Rapidly Pulsed Synchrotron Acceleration Chain for a Fermilab Sited Muon Collider

K. G. Capobianco-Hogan*[1] J. S. Berg[2]

[1]Department of Physics and Astronomy
Stony Brook University

[2]Electron Ion Collider Directorate
Brookhaven National Laboratory

Lepton-Photon 2025
Monday, August 25, 2025

*kyle.capobianco-hogan@stonybrook.edu

Introduction

Goal:

- Design a lattice to accelerate $\mu^{\pm}$ beams starting from 63 GeV to *final energy*.

Figures of Merit:

- Parton center-of-momentum (pCM) *energy*
- *Luminosity*
- *Circumference* of each accelerator ring

Questions:

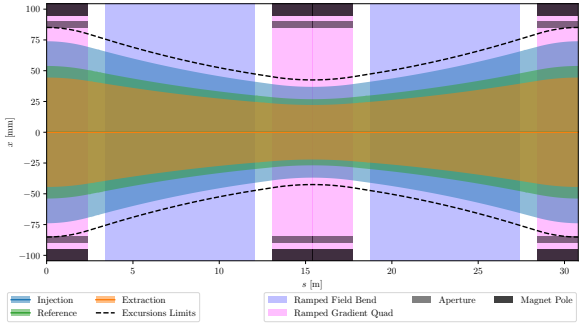
- What energy can we accelerate to on the Fermilab site?
- What will it take to accelerate to 5 TeV?

Types of Rapid Cycling Synchrotron

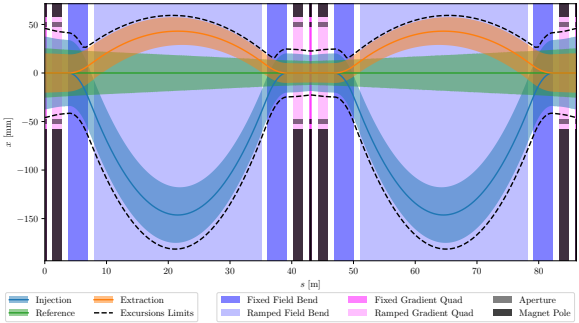
Conventional: using only ramped field magnets

Hybrid: using interleaved fixed and ramped field magnets

RCS 1 Arc Cell

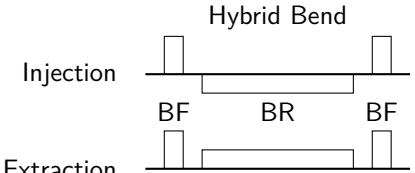


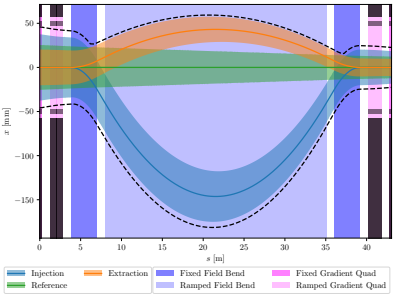
RCS 3 Arc Cell



“Hybrid” Magnets

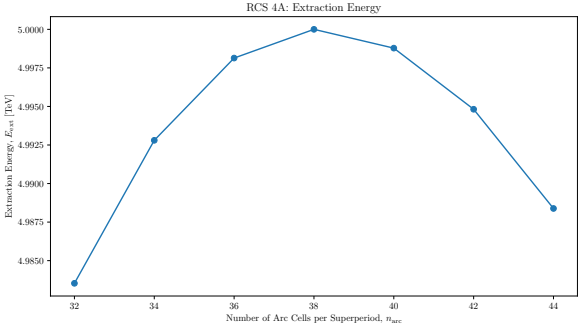
Magnets:	Iron Dominated	Superconducting Coil Dominated
Ramp Time	$\mathcal{O}(1\,\mathrm{ms})$	$\mathcal{O}(10^4\,\mathrm{s})$
Max Field	1.75 T for dipoles	14 T for dipoles
	1.2 T (at pole tip) for quads	12.5 T (at pole tip) for quads
Use Case	ramped field magnets	fixed field magnets



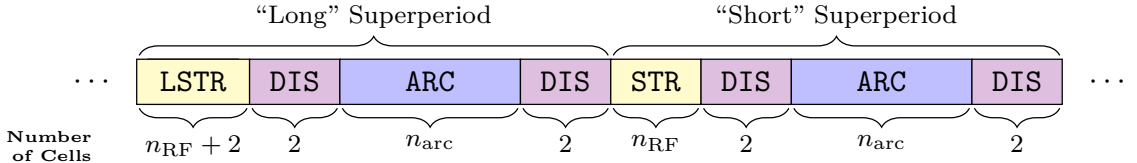


Cell Length Optimization

- *Dipole packing* **improves** with cell length.
- The **longer** the cells are, the greater the portion of the ring **occupied** by *dispersion suppressors*.
- There is an **optimal cell length** at which *extraction energy* (E_{ext}) is *maximized*.



RF Stations Distributed Around Each RCS



- To **reduce** the **mismatch** between the *beam energy* and the *field* of *ramped magnets*.
- So that the *synchrotron tune* divided by the *number of RF stations* (the "**superperiod synchrotron tune**") is much less than $1/\pi$.

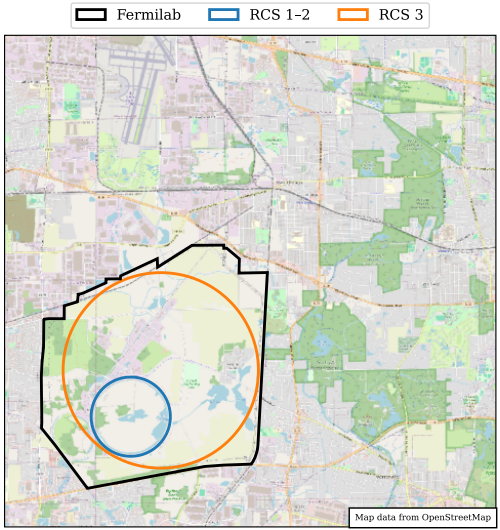
Survival Rate

$$\frac{N_{\mathrm{ext},i}}{N_{\mathrm{inj},i}} = \left(\frac{E_{\mathrm{ext},i}}{E_{\mathrm{inj},i}}\right)^{-\frac{m_\mu \mathrm{c}}{\mathrm{e} G_{\mathrm{avg}} \tau_\mu}}$$

- Increasing average accelerating gradient improves survival rate.
- Need to balance survival rate and energy ratio for each RCS ring.

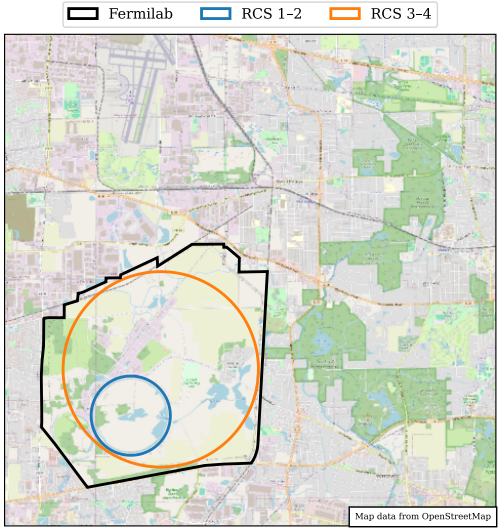
Maps depicting RCS rings in the slides that follow are for **illustration purposes only** and ***do not reflect actual positioning.***

Three Ring Scenario



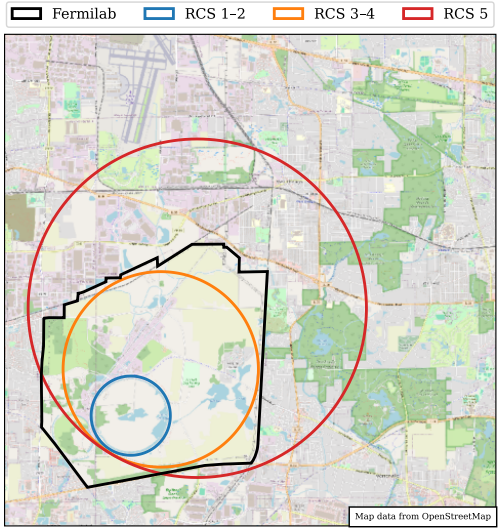
Parameter	RCS 1	RCS 2	RCS 3
E_{inj} (TeV)	0.063	0.174	0.454
E_{ext} (TeV)	0.174	0.454	1.54
$E_{\text{ext}}/E_{\text{inj}}$	2.76	2.61	3.39
Hybrid RCS	No	Yes	Yes
C_{ring} (km)	6.28	6.28	15.5
G_{avg} (MV/m)	2.50	2.00	2.00
Ramped bend (%)	33.1	26.7	42.0
Fixed bend (%)	0	7.48	9.63
Quadrupole (%)	28.9	11.0	8.05
Survival rate	0.937	0.926	0.907
Tot. survival rate	0.937	0.867	0.786
Num. of turns	7.04	22.3	35.1
Accel. time (ms)	0.148	0.468	1.81

Four (On-Site) Ring Scenario



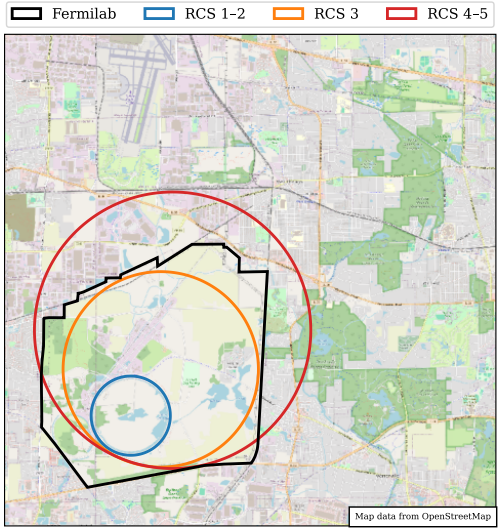
Parameter	RCS 3	RCS 4
E_{inj} (TeV)	0.454	1.54
E_{ext} (TeV)	1.54	2.71
$E_{\text{ext}}/E_{\text{inj}}$	3.39	1.76
Hybrid RCS	Yes	Yes
C_{ring} (km)	15.5	15.5
G_{avg} (MV/m)	2.00	1.00
Ramped bend (%)	42.0	45.1
Fixed bend (%)	9.63	20.5
Quadrupole (%)	8.05	4.07
Survival rate	0.907	0.913
Tot. survival rate	0.786	0.718
Num. of turns	35.1	75.4
Accel. time (ms)	1.81	3.90

Five Ring (One Off-Site) Scenario



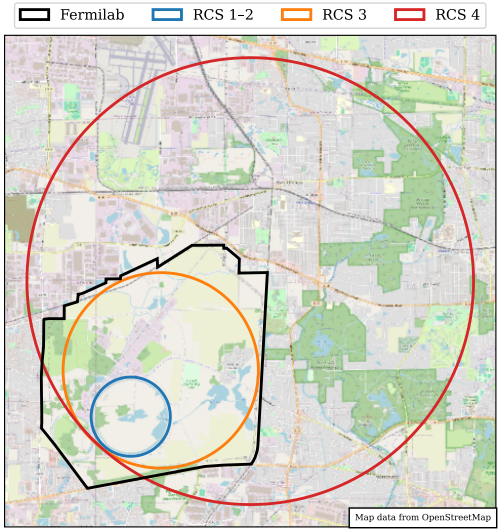
Parameter	RCS 3	RCS 4	RCS 5
E_{inj} (TeV)	0.454	1.54	2.71
E_{ext} (TeV)	1.54	2.71	5.00
$E_{\text{ext}}/E_{\text{inj}}$	3.39	1.76	1.85
Hybrid RCS	Yes	Yes	Yes
C_{ring} (km)	15.5	15.5	26.8
G_{avg} (MV/m)	2.00	1.00	1.00
Ramped bend (%)	42.0	45.1	51.1
Fixed bend (%)	9.63	20.5	21.5
Quadrupole (%)	8.05	4.07	3.40
Survival rate	0.907	0.913	0.906
Tot. survival rate	0.786	0.718	0.651
Num. of turns	35.1	75.4	85.3
Accel. time (ms)	1.81	3.90	7.64

Five Ring (Two Off-Site) Scenario



Parameter	RCS 3	RCS 4	RCS 5
E_{inj} (TeV)	0.454	1.54	3.46
E_{ext} (TeV)	1.54	3.46	5.00
$E_{\text{ext}}/E_{\text{inj}}$	3.39	2.25	1.44
Hybrid RCS	Yes	Yes	Yes
C_{ring} (km)	15.5	21.9	21.9
G_{avg} (MV/m)	2.00	1.00	1.00
Ramped bend (%)	42.0	52.5	41.9
Fixed bend (%)	9.63	17.1	28.9
Quadrupole (%)	8.05	4.37	3.02
Survival rate	0.907	0.878	0.943
Tot. survival rate	0.786	0.691	0.651
Num. of turns	35.1	87.7	70.0
Accel. time (ms)	1.81	6.42	5.12

Four Ring (One Off-Site) Scenario



Parameter	RCS 3	RCS 4
E_{inj} (TeV)	0.454	1.54
E_{ext} (TeV)	1.54	5.00
$E_{\text{ext}}/E_{\text{inj}}$	3.39	3.24
Hybrid RCS	Yes	Yes
C_{ring} (km)	15.5	35.4
G_{avg} (MV/m)	2.00	1.00
Ramped bend (%)	42.0	58.4
Fixed bend (%)	9.63	13.8
Quadrupole (%)	8.05	5.30
Survival rate	0.907	0.828
Tot. survival rate	0.786	0.651
Num. of turns	35.1	97.6
Accel. time (ms)	1.81	11.5

Key Points

Energy Reach:

- Able to reach 1.54 TeV (3.08 TeV pCM) *on-site* with 3 rings.
- Able to reach 2.71 TeV (5.42 TeV pCM) *on-site* with 4 rings.
- Able to reach 5 TeV (10 TeV pCM) with the use of one *off-site* tunnel (4 to 5 rings total).

Potential Improvements:

- Increasing the field range of **ramped magnets** would have a **greater impact** on the energy range of RCS rings/circumference of final ring than increasing the strength of *fixed field magnets*.
- Reducing **average accelerating gradient** can increase energy range/reduce final ring circumference (at the cost of *survival rate*), but **effectiveness varies** due to *discretization effects*.

Future Work:

- **Further refinement** of designs may *reduce energy range/increase* final ring *circumference*.
- **Tracking simulations** to *validate/adjust* design parameters and approximations.

See Also

K. G. Capobianco-Hogan and J. S. Berg, "Lattice design of a pulsed synchrotron for a muon collider fitting within the Fermilab site boundary," in *Proc. IPAC'24*, Nashville, TN, pp. 448–451, 2024.
doi:10.18429/JACoW-IPAC2024-MOPR01

K. G. Capobianco-Hogan and J. S. Berg, "Lattice design of a pulsed synchrotron for a muon collider fitting within the Fermilab site boundary," in *Proc. NAPAC'25*, Sacramento, CA, to be published, 2025.

Thank You for Your Attention