

ERL Drivers for FELs

(“Physics Issues for Modest Energy, High Power, FEL-Driving, Energy-Recovering Linacs”)

A tribute to Hunter S. Thompson

D. Douglas

Goal of Talk

- I struggled with what to say:
 - so many workshop participants the experts on the topics in question; you've been thinking about the physics while we've been off playing with spare (or "borrowed") CEBAF parts...
- Then, yesterday afternoon, an automotive analogy occurred to me...
 - ERL workshop participants – like design engineers for Mercedes-Benz, BMW, Infinity, or Ferrari – yesterdays talks discussed great ideas, had tremendous clarity, elegant designs & results
 - Our JLab SRF & CEBAF colleagues – like GM production engineers, building & operating robust, absolutely reliable, very cost effective systems
 - At the JLab FEL, we're like the guys at "Monster Garage" that wander in on Monday morning and ask, "Hey, what'll happen if we put that Chevy big-block V-8 in the '91 Volvo wagon?"

Usually, it doesn't work- but *every* so often it does...



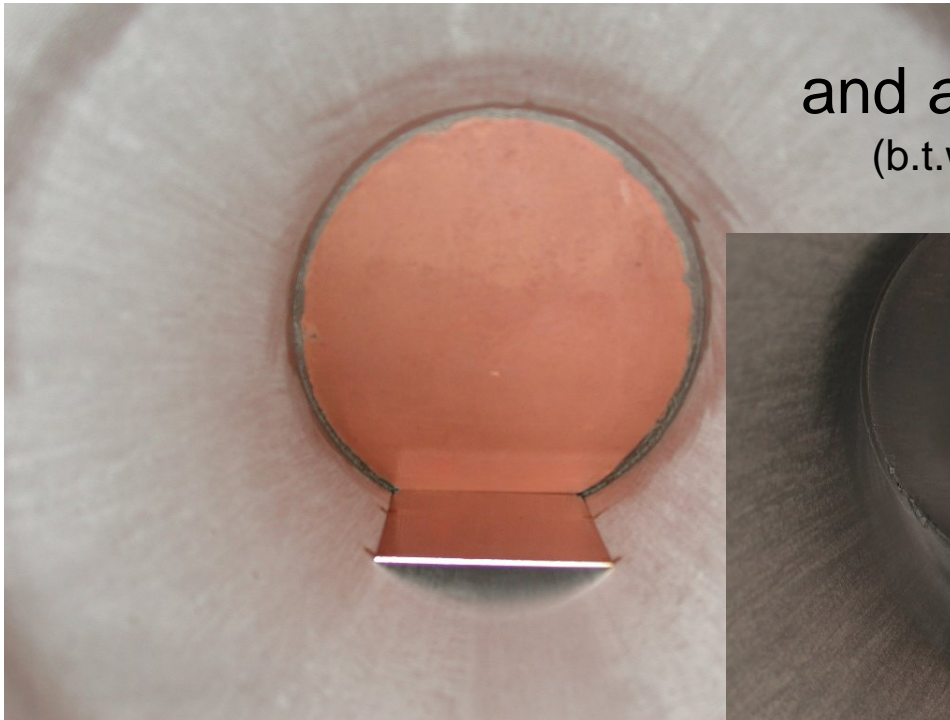
(my nephew and his boss rebuilt this '66 Goat)
and either way you learn a lot!

Philosophy of talk

- So, I thought I'd try to share with you the experiences we've had with ERLs here over the past 10 or 15 years
- This may help fiducialize the analyses and models, and tell you which effects have, in our corner of parameter space, proved problematic and which ones haven't...

True confessions...

- and, let you in on what we've burned up:



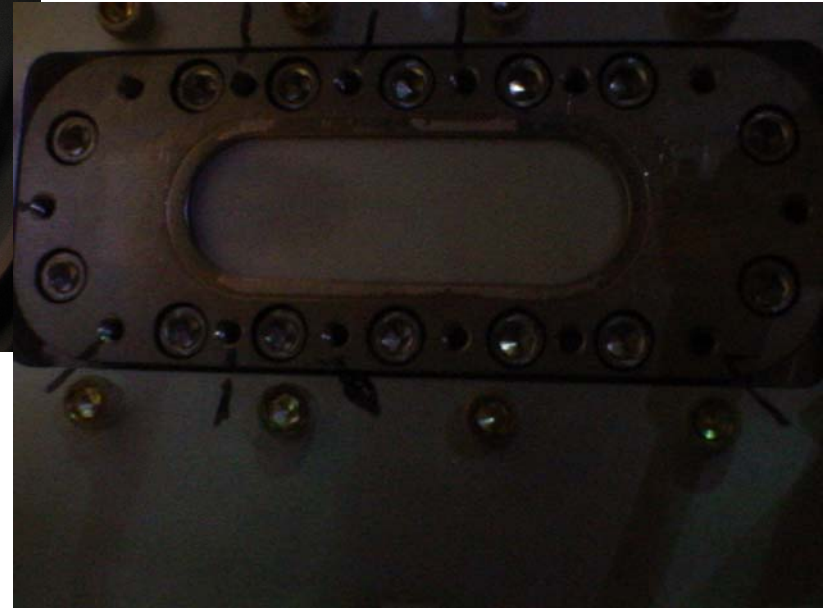
and *after* 2 years of 45 kW beam
(b.t.w., there's a reason for the location of the
sputtered stainless...)



Demo dump before,

And broken.

This used to be the emittance diagnostic (multislit) at linac injection.



And this is what an RF window looks like when you look to see if you cracked it (or its companions...)

Key points

- What FEL drivers are supposed to do
- Why they don't do it
 - physics issues that we encountered when dealing with our machines (audience participation encouraged – you'll pick the topics for discussion)
- Unsolicited advice

Design philosophy: The right machine exists for virtually any application. It is the designer's job to become common with its reality

(see Eugen Herrigel, Zen in the Art of Archery)

Technological philosophy: An FEL driver design is bricolage.

(see Douglas Harper, Working Knowledge, Skill and Community in a Small Shop)

Requirements on FEL drivers

- delivery to the user (FEL) of a beam with specific properties & quality
 - longitudinal & transverse phase space management
 - beam quality preservation
- recovery of exhaust beam from FEL
 - energy compression during energy recovery

Phase Space Management

- More or less, this means “get the matching right”
- “Transverse matching” seems pretty prosaic – “just measure the envelopes/emittance & set the quads”,
 - usually the intent is to control the beam size through the system and to produce an appropriate electron drive beam/optical mode overlap

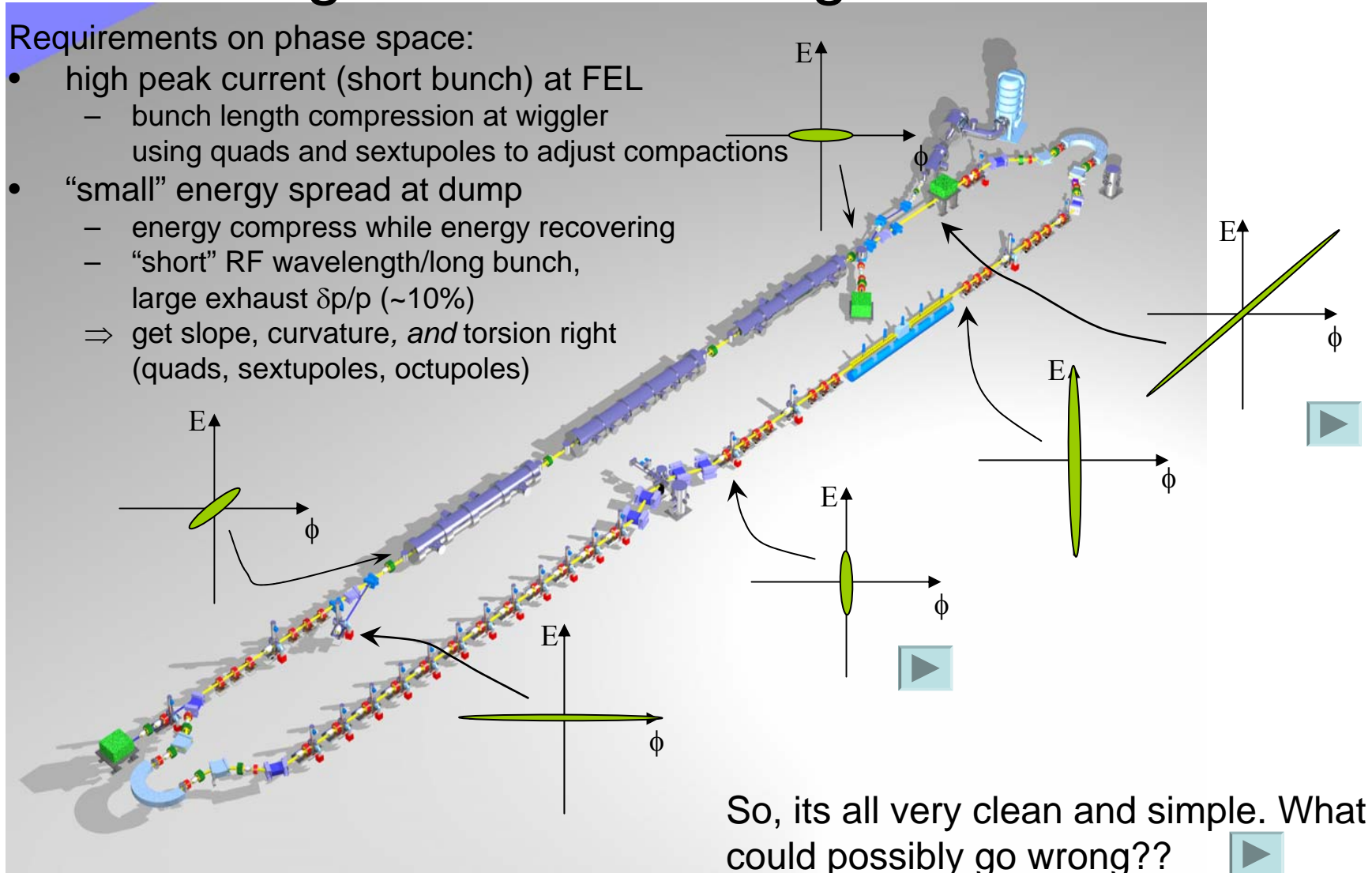
In practice, we waste more operational time on this issue than anything else

- 1st bit of advice: get decent quad power supplies!
- Longitudinal matching *is* pretty straightforward, “once you get your mind right”, as we say in the south - but I’ll review it just so you know what we do here.

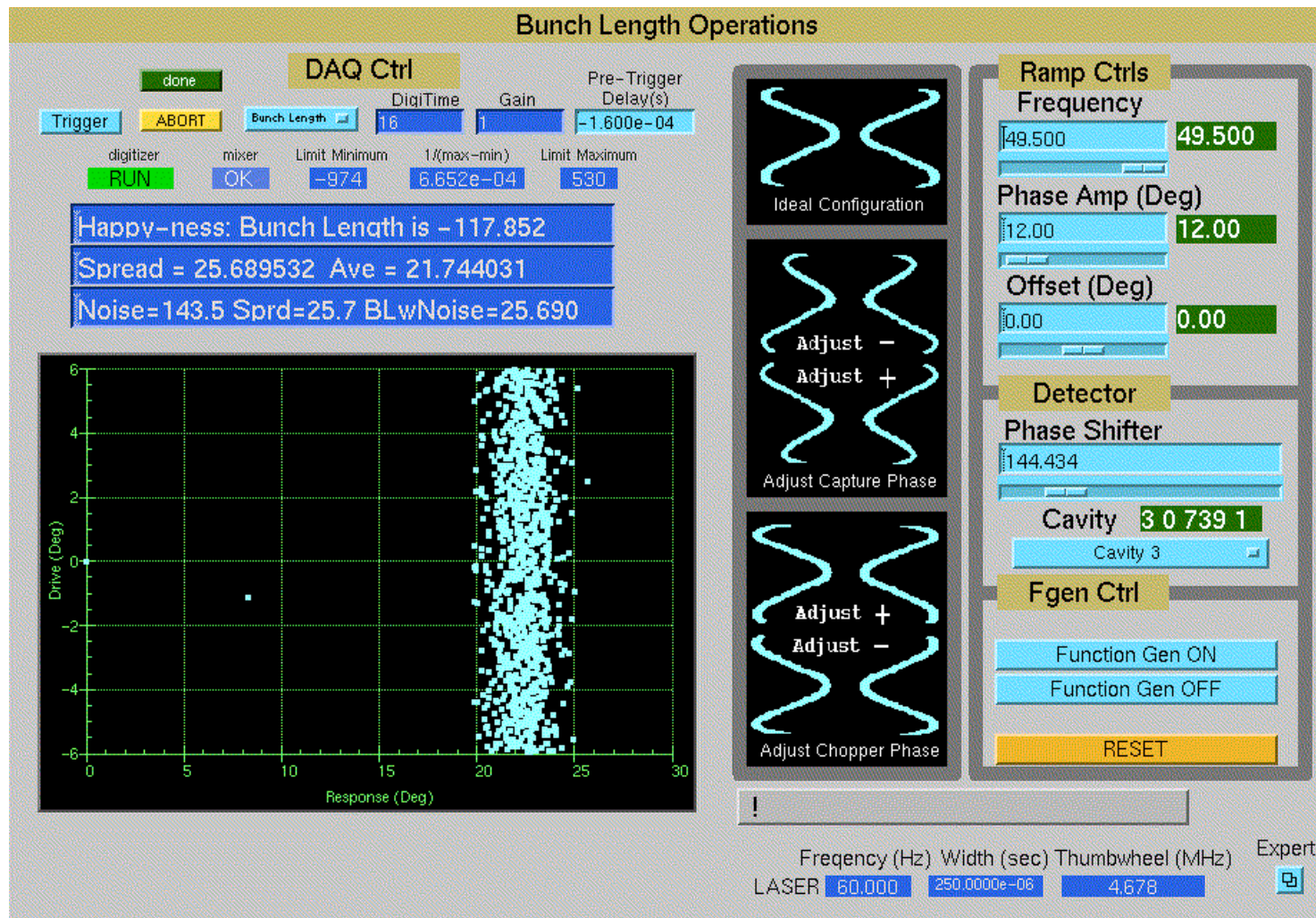
Longitudinal Matching Scenario

Requirements on phase space:

- high peak current (short bunch) at FEL
 - bunch length compression at wiggler
 - using quads and sextupoles to adjust compactions
 - “small” energy spread at dump
 - energy compress while energy recovering
 - “short” RF wavelength/long bunch,
 - large exhaust $\delta p/p$ ($\sim 10\%$)
- \Rightarrow get slope, curvature, and torsion right (quads, sextupoles, octupoles)



Injector to Wiggler Transport



Bunch Length at Wiggler

miniphase to 338 fsec - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://opweb.acc.jlab.org/CSUEApps/elog2/elog_item.php?elog_id=1225676

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1225676 miniphase to 338 fsec
21-Jul-04 09:21 D_Douglas FLOG

miniphased, got short bunch. Energy then shifted and longitudinal match changed, as indicated by the need to shift trim quads by +20 g to get csr to turn on

338 fsec isn't bad though, huh?

Figure 1

FEL Happed Interferometer - IR(Upstream)

Step Size (micron) 1.0
Number of Points 150
Number of Samples 1
Pre-Trig Delay (s) 4.000e-03
Current Position -1000.00

Mirror
Happed ☒
Viewer
Diode

Foil
Drop Foil
Raise Foil

Beam Current Plot
Manual Control

SAVE filename 072104a.scan
Saved in 072104a.scan

Start
Pause
Resume
ABORT

Moving
Stopped
0.002
Golay Cell

Intensity

Position (microns)

Golay Raw Data

FWHM (ps) = 0.338

~150 fsec rms

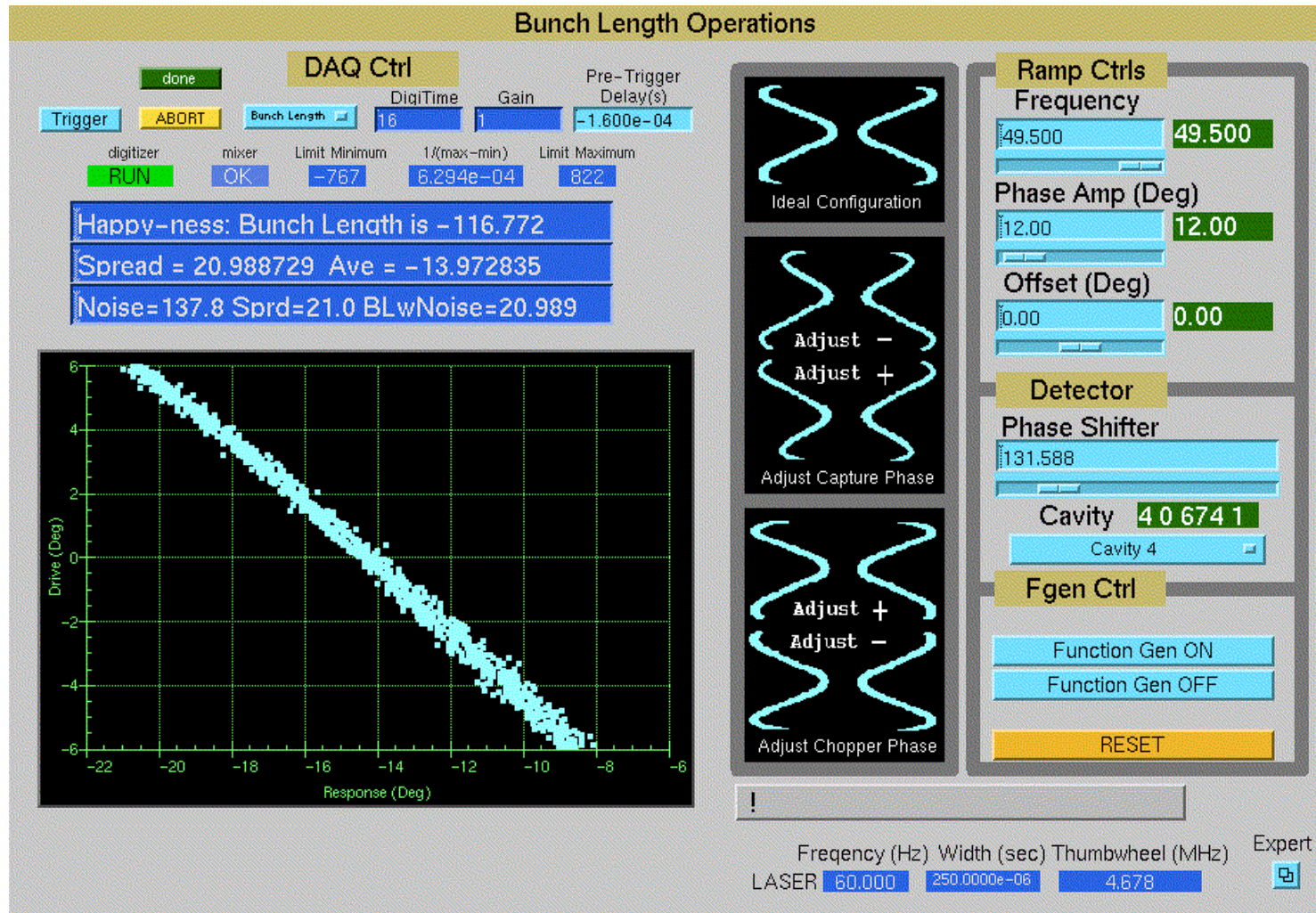
420 fs!

INDEX

Database query + PHP page generation time = 0 seconds

start may 2004 Injector talk NA... Yahoo! - Netscape miniphase to 33... Microsoft Power... Document1 - M... 4:31 PM

Injector to Reinjection Transport



Physics Issues (& who works on them here)

- [Beam formation & capture](#) (Hernandez-Garcia, Siggins, Benson)
- [BBU \(“solved”\)](#) (Pozdeyev, Tennant)
- [CSR](#) (Li, Williams, Neil, Zhang...)
- [environmental wakes/impedences](#) (Yunn, Merminga, Rimmer, Wang, Wu,...)
- [space charge](#) (Hernandez-Garcia)
- [modeling & design](#)
- [component quality](#)
- [transverse and longitudinal matching](#)



Proceed to
unsolicited advice

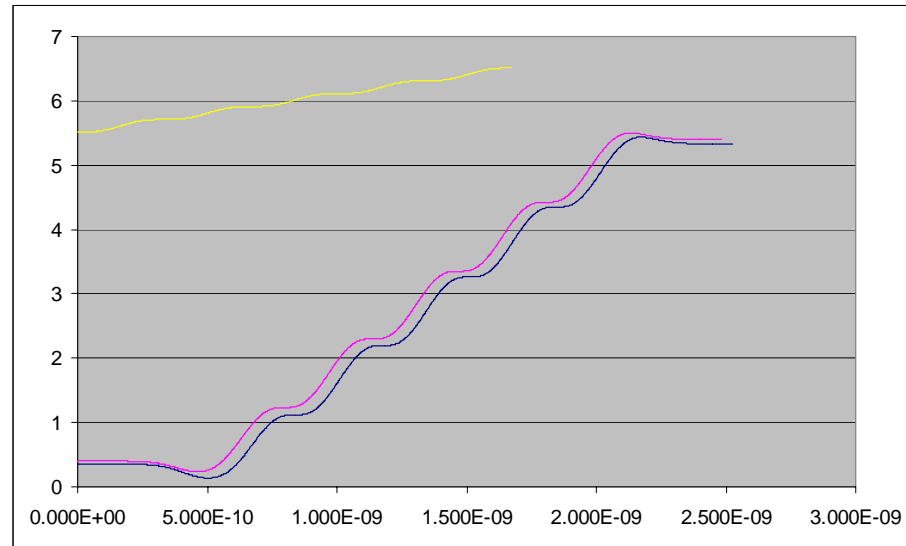
Beam formation and capture

- Carlos Hernandez-Garcia, Tim Siggins & Steve Benson can provide details
- Numerous features present themselves:
 - [deceleration by cavity fringe fields](#) (worse for low source voltage, for sure, worse for multi-cell cavities and at lower frequency?)
 - Multiple “stable” injection points
 - RF windows
 - [Halo](#)
 - Cathode lifetime (500+ C => ~10 min @ 1 A)



Deceleration by cavity fringe fields

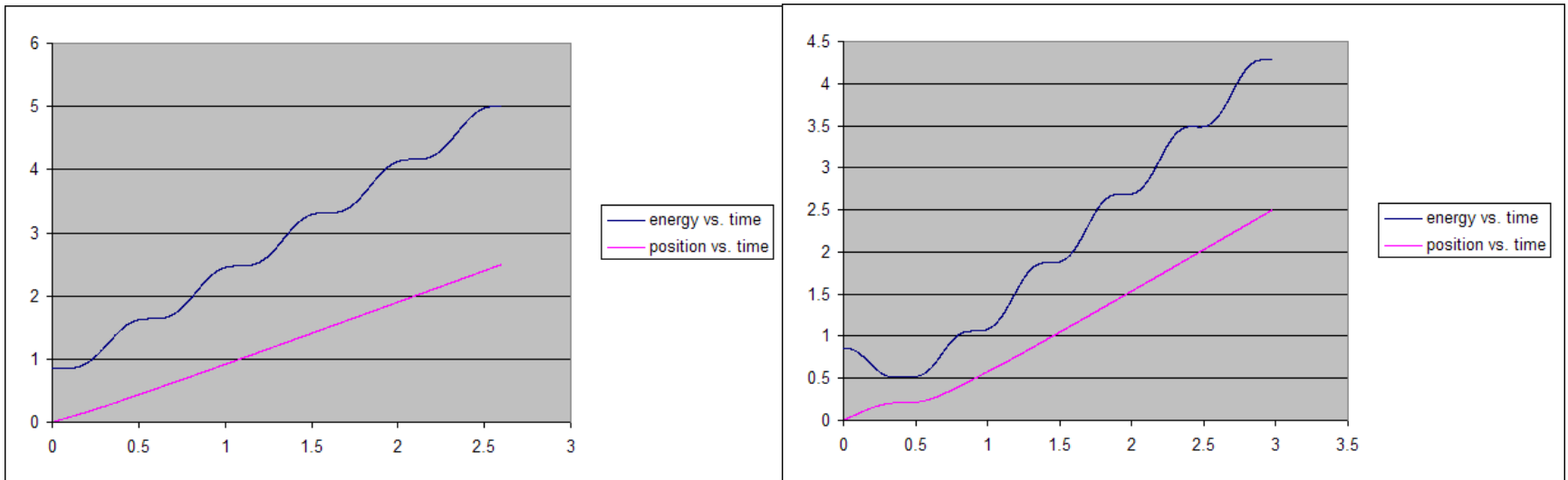
- Beam is *decelerated* before getting into first cavity of injector



- Provides ample opportunity for space charge to “do bad things”
- Amusing ancillary effect: multiple stable phases...

“Multistable” injection phases

- Carlos & Steve noticed that in addition to the “correct” phase for injection into the first SRF cavity (from front end), additional phases, about 140° (or, 220°) away, were also stable & accelerated
 - Beam quality poor
- This is readily understood by looking at energy profile through 1st cavity
 - “correctly phased” – accelerates
 - “out of phase” – decelerates; resultant phase slip so large that beam is retarded by $\frac{1}{2} \tau_{RF}$ and as a result gets captured on the subsequent RF cycle! Space charge clobbers the beam quality while at very low energy...



Halo Summary

- A *bit* of an issue for us (135 pC/10 mA)
- Comes more from more from scattered light & various emitters than from exotic effects - i.e., reality hits at currents well below those at which “space charge” matters
- Halo sources – things making low charge bunches that go on to be mishandled by the accelerator
 - Drive laser transport scattering light to nether regions of cathode
 - Drive laser ghost pulses
 - Cathode persistence
 - Field emitters on gun surfaces and in 1st SRF cavity
 - We saw well-defined beam spots that formed up from emitters in the first SRF cavity
 - Unresolved 2nd order dispersion (T_{166} , T_{266}) coupled to mismatched low charge bunches & driving momentum tails to large amplitude

these get longitudinally overfocused and blown out to large momenta/amplitude
- Need to either provide lots of aperture/acceptance (both physical and dynamic) to propagate this through system and/or a means of collimation
- Halo gets bad at high current, not only because the sources get bigger, but because the *mismatch* of source to system gets bigger:
 - If you have a few fC going down a machine set up for a few 10s of pC, you might be able to neglect it, but if you have a few pC going down a machine set up for a few nC, you are likely to get into trouble!
- Some propagates through to dump, some scrapes off, but remnant activation is low



back



more
abuse



Halo (2002)

“The stuff in the tails that you can’t use, can’t see, and probably don’t know about, but that CAN hurt you, or at least melt something”

- Beam loss scales with current, beam envelope (beam size and lattice contributions), and with the inverse of aperture

$$I_{\text{loss}} \sim C I_{\text{beam}} \beta / a_{\text{pipe}}$$

- CEBAF & Demo experience suggest $C \sim \frac{1}{2} \times 10^{-7}$, in turn suggesting (limit loss to 0.1 μA) you need $\beta / a_{\text{pipe}} \sim 20$ at 100 mA – or, a 10 cm bore & 1 m envelopes!

Halo (Jan 2004)

- See some evidence of halo
 - Localized activation on beam line
 - Steering independent BLM activity that can be modified by changing quad focusing and/or sextupoles
- Most noticeable at changes of aperture (3F01, 4F06, 5F10), at end of linac
- Not (so far – up to about 7 mA) an operational limitation
 - Minimal pressure rise \Rightarrow limited beam loss
 - Activation not out of bounds
 - Can work around by altering phase advance, betatron matching solution
 - Seems to collimate in 1st arc (there's 7 m/20 tons of steel between the linac/backleg!)

| | | | | | |
|---|--|---|--|---|--|
| E N/A | | Radiation Control Group Radiological Survey Form | | Page 1 of ____ | |
| (map reference if applicable) Free Electron Laser | | FEL Operating Conditions <div style="font-size: 1.2em;">80 MeV 6.8 mA</div> | | Instrument: <u>Bicron</u> Serial # <u>A136V</u> Cal due <u>4/20/04</u> | |

Reason for survey: Gun Recessite

Readings in mR/hr whole body (unless annotated)

----- Denotes posted area

COPY
Full Survey

Legend:

- Contact dose rate
- WB dose rate
- Item description

Summary

Types of Areas
(Circle all that apply)

Rad High Rad Cont

Areas posted ☒ N

at WB Dose Rate (mR/hr)

| | |
|-----|----------|
| Rad | High Rad |
| — | — |

| | | |
|--|----------------------------|---|
| Initial Entry Survey <input checked="" type="checkbox"/> N | Access Mode SWP Cont (Res) | Continuous Rad Escort Y <input checked="" type="checkbox"/> N |
|--|----------------------------|---|

| | | |
|------------------------|---------------------------------|--------------------------|
| led by: <u>G. N. i</u> | Date/time: <u>11/23/04 1620</u> | Crew Chief Review: _____ |
| | | RCG Review |

BBU

- Pozdeyev, Tennant will discuss in detail
- “solved”, up to 10+ mA CW in *our* machine
- In short –
 - Programmatic issues (cost & schedule) drove installation of SRF module with undesirable HOM spectrum and predicted instability threshold of only a few mA
 - Module installed, worked well save for fact that instability occurred right where predicted
 - Palliative methods (phase trombone, SQEEM) worked, raising threshold well beyond operating currents
- Remains a challenge for higher currents & large machines
 - Fix the problem (HOMs) or fix the symptom (instability)?
 - Propagating modes/power load!
 - (CWWT faults in demo)



back



more
abuse

BBU Lessons learned

- **Believe the models:**

- Simulations predicted 3 mA threshold, 1st effort at runs with Zone 3 went unstable at 3 mA

- **Believe Todd Smith:**

- Varying phase advance (phase trombone) and improving betatron matching to try to image BBU kick to node at offending cavity - to get single-turn transfer matrix of form

$$\begin{pmatrix} \pm I & 0 & 0 \\ 0 & \pm I & 0 \\ 0 & 0 & I \end{pmatrix}$$

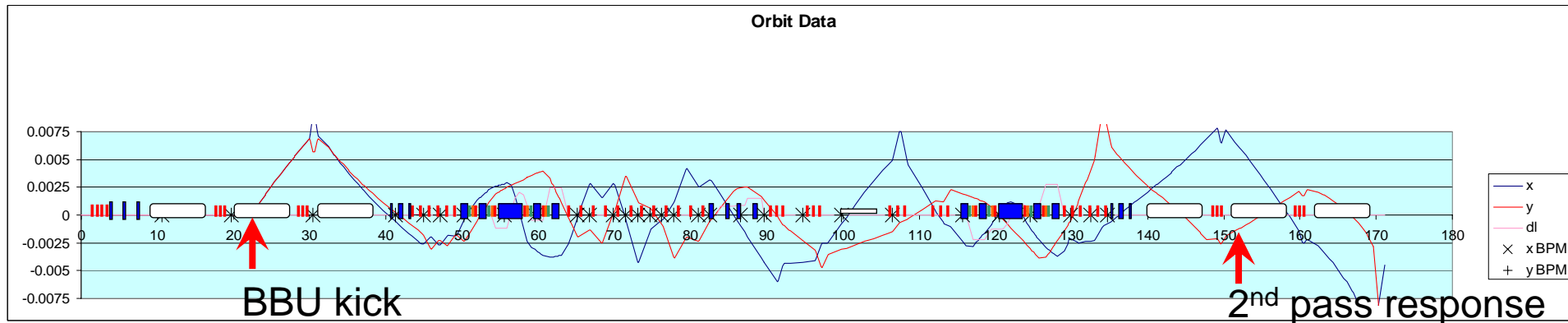


could vary threshold by several mA – from 1 mA to over 5 mA

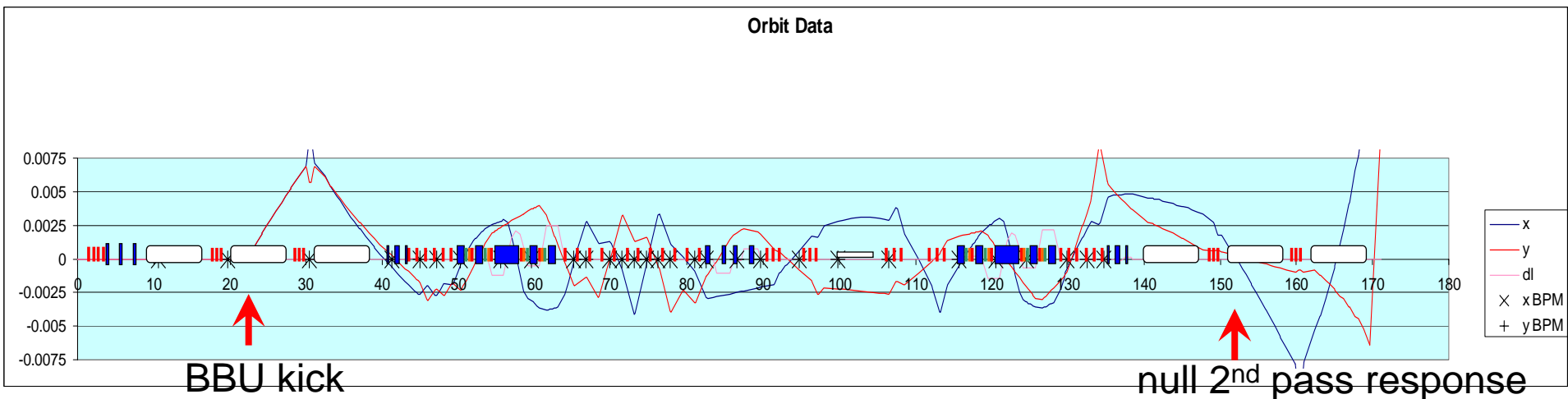


Phase Trombone

- 1 mrad kick in x and y at 1st cavity of zone 3:
uncompensated phase advances:




- Compensated phase advances:



- Using a 5-skew-quad reflection with matrix

$$\begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & I \end{pmatrix}$$

allowed operation at over 8 mA (pulsed and CW). In place during 10 kW run. 

- “reflection” is itself not really a rotation, but with the rest of the transport system, it *can* provide (and might even have *been providing*) a true rotation, with imaging from zone 3 back to itself

$$\begin{pmatrix} 0 & \pm I & 0 \\ \mp I & 0 & 0 \\ 0 & 0 & I \end{pmatrix}$$

- systematic studies characterizing these and other suppression methods performed (Pozdeyev, Tennant)



Skew Quad Eigenmode Exchange Module

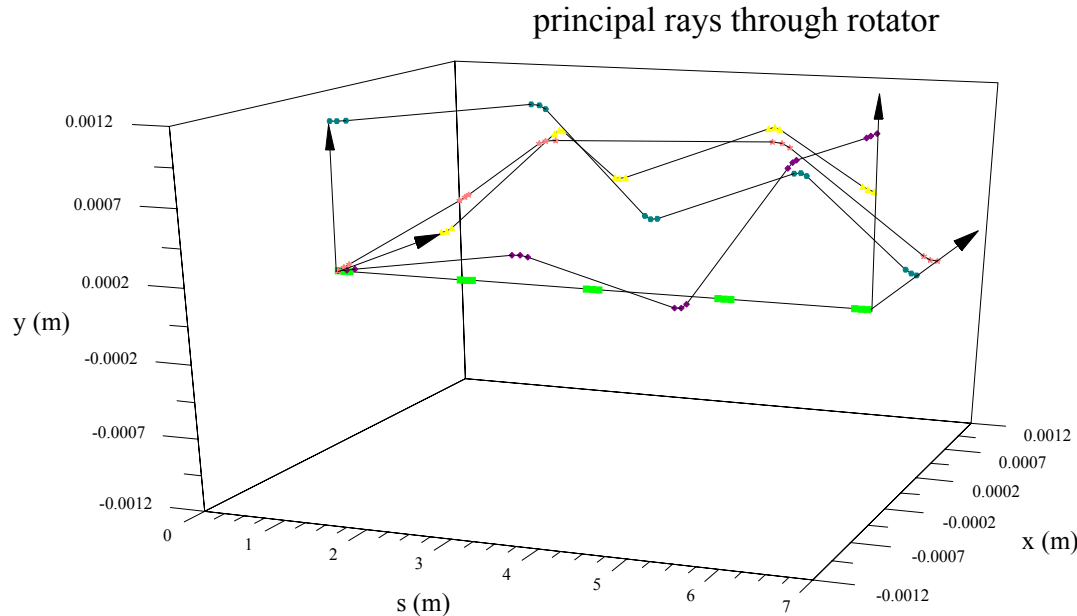
- “original” 3F region



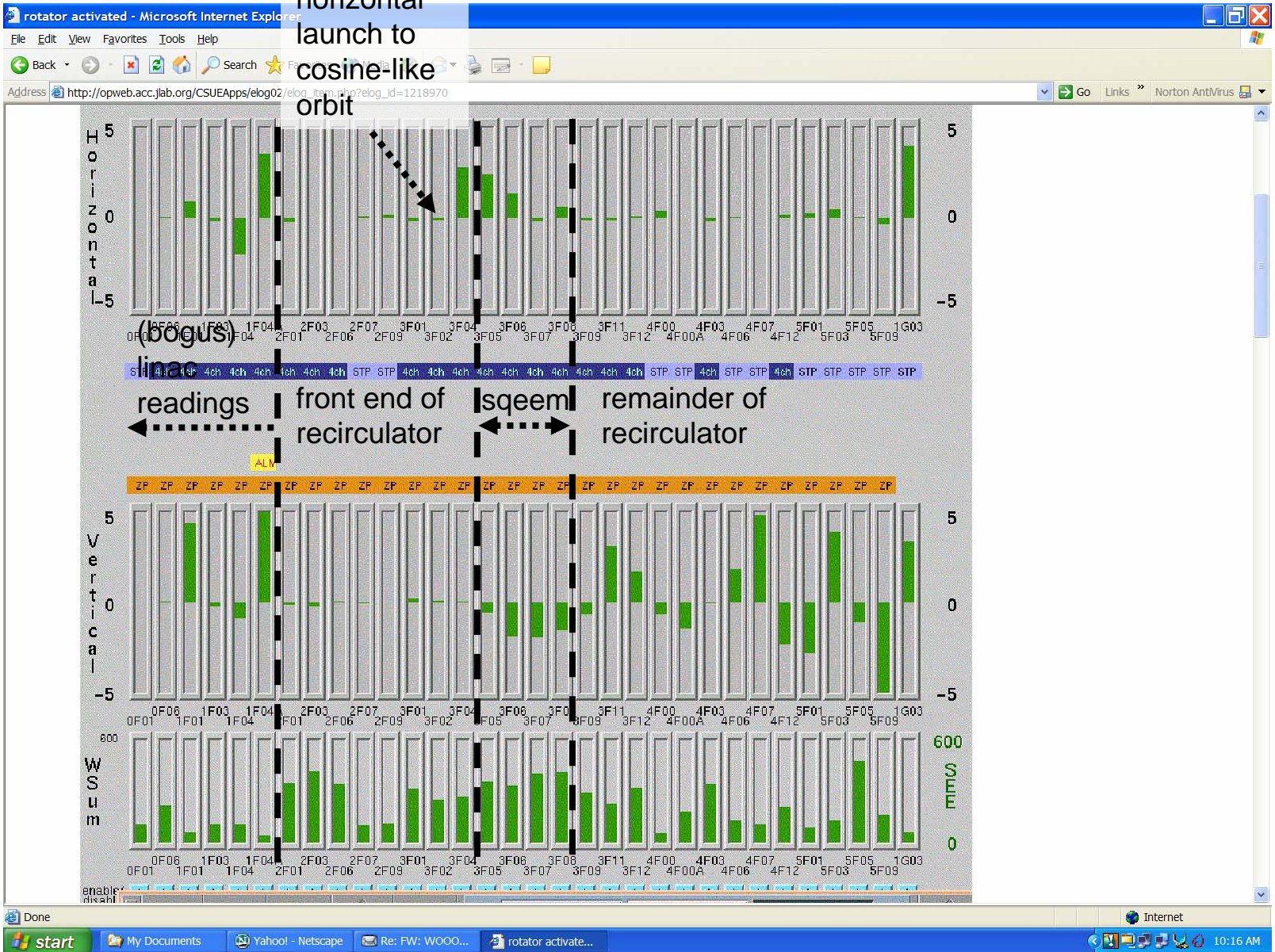
- 3F with sqeem activated

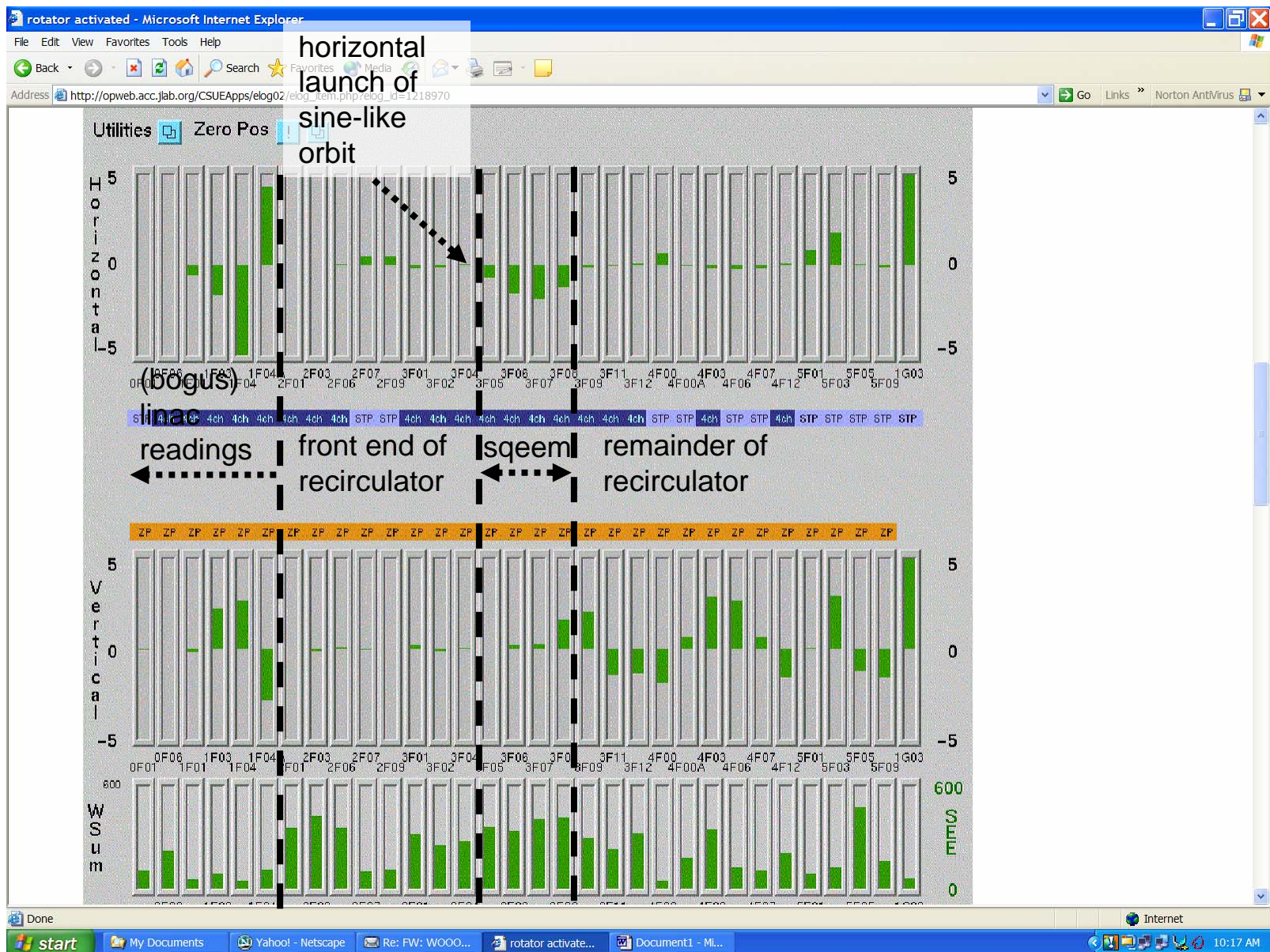


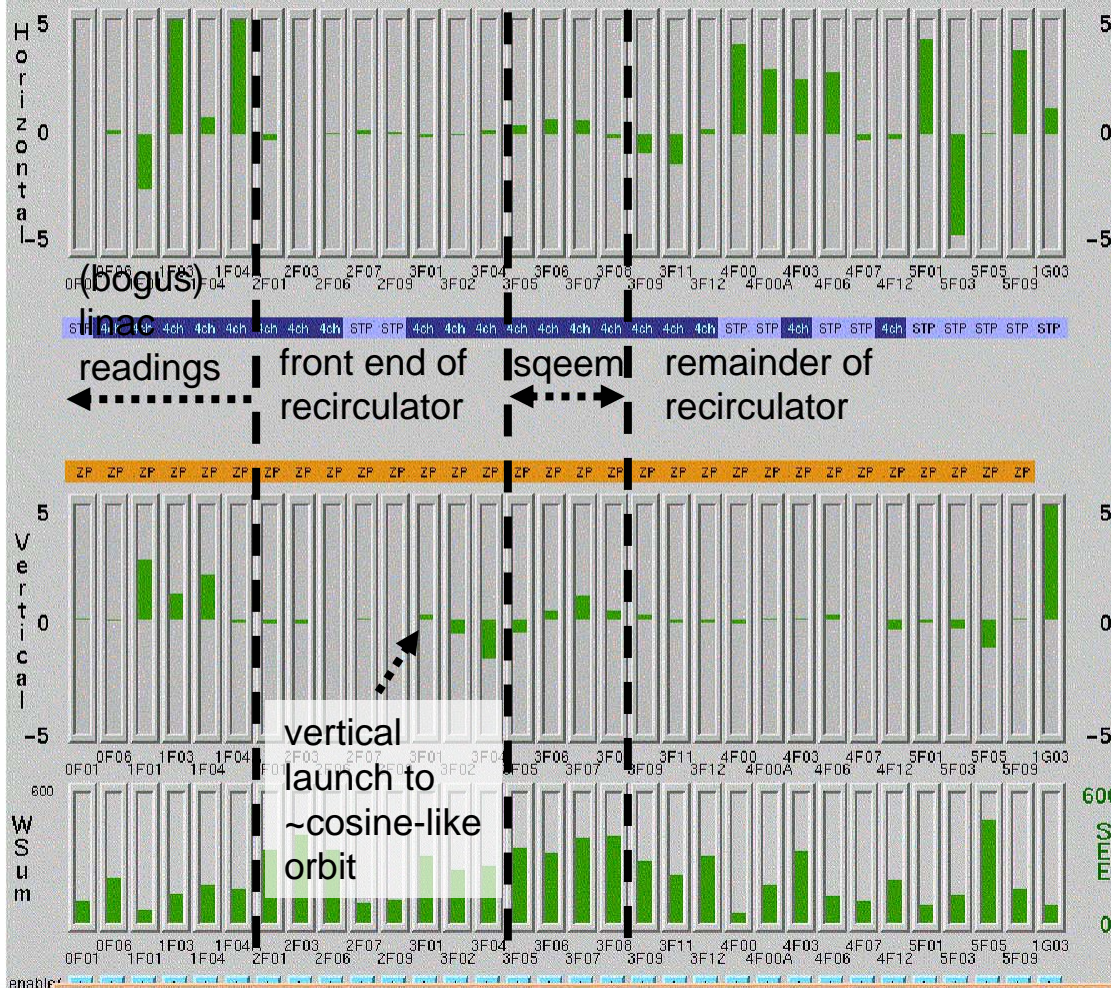
- Principle rays through sqeem



horizontal
launch to
cosine-like
orbit









CSR

- Not an operational impediment for the expected reasons...
 - Emittance not badly degraded by CSR, at least for IR ops
 - Thought we had problems but it turned out to be halo/ghost pulses
 - Much dread “parasitic compressions” in Bates arc not an issue (betatron amplitude-bunch length coupling keeps bunch quite long)
- *but rather for unexpected reasons!*
 - Made so much THz (CSR) that we heated the FEL mirrors up and distorted them, limiting power output
- Even so, it’s a silk purse, not a sow’s ear
 - Make lots of THz for happy potential users
 - Use it as a diagnostic for machine setup and performance
 - Entertainment value
 - [Video of filamentation](#) when we move energy around & vary bunch length by moving beam around in sextupoles
- Remains a problem if emittance is constrained (e.g. in a light source, maybe for short wavelength FELs, probably not for longer wavelength FELs, at least at modest parameters)



return

Environmental Wakes/Impedences

- keep bunch length until/unless you need it short...
- Make, enforce component impedance budget (even if its actually probably futile...)
- And, going back to BBU – not only are trapped HOMs a problem, if you run, say, 100 MW of electron beam *propagating* HOMs are going to fry something...
 - Demo CWWT epiphany...

Space Charge

- transverse not a problem for us at 0.1 nC, will likely be at 1 nC
- longitudinal: a serious problem even at 0.1 nC
 - LSC caused much confusion and initially kept us from getting to short bunches
 - initial signature: momentum spread asymmetric about linac crest, bunch longer than expected given apparent injected momentum spread
 - motivates us to keep bunch long => in long term should go to lower frequency or suffer large momentum spread (need good compaction control)
 - still not quite making longitudinal emittance spec



back

more

Overview of LSC

- Recognition of longitudinal space charge as issue led to significantly improved performance
 - re-optimized injector
 - ran final injector cavity 10° , rather than 20° , off crest
 - injected longer, low momentum spread bunch, alleviated LSC
- By end of last summer
 - $\delta p/p$ roughly symmetric around crest
 - bunch lengths consistently down to 200 fsec rms
- On “10 kW day” (7/21/04) even approached spec longitudinal emittance:
 - 1.25% full momentum spread at 145 MeV (450 keV rms)
 - 338 fsec bunch fwhm (150 fsec rms)
 - $\varepsilon_L \sim 450 \text{ keV} \times 0.15 \text{ psec} = 68 \text{ keV-psec}$



back

still more

“Best” Bunch Length

miniphase to 338 fsec - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://opweb.acc.jlab.org/CSUEApps/elog2/elog_item.php?elog_id=1225676

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Viewer
Diode

Foil
Drop Foil
Raise Foil

Beam Current Plot
Manual Control

SAVE filename 072104a.scan
Saved in 072104a.scan

Start
Pause
Resume
ABORT

Moving
Stopped
0.002
Golay Cell

Intensity

Position (microns)

Golay Raw Data

FWHM (ps) = 0.338

150 fsec rms

[420 fs!](#) [INDEX](#)

Database query + PHP page generation time = 0 seconds

start may 2004 Injector talk NA... Yahoo! - Netscape miniphase to 33... Microsoft Power... Document1 - M... 4:31 PM

Momentum Spread Asymmetry and Bunch Length: LSC

After considerable flailing by the rest of us (“It’s wakes!”, “It’s a cavity that’s off phase!” “It’s a fundamental flaw in the system design!”) both issues resolved by C. Hernandez-Garcia.

- Observed beam behavior:
 - Beam momentum spread when accelerating *ahead* of crest ~ 1.5 x smaller than when accelerating after crest; average of both \sim same as expected from PARMELA
 - M_{55} measurements verify lattice longitudinal behavior at design values for linac phases & compaction trims, but minimum bunch length *not* achieved at these values
 - Bunch length at wiggler “too long” even when fully “optimized”
- PARMELA simulation of beam behavior in the front end of the linac exhibited space-charge induced growth in both correlated and uncorrelated energy spread, with magnitudes completely consistent with observation
- Simulations also showed uncorrelated momentum spread (which dictates compressed bunch length) tracks correlated (observable) momentum spread

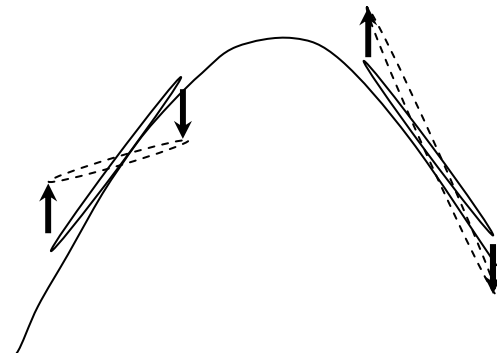


MEETINGS

NONE OF US IS AS DUMB AS ALL OF US.

Space-Charge Induced Degradation of Longitudinal Emittance

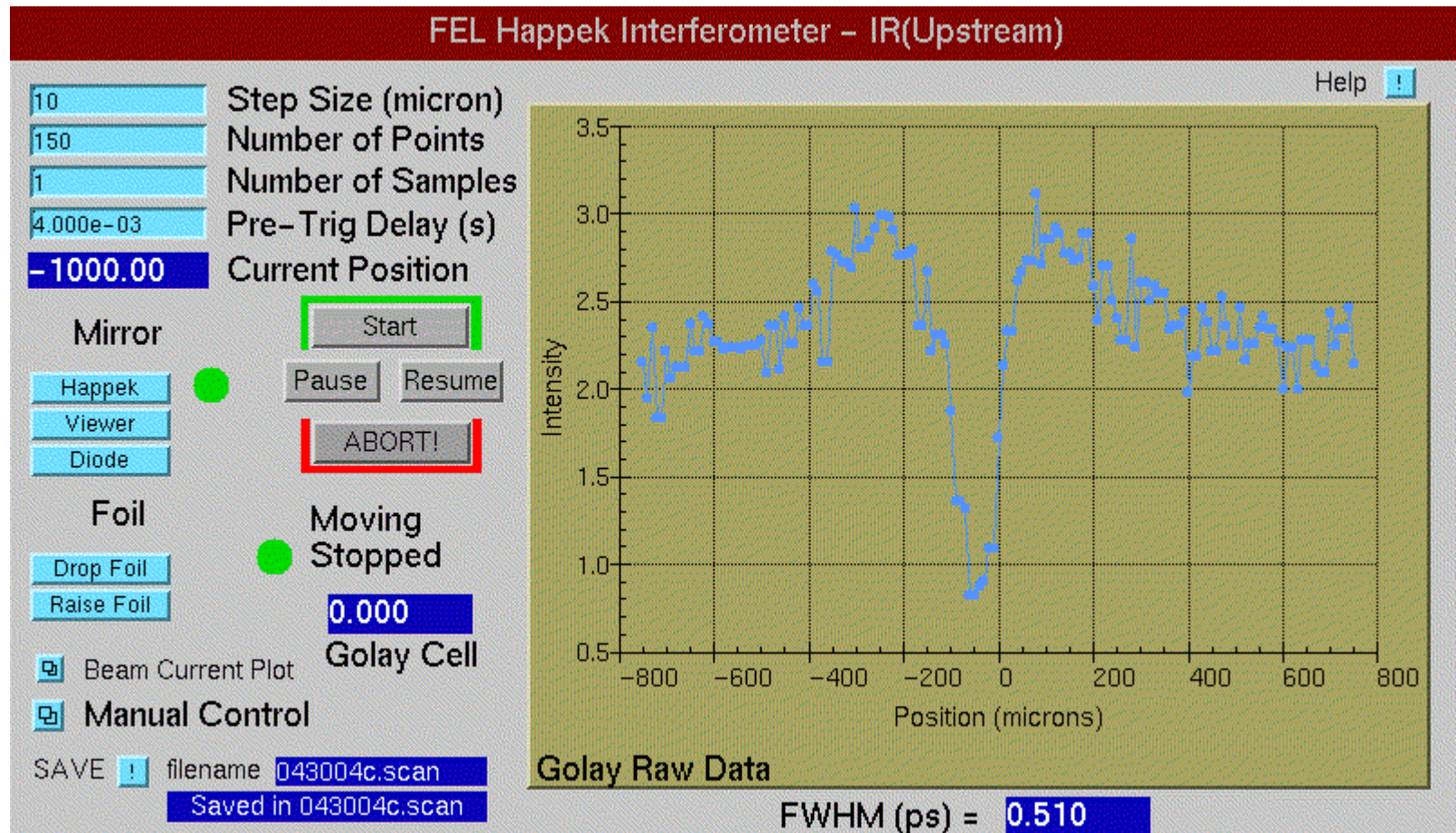
- Mechanism is obvious (in *retrospect*...) – bunch self-fields cause bunch to spread out
 - Head of bunch accelerated, tail of bunch decelerated, causing correlated energy slew
 - Ahead of crest (head at low energy, tail at high) observed momentum spread *reduced*
 - After crest (head at high energy, tail at low) observed energy spread *increased*
- Simple estimates show the imposed correlated momentum spread $\sim 1/L_b^2$ and $1/r_b^2$
 - The latter previously observed – bunch length clearly dependent on match into & through linac
 - The former quickly checked...



Solution

- PARMELA study quickly revealed that the injected bunch length could be controlled by varying phase of the final injector cavity.
 - Small changes in injector setup (shift in cavity phase from “traditional” 20° setpoint to 10°) gives bunch length increase from 7 psec to 11 psec, uncorrelated energy spread reduction from 50 keV to 25 keV
 - Reduces space charge driven effects – both correlated asymmetry and uncorrelated induced momentum spread
- When implemented in accelerator, final momentum spread increased from $\sim 2/3\%$ (full, ahead of crest) to $\sim 1 - 1\frac{1}{4}\%$, and reduction of bunch length from $\sim 800 - 900$ fsec FWHM to ~ 500 fsec FWHM or better

Happek Scan



back

Modeling & Design

- Key notion: keep it simple
 - In the JLab FEL group, we do most of our ops modeling with spreadsheets & design modeling with older codes or djinned up spreadsheets, quasi-analytic models, etc
 - Extremely involved computations are subject to Murphy, dominated by component errors when you get to the installed system
- its easy to get deceived in large acceptance systems: God only makes the transform analytic, He guarantees nothing about the convergence rate of its perturbative expansion
- geometric methods provide useful and robust information, allow you to avoid a lot of problems inherent in perturbative treatments
- Bottom line: *be careful*, but it doesn't really matter HOW you do the calculation or how you design the beamline, so long as you do it correctly and make sure the model describes the hardware as installed!



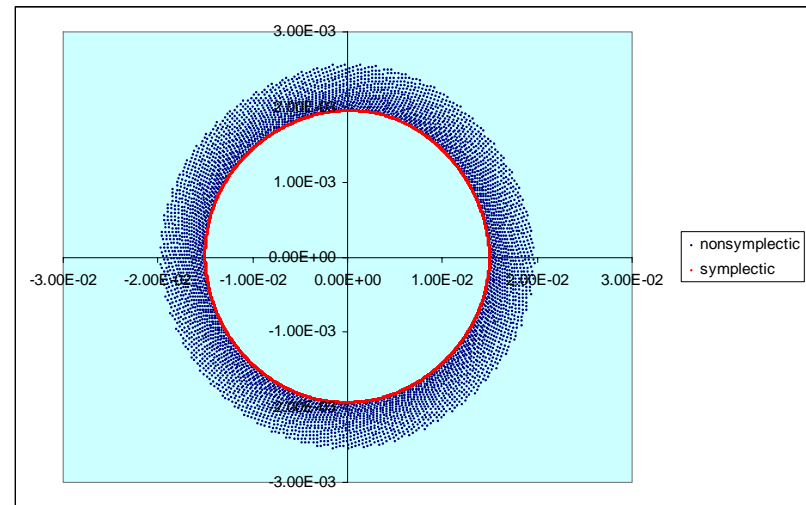
The problem

- Codes tend to emphasize the needs/interest of their “prime movers”, e.g.,
 - HEP labs – small bend angle/large radius approximations
 - Academic – very mathy, very general, very sophisticated, & often very impenetrable
- On occasion, can be “wrong” in some situation or another, and its usually the situation / want to be in!
- Some use questionable models/methods with acceleration (or, amusingly, *don't do acceleration*, even though we *design* accelerators!)
- May not allow fully coupled (H/V/synchrobetatron) modeling

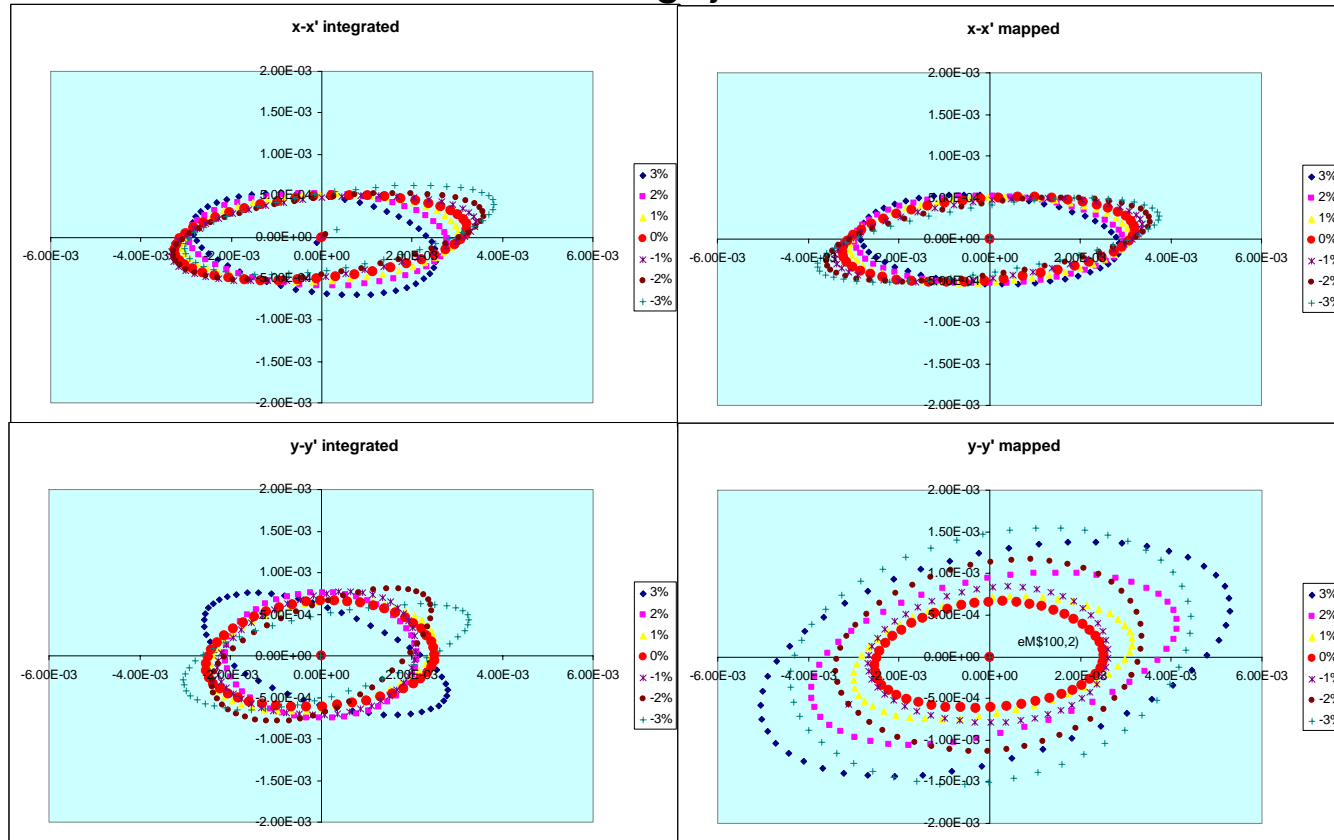


Example: I'll pick on DIMAD

- “Way back in 82...”
 - Tracking with nonsymplectic Taylor’s series in Kaon factory lattice
- Go to generating function approx
 - Adds in higher order terms to make symplectic – but are they the “right ones”?
 - Result: Much furor, new codes, lots of workshops...



- So, some 10 or 15 years later, we're working on the IR Demo...
 - R. Li noticed not only is the 2nd order transform not symplectic – it blows vertical phase space off-momentum in a single pass
 - But “TURTLE” mode tracking “just fine”:



System is vehemently nonlinear, but dynamically regular...



Geometric Methods

- As we go to larger acceptances, higher performance, perturbative methods become harder & harder to apply
- Other than applying Brown's principle ("don't mess with the beam") how to we then get guidance?

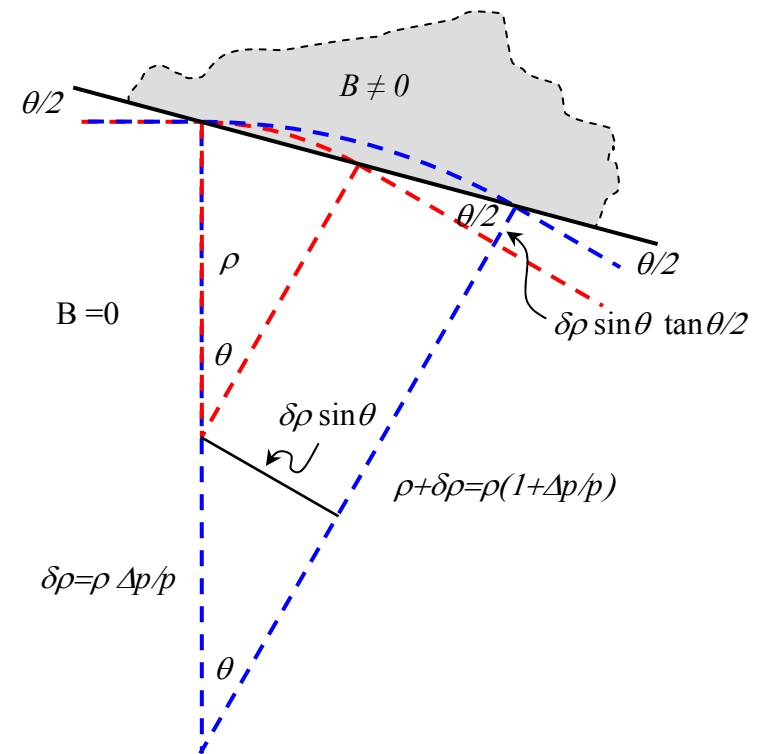
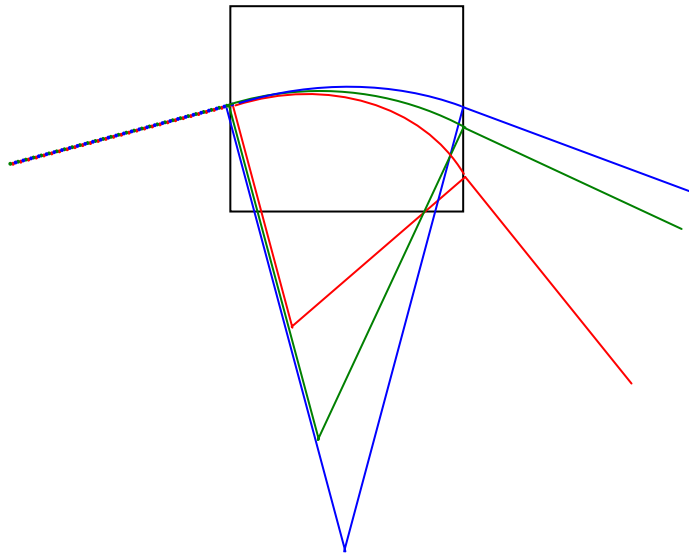
Well,

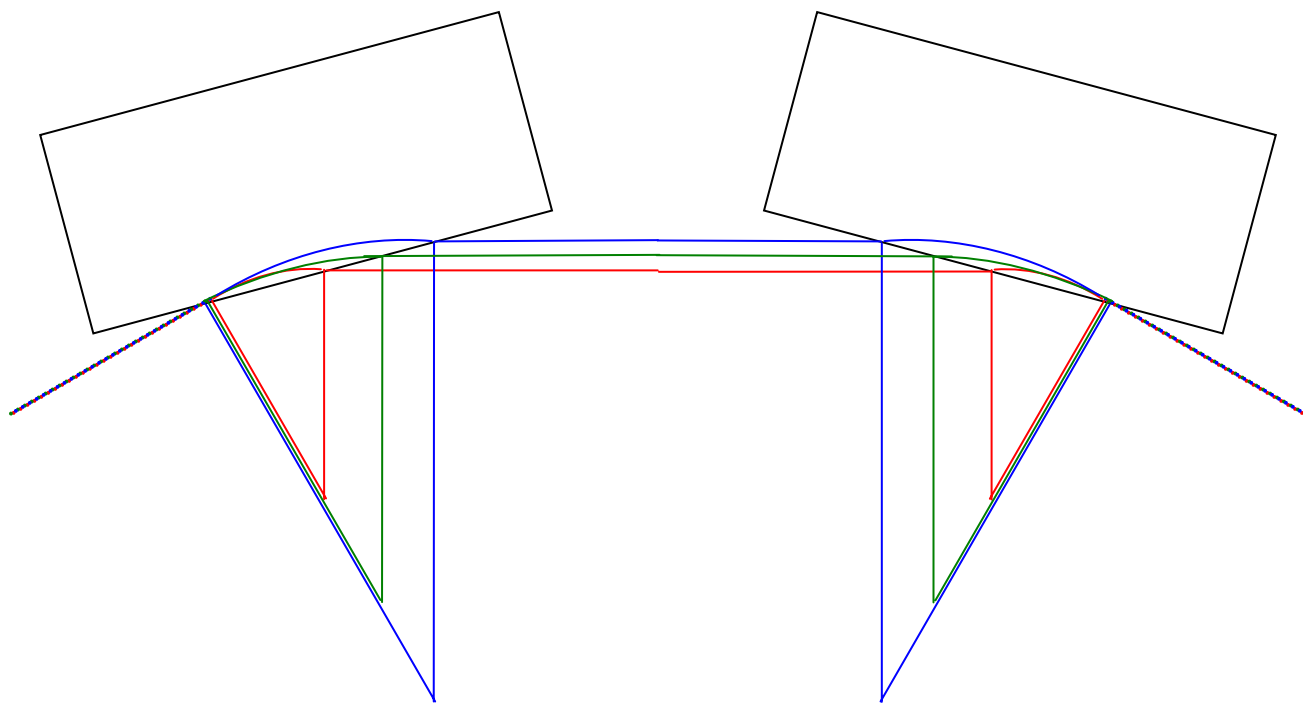
- Beam optics is just circles & straight lines (actually, just circles – straight lines are circles of ∞ radius)
- Perturbatory approach can be misleading – fix problems of linear optics (chromatics, aberrations – e.g., CEBAF T_{126} , etc) with sextupoles, fix aberrations from sextupoles with octupoles, etc. – just doesn't converge!
- Can't we do it all geometrically instead?

Maybe...

Example: Mirror Bend Achromat

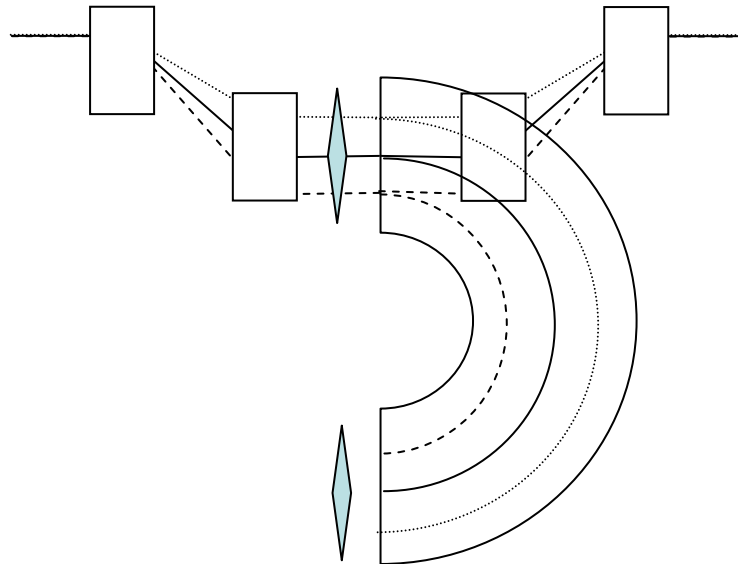
- hard to find, perturbatively, obvious, geometrically





Bates Recirculator

- We swiped this Sargent/Flanz design from MIT because it's really robust, really easy to operate (if you instrument it) and really simple (if you think about it the right way).



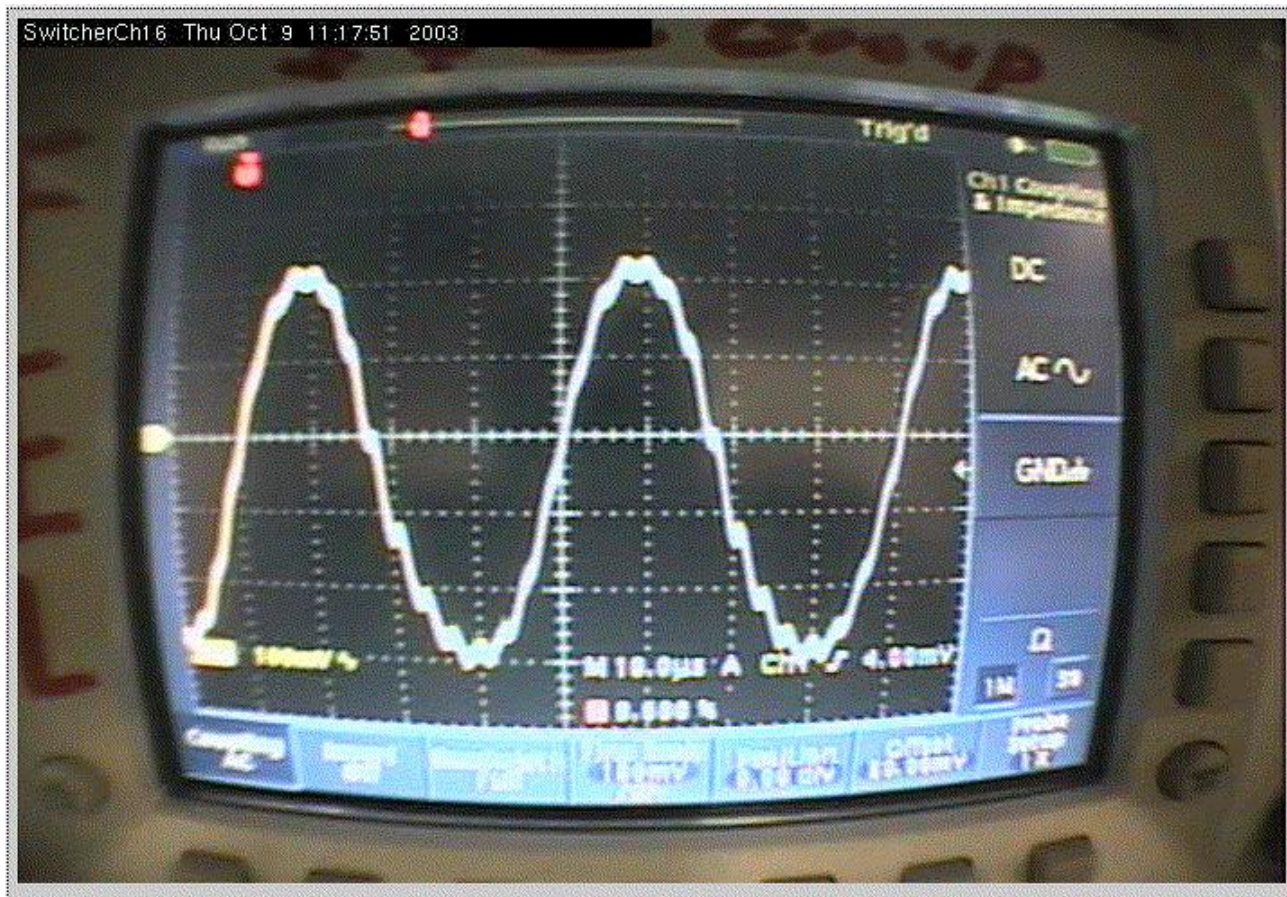
Component Quality

- Though relatively mundane, this will make or break a machine!
- Need to think in terms of relatively novel manifestations of errors
 - such as magnetic field errors & ripple causing timing errors, energy spread, etc...
- Power supply stability, resolution, etc – couples to, e.g.
 - timing stability at FEL (in compaction managed transport systems)
 - magnet reproducibility (a big issue for us; our quad power supplies don't track well and so the quads [which meet spec if “properly” powered] don't recover well and we have a lot of tune time)
- Magnetic field quality
 - Distorts not only transverse phase space, but also longitudinal



Magnet stability

- Lots of high frequency (low amplitude) noise, few significant noise sources (bad trim card, resonance in sextupole supply)

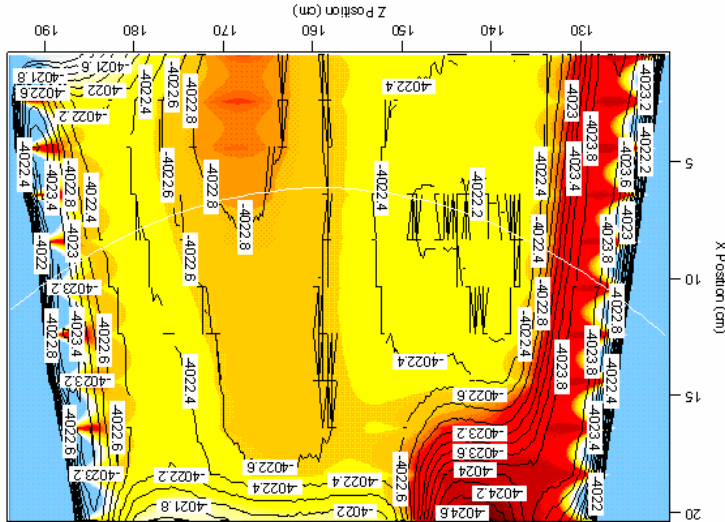


Magnets

- [Field quality](#): excellent, for all styles
- Field value & stability (power supplies)
 - Dipoles:
 - Very stable, very reproducible
 - dipole-ripple induced timing jitter unlikely (solid steel, tight power supply spec)
 - better than 10^{-4} recovery based on orbit
 - Quads:
 - Injector:
 - not a likely source of any injector puzzles (checked focal lengths with beam)
 - Recirculator:
 - stable but don't make set point (power supplies just aren't there);
 - trim quad/corrector sets have been fussy but are being resolved
 - Sextupoles:
 - potential jitter issues (commissioning activity)
 - “Sextupole lites”: recycled Demo sextupoles (budget issue)
 - adequate for turn-on,
 - modified several times to allow high energy, multi-family operation
- [Magnet field quality](#) couples to recovered energy spread, limits ERL performance

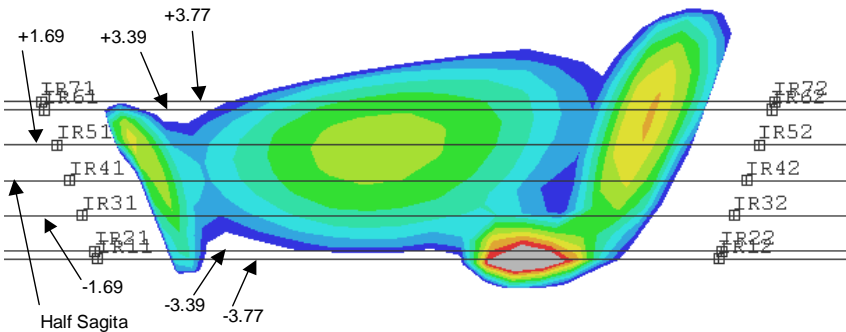


Example: GX at 145 MeV/c



- Top: measured field
- Bottom: design calculation

Contours at $1/2 \times 10^{-4}$



*Thanks to Tom Hiatt & the magnet
measurement facility staff, Chris
Tennant, and Tom Schultheiss*



Field Quality Limitations to ERL Performance

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

- $\Delta B \Rightarrow \delta x' = \Delta B / B\rho \sim \Delta B / (33.3564 \text{ kg-m/GeV} * E_{\text{linac}})$
- $\delta I \Rightarrow \Delta E_{\text{dump}} = \sin \phi_0 (2\pi M_{52}(\Delta B / 33.3564 \text{ kg-m}) / \lambda_{\text{RF}})$
(GeV)
- “Error field integral” $\Delta B I$ is *independent* of linac length/energy gain
 - tolerable relative field error falls as energy (required field) goes up
- Numbers for upgrade:
 - $\Delta E_{\text{dump}} \sim 3400 \text{ MeV} * (\Delta B / B)$
 - $\Delta E_{\text{dump}} \sim 0.16 \text{ keV/g-cm} * (\Delta B I)$



Matching

- transverse: cut & dried – measure the envelopes, do the match
- longitudinal
 - compaction management schemes vary for low & high energy [reverse bend @ low, dispersion modulate @ high]
 - incomplete energy recovery to provide energy compression (“stay out of trough”) – consequence of conservation of energy...



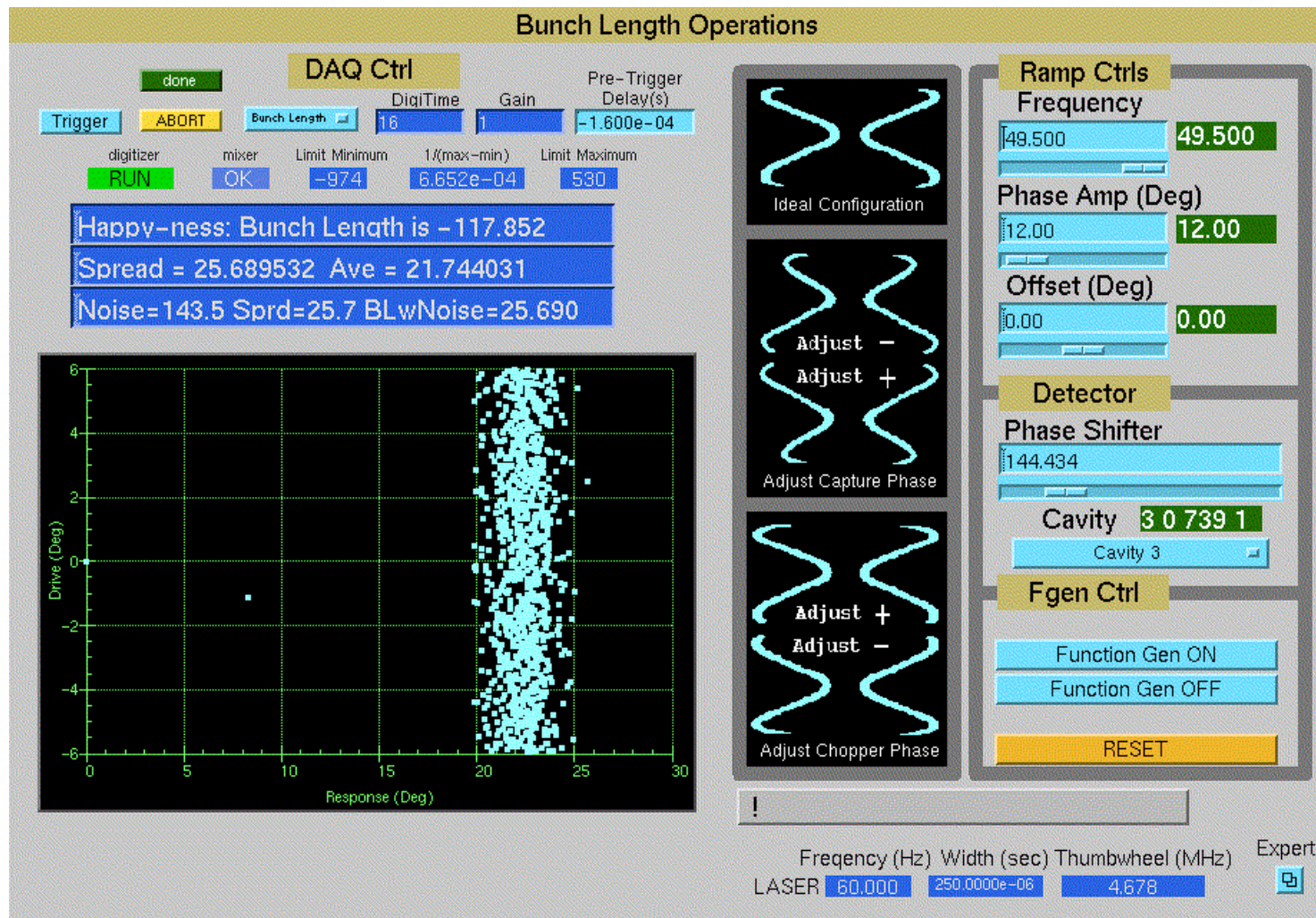
Longitudinal Matching Issues: Transport to Wiggler

- Observations *before* injected bunch length was increased & LSC corrected:
 - “M₅₅” system indicated transport system was properly set to compress bunch, *but bunch length not minimized*
 - Optimum bunch length provided by *mistuned* transport system

Indicates longitudinal mismatch of beam to lattice...
- When bunch lengthened and space charge was alleviated, the longitudinal mismatch was also alleviated
- Consistency of bunch length compression with model verified after calibration of sextupoles
 - Magnets measured; revised excitation curves utilized
 - Design code (DIMAD) values then provide compression at wiggler, isochronous transport from linac back to linac

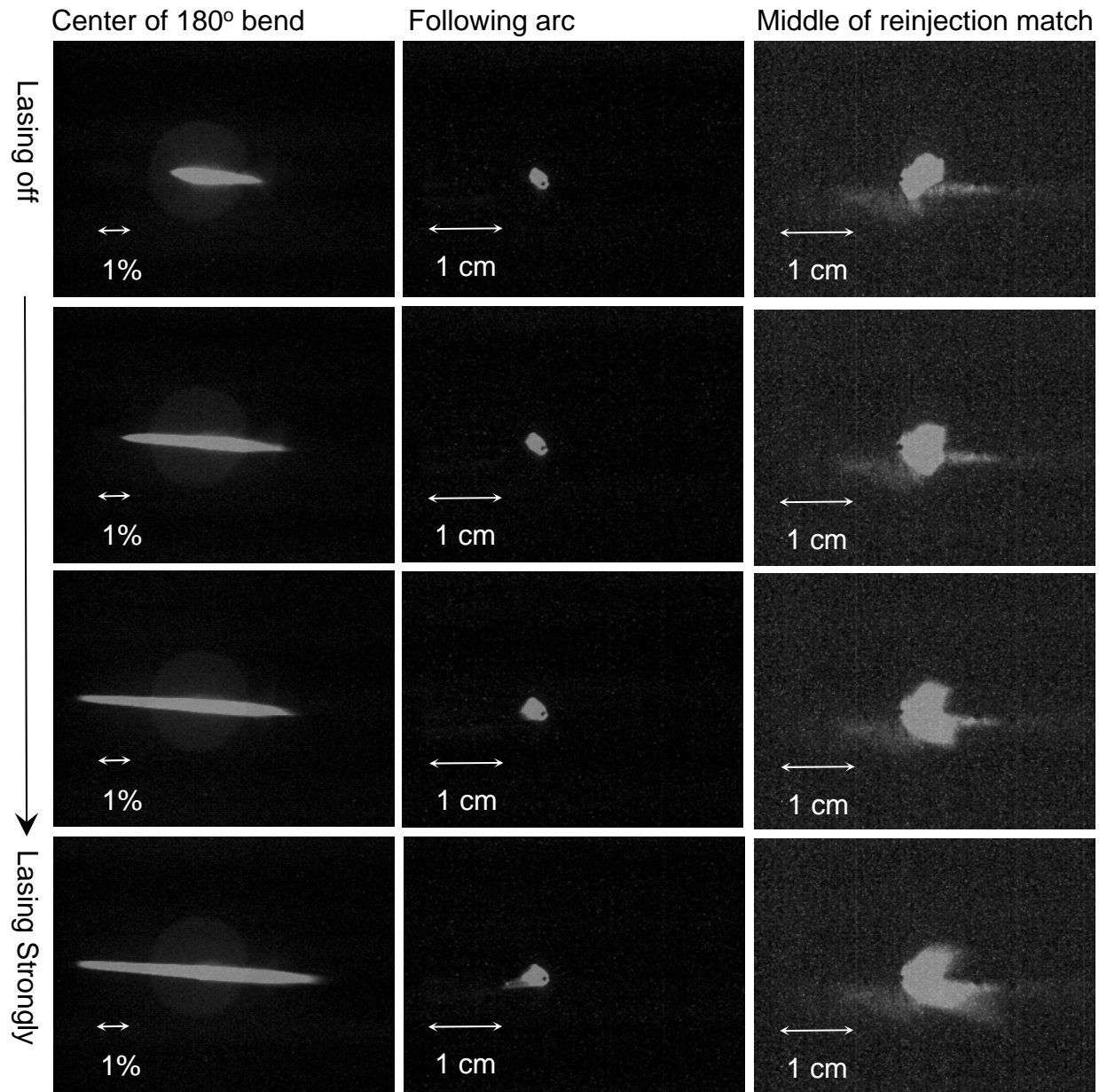
Conclusion: design/modeled values for trims and phases produce correct lattice and beam behavior; beam is properly matched to correctly tuned machine

Injector to Wiggler Transport

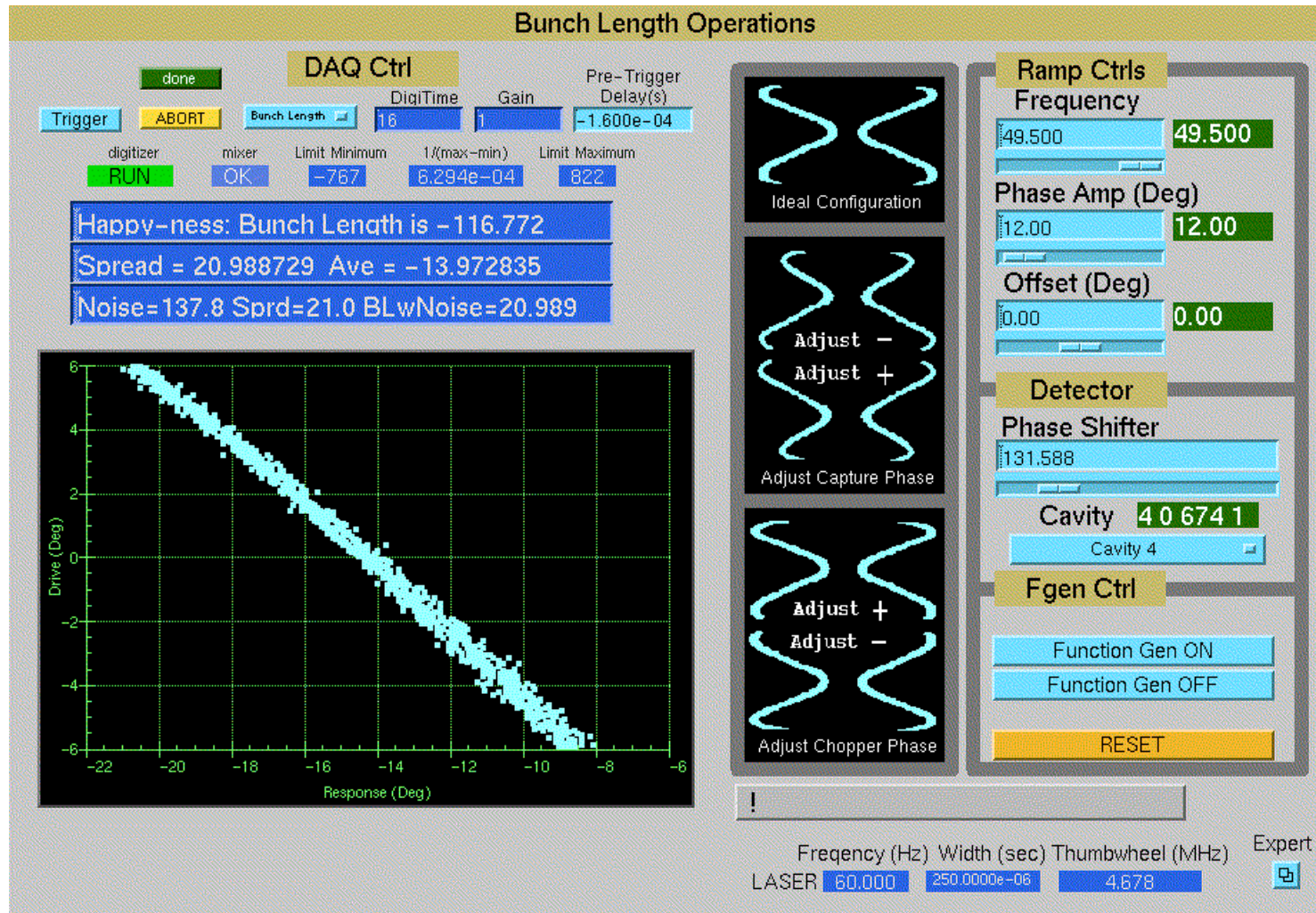


Longitudinal Matching Issues: Wiggler to Reinjection

- Lasing with 6 μm 2% outcoupler produced very large momentum spread of $\sim 10\%$
 - Beam spots not “clean” at reinjection
 - At 10° off-crest in linac, could not losslessly transport beam to dump
- “Distorted” beam spots due to 2nd order dispersion (T_{166} , T_{266}) & vertical envelope chromatic aberration in/generated by 2nd arc
- Corrected by using 2 family/4 sextupole solution Given calibrations from magnet measurements, design values provide appropriate compaction and off-momentum orbit correction



Injector to Reinjection Transport



Compression “Undervoltage” and Tail Management

- With correction of 2nd order aberrations, get additional acceptance, but still insufficient to compress 10% momentum spread 10° out of trough
 - RF “underfoot” (cf. “overhead”) too small at 10° to compress full momentum spread ($\cos 10^\circ \sim 0.985$, only have 1.5% compression above centroid)
- Move energy recovery phase farther from trough (S. Benson) and decelerate to higher energy (“incomplete” energy recovery) !!
 - Compensate by higher extraction dipole setting
- Octupoles complete picture – manage tails of distribution, provides 10(+) % momentum acceptance

Acceptance

- FEL induced momentum spread $5 - 6 \times \eta_{\text{FEL}}$
- 2% extraction efficiency $\Rightarrow \Delta E/E > 10\%$
- Need to recovery & energy compress; need good acceptance and means of linearization...
- Upgrade appears to have ~15% relative acceptance, when properly utilized – but you have to utilize it properly!

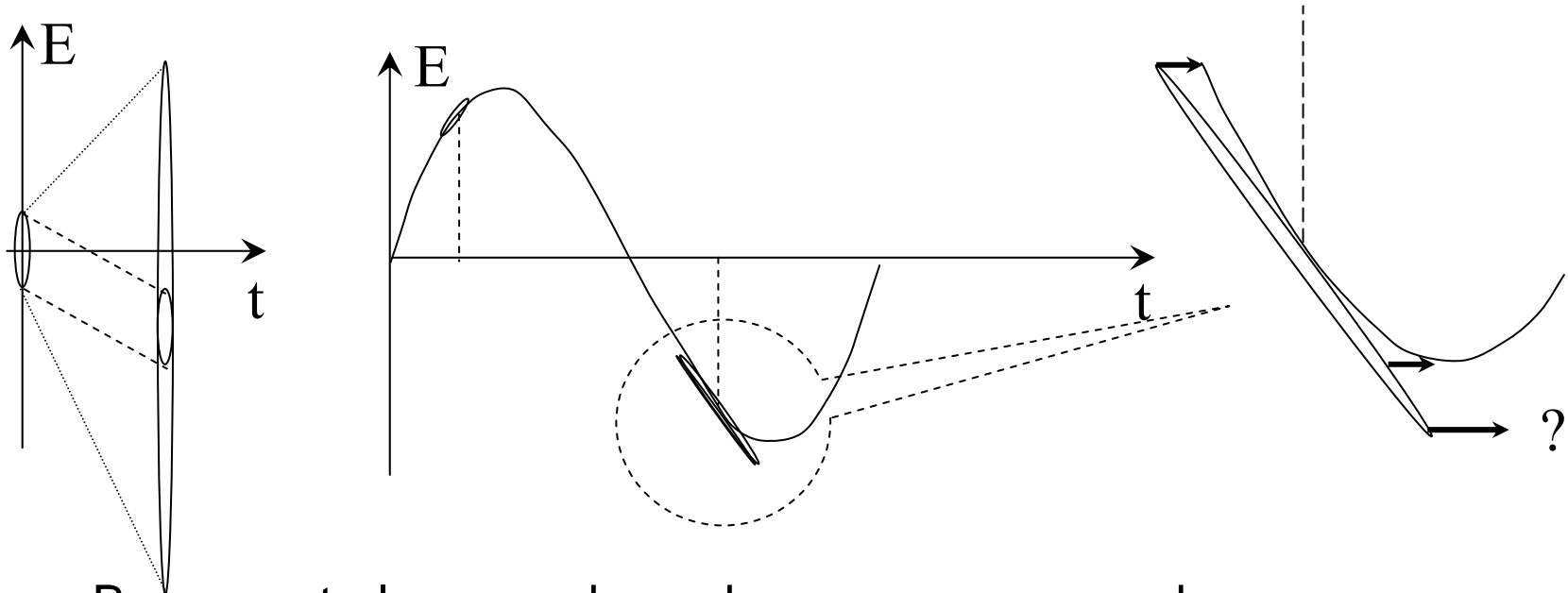
Backup – from fall 2002 review!

Implications

- We recover *power*, not *energy*
 - If power draw is null in linac, energy conservation means
 - the FEL output comes from the injector
 - $E_{\text{final}} < E_{\text{injected}}$ – in fact $E_{\text{final}} = E_{\text{injected}} - P_{\text{FEL}}/I_{\text{beam}}$
 - Seen in IR Demo: extraction buss run ~3% lower than injection buss; this corresponds to ~1.5 kW out of 45 kW (9 MeV & 5 mA) dumped beam power...
 - In 100 kW system, 10 MeV*100 mA (1 MW) will go to 9 MeV*100mA when lasing at full power
- You can't compress more energy than the available RF can give

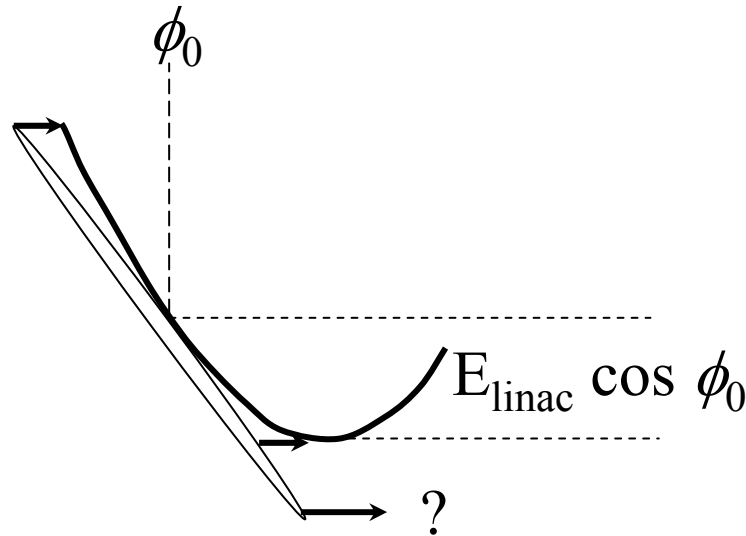
Backup – from fall 2002 review!

Energy Compression



- 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!

Limit of Energy Compression



- Quads rotate bunch to match waveform slope; sextupoles curve bunch to match waveform curvature; octupoles torque bunch to match waveform torsion
- No magnet can change largest energy offset to make up limit of available gradient!!

$$(\Delta E/E)_{\text{FEL}}/2 < E_{\text{linac}} \cos \phi_0$$

Limitations

- Pretty obvious from conservation of energy
- Seen in simulation – finally realized what was going on when an energy tail at the dump couldn't be removed, regardless of parameter choice
- Probably explains Demo behavior
 - Offset of beam on dump
 - Inability to run very high extraction efficiency
- Can get around by running farther off crest

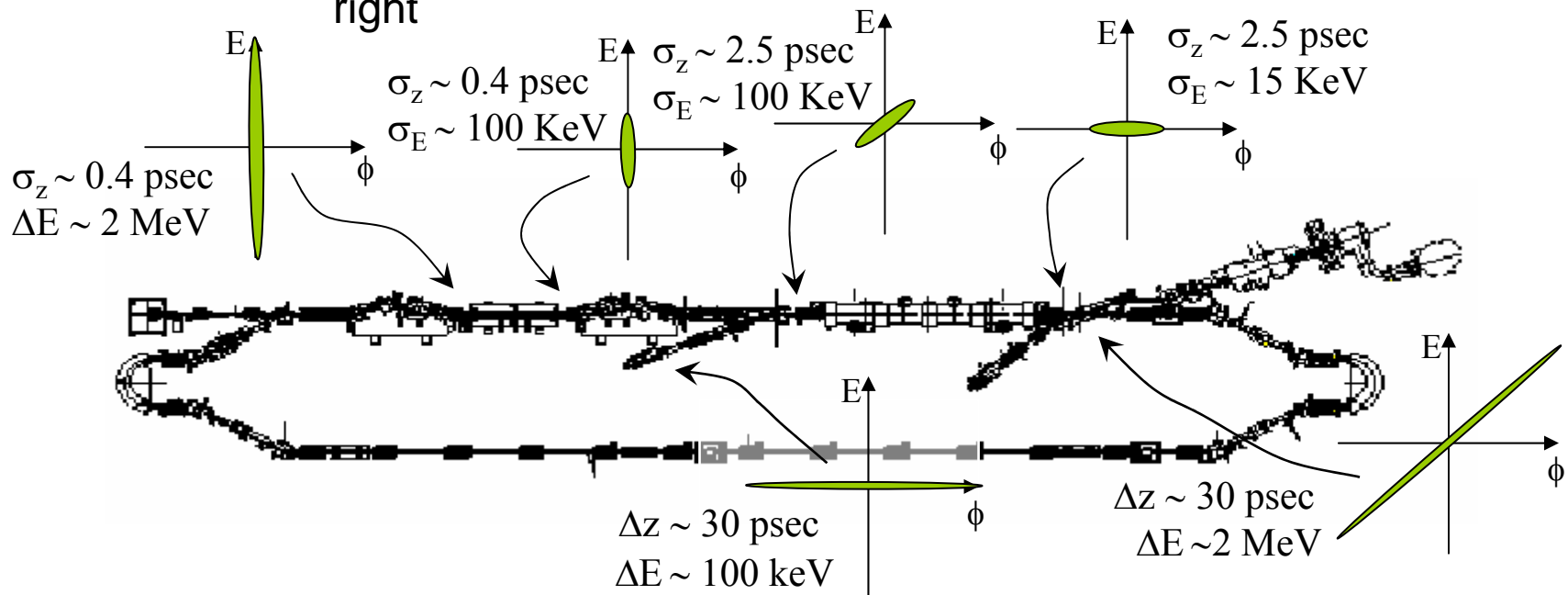
Backup – from fall 2002 review!

2. Energy Recovery

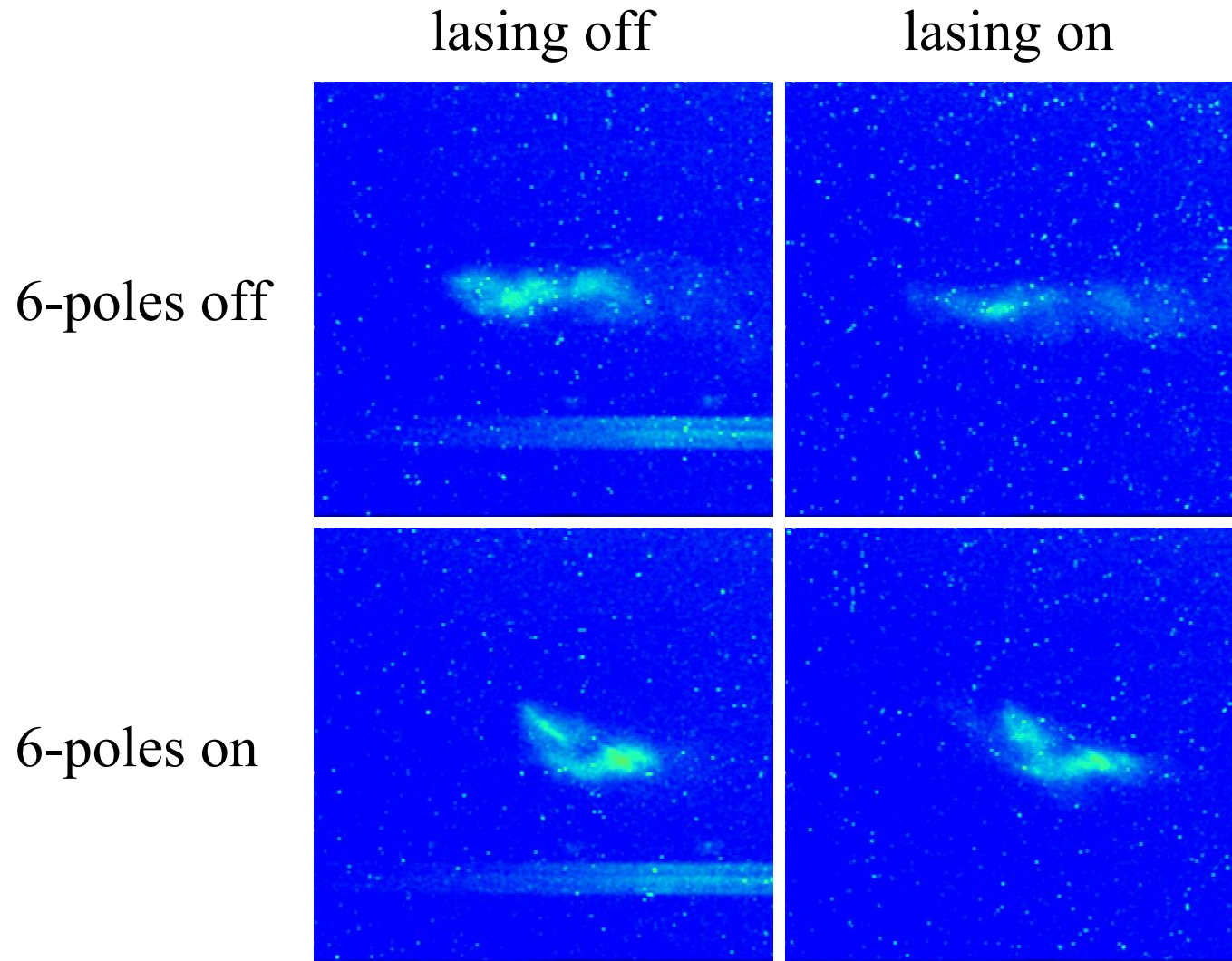
- Emerging as keystone technology for high efficiency/high performance/low cost accelerators (FEL drivers, colliders, light sources...)
 - alleviates RF system demands, cost, dumped radiation power, *but*
 - requires robust transport systems
- In FEL drivers, it relies on large acceptance, operationally flexible transport systems to provide appropriate longitudinal performance
 - IR Demo parameters (1497 MHz, $\Delta E/E > 5\%$) \Rightarrow longitudinal match through 2nd order to compensate lattice momentum compactions & RF waveform slope and curvature

Longitudinal Matching Scenario

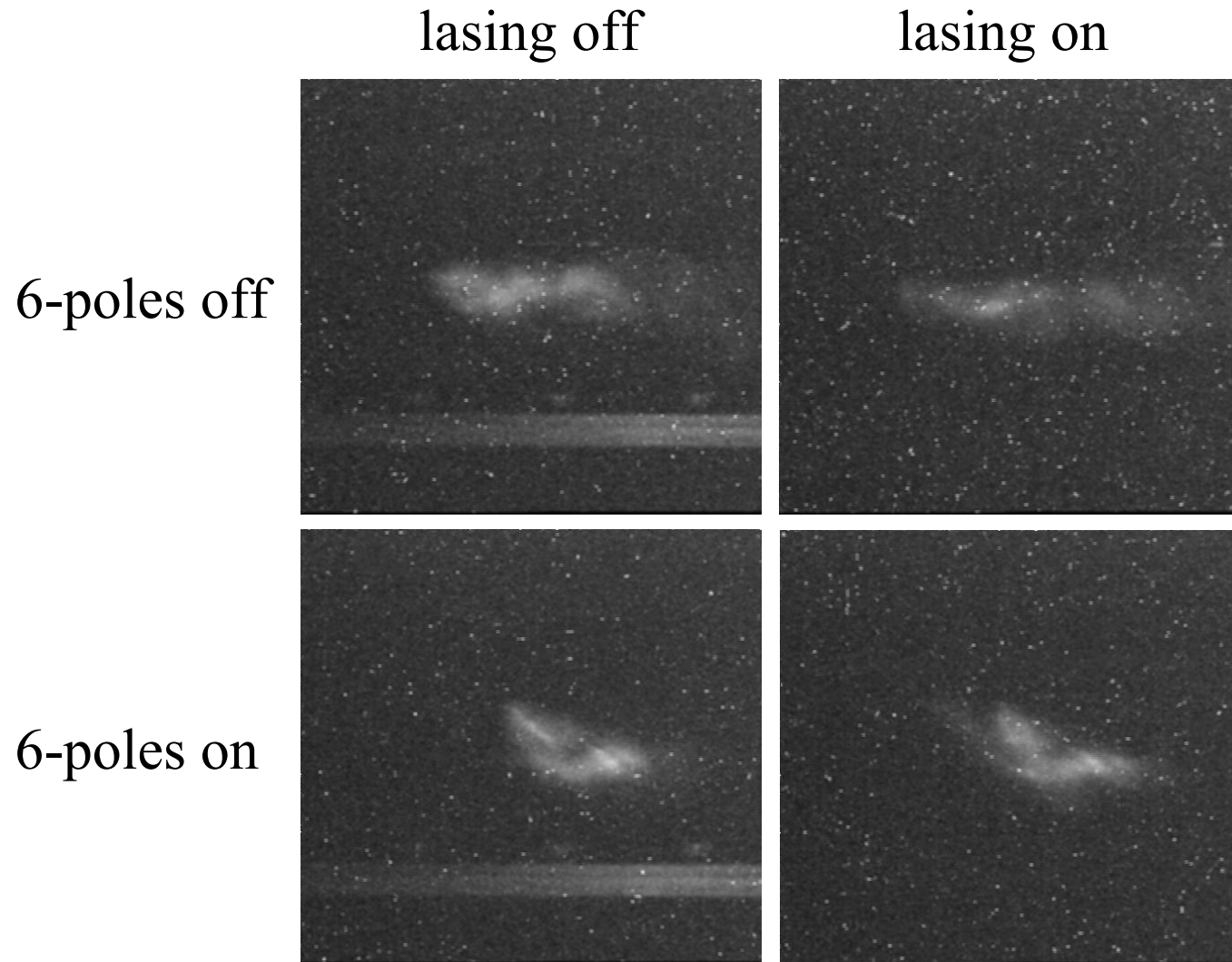
- Requirements on phase space:
 - high peak current (short bunch) at FEL
 - bunch length compression at wiggler
 - “small” energy spread at dump
 - energy compress while energy recovering
 - “short” RF wavelength/long bunch \Rightarrow get slope *and curvature* right



Why We Need the “Right” T_{566}



Why We Need the “Right” T_{566}

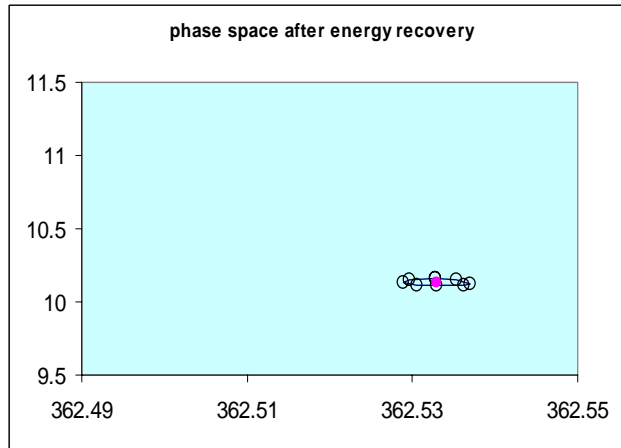


Phase space at 10 MeV Dump

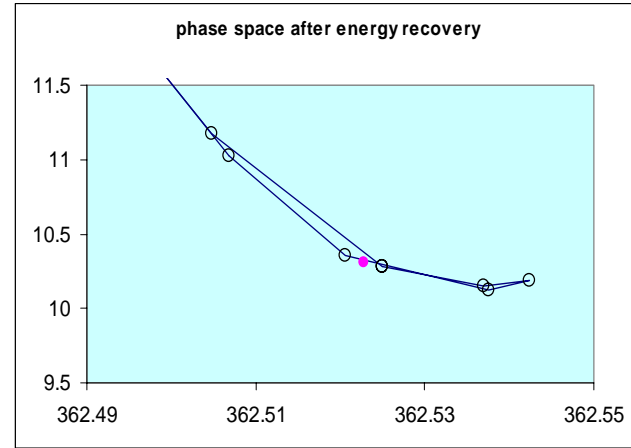
E (MeV)
t (nsec)

6-poles off

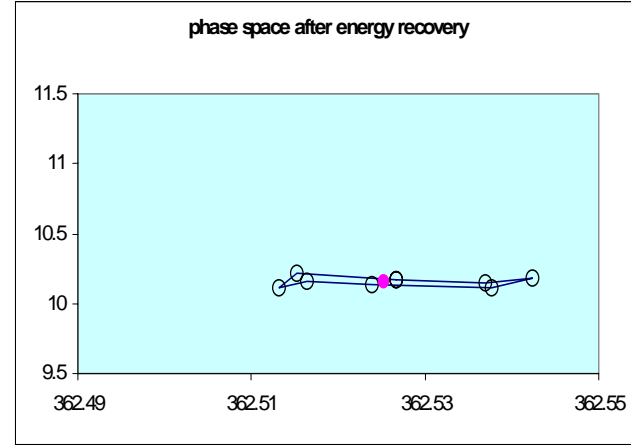
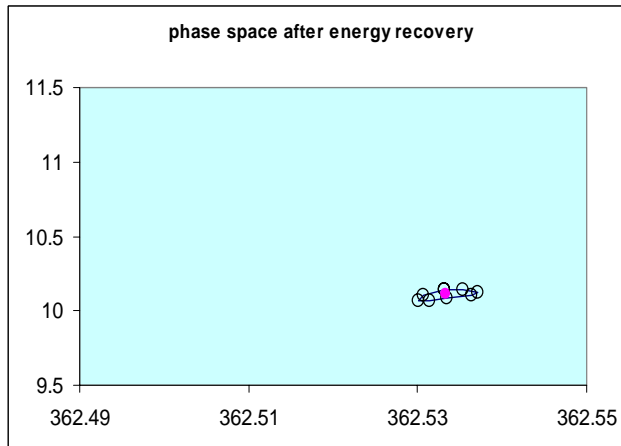
lasing off



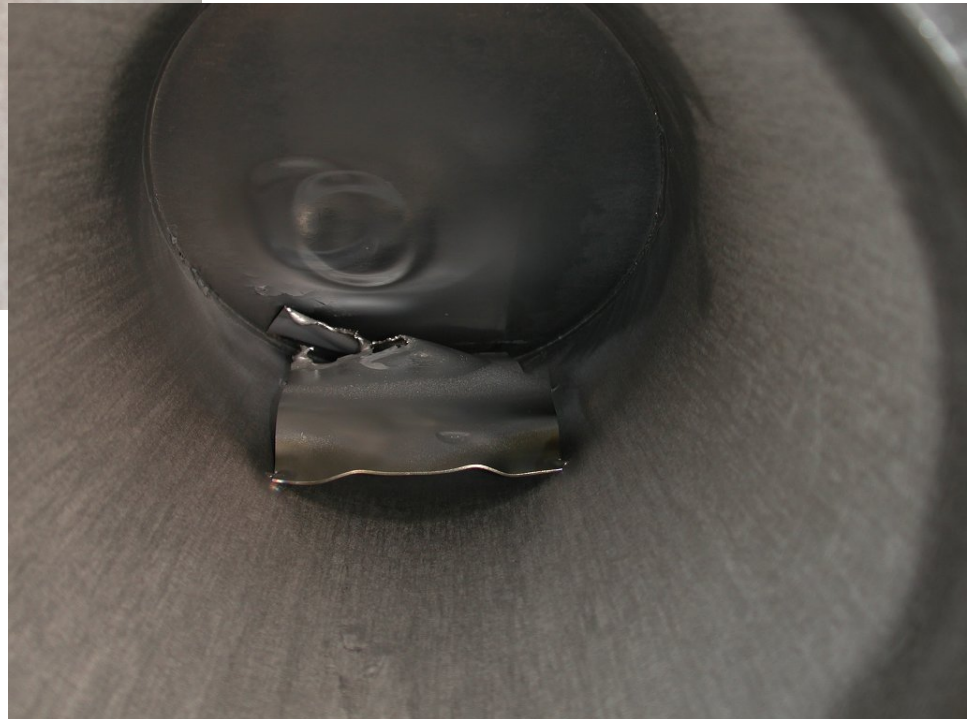
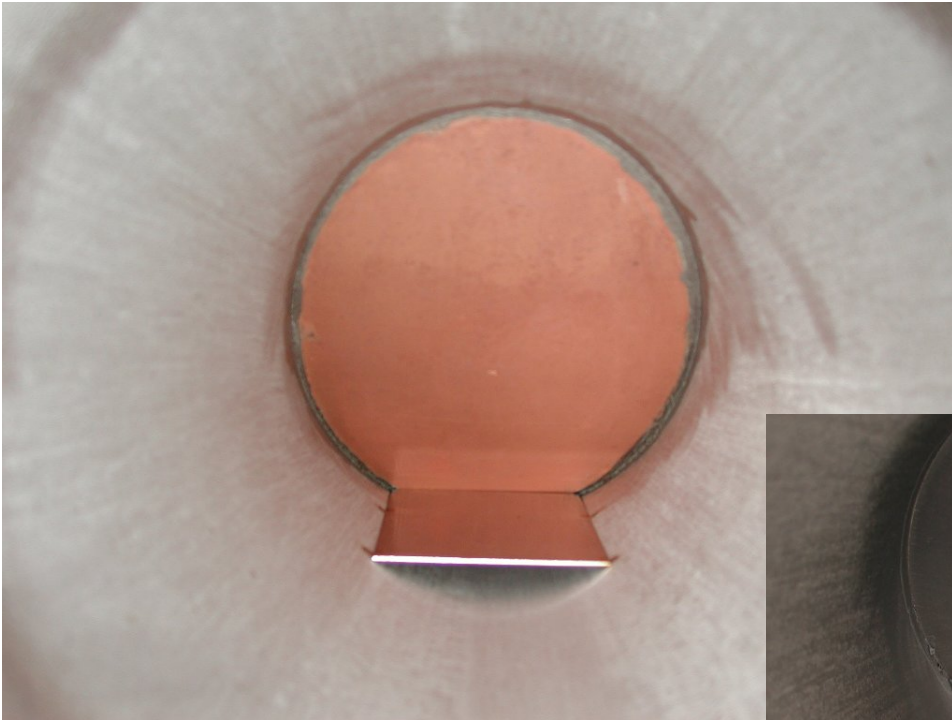
lasing on



6-poles on



Demo Dump – core of beam off center, even though
BLMs showed edges *were* centered



Backup – Demo experience!

Unsolicited Advice (Opinion)

- if you correctly execute a calculation based on accurate descriptions of the installed hardware, you will get/explain the observed behavior, so keep the models clean and simple and use high quality components!
 - just about *any* optics solution will be fine!
- learn from mistakes (I've lost a lot of beer...)
- don't believe any perturbative model; design geometrically
- BEWARE:
 - CSR
 - LSC
 - random component errors

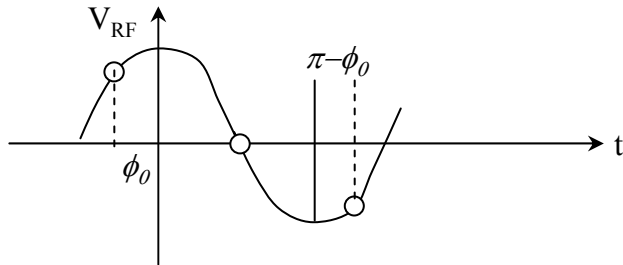
For Fun... *A Free Pass* (of Beam, not to Busch Gardens)

- A repeat of an early 1980s exercise by Jay Flanz and Phil Sargent (MIT-Bates linac; see PAC 1985, where they describe energy doubling, current doubling, and energy recovery in their machine)

IR Demo Multipass Operation

- “Aside” during ongoing difference-orbit studies in Demo
- Best viewed as test of compaction management capabilities
 - Change path length from nominal $\text{mod}(\lambda_{\text{RF}}/2)$ (energy recovery) to $\text{mod}(\lambda_{\text{RF}}/4)$
 - 2nd pass coasts down linac at zero crossing rather than energy recovering
 - 3rd pass energy recovers
 - Momentum spreads managed by off-crest acceleration, simultaneous bunch length compression at reinjection of 2nd pass and energy compression at dump (end of 3rd pass)

How Do We Run 3 Passes?



- Inject long, low momentum spread bunch
 - Accelerate off-crest
 - Recirculate to zero crossing ($\sim \lambda_{\text{RF}}/4$)
 - Compress bunch length at reinjection, minimizing 2nd pass momentum spread
-
- 2nd pass through recirculator biases bunch to energy compress during energy recovery (slope of waveform, compaction are matched), *provided* you
 - Energy recover *across* the trough (not 180° out...)

D. Douglas and C. Tennant, “Three-Pass Operation of the IR Demo Driver”, JLAB-TN-01-043, 28 August 2001;

D. Douglas, “Simultaneous Bunch Length and Energy Spread Compression During Recirculation of Multiple Passes in the IR Demo”, JLAB-TN-01-048, 4 October 2001

