plasma processes.
- Advance the engineering concepts towards an operational cavity. Evaluate the high-pressure safety.

## *Task 4: Dielectric-loaded RF cavity*

- Revisit?

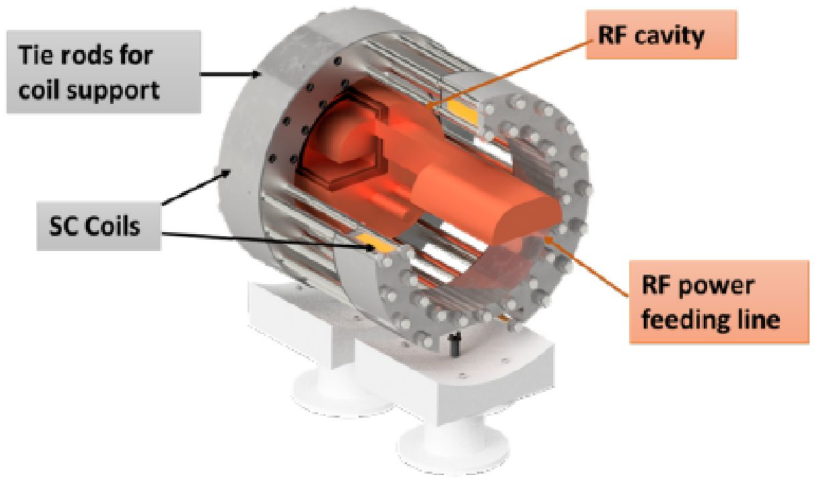
# R&D plan for the NCRF for cooling in the IMCC interim report

- **High gradient in strong *B* field breakdown study:**
  - Simulation to study the local thermal dilatation and its potential effect on the breakdown.
  - Test stand, two possible locations:
    - 3 GHz Radio-Frequency cavity in a Magnetic Field Test Facility (RFMTF) at INFN-LASA
    - 704 MHz test stand at CEA.




Conceptual 704 MHz cavity design (Barbagallo, Grudiev)

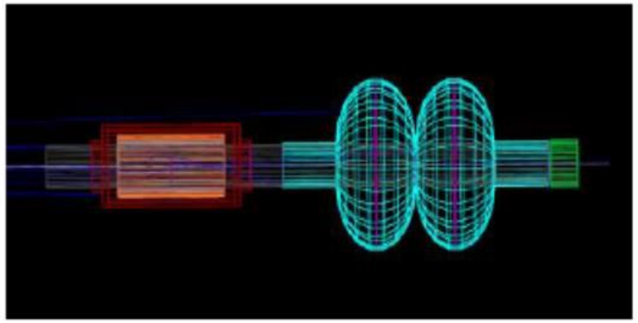
- **RF Cavity design:**
  - After determining the parameters of the cavity to be used in the demonstrator, carry out the advanced engineering design including 3D RF design, thermal-mechanical simulation, integration with SC solenoids.
  - Beam loading in the cavities and its mitigation.
- The construction of the prototype cavity and its testing at high gradients in strong *B* field are not covered by the current plan.




Sketch of the RFMFTA with a 3GHz cavity (Mauro, Giove)

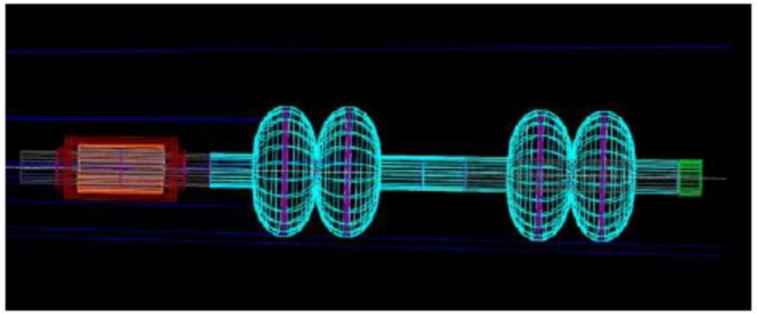
# SRF cavities for muon acceleration: Examples

## Low energy acceleration: SRF linac (0.255 – 1.25 GeV)



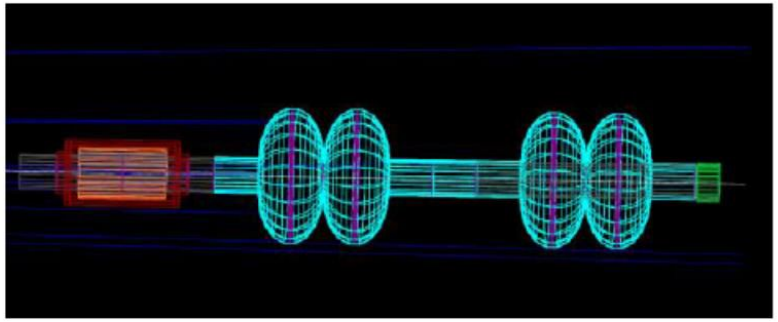
22 short cryos
(2.5 meter, 2-cell cavity)

20 MV/m, 325 MHz



30 medium cryos
(3.5 meter 4-cell cavity)

## Dog-bone RLA1 (1.25 – 5 GeV)



4 meter 90 deg. FODO cells
25 MV/m, 650 MHz, 2 × 4-cell cavity

## Dog-bone RLA2 (5 – 63 GeV)

## High energy acceleration in RCS’s

38 MV/m, 1300 MHz

35/MV/m, 1300 MHz

(ILC baseline is 31.5 MV/m)

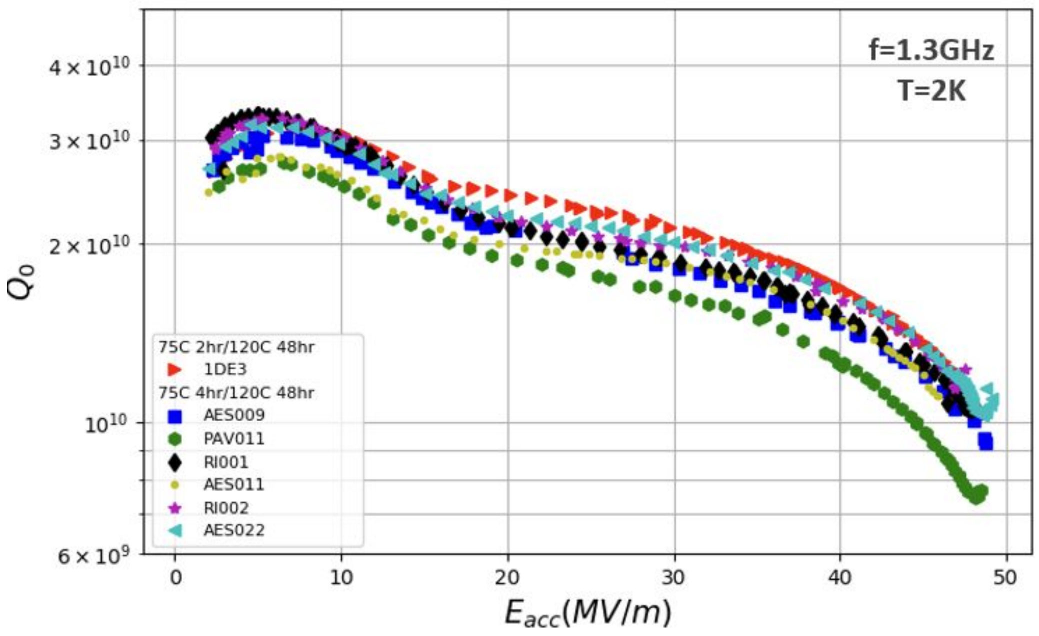
# Challenges for SRF

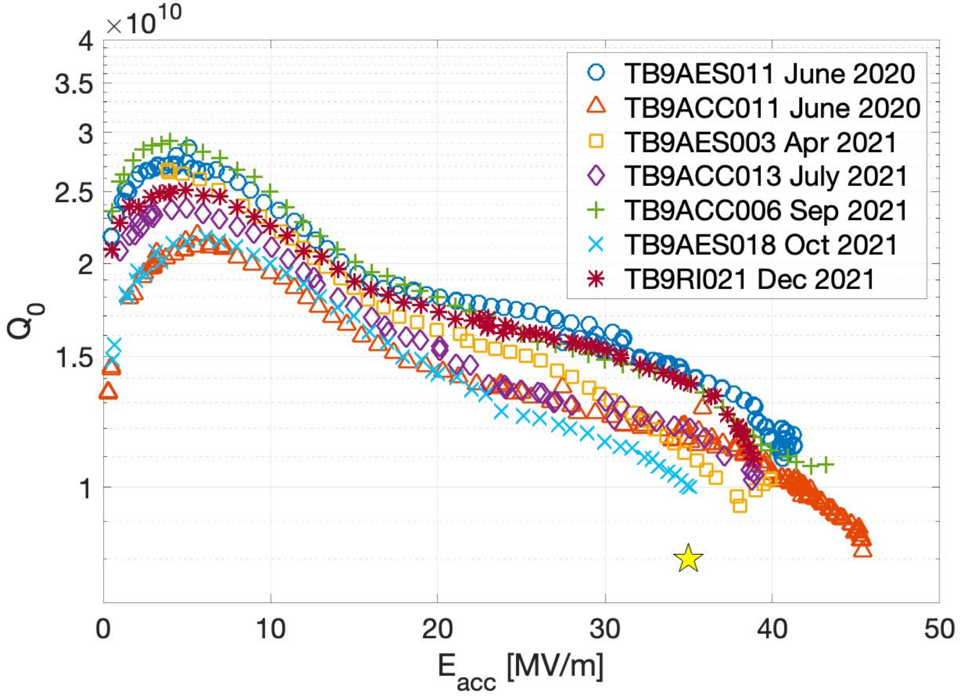
- Very high bunch intensity, $\sim 2\times10^{12}$ and possibly higher – favors lower frequencies
- Small aperture of 1300 MHz cavities – may require going to larger aperture and/or lower frequency. 800 MHz is a possible alternative frequency – synergy with FCC-ee SRF (booster and collider at ttbar energy)
- Demonstration high accelerating gradients in 800 MHz and 650 MHz muti-cell cavities – synergy with GARD program, FCC-ee, ACE at FNAL
- Achieving 20 MV/m at low frequency (Nb/Cu cavities at 325 MHz) – synergy with R&D for FCC-ee 400 MHz cavities
- Proximity to high-field magnets – developing good magnetic shielding and/or using alternative superconductors
- Muon decays – high radiation environment

# Recent achievements: 1300 MHz

- A combination of cold electropolishing (EP) and 2-step low-temperature baking allows reaching ~50 MV/m (confirmed by other labs)
- The recipe is transferred to 9-cell cavities (as part of ILC Cost Reduction effort and R&D toward 8-GeV SRF linac at Fermilab): average 40.4 MV/m!

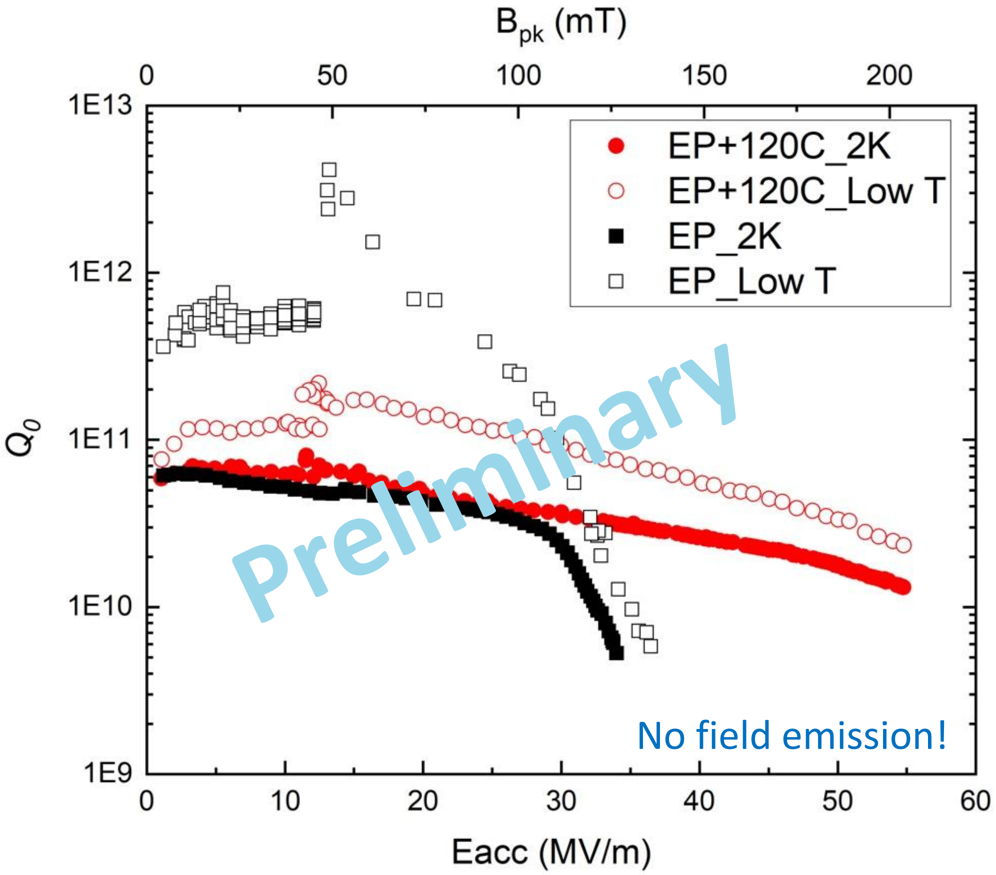
2-step low-temperature baking

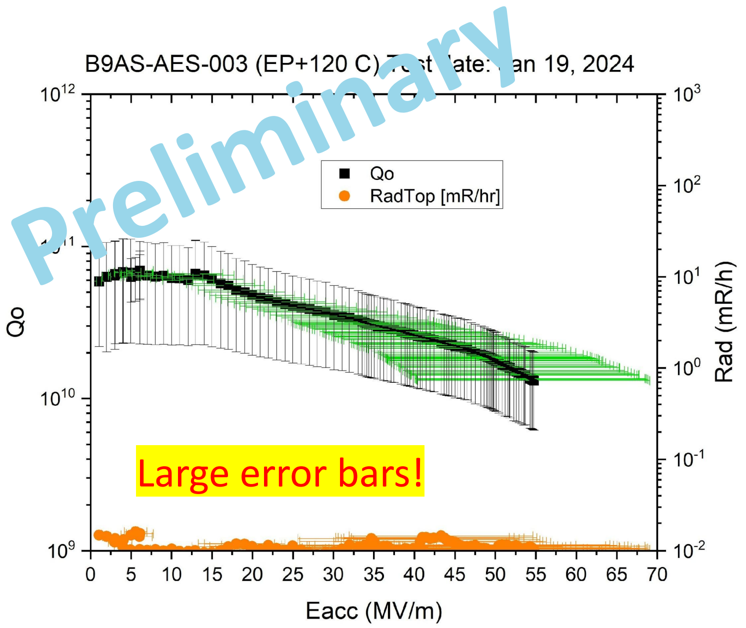


# Recent achievements: 650 MHz

- Single-cell HB650 (PIP-II shape) 650 MHz cavity has reached 54.8 MV/m (preliminary result) after modified EP recipe and low-temperature bake
- Very promising result, but very large error bars. The cavity will be re-tested with improved setup to reduce error bars



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# Key R&D priorities for the next 3-5 years. Task 1: SRF for RCS's

- Studies of beam interaction with SRF cavities at 1300 and 800 MHz, including acceleration, longitudinal beam dynamics, wakefields, bunch length, and energy spread control. Select RF frequency.
- Design SRF cavity at selected frequency, fabricate prototypes.
- Develop cavity treatment recipe for high gradient operation (~35 MV/m). Q factor is secondary but also very important to reduce the power consumption at high gradients. (The duty factor of the RCS is about 0.01). Demonstrate cavity performance in vertical cryostat testing.
- Design ancillary components and a cryomodule. Procure and test prototypes.
- Build a single-cavity cryomodule, demonstrate cavity performance, study possible effects of radiation and beam loss on the SRF cavity performance (how? where?).
- Build a prototype cryomodule and demonstrate the cryomodule performance.

# Key R&D priorities. Task 2: SRF for injector and RLA's

- Simulation studies similar to Task 1, but for 325 / 650 MHz. Simulate stray magnetic fields from focusing magnets located near the cavities.
- Design 650 MHz SRF cavity, fabricate prototypes – synergy with GARD program and PIP-II / ACE
- Develop cavity treatment recipe for high gradient and low sensitivity to residual magnetic field. Demonstrate the cavity performance in vertical testing.
- 325 MHz R&D (Nb/Cu) in close collaboration with CERN to demonstrate >20 MV/m
- Design ancillary components and a cryomodule. Design magnetic shielding. Procure and test prototypes.
- Build a single-cavity cryomodule, demonstrate cavity performance, study effects of stray magnetic field on the SRF cavity performance (where?).
- Build a prototype cryomodule and demonstrate the cryomodule performance.

# Key R&D priorities. Task 3: Alternative superconductors

- If an alternative superconductor (e.g., $Nb_3Sn$) R&D will demonstrate practicability of the material, evaluate its application to MuC SRF systems – synergies with GARD funded R&D, QIS SRF cavity R&D, development of industrial SRF accelerators, US-Japan collaboration, R&D in Europe.
- Potential advantages of such material: higher gradient, higher operating temperature (= better cryogenic efficiency), higher tolerance to residual magnetic field.



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# R&D plan for SRF

- Studies of beam interaction with SRF cavities at different frequencies, including acceleration, longitudinal beam dynamics, wakefields, bunch length, and energy spread control. Select RF frequencies for different accelerators.
- Using synergies with other programs, develop SRF cavity concept designs, select one or two most challenging to fabricate prototypes.
- Develop cavity treatment recipe for high gradient and low sensitivity to residual magnetic field. Demonstrate the cavity performance in vertical testing. Utilize synergies as much as possible.
- Potentially initiate collaboration with CERN on Nb/Cu low-frequency SRF.
- If there is a breakthrough in developing alternative superconductors for SRF, initiate R&D to achieve specific muon collider goals.