Laser driven plasma wakefield accelerators and radiation sources

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Outline of talk

- Large and small accelerators + high power lasers
- Laser driven wakes
- Ultra-short bunch electron production using wakefield accelerators
- Betatron gamma ray source
- Initial FEL experiments
- Conclusion

Plasma Replaces RF Cavities

Small Scale Source = Big Applications

The future of electron accelerators

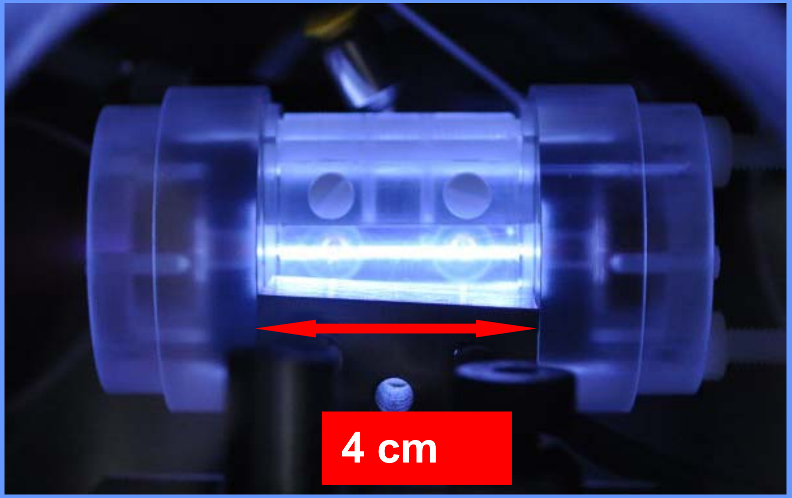
High energy electron beams in few mm

…..

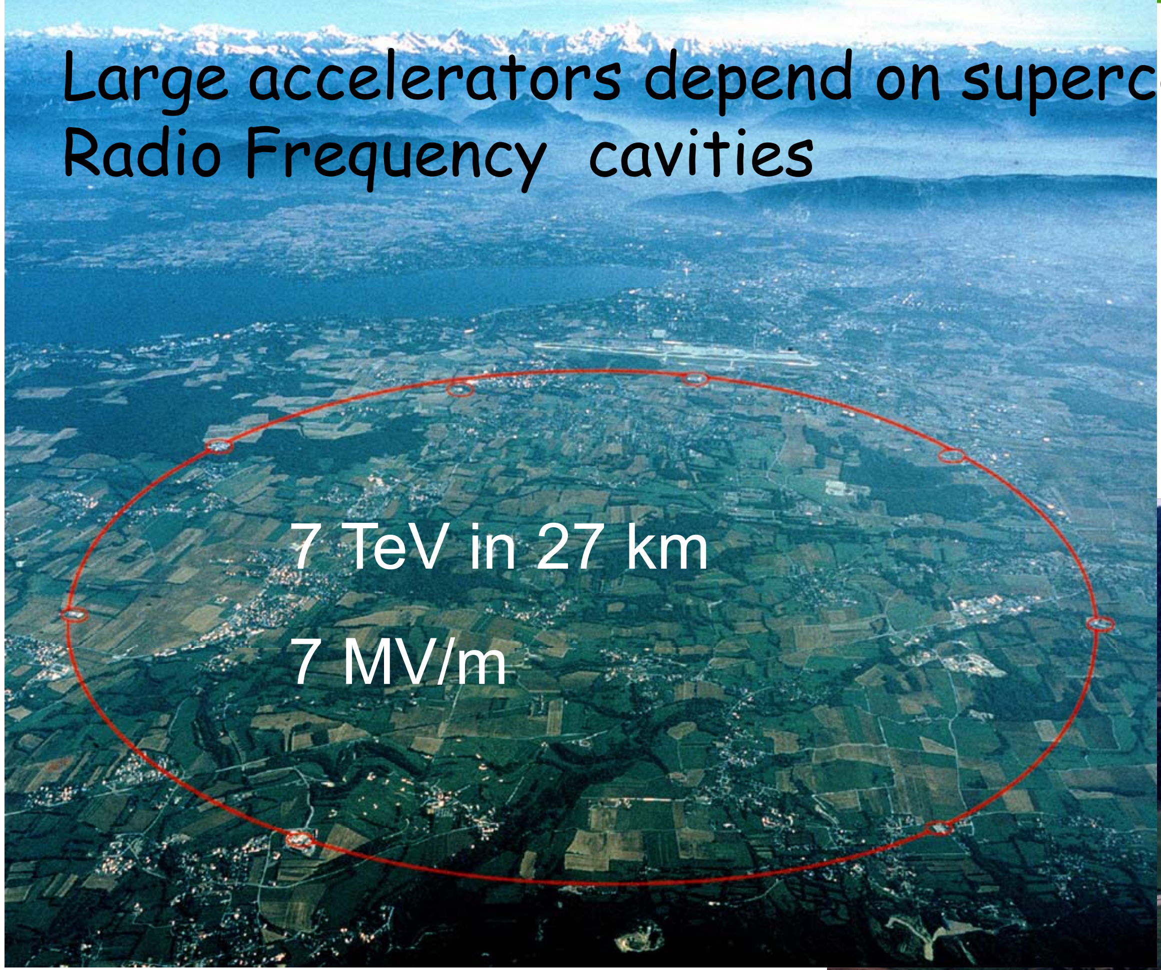
an industrial revolution?

Electrons energy:

50MeV - 1GeV



Large accelerators depend on superconducting Radio Frequency cavities

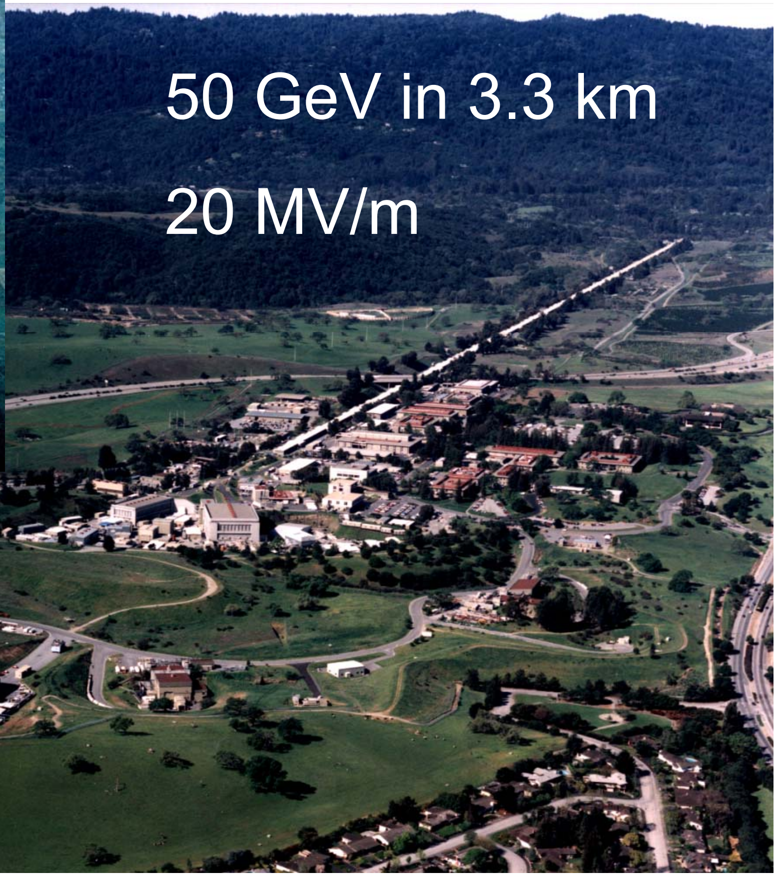


7 TeV in 27 km

7 MV/m

CERN – LHC
27 km
circumference

SLAC

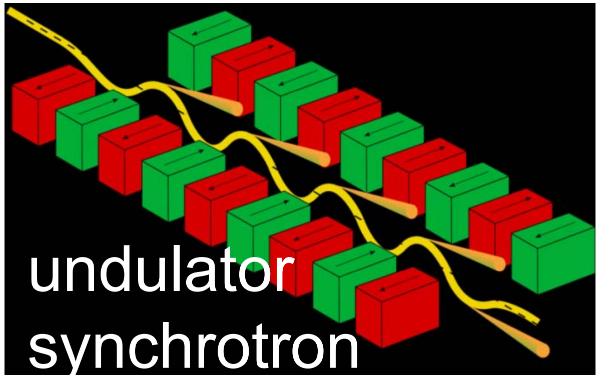


50 GeV in 3.3 km

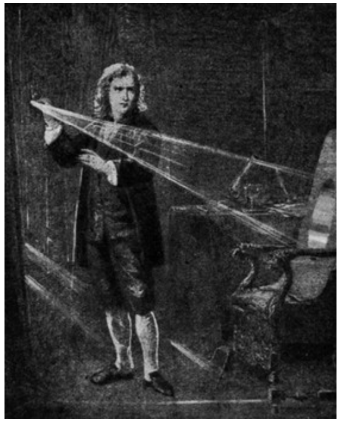
20 MV/m

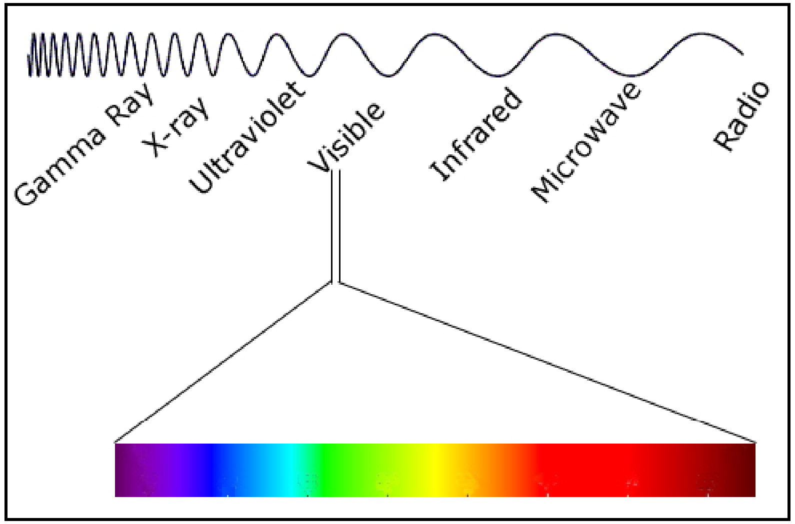
Synchrotrons light sources and free-electron lasers: tools for scientists

Synchrotron – huge size and cost is determined by accelerator technology

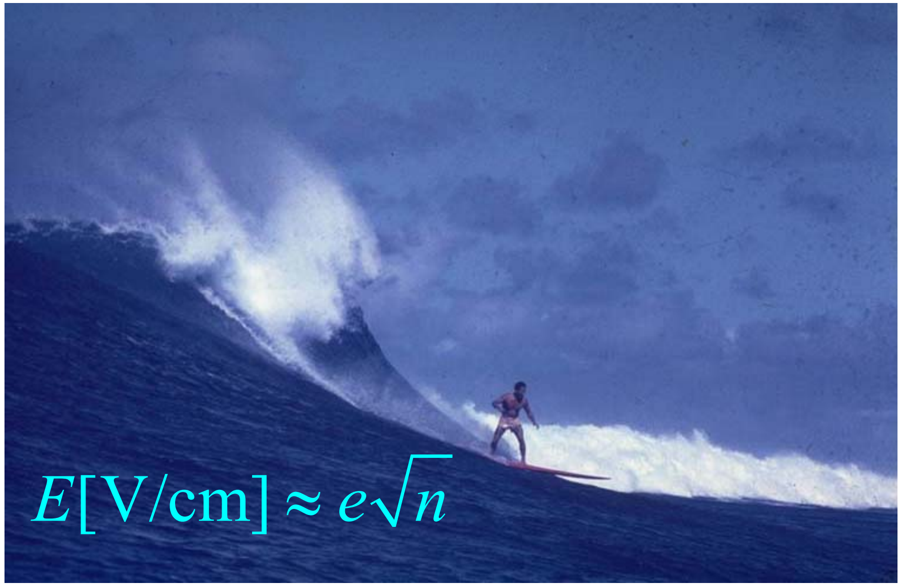


DESY undulator





Particles accelerated by electrostatic fields of plasma waves



$$\gamma_{\max} \approx \frac{2\gamma_g^2 a}{3}$$

Accelerators:

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

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

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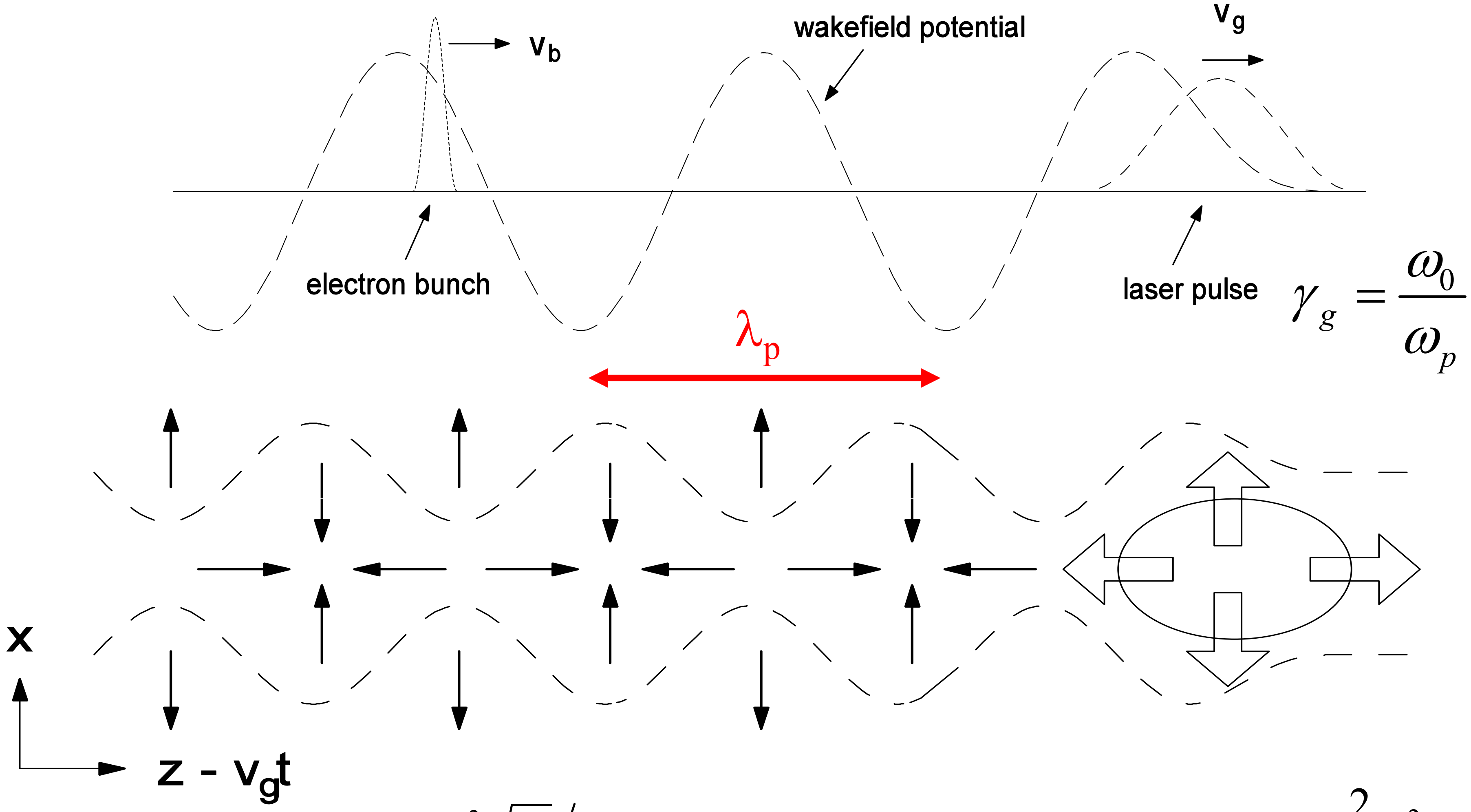
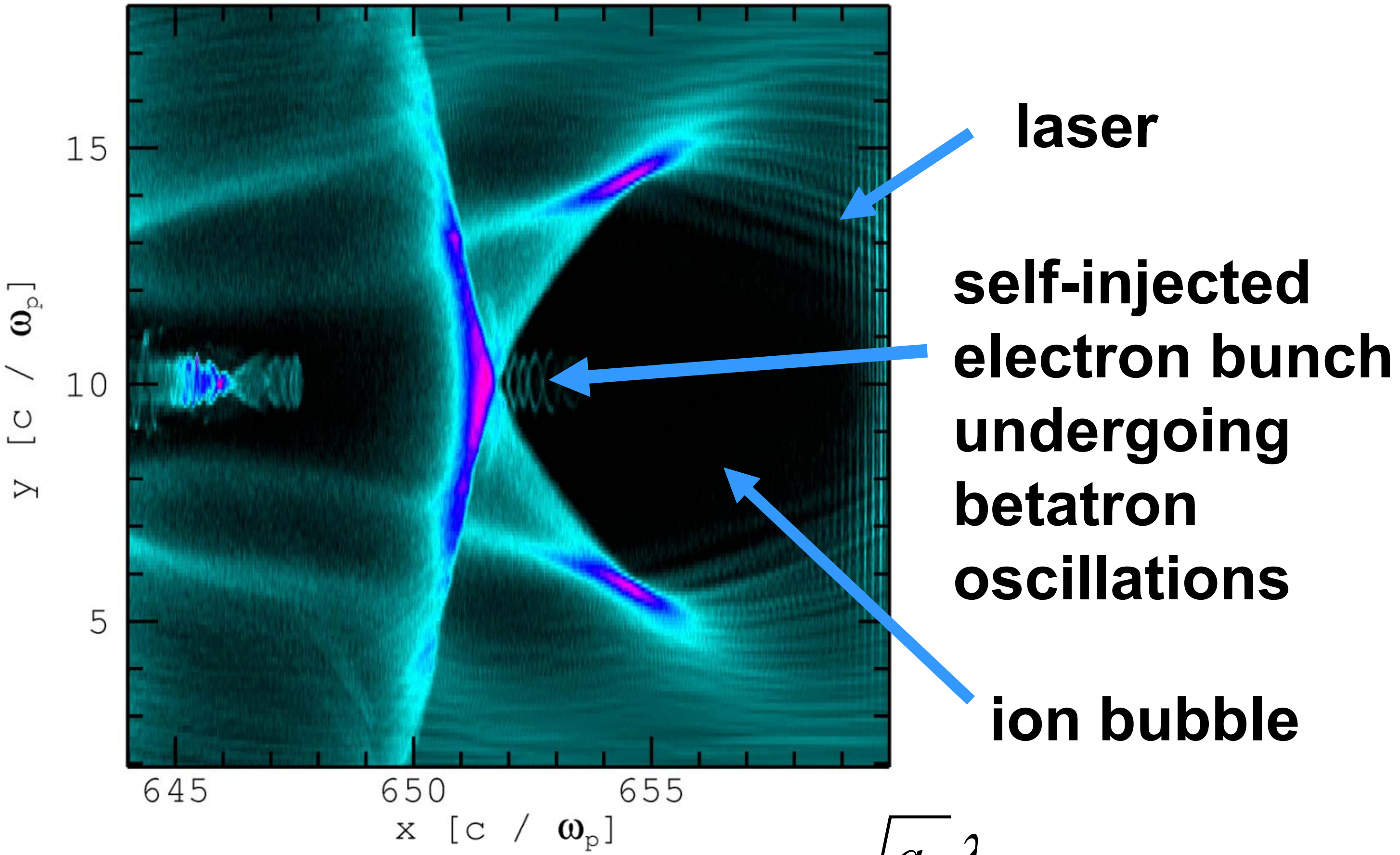
Wakefield acceleration



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

Dephasing length: $L_d = 4c\gamma_g^2\sqrt{a_0}/3\omega_p$, which gives a maximum energy: $\gamma \approx \frac{2}{3}\gamma_g^2 a_0$

Bubble structure - relativistic regime



laser

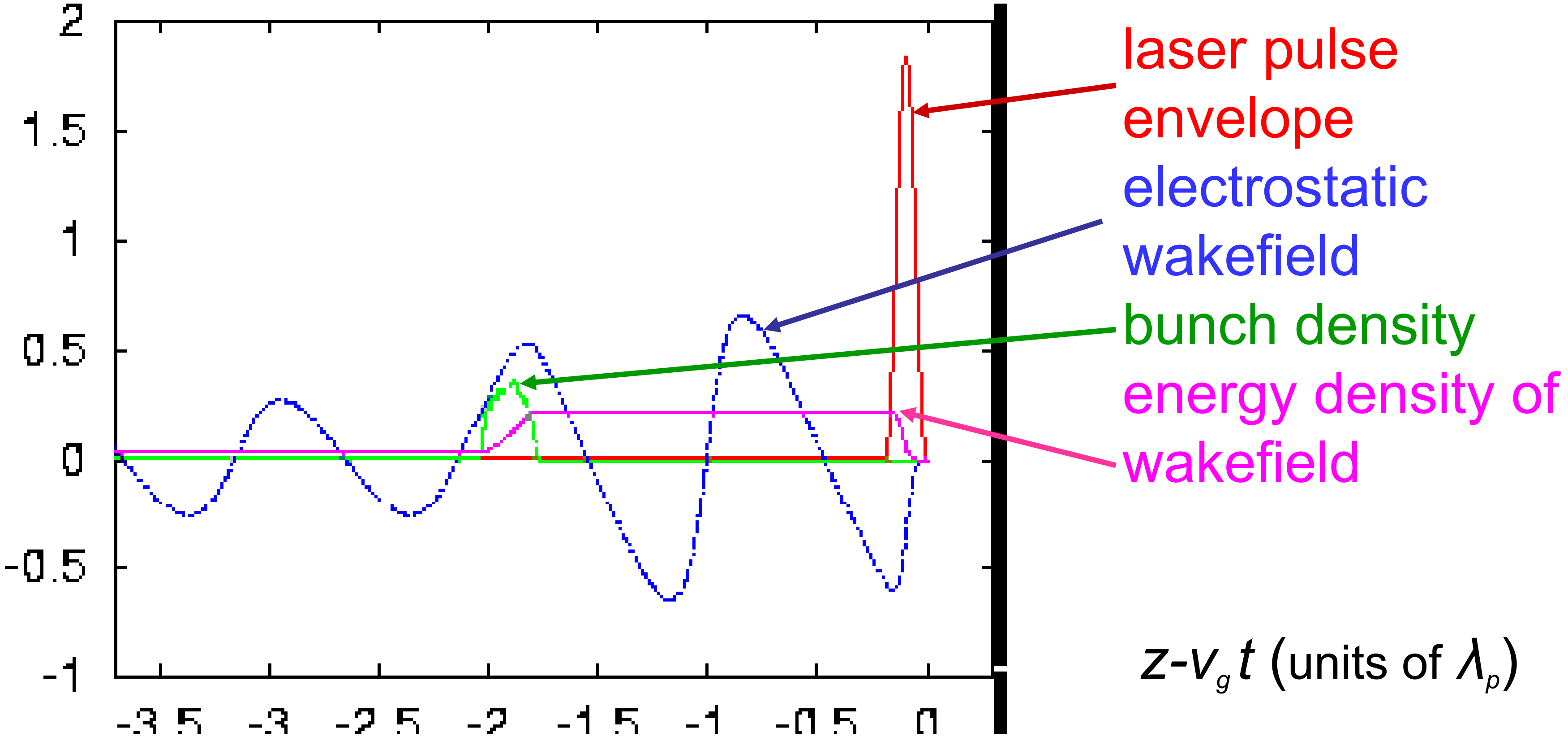
self-injected electron bunch undergoing betatron oscillations

ion bubble

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

Modelling of Laser Wakefield Acceleration

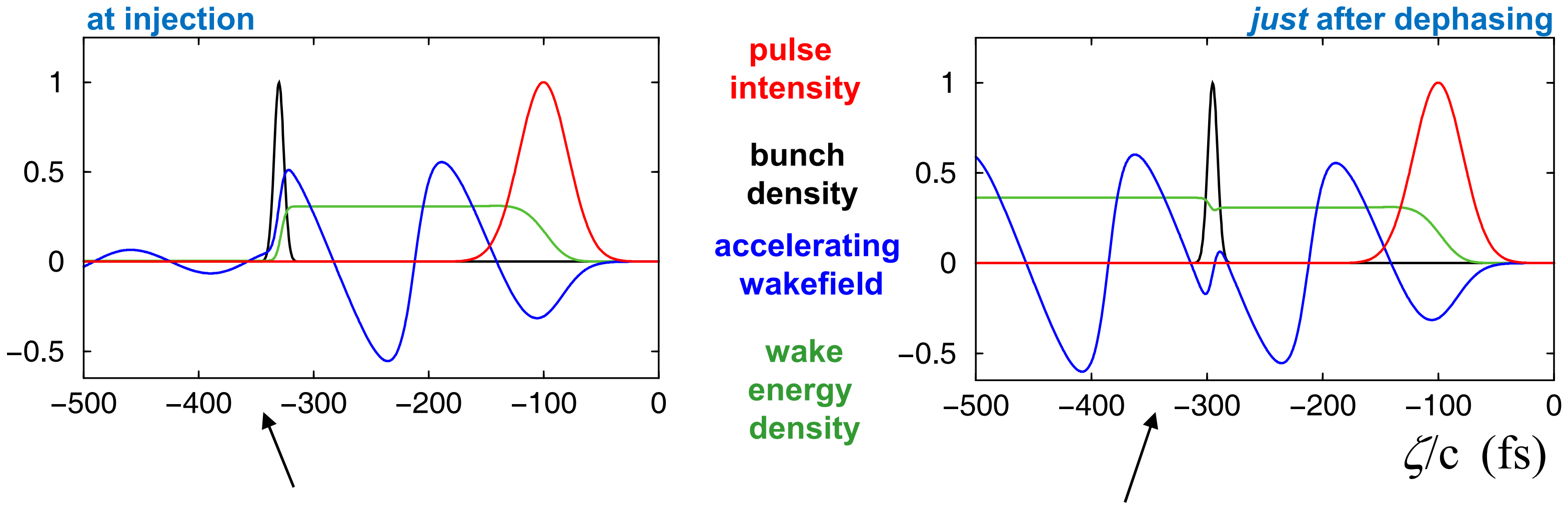
Strathclyde



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

Efficiency and beam loading

- Effect of bunch wakefield = beam loading
- important for wake-to-bunch energy transfer
- finite charge required for energy absorption from the wakefield



at injection

***just* after dephasing**

ideal (almost 100%) conversion of wake energy into bunch energy

all electrons accelerated

wakefield cancels at rear part of bunch

→ bunch slips out of ideal position

→ large spread of accelerating field induces large energy spread

slight loss of energy from bunch to wake

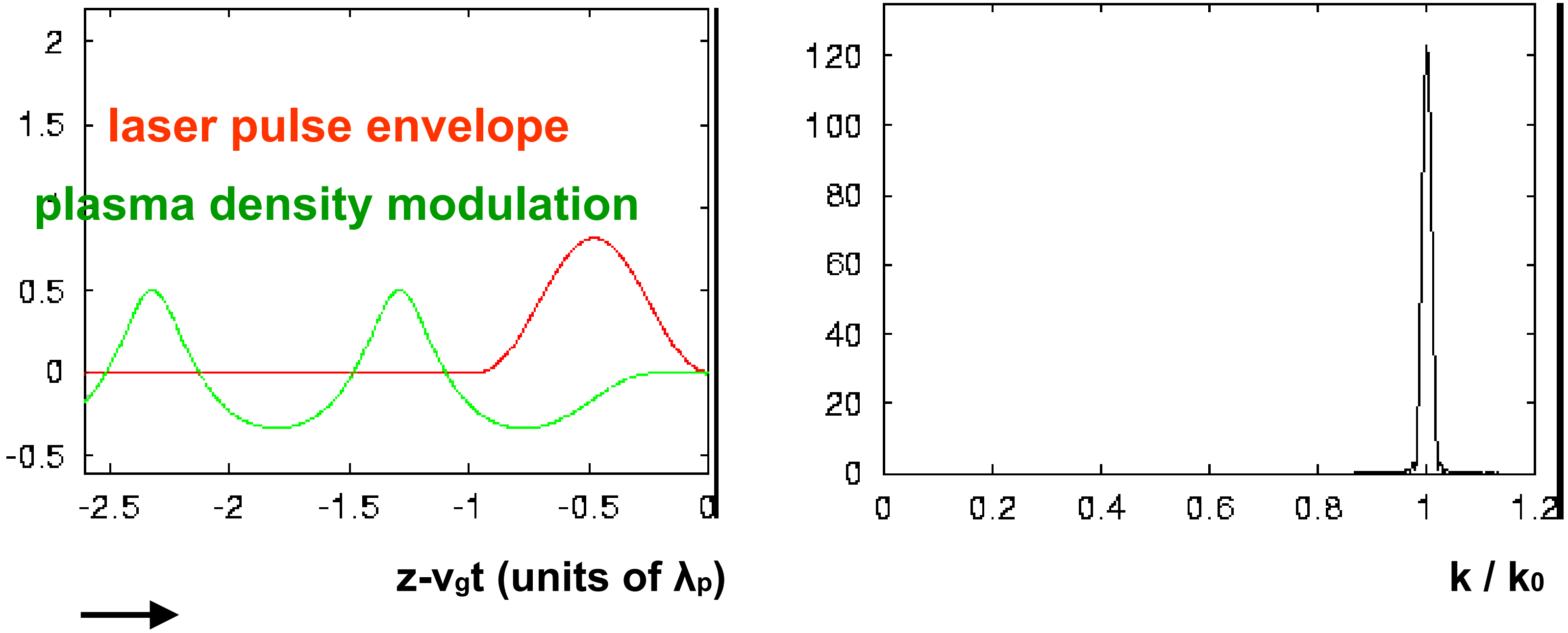
most electrons decelerated

complicated structure of accelerating field along electron bunch

Laser pulse envelope dynamics

laser pulse amplitude: a_0

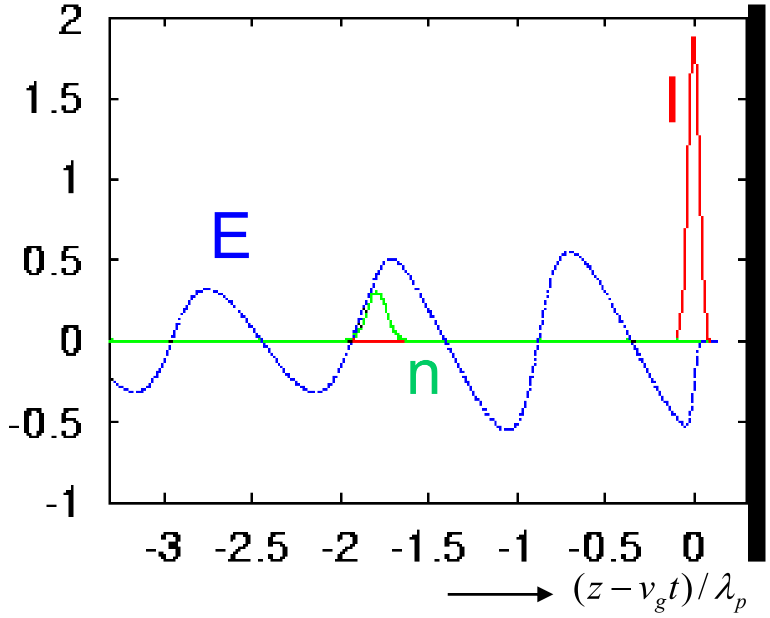
laser pulse energy depletion rate: $\omega_d \sim a_0^2\, \omega_s$



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

Example



- 1-D simulation of acceleration of electron bunch in a plasma wave
- movie taken in frame that moves with (front of) laser pulse
- laser pulse intensity I red
- electron bunch density n green
- electrostatic wakefield E blue

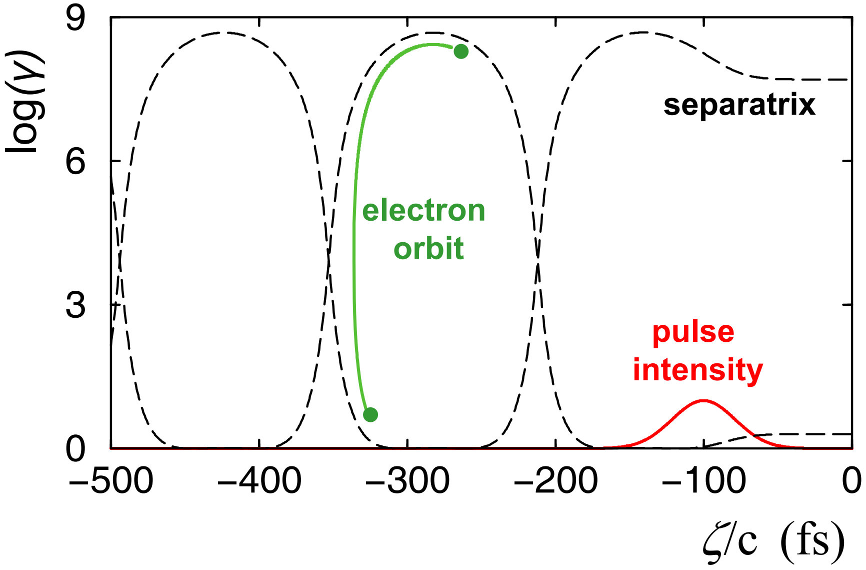
Movie shows

- laser pulse deforms as it transfers energy to the plasma and sets up wakefield
- wakefield changes as a result of laser pulse deformation
- electron bunch modifies wakefield as it takes energy from the plasma
- electron bunch slips from a region of E>0 to E<0 and reaches max. energy

Electron acceleration

- energy gain limited by *dephasing*, caused by difference

  between velocities of electron and wakefield $v_{el} \approx c > v_{wf} \approx v_g$
- *scaling* $\Delta\gamma \propto E \times L_{deph} \propto n_p^{1/2} n_p^{-3/2} \propto n_p^{-1}$ favours low plasma density

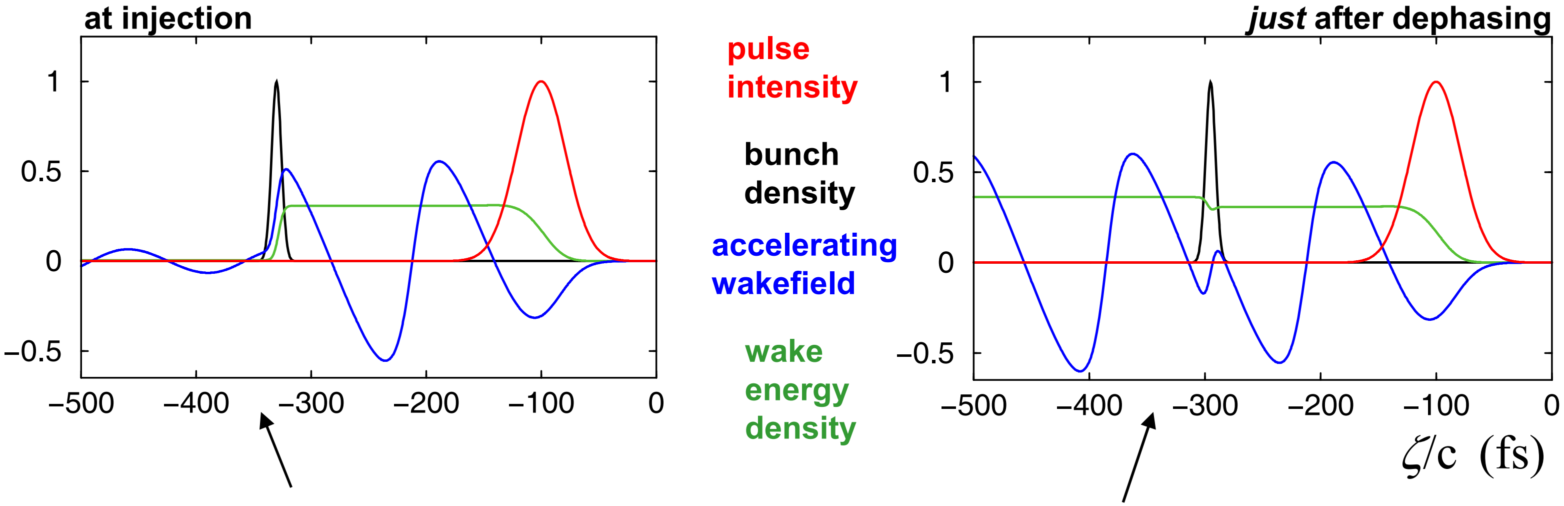


note logarithmic energy scale

Efficiency

effect of bunch wakefield = beam loading

- central to wake-to-bunch energy transfer,
- finite charge required for energy absorption from the wakefield



- ideal (almost 100%) conversion of wake energy into bunch energy
- all electrons accelerated
- wakefield to 0 at rear part of bunch

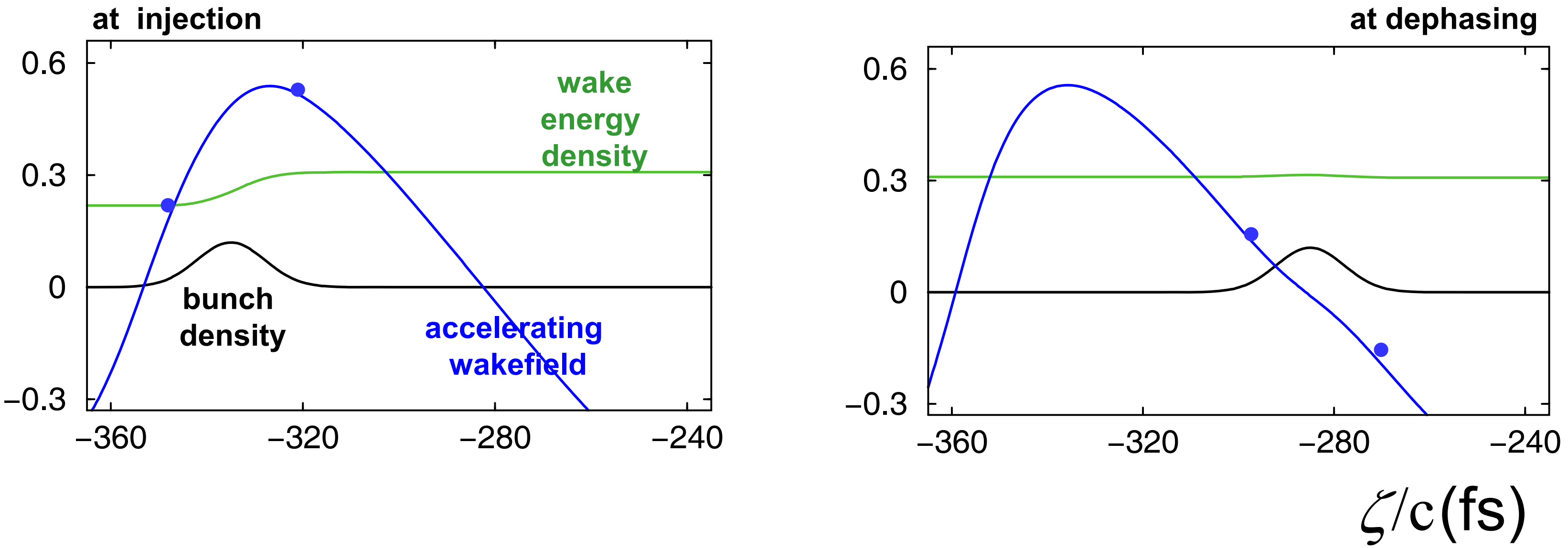
→ bunch slips out of ideal position

→ large spread of accelerating field induces large energy spread

- slight loss of energy from bunch to wake
- most electrons decelerated
- complicated structure of accelerating field along electron bunch

Energy spread

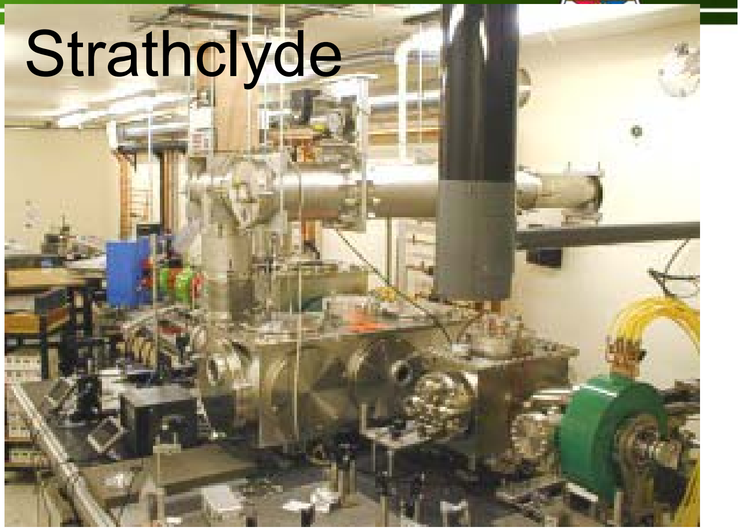
- energy spread induced by spatial variation of accelerating field along bunch
- can be compensated for by combined effect of dephasing and beam loading
- requires precise tuning of injection phase, bunch charge and bunch length



- during first half of acceleration, front of bunch gains more energy than rear
  → energy spread increases
- during second half of acceleration, rear of bunch gains more energy than front
  → energy spread decreases and reaches minimum

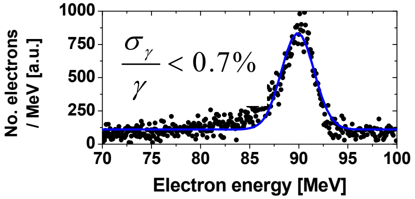
ALPHA-X Advanced Laser Plasma High-energy Accelerators towards X-rays

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

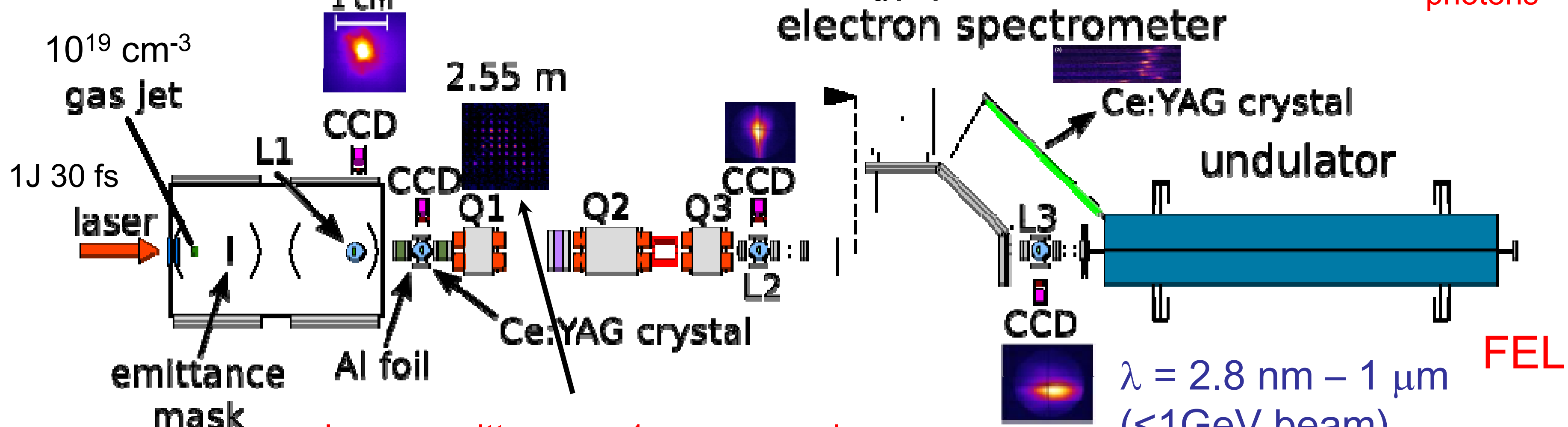

Strathclyde

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)

FEL

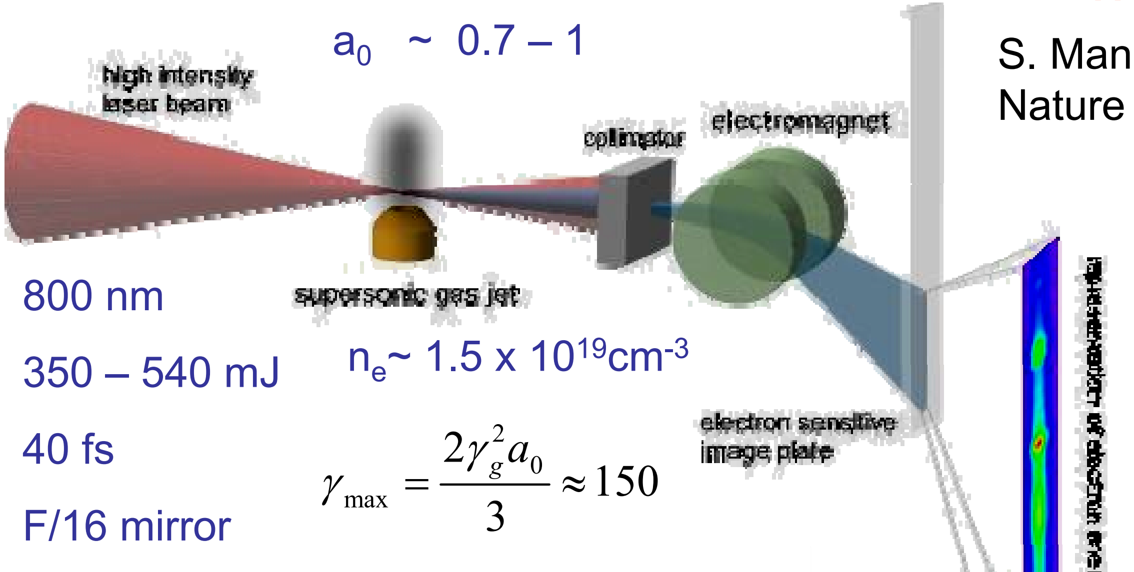
Brilliant particle source: 10 MeV → GeV, kA peak current, fs duration

ALPHA-X all-optical injection experiments on ASTRA

ALPHA-X: Imperial/RAL/Strathclyde

10^{18} Wcm^{-2} in 25 mm spot

$a_0 \sim 0.7 – 1$



800 nm

350 – 540 mJ

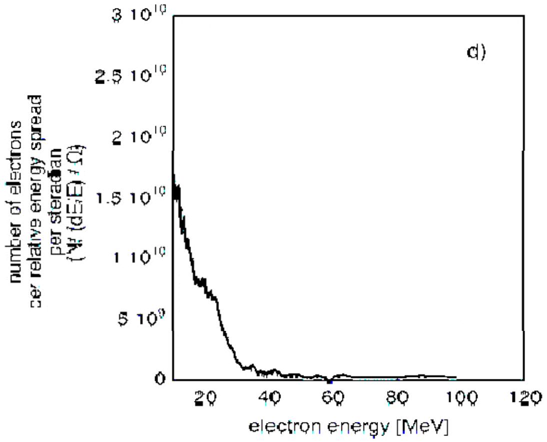
40 fs

F/16 mirror

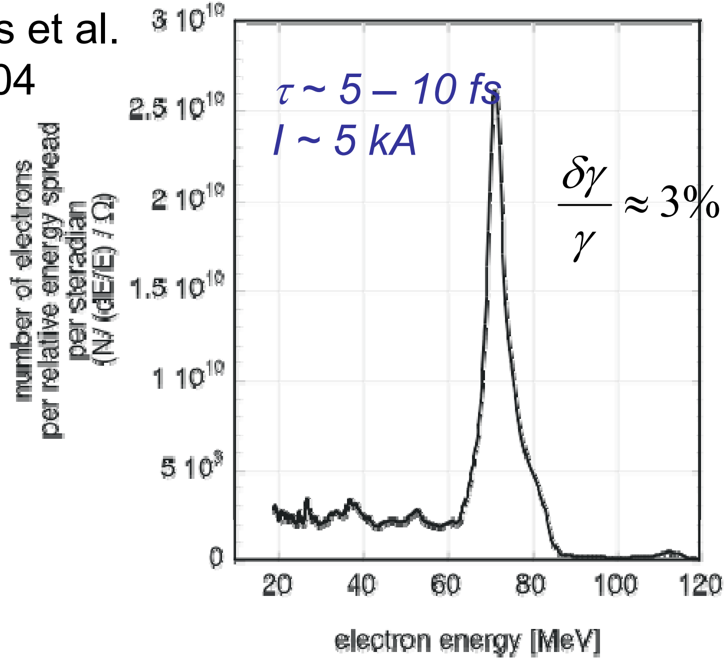
$\gamma_g \approx 10$

$n_e \sim 1.5 \times 10^{19}$cm^{-3}

$$\gamma_{\max} = \frac{2\gamma_g^2 a_0}{3} \approx 150$$



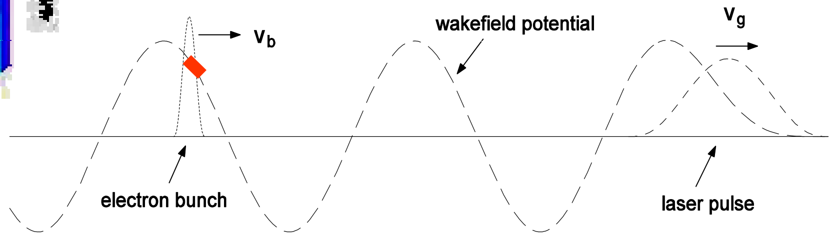
S. Mangles et al. Nature 2004



$\tau \sim 5 – 10$ fs

$I \sim 5$ kA

$$\frac{\delta\gamma}{\gamma} \approx 3\%$$

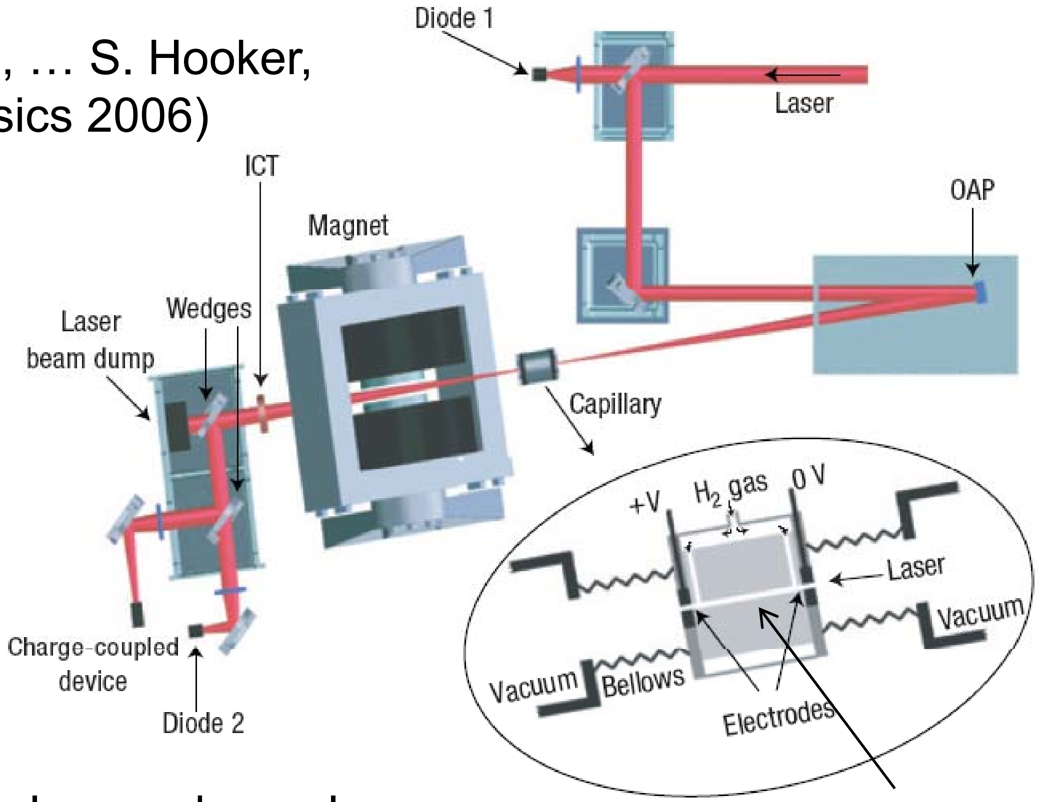


Few fs duration electron bunch

LBNL - Oxford campaign (ALPHA-X) team: GeV beams from capillary

W. Leemans, … S. Hooker,
(Nature Physics 2006)

ALPHA-X:
Oxford &
Berkeley

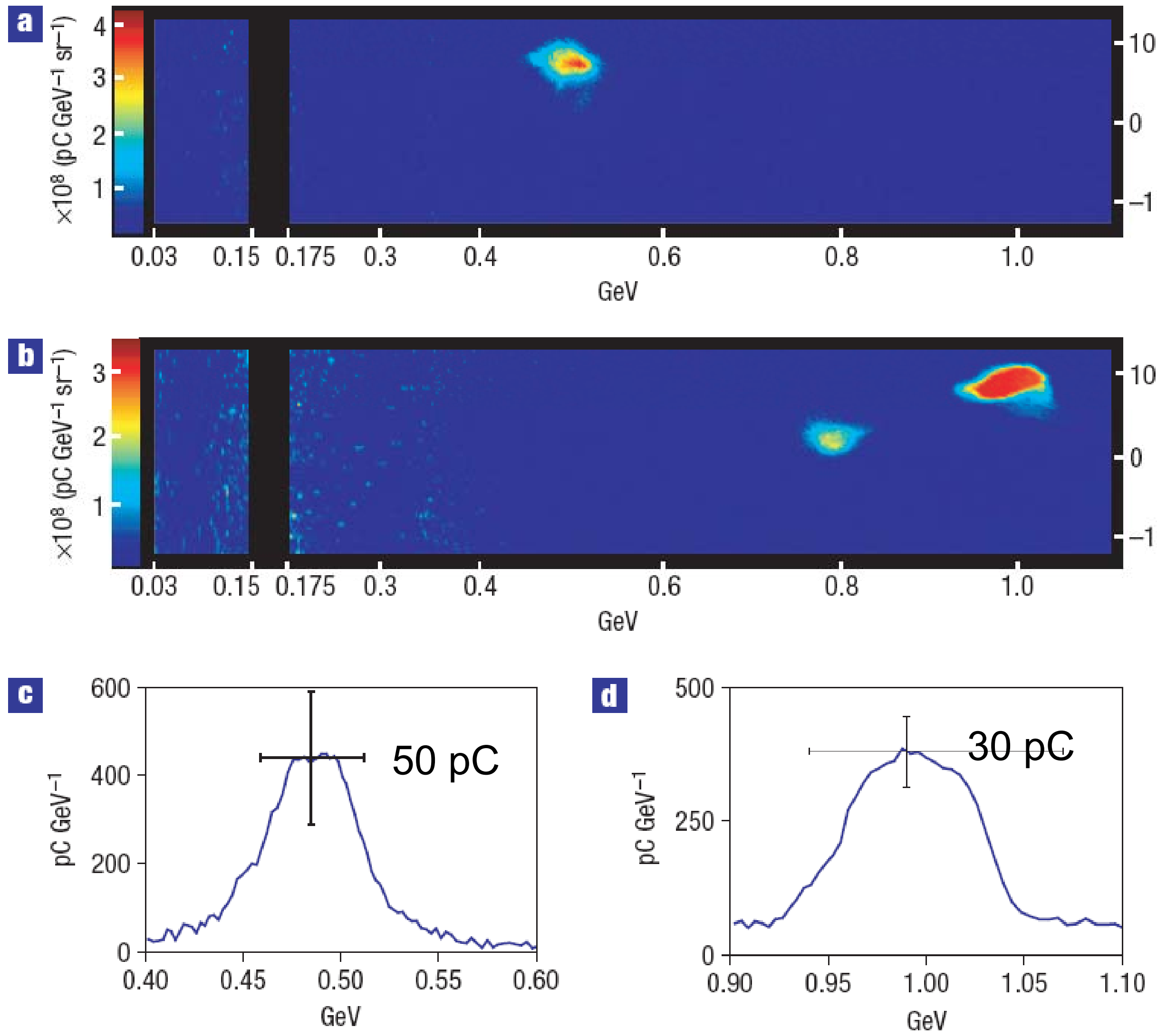


Pre-formed plasma channels – Spence & Hooker (PRE 2001)

Channels manufactured using laser machining techniques – Jaroszynski et al., (Royal Society Transactions, 2006)

1 GeV beams

ALPHA-X: Oxford & Berkeley



W. Leemans, … S Hooker, (Nature Physics 2006)

Acceleration to 1 GeV in 33 mm long pre-formed plasma channels

5% shot-to-shot fluctuations in mean energy

E = 0.48 GeV±6% and an r.m.s. spread <5%.

12TW (73fs) - 18TW (40fs)

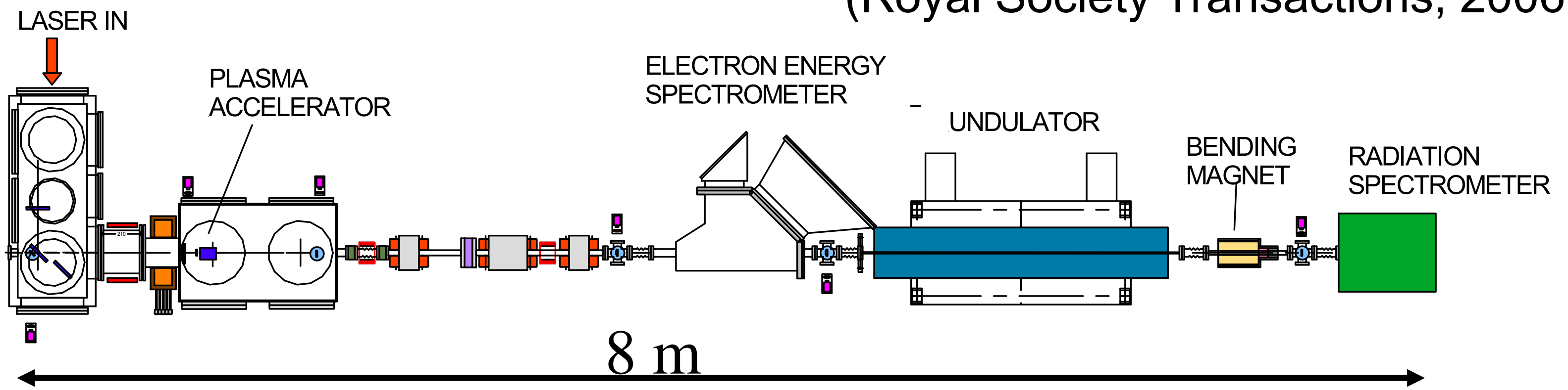
E = (0.50 +/-0.02) GeV
ΔE = 5.6% r.m.s
$\Delta\theta$ = 2.0 mrad r.m.s.
Q = 50 pC
Laser ~ 1 J
$\gamma_g \approx 30$

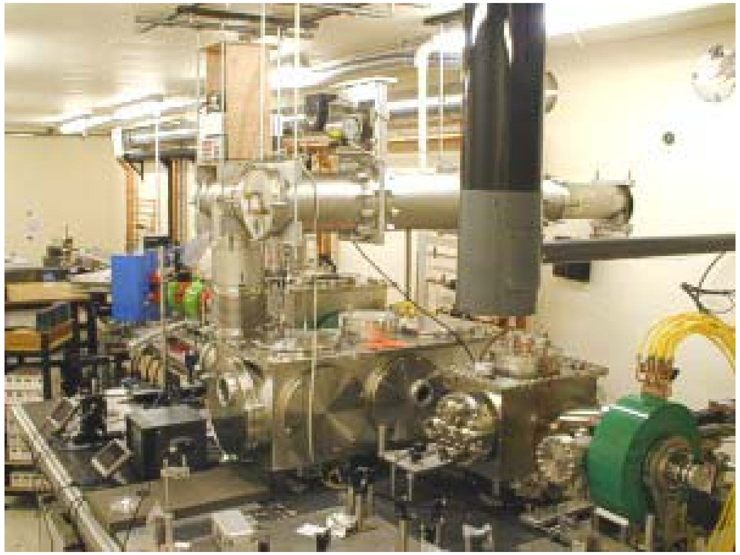
$$\gamma_{\max} = \frac{2\gamma_g^2 a_0}{3} \approx 2000$$

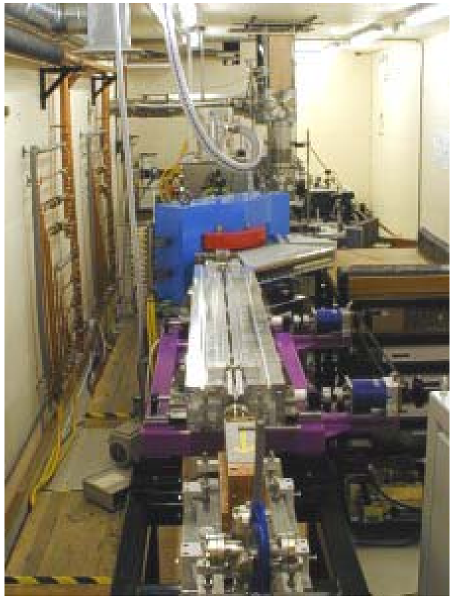
Strathclyde: ALPHA-X beam line

TOPS laser:
1 J @ 10 Hz
λ = 800 nm
30 fs

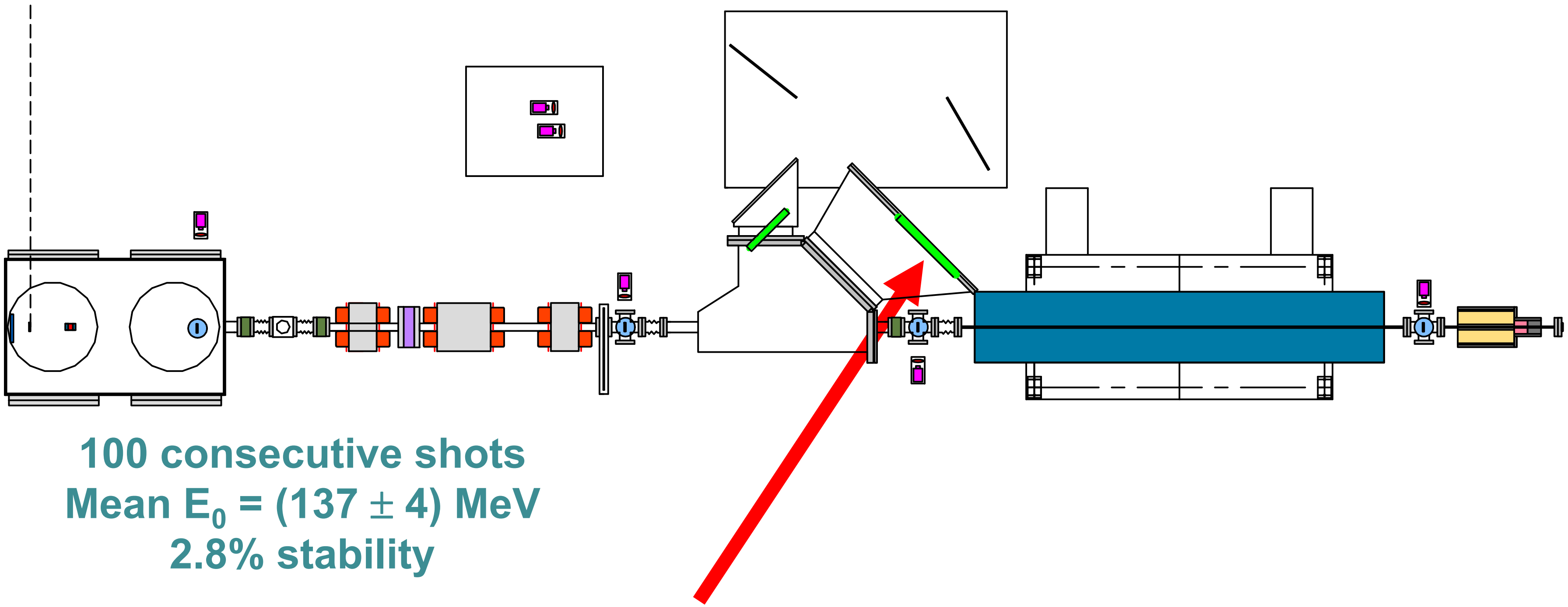
Jaroszynski et al.,
(Royal Society Transactions, 2006)





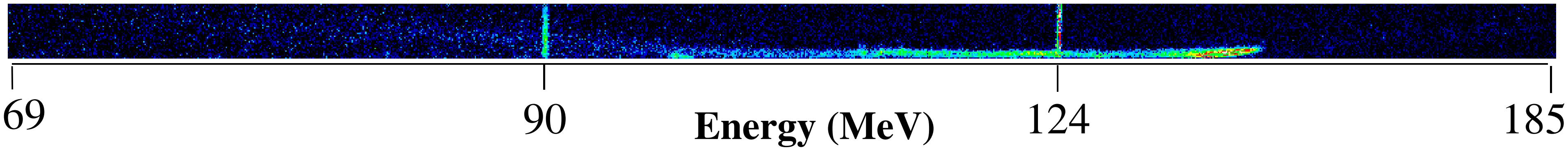


Experimental Results – energy stability



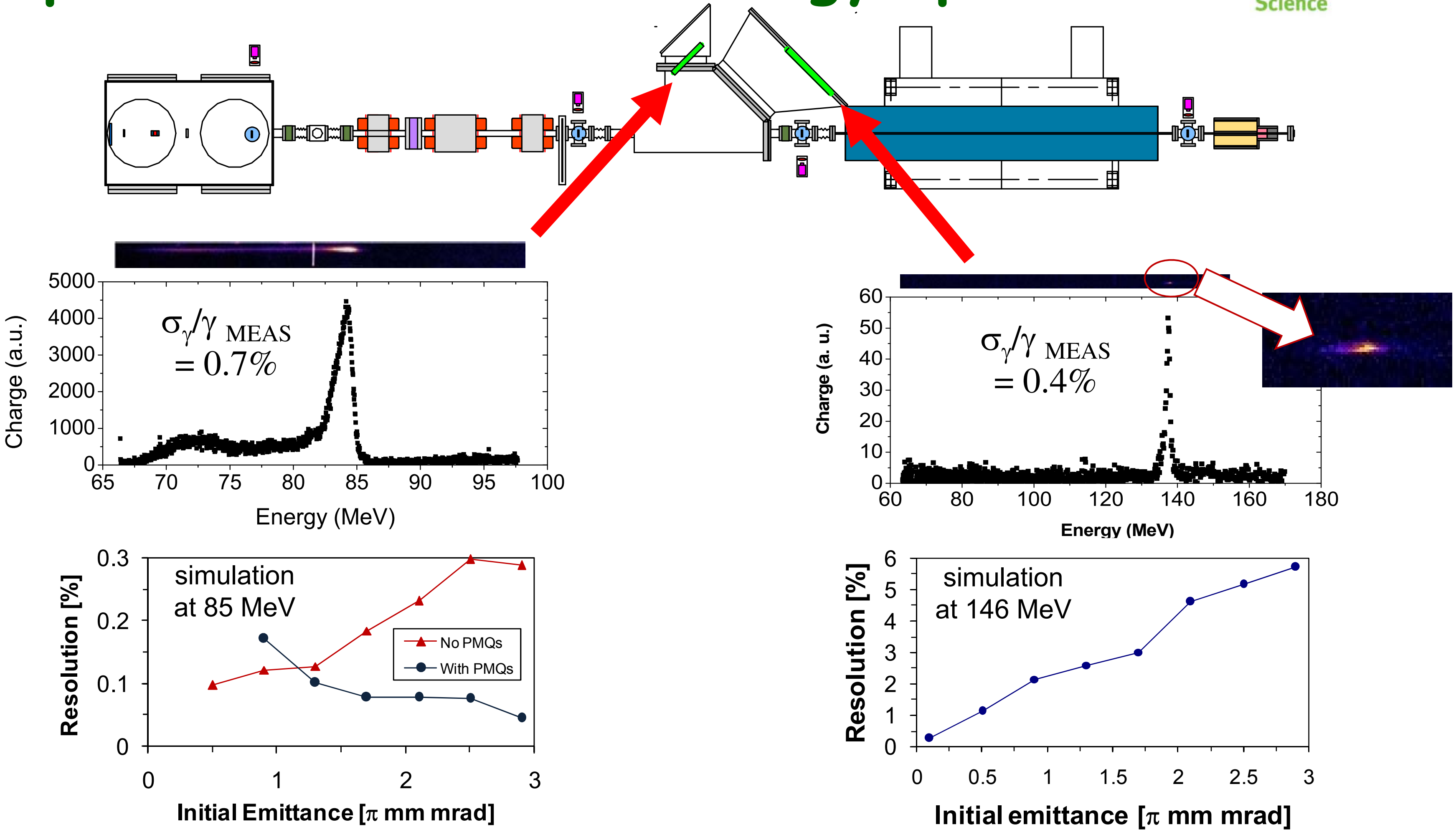
100 consecutive shots
Mean E_0 = (137 ± 4) MeV
2.8% stability

Electron Spectrometer: 200 consecutive shots (spectrum on 196 shots)



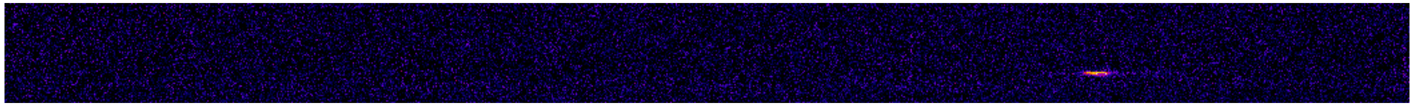
Highest energy achievable at Strathclyde: 360 MeV in 2 mm

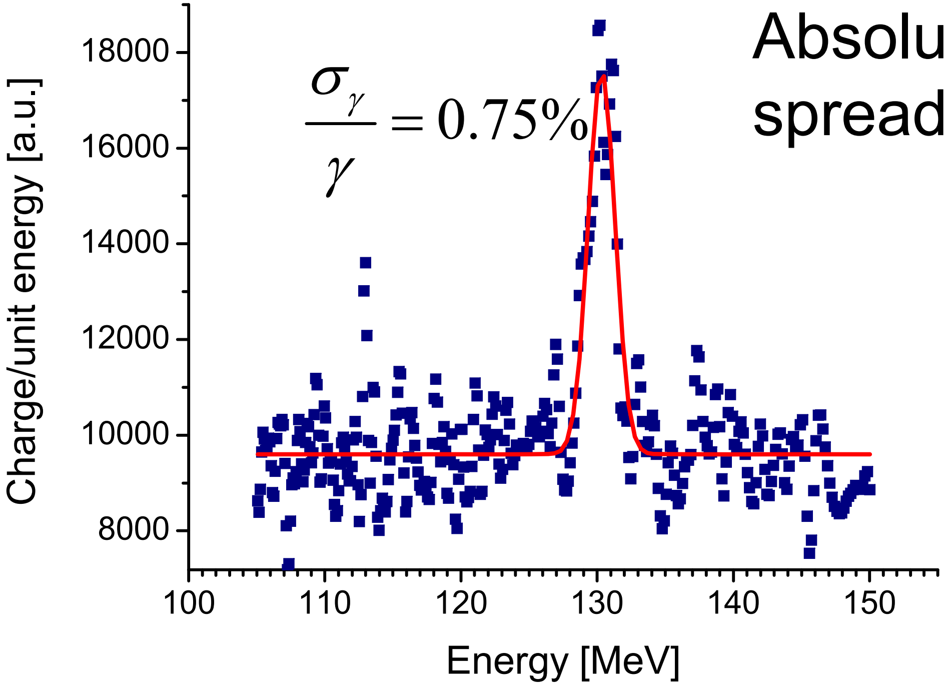
Experimental Results – energy spectra III



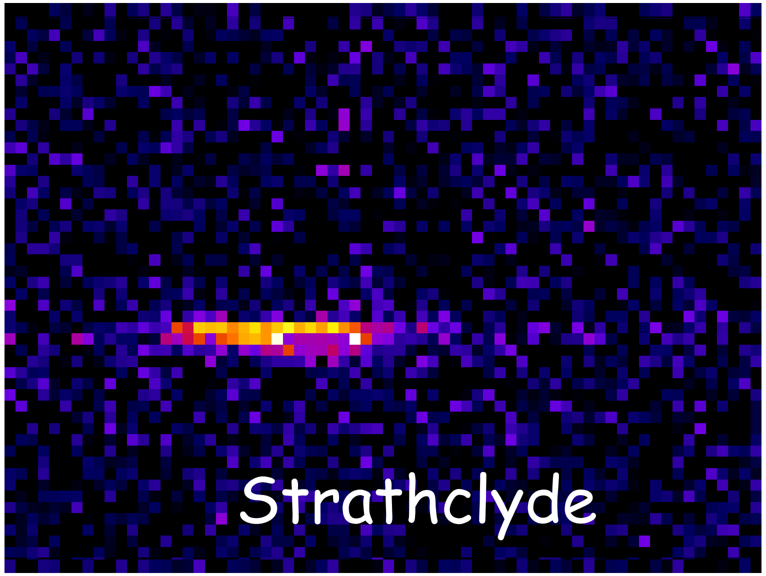
- Indicates fixed absolute energy spread ~ 600 KeV

Narrow energy spread beams





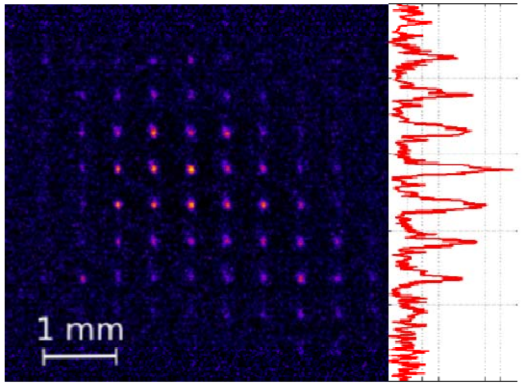
Absolute energy spread < 600 keV



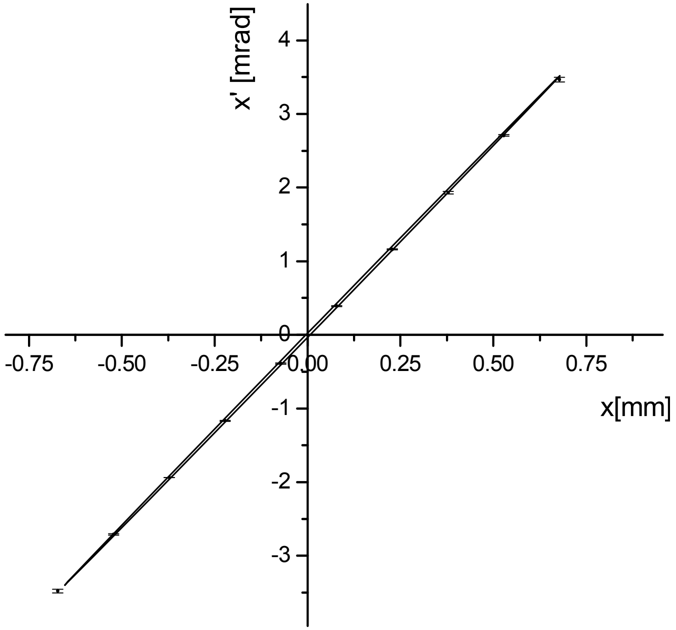
Maximum energy obtained in 2 mm = 360 MeV

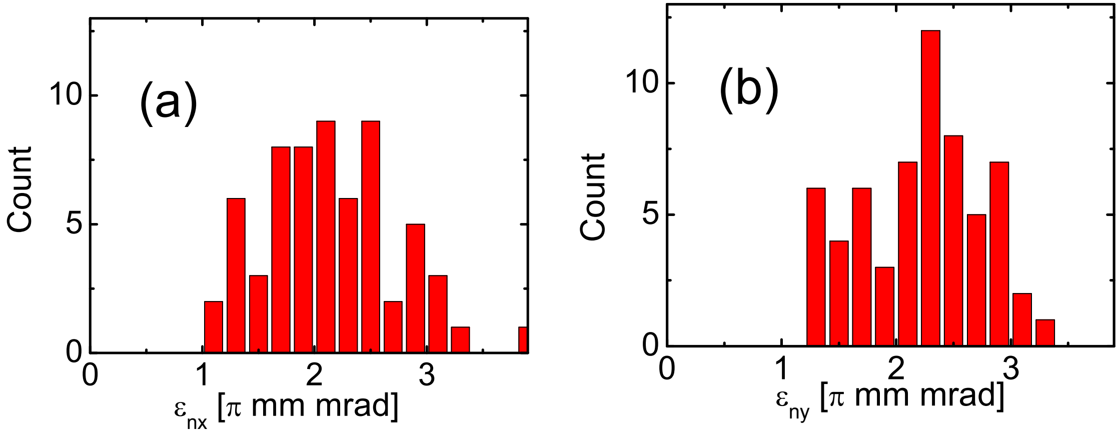
Experimental Results – emittance

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

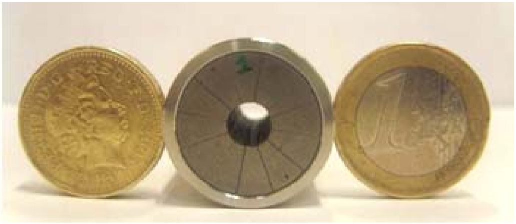


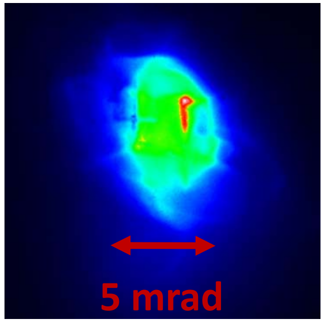
- divergence 1 – 2 mrad for this run with 125 MeV electrons
- average $\varepsilon_N = (2.2 \pm 0.7)\pi$ mm mrad
- best $\varepsilon_N = (1.0 \pm 0.1)\pi$ mm mrad
- Elliptical beam: $\varepsilon_{N,X} > \varepsilon_{N,Y}$
- Upper limit because of resolution

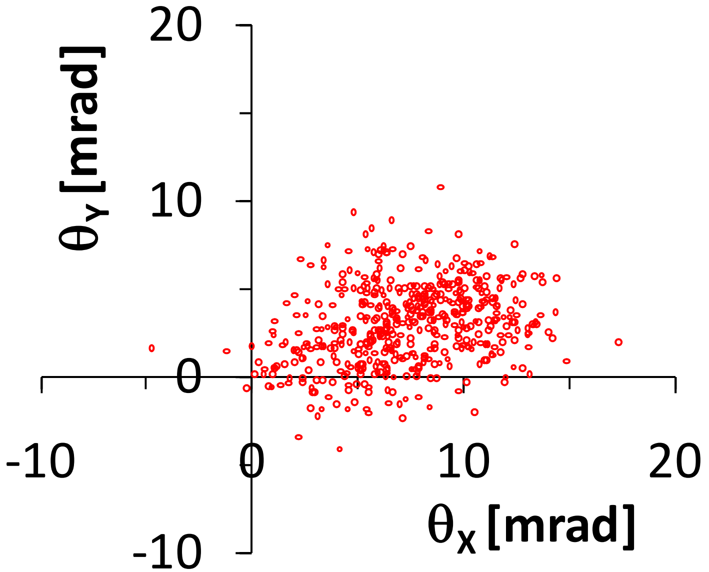




Experimental Results – beam pointing

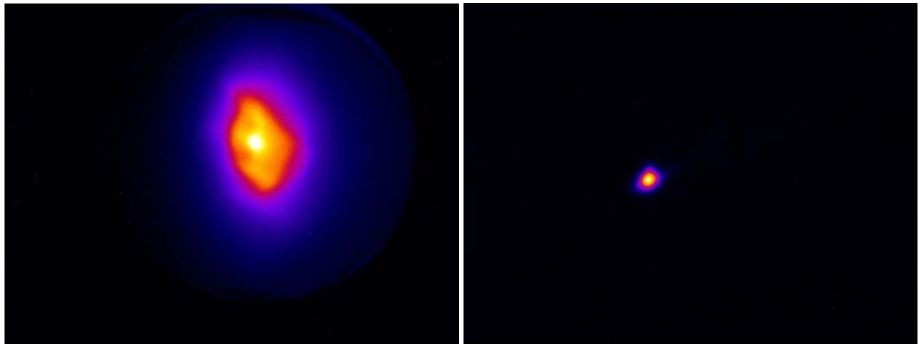




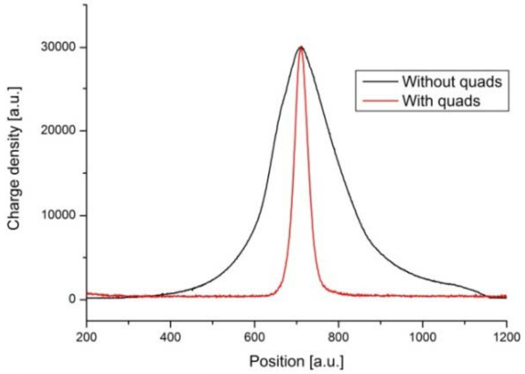


- 500 consecutive shots at Strathclyde
- narrow divergence (~2 mrad) beam
- wide divergence low energy halo
- $\theta_X = (7 \pm 3)$ mrad, $\theta_Y = (3 \pm 2)$ mrad

- 8 mrad acceptance angle for EMQs
- 25% pointing reduction with PMQs installed

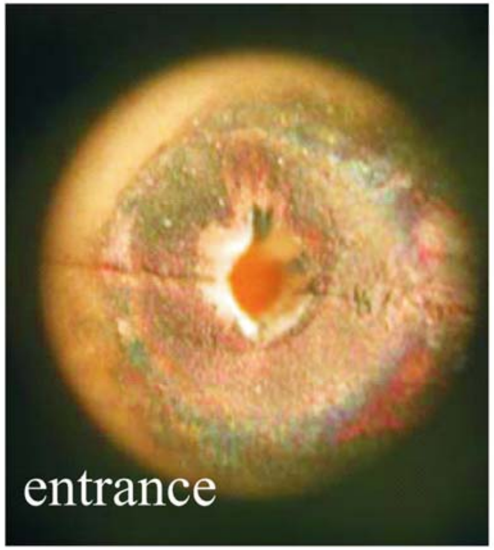


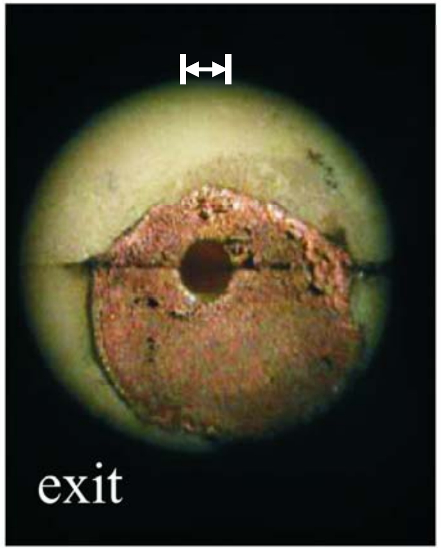
no PMQs PMQs in

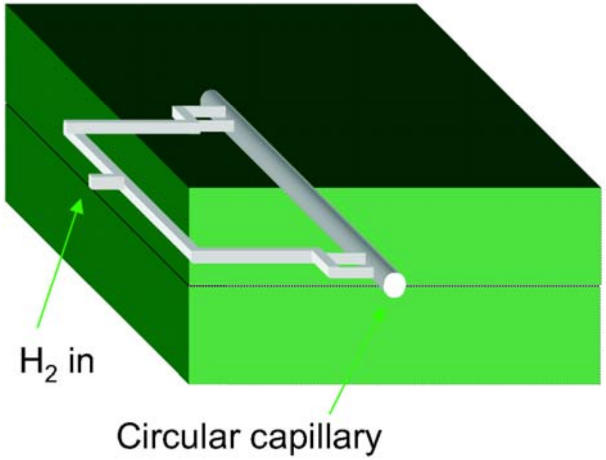


New method of manufacturing plasma capillaries for laser wakefield accelerators

Developed at Strathclyde in 2000





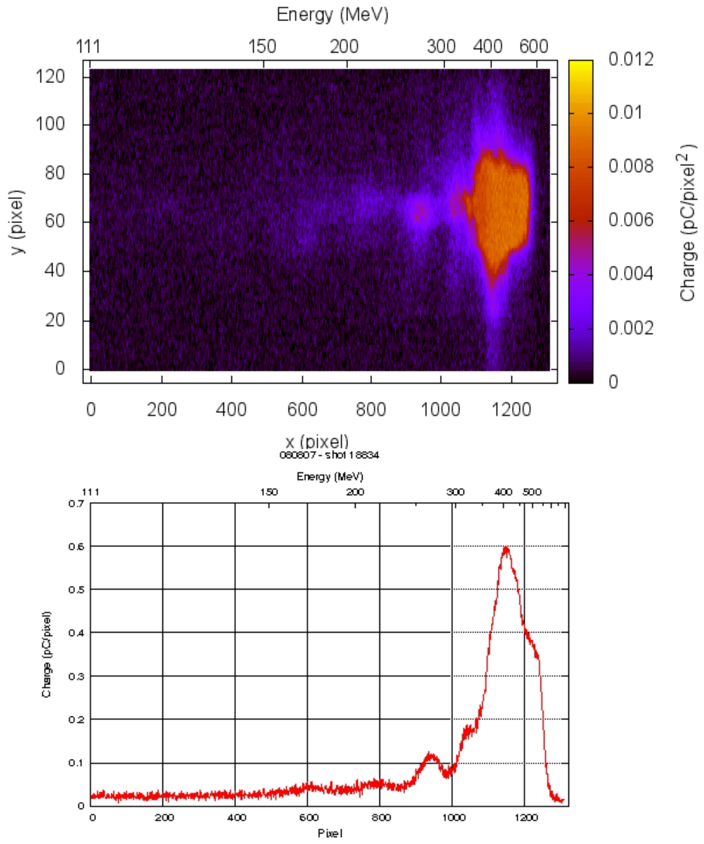


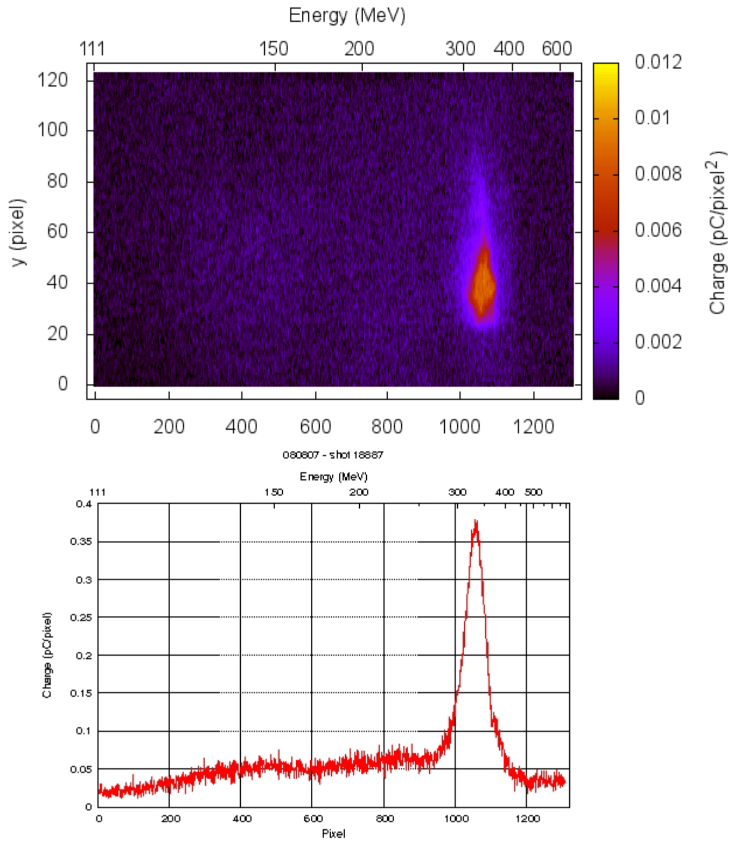
After one year…..

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

This method of manufacture is now used by all groups using plasma capillaries

Typical high energy spectra: RAL-Gemini experiment using plasma channel 85% of shots





Radiation sources: Synchrotron and Free-electron laser (FEL): a potential 5th generation light source

- Use output of wakefield accelerator to drive compact synchrotron light source or FEL
- Take advantage of electron beam properties
- Coherent spontaneous emission: prebunched FEL $I \sim I_0(N+N(N-1)f(k))$
- Ultra-short duration electron bunches: I >10 kA
- Operate in superradiant regime: FEL X-ray amplifier (self-similar evolution)

Potential compact future synchrotron source and x-ray FEL

Need a low emittance GeV beam with < 10 fs electron beam with I > 10 kA

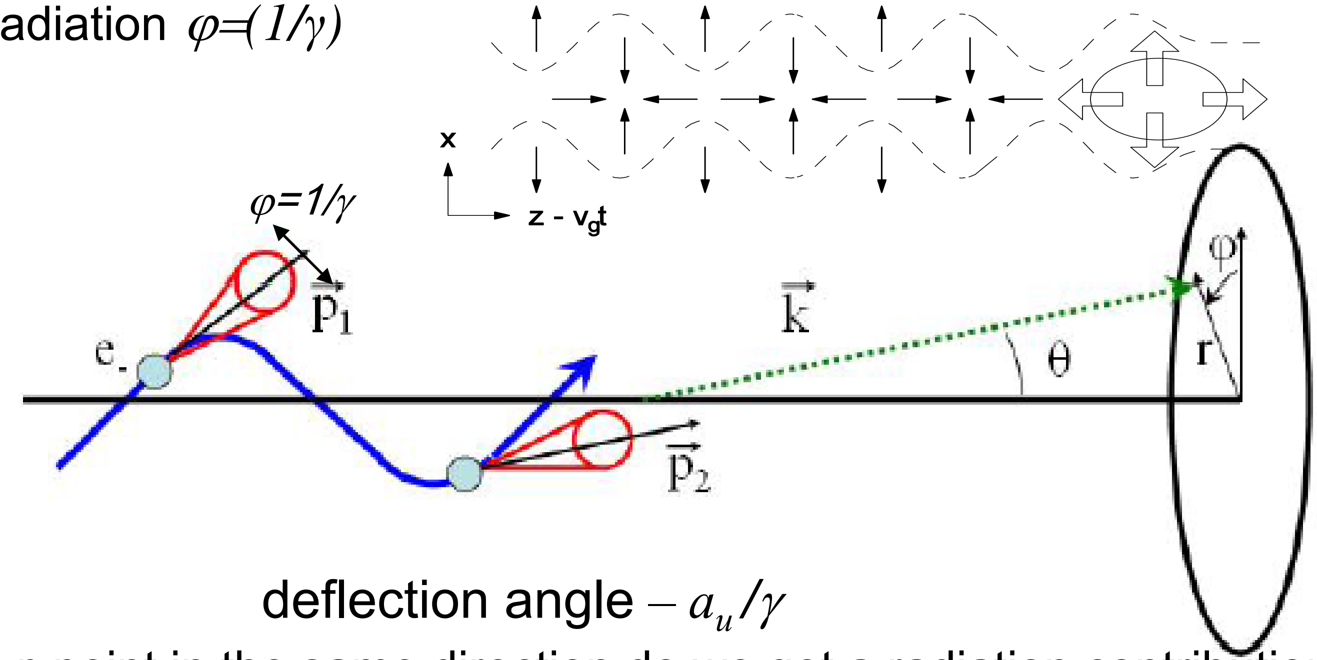
Operate in superradiant regime SASE alone is not adequate: noise amplifier

- Need to consider injection (from HHG source) or pre-bunching

Synchrotron radiation from an ion channel wiggler: betatron radiation

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

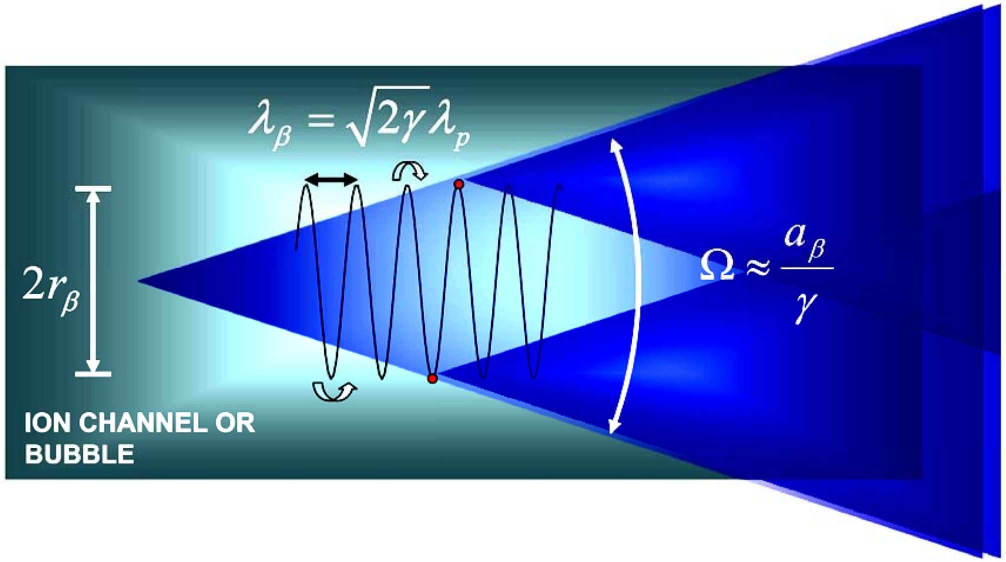
$$\gamma >> a_u >> 1$$



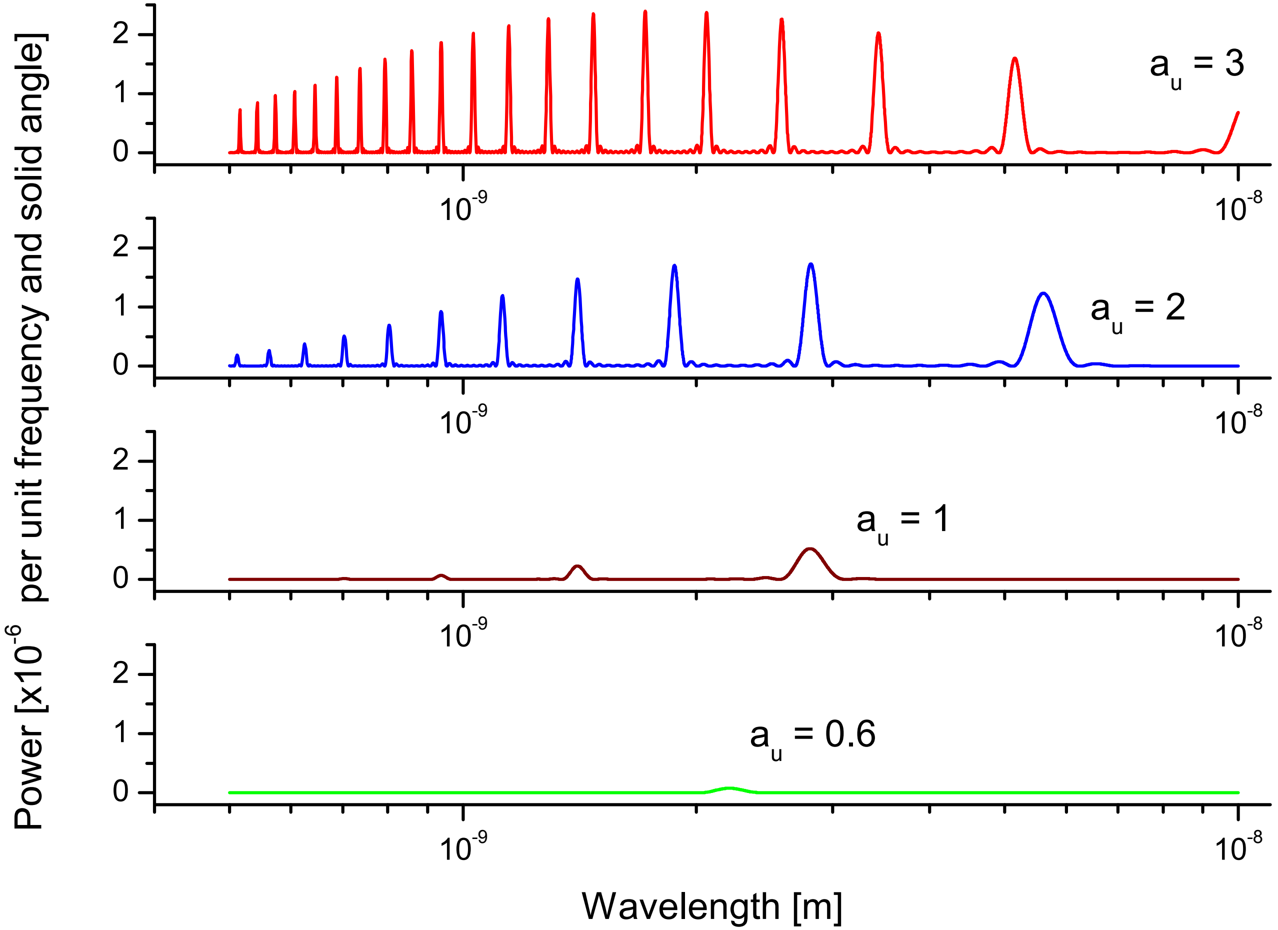
deflection angle – a_u/γ

- Only when *k* & *p* point in the same direction do we get a radiation contribution.
- Spectrum rich in harmonics – peaking at $h_{crit} \approx \dfrac{3a_u^3}{8}$
- Radiation rate $W \propto \gamma^2$ therefore only emission at dephasing length L_d

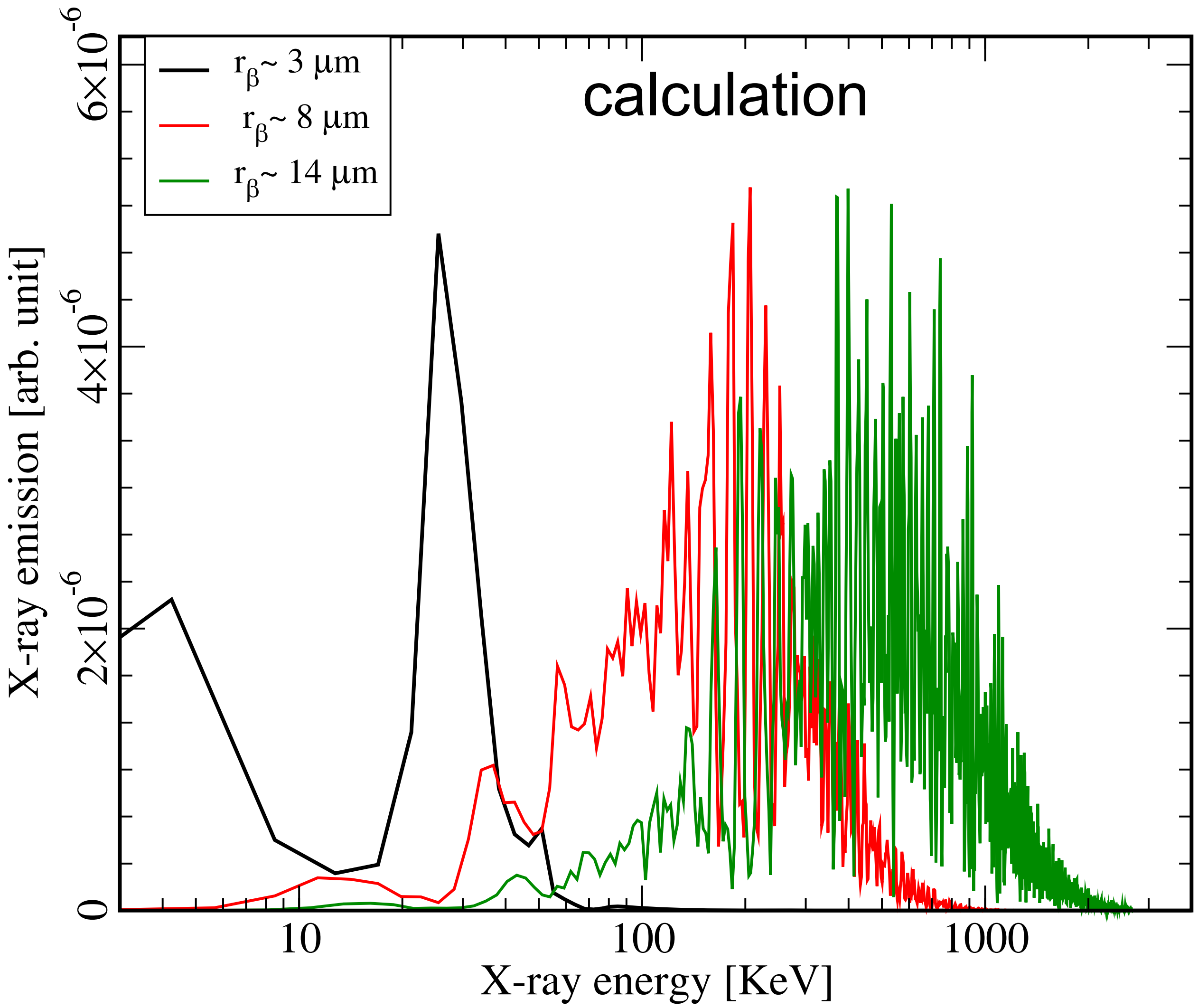
Betatron radiation



Increase in wiggler parameter

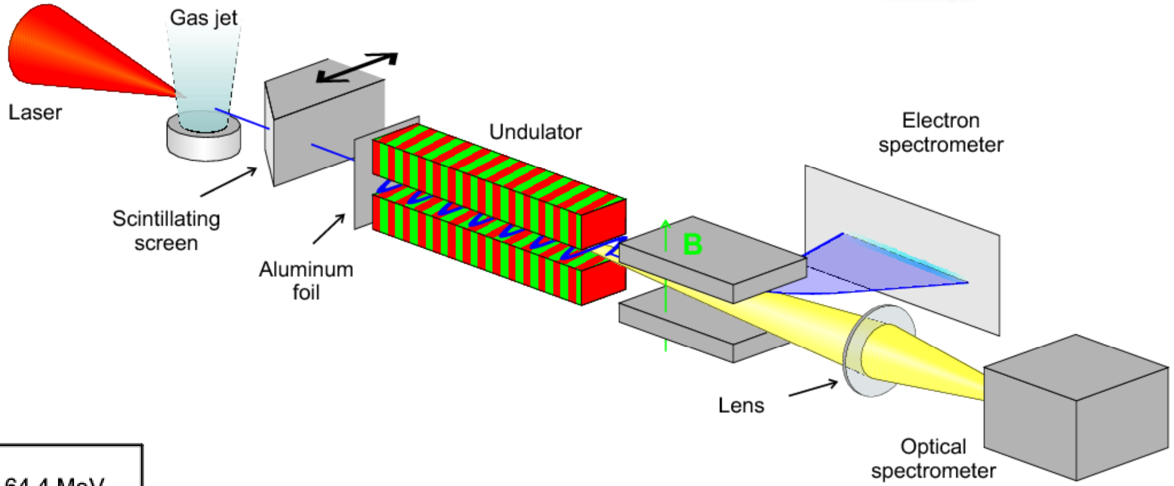


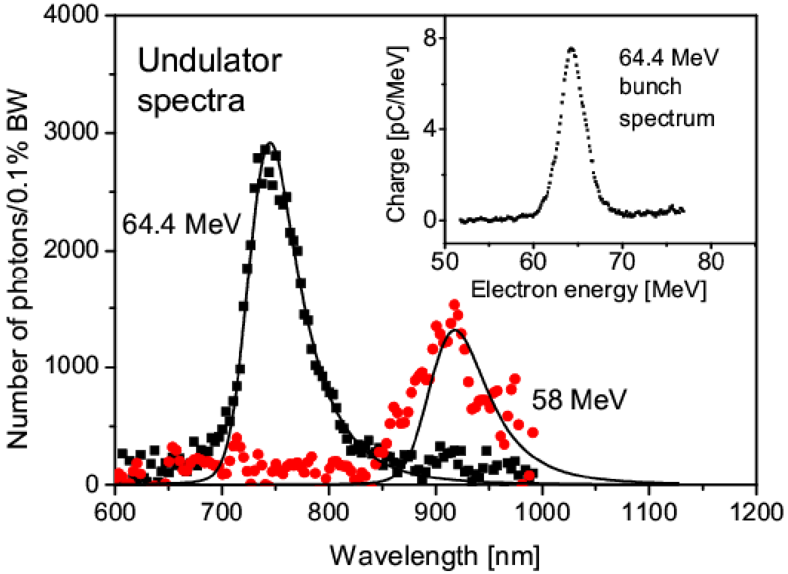
Extending to higher energies:



First undulator radiation demonstration with LWFA

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





- Measured $\sigma_\gamma/\gamma \sim 2.2 - 6.2\%$
- 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)

LWFA-driven FEL

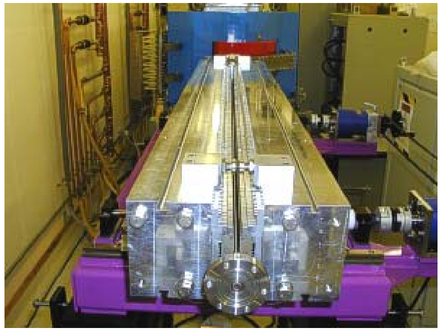
- High FEL gain criteria: $\varepsilon_n < \lambda\gamma/4\pi$ & $\sigma_\gamma/\gamma < \rho$
- Experimental $\varepsilon_n \leq 0.8\pi$ mm mrad & $\sigma_\gamma/\gamma \leq 0.007$
- For fixed σ_γ = 0.6 MeV, σ_γ/γ reduces at short λ

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

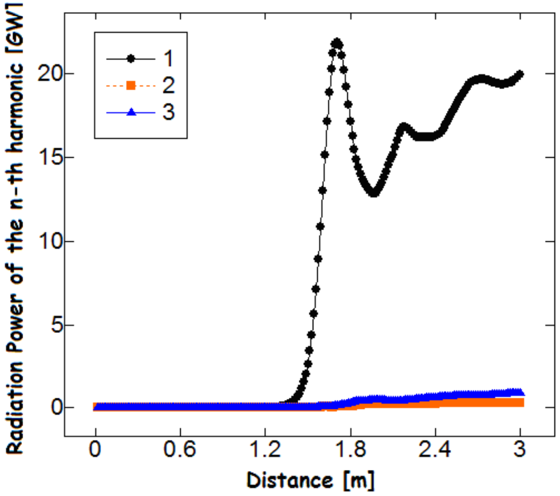
R. Bonifacio et al., 1984

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

Synchrotron, betatron and FEL radiation peak brilliance

$I(k) \sim I_0(k)(N+N(N-1)f(k))$

$\lambda_u = 1.5$ cm

$\varepsilon_n = 1\ \pi$ mm mrad

$\tau_e = 10$ fs

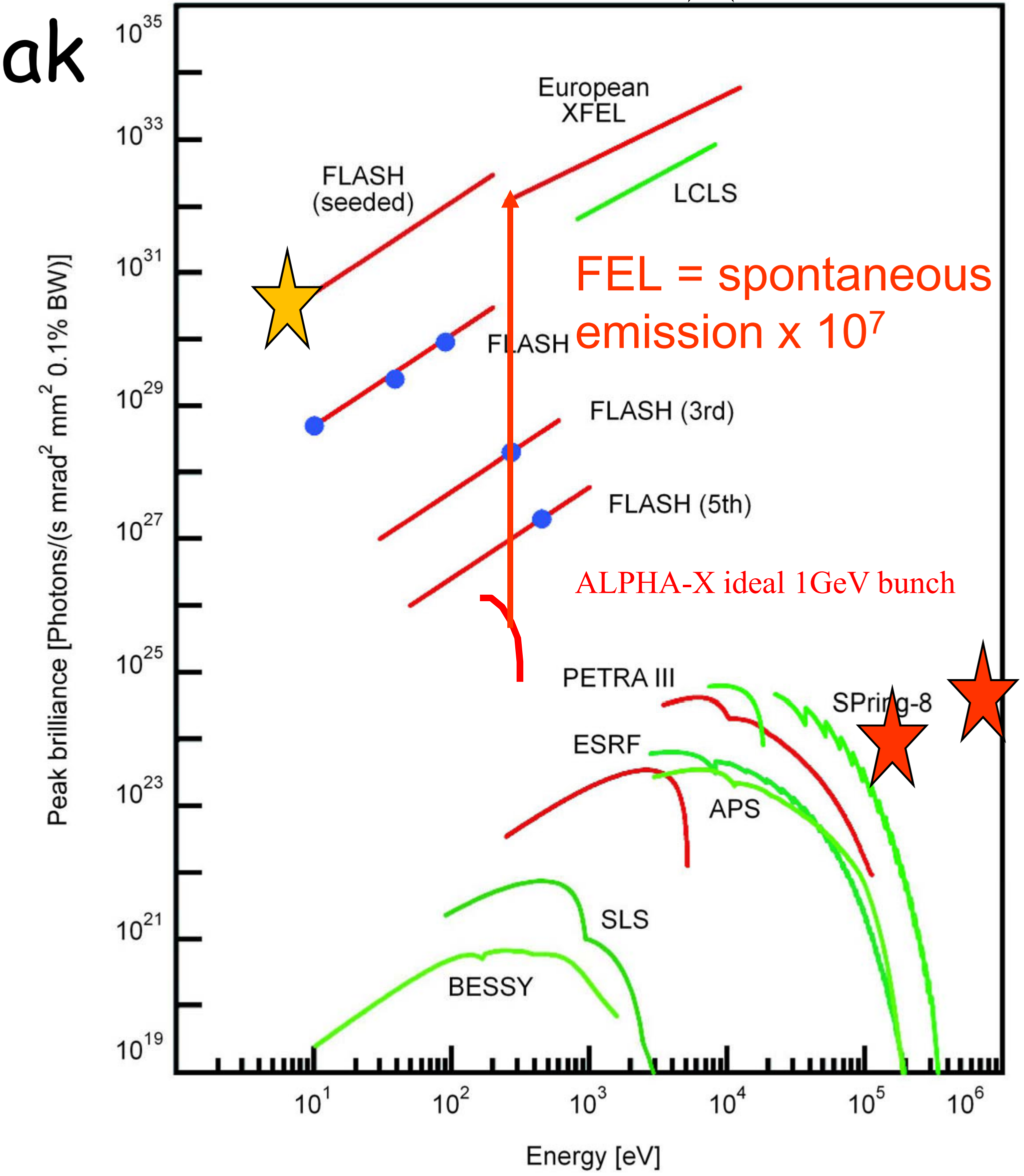
$Q = 100 – 200$ pC

$I = 25$ kA

$\delta\gamma/\gamma < 1\%$

FEL: Brilliance 5 – 7 orders of magnitude larger

betatron source ★



FEL = spontaneous emission x 10^7

ALPHA-X ideal 1GeV bunch

The Scottish Centre for the Application of Plasma Based Accelerators: SCAPA

1000 m^2 laboratory space: 200-300 TW laser and 10 “beam lines” producing particles and coherent and incoherent radiation sources for applications: nuclear physics, health sciences, plasma physics etc.

Conclusions

- Laser driven plasma waves are a useful way of accelerating charged particles and producing a compact radiation source: 100 – 1000 times smaller than conventional sources
- Some very good properties: sub 10 fs electron bunches potentially shorter (< 1 fs?) and high peak current (up to 35 kA?), $\varepsilon_n < 1\ \pi$ mm mrad, $\delta\gamma/\gamma < 1\%$?.
- Slice values important for FEL - potentially 10 times better. Wide energy range, wide wavelength range: THz – x-ray
- Good candidate for FEL – coherence & tuneability
- Betatron radiation – towards fs duration gamma rays
- Still in R&D stage – need a few years to show potential
- Challenges: rep rate, stability, energy spread and emittance, higher charge and shorter bunch length, beam transport
- Synchronised with laser – can combine radiation, particles (electrons, protons, ions), intrinsic synchronisation
- A compact light source for every university or 5th Generation light source? A paradigm shift?
- Setting up a new centre of excellence: **SCAPA: the Scottish Centre for the Application of Plasma based Accelerators:** based in Glasgow and part of a pooling effort: **SUPA – The Scottish Universities Physics Alliance**

ALPHA-X project

Strathclyde (students and staff):

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Collaborators: Gordon Rob, Brian McNeil, Ken Ledingham and Paul McKenna

ALPHA-X: Current and past collaborators:

Lancaster U., Cockcroft Institute / STFC - ASTeC, STFC – RAL CLF, U. St. Andrews, U. Dundee, U. Abertay-Dundee, U. Glasgow, Imperial College, IST Lisbon, U. Paris-Sud - LPGP, Pulsar Physics, UTA, CAS Beijing, LBNL, FSU Jena, U. Stellenbosch, U. Oxford, LAL, PSI, U. Twente, TUE, U. Bochum, ...

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consortium

FIN

Thank you