Seeding, Controlling and Benefiting from Microbunching Instability

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on behalf of Sergei Seletskiy, Boris Podobedov and Yuzhen Shen

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References

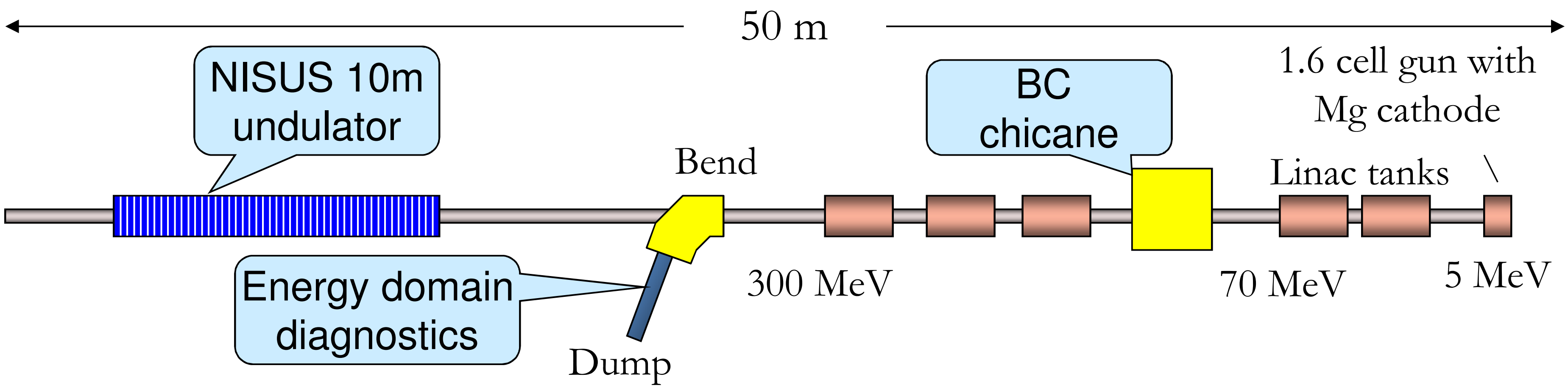
- **This presentation is based on:**
  - **S. Seletskiy, B. Podobedov, Y. Shen, and X. Yang, PRL 111, 034803 (2013)**
  - **Y. Shen et al., PRL 107, 204801 (2011)**
  - **S. Seletskiy et al., Phys. Rev. ST Accel. Beams 14, 110701 (2011)**

- A number of important results on microbunching instability were obtained in experiments performed by our colleagues at SDL in previous years:
  - T. Shaftan and Z. Huang, Phys. Rev. ST Accel. Beams 7, 080702 (2004).
  - T. Shaftan et al., Nucl. Instrum. Methods Phys. Res., Sect. A 528, 397 (2004).
  - H. Loos et al., in Proceedings of the 8th EPAC, Paris, 2002, TUPRI103.
  - T. Shaftan et al., in Proceedings of the 20th PAC, Portland, OR, USA, 2003, TOPD005.
  - J.G. Neumann et al., Proceedings of the 2004 FEL Conference, pp 586-589.

Outline

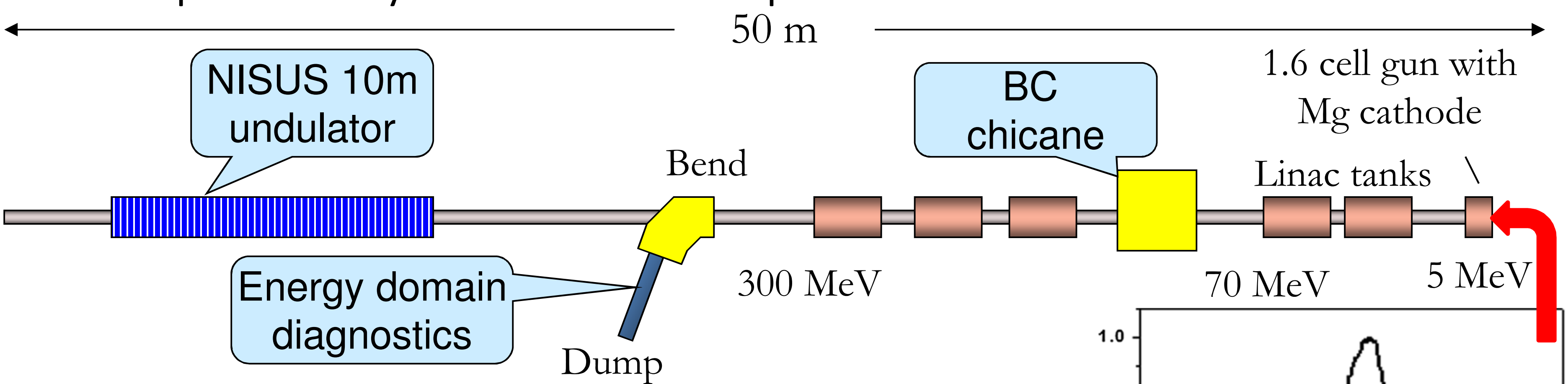
- Introduction
- Origin of microbunching instability at SDL
- Controlled seeding at SDL
- Using controlled seeding for direct microbunching gain measurements
- Possible scheme of enhancing tunable multi-cycle THz sources
- Summary

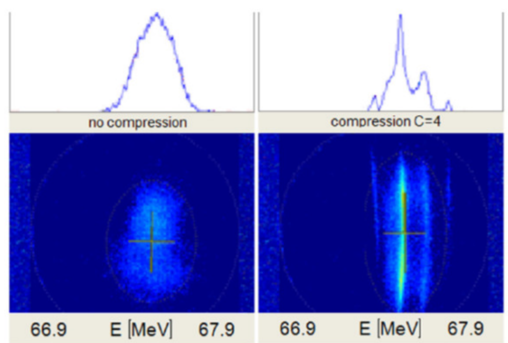
Introduction: the SDL



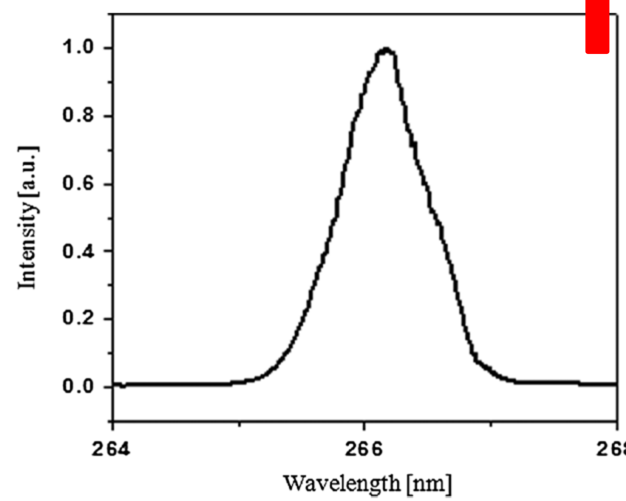
Introduction: Microbunching Instability at SDL

- Microbunching instability can be seeded by both the shot-noise and temporal modulation of photocathode laser (in photoinjectors).
- The SDL photoinjector has a small microbunching gain ~100. Therefore, the only source of detectable microbunching is the laser modulation.
- We experimentally checked this assumption.





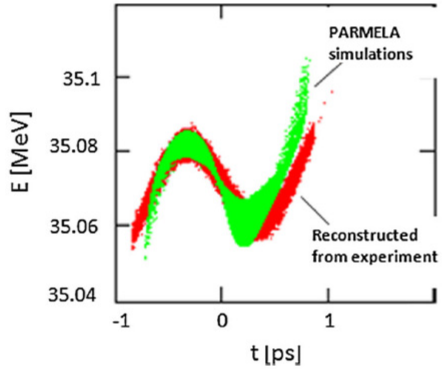
Spectra of uncompressed (left plot) and compressed (right plot) beams.



The transform-limited 100 fs-long laser pulse used in the experiment.

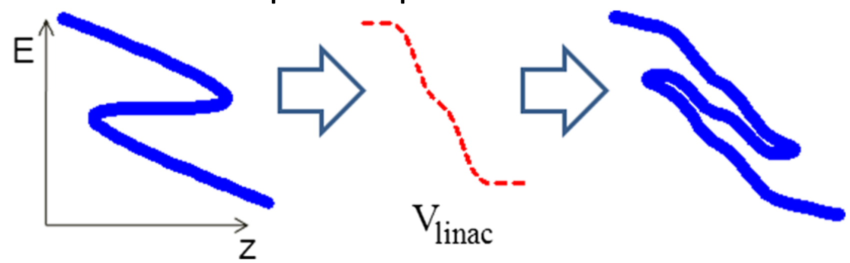
Origin of Microbunching Instability at SDL

At low energies, space charge effects dominate the evolution of the beam longitudinal phase space.



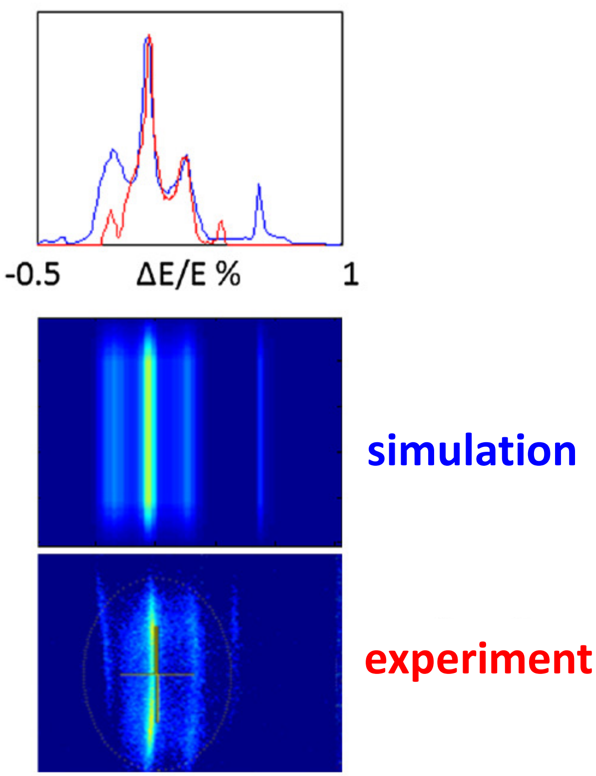
Beam longitudinal phase space before linac tank 2.

The BC rotates the phase space.



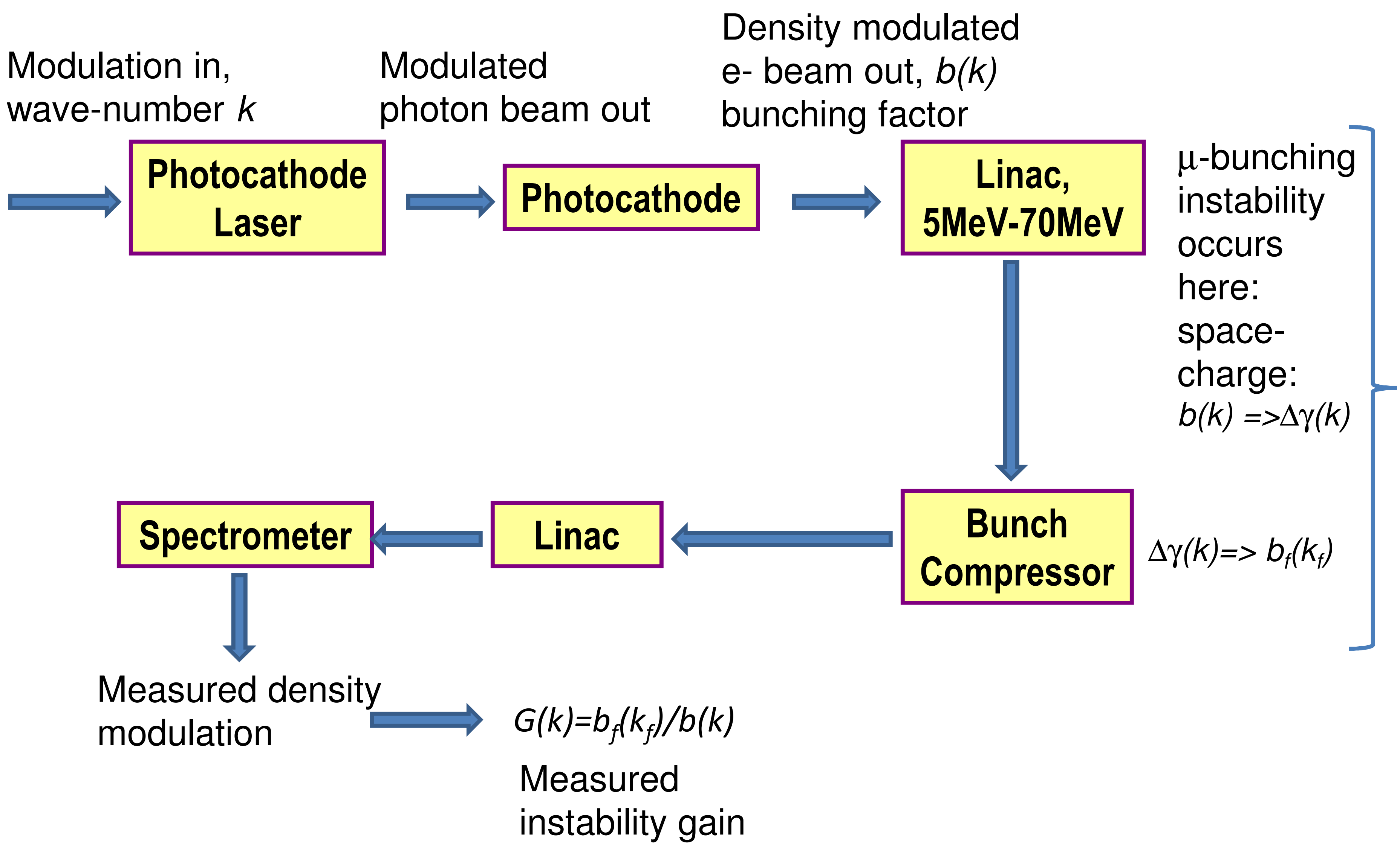
At higher energies linac wake is stronger than LSC.

From Elegant simulations, at spectrometer:

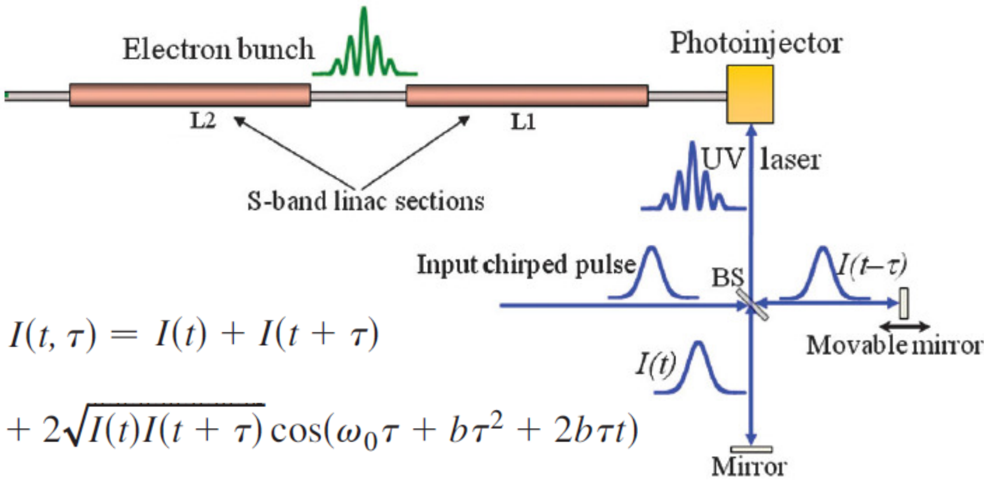


- We understand beam dynamics at SDL
- Main factors: LSC at low E, linac wake at high E, phase space rotation in the BC
- **For clean laser there is no noticeable uB instability at SDL**

Main Idea: Driven Micro-bunching Instability

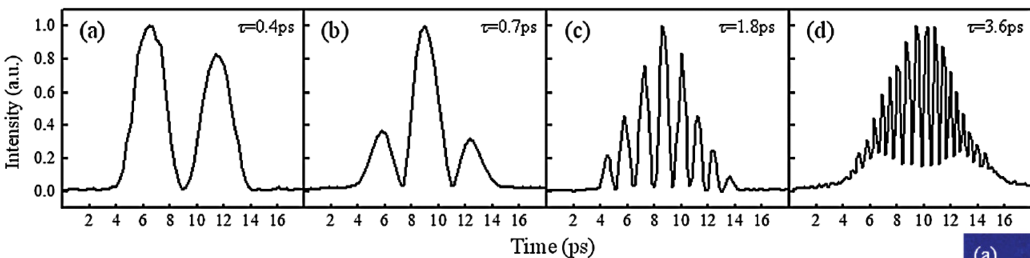


Controlled Laser Seeding

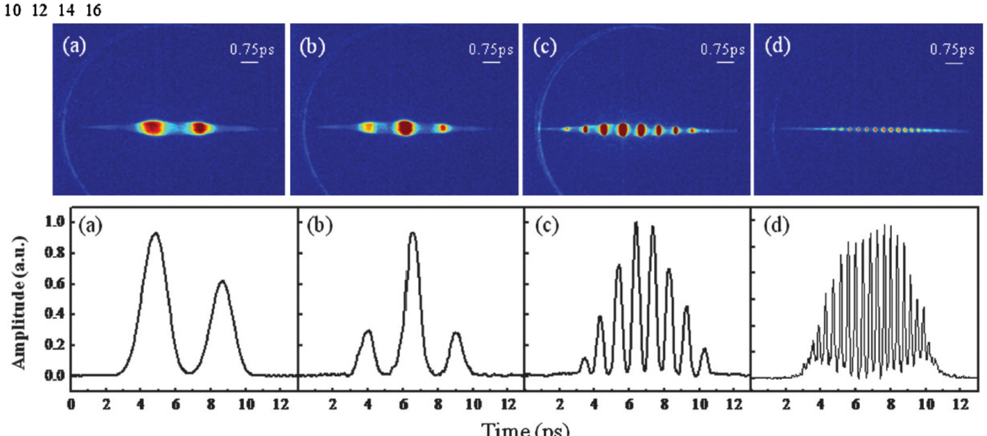


$$I(t,\tau) = I(t) + I(t+\tau) + 2\sqrt{I(t)I(t+\tau)}\cos(\omega_0\tau + b\tau^2 + 2b\tau t)$$

- Chirp the laser pulse (chirp rate *b*) and then split the chirped pulse into two pulses.
- Delay one pulse by a variable interval *τ* with respect to the other.
- Recombine two pulses.
- The resultant output pulse has a Gaussian envelope modulated by a cosine function that is easily tuned by varying *τ* or *b*.



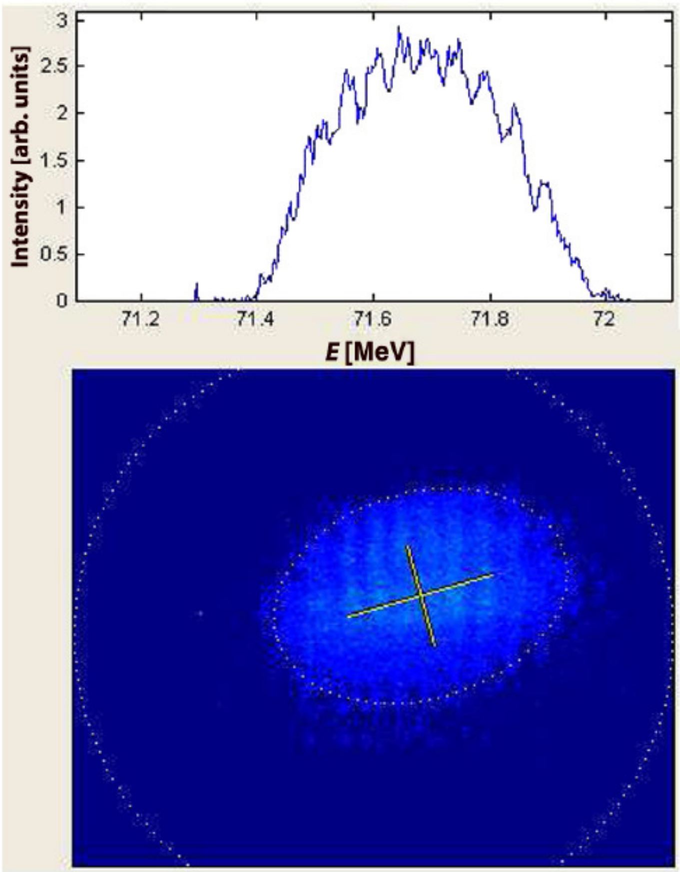
Temporal profiles of the photocathode drive laser pulses for different time delays.



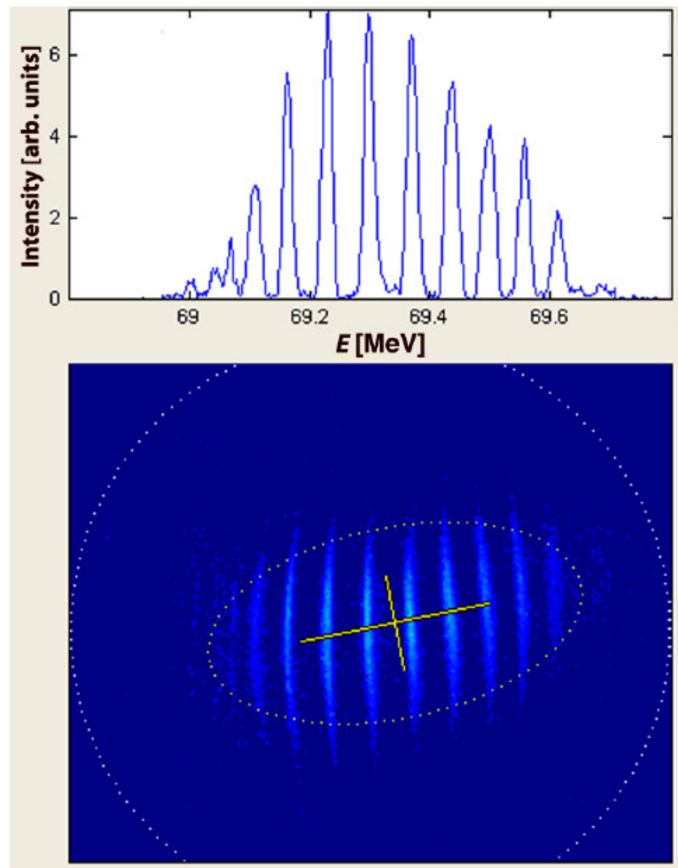
Measured longitudinal distributions at the spectrometer (top row) and projected electron density distribution (bottom row) for a temporally modulated electron bunch.

Direct measurement of microbunching gain

- We modulate electron bunch in a controlled fashion.
- We perform zero-phasing measurement to find beam density modulation.
- We find the microbunching gain by taking the ratio of measured amplitudes of density modulation of the compressed and uncompressed bunches.



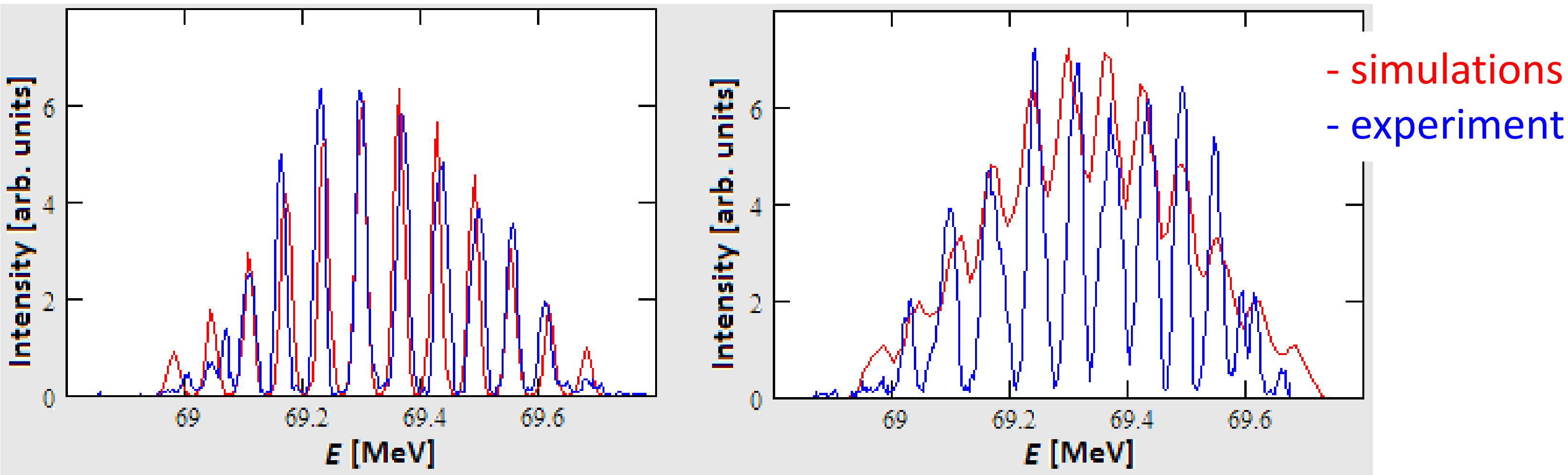
The zero phasing of the 90 pC beam produced by the longitudinally modulated photocathode laser. The wavelength of the induced modulation is about 60 um.



The zero phasing of the compressed 90 pC beam. The BC compression factor is 2.5.

Energy Modulation or Density Modulation

- Energy modulation can be misinterpreted as density modulation.
- Partial tomography (zero-phasing was done at two opposite phases at several amplitudes) proves that it is not the case.

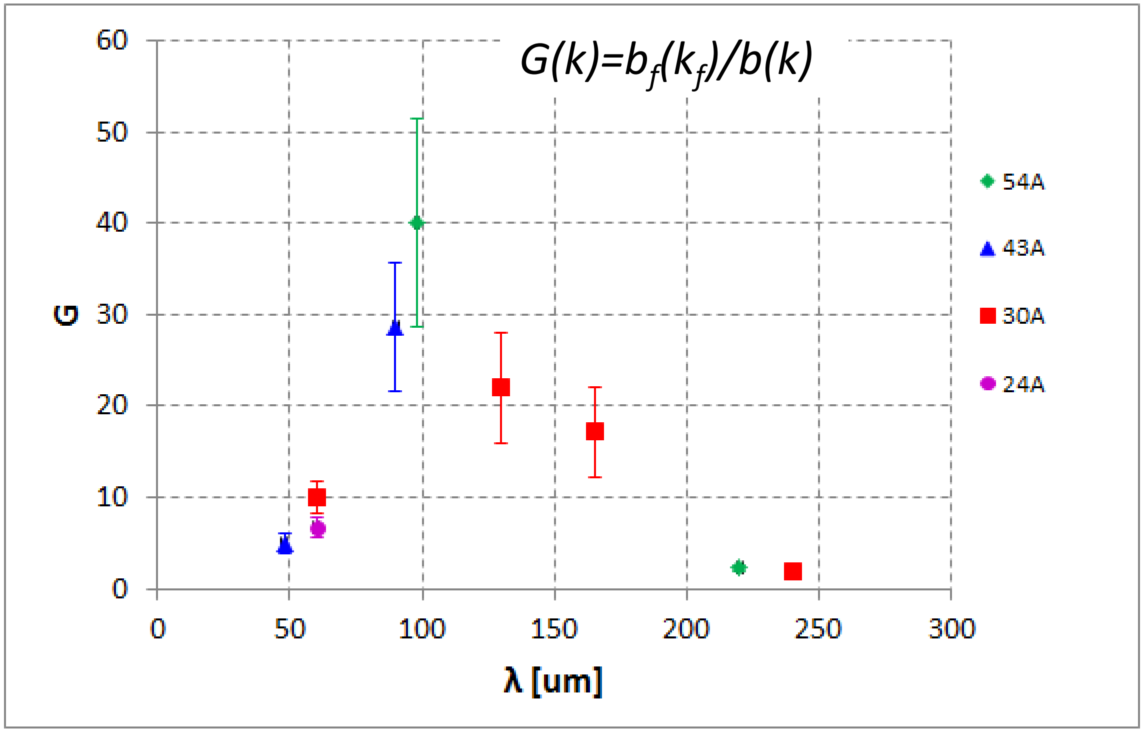


Strong energy modulation (simulations) would lead to asymmetry between opposite zero crossing phases.

Experiment shows mirror symmetry for opposite zero-crossing phases.

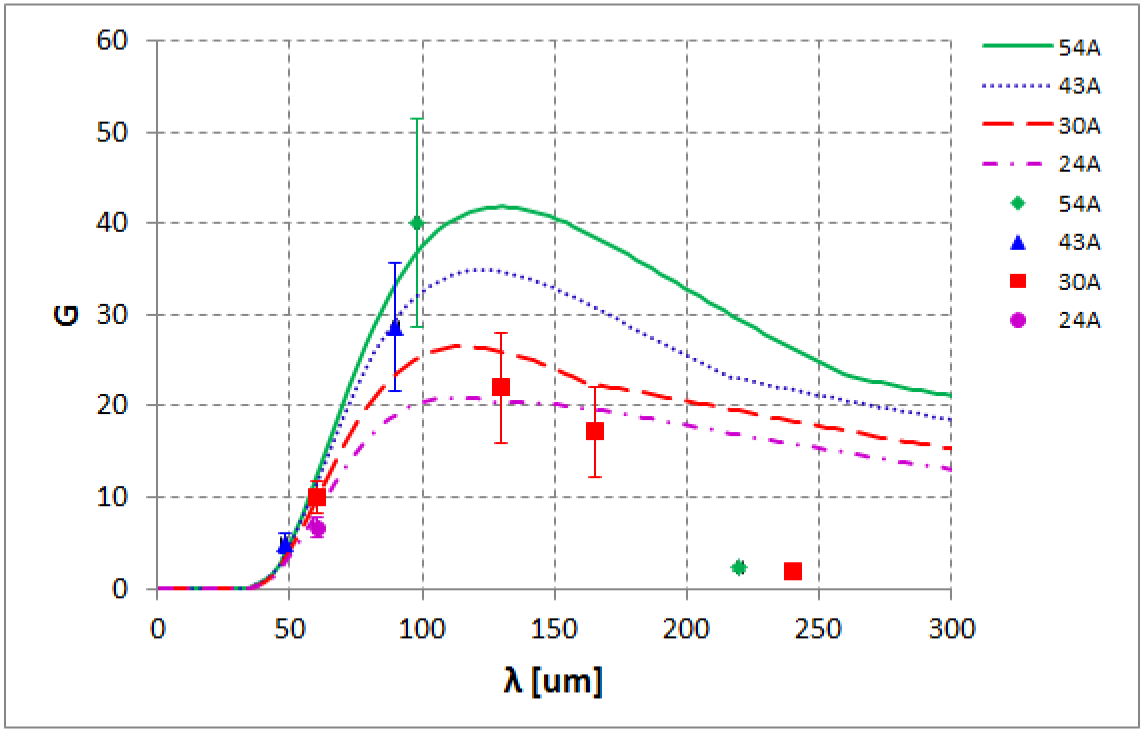
- Increasing the zero-phasing amplitude did not affect the depth of the observed modulation.
- The THz interferograms (for beams with close parameters) show that electron bunch spectrum accurately represents the bunch density modulation.

Direct measurement of microbunching gain



- We measured the microbunching gain by dividing the modulation amplitude of the compressed beam on the amplitude of the uncompressed beam.
- We used the bunches of several charges modulated with various frequencies and amplitudes.
- The error bars at high gain values are mostly driven by shot-to-shot variations; at low gain, the error is determined by both these variations and the background noise.

Comparing measurement to theory



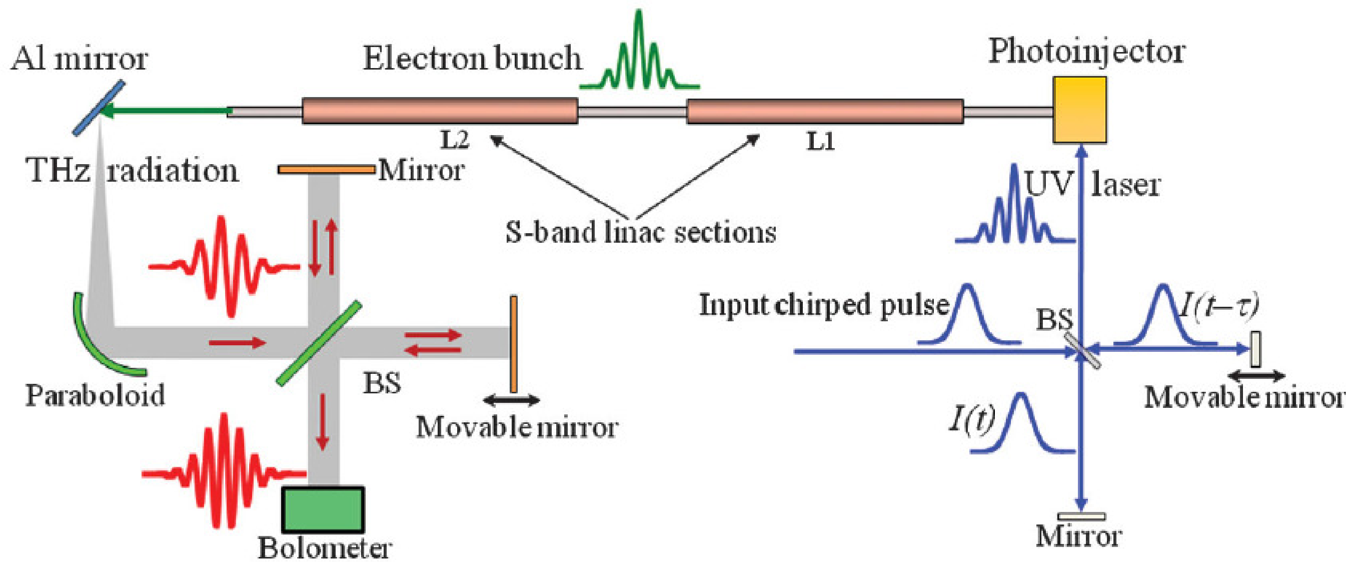
$$G(k) = \left| CkR_{56}\frac{\Delta\gamma(k)}{\gamma b(k)} \right| e^{-[(CkR_{56}\sigma_E)^2/2E^2]}$$

$$\Delta\gamma(k) = -\frac{4\pi I}{Z_0 I_A}\int_0^L Z(k,z)b(k,z)dz$$

- We compare our measurements to the formula of E. Saldin, E. Schneidmiller and M. Yurkov (*Nucl. Instrum. Methods Phys. Res., Sect. A 483, 516 (2002)*)
- SSY formula is derived under assumptions: $\rho_{in} << \rho_{fin} << 1$ and $\lambda_{mod} << \sigma_z$. It is often extrapolated to saturation ($\rho_{fin} \approx 1$)
- **Our data agree reasonably well with SSY equation for all data points, except at $\lambda_{mod} \approx \sigma_z$**

Application: enhancement of linac-based THz sources

- Microbunching instability = LSC amplifier (*E. A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 13, 110701 (2010)*).
- Laser-seeded, single-stage LSCA enhances linac-based THz sources(spectral tunability, intensity and flexible number of cycles).



- THz source needs high charge and wide range of λ_{mod} : LSC fights it.
- Our scheme overcomes this limitation. SDL example:
  - Without LSCA, 100% density modulation at (100 pC, λ_{mod} =115 um).
  - With LSCA, 100% density modulation at (120 pC, λ_{mod} =24 um) and (250 pC, λ_{mod} =38 um)

Summary

- In our experiments we used a well characterized and precisely controlled longitudinally modulated photocathode laser, which allowed for straightforward interpretation of electron bunch spectra and instability gain measurements.
- By comparing the premodulated electron beams before and after the compression, we directly measured the microbunching gain.
- Our results are fitted reasonably well by the formula of Saldin, Schniedmiller and Yurkov.
- We demonstrated the feasibility of LSCA idea.
- We showed how a single stage LSCA can be applied to significantly enhance the tunability of the linac-based THz sources.