Longitudinal Phase Space Tomography

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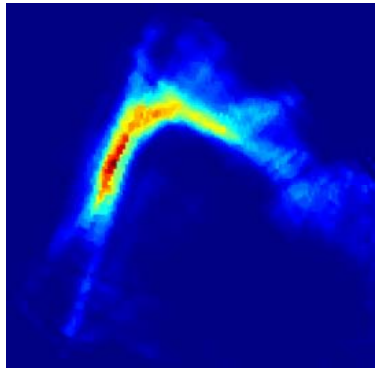


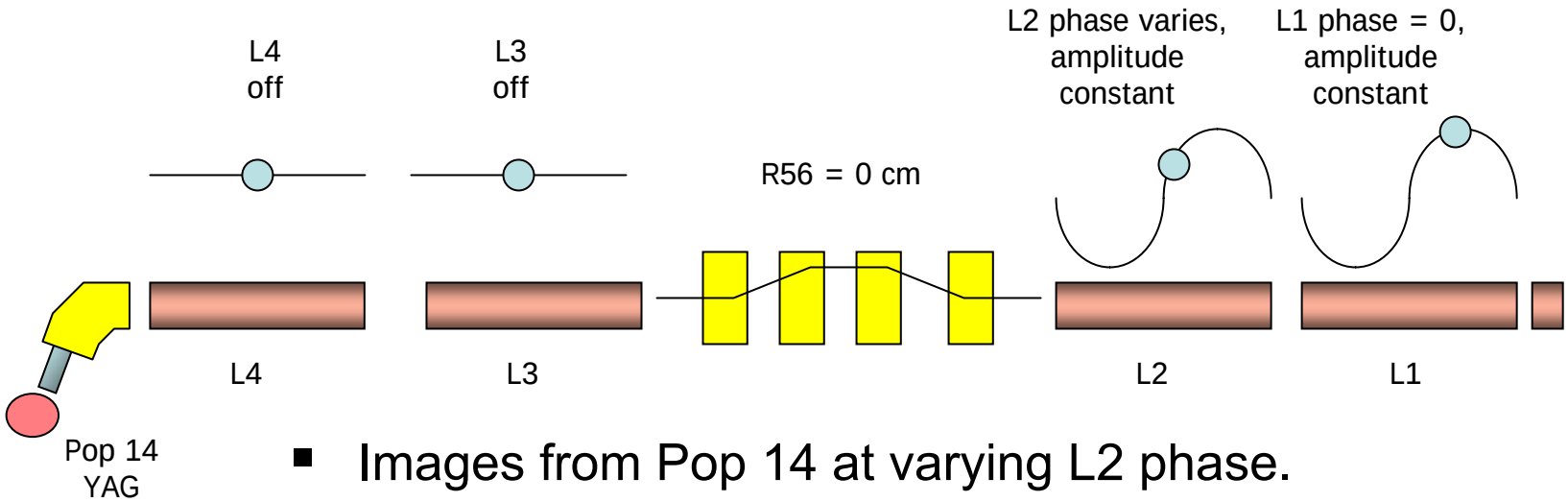
Outline

- Motivation
- Tomographic reconstruction
  - Algebraic reconstruction technique (ART)
  - Maximum entropy (MENT)
- Application at DUV-FEL and GTF
- Non-destructive options for ERLs
  - Diagnostics requirements
  - Beam projection measurements
  - Phase space manipulations
- Summary

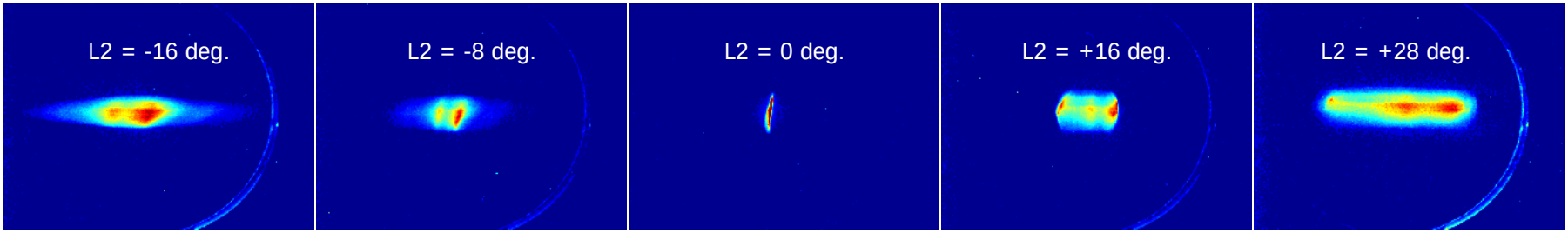
Tomography for Phase Space Reconstruction

- Obtain 2D-distribution from 1D-projections.
- Measure energy spectrum for different energy chirps.
- Resolves time distribution and time-energy correlations.
- RF zero-phase method maps time distribution on energy spectrum only in absence of nonlinear correlations.
- Can be done by varying rf-phase or rf-amplitude.
- Multi-shot technique, requires stable beam.
- Utilizes only accelerator and energy spectrometer.
- Alternative: measure time distribution with varying pulse compression.

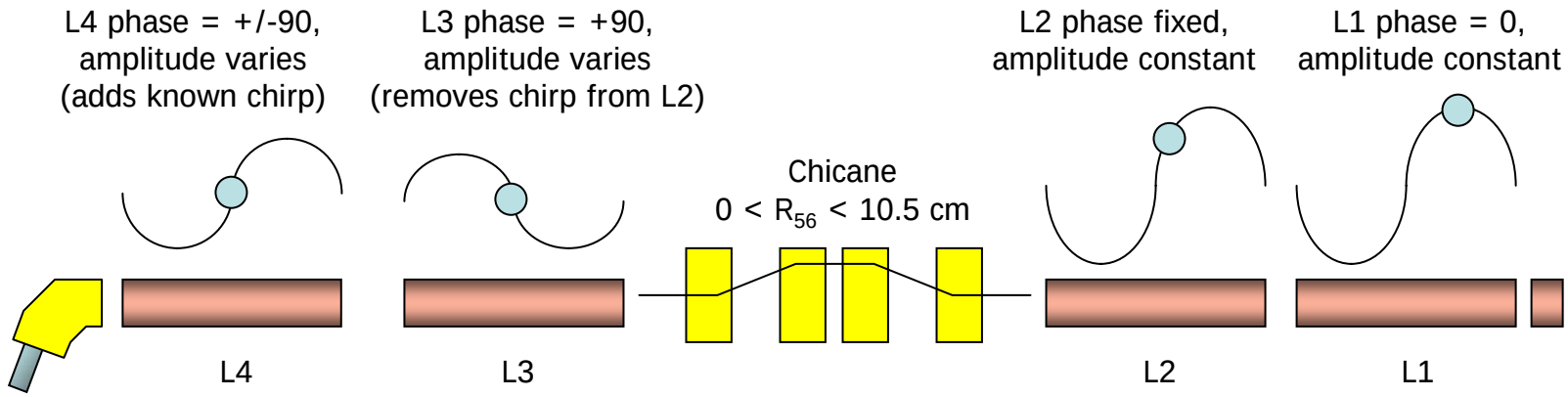
Energy Spectra From Tank 2 Phase Scan



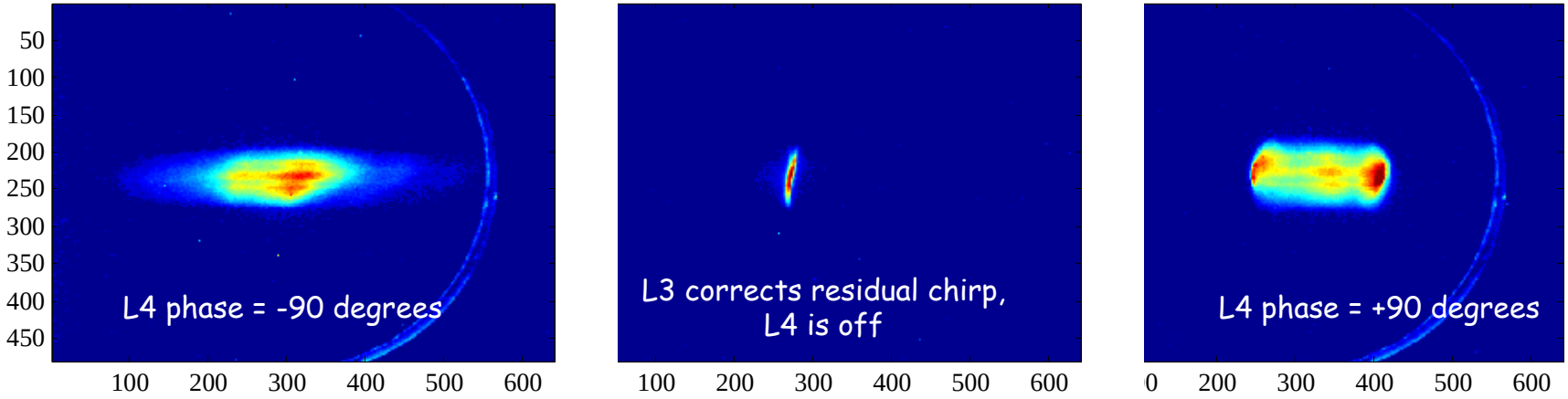
- Images from Pop 14 at varying L2 phase.
- Different projections of longitudinal phase space.
- Chirp is $k = -V\,\omega\,\sin(\phi)$ with energy gain V.



RF zero-phase time profile



- Scan L4 amplitude to generate set of projections

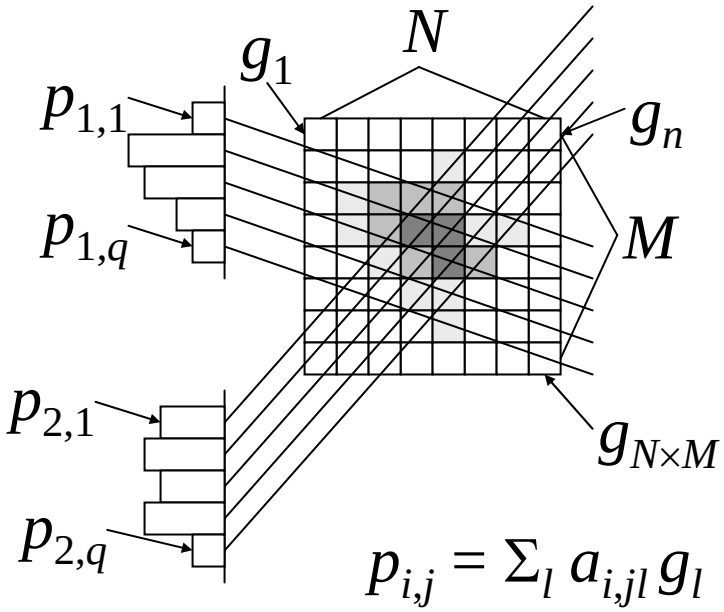


Reconstruction Methods

- Inverse Radon Transform
  - Developed for rotation of geometric object.
  - No unique definition of angle in phase space.
  - Inter- and extrapolation of projections necessary.
- ART (Algebraic Reconstruction Technique)
  - Works for arbitrary set of linear and nonlinear phase space transformations.
  - Constraints on solution can be implemented.
- MENT (Maximum Entropy)
  - Same as ART but:
  - Guarantees nonnegative solution.
  - Better suppression of artifacts than ART.
  - Longer calculation time.

Algebraic Reconstruction Technique

- Many different transformations of an image g generate a set of histograms or projections p_i.
- Find the transport matrix a_i, so that $p_{i,j} = \Sigma_l\, a_{i,jl}\, g_l$.
- The algorithm iterates an initial guess $g^{(0)}$ for each projection i according to



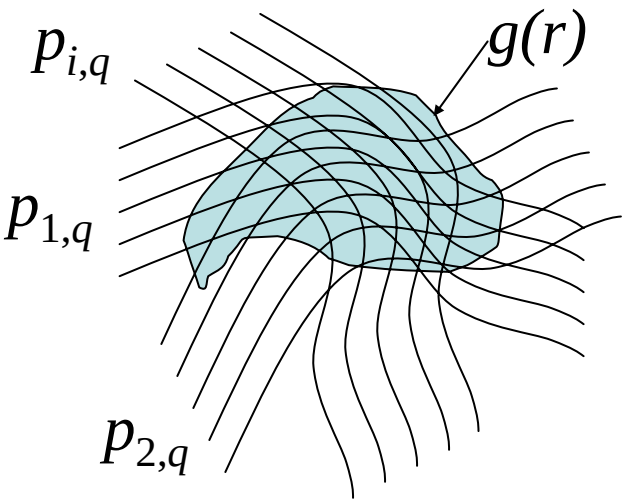
$$g_q^{(k+1)} = g_q^{(k)} + \Sigma_j \left[a_{i,jq}\,(p_{i,j} - \Sigma_l\, a_{i,jl}\, g_l^{(k)}) \,/\, \Sigma_l\, a_{i,jl}\right] / \,\Sigma_j\, a_{i,jq}$$

until each projection has been used.

- Repeat until convergence achieved.

MENT With Nonlinear Transformation

- Coordinates x,y of image g are transformed with nonlinear transformation and integrated into projections p



- Image $g(r)$ is composed as product of coefficients Λ

$$g(r) = g_0(r)\, \Pi_i\, \Lambda_{i,l(i,r)}$$

- $l(i,r)$ is bin# in i^{th} projection# of coordinate r

- Entropy maximized with iteration for each projection i

$$\Lambda_{i,q}^{(k+1)} = \Lambda_{i,q}^{(k)}\, p_{i,j}^{(0)} / p_{i,j}^{(k)}$$

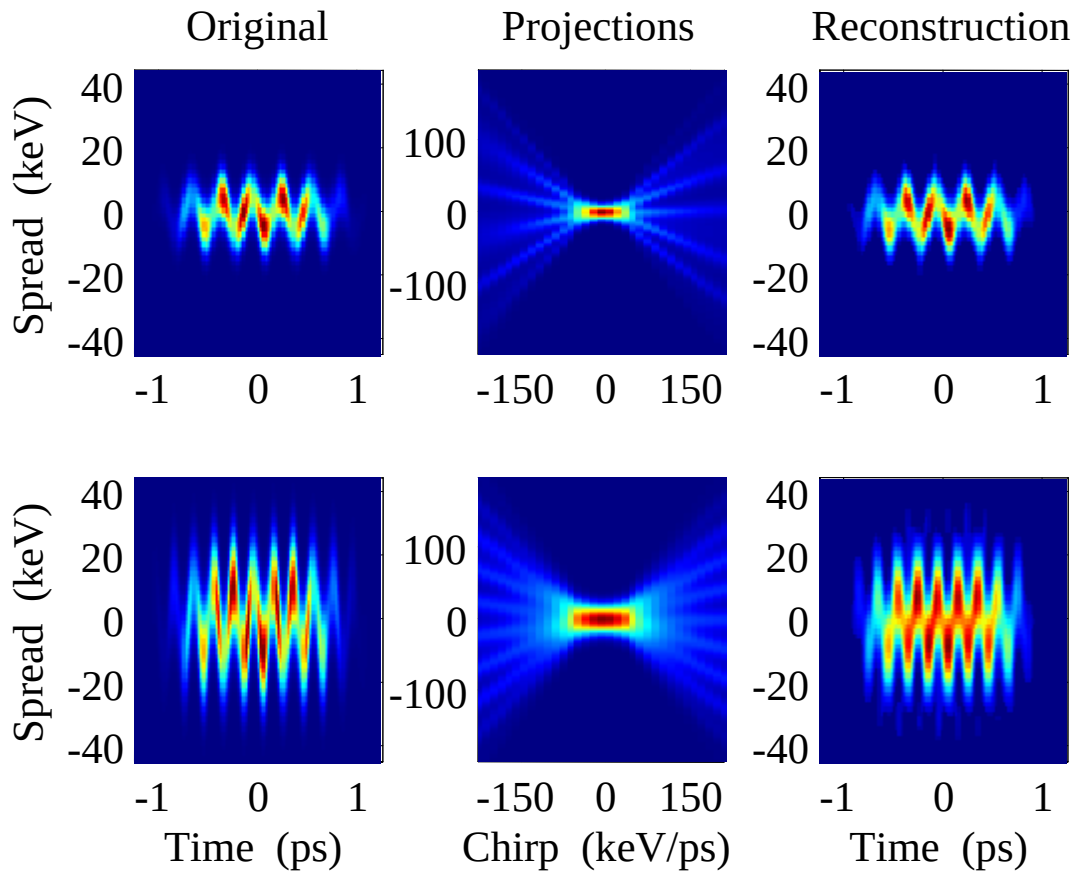
- Calculate new projections $p_{i,j}^{(k+1)}$ from iterated image g
- No inversion of particle transformation necessary

Resolution Test

Chirp k_{max} = 220 keV/ps for GTF experiment

- Slice energy spread $\delta_0 = 5$ keV
- Energy modulation $f_\delta = 3$ THz
- Current modulation $f_\tau = 5$ THz

$\delta = 10$ keV
$f_\delta = 5$ THz
$f_\tau = 7$ THz



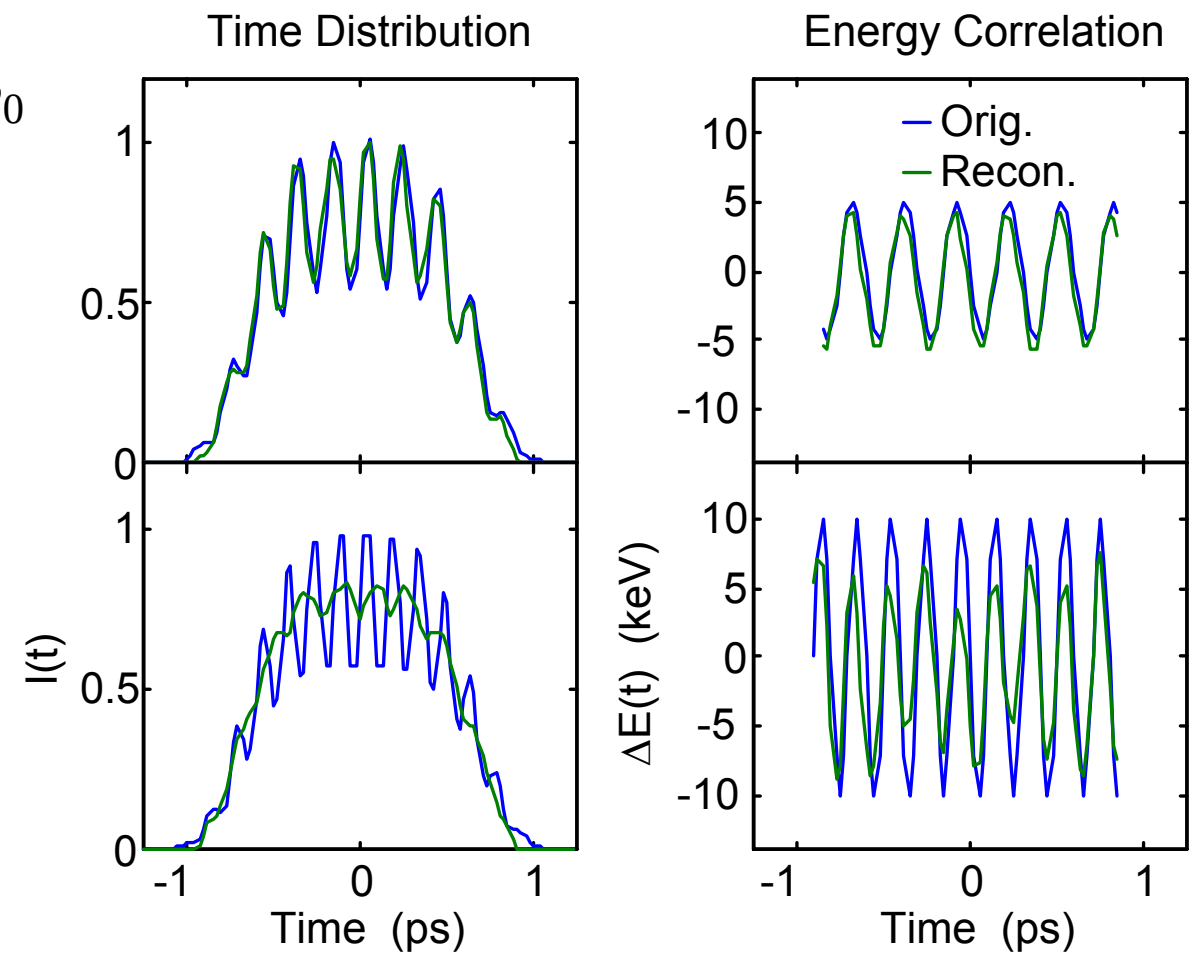
Simulation Result

Resolution

$f_{Res} = k_{max} / 2\pi\, \delta_0$

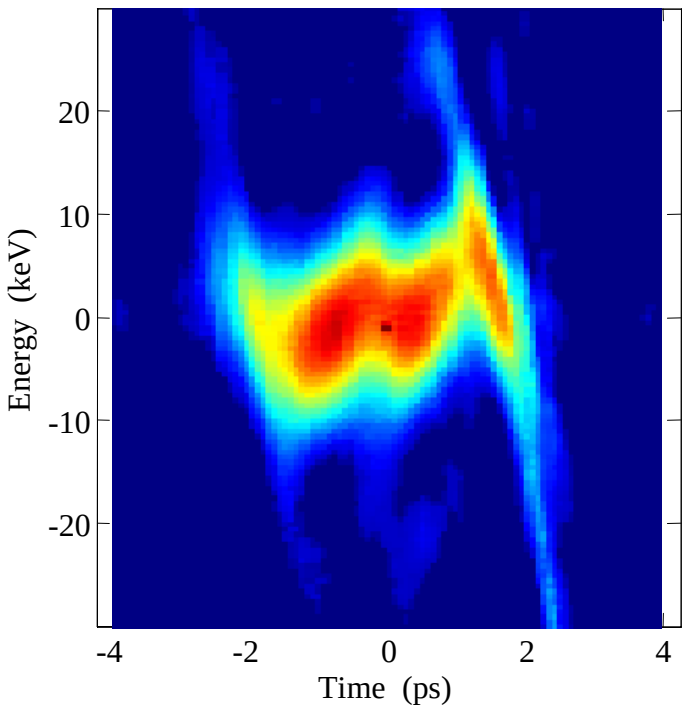
$\delta_0 = 5$ keV
$f_\delta = 3$ THz
$f_\tau = 5$ THz
$f_{Res} = 7$ THz

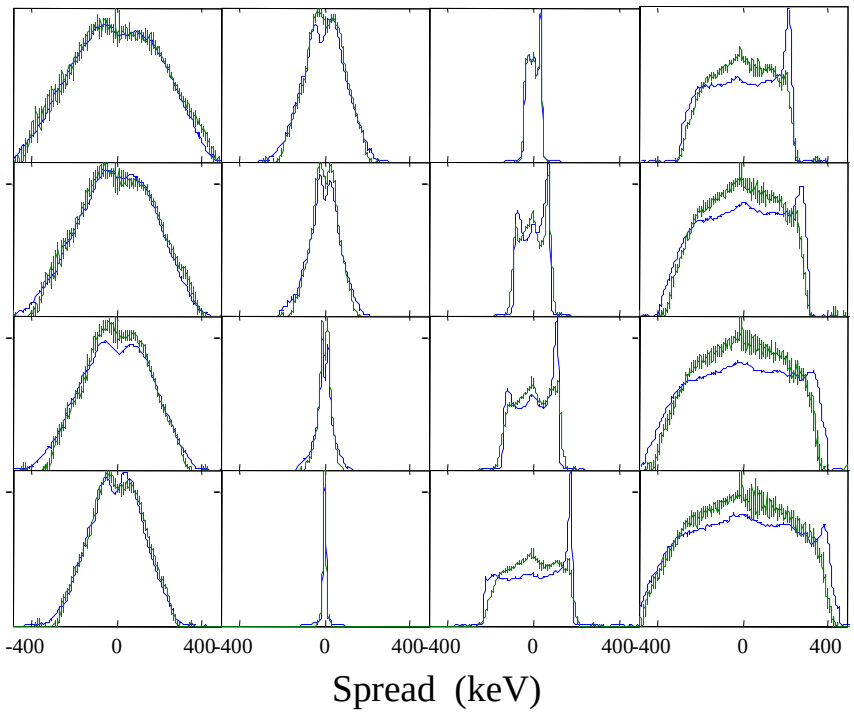
$\delta_0 = 10$ keV
$f_\delta = 5$ THz
$f_\tau = 7$ THz
$f_{Res} = 3.5$ THz



DUV-FEL Phase Space

200 pC charge, 38 MeV gain in Tank1
200 keV/ps max. chirp, f_{Res} = 4 THz



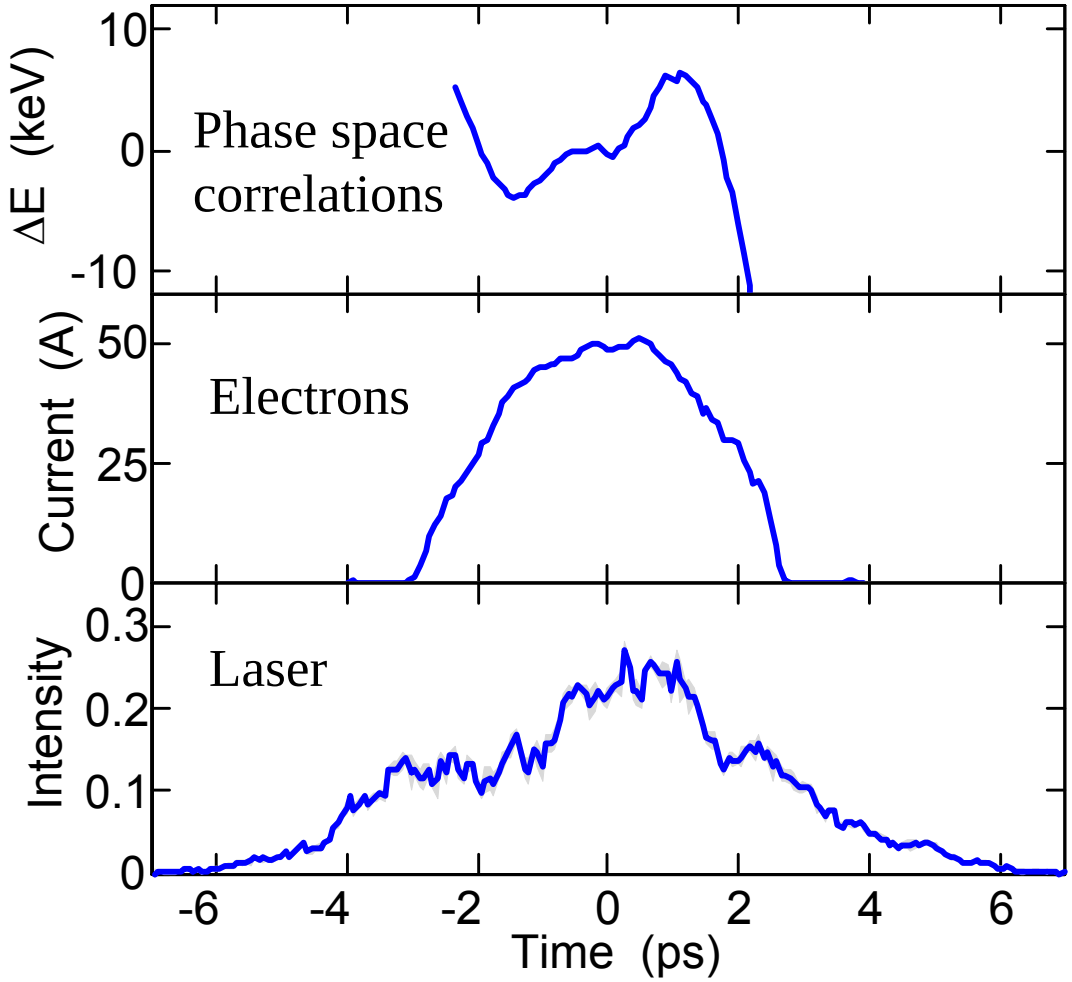


Comparison with Laser Profile

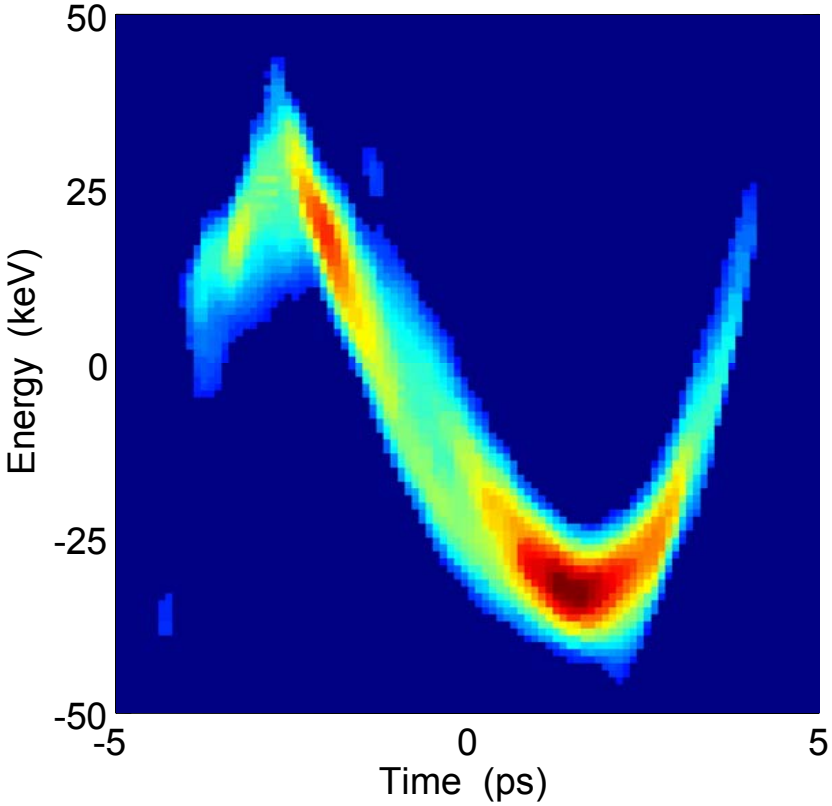
- e-beam 1.35 ps
- laser 2.35 ps

- 8 keV slice energy spread

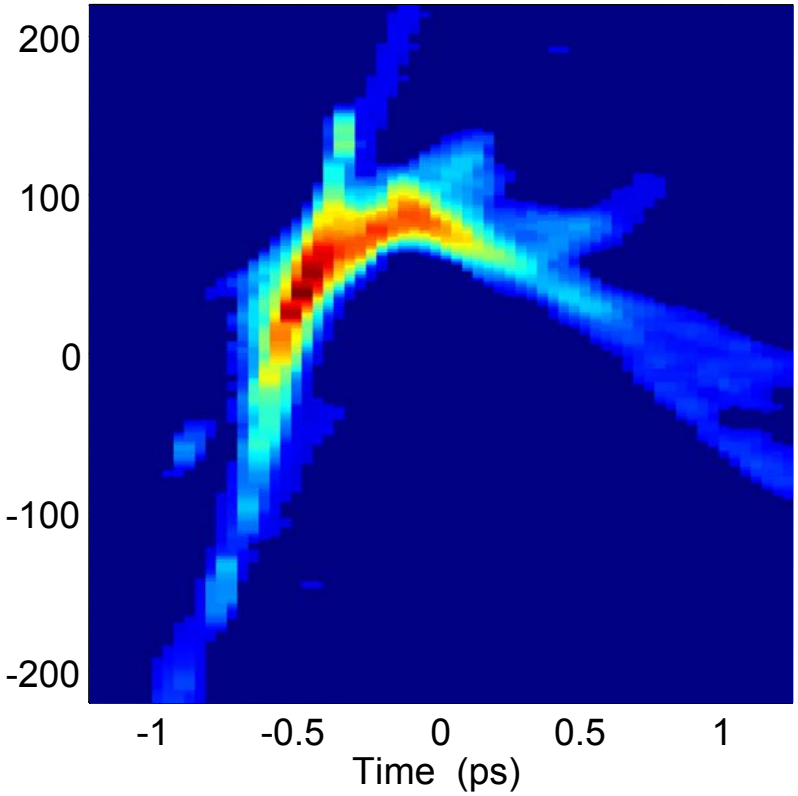
- Structure of laser not apparent in electron beam distribution.
- Structure visible only in energy correlation.



Uncompressed/Compressed Beam

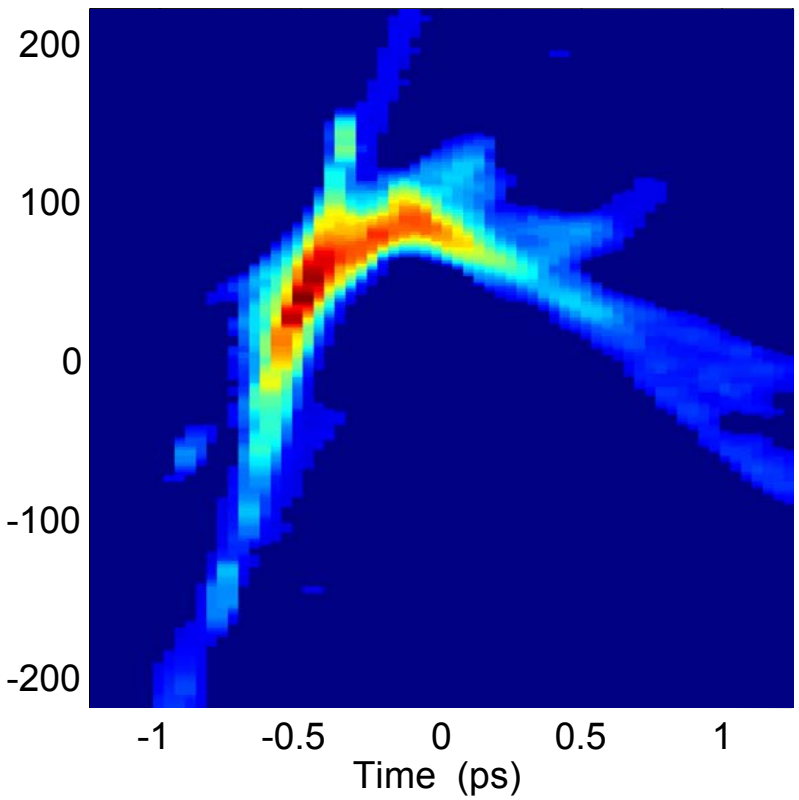


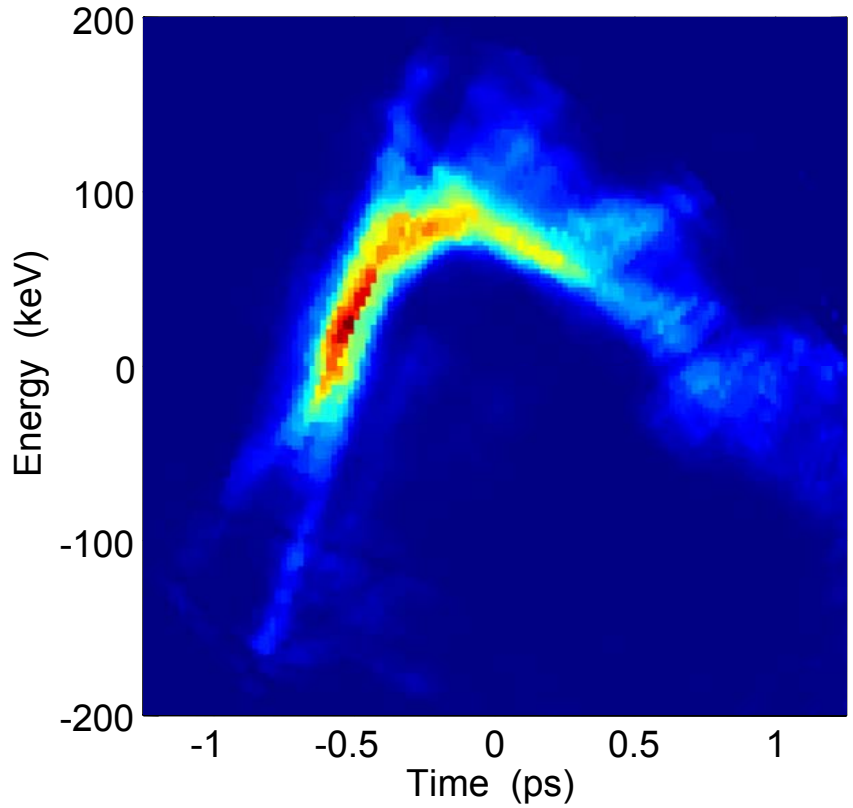
Tank 2 phase scan



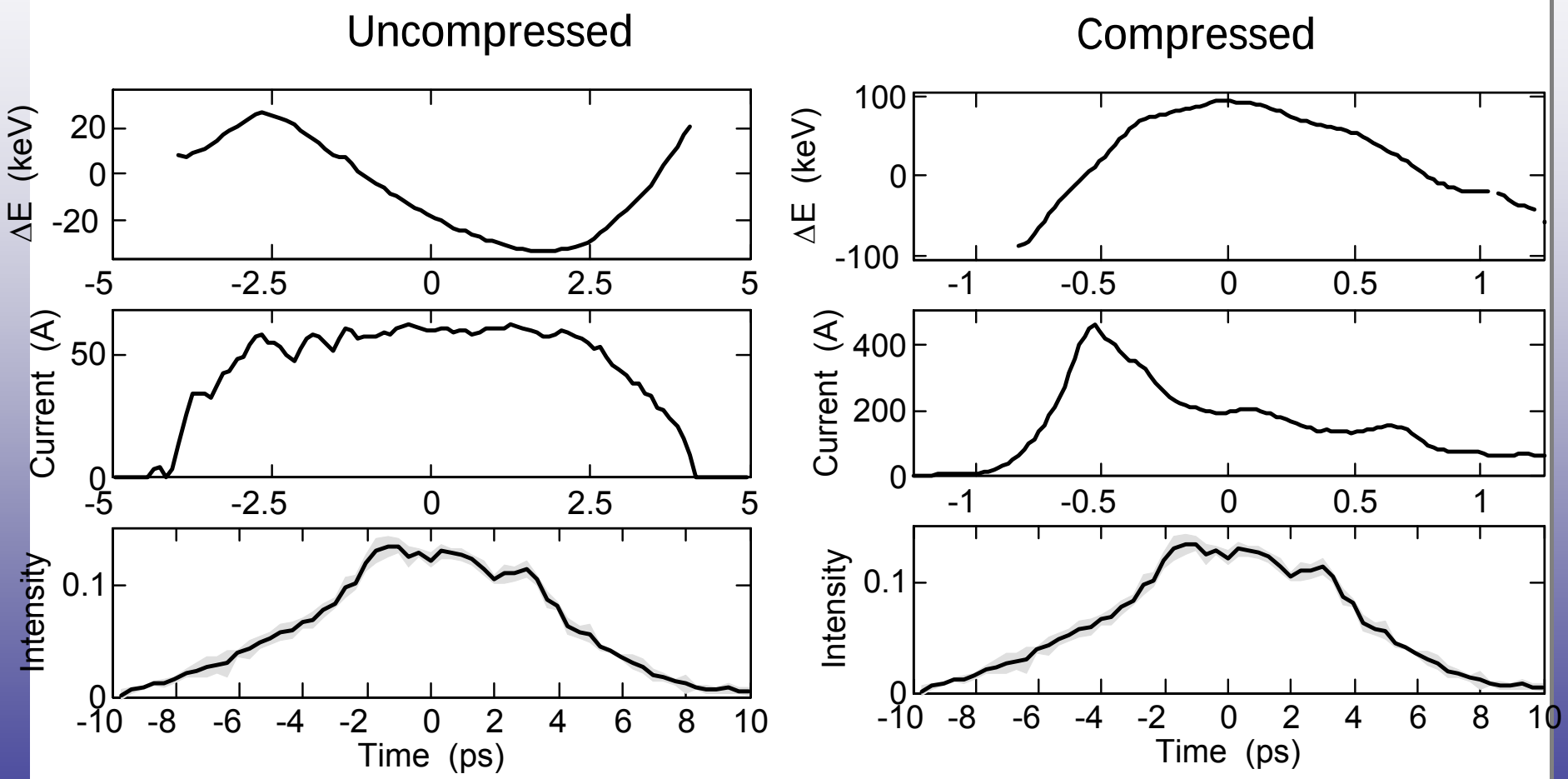
Tank 4 amp scan

ART vs. MENT Algorithm

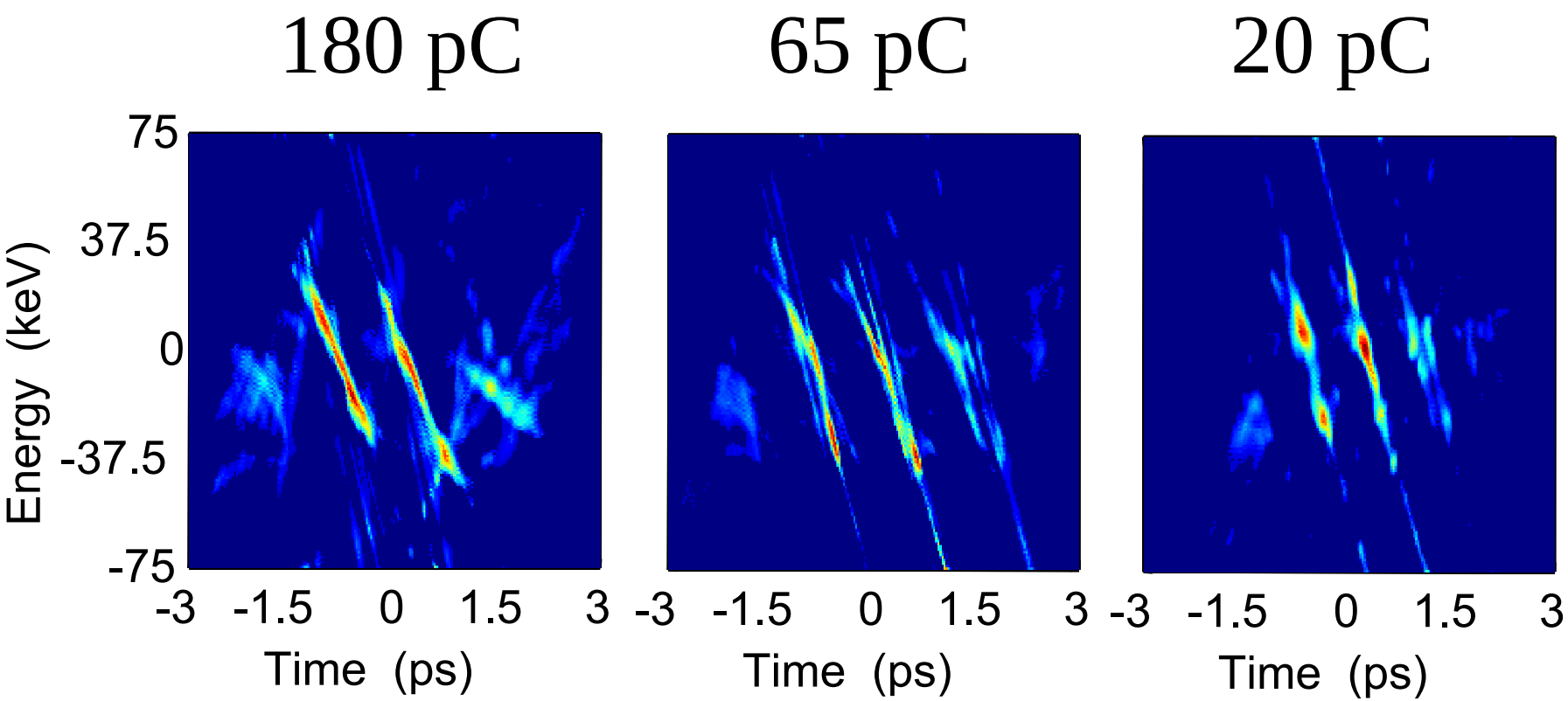




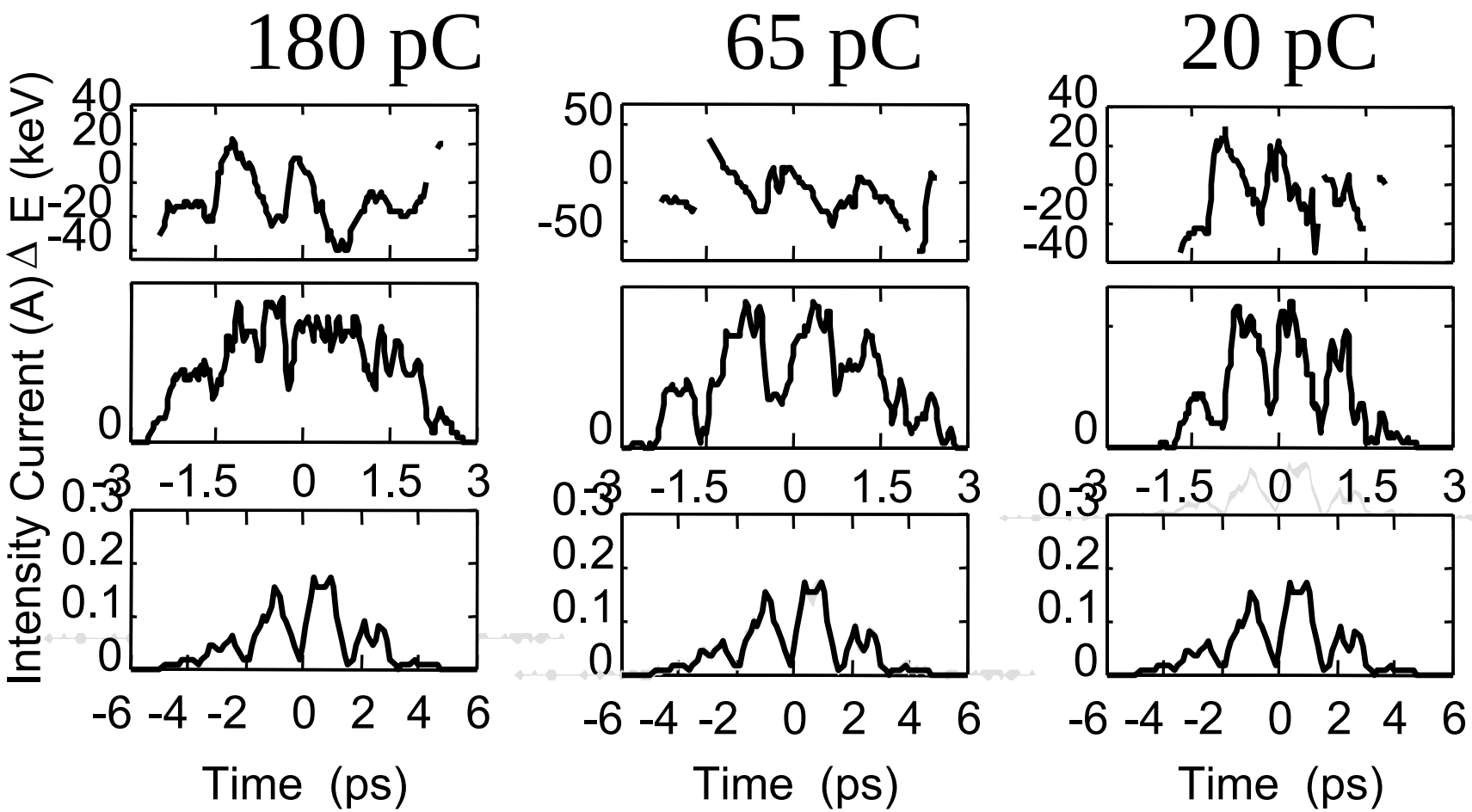
Time and Energy Distribution



Modulated Beam Studies



Modulated Beam Studies



Diagnostics Requirements for ERL

- Longitudinal projection measurements
  - can be energy or time,
  - have to be nondestructive,
  - must resolve minimum energy spread or pulse length.
- Phase space manipulations have to be
  - reversed after measurement for energy recovery,
  - within acceptance of energy recovery,
  - or affect only small fraction of bunches,
  - must be extensive enough to provide the desired resolution of the other phase space coordinate.

Beam Projection Measurements

- Energy profile
  - Related to nondestructive transverse measurements
  - Synchrotron radiation profile
  - Wire scanner
  - Laser wire
  - Undulator radiation spectrum
- Time profile
  - Spectrum of coherent diffraction radiation
  - Electro-optic measurement
  - SR distribution with streak camera

Phase Space Manipulations

- Main linac variable off-crest
  - Measure spectrum before compression in arc.
  - Provides sufficient chirp at 10° off-crest.
- NC pulsed rf structure
  - Located after arc.
  - Measure spectrum in return arc.
  - Beam loss acceptable?
- SC rf structure
  - Operate at zero phase to minimize rf power.
- Variable compression in arc or chicane
  - Fixed chirp from linac.
  - Measure different time projections.
  - Limited to low charge by CSR, LSC effects.

Requirements Examples

- Low energy (100MeV)
  - $\sigma_E = 2 \cdot 10^{-4}$, $\sigma_Z = 2$ps
  - SR: Resolution = 10μm (ρ = 1m bend)
  - Dispersion η = 0.5m
  - Resolution 2keV or $2 \cdot 10^{-5}$ sufficient.
  - Chirp $k = U\,\omega\,\sin(\phi)$ = 400keV/ps within 2% energy acceptance.
  - Time resolution of 100 fs possible.

Requirements Examples

- High energy (5GeV)
  - TBA cell: ρ = 30m, SR-resolution = 30µm
  - Dispersion η = 0.04m, Energy resolution = $6 \cdot 10^{-4}$
  - Needs lattice specifically designed for high resolution energy spread measurement.
- Variable compression
  - 15° off-crest @ 1.3 GHz is k = 13MeV/ps
  - Compaction R_{56} = 30cm
  - Sufficient for 1:1 over-compression

Summary

- Tomographic reconstruction from linac phase and amplitude scans using ART and MENT algorithms established.
- Reconstruction of uncompressed, compressed, and modulated electron beams achieved.
- Tomographic reconstruction of low energy ERL possible.
- High energy ERL needs specifically designed lattice.
- Performance depends on resolution of transverse diagnostics and lattice design.
- Simulations necessary to test reconstruction with nonlinear beam transport.

Acknowledgements

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DUV-FEL Facility Layout