Accelerator Transport Lattice Design Issues for High Performance ERLs

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Outline

- Abstract
- The ERL Design Process
- Incomplete Energy Recovery/Nonlinear Longitudinal Matching
- Transverse Matching: Chromatic Aberrations/Correction
- Collective Phenomena
- Halo
- Extrapolation to large-scale systems

Key Concepts in ERL Design

Some obvious to remind oneself when designing an ERL:

- ERLs are 6-dimensional systems
  - essentially time-of-flight spectrometer (well, maybe turned inside-out)
  - natural home for "emittance exchange"
- They are transport lines (not rings)
  - beam does not achieve equilibrium
  - "σ" not meaningful, in the sense of "I have 25 σ clear aperture"
    - designs must be observant of halo-imposed limitations
- ERLs do not have closed orbits
  - multiple passes may be in the same place - *but not at the same energy and/or time*
  - overall transport may/need not be betatron stable – no guarantee there are unique "matched" Twiss parameters

    "beam envelopes" ⇎ "optimized lattice functions" not the same!
- ERLs do not recover energy, they recover RF power – and power flow management is critical to their operation
  - Put power where you want it, avoid putting it where you don't!

The Design Process

- Establish user requirements
- Characterize source properties
  - beam defined by gun: “it doesn’t get better than this…”
- Define longitudinal match
  - primary driver in machine configuration - sets RF drive, wall plug power…
- Define transverse matching process
  - dominates acceptance: chromatic/geometric aberration management
  - must provide focusing tolerable to multiple beams at different energies on different passes
- Review/revise design (iterate) to address emergent issues
  - collective effects
  - power flow management (propagating HOMs, scraping/halo, CSR, etc)
  - imperfections in design, fabrication, installation of components

Longitudinal Matching in an ERL

- ERLs are – at one level - just systems for power management & distribution
- Significant power may go to users in the form of light – or be given up to phenomena such as HOMs, wakes, …
- Beam will degrade throughout acceleration/use/recovery
- Phase space gymnastics thus require
  - use of RF to compensate beam quality degradation
    - energy compression during energy recovery
  - use of RF power to cover user's power draw
- Can mitigate through optimization of longitudinal match

accelerated/recovered passes balance imperfectly

and/or

$E_{dump} \neq E_{injected}$ (imbalance may be < or >)

FEL Driver Energy Recovery: Details

Injector to Wiggler

- Inject long, low-energy-spread bunch (avoid LSC)
- Chirp on the rising part of the RF waveform
  - also counteracts LSC
  - phase set-point determined by
    - injected bunch length
    - required momentum spread at wiggler
- Compress (with nonlinear compensation) using recirculator compactions M_{56}, T_{566}, W_{5666},…

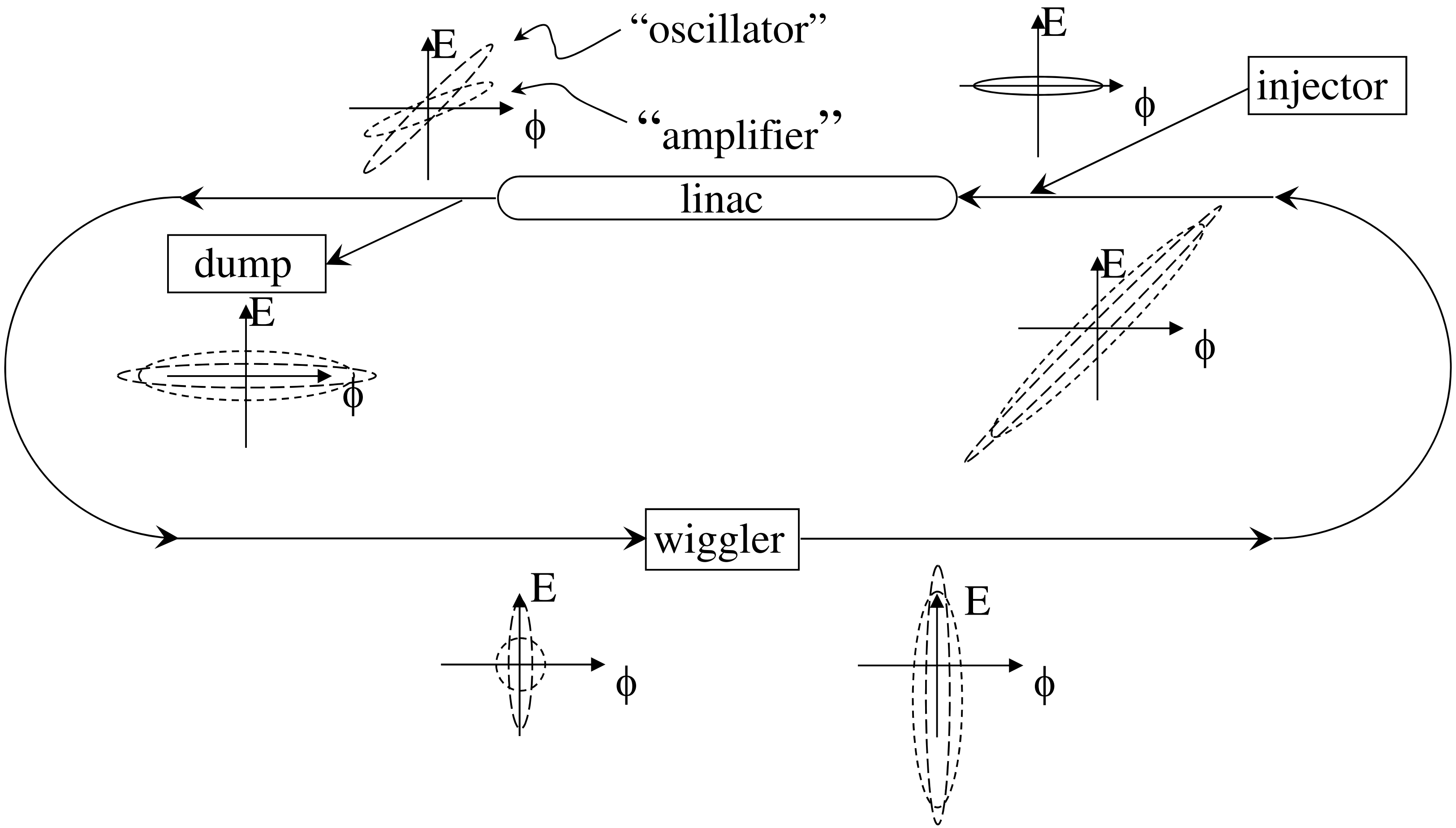
generates parallel-to-point longitudinal image from injector to wiggler

Longitudinal Match to Dump

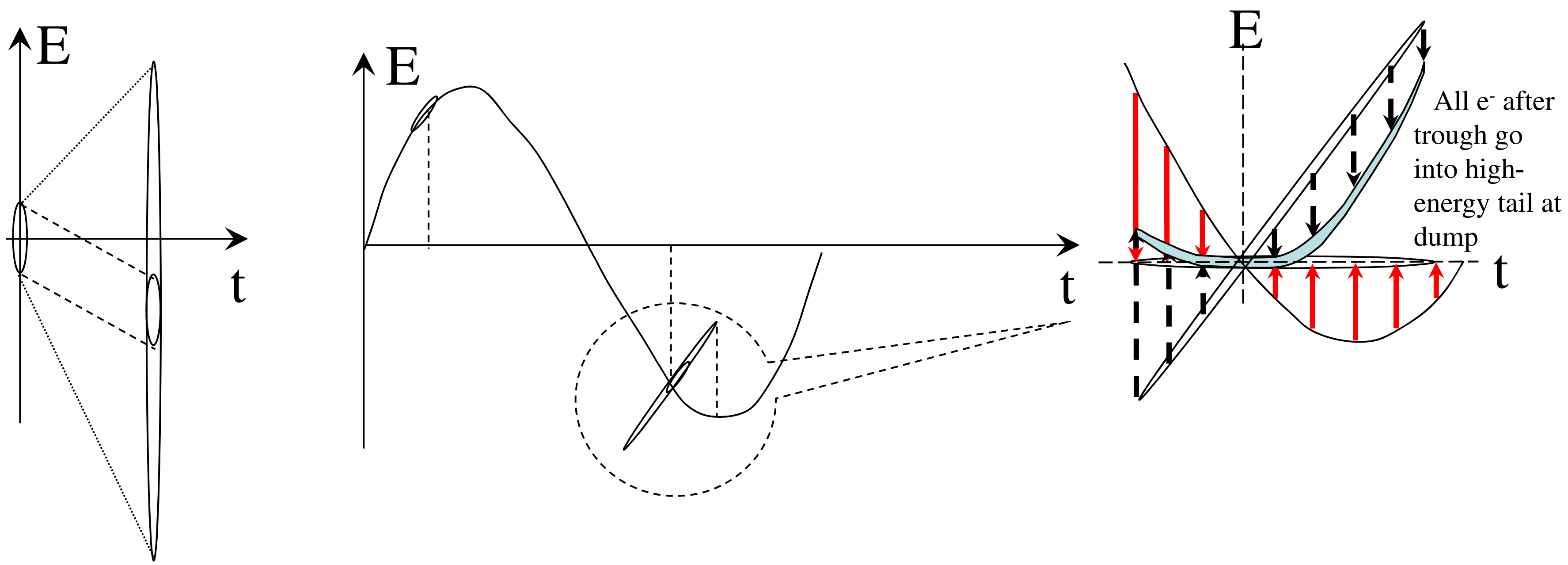
- Exhaust bunch short (<psec), large energy spread (10-15%)
  - compress energy spread during recovery to (avoid beam loss)
  - compactions (M_{56}, T_{566}, W_{5666},…) match beam to slope, curvature, torsion,… of RF waveform
- Recovered bunch *not* 180^o out of phase with accelerated
  - not all power recovered (“incomplete energy recovery”)
  - drives RF requirements (transient control…)
- Energy & energy spread at dump don’t depend on FEL efficiency, exhaust energy/energy spread
  - Only temporal centroid and bunch length change as lasing conditions change

constitutes point-to-parallel longitudinal imaging from wiggler to dump

Longitudinal Matching for FEL Driver ERL



Energy Compression During Recovery



- Beam central energy drops, beam energy spread grows
- Recirculator energy must be matched to beam central energy to maximize acceptance
- Beam rotated, curved, torqued to match shape of RF waveform
- Maximum energy can't exceed peak *deceleration* available from linac
  - Corollary: entire bunch must precede trough of RF waveform

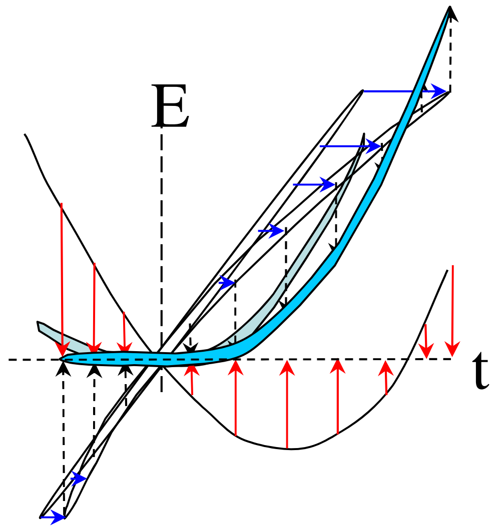
Higher Order Corrections

- Without nonlinear corrections, phase space becomes distorted during deceleration
- Curvature, torsion,… can be compensated by nonlinear adjustments
  - differentially move phase space regions to match gradient required for energy compression
- Required phase bite is $\cos^{-1}(1-\Delta E_{FEL}/E_{LINAC})$; at modest energy this is

  >25^o at RF fundamental for 10%

  >30^o for 15%

  - typically need 3^{rd} order corrections (octupoles)
  - also need a few extra degrees for tails, phase errors & drifts, irreproducible & varying path lengths, etc, so that system operates reliably
- In this context, **harmonic RF very hard to use…**



$$M_{56} = -\frac{\lambda_{RF}}{2\pi}\left(\frac{E_0}{E_{linac}}\right)\frac{1}{\sin\phi_0}$$

$$T_{566} = -\frac{1}{2}\left(\frac{2\pi}{\lambda_{RF}}\right)(M_{56})^2\frac{\cos\phi_0}{\sin\phi_0}$$

$$W_{5666} = -\left[\frac{1}{6}+\frac{1}{2}\frac{\cos^2\phi_0}{\sin^2\phi_0}\right]\left(\frac{2\pi}{\lambda_{RF}}\right)^2(M_{56})^3$$

$$U_{56666} \propto \left(\frac{2\pi}{\lambda_{RF}}\right)^3(M_{56})^4, \text{etc.}$$

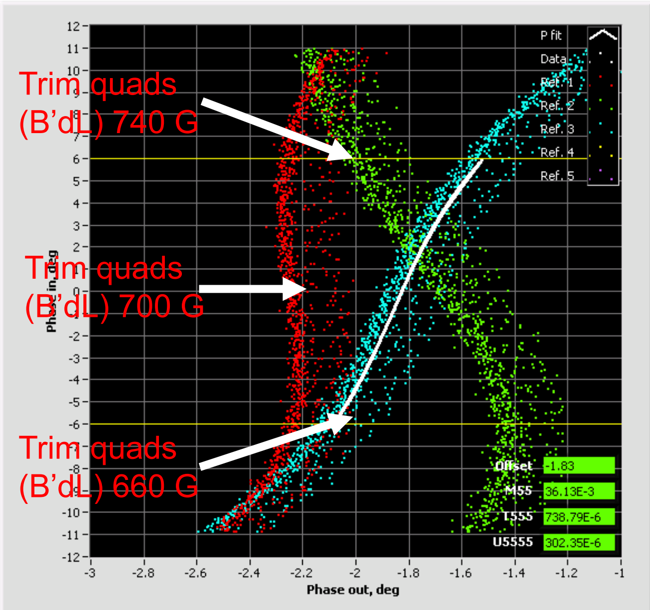
Key Features of Longitudinal Matches

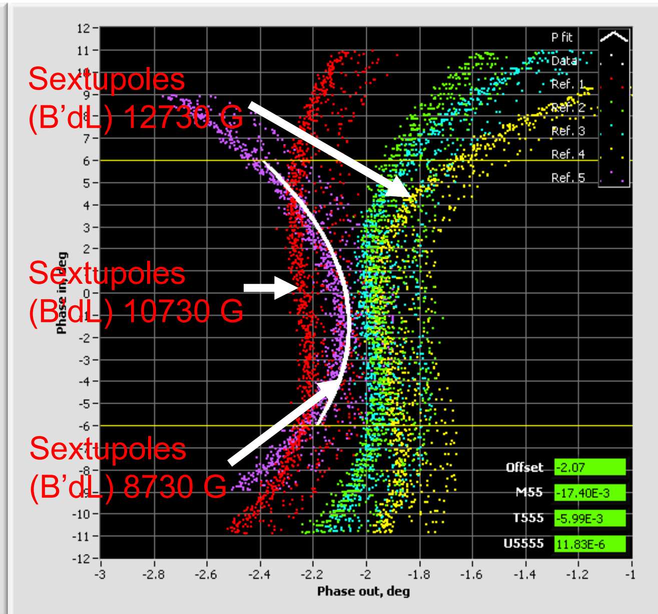
- Energy recovery can be **incomplete**
  - $E_{dump} \neq E_{injected}$
  - RF imbalance/transients define RF drive requirements
- **Chicanes unnecessary** for bunch compression
  - can achieve $M_{56}<0$ by dispersion modulation
  - can compress with $M_{56}>0$ by accelerating on falling part of RF waveform ("after crest")
- **Nonlinear compensation**
  - harmonic RF unnecessary
  - can correct curvature, torsion,… with sextupoles, octupoles, … in transport system

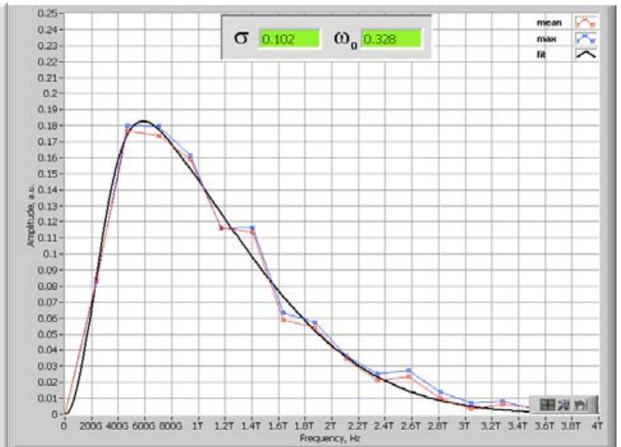
JLab FEL bunch compression and diagnostics

courtesy Pavel Evtushenko

- JLab IR/UV Upgrade FEL operates with bunch compression ration of 90-135 (cathode to wiggler); 17-25 (LINAC entrance to wiggler).
- To achieve this compression ratio nonlinear compression is used – compensating for LINAC RF curvature (up to 2nd order).
- The RF curvature compensation is made with multipoles installed in dispersive locations of 180° Bates bend with separate function magnets - D. Douglas design (no harmonic RF)
- Operationally longitudinal match relies on:
  a. Bunch length measurements at full compression (Martin-Puplett Interferometer)
  b. Longitudinal transfer function measurements R_{55}, T_{555}, U_{5555}
  c. Energy spread measurements in injector and exit of the LINAC





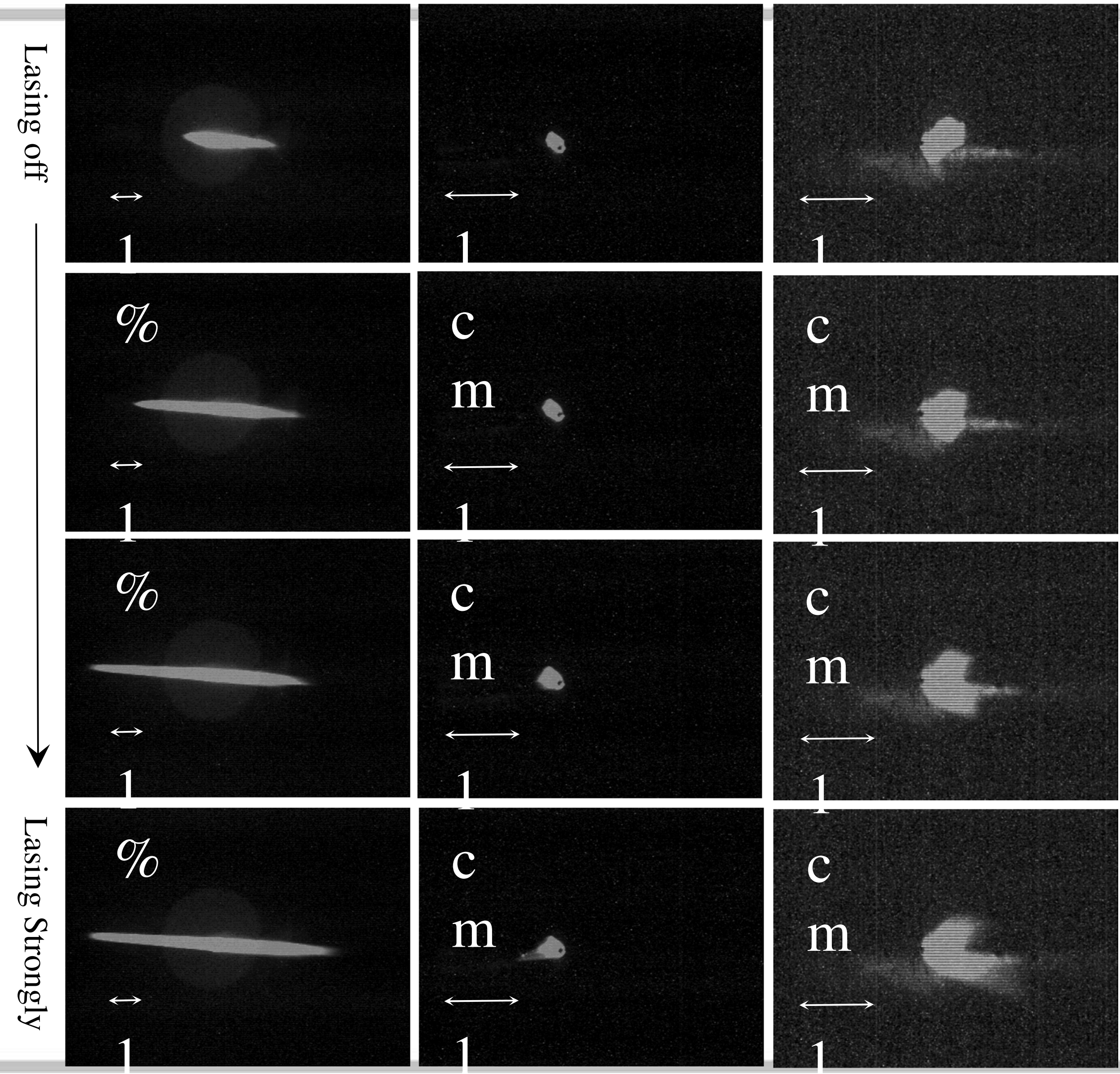


Martin-Puplett Interferometer data in frequency domain – give upper limit on the RMS bunch length

Transverse Matching

- Must include
  - details of RF focusing (esp. at low energy)
  - space charge effects
  - Capture pass-to-pass variation of focusing -
    - multiple beams of differing energy in same quad(s)
- Have to
  - avoid mismatch of core beam
  - control halo (provide focusing knobs that tune halo independently of core beam)
    - e.g., quads at points of small core beam envelope
  - suppress chromatic/geometric aberrations
- *Transverse match is key driver of acceptance*
  - Chromatic variation of beam envelopes lead to phase space distortion

Center of 180° bend Following arc Middle of reinjection match



Certify Designs With "Old School" Ring Characterization: Momentum Scans

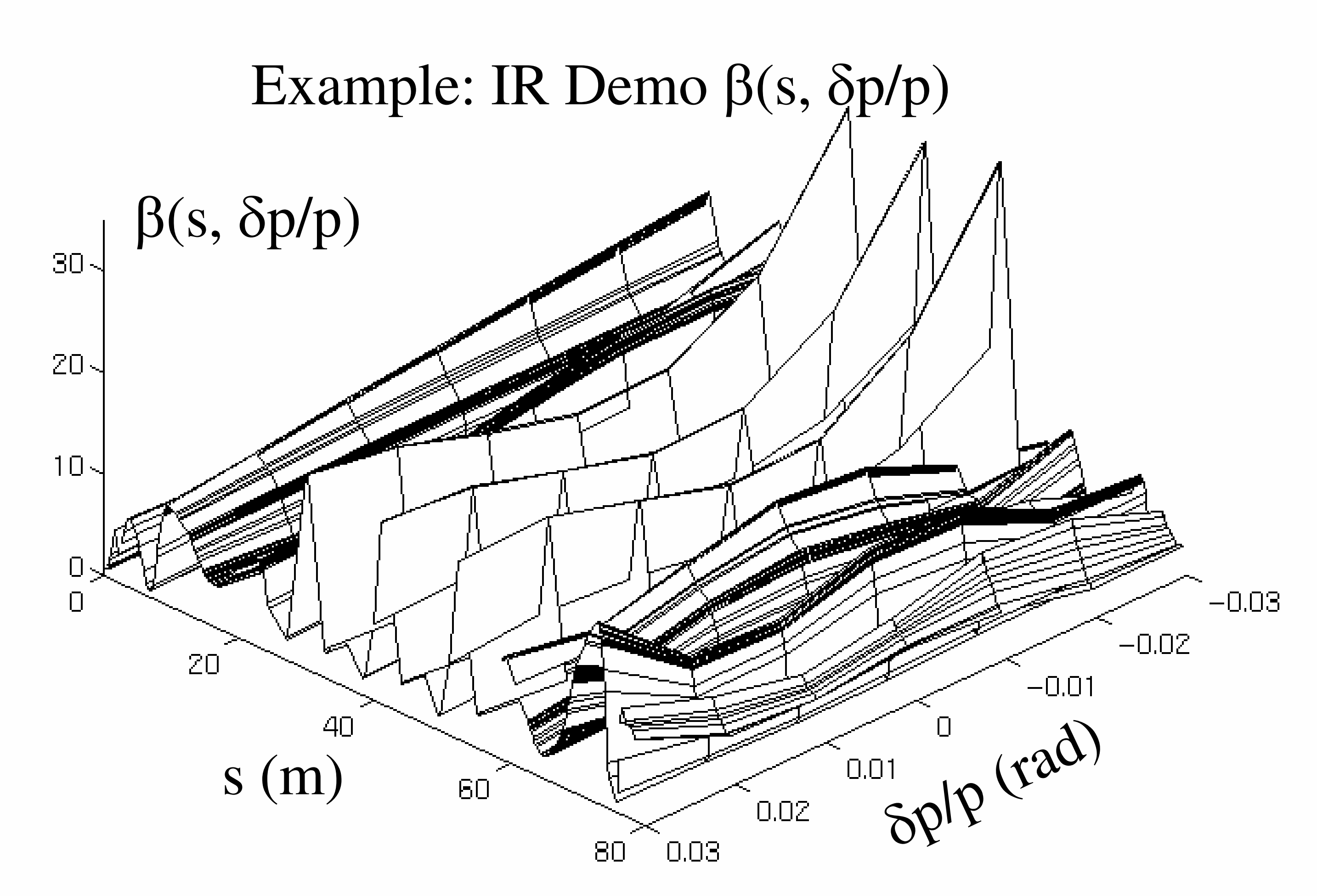
- Evaluate spatial transfer function (4x4 matrix) & reference orbit at numerous momenta over some range

$$M(\delta p/p):(x_i,x_i',y_i,y_i') \rightarrow (x_f,x_f',y_f,y_f')$$
$$(0,0,0,0) \text{ -> } (x_o(\delta p/p),\ x_o'(\delta p/p),\ y_o(\delta p/p),\ y_o'(\delta p/p))$$

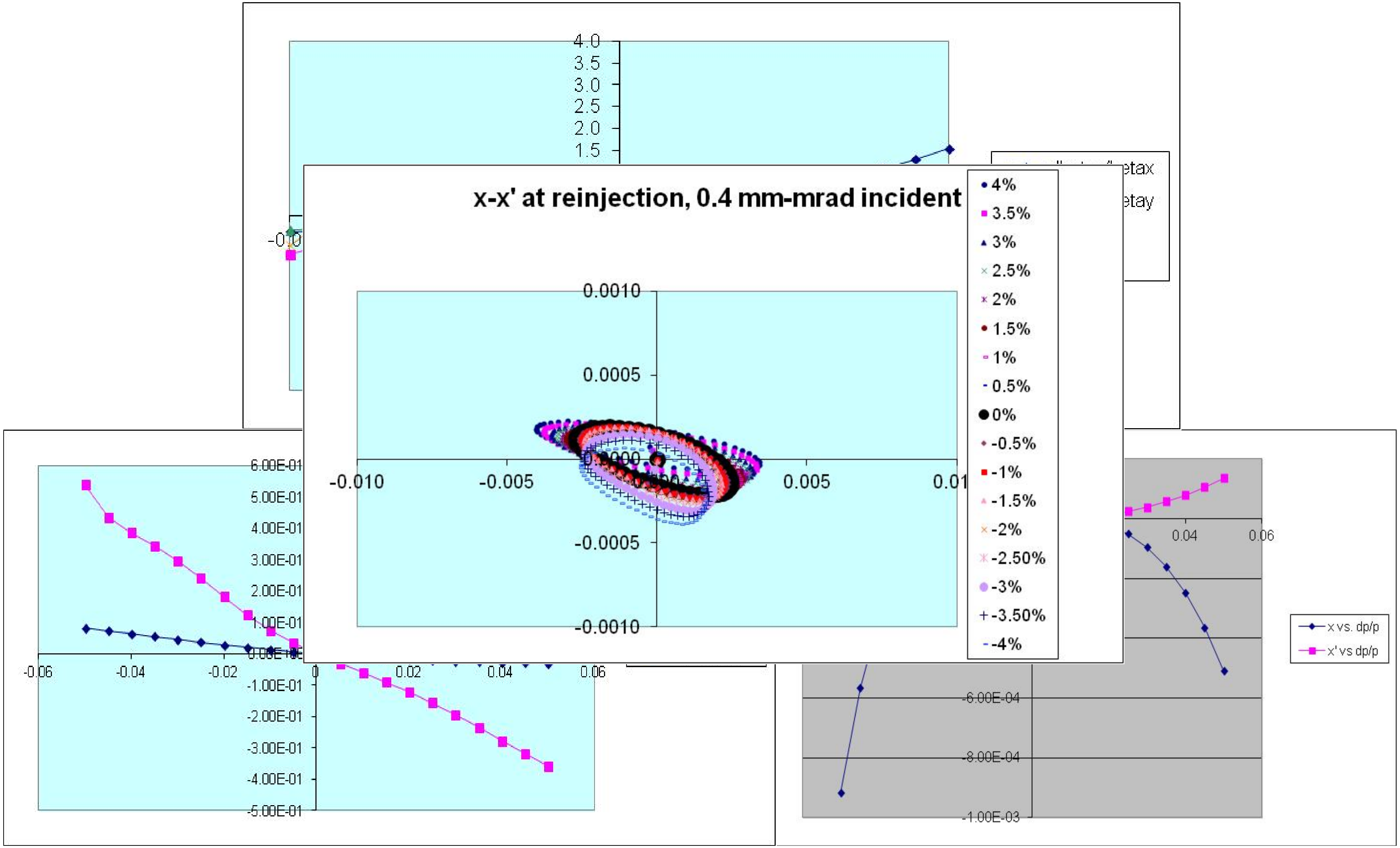
- Use result to propagate notionally matched beam envelopes for monoenergetic beam for each momentum
- Design system to keep $\beta(\delta p/p)$, $\alpha(\delta p/p)$, $x(\delta p/p)$, $x'(\delta p/p)$,… invariant over the full momentum range
  - Typically have to invoke multiple sextupole families;

    and/or
  - construct destructive interferences amongst quad telescopes
- Must avoid introducing *geometric* aberrations when correcting chromatics

IR Demo - β(s,δp/p)

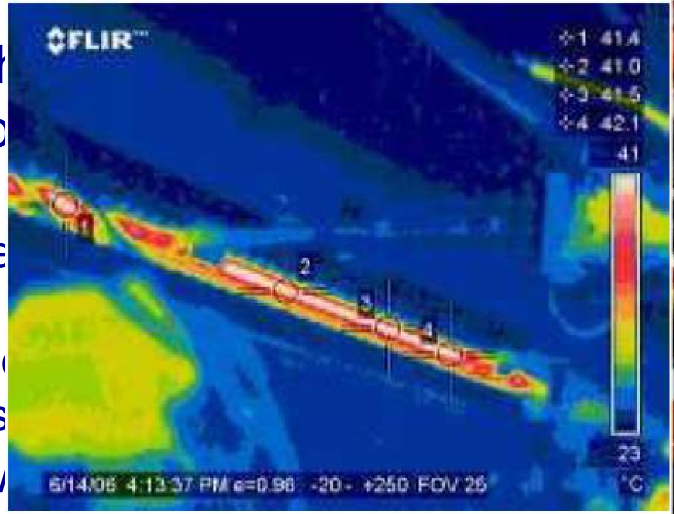


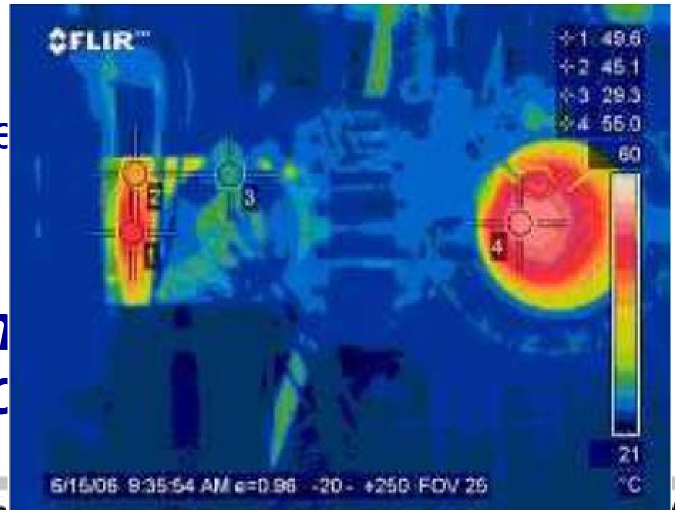
Momentum Scans/Geometric Aberrations



Collective Effects

- ERLs live to generate high
- Collective effects are a “lo
- JLab systems have been
  - Longitudinal space charge
  - BBU (limited current)
  - CSR (potential emittance
  - Enviromental wakes, resis
- Larger/brighter systems w
  - Intrabeam scattering, Touschek effect, beam/gas scattering formation, beam loss)
- Must be able to observe, characterize, quantify effects
  - e.g. power into HOMs for BBU
  - Disentangle source of inappropriate behavior
    - e.g. poor dispersion suppression vs. lattice energy shift from CSR…





Lattice must support diagnosis, con compensation, and suppression c

Examples

- LSC
  - LSC limited JLab IR Upgrade performance
    - "fix" by changing longitudinal match: inject longer bunch (with larger emittance)

Best injected emittance doesn't give best delivered emittance…

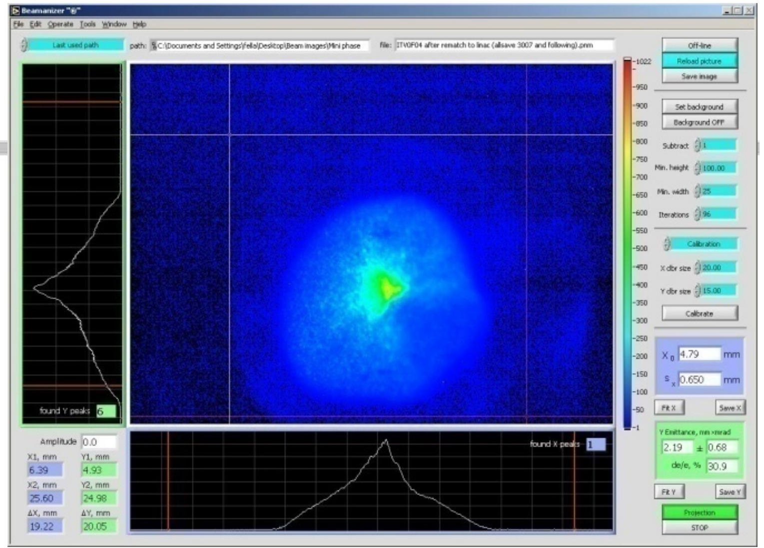
- BBU
  - Various control options available
    - compensate by direct feedback on modes or beam ($$$)
    - suppress by choice of phase advance/turn-to-turn transform
      - Most effective in short linac
    - Eliminate with phase space exchange (only works for single-loop system)

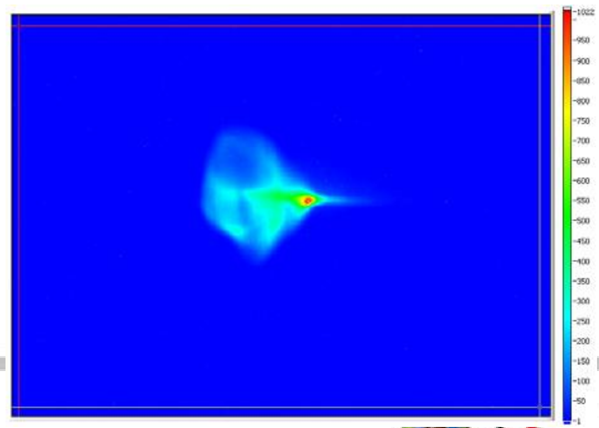
6d design

- CSR
  - Avoid parasitic compressions
    - Can avoid in systems with M_{56}>0 (at cost of potential LSC hit during acceleration)
    - Not entirely possible in systems with M_{56}<0
      - "final" compression occurs in semifinal dipole (M_{56}>0 in last dipole)
  - virtue in abrupt final compression at point of large dispersion?
    - dispersion modulation with final dispersion correction in small angle dipole

Halo

- Huge operational problem
- Many potential sources
  - Ghost pulses from drive laser
  - Cathode temporal relaxation
  - Scattered light on cathode
  - Cathode damage
  - Field emission from gun surfaces
  - Space charge/other nonlinear dynamical processes
  - Dark current from SRF cavities…
- We see multiple sources
  - CW beamlets at various energies (even with beam off)
  - large-amplitude energy tails
  - spatial halo (e.g. at wiggler)
  - Tends to be mismatched to, out of phase with, core beam
- Much tune time spent getting halo to “fit”
  - can’t throw it away – get activation & heating damage;
  - can’t collimate it, (“it just gets mad…”)
  - We “tweak” it through –this might not work a large system….
    - Look at activation patterns, beam loss, tune on BLMs





Halo Issues

- Calibration: like to keep loss to W/m levels
  - 100 mA x 5 GeV = ½ GW full energy
  - 1 km full length => 1 kW integrated loss
  - ΔI/I ~ 1000/500,000,000 = **2 ppm loss**
- "But I have 25σ aperture!!!"
  - **It's not a ring** – it doesn't reach equilibrium – **beam is not Gaussian**
  - Overall transport need not be betatron stable – no guarantee there are "matched" Twiss parameters
  - "beam envelopes" and "optimized lattice functions" not the same
  - Halo is mismatched to core beam & propagates with different envelopes

    beam and lattice are different
  - "σ" not meaningful, in the sense of "I have Nσ clear aperture"

    must observe halo-imposed limitations

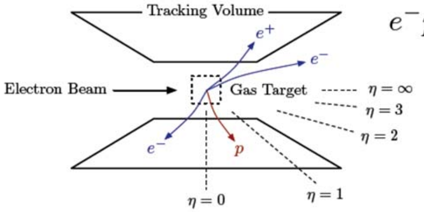
Think of it as the injection chain for ring – if ppm loss occurs during ring fill/top-off, loss* will *be issue in ERL!

Halo Mitigation

- Lattice design requirements:
  - locations to disentangle halo from core
    - large dynamic range diagnostic development
  - knobs for independent control of halo & core
  - allowance for collimation systems to protect long, small gap undulators
    - multiple stages with appropriate phase separation

DARKLIGHT

Electron-Proton Collisions

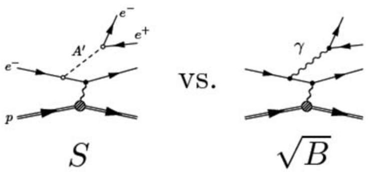


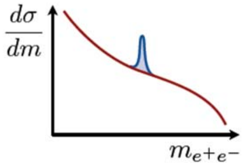
$$e^- p \to e^- p + A'$$
$$\hookrightarrow e^+ e^-$$

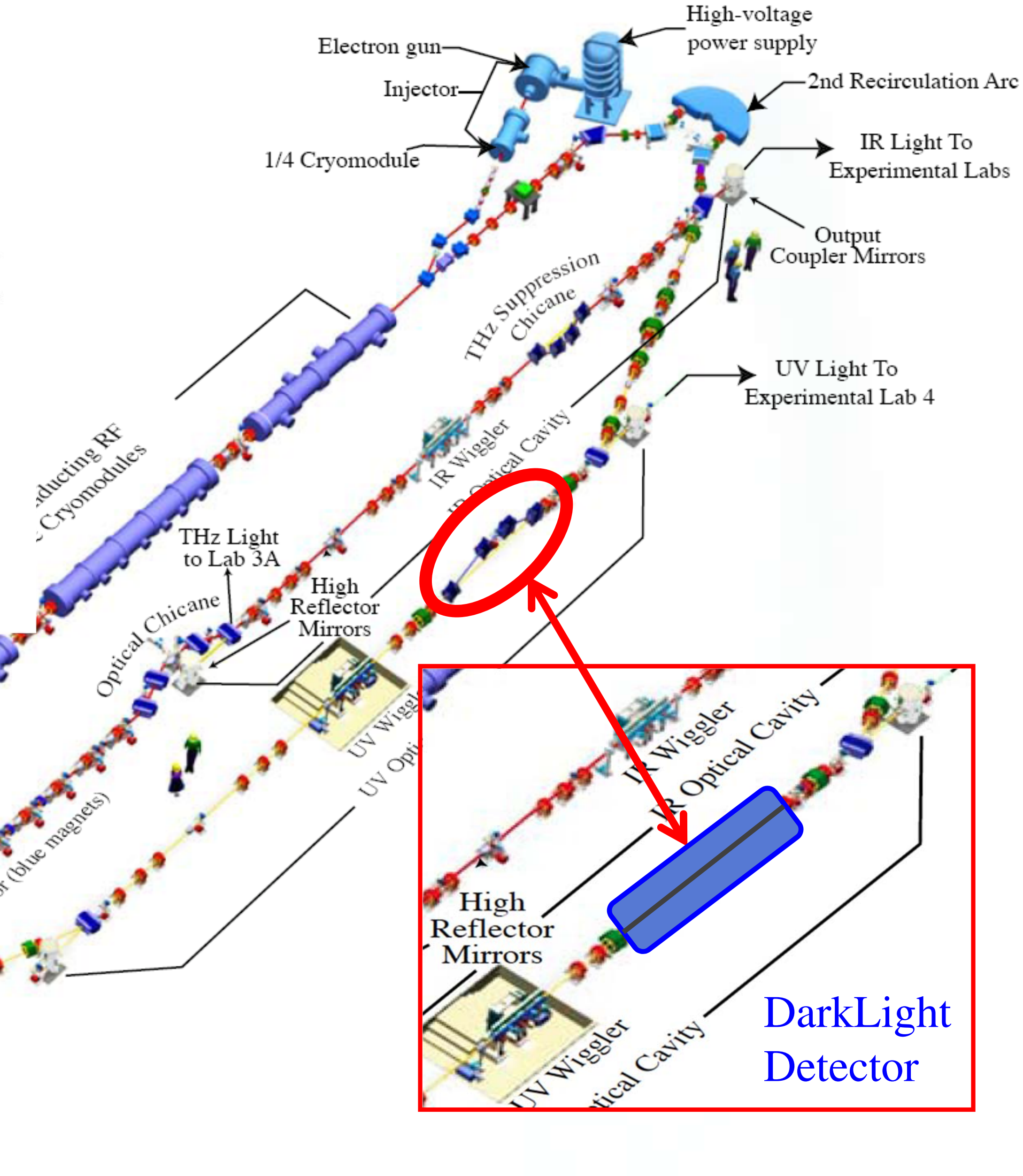
$E_{\mathrm{beam}} \lesssim 140$ MeV

ab^{-1}/month

Narrow Resonance on Huge QED Background







Issues for Large Systems

- Multi-pass focusing & steering in linac
  - "graded gradient" focusing, "shielded linac", various other schemes provide means of accommodating common focusing of multiple beams at various energies
  - Split/asymmetric linac(s) to control beam envelopes
- Accomodations for beam dynamics
  - ISR, CSR, BBU, wakes, scattering…
- Halo
- Dynamic range ($E_{full} \Leftrightarrow E_{injection}$)
  - Degradation of phase space $\Leftrightarrow$ adiabatically anti-damping to low energy (exceeding dump acceptance)
  - Magnet field quality

Magnet Field Quality

Provides significant obstacle to ERL performance:

- differential field error =>
- differential angular kick =>
- differential betatron oscillation =>
- accumulated path length error=phase error=>
- energy error=>
- failure of energy compression/beam loss at dump

May have been source of performance-limiting loss in CEBAF-ER during operation with 20 MeV injection

Sets limits on tolerable field errors

ERL Field Quality Requirement

- $\Delta B \Rightarrow \delta x' = \Delta Bl/B\rho = (\Delta B/B)\,\theta$ (dipole)
- $\delta x' \Rightarrow \delta l = M_{52}\,\delta x'$
- $\delta l \Rightarrow \Delta E_{dump} = E_{linac} \sin \phi_0\,(2\pi\,\delta l/\lambda_{RF})$

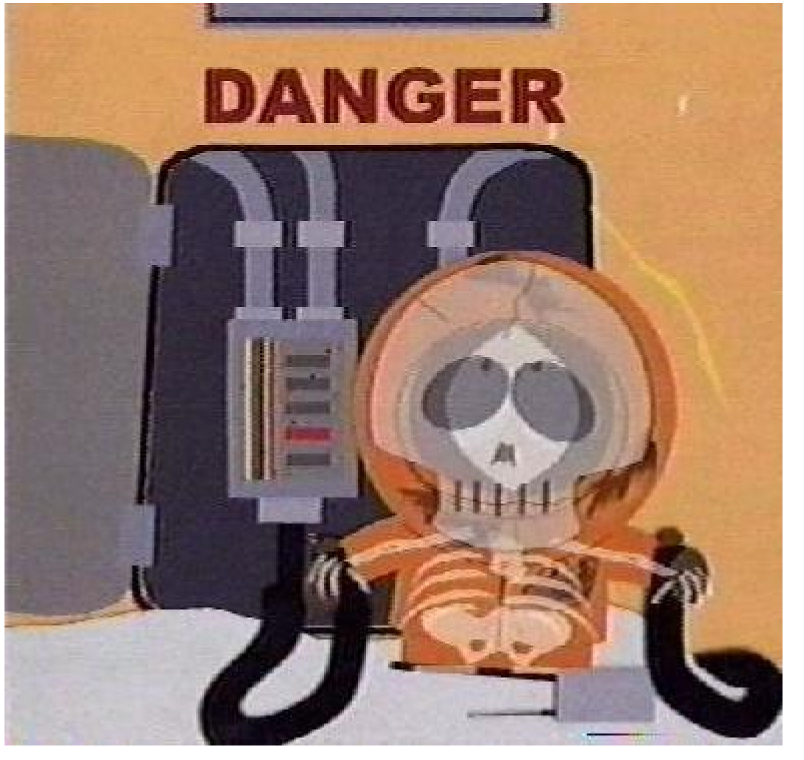
  $= E_{linac} \sin \phi_0\,(2\pi\, M_{52}(\Delta B/B)\theta/\lambda_{RF})$
- "Field quality" $\Delta B/B$ needed to meet budgeted ΔE_{dump} must improve (get smaller) for longer linac (higher E_{linac}), shorter λ_{RF}, larger dispersion ($M_{52}=M_{16}$)
- must
  - make better magnets
  - use lower energy linac
  - reduce M_{52} (dispersion)
  - provide means of compensation (diagnostics & correction knobs)

Put ANOTHER Way…

- $\Delta B \Rightarrow \delta x' = \Delta BI/B\rho \sim \Delta BI/(33.3564 \text{ kg-m/GeV} * E_{linac})$
  (field error integral)
- $\delta I \Rightarrow \Delta E_{dump} = \sin \phi_0 \, (2\pi \, M_{52}(\Delta BI/33.3564 \text{ kg-m})/\lambda_{RF})$
  (GeV)
- "Error field integral" ΔBI is *independent* of linac length/energy gain
  - tolerable relative field error falls as energy (required field) goes up
- Numbers for Jlab FEL driver:
  - $\Delta E_{dump} \sim 3400 \text{ MeV} * (\Delta B/B)$
    (which we see: we have 10^{-4} and see few 100 keV)
  - $\Delta E_{dump} \sim 1.6 \text{ keV/g-cm} * (\Delta BI)$

Conclusions

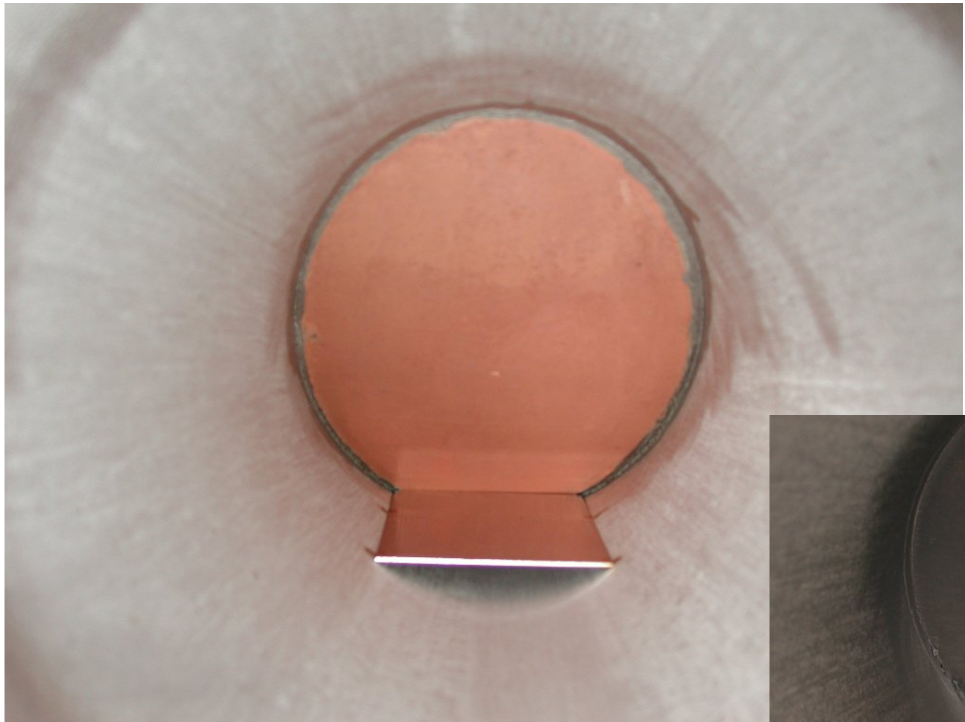
- Path forward to higher power/higher energy/higher brightness is clear, but challenging…
- We're doomed



Backups

- LSC
- BBU
- CSR

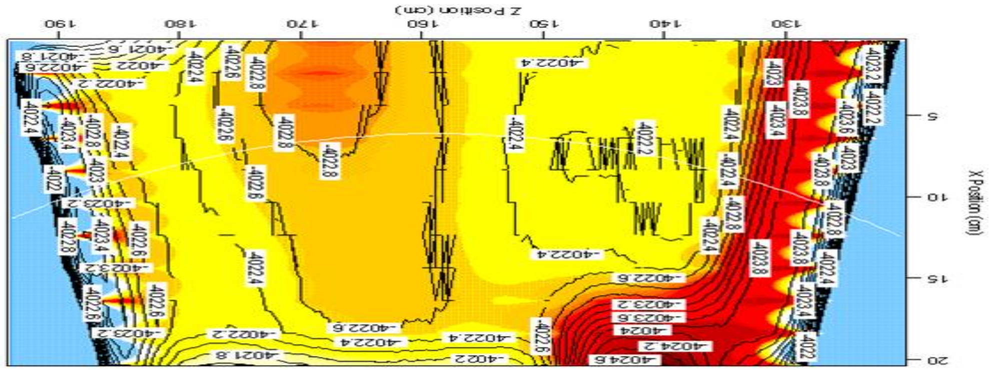
JLab IR Demo Dump

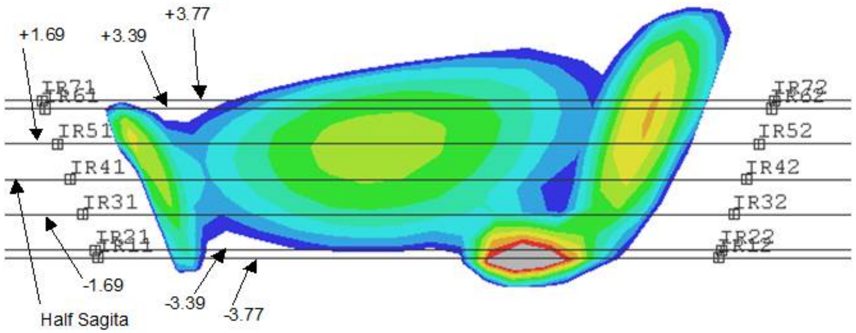


core of beam off center,
even though BLMs showed
edges were centered
(high energy tail)

Achieved Magnet Field Quality

Magnet field quality is excellent so as to avoid corruption of longitudinal phase space/impediments to energy recovery





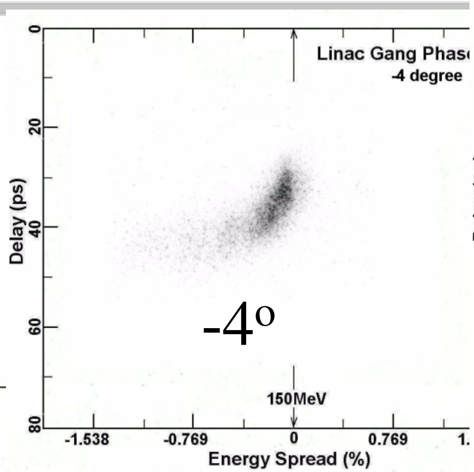
- e.g. "GX" at 145 MeV/c
  - Top: measured field
  - Bottom: design calculation
    (contours @ 1/2x10^{-4})

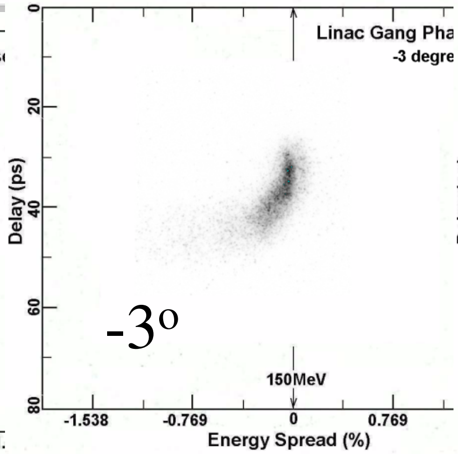
  (Thanks to George Biallas, Tom Hiatt & the magnet measurement facility staff, Chris Tennant, and Tom Schultheiss)

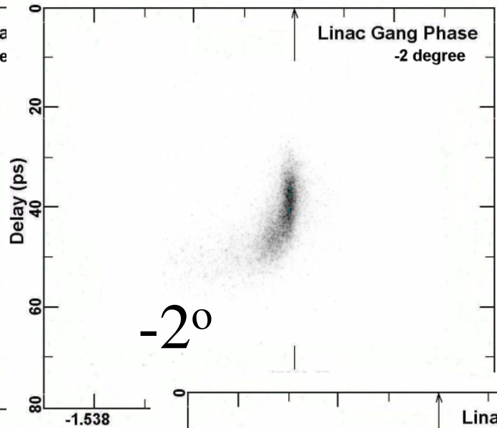
In our system - reproducibility:

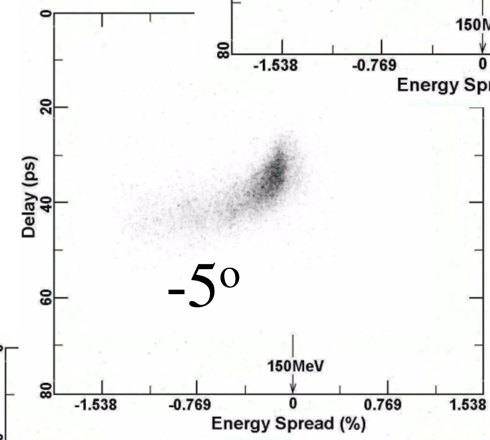
- Large magnets – great
- Small magnets – bad (consumes a lot of tune time)

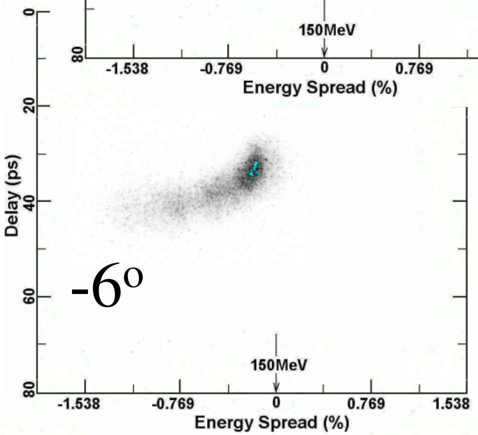
LSC: Streak Camera Data, IR Upgrade



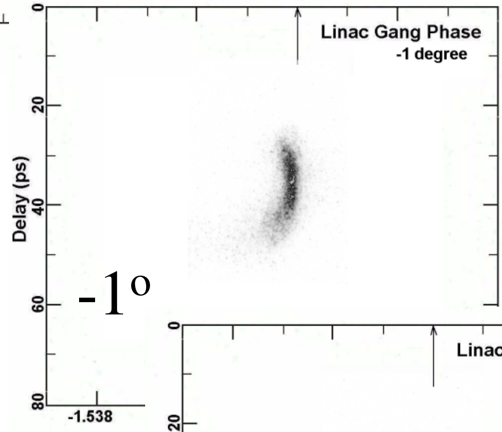


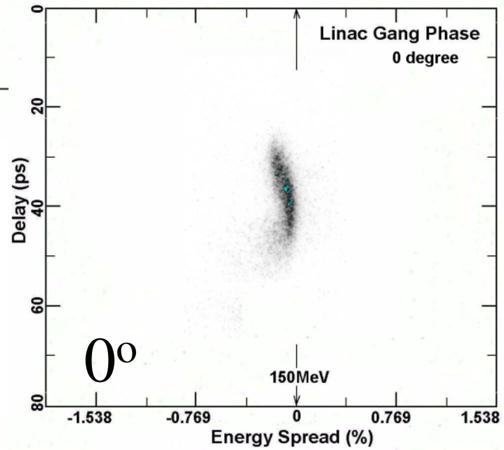






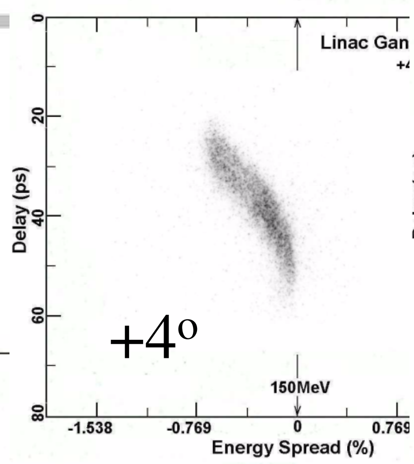
(t,E) vs. linac phase after crest

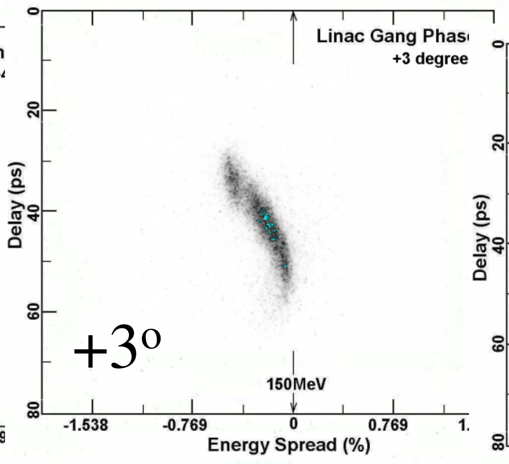


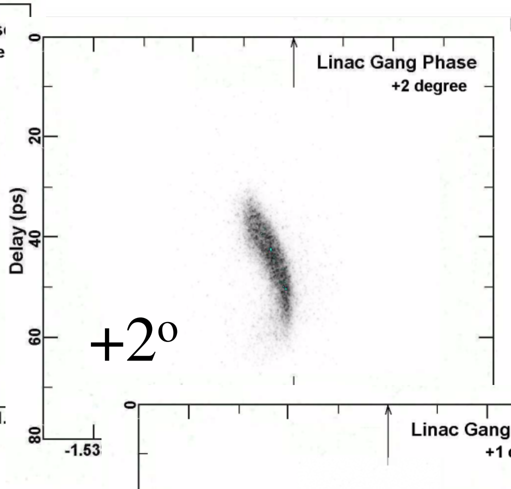


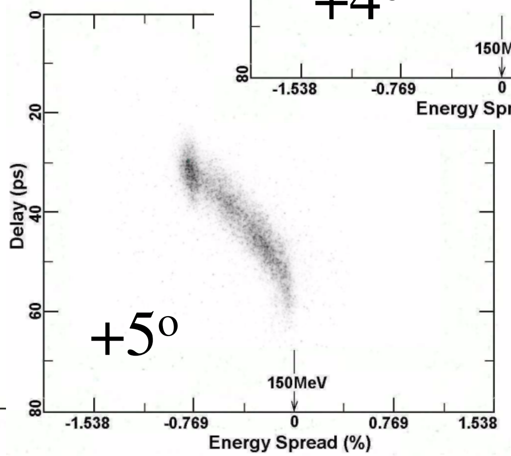
(data by S. Zhang, v.g. from C. Tennant)

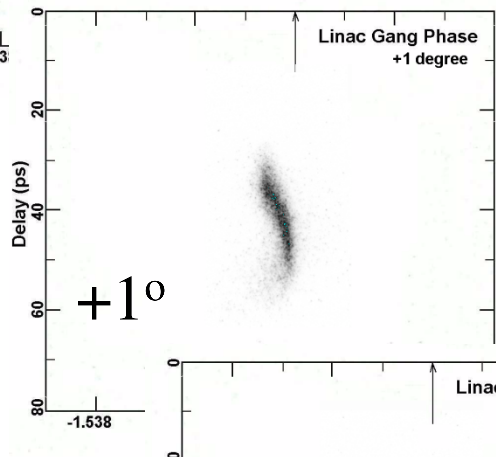
IR Upgrade, cont.

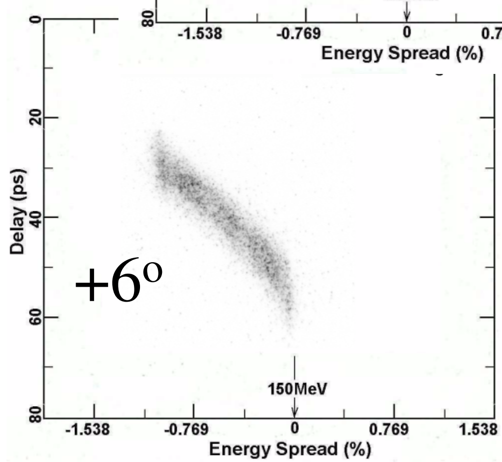


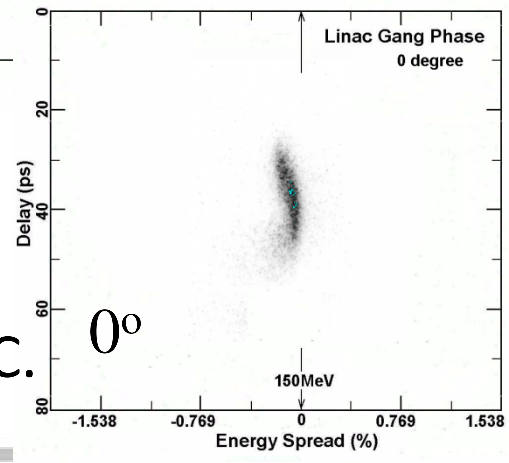










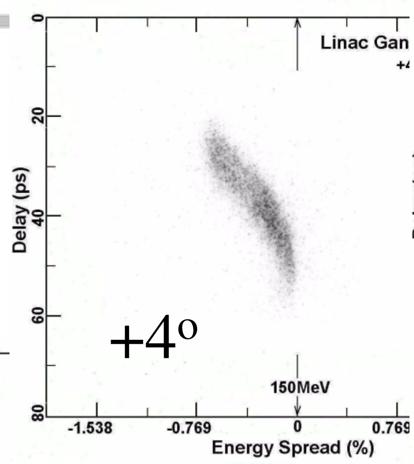


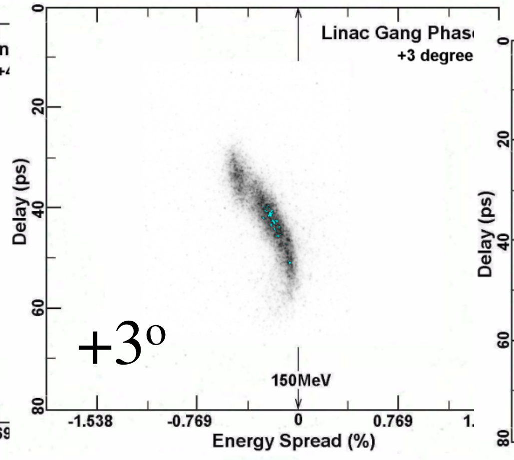
(t,E) vs. linac phase, before crest

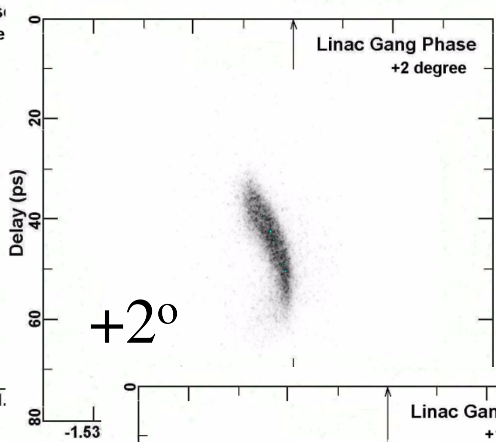
asymmetry between + and - show effect of longitudinal space charge after 10 MeV

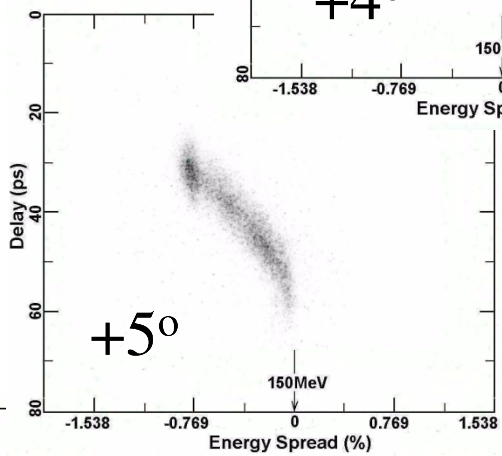
(data by S. Zhang, v.g. from C. Tennant)

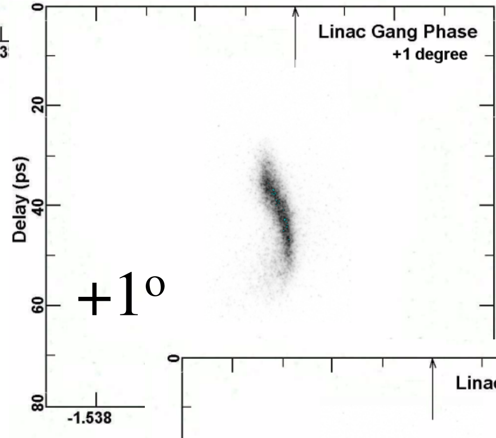
IR Upgrade, cont.







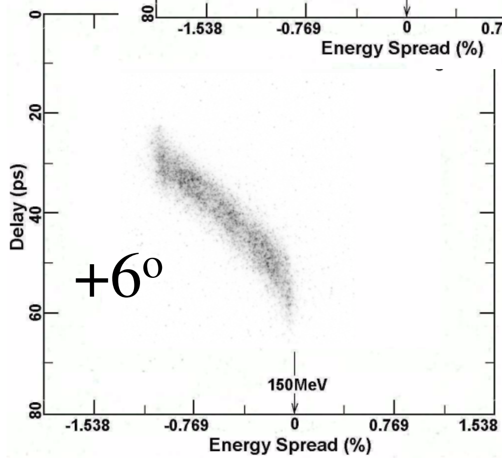


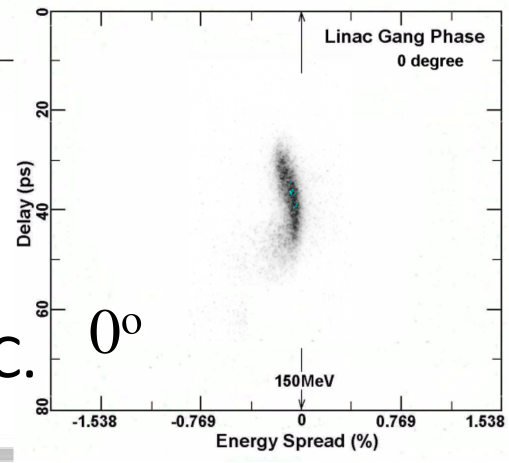


(t,E) vs. linac phase, before crest

asymmetry between + and - show effect of longitudinal space charge after 10 MeV

(data by S. Zhang, v.g. from C. Tennant)

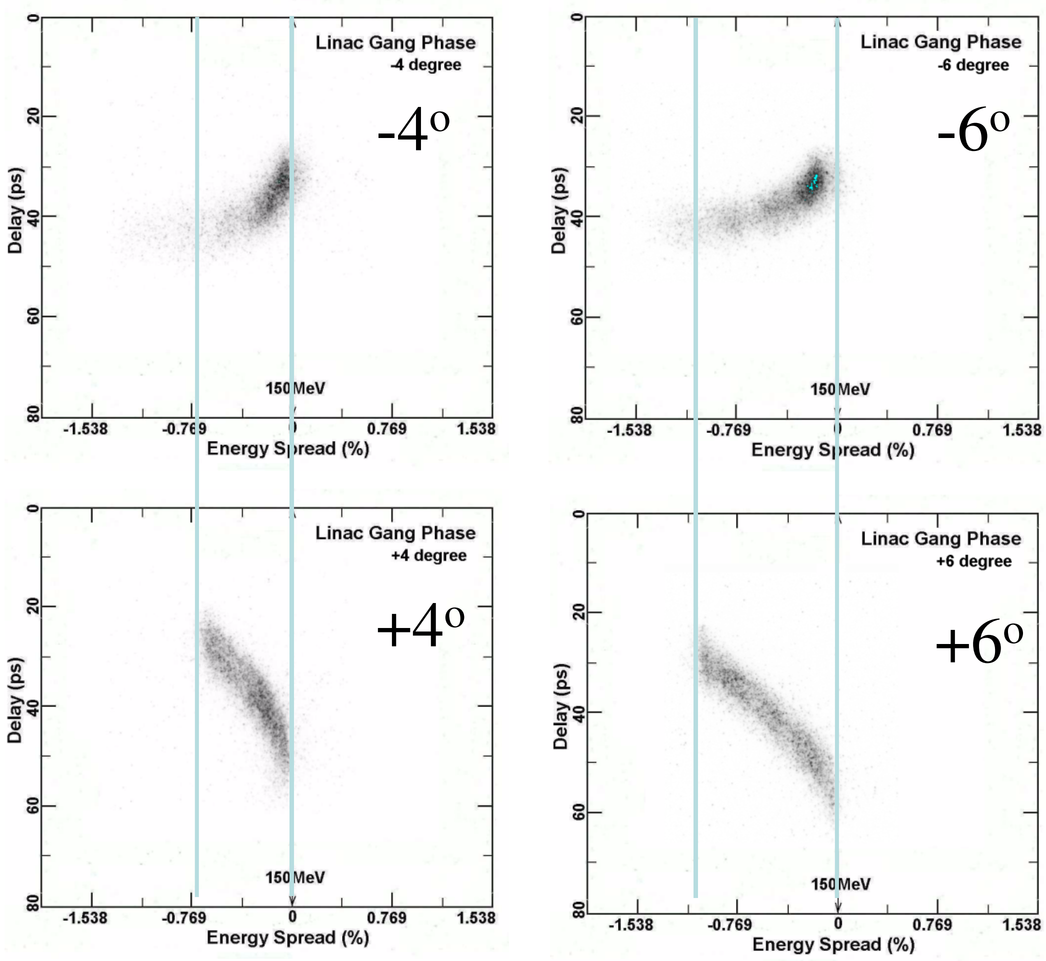


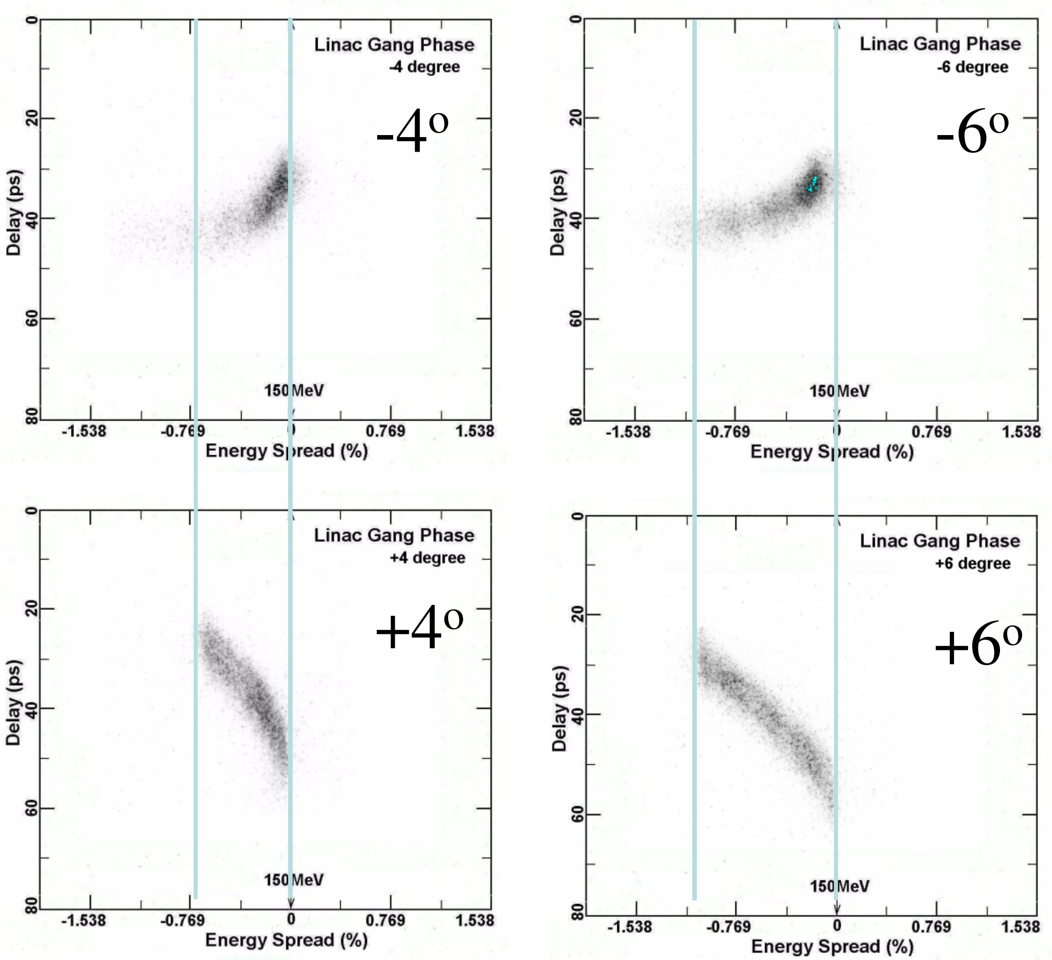


±4 and ±6 degrees off crest

- "+" on rising, "-" on falling part of waveform
- L_{bunch} consistent with dp/p and M_{56} from linac to observation point
- dp/p(-)>dp/p(+)
- on "-" side there are electrons at energy *higher* than max out of linac
- distribution evolves "hot spot" on "-" side (kinematic debunching, beam slides up toward crest…)

=> LSC a concern…




Linac Gang Phase
-4 degree
-4°
Delay (ps)
Energy Spread (%)
150 MeV
-1.538
-0.769
0
0.769
1.538
0
20
40
60
80
Linac Gang Phase
-6 degree
-6°
Linac Gang Phase
+4 degree
+4°
Linac Gang Phase
+6 degree
+6°

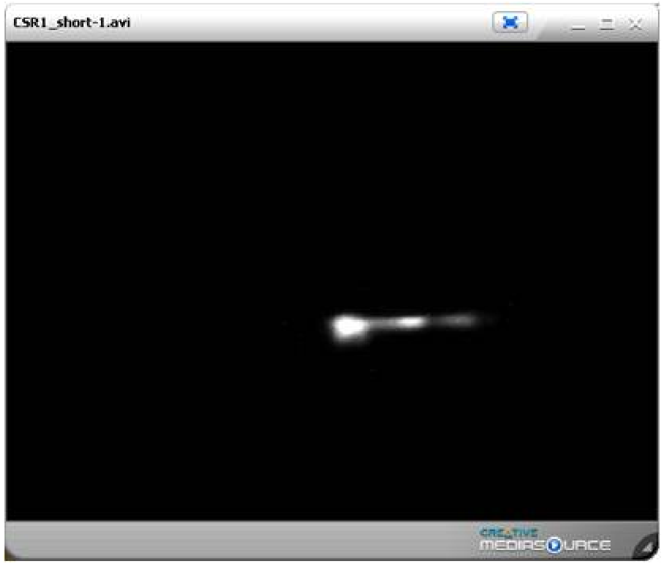
BBU

- Beam initially unstable at 2.5 mA
- After considerable effort, stability is usually a nonissue
  - A bad setup can have ½ mA threshold
  - A good setup can be absolutely stable (skew quad rotator)
  - Threshold sometimes lasing dependent (laser on>laser off) – but with bad match…
- Propagating modes *can* be an issue (well, a nusiance) – even at our low beam powers
  - High frequency from beam talks to cold window temp. monitors in waveguide; trips us off (CWWT)
  - Typically run masked, monitor values & determine response to beam is prompt, not thermal…
  - Good example of "power going to the wrong place at the wrong time"
- Needed good lattice diagnostics to control phase advance, betatron match, manage coupling & stabilize instability

BBU video courtesy C. Tennant

CSR/LSC

- 135 pC/0.35 psec bunch ~ 400 A peak current
- CSR/LSC effects evident
  - Enhanced by parasitic compressions (Bates bend)
  - Initial operation irradiated outcoupler – THz heating (next slide…)
  - Use CSR enhancement at tuning cue



CSR video courtesy K. Jordan