Mitigating a Large Energy Spread in LPA-driven FEL w/FEL Beam Conditioning

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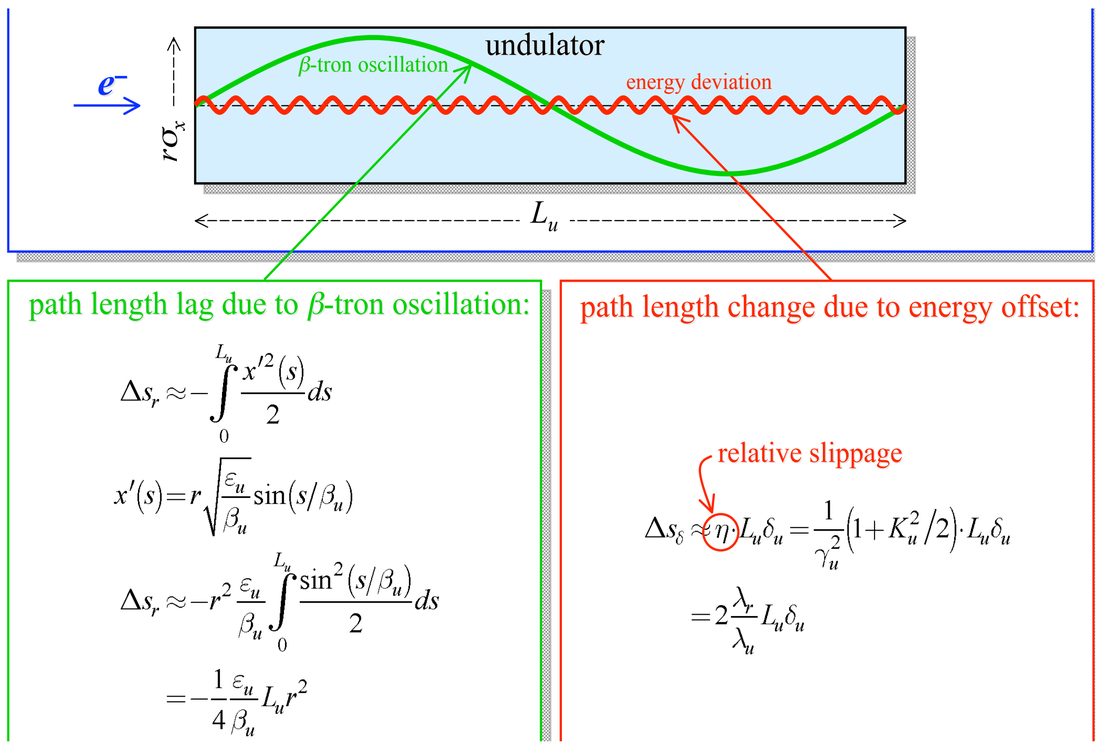
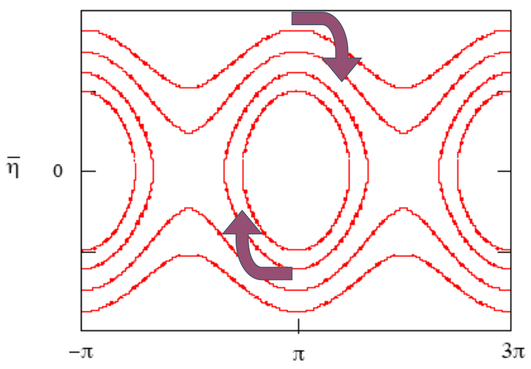
The concept of FEL beam conditioning was proposed* in early 90s, as a method to mitigate excessive (at the time) beam emittances in FEL. In its essence, within the ideally conditioned beam, the off-axis electrons undergo larger betatron oscillations should also be faster, and thus on average phase-matched to the slower on-axis electrons, resulting in an overall FEL gain improvement. Today, the much improved beam emittances from photoinjectors are less of a limiting factor for FELs, whereas the ascent of LPAs introduced a new need – to mitigate excessive energy spreads.

Thus we propose to readopt the FEL beam conditioning for LPA FEL energy spread mitigation. To improve gain, we use the chromatic aberrations in the focusing channel after the plasma exit to induce a transverse distribution at the FEL entrance, dispersing faster electrons further away from the axis, and slower electrons closer to the axis. Here we show the initial results of the FEL dynamics studies in the context of the upcoming BELLA LPA-FEL experiment at LBNL using VISA 4-meter undulator.

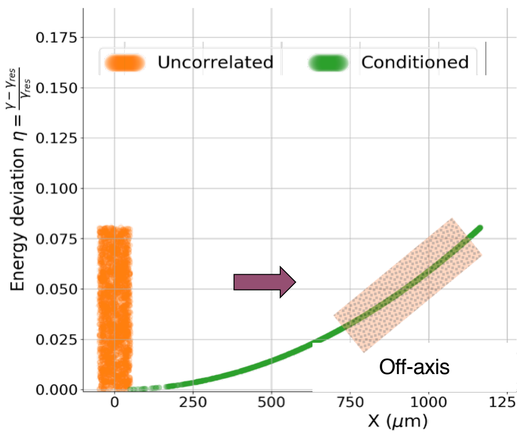
*A. M. Sessler, D. H. Whittum, and L.-H. Yu, "Radio-frequency beam conditioner for fast-wave free-electron generators of coherent radiation," PRL **68**(3), 309–312 (1992).

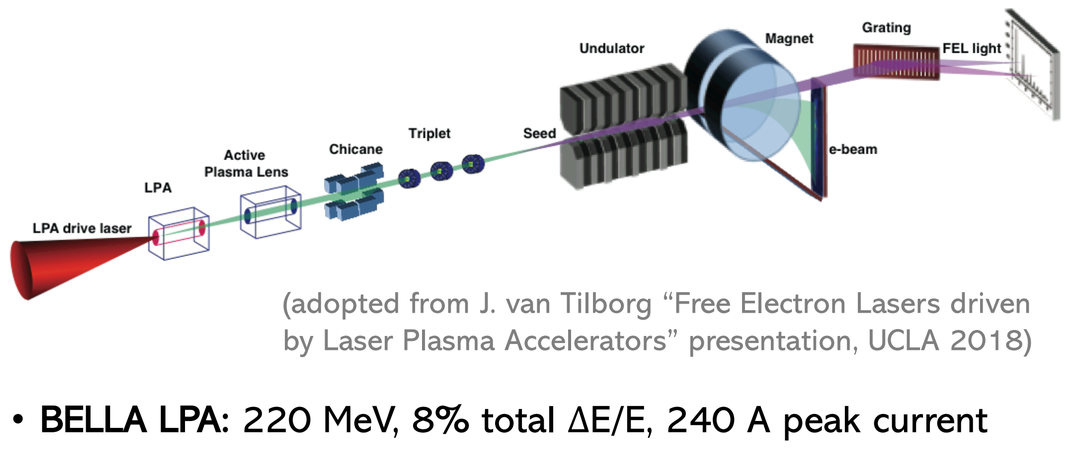


(graphics copied from P. Emma and G. Stupakov presentation "Limitations of Electron Beam Conditioning in Free-Electron Lasers", SLAC 2003)



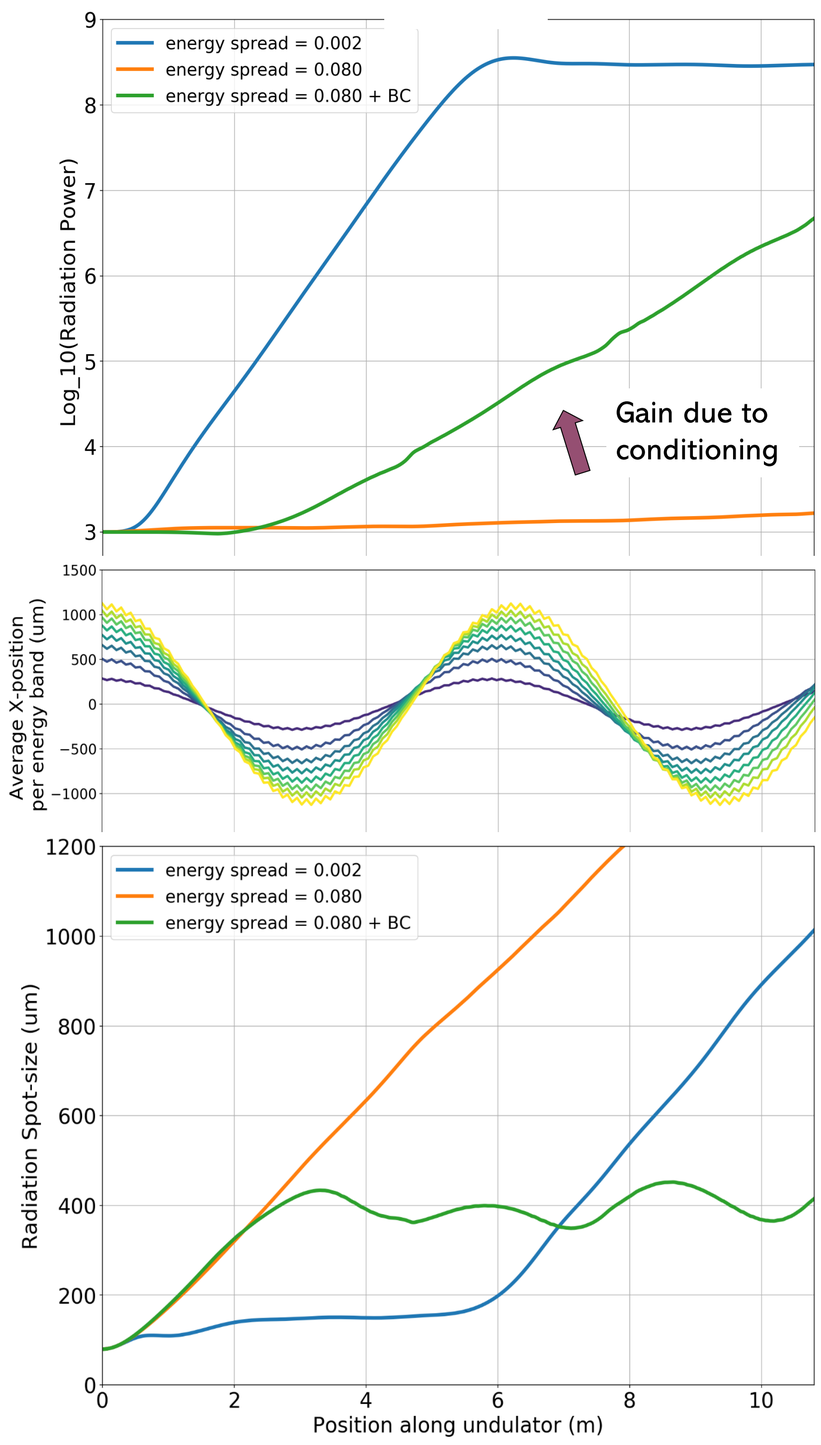
- Large energy spread beam does not lase, since most electrons are not trapped in the ponderomotive bucket
- Beam conditioning forces electrons in the energy tails to remain on average in phase with the centroid electrons, thus reducing gain degradation due to energy spread
- However, the direct conditioning makes e-beam transversely too big (equivalent of a very large emittance), which is also deteriorating for FEL gain
- To find the compromise we have to launch the beam off-axis (quadratic dependence enables to pack larger energy spread into smaller transverse envelope off axis)
- The balancing factor is gain guiding (large centroid betatron oscillations are detrimental to radiation coupling).





(adopted from J. van Tilborg "Free Electron Lasers driven by Laser Plasma Accelerators" presentation, UCLA 2018)

- **BELLA LPA:** 220 MeV, 8% total ΔE/E, 240 A peak current
- **VISA undulator:** 1.8-cm period, strong focusing, 4 m long
- deep UV FEL (90 nm); BELLA plans to achieve FEL gain is by inducing strong chirp thus reducing sliced energy spread at the expense of peak current
- we tried Genesis simulations of the conditioning approach:



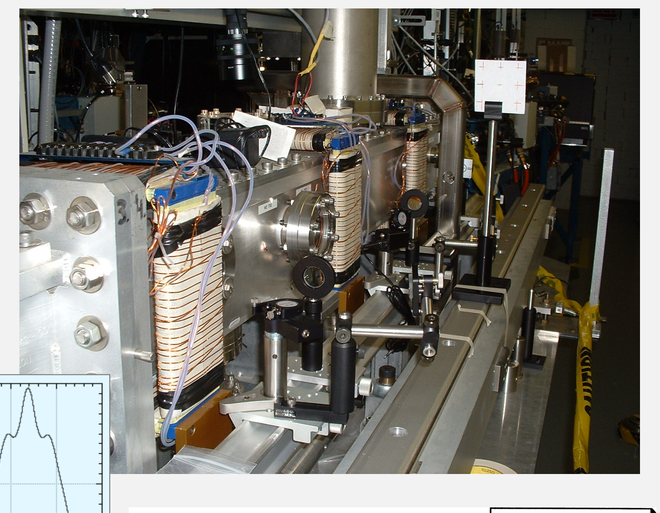
- We hypothesize that an off-axis launched and partially conditioned beam may result in a higher FEL gain in an off-axis radiation mode, and here is some evidence to that from the past.

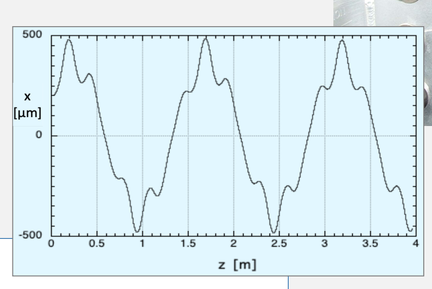
Good old VISA FEL experiment at ~ 800 nm (2001)

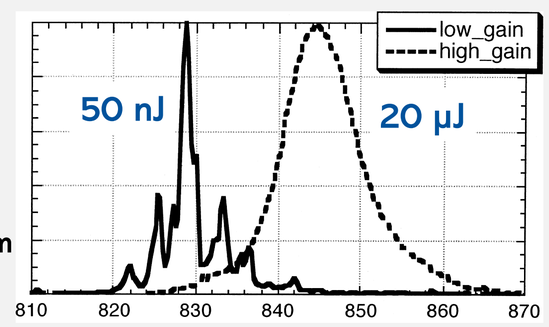
- driven by 72 MeV e-beam at ATF BNL
- achieved saturation in 3.6 m using non-linear compression in dog leg (peak current ~ 300 A)

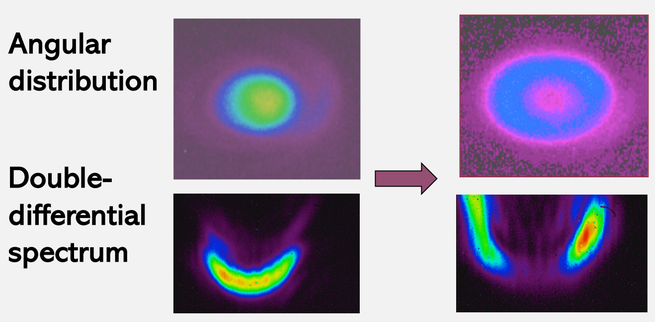
The empirically discovered non-linear compression was associated with:

1. large energy spread (~ 1 %);
2. very high gain (Lg ~ 17 cm), saturation;
3. annular radiation mode;
4. a significant trajectory offset.









Conclusions:

- ✓ The FEL beam conditioning (BC) offers a potential path (one of many, i.e. TGA) to mitigate high energy spread in LPA driven FEL
- ✓ The initial simulations using BELLA FEL parameters supports the concept
- ✓ There is also an empirical evidence from the old VISA data, indicating unintentional BC regime
- ✓ A much more thorough simulations on FEL dynamics and beam transport are needed to explore BC concept beyond this study.