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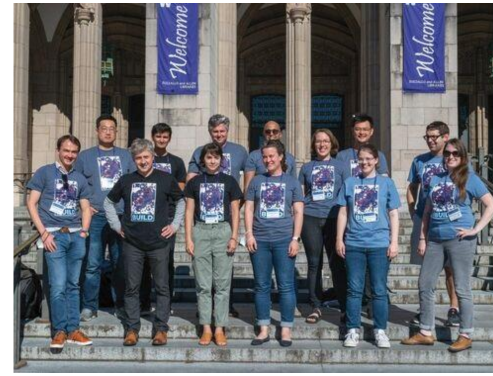
Muon Collider at Fermilab

David Neuffer
Wilson Fellow (1979-1983)
Fermilab (2024 Graduate)

July 2024

Snowmass → 2023 P5 Report



NEWS | 08 August 2022 | Correction 11 August 2022

Particle physicists want to build the world's first muon collider

The accelerator would smash together this heavier version of the electron and, researchers hope, discover new particles.

By Elizabeth Gibney

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A "muon shot" aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

Share full article 96

A tunnel of the Superconducting Super Collider project in 1993, which was abandoned by Congress. Ron Heflin/Associated Press

By Dennis Overbye and Katrina Miller

Published Dec. 7, 2023 Updated Dec. 8, 2023

4

symmetry
dimensions of particle physics

Illustration by Sandbox Studio, Chicago with Corinne Mucha

'This is our Muon Shot'

04/10/24 | By Laura Dattaro

The US physics community dreams of building a muon collider.

In the spring of 2022, Karri DiPetrillo was gearing up for the final step of the Snowmass particle physics community planning process. It would be a once-a-decade meeting at which physicists in the United States would discuss the future of the field. For DiPetrillo, who earned her PhD from Harvard in 2019, such a discussion could define the direction of the majority of her professional life. She and other early-career scientists wanted to be sure their voices were heard.

DiPetrillo, now an assistant professor at the University of Chicago and a member of the ATLAS collaboration, went into Snowmass excited about the prospect of a new kind of particle

Muon Fever ?

Outline

- The First 45 years
  - Wilson fellow 1979-83

  - R. Palmer 1994
    - High-luminosity muon collider
    - NFMCC → MAP
    - MICE

  MAP program
  2011-2014

  - 2014 P5 plan

  - CERN Long–Range plan
    - IMCC
    - Snowmass
  - 2023 P5

- The Next 45 years ?

In the beginning …

- **First RR Wilson Fellow-1979**

$$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\gamma^4}{R} = \frac{e^2}{3\varepsilon_0 R}\left(\frac{E_0}{m_e}\right)^4$$

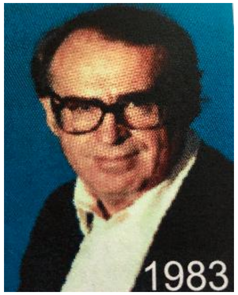
- **e+-e- limited by radiation (to~100GeV)**
  - **-> linear collider?**
- **Change mass of electron**
  - **$m_e \rightarrow m_\mu$**
- **D. Cline – use μ storage ring for neutrinos**
  - **→ ~nuSTORM**
- **J. D. Bjorken**
  - **Add foil cooling that the Russians are developing**

COLLIDING MUON BEAMS AT 90 GeV

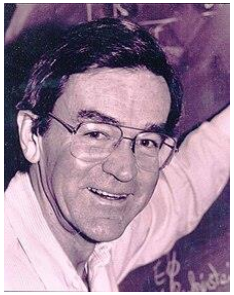
D. Neuffer

FN-319
2252.000

July 1979



D. Cline


Bjorken

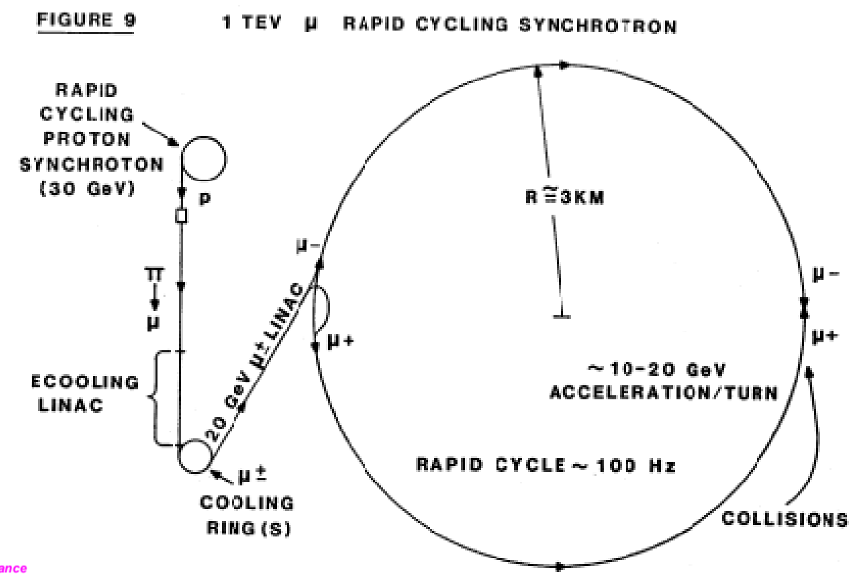
Principles and Applications of Muon Cooling - FN-378

Particle Accelerators 14, 75 (1983)

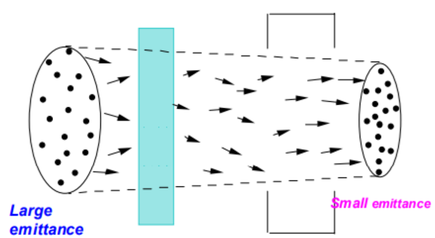
SLAC-121

- **M. Sands "Physics of Electron Storage Rings"**
  - Synchrotron radiation → dE/dx, PDG Handbook, Wang

2 TeV Collider (1983 version)



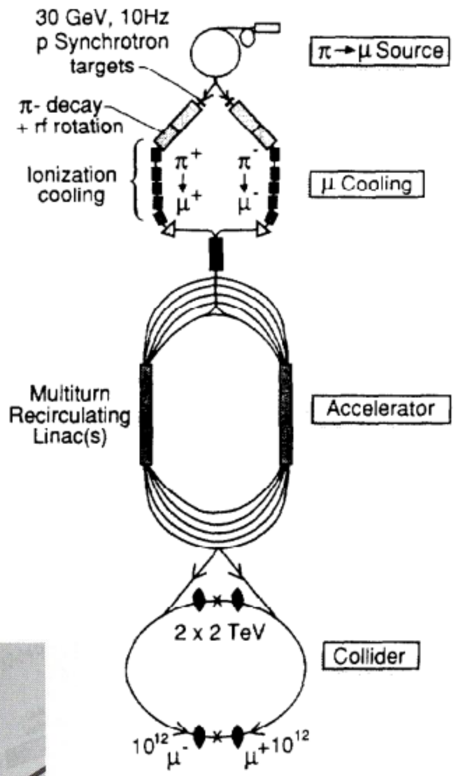
- **Muon Collider Components**
  - **Proton source**
    - ~10^{14} protons ~1m bunch
  - Muon source and cooling
  - Accelerator and Collider
    - Fast-cycling



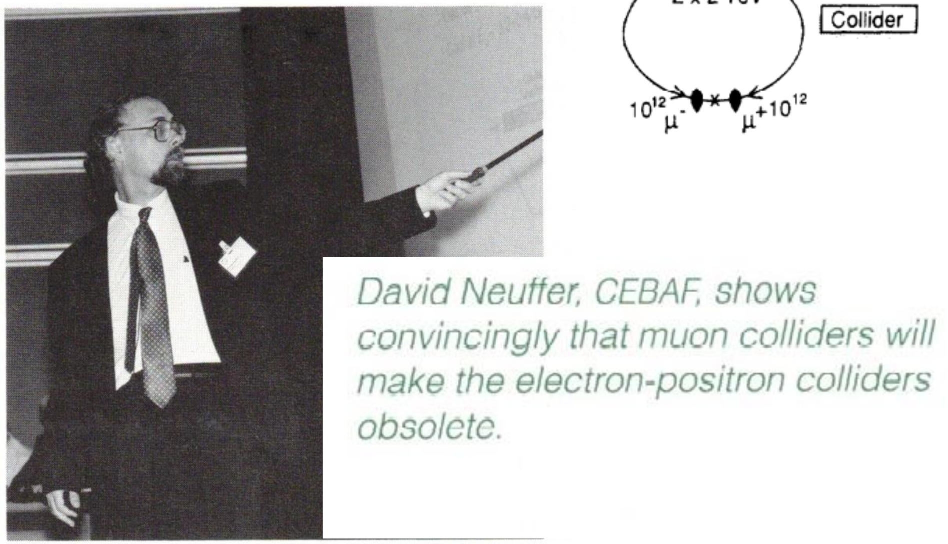
- **1984-1993**
  - Presentations at Advanced Accelerator Concepts, etc.
  - Search for Collaborators …

1994-

- **R. Palmer became interested**
  - After Isabelle, SSC …
  - **Collaboration paper for EPAC94**



- **Collaboration with Fermilab, LBL, BNL**
  - **J. Peoples, A. Tollestrup, A. Sessler,**



F Close, SLAC beamline

- **Muon Collider Collaboration**
  - **Snowmass 96**
  - **Return to Fermilab**

Neutrino Factory- Muon Collider Collaboration

- **Large Outbreak of "Muon Fever"**

Muon properties seem matched to "challenging and difficult"

Lifetime, cooling, detectors, acceleration

- **Many Innovations from many contributors**
  - Cooling
  - Neutrino Factory (S. Geer)
    - Collider front end + storage ring
    - Similar to Tevatron

Innovation	Innovator
Mercury Jet Target	T. Kirk and Kirk MacDonald
High-field capture solenoid	
E-Z Rotation	R. Palmer
hgh-freq. fi-E rotation	DN, A. Van Ginnekin
Chicane	C. Rogers
granular W target	C. Densham
Solenoidal cooling lattices	A. Sessler
Helical cooling channel	Y. Derbenev, R. Johnson
rectilinear cooling channel	V. Balbekov
Helical snake	Y.Alexahin
integrated cooling channels	Palmer, Stratakis, Balbekov, Yonehara, ...
gas-filled rf breakdown mitigation	Tollestrup,
RLA lattice innovations	A. Bogacz
hybrid RCS	D. Summers, S. Berg
non scaling FFAG	C. Johnstone
Vertical FFAG	S. Brooks
Dynamic neutrino flux mitigation	D. Schulte
Collider lattices	Y. Alexahin, E. Gianforte-Wendt
spin precession energy	Raja, Tollestrup
nu radiation	B. J. King
neutrino factory	S. Geer
nuSTORM	A. Bross, A. Liu, DN
Be/Al Breakdown mitigation	D. Bowring
LEMC (positron-e source)	Antonelli, Boscolo, Rimundi et al.
EMMA	S. Sheehan
Detector timing	Raja
rf with Be windows	D. Li
gas filled rf	Muons, Inc.
g-2 dp wedge	D. Stratakis, DN
delay line combiner	C. Ankenbrandt

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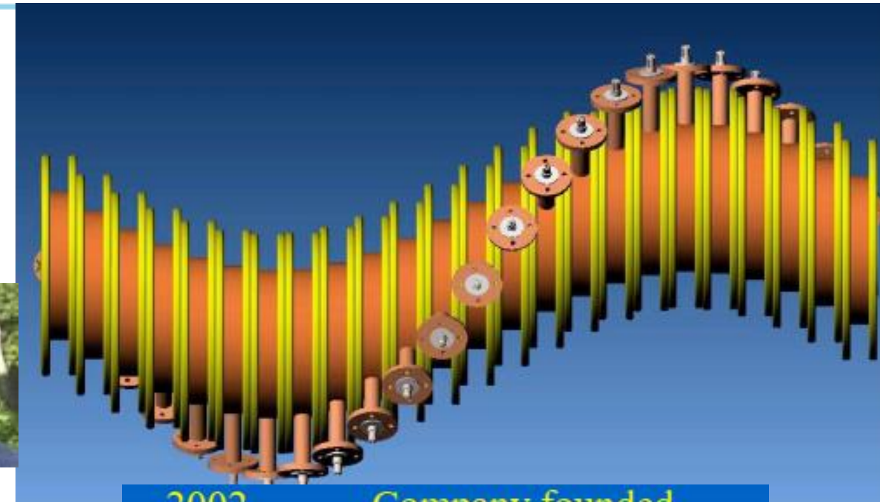
Example: R. Johnson → Muons, Inc.

- **Rolland Johnson**
  - Fermilab graduate

- **Helical Cooling Channel**
  - Derbenev and Johnson

- **Started company to participate in muon collider research (2002)**

- **Large Number of innovations and contributions**



2002	Company founded
2002-5	High Pressure RF Cavity
2003-7	Helical Cooling Channel
2004-5	MANX demo experiment
2004-7	Phase Ionization Cooling
2004-7	H2Cryostat - HTS Magnets
2005-8	Reverse Emittance Exch.
2005-8	Capture, ph. Rotation
2006-9	G4BL Simulation Program
2006-9	MANX 6D Cooling Demo
2007-10	Stopping Muon Beams
2007-10	HCC Magnets
2007-8	Compact, Tunable RF
2008-9	Rugged RF Windows
2008-9	H2-filled RF Cavities

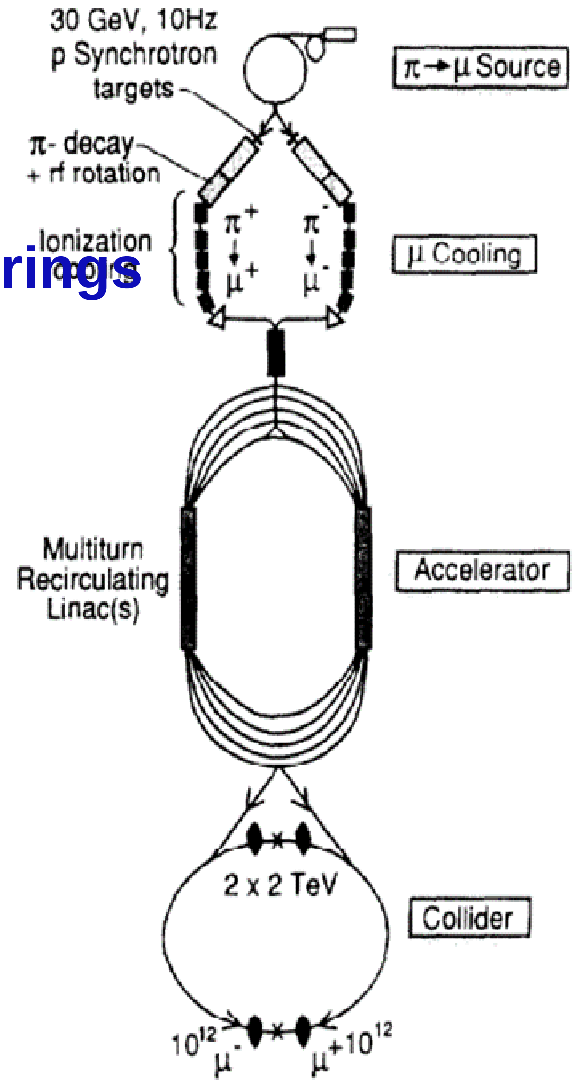
Muon Accelerator Program

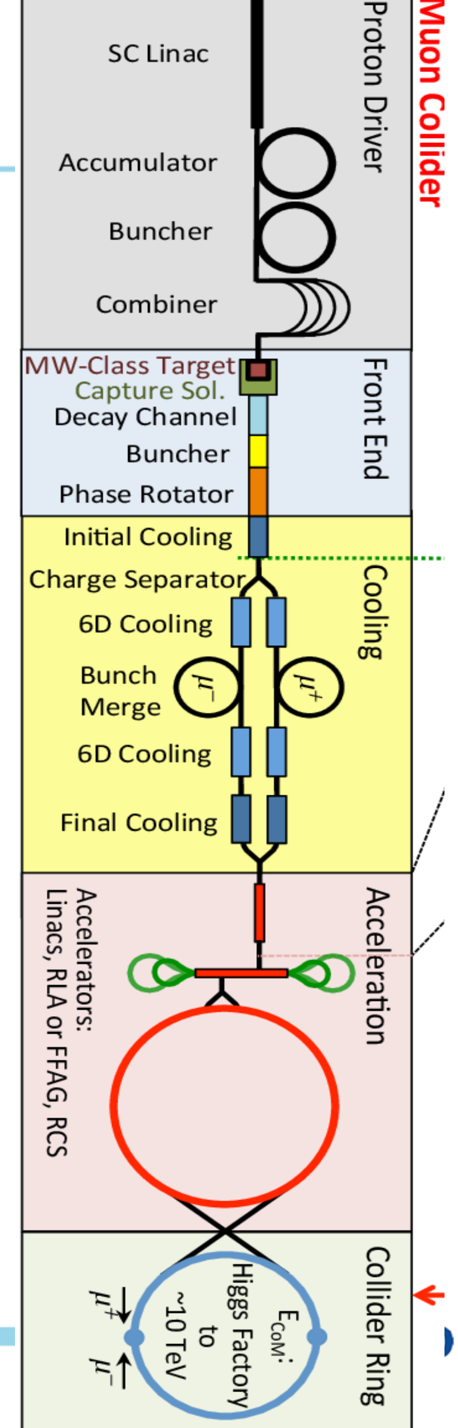
- **MAP Design Study**
  - **2010-2014, M. Palmer, director**
- **Directed toward implementation of a muon program**
  - **Toward specific designs**
- **Staged approach**
  - **Proton driver upgrade (~ Project X)**
  - **Muon and neutrino program**
  - **Staged cooling**
  - **Staged accelerators and colliders**
- **rf studies**
  - **Gas filled rf, breakdown in magnetic field**
- **Implemented MICE experiment**

M. Palmer

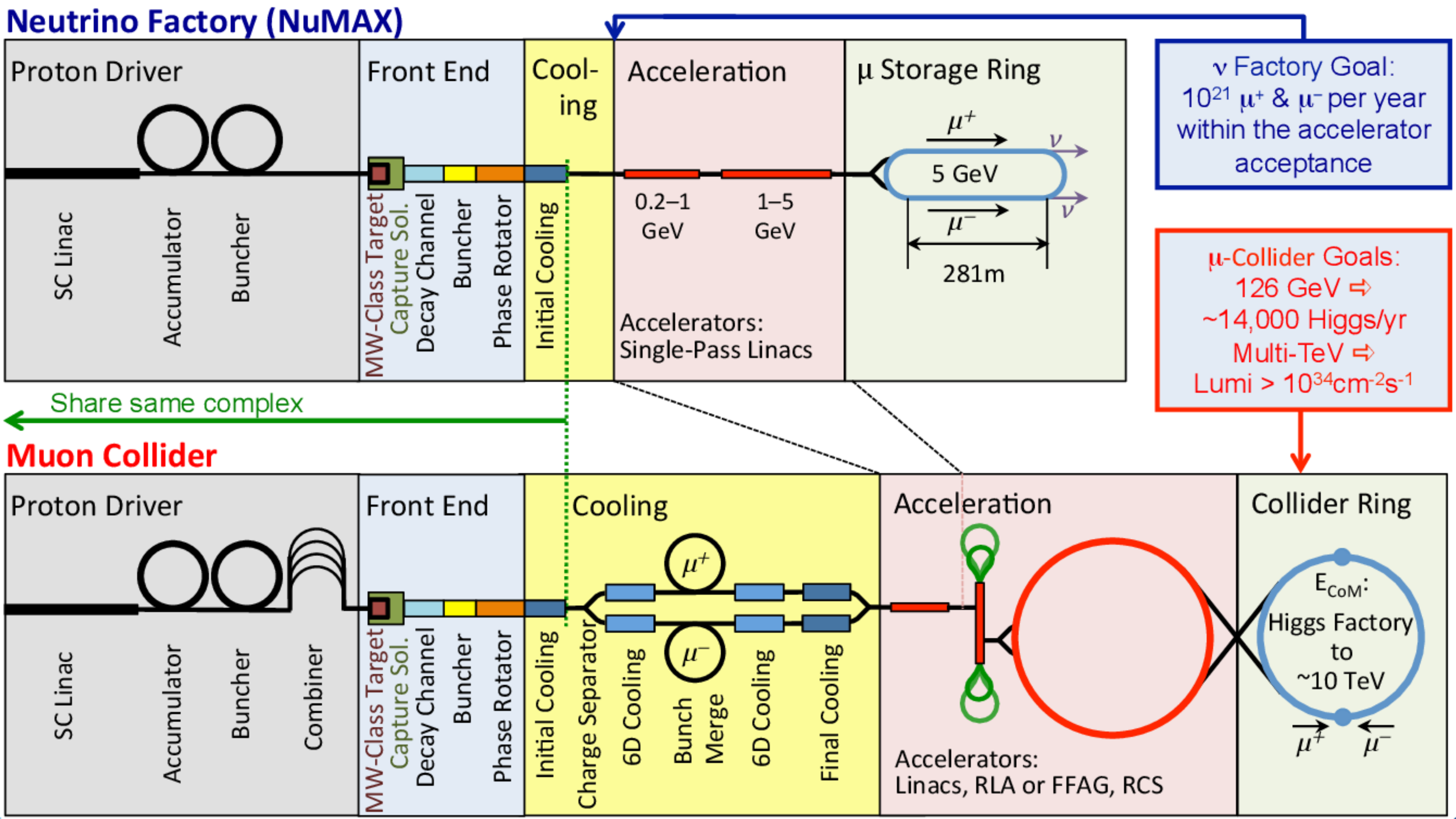
1994→ 2014

- **Proton Driver**
  - **RCS → Linac + Storage rings**
- **Front End & Cooling**
  - **Li lens**
  - **-> solenoids**
- **Acceleration**
  - **Recirculating Linacs →**
  - **Rapid Cycling Hybrid Synchrotrons→**
- **Collider**
  - **4 TeV → 10 TeV**
    - **8T → ~16 T**





MAP Program



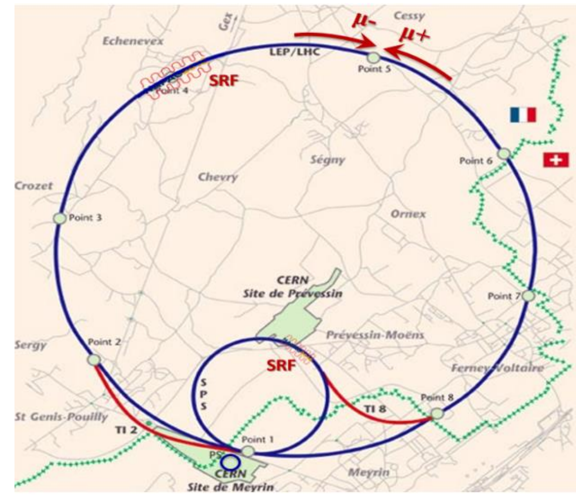
Neutrino Factory (NuMAX)
Proton Driver
SC Linac
Accumulator
Buncher
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cool-ing
Initial Cooling
Acceleration
0.2–1 GeV
1–5 GeV
Accelerators: Single-Pass Linacs
μ Storage Ring
μ+
5 GeV
μ−
ν
281m
ν Factory Goal: 10^21 μ+ & μ− per year within the accelerator acceptance
μ-Collider Goals: 126 GeV ⇨ ~14,000 Higgs/yr Multi-TeV ⇨ Lumi > 10^34cm^-2s^-1
Share same complex
Muon Collider
Proton Driver
SC Linac
Accumulator
Buncher
Combiner
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cooling
Initial Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
μ+
μ−
Acceleration
Accelerators: Linacs, RLA or FFAG, RCS
Collider Ring
E_CoM: Higgs Factory to ~10 TeV
μ+
μ−

2014 P5 report – limited resources

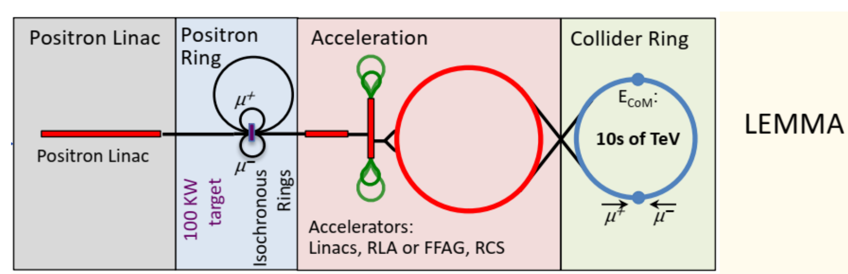
- **Emphasis on developing an affordable flagship project**
  - **DUNE + LBNF neutrino project**
- **MAP program progress**
  - **Too expensive**
- **MAP and related programs completely canceled**
- **No compensatory General Accelerator R&D increase**
- **PIP-II (initial part of Proton Driver) funded**

After p5 2014

- ➢ **Muon Collider Effort severely restricted**
  - **Muon Collider → Heavy Lepton Collider**
    - **MTA: rf in magnetic fields**
- ➢ **MICE experiment continues**
  - **Published results (2000)**



  - **14 TeV Muon Collider at CERN (IPAC 18, JINST**
    - **D. Neuffer & V. Shiltsev**
  - **"Low EMittance Muon Accelerator**
    - Phys. Rev. Accel. and Beams 21, 061005 (2018)
    - M. Boscolo, P. Raimondi, et al



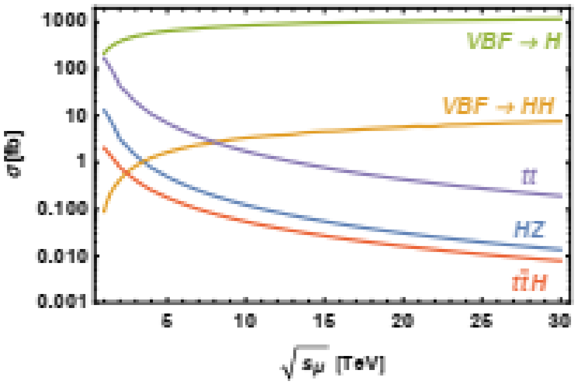
- ➢ **COVID March 2000**
  - ➢ **Travel → ZOOM**

European based Collaboration

- An **international collaboration** on Muon Collider
  - MUST (MUon STudy)
- 3 → 10→ 14 TeV Collider
- μμ Collider R&D included in European Strategy Document

Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}$	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

Future high energy colliders and options for the U.S
P. Bhat, S. Jindariani et al.

- **Largest**

Radius is ~2.7 km

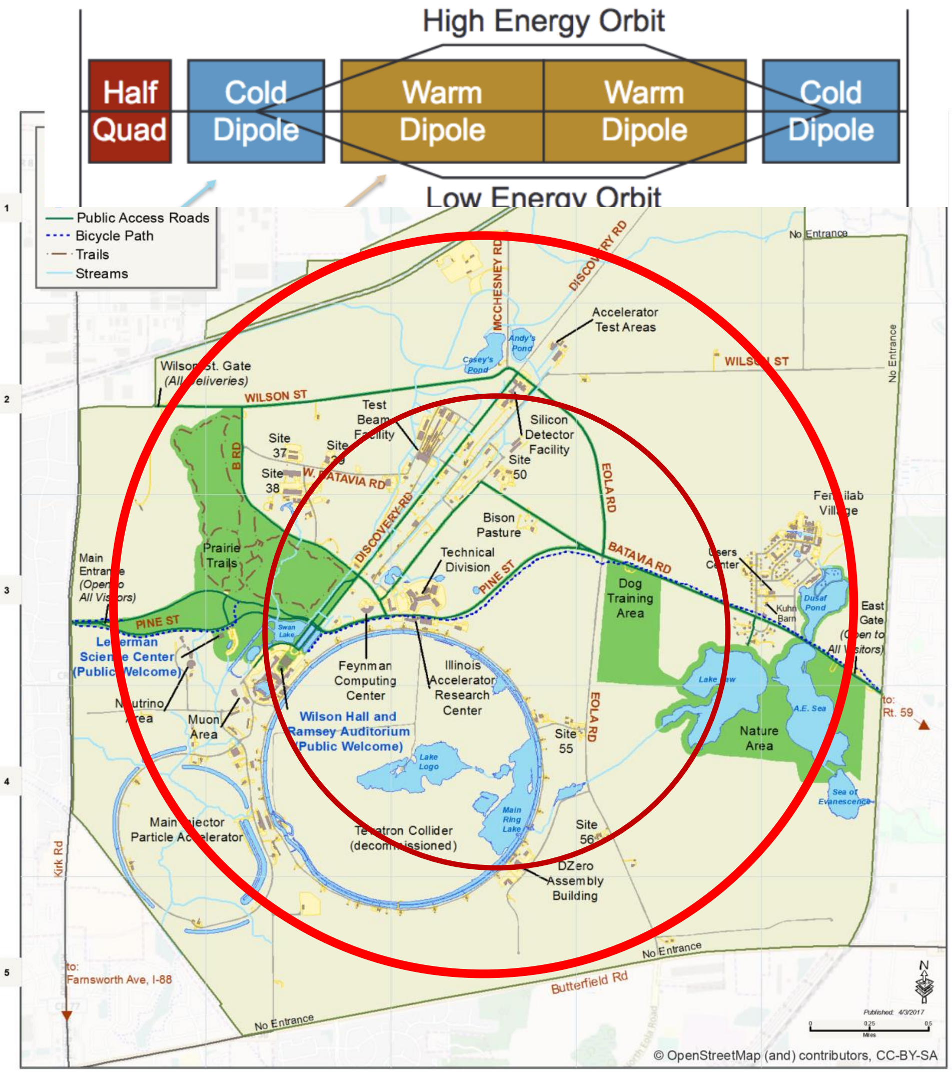
- **~17km Circumference**
  - **~2/3 LHC**

- **5 TeV Accelerator**

  $B_{ave} = 6\ T \rightarrow E_{\mu} = 5\ TeV$

  $(B_{max} = 16T,\ B_{pulse} = \pm 2T)$

- **10 TeV Collider Ring**
- $B_{ave} = 10\ T$



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

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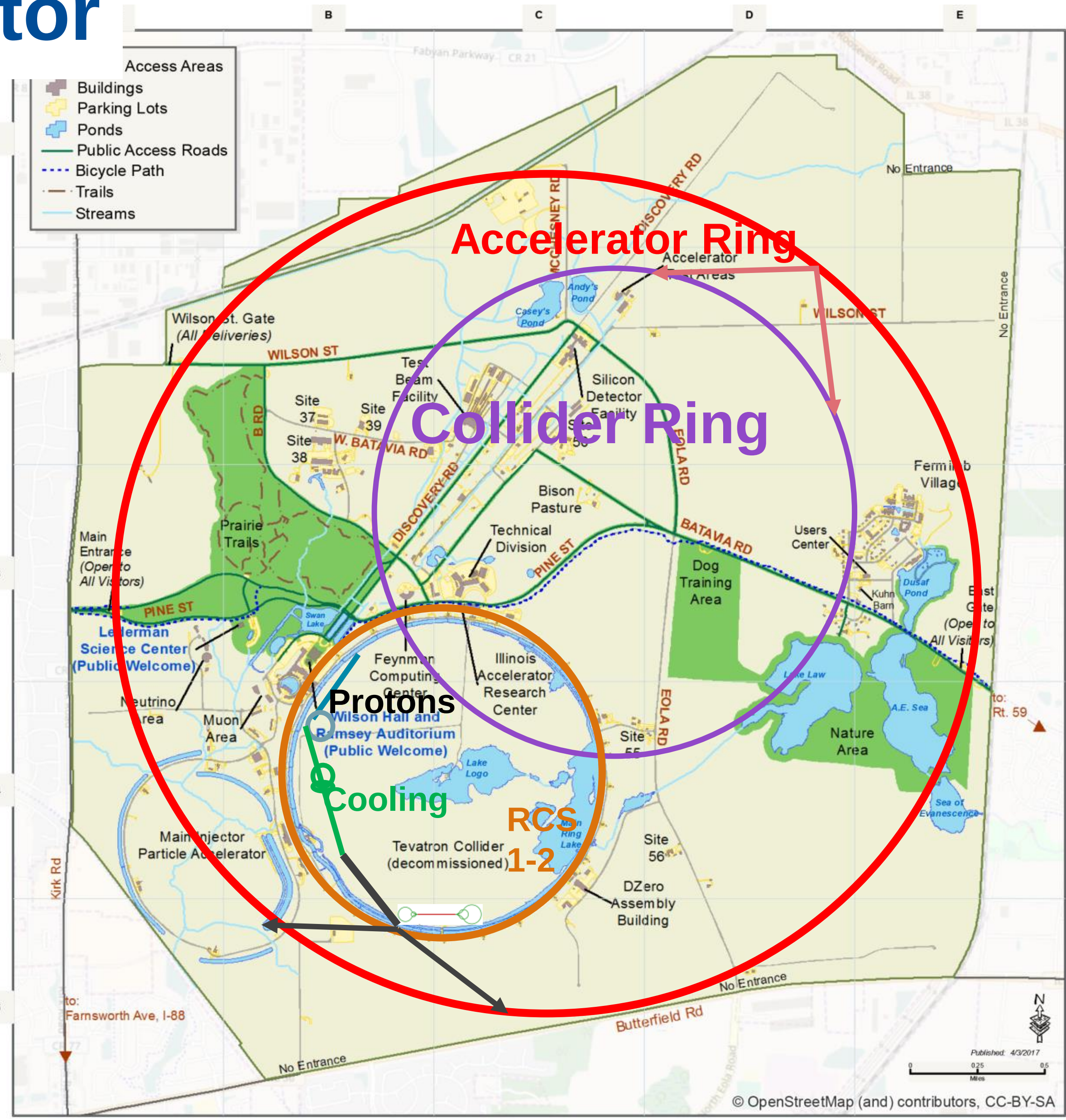
Site filler Accelerator

- **Proton Source**
  - PIP-III→target
- **μ Cooling**

- **Linac + RLA → 65 GeV**

- **RCS 1 and 2 → 1000 GeV**
  - Tevatron-size

- **RCS 3&4 → 5 TeV**
  - Site filler accelerator



10 TeV collider

Collider Ring ~10 km

5 TeV with 16 ± 2 T RCS components

➢0-65 GeV Linac + 10-turn RLA

3 GeV Linac
- 650 MHz SRF

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

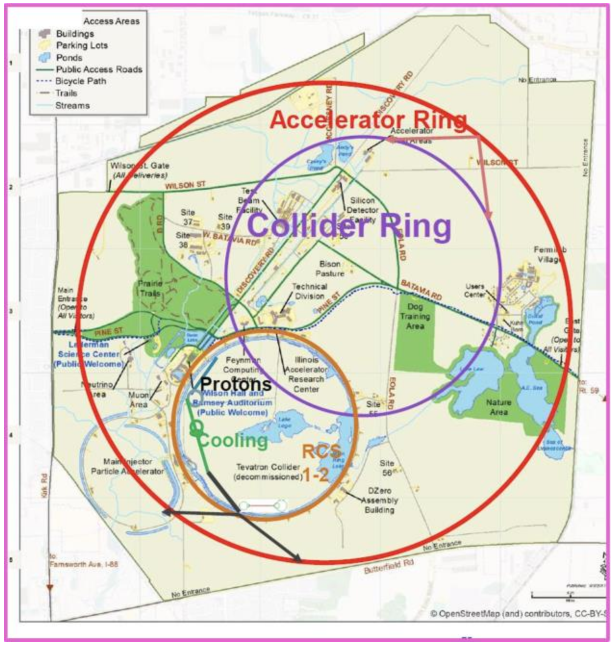
➢65 GeV → 5 TeV

- **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 and 4 – 1 → 5 TeV**
  - **Hybrid 16±2 T**

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

Muon Fever



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What changed since the last P5?
Sergo & Diktys

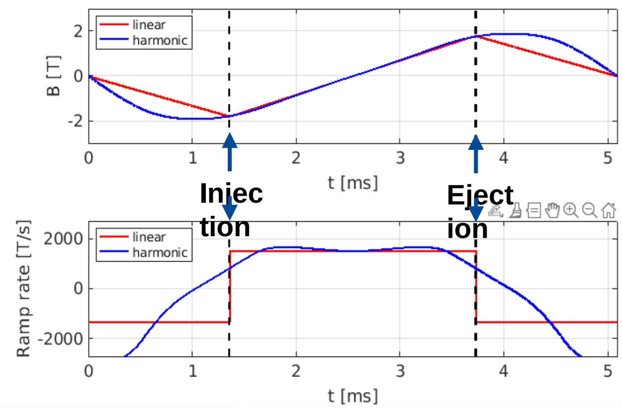
- **Physics:** Strong surge of interest in Muon Colliders within the theoretical and experimental communities. Shift of emphasis in Muon Colliders from 125 GeV to 10 TeV energy [ref]
- **Accelerator Technology**:
  - Muon Accelerator Program (MAP) results completed and published, including designs of various subsystems [ref]
  - Important technological progress: multi-MW proton sources [ref], demonstration of RF in magnetic field [ref], high field solenoids [ref], good solution for neutrino flux mitigation, etc.
  - Muon Ionization Cooling Experiment (MICE) confirmed muon ionization cooling principle, results published [ref]
- **Detector technology :** Large leap in detector technologies in part from R&D done for HL-LHC upgrades. Feasibility of good quality physics established in simulation [ref]
- **International Muon Collider Collaboration (IMCC) established.** The process of forming US organization is ongoing.

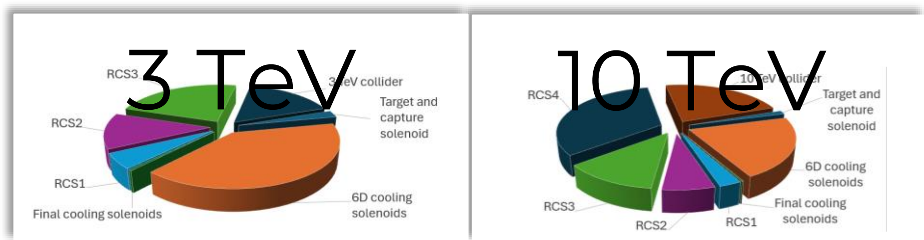
International Muon Collider Collaboration 2021 -

- **International muon fever outbreak**
- **Large enthusiastic collaboration**
  - **Students, postdocs**
- **Major research effort**
  - **>200 scientists/engineers/**
- **Acceleration**
  - **Hybrid RCS design & simulation**
  - Vertical FFA alternative
- **Magnets**
  - **HTS magnet designs**
  - **Complete assessment**

International MUON Collider Collaboration

D. Schulte





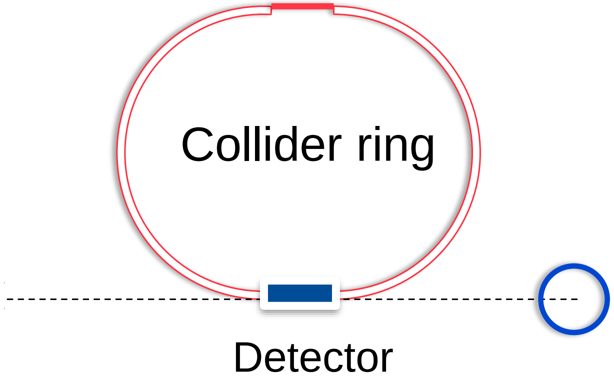
IMCC R&D

➢Collider Rings

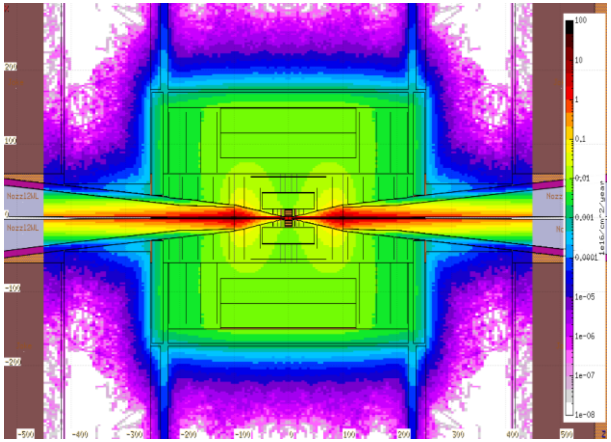
- **3 and 10 TeV Colliders and Detectors**

- **Collider Ring Location**
  - **Nu flux < 1 mrem/year from arcs**
  - **Straight sections point to Jura Mountains (Nu detectors)**
  - **And Mediterranean Sea**

B_{ve}= 6 T



- **Detectors**
  - **LHC + CLIC experience + improving electronics**



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$\mu^+\mu^-$ Collider will also be $p^+\ \mu^-$ Collider

- ➢ **Muon accelerator chain will also accelerate protons**

- ➢ **~100 GeV → 5 TeV proton accelerator**
  - Useful debugging mode for
  - Muon accelerator

- ➢ **Very natural to store p's in collider ring**
  - Can inject μ^- for Collisions

- ➢ **Luminosity can be large**

Fermilab has compatible proton source

E. μ-p Collider

A significant advantage of muons over electrons is that they can be stored in the same storage ring as protons for lepton-proton collisions. In Fig. 8, the storage ring could contain protons before μ injection at full energy, or in Fig. 9 protons could be injected with μ^- for acceleration. Luminosities can be higher than in $\mu^+\mu^-$ scenarios because of the larger number of protons, and as discussed above it is easy to match μ and p emittances.

The two revolution frequencies are naturally mismatched because of the different velocities at equal energies. They could be rematched by displacing the two beams in energy under the condition

$$\frac{\Delta p}{p}\left[\frac{1}{{\gamma_T}^2}-\frac{1}{\gamma^2}\right] \cong \frac{1}{2{\gamma_p}^2}-\frac{1}{2{\gamma_\mu}^2}, \qquad (27)$$

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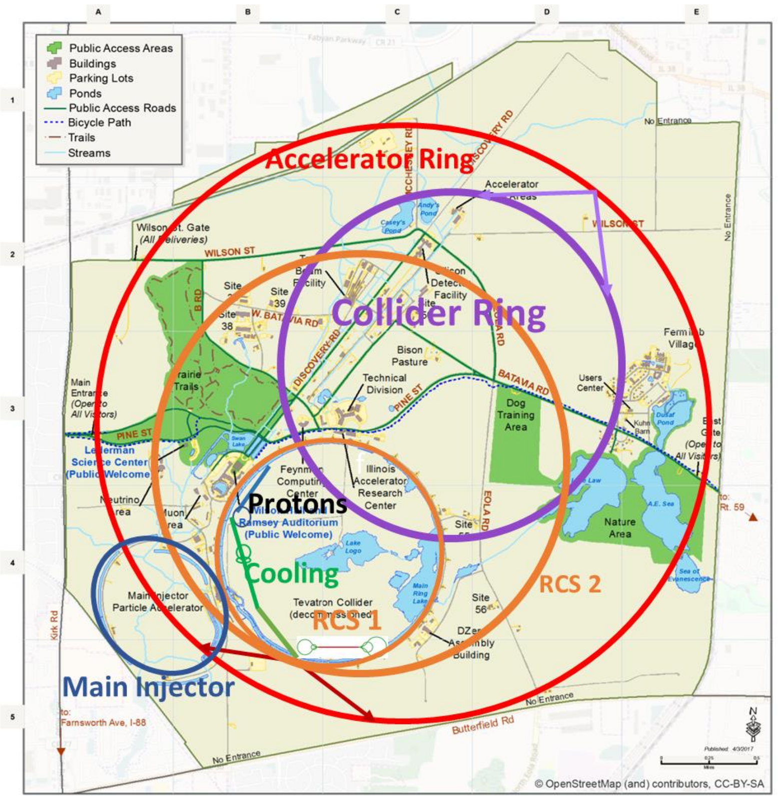
Acceleration variant

- ➢ B_{max}: 16 → 15 T
- ➢ B_{cycle}: ±2 → ±1.8 T



New Acceleration Scenario Parameters

Parameter	Symbol	Unit	RCSI	RCS2	RCS3	RCS4
Hybrid RCS			No	Yes	Yes	Yes
Repetition rate	f_{rep}	Hz	5	5	5	5
Circumference	C	m	6280	10500	16500	16500
Injection energy	E_{in}	GeV	125	450	1725	3560
Ejection energy	E_{ej}	GeV	450	1725	3560	5000
Energy ratio	E_{ej}/E_{in}		3.60	3.83	2.06	1.40
Decay survival rate	N_{ej}/E_{in}		0.85	0.83	0.85	0.89
Acceleration tirne	τ_{acc}	ms	0.86	3.71	8.80	9.90
Revolution period	T_{rev}	µs	21	35	55	55
Number of turns	N_{turn}		41	106	160	180
Required energy gain per tum	AE	GeV	8	12	11.5	8.0
Average accel. Gradient	G_{avg}	MV/m	1.27	1.15	0.70	0.48
Bunch population at injection	N_{in}	10^{12}	3.3	2.83	2.35	2.0
Bunch population at ejection	N_{ej}	10^{12}	2.83	2.35	2.0	1.8
Vertical norm. emittance	$\varepsilon_{v,N}$	mm-mrad	25	25	25	25
Horiz. norm. emittance	$\varepsilon_{v,n}$	mm-mrad	25	25	25	25
Long, norm. emittance ε	$\varepsilon_{z,n}$	eV-s	0.025	0025	0.025	0.025
Total straight length	Lstr	m	1068	1155	2145	2145
Total NC dipole length	L_{NC}	m	5233	7448	10670	8383
Total SC dipole length	Lsc	m		1897	3689	5972
Max. NC dipole field	B_{NC}	T	1.80	1.80	1.80	1.80
Max. SC dipole field	B_{SC}	T		12	15	15
Ramp rate	B'	T/s	1512	970	440	363
Main RF frequency	f_{rf}	MHz	1300	1300	1300	1300
Total RF voltage	V_{rf}	MV	9238	13860	13280	9238

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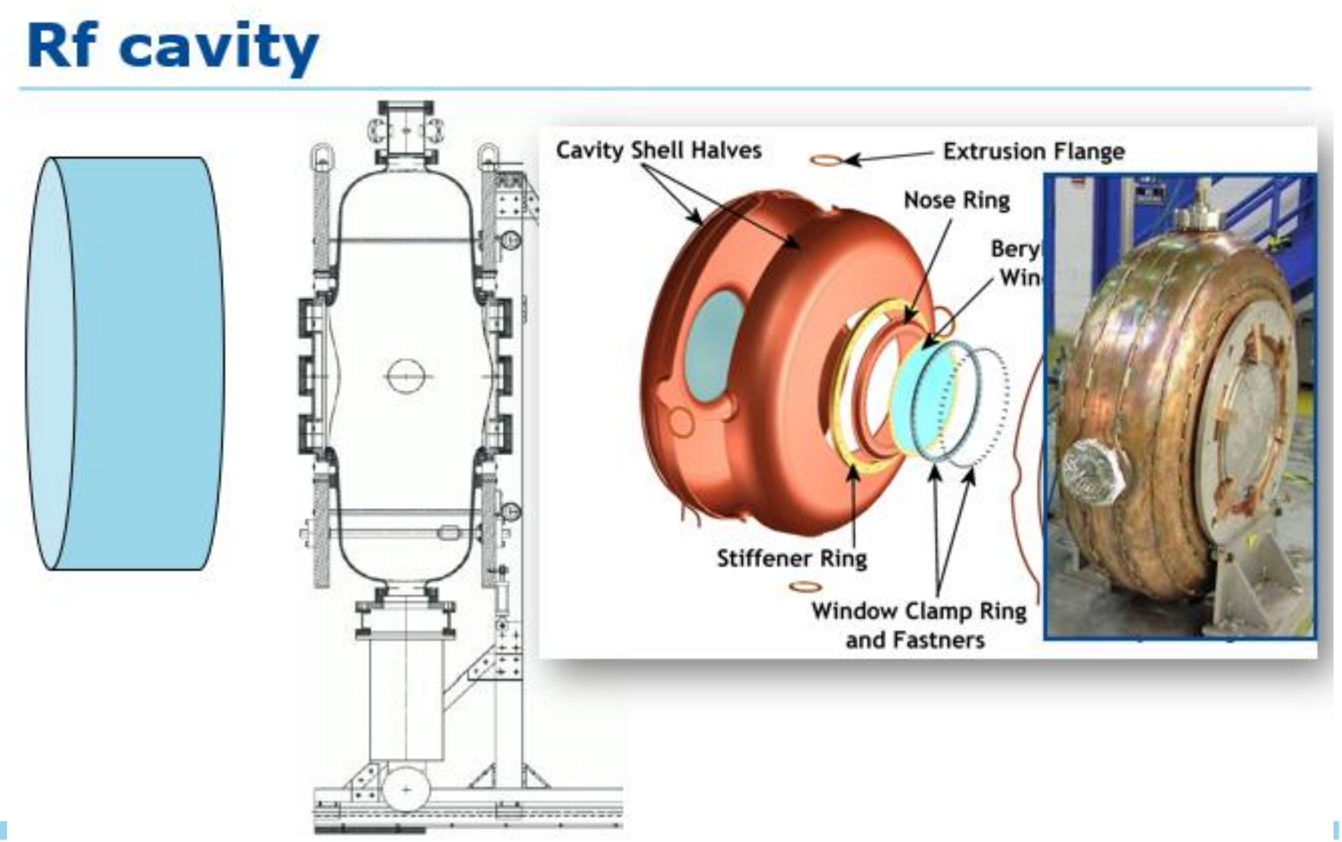
The next 45 years?

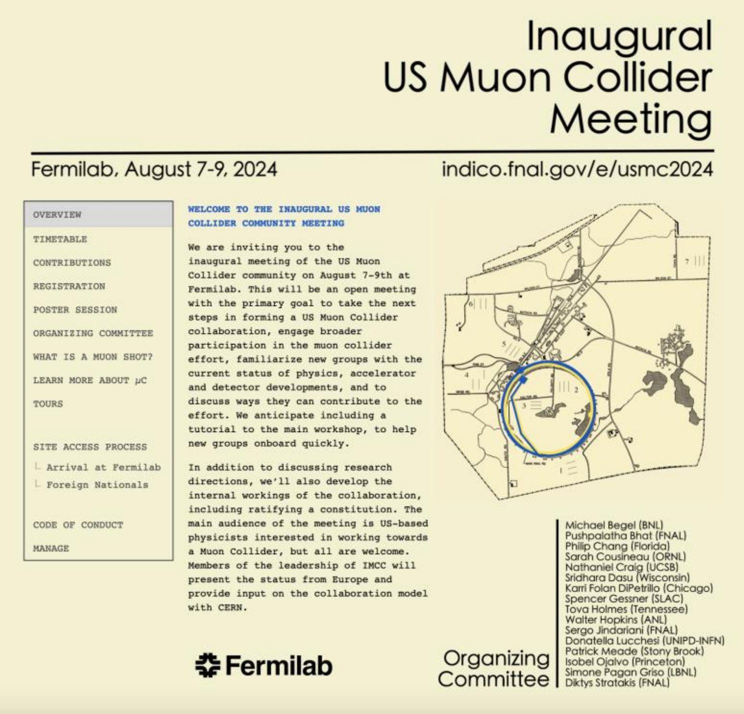
- **Many inventions/innovations/improvements needed**

- **Need to turn concepts into objects**



Upcoming Muon Collider Meetings at Fermilab

- US Muon Collider Community Meeting August 7-9th, 2024 at Fermilab: https://indico.fnal.gov/e/usmc2024



IMCC Demonstrator Workshop Oct 30th – Nov 1st, indico will be available soon

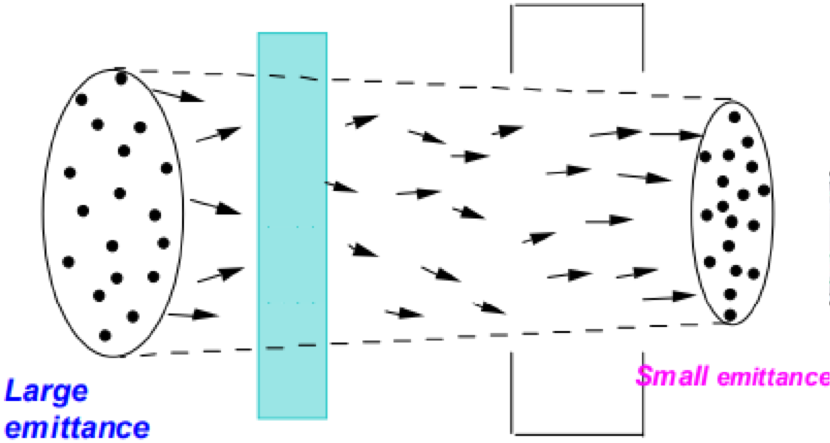
Summary

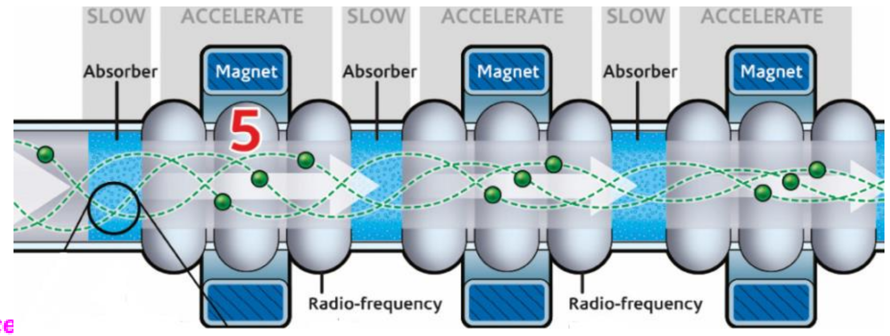
- Fermilab site filler
  - ~10 TeV Collider could be built at Fermilab
  - (5 × 5 TeV)
- "Difficult but perhaps not impossible…" (FN-348, July 1979)

Fermilab

Thank you for your attention

Fermilab


Large
emittance
Small emittance


SLOW
ACCELERATE
SLOW
ACCELERATE
SLOW
ACCELERATE
Absorber
Magnet
Absorber
Magnet
Absorber
Magnet
5
Radio-frequency
Radio-frequency