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

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Overview

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Review of pre-bunching

Cascaded modulator-chicane pre-bunching

- motivation
- design

The experiment

- Rubicon IFEL & pre-bunching
- The set-up, the results

Potential impact (Single buncher vs. Double buncher)

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

Conclusion

Single Buncher

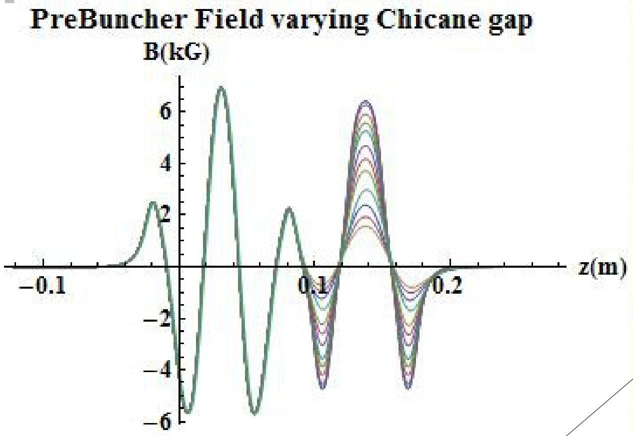
- Single period, planar, halbach undulator

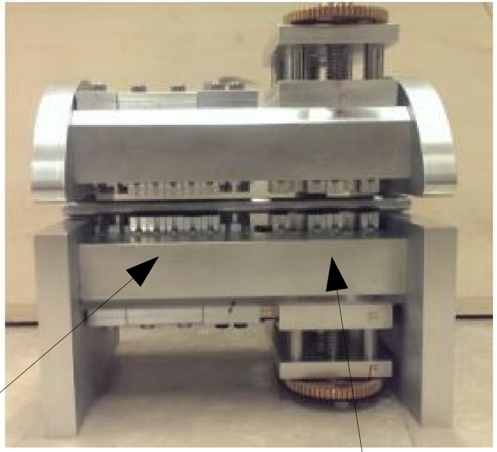
- Permanent magnet, variable gap chicane

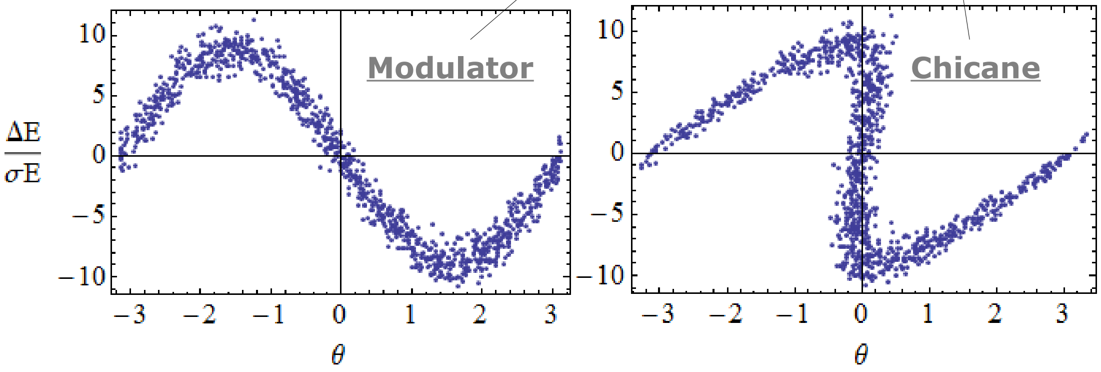
- Laser imparts sinusoidal energy modulation

- Chicane dispersion converts to density modulation

- Chicane delay allows for control of injection phase





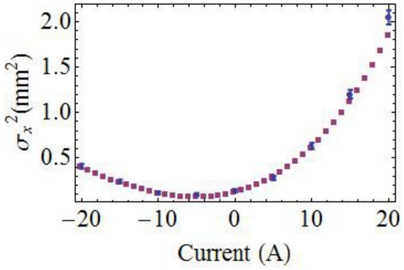


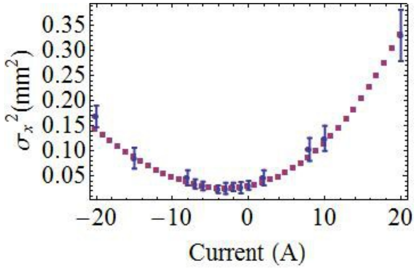
Rubicon results

Single Buncher

Un- accelerated beam **Accelerated beam**

2.3 µm emittance **2.4 µm emittance**





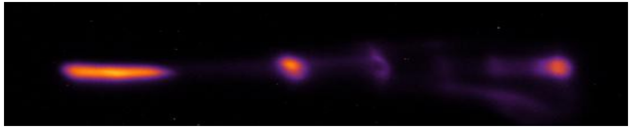
Rubicon IFEL experiment

52 MeV → 95 MeV

Strongly tapered helical undulator

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

Increased fraction accelerated: 30% → 60%

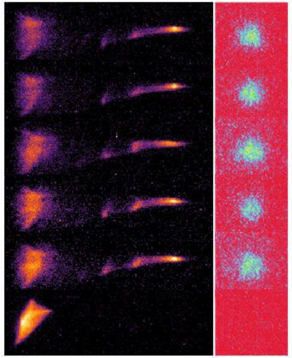


Nocibur high efficiency energy extraction

65 MeV → 35 MeV

45% decelerated – 30% efficiency

Increased efficiency by factor of 3



RubiconICS

12 KeV X-Rays from 80 MeV

The double buncher

Simple model

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

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

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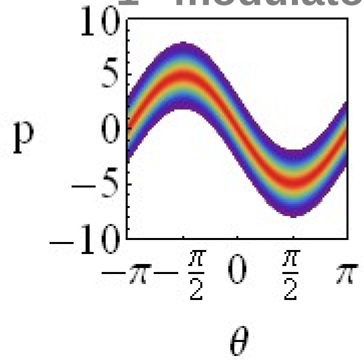
(Received 24 October 2012; published 28 January 2013)

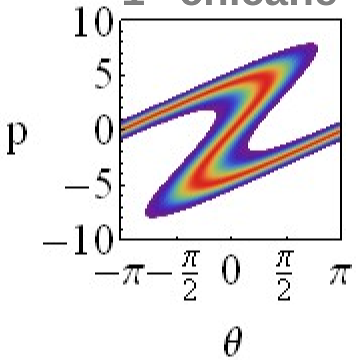
½ period planar undulator
(small modulation)
p=Δγ/σγ **A1**
p' = p+ A1*sin[θ]

1st modulator



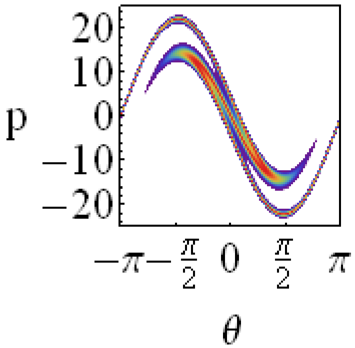
Large R56 chicane compressor
(over-rotate) **B1**
θ'=θ+B1*p'
π/A1B1~1

1st chicane



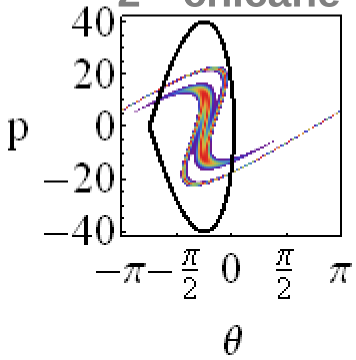
1 period planar undulator
(large modulation)
Utilize pre-existing pre-buncher
A2

2nd modulator



Small R56 chicane compressor
(bunch)
~97% of particles inside of pondermotive bucket
π/A2B2~2 **B2**

2nd chicane



Rubicon double buncher

design of the double buncher

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

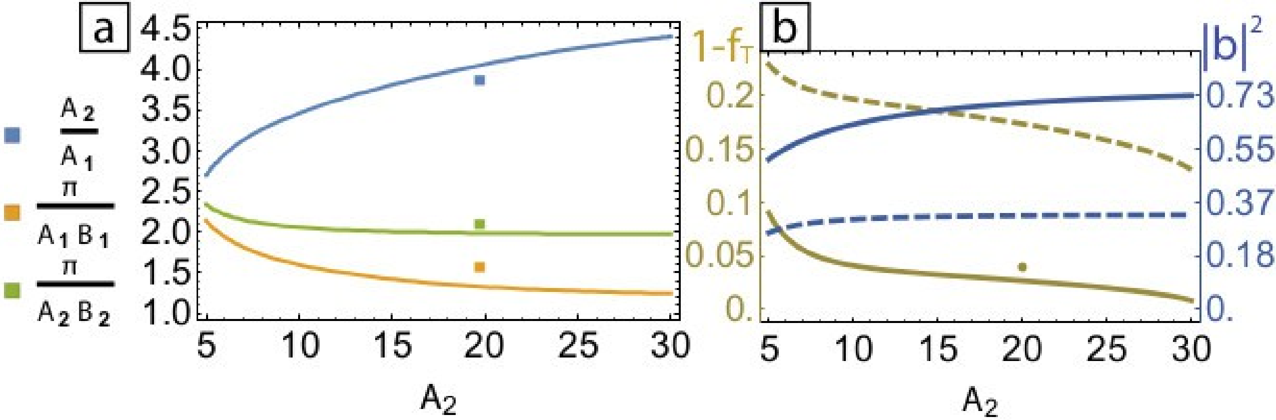
- Double buncher parameters optimized relative to second modulation

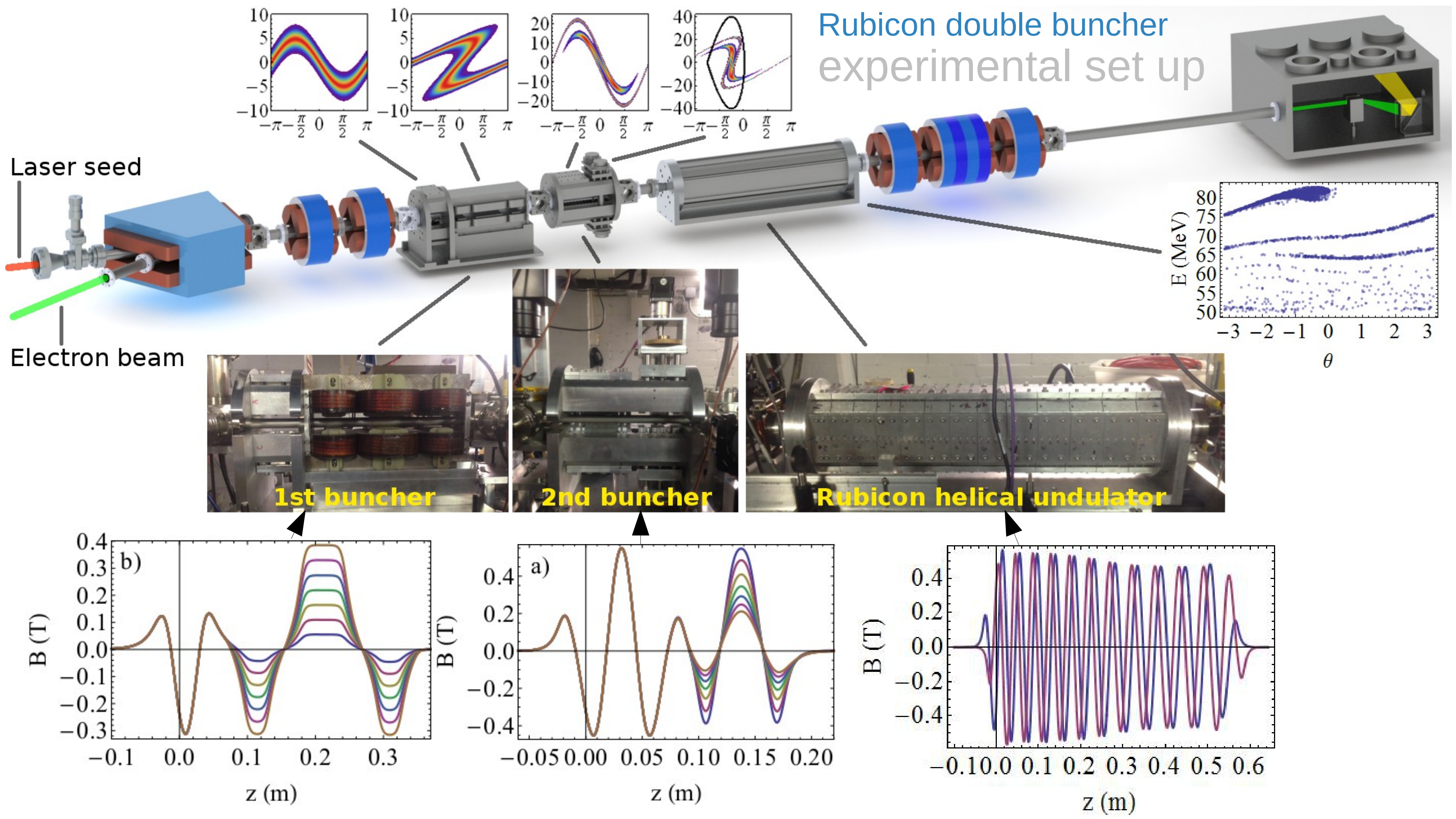
- A1*B1 = phase rotation of 1st energy modulation peak

- A2*B2 = phase rotation of 2nd energy modulation peak

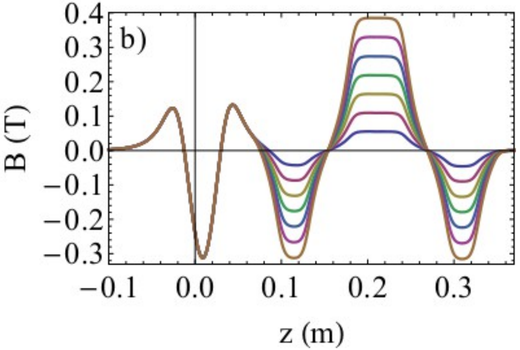
- A2/A1 = ratio of modulations
    - A1 > 1 for any noticeable effect

- Comparison with single pre-buncher:
    - Injection losses (detrapped particles) decrease by an order of magnitude: 20% to 2%
    - bunching factor squared increases by a factor of 2



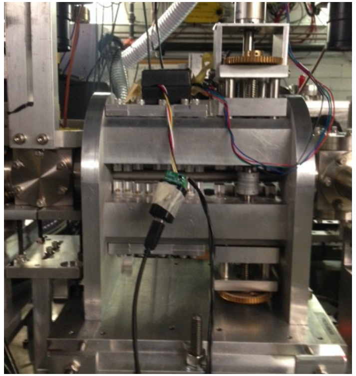


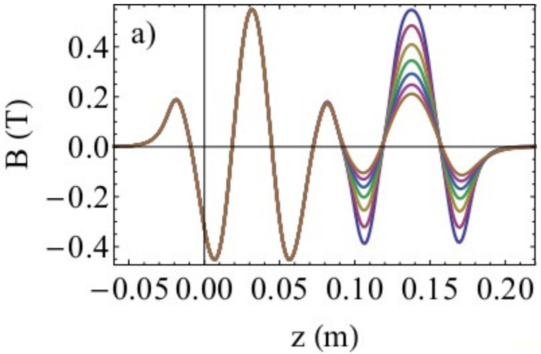
Rubicon double buncher
experimental set up
Laser seed
Electron beam
1st buncher
2nd buncher
Rubicon helical undulator
E (MeV)
θ
B (T)
z (m)
b)
a)



1st buncher

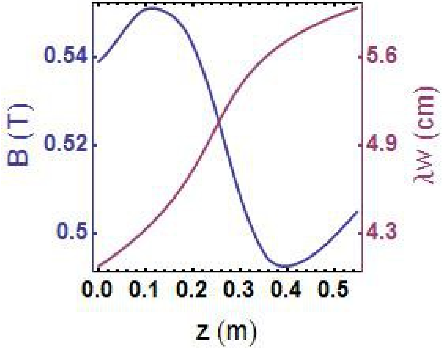
- 7 cm - half period – planar undulator
- electro-magnetic chicane
    - R56 0-900 um





2nd buncher

- 5 cm - 1 period – planar undulator
- variable gap permanent magnet chicane
    - R56 40-90 um



Rubicon undulator

- 4-6 cm period – 11 period - helical undulator
- gap tapered
- resonant phase: -π/4
- resonant energy: 52- 82 MeV

design of the double buncher

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

Design considerations

- Original pre-buncher as second buncher

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

- A2 < initial bucket height
  - laser diffraction
  - planar vs. helical coupling

Experimental parameters

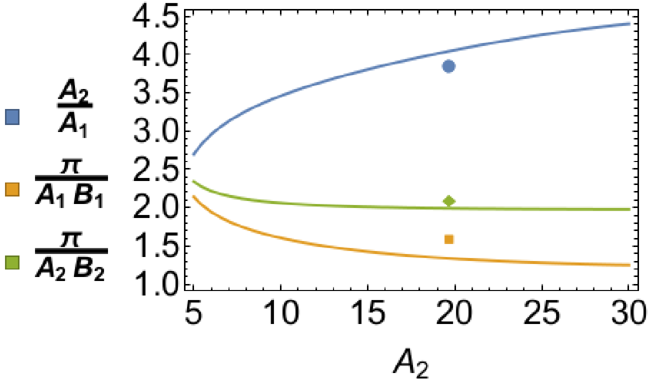
- energy spread: **σγ/γ = 0.0015**
- Laser power: 75 GW

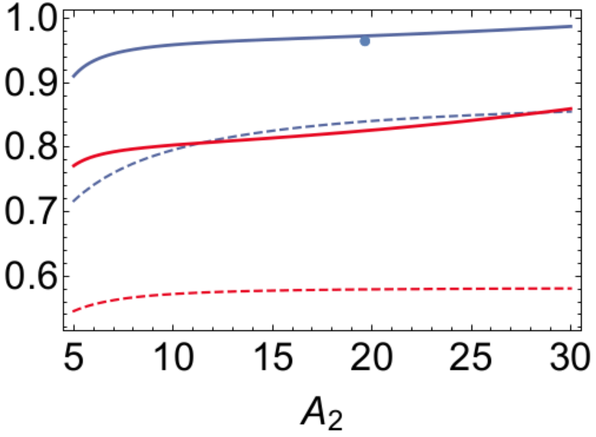
- A1 ~ 5.1 (0.4 MeV)
- B1 ~ 0.44 (R56 = 480 um)
- A2 ~ 20 (1.6 MeV)
- B2 ~ 0.075 (R56 = 80 um)

- A2/A1~ 3.9

- π/(A1*B1) ~ 1.4

- π/(A2*B2) ~ 2.1





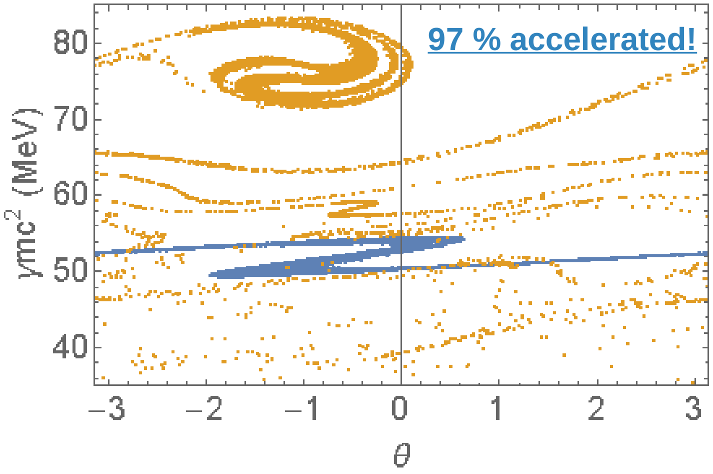
The double buncher

Simulations

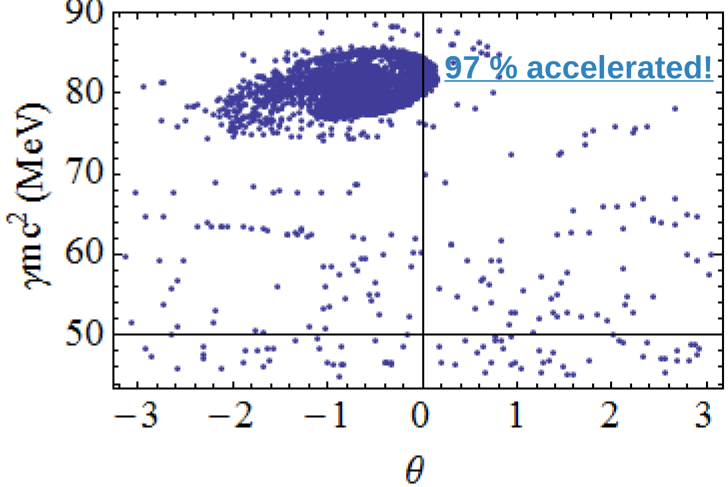
3-D simulation parameters

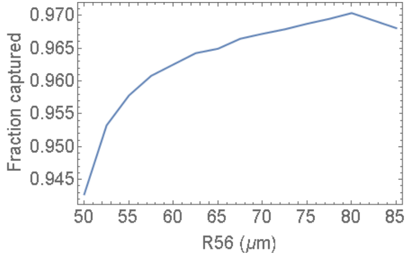
- emittance: 2.5 um
- electron beam waist: 80 um
- electron beam waist position at entrance of 2nd buncher
- laser waist: 1.06 mm
- rayleigh range: 34 cm
- laser waist at center of Rubicon undulator

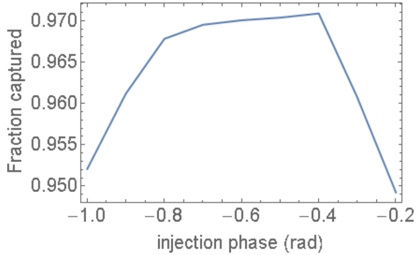
Genesis – 3D Time Dependent

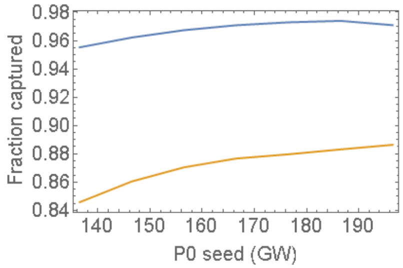


GPT – 3D Radia field maps





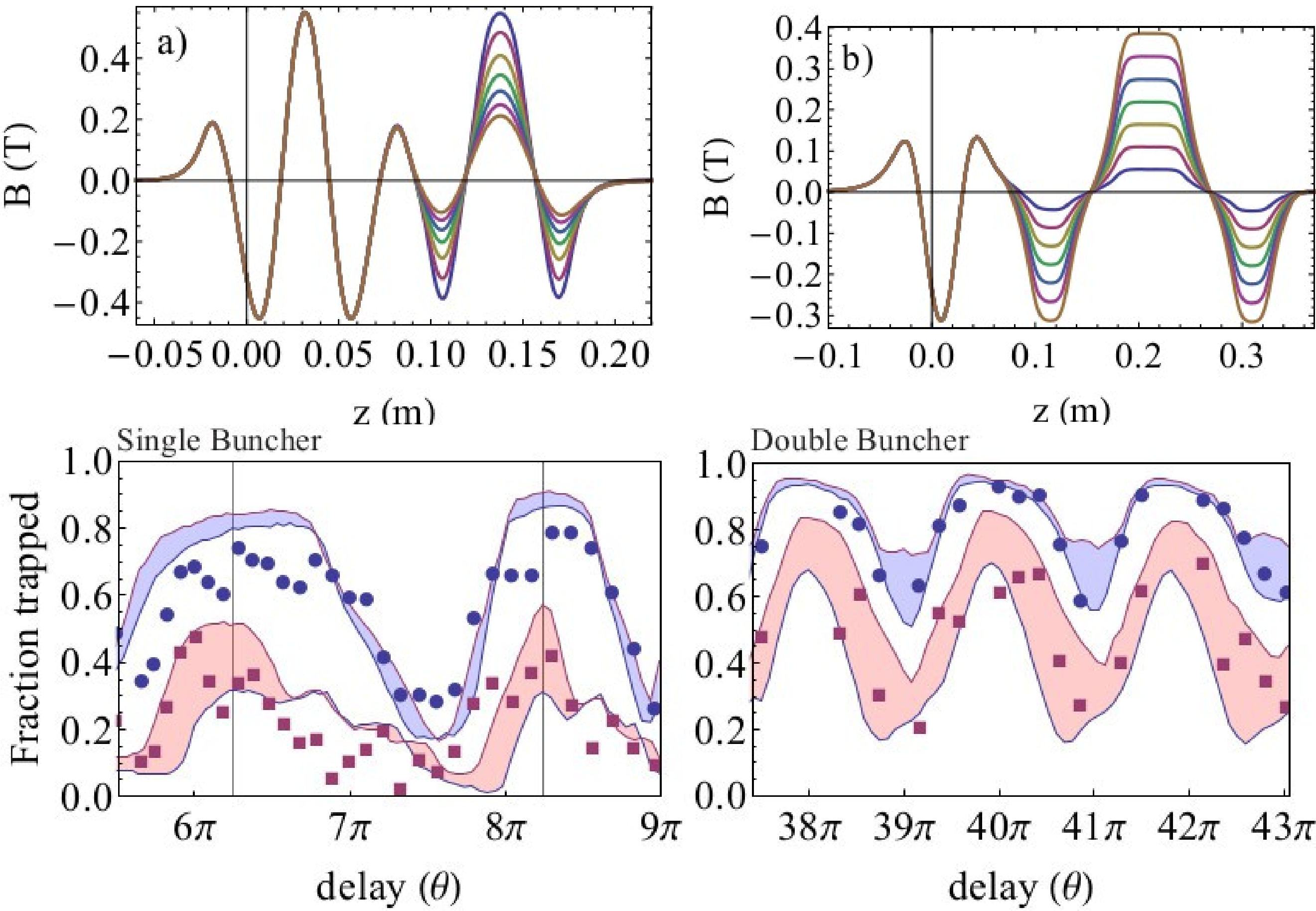




Rubicon double buncher

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



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

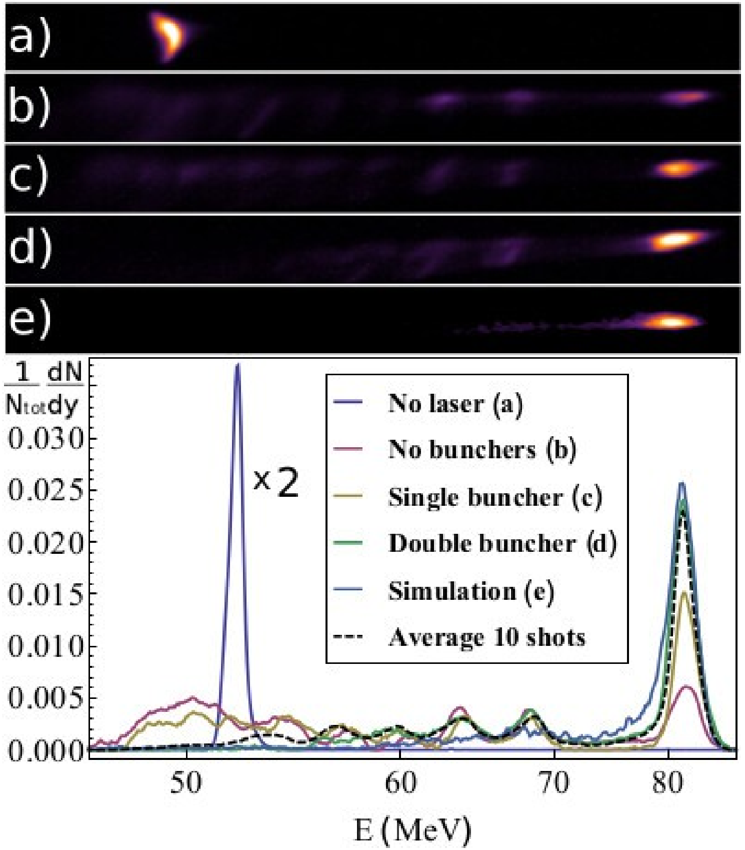
a) No laser (blue)

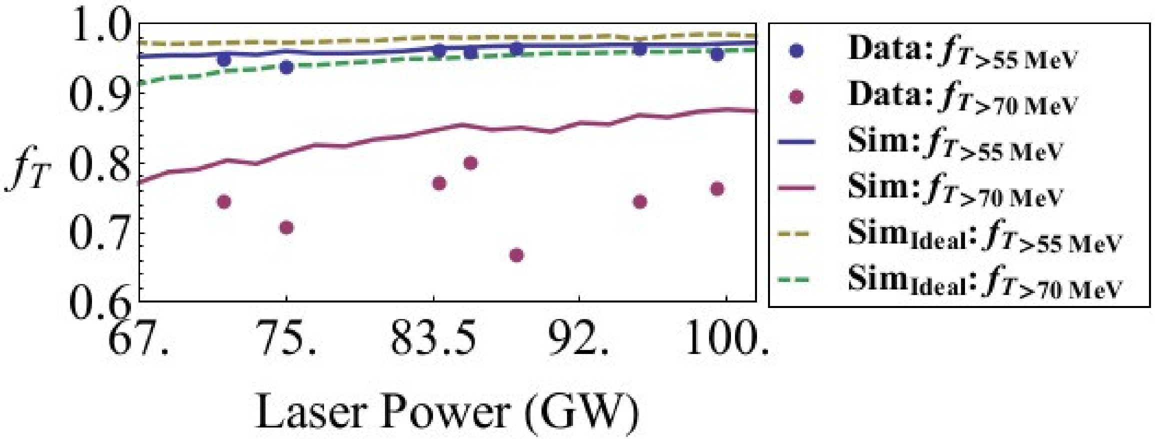
b) No pre-bunching: ~25% accelerated (red)

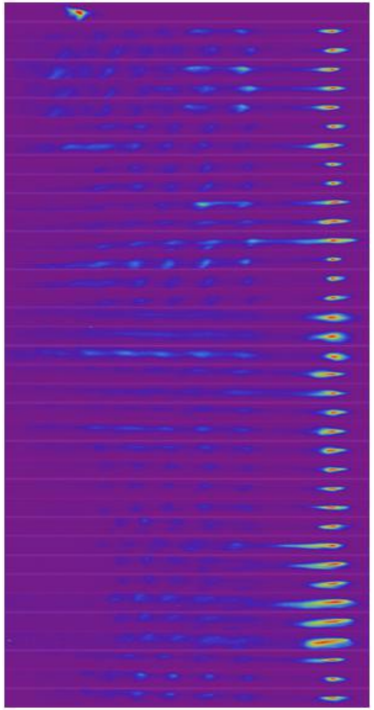
c) Single buncher: ~45% accelerated (yellow)

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

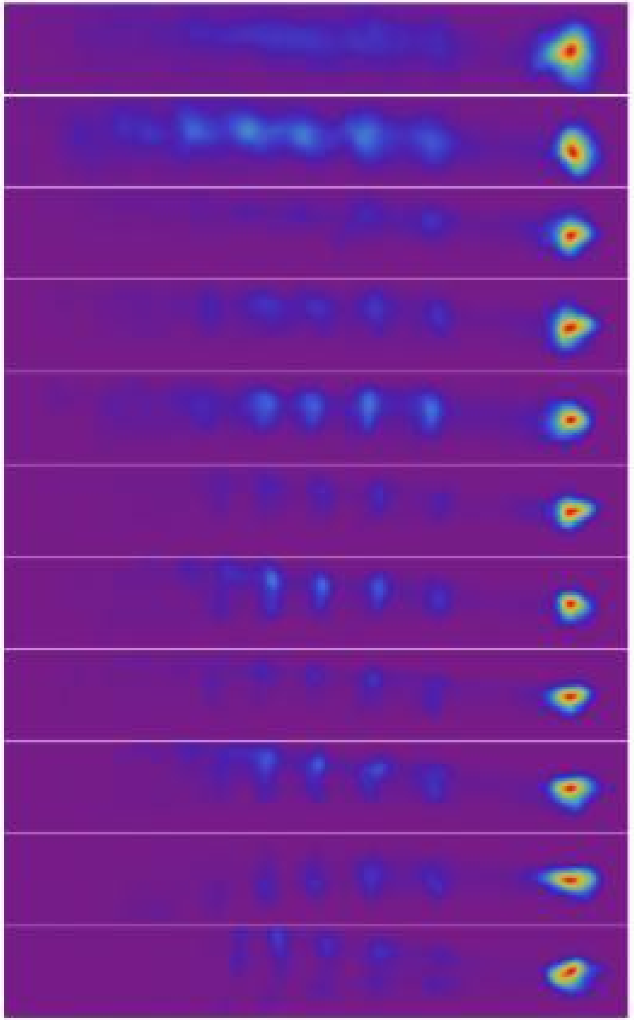
Q=-2A

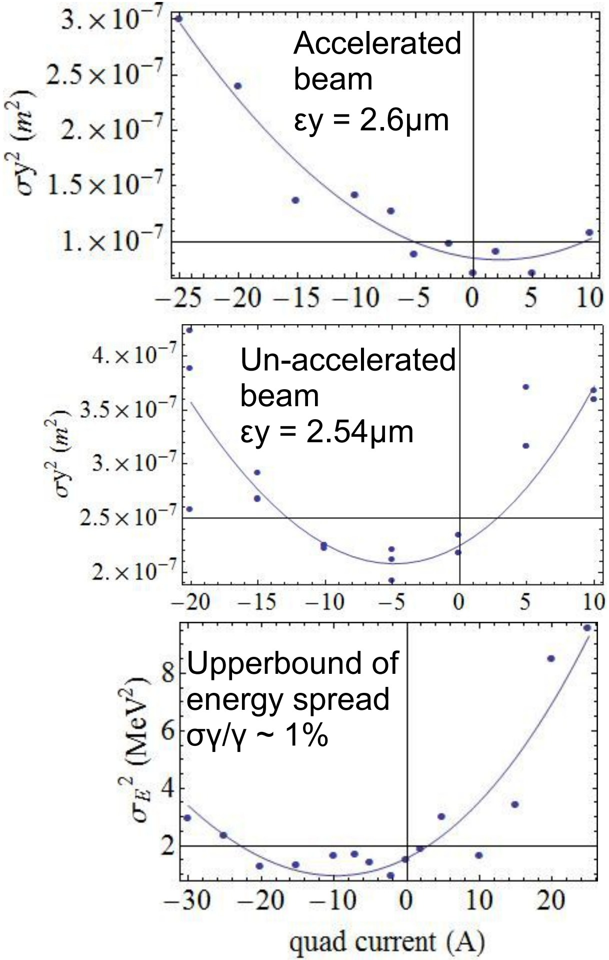
Q=0A

Q=2A

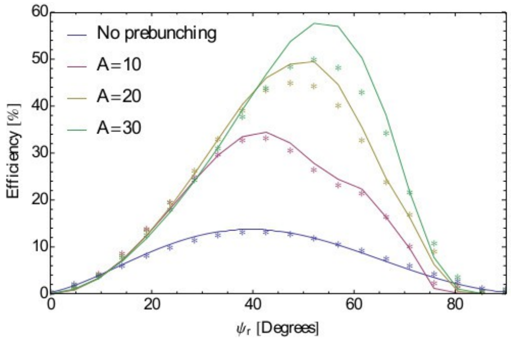
Q=5A

Q=10A





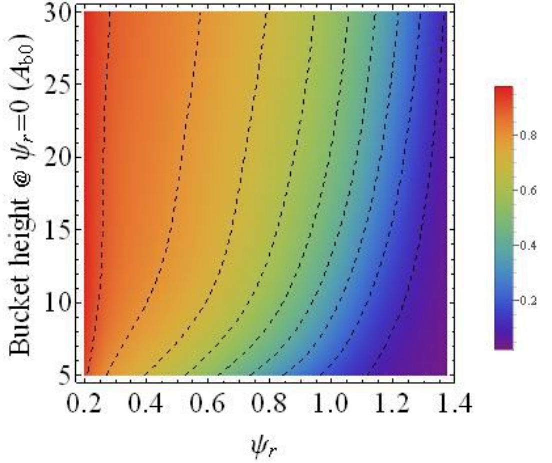
Courtesy of Claudio Emma

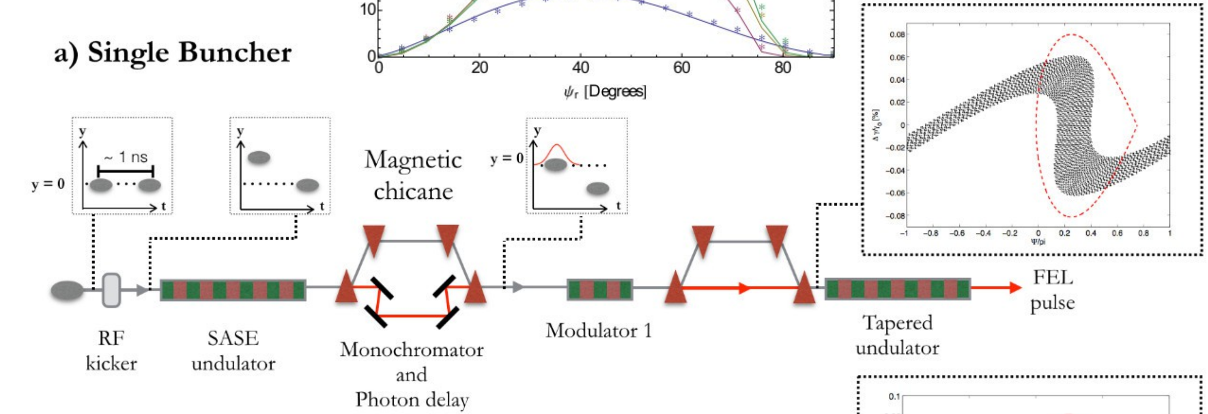


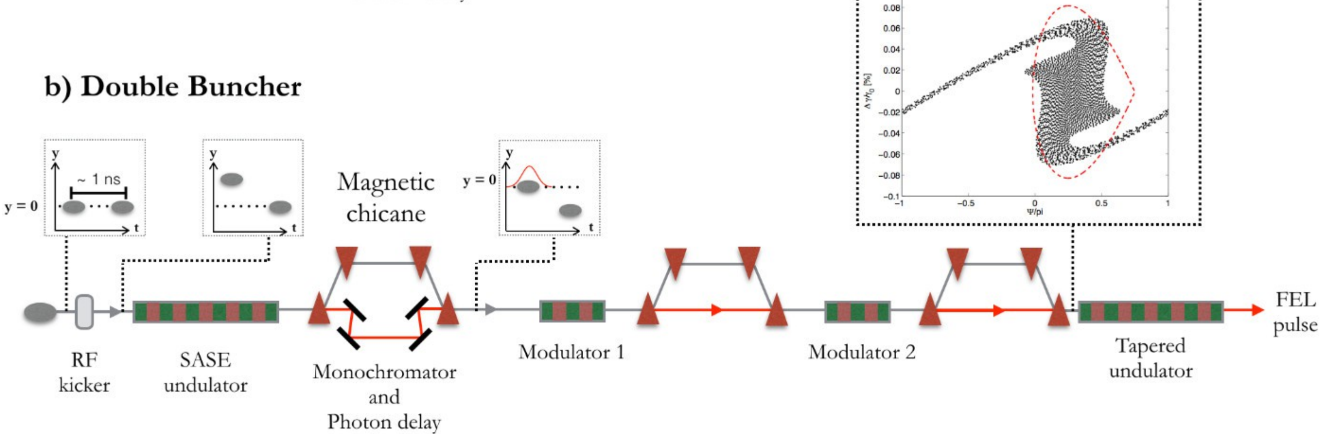
Potential uses

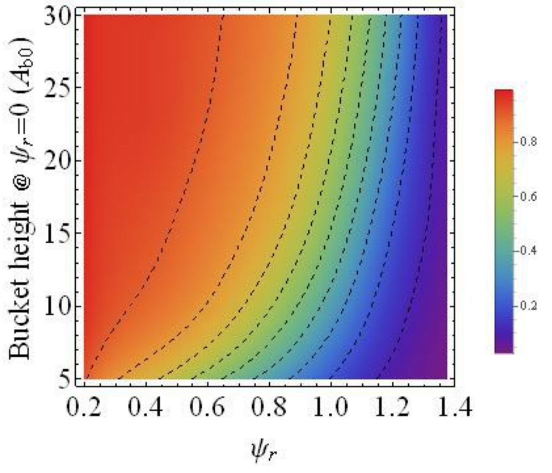
High efficiency FEL

Fresh bunch self seeding





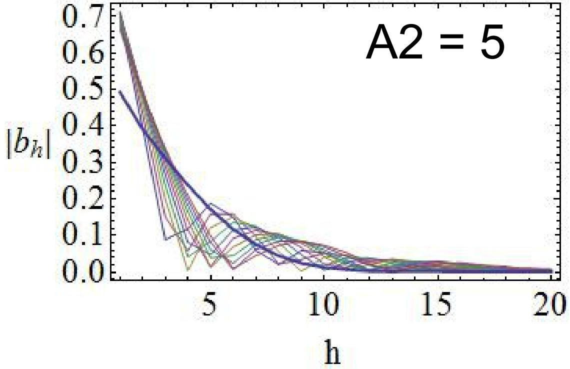


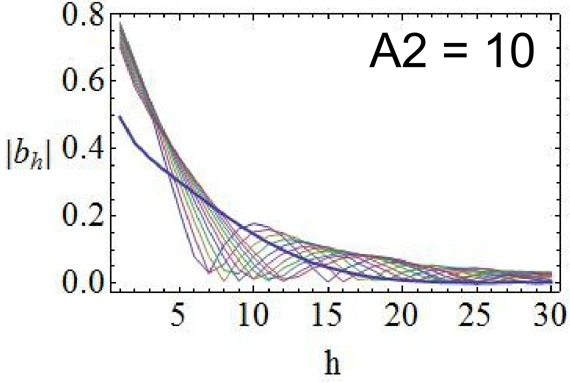


Potential uses

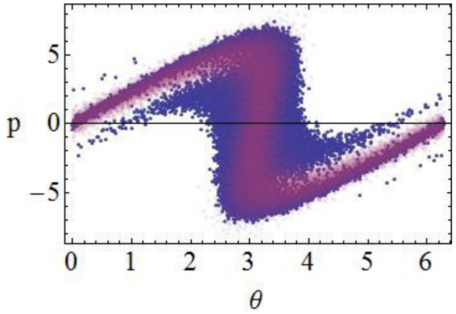
Harmonic content

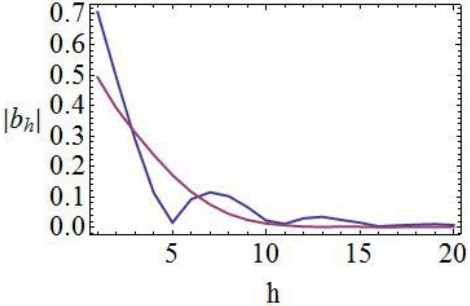
Harmonic content varying A2/A1 slightly
(blue line: single buncher)



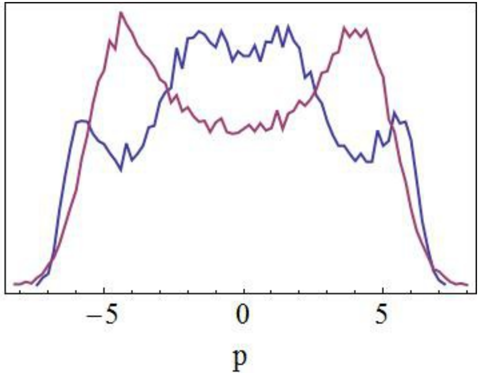


Example: A2 = 5

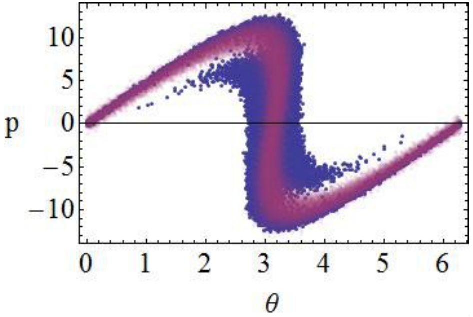


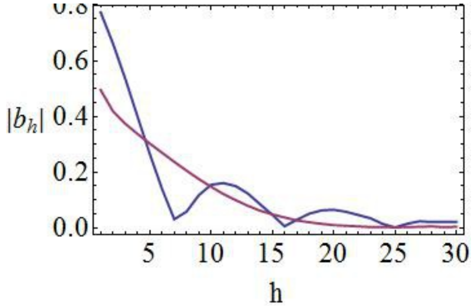


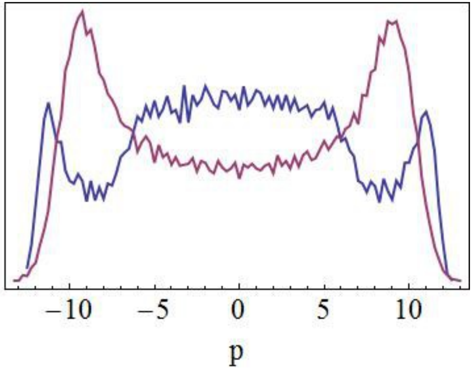
Energy distribution →



Example: A2 = 10





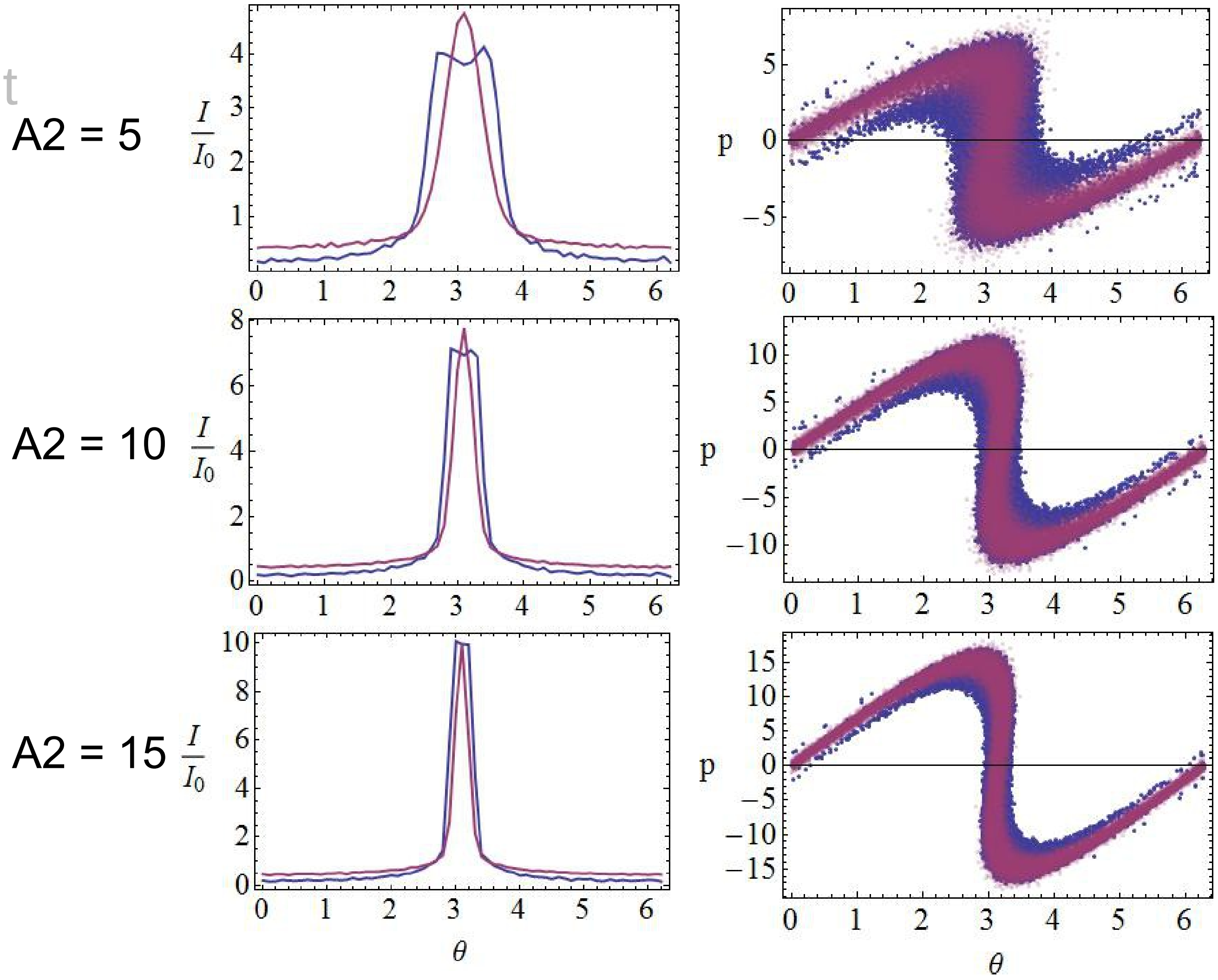


Current enhancement

- 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



Chirp problems

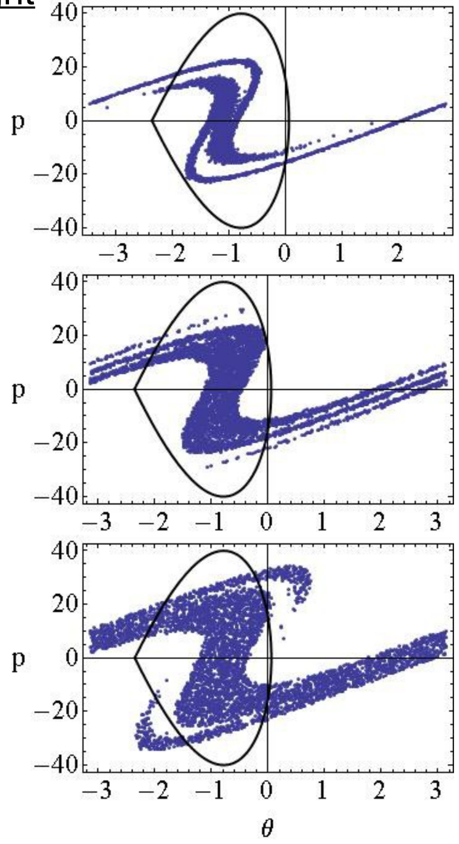
<u>Bucket height</u>

A_b = 40

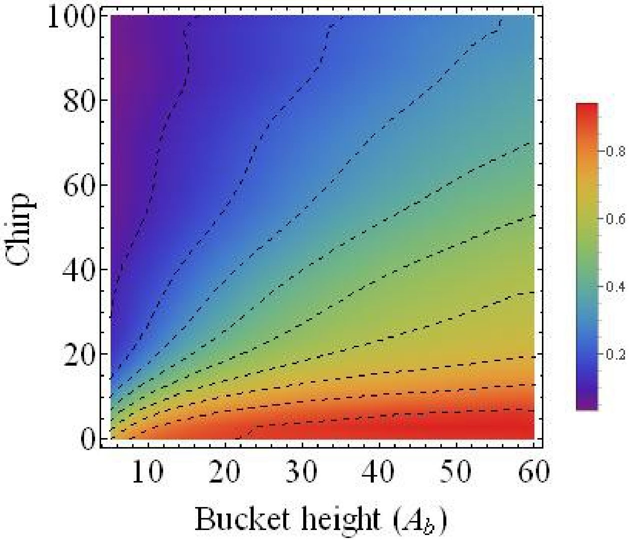
Chirp = 0

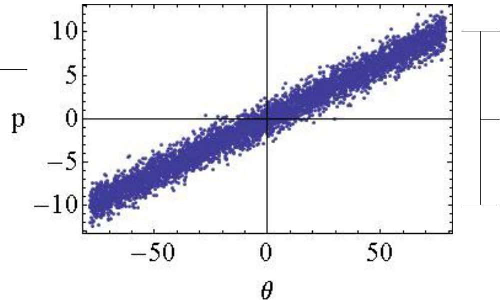
Chirp =10

Chirp =20



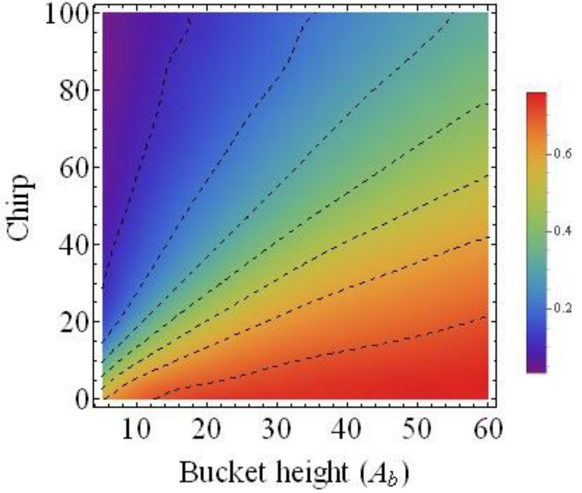
<u>Double buncher trapping:</u> f_{TDB}

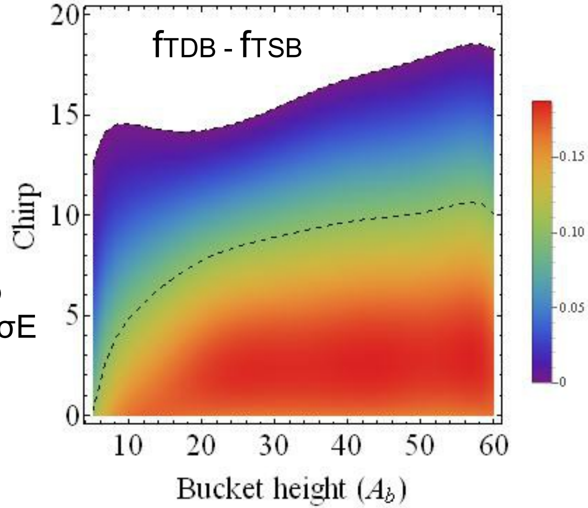




Chirp ≡ΔE/σE = 20

<u>Single buncher trapping:</u> 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