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RLAs for Muon Collider

Alex Bogacz

in collaboration with

Rol Johnson
and
Guimei Wang

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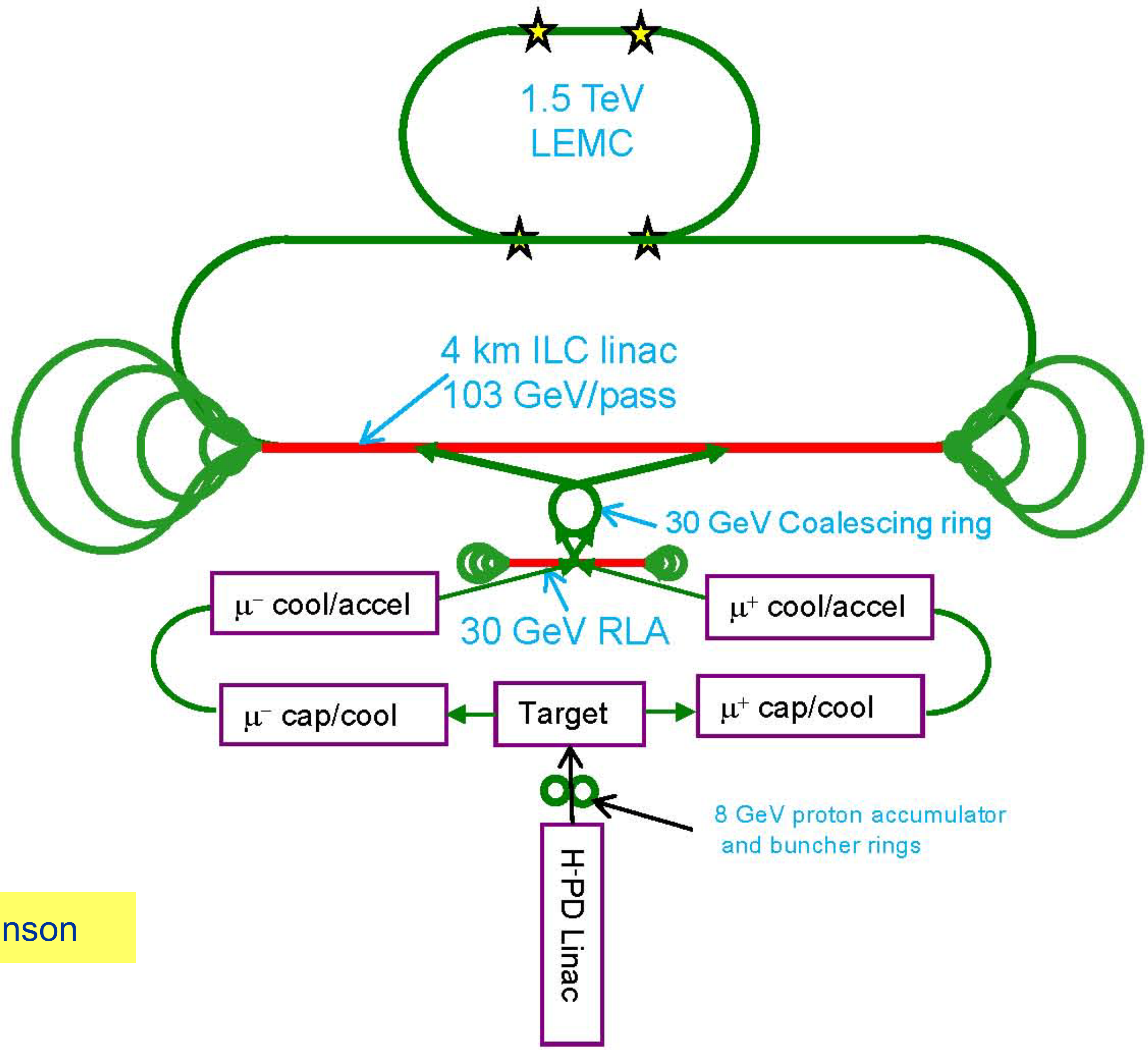
LEMC Scenario

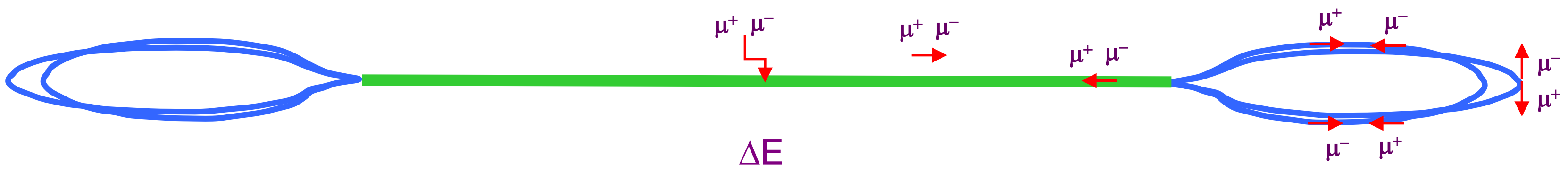


Rol Johnson

RLA for Muons (MC)

- **'Dogbone'** (Single Linac) RLA has advantages over the 'Racetrack'
  - better orbit separation at linac's end ~ energy difference between consecutive passes (2ΔE)
- **FODO** bisected linac Optics is superior to Triplet focusing – more passes transported.
- **Pulsed linac** Optics…. proposed by Rol Johnson ....even larger number of passes is possible if the quadrupole focusing can be increased as the beam energy increases…..subject to a new SBIR with Muons Inc.
- **Flexible Momentum Compaction** (FMC) return arc Optics to accommodate two passes (two neighboring energies) – FFAG line Optics based on the opposing bend combined function magnets (proposed by Dejan Trbojevic)
- **Pulsed arc** Optics? – ramping arc magnets to further reuse the arcs (twice)

'Dogbone' RLA (both μ^+ and μ^-)



'Dogbone' RLA with FODO Focusing

- Beam dynamics challenges – RLA Optics solutions
  - Phase slippage in the linacs
  - Multi-pass linac optics
  - 'Droplet' arc lattice
  - Orbit separation - switchyard
- 8-pass Dogbone RLA - Linear Optics/Lattices designed

Linac multi-pass Optics - FODO bisected

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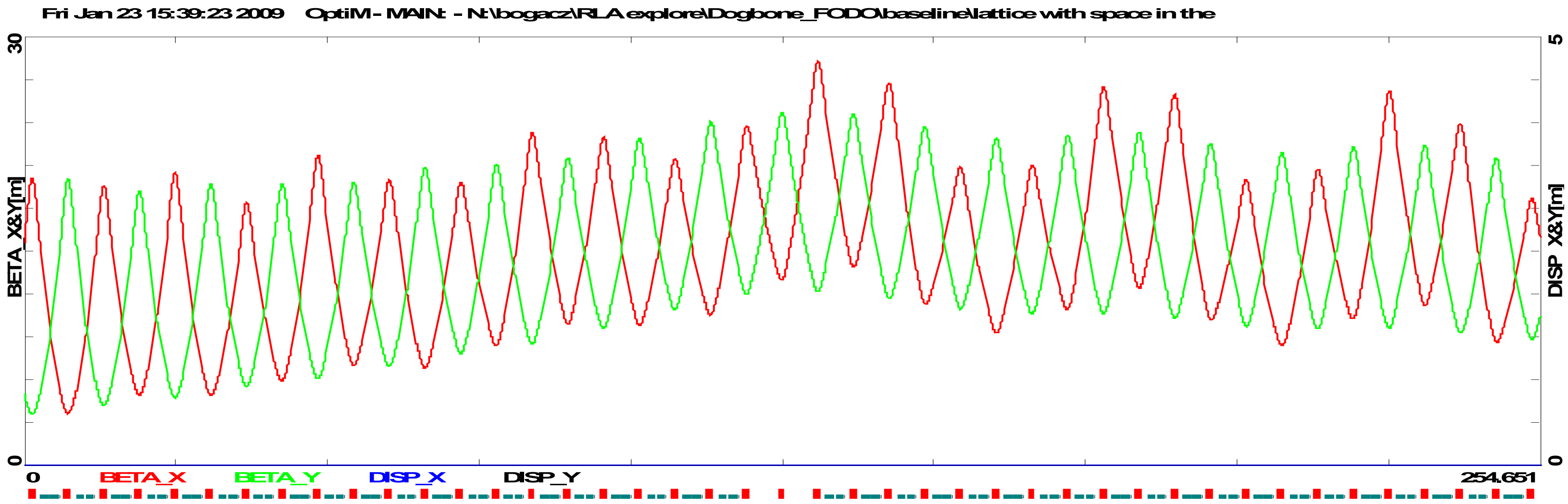
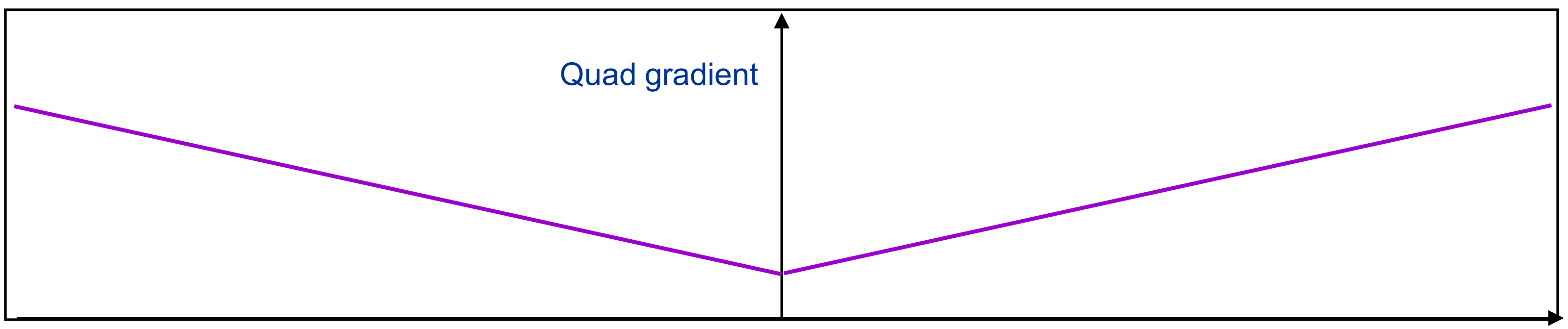
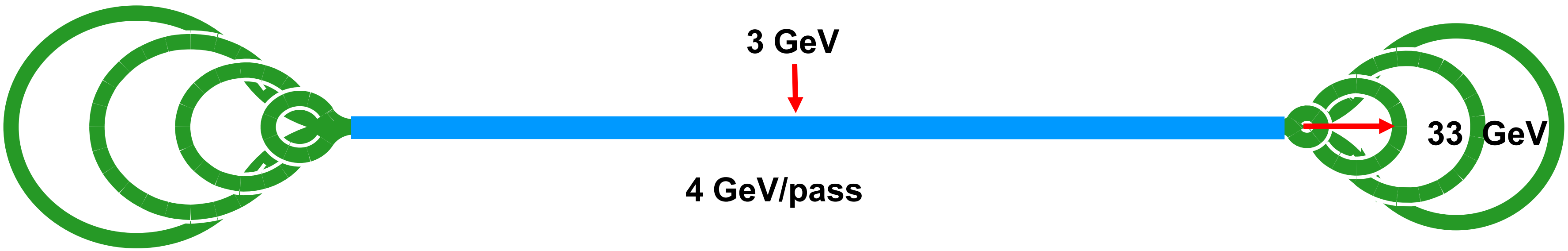
1-pass, 4.6 -6.6 GeV

mirror symmetric quads in the linac





'Pulsed' linac Dogbone RLA (7.5-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' linac RLA – quad ramping

- For simplicity, we consider a linear ramp according to the following formula:

$$G(t) = G_0 + \frac{G^{max} - G_0}{\tau} t$$

- A single bunch traveling with a speed of light along the Linac with quads ramped as above 'sees' the following quad gradient passing through i-th cell along the Linac (i = 1,…20)

$$G_i = G_0 + \frac{G^{max} - G_0}{\tau} \frac{\ell_{cell}}{c} i$$

where $\ell_{cell} = 25m$ is the cell length and i defines the bunch position along the Linac.

- For multiple passes through the Linac (the index n defines the pass number) the above formula can be generalized as follows:

$$G_i^n = G_0 + \frac{G^{max} - G_0}{\tau c} \left[(n-1)\left(\ell_{linac} + \frac{n}{2} \ell_{arc} \right) + i \ell_{cell} \right]$$

where ℓ_{linac} is the full Linac length and ℓ_{arc} is the length of the lowest energy droplet arc. Here we also assume that the energy gain per linac is much larger than the injection energy.

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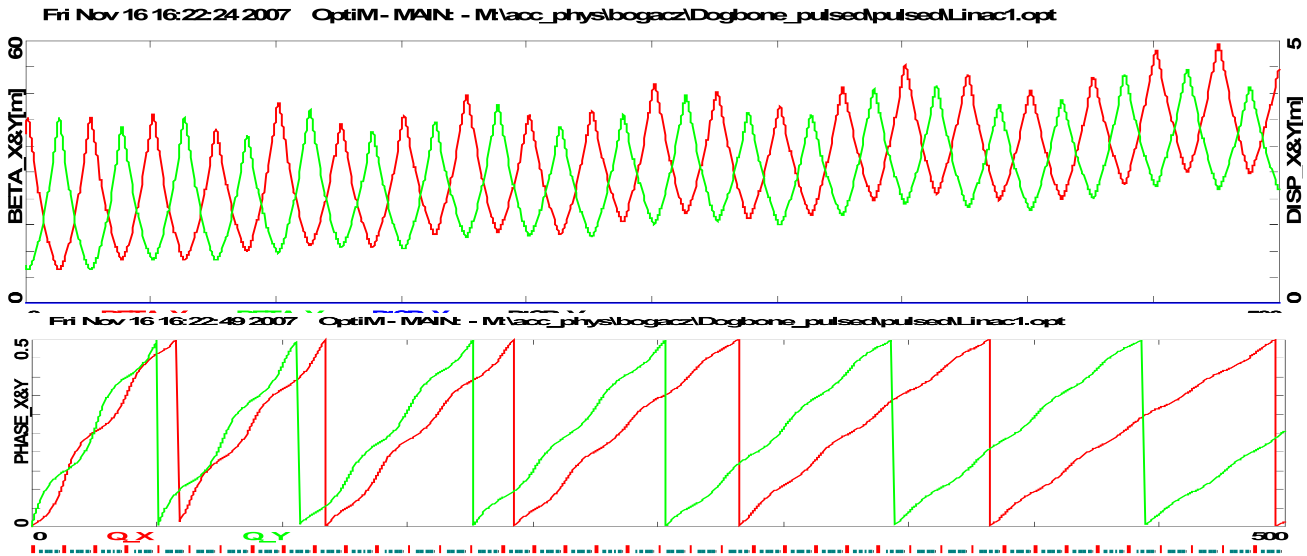
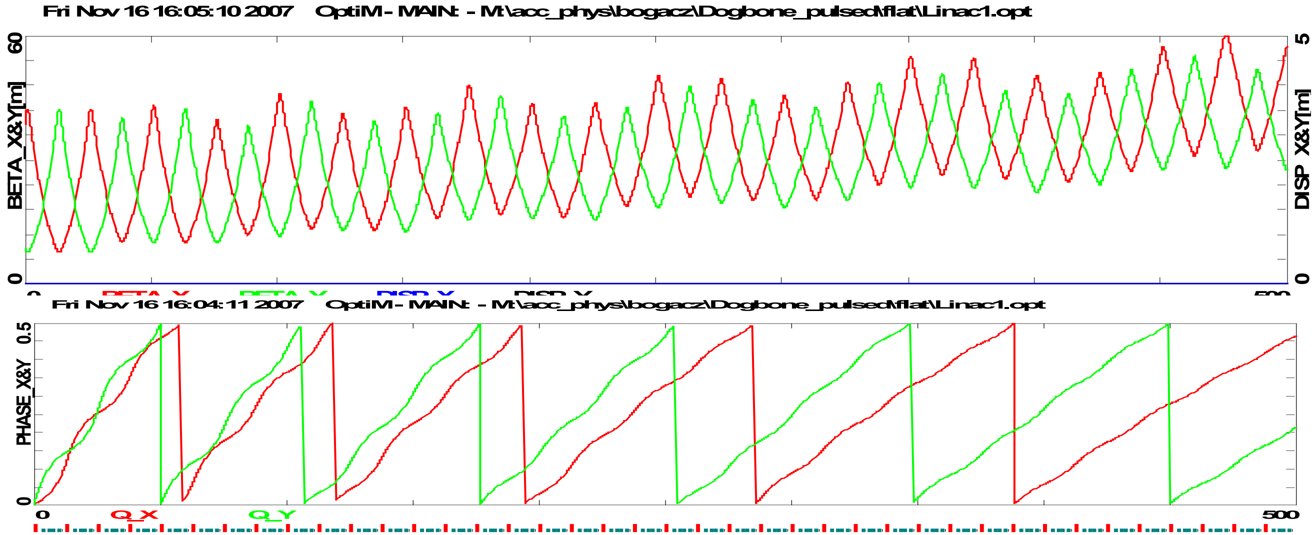
‘Pulsed’ vs ‘Fixed’ Dogbone RLA (8-pass)

Pulsed

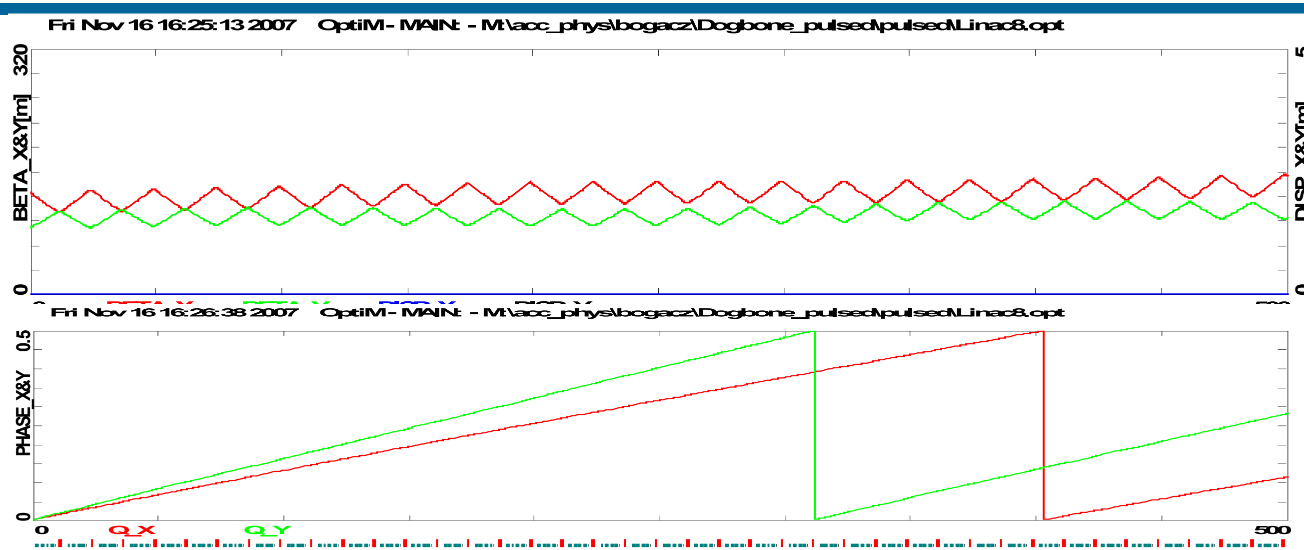


1-pass, 3-7 GeV

Fixed

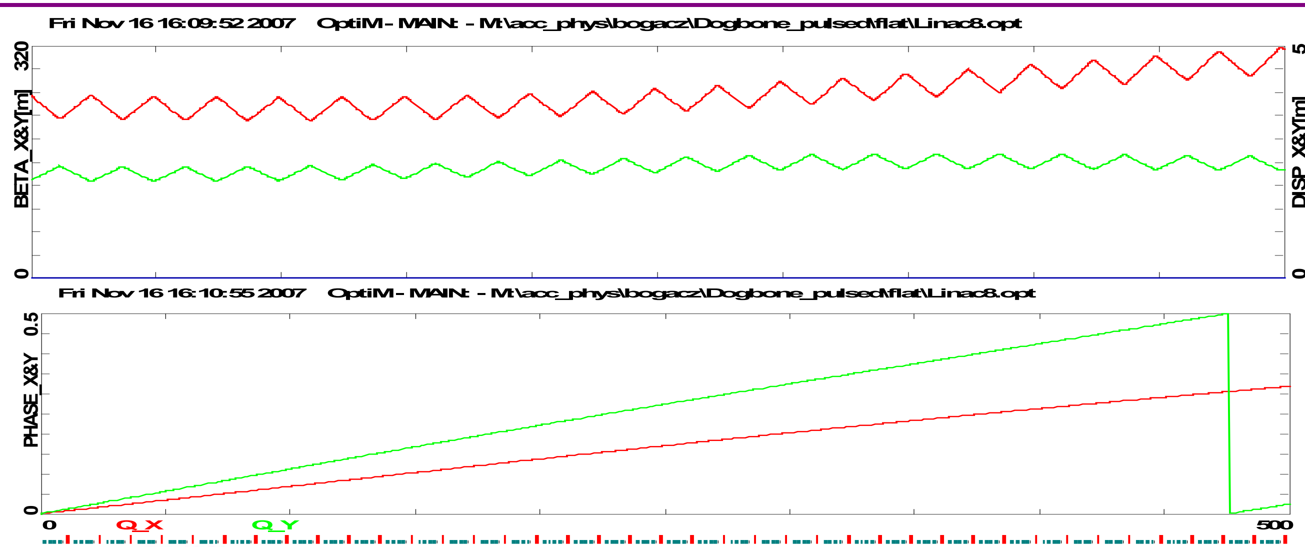


'Pulsed' vs 'Fixed' Dogbone RLA (8-pass)



Pulsed

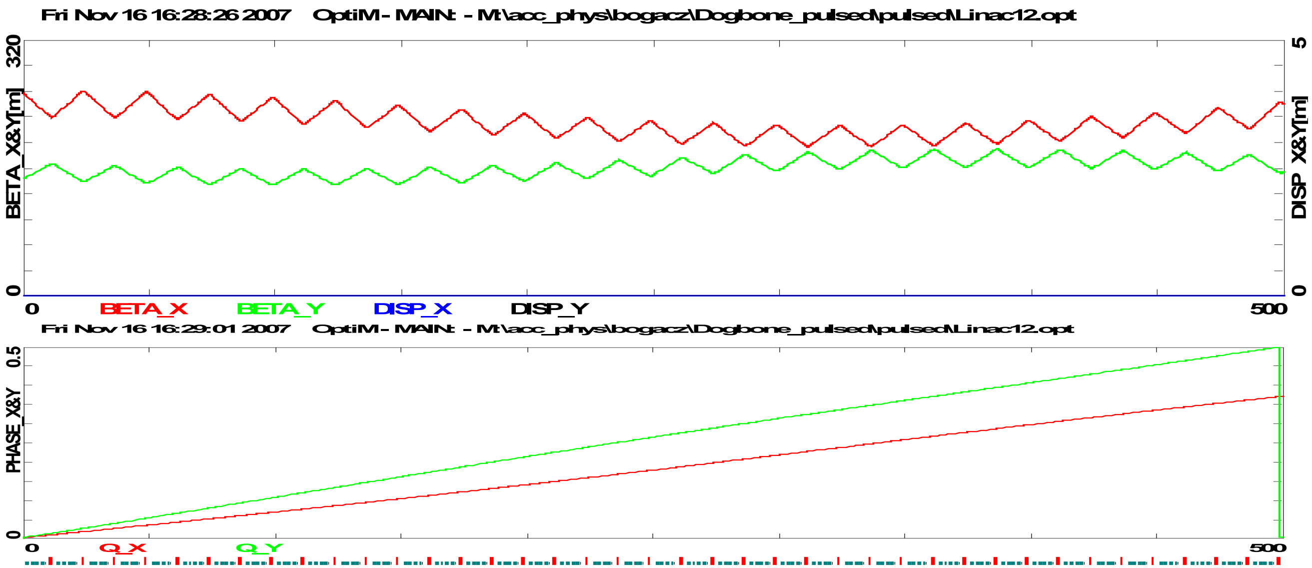
8-pass, 28-32 GeV



Fixed

phase adv. diminishes down to 180^0

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



Pulsed

phase adv. diminishes down to 180^0

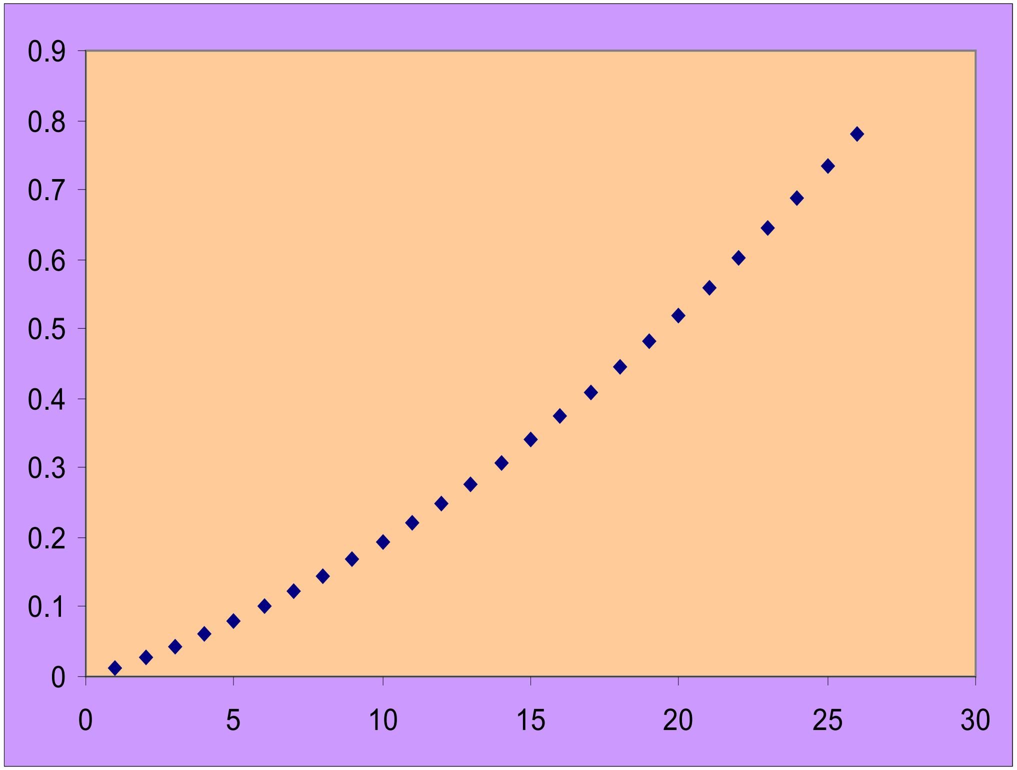
12-pass, 47-51 GeV

Fixed

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

'Pulsed' Dogbone ILC - example

$$\frac{T}{\tau}$$



number of passes

$$\ell_{linac} = 4000m$$

$$\ell_{arc} = 200m$$

$$\tau = 1\times 10^{-3}\ \sec$$

$$T = \frac{1}{c}\left[(n-1)\left(\ell_{linac} + \frac{n}{2}\ell_{arc}\right) + i\ell_{linac}\right]$$

Ramped Quadrupoles

What is needed?

1m x 5 cm radius bore, pole field 1 T, G^{max} = 2 kG/cm = 20 T/m, Dt = 1 ms

What has been done?

FNAL booster ramped multipole (2,4,6): (V.S.Kashikhin et al, PAC05, MPPT010)

23cm x 2.54 cm bore, pole field 0.01 T, G^{max}= .04 kG/cm = 0.4 T/m, Dt = 1 ms

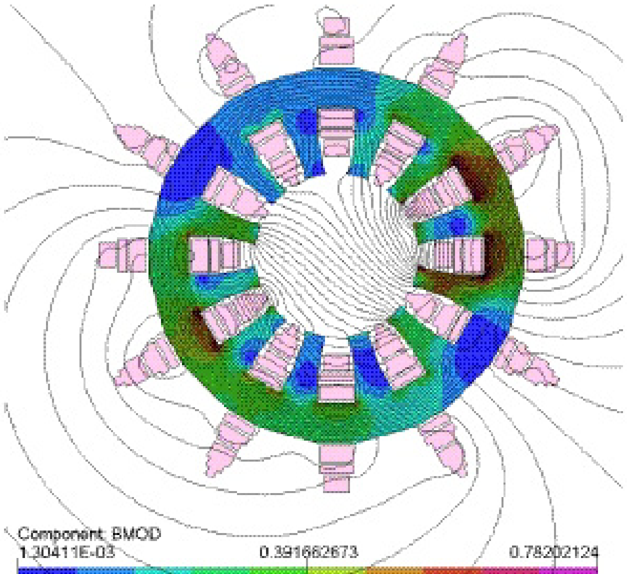


Figure 4: Flux density and flux line distribution at maximum current in all windings.

Simple Scaling: RLA vs FNAL

Kevin Beard

- active volume ~ 4:1
- quadrupole gradient ~ 50:1
- stored energy/length ~ (quad:quad+dipole) = 300:1
- W total stored energy ~ 1000:1
- dW/dt ~ 500:1

- 1m quadrupole stored energy $W = \frac{1}{2} L I^2 \sim 1.6$ kJ

$\Rightarrow$ dW/dt ~ 1.6 MW = L I dI/dt = I V

$\Rightarrow$using K.Bourkland's 5kV limit* => ~ 300 A

* D.Summers' LEMC2007 talk - http://www.muonsinc.com

Thinking about it…

- RLA quads are simpler than Kashikhin's combined function magnets
- Fortunately, D.Summers has thought about ramping magnets (D.Summers, et al, PAC03 THMPS082)

Kevin Beard

G^{max}= 20 T/m, R_o= 5 cm, Dt = 1 ms =>

W_{RLA} ~ 1.6 kJ/m, dW/dt ~ 1.6MW/m

- Simplest possible quadrupole:

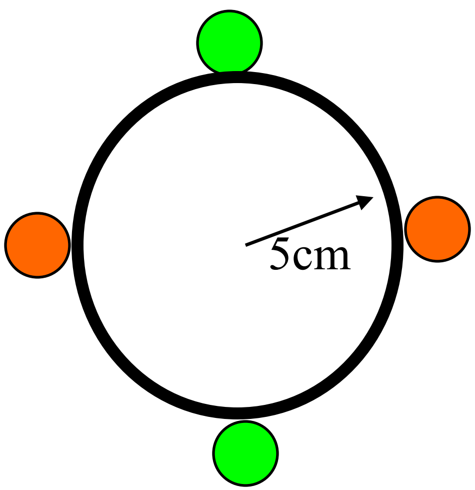
$G^{max} = 2 m_o I / p R^2$ => $I = G^{max} p R^2 / 2 m_o = 60$ kA

$L = 2 W / I^2 = 0.8\ \mu H$

resonant circuit of some kind? f ~ 250 Hz

$C = 1/L(2pf)^2 = 0.5$ F

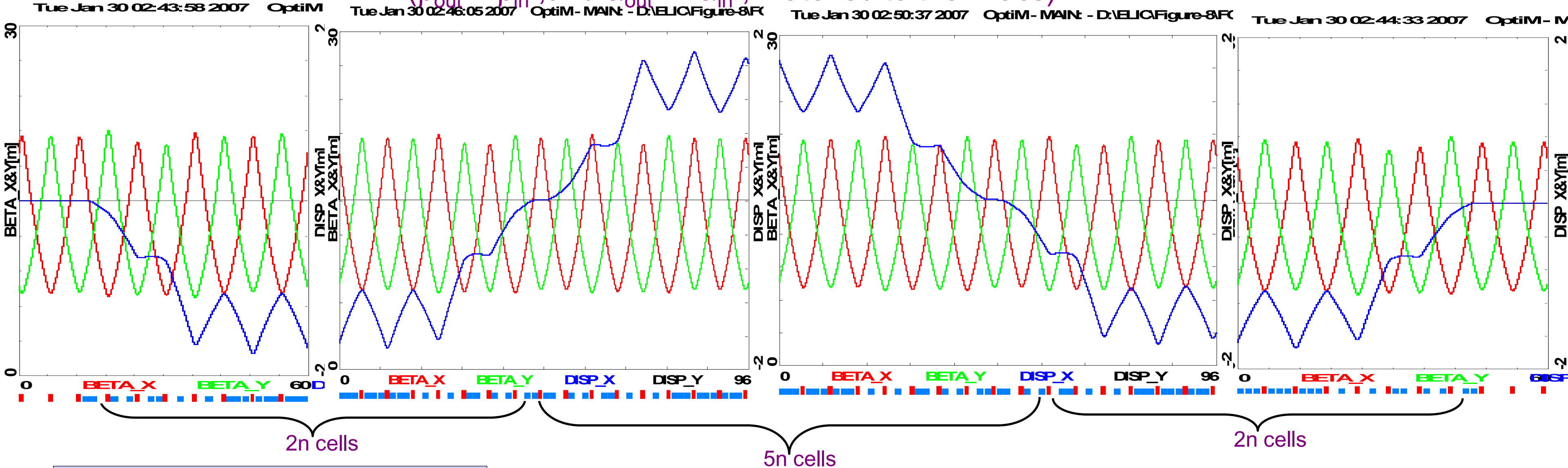
$V = \sqrt{(2 W/C)} = 80$ V

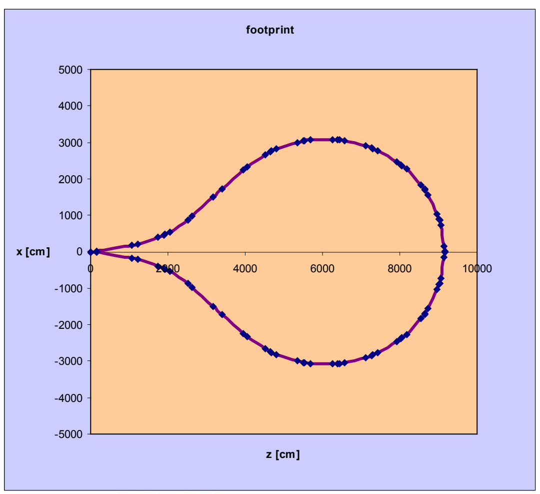


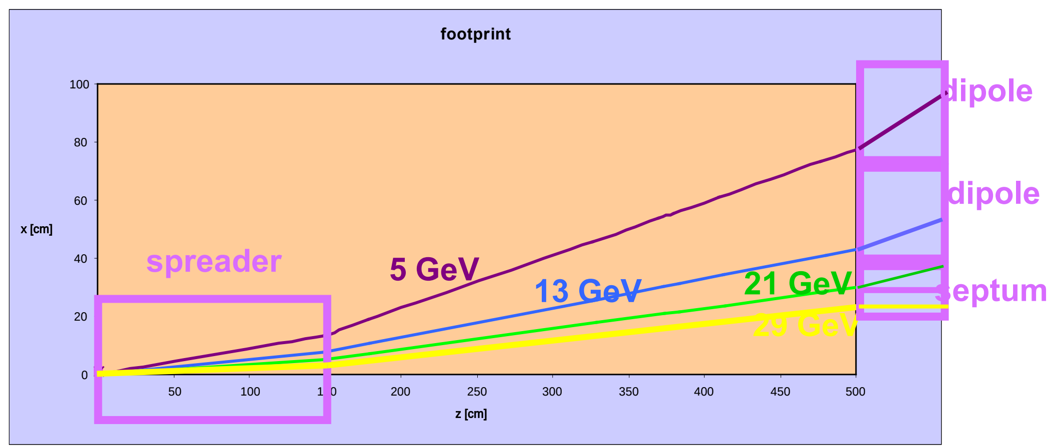
nearly iron-free quad

Mirror-symmetric ‘Droplet’ Arc – Optics

($\beta_{out} = \beta_{in}$,and $\alpha_{out} = -\alpha_{in}$, matched to the linacs)



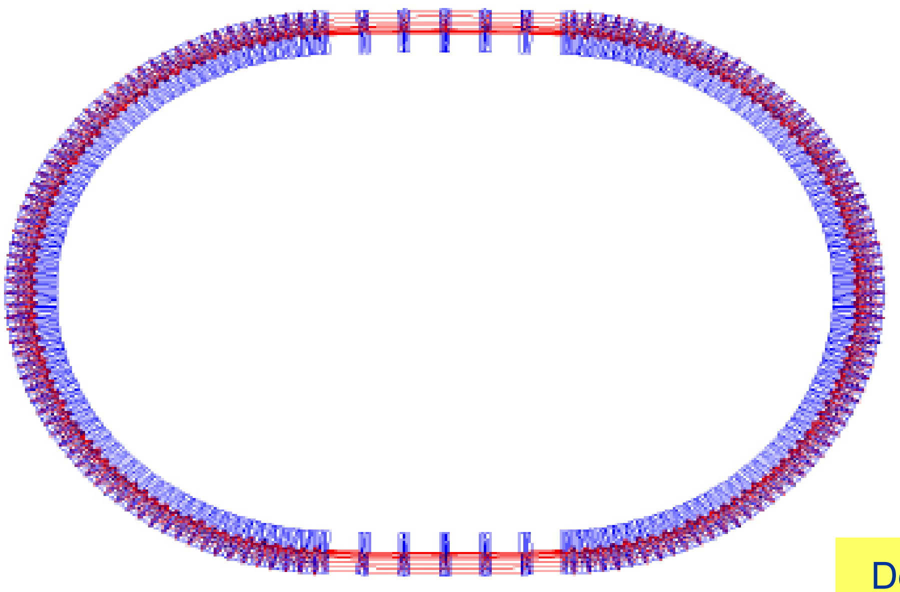


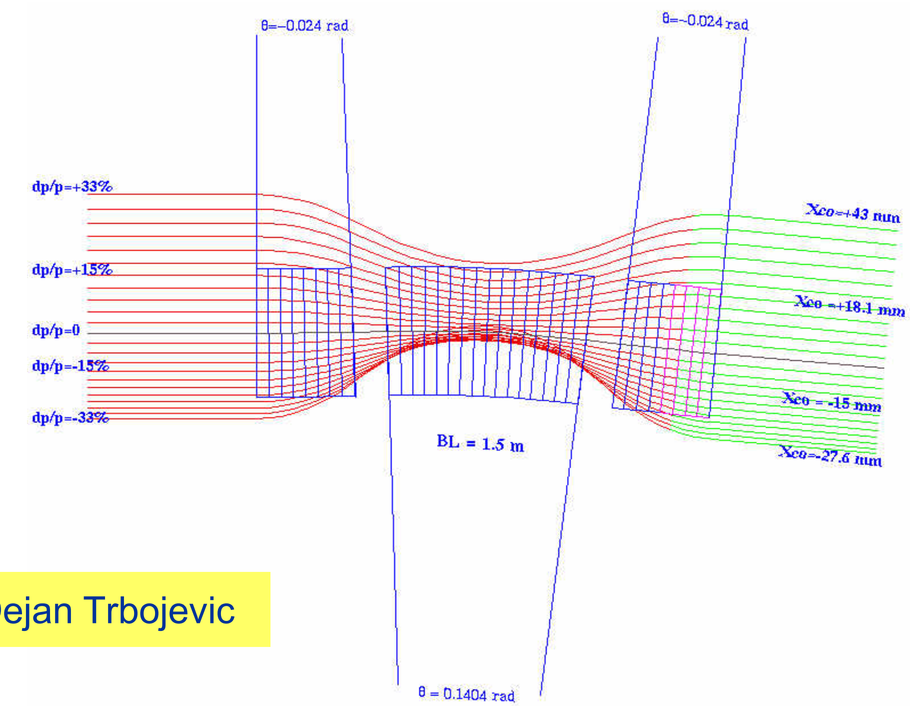


Prototype Arc design NS-FFAG

NS-FFAG (Non-Scaling Fixed Field Alternating Gradient)

- ‘Racetrack’ RLA to accommodate large momentum range (~60%)





Dejan Trbojevic

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

Basic cell structure in ARC (combined function magnet with extremely strong focusing)

Reference: Flexible Momentum Compaction Return Arcs for RLAs, D. Trbojevic, R.P. Johnson, EPAC, 2578-2580

Multi-pass 'Droplet' Arc

- FMC Optics (NS-FFAG-line)
- Compact triplet cells based on opposed bend combined function magnets
  - Middle magnet – high gradient bend (QD) having a strong central field and negative gradient at the center
  - Flanked by a pair of negative bending magnets QF that are horizontally focusing

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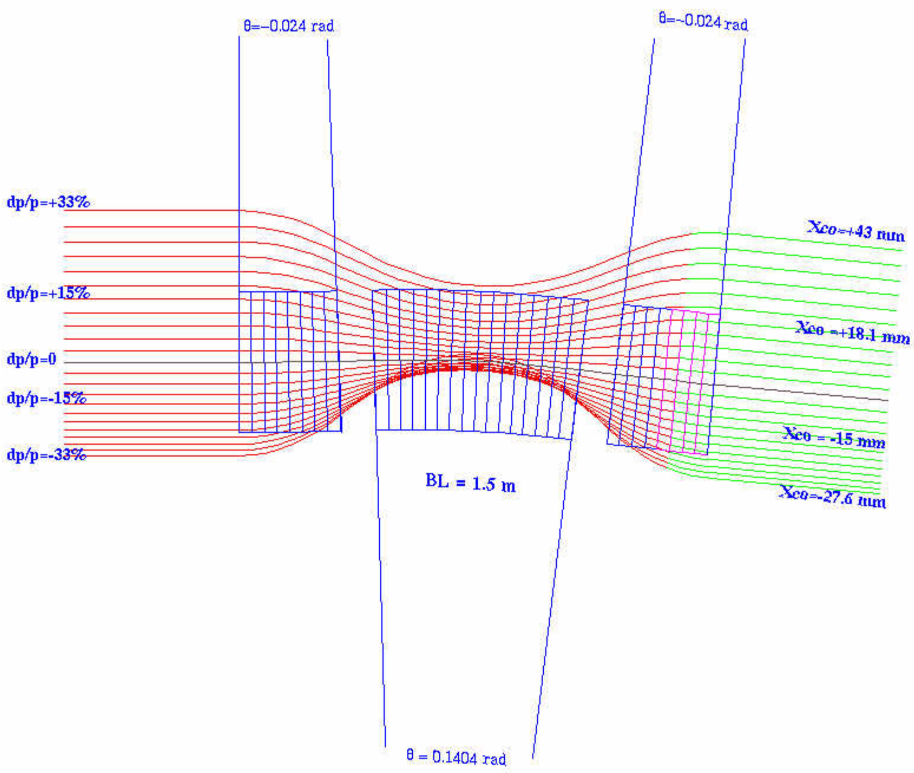
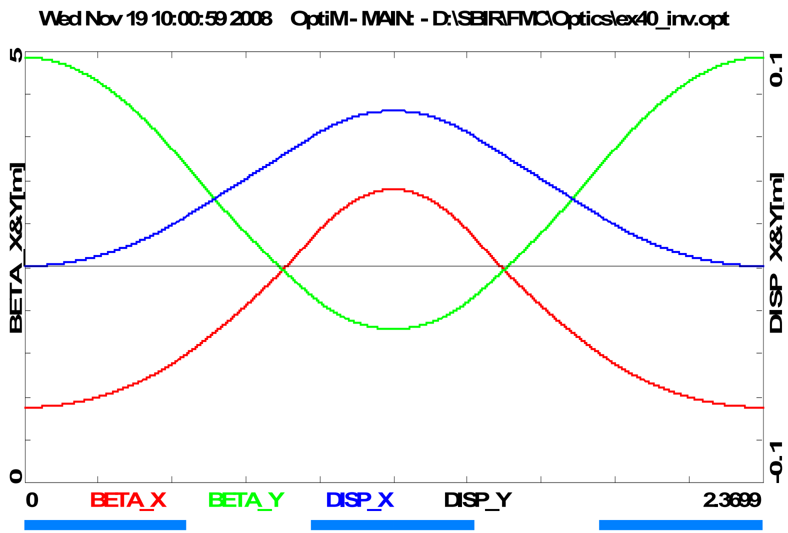
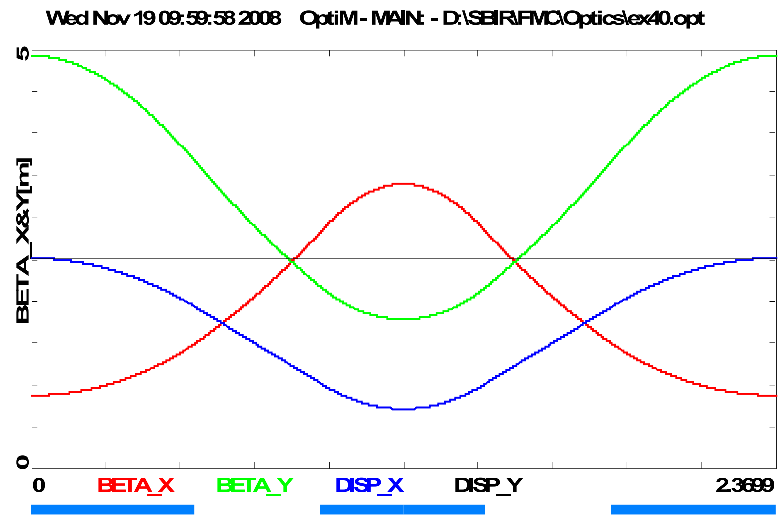


$$B_y = B_0 + Gx$$
$$B_x = Gy$$

Flexible Momentum Compaction Cells

Guimei Wang

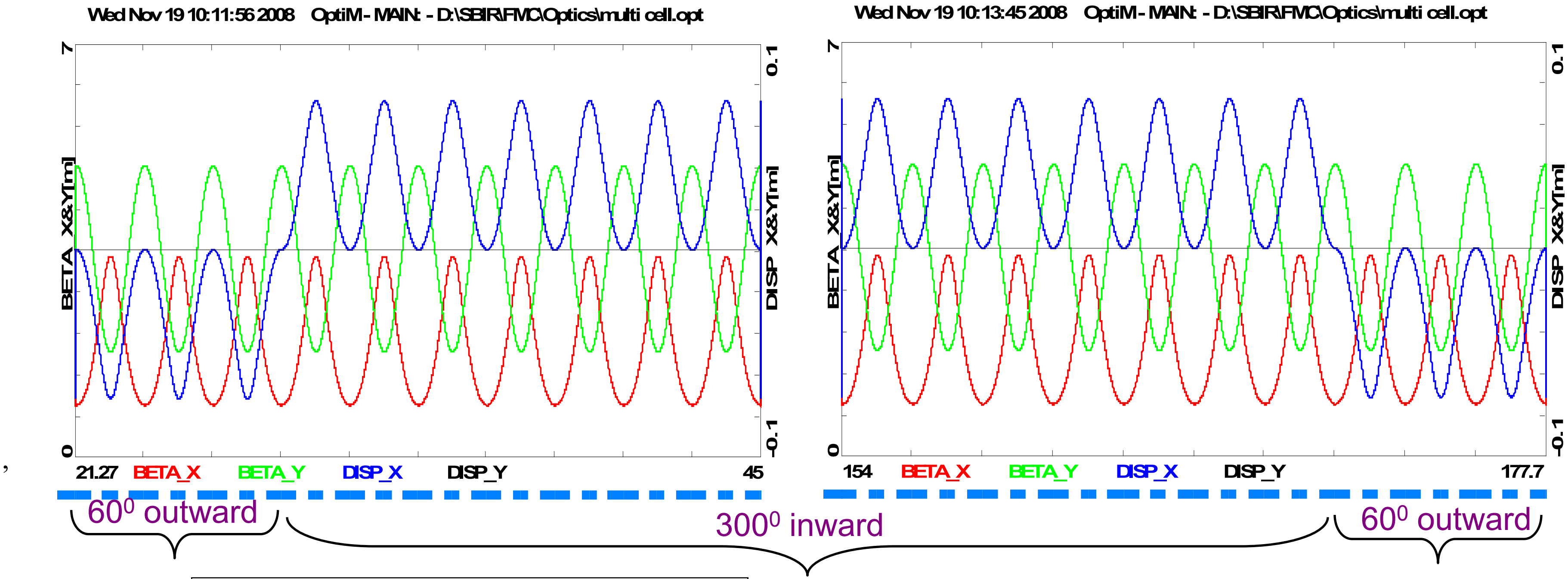


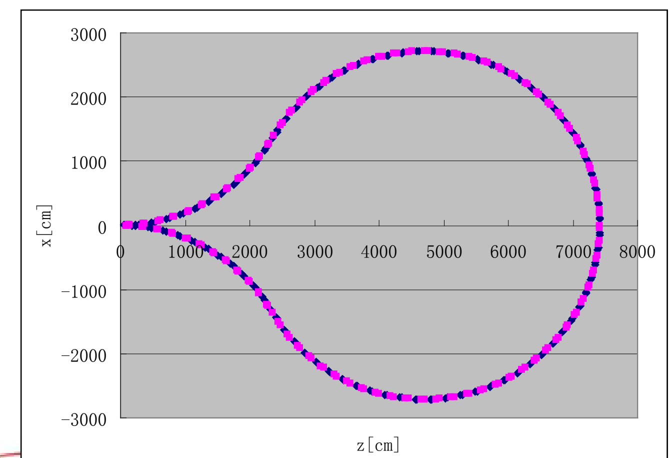


Mag.	L(cm)	B(kG)	G(kG/cm)	θ (deg)	D(cm)
BD	0.5233	35.08	-2.28	5	0<D<0.023
BF	0.5233	-35.08	5.60	-5	0.06<D<0.072
BDre	0.5233	-35.08	-2.28	5	-0.023<D<0
BFre	0.5233	35.08	5.60	-5	-0.072<D<-0.06

- 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



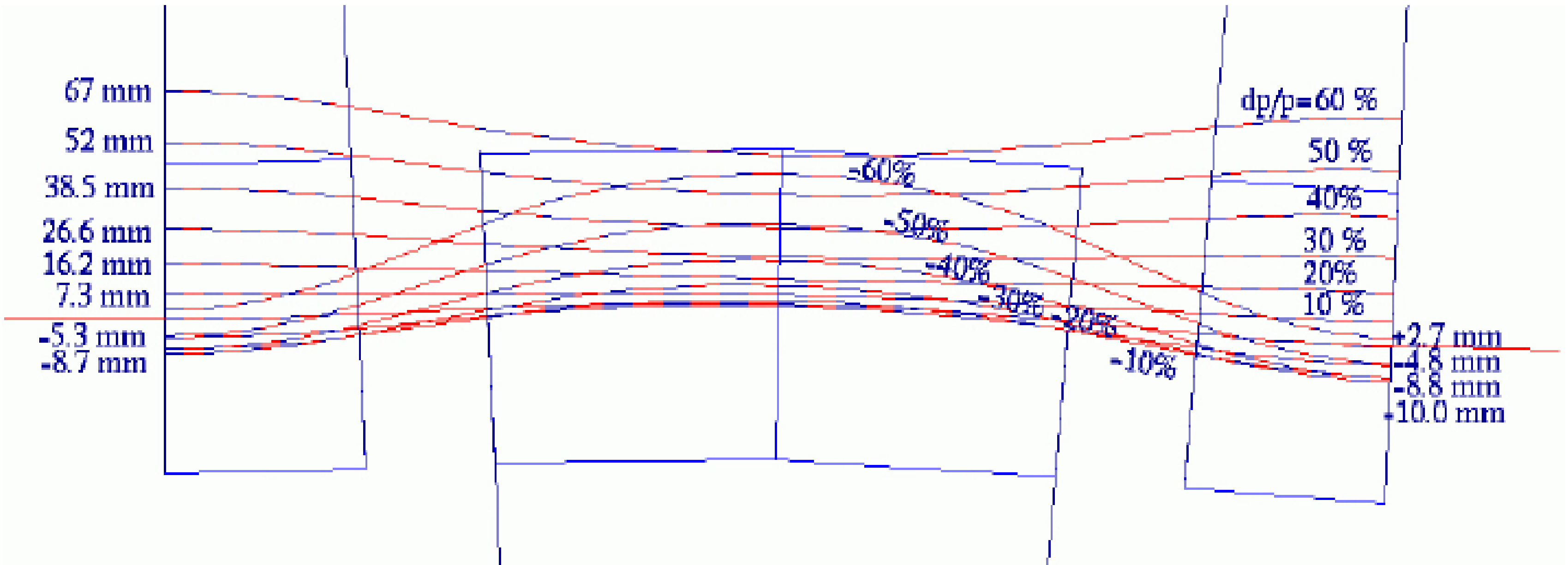


- MADX-PT – Polymorphic Tracking Code is used to study multi-pass beam dynamics for different pass beams: path length difference, optics mismatch between linac and arcs, orbit offset and tune change is being studied.

Large Momentum Acceptance Arc

Guimei Wang

- Lattice requirements:
  - Mirror symmetry arc structure for both μ^+ μ^- acceleration
  - Large momentum acceptance (factor of two?)
  - Achromat Optics at both energies
  - Optics match between Linac and Arc, mismatch sensitivity
  - Path length control to match beam phase in the linac



Beta functions vs. Energy

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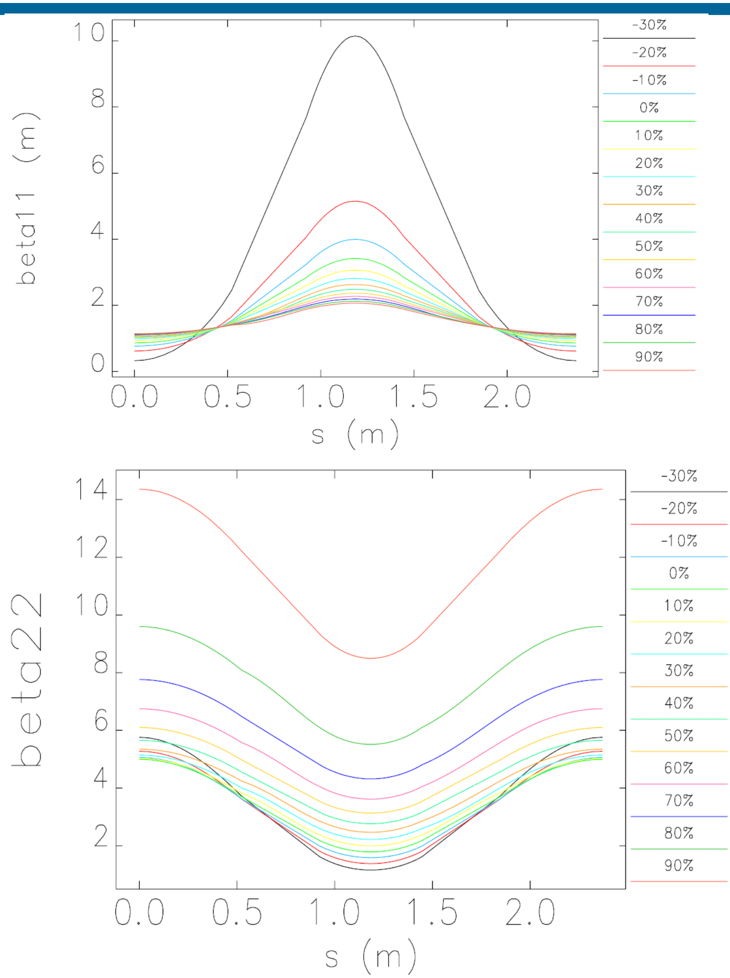
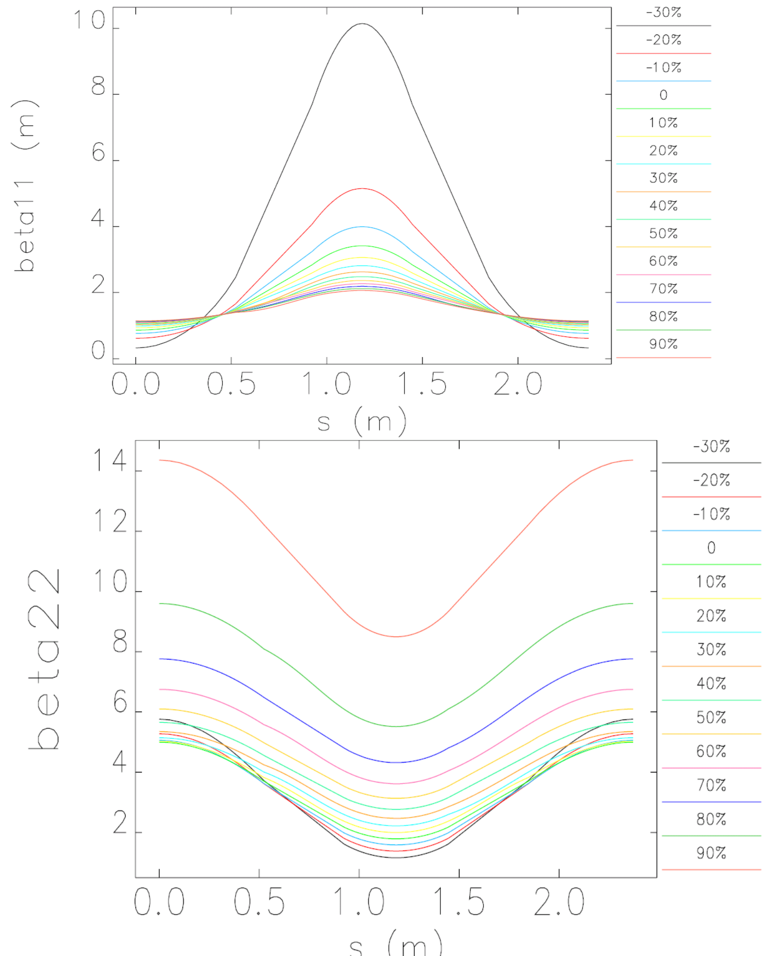


Inward bending cell



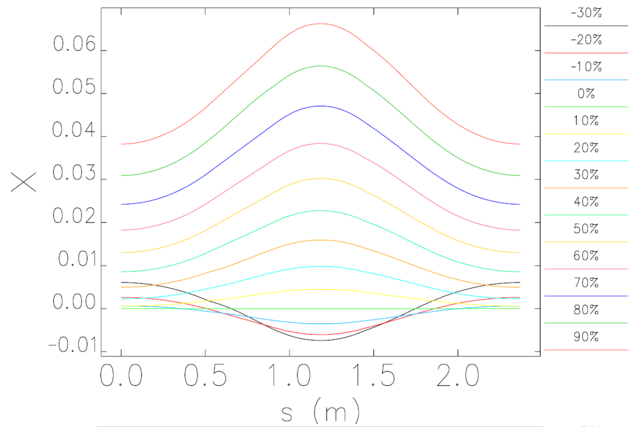
Outward bending cell

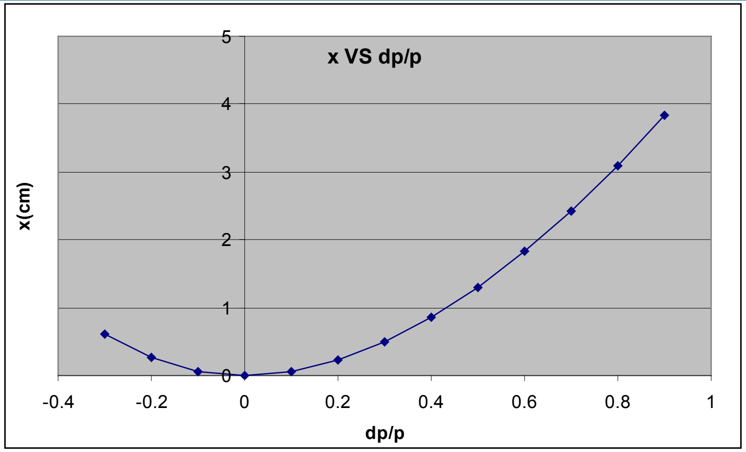
Guimei Wang

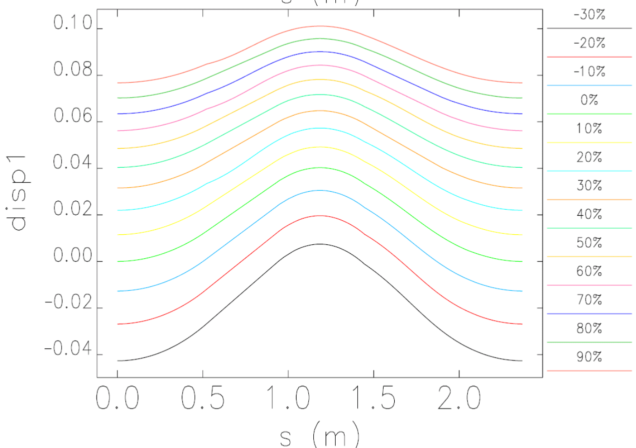
For different energy spread, ~the same beta function in opposite bending cell.

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

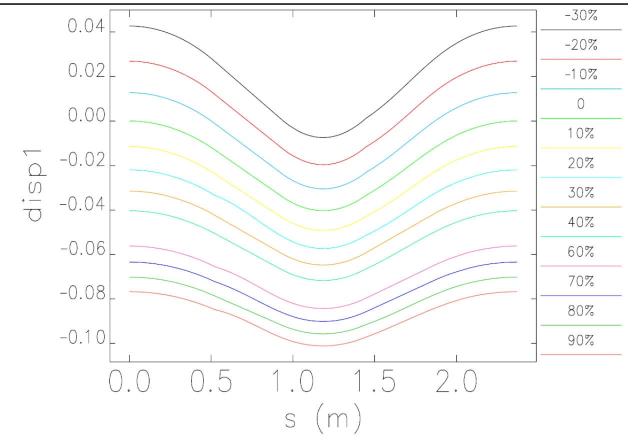
Dispersion vs. Energy







Inward bending cell



Outward bending cell

Guimei Wang

For different energy spread, opposite offset and dispersion in opposite bending cell.
Beam offset <10cm, dispersion < 0.1 m.
Possible solution: (1) Matching cell with –I matrix in x plane, and +/- I matrix in y plane.

Analysis with multipoles components

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$$B_y = B_0 + G_0 x + S_0 x^2/2 + O_0 x^3/3! + H_0 x^4/4!$$

$$G = G_0 + S_0 x + O_0 x^2/2 + H_0 x^3/3!$$

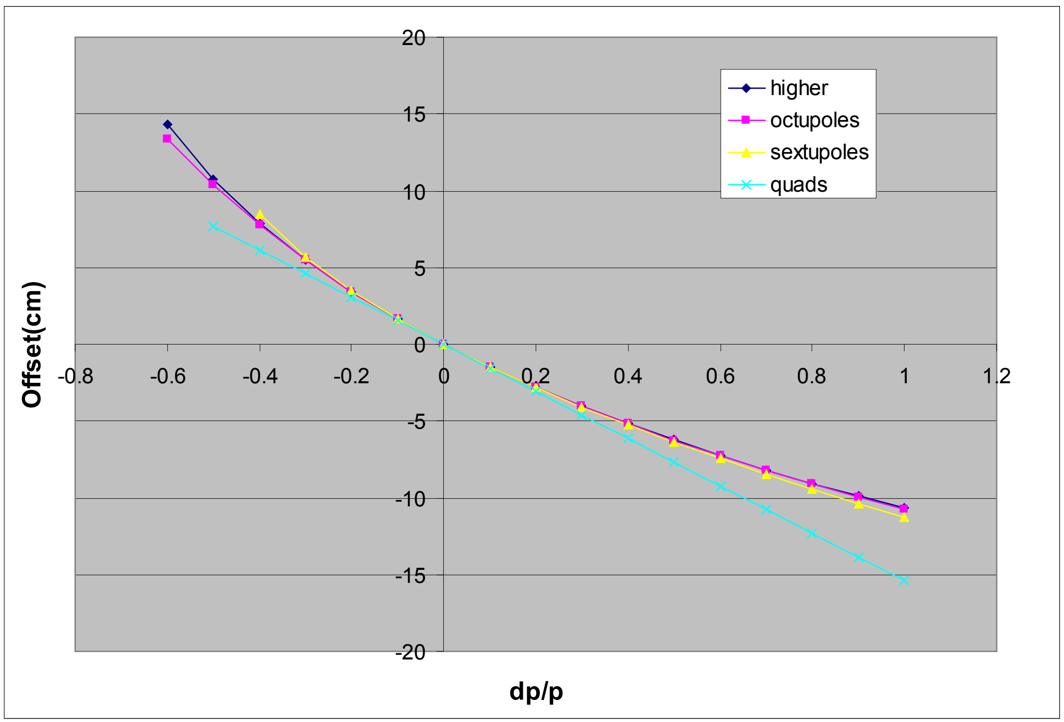
$$S = S_0 + O_0 x + H_0 x^2/2$$

$$S_0 = G_0^2 / B_0$$

$$O_0 = G_0^3 / B_0^2$$

$$H_0 = G_0^4 / B_0^3$$

Same bending raduis, same optics, same chromaticity



Guimei Wang

Beam offset vs energy spread

Conclusions

- **'Dogbone'** RLA – preferred configuration
  - better orbit separation for higher passes
  - offers symmetric solution for simultaneous acceleration of μ^+ and μ^-
- **FODO** bisected linac Optics – large number of passes supported
  - 8-pass RLA example
- **Pulsed linac Optics** Dogbone RLA – looks very encouraging
  - Increase from 8-pass (Fixed Optics) to 12-pass (Pulsed Optics) for 500 m long 4 GeV pass example
- **Flexible Momentum Compaction** (FMC) return arc Optics allowing to accommodate two passes (two neighboring energies) – under studies