



Siting Overview: US/Fermilab

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- Diktys Stratakis
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US/Fermilab Siting

The particularities of Fermilab's infrastructure for muon collider.

- "Site-filler" Muon RCS (~15.5km circle).
- Re-use of the Tevatron tunnel (6.28km circle).
- Synergistic neutrino program (1300km baseline from DUNE).
- Experience & Infrastructure in Intensity & Energy Frontier accelerators.

I want to distinguish this from a couple related topics:

- Scenarios developed for Fermilab, but are universally applicable.
 - including legacy effects (8-GeV ring, 53 MHz RF, 1.3 GHz RF, CW linac).
- Fermilab-sited muon collider R&D projects.
 - Proposed muon ionization cooling at Main Injector or Muon Campus.
 - Fermilab's SC magnet, SRF, targetry, or space-charge research programs.

The Fermilab Site-Filler, RCS Design, & Tevatron Tunnel



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Muon Collider- MAP Concept



Design choices at each stage, with each stage mostly decoupled from the other as long as the final parameters for the collider are consistent.

Parameter	Symbol	unit		8 92	
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	\mathcal{L}	$10^{34} {\rm cm}^{-2} {\rm s}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Average field	$\langle B \rangle$	Т	7	10.5	10.5
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5
Transverse emittance	ϵ	$\mu \mathrm{m}$	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP betafunction	β	mm	5	1.5	1.07
IP beam size	σ	μ m	3	0.9	0.63

Table 1: Tentative target parameters for a muon collider at different energies.



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Dipoles & RF Technology

Magnetic Fields:

- Conventional (Ferrite): ~2T
- Superconducting (NbTi): ~8T
- Superconducting (Nb3Sn): ~16T
- Future HTS (REBCO): ~40T?

Pulsed Magnets:

- Conventional: +/- ~2T
- Future HTS (REBCO): +/- ~4T, ~200 T/s?
 - Piekarz et al. NIM A 943, 162490 (2019)
 - Piekarz et al. Fermilab-conf-21-695 (2021)

RF Acceleration:

- 650 MHz PIP-II:17 MV/m
- 1300 MHz SLS-2: 30 MV/m
- Future: 40-120 MV/m?
 - Cold Cu?





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Muon Acceleration Architecture

Linear Accelerator:

- requires >100km (not practical)

Race-track Recirculating Linac (RLA):

- separated arcs, multi-pass RF.

Hybrid Rapid-Cycling Synchrotron (RCS):

- Strong cold dipoles, DC
- Ramped warm dipoles, AC
- Circumference, Energy set by Bave

 $B_{ave,max} = B_{cold}f_{cold} + B_{warm}f_{warm}$ $B_{ave,min} = B_{cold}f_{cold} - B_{warm}f_{warm}$

$$C = 2\pi R = 2\pi (B\rho)/B_{ave}$$



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Muon Facility Site Map (RLA)

Shows a 4 TeV collider with RLA

- 8T bending magnets.
- 30 MV/m.
- 18 turns (50 GeV/linac/turn).

Or a 8 TeV collider with 16T magnets, and 60 MV/m.

- Maybe room for ~50% bigger RLA.

Also possible to start with smaller RLA, and then switch to RCSs.





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RLAs & Fixed Field Accelerators

Fixed Field Accelerators (FFAs) are similar to RLAs, except that the arcs are horizontally open arcs to accommodate many passes not overlapping.

- Like RCS, except the magnets don't ramp.

Racetrack architecture:

Long dispersion-free RF sections.

Round architecture:

Distributed RF accomodating dispersion.



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Hybrid Rapid-Cycling Synchrotron (RCS)

Design by Berg & Capobianco-Hogan (evening parallel session tomorrow).

Four RCSs, 14T cold dipoles, +/- 1.75 T ramped dipoles.

First RCS is Tevatron circumference, final three are site-filler circumference.

Optimized to minimize muon decay loss, but some tradeoff with max collision energy.





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Muon Facility Site Map (RCS)

This is where the site-filler RCS comes from

- For a given circumference, increasing the RF fraction minimizes muon decay at the cost of final collision energy.

- For a given collision energy, increasing the circumference, allows for higher energy and/or reduced muon decay loss.

The actual collider is all cold magnets so if the final RCS fits on site, the collider fits on site.

The proton driver and cooling channels fit easily within the Tevatron field.



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Muon Ring Neutrino Program (NuFACT/NuSTORM/NuMAX)

1) Built Proton Driver

2) Built separate muon ring for neutrino program.



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Vastly improves δ_{CP} resolution. Unitarity tests of PMNS matrix.



Proton Driver for Muon Collider (FNAL-inspired designs)



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ACE Booster Replacement (upgrade for LBNF)

8GeV Linac + 8GeV AR



Detailed proposals to replace Fermilab Booster with an 8-GeV Linac & 8-GeV Accumulator Ring.

Goal of reliability for Fermilab Main Injector program.

But scenarios included 0.8 MW at 8-GeV, which starts to look like a proton driver!

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IPAC 2024: FNAL MuC Proton Driver Scenario

Existing ACE design for an 8-GeV Linac

- 10 Hz x 5 mA x 2 ms x 8 GeV = 0.8 MW
- ILC style cavity, LCLS-II style cryomodule, E-XFEL style RF power.
- Use higher linac current of 6-25mA, that becomes 1-4 MW.

H⁻ Injection in 8-GeV Accumulator Ring (AR)

- Ideally, use laser-stripping H⁻ injection
 - Valuable R&D ongoing at SNS & J-PARC rings.

Transfer to Compressor Ring (CR)

- Four bunches compressed into four ~1-3ns bunches.

Next to four bunch combiner, targetry, muon production..



Macropulse & Micropulse Considerations

At IPAC24, <u>FNAL</u> & <u>CERN</u> proton driver scenarios have similar approach to linacs.

Johanesson et. al. suggests a sensible AR fill pattern with a factor of 60 bunch compression.

Eldred et al. has an **implausibly large micropulse current**, but a factor of 10 bunch compression.

Parameter	CERN	FNAL
Energy	$10 { m GeV}$	$8 { m GeV}$
Rep Rate	$5~\mathrm{Hz}$	$10 \mathrm{~Hz}$
Macro Linac Current	40 mA	25 mA
Macro Pulse Duration	$2 \mathrm{ms}$	$2 \mathrm{ms}$
Number of Bunches	6	4
Bunch Length in AR	120 ns	20 ns
Micro pulse Duration	720 ns	80 ns
Micro pulse Current $(1\mu s AR)$	55 mA	310 mA
Micro pulse Duty Factor $(1\mu s AR)$	72%	8%

Out of the two, I much prefer the CERN approach, but consider some alternatives:

Middle Values: 40ns bunch, factor of 20 bunch compression, 6 bunches, 103mA micropulse.

Super Combiner: 20ns bunch, 24 bunches, 52mA micropulse

- Each bunch has a proportionally smaller transverse emittance, same charge density.

Long Macropulse: 10ms macropulse, 5mA macropulse, 62 mA microcurrent.

- Linac uses solid-state amplifiers, CW operation. PIP-II / Project X approach.

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FNAL Proton Driver Scenario & Space-charge

	-		
Energy	$8 { m GeV}$	Superconducting magnets may be necessation	
Pulse Intensity	320 e12		
Number of bunches	4	lor boom bompaot mig design.	
Pulse rate	10 Hz	Choose two of the four parameters:	
Beam Power	$4 \mathrm{MW}$		
Bunch length (AR)	3-10 ns	1) shortest bunch (1 ns)	
Bunch length (CR)	1-3 ns	2) smallest emittance (120 π mm mrad)	
Ring Circumference	300-600 m	2) moderate appear observe (0.2)	
95% Norm. Emittance	120-216 π mm mrad	3) moderate space-charge (0.2)	
Laslett Space-Charge limit	0.2-0.6	4) full beam power (4 MW)	

MuC Proton Driver (AR/CR):

Bunch compression at extreme space-charge limit as a valuable R&D topic for MuC

- Possible accelerator R&D experiment at FAST/IOTA, SNS or elsewhere.



Summary

We have an international muon collider design efforts, but the most of the major design choices are actually site agnostic.

Fermilab footprint is a constraint, but still accommodates compelling muon collider designs. Fermilab baseline distance from DUNE provides valuable neutrino program synergies.

Recent US design work in muon RCS design and proton driver design.

With so much R&D work ahead of us, the most important thing is not "where" but "who"!



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Muon Cooling Demonstrator Proposal

Next **5 years:** (1) A conceptual design of a demonstrator facility that allows testing the technology for cooling (2) Site exploration & cost estimate of a demo facility (3) Engineering design & start fabrication of a 1.5 prototype cooling cell



We are exploring Fermilab's Muon Campus (8-GeV protons / 3-GeV muons) as a possible site for this proposed muon cooling demonstrator.

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Bunch Compression at FAST/IOTA (Simulation)

Proposed IOTA proton experiment IOTA h=4, Snap bunch rotation with intense space-charge. **RF Capture:**

	IOTA (h=1)	IOTA (h=4)
$\Delta p/p$	0.001	0.001
K.E.(MeV)	2.5	2.5
h	1	4
β	0.07285	0.07285
η	-0.92568	-0.92568
$V_{cap}(3\sigma)$	161.17V	644.7V
$V_{compression}(3\sigma)$	644.7V	2.58kV
$Q_s(1\sigma)$	1.45×10^{-3}	5.81×10^{-3}
$Q_s(3\sigma)$	4.36×10^{-3}	1.74×10^{-2}

RF voltage requirements for a factor of two bunch compression ratio is shown for h=1 and h=4 case.

Credit: Simons (NIU)





Sample collider lattice-

- ≻6 TeV (3x3) lattice MAP
- > Wang, Nosochkov, Cai and Palmer JINST 11, P09003
- •C=6.3 km (B_{ave}= 10 T)
- Max pole-tip fields
- 15-20 T dipoles, 15 T quads
 - » ~16 T bending
- ~isochronous
- Extrapolate to 10 TeV
- •C→10.5 km, R=1.67 km
- Fits within Fermilab site
- **>**First draft lattice
- Kyriacos Skoufaris and Christian Carli
- C=8.06 km +
- >Accelerator is larger
- Includes rf, cycling elements

