Enhanced Betatron Radiation from a Laser Wakefield Accelerator in a Long Focal Length Geometry

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Acknowledgements

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Contents

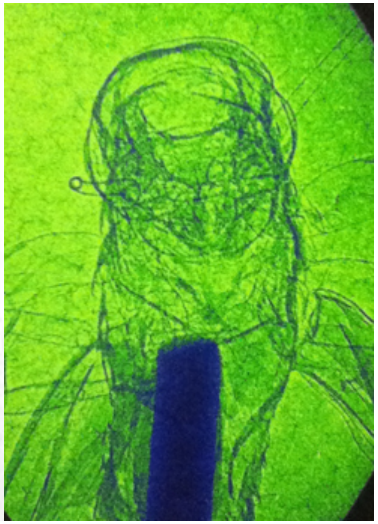
- High Brightness X-ray Sources.
- Betatron Radiation from Laser Wakefield Accelerators.
- Greater than 10-fold increase in Betatron Brightness with long focal length driver.
- Explanation via PIC simulation.

Importance of X-ray Sources

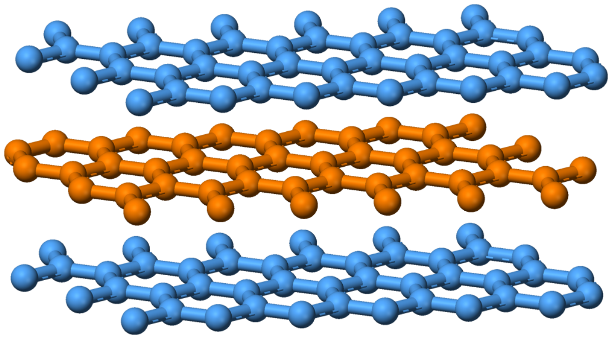
Imaging: absorption and phase contrast.

$$\eta = 1 - \delta + i\beta$$

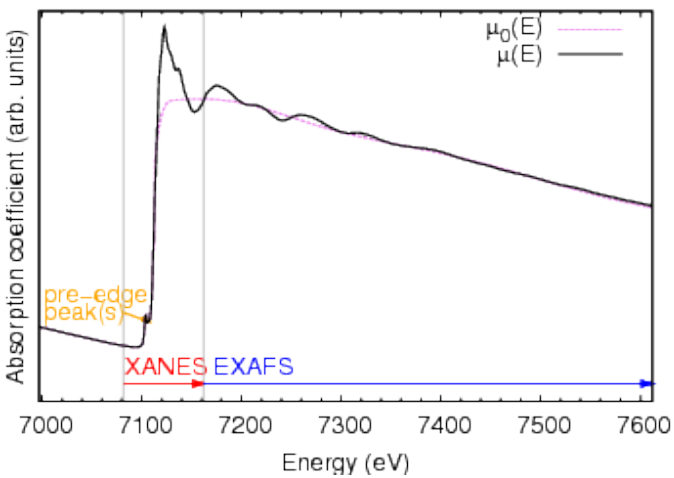
$\delta \gg \beta$ at high E
If the x-rays are coherent you can do phase-contrast imaging (xPCI). Pick up gradients in δ, get edge enhancement.



Material structure at the atomic scale:



E.g. graphite: distance between planes d = 0.335 nm (3.7 keV) -> hard x-ray diffraction.



Atomic structure from 'ringing' in absorption spectrum near K-edge.

Importance of Bright X-ray Sources

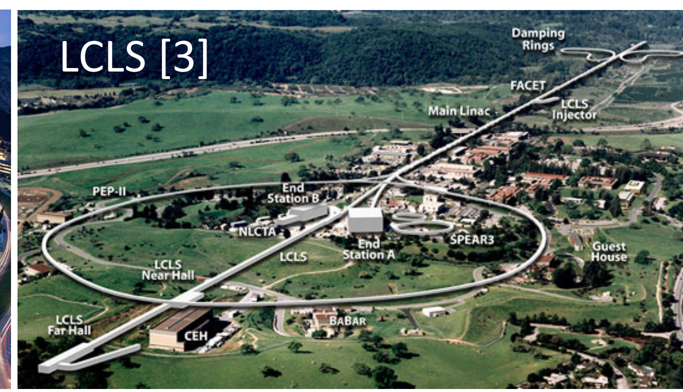
$$B\,/\text{photons}/\text{s}/\text{mm}^2/\text{mrad}^2/0.1\%\text{BW}$$

- Look at fast processes
- Small source size means high res. lens-less imaging in compact geometry.
- High flux- high SNR or high magnification
- Important for structural studies, less so for imaging.

Achievable with sources based on relativistic electron beams.

ESRF: B = 10^{23}-10^{24} @ 10-20 keV
LCLS: B = 10^{31}-10^{34} @ 10 keV [1]

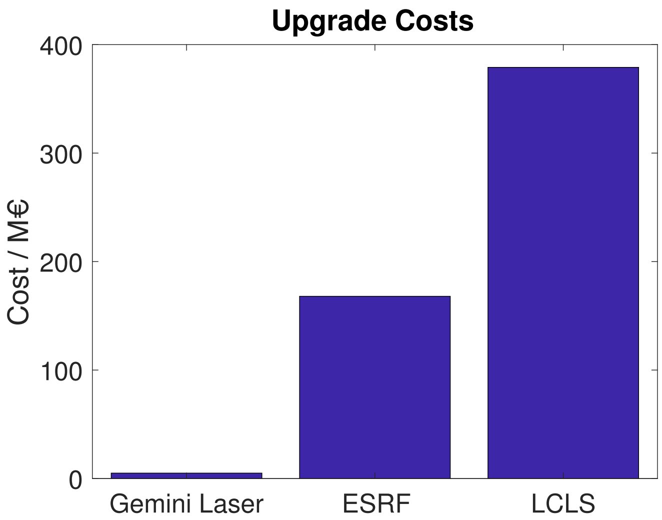

ESRF [2]



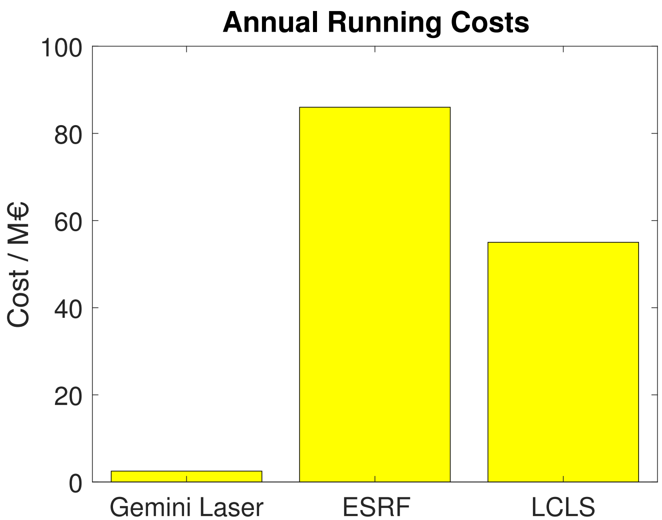
LCLS [3]

[1] http://photon-science.desy.de/research/studentsteaching/sr_and_fel_basics/fel_basics/tdr_spectral_characteristics/index_eng.html
[2] https://www.engelskagymnasiet.se/sites/engelskagymnasiet.se/files/esrf-01l.jpg
[3] http://web.stanford.edu/group/suncat/cgi-bin/suncat/sites/default/files/lcls_0.jpg

Why a Laser Based Source?

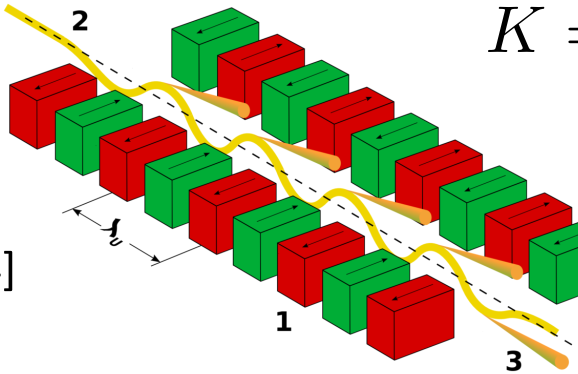


- High rep rate of conventional sources is not always required, especially for dynamic experiments e.g. HEDP.
- Laser pulse duration 10s fs (XFEL is 10s fs, synchrotron is 10s-100 ps).
- Large market: 47 synchrotron light sources worldwide, 3 current hard x-ray FEL's. 4 more being built.



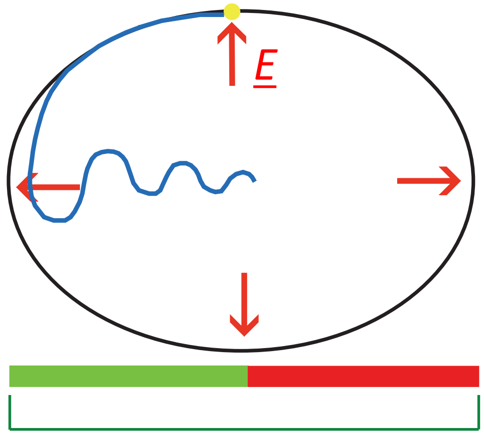
Betatron Radiation = Plasma Wiggler Radiation

Focussing forces of bubble means it acts as a plasma wiggler for electrons.



[4]

$$K = \gamma k_\beta r_\beta$$



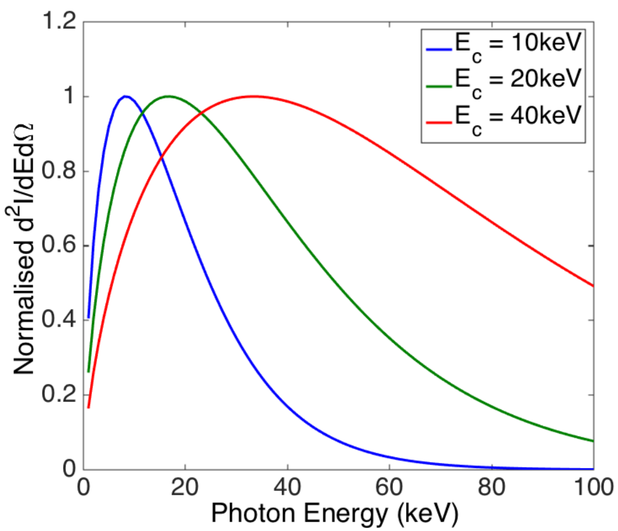
$$\lambda_b \approx \lambda_p \sqrt{a_0}$$

$$a_0 = \gamma_q \beta_q \approx 0.86\sqrt{I_{18}\lambda^2}$$

Well collimated. Emission cone angle $\theta \approx K/\gamma$

K > 1 for betatron source: hard, broadband radiation.

Well approximated by on axis synchrotron spectrum [5]. Spectrum defined by critical energy $E_c = \frac{3\hbar}{4c}\gamma^2{\omega_p}^2 r_\beta$



[4] CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=537945
[5] E. Esarey et. Al. Physical Review E, 65(5):056505, May 2002.

High Brightness Betatron Experiments

Laser	a_0	E_c / keV	No. photons	Brightness ph./s/mm^2/ mrad^2/0.1% BW	Source size (um)
Hercules [6]	4.7	8-21	5×10^7	1×10^{22}	1
Gemini [7]	3.4	20-33	1.3×10^9	~ 1×10^{23}	1.6
Texas Petawatt [8]	-	8-18	10^8-10^9	Of order 10^{22}-10^{23}	-
Jupiter Laser Facility [9]	~3	15	5×10^8	1×10^{23}	

Ideal way to improve brightness: increase number of photons/mrad^2. Consequences:

Improve single-shot image quality, probe matter via XANES/ EXAFS (require $>10^6$ photons/eV for good stats [10]), Laue diffraction?

[6] S. Kneip et. al. Nature Physics 6(12):980-983,2010.
[7] J.M. Cole, J.C. Wood et. al. Scientific Reports 5:13244, 2015.
[8] X. Wang et. al. Nature Communcations 4:1988, 2013.
[9] Yan W. *et al*. PNAS 111(16):5825-5830, 2014.
[10] F. Albert et al. Plasma Physics and Controlled Fusion 56(8):084015.

How to Increase the Number of Betatron Photons

- Total emitted energy: $W_{tot} \propto N_e \; \gamma^{5/2} \; {r_\beta}^2$

- Maximum electron energy: $\gamma \propto \dfrac{1}{n_e}$

- Matched spot size for good laser guiding:

$$k_p w_0 \approx 2\sqrt{a_0} \implies w_0 \propto 1/\sqrt{n_e}$$

- Long focal lengths (big focal spots) allow us to be matched at lower density, increasing maximum energy gain.

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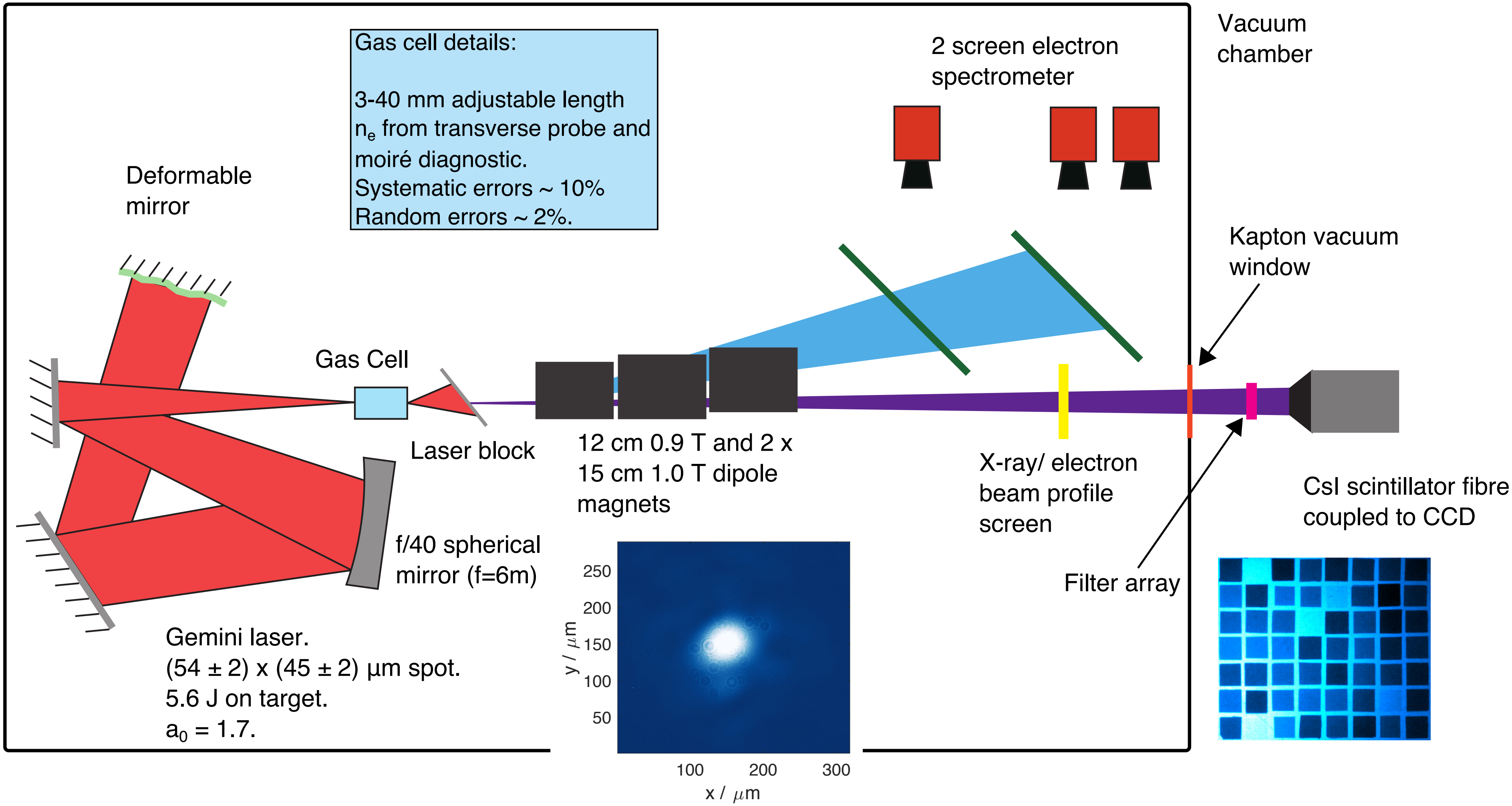
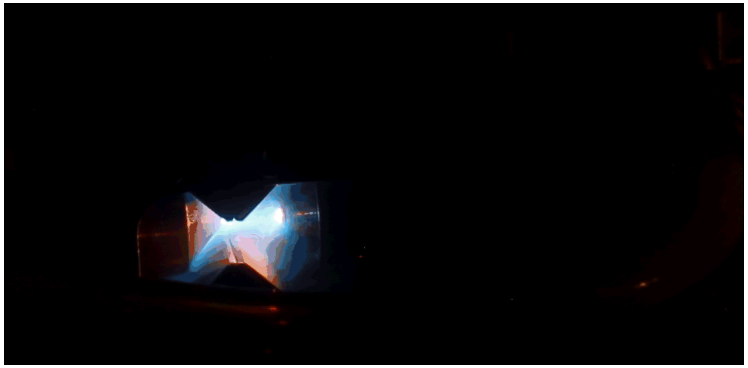
Typical electron energy at Gemini with f/20 focussing:
0.7 ± 0.1 GeV.
In optimal conditions:
E $\gtrsim$ 1 GeV.

Experiment Set-up

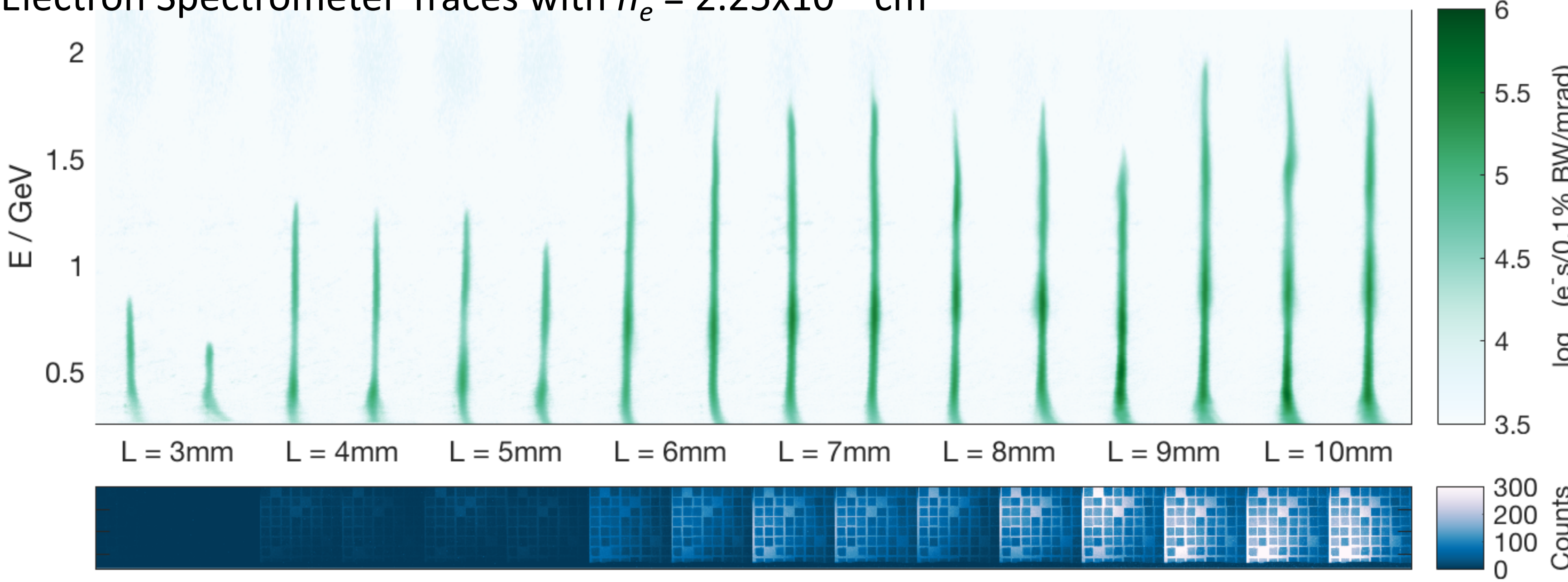


Electron and X-ray Results I

Performed scans at constant plasma density changing the length of the He plasma in the range 4-40 mm.

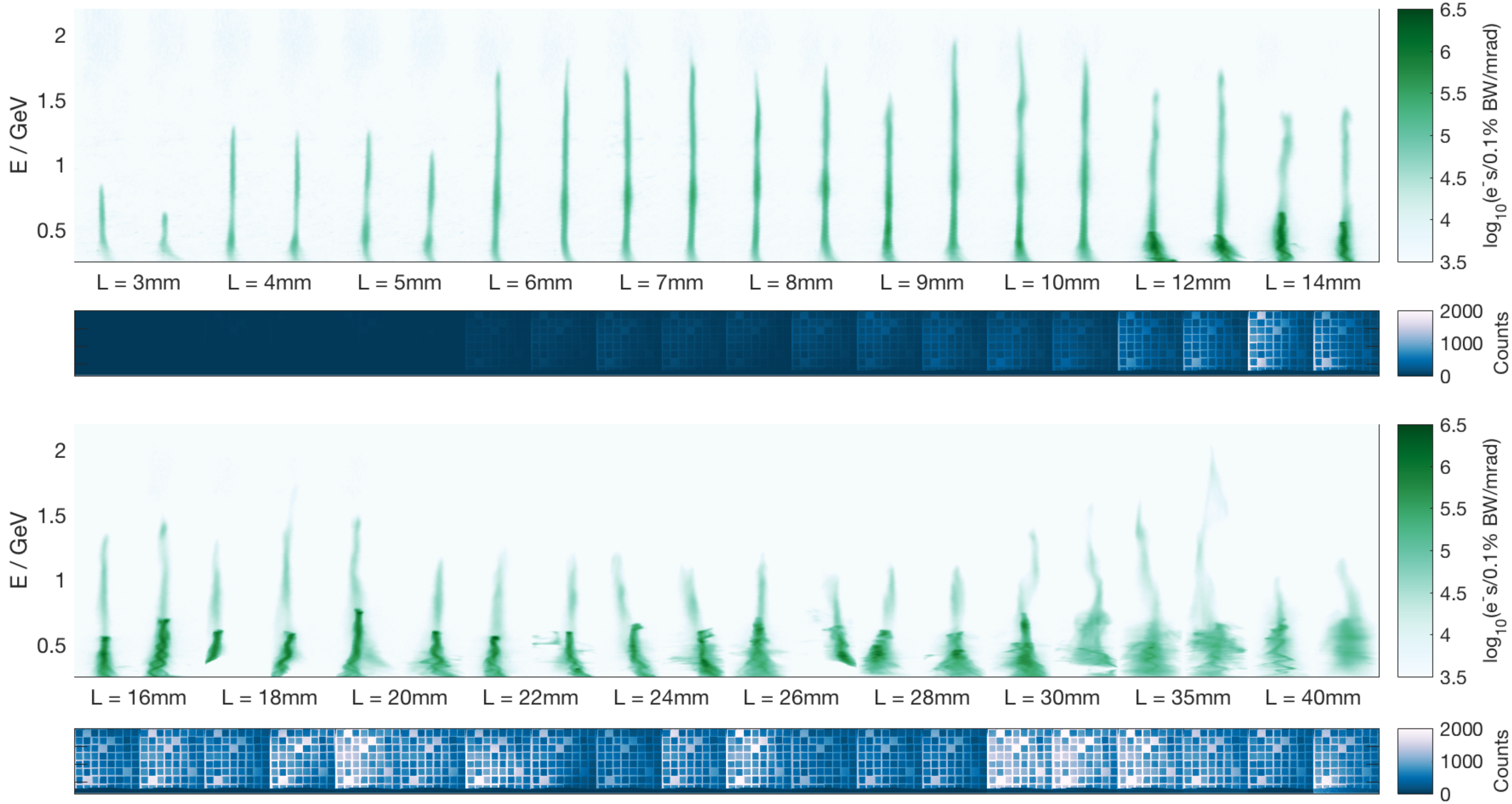


Electron Spectrometer Traces with $n_e = 2.25\text{x}10^{18}$ cm^{-3}



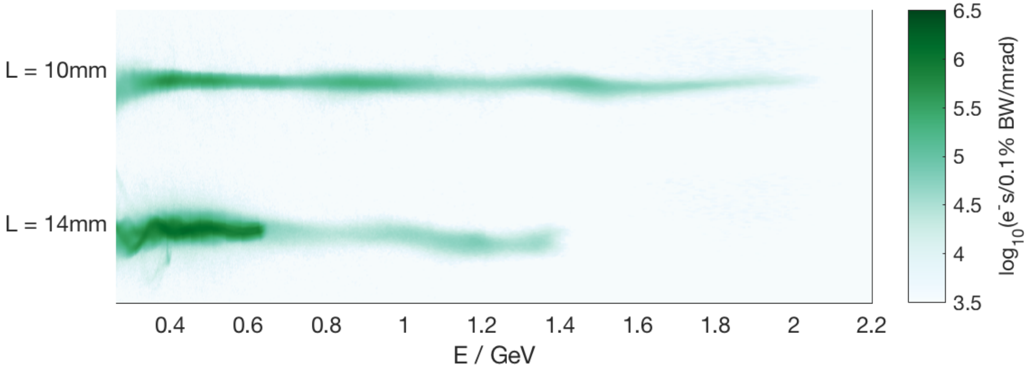
Betatron x-ray Images of Filter Array

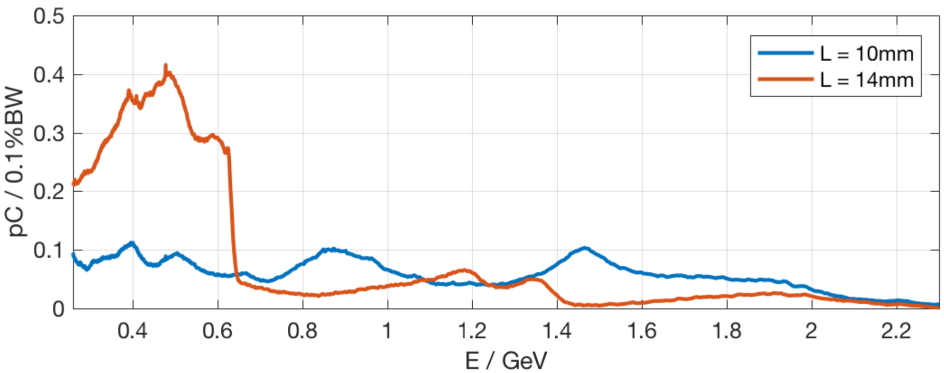
Electron and X-ray Results II

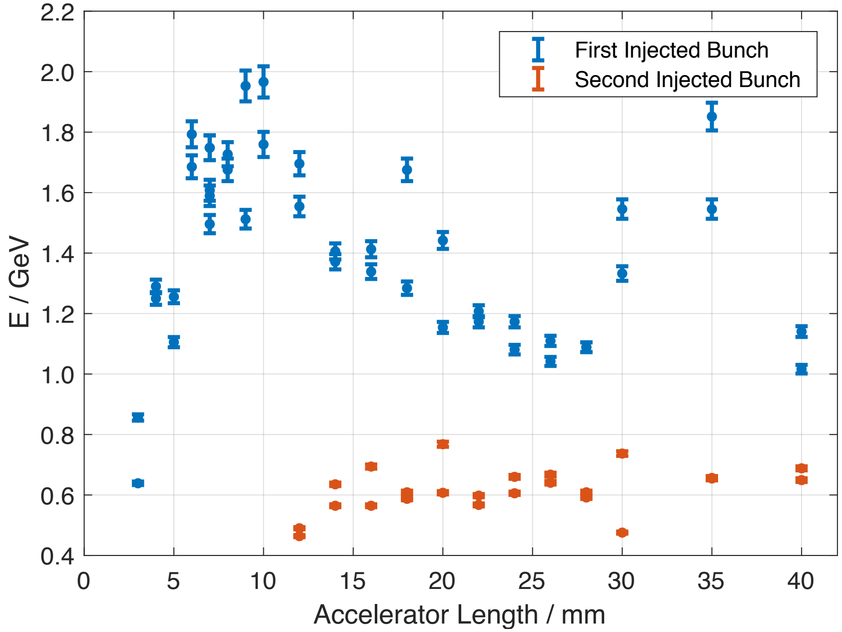


Injection of 2nd bunch with high charge/0.1%BW and large transverse momentum.
Second injection correlates with a large increase in the number of x-rays being detected.

Electron Beam Energy Spectrum



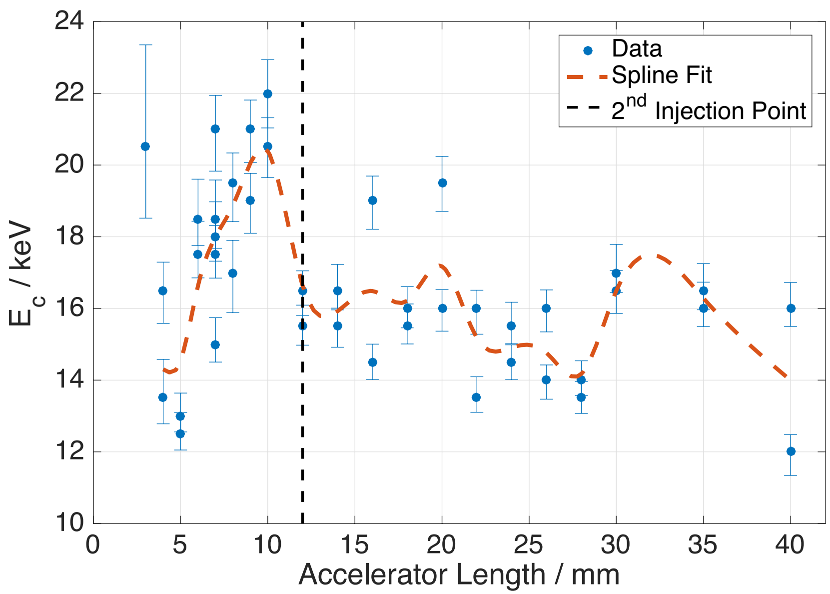


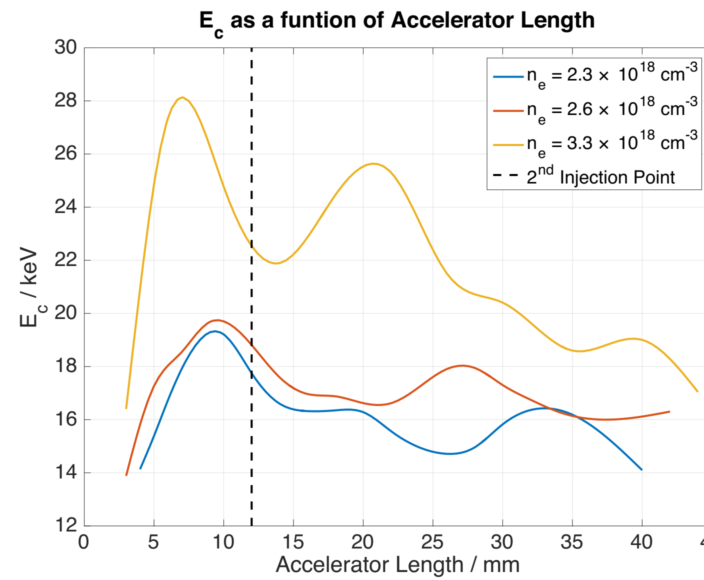


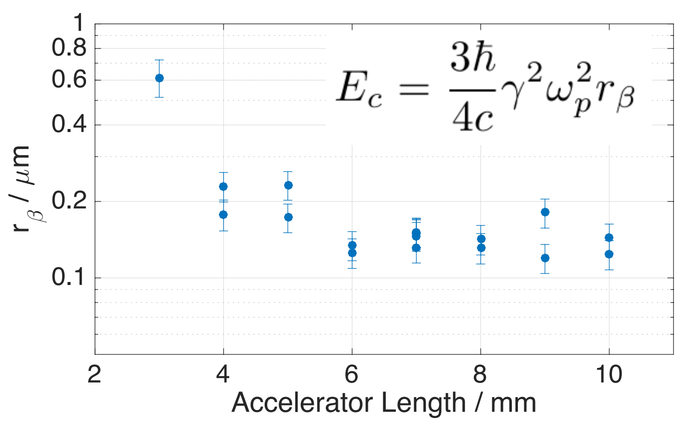
Above: Peak electron energies vs. accelerator length. Errors from uncertainty in screen position.

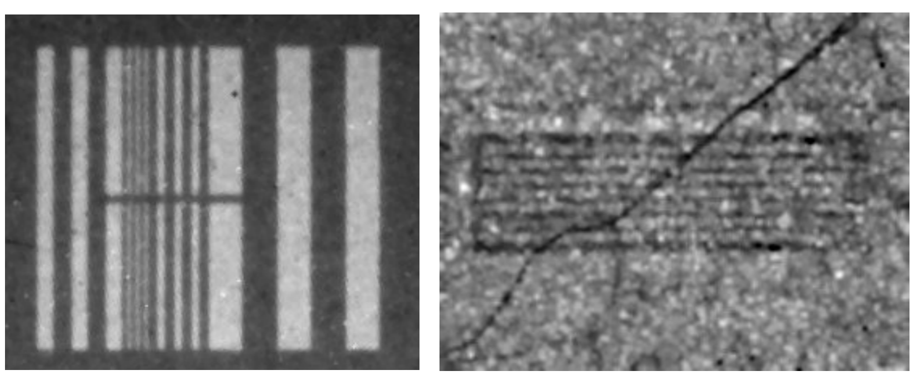
Second bunch has up to 4x the charge/ unit bandwidth.
Injection close to dephasing point of first bunch.
Limited acceleration of second bunch: never beyond 800 MeV.

Betatron Spectral Characteristics





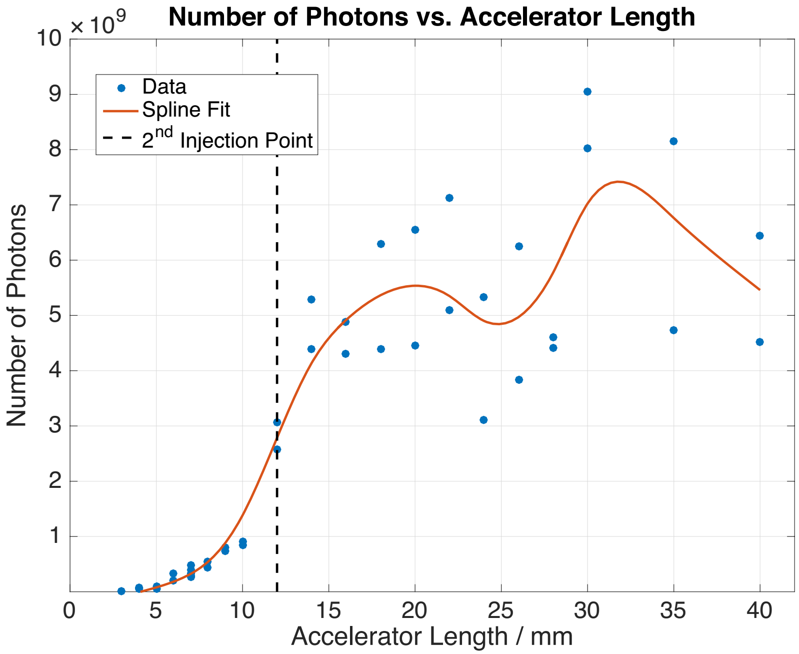


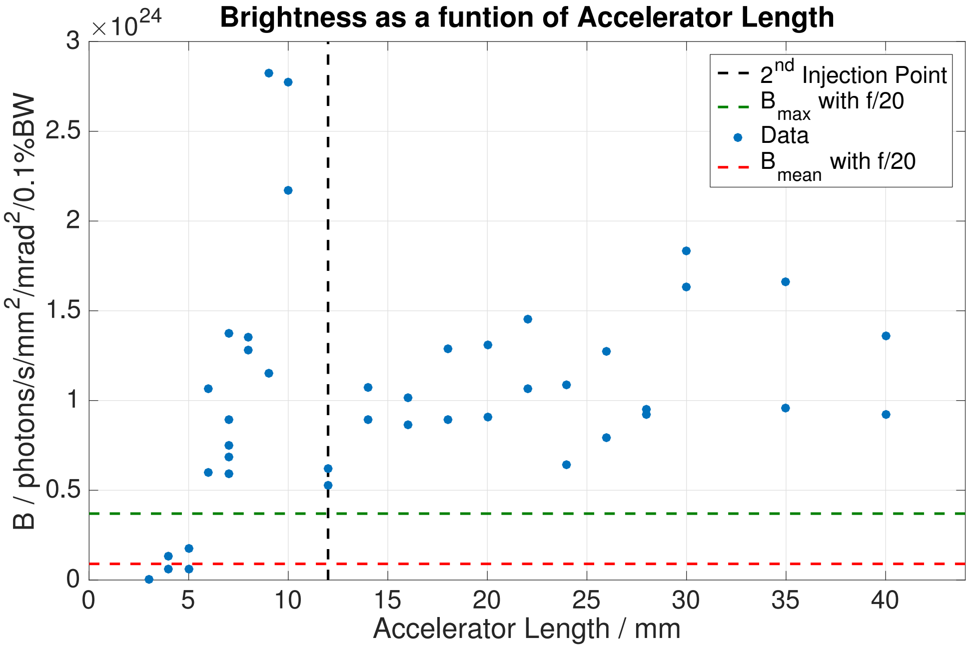


10 μm bars, M=11

4 μm bars, M=29

Betatron Brightness

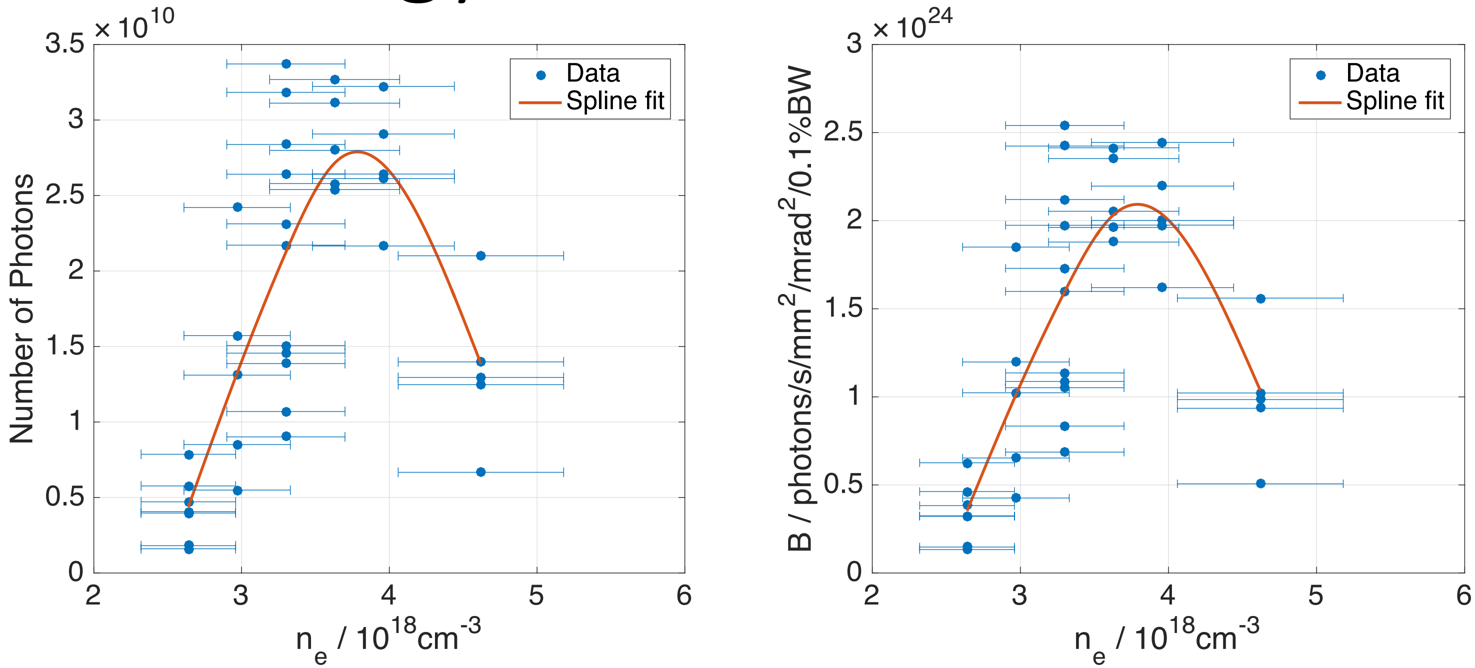




First injected bunch: high brightness driven by small source size.

With second bunch: relative reduction in brightness from rapid increase in source size. But we see a dramatic increase in the number of photons- good for applications!

Further Brightness Increase with Laser Energy

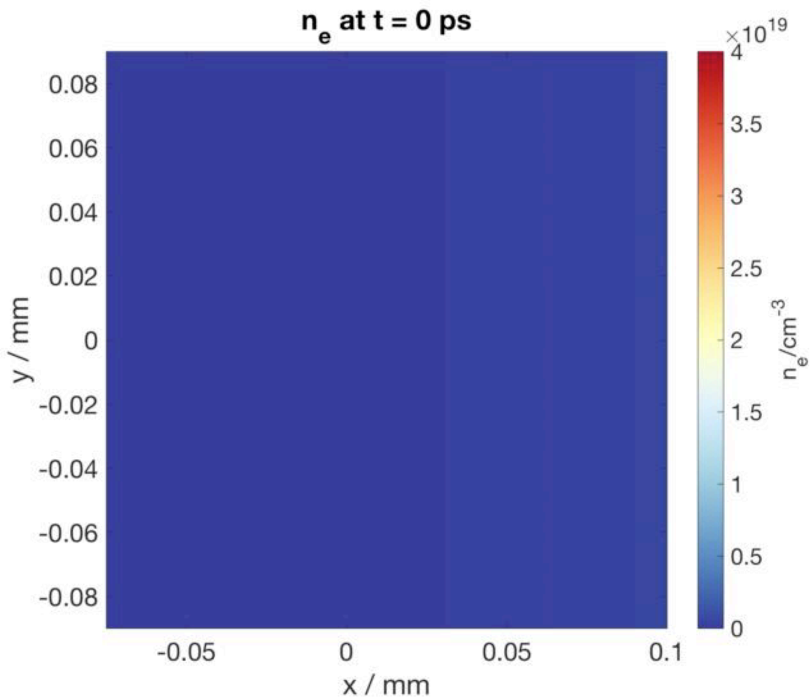


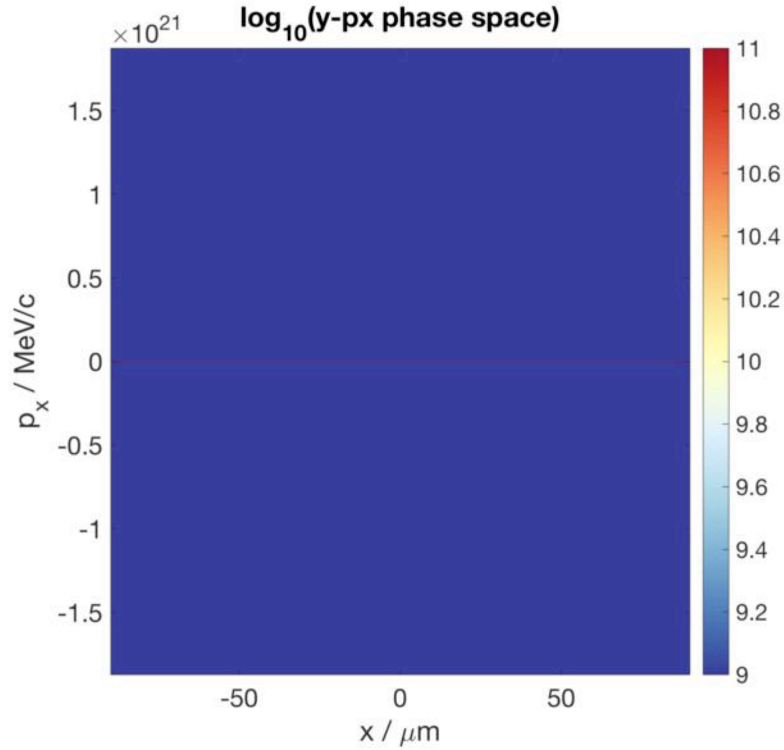
Increase in laser energy: 5.6 J to 11.3 J. $a_{0,max}$: 1.7 to 2.4
~70% increase in brightness in high photon regime. Approx. 6x more photons.

Good for applications. $1.4\text{x}10^6$ photons per eV @ 6-8 keV. B. Kettle talk, few shot XANES spectra. J. Cole talk, high quality medically relevant imaging. Both in WG4 right now.

PIC Simulations I

n_e = 2.5x10^{18} cm^{-3}, a_0 = 3.8



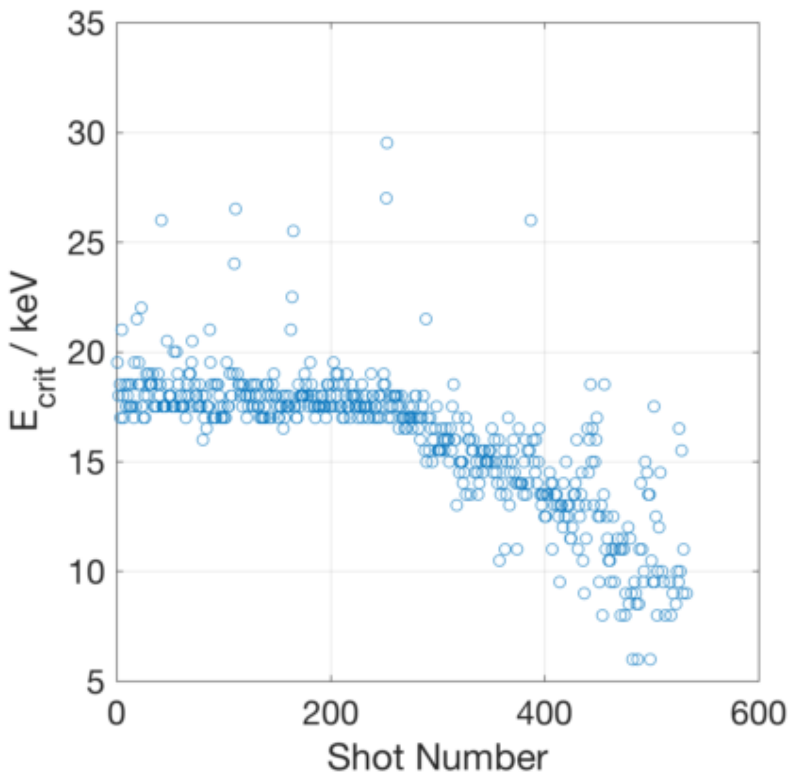


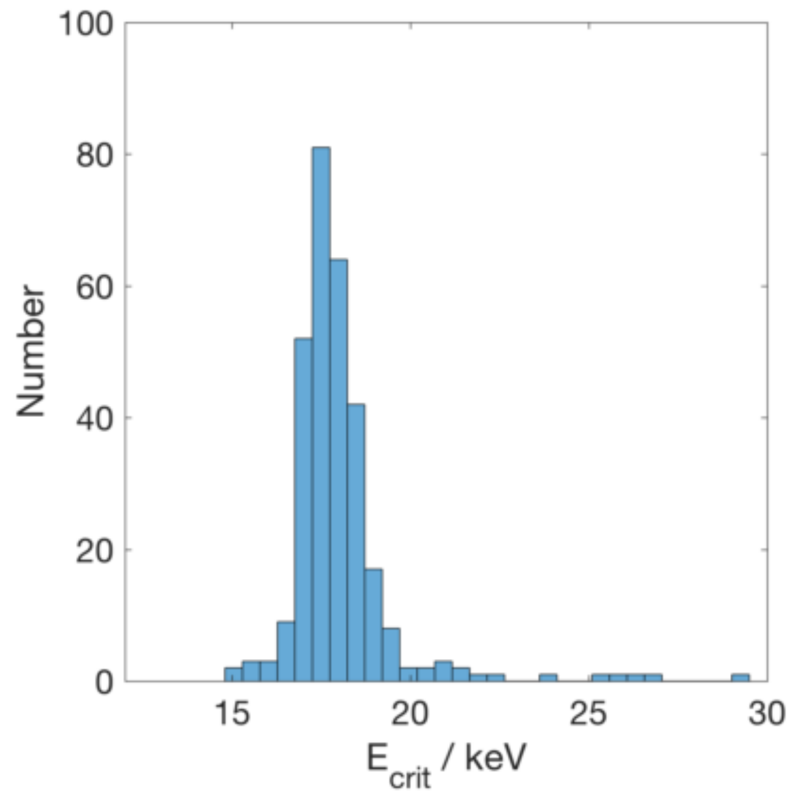
- First bunch injected very early- during wakefield formation. Second, high charge/ unit BW, bunch injected due to bubble expansion [11][12].
- Second bunch undergoes large oscillations ($W_{tot} \propto r_\beta^2$).
- Oscillations seem linked to bubble oscillation- explains coherent oscillation structure of some beams from the experiment.

Aakash Sahai

[11] S. Kalmykov et al. Phys. Rev. Lett. 103(13):1-4, 2009.
[12] S. A. Yi et al., PPCF 19(3):014012, 2012.

Reproducibility





- Dynamic injection and laser behaviour.
- Reproducible betatron x-ray spectrum.
- Excellent reproducibility for 300 shots.
- Mean: 18.0 keV. Standard Deviation: 1.6 keV.

Conclusions

- Long focal length wakefield experiment produced high brightness betatron beams in 2 regimes.
- First injection: few hundred nm source size.
- Second injection: high brightness and photon number.
  $> 10^6$ photons/eV,
  $> 10^{24}$ photons/s/mm^2/mrad^2/0.1%BW
- Results backed up by PIC simulation.