HIGH GRADIENT TESTS OF AN 88 MHZ RF CAVITY FOR MUON COOLING

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Abstract

The scheme for a Muon Cooling channel developed at CERN in the frame of Neutrino Factory studies foresees the use of 44 and 88 MHz cavities operating at a real-estate gradient as high as 4 MV/m. To assess the feasibility of this scheme, including high-gradient operation at relatively low frequency and the production and handling of high RF peak powers, a test stand was assembled at CERN. It included an 88 MHz resonator reconstructed from a 114 MHz cavity previously used for lepton acceleration in the PS, a 2.5 MW final amplifier made out of an old linac unit improved and down-scaled in frequency, and a PS spare amplifier used as driver stage.

After only 160 hours of conditioning the cavity passed the 4 MV/m level, with local peak surface field in the gap exceeding 25 MV/m (2.4 times the Kilpatrick limit). The gradient was limited by the amplifier power, the maximum RF peak output power achieved during the tests being 2.65 MW.

This paper presents the results of the tests, including an analysis of field emission from the test cavity, and compares the results with the experience in conditioning ion linac RF cavities at CERN.

INTRODUCTION

The interest in high gradient testing of 88 MHz cavities comes from their possible use in the CERN Neutrino Factory scheme [1].

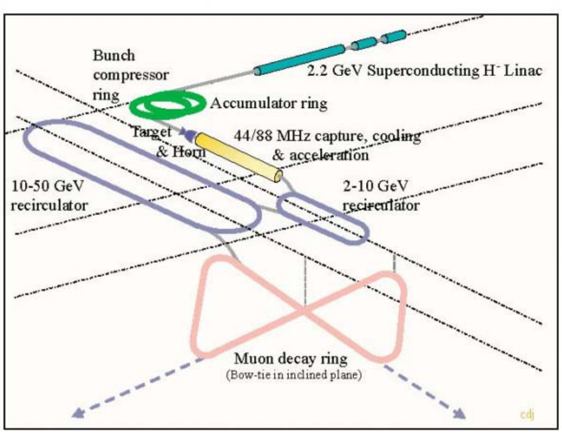

Figure1: The CERN scheme for a Neutrino Factory.

In the Neutrino Factory layout (Figure 1) a 4 MW proton beam (average power) is sent to a mercury target where pions are generated, with energies between 100 and 300 MeV. The collected pions then decay into muons along a 30 m decay channel, at the end of which two series of RF cavities, at 44 and 88 MHz, cool down the muon beam by means of phase rotation and hydrogen absorber cells. The muons are then accelerated to 1 GeV by more 88 MHz cavities of the same kind [2]. Cooling of the muon beam is particularly challenging in all Neutrino Factory schemes. The cooling channel must have a large acceptance, meaning large apertures at low frequencies, and has to provide extremely high gradients for compactness and to improve longitudinal acceptance. The cavities need to incorporate large solenoids for transverse focusing, and apart from the construction complications this leads to poor shunt impedance, meaning that an additional problem is the generation and feeding of very large amounts of peak RF power. In order to explore the gradient limit of 88 MHz cavities, for which little experimental data existed, an experimental set-up has been prepared at CERN using mostly recuperated equipment from different CERN accelerators. The goal was to demonstrate that 88 MHz cavities could operate at a real estate gradient of 4 MV/m with a peak RF power > 2 MW, and to gain experience in the RF power generation and handling and in the conditioning of muon cooling cavities. However, the duty cycle in the test stand was limited by the reduced cooling of the recuperated hardware. Maximum repetition frequency was 1 Hz, considerably lower than the nominal Neutrino Factory value of 50 Hz.

CAVITY CHARACTERISTICS

The 88 MHz cavity has been obtained by modifying an existing 114 MHz cavity previously used in the PS accelerator at CERN, to process the lepton beam for LEP.

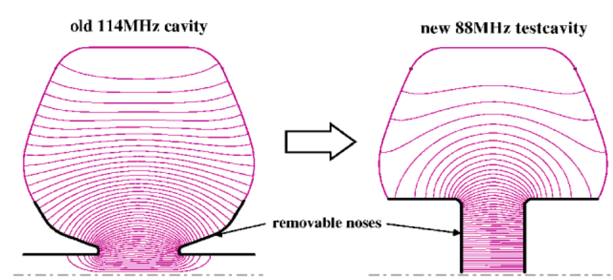

Figure 2: Modification of the 114 MHz cavity for 88 MHz.

In the CERN muon cavity design, a superconducting focusing solenoid is integrated around the beam pipe and close to the accelerating gap, avoiding the use of thin conducting windows, which produce a homogeneous gap field but which complicate the mechanical design and the muon beam dynamics. However, in transforming the existing 114 MHz cavity (Figure 2, left) it was impossible to reproduce exactly the gap structure of the muon cavity keeping the 88 MHz frequency. Instead a “parallel face gap” design (Figure 3, left) was preferred that has the same ratio between peak field and gradient as the ideal cavity (Fig. 3, right) and could be easily obtained by machining two new “half gaps” to be mounted in the existing cavity body. The length of the test cavity being 1 m, the goal was to reach a gap voltage of 4 MV, corresponding to a peak surface field (on the nose corners) of 2.3 times the Kilpatrick limit.

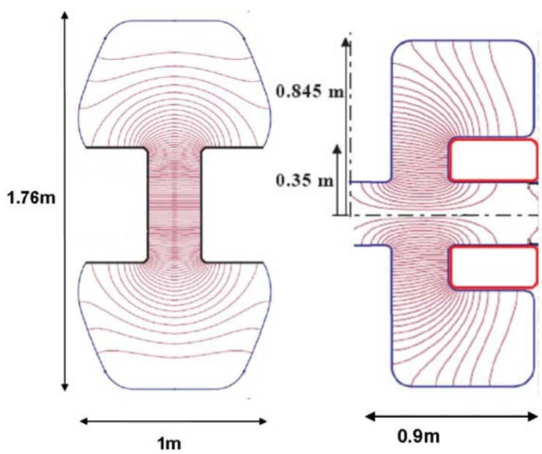

Figure 3: The test cavity (left) and the ideal 88 MHz cavity (right) compared. The ratio between peak field and gradient is preserved.

THE RF SYSTEM

In order to feed the cavity with the required >2 MW power at 88 MHz, a complex RF chain had to be prepared. An old CERN Linac1 202 MHz amplifier was significantly modified by adding a kapton anode blocker intended to increase the voltage holding capacity of the output resonator and by creating a double coaxial output limiting the power to ~1 MW per arm, a safe value for 6”1/8 standard rigid coaxial lines.

Figure 4: The 88 MHz test cavity.

The TH170R triode used in the amplifier has a nominal maximum output power of 2.5 MW. However, when correctly operated slightly higher powers could be expected, especially at the relatively low 88 MHz frequency. In order to get the maximum power at the final output, a 400 kW driver amplifier had to be prepared by modifying a spare PS 80 MHz final amplifier, building a new output cavity resonator and designing a 50 Ω RF output. The feed to the cavity was via two matched loops equipped with coaxial windows made out of PEEK, an easy to machine dielectric material resistive to radiation. The amplifier chain was ready by the end of July 2005.

Figure 5: The 2 MW amplifier; in the right corner its driver is visible.

RF CONDITIONING AND RESULTS

The preliminary measurements on the cavity indicated a Q-value of only 33’300, i.e. about 67% lower than the Superfish value of 50’000. As a consequence, the RF power required to achieve the nominal gradient of 4 MV/m was 2.5 MW, a value initially considered to be above the capability of the final amplifier. The RF conditioning of the cavity started in August 2005 and went on for an effective duration of 160 hours, without counting down and setting-up times. The repetition rate was kept at 1 Hz, while the pulse length was increased in steps. A radiation monitor was placed at the entrance of the test bunker, to regulate the access of the operator during conditioning and to give information about the conditioning status of the cavity itself.

With a cavity filling time of 250 μs, the pulse length was progressively increased from that value to 300 μs. Finally, a maximum RF power at the cavity input of 2.65 MW could be reached after 100 hours of conditioning time. The power was limited by sparking at the anode cavity of the final RF amplifier. However, at this very high power level the other critical elements of the RF chain (driver amplifier, final anode supply and coaxial lines) were clearly at their operational limit too, whereas sparking in the cavity was still at an acceptable level and rapidly improving.

The following picture summarizes the conditioning history (peak power as function of time) of the cavity.

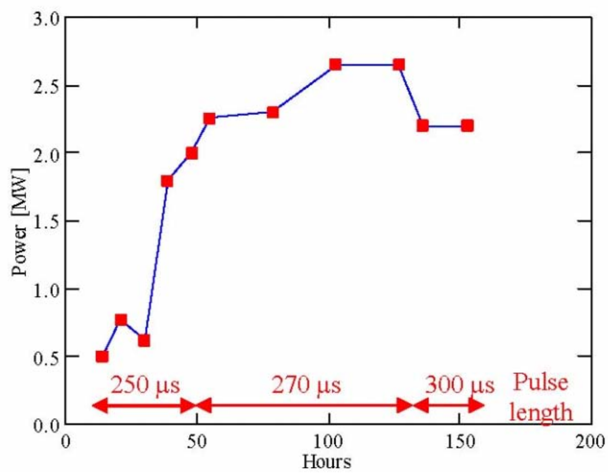

Figure 6: The conditioning history of the 88 MHz cavity.

The following Table summarizes the main cavity parameters at the maximum power reached at the end of the tests.

Table 2: Field levels at maximum power output

E-field gradient	4.1	MV/m
Gap field	14.7	MV/m
Peak surface field	25.9	MV/m
Kilpatrick factor	2.4	Kilp.
Output power	2.65	MW
Repetition frequency	1	Hz
Pulse length	270	μs

During preparation of the test, multipactoring was felt to be a critical issue that could make conditioning difficult. A detailed simulation campaign had been made in 2004 to try to identify the possible multipactoring levels by means of the code MultiP [3], identifying some multipactoring levels at voltages < 1 MV. During conditioning, some reduced multipactoring activity appeared below the 1 MV gap voltage, whereas the most disturbing was a multipactoring level at ≈ 3.1 MV gap voltage, which was not foreseen by the simulations.

Another phenomenon limiting the capability to transform RF input power into accelerating gradient is field emission or dark current. The impact of dark current is clearly shown by the additional RF power that is required to establish a certain gap voltage, with respect to that calculated from the cavity impedance value. In the case of the 88 MHz test (Figure 7) there was a considerable amount of additional power going to electrons around the multipactoring level at 3.1 MV, while only at 3.5 MV was there a rise in power going to field emission electrons.

The field emission current follows the well-known Fowler-Nordheim formula, which allows us to calculate the value of the enhancement factor parameter β, which provides interesting information about the gap surface conditions. From the 88 MHz power measurements a value of β = 170 was calculated, a standard value for copper plated surfaces that did not undergo any particular cleaning process.

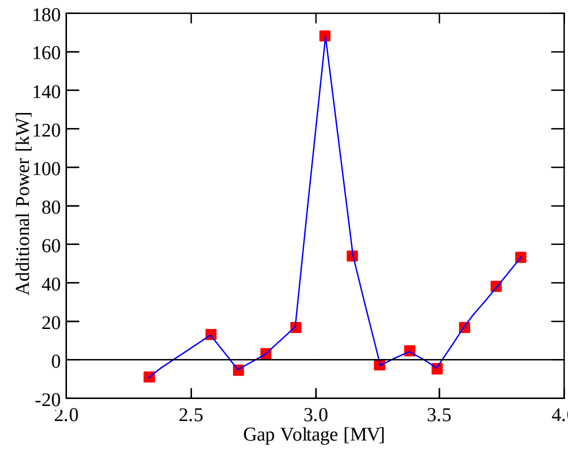

Figure 7: Evidence of multipacting at 3.1 MV and field emission effects above 3.5 MV on the RF input power.

The observed sparking rate in the cavity is also consistent with this value. The experience on the CERN linac RF cavities [4] indicates that after long periods of steady operation the enhancement factor can improve to values in the range of β = 60 to 100, reducing the sparking rate and allowing higher gradients to be reached.

CONCLUSION

The goal of demonstrating the feasibility of a real estate gradient as high as 4 MV/m in this kind of RF cavity has been achieved, with peak surface fields of 2.4 Kilpatrick. Conditioning was very easy, although limited to a repetition rate of 1 Hz. Multipactoring was not a major concern during conditioning, however the absence in the test stand of the solenoid field (1 T) foreseen in the real muon cooling cavities does not allow final conclusions on the multipactoring activity to be drawn, in particular when considering that the multipactoring simulation programs do not appear to be reliable enough to guide the design of this type of cavities.

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