Recap of the Nocibur experiment

And new results from the double buncher experiment

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Overview

UCLA

Introduction to Nocibur

- Rubicon backwards: Inverse Inverse Free Electron Laser mechanism

Motivation

- Using strong undulator tapering for high extraction efficiency

The experiment

- The set-up, the results

Future plans

- re-circulated Nocibur: measure some gain

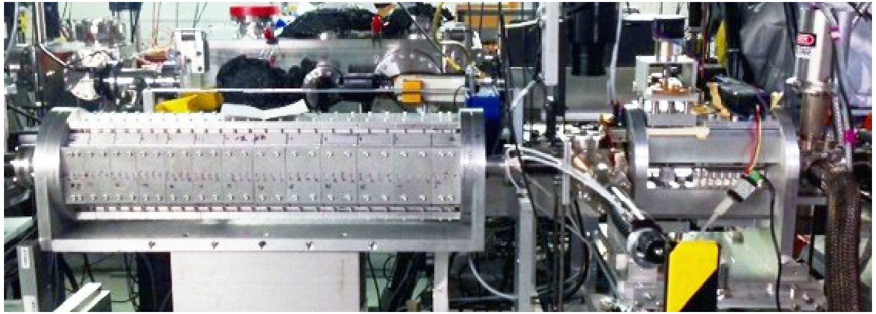
Introduction to Double Buncher

- concept, experiment, results

Conclusion

The Nocibur Inverse Inverse Free Electron Laser

The IIFEL



From IFEL to IIFEL

- Resonant energy exchange between a laser and electron beam inside of a tapered undulator:

$$\frac{\partial \gamma^2}{\partial z} = -2kK_l K \sin(\Psi) = \frac{\partial}{\partial z}\left(\frac{k(1+K^2)}{2k_w}\right) \qquad K_l = \frac{e\lambda E(z)}{2\pi mc^2} \qquad K = \frac{e\lambda_w(z) B(z)}{2\pi mc}$$

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

- choose design “resonant” phase and energy to satisfy above equation
    - $\psi r < 0$ → accelerating $\psi r > 0$ → decelerating
- Rubicon IFEL: Helical halbach undulator – CO_2 laser seed – BNL ATF
    - 52 MeV → 92 MeV
- Nocibur: reverse Rubicon IFEL and re-tune
    - 65 MeV → 35 MeV
- IIFEL vs. FEL
    - Post saturation regime: bunched beam, re-focused large seed, strong tapering for optimized energy extraction, stimulated emission: $(E_{seed} + E_{gain})^2 - (E_{seed})^2 = 2E_{seed} * E_{gain} + (E_{gain})^2$

Why Nocibur?

- FEL efficiency: proportional to ρ < 0.5%
- Tapering: extend FEL past saturation, increase efficiency
- ELF experiment: GHz frequencies – waveguide ~ 30% efficiency
- PALADIN: no waveguide optical wavelengths
- XFEL: tapering for TW level
  - TESSA
- Potential compact EUV radiation source
- Nocibur: Low gain regime of TESSA scheme. Demonstrate high extraction efficiency in "optical regime"

- Rubicon undulator available: tunable for resonant energies between ~30-100 MeV
- choose 65 MeV: max stable energy where ATF could run with chirp
- 100-300 GW: stable seed power from CO2 laser main amplifier
- Demonstration of high electro-optical conversion efficiency at "optical" wavelength

High efficiency, multiterawatt x-ray free electron lasers

C. Emma, K. Fang, J. Wu, and C. Pellegrini
Phys. Rev. Accel. Beams **19**, 020705 – Published 26 February 2016

Tapered undulators for SASE FELs ☆

William M. Fawley[a], Zhirong Huang[b], Kwang-Je Kim[b], Nikolai A. Vinokurov[c]

New Journal of Physics
The open access journal at the forefront of physics
DPG
IOP Institute of Physics

PAPER

Tapering enhanced stimulated superradiant amplification

J Duris[1], A Murokh[2] and P Musumeci[1]

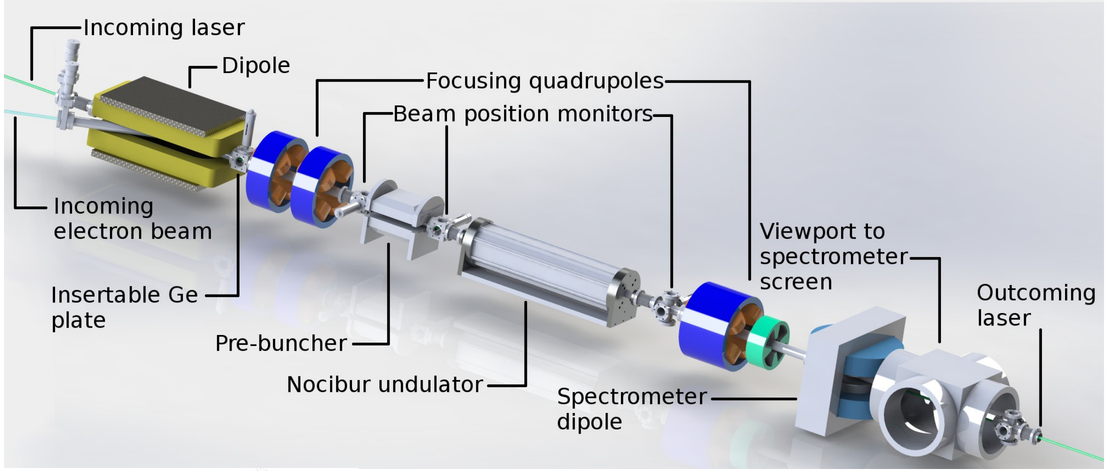
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 050704 (2012)

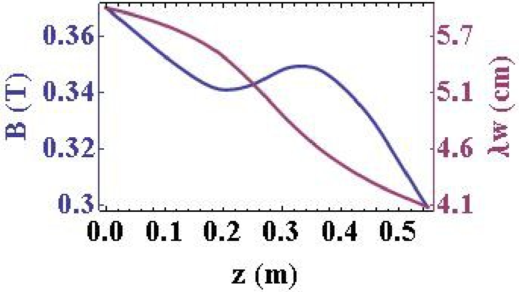
Modeling and multidimensional optimization of a tapered free electron laser

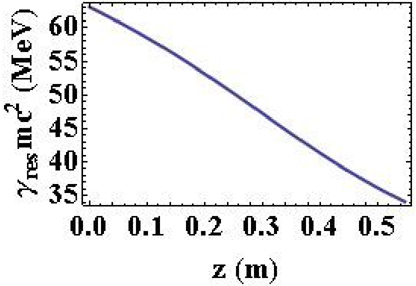
Y. Jiao,[1,2,*] J. Wu,[1,†] Y. Cai,[1] A. W. Chao,[1] W. M. Fawley,[1] J. Frisch,[1] Z. Huang,[1] H.-D. Nuhn,[1] C. Pellegrini,[1,3] and S. Reiche[4]

The experiment

E-Beam energy	**65 → 35 MeV**
emittance	**2 mm-mrad**
σxy (waist)	**100 μm**
Laser Wavelength	**10.3 μm**
Rayleigh Range	**0.3 m**
Laser Waist	**1 mm**
Laser Power	**200 GW**
E-beam current	**100 A**
E-beam charge	**100 pC**
λw buncher	**0.05 m (1 period)**
Chicane: R56	**21 → 59 μm**
period tapering	**0.06 - 0.04 m**
K tapering	**2.01 - 1.19**



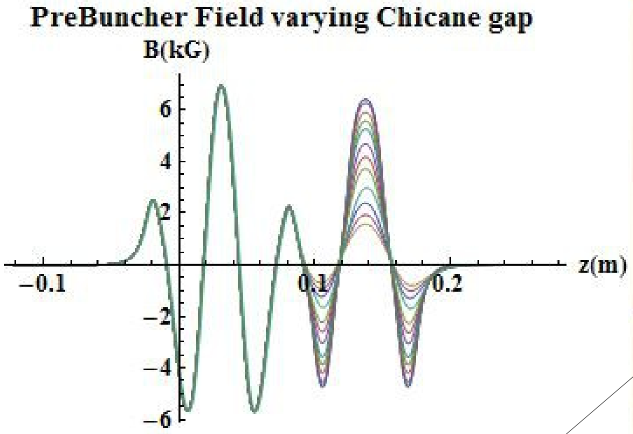


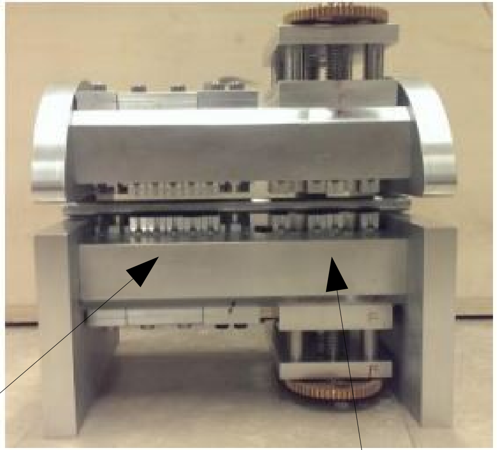


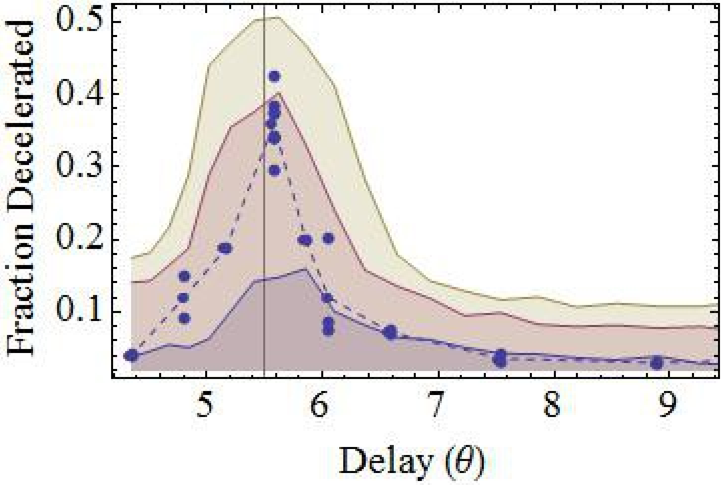
- Laser focused by 3.5 m NaCl lens
- e-beam focused by quadrupole doublet
- Laser e-beam timing: Ge switch
- fine timing: scan delay stage
- optimize injection phase: scan pre-buncher R56
- measure e-beam spectrum on phosphor screen

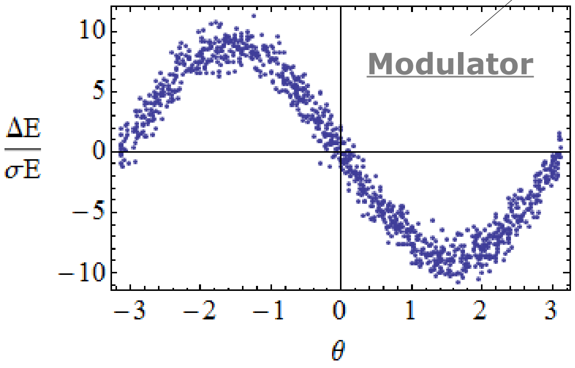
Pre Buncher

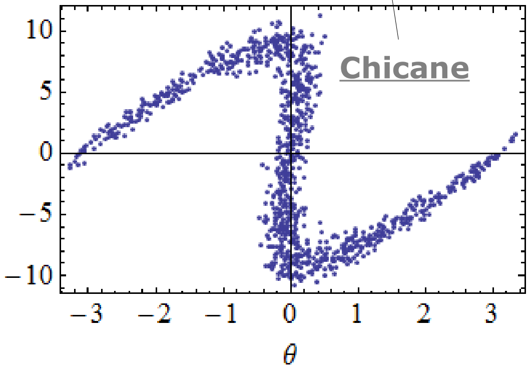
- Single period, planar, halbach undulator
- Permanent magnet, variable gap chicane
- Laser imparts sinusoidal energy modulation
- Chicane dispersion converts to density modulation
- Chicane delay allows for control of injection phase







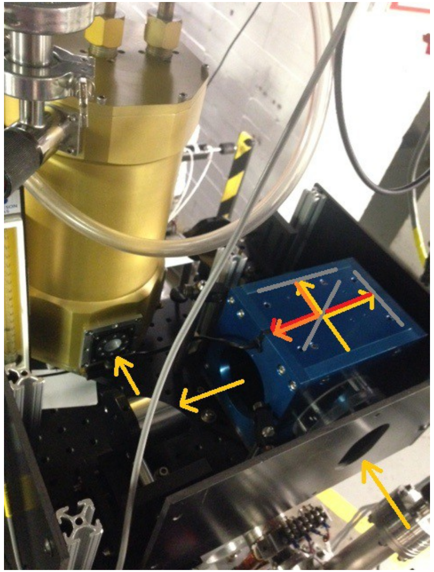


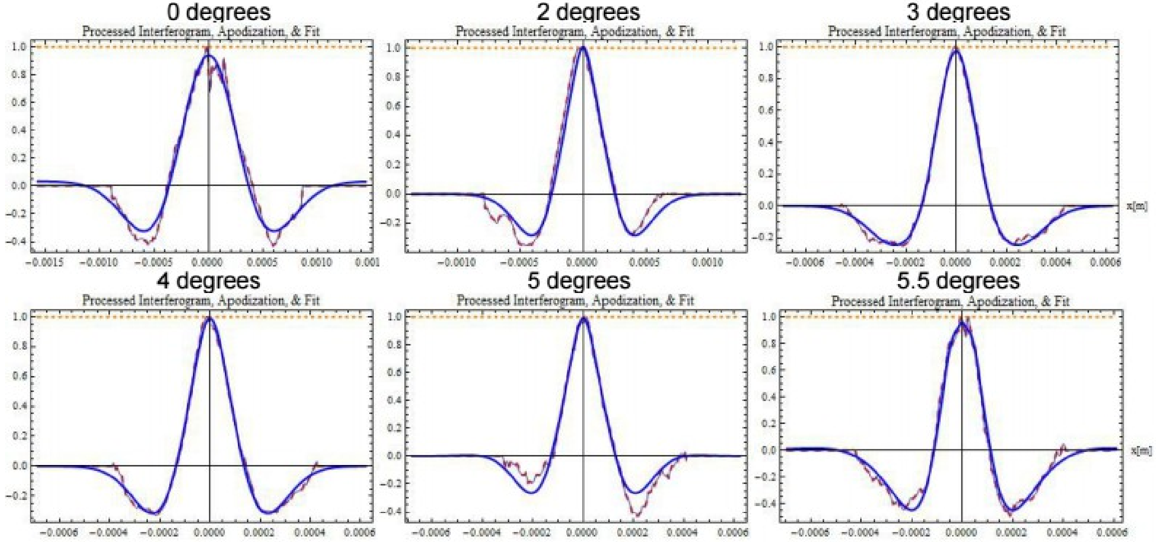


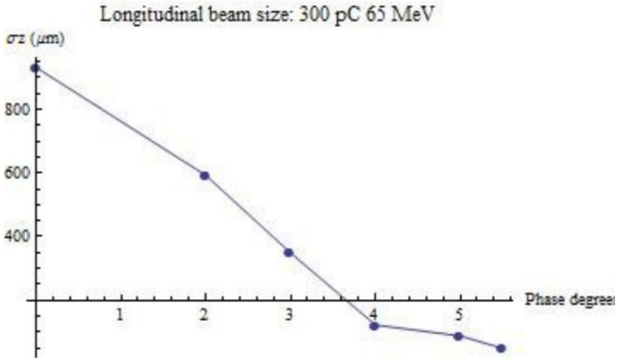
Nocibur

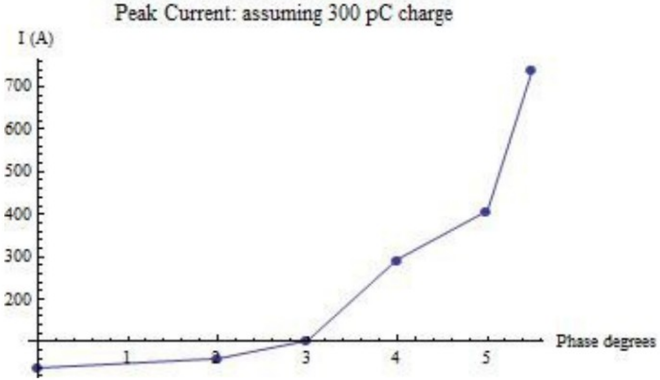
BLIS measurements

- Chirp e-beam (vary linac phase)
- compress with ATF chicane
- generate Coherent Transition Radiation
- measure auto correlation of CTR with Michelson interferometer
- 3 Gaussian fits to estimate bunch length



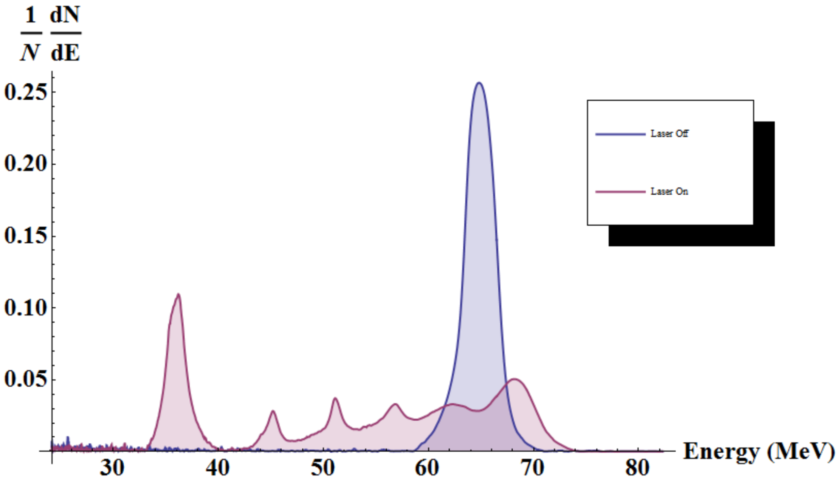


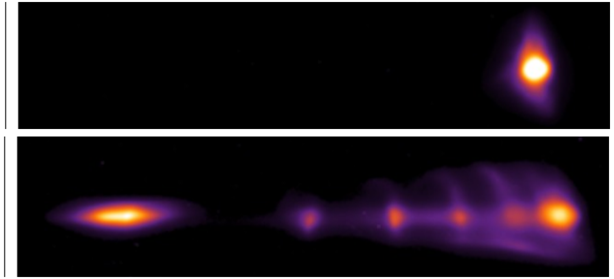




Nocibur

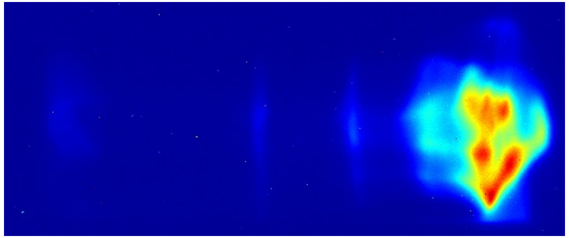
1st run: measuring the radiation



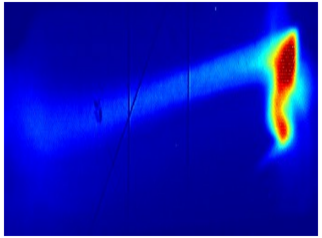


- ~30 % deceleration of 300 pC, 100 A beam from 65 to 35 MeV
- expect this energy extraction to produce ~ 1 GW of 10.3 µm radiation on top of ~ 100 GW → ~3 mJ of energy
- Trapping optimization:
  - Vary PreBuncher gap
    - Potential motor/gear slippage creates kick and mismatch with GPT simulation
  - Vary lens position
    - Possible clipping through PreBuncher pipe
  - Increase current
    - emittance growth

Spectrometer Data - 5 degree chirp



Compression at FPOP3

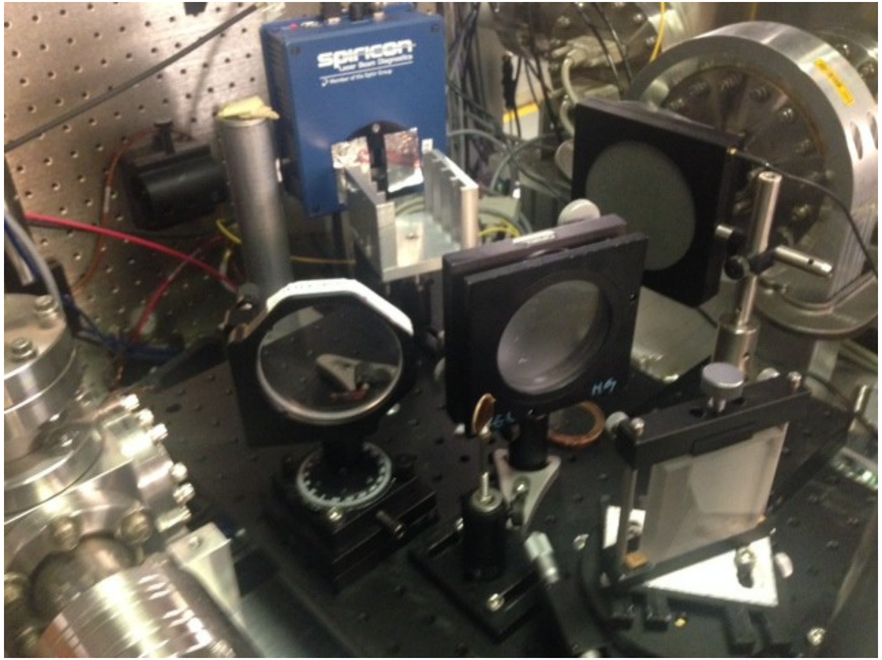


Nocibur

1st run: measuring the radiation

UCLA

- a misguided attempt: run with linear polarization, measure radiation in perpendicular polarization
    - separate gain from seed (Does not work)
- perpendicular polarization: No stimulated emission!

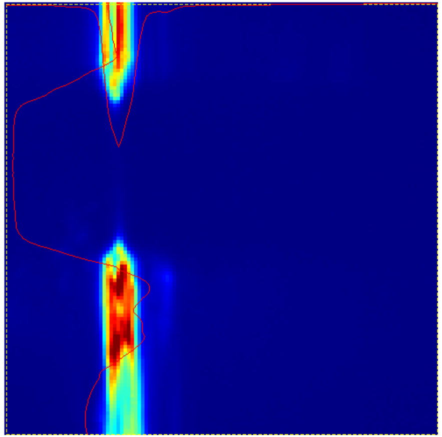


- spectral broadening of generated radiation
- larger diffraction of generated radiation
- No correlation between e-beam on and e-beam off

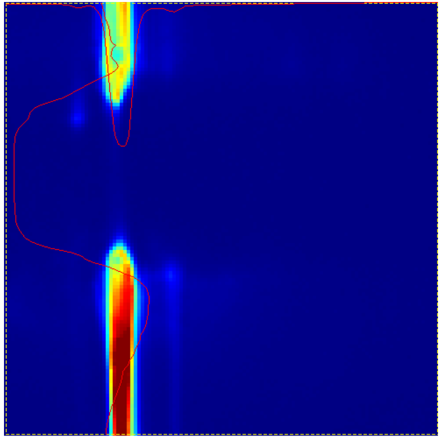
Pyro camera data

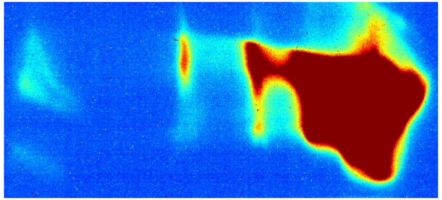
Spectrum measurement after brewster window, blocking core of spectrum

E-beam off – Laser: 0.782 J



E-beam on – Laser: 0.87 J





The experiment

Some results

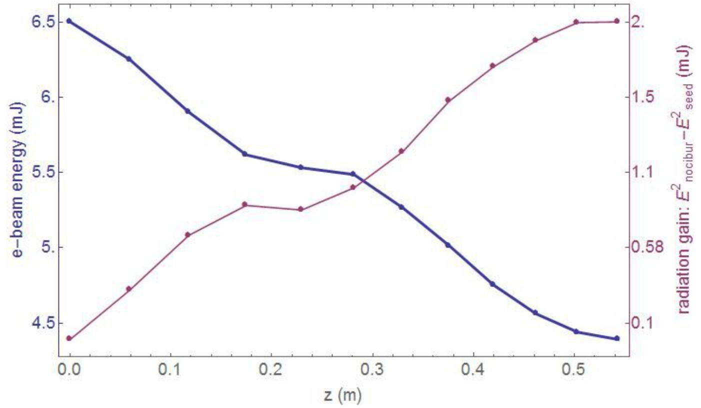
- 45% of particles decelerated from 65 → 35 MeV
- 30% conversion efficiency
- good agreement with GPT simulations
- couldn't measure radiation growth

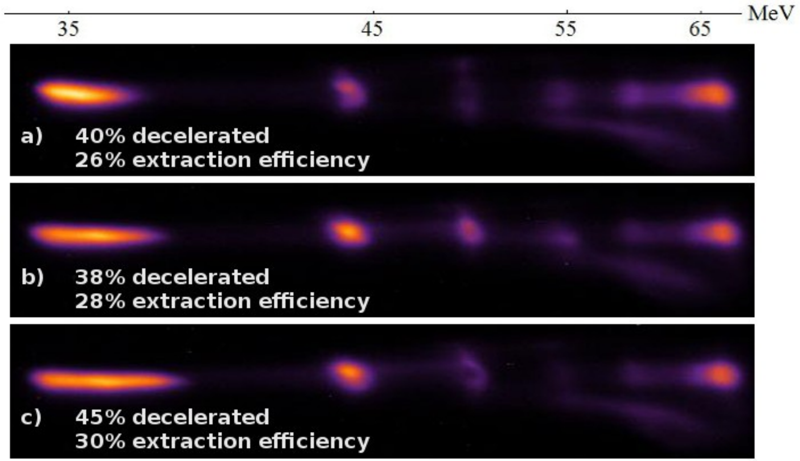
hindered by large seed – broke a pyro camera trying

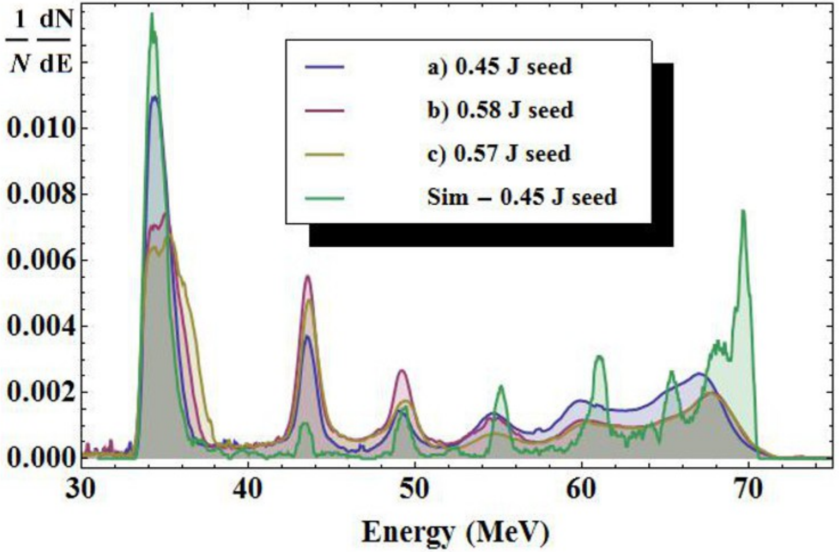
- Genesis simulations show expected radiation

growth for electron beam energy loss

$$\epsilon \propto (\vec{E}_{seed} + \vec{E}_{gain})^2 = |E_{seed}|^2 + 2\Re[\vec{E}_{seed} \cdot \vec{E}_{gain}] + |E_{gain}|^2$$





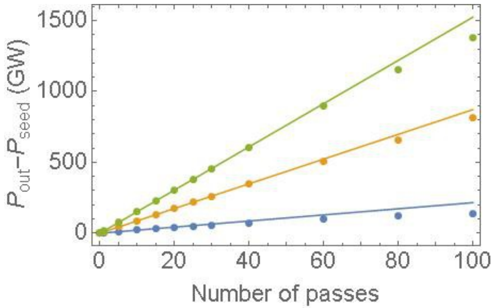


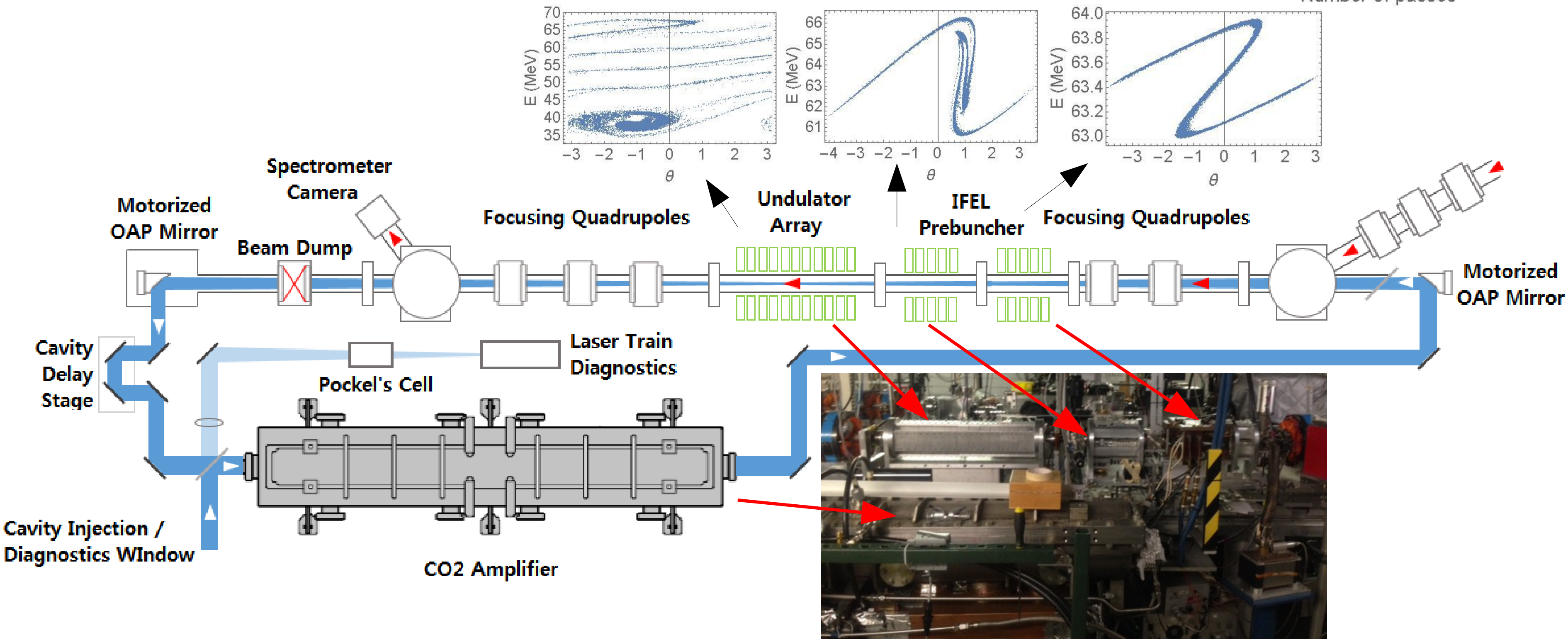
Potential future projects at ATF

rNocibur (cavity gain)

Measure gain from high efficiency Nocibur interaction via recirculation scheme

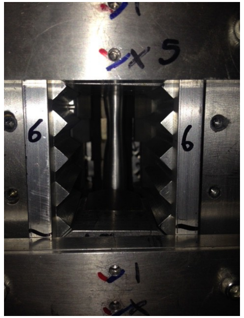
Increase efficiency with double buncher (90% decelerated – 40% efficiency)

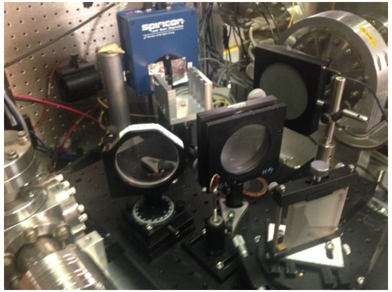




Conclusions

Trials & tribulations





UCLA

- Demonstrated 30% extraction efficiency in a laser driven strongly tapered undulator interaction: Low gain regime of TESSA mechanism

- High gain regime: requires a longer undulator and a brighter beam.

- Could potentially measure accumulated gain in recirculation scheme

PRL **117,** 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

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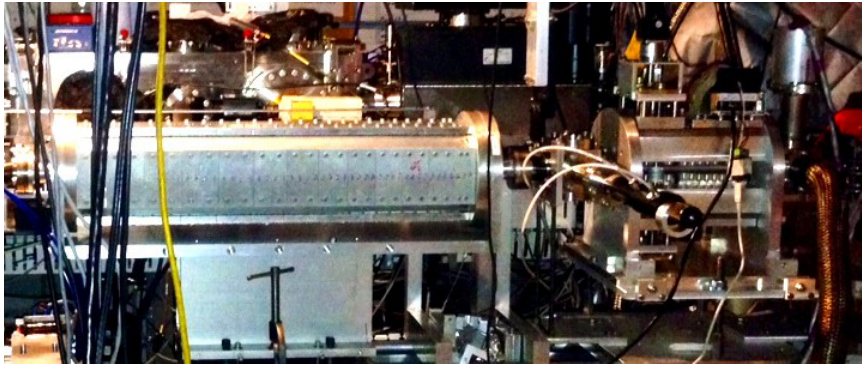
(Received 3 May 2016; published 19 October 2016)

Pre-bunching

Tapered undulators

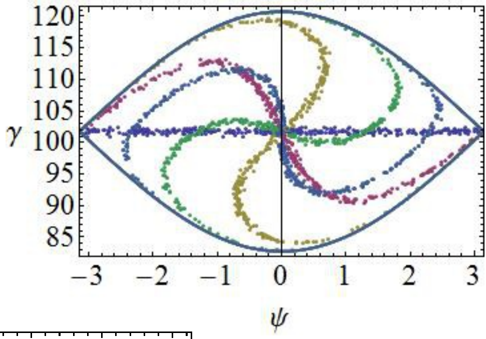


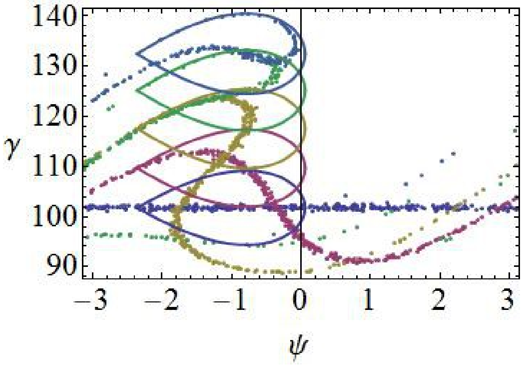
- Resonant energy exchange between a laser and electron beam inside of an undulator: $\frac{\partial \gamma^2}{\partial z} = -2kK_l K \sin(\Psi) = \frac{\partial}{\partial z}\left(\frac{k(1+K^2)}{2k_w}\right)$ $\quad K_l = \frac{e\lambda E(z)}{2\pi mc^2}$ $\quad K = \frac{e\lambda_w(z)B(z)}{2\pi mc}$

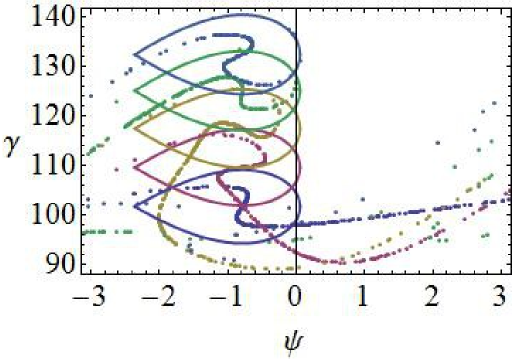
  gradient   phase synchronicity

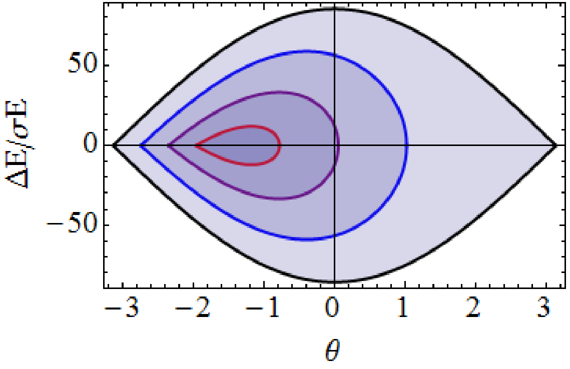
- choose design "resonant" phase and energy to satisfy above equation

- resonant phase +/- π/4: tradeoff between gradient and bucket size









Pondermotive Bucket

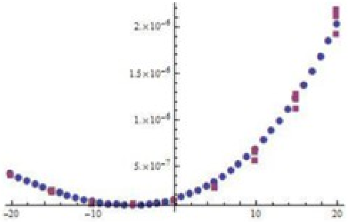
Resonant phase: 0, π/8, π/4, 3π/8

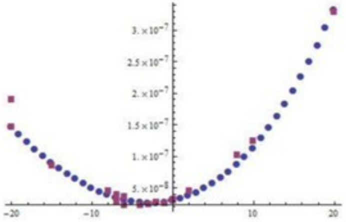
Pre-buncher: A work horse

Single Buncher

Un- accelerated beam | Accelerated beam

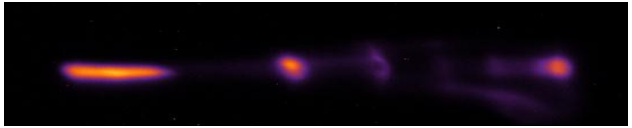
2.3 µm emittance | 2.4 µm emittance





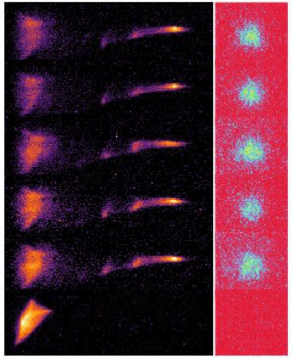
Rubicon IFEL experiment

- 52 MeV → 95 MeV
- 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

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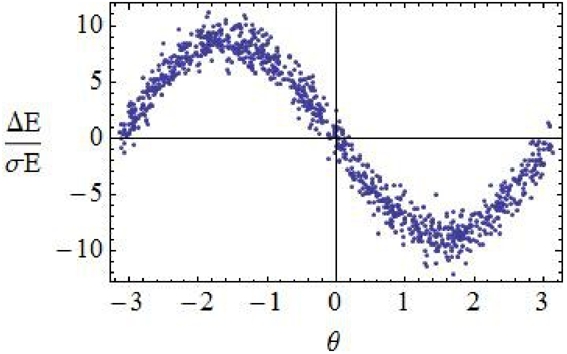
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 24 October 2012; published 28 January 2013)

The double buncher

Simple model

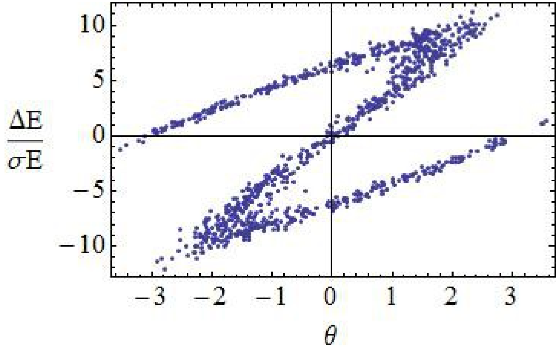
1st modulator

½ period planar undulator (small modulation)



1st chicane

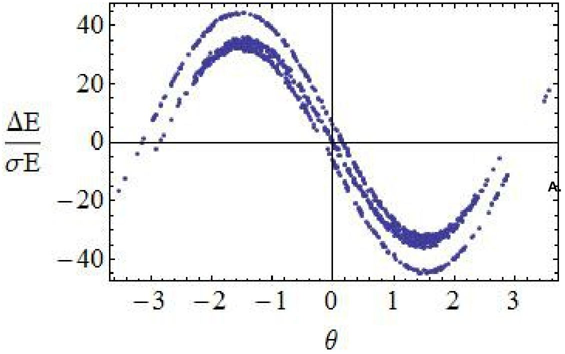
Large R56 chicane compressor (over-rotate)



2nd modulator

1 period planar undulator (large modulation)

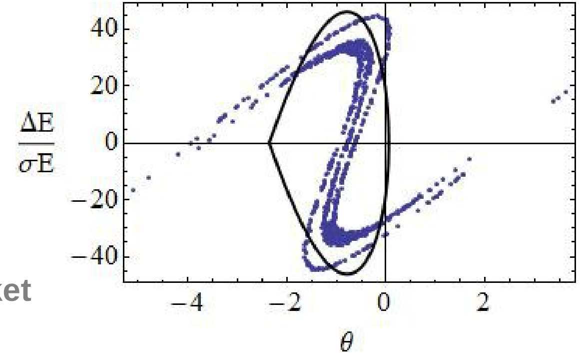
Utilize pre-existing pre-buncher



2nd chicane

Small R56 chicane compressor (bunch)

~97% of particles inside of pondermotive bucket



Rubicon double buncher

Theory: design of the double buncher

UCLA

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

$$b_{dbl}=2\left|\sum_{m=-\infty}^{m=\infty} J_{-m-1}[A_1B_2+(m+1)A_1B_1]J_m[A_2B_2]e^{-(B_2+(m+1)B_1)^2/2}\right|$$

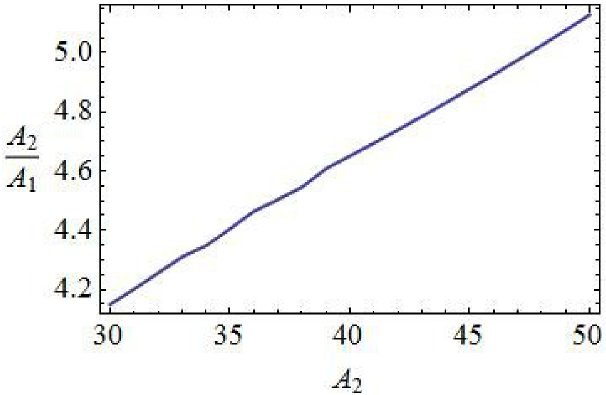
- Double buncher designed with original pre-buncher as second buncher

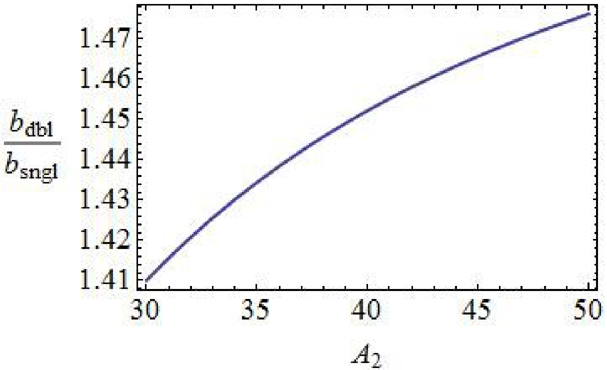
- Designed for Rubicon IFEL experiment:
    - 60 MeV/m gradient
    - resonant phase: -π/4
    - large initial ponderomotive bucket compared to energy spread

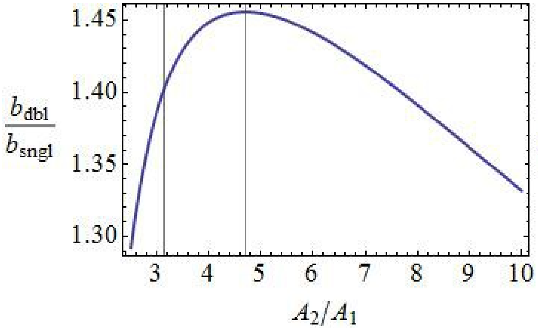
- Choose half period, 7 cm period undulator for new buncher
    - large gap (laser diffraction)
    - close to optimal A2/A1

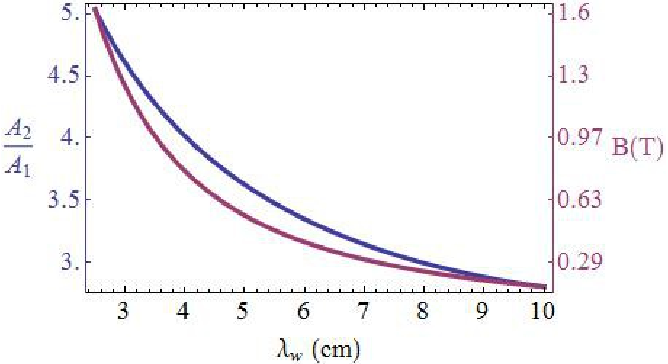
- optimize bunching factor, tweak parameters to maximize number of particles injected in bucket

- A2 < initial bucket height



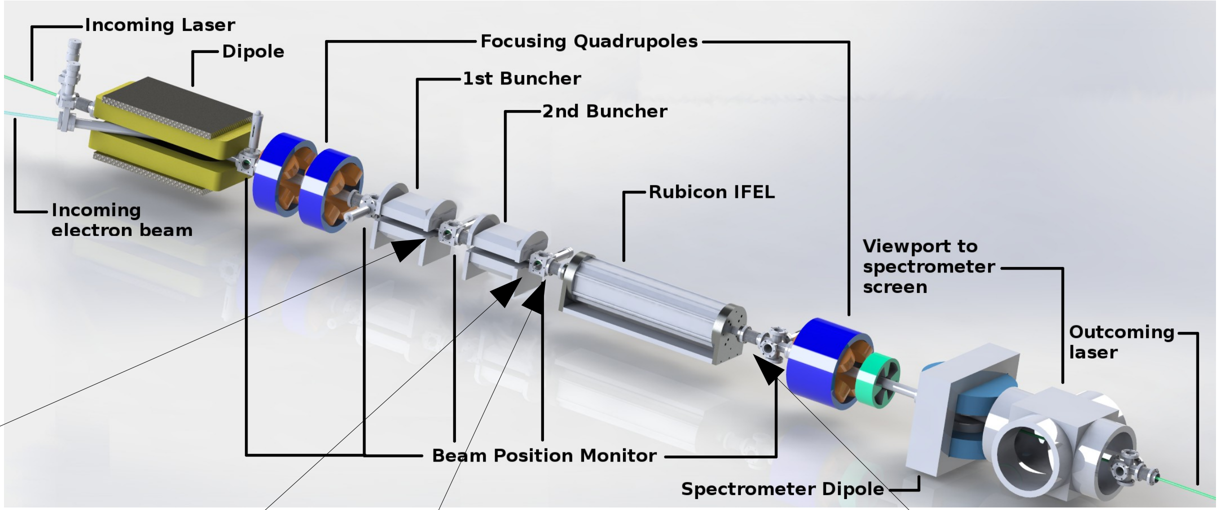


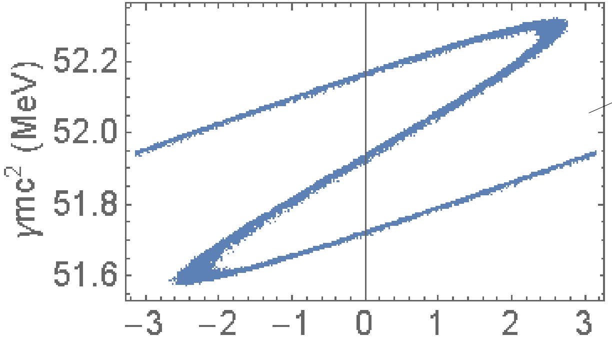


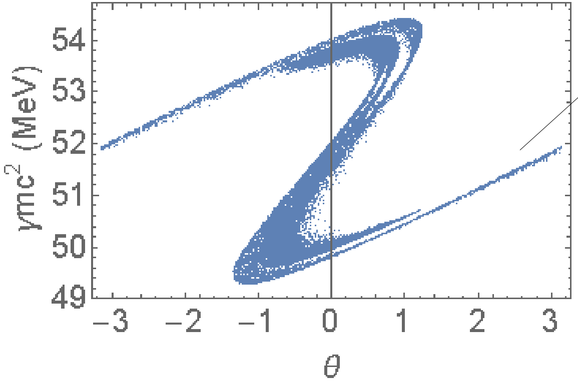


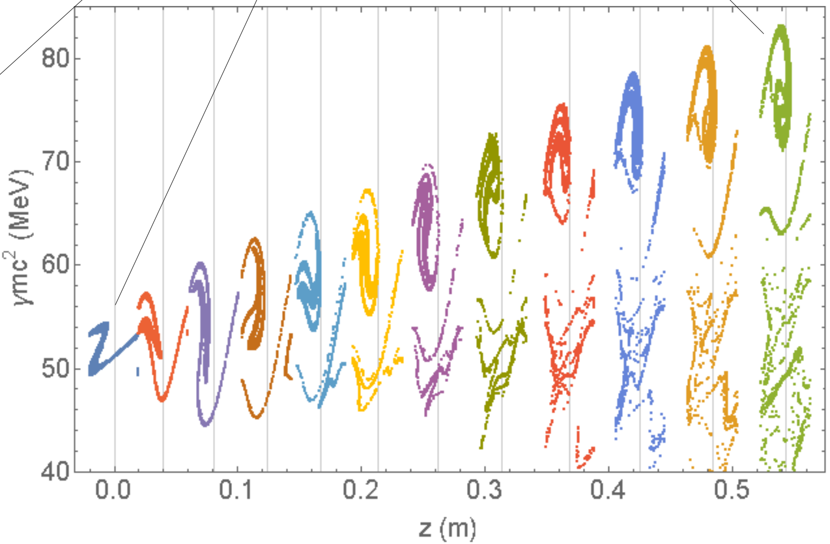
The double buncher

Genesis Simulations







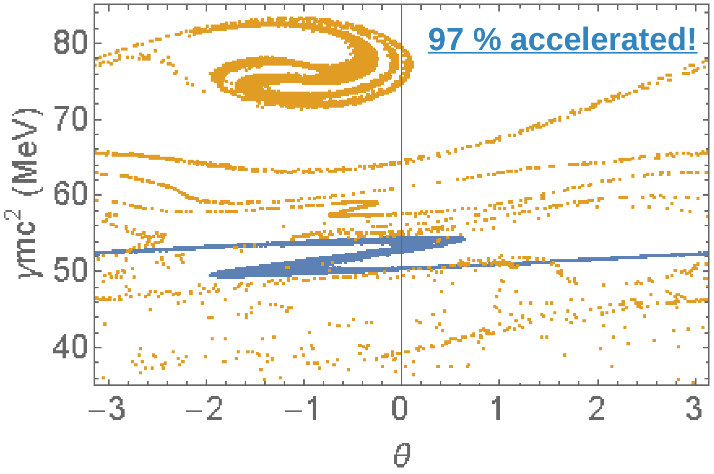


The double buncher

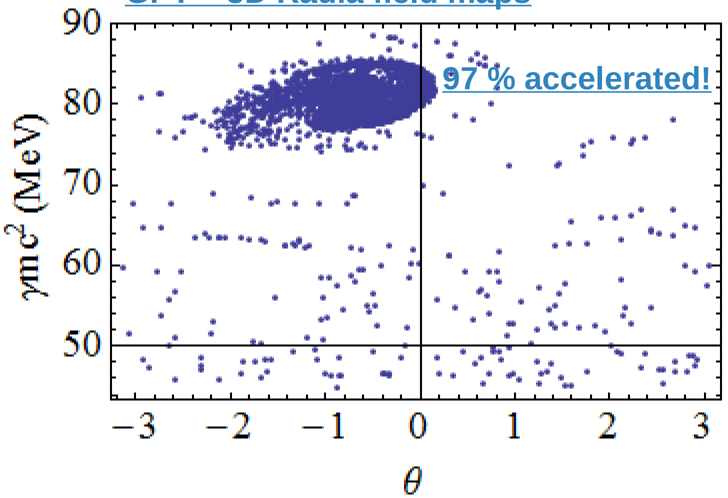
Simulations

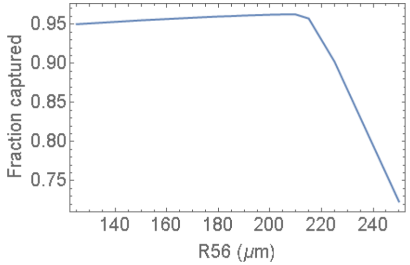
E-Beam energy	52 → 80 MeV
emittance	2 mm-mrad
σxy (waist)	100 μm
Laser Wavelength	10.3 μm
Rayleigh Range	0.55 m
Laser Waist	1.4 mm
Laser Power	166 GW
λw (1st modulator)	0.07 m (half period)
Chicane 1: R56	215 μm
λw (2nd modulator)	0.05 m (1 period)
Chicane 2: R56	80 μm
period tapering	0.04 -0.06 m
K tapering	2.03-2.56

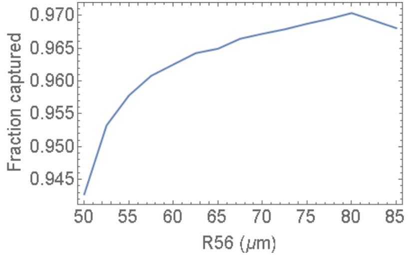
Genesis – 3D Time Dependent

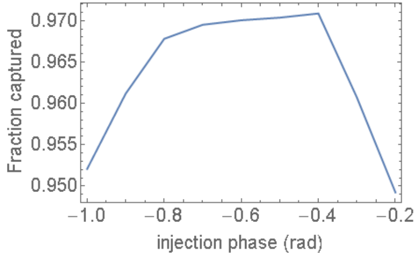


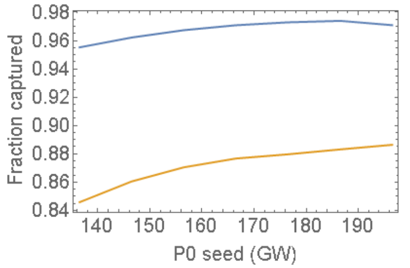
GPT – 3D Radia field maps











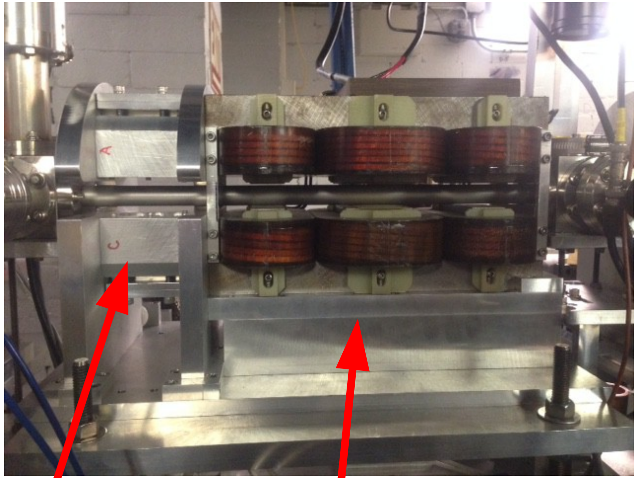
- Make use of electro-magnetic chicane (3/4” gap)
    - water cooled peak field ~ 0.4 T @ 140 A
    - Total length ~30 cm

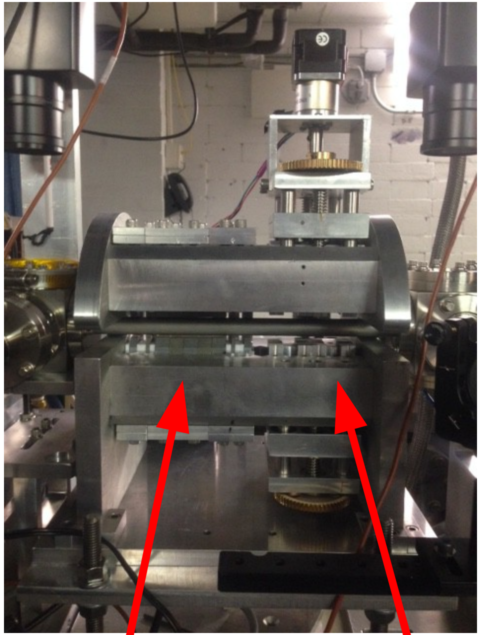
- build compact half period Modulator ~ 10 cm

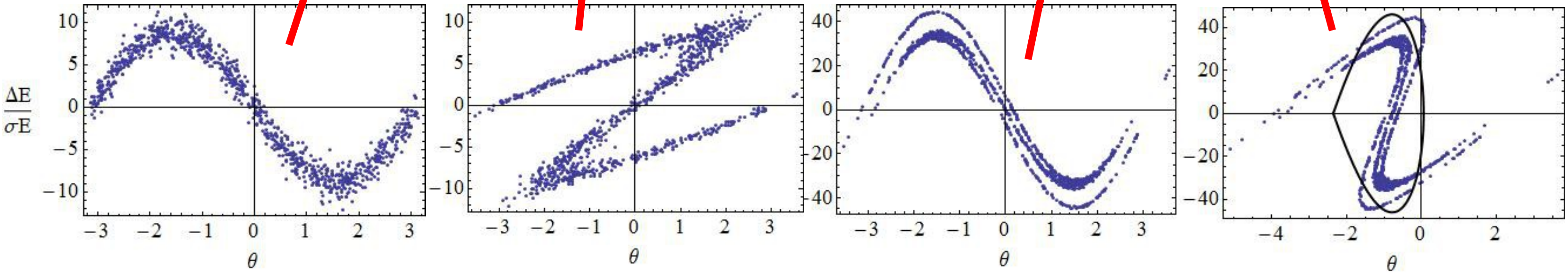
- Utilize old pre-buncher
    - total length ~ 30 cm

- Both new modulator and old pre-buncher can be removed from beamline.

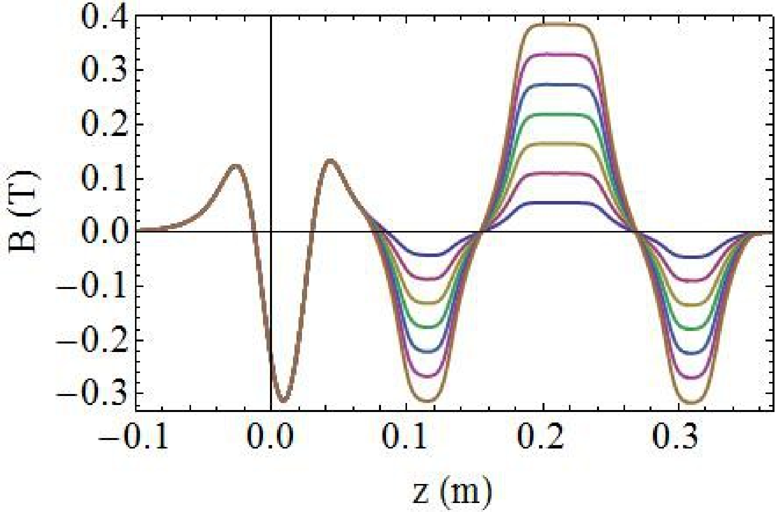
- EM chicane field can be zeroed after de-gaussing

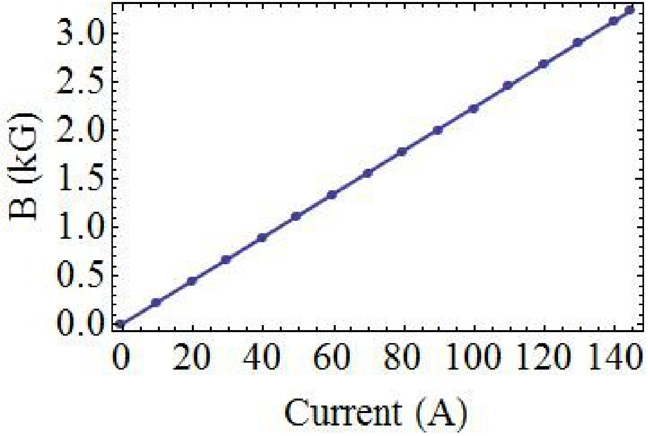


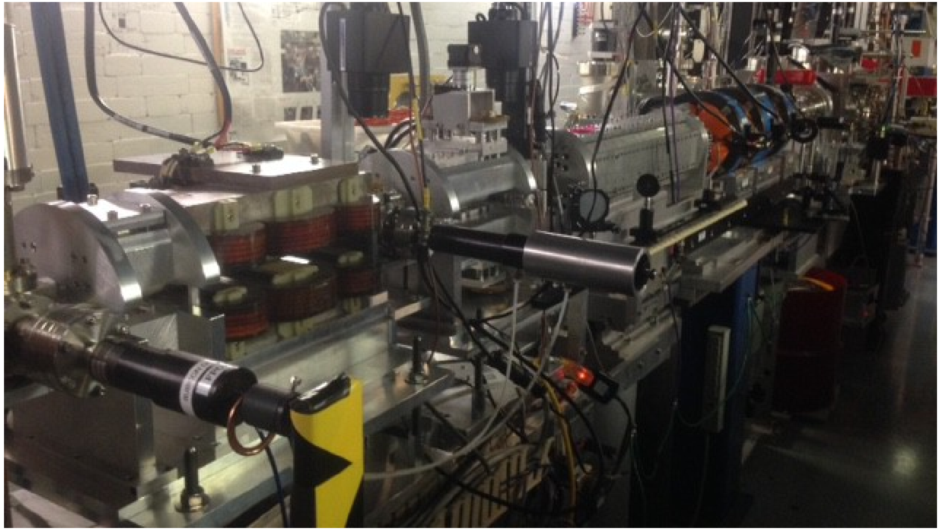




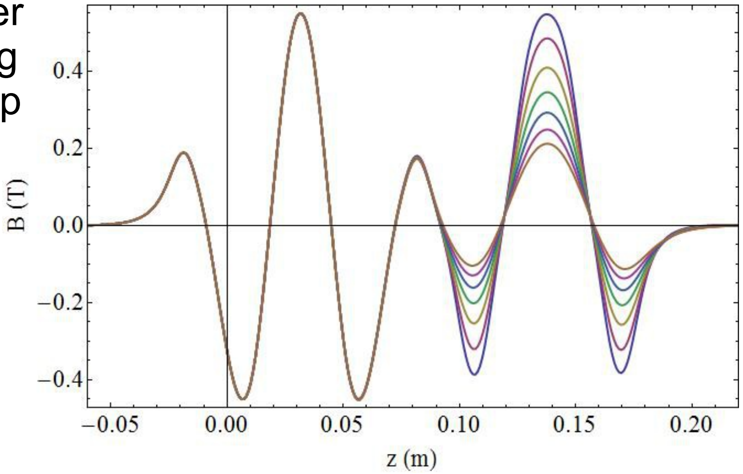
New buncher field varying EM chicane current

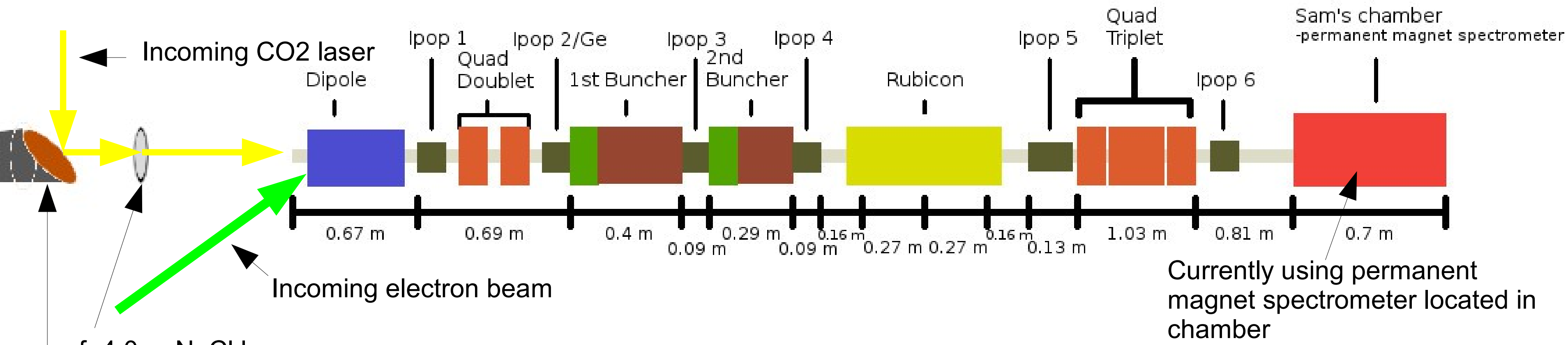




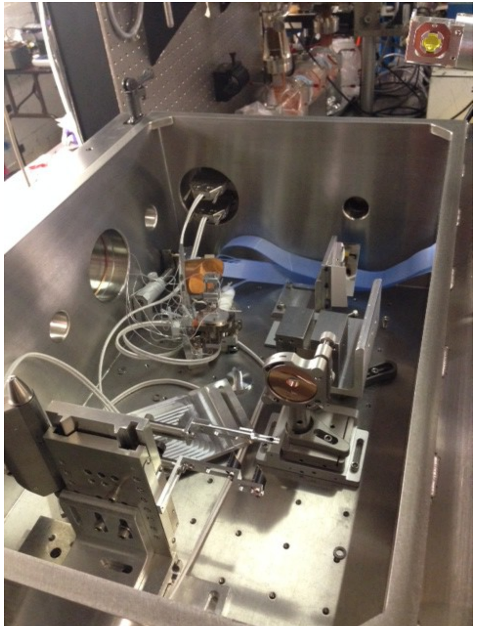


Old buncher field varying chicane gap





- Laser focused by 4 m NaCl lens, coupled into beamline through NaCl window.
- Overlaps with e-beam after dipole
- Note: Ipop 1-6 are beam position monitors
- Laser electron beam timing:
    - Germanium switch: look for transmission of CO2
    - adjust delay stage: optimize IFEL capture



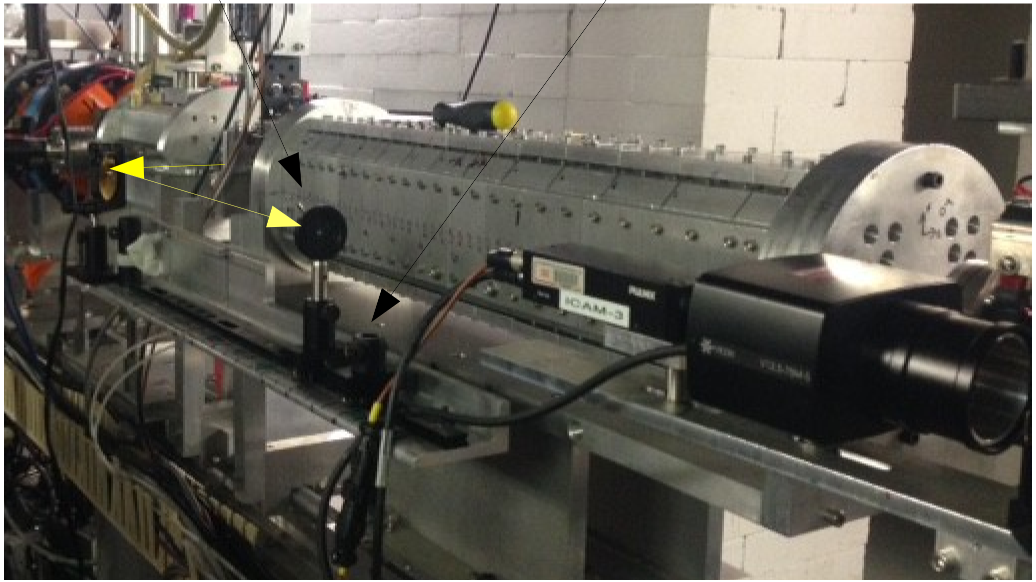
Pre-bunched Rubicon

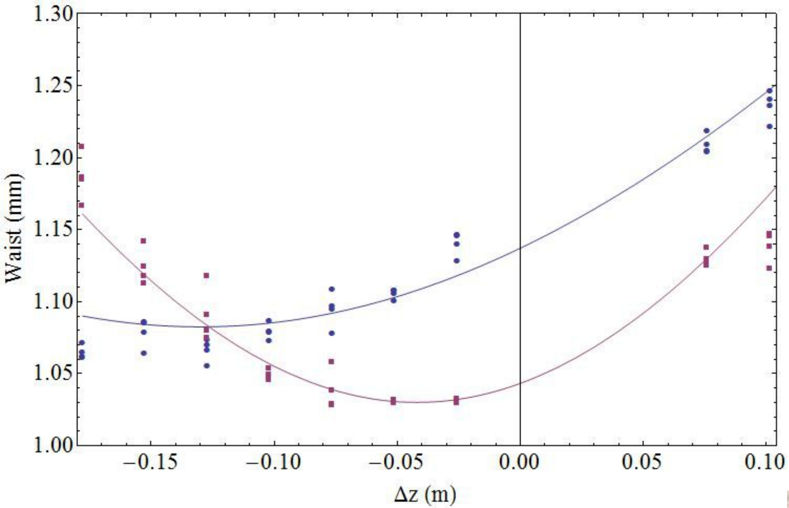
PBR: experimental set up pt. II

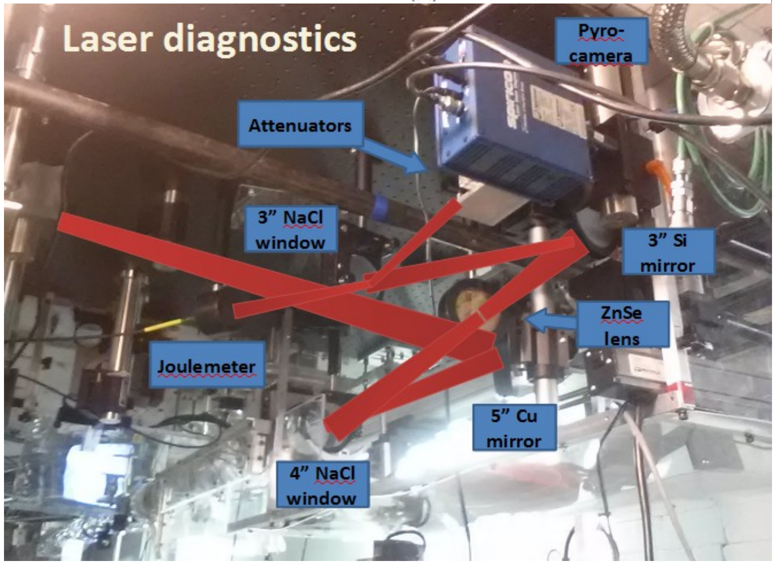
- vary laser polarization: rotate quarter wave plate
- vary laser waist position: move lens
- monitor high power laser energy and pointing stability on ceiling

Alignment iris

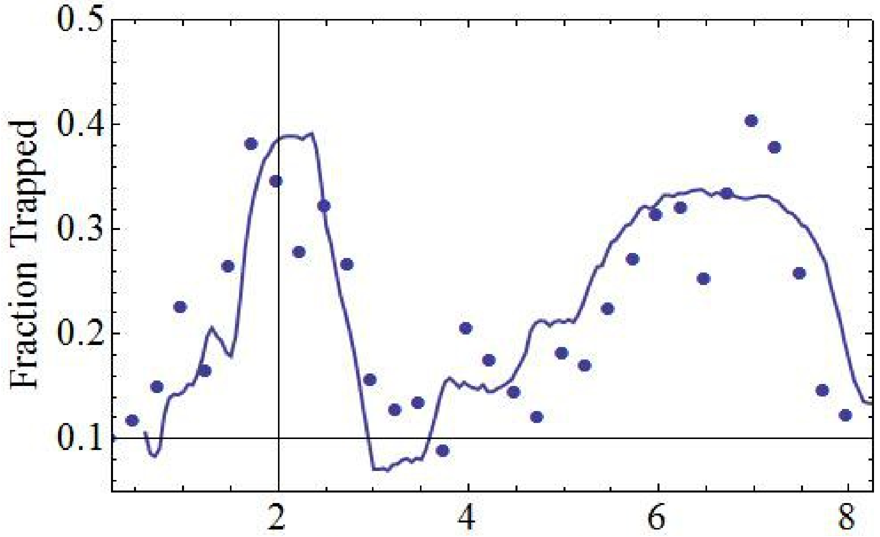
Pyro camera for waist scan or photodiode for Ge timing



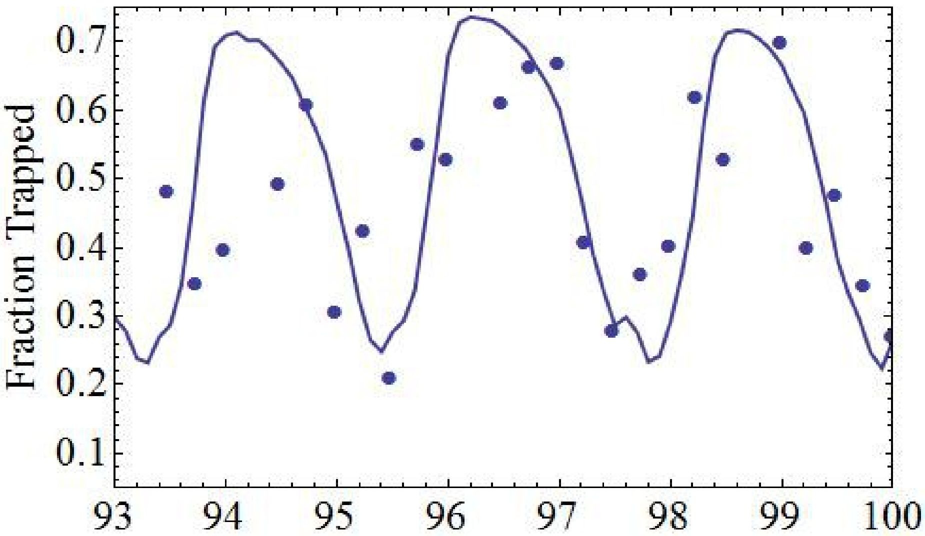




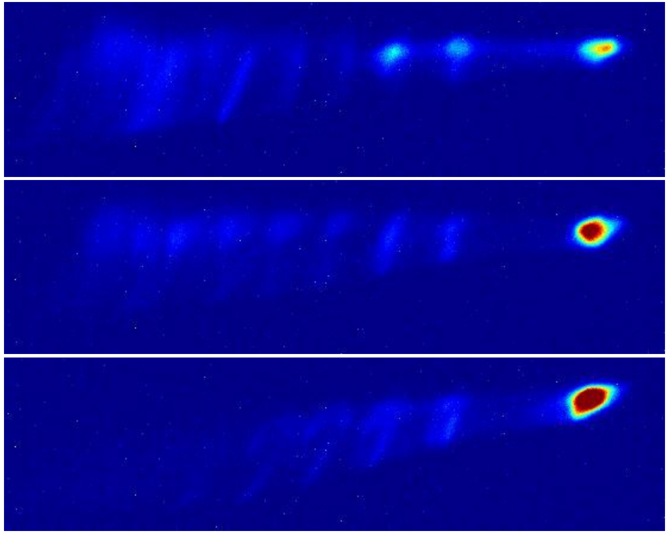
- After optimizing fine timing: scan over first pre-buncher chicane gap (only one buncher installed) varying injection phase and compression
- Set first chicane gap at peak: Scan over second buncher EM chicane current
- Blue lines show GPT simulation predictions. Note: need to take into account differing laser energy



Chicane motor steps (millions)



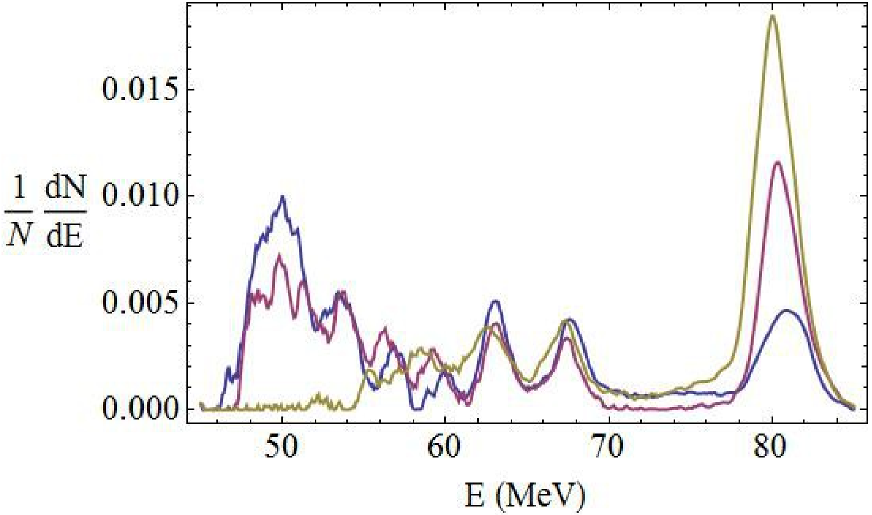
Chicane current (A)



No pre-bunching: ~25% accelerated (blue)

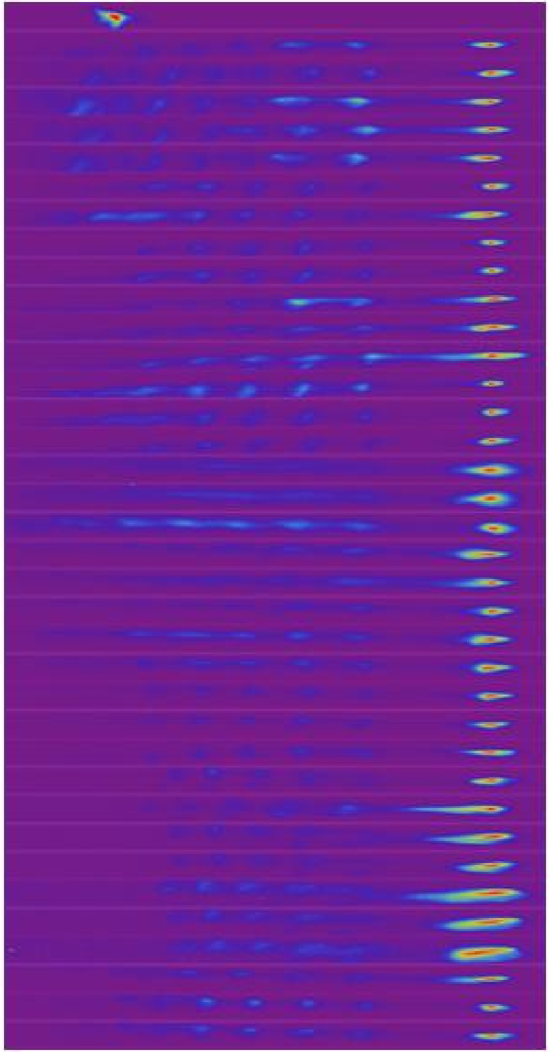
Single buncher: ~45% accelerated (red)

Double buncher: ~70% accelerated (yellow)

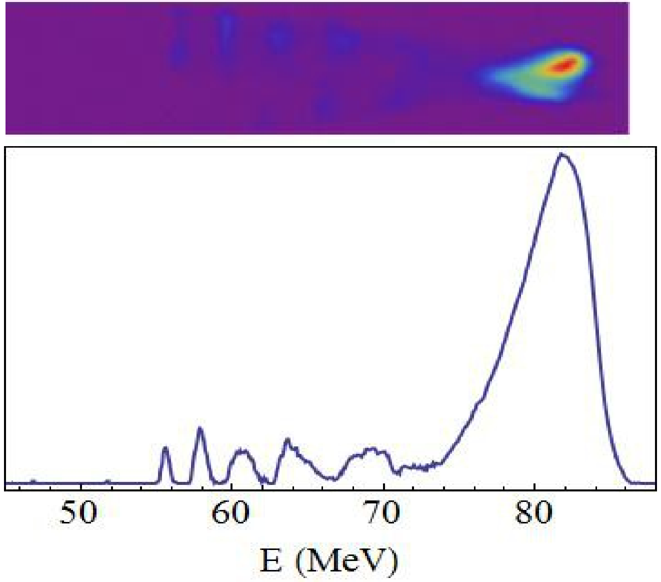


Nearly 100% of electrons accelerated past the initial energy (52 MeV)

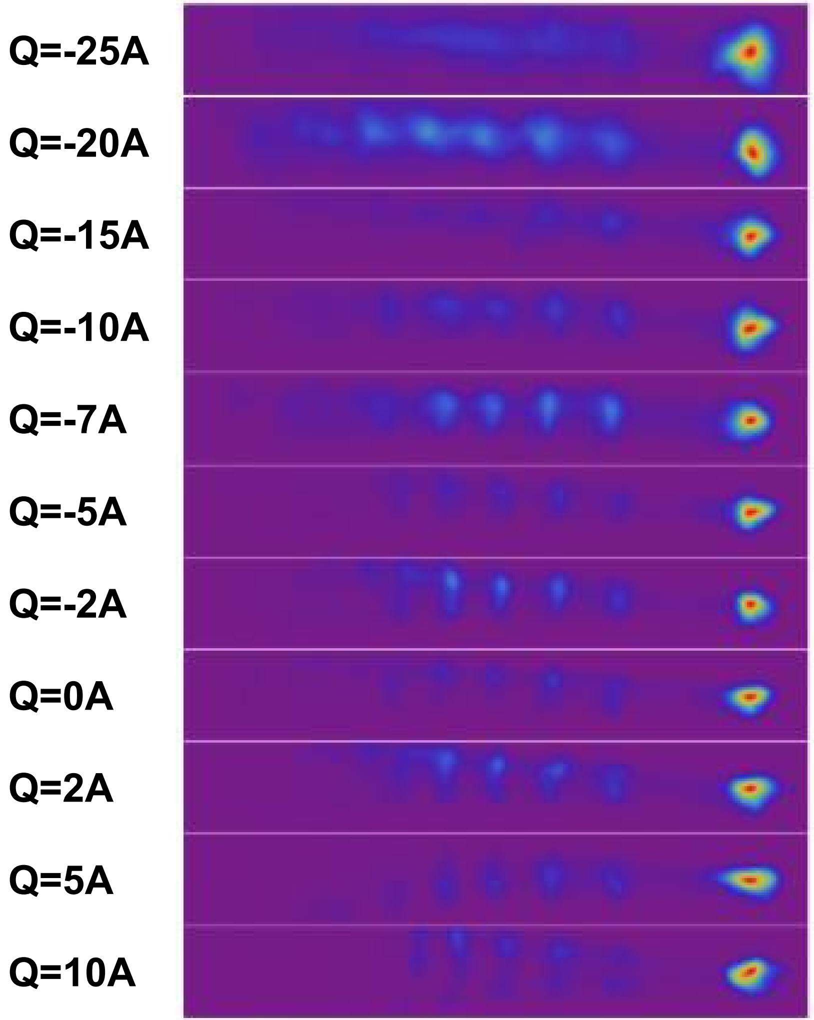
De-trapping before final energy may be due to laser rayleigh range not matching Rubicon tune, still investigating

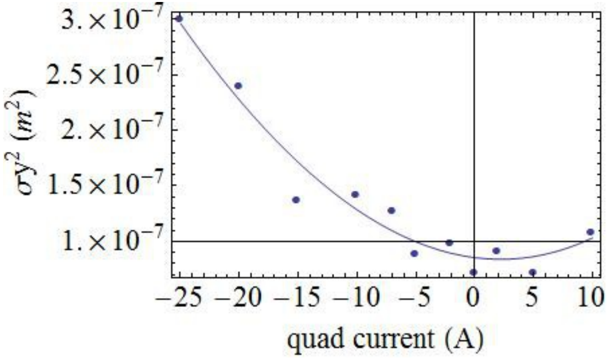


36 consecutive shots demonstrating IFEL double buncher stability. Note: top shot is the unaccelerated electron beam for reference.

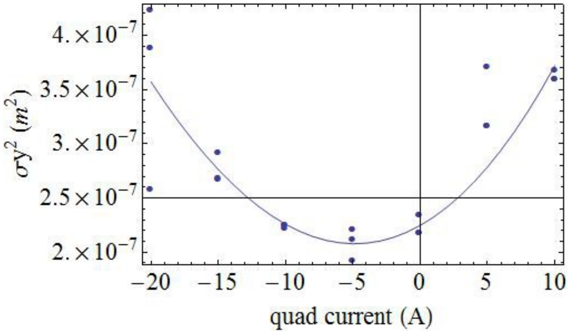


IFEL double buncher shot showing 80% acceleration. Note: This shot was taken during a quadrupole scan and the accelerated beam was defocused.

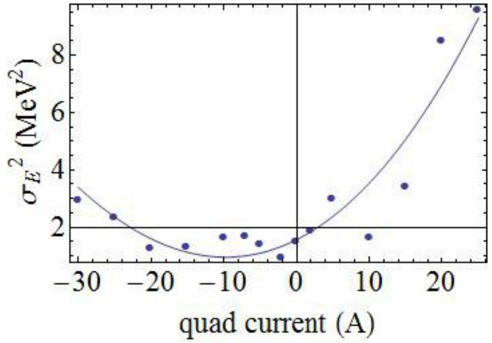




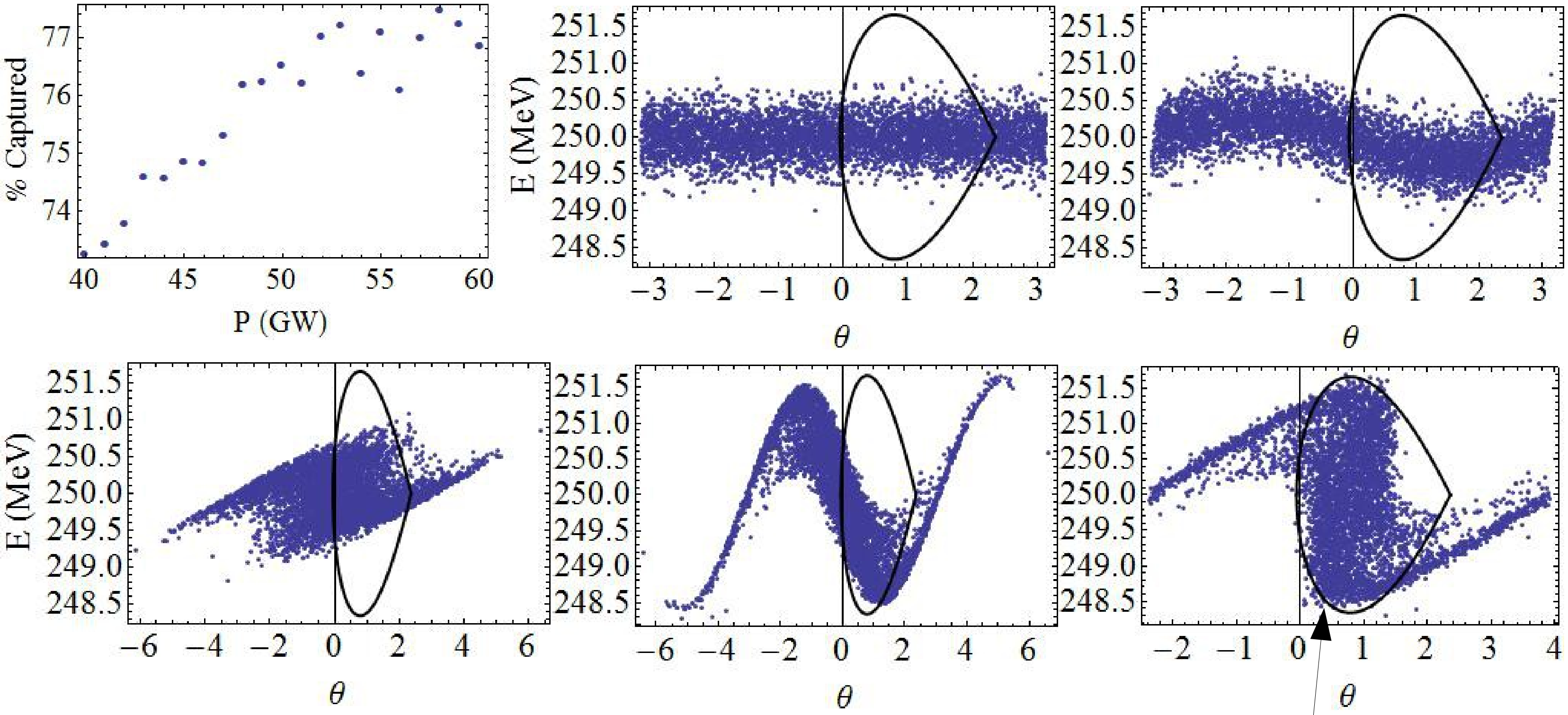
Accelerated beam
εy = 2.6 mm-mrad



Un-accelerated beam εy = 2.54 mm-mrad



Upperbound of energy spread σγ/γ ~ 1%



Potential issues:

- so far we've only looked in depth at the Rubicon case
    - large seed, large bucket compared to energy spread
    - short bunch length compared to laser (no compression/no chirp)
- small initial bucket compared to energy spread
- time dependent effects/short pulse laser

Only ~80% injected in bucket

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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