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CAVITY DESIGN FOR THE CERN MUON COOLING CHANNEL

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Abstract

The cooling channel of the CERN reference scenario for a possible neutrino factory requires an approximately 200 m long lattice, which provides solenoidal magnetic fields plus longitudinal electric fields at the same time. The electric real estate field gradient along the structure shall be 2 MV/m at 44 MHz, or 4 MV/m at 88 MHz respectively. The CERN approach incorporates the solenoids into the cavity geometry in oder to avoid the large dimensions of solenoids surrounding the cavity structure. Since the idealistic assumption of a constant solenoidal field along the cooling channel is broken by this approach, an iteration between beam dynamics requirements and RF engineering feasibility is necessary to define an optimized structure. In this paper we shall describe the various cavity design options that have been considered up to now and we report on the preparation of a cavity test stand for a 88 MHz cavity.

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1 First Generation

The high field strength (2 - 6 T) of the superconducting solenoids imposes the use of normalconducting technology for the RF cavities. To accommodate the large phase space of the muon beam a large acceptance is needed, yielding low frequencies, high gradients, and a large bore radius (see Table 1). These contradicting requirements can only be fulfilled by accepting a relatively poor power efficiency and bulky amplifiers with high peak power.

A common feature of all presented designs is the avoidance of thin conducting windows, which could be used to straighten the field lines in the gap, but which would complicate the mechanical design as well as the beam dynamics of the muon beam.

The first preliminary design approach tackled the problem of incorporating a superconducting solenoid into a cavity without substantial degradation of the RF performance.

Table 1: Cavity requirements

cavity	**bore radius**	**real estate gradient**	**amplifier power**
44 MHz	300 mm	2 MV/m	≤ 2 MW
88 MHz	150 mm	4 MV/m	≤ 2 MW

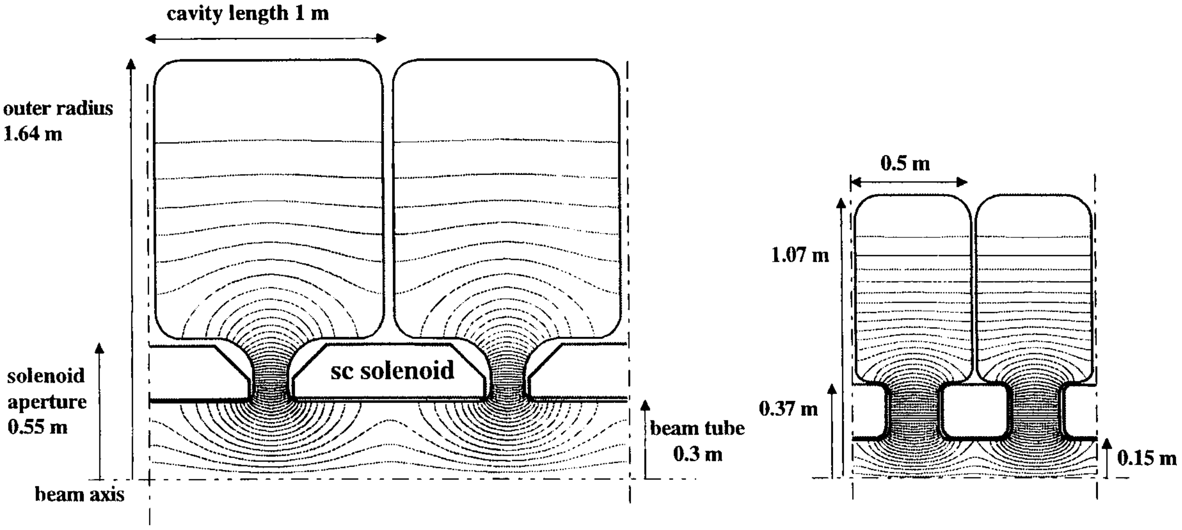

Figure 1: 1st scheme of assembling 44 and 88 MHz cavities with solenoids

As we can see from Table 2 the RF power consumption as well as the size of the amplifiers are still reasonable, while the dimensions of the cavities are huge (3.3 m diameter for the 44 MHz cavity), possibly yielding problems of mechanical stability. Although these cavities nicely incorporate the solenoids, the assemblage of such a multi cavity lattice is a serious problem (imagine the replacement of a solenoid or a cavity in case of maintenance). Furthermore the superconducting solenoids, which are exposed to considerable particle losses from the muon beam need constant supply of helium that is not foreseen in this preliminary design. As a consequence these designs might be suited for applications where single cavities are needed but not for a continuous chain.

2 Second Generation

The second approach takes care of the mechanical feasibility and features smaller cavity dimensions, which eases the mechanical construction but raises the power consumption and electric surface fields. By means of asymmetric designs with increased lengths, as shown in Figure 2, solenoid plus cavity can be constructed in units. Since the space for the solenoid supplies is almost independent from the solenoid size, the unit length was increased in order to obtain a

Table 2: Parameters (*) of the first generation of cavities for 50 Hz repetition rate

cavity	Z_{TT} [MΩ/m]	R/Q [Ω]	P_{peak} [MW/cav.]	τ [μs]	P_{mean} [kW/m]	Kilp.	$R_{cav.}$ [m]	solenoid [m]	$l_{sol.}/l_{cav}$
44 MHz	6.5	60.4	0.62	390	36.3	1.88	1.64	0.8 x 0.23	0.8
88 MHz	10.8	60	0.74	164	36.3	1.2	1.07	0.28 x 0.2	0.56

* the definitions for the above values are given in appendix A

better mechanical filling factor of solenoid length over unit length. The maximum length is limited by the resulting shape of the cavity (more copper surface per volume yields higher losses) and the maximum amplifier power (larger cavities with higher stored energy require higher peak power).

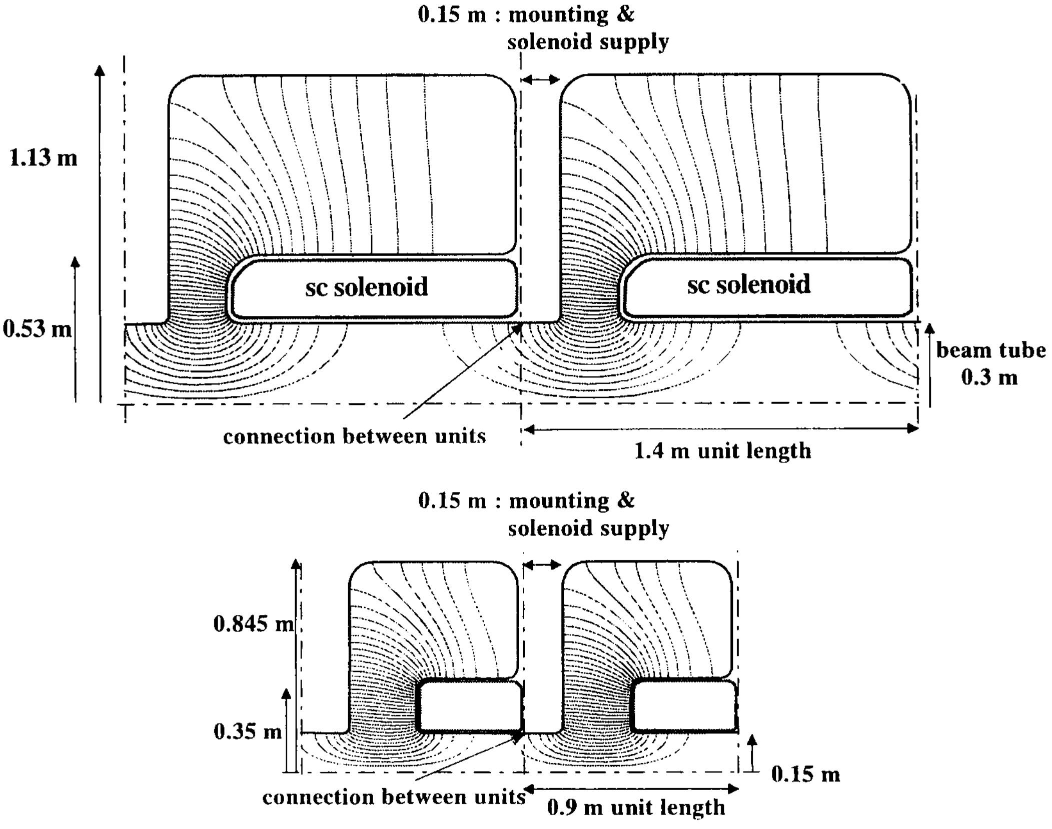

Figure 2: Actual scheme of assembling 44 (upper) and 88 MHz (lower) cavities with solenoids

Compared to the first designs the actual scheme consumes almost twice the power per meter and needs amplifiers with 3 times higher peak powers. On the other hand the design requires $\approx$ 45% less amplifiers, due to the longer cavities. The mechanical assemblage of the lattice is now straightforward and the peak electric field is still within technological feasibility (2.3 Kilpatrick for both cavities).

Since the beam dynamics of the cooling channel are still under study as well as the design of the solenoids, the final cavity dimensions are likely to change. In order to estimate the resulting RF parameters for different cavity spapes, we investigate the impact of three different geometrical changes (results in the appendix, Fig. 5 - 7):

1. change in gap length (and solenoid length) (see Fig. 5),
2. change in beam pipe radius while keeping the solenoid dimensions unchanged (see Fig. 6),
3. change in outer solenoid radius, while the beam tube radius is kept constant at 0.15 m (see Fig. 7).

Table 3: Parameters of the actual generation of cavities for 50 Hz repetition rate

cavity	Z_{TT} [MΩ/m]	R/Q [Ω]	P_{peak} [MW/cav.]	τ [μs]	P_{mean} [kW/m]	Kilp.	$R_{cav.}$ [m]	solenoid [m]	$l_{sol.}/l_{cav}$
44 MHz	3	103	1.86	296	59	2.3	1.13	0.96 x 0.21	0.69
88 MHz	7	144	2.04	159	54	2.3	84.5	0.4 x 0.17	0.44

The length of the unit is kept constant as well as the Kilpatrick level, meaning that the cavity diameter and nose radius are adapted to each design. From the Figures 5 to 7 one can see the relative change of the RF parameters, in case that "longer" or "thicker" solenoids become necessary. The changes are based on the values for the reference design (Table 3).

3 88 MHz Test Cavity

Obtaining high gradients with low frequency cavities is a challenging task, especially with the complication of strong magnetic fields penetrating parts of the cavity. In order to study the engineering issues of these cavities, a test stand is being prepared at CERN for a 88 MHz cavity whose geometry is similar to the "first generation" design. The cavity was originally used in the PS ring to accelerate electrons and positrons [3] with a gap voltage of 500 kV and resonated at 114 MHz. With the insertion of new "noses" (copper coated stainless steel, copper layer ≈ 40 μm $\approx 7\cdot$ skin depth), the cavity frequency is changed to 88 MHz (Table 4, Fig. 3).

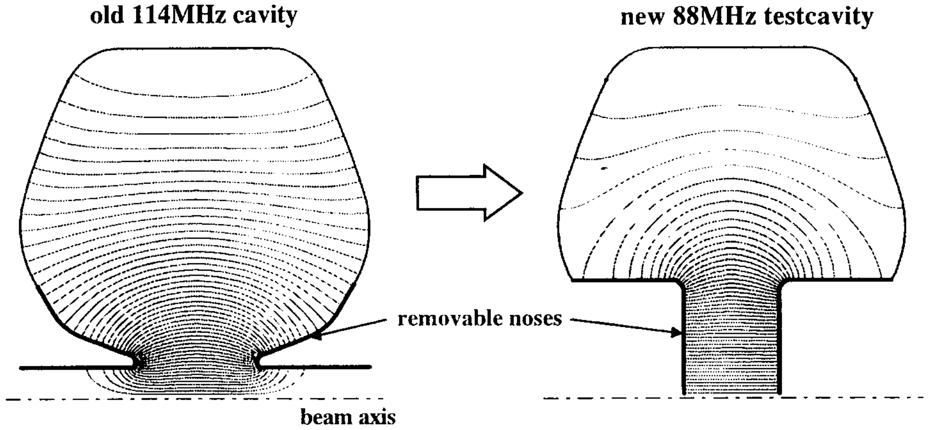

Figure 3: Modification of old 114 MHz cavity to a 88 MHz test-cavity

With a length of 1 m, the cavity is designed for the reference gradient of 4 MV/m and a Kilpatrick level of 2.3, corresponding to the actual value of the "second generation" design. The cavity will be pulsed at a lower repetition rate (1 Hz instead of 50 Hz) to lower the cooling requirements with respect to the final design. Table 5 compares the parameters of the test-cavity with the values for the "second generation" design and Figure 4 shows the expected loss distribution according to SUPERFISH [4].

First measurements of the cavity confirmed the frequency but showed a 30% lower quality factor than predicted by SUPERFISH, an indication that a new surface treatment could become necessary to achieve the design gradient. High power tests will start towards the end of the year, when a suitable amplifier will be available.

Table 4: Geometry of the 88 MHz test-cavity

length [m]	radius [m]	gap length [mm]	solenoid diameter [m]
1	0.88	280	0.51

Table 5: Parameters for the 88 MHz design- and test-cavities (calculated by SUPERFISH)

cavity type	f_{rep} [Hz]	E_0T [MV/m]	Q	R/Q [Ω]	t_{pulse} [ms]	$P_{amp.}$ [MW]	P_{mean} [kW/m]	Kilp.	$R_{cav.}$ [m]	$l_{sol.}$ [m]
design	50	4	44000	144	0.48	2.04	54	2.3	0.845	0.4
test	1	4	50000*	113	0.55	1.4	0.77	2.3	0.885	> 0.45

* measurements under vacuum without power coupler but with attached pumps: Q = 35000, f = 87.892 MHz

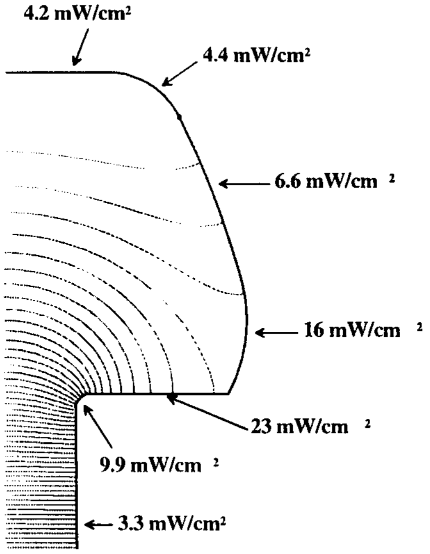

Figure 4: Loss distribution on the 88 MHz test-cavity

4 Conclusions

The RF performance of the cooling channel cavities is a crucial issue for the feasibility of the actual CERN reference scenario for a future neutrino factory. A scheme was developed that combines reasonable RF power requirements with a mechanically straightforward design, that also fulfils the needs of the present beam dynamics layout.

The upcoming RF tests of the 88 MHz cavity will reveal possible technical difficulties in achieving the desired gradient of 4 MV/m at a peak field level of 2.3 Kilpatrick. This test will also be an important benchmark for multipactor simulation codes that will be used to understand the multipactor mechanisms in the presence of strong magnetic fields. Our next goal is to proceed with the design of superconducting solenoids, enabling high power tests in the presence of high magnetic fields.

References

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[3] B.J. Evans et. al. The 1 MV 114 MHz Electron Accelerating System for the CERN PS, CERN/PS/RF 87-15. In *PAC*, 1987.

[4] J.H. Billen; L.M. Young. *Poisson, Superfish - Documentation LA-UR-96-1834*. LANL, Los Alamos, NM 87545, 1999.

A Definitions of shunt impedance and mean power

$$
\begin{aligned}
r &= r_s \cdot T^2 = \frac{V_0^2}{P_{wall}} \cdot T^2 && \textbf{shunt impedance} \quad (1)\\
\tau &= \frac{Q}{\pi \cdot f_{cavity}} && \textbf{filling time} \quad (2)\\
P_{mean} &= P_{wall} \cdot 3\tau \cdot f_{rep.} && \textbf{mean power} \quad (3)
\end{aligned}
$$

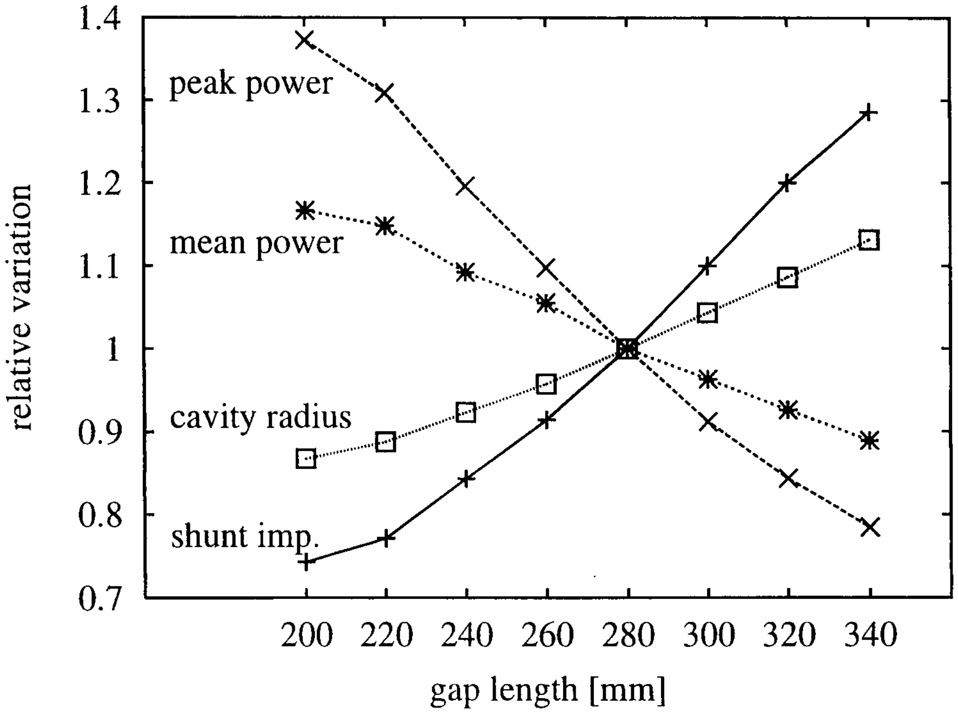

Figure 5: Relative variation of RF parameters of the 88 MHz cavity with respect to the gap length. We note that for a gap of 200 mm the upper nose radius (upper left corner of the solenoid) has to be 140 mm instead of 50 mm in order to keep the maximum field level at 2.3 Kilpatrick. A change that reduces the effective space, which is available for the solenoid

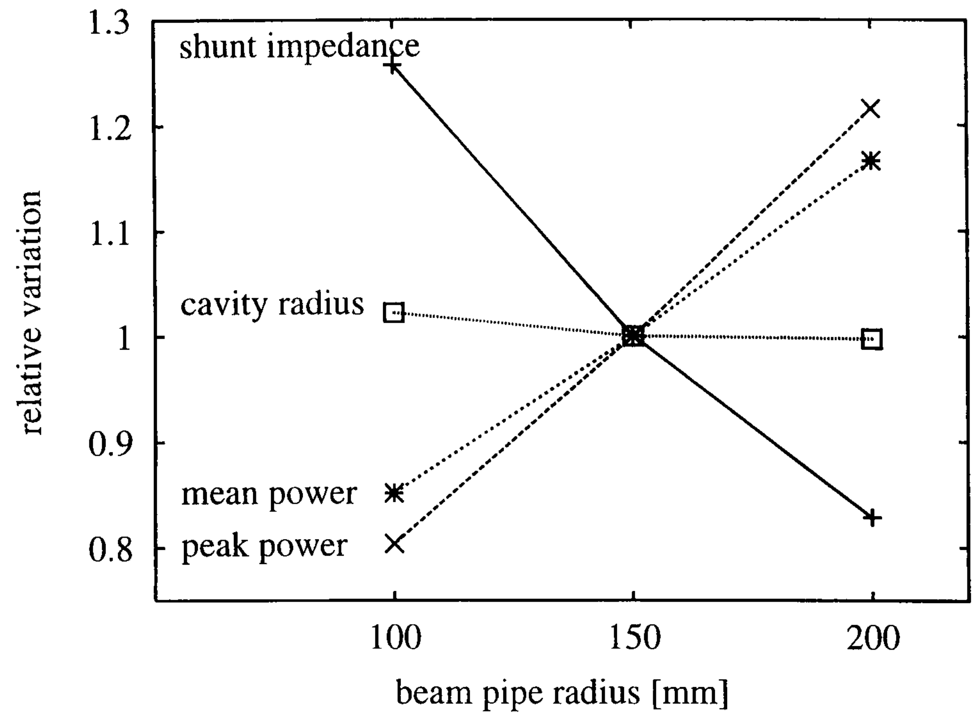

Figure 6: Relative variation of RF parameters of the 88MHz cavity with respect to the beam pipe radius

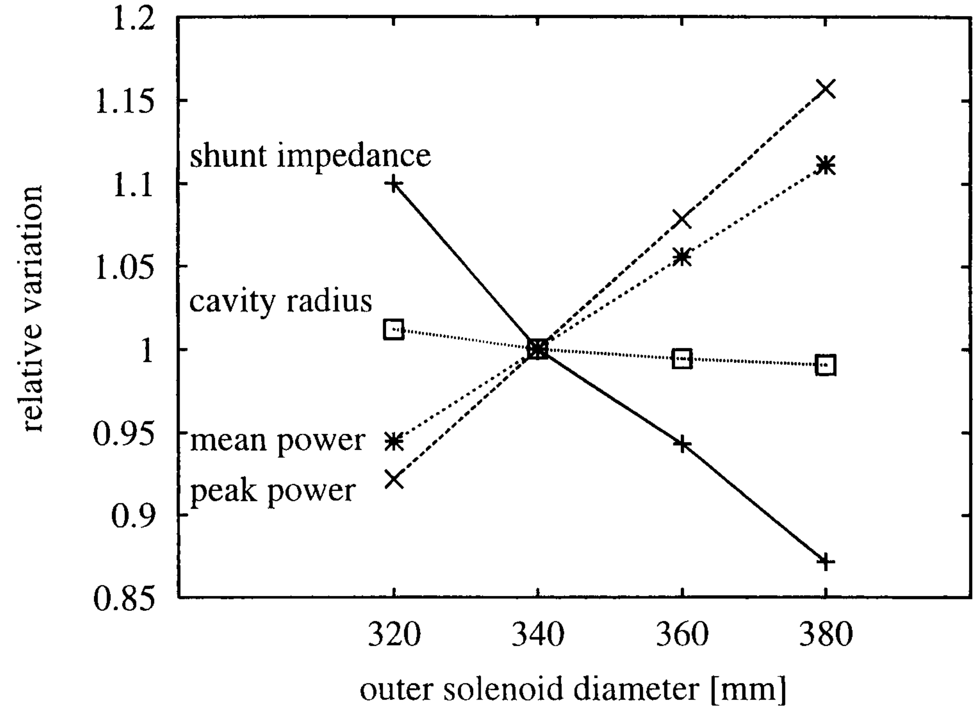

Figure 7: Relative variation of RF parameters of the 88MHz cavity with respect to the outer solenoid radius (constant inner radius)