Production of High-Brightness Muon Beams

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and the International Muon Collider Collaboration
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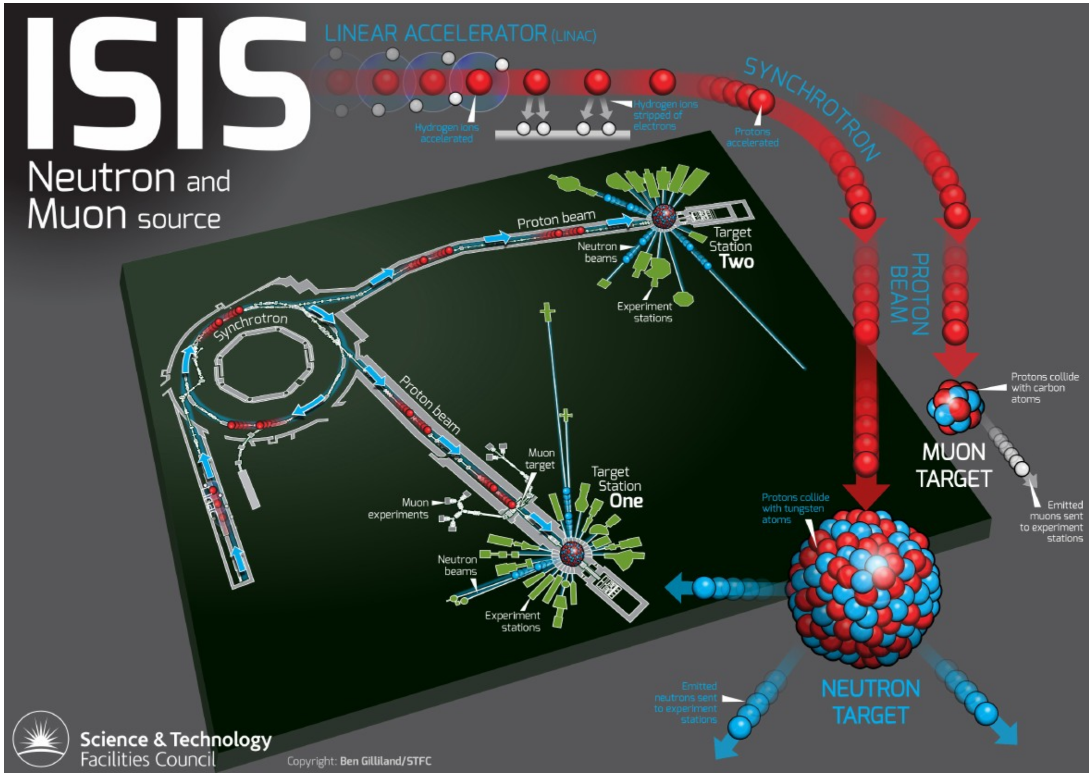
High Brightness Muon Beams

- Production of high brightness muon beams requires
  - Powerful proton source
  - Pion production and capture
  - Beam handling and cooling
- Review activities in context of:
  - Plans for ISIS upgrades
  - Plans for Muon Collider
- Focus on technology R&D aspects

ISIS

- ISIS
  - Most powerful pulsed spallation source in Europe
  - Neutrons for neutron scattering
  - Short pulse muon beams (mainly) for muSR
- Growing interest in upgrade
  - European neutron drought, even with ESS
  - MuSR lines oversubscribed



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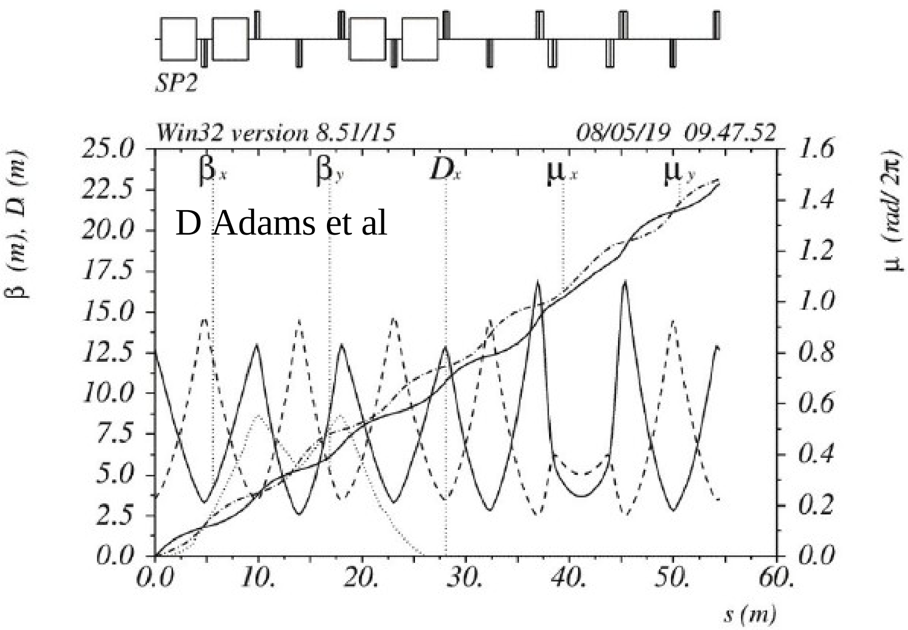
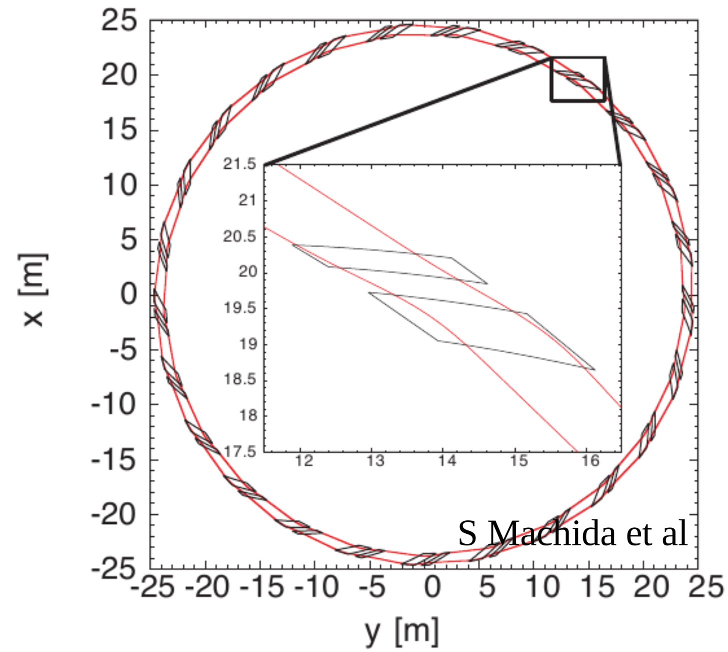
ISIS Upgrades

RCS option



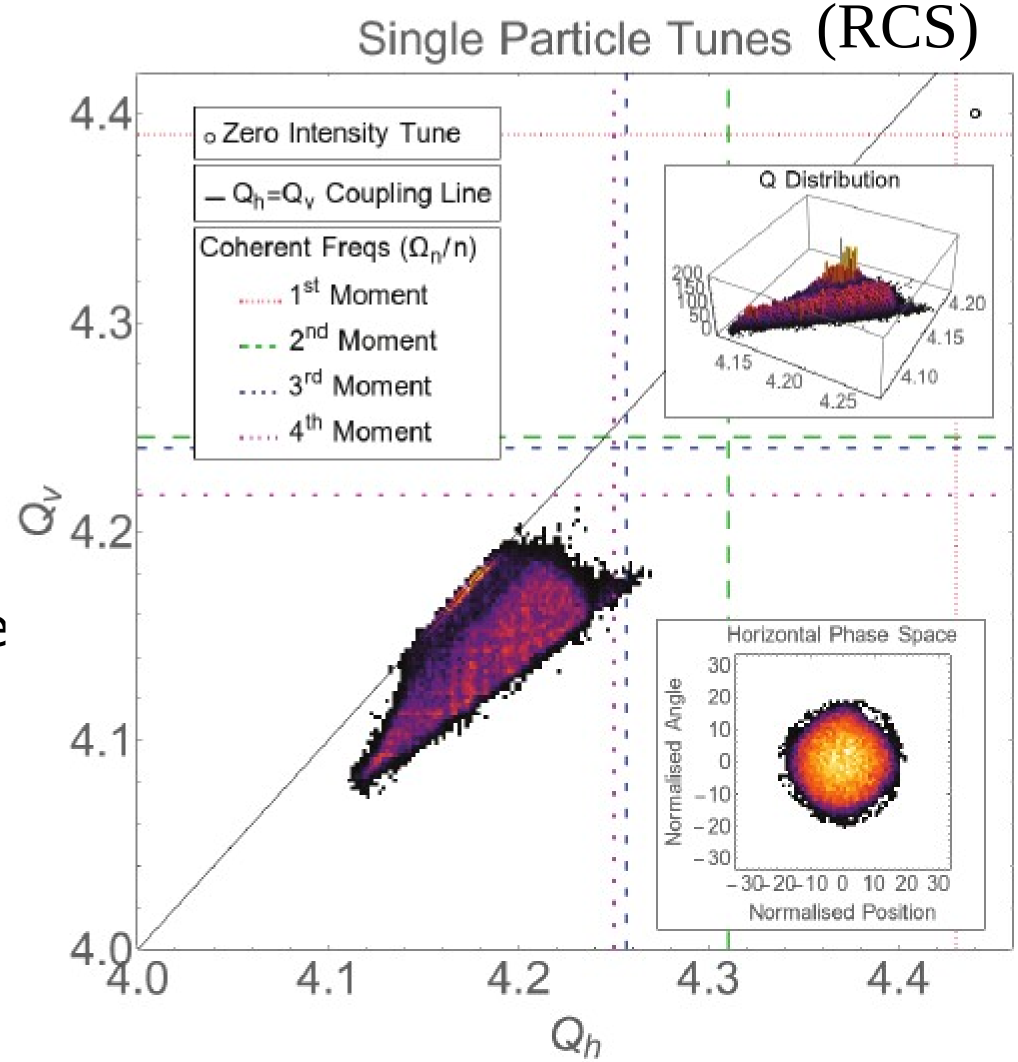
FFA option



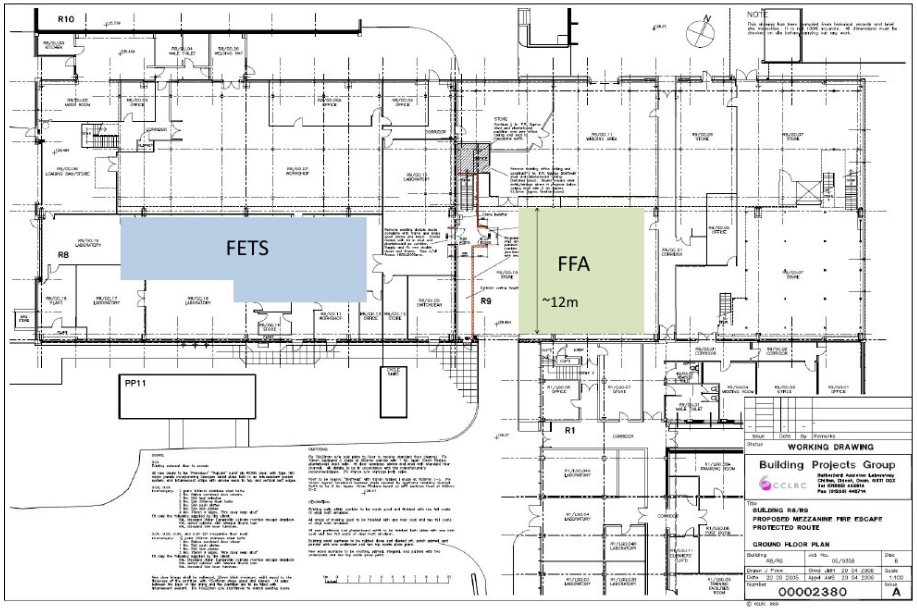
- Three possible upgrade paths under investigation
  - Rapid Cycling Synchrotron (RCS, e.g. JPARC, Fermilab)
  - Linac + accumulator ring (AR, e.g. SNS)
  - Fixed field alternating gradient accelerator
- Aim for O(MW) pulsed beams

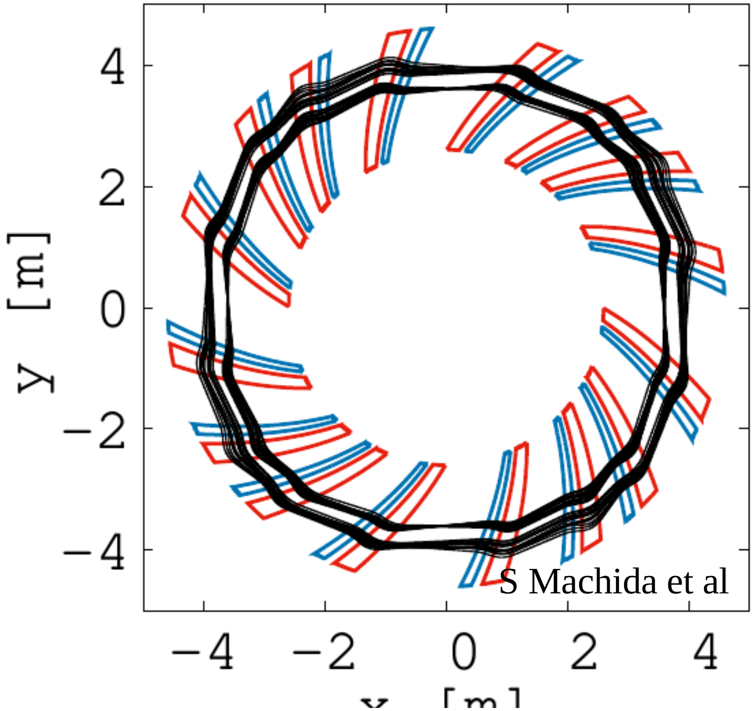
ISIS Upgrade Options

- RCS and AR attractive
- Can meet requirements
  - Injection
  - Foil heating
  - Management of space charge
- Significant wall plug power
  - Two stacked rings required
- But well-known solutions
- FFA is promising alternative
  - Likely lower power requirements
  - More versatile
  - But less well-established



ISIS Upgrades – FFA Test Ring



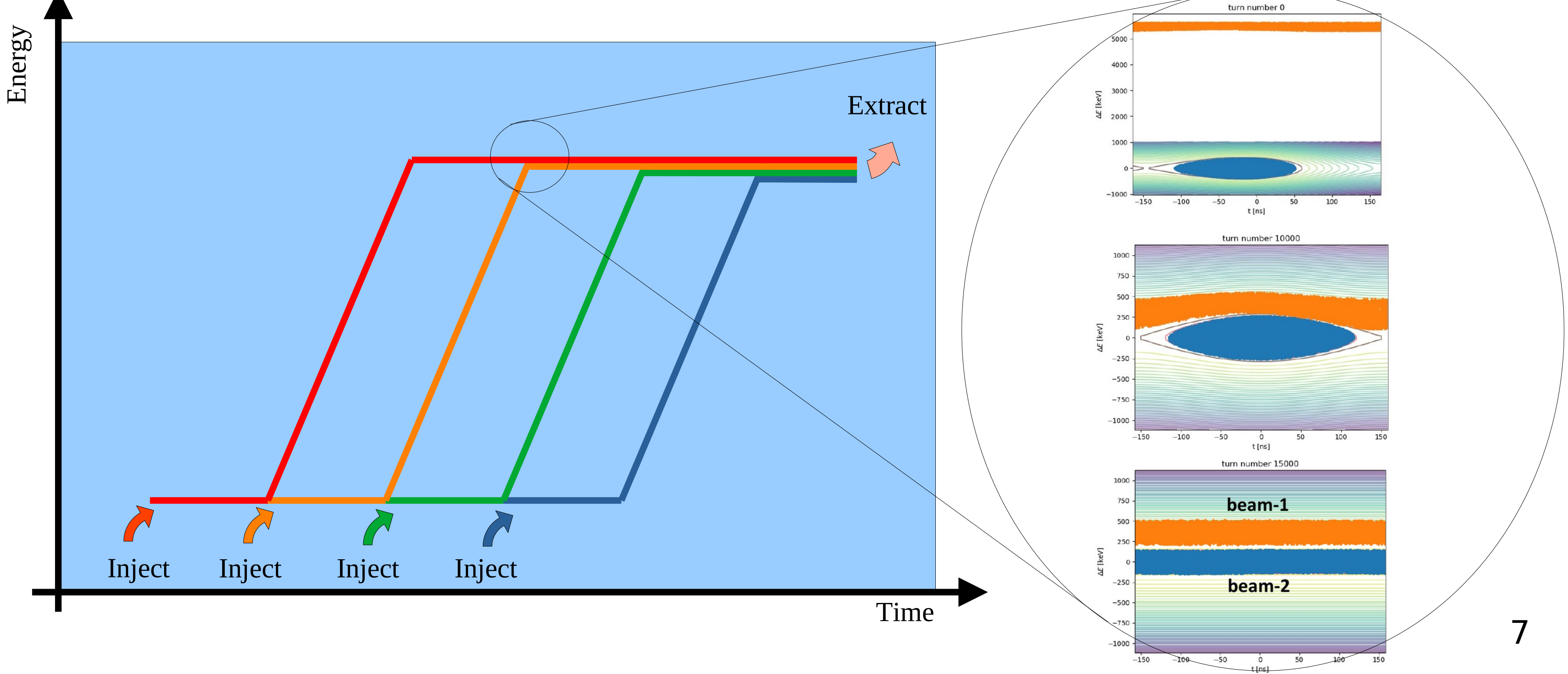


- Design effort focused on test ring
  - Demonstrate high intensity operation
  - Control of tune
  - Charge exchange injection & phase space painting
  - Longitudinal dynamics

Stacking

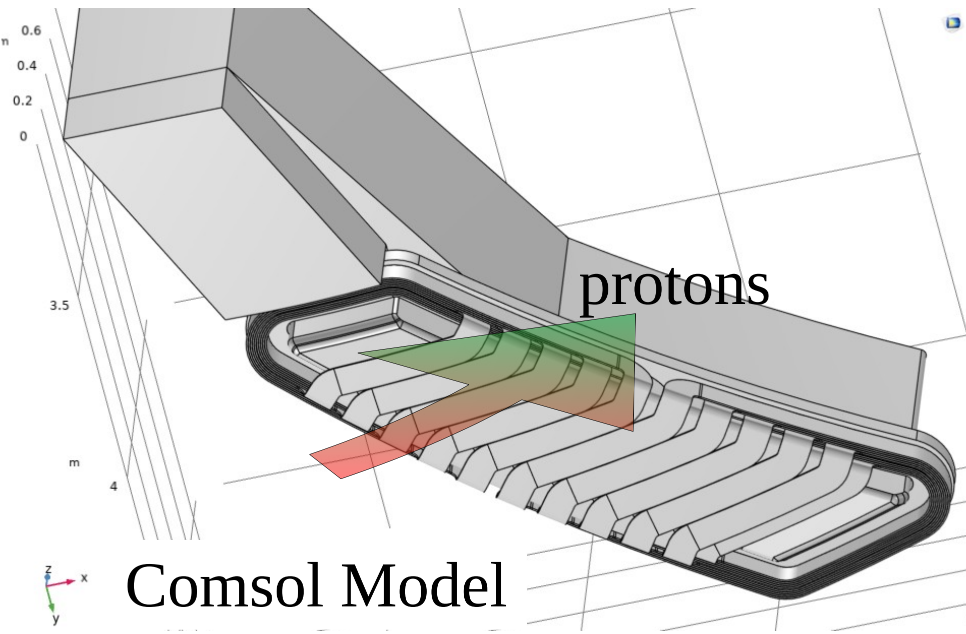
- Few fundamental limits to proton current e.g.
  - Foil heating
  - Target heating
  - **Space charge at injection**
- Inject at low energy, stack at high energy
  - → reduce drastically space charge at injection

D Kelliher

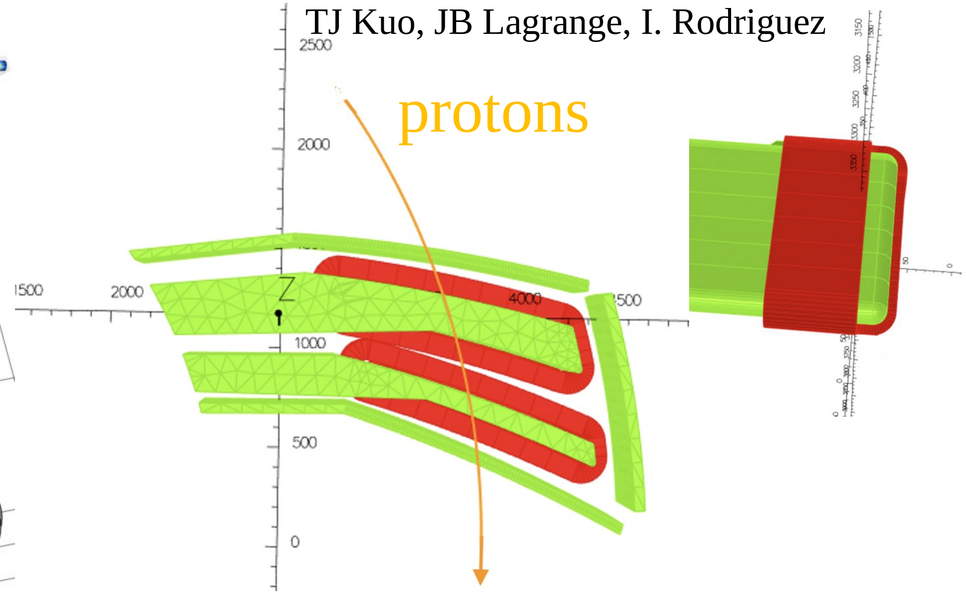


FFA Magnet modelling

TJ Kuo, JB Lagrange, I. Rodriguez



Comsol Model



Opera Model

- 3D magnet model developed
- Trims enable choice of field profile across the magnet
- Ensure correct focusing ‘k-value’ for the entire magnet
- Plan to build prototype 2025

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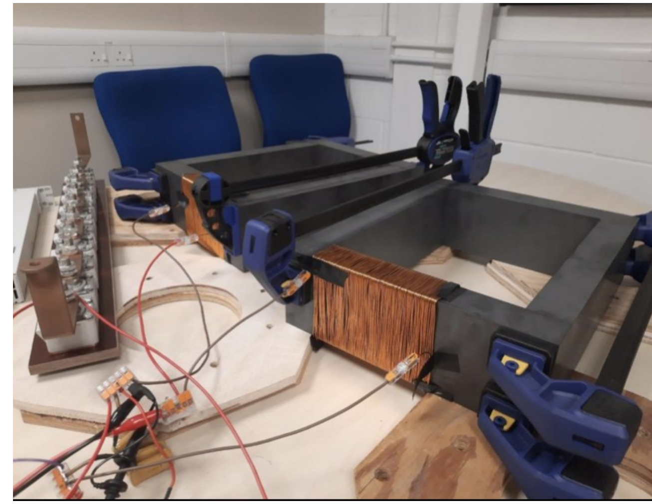
Low frequency RF

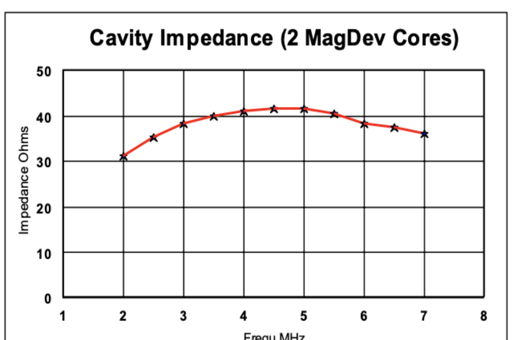
R Matthieson, I Gardner

- **Ferrite**
  - 8 4M2 blocks arrived December 2022.
  - Initial tests confirm Q~100.
  - Bias winding requires 2800 Amp turns to achieve frequency sweep.
- **MA core**
  - Initial impedance measurements of Magdev 1K107 and Hitachi FT3L cores have been made.
- High voltage tests of both Ferrite and MA underway

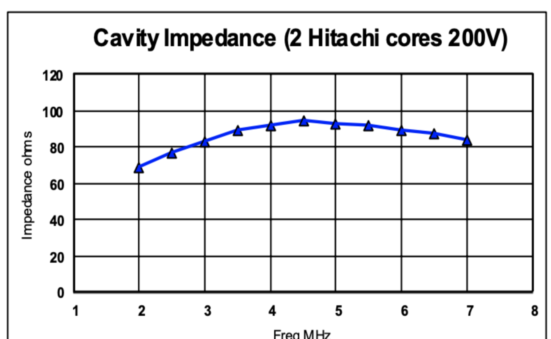


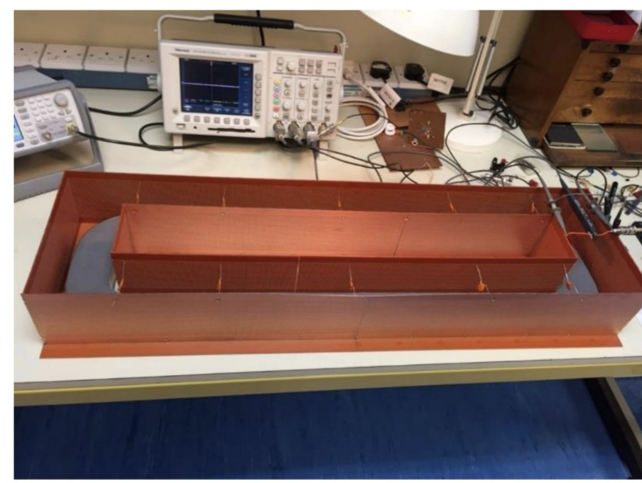
Ferrite frame

MagDev 1K107 Core Measurements



Hitachi FT3L Core Measurements

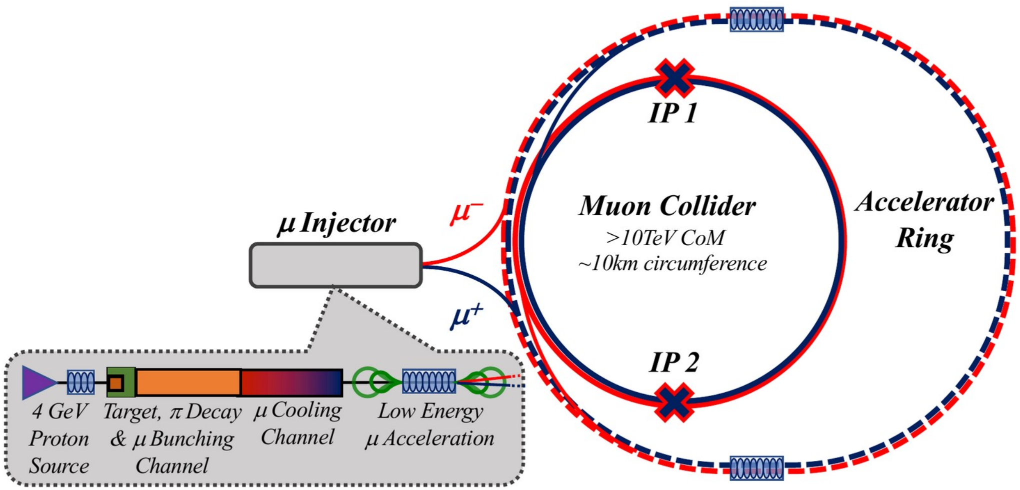




MA core

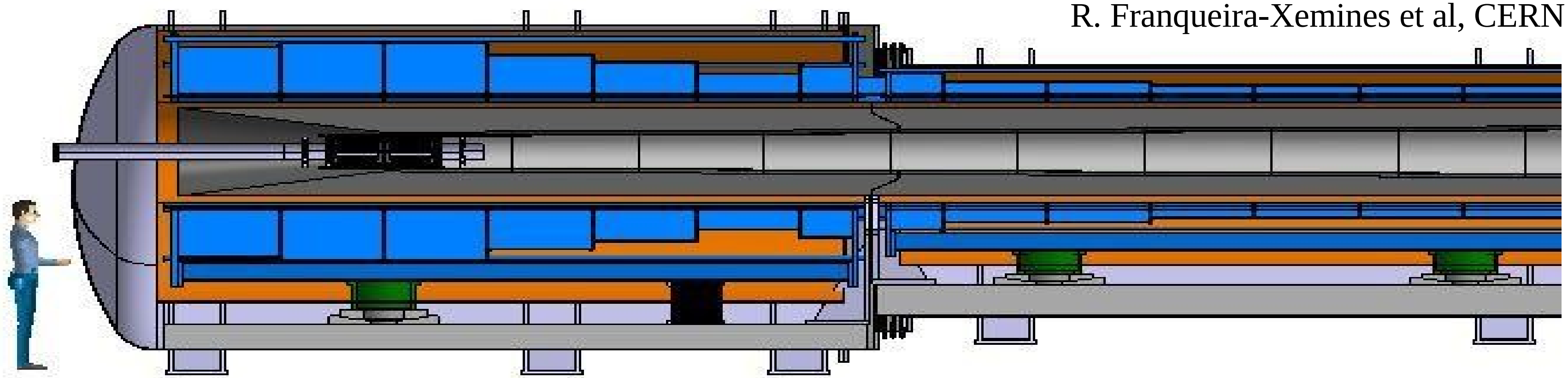
Muon Collider

- Muon collider → potential short cut to the energy frontier
  - Multi-TeV collisions in next generation facility
  - Combine precision potential of e^+e^- with discovery potential of pp
  - High-flux, TeV-scale neutrino beams for nuclear & BSM physics
  - High-flux, precision muon beams at low energy



Muons/bunch	N	10^{12}	2.2
Repetition rate	f_r	Hz	5
Beam power	P_{coll}	MW	5.3
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25

MuC Target

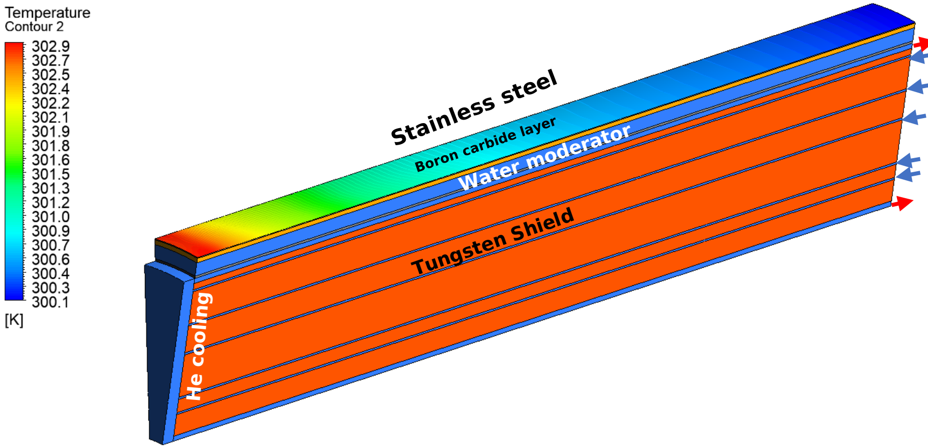


R. Franqueira-Xemines et al, CERN

- Protons on target → pions → muons
  - Graphite target takes proton beam to produce pions
    - Back up options under investigation
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Challenge: Solid target and windows lifetime
- Challenge: Energy deposition and shielding of solenoid

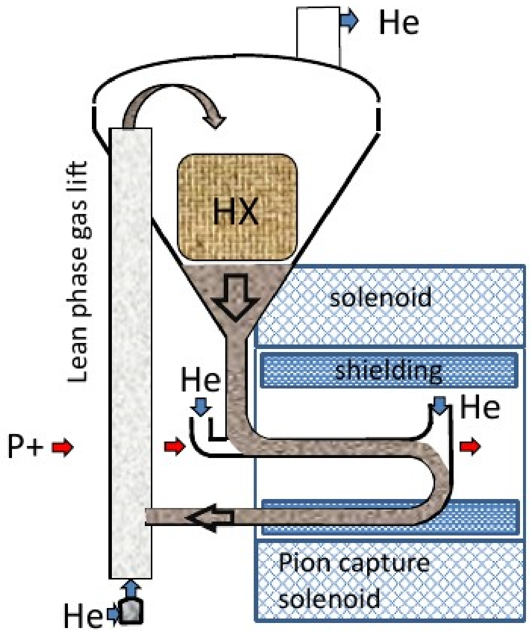
Magnet options

- Investigating force-flow cooled HTS cable
  - Operation at 20 K → more efficient cryo plant
  - Smaller footprint and stored energy than LTS
- Also strong synergy with
  - Fusion
  - UHF Magnets for science
- Radiation hardness under study

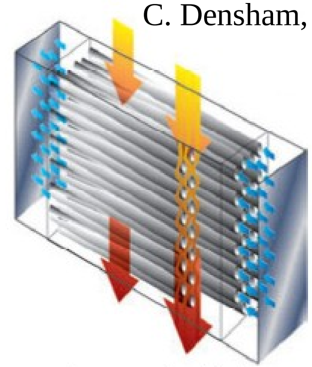


Fluidised Tungsten Target

International MUON Collider Collaboration



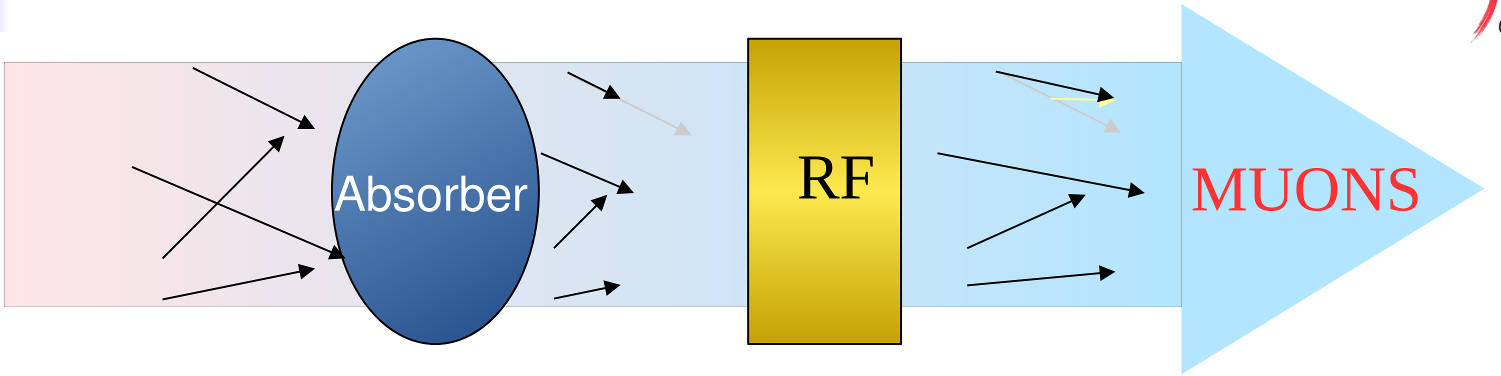
C. Densham, STFC



Example gravity fed granular flow heat exchanger

- Looking at fluidised Tungsten bed as possible target material
  - Alleviates many of the challenges surrounding fixed targets
  - Promising also as a neutron spallation target

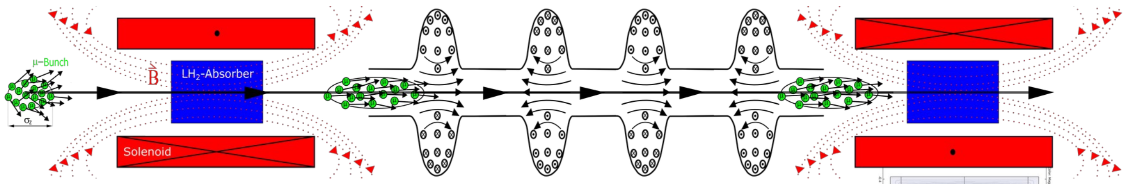
Ionisation Cooling

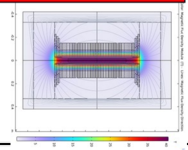


- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more parallel
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing → low β
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS cancels the cooling
- Verified by the Muon Ionisation Cooling Experiment (MICE)

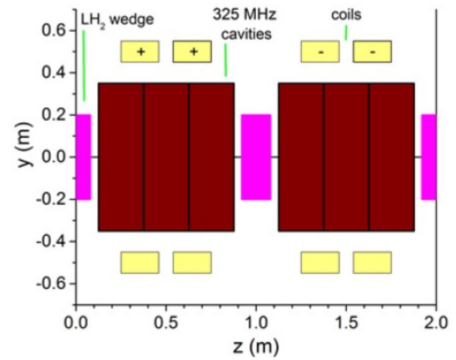
Muon Cooling

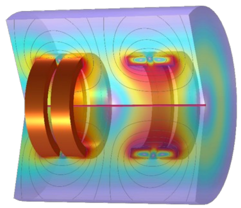
Fol et al



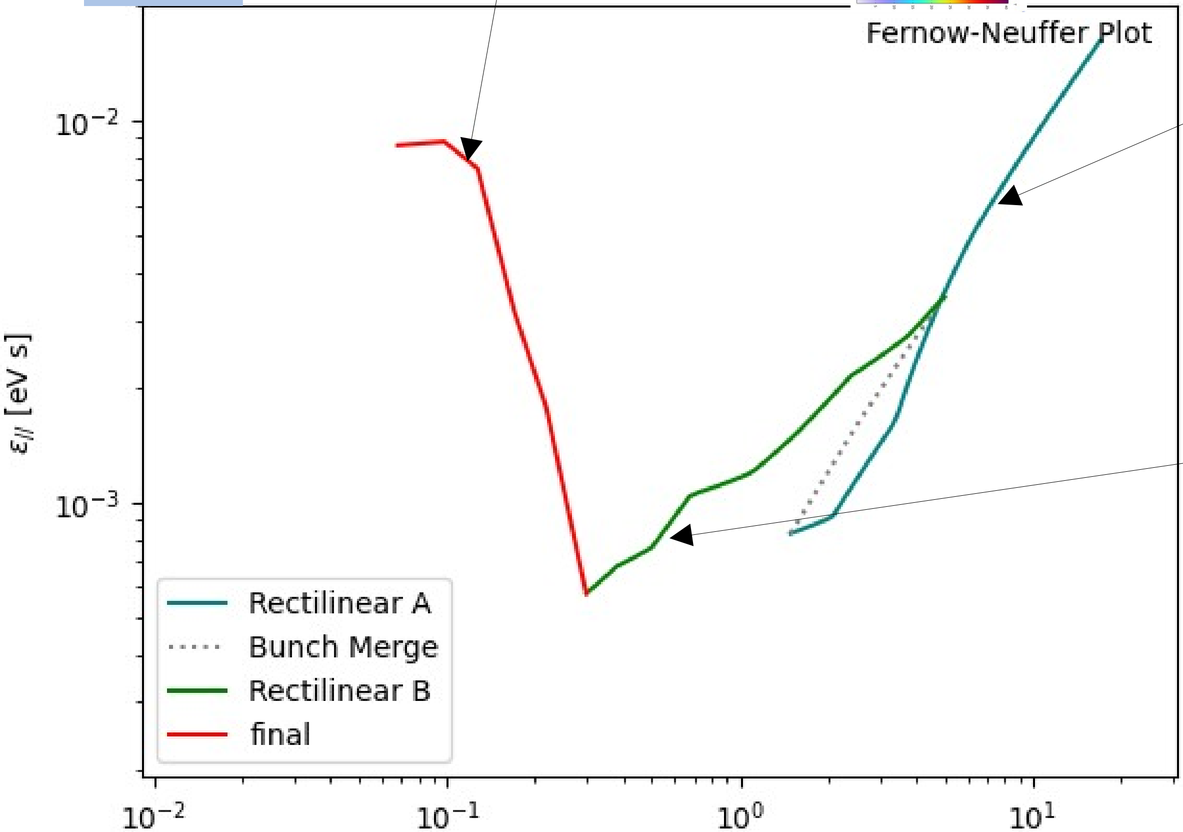


4D Final cooling

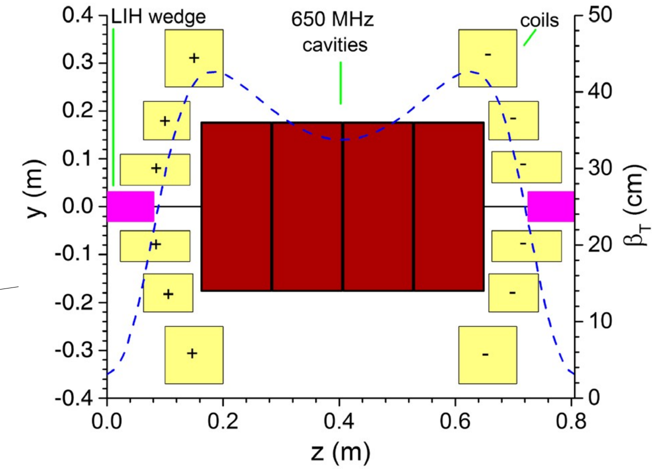


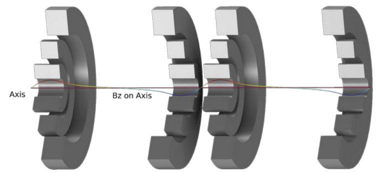


Rectilinear cooling

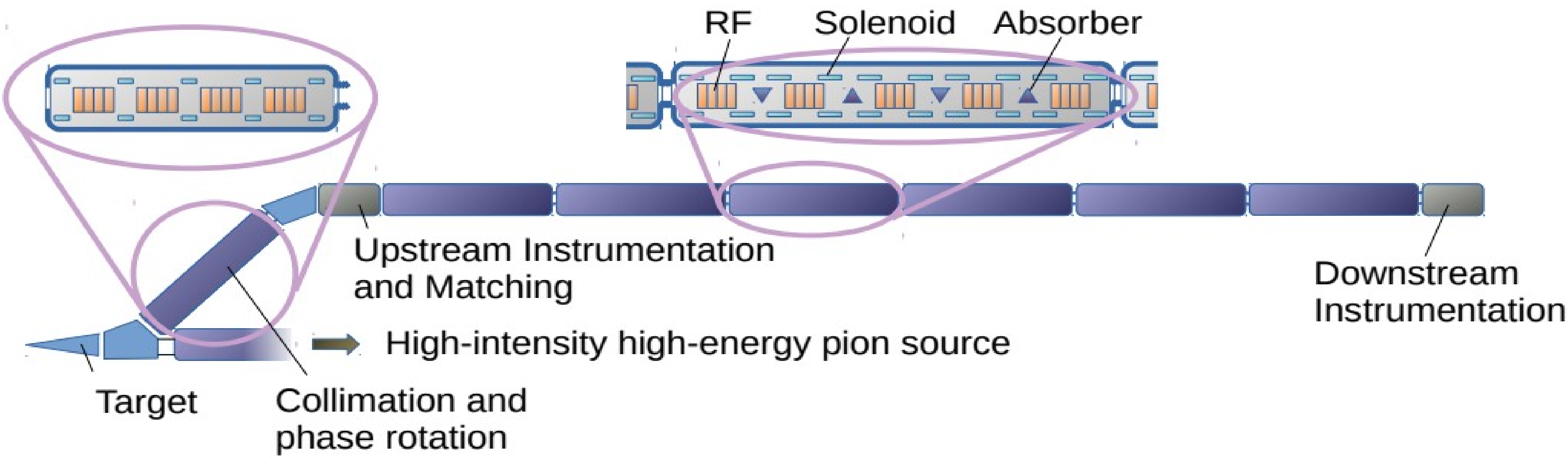


Stratakis et al

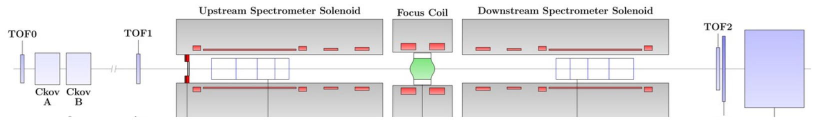


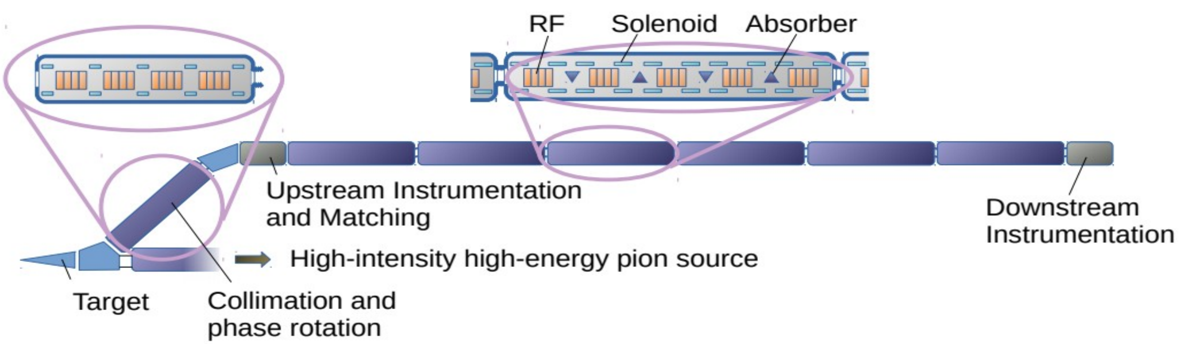


Cooling Demonstrator



Comparison with Existing Data





	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

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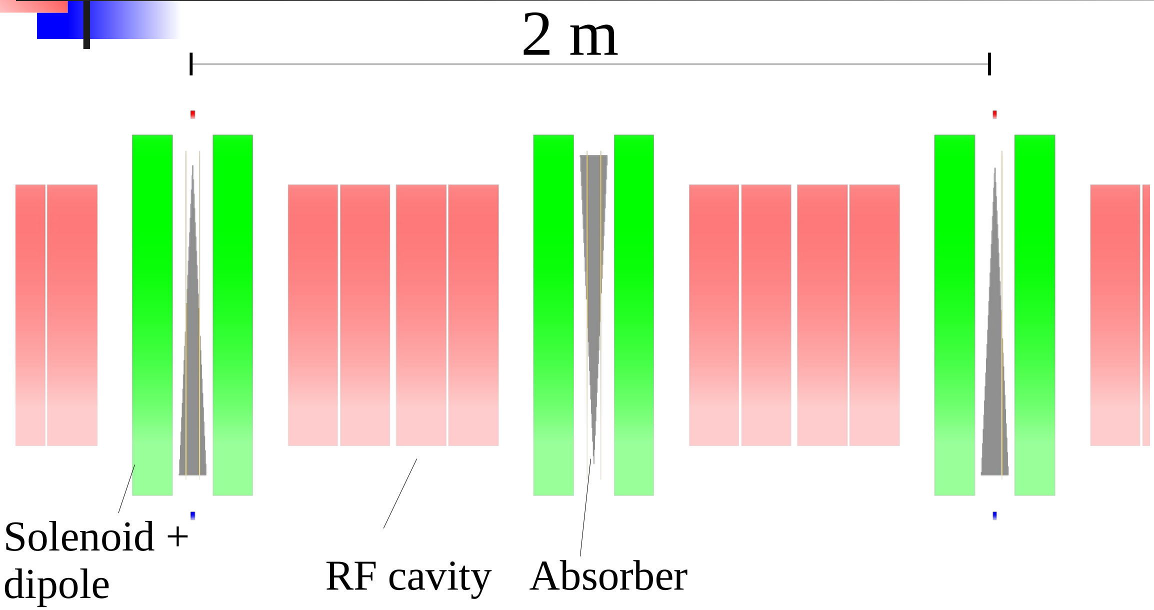
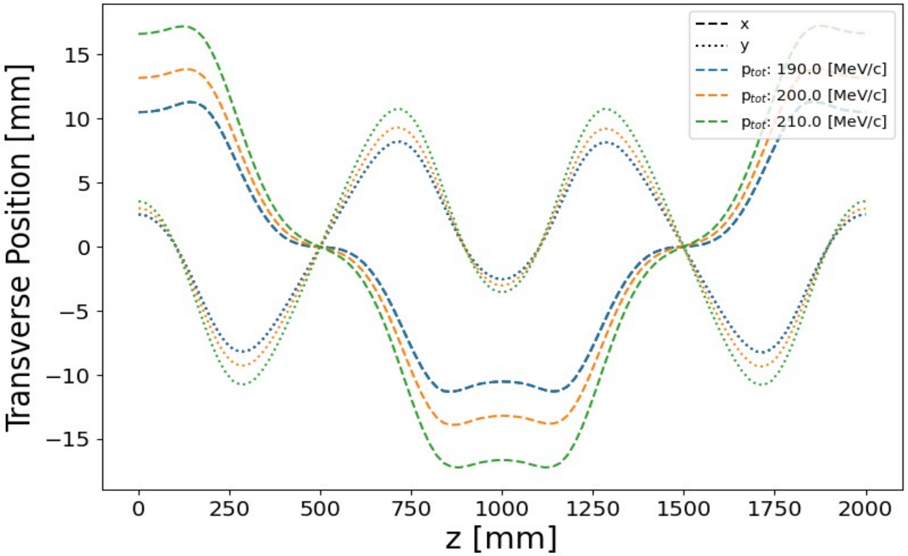
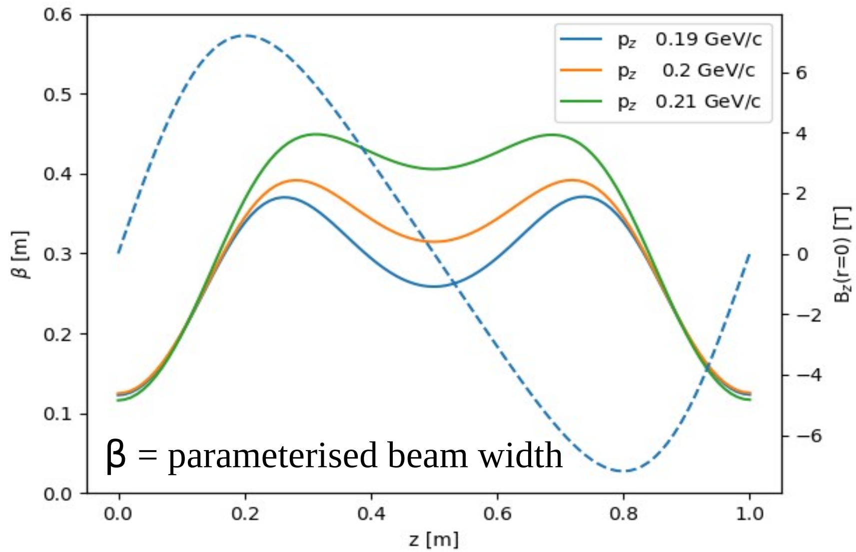
Preliminary Cooling Cell Concept

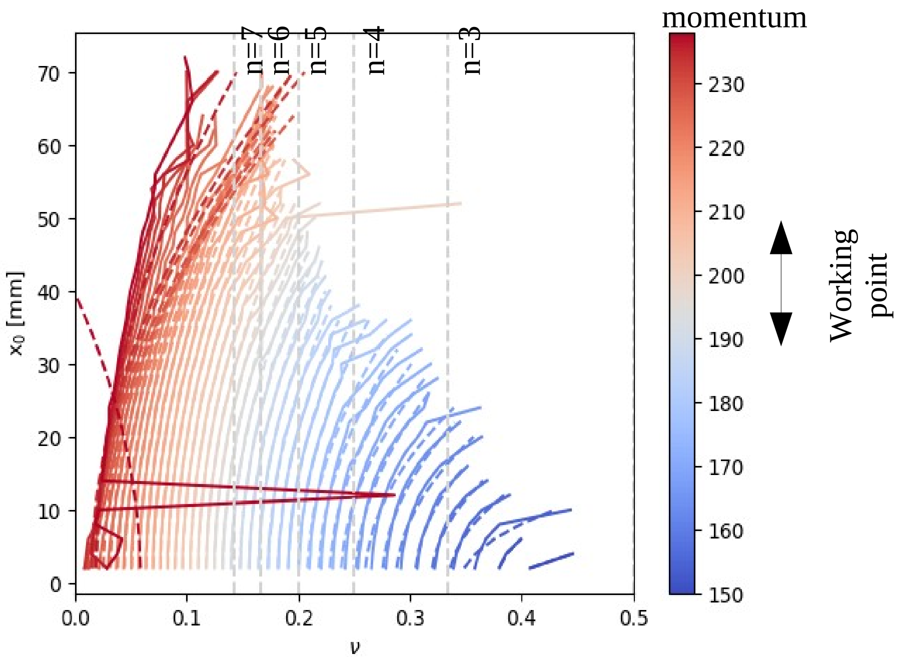


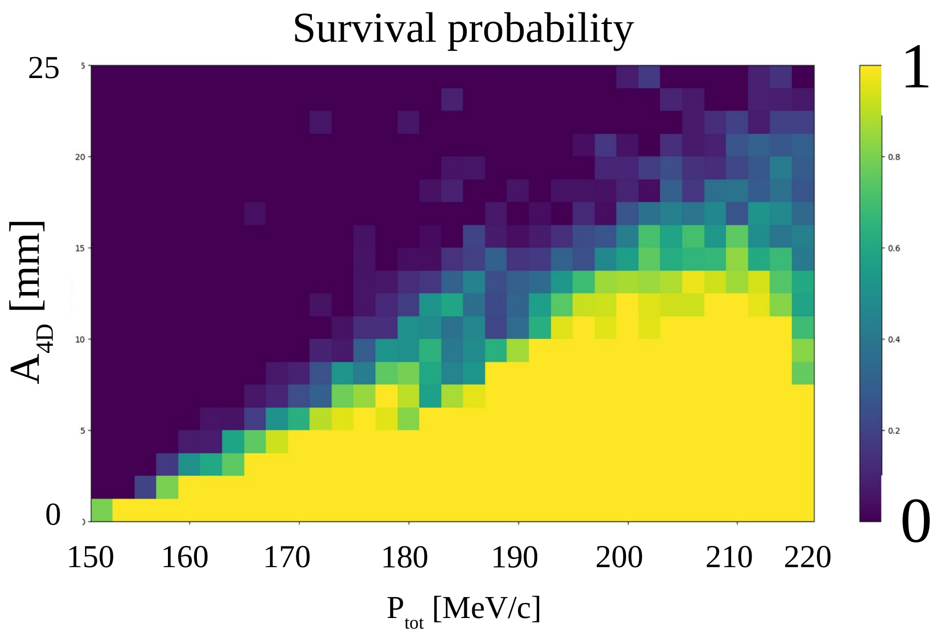
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH





Optics vs momentum





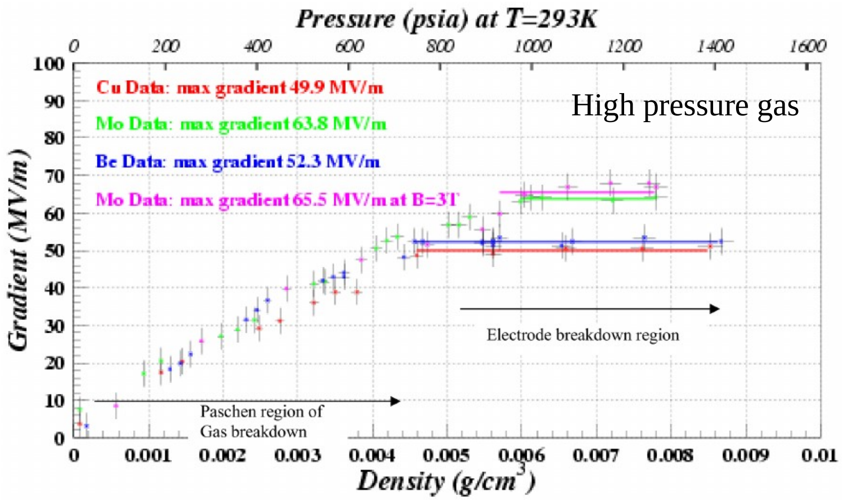
- Acceptance driven by tune consideration
  - Tune = number of focusing oscillations per magnetic cell
  - Acceptance for tune near to resonances

Integration issue: RF

- B-fields reduce RF Safe Operating Gradient (SOG)
  - e^- emitted from copper
  - B-field focuses on far wall
  - Induces sparks
- Muon cooling needs high RF gradient + B-field
- Two routes demonstrated
  - Either: Beryllium window resistant to damage
  - Or: High-pressure gas absorbs spark
- Other ideas
  - Operate at lN2 temperature
  - Short RF pulse to limit heating

Window material	B-field (T)	SOG (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$
Be/Cu	0	43.9 ± 0.5
Be/Cu	3	10.1 ± 0.1

Bowring et al



Yonehara et al

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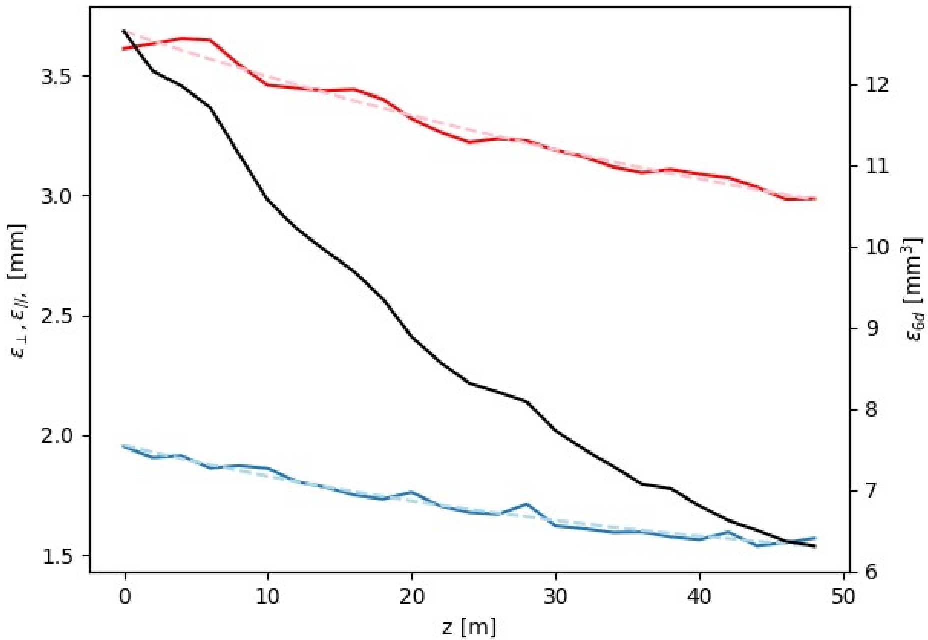
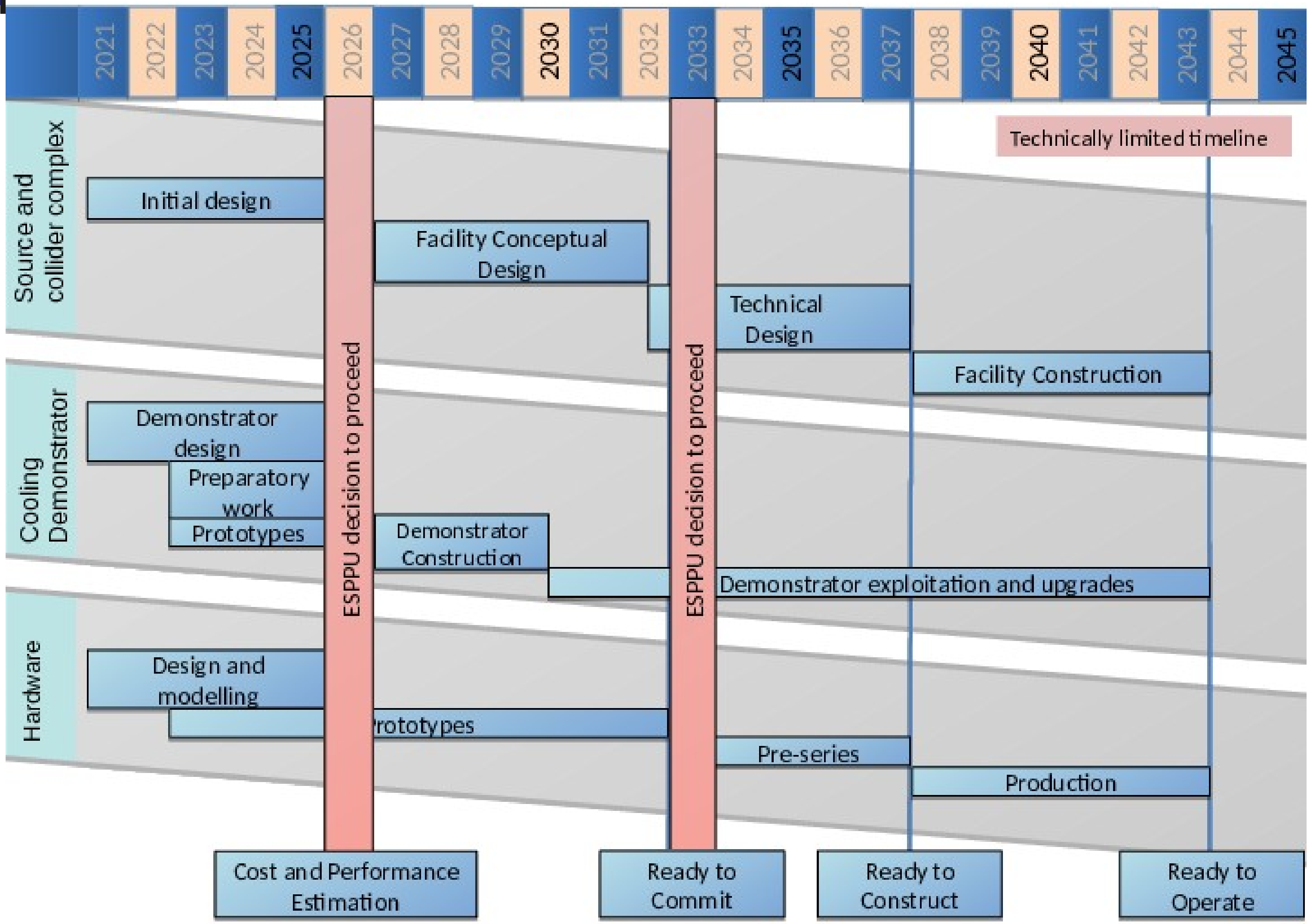
Be RF & LiH Performance

- Use Beryllium for RF cavity walls
- Use LiH in absorber
- Good cooling performance
  - Transverse and longitudinal emittance reduced by ~ 20 %
  - Approx factor two reduction in 6D emittance
- Optimisation ongoing
  - Assumes perfect matching for now
  - Assume LiH for now
    - Liquid Hydrogen performance likely better



Transmission losses	2.00%
Decay losses	4.00%
Trans ε in	1.95 mm
Trans ε out	1.57 mm
Long ε in	3.61 mm
Long ε out	2.99 mm
6D ε in	12.7 mm^3
6D ε out	6.3 mm^3

Timeline



- **Assumes full effort of major lab e.g. CERN, Fermilab**

Outlook

- Very exciting time for high brightness muon beam R&D
- Too much material to cover!
  - High power protons, including FFA R&D
  - Pion and muon production targets
  - Muon cooling studies
- Look forwards to further collaborations with US