Challenges for the Ionization Cooling for a 10 TeV Muon Collider

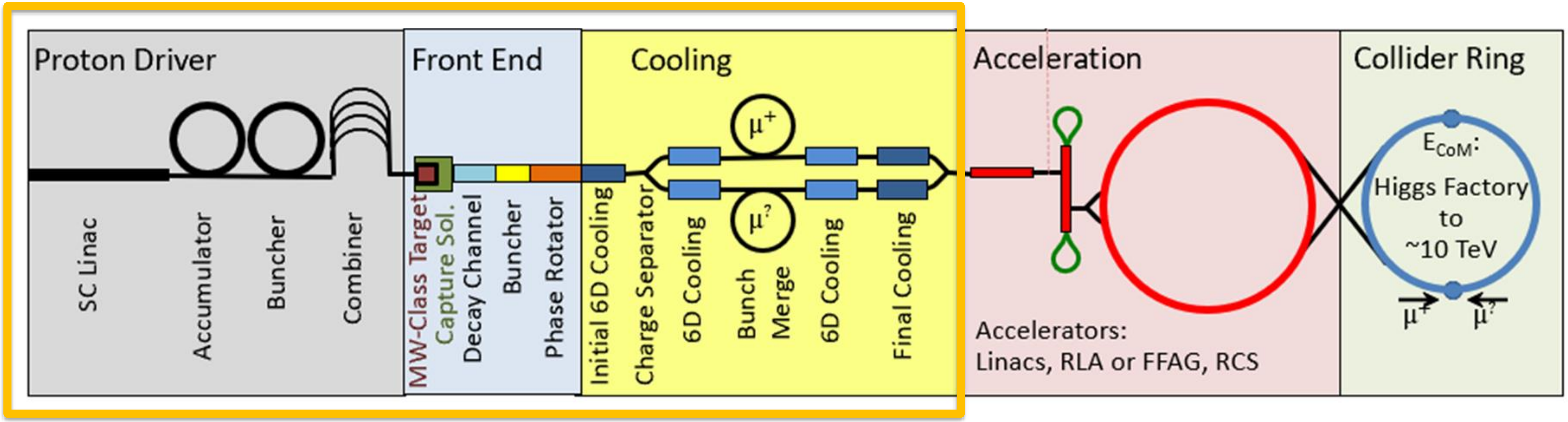
Tianhuan Luo, BACI ATAP

LBL Future Collider Forum, 08/14/2024

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

A high-brightness muon source is essential for a muon collider

Scheme of the MAP baseline MuC design



Number of muons per bunch

$$\mathcal{L} = \frac{N_{\mu^+} \cdot N_{\mu^-} \cdot f \cdot n_b}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

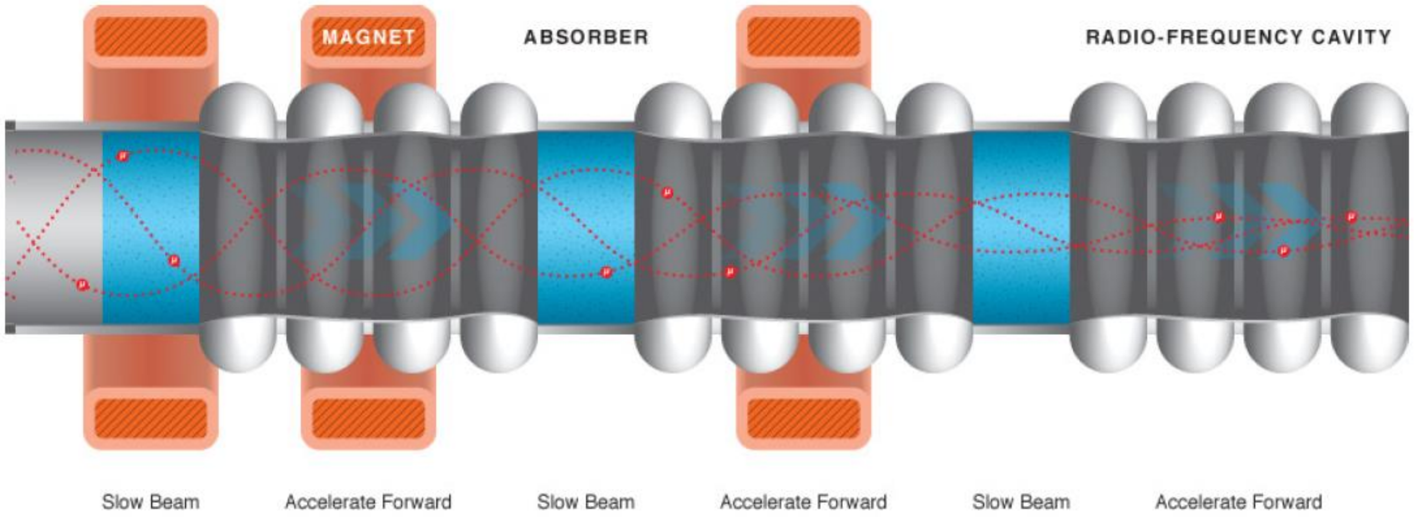
Beam spot size at collision point

For the 1.5 TeV muon collider design by MAP:

- $N = 2\times10^{12}$ particles/bunch
- $\sigma_{x,y} \sim 5.9\ \mu$m, $\beta^* = 10$ mm, $\varepsilon_{x,y}(norm) = 25\ \mu$m-rad
- $n_{turns} \sim 1000$
- $f_{bunch} = 15$ Hz (rate at which new bunches are injected)

$$\mathcal{L} \approx \frac{N_0^2 n_{turns} f_{bunch}}{4\pi \sigma_\perp^2} \approx 1.4 \times 10^{34}\ cm^{-2} s^{-1}$$

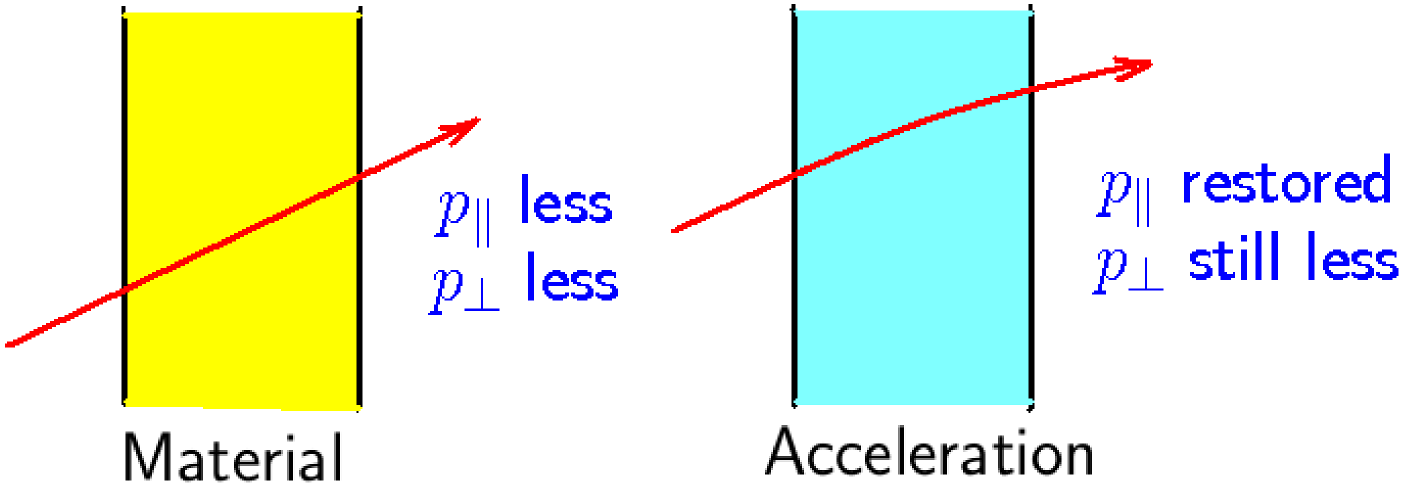
Why ionization cooling?



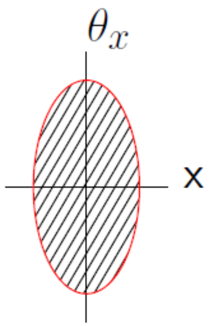
- MC is a tertiary beam machine (p $\rightarrow \pi \rightarrow \mu$). Beams coming out of the target are very large.
- Need intense μ beam $\Rightarrow$ need to capture as much as possible of the initial large emittance.
- Large aperture acceleration systems are expensive $\Rightarrow$ for cost-efficiency need to reduce emittances prior to accelerating ("cool the beam").
- MC designs assume significant ($O(10^6)$) six-dimensional cooling.
- Need to act fast since muons are unstable. Ionization cooling option fits the bill.

Transverse ionization cooling

- In Ionization Cooling, a particle loses energy by ionization loss passing through material. If the particle has a transverse component, then that is reduced.
- Subsequent rf acceleration restores the longitudinal component, but leaves the reduction in the transverse component.
- The minimum emittance achieved is now set by Coulomb scattering in the material.



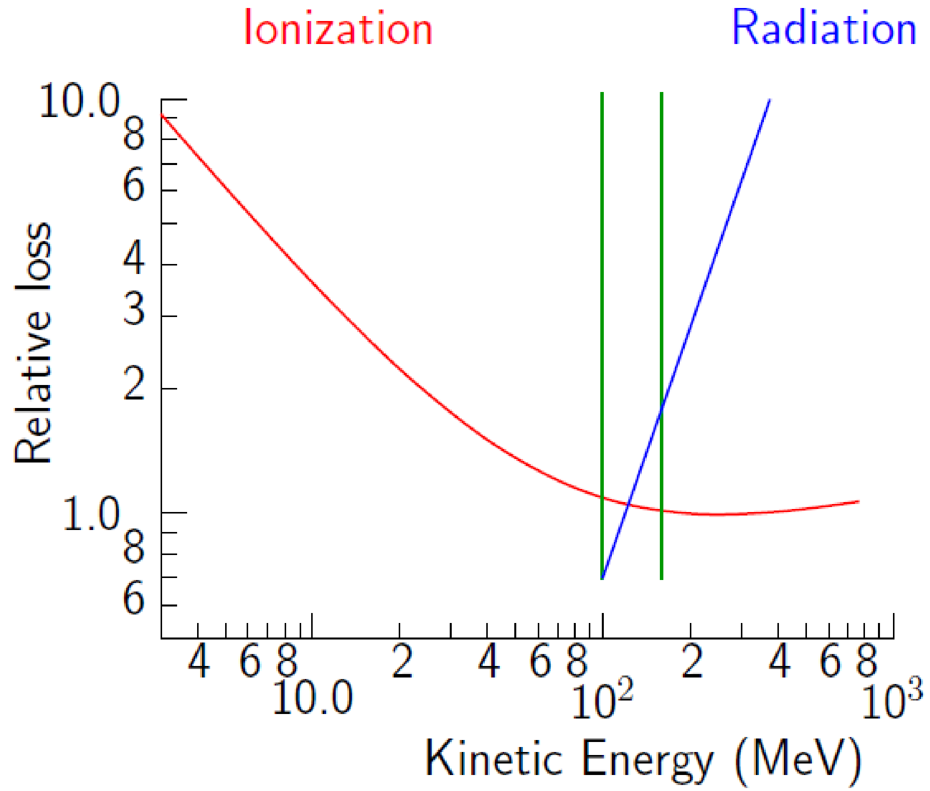
$$\epsilon_{x,y} = \gamma\beta_v \, \sigma_{x,y} \, \sigma_{\theta_{x,y}}$$



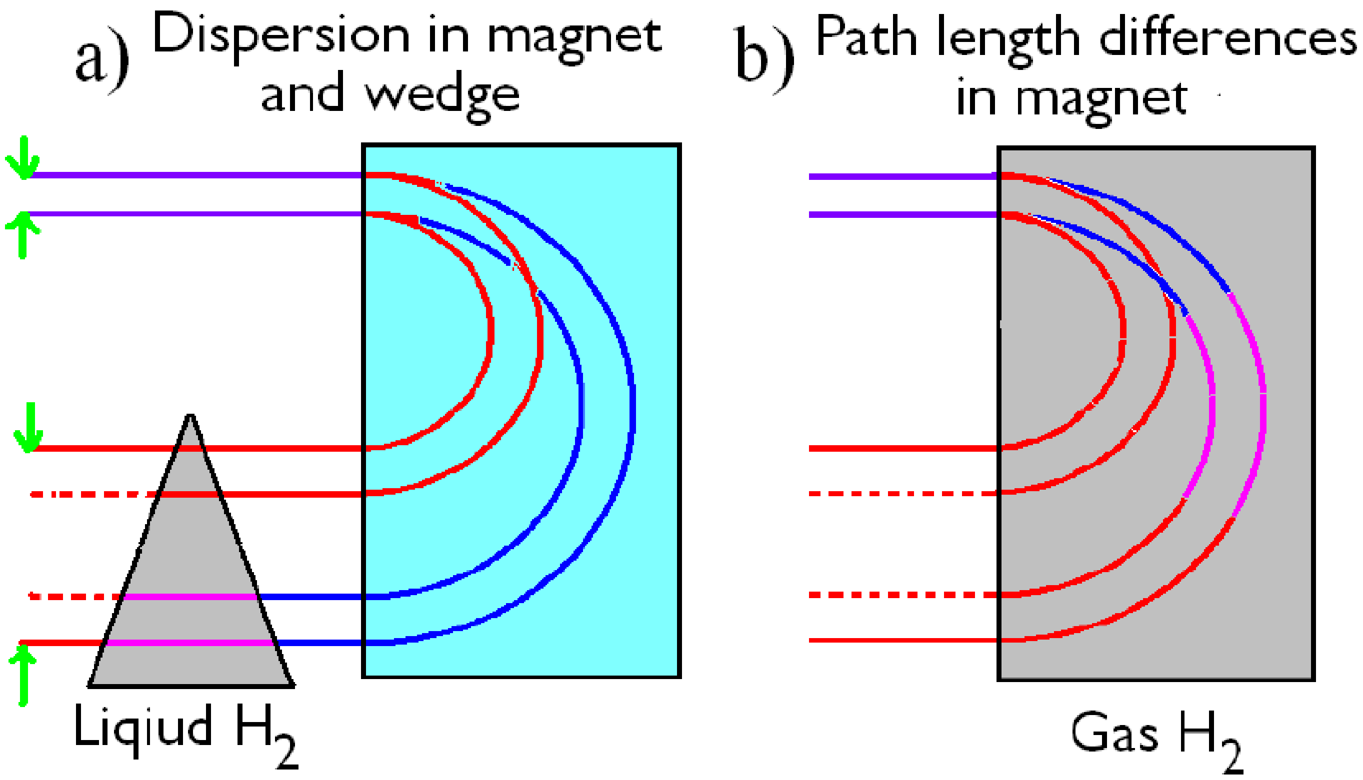
$$\beta_\perp = \left(\frac{\text{width}}{\text{height}} \text{ of phase ellipse} \right) = \frac{\sigma_x}{\sigma_\theta}$$

Longitudinal ionization cooling/heating

- To realize the longitudinal cooling, higher energy muons should loss more energy than the lower energy muons through the ionization process. But that’s not always the case, as shown on the right plot.
- Actually at low energy, we have longitudinal heating, and at higher energy, the longitudinal cooling effect is still weak.
- Choose an muon kinetic energy at ~ a few hundred MeV, where the longitudinal heating is weak and can be compensated by the transverse cooling through “emittance exchange”.



Emittance exchange



Higher momentum muons pass through more material than lower. Momentum spread and thus Longitudinal emittance is reduced. But the transverse beam size is increased.

- In practice, the muon is cooled at KE ~130 MeV where the longitudinally the beam is slightly “heated”.
- Emittance exchange is required to keep the beam stable longitudinally.

Heating from Coulomb Scattering and the equilibrium emittance

$$\epsilon_{x,y} = \gamma\beta_v \, \sigma_{x,y} \, \sigma_{\theta_{x,y}}$$

If there is no Coulomb scattering, or other sources of emittance heating, then σ_θ and $\sigma_{x,y}$ are unchanged by energy loss, but p and thus $\beta\gamma$ are reduced. So the fractional cooling $\Delta\epsilon\,/\epsilon$ is:

$$\frac{\Delta\epsilon(\mathrm{cooling})}{\epsilon} = \frac{\Delta p}{p} = \frac{\Delta E}{E}\frac{1}{\beta_v^2} \qquad (15)$$

which, for a given energy change, favors cooling at low energy.

Defining

$$C(mat, E) = \frac{1}{2}\left(\frac{14.1\ 10^6}{[mc^2/e]_\mu}\right)^2 \frac{1}{L_R\, d\gamma/ds}$$

then

$$\frac{\Delta\epsilon(\mathrm{heating})}{\epsilon} = dE\ \frac{\beta_\perp}{\epsilon\gamma\beta_v^3}\ C(mat, E)$$

Between scatters the drift conserves emittance (Liouiville).
When there is scattering, $\sigma_{x,y}$ is conserved, but σ_θ is increased.

$$\Delta(\epsilon_{x,y})^2 = \gamma^2\beta_v^2\ \sigma_{x,y}^2\Delta(\sigma_\theta^2)$$

$$\text{eq.11} \qquad 2\epsilon\ \Delta\epsilon = \gamma^2\beta_v^2\left(\frac{\epsilon\beta_\perp}{\gamma\beta_v}\right)\ \Delta(\sigma_\theta^2)$$

$$\Delta\epsilon = \frac{\beta_\perp\gamma\beta_v}{2}\ \Delta(\sigma_\theta^2)$$

$$\text{Rossi} \qquad \Delta(\sigma_\theta^2) \approx \left(\frac{14.1\ 10^6}{[pc/e]\beta_v}\right)^2 \frac{\Delta s}{L_R}$$

$$\Delta\epsilon(\mathrm{heating}) = \frac{\beta_\perp}{\gamma\beta_v^3}\ \Delta E\ \left(\left(\frac{14.1\ 10^6}{2[mc^2/e]_\mu}\right)^2 \frac{1}{L_R\ dE/ds}\right)$$

$$dE\ \frac{1}{\beta_v^2\ E} = dE\ \frac{\beta_\perp}{\epsilon\gamma\beta_v^3}\ C(mat, E)$$

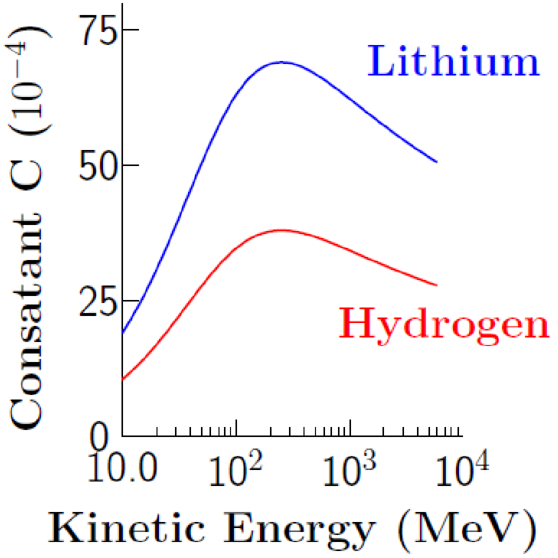
gives the equilibrium emittance without emittance exchange:

$$\epsilon_{x,y}(min) = \frac{\beta_\perp}{\beta_v}\ C(mat, E)$$

The choice of absorber material and the cooling beam energy

At energies such as to give minimum ionization loss, the constant C_o for various materials are approximately:

material	density kg/m^3	dE/dx MeV/m	L_R m	C_o 10^{-4}
Liquid H_2	71	28.7	8.65	38
Liquid He	125	24.2	7.55	51
LiH	820	159	0.971	61
Li	530	87.5	1.55	69
Be	1850	295	0.353	89
Al	2700	436	0.089	248



Liquid Hydrogen is the best material, even though it requires windows made of Aluminum or other material which somewhat degrade the performance.

Lower energies cool transverse faster, but longitudinal emittances rise faster there.

The cooling rate and the tapering of the equilibrium emittance

As one approaches the minimum emittance, the cooling rate will decrease:

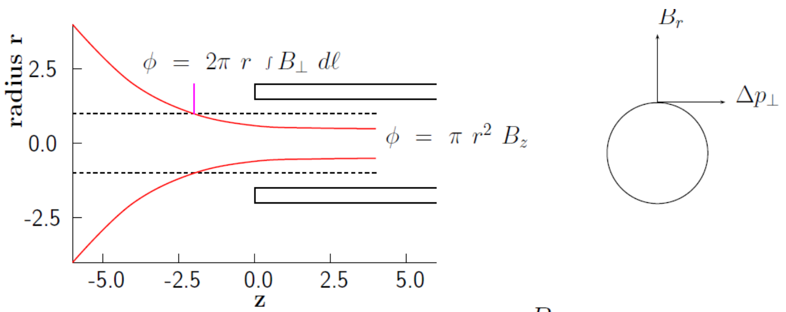
$$\frac{d\epsilon_{x,y}}{\epsilon_{x,y}} = \left(1 - \frac{\epsilon_{\min}}{\epsilon}\right) J_{x,y} \frac{dp}{p} \qquad (20)$$

Using an $\epsilon >> \epsilon(min)$ is impractical because of the excessive required angular acceptance

Using $\epsilon(min) \rightarrow \epsilon$ implies slow cooling with resulting losses to decay

Thus efficient cooling requires a 'tapered' sequence of 'stages' with ever decreasing βs, while keeping $\epsilon/\epsilon(min)$ in some reasonable range around 2

Keeping the diverged muon beam confined by continuous focusing solenoids in the cooling process



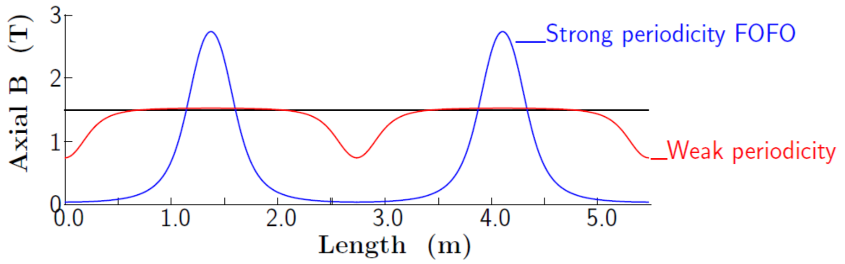
$$\Delta[pc/e]_\perp = \int B_r\, c\, dz = \frac{B_z\, r\, c}{2} \quad (13)$$

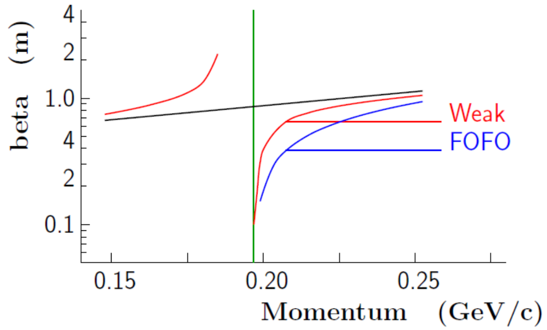
So for a case with zero initial transverse momentum,

$$[pc/e]_\perp = \frac{B_z\, r\, c}{2} \quad (14)$$

This azimuthal momentum, interacting with the axial field generated an inward focusing force. If r changes, the radial motion interacting with B_z maintains equation 14.

Decreasing $\beta_\perp$ in Solenoids by adding periodicity

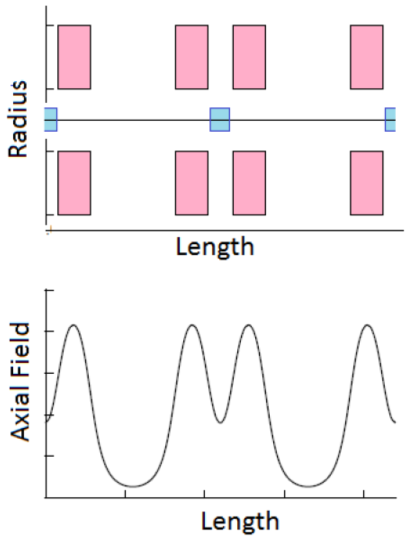




- Resonances introduced
- Betas reduced locally,
- But momentum acceptance small

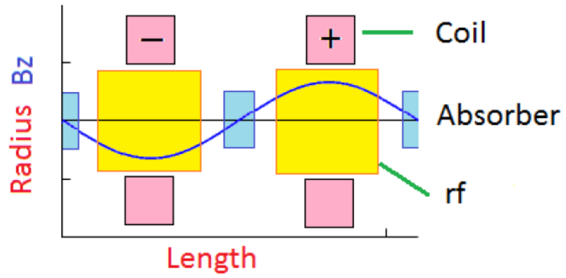
Super FOFO (Sessler)

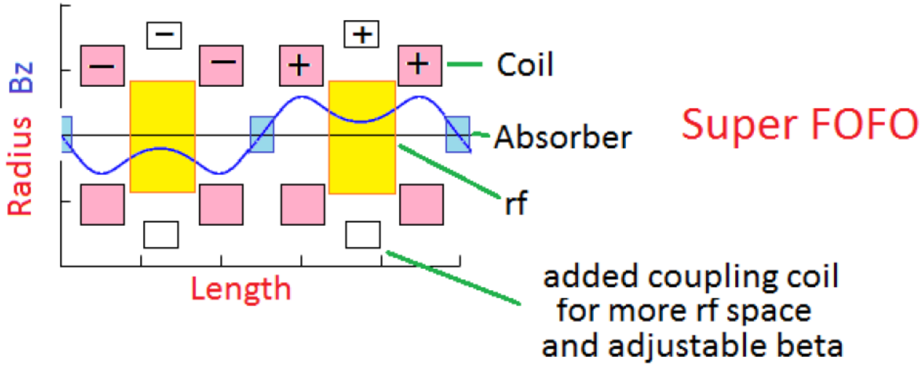
Double periodicity



Due to the energy loss in the absorber, the angular momentum is no longer preserved along the solenoids. Need to alternate the solenoid polarity to avoid angular momentum buildup.

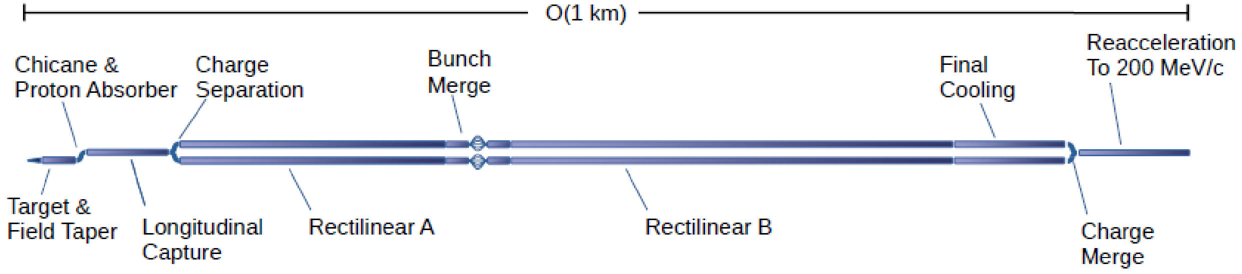
Lattices with many "flips"



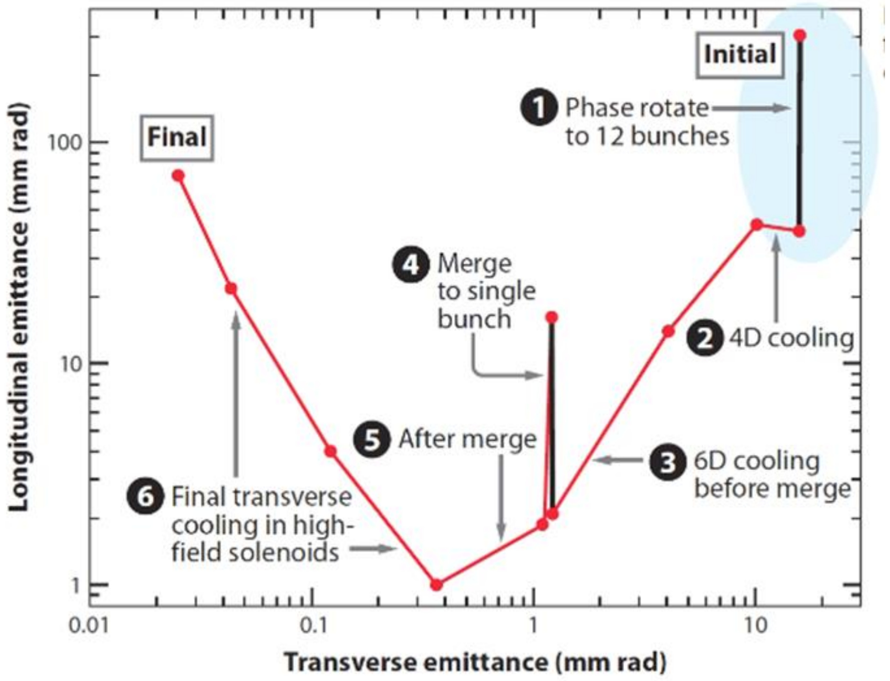


MuC ionization cooling channel design: to achieve O(10e6) emittance reduction within the short muon lifetime

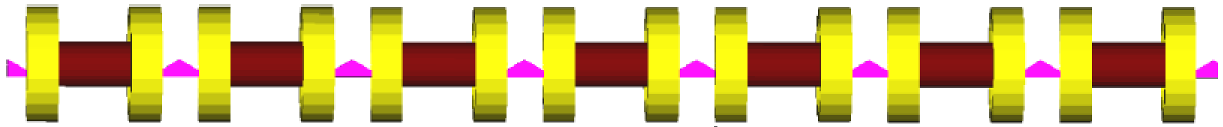
Muon production and cooling design in 2024 IMCC interim report



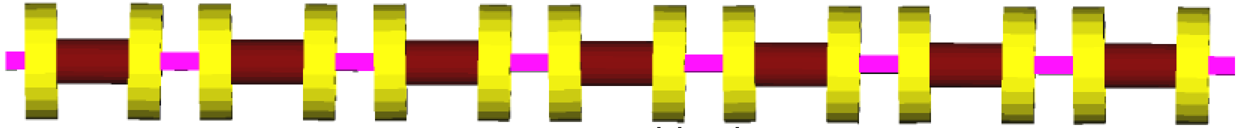
Emittance evolution through the cooling process



Rectilinear cooling lattice

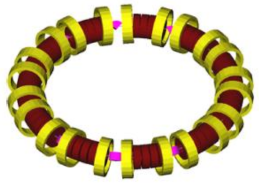


(a)Top view

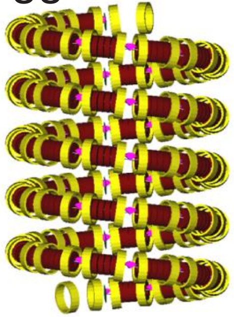


(b)Side view

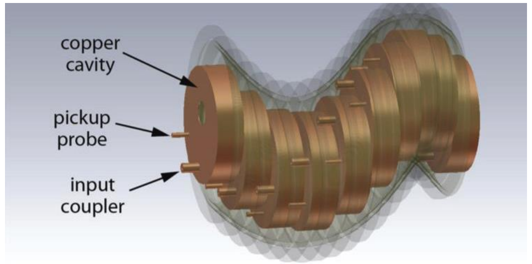
Cooling ring



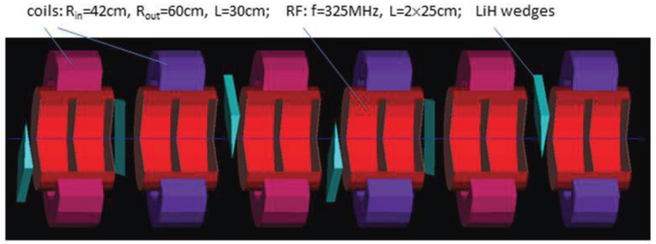
Guggenheim helix



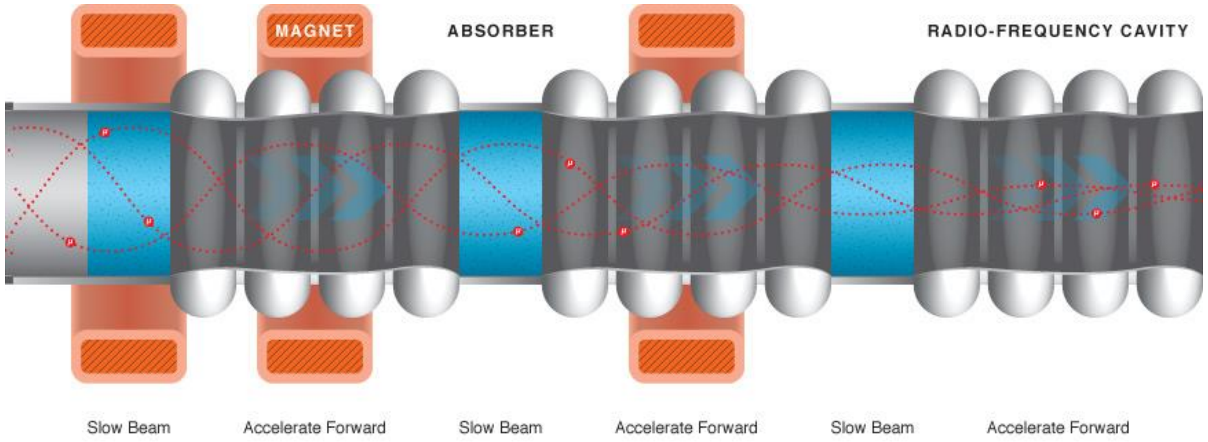
Helix cooling channel

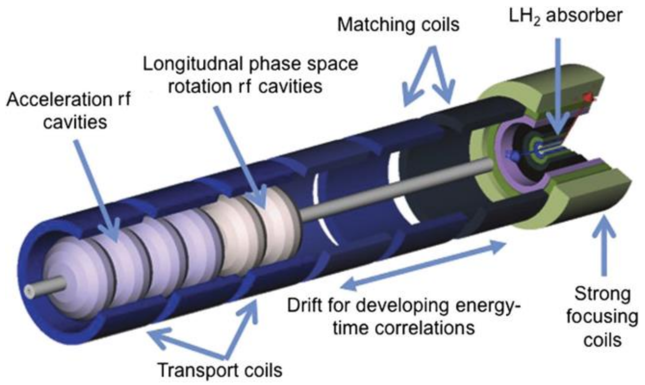


FOFO snake



Technology challenges for building the ionization cooling channel





- Main technology challenges:
  - High and very high magnets
    - Large bore solenoidal magnets for 6D cooling: on axis field from 2 T (500 mm IR), to 14 T (250 mm IR)
    - 30T or above solenoidal magnets for final cooling.
  - High gradient RF within multi-T field
    - Gradient ~ 30 MV/m, even higher is preferred.
    - Frequency ~ 200-800 MHz.
  - Absorbers that can tolerate large muon intensities
  - Integration: Solenoids coupled to each other, near high power rf & absorbers)

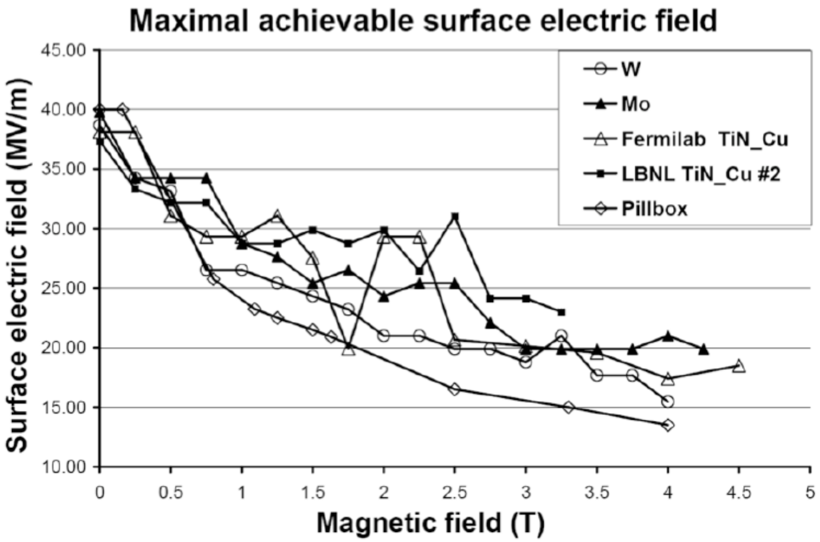
In the cooling channel, the surrounding multi-T solenoid field significantly reduces the achievable gradient in the RF cavity

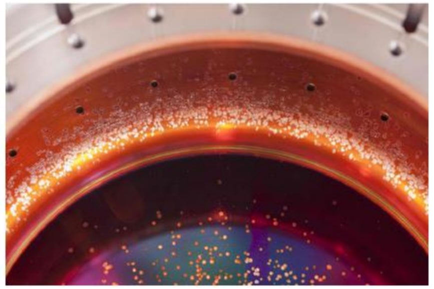
Kilpatrick criterion: the rule of thumb to estimate the RF gradient limit

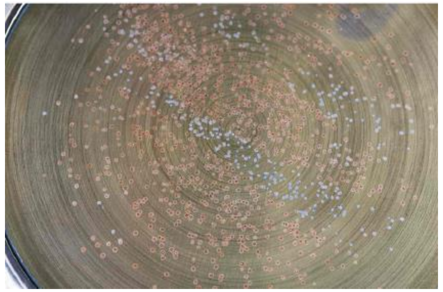
$$f = 1.64 \cdot E(MV/m)^2 \cdot e^{-8.5/E(MV/m)} \; MHz$$

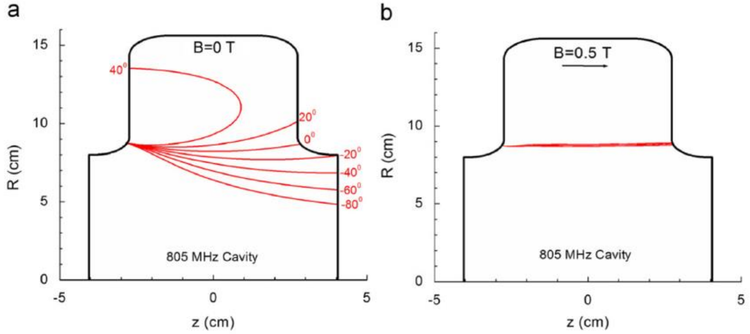
Thanks to the better vacuum and surface cleaning, nowadays we can comfortably expect a 2* threshold of the Kilpatrick criterion. 325 MHz -> 36 MV/m, 650 MHz -> 48 MV/m, sufficient for MuC ionization cooling.

Experimentally, when NCRF cavity is put into strong B field, the achievable gradient is significantly reduced.



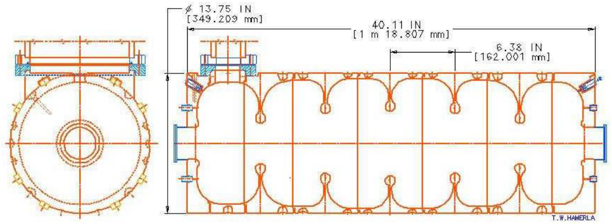




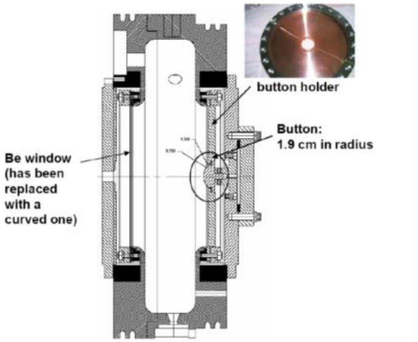


R&D on understanding the RF breakdown in multi-Tesla environment and its mitigation to achieve stable operation at required accelerating fields

805 MHz iris loaded cavity with a beam envelope matched aperture

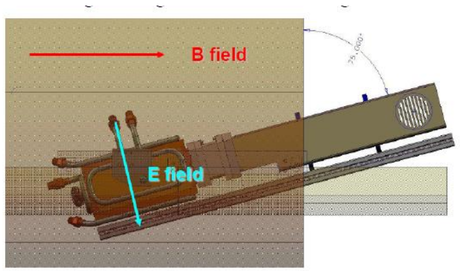


805 MHz Cavity Button test



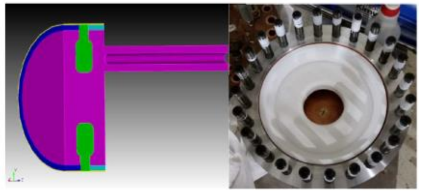
To find materials and coatings that can withstand high surface electric field in strong magnetic field.

805 MHz Box cavity



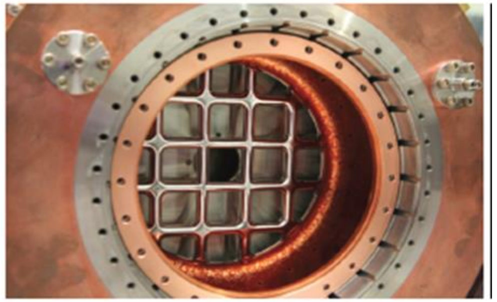
To study the breakdown mechanism with adjustable angle between E, B field directions

805 MHz cavity with alumina insert



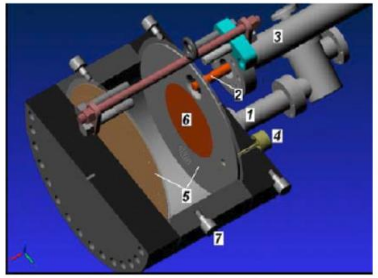
Shrink the diameter of the gas-loaded cavity

805 MHz Cavity with grid windows



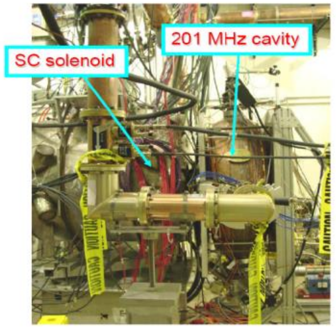
Alternative to the fully covered Be windows

805 MHz all-season cavity

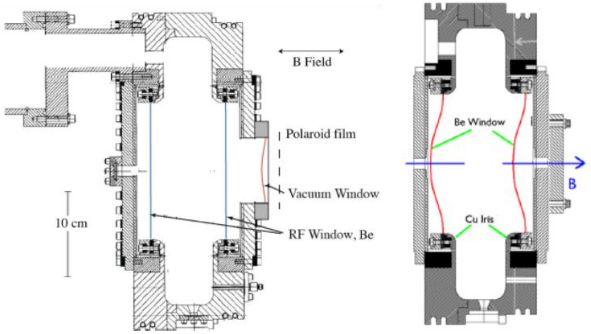


A versatile cavity for both vacuum and high-pressure test.

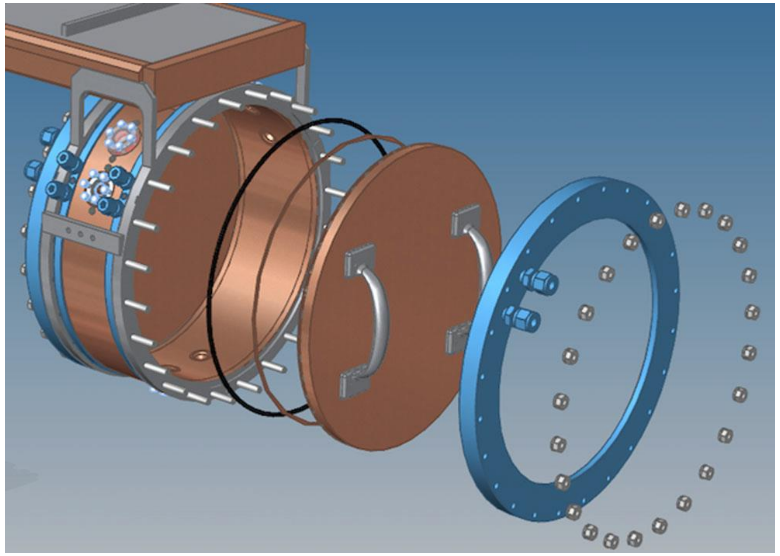
201 MHz prototype cavity

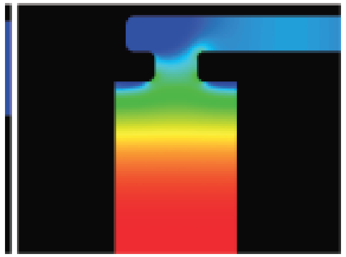


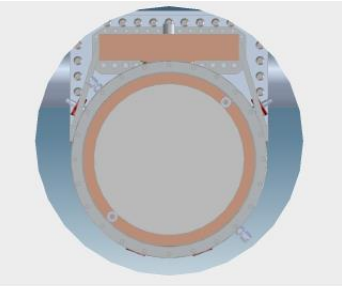
805 MHz LBL cavity with demountable windows

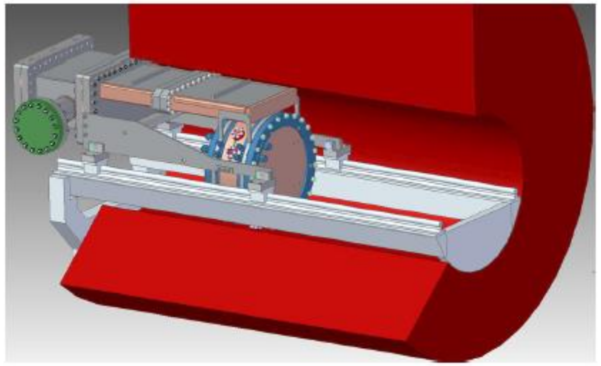


Vacuum modular cavity demonstration









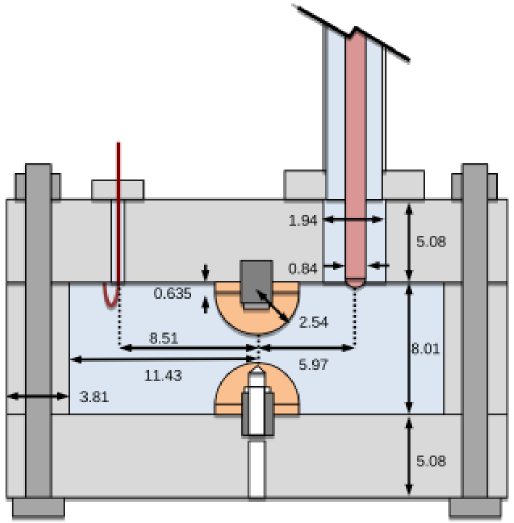
Material	*B*-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

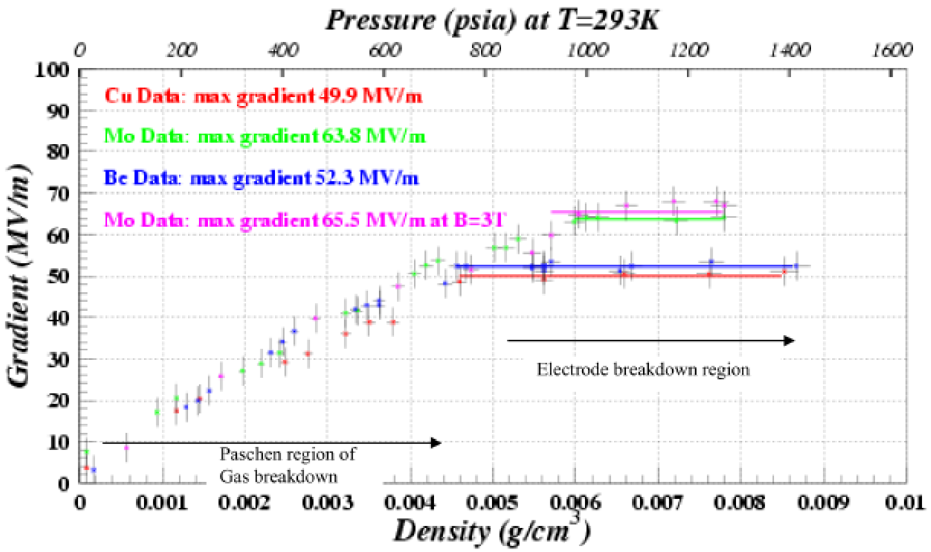
The latest R&D cavity is the 805 MHz modular cavity.

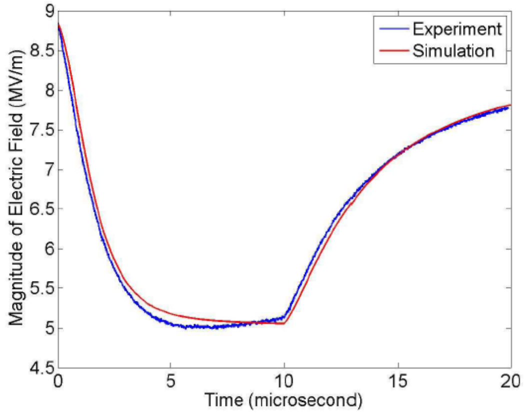
- The power feeding coupler is moved to torus to reduce E_peak at the coupler.
- Cavity geometry is optimized to minimize the effects of dark current and the multipacting with B field.
- Cleaning and polishing interior cavity surfaces to reduce the density of field emission sites.
- Investigating the role of material type, production, surface conditioning, etc. in the breakdown process.

Achieve the steady operation at ~ 50 MV/m in B=3T environment with Be walls.

Gas-filled cavity demonstration



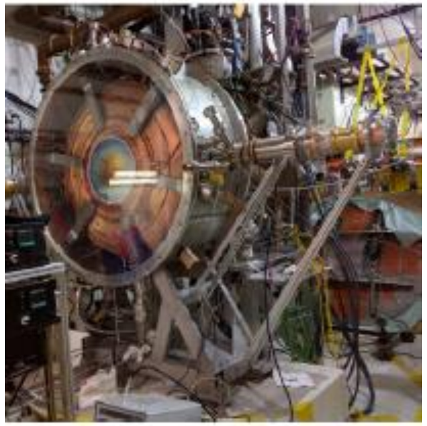




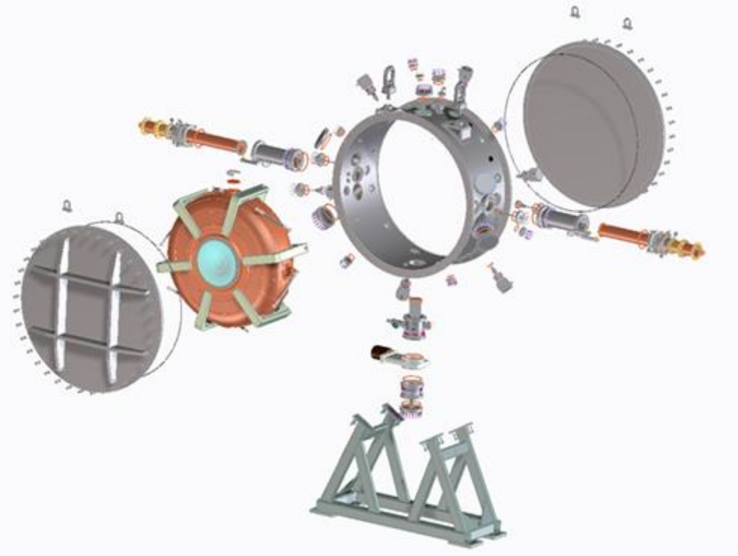
- The RF breakdown gradient of copper, molybdenum, and beryllium electrodes was determined using hydrogen gas. The breakdown gradient is the same for molybdenum electrode **with and without an external 3 T B field, achieving a gradient about 50 MV/m.**
- Beam test with proton beam has been carried out to characterize the effect of beam on the cavity performance, aka, plasma loading. Plasma loading reduces the cavity stored energy as well as the gradient.
- A 3D electromagnetic particle-in-cell code with atomic physics processes, SPACE, has been developed and benchmarked for predicting the plasma loading.

MICE RF module: a comprehensive engineering demonstration

- A prototype RF module was tested at Fermilab MTA and achieved the target operation level in a 4T solenoid fringe field.
- With further improvement, two RF modules were produced at LBNL, but eventually not operated at MICE due to limited resources.
- 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.
  - Etc.

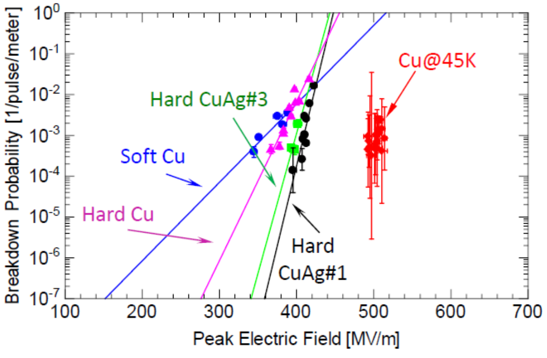


Parameter	MICE	MTA	Unit
Frequency	201.250	201.250	MHz
Peak gradient	10.3	10.6	MV/m
Average power	1.6	1.9	kW
Rf pulse width	1	1/6	ms
Rf rep rate	1	5	Hz
Tuner rep rate	1	1	Hz

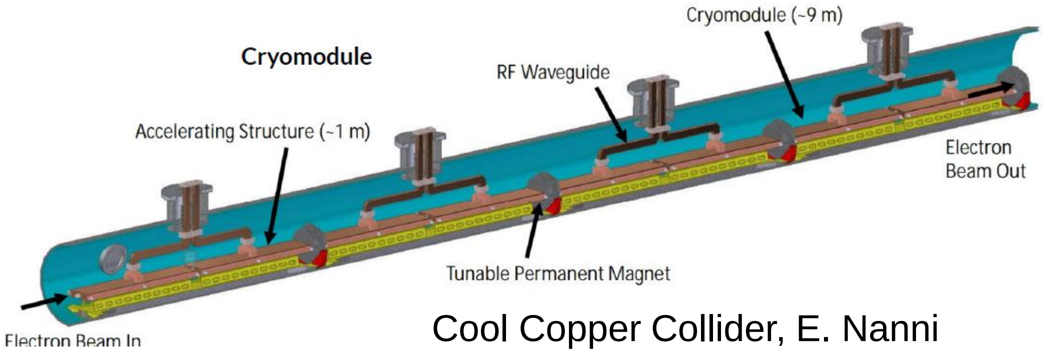


New possible approaches utilizing recent R&D advancements

- Besides continuing the pathway of current directions, the recent accelerator R&D advancements offer new possible approaches to develop high gradient RF cavities operated 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.
    - Discovered in the campaign for high gradient NCRF for future linear colliders.
    - This technology is being applied to the proposed linear collider C3 (with a demo planned for ~2029), high-brightness electron gun, etc.



A.Cahill

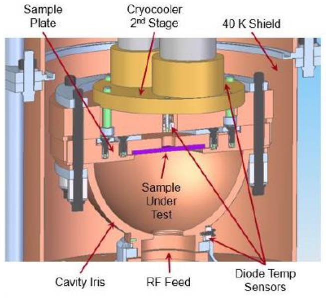


Cool Copper Collider, E. Nanni

- HTS Superconducting RF cavity
    - HTS coating developed for FCC-hh beam screen, RF cavity for dark matter axion search and high power RF for beam acceleration.
    - High critical B field in HTS material.
    - Low power RF tests show promising results.
    - High power RF tests are underway.

REBCO coated conductor cavity for Axion, T. Puig

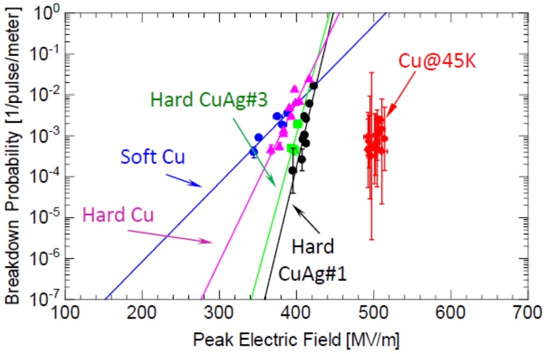
1st Axion cavity	CC coated cavity	Cu cavity
Q(0T, 4.2K)	80000	40000
Q(11T, 4.2K)	60000	40000



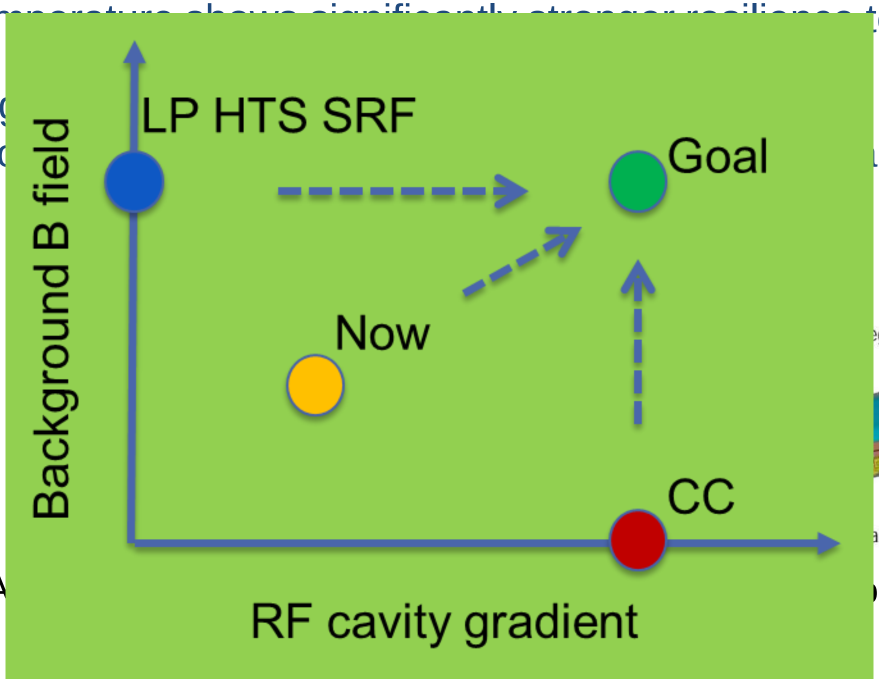
High power test set-up at SLAC

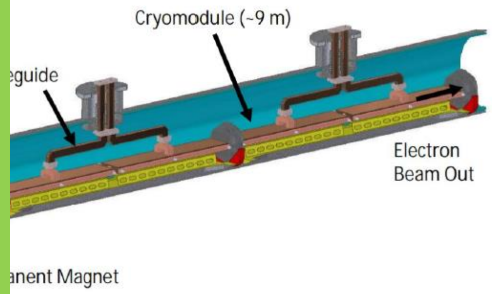
New possible approaches utilizing recent R&D advancements

- Besides continuing the pathway of current directions, the recent accelerator R&D advancements offer new possible approaches to develop high gradient RF cavities operated in strong B field.
- Cool copper RF cavity
  - Copper cavity operated at LN2 te… to RF breakdown than at room temperature.
  - Discovered in the campaign for hi…
  - This technology is being applied t… …nned for ~2029), high-brightness electron gun, etc.



A…



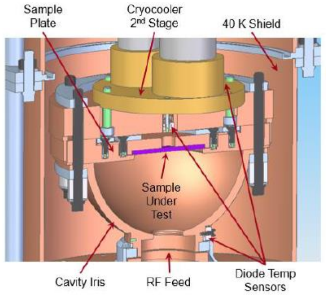


…pper Collider, E. Nanni

- HTS Superconducting RF cavity
  - HTS coating developed for FCC-hh beam screen, RF cavity for dark matter axion search and high power RF for beam acceleration.
  - High critical B field in HTS material.
  - Low power RF tests show promising results.
  - High power RF tests are underway.

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



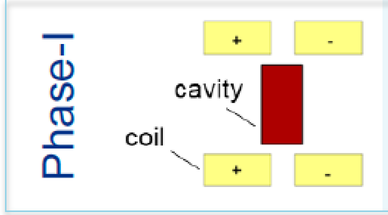
High power test set-up at SLAC

Besides RF cavities, SRF solenoids and absorbers have their own challenges as well

- Leave the review of SRF solenoids to my colleagues at SuperCon.
- A few comments on the absorbers:
  - Heating in the LH2 absorbers, ultra-thin absorber windows, LH2 alternatives.
  - Experimental data of high intensity muon's interaction with absorber materials.
    - Important for validating the cooling simulation.
    - Muon Ionization Cooling Experiment (MICE) experimentally benchmarked the LH2 and LiH for the low intensity muons.
- Compactly integrating the high power RF, SRF solenoids and absorbers is an engineering challenge of its own.

A staged demonstrator for the MuC high-brightness muon source

- Parameters are aspirational and may need modifications based on available funding and resources

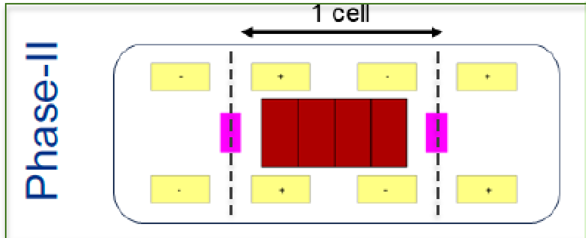


RF studies in B-fields

Material studies & cryogenic Cu

600-800 MHz NC cavity, with coils making 10-14 T on axis

< 7 years from today

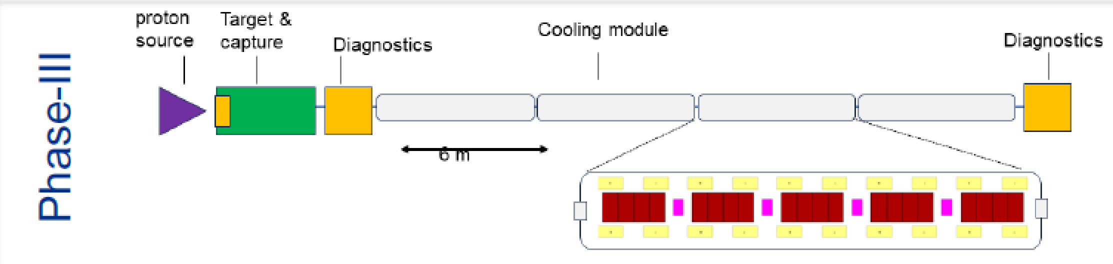


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

7-10 years



Full demonstrator with beam

Coils producing 7-10 T axial fields

Potential to achieve 50% or more 6D cooling

>10 years from today

Thank you!

BERKELEY LAB

ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION
ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

References

- P. Snopok, “Ionization Cooling”, inaugural meeting of the US Muon Collider.
- D. Stratakis, “Overview of Accelerator R&D Needs”, inaugural meeting of the US Muon Collider.
- R. Palmer, “The physics of ionization cooling”, MICE collaboration meeting CM38.
- M. Palmer, “MAP R&D as Input to the International Muon Collider Design Study”, 1st Muon Collider Community Meeting.