High-brightness electron beams with tunable modulation

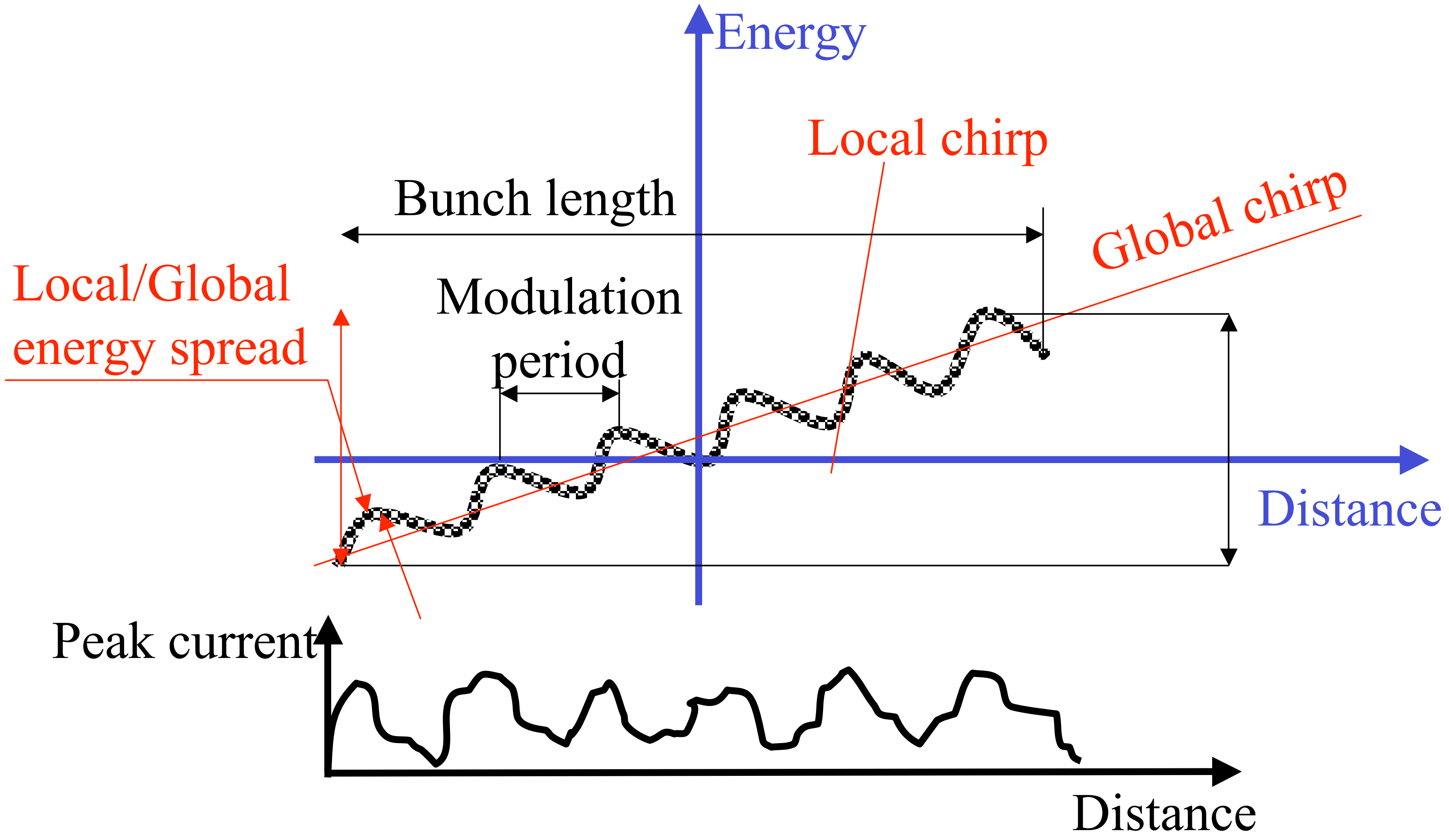
Timur Shaftan (BNL)

The Physics and Applications of High Brightness Electron Beams 2005, Erice, Italy, 2005

Outline

- Modulated beams, “tools” for longitudinal phase space
- Modulation generated by collective effects
  - Longitudinal Space Charge effect
  - Coherent Synchrotron Radiation effect
  - Cure: LCLS “laser-heater”
- Creating modulated beams for radiation sources
  - Seeded FEL schemes/Tunability
  - Study of modulated bunch with an energy chirp
  - Beams modulated at photocathode → THz generation
  - Self-seeded schemes
- Conclusion

Longitudinal phase space of modulated beam

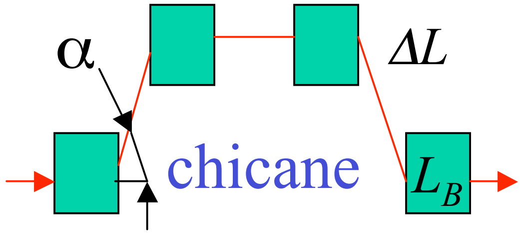


"Tools"

Dispersion in:

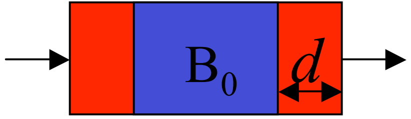
Storage ring

$|R_{56}| = \oint \eta / \rho \cdot ds$; **$R_{56}$ …~1 m**

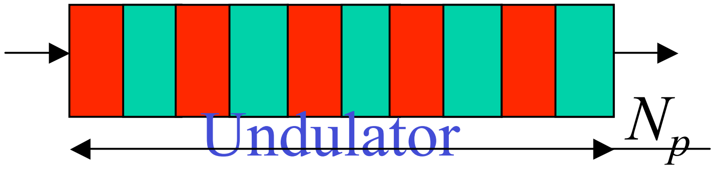


$|R_{56}| 2\alpha^2 (\Delta L + 2/3 \cdot L_B)$; **R_{56}~0.1 m**

Dispersion section



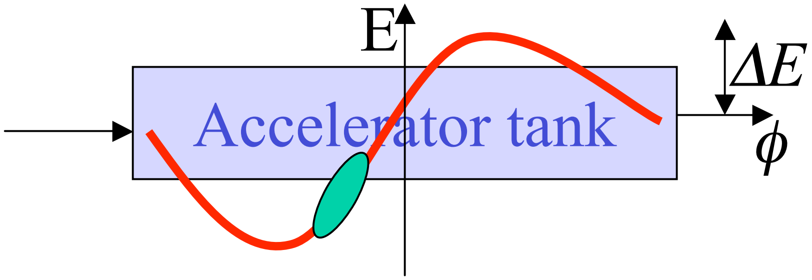
$|R_{56}| \approx 4/3 \cdot B_0^2 d^3 /(BR)^2$; **R_{56}~10^{-3} m**



$|R_{56}| \approx 2N_p\lambda$; **$R_{56}$~$10^{-4}$ m**

for medium energy

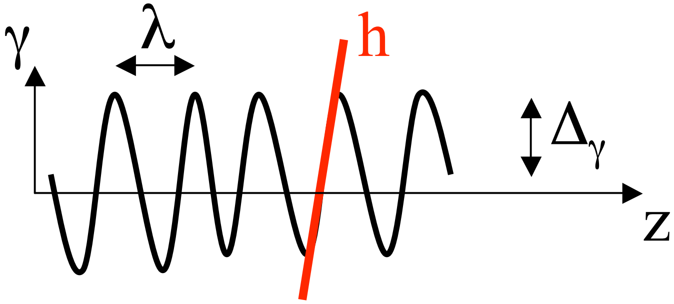
Chirp in:



$$|h| = \frac{2\pi}{\lambda_{RF}} \frac{\Delta E \sin(\phi)}{E_{in} + \Delta E \cos(\phi)}$$

h~10 m^{-1} for S-band

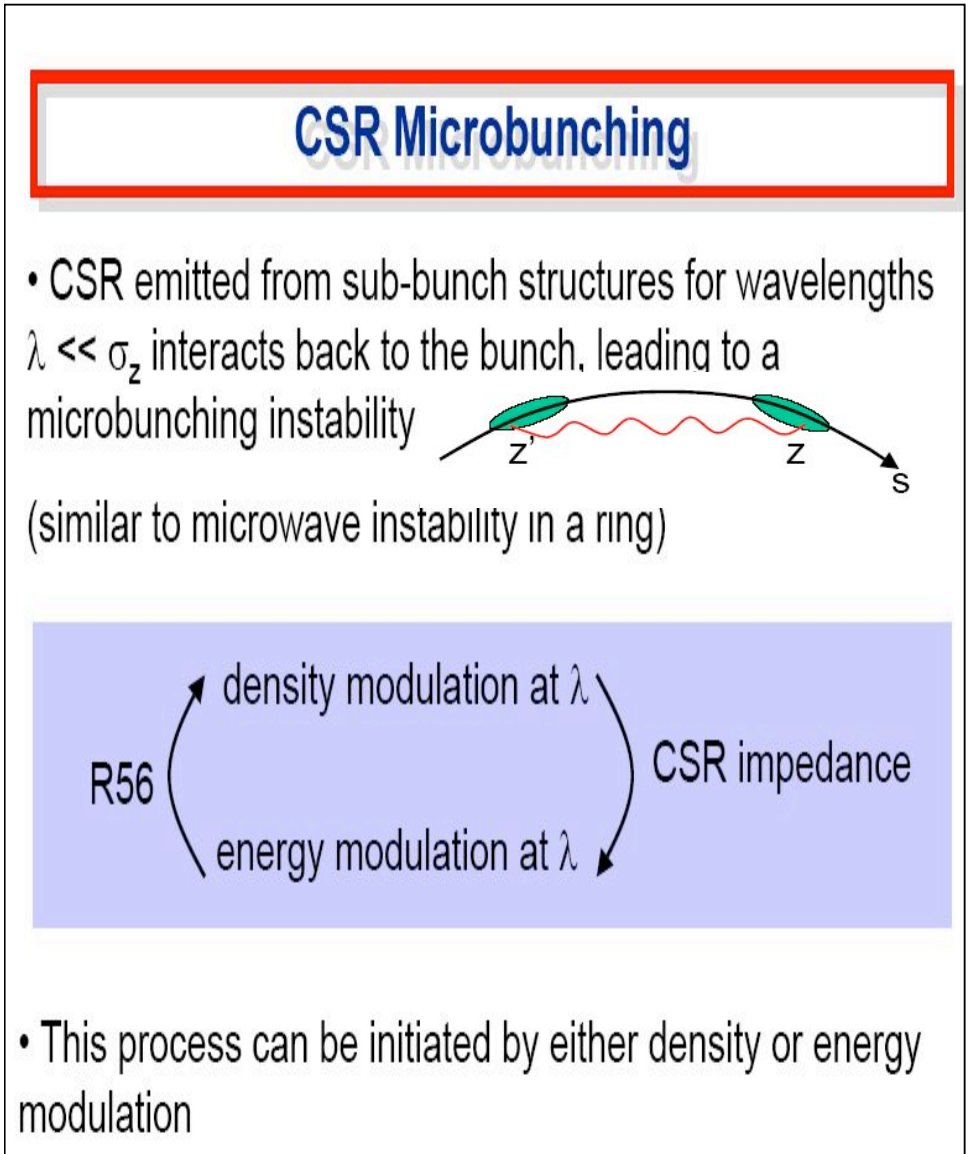
An energy modulated beam



$$|h| = \frac{2\pi}{\lambda} \frac{\Delta_\gamma}{\gamma_{in}}$$

h~10^3…10^4 m^{-1}

Modulation driven by collective effects



CSR Microbunching

- CSR emitted from sub-bunch structures for wavelengths $\lambda \ll \sigma_z$ interacts back to the bunch, leading to a microbunching instability

(similar to microwave instability in a ring)

density modulation at λ

R56

CSR impedance

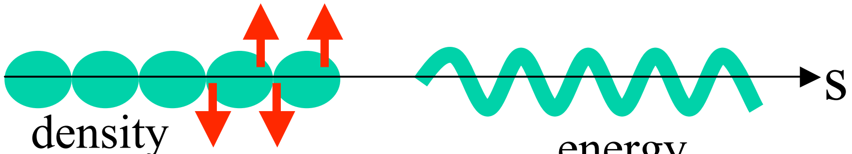
energy modulation at λ

- This process can be initiated by either density or energy modulation

from: Z.Huang et al., FEL-2002

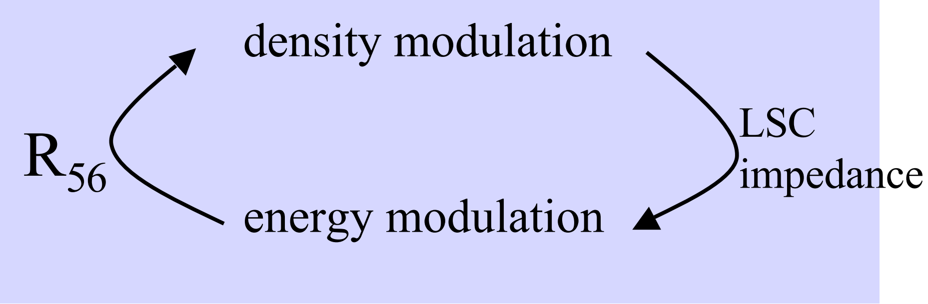
Longitudinal Space Charge

- LSC drives small density clusters into energy modulation



density modulation

energy modulation



density modulation

R_{56}

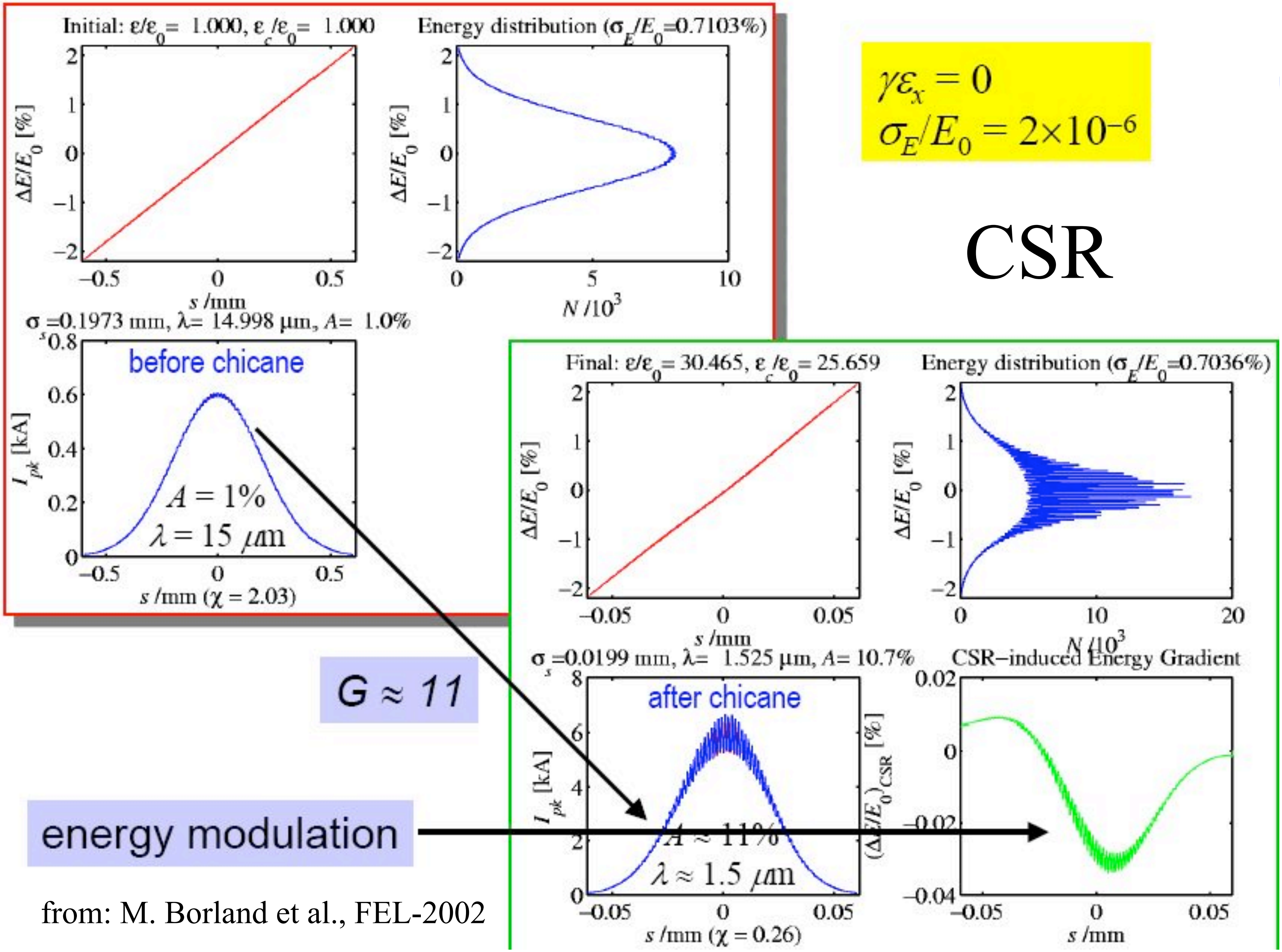
LSC impedance

energy modulation

- This process can be initiated by either density or energy modulation

$$\gamma\varepsilon_x = 0$$
$$\sigma_E/E_0 = 2\times10^{-6}$$

CSR



$G \approx 11$

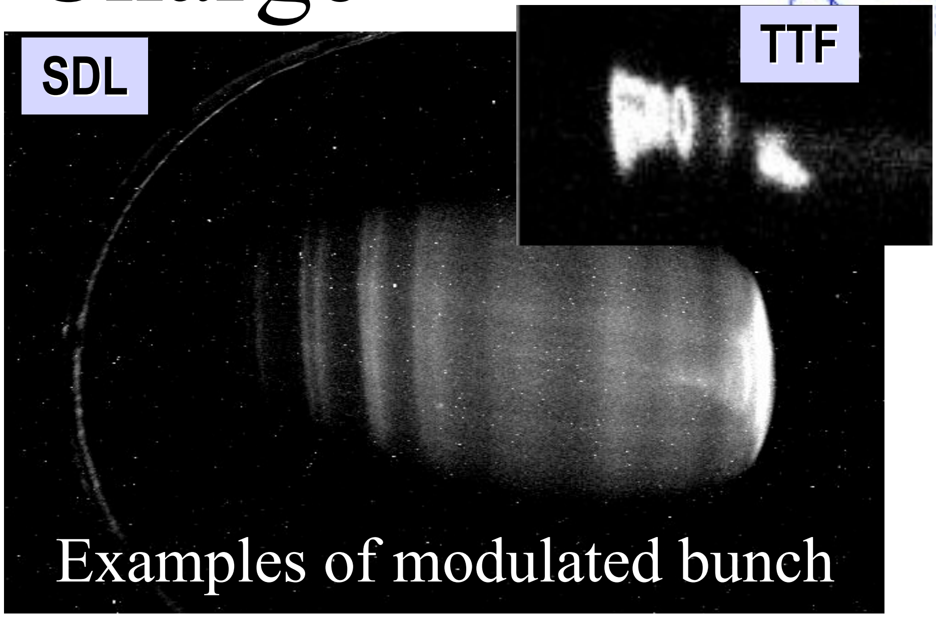
energy modulation

from: M. Borland et al., FEL-2002

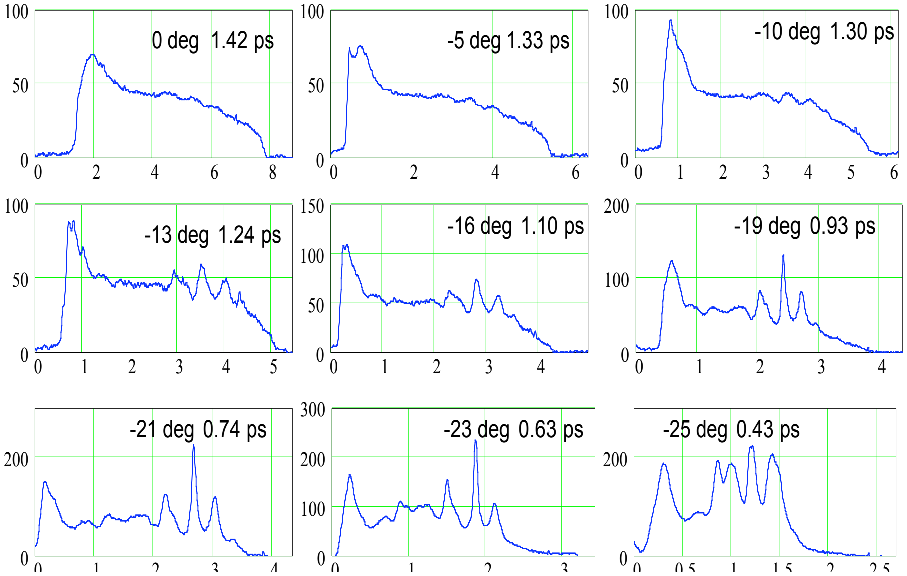
Longitudinal Space Charge

- LSC oscillation frequency: $\Omega = f(\lambda_{mod}, I_p, \ldots)$
- Compression (factor n) of modulated bunch: $I_p \uparrow$ n times, $\lambda_{mod} \downarrow$ n times: $\Omega \uparrow$ n times.
- → Energy modulation gets compressed together with faster growth of it's amplitude
- Initial modulation spectrum seeded by noise is amplified depending on what you do with the beam

Z. Huang, W. Graves, C. Limborg, H. Loos,
T. Shaftan, Z. Wu
From: W. Graves et al., PAC-2001,
H. Loos et al., EPAC-2002,
Z. Huang et al., FEL-2003
T. Shaftan et al., PAC-2003



Examples of modulated bunch



Compression of modulated bunch

LSC oscillation wavelength [m] versus modulation wavelength [um] for uncompressed (50 A) and compressed (220 A) beam

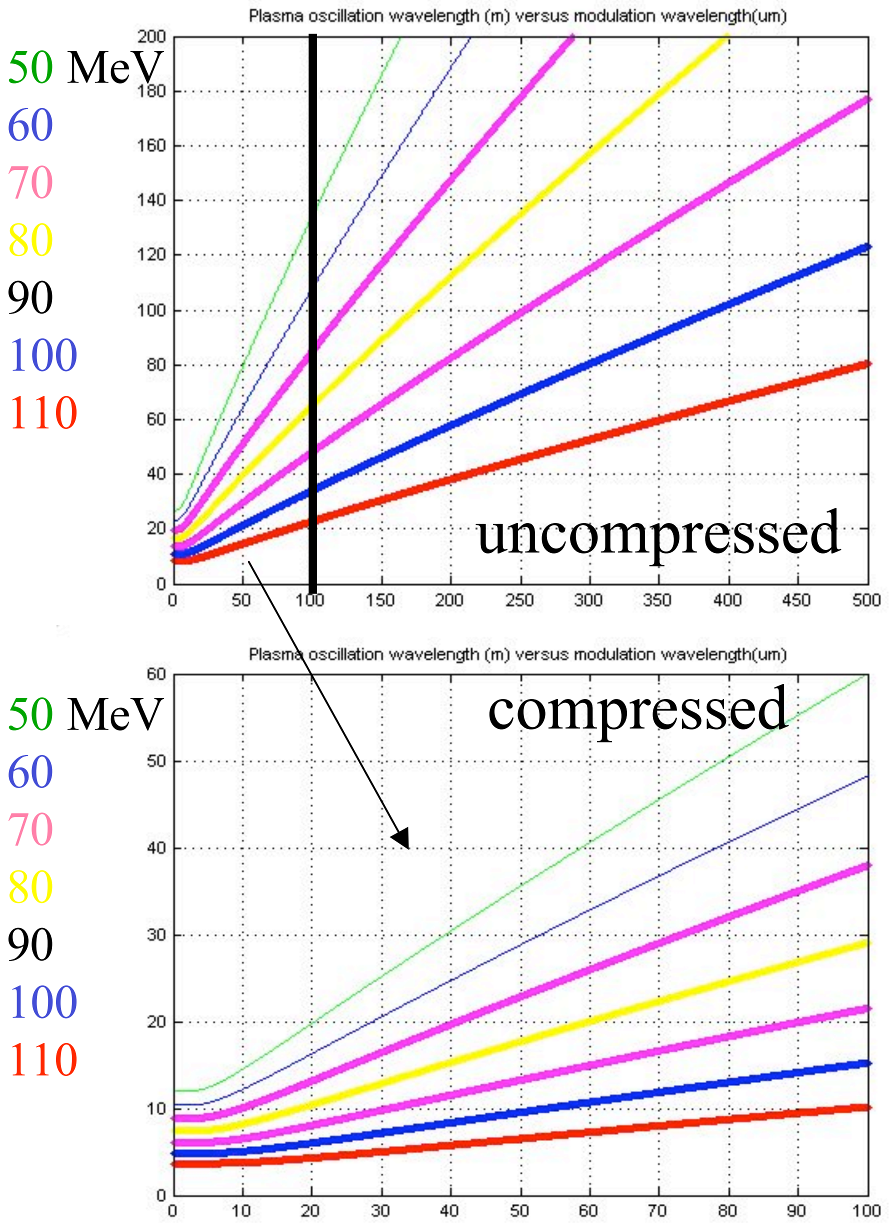
* Space charge impedance (Z. Huang):

$$Z(\lambda) = i\frac{Z_0\lambda}{2\pi^2 r_b^2}\left[1-\frac{2\pi r_b}{\gamma\lambda}K_1\left(\frac{2\pi r_b}{\gamma\lambda}\right)\right]$$

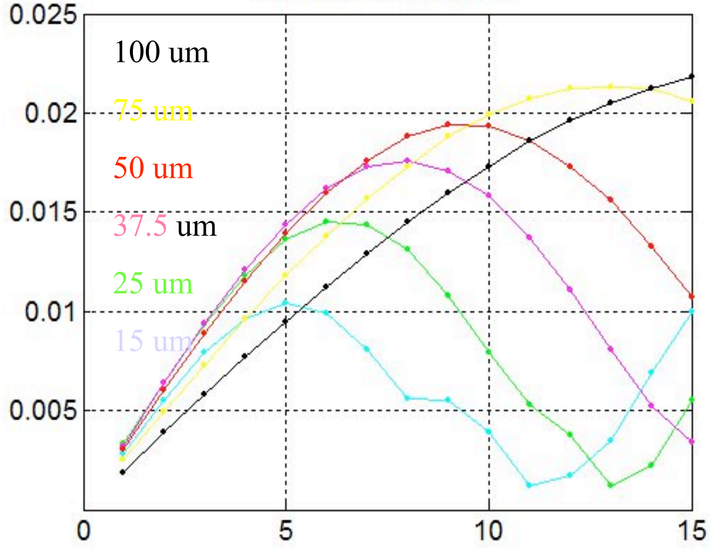
* LSC oscillation wavelength:

$$\Omega_{SC} = c\sqrt{\frac{8\pi^2 I_0}{\gamma^3 I_A}\frac{|Z(\lambda)|}{\lambda Z_0}}$$

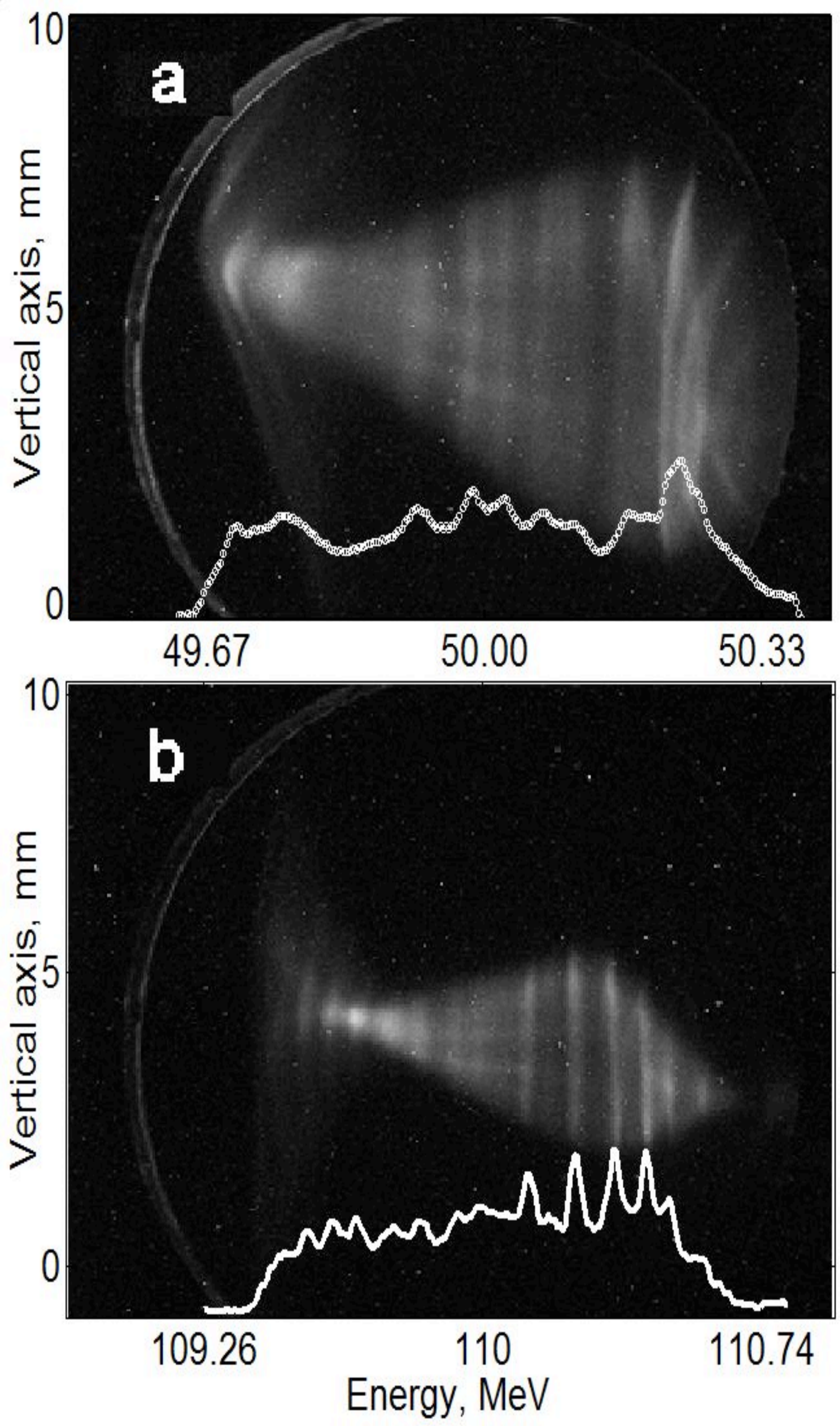
* Example: low-noise RF TWT.



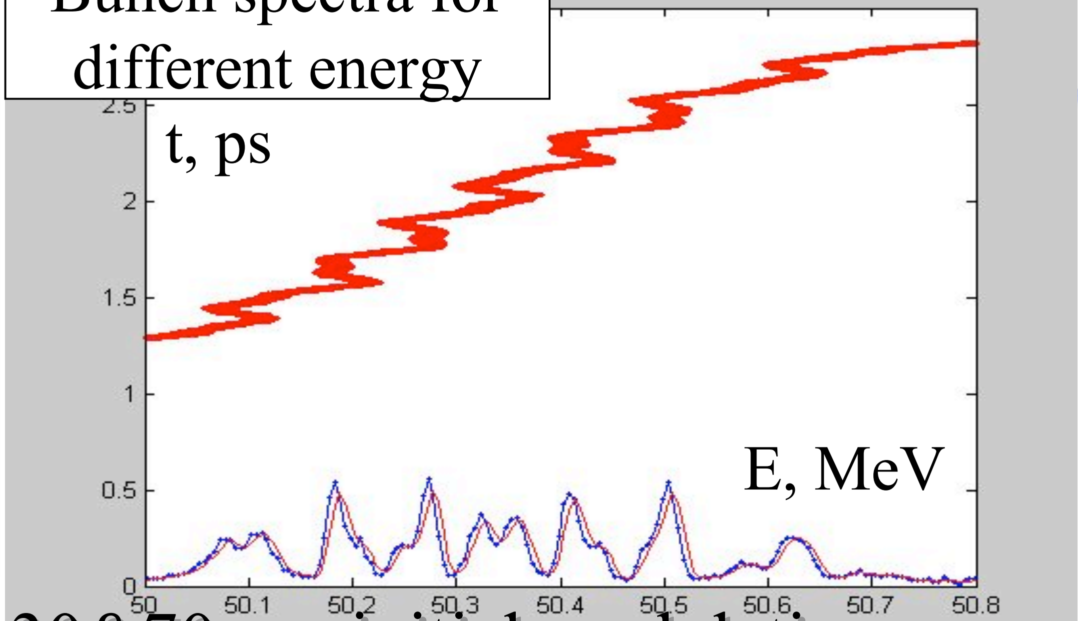
Energy modulation (MeV) versus distance (m)



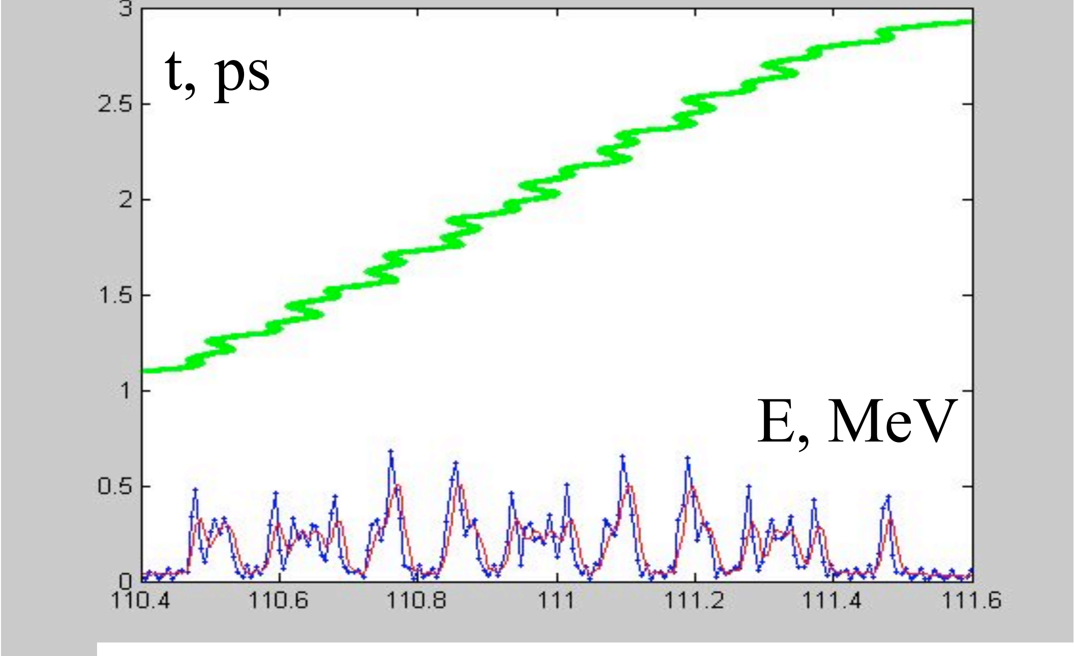
Br



Bunch spectra for different energy

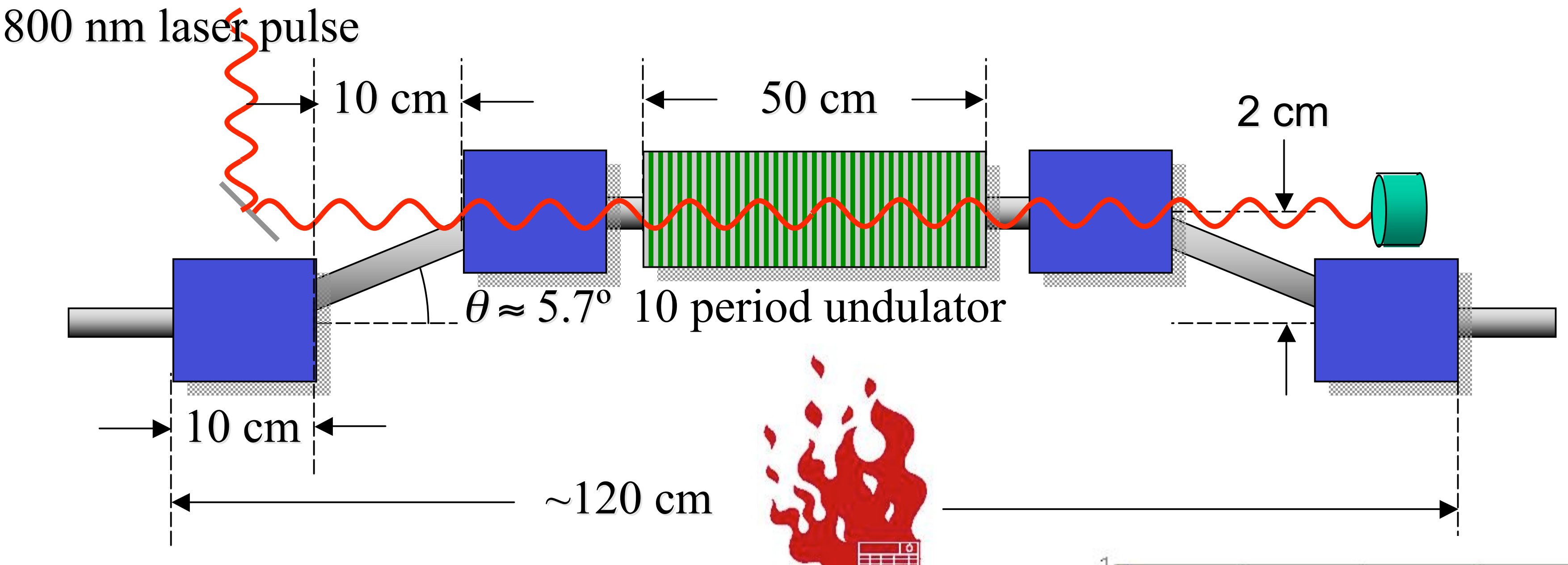


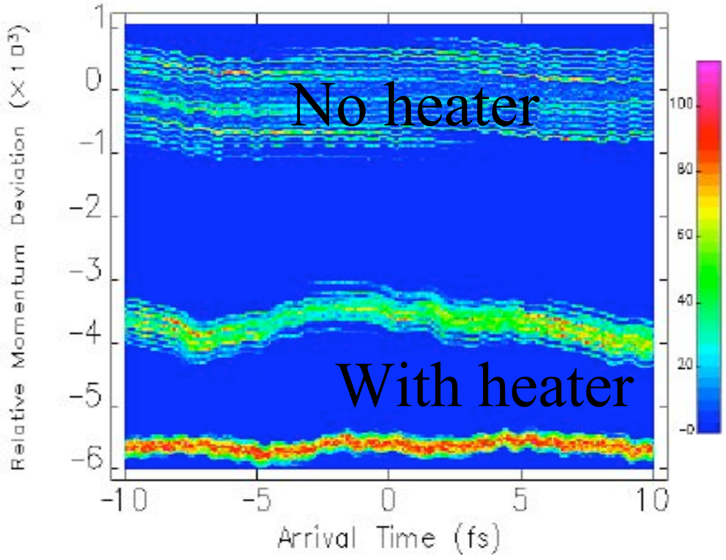
30&70 um initial modulation



From: T. Shaftan and Z. Huang, PRST-AB-2004

Laser Heater





- Laser-electron interaction in an undulator induces rapid energy modulation (at 800 nm), to be used as effective energy spread before BC1 (3 keV➔ 40 keV rms)

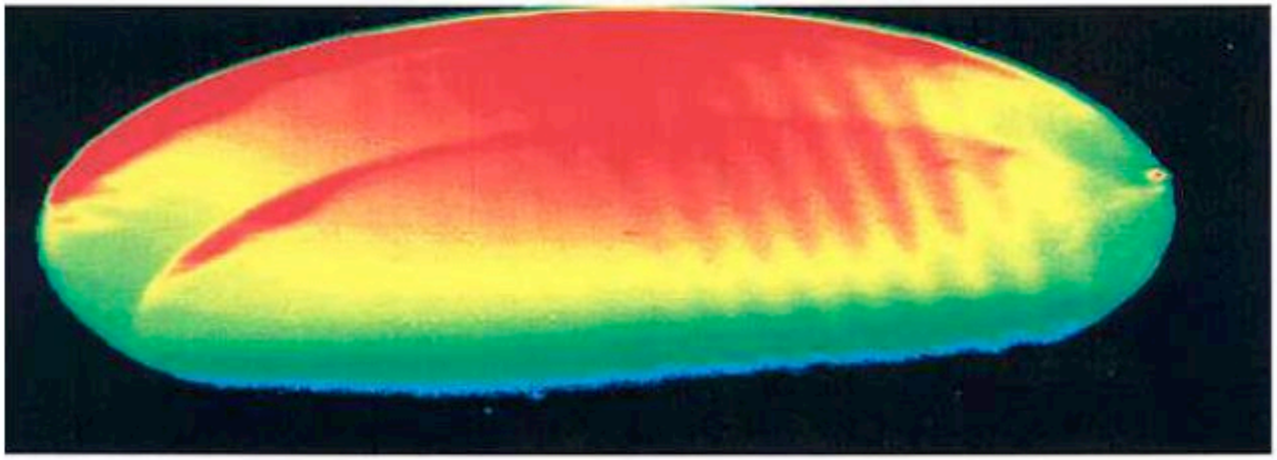
- Inside a weak chicane for easy laser access, time-coordinate smearing (emittance growth is completely negligible)

from: Z.Huang, M. Borland, P. Emma, C. Limborg et al., SLAC-PUB-10334, 2004

Modulation in Radiation Sources

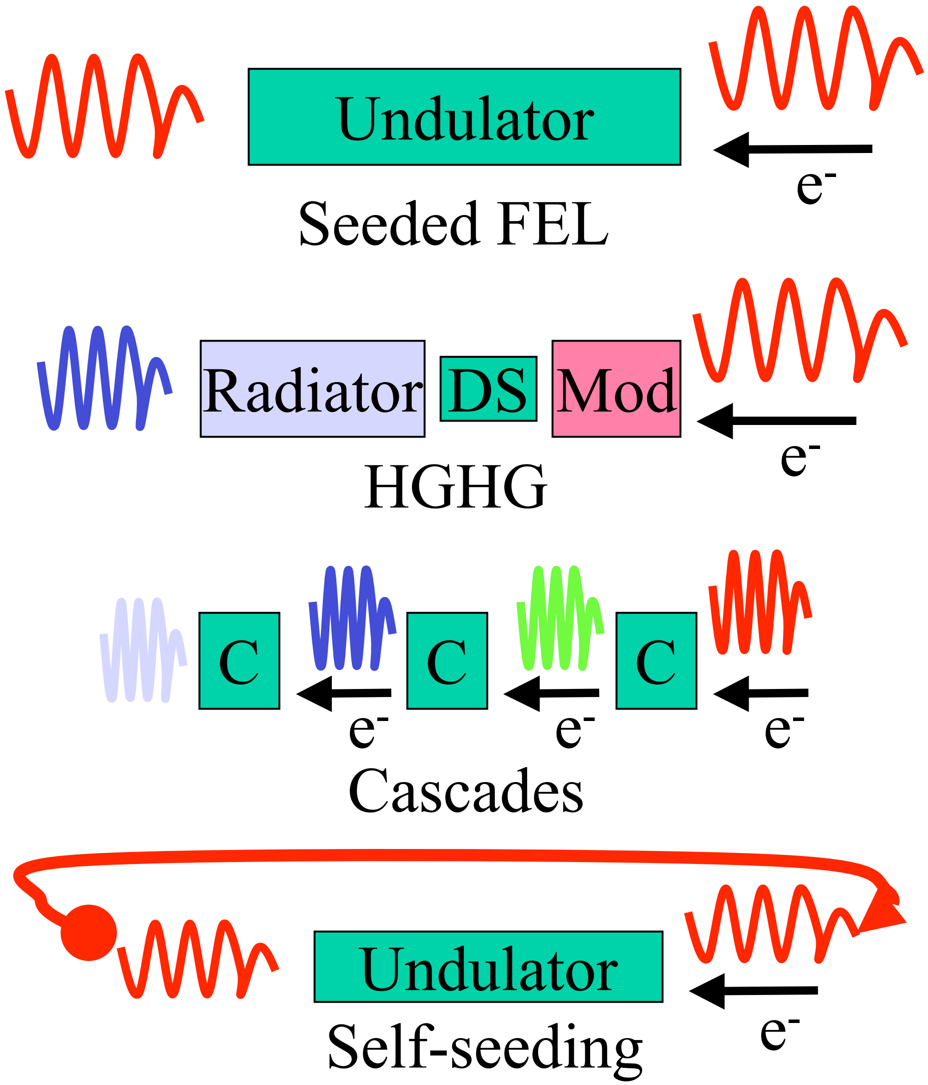
Early measurements of modulation after FEL
K.N. Ricci et al., in Proc. of FEL-2001

Experimental observation of microbunching at the 60 μm FEL Firefly, Stanford



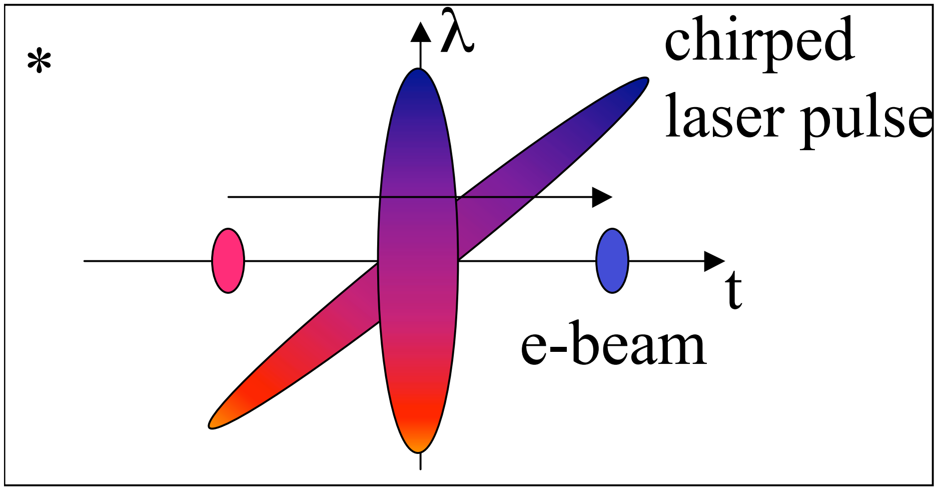
Seeded FELs

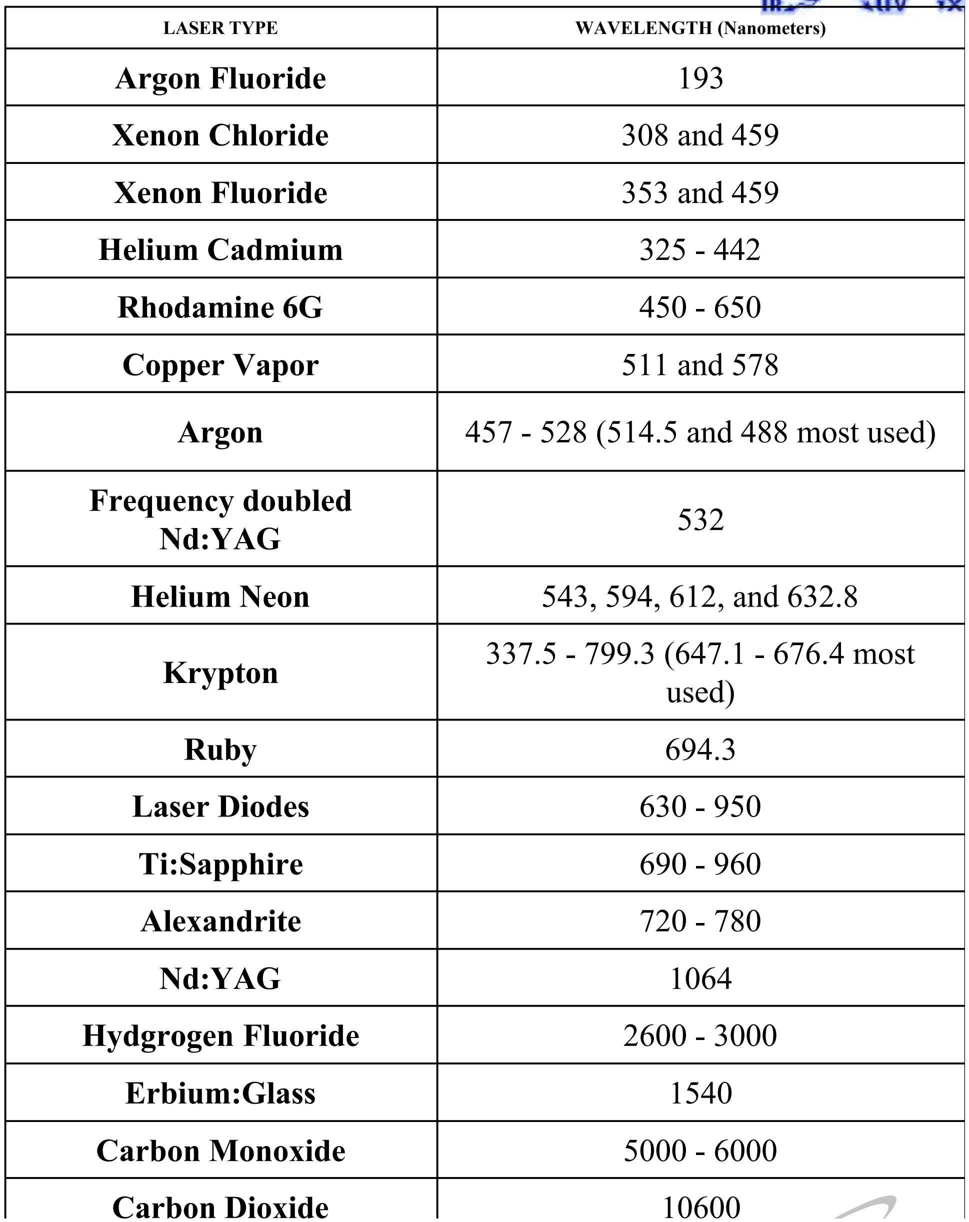
- R.Q.: How to modulate bunch?
- Seed source creates energy modulation → bunching at fundamental or harmonics
- FEL process takes off from a "known" signal, not from noise: longitudinal coherence
- Concepts: seeding with lasers and HHG sources, self-seeding, seeding with short pulse, …



Conventional lasers/Chirped pulses

- Tunable conventional seed lasers, OPA
- 13th harmonics of Ti:Sa at 61 nm, produced in Xe: M.-E. Couprie, in FEL-2005 (1 uJ, 50 fs, 10 Hz)





LASER TYPE	WAVELENGTH (Nanometers)
Argon Fluoride	193
Xenon Chloride	308 and 459
Xenon Fluoride	353 and 459
Helium Cadmium	325 - 442
Rhodamine 6G	450 - 650
Copper Vapor	511 and 578
Argon	457 - 528 (514.5 and 488 most used)
Frequency doubled Nd:YAG	532
Helium Neon	543, 594, 612, and 632.8
Krypton	337.5 - 799.3 (647.1 - 676.4 most used)
Ruby	694.3
Laser Diodes	630 - 950
Ti:Sapphire	690 - 960
Alexandrite	720 - 780
Nd:YAG	1064
Hydgrogen Fluoride	2600 - 3000
Erbium:Glass	1540
Carbon Monoxide	5000 - 6000
Carbon Dioxide	10600

http://www.fas.org/man/dod-101/navy/docs/laser/fundamentals.htm←Common Lasers and Their Wavelengths

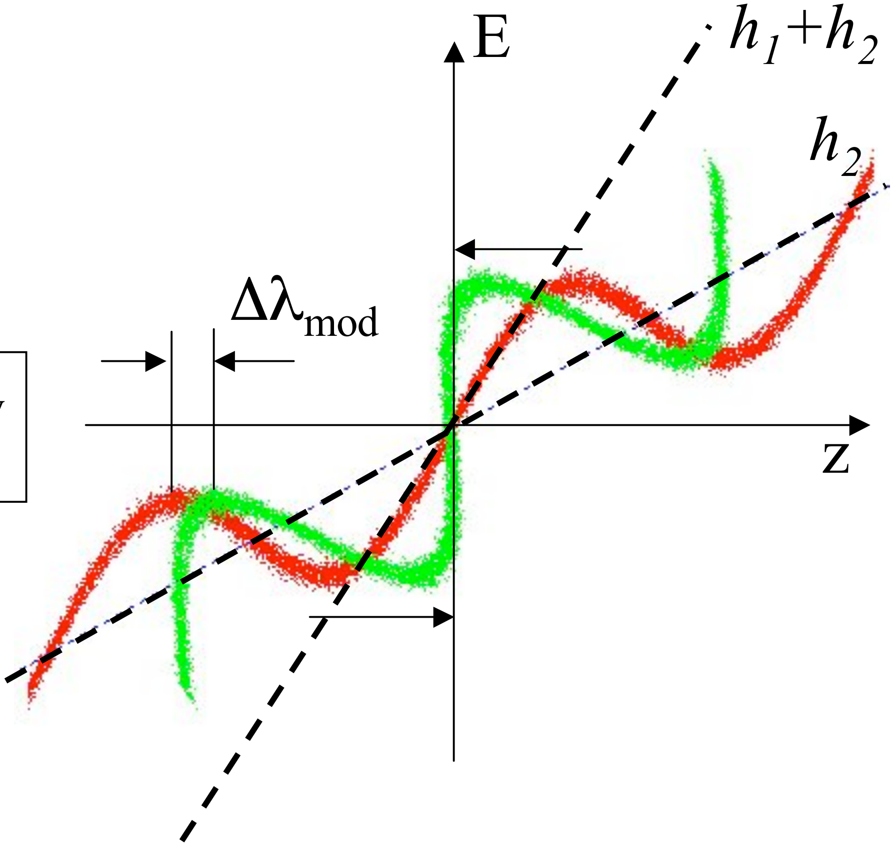
Compression of modulated bunch

- Compression of modulation wavelength ($h_1 >> h_2$):

$$\frac{\Delta\lambda_{\text{mod}}}{\lambda_{\text{mod}}} \approx \frac{h_2}{h_1} = \frac{\lambda_{\text{mod}}}{\lambda_{RF}} \cdot \frac{\Delta E_{chirp}}{\Delta E_{\text{mod}}} \rightarrow$$

$$\rightarrow \quad \frac{\Delta\lambda_{\text{mod}}}{\lambda_{\text{mod}}} \approx \underbrace{\boxed{\frac{\lambda_{\text{mod}}}{\sigma_z}}}_{\text{fixed}} \cdot \frac{\Delta E_{beam}}{\Delta E_{\text{mod}}}$$

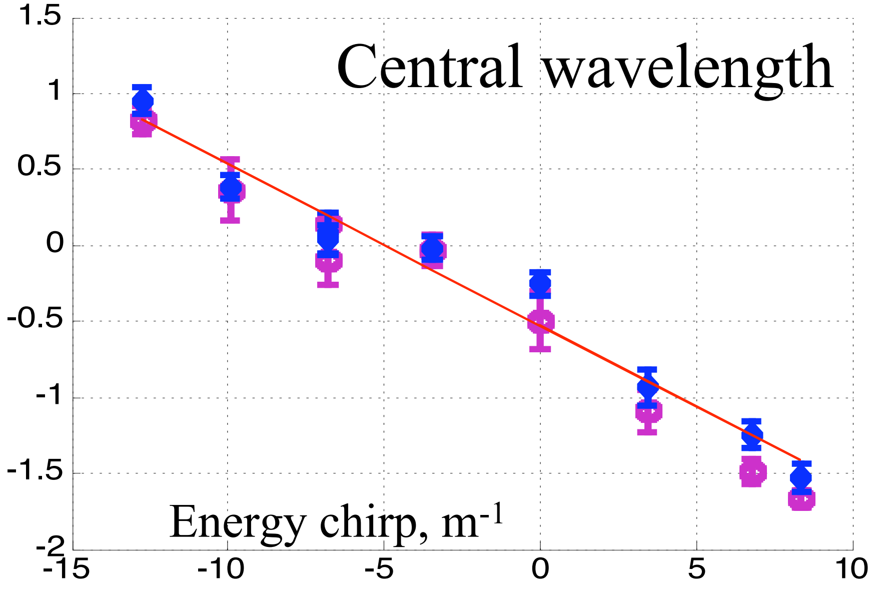
↓, >energy spread

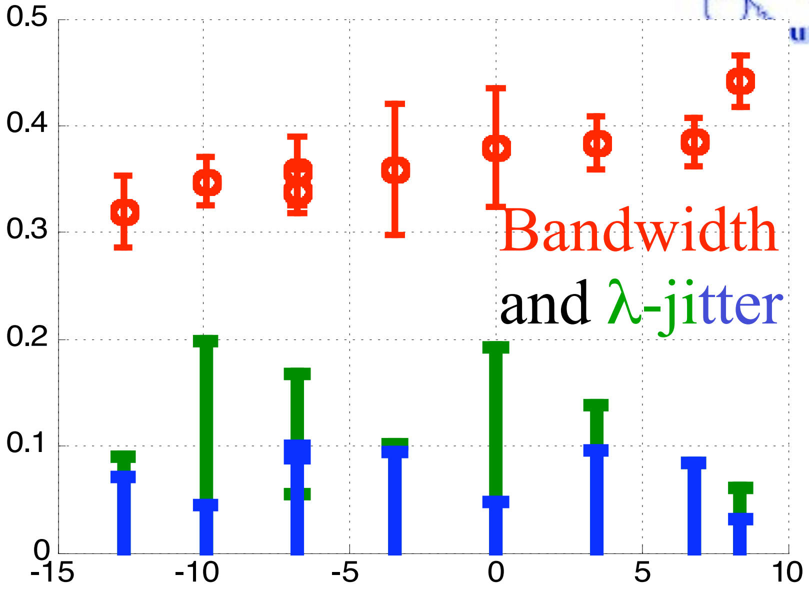


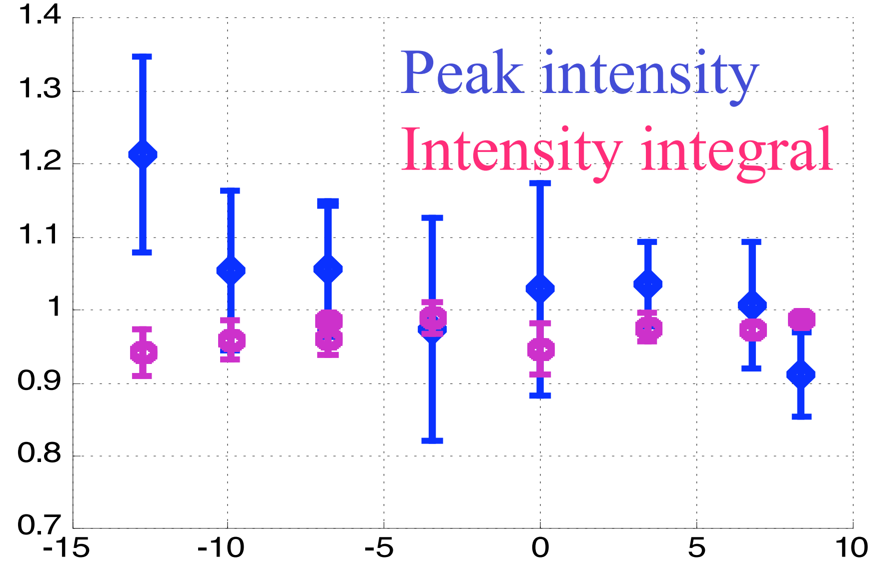
- ΔE_{beam} is determined by RF system (f.e., post-compressed chirp can be used)
- ΔE_{beam} is limited by the FEL dynamics: **how does chirp affect the FEL output?**

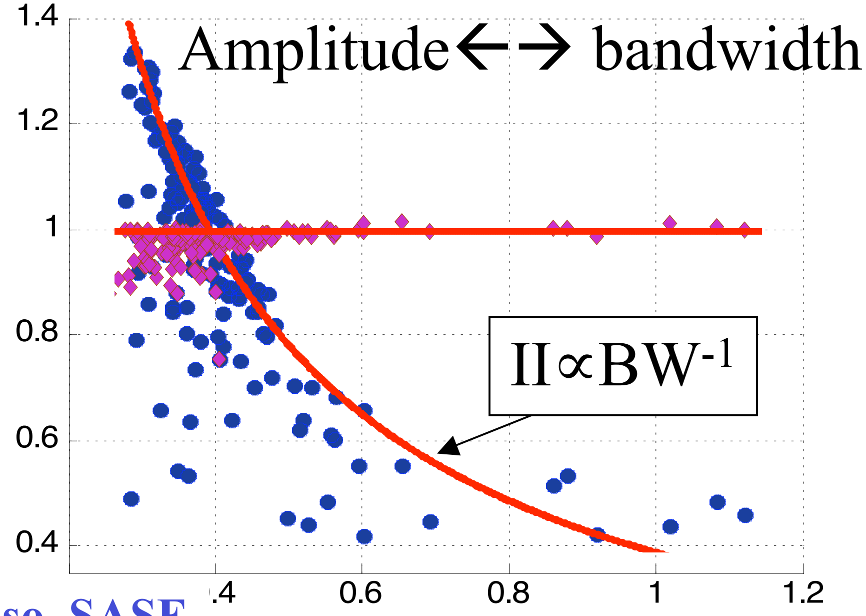
T. Shaftan and L.H. Yu, PRE-2005

How does energy chirp affect output radiation?



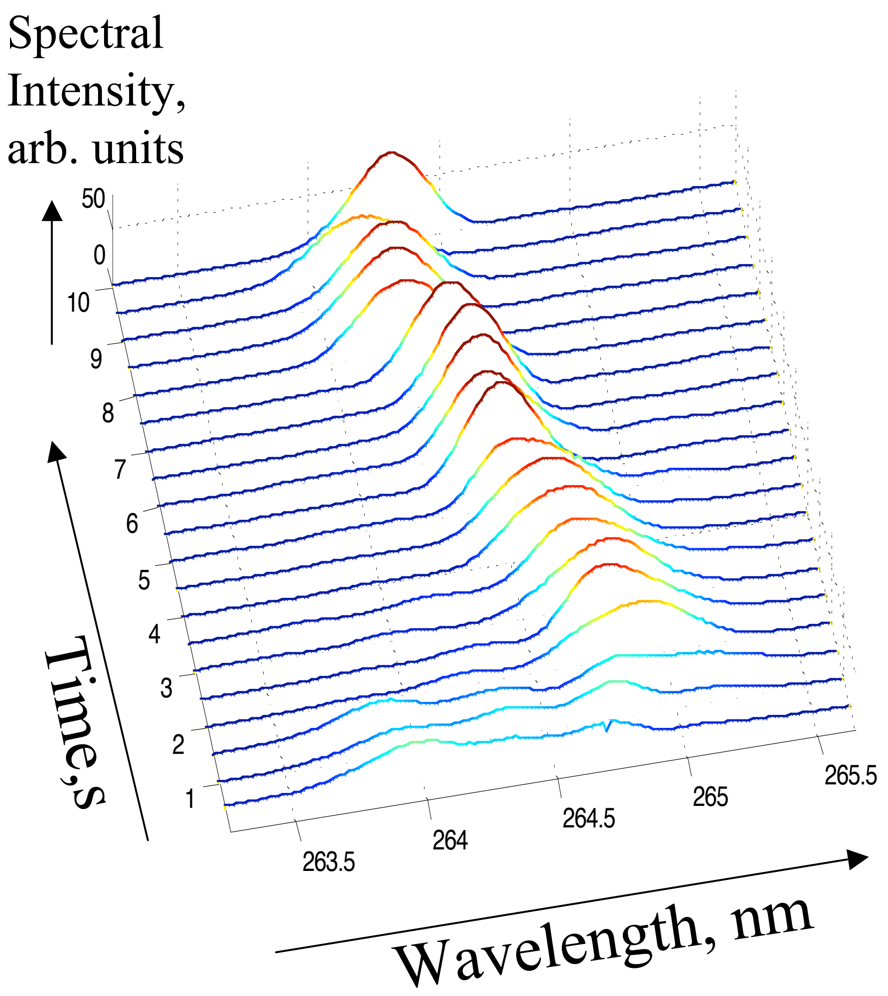




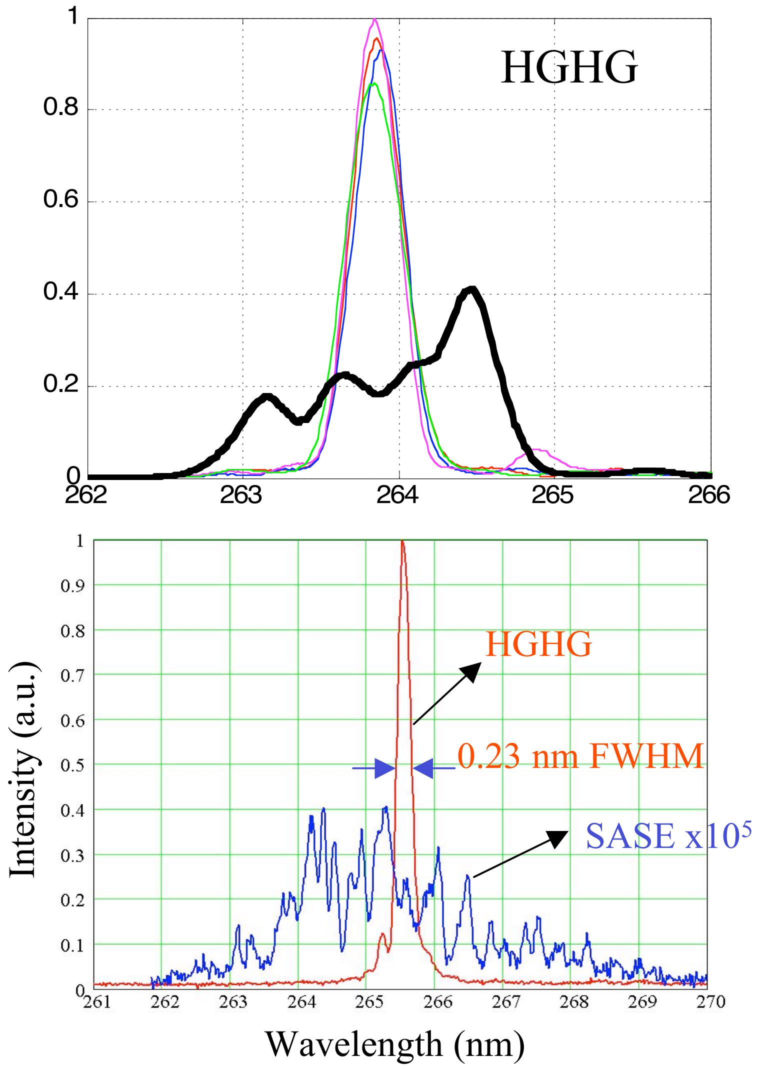


DUV-FEL experiments, in Proc. of FEL-2005; Also, SASE from chirped e-beam: G. Andonian et al., in PRL-2005

Trends in HGHG spectrum



Long-term (~10 s) wavelength drift due to accelerator-laser drifts



HGHG and SASE spectra

What may modulation content in electron beam look like?

- Symptoms: broadening of spectrum, reduction of peak intensity; loss of longitudinal coherence
- Trajectory/beam size are stable →

→ longitudinal effect

- Diagnosis: Detuning due to drive laser – RF phase drift

→ charge ↓

◊ compression ↓

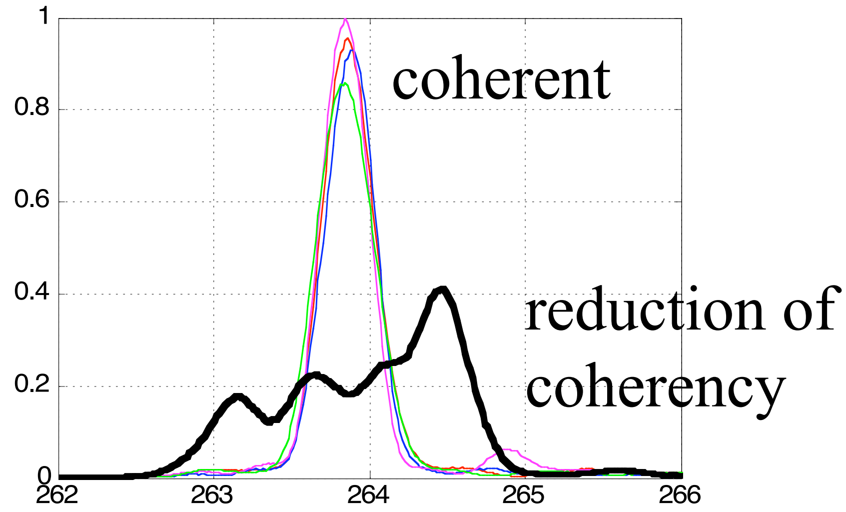
◊ → peak current ↓

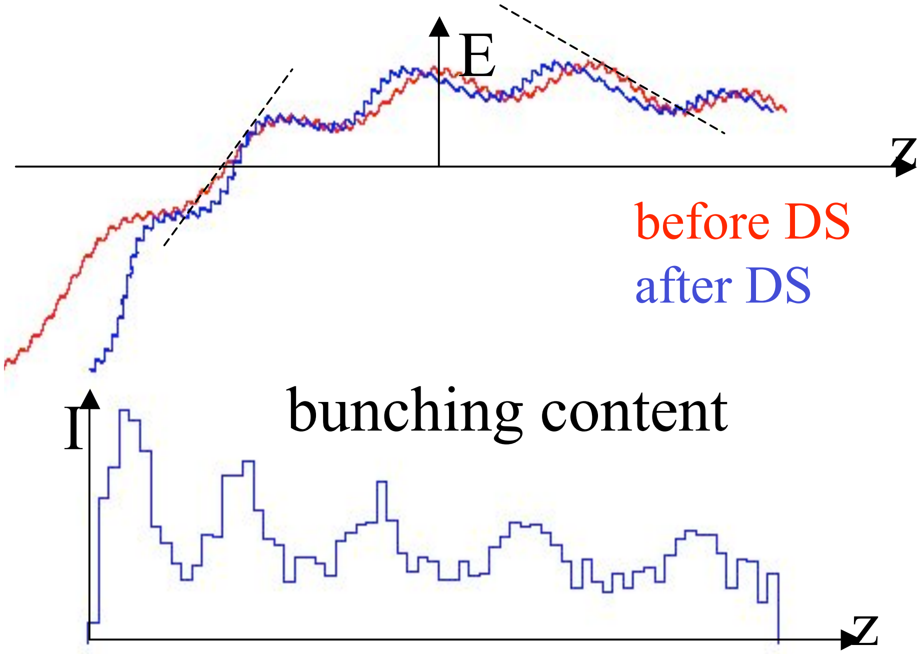
◊ energy ↓

◊ → FEL gain ↓

- saturation comes later in the radiator
- local chirp varies →can create modulation of peak current along the bunch

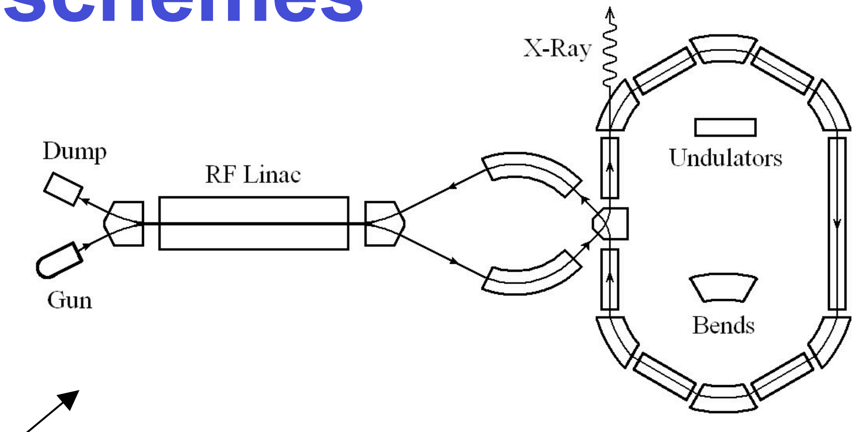
- this will affect FEL output spectrum

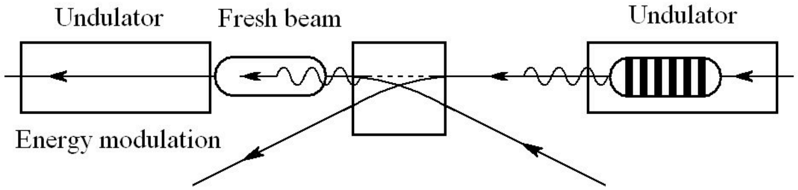


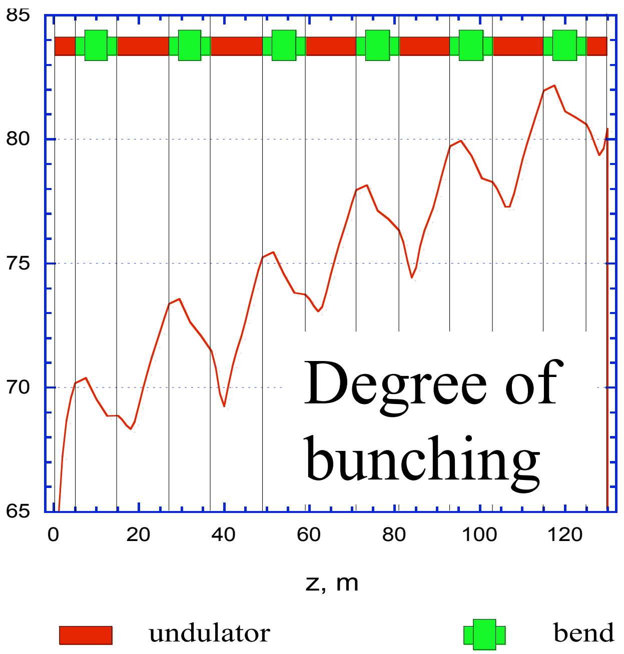


Self-seeded tunable FEL schemes

- Self-seeding schemes: Pellegrini et al., Saldin et al., S. Biedron et al.,
- Quasi-isochronous SR: D.A.G. Deacon (~1980)
- From: A. Matveenko, O. Shevchenko and N.A. Vinokurov, in FEL-2004 → wavelength of 50 nm
- Effect of quantum fluctuations of SR on microbunched beam transport is a limiting factor (V. Litvinenko, see also Optics-free FEL Oscillator in FEL Prize Talk, 2005, Å-scale feedback)
- Emittance, energy spread are limiting factors



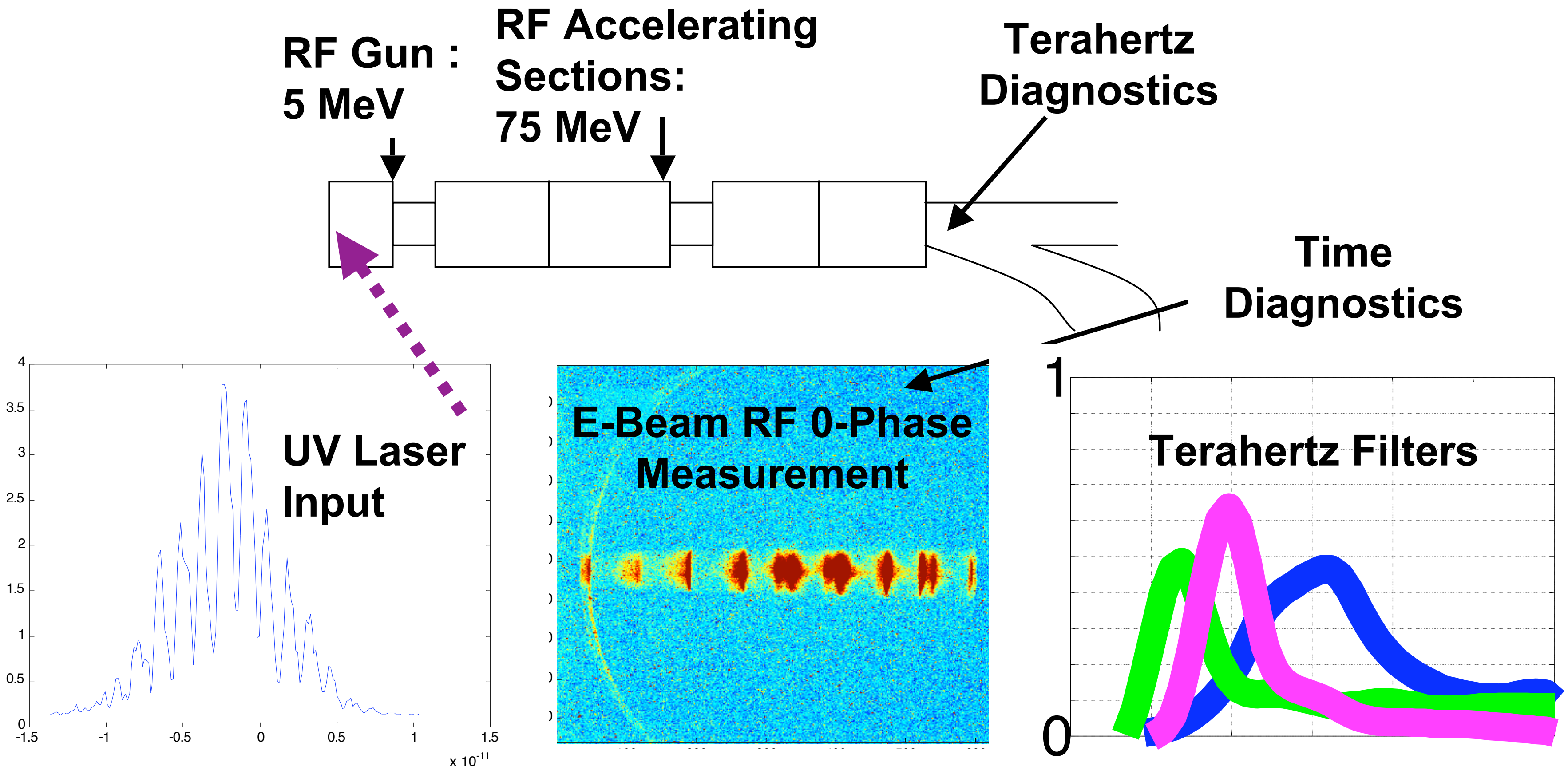




Electron Beam Premodulation at the Photocathode

Courtesy of J. Neumann

The Source Development Laboratory at
Brookhaven National Laboratory



RF Gun :
5 MeV

RF Accelerating Sections:
75 MeV

Terahertz Diagnostics

Time Diagnostics

UV Laser Input

E-Beam RF 0-Phase Measurement

Terahertz Filters

Limitations on tunability range: drive laser bandwidth and LSC

This work was carried out with the support of the U.S. Department of Energy, Division of Materials Sciences and Division of Chemical Sciences, under Contract No. DE-AC02-98CH10886, in addition to the Joint Technology Office, Army Research Laboratory and Office of Naval Research.

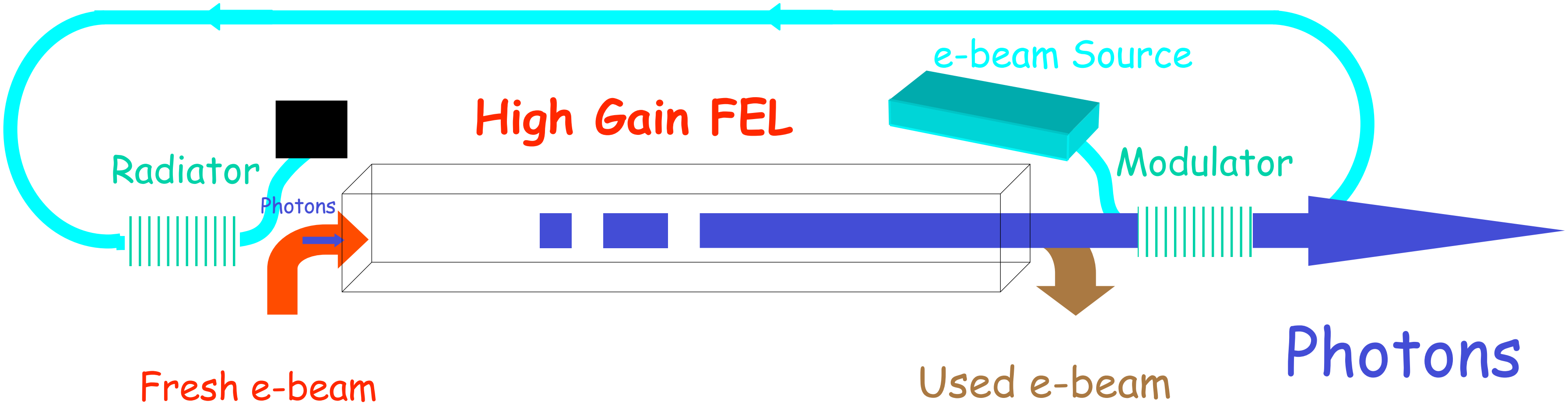
Conclusions

- Modulated beams in high-energy machines are rich and diverse phenomena
- There are harmful collective effects and effective cures for them
  - Landau damping, laser-heater
  - Elimination of noise sources that seed the effects
  - Irreproducibility and unpredictable time patterns of their appearance
  - Need for fast and reliable diagnostics on micro-scale
- Useful modulation in radiation sources
  - Seeding and chirping of high-brightness bunch
  - Tuning modulation wavelength
  - Premodulation at photocathode for THz production
  - Tunable self-seeded schemes

T. Watanabe, Superradiance in a single-pass seeded FEL, Thursday, WG-3

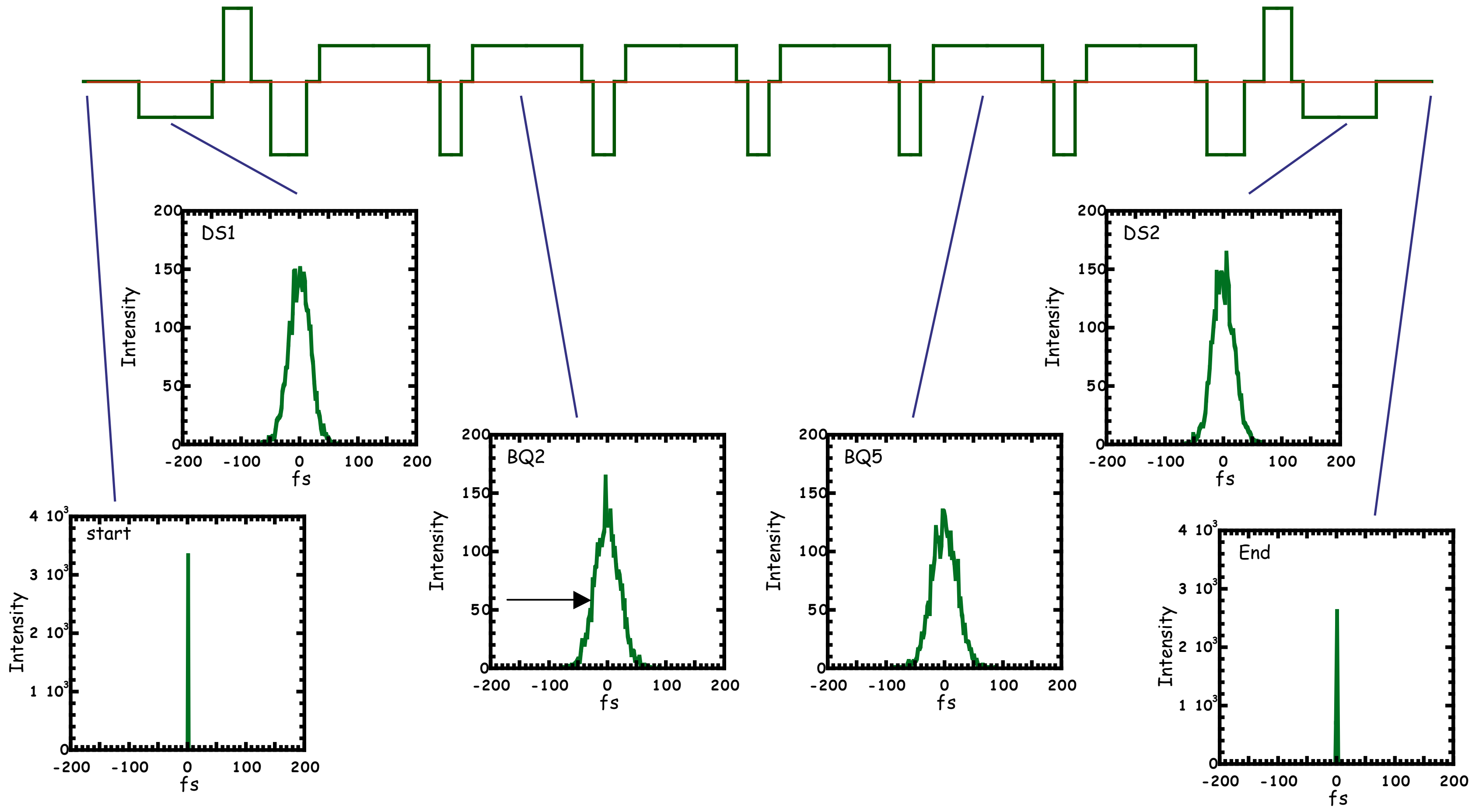
Å-scale Feed-back

- Use lower energy low current e-beam with VERY LOW emittance and low energy spread for the feed-back
- The feed-back-beam is energy-modulated and carries-on the modulation to the entrance of the FEL



Courtesy of V. Litvinenko, BNL

Isochronous THz ring: preserving bunch form



Tracking Result of Hamilton Equation in Curvilinear System

Courtesy of H. Hama, Tohoku University