USE OF MULTIPASS RECIRCULATION AND ENERGY RECOVERY IN CW SRF X-FEL DRIVER ACCELERATORS*

W. Akers, S. Benson, G. Biallas, K. Blackburn, J. Boyce, B. Bullard, J. Coleman, C. Dickover, D. Douglas, F. Ellingsworth, S. Fisk, P. Evtushenko, C. Gould, J. Gubeli, F. Hannon, D. Hardy, C. Hernandez-Garcia, K. Jordan, M. Klopf, J. Kortze, R. Legg, R. Li, G. Neil, M. Marchlik, W. Moore, T. Powers, D. Sexton, I. Shin, M. Shinn, C. Tennant, B. Terzic, R. Walker, G. Williams, G. Wilson, and *S. Zhang*

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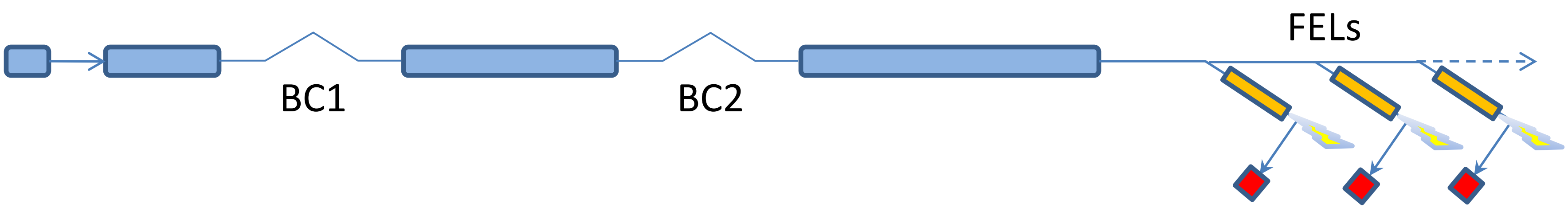
“Conventional” (CW) FEL Layout



- Source -> preaccelerator ->

  1st stage of (chicane) compression -> 1st stage acceleration ->

  2nd stage of (chicane) compression -> acceleration to full energy -> FEL(s) -> dump drive beam

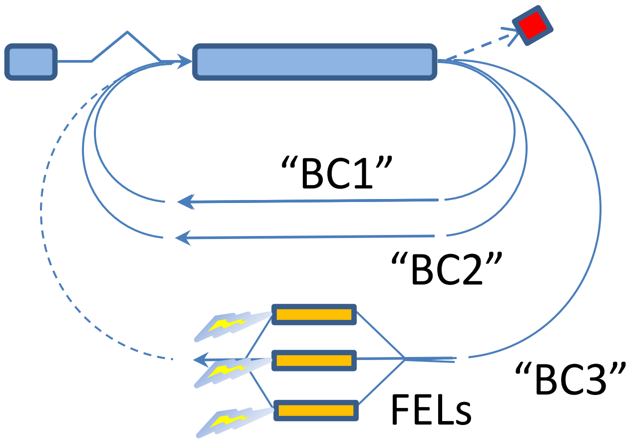
- Linac => bright beam…, *but*

  high cost (accelerator, cryo (assume SRF), RF drive)

  chicane compressors => curvature compensation

  via harmonic RF => higher cost

Recirculated/Energy Recovered FEL



- Source -> linac (via merger, serves as preaccelerator)

  1st recirculation (serves as 1st bunch compressor) ->

  Reinject for 2nd pass through linac ->

  2nd recirculation (serves as 2nd bunch compressor) ->

  Reinject for 3rd pass ->

  Transport to multiple FELs, lase ->

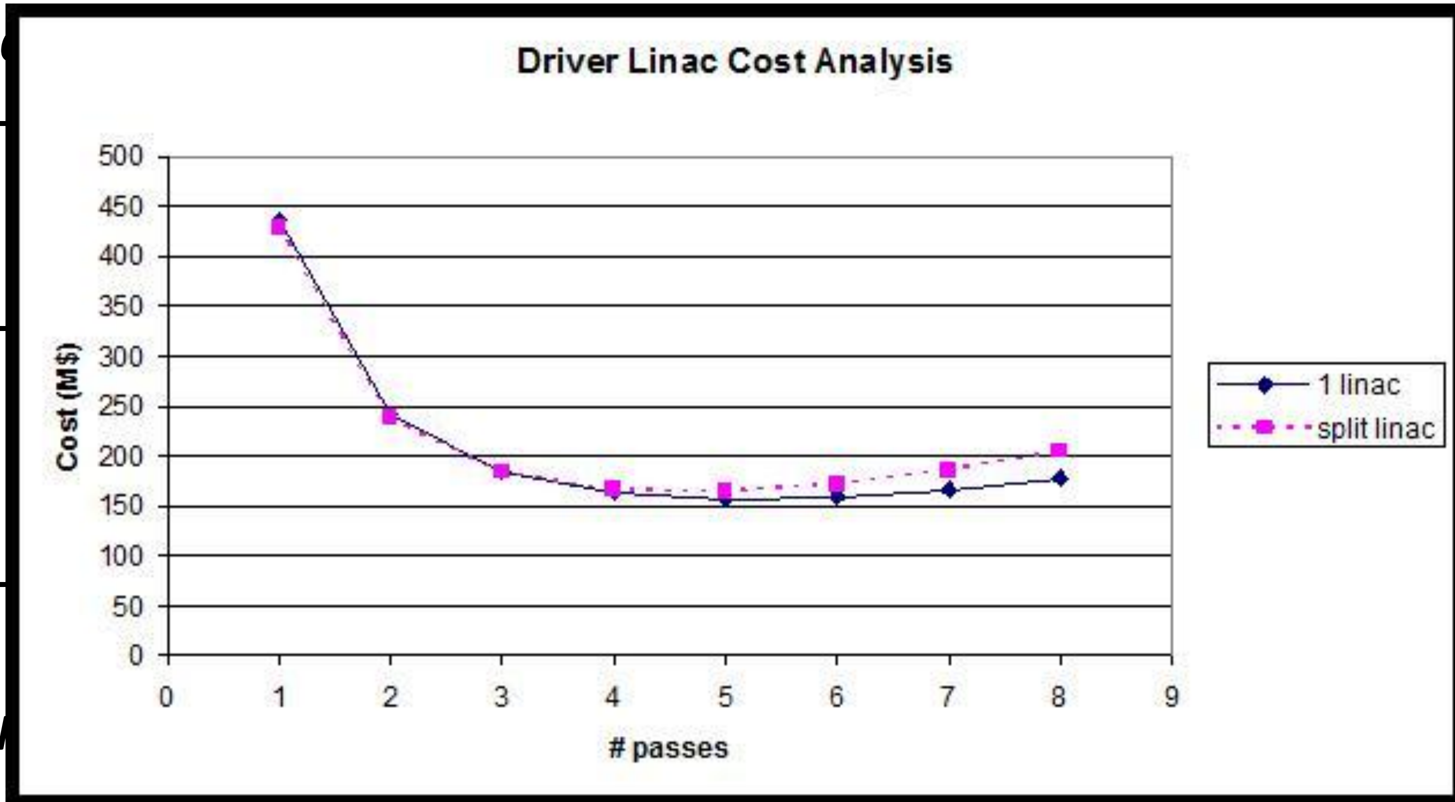
  Energy recover beam(s) (if cost effective [high beam powers])

Rationale for Recirculation and Energy Recovery

- *Recirculation*
  - Reduce linac length/single-pass energy gain => cost control
    - SRF, cryo costs high/beam transport costs low
    - Could save 100s M$ in cost of large system
  - Provide handles on phase space
    - Can provide intermediate stages of bunch compression & curvature correction
    - Betatron matching
  - Alters machine footprint (reduce length/increase width)
    - Aids/abets synchronization
- *Energy Recovery*
  - Reduce required RF power => cost control
  - Limit radiation losses (dump low energy beam)

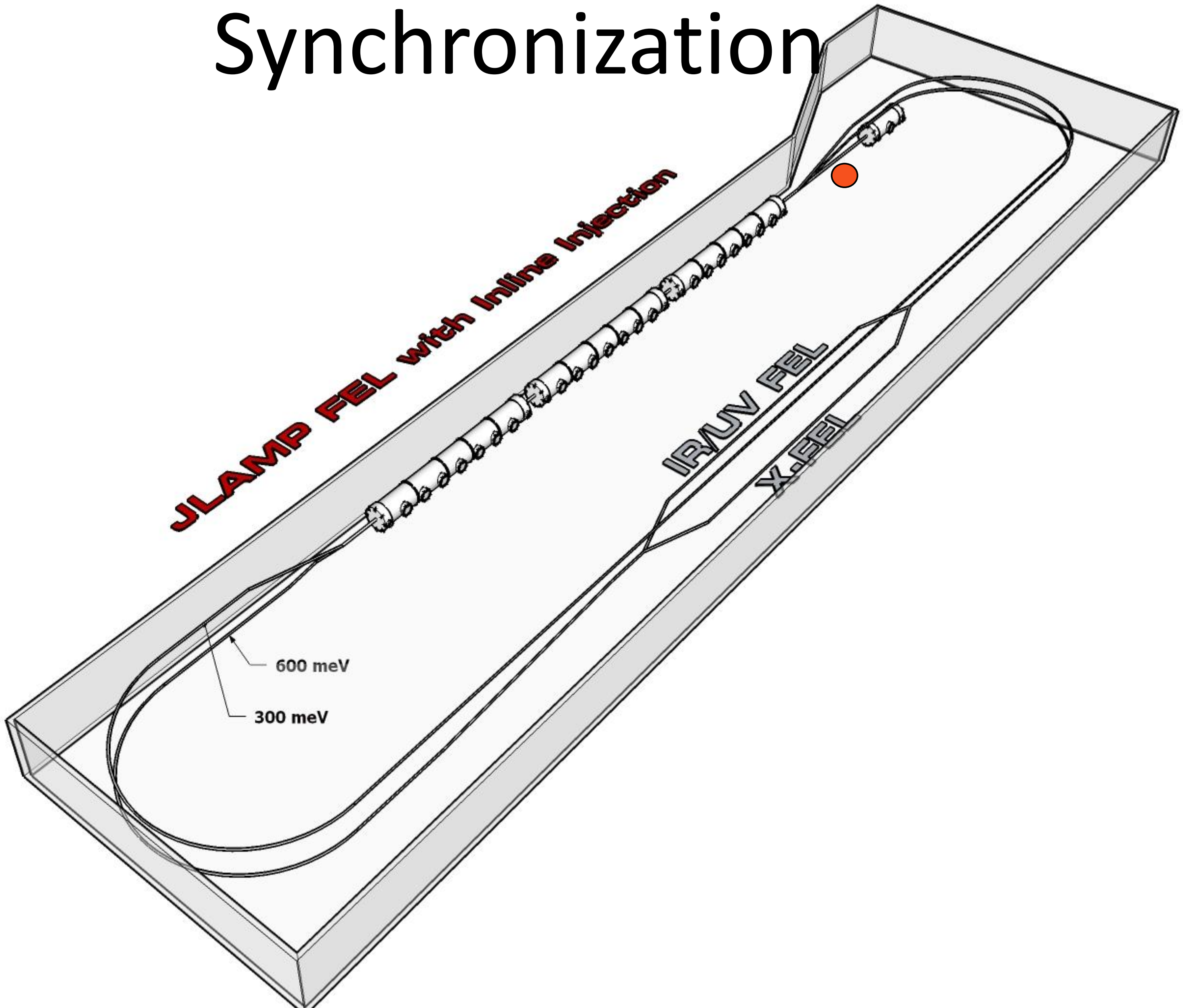
Rationale for Recirculation and Energy Recovery

- *R*
  - ntrol
  -)



- *E*
  - Reduce required RF power => cost control
  - Limit radiation losses (dump low energy beam)

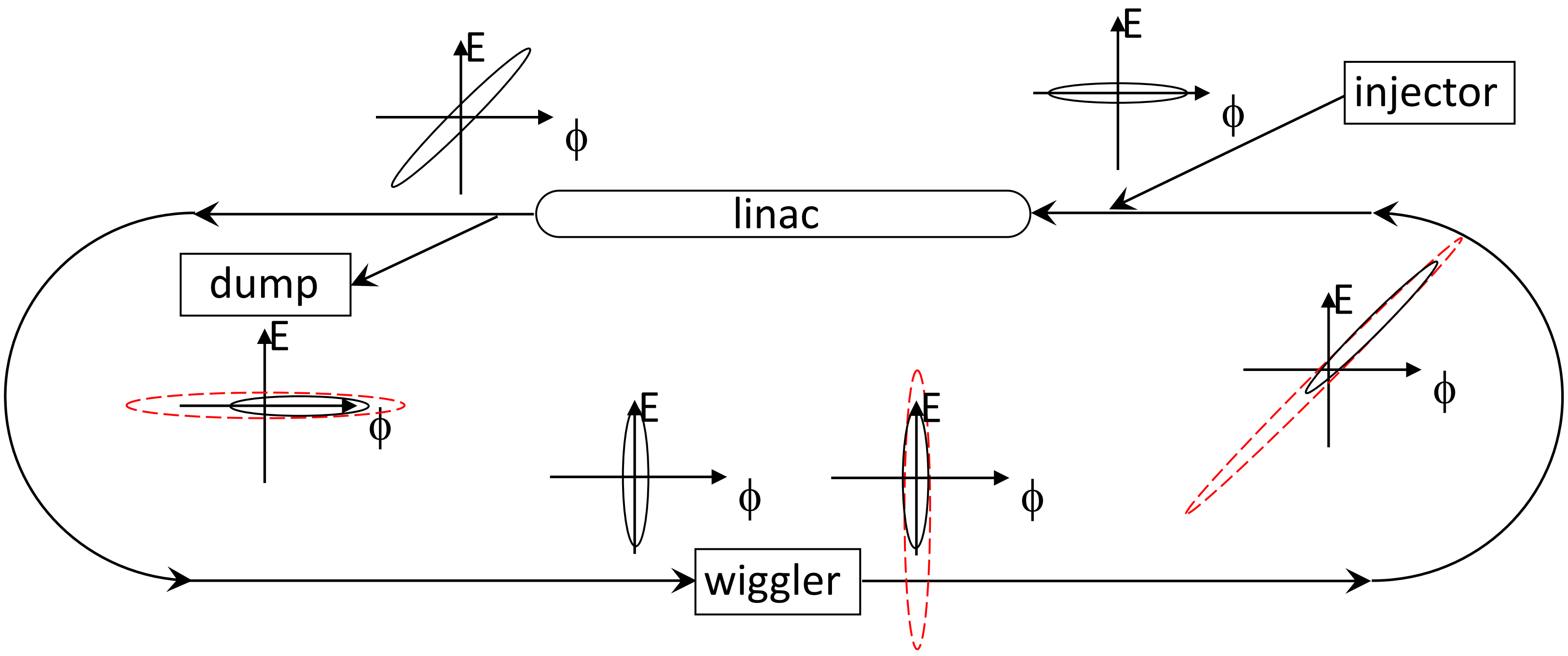
Synchronization



Key Issues for Successful Implementation of Multipass Recirculation

- Appropriate phase space management =>
  - Longitudinal matching cycle
  - Transverse control (betatron matching)
    - Must be observant of collective effects *and* lattice sensitivities…
- Preservation of beam quality during (protracted) acceleration, beam handling, energy recovery cycles

Schematic Longitudinal Match for ERL-Driven FEL



Important Features:

- Energy transient when FEL turns off/on => phase transient at reinjection => transient beam loading
- Must provide adequate RF power to manage these transients
- *No* energy transients at dump when system properly tuned
- Properly designed system can readily manage nonlinear effects:
  - Sextupoles compensate RF curvature, octupoles manage torsion…

Nonlinearity Control Validated By Measurement

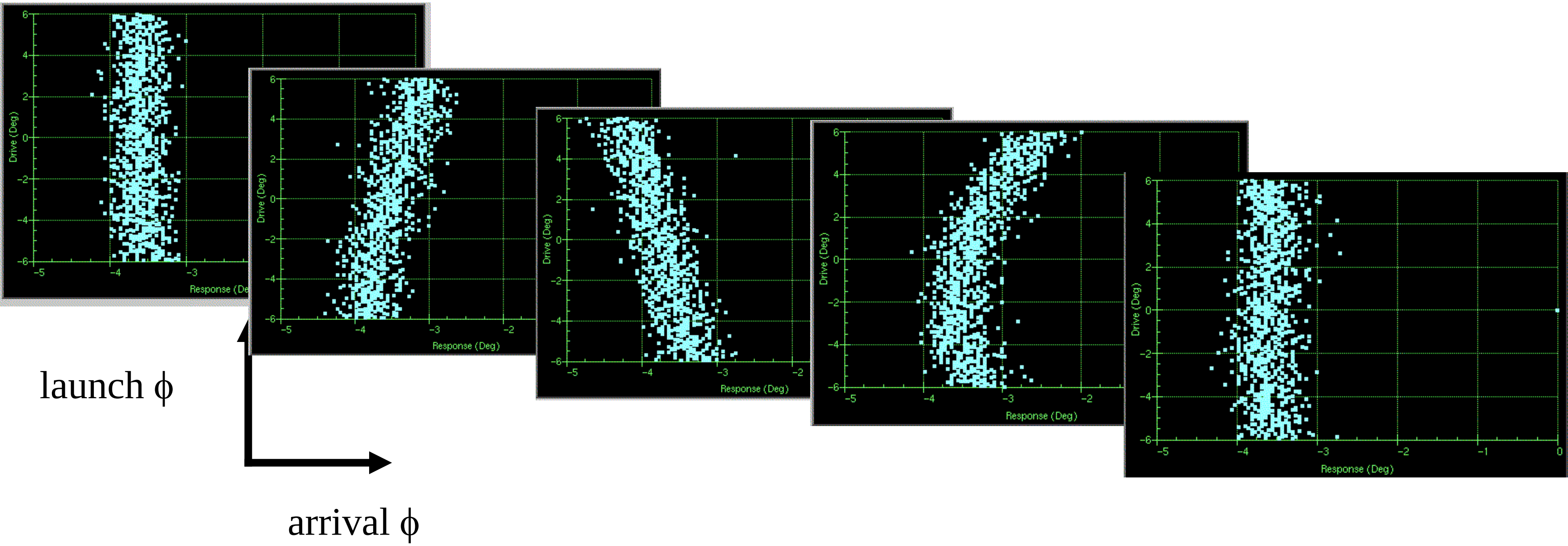
Figure 1: Inner sextupoles to 12726 g-cm and trim quads to -215 g

Figure 2: trim quads at -185 g with same sextupoles

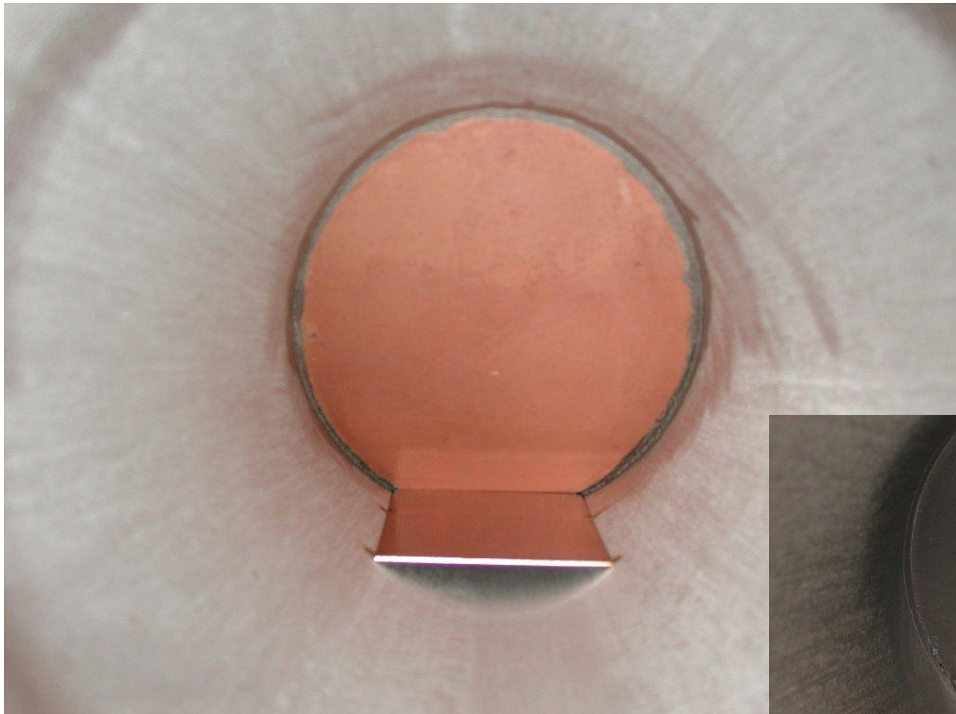
Figure 3: trim quads at -245 g

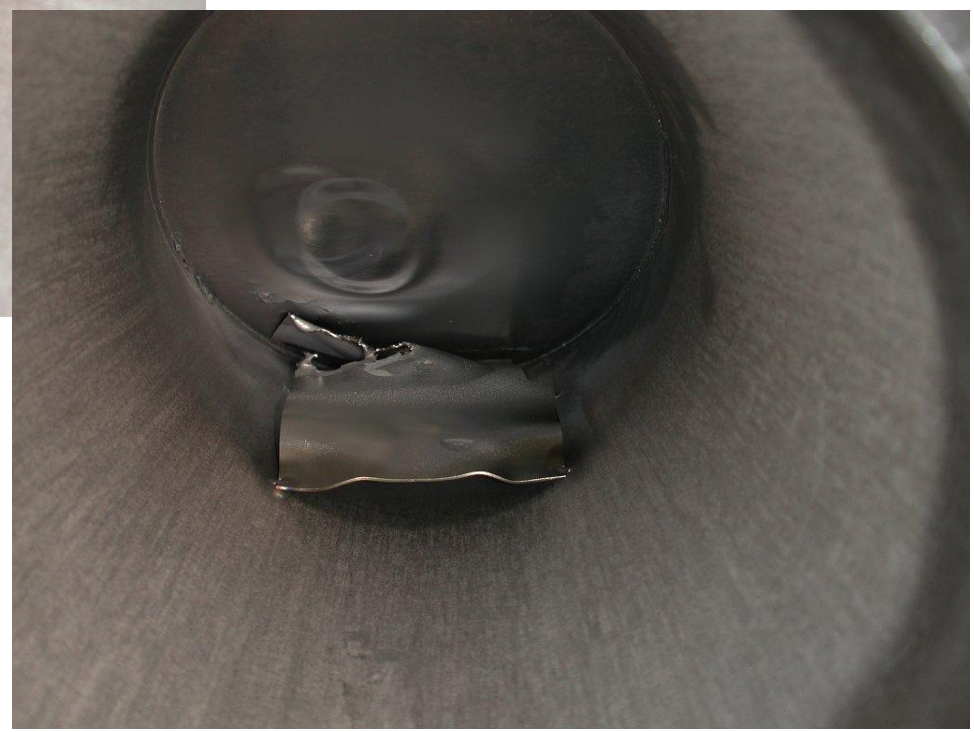
Figure 4: quads at -215, but sextupoles 3000 g below design, at 10726 g-cm

Figure 5: where we left it: trim quads -215 g sextupoles at 12726 g-cm



JLab IR Demo Dump





core of beam off center,

even though BLMs showed

edges were centered

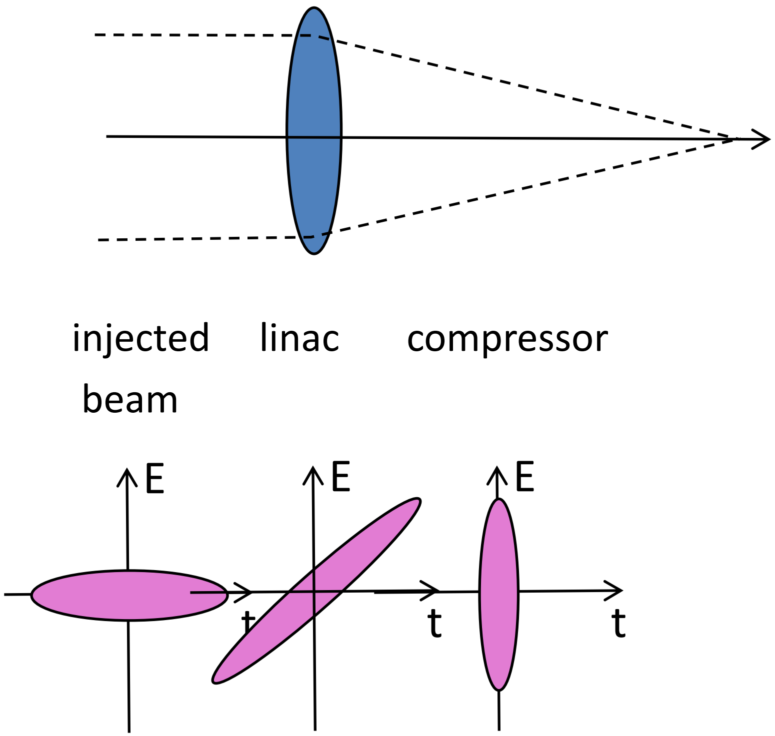
(high energy tail)

Extrapolation to Multi-pass System: Implementation of Multistage Compression

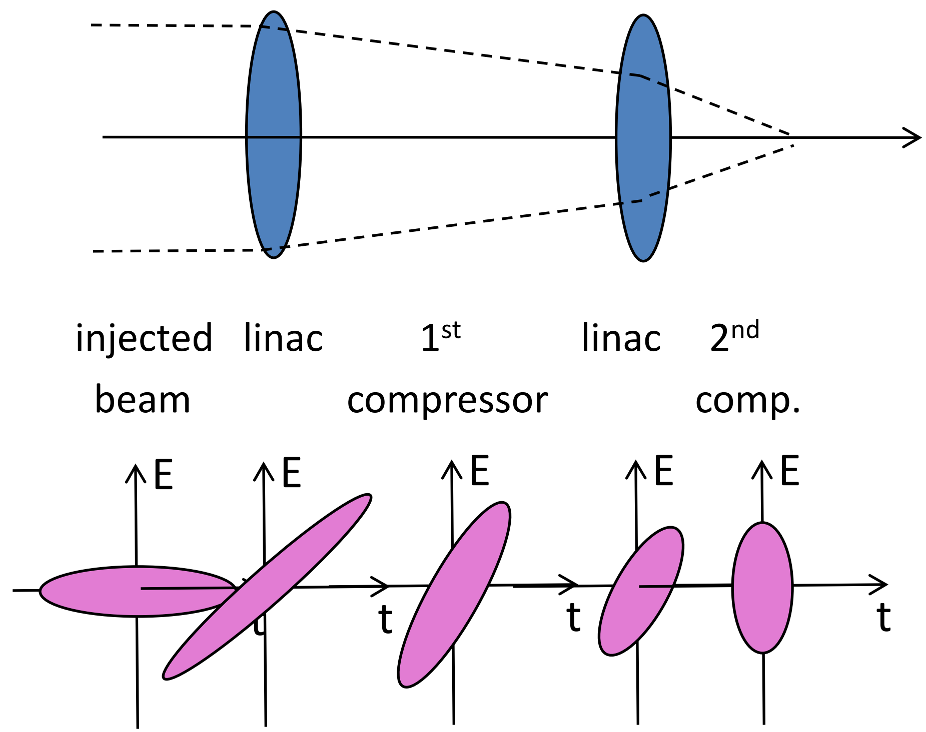
- Multi-pass linac naturally suited for multi-stage compression
  - Use recirculator compactions (M_{56}, T_{566}, W_{5666}…) to rotate and correct distortions in phase space
- Provides operational freedom in
  - choice of acceleration phase
  - bunch aspect ratio after compression
  - Tolerance of variable (longer) injected bunch (space charge mitigation)
- Avoids use of harmonic RF
  - additional cost
  - aperture constraints
    - Impedance burden
    - acceptance limitations (spatial, *and* in RF phase during energy recovery - when phase extent of beam can be large (~30^{o} at RF fundamental, 90^{o} at 3rd harmonic)

Comparison: Single/Multistage Compression

Single stage



Multistage



Beam Dynamics Issues – see ERL 2009!

- space charge
- BBU
- other wakes/impedances
  - linac, vacuum chamber, diagnostic impedences
    - MicrowaveStudio modeling of all components
    - impedance budget, policy, enforcement (impedence policing)
  - resistive wall
- vacuum effects
  - Ions
  - gas scattering
- intrabeam scattering
  - IBS
  - Touschek
- halo
  - Formation
  - gas scattering
  - beam formation processes
- CSR
  - CSR basic ("elegant")
  - 3-d modeling
  - microbunching instabilities
- ISR
  - emittance, $\delta p/p$...
- Error analysis
  - Alignment
    - Magnets, cavities, diagnostics
  - Powering
    - Excitation, ripple, reproducibility
  - field tolerance
    - Homogeniety, calibration
  - timing & synchronism
  - phase & gradient
  - diagnostic errors
- RF drive
  - transient analysis
- Operational simulations
  - threading, orbit correction
  - emittance measurement
  - lattice function tuning
  - longitudinal matching
    - phase transfer function
    - bunch length compression tuning
    - energy compression tuning

Example System: JLAMP

Notional upgrade of existing JLab CW UV FEL to an amplifier-based VUV/Soft X-Ray facility

Requirements

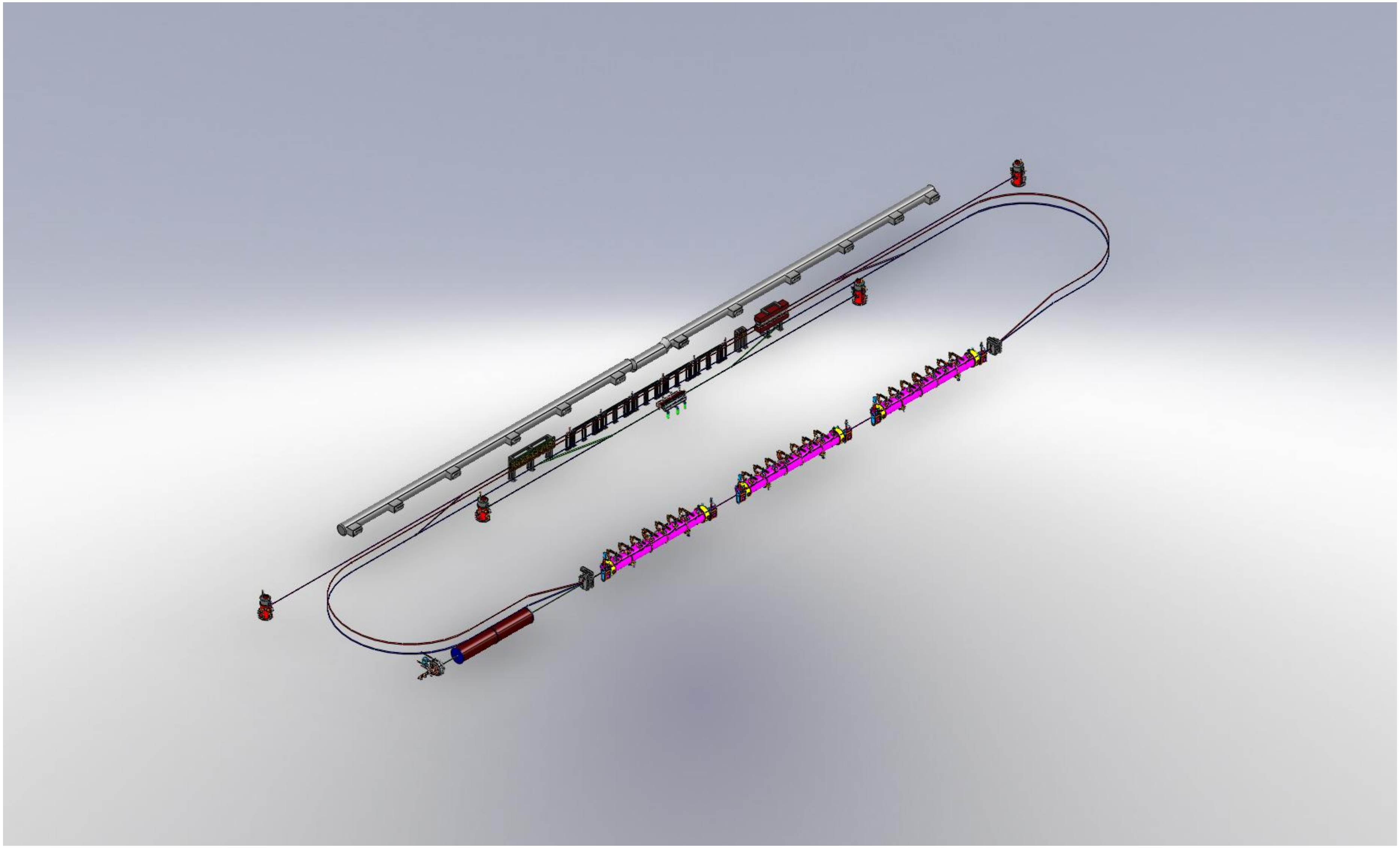
- Generate, accelerate, and deliver properly configured drive beam to FEL
  - 1 mm-mrad x 50 keV-psec x 200 pC
  - I_{peak} ~ 1 kA (200 fsec FWHM x 0.1% $\delta p/p$)
- Recover (degraded) exhaust beam
- Preserve beam quality, manage losses, avoid instabilities, etc etc
- Fit in vault (an *upgrade*)
- Cost < 100 M$

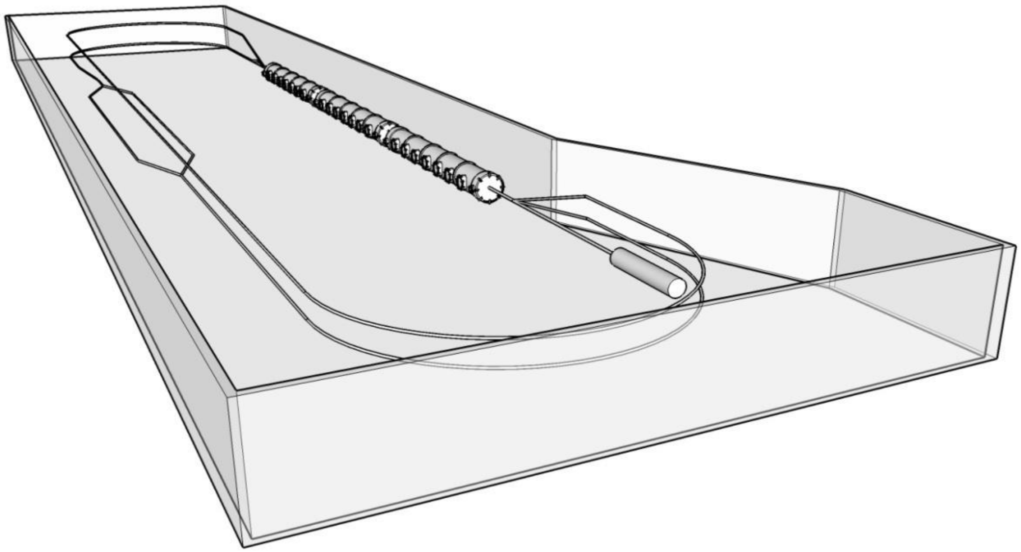
Design Parameters*

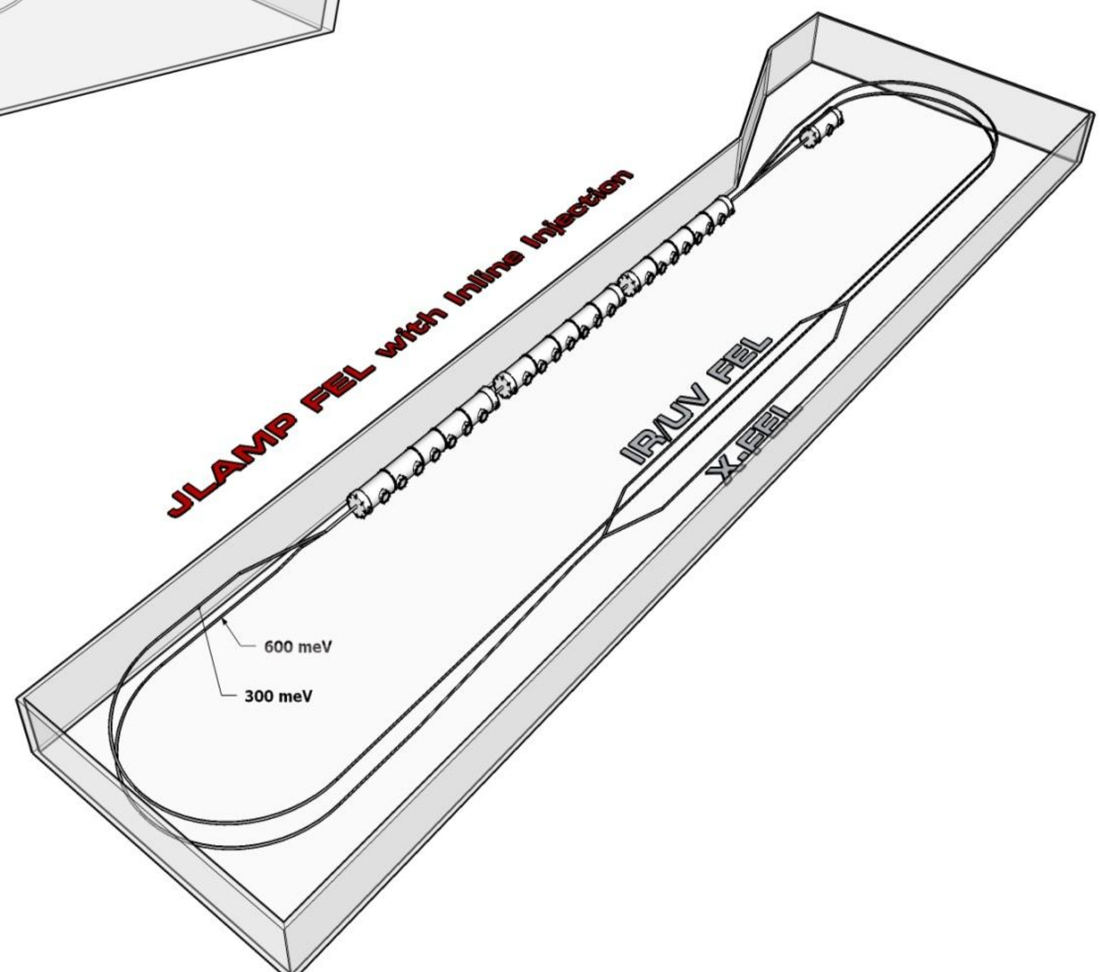
	2010	**2012**
Bunch charge (pC)	135	200
Bunch rep. rate (MHz)	75	4.68
Average current, max (mA)	10	1
Norm. transverse emittance at FEL (μm)	10	1
Longitudinal emittance at FEL (keV ps)	60	50
Energy spread at FEL (% rms)	0.4	0.1
Bunch length at FEL, rms (fs)	150	83
Bunch energy (MeV)	100	600

**F. Hannon et al., IPAC2010*

Driver Concept






JLAMP FEL with Inline Injection
IR/UV FEL
X-FEL
600 meV
300 meV

Analysis: Longitudinal Match, Space Charge, CSR

Initially obvious concerns:

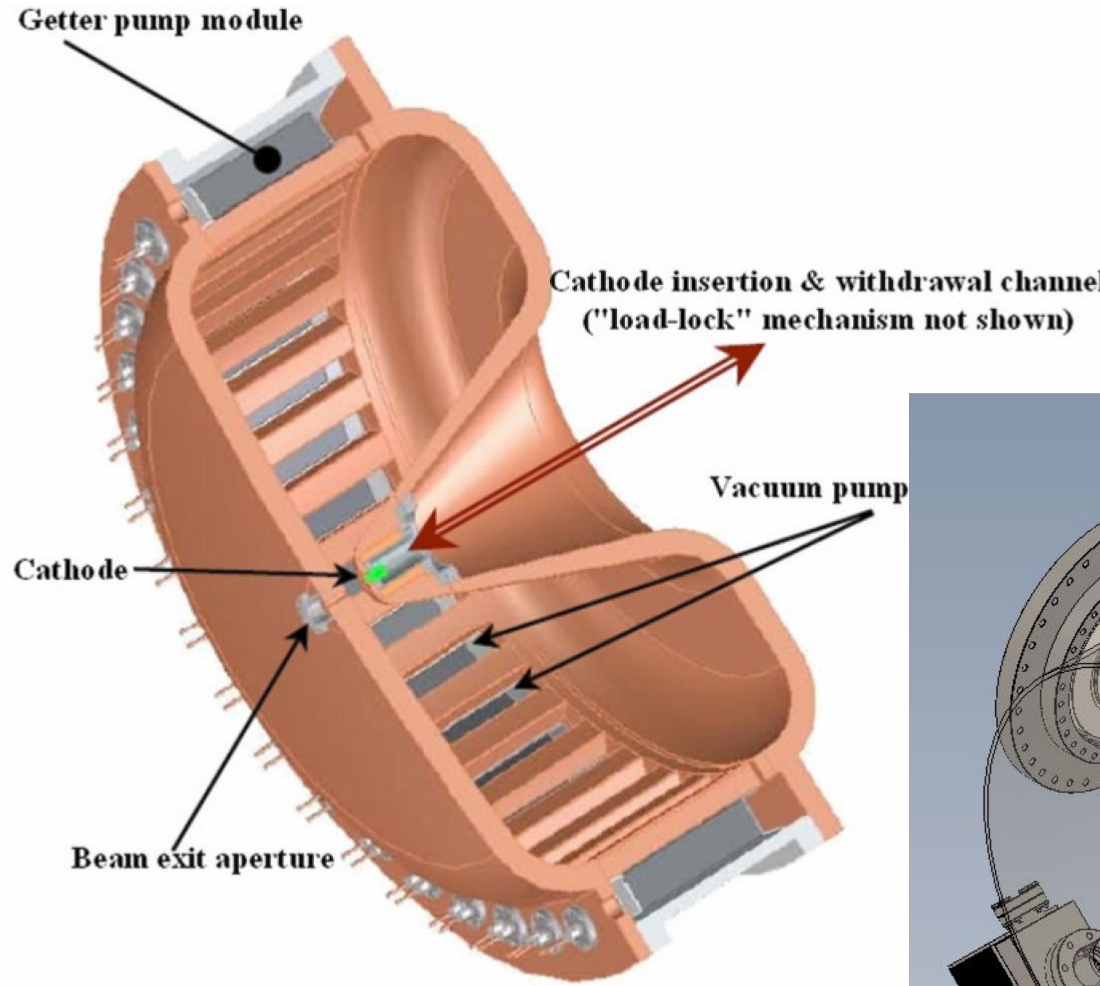
- CW Source/Injector Performance
- Phase space management scenario
- Beam quality preservation during
  - Acceleration (space charge)
  - Recirculation (CSR)

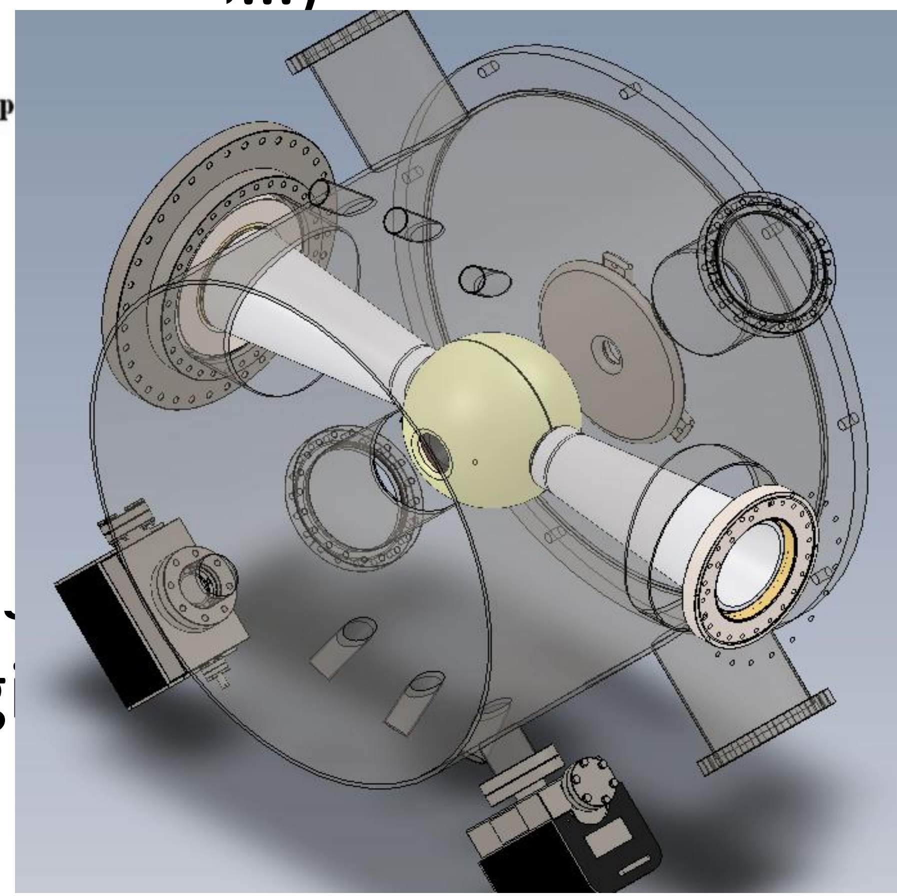
Source/Injector

- Initial challenge: generate LCLS-class beam, but ***CW*** (with lower gradients…)
- Studying various cathode materials, gun options
  - LBL NCRF, JLab DC inverted, U.W. SRF
- Exploring subharmonic (~750 MHz) injector designs with type/spacing of RF cavities tailored to specifics of gun
- Initial results encouraging

tor

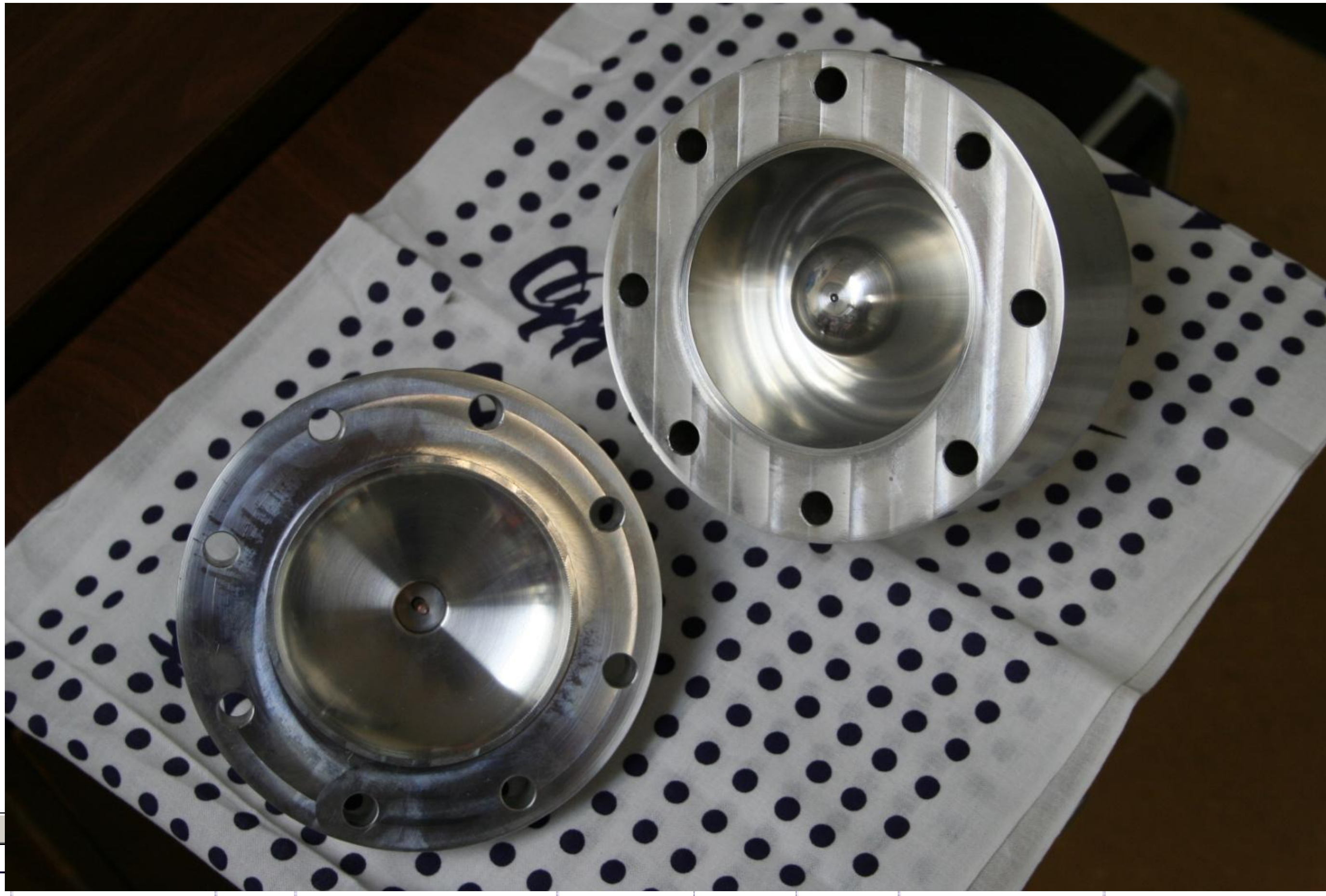
LS-class beam,
...)

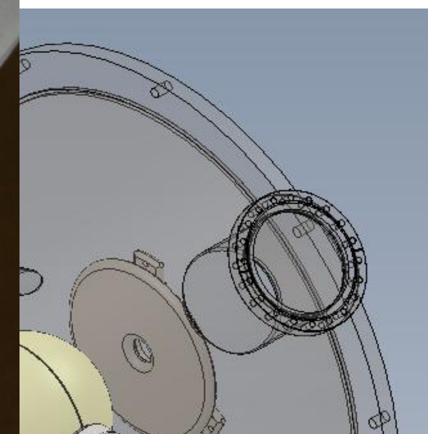


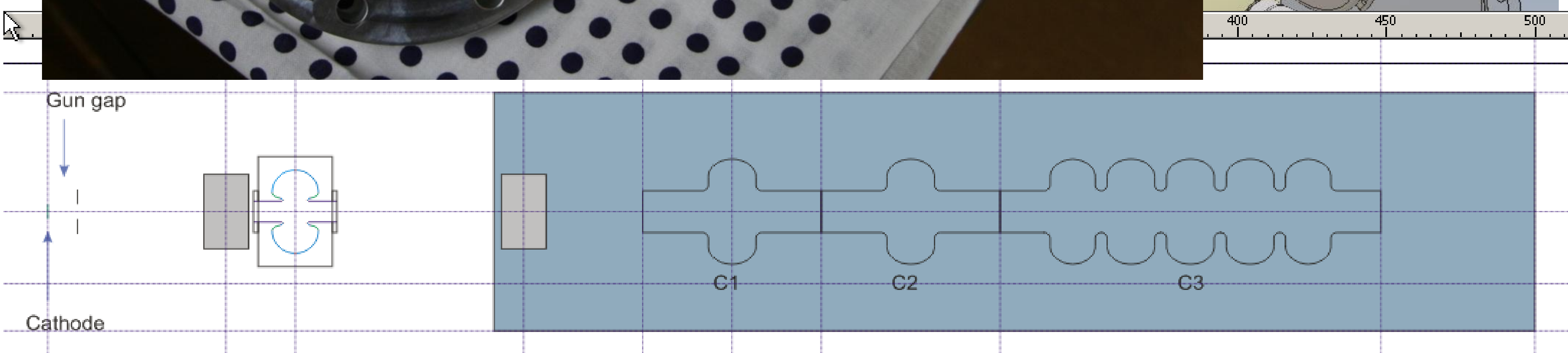


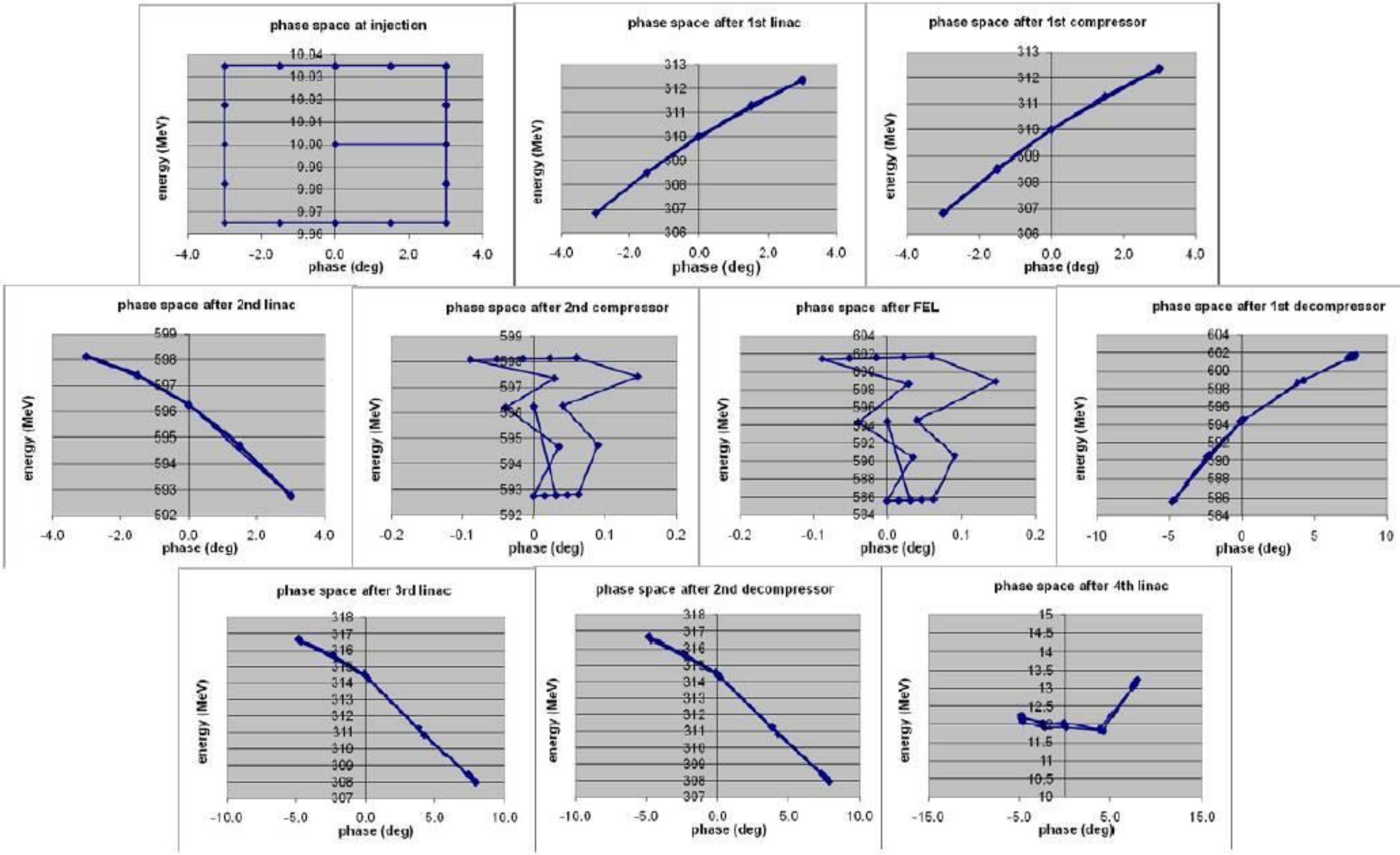
- Initial results encouragi

beam,

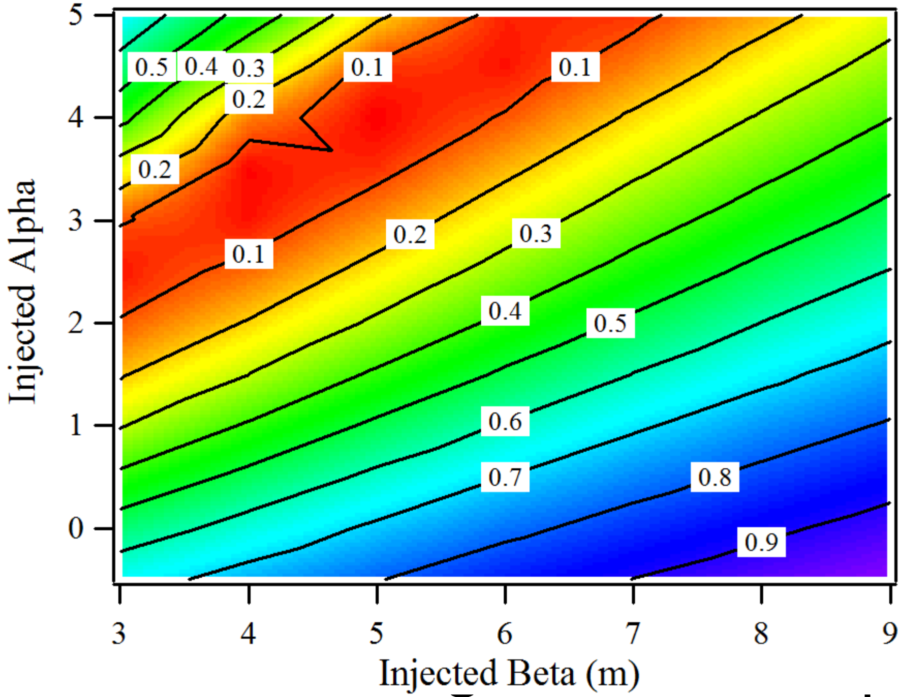


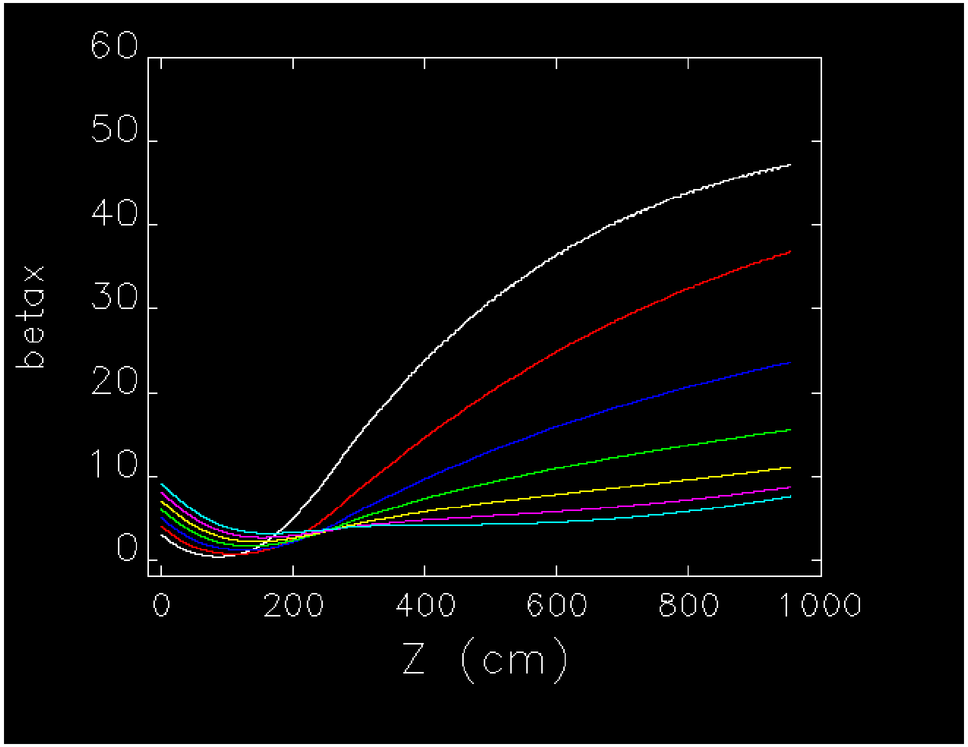






phase space at injection
energy (MeV)
phase (deg)
phase space after 1st linac
energy (MeV)
phase (deg)
phase space after 1st compressor
energy (MeV)
phase (deg)
phase space after 2nd linac
energy (MeV)
phase (deg)
phase space after 2nd compressor
energy (MeV)
phase (deg)
phase space after FEL
energy (MeV)
phase (deg)
phase space after 1st decompressor
energy (MeV)
phase (deg)
phase space after 3rd linac
energy (MeV)
phase (deg)
phase space after 2nd decompressor
energy (MeV)
phase (deg)
phase space after 4th linac
energy (MeV)
phase (deg)





- "other wrong match" => no space charge effects (good emittance), but lattice functions diverge

- Must negotiate between space-charge-driven emittance degradation & lattice sensitivity to instabilities (BBU) and error effects

Recirculator Design

- principle design driver: beam quality preservation
  - Manage aberrations
    - 2^{nd} order achromat (w/ M_{56}, T_{566},… control)
  - Configure system to avoid ISR
    - bend radii, lattice functions
  - mitigate CSR
    - Avoid parasitic compressions,
    - single stage of compression
    - abrupt final compression,
- Initial results (300 MeV recirculator) promising
  - ISR not significant
  - CSR
    - 1^{st} pass emittance well conserved ($\Delta\varepsilon_{trans}$ ~ 0.1 mm-mrad)
    - Some evidence of microbunching; analysis in progress

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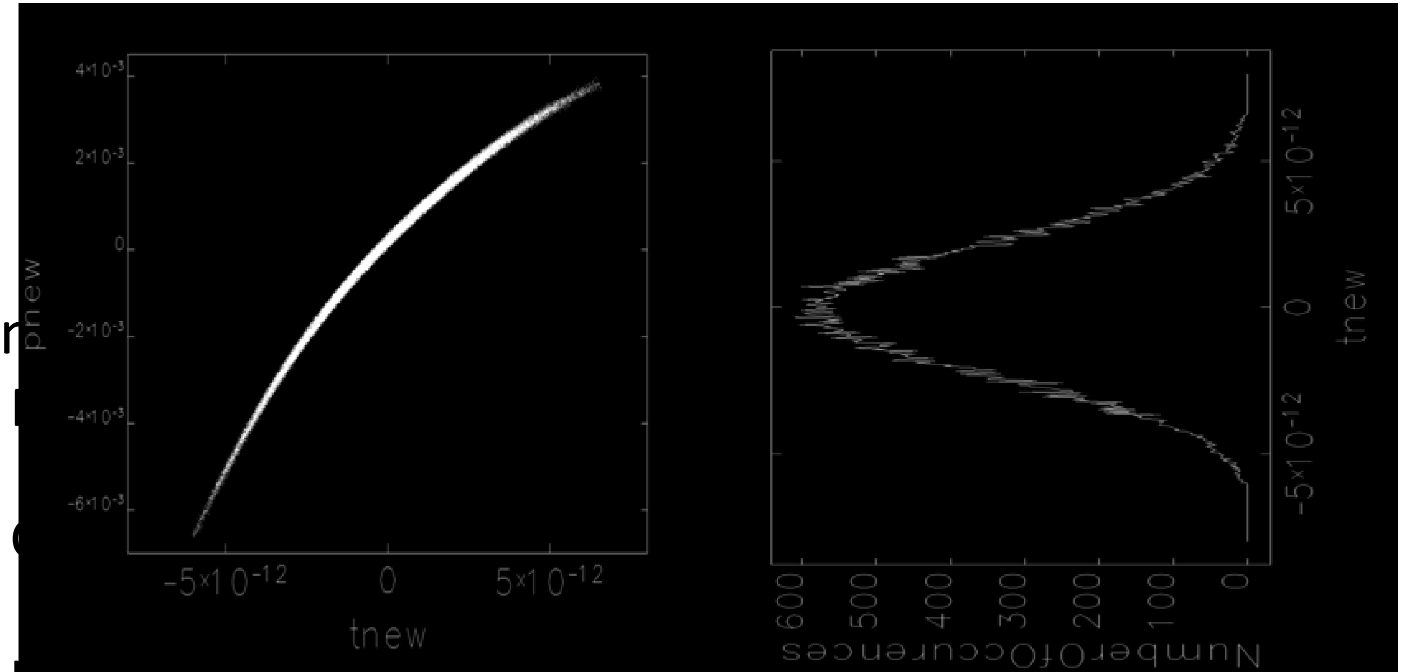

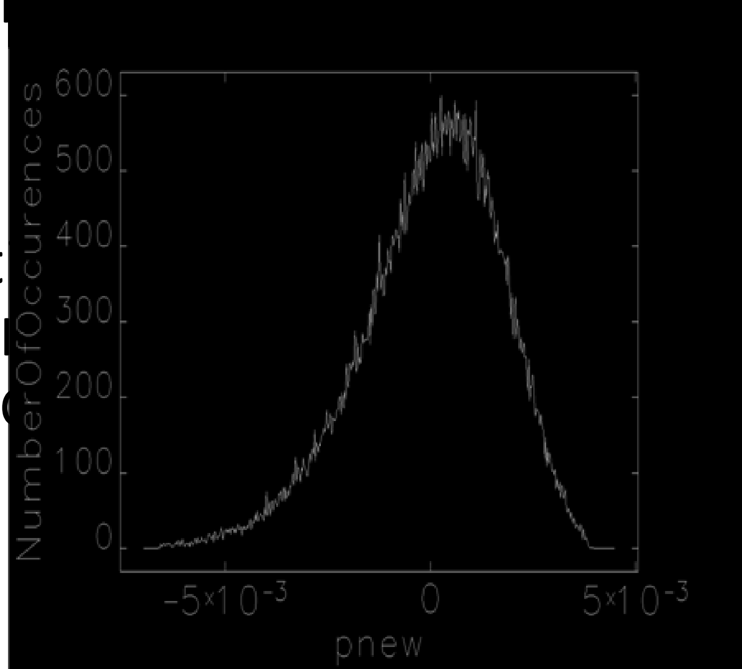

- Init … lator) promising
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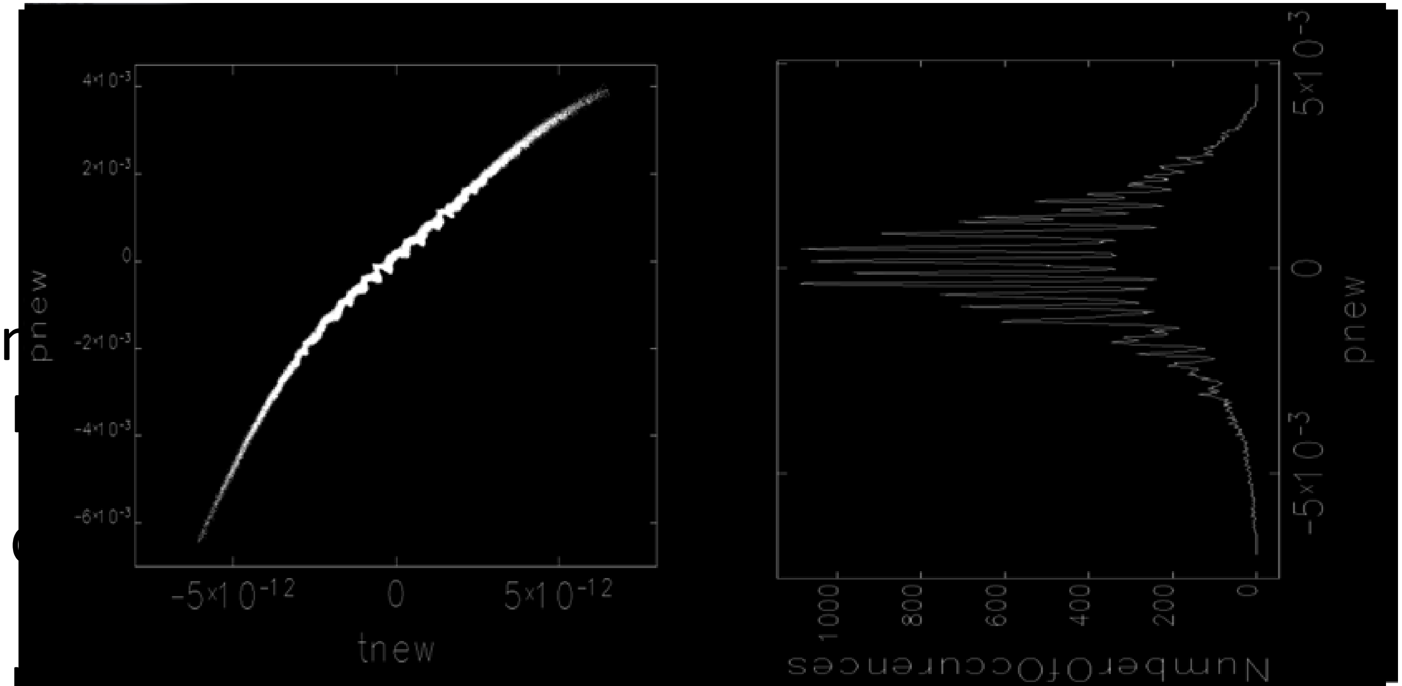
d ($\Delta\varepsilon_{trans}$ ~ 0.1 mm-mrad)

g; analysis in progress



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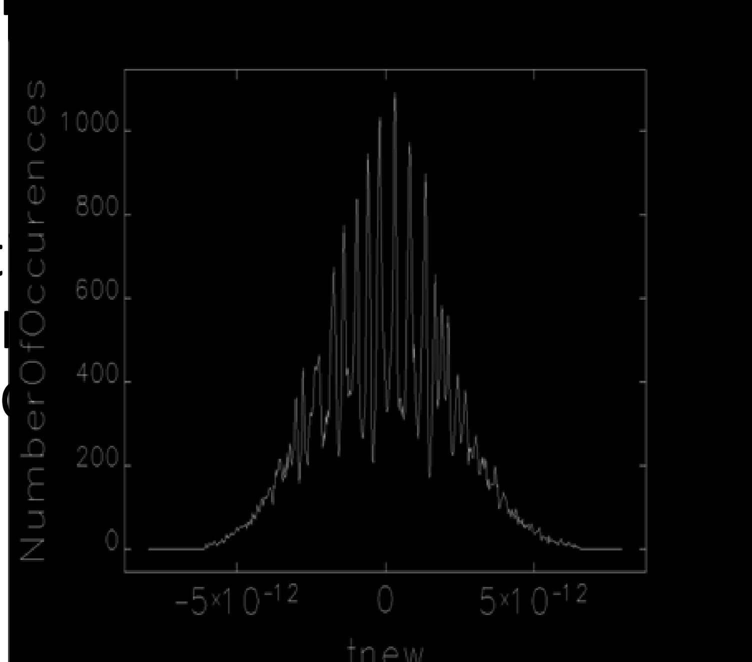

- Init ... ator) promising
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    d ($\Delta\varepsilon_{trans}$ ~ 0.1 mm-mrad)
    g; analysis in progress

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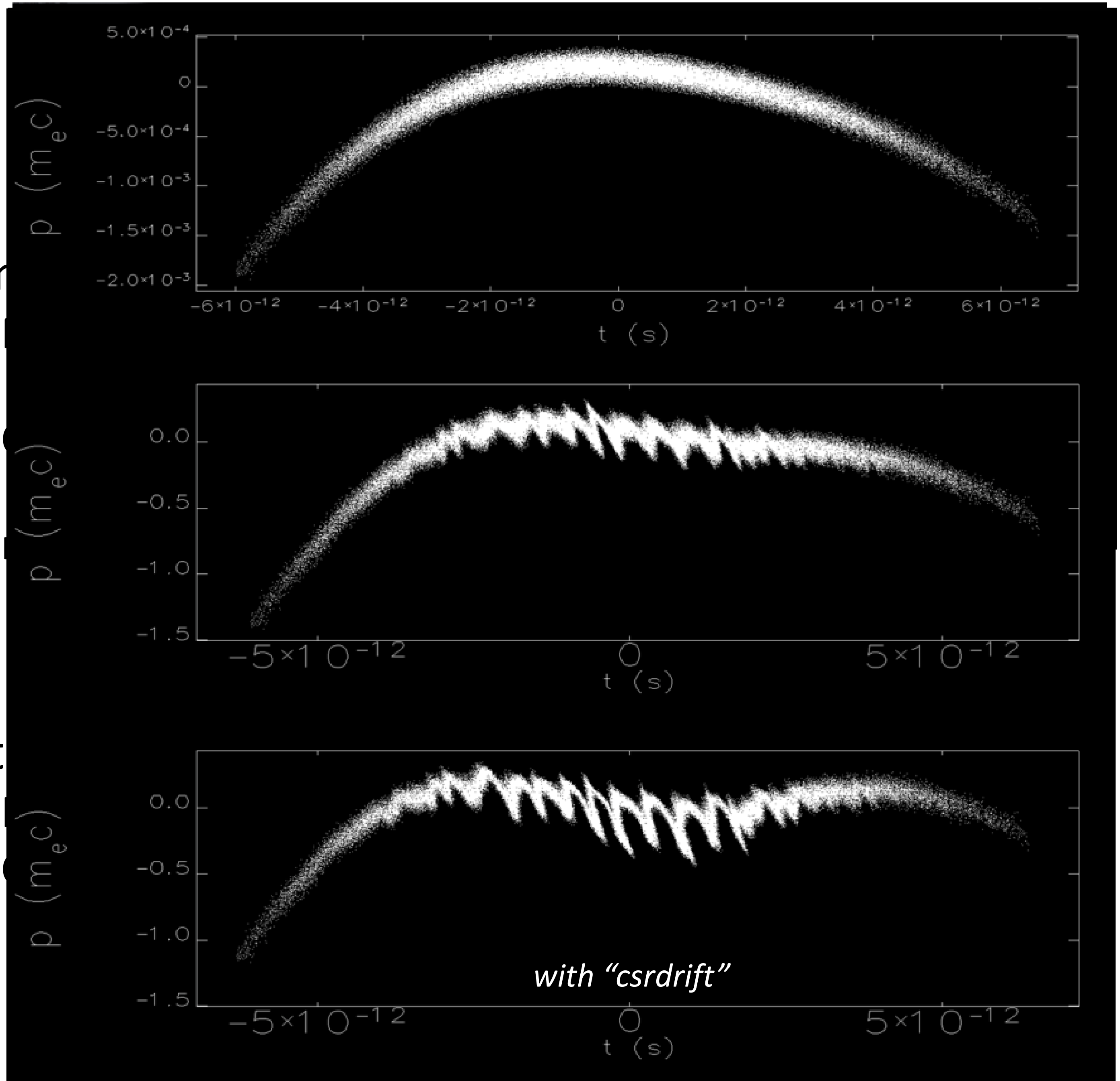


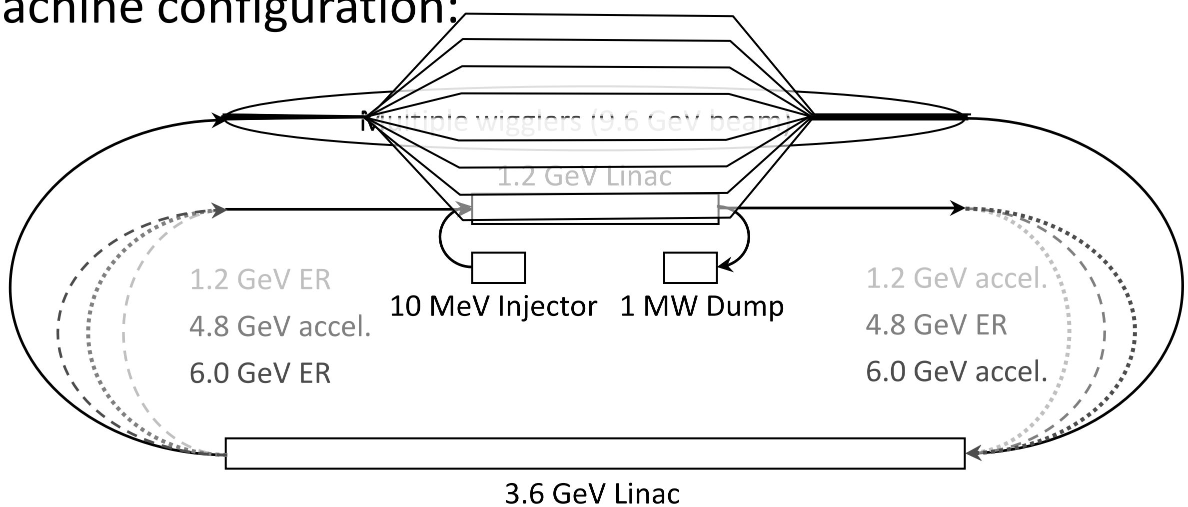
p (m_e c)
5.0×10^-4
0
-5.0×10^-4
-1.0×10^-3
-1.5×10^-3
-2.0×10^-3
-6×10^-12
-4×10^-12
-2×10^-12
0
2×10^-12
4×10^-12
6×10^-12
t (s)
p (m_e c)
0.0
-0.5
-1.0
-1.5
-5×10^-12
0
5×10^-12
t (s)
p (m_e c)
0.0
-0.5
-1.0
-1.5
with "csrdrift"
-5×10^-12
0
5×10^-12
t (s)

(Not-so-credible) Future Possibilities

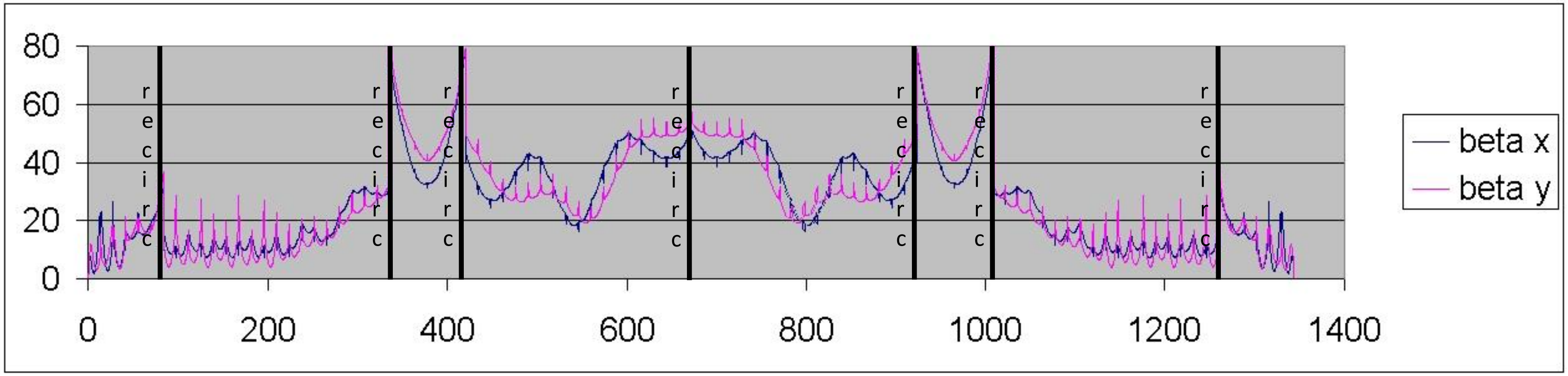
- High energy
- Many passes
- CW Service to multiple wigglers/undulators using RF switching (as in CEBAF)
  - Subharmonic deflecting cavities split bunch trains, directing them to different FELs
  - Can imprint different charges, rep rates on each subtrain
  - Recombine drive beams for recovery (if ERL) using second system of RF deflectors

GERBAL: A "Generic Energy-Recovered Bisected Asymmetric Linac

- Machine configuration:



- Transverse optics



Conclusions

- Recirculated, energy-recovered linacs offer a number of possible advantages over conventional architectures
  - Reduced cost
  - Flexible phase space management (magnetic compensation of RF curvature; multi-stage compression/decompression schemes)
  - Short time-of-flight paths for synchronization
- Numerous challenges remain
  - Beam quality preservation, beam stability, power deposition, halo…

but increasingly appear to be tractable