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RF Cavity Options for the Targetry R&D Program

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Abstract

An important part of the R&D program (BNL E951, [1]) for targetry and capture at a neutrino factory and muon collider source is the study of how well a low-frequency, high-gradient rf cavity can operate in a magnetic field of 1.25 T and near the pion-production target, when the latter is bombarded by pulses of up to 10^{14} protons. In this note we explore rf cavity geometries that are matched to the inserting of resistive magnet coils in the cavity "nosepieces".

1 System Requirements

The requirements on which the present study is based are:

1. The rf frequency is 70 MHz, compatible with the power source based on 8973 tetrodes now being recommissioned at LBL for this project. The frequency for the real cavity with be close to 71.2 MHz, the 32nd harmonic of the frequency corresponding to 6 bunches of 24-GeV protons in the AGS ring.

2. The rf cavity should operate with an accelerating gradient of $G = 6$ MeV/m for 185 MeV/c muons ($\beta = 0.84$). While even higher gradients would be better still, 6 MeV/m is acceptable performance for E951, and provides a basis for comparison of cavity options. The achieved accelerating gradient G is less than the peak electric field E_0 on the axis of the cavity due to transit-time effects, summarized by the transit-time factor $T = G/E_0$.

3. When operating at 6 MeV/m, the cavity can consume no more than 4.5 MW peak power. This requirement provides an margin of safety for operation with the system of four 8973 tetrodes, each expected to provide a maximum of 1.5 MW peak power.

4. The cavity length L should be of order 1 m, but need not be exactly this value.

5. Requirements 2-4 can be restated in terms of an effective shunt impedance per unit length $Z_{\rm eff}$ that includes the transit-time correction,

$$Z_{\rm eff} = \frac{ZT^2}{L}. \tag{1}$$

Thus, if we desire an energy gain G per unit length (energy gradient), and use a cavity of length L, the peak electric field is $E_0 = G/T$ and the power P required for this is

$$P = \frac{E_0^2}{Z} = \frac{G^2}{ZT^2} = \frac{G^2 L}{Z_{\rm eff}}. \tag{2}$$

Equivalently, to produce energy gradient G in a cavity of length L that consumes power P, the effective shunt impedance should be

$$Z_{\rm eff} = \frac{G^2 L}{P}. \tag{3}$$

For example, for $G = 6$ MeV/m, and $P = 4.5$ MW, we need $Z_{\rm eff} = 8L$ MΩ/m for a cavity of length L in meters..

6. The cavity should provide an aperture of 30 cm radius for passage of the beam.

7. The peak electric field on the walls of the cavity should be as low as possible to minimize breakdown problems. The surfaces where the field is large should have as large a radius of curvature as possible.

8. The form of the cavity should permit insertion of solenoid magnet sections that can provide a nearly uniform field of 1.25 T along the beam axis. These magnets cannot be superconducting due to the high level of energy deposition in them from particles from the primary target of E951. The magnets will be resistive, and must be powered for long periods of time during conditioning of the cavity. To minimize the electrical power bill, the magnets should contain as much copper as possible, which in turn requires as much space as possible, outside a radius of 30 cm, for the magnets.

We used the program SUPERFISH [2] to assess the cavity performance reported below. Section 2 discusses cavities of the type we favor, a quarter section of which is shown in Fig 1. Section 3 considers two variants on the cavity geometry that appear to be less desirable for our application.

2 Right Circular Cylinder Cavity with Iris

The basic cavity geometry under consideration is that shown in Fig. 1, and is based on a right circular cylinder for simplicity of fabrication. The inner radius of the irises is taken to be fixed at 30 cm in accordance with requirement 6.

We began with a cavity of overall length $L = 0.9$ m, and with nosepieces of radial extent ΔR_N of only 15 cm. The latter is rather restrictive for placement of magnets within the nosepieces, so we explored the consequences of increasing the radial gap ΔR_N.

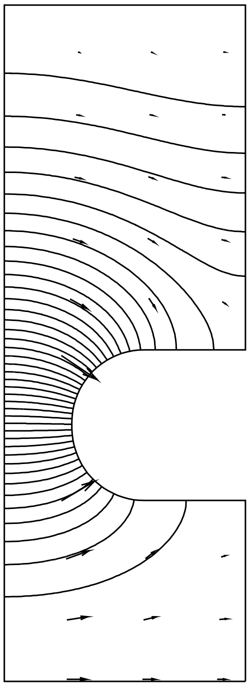

Figure 1: Quarter section of an rf cavity which is a right circular cylinder 80 cm long, with a 30-cm-radius iris and nosepieces of 25 cm radial extent.

All of the cavities studied satsified requirements 2 and 3, which are conveniently implemented in SUPERFISH via a constraint on the effective shunt impedance per unit length, $Z_{\rm eff}$. As discussed below eq. (3), our requirement for a cavity of length $L = 0.9$ m provide an accelerating gradient of 6 MeV/m using 4.5 MW power is that $Z_{\rm eff}$ be 7.2 MΩ/m.

As we increased ΔR_N, we increased the radius of curvature of the nosepiece, but always maintained an annular flat of 1 cm radial exent. Thus, the radius of curvature is $R_{\rm curv}$[m] $= (\Delta R_N - 0.01)/2$.

Table 1 summarizes the key parameters for a sequence of cavities of fixed length and accelerating gradient. As the radial exent of the nosepieces, ΔR_N, increases, so does the gap distance, $D_{\rm gap}$, between them. While a larger radial extent permits lower power magnets to be inserted in the nosepieces, the larger gap causes greater nonuniformities in the magnetic field. The larger radius of curvature associated with the larger radial extent of the nosepieces reduces the maximum electric field in the cavity, as is desirable.

We would like to maintain a large radial extent of the nosepiece, while reducing the gap between the nosepieces. This can be accomplished by reducing the overall length of the cavity. Table 2 presents a second sequence of calculations in which the radial extent ΔR_N and the accelerating gradient are held fixed while the cavity length is varied. As expected, shorter cavity length L corresponds to shorter gap distance $D_{\rm gap}$. However, shorter gap distance means higher peak electric field $E_{\rm max}$.

The criteria for chosing the best design are not yet entirely clear. We need to weigh the advantages of lower peak field against the desire for reasonably uniform magnetic field and low magnet power consumption.

Table 1: Parameters of rf cavities that are 90 cm long, with effective shunt impedance per unit length of 7.2 MΩ/m, operating at 4.5 MW so as to provide an accelerating gradient of 6 MeV/m.

ΔR_N (cm)	$R_{\rm outer}$ (cm)	$D_{\rm gap}$ (cm)	T	$E_{\rm max}$ (MV/m)
15	105.7	22.4	0.940	33.8
17	107.9	23.8	0.939	31.3
19	110.0	25.2	0.938	29.1
21	112.1	26.6	0.937	27.3
23	114.0	27.9	0.936	25.5
25	115.9	29.1	0.935	24.1

From the present survey of cavity options we favor a cavity of length $L = 80$ cm, and radial exent ΔR_N of the nosepieces, as illustrated in Fig. 1. Table 3 lists the SUPERFISH input geomtry for this cavity, and Table 4 lists the SUPERFISH output summary.

Table 2: Parameters of rf cavities that have radial exent $\Delta R_N = 25$ cm for the nosepieces and an accelerating gradient of 6 MeV/m.

L (cm)	$D_{\rm gap}$ (cm)	$R_{\rm outer}$ (cm)	$Z_{\rm eff}$ (cm)	T	$E_{\rm max}$ (MV/m)
70	16.7	108.5	5.6	0.952	28.9
80	22.5	112.2	6.4	0.943	26.2
90	29.1	115.9	7.2	0.935	24.1
100	36.8	119.7	8.0	0.923	22.7

3 Other Cavity Geometries

We explored two variants of cavity geometry besides that shown in Fig. 1.

Table 3: The SUPERFISH input geometry for the cavity shown in Fig. 1.

```
70 MHz Cavity  23 cm gap  Full length 80 cm
$reg nreg=2, dx=1.0, xmax= 40.0, ymax= 112.15, npoint=11, ndrive=1 $
$po x= 0.0,    y= 0.0 $
$po x= 0.0,    y= 112.15 $
$po x= 40.,    y= 112.15 $
$po x= 40.,    y=  55.  $
$po x= 23.232, y= 55.  $
$po nt=2, x0= 23.232, y0= 43., r= 12., theta= 180.  $
$po x= 11.232, y= 42.  $
$po nt=2, x0= 23.232, y0= 42., r= 12., theta= 270.  $
$po x= 40.,    y= 30.  $
$po x= 40.,    y= 0.0 $
$po x= 0.0,    y= 0.0 $
$reg  npoint=1 $
$po x= 0.0,    y= 112.15.  $
```

3.1 Rounded Cavity

It is often favorable to build cavities with more rounded outer walls. Here, we considered a cavity of overall length $L = 80$ cm, radial extent $\Delta R_N = 25$ cm for the nosepieces, and accelerating gradient of 6 Mev/m, as shown in Fig. 2. We found that rounding the outer walls required reducing the gap distance $D_{\rm gap}$ to 20.0 cm, which pushed the peak electric field up to 28.7 MV/m. This is 2 MV/m higher than the case of the 80-cm-long cavity based on a right circular cylinder, and so does not seem preferable.

3.2 Cavity with No Irises

An option that is conceivable in a muon beam is a cavity with no irises, such as that shown in Fig. 3. This will have a greatly reduced peak electric field compared to the cavities with irises.

We considered only cavities of overall length 80 cm, and inner radii of 55 cm to allow for a 30-cm-radius beam and 25 cm of magnet coils. First, we kept the gap distance fixed at $D_{\rm gap} = 22$ cm, but this requires 8.4 MW of power to achieve an acclerating gradient of 6 MeV/m.

A gap distance of $D_{\rm gap} = 31.5$ cm, as shown in Fig. 3 is required to reduce the power consumption to the nominal 4.5 MW when the accelerating gradient is 6 MeV/m. This large gap is unfavorable for the magnetic field uniformity.

4 Cavity Plus Magnets

Figure 4 shows a possible configuration for the rf cavity together with pulsed and continuous copper magnets for E951, using the rf cavity shown in Fig. 1. The dc magnets consume 1.1 MW to provide an average field of 1.25 T along the cavity axis.

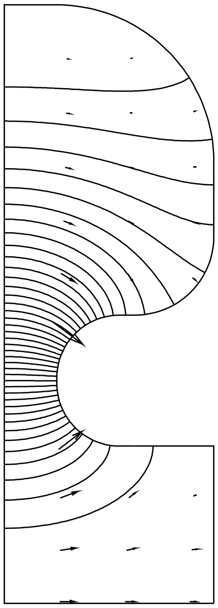

Figure 2: Quarter section of an rf cavity similar to that of Fig. 1 but with rounded outer walls.

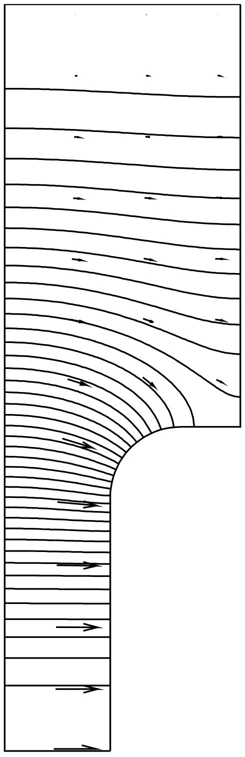

Figure 3: Quarter section of an rf cavity derived from the design of Fig. 1 but with no irises. The beam would pass through the walls of the cavity.

Table 4: The SUPERFISH results for the cavity shown in Fig. 1.

```
*******************************************************************************
*               POISSON/SUPERFISH GROUP OF CODES (RELEASE 4.00)              *
*   Copyright (c) 1965,1991 The Regents of the University of California      *
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PROB. NAME =  70 MHz Cavity  23 cm gap  Full length 80 cm

Full cavity length [2L]  =   80.0000 cm         Diameter =  224.3000 cm
Mesh problem length [L]  =   40.0000 cm
Full drift-tube gap [2g] =   22.4640 cm
Beta                     = 0.8400000       Proton energy =   790.952 MeV
Frequency [f] (starting value =  70.000) =                 70.028908 MHz
Eo normalization factor (CON(74)=ASCALE) for  1.000 MV/m =    8248.9
Stored energy [U] for mesh problem only =                 5712.84766 mJ
Power dissipation [P] for mesh problem only =               55634.36 W
Q (2.0*pi*f(Hz)*U(J)/P(W)) =                                   45182
Transit time factor [T] =                                    0.94332
Shunt impedance [Z] mesh problem only, ((Eo*L)**2/P) =       2.87592 Mohm
Shunt impedance per unit length [Z/L] =                        7.190 Mohm/m
Effective shunt impedance per unit length [Z/L*T*T] =          6.398 Mohm/m
Magnetic field on outer wall =                                  2210 A/m
Hmax for wall and stem segments at z= 40.00,r= 55.00 cm =       3875 A/m
Emax for wall and stem segments at z= 11.32,r= 44.41 cm =      4.119 MV/m

> Beta        T      Tp         S        Sp     g/L           Z/L
0.83999997  0.94332  0.07936  0.27230  0.18179  0.280800    7.189801

ISEG   zbeg     rbeg     zend     rend  Emax*epsrel   Power     df/dz    df/dr
>      (cm)     (cm)     (cm)     (cm)    (MV/m)       (W)         (MHz/mm)
Wall-----------------------------------------------------------------------Wall
> 2   0.0000 112.1500  40.0000 112.1500   0.0209  14787.4033   0.0000  -0.0525
> 3  40.0000 112.1500  40.0000  55.0000   0.3140  25487.8047  -0.0869   0.0000
> 4  40.0000  55.0000  23.2320  55.0000   1.1628   8953.6846   0.0000  -0.0262
> 5  23.2320  55.0000  11.2320  43.0000   4.1193   5708.3193   0.1081   0.0602
> 6  11.2320  43.0000  11.2320  42.0000   3.9935    112.0921   0.0111   0.0000
> 7  11.2320  42.0000  23.2320  30.0000   4.0672    569.7812   0.0814   0.0392
> 8  23.2320  30.0000  40.0000  30.0000   0.7561     15.2754   0.0000   0.0011
Wall----------------------------------- Total =   55634.3633 --------------Wall
```

5 References

[1] J. Alessi *et al.*, *An R&D Program for Targetry at a Muon Collider*, proposal to the BNL AGS (Sept. 1998), http://puhep1.princeton.edu/mumu/target/targetprop.ps

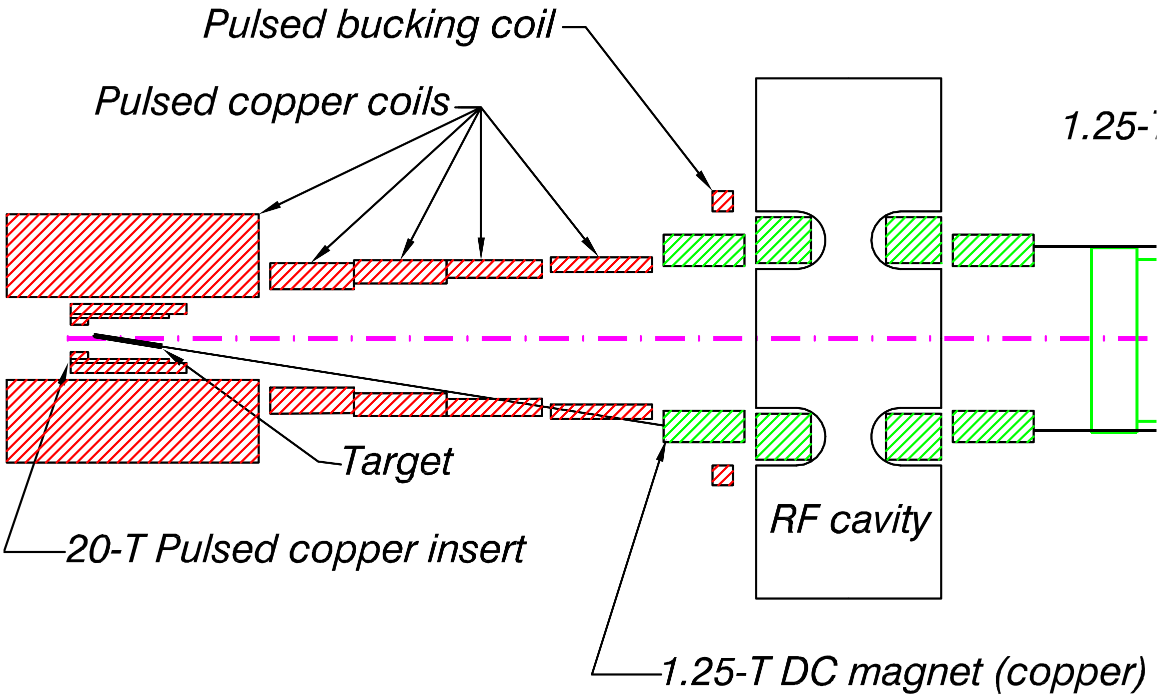

Figure 4: Layout of the pulsed and dc magnets plus an 80-cm-long rf cavity for E951.

[2] *POISSON/SUPERFISH Reference Manual*, LA-UR-87-126 (1 Jan. 1897), http://lib-www.lanl.gov/la-pubs/00202468.pdf