Rome 6-7 May 2024

International MUON Collider Collaboration

MuCol

RF Progress and Test Plan for the MUON COLLIDER cooling

Dario Giove

INFN-LASA –Milano

Thanks to Luigi Celona, Gino Sorbello, Davide Guarneri, Giorgio Mauro, Maria Rosaria Masullo, Guido Gentili (INFN- LNS, INFN-Na, Politecnico of Milan)

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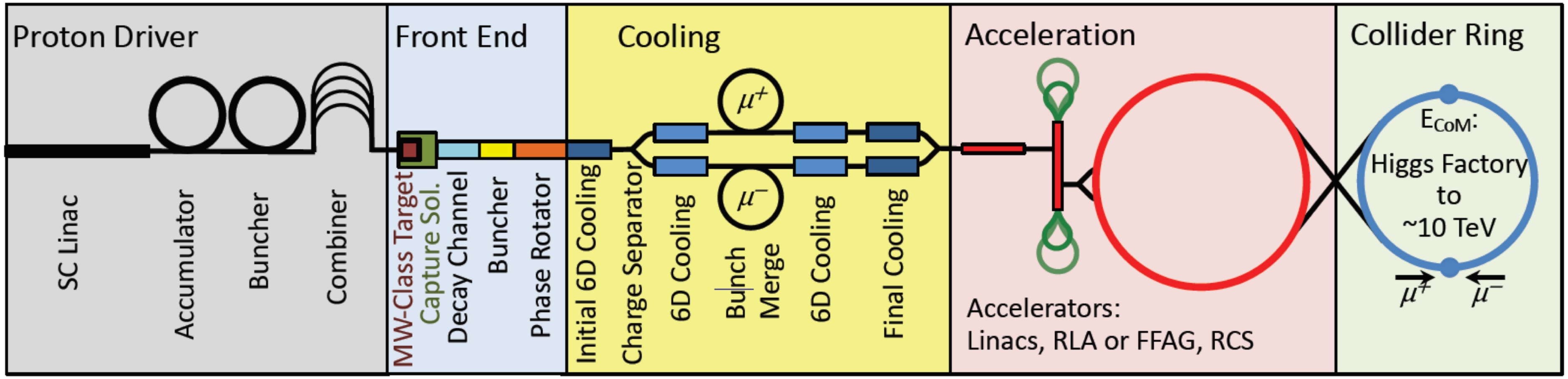
Muon collider and RF system challenges



The main challenges of a muon collider design are those arising from the short muon lifetime, which is 2.2 μs at rest, and the difficulty of producing large numbers of muons in bunches with small emittance.

The purpose of the cooling cell is to provide a reduction of the normalized transverse emittance by almost three orders of magnitude (from 1 × 10−2 to 5 × 10−5 m-rad), and a reduction of the longitudinal emittance by one order of magnitude of the Muon Beam generated by the collision of a proton beam with a production target, resulting in a shower of pions that will then decay into muons. Pions are generated with a large angular spread, and a large momentum spread as well.

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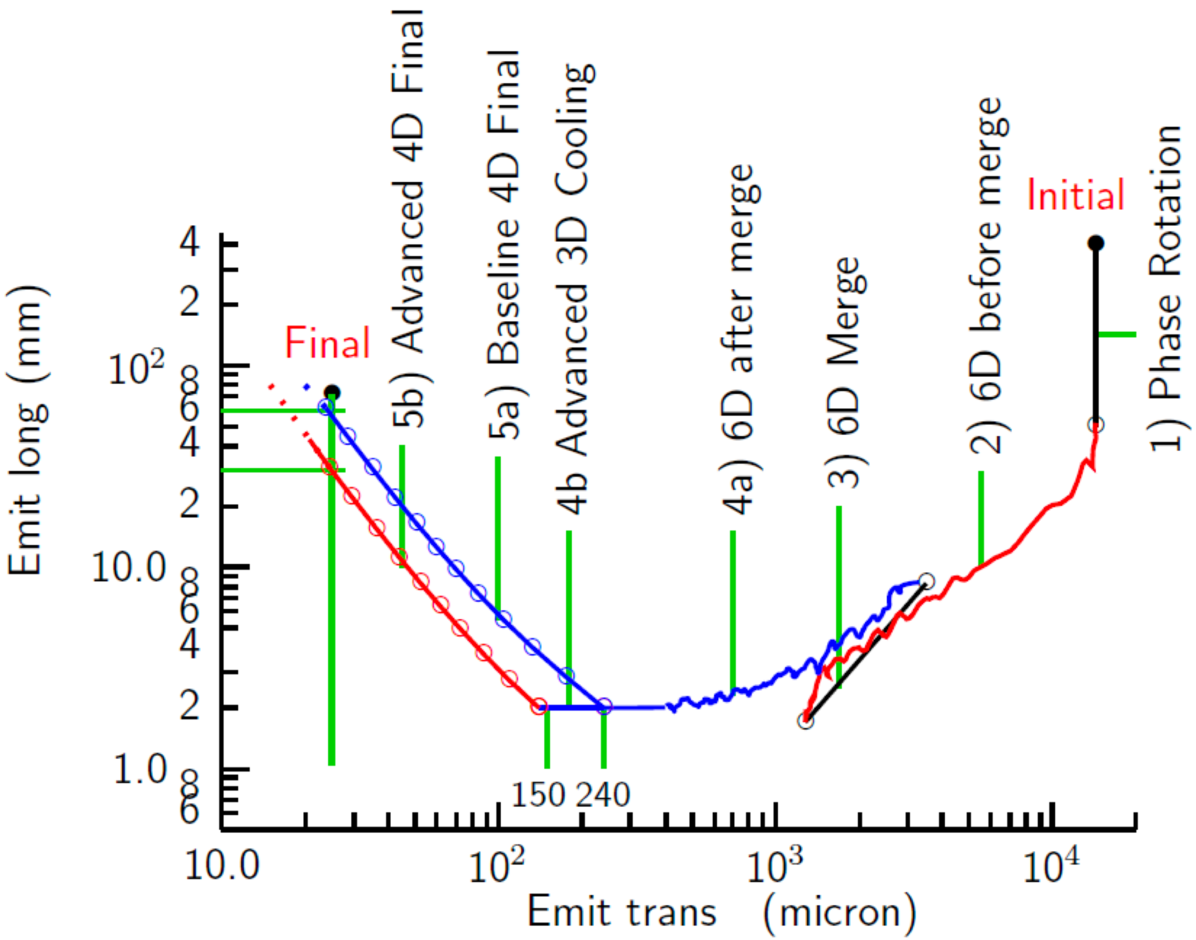
Cooling Cell Emittance Evolution



Normal conducting RF for capture and cooling

- **High-gradient cavities in high magnetic field**
- High charge, Huge beam size, Important beam losses
- Peak RF power

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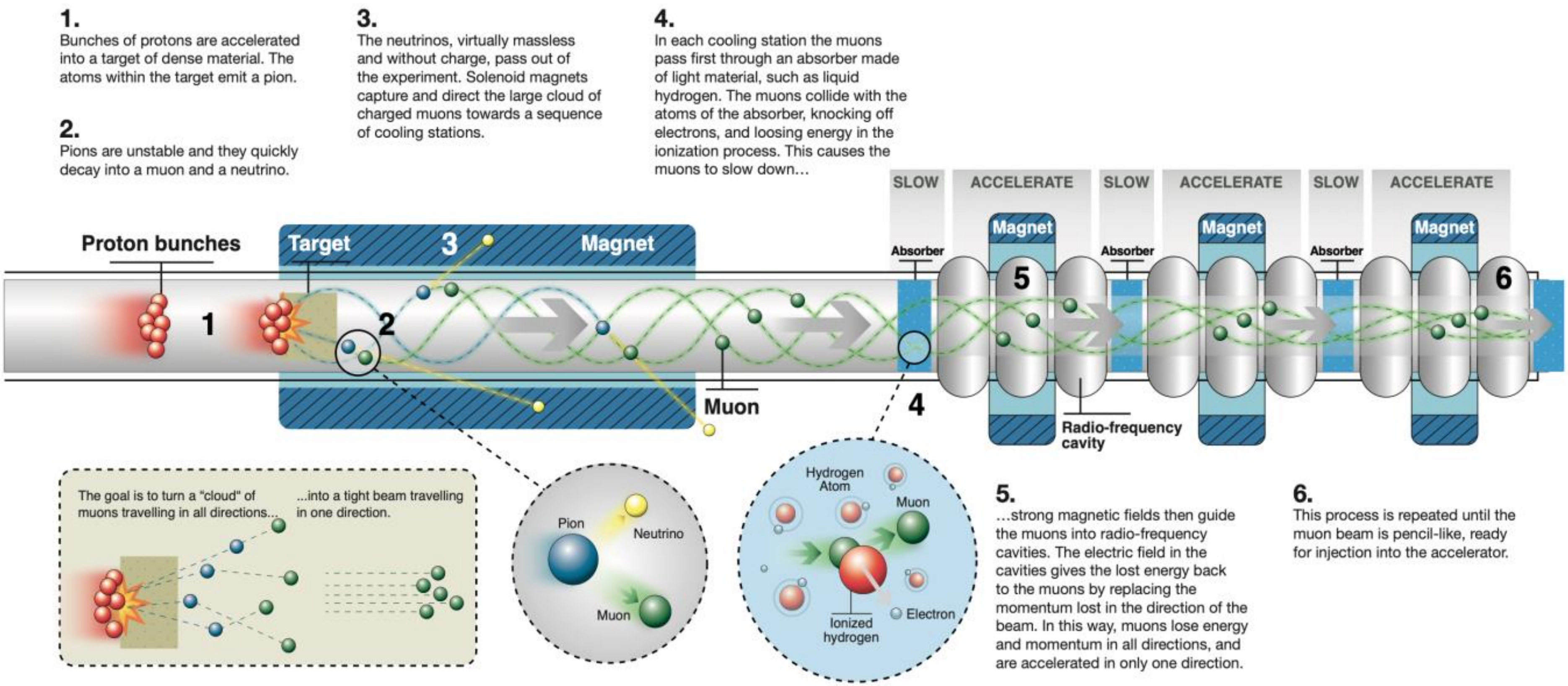
Cooling Cell Scheme



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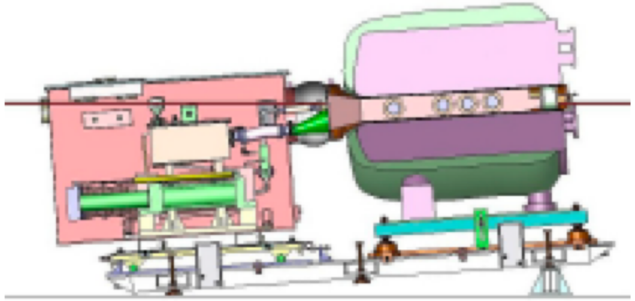
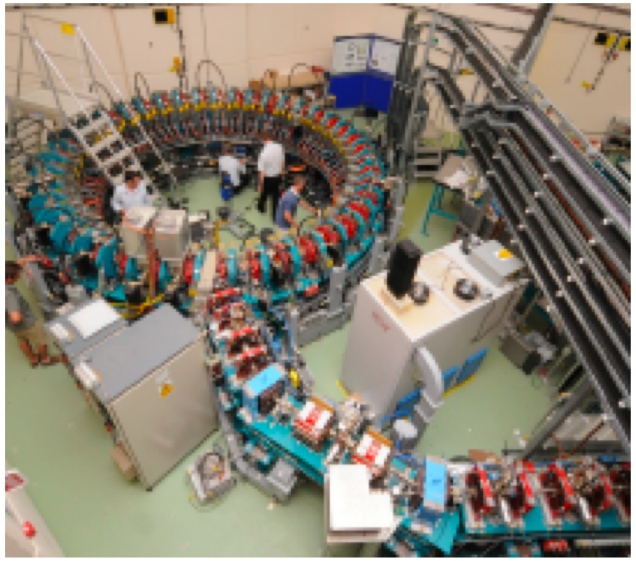
Muon Accelerator R&D





MERIT - CERN
Demonstrated principles of muon accelerator proton targetry/pion production

EMMA - STFC Daresbury Laboratory
Demonstrated fast acceleration in FFAGs

MUCOOL - PSI
Cavity R&D for ionisation cooling
Demonstrated operation of cavities at high voltage in magnetic field
Breakdown suppression using high pressure gas
Careful RF coupler design and cleaning in vacuum

MICE - Rutherford Appleton Laboratory (RAL)
Ionisation cooling demonstration

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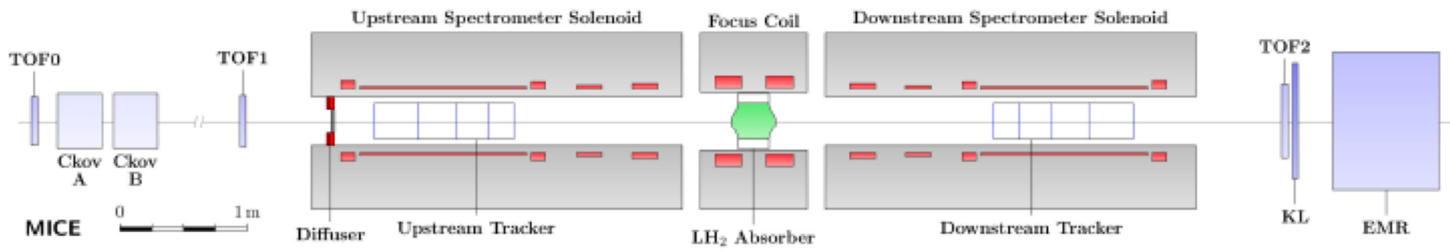
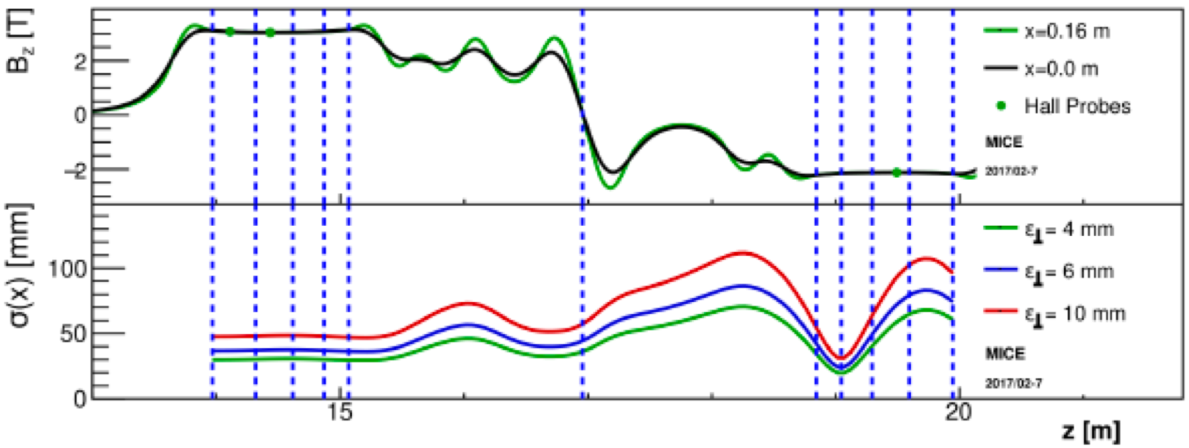
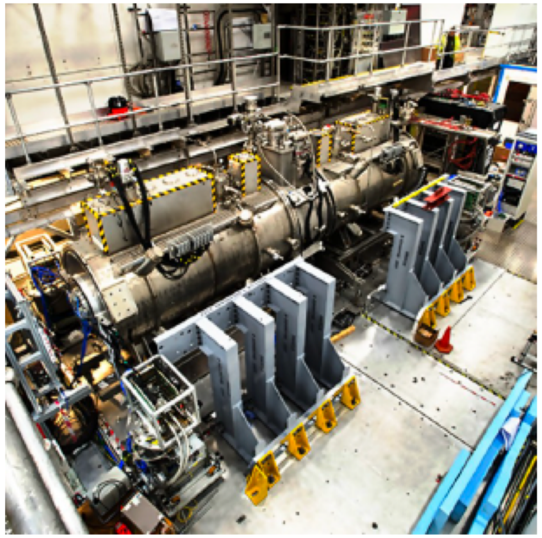
Muon Ionisation Cooling Experiment (MICE)







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Ionization Channel Parameters

Within the two main sections, 6D rectilinear cooling and final cooling there are about 20 different types of cells with various geometry, length, gradients, magnetic field strength and frequency. In order to decide which one is the more interesting to be designed in details, one has to look not only at scientific considerations, but also to practical aspects that would ensure the maximum result for the investment to be done.

➢ Cooling cells parameters (updated)

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
Cell length (m)	2.3	1.8	1.4	1.1	0.8	0.7	0.7	0.65	0.65	0.632
Stage length (m)	55.2	61.2	77.0	70.4	53.6	49	34.3	48.1	31.85	42.33
Pipe radius (cm)	23	19	12.5	9.5	6	4.5	3.7	2.65	2.2	2.1
$B_{z,max}$ (T)	3.1	3.9	5.1	6.6	9.1	11.5	13.0	15.8	16.6	17.2
Transverse beta β_T (cm)	35	30	20	15	10	6	5	3.8	3	2.7
Dispersion (mm)										
On-axis wedge length (cm)	37	32	24	20	12	11	10	7	7.5	7
Wedge apex angle (deg)	110	120	115	110	120	130	130	140	140	140
Wedge window thickness (μm)	100	100	100	100	50	20	20	20	10	10
RF frequency (MHz)	352	352	352	352	704	704	704	704	704	704
Number of RFs	6	5	4	3	5	4	4	4	4	4
RF length (cm)	25	22	19	22	9.5	9.5	9.5	9.5	9.5	9.5
Maximum RF gradient (MV/m)	21.01	22.68	24.27	25.03	23.46	30.48	30.22	25.76	17.49	20.22
RF phase (deg)	28.22	30.91	29.76	29.48	23.81	19.65	18.31	14.37	19.42	14.69
RF inner-radius (mm)	326.2	326.2	326.2	326.2	163.1	163.1	163.1	163.1	163.1	163.1
RF window thickness (μm)	50	50	50	50	50	20	20	20	10	10

(25.4.2024 by Ruiu Zhu)

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Cooling Cell: design, build and test

Looking at what has been above discussed, we may summarize in few points the main motivations to design, and in the future build and test a cooling cell:

Full 3D design that includes all the elements that constitutes a complete ionization cooling channel and the possibility to integrate them in a compact structure

The number and role of the magnets involved require a thorough study and prototype developments looking at the possibilities provided by High Temperature Superconductors (HTS) of the REBCO family aiming at the realization of a solenoid generating a field between 5T and 10T on its axis

The function of RF in the ionisation cooling is to transfer longitudinal momentum to muons in the fastest possible way. This calls for a design and a set of technological choices that would guarantee the highest possible gradient in the conditions and with the constraints so far discussed

For what concerns absorbers the best performance would be provided by liquid Hydrogen. There are unfortunately a number of drawbacks (the peak of overpressure that may be generated by the energy peak deposed by the beam passing inside the liquid, the fact that hydrogen is highly flammable). Litium Hydride is also a candidate material but since it is in solid phase and with limited safety hazards, it is considered a good choice for the first 3D integration exercise.

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RF Cavity and RF Structure Design

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A decision on the type of RF structure that will have to integrated in the cell requires taking into account a number of parameters that may be summarized as in the following:

- **the RF frequency**
- **the required real estate gradient of the electric field in a cell vs. the peak gradient achievable in the RF structure**
- **expected breakdown rate and eventual mitigation strategy, especially in the high magnetic field and high magnetic gradient they experience**
- **specific materials and surface treatments for the cavity bodies.**
- **the type of RF coupling from cell to cell in a RF structure**
- **the space available to fit ancillaries (e.g. tuners, power couplers, cooling pipes etc…), considering the tight interference with the cryomagnetic system**
- **the available or realistically feasible power sources**

Most of the parameters being used for simulations of the entire cooling section are at the edge or beyond the present state-of-the-art, therefore require careful evaluation of the feasibility of the corresponding technological solution.

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RF Frequency

The RF frequencies analyzed so far are the following:

704 MHz **(the today reference MC frequency in the design)**

805 MHz **(the frequency adopted in previous MC RF cells US based researches)**

1 GHz **(power Klystron available from CLIC drive beam researches ideal for RF structures test facility)**

3 GHz **(a well known reference for S band linacs)**

The interest for the 704 MHz frequency is due to the iris radius specification from BD and the availability of suitable power sources for RF cell tests.

The 3 GHz proposal is related to the possibility to design and build a compact RFMTF taking advantage from the knowledge available in S band technology and from a wide availability of power RF sources.

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Peak Gradient Achievable

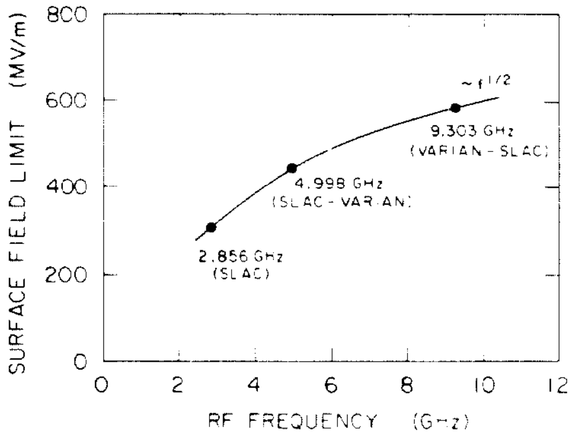
THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 28, NUMBER 10 OCTOBER, 1957

Criterion for Vacuum Sparking Designed to Include Both rf and dc*

W. D. KILPATRICK
Radiation Laboratory, University of California, Berkeley, California
(Received May 31, 1957)

An empirical relation is presented that describes a boundary between no vacuum sparking and possible vacuum sparking. Metal electrodes and rf or dc voltages are used. The criterion applies to a range of surface gradient, voltage, gap, and frequency that extends over several orders of magnitude. Current due to field emission is considered necessary for sparking, but—in addition—energetic ions are required to initiate a cascade process that increases the emitted currents to the point of sparking.

- Based on the idea that breakdown happens when regular Field Emission is enhanced by a cascade of secondary electrons ejected from the surface by ion bombardment.
- Useful for DC and AC voltages



An expression for the breakdown threshold was obtained empirically from early experimental data gathered in the 1950's:

$$Ee^{-4.25/E} = 24.4 \cdot [f(GHz)]^{\frac{1}{2}} \ \ MV/m$$

The expression was reformulated by T. J. Boyd[*] in 1982 as:

$$f = 1.64 \cdot E(MV/m)^2 \cdot e^{-8.5/E(MV/m)} \ \ MHz$$

➔ The threshold voltage varies as the square root of the applied frequency.

➔ Kilpatrick already pointed out in this paper that the threshold could be slightly raised by processing the electrode surfaces.

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Expected RF Breakdown Rate and Mitigation Strategy in High Magnetic Fields

High voltage breakdown in both vacuum and gas has been studied extensively. The presence of a multi-tesla external magnetic field provided a new variable, however. As ionization cooling depends on RF cavities operating in such an environment, the performance of said cavities must be understood and characterized.

Early experiments focused on 805 MHz vacuum RF cavities.

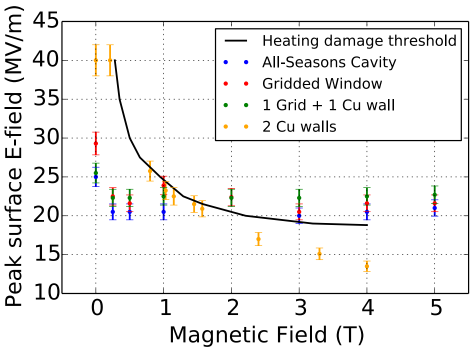
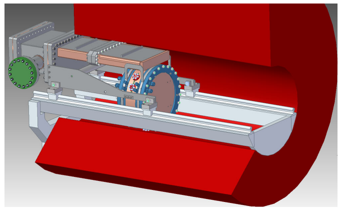


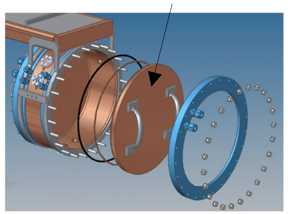
Figure 3: Peak surface electric field vs. external, applied *B*-field for cavity configurations described above. The black line indicates the threshold for surface fracture from beamlet heating, as discussed in [4].



Bowring et al, PRAB 23 072001, 2020

Material	B-field (T)	E-field (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$

Changeable Cu/Be walls



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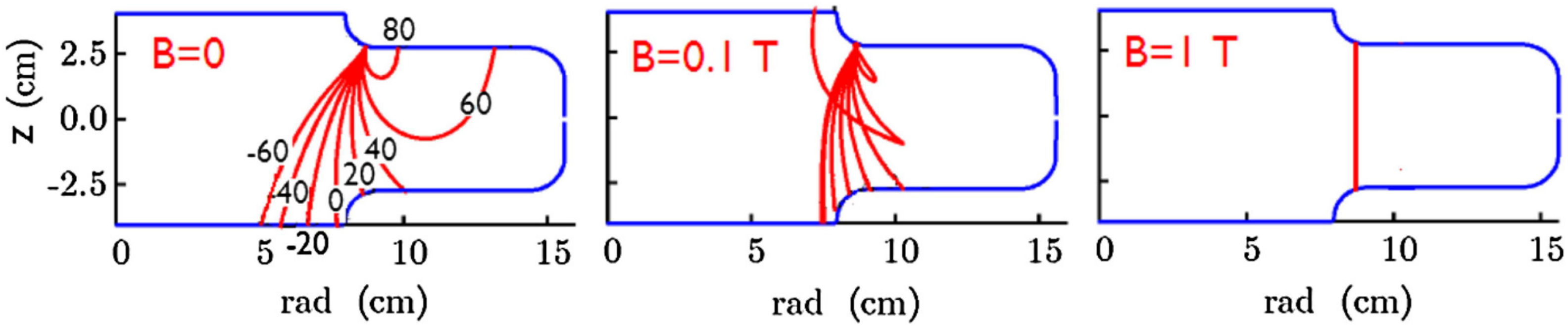
RF E-field in High Magnetic Gradients

A model to explain breakdown of RF cavities in external magnetic fields was proposed. In this model, the magnetic field focuses field emission electrons along trajectories with radii determined by the strength of the magnetic field. These "beamlets" of electrons impact the opposite surface of the cavity, depositing their energy. The surface heats after repeated bombardment, becoming damaged and creating new sources of field emission. This limits the achievable electric field. The stronger the magnetic field, the more focused the beamlets become, depositing energy in a smaller volume and more quickly leading to damage on the surface of the cavity.



B. Freemire in COOL 2015

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E-field in High Magnetic Gradients

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Why we are proposing to carry out tests in a DC based environment ?

- **Simple setup with respect to a RF based one**
- **Tests faster and more flexible**
- **Study on materials and surface treatments**
- **Additional input for further RF based experimental campaigns**
- **Field levels of the order of 100 MV/m (over max. 0.1 mm gp)**
- **Energy similar to the one involved in RF**
- **UHV conditions**
- **BD initial phenomena very similar**

We already have a possible setup (magnet @ 1 T with a 120 mm bore and HV power supplies, radiation detectors, experience on data and image acquisition and competence in material treatments)

1. study of innovative materials to create electrodes to be tested with a high DC static field in the presence of a magnetic field of at least 1 T or higher
2. study of surface finishing, coating and cleaning techniques for the above materials
3. DC high static field test in the presence of a magnetic field of at least 1 T or higher

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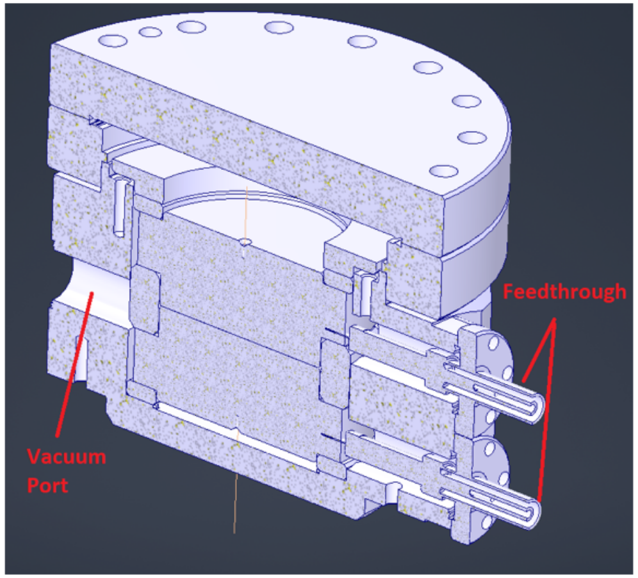
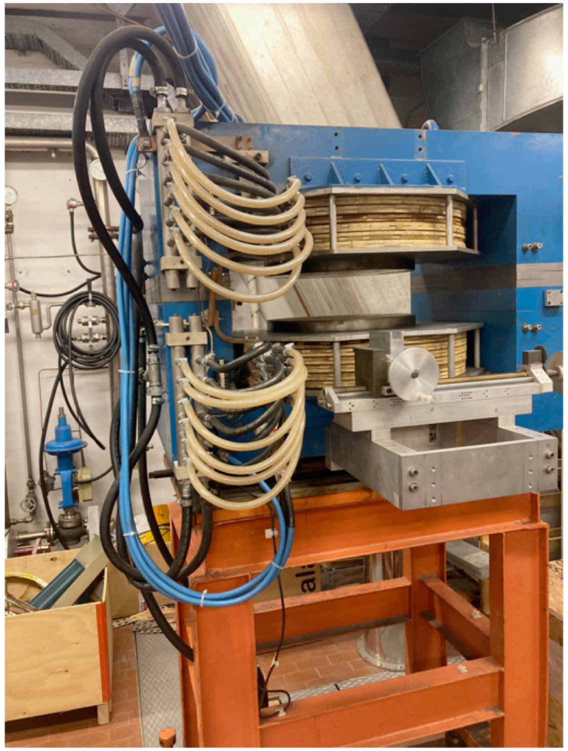
E-field in High Magnetic Gradients





The PVX-4110 pulse generator is a direct coupled, air cooled, solid state half-bridge (totem pole) design, offering equally fast pulse rise and fall times, low power dissipation, and virtually no over-shoot, undershoot or ringing. It has overcurrent detection and shutdown circuitry to protect the pulse generator from potential damage due to arcs and shorts in the load or interconnect cable.

Suitable to test different materials, surface finishing and treatments up to 50 MV/m

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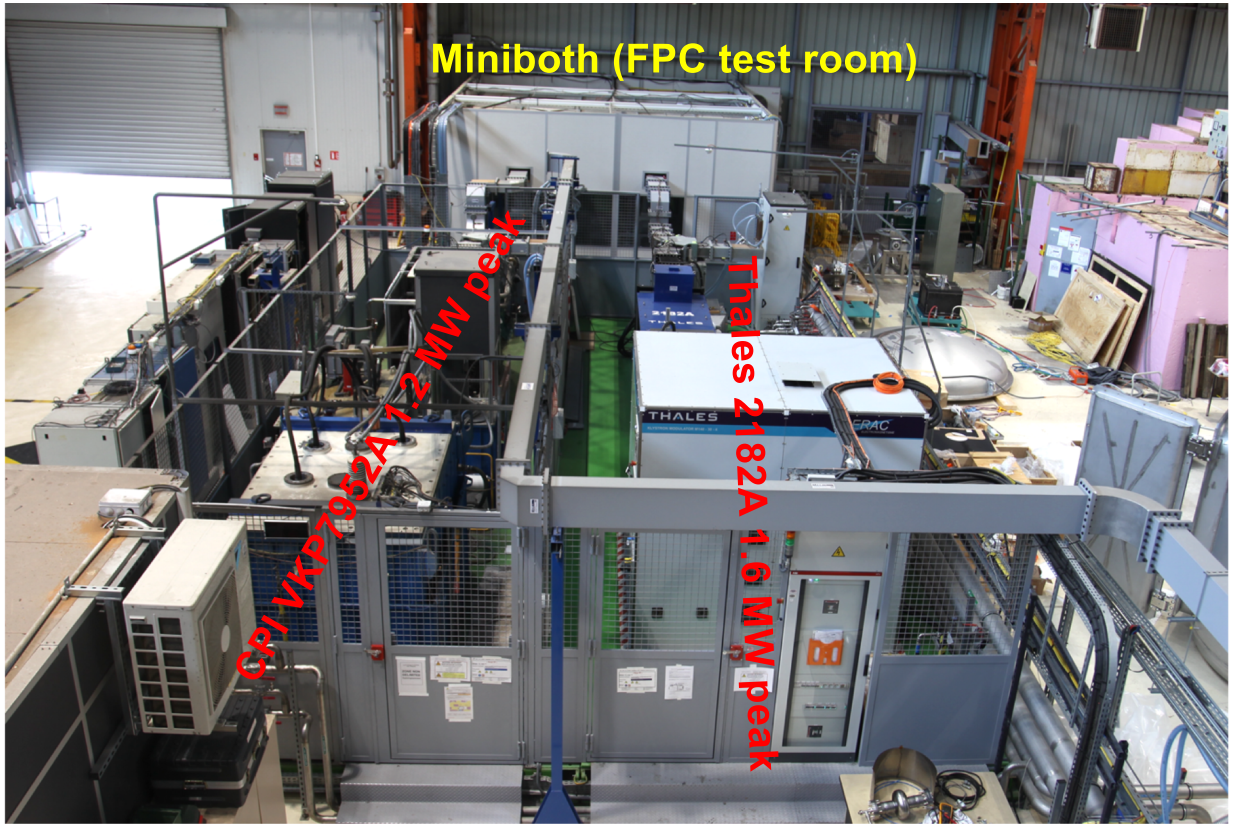
Test Stand Proposals: CEA



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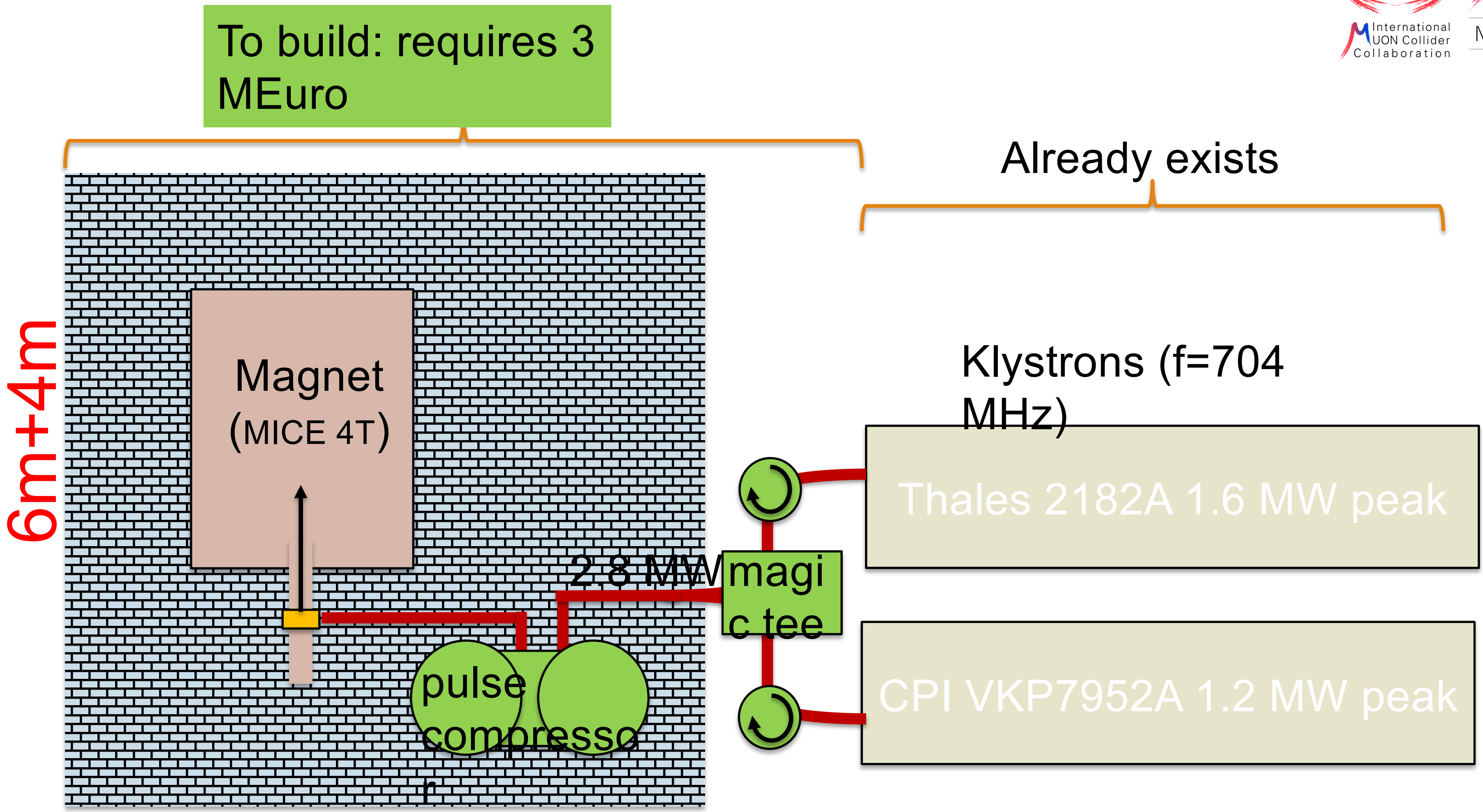

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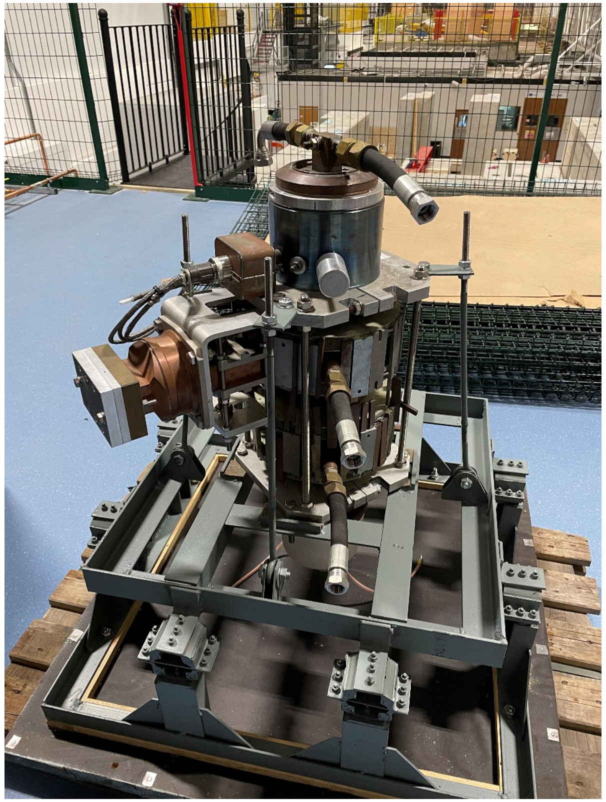
Test Stand Proposals: UK

- Radiation test bunker complete and handed over
- Have taken shipment of an 8 MW S-band klystron and modulator on loan from CERN.
- Circulator also on site, awaiting some waveguide. System should be operating by summer 2024
- Investigating the possibility of a SC magnet to do muon collider relevant research on breakdown in high magnetic fields



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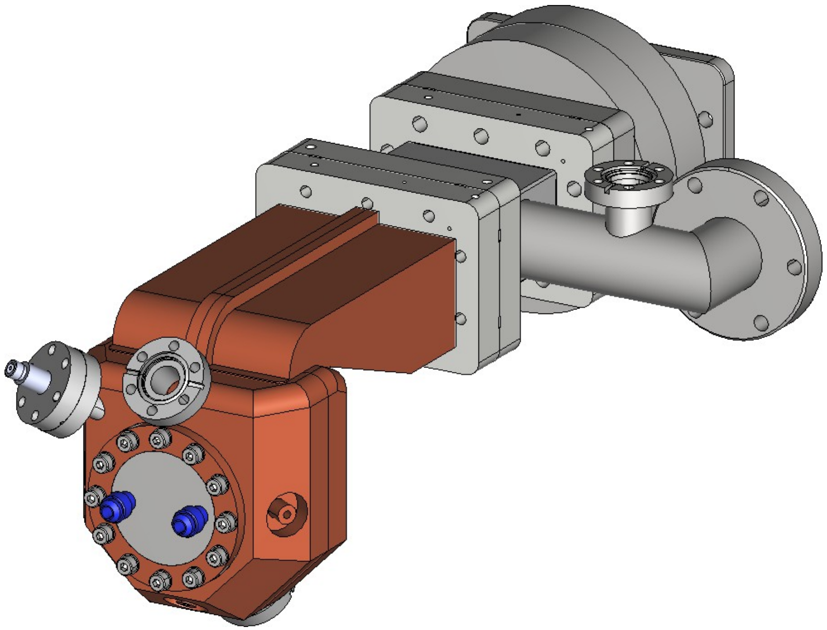
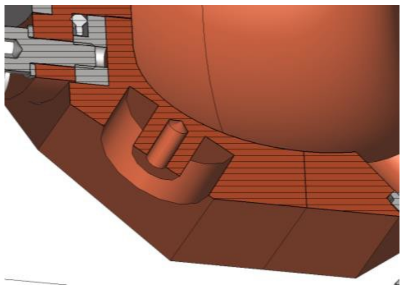
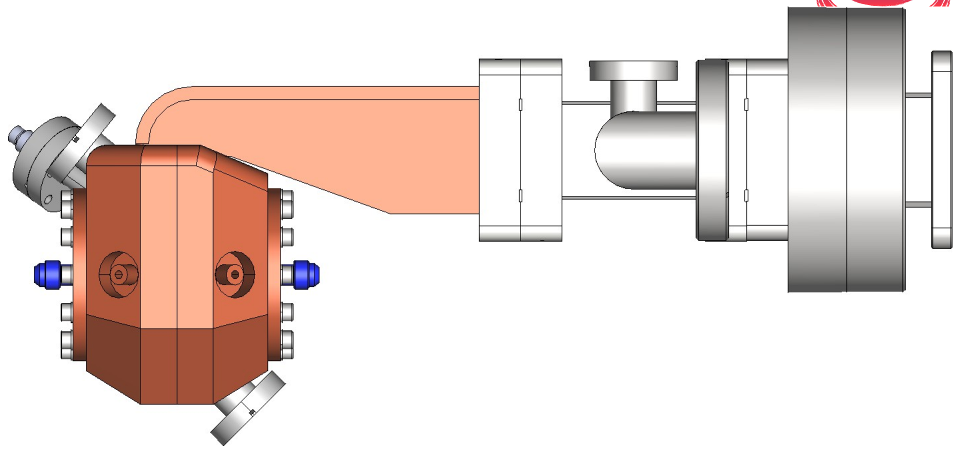
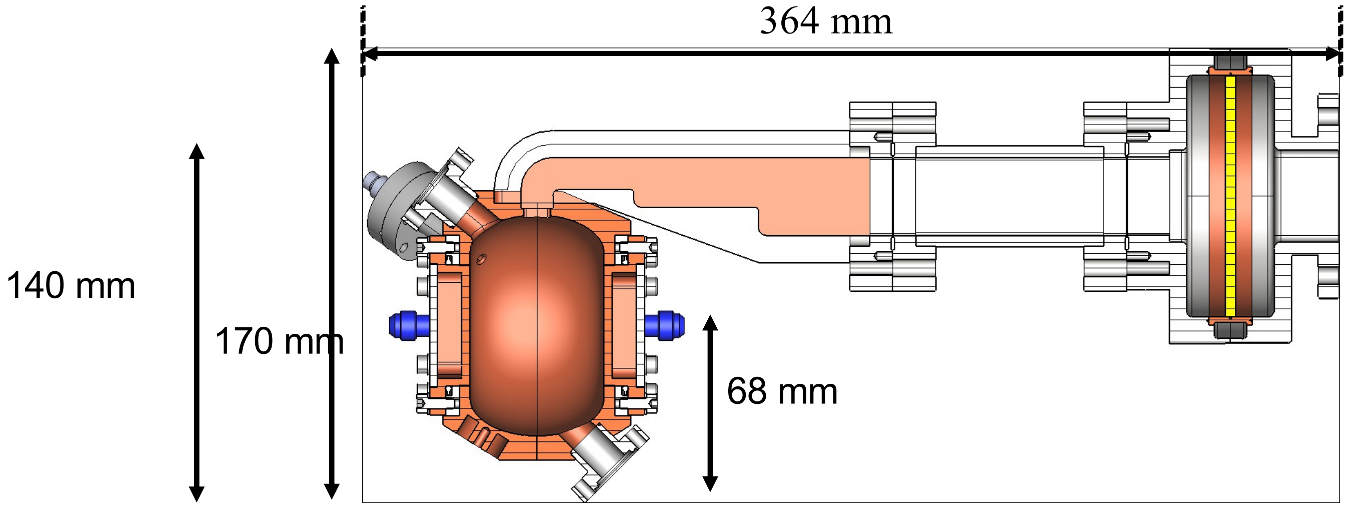
A 3 GHz Proposal for a INFN LASA Test Facility









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A 3 GHz Proposal for a INFN LASA Test Facility

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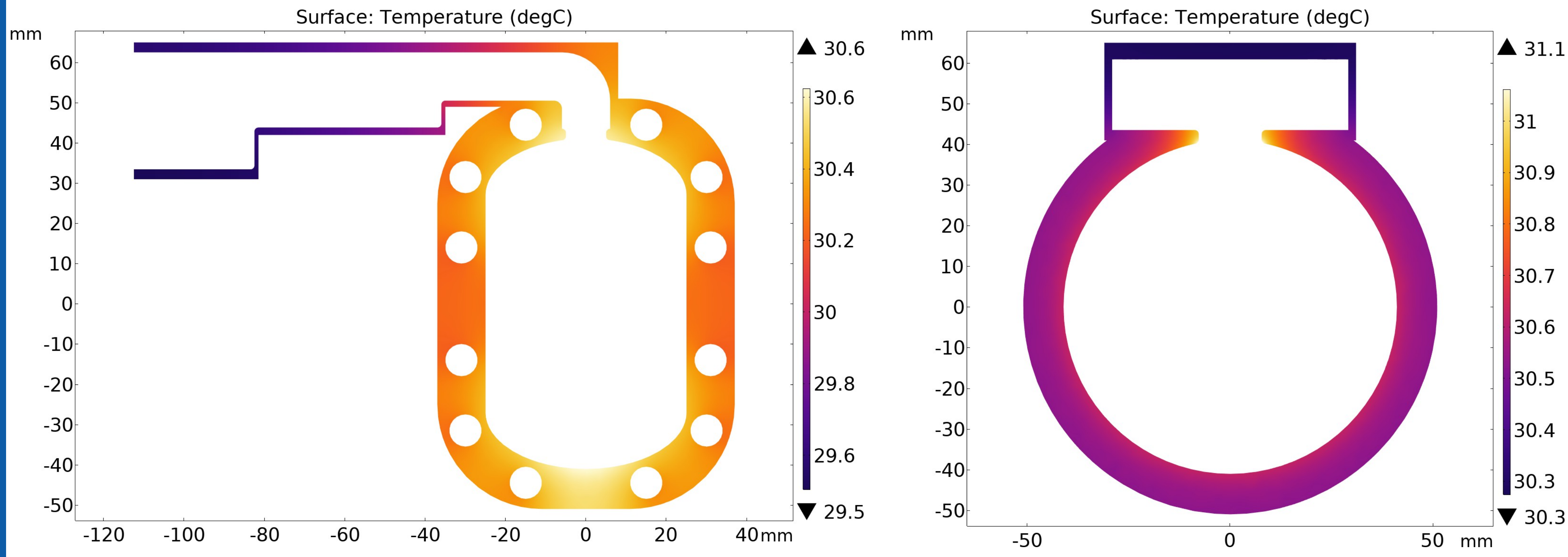
We considered a RF Duty Factor DF = 5e-4 (t_{pulse} = 5 µs, rep. rate = 100 Hz) → P_{avg} = 150 W



ΔT ~ 0.5 °C on cavity volume

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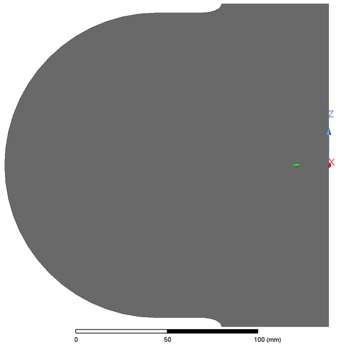
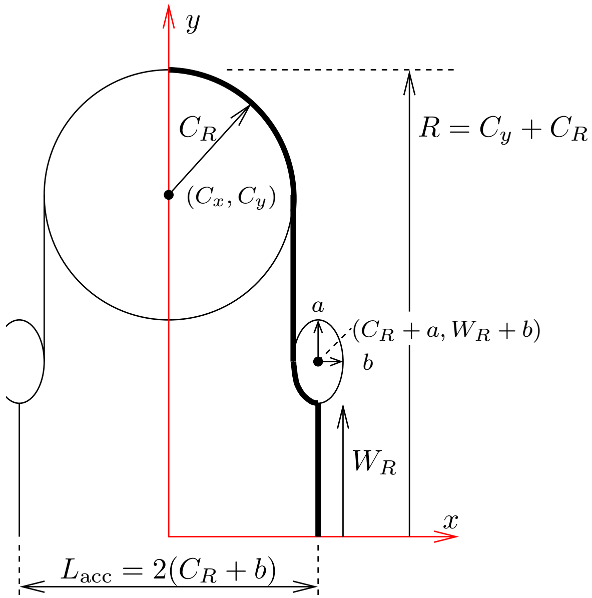
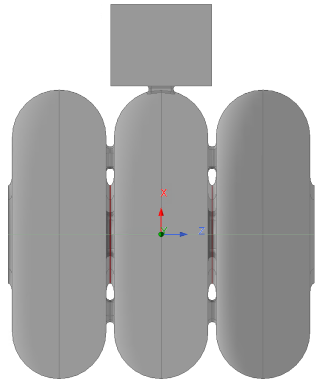
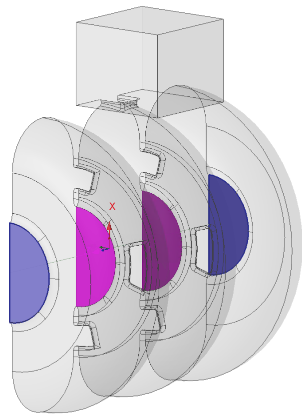
RF cell @704 MHz and 3 cells RF preliminary structure









Geometric parameters for $L_{acc} = 180$ mm

param.	value (mm)
R_c	85
R_i	60
R_v	181.35
a	5
b	11

Table 5: $E_{in} = 37.8$ J

Descrp.	Param.	Unit	INFN
Transit Time	T		0.67
Aver. Nom. gradient	E_0	MV/m	43.9
Accelerating gradient	E_{acc}	MV/m	29.4
Quality Factor (eig.)	Q		40600
Effect. Shunt Impedance	R	MΩ	6.81
Effective R over Q	R/Q	Ω	167.66
Dissipated power	P_{diss}	MW	4.12

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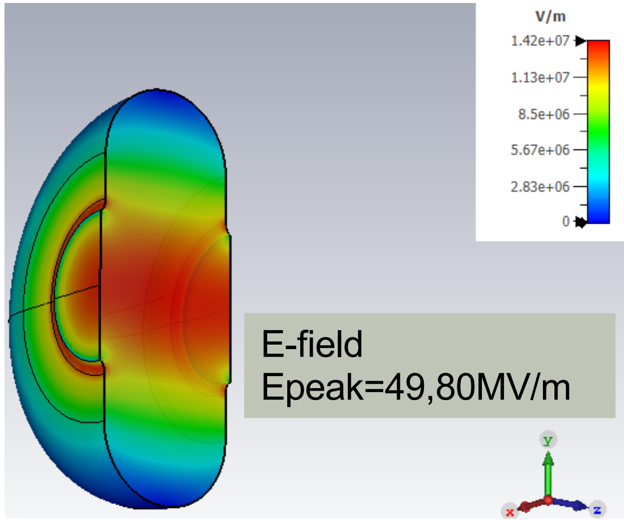
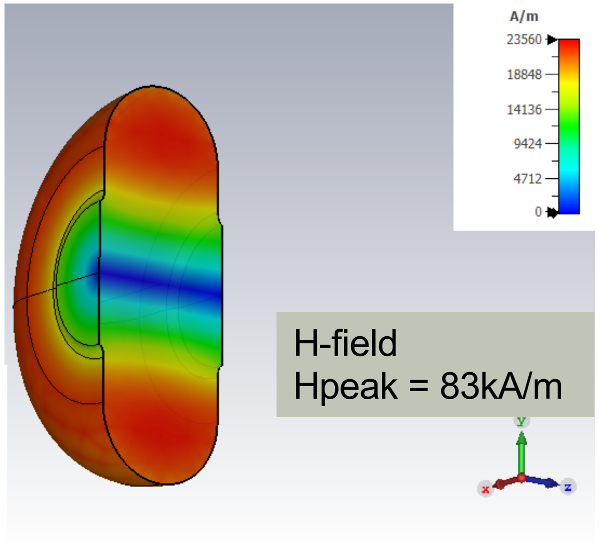
A 1 GHz Design

The availability of a high power Klystron from CLIC drive beam related activities recently suggested to perform a study of 1 GHz cavities powered by such a tube. The power available from this Klystron would be ideal to test a full RF structure.

The picture below shows the results obtained in preliminary computations with related set of parameters.





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INFN LASA

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A 1 GHz Design

Description	Parameter	units	Design
Cavity Length	Lacc	mm	97
Bore radius	Ri	mm	45
Radius cav	Rc	mm	44.49
Half cavity height	Rv	mm	125.2
Ellipse par1	a	mm	3.52
Ellipse par2	b	mm	7.74

A couple of possible geometries have been investigated so far.

International MUON Collider Collaboration

MuCol

The first one foreseen a design similar to the 3 GHz INFN proposal. The transverse size is of the order of 310 mm (with respect to the 395 mm of a 704 MHz design).

Description	Parameter	units	Design
Freq.	f	GHz	1
Transit time	T		0.794
Aver. Nom. grad	Eo	MV/m	44
Accelerating grad	Eacc	MV/m	34.94
Quality Factor	Q		2.67e4
Shunt imped.	Rsh	MOhm	4.94
R over Q	Rsh/Q	Ohm	185.39
Dissipated power in the cavity	Pdiss	MW	2.25

The second is devoted to the possibility to insert the RF cell structure along with the power coupler from an eventually available slot in the lateral structure of the solenoid. The longitudinal space required by the cell (and other services as cooling water and spark diagnostics) is at least of 140 mm and the height of the power coupler structure (a WR975 waveguide tapered in a suitable way) is of the order of 440 mm since the outside side of the cavity (310 mm).

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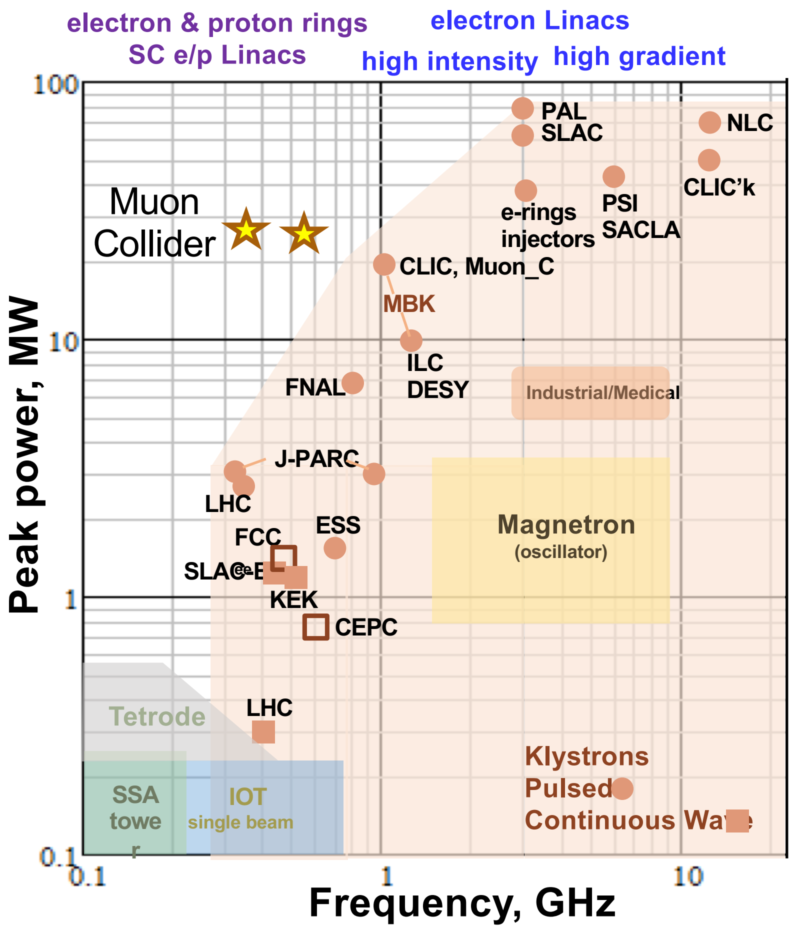
Realistically feasible power sources

The klystron is a key element of almost all particle accelerators.



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Realistically feasible power sources

What is available now at MC frequencies ?

ESS have

2.9 MW klystrons at 352 MHz

1.5 MW klystrons at 704 MHz CPI VKP-8292A and Canon E37504

	RFQ/DTL	MB/HB
Frequency (MHz)	352.21	704.42
Output Power (MW)	2.9	1.5
Bandwidth (MHz)	≥ ± 1	≥ ± 1
Pulse width (ms)	3.5	3.5
Repetition rate (Hz)	14	14
Efficiency	>53%	>63%
Output VSWR	Up to 1.2	Up to 1.2
Power Gain (dB)	≥ 40	≥ 40
Perveance ($A/V^{-3/2}$)	$1.3*10^{-6}$	$0.6*10^{-6}$
Maximum HV (kV)	110	115

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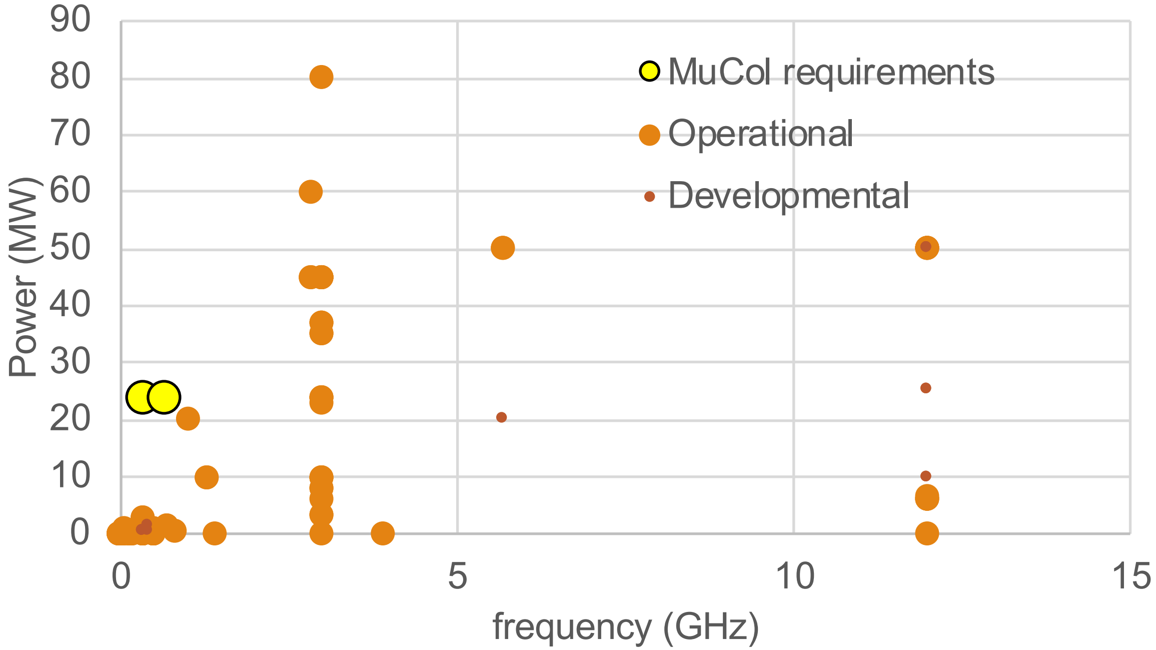
Realistically feasible power sources



While tubes >24 MW exist they are all above 3 GHz

There are 10-20 MW tubes developed for CLIC drive beam and ILC at 1-1.3 GHz

Nothing of this power exists at 325 or 650 MHz

Issue is typically that to get high power means high voltage which makes the tubes longer

For scaling at low frequency this used to not be feasible as length is inversely proportional to frequency for constant beam

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Conclusions

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- RF studies related to the ionizing cooling channel for a MC are an exciting field of research with possible positive effects on other areas
- Valuable progresses have been reached in RF cells and structures for the MC
- Experimental activities are starting using partially available equipment
- Design of more complex test stand for full power experiments at different frequencies and in high peak magnetic fields are in progress

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Thanks for your attention !

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