Review and Update on RF cavity Design

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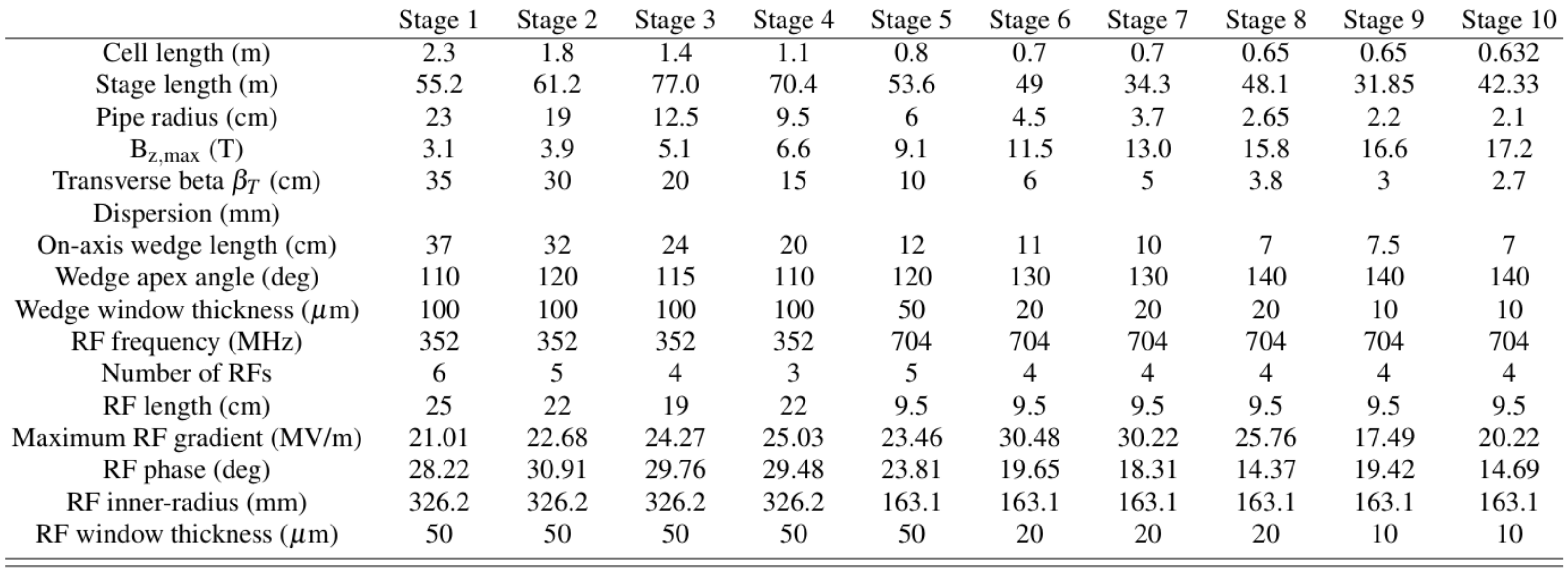
Thanks to Luigi Celona, Gino Sorbello, Davide Guarneri, Giorgio Mauro, Maria Rosaria Masullo,

Guido Gentili (INFN- LNS, INFN-Na, Politecnico of Milan)

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)

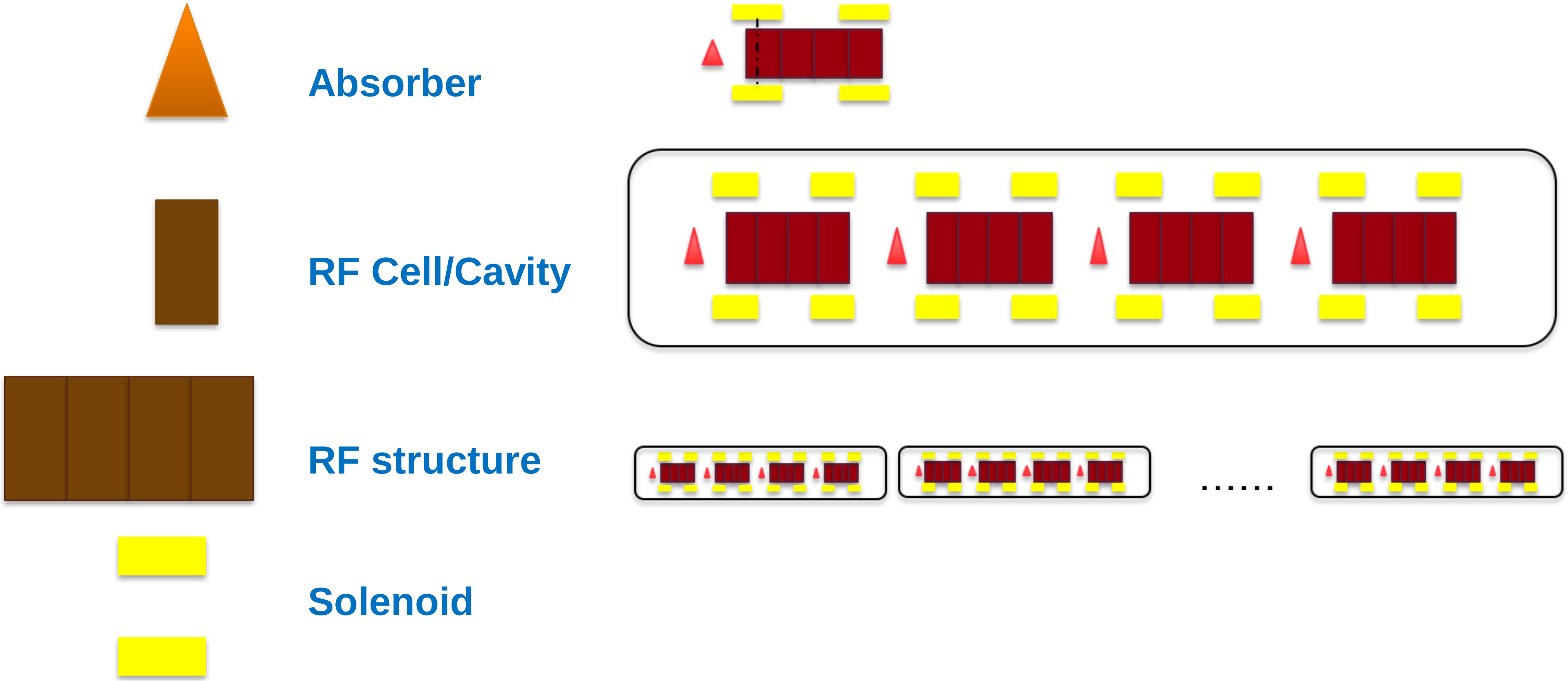


	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
Cell length (m)	2.3	1.8	1.4	1.1	0.8	0.7	0.7	0.65	0.65	0.632
Stage length (m)	55.2	61.2	77.0	70.4	53.6	49	34.3	48.1	31.85	42.33
Pipe radius (cm)	23	19	12.5	9.5	6	4.5	3.7	2.65	2.2	2.1
$B_{z,max}$ (T)	3.1	3.9	5.1	6.6	9.1	11.5	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)

Terminology

Before to discuss the panorama of the open points related to RF and the activities carried out in the last year, a definition of the terminology that we will use in the discussions has been defined.



Absorber

RF Cell/Cavity

RF structure

Solenoid

Cooling Cell

Cooling Module

Cooling Section

RF Cavity and RF Structure Design

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.

RF Frequency Range of Interest

The RF frequencies analyzed so far are the following:

704 MHz	**(the today reference MC frequency in the design)**
1 GHz	**(power Klystron available from CLIC drive beam researches ideal for RF demonstrator structures test facility)**

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.

Expected RF Breakdown Rate and Mitigation Strategy in High Magnetic Fields

Muon Collider RF meeting 1st October- 2024

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.

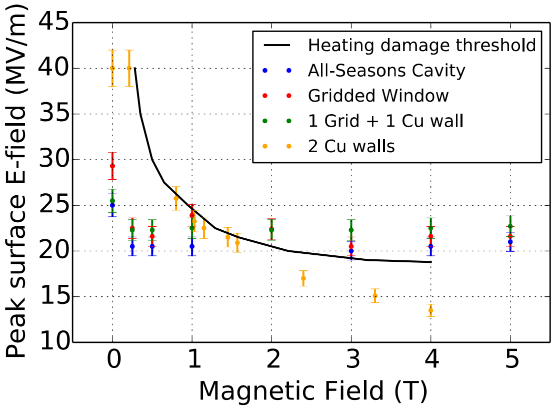
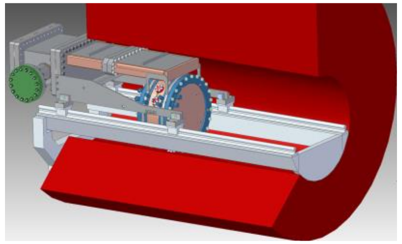


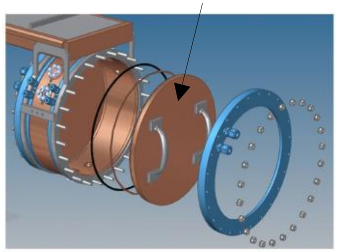
Figure 3: Peak surface electric field vs. external, applied *B*-field for cavity configurations described above. The black line indicates the threshold for surface fracture from beamlet heating, as discussed in [4].



Bowring et al, PRAB 23 072001, 2020

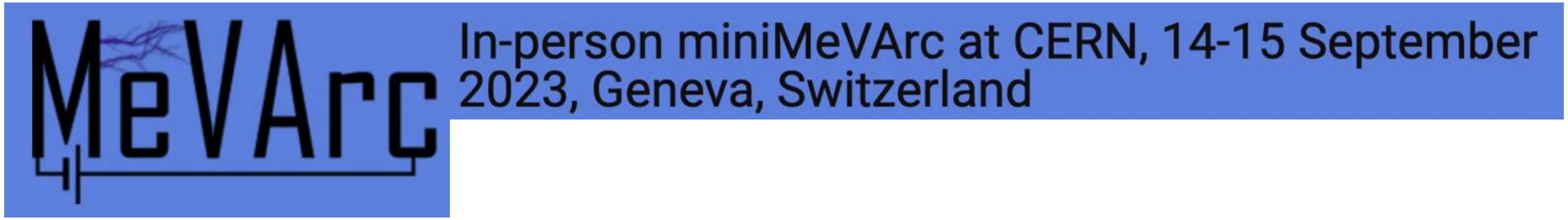
Material	*B*-field (T)	*E*-field (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$

Changeable Cu/Be walls

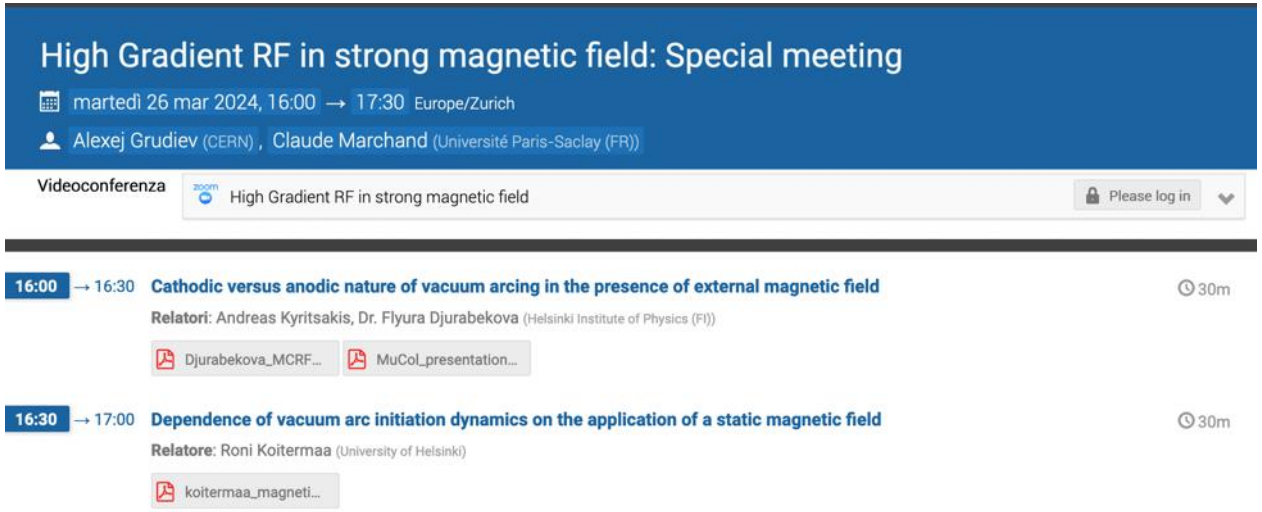


RF E-field in High Magnetic Gradients Studies

A couple of interesting events (a special meeting and a workshop) took place in the past months



In-person miniMeVArc at CERN, 14-15 September 2023, Geneva, Switzerland



High Gradient RF in strong magnetic field: Special meeting

martedì 26 mar 2024, 16:00 → 17:30 Europe/Zurich

Alexej Grudiev (CERN), Claude Marchand (Université Paris-Saclay (FR))

Videoconferenza: High Gradient RF in strong magnetic field

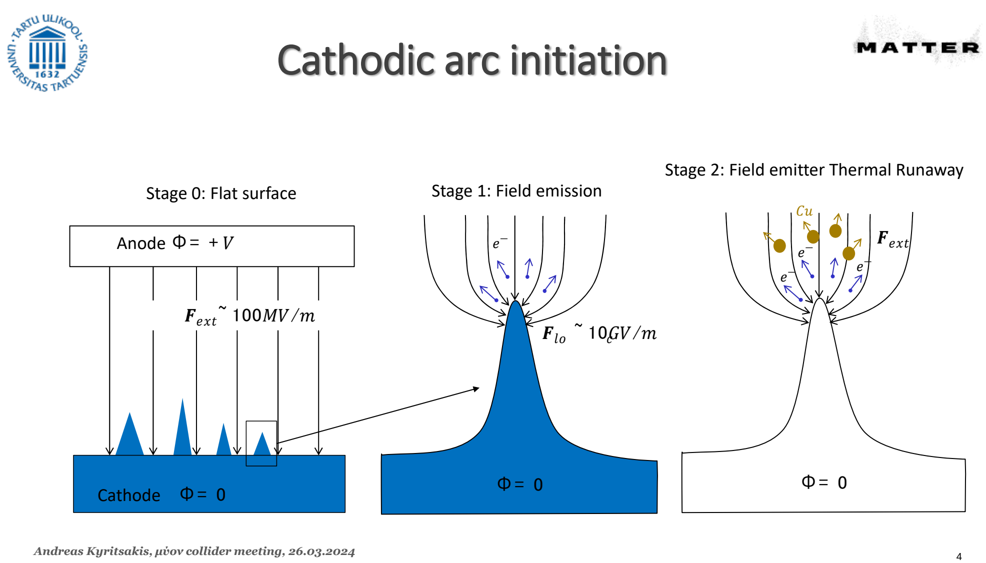
16:00 → 16:30 **Cathodic versus anodic nature of vacuum arcing in the presence of external magnetic field** 30m

Relatori: Andreas Kyritsakis, Dr. Flyura Djurabekova (Helsinki Institute of Physics (FI))

16:30 → 17:00 **Dependence of vacuum arc initiation dynamics on the application of a static magnetic field** 30m

Relatore: Roni Koitermaa (University of Helsinki)

RF E-field in High Magnetic Gradients Studies



Cathodic arc initiation

MATTER

Stage 0: Flat surface

Anode $\Phi = +V$

$F_{ext} \sim 100 MV/m$

Cathode $\Phi = 0$

Stage 1: Field emission

e^-

$F_{lo} \sim 10 GV/m$

$\Phi = 0$

Stage 2: Field emitter Thermal Runaway

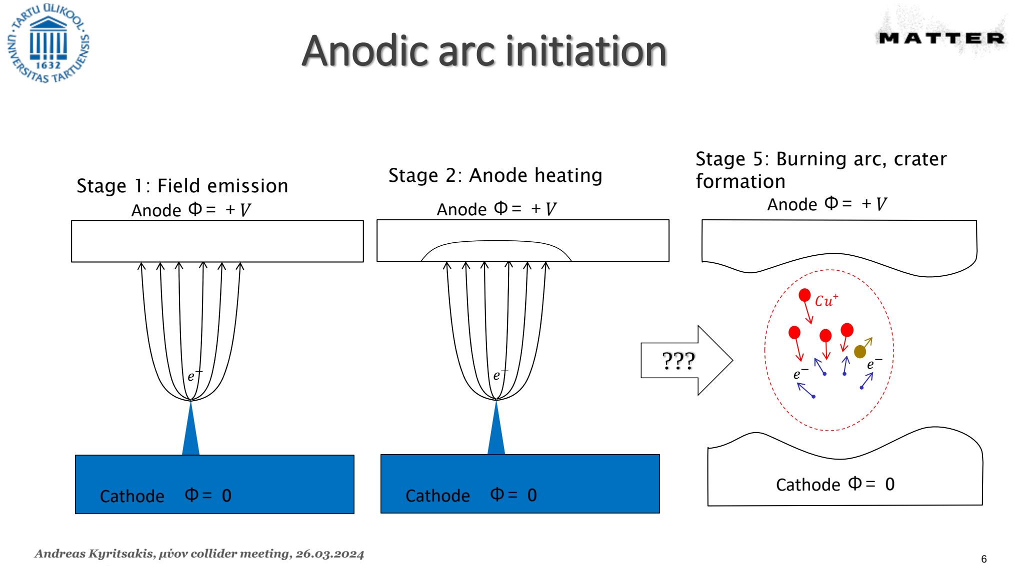
Cu

F_{ext}

e^-

$\Phi = 0$

Andreas Kyritsakis, μύον collider meeting, 26.03.2024



Anodic arc initiation

MATTER

Stage 1: Field emission

Anode $\Phi = +V$

e^-

Cathode $\Phi = 0$

Stage 2: Anode heating

Anode $\Phi = +V$

e^-

Cathode $\Phi = 0$

???

Stage 5: Burning arc, crater formation

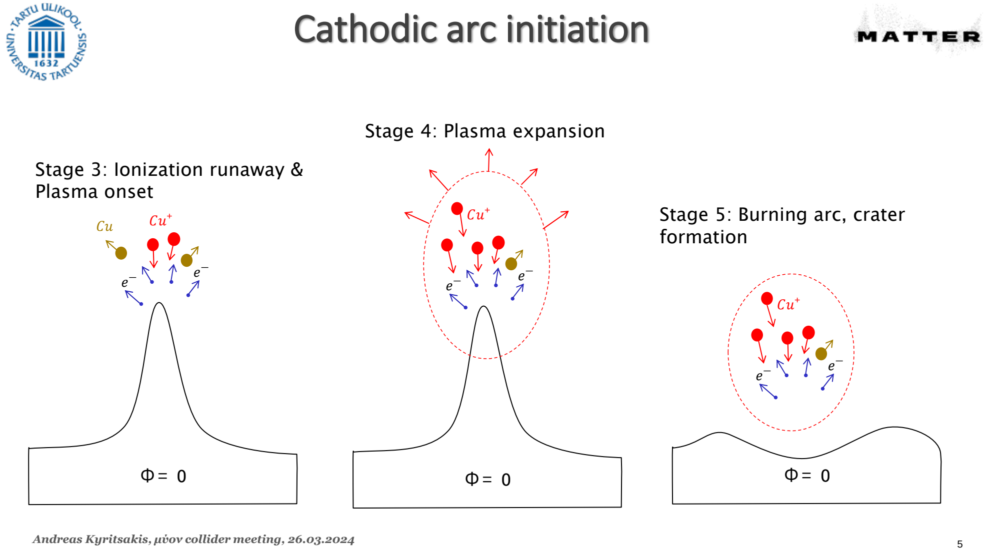
Anode $\Phi = +V$

Cu^+

e^-

Cathode $\Phi = 0$

Andreas Kyritsakis, μύον collider meeting, 26.03.2024



Cathodic arc initiation

MATTER

Stage 3: Ionization runaway & Plasma onset

Cu

Cu^+

e^-

$\Phi = 0$

Stage 4: Plasma expansion

Cu^+

e^-

$\Phi = 0$

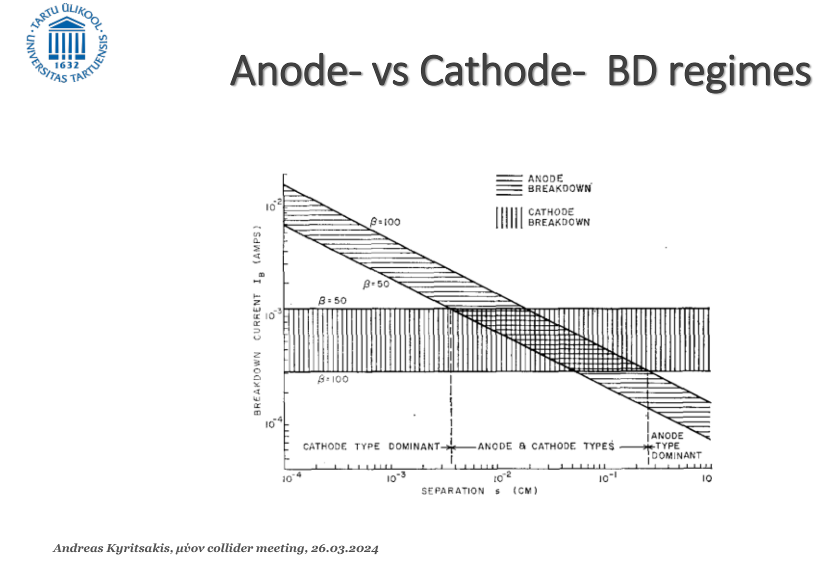
Stage 5: Burning arc, crater formation

Cu^+

e^-

$\Phi = 0$

Andreas Kyritsakis, μύον collider meeting, 26.03.2024



Anode- vs Cathode- BD regimes

ANODE BREAKDOWN

CATHODE BREAKDOWN

$\beta = 100$

$\beta = 50$

$\beta = 50$

$\beta = 100$

BREAKDOWN CURRENT I_B (AMPS)

10^{-2}

10^{-3}

10^{-4}

CATHODE TYPE DOMINANT

ANODE & CATHODE TYPES

ANODE TYPE DOMINANT

10^{-4}

10^{-3}

10^{-2}

10^{-1}

10

SEPARATION s (CM)

Andreas Kyritsakis, μύον collider meeting, 26.03.2024

E-field in High Magnetic Gradients

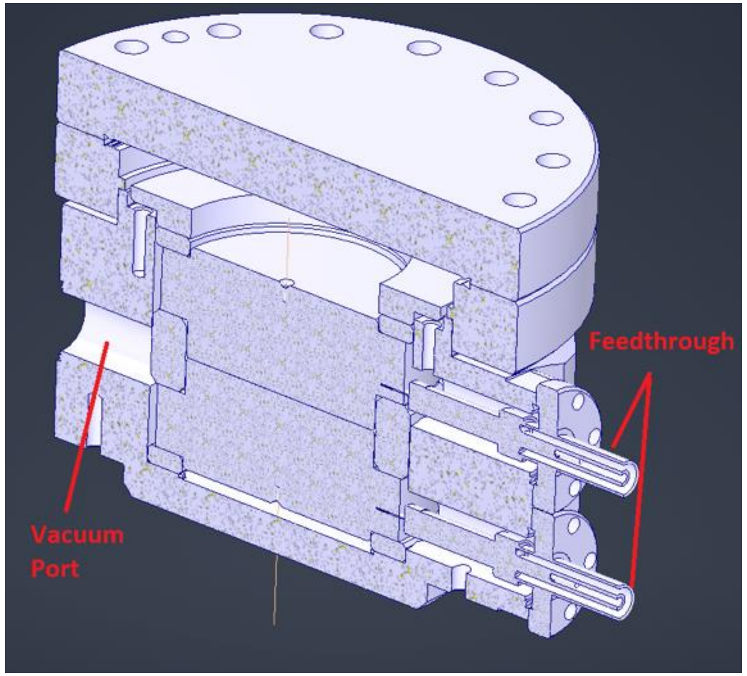
Why we are proposing to carry out tests in a DC based environment ?

- **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

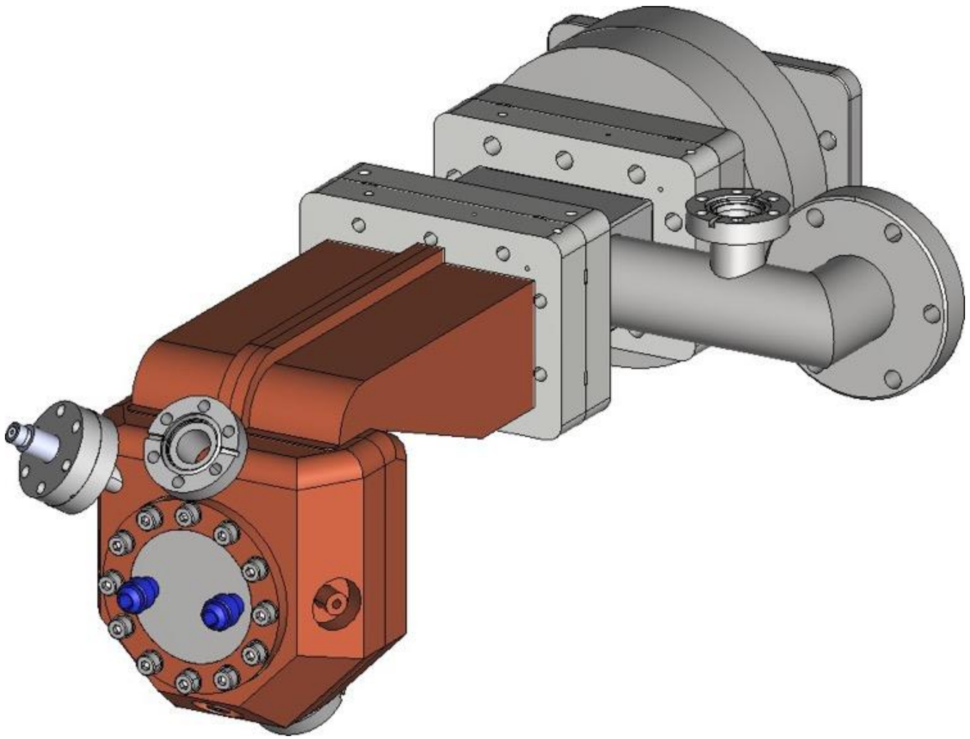
E-field in High Magnetic Gradients

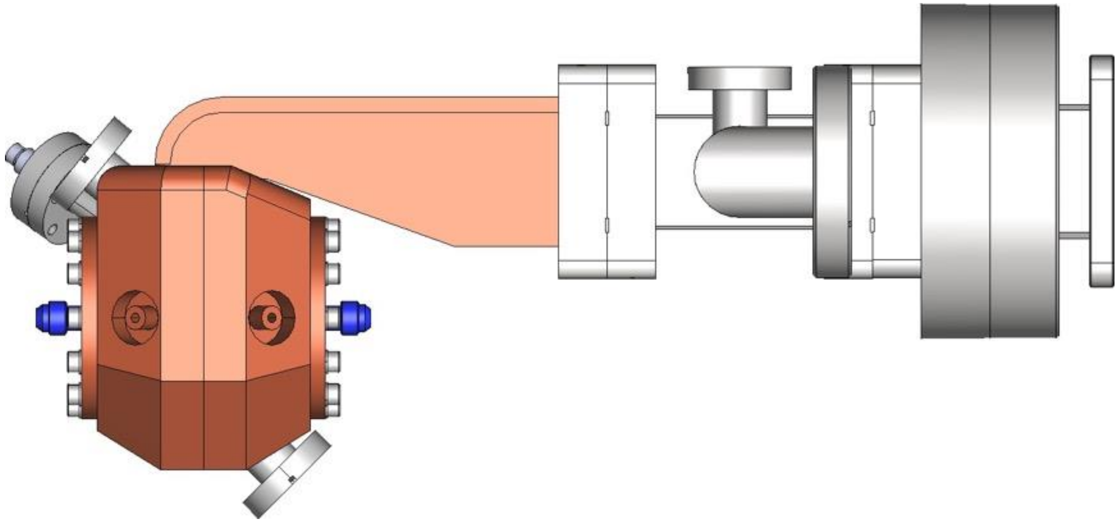


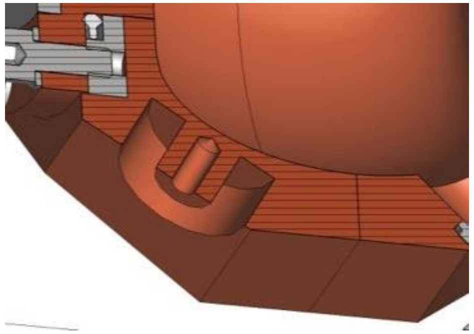
The PVX-4110 pulse generator is a direct coupled, air cooled, solid state half-bridge (totem pole) design, offering equally fast pulse rise and fall times, low power dissipation, and virtually no over-shoot, undershoot or ringing. It has overcurrent detection and shutdown circuitry to protect the pulse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

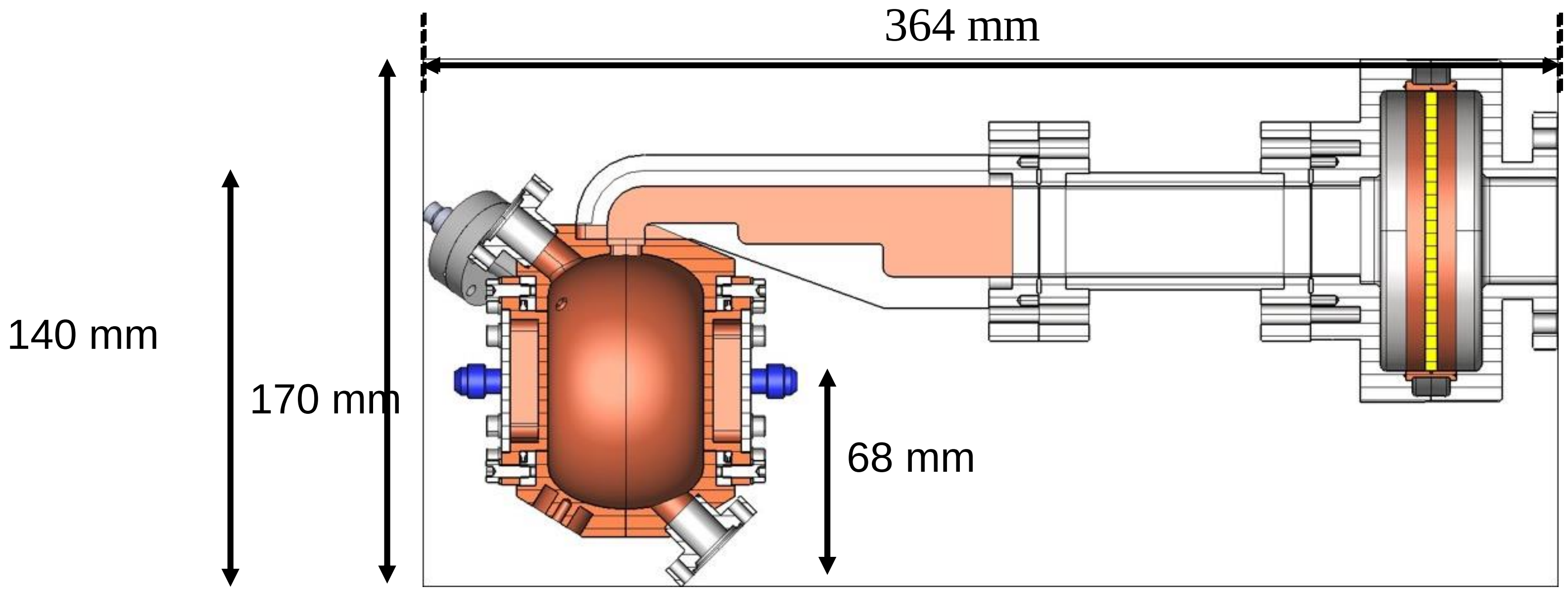
Suitable to test different materials, surface finishing and treatments up to 50 MV/m

A 3 GHz Proposal for a INFN LASA Test Facility









ESPP-INFN New proposal in September 2024

Breakdown rate studies of normal conducting structures operating at electric fields > 30 MV/m up to 100 MV/m embedded in magnetic fields up to 10 T (mostly with E and B fields parallel to each other) represents one of the most exciting and relevant areas in the development of new proposals for accelerating machines.

The lack of experimental data and, as a consequence, the difficulties to develop and verify theoretical models of the involved phenomena must be addressed in a short period and this requires a significant effort involving an approach that will start from material science up to accelerator related advanced technologies.

The present proposal represents a unique opportunity in the area due to the possibility to take advantage in a short period of already existing testing facilities at LNF for RF power studies and the knowledge process under development at LASA related to the design of suitable magnet structures and RF cavities.

ESPP-INFN New proposal in September 2024

The proposal arises from a series of activities already underway for several years **both at LNF and at LASA** and for which it is necessary to make a qualitative leap in the related studies in order to continue to maintain an adequate level of leadership at a global level.

At **LNF** the development of RF structures operating in C and X band has achieved impressive results in the maximum electrical field sustained in the past years. **The possibility to test in a devoted facility these structures resulted in the acquisition of a leading role in the international panorama**.

At **LASA** the design of normal conducting cavities with frequencies ranging from 650 MHz up to 3 GHz has been carried out for different accelerator projects. The construction of full scale prototypes was carried out with Italian companies allowing the development and maintenance of adequate technologies. **The completion of testing facilities underway allows to play a valuable role in projects such as the Muon Collider or ERL related components. The study, construction and technological developments related to high filed SC magnets represent the major activity underway at LASA.**

ESPP-INFN New proposal in September 2024

Design, specify and build (internally or commissioning to a company) a SC magnet feeded by a cryocooler and with a useful bore of 120 mm **to be used in the LNF TEX** facility for testing C and X band structures about the breakdown rate obtainable. The magnet will provide up to 4 T of magnetic field over a length of 200 mm.

Design, specify and build (commissioning to a company) **a couple of prototypes of single cells and power couplers** running at 704 MHz and 1 GHz and aimed for the Muon Collider (MC) project. These components will be tested at **low power in the RF laboratory under development at LASA within the previous ESPP funding**.

Design, specify and build (commissioning to a company) **a prototype of a full 3 RF cells element running at 704 MHz as the basic building block of the MC demonstrator structure**. Carry out low power tests at LASA and high power RF tests in a laboratory to be identified.

Design and build **a RF power coupler (up to few MW) for a 704 MHz and 1 GHz 3 RF cells structure.**

ESPP-INFN New proposal in September 2024

Design, specify and develop **a structure able to integrate a 7 T HTS based SC magnet with a full 3 RF cells elements as a prototype of the first cooling cell of the MC demonstrator structure**.

Continue **the technological developments underway at LASA and at LNL for the best materials and surface manipulation techniques to increase the breakdown rates and start studies that using the experimental results will allow to develop suitable theoretical studies of these phenomena**.

RF cell @704 MHz INFN studies

Muon Collider RF meeting 1st October- 2024

5 Cavity Design Parametrization and FoMs

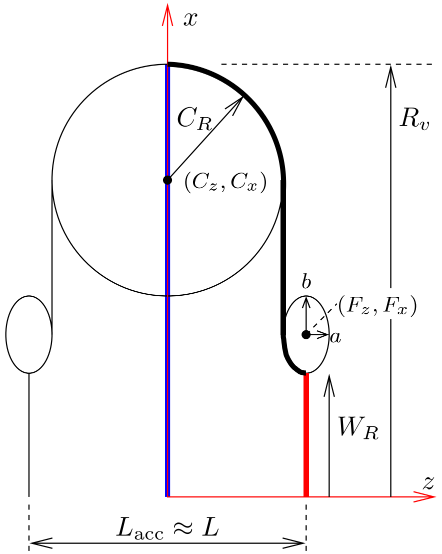
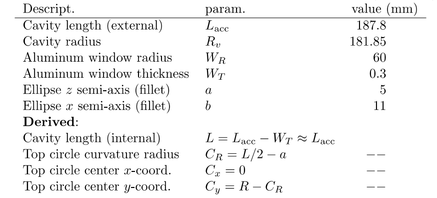


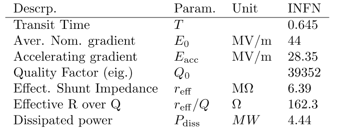
Figure 1: Adopted geometrical parametrization for the cavity designed.

Table 1: Geometrical parameters, $L_{\text{acc}} = 187.8$, $f_0 = 704$ MHz (see Fig. 1)



Descript.	param.	value (mm)
Cavity length (external)	L_{acc}	187.8
Cavity radius	R_v	181.85
Aluminum window radius	W_R	60
Aluminum window thickness	W_T	0.3
Ellipse z semi-axis (fillet)	a	5
Ellipse x semi-axis (fillet)	b	11
Derived:		
Cavity length (internal)	$L = L_{\text{acc}} - W_T \approx L_{\text{acc}}$	
Top circle curvature radius	$C_R = L/2 - a$	$--$
Top circle center x-coord.	$C_x = 0$	$--$
Top circle center y-coord.	$C_y = R - C_R$	$--$

Table 2: FoMs of the designed cavity. $E_{\text{in}} = 39.5$ J (Energy stored in the full cavity)



Descrp.	Param.	Unit	INFN
Transit Time	T		0.645
Aver. Nom. gradient	E_0	MV/m	44
Accelerating gradient	E_{acc}	MV/m	28.35
Quality Factor (eig.)	Q_0		39352
Effect. Shunt Impedance	r_{eff}	MΩ	6.39
Effective R over Q	r_{eff}/Q	Ω	162.3
Dissipated power	P_{diss}	MW	4.44

7 New Flat-Top Cavity Design; Geometrical Parametrization and FoMs

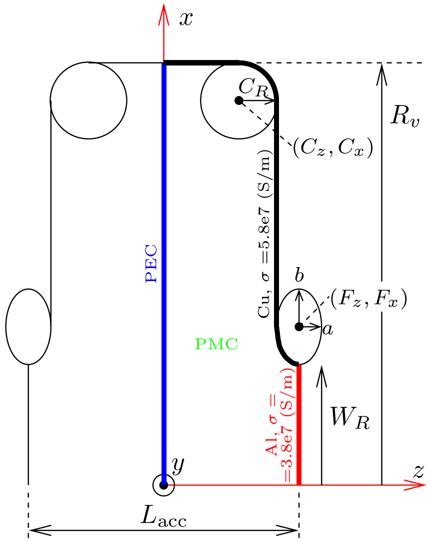
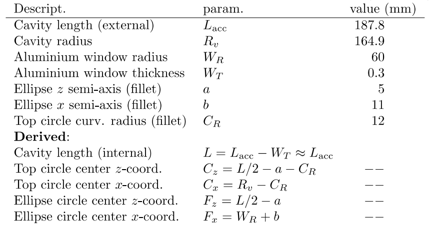
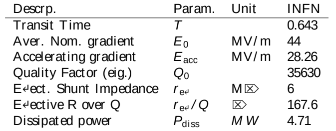


Table 3: Geometrical parameters, $L_{\text{acc}} = 187.8$, $f_0 = 704$ MHz (see Fig. 8)



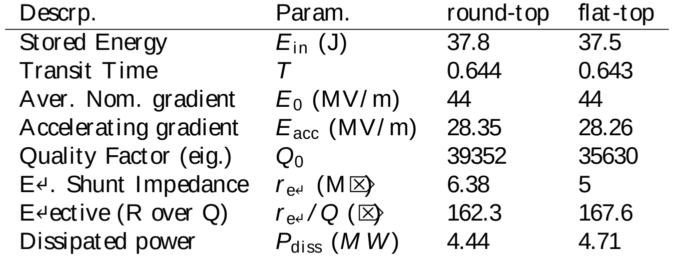
Descript.	param.	value (mm)
Cavity length (external)	L_{acc}	187.8
Cavity radius	R_v	164.9
Aluminium window radius	W_R	60
Aluminium window thickness	W_T	0.3
Ellipse z semi-axis (fillet)	a	5
Ellipse x semi-axis (fillet)	b	11
Top circle curv. radius (fillet)	C_R	12
Derived:		
Cavity length (internal)	$L = L_{\text{acc}} - W_T \approx L_{\text{acc}}$	
Top circle center z-coord.	$C_z = L/2 - a - C_R$	$--$
Top circle center x-coord.	$C_x = R_v - C_R$	$--$
Ellipse circle center z-coord.	$F_z = L/2 - a$	$--$
Ellipse circle center x-coord.	$F_x = W_R + b$	$--$

Table 4: FoMs of the designed cavity. $E_{\text{in}} = 38$ J (Energy stored in the full cavity)



Descrp.	Param.	Unit	INFN
Transit Time	T		0.643
Aver. Nom. gradient	E_0	MV/m	44
Accelerating gradient	E_{acc}	MV/m	28.26
Quality Factor (eig.)	Q_0		35630
Effect. Shunt Impedance	r_{eff}	MΩ	6
Effective R over Q	r_{eff}/Q	Ω	167.6
Dissipated power	P_{diss}	MW	4.71

Table 5: FoMs comparison between the round-top design and the flat-top design



Descrp.	Param.	round-top	flat-top
Stored Energy	E_{in} (J)	37.8	37.5
Transit Time	T	0.644	0.643
Aver. Nom. gradient	E_0 (MV/m)	44	44
Accelerating gradient	E_{acc} (MV/m)	28.35	28.26
Quality Factor (eig.)	Q_0	39352	35630
Eff. Shunt Impedance	r_{eff} (MΩ)	6.38	5
Effective (R over Q)	r_{eff}/Q (Ω)	162.3	167.6
Dissipated power	P_{diss} (MW)	4.44	4.71

3 cells RF preliminary structure

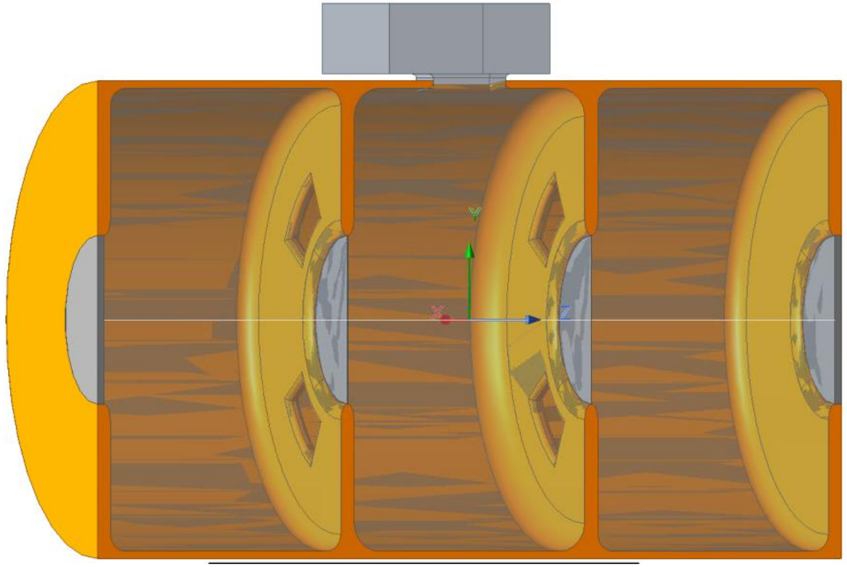
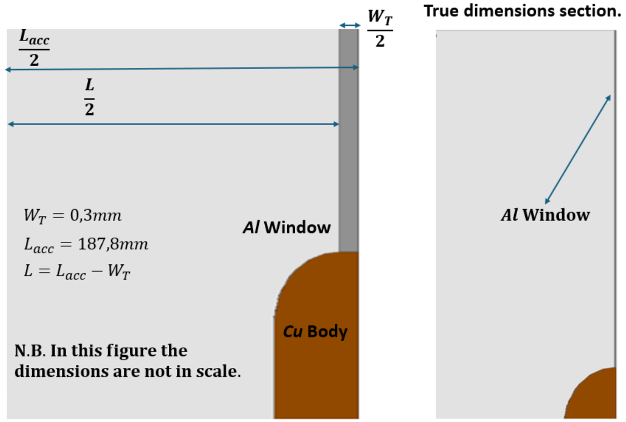


Figure 14: Preliminary design of 3 connected Flat-Top cells fed by waveguide.

WR975
Dimension: 9.75 Inches [247.65 mm] × 4.875 Inches [123.825 mm]
Cutoff Frequency of Lowest Order Mode: 0.605 GHz
No. 4 magnetic slots:

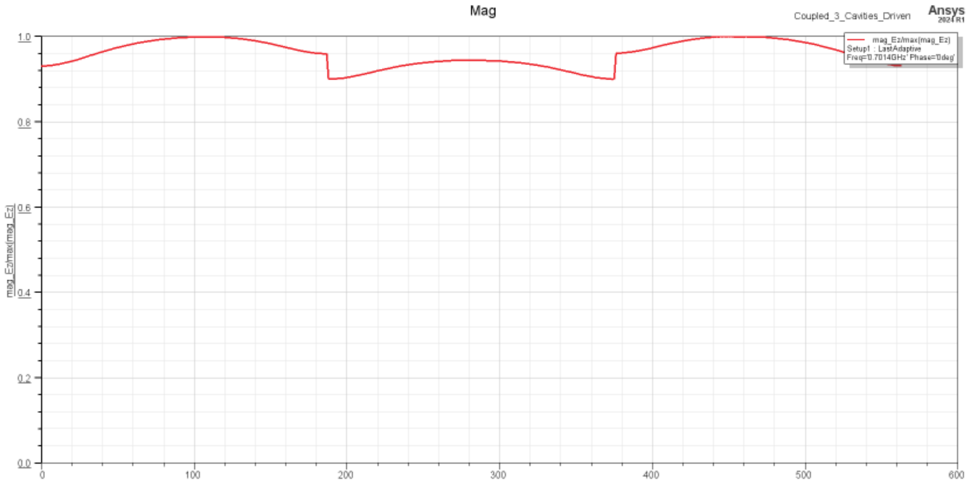
```
h_mag_slot 25 mm
angle_mag_slot 15 mm
```



$W_T = 0{,}3mm$
$L_{acc} = 187{,}8mm$
$L = L_{acc} - W_T$

N.B. In this figure the dimensions are not in scale.

Figure 11: Section of the Aluminum window



3 cells RF preliminary structure

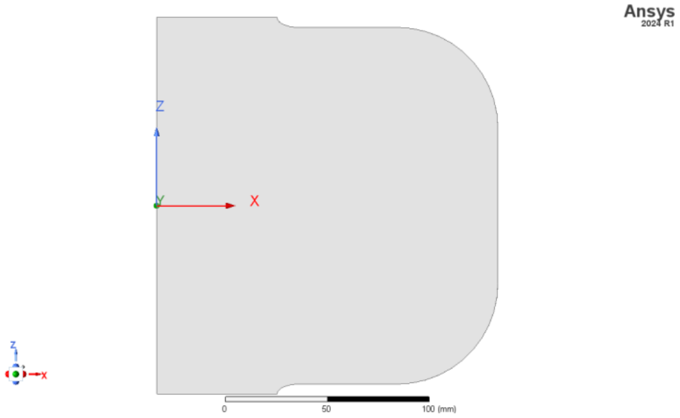


Figure 16: Section of the new design simulated cavity: $L_{\mathrm{acc}} = 187.8$ mm, $f_0 = 704$ MHz.

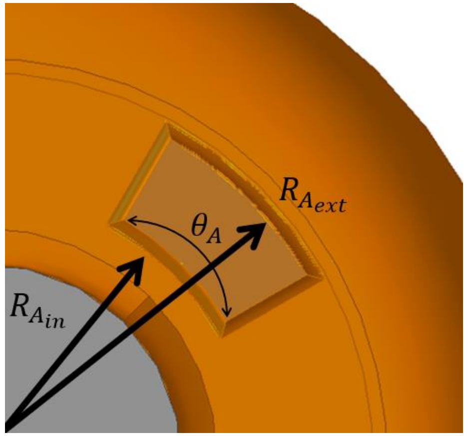


Figure 17: Magnetic coupling slots. There are four coupling slots spaced 90° degrees apart

Table 7: FoMs of the designed cavity. $E_{\mathrm{in}} = 38$ J (Energy stored in the full cavity)

Descrp.	Param.	Unit	INFN
Transit Time	T		0.643
Aver. Nom. gradient	E_0	MV/m	44
Accelerating gradient	E_{acc}	MV/m	28.37
Quality Factor (eig.)	Q_0		38345
Effect. Shunt Impedance	r_{eff}	MΩ	6.41
Effective R over Q	r_{eff}/Q	Ω	167.15
Dissipated power	P_{diss}	MW	4.43

Table 8: FoMs comparison between the designed cavities

Descrp.	Param.	round-top	flat-top first design	flat-top new design
Stored Energy	E_{in} (J)	39.5	38	38.4
Transit Time	T	0.644	0.643	0.643
Aver. Nom. gradient	E_0 (MV/m)	44	44	44
Accelerating gradient	E_{acc} (MV/m)	28.35	28.26	28.37
Quality Factor (eig.)	Q_0	39352	35630	38345
Eff. Shunt Impedance	r_{eff} (MΩ)	6.38	5	6.41
Effective (R over Q)	r_{eff}/Q (Ω)	162.3	167.6	167.15
Dissipated power	P_{diss} (MW)	4.44	4.72	4.43

Note that in the case of critical coupling, the energy dissipated in the cavity (Eigenmode solution) equals the input power (Driven solution).

The coupling has been achived by exploiting four slots spaced 90° degrees apart.

Table 6: Geometrical parameters, $L_{\mathrm{acc}} = 187.8$, $f_0 = 704$ MHz (see Fig. 8)

Descript.	param.	value	
Cavity length (external)	L_{acc}	187.8	mm
Cavity radius	R_v	170.2	mm
Aluminium window radius	W_R	60	mm
Aluminium window thickness	W_T	0.3	mm
Ellipse z semi-axis (fillet)	a	5	mm
Ellipse x semi-axis (fillet)	b	11	mm
Top circle curv. radius (fillet)	C_R	50	mm
Inner slot Radius	$R_{A_{in}}$	85	mm
External coupling slot Radius	$R_{A_{ext}}$	113.5	mm
Angular coupling slot Span	θ_A	15	deg
Fillet coupling slot		4	mm
Derived:			
Cavity length (internal)	$L = L_{\mathrm{acc}} - W_T \approx L_{\mathrm{acc}}$		
Top circle center z-coord.	$C_z = L/2 - a - C_R$		−−
Top circle center x-coord.	$C_x = R_v - C_R$		−−
Ellipse circle center z-coord.	$F_z = L/2 - a$		−−
Ellipse circle center x-coord.	$F_x = W_R + b$		−−

L_{acc} is chosen equal to $L_{\mathrm{ref}} = 187.8$ mm for π-mode operation at $f = 704$ MHz. R_v is tuned to have $f = 704$ MHz.

3 cells RF preliminary structure

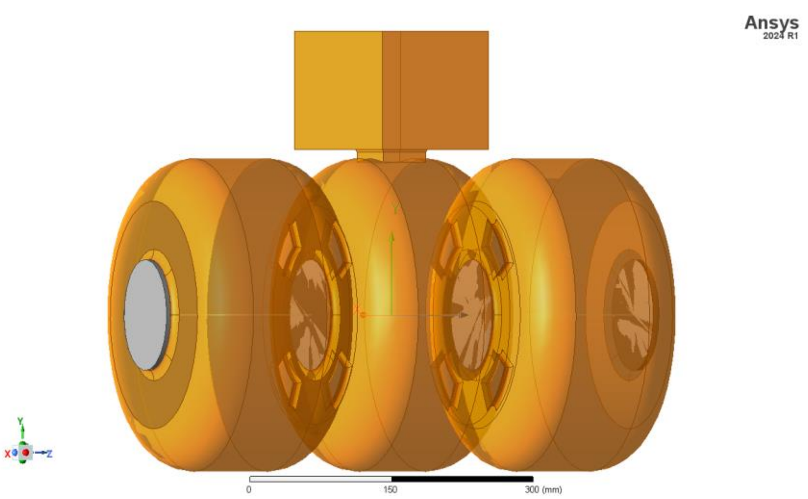


Figure 18: Design of 3 coupled cells centrally fed by a WR975 waveguide.

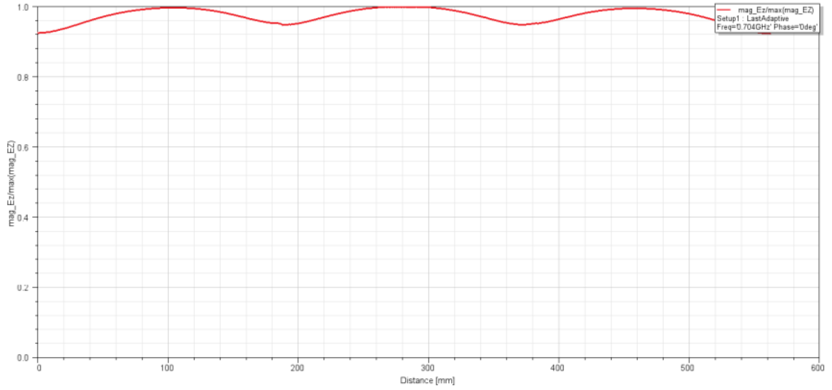


Figure 19: Electric field amplitude normalized to the max. $C_{R-1} = 46$, $C_{R0} = 50.25$ and $C_{R1} = C_{R-1}$ for the other geometric parameters refer to Tab. 6

The top circle curvature radius C_R is used to ensure the same accelerating gradient in the cells. In the plot C_R denotes the top circle curvature of the central cavity, whereas C_{R-1} and C_{R+1} denote the top circle curvature of the outer cavities.

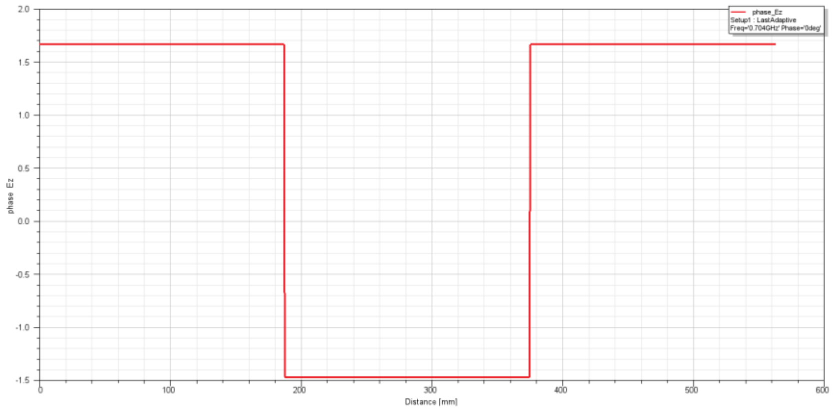


Figure 20: Electric field phase. $C_{R-1} = 46$, $C_{R0} = 50.25$ and $C_{R1} = C_{R-1}$

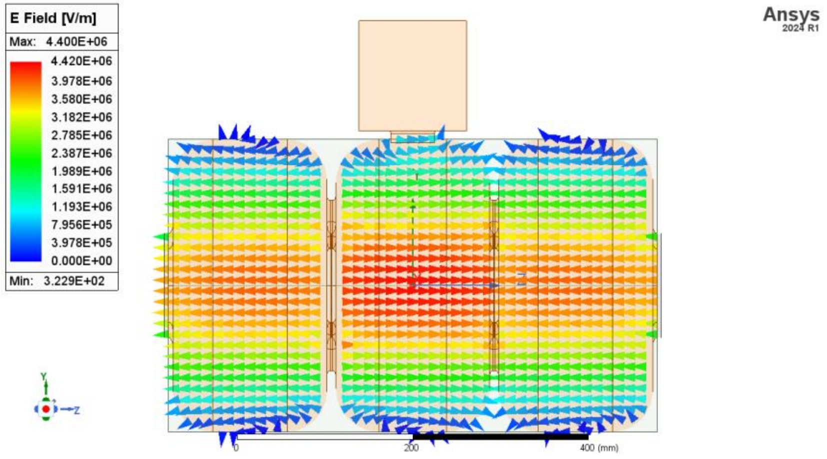
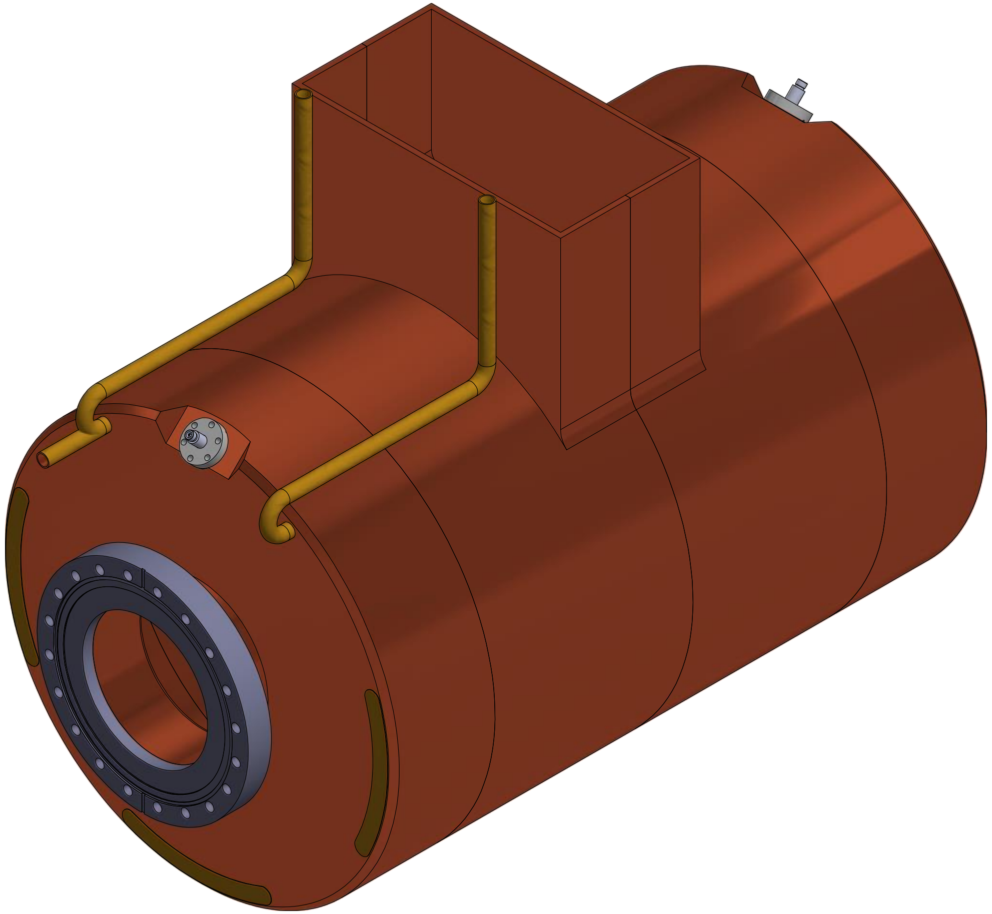


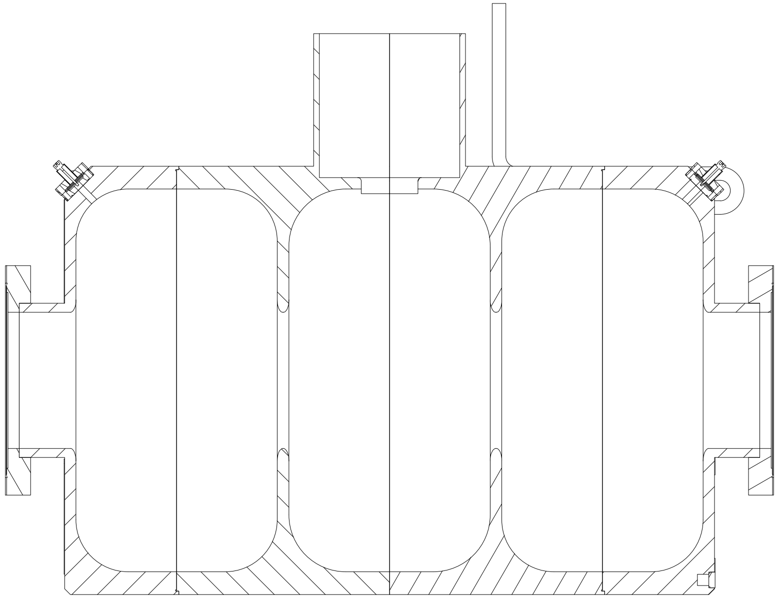
Figure 21: Electric Field Plot

References

[1] T. P. Wangler, *RF Linear accelerators*. John Wiley & Sons, 2008.

3 cells RF preliminary mechanical design



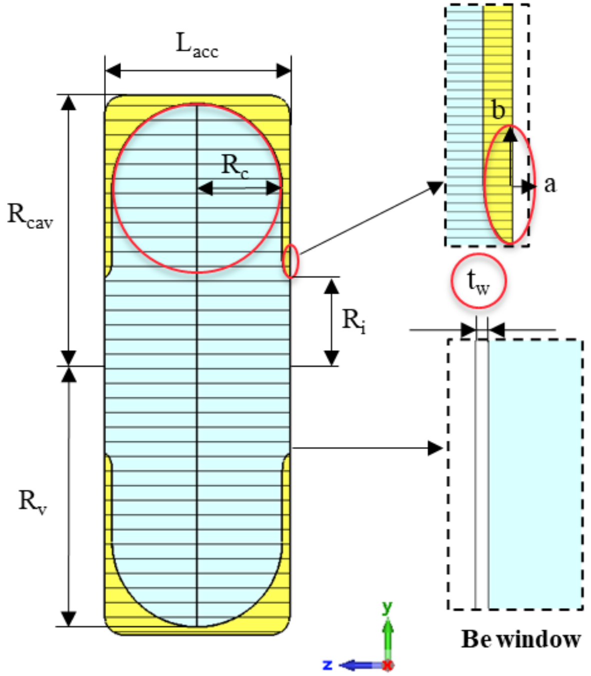


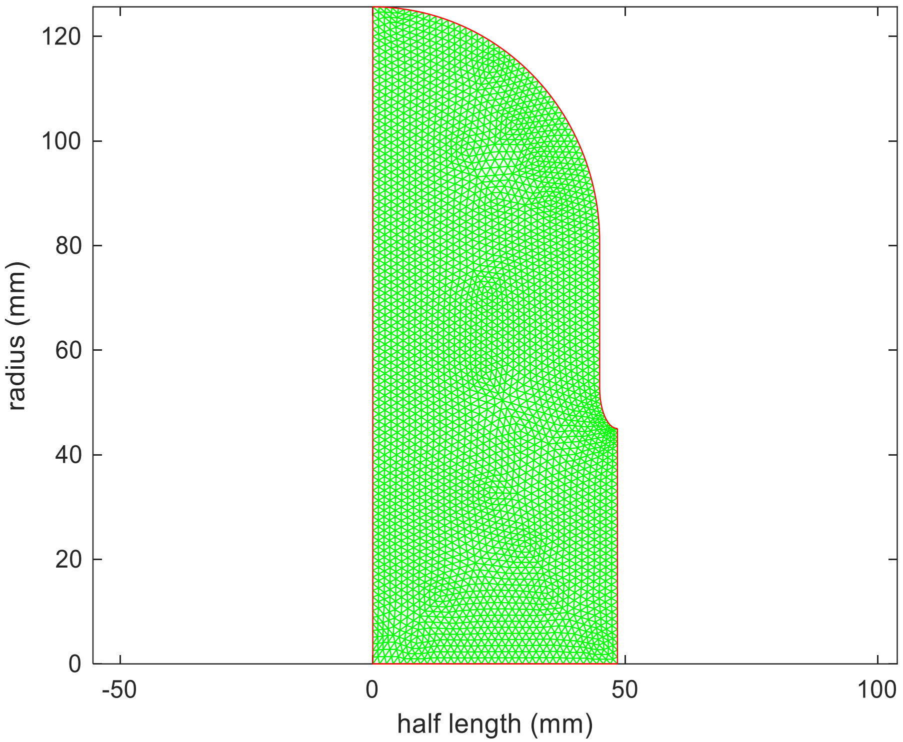
Copper weight: 180 kg
8 water channels
Max. external diameter: less than 500 mm

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.

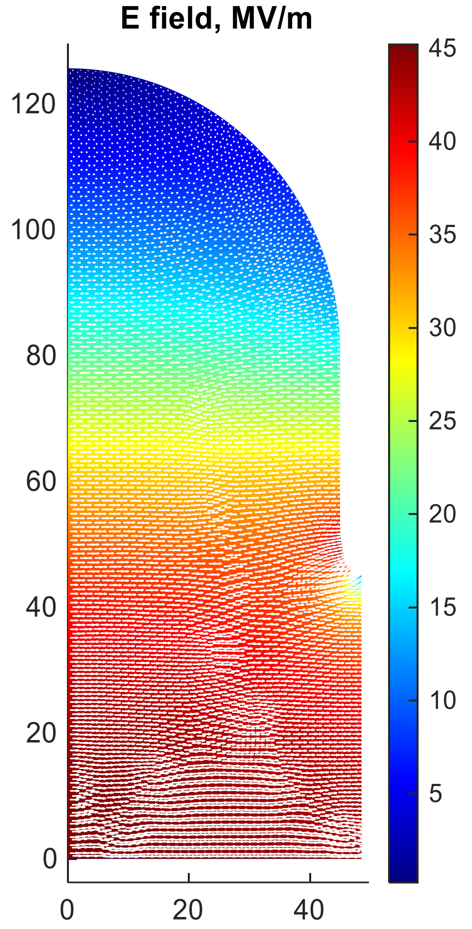
The picture below shows the results obtained in preliminary computations with related set of parameters.

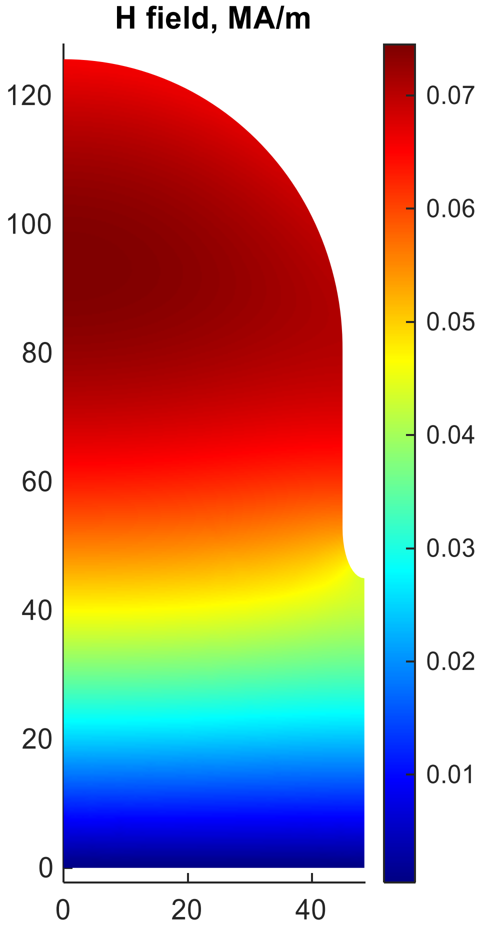


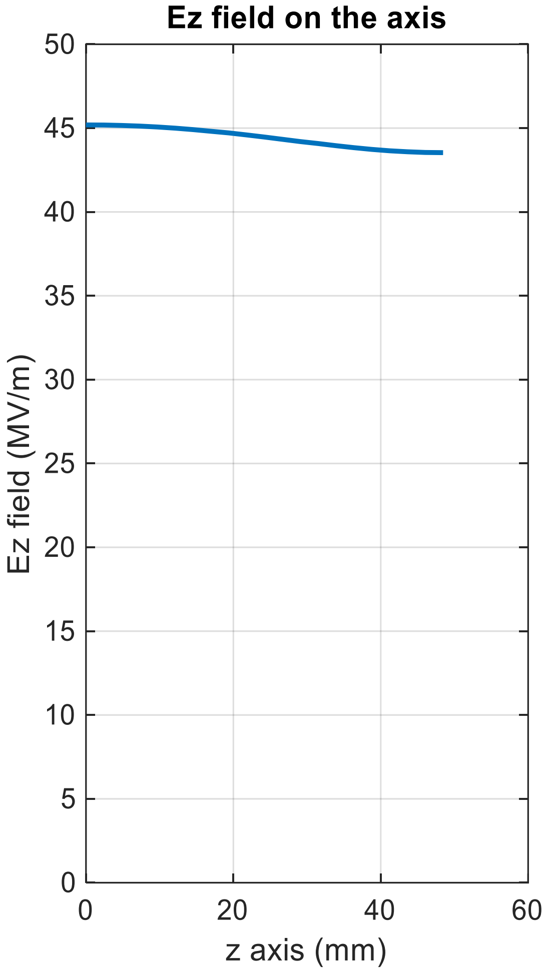


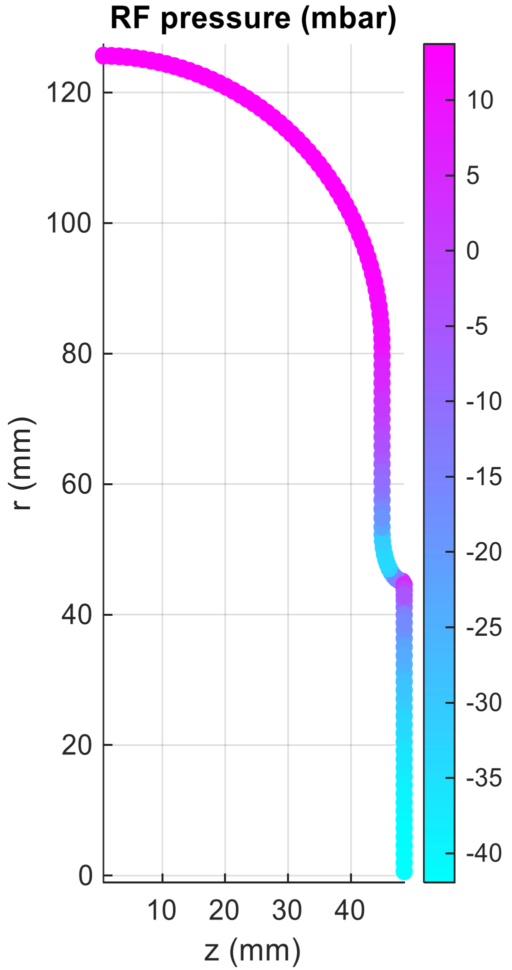
Size	[mm]
Lacc	96.92
Rc	44.94
Rv	125.65
Ri	45
a	3.52
b	7.74

A 1 GHz Design


E field, MV/m


H field, MA/m


Ez field on the axis


RF pressure (mbar)

Conclusions

- **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**

Thanks for your attention !