Conceptual design of an 805 MHz cavity with beryllium windows and distributed coupling

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BERKELEY LAB

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This talk is based on our recent IPAC2024 paper

CONCEPTUAL DESIGN OF AN 805 MHZ CAVITY WITH BERYLLIUM WINDOWS AND DISTRIBUTED COUPLING

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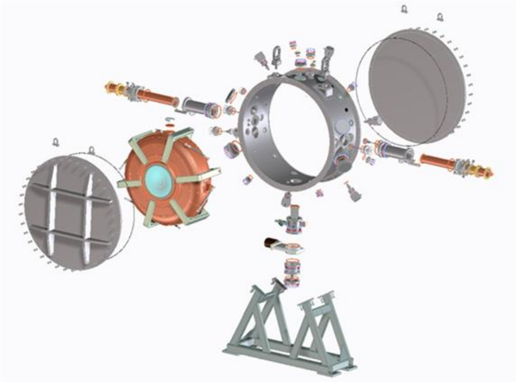
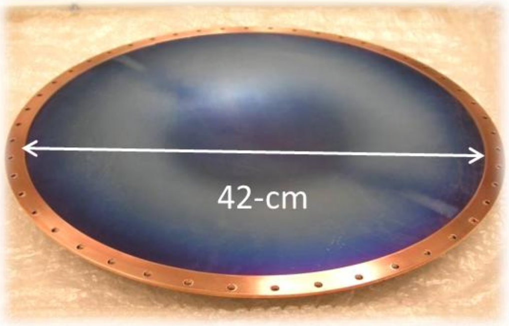
- https://www.jacow.org/ipac2024/pdf/TUPR12.pdf
- The basic idea is to implement the RF design and engineering experience learnt from MICE and MAP cavities to design a new cavity.
- Relatively high technical readiness.
- At least a moderate cavity gradient relevant for the ionization cooling demo.

The curved thin Be window in MICE 201 MHz cavity

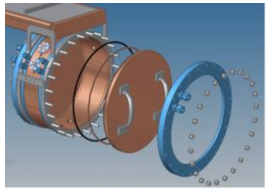
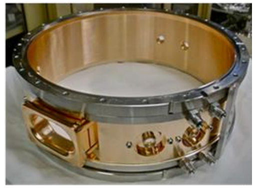
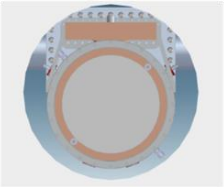
- 201 MHz MICE cavity has achieved the target gradient of 10.3 MV/m in the fringe field of a 4T solenoid field.
- One feature is the 0.38mm thick, 21cm radius Be window covering the cavity sidewalls.
- There are two main advantages of such a window:
  - Using low-Z material such as Be to cover the high E field surface area can reduce the local heating and the surface damage due to the electrons' impact, thus reduce RF breakdown probability.
  - Covering the cavity sidewall can significantly increases the cavity shunt impedance.
- The windows are curved to reduce the thermal stress.



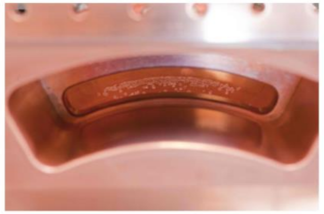
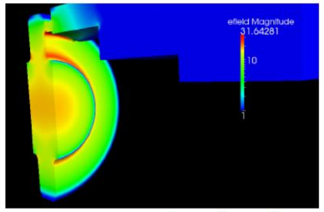


E field threshold achieved in the MAP 805 MHz modular cavity

- A modular pillbox cavity with changeable sidewalls to study breakdown in B field with different material types, production processes, surface conditionings, etc.
- Achieved over **50 MV/m** surface E field with Be sidewalls and ~**13 MV/m** surface E field with Cu sidewalls in the 3T SC magnet at Fermilab Mucool Test Area (MTA).
- Compared with previous 805 MHz cavities, the power coupling slot is moved from sidewall to equator to avoid high E field at the coupling slot and the corresponding RF breakdown.

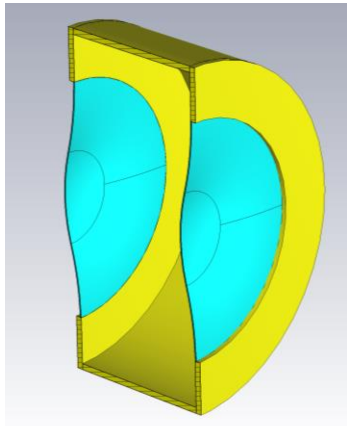

Material	*B*-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

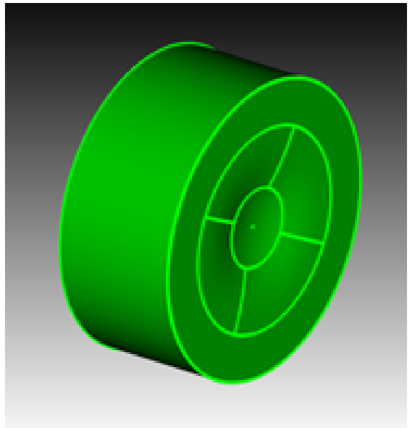
New cavity body design considerations

In the cavity body design, there are two major considerations:

- Based on the modular cavity results, the upper limit of the E field is set at 50 MV/m on Be surface and 13 MV/m on Cu surface to prevent the RF breakdown in the SC magnet field.
- Thin Be windows similar to MICE windows are implemented to cover both sidewalls. For this conceptual design we simply scale the MICE window to match the radius of the copper cell without detailed engineering considerations.



Shell model



Vacuum model

For a thin window, a smaller size is preferred for better heat dissipation and mechanical robustness. But from the RF breakdown perspective, a larger window size is preferred as the Be surface has a much larger E field threshold than the Cu surface, and the E field magnitude decreases along the radial direction. Thus the choice of the Be window size is a balance between these two competing factors.

New cavity body design: determining the cavity radius and length

- Without thorough exploration, we set Be window radius at 9.6 cm. The cavity radius is set at 142mmto achieve the 805 MHz operation frequency.
- The cavity length is determined by maximizing the shunt impedance per unit length $RT2/L$.

$$\frac{RT^2}{L} = \frac{T^2 \mu_0^2 c^2 L}{\pi (A + B)},$$

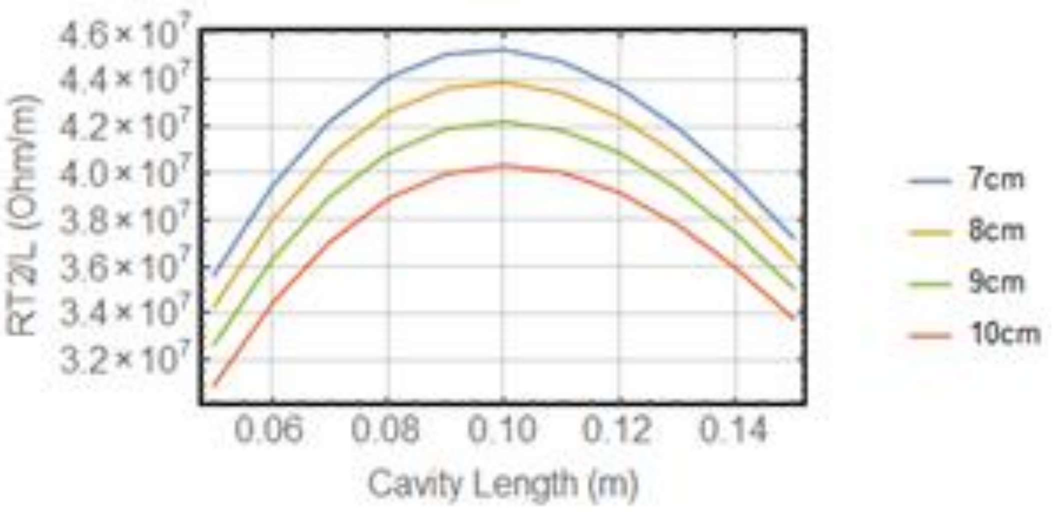
where

$$A = R_{s1}[R_1^2 J_1^2(2.405) - R_2^2 J_1^2(\eta) + R_2^2 J_0(\eta) J_2(\eta) + R_1 L J_1^2(2.405)],$$

$$B = R_{s2}[R_2^2 J_1^2(\eta) - R_2^2 J_0(\eta) J_2(\eta)],$$

$$\eta = 2.450 \frac{R_2}{R_1},$$

R_1 and R_2 are the radii of the Cu sidewall and the Be window, and R_{s1} and R_{s2} are the surface resistance of Cu and Be.



For our choice of window size at 9.6 cm, we choose the length at 10 cm.

New cavity body design

Omega3P simulation of the eigenmode

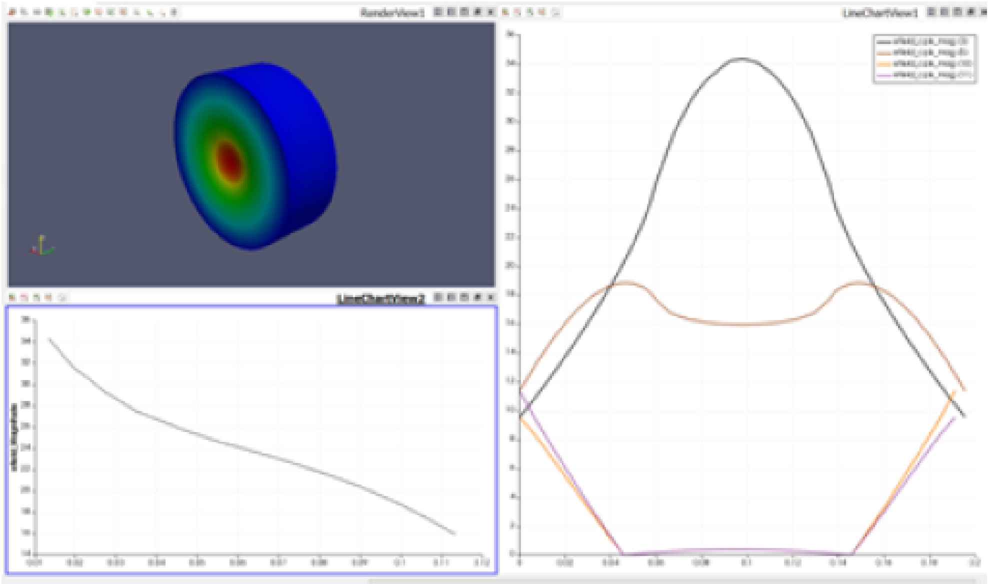


Figure 3: The E field in the cavity. Top left: the E field magnitude on the cavity surface, facing the curved-in window; bottom left: the E field across the cavity center, from curved-in window to curved-out window; Right: the E field on the surface in the middle plane, black: on the curved-in window, brown: on the curved-out window, orange and magenta: on the Cu torus.

The achievable acceleration is limited by the E field on the Cu surface, which should not exceed 13 MV/m.

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

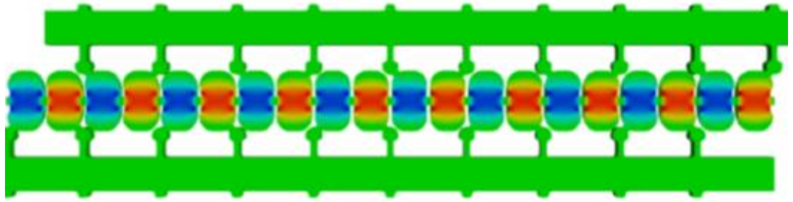
The achievable gradient, which is calculated as the total voltage divided by the cavity length, is 27.4 MV/m, comparable to the desired gradient for the rectilinear cooling channel.

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

Distributed coupling for RF power feeding

- Why distributed coupling?
  - In MAP modular cavity, the RF power coupling slot was moved from cavity sidewall to the torus, and the E field at the coupling slot was reduced to below the E field along the center axis. We want to keep this "power feeding from torus" practice for the new cavity design to raise the RF breakdown threshold, even if it means a slightly larger bore size of the SRF magnets.
  - Another consideration is that since each cavity cell is covered by the beam windows, there is no beampipe aperture to couple the RF fields between the adjacent cell. Each cell needs to be powered individually.
- Bottom left figure shows a conceptual idea for a 4-cell structure in one cooling cell.
- So far just a concept, the model with the proper coupling hasn't been designed yet.

Distributed coupling for C3 LINAC



Cavities will be slightly off-center in the cooling channel solenoids like MAP modular cavity.