NCRF and SRF technology and MC Needs

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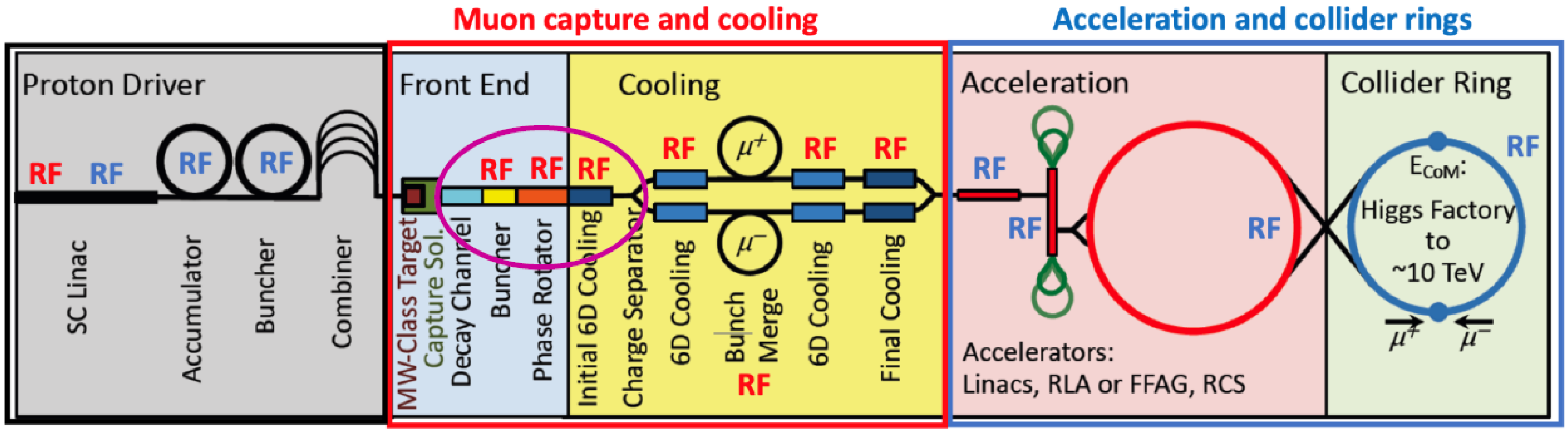
Muon collider RF system overview



- Complex and prevailing in the Muon collider, from the start of the proton driver to the final collider ring.
- Versatile functions: acceleration, ionization cooling, longitudinal beam manipulation, etc.
- Broad range of operation conditions: NCRF and SRF, frequency from dozens of MHz to a few GHz, gradients up to 30+ MV/m, etc.
- Unique features: strong magnetic field background, enclosed cavity apertures, gas-filled, muon decays, etc.

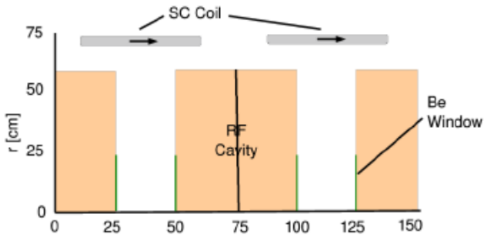
Summary of RF systems of CERN International Muon Collider

System			Driver			Front-End	Cooling			Acceleration			Collider	TOTAL	CLIC
Sub-system			Driver Linac H- (SPL like)		Accum &Comp	Capture& Bunching	Initial	6D (2 lines)	Final (2 lines)	Injector Linac	RLAs (2stages)	RCS (3stages)	Ring	IMC	Acceleration
Reference expert			F.Gerigk		?	D.Neuffer	C.Rogers	D.Stratakis	C.Rogers	A.Bogacz		S.Berg	E.Gianfelice		
	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500		1500
Beam (system exit)	# bunches (μ+ or μ-)	#	40 mA		1	12	12	1	1	1	1	1	1		312
	Charge/bunch	E12			500	3.57	2.56	7.21	4.39	3.73	3.17	2.22	2.20		3.72E-03
	Rep Freq	Hz	5	5	5	5	5	5	5	5	5	5	5		50
	Norm Transv Emitt	rad-m				1.5E-02	3.0E-03	8.3E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05		660/20E-06
	Beam dimens. (H/V) in RF	mm	?	?	?	?	?	?	?	?	?	?	?		1?
	Norm Long Emitt	rad-m				4.5E-02	2.4E-02	1.8E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03		
	Pulse/Bunch length	m	2.2 ms		0.6 (2ns)	1.1E+01	1.1E+01	9.2E-02	9.2E-02	4.6E-02	2.3E-02	2.3E-02	5.0E-03		4.4E-05
	Power (μ+ and μ-)	W	6.40E+04	2.2E+06	2.0E+06	1.8E+04	1.3E+04	3.0E+03	1.8E+03	7.6E+03	3.2E+05	5.4E+06	5.3E+06		2.8E+07
RF cavities	Technology		NC Linac4	SC	SC	NC	NC	NC Vacuum	NC	SC	SC	SC	SC		NC High Grad
	Number of cavities	#	23	244	2	120	367	7182	32	52	360	2694	?	11076	149000
	RF length	m	46	237	1	30	105	1274	151	82	1364	2802	?	6092	30000
	Frf	MHz	352	704	44	326to493	325	325-650	20-325	325	650-1300	1300	800	4 to 1300	12000
	Grf	MV/m	1-3.7	19 - 25	2	20	20 to 25	19-28.5	7.2-25.5	20	25 to 38	35	?	1 to 38	100
	Aperture	mm	28	80		?	?	?	?	300	150	75	120	28 to 300	2.75
	Magnetic Field	T	0	0		2	3T	1.7-9.6	1.5-4	0	0	0	0	0 to 9.6	0
	Installed RF field	MV	169	5700	4	434	2618	30447	1836	1640	50844	98062	250	1.92E+05	3.00E+06
	Beam Energy gain	MeV	160	4840	0	0	0	0	0	1250	62500	1437000	0	1.51E+06	1.50E+06
	Recirculations	#	1	1		1	1	1	1	1	4.5 to 5	13 to 23	1000	1 to 1000	1
	RF Power/pulse (η=0.6)	MW	25	220	3.E-01	99	429	1172	43	52	360	2024	1.98E-02	4425	1.2E+07
RF power sources	Technology		klystron	klystron						Klytron-IOT					Two Beam
	Cavities/Power Source	#	23	244		4				1 to 2	1 to 2				2
	RF Pulse (fill+beam) estim.	ms	2.20	2.20	3.20	1.00E-01	1.00E-01	1.00E-01	1.00E-01	3.00E-02	5.90E-02	7.25E-01	1.48E+01		1.42E-01
	Prf/Power Source	MW	11.7	1.93						1	1				15
	Total Power Sources	#	17	244		30				52	341			?	1638
	Installed Peak RF Power	MW	34	275		164	515	1407	52	52	341	2429	2.38E-02	5269	2.46E+04
	Average RF power (η=0.6)	MW	0.27	2.13	0.01	0.05	0.21	0.59	0.02	0.01	0.11	14.88	0.00	18.28	143
	Wall plug power (η=0.6)	MW	0.45	3.55	0.01	0.08	0.36	0.98	0.04	0.01	0.18	24.81	0.00	30.46	289

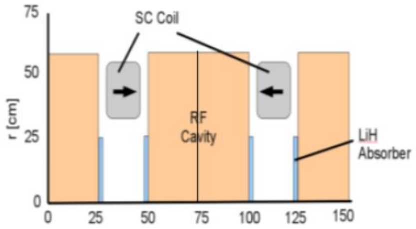
Courtesy of
J.P. Delahaye et al.

NCRF cavities in MC

Front end



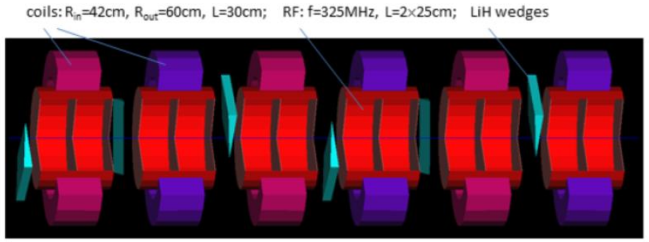
Buncher and rotator



4D initial cooler

Simulation with vacuum cavity and gas-filled cavity showed similar performance.
Frequency: 499 ~ 325 MHz, gradient: 0 ~ 25 MV/m

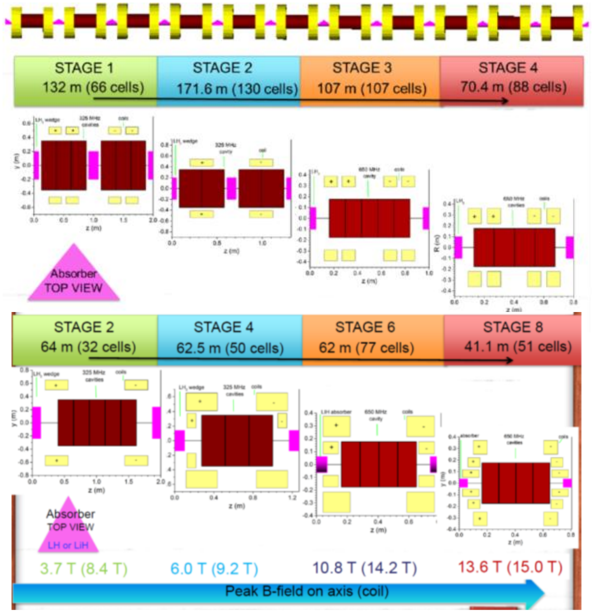
Magnetic field: 2T continuous solenoid field in Buncher and Rotator, alternation focusing solenoid field up to 2.8T on-axis.



Gradient 25 MV/m
Peak Bz on axis up to 4T
Vacuum or gas-filled

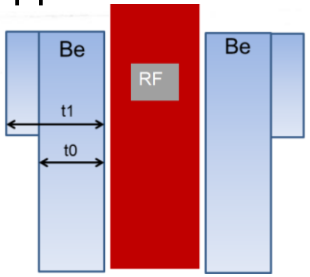
Helical FOFO 6D initial cooler

Rectilinear 6D cooling



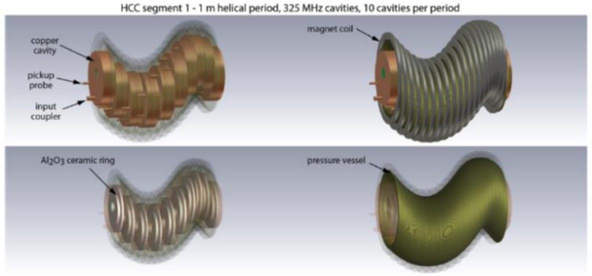
Frequency: 325 and 650MHz
Gradient: ~ 20 to 30MV/m
Peak Bz on axis: ~ 2 to 13T

Stepped Be window



For first 4 stages,
t0: from 0.3mm to 0.125mm

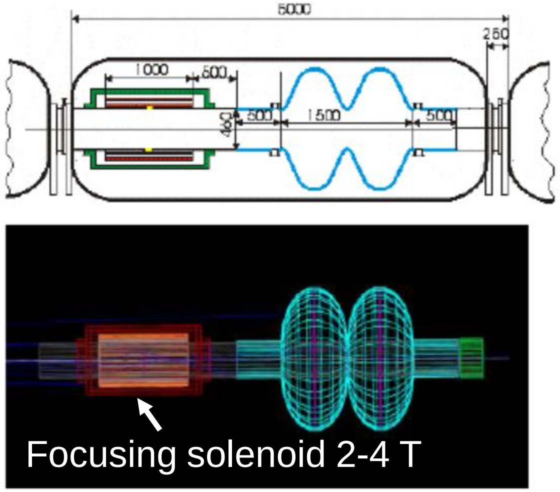
Helical Cooling Chanel for 6D cooling



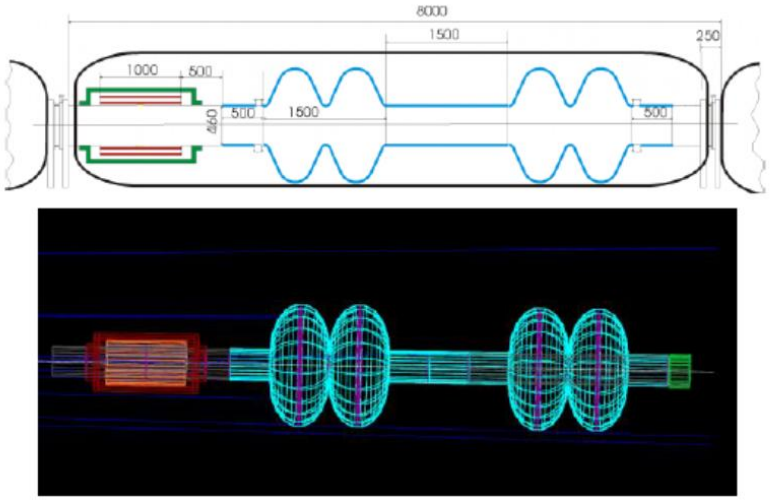
Peak RF gradient in the gas-filled RF cavities is 20 MV/m. Hydrogen gas pressure is 160 atm at room temperature. 30 um-thick Be RF windows are located at both ends of the RF cavity.

SRF cavities in MC

Low energy acceleration SRF: LINAC (0.255-1.25GeV)



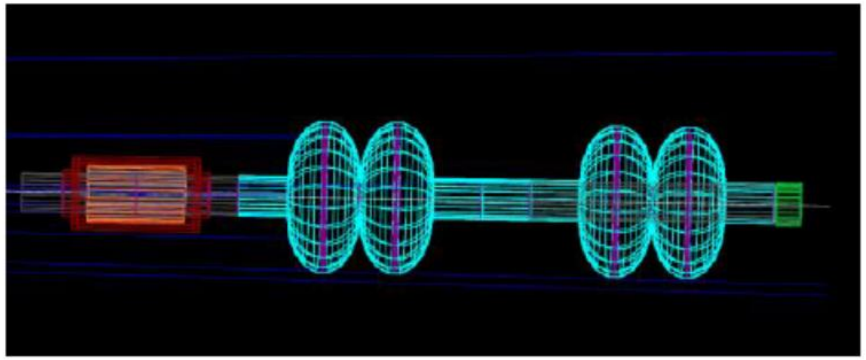
22 short cryos
(2.5 meter, 2-cell cavity)



30 medium cryos
(3.5 meter 4-cell cavity)

f=325 MHz, E=20 MV/m

Low energy acceleration SRF: dogbone RLA1 (1.25-5 GeV)



4 meter 90 deg. FODO cells
25 MV/m, 650 MHz, 2 × 4-cell cavity

Low energy acceleration SRF: dogbone RLA2 (5GeV – 63 GeV)

f=1.3 GHz, E=38 MV/m

High energy acceleration SRF

MAP specification

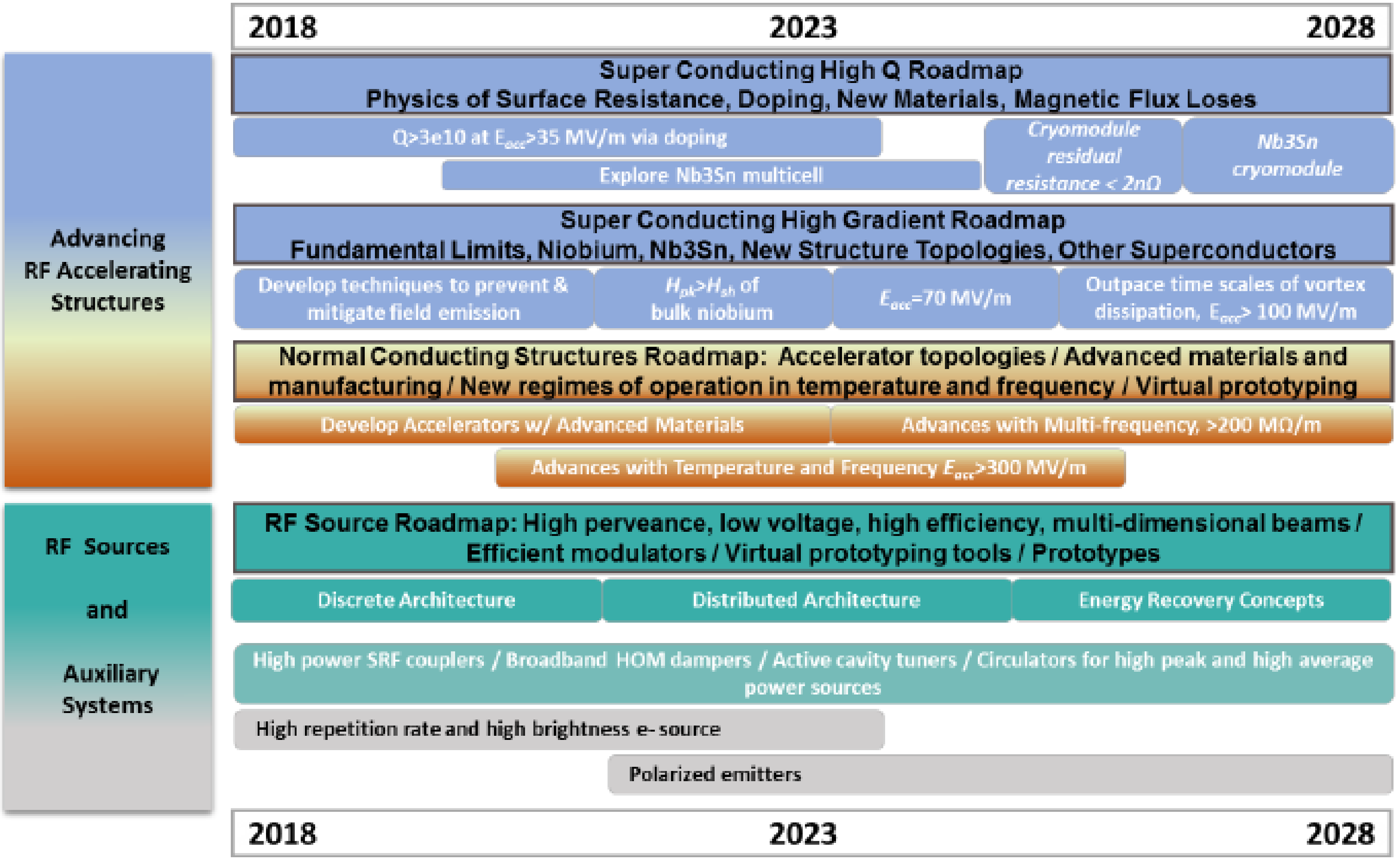
- Low repetition rate: 15 Hz
- Average gradient: 3.5 MV/m
  - 1.3 GHz cavities at 35 MV/m

FFA alternative

RF Frequency (MHz)	975	975
Cells/cavity	3	3
Gradient (MV/m)	30	30

E.g., ILC baseline 31.5 MV/m @ 1.3 GHz

Synergy with 10-year GARD-RF roadmap for SRF and NCRF



2018 2023 2028

Advancing RF Accelerating Structures

Super Conducting High Q Roadmap
Physics of Surface Resistance, Doping, New Materials, Magnetic Flux Loses

Q>3e10 at E_{acc}>35 MV/m via doping

Explore Nb3Sn multicell

Cryomodule residual resistance < 2nΩ

Nb3Sn cryomodule

Super Conducting High Gradient Roadmap
Fundamental Limits, Niobium, Nb3Sn, New Structure Topologies, Other Superconductors

Develop techniques to prevent & mitigate field emission

H_{pk}>H_{sh} of bulk niobium

E_{acc}=70 MV/m

Outpace time scales of vortex dissipation, E_{acc}> 100 MV/m

Normal Conducting Structures Roadmap: Accelerator topologies / Advanced materials and manufacturing / New regimes of operation in temperature and frequency / Virtual prototyping

Develop Accelerators w/ Advanced Materials

Advances with Multi-frequency, >200 MΩ/m

Advances with Temperature and Frequency E_{acc}>300 MV/m

RF Sources and Auxiliary Systems

RF Source Roadmap: High perveance, low voltage, high efficiency, multi-dimensional beams / Efficient modulators / Virtual prototyping tools / Prototypes

Discrete Architecture

Distributed Architecture

Energy Recovery Concepts

High power SRF couplers / Broadband HOM dampers / Active cavity tuners / Circulators for high peak and high average power sources

High repetition rate and high brightness e- source

Polarized emitters

2018 2023 2028

Figure 1: Ten-year integrated GARD-RF roadmap with a focus on improving accelerating structures and RF sources and auxiliary systems.

2017 General Accelerator R&D RF Research Roadmap Workshop Report

SRF: high Q, high gradient, etc.

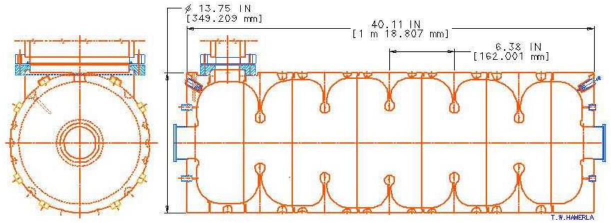
NCRF: topology, new regimes of operation.

RF sources

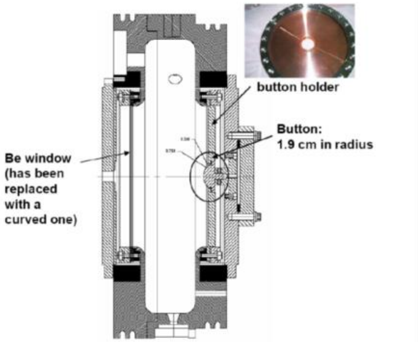
Auxiliary: HOM damping, power couplers, etc.

R&D on understanding the RF breakdown in multi-Tesla environment and its mitigation to achieve stable operation at required accelerating fields

805 MHz iris loaded cavity with a beam envelope matched aperture

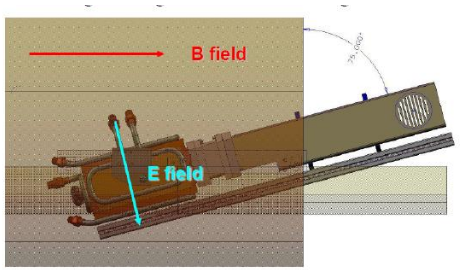


805 MHz Cavity Button test



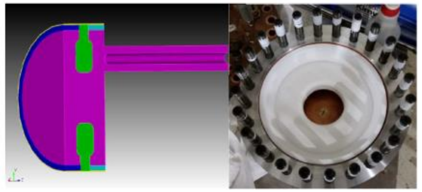
To find materials and coatings that can withstand high surface electric field in strong magnetic field.

805 MHz Box cavity



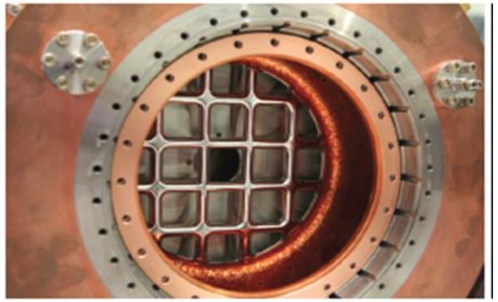
To study the breakdown mechanism with adjustable angle between E, B field directions

805 MHz cavity with alumina insert



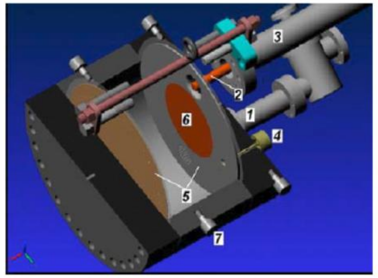
Shrink the diameter of the gas-loaded cavity

805 MHz Cavity with grid windows



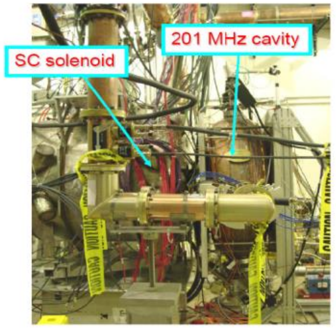
Alternative to the fully covered Be windows

805 MHz all-season cavity

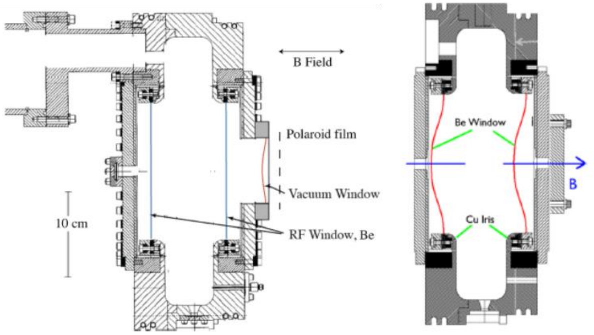


A versatile cavity for both vacuum and high-pressure test.

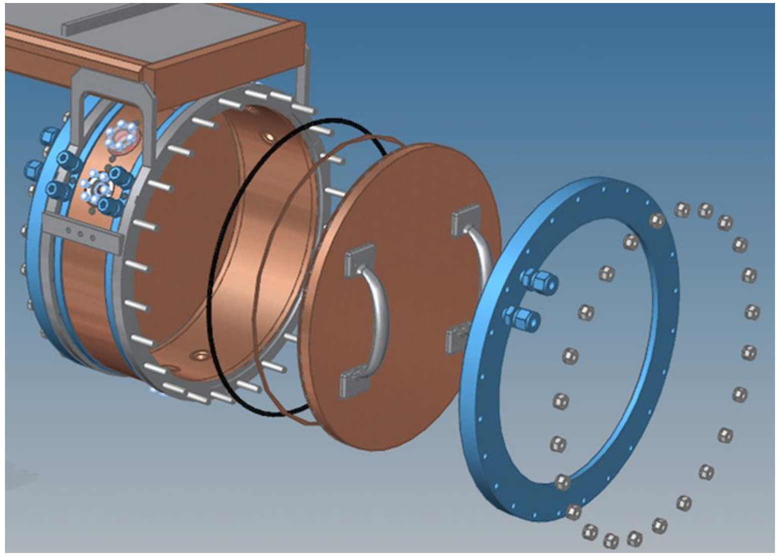
201 MHz prototype cavity

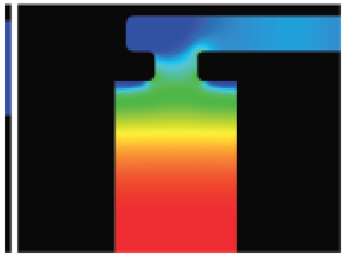


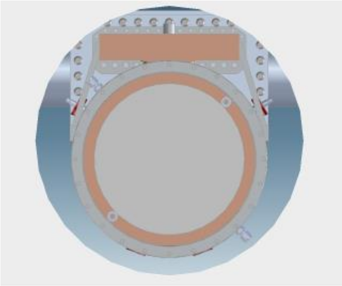
805 MHz LBL cavity with demountable windows

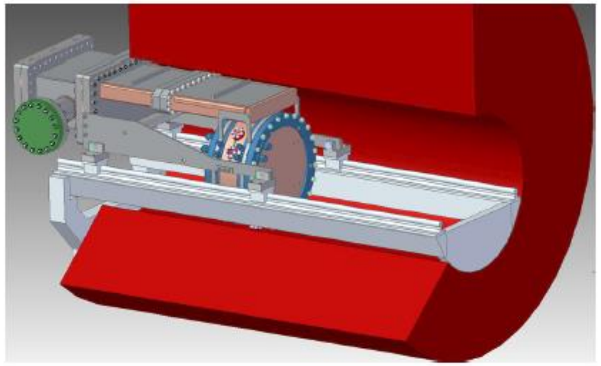


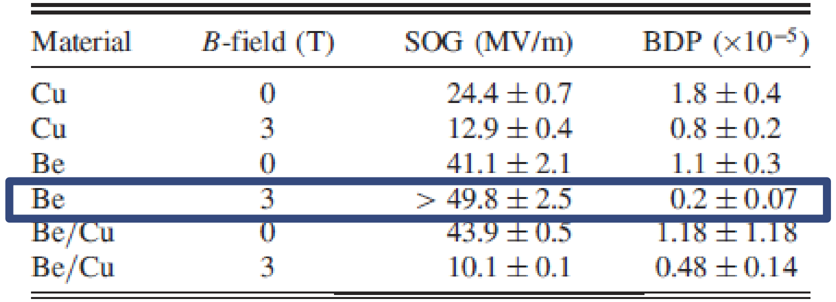
Vacuum modular cavity demonstration











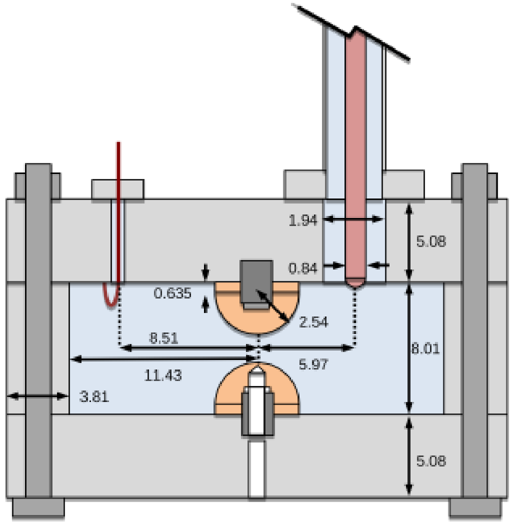
Material	B-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

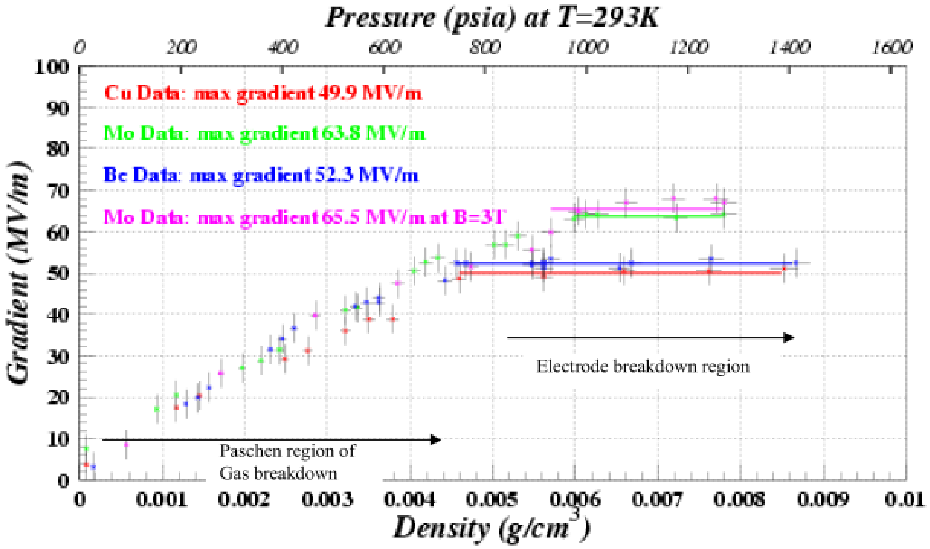
The latest R&D cavity is the 805 MHz modular cavity.

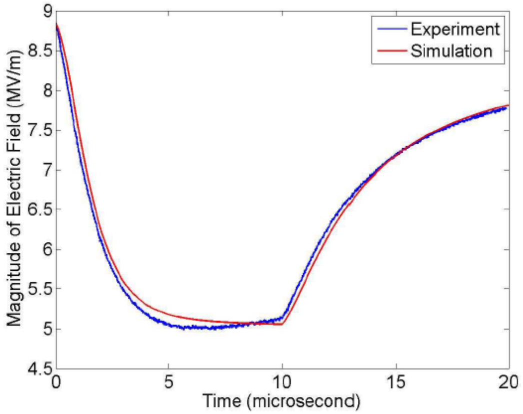
- The power feeding coupler is moved to torus to reduce E_peak at the coupler.
- Cavity geometry is optimized to minimize the effects of dark current and the multipacting with B field.
- Cleaning and polishing interior cavity surfaces to reduce the density of field emission sites.
- investigating the role of material type, production, surface conditioning, etc. in the breakdown process.

Achieve the steady operation at ~ 50 MV/m in B=3T environment with Be walls.

Gas-filled cavity demonstration



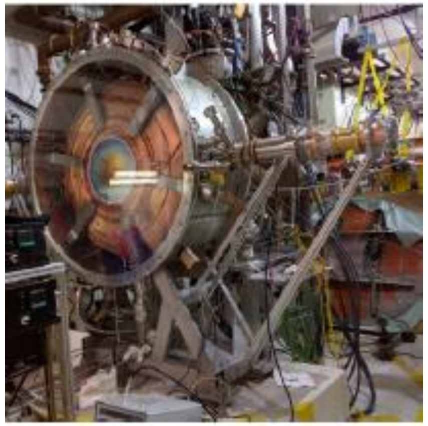


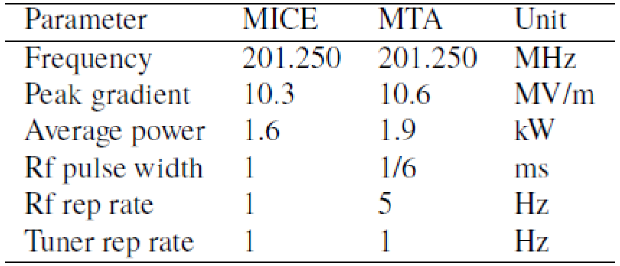


- The RF breakdown gradient of copper, molybdenum, and beryllium electrodes was determined using hydrogen gas. The breakdown gradient is the same for molybdenum electrode **with and without an external 3 T B field, achieving a gradient about 50 MV/m.**
- Beam test with proton beam has been carried out to characterize the effect of beam on the cavity performance, aka, plasma loading. Plasma loading reduces the cavity stored energy as well as the gradient.
- A 3D electromagnetic particle-in-cell code with atomic physics processes, SPACE, has been developed and benchmarked for predicting the plasma loading.

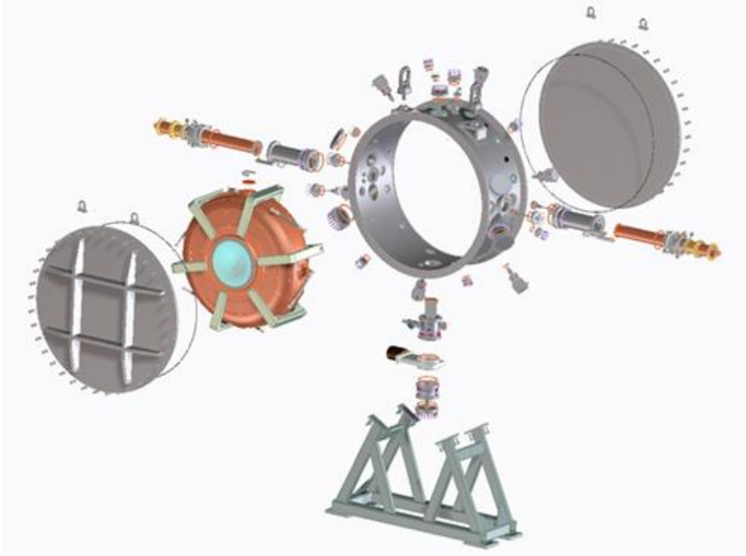
MICE RF module: a comprehensive engineering demonstration

- A prototype RF module was tested at Fermilab MTA and achieved the target operation level in a 4T solenoid fringe field.
- With further improvement, two RF modules were produced at LBNL, but eventually not operated at MICE due to limited resources.
- Several key engineering features for the ionization cooling NCRF cavities have been demonstrated or examined in MICE RF module:
  - An SRF-type polishing procedure to smooth the cavity surface thus to suppress the field emission.
  - Geometry design and TiN coating to suppress multipacting.
  - Curved beryllium windows of 0.38mm and the relevant thermal deformations and LFD.
  - Pressure regulation to protect Be windows from the vacuum burst.
  - Frequency tuning arms controlled by pressurized actuators.
  - Etc.





Parameter	MICE	MTA	Unit
Frequency	201.250	201.250	MHz
Peak gradient	10.3	10.6	MV/m
Average power	1.6	1.9	kW
Rf pulse width	1	1/6	ms
Rf rep rate	1	5	Hz
Tuner rep rate	1	1	Hz



Future R&D for the RF systems: SRF

- Identify the specification of the SRF cavity and power source in the MC baseline design, with input from the beam dynamics study and the lattice design.
- Collect the state-of-the-art SRF technology and provide limiting values for the MC design.
  - Gradient, Q , footprint, power, etc., from 300 MHz to 1.3 GHz
  - Tolerance to B fields, radiation, beam loss, etc.
- RF cavity design:
  - Identify the state-of-the-art designs to be used.
  - Moderately modify the state-of-the-art designs to accommodate the MC requirements.
- RF power source:
  - Identify the state-of-the-art RF power solutions to be used.
- Look for synergy in SRF technology with already ongoing projects and R&D activities that are relevant to the MC RF systems.
- Overall, the SRF system of MC is mainly built upon the state-of-the-art SRF technologies. We expected a low risk and limited R&D activities.

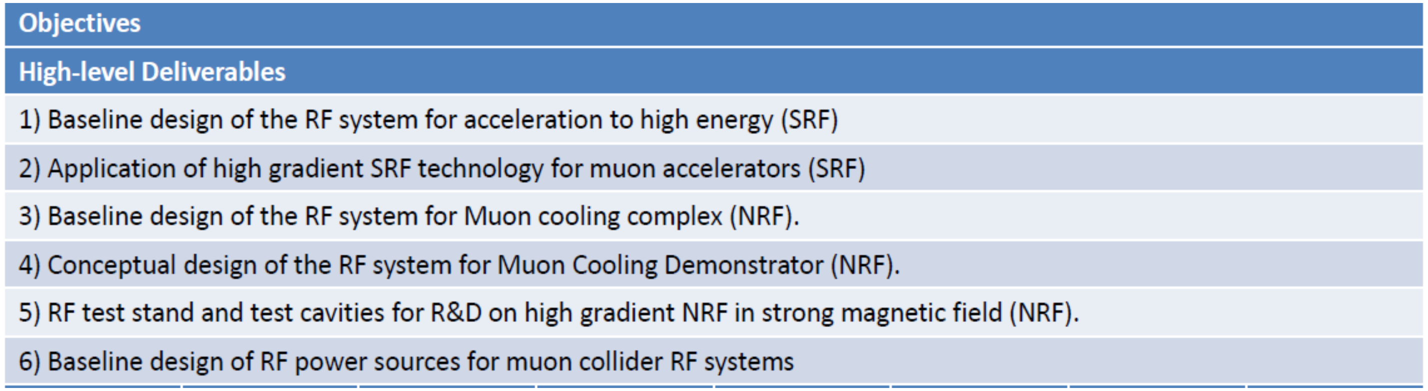
Future R&D for the RF systems: NCRF

- Identify the specification of the NCRF cavity in the MC baseline design, with input from the beam dynamics study and the lattice design: frequency, gradient, length, B-field, aperture (window size and thickness), gas species and density, etc.
- Review the previous R&D on the NCRF in the strong magnetic field.
  - Identify the achieved performances of the cavities (gradient, frequency, environment B field, operating stability, etc.) in the previous R&D.
  - Identify the gaps (deficit/surplus/uncovered parameters) between the baseline requirements and the demonstrated performances.
  - Gather the experience on how to make the cavity resilient to the external strong B field (surface treatment, etc.) and the general knowledge of the RF breakdown in the external strong B field.
- Based on available knowledge both experimental and theoretical, identify best concept for achievable accelerating gradient in magnetic field: material, pulse shape, temperature, gas.

Future R&D for the RF systems: NCRF

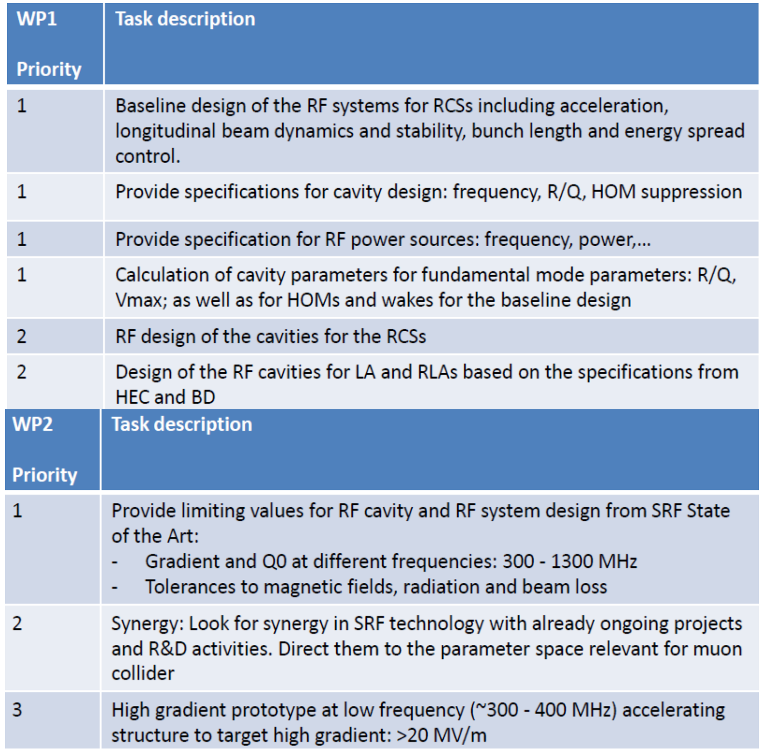
- Determine the parameters of all cavities and integrate them into the lattice design. There can be some iterations.
- Develop the RF system for a Muon Cooling Demonstrator with the chosen cavity concept.
  - RF design (cavity geometry optimization, power coupling, etc.)
  - Mechanical design (thin curved aperture windows, tuning mechanism, cooling, safety, etc.)
  - Hardware production, testing, and integration with the cryogenics and superconducting magnets.
- Look for synergy in NCRF technology with already ongoing projects and R&D activities that are relevant to the MC RF systems (the cryogenic copper cavity, the distributed power feeding, etc.)
- Overall, some critical performances have been demonstrated by the previous R&D. There are still gaps between the demonstrated performance and the MC design requirements. Significant engineering work is needed to build the fully-functional cavities and integrate with other subsystems. A dedicated demonstration program should be established.

A well-defined and comprehensive workplan has been made by CERN International Muon Collider Community



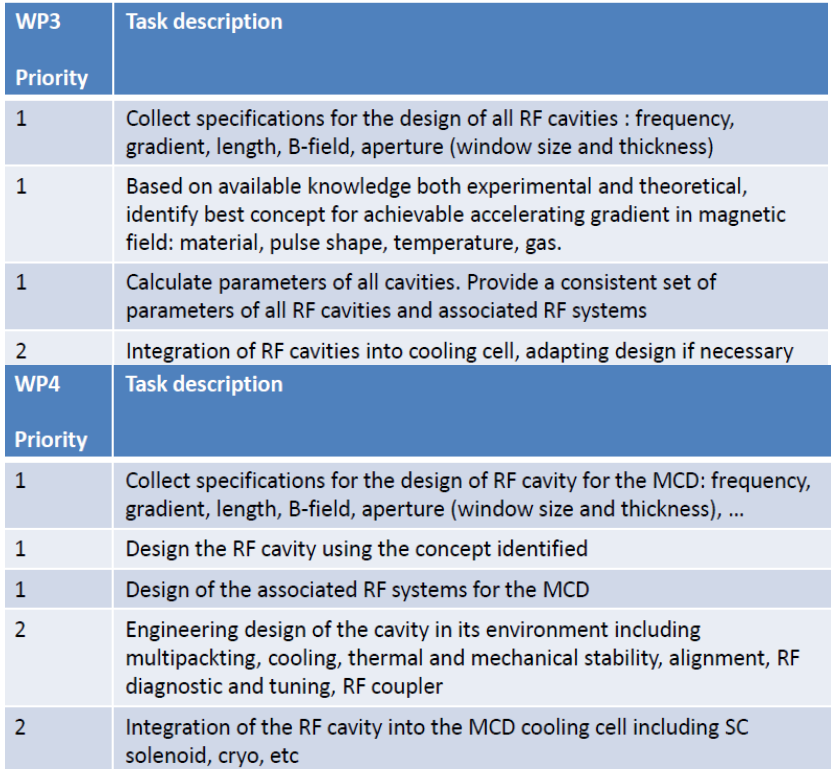
Objectives
High-level Deliverables
1) Baseline design of the RF system for acceleration to high energy (SRF)
2) Application of high gradient SRF technology for muon accelerators (SRF)
3) Baseline design of the RF system for Muon cooling complex (NRF).
4) Conceptual design of the RF system for Muon Cooling Demonstrator (NRF).
5) RF test stand and test cavities for R&D on high gradient NRF in strong magnetic field (NRF).
6) Baseline design of RF power sources for muon collider RF systems

J. P. Delahaye, et al. IMCC 3rd muon community meeting.



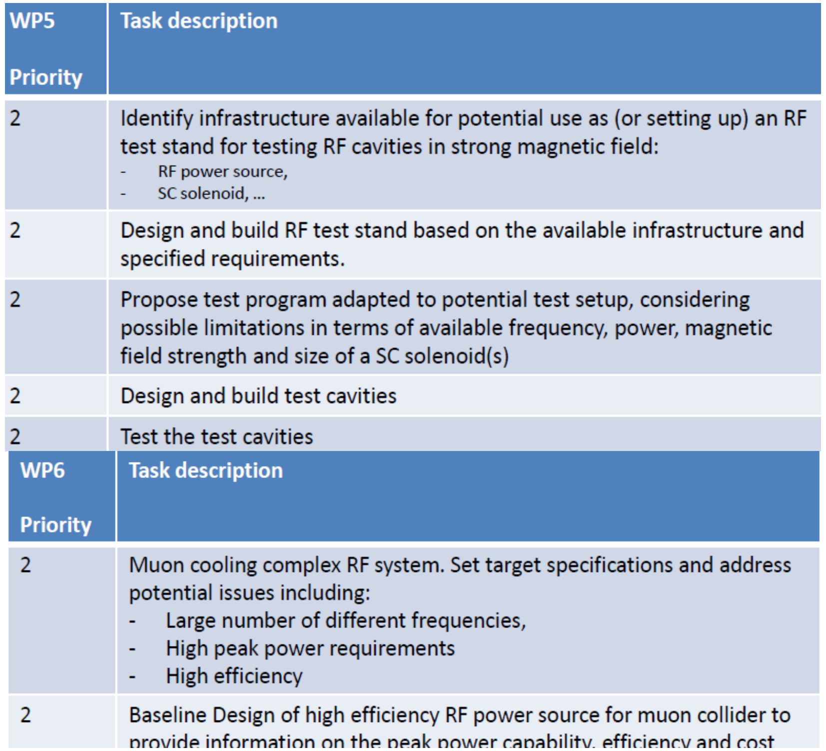
WP1 Priority	Task description
1	Baseline design of the RF systems for RCSs including acceleration, longitudinal beam dynamics and stability, bunch length and energy spread control.
1	Provide specifications for cavity design: frequency, R/Q, HOM suppression
1	Provide specification for RF power sources: frequency, power,...
1	Calculation of cavity parameters for fundamental mode parameters: R/Q, Vmax; as well as for HOMs and wakes for the baseline design
2	RF design of the cavities for the RCSs
2	Design of the RF cavities for LA and RLAs based on the specifications from HEC and BD

WP2 Priority	Task description
1	Provide limiting values for RF cavity and RF system design from SRF State of the Art: - Gradient and Q0 at different frequencies: 300 - 1300 MHz - Tolerances to magnetic fields, radiation and beam loss
2	Synergy: Look for synergy in SRF technology with already ongoing projects and R&D activities. Direct them to the parameter space relevant for muon collider
3	High gradient prototype at low frequency (~300 - 400 MHz) accelerating structure to target high gradient: >20 MV/m



WP3 Priority	Task description
1	Collect specifications for the design of all RF cavities : frequency, gradient, length, B-field, aperture (window size and thickness)
1	Based on available knowledge both experimental and theoretical, identify best concept for achievable accelerating gradient in magnetic field: material, pulse shape, temperature, gas.
1	Calculate parameters of all cavities. Provide a consistent set of parameters of all RF cavities and associated RF systems
2	Integration of RF cavities into cooling cell, adapting design if necessary

WP4 Priority	Task description
1	Collect specifications for the design of RF cavity for the MCD: frequency, gradient, length, B-field, aperture (window size and thickness), ...
1	Design the RF cavity using the concept identified
1	Design of the associated RF systems for the MCD
2	Engineering design of the cavity in its environment including multipackting, cooling, thermal and mechanical stability, alignment, RF diagnostic and tuning, RF coupler
2	Integration of the RF cavity into the MCD cooling cell including SC solenoid, cryo, etc



WP5 Priority	Task description
2	Identify infrastructure available for potential use as (or setting up) an RF test stand for testing RF cavities in strong magnetic field: - RF power source, - SC solenoid, ...
2	Design and build RF test stand based on the available infrastructure and specified requirements.
2	Propose test program adapted to potential test setup, considering possible limitations in terms of available frequency, power, magnetic field strength and size of a SC solenoid(s)
2	Design and build test cavities
2	Test the test cavities

WP6 Priority	Task description
2	Muon cooling complex RF system. Set target specifications and address potential issues including: - Large number of different frequencies, - High peak power requirements - High efficiency
2	Baseline Design of high efficiency RF power source for muon collider to provide information on the peak power capability, efficiency and cost

R&D efforts proposed in our Snowmass LOI “R&D of Vacuum Normal Conducting RF Cavities for the Muon Ionization Cooling”

1. **Design the compact multiple-cavity module, with efficient frequency tuning and RF power feeding systems.** In the cooling channel, the voltage in each segment requires multiple cavities or one LINAC with multiple cells. In order to have strong solenoid fields, the cavity design should be as compact as possible in transverse direction. The RF tuning and the power coupling designs should fit into the tight spaces and be resilient to the strong magnetic field background. Our newly developed cavity geometry design based on Multi-objective Optimization Algorithms can be applied. Novel ideas such as distributed power coupling structure can be explored.
2. **Study the effects of thin Be walls, such as the thermal deformation/detuning, LFD, mechanical feasibility and the cooling schemes.** Due to the scattering effect, the Be walls should be kept thin especially at the later stage of the cooling channel. As lessons learnt from MICE cavity, thin Be windows introduce new challenges on the mechanical design as well as the thermal management, thus should be carefully examined.
3. **Look into cavities at the frequencies of 325 MHz and 650 MHz.** Several current ionization channel designs call for cavities at 325 MHz and 650 MHz. From the conventional wisdom that lower frequency corresponds to lower Kilpatrick limit, they could be more susceptible to the RF breakdown than the demonstrated 805 MHz cavity. Thus, their performance in the strong magnetic field needs to be examined. Also, their transverse sizes are larger than the 805 MHz cavity, which could make it more challenging for the magnet design. How to keep them compact should be explored collectively with the superconducting solenoid design.

https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF4_AF7_Luo-093.pdf

Thank you

- This talk includes the work of D. Li, D. Neuffer, Y. Alexahin, K. Yonehara, S.A. Bogacz, B. Freemire, D. Stratakis, R. Palmer, D. Bowring, Y. Torun, A. Moretti, R. Geng, M. Palmer, and many others.