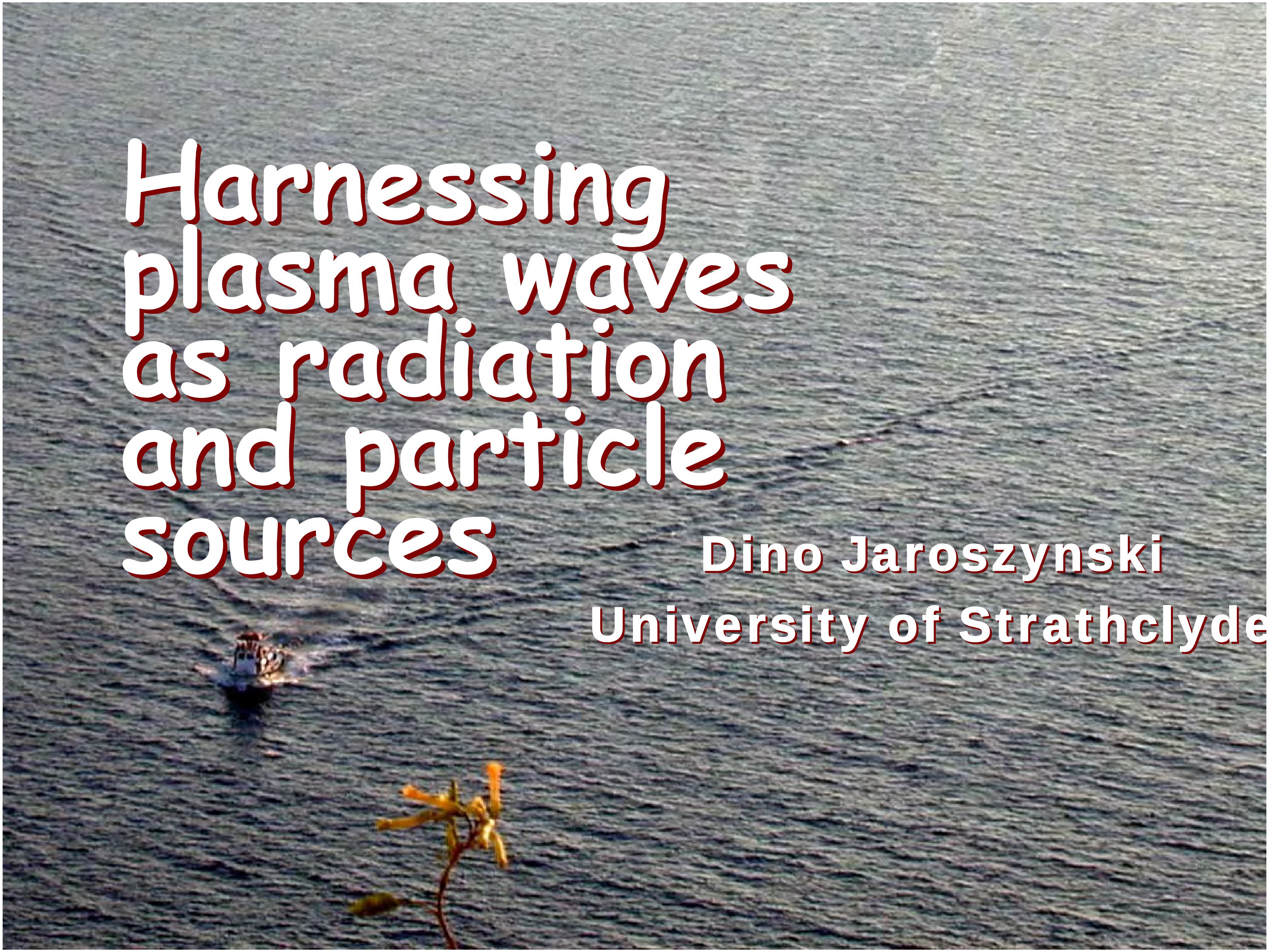


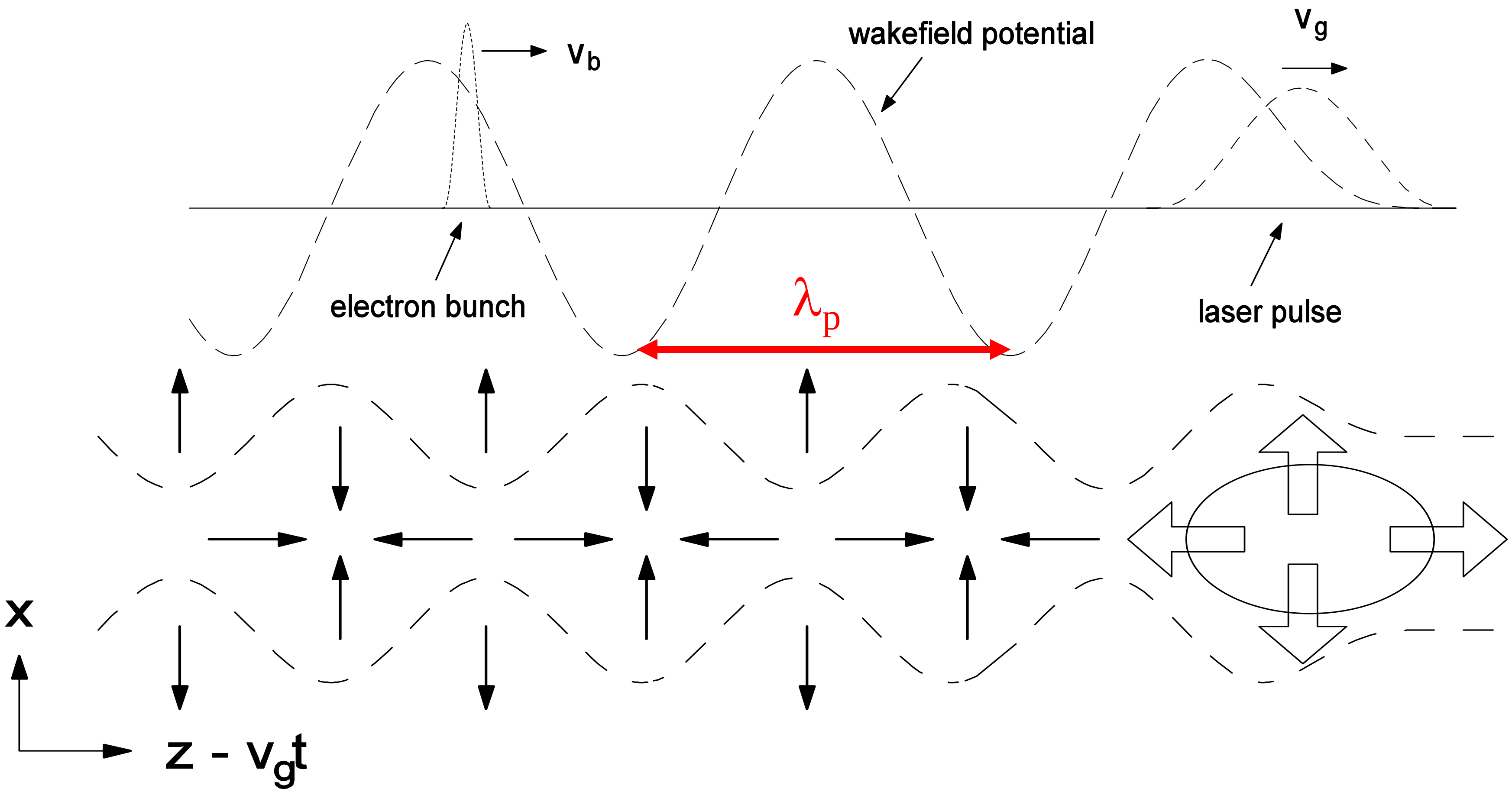
Harnessing plasma waves as radiation and particle sources

Dino Jaroszynski
University of Strathclyde

Outline of talk

- How can we use a laser-driven plasma wave to produce coherent electromagnetic radiation?
- Laser driven wakes
- Alpha-X
- Ultra-short bunch electron production using wakefield accelerators
- Synchrotron and free-electron laser sources
- Conclusion and outlook

Wakefield acceleration



Radiation sources: Synchrotron and Free-electron laser (FEL)

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

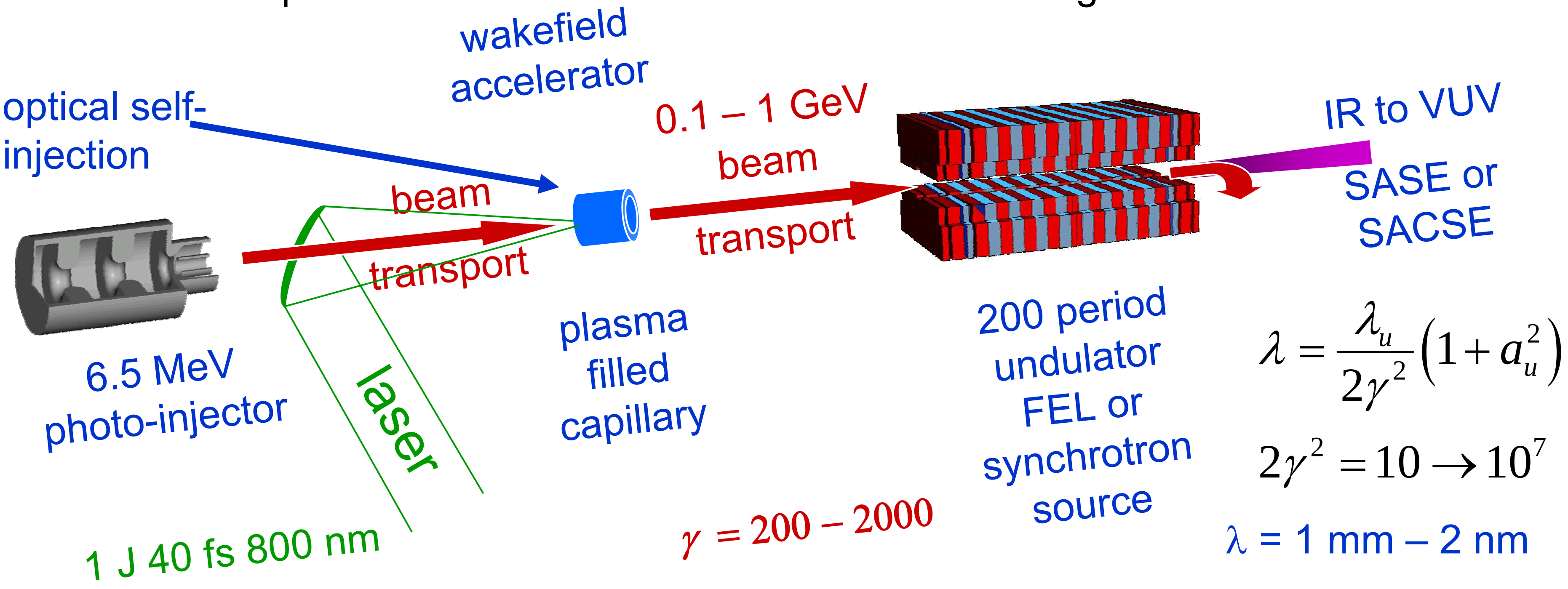
Potential compact future synchrotron source and x-ray FEL

- Need a low emittance GeV beam with < 50 fs electron beam with I > 1 kA
- Operate in **superradiant** regime: SASE alone is not adequate
- Need to consider injection or pre-bunching

ALPHA-X Programme

Main areas of research:

- Injectors (conventional and all-optical)
- Laser-plasma wake-field acceleration
- Plasma capillaries
- Free-electron laser (FEL)
- Beam transport systems
- Diagnostics



optical self-injection

wakefield accelerator

beam transport

0.1 – 1 GeV beam transport

IR to VUV

SASE or SACSE

6.5 MeV photo-injector

laser

plasma filled capillary

200 period undulator FEL or synchrotron source

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

$$2\gamma^2 = 10 \rightarrow 10^7$$

1 J 40 fs 800 nm

$\gamma = 200 - 2000$

λ = 1 mm – 2 nm

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

Advanced Laser Plasma High-energy Accelerators towards X-rays: ALPHA-X (a-x)

Collaborative project involving groups from the UK, EU and US

consortium

- Strathclyde – injector, laser-plasma & FEL: experiments & theory
- CCLRC RAL – theory & exps.: wakefield studies and diagnostics
- Oxford – plasma channels
- Imperial – all-optical injector, laser-plasma acceleration
- CCLRC Daresbury – Injector, undulator & FEL
- Dundee – injector, electron diagnostics & FEL
- St Andrews University – theory

GOALS: Accelerate to 1 GeV in 1cm using a wakefield accelerator.
Demonstrate laser-driven light source: synchrotron or FEL

Funded by the Research Councils UK Basic Technology Programme

People involved in project

- **Dino Jaroszynski, Klaas Wynne, Bob Bingham, Ken Ledingham, Albert Reitsma, Yuri Saviliev, Slava Pavlov, Riju Issac, David Jones, Bernhard Ersfeld, Steven Jamison, Jordan Gallcher, Andrey Lyachev, Enrico Brunetti, Mark Wiggins** – *Strathclyde*
- **Karl Krushelnick , Bucker Dangor , Zulfika Najmudin, Malte Kaluza, Alex Thomson, Stuart Mangles** – *Imperial College*
- **Bob Bingham, Henry Hutchinson, Peter Norreys, Raoul Trines, Kate Lancaster, Chris Murphy** – *RAL CCLRC*
- **Simon Hooker, Keith Burnett, Ian Walmsley, Justin Wark, Tony Gonsalves** – *Oxford*
- **Allan Gillespie, Allan McCloud, Steven Jamison,** – *Dundee, Abertay-Dundee*
- **Alan Cairns** – *St Andrews*
- **Mike Poole, Mike Dykes, Jim Clark** – *Daresbury CCLRC*
- **Robin Tucker** – *Lancaster University*
- **Roland Saurbrey, Heinrich Schwoerer** – *Jena*
- **Gennady Shvets** – *Austin Texas*
- **Nicola Piovella** – *Milan*
- **Terry Garvey** – *LAL Orsay*
- **Wim Leemans** - *LBNL*
- **Antonio Ting** – *NRL*
- **Chan Joshi, Warren Mori, Tom Katsouleas** – *UCLA, USC*
- **Brigitte Cros, Gregory Vieux** – *LPG, Orsay*
- **Padma Shukla** – *Bochum*
- **Tito Mendonca, Luis O Silva** – *IST Portugal*
- **Fred van Goor, Arsen Khachatryan, Kees van der Geer, Marieke Loos, Bas van der Geer, van der Wiel** – *The Netherlands*
- **Andrey Savilov, Vladimir Bratman** – *IAP, Nizhniy Novgorod*

Total of 63 people

Sources: TOPS ASTRA, and OXFORD

TOPS (Strathclyde): 5 TW source (800nm, 50fs 10Hz 250mJ)

upgrade to 1.1J (20 TW) October 2005

RAL: ASTRA 1 J, 20 TW source and Gemini: 0.5 PW (in 2007)

Oxford: 2 TW source

Strathclyde: 8 MeV High-brightness sub-picosecond photoinjector – being constructed

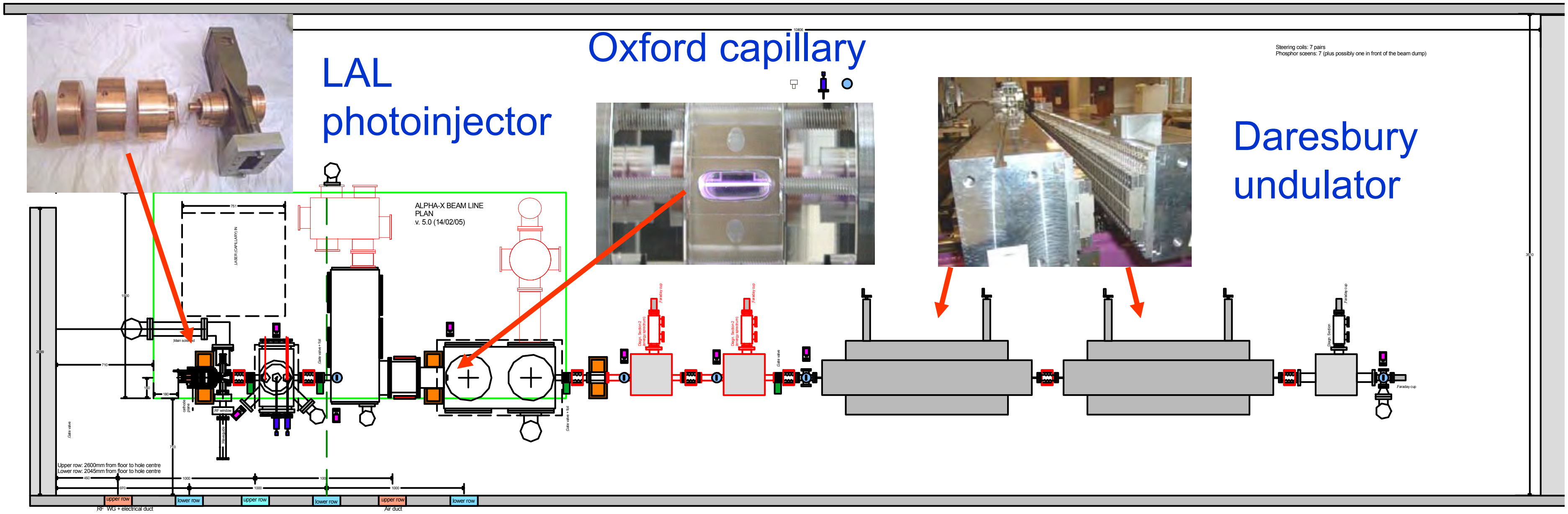
Other European facilities: FELIX, Lund, MPQ, DESY

General layout of ALPHA-X

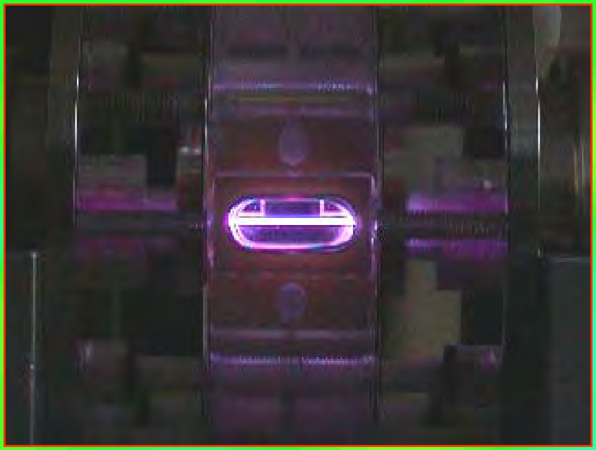
Compact femtosecond duration synchrotron or FEL source

λ = 2.8 nm – 1 mm (<1GeV beam)


Radiation containment chamber



Capillary: preformed plasma waveguide



$$n(r) = n_0 + \delta n \frac{r^2}{r_0^2}$$

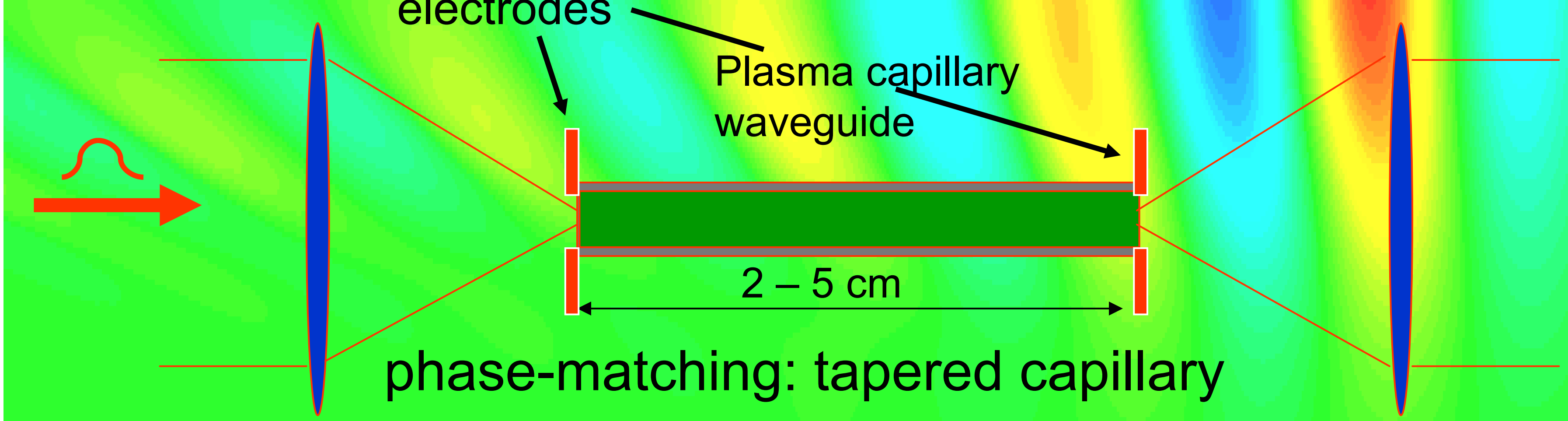
$$w_m = \left(\frac{r_0^2}{\pi r_e \delta n} \right)^{\frac{1}{4}}$$

r_0 = 150 μm capillary

$n(0) = 10^{18}$ cm^{-3}

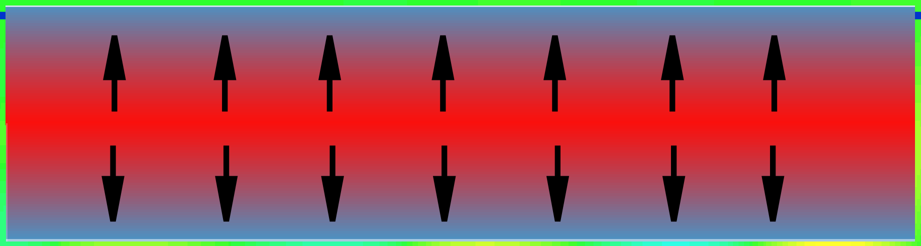
$I > 10^{17}$ W/cm^2

Plasma formed by electrical discharge between electrodes



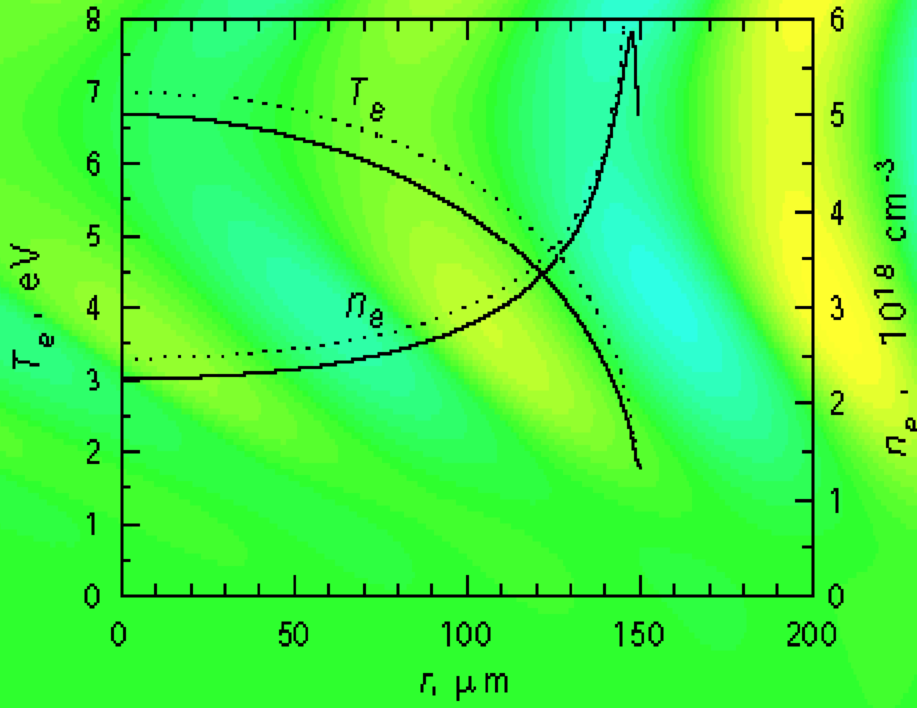
phase-matching: tapered capillary

Plasma waveguide formation



- After *t* ~ 80 ns plasma in quasi equilibrium.
- Ohmic heating of plasma balanced by conduction of heat to wall

$$\frac{1}{r}\frac{d}{dr}\left(r\kappa_{e\perp}\frac{dT}{dr}\right)+\sigma_{\perp}E^{2}=0$$



Solution of the heat flow equation yields scaling relation for matched spot size:

$$W_M[\mu m]=1.5\times10^{5}\frac{\sqrt{a[\mu m]}}{\left(\bar{N}_e[cm^{-3}]\right)^{1/4}}$$

(See S. Hooker et al)

Injection: Promising results

- Many groups have now observed mono-energetic beams
- Still need to demonstrate controlled acceleration
- Measurement of electron bunch duration needed to determine peak current

ALPHA-X all-optical injection experiments on ASTRA

10^{18} Wcm^{-2} in 25 μm spot

a_0 ~ 0.7 – 1

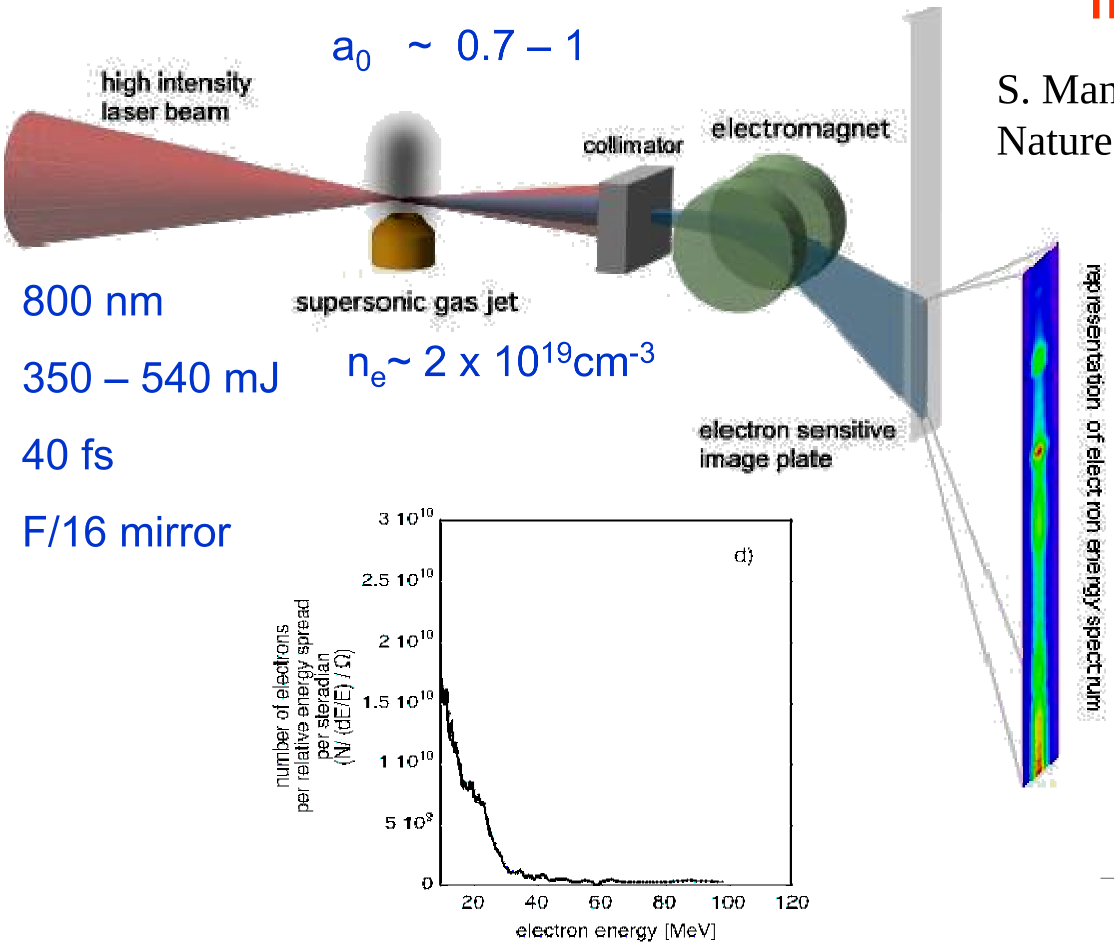
800 nm

350 – 540 mJ

40 fs

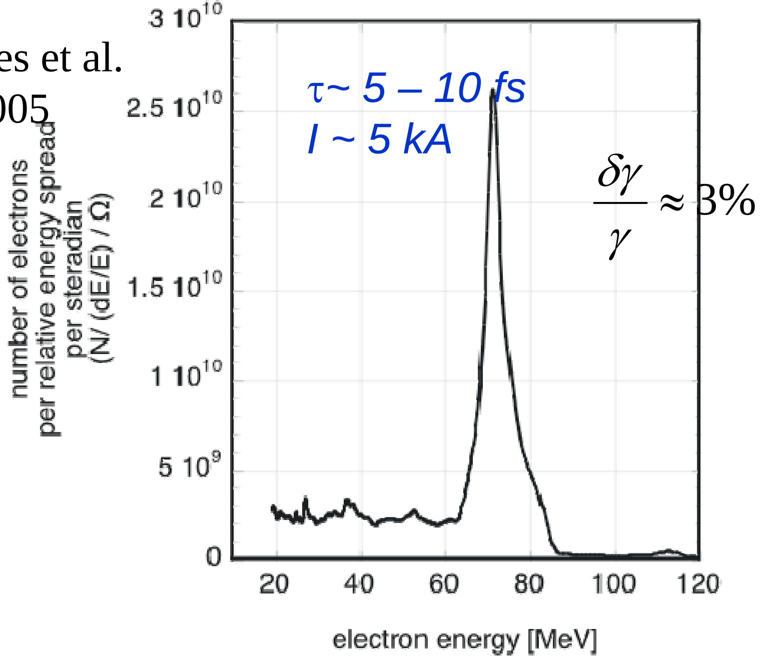
F/16 mirror

n_e~ 2 x 10^{19}cm^{-3}



Imperial/RAL/Strathclyde

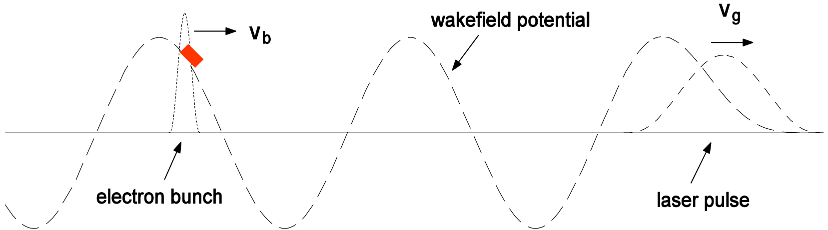
S. Mangles et al.
Nature 2005



τ~ 5 – 10 fs

I ~ 5 kA

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

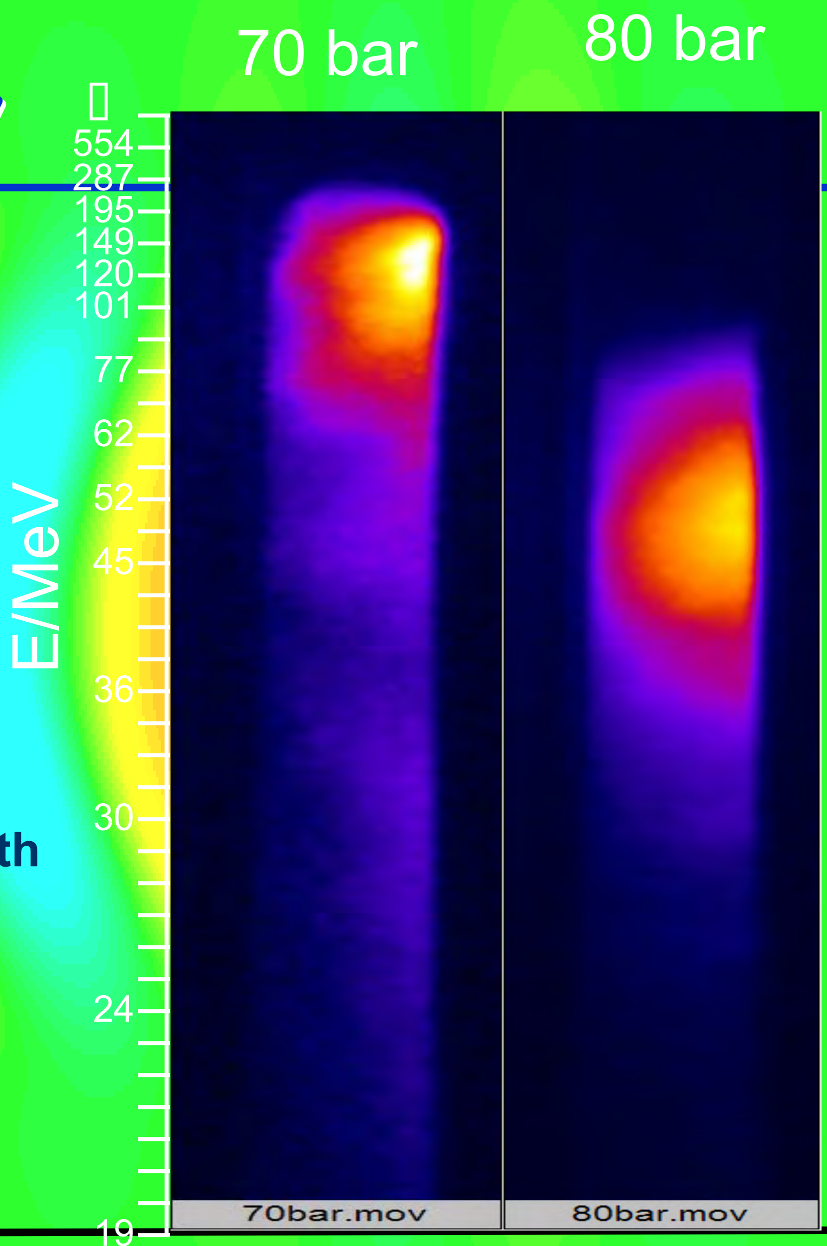


Interactions at higher power increases stability of beams

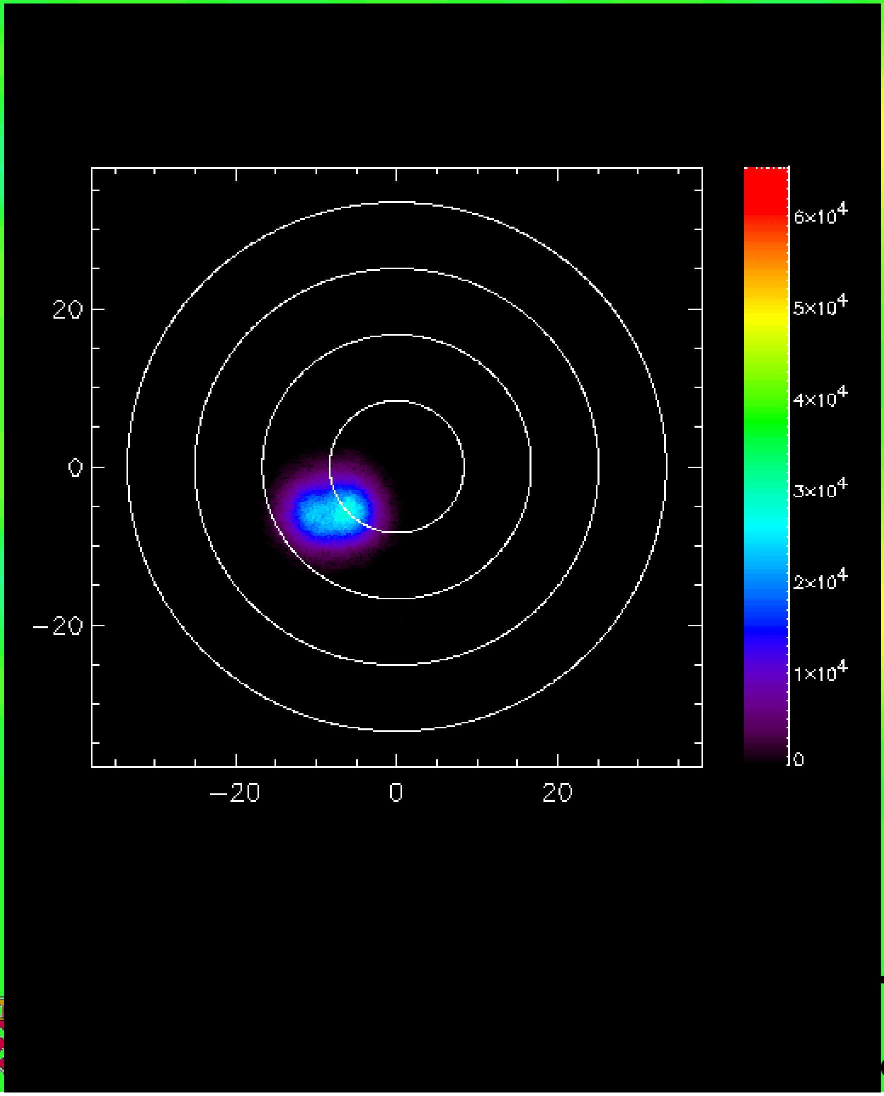
Lund Laser Centre Sept. 2005

~ 30 fsec, 600 mJ, 20 TW

(Imperial college ALPHA-X collaboration with F. Lindau, O. Lundh and C-G. Walstrom)



Beam stability: electron beam pointing

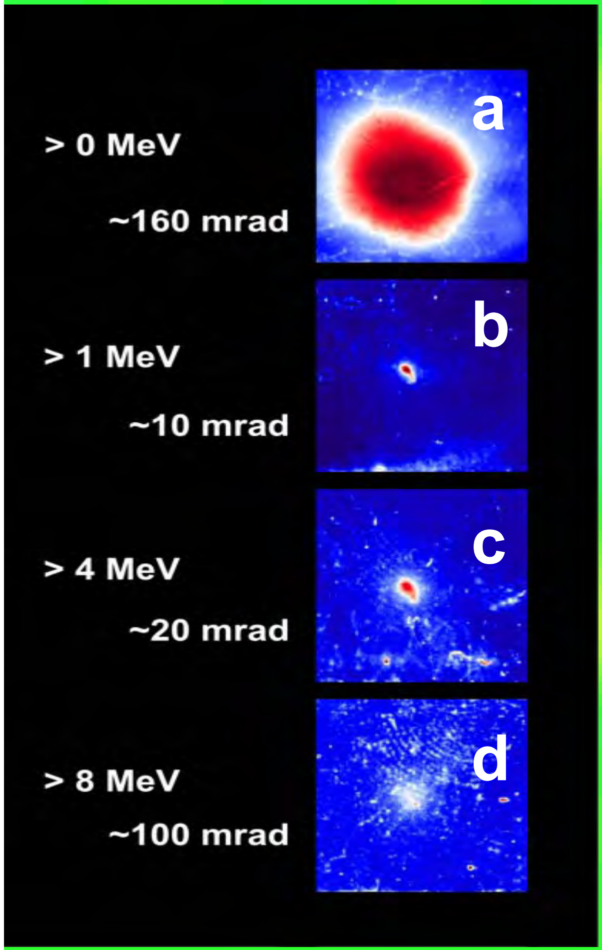


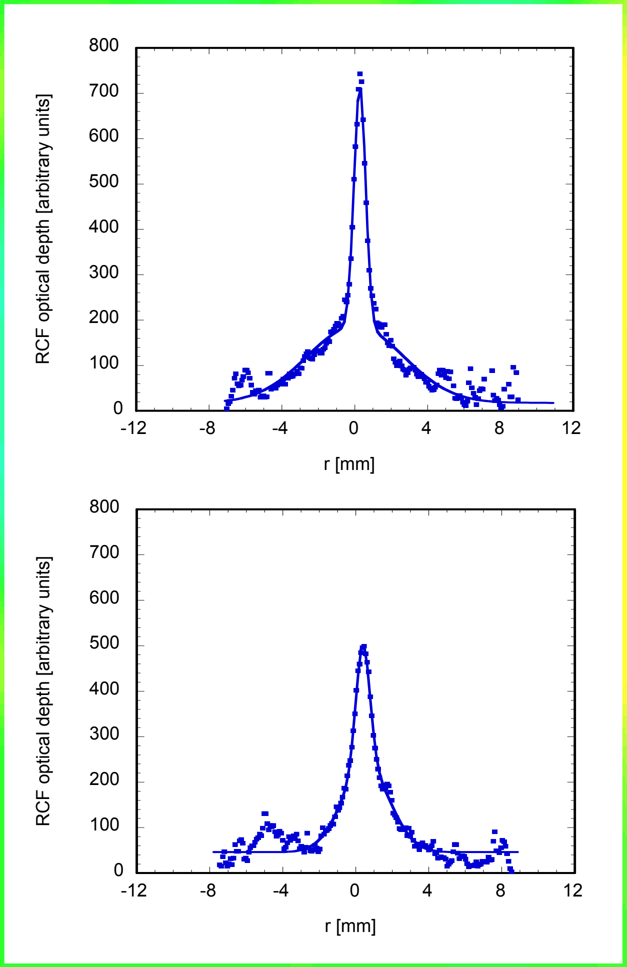
Krushelnick et al. Imperial College

- Electron beam profile for E > 11 MeV
- Pointing instability ~ 3°
- Multiple beamlets observed.

- Lanex screen 480mm from target
- Contours at 1°, 2°, 3°, 4°

Beams have very narrow divergence

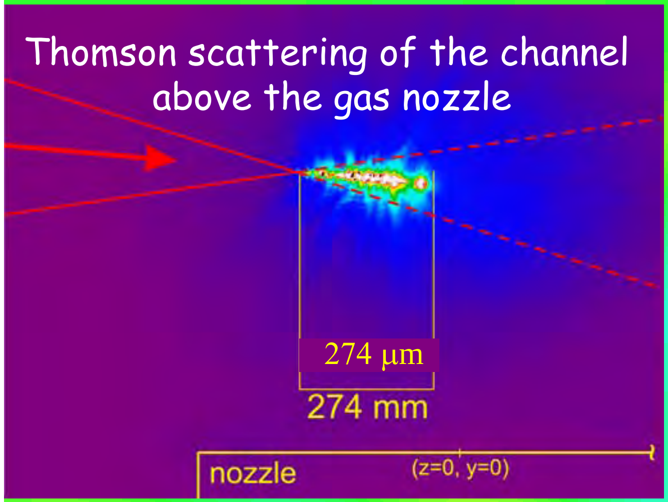




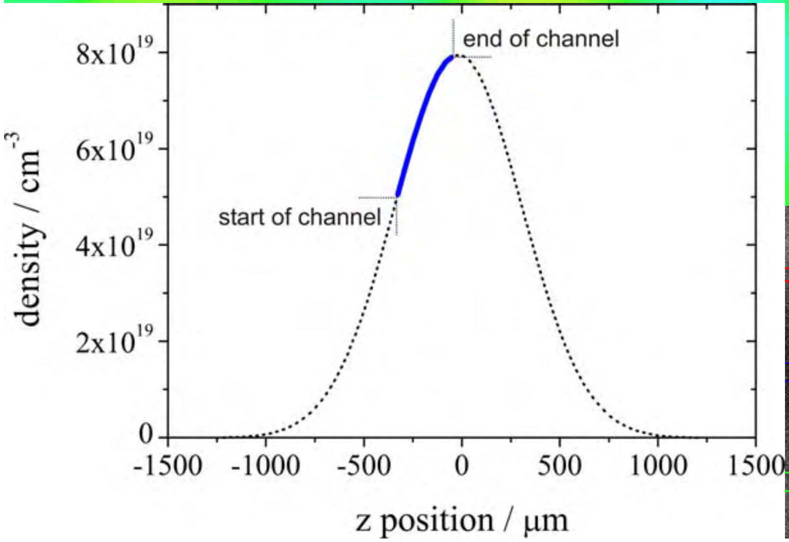
- Beam has two components
- Low energy (< 1 MeV) has high divergence $\theta_{FWHM} \sim 15^\circ$
- High energy has low divergence $\theta_{FWHM} < 2^\circ$

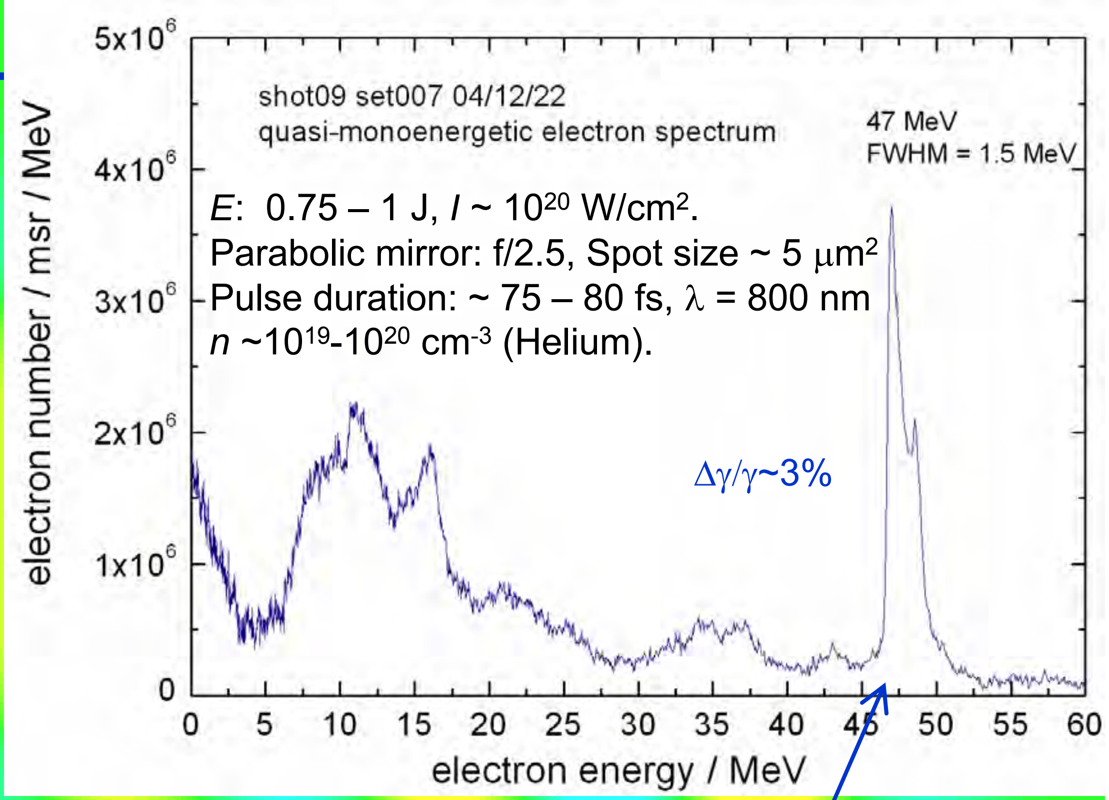
Krushelnick et al.
Imperial College

Jena measurements


Thomson scattering of the channel above the gas nozzle

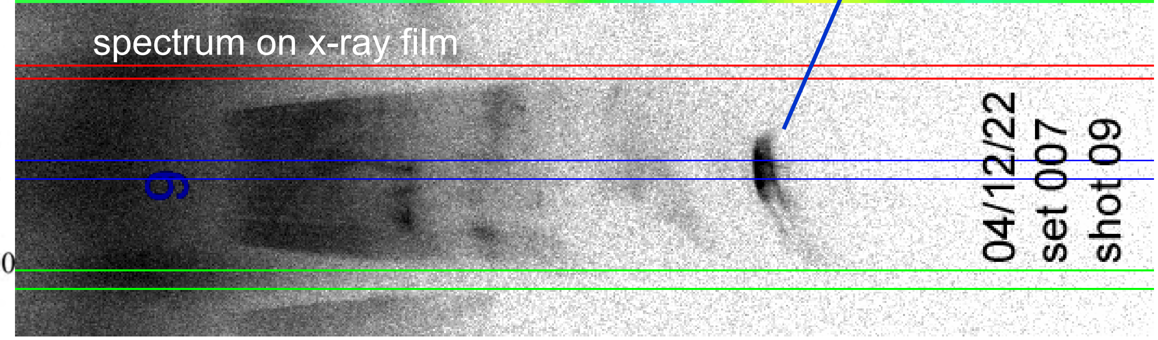
Channel location in the plasma profile




shot09 set007 04/12/22
quasi-monoenergetic electron spectrum

E: 0.75 – 1 J, I ~ 10^{20} W/cm^2.
Parabolic mirror: f/2.5, Spot size ~ 5 μm^2
Pulse duration: ~ 75 – 80 fs, λ = 800 nm
n ~10^{19}-10^{20} cm^{-3} (Helium).

Sauerbrey, Schwoerer, MPQ and ALPHA-X team


spectrum on x-ray film

LOA - Malka

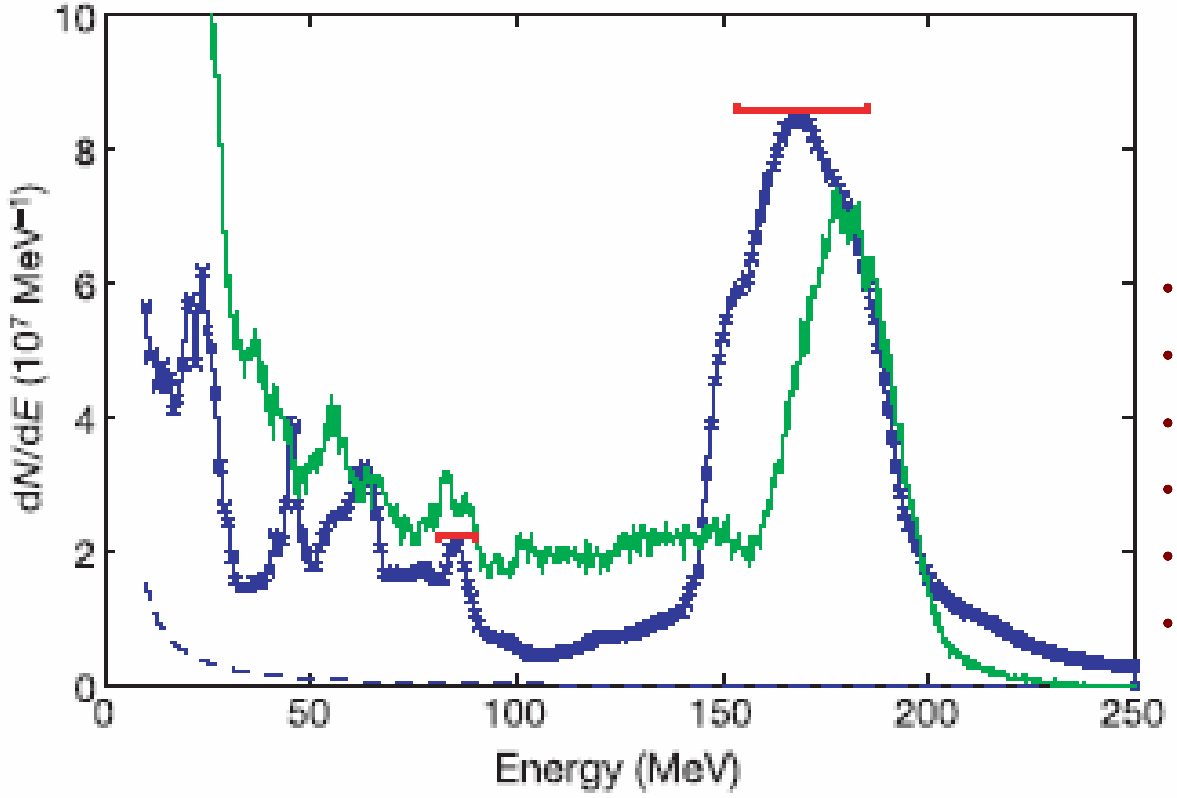


Figure 3 Experimental and simulated electron spectra. Blue line with crosses, electron spectrum corresponding to Fig. 2b, after deconvolution. Dashed line, estimation of the

- 3 mm gas jet
- *n* = 6×10^{18} cm^{-3}
- 1 J; 30 fs FWHM; *w* = 21 μm
- f/16 off axis parabola
- *I* = 3.2×10^{18} Wcm^{-2}
- *Q* = 500 pC

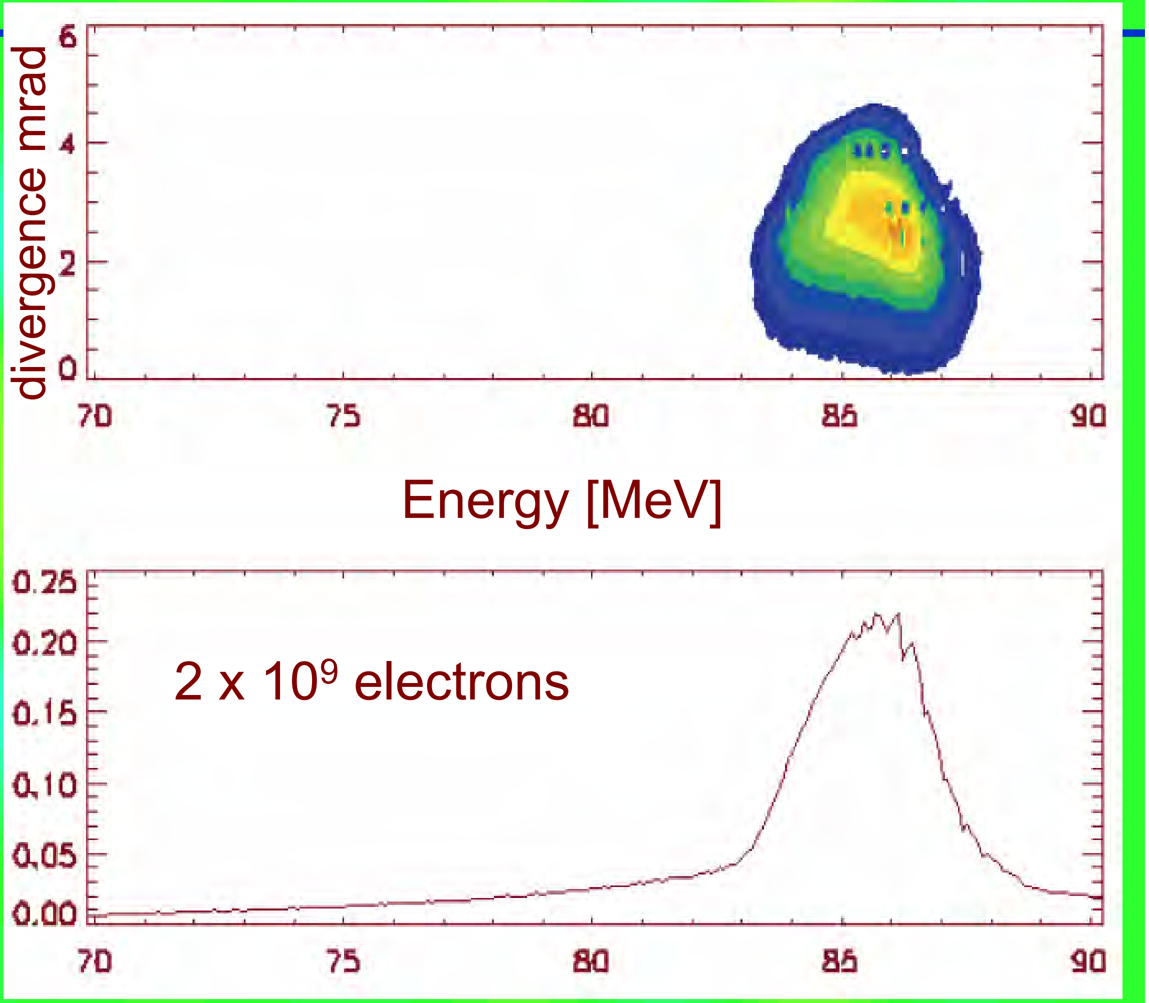
J. Faure et al.
Nature 2004

LBNL
Leemans

2004

- Channel guided wakefield accelerator
- 2.4 mm gas jet
- n = 4.5 x 10^{19} cm^{-3}
- E = 500 mJ; 55 fs FWHM; w = 8.5 μm
- f/4 off axis parabola
- I = 1.1 x 10^{19} Wcm^{-2}

C. Geddes et al. Nature 2004

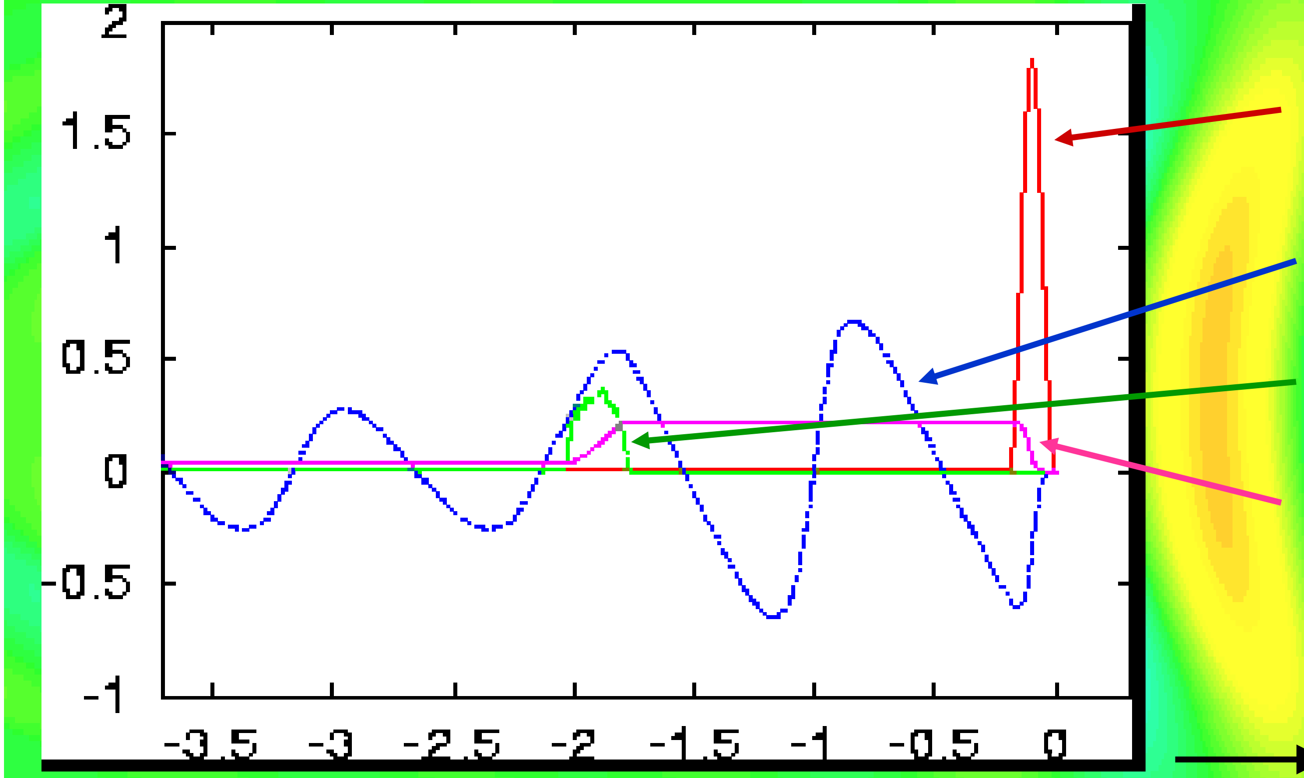


2 x 10^9 electrons

State-of-the-art laser driven wakefield accelerators

- Electron bunch charge of the order of 22 pC in the RAL experiments.
- In contrast, the LOA (gas jet) and LBNL (channel) experiments produced 500 pC, 170 MeV and 160 pC, 100 MeV bunches, at $n_e = 7 \times 10^{18}$ cm^{-3} and $n_e = 2 \times 10^{19}$ cm^{-3}, respectively.
- Estimated e-bunch length in these experiments – few femtoseconds
- Peak current should be multi-kilo-Amperes (~ 20 kA for 5 fs 100 pC).
- Emittance was estimated to be of the order of $\varepsilon \sim 1\,\pi$ mm mrad.
- The energy spread ~ 1 – 3 % suitable for FEL applications with more work on emittance and energy spread (need to get to 0.5% for FEL and linear collider stage)
- 6.5 MeV 100 fs photoinjector (BNL/Eindhoven/LAL gun)

Modelling of Laser Wakefield Acceleration



laser pulse envelope

electrostatic wakefield

bunch density

energy density of wakefield

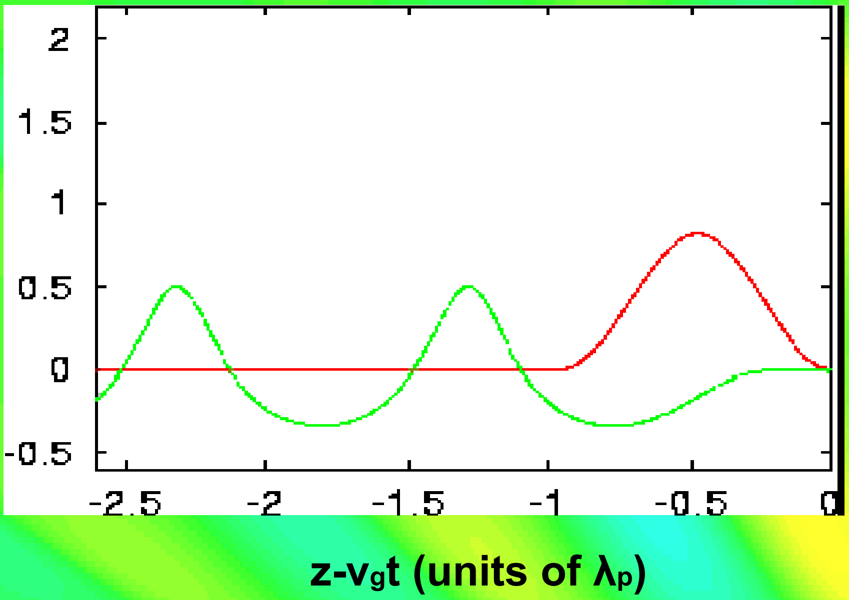
→ $z\text{-}v_g t$ (units of λ_p)

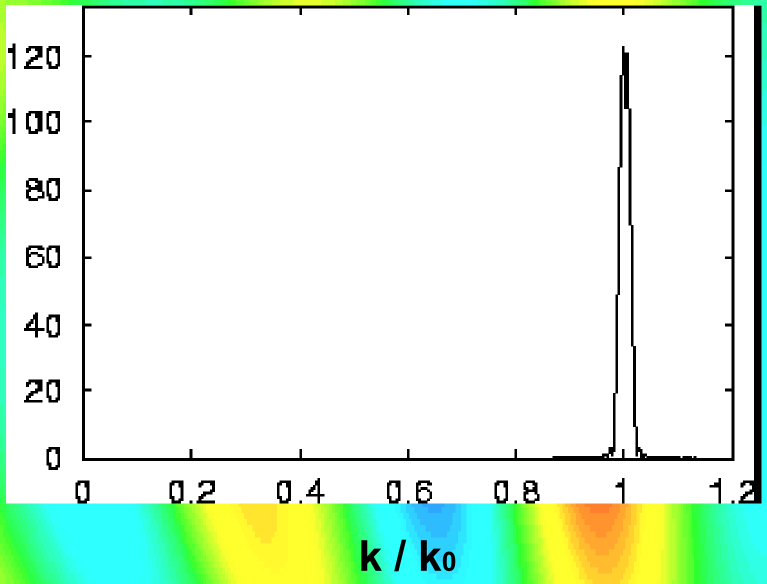
laser pulse envelope dynamics: ponderomotive wakefield excitation, electron bunch acceleration, phase slippage, beam loading

Laser pulse envelope dynamics

laser pulse amplitude: $\boldsymbol{a_0}$

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

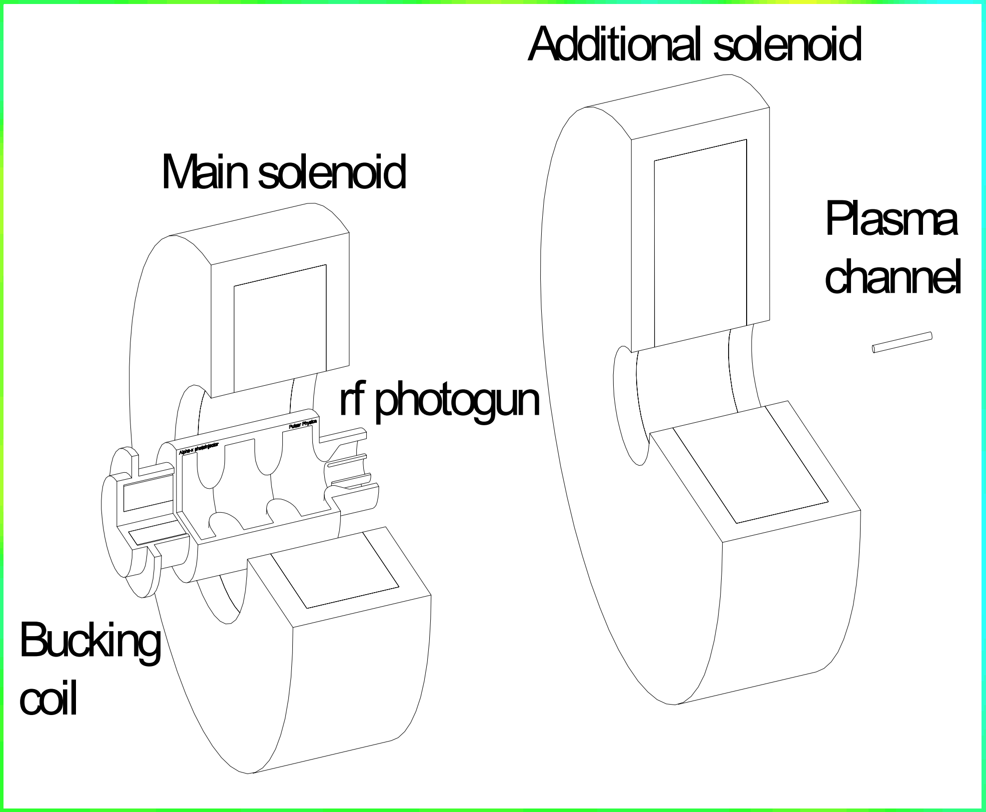




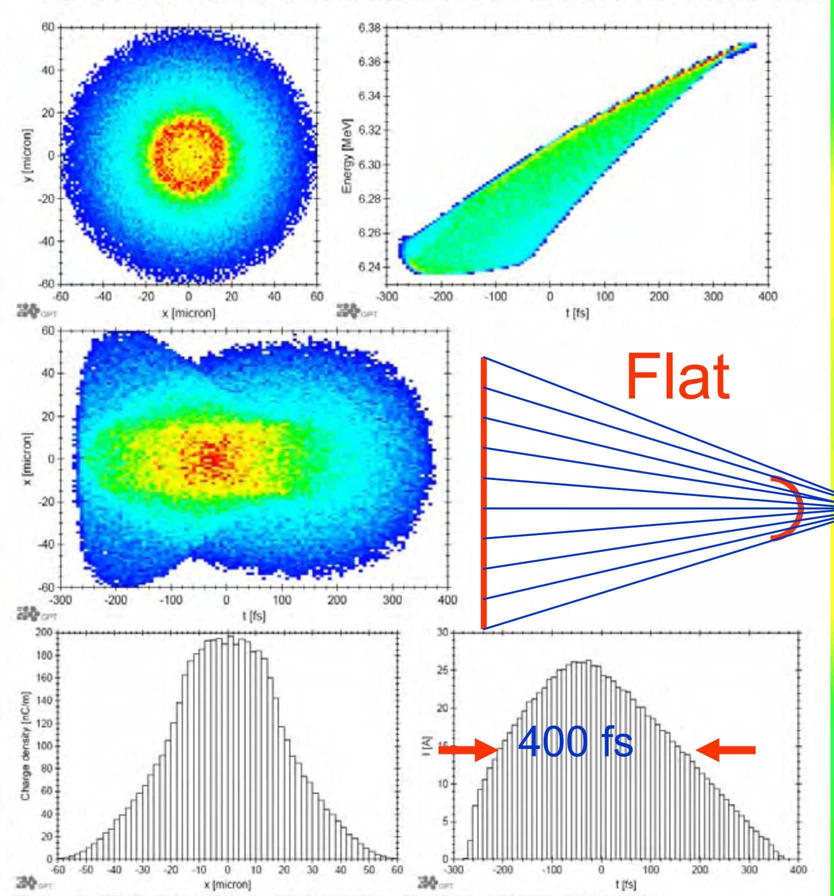
Linear regime: $a_0^2 \ll 1,\ \omega_d \ll \omega_s$: pulse energy loss through photon deceleration without envelope modulation, static wakefield, low energy efficiency

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

Beam line

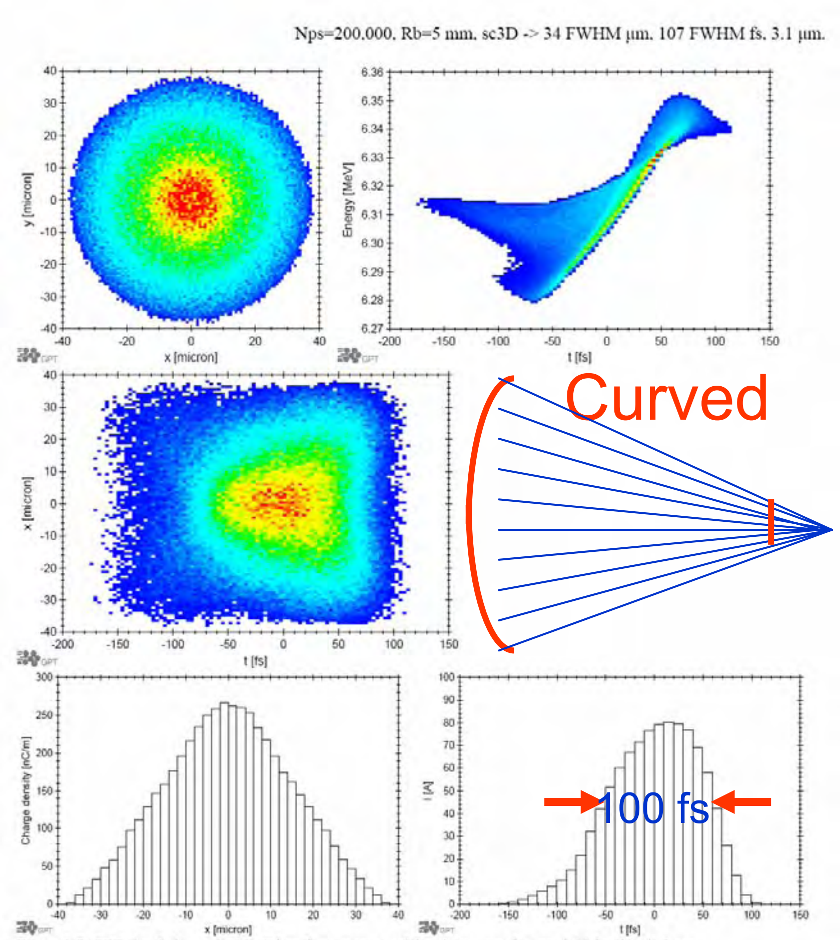

Additional solenoid
Main solenoid
Plasma channel
rf photogun
Bucking coil

Transport of flat and curved femtosecond bunches: buncher



Nps=200,000, Rb=1.8 mm, sc3D, rfsol=0.478, plasmasol=0.927 -> 46 FWHM µm, 331 FWHM fs, 1.73 µm.

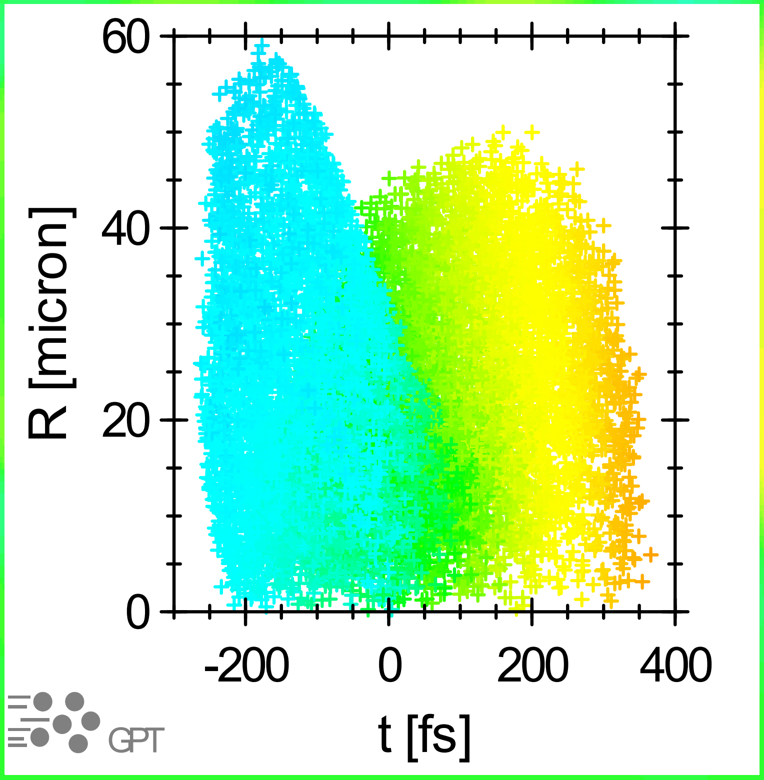
Figure 2-8: GPT simulations of a 10 pC bunch at entrance of the plasma accelerator, initial r=1.8 mm.

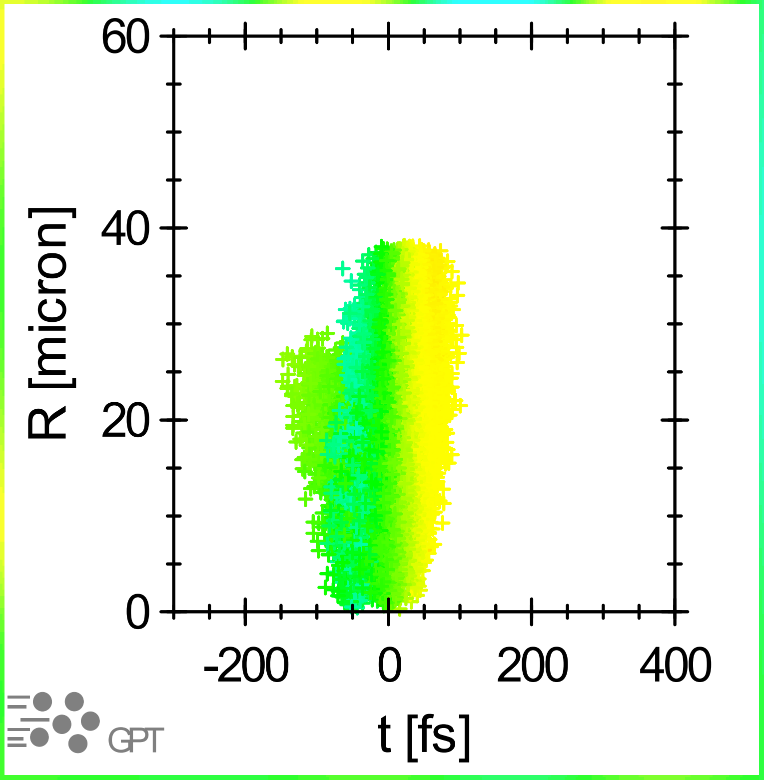


Nps=200,000, Rb=5 mm, sc3D -> 34 FWHM µm, 107 FWHM fs, 3.1 µm.

Figure 3-7: GPT simulations of a 10 pC bunch at entrance of the plasma accelerator, initial radius is 5 mm.

Electron distribution at capillary entrance


Flat beam


Curved beam

van der Geer et al. 2005

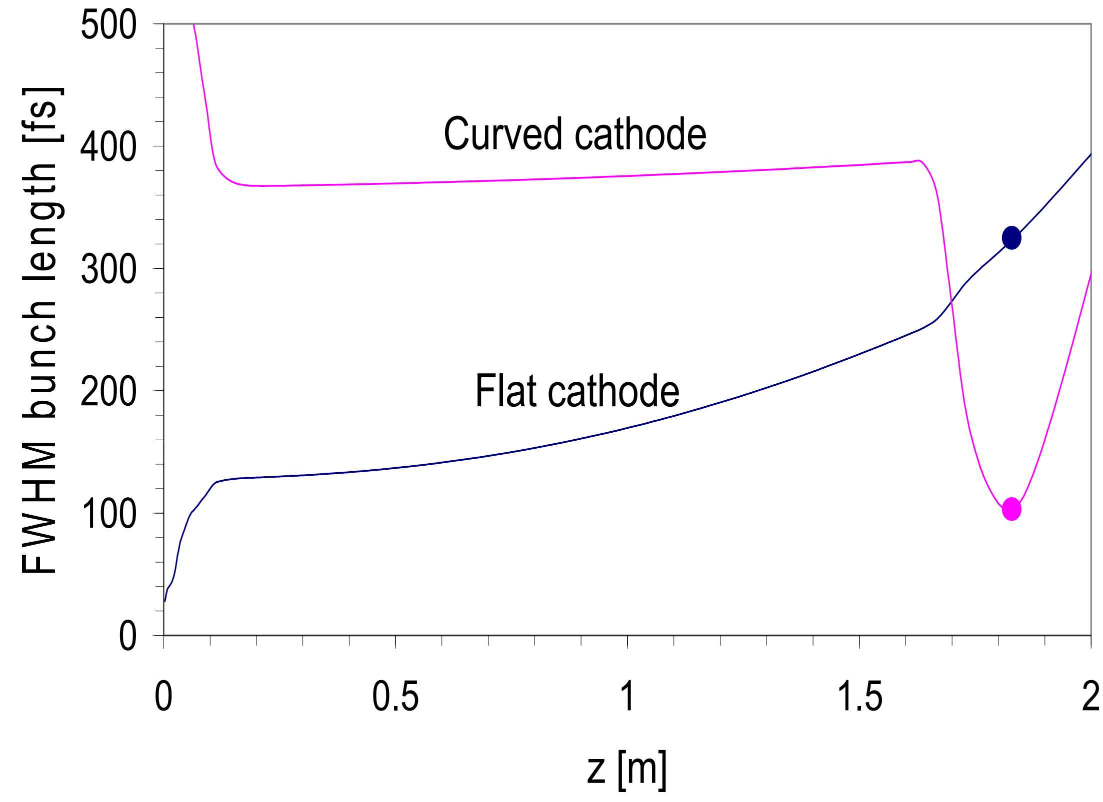
Electron bunch evolution: bunch compressor

Implications for wakefield accelerators:

electron bunches cannot be expanded radially:

beam will expand by 6 fs if expanded to 2 mm in 0.5 m

$\delta t = D^2/4fc$

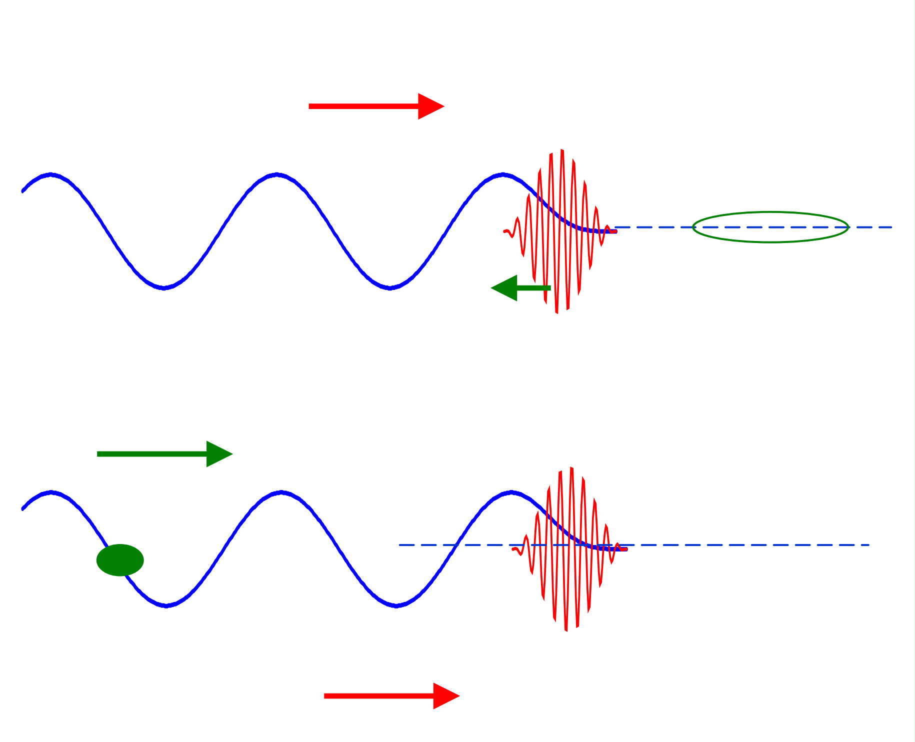


van der Geer et al. 2005

Injection-compression schemes

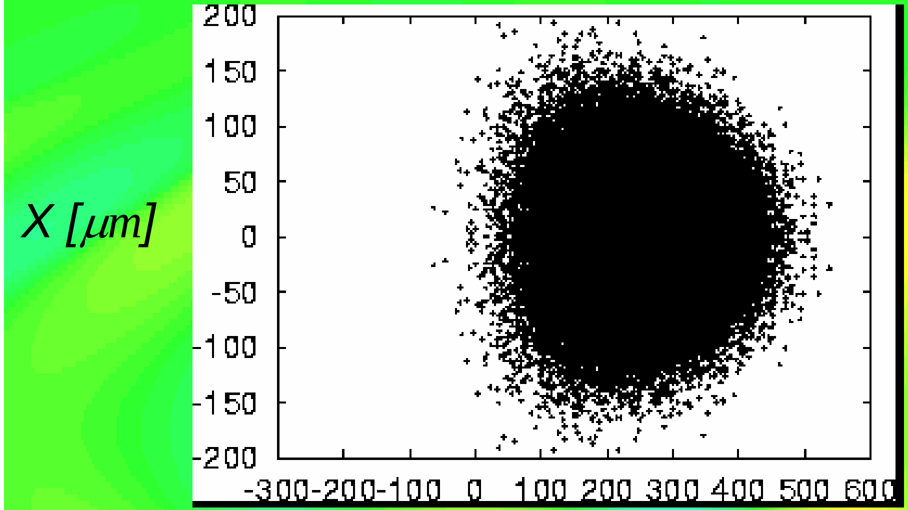
- to minimize energy spread, bunch duration *short* compared to *plasma period*
- very sensitive to *timing jitter* between laser pulse and electron bunch
- an interesting option: injection *in front of* laser pulse

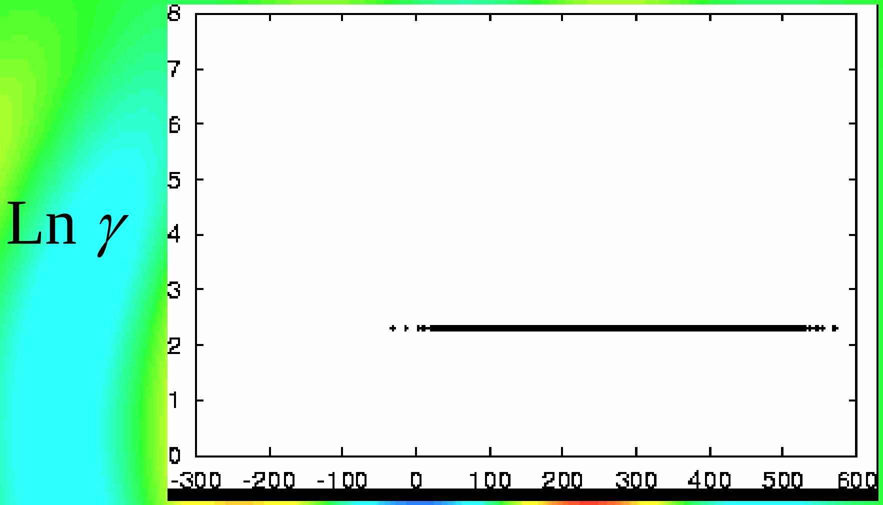
- initial electron energy low → bunch *slips backwards* through laser pulse
- electrons trapped *behind* laser pulse
- wakefield acts as *relativistic mirror* and accelerates electrons to *high energy*
- scheme depends on *overlap* of focusing and accelerating regions for *nonlinear* or *narrow channel* wakefields



Khachatryan et al. PRE 2005

Trapping and acceleration

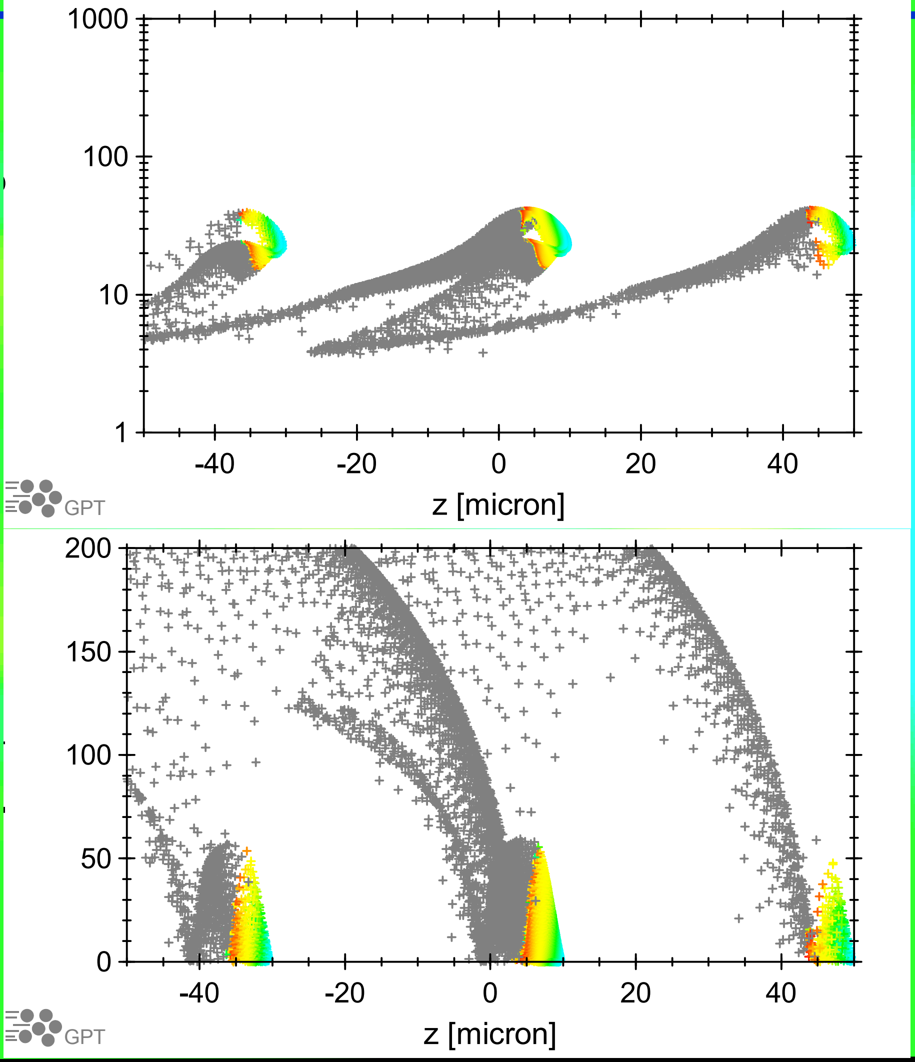




example:

- 4 MeV beam in 3.5 x 10^{17} cm^{-3} plasma
- Laser pulse acts as *filter*, rejecting electrons outside spot size
- Initial bunch spot size can be *larger* than laser spot size (i.e. if we accept losses)
- Contrast with conventional injection requires *small* bunch spot to avoid energy spread
- Accelerated bunch has *low transverse emittance*

Linear plasma model



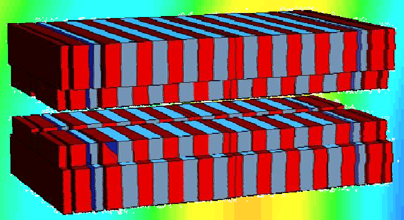
GPT: Loose and van der Geer (Pulsar)

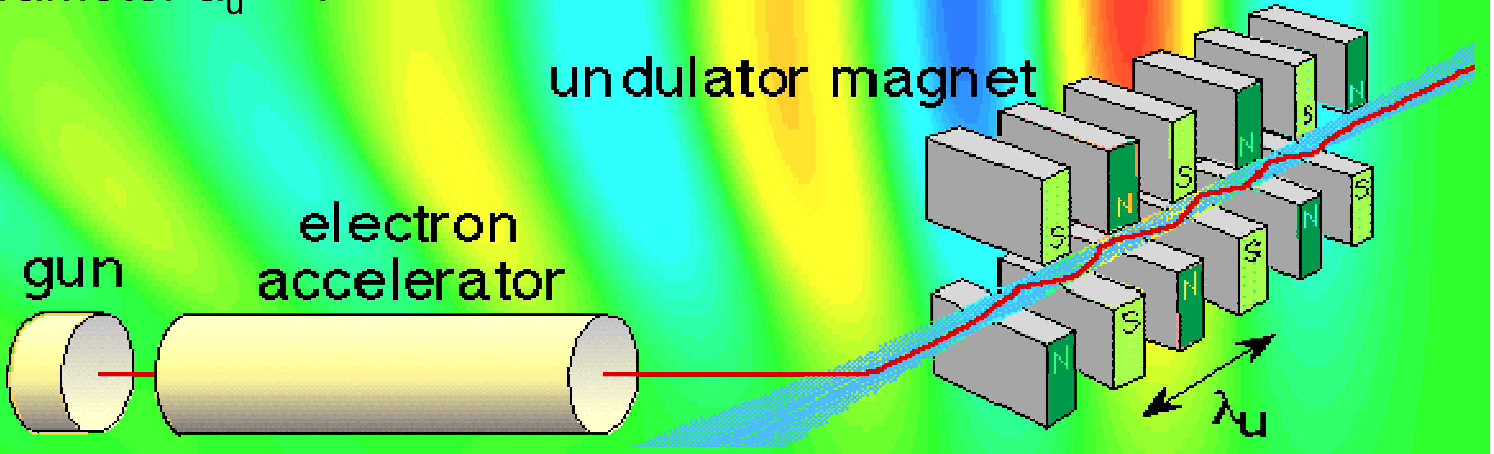
- Electron bunch longer than plasma period
- Quasistatic plasma model (Albert Reitsma)

Undulator: compact synchrotron source and free-electron laser

- Slotted pole focussing undulator (Daresbury)
- 200 period
- Undulator period 1.5 cm
- Minimum gap 5 mm
- Undulator parameter $a_u \sim 1$

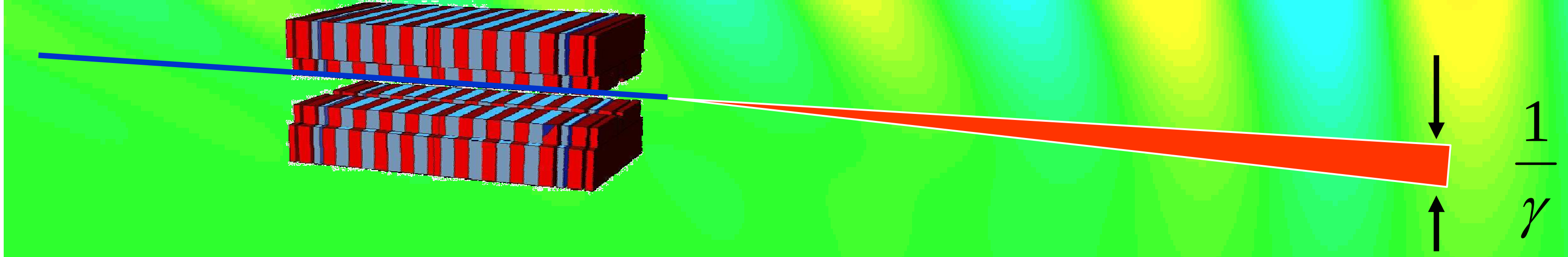
Strathclyde/Daresbury





Compact synchrotron source

- Undulator radiation emitted into cone $\theta \approx \frac{1}{\gamma}$
- Wavelength: $\lambda = \frac{\lambda_u}{2\gamma^2}(1+\frac{a_u^2}{2}+\gamma^2\theta^2)$; and $\frac{\Delta\lambda}{\lambda} \approx \frac{1}{2N_u}$
- Normalised undulator potential $a_u = \frac{e\hat{B}\lambda_u}{2\pi mc}$



ALPHA-X synchrotron source

- Radiation wavelength: 0.2 nm (1 GeV beam)
- Pulse length depends on $\Delta\gamma/\gamma$ (~ 2% measured) and electron bunch duration
- Ideal $\Delta\lambda/\lambda = 1/2N_u = 0.5\%$
- Ideal pulse length: sub-femtosecond (point charge)
- Synchrotron radiation pulse length ~ 10 fs

Energy spread and emittance

- Non-ideal electron beams degrade radiation properties: reduces brilliance and lowers FEL gain
- Emittance: area in transverse phase space

$$\varepsilon_{x,y} \approx \sigma_{x,y}\sigma'_{x,y}$$

- Approx. beam size times RMS beam divergence
- Normalised emittance: $\varepsilon_n = \gamma\beta\varepsilon$ needs to be ≈ 1 πmm mrad
- Energy spread: $\dfrac{\sigma_\gamma}{\gamma}$ needs to be < ρ <0.5%

Predicted synchrotron radiation peak brilliance

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

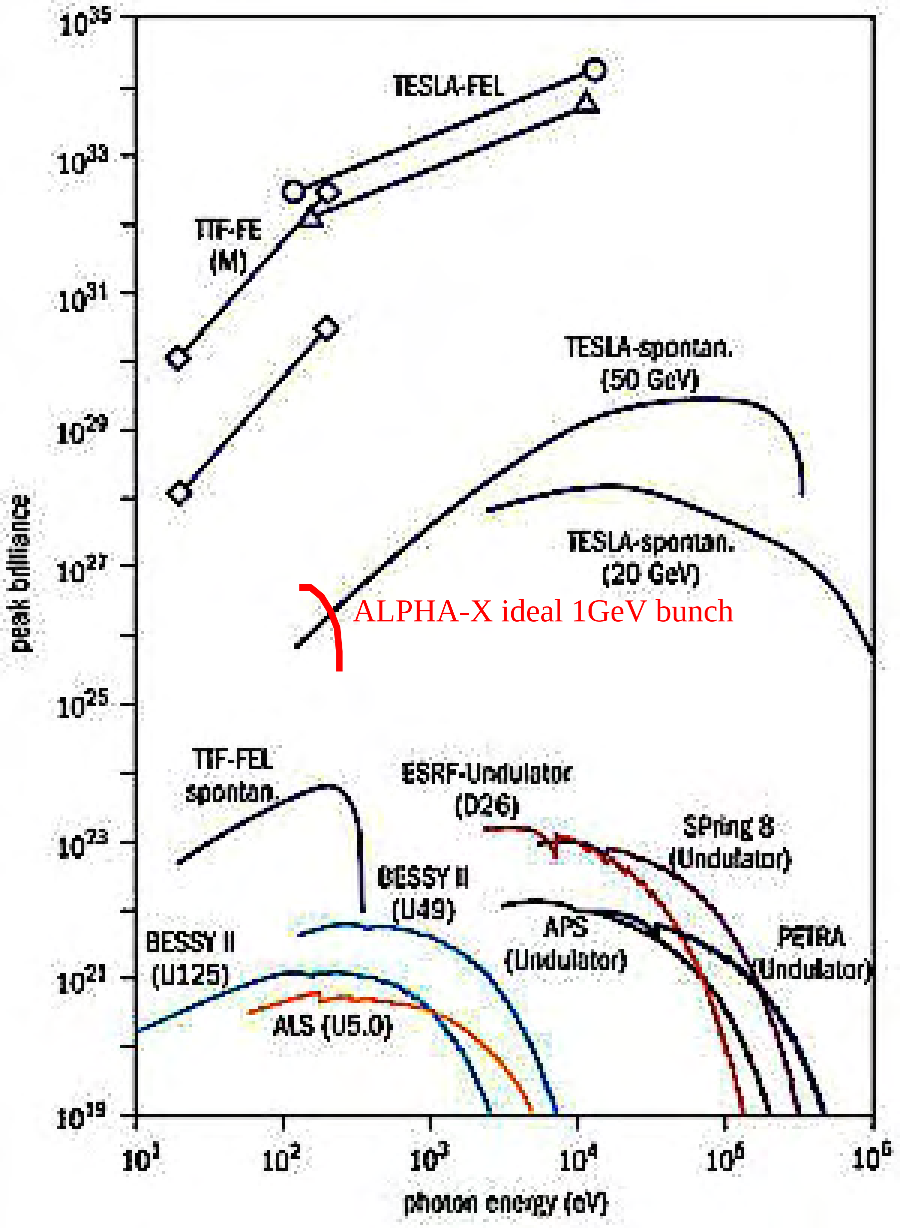
N_u = 200

ε_n = 1 π mm mrad

τ_e = 10 fs

Q = 100 – 200 pC

FEL: Brilliance 5 – 7 orders of magnitude larger



ALPHA-X ideal 1GeV bunch

Free-electron laser driven by wakefield accelerator

- Combination of undulator and radiation fields produces ponderomotive force which bunches electron on a wavelength scale
- Laser field grows exponentially at a rate governed by
- Matched electron beam: $\rho = 1.1\, \gamma^{-1} B_u\, \lambda_u^{4/3} I_{pk}^{1/3}\, \varepsilon_n^{-1/3}$
- *Gain length* $$L_g = \frac{\lambda_u}{2\pi\sqrt{3}\rho}$$
- *Need* $\delta\gamma/\gamma < \rho$ *and* $\varepsilon_n < 4\lambda\beta\gamma\rho/\lambda_u$ *or* $\varepsilon_n < \gamma\lambda$ *(matched)*

See Bonifacio et al. (Nuova Cimento 1990, 1992)

Free-electron laser

Ultimate goal of technology: $\lambda \sim 1.5$ nm x-ray FEL requiring ~ 1 GeV

- Growth of an injected or spontaneous field in a FEL amplifier is given by $I = I_0 \exp(gz)$,
- $g = 4\pi\rho 3^{1/2}/\lambda_u$ – small signal gain,
- ρ - FEL gain parameter - a function of the beam energy, current and emittance.
- $\varepsilon_n = \gamma\,\sigma\,\Omega$ is the normalised emittance of the beam.
- $\rho \sim 0.001$ to 0.02 for our expected electron beam parameters but need energy spread $\delta\gamma / \gamma < 2\rho$ i.e. 0.2 – 4%
- gain length $< 10\,\lambda_u$
- **Makes sense to optimise gain, if possible**

EXAMPLE: ALPHA-X: **4 nm source** assuming a **1 GeV beam** with **100 pC charge** and a **duration of 10 fs** we get a **peak current of 10 kA**. With a 1.5 cm period undulator with a field of B field of 1 T we get a $\rho \approx 0.005$, which gives a gain length of $10\lambda_u$ and a constraint on the energy spread of ≈ 1%, which may be achievable. To achieve saturation we need about 100 – 200 undulator periods.

Conclusion

- Femtosecond compact radiation sources feasible
- Compact synchrotron
- Compact FEL
- Large tuning range THz to x-ray (water window)
- Challenges: emittance, peak current, energy spread
- More challenges: synchronism, shot to shot jitter, bunch duration
- Outlook good with a lot of work – need a roadmap
- Linear collider application far away. Need to develop laser technology and schemes for staging

END