Ionization Cooling Prototyping and Demonstrator Program

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Outline

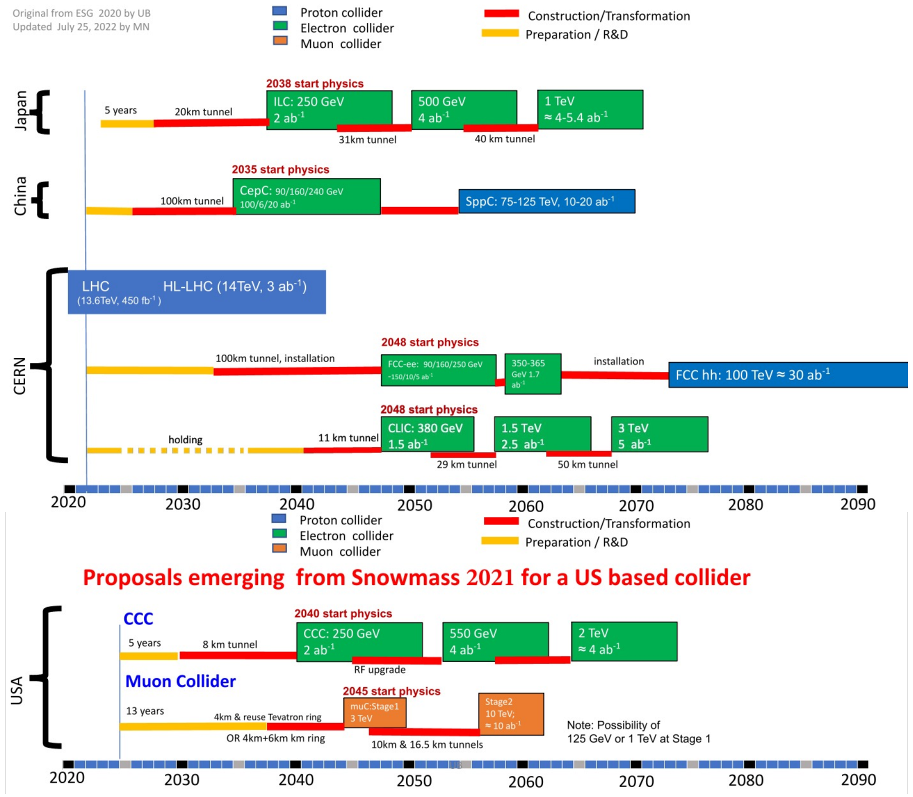
- Background: P5 and timelines
- The cooling demonstrator
- A cooling cell prototype
- Component R&D and prototyping

Muon Colliders and P5

- From the draft report:
  - "With a 10 TeV pCM muon collider at Fermilab as the long-term vision..."
  - "a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years"
  - "The US should pursue a leading role in the muon collider design effort, in concert with the International Muon Collider Collaboration (IMCC)"
- These are the boundary conditions for our ionization cooling prototyping and demonstration program

Timelines

- One aspect driving the physics motivation is that we could be doing energy frontier physics before FCC-hh (circa 2070)
- Timelines ("technically limited") talk about first muon collider physics in 2045
- This is not long. We need to
  - Prototype our most challenging components
  - Answer engineering questions to inform accelerator design
  - Finalize a machine design
  - Engineer and build/procure components
  - Build everything together into an accelerator



Narain *et al.*, arXiv:2211.11084

Cooling Demonstrator

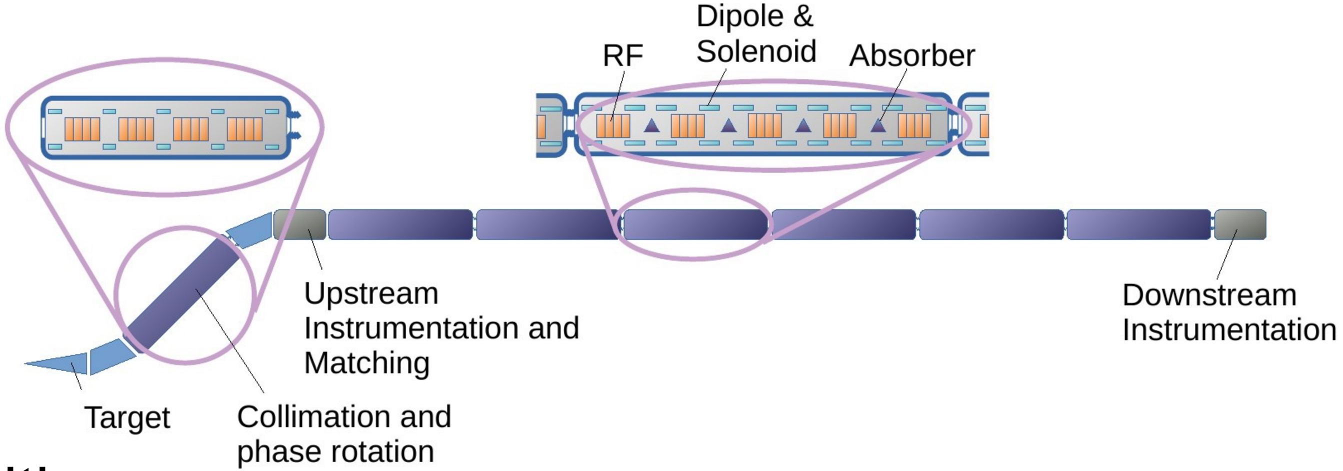
- Show significant cooling in a longer channel
  - A longer channel washes out (some) initial condition dependencies
- Face operational issues with a long string, such as
  - RF phasing & control
  - Quench protection
  - Diagnostics
- Unlikely to really see intensity-dependent effects (the most difficult effects to simulate), at least not with muons
- Build community confidence

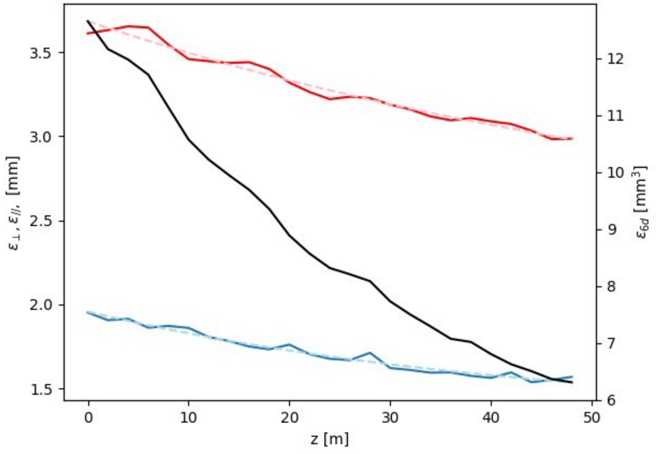
The Current IMCC Effort: MuCol WP8

- Quoting from the MuCol proposal, WP8:
  - ***The first objective*** of this workpackage is to select the technologies that are more suitable for a construction of a cooling cell that will demonstrate the feasibility of the concept including:
    - **absorbers**...
    - **Superconducting solenoids**...
    - **RadioFrequency Cavities**...
  - ***The second objective*** is to design each component of the cooling cell and integrate them in a single assembly to demonstrate that there is no showstopper for such systems.
- Note: this will likely be complete before we see significant funding

IMCC Demonstrator Layout and Lattice

- Chris Rogers proposed a demonstrator layout and a basic cooling cell to use
  - Cooling cell based on one of Diktys' cells, operating in the 2nd passband
  - 2 m cell length, 30 MV/m cavities
- Cooling performance simulated, not quite as much as I would expect
  - Close to equilibrium? Improve capture acceptance
  - Work in progress, expect to improve





Muon Beam and Diagnostics

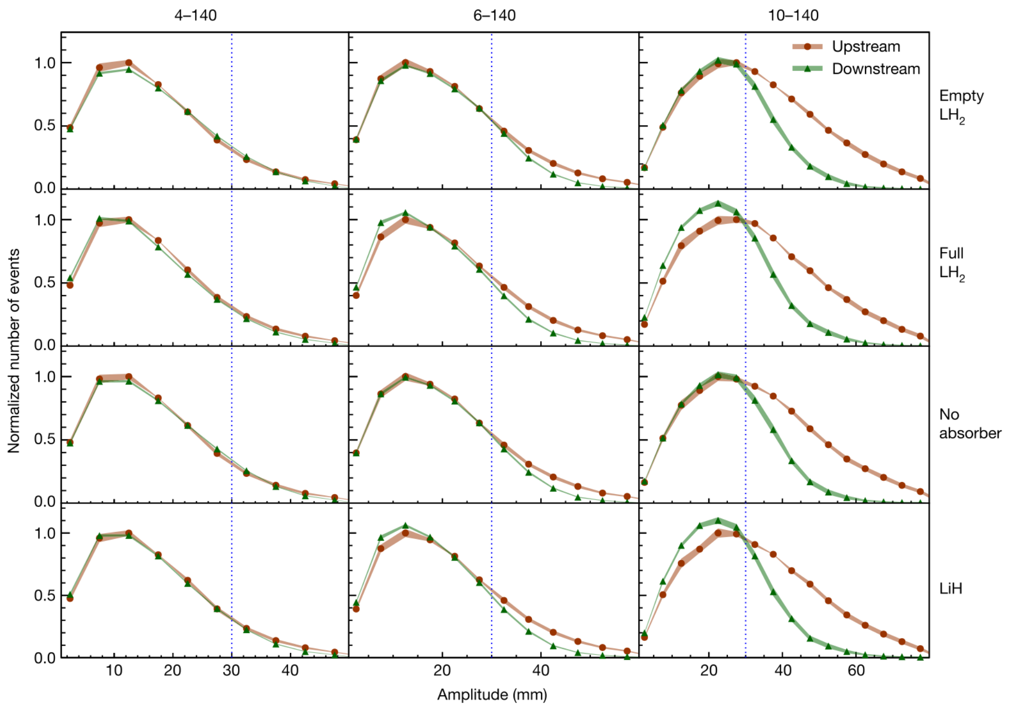
- IMCC layout currently only has diagnostics at beginning and end
- What diagnostics will we need/have in the muon collider?
  - Can we build those diagnostics into the demonstrator at intermediate locations?
- Conventional diagnostics typically want at least 10^8 particles
  - Have a proton source with target producing sufficient muons
  - Get good capture efficiency → large phase space area captured
- Solenoid (moderate field) capture and sign selection?
  - Up to 5 orders of magnitude fewer muons per pulse than collider

Cooling Prototyping and Demonstration

- A muon cooling demonstrator
  - Demonstrate significant ionization cooling
  - Requires multiple cells, each cell should have reasonable cost
  - Source will have large emittance, so should have large acceptance
  - Can (and should) achieve its purpose with easier to build cooling cells
- A cooling cell prototype
  - Design, build, and power the most challenging cooling cell
  - Should face all the challenging engineering issues
  - Convince the community (and us) that we can meet our specifications
  - Engineering design process will provide input to physics design

Demonstrating Ionization Cooling Physics

- The physics behind ionization cooling is well understood
  - Used regularly in the simulation of particle physics experiments
- The MICE experiment demonstrated that muon beam phase space density is increased by ionization cooling, and that the results are consistent with simulations
- Not critical to demonstrate that ionization cooling works



The MICE Collaboration, Nature **578**, 53 (2020)

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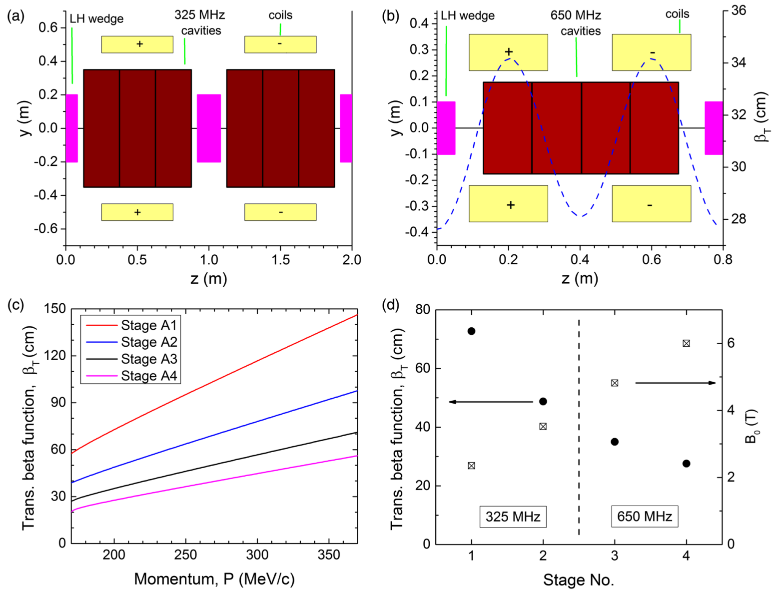
Key Requirements for Performance

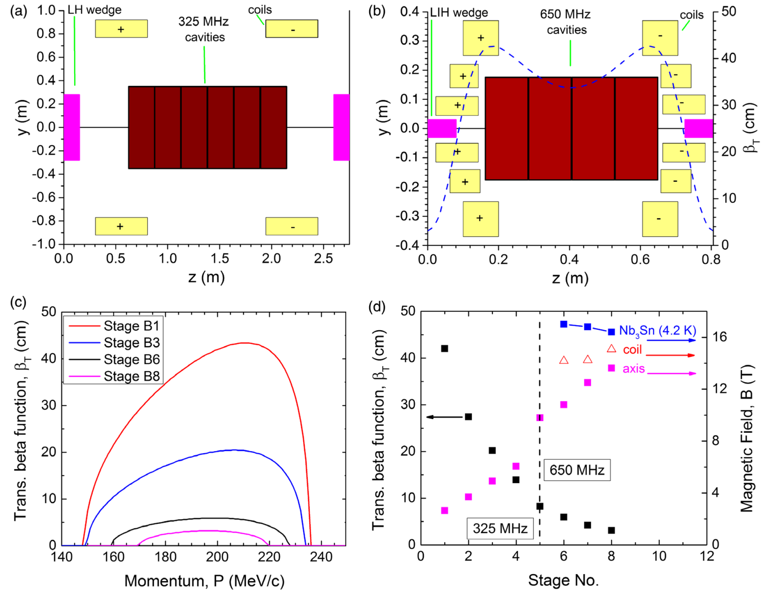
- Generate a high angular divergence at the absorber
  - High solenoid fields with rapid longitudinal variation
  - Compact cells
- High RF gradient
  - Accelerating gradient proportional to cooling rate
  - Need RF voltage to generate longitudinal focusing (bucket)
- Magnets in close proximity to RF
  - Breakdown in RF enhanced by magnetic fields
  - Force, cyrogenic management

Simulated Cooling Channel

- Simulated cooling down to ≈0.3 mm normalized trans. emittance
- Gives "physics design" of cooling channel cells
- Based on engineering input

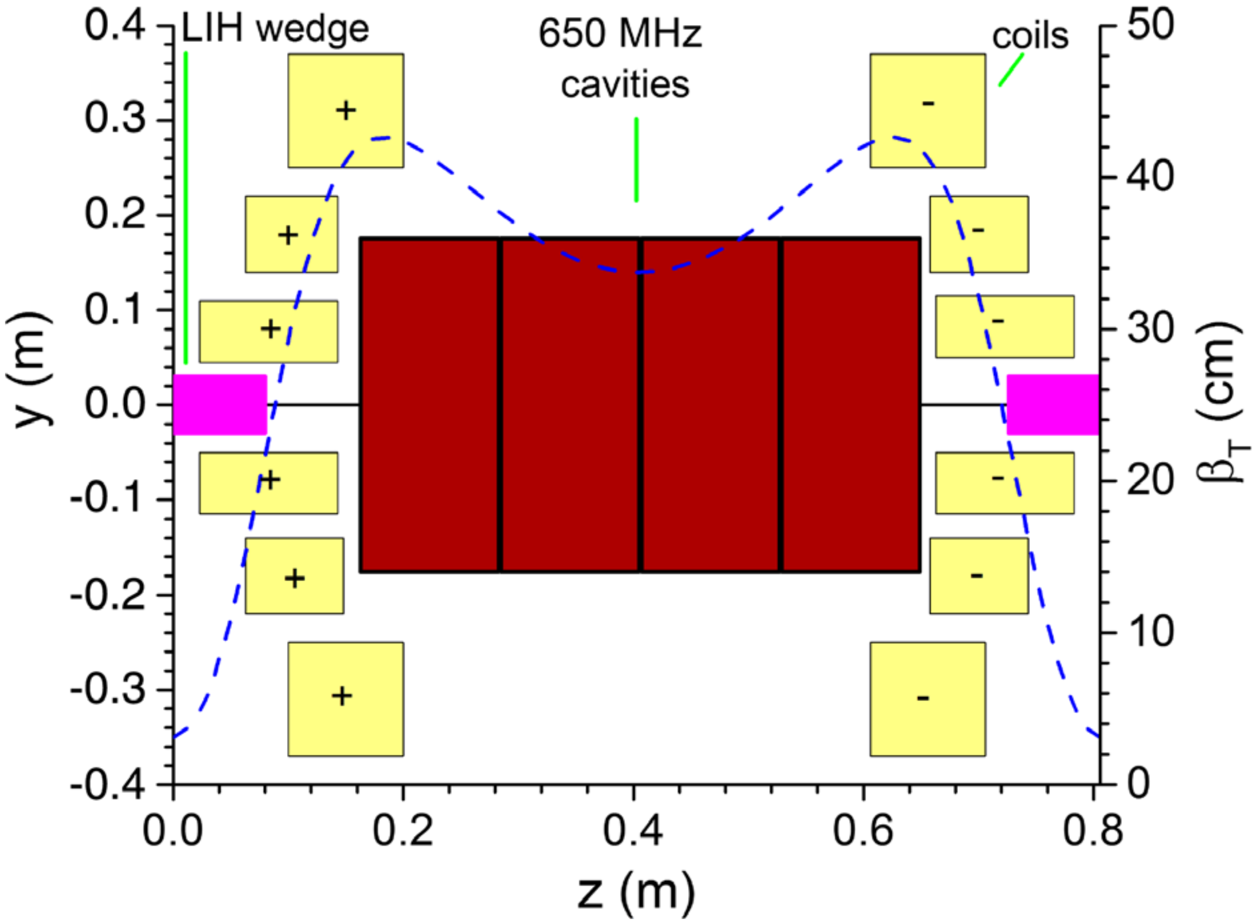


Stratakis PRSTAB 18, 031003 (2015)



Rectilinear Cell Reaching Lowest Emittance

- 6 solenoids per cell
- High solenoid fields: 15 T at coils
  - There's a dipole field too
- Superconducting coils very close to RF cavities
- 28 MV/m RF gradient
- Magnet design studied, appears reasonable (Witte 2014).



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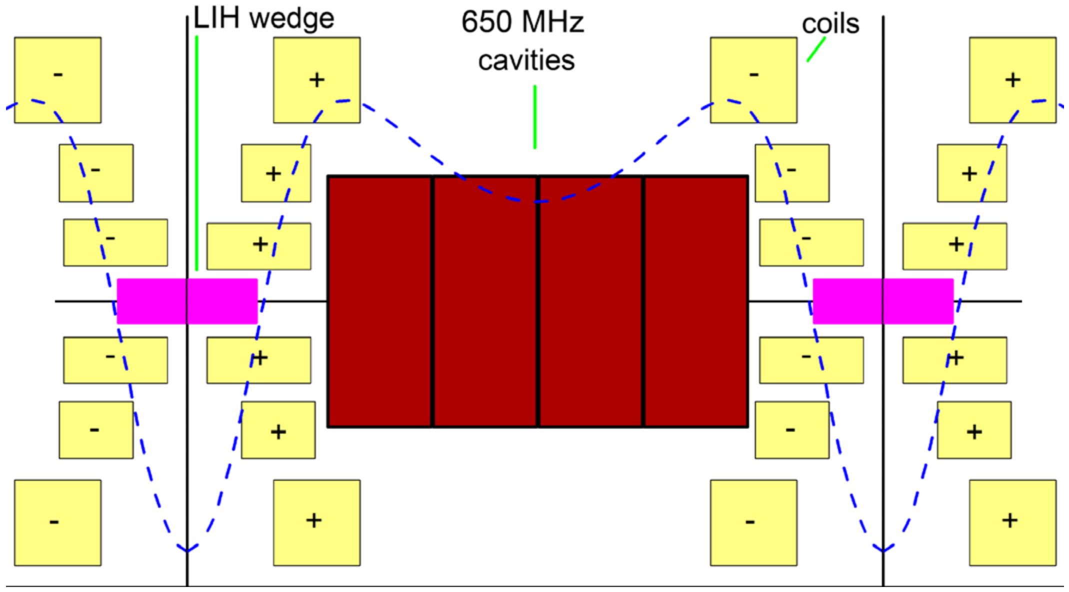
Why Prototype the most Difficult Cell?

- Want to demonstrate the hardware that will create the minimum emittance we can achieve
- Face the most challenging engineering issues
  - High field, large aperture solenoids
  - Force management within and between coils
  - Tight spacing between coils themselves and to RF
- The engineering design process will provide input to the physics design
  - Minimum spacing between components
  - Limits of magnets and design compromises needed
- Success here is the real test showing we can achieve our emittances

1.5 Cell Prototype

- 2 cells of magnets, one cell of RF
  - Magnets will see similar forces to full system
  - RF in magnetic field of full system
  - Not just solenoids: dipole component
- Magnets powered to full current
- RF powered to full voltage
  - Demonstrate required gradients in magnetic field
- Simulate beam heating of absorber?
- Vacuum, diagnostics

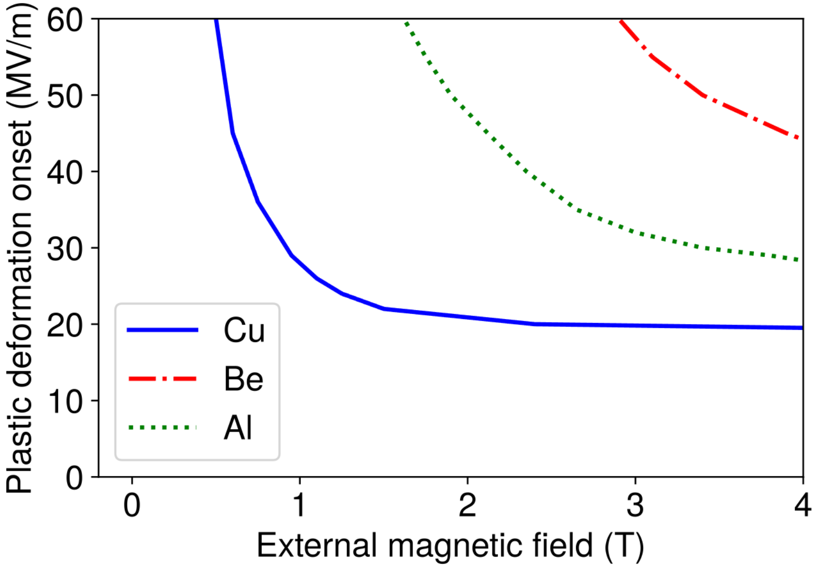


Component Prototyping

- Will require component prototyping for both cooling demonstrator and cooling cell prototype
  - Demonstrator prototyping need only be sufficient for demonstrator
  - For cooling cell prototype, should meet/determine collider requirements
- Solenoids
- RF cavities
  - Cavity designs for demonstrator/prototype
  - Continued testing of RF in magnetic fields, cavity materials
  - RF power supplies

MTA RF Gradient Demonstration

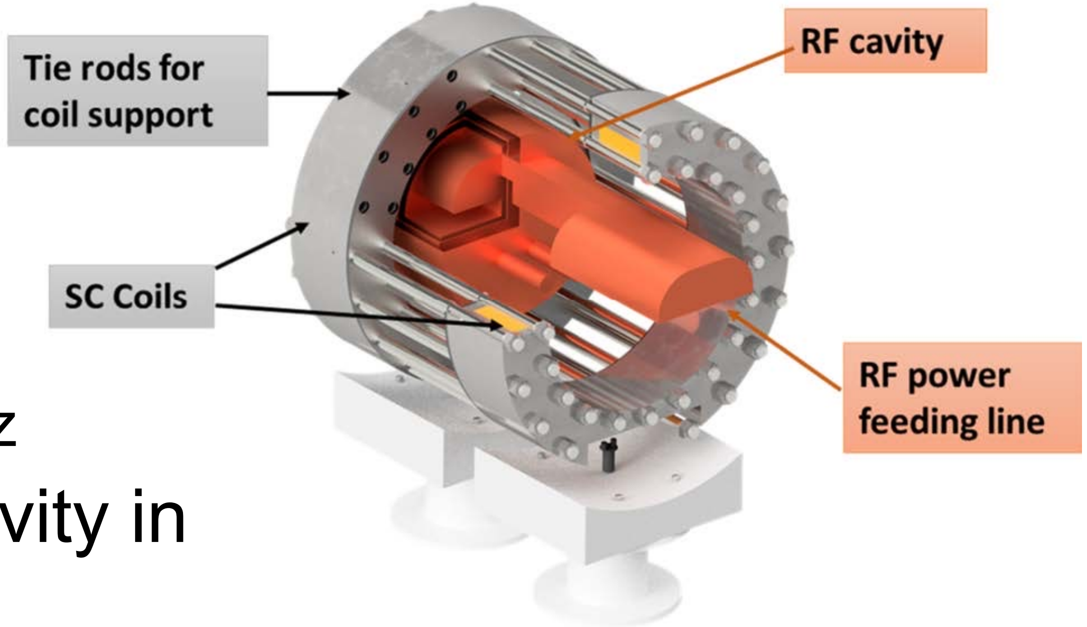
- Concern: RF cavity breakdown worse in high magnetic field
- MTA demonstrated 50 MV/m RF gradients at 800 MHz in 3 T magnetic field (Bowring 2020) with Be walls
- Safety concerns with Be
- Theory hints that Al may provide acceptable gradient
- High frequency RF studies suggest other materials
  - Hard copper alloys
  - Copper at 77 K



Bowring, PRAB **23**, 072001 (2020)

IMCC Efforts

- Initial proposals made by CEA and INFN
- CEA has some 704 MHz klystrons available
- INFN beginning a design for a 3 GHz RF in magnetic field test setup
  - With a view to later testing of 704 MHz
- Studies of powering scenario for cavity in demonstrator
  - Traveling/standing wave, pi mode or not

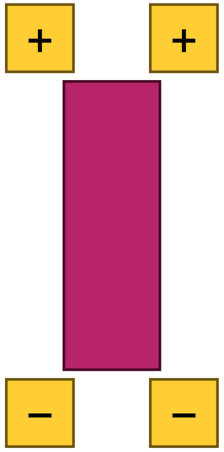


Solenoid Program

- Solenoids to be designed/prototyped for demonstrator
- First as single solenoids
- Then need to include neighboring solenoids
  - Insure with have a path for RF power
- Earliest designs for demonstrator and for RF test program
- How do we create the dipole field?
  - Tunability of dipole component is important, especially for the demonstrator
  - Layers, canted, with two opposite cantings, separate circuits?
- Cryogenics, insulation, integration with RF, quench, ...

Collider/Prototype Cavity Program

- Need to design/prototype cavity for demonstrator
  - Cavity design
  - Method to supply power (impacts cavity design)
- Continue studies of RF cavity materials and achievable gradients
  - Hints the aluminum may provide good performance
  - Other materials to study (e.g., Cu/Au alloy)
  - Copper at 77K
  - Don’t want to be limited by power source: want to determine limits
  - Cavity frequency in correct range: 650–800 MHz
- Flexible magnetic field configuration
  - Solenoid pair, independently powered
  - Use largest solenoids from cooling cell prototype design
  - High enough field to understand limits



Strawman Prototype Program

1. Components for cavity material/limitation testing, design/build
   - Cavity and power supply
   - Solenoids to supply fields
2. RF experiments, continue 1.5 cell prototype design
   - Test cavity materials, determine gradient limits: choose technology
   - Design/test remaining solenoids, engineering for all together
   - Begin to address other integration issues (vacuum, cryo, absorber...)
3. Full cavity design, RF power supply, and integration of all components for 1.5 cell prototype
4. Build it and power it up...

Summary and Last Thoughts

- There is broad interest in demonstrating a long cooling channel with beam
- A cooling cell prototype for our most challenging cell could show we can meet the engineering specifications to achieve our desired emittances
- All of these requires prototyping of individual components
- High RF gradients and magnet fields are essential for performance
  - Need to learn the limits
  - Need input for our collider design
- If we hope to even approach technically limited timescales for muon collider physics
  - Demonstrator and prototyping to test limits should occur in parallel
  - There are synergies in the component prototyping program
- We need to work together with the IMCC, need everyone we can get