Progress on TeV acceleration for the Fermilab Muon Collider

K. G. Capobianco-Hogan

Stony Brook University

Second Annual US Muon Collider Meeting

Thursday, August 7, 2025

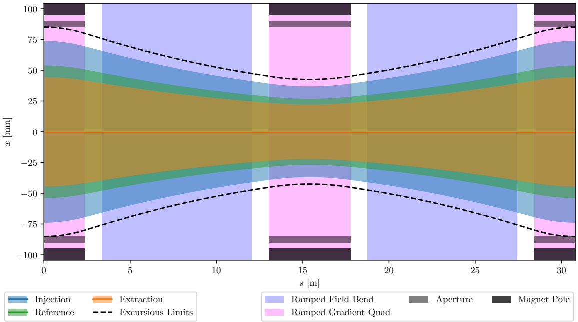
Introduction

- Accelerate $\mu^{\pm}$ beams from 63 GeV to 5 TeV
- What energy can we accelerate to on the Fermilab site?
- What will it take to accelerate to 5 TeV?

Design: Rapid Cycling Synchrotron (RCS)

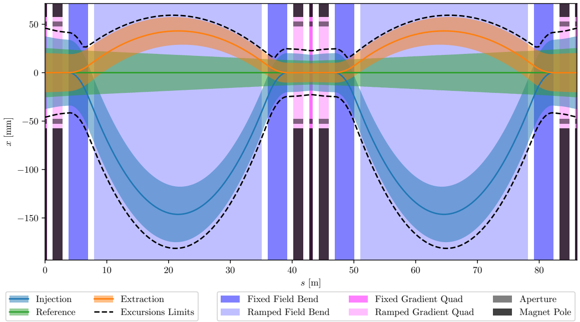
- **Conventional:** using only ramped field magnets

RCS 1 Arc Cell



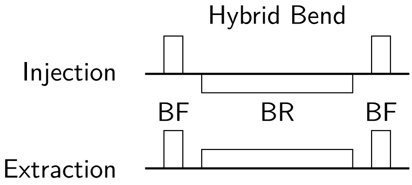
- **Hybrid:** using interleaved fixed and ramped field magnets

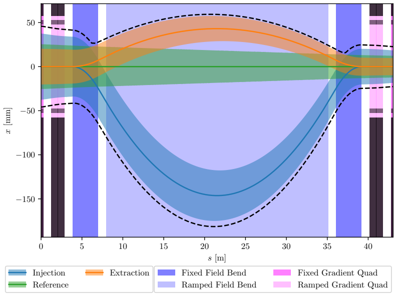
RCS 3 Arc Cell



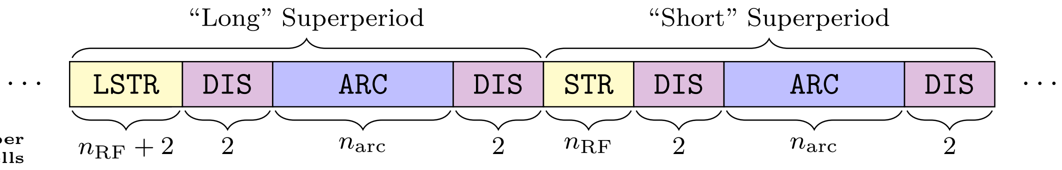
“Hybrid” Magnets

Magnets:	Iron Dominated	Superconducting Coil Dominated
Ramp Time	$\mathcal{O}(1\,\text{ms})$	$\mathcal{O}(10^4\,\text{s})$
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



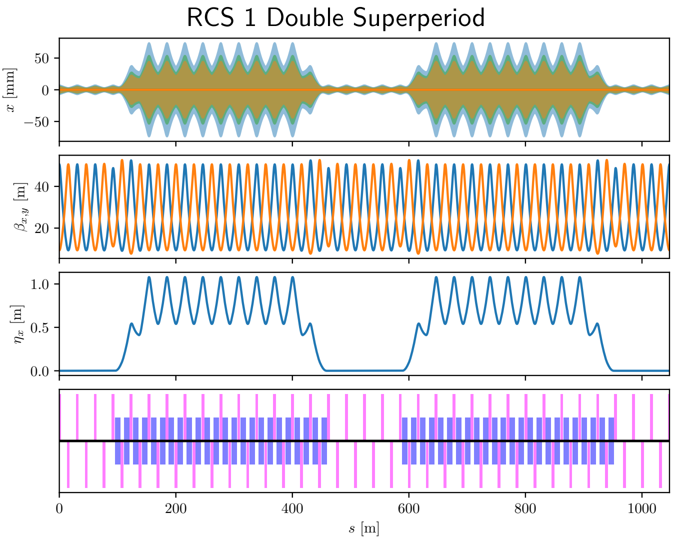


Layout



- Each RCS is divided into *nearly* identical superperiods
- Each superperiod consists of:
  - a straight section,
  - a dispersion suppressor,
  - an arc section, and
  - a second dispersion suppressor.
- Two types of superperiods, "long" and "short"
  - "long" superperiods have two additional cells (without RF) in their straight sections

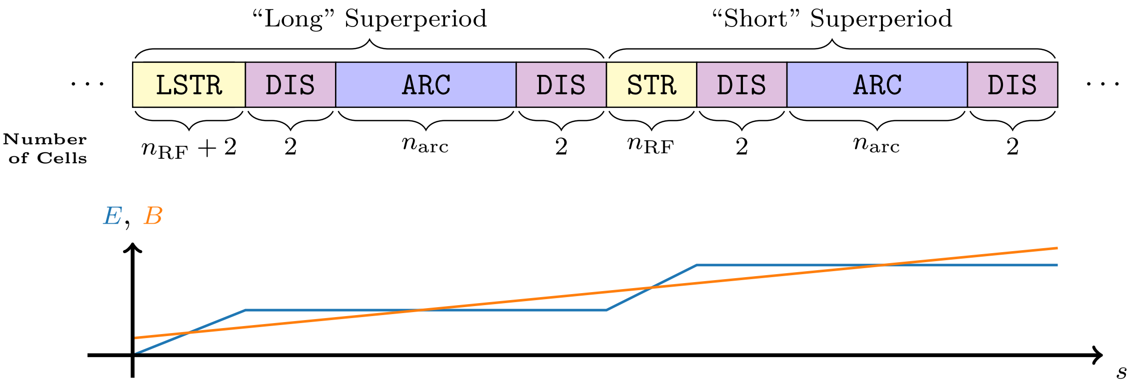
Ring Geometry



- A phase advance per cell of 90° in both x and y is chosen to simplify the future inclusion of sextupoles (if needed).
- A half-bend dispersion suppression scheme is used.

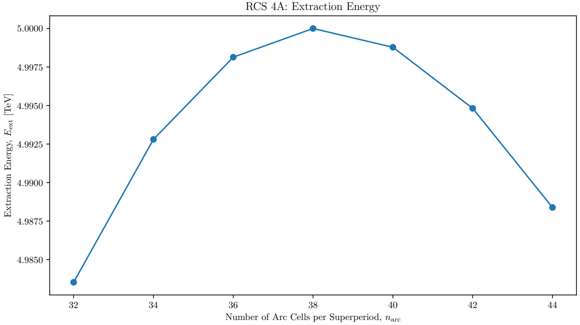
Layout Considerations, I

- RF stations are **distributed** around the ring:
  1. To **reduce** the **mismatch** between the *beam energy* and the *field* of *ramped magnets*.
     - The mismatch can lead to a significant **increase** in **quadrupole apertures** if unconstrained.
  2. So that the *synchrotron tune* divided by the *number of RF stations* (the "**superperiod synchrotron tune**") is much less than $1/\pi$.



Layout Considerations, II

- *Quadrupole length* increases with cell length, but cell length increases **faster**.
  - *Dipole packing* **improves** with cell length.
- All cells are the **same length** in this design.
  - **Longer cells** mean *straight* and *dispersion suppressor* cells **take up more space**.
  - Longer straight cells can fit more RF cavities.
  - This **lowers** the *number of straight cells per superperiod* (n_{RF}) required for the *average accelerating gradient* (G_{avg}).
  - However, 4 dispersion suppressor cells are needed per straight section, **regardless of cell length**.
  - ***End Result:*** There is an **optimal cell length** at which *extraction energy* (E_{ext}) is *maximized*.



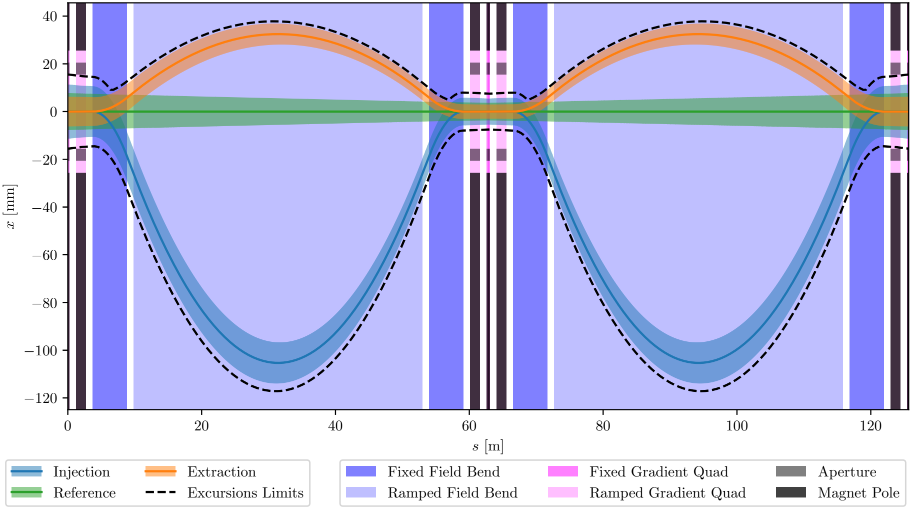
Layout Considerations, III

- Survival rate increases with average accelerating gradient according to

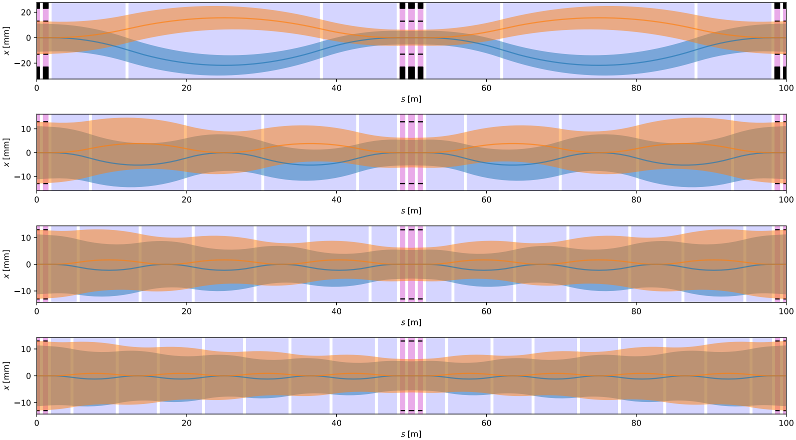
$$\frac{n_{\text{ext}}}{n_{\text{inj}}} = \left(\frac{E_{\text{ext}}}{E_{\text{inj}}}\right)^{-\dfrac{m_\mu c}{eG_{\text{avg}}\tau_\mu}}.$$

  - Need to strike a balance between n_f/n_i and E_{ext}.

Beam Size and Excursions (RCS 4A Arc Cell)



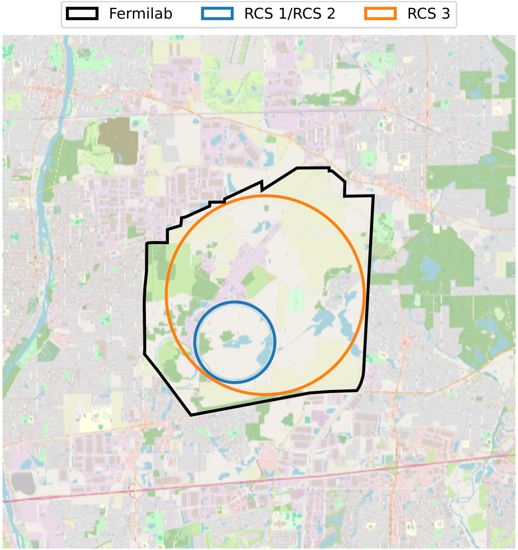
Subdivision of Hybrid Bends



- Example of hybrid bend subdivision from an earlier iteration of the lattice design that had neither straight cells (RF) nor dispersion suppression cells.

Bends per Half-Cell	E_{inj} [TeV]	E_{ext} [TeV]
1	3.60	5.00
2	3.66	5.00
3	3.72	5.00
4	3.78	5.00

63 GeV to 1.54 TeV Acceleration Chain I



63 GeV to 1.54 TeV Acceleration Chain II

Parameter	**RCS 1**	**RCS 2**	**RCS 3**
Injection energy (TeV)	0.063	0.174	0.454
Extraction energy (TeV)	0.174	0.454	1.54
Energy ratio	2.76	2.61	3.39
Hybrid RCS	No	Yes	Yes
Circumference (km)	6.28	6.28	15.5
Average accelerating gradient (MV/m)	2.50	2.00	2.00
Number of superperiods	12	12	12
RF cells per superperiod	4	2	2
arc cells per superperiod	8	4	8
Packing fraction, ramped bend (%)	33.1	26.7	42.0
fixed bend (%)	0	7.48	9.63
quad (%)	57.9	11.0	8.05

63 GeV to 1.54 TeV Acceleration Chain III

Parameter	RCS 1	RCS 2	RCS 3
Injection energy (TeV)	0.063	0.174	0.454
Extraction energy (TeV)	0.174	0.454	1.54
Energy ratio	2.76	2.61	3.39
Average accelerating gradient (MV/m)	2.50	2.00	2.00
Synchronous phase[1] ($^\circ$)	57.0	57.2	43.0
Superperiod synchrotron tune $\left(10^{-2}\right)$	6.91	5.85	4.47
σ_{p_z} $\left(10^{-4}\right)$	136	49.2	25.5
$\Delta E_{\text{sup}}/E_{\text{inj}}$ $\left(10^{-4}\right)$	208	60.3	56.9

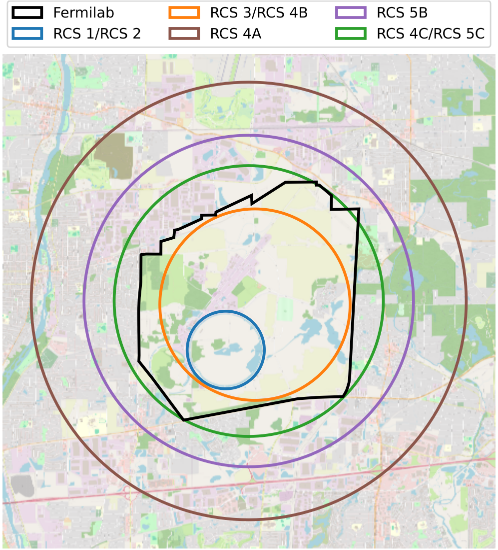
[1] Synchronous phase relative to crest.

63 GeV to 1.54 TeV Acceleration Chain IV

Parameter	RCS 1	RCS 2	RCS 3
Injection energy (TeV)	0.063	0.174	0.454
Extraction energy (TeV)	0.174	0.454	1.54
Energy ratio	2.76	2.61	3.39
Survival rate	0.937	0.926	0.907
Total survival rate	0.937	0.867	0.786
Number of turns	7.04	22.3	35.1
Acceleration time (ms)	0.148	0.468	1.81
Injection kicker length (m)	0.861	1.31	1.73
Extraction kicker length (m)	1.81	2.70	4.50
Utility drift length[2] (m)	12.0	19.4	38.6

[2] Two utility drifts per straight cell.

1.54 TeV to 5 TeV Scenarios I



1.54 TeV to 5 TeV Scenarios II

Parameter	RCS 4A	RCS 4B	RCS 5B	RCS 4C	RCS 5C
Injection energy (TeV)	1.54	1.54	2.71	1.54	3.46
Extraction energy (TeV)	5.00	2.71	5.00	3.46	5.00
Energy ratio	3.24	1.76	1.85	2.25	1.44
Hybrid RCS	Yes	Yes	Yes	Yes	Yes
Circumference (km)	35.4	15.5	26.8	21.9	21.9
Average accelerating gradient (MV/m)	1.00	1.00	1.00	1.00	1.00
Number of superperiods	6	6	6	6	6
RF cells per superperiod	3	2	2	2	2
arc cells per superperiod	38	24	30	28	28
Packing fraction, ramped bend (%)	58.4	45.1	51.1	52.5	41.9
fixed bend (%)	13.8	20.5	21.5	17.1	28.9
quad (%)	5.30	4.07	3.40	4.37	3.02

1.54 TeV to 5 TeV Scenarios III

Parameter	RCS 4A	RCS 4B	RCS 5B	RCS 4C	RCS 5C
Injection energy (TeV)	1.54	1.54	2.71	1.54	3.46
Extraction energy (TeV)	5.00	2.71	5.00	3.46	5.00
Energy ratio	3.24	1.76	1.85	2.25	1.44
Average accelerating gradient (MV/m)	1.00	1.00	1.00	1.00	1.00
Synchronous phase[3] (°)	32.4	37.9	31.9	36.1	31.1
Superperiod synchrotron tune $\left(10^{-2}\right)$	3.87	3.28	3.15	3.72	2.53
σ_{p_z} $\left(10^{-4}\right)$	10.1	8.5	5.80	8.98	4.65
$\Delta E_{\text{sup}}/E_{\text{inj}}$ $\left(10^{-4}\right)$	38.3	16.8	16.5	23.7	10.5

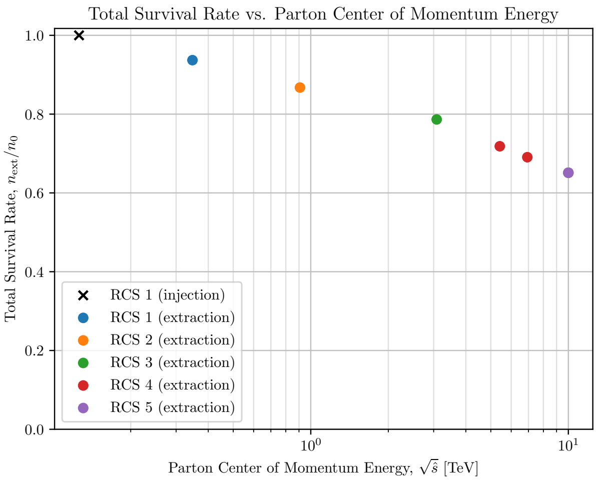
[3] Synchronous phase relative to crest.

1.54 TeV to 5 TeV Scenarios IV

Parameter	RCS 4A	RCS 4B	RCS 5B	RCS 4C	RCS 5C
Injection energy (TeV)	1.54	1.54	2.71	1.54	3.46
Extraction energy (TeV)	5.00	2.71	5.00	3.46	5.00
Energy ratio	3.24	1.76	1.85	2.25	1.44
Survival rate	0.828	0.913	0.906	0.878	0.943
Total survival rate	0.651	0.718	0.651	0.691	0.651
Number of turns	97.6	75.4	85.3	87.7	70.0
Acceleration time (ms)	11.5	3.90	7.64	6.42	5.12
Injection kicker length (m)	3.33	4.74	5.55	3.93	7.77
Extraction kicker length (m)	8.89	7.66	9.40	7.77	10.71
Utility drift length[4] (m)	58.1	35.4	53.8	45.9	45.3

[4] Two utility drifts per straight cell.

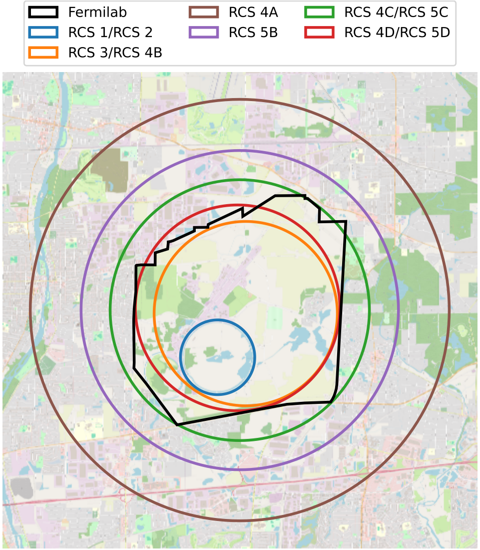
Total Survival Rate



Can we reach 5 TeV on with only the industrial area?

- Industrial area allows for circumference of 17.3 km.
- This will require stronger ramped field magnets.
- An alternate CERN sited design proposes the use of coil dominated HTS magnets to reach 3 T with a ramp rate of up to 500 T/s.
  - Assuming this can be done, would it be enough?

1.54 TeV to 5 TeV Bonus Scenario I



1.54 TeV to 5 TeV Bonus Scenario II

Parameter	**RCS 4C**	**RCS 5C**	**RCS 4D**	**RCS 5D**
Injection energy (TeV)	1.54	3.46	1.54	3.57
Extraction energy (TeV)	3.46	5.00	3.57	5.00
Energy ratio	2.25	1.44	2.31	1.40
Hybrid RCS	Yes	Yes	Yes	Yes
Circumference (km)	21.9	21.9	17.3	17.3
Average accelerating gradient (MV/m)	1.00	1.00	0.50	0.40
Number of superperiods	6	6	6	6
RF cells per superperiod	2	2	3	3
arc cells per superperiod	28	28	24	24
Packing fraction, ramped bend (%)	52.5	41.9	47.7	33.8
fixed bend (%)	17.1	28.9	22.1	37.1
quad (%)	4.37	3.02	3.83	2.63
Ramped field (T)	1.75	1.75	2.57	2.57
Fixed field (T)	14.0	14.0	14.0	14.0

1.54 TeV to 5 TeV Bonus Scenario III

Parameter	**RCS 4C**	**RCS 5C**	**RCS 4D**	**RCS 5D**
Injection energy (TeV)	1.54	3.46	1.54	3.57
Extraction energy (TeV)	3.46	5.00	3.57	5.00
Energy ratio	2.25	1.44	2.31	1.40
Average accelerating gradient (MV/m)	1.00	1.00	0.50	0.40
Synchronous phase[5] ($^\circ$)	36.1	31.1	43.1	38.7
Superperiod synchrotron tune $\left(10^{-2}\right)$	3.72	2.53	2.69	1.66
σ_{p_z} $\left(10^{-4}\right)$	8.98	4.65	7.49	3.61
$\Delta E_{\mathrm{sup}}/E_{\mathrm{inj}}$ $\left(10^{-4}\right)$	23.7	10.5	9.36	3.23

[5] Synchronous phase relative to crest.

1.54 TeV to 5 TeV Bonus Scenario IV

Parameter	**RCS 4C**	**RCS 5C**	**RCS 4D**	**RCS 5D**
Injection energy (TeV)	1.54	3.46	1.54	3.57
Extraction energy (TeV)	3.46	5.00	3.57	5.00
Energy ratio	2.25	1.44	2.31	1.40
Survival rate	0.878	0.943	0.764	0.873
Total survival rate	0.691	0.651	0.600	0.525
Number of turns	87.7	70.0	234	207
Acceleration time (ms)	6.42	5.12	13.5	12.0
Injection kicker length (m)	3.93	7.77	4.22	8.60
Extraction kicker length (m)	7.77	10.71	8.60	11.6
Utility drift length[6] (m)	45.9	45.3	41.6	40.7

[6] Two utility drifts per straight cell.

Key Points and Next Steps

Key points:

- **Able to reach** 5 TeV, though it requires an off-site tunnel with one or two rings (depending on scenario).
- **Multiple scenarios** to get from 1.54 TeV to 5 TeV.
- 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.

Next steps:

- **Reduce mismatch** between intermittently ramped beam energy and continuously ramped magnet fields by *increasing number of superperiods and/or reducing average accelerating gradient.*
- **Reduce excursions** in hybrid bends by *subdividing hybrid bends* (see Previous Work).
- **Tracking simulations** to *validate/adjust* design parameters and approximations.

Thank You for Your Attention