High gradient challenges in normal conductive RF cavities

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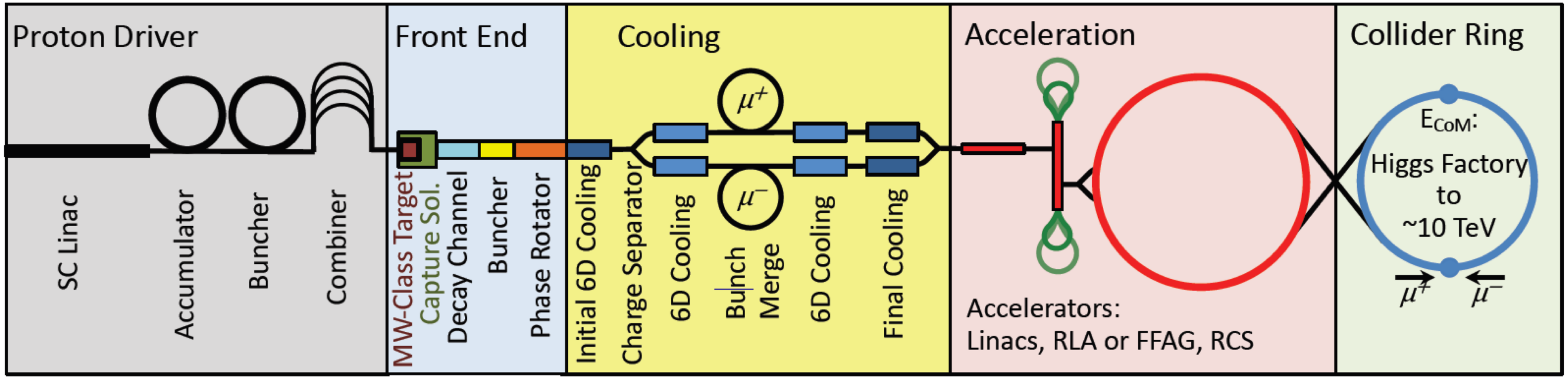
17th October 2023

Muon Collider Schematic Layout

Proton driven Muon Collider Concept (MAP collaboration)



Proton driver complex produce high power (few MW) **proton beam**

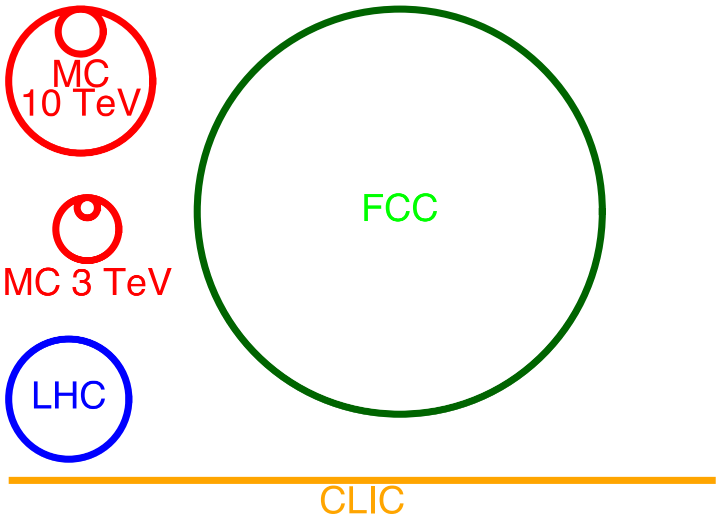
Proton beam hit the **target** and produce muons

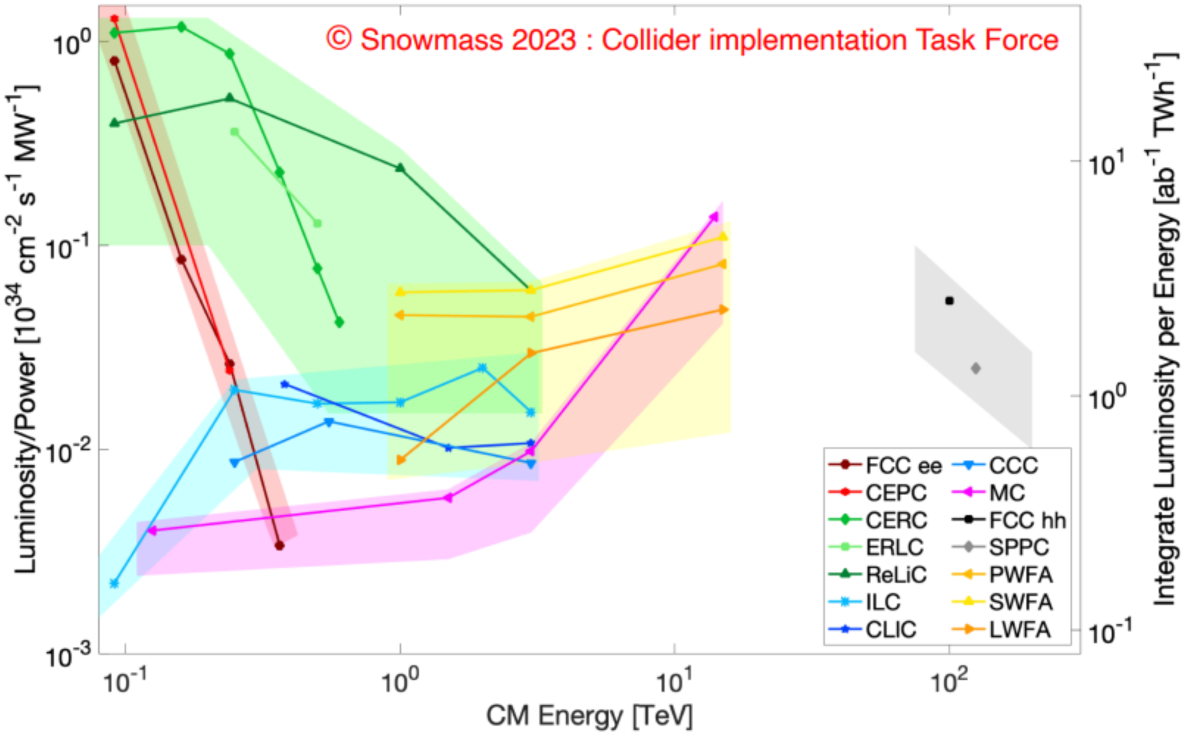
Muons are captured and cooled to produce **low emittance muon beam**

Muon beams are accelerated to **high energy**

Positive and negative muon beams collide

Muon Collider promises: Cost and Sustainability





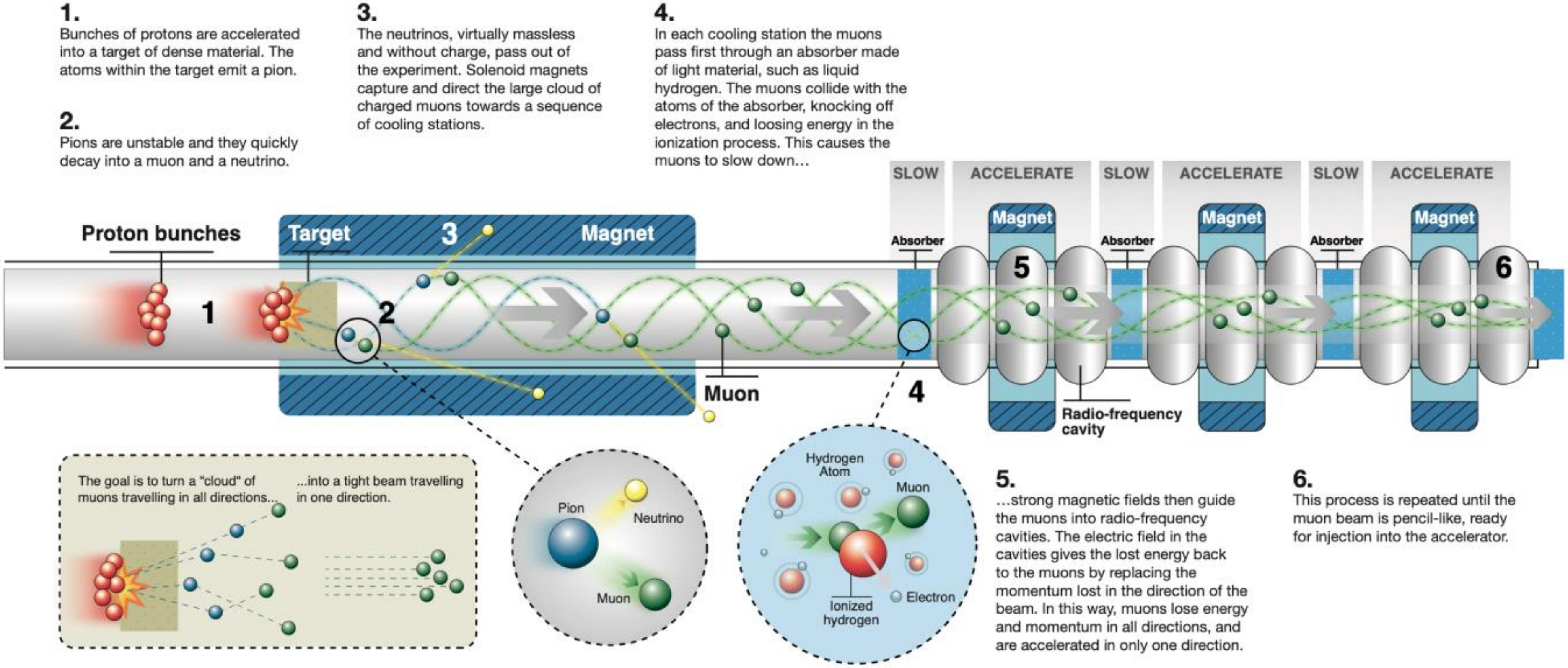
Compactness promises **cost effectiveness**
And low CO_2 footprint for construction

Increasing luminosity per beam power promises
power efficiency

Staging is possible
Unique opportunity for a **high-energy, high-luminosity lepton collider**

Courtesy of A. Grudeiev

Cooling Cell Scheme



1.
Bunches of protons are accelerated into a target of dense material. The atoms within the target emit a pion.

2.
Pions are unstable and they quickly decay into a muon and a neutrino.

3.
The neutrinos, virtually massless and without charge, pass out of the experiment. Solenoid magnets capture and direct the large cloud of charged muons towards a sequence of cooling stations.

4.
In each cooling station the muons pass first through an absorber made of light material, such as liquid hydrogen. The muons collide with the atoms of the absorber, knocking off electrons, and loosing energy in the ionization process. This causes the muons to slow down…

5.
…strong magnetic fields then guide the muons into radio-frequency cavities. The electric field in the cavities gives the lost energy back to the muons by replacing the momentum lost in the direction of the beam. In this way, muons lose energy and momentum in all directions, and are accelerated in only one direction.

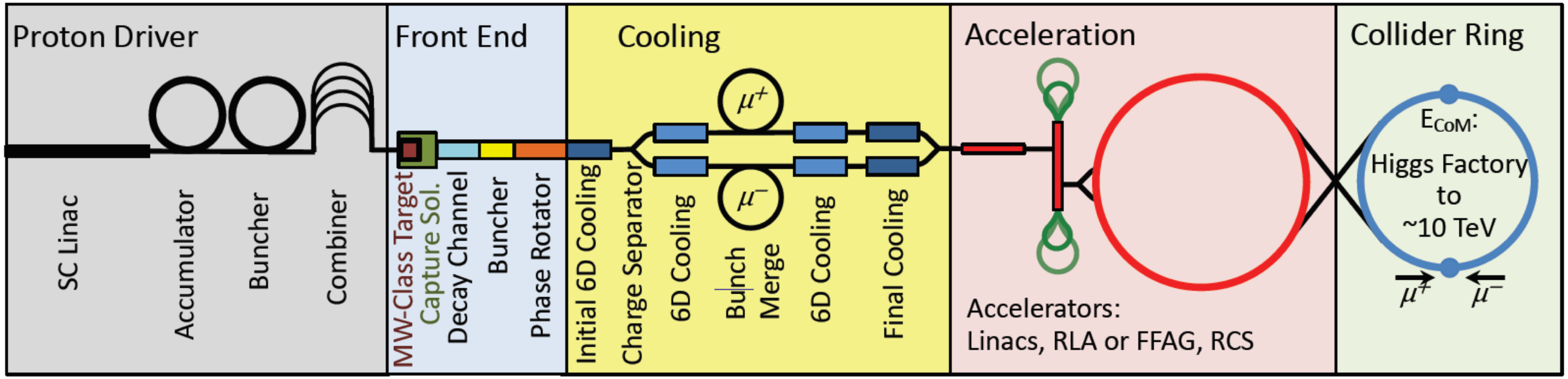
6.
This process is repeated until the muon beam is pencil-like, ready for injection into the accelerator.

The goal is to turn a "cloud" of muons travelling in all directions…

…into a tight beam travelling in one direction.

Fig. 3: Principle of the Muon Ionisation Cooling

Muon collider and RF system challenges



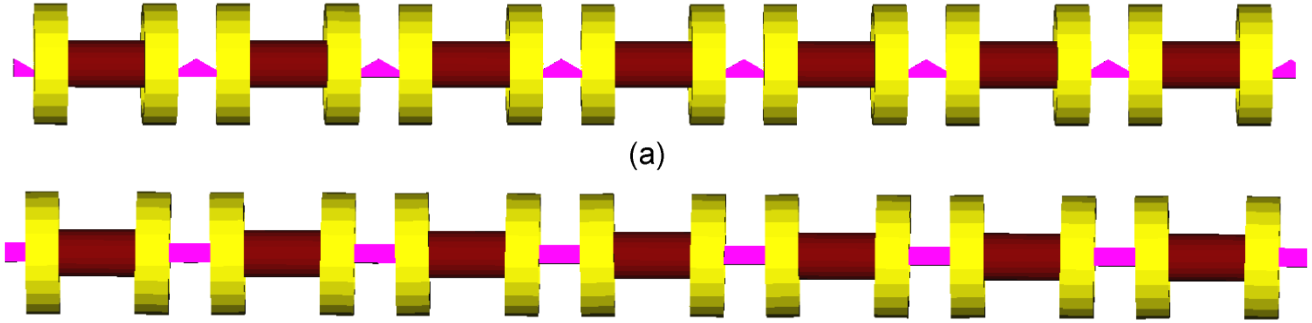
The main challenge of the Muon Collider is finite ~2us lifetime of the muons.

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

Everything must be fast ! --→ High Gradient !!!

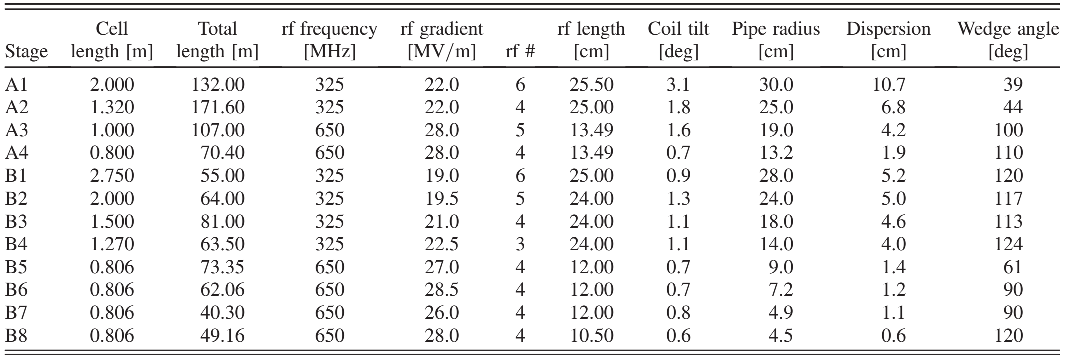
Cooling Channel


(a)

(b)

FIG. 2. Conceptual design of a rectilinear channel: (a) top view; (b) side view.

TABLE I. Main parameters of a 12-stage rectilinear 6D cooling lattice before and after recombination. Stages A1–A4 and B1–B4 use LH absorber while stages B5–B8 use LiH absorber. Dispersion is calculated at the absorber center at the reference momentum of 200 MeV/c.



Stage	Cell length [m]	Total length [m]	rf frequency [MHz]	rf gradient [MV/m]	rf #	rf length [cm]	Coil tilt [deg]	Pipe radius [cm]	Dispersion [cm]	Wedge angle [deg]
A1	2.000	132.00	325	22.0	6	25.50	3.1	30.0	10.7	39
A2	1.320	171.60	325	22.0	4	25.00	1.8	25.0	6.8	44
A3	1.000	107.00	650	28.0	5	13.49	1.6	19.0	4.2	100
A4	0.800	70.40	650	28.0	4	13.49	0.7	13.2	1.9	110
B1	2.750	55.00	325	19.0	6	25.00	0.9	28.0	5.2	120
B2	2.000	64.00	325	19.5	5	24.00	1.3	24.0	5.0	117
B3	1.500	81.00	325	21.0	4	24.00	1.1	18.0	4.6	113
B4	1.270	63.50	325	22.5	3	24.00	1.1	14.0	4.0	124
B5	0.806	73.35	650	27.0	4	12.00	0.7	9.0	1.4	61
B6	0.806	62.06	650	28.5	4	12.00	0.7	7.2	1.2	90
B7	0.806	40.30	650	26.0	4	12.00	0.8	4.9	1.1	90
B8	0.806	49.16	650	28.0	4	10.50	0.6	4.5	0.6	120

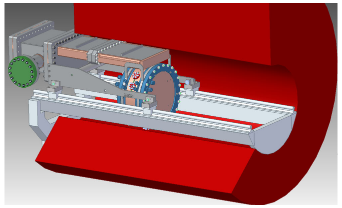
12 GW of RF power !

Cooling Channel

Objectives

- The RF cavities for the cooling channel of the MuCol project require a medium/high electric field (nominally 28-30 MV/m) in high magnetic fields (13-15 T)
- This call for a deep understanding of the breakdown phenomena in NC RF cavities taking into account the influence of the magnetic field
- The subject is complicated by the wide range of conditions foreseen in the design and by the inherent difficulties of designing experimental test stands

State of the Art



Challenges:

- High Gradient
- High magnetic field
- High radiation
- Technology far

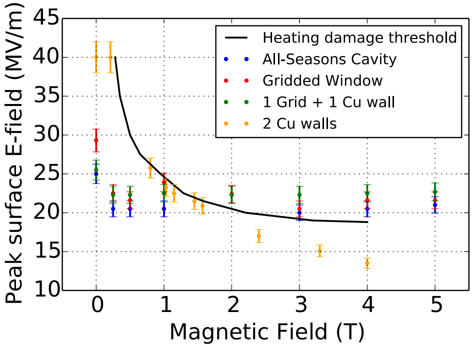


Figure 3: Peak surface electric field vs. external, applied *B*-field for cavity configurations described above. The black line indicates the threshold for surface fracture from beamlet heating, as discussed in [4].

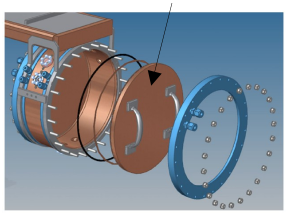
RF BREAKDOWN OF 805 MHZ CAVITIES IN STRONG MAGNETIC FIELDS*

D. Bowring, A. Kochemirovskiy, M. Leonova, A. Moretti, M. Palmer, D. Peterson,
K. Yonehara, FNAL, Batavia, IL 60150, USA
B. Freemire, P. Lane, Y. Torun, IIT, Chicago, IL 60616, USA
D. Stratakis, BNL, Upton, NY 11973, USA
A. Haase, SLAC, Menlo Park, CA 94025, USA

Bowring et al, PRAB 23 072001, 2020

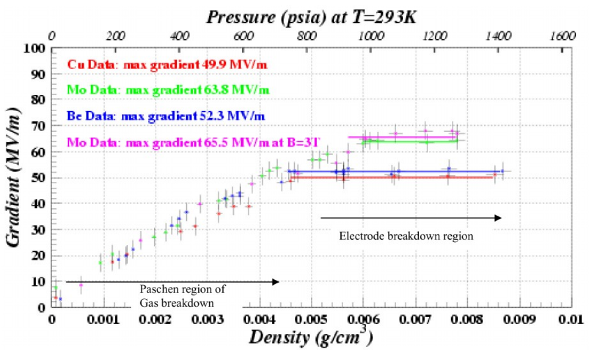
Material	*B*-field (T)	*E*-field (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	> 49.8 ± 2.5

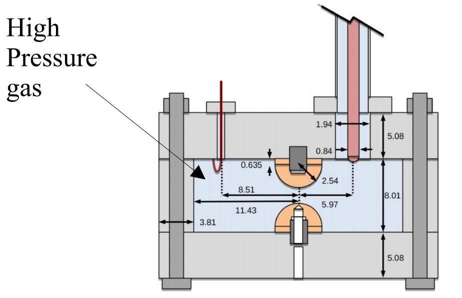
Changeable Cu/Be walls



Freq.
804 MHz

Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration





Freemire et al, JINST 13 P01029, 2018

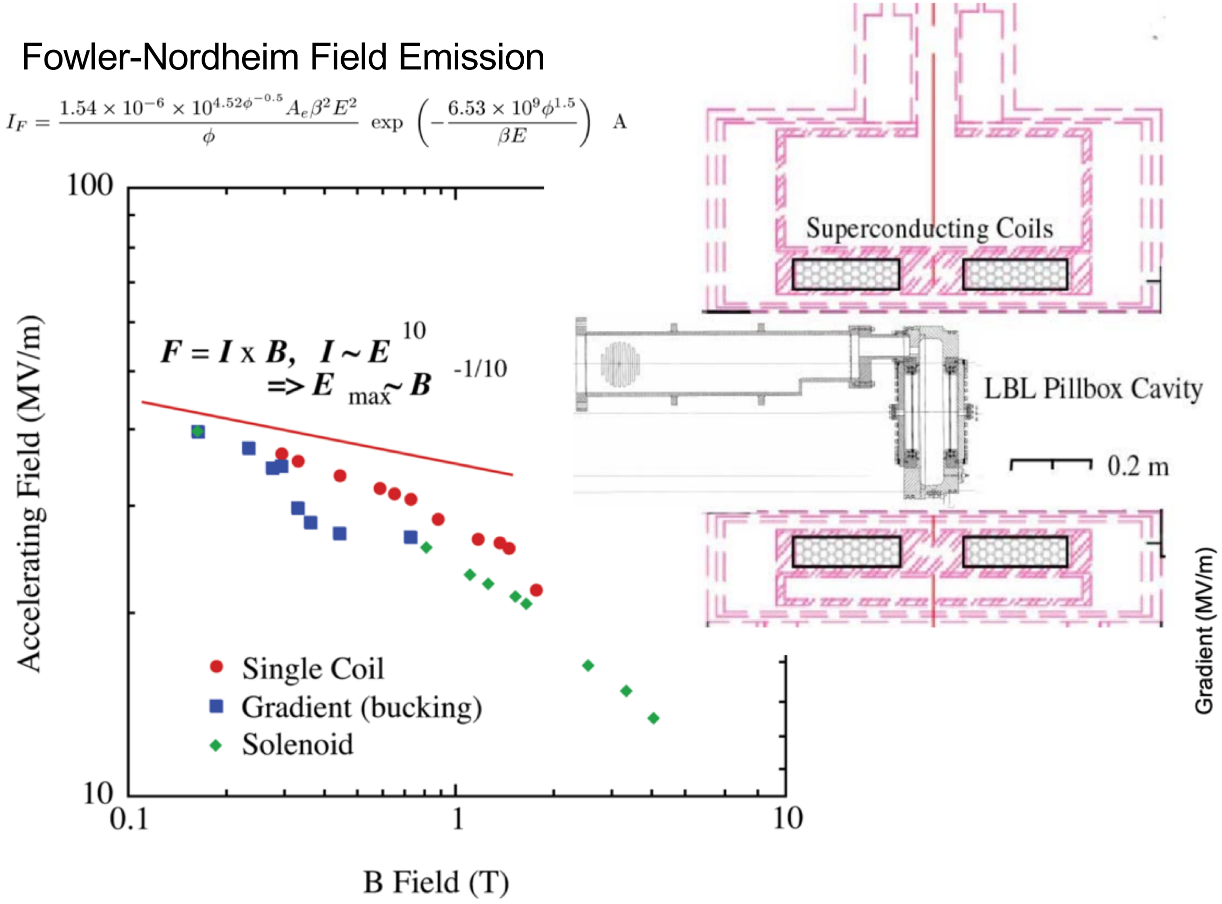
Freq.
800 MHz

Initial Results for 805 MHz Pillbox

A. Moretti *et al.*, Effects of high solenoidal magnetic fields on rf accelerating cavities, **Phys.Rev.Acc.Beams** 8, 072001 (2005)

Fowler-Nordheim Field Emission

$$I_F = \frac{1.54\times10^{-6}\times10^{4.52\phi^{-0.5}}A_e\beta^2E^2}{\phi}\exp\left(-\frac{6.53\times10^{9}\phi^{1.5}}{\beta E}\right)\ \mathrm{A}$$



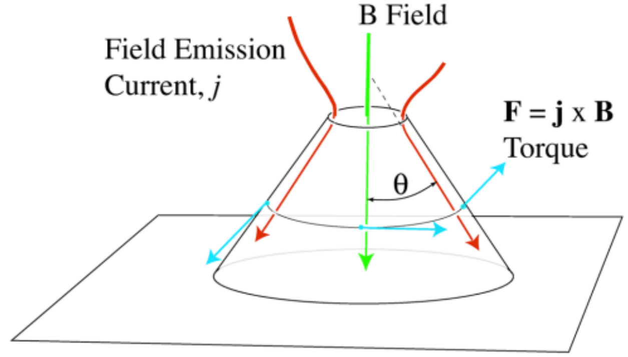
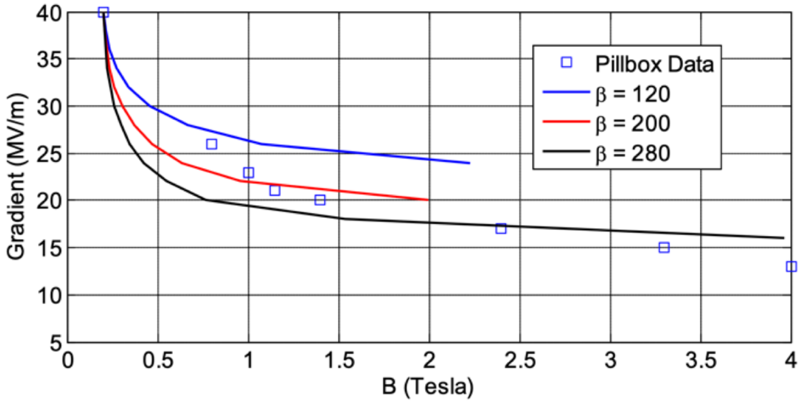
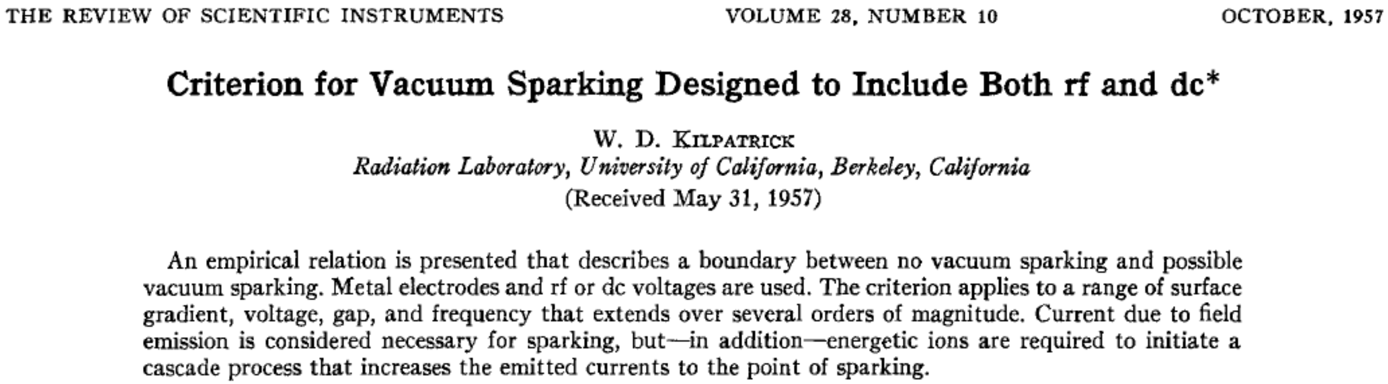


FIG. 4. (Color) Forces due to field emission currents are present in the field emitters.



Kilpatrick's Criterion



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

Kilpatrick’s Criterion

RF BREAKDOWN STUDIES IN COPPER ELECTRON LINAC STRUCTURES
J. W. WANG AND G. A. LOEW
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

1989

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

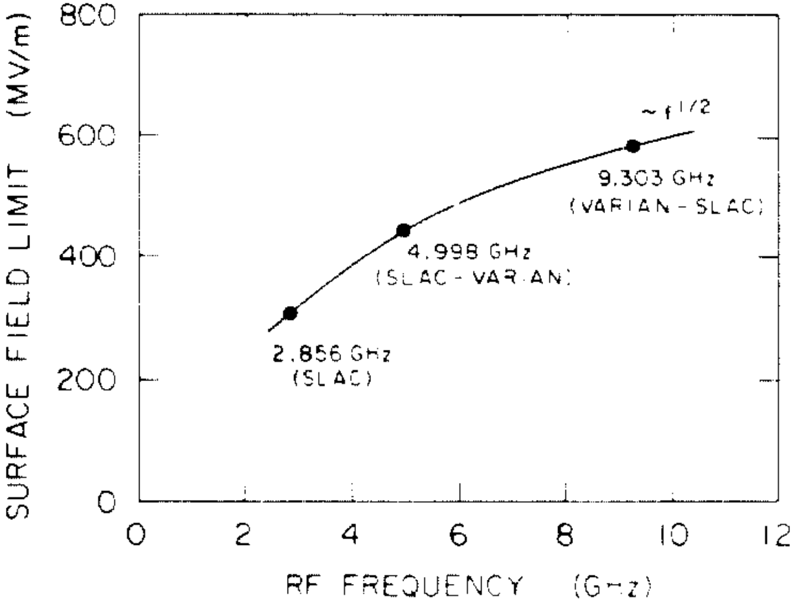
$$Ee^{-4.25/E} = 24.4 \cdot [f(GHz)]^{\frac{1}{2}} \ \ MV/m$$

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

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

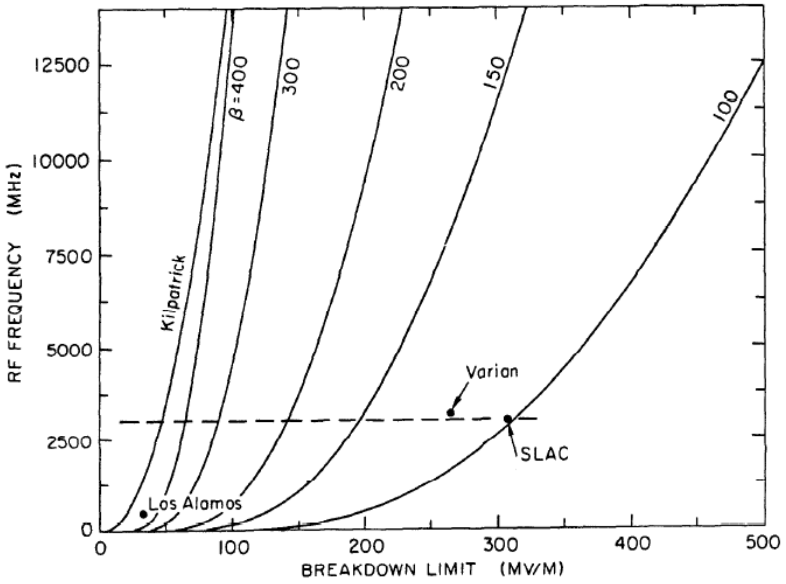
➔ The threshold voltage varies as the square root of the applied frequency.

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



Kilpatrick’s Criterion

Year	*Author*	*Quantity*	*Characteristics*
1963	Nicolaev	90 MV/m peak surface	~11 Kilp., 23.6 MHz
1979	Williams (Los Alamos)	50 MV/m peak surface	~1.6 Kilp., 100 μs pulse, 425 MHz
1984	Tanabe (Varian)	150 MV/m acc. field 300 MV/m peak surface	~6 Kilp., 4.5 μs pulses in S-band, ”half” single cavity
1985	Loew, Wang (SLAC)	150 MV/m acc. field 300 MV/m peak surface	~6 Kilp., 2.5 μs pulses in S-band, SW 2π/3 mode linac
1986	Tanabe, Loew, Wang	445 MV/m peak surface	~7 Kilp., 5 GHz, single cavity
1986	Tanabe, Loew, Wang	572 MV/m peak surface	~7 Kilp., 9.3 GHz, single cavity
1994	SLAC/CERN	150 MV/m acc. gradient	130 ns pulse length at 30 GHz, small iris structure
2002	CLIC	130 MV/m acc.gradient	15 ns, operated without breakdowns



Test Stand Proposals

We are in an advanced phase of design related to a couple of tests stands:

- A DC HV test stand with pulsed capabilities embedded in 1 T magnetic field
- A high power (10 MW) S band RF test stand to power a RF cavity installed in the bore of a SC magnet.

The DC Test Stand will be put into operation by the beginning of 2024 (orders are underway) in an existing experimental area @ LASA. This test stand is very similar in the basic design to a reference one designed and installed at CERN (S. Calatroni and the researchers of his group). We added the possibility to have a parallel magnetic field.

The S band RF test stand may be installed @ LASA (see final slides of this talk).

DC based experimental test stand

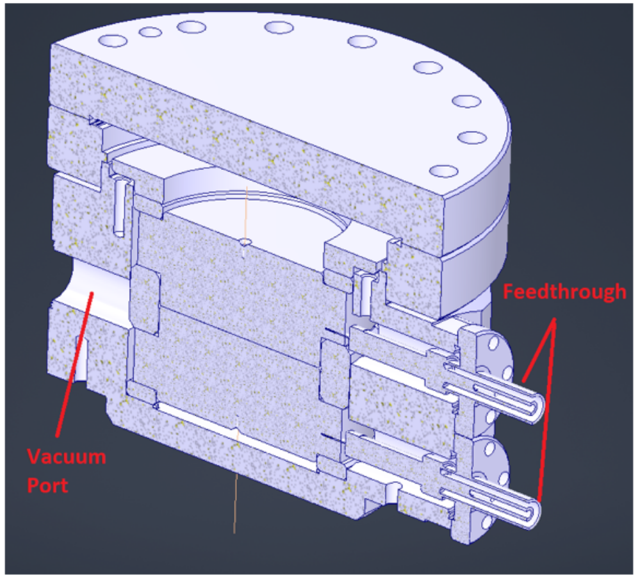
Why we are proposing to carry out tests in a DC based environment ?

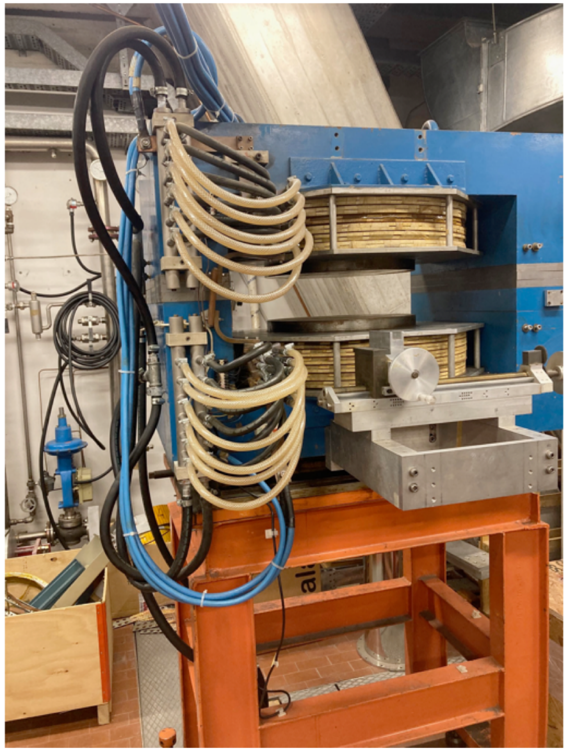
- **Simple setup with respect to a RF based one**
- **Tests faster and more flexible**
- **Study on materials and surface treatments**
- **Additional input for further RF based experimental campaigns**
- **Field levels of the order of 100 MV/m (over max. 0.1 mm gp)**
- **Energy similar to the one involved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

DC based LASA Test Stand

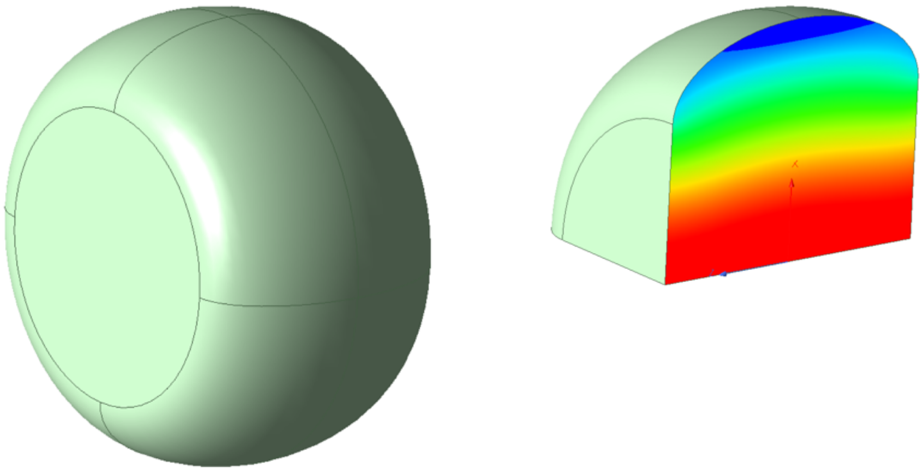




The PVX-4110 pulse generator is a direct coupled, air cooled, solid state half-bridge (totem pole) design, offering equally fast pulse rise and fall times, low power dissipation, and virtually no over-shoot, undershoot or ringing. It has overcurrent detection and shutdown circuitry to protect the pulse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

HG2023 – INFN Frascati 16-20 October 2023

A 3 GHz Proposal for a LASA Test Facility

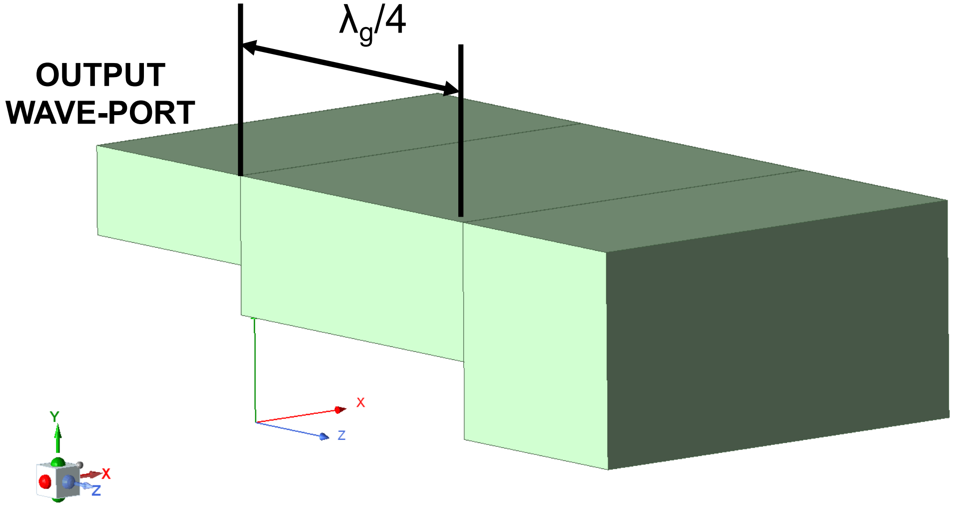


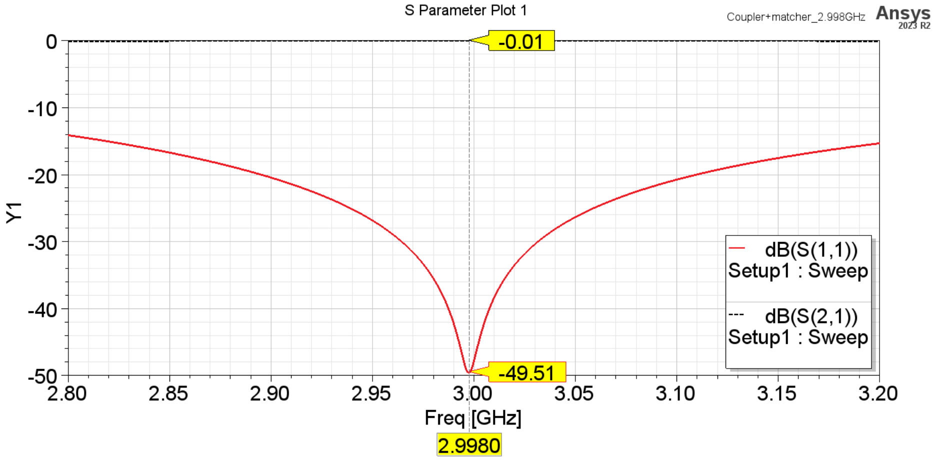
The simulated models consist of a vacuum volume with finite conductivity (copper) boundary condition

- Cavity diameter: D = 82.208 mm
- Cavity length: $\beta\lambda/2$ = 50 mm
- Operational frequency: f_0 = 2.998 GHz
- Unloaded quality factor: $Q_0 = \frac{\omega_0 U}{P_{Cu}} = 20714$
- Shunt impedance: r_{SH} = 9.57 MΩ
- $r_{SH}/Q_0 = 462$

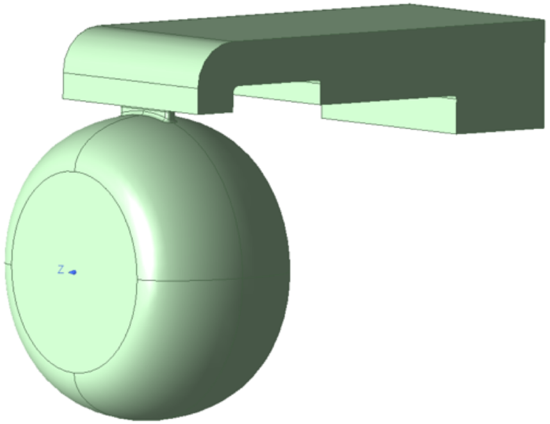
A 3 GHz Proposal for a LASA Test Facility

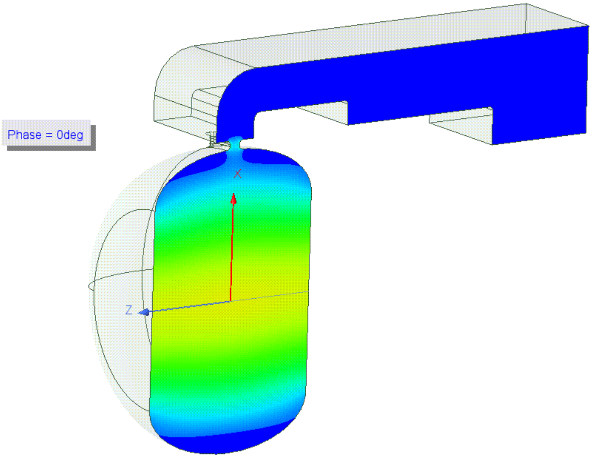
- Waveguide coupler with standard WR229 input.
- $\lambda_g/4$ central section in order to improve the matching between first and last sections.

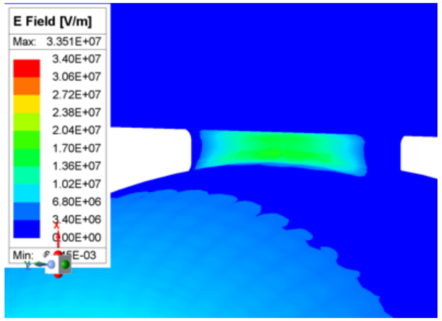


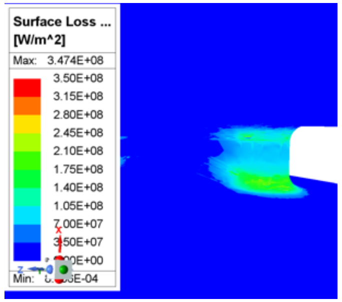


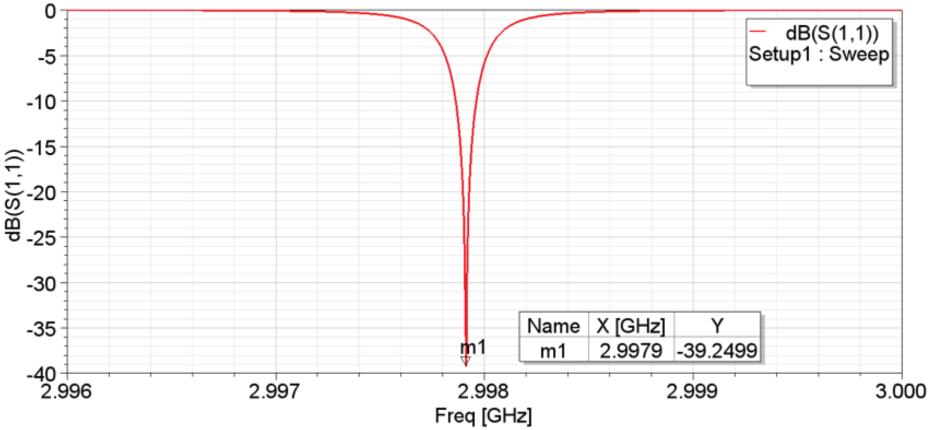
A 3 GHz Proposal for a LASA Test Facility



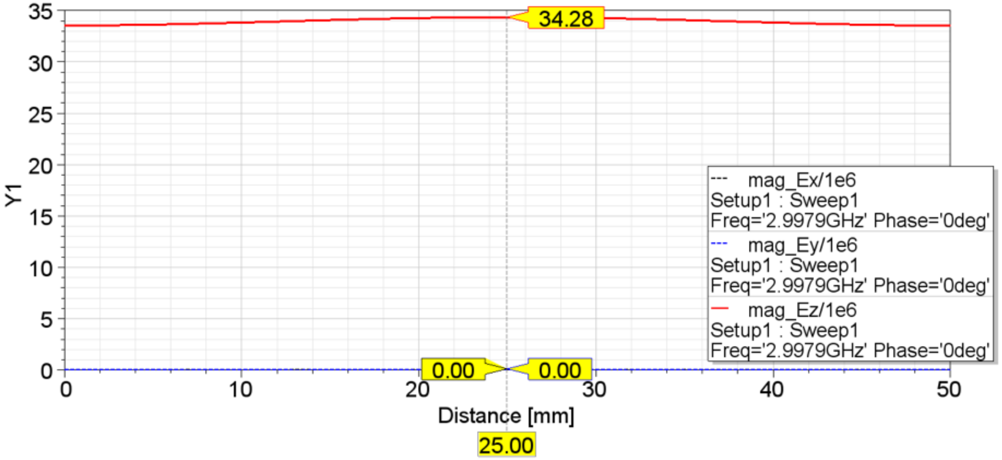




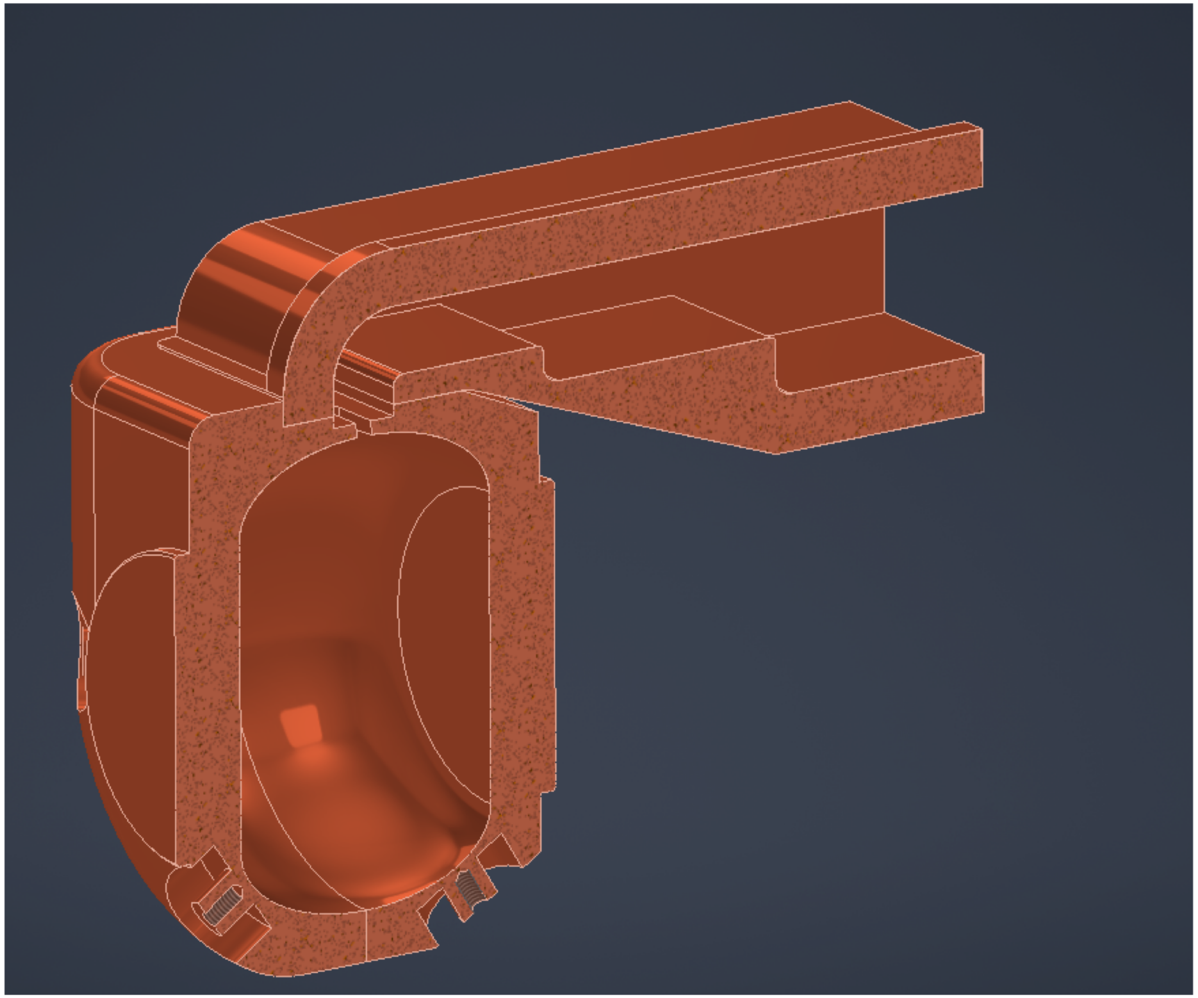




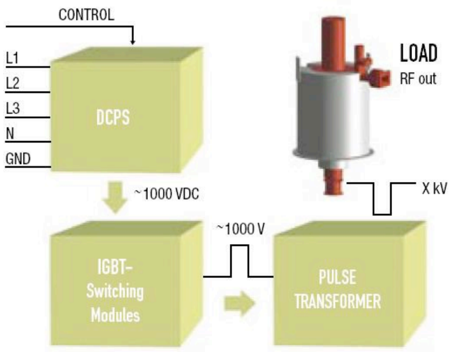
Name	X [GHz]	Y
m1	2.9979	-39.2499



A 3 GHz Proposal for a LASA Test Facility

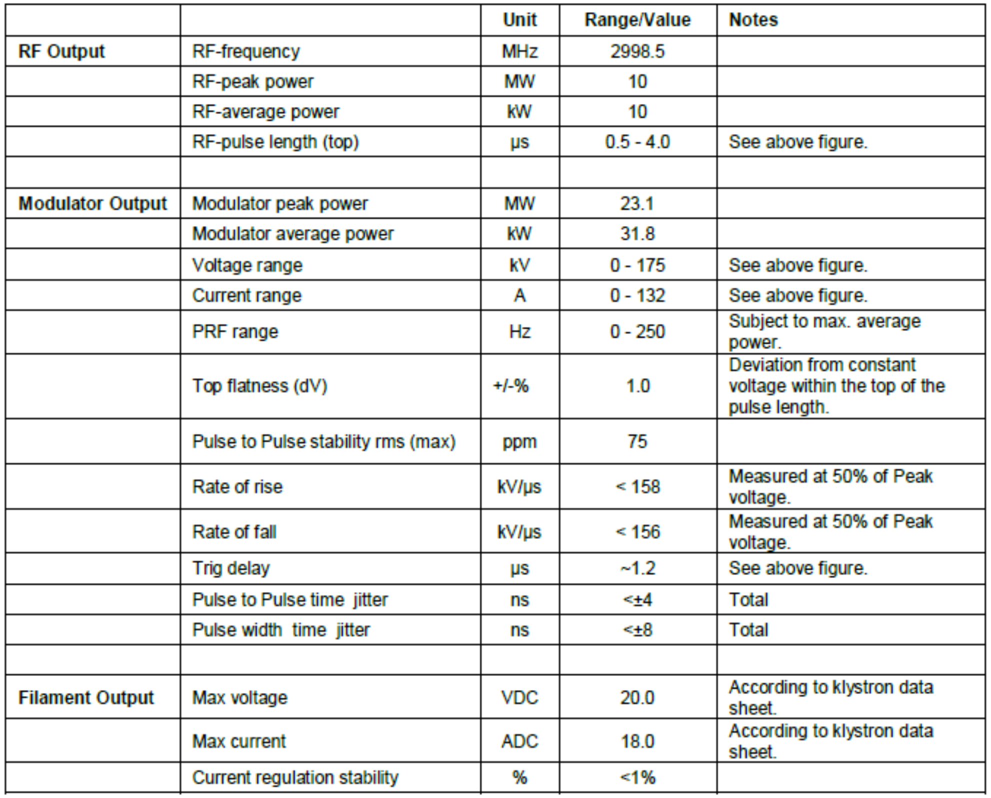


Scandinova and Canon Power Plant



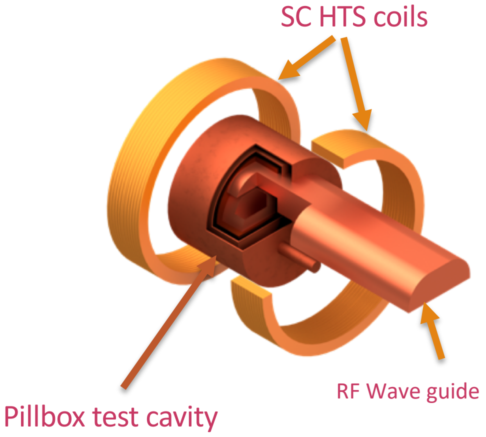
5MW K100, PRF 100Hz and pulse length 2-3us, equipped with Canon E3779,B

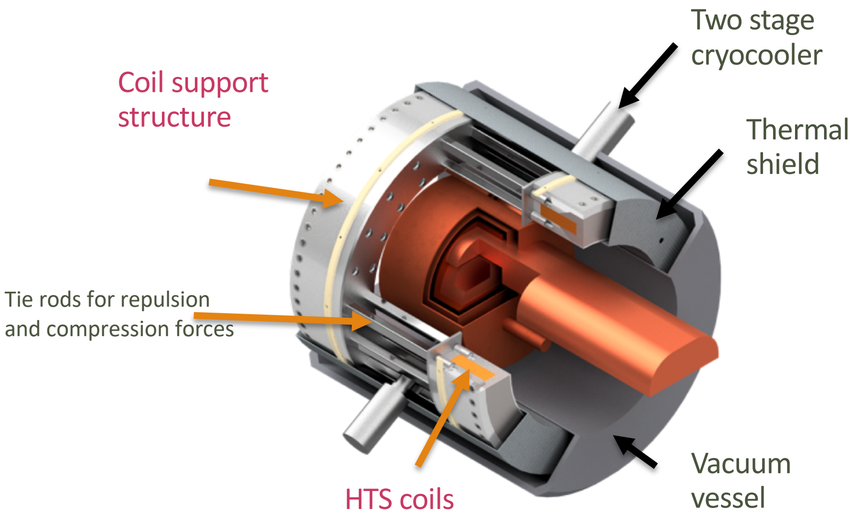
Price of the order of 500-700 kEuro (+ taxes)



		Unit	Range/Value	Notes
RF Output	RF-frequency	MHz	2998.5	
	RF-peak power	MW	10	
	RF-average power	kW	10	
	RF-pulse length (top)	µs	0.5 - 4.0	See above figure.
Modulator Output	Modulator peak power	MW	23.1	
	Modulator average power	kW	31.8	
	Voltage range	kV	0 - 175	See above figure.
	Current range	A	0 - 132	See above figure.
	PRF range	Hz	0 - 250	Subject to max. average power.
	Top flatness (dV)	+/-%	1.0	Deviation from constant voltage within the top of the pulse length.
	Pulse to Pulse stability rms (max)	ppm	75	
	Rate of rise	kV/µs	< 158	Measured at 50% of Peak voltage.
	Rate of fall	kV/µs	< 156	Measured at 50% of Peak voltage.
	Trig delay	µs	~1.2	See above figure.
	Pulse to Pulse time jitter	ns	<±4	Total
	Pulse width time jitter	ns	<±8	Total
Filament Output	Max voltage	VDC	20.0	According to klystron data sheet.
	Max current	ADC	18.0	According to klystron data sheet.
	Current regulation stability	%	<1%	

RF Cavity tested within a SC magnet





The construction of a test bed is an important push toward the definition of a baseline technology

Beside being a **key tool for RF tests**. However the first rough evaluation was in the **4 M€ range…**

Courtesy of L. Rossi

RF Cavity tested within a SC magnet

- Redesign to 350 mm free bore
  - → coil dia. ~ 400 mm
  - → good for 3 GHz test or higher frequency
  - 7 T, parallele and antiparallel coil excitation
- Try to optimize solution for cost saving
- Redesign **by end of 2023**
  - Conclude the 600 mm design
  - Detailed design of the 350 mm → cost target < 2 M€

Courtesy of L. Rossi

A 3 GHz Proposal for a LASA Test Facility

As part of the PNRR-IRIS program and with a significant specific contribution provided by the INFN in 2023, the construction of **an extension based on two laboratories** will begin within the LASA premises: one called **SML (Superconducting Magnet Laboratory)** and the other **AATF (Advanced Accelerator Test Facility)** for a total of 2100 m^2 spread over an underground bunker and two external floors.

These new laboratories will be available in 2025.

Thanks for your attention !