TeV Scale Muon RLA Complex – 'Large Emittance' MC Scenario

Alex Bogacz and Kevin Beard

Outline

- ‘**Large Emittance MC**’ Neuffer’s Collider
- **Acceleration** Scheme with three Dogbone RLAs
  - **Linac + RLA I: 0.3-4 GeV 4.5-pass (200 MHz SRF)**
  - **RLA II: 4-52 GeV 12-pass (400 MHz SRF)**
  - **RLA III: 52 - 1000 GeV 12-pass (800 MHz SRF)**
- **Muon RLA** – Beam dynamics choices
- **Fesibility/Cost** considerations

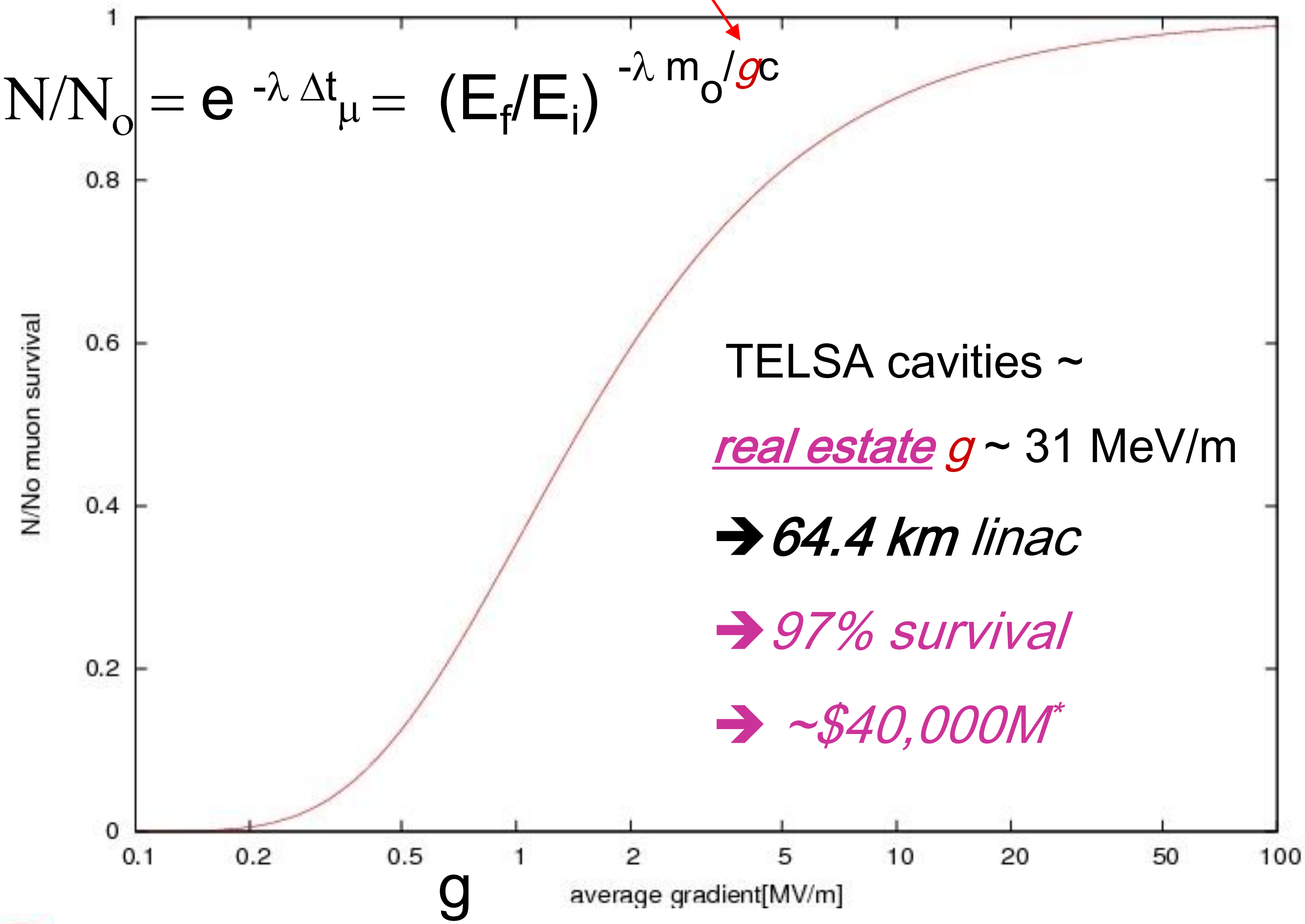
Muon RLA – Beam dynamics choices

- **'Dogbone'** (Single Linac) RLA – better orbit separation at the linac ends
- **Longitudinal Compression** via synchrotron motion
- **'Bisected'** linac Optics – mirror symmetric quad gradient along the linac
- **Pulsed linac** Optics…. even larger number of passes is possible if the quadrupole focusing can be increased as the beam energy increases (proposed by Rol Johnson)
- **Flexible Momentum Compaction** return arc Optics to accommodate two passes (two neighboring energies) – NS-FFAG like Optics (proposed by Dejan Trbojevic)
- **Pulsed arcs**? – ramping arc magnets to further reuse the arcs

How to get μs from 3 GeV to 2 TeV before they all decay away?

- average gradient over whole path determines μ survivability

$$N/N_o = e^{-\lambda \Delta t_\mu} = (E_f/E_i)^{-\lambda m_o/gc}$$



TELSA cavities ~

real estate g ~ 31 MeV/m

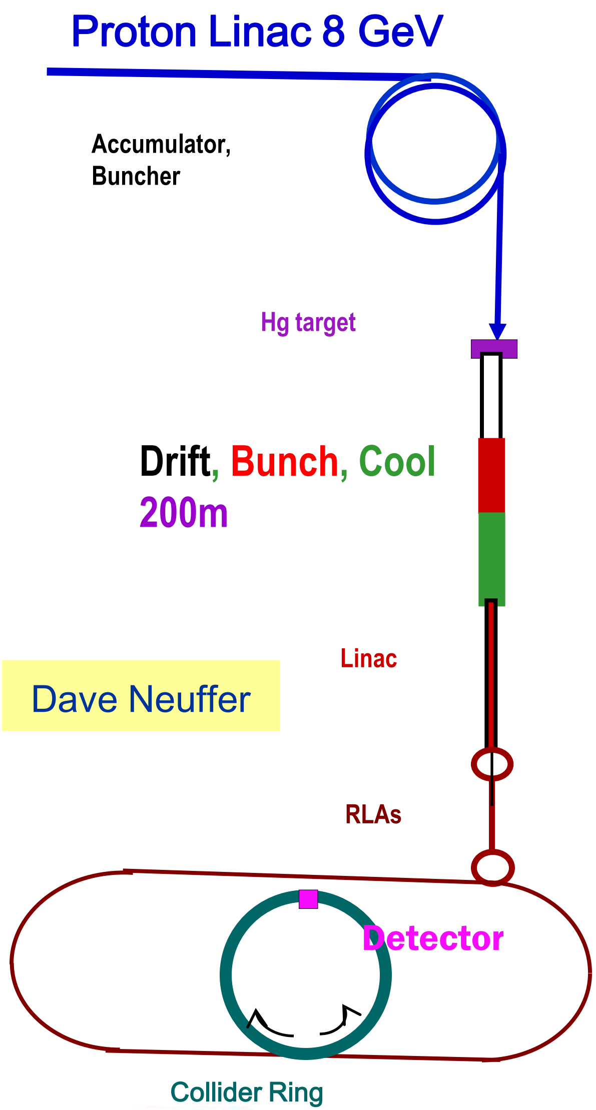
→ *64.4 km linac*

→ *97% survival*

→ *~$40,000M**

@Jlab ~ $20M/GeV

'Large Emittance MC' Scenario

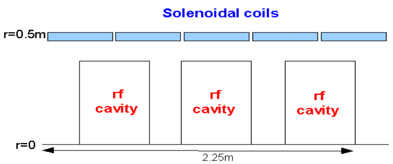


Parameter	Symbol	Value
Proton Beam Power	P_p	2.4 MW
Bunch frequency	F_p	60 Hz
Protons per bunch	N_p	3 10^{13}
Proton beam energy	E_p	8 GeV
Number of muon bunches	n_B	12
$\mu^{+/-}$/ bunch	**N_μ**	**10^{11}**
Transverse emittance	**$\varepsilon_{t,N}$**	**0.003m**
Collision β^*	β^*	0.05m
Collision β_{max}	β^*	10000m
Beam size at collision	$\sigma_{x,y}$	0.013cm
Beam size (arcs)(β^*=100m)	$\sigma_{x,y}$	0.55cm
Beam size IR quad	σ_{max}	5.4cm
Collision Beam Energy	**$E_{\mu+},E_{\mu\_}$**	**1 TeV (2TeV total)**
Storage turns	N_t	1000
Luminosity **$L=f_0 n_s n_b N_\mu^2/4\pi\sigma^2$**	**L_0**	**4 10^{30}**

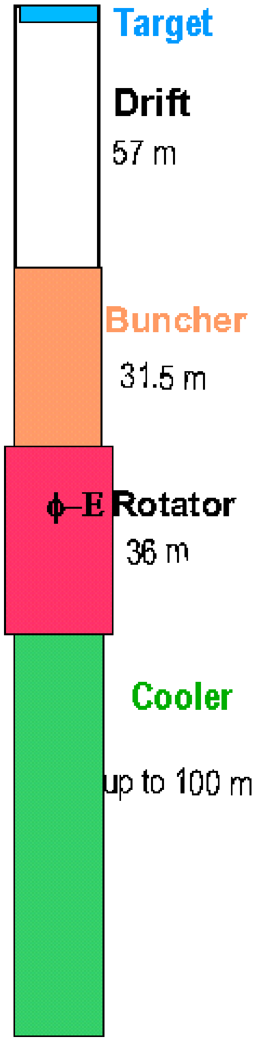
Muons, Inc.

Bunch train for ‘Large Emittance’ MC

- Drift, buncher, rotator to get “short” bunch train (n_B = 10):
  - 217m ⇒ **125m**
  - **57m drift, 31m buncher, 36m rotator**
  - **Rf voltages up to 15MV/m (×2/3)**
- Obtains ~0.1 μ/p_8 in ref. acceptance
  - **A_t < 0.03, A_L <0.2**
  - **Choose best 12 bunches**
    - **~0.008 μ/p_8 per bunch**
    - **~0.005 μ/p_8 in acceptance**
- 3 × 10^{13} protons
  - **1.5× 10^{11} μ/bunch in acceptance**
  - **$\varepsilon_{t,rms,\ normalized}$ ≈ 0.003m (accepted μ’s)**
  - **$\varepsilon_{L,rms,\ normalized}$ ≈ 0.034m (accepted μ’s)**



Dave Neuffer



'Large Emittance MC' – Front End

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
12, 070101 (2009)

Low-energy neutrino factory design

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The design of a low-energy (4 GeV) neutrino factory (NF) is described, along with its expected performance. The neutrino factory uses a high-energy proton beam to produce charged pions. The $\pi^{\pm}$ decay to produce muons ($\mu^{\pm}$), which are collected, accelerated, and stored in a ring with long straight sections. Muons decaying in the straight sections produce neutrino beams. The scheme is based on previous designs for higher energy neutrino factories, but has an improved bunching and phase rotation system, and new acceleration, storage ring, and detector schemes tailored to the needs of the lower energy facility. Our simulations suggest that the NF scheme we describe can produce neutrino beams generated by $\sim 1.4 \times 10^{21}$ μ^+ per year decaying in a long straight section of the storage ring, and a similar number of μ^- decays.

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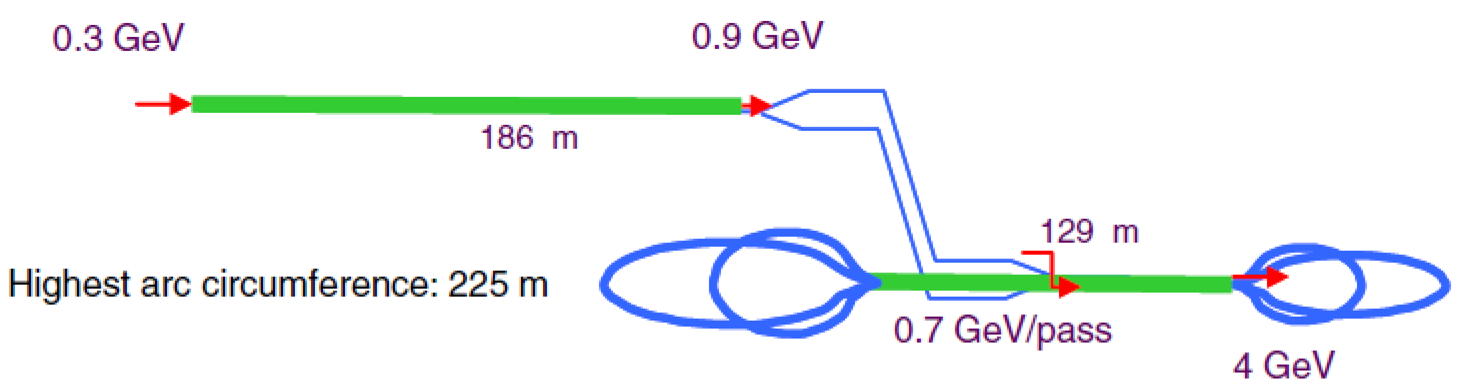
‘Large Emittance MC’ – Front End

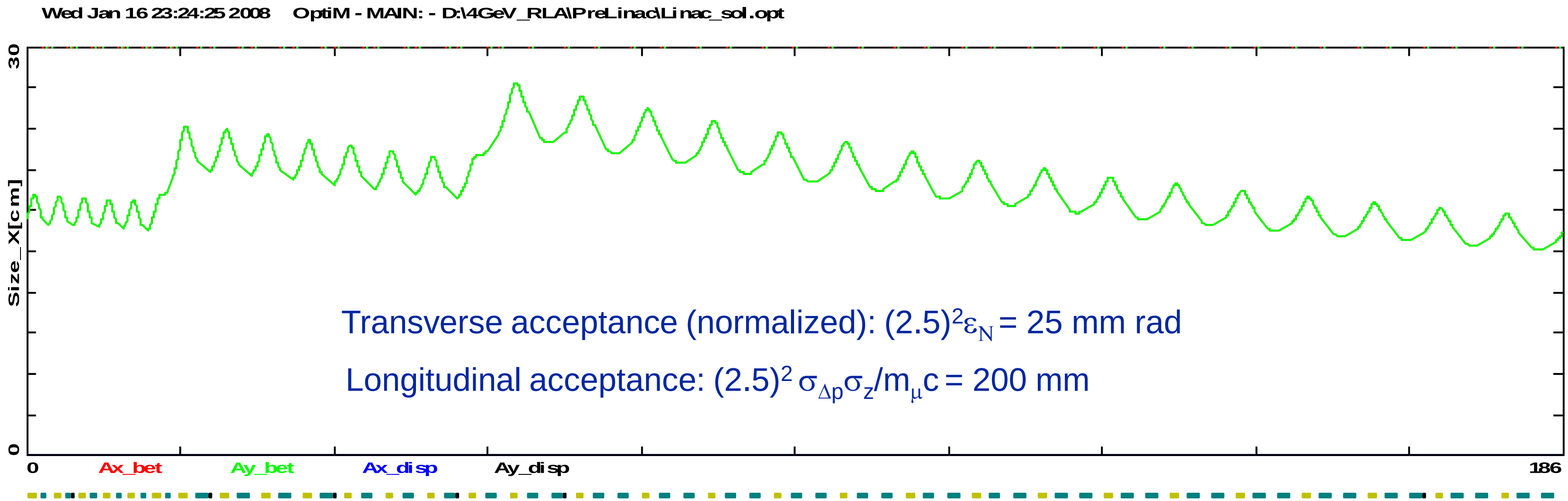
C. ANKENBRANDT *et al.* Phys. Rev. ST Accel. Beams **12,** 070101 (2009)

TABLE III. Beam emittance/acceptance after the cooling channel at 273 MeV/c. Note that the longitudinal normalized acceptances are defined as $2.5\sigma_{\rm rms}$.

Parameter		$\varepsilon_{\rm rms}$ or $\sigma_{\rm rms}$		$A = (2.5)^2\varepsilon$ or $2.5\sigma_{\rm rms}$
Normalized emittance	ε_x, ε_y (mm rad)	4.0	3.0	25
Longitudinal emittance ($\varepsilon_l = \sigma_{\Delta p}\sigma_z/m_\mu c$)	ε_l (mm)	36	34	200
Momentum spread	$\sigma_{\Delta p/p}$	0.1		± 0.25
Bunch length	σ_z (m)	0.16		± 0.4



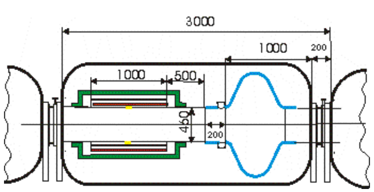
Pre-accelerator – Longitudinal dynamics



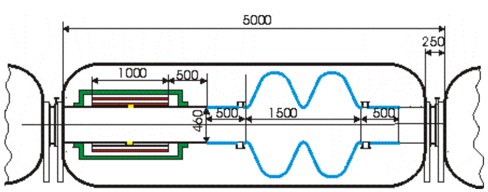
6 short cryos 12 MV/m

8 medium cryos 12 MV/m

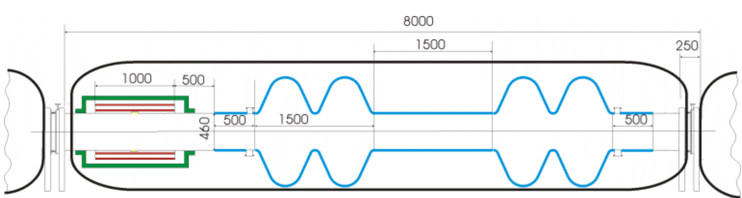
16 long cryos 12 MV/m



1.1 Tesla solenoid



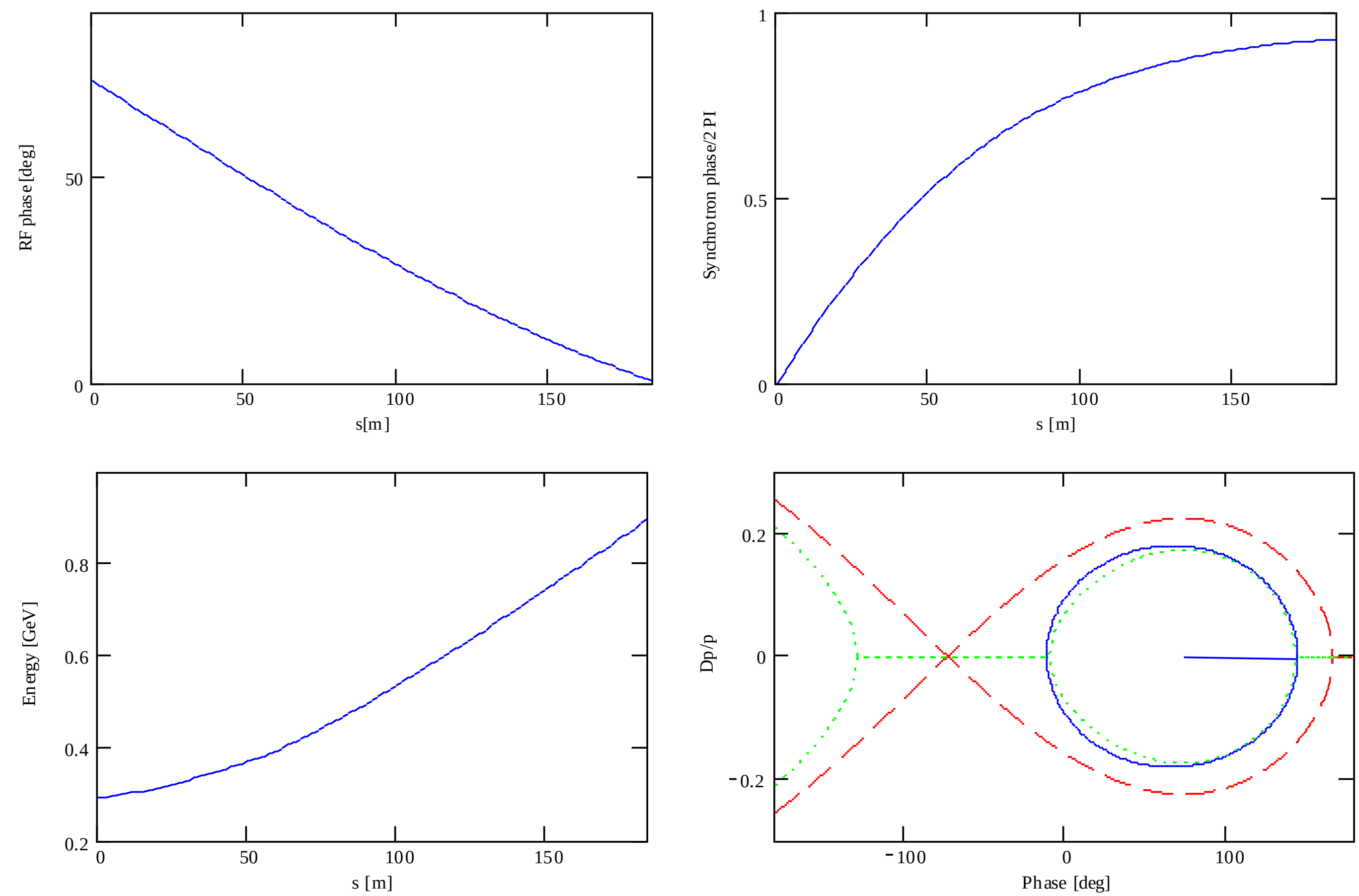
1.2 Tesla solenoid



2.4 Tesla solenoid

Longitudinal matching – Synchrotron motion

Longitudinal acceptance: $\Delta p/p=\pm 0.17$ or $\Delta\phi = \pm 93$ (200MHz)



4 GeV RLA – Longitudinal compression

LOW-ENERGY NEUTRINO . . .   Phys. Rev. ST Accel. Beams 12, 070101 (2009)

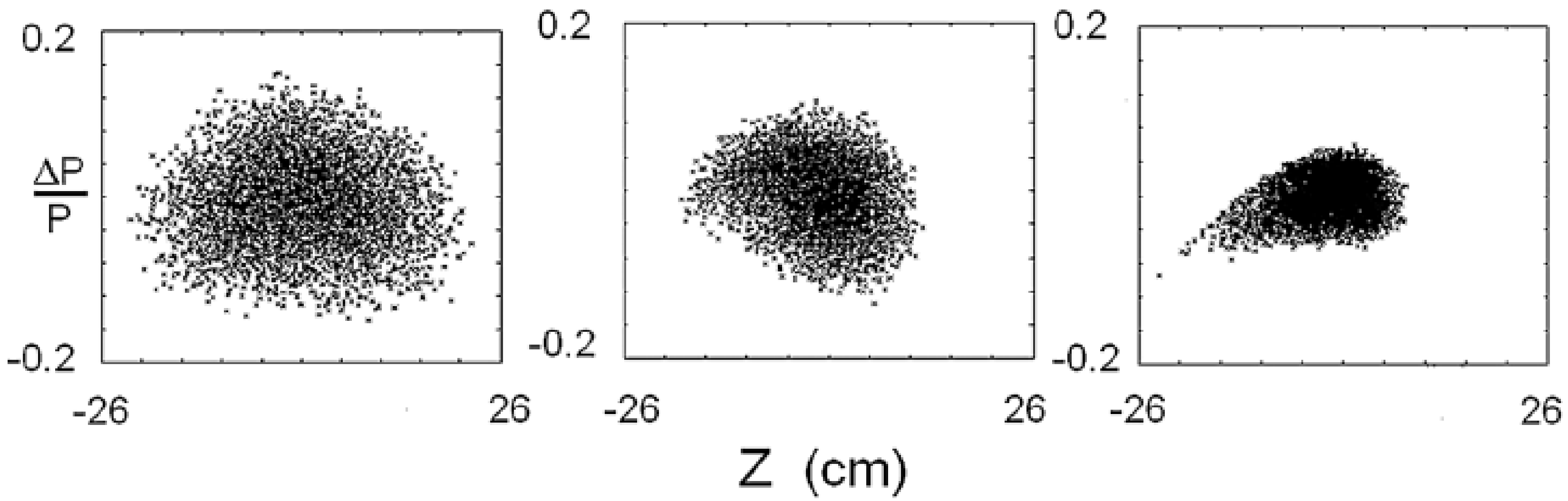


FIG. 8. Particle tracking results showing adiabatic bunch compression along the linac. The longitudinal phase space (z, $\Delta p/p$) is shown before (left), in the middle (center), and at the end (right) of acceleration.

4 GeV RLA – Accelerator Performance

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LOW-ENERGY NEUTRINO ... Phys. Rev. ST

$$\begin{pmatrix} \tau_{i+1} \\ E_{i+1} \end{pmatrix} = \begin{bmatrix} \tau_i + \frac{h_i m_\mu}{c\sqrt{E_i^2 - m_\mu^2}} \\ E_i + qV_i \cos(\phi_{ci}) \end{bmatrix}.$$

$$\frac{N_i}{N_0} = \exp\left(-\frac{\tau_i}{\tau_0}\right), \qquad \tau_0 = 2.2\ \mu\text{s}.$$

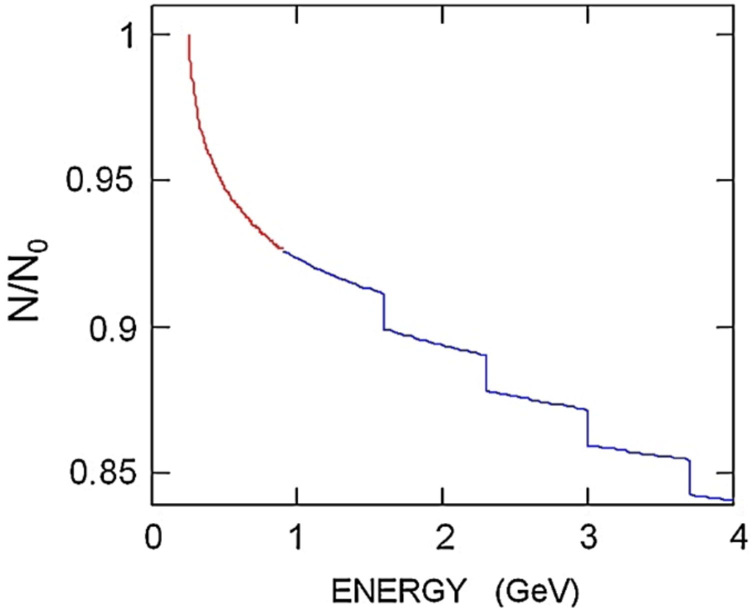

TABLE IV. Beam parameters at the end of the 4 GeV acceleration system.

		$\varepsilon_{\rm rms}$, σ	$A = (2.5)^2\varepsilon$ or 2.5σ
Normalized emittance	ε_x, ε_y (mm rad)	5.4	34
Longitudinal emittance ($\varepsilon_l = \sigma_{\Delta p}\sigma_z/m_\mu c$)	ε_l (mm)	44	280
Momentum spread	$\sigma_{\Delta p/p}$	0.012	± 0.03
Bunch length	σ_z (mm)	86	± 215

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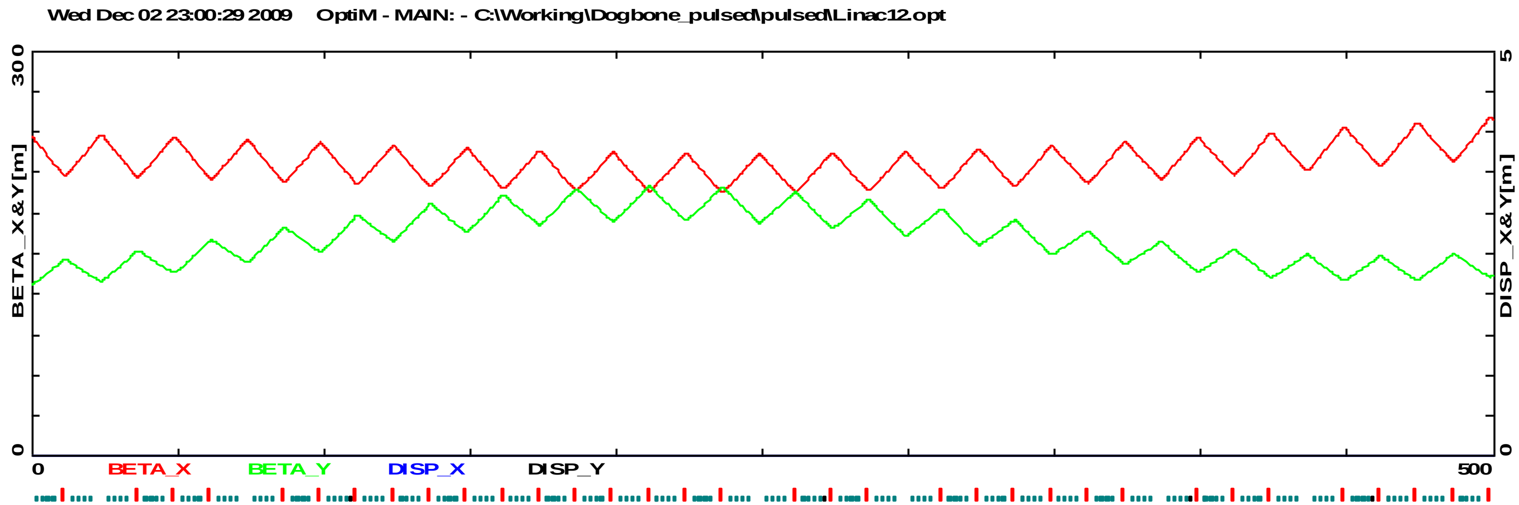
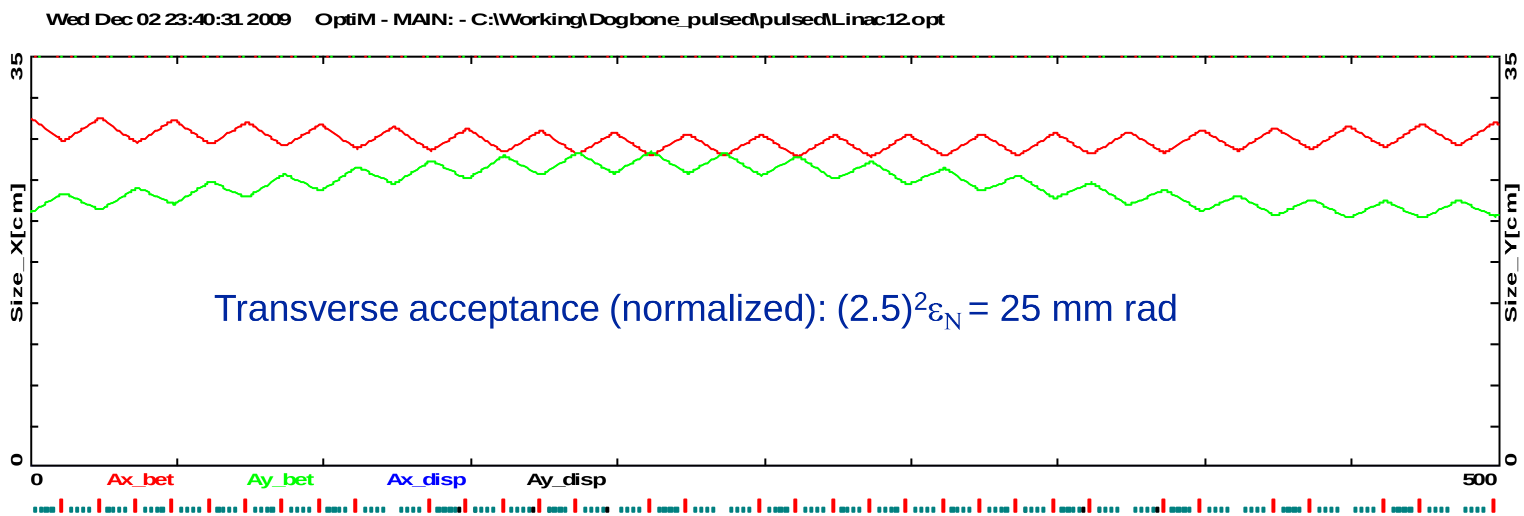
Beam envelopes end of RLA II (50 GeV)



Pass 12



A few thoughts on scaling…

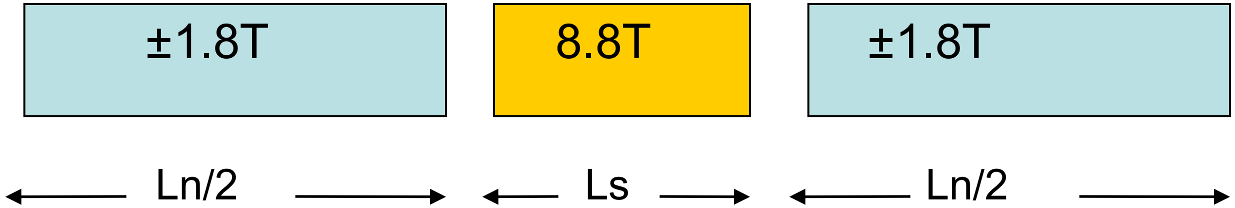
- for dipoles, the stored energy ~ power ~ cost

$\rightarrow \sigma_\perp^2 \bullet B^2$

- for quadrupoles, stored energy ~ power ~ cost

$\rightarrow \sigma_\perp^4 \bullet G^2$

Hybrid magnets… *3.0T is the best we can do*



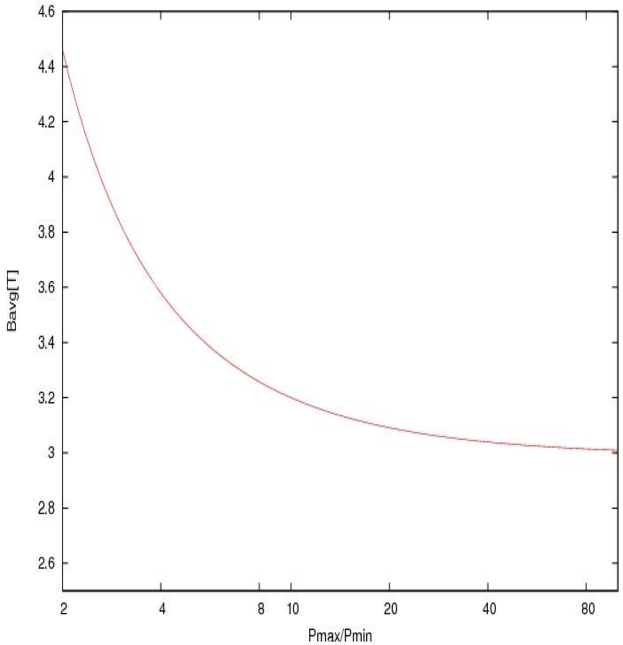
Don Summers

$$P_{max}/P_{min} = B_{max}/B_{min} = \frac{(Bs \bullet Ls + Bn \bullet Ln)}{(Bs \bullet Ls - Bn \bullet Ln)}$$

$$x \equiv (P_{max}/P_{min} - 1)/(P_{max}/P_{min} + 1)$$

$$B_{avg} = f\,(x+1)/(x/Bn + 1/Bs)$$

$B_{avg}[T]$



P_{max}/P_{min}

$$P_{max}/P_{min} \to \infty,\ \underline{B_{avg} \to 3.0T}$$

$P_{max}/P_{min} \to \infty$, $Bs \to \infty$ $B_{avg} \to 2\ Bn$

'Large Emittance' MC vs LEMC

….rough numbers for normal 1.8T magnets…

- LEMC emittance (153 GeV, $\beta \approx 200$ m)

  $\sigma_{\perp N} \approx$ ~~2.1~~ mm-mrad → 10 $\sigma_\perp \approx$ **5 mm** 90mm

- small aperture → little stored energy ~ ~~37 J/m~~ 11.5kJ/m
- power ~ ~~22 kW/m~~ 7 MW/m

‘Large Emittance’ MC – Conclusions

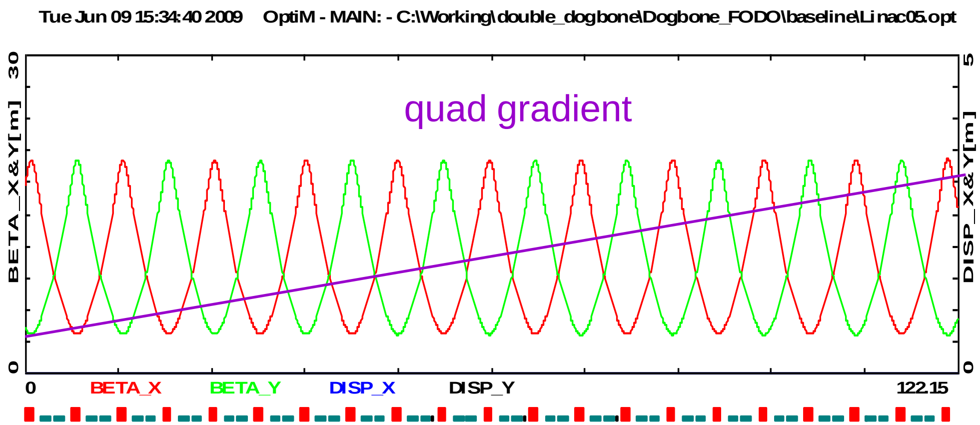
- ramped dipole magnets mean large arcs
- *low emittance makes for small apertures* →

  little stored energy, power, costs
- most schemes require fast pulsed magnets of some kind

Multi-pass 'bisected' linac Optics

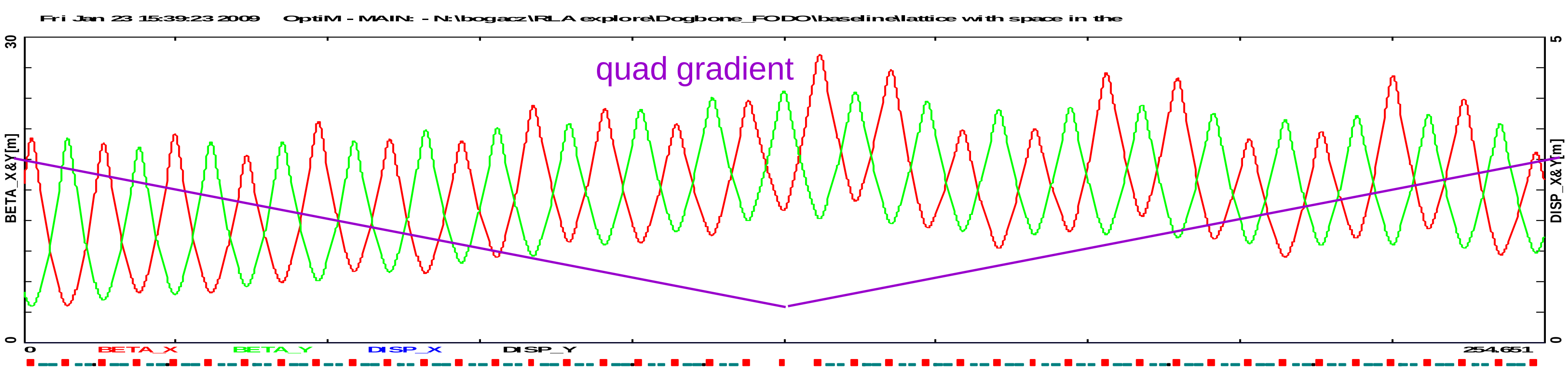
'half pass' , 4-6 GeV

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



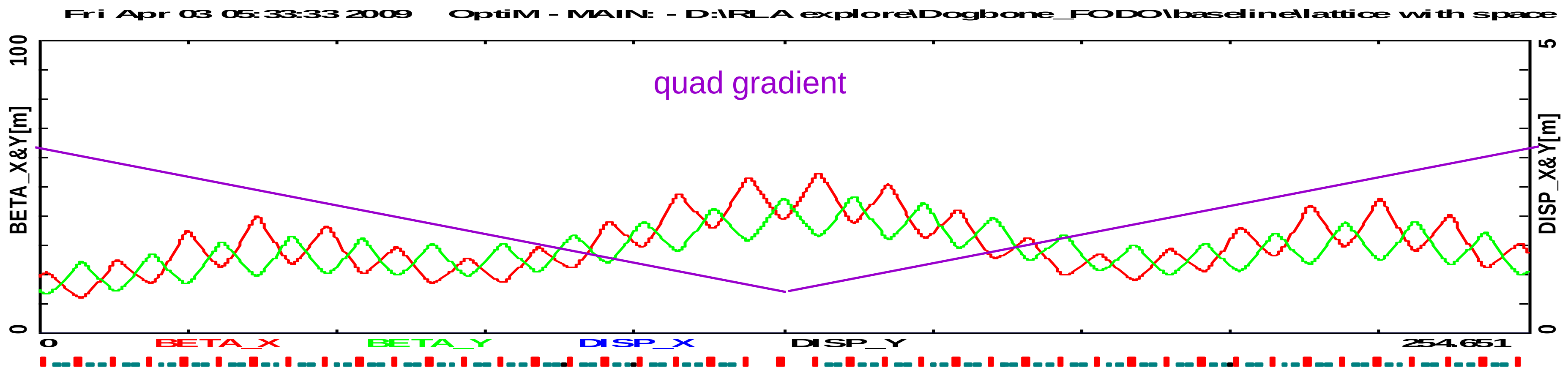
1-pass, 6-10 GeV

mirror symmetric quads in the linac

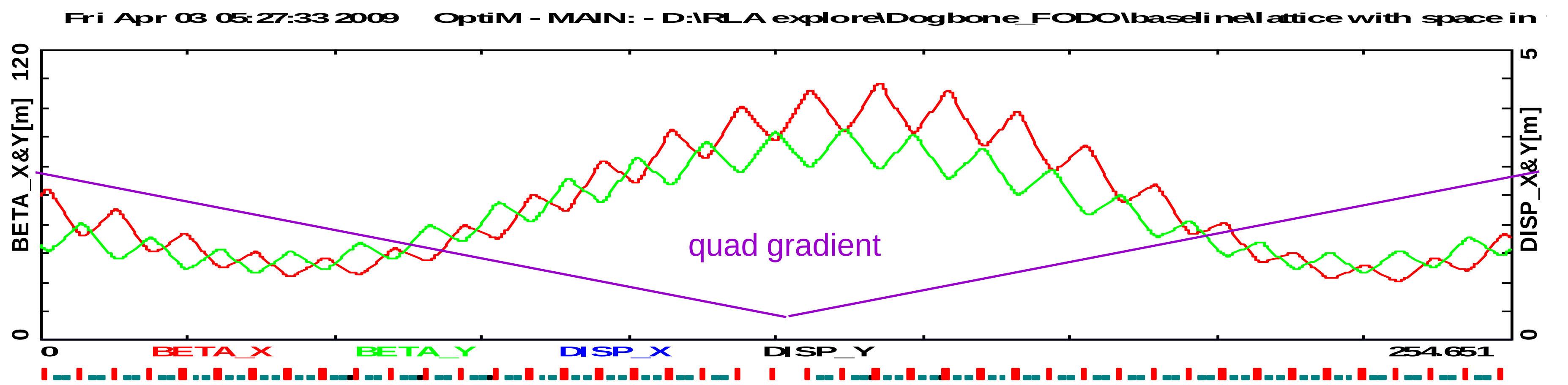


Multi-pass linac Optics

4-pass, 18-22 GeV

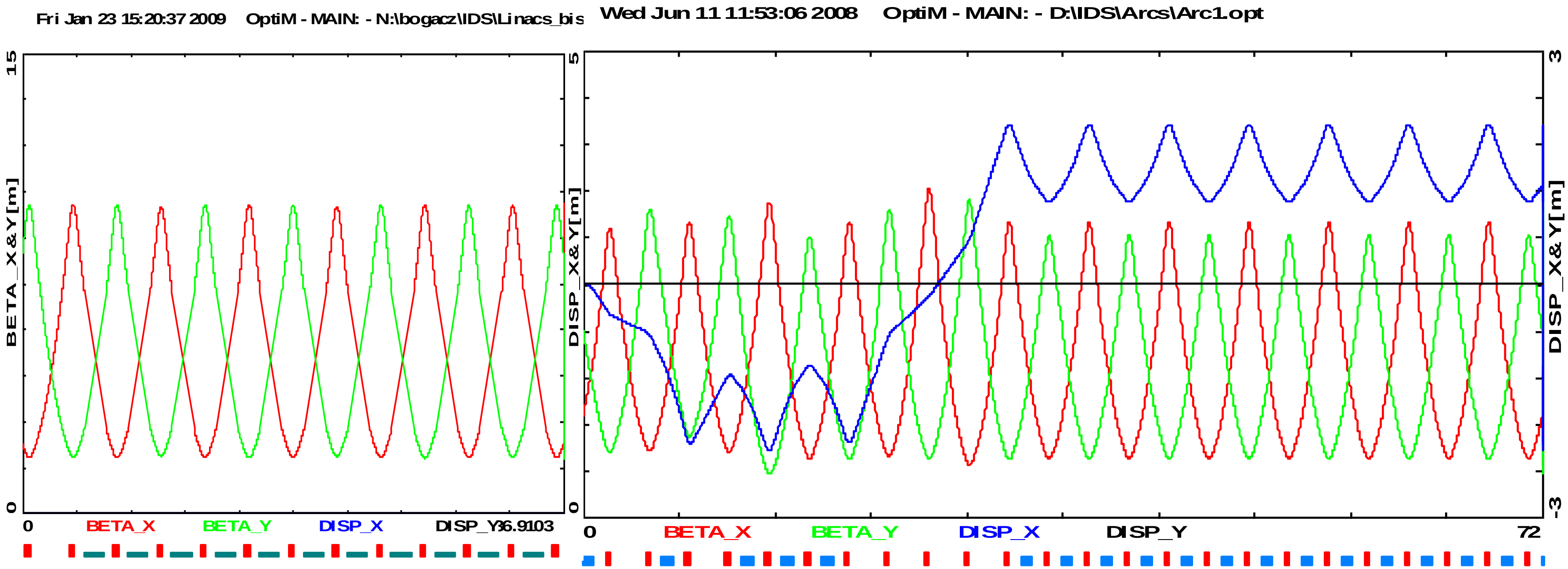


7-pass, 30-34 GeV



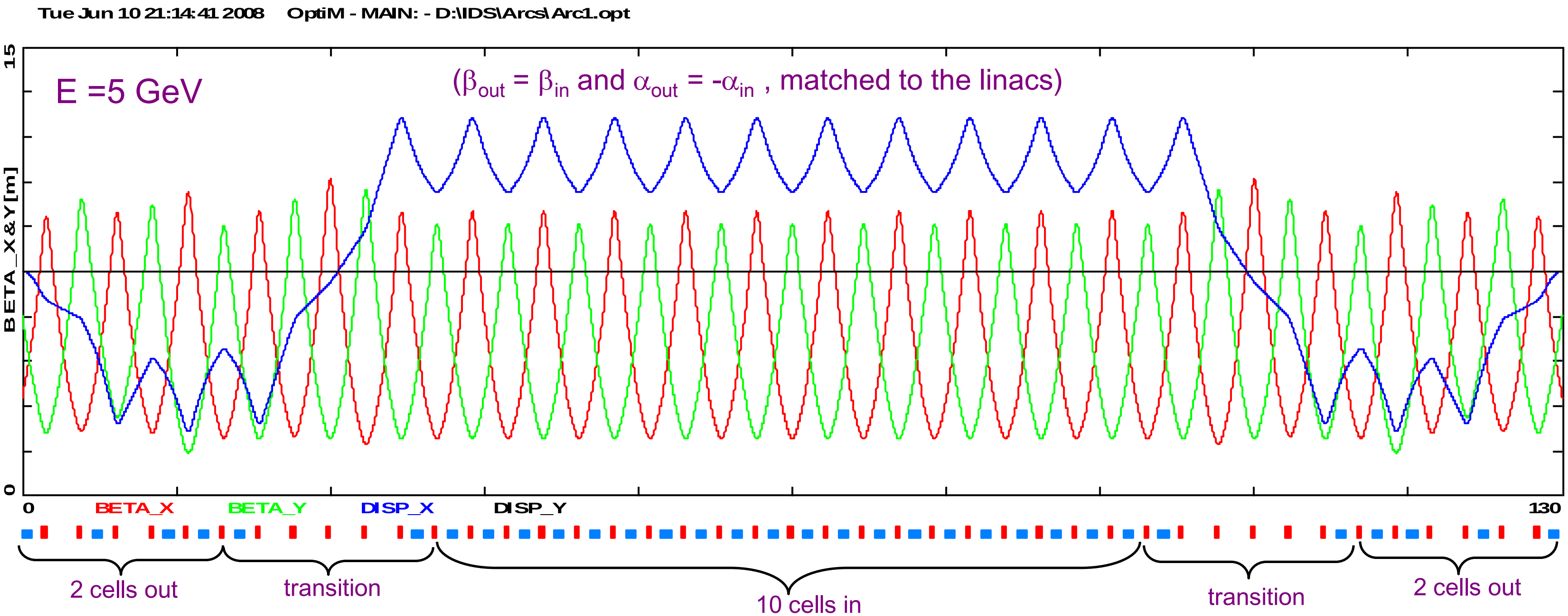
Linac-to-Arc Beta Match

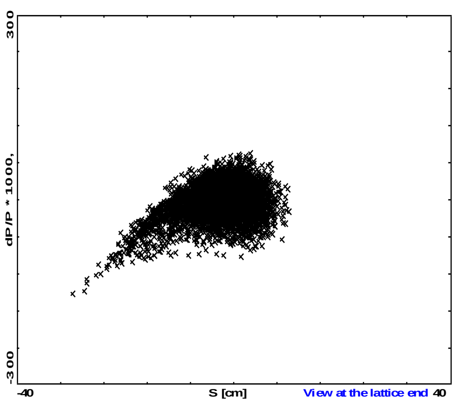
E =5 GeV

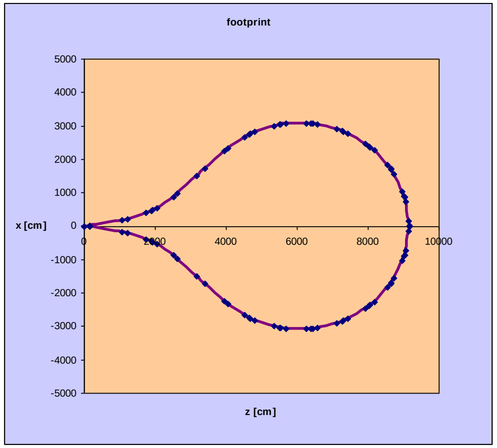


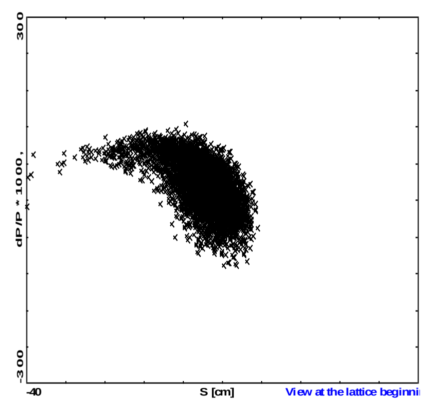
- Matched ‘by design’
- 90^0 phase adv/cell maintained across the ‘junction’
- No chromatic corrections needed

Mirror-symmetric ‘Droplet’ Arc – Optics

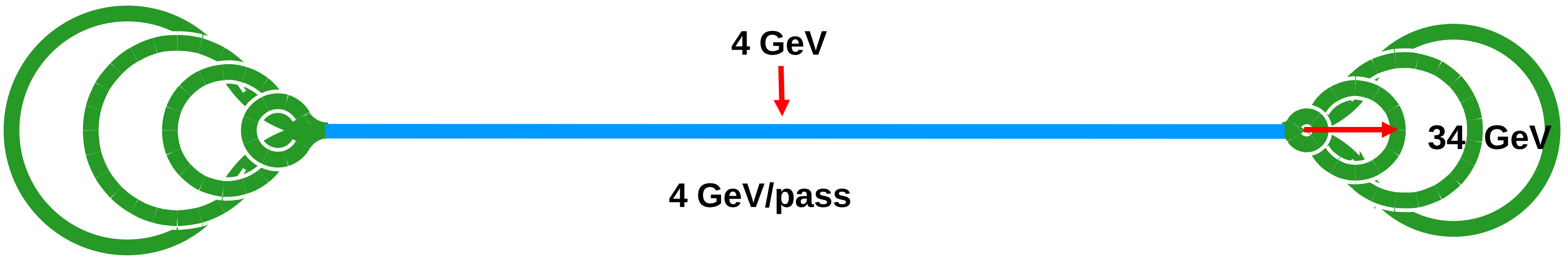








'Pulsed' linac Dogbone RLA (8-pass)

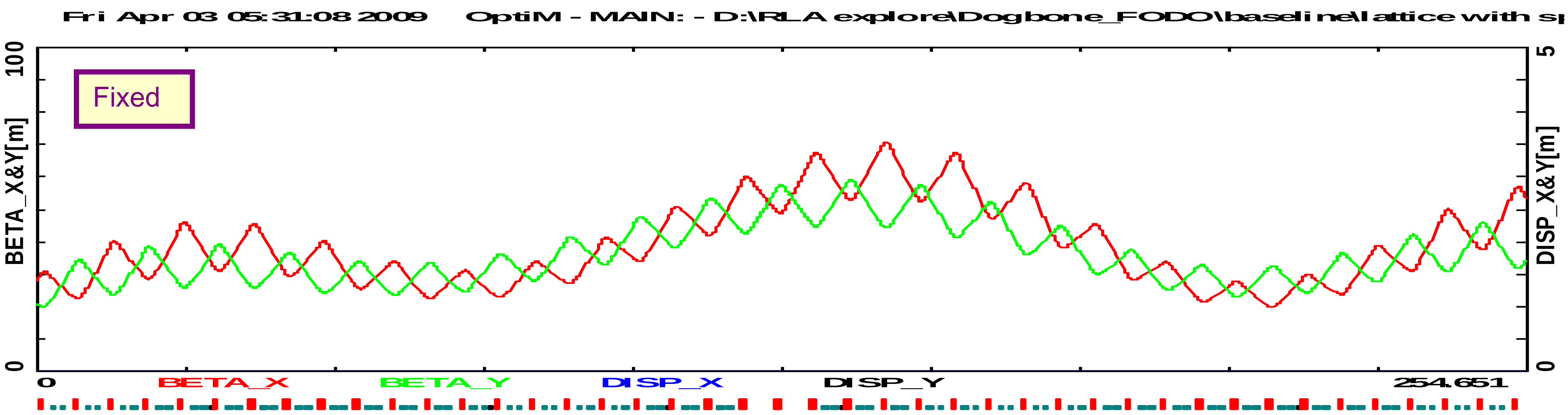


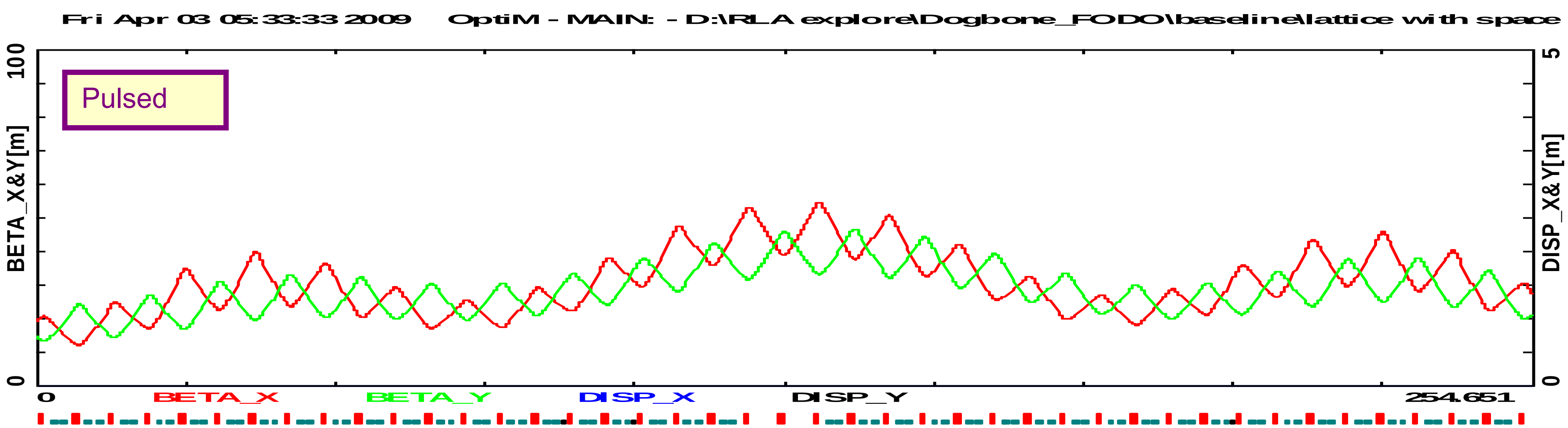
- Quad pulse would assume 500 Hz cycle ramp with the top pole field of 1 Tesla.
- Equivalent to: maximum quad gradient of G_{max} =2 kGauss/cm (5 cm bore radius) ramped over τ = 10^{-3} sec from the initial gradient of G_0 =0.1 kGauss/cm (required by 90^0 phase advance/cell FODO structure at 3 GeV). 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

$$T \approx 8 \times \frac{200+250}{3\times 10^{-8}} \sec = 10 \times 10^{-6} \sec$$

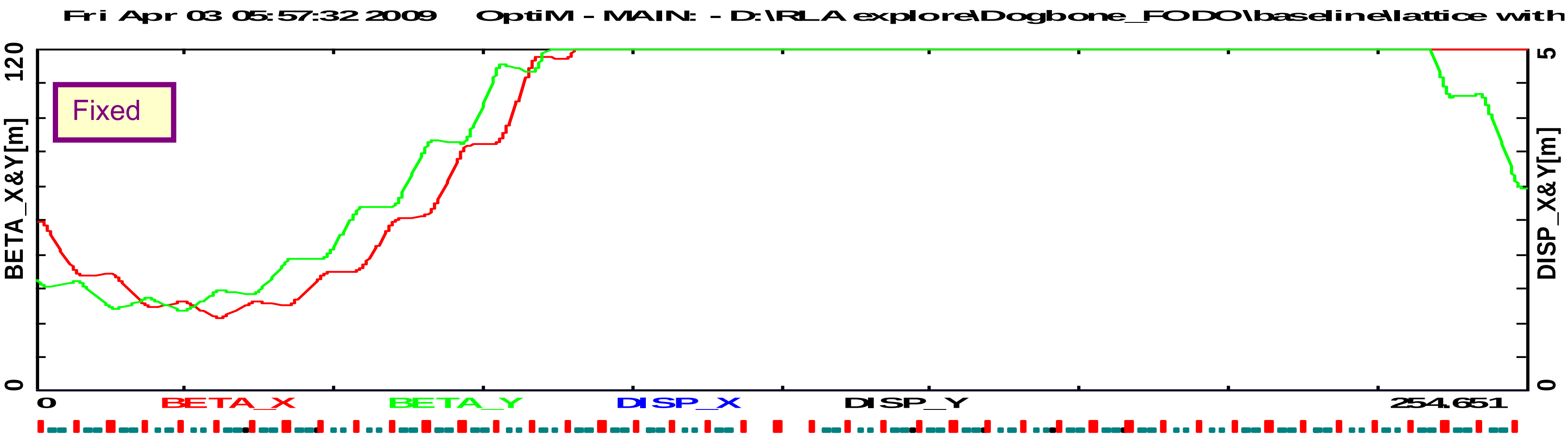
$$\frac{T}{\tau} \approx 10^{-2}$$

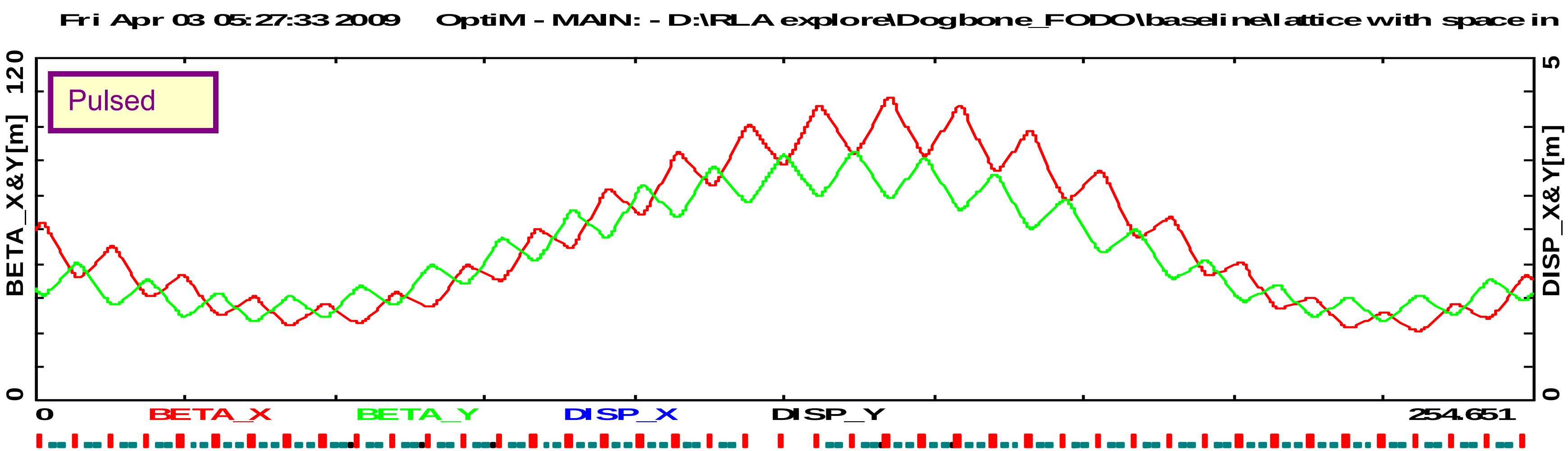
‘Fixed’ vs ‘Pulsed’ linac Optics (8-pass)





‘Fixed’ vs ‘Pulsed’ linac Optics (12-pass)





Multi-pass Arc besed on NS-FFAG

Dejan Trbojevic

1. Large energy acceptance
2. Very small orbit offsets
3. Reduce number of arcs
4. Very compact structure

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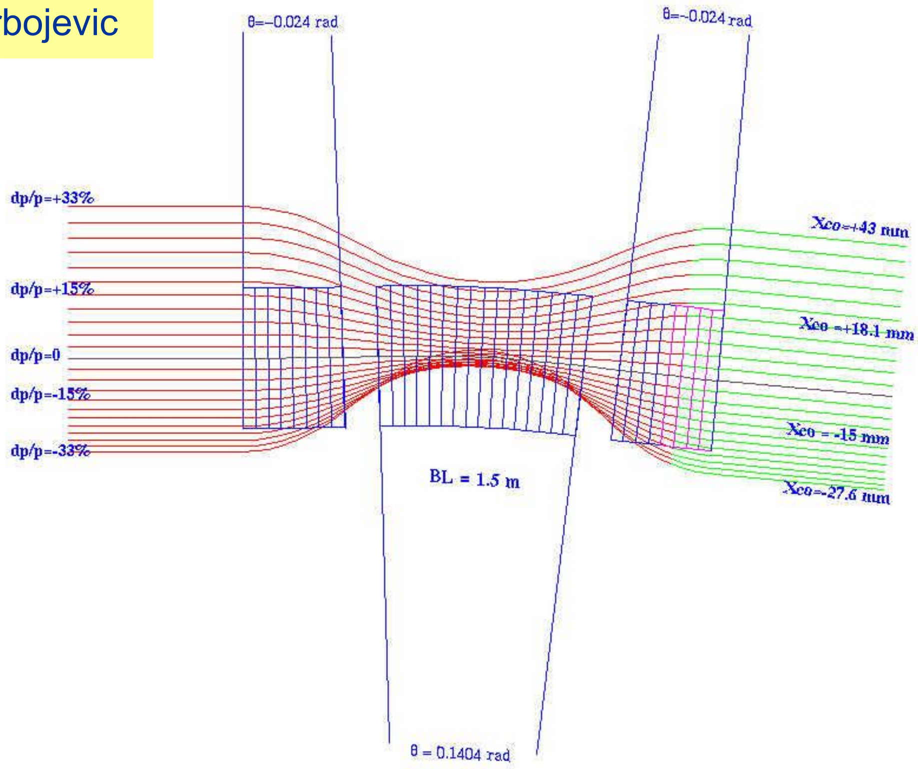
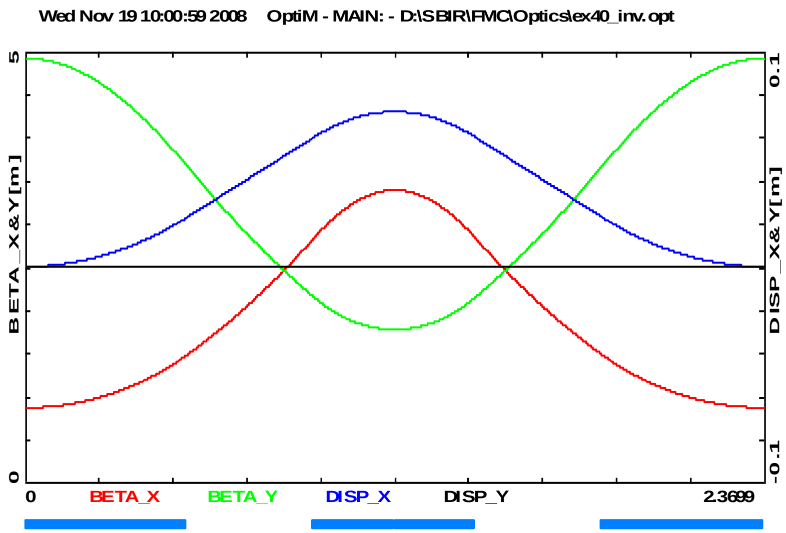
- FMC Optics (NS-FFAG-line)
- Compact triplet cells based on opposed bend combined function magnets

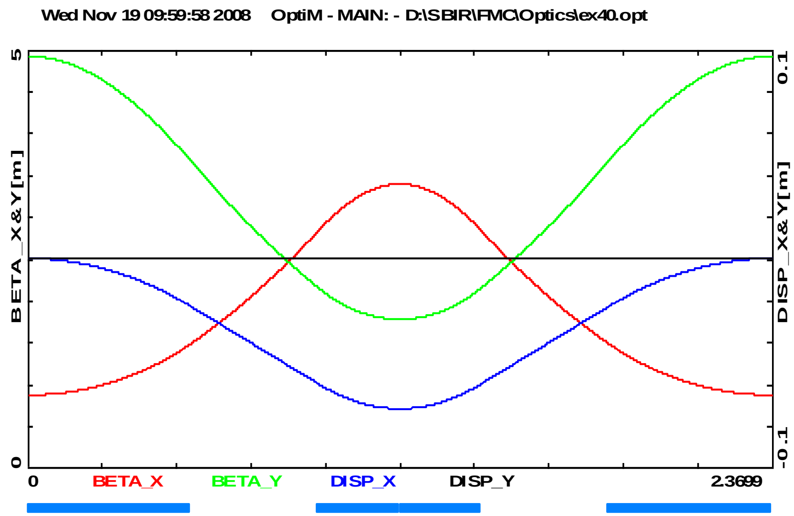


$$B_y = B_0 + Gx$$
$$B_x = -Gy$$

Flexible Momentum Compaction Cells

Guimei Wang

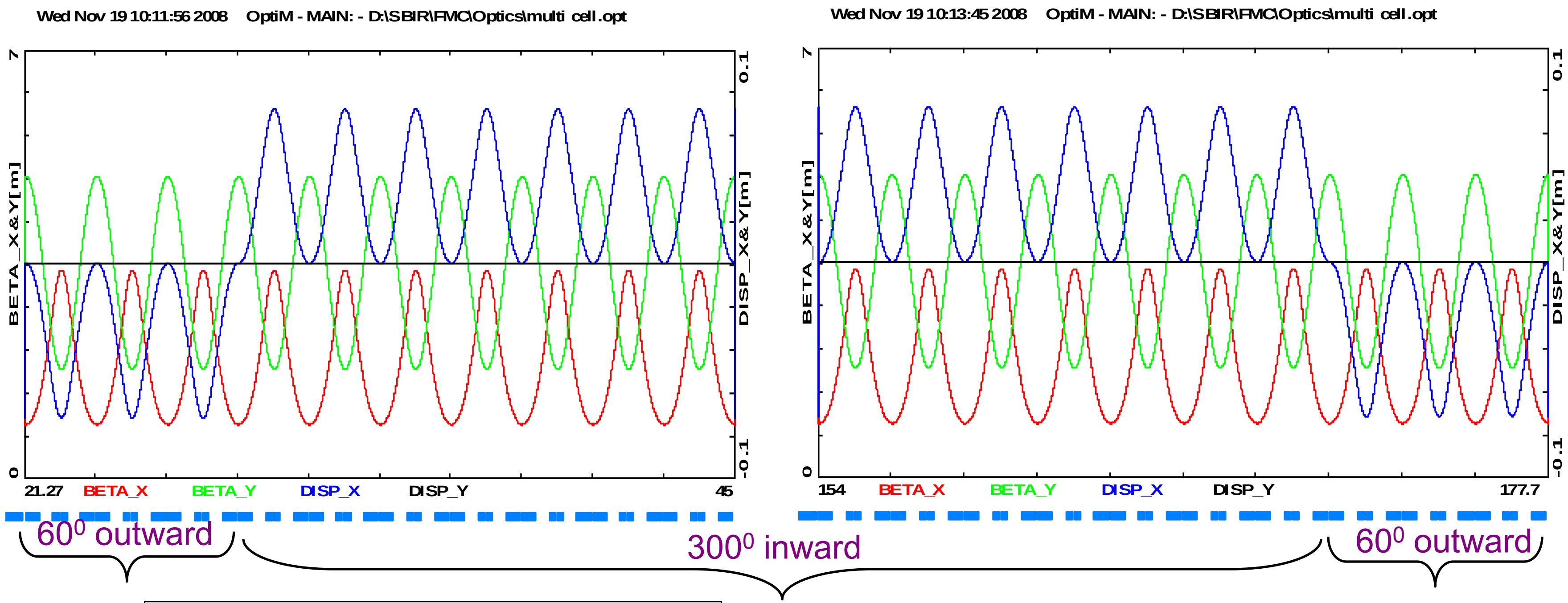


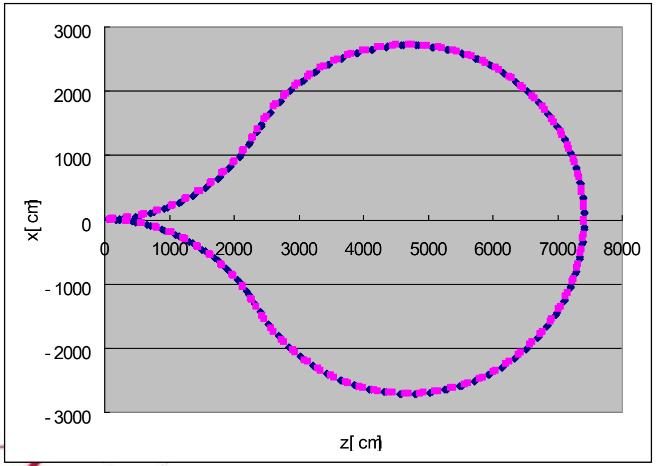


Mag.	L(cm)	B(kG)	G(kG/cm)	θ (deg)	D(cm)
BD	0.5233	35.08	-2.28	5	0<D<0.023
BF	0.5233	-35.08	5.60	-5	0.06<D<0.072
BDre	0.5233	-35.08	-2.28	5	-0.023<D<0
BFre	0.5233	35.08	5.60	-5	-0.072<D<-0.06

- Strong focusing (middle magnet) yields very small beta functions and dispersion
- Momentum offset of 60% corresponds to the orbit displacement of about 4.3 cm.

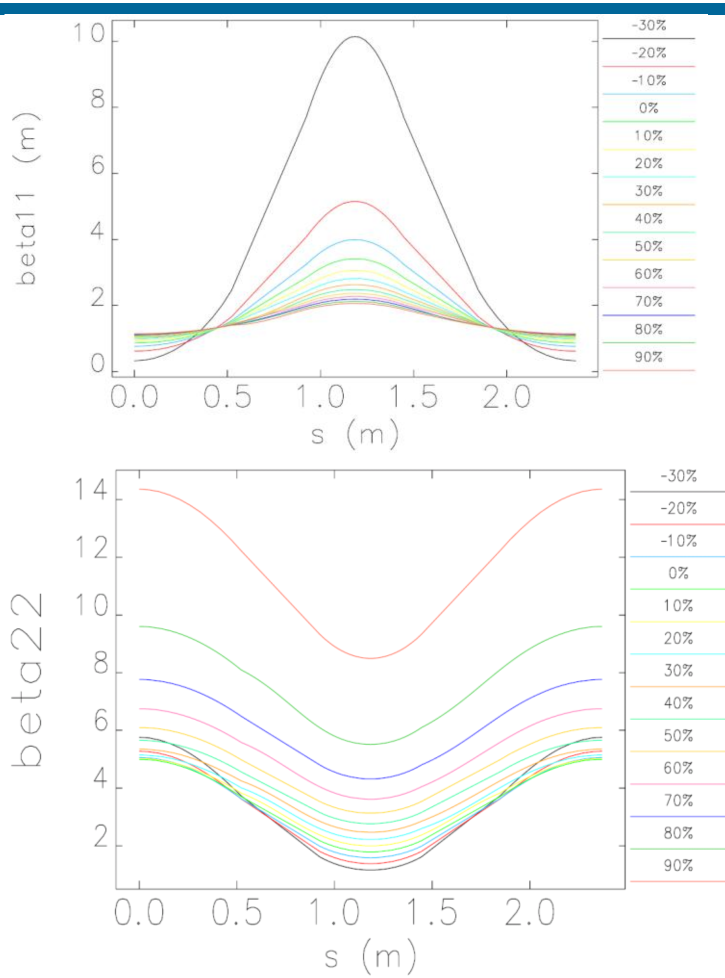
NS-FFAG multi-pass 'Droplet' Arc



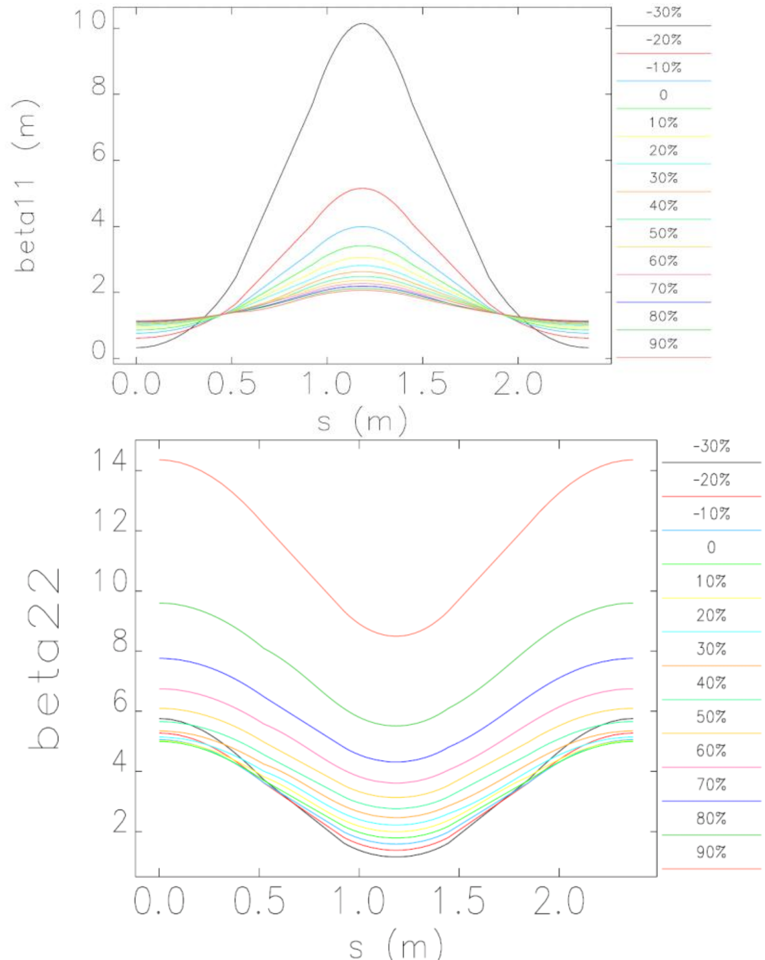


- MADX-PT – Polymorphic Tracking Code is used to study multi-pass beam dynamics for different pass beams: path length difference, optics mismatch between linac and arcs, orbit offset and tune change is being studied.

Beta functions vs. Energy



Inward bending cell



Outward bending cell

For different energy spread, ~the same beta function in opposite bending cell.

With MADX- Polymorphic Tracking Code. Energy spread changes from -30% to 90%

Summary

- **'Large Emittance' MC – Acceleration** Scheme with three Dogbone RLAs
  - **Linac + RLA I: 0.3-4 GeV 4.5-pass (200 MHz SRF)**
  - **RLA II: 4-52 GeV 12-pass (400 MHz SRF) still large tr. beam size**
  - **RLA III: 52 - 1000 GeV 12-pass (800 MHz SRF) serious problems with big magnets**
- **FODO** bisected linac Optics – large number of passes supported (8 passes)
- **Pulsed linac Optics** – further increase from 8 to 12-pass
- **Flexible Momentum Compaction** (FMC) return arc Optics allows to accommodate two passes (two neighboring energies)