Design of the Muon Cooling Cavities Status and Plans

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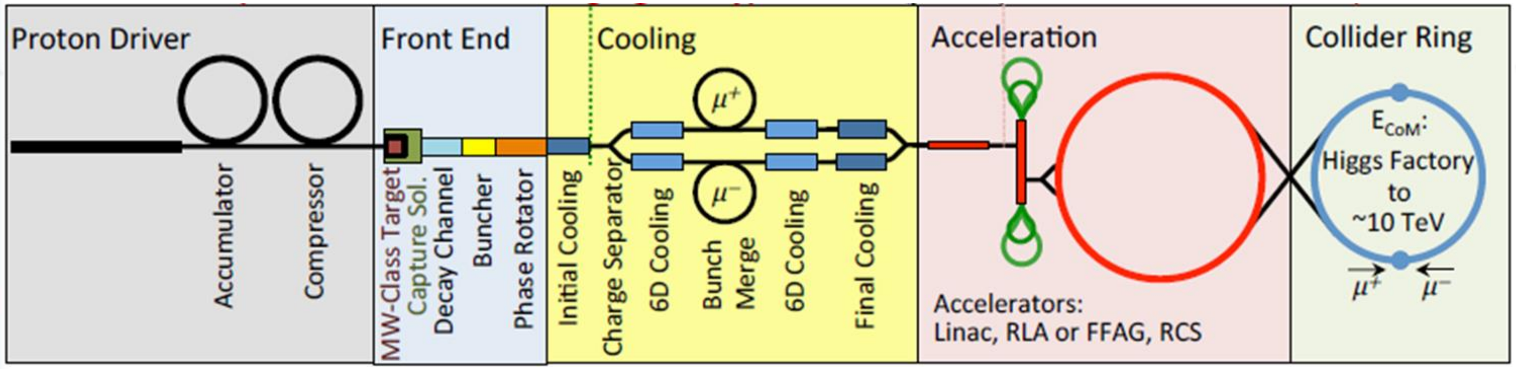
INFN
IMCC Annual Meeting 2023

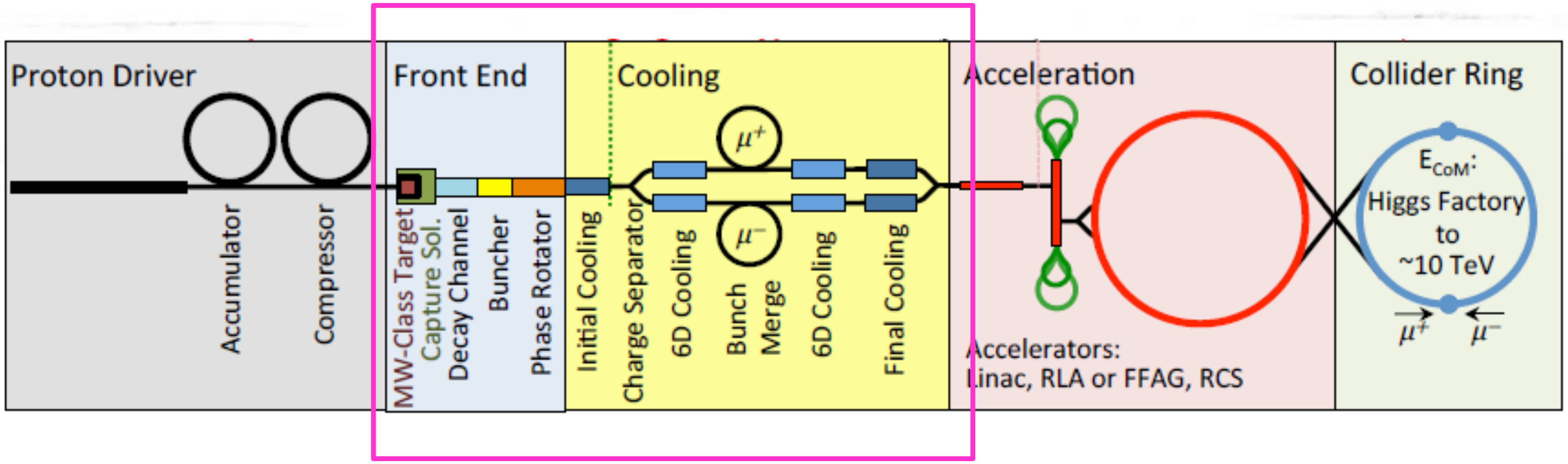
Muon collider and RF systems

Proton driven Muon Collider Concept (MAP collaboration)



- The desired 6D emittance for a Muon Collider (MC) is 5-6 orders of magnitude less from the emittance of the muon beam at the production target
- As a result, significant "muon cooling" is required.

Cooling Channel

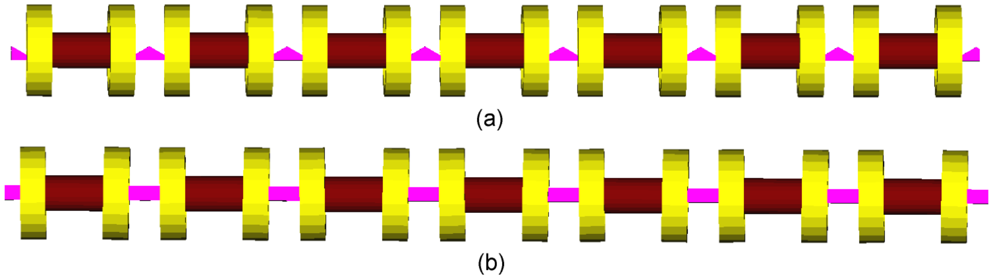


- Front-end produces 21 well aligned muon bunches
- Two sets of 6D cooling schemes
  - One before recombination (trans ε≈1.5 mm)
  - One after recombination (trans ε≈ 0.30 mm or less)
- Final cooling to shrink trans ε by an order of magnitude more

Cooling Channel

We consider a four-stage (A1–A4) tapered channel, where each stage consists of a sequence of identical cells and some of the main lattice parameters are summarized in Table I.

After bunch merging, both longitudinal and transverse emittances of the now single muon bunch increase by a factor ~4 and thus are comparable to their initial values. It can thus be taken again through the same cooling system but with one important difference. While only a modest transverse cooling to ~1.5 mm was required before the bunch-merging system, the new single muon bunch needs to be cooled by an additional order of magnitude before it can be sent to the accelerator systems. We consider eight tapered stages (B1–B8) to achieve this goal


(a)

(b)

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

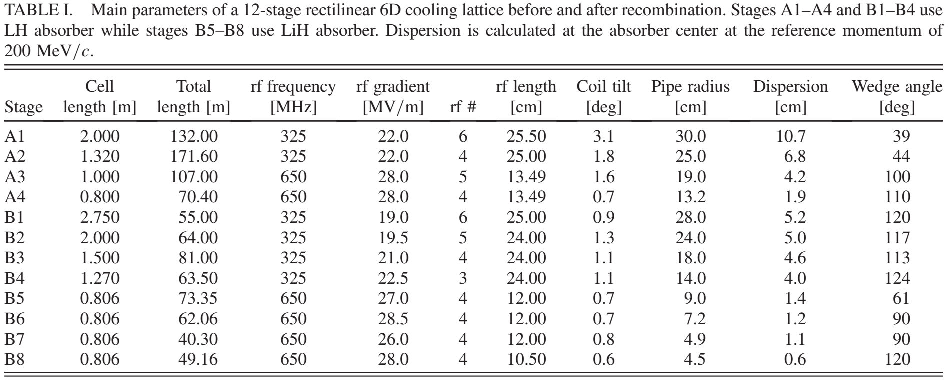


TABLE I. Main parameters of a 12-stage rectilinear 6D cooling lattice before and after recombination. Stages A1–A4 and B1–B4 use LH absorber while stages B5–B8 use LiH absorber. Dispersion is calculated at the absorber center at the reference momentum of 200 MeV/c.

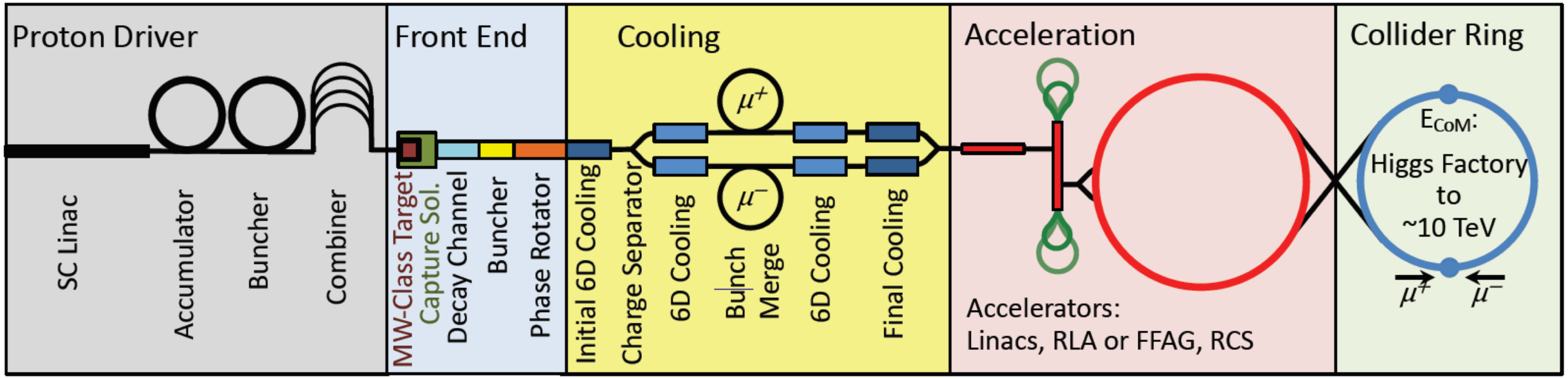
Stage	Cell length [m]	Total length [m]	rf frequency [MHz]	rf gradient [MV/m]	rf #	rf length [cm]	Coil tilt [deg]	Pipe radius [cm]	Dispersion [cm]	Wedge angle [deg]
A1	2.000	132.00	325	22.0	6	25.50	3.1	30.0	10.7	39
A2	1.320	171.60	325	22.0	4	25.00	1.8	25.0	6.8	44
A3	1.000	107.00	650	28.0	5	13.49	1.6	19.0	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

NC RF system for muon capture and cooling

Region	Length [m]	N of cavities	Frequencies [MHz]	Peak Gradient [MV/m]	Peak RF power [MW/cav.]
Buncher	21	54	490 - 366	**0 - 15**	1.3
Rotator	24	64	366 – [illegible]5 TBD	**20**	2.4
Initial Cooler	126	360	325	**25**	**3.7**
Cooler 1	400	1605	325 [illegible]50 TBD	**22, 30**	
Bunch merge	130	26	10[illegible] 1950	**~ 10**	
Cooler 2	420	1746	3[illegible] 650 TBD	**22, 30**	
Final Cooling	140	96	325 - 20		
Total	**~1300**	**3951**			=> **~12GW**

It is a very large and complex RF system with high peak power

RF pulse length and frequency landscape



Linac: ~1-5 ms

- SNS: **402.5, 805** MHz
- ESS, SPL, CERN-L4: **352, 704** MHz
- PIP-II: **325, 650** MHz

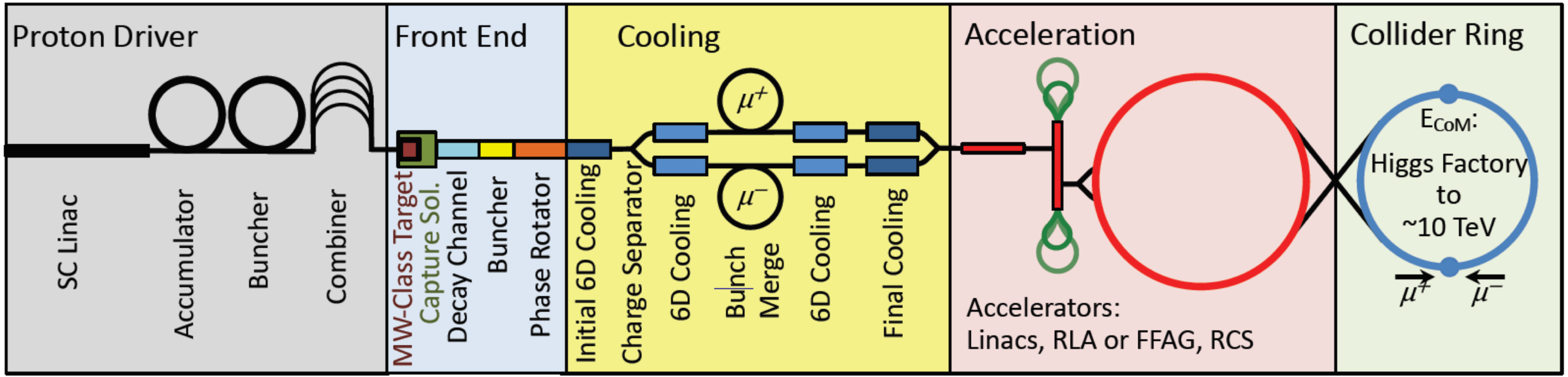
Muon cooling RF

- Many frequencies in Buncher, Rotator, Merge, Final Cooling
- Cooling cells have two harmonic frequencies:
  - MAP: **325, 650** MHz
  - Alternative: **352, 704** MHz

Accelerator SRF

- LA, RLA: ~1-10 ms
  - MAP: **325, 650** MHz
  - CERN-L4, SPL, ESS: **352, 704** MHz
- Rings: CW
  - MAP: 1300 MHz (very high)
  - LEP: 352 MHz; LHC: 400 MHz
  - FCC: 400, 800, 650(?) MHz
  - CEPC: 650 MHz

Beam time structure and RF frequency



Two RF harmonics are used for low and high energy part of the linac

Single p-bunch

Many frequencies are used for bunch manipulations, Majority of cavities at two RF harmonics in 6D cooling

Two single μ+ & μ- bunches

Several RF frequencies are used for low and high energy part of the accelerator complex. Not necessarily harmonics.

Single bunch operation does NOT require the RF frequency in proton driver linac, muon cooling and accelerator complexes be related

RF cavities for muon cooling

Challenges:

- High Gradient
- High magnetic field
- High radiation
- Technology far from been common

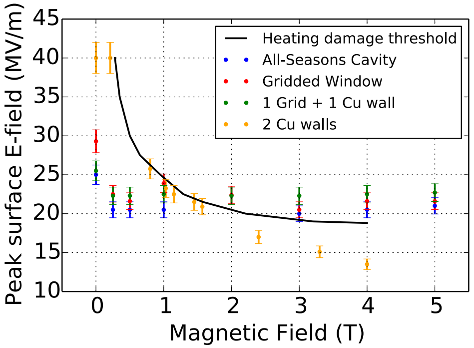


Figure 3: Peak surface electric field vs. external, applied *B*-field for cavity configurations described above. The black line indicates the threshold for surface fracture from beamlet heating, as discussed in [4].

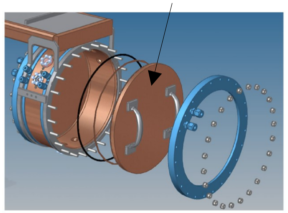
RF BREAKDOWN OF 805 MHZ CAVITIES IN STRONG MAGNETIC FIELDS*

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

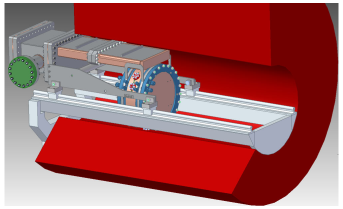
Bowring et al, PRAB 23 072001, 2020

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	$> 49.8 \pm 2.5$

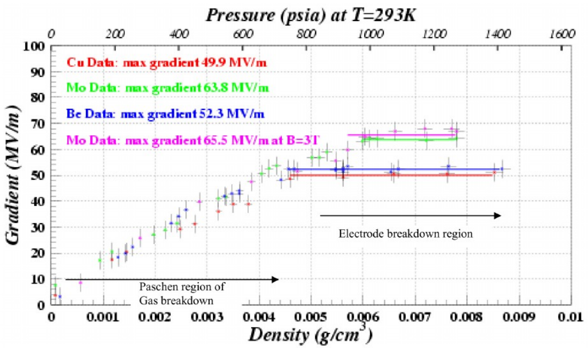
Changeable Cu/Be walls



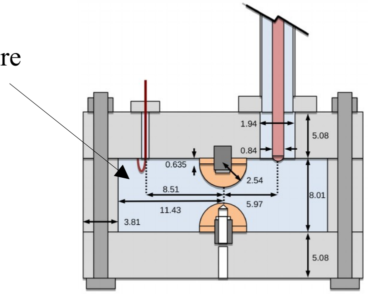
Freq. 804 MHz



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



High Pressure gas

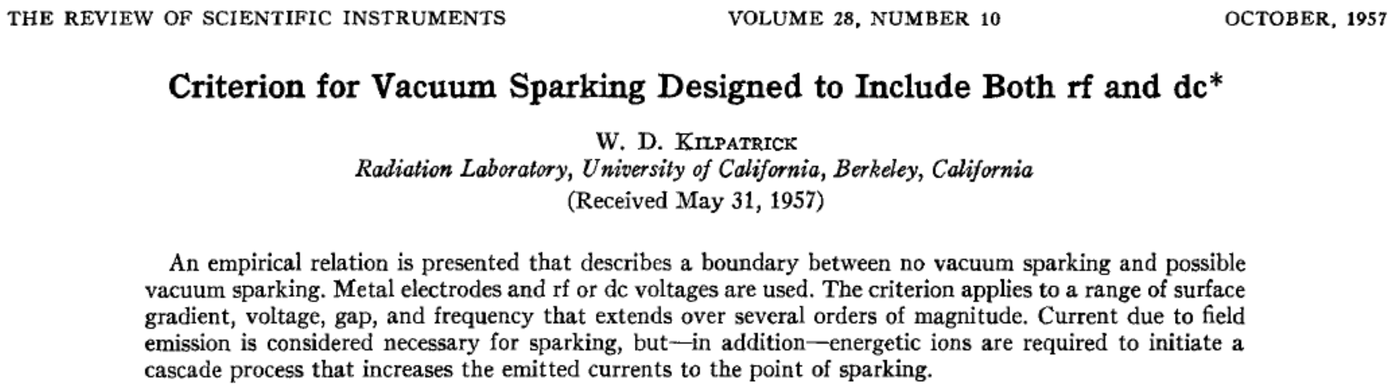


Freemire et al, JINST 13 P01029, 2018

Freq. 800 MHz

Kilpatrick’s criterion:

an empirical voltage threshold for vacuum sparking



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 frequency dependance

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:

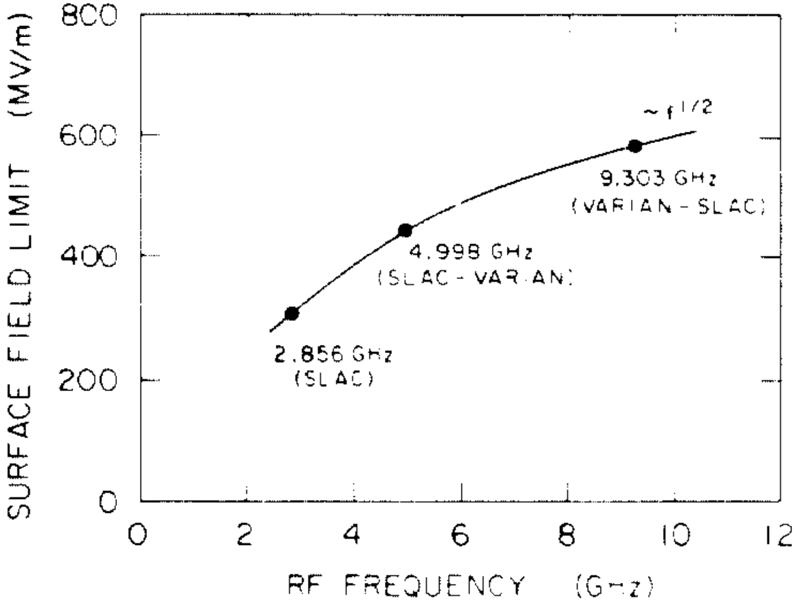
$$Ee^{-4.25/E} = 24.4 \cdot [f(GHz)]^{\frac{1}{2}} \ \ MV/m$$

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

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

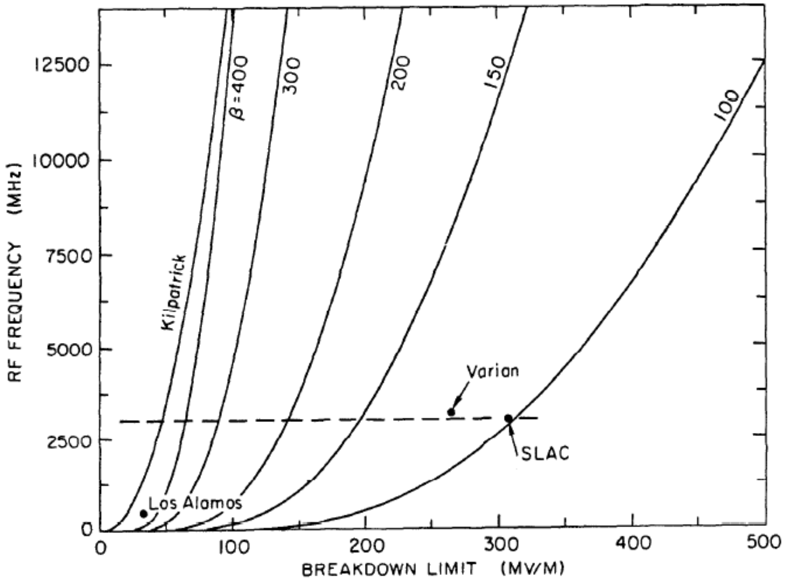
→ The threshold voltage varies as the square root of the applied frequency.

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



Kilpatrick frequency dependance

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



R&D directions

- Stage 1: High gradient RF test facility
  - Frequency: to be defined according to physical significance and costs evaluation
  - Magnetic field: 0 - 5T, different field configurations
  - Different materials: Cu, Be, Al, …
  - Different temperatures: Cryogenic NC
  - Different gases and pressure: 0 – few Bars
  - Different designs

- Stage 2: Prototype(s) for cooling test facility
  - Design of realistic cavity prototypes: frequency, beam aperture, integration
  - Specifications defined based on the results of Stage 1 and the (re-)design of the muon cooling complex (higher gradient,…)
  - May include irradiation capability to check its impact on the performanc

Baseline design of the RF system

Task 6.2 Baseline concept of the RF system for the Muon Cooling Complex (MCC) (CEA and INFN LASA)

The focus of this task, **led in conjunction by CEA and INFN LASA**, is to lay out a conceptual design of the RF systems for the MCC, based on a consistent set of parameters for all RF cavities and associated systems to be integrated into the cooling cells of the MCC obtained from inputs given by WP4 and WP8. For the muon cooling section, one challenge already pointed out in the preliminary MAP study, is to achieve gradients of at least 30 MV/m in RF cavities that will be placed in magnetic fields of 13 T, and explore whether it is possible to push these values at the light of the latest developments in RF and magnet technology. At first, specifications for the design of all RF cavities will be collected (frequency, gradient, length, B-field, aperture). Then, based on the guidance given by WP4, full set of parameters for the cavities will be calculated, serving as a base for their conceptual design and integration in the cooling cells. The impact of beam loading on the muon energy spread will also be assessed at this stage and appropriate mitigating actions will be recommended.

Task 6.3 Break down mitigation studies for cavities of the muon cooling cells (CEA)

The goal of this task, **led by CEA**, is to study and enhance the present comprehension of the intrinsic concepts that influence the break down rate of RF cavities submitted to strong magnetic fields. We plan to extend existing theoretical studies, and with additional inputs from previous experimental studies at CERN for CLIC and FermiLab for MAP, as well as from additional tests performed in the scope of this task, realistic solutions to mitigate the breakdown and provide guidance for the design and the fabrication of high gradient RF cavities that stand strong magnetic fields in the MCC will be proposed.

Development Plan

YEAR	1	2	3
Collect specifications for the design of **all** RF cavities : frequency, gradient, length, B-field, aperture (window size and thickness)	🟨	🟨	
Based on available knowledge both experimental and theoretical, identify best concept for achievable accelerating gradient in magnetic field: material, surface preparation, pulse shape, temperature, gas	🟨	🟨	
Calculate parameters of all cavities specified in 1. Provide a consistent set of parameters of **all** RF cavities and associated RF systems		🟨	🟨
Integration of RF cavities into cooling cell, adapting design if necessary			🟨

Thanks !!!