A study of high gradient 201 MHz cavities in strong magnetic fields for the MICE experiment[1]

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Abstract. The early sections of the neutrino factory current design comprise high gradient normal conducting radio-frequency (RF) cavities embedded in high magnetic field. The performance of these cavities is known to degrade with magnetic field; but the exact nature of the phenomenon, its reproducibility and limitations are not well known. It is proposed to make use of the superconducting M1 magnet at CERN and surrounding infrastructure to test this behaviour. In a first step, which is the object of the present proposal, the 201 MHz RF cavities for the Muon Ionization Cooling Experiment (MICE) will be tested in a systematic way. The ten cavities built at Lawrence Berkeley National Laboratory (LBNL) will be brought to CERN and tested inside a standalone vacuum vessel, presently under design, to an accelerating gradient of the order of 10 MV/m or more as a function of magnetic field up to 3 T. The rate and spectrum of emission of electrons and x-rays will be measured. The experimental setup and instrumentation are described. The request from CERN amounts to 6 man months of technical manpower and up to 419 kCHF. On a longer time scale these measurements, which are complementary to those performed at Fermi National Accelerator Laboratory (Fermilab) for the neutrino factory and muon collider projects, can open the way to systematic studies of normal conducting cavity materials, in synergy with other projects involving warm RF cavities.

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MOTIVATION

In the neutrino factory (NF) design [1], the initial muon beam preparation sections, namely phase rotation, bunching and ionization cooling, have in common high gradient RF cavities (up to 16 MV/m in the cooling section) embedded in a rather high axial magnetic field of typically 2-3 T generated by external coils. This condition is quite unusual for RF cavities used in high energy physics accelerators.

Experiments performed at the MuCool Test Area (MTA) [2] have shown that the peak gradient that can be achieved by 201 MHz and 805 MHz cavities degrades in presence of a high intensity longitudinal magnetic field, thus reducing the muon cooling performance. The extent of the degradation may depend on the geometry and other parameters such as the orientation of the magnetic field. Results from the MTA on a single pillbox test cavity, at 201 MHz, have shown a limitation of the gradient achievable without breakdown, at around 10 MV/m, in presence of magnetic field as low as 0.5-1 T.

The behaviour of RF cavities in a magnetic field affects the neutrino factory (and the muon collider) design in that it potentially limits the accelerating gradient, thus reducing the muon capture and cooling performance or forces the use of alternative designs where the cavity is shielded from the magnetic field, thus increasing the cost. The International Design Study for a Neutrino Factory (IDS-NF) [3] and EUROnu [4] collaborations will deliver by the end of 2012 (beginning of 2013) a Reference Design Report (RDR) in which the feasibility study of the neutrino factory baseline as well as costing, risks and mitigations will be addressed. Furthermore, as the cost of the muon front-end (drift, rotation, bunching and cooling) is high in comparison with the total cost of the facility [5], in order to keep the cost down, a study of RF cavities' behaviour in a magnetic field is necessary and its results will strongly influence the accelerator design.

For a neutrino factory construction to be seriously considered, it is also essential that the feasibility of muon ionization cooling is demonstrated. The MICE [6] experiment at the Rutherford Appleton Laboratory (RAL) will study muon ionization cooling using different absorber materials and various optics in a custom built muon beam of 140-240 MeV/c. The experiment has now completed the beam commissioning phase. A total of ten cavities are being built, of which the eight best cavities will be chosen, prior to their installation in the experiment, foreseen in 2012. Thus, a measurement of the behaviour of each of the cavities is necessary. It would constitute both an important precaution and a precious source of information. Furthermore, in MICE configuration, the dark currents generated during cavity operation are an issue for the detectors located in the experiment. The knowledge of the behaviour of the instrumentation in presence

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[1] The authors listed explicitely are those who expressed interest and availability in taking part in the execution of the tests.

of RF noise would also constitute an important milestone for the success of MICE. In addition, the Muon Accelerator Program (MAP) management emphasized both the importance of MICE and the possibility of measuring the cavities before their installation in the experiment [7]. The arrival at RAL of the first module of RF cavities is expected in the second half of 2012.

Given the aforementioned time scales for MICE and the IDS-NF RDR, we have investigated the possibility of using a large bore magnet at CERN in support of the MTA and the MICE RF tests, and identified the M1 magnet, located in the H2 Test Beam Area, as a good candidate. The experimental area could be ready to receive a RF cavity for installation by June 2011. Such RF test area could be prepared and exploited for a modest cost by making use of the existing CERN infrastructure. The results that will be obtained will be crucial not only to the MICE experiment but also to the neutrino factory feasibility study and to the progress of accelerator technology in general.

The proposed measurements are complementary to those being carried out at Fermilab in the MTA which will address in 2011:

- test of a 805 MHz pillbox cavity with buttons
- test of a high-pressure hydrogen filled cell in beam
- test of a 201 MHz cavity w/wo magnetic field (limited to $B < 1.5$ T)
- test of Atomic Layer Deposition (ALD) surface treatment (805 MHz button cavity)

EQUIPMENT, LOCATION AND COST

Magnet

The CERN M1 [8] superconducting magnet was built for the European Hybrid Spectrometer (EHS) [9] in the 1970s. It consists of two separate Helmoltz-type circular coils, assembled into a massive iron structure. It provides a central field of 3 T [10] in a useful volume of 1.4 m in diameter and 0.82 m gap with a completely azimuthally free acceptance of $\pm$ 18° from the central plane.

There are four types of access points to the magnet: through the coil bores by a circular hole of 1.4 m, through the magnet side (0.82 m width × 2.2 m height), through the top by a rectangular hole in between the coils of size 0.82 × 1.55 m or from the bottom through a hole of size 0.82 m × 2.2 m and 0.67 m of height available. A system of horizontal rails has been inserted between the magnet coils leaving a vertical distance from the top of the rails to the coils axis of 0.9 m.

The magnet operates with an average current density of 2500 A/cm^2. It possesses also an elaborate support structure required by the particular force configuration within the iron structure. There is no return yoke, and the fringe field generated by the magnet has been measured in several points around the magnet [11]. The fringe field is about 50 mT, 2 m away on the axis of symmetry between the two coils and about 15 mT, at a

TABLE 1. Estimation of the magnet operation cost.

	Description	Cost
1	liquid He for 6 months of cold (including cooling down) operation	5 kCHF
2	power consumption for 1000 hours of operation	17 kCHF
3	1000 hours of magnet experts	10 kCHF
	Total estimated cost	32 kCHF

distance of 4 m, on the central axis of the coils. Depending on the tolerance of the RF power system to magnetic field, additional shielding of sensitive equipment that needs to be operated in the area when the magnet is powered may be required.

In its present configuration, during the magnet current ramp-up and operation, a safety control system in charge of monitoring any current deviation will power off the magnet current as soon as a shift in the current value between the two coils is detected. This prevents operation with one coil powered ON and one coil OFF, with different current settings on the coils or inverted currents direction for each coil. It is believed that such operation conditions would create forces on the cryostat structure and magnet frame able to damage it. The current direction can be inverted on both coils, in order to operate with a magnetic field in the reverse direction.

It takes about 3-4 weeks to cool down the magnet with He, with one week of gas phase and about two to three weeks of liquid phase and temperature stabilization. When the magnet is warm a nitrogen cover gas is used in replacement of the He gas.

The estimated cost of the magnet operation is reported in Table 1.

Experimental area

The H2 beamline provides primary protons of 450 GeV from the SPS or secondaries (such as electrons, pions and muons) from 10 to 350 GeV. NA61 [12] experiment is located upstream of the H2 Test Beam Area. The layout of the H2 Test Beam Area can be found in Figure 1. As current for year 2010, there is no experiment requiring beam downstream of the H2 Test Beam Area. When NA61 is taking data, it completely stops the beam and access to the M1 magnet is possible. When R&D test beams are taking place, access to the magnet is not possible. In addition, many devices used in R&D projects located in the magnet area do not operate well in the magnetic fringe field.

Based on the current occupancy of the magnet area and NA61 beam request for 2011, it is conceivable that test beam activities in H2 Test Beam Area will not last more than two months per year. This gives $\sim$ 10 months of theoretically available time in 2011 and 12 months in 2012. Restrictions on the area use, such as work on the magnet refurbishment and annual stops of chilled water (usually taking place between December and March) may apply. The chilled water stop date can be negotiated if the request

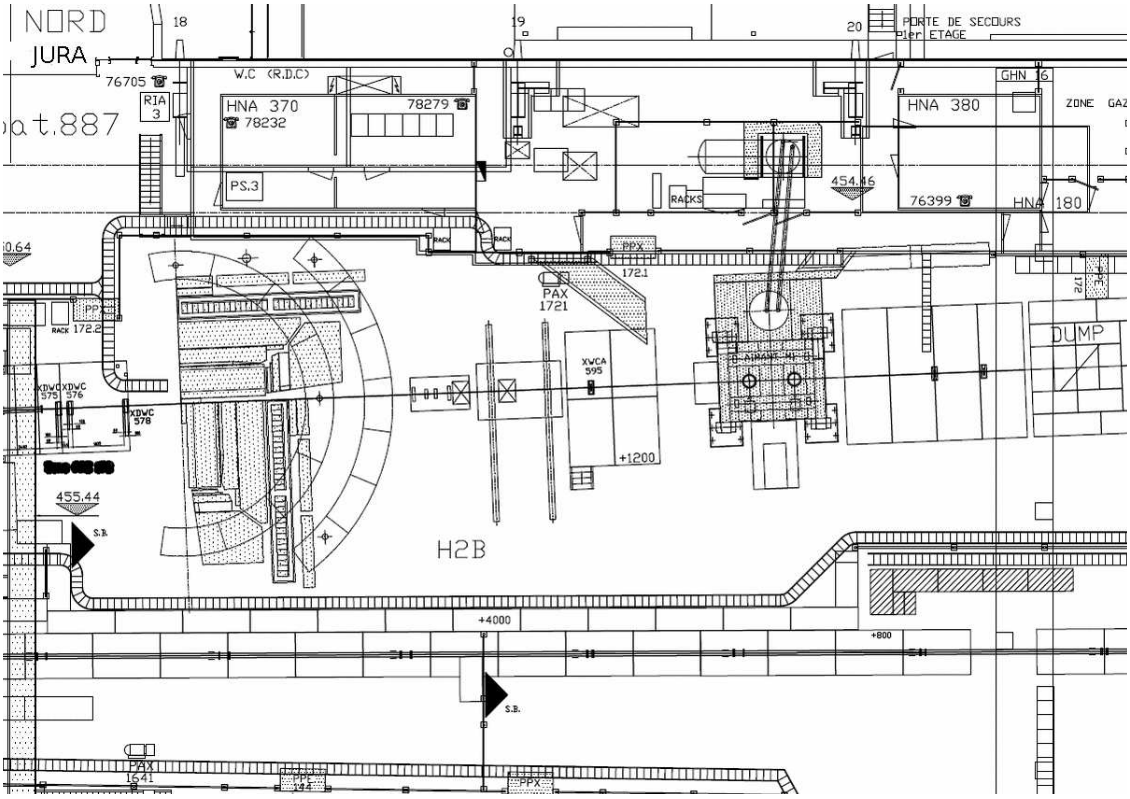

FIGURE 1. Layout of H2 Test Beam Area (courtesy D. Lazic), the beam direction is from left to right.

is made in advance (estimated to three months advance warning). As the recent decision of not having beam in 2012 may result in having a more intense use of the Test Beam Area in 2011 than in 2010, we have to carefully prepare and time for the period we want to spend in the Test Beam Area and avoid possible interference and conflict with other projects sharing the same space. We estimate that a window of 16 weeks of access to the area for installation and commissioning, 20 weeks (assuming two weeks per cavity for a total of ten cavities) for test, and 4 weeks of access of to the area for dismantling would be enough to perform the experiment. The timeline for performing this experiment, assuming the installation work starts in January 2011, is summarized in Table 2. The schedule may shift by up to two months if all the cavities testing needs to be performed in 2011. Assuming a smaller time window for magnet running as interventions on the magnet and possible repairs of the controls could decrease the magnet livetime, one can assume reasonably that at least half the cavities could be tested in 2011 and the other half would be tested in 2012 if magnet running time could also be given in 2012.

During magnet operation, the corridor on the ground level and the passerelle on the first floor are not accessible, due to the presence of the fringe field. The area is equipped with rooms that can be used as control room for any of the equipment that needs to be operated remotely. It can also host also electronics for the instrumentation or necessary monitoring system.

TABLE 2. Estimation of the magnet operation cost.

Description	Date
Installation and commissioning	January-April 2011
Cavities testing	May-September 2011
Dismantling	October 2011

Shielding

For personnel safety, additional shielding from the low-energy electrons and x-rays coming from the cavities will be necessary. For example, when required to build an RF cave at Fermilab, 2 m of shielding (wall and ceiling) was required for x-ray protection. MICE has 8 MW of power going to 8 cavities with a gradient of 8 MV/m per cavity (integral of 23 MV). The shielding provided by the beam dump, which is 92 cm thick, is considered as a sufficient protection to allow personnel to walk behind it.

The electrons produced are expected to have energies on the order of a few MeV and can be directed along the magnetic axis. A standard practice for shielding of beta-emitters (which are comparable to the low-energy electrons we get) is to use a low-Z inner shield such as plastic (e.g., polymethyl methacrylate) and a high-Z outer shield (e.g., lead) as bremsstrahlung production from electrons of a few MeV when they penetrate high-Z material is not negligible.

One option would be to place plastic and lead shielding around the cavity, which would also protect the magnet coils from quenching but the space around the cavity is limited, in addition one wants to leave access to the cavity windows for the instrumentation responsible for monitoring the particles emitted.

The other option is to use concrete blocks of adequate thickness everywhere personnel and sensitive equipment need to be protected. It is already clear that on one side (direction of the Jura mountain) of the magnet bore a wall of concrete blocks will need to be built. An additional layer of concrete is also necessary to protect people walking behind the door at the ground level located in PPE 172. The wall should be high enough to protect the personnel working in the control room located on the first floor in between the two doors that close the area when the magnet is in use, else the access to this control room should be prevented when the magnet and RF are on. Additional shielding by increasing the height of the concrete wall separating H2 from H4 as well as to protect the personnel walking behind the door located in PPX 172.2 may be necessary.

A calculation of the thickness of plastic and lead shielding necessary for few MeV electrons has to be performed in order to assess if the space alloted around the cavity would permit its installation. Magnet quenching limitation will also have to be calculated in order to check if additional shielding around the magnet coils is necessary. It is expected that a mixture of plastic+lead and concrete would provide adequate shielding in compliance with the CERN safety rules.

TABLE 3. Estimated cost (preliminary) for experimental area shielding

	Description	Cost
4	electron shielding with plastic + x-ray shielding with lead	1 kCHF
5	test area infrastructure	20 kCHF
	Total estimated cost	21 kCHF

The sensitive equipment that has to be shielded from electrons and x-rays as well as magnetic field has to be defined, and proper shielding has to be identified including its cost. The cost for shielding is reported in Table 3 as a preliminary estimate of the required shielding.

RF cavities and RF operation

The MICE RF cavity has a wheel shape of 1.219 m outer diameter and 0.417 m thickness. It will be surrounded by a vacuum vessel which is presently under design at LBNL. A stiffener ring permits to lift and move the cavity; and, when in the vacuum vessel, the cavity is suspended by a hexapod strut arrangement (see Figure 2). When the tuner, vacuum pump and holding support are in place the overall size of the cavity will reach 2.366 m height (including getter pump, support and tuner ports) for a diameter of 1.512 m and 0.80 m thickness. The total width is 3.277 m including the RF input couplers. Whereas the magnet volume can still accommodate the vacuum vessel overall dimension, the getter pump (ideally sitting on the top of the cavity), and the couplers will have to be installed after the cavity is in place in the magnet. We assumed it will take two weeks to run and condition the cavity before performing the tests inside the magnet. A second vacuum vessel is in consideration, allowing different cavity orientation (different supporting and cooling positions) and thus also permitting to speed up the switching between cavities.

The 201 MHz cavity in the MICE configuration is operated by means of a 300 kW pre-drive amplifier, feeding a 2 MW amplifier (using a TH116 triode) with a 3 1/8 inch coaxial line. The high power output is transmitted to the two RF cavity couplers by two 6 inch coaxial lines through phase shifters and directional couplers. The high power RF system needs 4 racks plus 1 for the HV power supply. The 300 kW pre-drive needs 1 rack, plus 1 for its power supply. All the racks, pre-drive amplifier and 2 MW amplifier may have to be shielded from the stray field coming out from the magnet. A logical and easy location for the RF amplifiers and racks would be the concrete platform located downstream of the magnet (480 cm long $\times$ 640 cm wide), provided that the stray field in this area is tolerable. If this is not the case, the RF equipment could be located further away from the magnet, at the cost of a longer high power coaxial feeder line. The availability of steel or soft iron plates for shielding will be investigated. Some additional shielding with mu-metal will be used if exceptionally low fields prove to be necessary. The field contours have been measured, and a test of the equipment in the presence of a

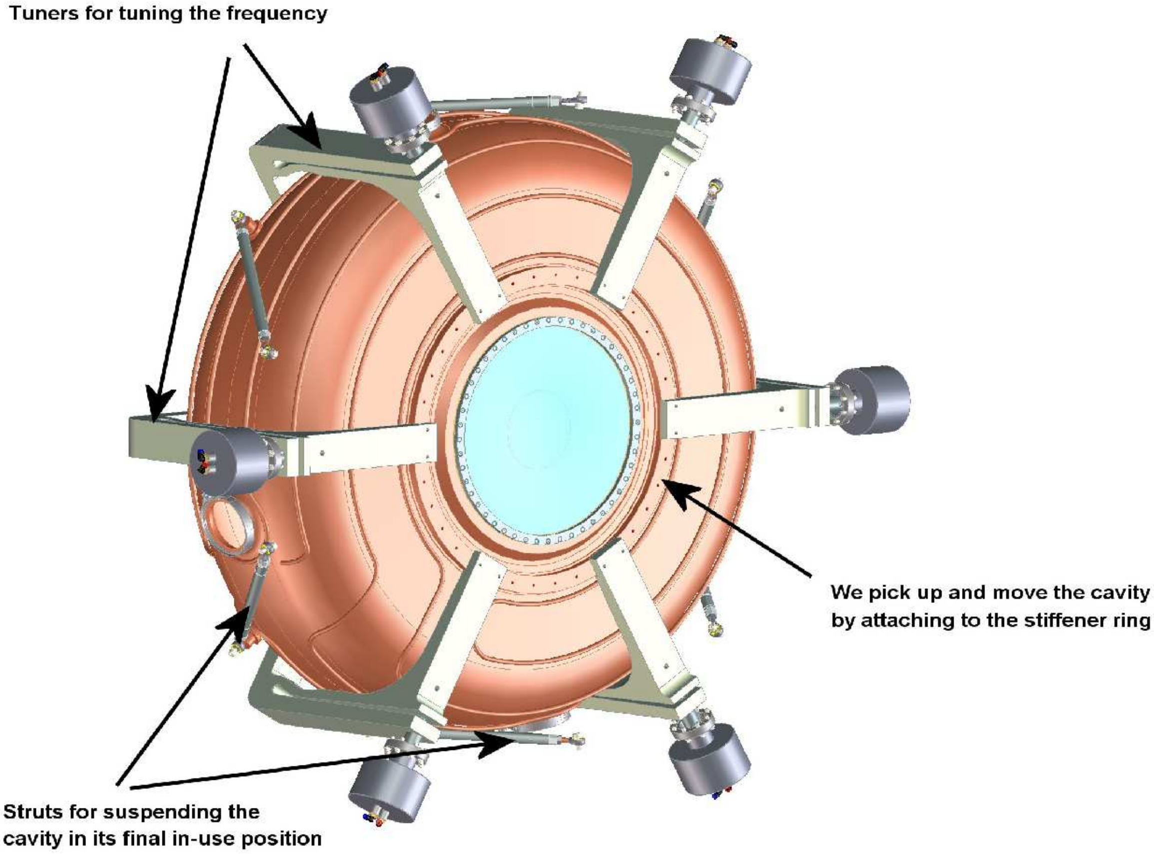

FIGURE 2. Layout of the MICE RF cavity (courtesy A. DeMello).

low fringe field will be another important gain of knowledge for the success of MICE experiment.

A 2 MW unit will be shipped from Daresbury Laboratory (DL) to CERN for the purpose of this experiment and its estimated cost is reported in Table 5.

The option of assembling at CERN a 300 kW amplifier using SPS spare parts that could be loaned for the duration of this experiment has been discussed in detail. Its cost was evaluated as well as the restrictions applying to this scenario.

MICE is interested in acquiring a 300 kW amplifier required for step VI of the experiment (second half of 2013). If some new parts could be purchased by MICE in order to have a similar 300 kW amplifier being assembled at CERN and shipped at RAL, this would constitute an interesting option for MICE. But as this scenario feasibility was not evaluated in detail, this option is not discussed here.

The following chain for construction of a 300 kW amplifier is required:

- one 1 kW transistorized driver amplifier
- one 25 kW second stage driver amplifier
- 4× 60 kW stage amplifiers based on RS2058 ex-SPS/SWC units

In order to build the different amplifiers stages described above, one would need to buy or construct some distribution boxes for the 1 kW amplifier, the water distribution pipes, a 8:1 combiner (8 inputs, 1 combined output). One would need to buy or construct a complete high-voltage power supply and some voltage control boxes for the 25 kW unit. For the 4 × 60 kW units one would need to buy or construct the output lines for the hybrid connection, new control grid power supplies (Ug1) for the tetrode and cabling. The total cost estimated to 185 kCHF[2] is described in Table 4.

TABLE 4. 300 kW RF amplifier assembly cost.

	Description	Cost
6	components	50 kCHF
7	tubes (4×RS2058 + 1× YL1520)	110 kCHF
8	FSU	25 kCHF
	Total estimated cost	185 kCHF

The manpower and time needed to build and operate the drive amplifier is estimated to 4 weeks of 1 staff FTE experienced with these amplifiers from the CERN RF group for design and project follow-up, and 2 weeks with 2 staff FTE for construction and commissioning. In addition one would need 8 weeks of Field Support Unit (FSU) FTE for the construction and commissioning of the project. One has to be aware that the following major restrictions apply. As some components are the SPS spares, if the SPS machine operation requires it, SPS exploitation has priority, meaning that the test will have to be stopped if some key components are needed. It takes about 2 days to disconnect any major component. The staff manpower to work on the disconnection is estimated to 2 FTE days and FSU manpower is estimated to 4 FTE days (2 days x 2 FTE) presenting an approximate cost of 2 kCHF. The cost of the material is estimated to be 1 kCHF (tooling, packing and transport). The CERN RF group plans to use all these components, to operate a diacrode which is under development, to upgrade the "Siemens" plant drivers with RS2058, for the SPS power coupler upgrade or the PS 200 MHz power plant renovation. This means that this power station could only be loaned for a predefined maximum period of two years. In case there would be a major show stopper to the assembly of a 300 kW amplifier, the option of shipping from DL to CERN a 300 kW amplifier will have to be discussed as a fallback option.

The estimated manpower to assemble the full chain (pre-drive and 2 MW stage amplifiers) is two man weeks accounting for a total of 40 kCHF.

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[2] Component costs do not include local connection to an 18 kV network, or packing and transportation to final destination.

For the RF operation, assuming 40% efficiency only from the electrical power in input to the power delivered to the RF cavity about 5 MAV/h are needed for a 2 MW RF output assuming continous wave operation. If the cavity is running in pulsed mode, for a duty cycle ratio of 1/1000 the required power can be reduced to 5 kAV/h.

Assuming a total of 51 hours to load one cavity into the single cavity vessel, and a CERN technician cost of 150 CHF/h, the total cost for manpower is 76.5 kCHF. The estimated cost for RF cavity and RF operation is reported in Table 5.

TABLE 5. Estimated cost for RF shipment, installation and operation.

	Description	Cost
9	2 MW RF power shipment	2.5 kCHF
10	RF amplifier installation	40 kCHF
11	RF cavity installation	76.5 CHF
12	RF additional coax (350 mm diameter - 50 m long)	60 kCHF
13	RF amplifier disconnection work	2 kCHF
	Total estimated cost	181 kCHF

Instrumentation

Measurements of electrons and x-rays resulting from the RF cavities operation will be the responsibility of University of Geneva (UNIGE). The instrumentation has been developed at FNAL. Some of it can be reproduced easily and, if identical to the MTA one, it can provide cross-normalization. These mostly consist of scintillator detectors with Photo-Multiplier Tubes (PMTs) of which UNIGE has a number either in stock, or that can be purchased.

The readout and data acquisition (DAQ) system will also be the responsibility of UNIGE, in a similar way as what has been developed for the MICE DAQ. In passing this will be an extremely useful benchmarking for the development of the data acquisition for the MICE step V in which the RF cavity pulse structure, amplitude and phase will need to be recorded, together with possible detectors monitoring the activity generated by the MICE RF system when in operation at RAL. Additional monitoring will be provided by an x-ray spectrum analyser which is available at CERN.

In developing the instrumentation for monitoring the x-rays and electron emission, one interesting device was a telescope made of photographic paper interleaved with sheets of aluminium [13]. Polaroid pictures were also taken during monitoring of breakdown events [14]. Most interesting evidence of darker spots were seen, indicating that radiation in the cavity exposed to magnetic field develops from a finite number of local emitters generating small beams of electrons focused by the magnetic field. An example of dark spot appearance is shown in Figure 3. More details on the variety of instrumentation techniques which have been used to monitor dark currents and radiation can be found in [15]. Dark current beams that were detected were very strong (order of μA to mA). While the manual method with photographic paper can be reproduced, an interesting development to pursue would be to replace it with a more quantitative (and automatic) device constructed of planes of arrays of geiger mode avalanche photodiodes (MPPCs). Not only it is important to be able to record the data but some confidence in the system stability, dynamic range and linearity are also very important.

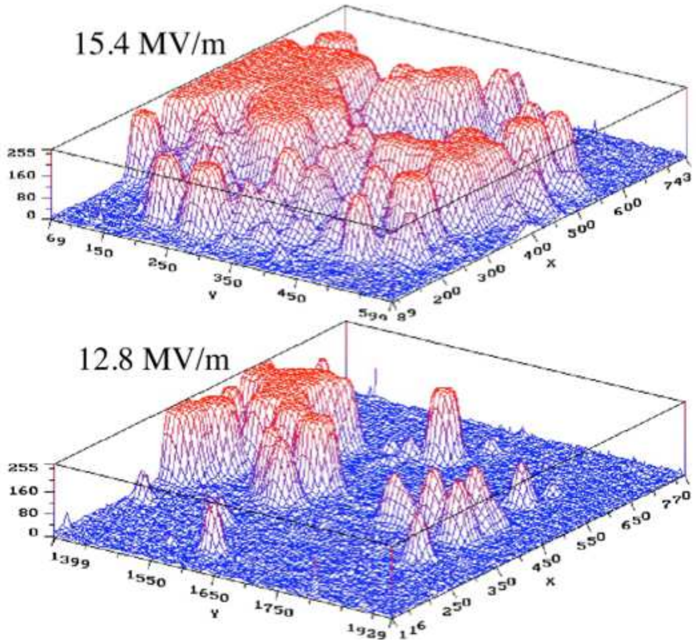

FIGURE 3. 7 cm × 7 cm digitized images of the field emitted currents for two different gradients.

The estimated cost for the instrumentation is reported in Table 6.

TABLE 6. Estimated cost for the instrumentation.

	Description	Cost
14	DAQ system	20 kCHF
15	detector, PMTs scintillators and mechanics	20 kCHF
16	miscellanea	10 kCHF
	Total estimated cost	50 kCHF

It is foreseen that a post-doc and a student from UNIGE will spend some time with the instrumentation for this experiment. The cost of the instrumentation will be covered by UNIGE and other external institutes willing to participate in the instrumentation development and installation.

FINANCING AND DIVISION RESPONSIBILITIES

Although a detailed distribution of tasks between contributors is premature, the following guidelines are nevertheless already clear:

- the 201 MHz RF cavities will be provided by LBNL on behalf of MICE;
- the 2 MW amplifier will be one of the refurbished CERN devices prepared for MICE by DL;
- CERN is considering the possibility to assemble an adequate pre-driver, using SPS spares. The option of a pre-driver assembly at CERN using new parts and paid by MICE will also be discussed. In case one of the above options is not adopted, we have to investigate the possibility to have one of the LBNL pre-drive amplifiers shipped from DL to CERN;
- depending on the scenario adopted for the 300 kW amplifier choice, the share of the cost of its assembly covered by MICE and CERN will differ;
- technical/scientific manpower from the MICE collaboration will be sent to CERN for helping with the assembly and set-up of the RF installation;
- the instrumentation is UNIGE responsibility and its cost will be covered by UNIGE and/or some other external institutes;
- an RF expert from CERN who can take over the project supervision will have to be identified. This is a condition for performing this experiment.

The technical manpower is estimated to 6 man months assuming 1 man month for the RF amplifier assembly and 5 man months for the RF operation.

A summary of the money requirement can be found in Table 7.

TABLE 7. Summary of the money requirement

Description	Cost
magnet operation	32 kCHF
experimental area infrastructure	21 kCHF
300 kW amplifier assembly	185 kCHF
RF installation and operation	181 kCHF
Total estimated cost	419 kCHF

OTHER PERSPECTIVES

While RF cavities in magnetic field are quite unusual, the issue of warm RF cavity breakdown is relevant for many applications. While frequencies, size and conditions of operation of accelerating structures are very different from e.g., CLIC, the underlying science has a number of commonalities which should allow, for instance, testing hypotheses on sources of emission or breakdown, and validation of simulation codes.

CONCLUSION

A unique RF R&D experimental facility can be assembled at CERN for a modest cost, thanks to the availability of the CERN M1 magnet in the SPS North Area. In the short term ($\sim$ 24 months), it would provide a crucial support to the MICE activities. In the longer term its results are likely to have a decisive impact on the design of a future neutrino factory and/or muon collider.

The overall estimated cost is up to 419 kCHF and the required manpower of 6 man months. If the experimental area can be ready by summer 2011 to run this experiment, this would be of total benefit to MICE and CERN as there will not be a magnet that can be ready to receive an RF cavity before that time.

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