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CONSIDERATIONS ON LOW FREQUENCY HIGH GRADIENT CAVITIES FOR MUON CAPTURE AND COOLING

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Abstract

In this note we discuss some alternatives in the design of low frequency cavities for Muon capture and cooling in a Neutrino Factory.

Both solutions with closed and open irises are considered. The comparison between the various solutions is based on dimensions and power per unit length, for a given accelerating gradient.

INTRODUCTION

A neutrino factory [1] comprises schematically a proton acelerator, a target on which the protons produce pions which decay into muons, a capture and cooling pre-accelerator, various recirculating linacs and a decay ring. Muons are unstable, their rest frame lifetime being 2.2 µs, so they must be accelerated in the shortest possible time in order to increase their lifetime and avoid losses before injection into the decay ring . Moreover the beam tube must be large so as to accept a large number of particles.

The accelerating cavities in the first section of the capture channel should have low frequency to allow a large bore and the electric field gradient should be the highest compatible with breakdown limits. There has to be moreover an axial confining magnetic field superimposed on the accelerating electric field. Two configurations have been proposed : 1) at Fermilab, large diameter solenoid enclosing 200 MHz cavities [2] and 2) at CERN, 44 MHz cavities and smaller diameter solenoids directly on the beam tube [3]. The specifications of the CERN study are an accelerating gradient larger than 2 MV/m and an axial magnetic field of 1.8 T/m. The beam pulse lasts only 3 µs with a repetition rate of 100 Hz, therefore by using short RF pulses one lower the average power, but a lower limit is set by the cavity filling time.

CAVITY DESIGN

The first solution requires radially compact cavities; this is difficult to implement at the low 44 MHz frequency proposed at CERN. One way around this difficulty is to use the folded coaxial configuration. The optimization of the cavity shape must respect the limits of the available RF generator power and of the peak surface field. For the power we have assumed 2 MW per coupler for a duty cycle of a few percent and for the field twice the usual Kilpatrick limit which, at 44 MHz, is about 8 MV/m. In Fig 1 is shown a typical shape of the cavity. We have made a parametric study by varying the length and the outer radius while keeping the resonant frequency constant , an accelerating gap of 16 cm and the distance between conducting surfaces larger than 10 cm. The inner radius is 35 cm as dictated by the 30 cm acceptance required for the channel plus a margin for the vacuum pipe and cavity wall dimensions. The iris is supposed to be covered by conducting planes formed by Berillium sheets or tube grids so thin as to be transparent to muons. In Figs 2 and 3 are shown the shunt impedance and the form factor as a function of cavity length for various outer diameters . The parameters of the cavities have been computed by code URMEL [7].

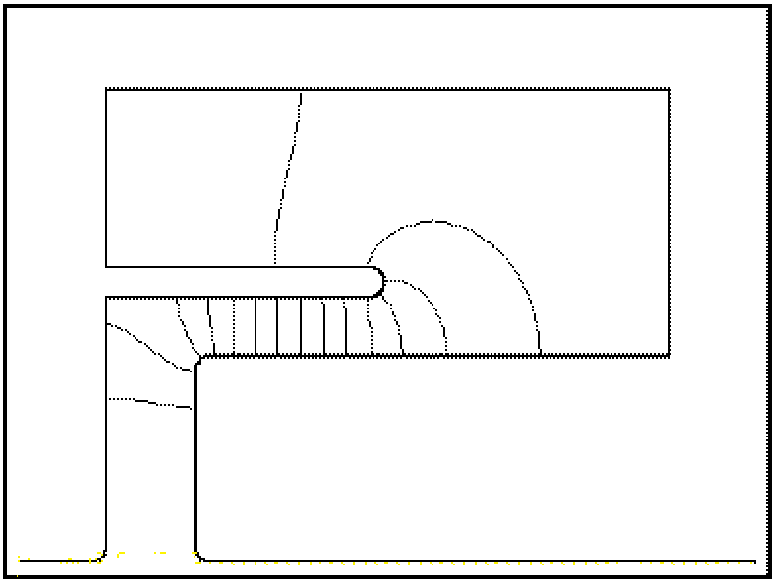

Fig. 1 – Folded coaxial cavity shape.

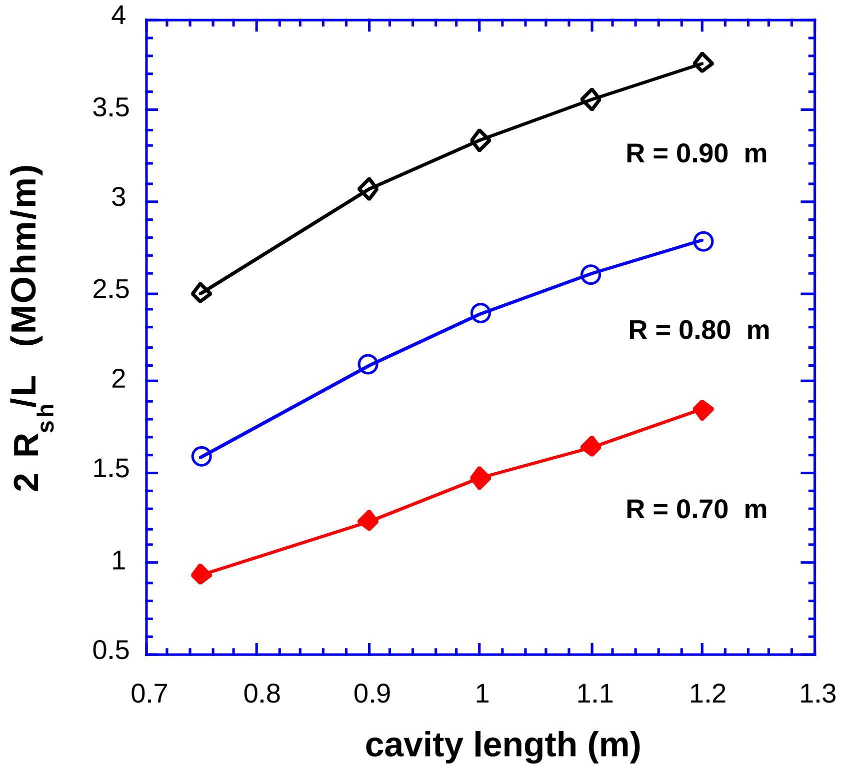

Fig. 2 – Shunt impedance vs cavity length.

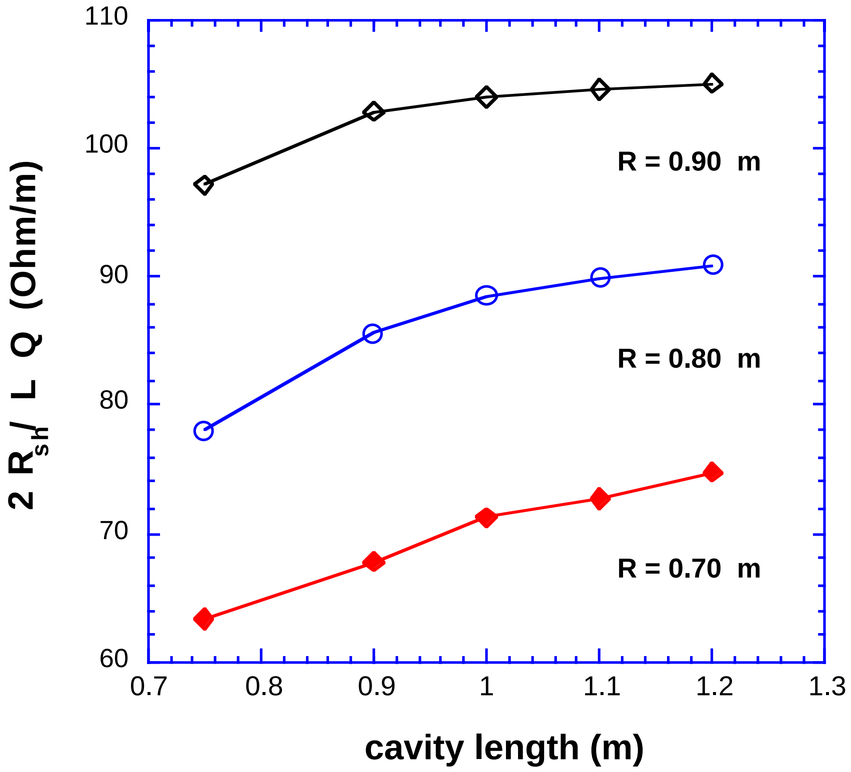

Fig. 3 – Form factor vs cavity length.

In Table 1 is shown a comparison between a solution chosen from the above diagram and the CERN solution. We observe that for a radius about one half of the CERN one, the so called Frascati solution shows a lower shunt impedance, because of the more unfavourable ratio of surface to volume. However the filling time results shorter so that the average dissipated power can be kept constant by decreasing the duty cycle.

Table 1 – Radially compact vs pill box.

	CERN	FRASCATI
Freq	44 MHz	44 MHz
Radius	1.44 m	0.80 m
Gap	0.16 m	0.16 m
Length	1 m	1 m
Gradient	2 Mv/m	2 MV/m
2Rsh/LQ	114 Ω/m	88 Ω/m
Q	48000	26900
2Rsh/L	5.5 MΩ/m	2.4 MΩ/m
Power	0.73 MW/m	1.6 MW/m
Avg. power	60 kW/m	64 kW/m
Duty cycle	8%	4%
T fill	350 μs	195 μs

A similar study has been performed for the second configuration (solenoids on beam tube) with the aim of obtaining a more compact cavity in the axial direction, allowing for a larger outer radius than in the first solution. It is thus possible to pack more cavities per unit length and so to achieve a larger effective accelerating gradient. In Fig 4 is shown a typical cavity shape.

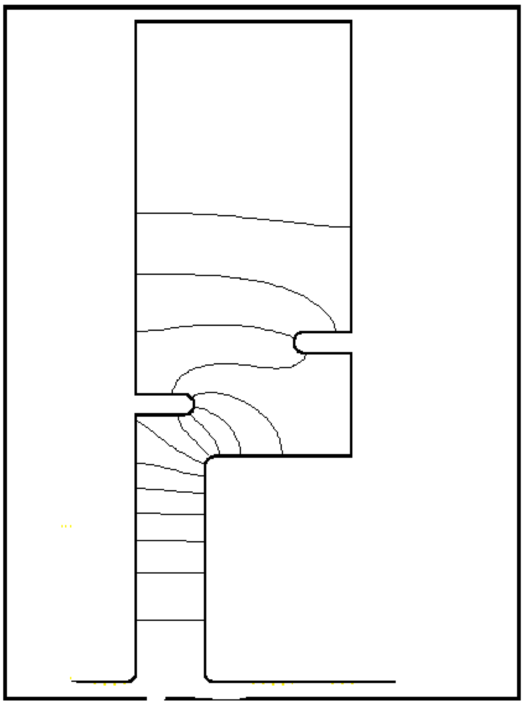

Fig. 4 – Axially compact cavity.

In Figs. 5 and 6 are shown shunt impedance and form factor versus cavity length for various outer radii and in Tab 2 a comparison between the CERN and the Frascati solutions. It is to be noticed that for the same average power per meter a higher effective accelerating gradient can be obtained with a lower peak field on the surface

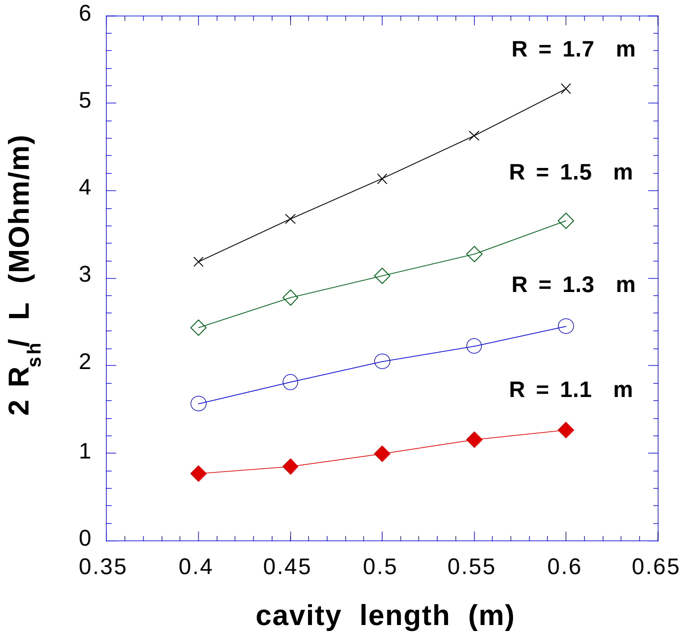

Fig. 5 – Shunt impedance vs cavity length.

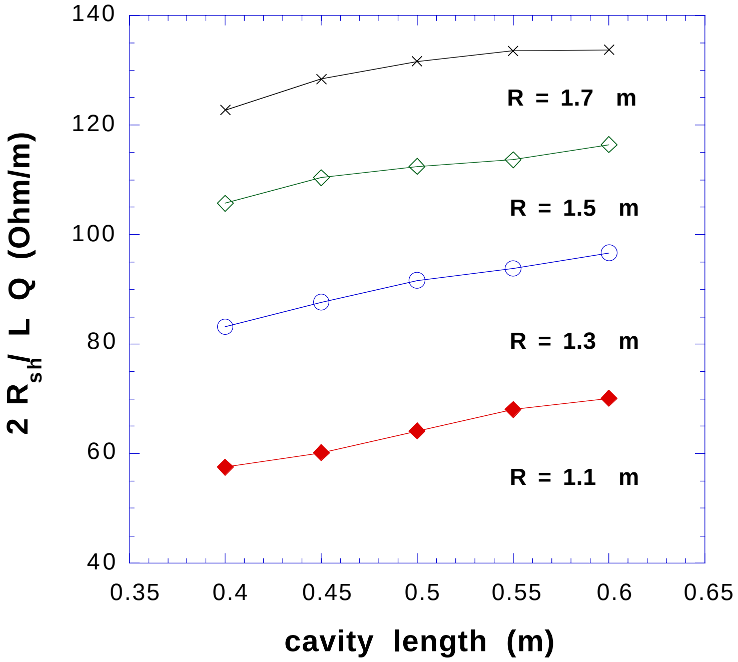

Fig. 6 – Form factor vs cavity length.

Table 2 – Axially compact vs pill box.

	CERN	FRASCATI
Freq	44 MHz	44 MHz
Radius	1.44 m	1.6 m
Gap (d)	0.16 m	0.16 m
Length (l)	1 m	0.5 m
Gradient (E)	3 MV/m	3.4 MV/m
Ep (*)	18.7 MV/m	10.6 MV/m
Ep/Ekil	2.34	1.32
2 Rsh/l	5.5 MΩ/m	3.5 MΩ/m
Power	1.6 MW/m	3.2 MW/m
Pav	130 kW/m	130 kW/m
Duty cycle	8%	4%
Tfill	350 µs	227 µs

(*) $Ep \approx E\, l/d$

In Fig. 7 is shown a sketch of the assembly of a succession of cavities.

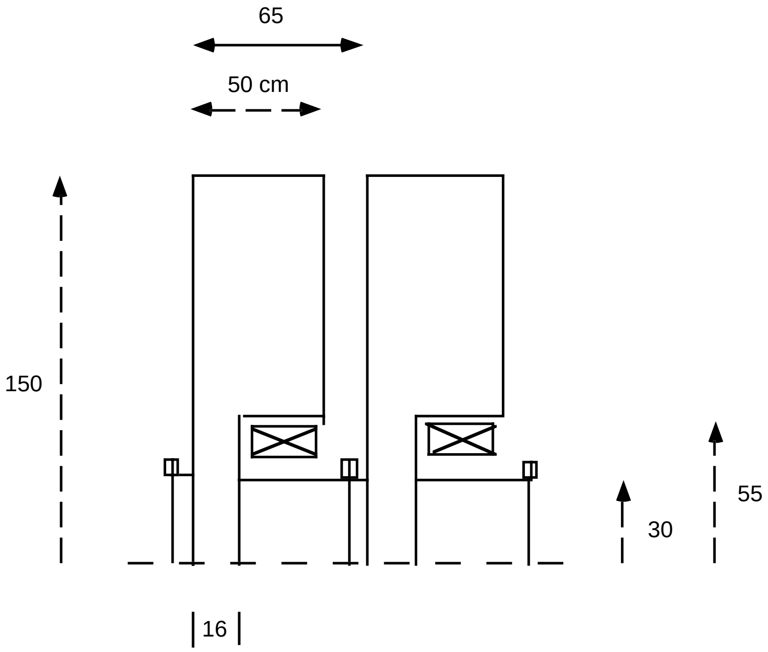

Fig. 7 – Sketch of cavity chain.

OTHER SOLUTIONS

Another configuration (which we denote by “mushroom”) that allows compact radial dimensions is shown in Fig 8. It can be considered as a cascade of a radial line and a folded coaxial [4]. In Table 3 are shown its parameters.

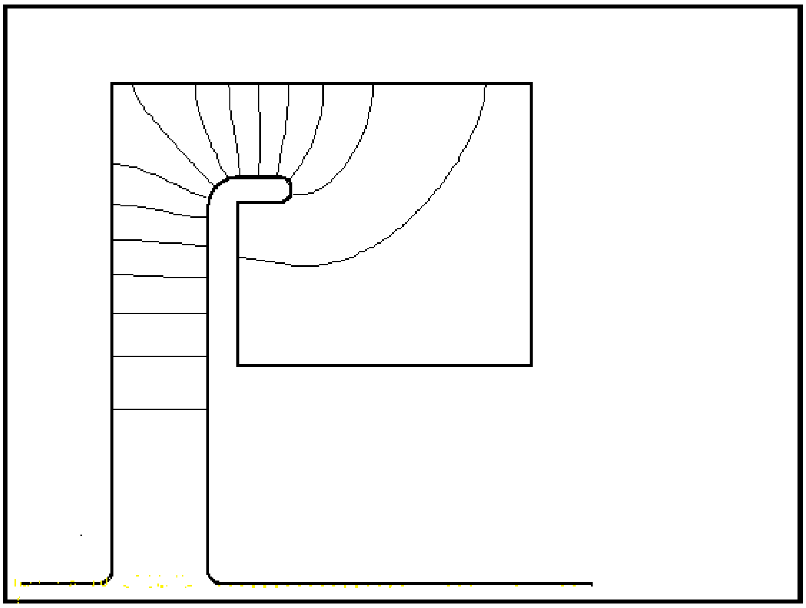

Fig. 8 – "mushroom" compact cavity.

Table 3 - Parameters of "mushroom" cavity.

Freq	44 MHz
2Rsh/Lq	80 Ω/m
2Rsh/L	1.7 MΩ/m
Q	21000
P	2.4 MW/m
Pavg	96 kW/m
Tfill	152 µs
Radius	0.8 m
Length	0.70 m

CAVITY WITH OPEN IRISES

The conducting foils on the irises interact with the muon beam. If the cooling function is reserved to a separate medium (i.e. liquid Hydrogen), these foils represent a perturbation and their effect on emittance should be taken into account . It is possible that the iris foils themselves could constitute the cooling media. Berillium foils however are very thin and can easily be broken by occasional discharges in the gap. Tube grids are more resistant but suface dissipation and beam scattering must be accurately evaluated.

For completeness we report the case of a mushroom cavity with open irises. It is evident that the electric field lines in the gap are very curved with respect to the closed iris case. There is therefore a strong radial component increasing with the distance from the cavity axis which could cause defocusing effects. In Fig 9 is shown the shape of such a cavity and in Tab 4 the corresponding parameters.

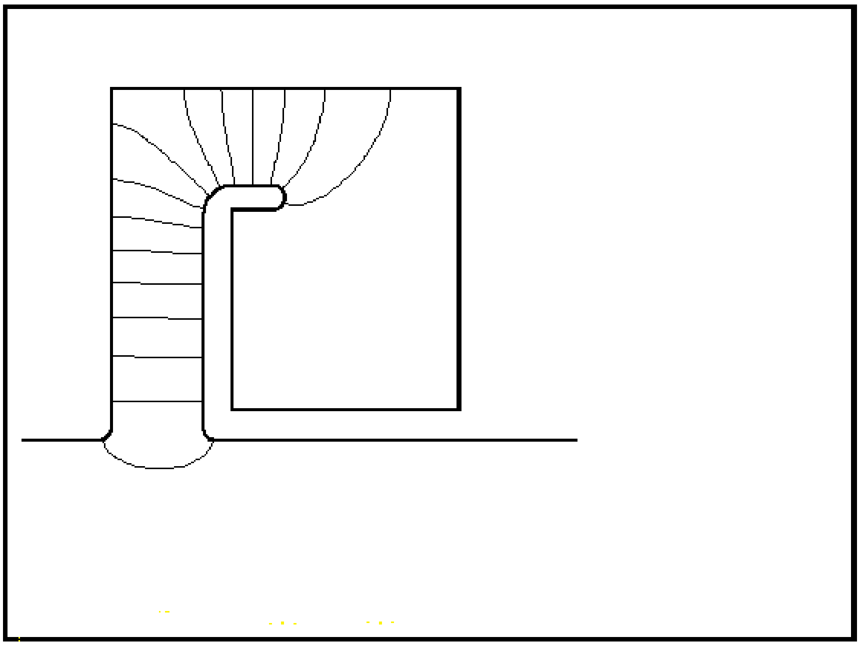

Fig. 9 – Compact cavity with open irises.

Table 4 – Parameters of the cavity with open irises.

Freq	44 MHz
2Rsh/LQ	46 Ω/m
2Rsh/L	0.94 MΩ/m
Q	20500
P	4 MW/m
Pavg	160 kW/m
Tfill	148 μs
Length	0.6 m
Radius	0.88 m

CONCLUSIONS

Cavity configurations that are more compact than the simple pill box with re-entrant noses can be obtained by capacitive loading and folded coaxials. The shunt impedances, though lower than that of the simple pill box , allow comparable average dissipated power by decreasing the duty cycle. Anyway the average power per meter remains high and can be lowered only by decreasing the repetition rate. Several compact cavities have been built in this frequency range [5,6], but generally they were designed for CW operation in circular machines and not tested with short high power pulses. Therefore the peak field holding capacity which has been assumed in the above examples is only indicative and must be ascertained on a prototype. The design of such a prototype must foresee room for the superconducting solenoids. The stray static magnetic fields from these could be beneficial in suppressing some multipacting levels.

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