Fermilab

Muon Colliders: Progress and Plans

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Motivation

- We want high-luminosity multi-TeV lepton-lepton collisions!

→ we need accelerator R&D!

- The Muon Collider concept is attractive because muons do not radiate as readily as electrons (m_μ / m_e ~ 207):

- Circular (compact) multi-TeV Lepton Collider that would fit on an existing laboratory site → hope that Muon Colliders will be affordable.

- Very small beam energy spread enabling precise scans and width measurements → Muon Colliders may have a special role for precision measurements.

The Challenge

• To produce sufficient luminosity for an interesting physics program ($L = 10^{34}$-10^{35} $cm^{-2}s^{-1}$ at $\sqrt{s}$ = 1-few TeV) will require very bright muon beams. This is challenging because:

$\rightarrow$ Muons produced as a tertiary beam that occupies a large longitudinal & transverse phase space. The beam must be cooled by a large factor: a longitudinal emittance reduction of about $\times 14$ & a transverse emittance reduction of about $\times 400$ $\rightarrow$ 6D reduction of $\sim 14 \times 400 \times 400 = 2 \times 10^6$; cf NF which requires transverse emittance reduced by factor of a few.

$\rightarrow$ Muons decay ($t_0 = 2\mu s$). Beam manipulation & acceleration must be rapid.

• If we can meet this challenge, we will also have the technology for neutrino factories and for low energy muon experiments using up to $\sim 10^{21}$ muons/year !

Muon Collider Baseline Parameters

Energy	0.1 TeV	3 TeV
Proton Srce Power	4 MW	3.5 MW
Rate	15 Hz	30 Hz
Muons / bunch	4×10^{12}	2×10^{12}
Bunches	1×1	2×2
Circumference	0.35 km	6 km
Effective turns	450	900
$\beta_\perp$	9.4 mm	3 mm
$\varepsilon_\perp$ (mm radians)	0.195	0.05
$\varepsilon_{//}$	5 mm	72 mm
$\Delta\nu$	0.022	0.044
$\Delta p/p$	0.01 %	0.16 %
Luminosity ($cm^{-2}\ s^{-1}$)	2.2×10^{34}	7×10^{34}

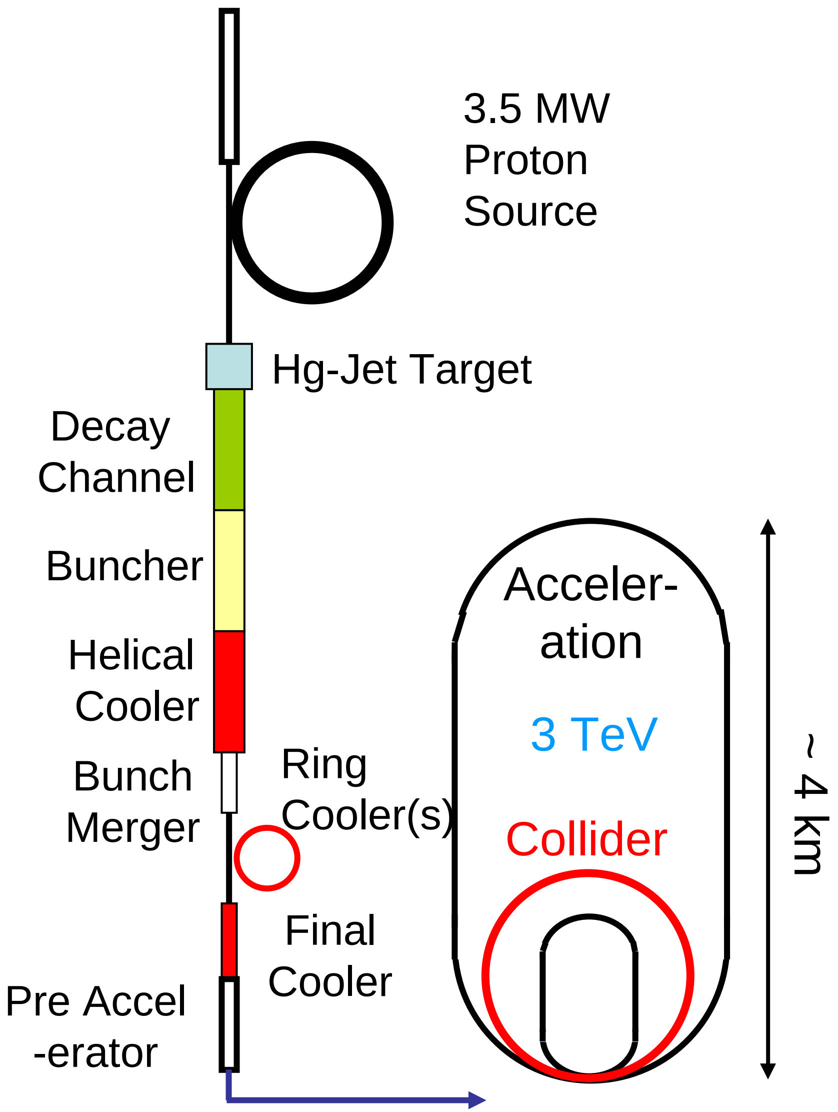
Requires 1×10^{21} μ^+ / year
Similar to (a little more than) number of muons expected from Neutrino Factory front-end

Collider energy limited by "neutrino radiation" (high energy muon decays in straight sections produce collimated beam of neutrinos that interact in Earth to produce a radiation field at exit point). $\sqrt{s}$=3 TeV considered safe, $\sqrt{s}$=4 TeV marginal.

If beam-beam tune shift can be corrected, lower emittance beams would enable use of fewer muons $\rightarrow$ higher energy colliders plausible (but dose ~ E^4 … win slowly).

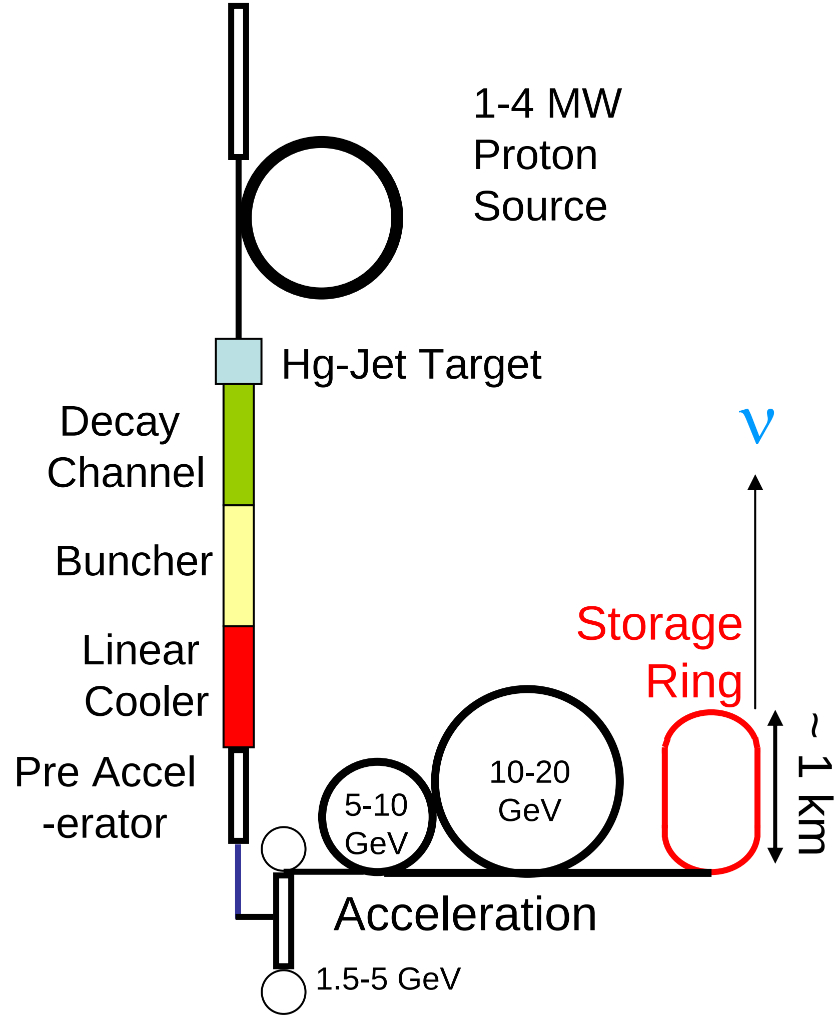
Muon Collider Ingredients

- Proton Driver
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce 6D emittance
- Acceleration
  - 130 MeV $\rightarrow$ up to 1.5 TeV
- Storage Ring
  - store for ~1000 turs
  - One IP



Neutrino Factory Ingredients

- Proton Driver
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce transverse emittance
- Acceleration
  - 130 MeV $\rightarrow$ 20 GeV
- Storage Ring
  - store for 500 turns; long straight section



US Design schematic

News from the Recent Past

US front-end MC & NF designs used to be very different.

NF design: The bunching/phase rotation/cooling $\rightarrow$ many muon bunches.

MC design: Want to end up with 1 or 2 muon bunches / cycle to maximize luminosity. We used to think the best way to achieve this was to make one bunch at the beginning, & keep hold of it through the entire front-end.

This meant using low frequency rf systems. We did not succeed in producing a practical, self-consistent cooling channel that reduced the emittance by the $O(10^6)$ factor needed for a MC.

In the last 2 years it has been realized that it is easier to start with many bunches, & combine in the middle of the cooling scheme $\rightarrow$ first complete self-consistent MC cooling channel designs and …

the MC & NF front-ends (up to the beginning of the cooling) are the same !

(See talks from the Low Emittance Muon Collider Workshop, Fermilab 6-10, 2006: http://www.muonsinc.com/)

Neutrino Factory vs Muon Collider

	NF	MC
Proton Beam	Yes	Same
Target	Yes	Same
Capture & Decay	Yes	Same
Buncher	Yes	Same
Phase Rotation	Yes	Same
Early Cooling	Yes	Same ?
More Cooling	No	Yes
Early Acceleration	Yes	Different
More Acceleration	No	Yes
Storage Ring	Yes	Different
Detector	Yes	Different

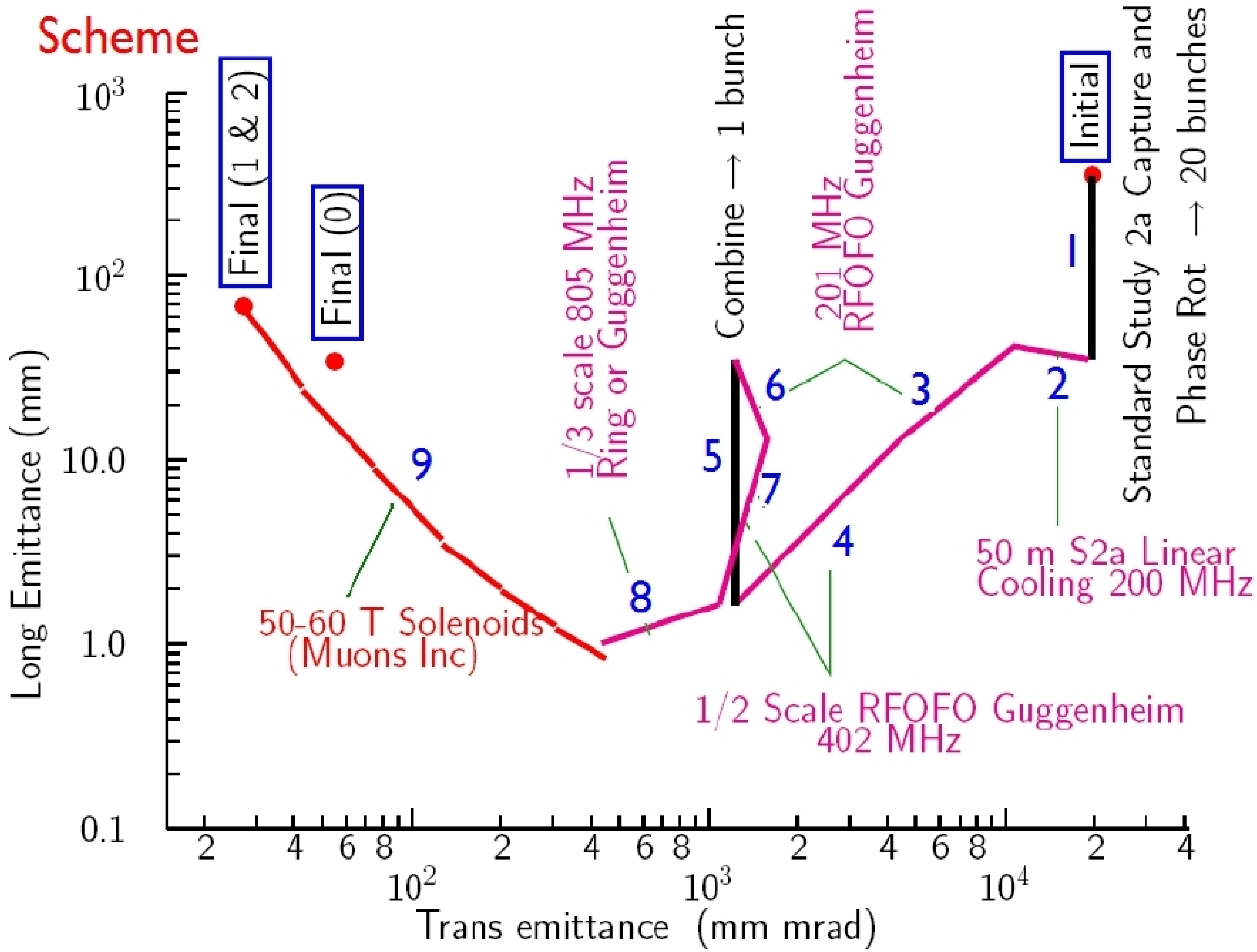
We will need to choose which neutrino source will best serve our long-term needs.

The choice may not be independent of the bigger "we want a multi-TeV lepton collider" picture.

Neutrino Factories & Muon Colliders are linked by their common R&D and possible staging path.

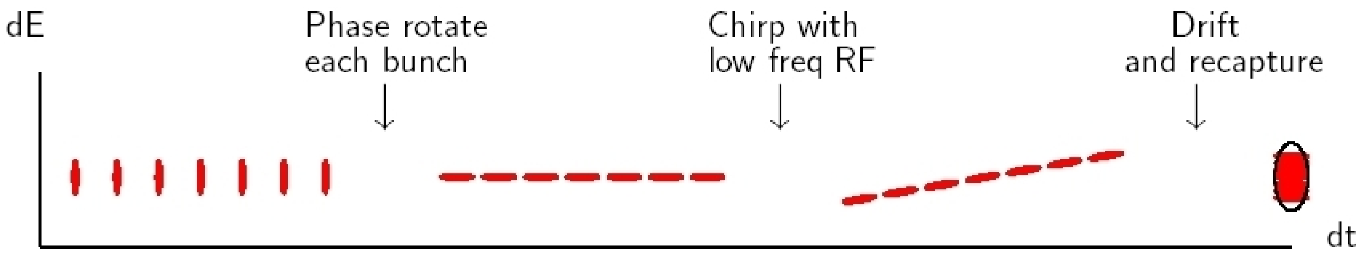
News: A Complete Cooling Scheme

(Palmer et al)

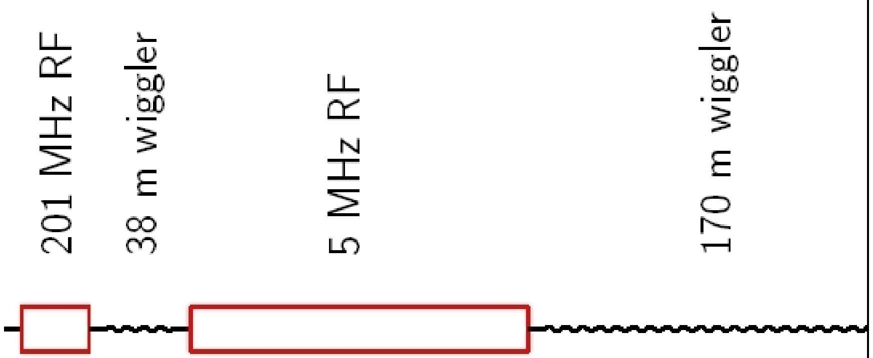


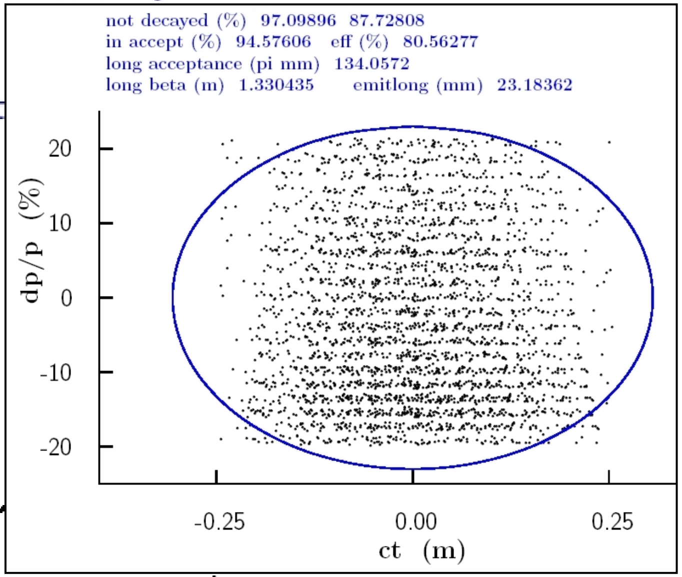
Bunch Merging is Critical

(Palmer et al)



- First rotation with sawtooth RF rotates all bunches individually
- Second rotation with single ramp rotates all bunches
- Merged bunches captured with standard 201 MHz RF





Using ICOOL simulated wigglers to maximize momentum compaction

Cooling Technologies

There are competing ideas (using different technologies) for the various steps in the cooling chain:

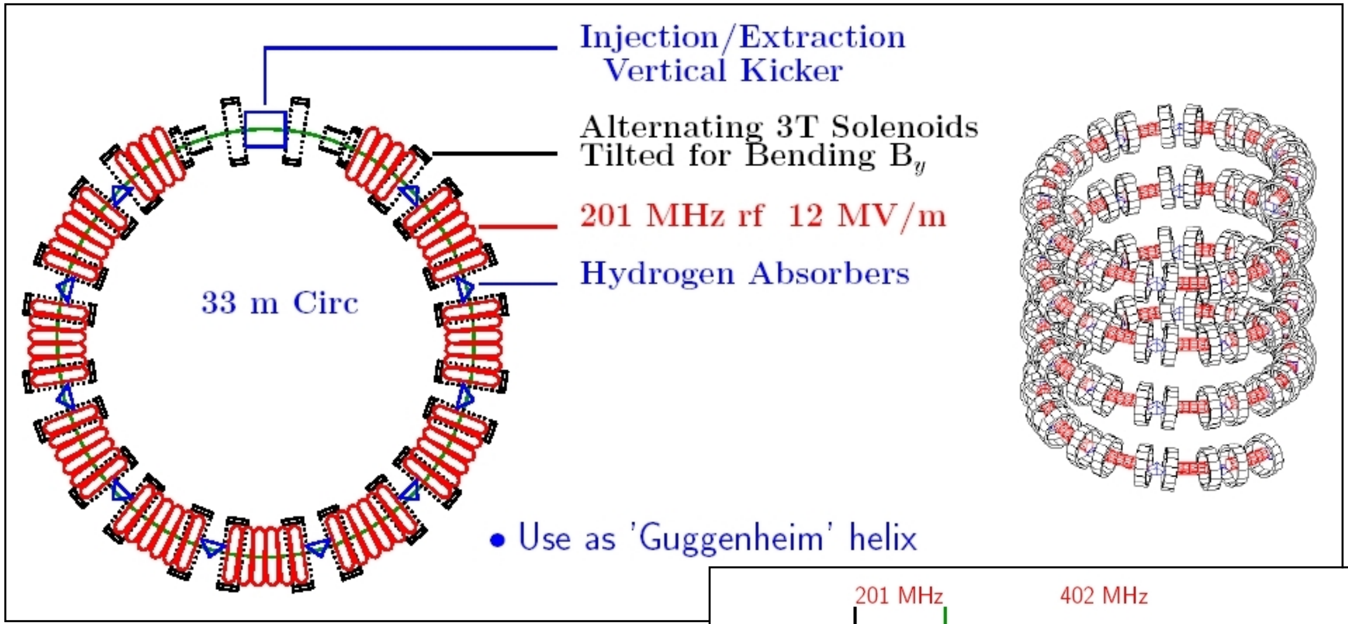
Palmer et al:
RFOFO Ring
Guggenheim
50-60T Solenoid Channel

And new ideas are still emerging

Muons Inc.
High pressure gas-filled cavities
Helical Cooling Channel
Reverse Emittance Exchange
Parametric Resonance Induced Cooling

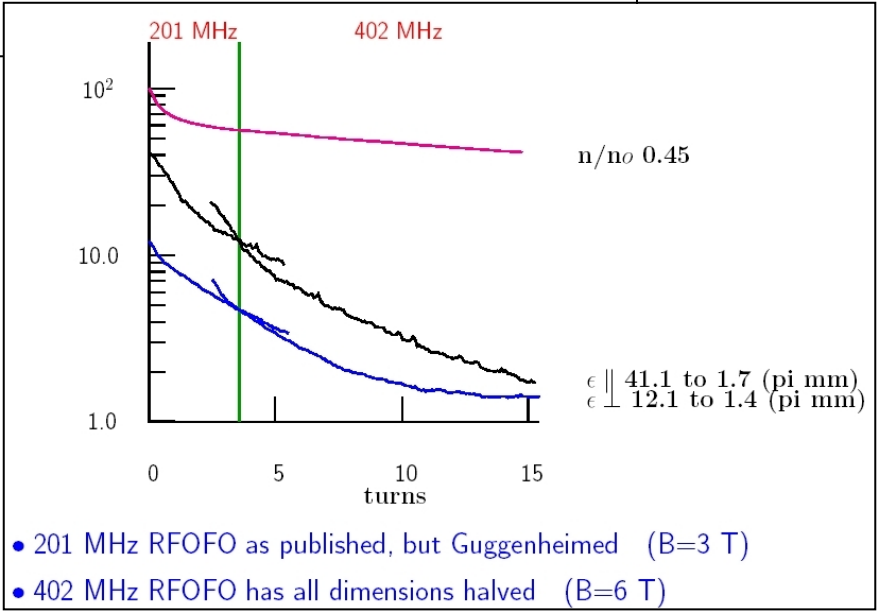
(I think) our task for the next couple of years will be to sort through the ideas with enough engineering input to identify the best bet(s) and define the required component R&D.

One Example from Palmer et al.



Steps 3 & 4 in Palmer et al scheme

RFOFO RING &
The GUGGENHEIM

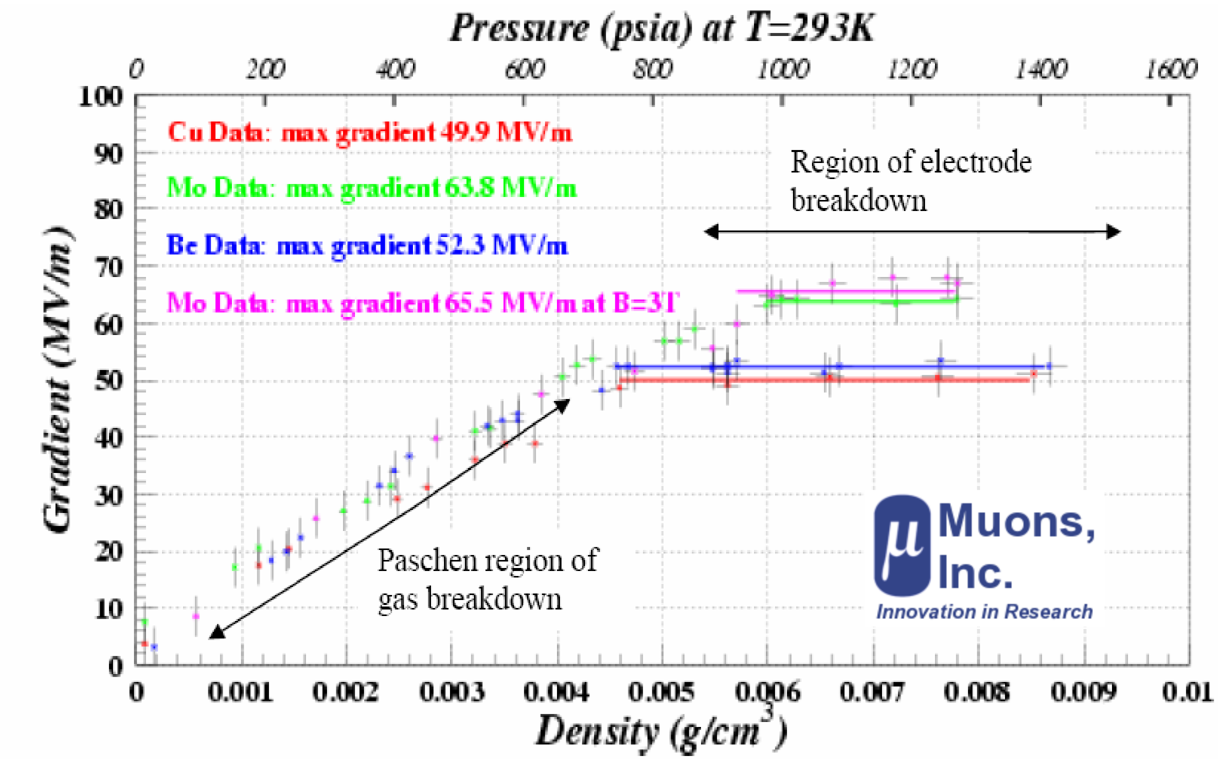


One Example from Muons Inc.

MUCOOL R&D → achievable in a normal rf cavity may be limited if the cavity operates within a significant magnetic field. If this turns out to be the case we will have to redesign our baseline cooling channel lattices.

Muons Inc have proposed using cavities filled with hydrogen (or helium) at high pressure (suppresses breakdown and provides energy-loss medium). Test cell results at 805 MHz are encouraging.

Latest News: Performance seems unaffected by magnetic Field.



The End of The Cooling Channel

The last few meters of cooling will (probably) require the most challenging cooling channel technology.

Presently favored idea is to use liquid hydrogen absorber in ~50T solenoids.

These could be like the 45T solenoid at the High Field Magnet Lab in Florida … but we need a handful of these & their power consumption is phenomenal $\rightarrow$ need a new technology.

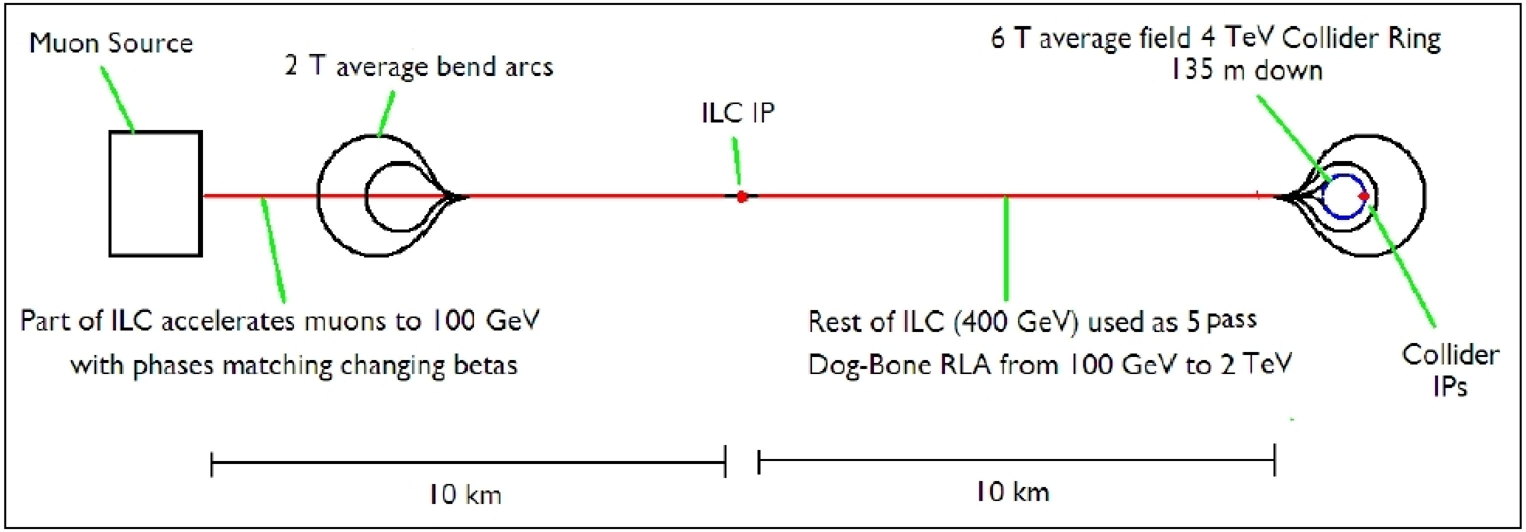
One approach to explore is to use high-T_c Superconductor, run cold to get to very high fields. This technology is developing fast, but we need some basic engineering studies to understand if 50T high-T_c cooling channel solenoids are plausible.

Acceleration

After the cooling, cost-effective (affordable) acceleration is next on the list of TeV-scale Muon Collider challenges.

Over the last couple of years there have been several dreams of using ILC accelerating structures to accelerate muons to TeV energies, reconfiguring some of the ILC into an on-site RLA.

Latest dream: use ILC as-is:



More studies needed before we know if this is plausible. If not, there are alternative schemes using linacs and rapid cycling synchrotrons.

Storage Ring

Needs to store beam for ~1000 turns

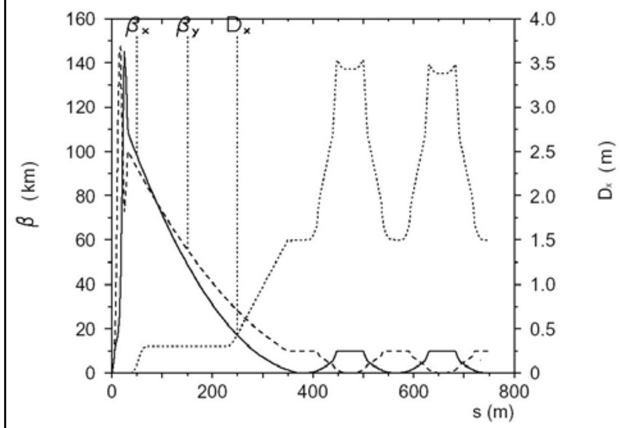
3TeV & Higgs Factory lattices have been studied (PRST-AB 2, 081001 (1999))

To achieve required luminosity at 3 TeV will need $\beta^* \sim 3$ mm at Interaction Point
$\rightarrow$ bunch lengths no larger than this
$\rightarrow$ almost isochronous ring.

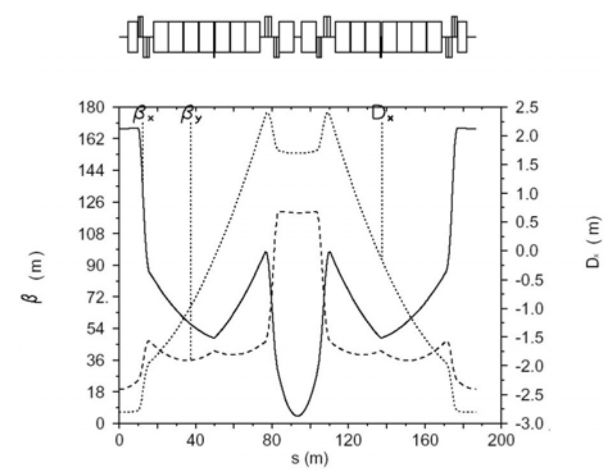
IR studied in detail (including shielding & detector backgrounds)

Dynamic Aperture ~OK (but needs some more study)

3 TeV IR Lattice with chromatic correction



3 TeV Arc Lattice



Detector Issues

Detailed GEANT & MARS studies of detector backgrounds were made in 1996-98 for a 4 TeV muon collider: 2×10^{12} muons/bunch $\rightarrow$ 2×10^{5} decays/m. Mean electron energy = 700 GeV.

With careful design of final focus, most electrons can be swept into shielding, but the forward physics (20 deg) is sacrificed.

R (cm)	γ	n	p	π	e	μ
5	2700	120	0.05	0.9	2.3	1.7
10	750	110	0.20	0.4	-	0.7
15	350	100	0.13	0.4	-	0.4
20	210	100	0.13	0.3	-	0.1
50	70	120	0.08	0.05	-	0.02
100	31	50	0.04	0.003	-	0.008

GEANT Results:
Radial fluxes / cm^2 / crossing

Thresholds:
E_γ = 25 keV; E_n = 40 keV
E_p = 10 MeV; E_π = 10 MeV

Corresponds to 0.4% occupancy in 300 x 300 μm^2 pixels at r = 10 cm & 1.3% occupancy at r = 5 cm; with doses comparable to LHC at 10^{34} cm^{-2} s^{-1}

Calorimeter backgrounds also look OK provided spikes from Bethe-Heitler muons can be removed by pattern recognition

Next Steps

Muon Collider & Neutrino Factory R&D have tremendous overlap.
It is important that we succeed with the NF R&D program (MICE, MERIT, ISS follow-on …).

Given the recent progress on Muon Collider cooling channel ideas, and steady progress with the relevant NF R&D, now is a good time to revisit the overall Muon Collider concept with an emphasis on the cooling channel design, acceleration scheme, and storage ring.

> Which of the cooling channel ideas are feasible and what component R&D is required ?
>
> Is a high-T_c 50T final-cooling section plausible ?
>
> Is using ILC accelerating structures OK ? (Great idea if it is!)

To make significant progress on these questions in the next couple of years will require more people and more accelerator R&D resources than we presently have.

News from Fermilab

As a step towards establishing an enhanced Advanced Accelerator R&D Program at Fermilab, the Fermilab Director has requested:

> “ … a Task Force to develop a plan for an advanced R&D program aimed at the technologies required to support the long term prospects of a Muon Collider. “

It is hoped this will bring in new people and advanced accelerator R&D resources so that significant progress can be made on the critical issues.

The first step, to be completed by end of September, is to develop an R&D proposal.

Summary

There is tremendous overlap between Neutrino Factory R&D and Muon Collider R&D.

Muon Colliders require much more beam cooling than Neutrino Factories, and (right now) this presents the biggest Muon Collider challenge.

New Muon Collider cooling channel ideas have emerged. The front-ends (proton source, targetry & collection, decay channel, phase rotation, and possibly early cooling) are now the same for Muon Colliders & Neutrino Factories.

Its time to look deeper at the competing candidate cooling technologies. Which are practical ? What component R&D is needed ? This needs a critical study with more people & resources.

Its also time to revisit the overall Muon Collider design, and explore further the idea of using ILC accelerating structures.

Lots of challenges, but also lots of progress. Keep tuned !

Muon Collider Parameter Table

C. Ankenbrandt et al., PRST-AB 2, 081001 (1999)

TABLE I. Baseline parameters for high energy and low energy muon colliders. Higgs/yr assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV, 1 yr $= 10^7$ s.

COM energy (TeV)	3	0.4		0.1	
p energy (GeV)	16	16		16	
p's/bunch	2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill	4	4		2	
Rep. rate (Hz)	15	15		15	
p power (MW)	4	4		4	
μ/bunch	2×10^{12}	2×10^{12}		4×10^{12}	
μ power (MW)	28	4		1	
Wall power (MW)	204	120		81	
Collider circum. (m)	6000	1000		350	
Ave bending field (T)	5.2	4.7		3	
rms $\Delta p/p$ (%)	0.16	0.14	0.12	0.01	0.003
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)	785	700	450	450	450
Luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/yr			1.9×10^3	4×10^3	3.9×10^3