



Muons, Inc.

A Low-Emittance Muon Facility using the Fermilab Linear SC Proton Driver

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<http://www.muonsinc.com/mcwfeb06/presentations/LEMCWorkshop.pdf>

- New ideas merged with older ones into a plan leading to an energy frontier muon collider (MC)
- A Fermilab-site specific baseline MC design based on SC RF
 - Using proposed proton driver Linac to also accelerate muons
- A staged plan to get to the energy frontier
 - Each step a funding package with an exciting experimental physics goal
 - Each step adds accelerator physics goals
 - Implies an exceptional neutrino factory as an intermediate step



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New inventions, new possibilities

- Muon beams can be cooled to a few mm-mr (normalized)
 - allows HF RF (implies Muon machines and ILC synergy)
- Muon recirculation in ILC cavities: high energy for lower cost
 - Affordable neutrino factory, which by coalescing, becomes
 - A muon collider injector for
- A low-emittance high-luminosity collider
 - high luminosity with fewer muons
 - LEMC goal: $E_{\text{com}} = 5 \text{ TeV}$, $\langle L \rangle = 10^{35}$
- Many new ideas in the last 5 years.
 - Need to convince the HEP community that it's a new ball game!

Recent Inventions and Developments

- **New Ionization Cooling Techniques**
 - Emittance exchange with continuous absorber for longitudinal cooling
 - Helical Cooling Channel
 - Effective 6D cooling (simulations: cooling factor 50,000 in 150 m)
 - Momentum-dependent Helical Cooling Channel
 - 6D Precooling device
 - 6D cooling demonstration experiment (>500% 6 D cooling in 4 m)
 - 6D cooling segments between RF sections
 - Ionization cooling using a parametric resonance
- **Methods to manipulate phase space partitions**
 - Reverse emittance exchange using absorbers
 - Bunch coalescing (neutrino factory and muon collider share injector)
- **Technology for better cooling**
 - Pressurized RF cavities
 - simultaneous energy absorption and acceleration and
 - phase rotation, bunching, cooling to increase initial muon capture
 - High Temperature Superconductor for up to 50 T magnets
 - Faster cooling, smaller equilibrium emittance
- See LEMC workshop for survey of some of these techniques



Muons at Fermilab

- An implementation plan with affordable, incremental, independently-fundable, sequential, steps:

	(RoI WAG \$M)
1. attractive 6D Cooling experiment	(10)
2. double-duty proton driver Linac	(500)
3. intense stopping muon beam	(500)
p accumulator/buncher, target, muon cooling	
4. exceptional neutrino factory (23 GeV)	(500)
more cooling, recirculation, PDL upgrade, decay racetrack	
5. Higgs factory (~300 GeV com)	(1500)
more cooling, RLA, coalescing & collider rings, IR	
6. energy frontier muon collider (5 TeV com)	(3000)
more RLA, deep ring, IRs	

1. MANX 6-d demonstration experiment

Muon Collider And Neutrino Factory experiment

- To Demonstrate
 - Longitudinal cooling
 - 6D cooling in cont. absorber
 - Prototype pre-cooler
 - Helical Cooling Channel
 - Alternate to continuous RF
 - $5.5^8 \sim 10^6$ 6D emittance reduction with 8 HCC sections of absorber alternating with (SC?)RF sections.
 - New technology



2. double-duty proton driver Linac (accelerates protons, then cooled muons)

- Basic Linac described by Foster et al.
- See talk by Milorad for muon components
- Replacement/upgrade of present 8 GeV injector complex
- Basic element of future Fermilab activities
 - (neutrino program esp.)
- Muon acceleration capability follows from extreme muon cooling and some acceleration
- ILC string test

3. intense stopping muon beam

- However, after producing and cooling but before reaccelerating the muons, stopping muon beams are needed
- HEP research
 - g-2
 - MECO
- Fundamental research
 - μ CF
 - μ SR

4. Neutrino Factory

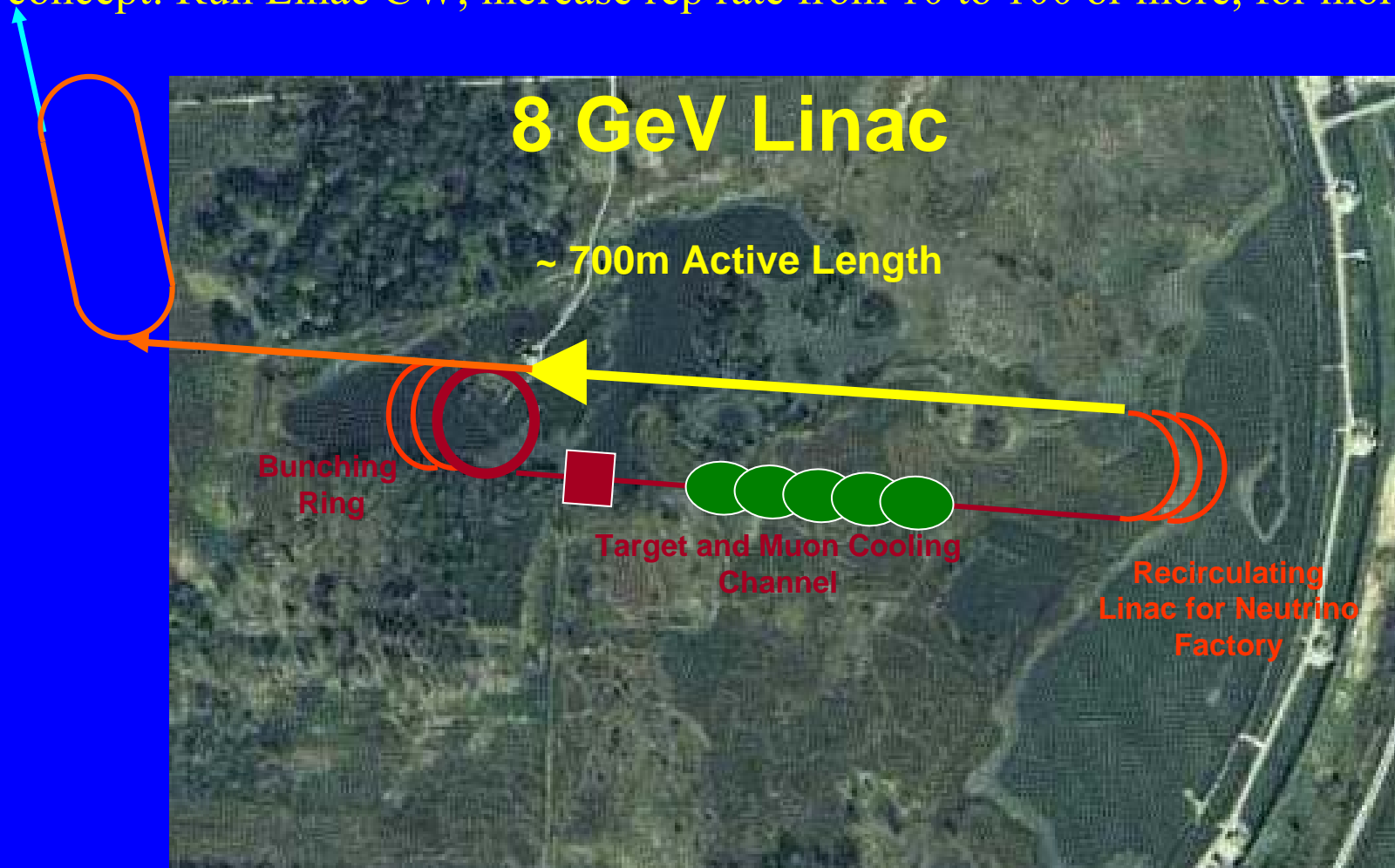
- neutrino factory based on
 - extreme muon cooling
 - ILC RF
 - Muon recirculation through p-driver Linac
 - High rep rate capability
 - Can out do other approaches
 - Limits are cooling, RF power, refrigeration

Neutrinos from an 8 GeV SC Linac

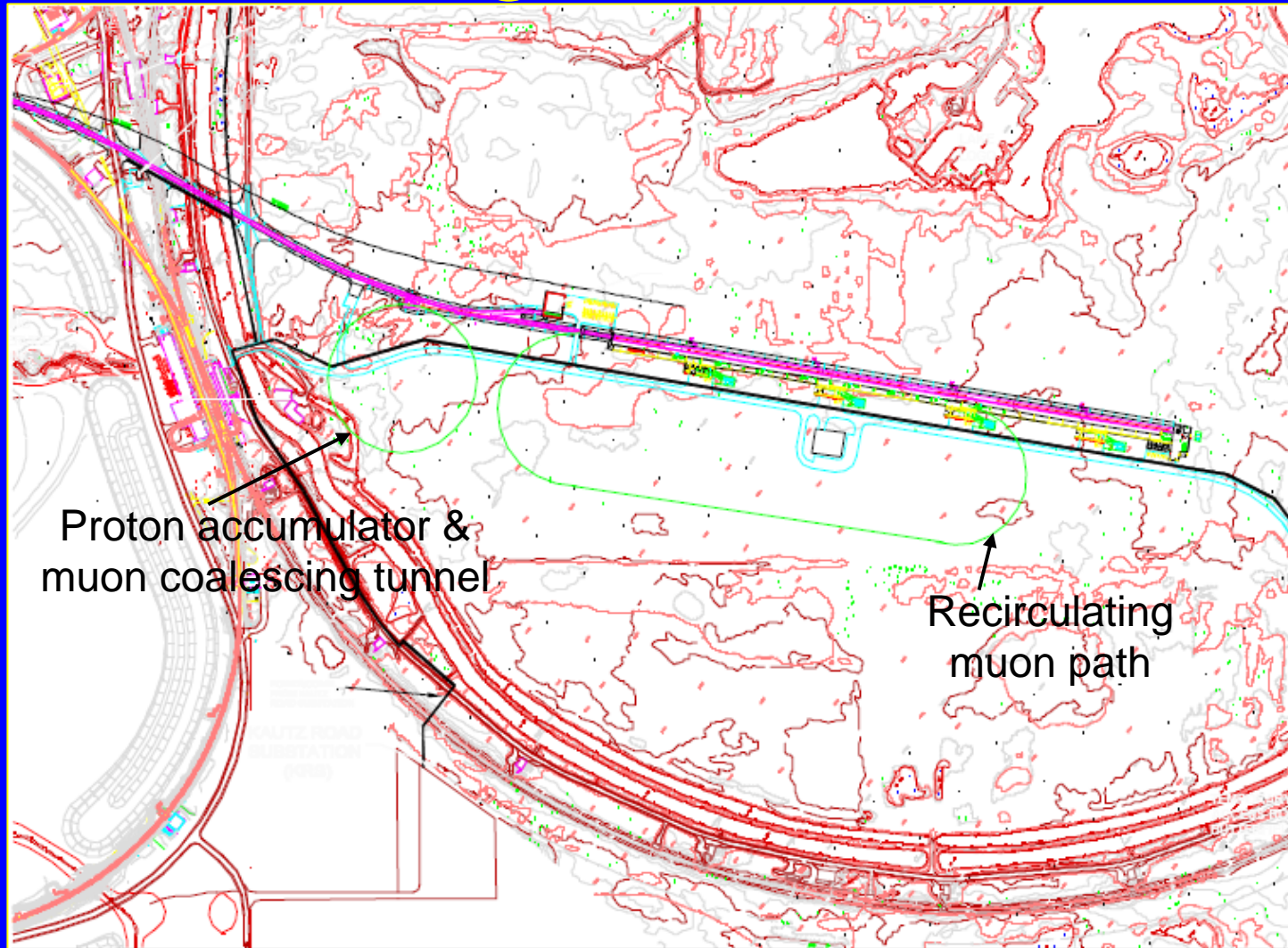
Muon cooling to reduce costs of a neutrino factory based on a storage ring.

Cooling must be 6D to fit in 1.3 GHz SC RF, where the last 6.8 GeV of 8 GeV are $\beta=1$.

New concept: Run Linac CW, increase rep rate from 10 to 100 or more, for more vs.



Recirculating muons in the PDL

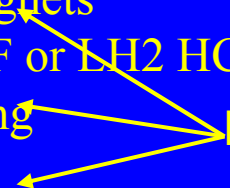


700 m muon Production and Cooling

(showing approximate lengths of sections)

- 8 GeV Proton accumulator/buncher ring, loaded by Linac
 - 2 T average implies radius= $8000/30 \times 20 \sim 14$ m
- Pi/mu Production Target, Capture, Precool sections
 - 100 m (with HP RF, maybe phase rotation)
- 6D HCC cooling, ending with 50 T magnets
 - 200 m (HP GH2 RF or LH2 HCC and SCRF)
- Parametric-resonance Ionization Cooling
 - 100 m
- Reverse Emittance Exchange (1st stage)
 - 100 m
- Acceleration to 2.5 GeV
 - 100 m at 25 MeV/c accelerating gradient
- Reverse Emittance Exchange (2nd stage)
 - 100 m
- Inject muons into Proton Driver Linac
- Total effect:
 - Initial 40,000 mm-mr reduced to 2 mm-mr in each transverse plane
 - Initial $\pm 25\%$ $\Delta p/p$ reduced to 2% , then increased
 - exchange for transverse reduction and coalescing
 - about 1/3 of muons lost during this 700 m cooling sequence

Detailed theory in place,
simulations underway.

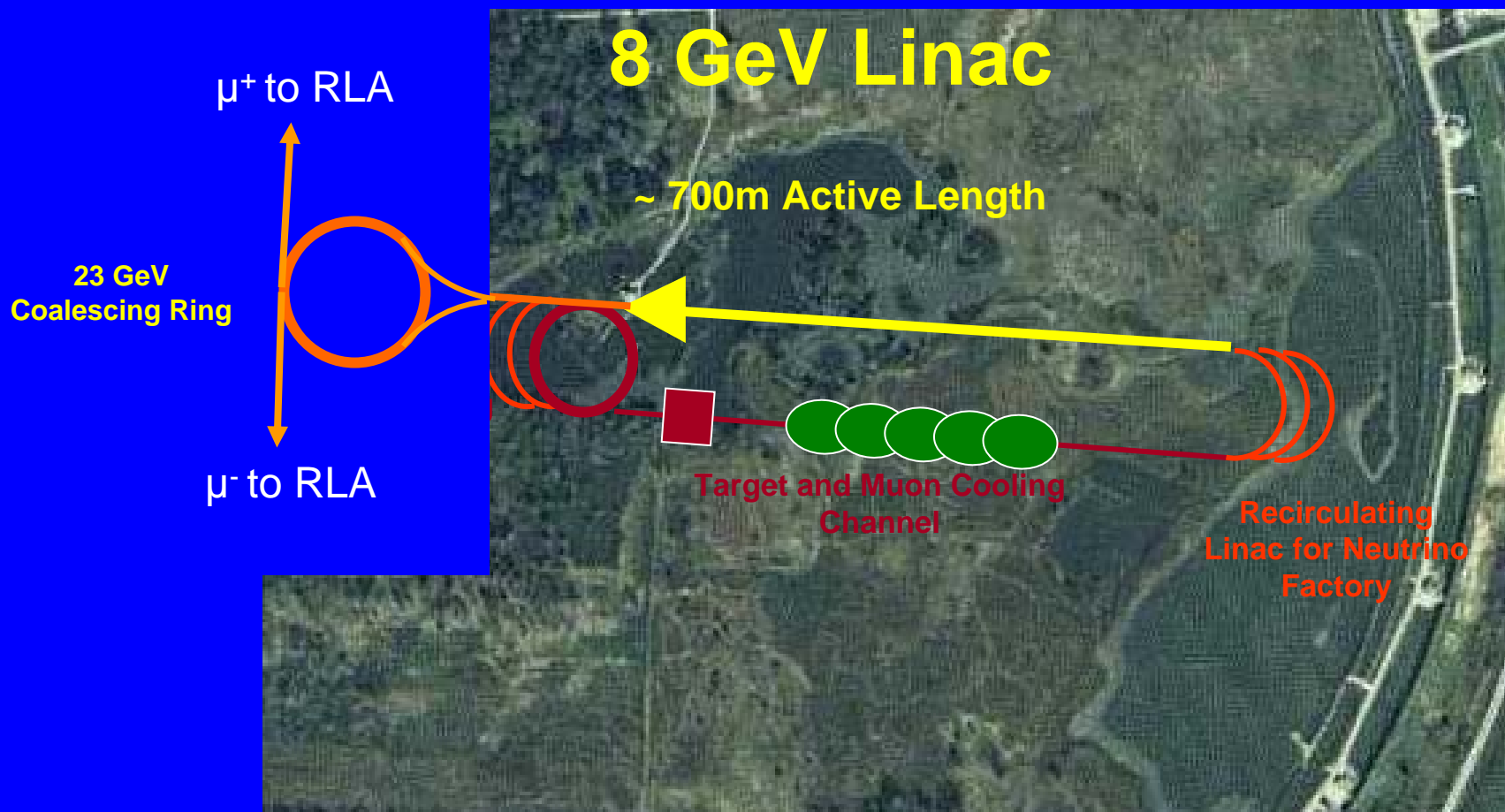


5. First Muon Collider (Higgs Factory)

- Coalescing ring forms higher intensity bunches
 - After three passes through the PDL the muons reach $2.5+3 \times 6.8=22.9$ GeV
 - RF cavities operating off-frequency at the end of the Linac create a momentum-offset for the bunches in each batch
 - Positive and negative muons are injected into a 23 GeV storage ring
 - Waiting for ~ 50 turns, the bunches in a batch are aligned, recaptured, accelerated, injected to a small ring
- Higgs factory using muons needed for initial energy state resolution
- S-channel Higgs cross-section boosted by 40,000 over e^+e^-

Muon Collider use of 8 GeV SC Linac

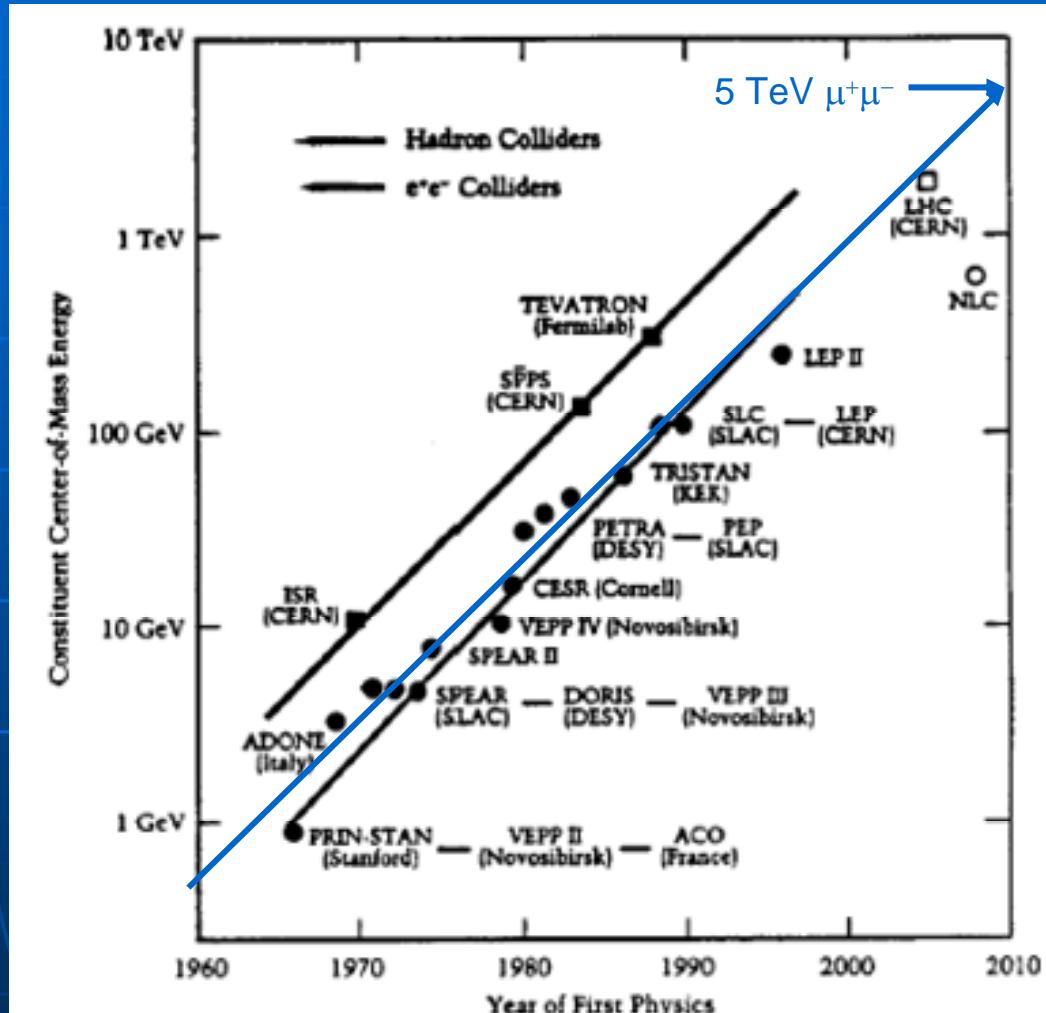
Instead of a 23 GeV neutrino decay racetrack, we need a 23 GeV Coalescing Ring. Coalescing done in 50 turns ($\sim 1.5\%$ of muons lost by decay). 10 batches of $10 \times 1.6 \times 10^{10}$ muons/bunch become 10 bunches of 1.6×10^{11} /bunch. Plus and minus muons are coalesced simultaneously. Then 10 bunches of each sign get injected into the RLA (Recirculating Linear Accelerator).



My interpretation of Theory talks

- If the LHC shows no interesting physics to be explored in the reach of the ILC
 - An energy frontier muon collider is needed
 - ILC R&D is only useful for a low emittance muon collider
- If the LHC indicates interesting physics in the reach of the ILC
 - A muon collider to do precision measurements is needed since the beams in an ILC are not so precise
 - An energy frontier muon collider is needed for the higher mass states that must be above the reach of the ILC
- The energy frontier is always the way to go and muons may have a special advantage

6. Energy Frontier Muon Collider



Modified Livingston Plot taken from: W. K. H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, s121-s132 (1999)

Benefits of low emittance approach

Lower emittance allows lower muon current for a given luminosity.

This diminishes several problems:

- radiation levels due to the high energy neutrinos from muon beams circulating and decaying in the collider that interact in the earth near the site boundary;
- electrons from the same decays that cause background in the experimental detectors and heating of the cryogenic magnets;
- difficulty in creating a proton driver that can produce enough protons to create the muons;
- proton target heat deposition and radiation levels;
- heating of the ionization cooling energy absorber; and
- beam loading and wake field effects in the accelerating RF cavities.

Smaller emittance also:

- allows smaller, higher-frequency RF cavities with higher gradient for acceleration;
- makes beam transport easier; and
- allows stronger focusing at the interaction point since that is limited by the beam extension in the quadrupole magnets of the low beta insertion.

5 TeV ~ SSC energy reach

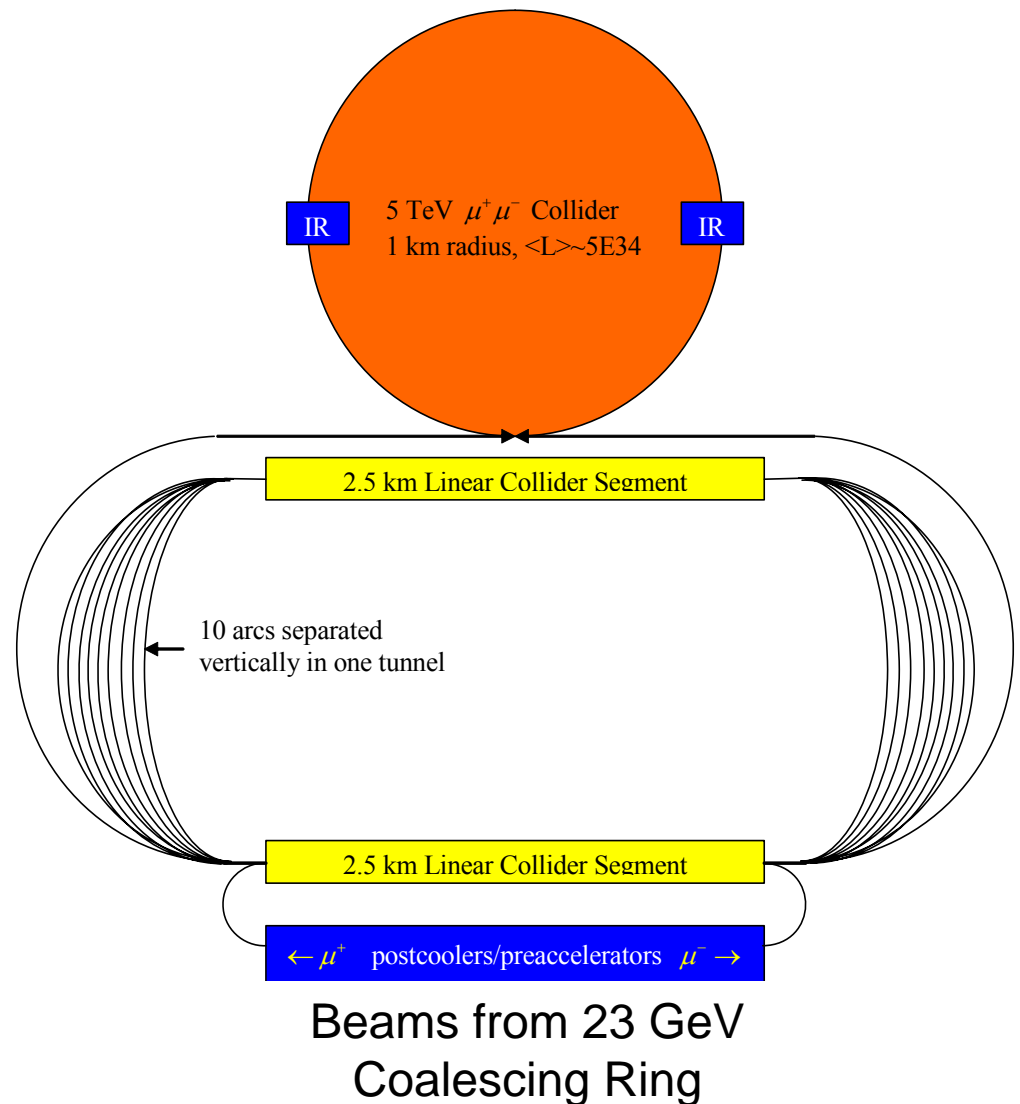
~5 X 2.5 km footprint

Affordable LC length (half of baseline 500 GeV ILC), includes ILC people, ideas

High L from small emittance!

1/10 fewer muons than originally imagined:

- a) easier p driver, targetry
- b) less detector background
- c) less site boundary radiation



Muon Collider Emittances and Luminosities (parameters & calculations need updating)

• After:	ϵ_N tr	ϵ_N long.
– Precooling	20,000 μm	10,000 μm
– Basic HCC 6D	200 μm	100 μm
– Parametric-resonance IC	25 μm	100 μm
– Reverse Emittance Exchange	2 μm	2 cm

At 2.5 TeV on 2.5 TeV

$$L_{peak} = \frac{N_1 n \Delta v}{\beta^* r_\mu} f_0 \gamma = 10^{35} / \text{cm}^2 - \text{s}$$

$$\gamma \approx 2.5 \times 10^4 \quad n = 10$$

$$f_0 = 50 \text{kHz} \quad N_1 = 10^{11} \mu^-$$

$$\Delta v = 0.06 \quad \beta^* = 0.5 \text{cm}$$

$$\sigma_z = 3 \text{mm} \quad \Delta \gamma / \gamma = 3 \times 10^{-4}$$

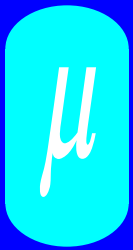
$$\tau_\mu \approx 50 \text{ms} \Rightarrow 2500 \text{turns} / \tau_\mu$$

20 Hz Operation:

$$\langle L \rangle \approx 4.3 \times 10^{34} / \text{cm}^2 - \text{s}$$

$$Power = (26 \times 10^9)(6.6 \times 10^{13})(1.6 \times 10^{-19}) = 0.3 \text{MW}$$

$$0.3 \mu^+ / p$$



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