Laser particle acceleration

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TR 18

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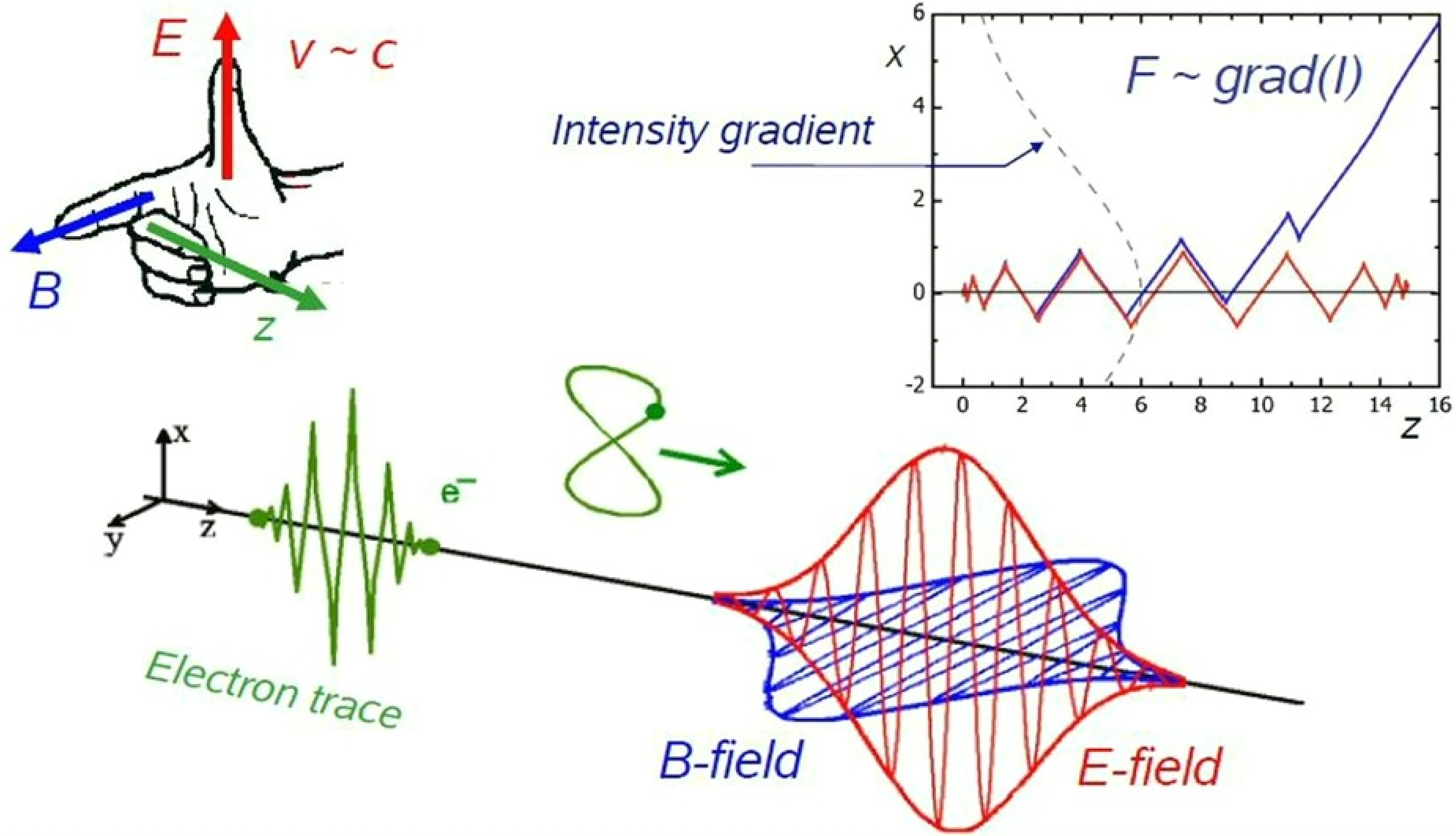
OncoRay
Radiation Research in Oncology

single electron dynamics



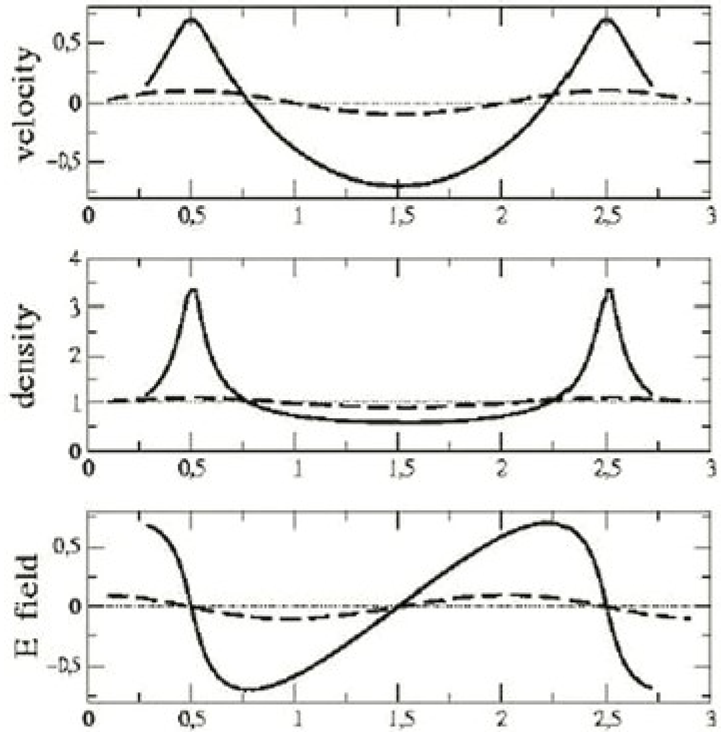
short pulse laser driven wake field

In a transparent plasma a relativistic laser pulse with $L < \lambda_p = c/\omega_p$ drives a longitudinal plasma wave

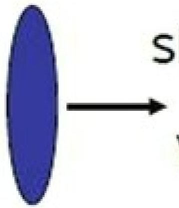
v/v_{ph}

n/n_0

E_x/E_0



$(x-v_{ph}t)/\pi$



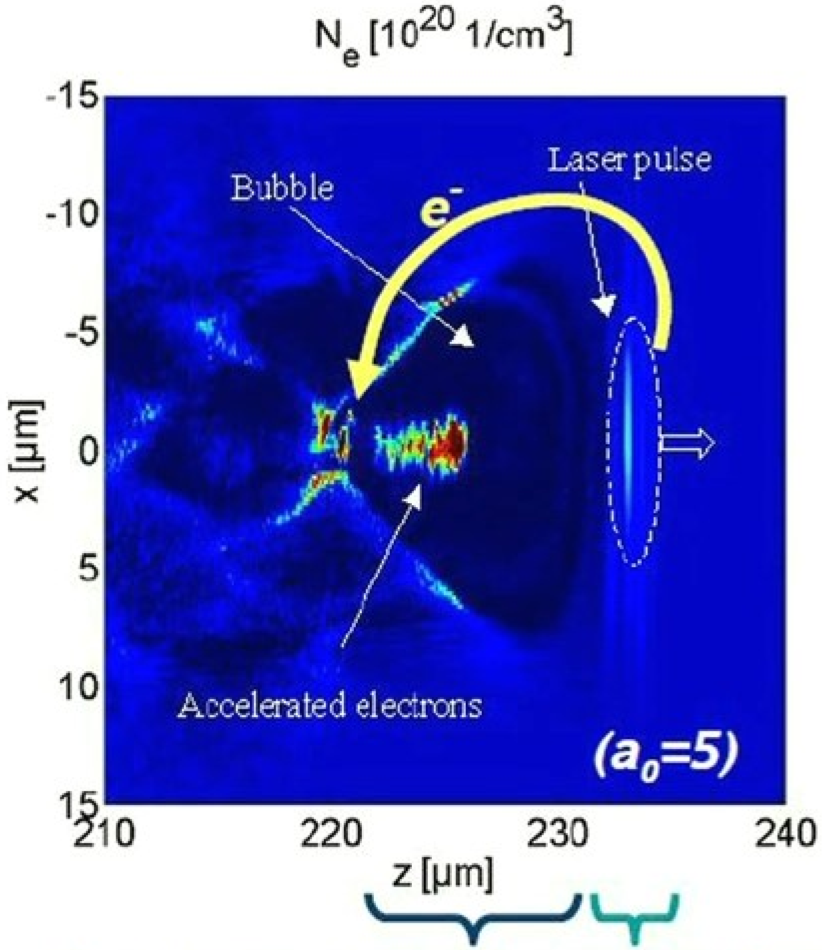
short laser pulse

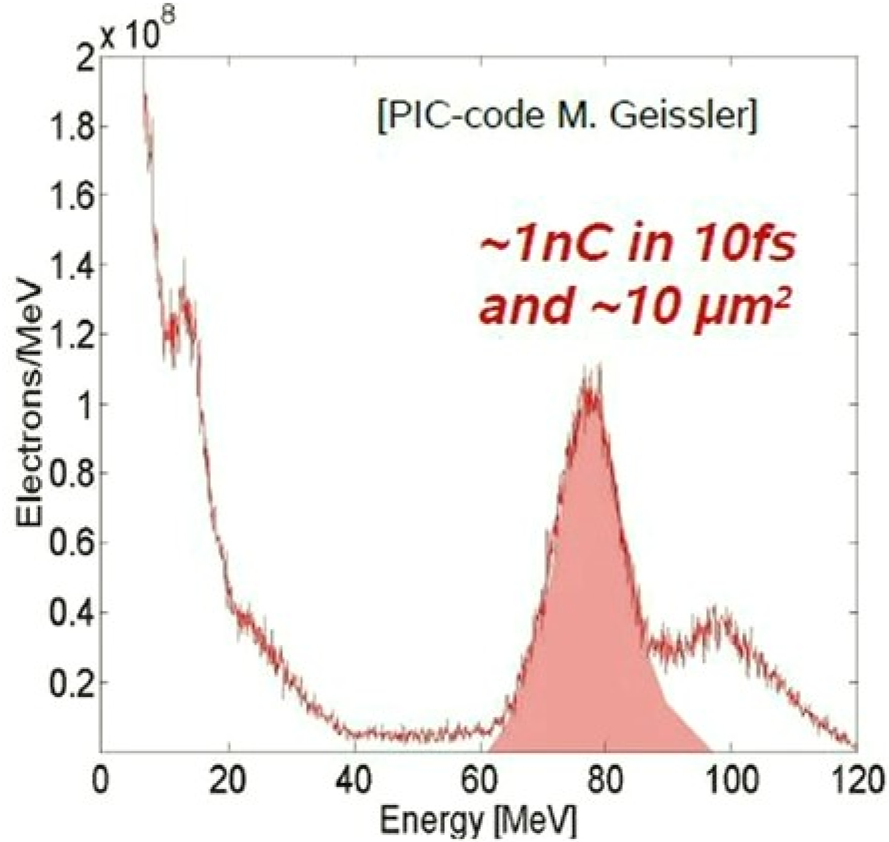
$v_g^{laser} = v_{ph}^{plasma} \sim c$

non-linear plasma wave for relativistic intensities

typical scale:
GeV/cm for 5×10^{18} e/cm^3

bubble acceleration

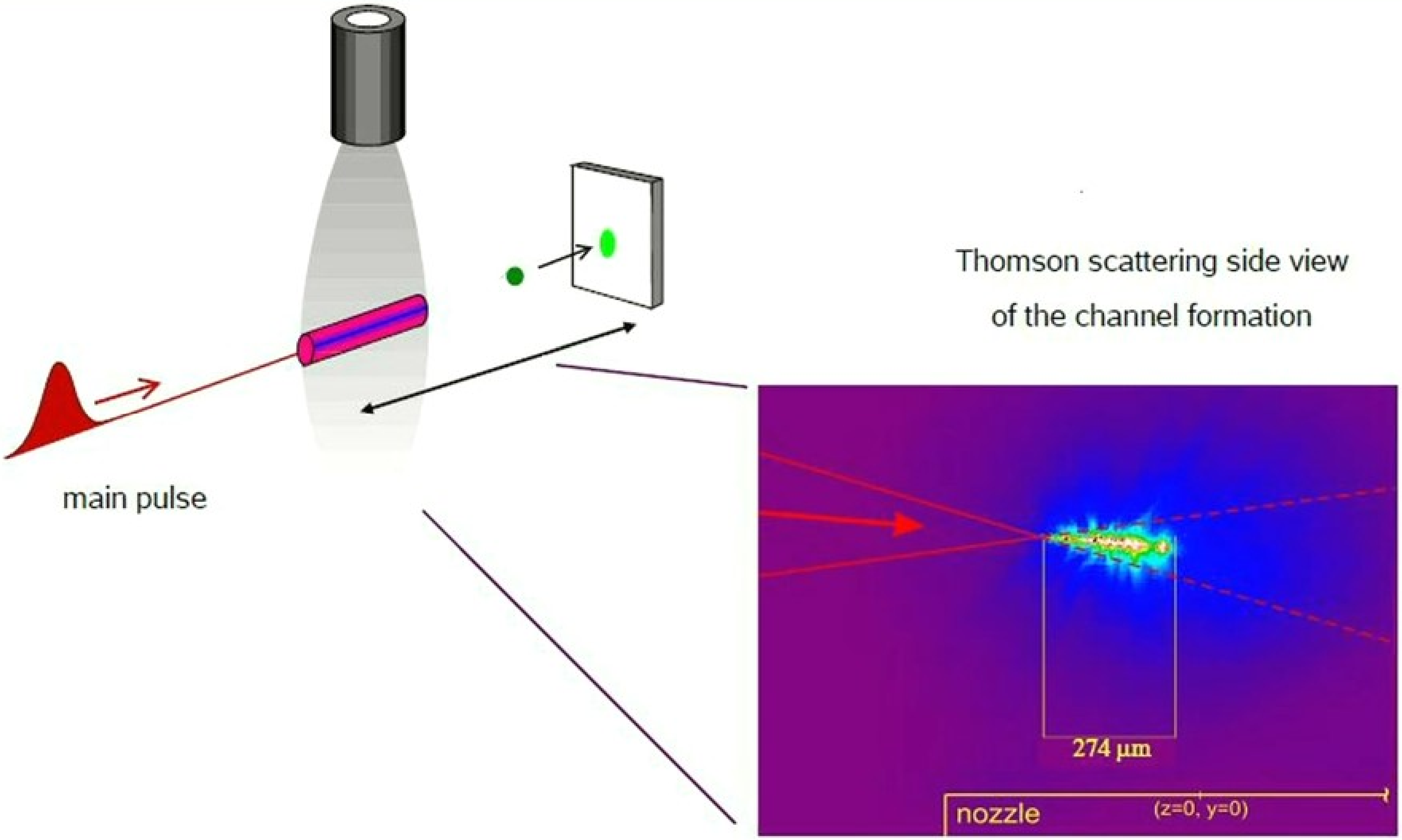




plasma wavelength < pulse length

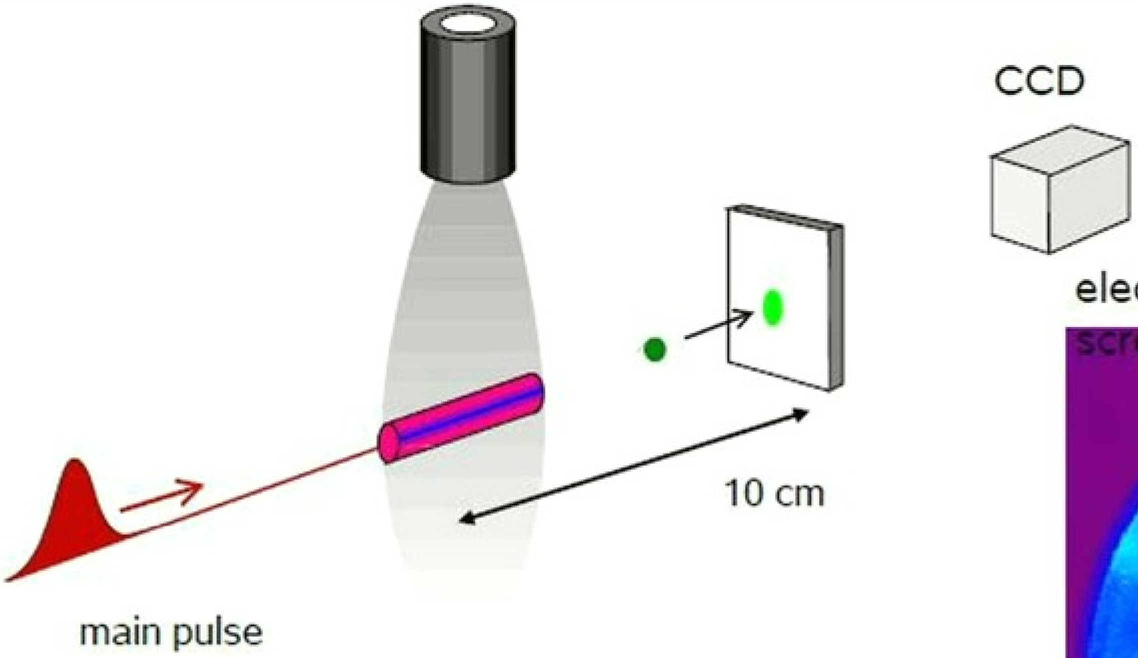
`mono-energetic' pulse

Setup for Laser Electron Acceleration

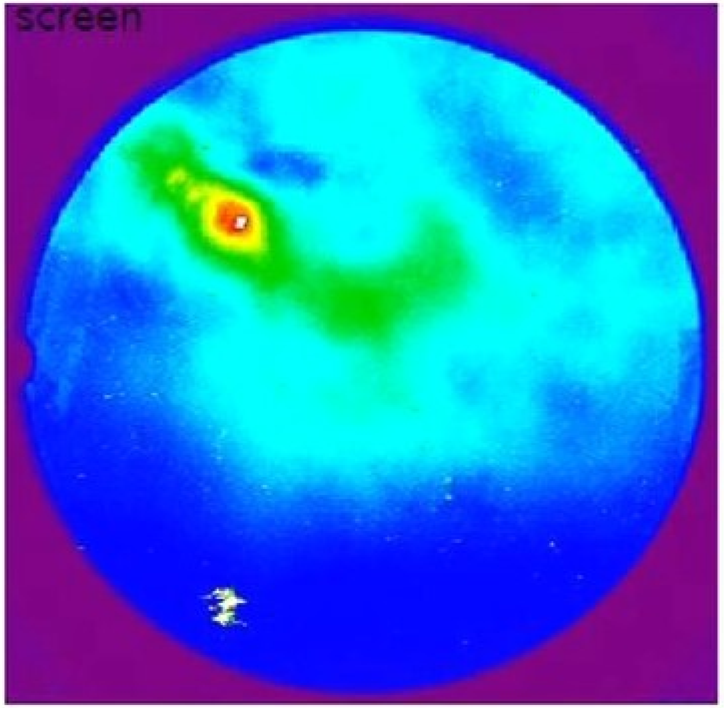


Thomson scattering side view of the channel formation

Setup for Laser Electron Acceleration

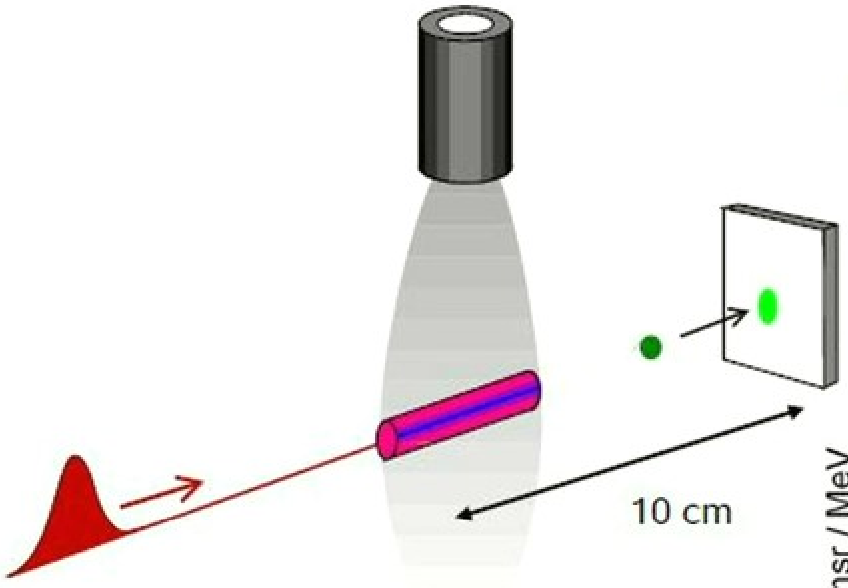


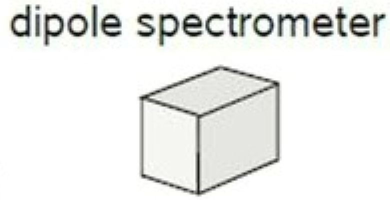
electron beam on scintillating screen

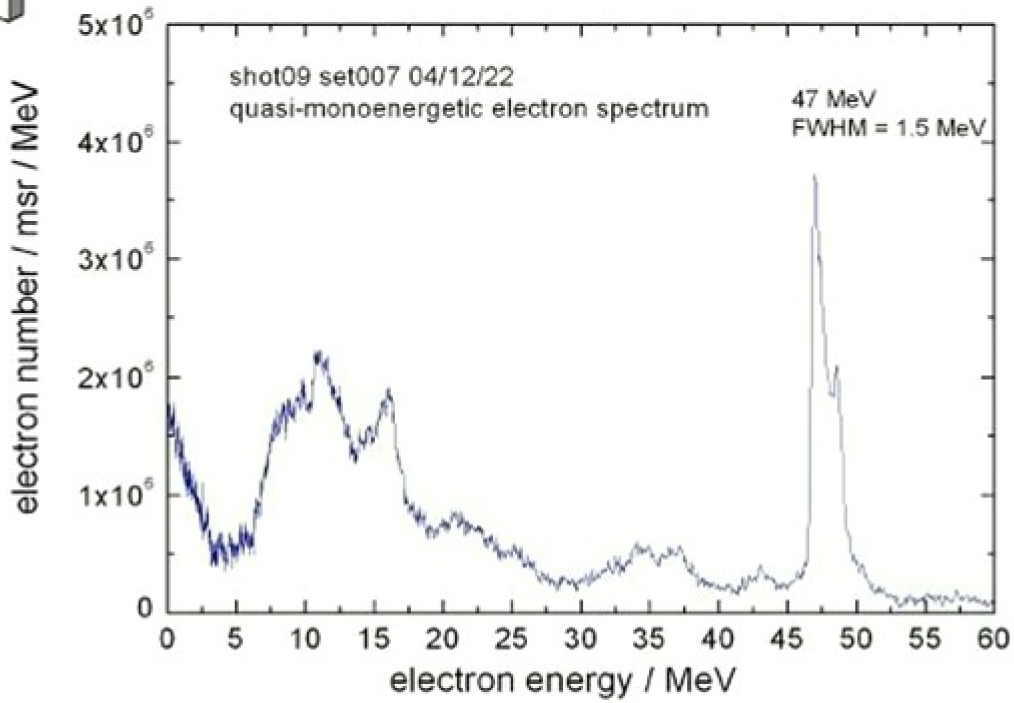


- profiles of the electron beam indicate a beam divergence of 10 mrad
- high pointing stability

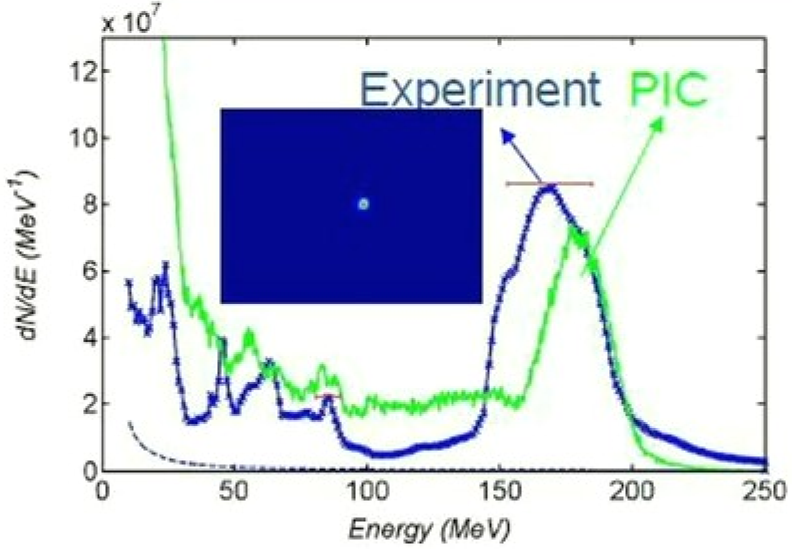
Setup for Laser Electron Acceleration





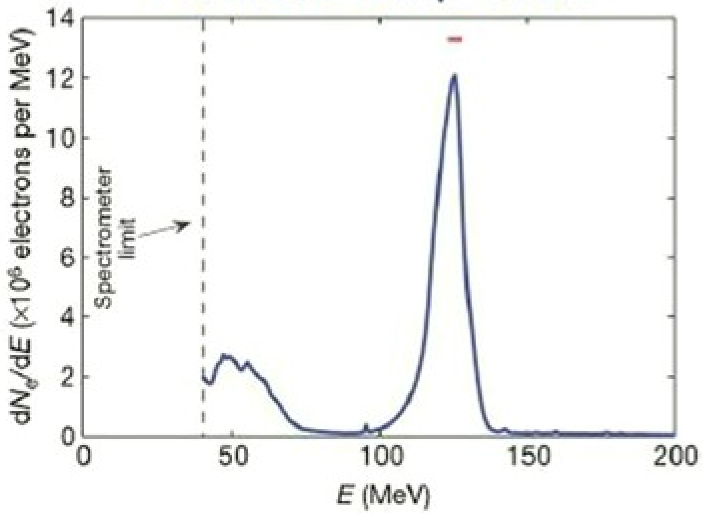


Recent developments



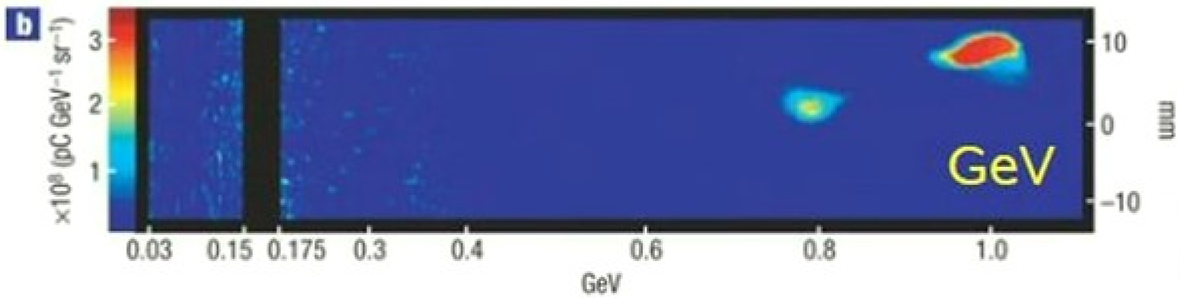
S. Mangles et al., C. Geddes et al., J. Faure et al.,
in Nature 431 (2004)

controlled injection



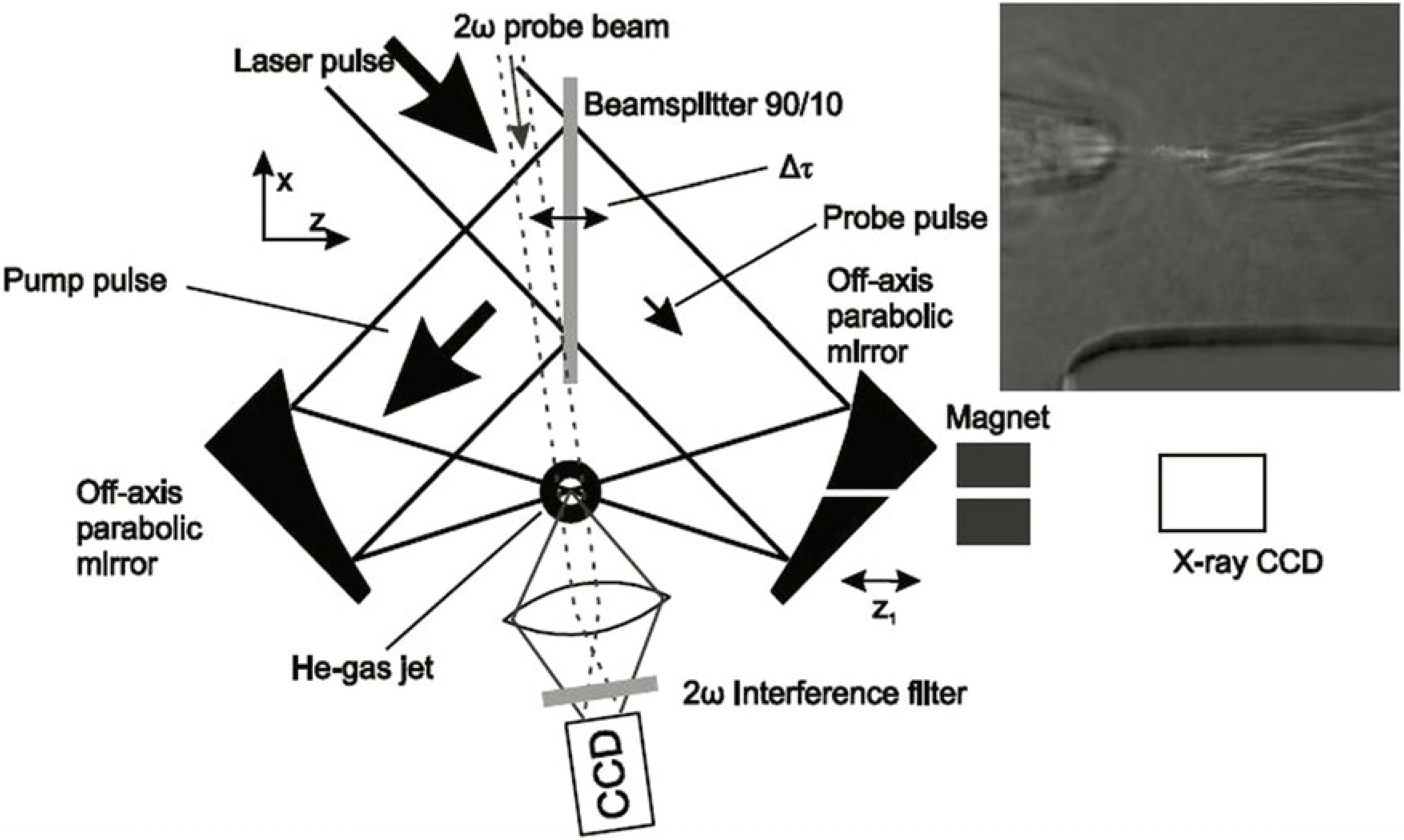
J. Faure, et al., Nature 444 (2006) 737

matched discharge capillary

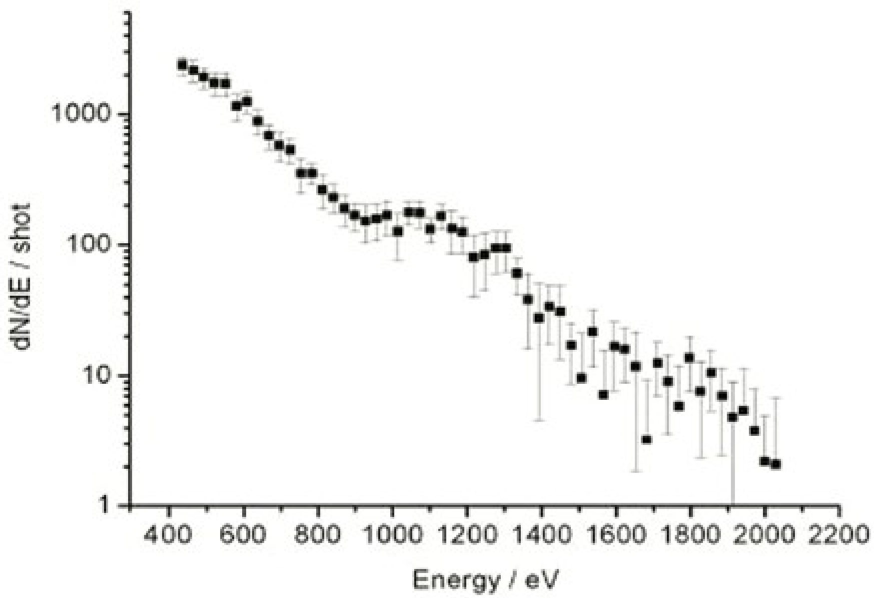


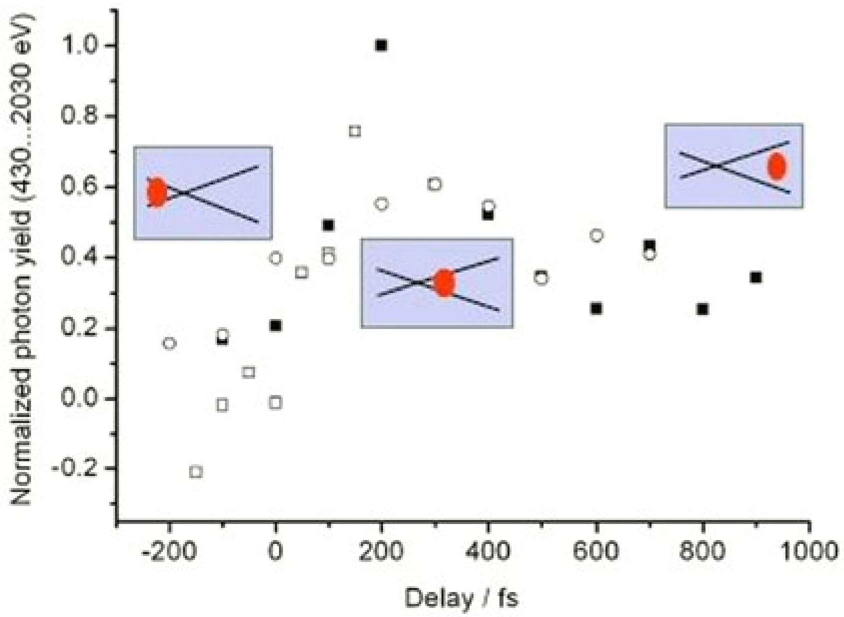
W. Leemans, et al.,
Nature physics 2 (2006) 696

Thomson-Backscattering from Laser Accelerated Electrons



Thomson-Backscattering from Laser Accelerated Electrons





Spectrum of Thomson back scattered laser photons

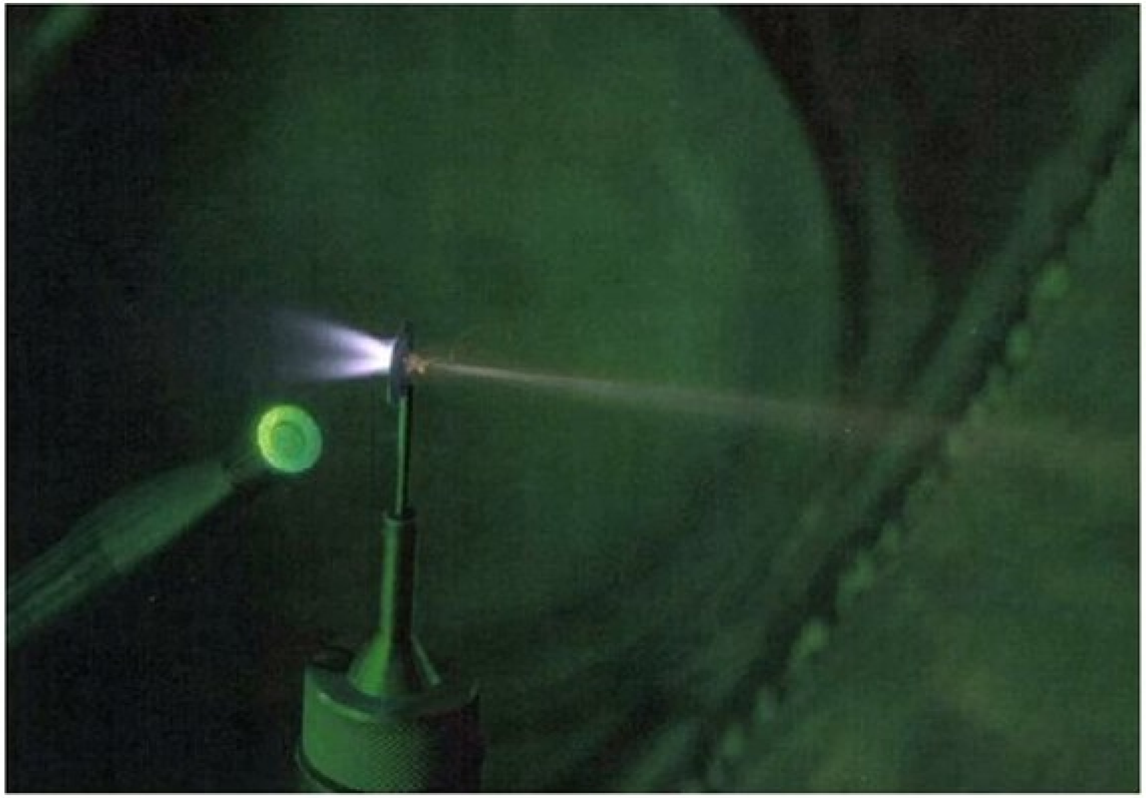
$$h\nu_x = 4\gamma^2 h\nu_L$$

H.Schwörer et al. PRL **96**, 014802 (2006)

Integrated photon yield from Compton back scattered laser photons

(0.8 keV < E_γ <2.4 keV) as function of relative pulse delay

Laser acceleration of ions

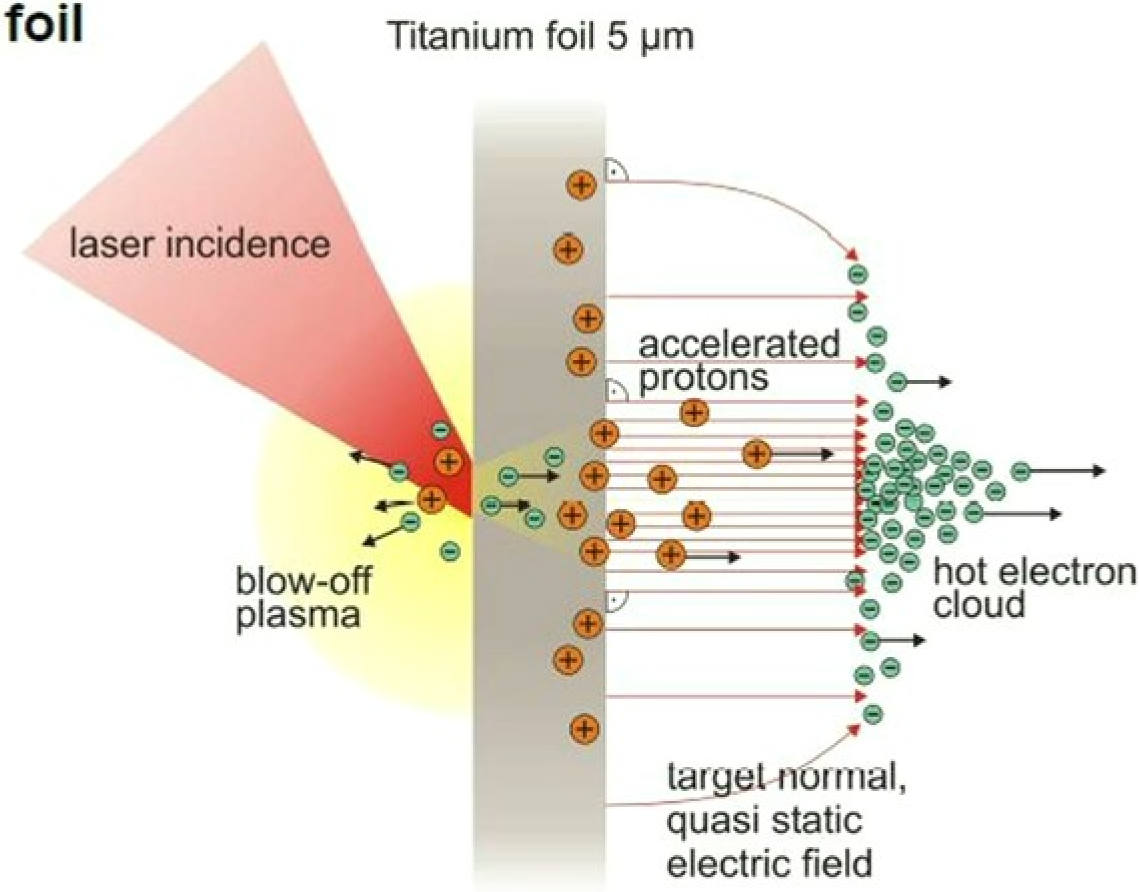


LLNL Petawatt 1999

Laser driven, local charge separation accelerates ions perpendicular to the back surface of a thin foil

proton acceleration by TNSA

- hot electrons traversing the foil (divergence, pulse length)
- quasi static field normal to target surface (inhomogeneous)
- source size >> laser spot



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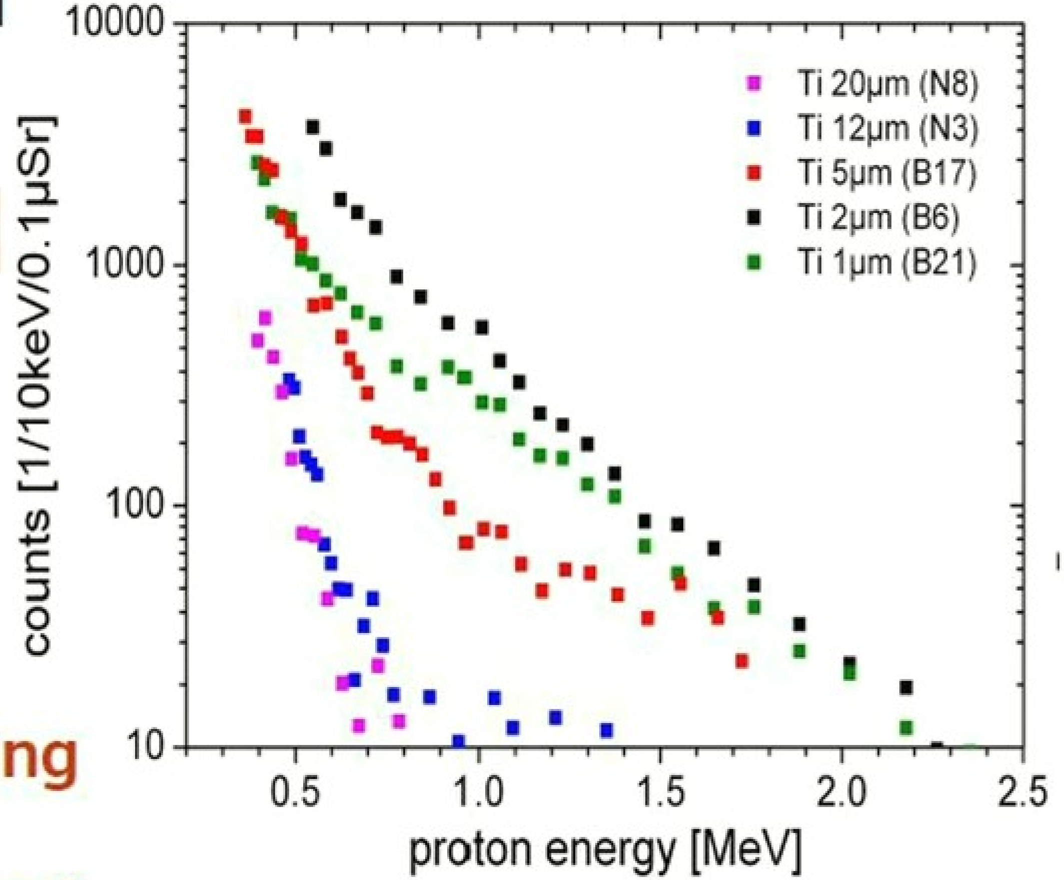
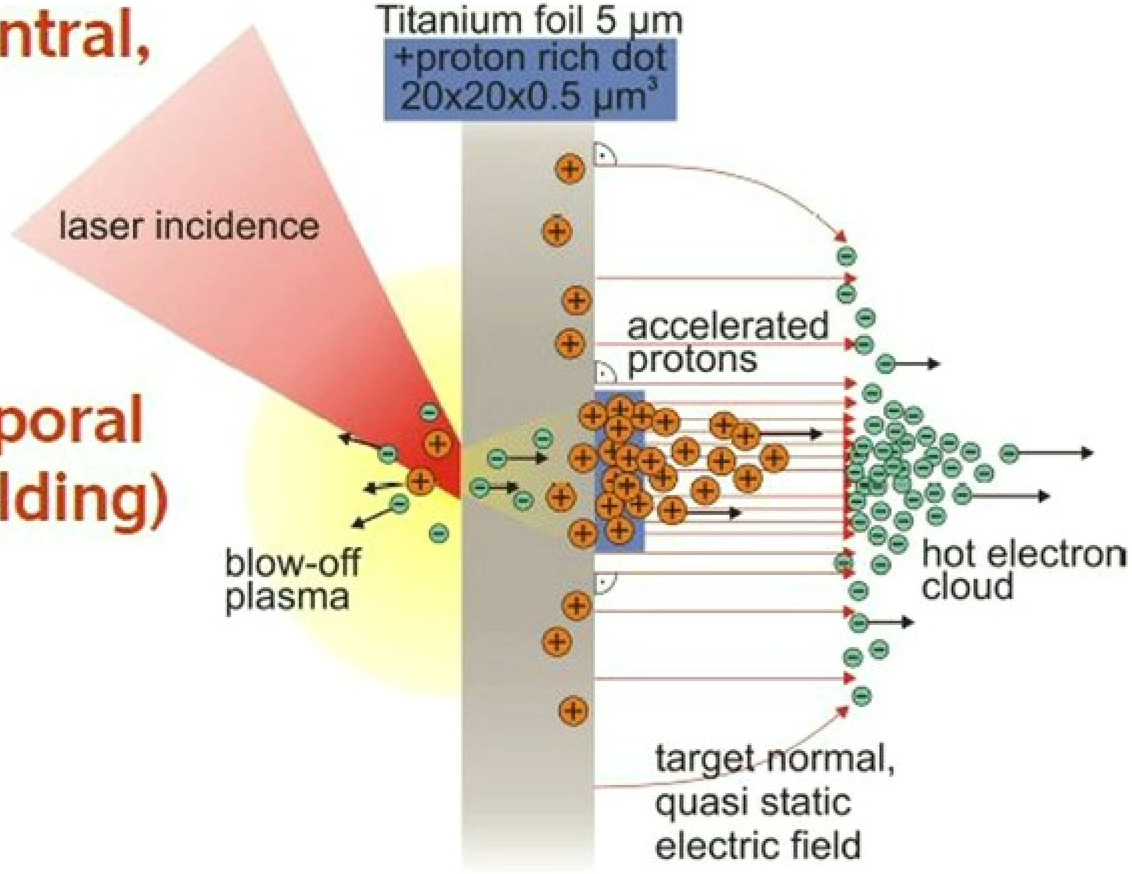


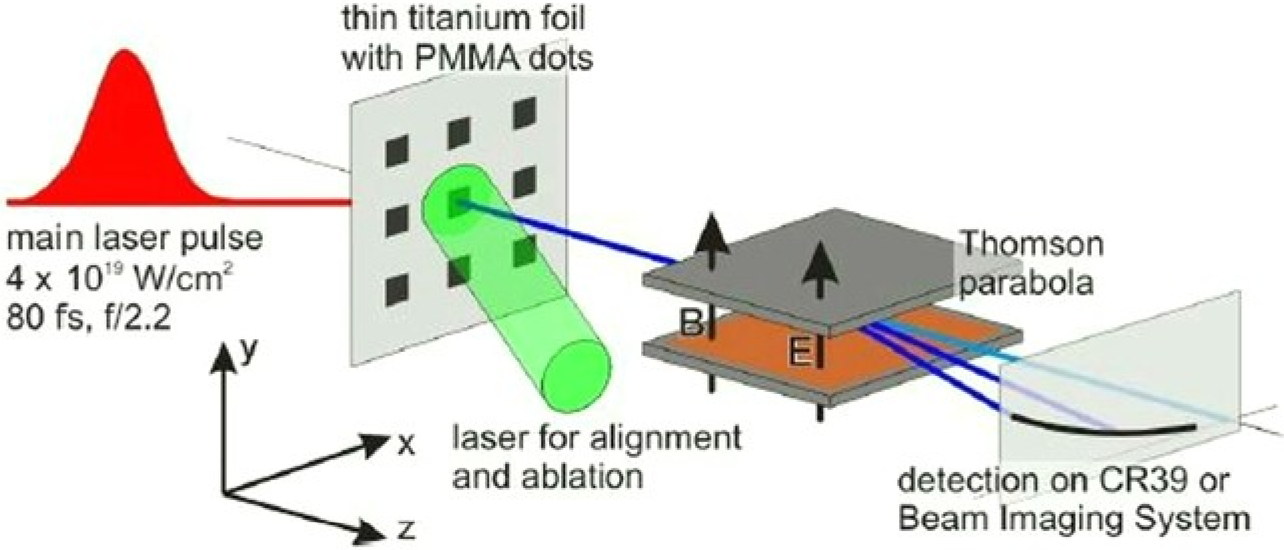
broad energy distribution (with max. energy depending on laser pulse duration, energy, and target thickness)

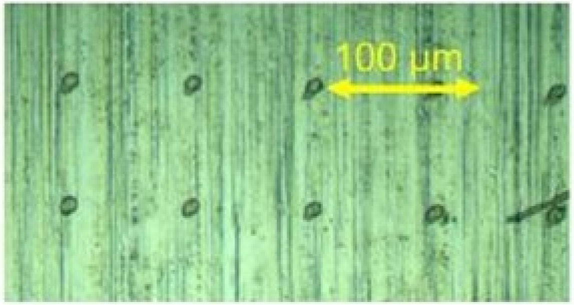
idea for narrow band distribution

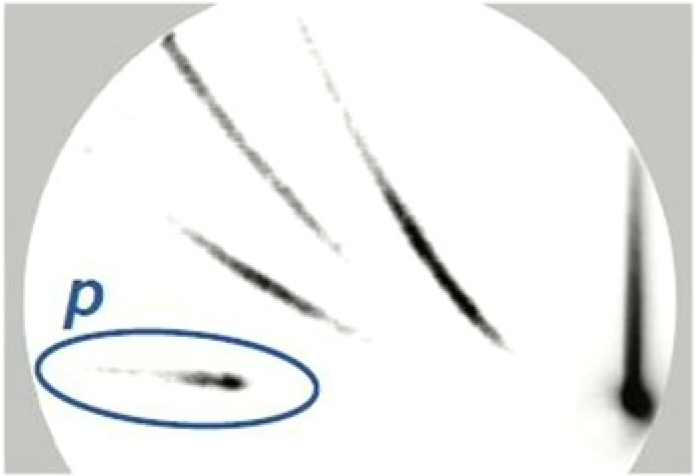
- Enhance yield in the central, homogeneous region, thus apply a proton rich dot
- use thin dot (avoid temporal field depletion and shielding)



exp. status in Jena

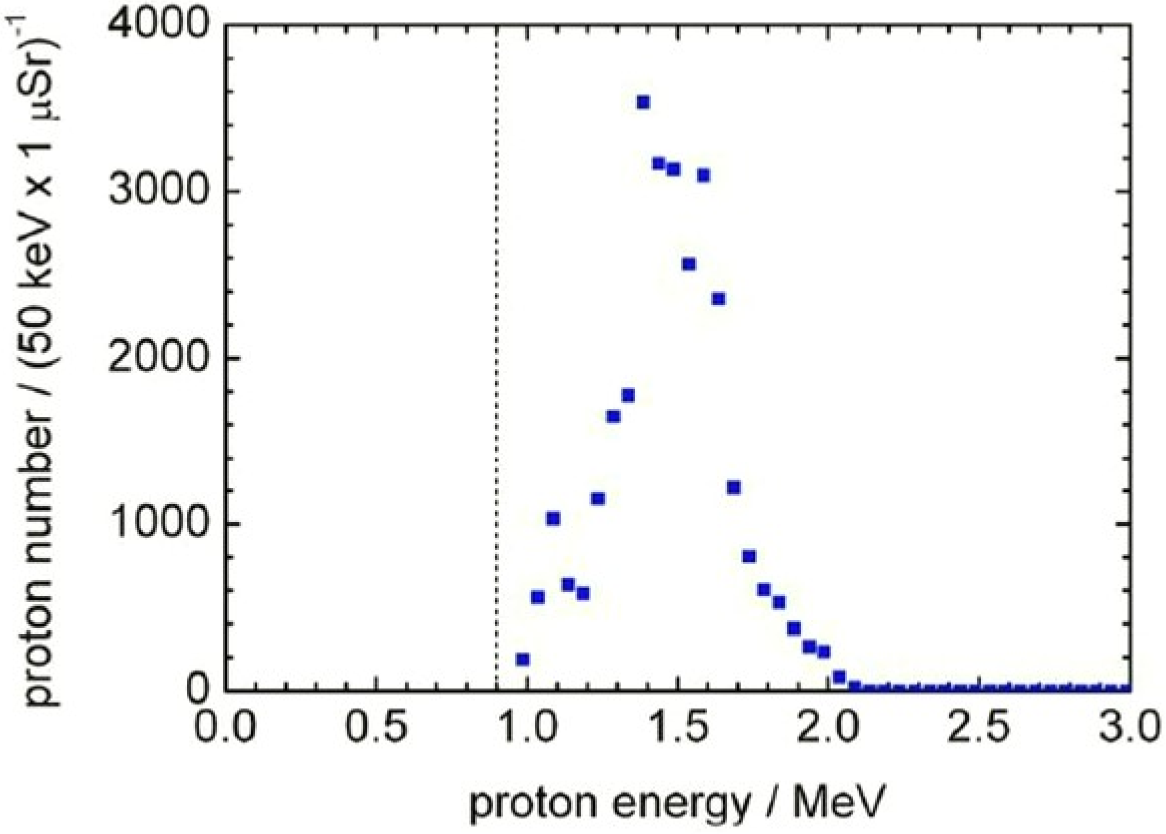






Lith. polymer coating on Ti-foil
8 x 8 – 20 x 20 µm² base area
0.15 – 1.0 µm height

exp. status in Jena

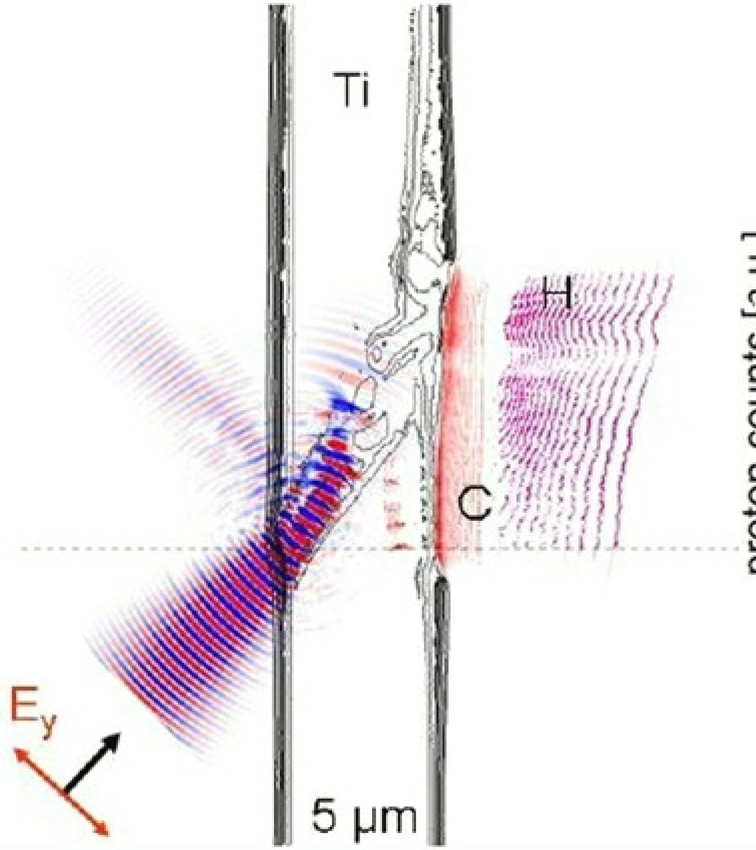


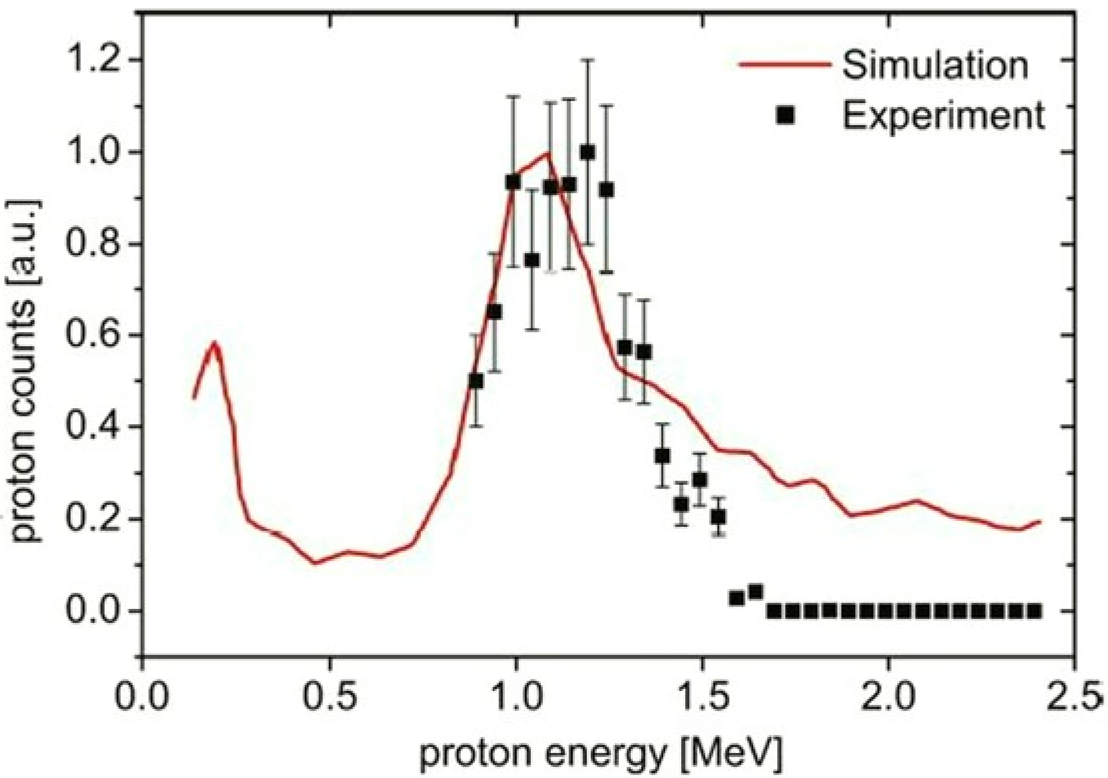
(overall number of ions about 10^8 in 20msr)

2 D Particle in Cell Simulation

2D-PIC simulation by T. Esirkepov for following conditions :

$I_L = 3 \times 10^{19}$ W/cm², 5 μm Ti-foil + 0.5 μm PMMA dot (20×20) μm²

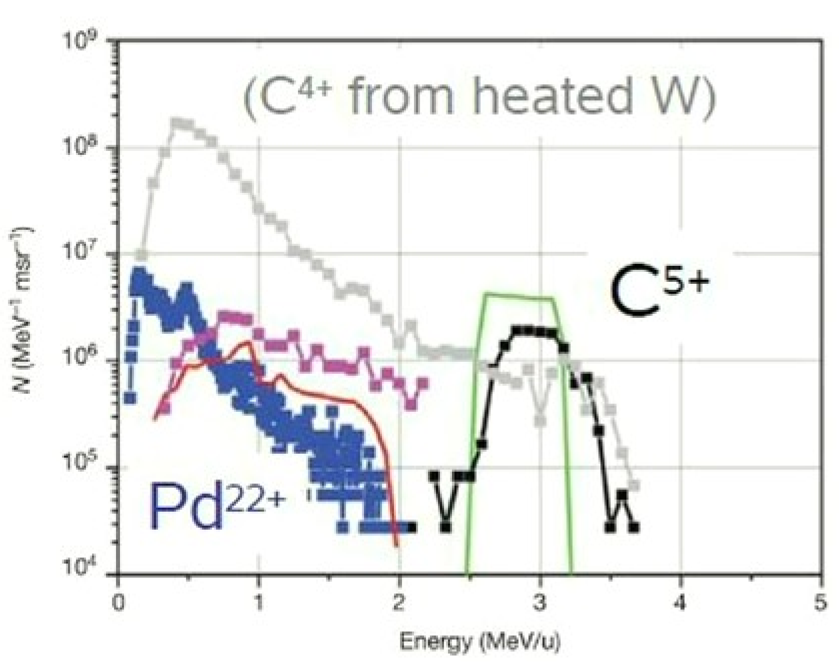




alternative approaches

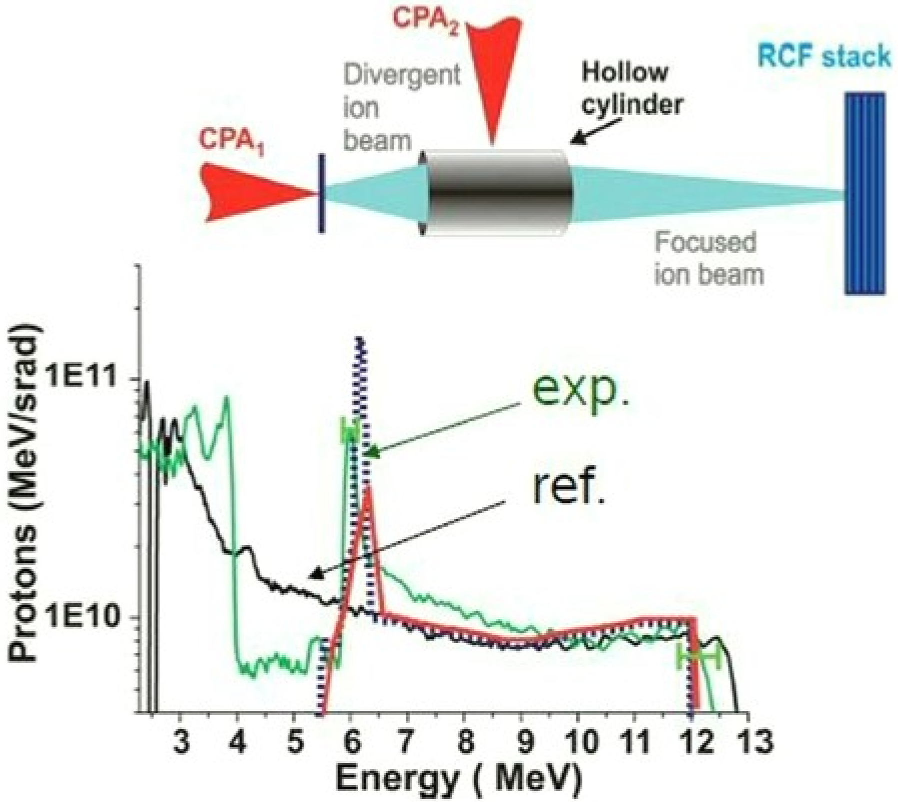
Carbon mono-layer source
(catalytic reaction on Pd substr.)

-> temporal selection



M. Hegelich et al., Nature 439 (2006) 441

Focusing and energy selection
with transient lense



T. Toncian et al., Science 312, 410 (2006)

Prospects: Petawatt Scaling

POLARIS laser system:

- Petawatt laser available in Jena by 2008 (diode pumped Yb^{3+}:Glass)
- 4 out of 5 amplification stages realized including compressor (8 J,150 fs)

$$I_{POLARIS} = 10^{21}\ W/cm^2 \quad @ \quad 0.1\ Hz$$

$$(E = 150\ J,\ \lambda = 1042\ nm,\ \ \tau = 150\ fs)$$

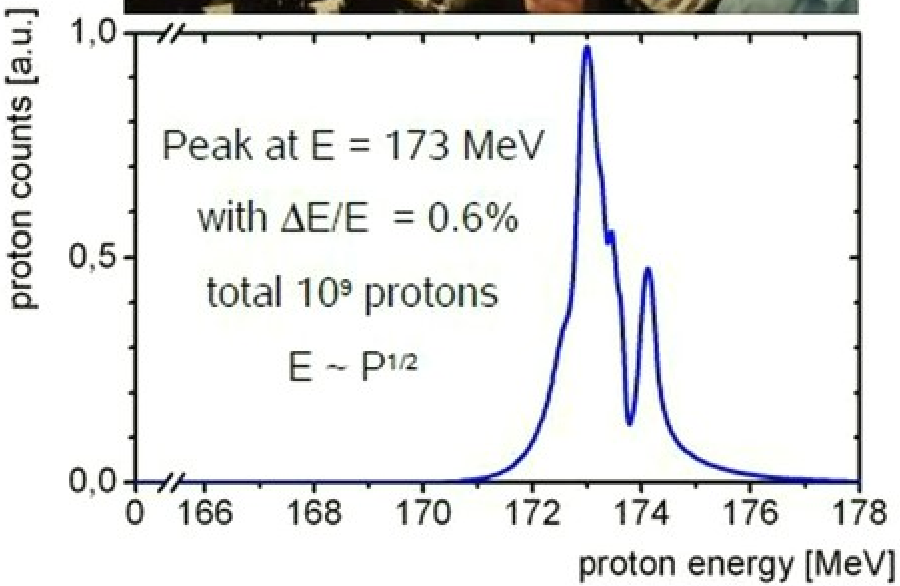
POLARIS simulation:

Hein et al.: Diode-pumped chirped pulse amplication to the joule level. *Applied Physics B - Lasers and Optics* 79, 4 (2004)

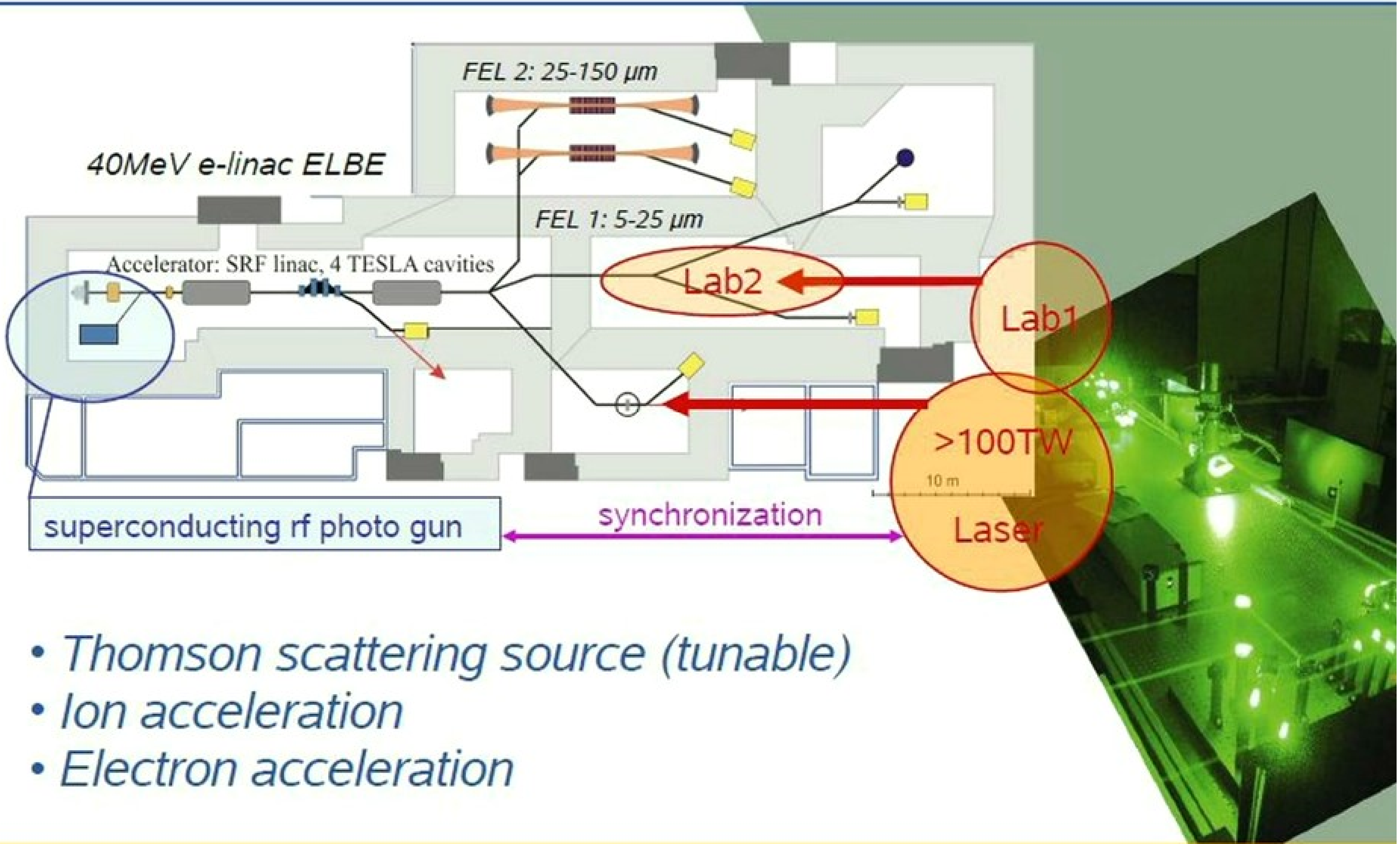
$I_{POLARIS} = 10^{21}\ W/cm^2$

2,5 µm Ti-foil + 0.1 µm PMMA Dot (Ø 2.5 µm)

$\tau_{ASE} = 1\ ns \quad @ \quad I_{ASE} / I_{POLARIS} = 10^{-7}$



Combined 100TW laser / accelerator lab @ FZD



- *Thomson scattering source (tunable)*
- *Ion acceleration*
- *Electron acceleration*

Thomson backscattering

can be treated as a counterpropagating undulator

$$\lambda_L = \frac{\lambda_{laser}}{4\gamma^2}\left(1 + \frac{a^2}{2} + \gamma^2\theta^2_{obs.}\right) \qquad \theta_{emission} \sim \frac{1}{\gamma\sqrt{N_{laser}}}$$

short laser wavelength allows for X-rays at lower electron energies -> *compact*

- e-beam divergence defines radiation properties combination with *compact* high brilliance accelerator

Thomson backscattering

yield determined by small cross-section $(\sim r_e^2)$

$$N_{emission} \sim \alpha \cdot a_0^2 \cdot N_e \cdot N_{laser} \cdot f_{rep}$$

- example: 2 nC, ε_n= 1.5 mm mrad, <40 MeV } **< 30 keV**

  $\left.\begin{array}{l}\text{100 µJ, 100kHz, 300 fs} \\ \text{1 J, 10Hz, 30fs}\end{array}\right\}$ **10^9-10^{10} photons / s**

Thomson backscattering

yield determined by small cross-section ($\sim r_e^2$)

$$N_{emission} \sim \alpha \cdot a_0^2 \cdot N_e \cdot N_{laser} \cdot f_{rep}$$

thus either use „larger electrons“ (coherent emission)
microbunching, seeding,
high gain harmonic generation

and / or recycle the laser light (optical cavity)
high electron repetition rate required for
reasonable cavity length, 13MHz ~11.5m
to increase rep-rate and/or intensity

laser-induced vacuum birefringence

QED regime:

- *small photon energy (compared to $m_e c^2$)*
- *highest intensity (yet low compared to $I_c = 4 \cdot 10^{29}$ W/cm²)*

dispersive effect (vacuum polarization) calculated in lowest non-trivial order O(I) and O(ω^2_{probe}) -> birefringence

phase shift $$\Delta\varphi = 2\pi \frac{d}{\lambda_{probe}} \cdot \Delta n = \frac{4\alpha}{15} \frac{d}{\lambda_{probe}} \cdot \frac{I}{I_c}$$

resulting ellipticity

phase shift

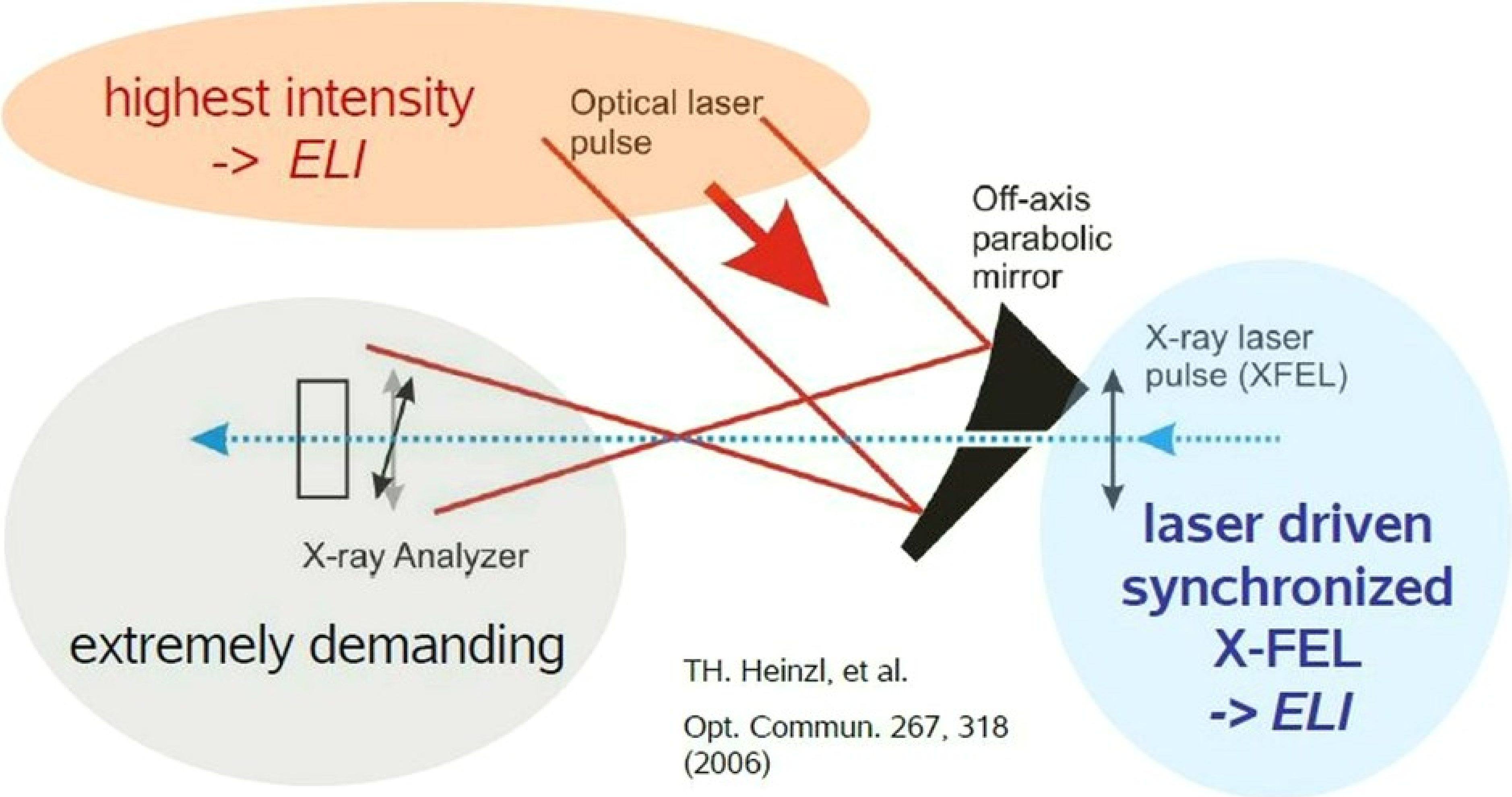
$$\Delta\varphi = 2\pi \frac{d}{\lambda_{probe}} \cdot \Delta n = \frac{4\alpha}{15} \frac{d}{\lambda_{probe}} \cdot \frac{I}{I_c}$$

measurable ellipticity (intensity measurement)

$$\delta^2 \sim \left(\Delta\varphi / 2\right)^2 \sim \boxed{\omega_{probe}^2} \cdot \boxed{\left(z_0 \frac{I}{I_c}\right)^2}$$

brilliant X-ray probe **high intensity and interaction length**

experimental realization



TH. Heinzl, et al.

Opt. Commun. 267, 318 (2006)

Summary

- great advances in laser electron acceleration based on theoretical progress and refined laser/target technology
  - ✓ *mono-energetic high quality beams up to GeV*
  - ✓ *high peak currents*
  - ✓ *controlled injection*
- first mono-energetic ion acceleration demonstrated
- prospects for applications in
  ion radiation therapy, staged compact electron accelerators, high peak current beams driving brilliant X-ray sources

S. Bock, S. Kraft, T. Kluge, K. Zeil, the ELBE team
R. Sauerbrey, U. Schramm

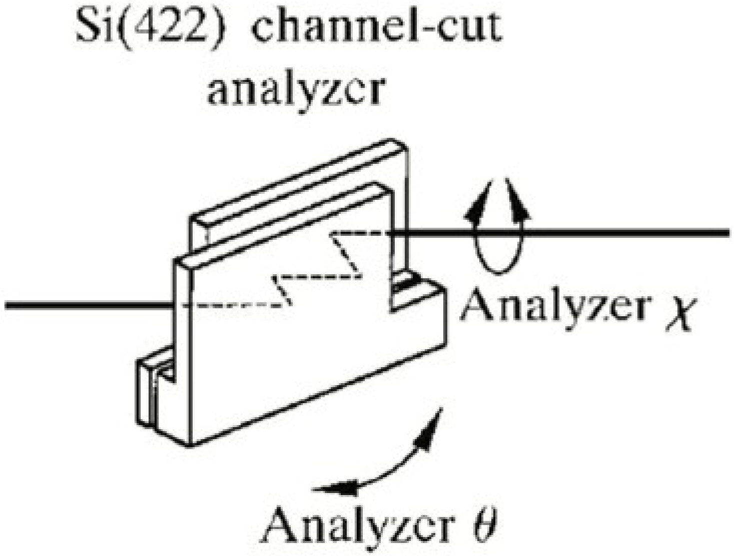
H. Schwoerer, B. Liesfeld, K.-U. Amthor, W. Ziegler, O. Jäckel, S. Pfotenhauer, S. Podleska, M. Siebold, R. Bödefeld, J. Hein, J. Polz, F. Ronneberger, H.-P. Schlenvoigt, B. Beleites

K. Ledingham

T. Esirkepov,
Kansai Research Establishment, Kyoto, Japan

M. Geissler, S. Karsch, et al., MPQ and LMU Munich
B. Hidding, G. Pretzler, et al., Univ. Düsseldorf

detector (analyzer) technology



High contrast x-ray analyzers
(Hart 1991, Hasegawa 1999, Alp 2000):

- Multiple Bragg reflections from perfect crystals
- Contrast in the multi-keV range from 10^6 (measured) to possibly 10^{11} (calculated)
- Requiring perfect X-ray beam quality (in polarization and geometry)

FZD superconducting photo injector