SUPA Scottish Universities Physics Alliance

THE UNIVERSITY OF STRATHCLYDE IN GLASGOW

Ultra-short duration electron and radiation pulses from the laser-plasma wakefield accelerator

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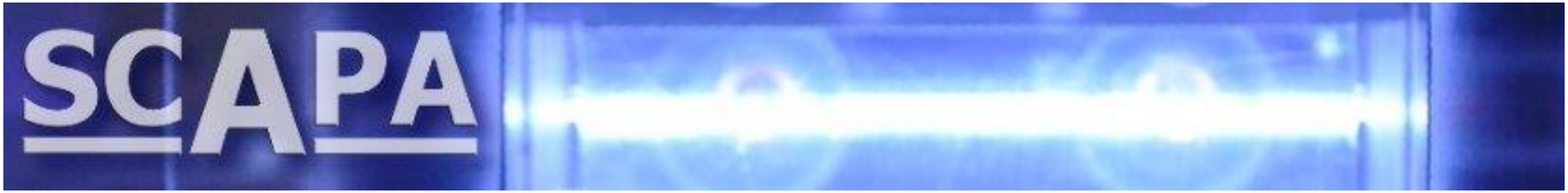

ELI-NP Sept. 2015 dino@phys.strath.ac.uk

SUPA: Scottish Universities Physics Alliance

SUPA Physics Scotland

University of Strathclyde Science


Schiehallion experiment

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THE UNIVERSITY OF EDINBURGH

University of St Andrews

University of Glasgow

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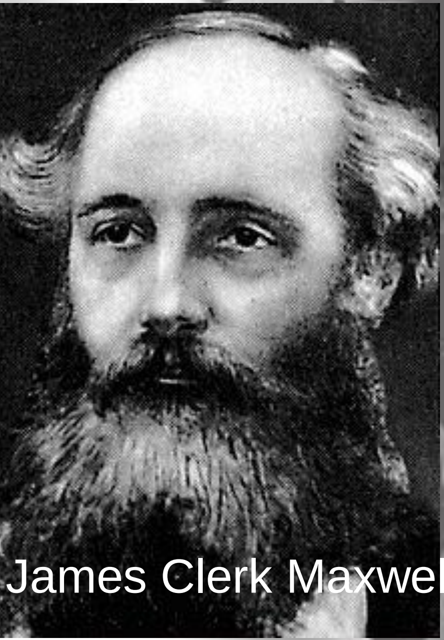
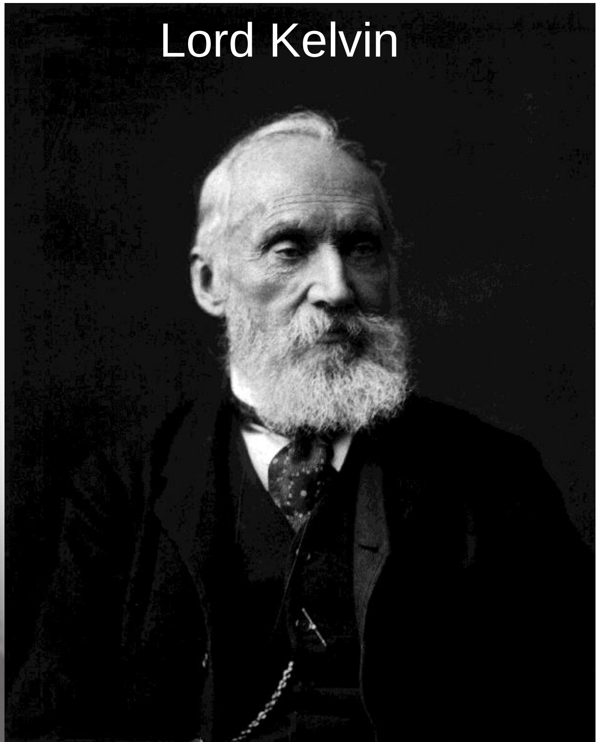

James Clerk Maxwell

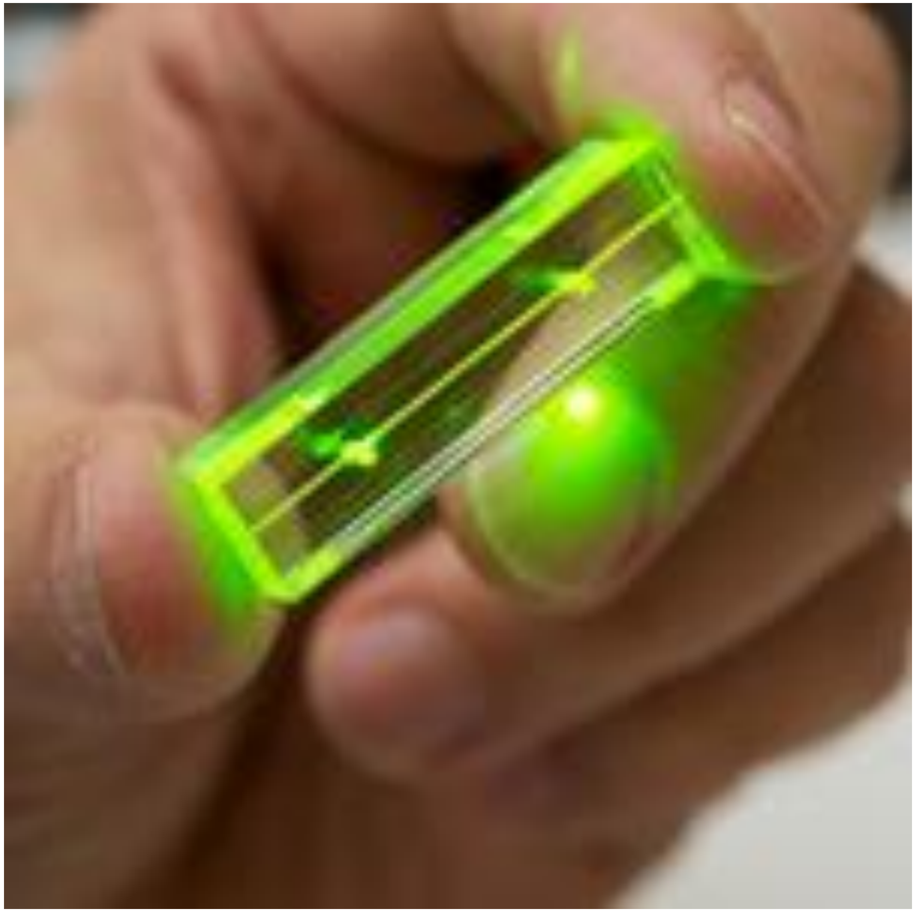
Maxwell's equations

$dF = 0$

$d * G = j$


Lord Kelvin

Laser-plasma accelerators



Undulator radiation

Betatron radiation

Ion channel laser

Applications:

Phase contrast imaging

Radiotherapy

Radio-isotope production using lasers

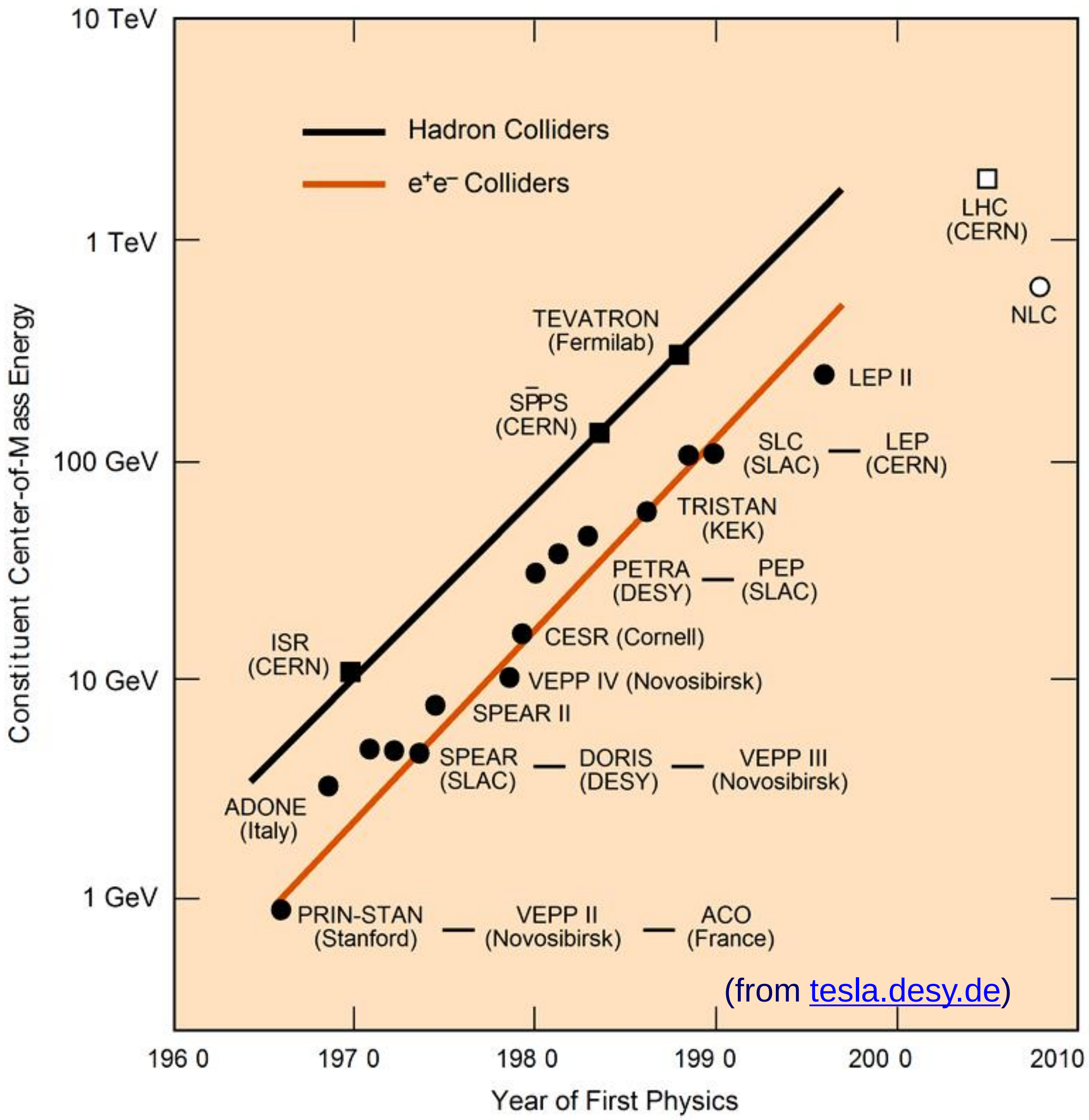
Livingston plot

Growth of accelerator energy since 1960s

New ideas lead to new technologies

Acceleration gradient currently limits maximum energy

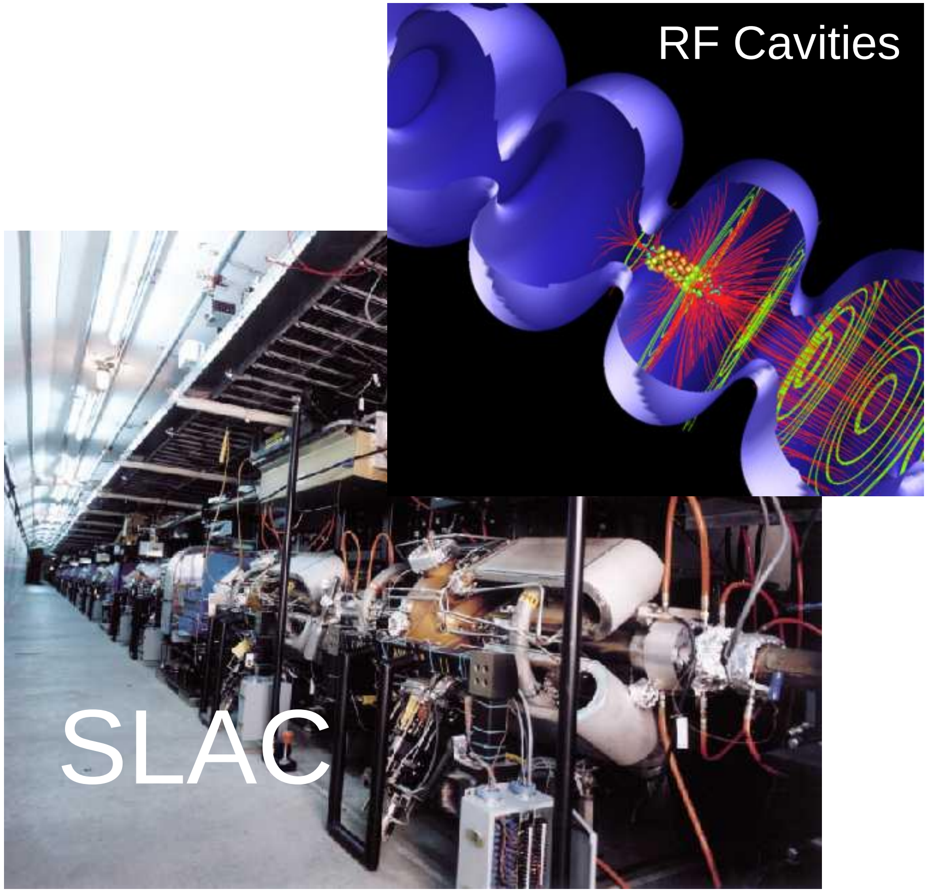
Laser wakefield accelerators?



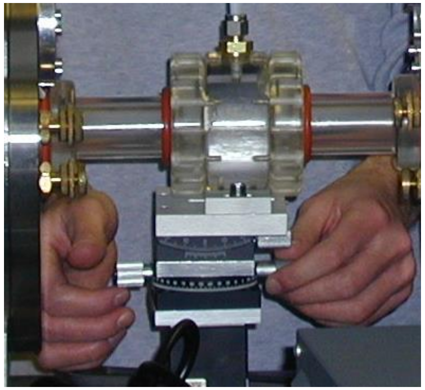
(from tesla.desy.de)

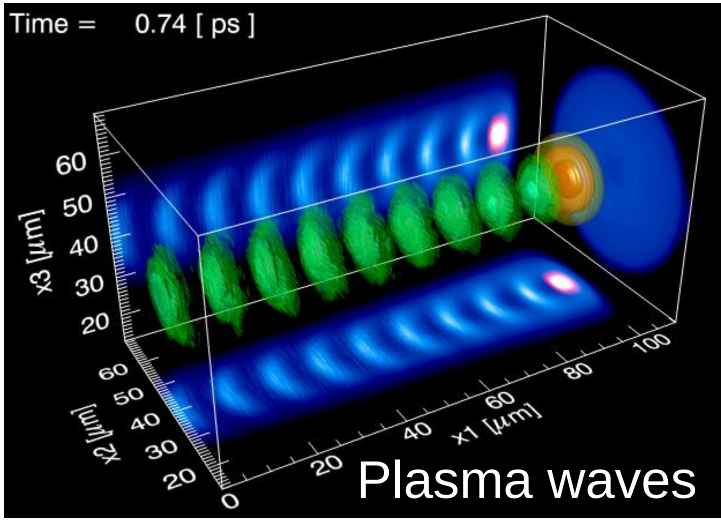
Conventional accelerators are based on RF cavities

- Conventional accelerator



Laser-plasma wakefield
Accelerator is
x1000 smaller
x1000 more
acceleration
x1000 less
Expensive??

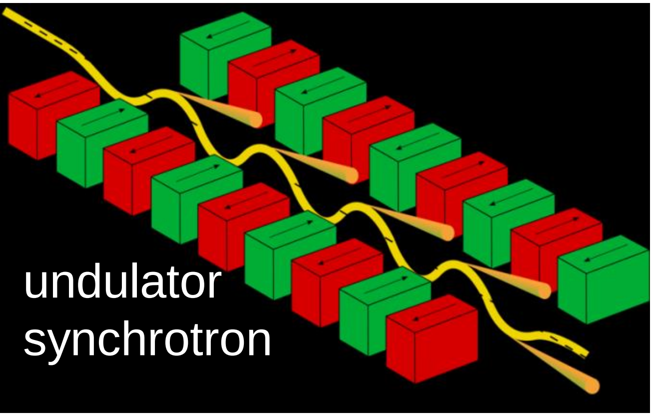




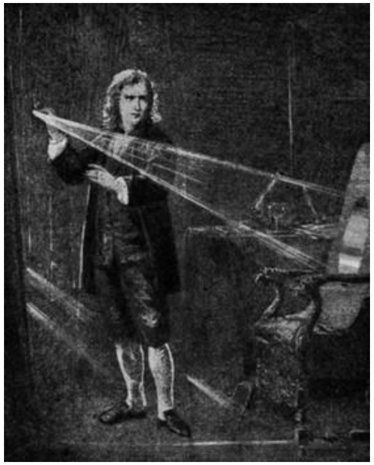
Plasma waves

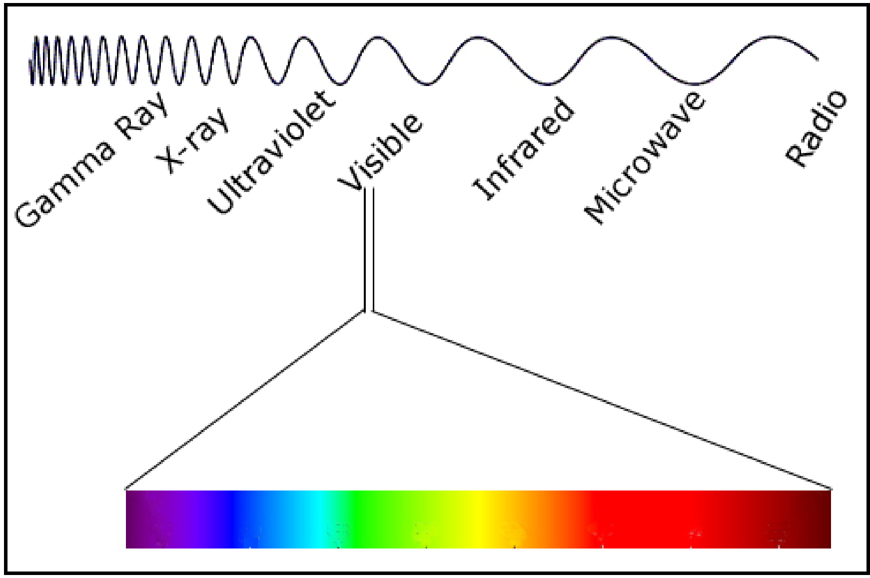
Synchrotrons light sources and free-electron lasers: tools for scientists

Synchrotron – huge size and cost is determined by accelerator technology



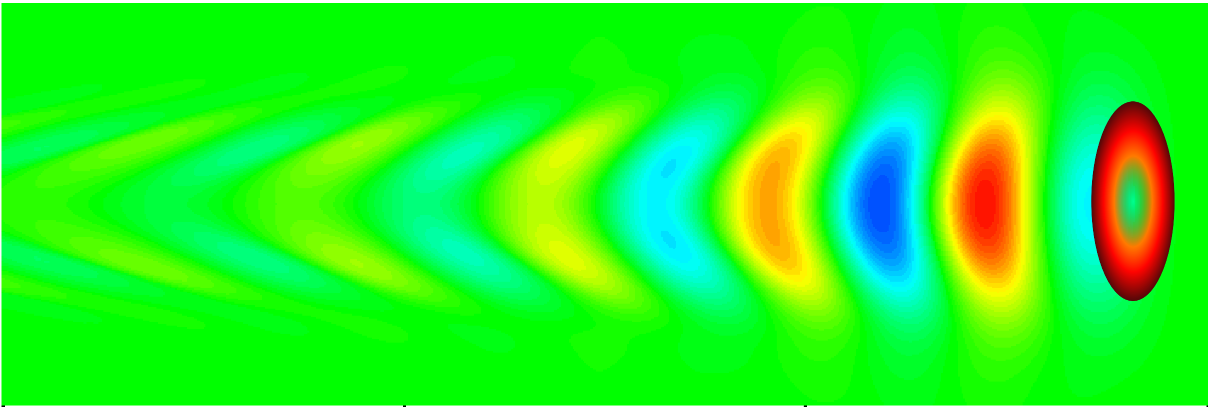
DESY undulator





Wakefield accelerator

UCLA: Tajima + Dawson 1979



Wake behind optical pulse travels and laser group velocity

$$v_g = c\sqrt{1-\frac{\omega_p^{\,2}}{\omega_0^{\,2}}}$$

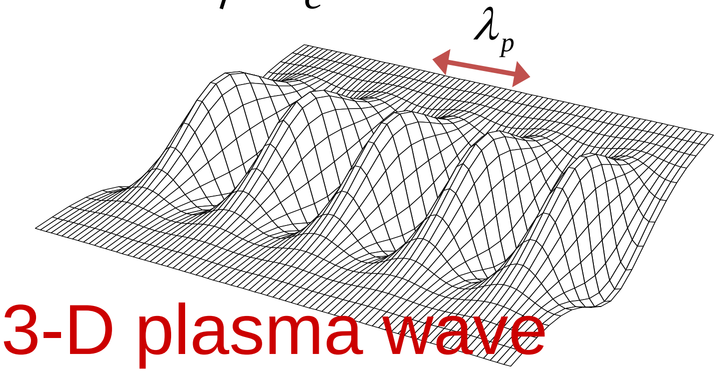
The ponderomotive force is given by the gradient of the light pressure

$$F_{pond} = -\nabla P$$

$$F_{pond} = -\frac{e^2}{4m\omega^2}\frac{dE^2}{dz} = -mc^2\frac{d}{dz}\left(|a|^2\right)$$

$$a = eA/m_e c^2$$

The electrons are pushed out of high intensity regions by the ponderomotive force



3-D plasma wave

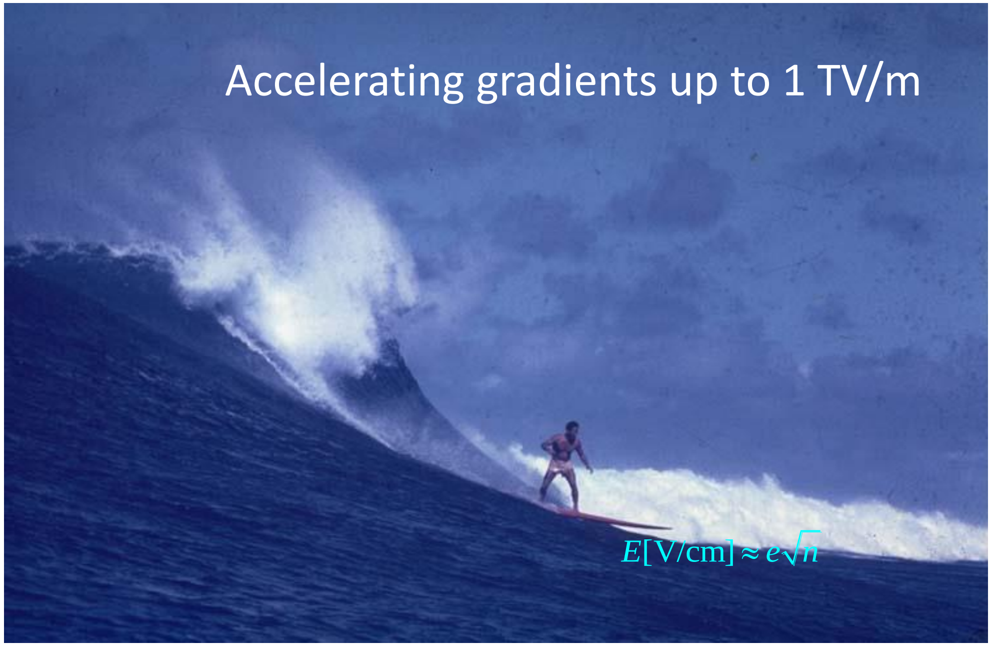
Group Lorentz factor $\gamma_g = \sqrt{1/(1-v_g^2/c^2)} = \frac{\omega_0}{\omega_p}$

Critical density for 800 nm: $n_c = 1.75\times10^{21}\,\mathrm{cm}^{-3}$

$$\omega_p = \sqrt{n_p e^2/\varepsilon_0 m_e}$$

Particles accelerated by electrostatic fields of plasma waves

Tajima and Dawson
1979



Accelerating gradients up to 1 TV/m

$E[\mathrm{V/cm}] \approx e\sqrt{n}$

Accelerators:

Surf a 10’s cm long microwave – **conventional technology**

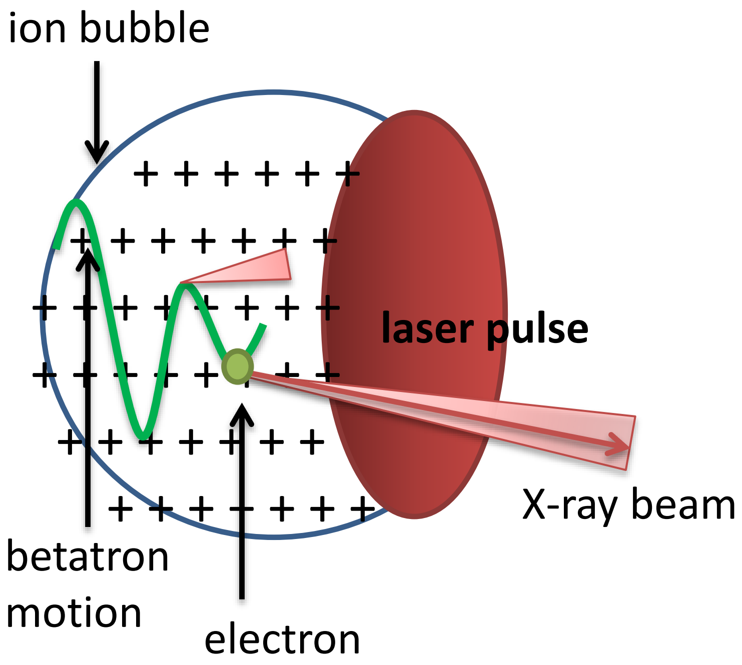
Surf a 10’s μm long plasma wave – **laser-plasma technology**

$$\gamma_{\max} \approx \frac{2\gamma_g^2 a_0}{3} \qquad \gamma_g = \frac{\omega_0}{\omega_p}$$

LWFA

BUBBLE REGIME

- Laser ponderomotive force creates stable evacuated spherical structures trailing the laser pulse
- Trapped electrons undergo transverse oscillations while accelerating
- Synchrotron like radiation is emitted in a narrow cone



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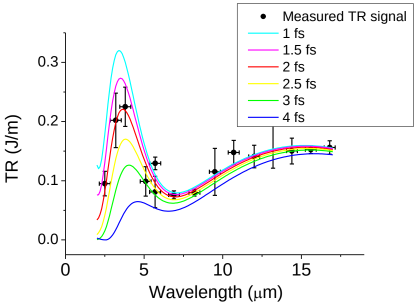
ALPHA-X: Advanced Laser Plasma High-energy Accelerators towards X-rays

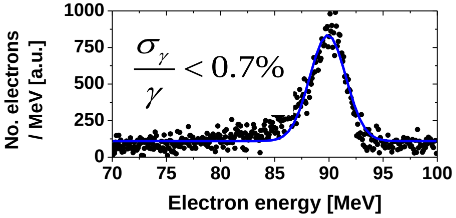
Compact R&D facility to develop and apply femtosecond duration particle, synchrotron, free-electron laser and gamma ray sources

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

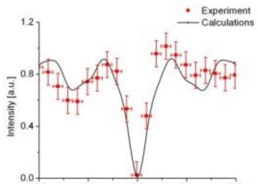
CTR: electron bunch duration: 1-3 fs

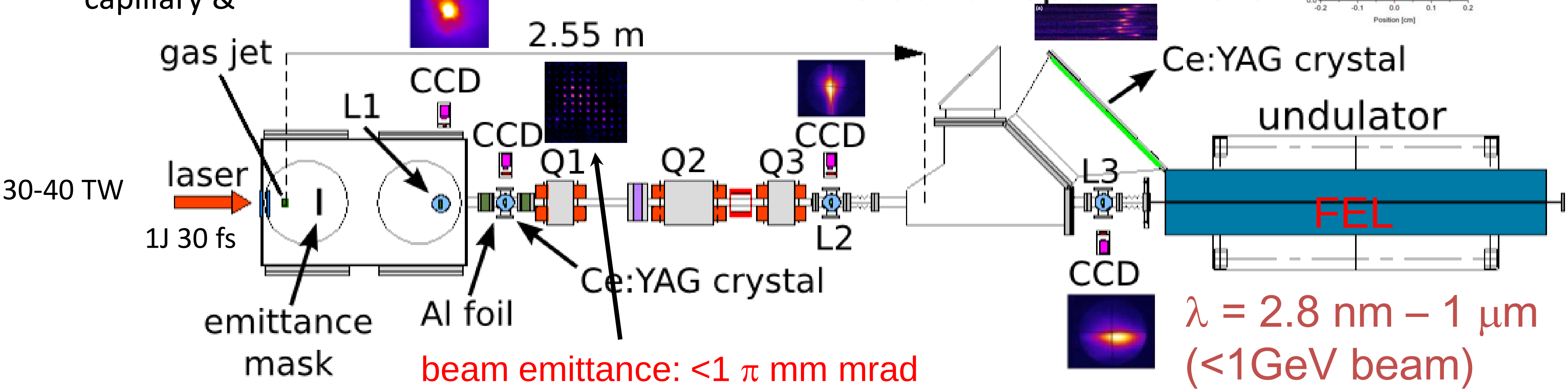


electron beam spectrum



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

Bubble structure – relativistic regime

ion bubble radius $R \approx \dfrac{\sqrt{a_0}\lambda_p}{2}$

nature

Dream beam

The dawn of compact particle accelerators

Disease control
Europe plays catch-up

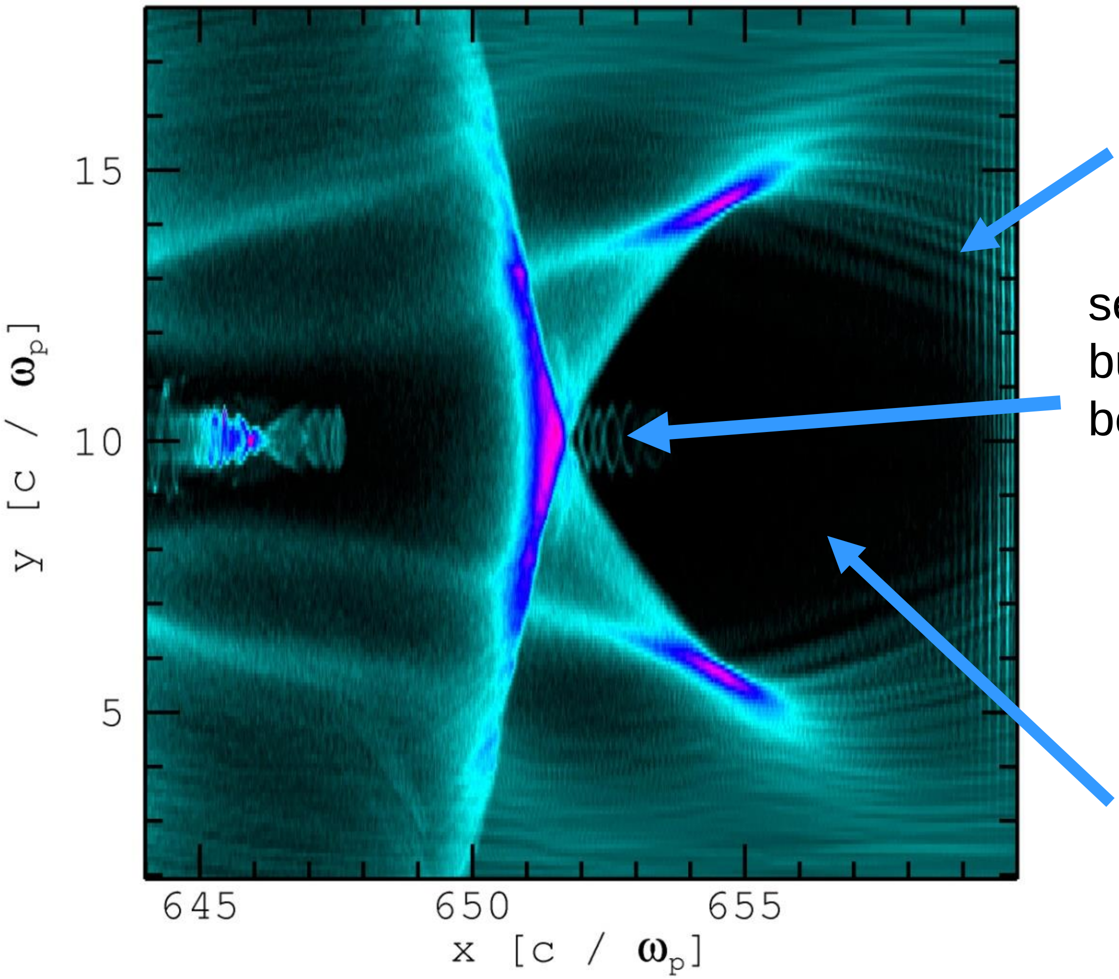
Protein folding
Escape from the ribosome

The Earth's hum
Sounds of air and sea

Human ancestry
One from all and all from one

First experiments on controlled acceleration:
2004

- ALPHA-X (UK: IC, Strathclyde, RAL)
- LBNL (US)
- LOA (France)



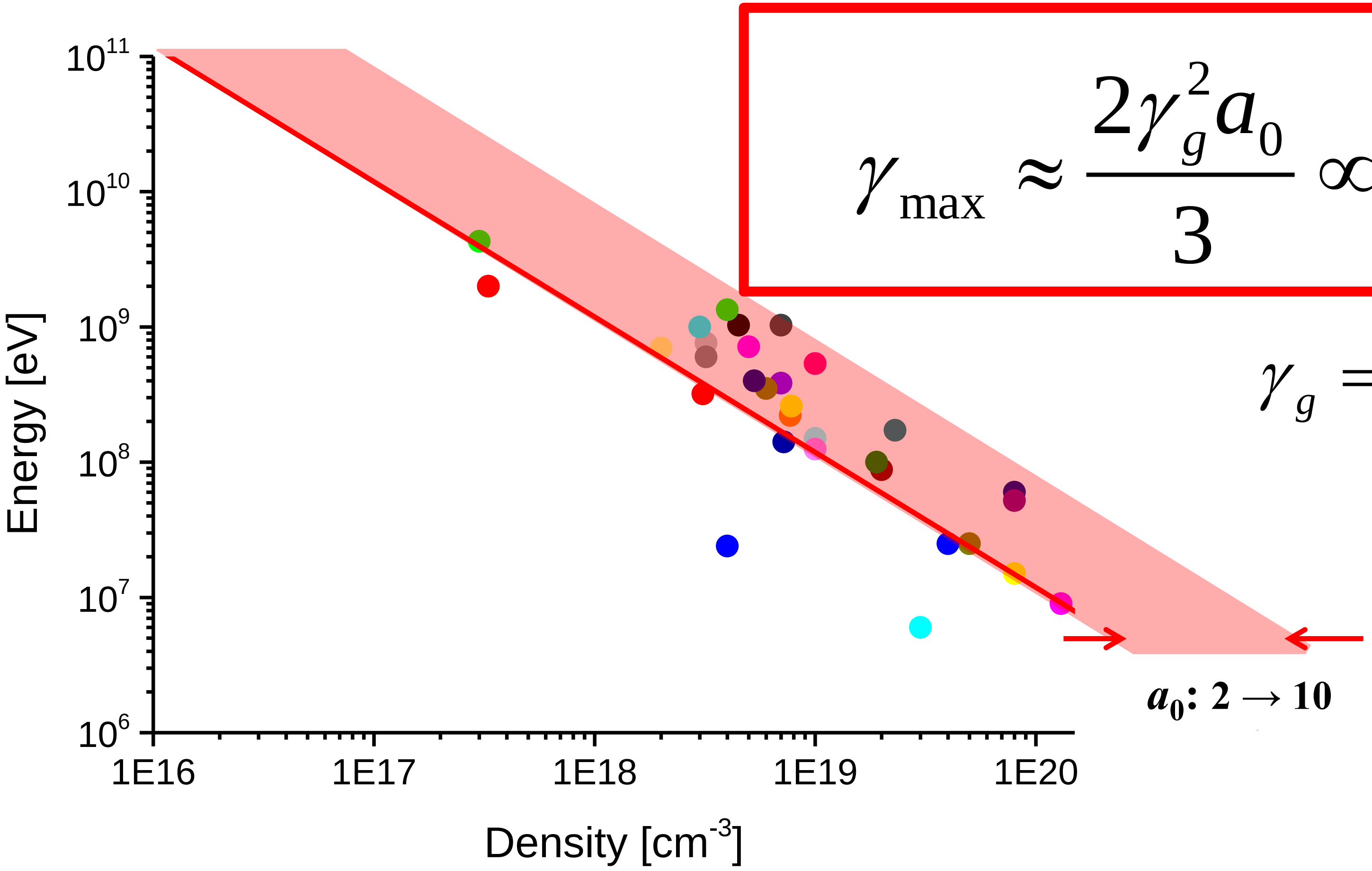
laser

self-injected electron bunch undergoing betatron oscillations

ion bubble

Energy Scaling

Data points refer to experimental demonstrations



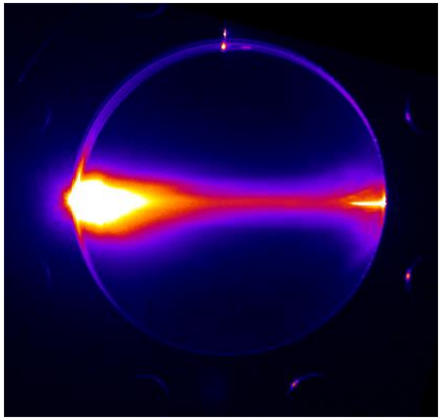
$$\gamma_{\max} \approx \frac{2\gamma_g^2 a_0}{3} \propto \frac{1}{n}$$

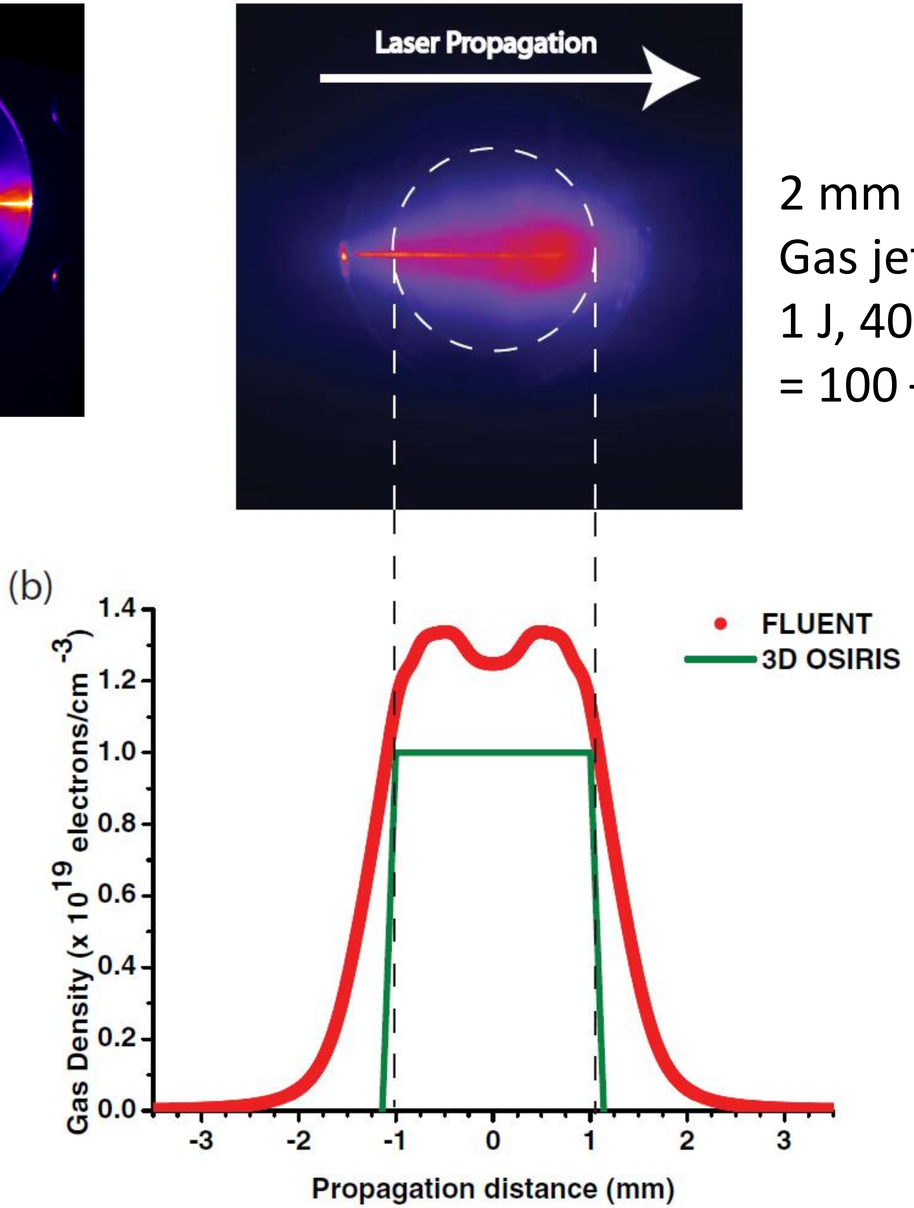
$$\gamma_g = \frac{\omega_0}{\omega_p}$$

Need a combination of bubble regime (must be above critical power for relativistic self-focussing) and linear regime to get to very high energies

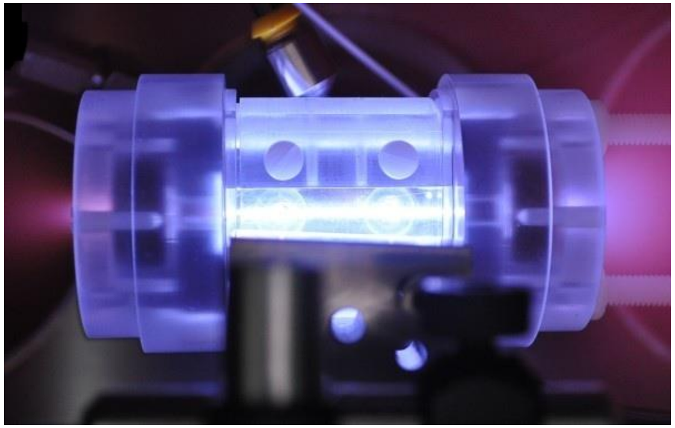
Plasma media: capillary, gas jet and plasma cells

4 cm long gas
Cell
10 J, 50 fs
= 850 MeV
(RAL)



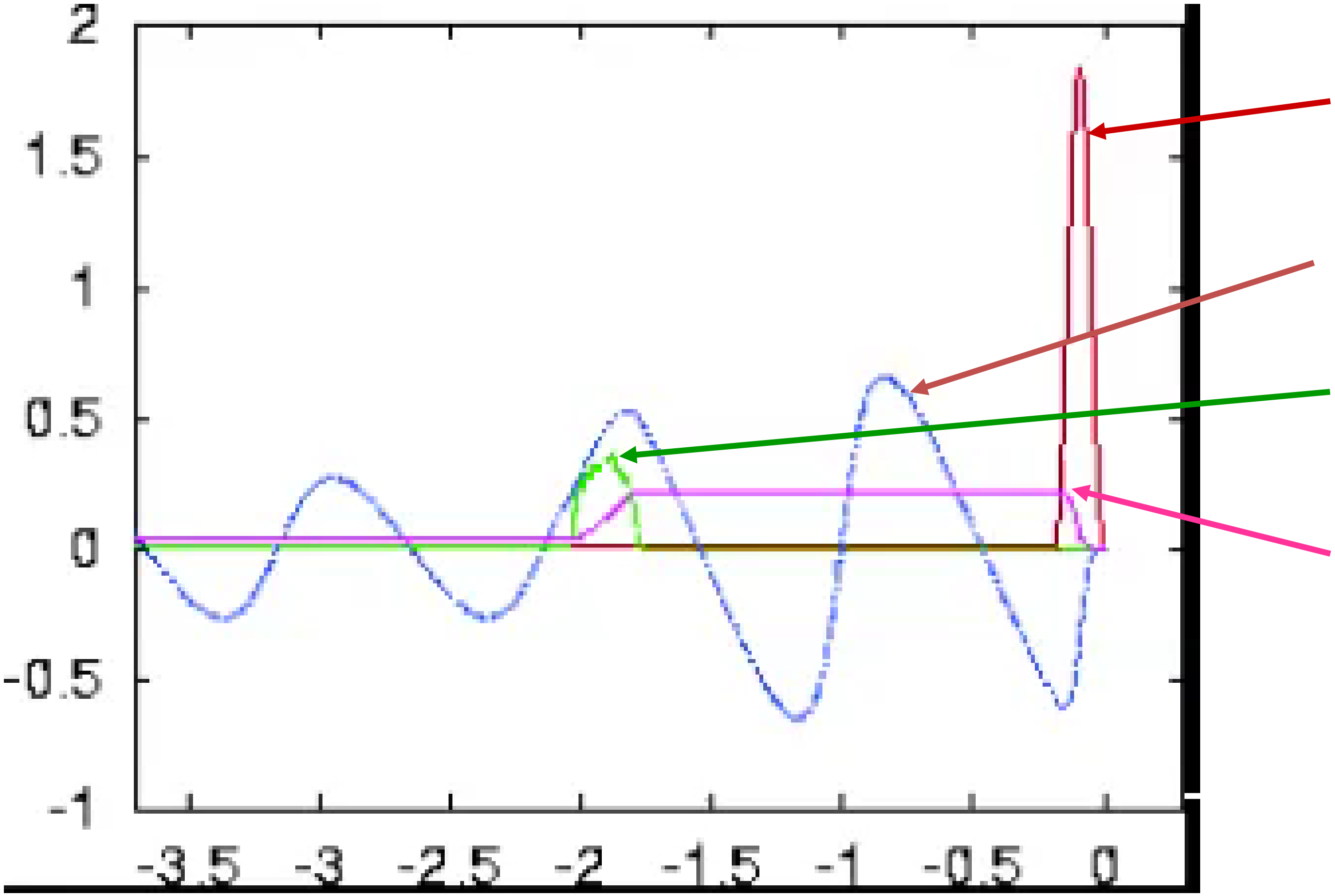


2 mm
Gas jet
1 J, 40 fs
= 100 – 300 MeV



4 cm
Plasma capillary
10 J, 50 fs
~ 1 GeV (RAL)

Modelling of Laser Wakefield Acceleration



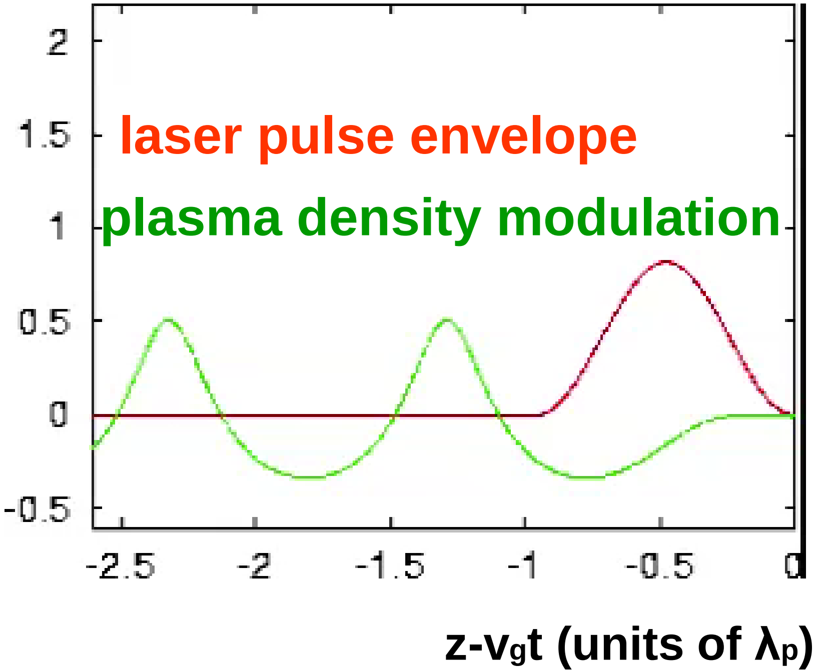
laser pulse envelope
electrostatic wakefield
bunch density
energy density of wakefield

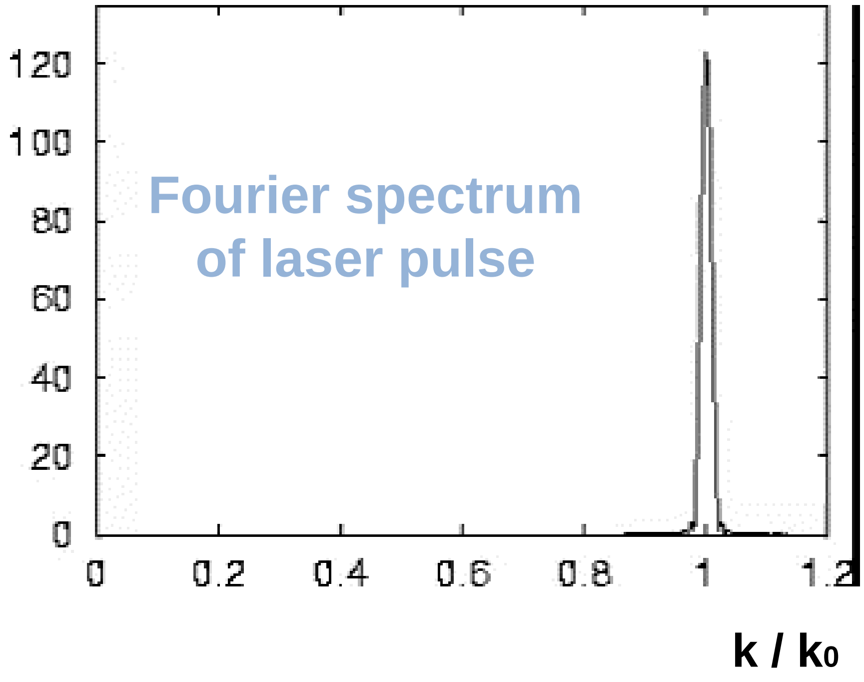
$z\text{-}v_g\,t$ (units of λ_p)

laser pulse envelope dynamics: ponderomotive wakefield excitation - electron bunch acceleration - phase slippage - beam loading

Laser pulse envelope dynamics

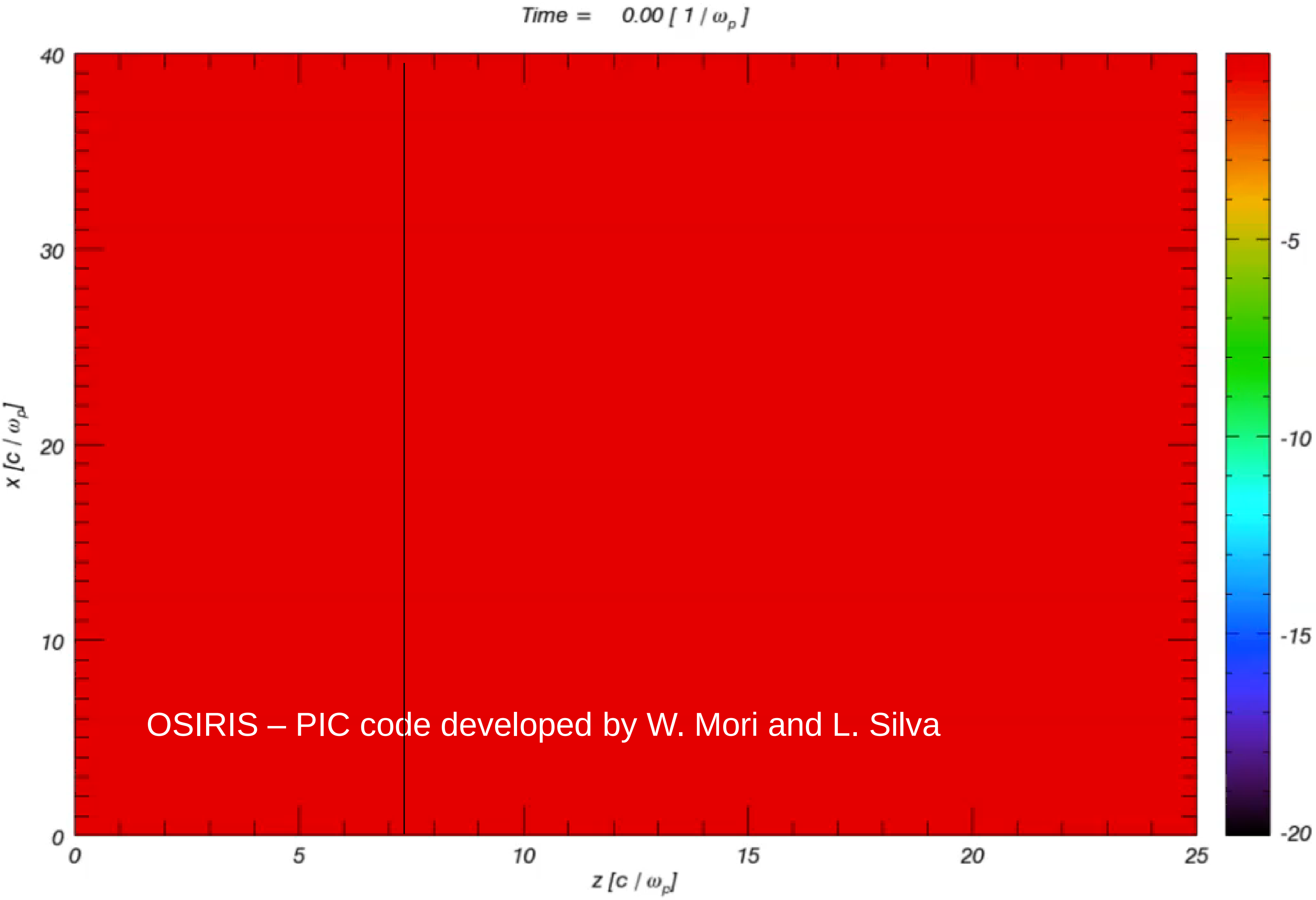
laser pulse amplitude: a_0
laser pulse energy depletion rate: $\omega_d \sim a_0^2\, \omega_s$





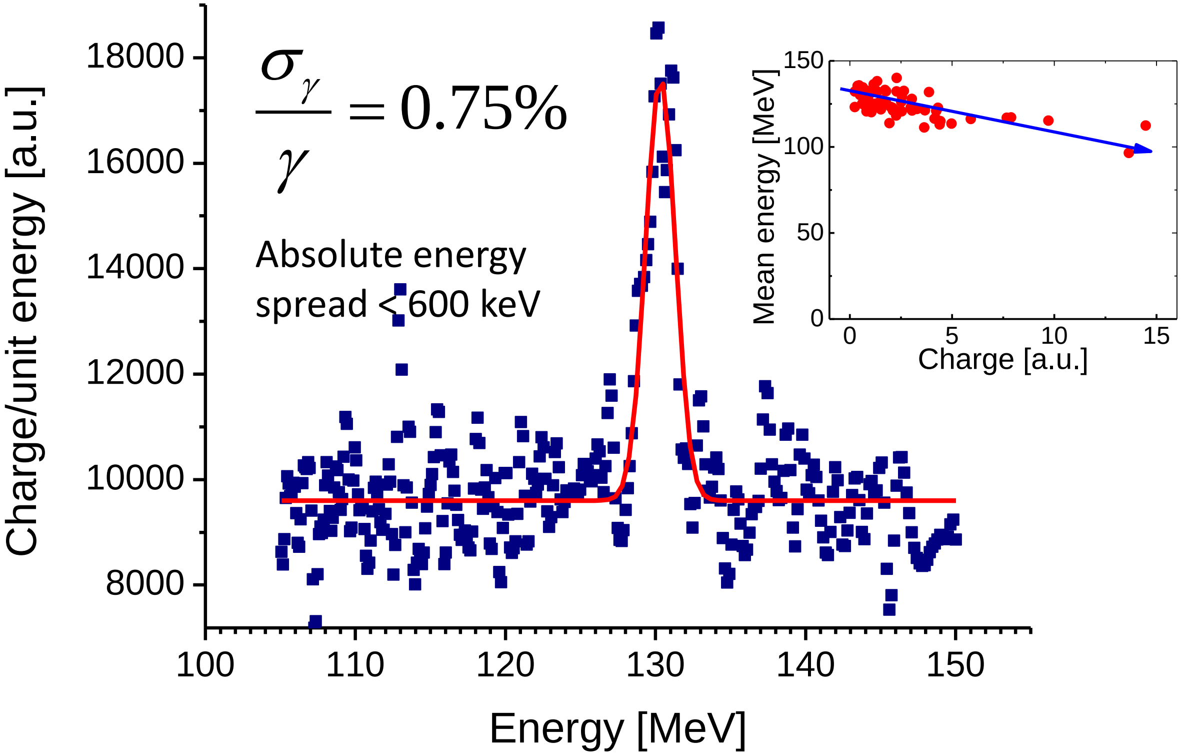
Linear regime: $a_0^2 \ll 1, \omega_d \ll \omega_s$: pulse energy loss through photon deceleration without envelope modulation, static wakefield, low energy efficiency

Nonlinear regime: $a_0^2 \sim 1, \omega_d \sim \omega_s$: pulse energy loss through photon deceleration and strong envelope modulation, dynamic wakefield, better energy efficiency



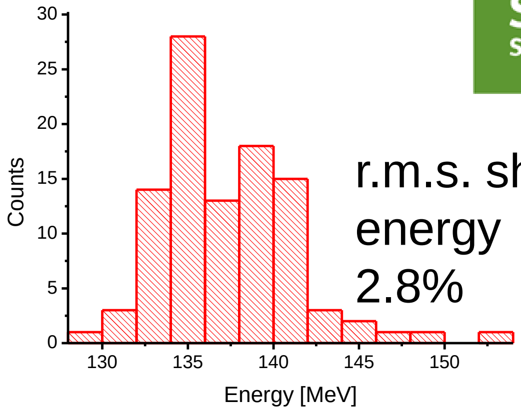
OSIRIS – PIC code developed by W. Mori and L. Silva

Energy spread, beam loading and stability



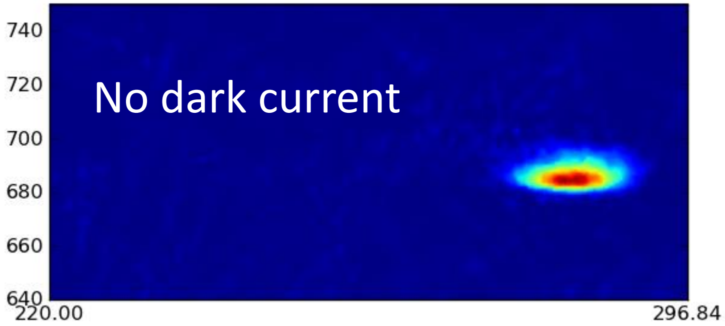
$$\frac{\sigma_\gamma}{\gamma} = 0.75\%$$

Absolute energy spread < 600 keV

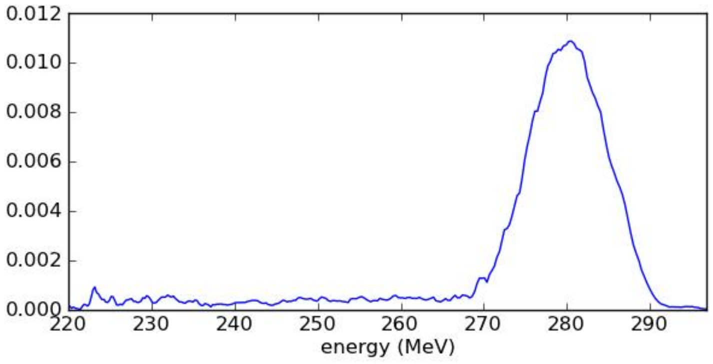


r.m.s. shot to shot energy variation 2.8%

Wiggins, et al., Plasma Physics & Controlled Fusion 2010

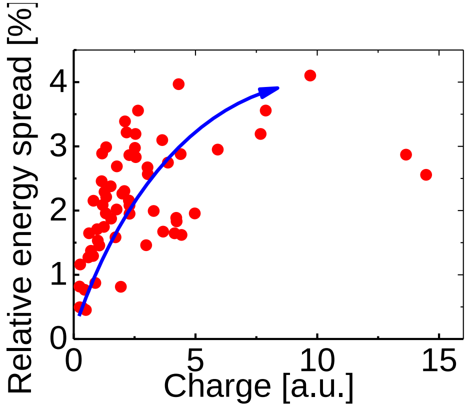


No dark current

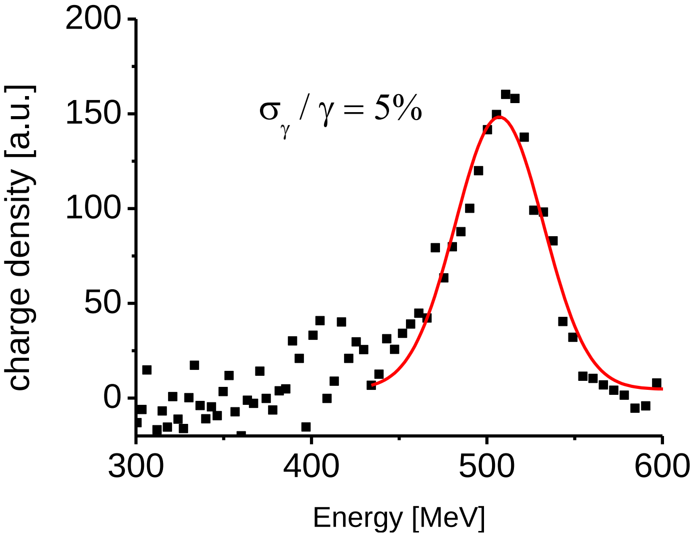


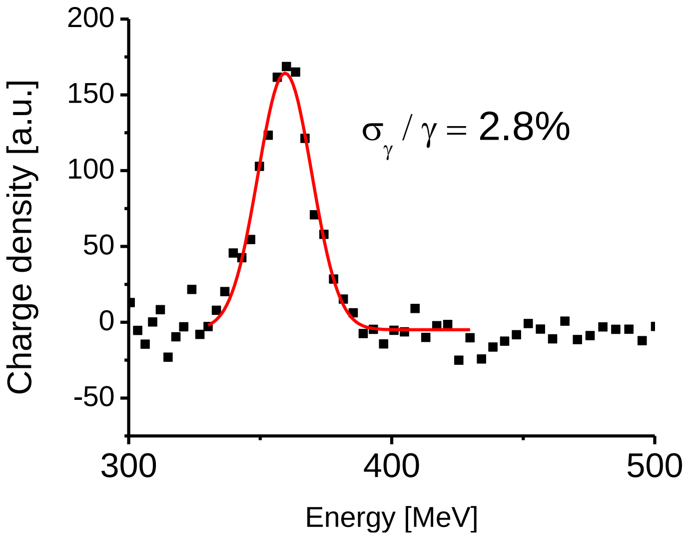
Maximum energy obtained in 2 mm ≈ 300 MeV

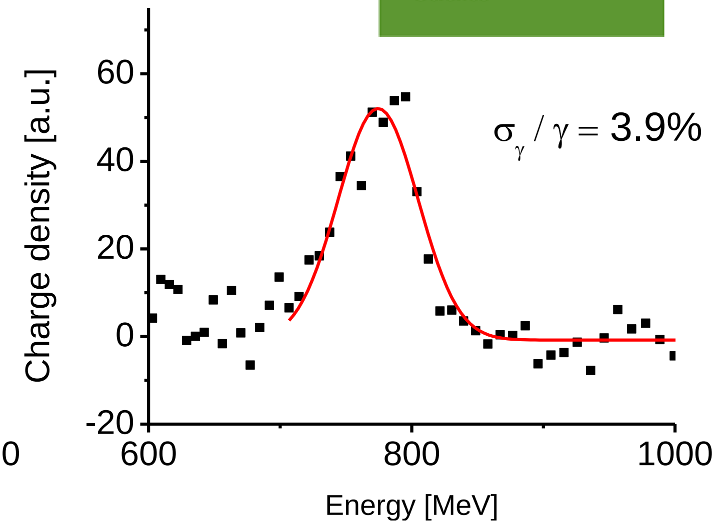
- With stable laser and gas jet
- Necessary to work close to threshold to obtain good beams



5 J laser at RAL: Electron Beams from Capillary

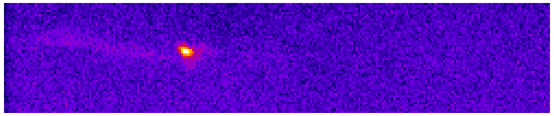




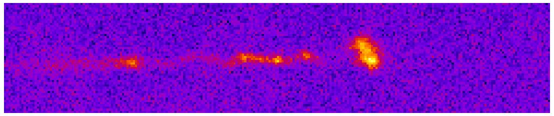


RAL GEMINI: limited by spectrometer resolution – maximum energy measured 850 MeV from 4 cm capillary.

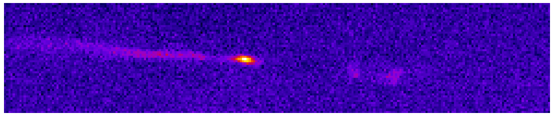
$$\gamma_d \approx 2\gamma_g^2 a_0 / 3$$



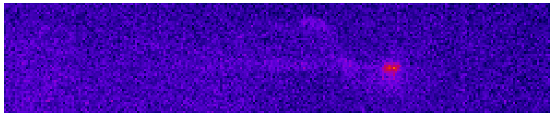
E_0 = 260 MeV, $\sigma_\gamma/\gamma_{MEAS}$ ~ 2.5%



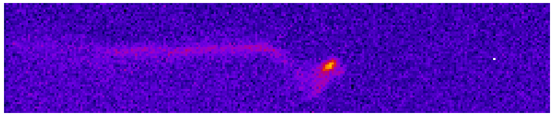
E_0 = 610 MeV, $\sigma_\gamma/\gamma_{MEAS}$ ~ 4.5%



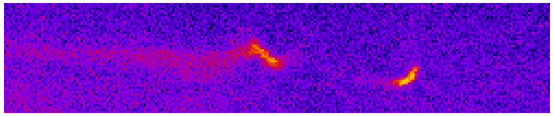
E_0 = 340 MeV, $\sigma_\gamma/\gamma_{MEAS}$ ~ 2.5%



E_0 = 690 MeV, $\sigma_\gamma/\gamma_{MEAS}$ ~ 4%

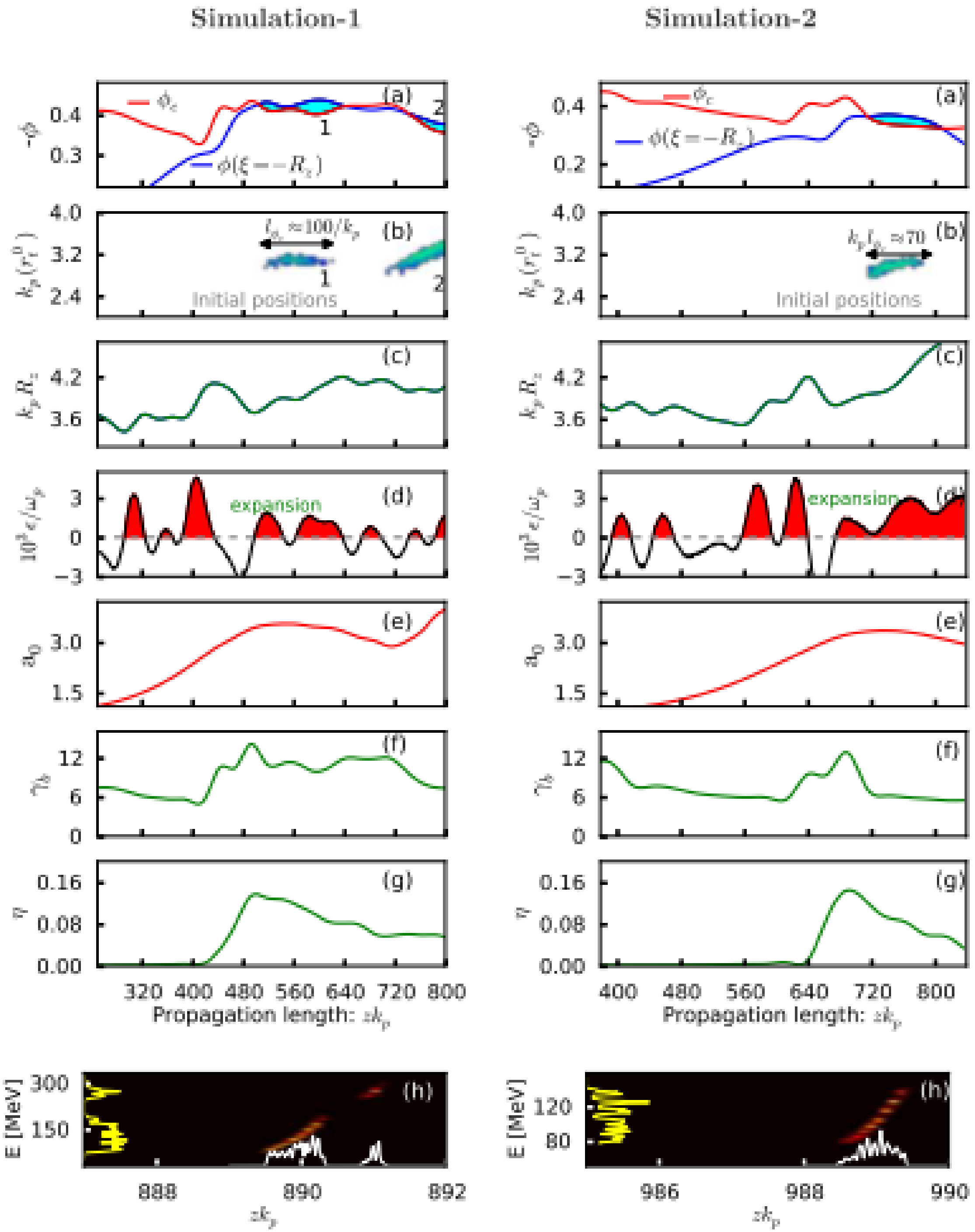


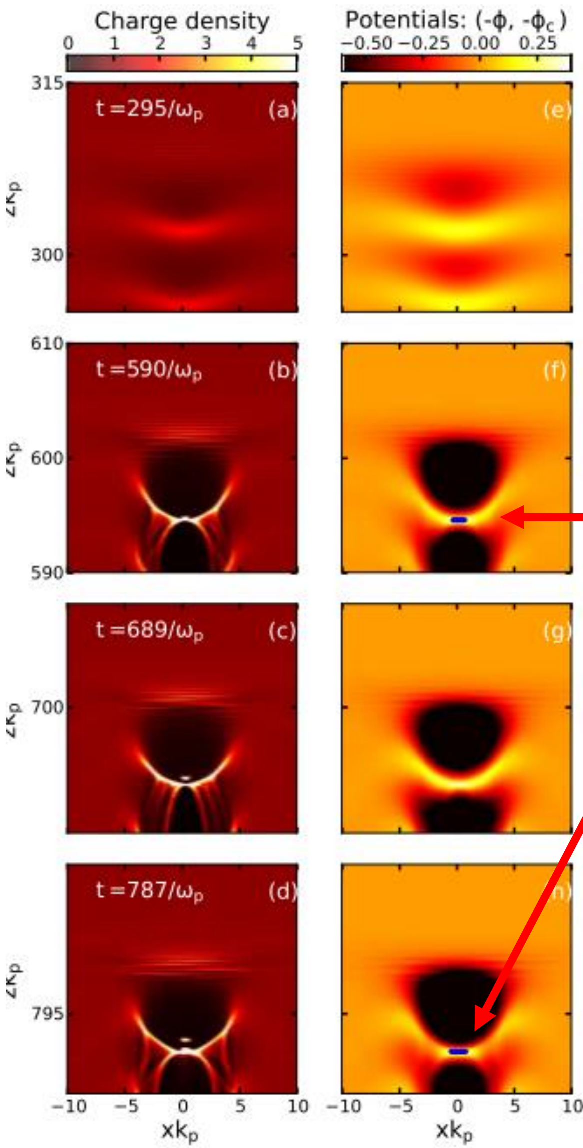
E_0 = 510 MeV, $\sigma_\gamma/\gamma_{MEAS}$ ~ 3%



E_0 = 770 MeV, $\sigma_\gamma/\gamma_{MEAS}$ ~ 4%

Injection of ultra-short bunches





Charge build-up at the back of the bubble

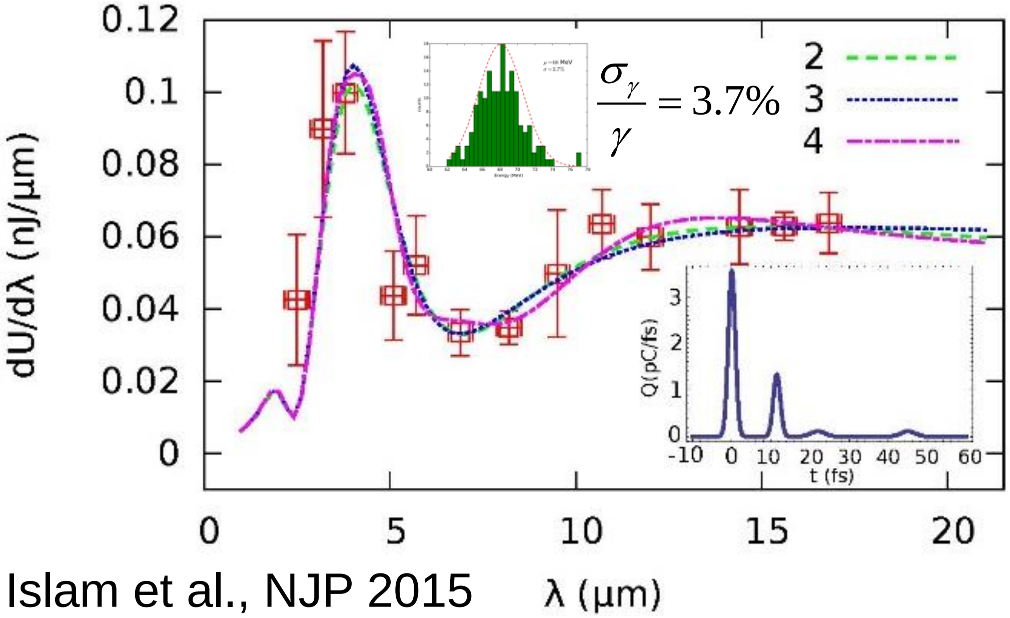
Islam et al., NJP 2015

Bunch length measurements: Coherent Transition Radiation

Coherent transition radiation spectrum gives bunch length

Chirp:

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

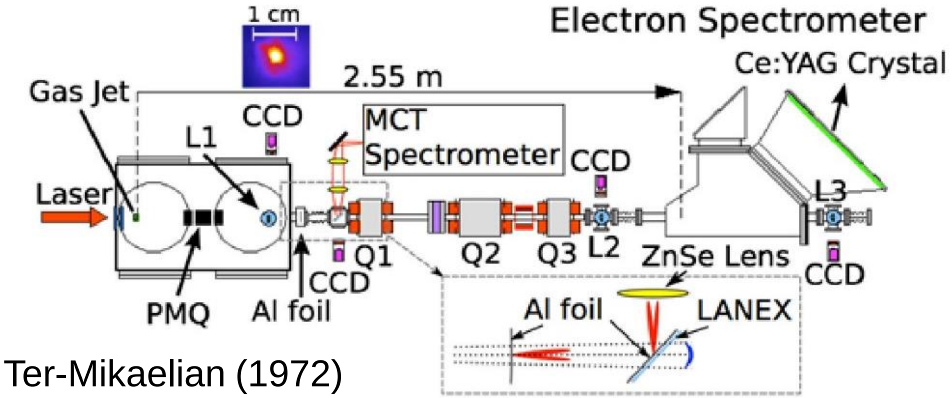


Islam et al., NJP 2015

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

Ter-Mikaelian (1972)

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

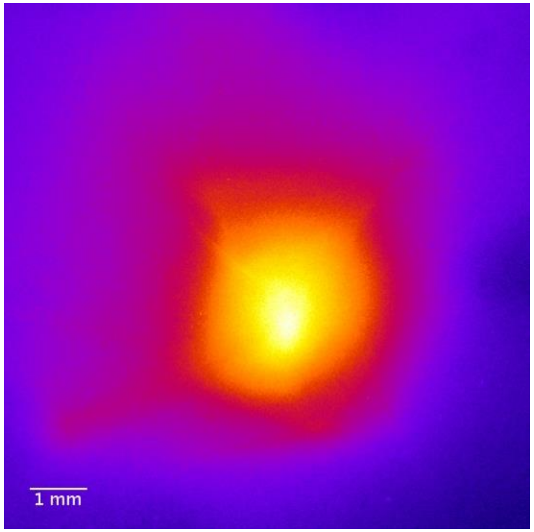
$$N_{photons} = \frac{\alpha}{\pi}[2\ln\gamma - 1]\ln(\omega_2/\omega_1) \qquad \omega > \omega_{cr} = \gamma\omega_p$$

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

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

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

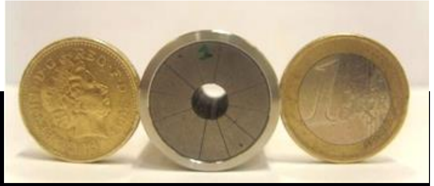
Electron Beam- Pointing Stability



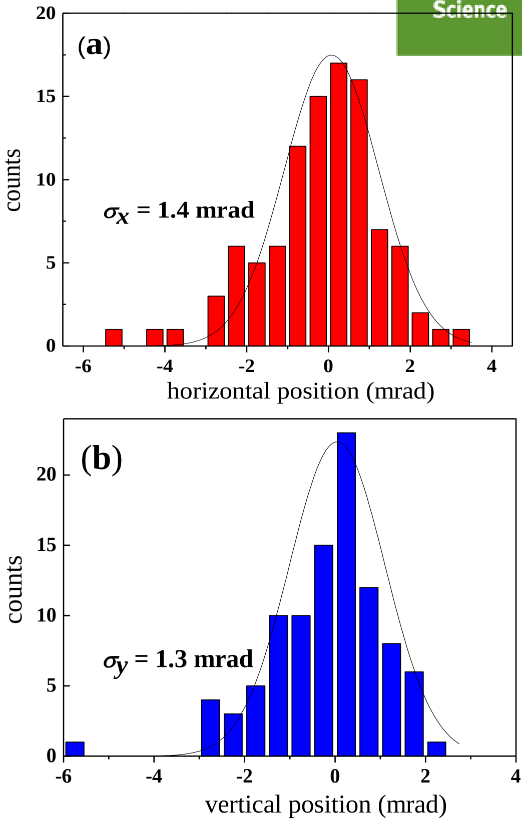
Electron beam recorded on YAG screen

High resolution

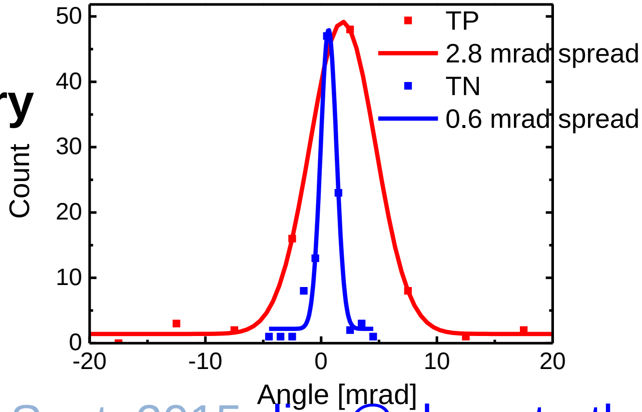
Electron beam pointing deviation is less than one spot size



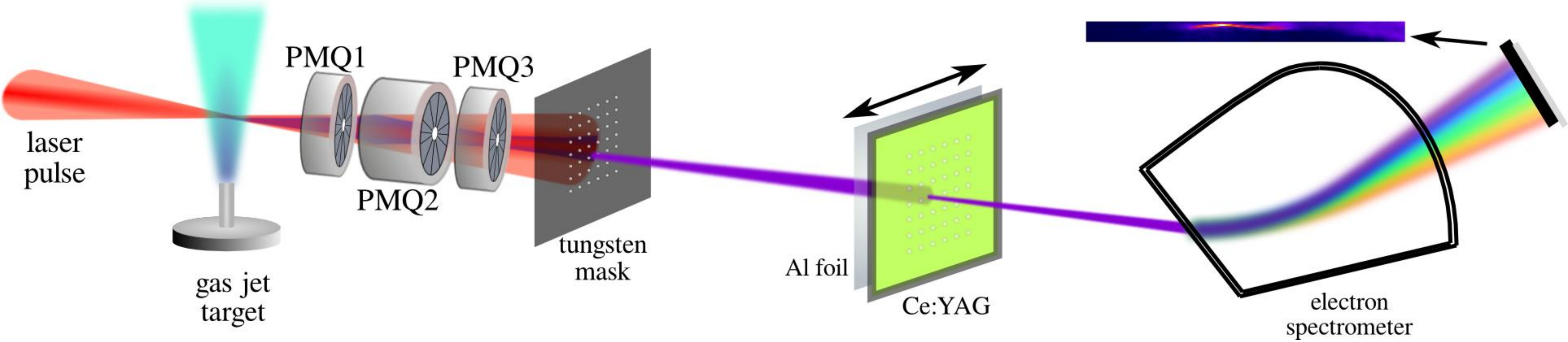
Gas jet

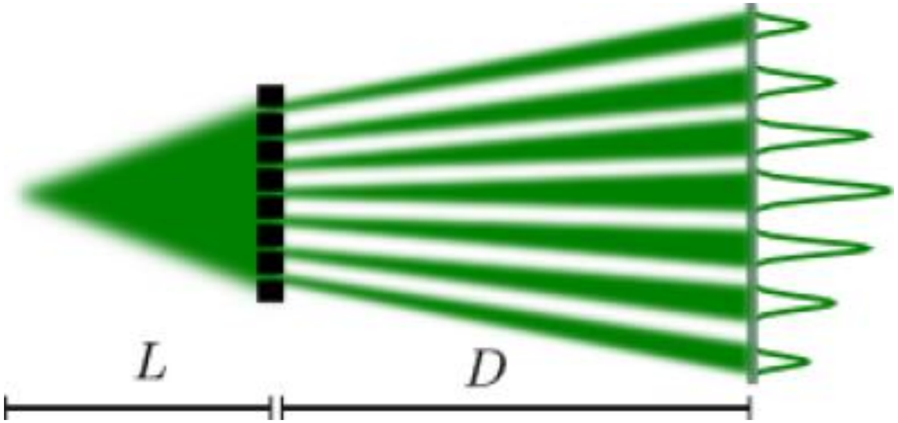


Capillary



Measuring emittance

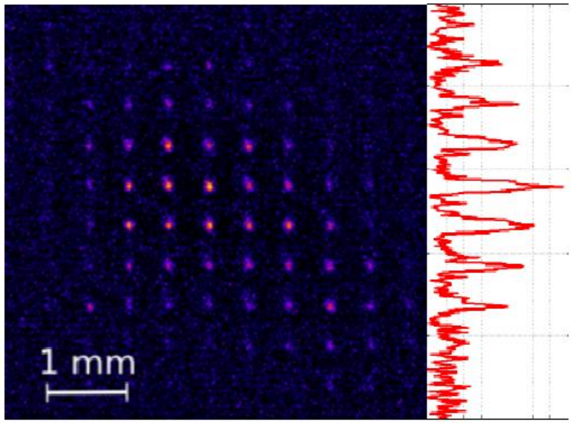




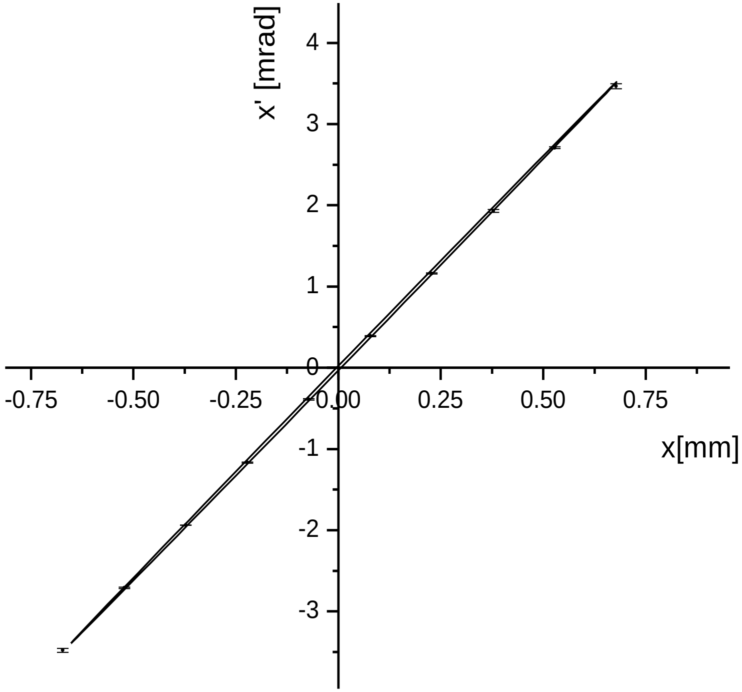
Brunetti et al., PRL (2010)
Manahan et al., New J. Phys. (2014).
Measured emittance: $\varepsilon = 1\ \pi$ mm mrad

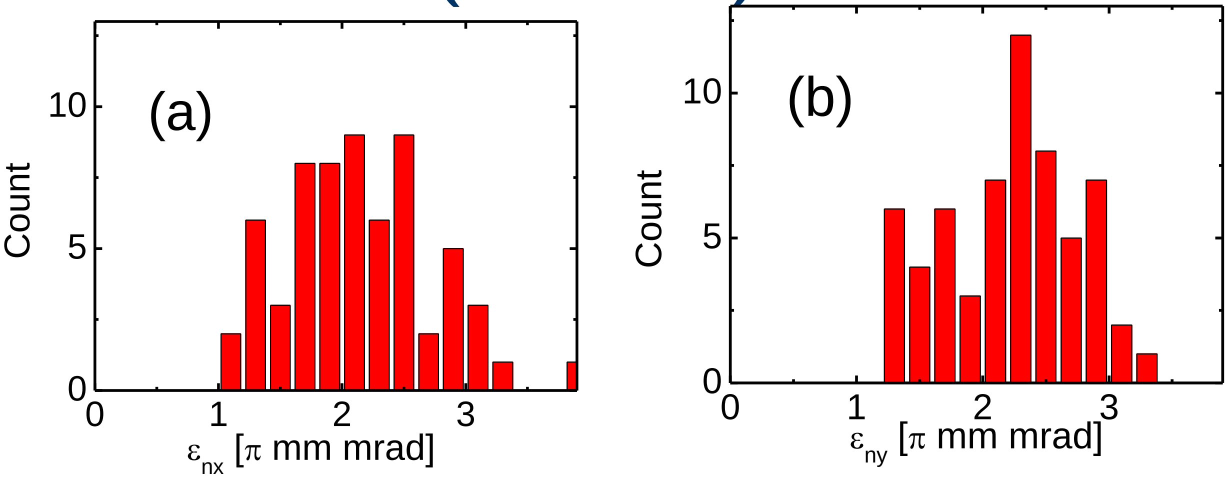
Emittance

- Thin tungsten mask with holes $\phi \sim 25\ \mu m$



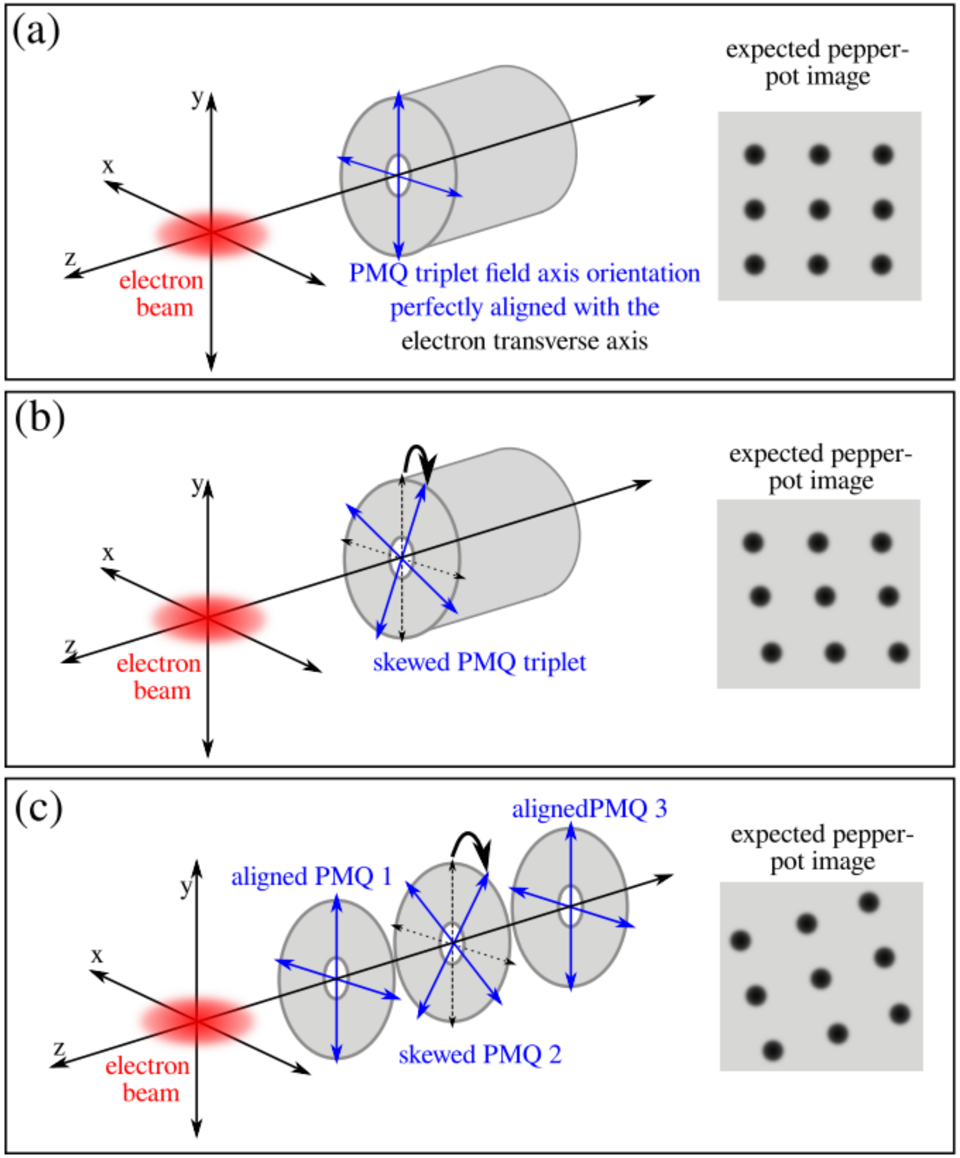
- divergence 1 – 2 mrad with 125 MeV electrons
- average $\varepsilon_N = (2.2 \pm 0.7)\pi$ mm mrad
- best $\varepsilon_N = (1.0 \pm 0.1)\pi$ mm mrad
- Elliptical beam: $\varepsilon_{N,X} > \varepsilon_{N,Y}$
- Upper limit because of resolution
- **With PMQs emittance grows by factor of 5 (measured)**

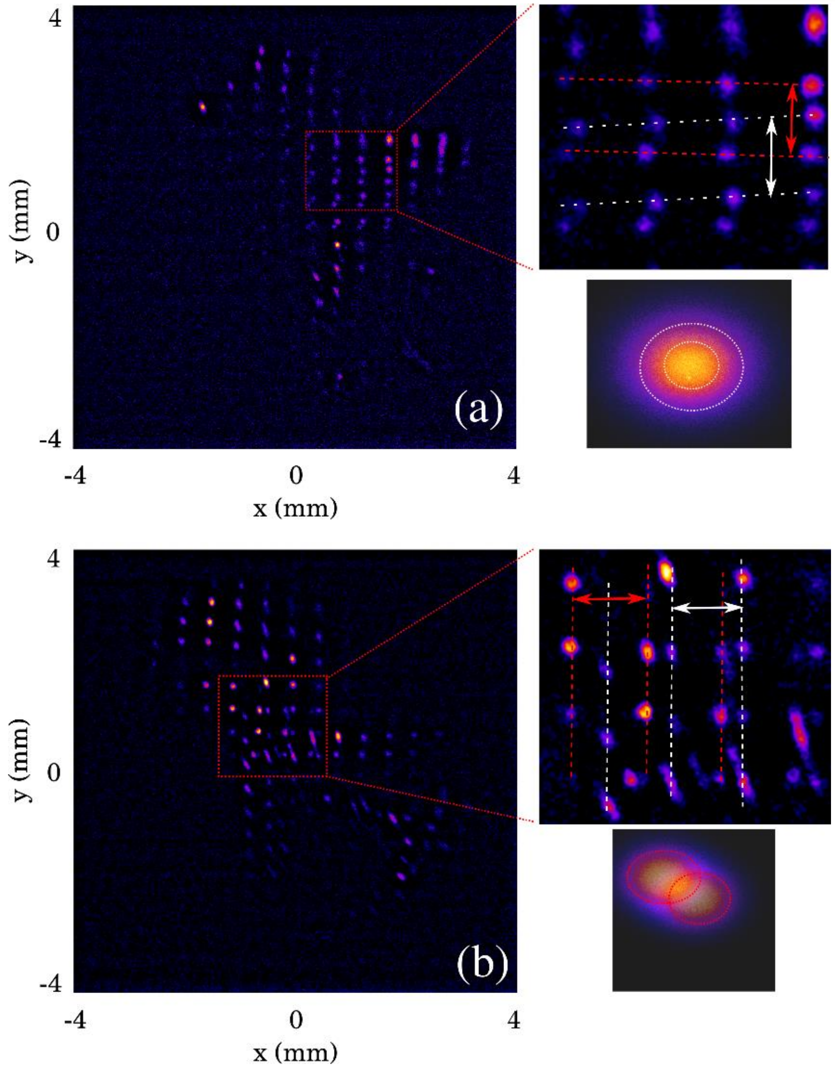




Brunetti et al., PRL (2010)

Evidence of multiple beams

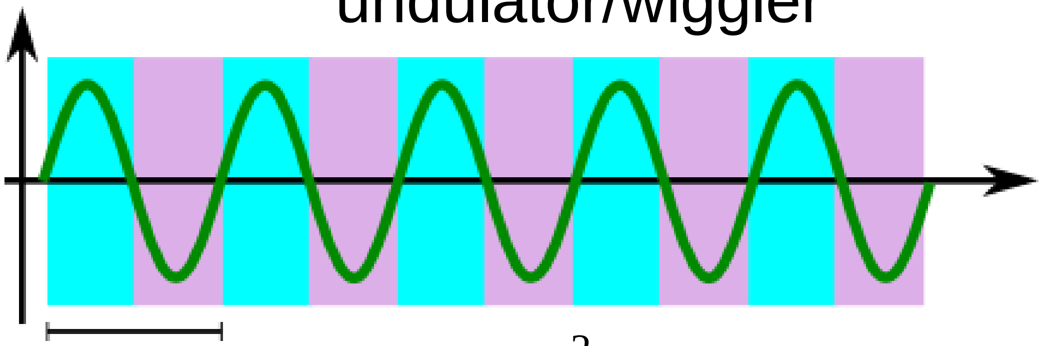




Manahan et al., New J. Phys. (2014).

Radiation from relativistic electrons

undulator/wiggler



$$\omega = \frac{4\pi c\gamma^2}{\lambda_u\left(1 + a_u^2/2 + \gamma^2\theta^2\right)}$$

$$z(t) = \left(1 + \frac{a_u^2}{4\gamma^2}\right)vt - \frac{a_u^2}{8\gamma^2 k_u}\cos(2\omega_u t)$$

$$\mathrm{x(t)} = \frac{a_u}{k_u\gamma}\cos(\omega_u t)$$

$$\omega_u = k_u\left(1 + \frac{a_u^2}{4\gamma^2}\right)v$$

$$k_u = 2\pi/\lambda_u$$

Photons per electron
per undulator period

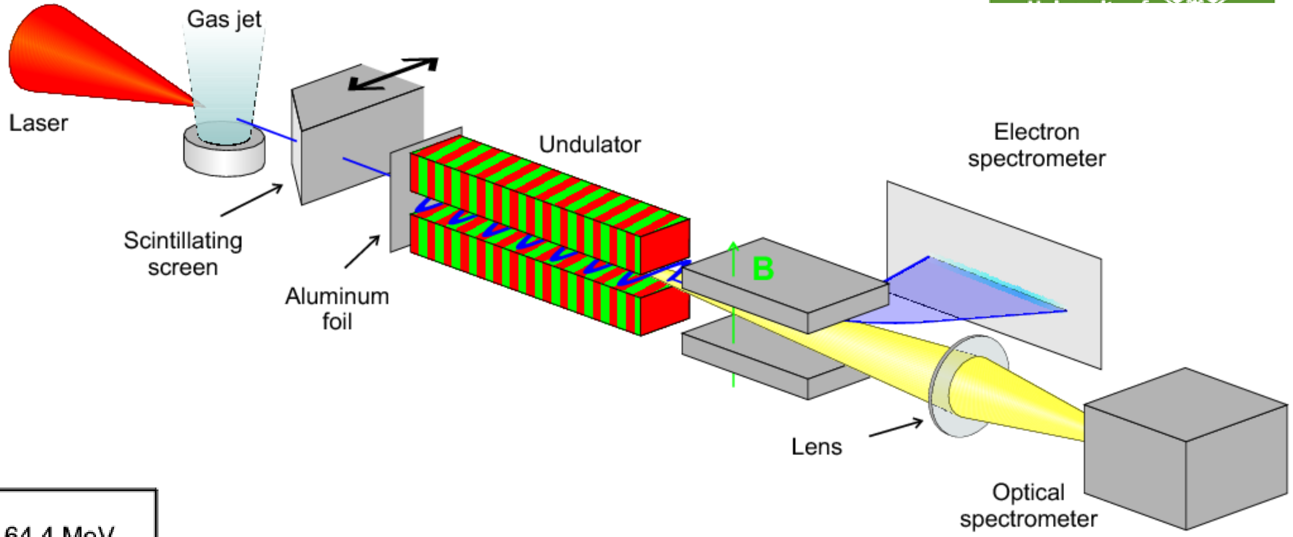
$$N_{phot} = \frac{2\pi}{3}\alpha a_u^2, \quad a_u < 1$$

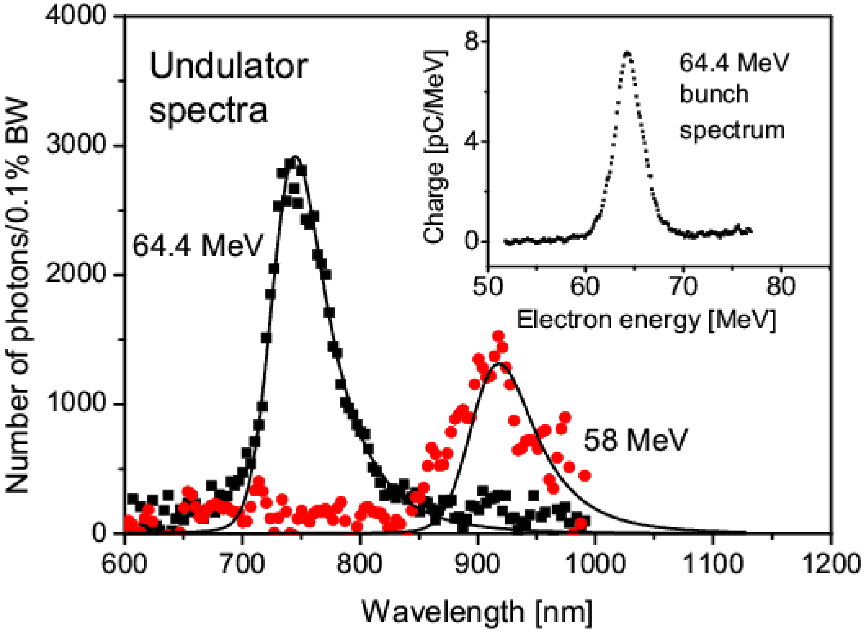
$$N_{phot} = \frac{5\sqrt{3}\pi}{6}\alpha a_u, \quad a_u > 1$$

a_u <1: undulator radiation
a_u >1: wiggler radiation
α: fine structure constant

Undulator radiation

- Strathclyde, Jena, Stellenbosch collaboration
- 55 – 70 MeV electrons
- VIS/IR synchrotron radiation





- Measured σ_γ/γ ~ 2.2 – 6.2%
- Analysis of undulator spectrum and modelling of spectrometer

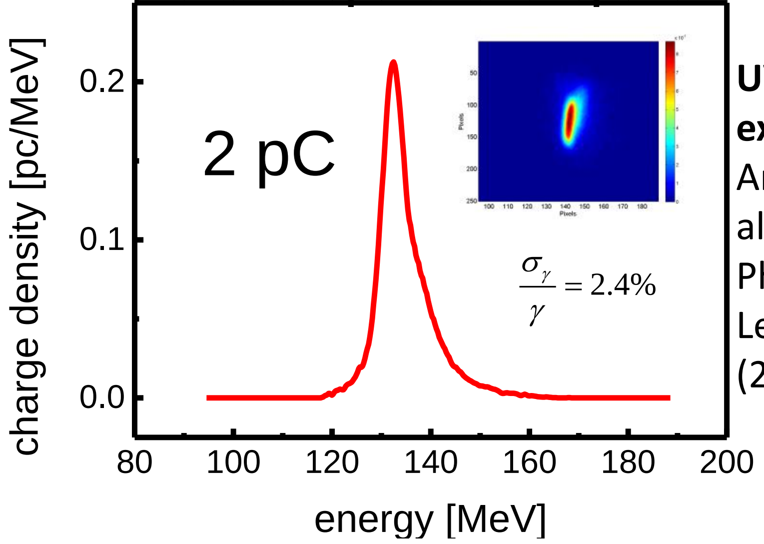
  σ_γ/γ closer to 1%

Schlenvoigt .., Jaroszynski et al., Nature Phys. **4**, 130 (2008)
Gallacher, ….Jaroszynski et al. Physics of Plasmas, Sept. (2009)

Strathclyde UV undulator measurements

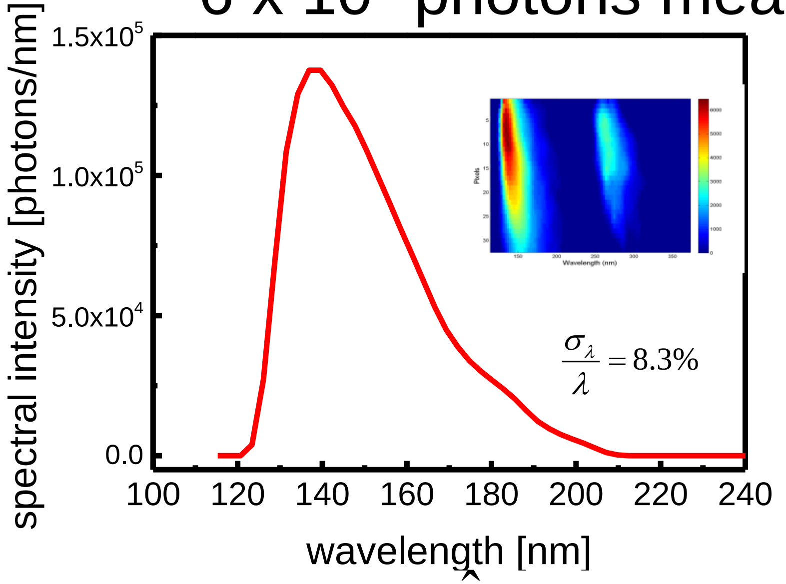
University of Strathclyde Science

10^7 photons predicted



UV experiment: Anania, et al., Applied Physics Letters (2014)

6×10^6 photons measured

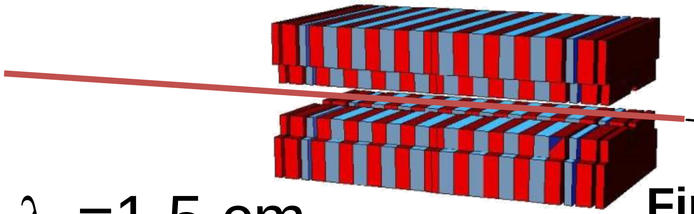


42 fs

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{a_u^2}{2} + \gamma^2\theta^2\right);$$

$$\frac{\Delta\lambda}{\lambda} \approx \frac{1}{2N_u}$$

$$a_u = \frac{e\hat{B}\lambda_u}{2\pi mc}$$



$$2\sigma_\gamma / \gamma \approx \left[\left(\sigma_\lambda / \lambda\right)^2_{measured} - (\vartheta^2\gamma^2)^2 - 1/N_u^2 \right]^{1/2}$$

$$\frac{1}{\sqrt{N_u \gamma}}$$

N_u=100, λ_u=1.5 cm
1 GeV beam λ = 2-4 nm
10 GeV beam λ = 0.2 Ångström

First experiments in visible:
HP Schlenvoigt, et al.,
Nature Physics 2008

LWFA-driven FEL

- High FEL gain criteria: $\varepsilon_n < \lambda\gamma/4\pi$ & $\sigma_\gamma/\gamma < \rho$
- Experimental $\varepsilon_n \leq 0.8\pi$ mm mrad & $\sigma_\gamma/\gamma \leq 0.007$
- For fixed $\sigma_\gamma = 0.6$ MeV, σ_γ/γ reduces at short λ

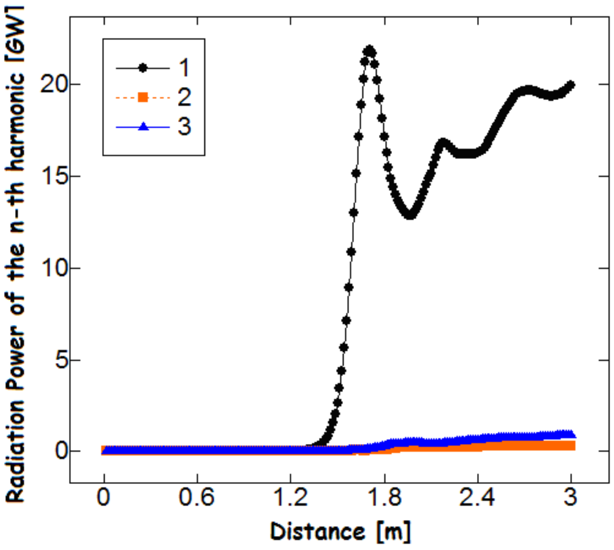
$$\rho = \frac{1}{2\gamma}\left[\frac{I_p}{I_A}\left(\frac{\lambda_u a_u}{2\pi\sigma_x}\right)^2\right]^{1/3}$$

R. Bonifacio et al., 1984

Electron energy (MeV)	Radiation λ (nm)	Emittance criterion (π mm mrad)	Gain parameter ρ	Relative energy spread
90	261	3	0.011	0.007
150	94	2	0.006	0.004
500	8	0.6	0.002	0.001(?)

ALPHA-X Undulator

λ_u = 15 mm, N = 200, a_u = 0.38



STEADY STATE SIMULATION RESULTS (100 MeV electrons)

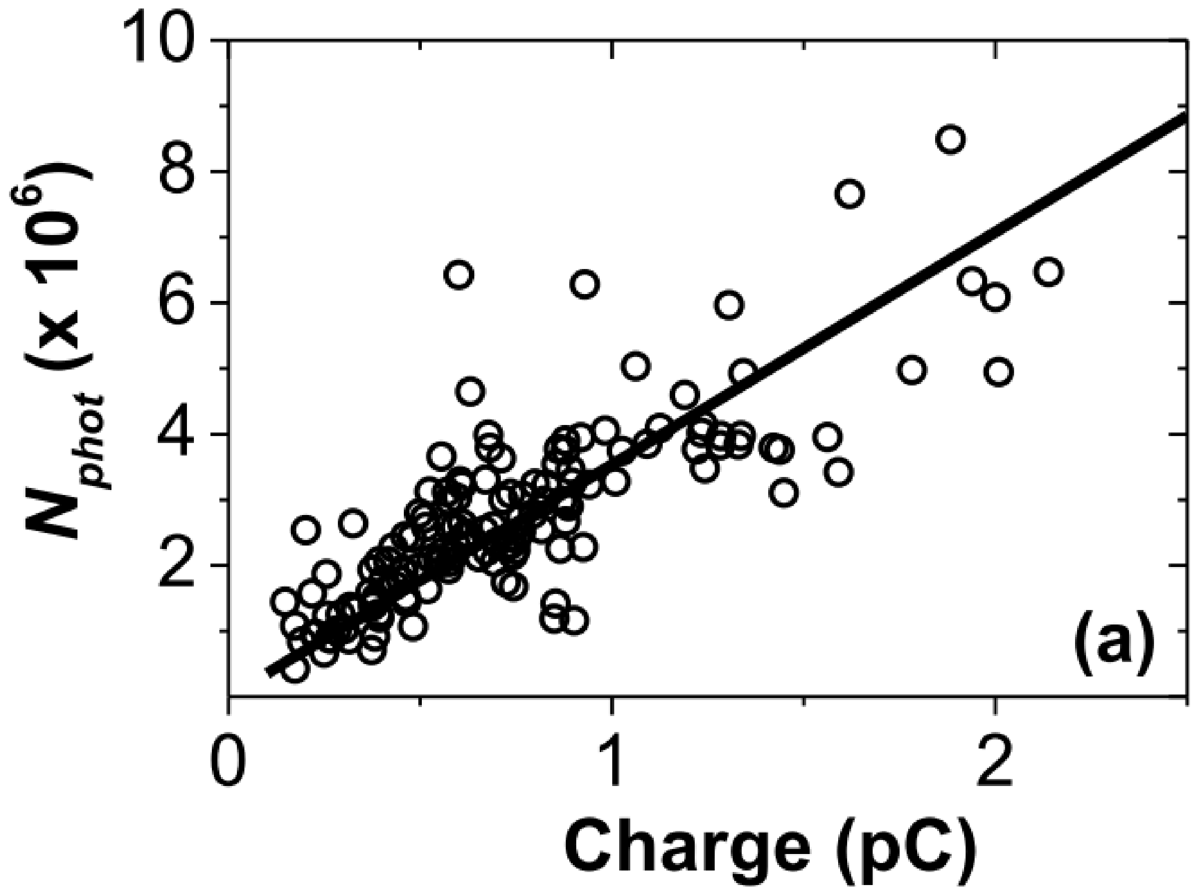
Saturation power(1st harmonic): 20 GW

@ saturation distance: 1.8 m

UNDULATOR RADIATION EXPERIMENTS

In progress for improving beam transport and observing gain

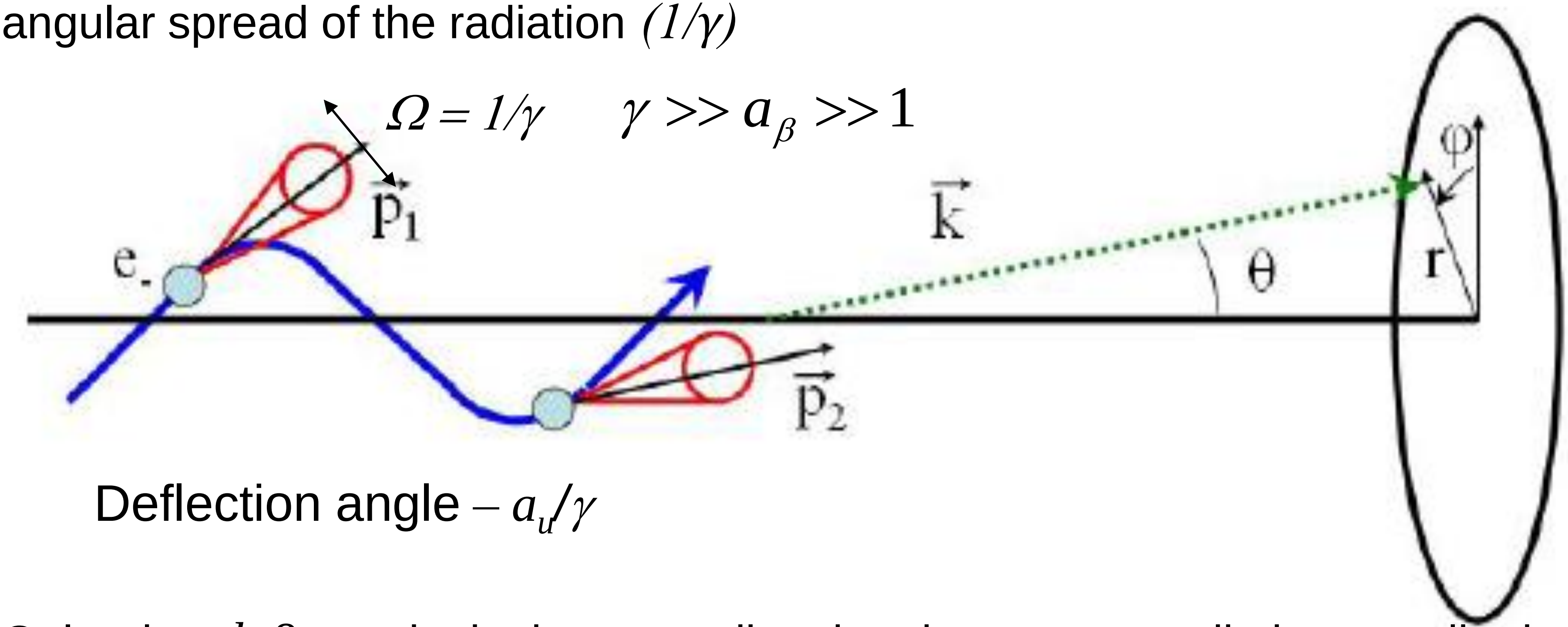
Number of photons vs charge



UV experiment:
Anania, et al., Applied Physics Letters (2014)

Plasma wiggler

- Wiggler motion – electron deflection angle $\theta \sim (p_x/p_z)$ is much larger than the angular spread of the radiation $(1/\gamma)$

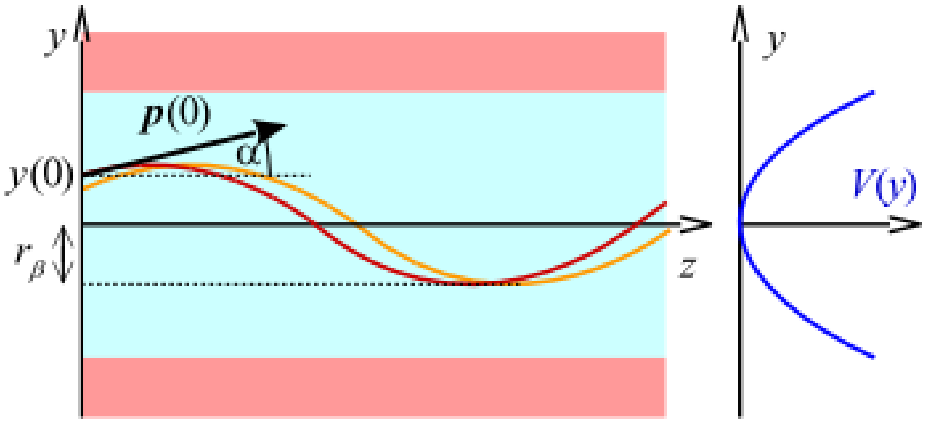


$\Omega = 1/\gamma$ $\gamma >> a_\beta >> 1$

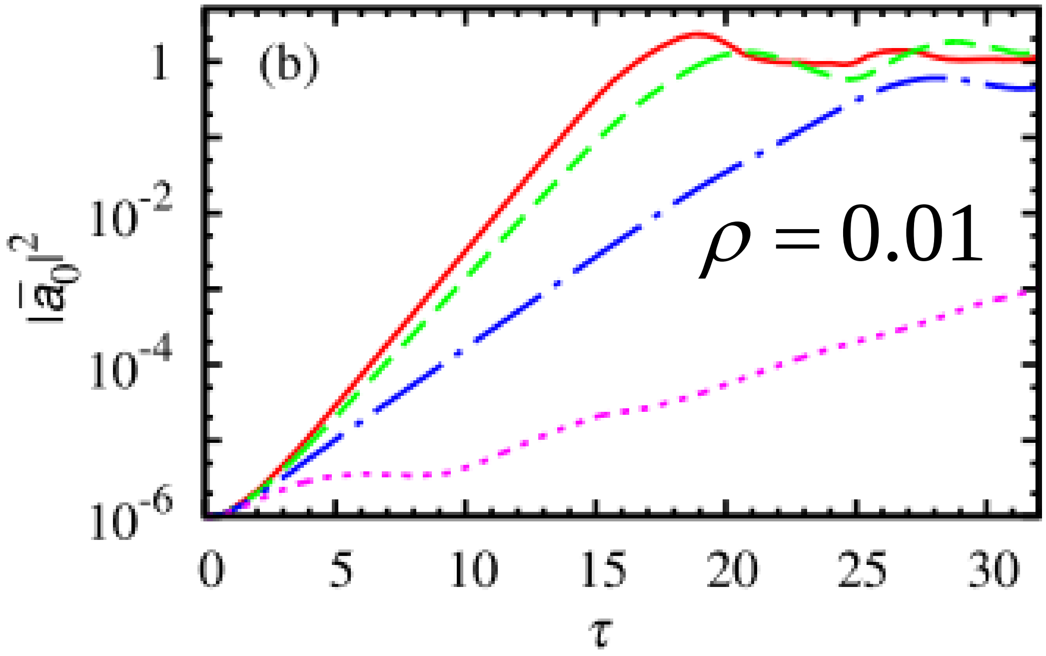
Deflection angle – a_u/γ

- Only when k & p point in the same direction do we get a radiation contribution.
- Spectrum very rich in harmonics – peaking at $n_{crit} \approx \dfrac{3a_\beta^3}{8}$

Ion Channel Laser

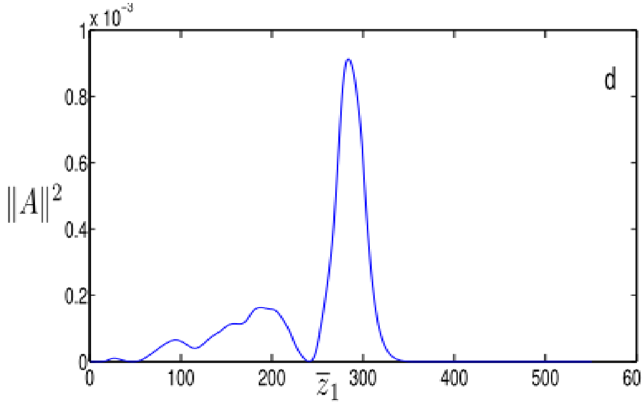


$$\rho = \left[\eta_{\mathrm{h}}^2 \eta_{\mathrm{m}} \bar{\eta}_{\mathrm{f}} \omega_{\mathrm{b}}^2 R_\beta^2 \Big/ \left(8 \tilde{\gamma}_0 c^2\right)\right]^{1/2} \approx 3.3 \times 10^{-3} \left[\left(n_{\mathrm{b}} / 10^{18}\ \mathrm{cm}^{-3}\right) \Big/ \tilde{\gamma}_0\right]^{1/2} \left(R_\beta / \mu\mathrm{m}\right).$$

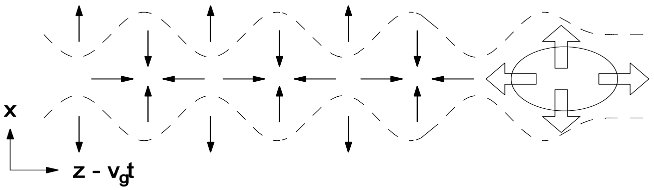


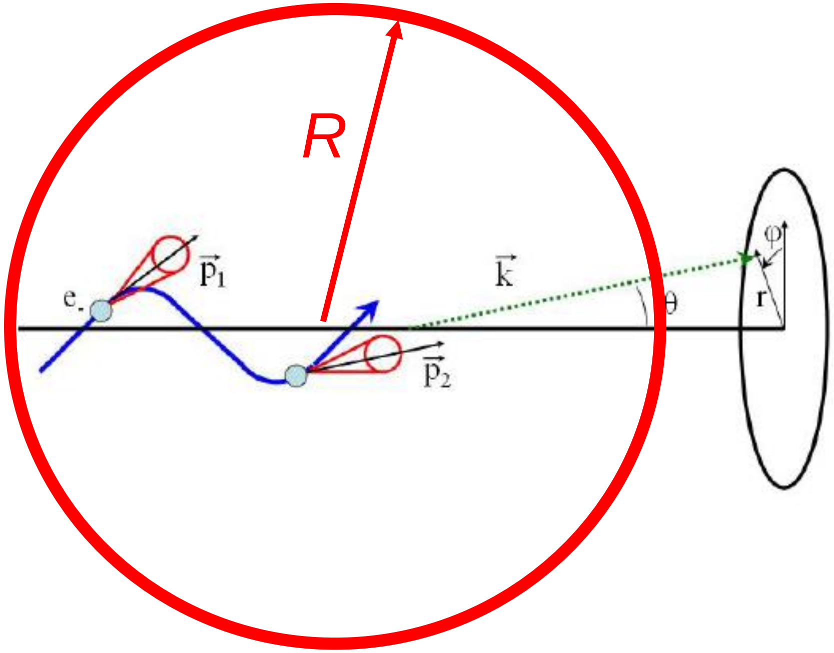
Similar to FEL but with variable wiggler parameter for each electron

Ersfeld et al., NJP (2014)



Betatron radiation





$$k_p = \frac{\omega_p}{c} \qquad \lambda_p = \frac{2\pi}{k_p}$$

$$a_\beta = r_\beta k_p \sqrt{\frac{\gamma}{2}} \qquad h_{crit} \approx \frac{3a_u^3}{8}$$

$$\lambda_\beta = \lambda_p \sqrt{2\gamma}$$

$$R \approx \frac{\lambda_p \sqrt{a_0}}{\pi}$$

$$\hbar\omega = \frac{2\gamma^2 \hbar\omega_\beta}{1 + a_\beta^2/2}, \quad N_{phot} \approx 0.0153 a_\beta^2 \quad a_\beta < 1$$

$$\hbar\omega_c = \frac{3}{2} a_\beta \gamma^2 \hbar\omega_\beta, \quad N_{phot} \approx 0.0331 a_\beta \quad a_\beta > 1$$

deflection angle – a_u/γ

Betatron radiation emission during LWFA

BETATRON RESONANCE

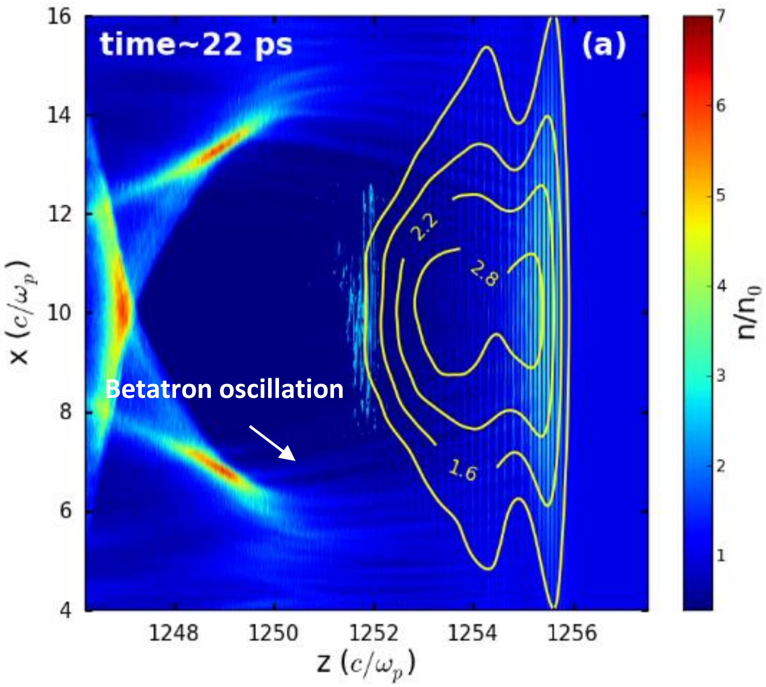
- The bubble partially filled by laser pulse

$$\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

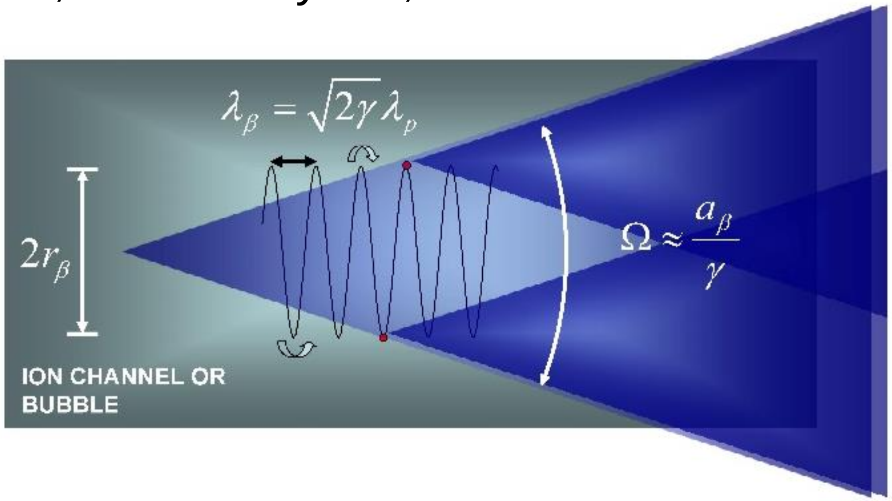
- Electrons enter into resonance with the laser field
- Laser drives larger amplitude betatron oscillations:

Increase in r_β, a_β, E_c

$$\lambda_i = \frac{\lambda_\beta}{2\gamma_{z,i}^2 h} = \frac{\lambda_\beta}{2\gamma^2 h}\left(1 + \frac{a_{\beta,i}^2}{2} + \gamma^2\vartheta^2\right) = \frac{\sqrt{2}\lambda_p}{\gamma^{3/2} h}\left(1 + \frac{a_{\beta,i}^2}{2} + \gamma^2\vartheta^2\right),$$



Cipiccia et al., Nature Physics, 2011



Betatron radiation emission during LWFA

Cipiccia et al., Nature Physics, 2011

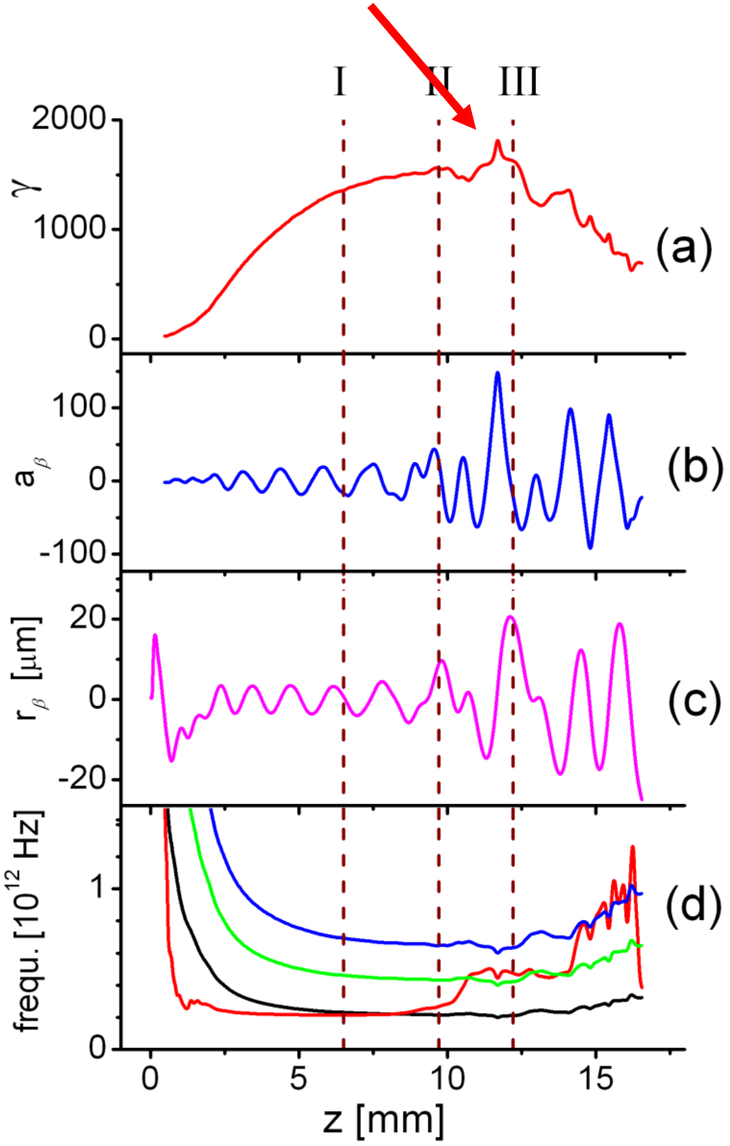
- Three different regimes:
  - Non resonant (I)
  - Weakly resonant (II)
  - Strongly resonant (III)

$$\ddot{y} + \Gamma \dot{y} + \omega_\beta^2 y = F_{Ly} /(m\gamma)$$

$$\Gamma = \dot{\gamma} / \gamma \qquad F_{Ly} = e(dA/dt - \dot{y}\,\partial A/\partial y)$$

$$\tilde{\omega} = \omega'_0 \left(\frac{1}{2\bar{\gamma}_z^2} + \frac{1}{2\gamma'^2_g} \right) \quad \bar{\gamma}_z = \gamma(1 + a_\beta^2 / 2)^{-1/2}$$

Direct laser acceleration



Betatron radiation emission during LWFA

SCALING LAWS

Acceleration:

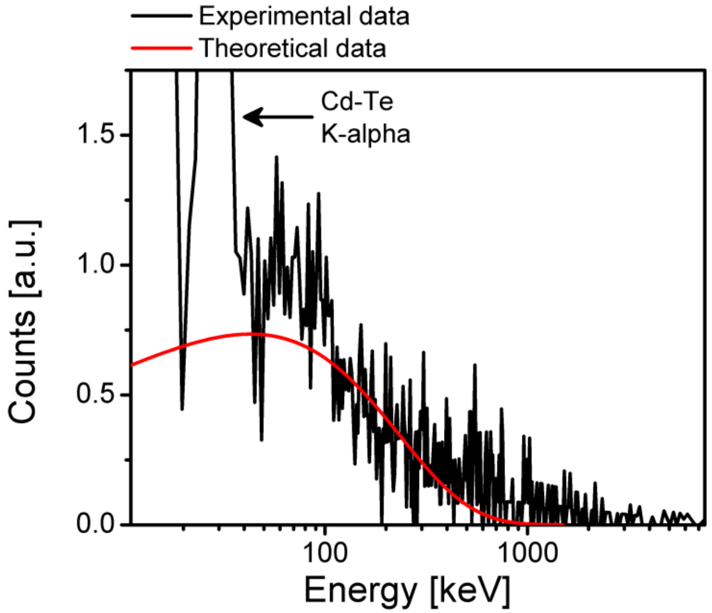
- Bubble radius: $R = 2\sqrt{a_0}/k_p$
- Dephasing Length: $L_d \simeq 2/3\omega_0^2/\omega_p^2,\ \ \omega_p = \sqrt{4\pi n_e e^2/m_e}$
- Max Energy: $\gamma_d \approx 2\gamma_g^2 a_0/3$

Betatron Radiation:

- Betatron Frequency: $\omega_\beta = \omega_p/\sqrt{2\gamma}$
- Transverse momentum: $a_\beta \propto \sqrt{\gamma n_e r_\beta}$
- Divergence: $\vartheta = a_\beta/\gamma$
- Critical photon Energy: $E_c \propto \gamma^2 n_e r_\beta$ $\qquad h_c \approx 3a_\beta^3/8$
- Efficiency: $N_{phot/cycle} = \alpha a_\beta$

ASTRA Gemini: Experimental Results

Case II Weakly Resonant

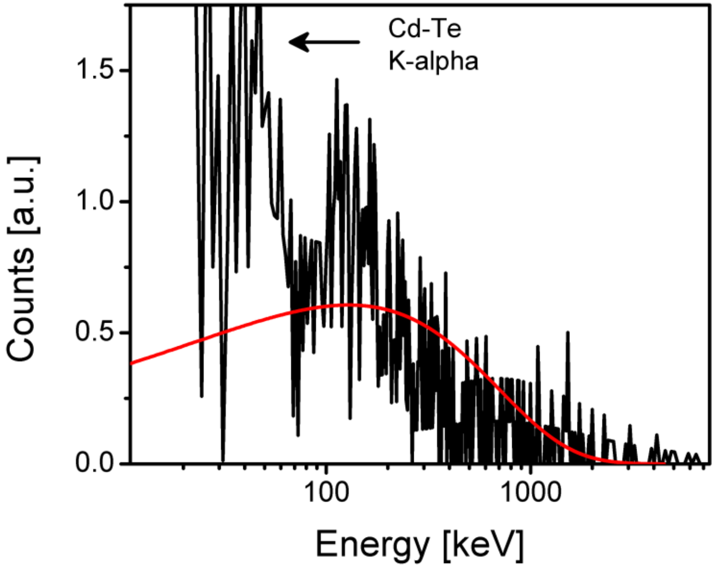


E_c = 150 keV

r_β = 7 mm

a_β = 50

Case III: Strongly Resonant:



E_c = 450 keV

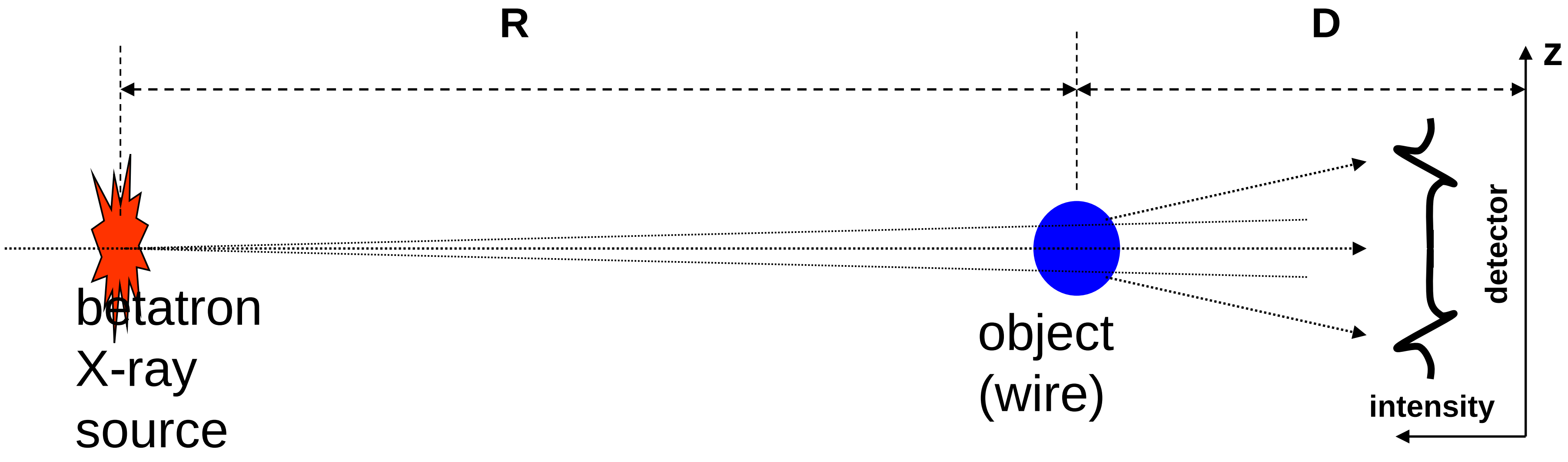
r_β = 20 μm

a_β = 150

Cipiccia et al., Nature Physics, 2011

Phase contrast imaging

$$n = 1 - \delta - i\beta \qquad \beta = \frac{\mu\lambda}{4\pi} \qquad \delta = \frac{\lambda^2 r_e n_e}{2\pi}$$

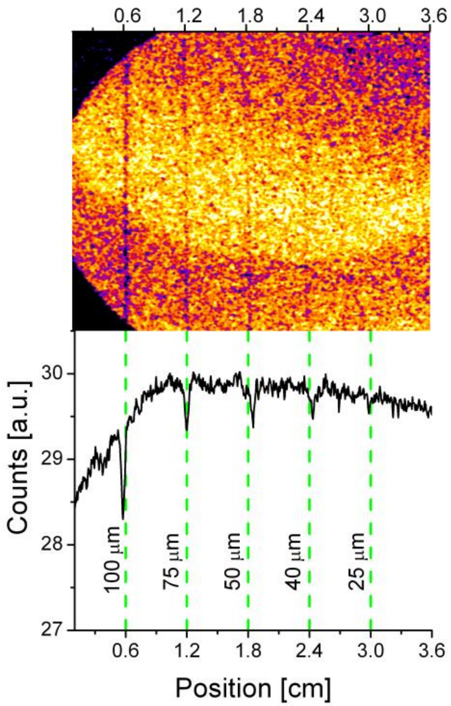


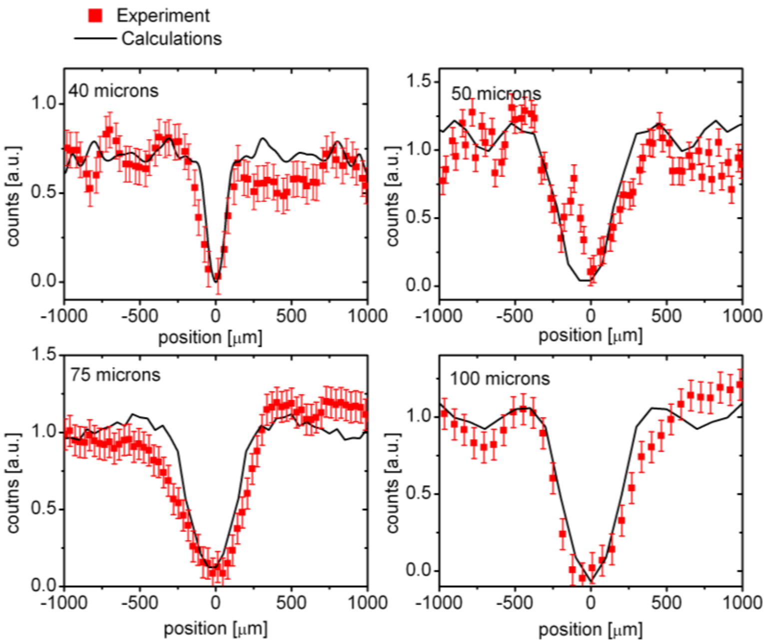
$\delta \approx 10^{-6}$ and $\beta \approx 10^{-9}$ for hard X-rays

Small spatial variation in the refractive index detectable: suitable for soft tissue

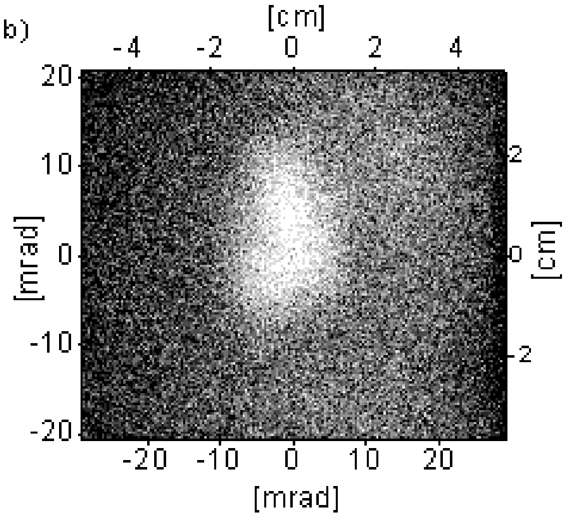
Betatron Radiation: phase contrast imaging

Divergence and source size





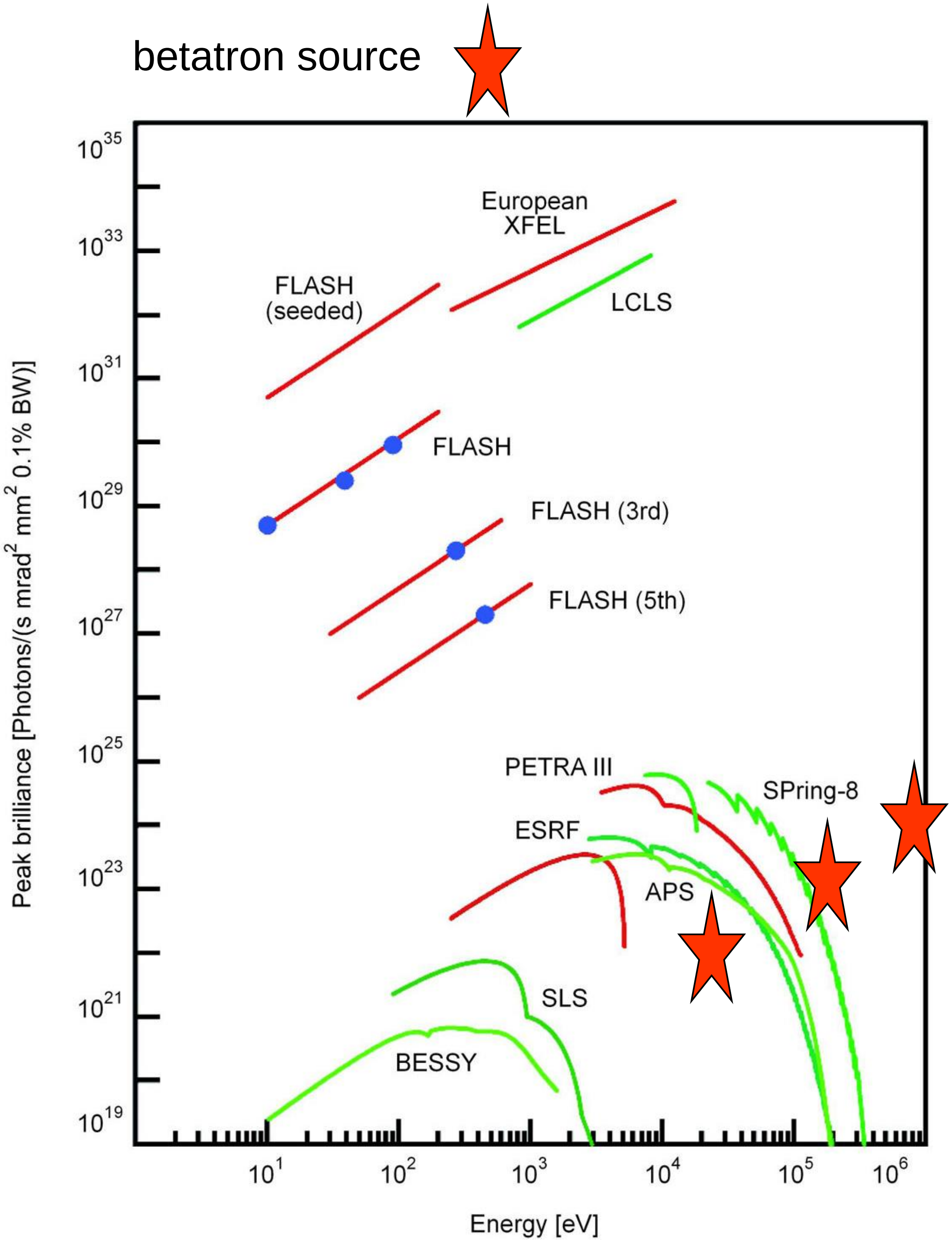
$r_\beta = 7$ μm source size



- divergence ≈14 mrad

Cipiccia et al., Nature Physics, 2011

Peak Brilliance



betatron source

Betatron peak brilliance

10^{22} - 10^{23} photons/s mrad^2 mm^2 0.1% B.W

Laser: 18 J, $a_0 = 4$

10^{24} photons/s mrad^2 mm^2 0.1% B.W

Note that this figures shows the peak brilliance and **not** the average brilliance, which is important in utilising the sources. The average brilliance depends on the repetition rate, which is currently **very low for laser-driven sources**.

Scaling the photon energy

Current:

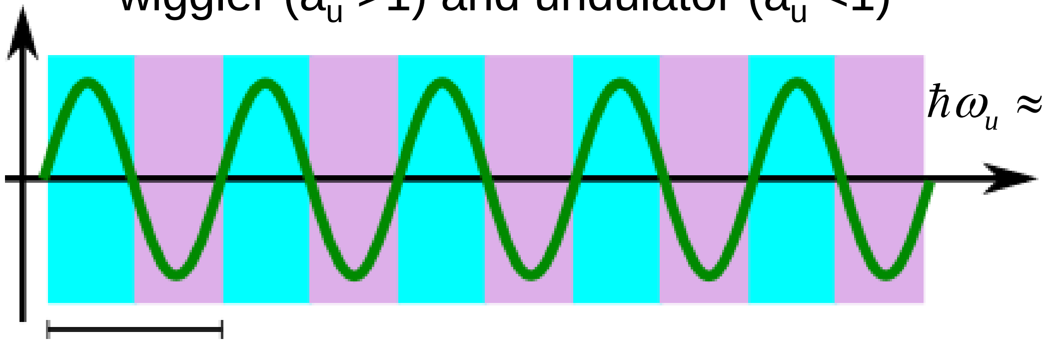
- Laser Energy: 4-5 J
- Pulse length: 50-60 fs
- Initial a_0: 2
- E_c = 10 – 150 keV
- No. photons/shot: >3 x 10^{10}

Bigger laser:

- Laser: 18 J, $a_0 = 4$
- Max electron energy : 1.5 GeV
- Electron beam charge: 300 pC
- N photon/shot 5-25 MeV = $6x10^8$
- Max repetition rate: 10 Hz
- 10^{10} 10 MeV photons per second:
- 10 mW of 10 MeV photons

Summary – radiation sources

wiggler (a_u >1) and undulator (a_u <1)



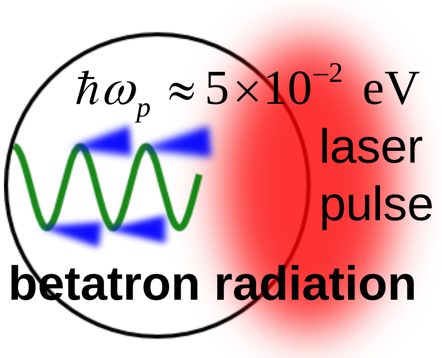
$\hbar\omega_u \approx 10^{-4}$ eV

λ_u : mm to cm; γ: 10^3 – 10^4; $\hbar\omega$: up to 100’s keV

$$\lambda = \frac{\lambda_w}{2\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2)$$

$$N_{phot/cycle} \approx .015\, a_{\beta,0}^2 \text{ for } a_{\beta,0} < 1$$

$$N_{phot/cycle} \approx .033\, a_{\beta,0} \text{ for } a_{\beta,0} > 1$$



$\hbar\omega_p \approx 5\times10^{-2}$ eV

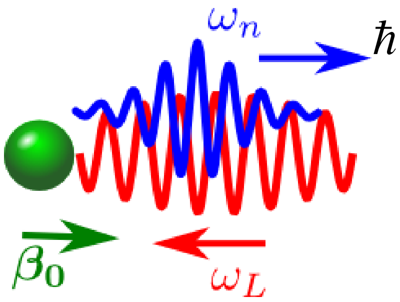
betatron radiation

$$\lambda_\beta = \sqrt{2\gamma}\lambda_p$$

$$\hbar\omega \approx 1.4\hbar\omega_p\gamma^{3/2} \text{when } a_\beta < 1 \text{ (10 keV)}$$

$$\hbar\omega_c \approx \hbar\omega_p\gamma^{3/2}a_\beta \text{ when } a_\beta >> 1 \text{ (10 MeV)}$$

- Max: $\gamma \approx 10^4$ (5 GeV)
- Undulator: <10 keV
- Wiggler: <100 keV
- Betatron: <20 MeV
- Thomson: <400 MeV
- Compton: Linear and nonlinear < 5 GeV



$\hbar\omega_0 \approx 1$ eV

$$\hbar\omega \approx 4\hbar\omega_0\gamma^2 \text{when } a_0 < 1 \text{ (4 - 400 MeV)}$$

$$\hbar\omega_c \approx 3\hbar\omega_0\gamma^2 a_0 \text{ when } a_0 >> 1 \text{ (< 1 GeV - nonlinear Compton)}$$

Thomson/Compton back-scattering