Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Fermilab “Site Filler”:

Muon Collider?

David Neuffer
Fermilab

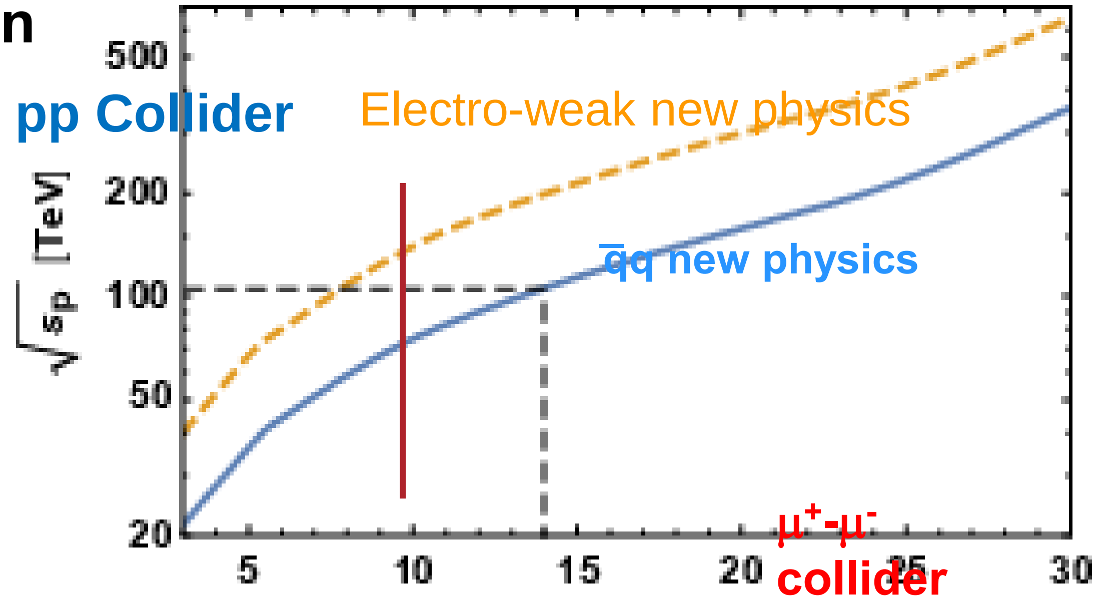
January 2022

Outline

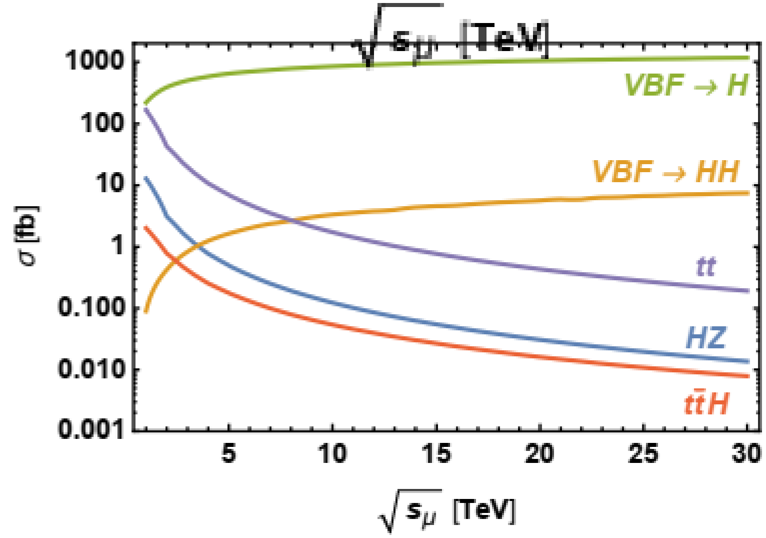
- **Fermilab –**
  - Site filler - Muon Collider ?
    - possible future high-energy facility on Fermilab site
- **Motivation**
  - “Energy Frontier”
- **Muon Collider Components**
  - Muon source
  - Accelerator
    - Fast-cycling
  - Collider Ring
- **Parameters**
  - Up to ~10 TeV Muon collider “site-filler”
- **Scenarios, Time lines, etc.**

Energy Frontier

- 10TeV μ^+-μ^- collider has an energy reach of 100 TeV pp collider

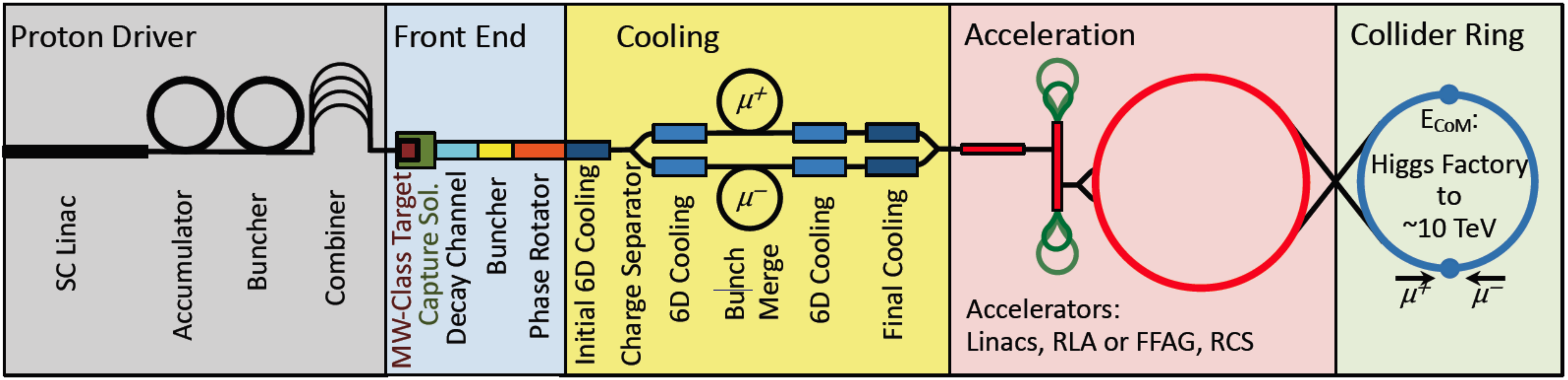


- Need High- Luminosity
  - (q̄q events $\sigma \sim 1/s$)
  - Vector boson fusion
    - $\sigma \sim \ln(s)$



- Goal is ~ 2 attobarn^{-1}/year
  - $L = 2\ 10^{35}\ cm^{-2}s^{-1}\ 10^{7}$ s/year

Muon Collider - MAP Concept



Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Average field	$\langle B \rangle$	T	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	μm	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	μm	3	0.9	0.63

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

Site filler Accelerator

- Largest
Radius is ~2.65 km
  - ~16.5 km Circumference
    - ~2/3 LHC

~RCS accelerator

If B_{ave}= 3 T → E_{μ}= 2.4 TeV

(B_{max} = 8T, B_{pulse} =±2T)

Doubled ?

B_{ave}= 6.3 T → E_{μ}= 5 TeV

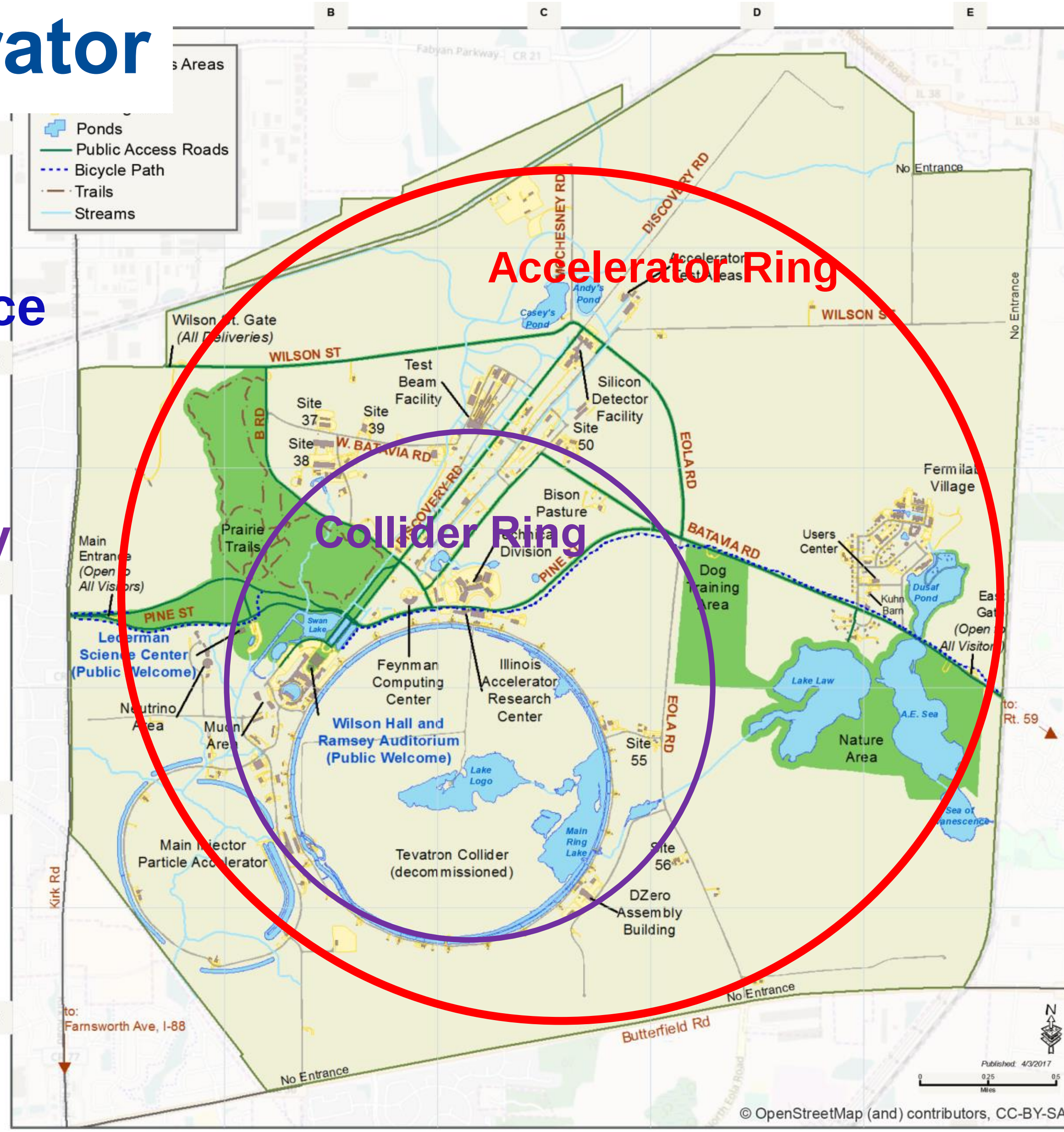
(B_{max} = 16T, B_{pulse} =±4T)

10 TeV collider

Collider Ring ~10 km

B_{ave} = 10 T

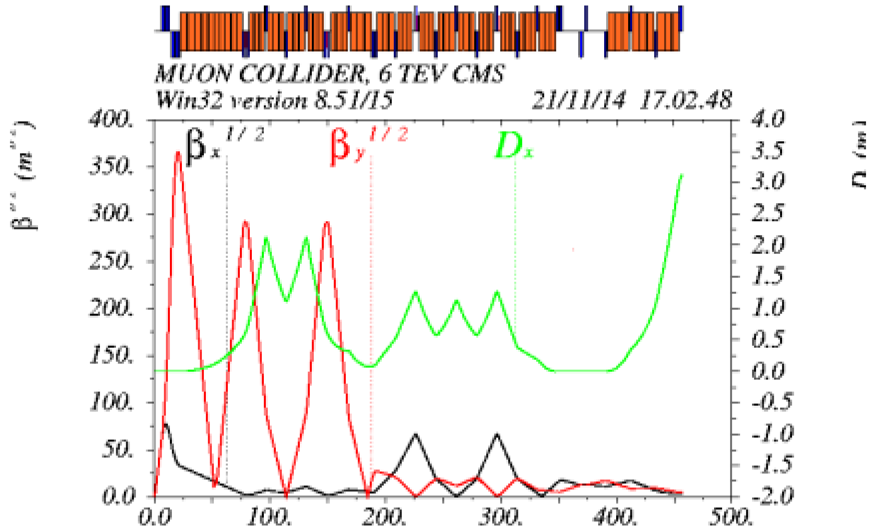
τ_{μ} = 0.104 s



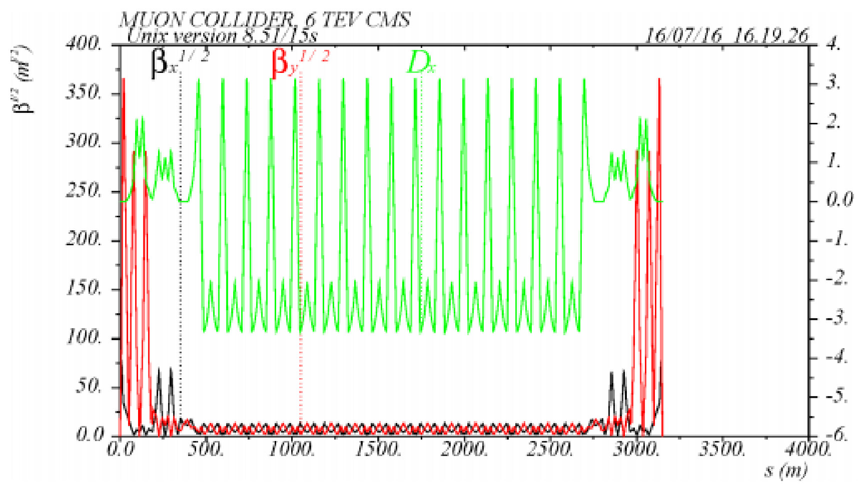
$$R = \frac{B\rho}{B} = \frac{P(GeV/c)}{0.3B(T)} m = \frac{P(TeV/c)}{0.3B(T)} km$$

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**

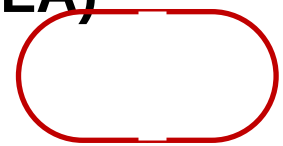


- ➢ **Accelerator is larger**
  - **Includes rf, cycling elements**

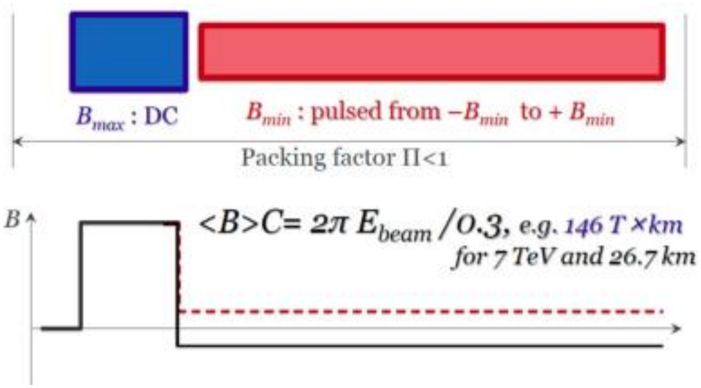
Fermilab

Acceleration methods

- **Linear Accelerator**
  - **5 TeV → > 100 km**



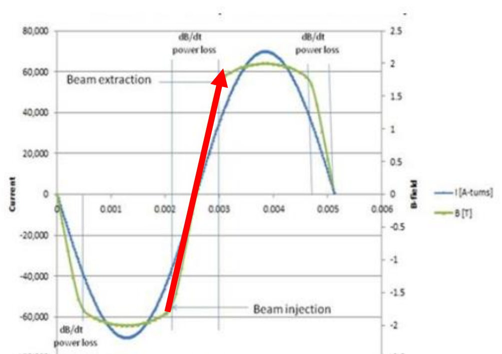
- **Race-track Recirculating Linac (RLA)**
  - **(like CEBAF)**
  - **Separate return transports**
    - **5-6 turns → ??**
    - **cost/complexity of multiple turns**



- **Rapid Cycling Synchrotron**
  - **B_{typ} = ~1.5 T, 15- 60 Hz**
  - **Hybrid – High field + pulsed**
  - **Example:**

    B_{max}=8T B_{pulsed}=±2.0, f= 0.25

    → 3.5 / 0.5 T



$$B_{ave} = f\,B_{max} + (1-f)\,B_{pulsed}$$

Bending, Accelerating fields:

- **Conventional (Ferric)**
  - **~ 2T**
- **Superconducting –NbTi**
  - **Tevatron ~4 T**
  - **LHC ~8 T**
- **Superconducting Nb_3Sn**
  - **HL-LHC + → 16T**

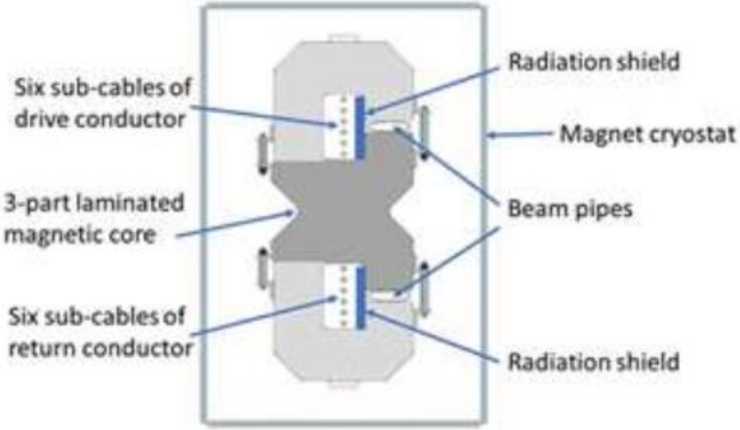
- **HTS superconductor …**
  - **REBCO → 40 T ?**

- **Pulsed magnets**
  - **±2 T → ± 4 T ~200-600 T/s**
    - **12 T/s HTS → 270 T/s**
    - **Piekarz et al. NIM A 943, 162490 (2019)**
    - **Piekarz et al. Fermilab-conf-21-695 (2021)**

SRF accelerating fields
- **17 MV/m (650 MHz PIP-II)**
- **30 MV/m (1300 MHz SLS-2)**

- **Future upgrades**
  - **40 → 50 MV/m → 80??**

- **Pulsed rf – Cu → ??**
  - 50 → 100 MV /m



Acceleration to 5 TeV at Fermilab

➢0-65 GeV Linac + 10-turn RLA

3 GeV Linac
- **650 MHz SRF**

~6 GeV Recirculating Linac
- **650 MHz**
- **~10 turns to 65GeV**

➢65 GeV → 5 TeV

- **RCS 1 – 65→330 GeV r=1km**
  - Normal conducting: 0.3→1.55T
- **RCS 2 – 330→1000 GeV r=1km**
  - Hybrid 8±2 T
- **RCS 3 – 1 → 5 TeV "site filler"**
  - **Hybrid 16±4 T**

65 GeV → 5 TeV Scenario

	RCS-LE(nc)	RCS-HE(hybrid)	RCS-HF 16/4 hybrid
Input Energy	65	330	1000 GeV
Output Energy	330	1000	5000 GeV
Circumference	6.28	6.28	16.5 km
Pack Fraction	0.75	0.83	0.88
Total straight section	1.57	1.07	1.96
B-highfield		**8**	**16 T**
B-lowfield		**±2 T**	**±3.95 T**
B_{ave}	0.3→1.55 T	1.4→4.4 T	1.44→7.2 T
Fraction high-field		0.34	0.27
Acceleration Scenario			
Acceleration turns	36	97	270
Acceleration Time	0.76	2.03	15 ms
Beam survival	0.80	0.85	0.75
Rf voltage (ϕ_s = 60°)	8.63 GV	7.94 GV	17.1 GV
Ramp Rate	1650 T/s	1970 T/s	530 T/s

Fermilab

5 TeV with ±2 T RCS components

- Requires additional site-filler RCS ring
  - 1->3.25 TeV
    - 19% 16 T magnets
  - 3.25→ 5 TeV
    - 37% 16 T magnets

- ~ 10 GV more rf
  - Decay losses higher

65 GeV → 5 TeV Scenario

	RCS-LE(nc)	RCS-HE(hybrid)	RCS-HE 1	RCS-HE 2
Input Energy	65	330	1000 GeV	3250 GeV
Output Energy	330	1000	3250 GeV	5000 GeV
Circumference	6.28	6.28	16.5 km	16.5 km
Pack Fraction	0.75	0.83	0.88	0.88
Total straight section	1.57	1.07	1.96	1.96
B-highfield		8	16 T	16 T
B-lowfield		±2 T	±2.0 T	±2.0 T
B_{ave}	0.3→1.55T	1.4→4.4 T	1.44→4.7 T	4.7→7.2T
Fraction high-field		0.34	0.192	0.37
Acceleration Scenario				
Acceleration turns	36	97	161	249
Acceleration Time	0.76	2.03	8.9 ms	13.7 ms
Beam survival	0.80	0.85	0.80	0.85
Rf voltage (ϕ_s = 60°)	8.63 GV	7.94 GV	16.1 GV	8.1 GV
Ramp Rate	1650 T/s	1970 T/s	450 T/s	290 T/s

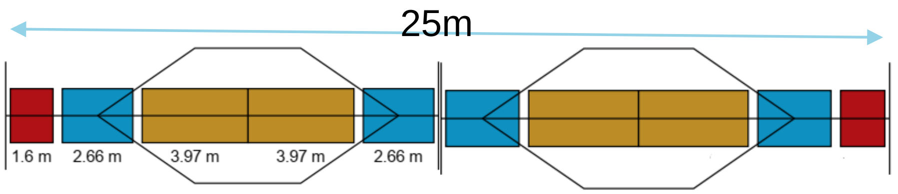
Hybrid RCS Acceleration

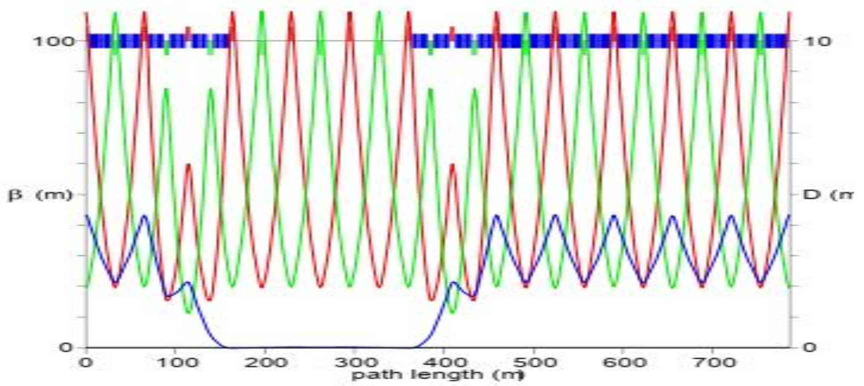
- **High-field fixed and low-field cycling magnets interleaved**

  - **Orbit through cycling magnet varies in acceleration**

  - **Quadrupoles needed**
    - Fixed or ramped ?
      - Fixed fields probably not stable
    - Limited to ramping fields
      - 0→2 T (or 0→4 T at pole tips)
      - Extra length for ramping quads must be included in lattice

- **Sample Lattice**
  - **A. Garren and S. Berg**
    - MAP-doc-4307 (2011)
  - **750 GeV in Tevatron**



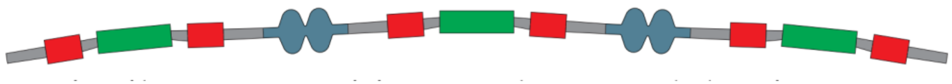


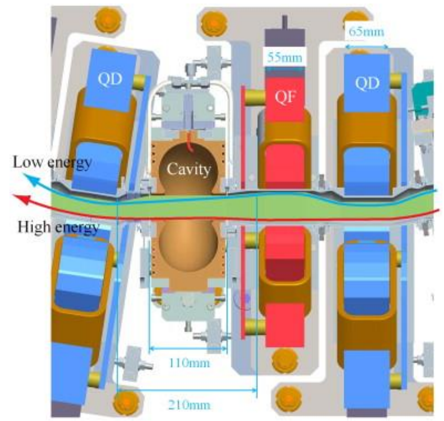
  - **Quadrupoles are ramped to keep tune constant**

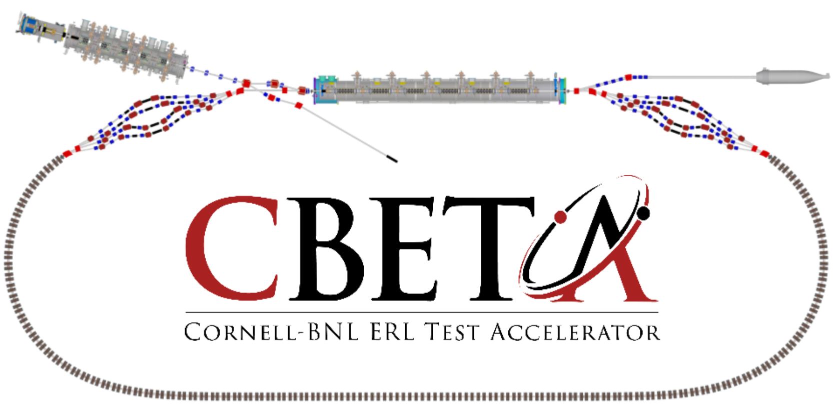
Fixed Field Accelerators

- Fixed field alternating-gradient (FFA)
  - Scaling -> edge focusing
    - Constant tunes
  - Non-scaling
    - Crosses integer tunes

- CBETA
  - ~RLA with FFA arcs
  - Tests concept







FFA acceleration

- **Vertical FFAG**

  S.Brooks, PRSTAB 16, 084001 (2013)

  - ~same circumference for all energies
  - More isochronous
  - **Edge focusing**

- **Scaling → non-scaling**

- **Adaptable to muons ?**

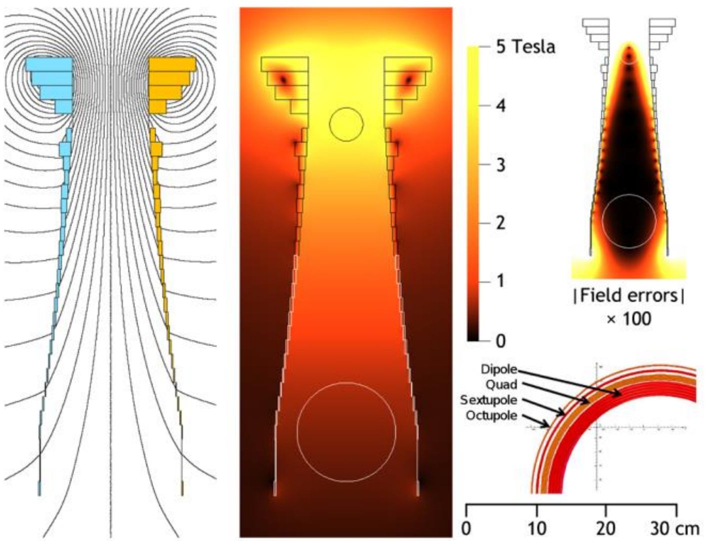


FIG. 5. 2D scaling VFFAG magnet design using block coils:

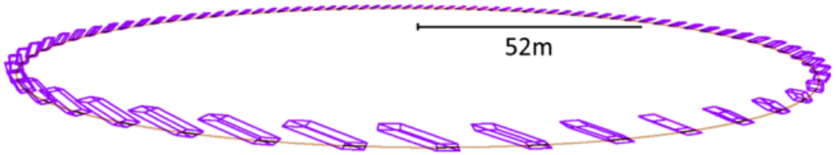


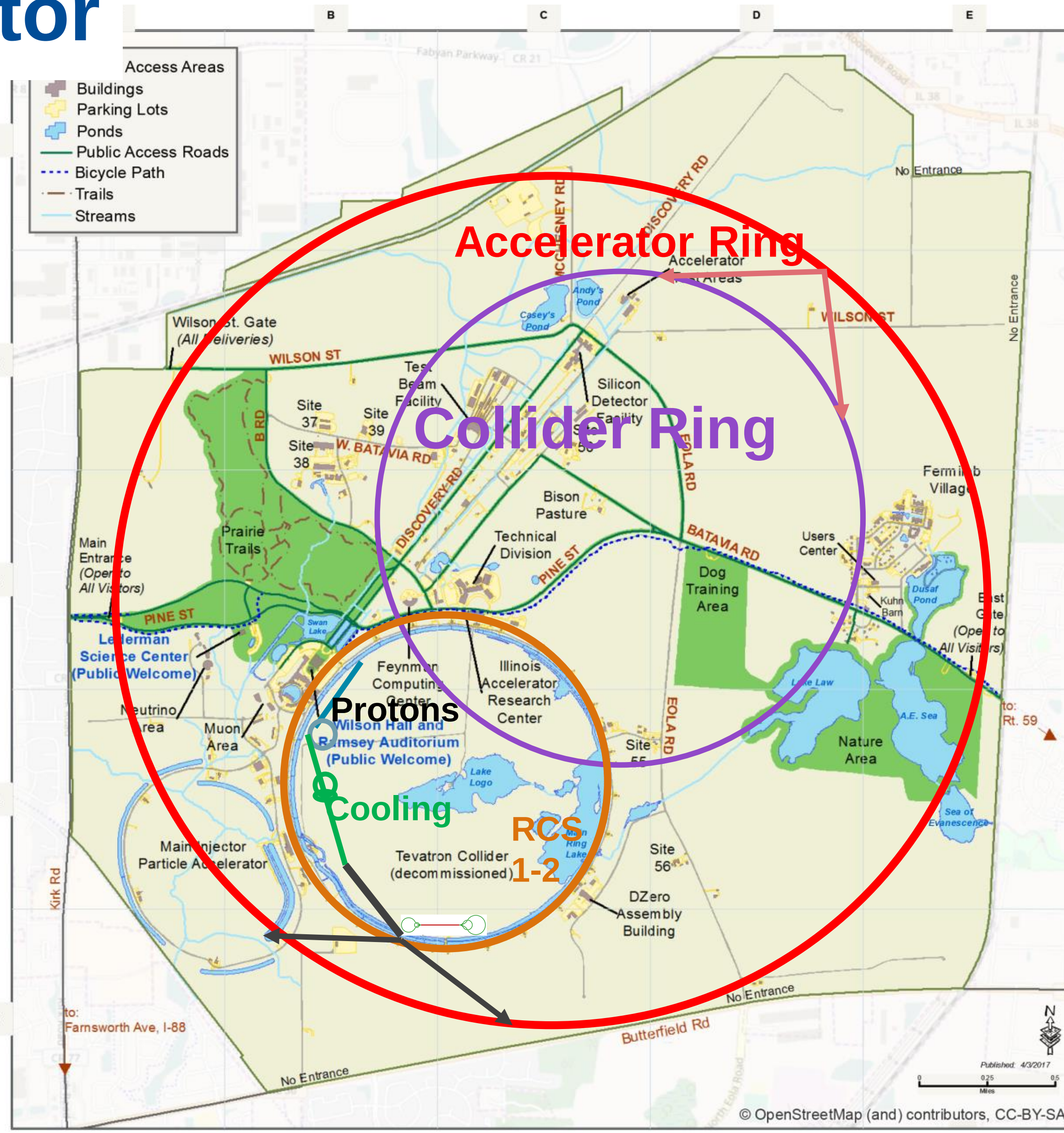
FIG. 8. Perspective view of the 12 GeV ring.

Site filler Accelerator

- **Proton Source**
  - PIP-III→target
- **μ Cooling**
- **Linac + RLA → 65 GeV**
- **RCS 1 and 2 → 1000 GeV**
  - Tevatron-size
- **RCS 3 → 5 TeV**
  - Site filler accelerator

10 TeV collider

Collider Ring ~10 km



Fermilab

Costs ??

- **Affordable?**
  - **according to Shiltsev cost model (JINST 9 T07002 (2014)):**

$$TPC \cong \alpha\left(\frac{L}{10\,km}\right)^{\frac{1}{2}} + \beta\left(\frac{E_{cm}}{1TeV}\right)^{\frac{1}{2}} + \gamma\left(\frac{P}{100\,MW}\right)$$

- $\alpha \cong$ 2B$ for civil construction,
- $\beta \cong$ 1, 2 or 10 B$
- for NC, SC magnets or SRF
- $\gamma \approx$ 2B$ wall plug power

- L=16, 60 GV rf, E_{cm}=10, P= ? MW
  - **~$10^{1\pm0.5}$ G$?**

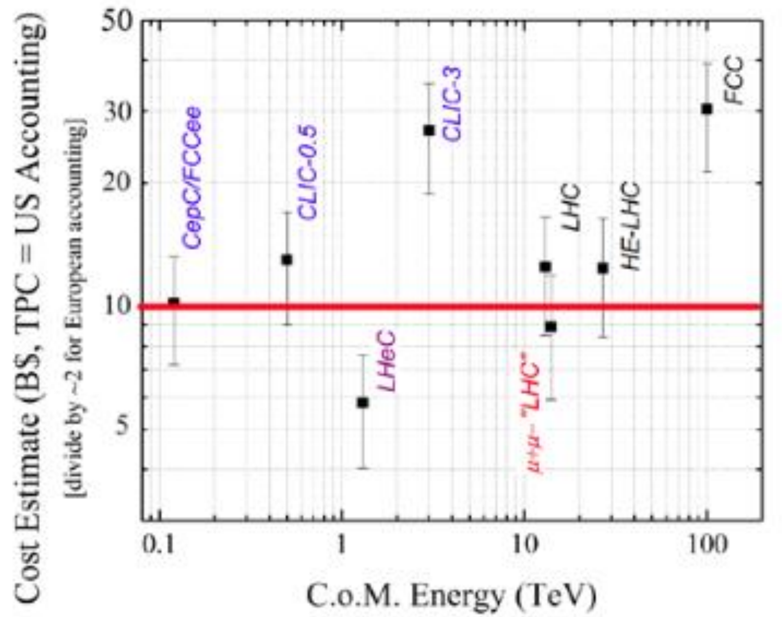


Figure 4: Cost estimates of various future colliders.

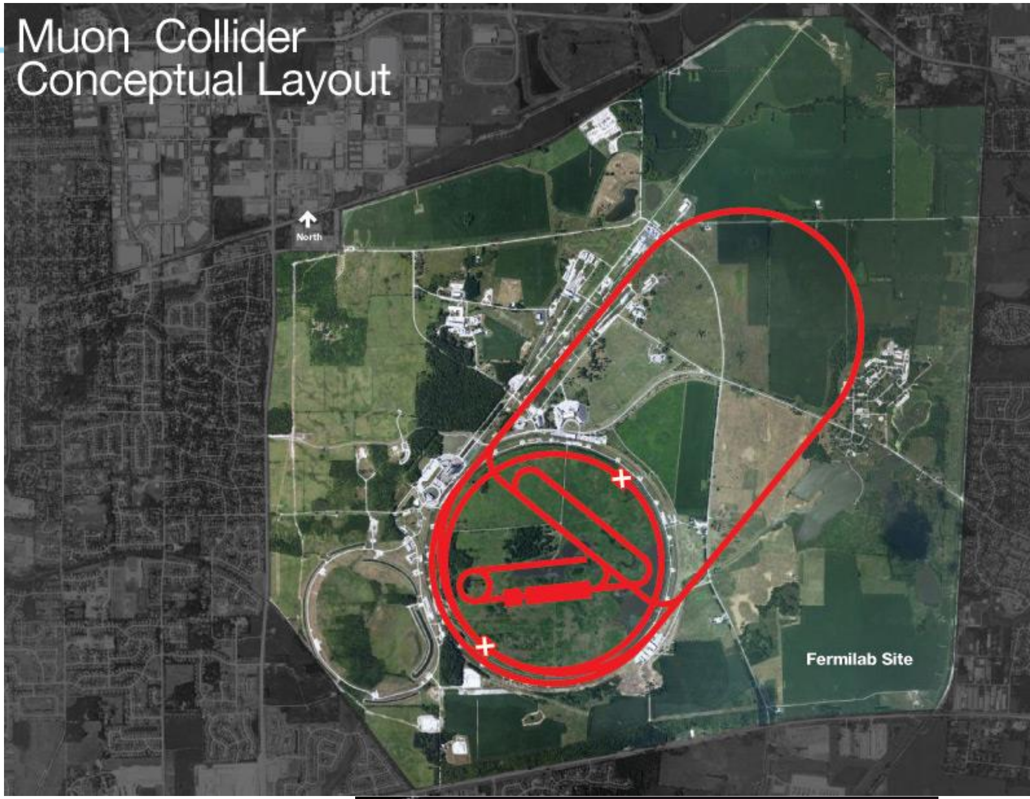
Summary

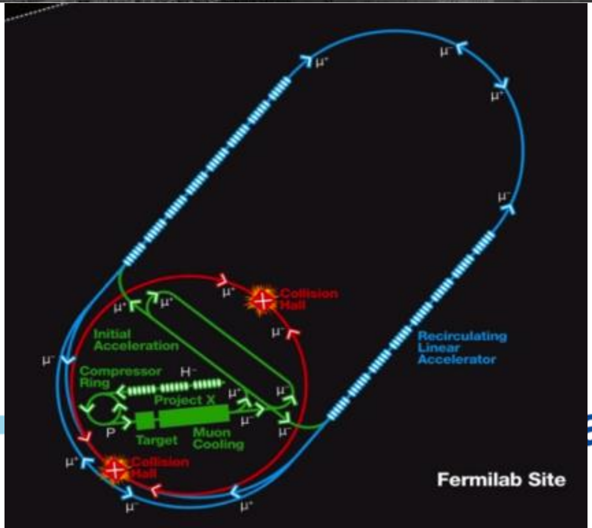
- Fermilab site filler
  - Muon Collider up to ~10 TeV Collider is possible goal
    - (5 × 5 TeV)
    - Requires ~16 T dipoles , in RCS scenarios
      - With rapid-cycling 2—4 T magnets

Thank you for your attention

~4 TeV (2 x 2) Muon Collider (~2005)

- **Muon Collider**
  - **2 TeV ring (~8T magnets)**
  - **RLA accelerator**
  - **~18 turns**
    2km linacs -50 GeV each
    ~30 MV/m rf
    Arcs are ~8T magnets each
- **Not quite site filler**
  - **Easily expand to 2.5x2.5**
  - **(5 TeV)**





- **Double gradients, B_{max}**
  - **10 TeV (5 x 5) – (16 T – 60 MV/m)**