Demonstration of cascaded modulator-chicane pre-bunching for enhanced trapping in an Inverse Free Electron Laser

Nicholas Sudar
UCLA Department of Physics and Astronomy

Overview

UCLA

Introduction to IFEL

- Inverse Free Electron Laser mechanism
- Rubicon IFEL & pre-bunching

Cascaded modulator-chicane pre-bunching

- motivation
- design

The experiment

- The set-up, the results

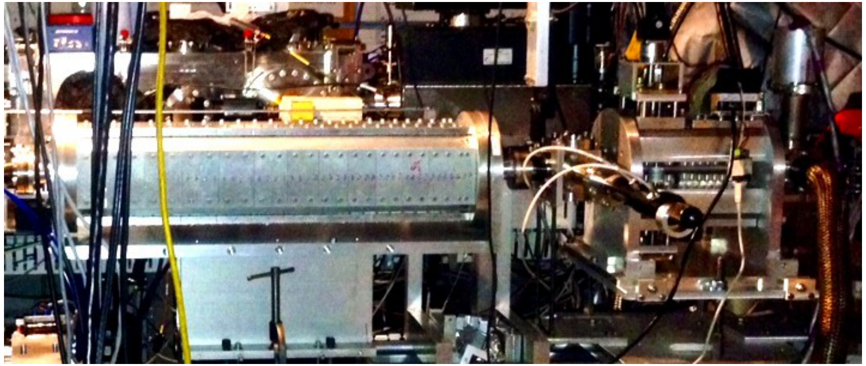
Potential uses (Single buncher vs. Double buncher)

- harmonic content, current enhancement, high efficiency FEL, chirp problems

Conclusion

The Rubicon Inverse Free Electron Laser

The IFEL

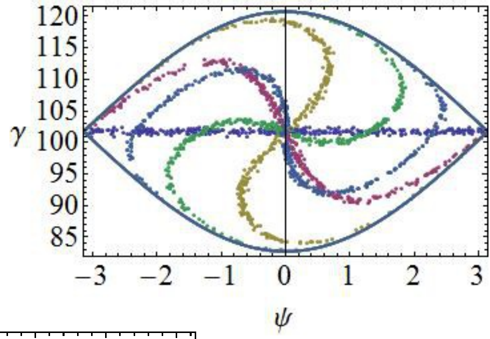


What is an IFEL?

- FEL resonance: $$\frac{\partial \Psi}{\partial z} = 0 = k_w - \frac{k(1+K^2)}{2\gamma_r^2} \Rightarrow \gamma_r^2 = \frac{k(1+K^2)}{2k_w}$$

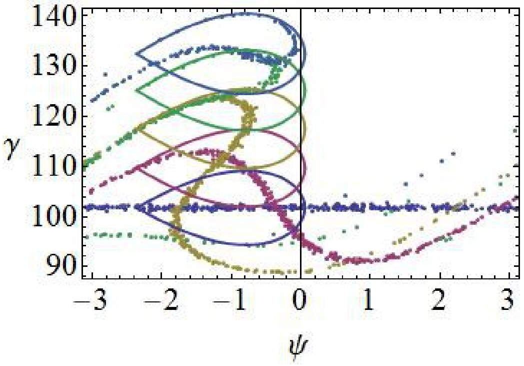
- Resonant energy exchange between a laser and electron beam inside of an undulator: $$\frac{\partial \gamma_r^2}{\partial z} = -2kK_l K \sin(\Psi_r) = \frac{\partial}{\partial z}\left(\frac{k(1+K^2)}{2k_w}\right) \qquad K_l = \frac{e\lambda E(z)}{2\pi mc^2} \qquad K = \frac{e\lambda_w(z)B(z)}{2\pi mc}$$

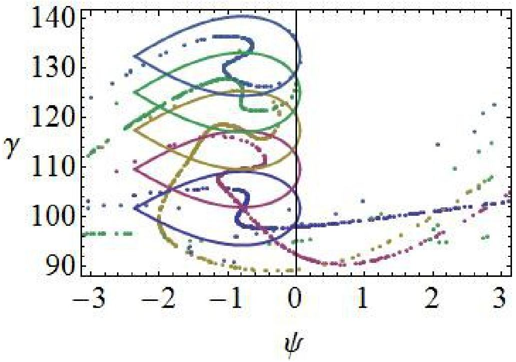
<u>gradient</u> <u>phase synchronicity</u>

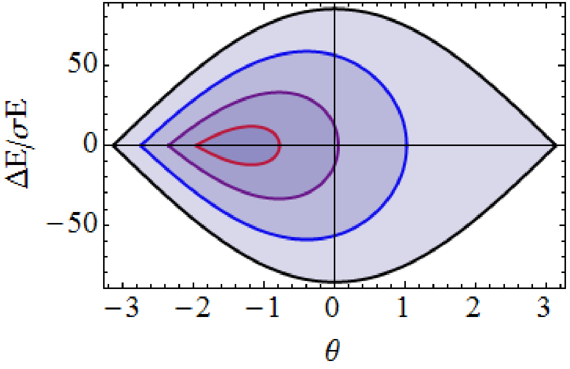


- Rubicon IFEL: Helical halbach undulator – CO_2 laser seed – BNL ATF

- choose design “resonant” phase and energy to satisfy above equation







<u>Pondermotive Bucket</u>

Resonant phase: 0, π/8, π/4, 3π/8

The pre-buncher

Single Buncher

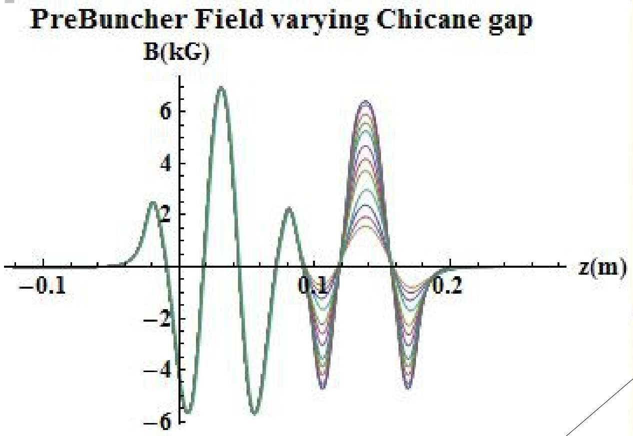
- Single period, planar, halbach undulator

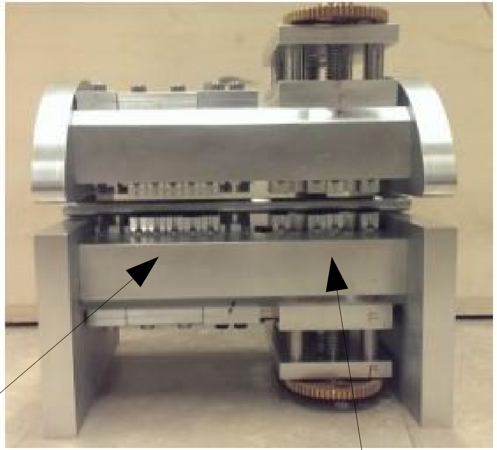
- Permanent magnet, variable gap chicane

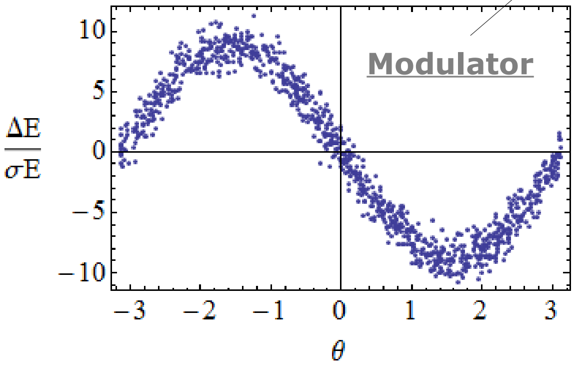
- Laser imparts sinusoidal energy modulation

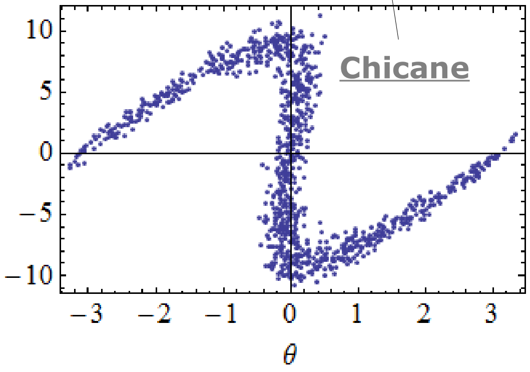
- Chicane dispersion converts to density modulation

- Chicane delay allows for control of injection phase









Rubicon results

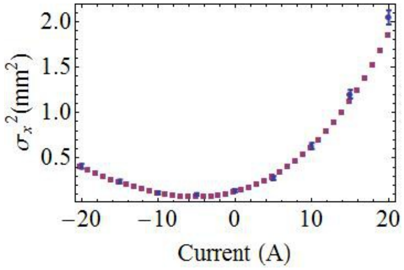
Single Buncher

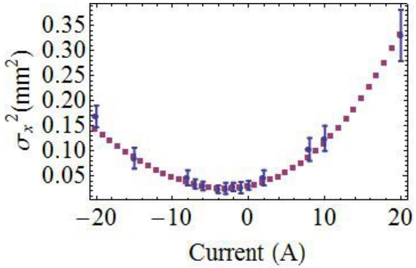
Un- accelerated beam

2.3 µm emittance

Accelerated beam

2.4 µm emittance





Rubicon IFEL experiment

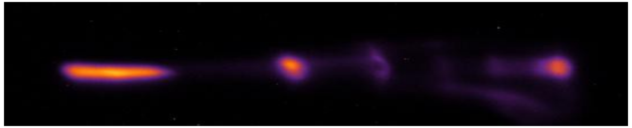
52 MeV → 95 MeV

Strongly tapered helical undulator

Period tapered (4 cm → 6cm) & gap tapered

Increased fraction accelerated: 30% → 60%

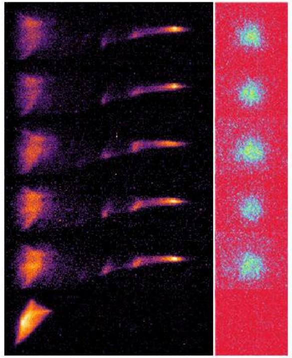
Demonstrated emittance conservation



Nocibur high efficiency energy extraction

65 MeV → 35 MeV

45% decelerated – 30% efficiency



RubiconICS

12 KeV X-Rays from 80 MeV

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 010706 (2013)

Cascaded modulator-chicane modules for optical manipulation of relativistic electron beams

Erik Hemsing and Dao Xiang
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 24 October 2012; published 28 January 2013)

The double buncher

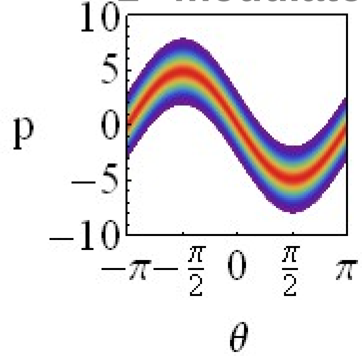
Simple model

½ period planar undulator (small modulation)

p=Δγ/σγ **A1**

p' = p+ A1*sin[θ]

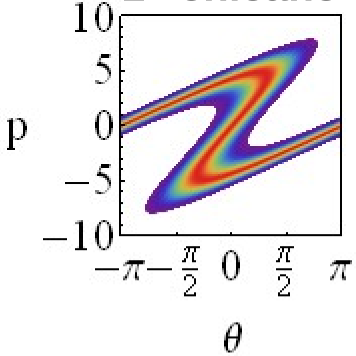
1st modulator



Large R56 chicane compressor (over-rotate) **B1**

θ'=θ+B1*p'

1st chicane

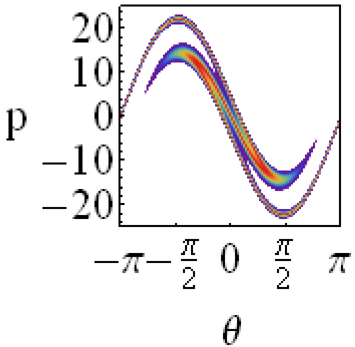


1 period planar undulator (large modulation)

Utilize pre-existing pre-buncher

A2

2nd modulator

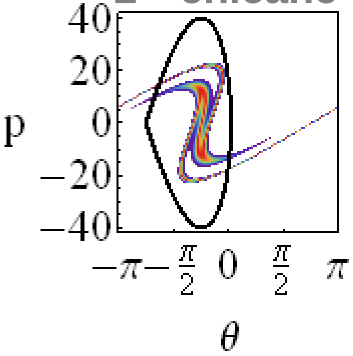


Small R56 chicane compressor (bunch)

~97% of particles inside of pondermotive bucket

B2

2nd chicane



design of the double buncher

UCLA

$$p=\frac{\gamma-\gamma_r}{\sigma_\gamma} \quad A=\frac{k\,K\,K_l[J_0(\zeta)-J_1(\zeta)]N_w\lambda_w}{2\gamma_r\sigma_\gamma} \quad \zeta=\frac{K^2}{4(1+K^2)} \quad B=\frac{R_{56}\sigma_\gamma k}{\gamma_r}$$

- Double buncher designed with original pre-buncher as second buncher

- Designed for Rubicon IFEL experiment:
  - 60 MeV/m gradient
  - resonant phase: -π/4
  - large initial ponderomotive bucket compared to energy spread Ab ~ 40

- Choose half period, 7 cm period undulator for new buncher
  - large gap (laser diffraction)
  - close to optimal A2/A1

- optimize bunching factor, tweak parameters to maximize number of particles injected in bucket

- A2 < initial bucket height

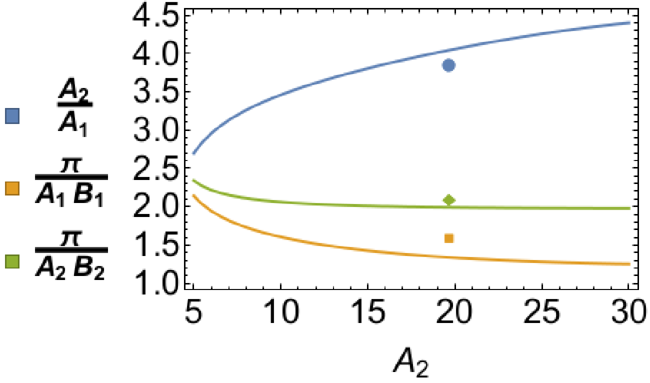
- energy spread: **σγ/γ = 0.0015**

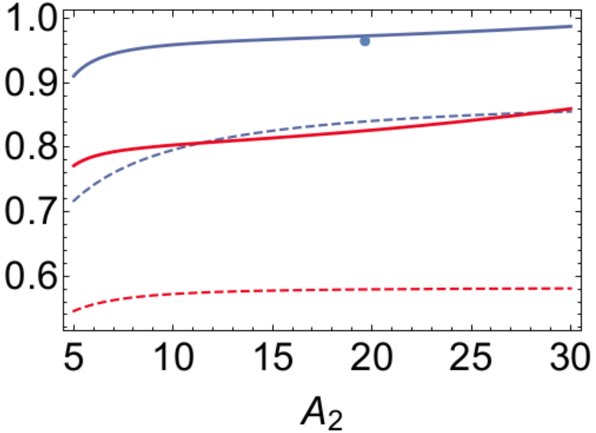
- Second modulation, A2 ~ 20 given expected laser energy

- ratio of modulations, A2/A1 ~ 4
  - Experiment: A2/A1~ 3.9

- first chicane rotates peak of 1st modulation by ~ π → π/(A1*B1) ~ 1
  - Experiment: π/(A1*B1) ~ 1.4 R56 = 480 um
- Use EM chicane: R56 = 0-900um

- Second chicane rotates peak of 2nd modulation by ~ π/2 → π/(A2*B2) ~ 2
  - Experiment: π/(A1*B1) ~ 2.1 R56 = 80 um
- Use permanent magnet chicane (variable gap): R56 = 40-90 um



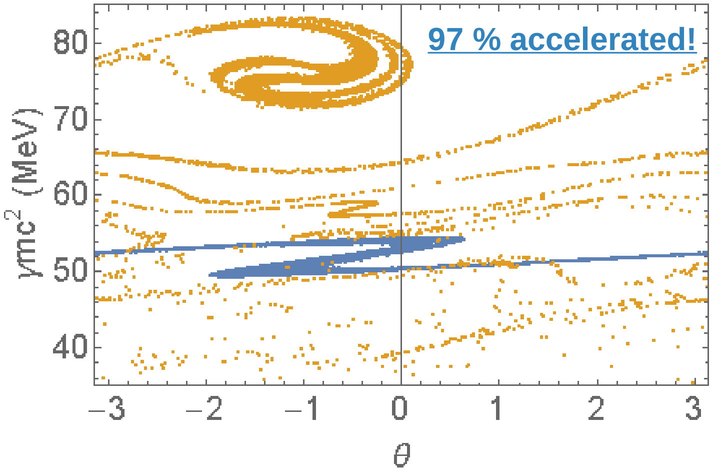


The double buncher

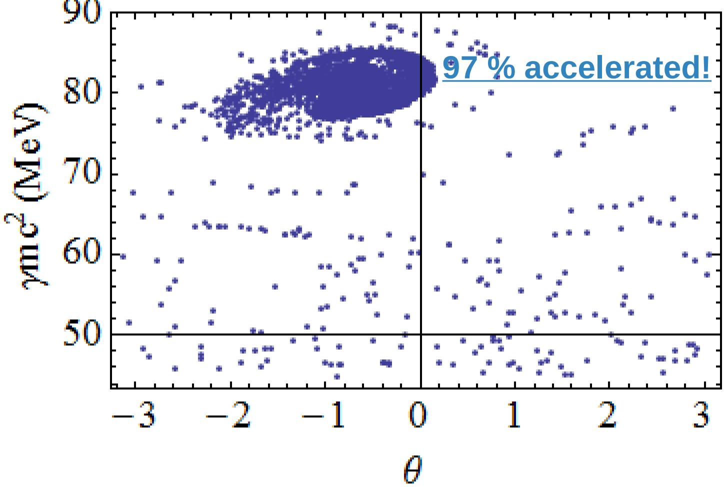
Simulations

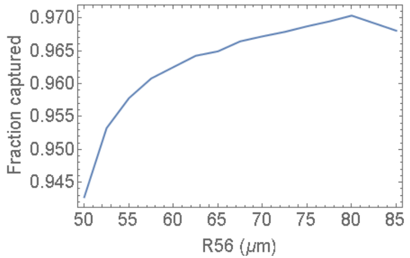
E-Beam energy	52 → 82 MeV
emittance	2.5 mm-mrad
σxy (waist)	80 μm
Laser Wavelength	10.3 μm
Rayleigh Range	0.34 m
Laser Waist	1.06 mm
Laser Power	75 GW
λw (1st modulator)	0.07 m (half period)
Chicane 1: R56	480 μm
λw (2nd modulator)	0.05 m (1 period)
Chicane 2: R56	80 μm
period tapering	0.04 -0.06 m
K tapering	2.03-2.56

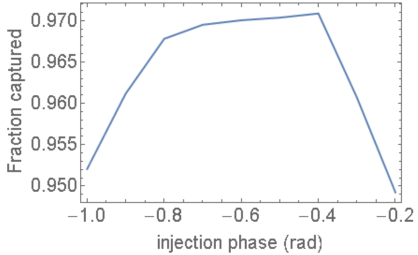
Genesis – 3D Time Dependent

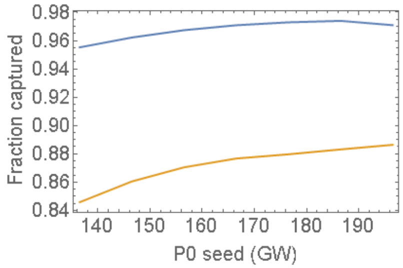


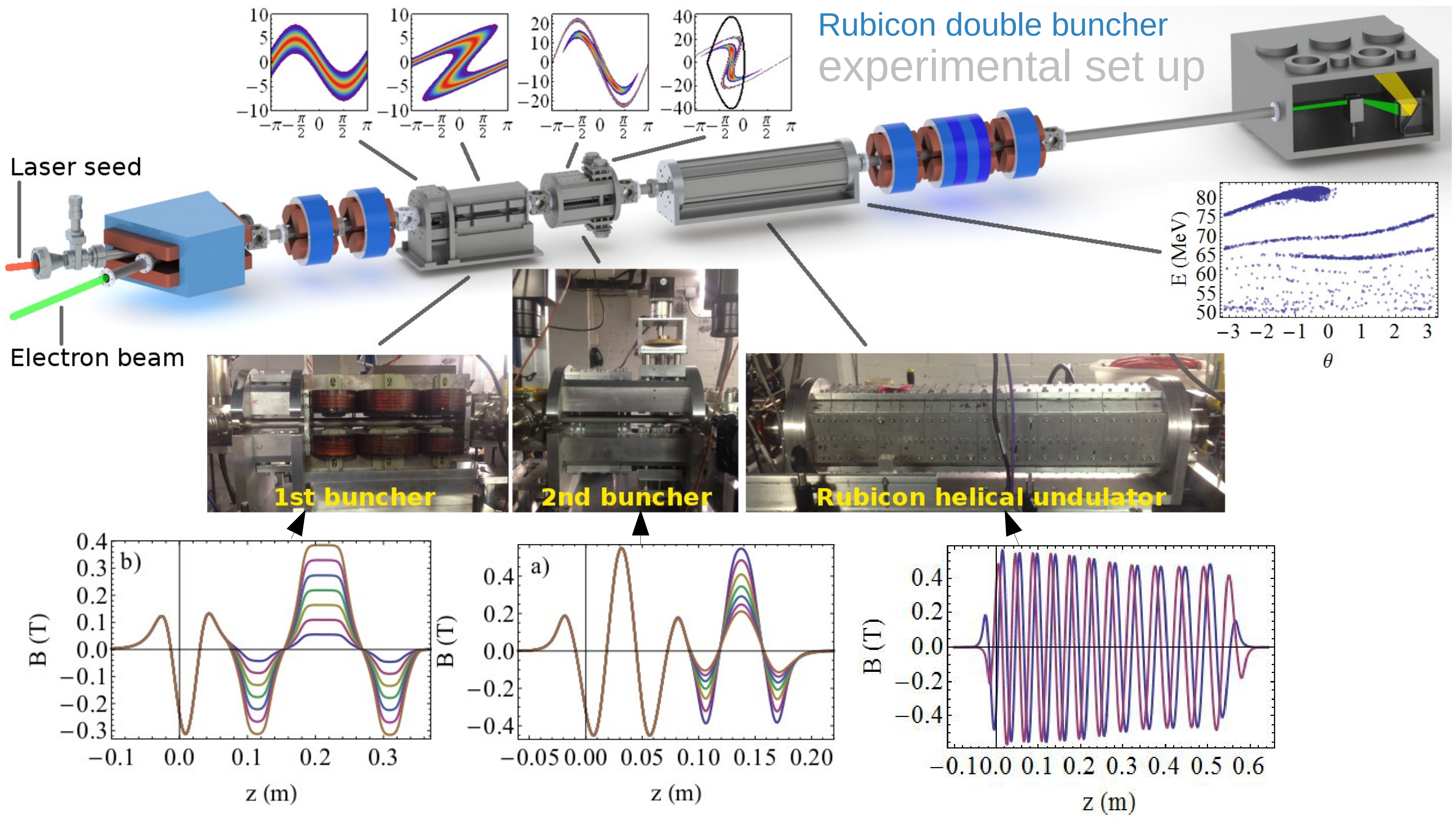
GPT – 3D Radia field maps







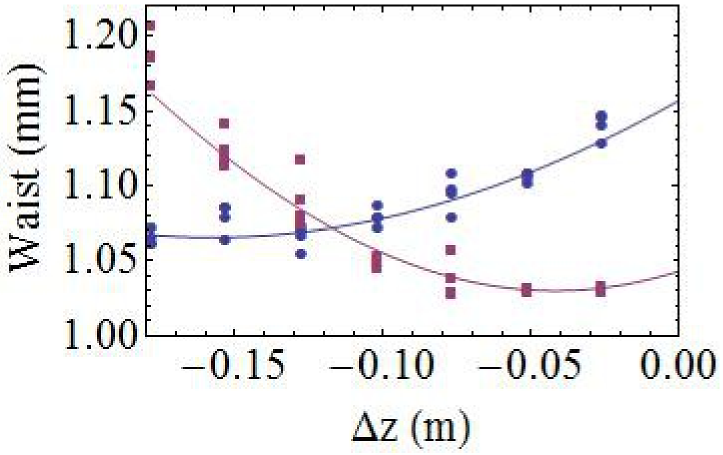



Rubicon double buncher
experimental set up
Laser seed
Electron beam
1st buncher
2nd buncher
Rubicon helical undulator
E (MeV)
θ
B (T)
z (m)
b)
a)

Rubicon double buncher

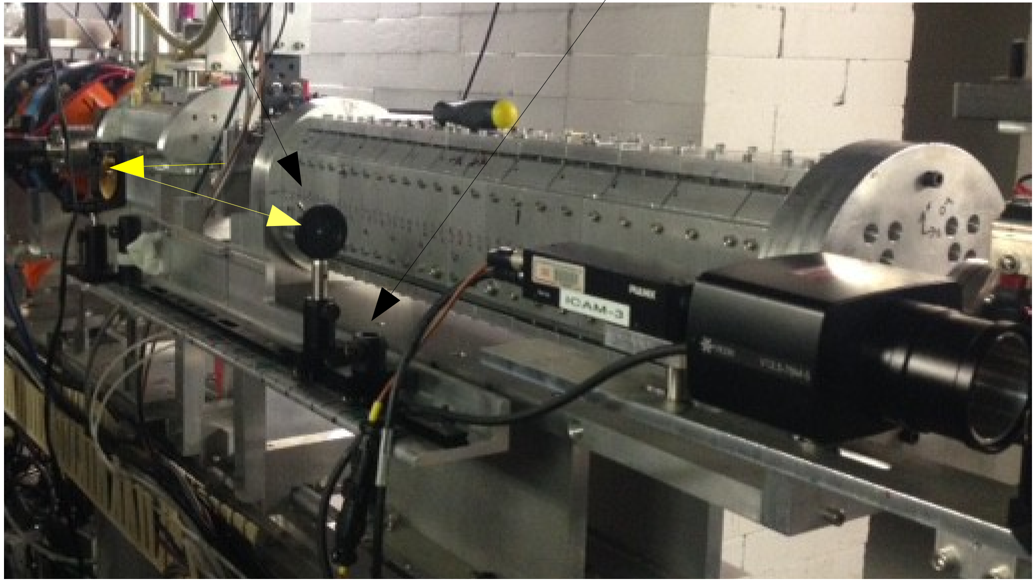
experimental set up pt. II

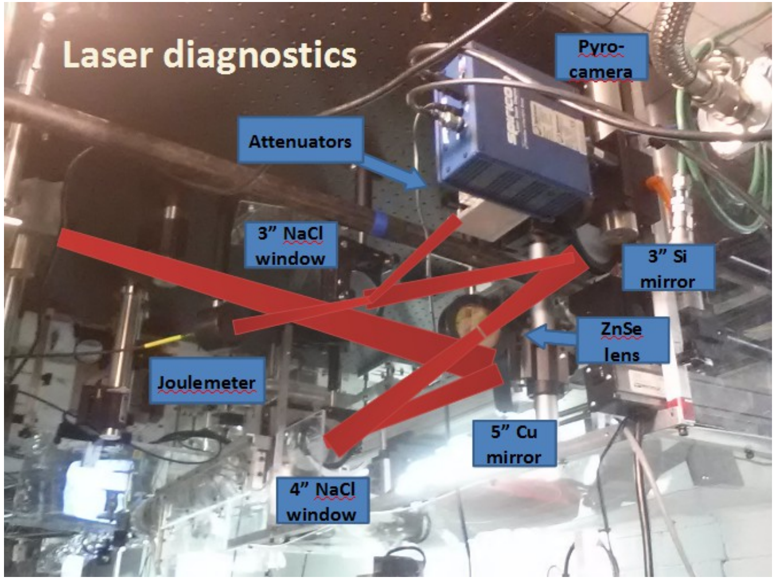
- e-beam laser pS scale timing achieved by e-beam controlled transmission through Ge slab – fine timing: delay stage
- vary laser polarization: rotate quarter wave plate
- vary laser waist position: move lens
- monitor high power laser energy and pointing stability on ceiling



Alignment iris

Pyro camera for waist scan or photodiode for Ge tir

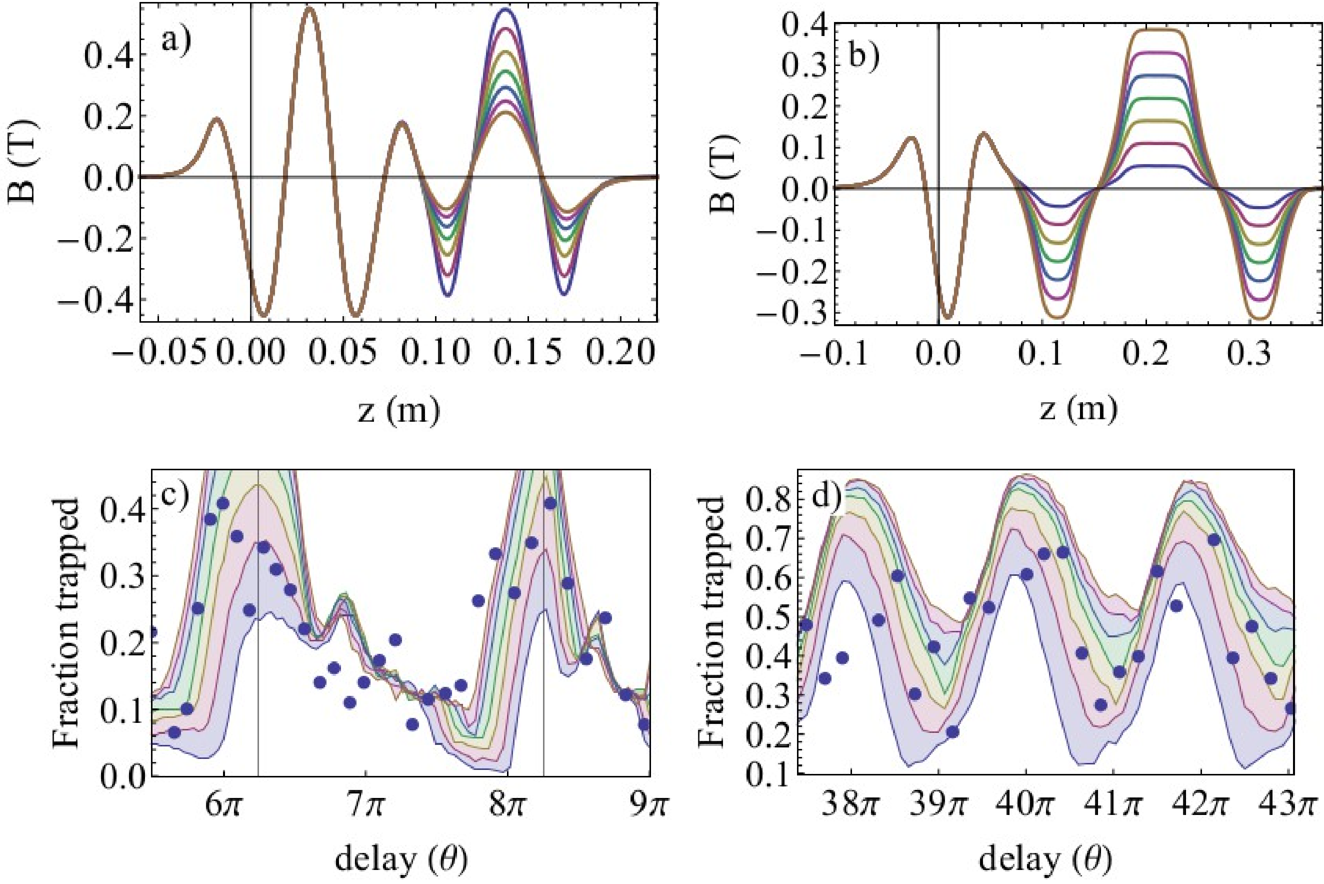




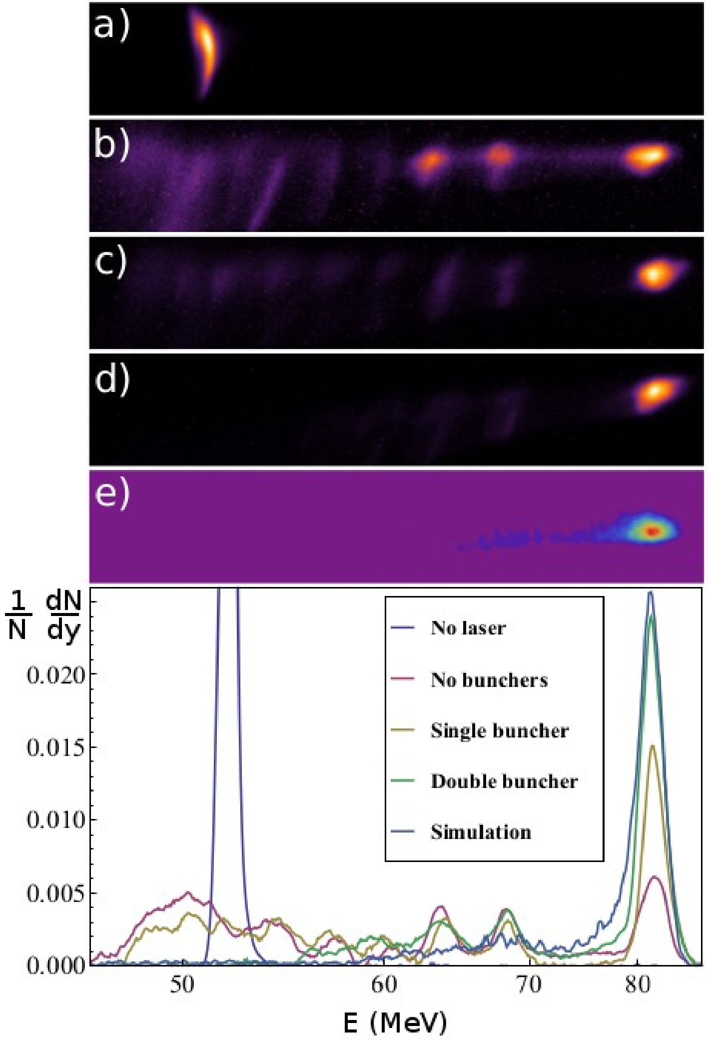
Rubicon double buncher

Optimization

- After optimizing fine timing: scan over first pre-buncher chicane gap (only one buncher installed) varying injection phase and compression
- Set first chicane gap at peak: Scan over second buncher EM chicane current
- lines show GPT simulation predictions with laser energy 70-100 GW in steps of 8 GW



all shots from same run with 75 GW
Simulation done with experimental e-beam and laser focusing



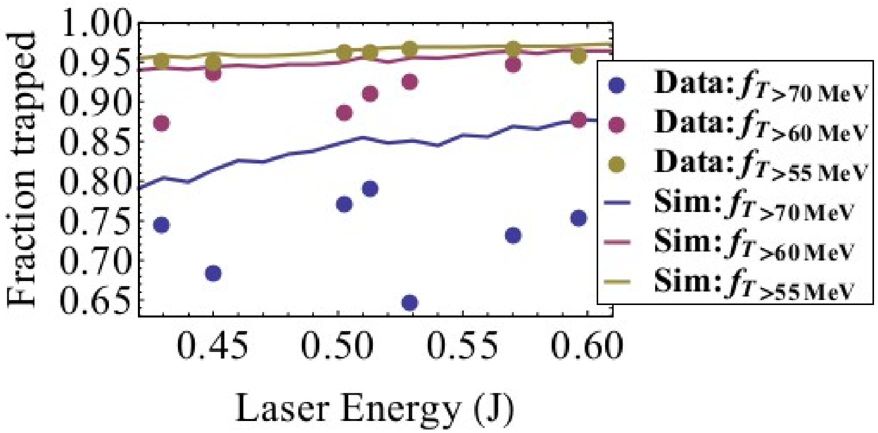
a) No laser (blue)

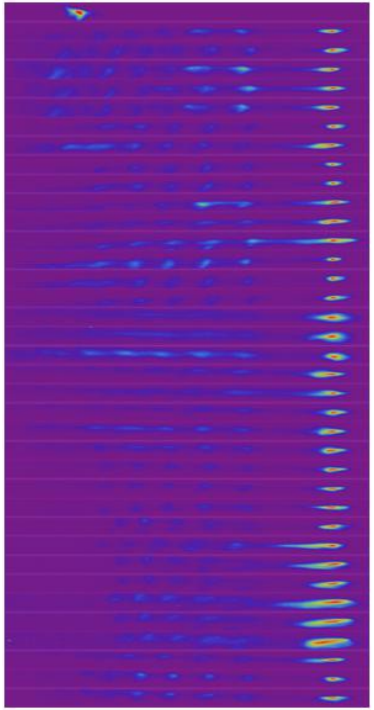
b) No pre-bunching: ~25% accelerated (red)

c) Single buncher: ~45% accelerated (yellow)

d) Double buncher: ~70% accelerated (green)

e) GPT Simulation: ~80% accelerated (blue)





36 consecutive shots demonstrating IFEL double buncher stability. Note: top shot is the unaccelerated electron beam.

Q=-25A

Q=-20A

Q=-15A

Q=-10A

Q=-7A

Q=-5A

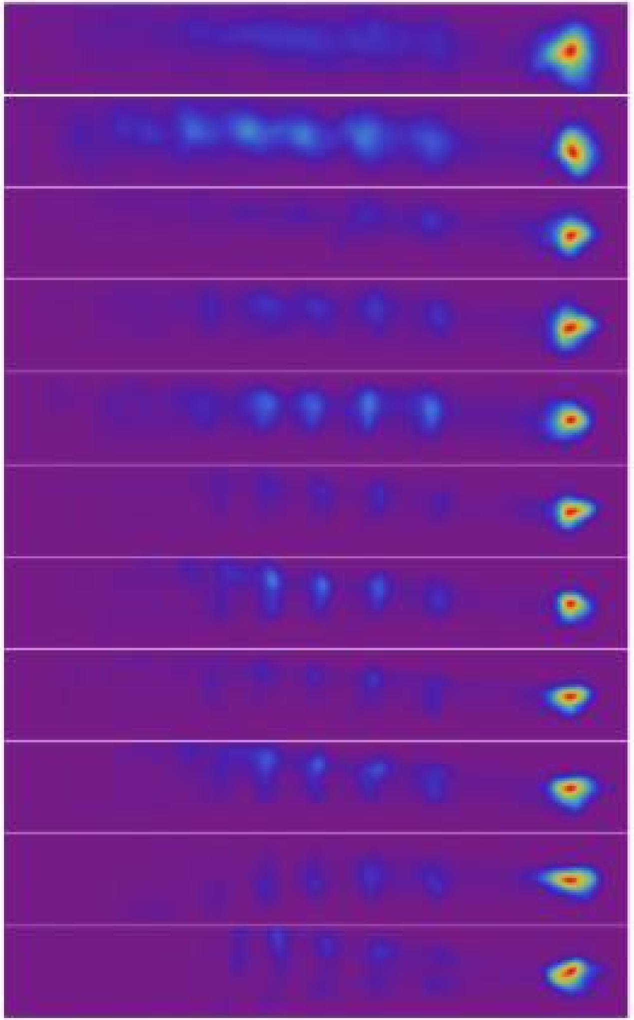
Q=-2A

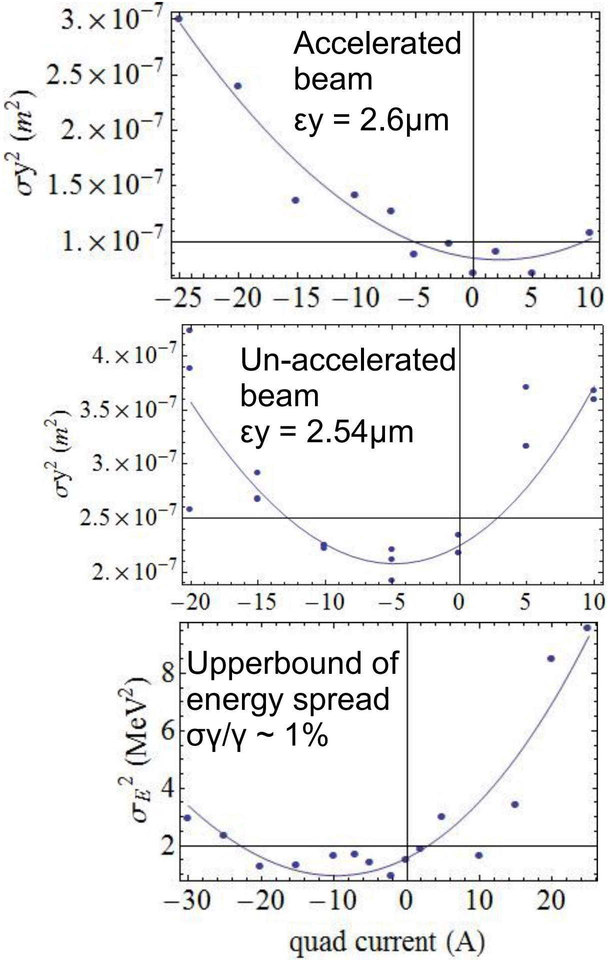
Q=0A

Q=2A

Q=5A

Q=10A

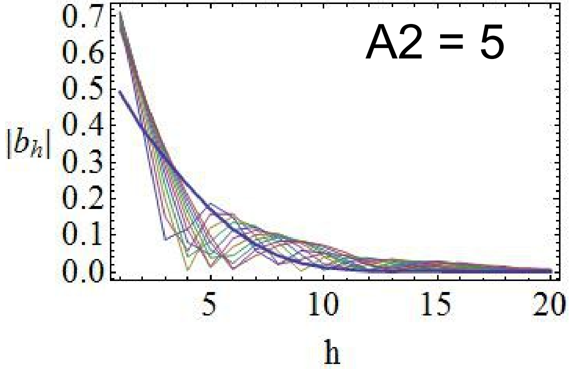


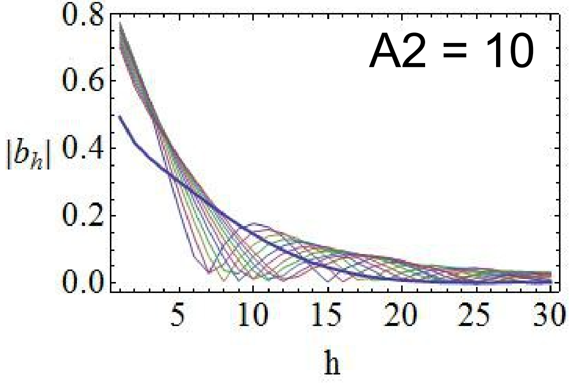


Potential uses

Harmonic content

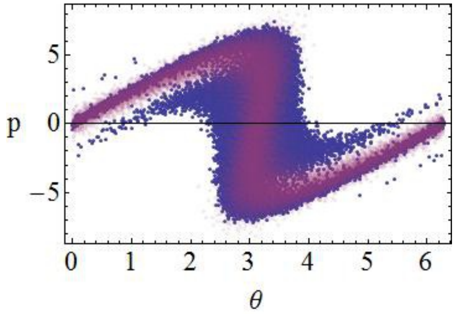
Harmonic content varying A2/A1 slightly
(blue line: single buncher)

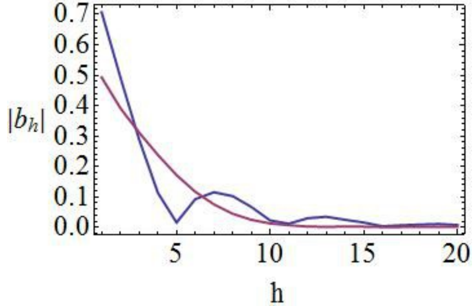


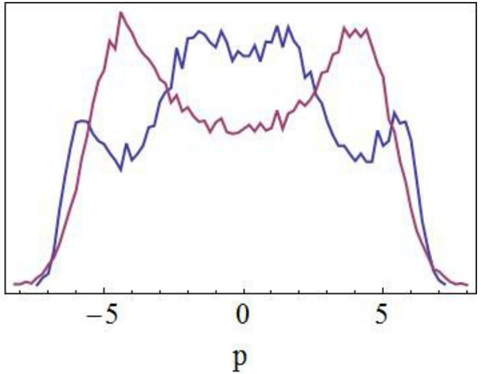


Energy distribution

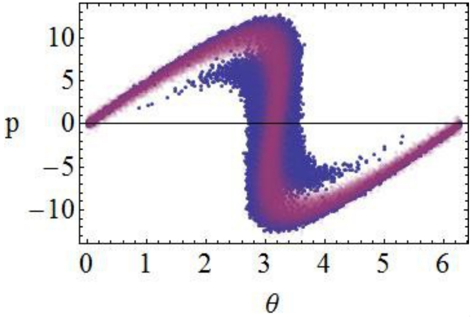
Example: A2 = 5

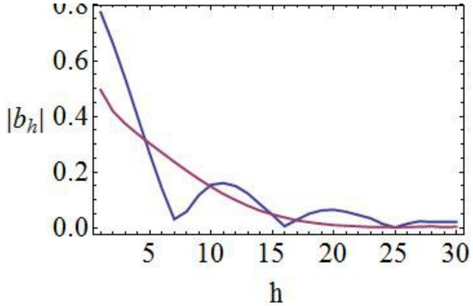


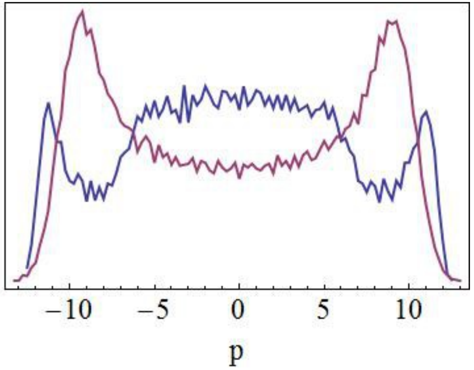




Example: A2 = 10







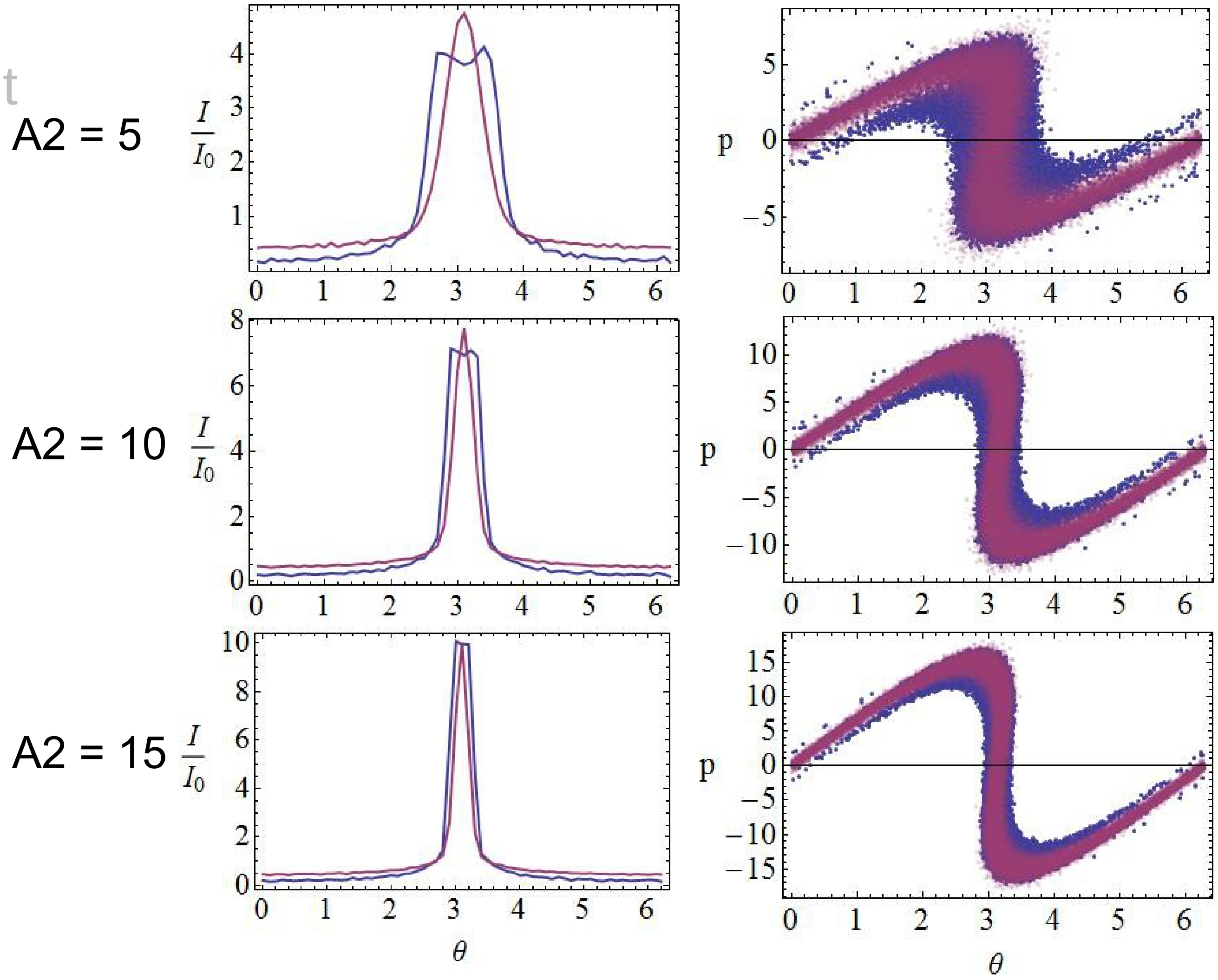
Potential uses

Current enhancement

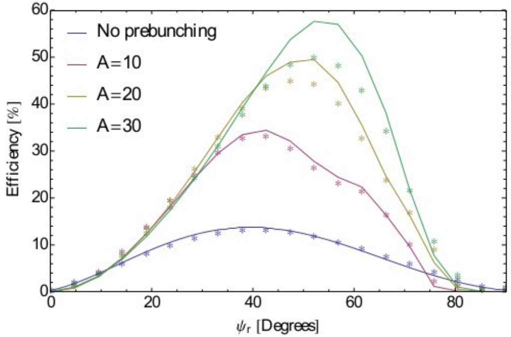
- Modulator-chicane pre-bunching with long wavelength lasers proposed for production of a current spike resulting in reduction of the gain length and pulse length for FEL's (e-sase)

- Double buncher peak current comparable to single buncher for small modulations

- Flat top distribution could be advantageous for pulse lengths comparable to slippage length



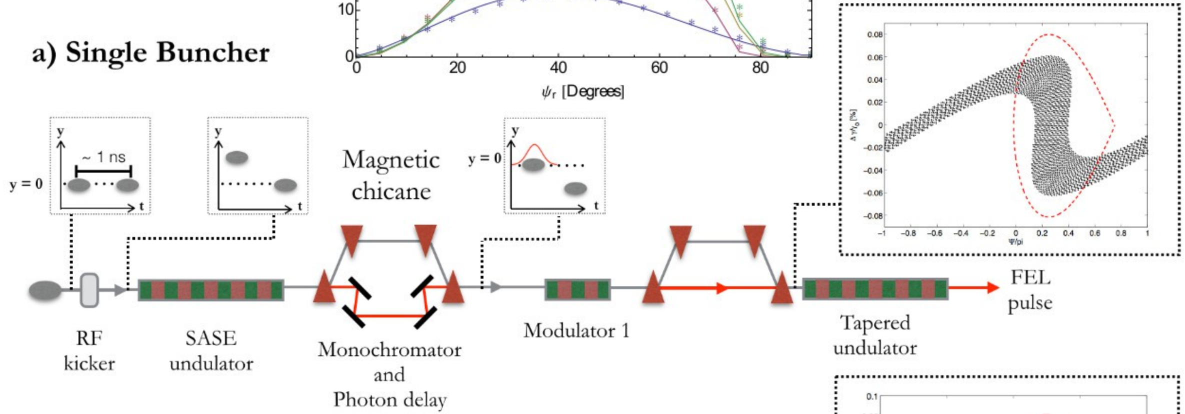
Courtesy of Claudio Emma

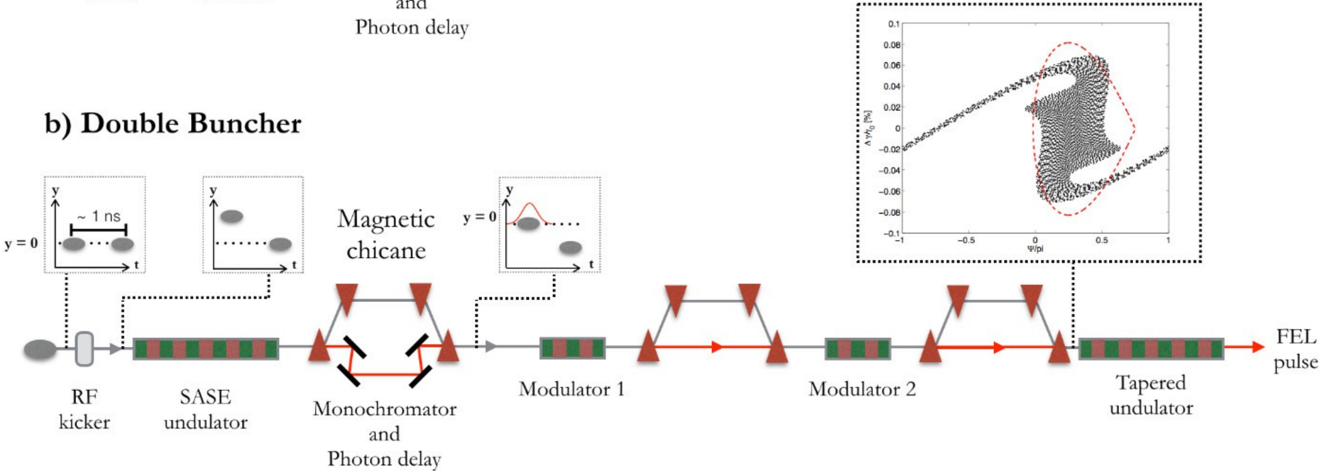


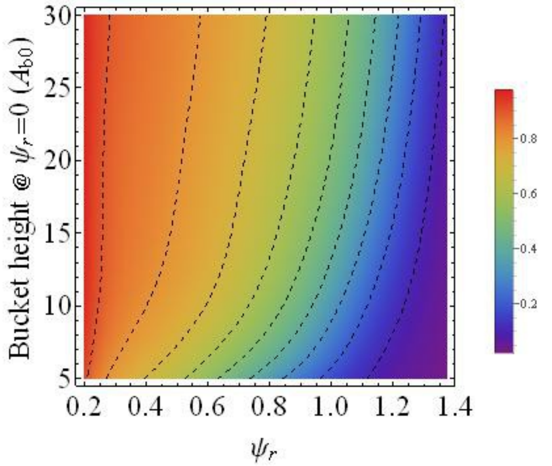
Potential uses

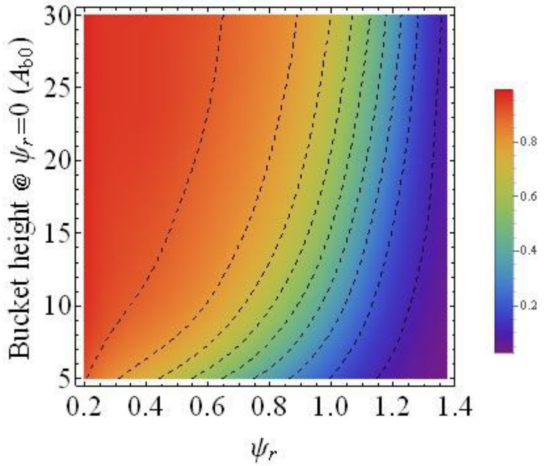
High efficiency FEL

Fresh bunch self seeding









Potential uses

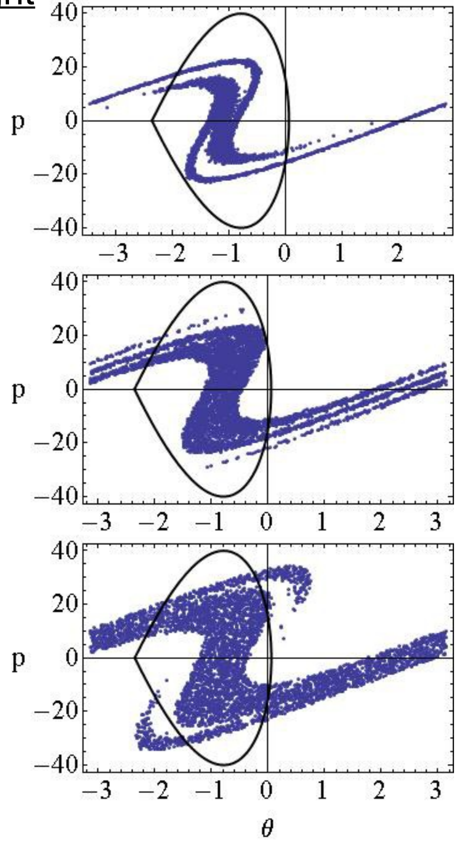
Chirp problems

Bucket height
A_b = 40

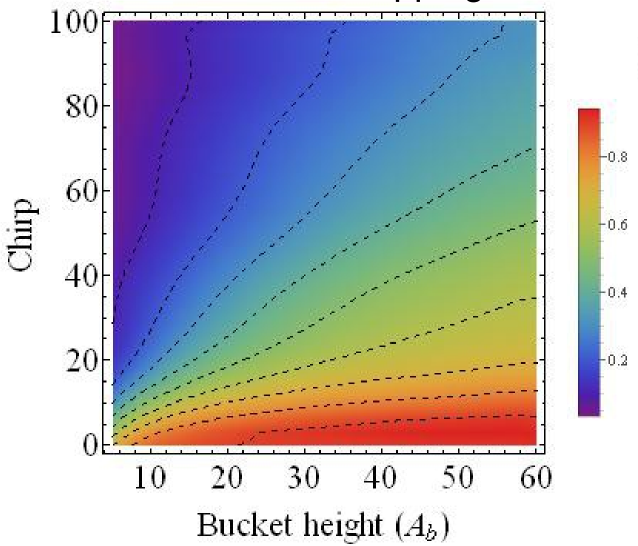
Chirp = 0

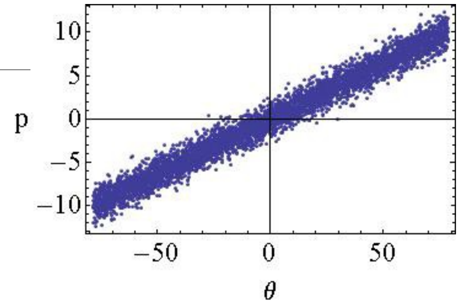
Chirp =10

Chirp =20



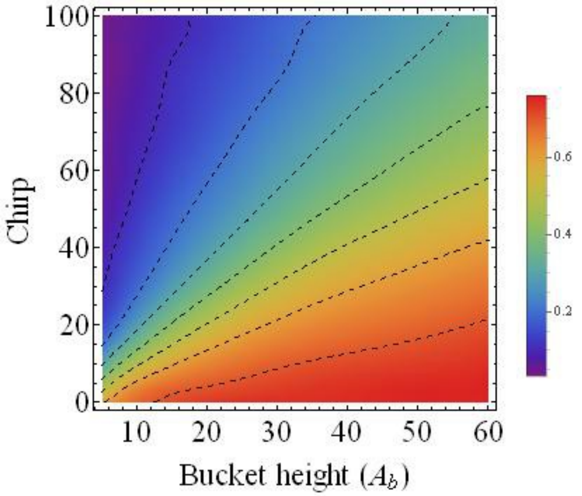
Double buncher trapping: f_{TDB}

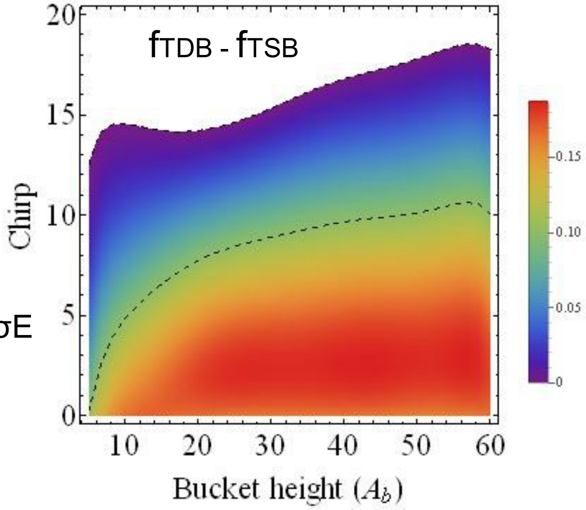




Chirp ≡ΔE/σE = 20

Single buncher trapping: f_{TSB}





Conclusion

- Validation of cascaded modulator-chicane pre-bunching scheme.

- Demonstration of up to 96% initial trapping of a relativistic electron beam in an Inverse Free Electron Laser using cascaded modulator-chicane pre-bunching.

- Acceleration of 78% of the beam to final energy 52 MeV to 82 MeV

- Stable acceleration, stable output energy, good beam quality

- Harmonic content and current enhancement may be beneficial compared to single buncher

- Chirps are a problem!

UCLA

UCLA: P. Musumeci, J. Duris, I. Gadjev, Y. Sakai

ATF: I. Pogorelsky, M. Polyanskiy, M. Fedurin, C. Swinson, M. Babzien, K. Kusche, M. Montemagno, P. Jacob, G. Stenby, B. Malone, M. Palmer

Radiabeam: A. Murokh

Work supported by: U.S. DHS DNDO under Contract No. 2014-DN-077-ARI084-01, NSF grant 145583 and DOE grant No. DE-SC0009914

Thanks