Lattice Design for a High-Power Infrared FEL

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Acknowledgments

- Work by the Jefferson Lab FEL Team, Accelerator Design Department, and consultants

- FEL enlightenment by Steve Benson, George Neil, Michelle Shinn

- Major lattice design input from

  Joe Bisognano, Court Bohn, Fred Dylla, Christoph Leeman,
  Bob Legg, Rui Li, Hongxiu Liu, Byung Yunn – Jefferson Lab

  Jay Flanz – MGH

- Support by Department of Energy, Office of Naval Research, Commonwealth of Virginia, and Laser Processing Consortium industrial members

1 Project Overview

A high-power infrared FEL for industrial, defense, and related scientific applications is under construction at Jefferson Lab

- FEL:
  - o 1 kW, 3–6.6 μm photon beam
  - o compact, superconducting radio-frequency (SRF) energy-recovering CW linac driver

- Driver accelerator:
  - o injector
  - o linac – a single, high-gradient Jefferson Lab cryomodule (8 SRF cavities)
  - o wiggler and optical cavity
  - o energy-recovery recirculation arc

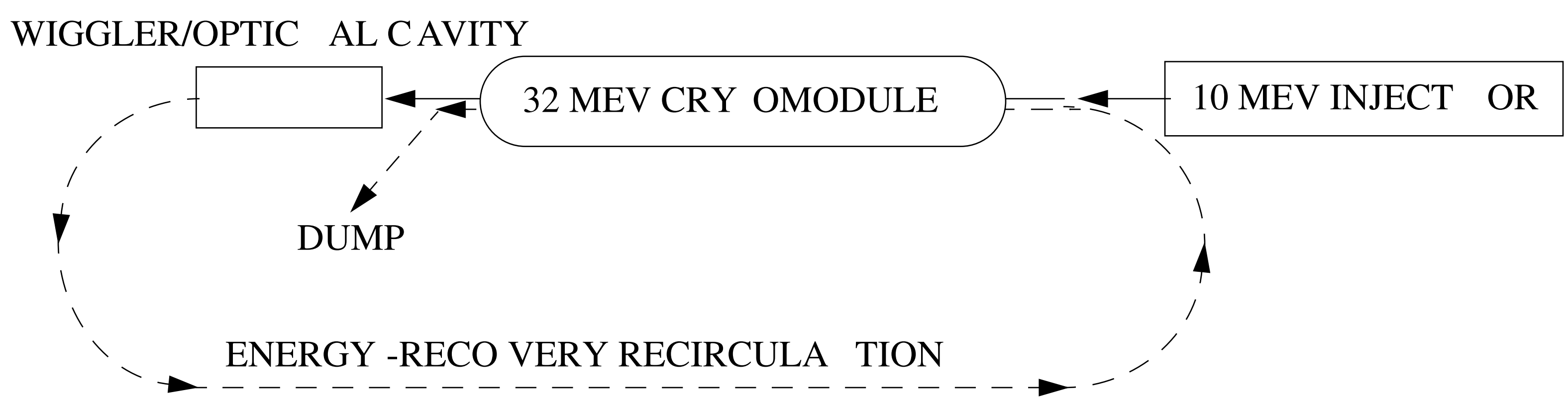


Table 1: Driver Accelerator Parameter List

Beam current		5	mA
Acceleration Cycle		$10 \rightarrow 42 \rightarrow 10$	MeV
FEL extraction efficiency		0.5	%
$\varepsilon_{normalized}^{rms}$		<13	mm-mrad
$\delta p/p$	rms at wiggler	<0.5	%
	full after wiggler	5	%

- Energy recovery used to limit cost/technical risk by reducing RF power requirements
- Schedule:
  - Project Start — June 1996
  - Construction End — October 1997
  - First Light — Spring 1998
  - High-Power Operations — Summer 1998
- Details:
  - C. L. Bohn, paper 3V.44
  - Jefferson Lab home page – http://www.jlab.org/

2 Lattice Design Requirements

2.1 Two Fundamental Requirements

1. *Deliver e$^-$ beam with appropriately configured phase space to FEL*

- FEL :
  - 8 m optical cavity resonator; 0.5% extraction efficiency
  - wiggler: N_{PER}=40, L_W=1.08 m
  - modest instantaneous power output
  - high repetition rate ⇒ high average output power
    - avoids problems of low-rep-rate, high-peak-power systems
- System optimized for :
  - 135 pC/bunch; 37.425 MHz rep rate
  - $\varepsilon^{rms}_{normalized}$ < 13 mm-mrad; $\sigma_{\delta p/p}$ <0.5%
- Electron beam/optical mode overlap : ⇒ careful steering, betatron matching into wiggler
  - steer to 30 µm/30 µrad
  - match to round beam waist at wiggler center ($\beta_{x,y}$~0.5 m)
- Peak current needed for design FEL gain : ⇒ longitudinal phase space management
  - bunch length compression to ~1 psec at wiggler

2. Transport "spent" beam from FEL back through accelerator for energy recovery

- <u>Energy recovery</u>:
  - o reduce RF power demands, cost, radiation
- BUT – <u>need large acceptance transport system</u>:
  - o $\Delta p/p$ after wiggler ~5%

2.2 Related Physical Phenomena/System Constraints

1. Cost and schedule –
   - project time scale (1.5 yr.) ⇒ use standard Jefferson Lab components
     - M. Wiseman *et al.*, paper 3P.35
   - low instantaneous FEL power/high rep rate ⇒ use CW driver

2. Phase space management at wiggler requires
   - quadrupole matching telescopes
   - bunch length compressor

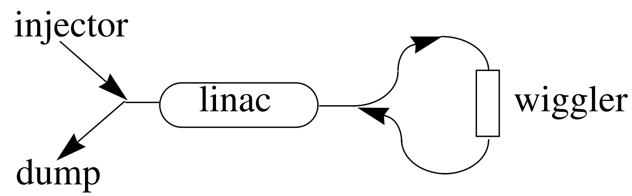
3. Collective effects – ("high" current/"low" energy)
   - avoid space-charge ⇒ moderate injection energy
   - avoid beam breakup (BBU), other impedance-driven instabilities
   - manage coherent synchrotron radiation (CSR) – preserve beam emittance
     - R. Li *et al*., papers 2V.23 and 2V.24
   - assure RF stability (FEL and energy recovery turn-on transients)

4. Energy-recovery transport
   - large acceptance – ($\Delta p/p$ after wiggler ~5%)
     - control beam properties, lattice aberrations over large volume of phase space
   - provide variable momentum compaction (RF gymnastics)
     - energy compression; RF testing, experimentation, optimization

There are many potential configurations – most are eliminated by project constraints, physical effects

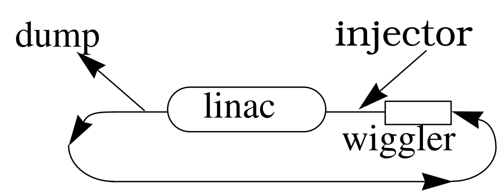
Standard JLab cryomodules cannot drive antiparallel beams (phase constraints on cavity pairs)

- Use of existing hardware designs (cost and schedule) precludes “tadpole” geometries



FEL placement dictated by relative importance of various physical phenomena

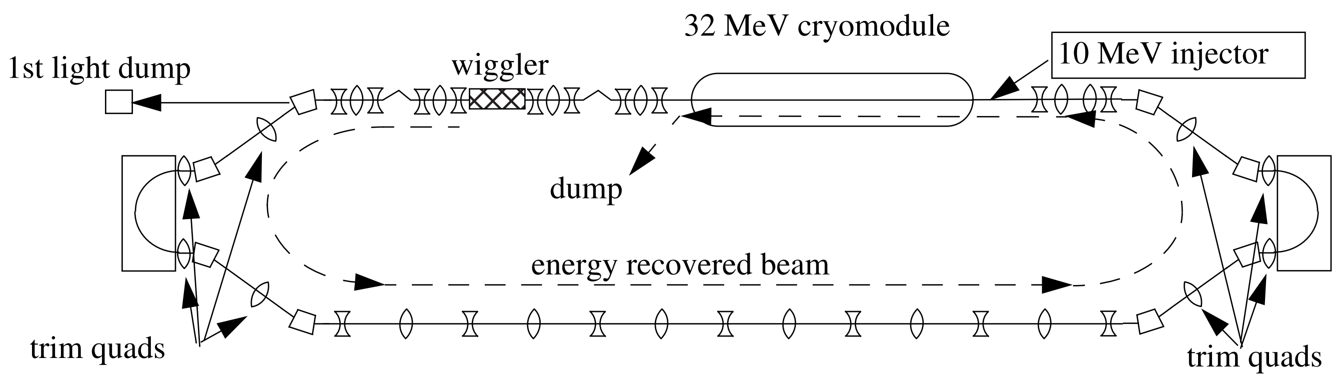
- recirculation before wiggler avoids transport of large momentum spread “spent” beam, BUT leaves CSR- and space-charge-driven emittance growth as problem



3 Lattice Solution

FEL placed downstream of linac (upstream of energy recovery recirculation)

- Reduces impact of CSR and space charge
- Increases complexity of energy recovery transport
- Allows "straight-ahead" operation of machine – "1st light" running



3.1 System Specifications/Overview

System Concept:

1) 10 MeV injector ,
2) Jefferson Lab cryomodule accelerating to 42 MeV ,
3) transport to wiggler , and
4) energy recovery transport

Specifications on segments:

1. Module to wiggler transport – transverse matching; bunch length compression

2. Energy recovery transport – large momentum acceptance; variable momentum compaction

Global specifications

1. Small spots and beam envelopes (β < 25–30 m)

2. Simple, robust components (in inventory)

3. Low beam energy $\Rightarrow$ dipole angles large, focussing strong
   - include edges, gaps, field rolloff in computations

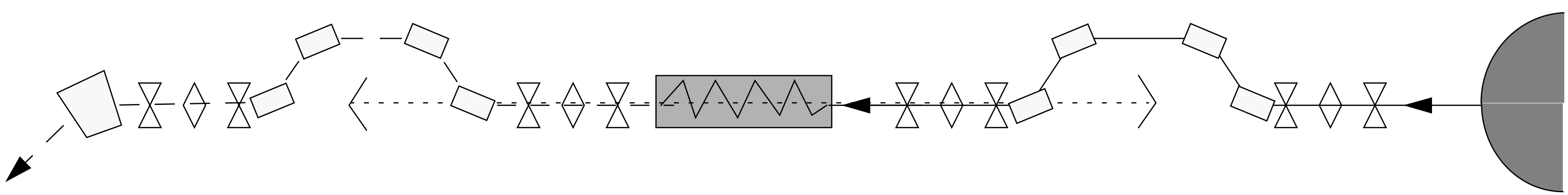
4. Avoid exciting collective effects (CSR, BBU, ...)

3.2 Transport to Wiggler

Following injection, beam is accelerated/manipulated during transport to wiggler

- Driver linac:
  - o single high-gradient cryomodule
  - o acceleration ~10^{o} off-crest for compression
  - o RF focussing $\Rightarrow$ beam envelope control

- Cryomodule to Wiggler:
  - o quad telescope matches to wiggler
  - o dipole chicane separates electron/optical beams, compresses bunch length

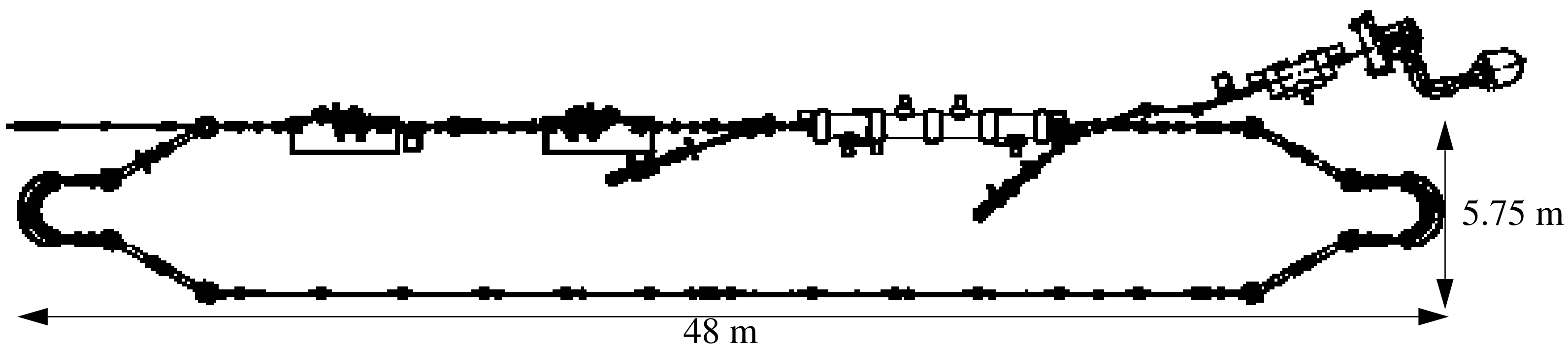


- Space charge – not important at 42 MeV; *does* affect low energy transport and matching. To ramp current for machine turn on (reduce transients)
  - o set match and ramp bunch charge (low charges mismatched), or
  - o set match and use fixed bunch *charge* /ramp repetition rate (match holds throughout ramp)

3.3 Energy-Recovery Transport

Following wiggler, beam has 5% full momentum spread. Transport comprises

1) match from wiggler,
2) arc (Bates-style end loops/backleg transport),
3) reinjection match, and
4) energy recovery within module



- Wiggler to arc:
  - quad telescope matches beam to recirculation – limits aberrations, error sensitivities
  - dipole chicane separates electron/optical beams, expands bunch length (space charge, CSR)

- Recirculation arc:
  - various solutions tested for quasi-isochronous, large-momentum-acceptance line
    - MIT/Bates design copied
  - end loop dipole parameters, drift lengths set to provide
    - $M_{56}=0$, wiggler to reinjection point
    - stable motion in x ($\nu_x=5/4$ across each loop)
    - imaging in y ($M_y=-I$ across each loop)
  - end loops joined by six 90^o FODO cells; $M_{x,y}=-I$
    - end loop, backleg phasing + reflective symmetry $\Rightarrow$ aberration suppression
  - trim packages:
    - trim quads – dispersion/compaction control (M_{56} variable over ± 0.25 m)
    - sextupoles – aberration suppression; $T_{166}, T_{266}, T_{566} = 0$
    - path length correction ($\pm\lambda_{RF}/2$ by steering in 180^o dipoles)

- Reinjection match: Quad telescope matches into driver linac
  - not strictly necessary – RF focussing adequate
  - included to simplify installation of energy upgrades (RF focussing reduced)

- Energy recovery: RF focussing confines beam until dumped at 10 MeV

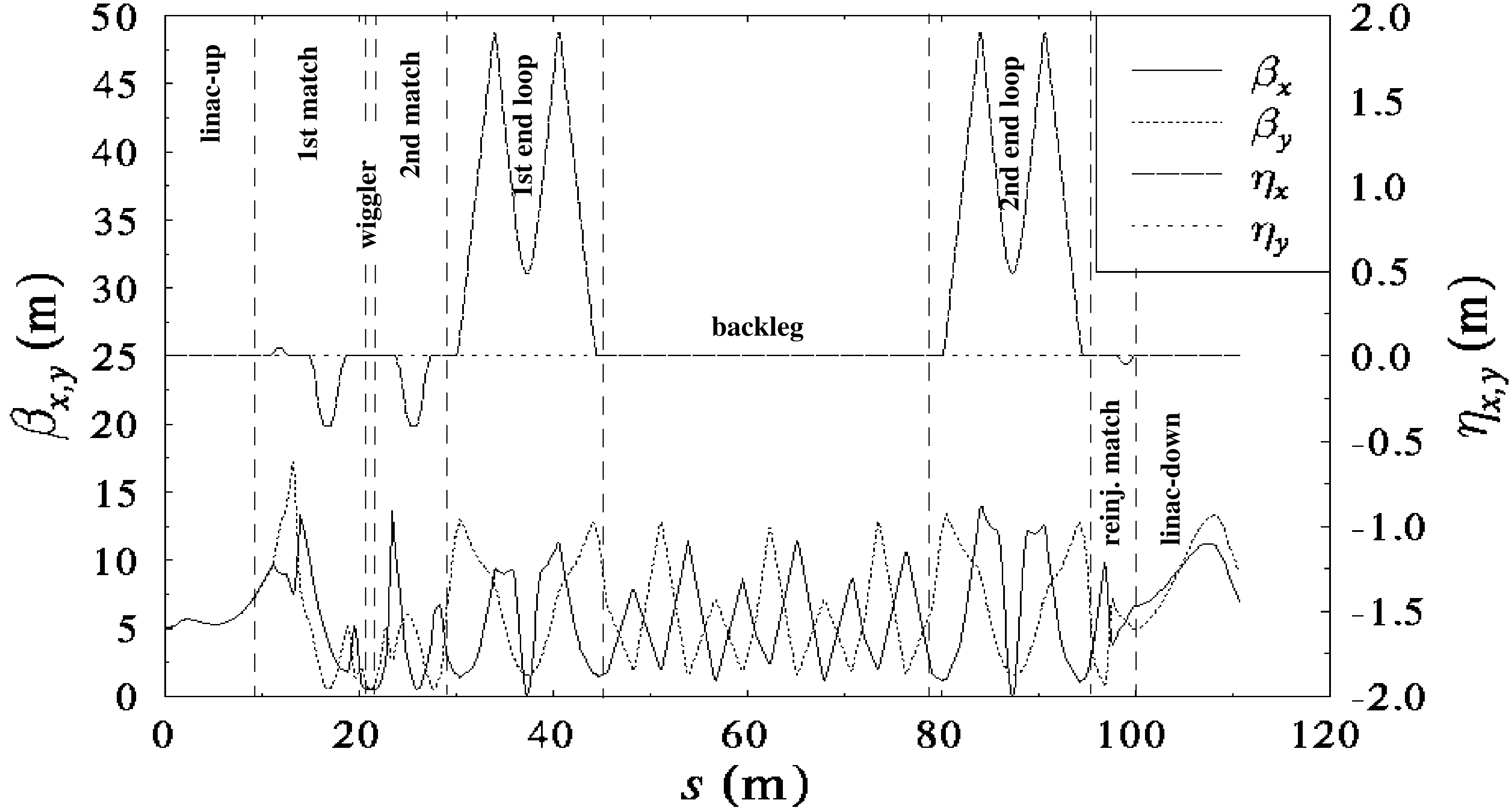
- Diagnostics/Correction System:
  - beam viewers (OTR) and BPMs
    one diagnostic every ~1/4 betatron wavelength
  - steering dipoles next to diagnostics (orbit correction, diagnostic steering)
  - instrumentation supports detailed program of experiments to characterize CSR

Table 2: Transport System Components

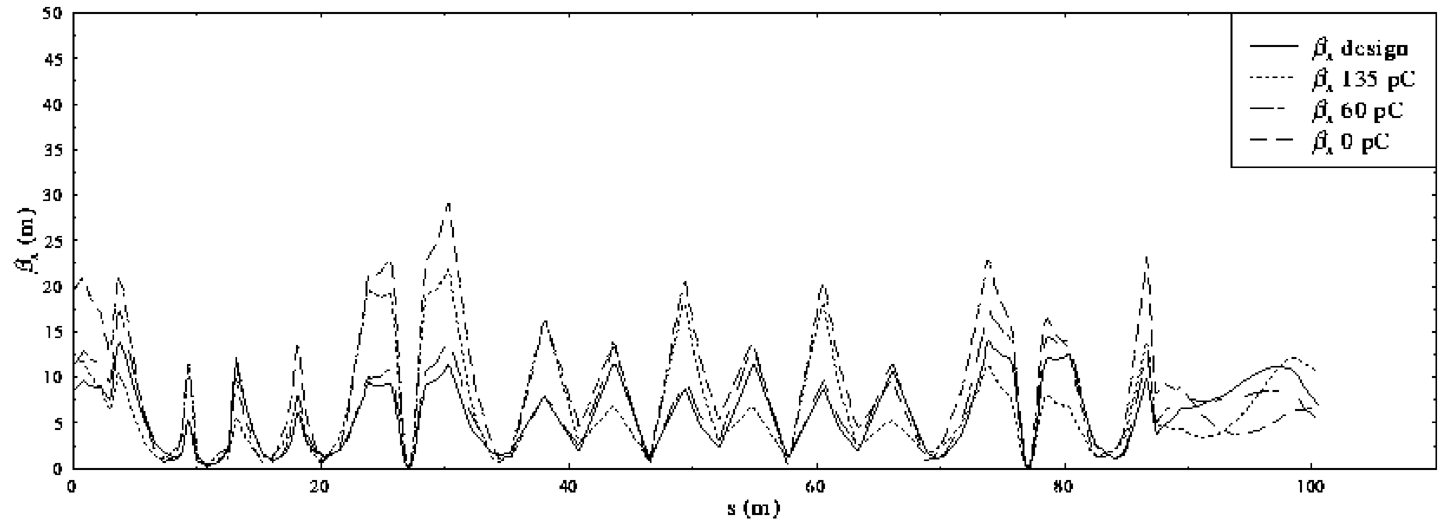
Segment	*Bends*	*Quads*	*Sextupoles*	*H/V correctors*	*BPM/OTR*
Injection line	3	4	0	4/4	2/3
Transport to wiggler	7	6	0	3/3	3/6
Match to recirculation	4	6	0	3/3	3/3
Reinjection match	2	4	0	2/2	2/0
Recirculation	10	21	8	16/11	19/8

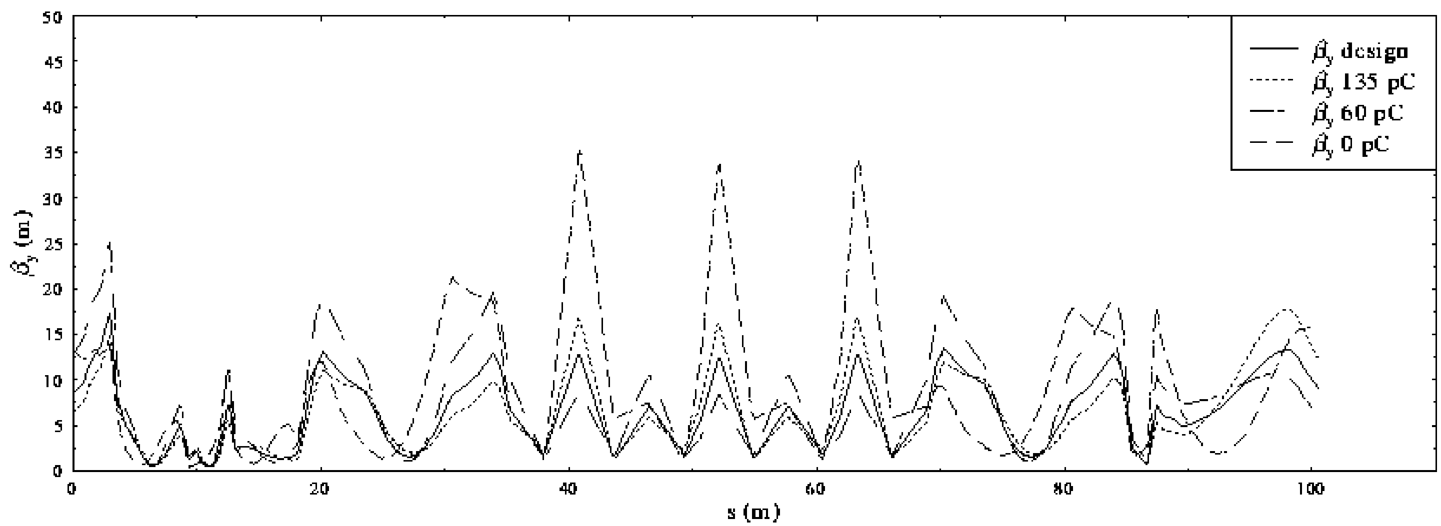
4 System P erformance

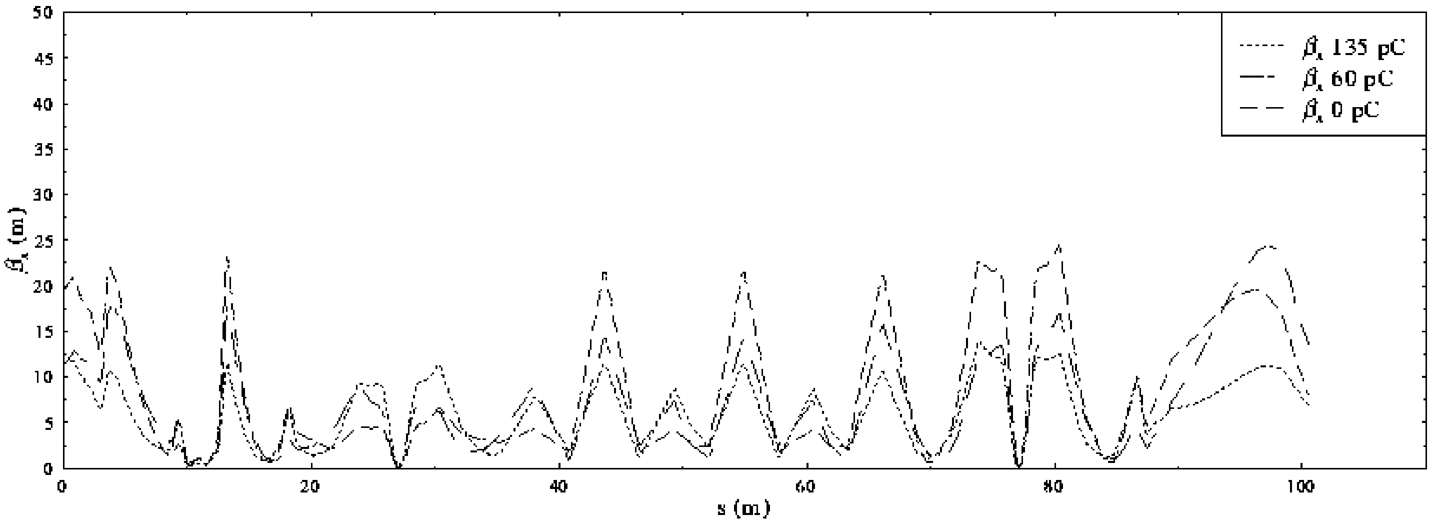
4.1 Linear Optics

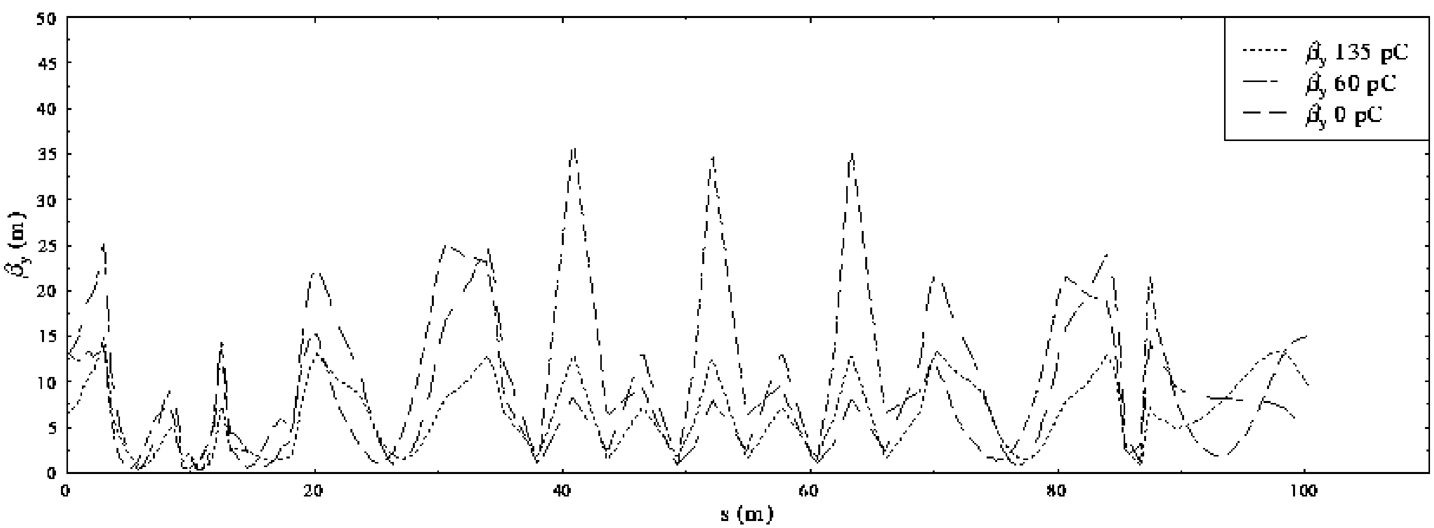


- Beam envelopes , dispersions modest, well beha ved
  - o Expect low error sensitivities , low losses , good aperture
  - o BBU estimates ⇒ instabilities a voided (threshold 50–100 mA)


β_x design
β_x 135 pC
β_x 60 pC
β_x 0 pC
β_x (m)
s (m)


β_y design
β_y 135 pC
β_y 60 pC
β_y 0 pC
β_y (m)
s (m)


β_x 135 pC
β_x 60 pC
β_x 0 pC
β_x (m)
s (m)

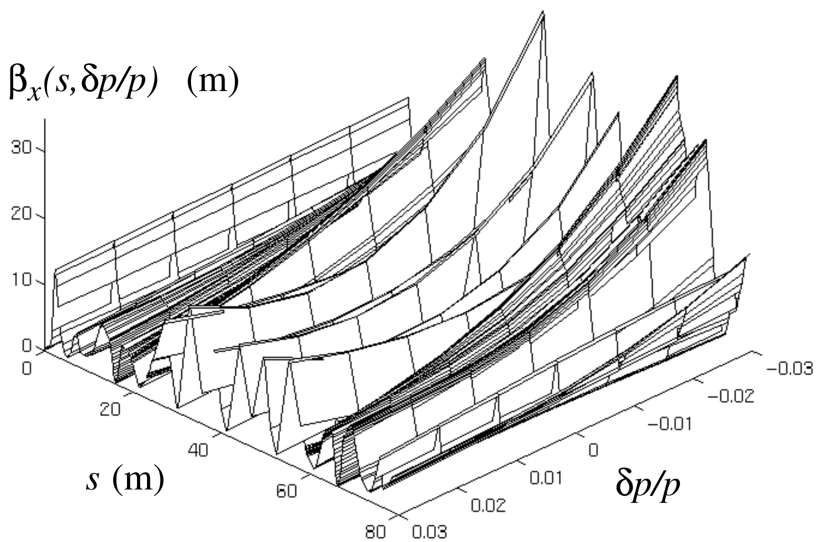

β_y 135 pC
β_y 60 pC
β_y 0 pC
β_y (m)
s (m)

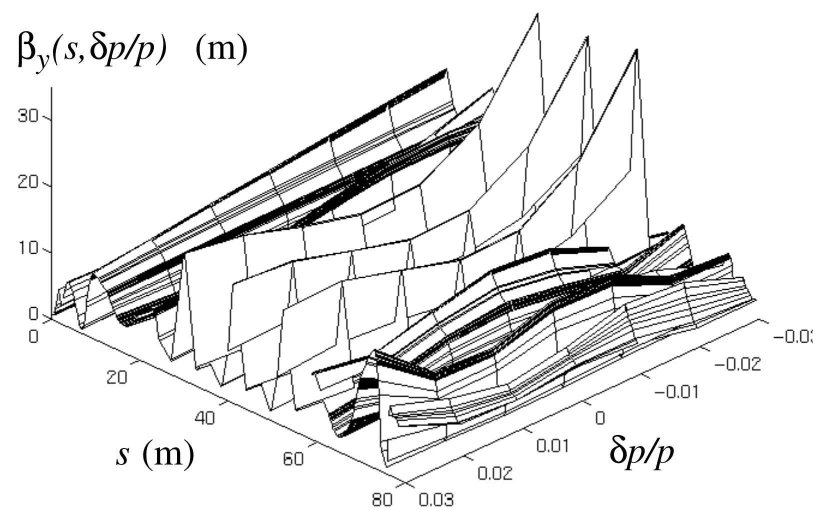
4.2 Aberration Analysis

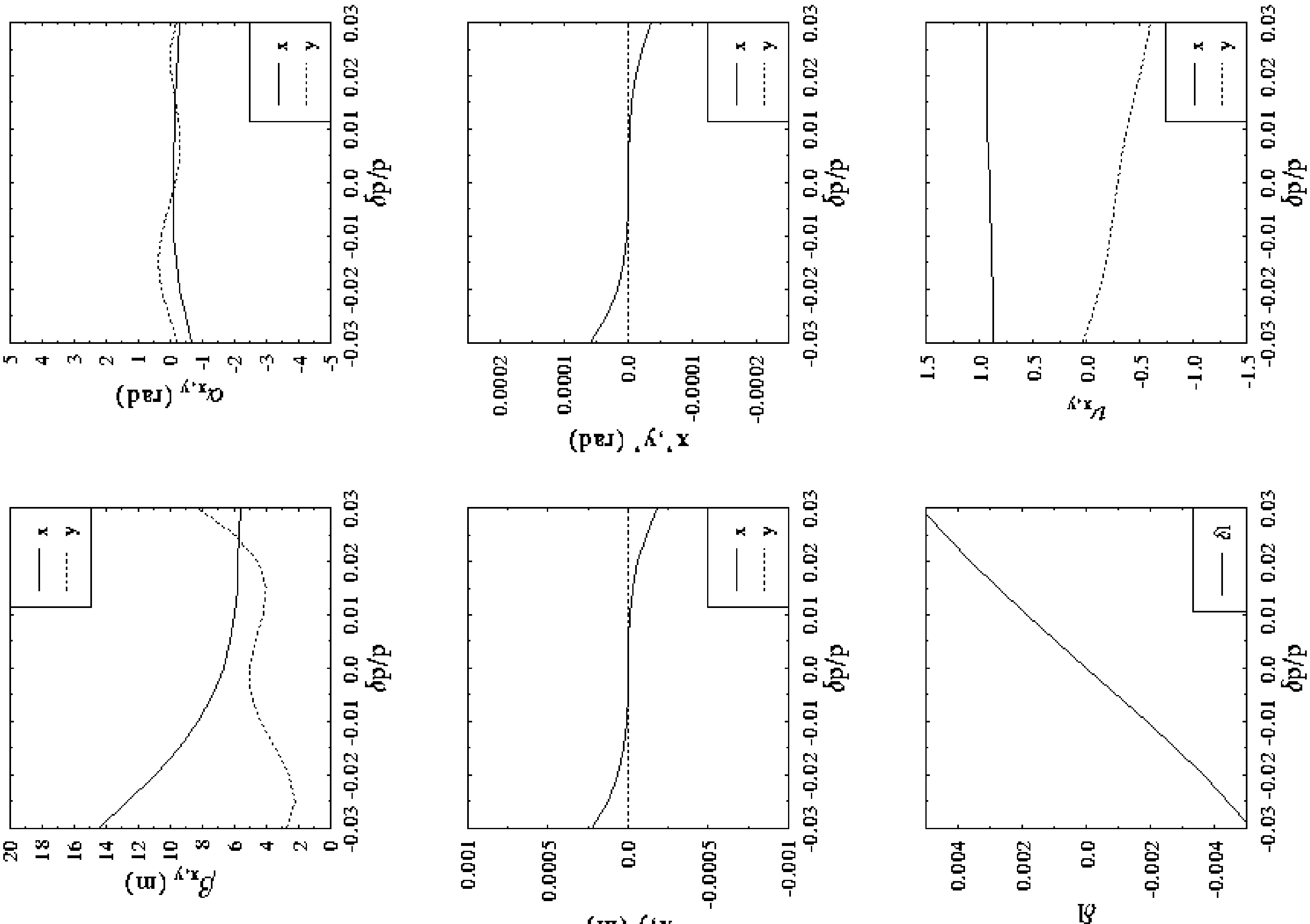
- Design limits aberrations though choice of element/system parameters, use of sextupoles
- 2nd order terms (T_{ijk}) evaluated/adjusted
    - generally modest, expect good behavior
    - T_{336}, T_{346}, T_{436}, T_{446} from wiggler to linac of some concern; couple to steering errors to cause dispersive effects at reinjection
        - spot growth limited by managing aberrations, careful steering at wiggler (30 µm/30 µrad)
- Higher order chromatic, geometric aberrations studied numerically (DIMAD, TLIE)

4.3 Chromatic Performance

Momentum scans of beam/lattice parameters indicate system performance adequate over 6% range





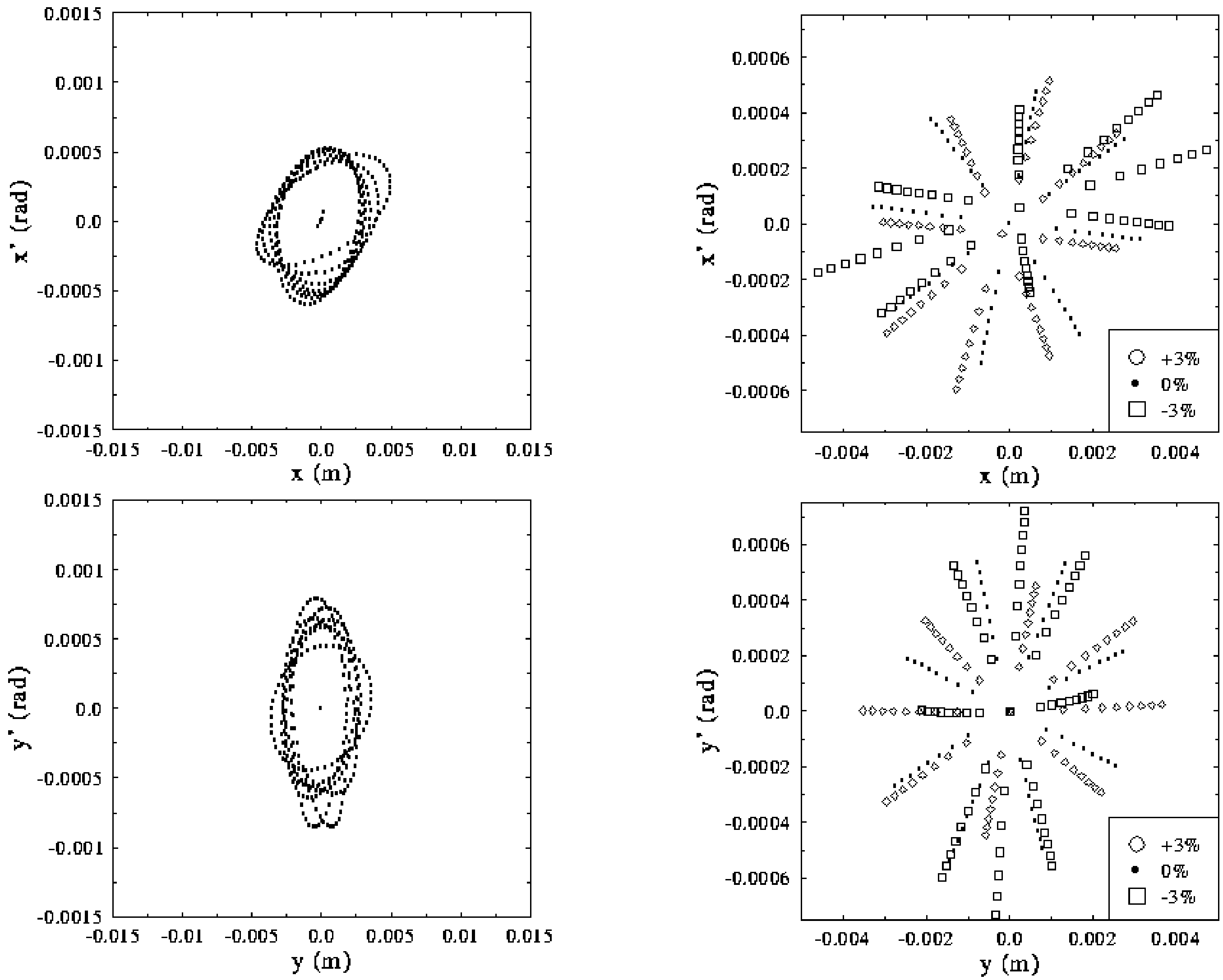


βx,y (m)
αx,y (rad)
x,y (m)
x',y' (rad)
δl
ψx,y
δp/p
x
y

4.4 Geometric Performance

Large amplitude behavior studied by ray-tracing.

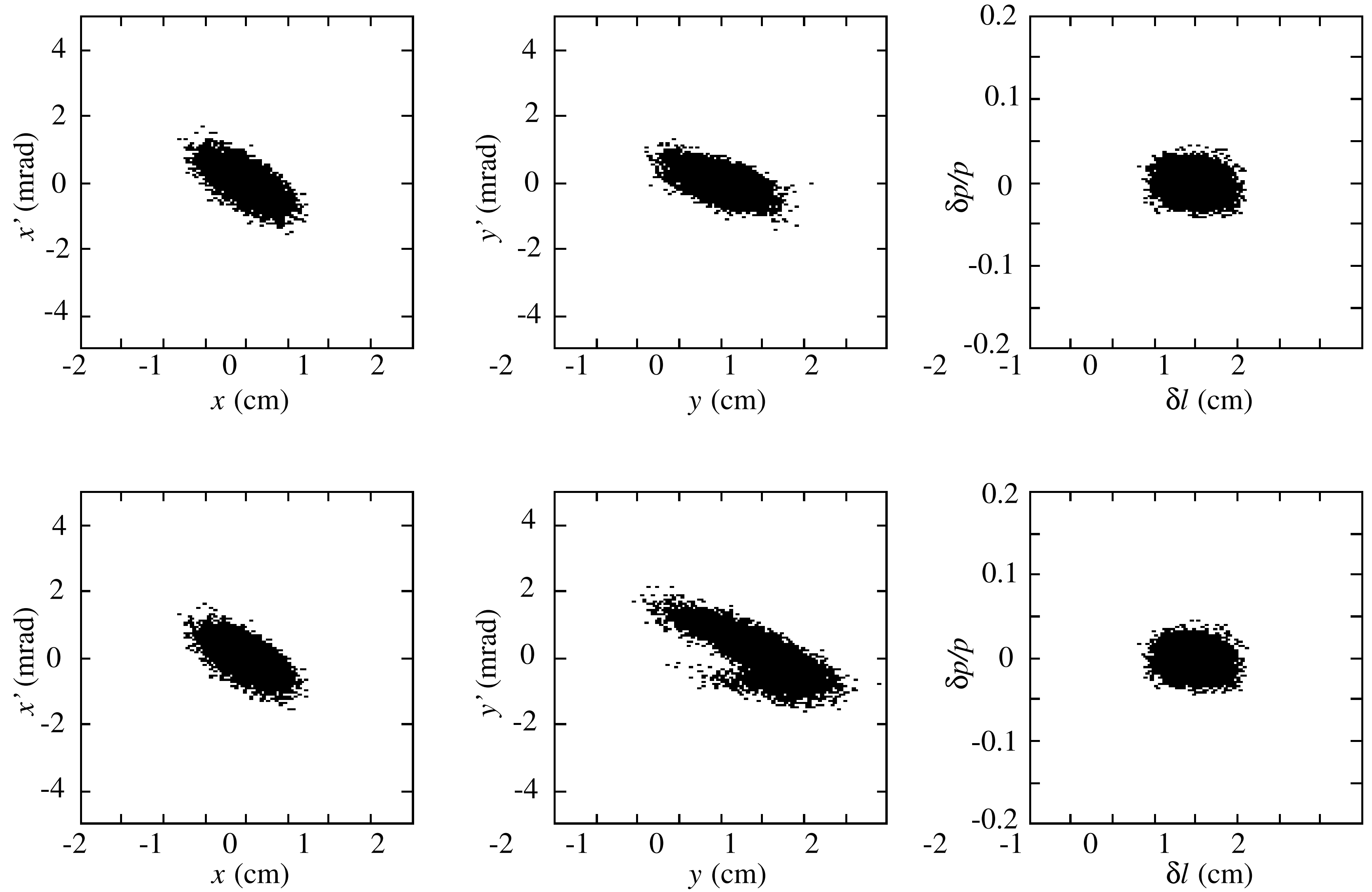
- Over system momentum acceptance/10 times design emittance
  - phase space distortion is modest ($\Delta\varepsilon/\varepsilon \sim 0.3$)
  - phase advance variation with amplitude small
  - H/V coupling effects are negligible


x' (rad)
x (m)
y' (rad)
y (m)
+3%
0%
-3%

4.5 Simulation of Energy Recovery

Lattice performance verified by (space-charge free) simulation of energy recovery.

- 10000 particles ray-traced from wiggler to energy recovery point
- phase space well behaved if steering good; T_{346} aberration/ $\partial\psi_y/\partial\delta$ distorts poorly steered beam
  - vertical beam size doubles if steering 30 x FEL steering tolerance
- large amplitude tracking through recirculator
  - verify apertures
  - identify potential loss points (high current beam!)
  - position scrapers


x’ (mrad)
x (cm)
y’ (mrad)
y (cm)
δp/p
δl (cm)
x’ (mrad)
x (cm)
y’ (mrad)
y (cm)
δp/p
δl (cm)

5 Error Effects

5.1 Overview

- Error effects studied to evaluate mac hine sensitivities , develop component specifications

- Primary concerns center on managing spot size growth, ensuring mac hine reproducibility

- Project scope/sc hedule prec ludes detailed simulation based studies
  - o analytic methods used to establish “error budget” for all components , set component specifications
  - o error budget verified by simulation (in progress)

5.2 Error Budget

- Basis for error budget:
  - During energy recovery, full beam can occupy 1/3 to 1/2 of machine physical aperture
  - Require beam size growth due to errors be limited to ~10% of nominal spot size to avoid losses
  - Set tolerances to limit spot growth due to any single error source to 0.1 – 1%

- Simulation used to certify budget is sufficient:
  - Sufficient, though perhaps more conservative than necessary

Table 3: Typical Error Tolerances for System Components

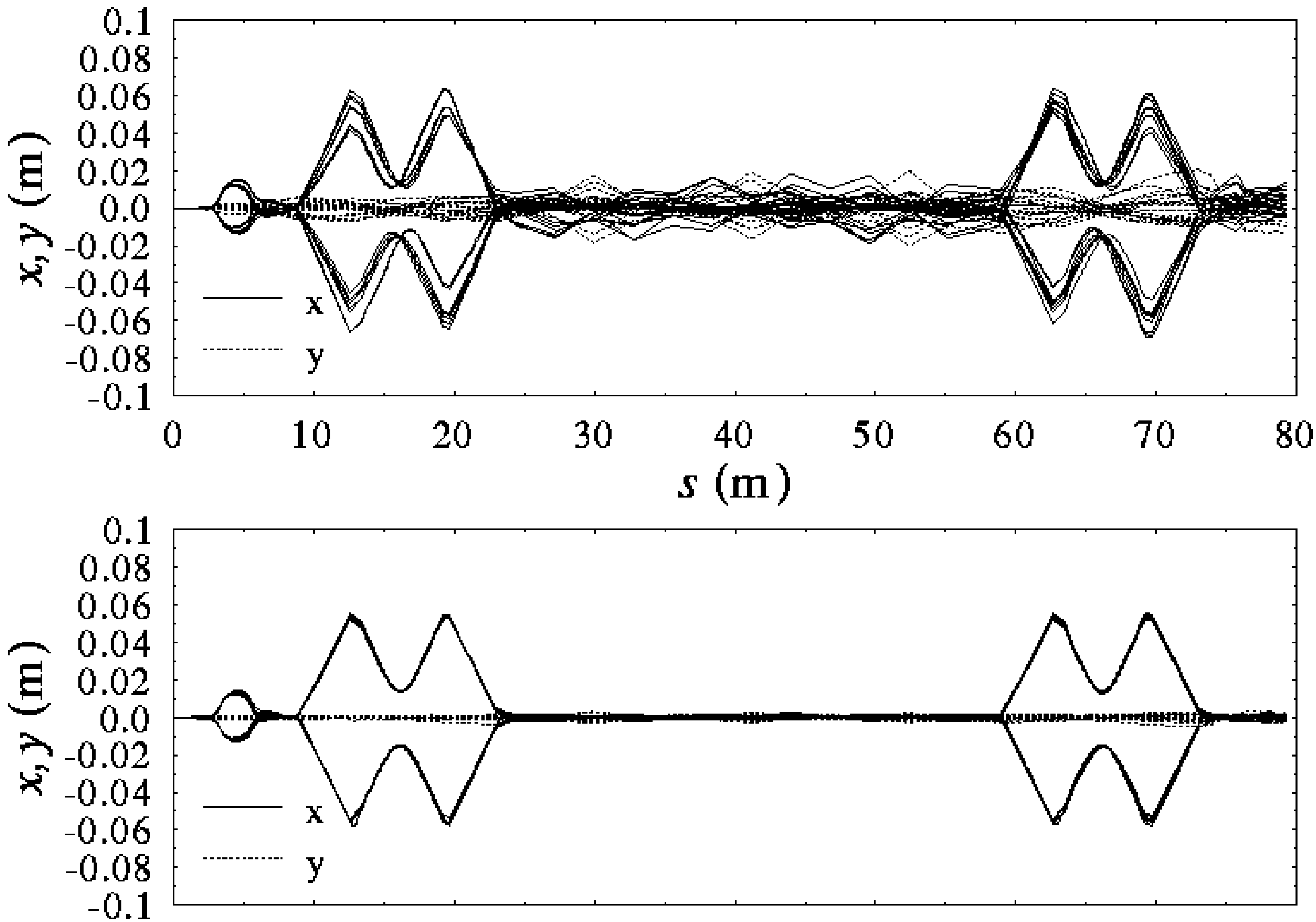
Error		*Dipole*	*Quad*	*Comments*
Alignment		1 mm	0.5 mm	rms transverse
Excitation	DC	10^{-3}	10^{-3}	DC rms field error
	AC	10^{-5}	10^{-4}	rms AC "ripple"
Field quality	$\Delta B/B$	10^{-4}		variation over aperture
	$\Delta B/B$		10^{-3}	error at half aperture
	K_1	0.27 ± 0.05		end-field rolloff integral

5.3 Results

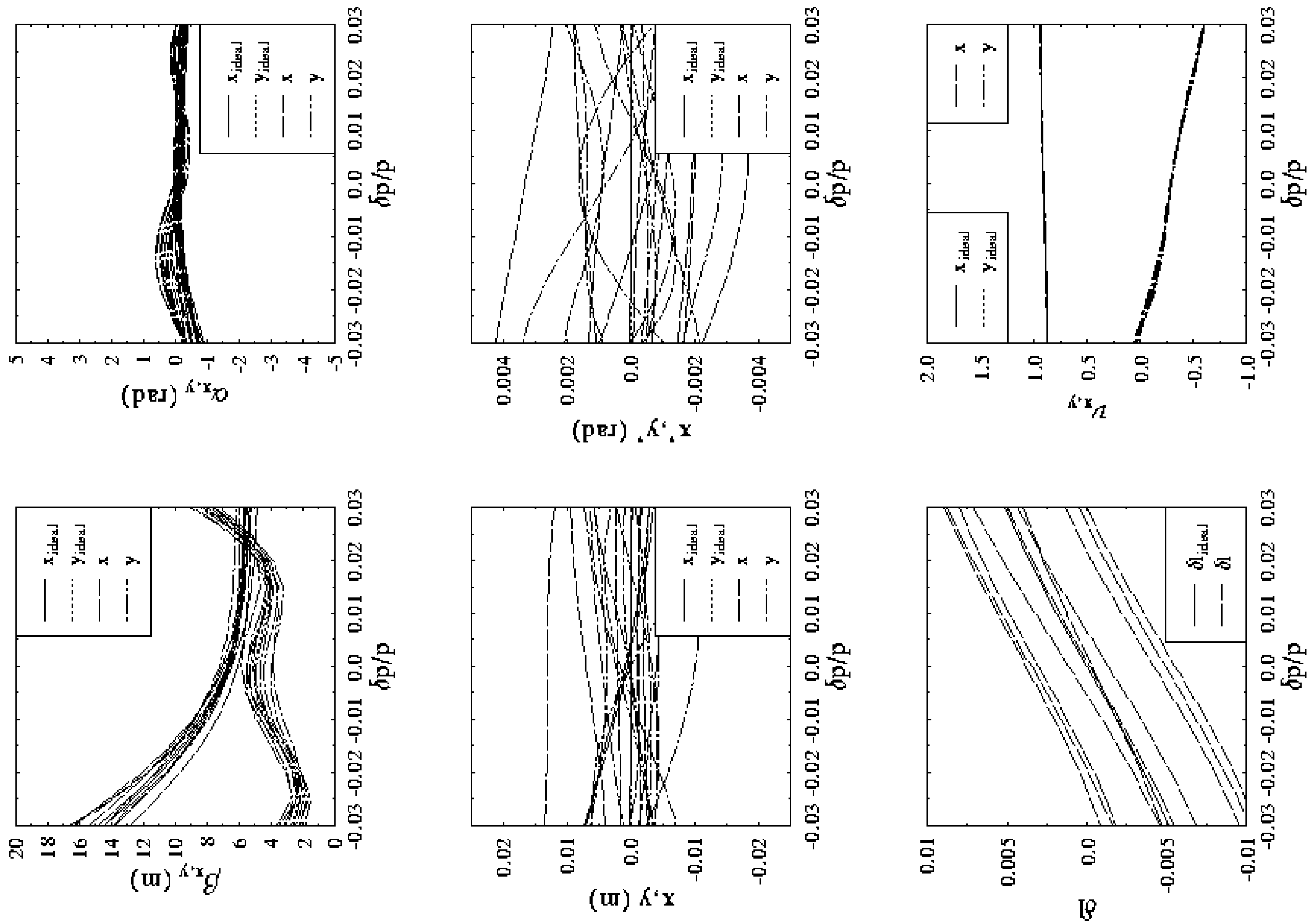
- System response to errors similar to or weaker than in CEBAF:
  - o confirms suitability of using standard Jefferson Lab components
  - o dipoles are an exception:
    - bend angles, dispersions, beam size large $\Rightarrow$ need good field control/quality
    - effort made to insure fields uniform/well characterized (see J. Karn *et al*., paper 7P.45)
    - design computations done including field roll-off effects

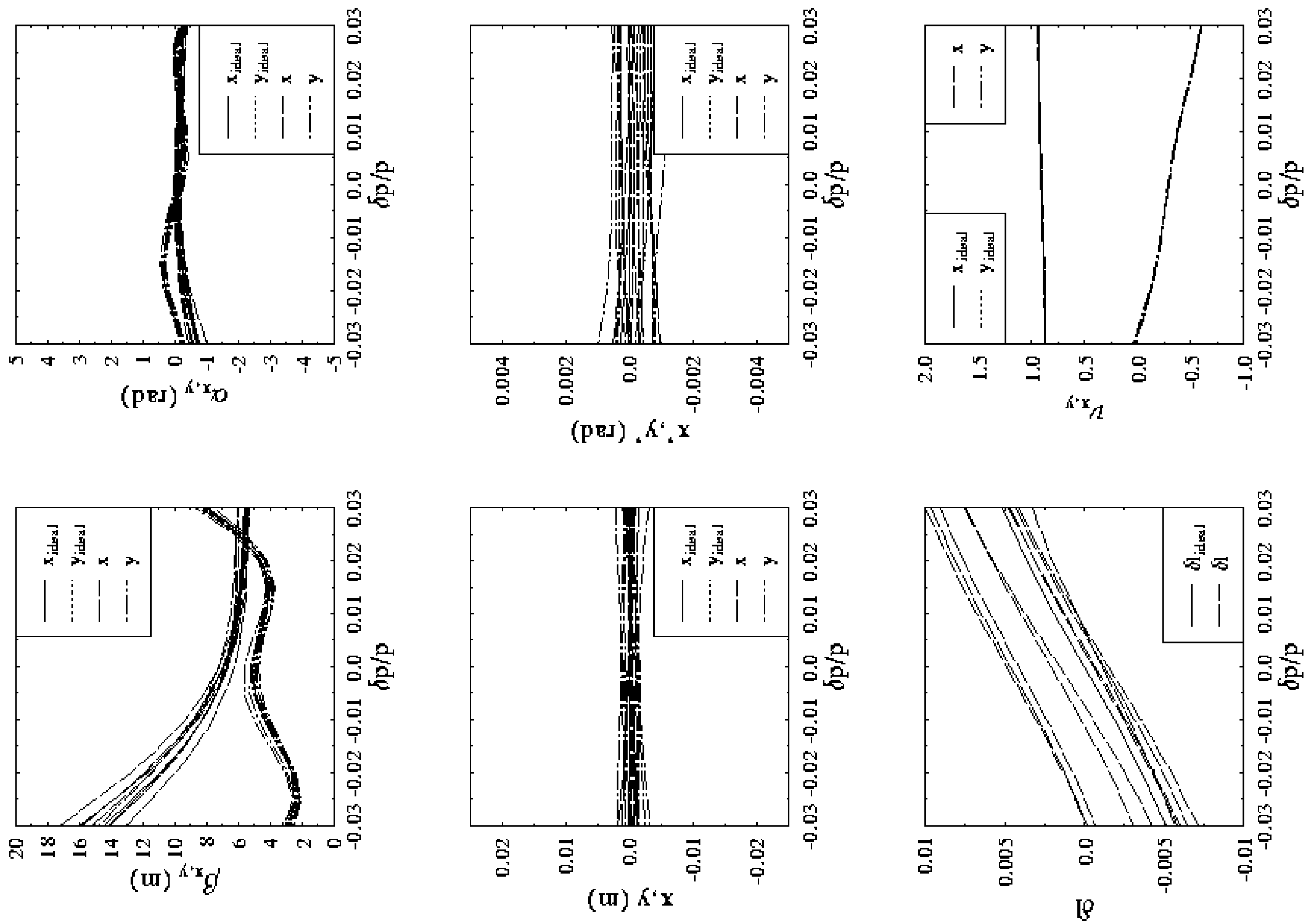
- Most analytically derived tolerances confirmed numerically
  - o array of BPMs, OTRs, steerers every 1/4 betatron wavelength allows machine operation with anticipated errors, avoids beam quality degradation
  - o studies with multiple error sets verified numerous performance criteria are met:
    - central orbits
    - chromatic behavior of orbit (off-momentum orbits, dispersion, momentum compactions), beam behavior about orbit (beam and lattice properties)
    - large amplitude behavior (geometric aberrations, phase space distortion, H/V coupling)

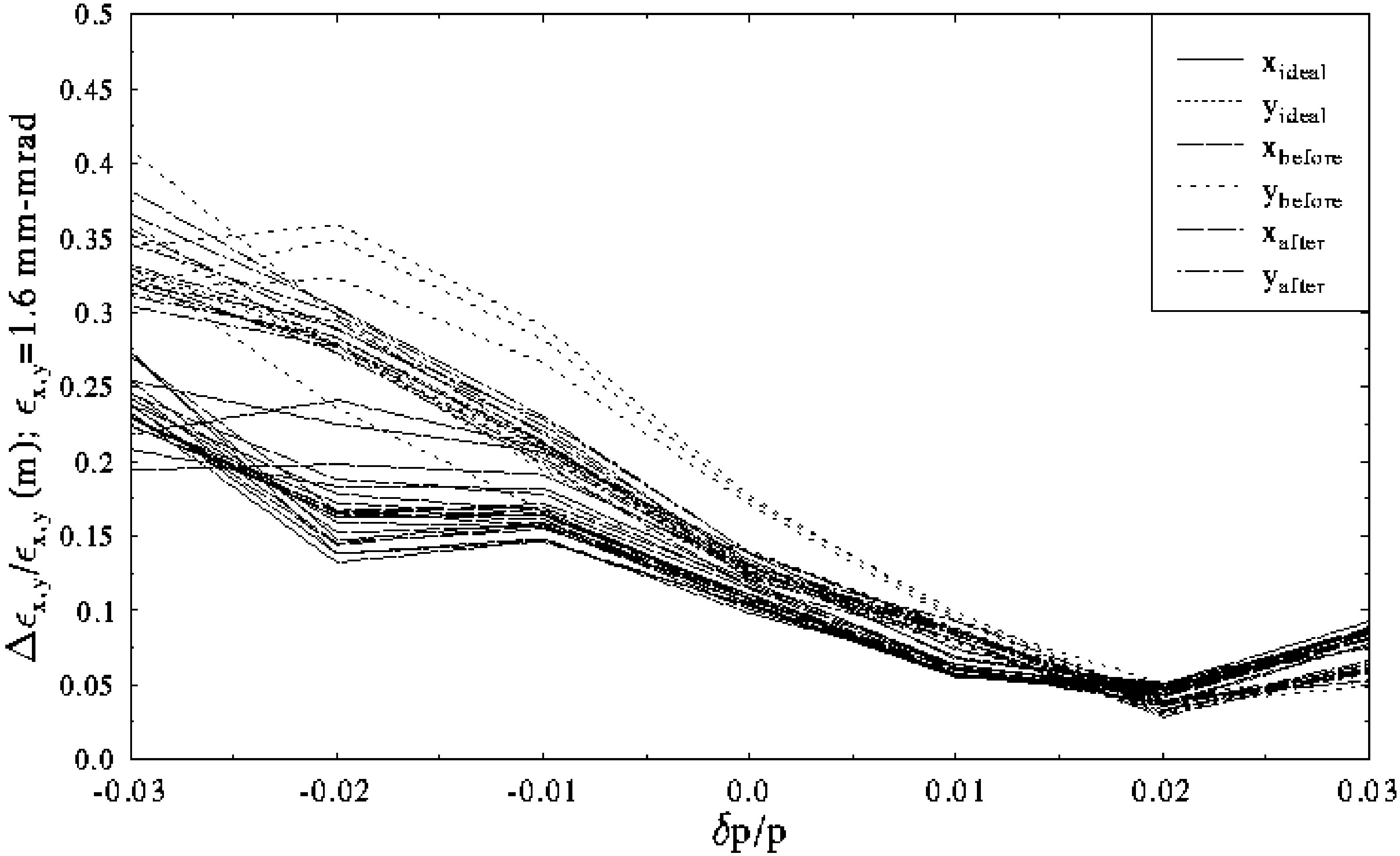
- Studies are ongoing, will be extended to
  - o include field inhomogenieties in magnets, cavities
  - o simulate space charge effect through acceleration/energy recovery cycle
  - o support commissioning and operational activities



0.1
0.08
0.06
0.04
0.02
0.0
-0.02
-0.04
-0.06
-0.08
-0.1
x, y (m)
x
y
0
10
20
30
40
50
60
70
80
s (m)
0.1
0.08
0.06
0.04
0.02
0.0
-0.02
-0.04
-0.06
-0.08
-0.1
x, y (m)
x
y


$\beta_{x,y}$ (m)
$\alpha_{x,y}$ (rad)
x,y (m)
x',y' (rad)
δl
$\nu_{x,y}$
$\delta p/p$
x_{ideal}
y_{ideal}
x
y
δl_{ideal}
δl


$\beta_{x,y}$ (m)
$\alpha_{x,y}$ (rad)
x,y (m)
x',y' (rad)
δl
$\nu_{x,y}$
$\delta p/p$
x_{ideal}
y_{ideal}
x
y
δl_{ideal}
δl



0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0.0
-0.03
-0.02
-0.01
0.0
0.01
0.02
0.03
$\delta p/p$
$\Delta\epsilon_{x,y}/\epsilon_{x,y}$ (m); $\epsilon_{x,y}$=1.6 mm-mrad
x_{ideal}
y_{ideal}
x_{before}
y_{before}
x_{after}
y_{after}

6 Conclusions

- Design meets requirements/performance criteria
- Construction in progress, injector beam operations underway
- Driver beam operations in late 1997; FEL operations in early 1998