Bunch Recombination and Acceleration

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Outline – Coalescence and Acceleration

- Introduction
- Overview of Neutrino Factory/Muon Collider architecture
- Bunch Coalescing
  - Examples of coalescing
  - Motivation and background
- Coalescing ring for muon collider/neutrino factory
  - 20 GeV coalescing ring parameters, scenarios, model lattice
- Acceleration up to 750 GeV
  - Recirculating LINACs (RLAs)
  - Circular accelerator in Tevatron tunnel
- Summary
- References

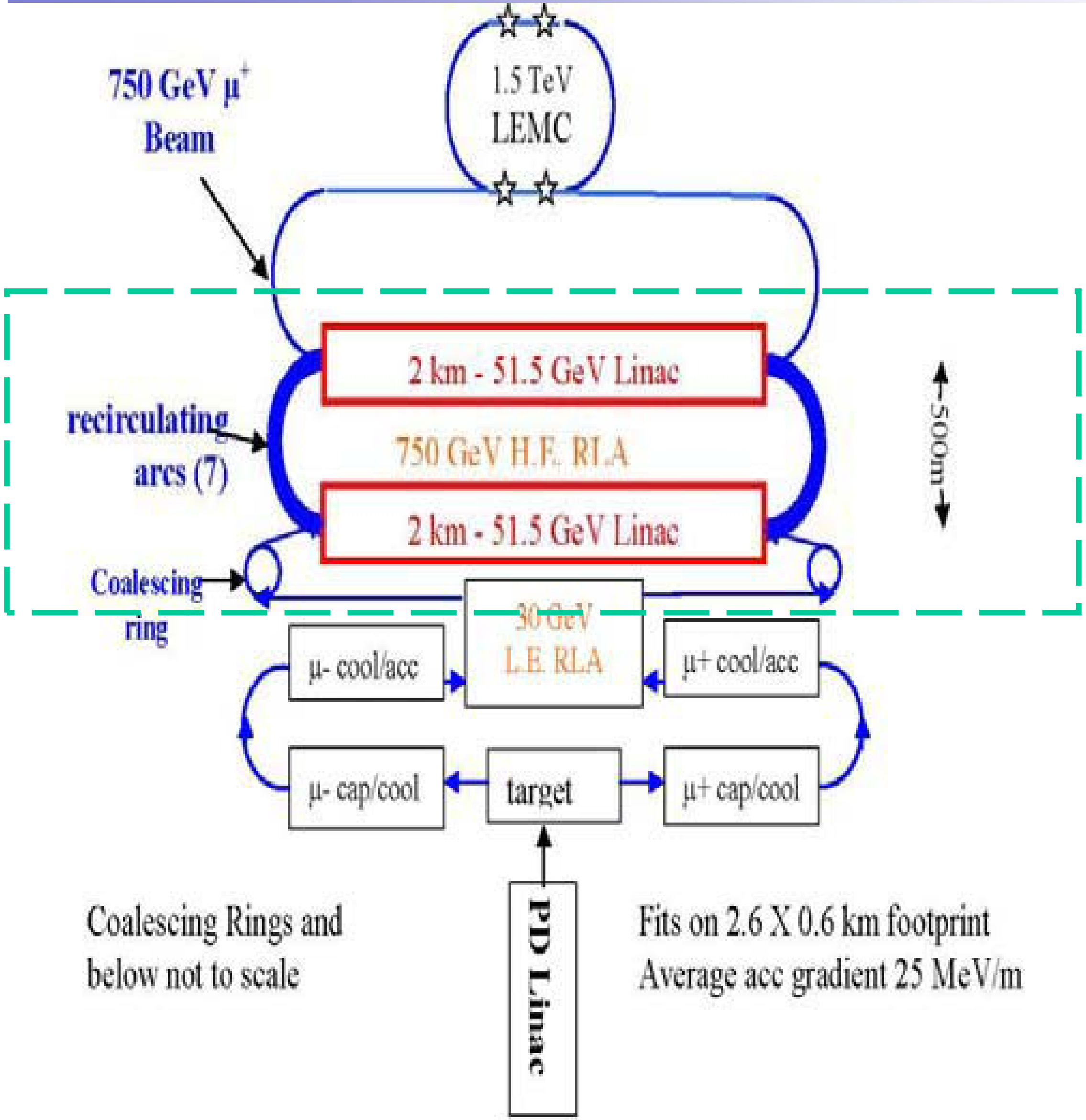
Introduction

- Disclaimer
  - **Non-expert view of concepts and recent progress**
  - **No original contributions by RJA, see references**
  - **Fermilab-centric**
  - **Apologies if I may have omitted someone’s work**
  - **Any mistakes mine**
- New Fermilab Initiatives/Priorities that may affect NF/MC prospects at FNAL
  - **Completion of Tevatron Era, support for existing v program (short term)**
  - **Significant involvement in LHC (short/intermediate term)**
  - **Pursue ILC bid, ILC test facilities, ILC R&D, components (short/intermediate term)**
  - **FNAL Steering committee : Project X, intensity frontier physics (intermediate term)**
  - **Neutrino factory/Muon collider R&D (intermediate/long term)**
    - **Compatibility and coordination of NF/MC with ILC and Project X programs important**

Schematic NF/LEMC Architecture

Elements covered

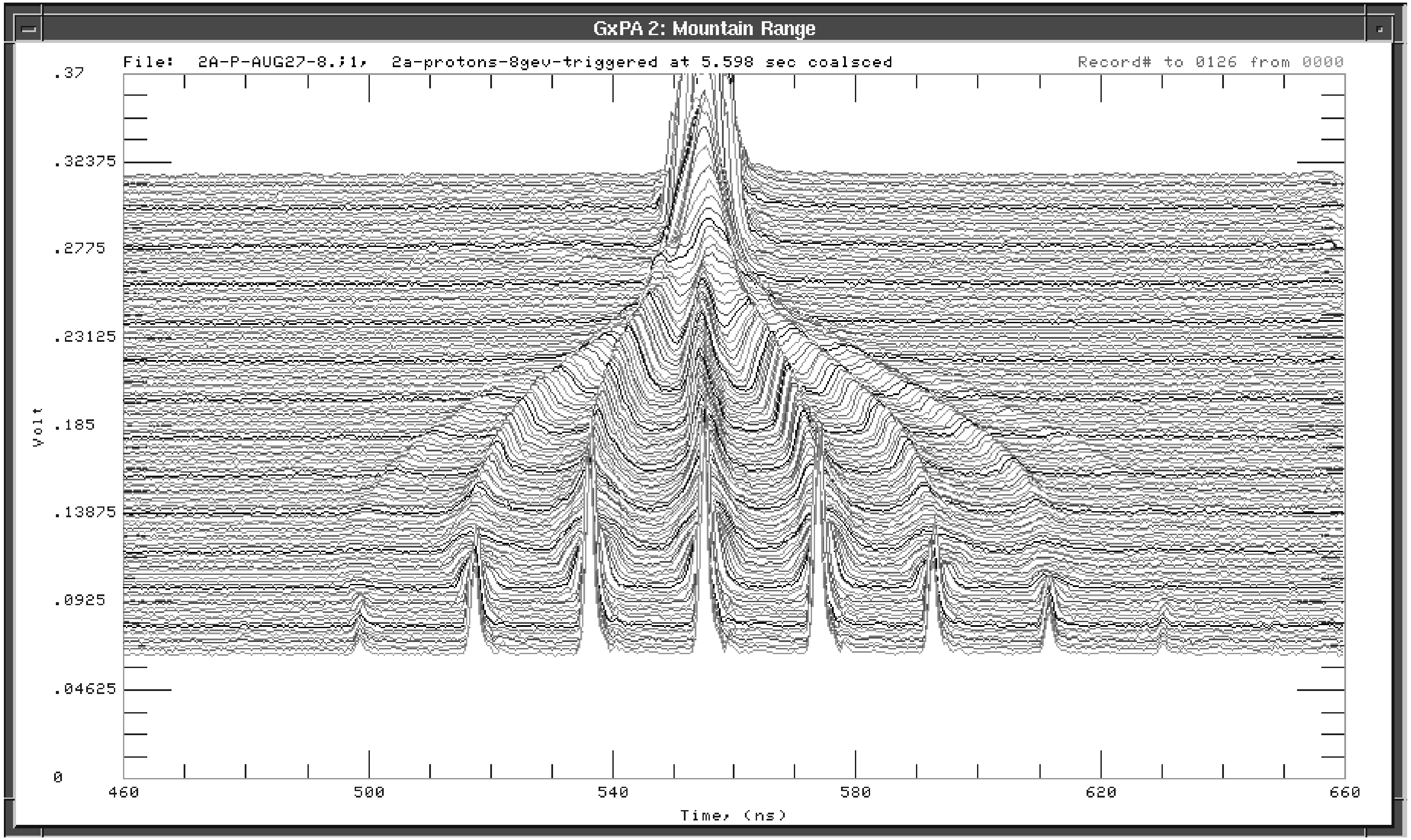
In this presentation



Bunch Coalescing: An Existing Technology

- Some Previous Applications
  - BNL AGS/RHIC
    - Coalesced 4 AGS bunches into single bunch for injection to RHIC main ring
  - FNAL Main Injector (MI)
    - Coalesce up to 16 bunches into single bunches in Main Injector to improve Tevatron Run II luminosity (C. Bhat)
- Application to Muon Collider
  - Increase luminosity and provide a better time structure for experiments

Proton Coalescing Measurement at FNAL



Trace separation ~ 1 ms. Stable particles can be coalesced over a long ime

Bunch Coalescing

- How to do bunch recombination (coalescing)? Scenario:
  - Capture short bunches in high frequency RF buckets
  - Capture bunch train in lower frequency RF bucket
  - Manipulate bunch train: rotate of bunches within larger RF bucket by applying lower frequency RF
  - Coalesce sub-bunches into a single, larger bunch (adiabatically)
- At what point in the acceleration should bunches be coalesced?
  - In LINAC at relatively low energy?
  - In dedicated coalescing ring(s) after LINAC at higher energy?

Coalescing Muons at High Energy

Advantages of coalescing multiple muon bunches at high energy

- Higher energy muons live longer for more RF manipulation time. Longer decay lengths allow more turns before decay.

- Reduces problems with high intensity bunches in Linac,
  - e.g. Beam loading and wake-field effects
    - image current of beam → E-field opposite to cavity E-field
- Reduces problems of space-charge detuning for PIC/REMEX schemes

$$\Delta \nu_{sc} = \frac{3}{2} \frac{r_o}{\varepsilon_n \pi} \frac{N}{B\beta\gamma^2}$$

where *N* is no. of charges per unit length, r_0 is classical electron radius, $\Delta\nu$ is tune spread

- Improves synergy between neutrino factory and Muon collider designs (see next slide)

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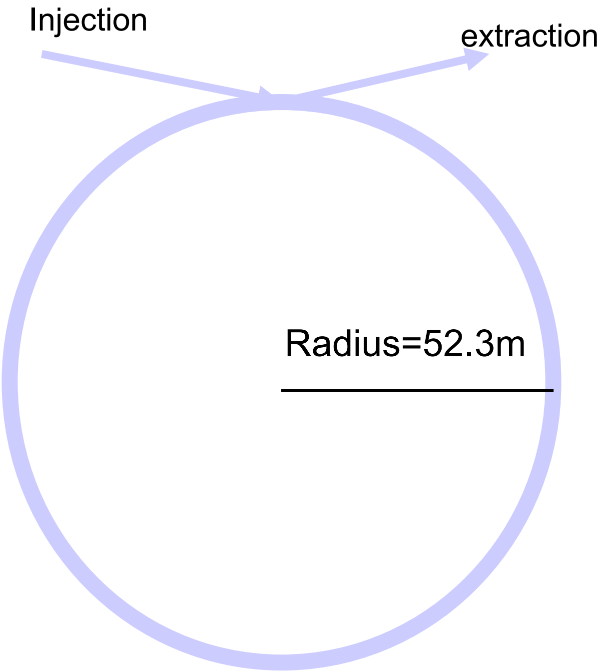
Coalescing at ~20 GeV: NF/MC Synergy

- At ~ 20 GeV muons have been accelerated one stage beyond LINAC to energy range that is useful for neutrino factory
  - The components for the NF can be reused for a muon collider front end
  - The additional components for the muon collider, coalescing rings and additional accelerators, collider ring, may be added as extensions of NF
  - The high frequency time structure is suitable for neutrino experiments
  - The coalesced bunches are suited to acceleration to full energy in the MC

Example: Muon Coalescing Ring - Parameters

Some typical parameters used by C. Bhat for simulations, Ankenbrandt et al



Constraints:
Muon mean-life = 2.2us (rest frame)
Muon mean-life in lab = 418us for 20 GeV beam
Time (90% survival) = 43.8us

Injection beam : 1.3GHz bunch structure
# of bunches/train = 17

Ring Radius = 52.33m; Revolution period= 1.09μs
Energy of the muon = 20 GeV (gamma = 189.4)
gamma_t of the ring = 4

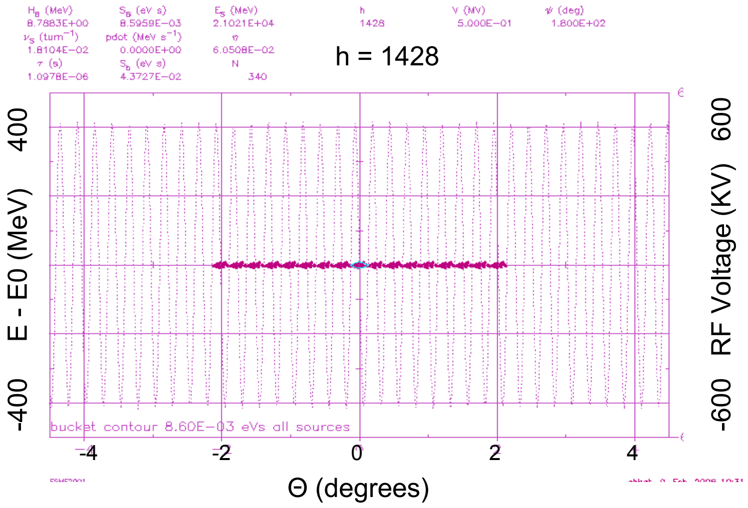
If we assume
Ring-Radius/rho (i.e., fill factor) = 2, then B-Field = 2.54T
(This field seems to be reasonable)

h for the coalescing cavity = 42, 84
Number of trains/injection = less than 37
(assuming ~100ns for injection/extraction)
RF voltage for the coalescing cavity = 1.9 MV (h=42)
= 0.38 MV (h=84)

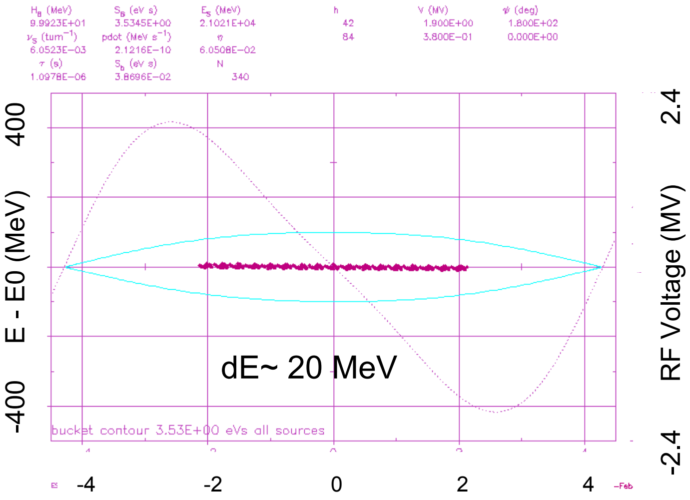
fsy ~ 5.75E3Hz
Tsy/4 = 43.5us
Number of turns in the ring ~40

Coalescing Scenario 1: RF cavities in the coalescing ring

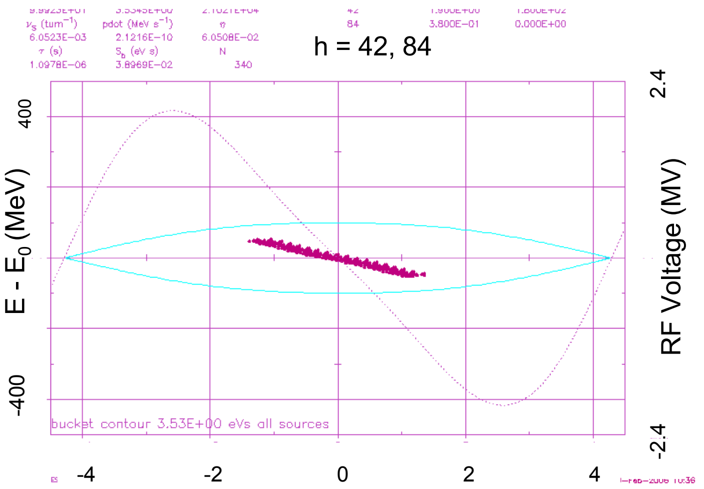
(a) Muon bunch train from the LINAC



(b) Initial bunch train in the coalescing bucket t=0 sec

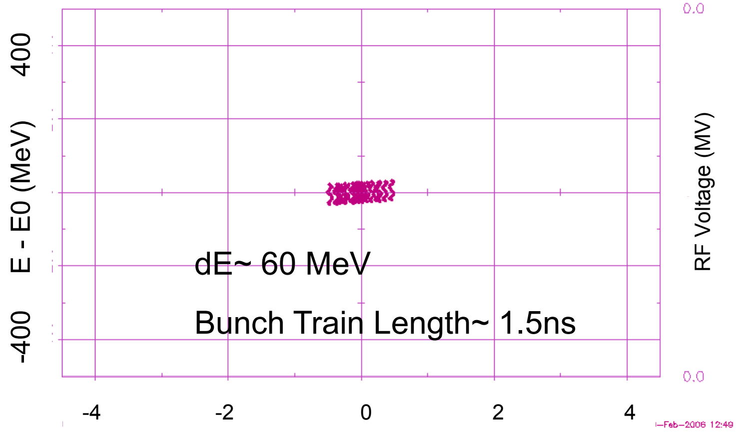


(c) Rotated bunch train in the coalescing bucket, t= 31.6 μsec

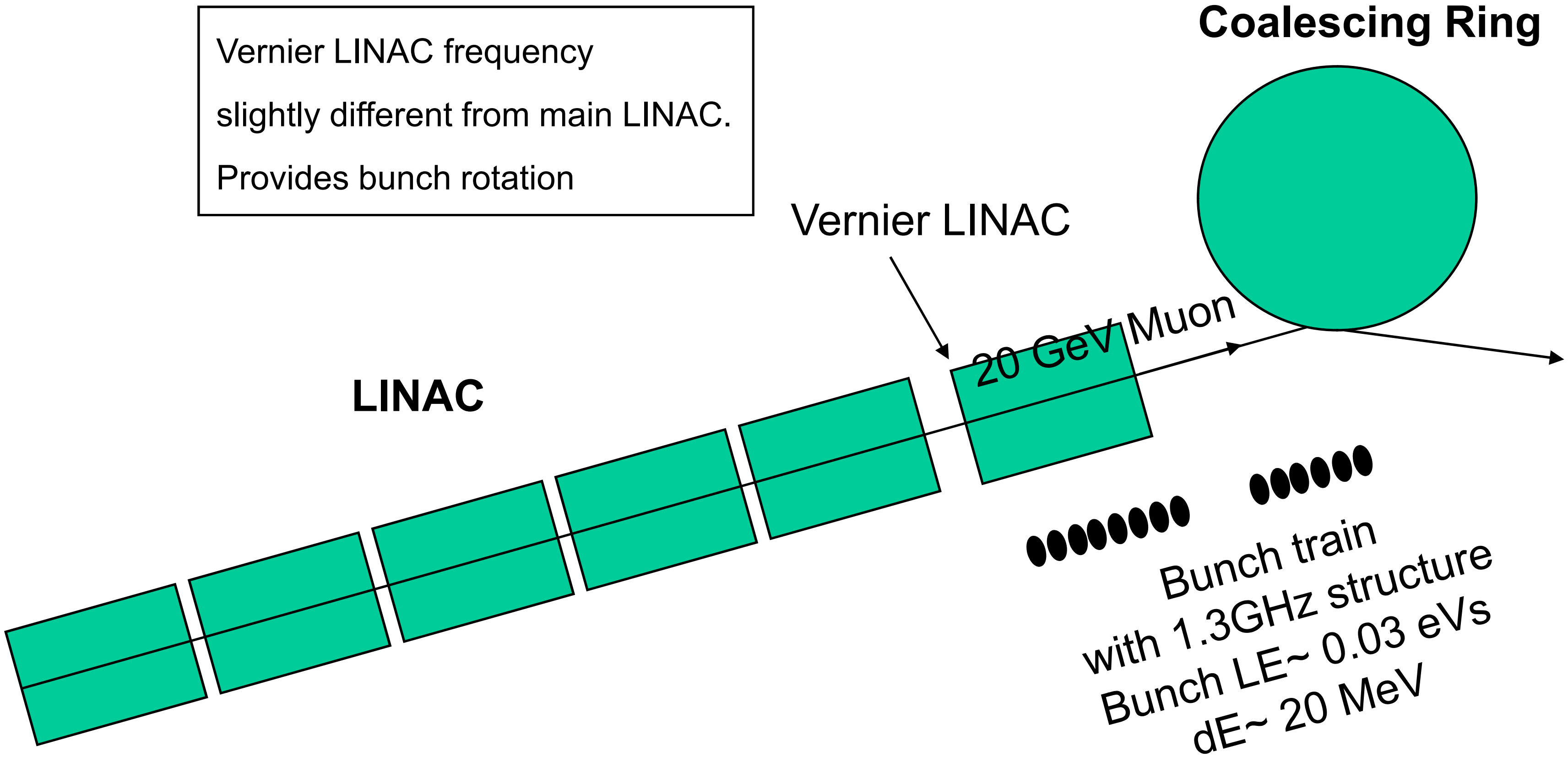


(d) Coalesced bunch train in the coalescing bucket, t= 54 μsec

RF Voltage off



Schematic of LINAC and Coalescing Ring with Vernier-LINAC (Popovic)



Vernier LINAC frequency

slightly different from main LINAC.

Provides bunch rotation

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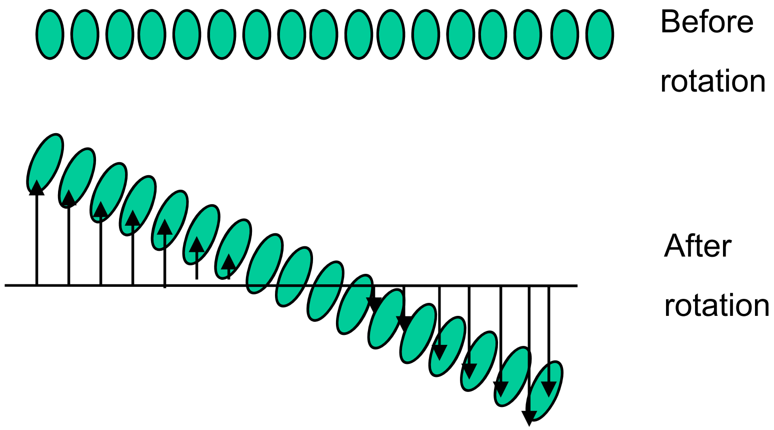
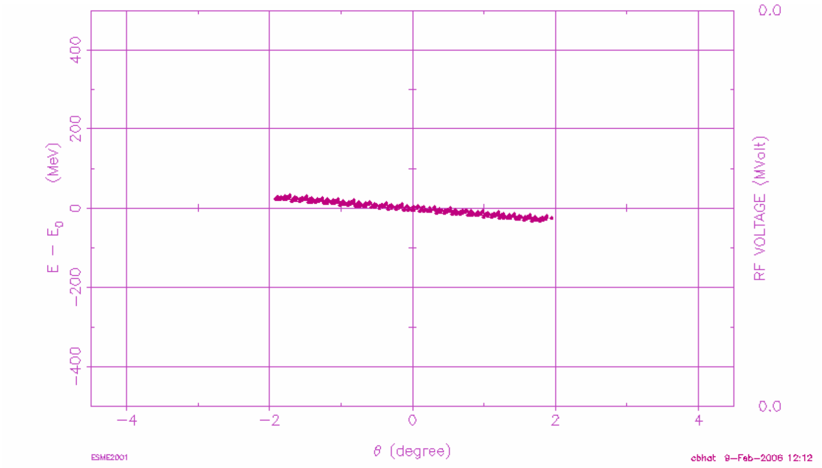
Scenario 2: Vernier-linac tilts bunch train before injection in coalescing ring, no RF in ring

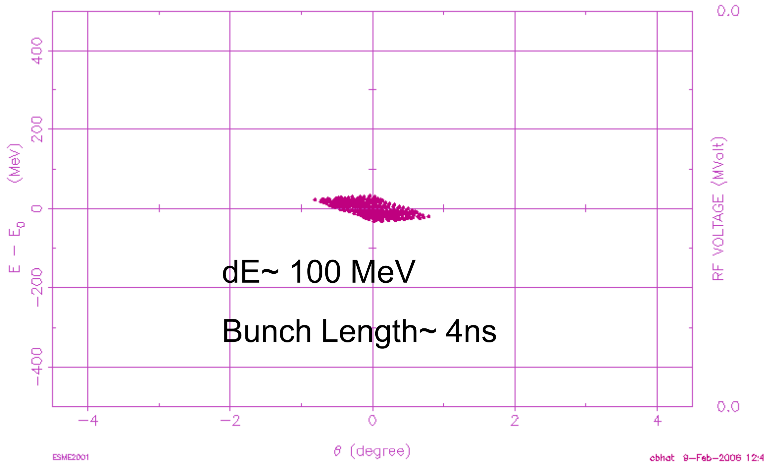
(a) Bunch train before and after the vernier-linac.



(b) Rotated Muon Bunch train in the Coalescing Ring, t=0 sec



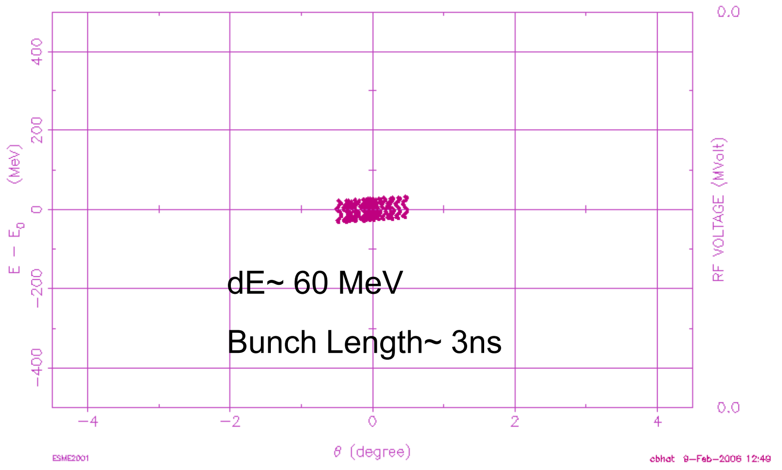
(c) Muon Bunch train in the Coalescing Ring, t=46 μsec



dE~ 100 MeV

Bunch Length~ 4ns

(d) Muon Bunch train in the Coalescing Ring, t=71 μsec

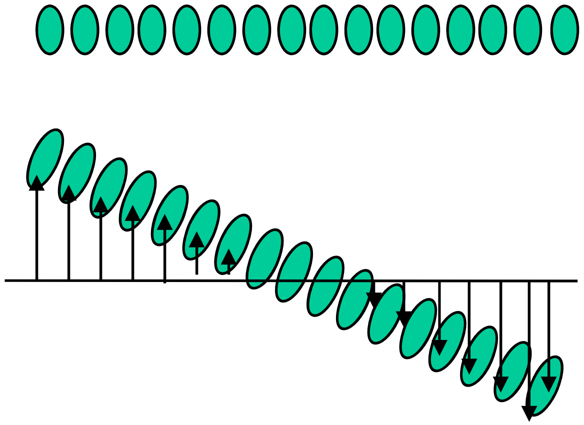


dE~ 60 MeV

Bunch Length~ 3ns

Scenario 3: Vernier linac and RF cavities in the ring

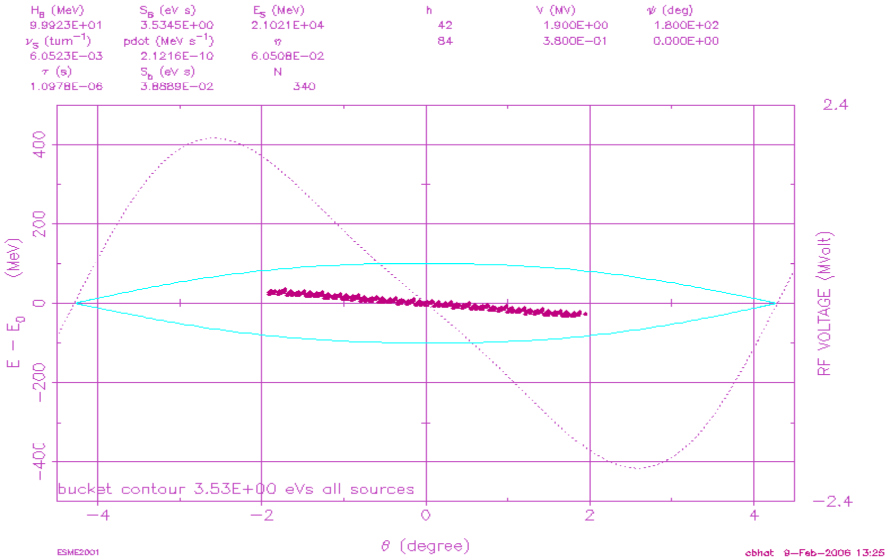
(a) Bunch train before and after the vernier pre-linac



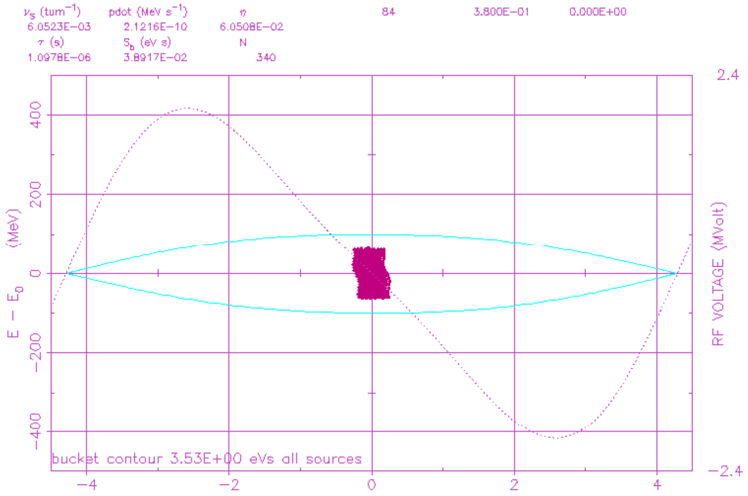
Before rotation

After rotation

(a) Muon Bunch train in the Coalescing Ring, t=0 sec



(b) Muon Bunch train in the Coalescing Ring, t=38 μsec



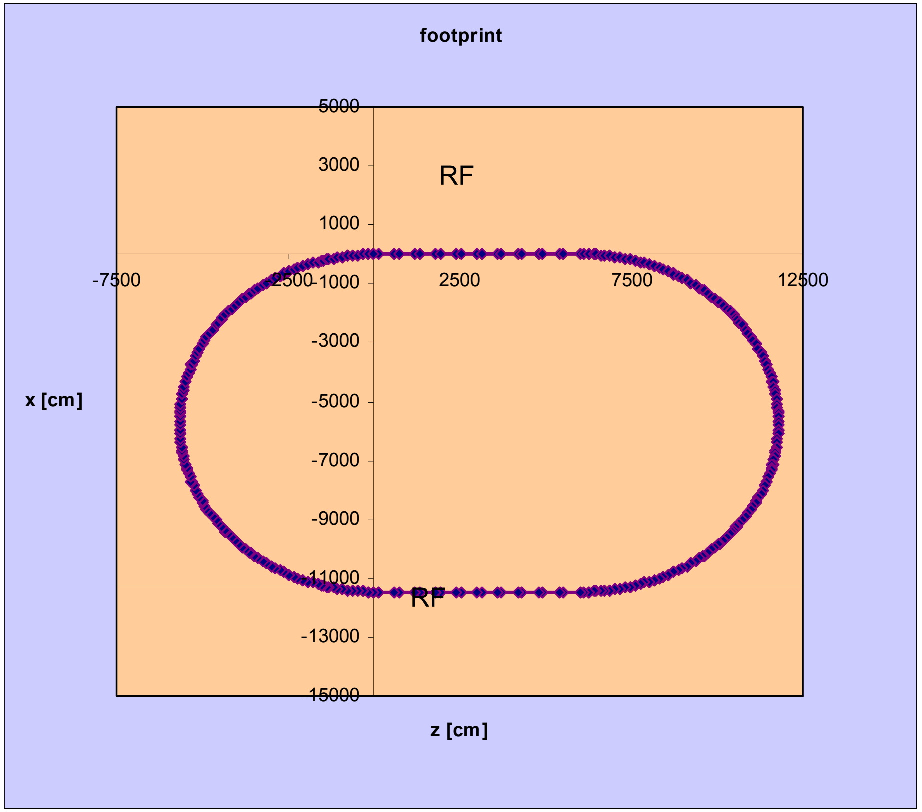
Model Lattice for Coalescing Ring (A. Bogacz)

- Requirements and objectives
  - Large momentum compaction
  - Minimize muon decay losses
  - Maintain small betas
    - Low transition gamma
    - Large radial aperture

Model Layout for 20 GeV Coalescing Ring

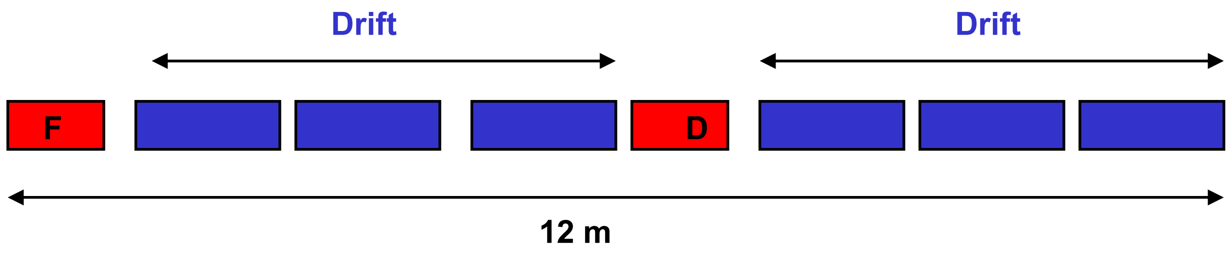
- Racetrack Configuration
  - RF in 2 straight sections
  - Bunch rotation then coalescence
  - Periodic FODO-based design

- Footprint
  - Racetrack ~ 110m x 180m



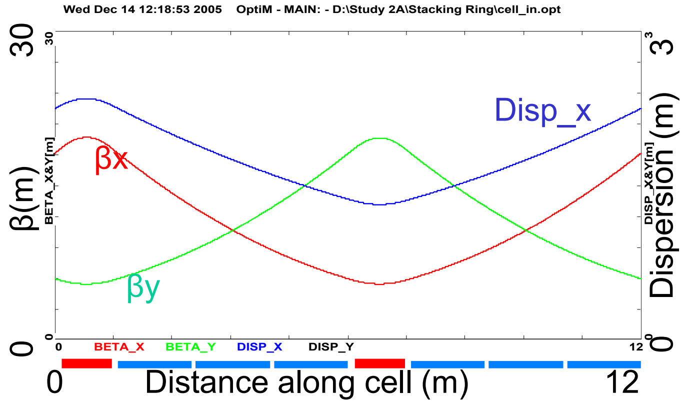
Lattice Characteristics

- Basic cell
  - FODO (focus-drift-defocus-drift) 12 m long
  - Drift space filled with dipoles in curved sections
  - Drift space in straight sections: RF, injection, extraction elements
  - Magnets: (1.5m, 1.6T dipoles), (1.0m, 14 T/m quadrupoles)

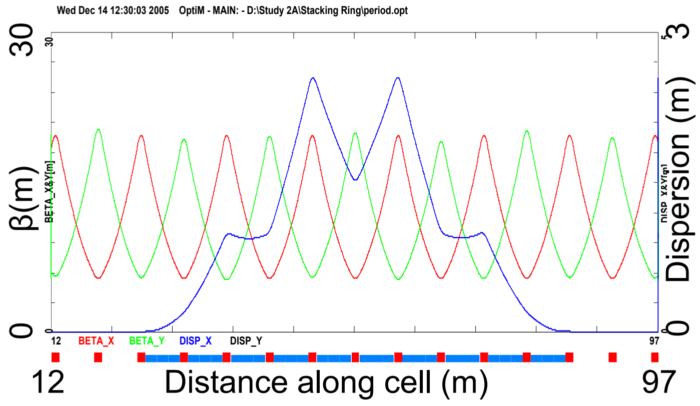


20 GeV Lattice Calculation (from PAC07)

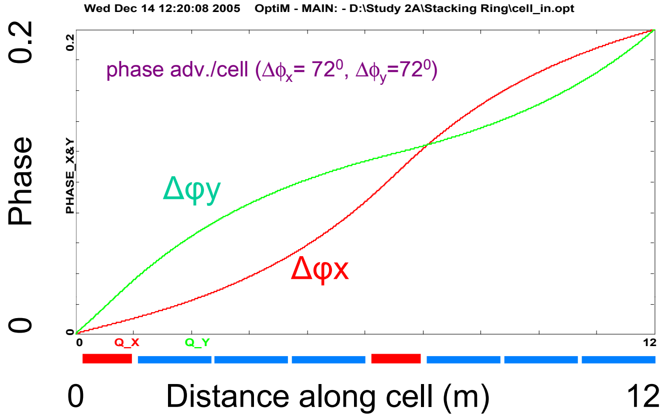
Basic Cell Twiss Parameters



Super-period – 5 Cells

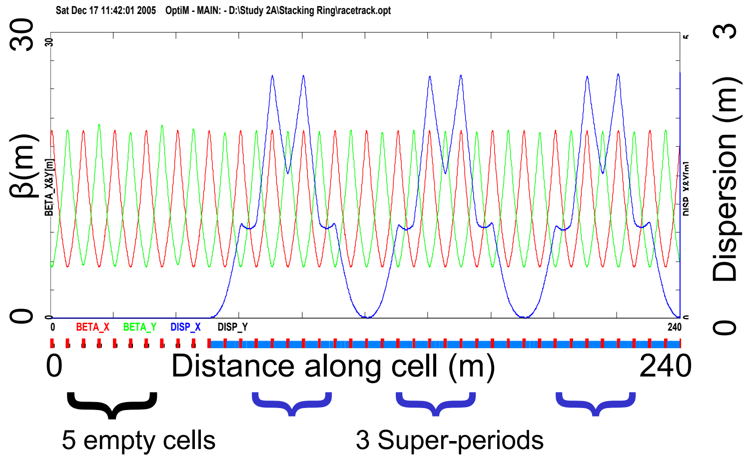


Basic Cell Betatron Phase Advance



72 degree (2π/5) betatron phase advance per FODO cell

Half Racetrack Lattice



Coalescing Rings: For Further Study

- Continue investigation of vernier LINAC rotator concept
- Refine RF manipulation to achieve optimization of bunch width and coalescing time
- Investigate single coalescing ring for both μ^+ and μ^-.

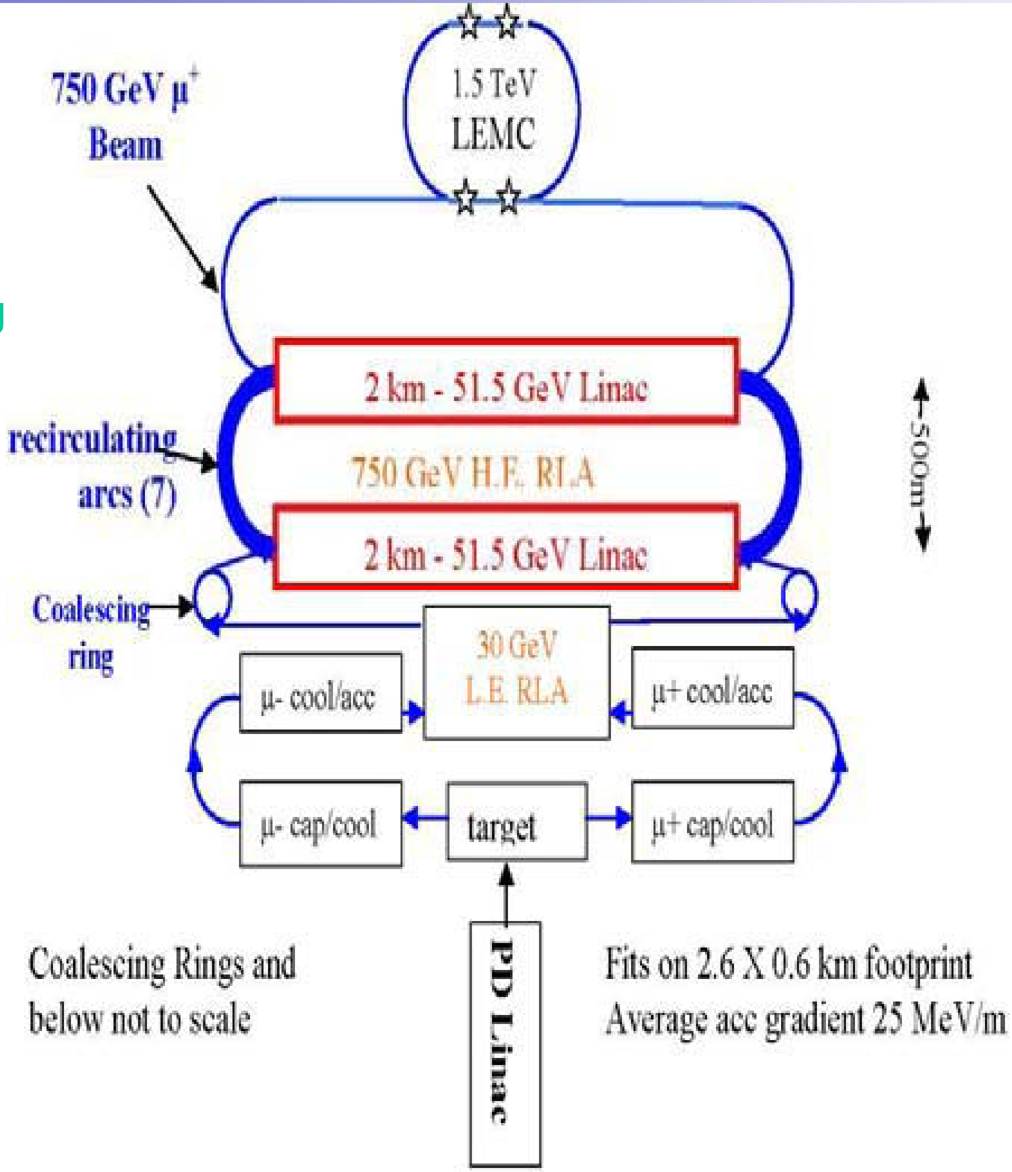
Acceleration from ~20 GeV to ≥ 750 GeV

- Why 750? Fermilab Directorate urged focusing on 1.5 TeV muon collider (instead of maximum energy muon collider ring within FNAL site). Also, theoretical reasons for > 500 GeV (Eichten, this conference)
- Two acceleration schemes presented here:
  - Recirculating Linear Accelerators (RLA), JLab, FNAL, MuonsInc study
  - Muon collider inside TeVatron tunnel, U. Miss., BNL et al study

Schematic Layout of LEMC

MC Accelerating

Section

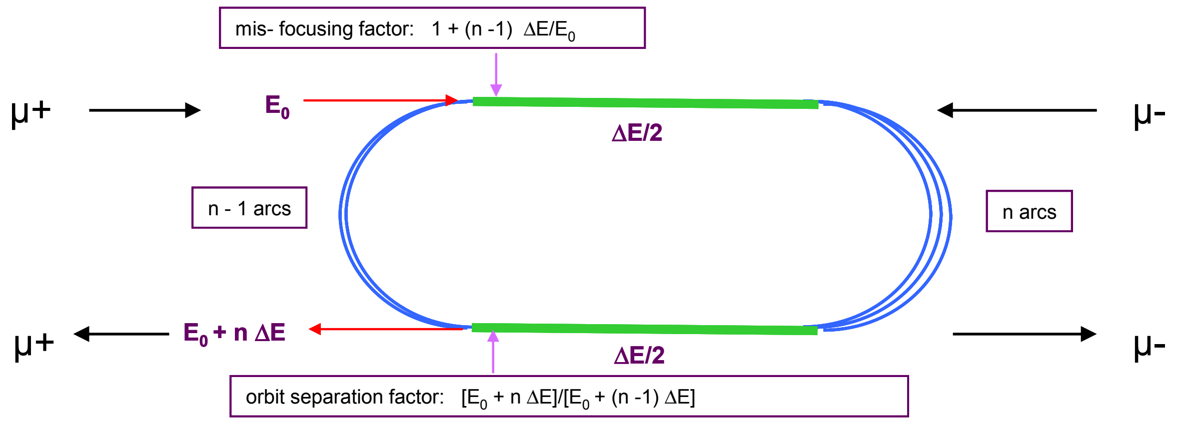


Coalescing Rings and
below not to scale

Fits on 2.6 X 0.6 km footprint
Average acc gradient 25 MeV/m

RLA 20 GeV to 750 GeV: 2 Versions

Racetrack design



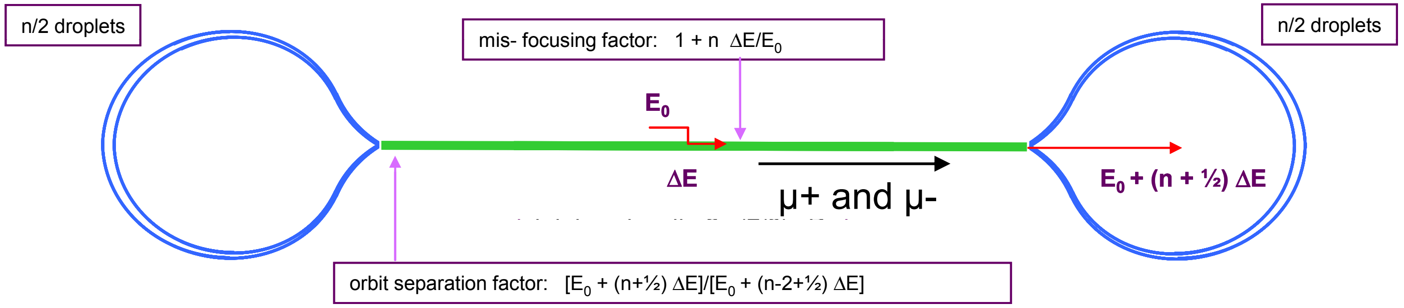
mis- focusing factor: 1 + (n -1) $\Delta E/E_0$

n - 1 arcs

n arcs

orbit separation factor: $[E_0 + n\,\Delta E]/[E_0 + (n-1)\,\Delta E]$

Dogbone design



n/2 droplets

mis- focusing factor: 1 + n $\Delta E/E_0$

n/2 droplets

orbit separation factor: $[E_0 + (n+½)\,\Delta E]/[E_0 + (n-2+½)\,\Delta E]$

Pros and Cons of Dogbone Design

- Advantages of the Dogbone configuration over Racetrack
  - One set of RF cavities instead of two
  - Energy gain per trip (droplet) in Dogbone is a factor of two larger than in Racetrack.
  - Greater energy separation in Dogbone gives better orbit separation in droplet arcs compared to Racetrack circular arcs
  - μ^+ and μ^- traverse linac in the same direction, accelerate simultaneously in the Dogbone configuration, gives more uniform focusing profile.
  - Racetrack Linacs' separation determined by maximum arc diameter. Dogbone droplets sizes can be smaller for lower energies. Muon decay losses less for dogbone.
- Disadvantage of the Dogbone configuration
  - Requirement of mirror symmetric optics for simultaneous acceleration of μ^+ and μ^- .
    - **May be apparent disadvantage - Racetrack may also require mirror symmetry**

RLA: For Further Study

- Further pros and cons of racetrack vs. dogbone designs
- Lattice designs, especially for droplet-shaped arcs
- Incorporation of ILC-type LINAC elements (1.3 GHz)
    - Project X impact and compatibility
- Maximum number of passes allowed
    - Are multiple stages needed to reach 750 GeV? How many?
- Refinement of optics designs

Scheme for Muon Acceleration in Tevatron Tunnel

- **Summers, et al paper (PAC07 THPMS082)**
- **Use existing FNAL Tevatron tunnel with 2 rings, 1000m radii**
  - **Reduces construction costs**
  - **Estimate of radiation produced appears to be within acceptable limits**
- **Assume muons produced, cooled, coalesced, accelerated up to 30 GeV**
- **!st ring accelerates from 30 GeV to 400 GeV**
  - **28 orbits, 0.59 msec, muon survival during acceleration = 80%.**
  - **14 GV SRF at 1.3 GHz, 31MV/m SRF cavities, 42 stations spaced equally along ring.**
- **Lattice and magnets for 1st ring**
  - **FODO Lattice 30.45m long half cell, similar to FNAL lattice.**
  - **1.7 m, 400 Hz, 30 T/m Quadrupoles (conventional).**
  - **6.3 m, 400 Hz, 1.8 Tesla Dipoles (conventional), bore 30mm x 6 mm, 8 dipoles per cell, 800 total.**
  - **Magnets on for half cycle, 13 times per second (reduces power consumption)**
  - **Grain Oriented 3% Silicon Steel EI Transformer Laminations for rapid ramping**
  - **Other magnet characteristics have been calculated**

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Muon Acceleration in Tevatron Tunnel (2^{nd} Ring)

- 2nd ring accelerates from 400 GeV to 750 GeV, 44 orbits (0.92 ms), 92% muon survival
- 8 GV RF at 1.3 GHz , 12 RF stations along ring.
- Hybrid ring consists of conventional and superconducting dipoles
- Lattice half cell, FODO 30.45 m long, 5 dipoles (F B_1 B_2 B_3 B_2 B_1 D)
  - B_1 are ramping magnets 3.75 m long, +/-1.8 T, 550 Hz, 5mm x 50 mm bore
  - B_2 are DC magnets 4.2 m long, 8T superconducting
  - B_3 are ramping magnets 7.5 m long, +/-1.8 T, 550 Hz
- At injection (400 GeV) ramping dipoles oppose DC dipoles
- At extraction (750 GeV) ramping dipoles act along with DC dipoles
- Quadrupoles are 3.2 m long, also ramp: 16 to 37 T/m (no sign change)

Tevatron-Tunnel Muon Collider: Further Study

- Fitting into 1.3GHz RF, 5mm or 10mm bunch length?
- Longitudinal dynamics, head/tail...
- Wakefields with 8% beam loading.
- Momentum compaction of the 400 to 750 GeV hybrid ring.
- Momentum acceptance and magnet apertures.
- Design complete lattices.
- Multipole B fields from eddy currents in the pole faces.
- Magnetic field quality with small aperture magnets.
- Forces on fast ramping magnet pole faces.
- Build a short prototype fast ramping dipole.

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Summary

- Described schemes for bunch coalescing at ~20 GeV
  - Acceptable coalescing times demonstrated by simulations
- Described 2 types of accelerators for acceleration of muons from ~20 GeV to 750 GeV
  - RLAs with RF in long straight section(s)
  - Circular ring with RF distributed along ring that fits in Tevatron tunnel

References

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3. R. Johnson, et al, PAC07 THPMN095: Muon Bunch Coalescing,
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6. D. Summers, et al, PAC07 THPMS0825: Muon Acceleration to 750 GeV in the Tevatron Tunnel for a 1.5 TeV Mu+ Mu- Collider