High Pressure Gas-Filled RF Cavities for Use in a Muon Cooling Channel

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A Muon Accelerator

- Most beam and RF parameters in this talk will be taken from the report coming from Snowmass 2013
- A staged facility is planned
- Sited at Fermilab, based on Project X

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U.S. Muon Accelerator Program

Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the U.S.:

A White Paper Submitted to the 2013 U.S. Community Summer Study of the Division of Particles and Fields of the American Physical Society

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Contributed by the U.S. Muon Accelerator Program (MAP) and Associated Collaborators

- Three programs are proposed:
  - Neutrinos from STORed Muons (nuSTORM)
  - Neutrinos from Muon Accelerators at Project X (NuMAX)
  - Muon Collider (MC)

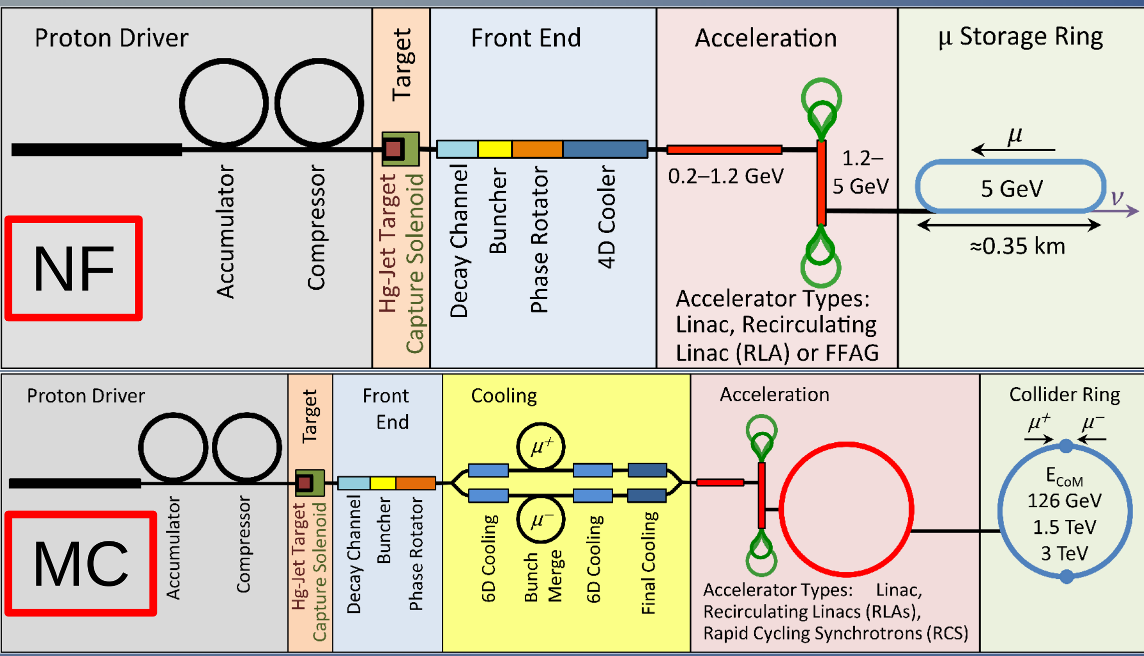
Facility Parameters

- Each facility has slightly different beam and RF requirements
- Definition: A beam *pulse* is comprised of (potentially) multiple *bunches*

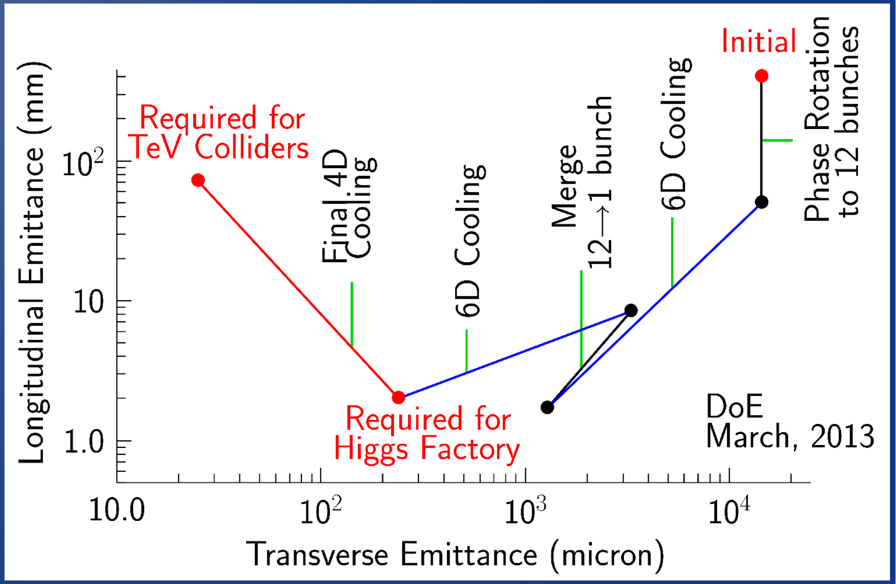
- nuSTORM and NuMAX:
  - No cooling (i.e. not relevant in this talk)
- NuMAX+:
  - 4D cooling
  - ~10^{10} μ/bunch
  - Not as challenging in terms of cooling
- I will focus on colliders

- Higgs Factory:
  - 10^6 reduction in 6D emittance
  - 2-4x10^{12} μ/pulse
  - bunched at 201 or 325 MHz
  - σ_s ~ 6 cm
- TeV Collider:
  - 10^6 reduction in 6D emittance
  - 2x10^{12} μ/pulse
  - bunched at 201 or 325 MHz
  - σ_s = 0.5 – 1 cm

Cooling



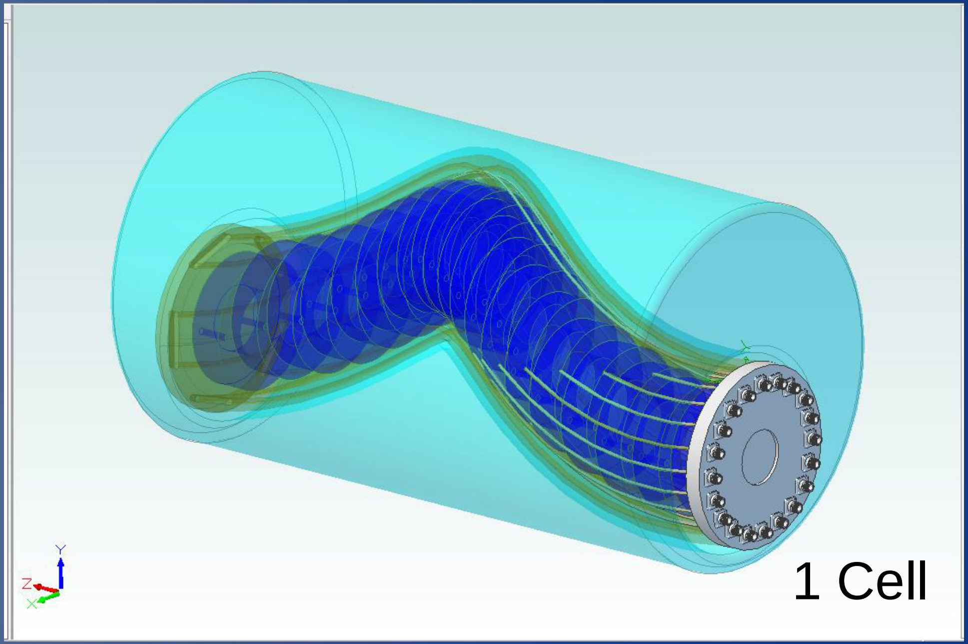
- Synergy between accelerator designs
- Bunch intensity less for NF than MC (10^{10} vs. 10^{11-12})
- Plasma loading within a bunch is negligible
- After the merge: only one bunch → ~millisecond recovery time

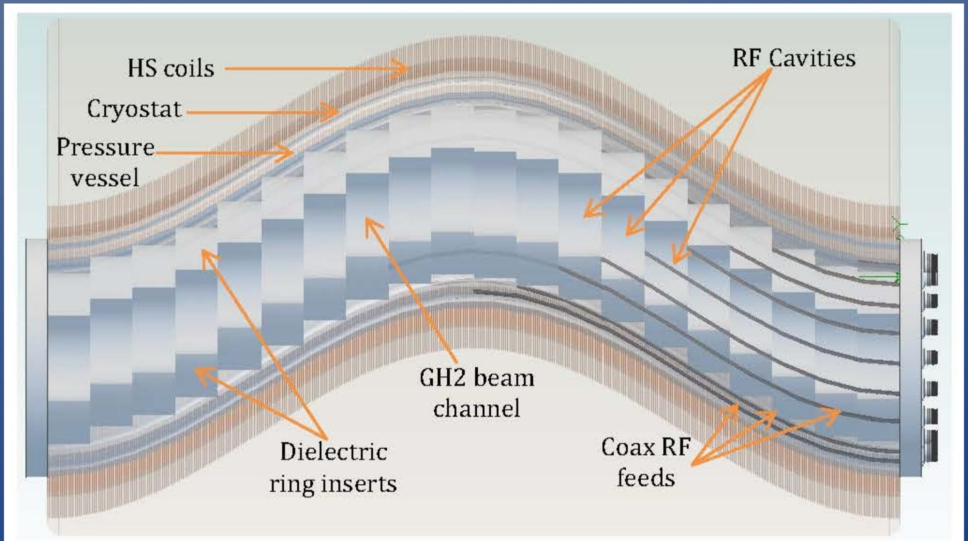


- Bunching and phase rotation in diagram shown at right is done at 201 MHz, i.e. 12 bunches with 5 ns spacing
- If beam is bunched at 325 MHz (i.e. Project X), 21 bunches with 3 ns spacing → bunch intensity decreases
- I will consider the 325 MHz case

Helical Cooling Channel (HCC)

- An HCC uses HPRF cavities arranged in a helix within a solenoid
- This provides dispersion, which when combined with ionization cooling produces continuous 6D cooling through emittance exchange
- A series of six HCC cells ~230 m long reduces the 6D emittance by a factor of 175,000





- The RF cavities contain a dielectric insert, are terminated with thin Be windows, and are thermally isolated from the magnets
- A magnetron supplies RF power through coaxial RF feedthroughs to each cell
- See posters for more information

HPRF Concept

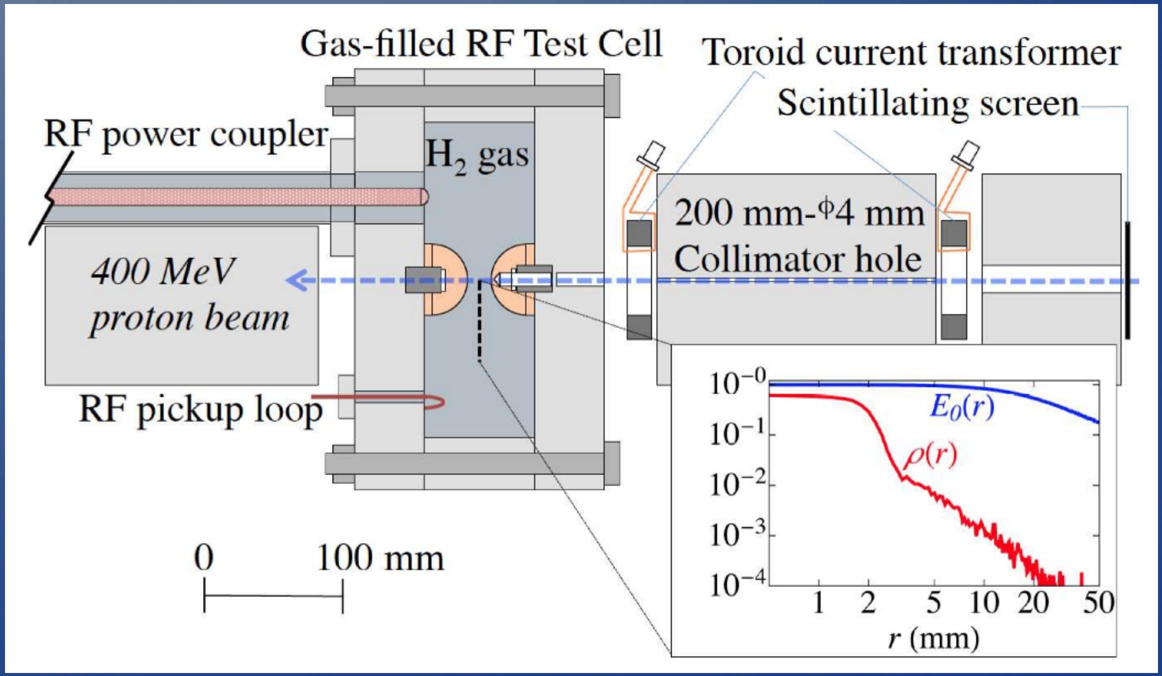
- As a beam of particles traverses a gas-filled cavity, it ionizes the gas
- The number of electron-ion pairs can be calculated:

$$N_{pairs} = \frac{\frac{dE}{dx}\rho\ L}{W_i}$$

$\frac{dE}{dx} = stopping\ power$

$\rho = gas\ density$ $\quad L = path\ length$

$W_i = average\ ionization\ energy$



Plasma Loading

- Ionization electrons collide with gas molecules and transfer energy from the cavity to the plasma – this is called plasma loading
- Ions also contribute to plasma loading, however this effect is ~100x smaller than electrons
- Electrons quickly come into equilibrium and drift with the applied electric field
- The energy absorbed by a charged particle can be evaluated:

$$dw = q \int v \, E_0 \sin(\omega t) \, dt = q \int \mu \, E_0^2 \sin^2(\omega t) \, dt$$

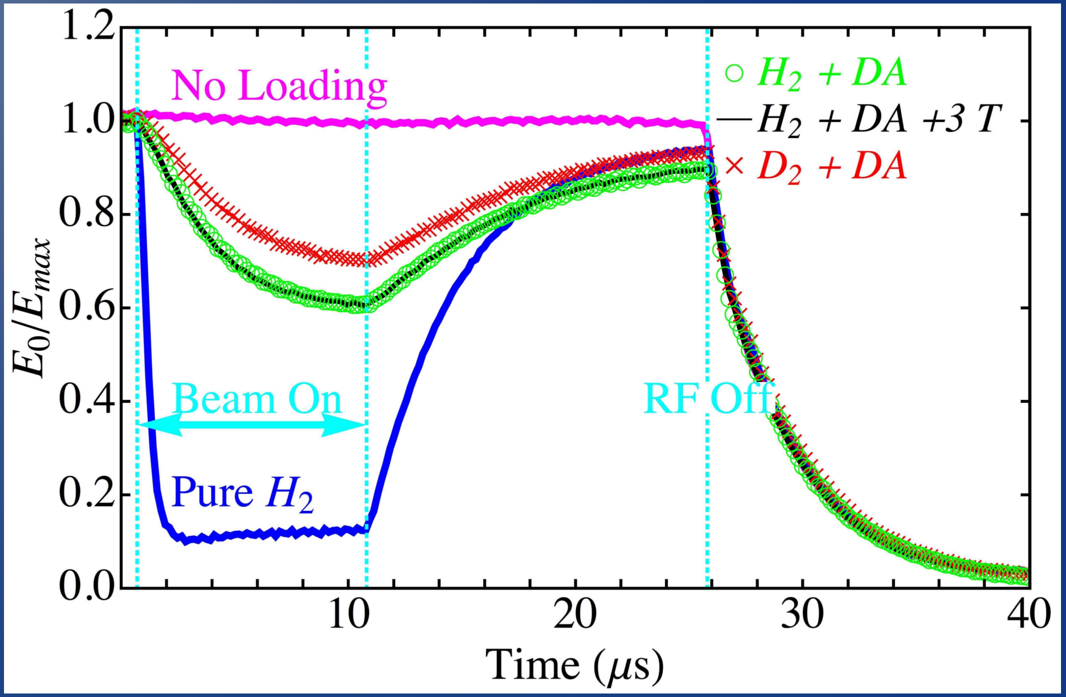
$v = drift \ velocity$

$\mu = mobility$

- The addition of an electronegative gas dopant decreases the electron's lifetime and minimizes plasma loading

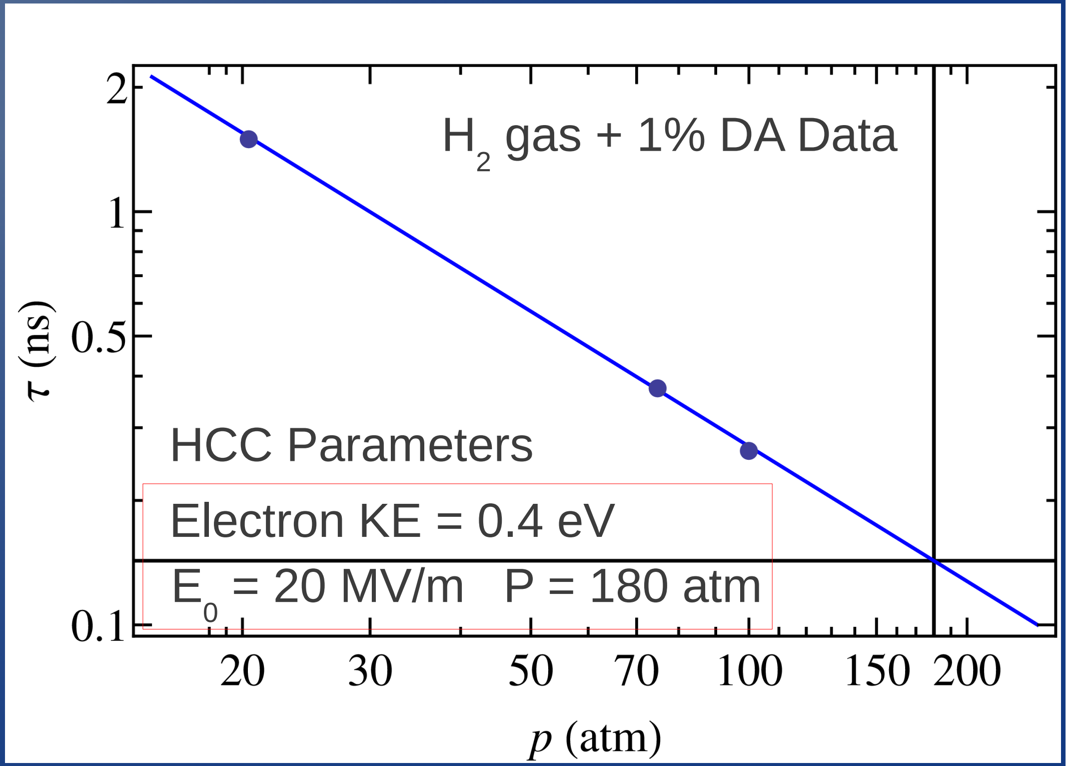
HPRF Beam Test

- A beam test of an HPRF test cell was performed at the MuCool Test Area at Fermilab
- Hydrogen and deuterium parent gases were doped with dry air and sulfur hexafluoride
- Dopants dramatically improved the cavity performance
- Many conditions of a real HCC were producible (electric & magnetic fields, electron KE)
- Gas density (100 atm → 180 atm) and plasma density (7×10^{11} cm^{-3} → 5×10^{15} cm^{-3}) will be higher in an HCC
- Extrapolation is necessary



Extrapolating to Muon Cooling Channel Parameters

- To minimize plasma loading, fast negation of electrons through attachment to oxygen or recombination with hydrogen ions is desired
- Ion-ion recombination is also important
- The time constant for electron capture at varying pressures, dopant concentrations and electric fields has been measured
- The ion-ion recombination rate has also been measured, and shows only slight pressure dependence



Plasma Loading

- A plasma loading calculation with:
- Beam parameters
  - 21 bunches
  - 10^{11} or 10^{12} μ/bunch (delta function)
  - bunched at 325 MHz
  - inject at 160° RF phase
- Plasma dynamics
  - electron attachment time, electron-ion recombination rate, ion-ion recombination rate based on extrapolations of measurements made at the MTA
  - energy loss for charged particles based on measurements made at the MTA and ion mobilities from the Literature
- HPRF cavity parameters
  - E_0 = 20 MV/m
  - P = 180 atm
  - f = 325 or 650 MHz
  - 10 cm long
  - U = 19 or 4.7 J

Plasma Loading Calculation Results

- 10^{12} μ/pulse dicates 10^{11} – 10^{12} μ/bunch to account for losses
- Any decrease in accelerating voltage subsequent bunches see will increase longitudinal emittance

RF freq.	MHz	325		650	
Bunch int.	μ/bunch	10^{12}	10^{11}	10^{12}	10^{11}
Energy dissipated	J	1.84	0.292	1.98	0.317
% of total energy	-	9.7	1.5	42	6.7
% V_{accel} last bunch sees	-	95	99.2	76	96.6

Conclusions

- Initial evidence is that HPRF cavities would work in an HCC
- Effects of higher gas and plasma density must be considered
  - Simulations underway to address this
  - Evidence suggests that higher densities have a positive effect on cavity performance
- Wakefields and beam loading have not been considered
  - Serious consideration for 10^{11} – 10^{12} μ/bunch
  - Not unique to HPRF cavities
  - Impact and mitigation being investigated
- End-to-end HCC simulation with real parameters underway

Backup Slides

Facility Parameters

System	Parameters	Unit	nuSTORM	NuMAX	NuMAX+	IDS-NF
Perfor-mance	Stored μ+ or μ-/year		8×10^{17}	2×10^{20}	1.2×10^{21}	1×10^{21}
	ν_e or ν_μ to detectors/yr		3×10^{17}	8×10^{19}	5×10^{20}	5×10^{20}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND
	Distance from Ring	km	1.9	1300	1300	2000
	Mass	kT	1.3	30 / 10	100 / 30	100
	Magnetic Field	T	2	0.5-2	0.5-2	1-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	2.7	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum (P_μ)	GeV/c	3.8	5	5	10
	Circumference (C)	m	480	600	600	1190
	Straight section	m	185	235	235	470
	Arc Length	m	50	65	65	125
Acceleration	Initial Momentum	GeV/c	-	0.22	0.22	0.22
	Single-pass Linac	GeV/pass	-	0.95	0.95	0.56
		MHz	-	325	325	201
	4.5-pass RLA — RLA I	GeV/pass	-	0.85	0.85	0.45
		MHz	-	325	325	201
	RLA II	GeV/pass	-	-	-	1.6
		MHz	-	-	-	201
Cooling			No	No	4D	4D
Proton Source	Proton Beam Power	MW	0.2	1	3	4
	Proton Beam Energy	GeV	120	3	3	10
	Protons/year	1×10^{21}	0.1	41	125	25
	Repetition Frequency	Hz	0.75	70	70	50

Muon Collider Baseline Parameters

		Higgs Factory		Multi-TeV Baselines	
Parameter	***Units***	Startup Operation	Production Operation		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	$4^{\#}$	4	4	4

Could begin operation with Project X Stage 2 beam