EuPRAXIA

Yearly meeting 2016
Ecole Polytechnique
27-28 October

WP13：Alternative Radiation Generation

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Tasks and challenges

- **Task 13.1: Investigations of injection schemes for high quality electron bunches**

Challenges: robust control of electron injection for beams with > 1 GeV, > 50 pC, < 1% energy spread with a commercial ~200 TW laser system. (Options: Ionization injection, density gradient injection, hybrid schemes,….)

- **Task 13.2: Extension of spectral range of plasma-based radiation sources to gamma-rays and the far infra-red**

Challenges: quasi-monoenergetic gamma-ray source with high brilliance. (Options: betatron radiation, Compton scattering, radiation reaction, laser-gas or laser-solid interaction, use of plasma channels, ...)

Tasks and challenges

- **Task 13.3: Investigations of coherence development in plasma-based radiation sources**

Challenges: Potential plasma based coherent radiation different from conventional FELs. (Beam injection control, ion channel laser, development of coherence, …)

Related to tasks 1 and 2

- **Task 13.4: Development of diagnostic systems for investigating plasma-based radiation sources**

Several diagnostic systems are already in use at Strathclyde and some are under development.

- Emittance
- Energy spread
- Beam pointing stability
- Bunch length measurements
- SCAPA

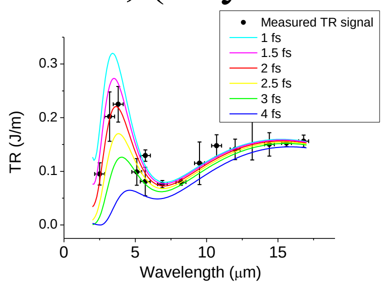
ALPHA-X: Advanced Laser Plasma High-energy Accelerators towards X-rays

University of Strathclyde Science

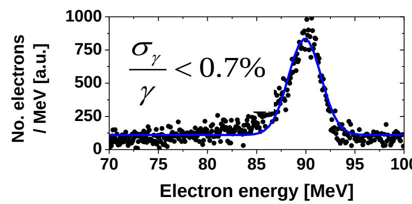
Compact R&D facility to develop and apply femtosecond duration particle, synchrotron, free-electron laser and gamma ray sources

Jaroszynski et al., (Royal Society Transactions, 2006)

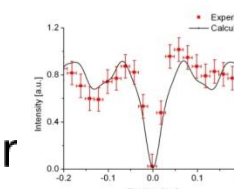
CTR: electron bunch duration: 1-3 fs

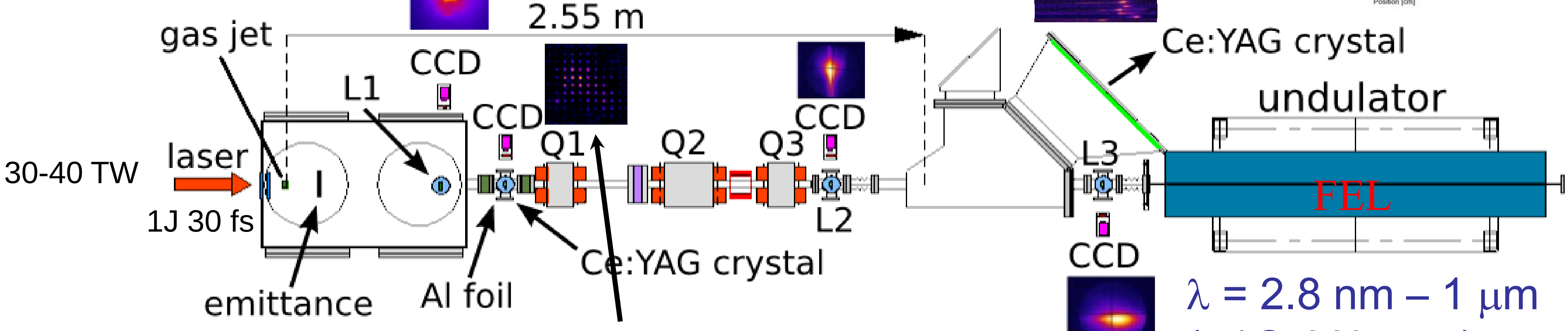


electron beam spectrum



phase contrast imaging with 50 keV photons



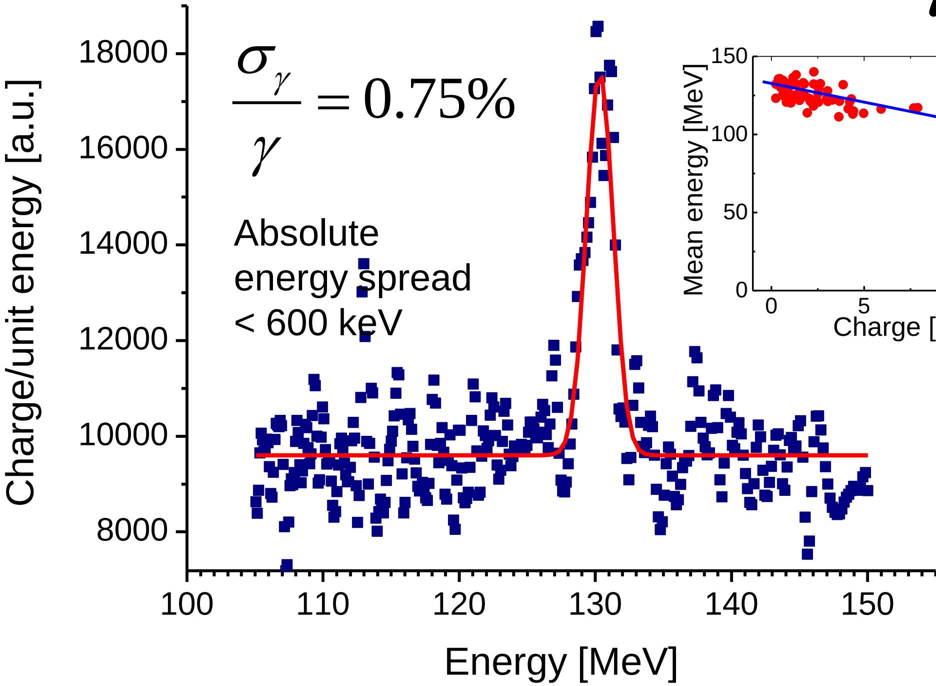


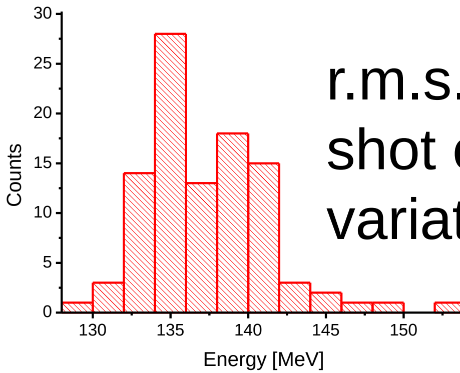
beam emittance: <1 π mm mrad

λ = 2.8 nm – 1 μm (<1GeV beam)

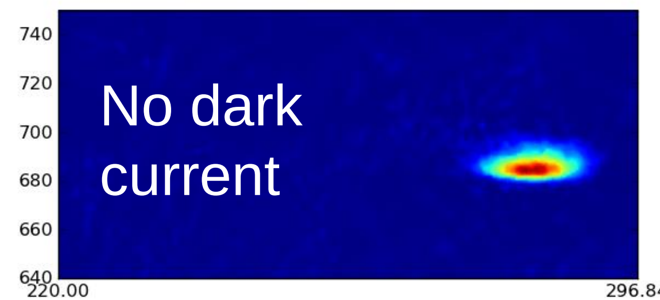
Brilliant particle source: 10 MeV → GeV, kA peak current, fs duration

Energy spread, beam loading and stability

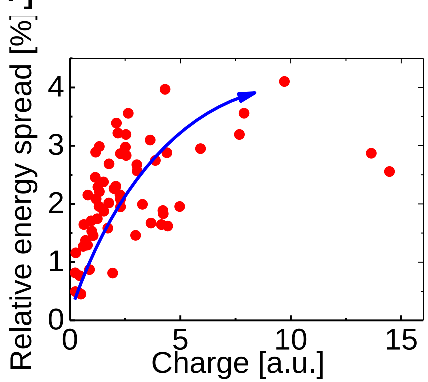


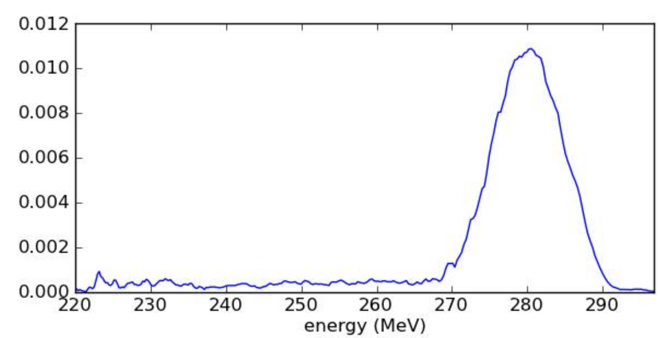


r.m.s. shot to shot energy variation 2.8%



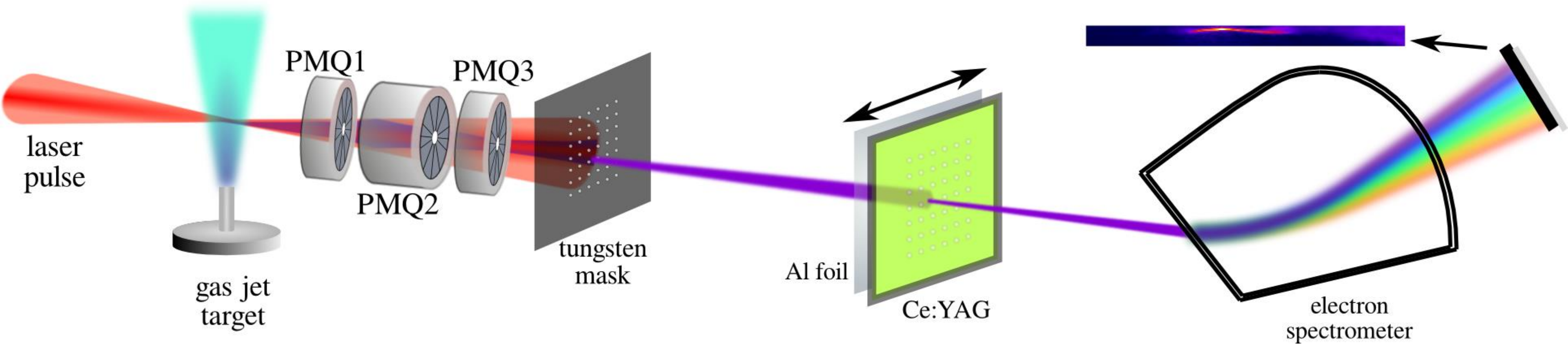
Maximum energy obtained in 2 mm ≈ 300 MeV

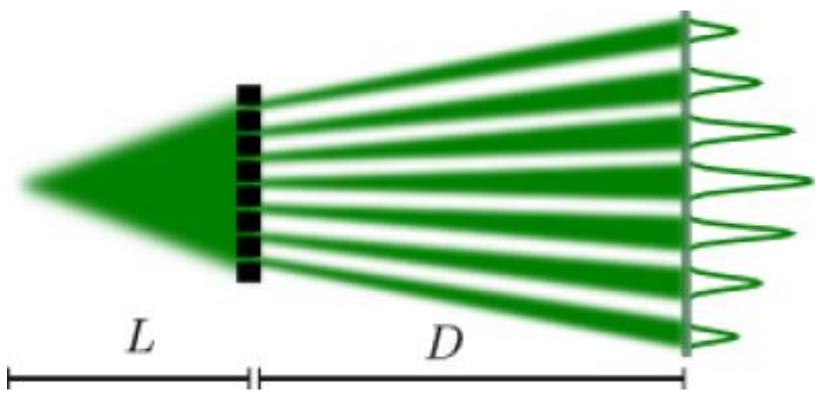




With stable laser and gas jet

Measuring emittance

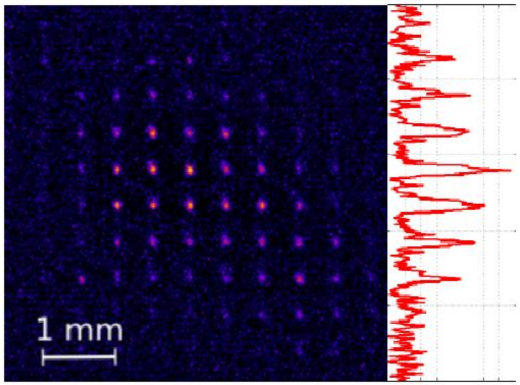




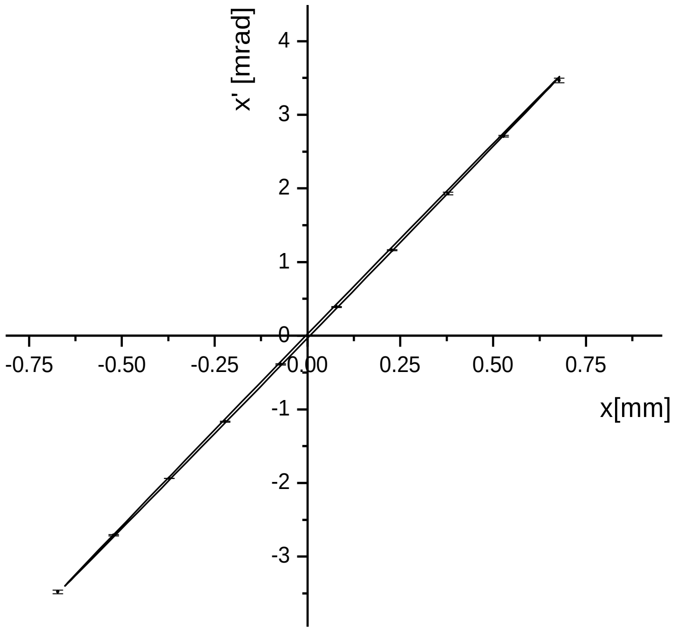
Brunetti et al., PRL (2010)
Manahan et al., New J. Phys. (2014).
Measured emittance: ε = 1 π mm mrad
Divergence 1 – 2 mrad
Source size < 1 μm

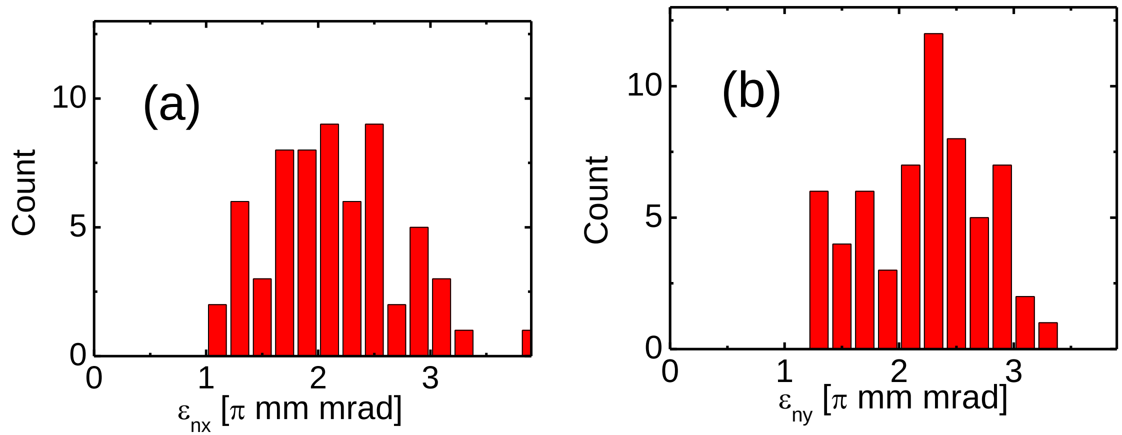
Experimental Results – emittance

- Second generation mask with hole ϕ ~ 25 μm and improved detection system



- divergence 1 – 2 mrad for this run with 125 MeV electrons
- average ε_N = $(2.2 \pm 0.7)\pi$ mm mrad
- best ε_N = $(1.0 \pm 0.1)\pi$ mm mrad
- Elliptical beam: $\varepsilon_{N,X} > \varepsilon_{N,Y}$





Measurements of multiple beams

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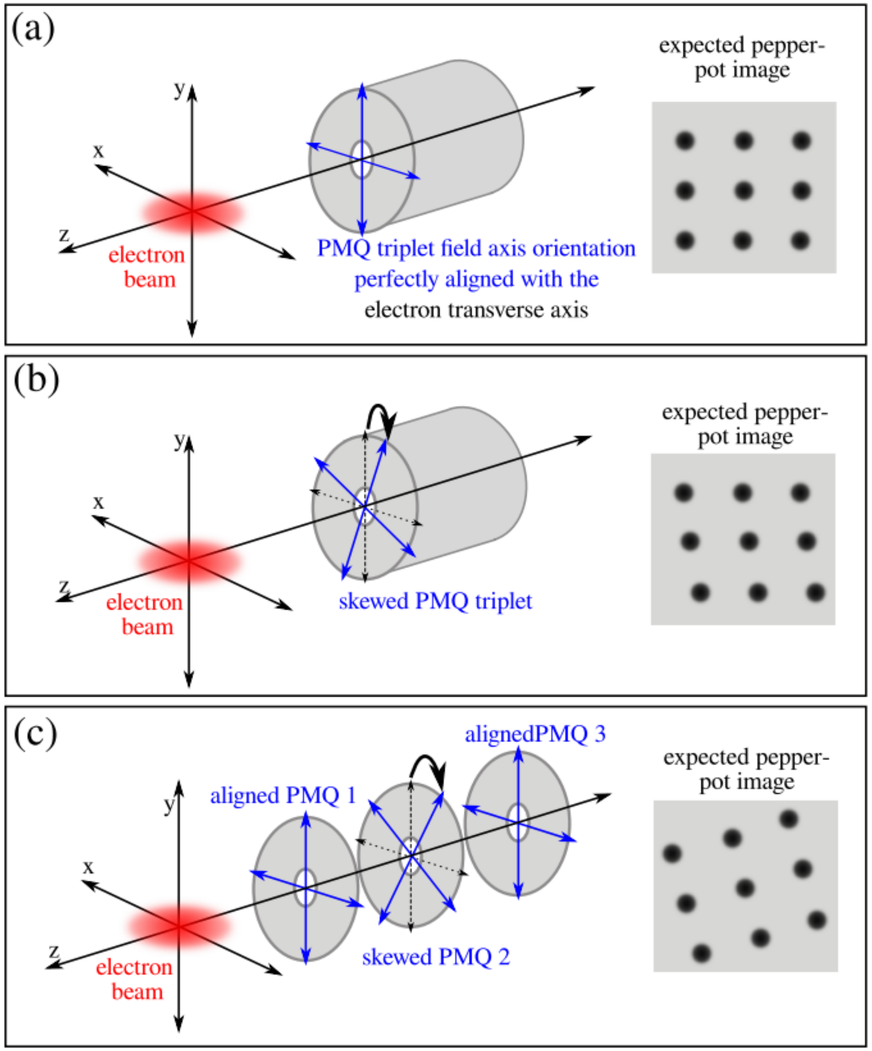

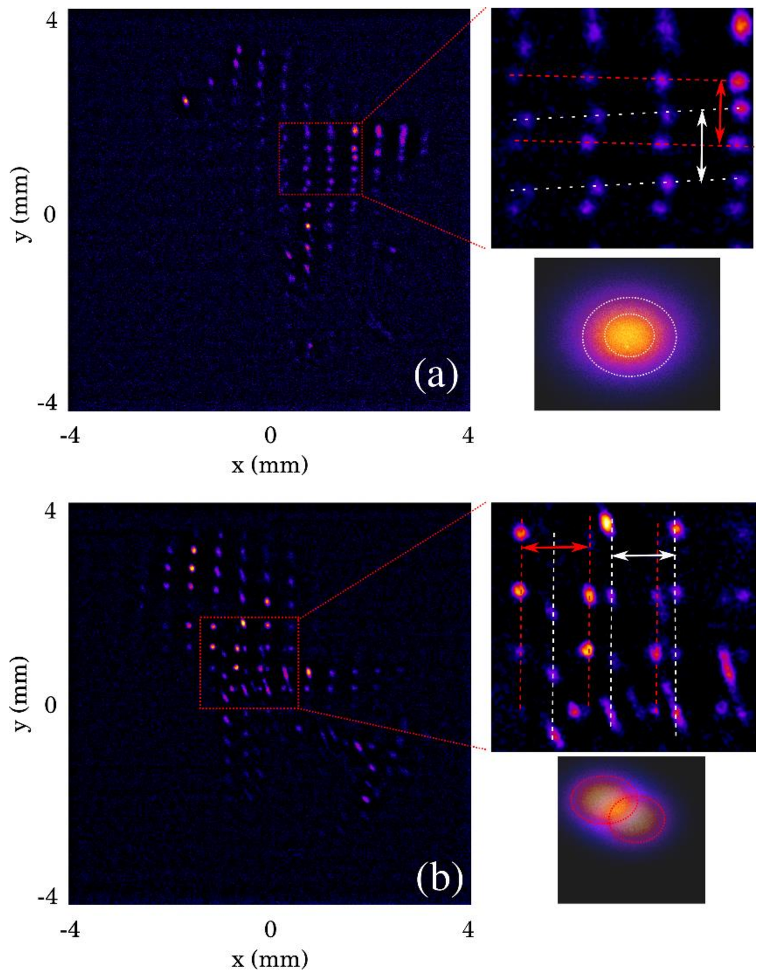

Manahan et al., New J. Phys. (2014).

Electron Beam- Pointing Stability

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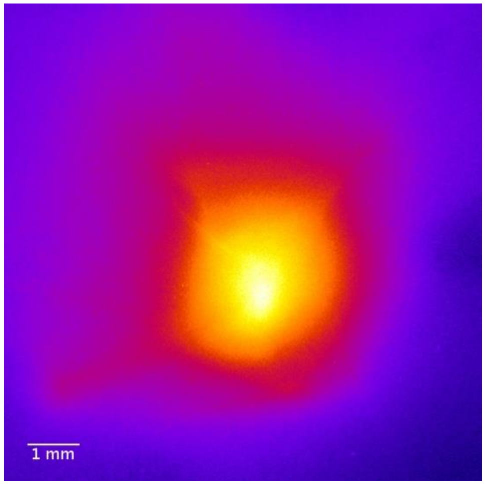
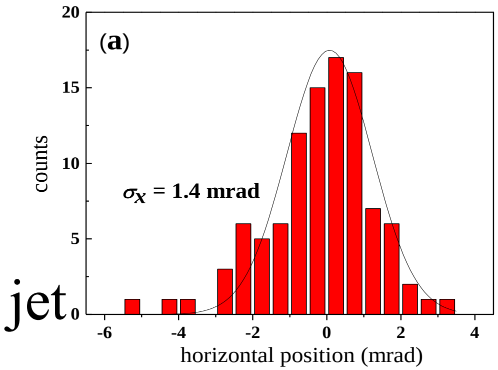
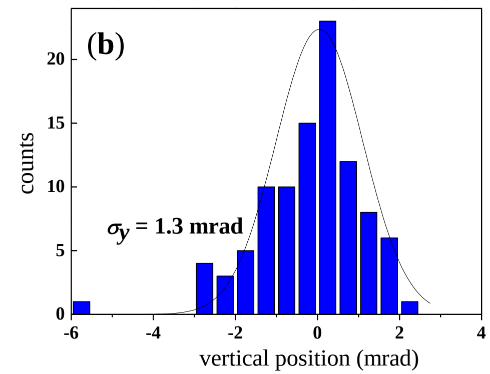


Electron beam recorded on YAG screen

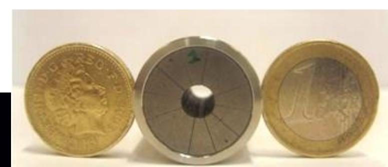
High resolution

Gas jet

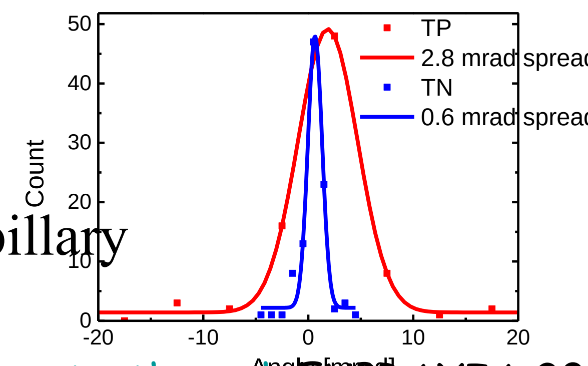




Electron beam pointing deviation is less than one spot size



Capillary



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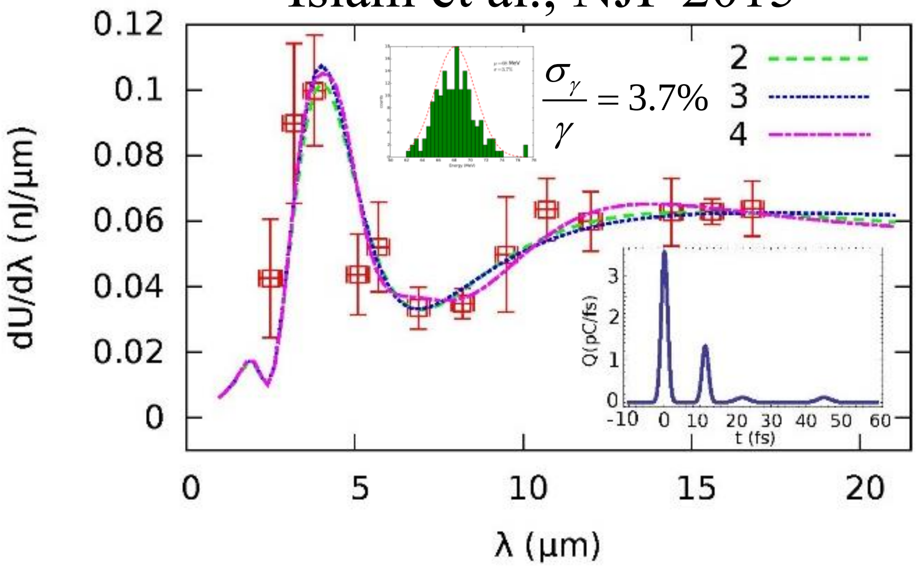
Bunch length measurements: Coherent Transition Radiation

Islam et al., NJP 2015



Coherent transition radiation spectrum gives bunch length

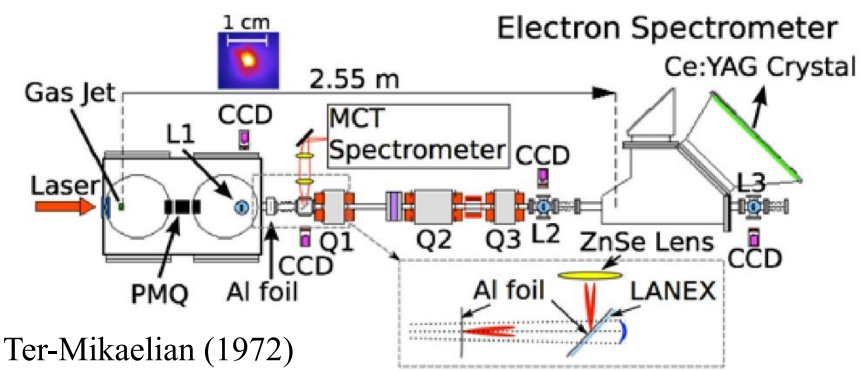
Chirp: $\frac{\delta\gamma}{\delta z} \approx \frac{2(z-R)\gamma_{\max}}{R^2}$

2 fs bunch measured at 1 m from source

$$\delta_{foil} = \delta_{acc} + \frac{D\delta_\gamma}{\gamma_0^3}$$

Ultra-short bunches: ~ 1 fs at source – Peak current several kA

THz pulse – 1 MW peak power



$$\frac{dU}{d\omega d\Omega} = [N + N^2 f(\omega)]dU / d\omega d\Omega$$

$$f(\omega) = \left|\int f(\vec{x})\exp(-i\vec{k}.\vec{x})d^3x\right|^2$$

Ter-Mikaelian (1972)

$$\frac{dI}{d\omega} = \frac{e^2}{\pi c}\left[\left(1+2\frac{\omega^2}{\omega_{cr}^2}\right)\ln\left(1+\frac{\omega_{cr}^2}{\omega^2}\right)-2\right] \qquad \frac{dI}{d\omega} = \frac{e^2}{6\pi c}\left(\frac{\omega_{cr}}{\omega}\right)^4$$

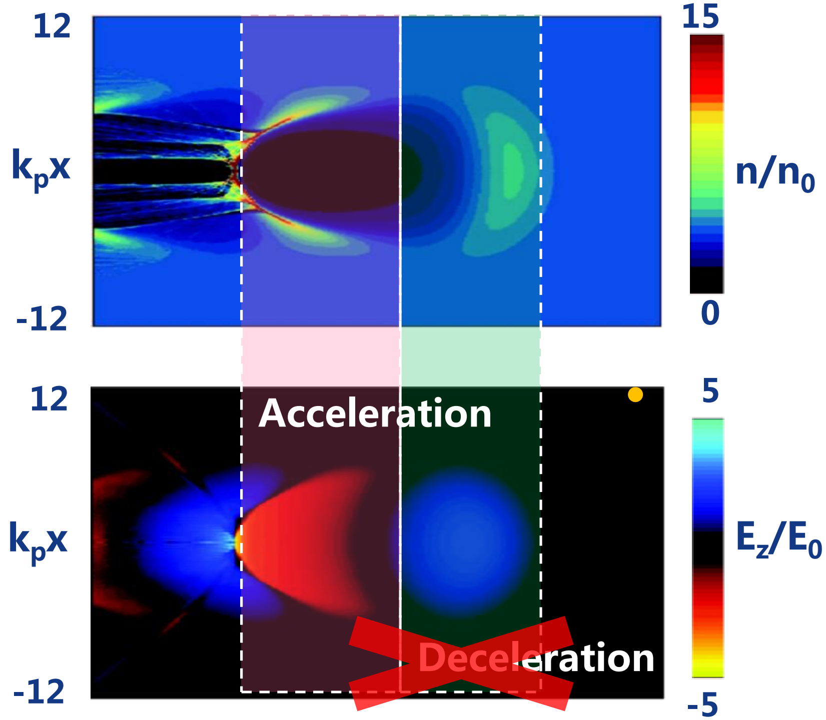
metal: $\omega_p = 10^{16}$ Hz

$$N_{photons} = \frac{\alpha}{\pi}[2\ln\gamma - 1]\ln(\omega_2/\omega_1) \qquad \omega > \omega_{cr} = \gamma\omega_p$$

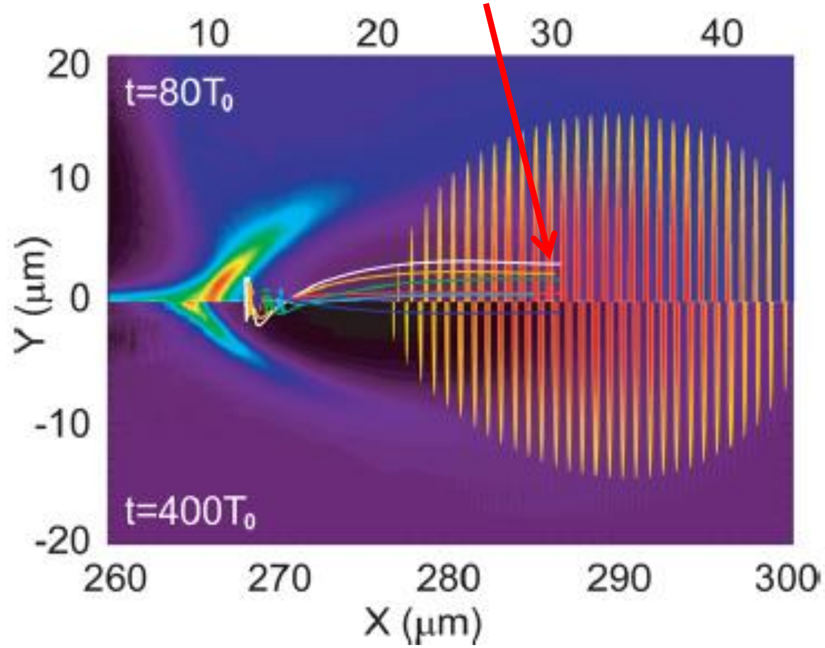
Outlines

- **Controlled injection: ionization injection, density gradient controlled injection**
- **Incoherent and coherent X-ray radiation from LWFA electron beams**

Using inner shell ionization for e⁻ injection



Only when the laser is strong enough, ionization happens

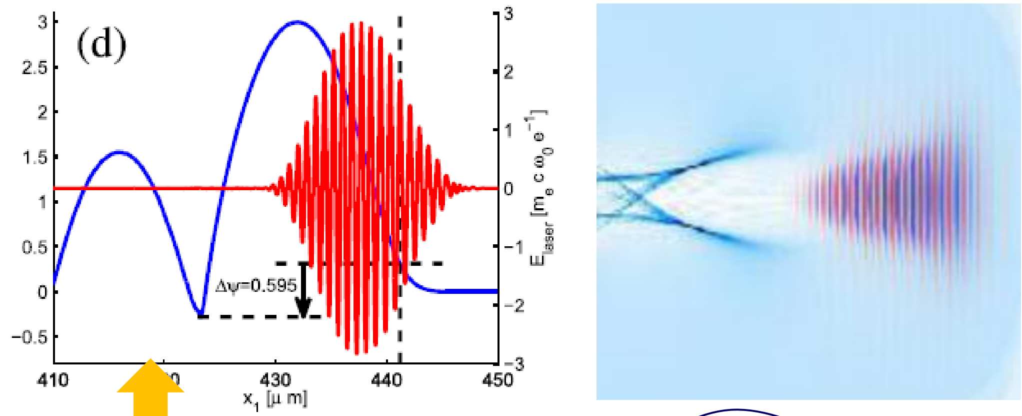


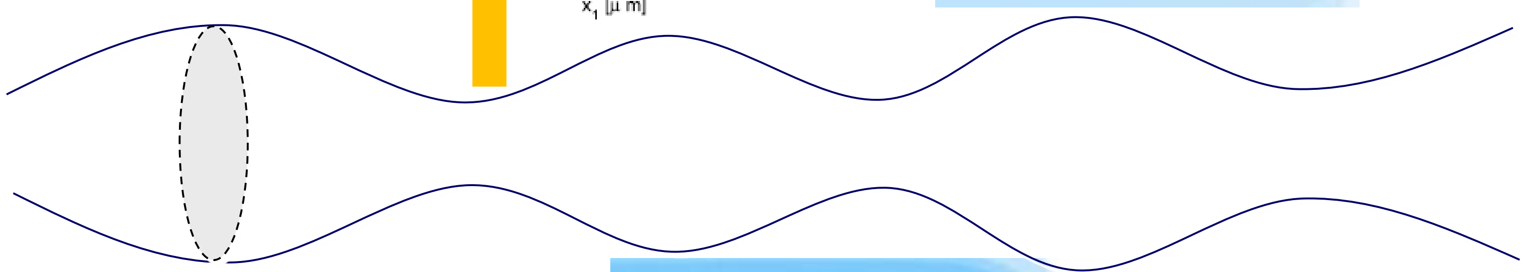
Principle : using the atomic potential to protect the electrons from deceleration by the wakefield and directly injected into the acceleration phase.
M.Chen, Z.M. Sheng, Y.Y. Ma and J. Zhang, "Electron injection and trapping in a laser wakefield by field ionization to high-charge states of gases" *J. Appl. Phys.* 99, 056109 (2006)

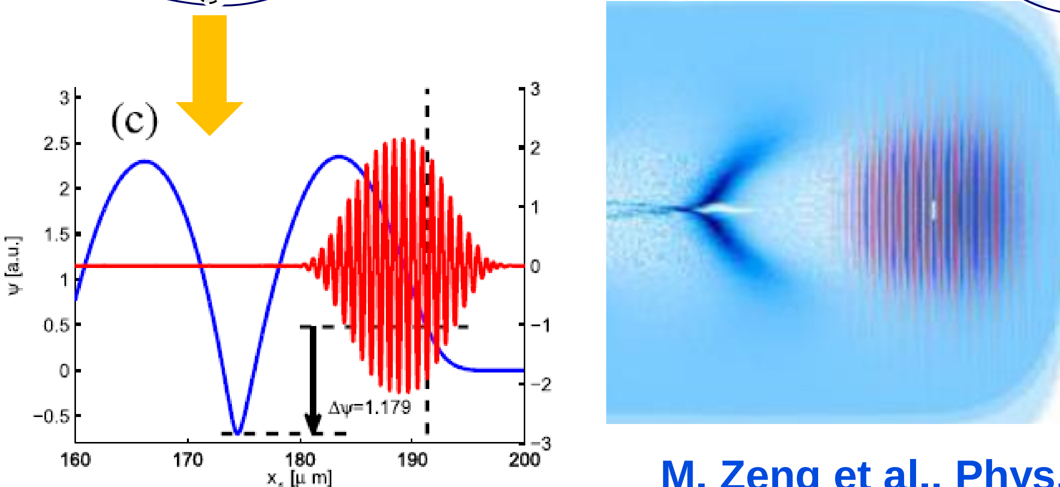
Laser self-evolution controlled injection

Under the condition

$$k_{\mathrm{p}}W_0 \neq 2\sqrt{a_0}$$







Injection occurs when $\Delta\psi \geq 1$

M. Zeng et al., Phys. Plasmas 21, 030701 (2014).

Experiment demonstration of self-truncated ionization injection

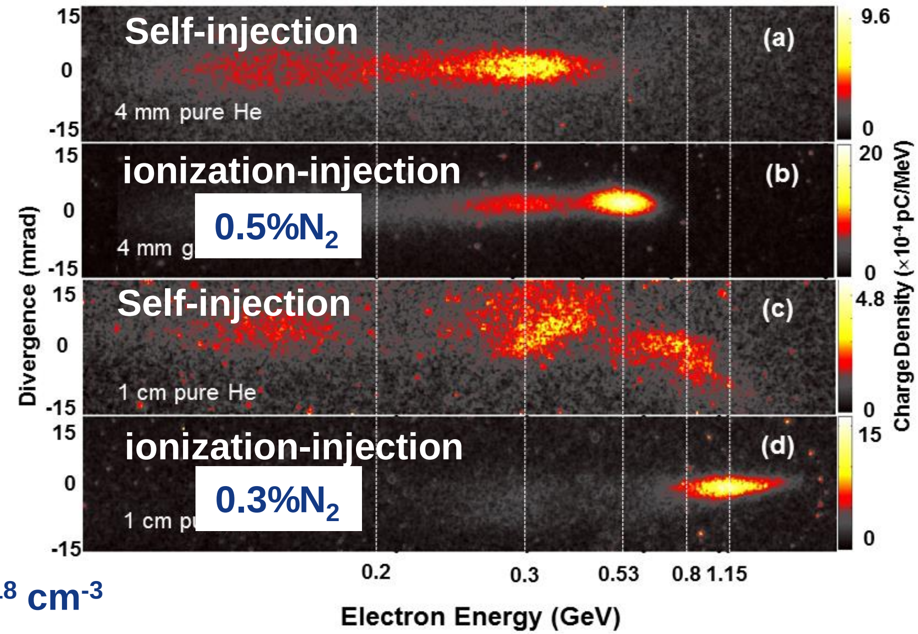
6.5 (±0.5)×10^{18} cm^{-3}

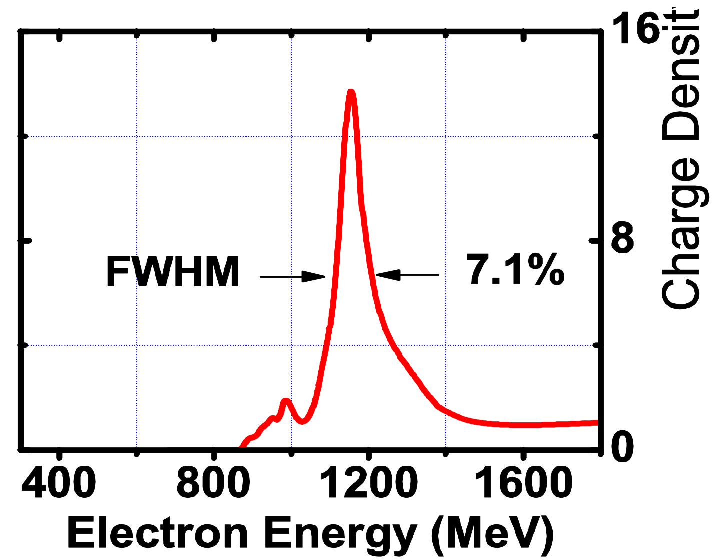
118TW

103TW

114TW

118TW





1.8×10^{18} cm^{-3}

$$k_p w_0 \approx 7.1 > 2(a_0)^{1/2} \approx 2.85$$

(a) E =300±4.5 MeV, Q =21 pC $\Delta E/E \approx$ 25% divergence angle of 7.6 mrad

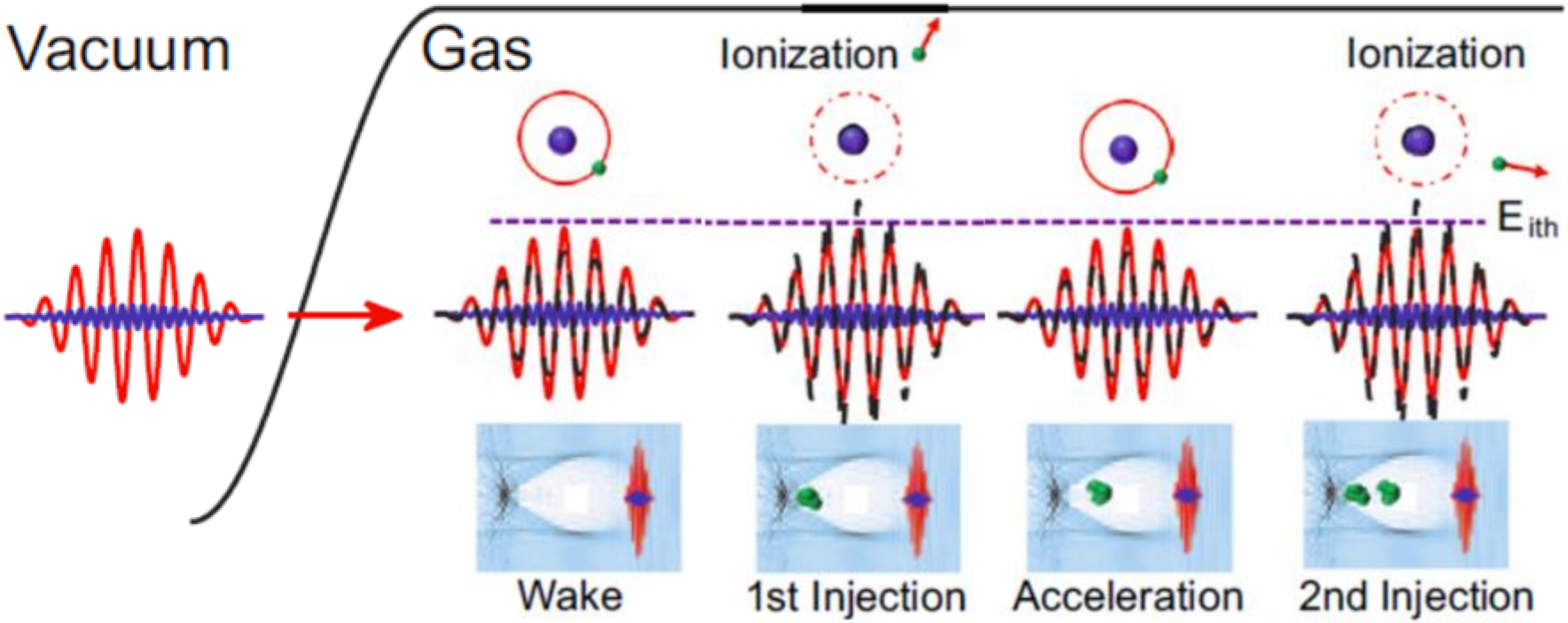
(b) E_{QME} = 530±8 MeV, Q (charge) =25 pC, $\Delta E/E \approx$ 8 %, divergence angle of 5.2 mrad

(d) E_{QME} = 1.2±0.03 GeV, Q (charge) =16 pC, $\Delta E/E \approx$ 7 %, divergence angle of 4.7 mrad

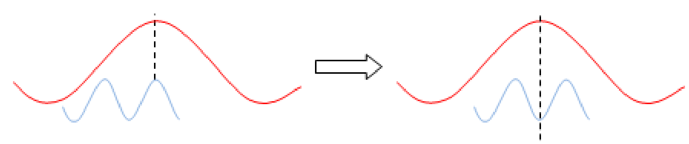
M. Mirzaie, *et al*., Scientific Reports 2015

Two color laser ionization injection to get extreme low energy spread electron beam

Laser pulses with different frequency have different $v_{p.}$



$$\Delta s = \frac{4\pi}{\omega_p^2(\omega_2 - \frac{1}{\omega_2})}$$

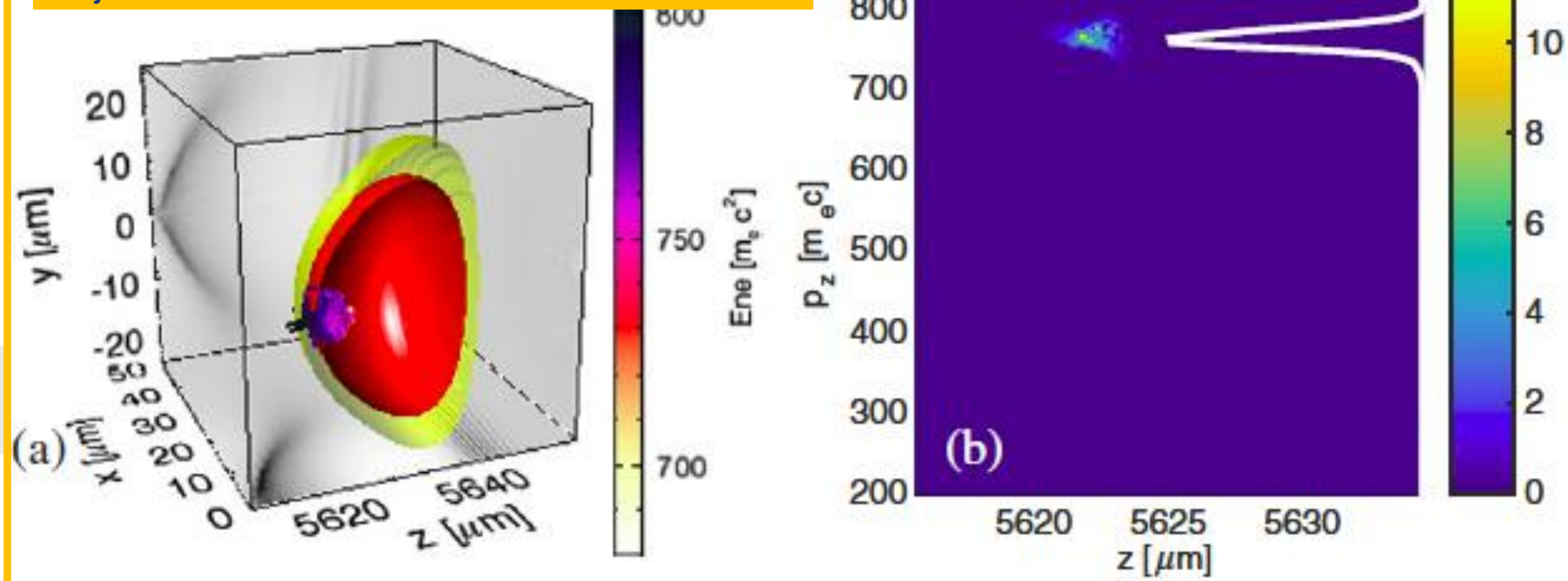


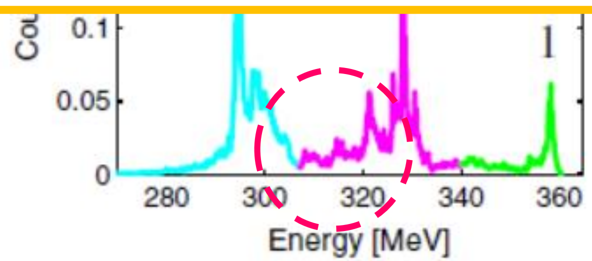
Ionization happens locally within tens of μm and local wake phase.

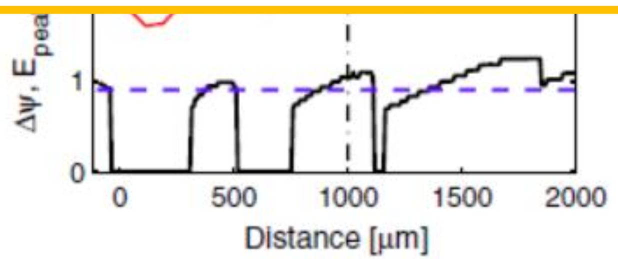
M. Zeng, M. Chen*, *et al*., PhysRevLett.114.084801 (2015)

Comb like energy spectrum

L_{inj}=1mm, Energy spread~ 1%, >10pC



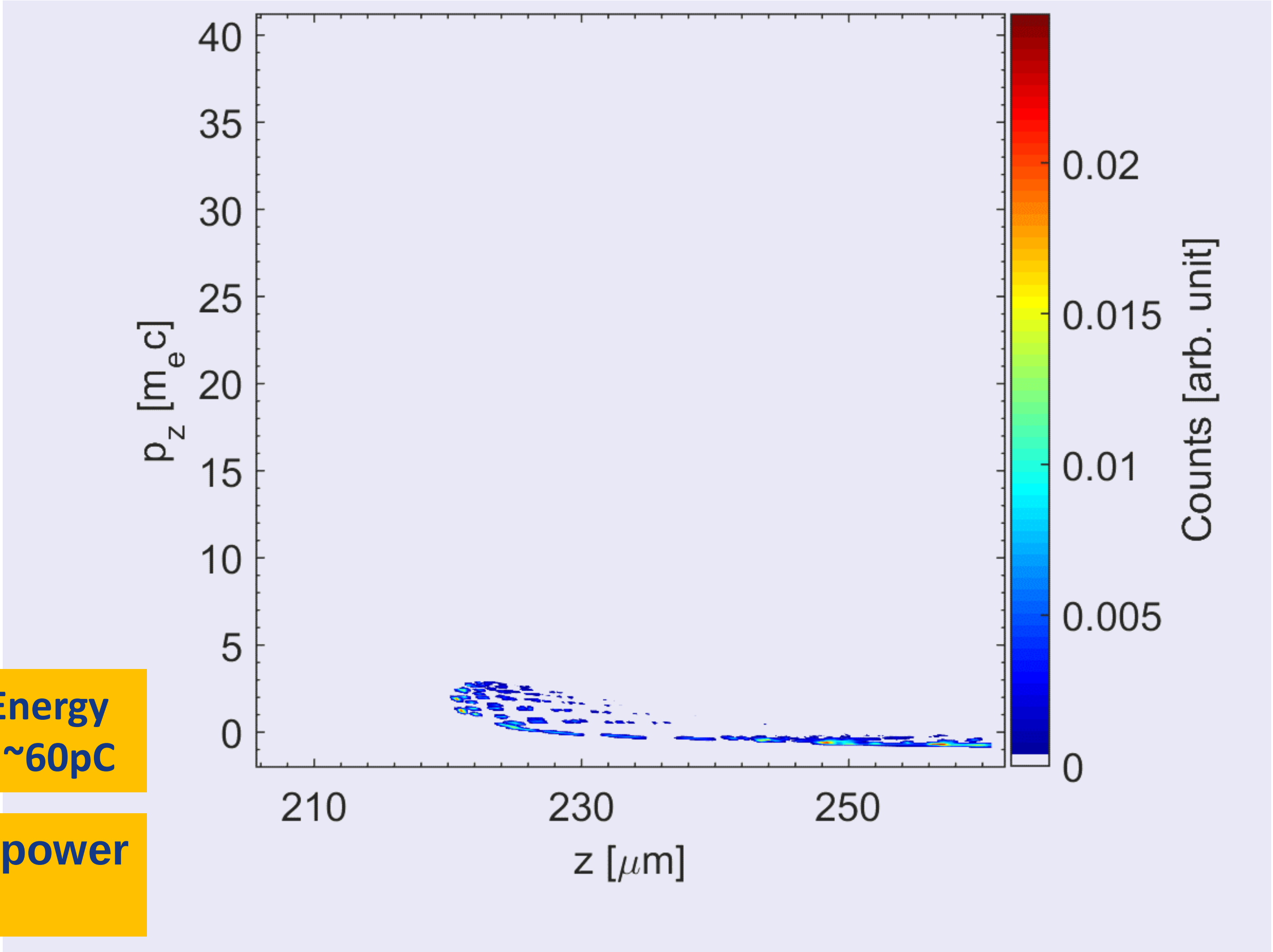




$$N_{\text{bunch}} = \left[L_{\text{inj}} / \left(\frac{c\Delta s}{\omega_1} \right) \right]$$

Two-color lasers at 2.4um and 0.8um in CO_2 gas

M. Zeng et al., Physics of Plasmas **23**, 063113 (2016).



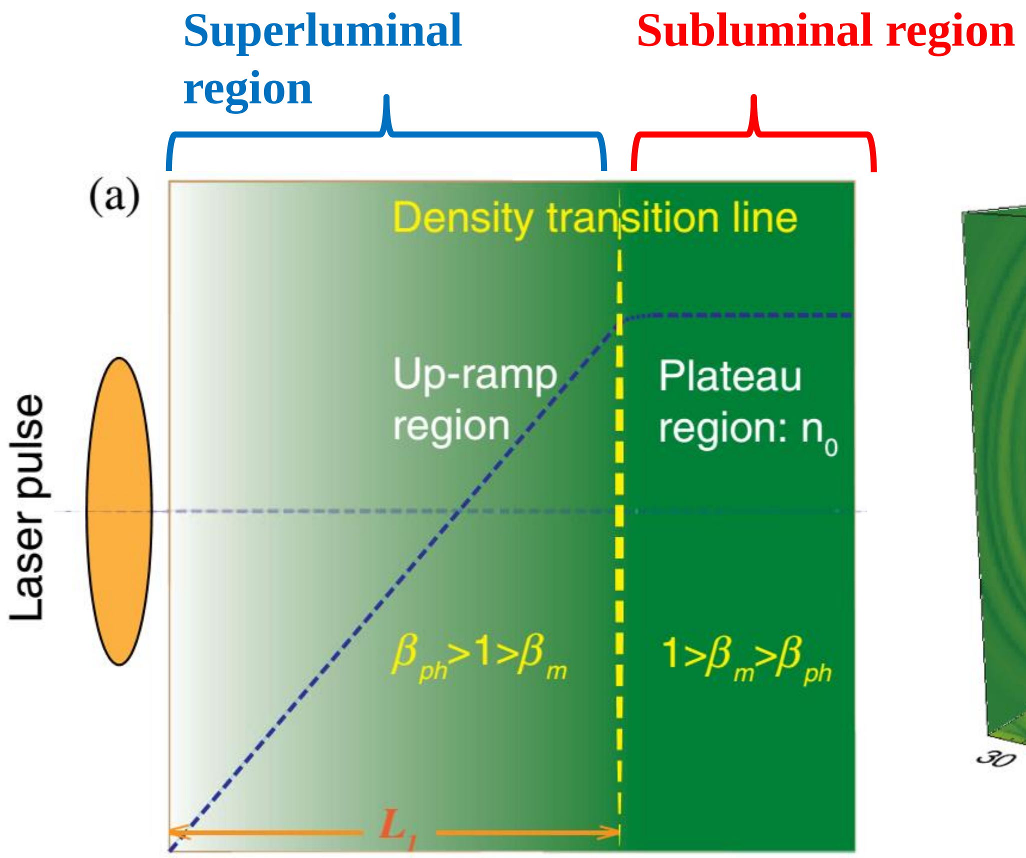
C^{+4}

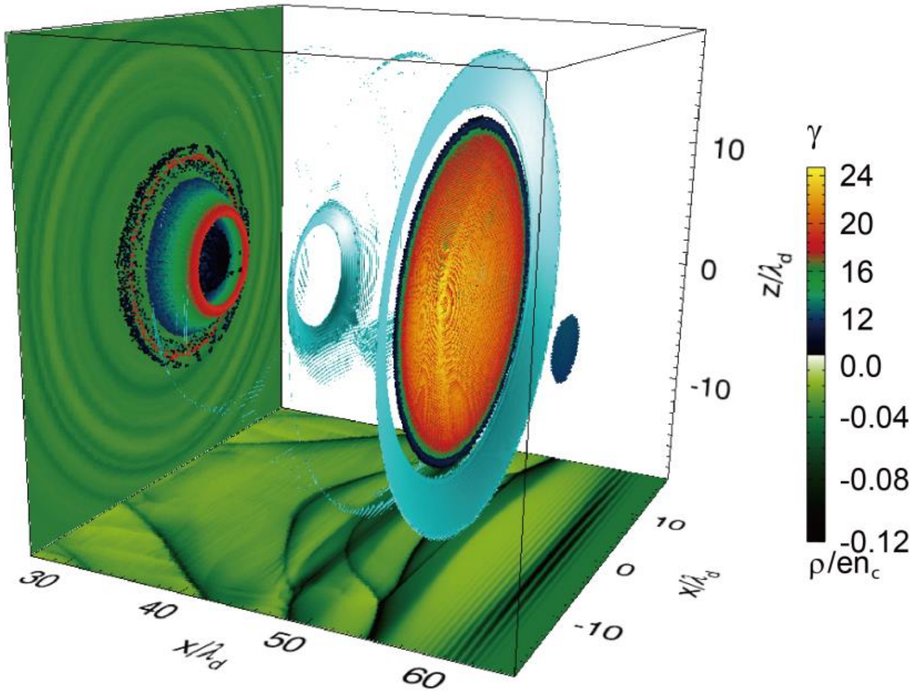
L_{inj}=1mm, Energy spread~ 1%, ~60pC

Total laser power ~ 80TW

Injection of dense attosecond electron sheets

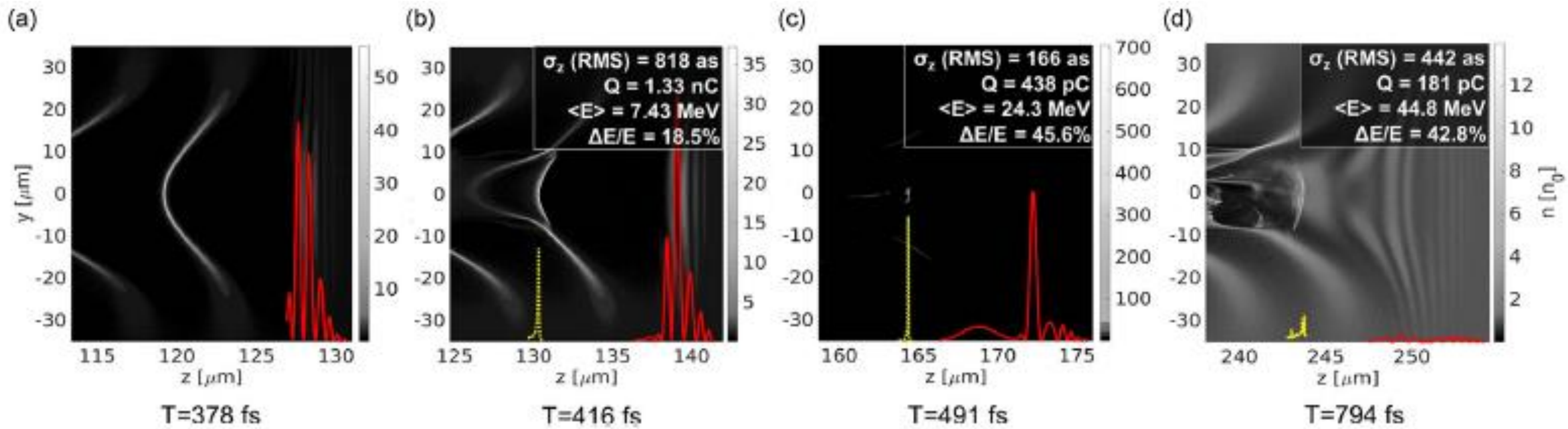
F. Y. Li et al., PRL 2013





Attosecond electron sheet injection in 3D simulation

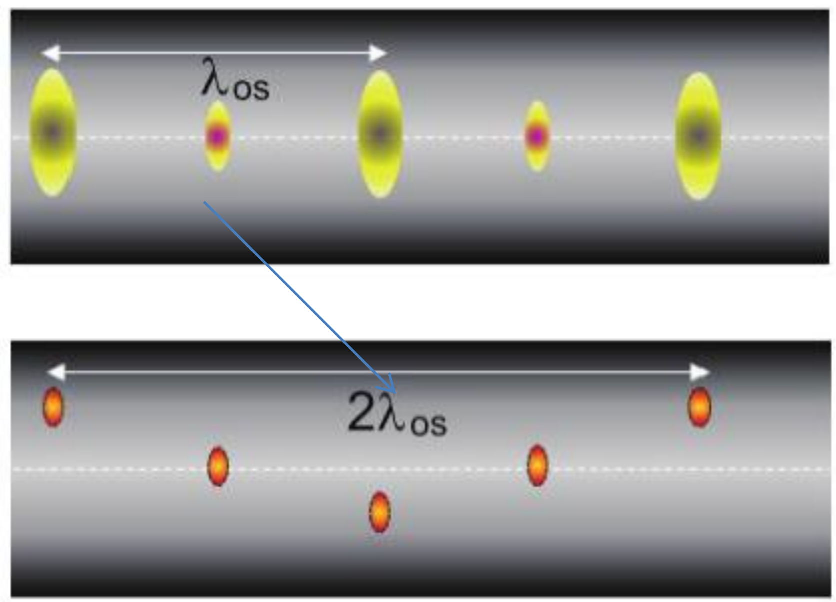
✓ **Synchronous longitudinal injection**



Problem: instability during the acceleration due to high charge.

M.K. Weikum et al., Nucl. Instr. Meth. Phys. Res. A (2016)

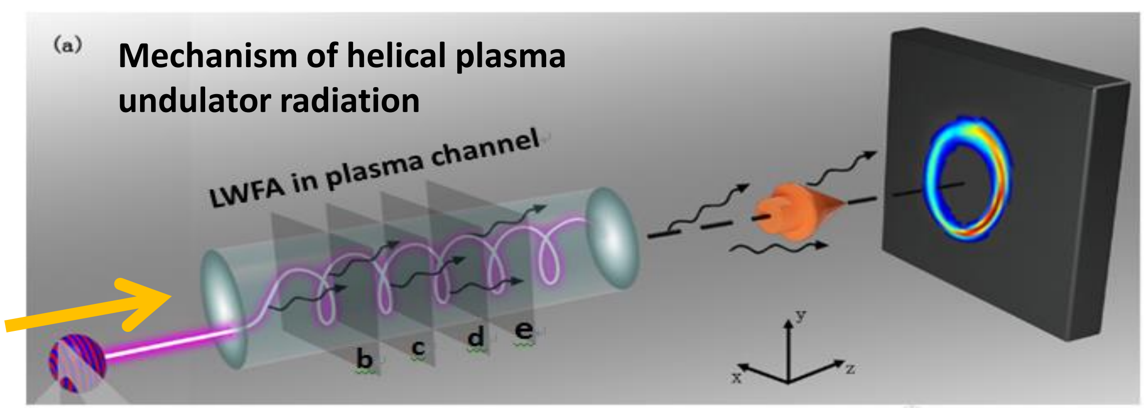
Using plasma channels to control radiation



Along the laser axis injection—self-focusing and defocusing

Off-axis injection along the plasma channel

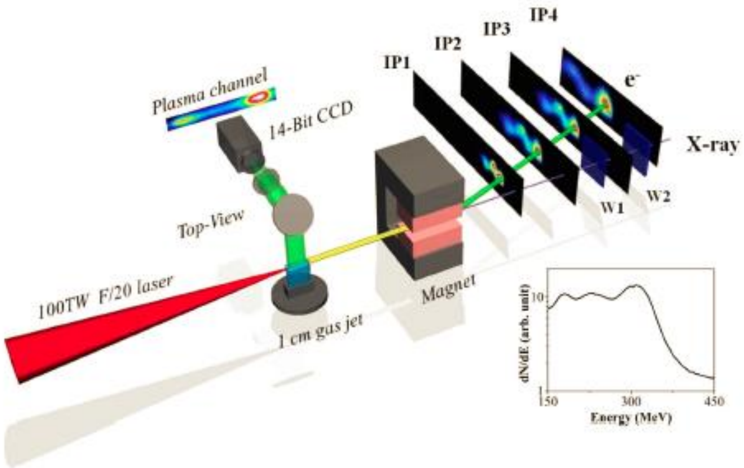
M. Chen *et al.*, Light—Science & Applications 5, e16015 (2016)



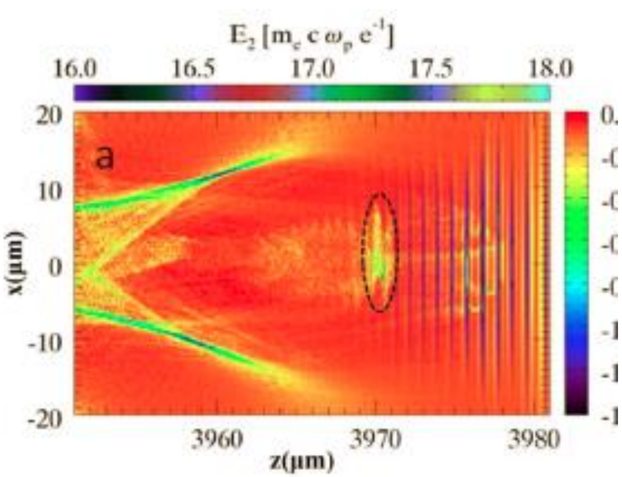
Oblique injection along the plasma channel

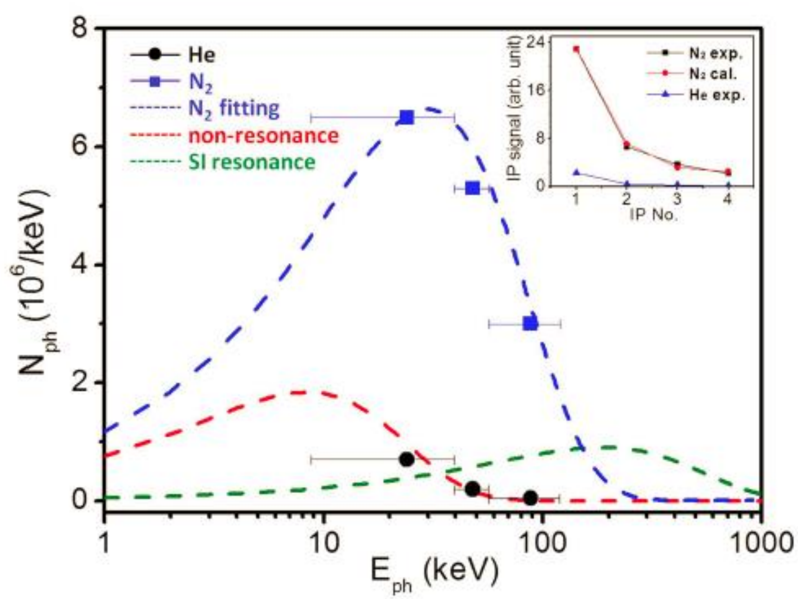
J. Luo *et al*, Sci. Rep. 6, 29101 (2016)

Enhanced betatron radiation from laser wakefield acceleration (experiment)



With N_2 gas, ionization injection leads to enhanced betatron oscillation of electrons and subsequently enhanced betatron radiation

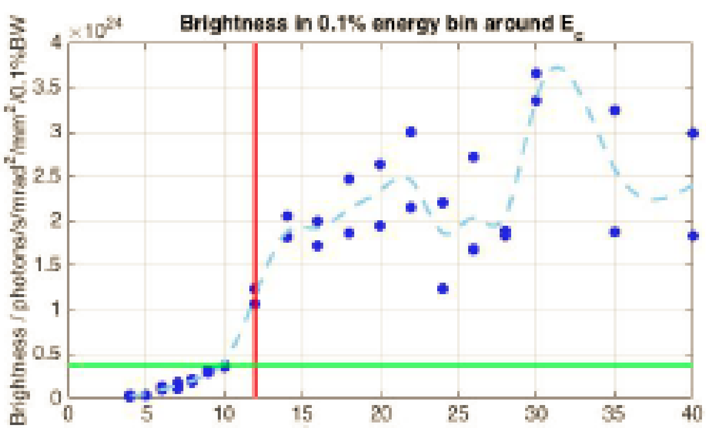


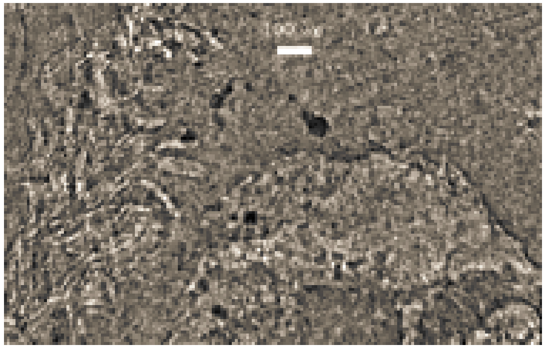


K. Huang et al., Scientific Reports 6:27633 (2016).

Astra Gemini β-tron Radiation Source

- β-tron radiation peak brightness >10^{24} photons / sec mrad^2 mm^2 0.1%BW
- Soft tissue imaged with ~ µm resolution, bone and mouse βCT performed with ~ 10 µm resolution
- Time averaged brigtness/flux comparable to micro-CT, but with room for improvement





Scottish Centre for the Application of Plasma-based Accelerators

http://www.scapa.ac.uk/

SCAPA

Director: Dino Jaroszynski

University of Strathclyde Science

APPLICATIONS of Plasma-Based Accelerators:

Radiobiology, Ultrafast Probing, High-Resolution Imaging

Radioisotope Production, Detector Development

Radiation Damage Testing

- **~£8m University + SUPA , university strategic investment**
- **~1200 m^2 over two levels**
- **3 concrete shielded bunkers (~2000 tons of concrete shielding)**
- **350 TW @ 5 Hz fs laser system, (delivery late-2016)**
- **40 TW @ 10 Hz fs laser system**
- **High-energy proton, ion and electron bunches.**
- **High-brightness fs duration X-ray & gamma-ray pulses.**

SCAPA Update Oct 16

350TW laser getting delivered 6th Oct

ALPHA-X beam line installation nearing completion in Bunker C

Thales installation & commissioning 17th Oct – 16th Dec

40TW laser operational for Bunker C

350TW laser getting unpacked

350TW laser installation underway in clean room

The End

Thank you for your attention!