Linacs for Future Muon Facilities*

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Motivation – Scientific Case

- **Muon Colliders** and **Neutrino Factories** are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies (e.g. to mass-produce Higgs bosons in s-channel) and precision measurements of parameters of the neutrino mixing matrix with intense (10^{14} μ/sec), small divergence neutrino beams with well-understood systematics.
- Their performance and feasibility depend strongly on how well a muon beam can be produced, cooled and accelerated to multi-GeV and TeV energies.
- Recent progress in muon cooling and accelaration (International Design Study and prototype tests) encourages the hope that such facilities can be built during the next decade…

Opportunities and Challenges

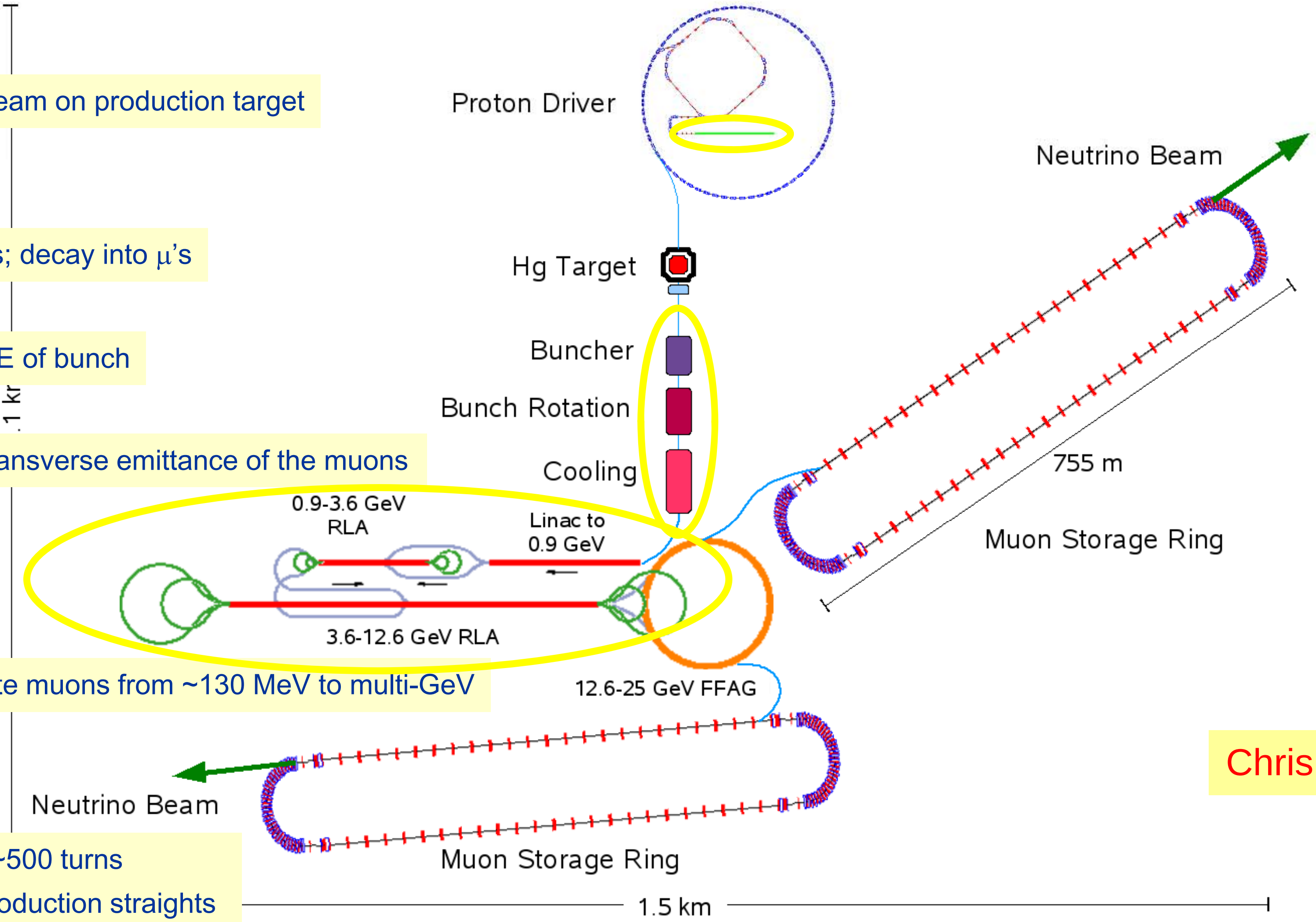
- Future **Muon Colliders** and **Neutrino Factories** based on muon storage rings will require innovative linacs to:
  - produce the muons
  - cool them
  - longitudinally compress and 'shape' them into a beam
  - rapidly accelerate them to multi-GeV (NF) and TeV (MC) energies
- Each of these four linac applications has new requirements and opportunities that follow from the nature of the muon in that:
  - it has a short lifetime (2.2 μsec) in its own rest frame
  - it is produced in a tertiary process into a large emittance ($p + A \to \pi \to \mu$)
  - it does not undergo nuclear interaction with matter; it only 'sees' Coulomb forces
  - its electron, photon, and neutrino decay products can be more than an annoyance… high backgrounds

Linacs for Muons - Applications

- **Production** – A superconducting 8 GeV proton linac capable of CW operation is being studied as a versatile option for muon production for diverse purposes [M. Popovic et al., MOP011, LINAC 2008]
- **Cooling** – A linac filled with high pressure hydrogen gas and imbedded in strong magnetic fields has been proposed to rapidly cool muon beams [R.P. Johnson, LINAC 2004]
- **Longitudinal Compression/Emittance Exchange**
  - **NF**: A GeV scale superconducting linac with individually phased RF cavities; far off-crest at the beginning of the linac and gradually brought on-crest by the linac end. Induced synchrotron motion is allowing for longitudinal bunch compression in both length and momentum spread.
  - **MC**: combined with cooling and acceleration - emittance exchange via 'wedge' absorbers
- **Acceleration** – Recirculating Linear Accelerators (RLA) are possible because muons do not generate significant synchrotron radiation even at extremely high energy and in strong magnetic fields (m_μ = 105 MeV/c^2)
  - single linac 'Dogbone' RLA capable of simultaneous acceleration of both μ^+ and μ^- species
  - pulsed Linac quadrupoles to allow the maximum number of passes [Bogacz and Johnson, EPAC08]

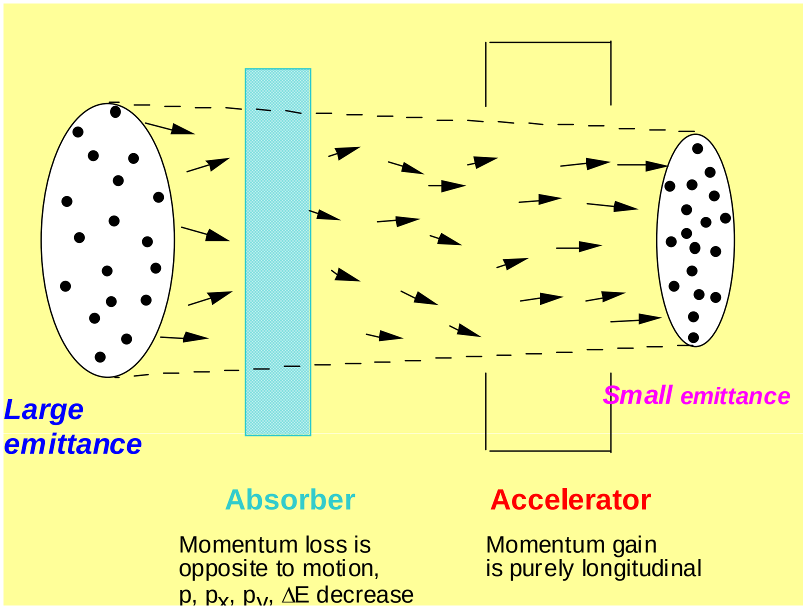
Neutrino Factory – International Design Study hosted by RAL

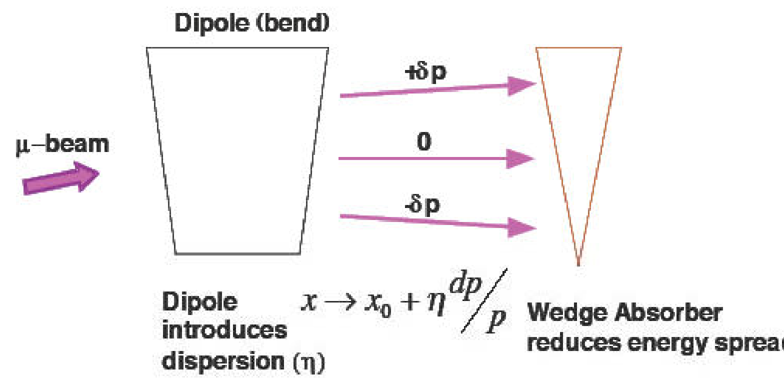
- primary beam on production target
- create π's; decay into μ's
- reduce ΔE of bunch
- reduce transverse emittance of the muons
- accelerate muons from ~130 MeV to multi-GeV
- store for ~500 turns
- Long ν production straights

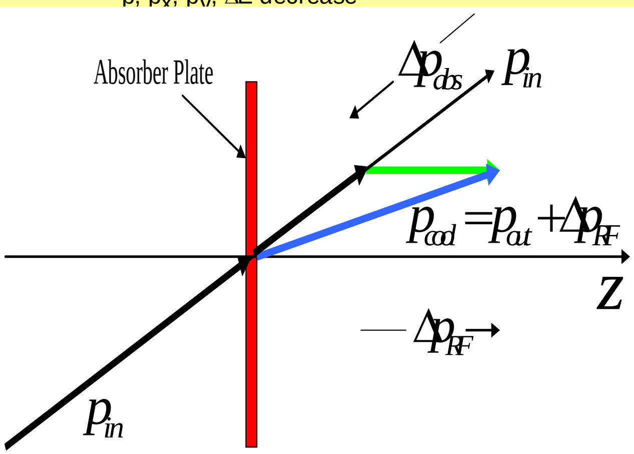


Chris Prior

Muon Ionization Cooling





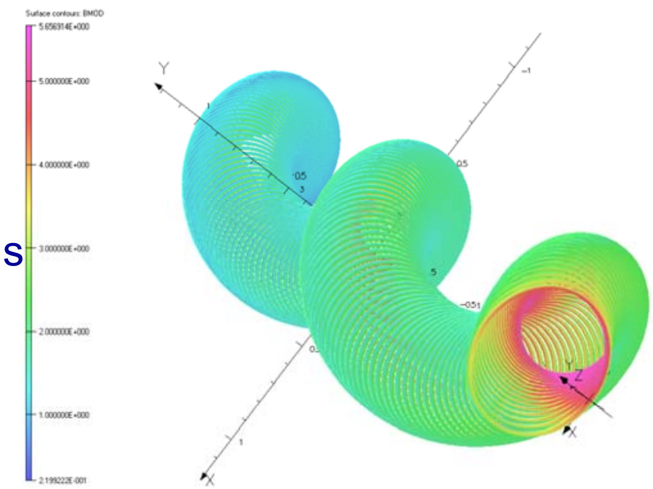


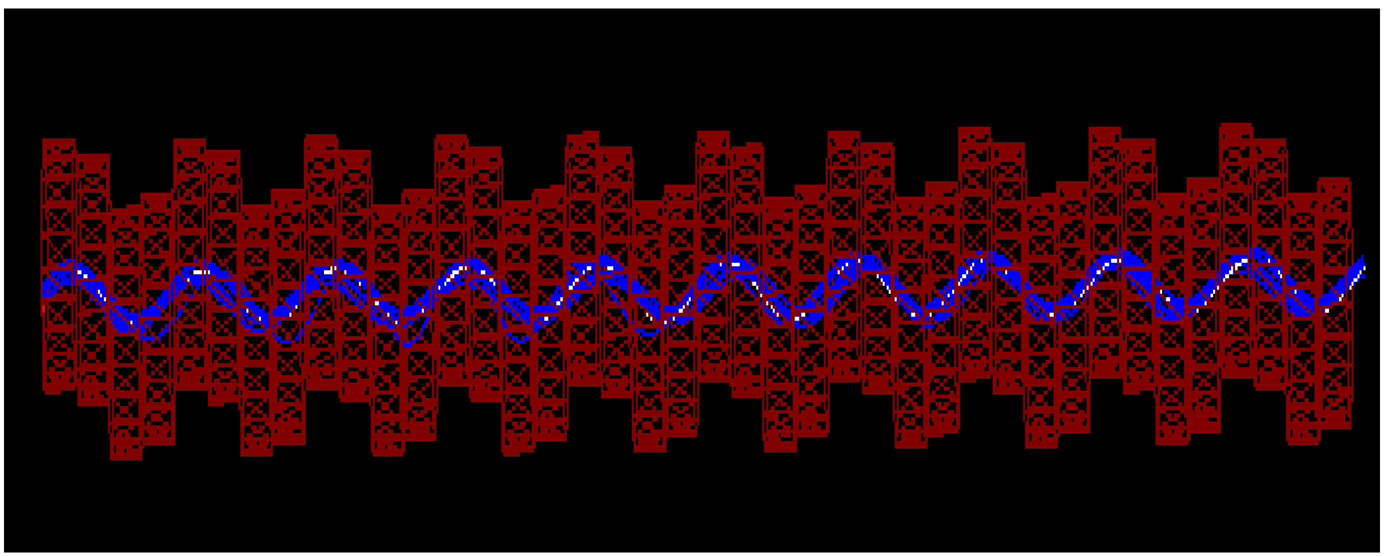
Longitudinal - Emittance Exchange

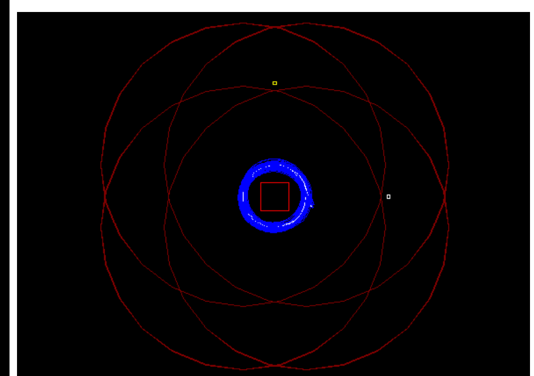
Transverse

6-Dimensional Cooling in a Continuous Absorber

- Helical Cooling Channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - Incorporate RF cavity in helical solenoid coil







Derbenev, Yonehara

Muon Acceleration – Choice of Technology

- To ensure adequate survival rates of short-lived muons the accelerator must provide high average gradient, while maintaining very large transverse and longitudinal accelerator acceptances.
  - The above requirement drives the design to low RF frequency, e.g. 200 MHz.
  - If normal-conducting cavities at that frequency were used, the required high gradi-ents would demand uneconomically high peak RF sources.
  - Superconducting RF is a much more attractive solution – the RF power can then be delivered to the cavities over an extended time, and thus RF source peak power can be reduced.
- While recirculation (RLA) provides significant cost savings over a single linac, it cannot be used at low energy since the beam is not sufficiently relativistic and will therefore cause a phase slip for beams in higher passes

Choice of Linac Repetition Rate

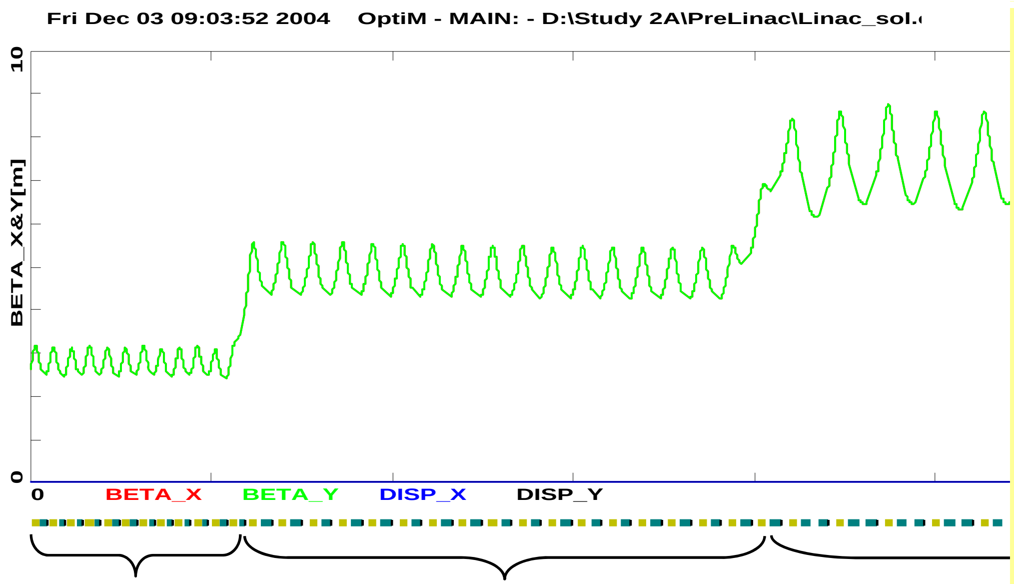
- For optimum performance – to maximize number of events ($\mu \rightarrow \nu$ decays NF, $\mu^{\pm}$ collisions MC) – the Linac repetition rates should scale inversely with the laboratory lifetime of the muon in its storage ring,
  - something as high as 1 kHz for a 40 GeV Neutrino Factory
  - or as low as 20 Hz for a 5 TeV Muon Collider.

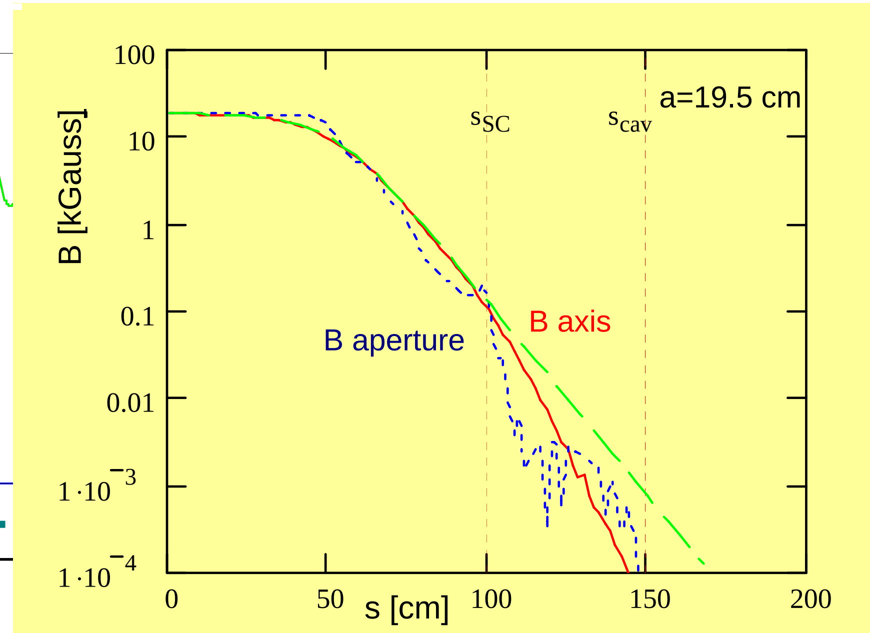
Neutrino Factory - Large Acceptance Challenge

Initial beam emittance after cooling at 220 MeV/c

International Design Study		ε_{rms}	$A = (2.5)^2\ \varepsilon$
normalized emittance: $\varepsilon_x/\varepsilon_y$	mm·rad	**4.8**	**30**
longitudinal emittance: ε_l $(\varepsilon_l = \sigma_{\Delta p}\ \sigma_z/m_\mu c)$ momentum spread: $\sigma_{\Delta p/p}$ bunch length: σ_z	mm mm	**27** **0.07** **176**	**150** **±0.17** **±442**

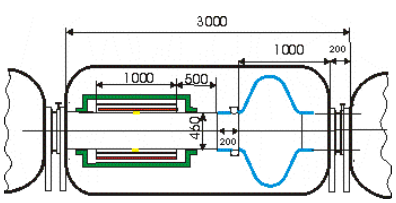
NF Linear Pre-accelerator – 3 GeV



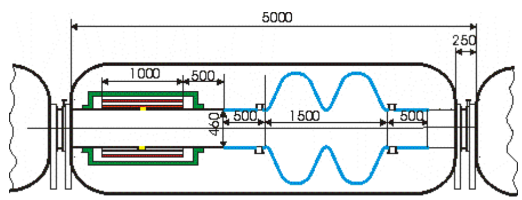


12 short cryos

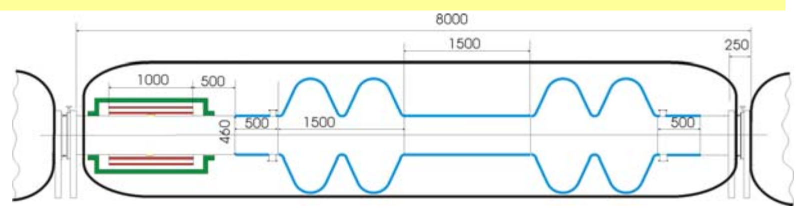
18 medium cryos



1.5 Tesla solenoid



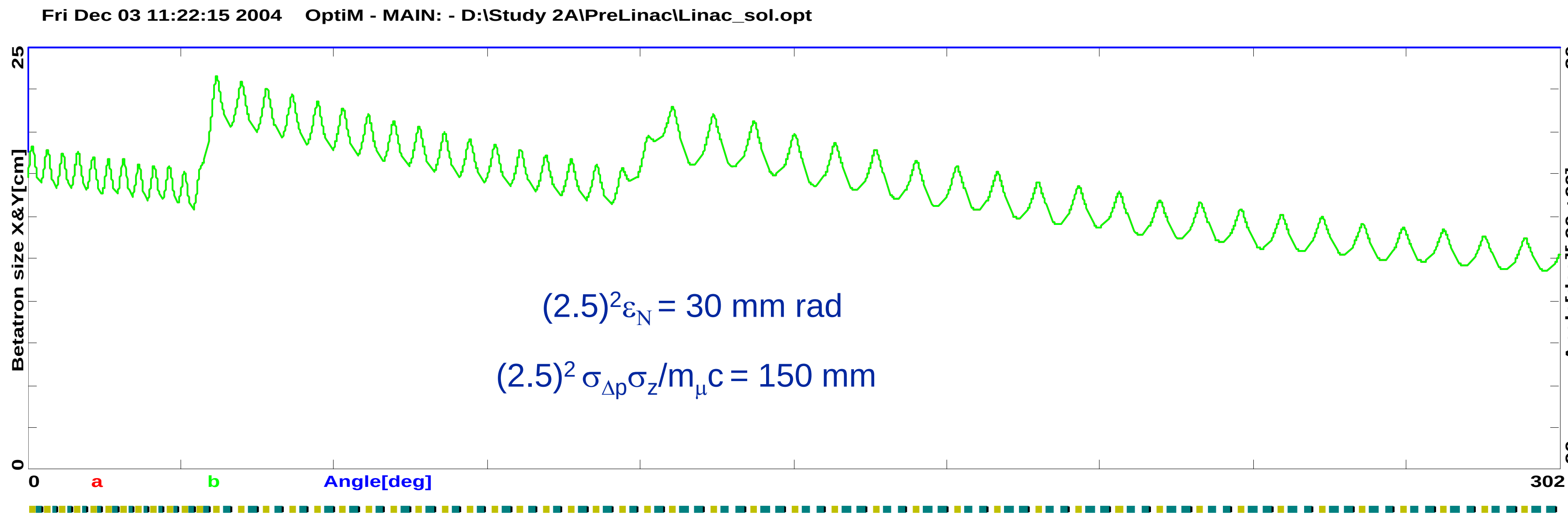
2 Tesla solenoid

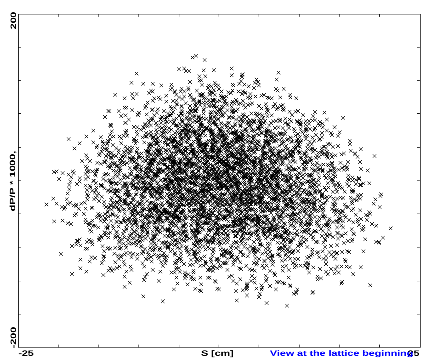


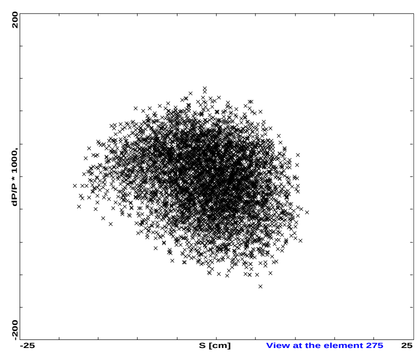
4 Tesla solenoid

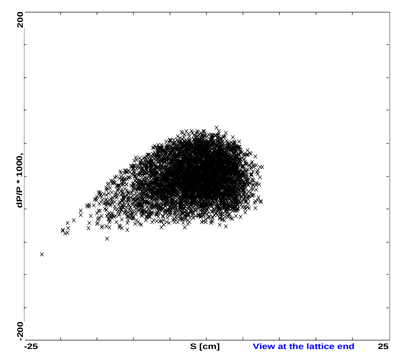
To achieve fast field drop from solenoid to cavity the solenoid has an **outer counter-coil**, which intercepts its magnetic flux, and the cavity has a **SC shielding** at its outer surface. That allows one to achieve magnetic field less than **0.1 G** inside the cavity

NF Linear Pre-accelerator – Longitudinal dynamics





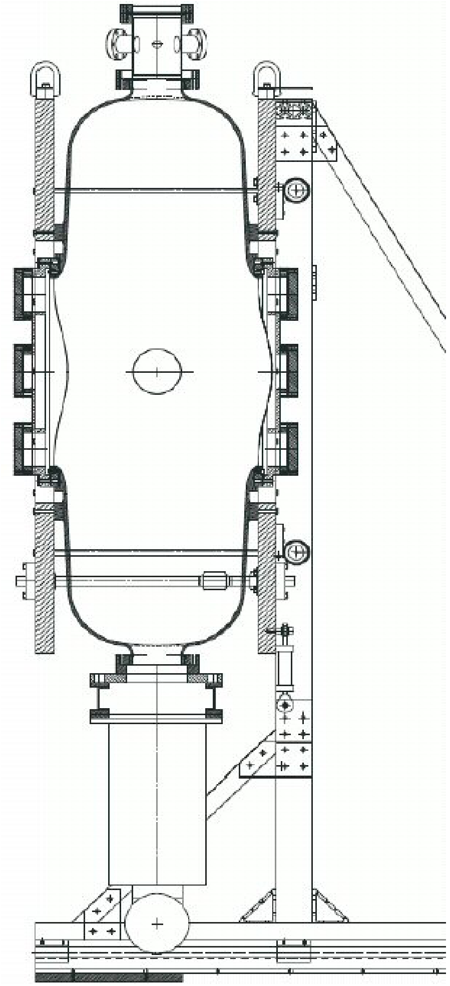




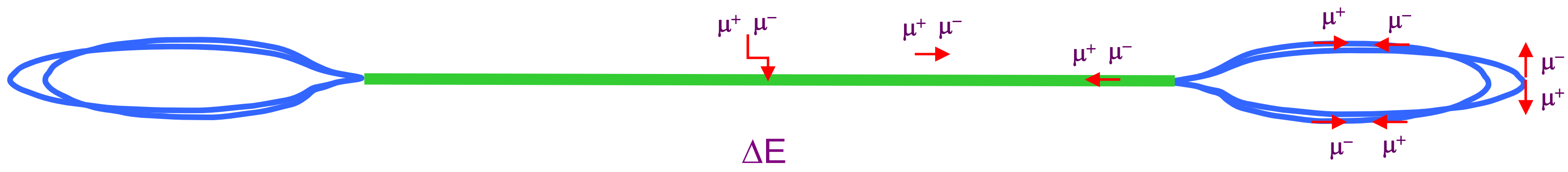
Longitudinal phase-space (s, $\Delta p/p$) axis range: s = ±25 cm, $\Delta p/p$ = ±0.2

201 MHz Cavity Design R&D at J-Lab

The 201 MHz Cavity was tested to the design gradient of 16MV/m at B=0 and at B ~ a few hundred Gauss

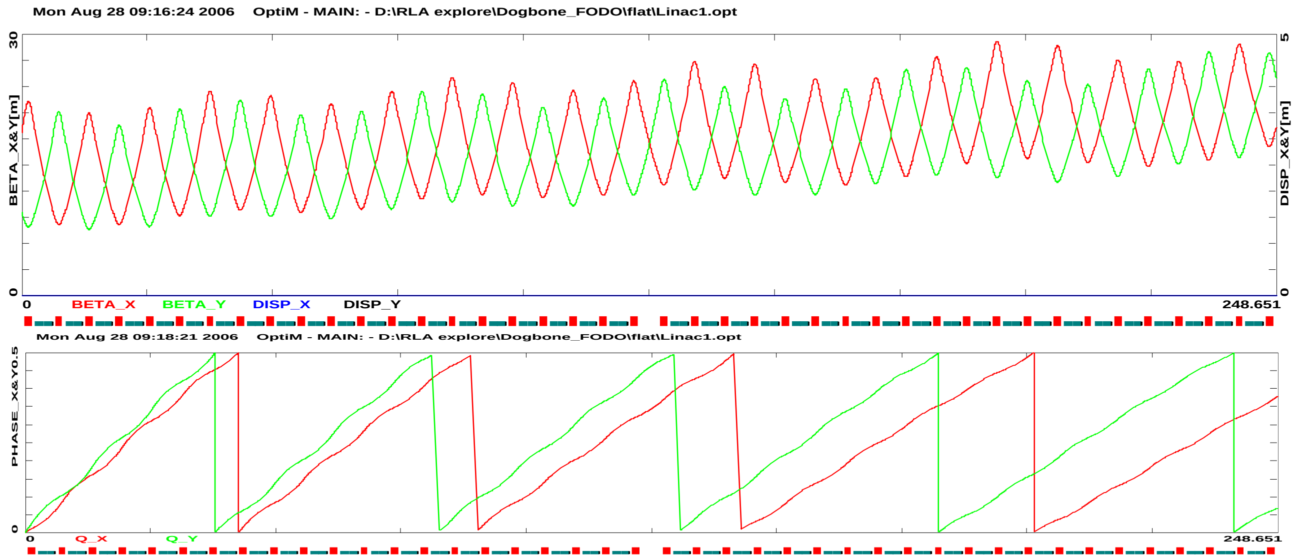


‘Racetrack’ vs ‘Dogbone’ RLA (both μ^+ and μ^-)



- better orbit separation at linac’s end ~ energy difference between consecutive passes (2ΔE)
- allows both charges to traverse the Linac in the same direction (more uniform focusing profile
- the droplets can be reduced in size according to the required energy
- both charge signs can be made to follow a Figure-8 path (suppression of depolarization effects)

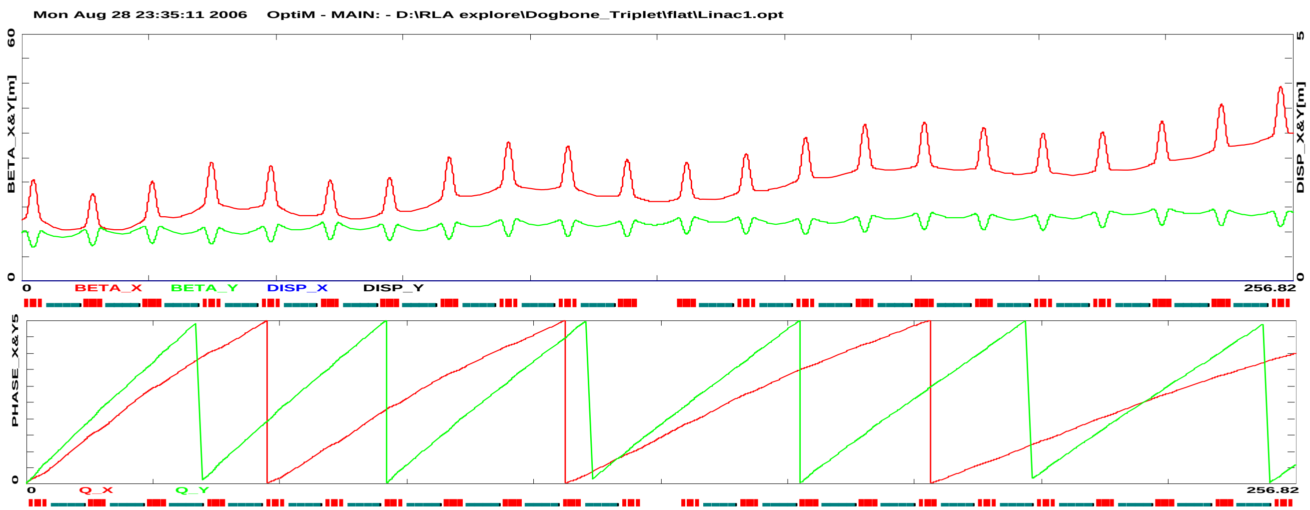
FODO vs Triplet focusing – 'flat focusing' profile



FODO

phase adv. diminish uniformly in both planes

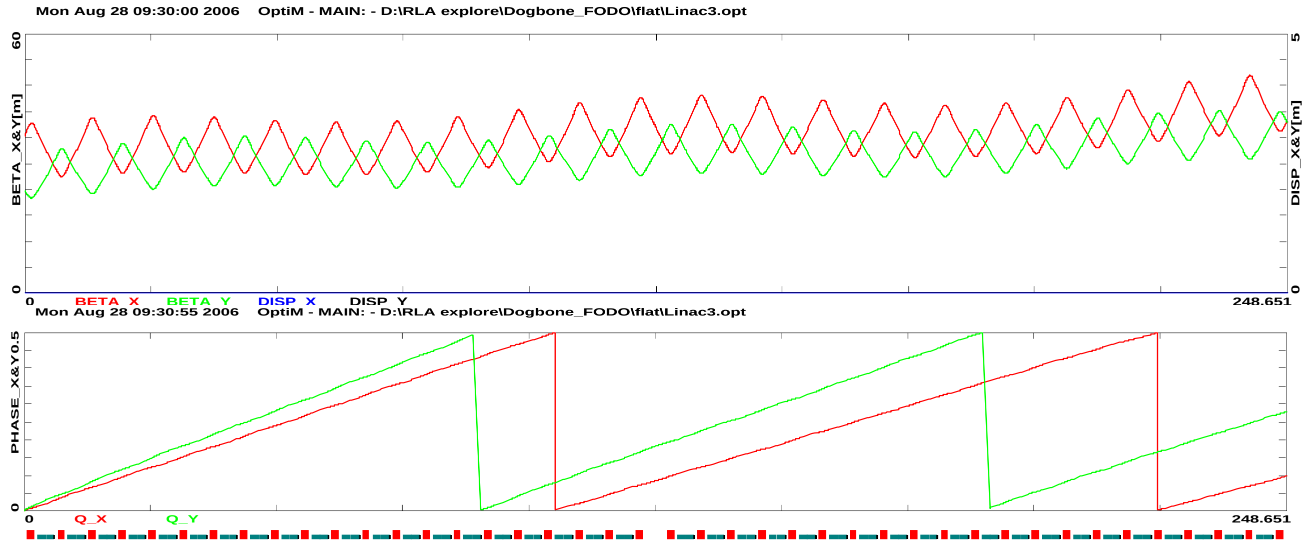
1-pass, 3-5 GeV



Triplet

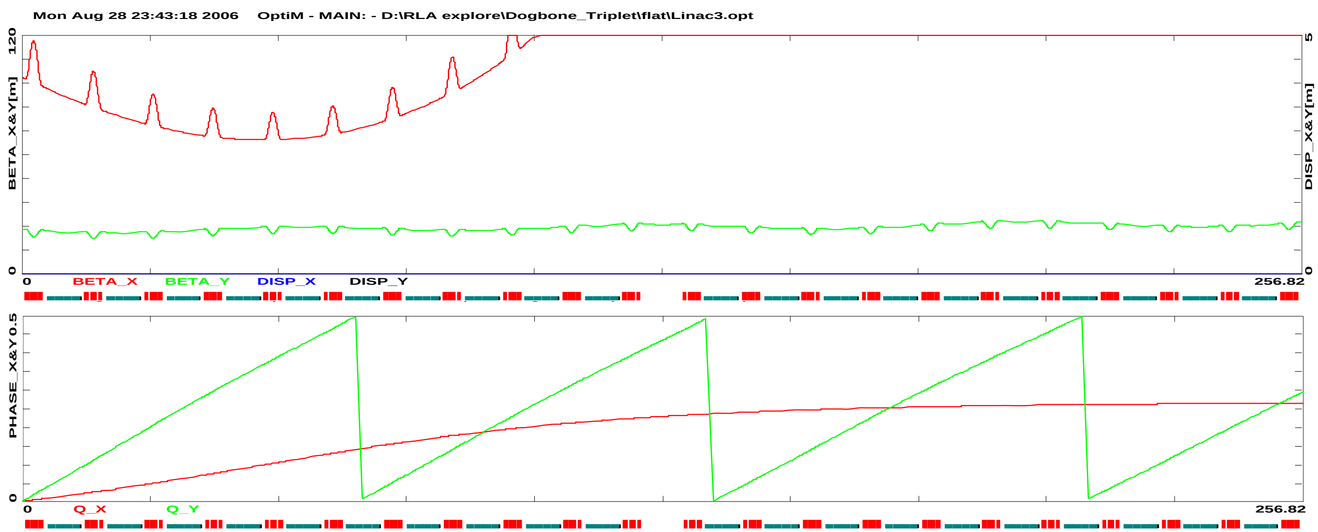
phase adv. drops much faster in the horizontal plane

FODO vs Triplet focusing – ‘flat focusing' profile



FODO

3-pass, 7-9 GeV



Triplet

no phase adv. in the horizontal plane

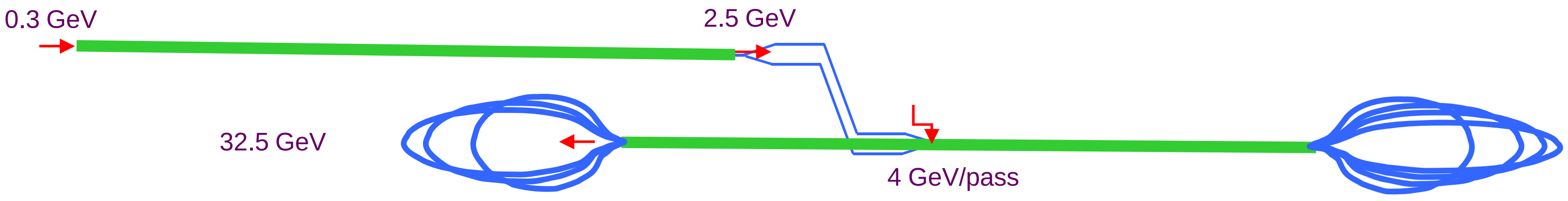
RLA based TeV scale Acceleration Scenario

Dogbone RLA I

(0.3-33 GeV)

7.5 pass

$$\frac{E_f}{E_0} = 13$$

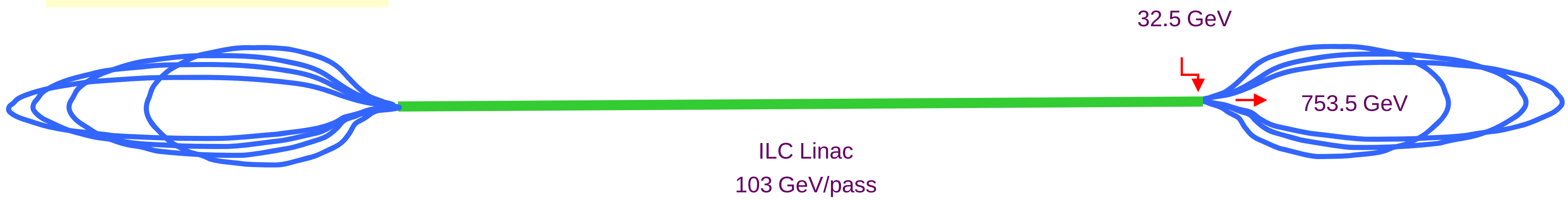


Dogbone RLA II

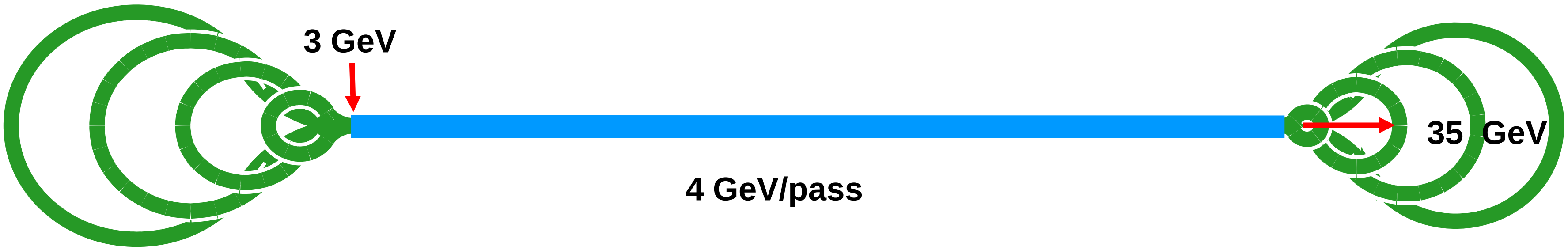
(33-753 GeV)

7 pass

$$\frac{E_f}{E_0} = 23$$



'Pulsed' vs 'Fixed' Dogbone RLA (8-pass)

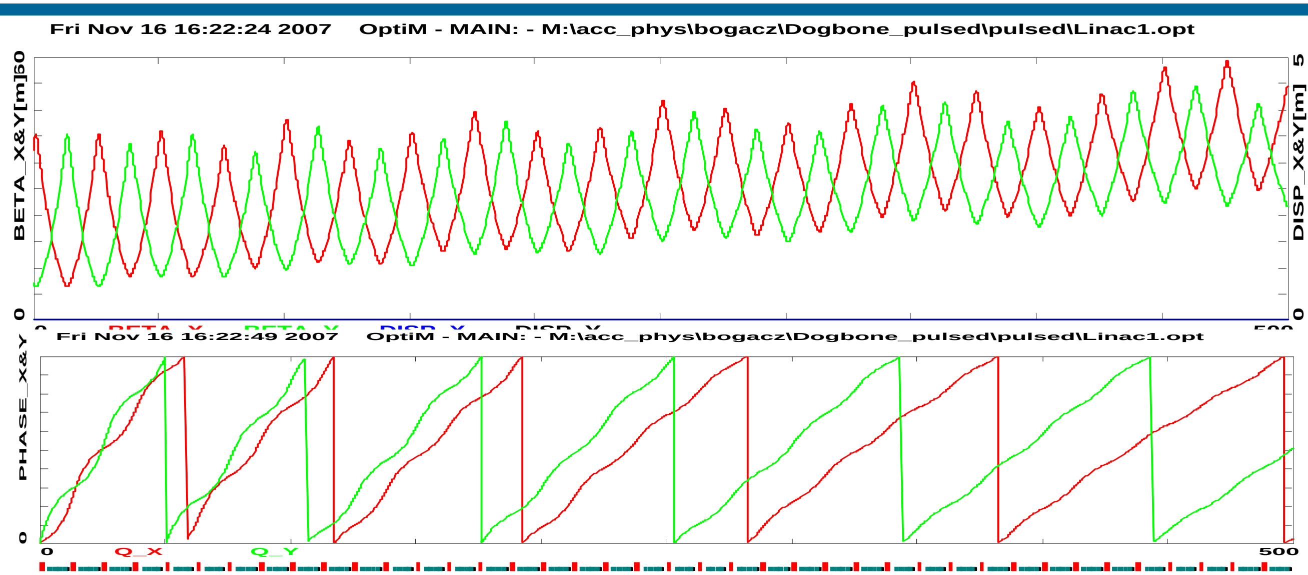


- Quad pulse would assume 500 Hz cycle ramp with the top pole field of 1 Tesla.
- Equivalent to: maximum quad gradient of G_{max} =2 kGauss/cm (5 cm bore radius) ramped over τ = 10^{-3} sec from the initial gradient of G_0 =0.1 kGauss/cm (required by 90^0 phase advance/cell FODO structure at 3 GeV) G_8 =13 G_0 = 1.3 kGauss/cm
- These parameters are based on similar applications for ramping corrector magnets such as the new ones for the Fermilab Booster Synchrotron that have 1 kHz capability

$$T \approx 8 \times \frac{500+250}{3\times 10^{-8}} \sec = 2\times 10^{-5} \sec$$

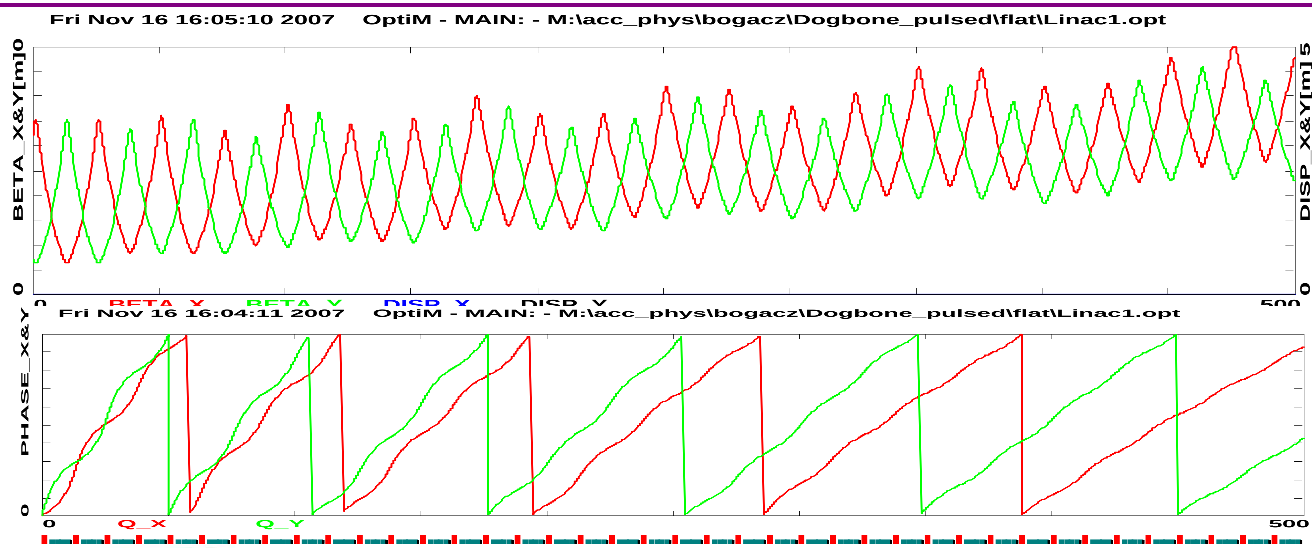
$$\frac{T}{\tau} \approx 2\times 10^{-2}$$

'Pulsed' vs 'Fixed' Dogbone RLA (8-pass)



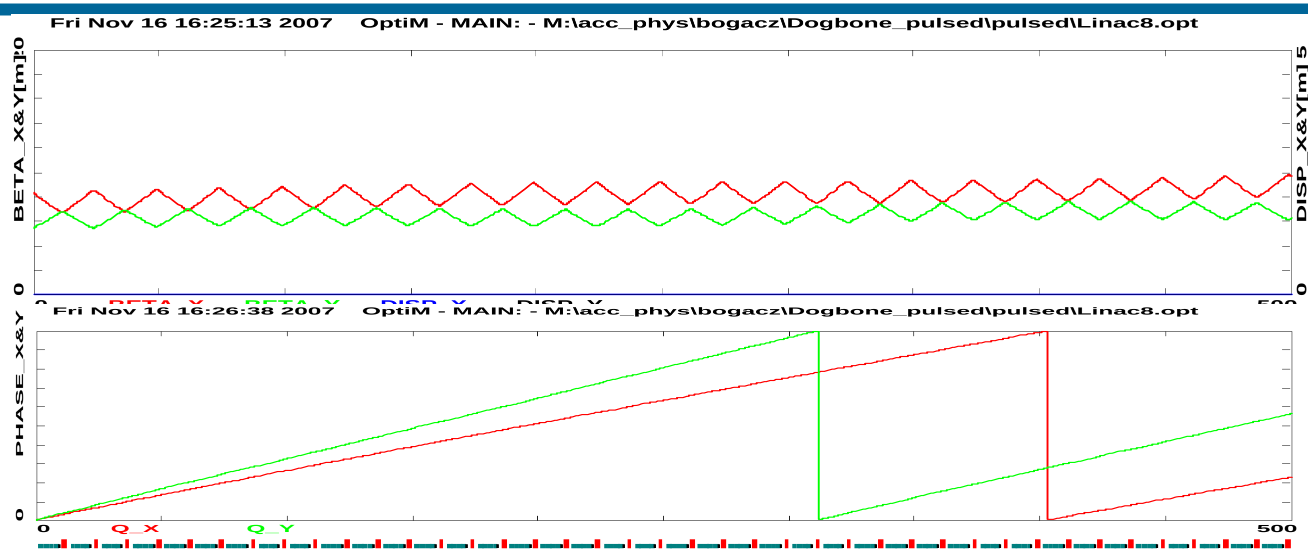
Pulsed

1-pass, 3-7 GeV



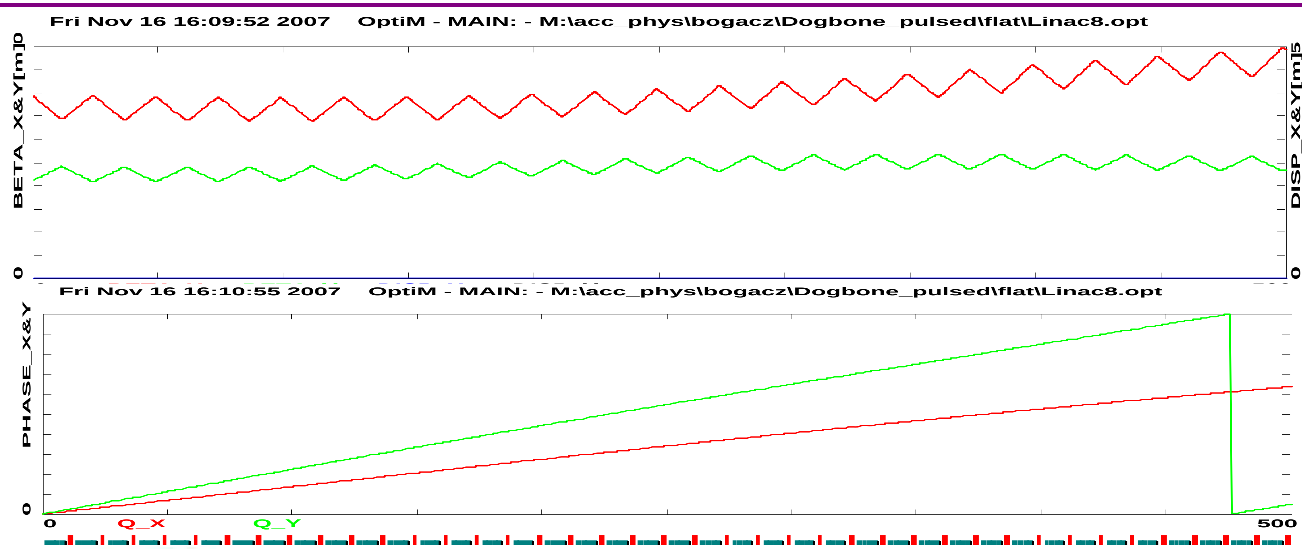
Fixed

‘Pulsed’ vs ‘Fixed’ Dogbone RLA (8-pass)



Pulsed

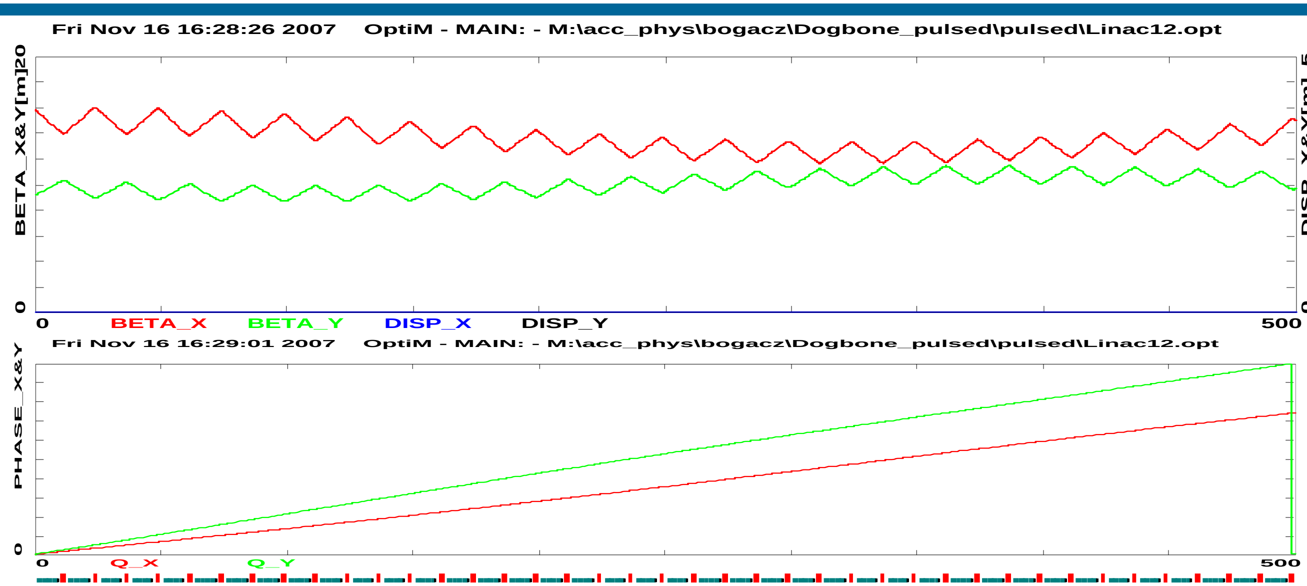
8-pass, 28-32 GeV



Fixed

phase adv. diminishes down to 180^0

‘Pulsed’ vs ‘Fixed’ Dogbone RLA (8-pass)



Pulsed

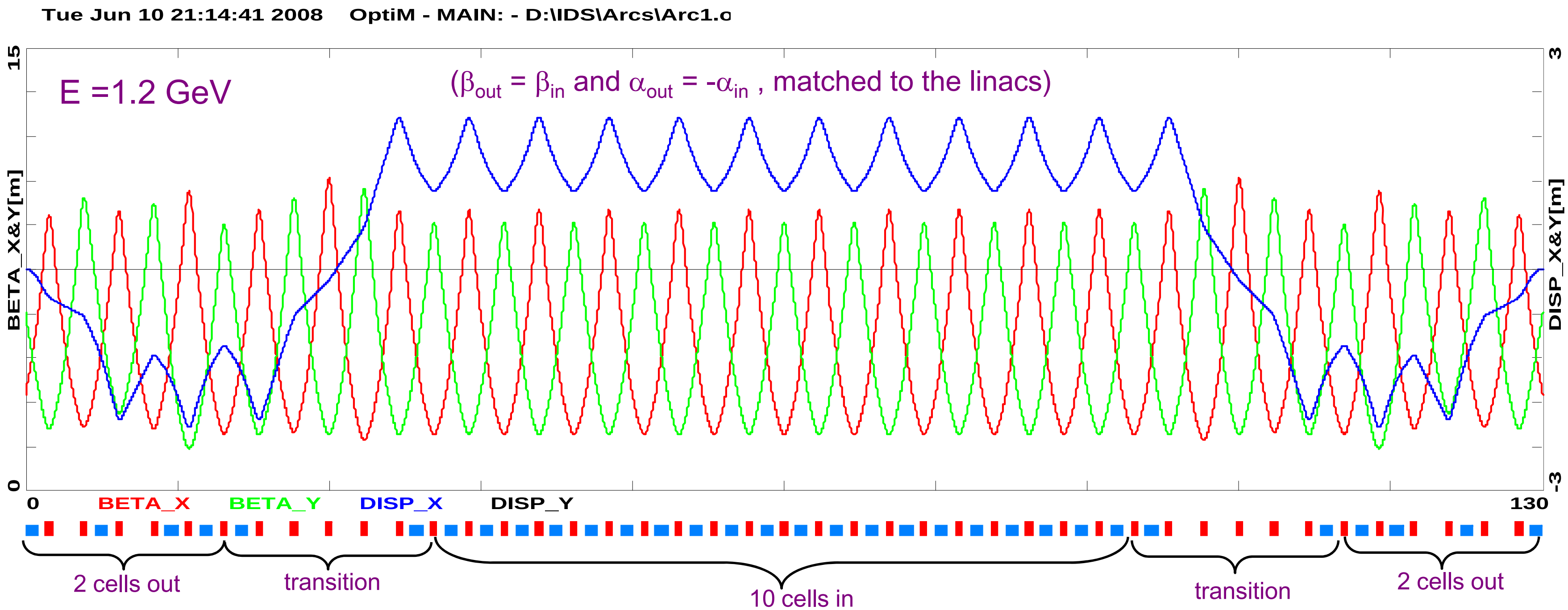
phase adv. diminishes down to 180^0

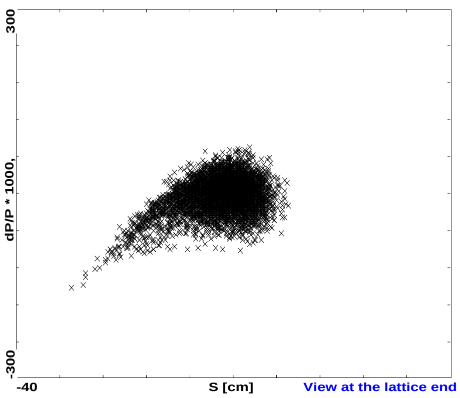
12-pass, 47-51 GeV

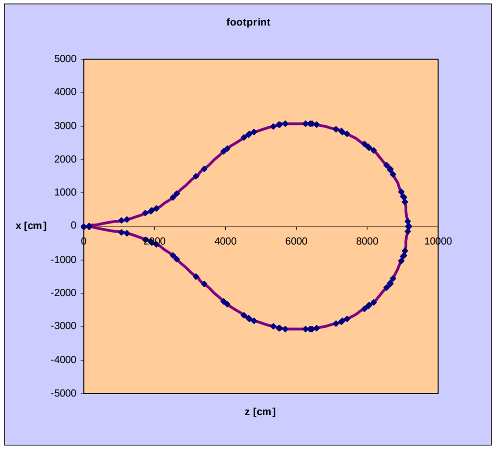
Fixed

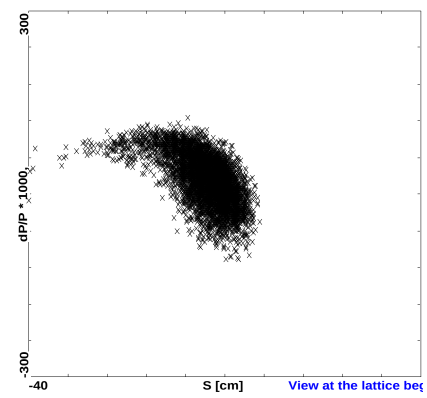
no phase adv. across the linac- beam envelopes not confined

Mirror-symmetric 'Droplet' Arc – Optics









Conclusions

- **Muon Colliders & Neutrino Factories** will require innovative linacs to: **produce** the muons, **cool/compress** and **'shape'** them into a beam and finally to rapidly **accelerate** them to multi – GeV (NF) & TeV (MC) energies
- Large acceptance Muon Linac provides rapid acceleration and effective longitudinal bunch compression via induced synchrotron motion
- 'Dogbone' (Single Linac) RLA has advantages over the 'Racetrack'
  - better orbit separation for higher passes
  - offers symmetric solution for simultaneous acceleration of μ^+ and μ^-
- FODO Optics is superior to Triplet focusing – more passes can be supported
  - uniform phase advance decrease in both planes
- Pulsed linac Optics….even larger number of passes is possible if the quadrupole focusing can be increased as the beam energy increases
  - Increase from 8-pass (Fixed Optics) to 12-pass (Pulsed Optics) for 500 m long 4 GeV pass RLA
  - looks very encouraging and opens possibility for a TeV scale RLA …vigorous R&D efforts...