Development of an advanced laser plasma wakefield accelerator as a compact coherent radiation source

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ELAN May 2004 Frascati

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Advanced Laser Plasma High-energy Accelerators towards X-rays: ALPHA-X ($\alpha-\xi$)

Collaborative project involving groups from the UK, EU and US

- 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
- Abertay-Dundee – injector, electron diagnostics & FEL
- St Andrews University – theory

GOALS: Accelerate to 1 GeV in 1cm using a wakefield accelerator. Demonstrate coherent radiation source: FEL

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Outline

- Overview and involvement
- Laser-plasma wakefield accelerator
- Plasma channel
- Injector development
- Free-electron laser
- Diagnostics

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People involved in project

- **Dino Jaroszynski, Klaas Wynne, Bob Bingham, Ken Ledingham, Albert Reitsma, Yuri Saviliev, Slava Pavlova, Riju Issac, David Jones, Bernhard Ersfeld, Steven Jamison, Gregory Vieux, Enrico Brunetti** – *Strathclyde*
- **Karl Krushelnick, Bucker Dangor , Zulfika Najmudin, Stuart Mangles** – *Imperial College*
- **Bob Bingham, Henry Hutchinson, Peter Norreys, Stefan Karsch, Chris Murphy** – *RAL (CCLRC)*
- **Simon Hooker, Justin Wark, Keith Burnett, Ian Walmsley, David Spence, Tony Gonsalves** – *Oxford*
- **Allan Gillespie, Allan McCloud, Steven Jamison,** – *Abertay-Dundee*
- **Alan Cairns** – *St Andrews*
- **Mike Poole, Jim Clark** – *Daresbury (CCLRC)*
- **Gennady Shvets** – *Fermilab*
- **Terry Garvey, J Roudier** – *LAL Orsay*
- **Antonio Ting** – *NRL*
- **Chan Joshi, Warren Mori** – *UCLA*
- **Tom Katsouleas** – *USC*
- **Padma Shukla** – *Bochum*
- **Tito Mendonca, Nelson Lopes, Luis Silva** – *IST Portugal*
- **Kees van der Geer, Marieke Loos, Bas van der Geer** – *The Netherlands*
- **Andrey Savilov, Vladimir Bratman** – *IAP, Nizhniy Novgorod*

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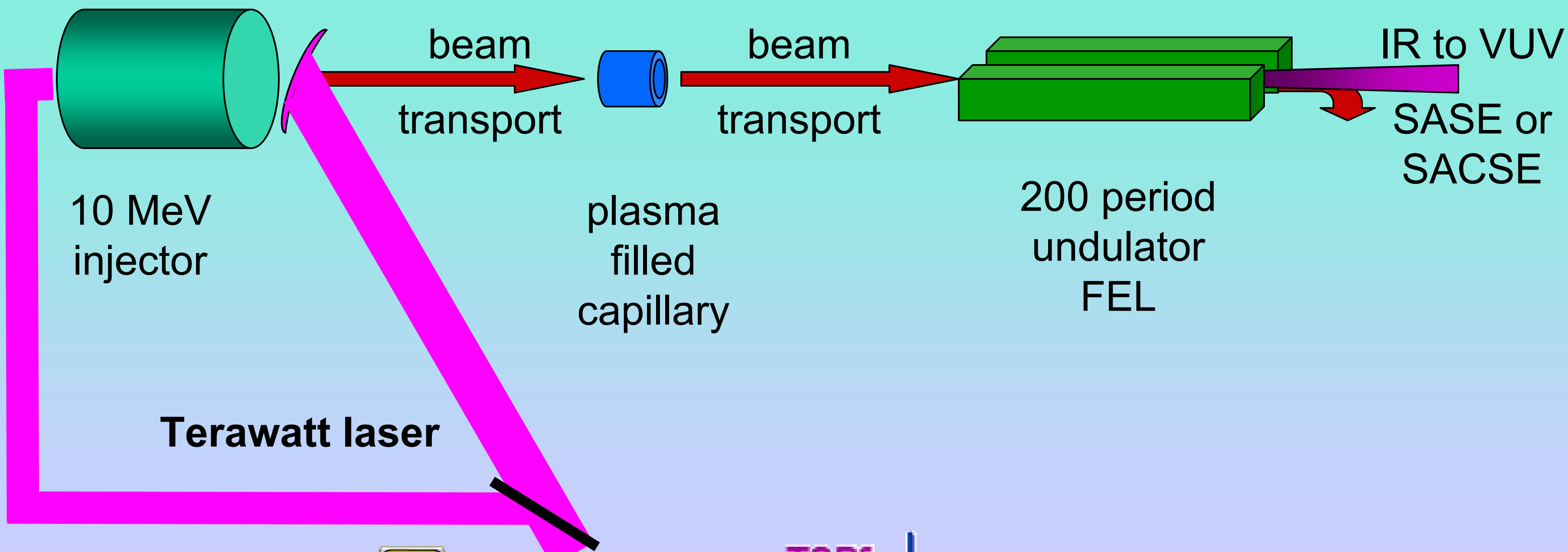
ALPHA-X Programme

Main areas of research:

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



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α–ξ Sources: ASTRA, TOPS and OXFORD

TOPS (Strathclyde): 5TW source (800nm, 50fs 10Hz 250mJ) upgrade to 1J (20 TW)

ASTRA (RAL): 10 TW source (800nm, 50fs, 10Hz, 500 mJ) upgrade to 1J

Oxford: 2 TW source (800nm, 50fs, 10Hz, 100 mJ)

Strathclyde: 10 MeV High-brightness sub-picosecond photoinjector – being constructed

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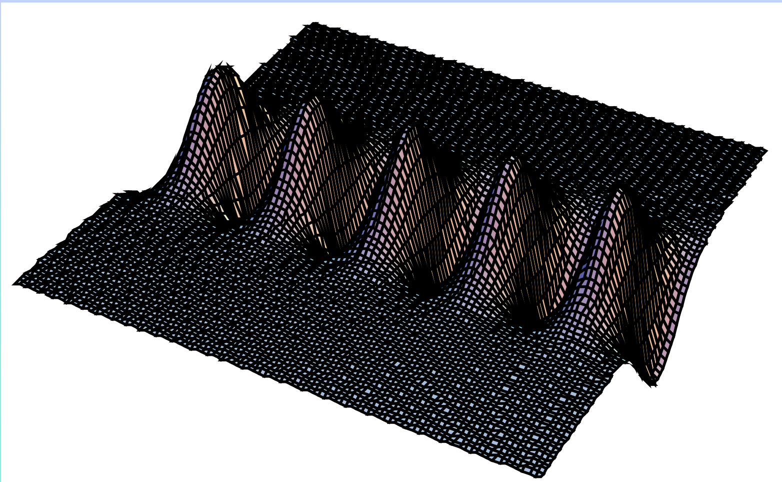
Wakefield accelerator



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

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

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

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

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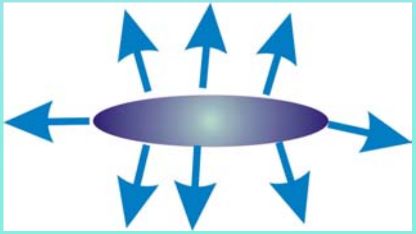
Wakefield accelerator

- Acceleration field in plasma $E \sim \frac{\delta n_e}{n_e} m_e c \omega_p$ acceleration gradients > GeV/cm
- Electron is trapped in wave and gains energy $\Delta W \sim 2 \frac{\delta n_e}{n_e} \gamma_\phi^2 m_e c^2$ where $\gamma_\phi^2 \sim \frac{\omega^2}{\omega_p^2}$
- Charge 100 pC
- Bunch duration 100 fs
- Peak current 1 kA
- Emittance $\varepsilon_n < 1\pi$ mm mrad $\varepsilon_n = \gamma \, \sigma \, \Omega$
- Energy spread < 1%
- Brightness $(B = I / 4\pi\varepsilon_n^2) > 10^{14}$ A/m^2
- Plasma density $10^{17} – 10^{18}$ cm^{-3}
- Laser 800 nm 1 J 30 fs



Laser ponderomotive force creates wake

Main challenges

- Inject relativistic electron bunch into a small volume of phase-space
- Injecting e-m radiation and electron beam into channel
- Diagnostics

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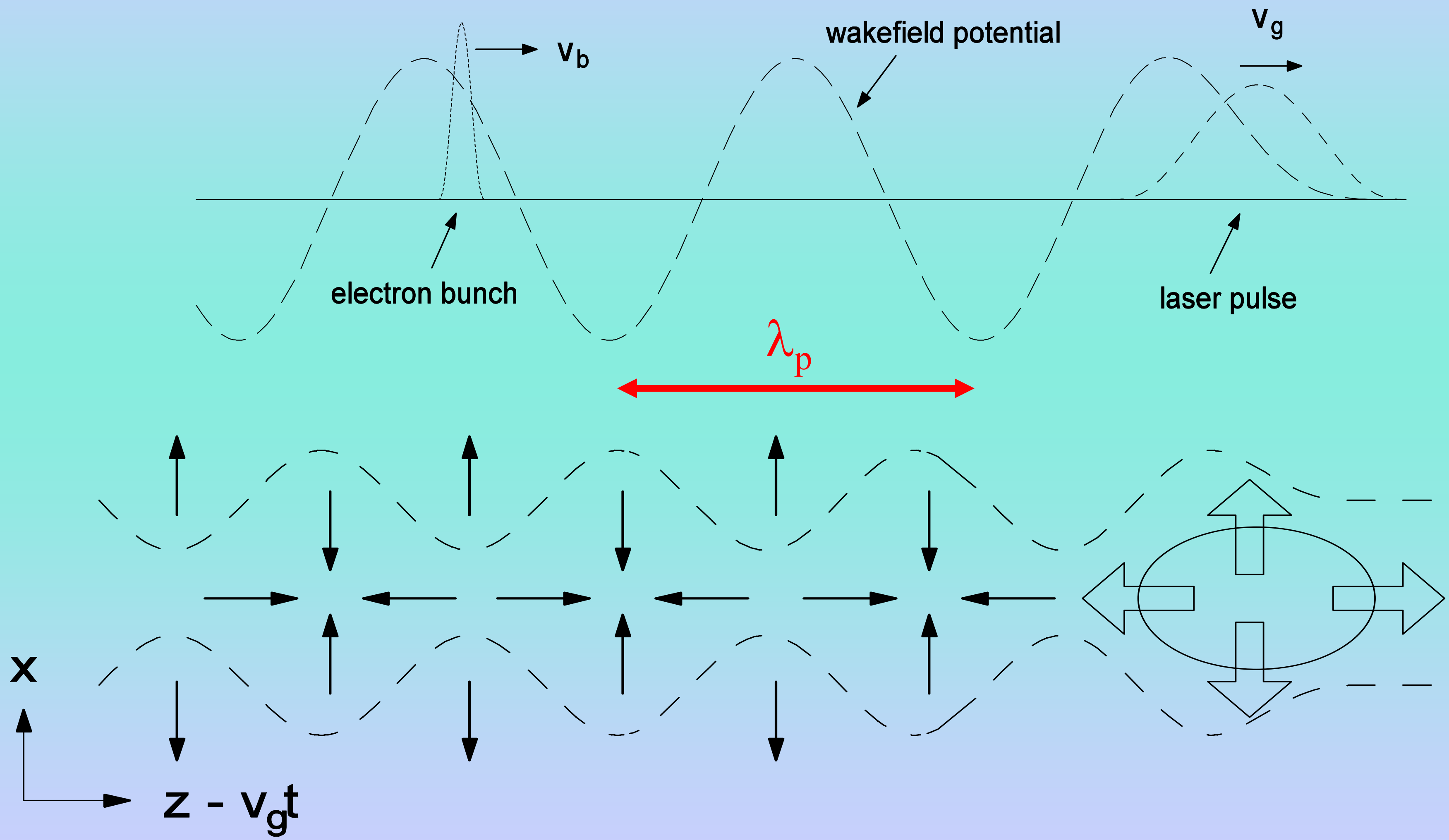
Wakefield acceleration



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Simulations for Alpha-X

Conventional injector

Collaboration with Pulsar Physics from The Netherlands for DC/RF design & beam transport study.

Use of the general-purpose GPT particle tracking code

All-optical injector

Use of Osiris PIC-code in collaboration with visiting fellows from UCLA (USA) & IST (Portugal)

Wakefield accelerator

Use of our own (fast) codes for laser pulse & electron bunch dynamics in laser wakefield accelerator

→ *see next slide*

Free-electron laser

GPT contains elements for self-consistent FEL calculations

Plasma channel

At this time, no plasma channel calculations are performed

Wakefield accelerator

- *Fully self-consistent 1-D model of coupled laser pulse, wakefield and e-bunch evolution*

$$H_{ph} = \omega - v_g k$$

Hamiltonian

$$\omega^2 = c^2 k^2 + \omega_p^2/(1+\varphi)$$

local dispersion relation

$$H_{el} = mc^2(\gamma - \varphi) - v_g p$$

Hamiltonian

$$\frac{d\zeta}{dt} = \frac{\partial H_{ph}}{\partial k}, \quad \frac{dk}{dt} = -\frac{\partial H_{ph}}{\partial \zeta}$$

ray-tracing equations

$$c^2 \frac{\partial^2 \varphi}{\partial \zeta^2} = \omega_p^2 \left(\frac{1 + |a|^2 - (1+\varphi)^2}{2(1+\varphi)^2} + \frac{n_b}{n_p} \right)$$

quasi-static wakefield equation

$$\frac{d\zeta}{dt} = \frac{\partial H_{el}}{\partial p}, \quad \frac{dp}{dt} = -\frac{\partial H_{el}}{\partial \zeta}$$

equations of motion

$$|a|^2 \propto \int (f_p/\omega)\, dk$$

intensity

$$n_b \propto \int f_b\, dp$$

density

$$f_p(\zeta, k)$$

laser pulse

$$f_b(\zeta, p)$$

electron bunch

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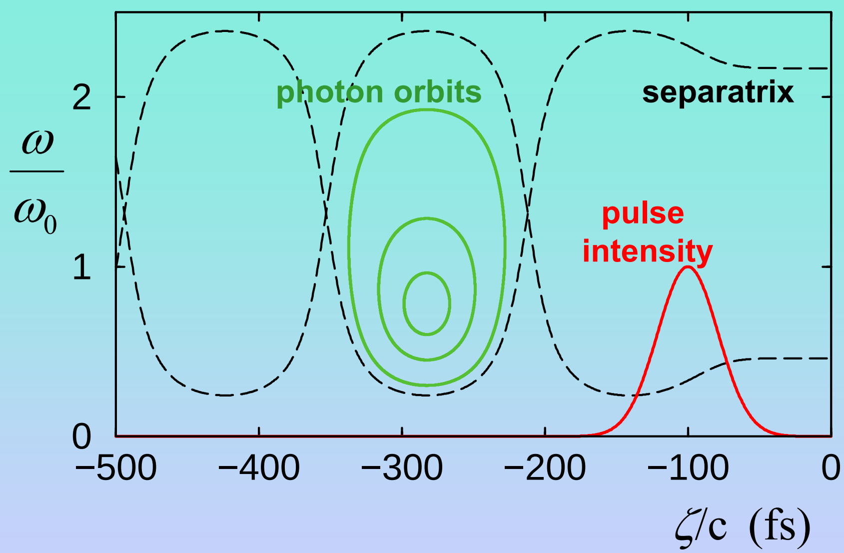
Photon kinetic theory

- describes photon collective behaviour in plasma with ray-tracing equations
  → frequency change due to spatio-temporal refractive index variation

- valid if refractive index changes slowly compared to optical cycle/wavelength
  → refractive index determined by quasi-static plasma electron density profile
  → frequency goes up/down in accelerating/decelerating part of wakefield



example: photon dynamics in a plasma wave

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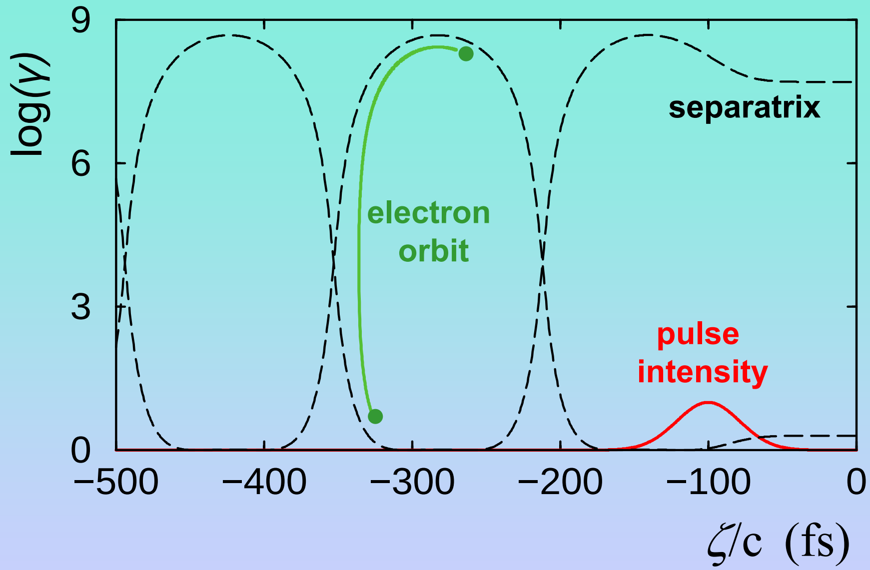
Electron acceleration

- 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

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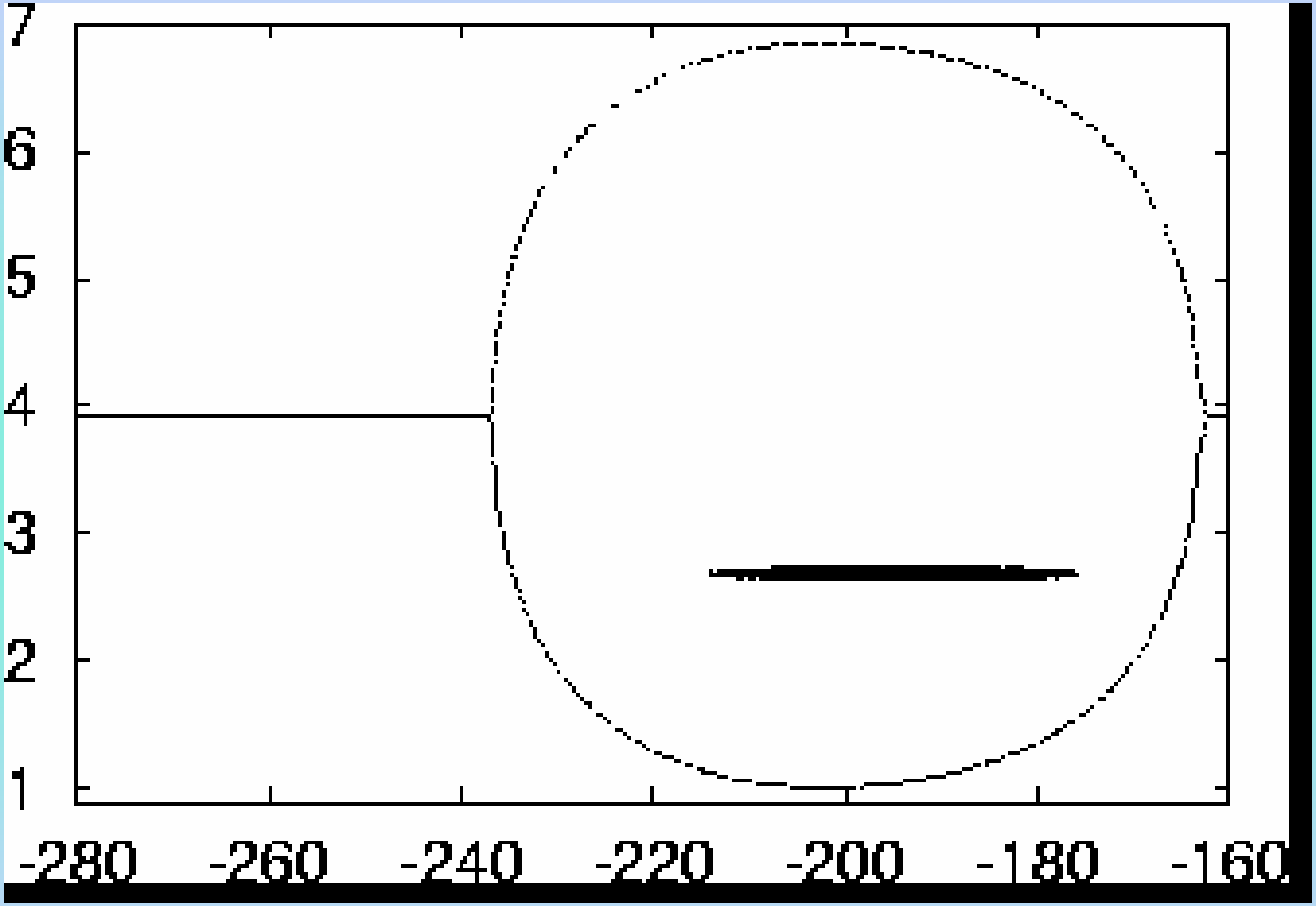
Phase-space evolution



log γ

z / v_g - t (fs)

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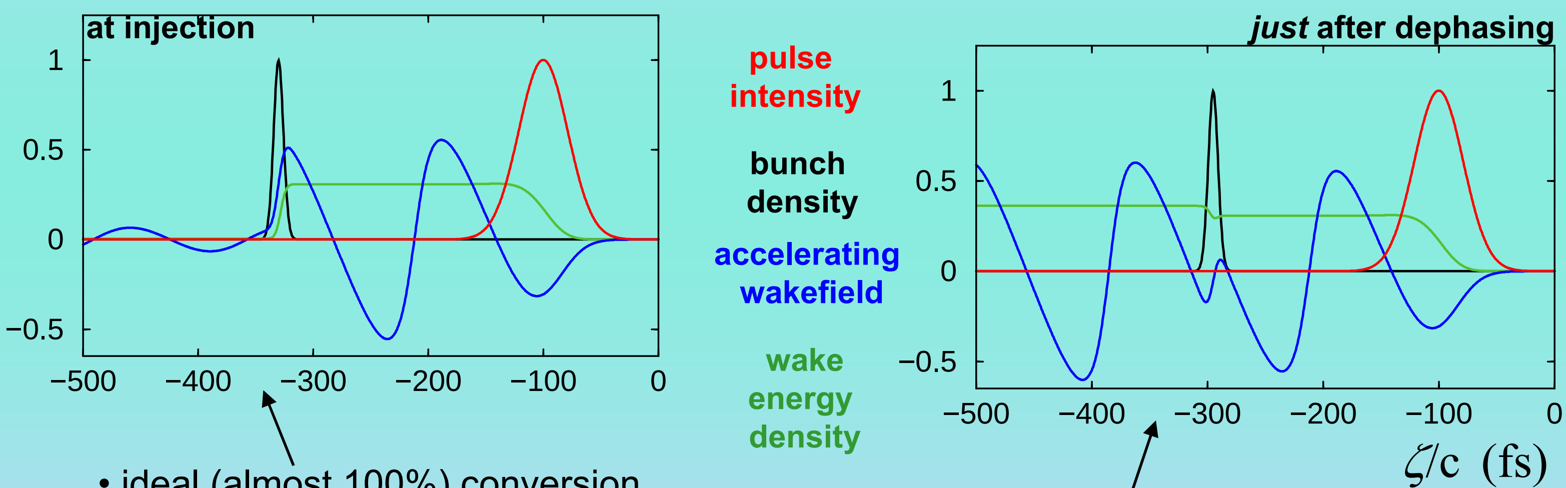
Efficiency

effect of bunch wakefield = beam loading

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

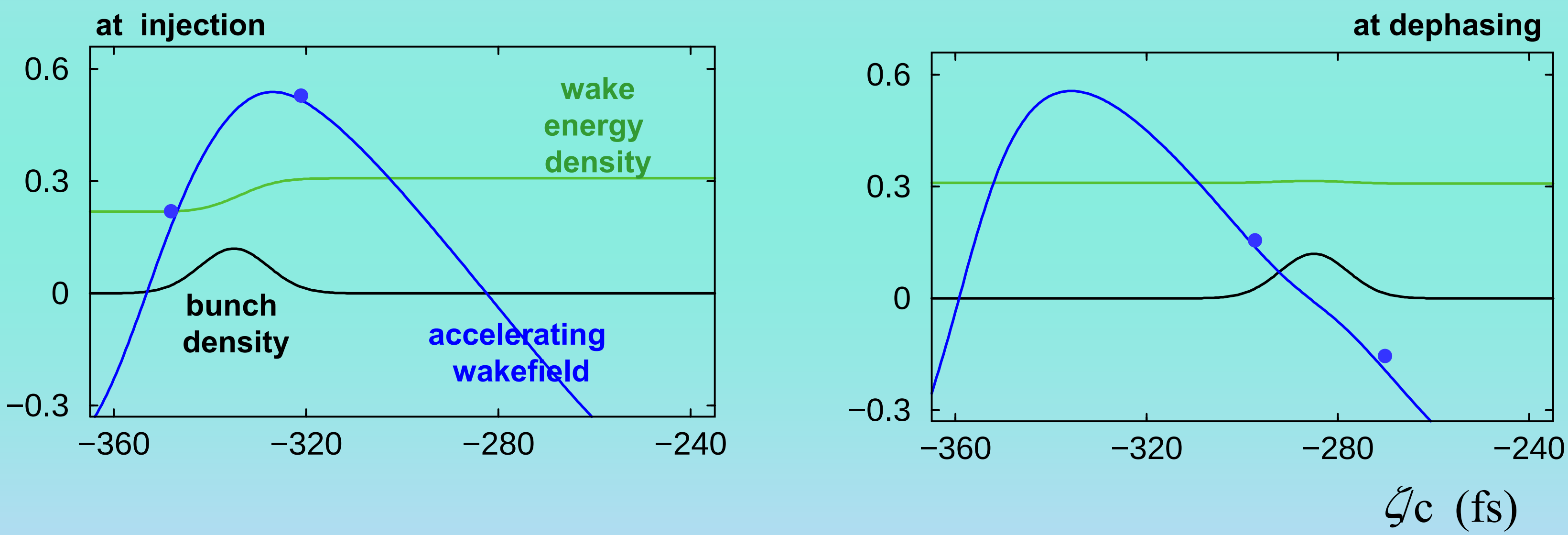


- ideal (almost 100%) conversion of wake energy into bunch energy
- all electrons accelerated
- wakefield suppressed at rear part of bunch
  → bunch slips out of ideal position
  → large spread of accelerating field induces large energy spread

- 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

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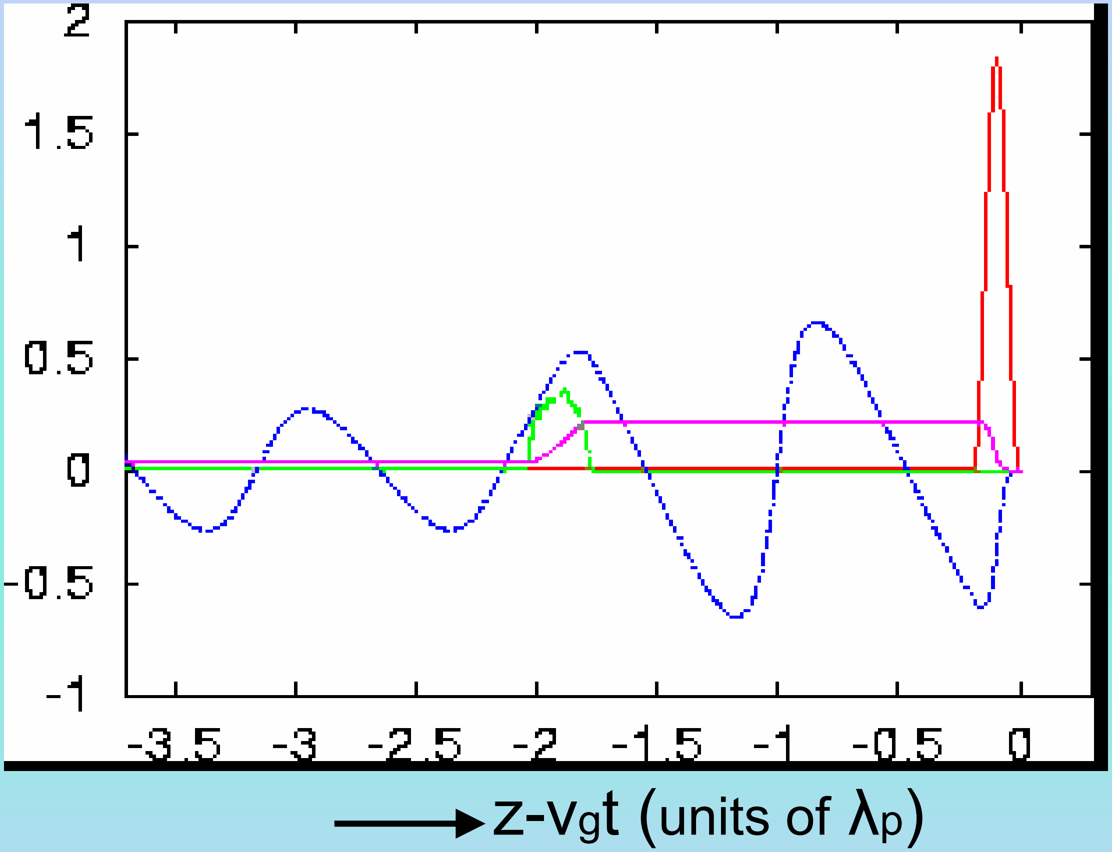
Laser Wakefield Acceleration



laser pulse envelope

electrostatic wakefield

bunch density

energy density of wakefield

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

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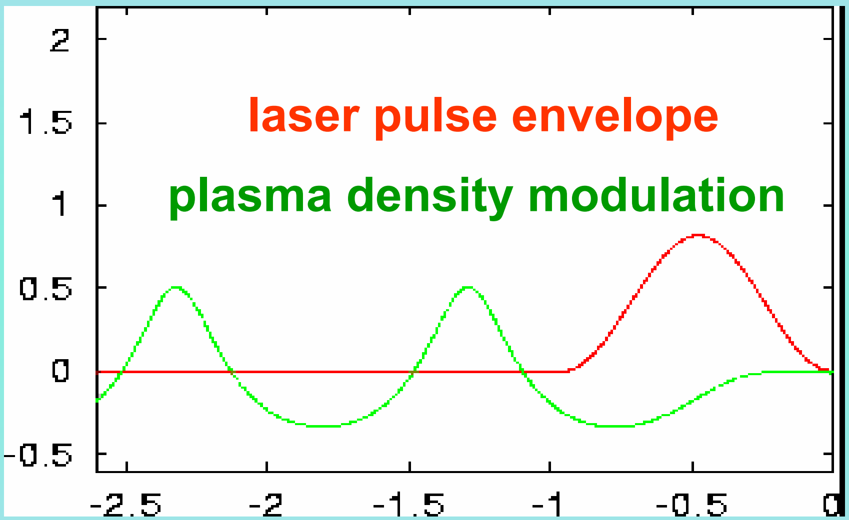
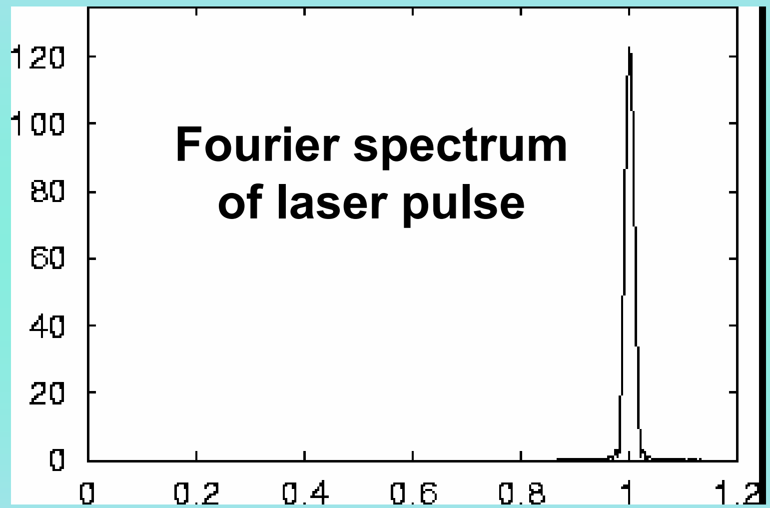
Laser pulse envelope dynamics

laser pulse amplitude: a_0

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



→ z-v_gt (units of λ_p)



→ k / k_0

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

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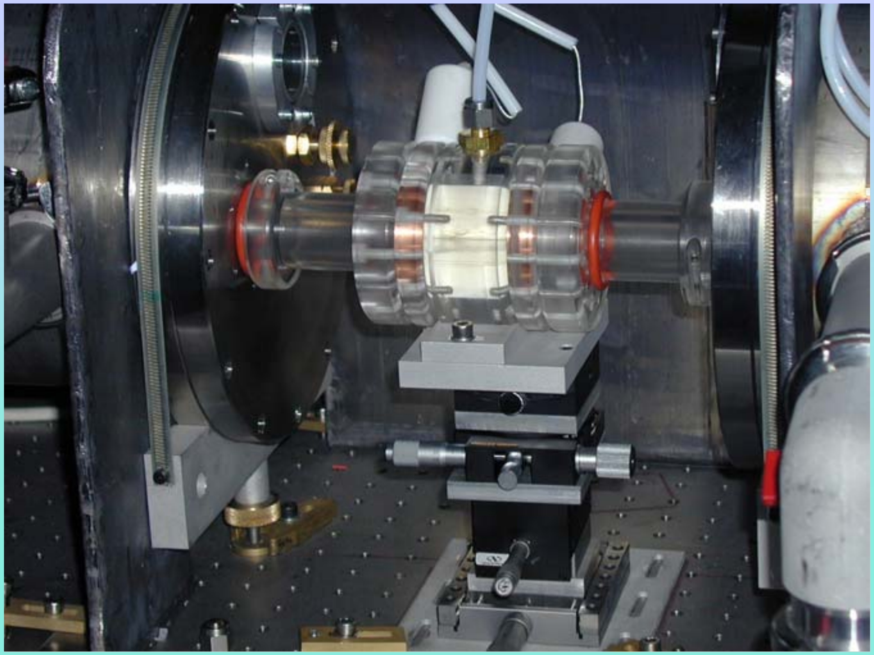
α–ξ Capillary: preformed plasma waveguide



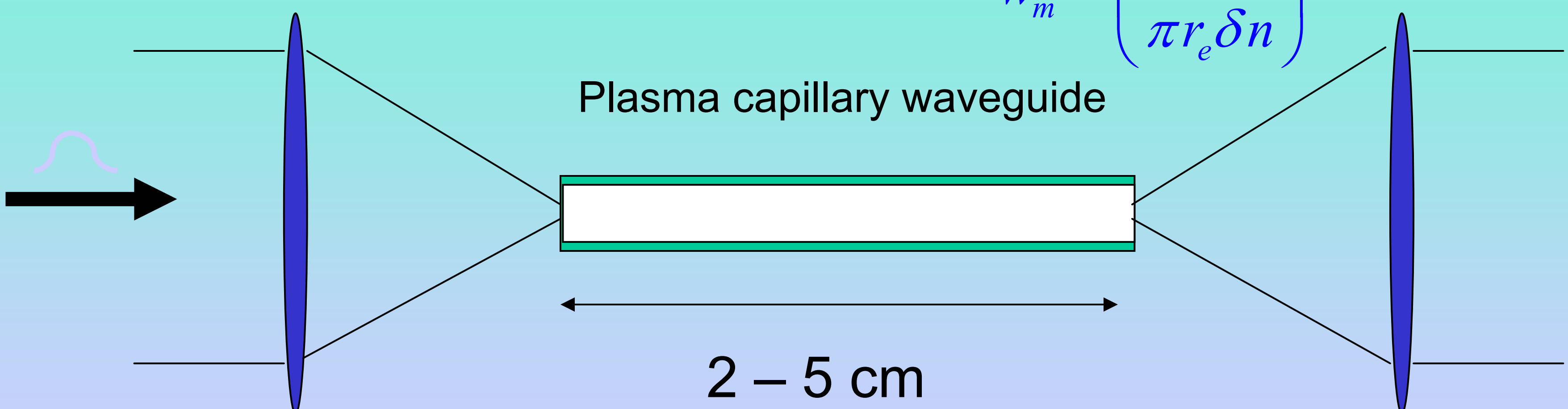
r_0 = 150 μm capillary

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

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

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

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



Phase-matching possible using tapered capillary

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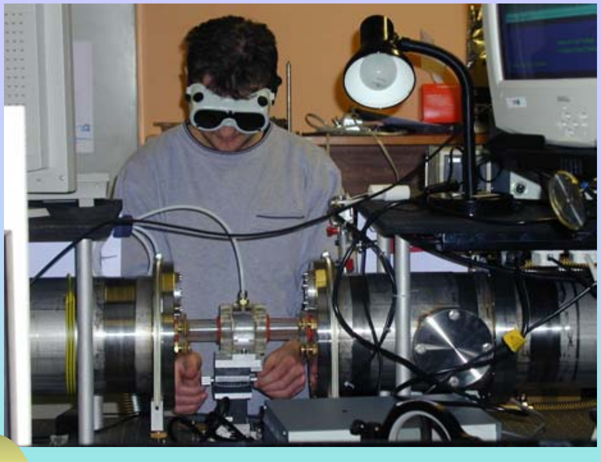
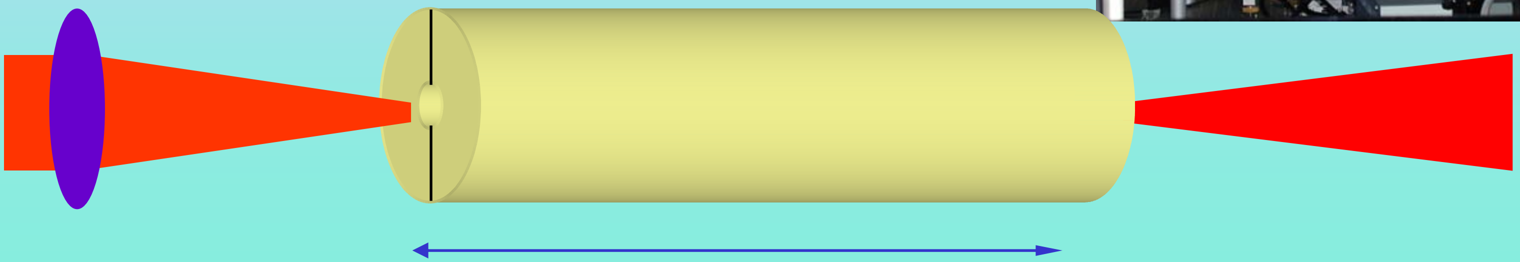
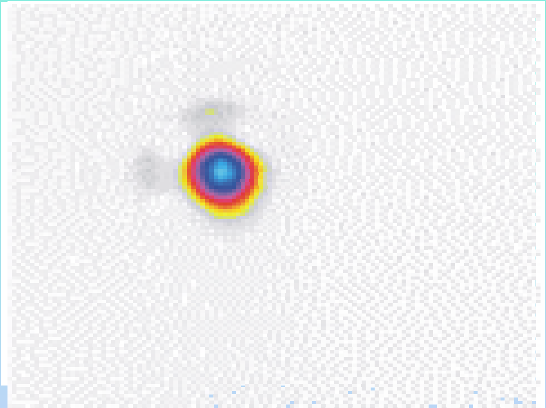
Measurements of guiding in plasma capillaries at Strathclyde

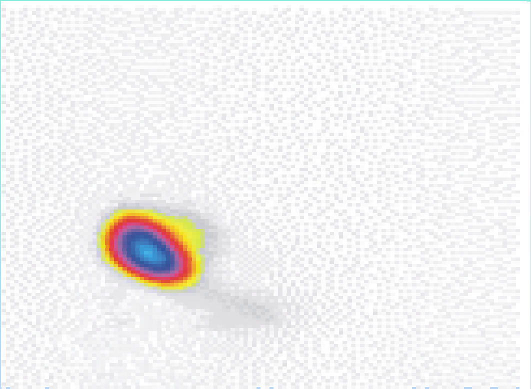




400 mm



~ 60 μm dia.



~ 60 μm dia.

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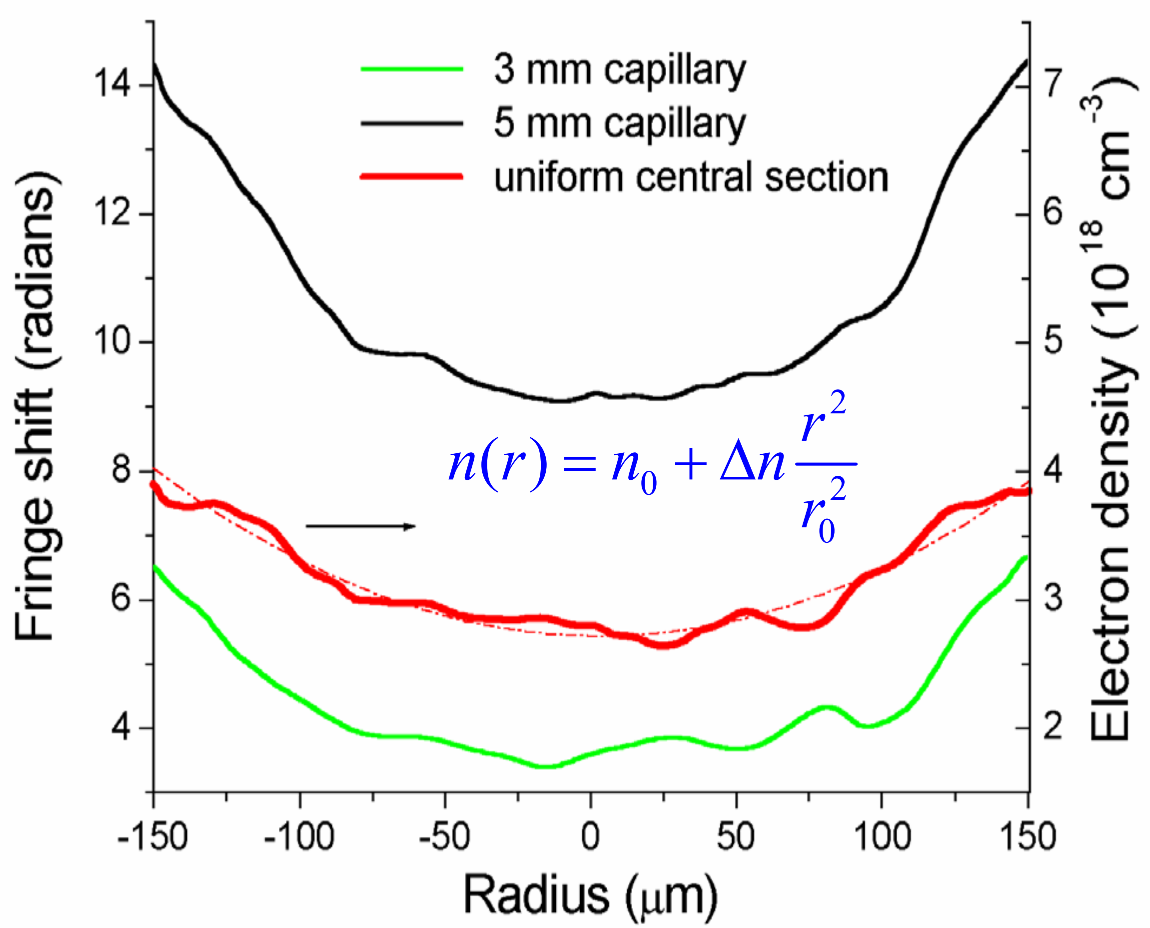
Plasma-filled capillary waveguide: electron density profile measured at Oxford

D. J. Spence & S. M. Hooker *Phys. Rev. E* **63** 015401 (2000)



- Electron density measured with Mach-Zender interferometer for τ = 60 ns.
- Initial hydrogen pressure is 63 mbar.
- Central section **parabolic** electron density profile: matched spot size 37 μm.
- 90 % transmission over 4 cm channel
- > 10^5 shots

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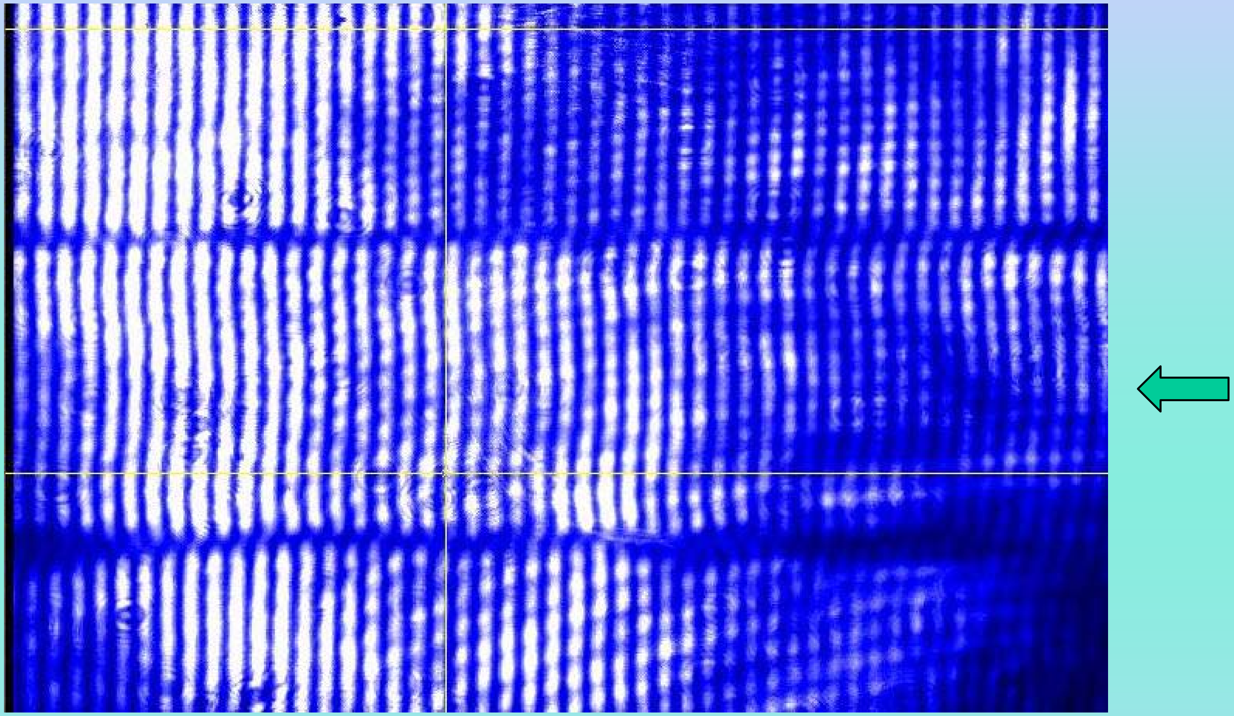
Transverse interferometry of plasma channels



- Transverse interferometry of a plasma channel
- Initial hydrogen pressure ~ 100 mbar

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Development of injector technology

- **Conventional accelerator Technology: Combined DC and RF accelerator**
- **All optical injectors: self-modulated wakefield & wavebreaking**
- **Pre-buncher**

Main challenges

To Achieve:

- synchronisation (< 20 fs)
- sufficient charge – goal: 100 pC
- short duration – goal: < 100 fs $(<\lambda_p/2)$
- good emittance – goal: $\varepsilon = \gamma\sigma\Omega < 1\pi \text{ mm mrad}$
- modest energy spread
- combat space-charge effects and electron broadening due to CSE

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Conventional injector technology

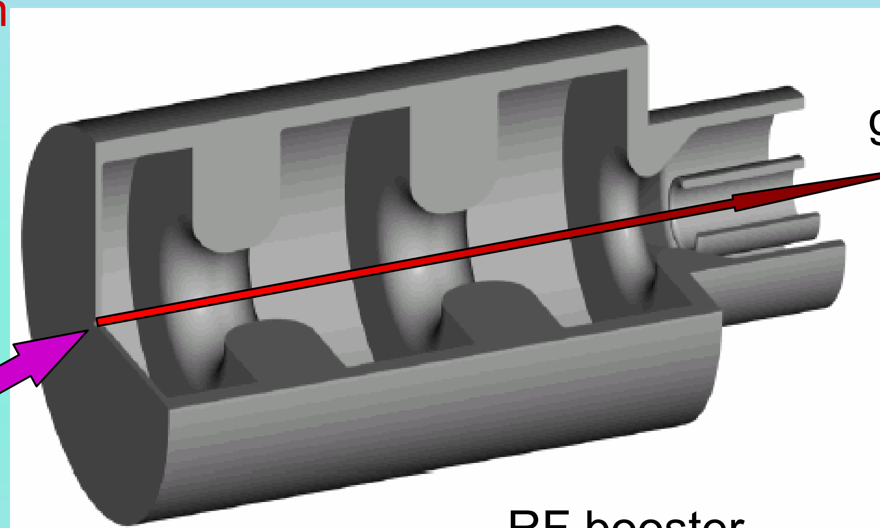
10 MeV Hybrid DC/RF accelerator – based on design by Marnix van der Wiel's group in Eindhoven

Photocathode ensures synchronisation

DC pre-accelerator

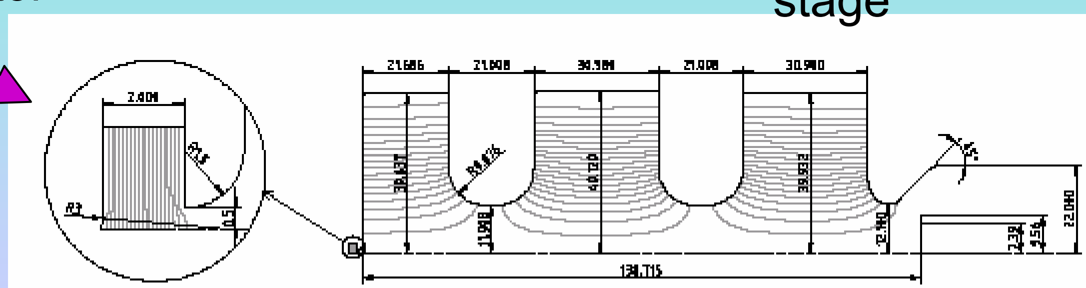
HV: 1ns 1 MV

photoinjector



DC pre-accelerator

RF booster stage



RF accelerator

S-band (3 GHz)

10 MW to produce a gradient of 100 MV/m

100 pC - 1 nC

8 MeV

100 fs bunches

2% energy spread

ε < 1 π mm mrad

(design by van der Wiel, Geer and Loos, 2001)

2 ½ cell booster

Based on original design by BNL

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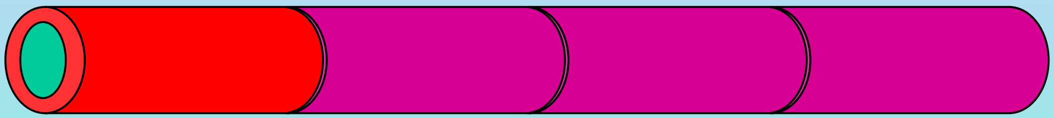
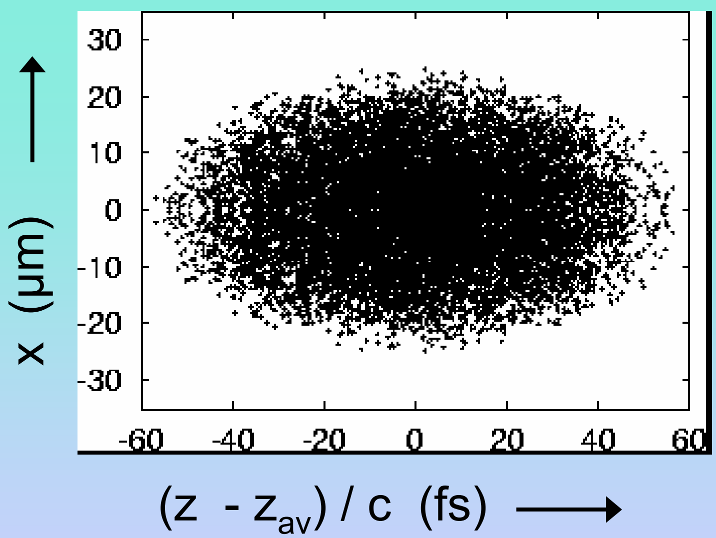
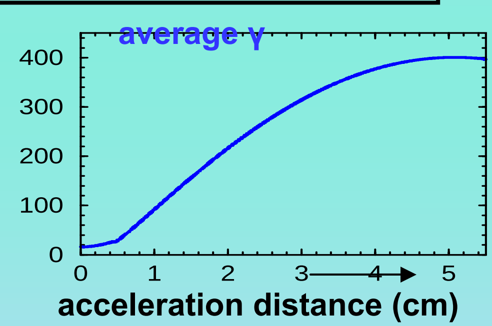
Compression in two-stage accelerator

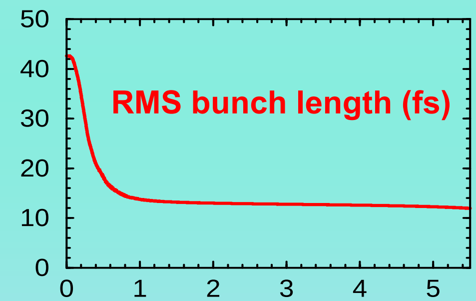


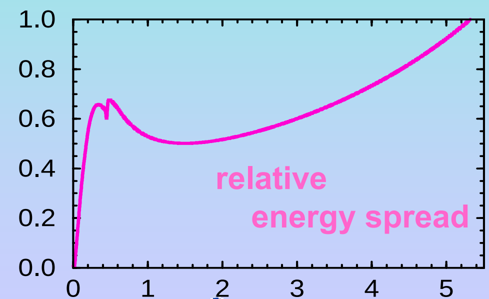
1 - low plasma density	2 - high plasma density
long plasma wavelength for compression	high gradient for acceleration

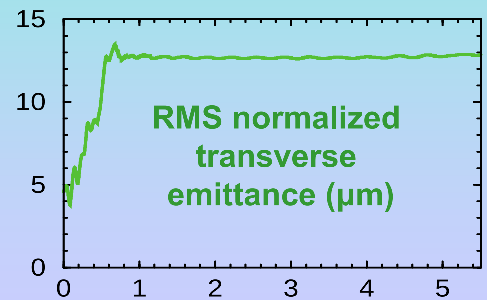
example:
0.4 cm plasma density 1.7 x 10^{17} cm^{-3}
followed by
5 cm plasma density 5.4 x 10^{17} cm^{-3}











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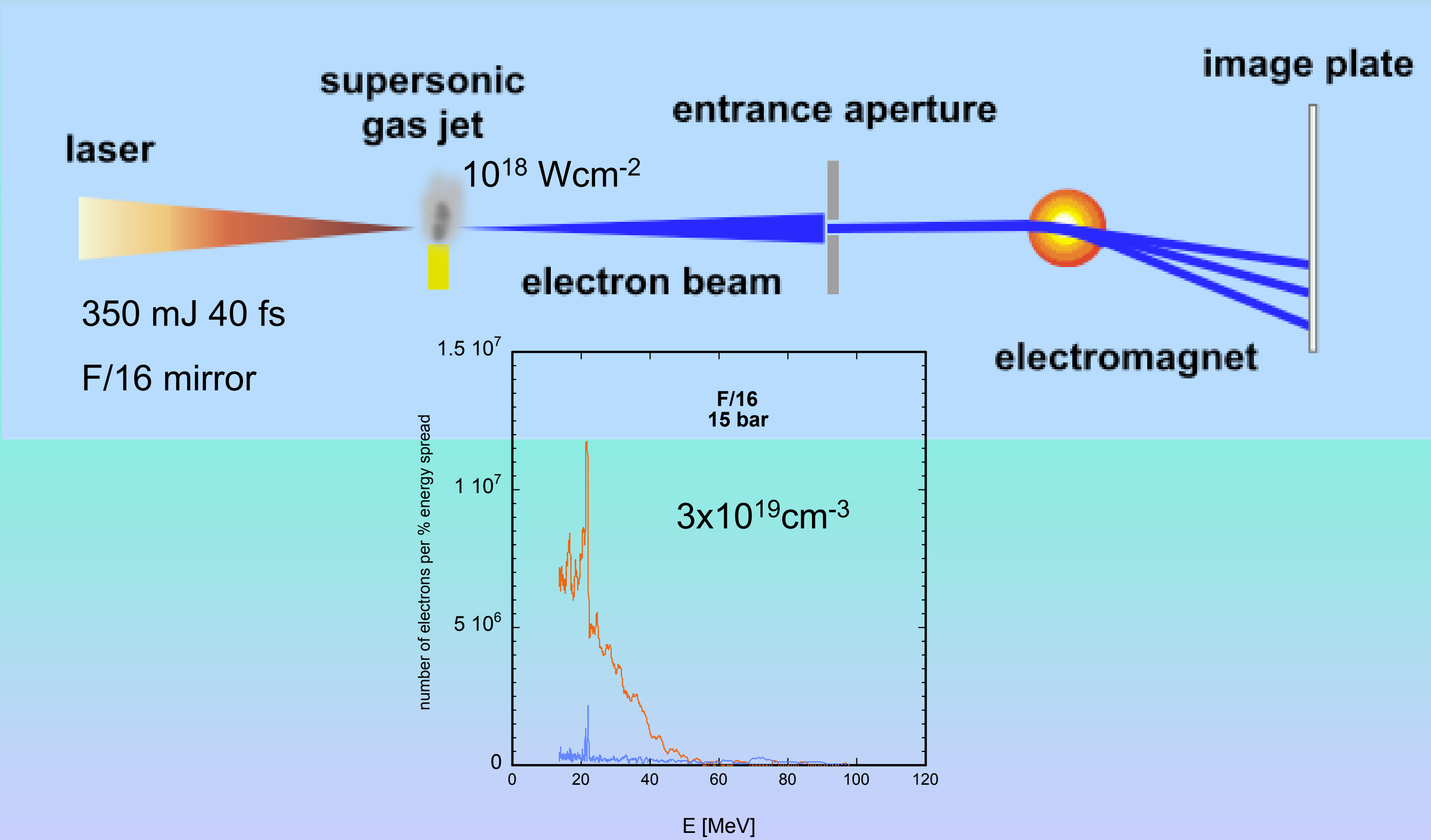
All-optical injection experiments on ASTRA: Imperial College and RAL



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Coherent radiation source: Free-electron laser (FEL)

- Use output of wakefield accelerator to drive FEL
- Take advantage of electron beam properties
- Coherent spontaneous emission: prebunched FEL
- Operate in superradiant regime: FEL amplifier

Potential compact future x-ray FEL

- Need GeV beam with < 50 fs electron beam with I > 1 kA
- Need to operate in superradiant regime to provide useable beam: SASE alone is not adequate
- Need to consider injection

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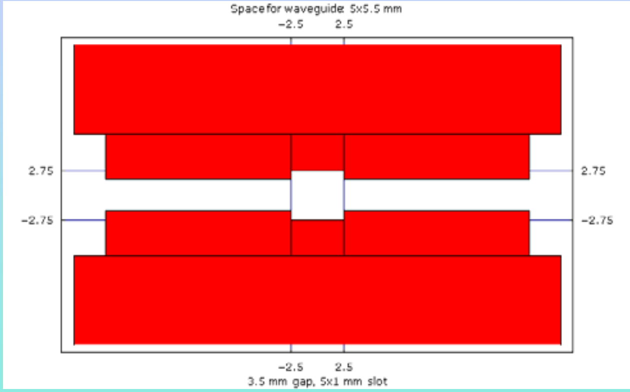
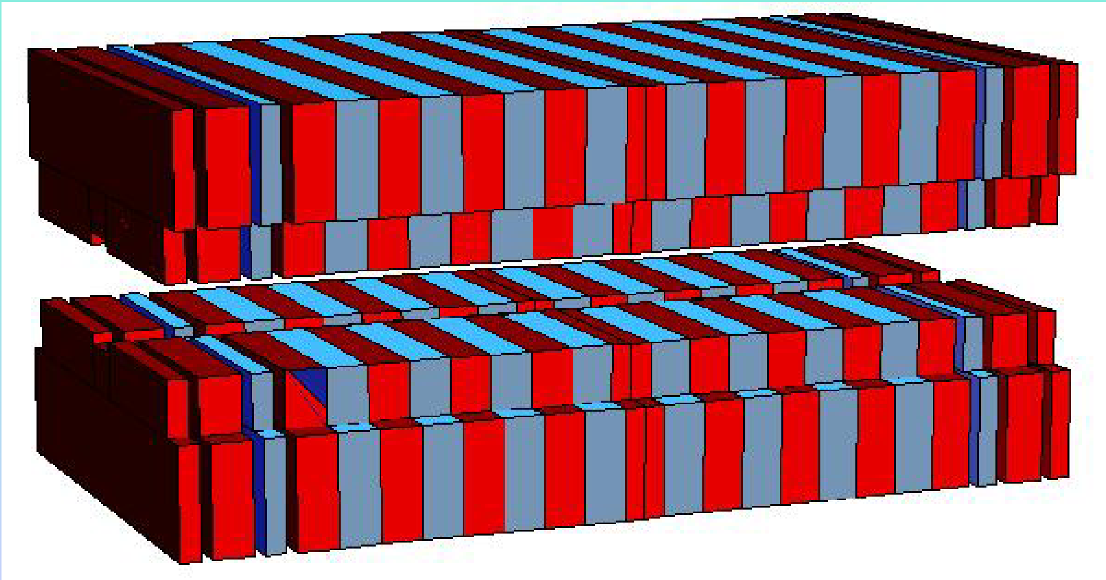
Undulator design

Focussing poles



slotted



Design by J. Clark and B. Shepherd (Daresbury) and Kees van der Geer (Netherlands)

$$\lambda_u = 1.5 \text{ cm}$$
$$N_u = 200$$
$$a_u = 1$$

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Diagnostics: Single-shot electro-optic detection (Abertay & Strathclyde)

  - Spectral encoding
  - Cross-correlation
- Electrons from gas-jets
- FELIX electron bunch measurements
- FEL far-infrared measurements

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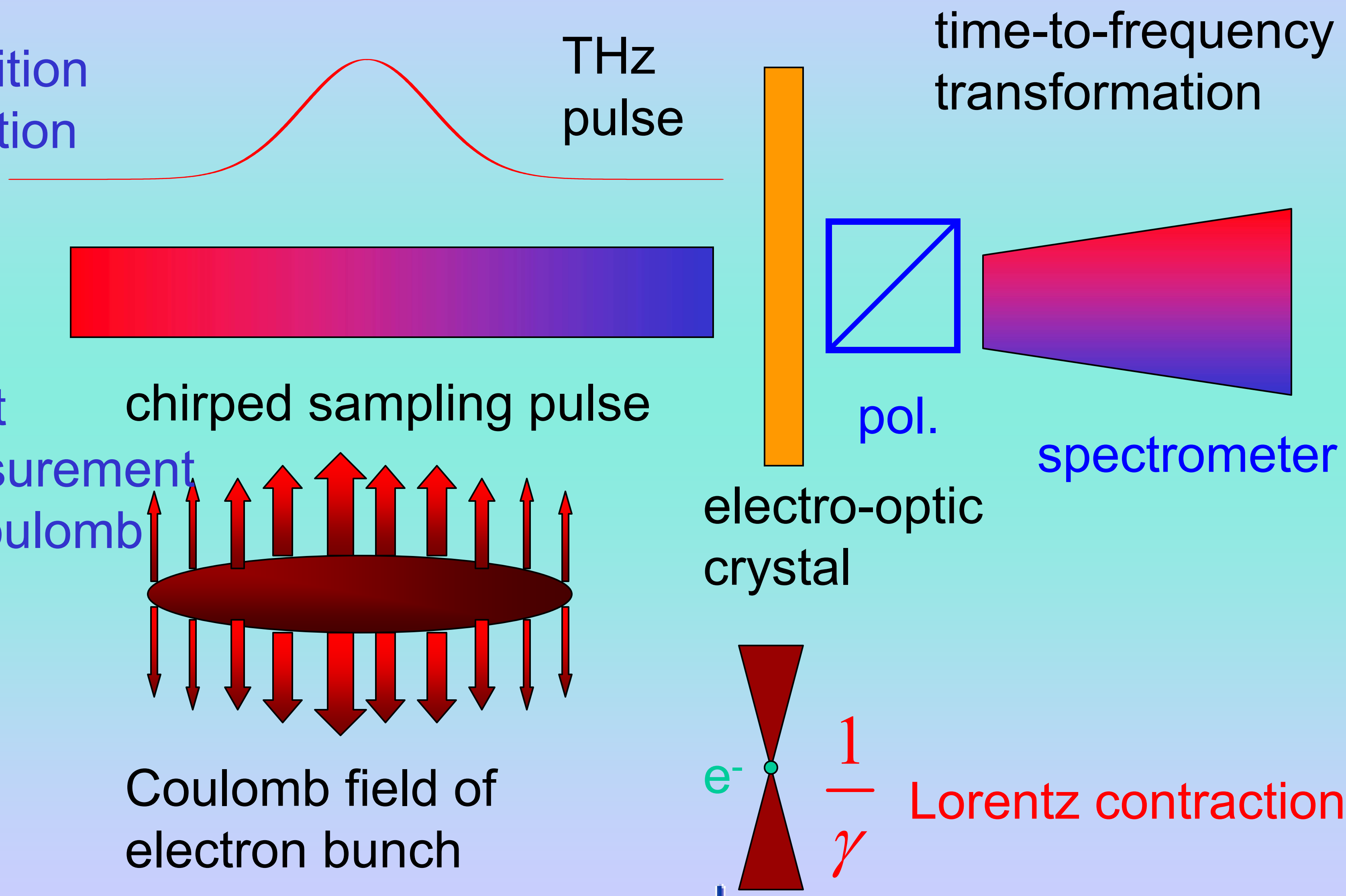
Single-shot and direct measurements

transition radiation

or

direct measurement of Coulomb field



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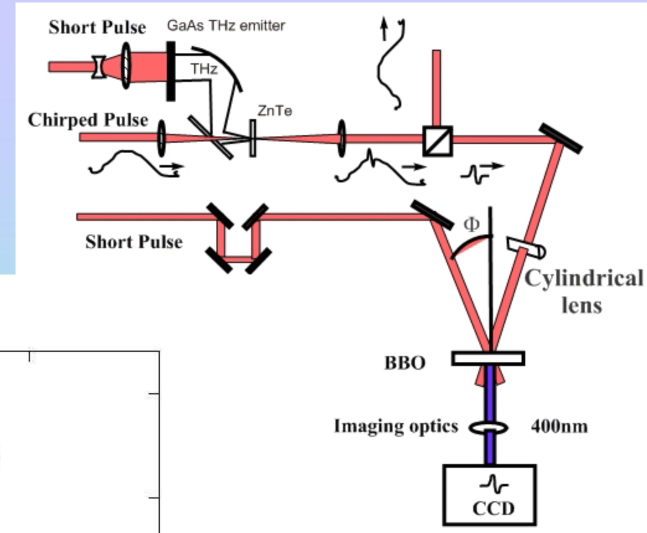
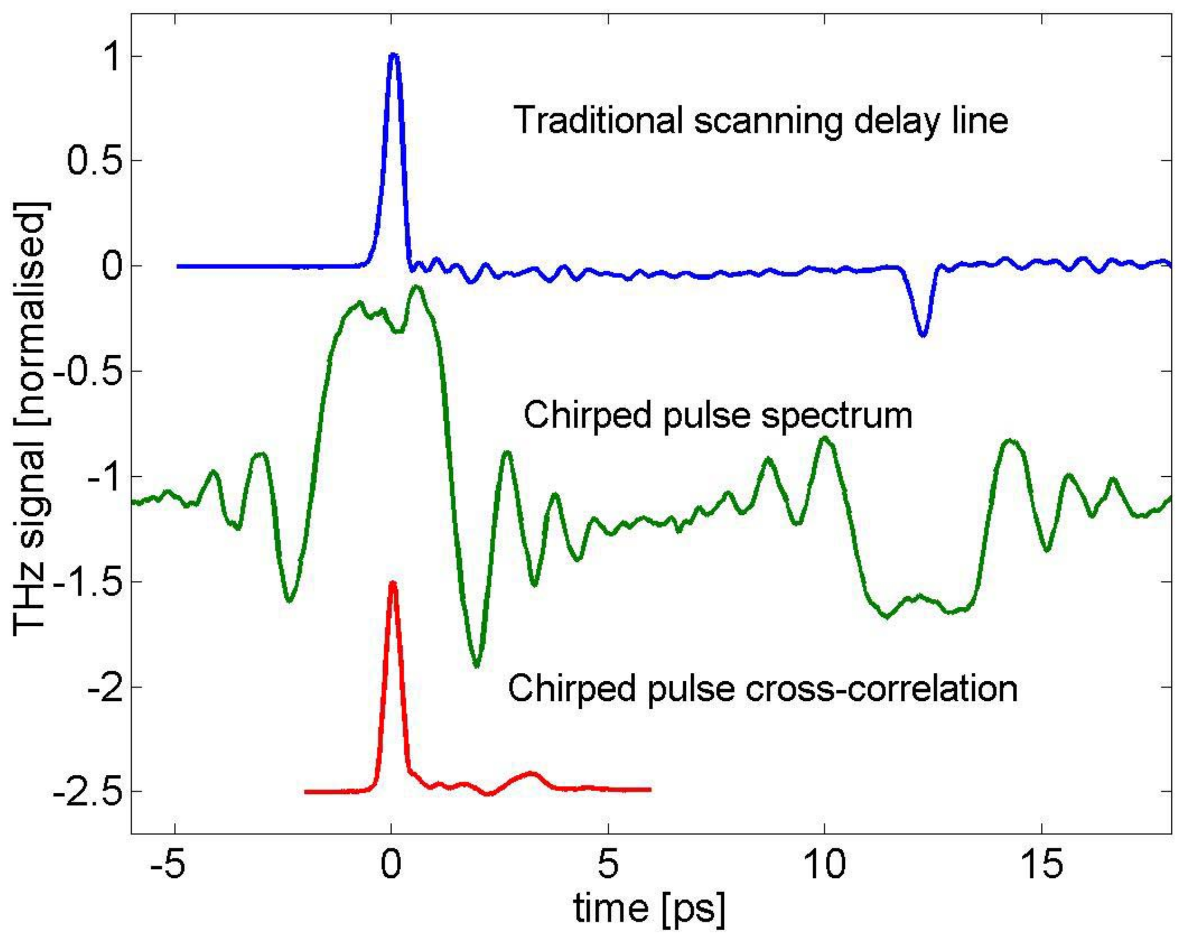
Comparison of techniques (Strathclyde)





Jamison, et al.
Optics Letters
(2003)

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TOPS THE STRATHCLYDE ELECTRON AND TERAHERTZ TO OPTICAL PULSE SOURCE

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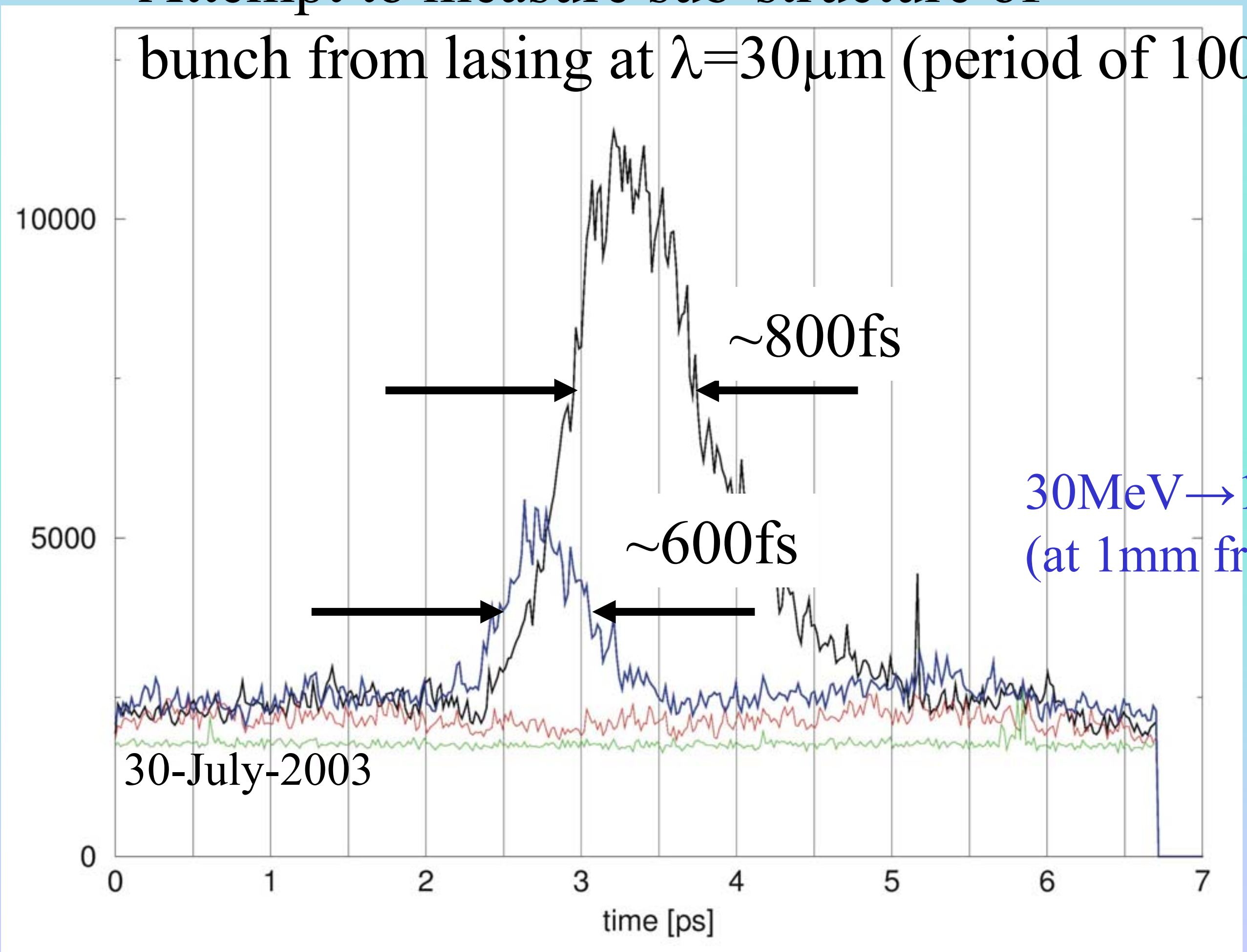
Measurement of bunch after FELIX undulator during lasing

Attempt to measure sub-structure of bunch from lasing at λ=30μm (period of 100fs)



30MeV→110fs resolution (at 1mm from beam)

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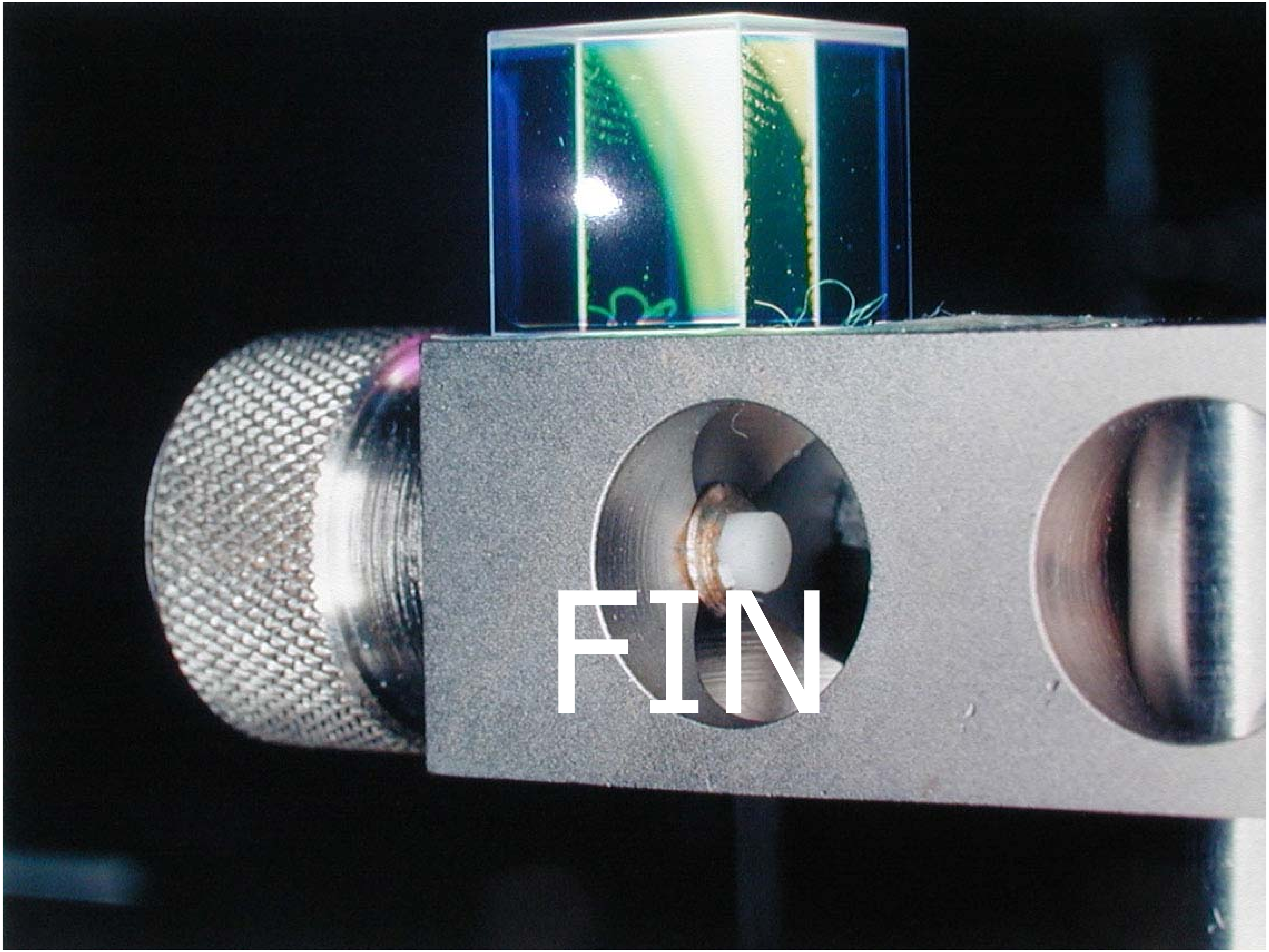
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