Explore feasibility and limiting factors of large-acceptance Recirculating Linear Accelerators (RLAs) based on Superconducting RF

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CASA

Director's Review of Accelerator R&D
March 20, 2009

Outline

- Design of multi-GeV muon accelerator complex for future Neutrino Factory – International Design Study
- TeV-scale muon acceleration for future Muon Collider
- Extreme muon cooling schemes for Low Emittance Muon Collider
- Collaborations & Partnerships
- Summary

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 cooled and accelerated to multi-GeV and TeV energies.**

- **Recent progress in muon cooling and acceleration (International Design Study and prototype tests) encourages the hope that such facilities can be built during the next decade…**

- **Funding for these studies provided by: HEP and SBIR/STTR grants**

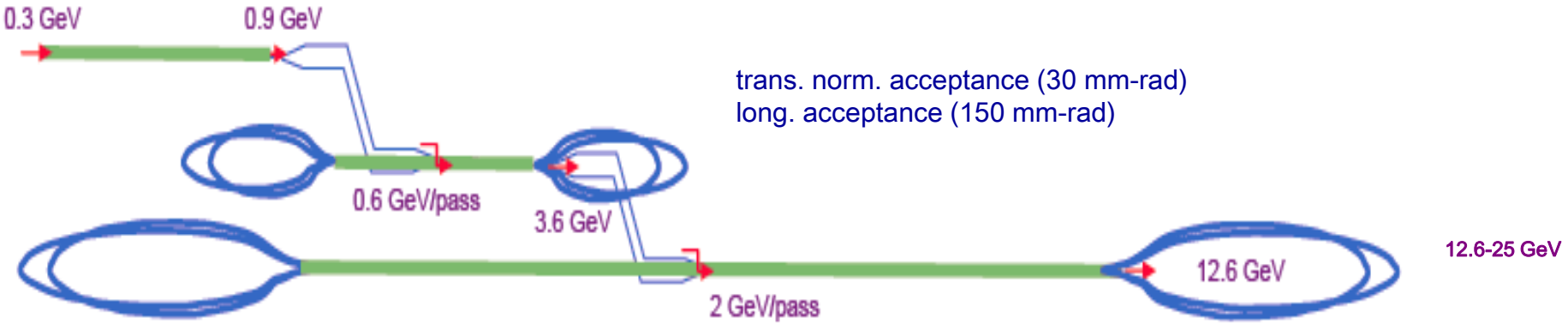
Opportunities and Challenges

- **Future Muon facilities based on muon storage rings will require innovative SRF linacs to:**
  - **Longitudinally compress and 'shape' them into a beam**
    - **μs are produced in a tertiary process into a large emittance ($p + A \rightarrow \pi \rightarrow \mu$)**
  - **Rapidly accelerate them to multi-GeV (NF) and TeV (MC) energies**
    - **it has a short life time (2.2 μsec) in its own rest frame**
    - **high gradient, fixed field accelerator**
- **Why Recirculating Linear Accelerators based on SRF?**
  - **RLAs are possible because muons do not generate significant synchrotron radiation**
    - **high energies and in strong magnetic fields (m_μ = 105 MeV/c^2)**
  - **Huge initial phase-space requires large acceptances (both trans/longit)**
  - **Large intensities call for RF operating at stored energy**

Design of multi-GeV muon accelerator complex for future Neutrino Factory – International Design Study

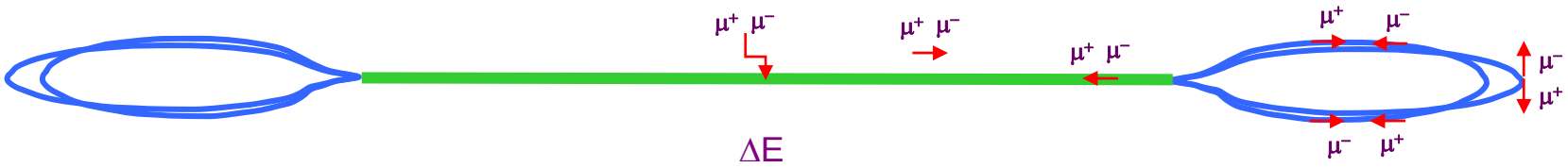
Multi-GeV muon RLAs for Neutrino Factory

- **Conceptual design of an RLA based Muon Accelerator Complex (as part of NF International Design Study)**



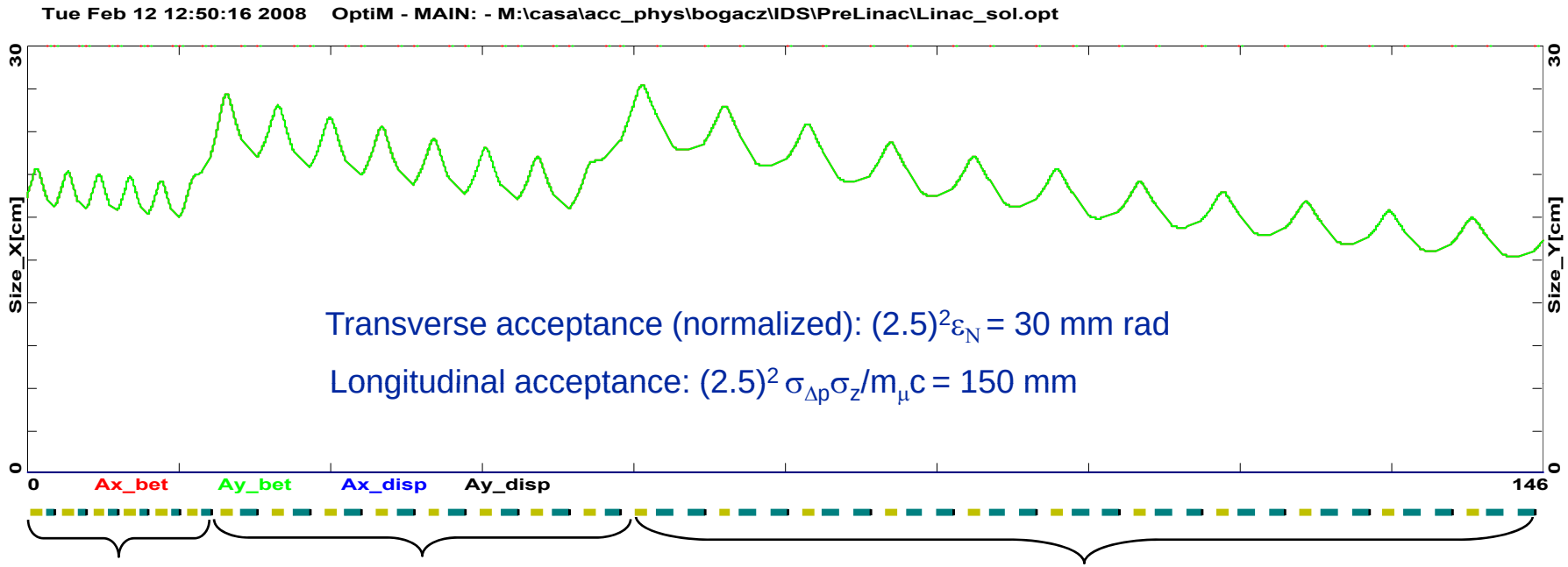
- 200 MHz SRF Linac (0.3 to 0.9 GeV)
  - Rapid acceleration of short lived muons, high gradient SRF
  - 'Full bucket' acceleration and longitudinal bunch compression
- Two-step, vertically stacked 'dogbone' RLAs (0.9 to 12.6 GeV)
  - phase slippage, RF cavities synchronized for a speed of light particle
  - simultaneous acceleration of μ^+ and μ^- charge species

‘Dogbone’ vs ‘Racetrack’ 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

Linear Pre-accelerator – 240 to 900 MeV

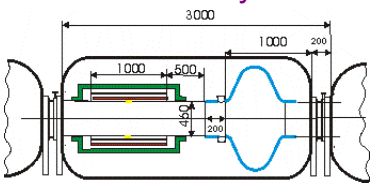


6 short cryos

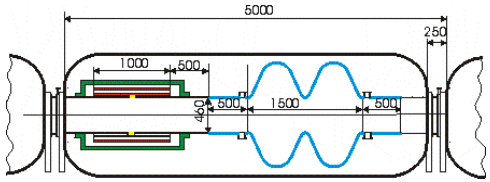
8 medium cryos

17 MV/m

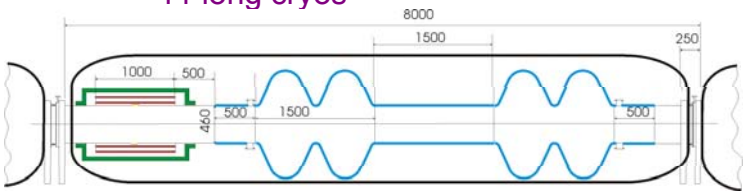
11 long cryos



1.1 Tesla solenoid



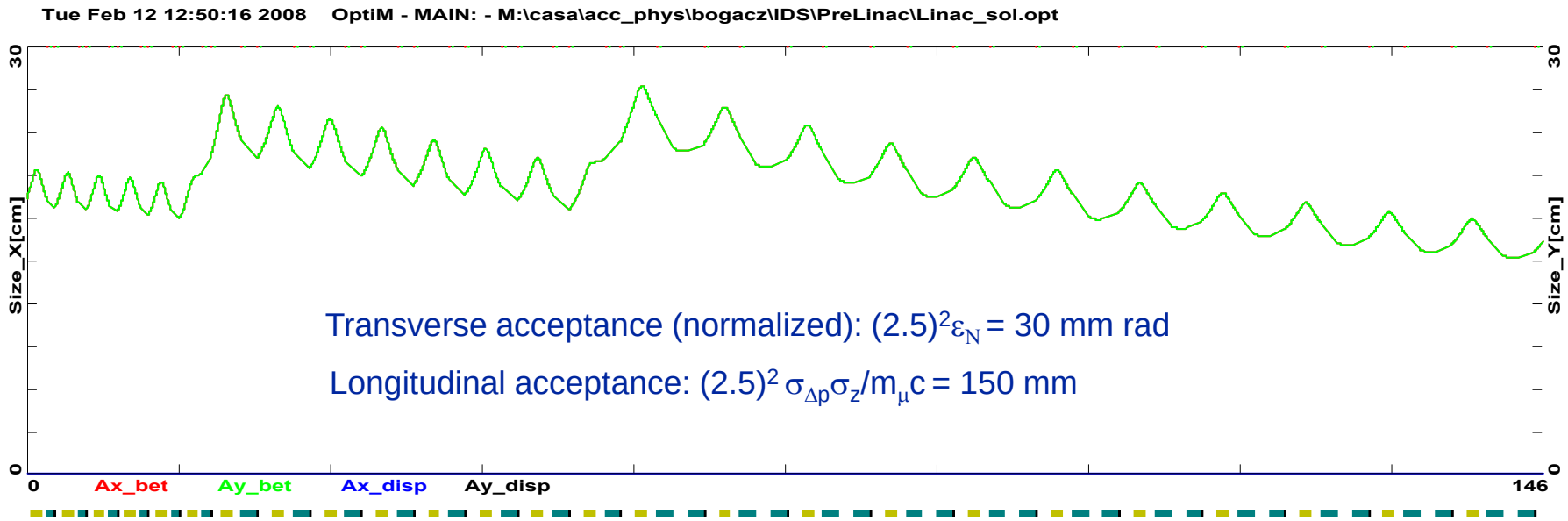
1.4 Tesla solenoid

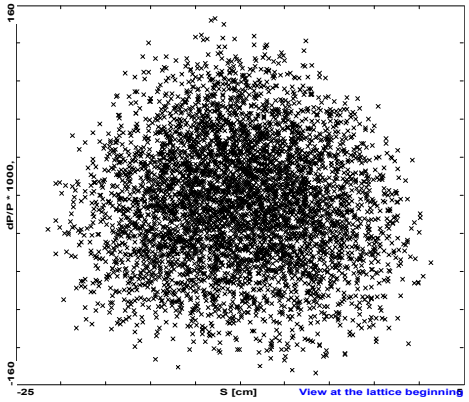


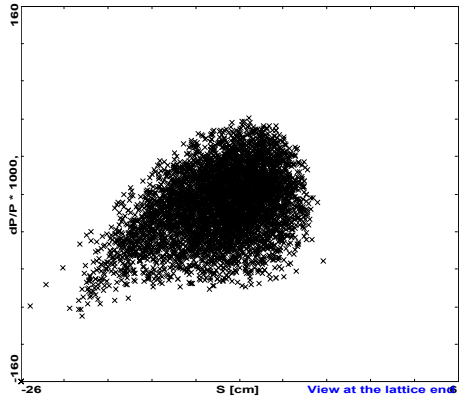
2.4 Tesla solenoid

SRF 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

Pre-accelerator – Longitudinal compression



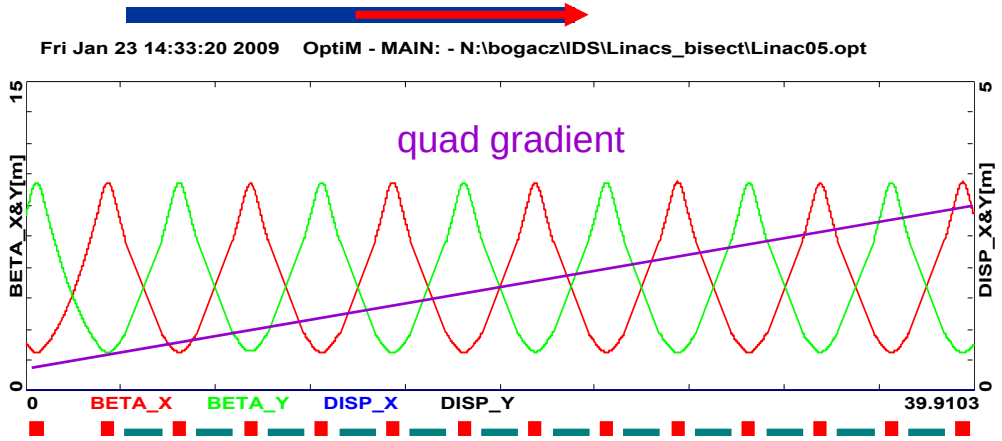




Longitudinal phase-space (s, Δp/p) axis range: s = ±25 cm, Δp/p = ±0.2

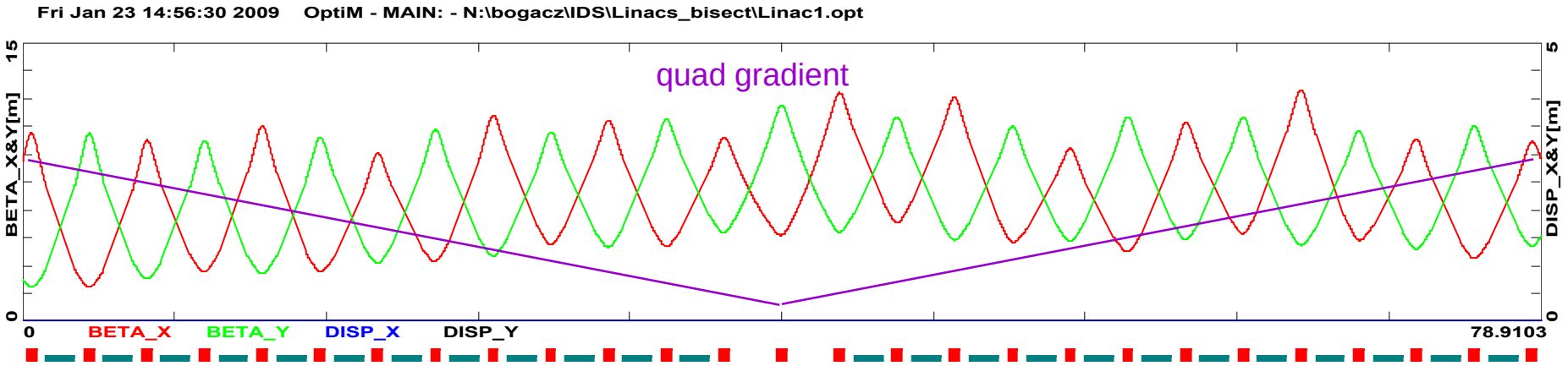
Multi-pass linac Optics

‘half pass’ , 900-1200 MeV



initial phase adv/cell 90 deg. scaling quads with energy

1-pass, 1200-1800 MeV

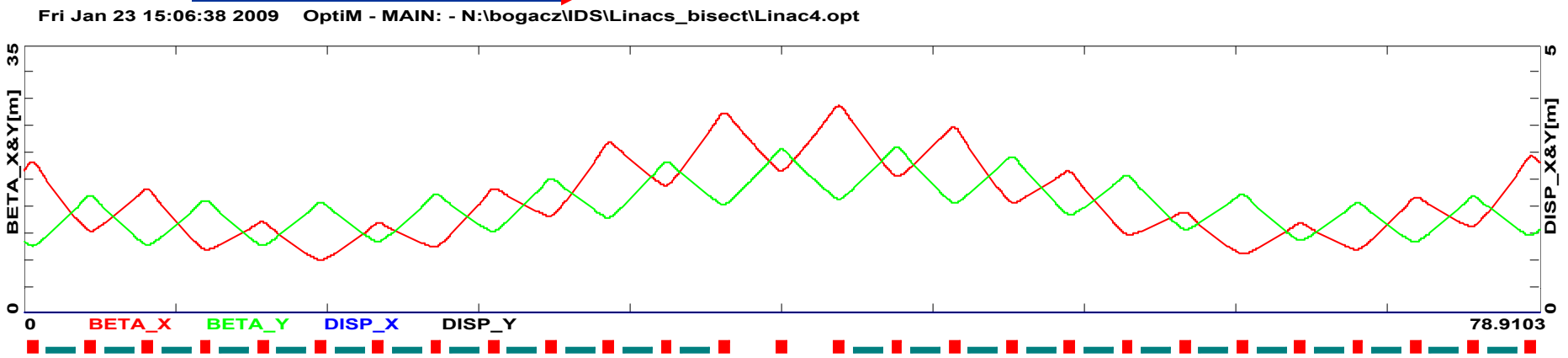


mirror symmetric quads in the linac

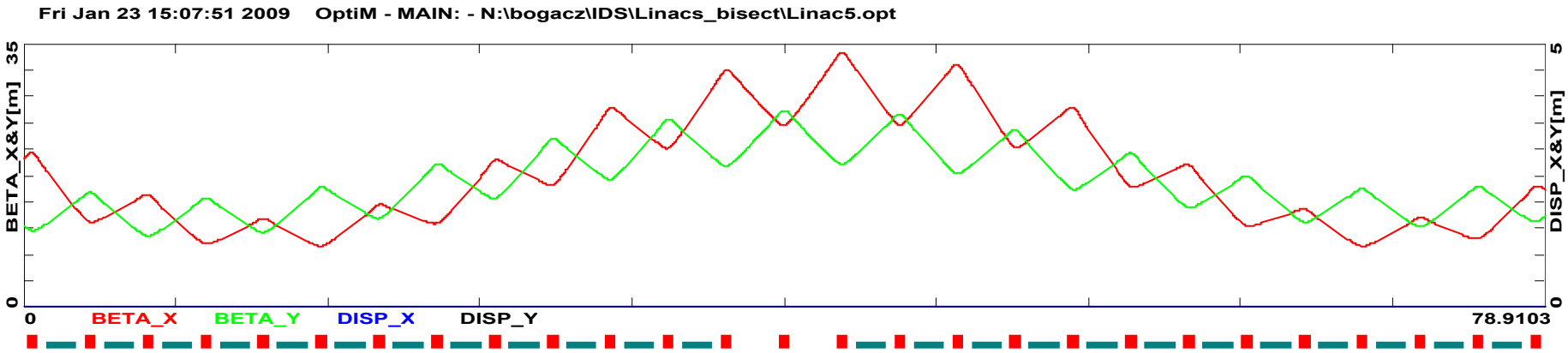
Multi-pass linac Optics

4-pass, 3000-3600 MeV

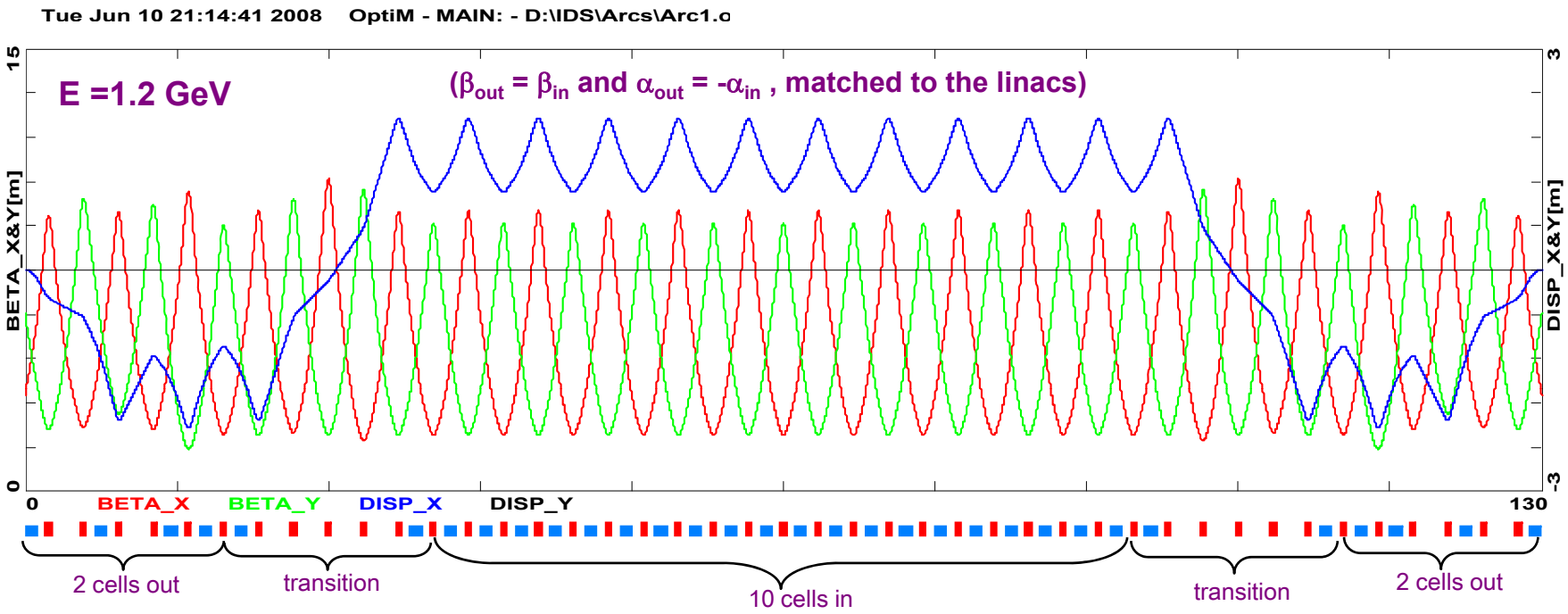
phase adv. still larger then 180 deg. in both planes

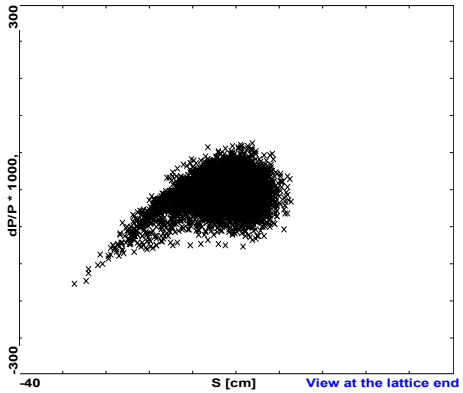


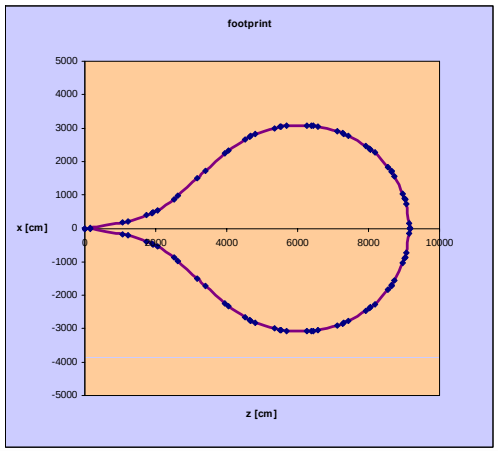
5-pass, 3600-4200 MeV

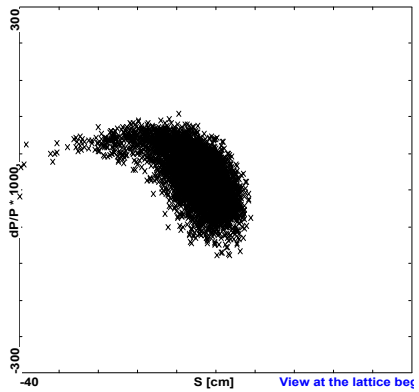


Mirror-symmetric ‘Droplet’ Arc – Optics



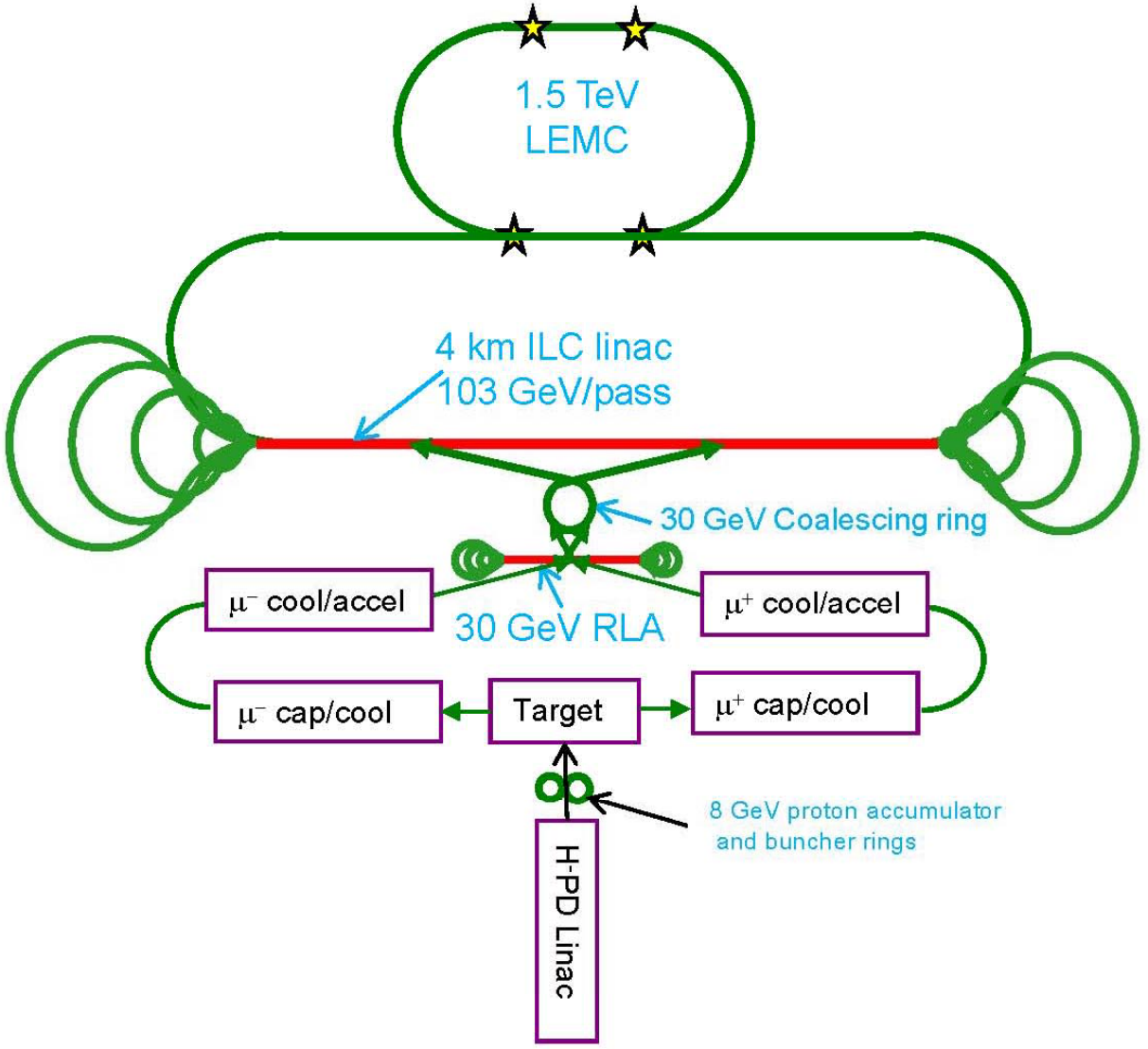






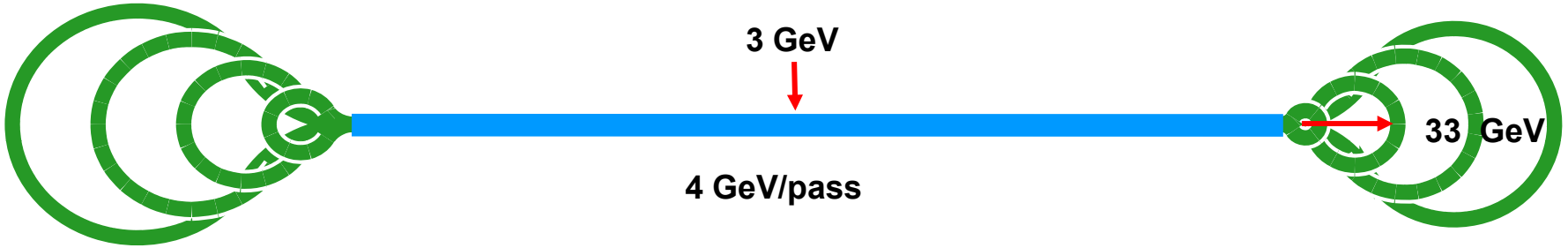
TeV-scale muon acceleration for future Muon Collider

Low Emittance Muon Collider Scenario



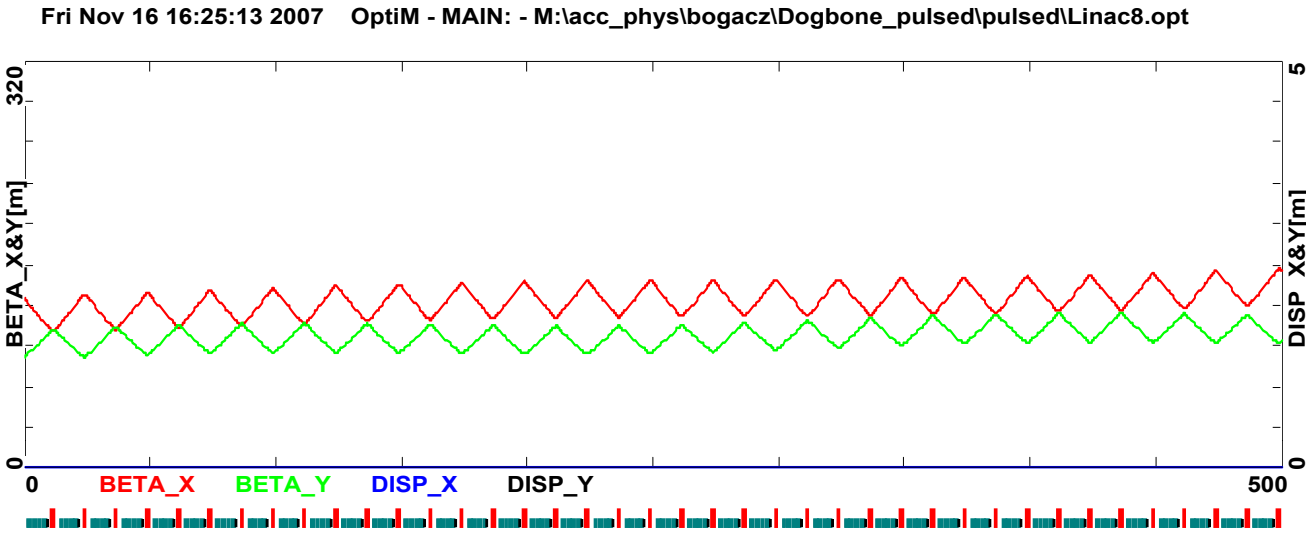
‘Pulsed’ linac Dogbone RLA

- **Design of a muon RLA based on ILC linac (solicited by Muon Collider Task Force at Fermilab)**



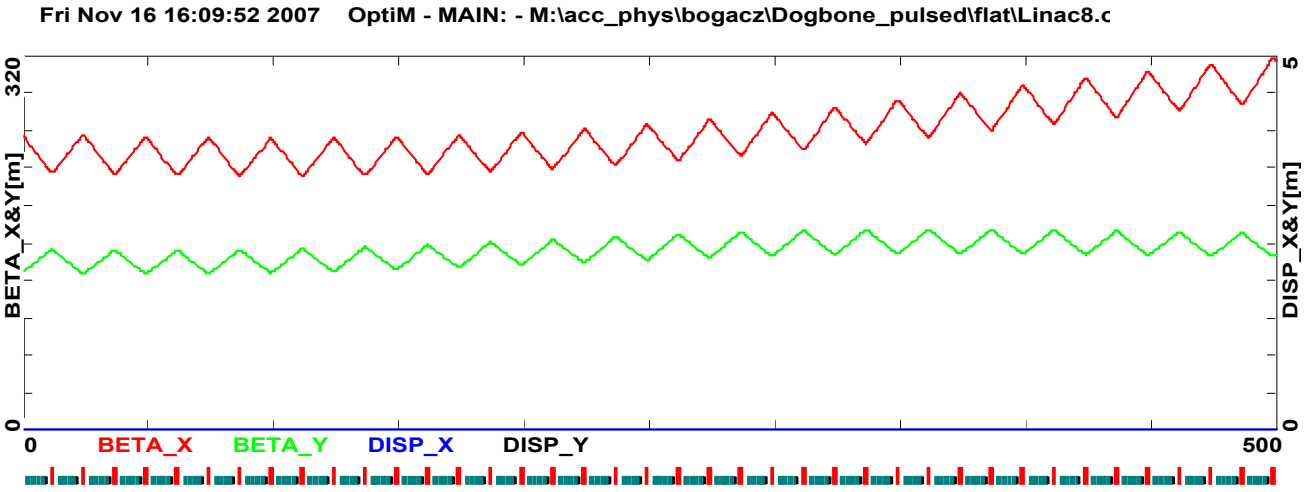
- **Multi-pass linac optics with pulsed quads** – newly awarded SBIR with Muons Inc
  - Quad pulse would assume 500 Hz cycle ramp with the top pole field of 1 Tesla.
  - Mitigation of focusing deficiency - larger number of passes

‘Pulsed’ vs ‘Fixed’ Dogbone RLA



Pulsed

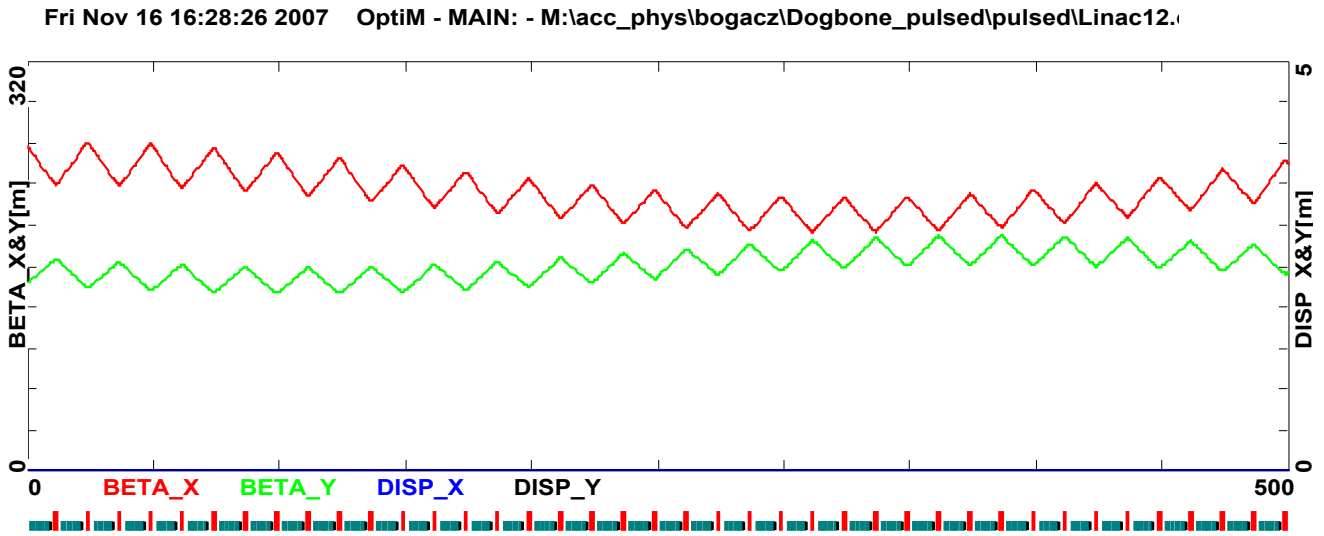
8-pass, 28-32 GeV



Fixed

phase adv. diminishes down to 180^0

‘Pulsed’ vs ‘Fixed’ Dogbone RLA



Pulsed

phase adv. diminishes down to 180^0

12-pass, 47-51 GeV

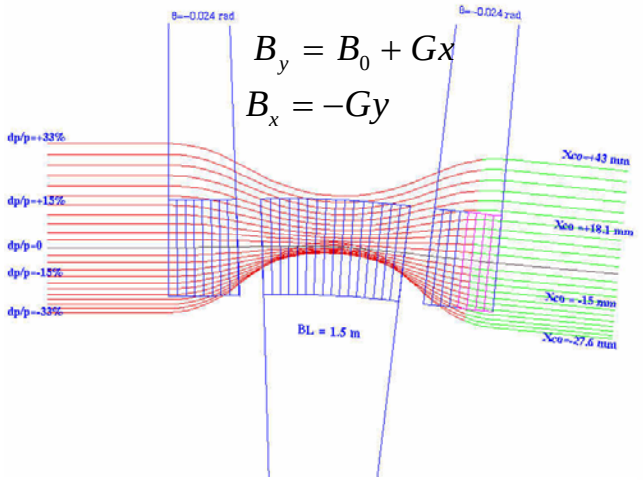
Fixed

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

Large momentum acceptance multi-pass Arc

- **Non Scaling FFAG Optics**
  - **Compact triplet cells based on opposed bend combined function magnets**

$$B_y = B_0 + Gx$$
$$B_x = -Gy$$



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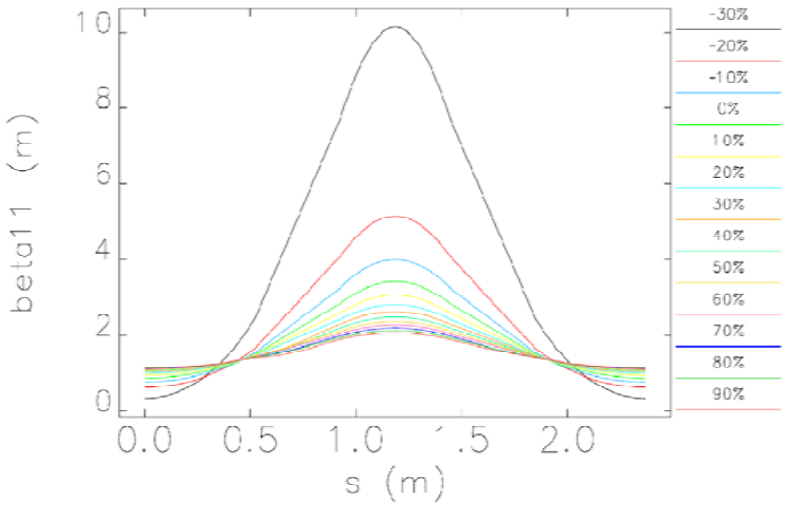
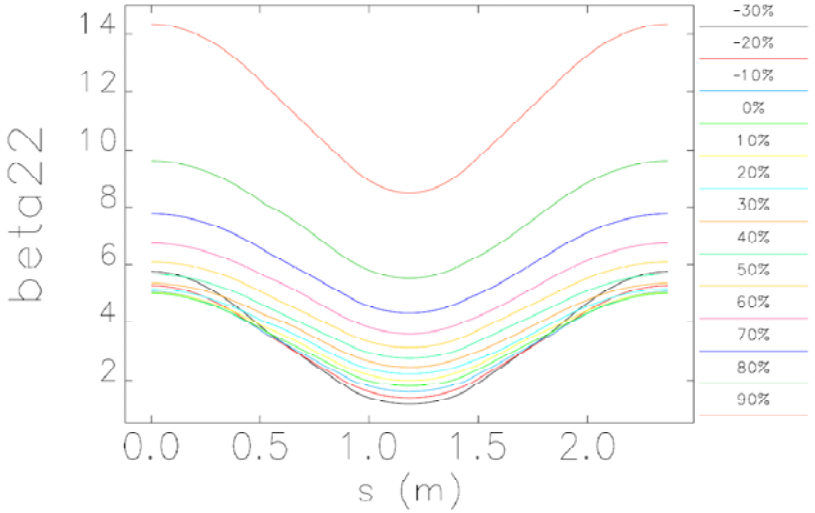
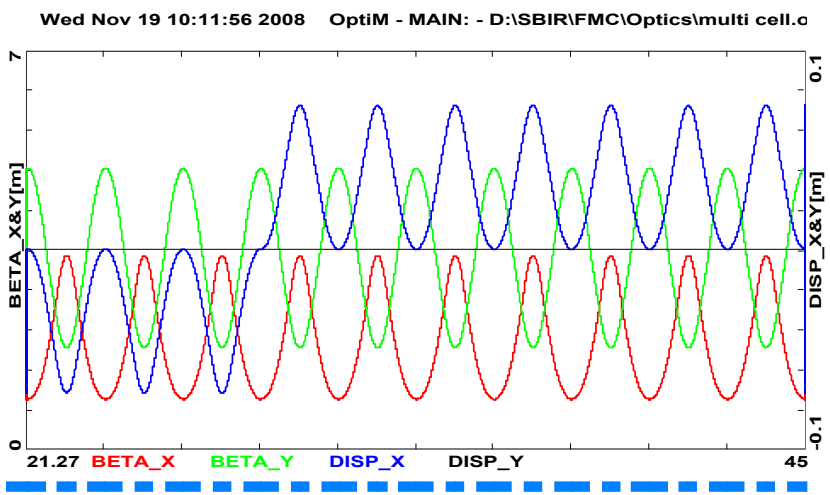


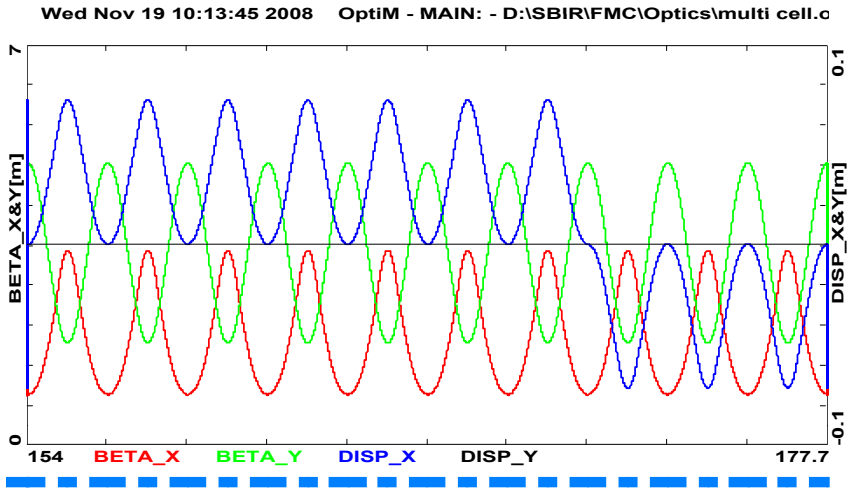


For different energies self-similar beta functions in a periodic cell

MADX- Polymorphic Tracking Code. Energy acceptance: -30% to 90%

NS-FFAG multi-pass 'Droplet' Arc

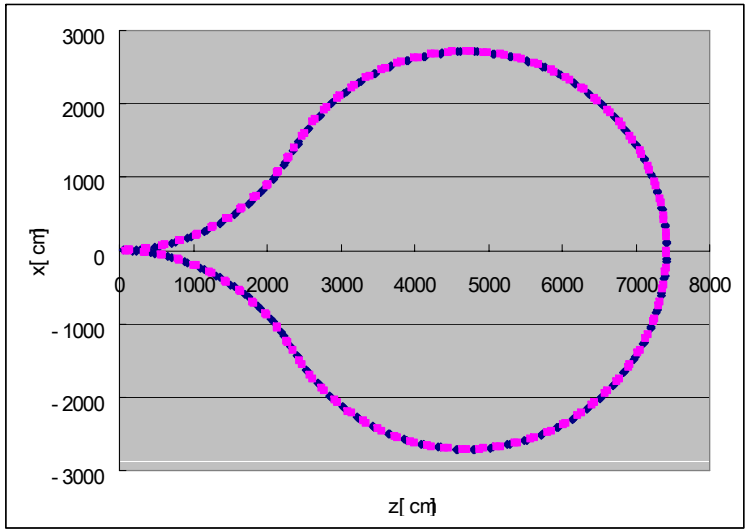




60^0 outward

300^0 inward

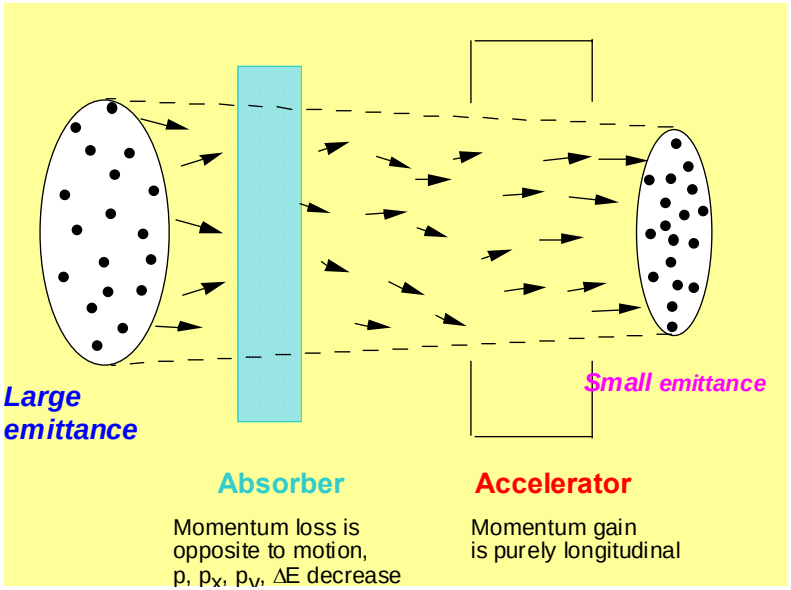
60^0 outward

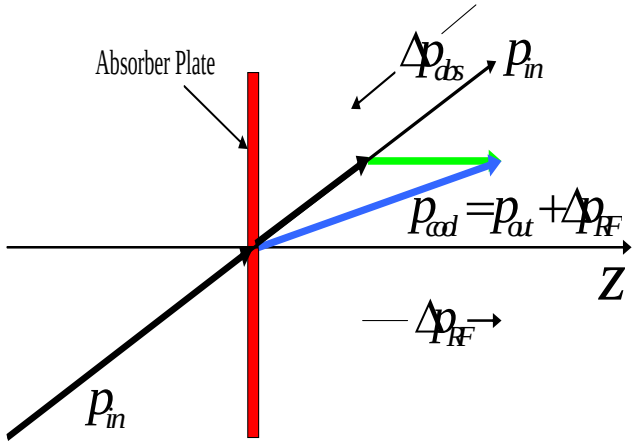


- **MADX-PT – Polymorphic Tracking Code is used to study multi-pass beam dynamics for different pass beams: path length difference, optics mismatch between linac and arcs, orbit offset and tune change is being studied.**

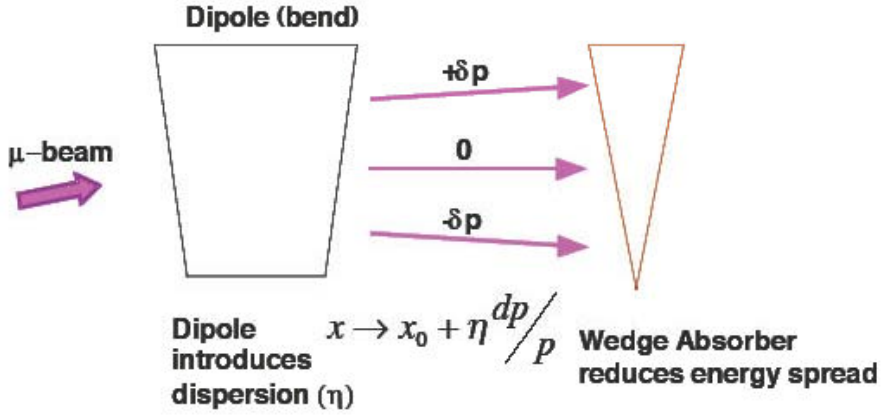
Extreme muon cooling schemes for Low Emittance Muon Collider

Muon Ionization Cooling





Transverse cooling



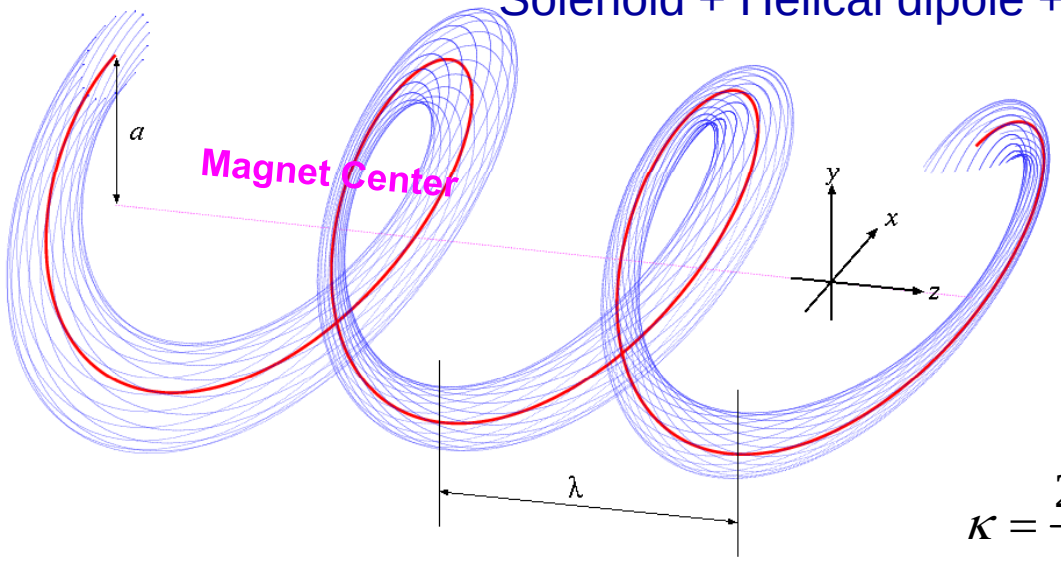
Longitudinal Emittance Exchange

Helical Cooling Channel

A linac filled with high pressure hydrogen gas and imbedded in strong magnetic fields has been proposed to rapidly cool muon beams

Combined function magnet (invisible in this picture)

Solenoid + Helical dipole + Helical Quadrupole



Red: Reference orbit

Blue: Beam envelope

Dispersive component makes longer path length for higher momentum particle and shorter path length for lower momentum particle.

$$\kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

$f_\uparrow \propto b_\varphi \cdot p_z$ Repulsive force

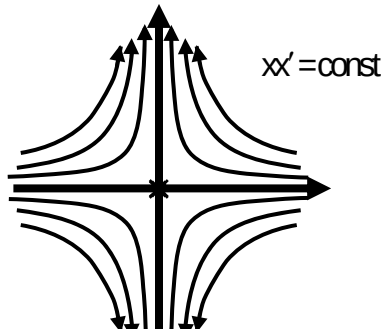
$f_\downarrow \propto -b_z \cdot p_\varphi$ Attractive force

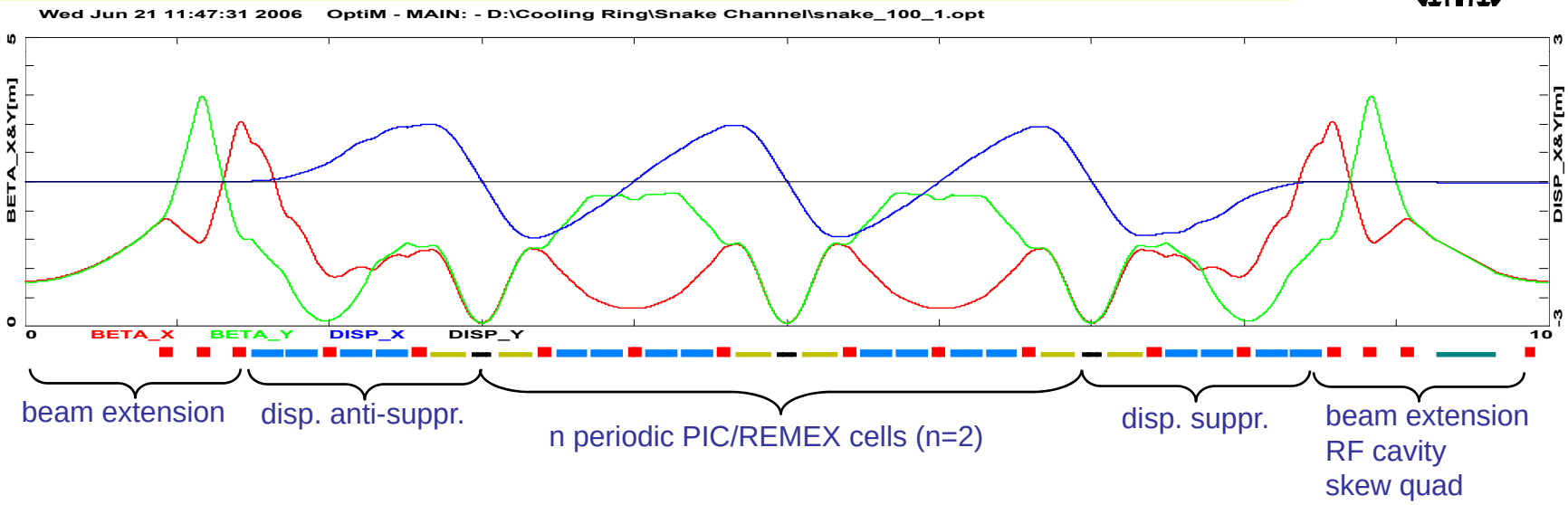
$$f_{central} = \frac{e}{m}(b_\varphi \cdot p_z - b_z \cdot p_\varphi)$$

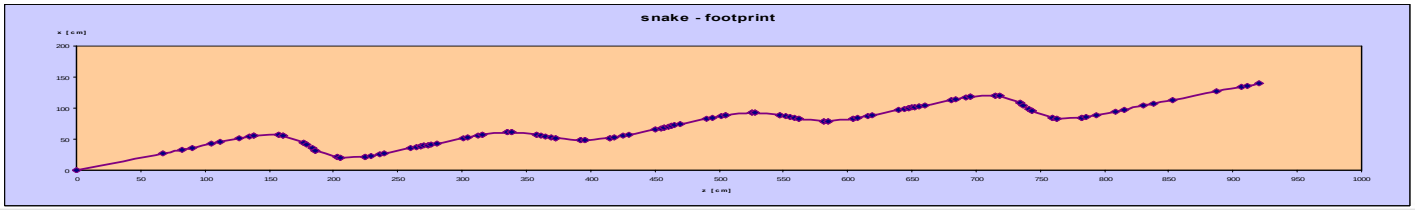
Both terms have opposite signs.

Parametric Resonance Cooling

- Transport channel (between consecutive absorbers) designed to replenish large angular component, x', sector of the phase-space, 'mined' by ionization cooling process.
- Normal elliptical motion of a particle's transverse coordinate in phase space becomes hyperbolic (half-integer resonance) – resulting beam emittance has a wide spread in x' and very narrow spread in x.



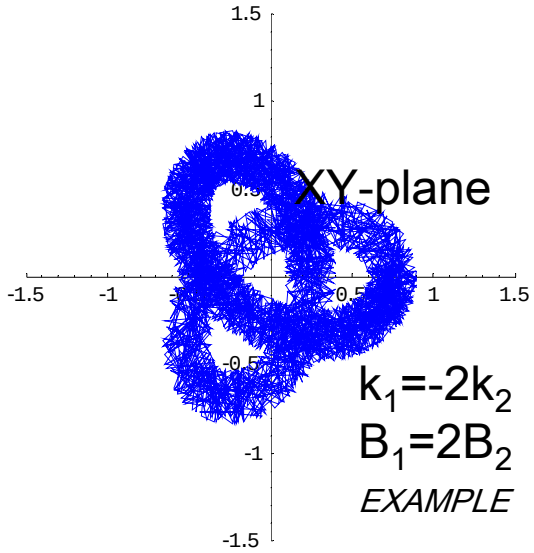


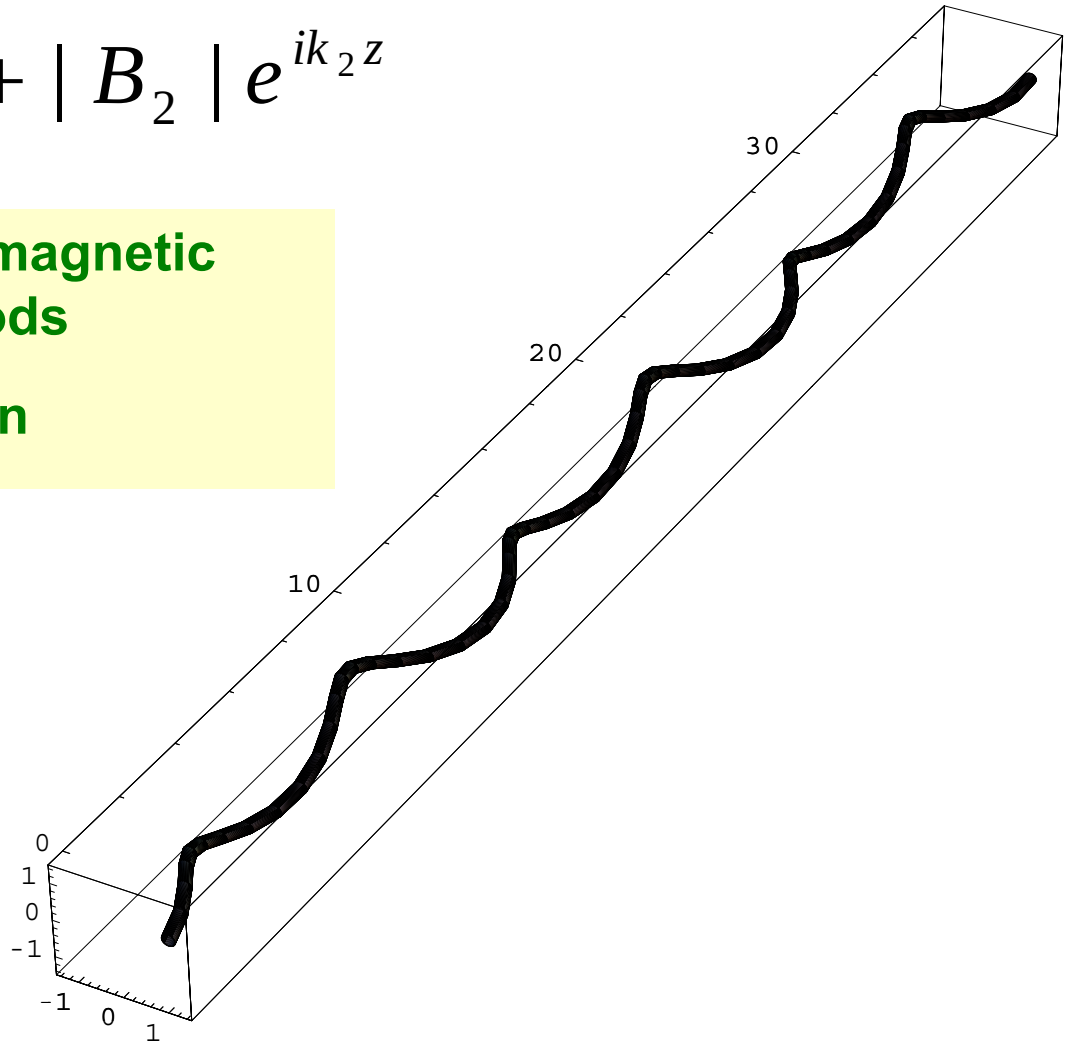


Epicyclic Helical Solenoid

$$B_T = | B_1 | e^{ik_1 z} + | B_2 | e^{ik_2 z}$$

- **Superimposed transverse magnetic fields with two spatial periods**
- **Variable dispersion function**





Collaborations & Partnerships

Neutrino Factory Muon Collider Collaboration

US

National Labs
Argonne
BNL
Fermilab
LBNL
Oak Ridge
Jefferson Lab

Universities
Columbia
Cornell
IIT
Indiana
Michigan State
Mississippi
Northern Illinois
Princeton
UC-Berkeley
UC-Davis
UC-Los Angeles
UC-Riverside
University of Chicago

International

National Labs
Budker
DESY
INFN
JINR, Dubna
KEK
RAL
TRIUMF

Universities
Karlsruhe
Imperial College
Lancaster
Osaka
Oxford
Pohang
Tel Aviv

Corporate Partners
Muons Inc*
Tech-X Corporation

Muon Collider Design Workshop
Jefferson Lab
December 8-12, 2008

International Design Study – Neutrino Factory

JLAB-2008-12-14/ Agenda

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Monday, 15 December 2008

09:00-12:30	Front end session - cooling and end2end simulation	
	Discussion of ICOOL, GEANT4 Material Model	All
	Alternate lattices; optimisation algorithms	Chris Rogers
09:00-12:30	Acceleration session - FFAG	
	FFAG lattice with chromaticity correction	(JPa obo) Shinji Machida
	FFAG injection studies	Jaroslaw Pasternak
	FFAG studies	Scott Berg
12:30-13:30	Lunch	
13:30-16:00	Joint front end and acceleration session	
	Front end - plans and schedule	Fernow/Rogers
	Acceleration - plans and schedule	Bogacz/Pozimski

Files Page

https://www.ids-nf.org/wiki/JLAB-2008-12-14 www.ids-nf.org

SBIR/STTR Grants

Muons, Inc.

Summary

- Muon Colliders & Neutrino Factories will require innovative SRF linacs to: cool/compress and 'shape' them into a beam and finally to rapidly accelerate them to multi – GeV (NF) & TeV (MC) energies
- Large acceptance Recirculating Linacs – rapid acceleration and effective longitudinal bunch compression
- '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^-
- Pulsed linac multi-pass Optics….even larger number of passes is possible if the quadrupole focusing can be increased as the beam energy increases
- Extreme Cooling – A linac filled with high pressure hydrogen gas and imbedded in strong magnetic fields has been proposed to rapidly cool muon beams
  - Helical Cooling channel
  - Parametric Resonance – Epicyclic channels