RF Cavity Needs for Future Muon Accelerators

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Introduction

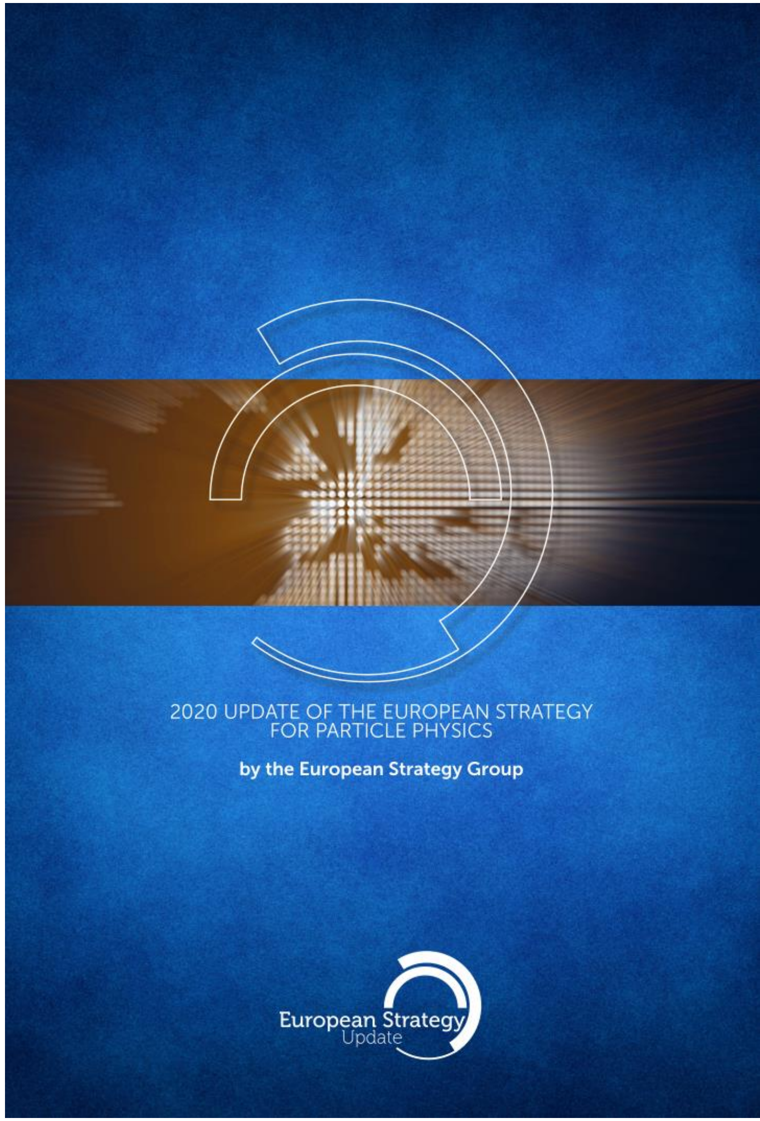
- Aims for this talk:
  1. Review RF-related muon accelerator accomplishments
     - Both design & technology
  2. Point out areas that still need work
  3. Start a discussion
- Proton on target production scheme will be the focus, rather than pair production through positrons

History

- Muon collider "old" idea – first proposed 1969 (G. Budker)
- Gained momentum in 1990s when it was realized muon accelerators are an easy way to produce neutrinos
- Tertiary muon beams really developed in 2000s & 2010s
  - Muon Ionization Cooling Experiment
- Culminated with US Muon Accelerator Program (2010-2017)
  - Significant R&D on many critical systems:
    - Proton driver, target system, beam cooling & acceleration, collider ring…

Renewed Interest

- 2020 Update of the European Strategy for Particle Physics
- 2022 European Strategy for Particle Physics - Accelerator R&D Roadmap
- International Muon Collider Collaboration formed at CERN
- Snowmass 2021
  - 6 reports submitted
- Muon accelerator technologies need to be revisited!



International MUON Collider Collaboration

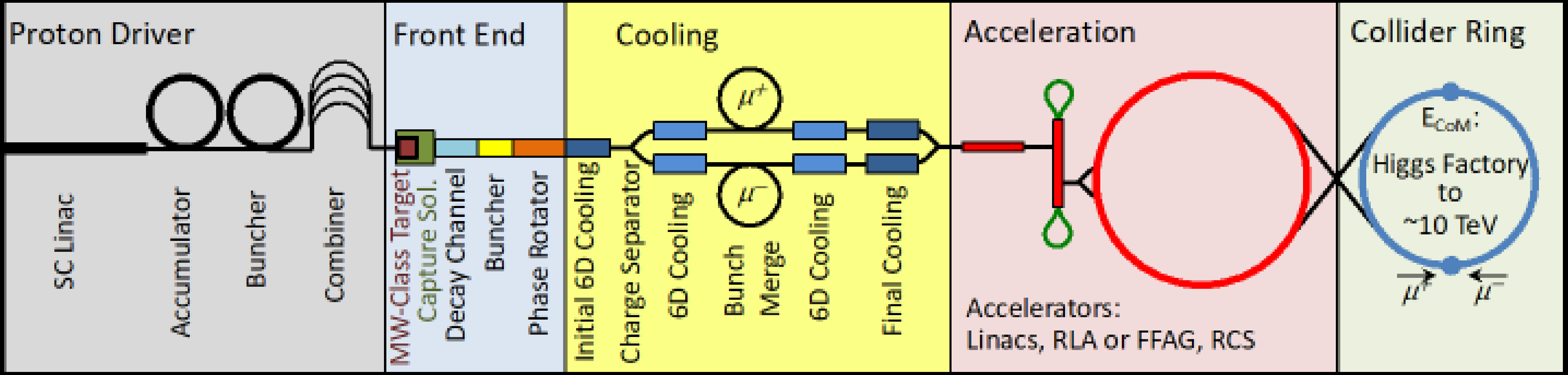
April 1, 2022
https://muoncollider.web.cern.ch

A Muon Collider Facility for Physics Discovery

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Proton-Driven MC Concept

Muon Collider



Short & intense proton bunches to deliver hadronic showers

p→π→μ → bunched beams

Ionization cooling reduces the transvers & longitudinal emittance

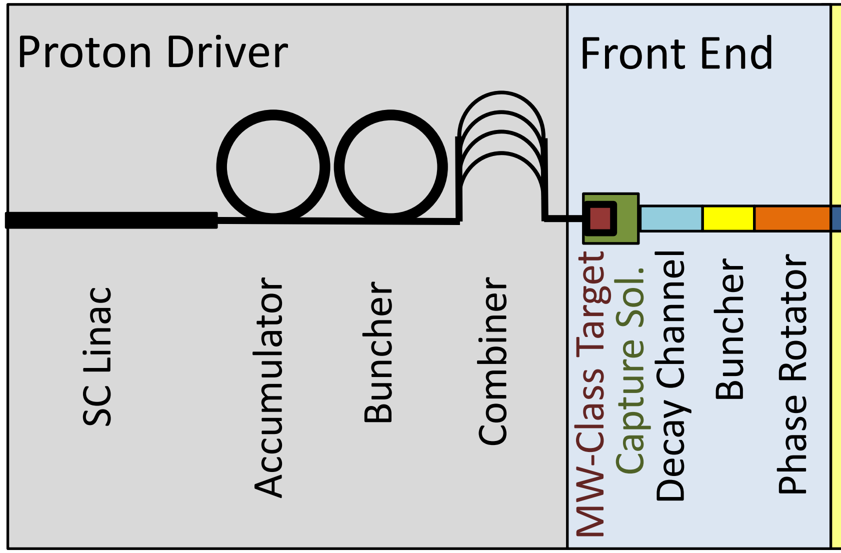
Rapid acceleration to high energy to avoid μ losses

∝-Collider Goals:
126 GeV ⇨ ~14,000 Higgs/yr
Multi-TeV ⇨ Lumi > $10^{34} cm^{-2} s^{-1}$

Accelerator design is driven by the short muon lifetime

Muon Collider Proton Driver & "Front End"

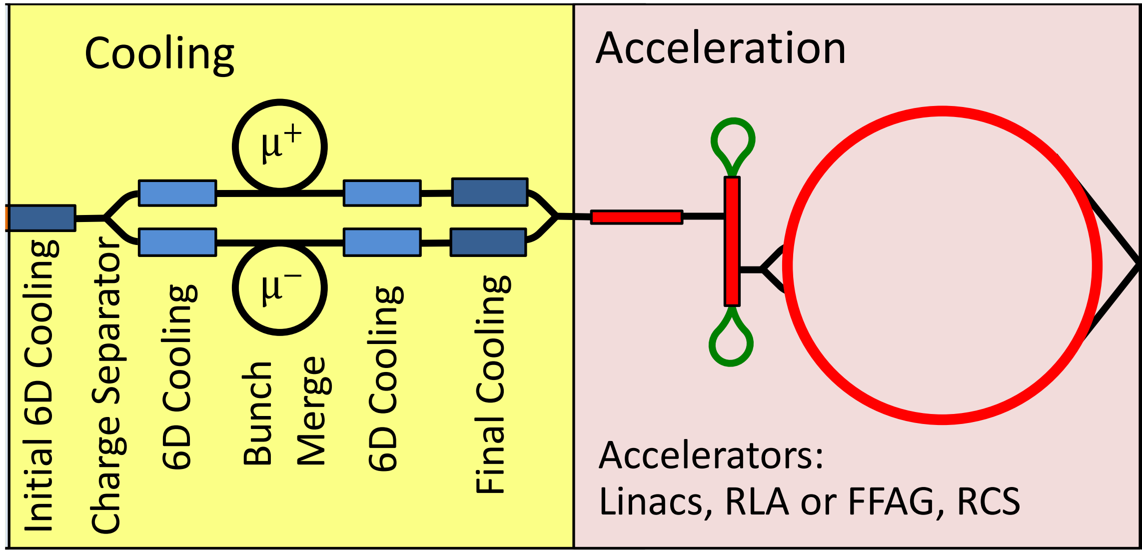
- Proton driver based on PIP-II, i.e. high current superconducting linac
  - Assumed to be "solved" (up to 1.2 MW) before MC breaks ground



- Front End challenging from target and magnet perspective
- RF cavity constraints driven by two factors:
  - Large acceptance needed
  - Operation in magnetic fields
- Conventional* NC cavities with moderate (≤20 MV/m) gradient

Muon Collider Cooling & Acceleration

- Major constraint for cooling and acceleration is muon lifetime
  - Only fast processes allowed
- High field magnets needed for both

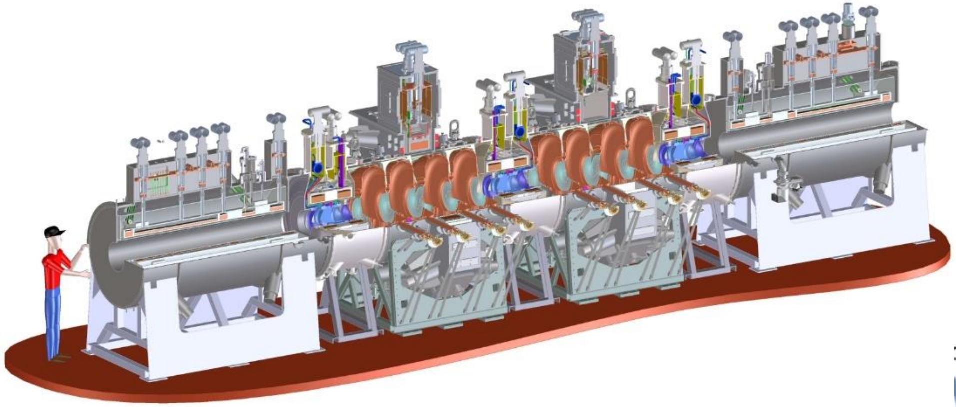


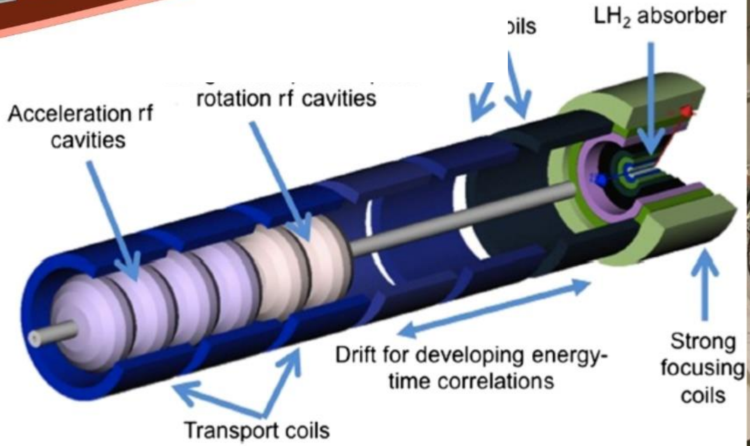
- Cooling requires RF cavities operating in >10 T magnetic fields
- Acceleration requires large gradient & withstanding significant beam loading
  - Several options have been studied

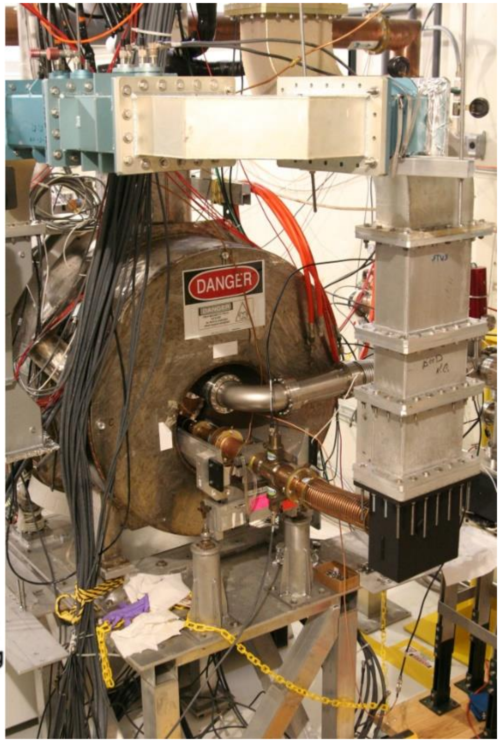
$$\frac{d\epsilon_N}{ds} = -\frac{\epsilon_N}{\beta^2 E}\frac{dE}{ds} + \frac{\beta_\perp E_s^2}{2\beta^3 mc^2 L_R E}$$

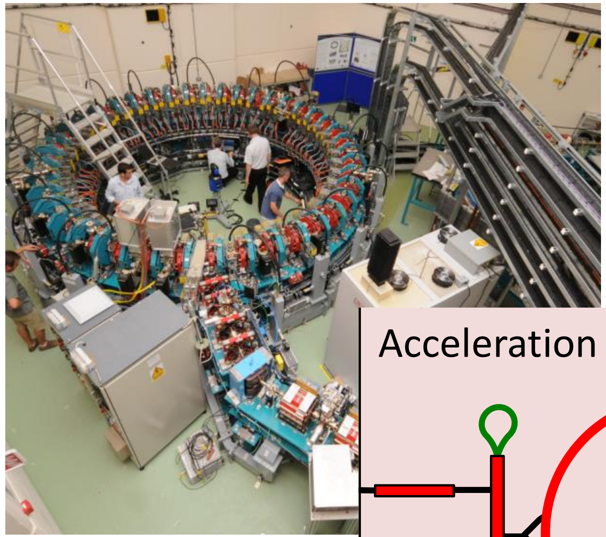
Prior RF R&D Thrusts

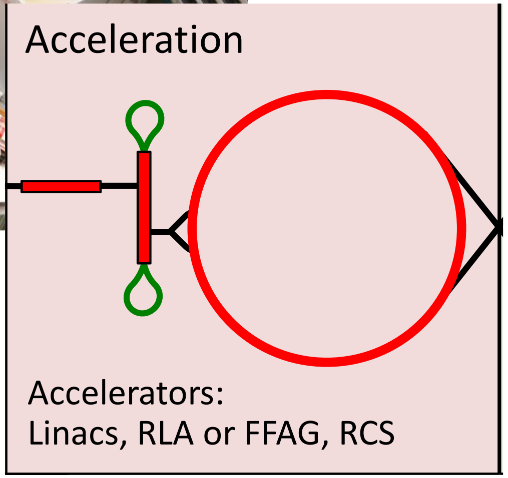
- Demonstration of ionization cooling
  - MICE
- Cooling channel design & technology
  - MAP
- Accelerator design & technology
  - EMMA, MAP



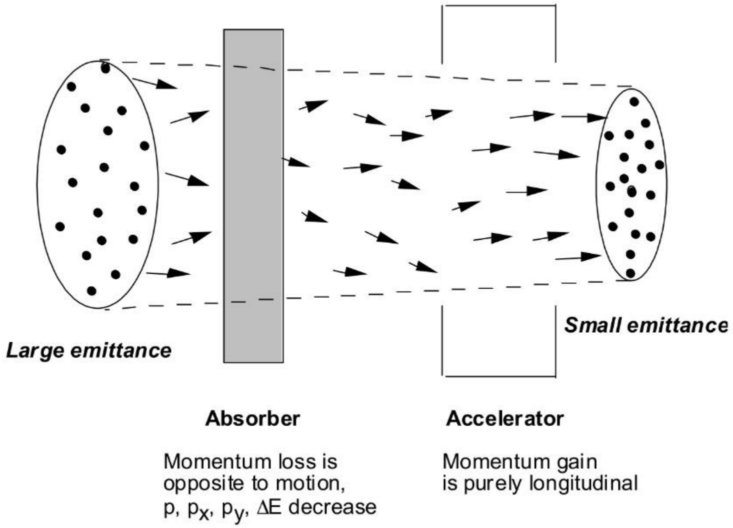






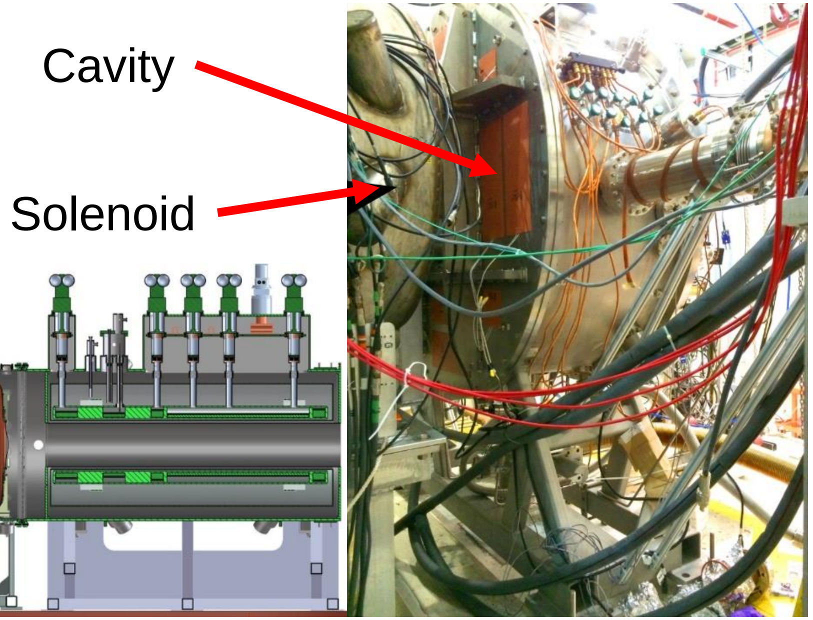


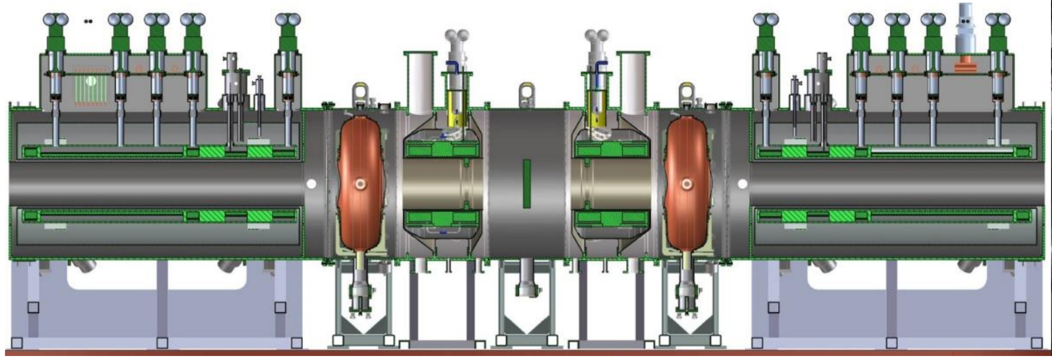
Muon Ionization Cooling Experiment



- Ionization cooling only effective option for cooling beam within muon lifetime
- MICE recently published first ever demonstration of cooling (*Nature* 578)
  - No RF cavities
- But, MICE prototype cavity operated *without breakdown* in 5T solenoid fringe field
  - Similar to MICE configuration
  - 3M pulses @ ~11 MV/m

Torun IPAC'15



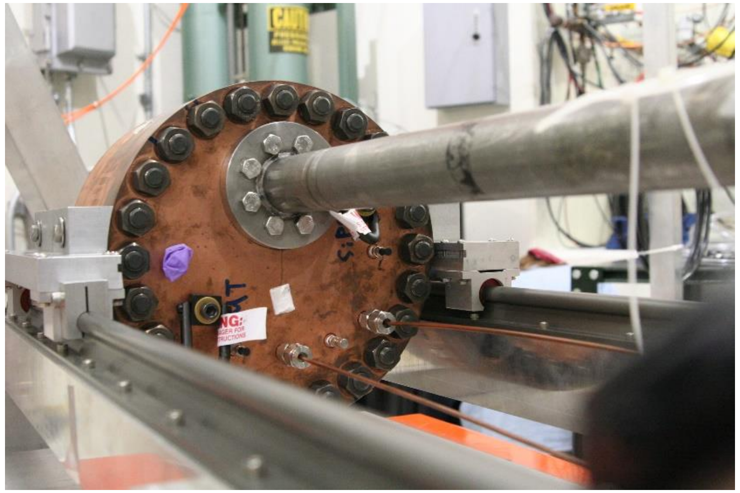


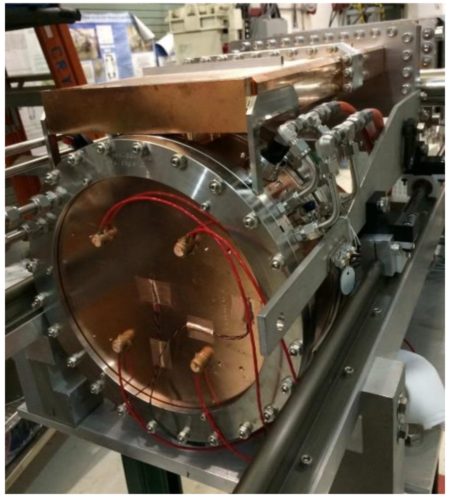
RF Cavities in Magnetic Fields

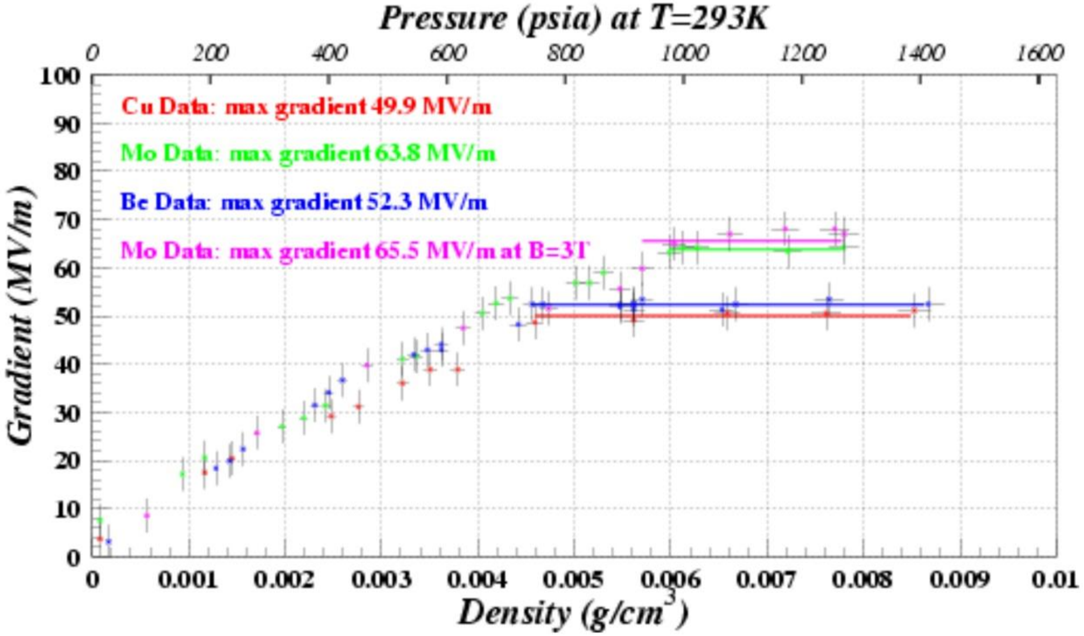
M. Chung PRL 2013
D. Bowring PRAB 2020

- One of the main MAP R&D items
- Two solutions identified
  - Vacuum cavities with TiN coated Be walls
  - High pressure gas filled cavities
- Gradients of 50 MV/m (vacuum) and 65 MV/m (gas) were demonstrated in 3T

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

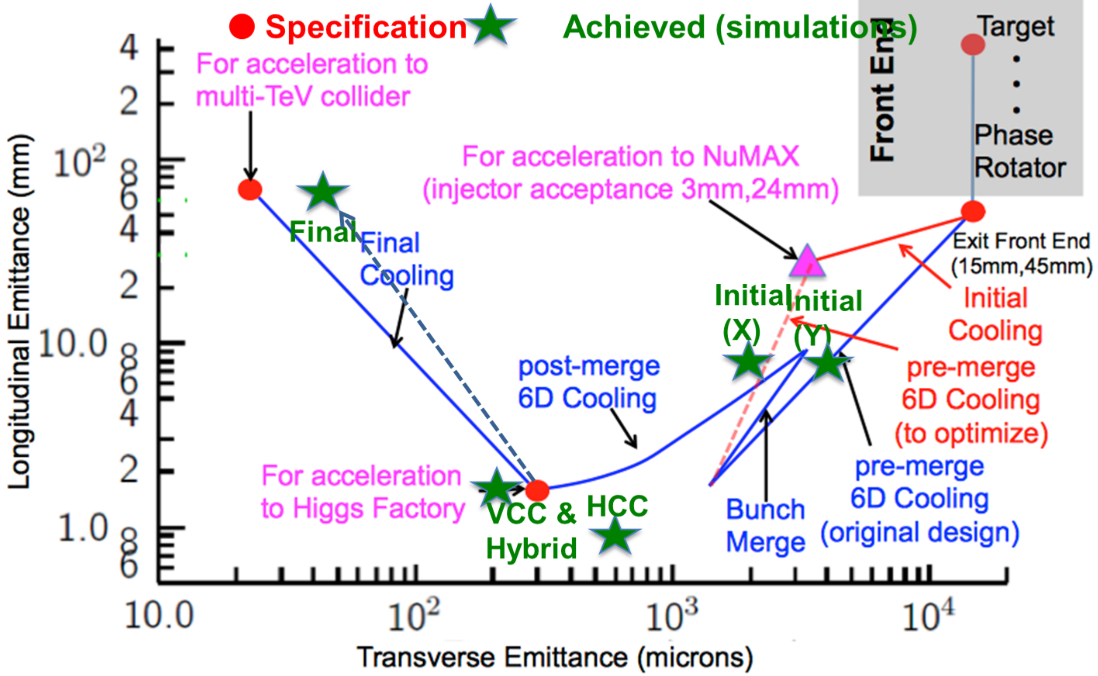


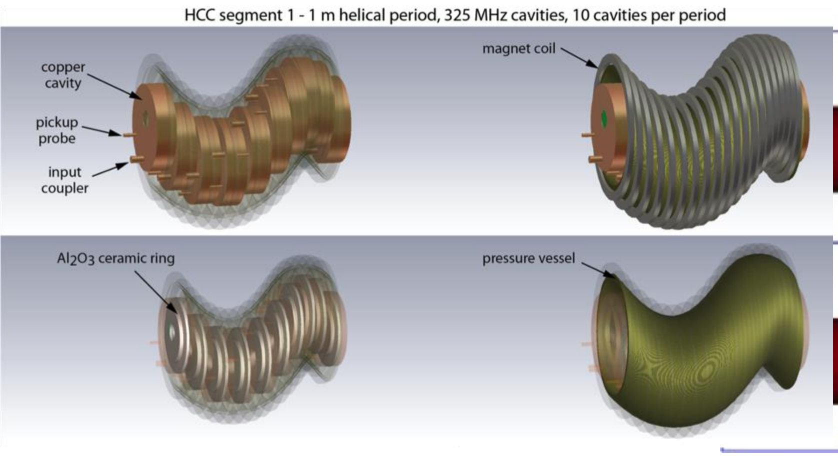


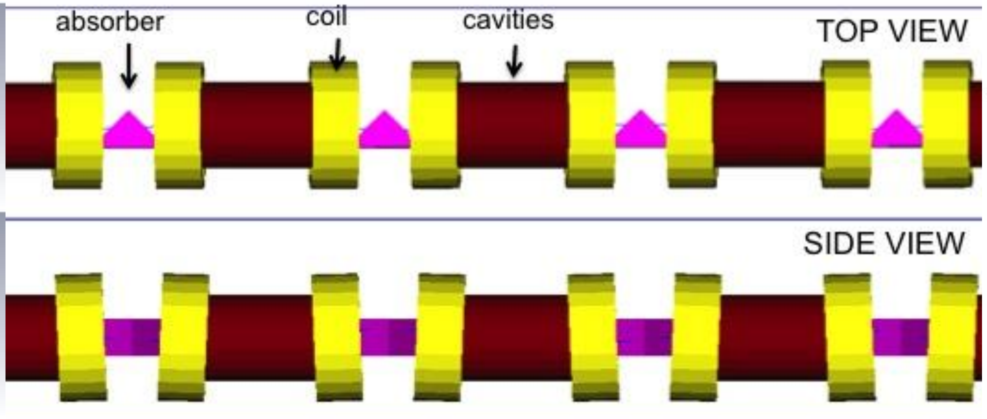


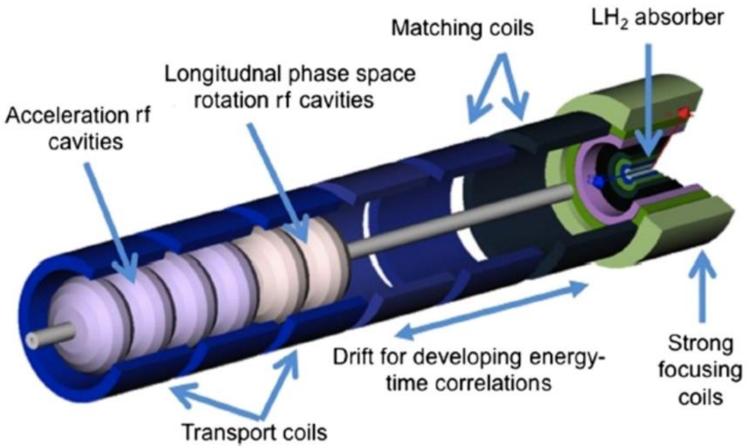
Cooling Channel Designs

- Several cooling channel designs at various stages of development
  - Rectilinear, Helical, Quadrupole, Parametric Resonance, Passive Plasma Lens…
  - Separated into initial (4D) and final (6D) cooling
- Performance in terms of emittance & transmission studied
- Initial concepts for integrating magnets, RF, plumbing, etc. exist



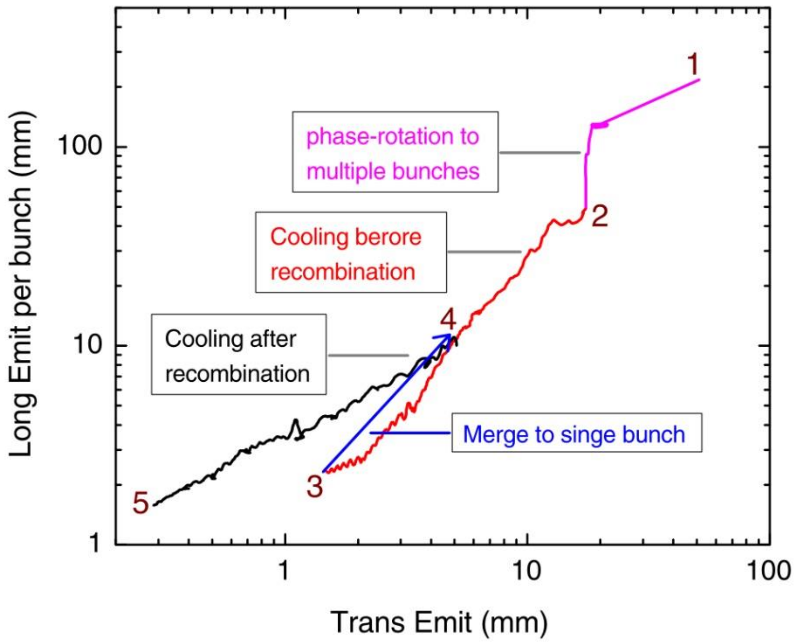


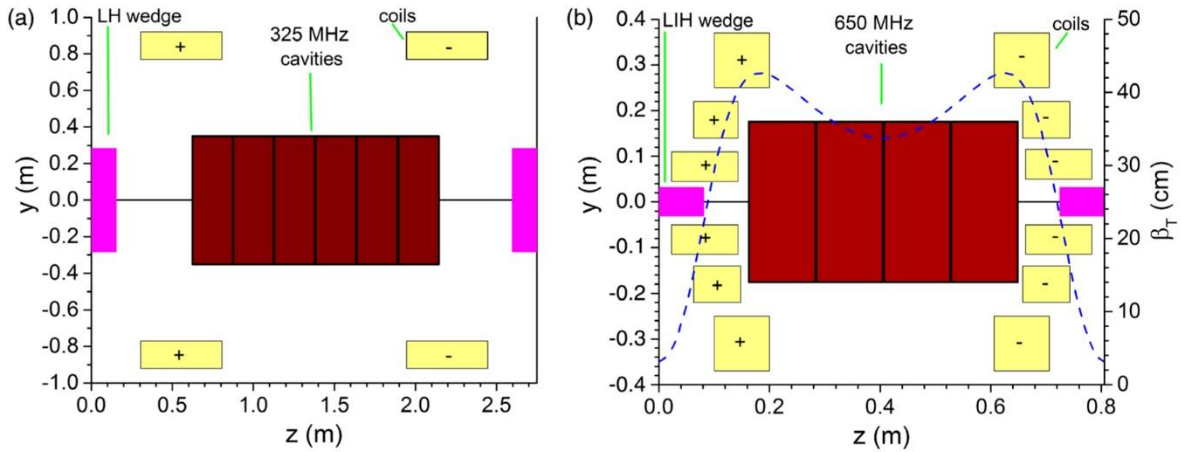


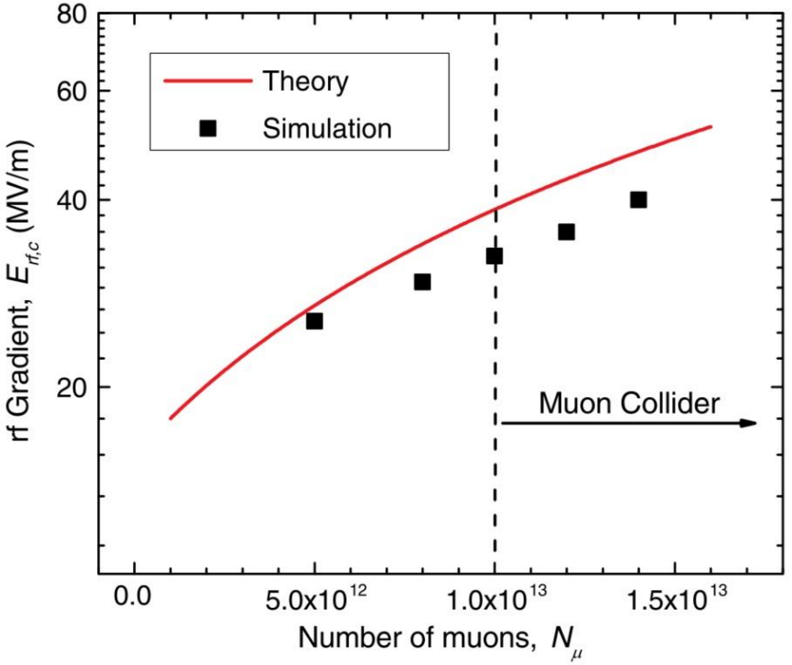


Rectilinear Cooling Channel

- Cooling channel performance simulated
  - ~500 m, 12 stages, 2 frequencies, multiple & single bunch
  - 40% transmission (with decays on), cooling performance meets specifications
- Space charge dictates RF gradient needed for goal longitudinal emittance
  - 32.5 MV/m, 15.8 T
- No comprehensive feasibility study of RF gradient, absorber type, window thickness, magnetic field
- Engineering issues not addressed





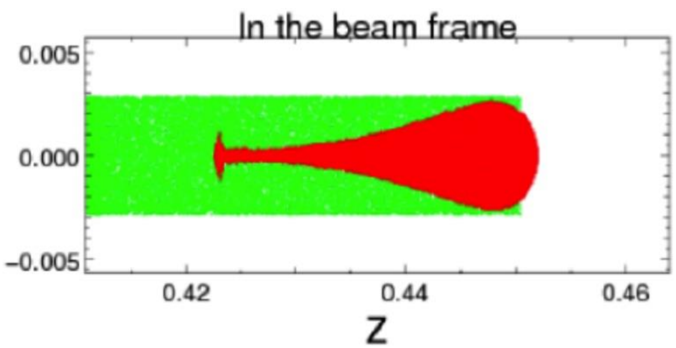


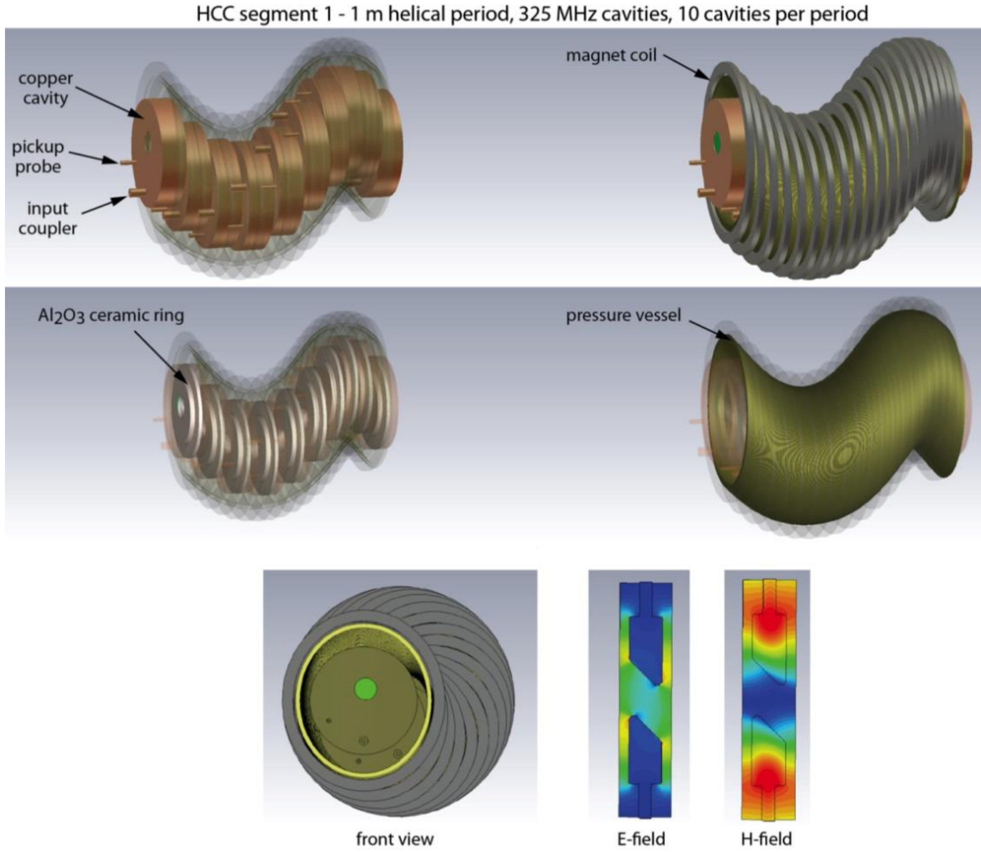
Stratakis PRSTAB 2015
Stratakis PRSTAB 2015

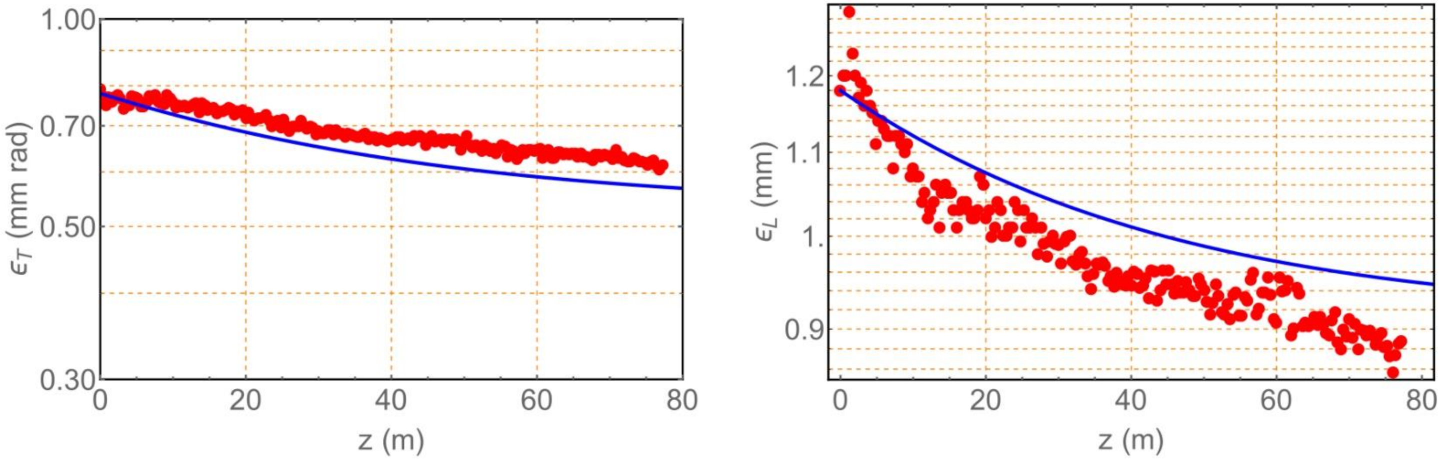
Helical Cooling Channel

[Yonehara JINST 2018](#)

- Cooling channel performance simulated
  - ~320 m, 4 stages, 2 frequencies, Be windows included
  - 58% transmission (with decays on), cooling performance nearly meets specifications
  - 20 MV/m, 11 T
- Complex magnet system
- Engineering design begun, needs development
- Plasma provides both focusing & loading
  - Comprehensive simulation does not exist

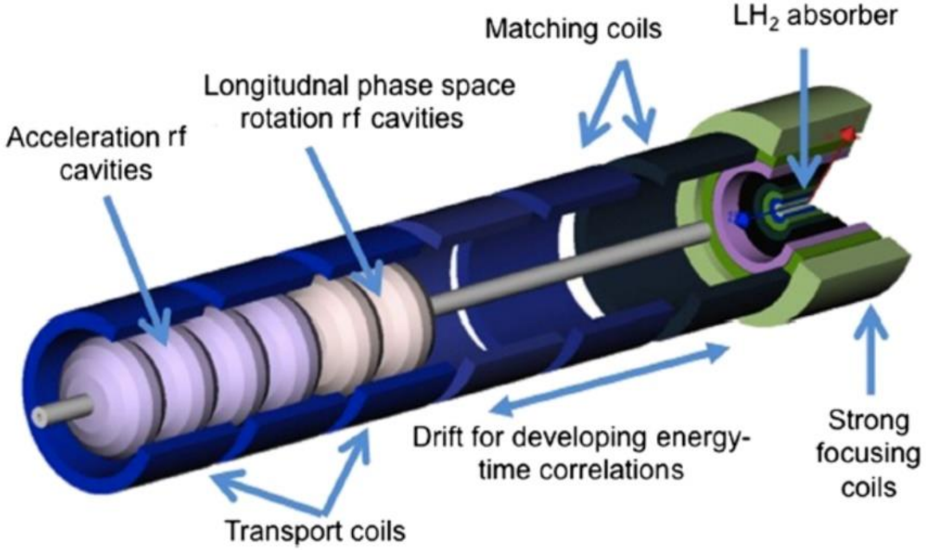


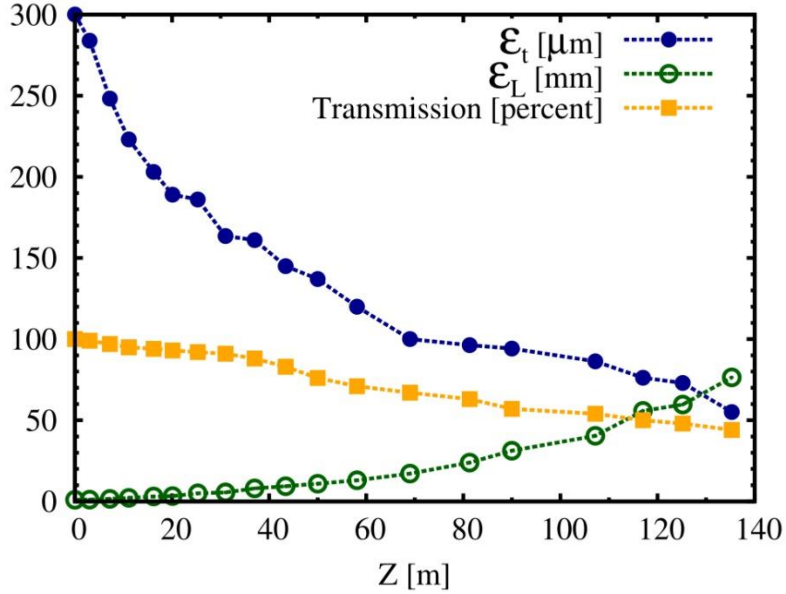




Final Cooling Channel

- Baseline utilizes low momentum muons + high field solenoids (30+T)
  - 135 m, 16 stages, RF frequencies 325 → 20 MHz, muon momentum 135 → 70 MeV/c
  - Complicated phase space manipulation required
  - Bunch length 180 cm at end of channel (5 cm at beginning)
- Transverse emittance reached 2x design goal
  - 50% particle loss

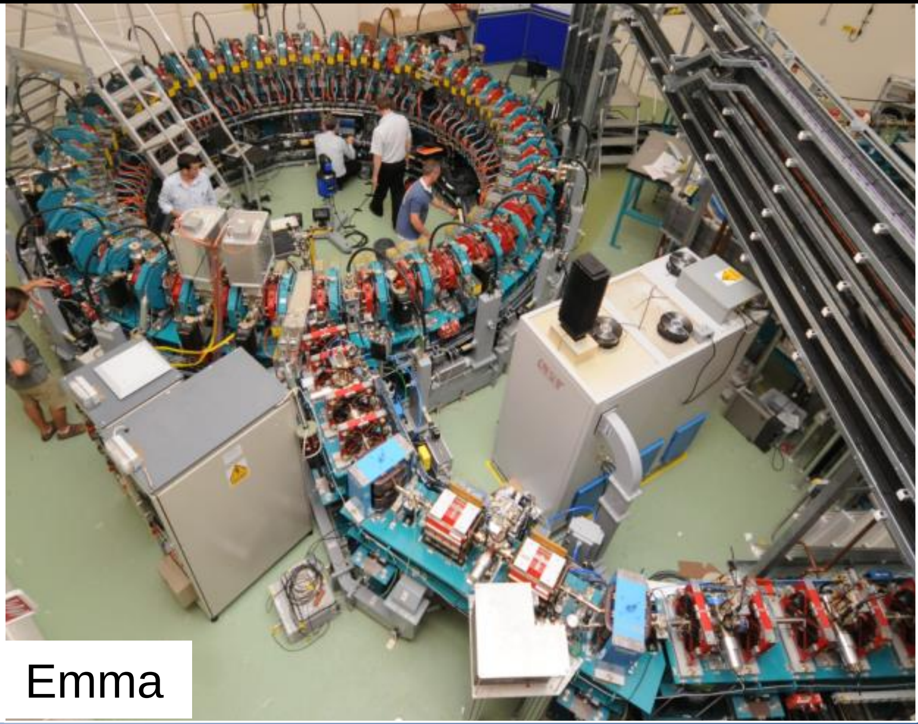




[Sayed PRSTAB 2015](#)

Acceleration Concepts

- Muon lifetime dictates fast acceleration
- Several concepts investigated
  - Higgs Factory (more developed)
    - Superconducting linacs
    - Recirculating linear accelerators (RLAs)
  - TeV scale collider (less developed)
    - Hybrid rapid cycling synchrotons (RCSs)
    - Fixed field alternating gradient rings (FFAGs)
- Fast ramping magnets largest technological challenge
  - Beam loading from large bunch charge (~10^{12}) largest RF issue



Emma

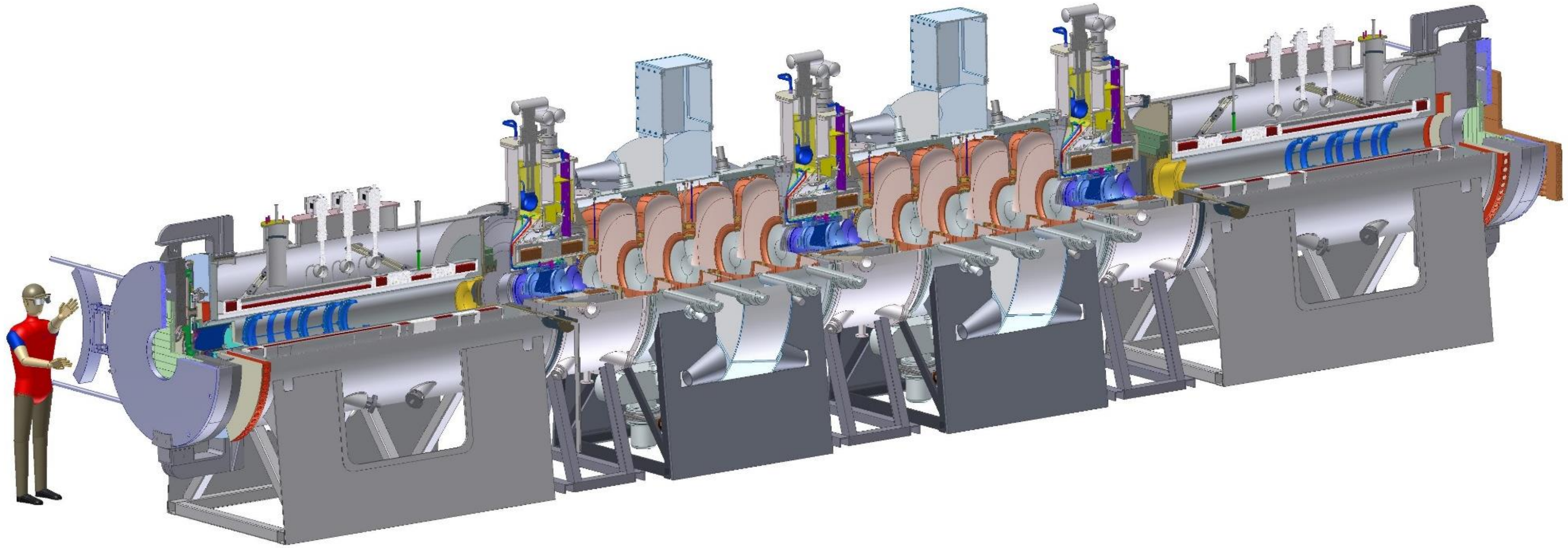
What needs to be done for Initial Cooling?

- Design:
  - Optimize cooling performance based on best RF cavity in magnetic field data (20-30 MV/m → 40-50 MV/m)
    - Larger gradient = shorter channel = fewer particle decays & cheaper construction cost
  - Realistic cavity geometry and field configuration (single cell pillboxes used so far)
    - What effect does this have on beam dynamics/cooling performance?
  - Integration of RF cavities, magnets, absorbers, plumbing, instrumentation, etc.
  - Determine RF power required
    - Estimate of rectilinear channel is about 5 MW (3.8 MW @ 325 MHz + 1.1 MW @ 650 MHz) (Hart JINST 2020)

Machine	Frequency [MHz]	No. of RF cavities	RF length [m]	No. of Kly-strons	Klystron peak [MW]	Peak power [MW]	Pulse Length [μs]	Rep Rate [Hz]	Average Power [MW]
Rectilinear [42]	325	1562	387	TBD	TBD	6814	37.2	15	3.8
Rectilinear	650	2003	250	TBD	TBD	4584	15.2	15	1.1
SLAC [52, 53]	2856	75000	2926	245	65	15925	3.5	120	6.7
LEP [54]	352	1376	585	40	0.6	24	CW	CW	24.0
LAMPF [55]	201.25			4	2.5	10	1000	120	1.2
LAMPF	805			44	1.2	52.8	1000	120	6.3

What needs to be done for Initial Cooling?

- Experimental:
  - Test RF cavities in magnetic fields >3 T
  - Demonstrate ionization cooling with reacceleration (4D cooling)
  - 6D cooling demonstration
    - Integration of RF cavities, magnets, absorbers, plumbing, instrumentation, etc.
      - MICE taught us translation from paper to reality can be challenging

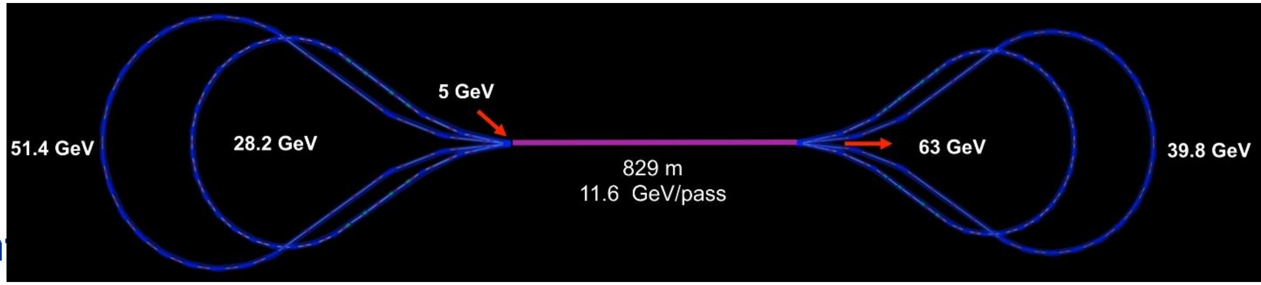


What needs to be done for Final Cooling?

- Final cooling concepts flushed out
  - Baseline complicated, could be simpler
    - Re-optimization with current magnet technology
  - Li Lens
    - 200-100 MHz RF
    - High rep. rate probably means liquid lenses
  - Bunch slicing
    - Avoids need for low momentum, low RF freq.
    - Requires complex beam transformation
  - Additional alternatives that haven’t been developed very far:
    - Parametric resonance ionization cooling
    - Thick wedge emittance exchange
    - Quadrupole based focusing
- <u>Some demonstration experiment</u>

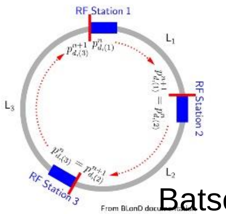
What needs to be done for Acceleration?

- Higgs Factory (126 GeV COM) – Not much
  - 5 pass RLA used for 5 → 63 GeV
    - SRF 20 MV/m @ 325 MHz & 25 MV/m @ 650 MHz
  - Beam loading only concern
- TeV Collider
  - RLAs, FFAGs, RCSs →
    - Performance/cost study
    - Beam loading & wakefield studies
      - Initial indications are that these do not harm the beam transport with only small emittance growth
  - RF power required?
- 325 & 650 MHz SRF cavities being built for several facilities (US, China, Korea, …)
  - Accelerating gradient targets of 10 & 20 MV/m
    - Limited by surface fields
  - Demonstration of 20 & 25 MV/m accelerating gradients required
    - Three 650 MHz 2-cell cavities reached >25 MV/m recently

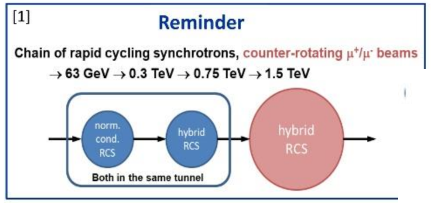


In

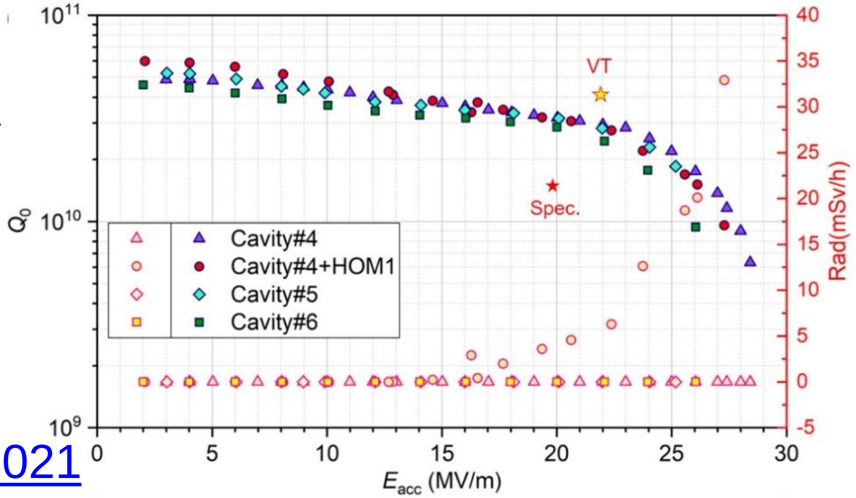
- Studies for three RCSs [1] of the high-energy accelerator chain up from 63GeV to 1.5TeV, parameters summarized below [2] and in this table
- Using the BLonD code to observe effects of the synchrotron tune and the short-range wakefields, beam loading,…
- BLonD: (Beam Longitudinal Dynamics code) macro-particle tracking code, developed at CERN from 2014 on. Links: documentation and github
- Studies with multiple RF stations along ring, 1.3 GHz TESLA cavities, 30 MV/m in cavity



Batsch,
IMCC Accel. Design Meet.



[2]		Unit	RCS-LE	RCS-ME	RCS-HE
Injection energy	E_{inj}	[GeV]	63	314	750
Ejection energy	E_{ej}	[GeV]	314	750	1500



Sha SRF2021

Possible Improvements

- Cold operation (cooling channel)
  - Higher gradient
  - Beneficial for HPRF cooling channel
  - Does RF power gained outweigh cooling power spent?
- Short RF pulses
  - Higher gradient
  - Is this only applicable to acceleration, or can it be used for cooling?
    - ~2 ns in collider ring
    - Bunch length relatively large in cooling section
- Travelling Wave SRF cavities
  - Advantages: lower peak electric & magnetic fields, higher R/Q
- Unconventional materials for cooling channel cavities
  - Be, Be-Cu, Al
    - Promising, needs more investigation
  - Dielectric loaded
    - Already investigated somewhat for HPRF cooling channel
    - How much benefit would this provide?

Concluding Remarks

- Muon accelerators are being reconsidered as a route to a 10 TeV collider
- Significant work has been done to demonstrate the feasibility of a muon collider
- Prior designs should be revisited in light of recent technological advances
- It is critical to provide convincing demonstrations of all key components
- Most promising designs should be pursued for experimental validation
  - Will require a significant monetary investment