NCRF vacuum cavities for the ionization cooling at the Muon Collider

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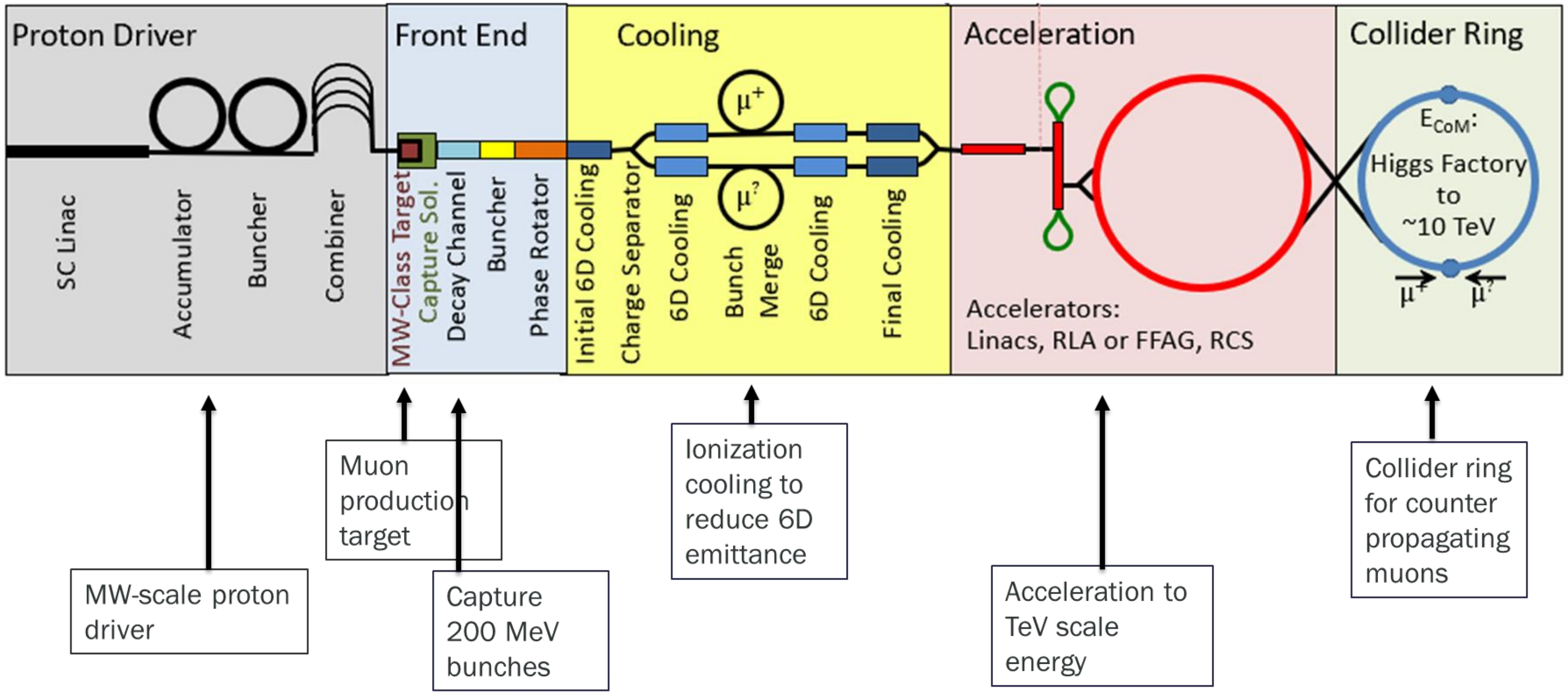
GARD RF Roadmap Update – NCRF

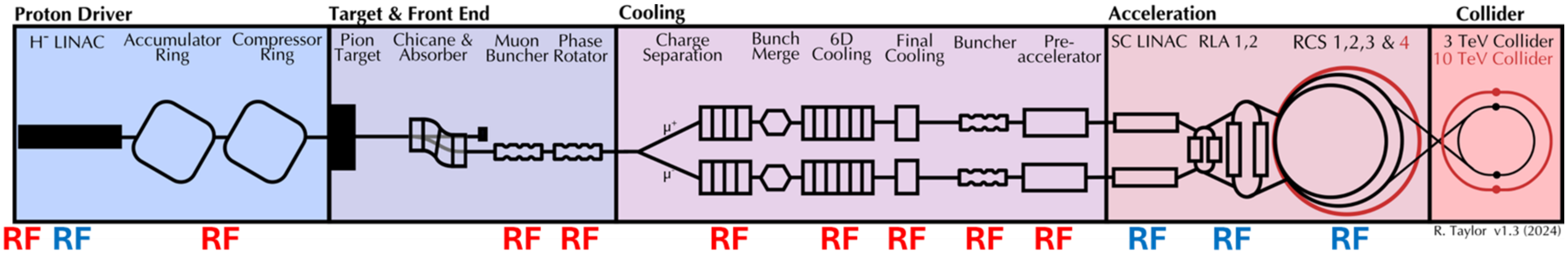
Jan 20th, 2026

Muon Collider is a promising yet challenging path to a 10-TeV HEP collider

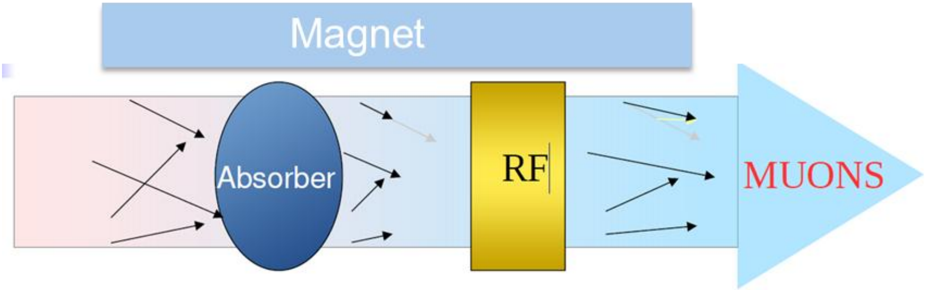
- Muon: a lepton ~ 200 times heavier than electron, with a lifetime in lab frame ~ 2.2 us.
- Advantages of a muon collider (from accelerator perspective):
  - Much less synchrotron radiation than electron:
    - Enabling a ring collider with a compact size.
    - Much smaller beamstrahlung effect at the IP.
  - An elementary particle compared with proton:
    - Requiring ~10 times less energy than hh collider to study the same physics.
- Challenges of a muon collider (from accelerator perspective):
  - Non-trivial to generate high-flux, low emittance muon beams.
  - Racing with muon’s short lifetime by time dilation, accelerating to high energy as fast as possible.
  - Radiation energy and secondary particles from the muon decay.

The current baseline MuC design based on a proton driver

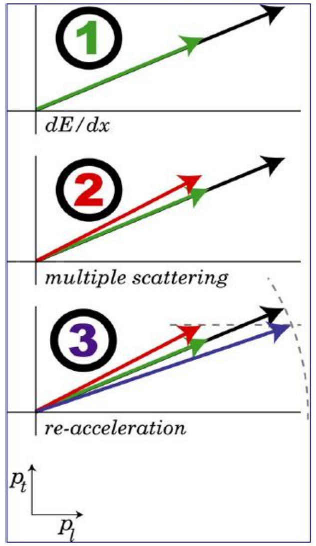




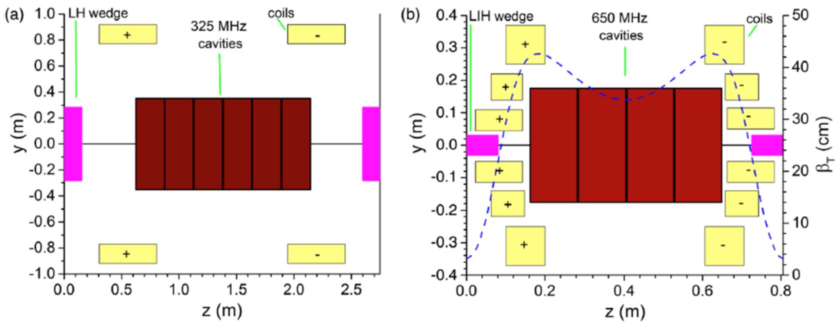
Ionization Cooling to fast reduce the muon beam 6D emittance

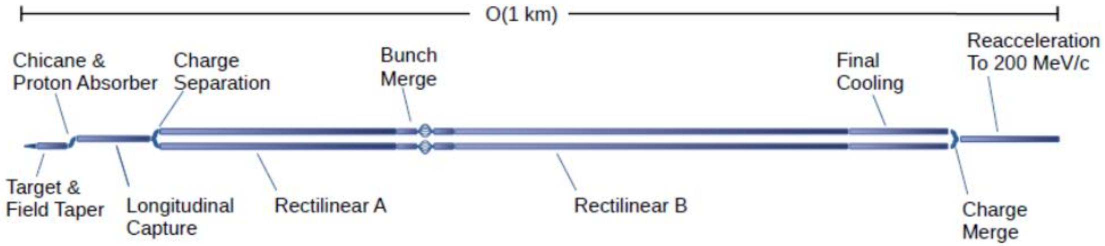


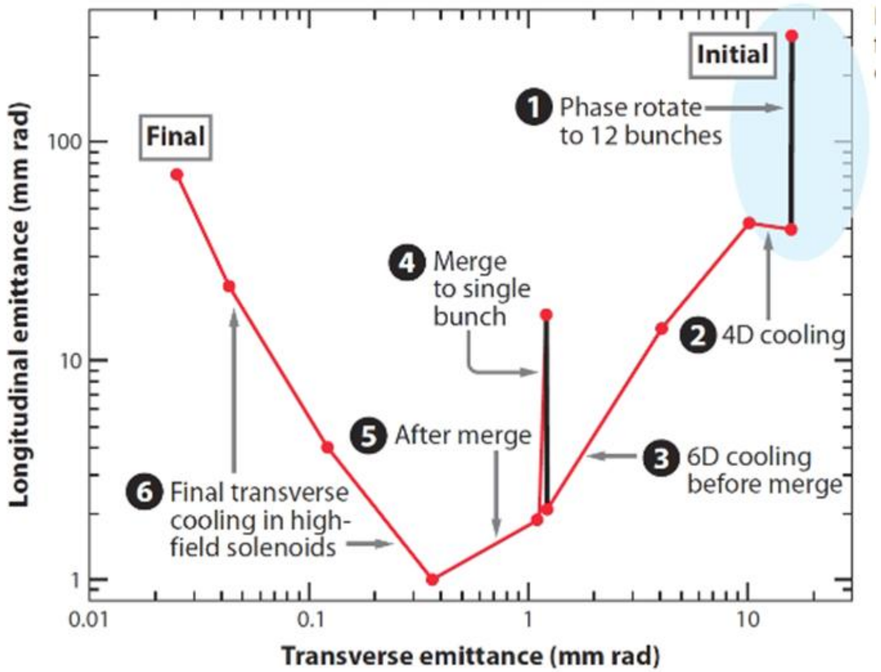
The initial muons, made by the decay of pions from a target in a proton beam, have very large longitudinal and transverse emittances. They must be cooled using ionization cooling — the only method fast enough — by approximately a factor of 1000 in each of the two transverse phase spaces, and by about 10 in the longitudinal.



$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (13.6\, MeV/c)^2}{2\beta^3 E_\mu m_\mu X_0},$$







The NCRF cavity in the ionization cooling channel

- In the ionization cooling channel, the NCRF cavities provide:
  - Acceleration to replenish the energy loss in the absorber.
  - Longitudinal focusing.
- Frequency: mostly ~200 MHz to 800 MHz, to accommodate the evolving bunch lengths.
- High gradient: ~ 25 MV/m or above. Higher gradient is preferred for the beam cooling, beam focusing, beam loading compensation, etc.
- High peak power (~MW), short pulse length, and low rep rate (~Hz).
- Tightly packed with surrounding SC solenoids and absorbers.

TABLE I. Main parameters for the cooling cells in each stage. A and B denote the premerge and postmerge section, respectively. Liquid hydrogen is used as the wedge absorber material for all stages.

Stage	Cell length (m)	Stage length (m)	Pipe radius (cm)	Maximumon-axis B_z (T)	Integrated B_y (T · m)	Transverse beta (cm)	Dispersion (mm)	On-axis wedge length (cm)	Wedge apex angle (deg)	rf frequency (MHz)	Number of rf cells	rf cell length (cm)	Maximum rf gradient (MV/m)	rf phase (deg)
A1	1.8	104.4	28	2.5	0.102	70	−60	14.5	45	352	6	19	27.4	18.5
A2	1.2	106.8	16	3.7	0.147	45	−57	10.5	60	352	4	19	26.4	23.2
A3	0.8	64.8	10	5.7	0.154	30	−40	15	100	704	5	9.5	31.5	23.7
A4	0.7	86.8	8	7.2	0.186	23	−30	6.5	70	704	4	9.5	31.7	25.7
B1	2.3	50.6	23	3.1	0.106	35	−51.8	37	110	352	6	25	21.2	29.9
B2	1.8	66.6	19	3.9	0.138	30	−52.4	28	120	352	5	22	21.7	27.2
B3	1.4	84	12.5	5.1	0.144	20	−40.6	24	115	352	4	19	24.9	29.8
B4	1.2	66	9.5	6.6	0.163	15	−35.1	20	110	352	3	22	24.3	31.3
B5	0.8	44	6	9.1	0.116	10	−17.7	12.5	120	704	5	9.5	22.5	24.3
B6	0.7	38.5	4.5	11.5	0.0868	6	−10.6	11	130	704	4	9.5	28	22.1
B7	0.7	28	3.75	13	0.0882	5	−9.8	10	130	704	4	9.5	28.5	18.4
B8	0.65	46.15	2.85	15.8	0.0726	3.8	−7.0	7	140	704	4	9.5	27.1	14.5
B9	0.65	33.8	2.3	16.6	0.0694	3	−6.1	7.5	140	704	4	9.5	29.7	11.9
B10	0.63	29.61	2	17.2	0.0691	2.7	−5.7	6.8	140	704	4	9.5	24.9	12.2

Zhu et al. Phys. Rev. Accel. Beams 28, 041003

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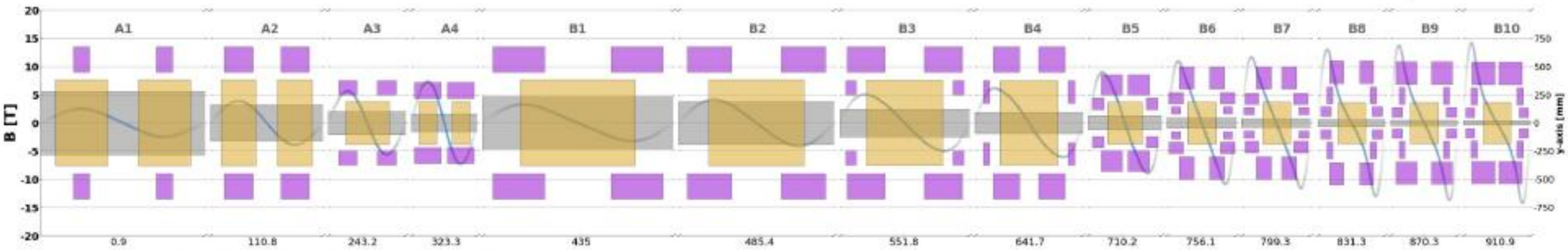
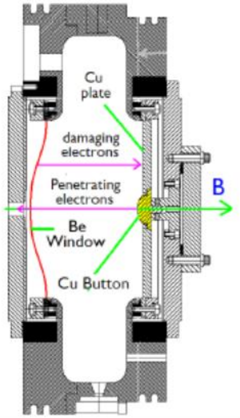


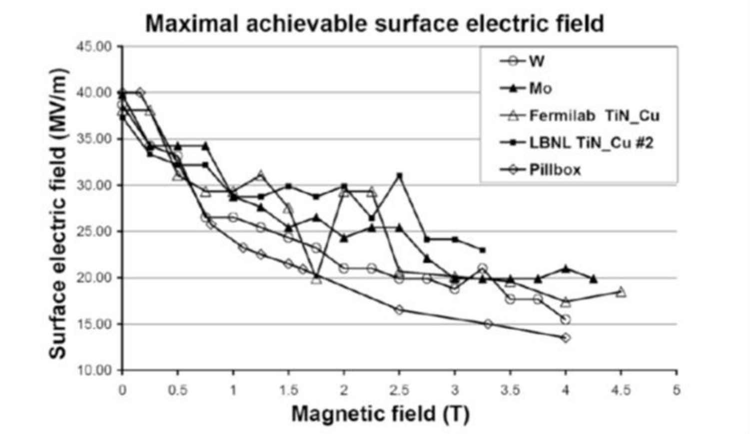
S. Fabbri et al, IMCC Annual Meeting, 2025

Past experiments have shown the achievable cavity gradient is severely compromised by the surrounding SC magnetic field

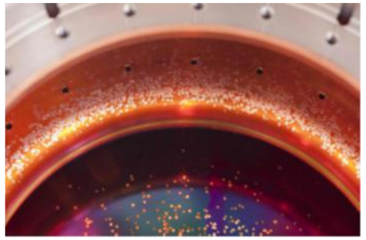
- Kilpatrick criterion: an empirical rule of thumb to estimate the NCRF copper cavity surface field limit: $f = 1.64 \times E^2 \times e^{-8.5/E}$ MHz, where *E* is the gradient limit in MV/m.
- Thanks to the better vacuum and surface cleaning, nowadays we can comfortably expect a 2*Kilpatrick limit.
- For MuC cooling cavity, 325 MHz corresponds to a E limit of 36 MV/m, and 650 MHz of 48 MV/m, both sufficient for the cooling design.
- However, it turned out the presence of the DC magnetic field strongly affects the NCRF performance and reduces the achievable cavity surface field to below the required values.

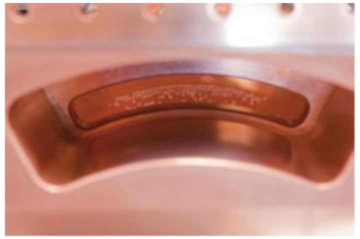
RF testing at Fermilab MTA on an 805 MHz cavity with exchangeable buttons





The achievable gradient is dropped to below 20 MV/m at 4T.



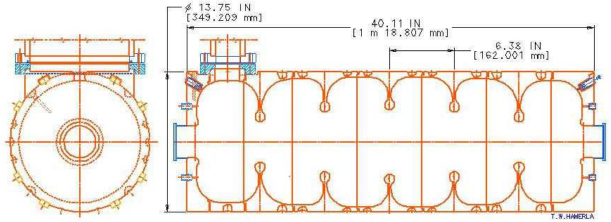


Cipper button after 28 MV/m & 3 T

Typical surface damage associated with RF breakdown is observed at cavity iris and intruded button where E field is high.

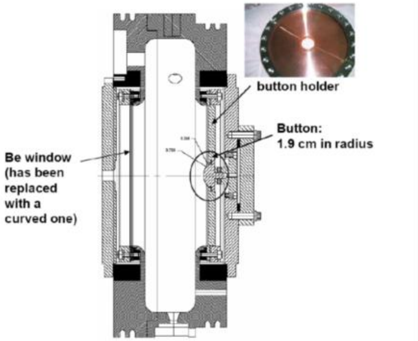
Many R&D works on understanding the gradient limit due to the external B field and developing the mitigation methods to achieve the required gradient

805 MHz iris loaded cavity



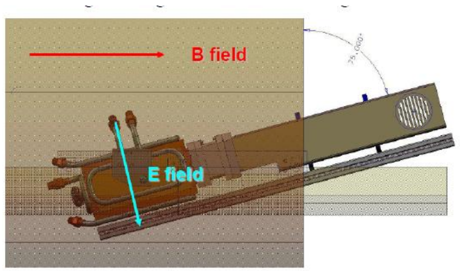
First cavity tested in B field. Achieved over 40 MV/m, beam window severely damaged by emitted electron and vacuum lost.

805 MHz Cavity Button test



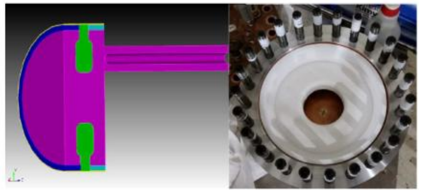
To find materials and coatings that can withstand high surface electric field in strong magnetic field.

805 MHz Box cavity



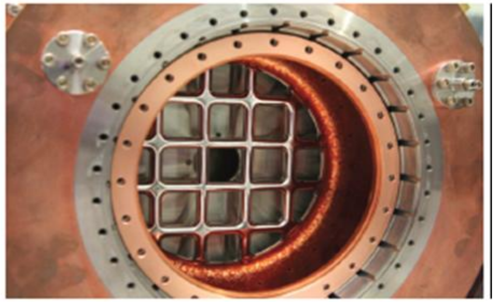
To study the breakdown mechanism with adjustable angle between E, B field directions

805 MHz cavity with alumina insert



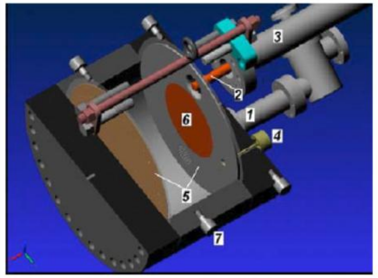
Shrink the diameter of the gas-loaded cavity

805 MHz Cavity with grid windows



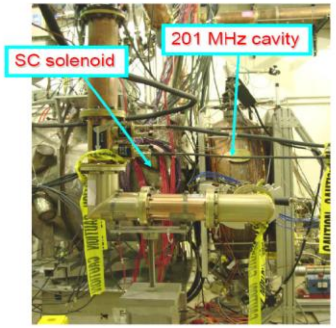
Alternative to the fully covered thin-film beam windows

805 MHz all-season cavity

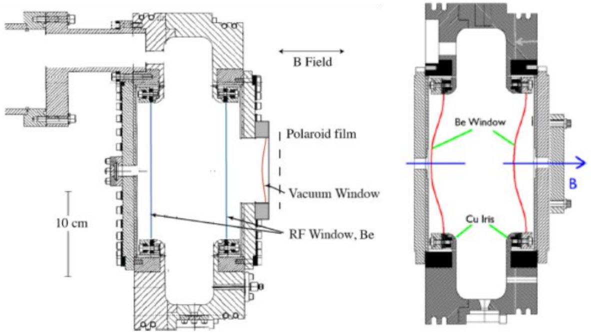


A versatile cavity for both vacuum and high-pressure test.

201 MHz prototype cavity

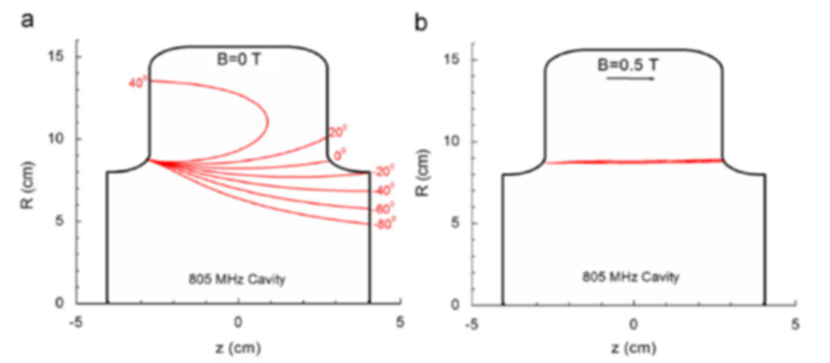


805 MHz LBL cavity with demountable windows



One proposed mechanism for the B field induced RF breakdown: a thermal-mechanical beamlet model

- The emitted electrons are focused by the external B field, thus concentratedly bombard on a small spot on the cavity metal surface.
- The focused electrons deposit energy in the metal, causing enhanced local heating.
- Heating -> melting, thermal cycle fatigue, surface damage -> new emission spots -> RF breakdown.



D. Stratakis et al., "Effects of external magnetic fields on the operation of high-gradient accelerating structures"
R. B. Palmer et al., "RF breakdown with external magnetic fields in 201 and 805 MHz cavities"

The deposit power per unit volume in the cavity wall:

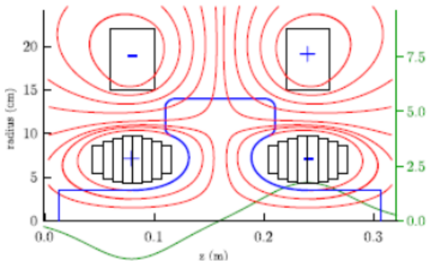
$$W = \frac{I}{q(\pi R_f^{\,2})}\frac{dE}{dz} \propto \frac{B^2}{q(\pi I^{2j-1})}\frac{dE}{dz}$$

- Stronger B field -> smaller beamlet radius -> larger W
- Smaller stopping power dE/dz -> smaller W

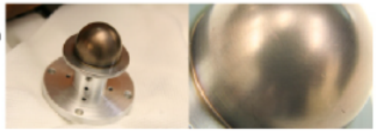
From the thermal conduction equation, the temperature rise can be calculated as:

$$\Delta T = \frac{\alpha_d}{K_{th}} \int_0^{\tau_{add}} \int_0^{D} \int_0^{R_f} G_{Rz} W(R',z',t') 2\pi R' \, dR' \, dz' \, dt'$$

, where α_d is thermal diffusivity and K_{th} the thermal conductivity



Beryllium button after 33 MV/m & 3 T



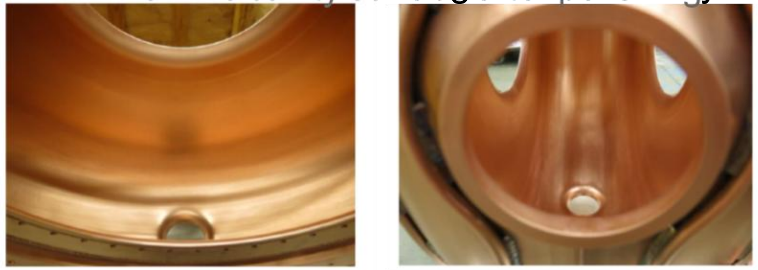
Possible mitigations:

- Design the cooling lattice that has no strong B field around high E region.
- Smooth surface to suppress field emission.
- Alternative materials: smaller stopping power, larger thermal conductivity, stronger mechanical hardness, etc.

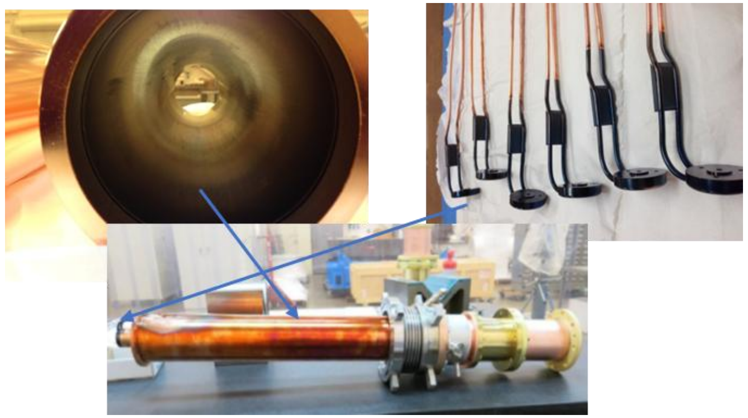
MICE/MAP cavities have implemented effective approaches to mitigate the B field induced RF breakdown

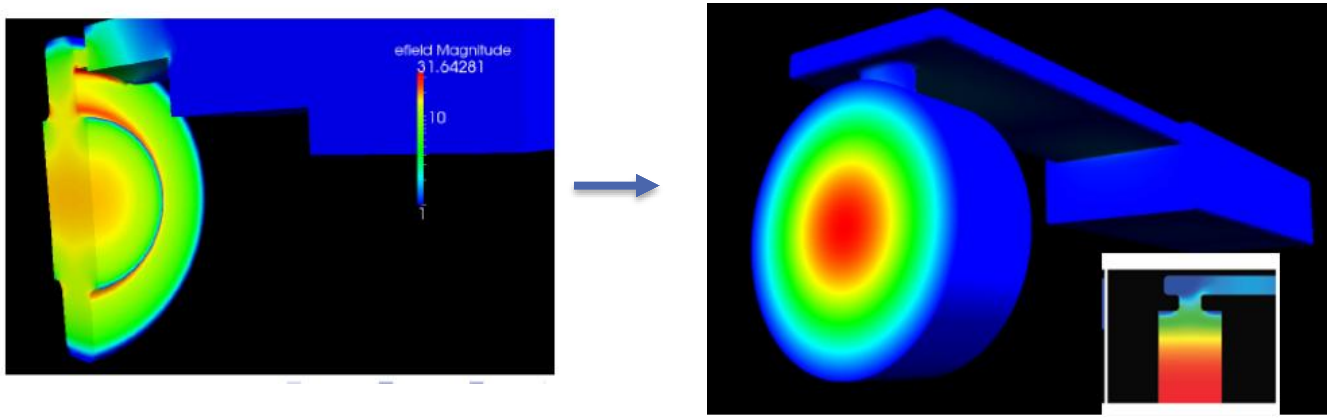
- Reduce the cavity surface field emission in the first place:
  - In RF design, avoid the high surface E_peak, especially where it doesn't contribute to the acceleration.
  - Apply surface treatments to make the cavity surface as clean and smooth as possible: hand polishing, electro-polishing, bright-dipping, dry-ice cleaning, etc.
- Suppress multipacting:
  - Cavity geometry design to avoid MP, especially at the normal operating power level
  - Ti-N coating the MP sensitive area.
- Replace copper by other materials of smaller dE/dz:
  - Thin Be beam window in MICE cavity
  - Be wall in MAP modular cavity.

Mirro-like surface finishing in MICE cavity



TiN coating of coaxial power coupler in MICE cavity

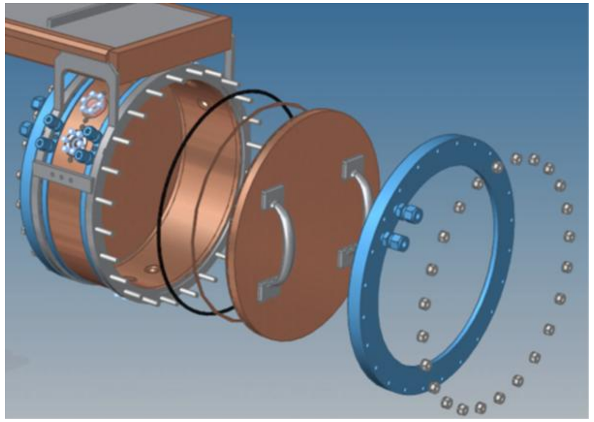


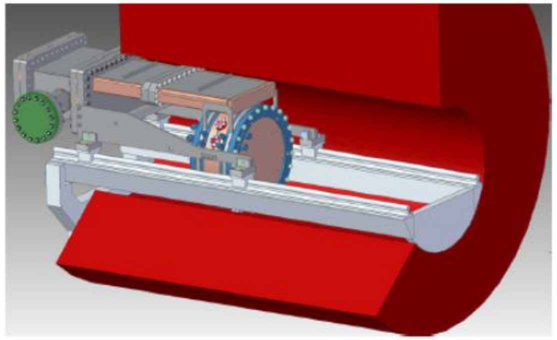


In 805 MHz cavity, moving the RF power coupling slot from flat side wall to radial side wall to significantly reduce the local surface E field, thus suppress the RF breakdown at the coupling slot.

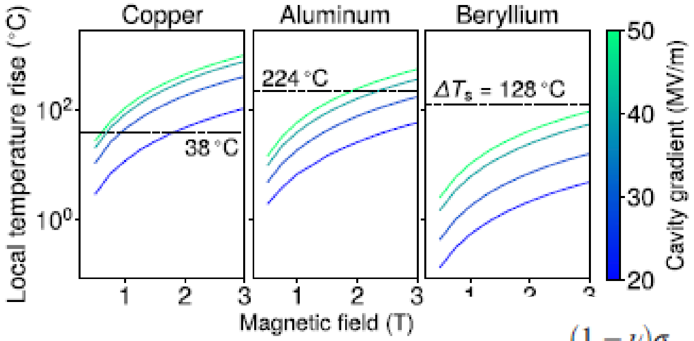
The MAP 805 MHz Modular cavity has demonstrated a gradient of 50 MV/m in a 3T B field

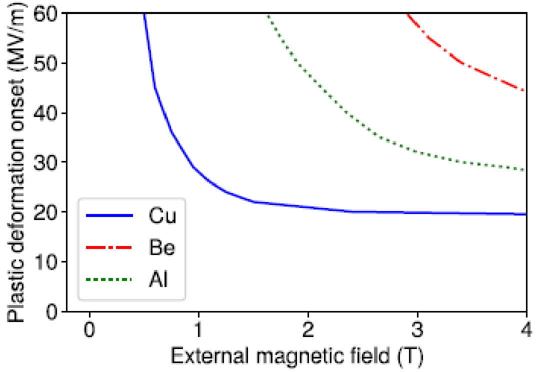
- A cavity designed for studying the RF breakdown in strong B field.
- Modularized design for systematically testing different cavity materials, surface treatments, cavity lengths, etc. Also made convenient to access all the surface areas for inspections.
- Being the last R&D cavity of MAP, the Modular cavity has implemented the best practices learnt from the previous R&D on cavity design, surface treatment, RF operations, etc.
- The cavity is tested in a 3T SC solenoid. With Be walls on both ends, it has achieved a peak surface E field over 50 MV/m, significantly higher than all previous 805 MHz vacuum cavities.
- This testing has demonstrated the RF down resilience of Be, consistent with the thermal-mechanical beamlet model.





Analytical calculation of the surface E field limit for different materials





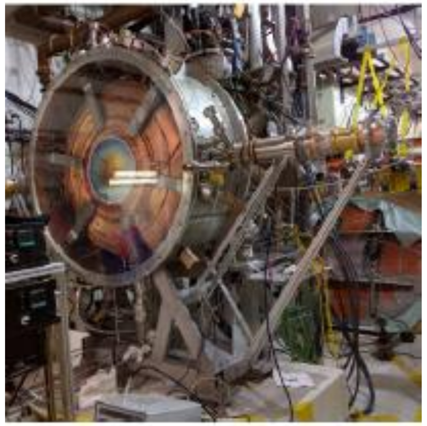
Temperature rise threshold: $$\Delta T_s = \frac{(1-\nu)\sigma_y}{\epsilon\alpha}$$

D. Bowring et al., "Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration"

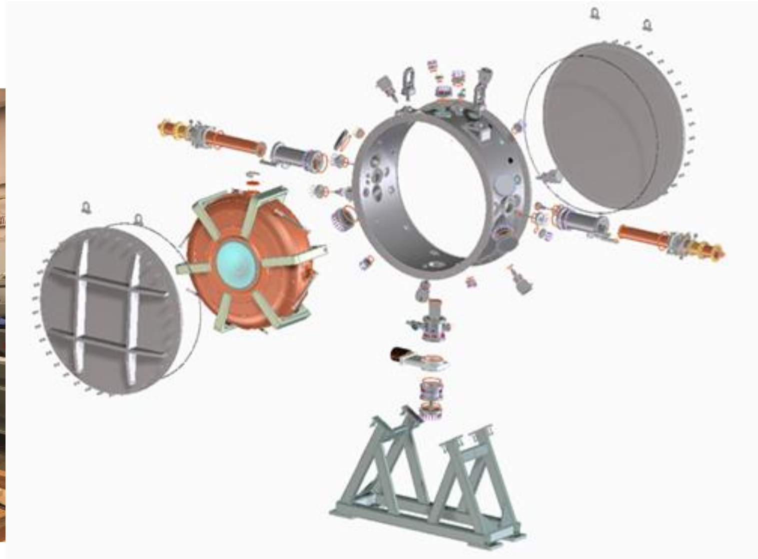
Material	*B*-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

The MICE 201 MHz RF module is a complete engineering demonstration of a fully operational RF cavity unit with thin Be windows and other features

- Muon Ionization Cooling Experiment originally includes two 201 MHz RF modules for re-acceleration.
- A prototype RF module was tested at Fermilab MTA and achieved the target operation level ~ 11MV/m in a 4T solenoid fringe field.
- Two RF modules were produced at LBNL, but eventually not included in the final MICE operation.
- Several key engineering features for the ionization cooling NCRF cavities have been demonstrated or examined in MICE RF module:
    - An SRF-type polishing procedure to smooth the cavity surface thus to suppress the field emission.
    - Geometry design and TiN coating to suppress multipacting.
    - Curved beryllium windows of 0.38mm and the relevant thermal deformations and LFD.
    - Pressure regulation to protect Be windows from the vacuum burst.
    - Frequency tuning arms controlled by pressurized actuators.



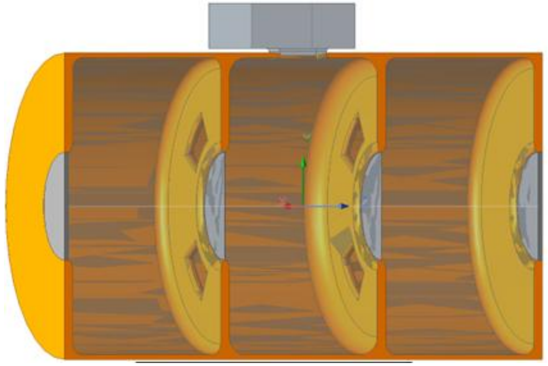
Parameter	MICE	MTA	Unit
Frequency	201.250	201.250	MHz
Peak gradient	10.3	10.6	MV/m
Average power	1.6	1.9	kW
Rf pulse width	1	1/6	ms
Rf rep rate	1	5	Hz
Tuner rep rate	1	1	Hz



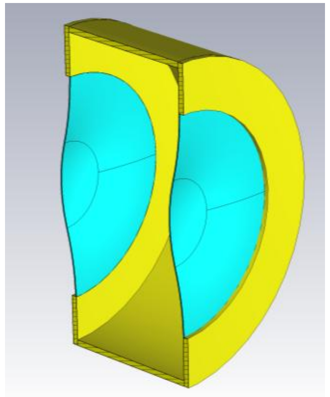
Paths forward if we can restart the NCRF vacuum cavity development for the MuC ionization cooling after a decade of hibernation

- Path 1: carry on the development of a room temperature Cu cavity with Be beam windows, build a fully operational 650/704 MHz cavity.
  - Cavity body RF design is straight forwardly derived from MICE/MAP cavities.
  - RF power coupling can adopt the distributed coupling for multi-cell.
  - Engineering design and manufacturing are the main focus.
  - Based on the performance demonstrated in MAP modular cavity, this cavity should achieve ~27 MV/m. Maybe sufficient for the demonstrator, but not enough for the cooling channel.
  - Be material can be a safety concern. Al hasn't been tested with high gradient and causes too much emittance growth at the later cooling stage.

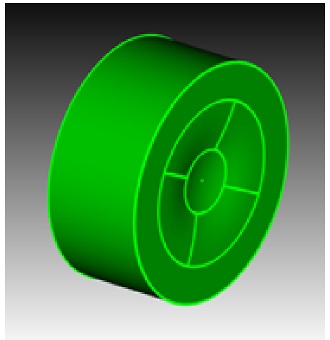
3-cell RF cavity design by IMCC



D. Giove, presented at Demonstrator workshop 2025



Shell model

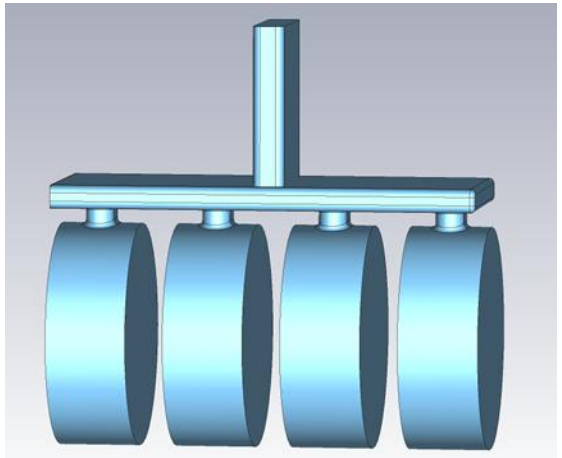


Vacuum model

Table 1: Cavity Key Parameters

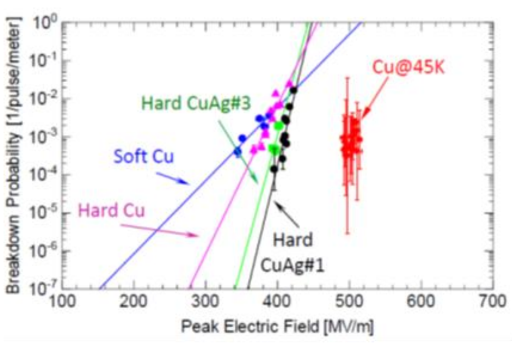
Average E gradient w/o transient factor (MV/m)	27.4
E max on the Cu surface (MV/m)	13.0
E max on the Be surface (MV/m)	39.1
r/Q (Ω) w/o transient factor	259
Q_0	21320
RF power (MW)	1.36

Distributed coupling concept

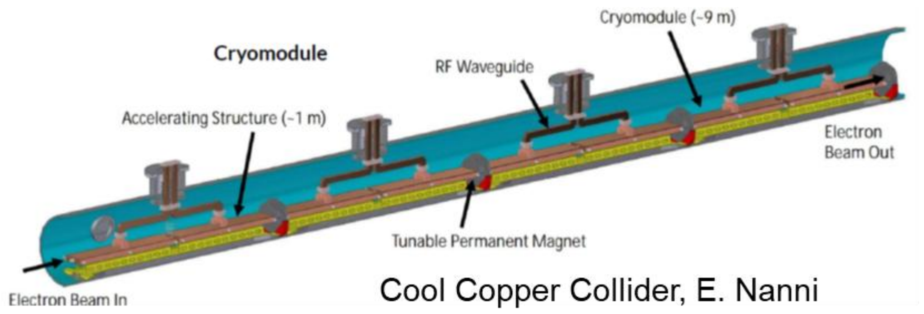


The R&D progress of NCRF breakdown in the last decade provides new possible approaches

- Path 2: explore new methods to significantly increase the achievable surface E field in strong B field
  - Cool copper RF cavity
    - Copper cavity operated at LN2 temperature shows significantly stronger resilience to RF breakdown than at room temperature.
    - Developing fast with applications to linear collider, high-brightness electron source, medical LINAC, etc.
    - Naturally compatible with the cryogenic environment of the SC solenoids in the cooling channel.
  - Explore other breakdown-resilient materials such as cooper alloy, cryogenic aluminum, possibly aluminum for the beam window.
  - HTS Superconducting RF cavity: high critical B field in HTS material; promising low power test results and high power tests are underway.
  - Short pulse operation.
- Extend the existing RF breakdown studies from several GHz to several hundred MHz and add the strong B field background.
- Can fundamentally affect the cooling channel properties and the engineering development.
  - With more RF breakdown resilient cavity material, the beam window could be removed in the later cooling stages, and it results conventional RF cavities.



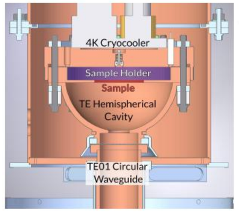
A.Cahill



Cool Copper Collider, E. Nanni

REBCO coated conductor cavity for Axion, T. Puig

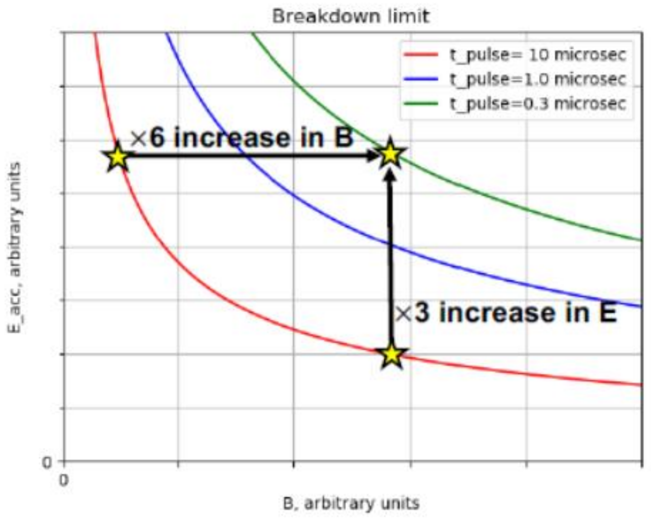
1st Axion cavity	CC coated cavity	Cu cavity
Q(0T, 4.2K)	80000	40000
Q(11T, 4.2K)	60000	40000



RF testing stand at SLAC, A. Dhar

Preliminary simulations based on the thermal-mechanical beamlet model indicate higher achievable surface E field with new approaches

Shorter pulse length



$$B^2 = \rho C_s \frac{2(1-\nu)\sigma_t}{E\alpha_{th}} \times \frac{e\pi\xi^2}{I_{em}^{\frac{1}{3}}\left(\frac{dE}{dz}\right)} \times \frac{1}{t_{pulse}}$$

Magnetic field at breakdown; Wall material properties; Cavity-dependent constant; Pulse length; Electron energy loss; Emission current $I(E_{acc})$

- Reducing pulse length from 10 μs to 300 ns drastically increase surface E threshold.
- Muon bunch train (21 bunches) < 100 ns
- Need more peak power and over-couple the cavity.

S. Arsenyev et al. presented at IMCC RF meeting, June 2021.

Cold copper

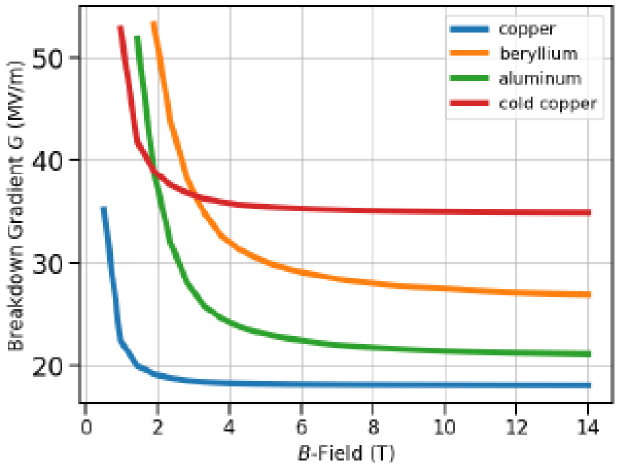


Figure 6: Breakdown gradient as a function of external magnetic fields for various materials.

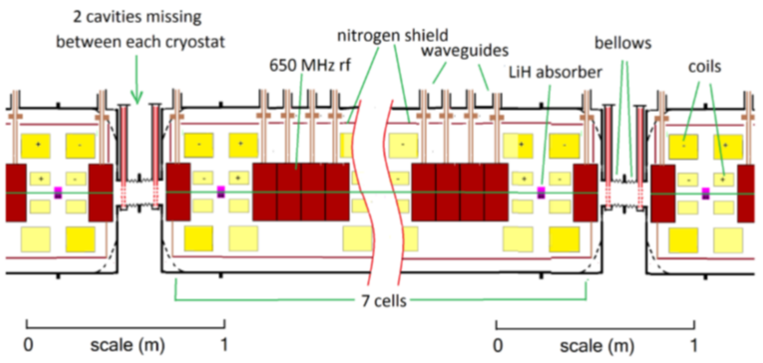
- At lower B fields, Al and Be outperform Cold Cu due to higher temperature thresholds.
- At stronger B fields, decreased electron spot size increases power density, and Cold Cu outperforms all other materials thanks to the combination of the reduced field-emitted current and increased thermal diffusivity.

D. Merenich et al, NAPAC2025

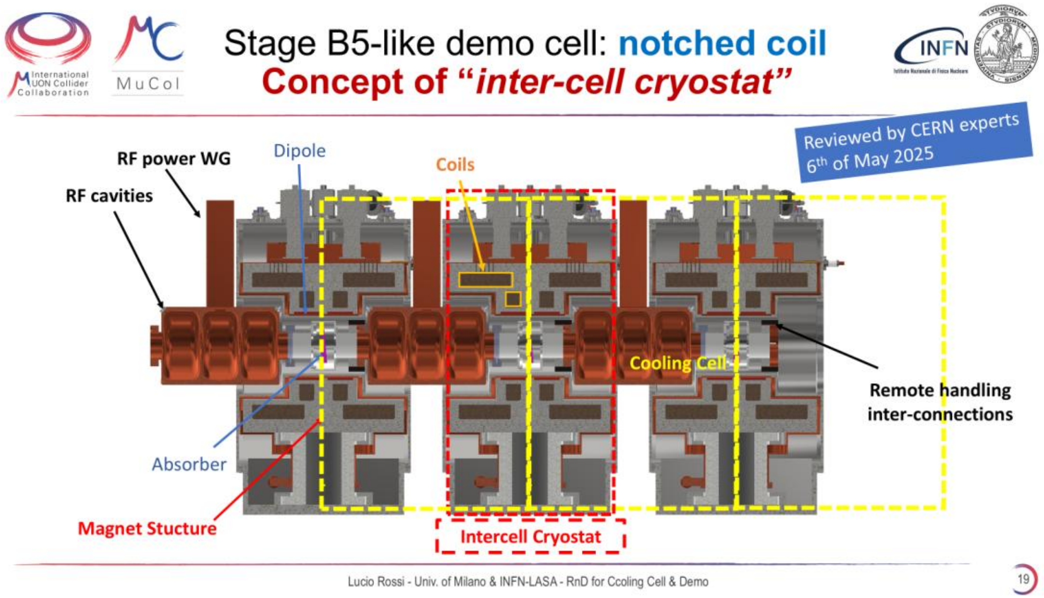
Other R&D needs besides the RF breadown

- Compact integration with other subsystems in the cooling channel such as SC solenoid, absorber, cryogenics, etc.
- High peak power (~MW), short pulse length (~us) RF power source at hundreds of MHz are not readily available yet.
- Large variety of cavity parameters (gradient, frequency, surrounding B field, beam window thickness, etc.).
- Large bunch charge (~uC) -> large beam loading and the compensation methods.
- New simulation capabilities:
  - Large bunch charge + large beam size + sub-relativistic -> non-trivial HOMs/space charge calculation.
  - The treatment of concealed cavity apertures.
- …….

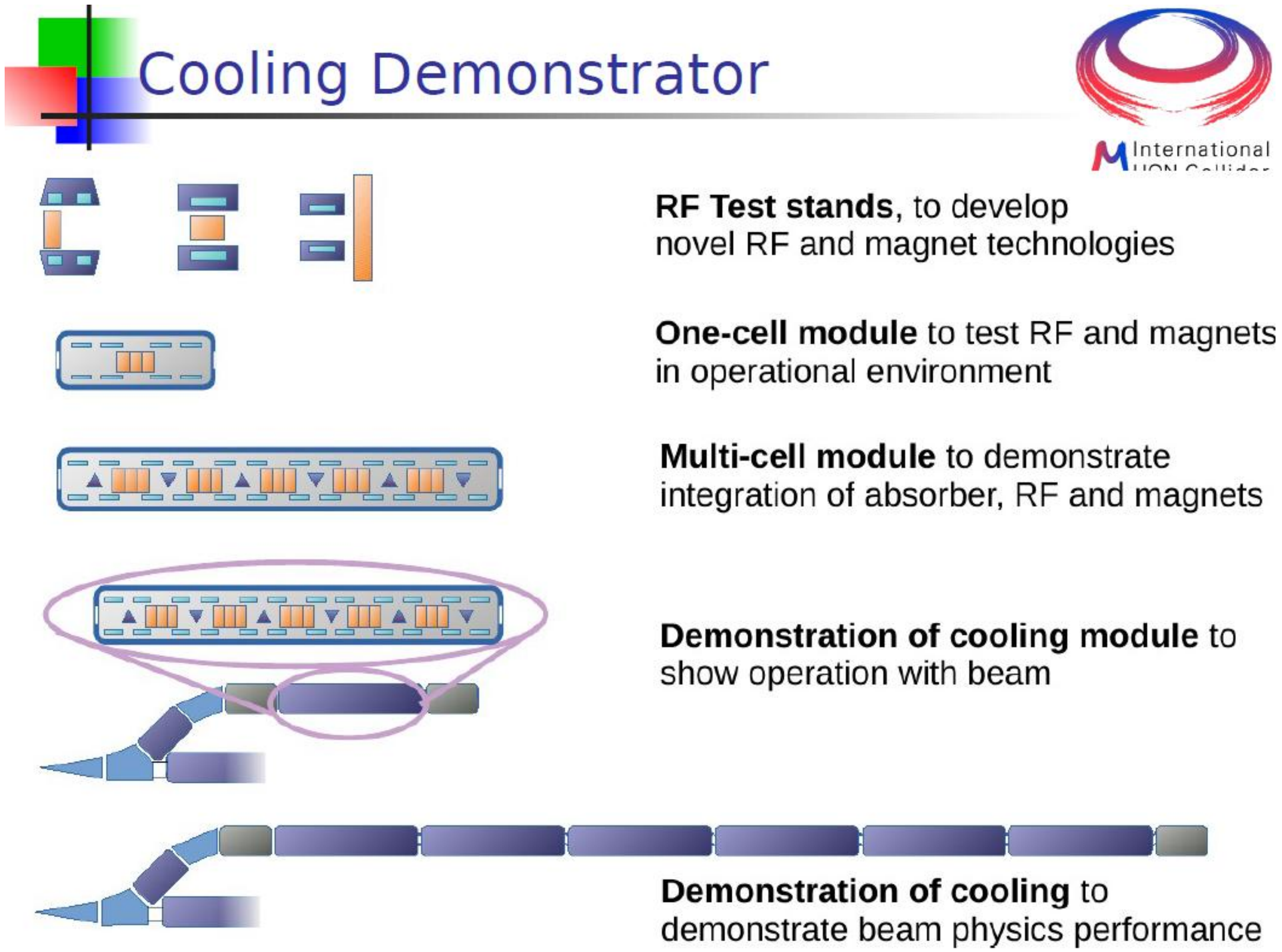
Preliminary engineering concept for a cooling module



S. Berg et al. IPAC24



A near term goal of NCRF Cooling Cavity R&D is to deliver the cavities for the cooling demonstrator



Demonstrator cooling cell parameters

Parameter	Unit	Value	
Cooling Cell Length	mm	1000	
Beam Physics			
Momentum	MeV/c	200	
Twiss beta function	mm	130	
Dispersion in X	mm	-61.5	
Dispersion in Y	mm	-19.7	
Beam Pipe Radius	mm	81.6	
Solenoid Parameters			
	Unit	Value	Tol
B0	T	7	0.25
B0.5	T	0	0.02
B1	T	1	0.025
B2	T	0	0.5
Coil Geometry			
Inner Radius	mm	250	
Length	mm	140	
Radial Thickness	mm	169.3	
Z Centre Position	mm	100.7	
Current Density	A/mm^2	500	
RF Cavity			
Center-to-centre distance	mm	188.6	
Gradient E0	MV/m	30	
Iris Radius	mm	81.6	
Number of RF Cells		3	
Frequency	GHz	0.704	
Synchronous Phase	degree	20	
Window Thickness	mm	0.1	
Window Material		Beryllium	
Wedge			
Material		LiH	
Opening Angle	degree	10	
Thickness	mm	20	
Alignment		Horizontal	
Dipole			
Length	mm	100	
Polarity		+ - - +	
Field	T	0.2	
Z Centre Position	mm	160	
Field Direction		Vertical	

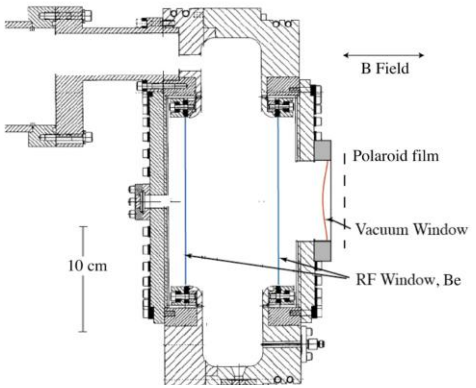
C. Rogers, R. Zhu, presented at IMCC Demostrator workshop 2025

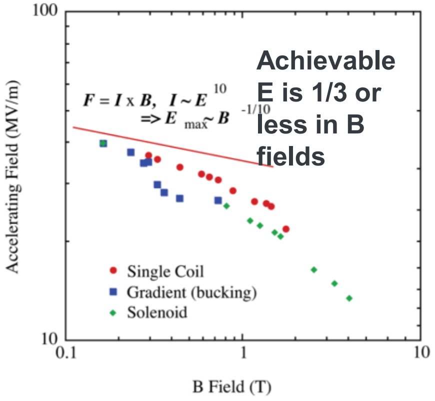
Historical view of gas-filled RF tests

K. Yonehara

2005 | 2006 | 2008 | 2013

2005: B-field limits vacuum RF gradient

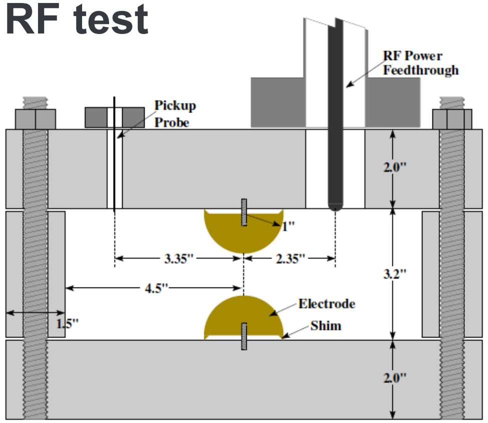


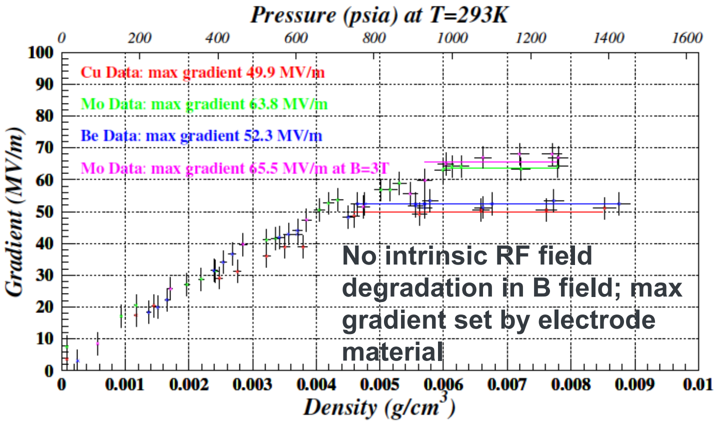


Achievable E is 1/3 or less in B fields

Moretti et al., PRSTAB 8, 072001 (2005)

2006: First 805 MHz Gas-Filled RF test

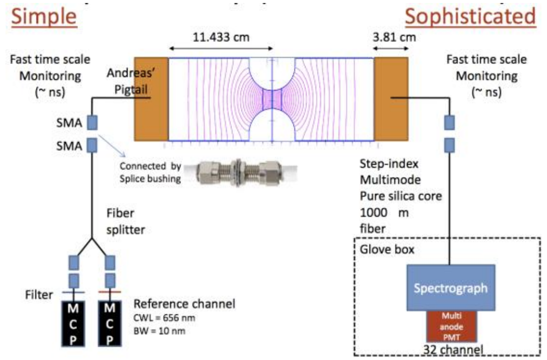


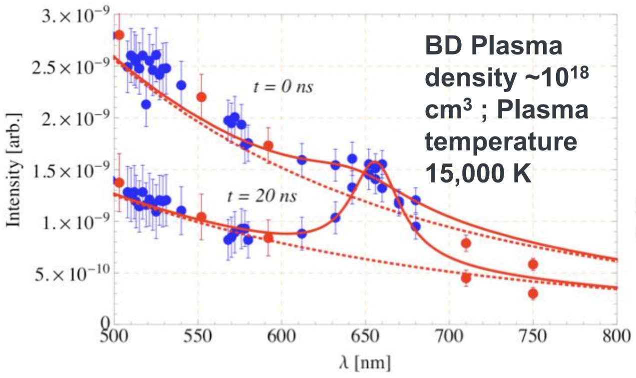


No intrinsic RF field degradation in B field; max gradient set by electrode material

Hanlet et al., EPAC2006, TUPCH147

2008: Gas BD spectroscopy → plasma parameter

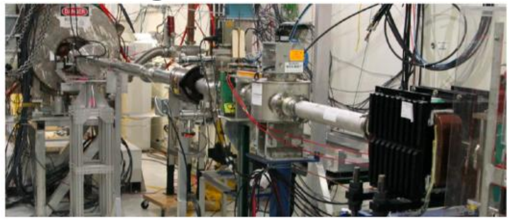


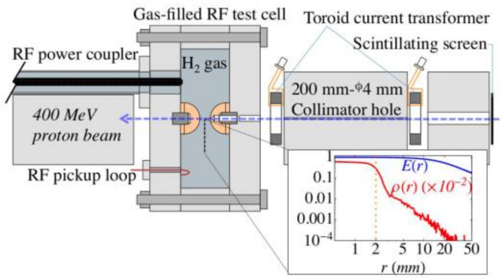


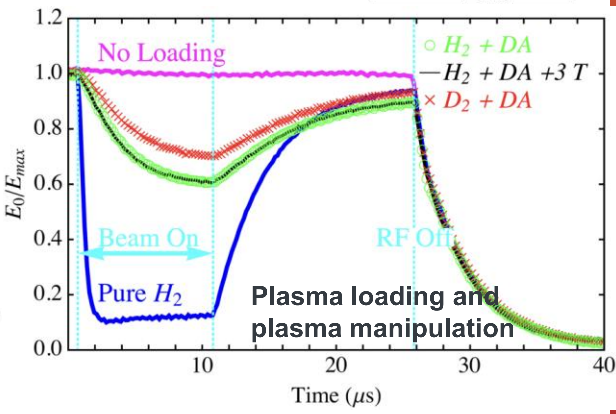
BD Plasma density ~10^{18} cm^3 ; Plasma temperature 15,000 K

Yonehara et al., IPAC2010, WEPE069

2013: Beam-induced plasma loading & control







Plasma loading and plasma manipulation

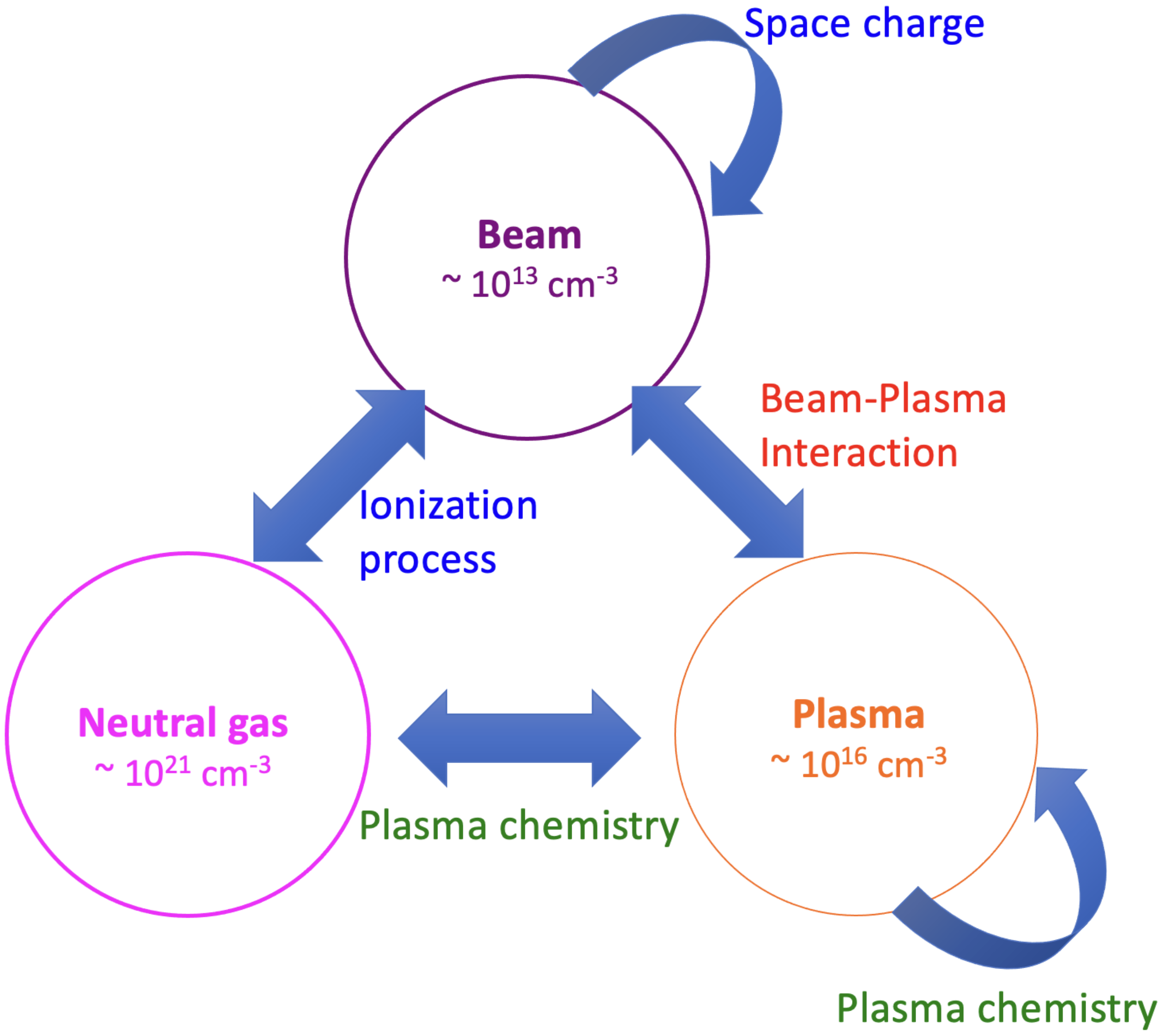
Chung et al., PRL 111, 184802 (2013)

Concept of Hydrogen Gas-filled RF for ionization cooling

K. Yonehara

- Key idea
  - Hydrogen gas simultaneously enables efficient ionization cooling and stable high-gradient RF operation
- Why Hydrogen gas
  - Provide high ionization energy loss per density
  - Exhibits the lowest stochastic heating from Coulomb scattering
  - Acts as an effective coolant for the RF beam window
- Why gas-filled RF works
  - Dense gas suppress dark current which arises from Folwer-Nordheim field emission
  - When dark current is suppressed
    - BD voltage is determined by electrode material
    - RF wall conditioning is not required
- Typical parameters for muon ionization cooling
  - Gas density ~0.035 g/cm^3 (half of Liquid Hydrogen); Gas pressure 28 atm at 20 Kelvin (or 427 atm at room temperature)
  - Peak RF gradient 30 MV/m

Beam-Gas-Plasma interaction in ionization cooling



- **Beam-induced plasma formed in fs order**
- **Plasma absorbs RF power (plasma loading)**
- **Mitigating plasma loading has been done experimentally by controlling plasma chemistry, which takes place on ps order**
- **Plasma provides beam charge neutralization**
- **Self-induced azimuthal magnetic field focuses the beam (plasma Z pinch effect)**
- **This additional beam focusing enhances ionization cooling**

K. Yonehara

Remaining challenges

K. Yonehara

- Key goal
  - Establish scalable, high-gradient gas-filled RF operation for muon ionization cooling
- Plasma Z pinch effect
  - Quantify beam effects by using plasma simulations
  - Experimental validation
- Frequency scaling beyond 805 MHz
  - To date, gas-filled RF tests have been performed at 805 MHz
  - If the dark current is effectively suppressed by the gas, the BD scaling should follow Kilpatrick's law
- Plasma loading mitigation
  - Investigate plasma chemistry control
  - Study gas density effect, including possibly quantum effects
  - Optimize conditions to minimize RF power loss while preserving Z-pinch beam focusing

Summary

- Ionization cooling is a key process to achieve the required the muon beam emittance for the future muon collider.
- NCRF is essential for ionization cooling, providing both the energy compensation and the longitudinal focusing.
- The presence of surrounding multi-T B field significantly limited the achievable cavity gradient. The cooling cavity development has been one major R&D for MuC.
- MICE/MAP R&D provides viable path to (at least) moderately useable gradient by Cu vacuum cavity + beam windows. Still need significant engineering and manufacturing effort to make a fully operational cavity at the target frequencies.
- The RF breakdown study progress in last decade provides new potential solutions to this B-field-induced breakdown problem. We should test these approaches, and the results can be very impactful to the ionization cooling channel performance and cost.
- Gas-filled RF cavity is also effective at overcoming the RF breakdown in B field, and can potentially provide extra beneficial transverse focusing. The major remaining challenges include the plasma loading, scaling to other frequencies besides 805 MHz and engineering development.