Laser Assisted Bunch Compression for High Energy X-ray Free Electron Lasers

by Petr M. Anisimov, Quinn R. Marksteiner, River R. Robles, John Lewellen, Nikolai A. Yampolsky and Bruce E. Carlsten

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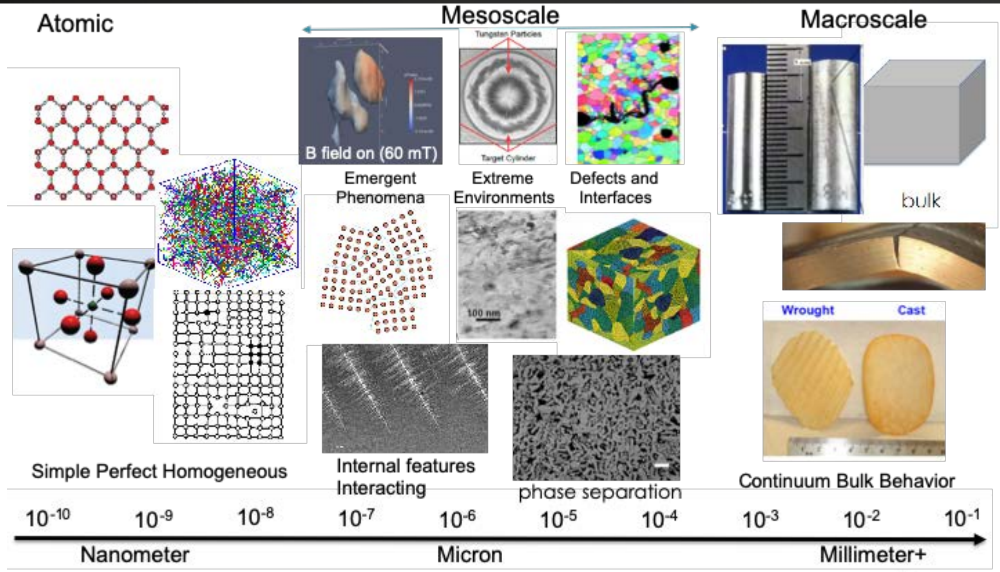
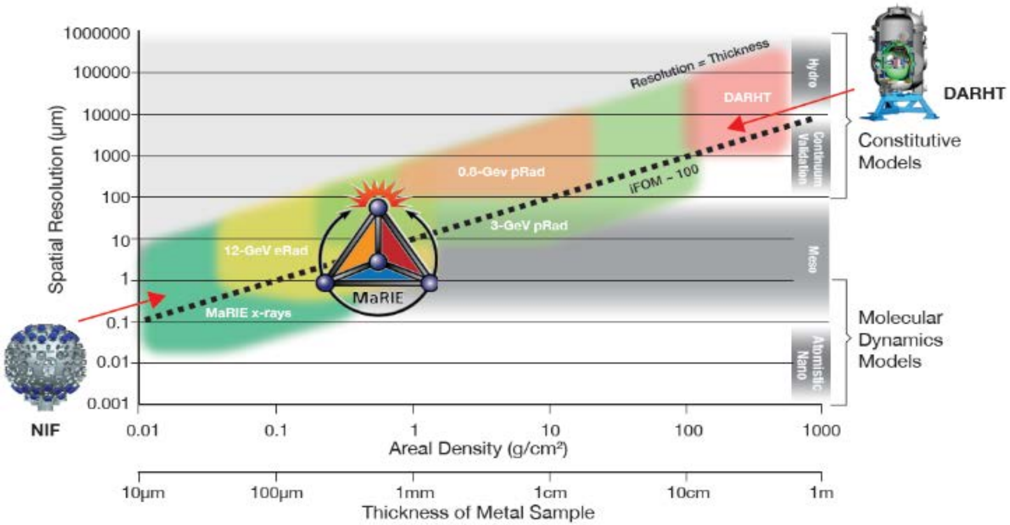
National Nuclear Security Administration

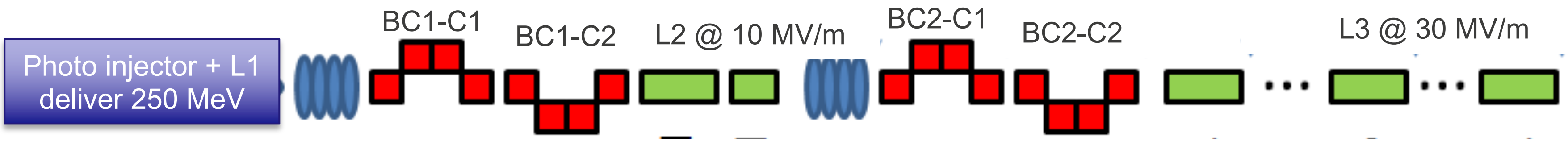


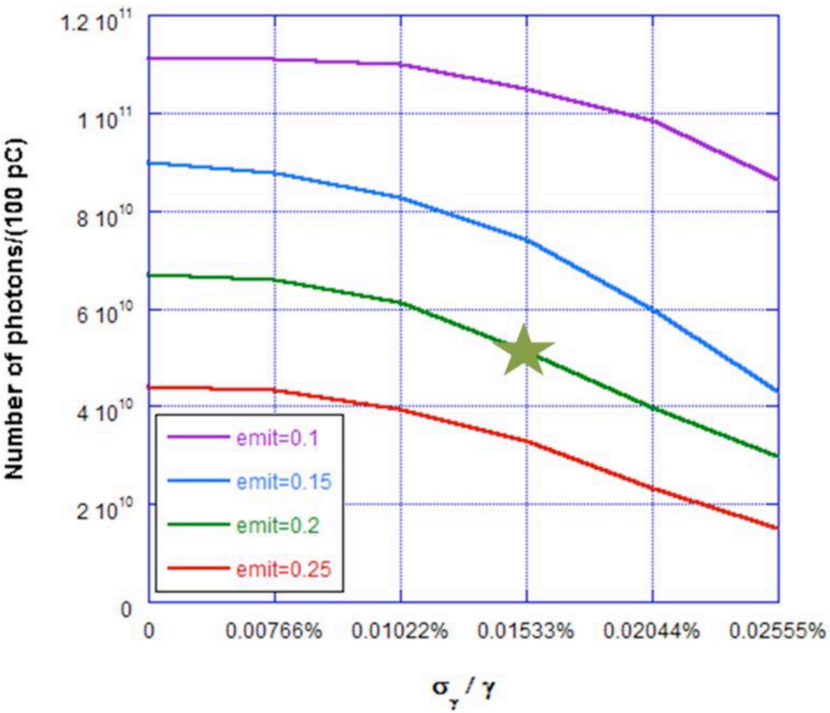


Dynamic Mesoscale Materials Science Capability (DMMSC)

- Los Alamos National Laboratory leads the effort to design a solution for DMMSC;
- A DMMSC seeks to probe inside multigranular samples of condensed matter;
- Researchers at LANL have scoped out a potential XFEL for this mission, known as the Matter-Radiation Interactions in Extremes (MaRIE) XFEL.

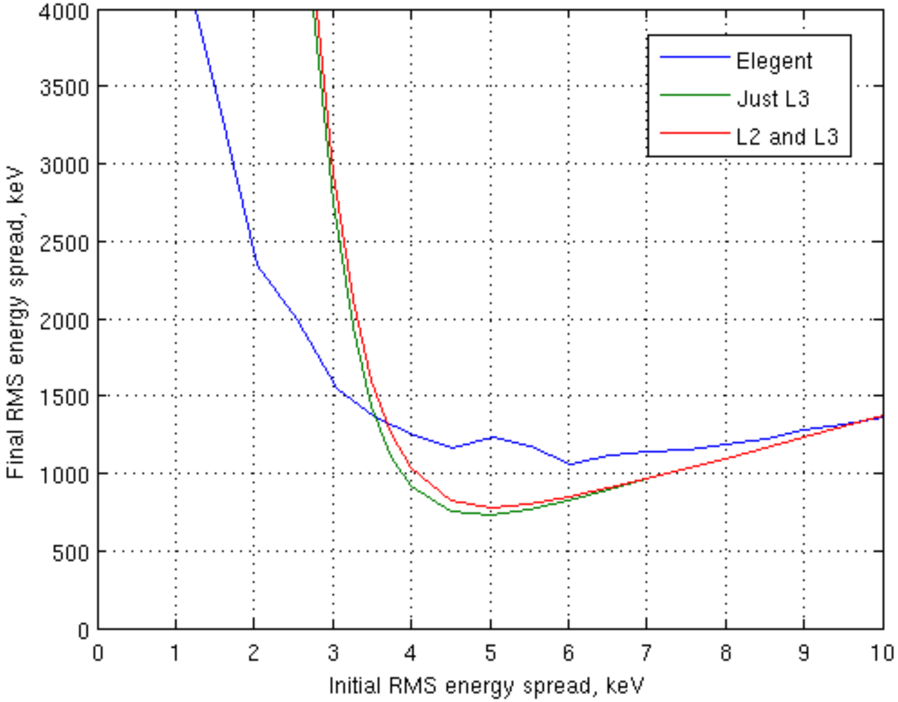
Matter-Radiation Interactions in Extremes XFEL Concept





- Existing MaRIE design is based on 2 bunch compressors at 250 MeV and 1 GeV in order to reach 3 kA current;
- It uses 12 GeV electron beam to produce ~5x10^{10} 42+ keV photons;
- For this to XFEL concept to work one would need
  ~0.2 µm normalized emittance,
  ~1.5x10^{-4} relative energy spread and
  ~ 14 A current from the source.

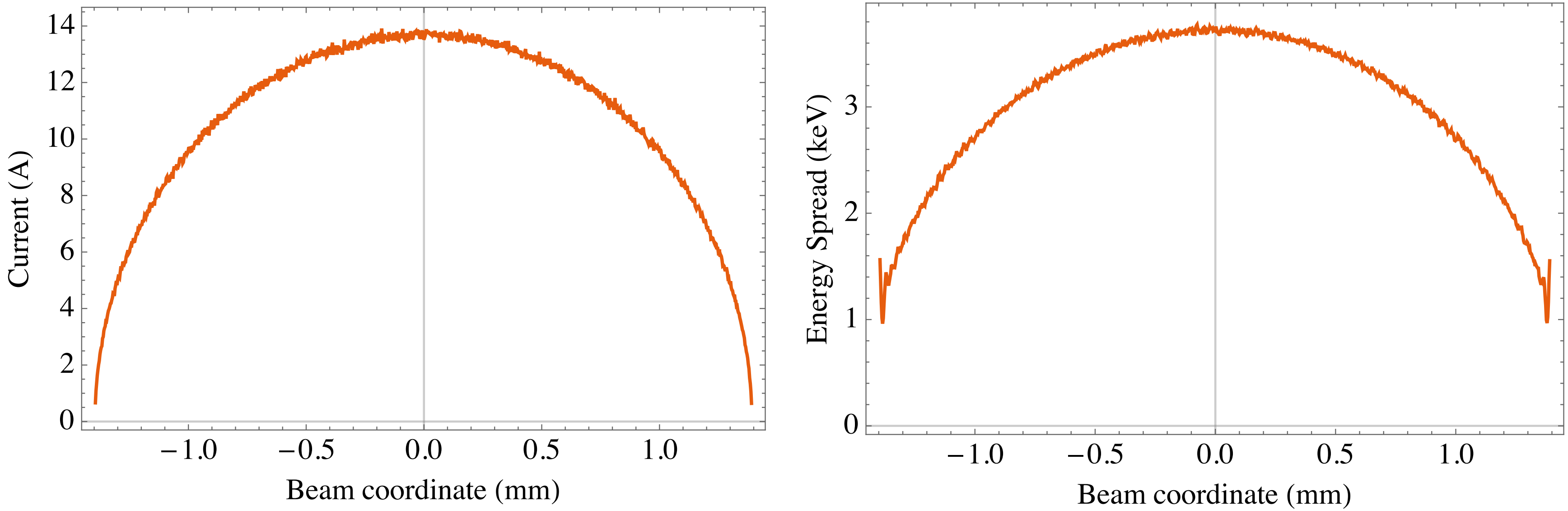
Optimal Laser Heater Energy for Suppression



- Elegant simulations agree well with optimal laser heater energy predicted by theory.
- Minimum energy spread is somewhat greater in Elegant simulations – this is likely due to extra physics effects (ISR, CSR, changing transverse beam size) that cannot be easily separated from microbunching.

Microbunching instability analysis by Quinn Marksteiner and Nikolai Yampolsky

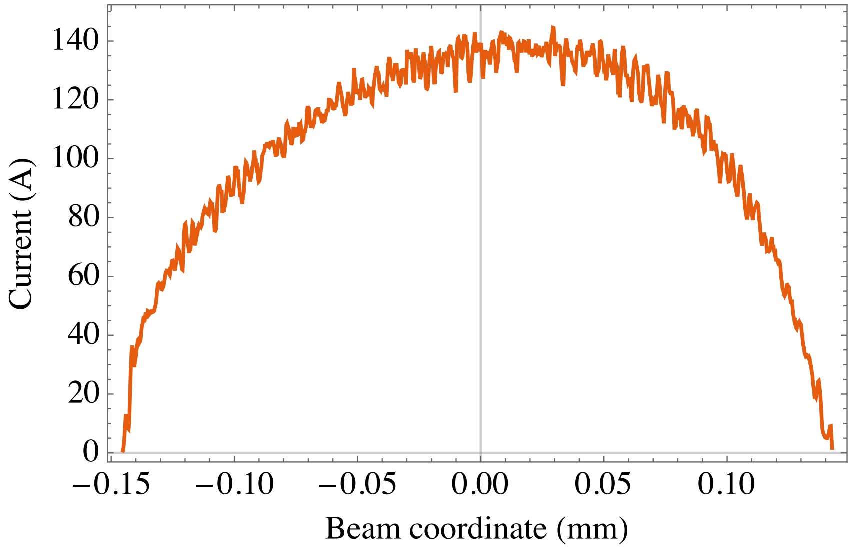
Idealized Model with 4 keV Heater

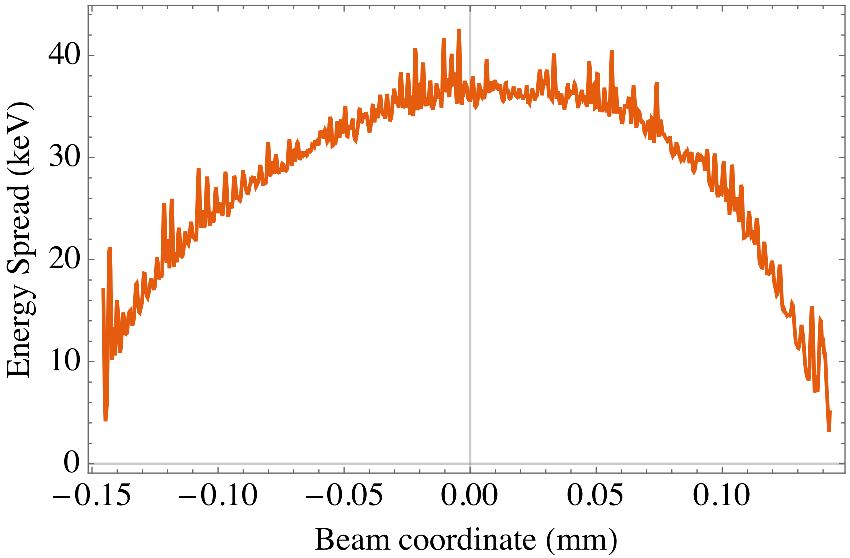


Superconducting L-band RF LINAC analysis by John Lewellen

Idealized Model with 4 keV Heater

We compress by 10x in S-shape chicane.
A 1keV cold beam starts its degradation at this stage.

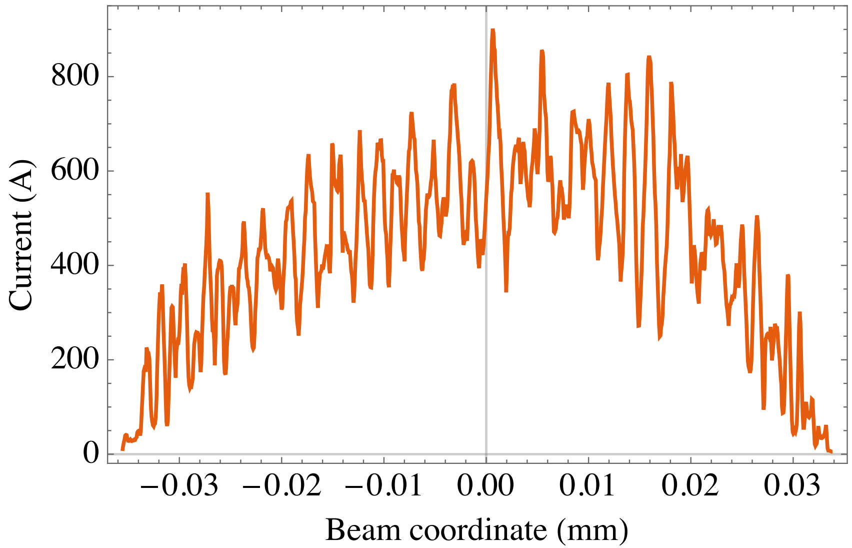


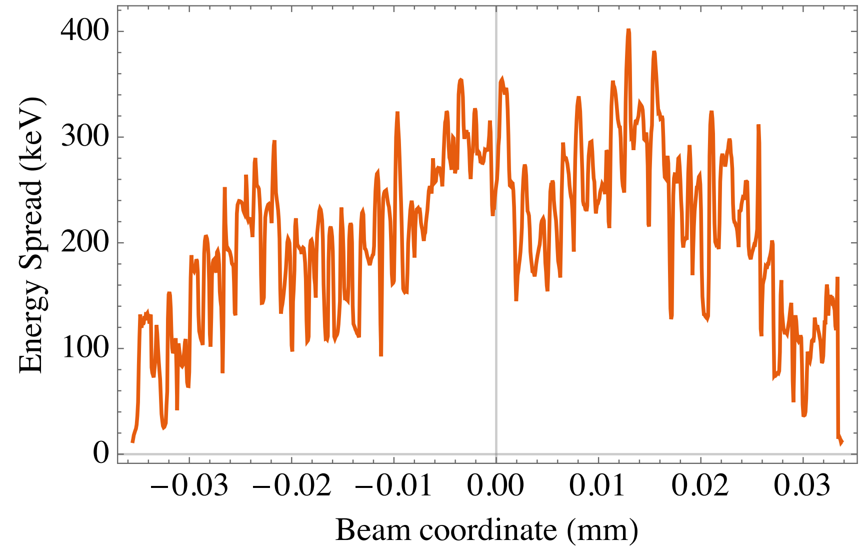


Superconducting RF LINAC analysis by John Lewellen

Idealized Model with 4 keV Heater

After off-crest acceleration in L2, BC2-C1 compresses by about 5x.
This is a half way point in S-shaped chicane where even warm beam degrades.



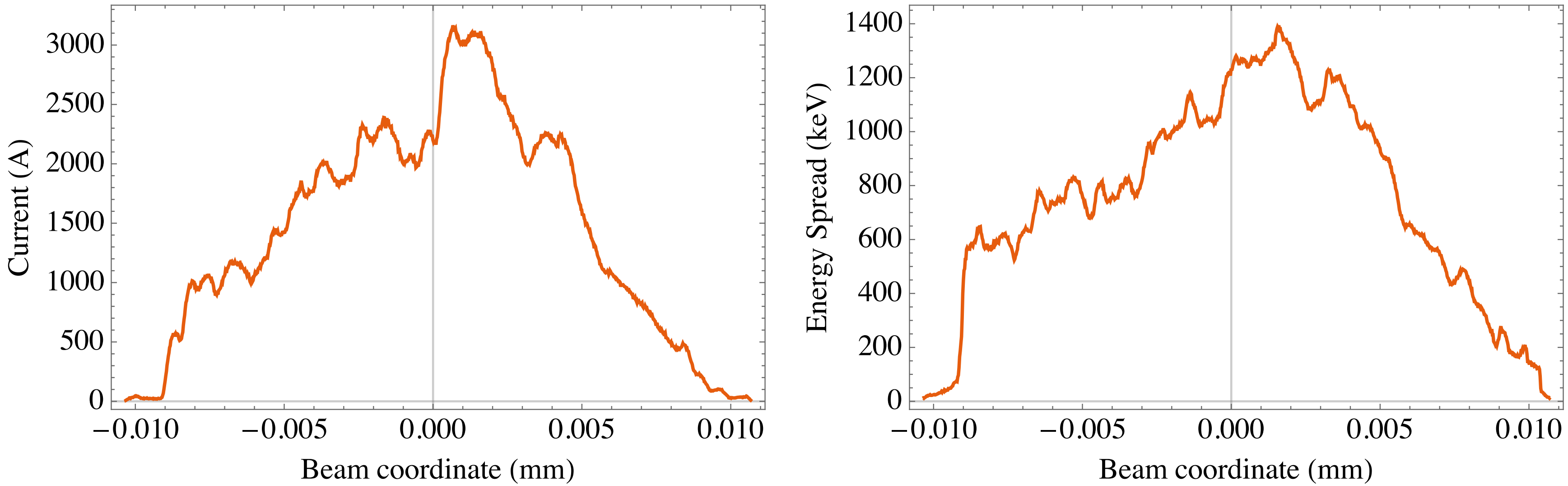


Off-crest acceleration is inefficient but necessary to provide a large chirp for low R56 compression.

Superconducting RF LINAC analysis by John Lewellen

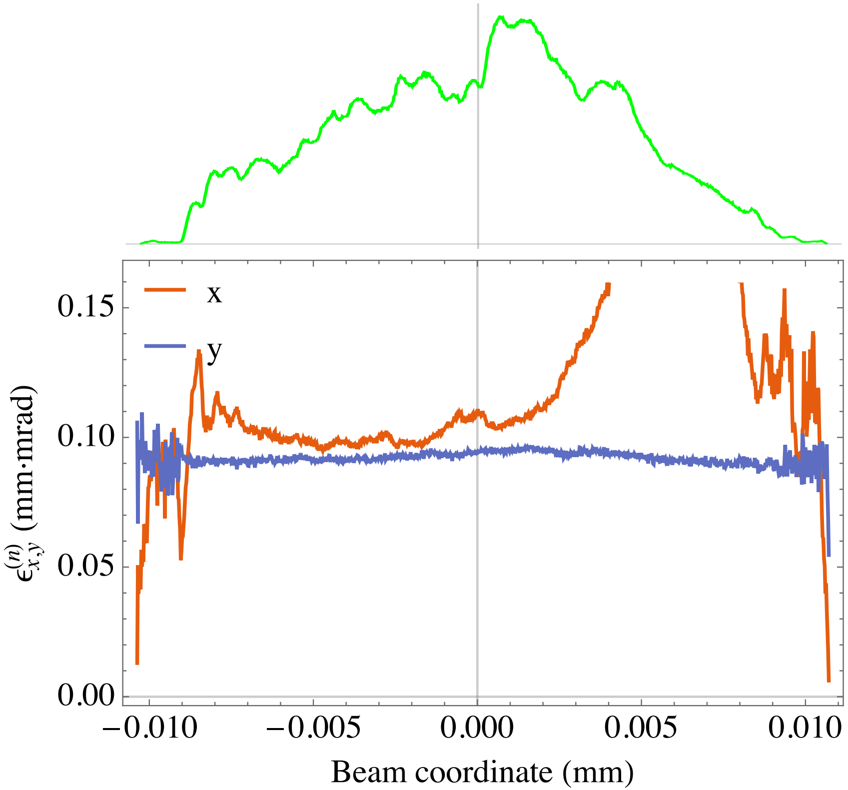
Idealized Model with 4 keV Heater

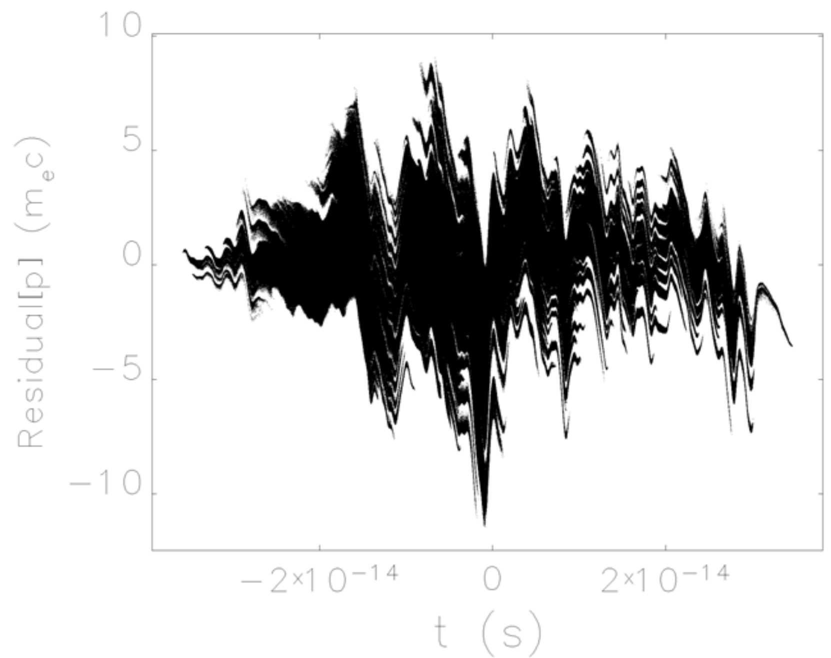
After BC2-C2 compression by about 4x and acceleration to 12 GeV.



Superconducting RF LINAc analysis by John Lewellen

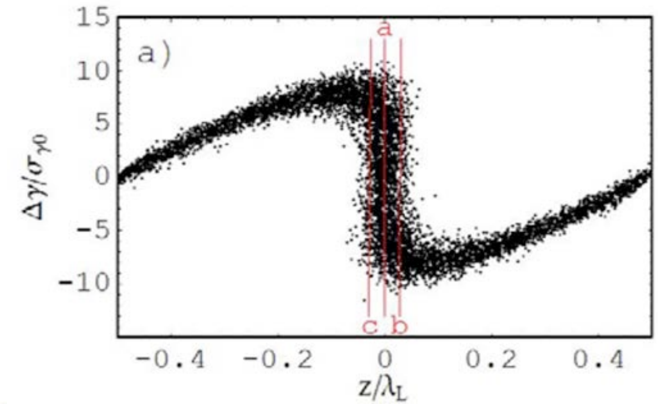
Final Results of the Idealized Model with 4 keV Heater



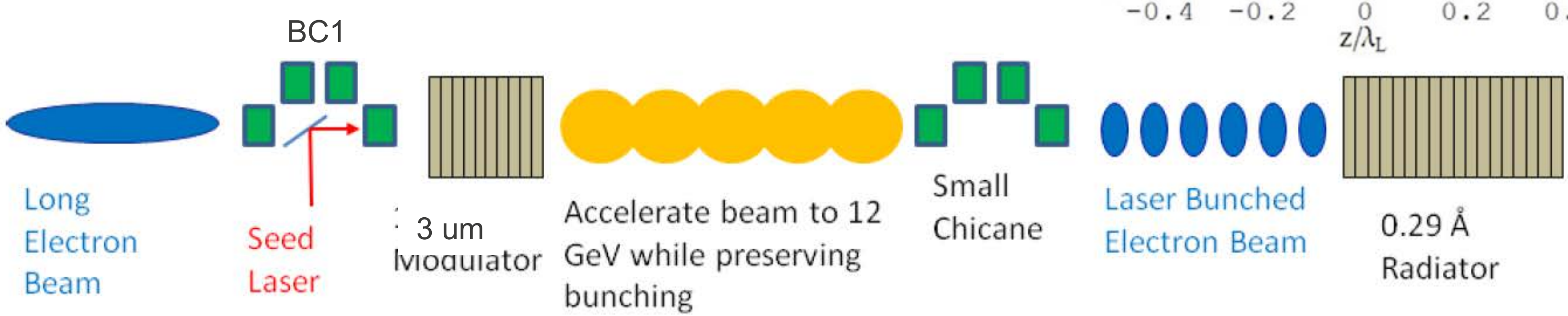


Superconducting RF LINAC analysis by John Lewellen

Alternative Design Inspired by eSASE

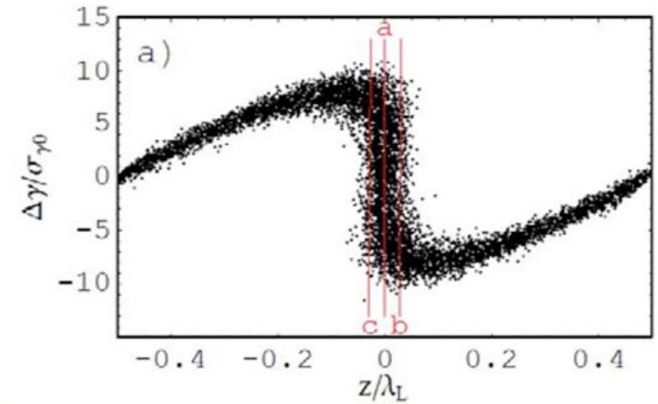


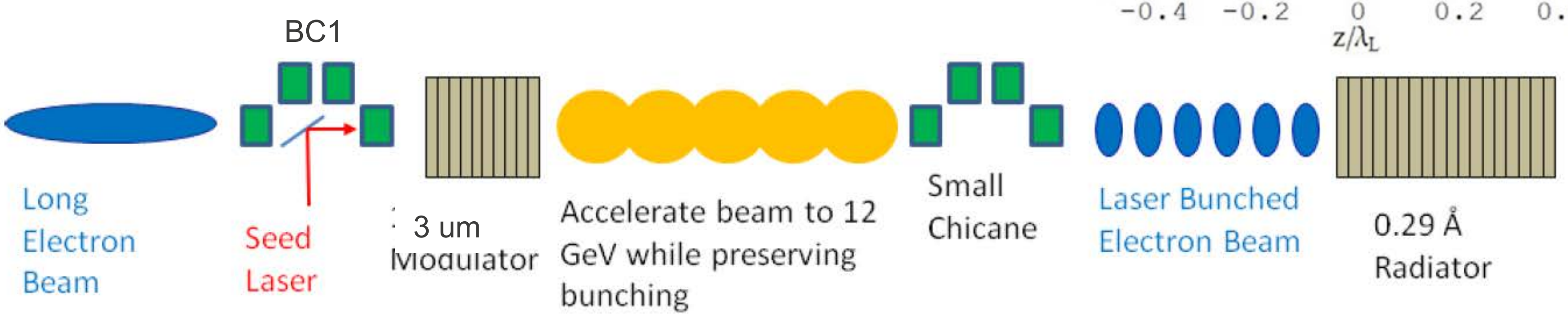
- eSASE, enhanced Self-Amplified Spontaneous Emission, was proposed by Alexander A. Zholents in Phys. Rev. ST Accel. Beams **8,** 040701 (2005);



- In our design, we use eSASE to eliminate the second bunch compressor. Our final current however is the same current as before, 3 kA;
- We end up with a train of electron bunches instead of a single bunch.

Alternative Design Inspired by eSASE





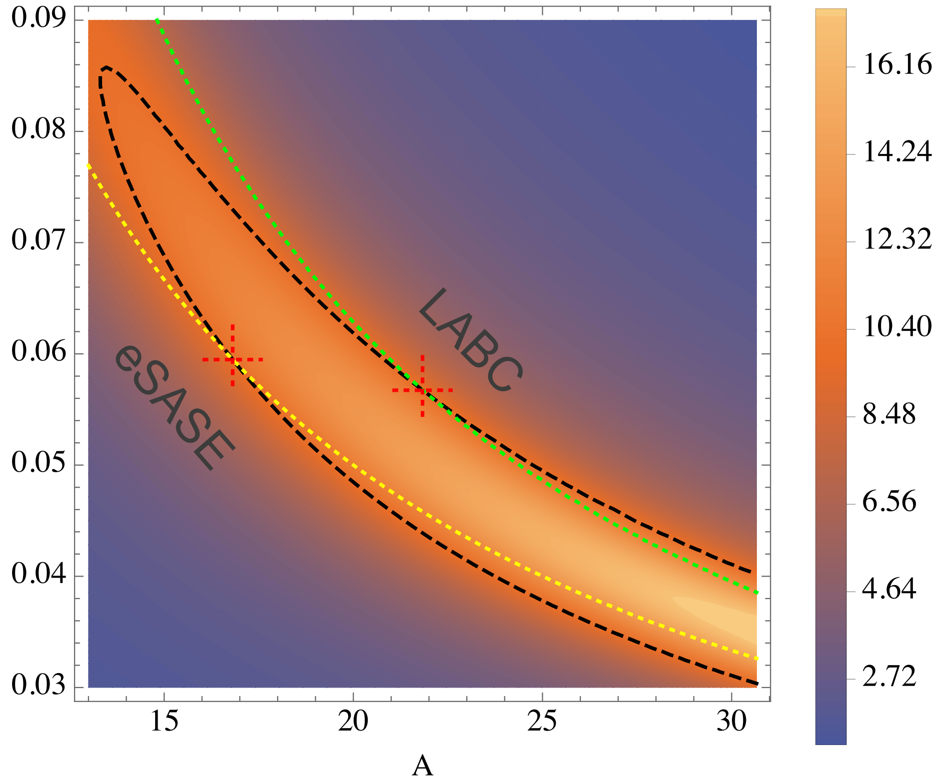
- Two dimensionless parameters characterize the lase assisted compression:
  - $A = \Delta\gamma_L / \sigma_\gamma$ defines modulator requirements;
  - $B = R_{56} k_L \sigma_\gamma / \gamma$ defines requirements for the chicane.

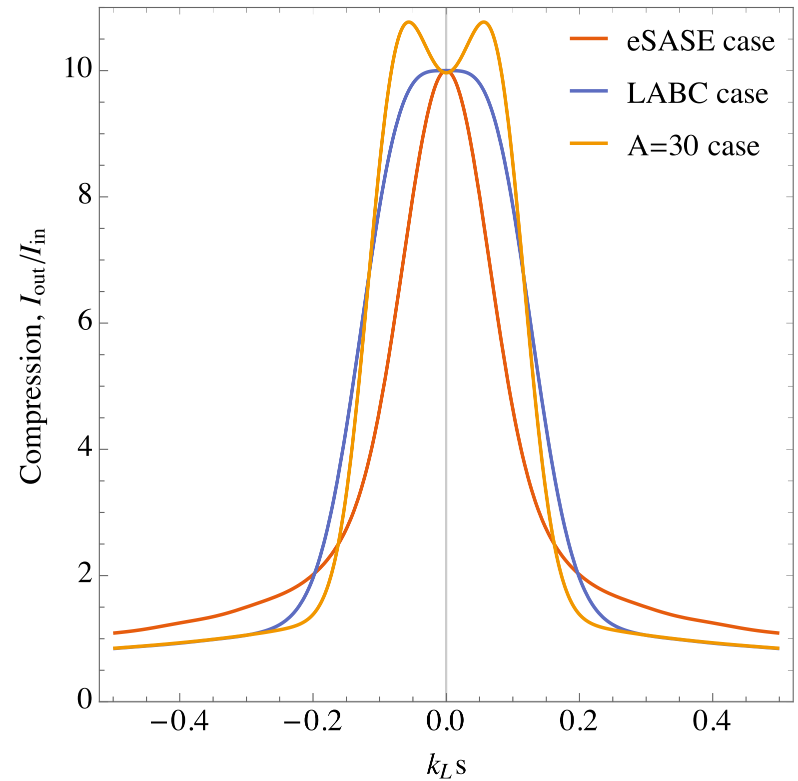
here $\Delta\gamma_L = \sqrt{\frac{P_L}{P_A} \frac{2KL_u JJ}{\gamma\, w_0}}$ is the laser induced energy modulation, where $P_A = 8.7\ GW$

Laser Assisted Bunch Compression (LABC) scheme

Black dashed line is 10x compression

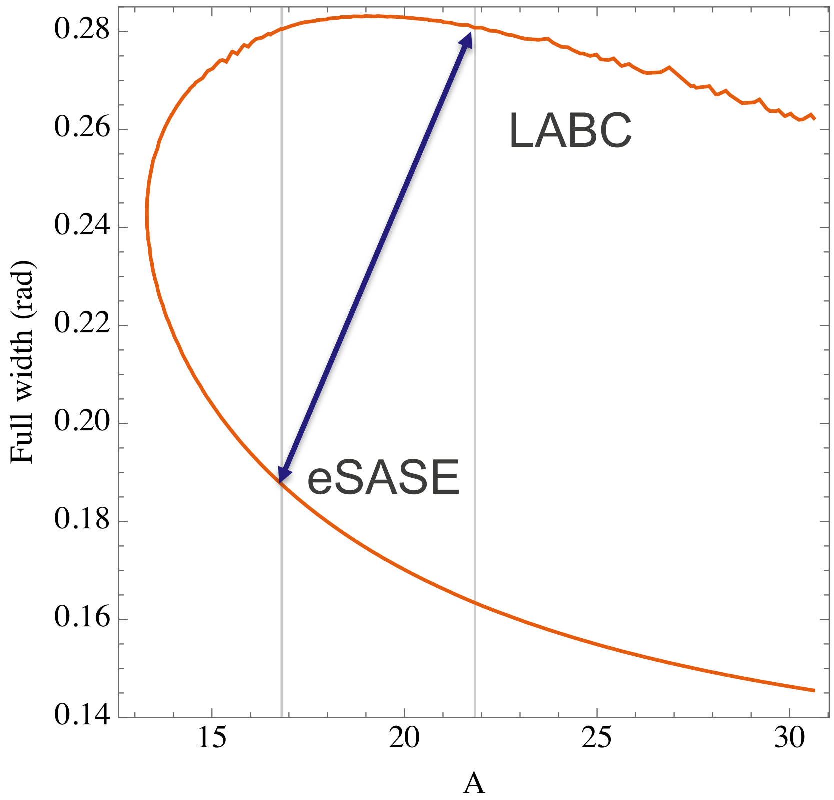
High R56 and CSR energy spread

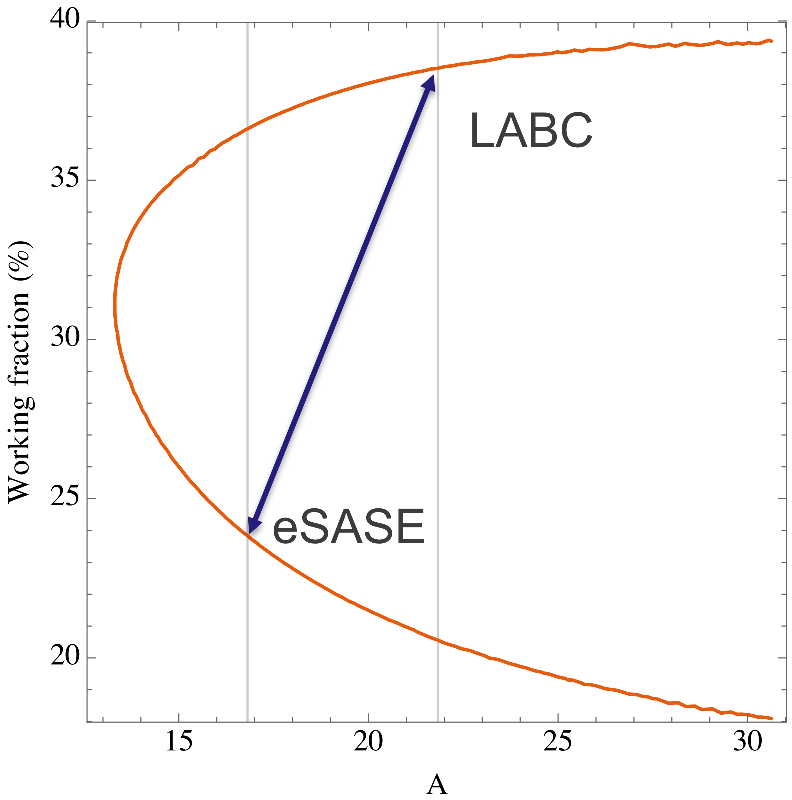




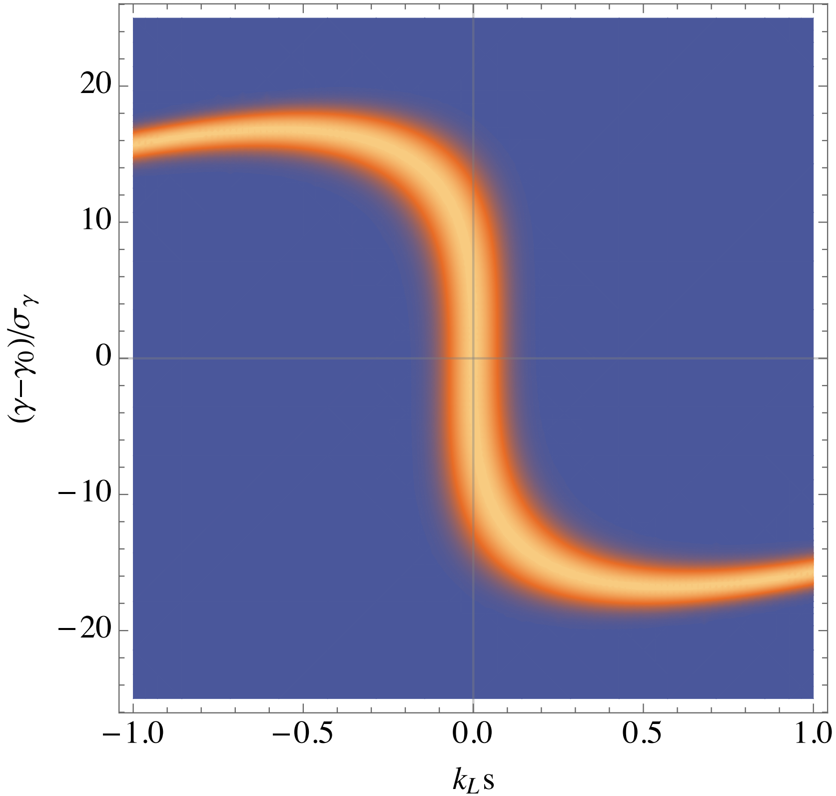
High laser power and final energy spread

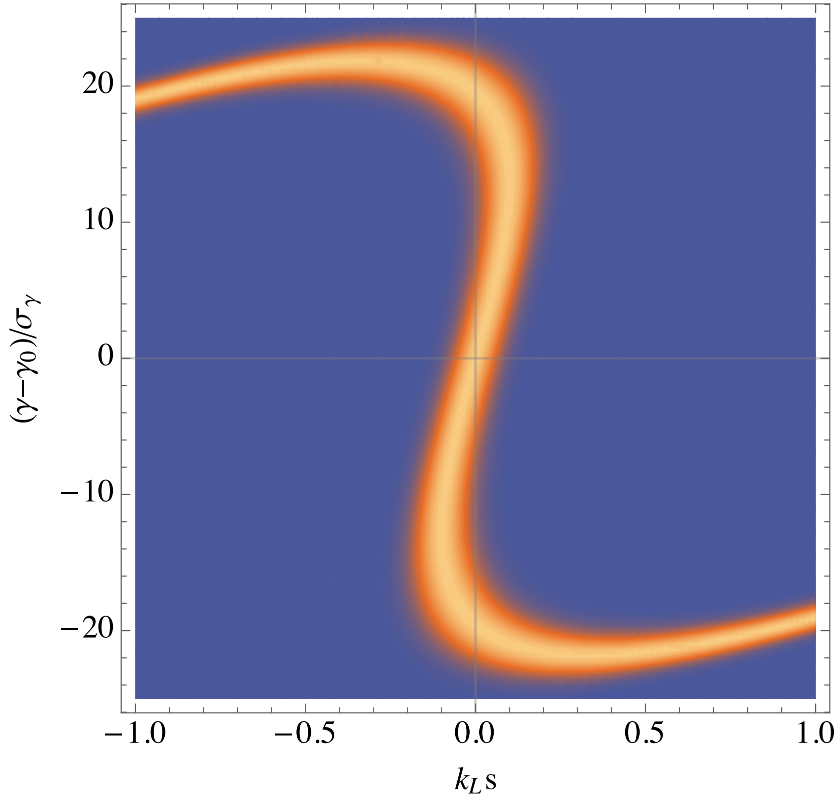
Laser Assisted Bunch Compression (LABC) scheme
10x compression





Comparison of eSASE vs LABC working points

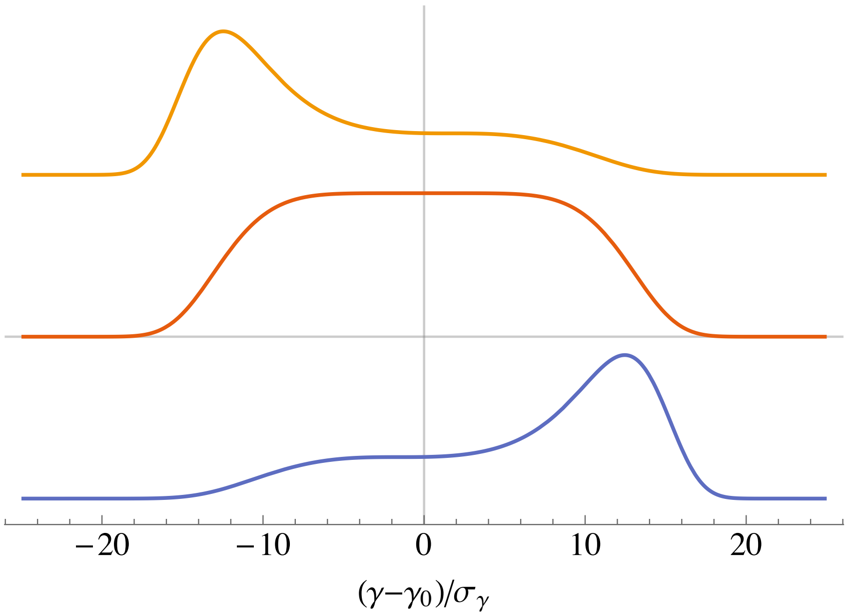


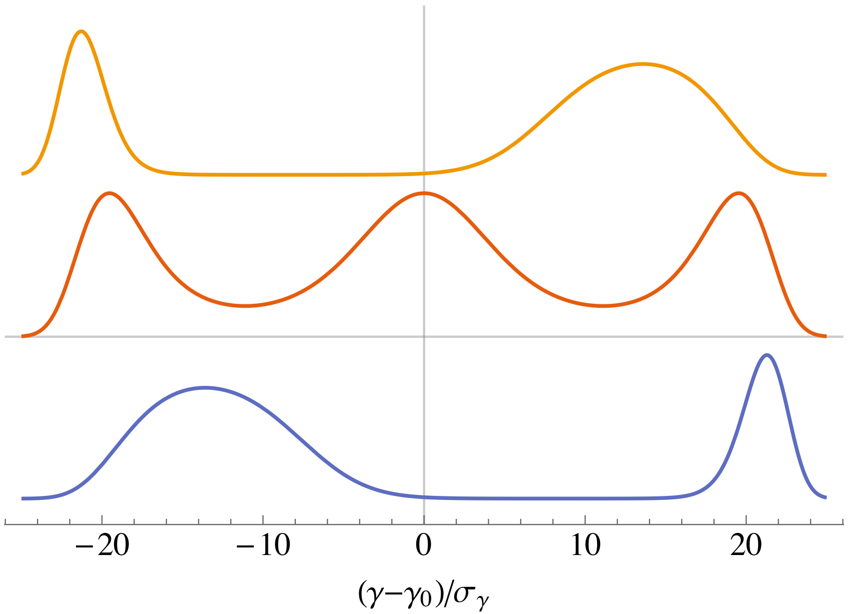


FWHM is 0.19 rad for eSASE and 23.8145% fraction of trapped electrons

FWHM is 0.28 rad for LABC and 38.5159% fraction of trapped electrons

Comparison of eSASE vs LABC working points: Energy profiles at $\theta = -HWHM, 0, HWHM$

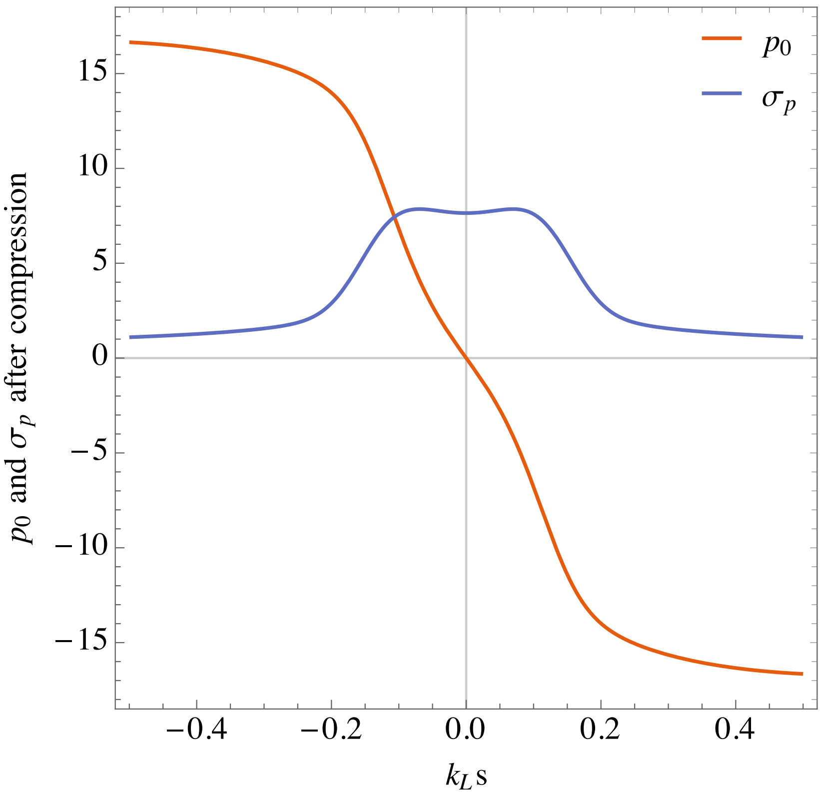


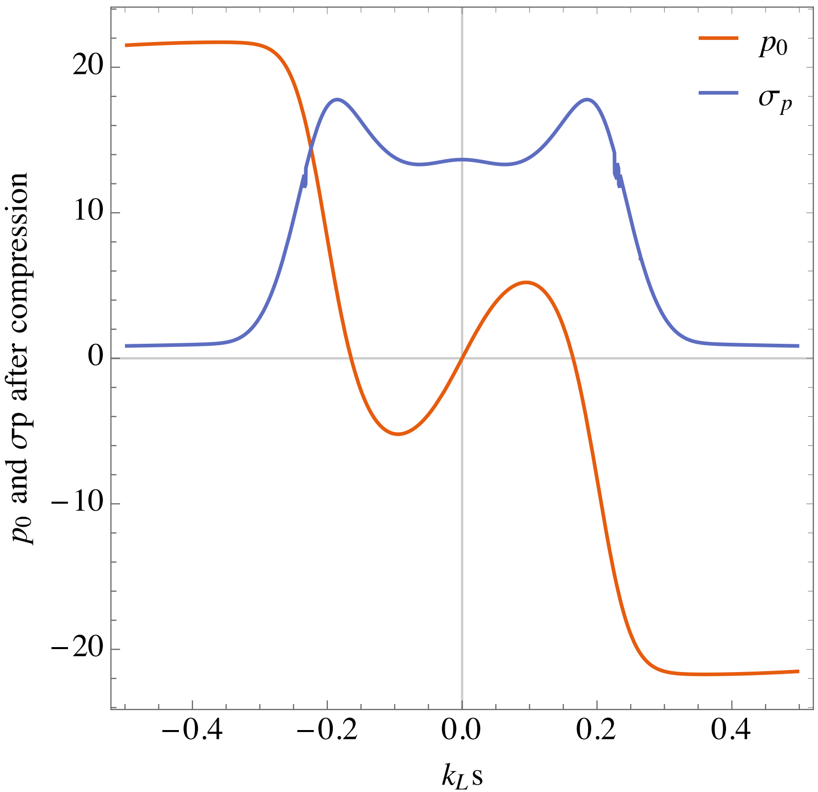


FWHM is 0.19 rad for eSASE and 23.8145% fraction of trapped electrons

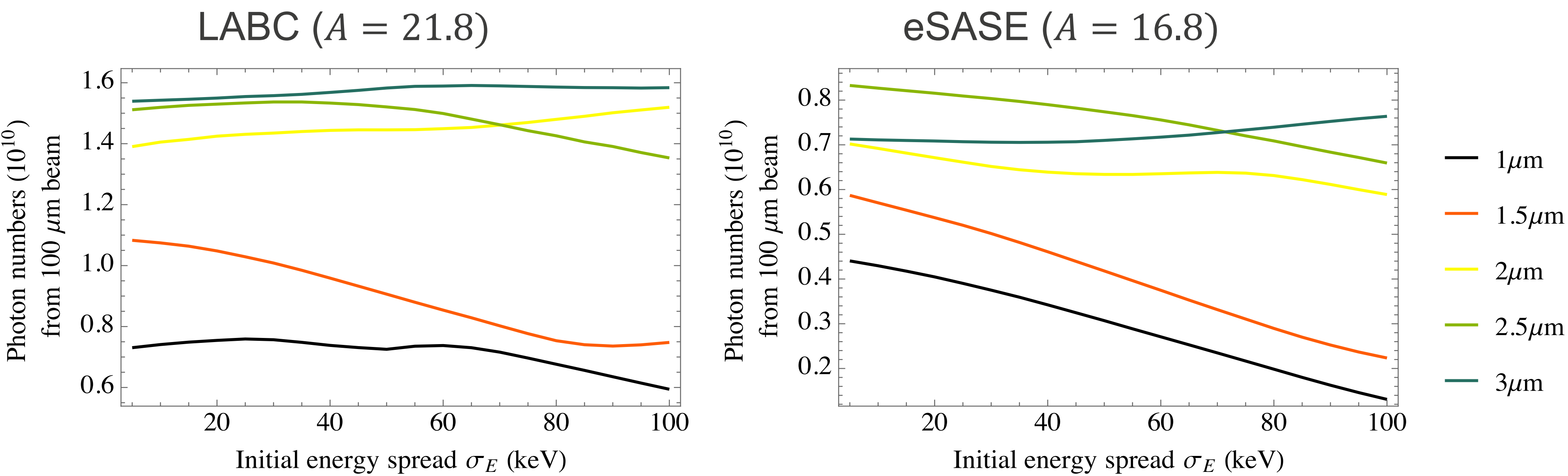
FWHM is 0.28 rad for LABC and 38.5159% fraction of trapped electrons

RMS Characterization of the Phase Space Distributions



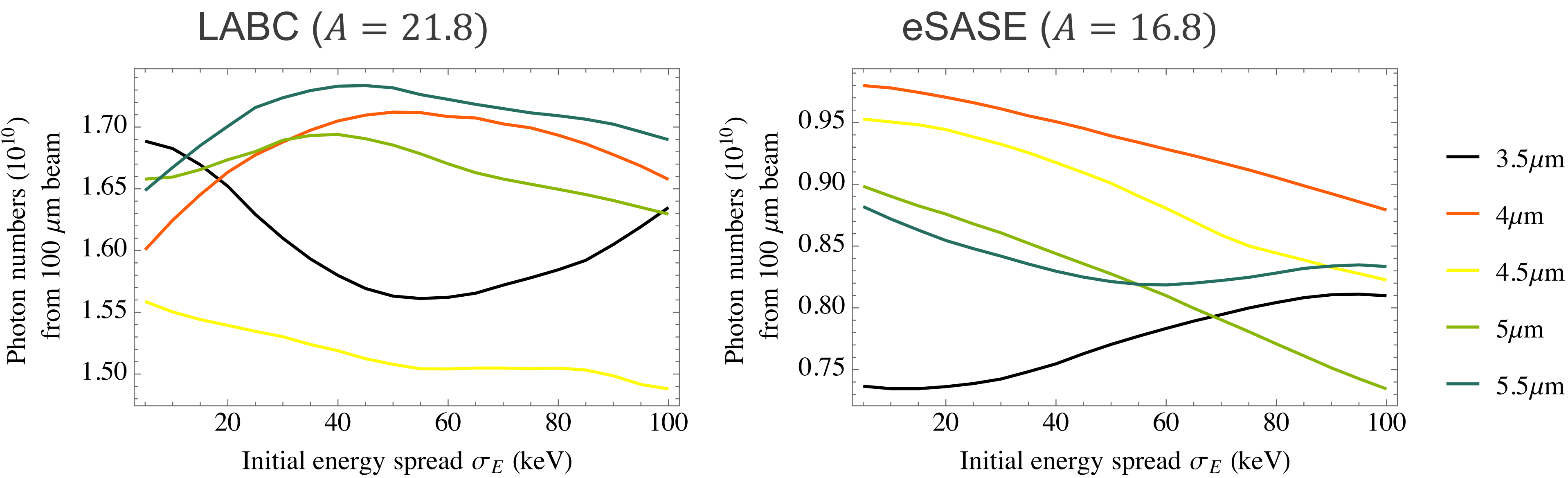


Non RMS GENESIS Studies of a Single Current Spike



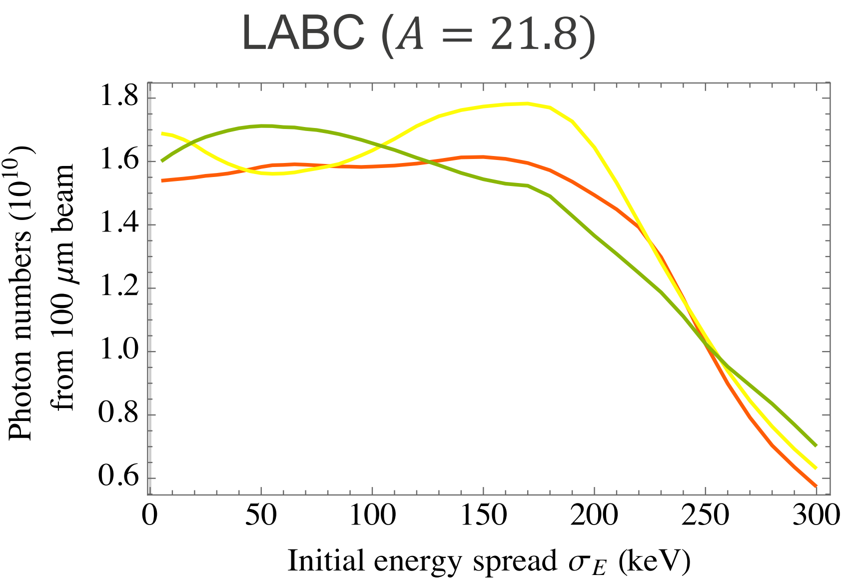
- At least 2 μm wavelength is required to avoid slippage effect;
- Coherence length is 31 nm and the slippage length is 115 nm;
- eSASE produces 0.5 time LABC while trapping fraction is only 0.62 less.

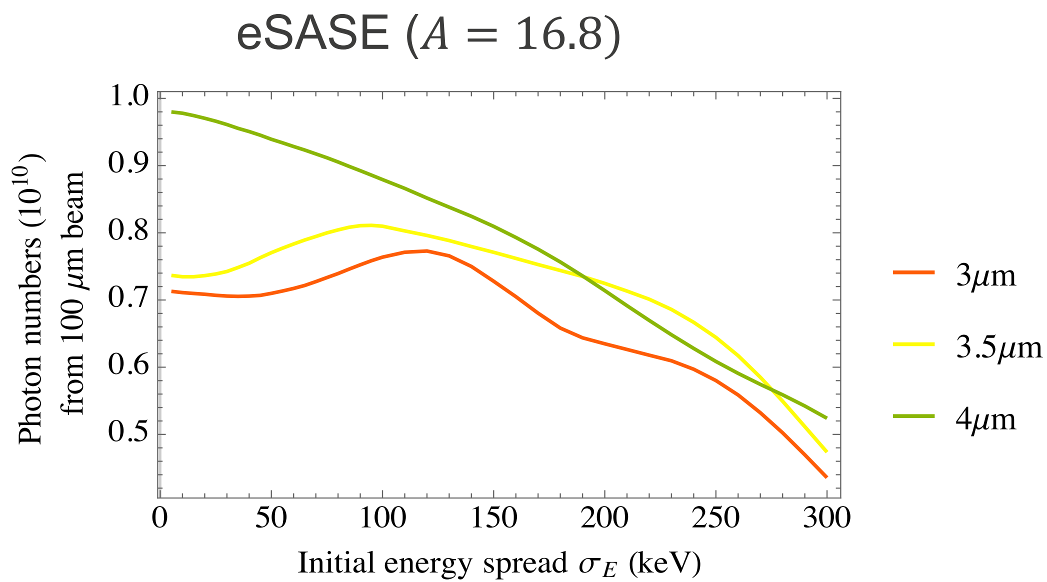
Non RMS GENESIS Studies of a Single Current Spike



- Longer wavelength do not increase the photon numbers further.

Non RMS GENESIS Studies of a Single Current Spike: Extended Scanning of the Energy Spread

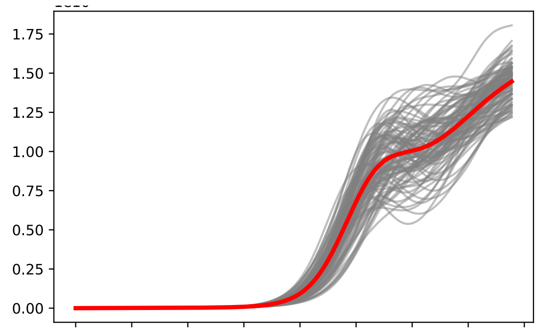




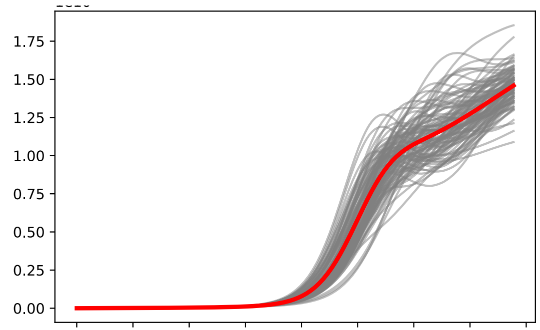
- LABC maintains its photon numbers till 200keV energy spread;
- eSASE @ 4 um benefits from longer current spike;
- eSASE performance continuously degrades with energy spread.

$3.0\ \mu m$ LABC Single Spike Photon Number Fluctuations

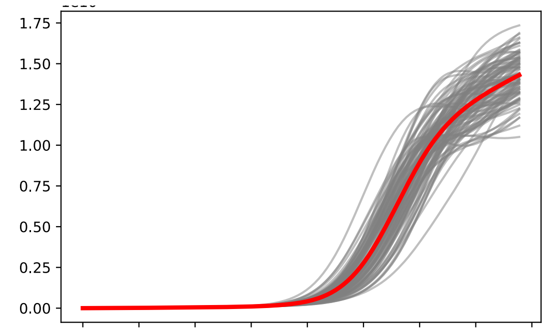
100 simulations(grey) averaged to the red line



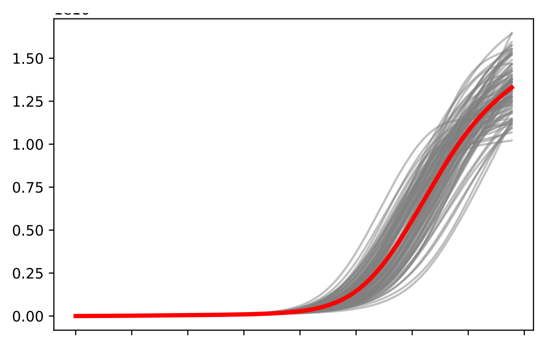
5 keV



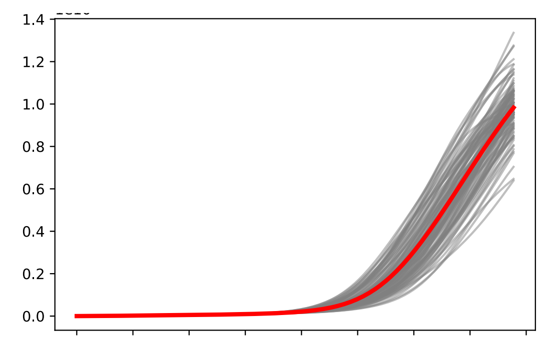
80 keV



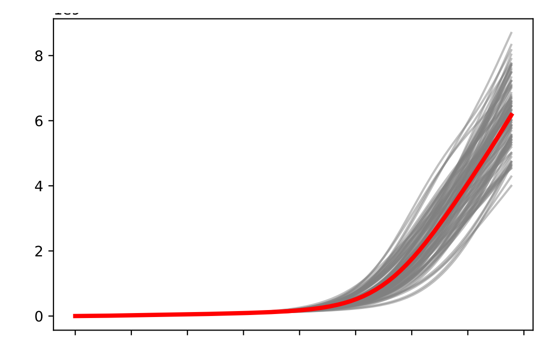
150 keV



200 keV



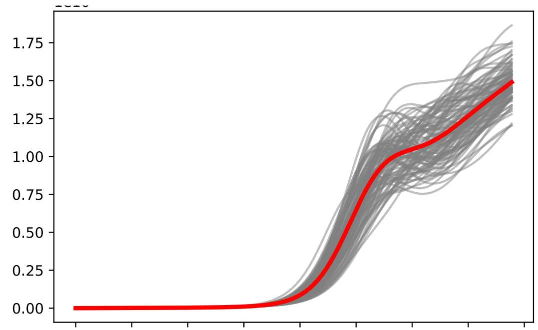
250 keV



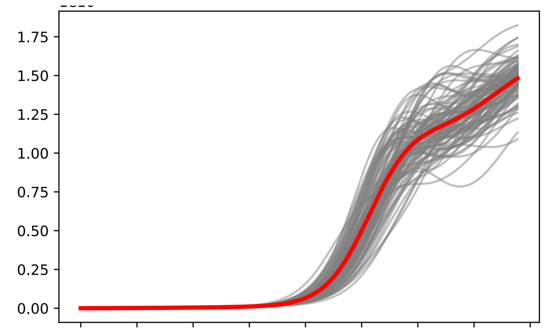
300 keV

$3.5\ \mu m$ LABC Single Spike Photon Number Fluctuations

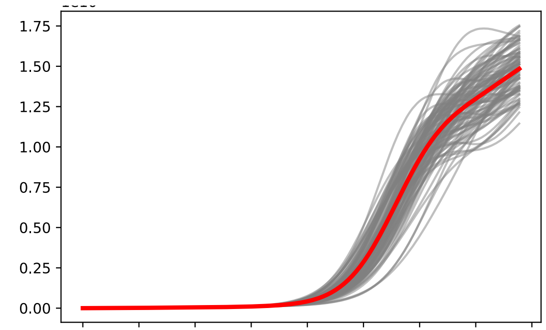
100 simulations(grey) averaged to the red line



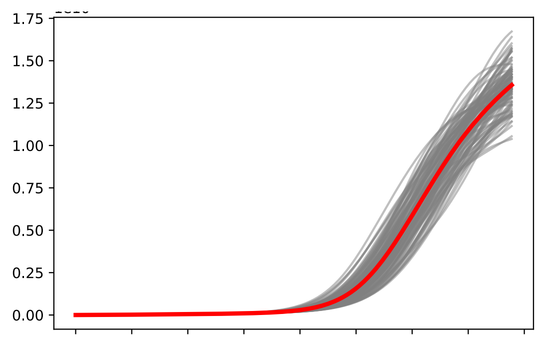
50 keV



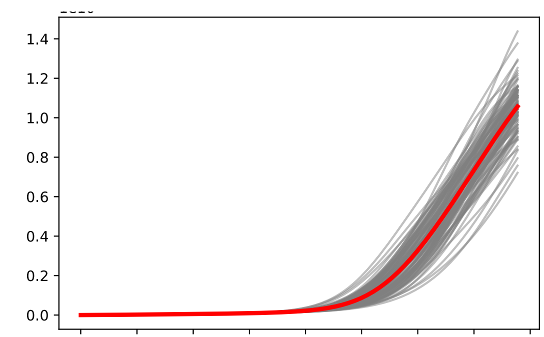
100 keV



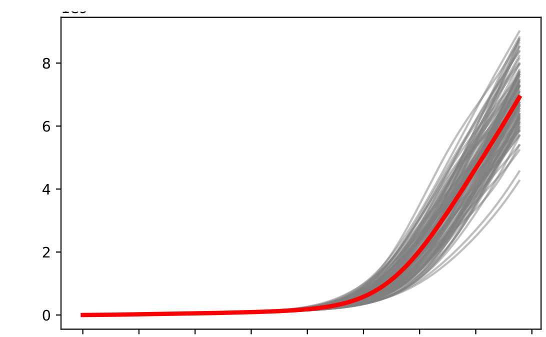
150 keV



200 keV

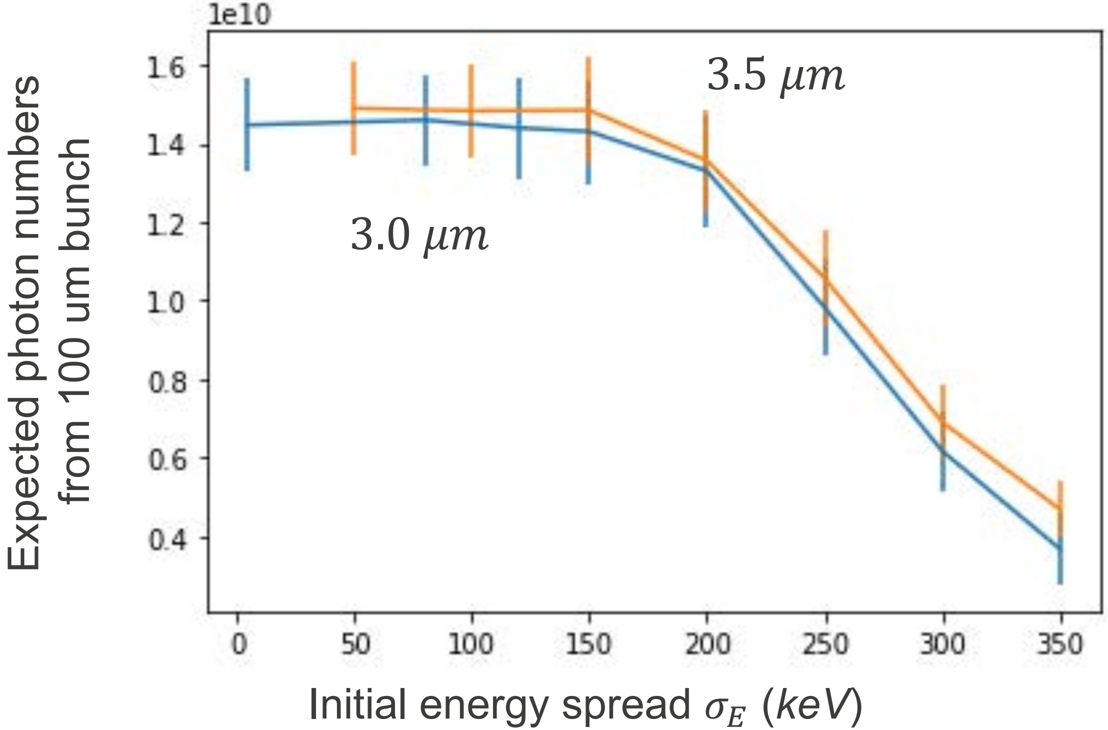


250 keV



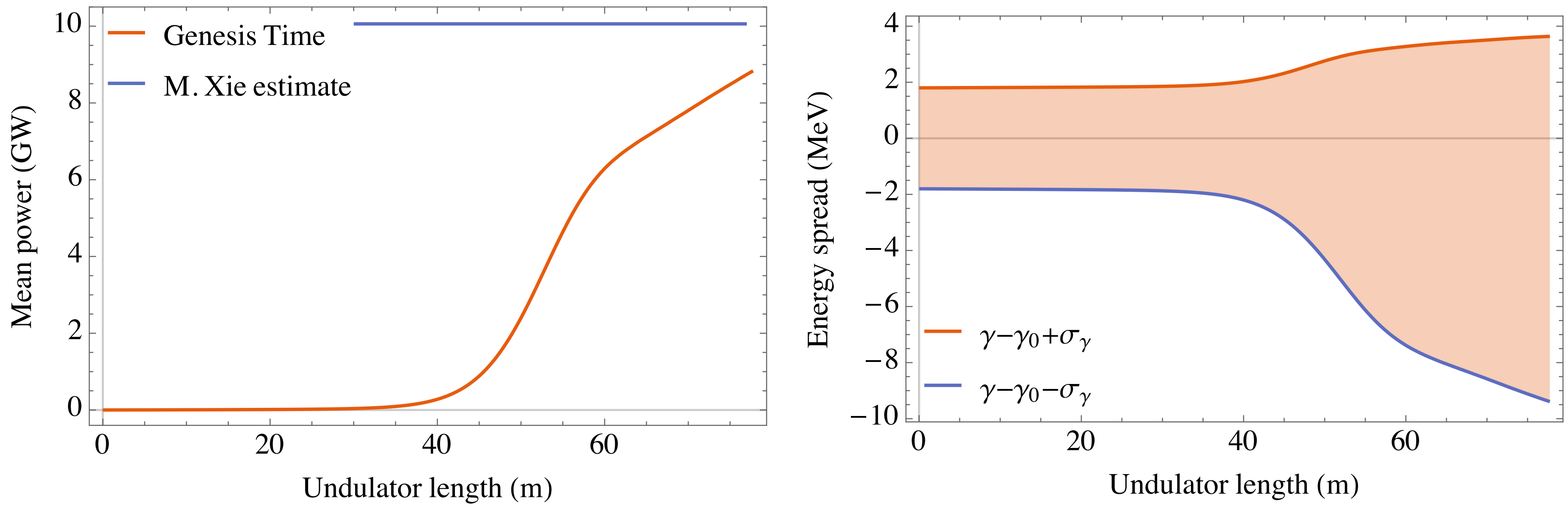
300 keV

LABC Single Spike Photon Number Fluctuations



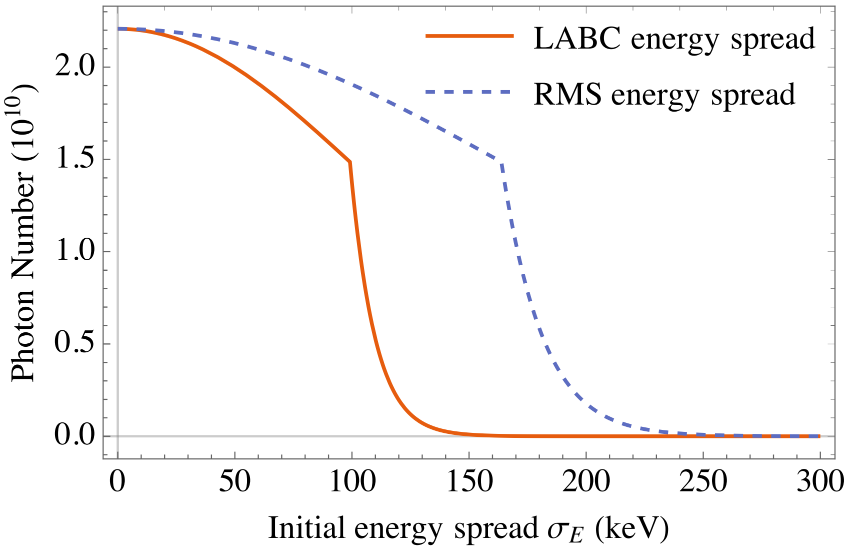
- Photon number degradation point coincides with the condition that saturation length exceed the undulator length of 77 m.
- $3.5\ \mu m\ FWHM_{current} \approx L_{slippage} + L_{cocherence}$

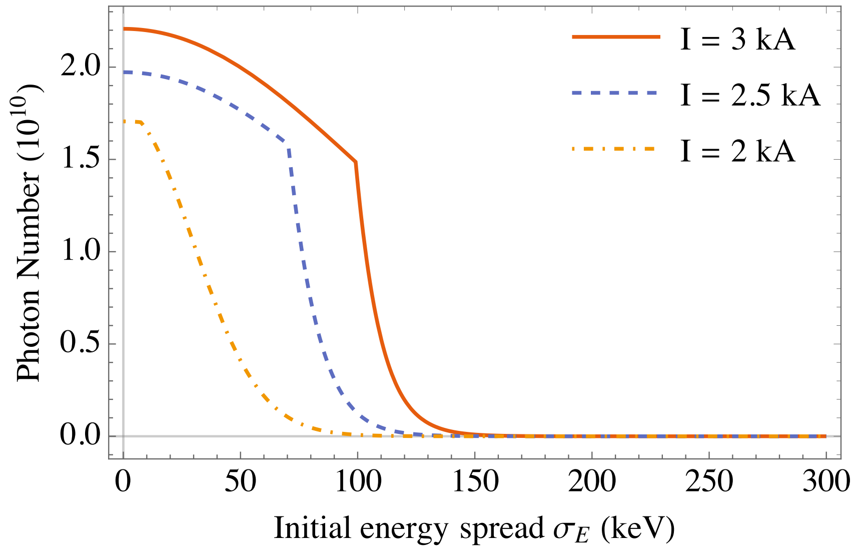
SASE Predictions for an Ideal 10 μm Bunch



- XFEL saturates when the energy spread becomes too large;
- M. Xie overestimates a mean Genesis simulated power by 12%.

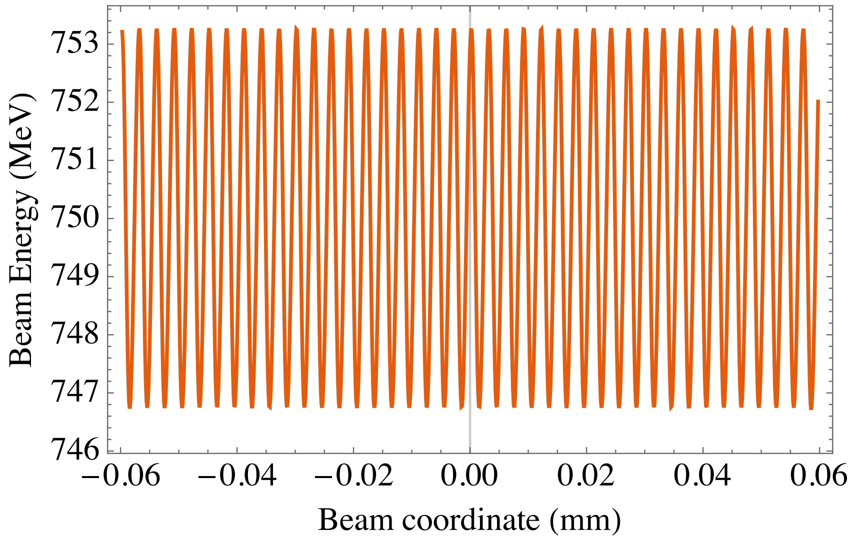
M. Xie Estimate of the Photon Numbers: for $\beta = 18\ m$ and $L_u = 77\ m$



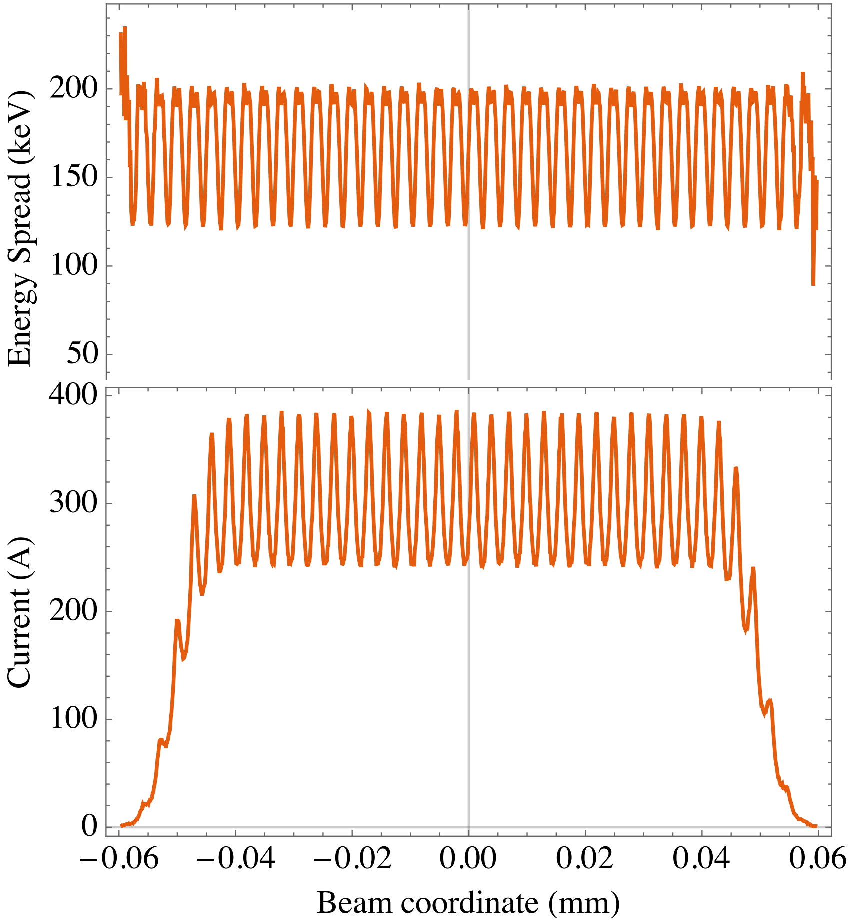


- LABC increases energy spread yet we do not see power drop @ 100 keV;
- Using RMS energy spread estimate brings us closer to 200 keV;
- Current decrease drops the power so LABC current profile is better than eSASE current profile.

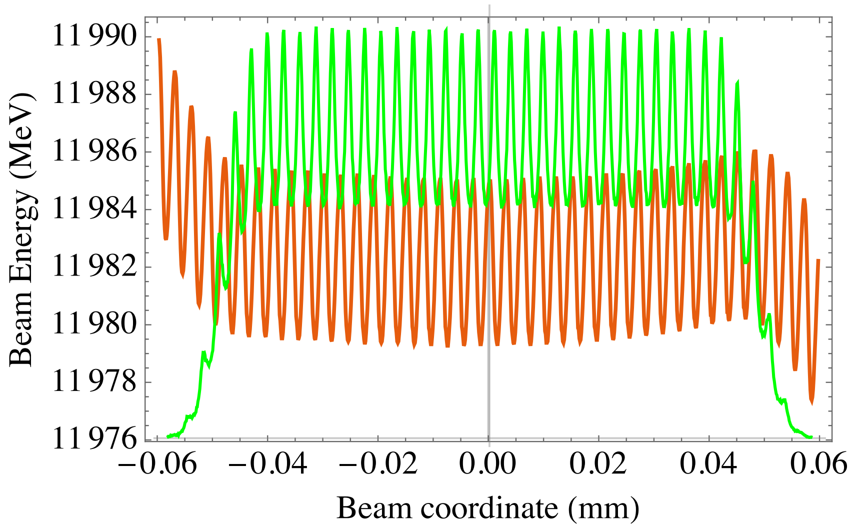
ELEGANT Simulations of the Laser Modulator

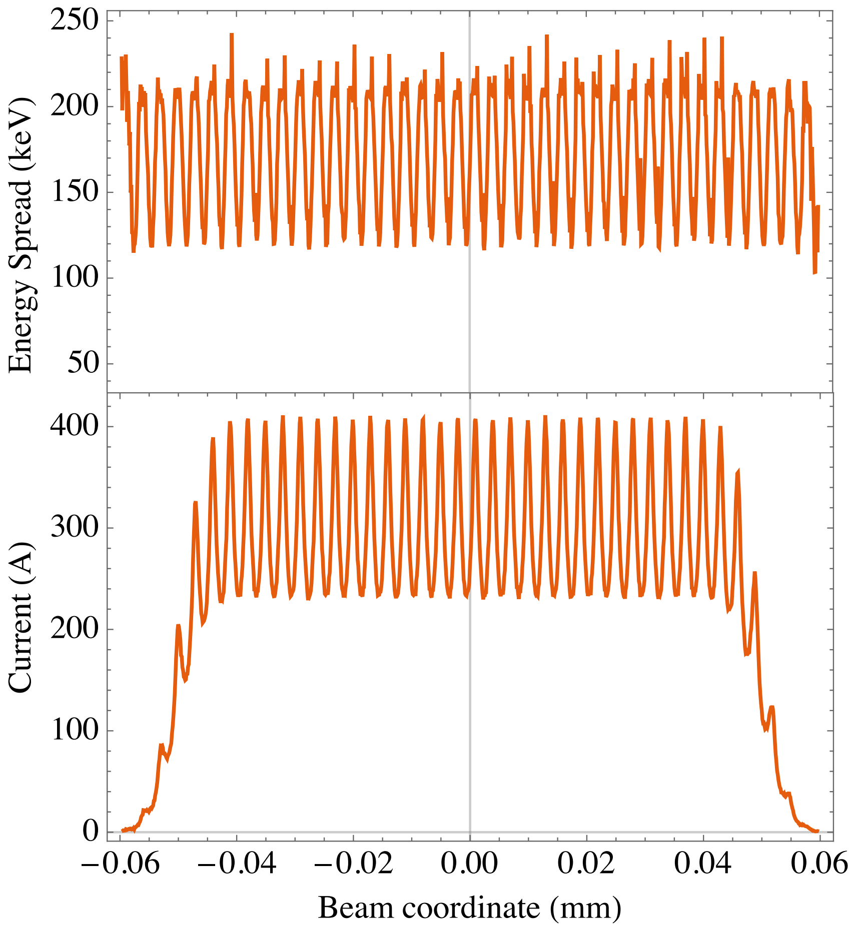


- $A = 21.8$ at $3\ \mu m$ for $750\ MeV$ beam with $\sigma_E = 150\ keV$ requires:
- $K = 12.77$ for $\lambda_u = 15\ cm$ undulator and
- $P = 1.07\ GW$ focused to $w_r = 524\ \mu m$ spot
- assuming $N_u = 10$.



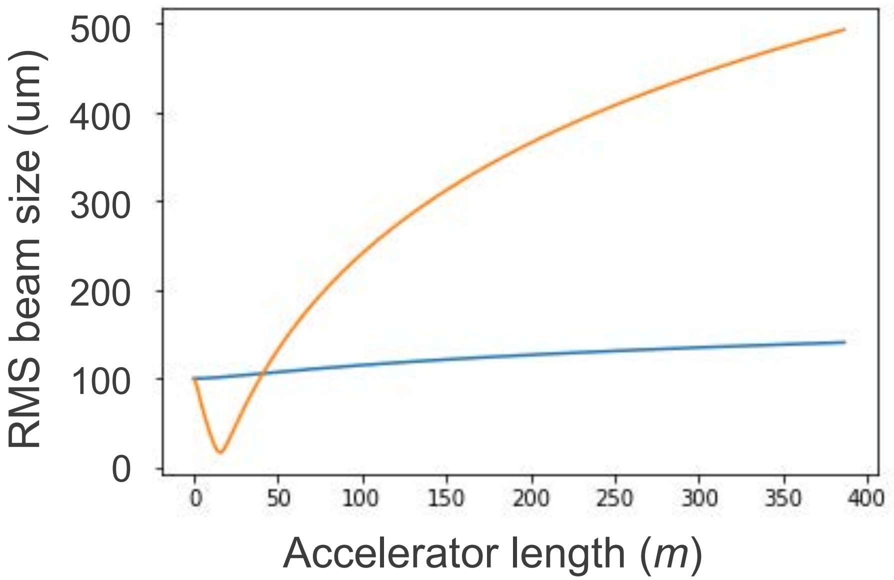
ELEGANT Simulations of 30 MV/m C-band acceleration

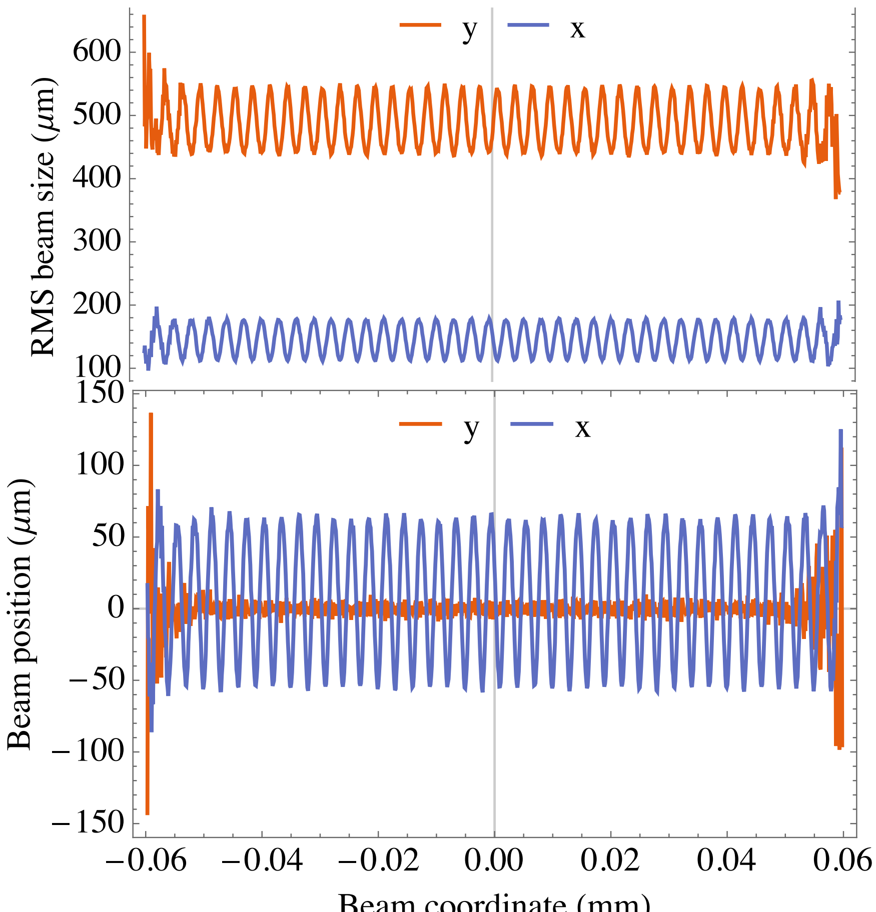




- Acceleration 13.6° of crest and C-band wakes remove RF curvature;
- No significant space charge effects on current or energy spread;
- Ballistic compression in the accelerator.

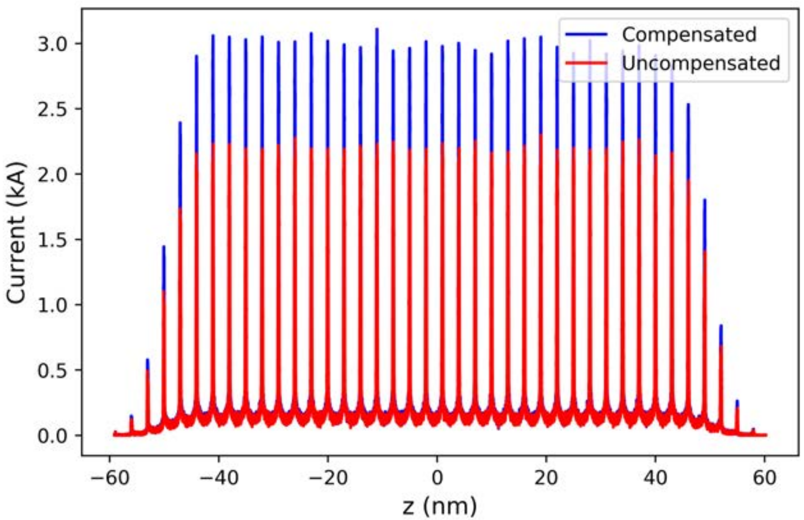
ELEGANT Simulations of 30 MV/m C-band acceleration

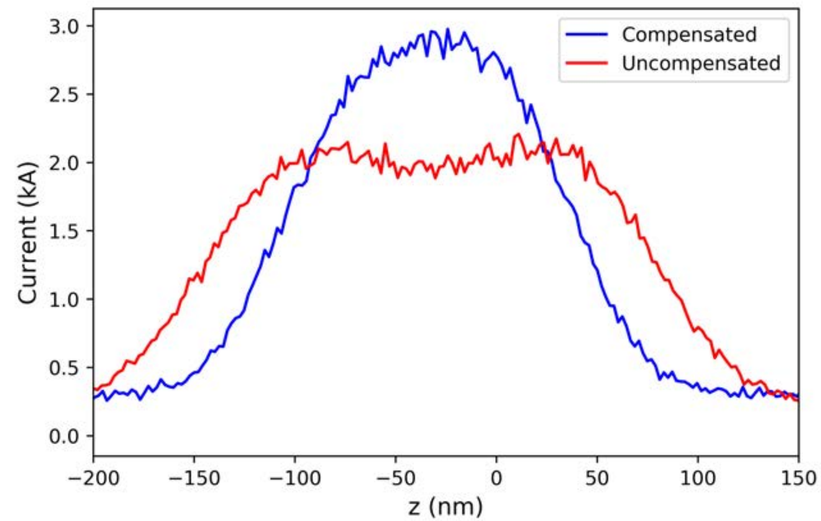




- A simple "toy" model without transverse focusing or gaps between RF tanks;
- Transverse wakes have been included.

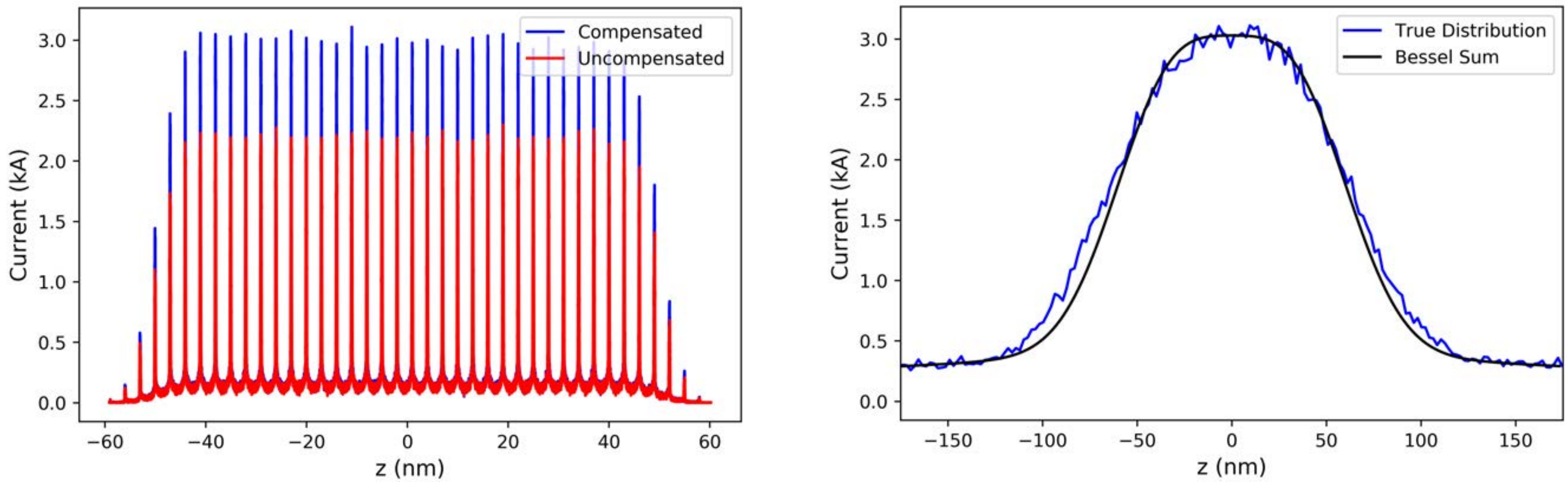
Ideal Bunch Compression after 120 MV/m acceleration





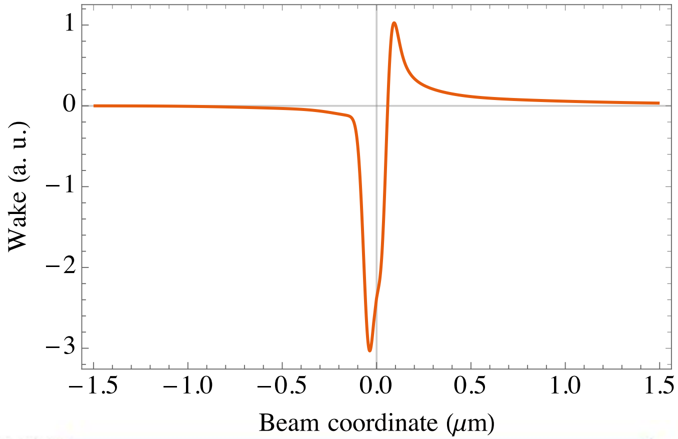
- LABC operating point has $B = 0.0567$ which corresponds to $R_{56} = 2.17\ mm$;
- Reduced $R_{56} = 1.95\ mm$, which corresponds to $B = 0.051$, requires to achieve $I = 3\ kA$;
- This R_{56} reduction is due to the laser modulator alone.

Ideal Bunch Compression after 120 MV/m acceleration

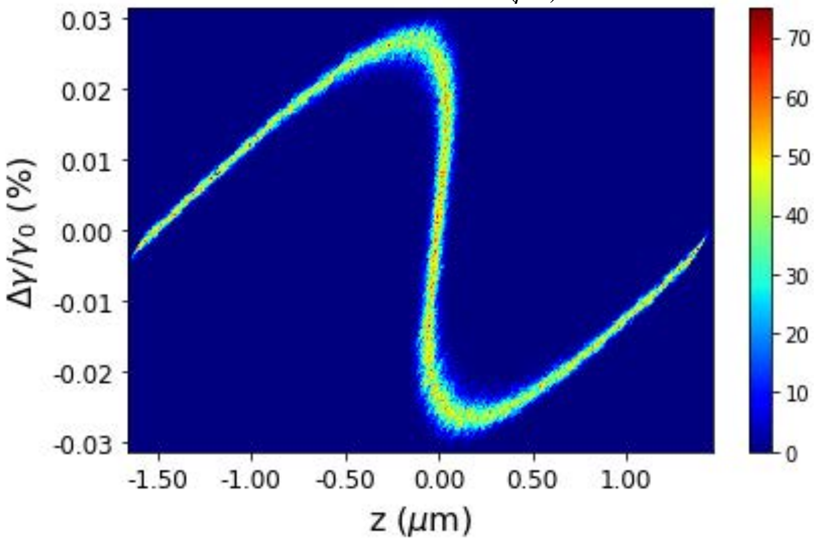


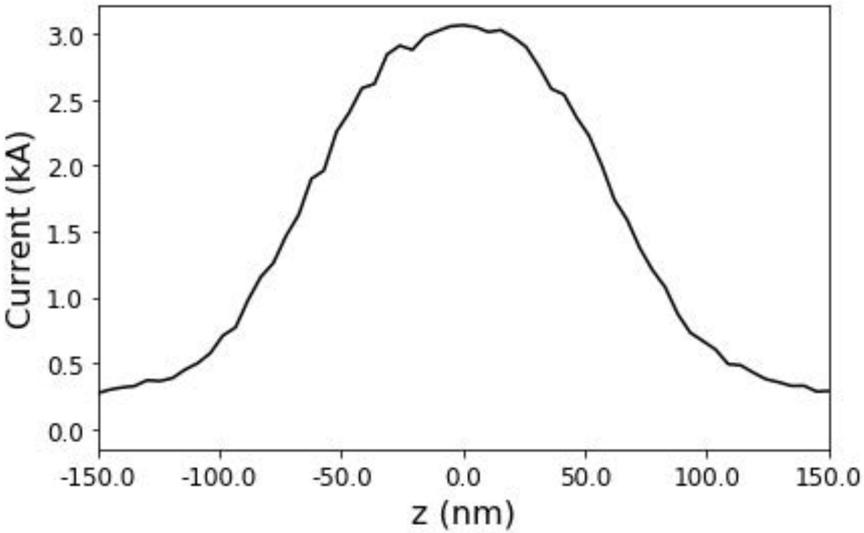
- Ballistic compression in the accelerator reduces to $R_{56} = 1.9\ mm$, which corresponds to $B = 0.05$, $I = 3\ kA$ peak matches theoretical shape well;
- Even smaller R_{56} can be used in the case of higher σ_E since $B = \frac{R_{56} k_L \sigma_E}{\gamma m c^2}$.

Simple Four Magnet Chicane Compression

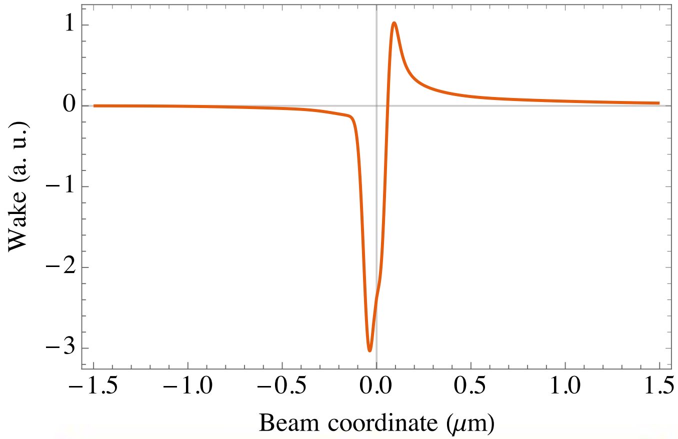


no CSR wake;
no ISR wake;
$L_d = 1\, m$ drifts;
$L_b = 0.2\, m$ bend magnets.

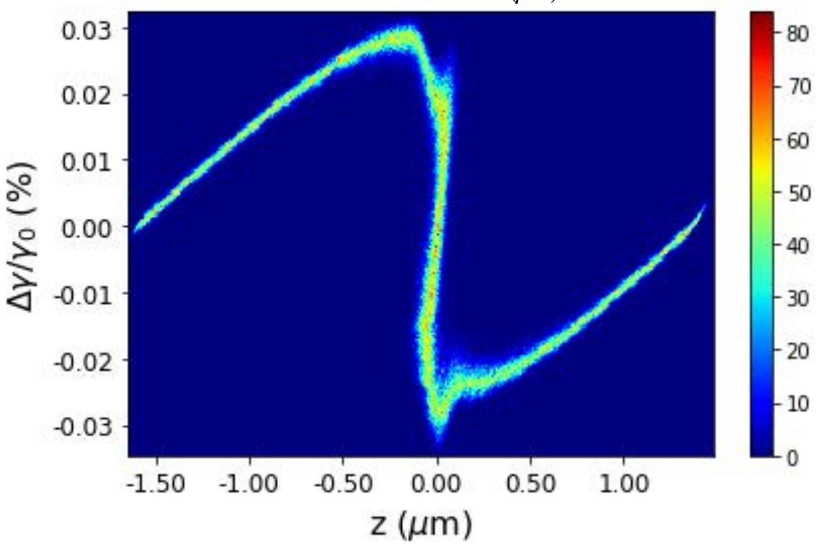


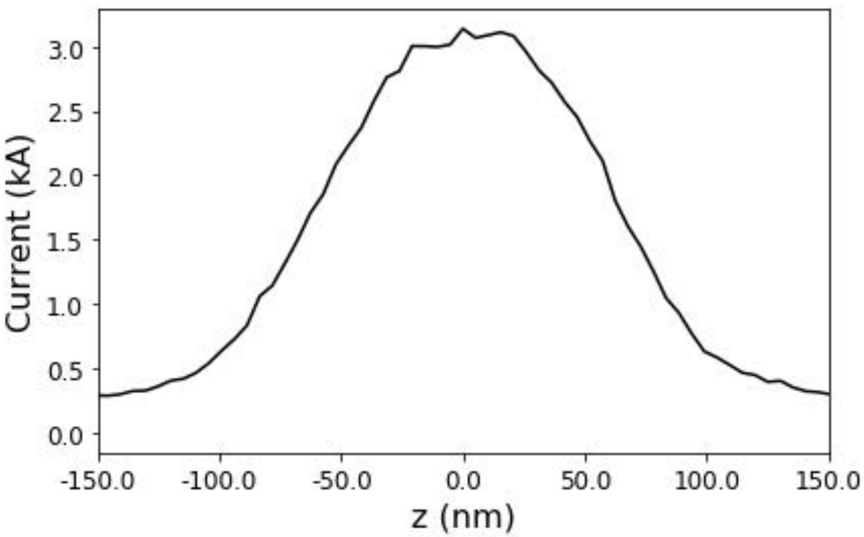


Simple Four Magnet Chicane Compression



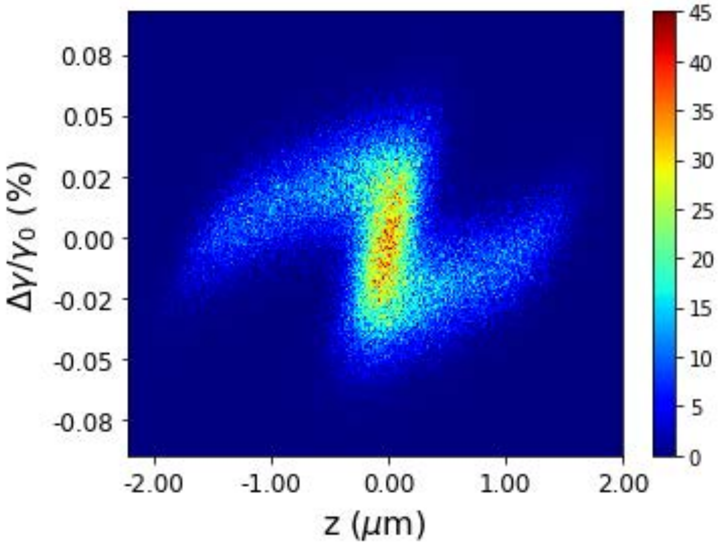
yes CSR wake;
no ISR wake;
$L_d = 1\,m$ drifts;
$L_b = 0.2\,m$ bend magnets.

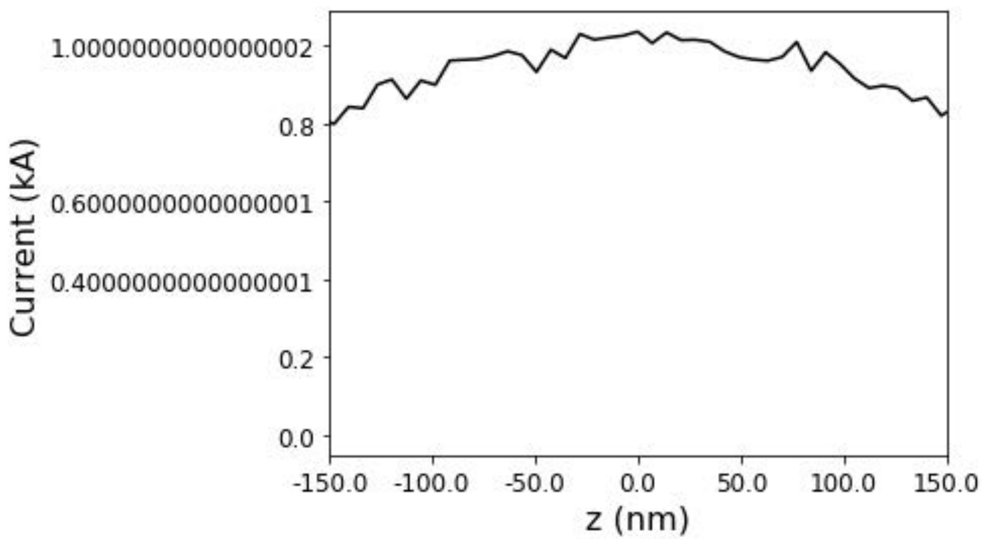




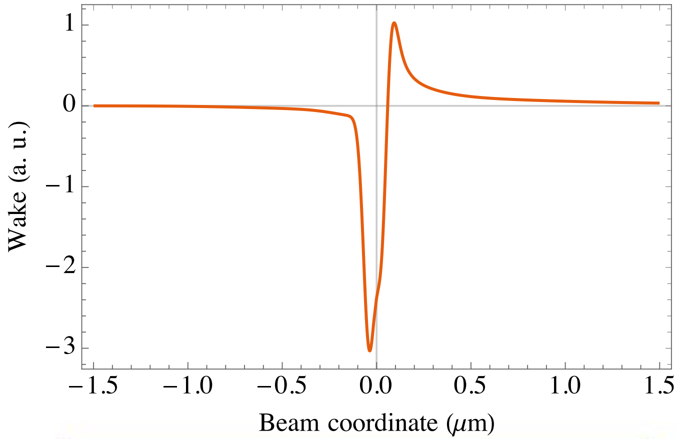
Simple Four Magnet Chicane Compression

yes CSR wake;
yes ISR wake;
$L_d = 1\ m$ drifts;
$L_b = 0.2\ m$ bend magnets.

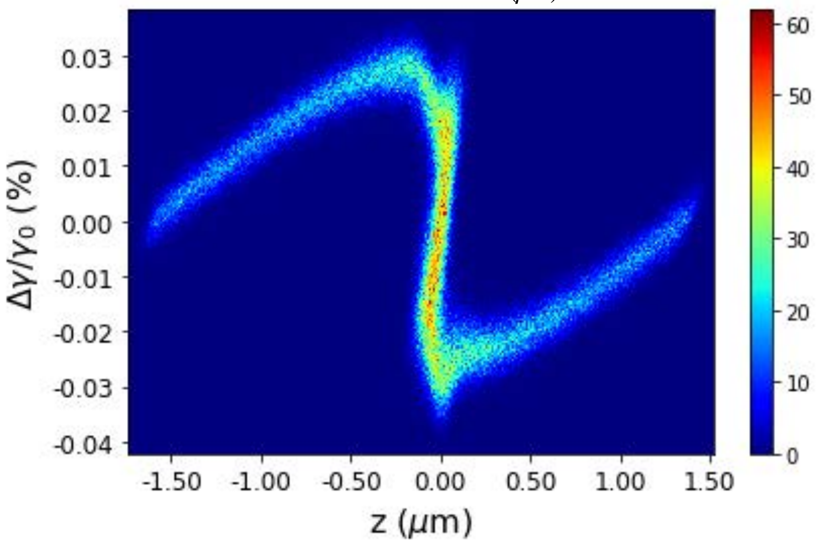


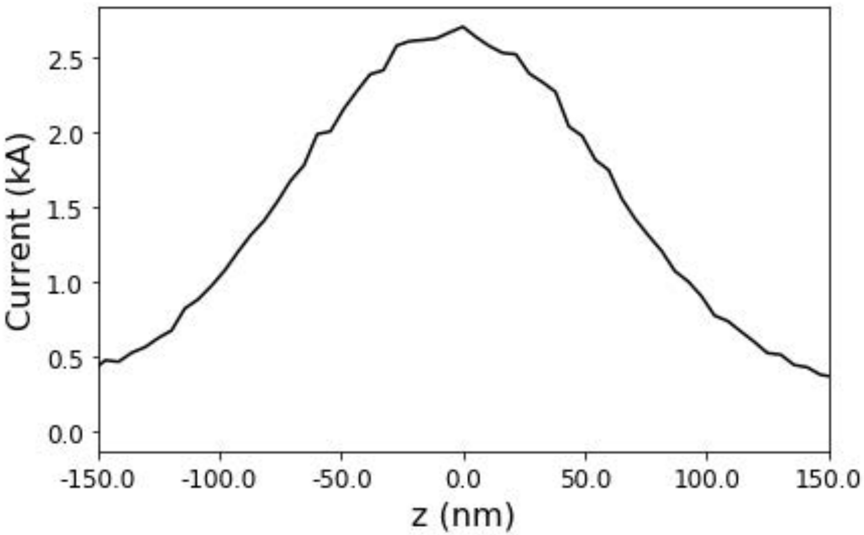


Simple Four Magnet Chicane Compression



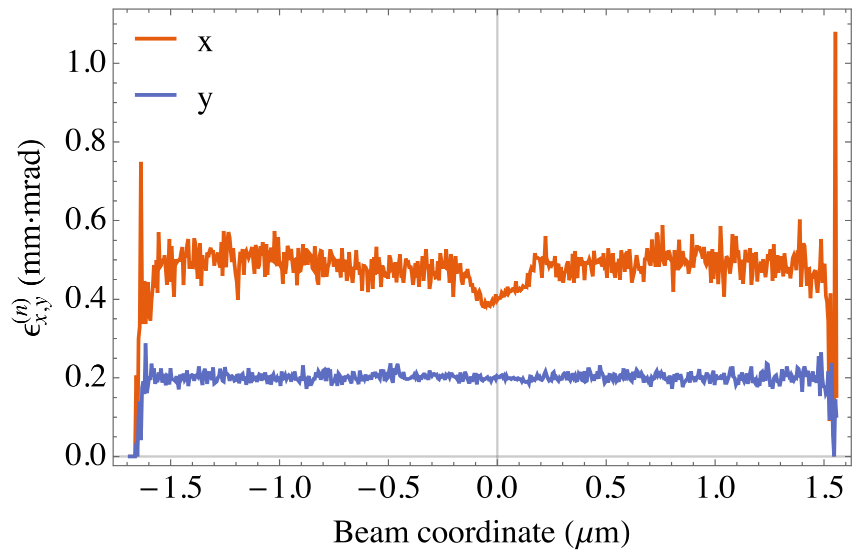
yes CSR wake;
yes ISR wake;
$L_d = 10\ m$ drifts;
$L_b = 0.2\ m$ bend magnets.



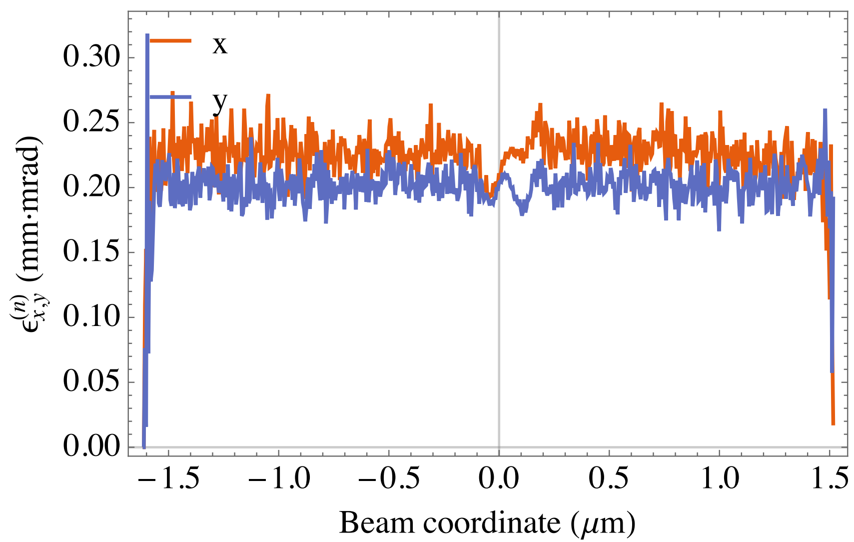


Simple Four Magnet Chicane Compression: Emittance degradation

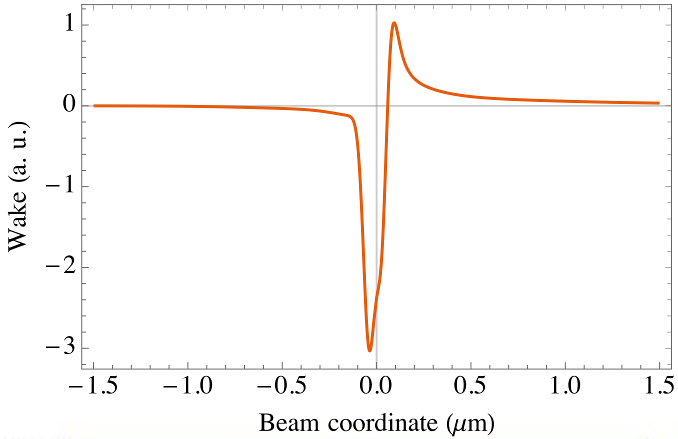
$L_b = 0.2\ m$



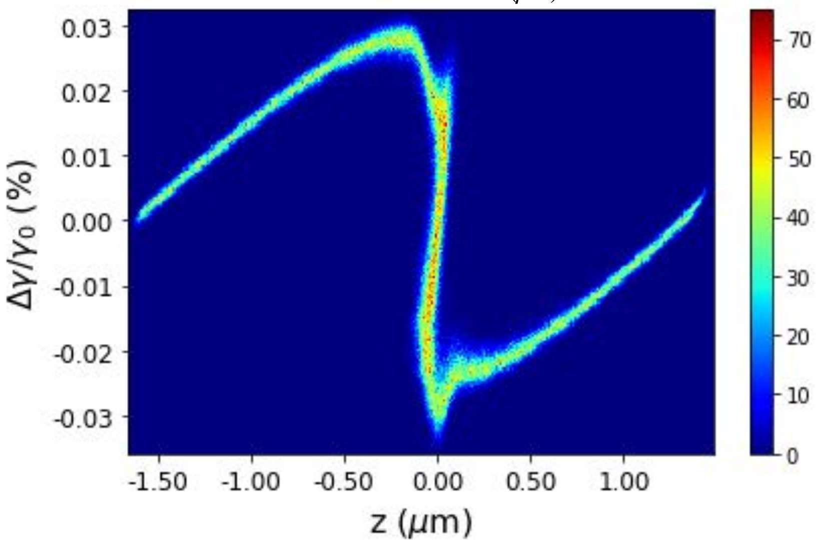
$L_b = 1.0\ m$

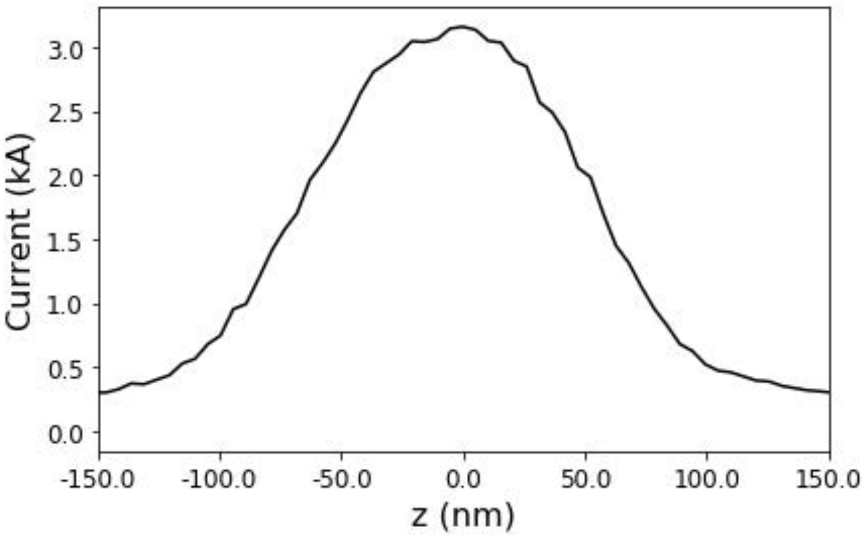


Simple Four Magnet Chicane Compression



yes CSR wake;
yes ISR wake;
$L_d = 10\ m$ drifts;
$L_b = 1.0\ m$ bend magnets.





The Study of LABC scheme is on-going Takeaways

- eSASE is not the best working point:
  - Narrow current spikes lead to low working fraction;
- eSASE does not compress 100% of the bunch:
  - Higher compression results in lower working fraction;
- Asymptotically $\frac{I_f}{I_0} \sim A^{2/3}$ for eSASE:
  - higher compression induces even higher energy spread;
- LABC increases working fraction and gives a flatten current profile;
- GENESIS simulations suggest that 200 keV of initial energy spread could be tolerated in MaRIE even with A=21.8 of the LABC point;
- Laser wavelength should be > 3 um for 10x compression in MaRIE.

The Study of LABC scheme is on-going Takeaways

- 1 GW laser power focused in ~500 um is needed;
- On-crest RF acceleration makes more efficient use of RF and reduces space charge effects;
- C-band wakes do not seem to hurt but actually help by removing RF curvature;
- 12 GeV bunch compression seems to be possible without significant beam degradation due to CSR and ISR;

- CSR energy spread < LABC energy spread < FEL tolerance:
  - This puts constrains on A and B values;
  - This puts constrains on maximum compression ratio.