Quasi-Crystalline Beam (QCB) Formation in Strongly Accelerating Intense Electron Distributions

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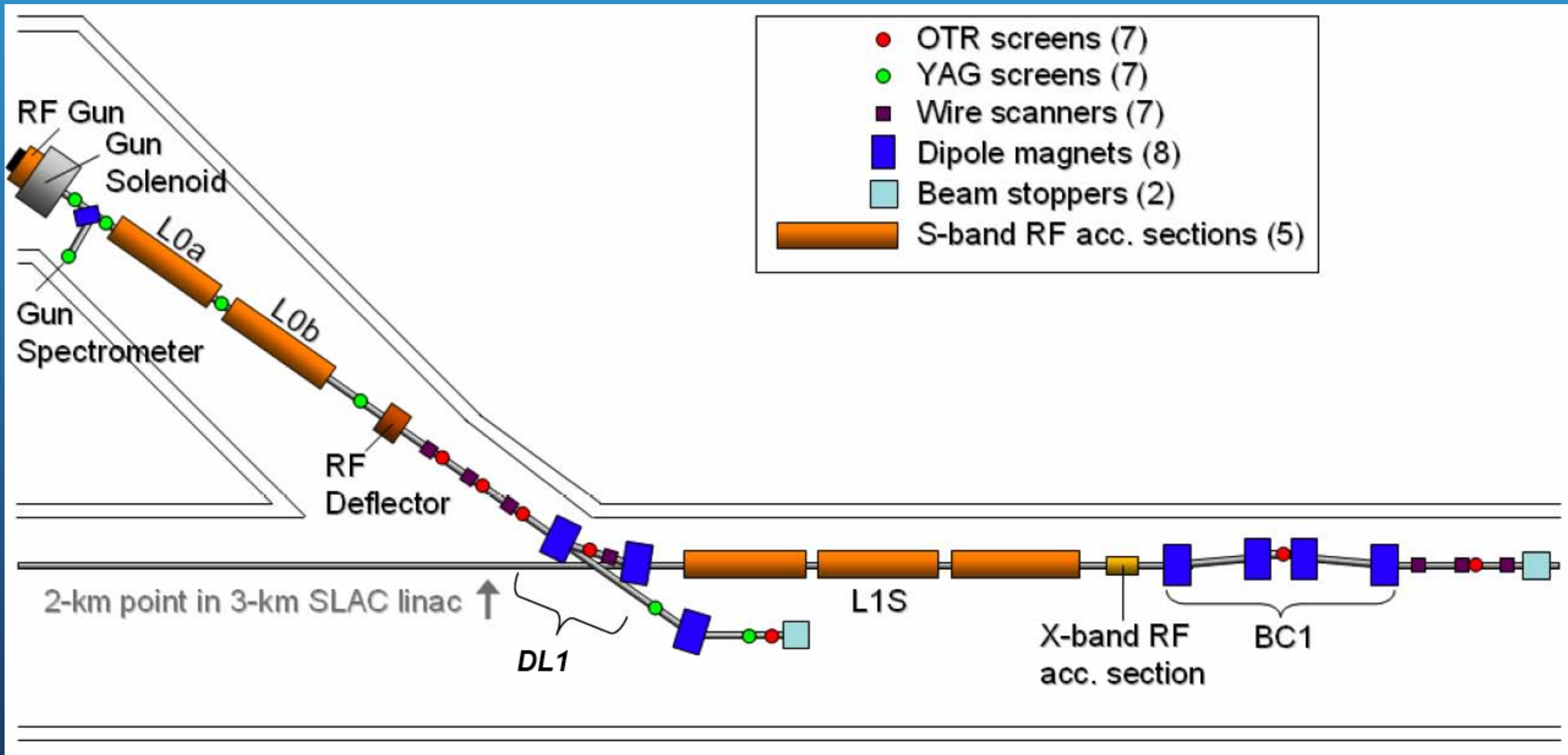
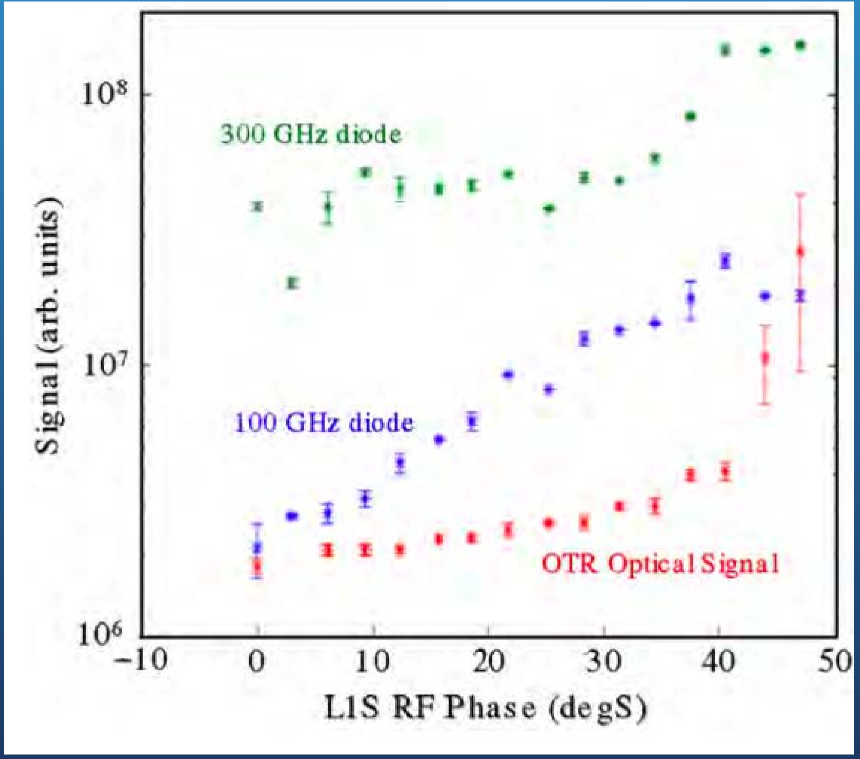
The Problem

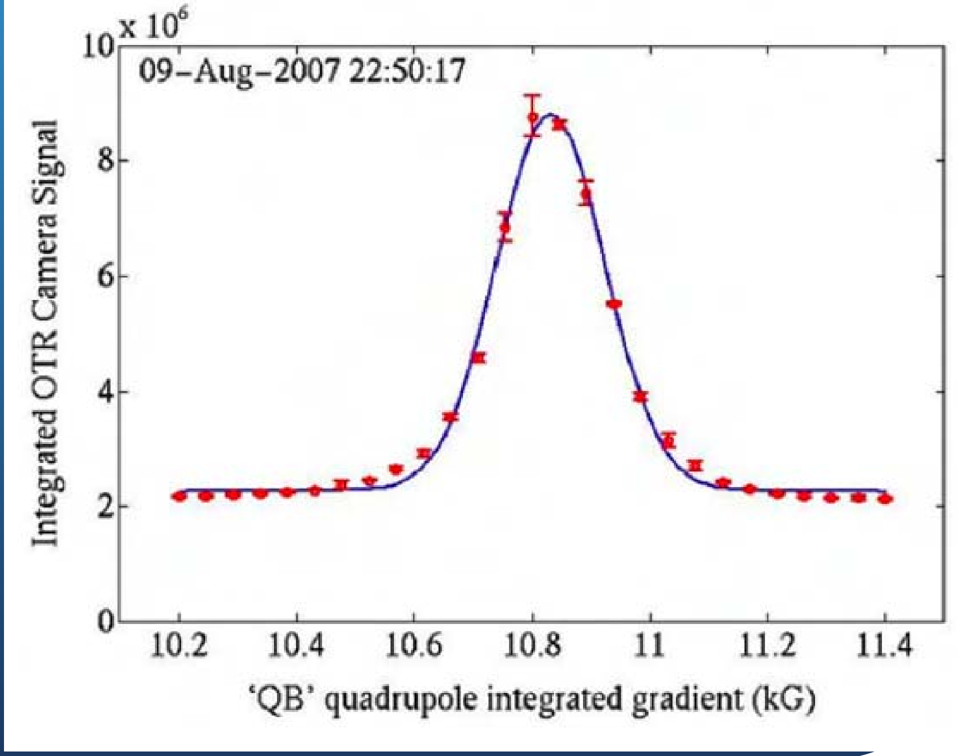
- Observed coherent *optical* transition radiation (COTR) from LCLS photoinjector beam
- Some structure in beam at microscopic (<μm) level. How?



Observations

- *No COTR* upstream of bends
- Up to 4x enhancement after 1st bends
- Over 10x with additional (linac off-crest) bunching > BC1





D. Dowell, *et al. PRST-AB* 11, 030703 (2008)

Indications of coherence

- Integrated intensity dependence stronger than *N*
- Diffraction ring formation
- Spectral spikes
- Stochastic intensity, total power

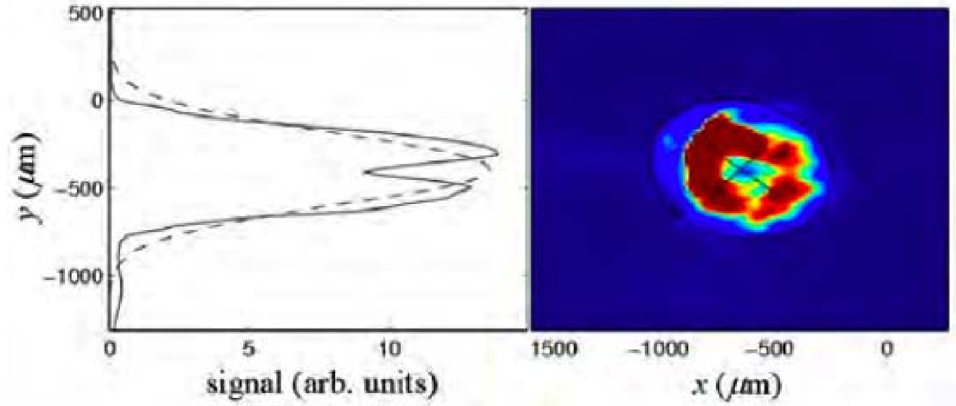


FIG. 43. (Color) An image of the COTR radiation after BC1 observed with extreme bunch compression.

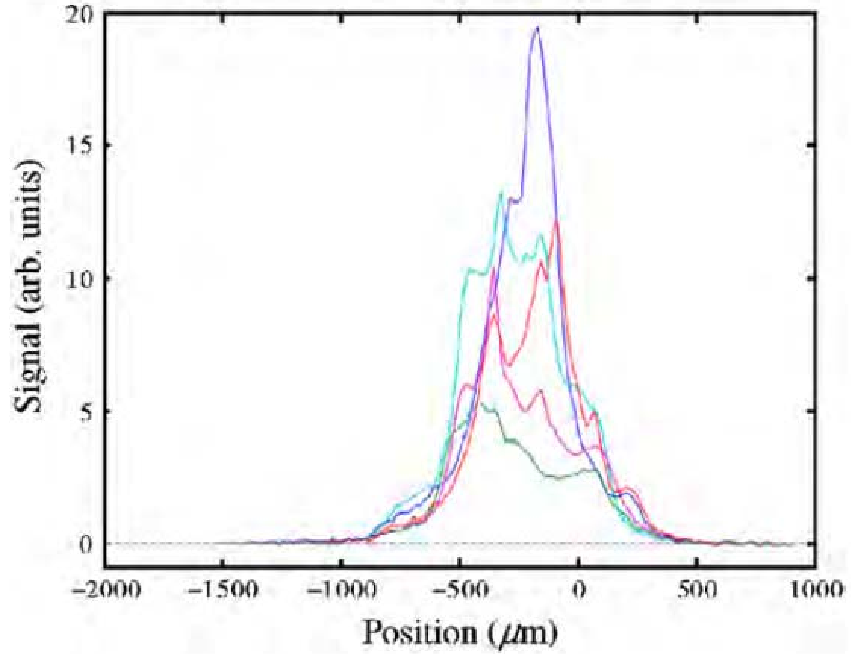
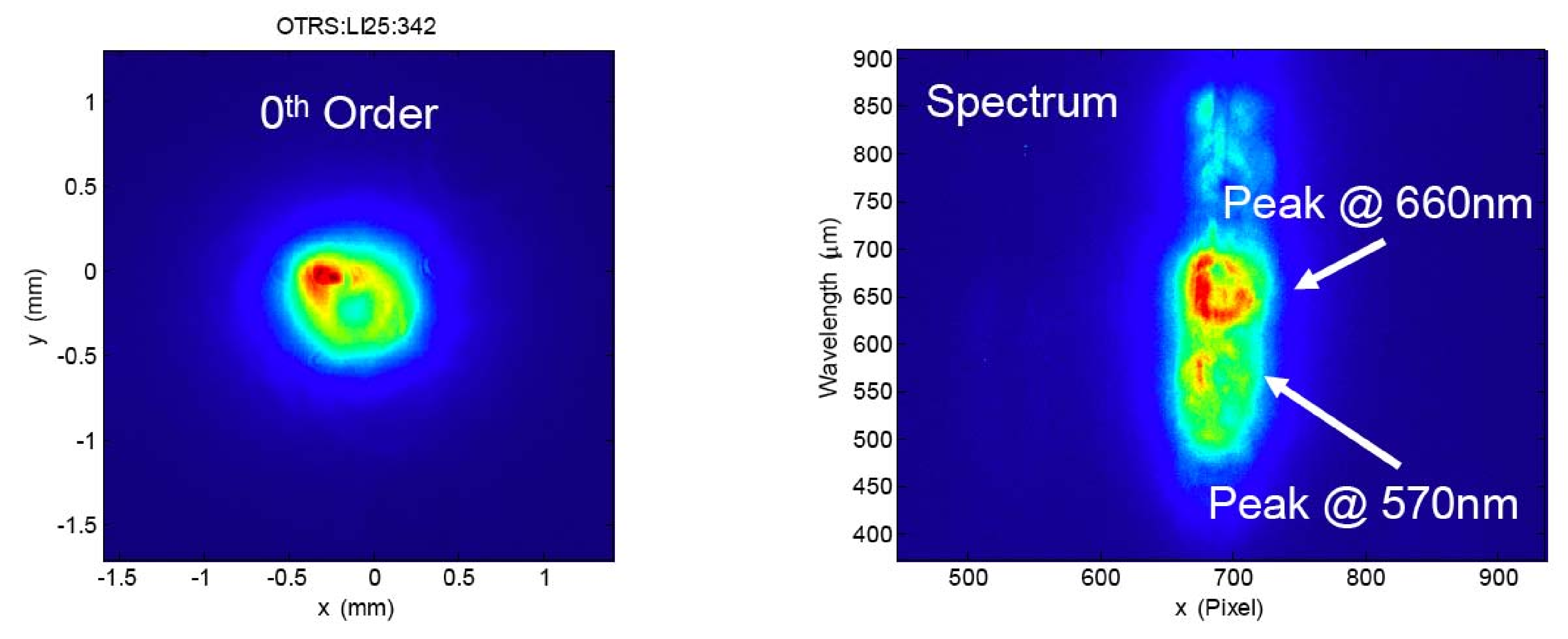


FIG. 42. (Color) OTR screen profile projections for five consecutive beam pulses when the L1S rf phase is set at 50 degS off crest, in conditions of extreme compression.

Spectrum: transmission grating



Evidence for spectral peaks (H. Loos, SLAC)

DESY FLASH Measurements

- Approximate scaling law: $f_{COTR} \sim f_{RF}$
- Born out by analogous data?
- High resolution results reported (FEL 2008, Schmidt, *et al*.)
  - Multi-spike spectra
  - Much more complete picture

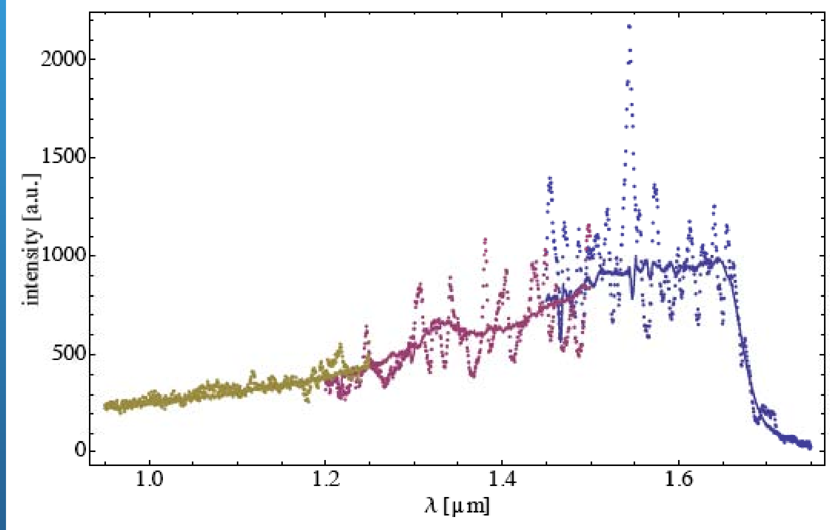
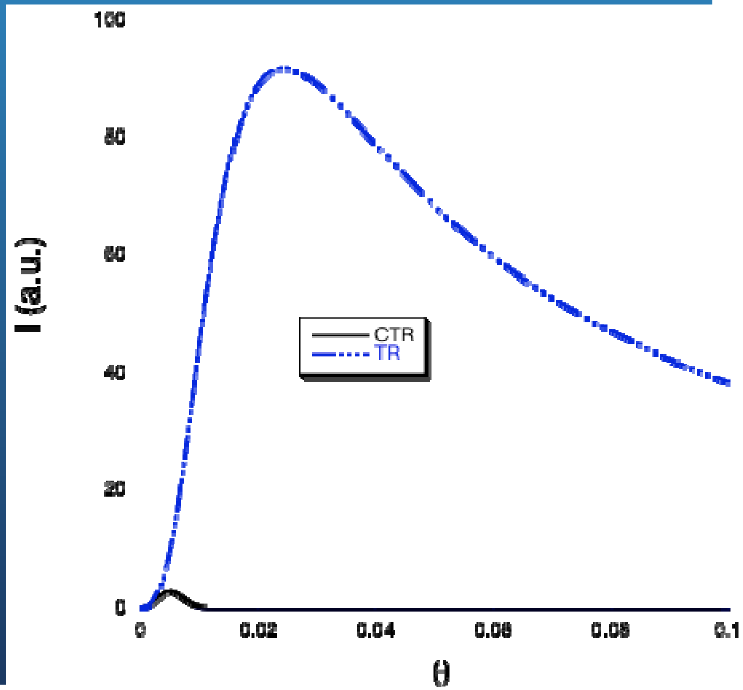


Figure 7: Single shot (dots) and averaged (line) CTR spectrum between 0.95 μm and 1.7 μm measured with a commercial InGaAs spectrograph. The response of the detector is basically flat between 1.0 μm and 1.7 μm.

What does COTR tell us?

- Bunching factor on harmonic: b_n
- ~Total energy on n^{th} harmonic
- Coherence angle smaller than natural TR angle for energies <500 MeV
- Very small transverse beam structures (<10 microns) do not radiate coherently
  - Coherence angle large
  - "Speckle" is outside of γ^{1} cone
- Very wide beam structures also do not radiate coherently
- Transverse distribution Fourier xfm...?



Estimate bunching factor observed

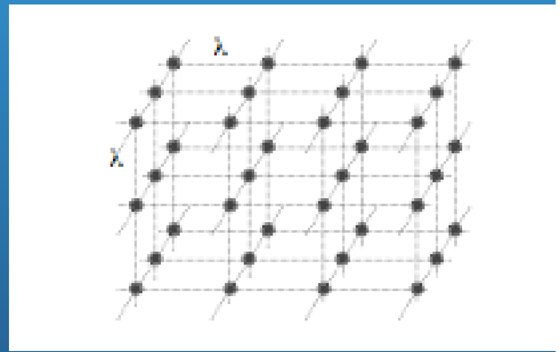
- Assume narrow band spectrum
- Compare to incoherent TR photon number
- Use LCLS parameters, experimental results
- Solve for estimated bunching
- This is a big number; probably an underestimate (assumes perfect *beam transverse coherence*)

Hypotheses: old and new

- "Microstructures" in beam (spikes). Due to:
  - Longitudinal space-charge
  - Coherent synchrotron radiation (CSR)
  - Phase space folding in compression, end-spikes
- Quasi-crystalline beam formation. Due to:
  - Microscopic longitudinal space-charge
  - Can't happen in coasting beams; need acceleration
  - Longitudinal motion "freezes"; F_z integrated
  - Final spatial rearrangement in chicane
  - Truly *microscopic*, at mean inter-particle spacing level

Crystalline beams

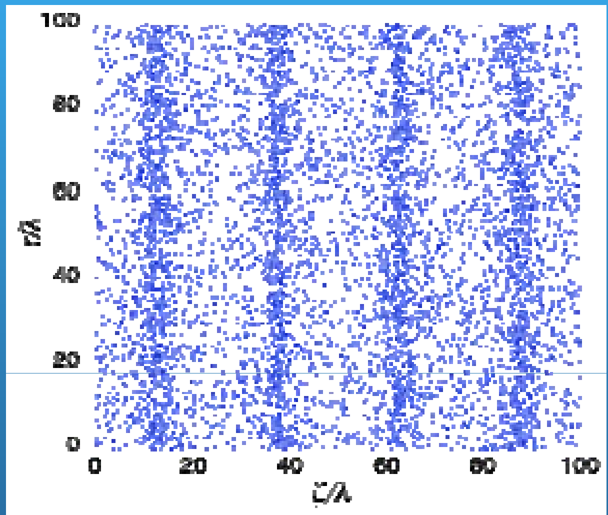
- Emittance dominated beam: gas
- Space-charge dominated beam: liquid
- Coulomb (Wigner) crystal: solid
- Density
- Compare ratio of
  - Potential energy
  - Kinetic energy
- Crystal formed when
- Evaluate in rest frame



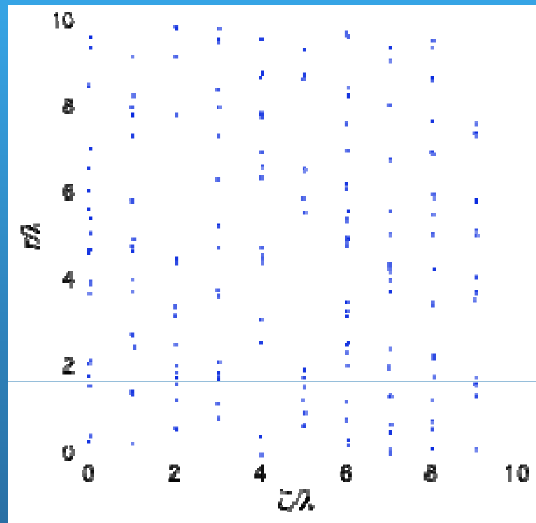
Do we have Coulomb crystalline conditions in photoinjector?

- Transverse focusing gives higher temperatures Γ small and time dependent conditions
  - No transverse crystallization possible
- Longitudinal 1D crystal OK
  - Observed in storage rings (e.g. Aarhus)
  - Schottky spectral signature: noise suppression, spectral spikes near crystal λ
  - Still have Γ too small at linac entrance
    - $k_B T_z$=1 eV
    - λ = 2.5 micron, rest (1.1 micron lab)
    - Overtaking of particles in ζ possible
    - Secret ingredient: acceleration

How is 1D crystal different than microbunching?



Microbunching schematic

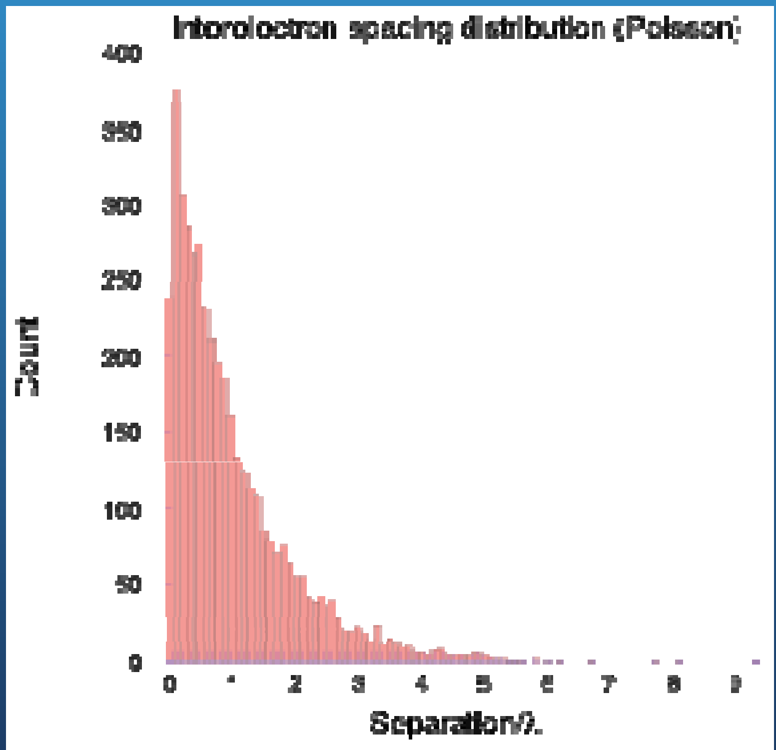


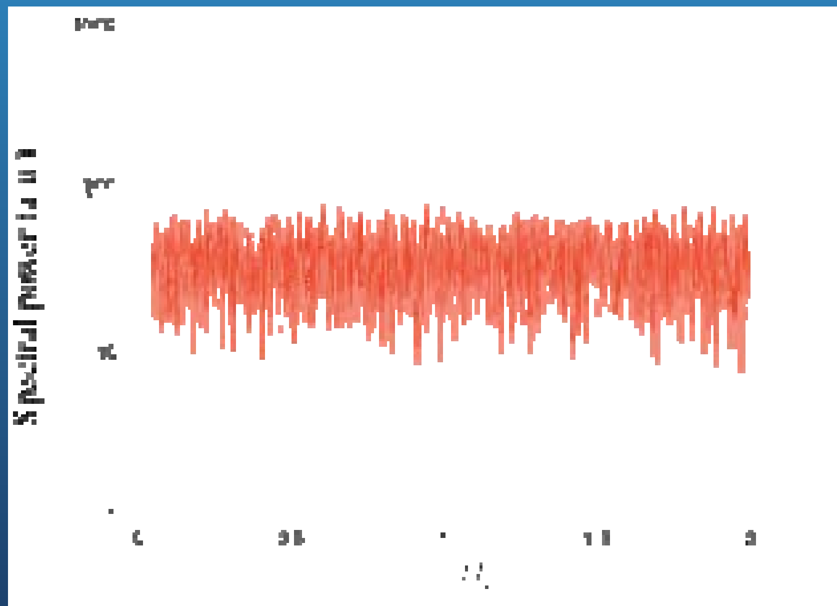
1D crystalline distribution

- Mircrobunching: periodic compression-dilation of electron longitudinal positions
- 1D crystal: complete regularity in spacing of the longitudinal distribution

Experimental signature: statistics of random longitudinal distribution

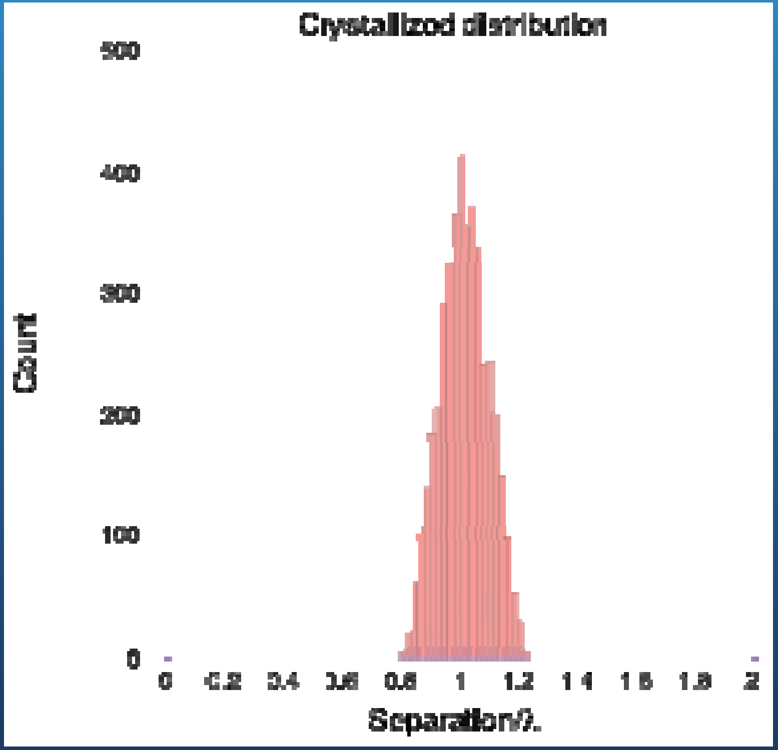
- Random (Poisson) distribution in inter-electron distances
- Schottky noise in beam spectrum (f_λ mean inter-electron freq.); reflected well in OTR spectrum

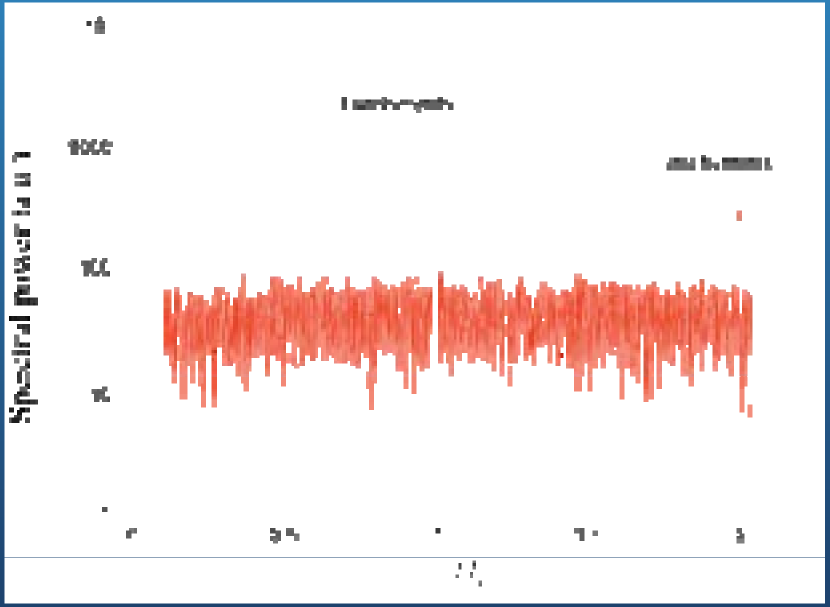




Statistics of 1D crystalline distribution

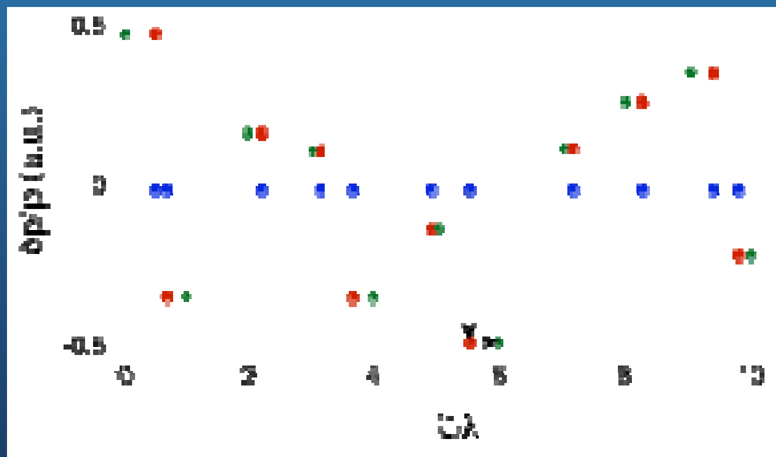
- Ordered distribution in inter-electron distances
- Spectral peaks above noise (f_λ and harmonics)





Formation of the quasicrystal

- Strongly damped longitudinal motion during acceleration
  - No longitudinal nonlaminarity
- Longitudinal space-charge adds ~ coherently
  - Energy modulation
- Chicane rearranges the electrons longitudinally
  - Longitudinal distribution uniform at *microscopic* level
  - Observed coherence in OTR from longitudinal crystal



QCB formation:
Effects of acceleration

- Stretching (length contraction)
- In lab frame, 1st electrons begin acceleration earlier
- With E=20 MV/m, an e- lagging by λ sees the preceding electron gain 23 eV. Overtaking (*longitudinal nonlaminarity*) strongly suppressed
- Scenario: ~frozen positions in $\zeta=z-ct$. the longitudinal space charge keeps adding to energy modulation, but without changing ζ

Note on slice energy spread

- Total slice energy spread in simulation ~1 keV, not 1 eV
- Consistent with observation
  - Resolution limited
- Energy errors are mainly due to non-synchronous spatial harmonics in gun, correlated strictly to radius
  - Non-relativistic region
- *Local* (in *r*) energy spread still very small (~eV)
- Correlation in *r-z* gives distorted (bent) crystal
  - Larger coherent angle (smaller effective source width)

Lab frame analysis: Coasting beam

- Use beam-centered coordinate
- Density
  - Laminar integral
- Equation of motion
- Plasma frequency scales as
  - Density difference
  - Time dilation

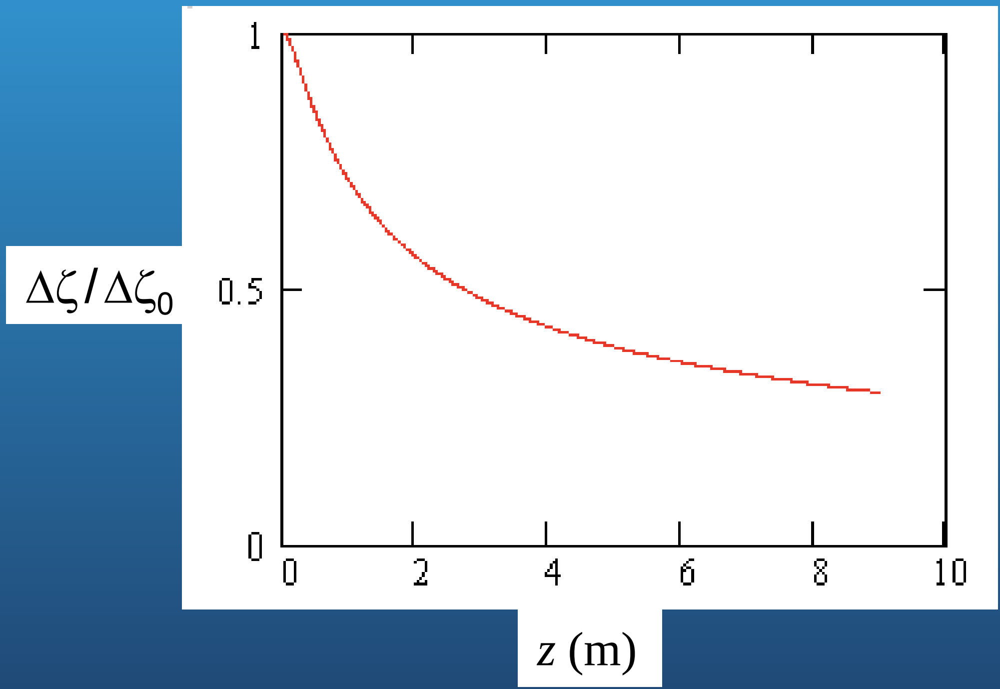
Include acceleration

- Constant acceleration
- Equations of motion
- Damping and longitudinal focusing included
  - Focusing often cancels macroscopic space-charge defocusing
- Running on *invariant envelope*, new scaling of external forces
- Solution approach

With cold initial state...

"Frozen position" after damping

- Full solution for SPARC scenario validates analysis



Analytical prediction

Tolerance on initial energy spread

- Arbitrary initial conditions

- Crystal breaking ("wavebreaking") at $\Delta\zeta$=0, in limit of very large γ

- In physical terms, the minimum initial thermal velocity for nonlaminarity is, taking e.g. $\Delta\zeta_0$=0.5 μm, γ_0=11, γ'=26 m^{-1}

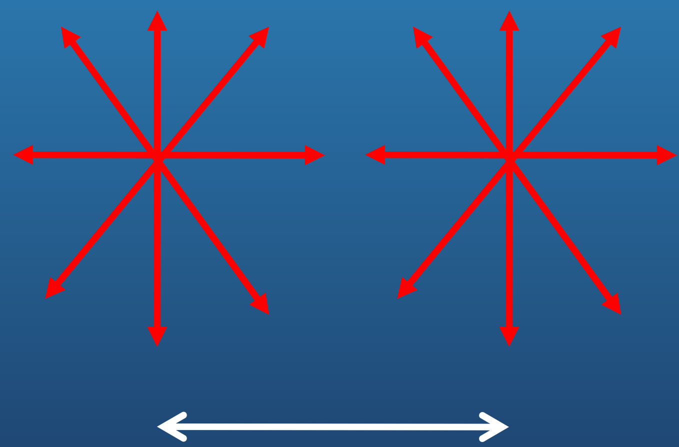
keV

Strong damping of longitudinal motion: an approximate view

- Derivative of longitudinal motion:
- With “frozen” approximation
- Upper limit from expt.
- Asymptotic solution
- Approximation consistent

Is this *energy spread* consistent?

- Three dimensional effects important in forces, dynamics
- Uniformity aided by transverse mixing (emittance)
- Forces more uniform due to length dilation in rest frame
- Estimate peak field. Distance between charges ~$\gamma\lambda$, but total "coherent charge" ~$(\gamma\lambda)^2$

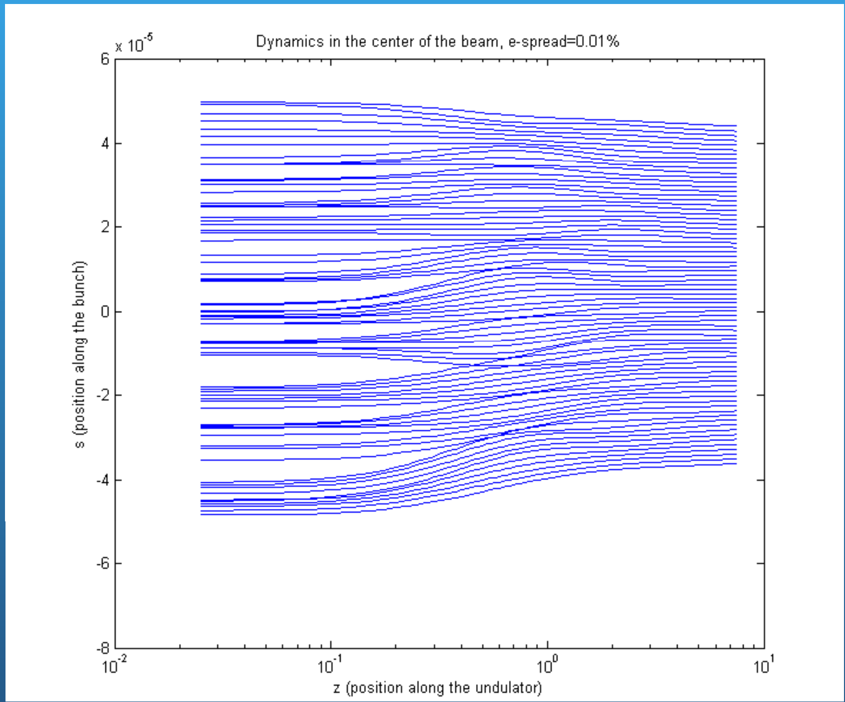


- Note!

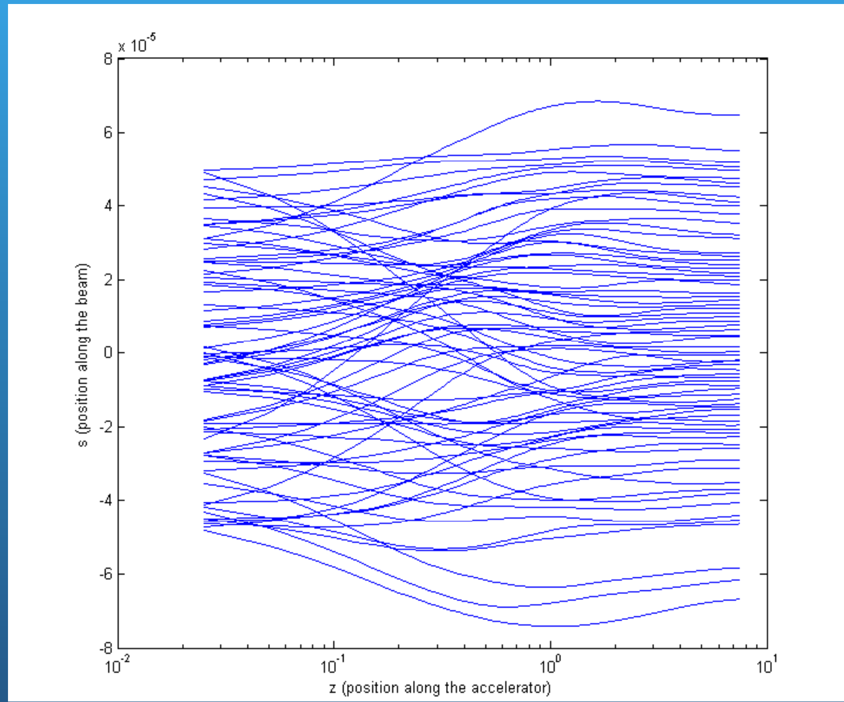
Microscopic dynamics modeling

- Step 1: coherent slice model, use disk-like beams
- Include all acceleration and focusing
- Investigate:
  - Dynamics in linac
  - Effects of R_{56}
  - Tolerance to initial energy spread
  - Expected spectra
  - Advanced topics: velocity bunching

Initial energy spread



0.01% initial energy spread (500 eV)

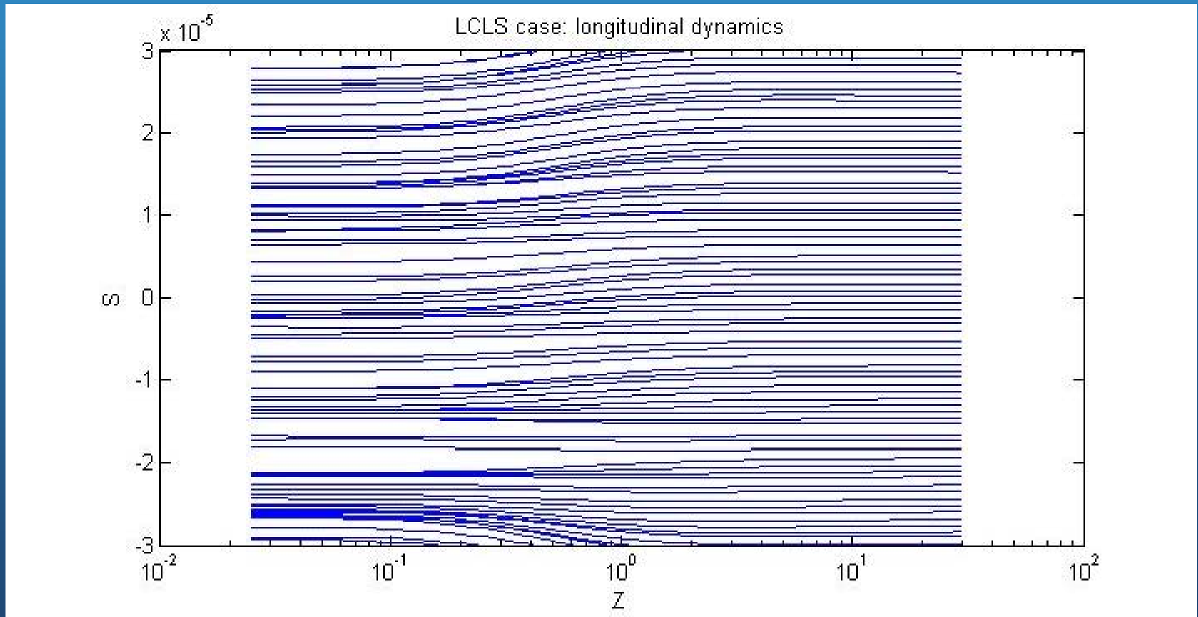


1% initial energy spread

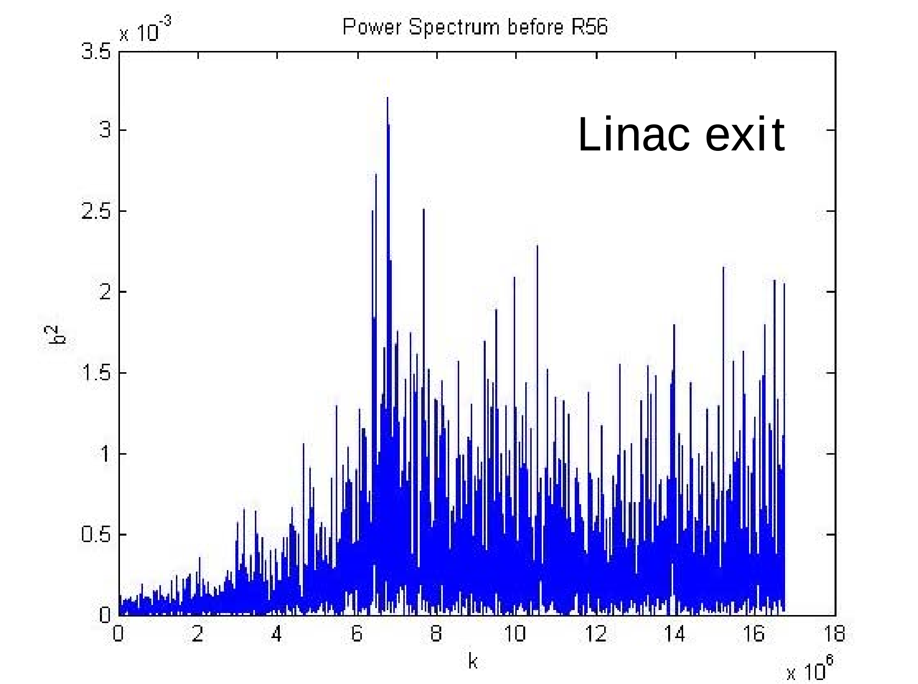
Several keV initial energy spread tolerated

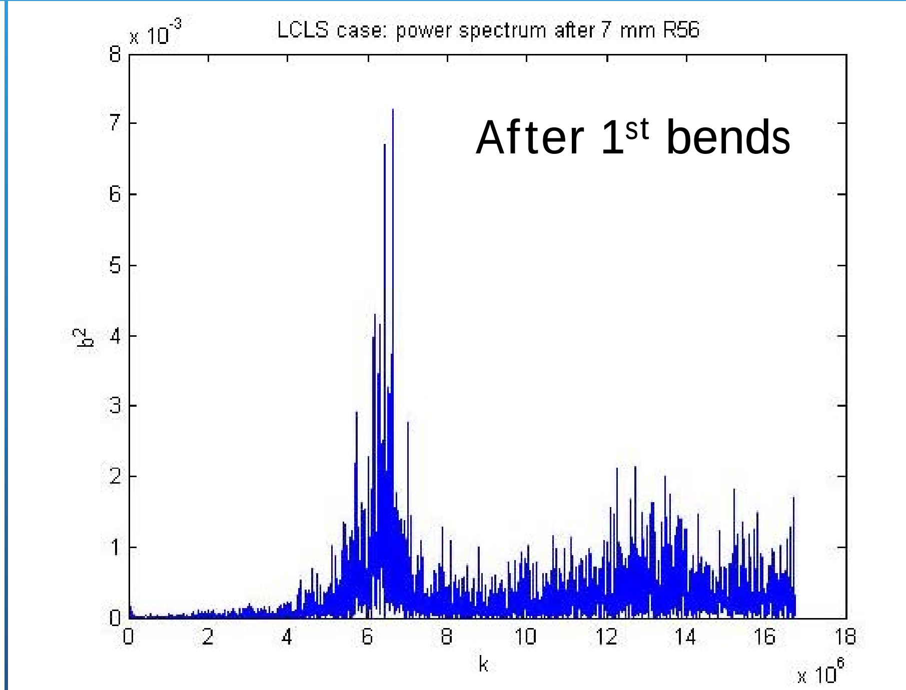
Latest results: LCLS analysis

- Dynamics influenced by external focusing
- Notable quasicrystal after first bend, not before…



Spectral view of LCLS case

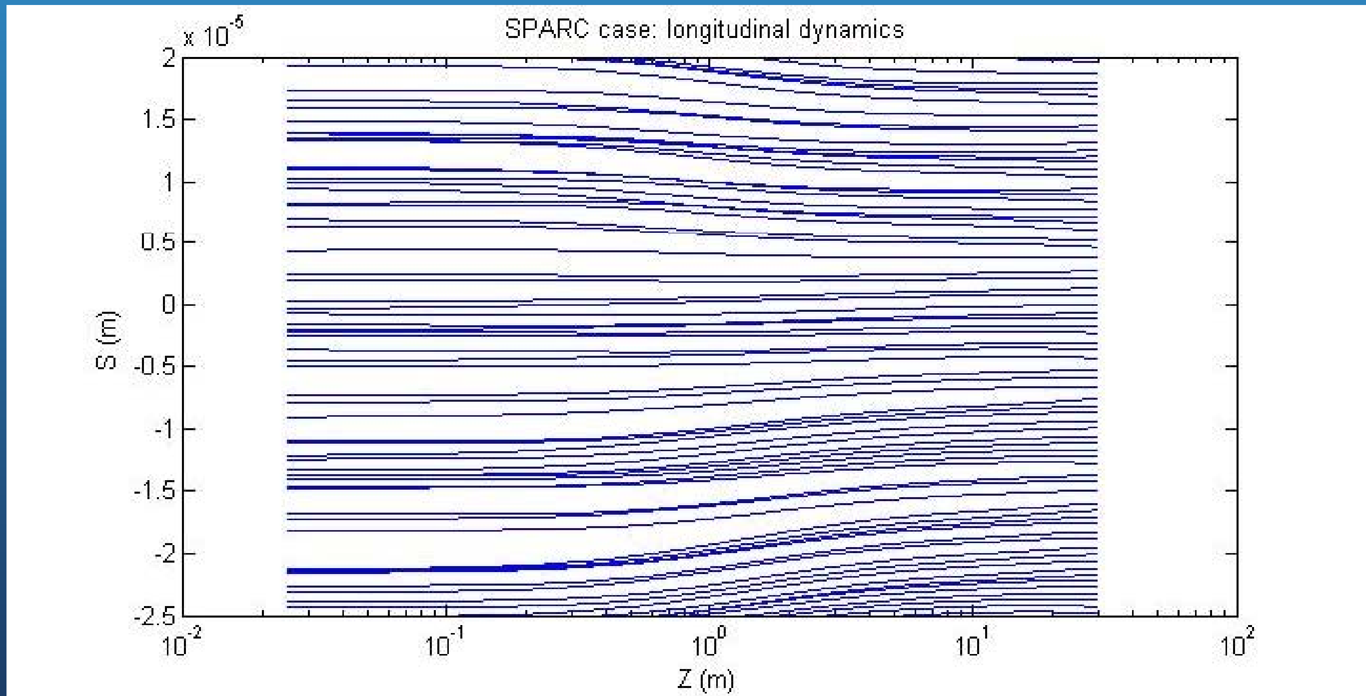




Notable peak near 1 micron develops after bends

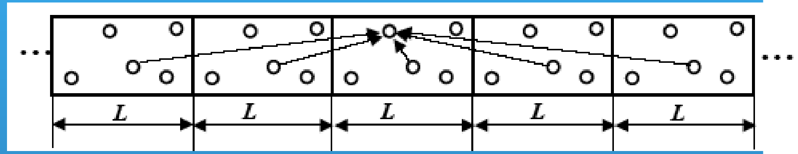
New topic: velocity bunching

- Experiment at SPARC
  - Optimized for velocity bunching
  - Do we need bends?



Molecular dynamics model

- Need microscopic calculations
  - "Molecular dynamics"; in progress
    - Periodic system, <1000 particles
    - Box with evolving dimensions
      - Compression in *x*, *y*
      - Stretching in ζ
    - Use Fourier fields…
      - Careful with spectral resolution
  - <u>What sets exact crystalline lengths?</u>
    - Rest frame density *constant*
    - But *stretched aspect ratio*



$$U_{sc}(s,r) = \frac{1}{4\pi\varepsilon_0}\left(\frac{q}{a} + \frac{2q}{L}\int_0^\infty \frac{J_0(kr/L)\cosh(ks/L)-1}{\exp(k)-1}\,dk\right)$$

Future topics

- More experimental input needed
  - Longitudinal spectrum: Fourier xfm of ζ distribution
  - Transverse far-field distibution: Fourier xfm of x,y distributions; information on transverse size of structures
  - Grain size information
- Experimental tests at BNL
  - Photoinjector similar; energy lower (70 MeV), UCLA chicane
  - Spectrometer, other coherence measurements key
  - Measure far-field angular distribution for added information
- Future experiments
  - FLASH: excellent diagnostic capabilities. To discuss!
  - SPARC: *Velocity bunching*