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AE77: Recap of the double buncher experiment and future plans

(advanced IFEL part 1)

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Overview

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Introduction to IFEL

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

Cascaded modulator-chicane pre-bunching (double buncher)

- motivation
- design

The experiment

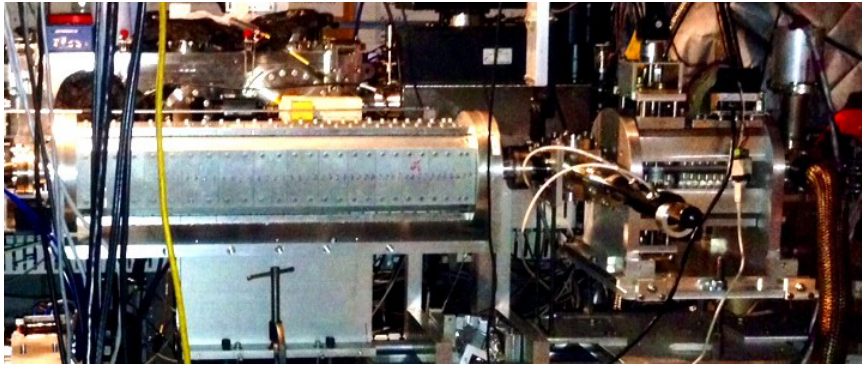
- The set-up, the results

Future plans

- imaging the longitudinal phase space with the deflector and EOB spectrometer

Conclusion

The IFEL



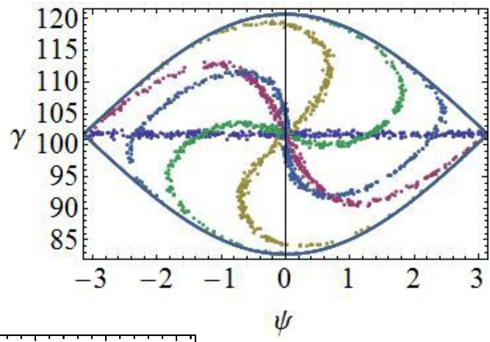
What is an IFEL?

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

- Ponderomotive gradient: $\frac{\partial \gamma^2}{\partial z} = -2kK_l K \sin(\Psi)$

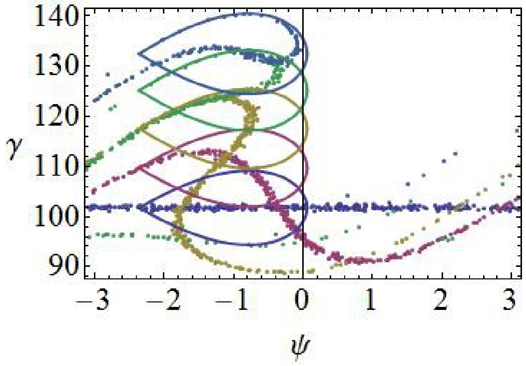
- Resonant energy exchange between a laser and electron beam inside of an undulator: $\frac{\partial \gamma_r^2}{\partial z} = -2kK_l K \sin(\Psi_r) = \frac{\partial}{\partial z}\left(\frac{k(1+K^2)}{2k_w}\right)$ $\quad K_l = \frac{e\lambda E(z)}{2\pi mc^2} \quad K = \frac{e\lambda_w(z) B(z)}{2\pi mc}$

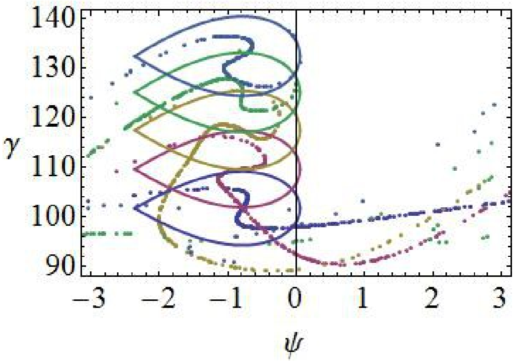
  gradient — phase synchronicity

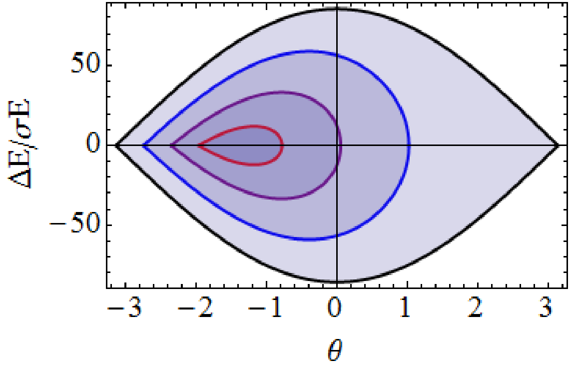


- Rubicon IFEL: Helical halbach undulator – CO_2 laser seed – BNL ATF

- choose design "resonant" phase and energy to satisfy above equation







Pondermotive Bucket

Resonant phase:
0, π/8, π/4, 3π/8

The pre-buncher

Single Buncher

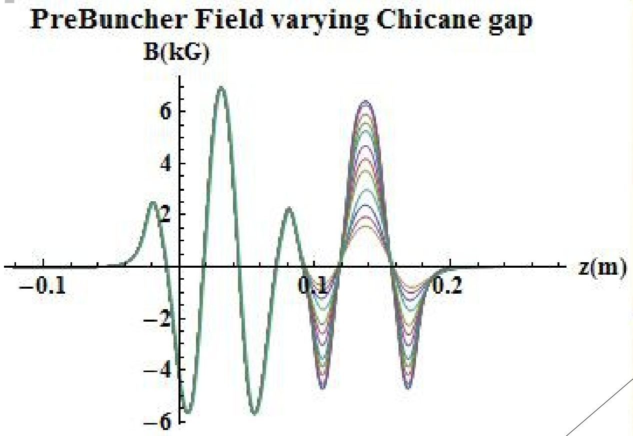
- Single period, planar, halbach undulator

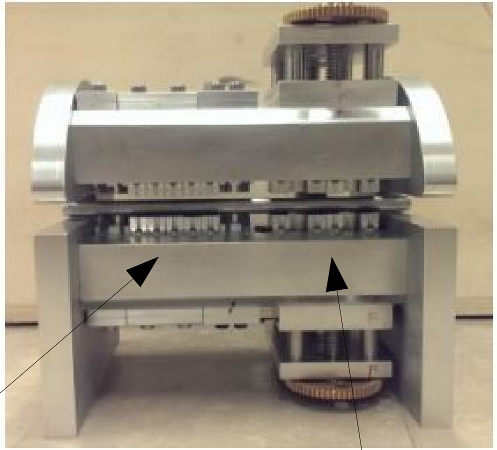
- Permanent magnet, variable gap chicane

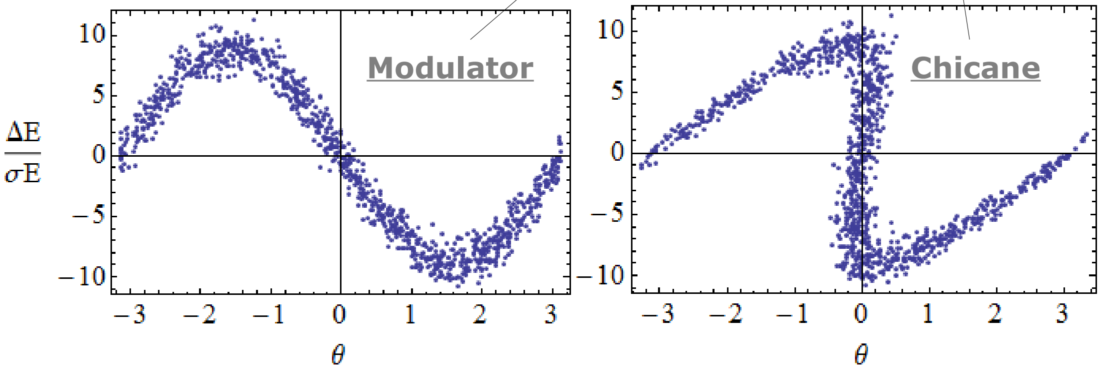
- Laser imparts sinusoidal energy modulation

- Chicane dispersion converts to density modulation

- Chicane delay allows for control of injection phase







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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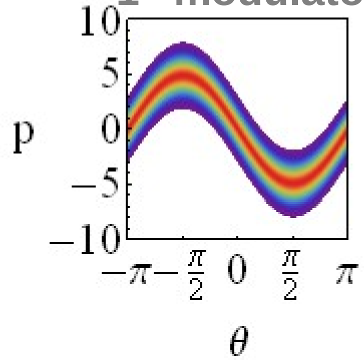
(Received 24 October 2012; published 28 January 2013)

½ period planar undulator (small modulation)

p=Δγ/σγ **A1**

p' = p+ A1*sin[θ]

1st modulator

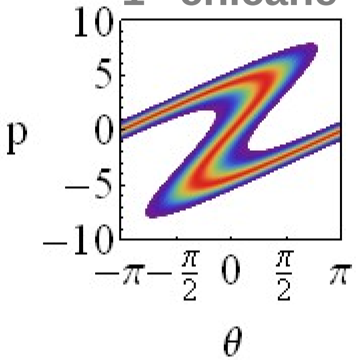


Large R56 chicane compressor (over-rotate) **B1**

θ'=θ+B1*p'

π/A1B1~1

1st chicane

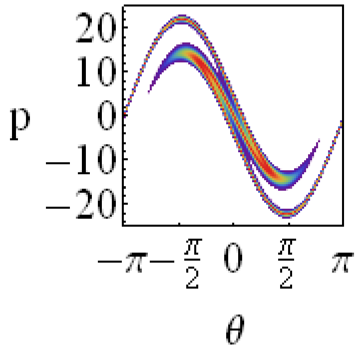


1 period planar undulator (large modulation)

Utilize pre-existing pre-buncher

A2

2nd modulator

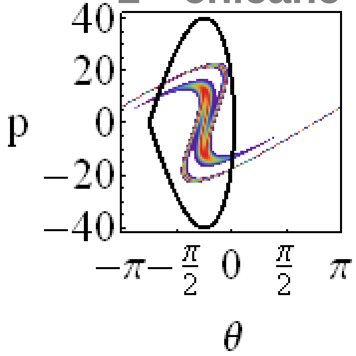


Small R56 chicane compressor (bunch)

~97% of particles inside of pondermotive bucket

π/A2B2~2 **B2**

2nd chicane



Rubicon double buncher

design of the double buncher

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

- 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
  - Single laser/e-beam focus

- 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

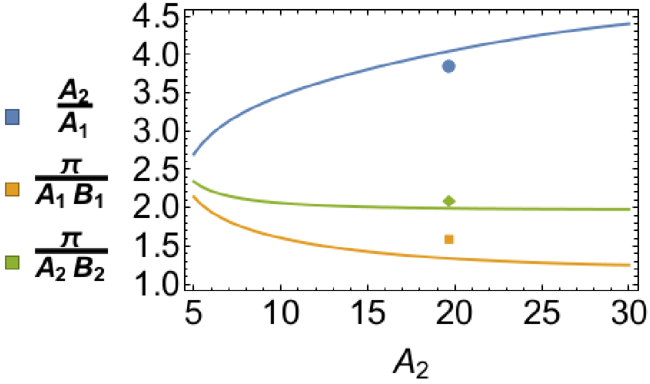
- energy spread: **σγ/γ = 0.0015**

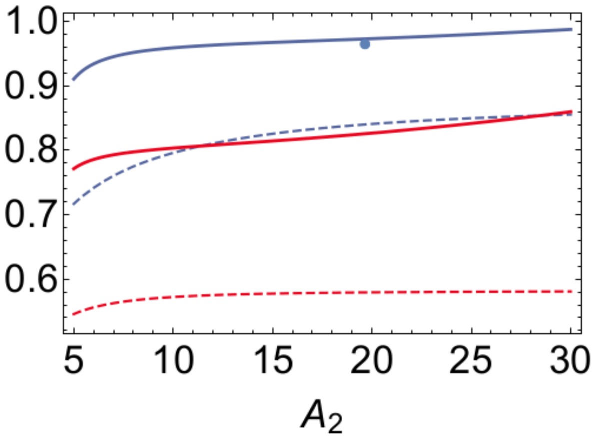
- Second modulation, A2 ~ 20 given expected laser energy

- 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



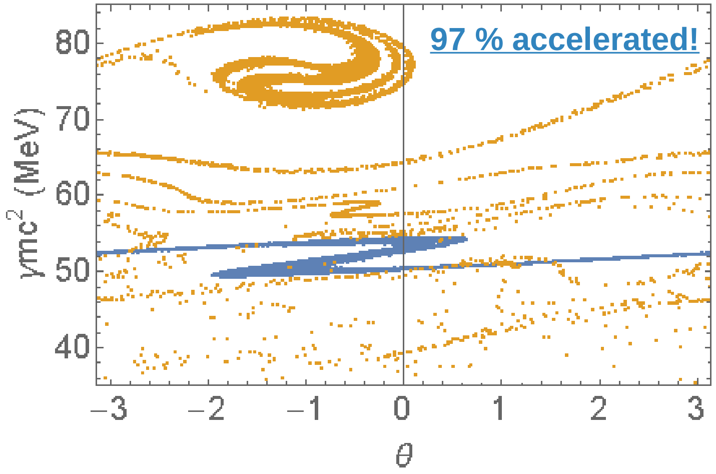


The double buncher

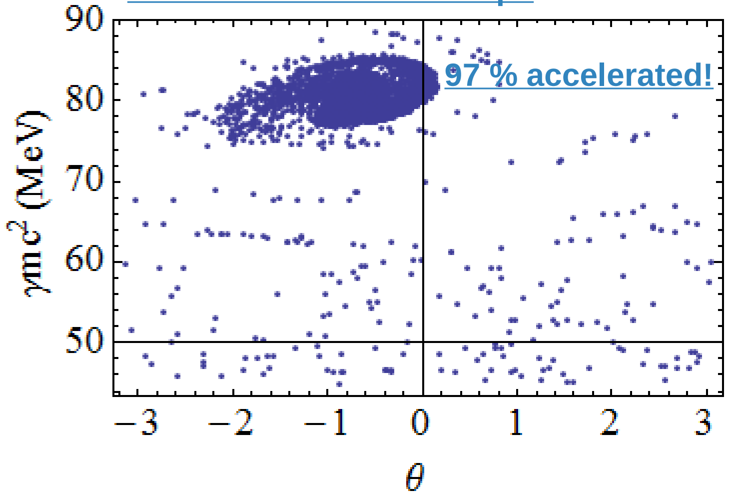
Simulations

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 Energy	**0.5 J**
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



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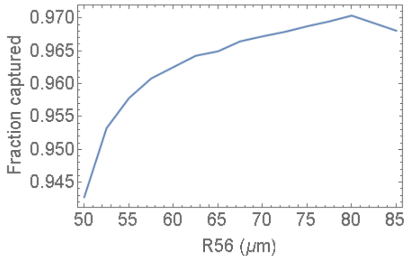
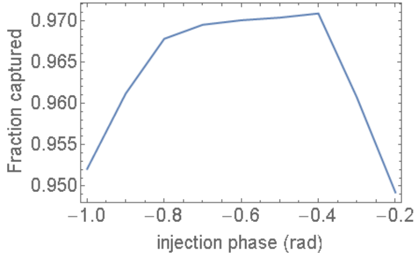
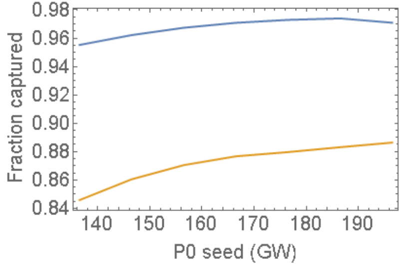
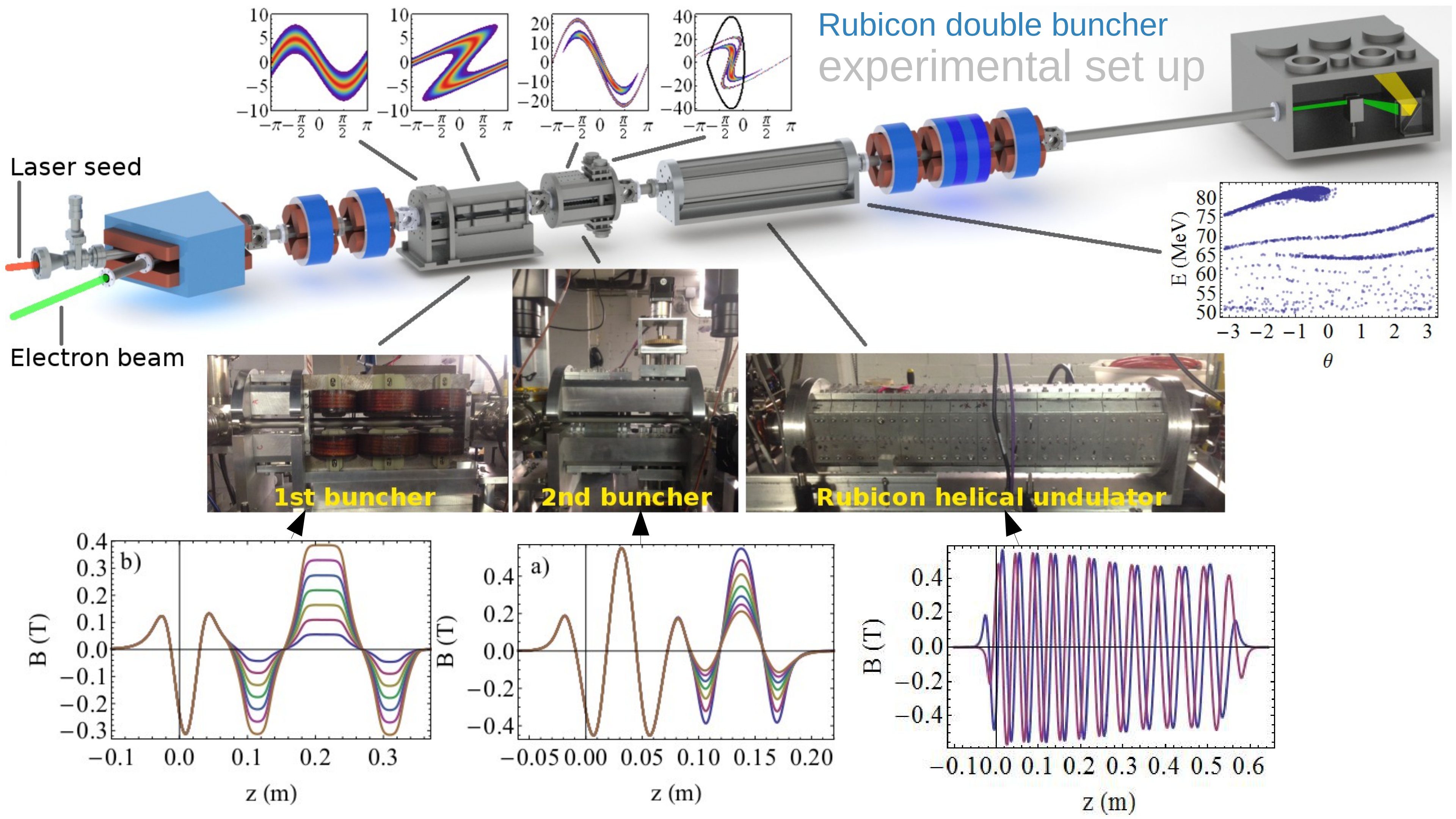




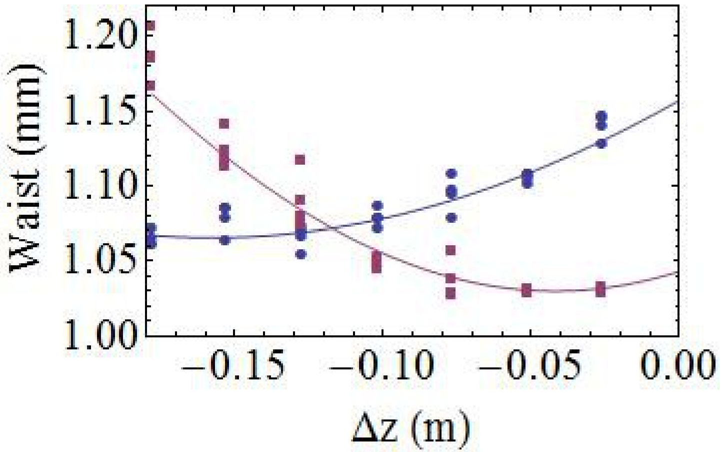



Rubicon double buncher
experimental set up
Laser seed
Electron beam
1st buncher
2nd buncher
Rubicon helical undulator
b)
a)
B (T)
z (m)
E (MeV)
θ

Rubicon double buncher

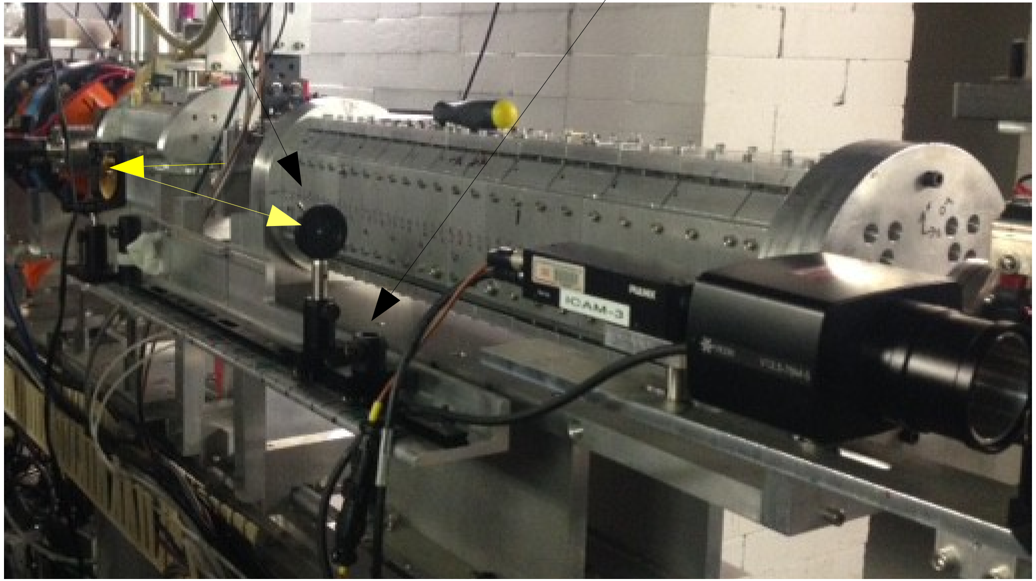
experimental set up pt. II

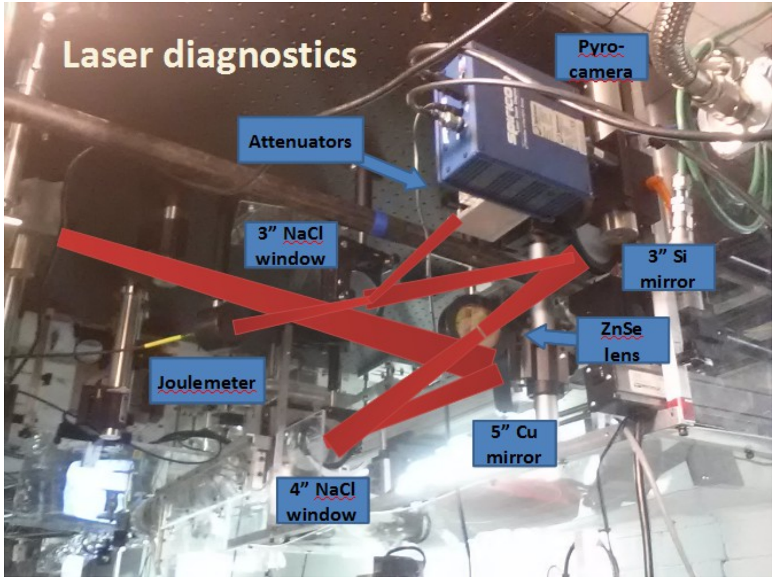
- e-beam laser pS scale timing achieved by e-beam controlled transmission through Ge slab – fine timing: delay stage
- vary laser polarization: rotate quarter wave plate
- vary laser waist position: move lens
- monitor high power laser energy and pointing stability on ceiling



Alignment iris

Pyro camera for waist scan or photodiode for Ge tir

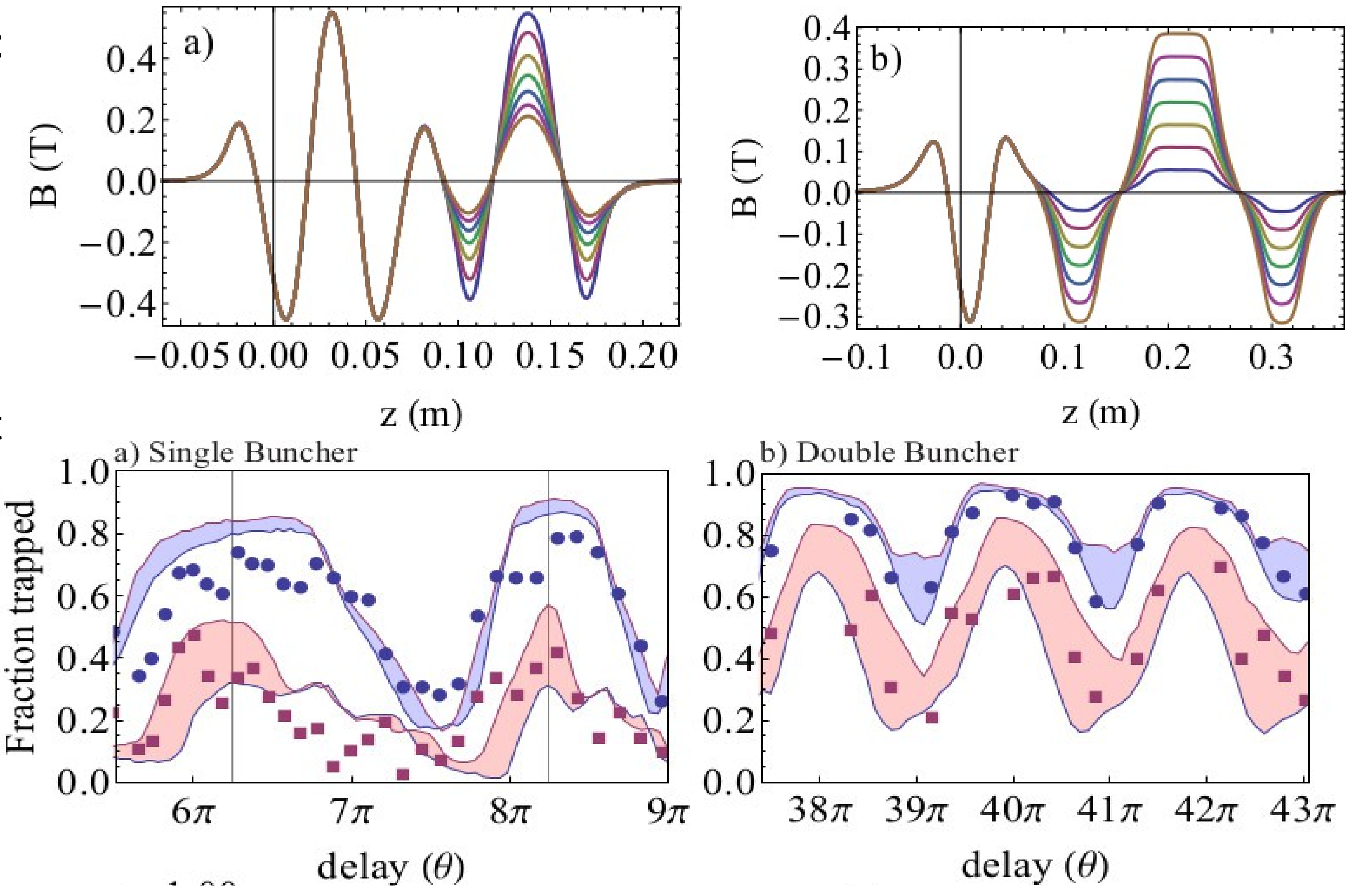


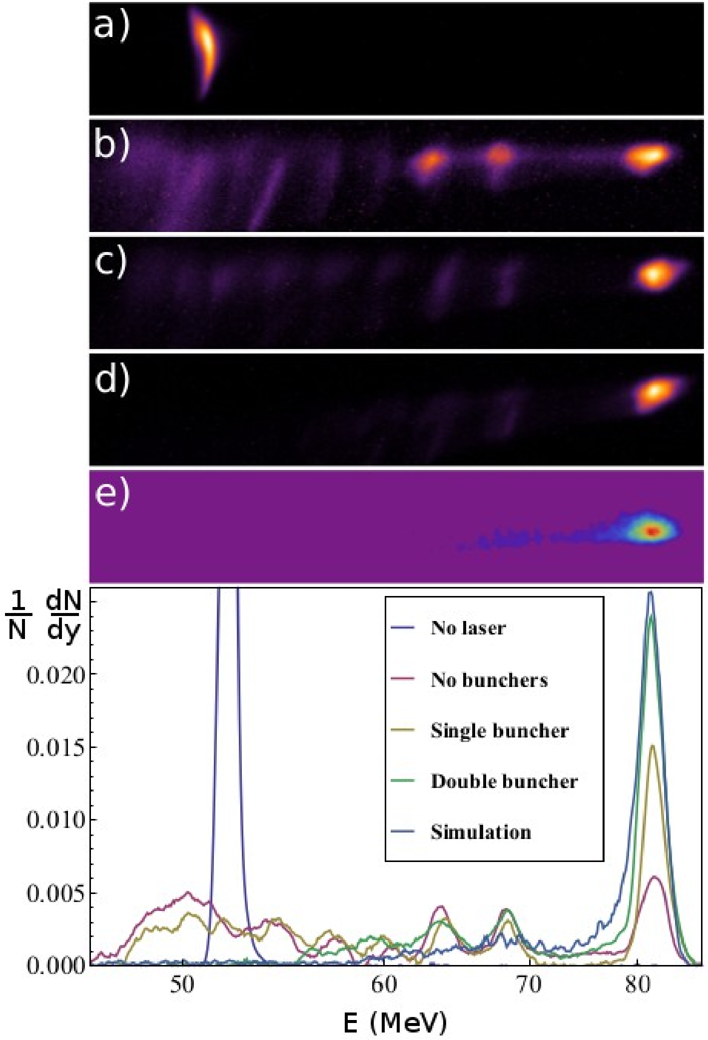


Rubicon double buncher

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 0.4-0.6 J
- fT>55 MeV (Blue)
- fT> 75





all shots from same run with 0.5 J
Simulation done with experimental e-beam and laser focusing

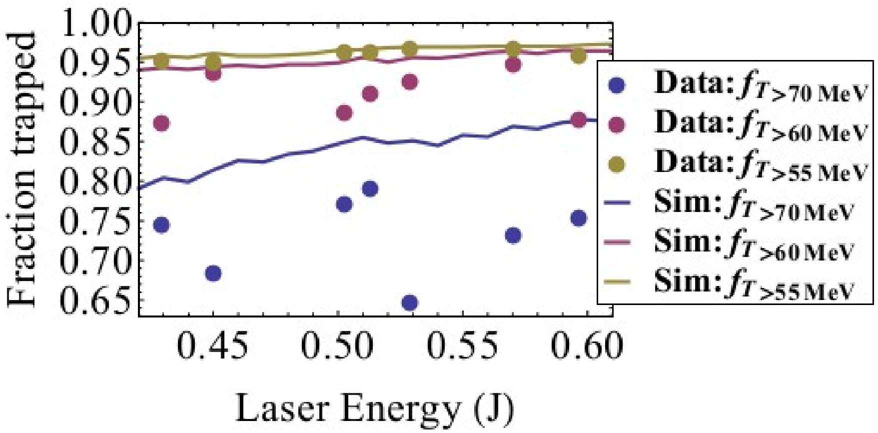
a) No laser (blue)

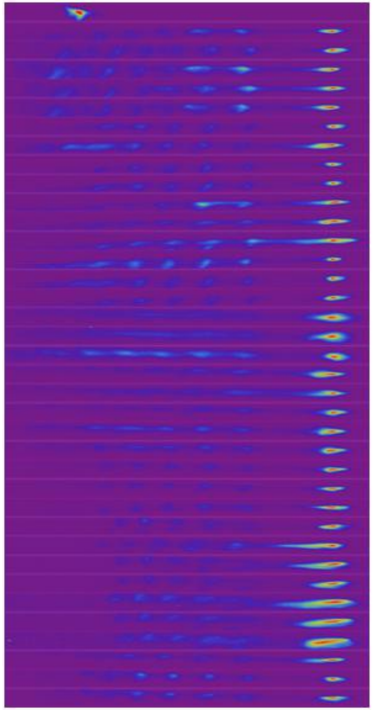
b) No pre-bunching: ~25% accelerated (red)

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

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

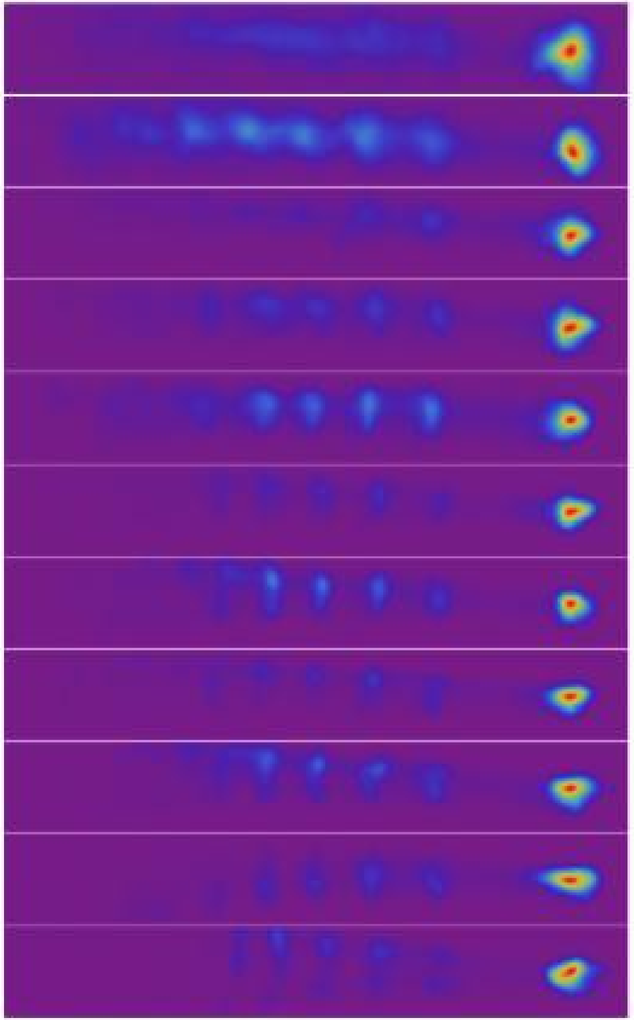
e) GPT Simulation: ~80% accelerated (blue)

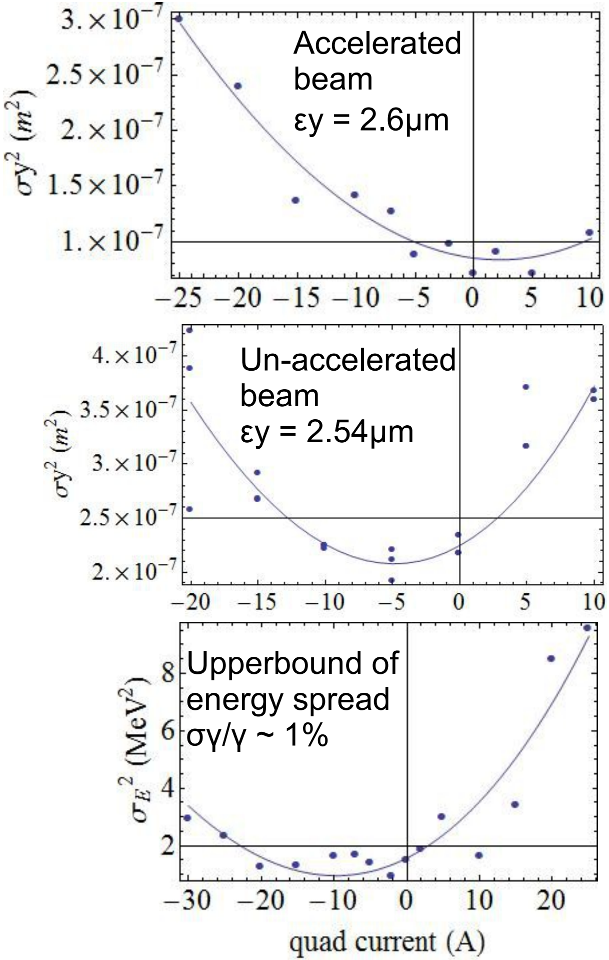




36 consecutive shots demonstrating IFEL double buncher stability. Note: top shot is the unaccelerated electron beam.

Q=-25A
Q=-20A
Q=-15A
Q=-10A
Q=-7A
Q=-5A
Q=-2A
Q=0A
Q=2A
Q=5A
Q=10A

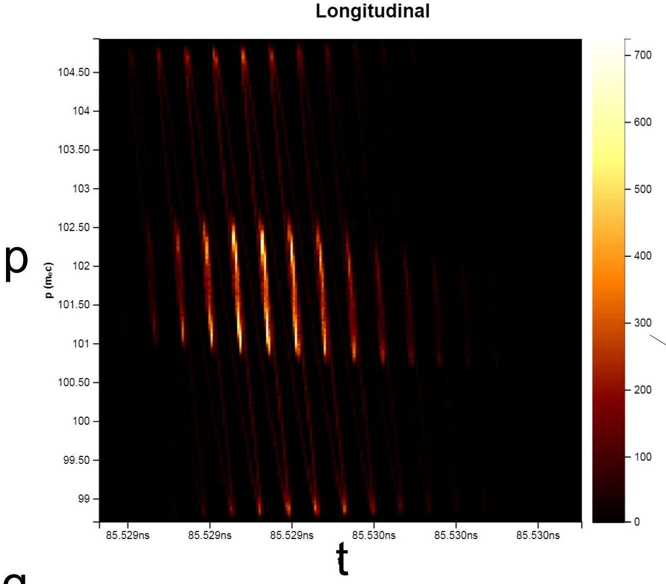


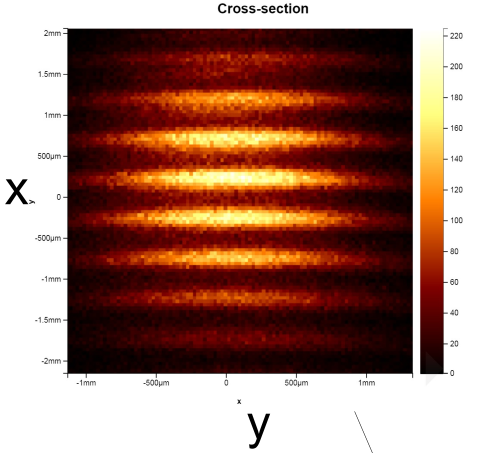


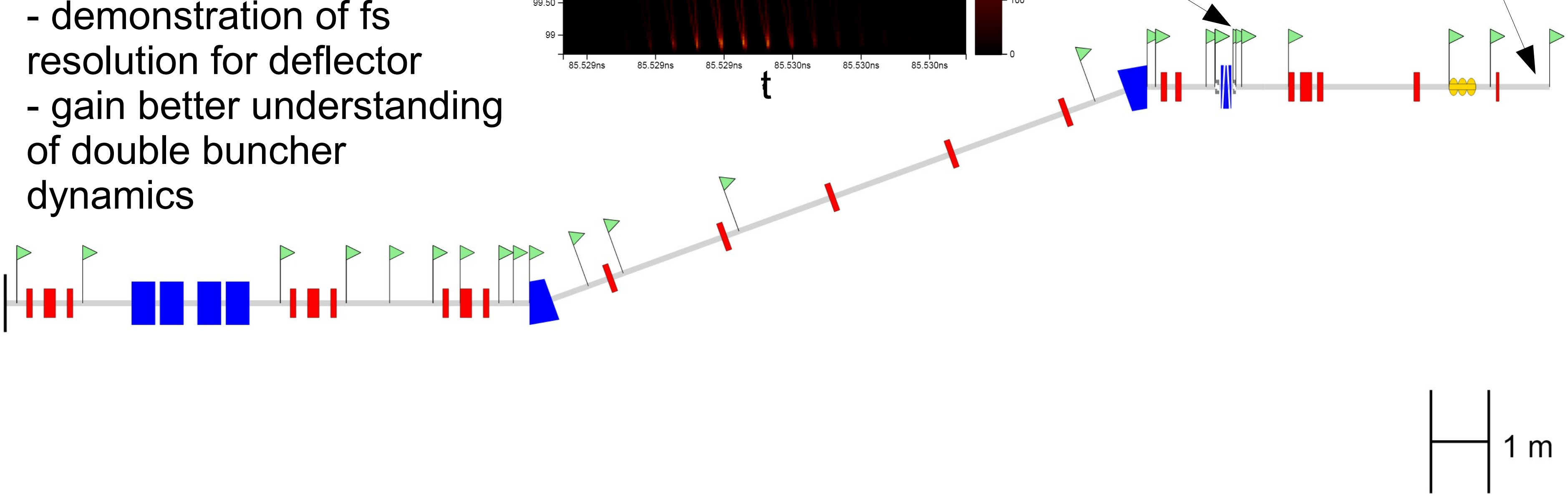
Double buncher

Future plans: Imaging the longitudinal phase space

- Direct measurement of micro-bunching
- demonstration of fs resolution for deflector
- gain better understanding of double buncher dynamics

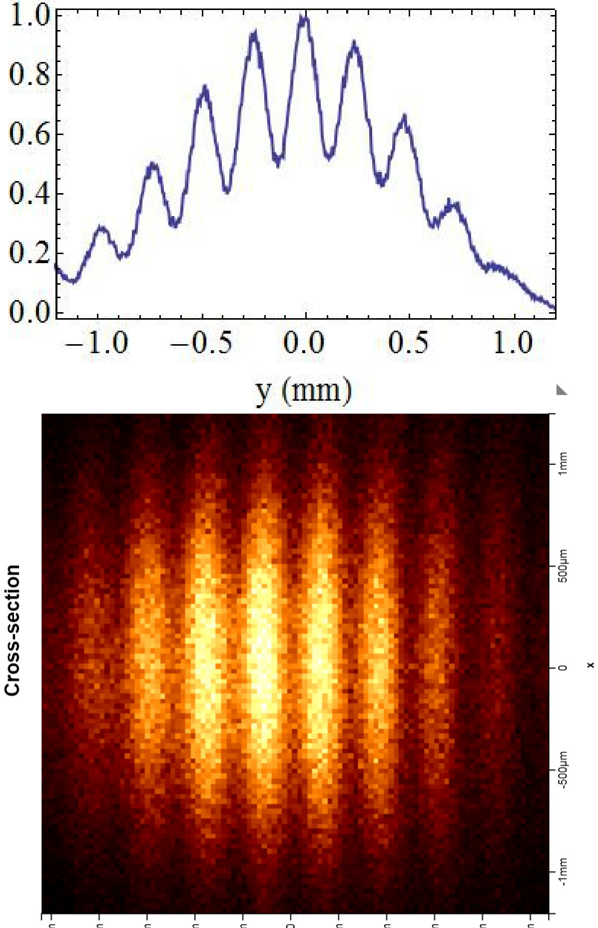




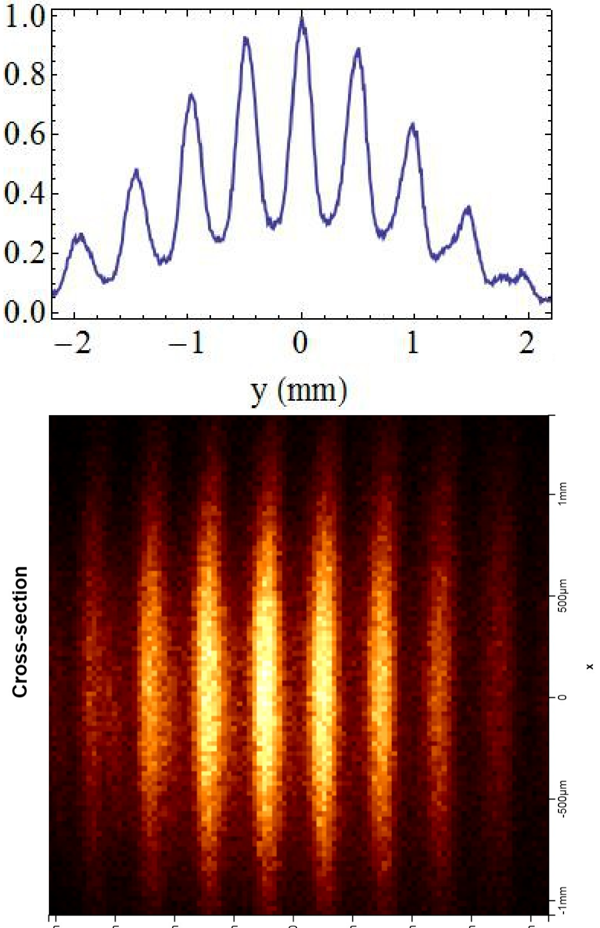


Deflecting Voltage

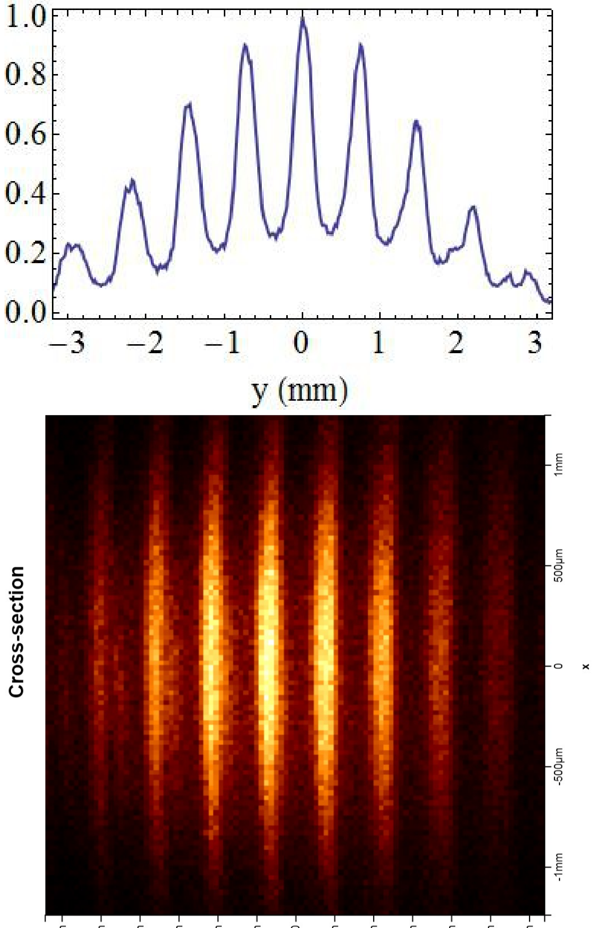
4 MV



8 MV



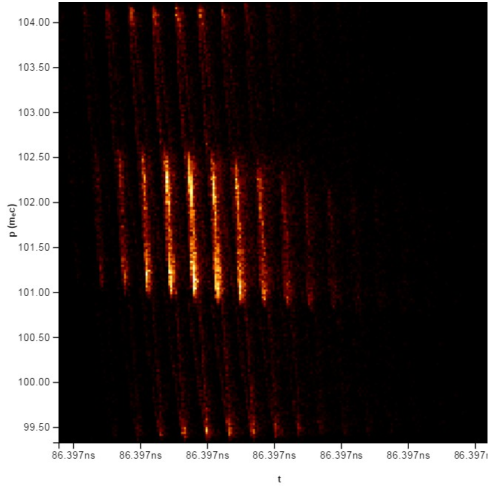
12 MV

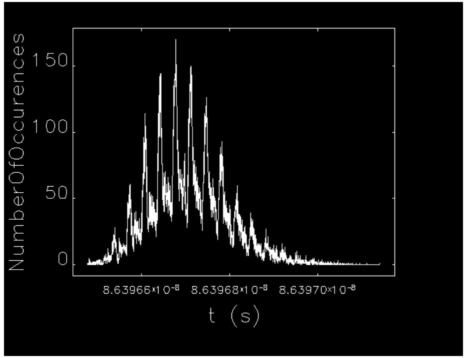


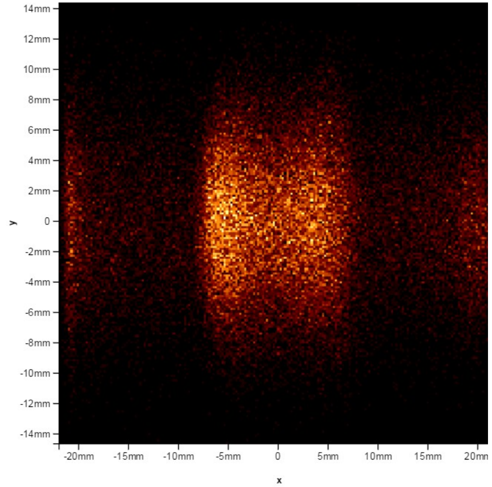
P vs. t after buncher

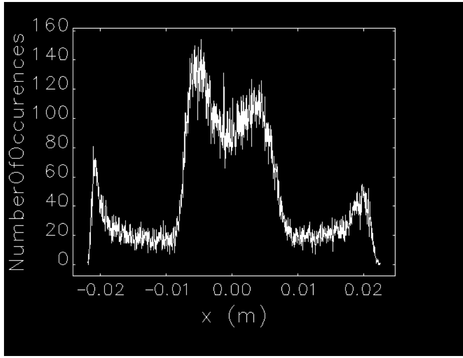
Y vs. X @ spectrometer screen

Double buncher

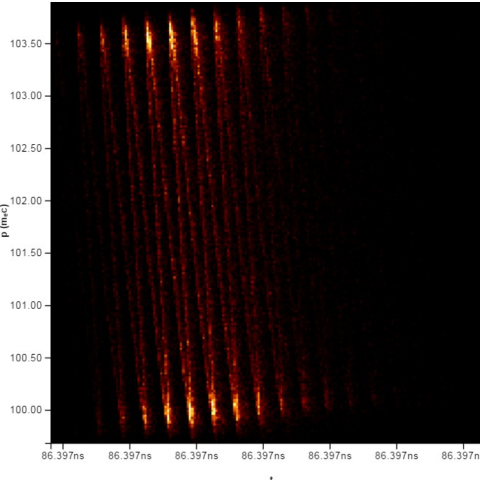


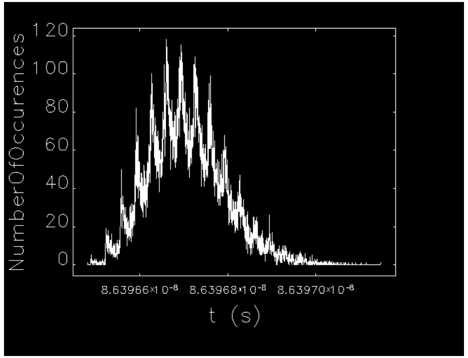


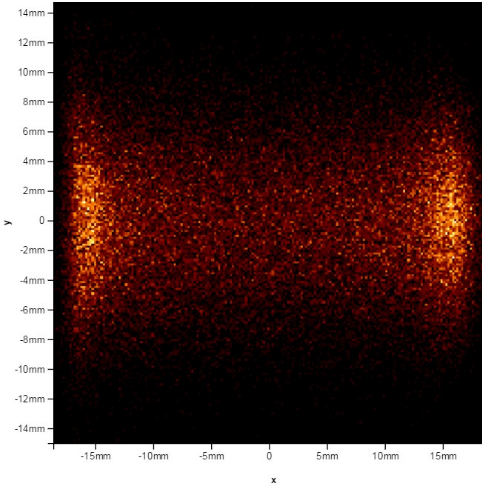


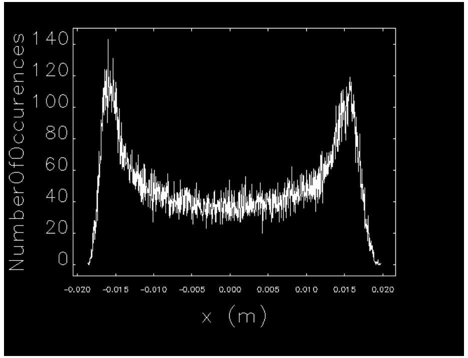


Single buncher



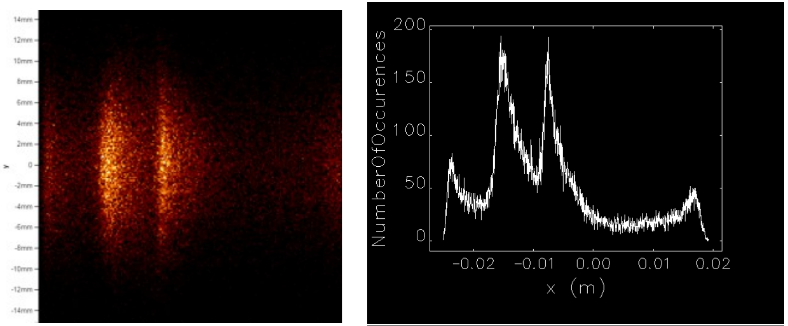




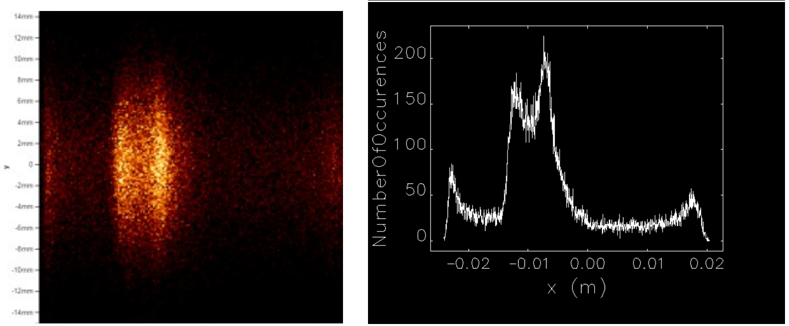


Vary 1st buncher phase delay about optimal value

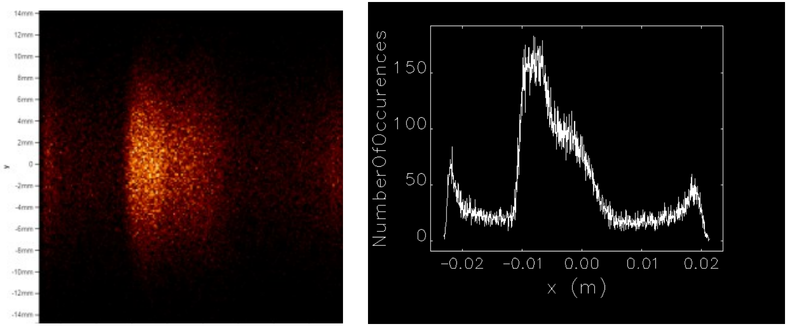
Δ θ = 1.2



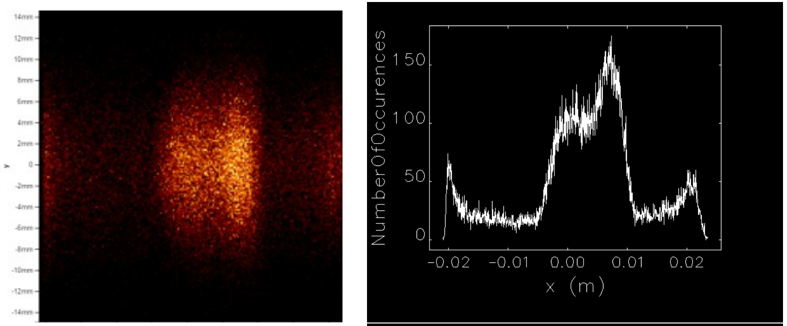
Δ θ = 0.8



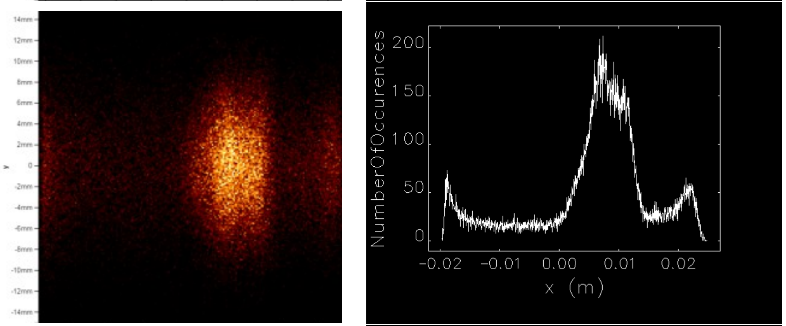
Δ θ = 0.4



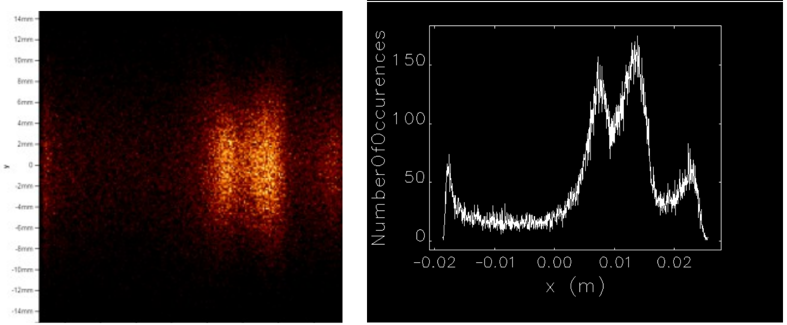
Δ θ = -0.4



Δ θ = -0.8



Δ θ = -1.2



Double buncher

What we're asking for:

- 2 weeks of beam time
    - 1 week installation/e-beam tuning
    - 1 week e-beam and laser (0.1 - 0.3 J)
- 52 MeV, 80-300 pC
- $\varepsilon = 2\ \mu m$, $\sigma\gamma = 0.001$
- deflecting voltage > 5 MV
- 10 μm/pix resolution on screen

IFEL research in the distant future?

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ATF - UCLA

Experiment for

MeV

ICS photons from a

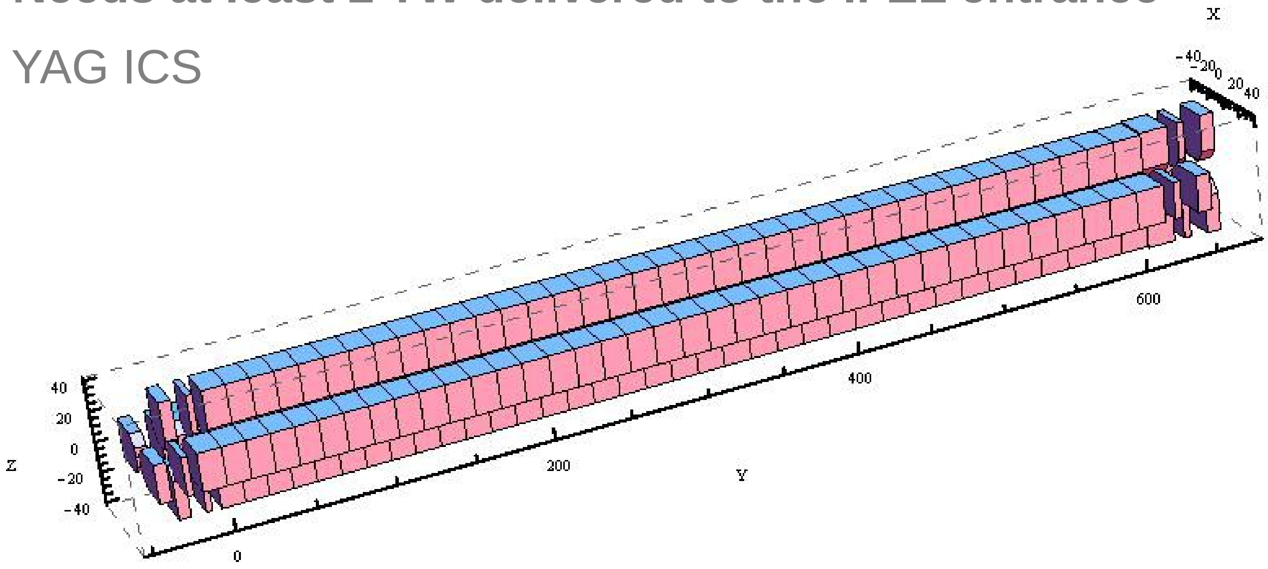
Laser driven

IFEL

Accelerator

Realizing Aemilia:

- 2 staged IFEL acceleration to 250 MeV using existing Rubicon IFEL as first stage
- **Needs at least 2 TW delivered to the IFEL entrance**
- YAG ICS



Aemilia: Advanced IFEL

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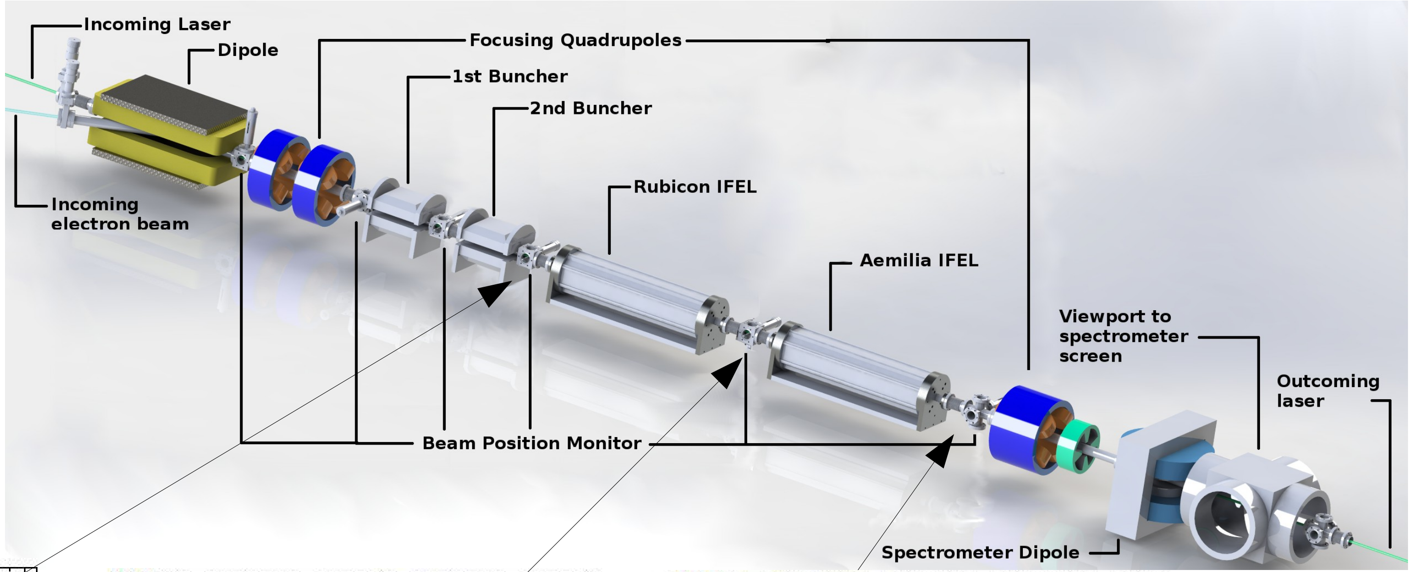
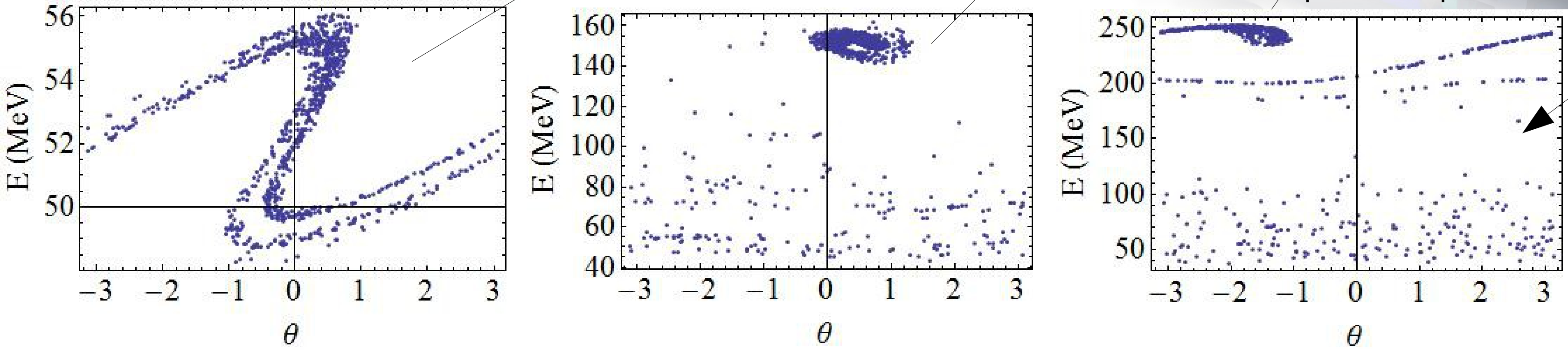
- Add 2nd IFEL stage after Rubicon
- Retune Rubicon for final energy of 150 MeV
- 2nd stage boosts energy to 240-250 MeV
- Use double buncher for high capture





GPT simulations

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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

- Would like to use the deflector and EOB spectrometer to take measurements of the longitudinal phase space

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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

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Thanks