Controlling CSR-Induced Emittance Growth and μBI In ERL Arcs

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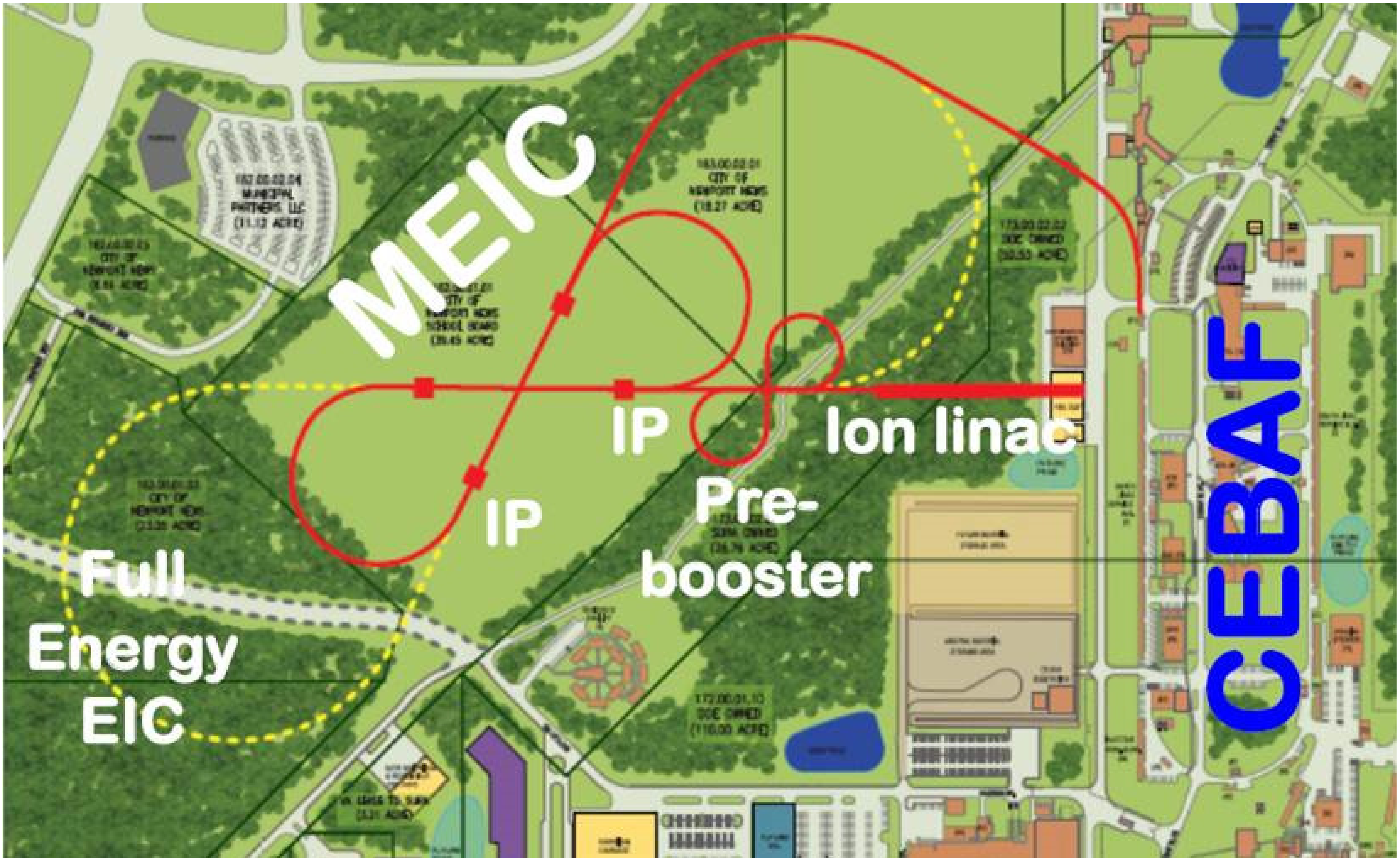
Outline

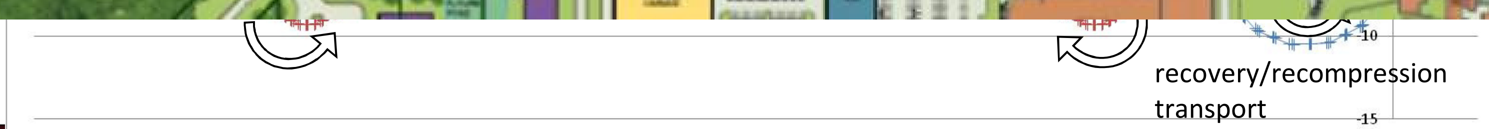
- Motivation
- Use of Optics Balance for CSR Control
- Low Energy Example
- High Energy Example
- A Cautionary Tale: *Bad* High Energy Example
- Compressors

Motivation

- *Collision of several trains of thought:*
  - Continuing work on CSR/LSC/μBI issues (R. Li)
  - CSR studies on JLab IR FEL driver ERL (C. Hall)
  - Beam dynamics challenges encountered in design of cooling system for MEIC (proposed electron/ion collider at JLab)
  - Ongoing interest in recirculated linacs & ERLs:
    - Linac/ring collider options for EIC
    - Longstanding fantasy re: CEBAF as FEL driver
    - FEL driver ERLs
  - Test of novel chicanery-free bunching scheme in UV FEL
    - Accelerate on falling side of RF waveform, compress with $M_{56}>0$
- ***Goal of studies**: preserve beam quality while recirculating high-brightness e^- beam*
- ***Goal of presentation**: get a reality check…*

Immediate Interest Driven by MEIC



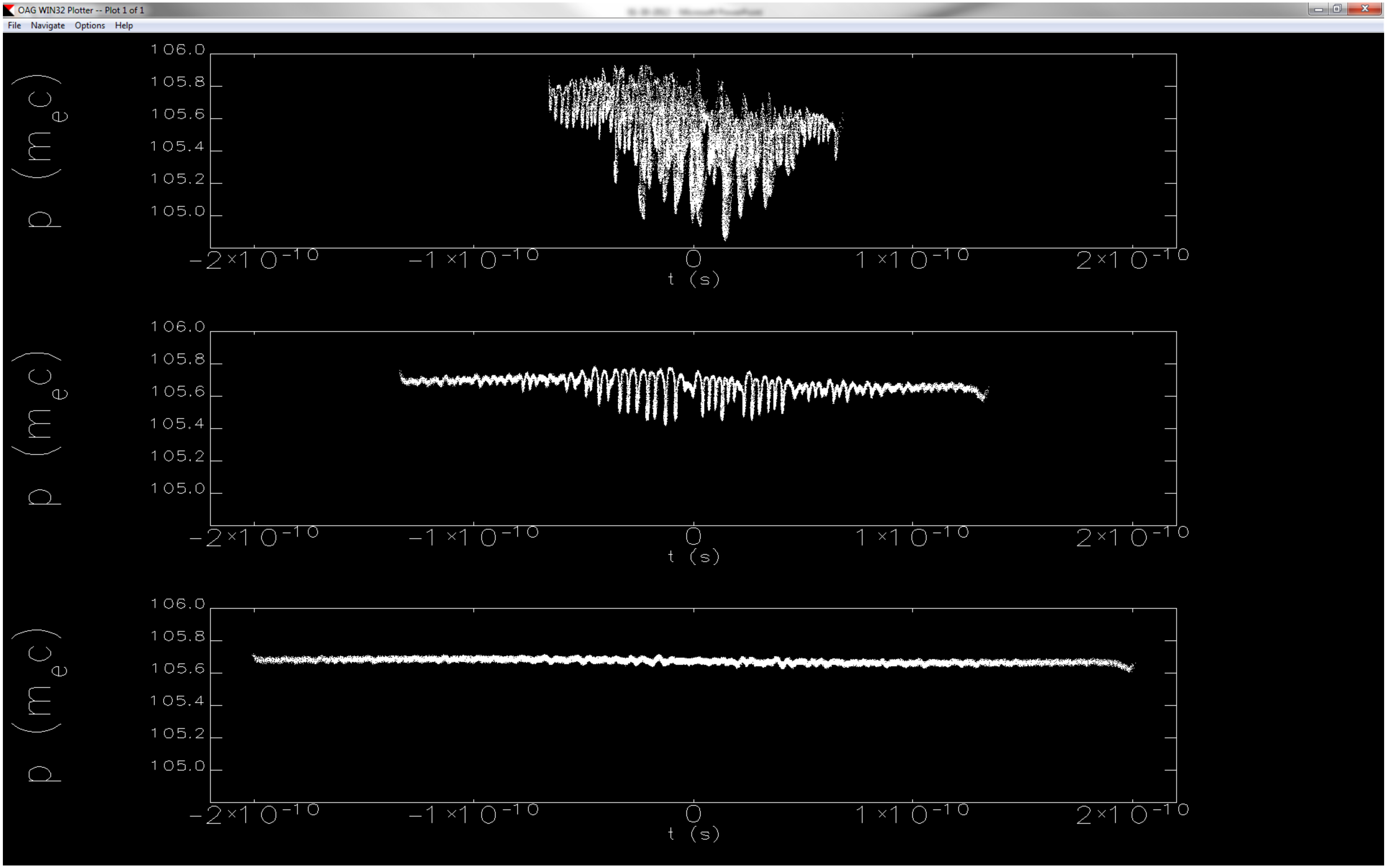


Showstoppers…

- High charge x low energy is nontrivial…
- CW MHz, rep rate, nsec-rise/fall time kickers even less trivial…
- CSR/μBI, space charge… ***fatal***

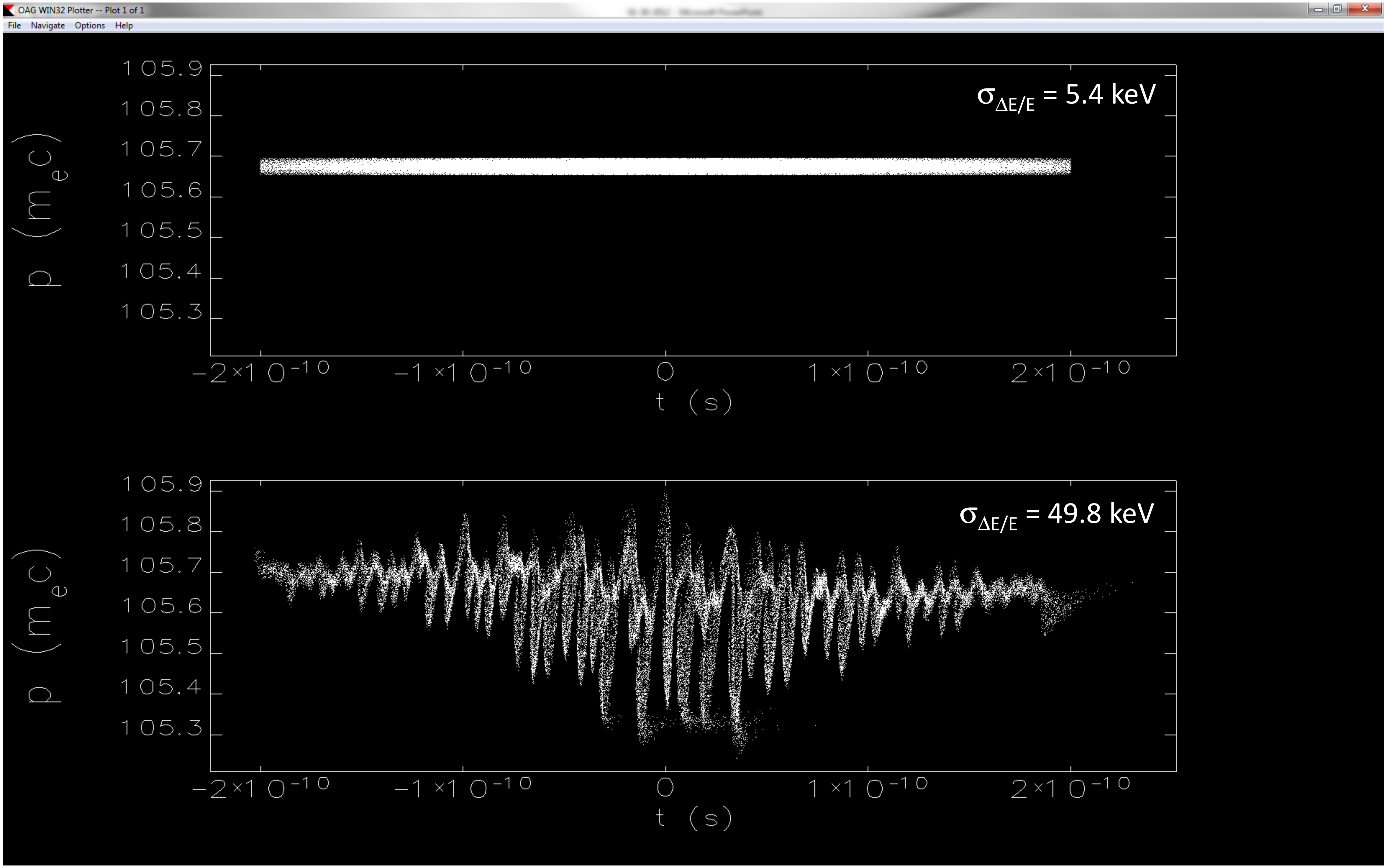
Longitudinal Phase Space Evolution

- Track bunches with σ_z=(1.0, 2.0, 3.0) cm for 10 turns



100 Turns

- 0.5 nC with 3 cm long bunch (rms) tracked for 100 turns with CSR



CSR Management

- What to do? Must manage CSR effects to keep beam bright enough to cool ions…
- diMitri/Cornacchia/Spampinati PRL Jan'13 => give potential methodology
- Use of longitudinally *periodic* achromat with small amplitude compaction modulation
  - CSR control
  - μBI suppression

    (note: method discussed by Borland 2006…)

cf. initial CCR design => longitudinally aperiodic/large amplitude compaction oscillation achromat => μBI enhancement

Recirculation With CSR Control

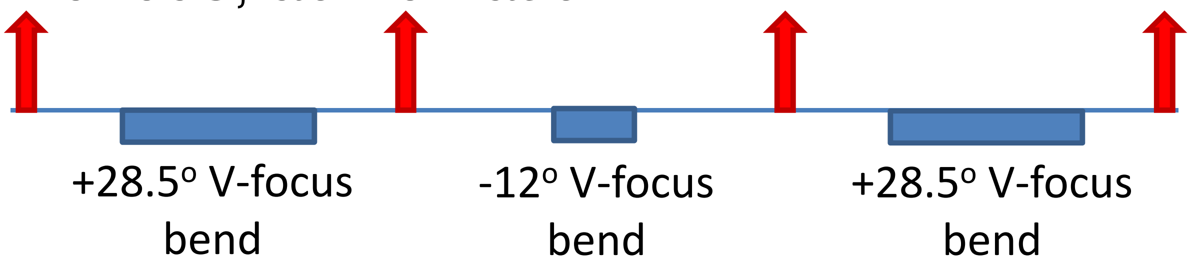
- A second-order achromat based on individually isochronous and achromatic superperiods meets all requirements stated in dM/C/S for compensating CSR-driven emittance dilution
  - every emittance-degrading CSR-induced momentum shift is matched by an identical one generated at a location with the same bunch length, same Twiss parameters, *but (modulo) a half-betatron wavelength away*
- Can readily generate lattices over broad range of energies that satisfy such conditions
  - have solutions for ~200 MeV through a few GeV

Isochronous Recirculation Arcs

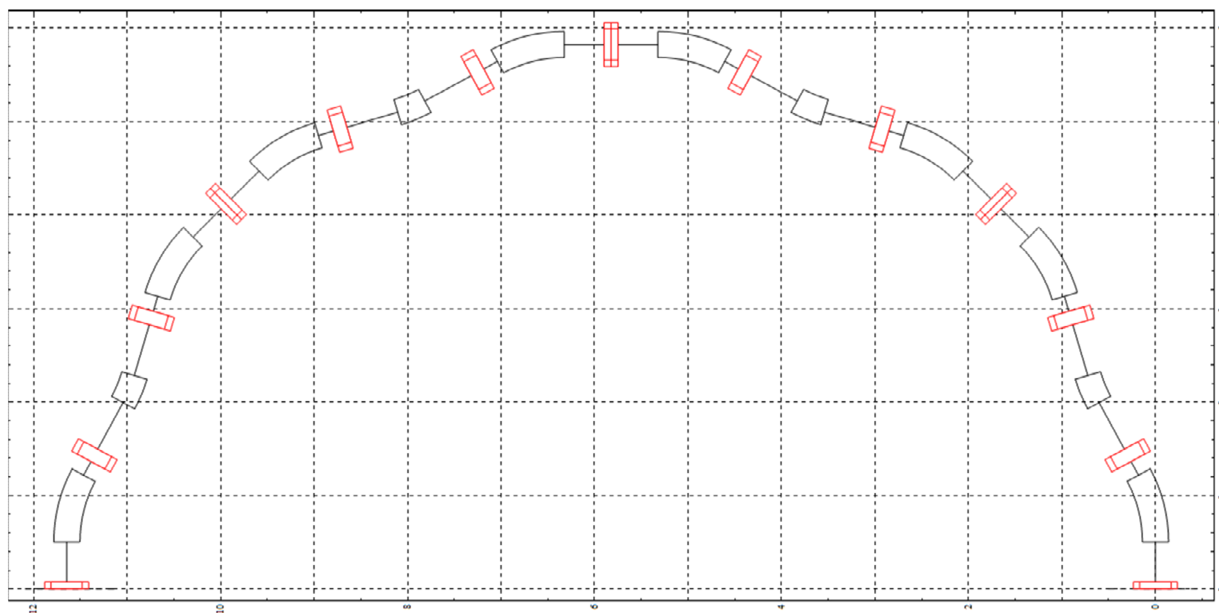
- Designed a simple (and hopefully) emittance-preserving transport line
  - 2nd order achromat composed of multiple individually isochronous & achromatic superperiods self-compensates CSR-induced emittance effects and suppresses microbunching instability
- Compact arc based on 1990's vintage three-bend isochronous achromat (Robin, Neuffer)
  - TBA with small-angle reversed center bend
    - alleviates focusing strength required in, e.g., Steffan system
  - individually achromatic/isochronous superperiods with ¾ integer bend-plane tunes
  - 4 periods = 2nd order achromat
    - very good chromatic properties
  - extremely robust suppression of CSR-induced emittance growth and microbunching

Layout: Single Superperiod/Arc

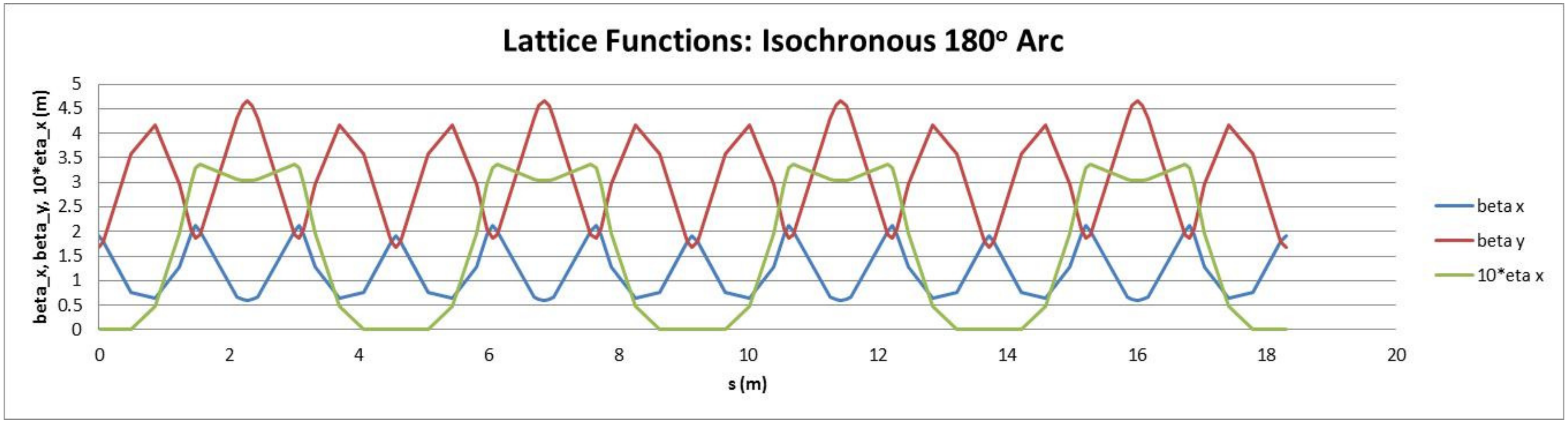
- Superperiod structure (45^o net bend)
  - Isochronous, achromatic

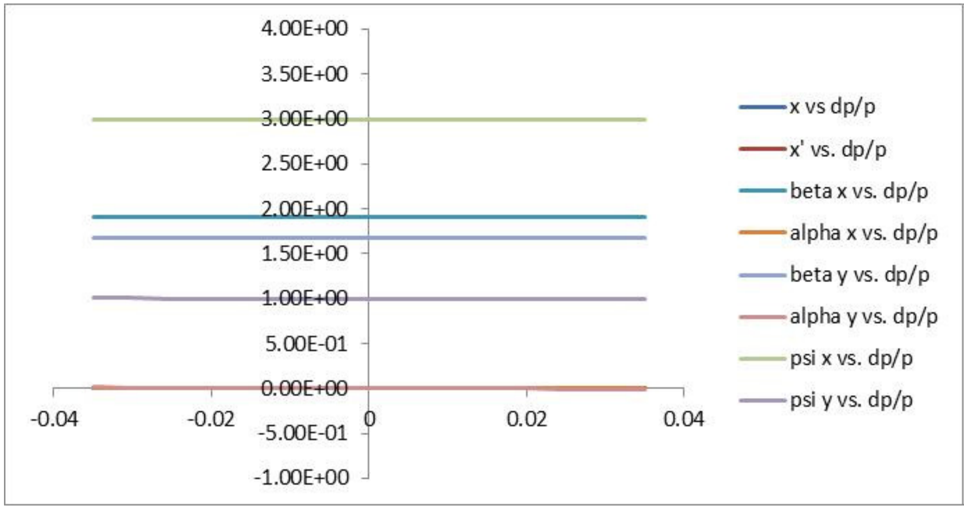


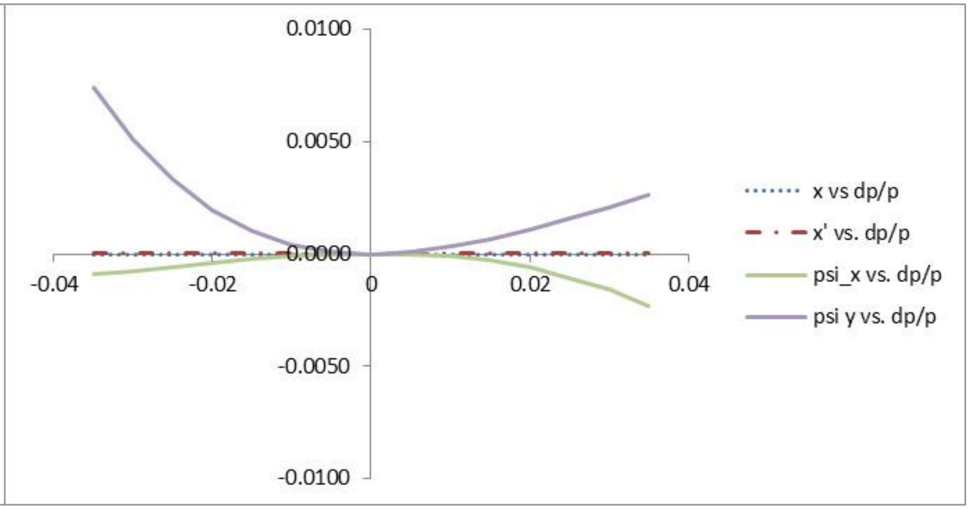
- Arc Layout (4 superperiods)



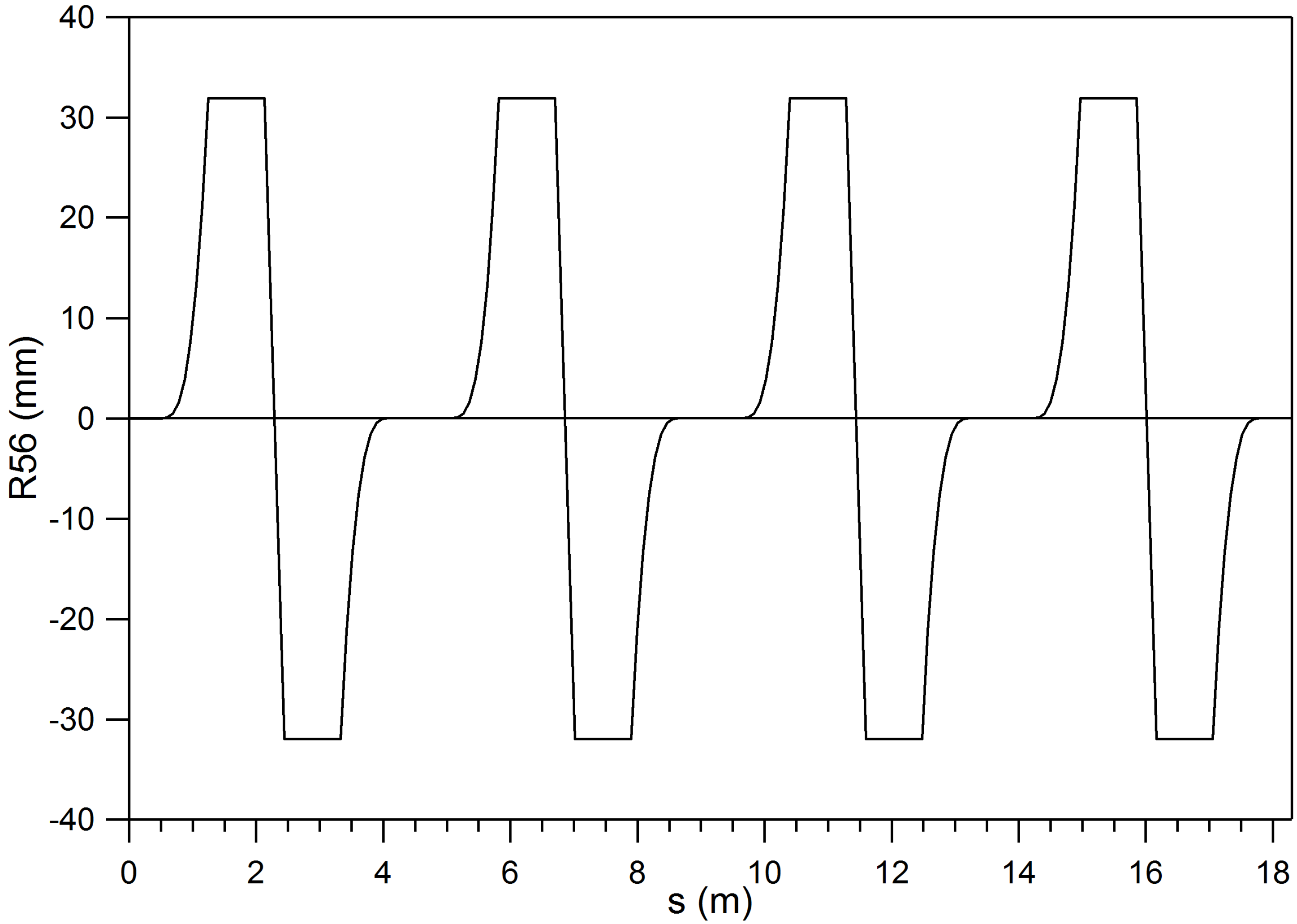
Lattice Functions, Momentum Scan



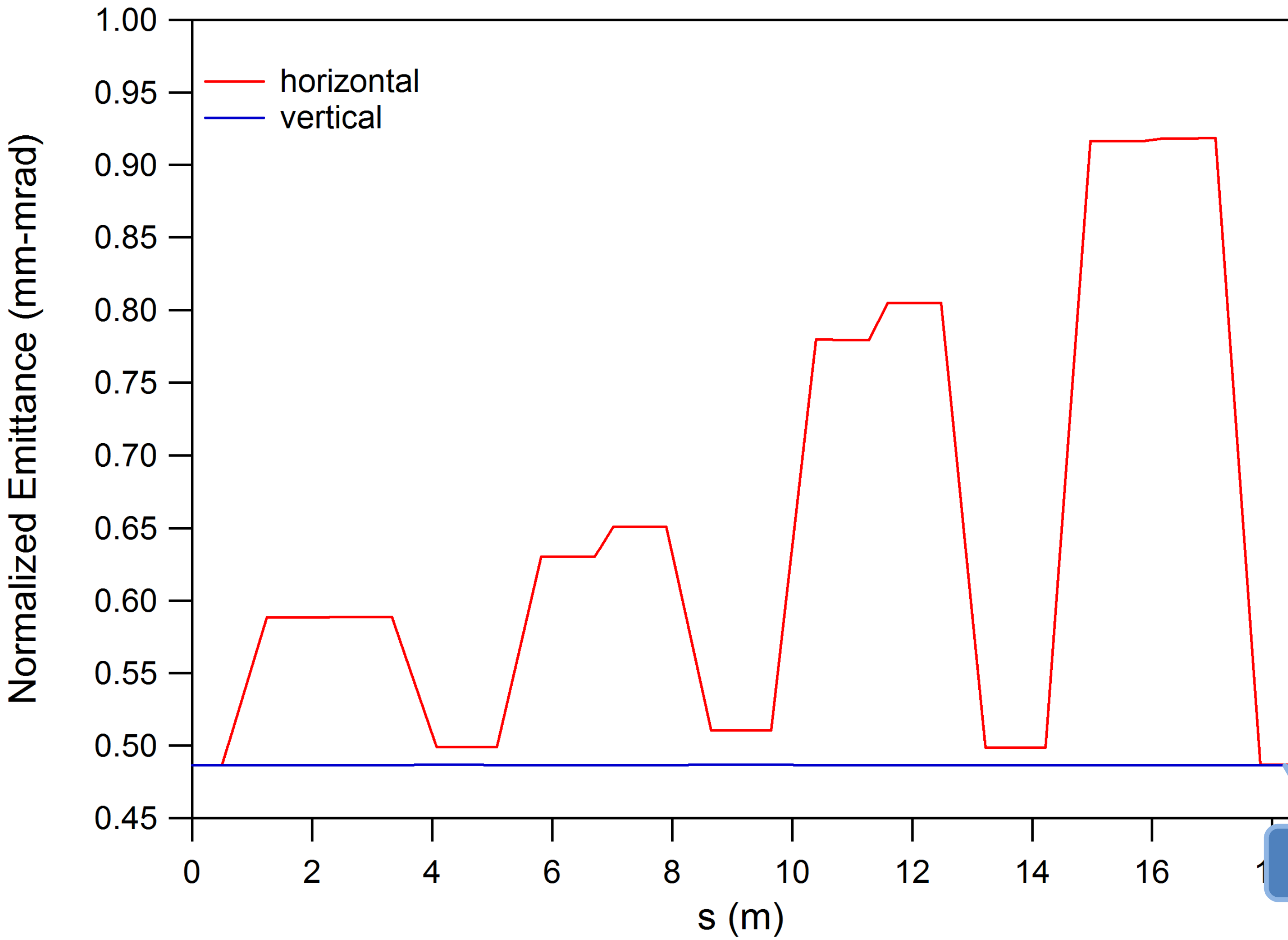




R_{56} Evolution

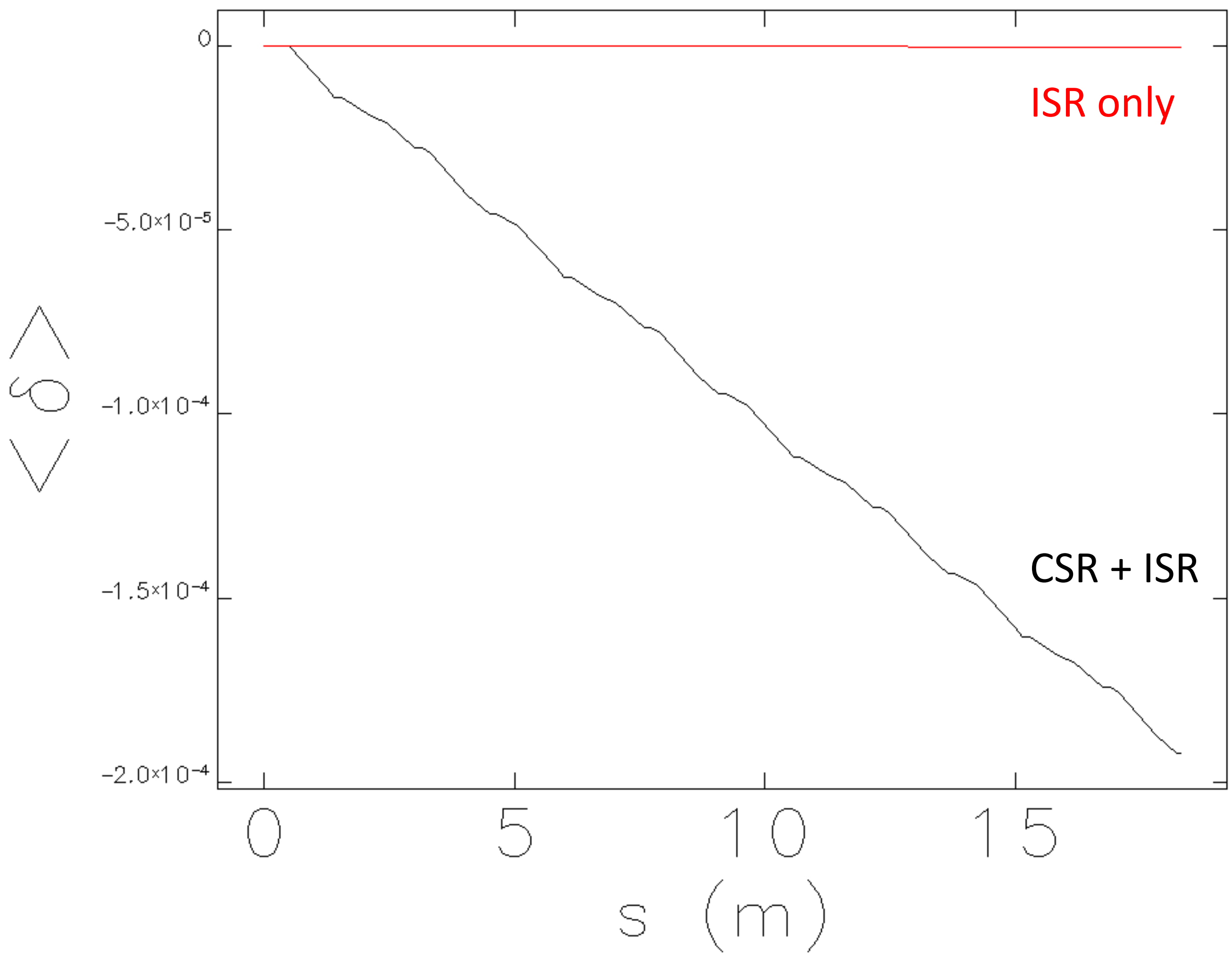


Normalized Emittance Evolution



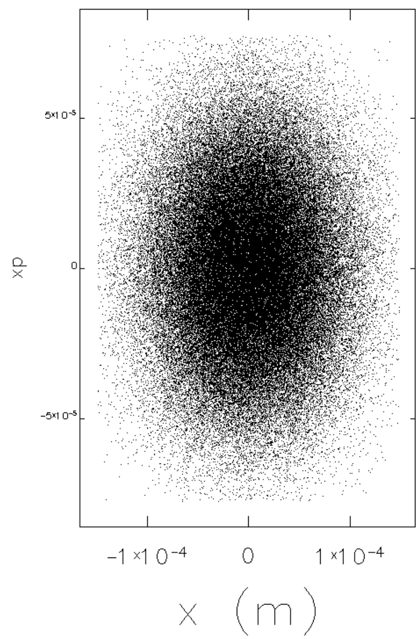
See ***no*** growth!

Energy Loss due to ISR, ISR+CSR (182 MeV)

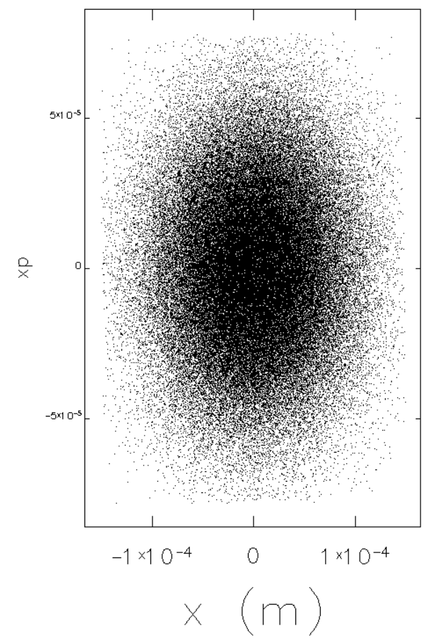


Transverse Phase Space

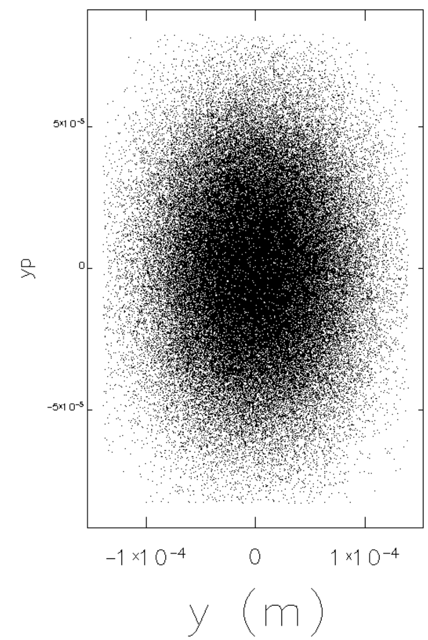
start of arc



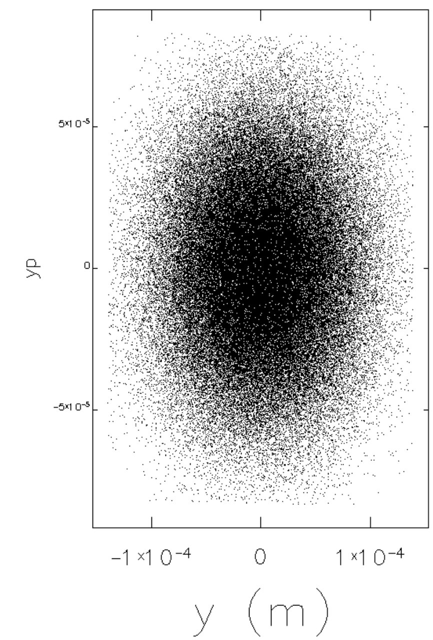
end of arc



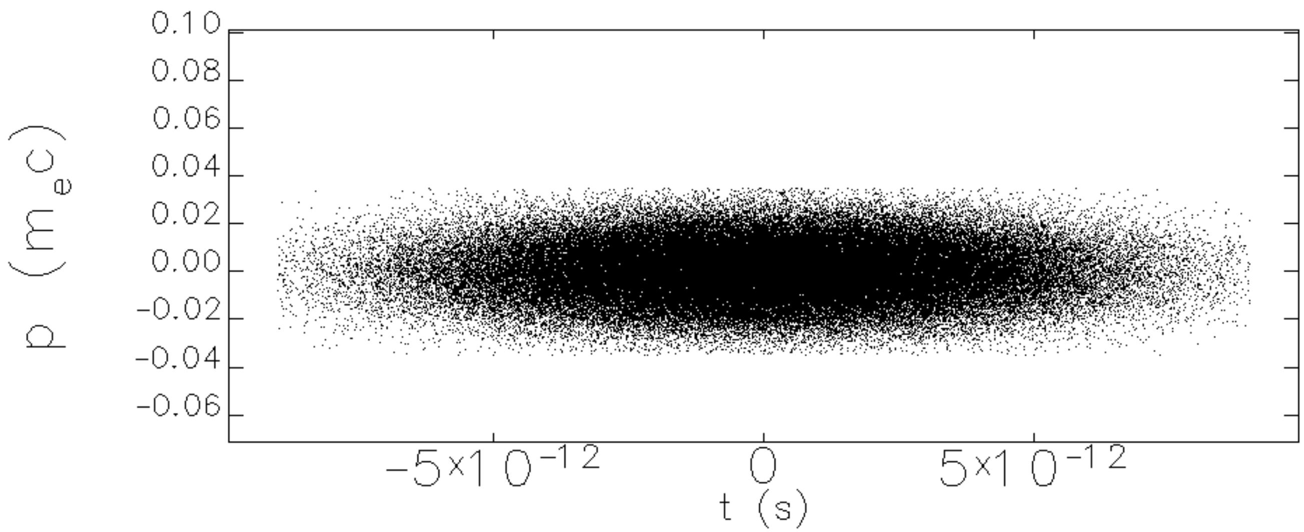
start of arc

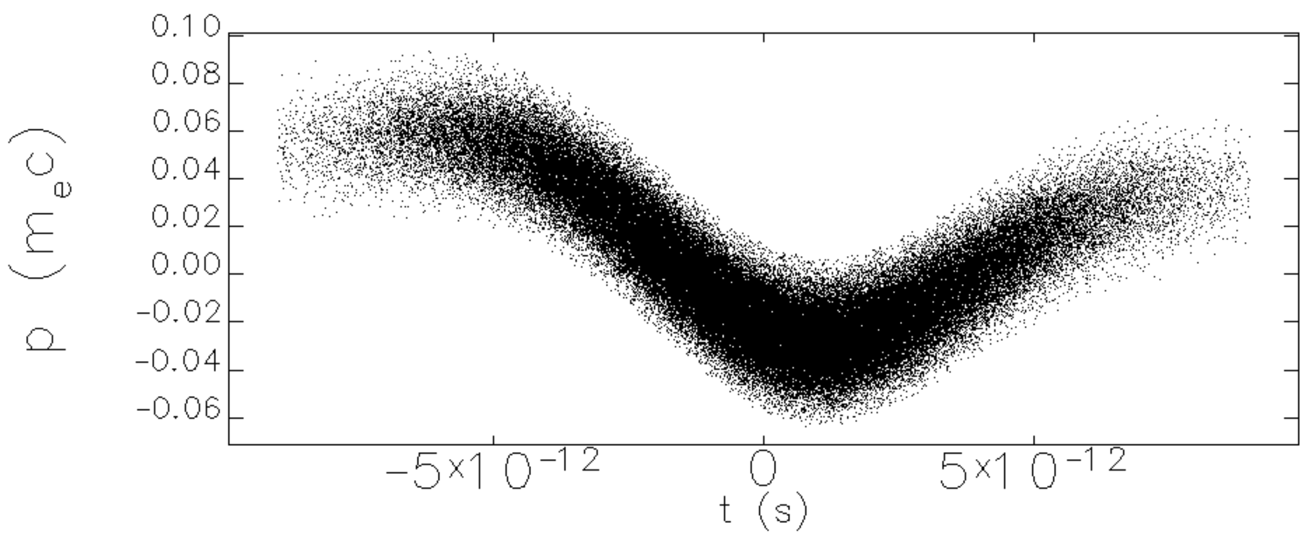


end of arc



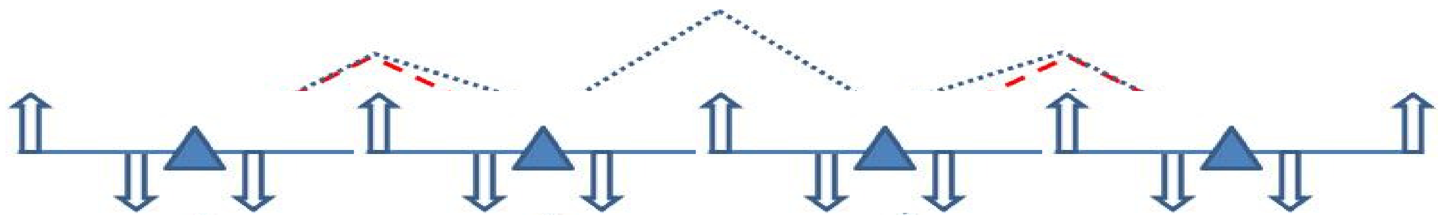
Longitudinal Phase Space



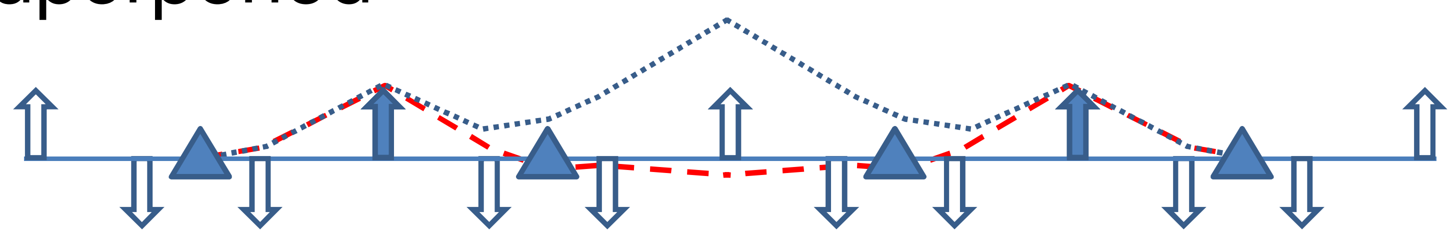


Second (High Energy) Example

- CEBAF superperiod

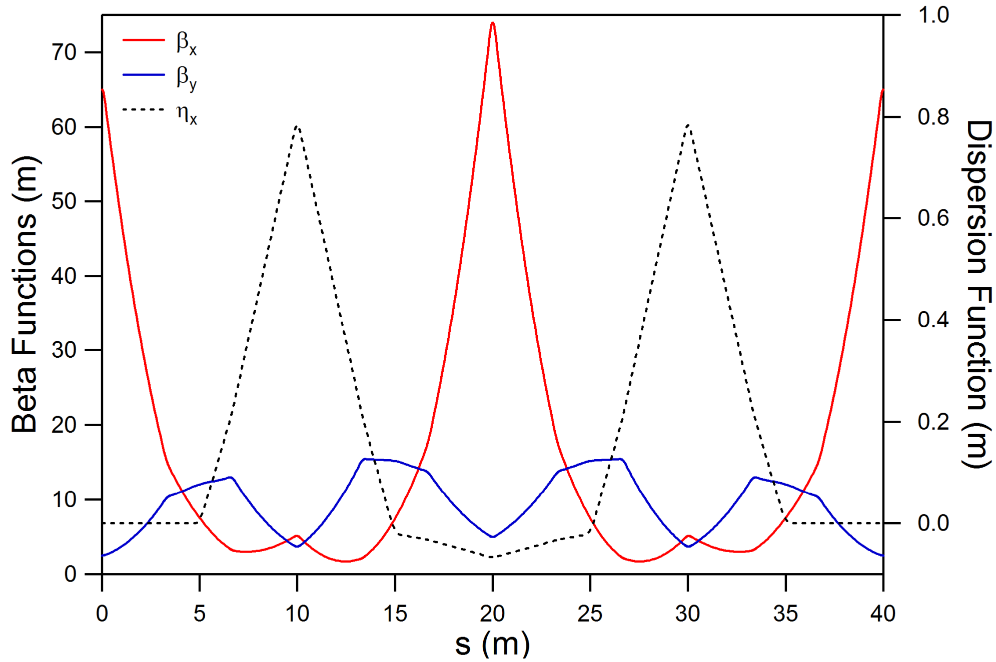


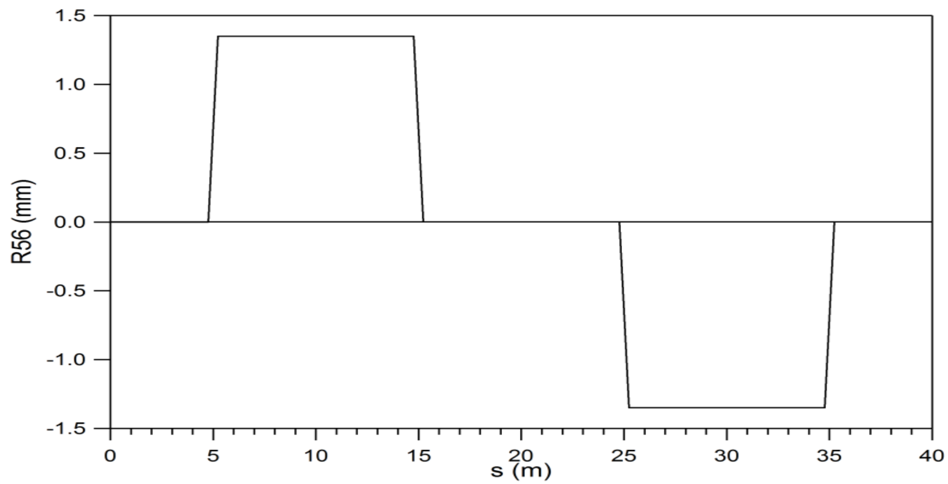
- Modified CEBAF recirculation arc superperiod



- 4 or 6 superperiods => 2^{nd} order achromat

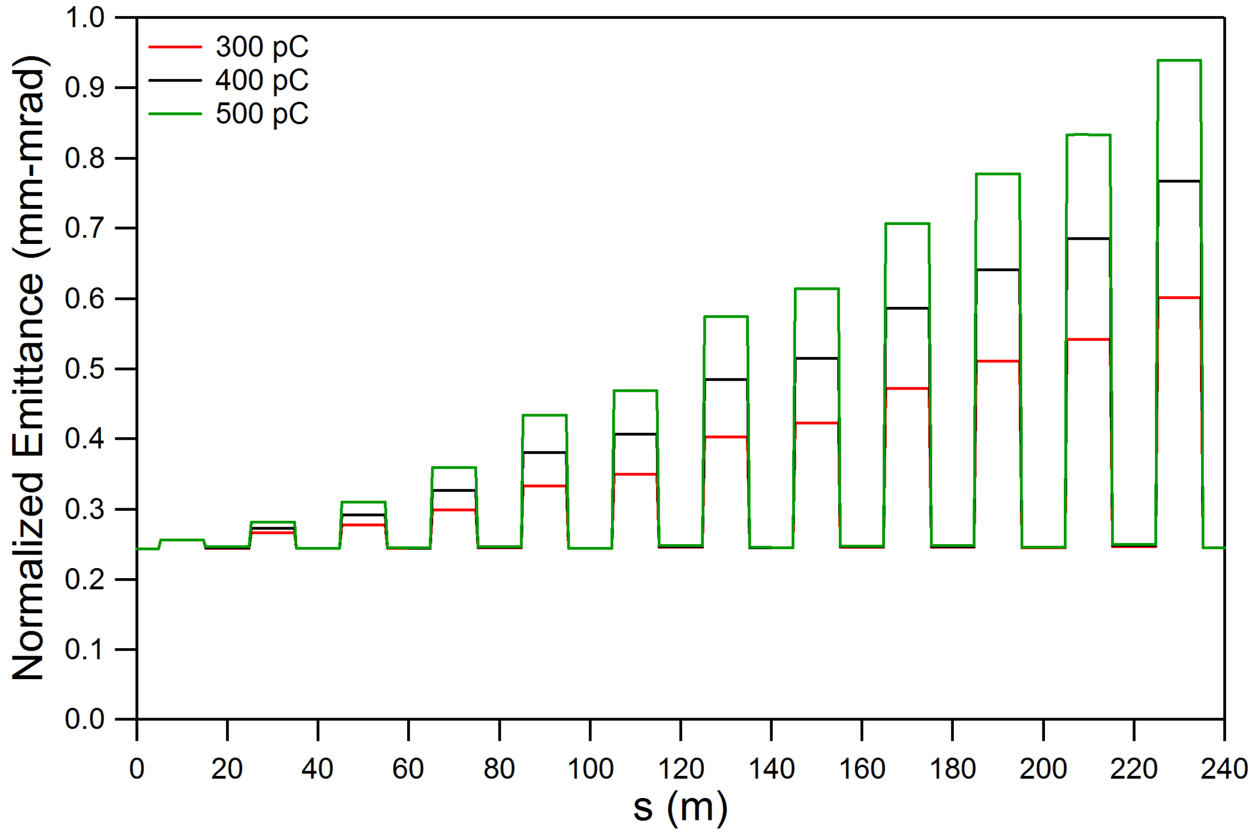
Supercell – Periodic Arc



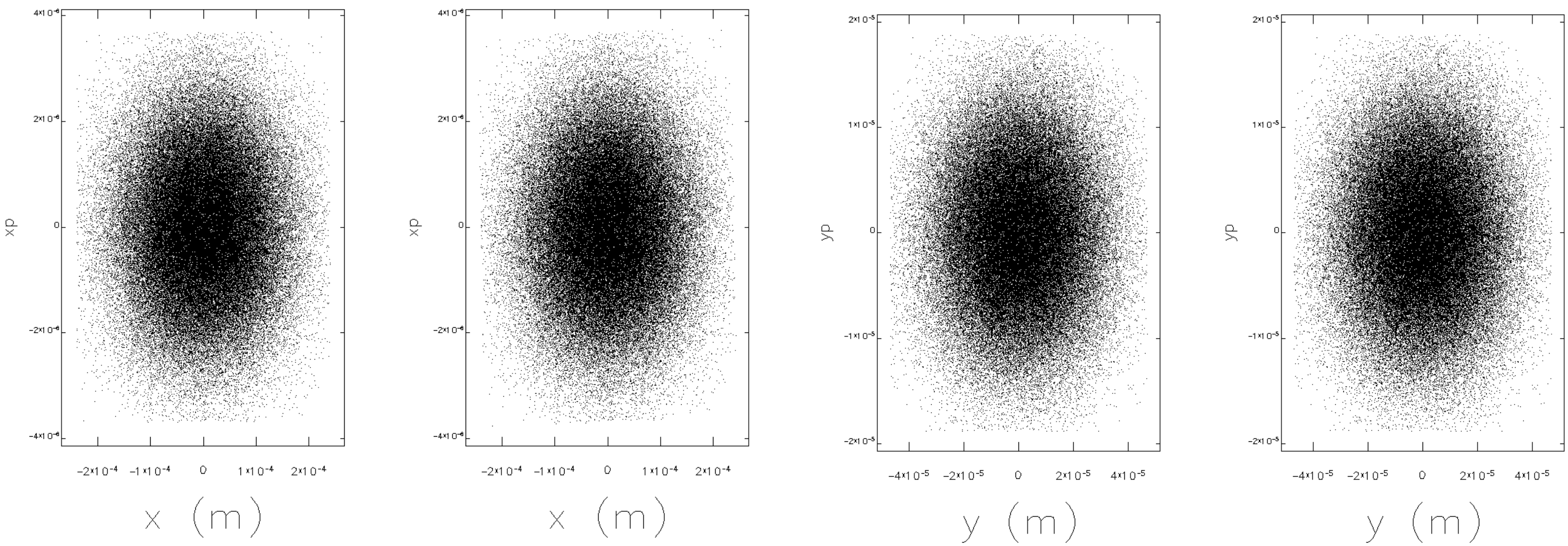


Propagated Emittance vs. Charge

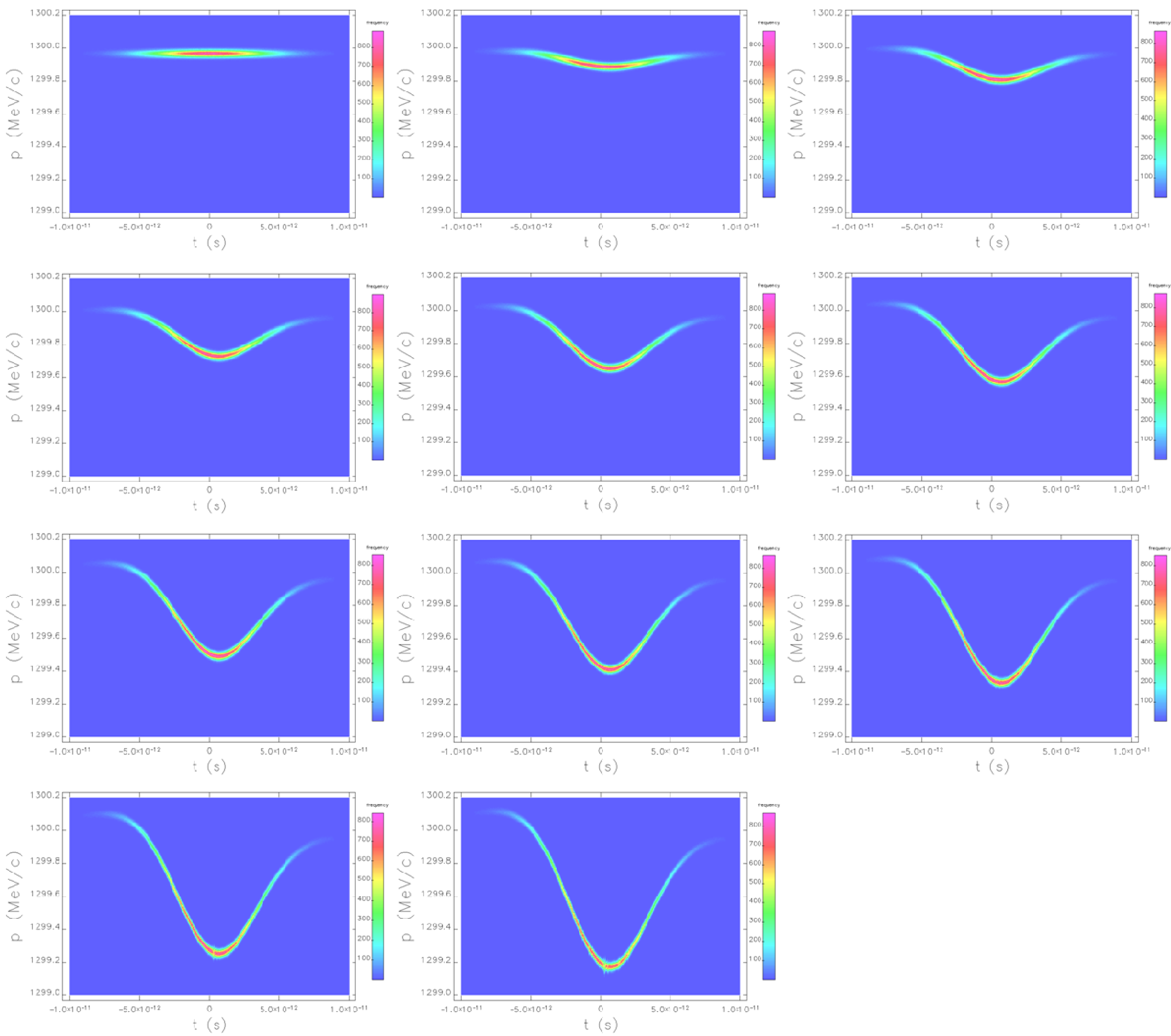
- E = 1300 MeV
- Q_b = 300, 400, 500 pC
- $\varepsilon_x = \varepsilon_y$ = 0.25 mm-mrad
- 3 psec x 11.67 keV (upright) longitudinal



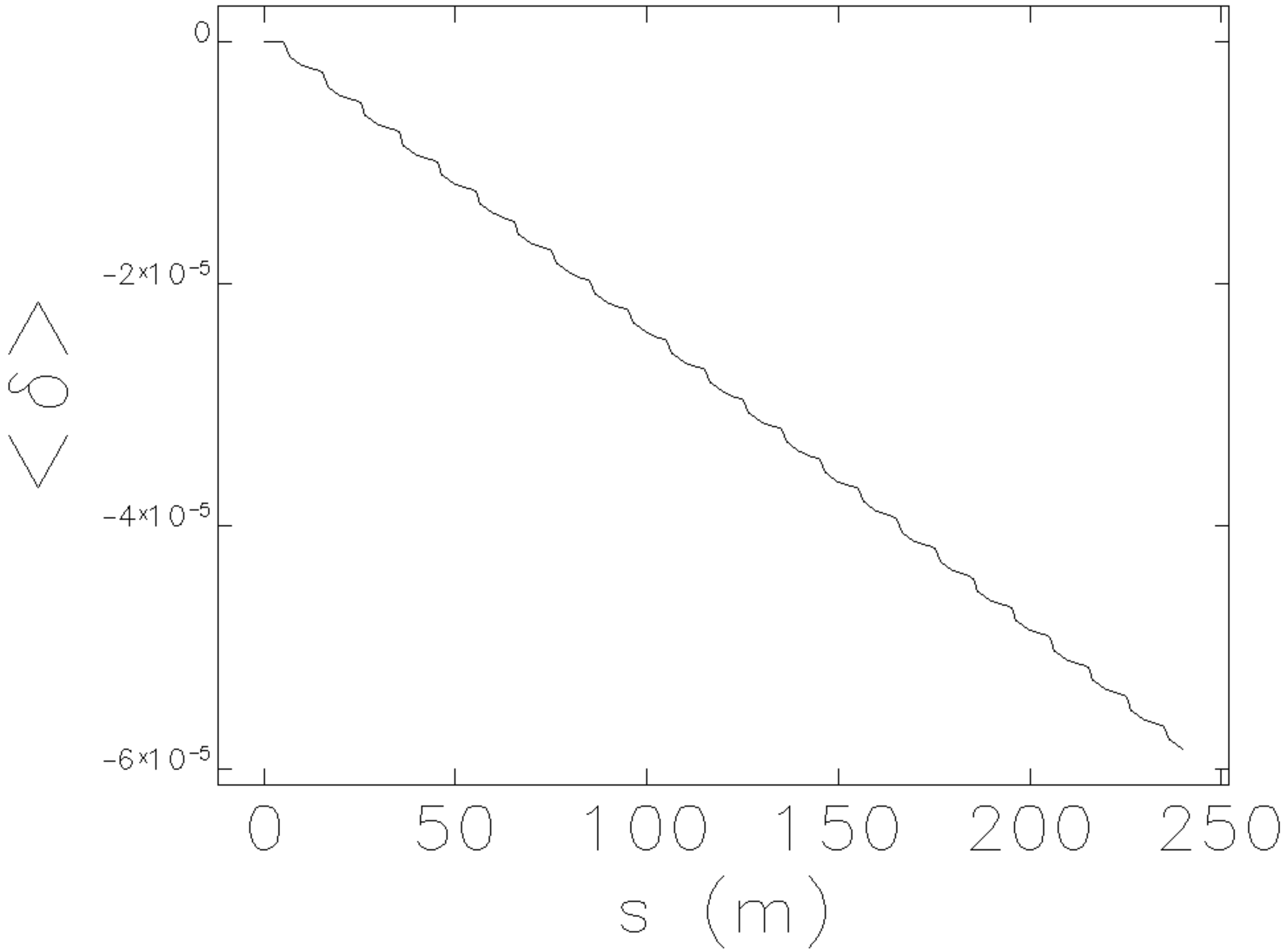
Transverse Phase Space at 300 pC



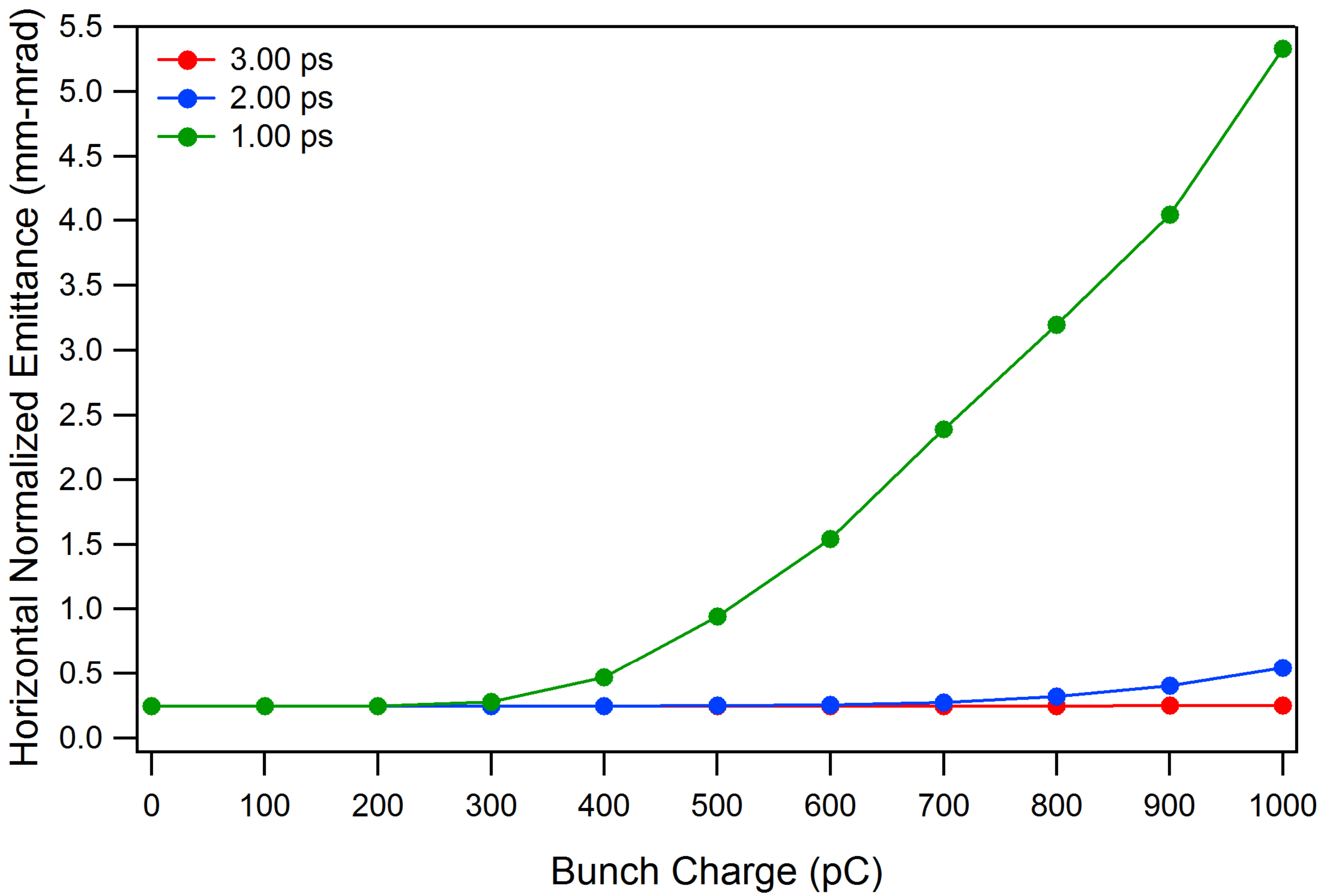
Longitudinal Phase Space vs. Charge (0, 100, 200, …. pC)



Energy Loss to ISR+CSR at 300 pC



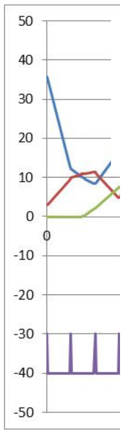
Emittance vs. Charge at Various Bunch Lengths

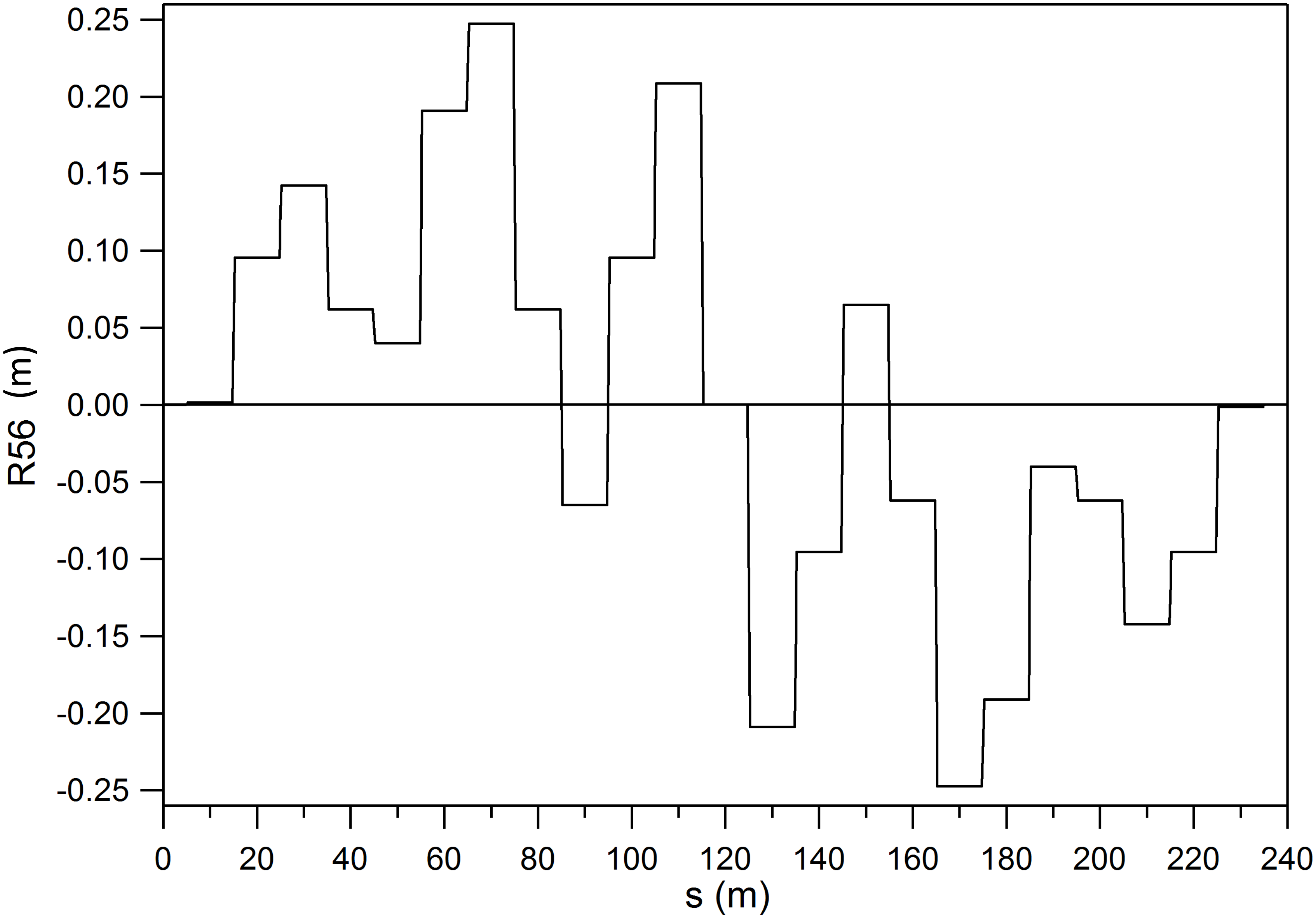


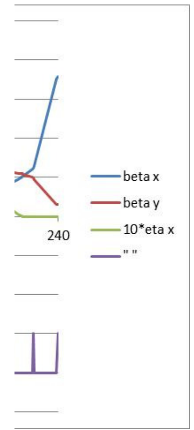
What about μBI?

- Initial simulations of recirculation with periodically isochronous/achromatic 2nd order achromat exhibited few effects
- Notional comparison of MEIC CCR to test arc: large R_{56} oscillations in CCR ⇔ small in test arc => possible mechanism?
- Retuned test arc to retain same global longitudinal & similar local betatron behavior - *but with large internal dispersion and R_{56} oscillations…* **observed significant μB!**

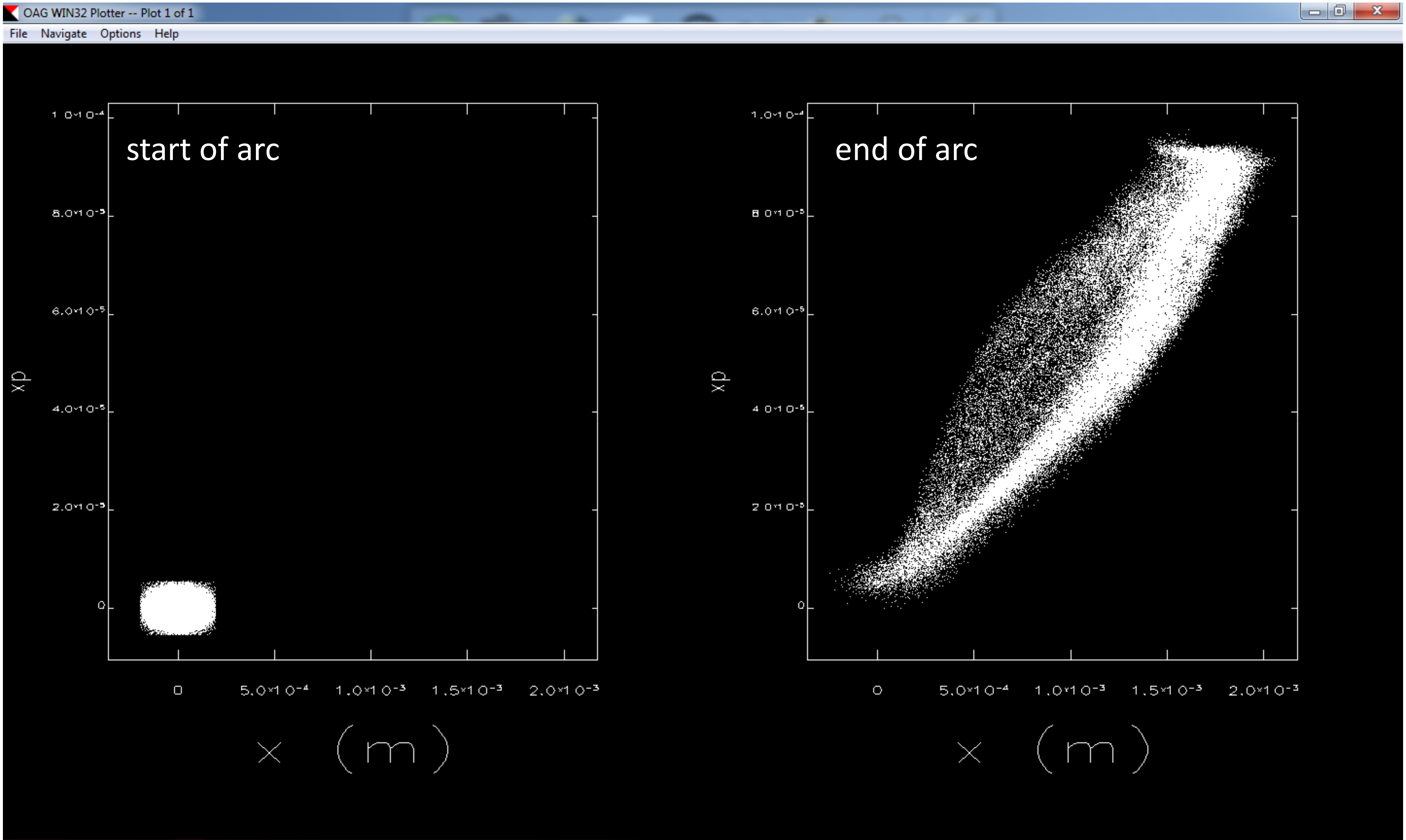
Aperiodic Test Arc



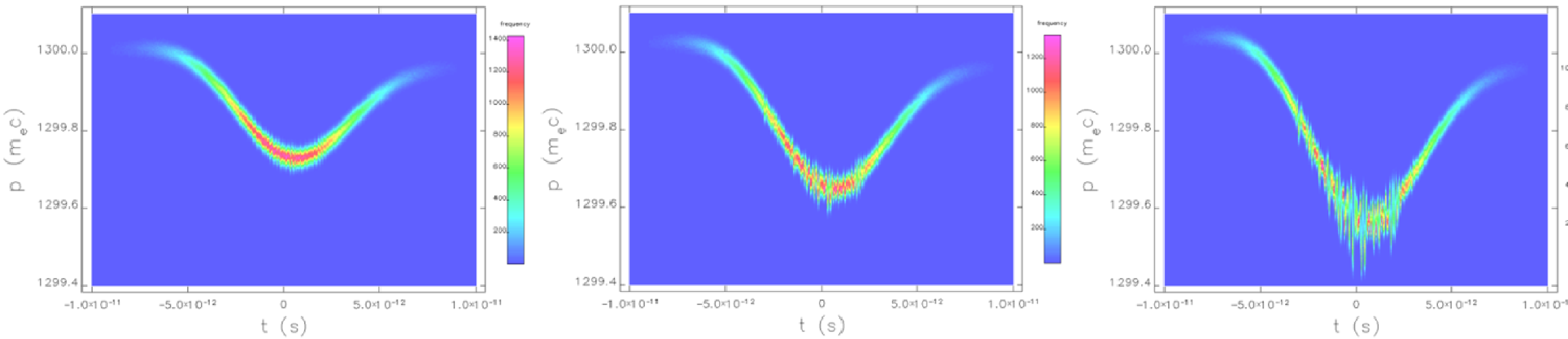




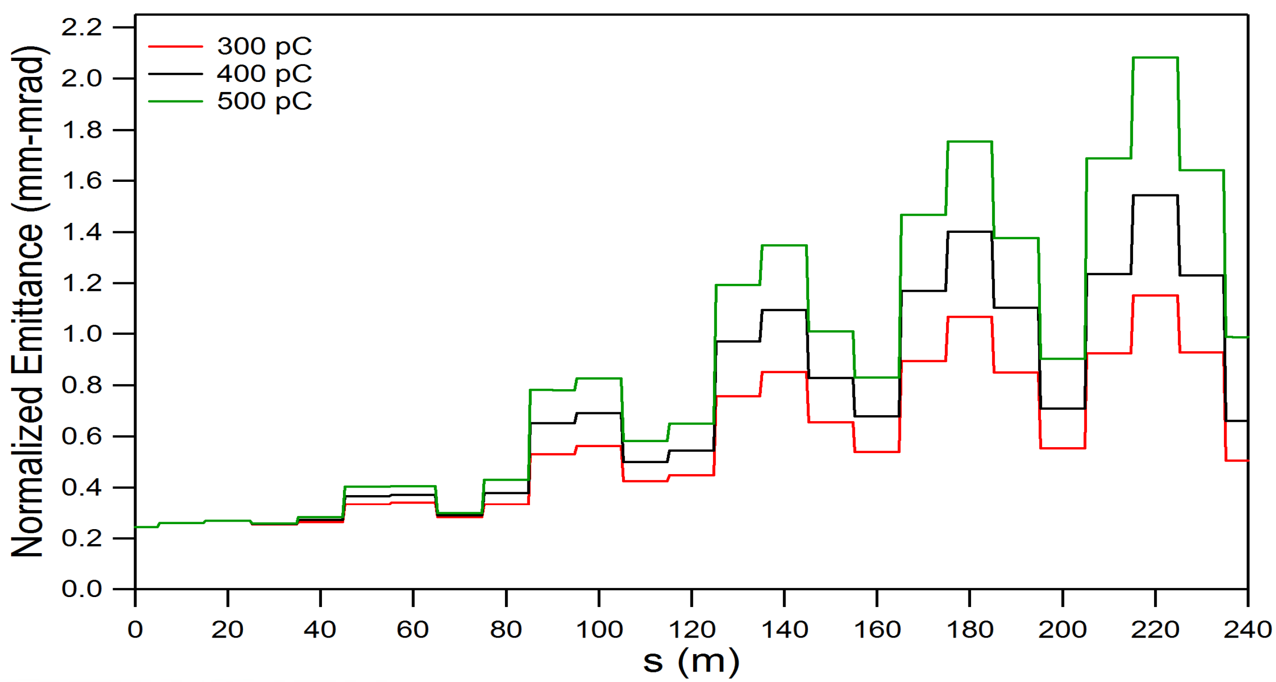
Aperiodic Arc: Horizontal Phase Space



Longitudinal & Emittance @ 300, 400, 500 pC



Transverse emittance



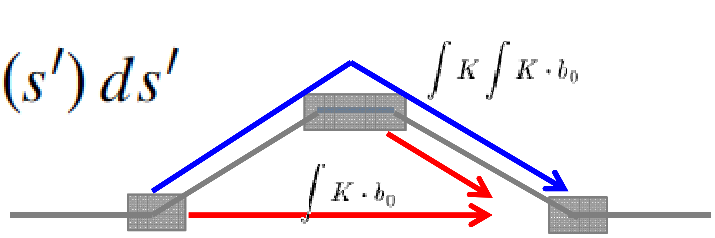
Analysis of Microbunching

- Three-way comparison of
  - CCR
  - periodic test arc
  - aperiodic test arc
- CCR, aperiodic test arc both are
  - achromatic & isochronous
  - Large R_{56} oscillations
- Periodic test arc is
  - 2^{nd} order achromat
  - individually isochronous & achromatic superperiods
  - Small R_{56} oscillations
- Large R_{56} ⇔ μBI; small R_{56} ⇔ no μBI
- Analysis of μB gain consistent with observations: period arc has small gain, other two have large gain

Theoretical background

- **Linearized Vlasov equation**
  - S. Heifets, G. Stupakov and S. Krinsky, PRST-AB **5**, 054402 (2002), Z. Huang and K. Kim, PRST-AB **5**, 074401 (2002)

$$g_k(s) = g_k^{(0)}(s) + \int_0^s K(s,s')g_k(s')\,ds'$$



- The **iterative** solutions give

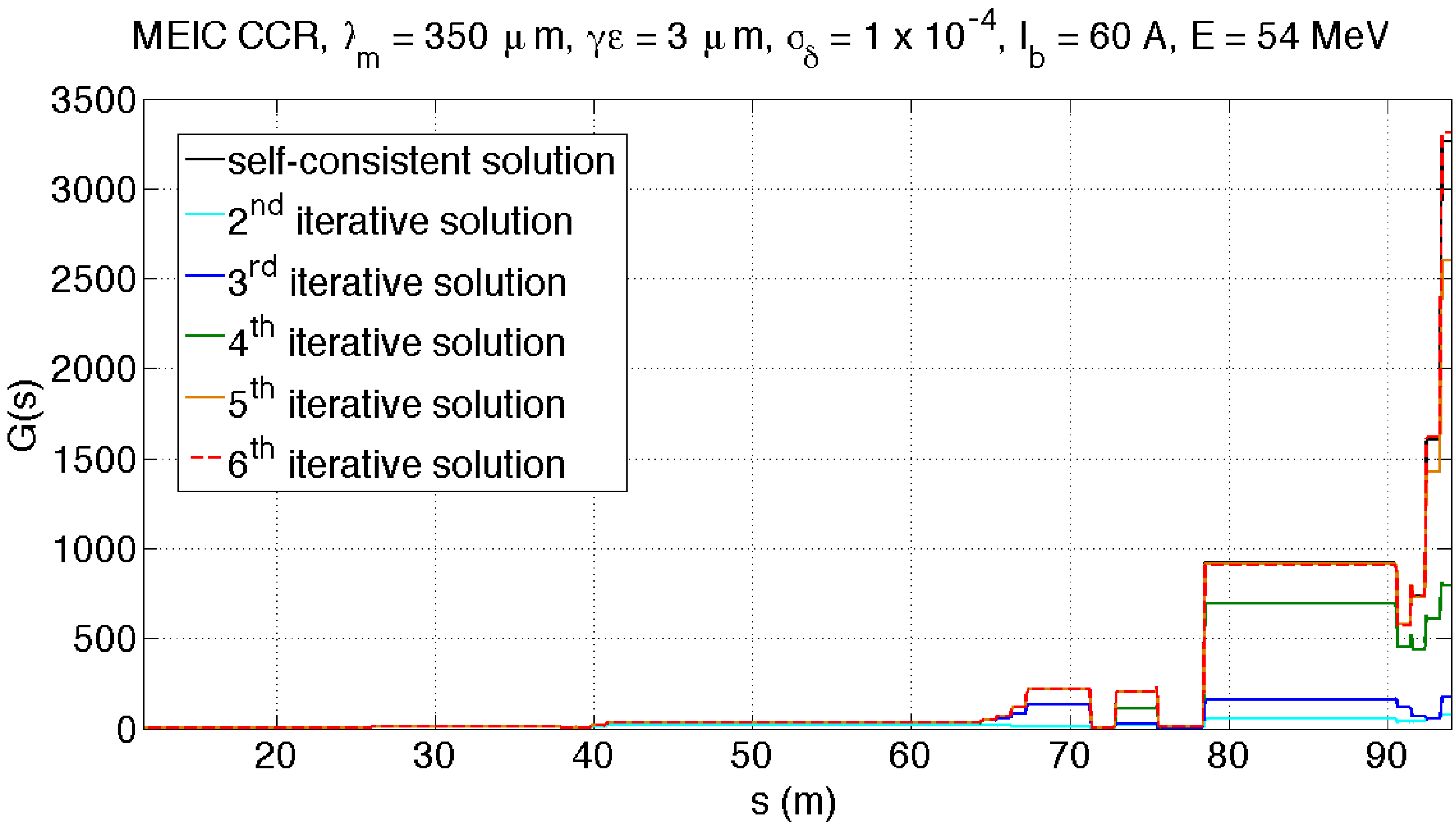
$$g_k^{(1)}(s) = g_k^{(0)}(s) + \int_0^s K(s,s')g_k^{(0)}(s')ds' \equiv (1+\mathbf{K})g_k^{(0)}(s)$$

$$g_k^{(2)}(s) = (1+\mathbf{K}+\mathbf{K}^2)g_k^{(0)}(s)$$

…

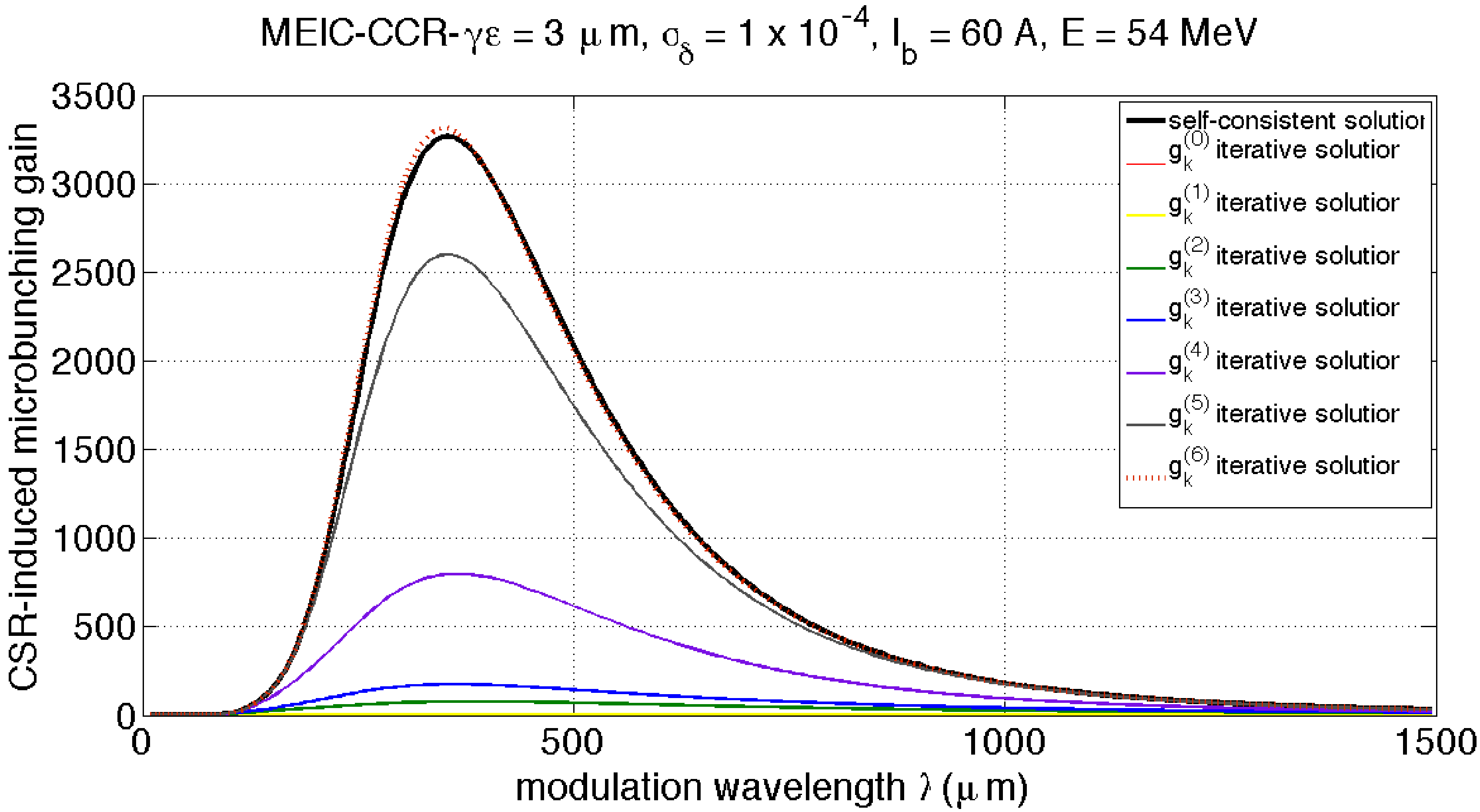
$$g_k(s) = \cdots = (1+\mathbf{K}+\mathbf{K}^2+\mathbf{K}^3+\cdots)g_k^{(0)}(s) = (1-\mathbf{K})^{-1}g_k^{(0)}(s)$$

MEIC CCR – gain function



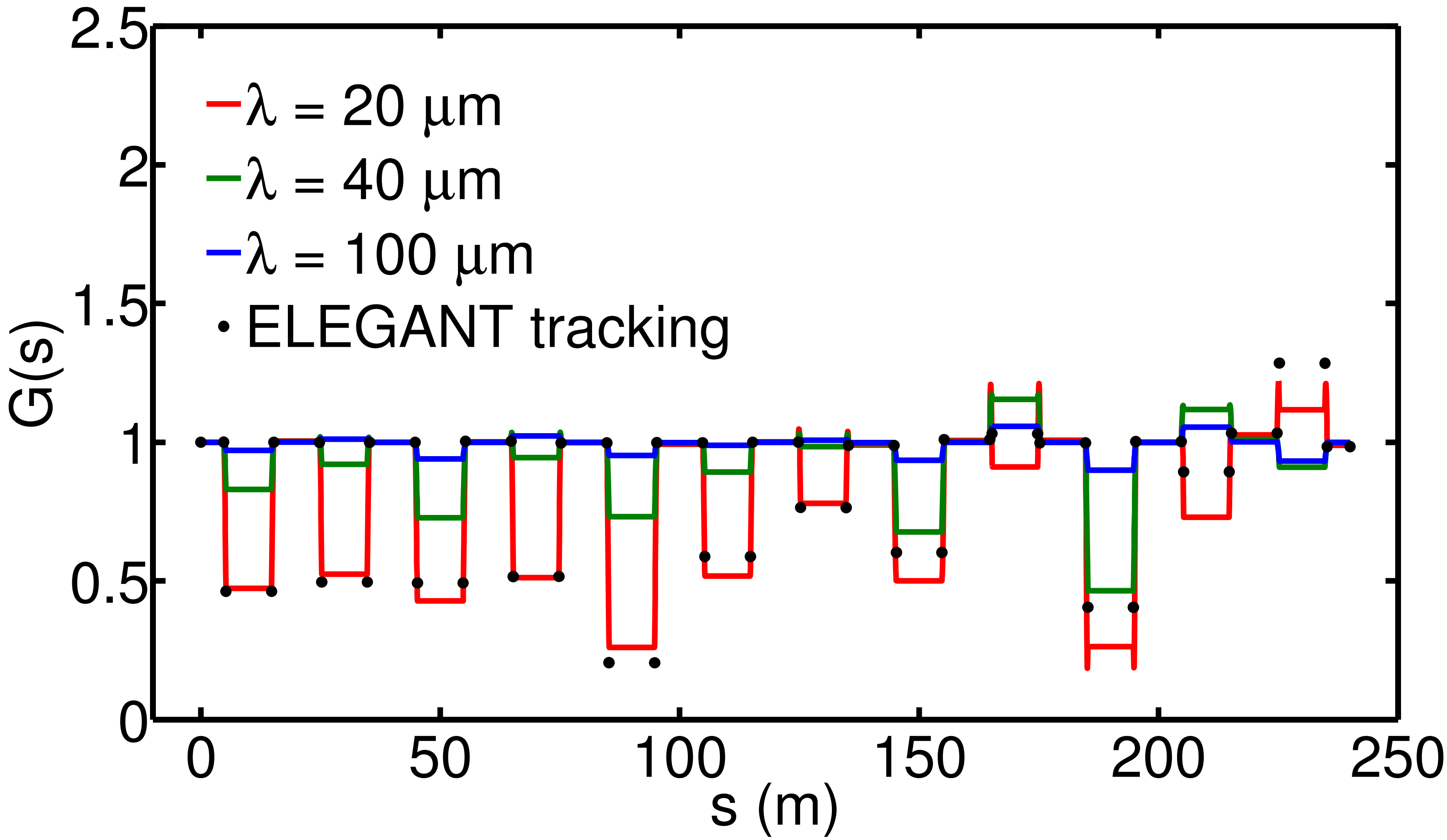
CSR-induced gain evolution for MEIC Circulator Cooling Ring, obtained by solving linearized Vlasov equation for specific modulation wavelength 350 μm.
It is seen that CSR gain may change within dipoles and keeps constant outside dipoles.

MEIC CCR – gain spectrum

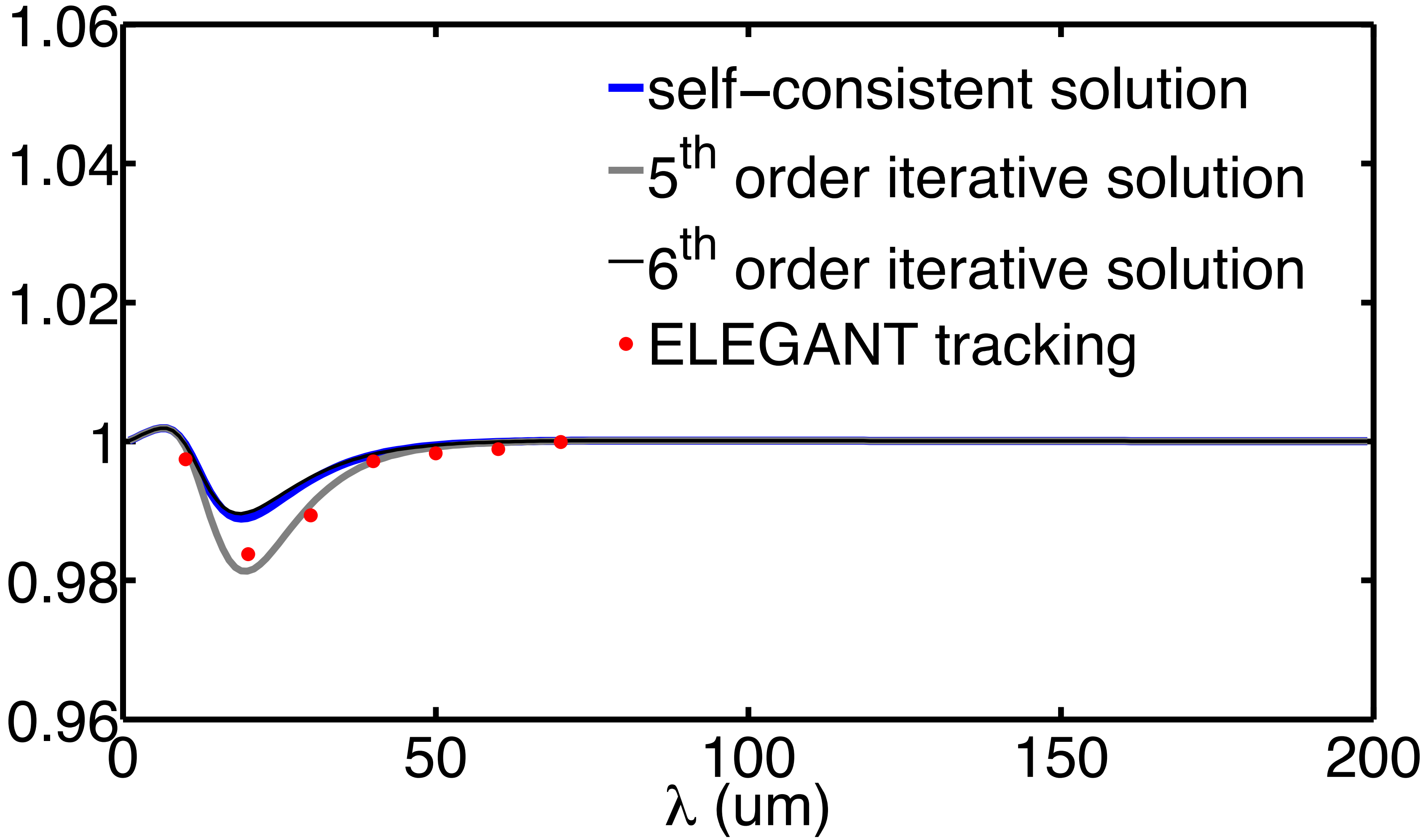


Comparison of CSR-induced spectral gains, obtained by self-consistent and iterative approaches. As shown, 6th order iterative solution (i.e. up to 6th staged amplification) dominates the microbunching amplification mechanism.

Periodic TEST ARC – Gain

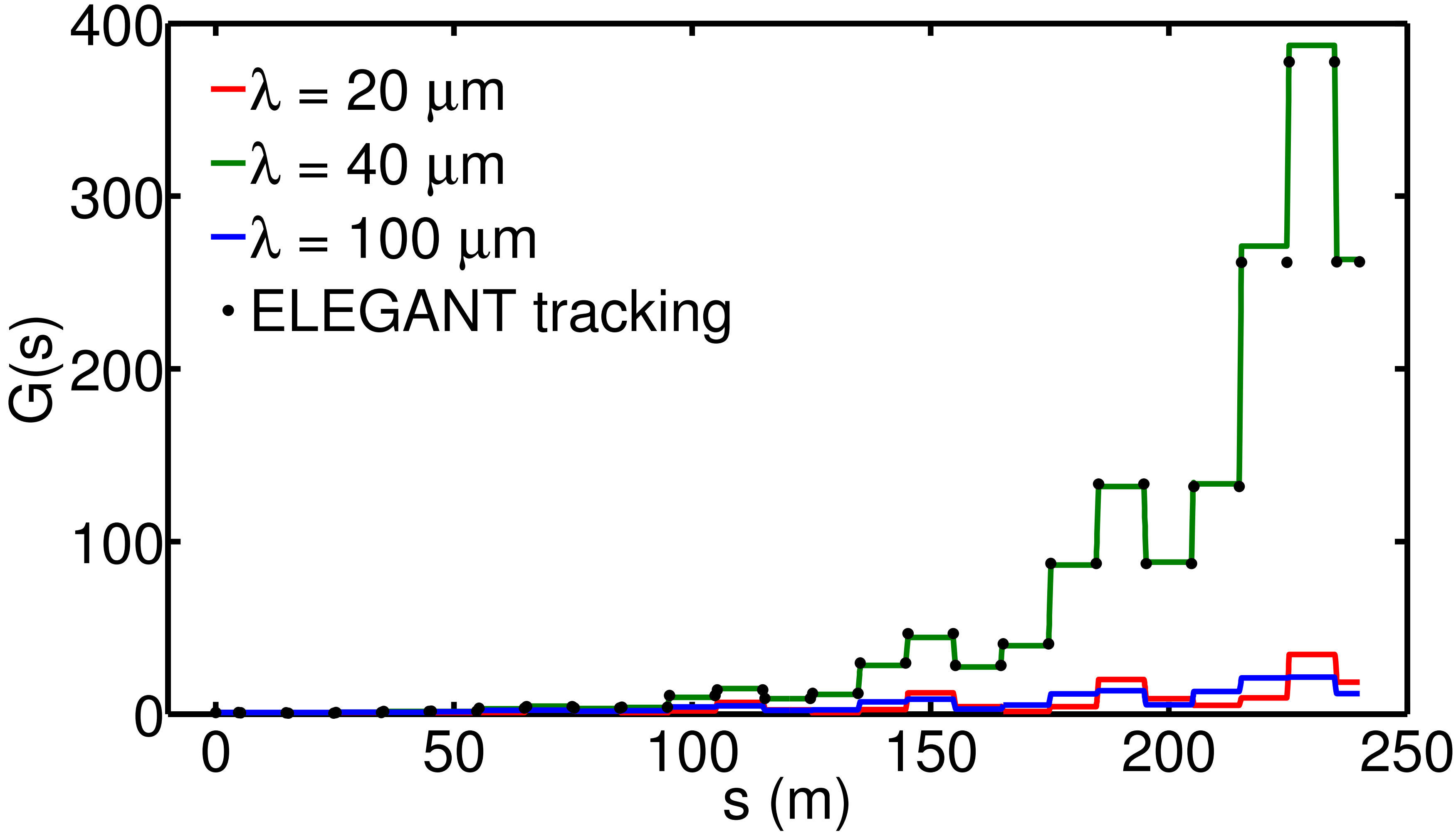


Periodic TEST ARC – spectrum

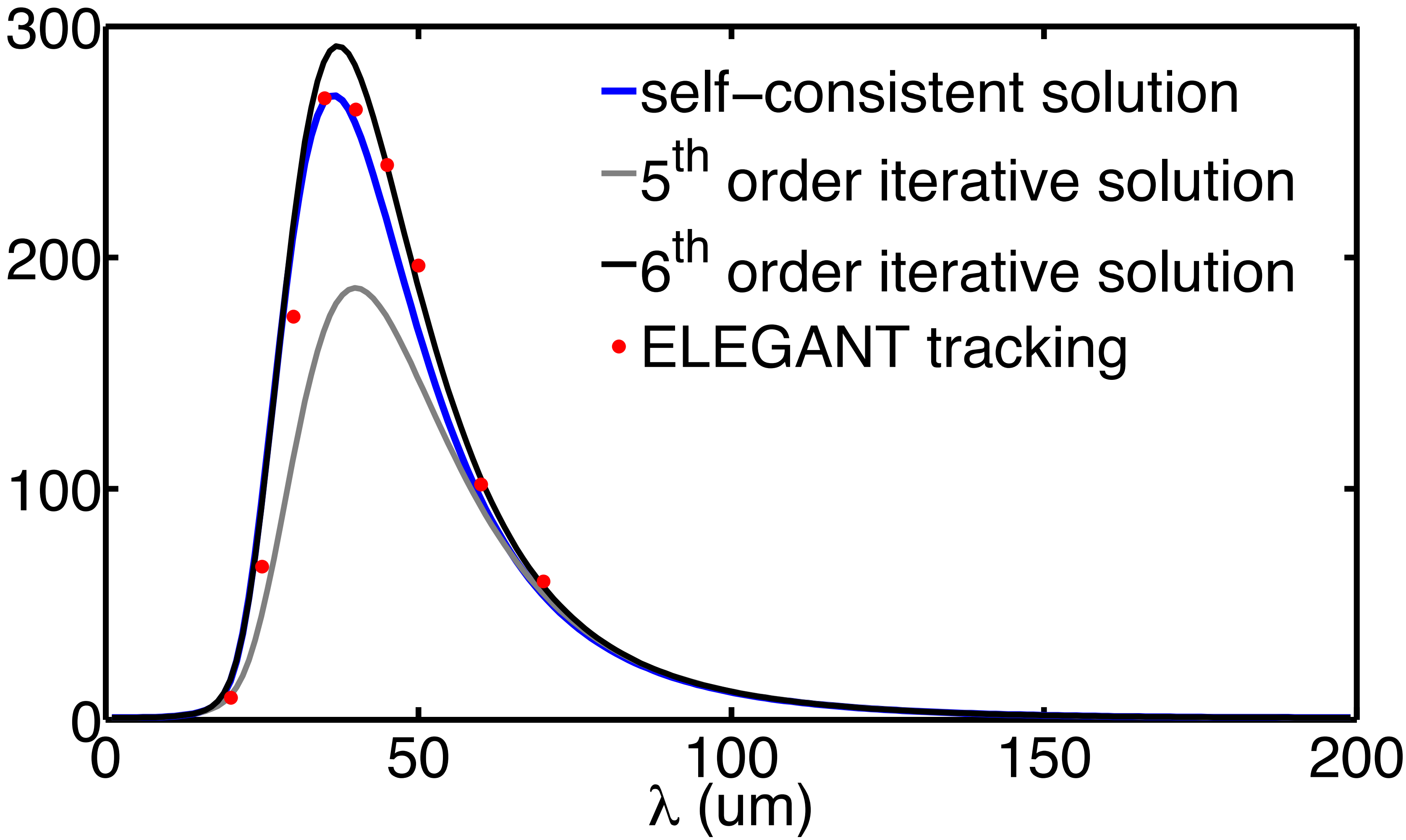


The overall gain is around 1, not subject to CSR microbunching instability.

Aperiodic TEST ARC – gain



Aperiodic TEST ARC – spectrum



It can be seen that 6th-order iteration (6-staged amplification) can roughly describe the whole mechanism.

Conclusions

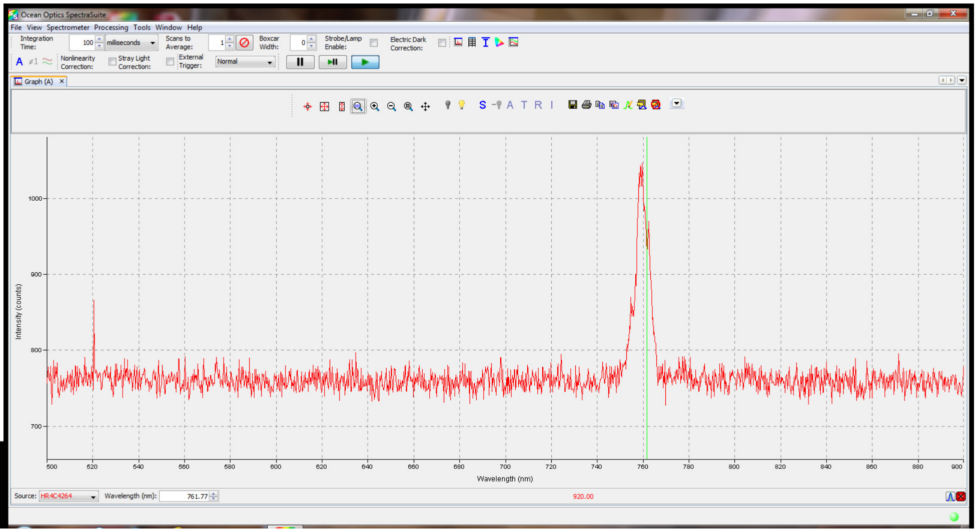
- Can recirculate bright/high charge beam & preserve quality
- Longitudinal distortions unavoidable – but can be managed in the same way as lattice aberrations
  - Slope, curvature, torsion corrections with quads, sextupoles, octupoles…
- Many potential applications
  - Recirculated/ERL drivers for FELs
  - Linac/ring EICs
  - Magnetic correction of RF curvature
  - Positive compaction compressors
- Status:
  - Applying to MEIC CCR design
  - Test in CEBAF in planning stages

Positive Compaction Compressor

- Can we extend these methods to compressors & avoid μBI?
- Key elements of CSR control methods:
  - reduce driving terms
    - Small angles, radii, long bunch, small compaction modulation…
  - reduce lattice response
    - Small lattice functions, dispersion, strong focusing…
  - match downstream acceptance to degraded output
  - introduce symmetries that generate emittance compensation
- Proper "balance" of elements can suppress effects in compressors
  - *increase* driving terms & *manage* lattice response when CSR effects are small, and use resulting distortions to induce emittance compensation of distortions generated during final bunching
- Use of $M_{56}>0$ (accelerating on falling side of RF waveform) can simplify this process
  - Avoids parasitic cross-over in penultimate dipole
  - Allows use of conventional arc (nice for recirculation)
    - Provides lots of symmetry/simplifies optics balance
  - Gives a "back door" to escape LSC/CSR effects

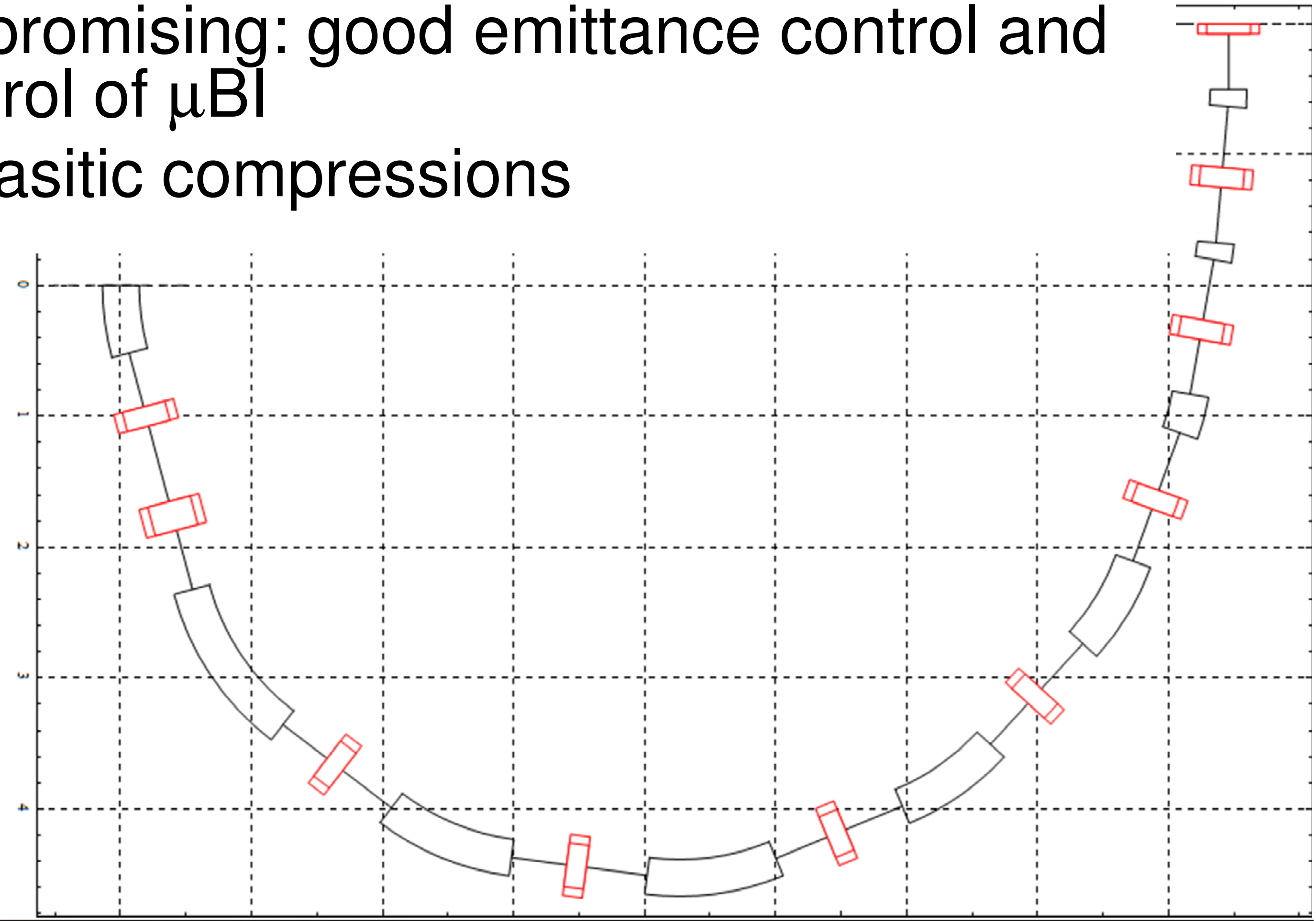
Test of Lasing with M_{56}>0

- JLab UV ERL has robust control over ϕ_{linac}, M_{56}, T_{566}
- As (half-shift) test of concept:
  - Accelerated on falling side of waveform
  - Switched signs of compactions (eliminating one parasitic compression)
  - Set up with energy recovery
  - Lased
- Lasing was challenged by fact that wiggler gap control software unavailable; wavelength "stuck" at value for which optical cavity mirrors performed poorly (50+% losses)
  - "high" reflector had higher transmission than outcoupler
  - required >200% single-pass gain just to lase
- Lased ***well***; after optimization:
  - 762 nm
  - 10-11 μm detuning curve (typical)
  - 9.5-10 μsec turn-on time (<10 μsec typical)

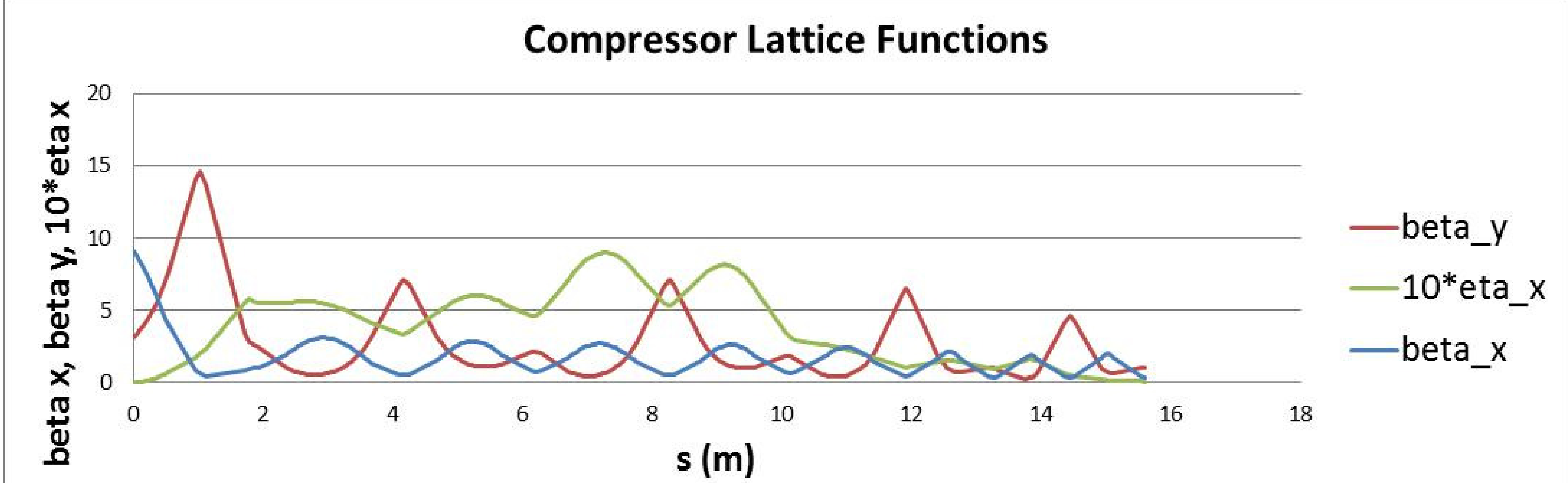


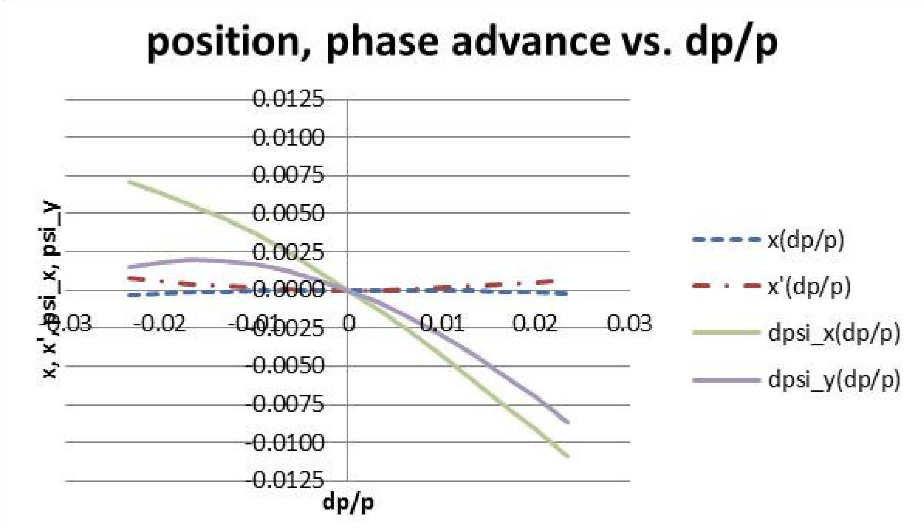
Arc Compressor

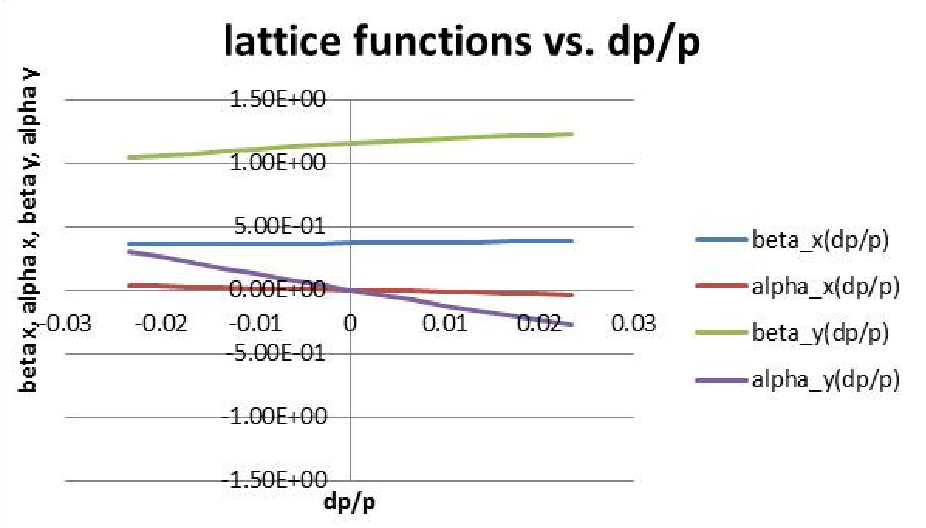
- Use same "optics balance" as when recirculating
  - "bend hard early, soft at end" to produce constructive interferences in phase space distortion
- Initial results promising: good emittance control and apparent control of μBI
- Avoids all parasitic compressions



Lattice Functions, Momentum Scan



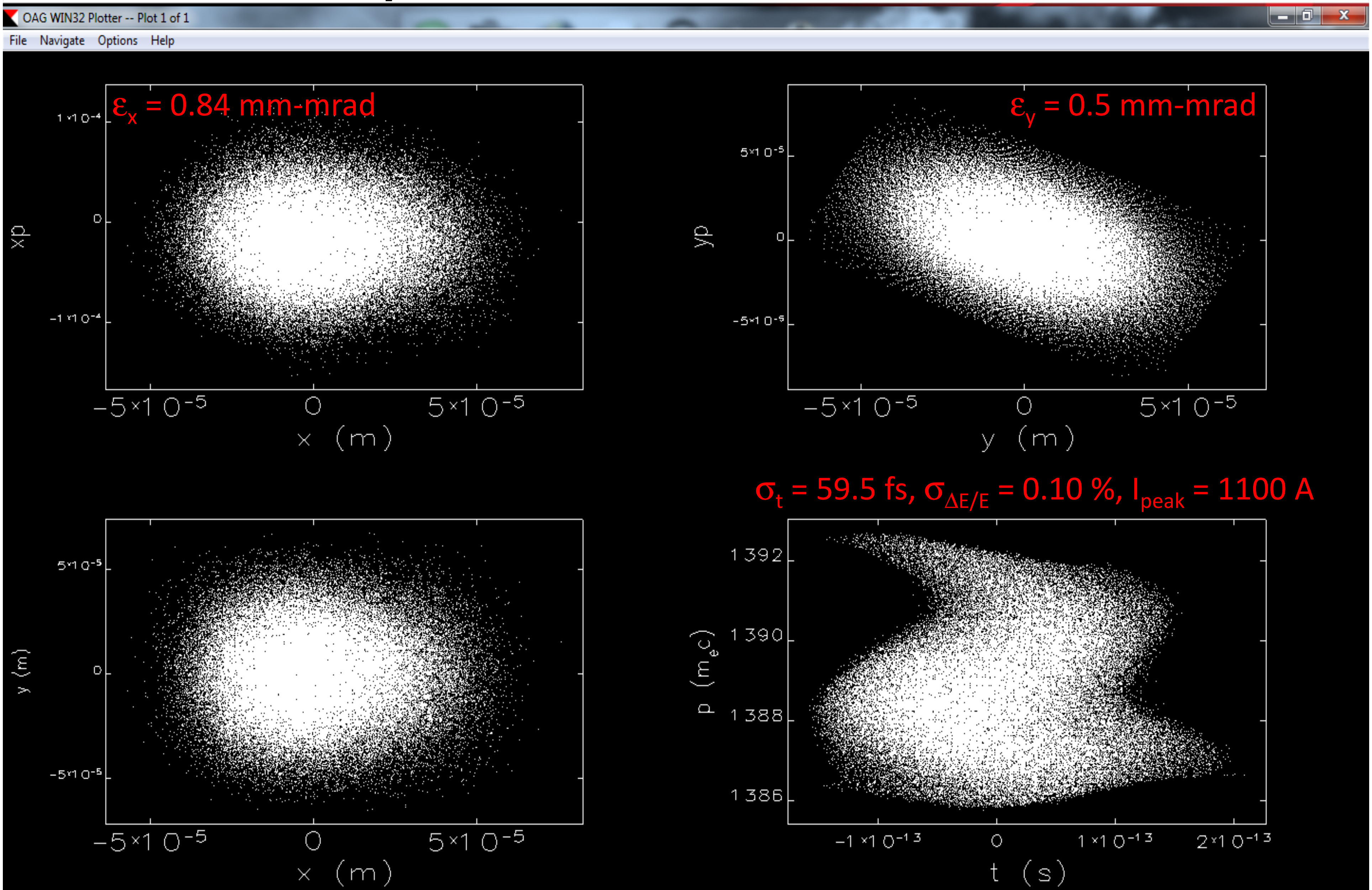




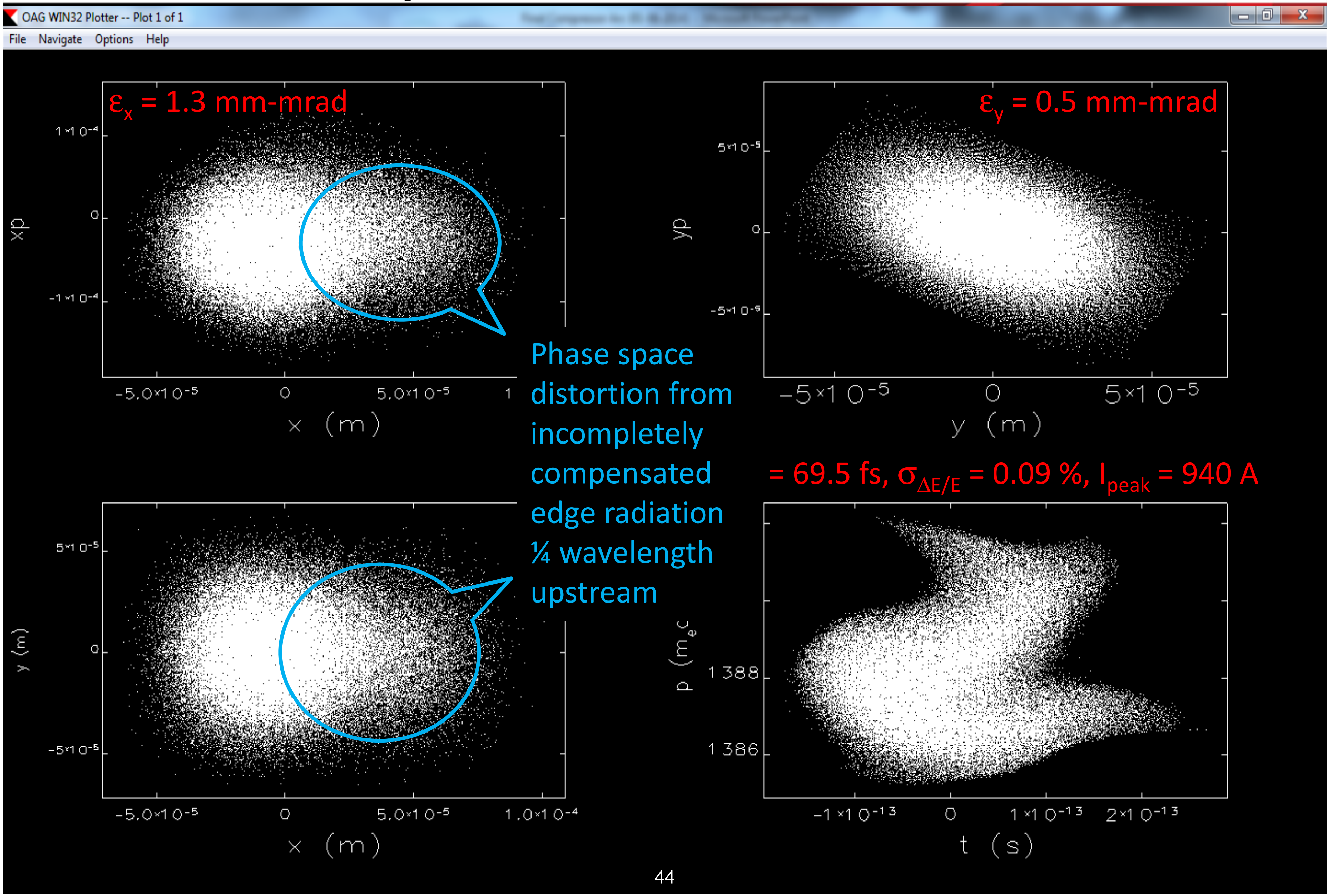
Simulations of Compression with CSR

- Very good suppression with only roughly optimized system
- Working to optimize with CSR drifts
  - Systematic effect – simulated, but not yet included in the design optimization
  - Will use similar compensation scheme:
    - Enhance effect early on, suppress toward end, use phase advance/betatron match/lattice functions to generate interference/emittance compensation

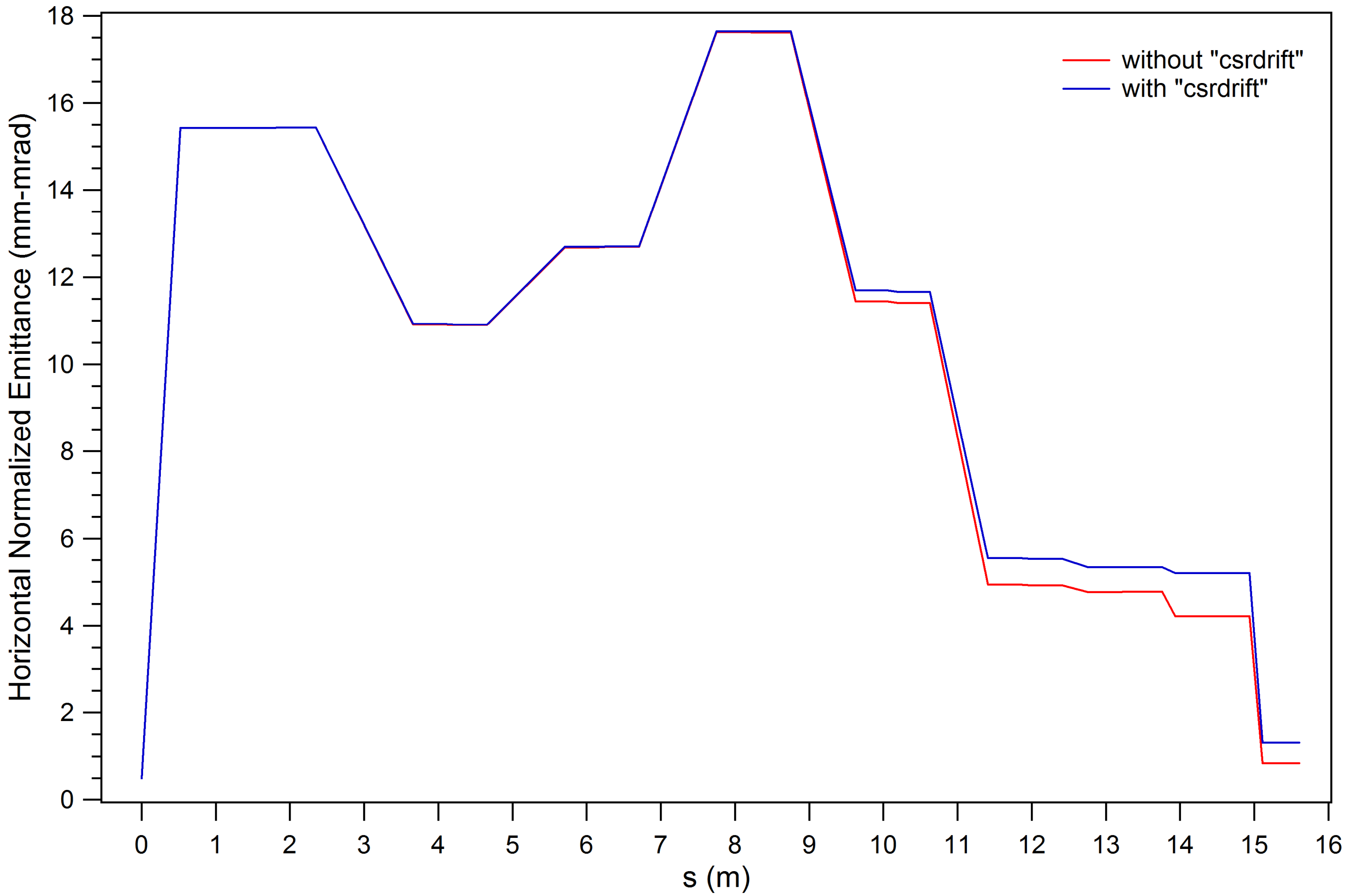
Phase Space at Arc Exit (without *csrdrifts*)



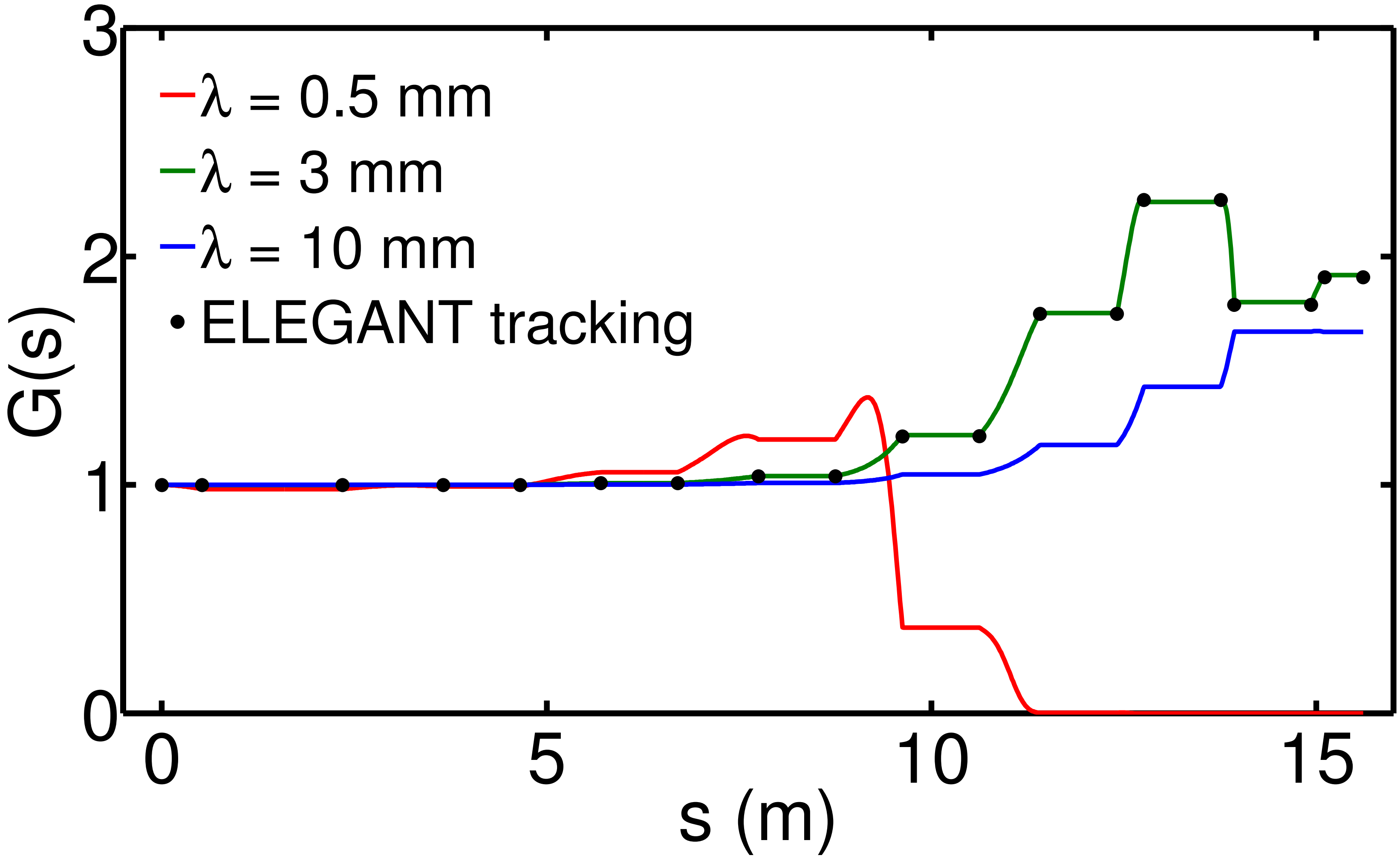
Phase Space at Arc Exit (with *csrdrifts*)



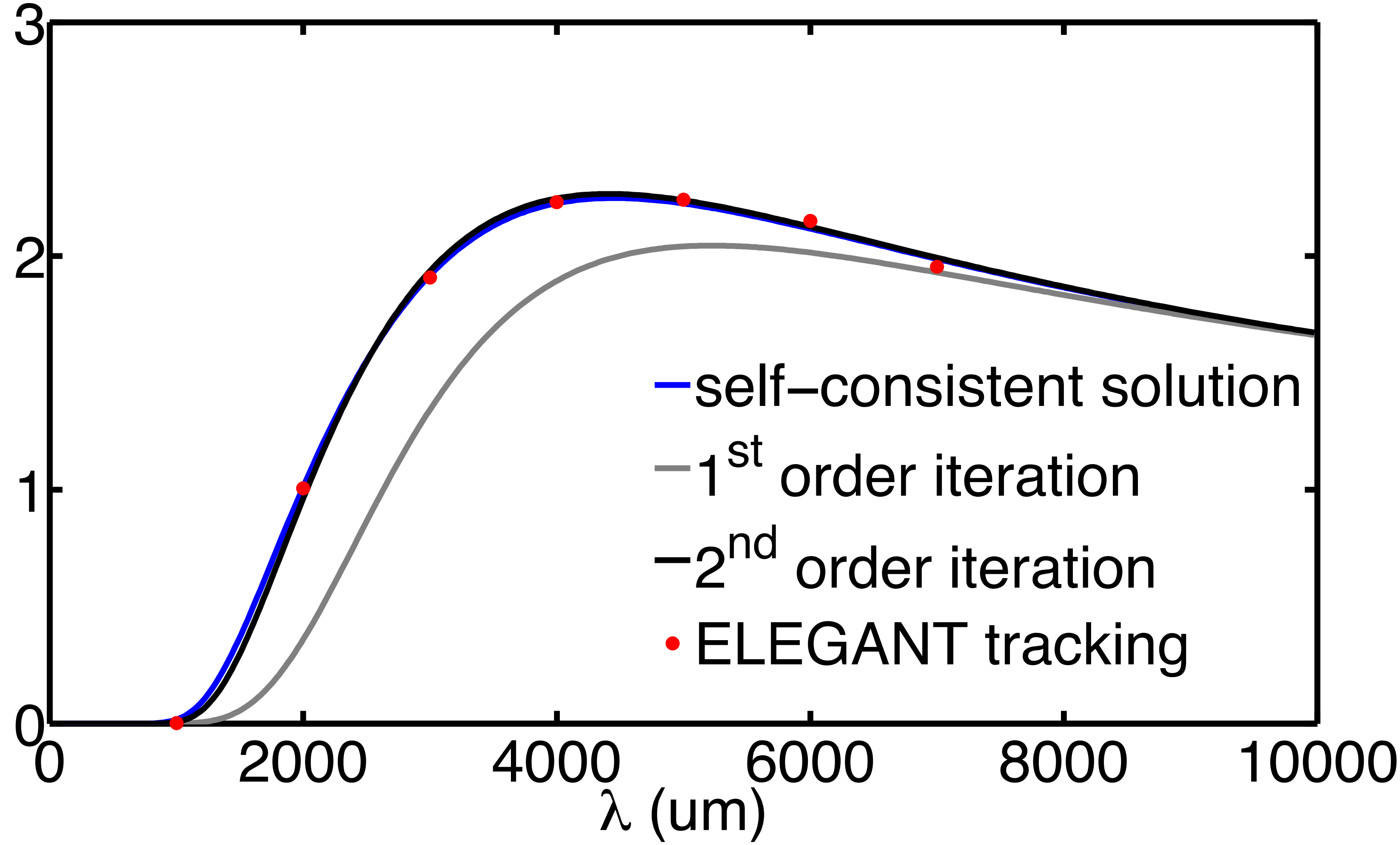
Emittance Evolution



Microbunching Gain is Low



Microbunching Spectrum



Preliminary Conclusions

- $M_{56}>0$ works in practice, may have advantages
- Optics balance can provide emittance compensation during compression (just like in well-designed chicane compressors)
- Wake signature on longitudinal phase space can be managed in same way as RF curvature, lattice aberrations

Acknowledgments

- Thanks to the organizers for the opportunity to discuss this with you
- Thank you for your interest and feedback
- Thanks to my co-authors their insights and activities, especially:
  - Chris Tennant for CSR simulations,
  - Cheng-Ying Tsai and Rui Li for μBI gain analysis,
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Backups

uBI gain analysis parameters

Table of parameters for 1.3 GeV TEST ARCs

Name	Example 1 large R_{56}	Example 2 small R_{56}	Unit
beam energy	1.3	1.3	GeV
bunch current	64	64	A
normalized emittance	0.3	0.3	μm
Initial beta function β_{x0}	35.81	65.0	m
Initial alpha function α_{x0}	0	0	
relative energy spread	1.23×10^{-5}	1.23×10^{-5}	
chirp	0	0	m^{-1}

Table of parameters for Compressor Arc

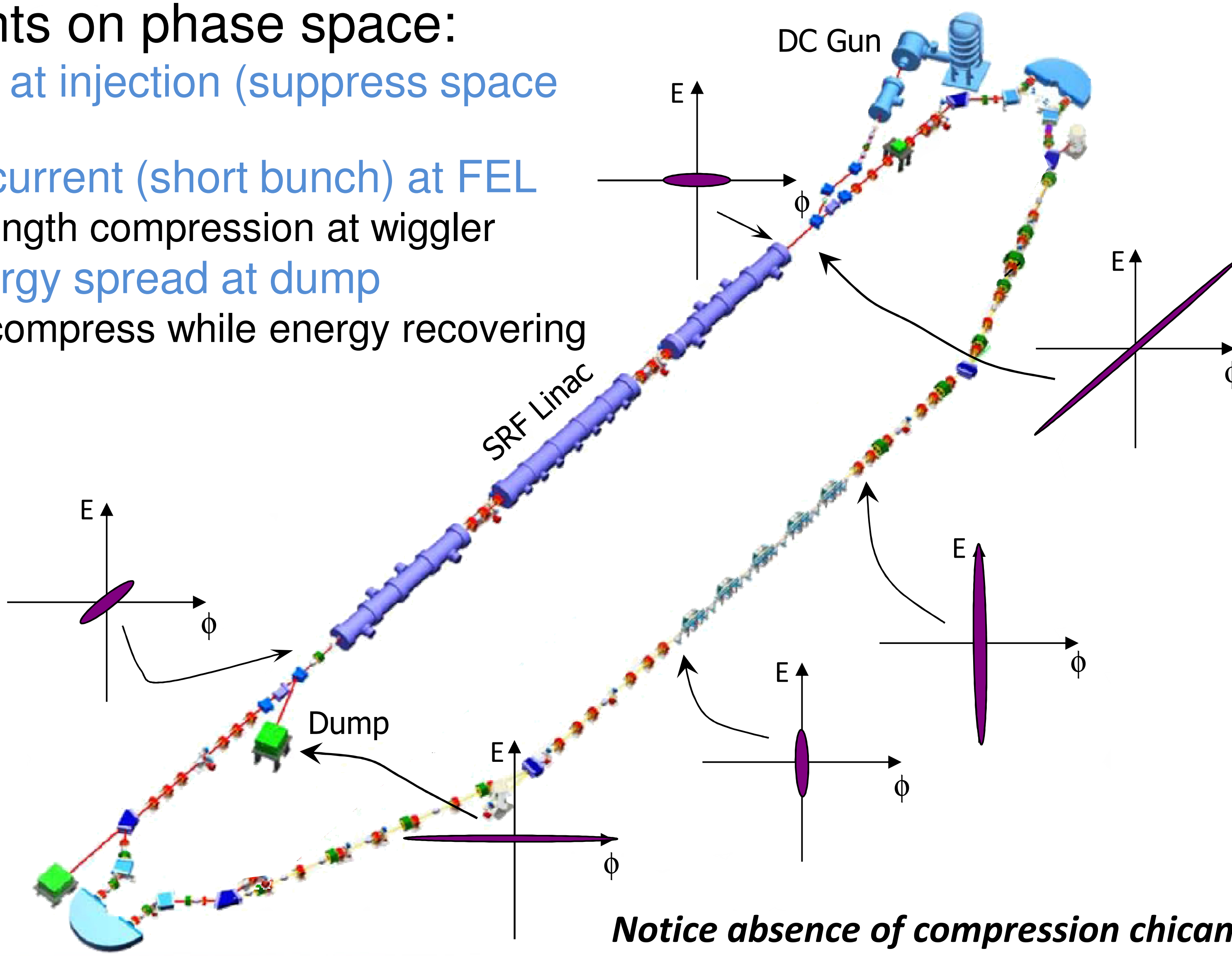
Name%	Value%	Unit%
beam energy	0.75	GeV
beam currents (before, after compression)	7.9 , 405	A
Initial beta function β_{x0}	9.059	m
Initial alpha function α_{x0}	3.7662	m
chirp	-0.635	m^{-1}
compressor factor	53.422	
dipole radius	2	m
total length of the arc	15.608	m
fractional energy spread (uncorrelated)	1.13×10^{-5}	
normalized transverse emittance	0.75	µm

Longitudinal Phase Space Linearization

Phase Space Management

Requirements on phase space:

- long bunch at injection (suppress space charge)
- high peak current (short bunch) at FEL
  - bunch length compression at wiggler
- “small” energy spread at dump
  - energy compress while energy recovering



Notice absence of compression chicanes

RF Curvature/Multistage Compression

Impact of RF curvature

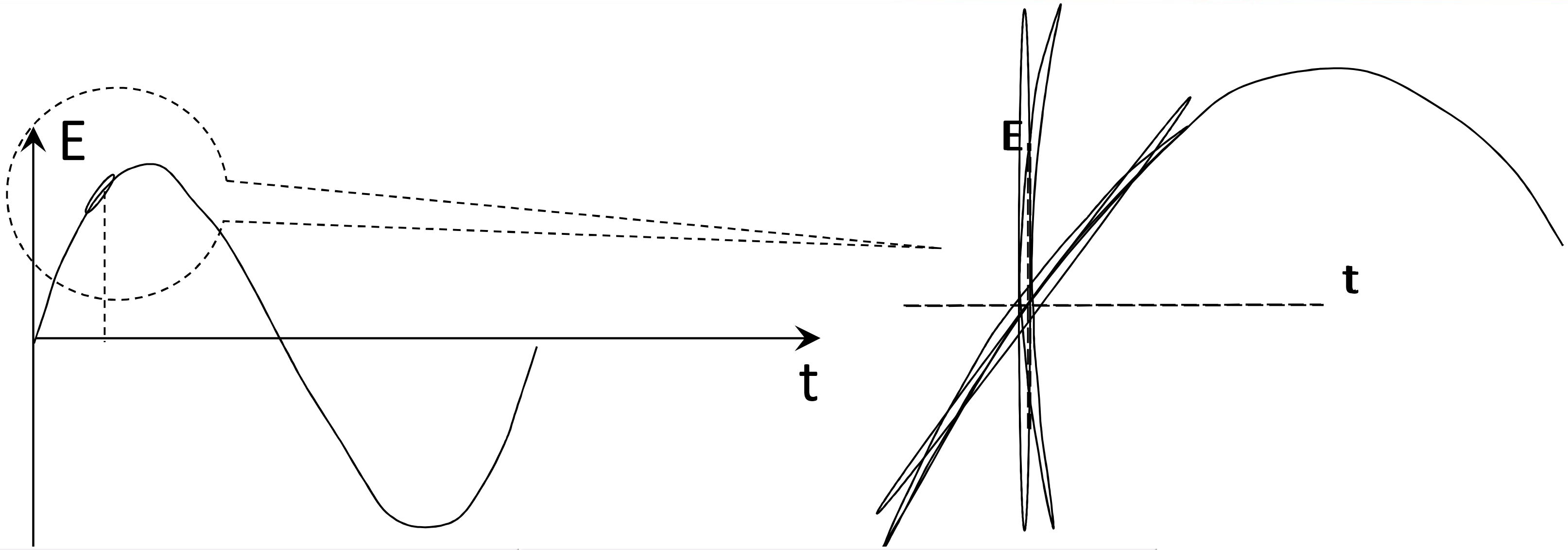
- RF waveform is not linear ("aberration"); distorts phase space of (long) injected bunch
- Correction with nonlinear focusing
  - 3rd harmonic RF inapplicable to ERLs: inadequate phase acceptance

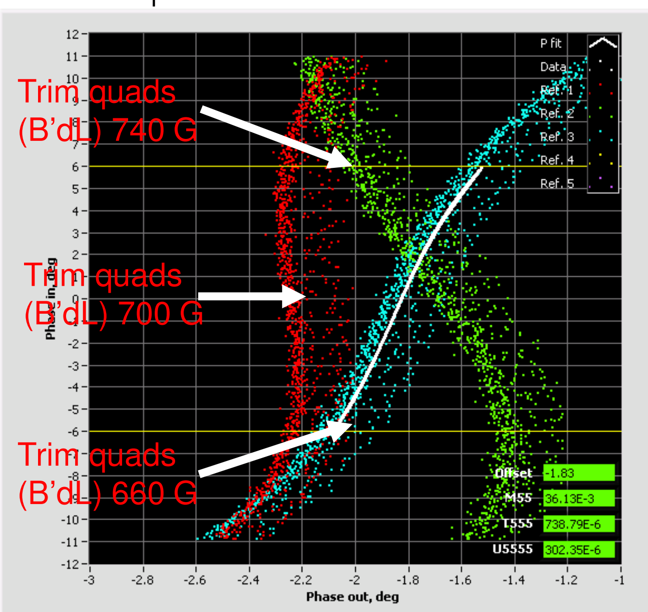
Limits on single stage compression

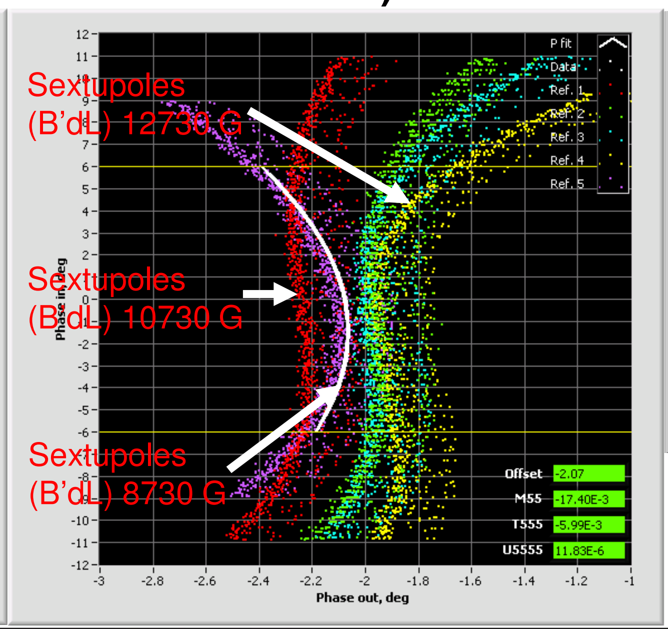
- Parallel to point image: can't change aspect ratio
- Short wavelength/small bandwidth → need small $\delta p/p$ at FEL; can't get it using existing sources with parallel-to-point image
- use "multistage compression" – as in XFELs
  - Equivalent to imaging with "telescope" rather than single lens
  - Allows modification of aspect ratio

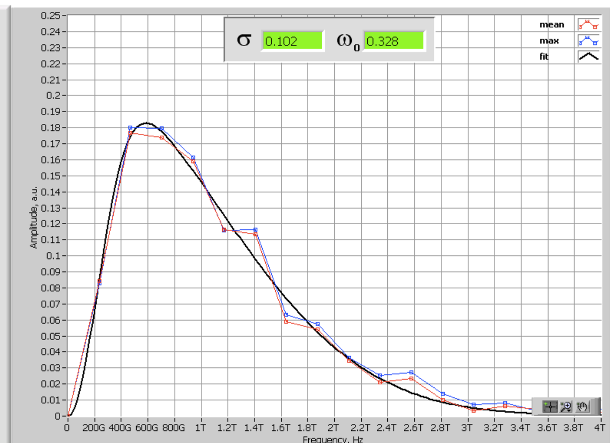
Must use intermediate stages of compression/decompression to meet design requirements at shorter wavelength

RF Curvature







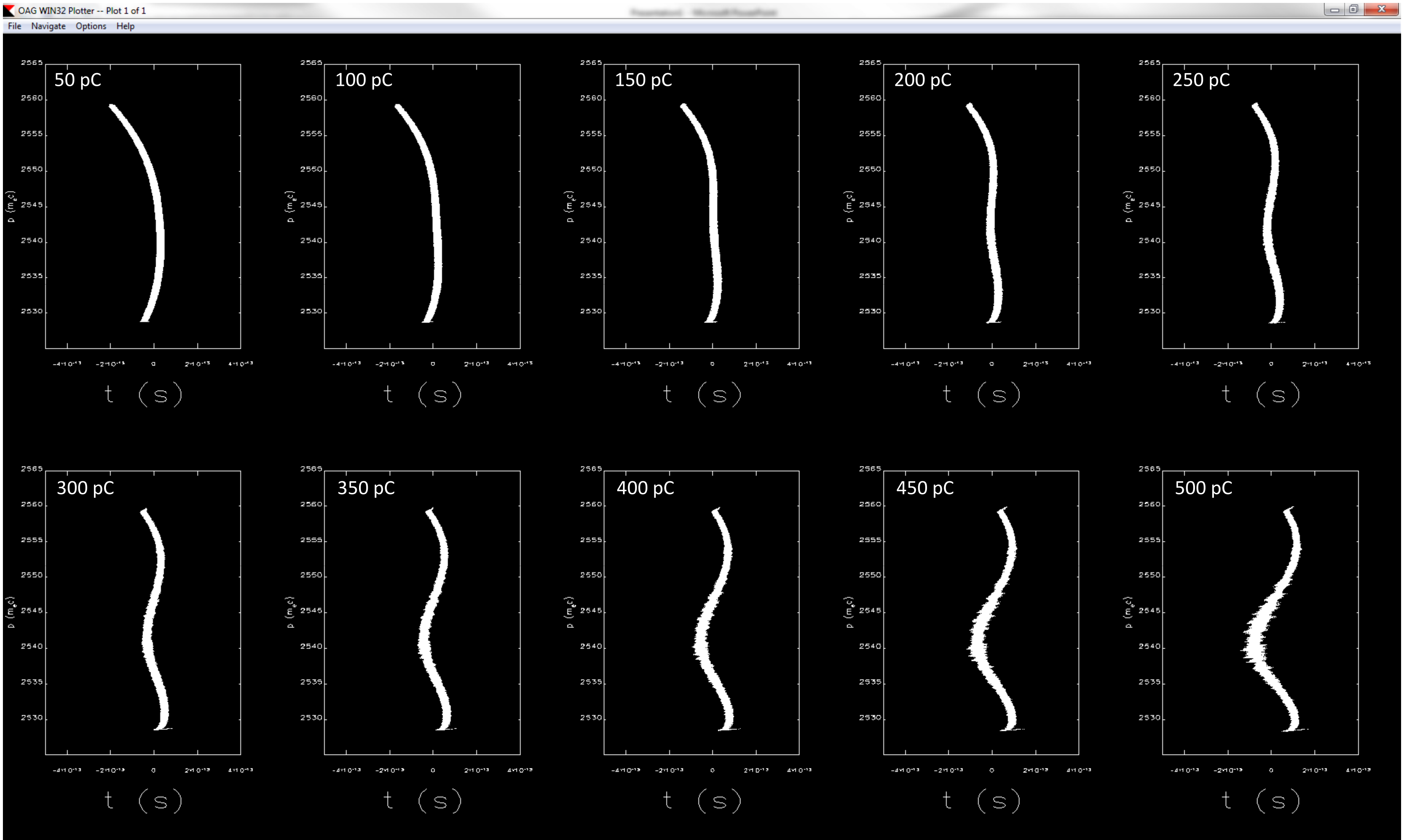


Martin-Puplett Interferometer data in frequency domain – give upper limit on the RMS bunch length

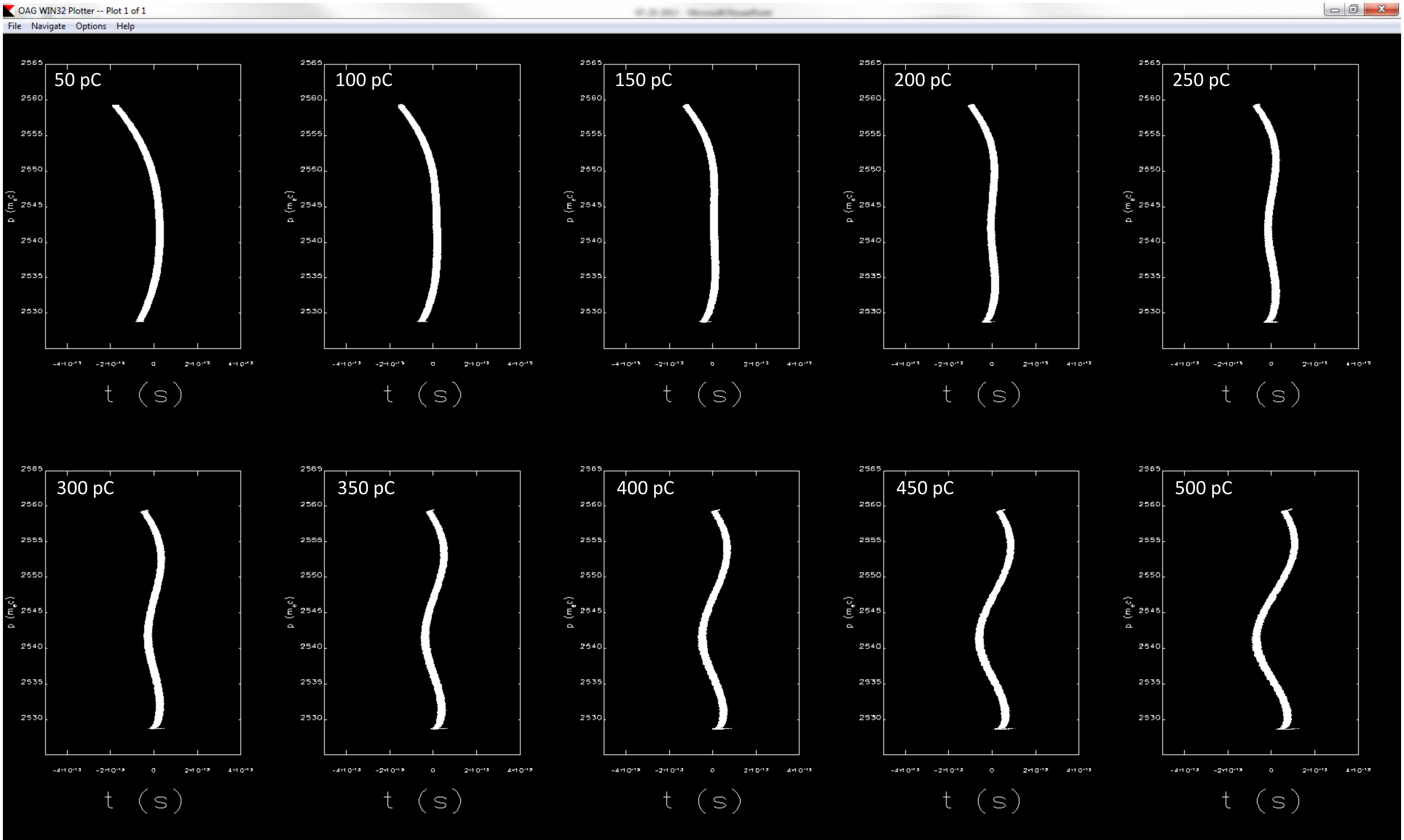
- By using nonlinear transport, can
  - Correct RF curvature & transport aberrations
  - Raise peak current at FEL (higher performance)
  - Compress energy spread out of FEL (recover higher current more cleanly)
- Operationally straightforward

High Energy Arc – bunch length/charge dependances

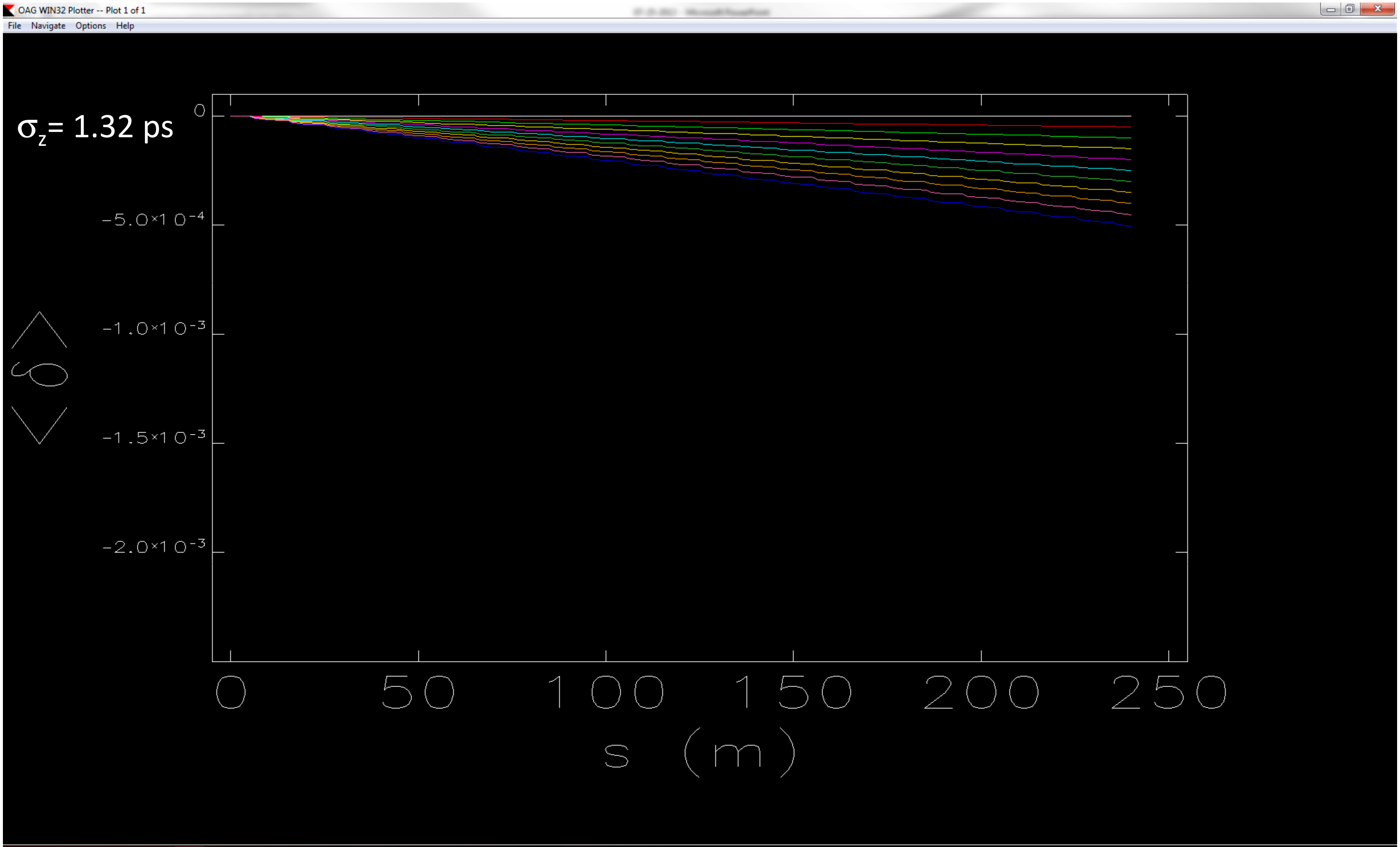
Longitudinal Phase Space at Arc Exit: σ_z = 1.32 ps



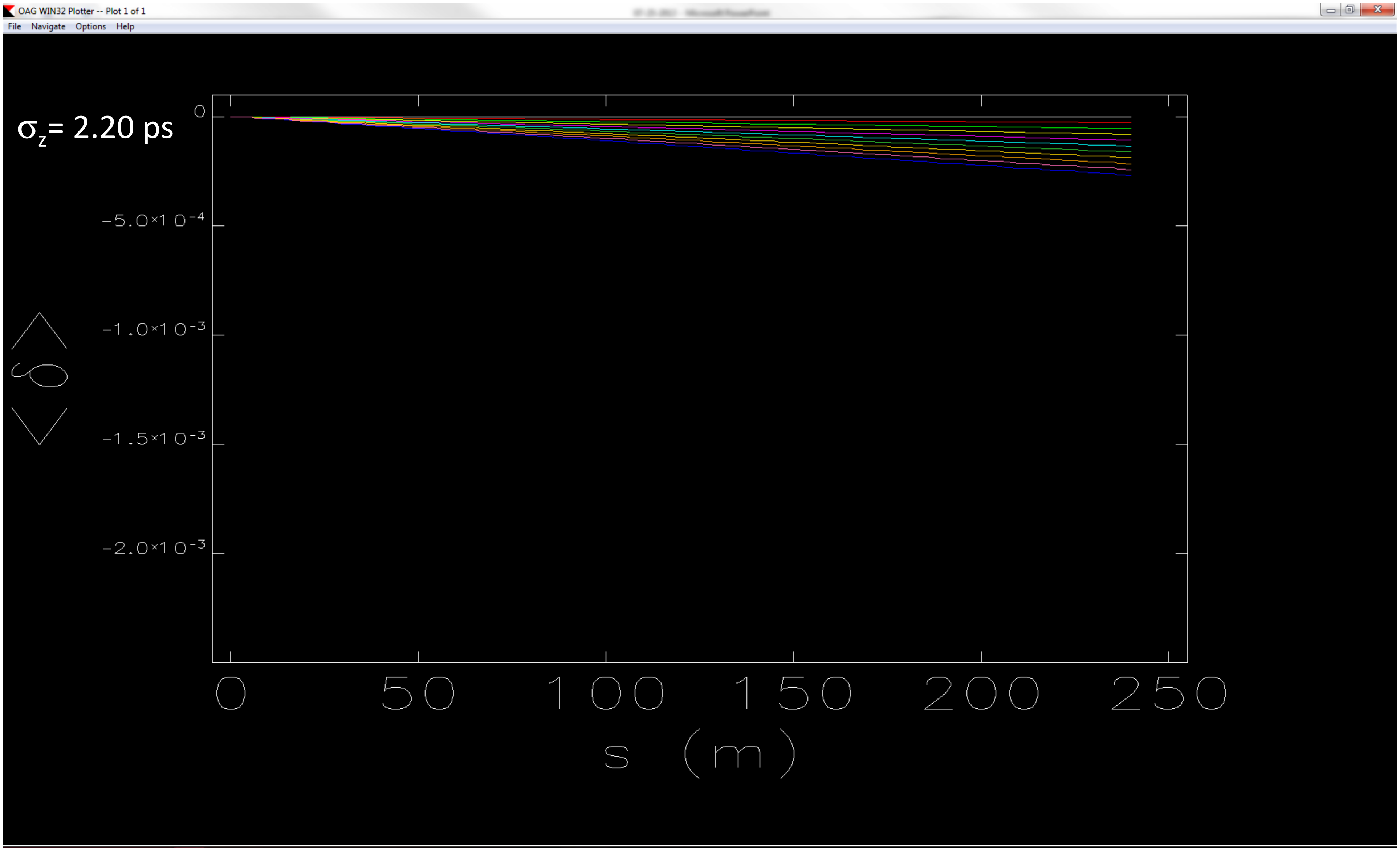
Longitudinal Phase Space at Arc Exit: σ_z = 2.20 ps



Fractional Energy Loss as a Function of Bunch Charge



Fractional Energy Loss as a Function of Bunch Charge



Compressor “Back Door”

Background

- CSR/LSC/μBI severely constrain compression of high brightness beams
- "optimum" compression scheme strongly dependent on FEL requirements, source properties
  - Short wavelength FEL => narrow bandwidth => minimize delivered $\delta p/p$
  - RF gun => very small intrinsic $\delta p/p$ at injection => susceptibility to μBI

    These push optimum toward "laser heater, compress, accelerate to damp" (and give two-horned distribution)
  - Longer wavelength, broader band FEL => tolerate larger delivered $\delta p/p$
  - DC gun => "dimmer" source, larger dp/p => reduction in mBI sensitivity

    Push optimum to full compression at full (or high) energy and/or dechirp rather than damp

Incompressibility

Schematic evolution of moderately (top) and extremely (bottom) bright longitudinal phase space at injection (left), after acceleration (left of center), and after compression (right of center). Resulting bunch length/temporal distribution at right.