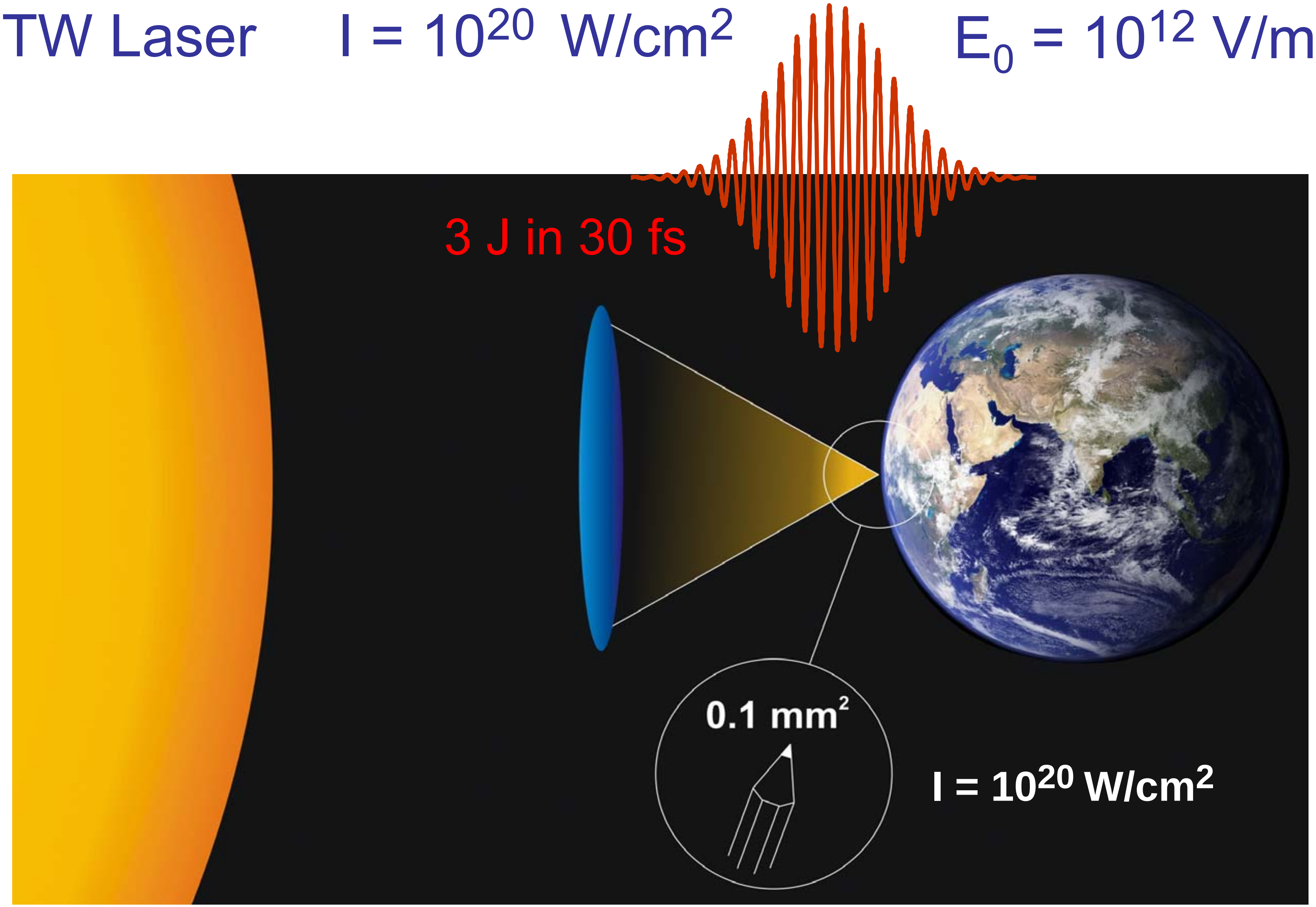
Moderne Beschleunigerkonzepte und ihre Anwendung in der Medizin

Kompakte Laserbeschleuniger

U. Schramm

100 TW Laser $I = 10^{20}$ W/cm^2 $E_0 = 10^{12}$ V/m



Beschleunigen mit Licht

Ia. Wie wird ein Elektron beschleunigt ?

Ib. Was ändert sich in einem dünnen Plasma ?

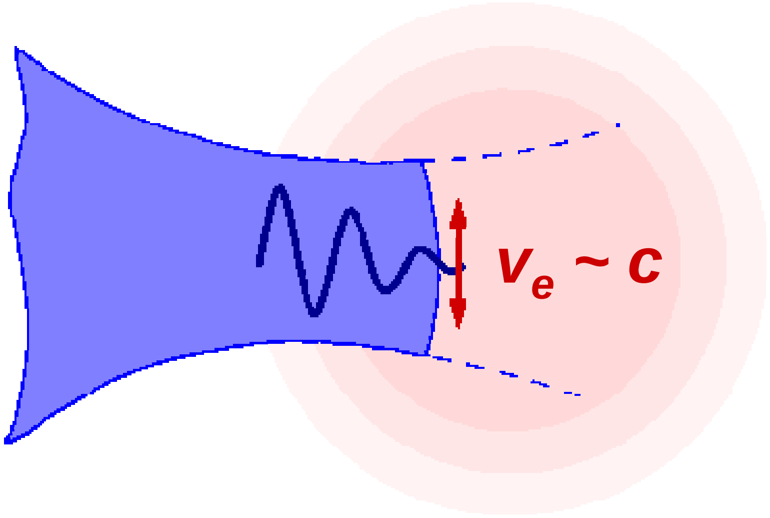
Ic. Wie erzeugt man einen monoenergetischen Elektronenstrahl ?

II. Wie erreicht man die viel schwereren Ionen ?

III. Mögliche medizinische Anwendungen

For laser intensities exceeding $I \sim 10^{18}\ W/cm^2$, the electron quiver motion becomes relativistic within half a period

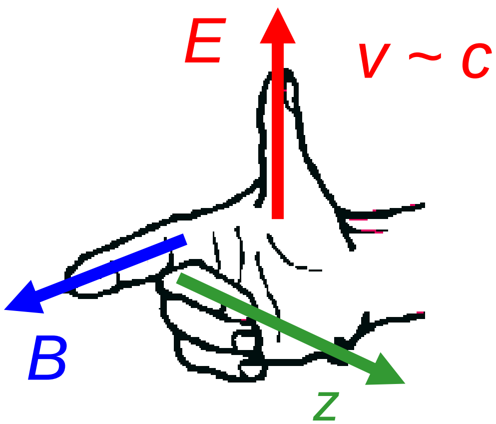
target: one electron



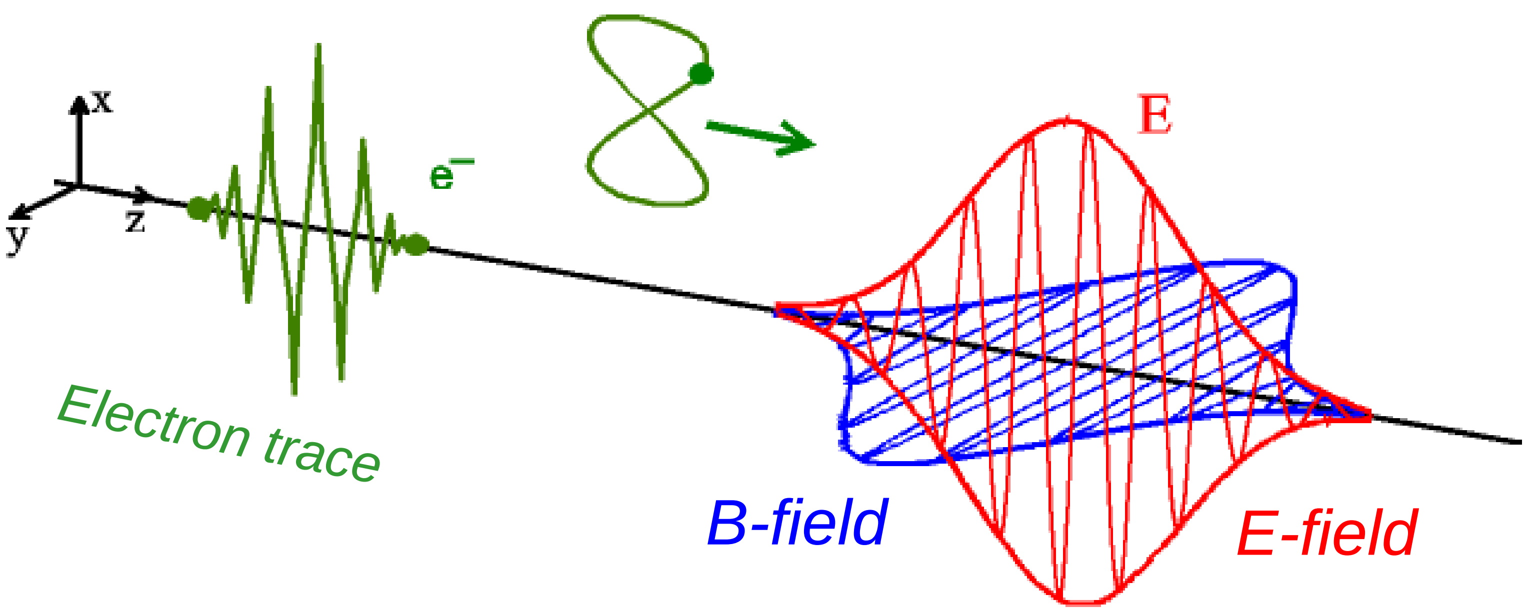
- ***mass increase***
- ***forward acceleration due to Lorentz force***
- ***anharmonic osc.***

$$a_0 = \frac{eE_0}{\omega m_e c} \qquad I = \frac{E_0 B_0}{\mu_0} = \frac{E_0^2}{\mu_0 c} = \frac{a_0^2}{\lambda^2[\mu m]} \cdot 1.4 \cdot 10^{18}\, \frac{W}{cm^2}$$

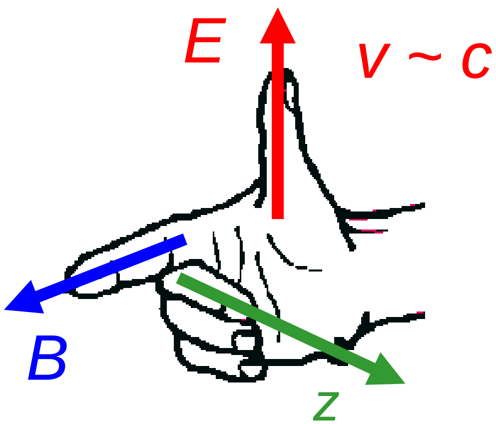
single electron dynamics



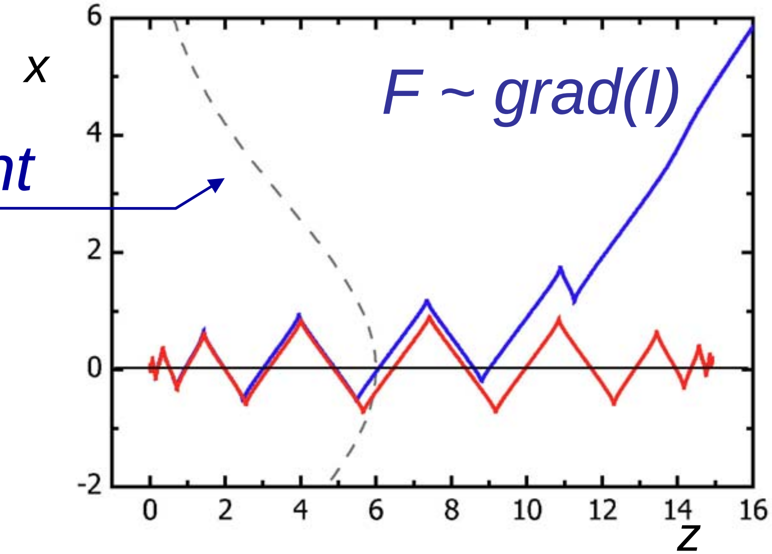
$$\vec{F} = e\vec{E} + e\,\vec{v} \times \vec{B} \qquad \left(B_0 = E_0/c\right)$$

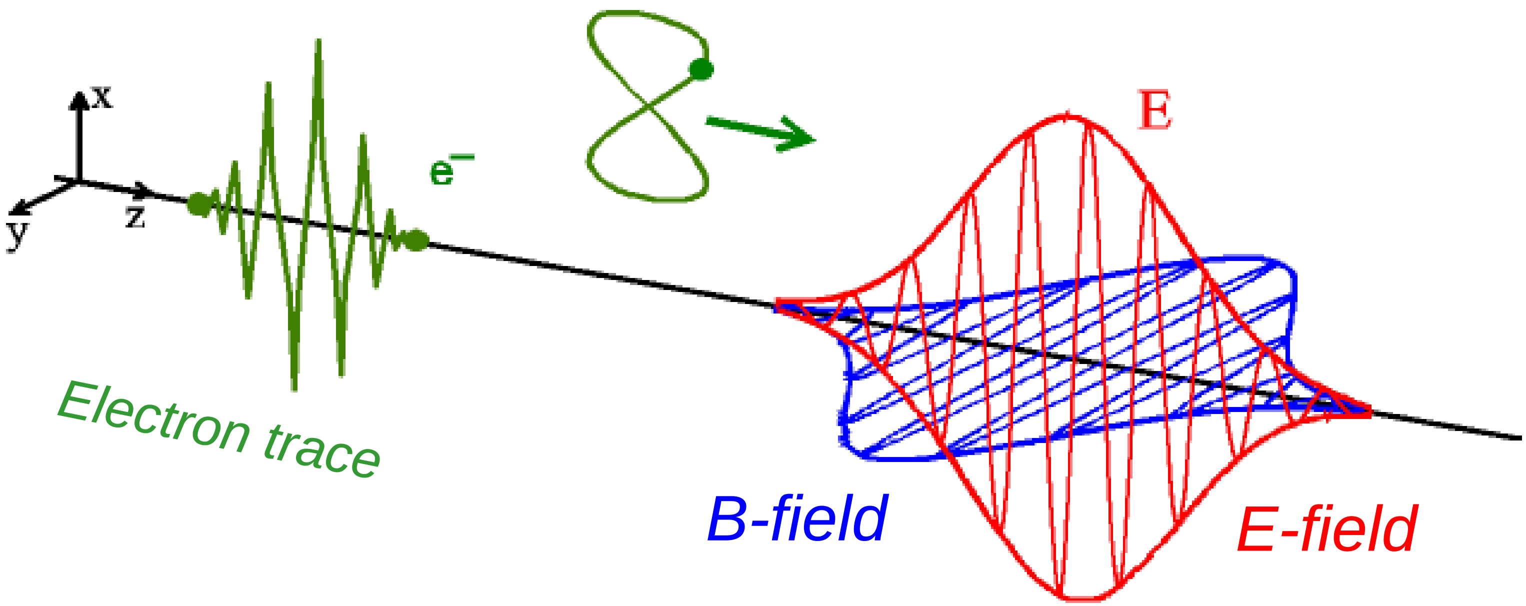


single electron dynamics



intensity gradient
ponderomotive
acceleration





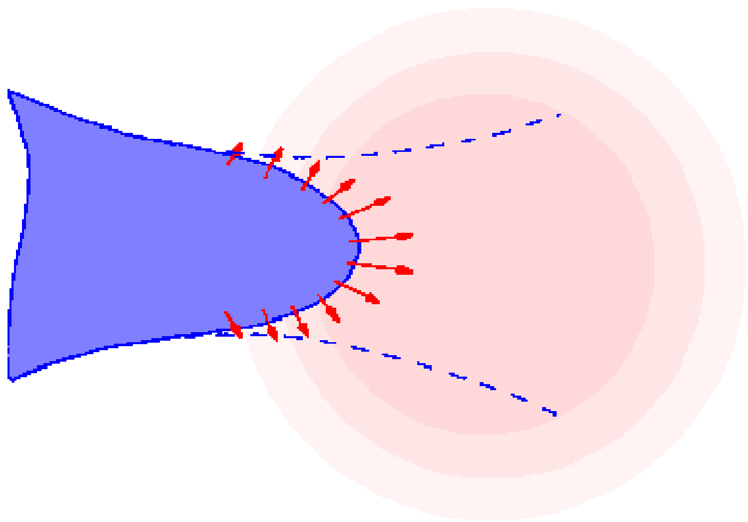
Beschleunigen mit Licht

Ia. Wie wird ein Elektron beschleunigt ?

Ib. Was ändert sich in einem dünnen Plasma ?

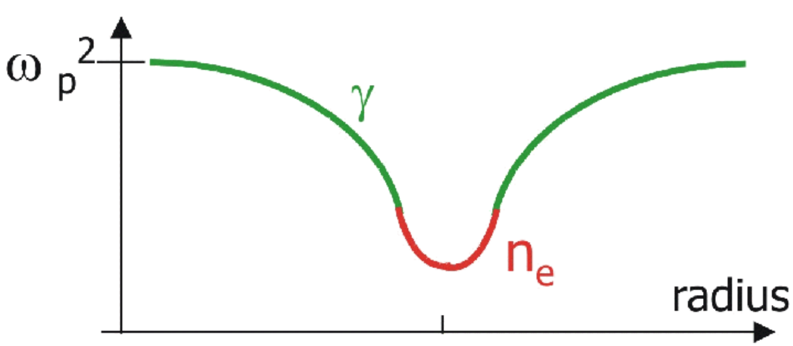
Ic. Wie erzeugt man einen monoenergetischen Elektronenstrahl ?

target: underdense (=transparent) plasma



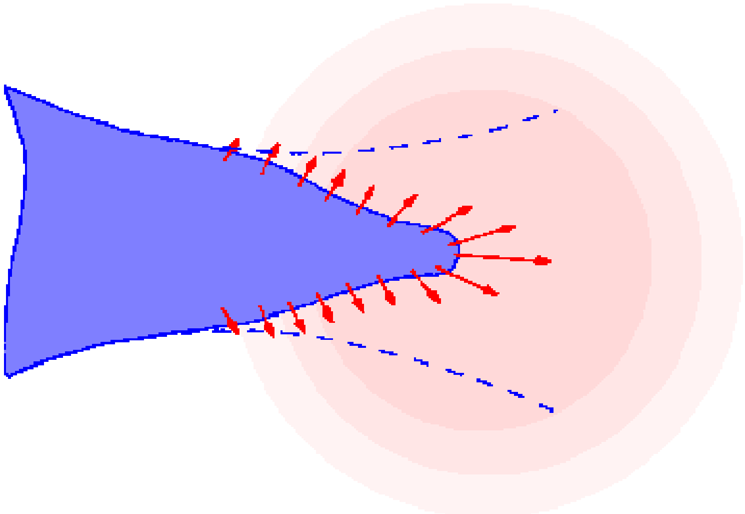
plasma frequency

$$\omega_p^2 = \frac{e n_e}{\varepsilon_0 \gamma m_e}$$

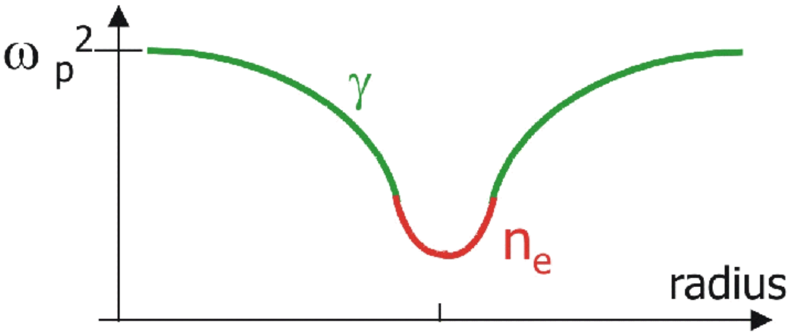


- mass increase
- density reduction

Index of refraction *n* locally increases -> relativistic self focusing



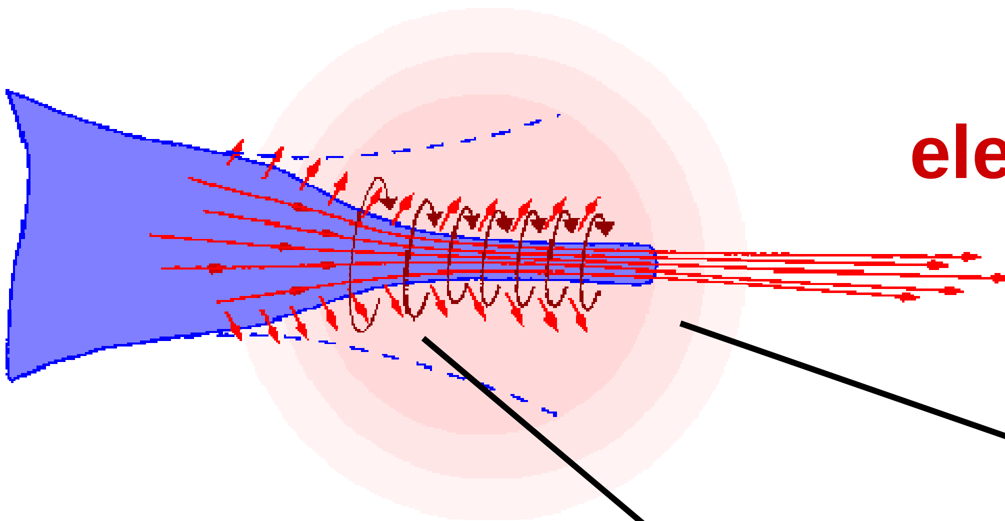
$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$



$$v_{ph} = c/n \quad v_{gr} = c \cdot n \quad n_{19} = 0.999 \quad n_0 = 0.995$$

relativistic optics

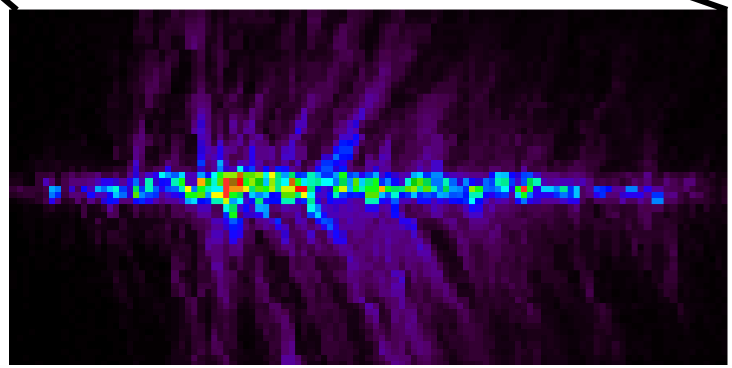
channel formation



electron jet

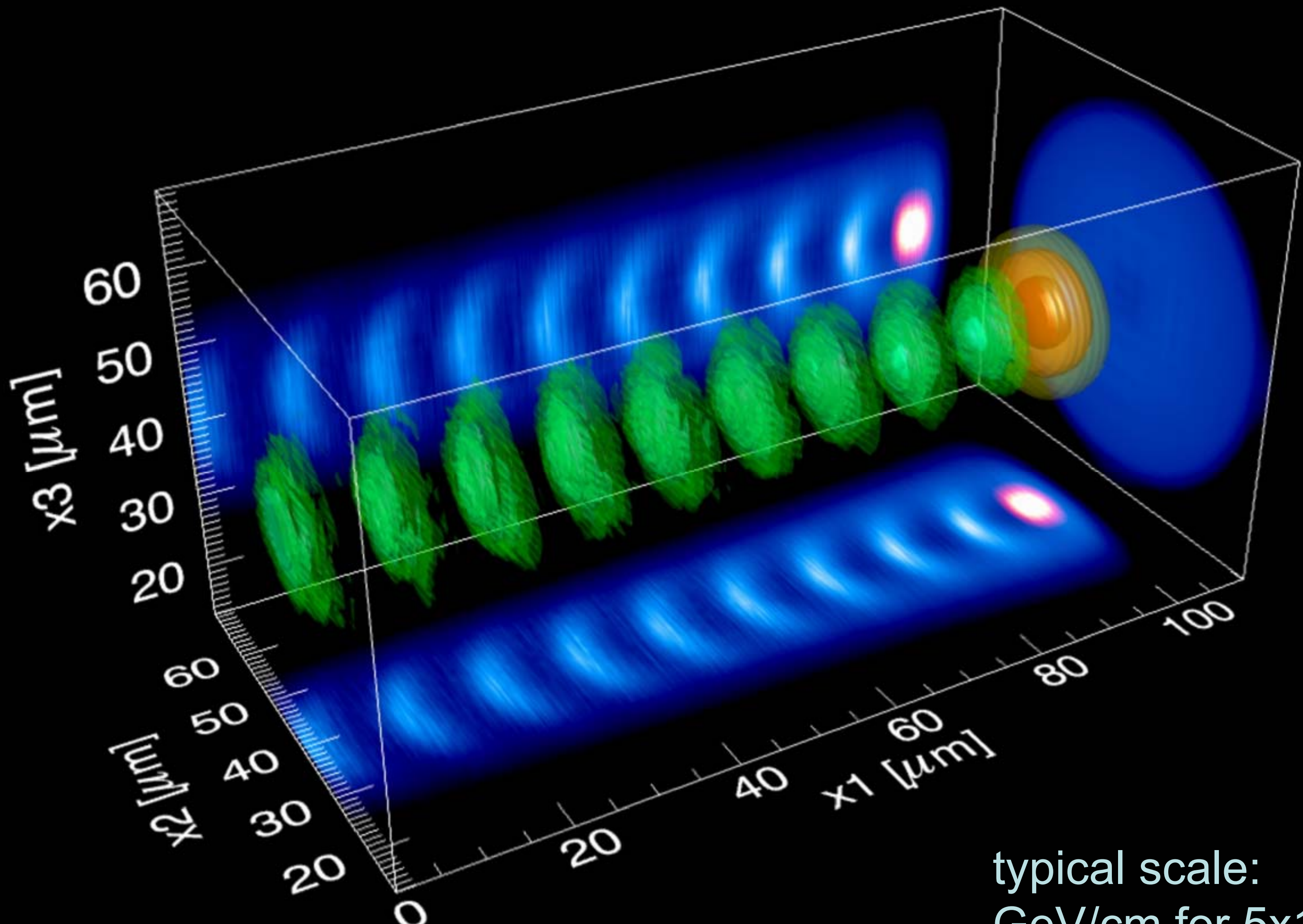
Thomson scattering @ 2ω

(length 0.4mm = 400 λ)



excitation of a longitudinal wave (wake)

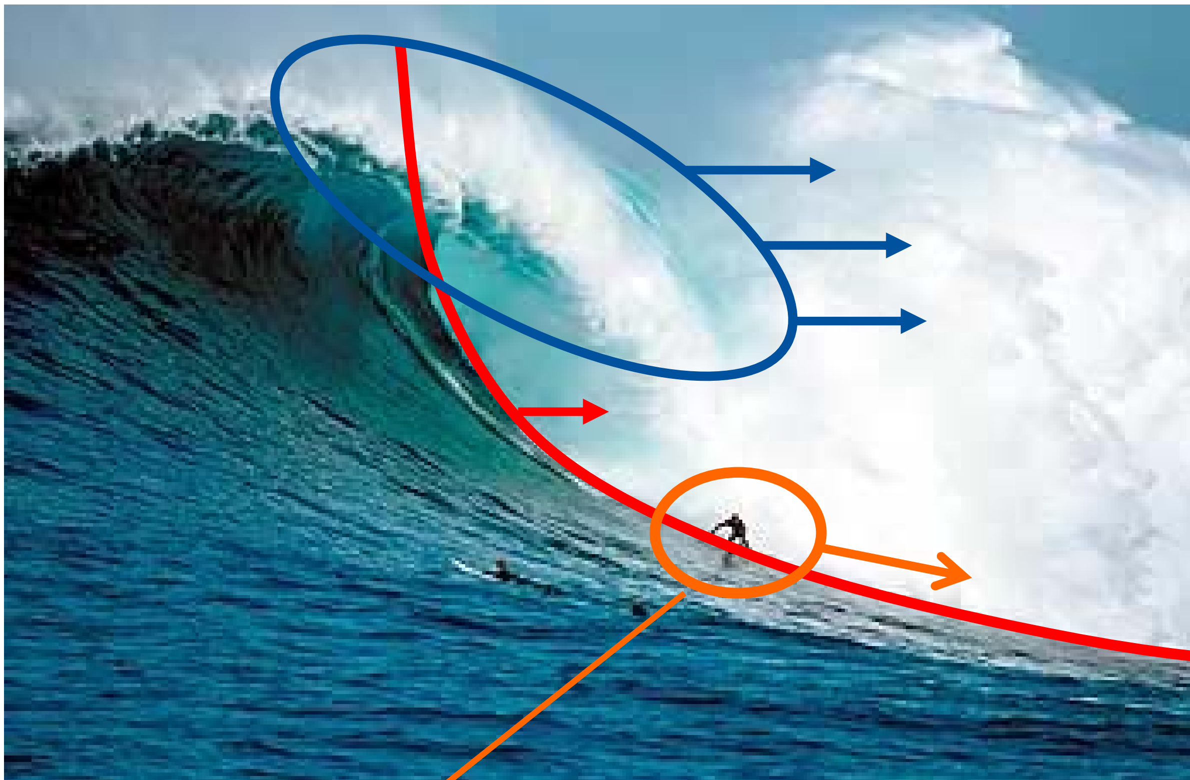
wakefield formation



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

3D PIC Simulation courtesy L. Silva, W. Mori

nonlinear wavebreaking (self injection) $v > v_{ph}$



dephasing

test particle $v_e > v_{ph}$
(external injection)

acceleration potential
(anharmonic, moving with v_{ph})

… effective, but rather hard to control

and normally destructing the accelerating wave (or wake)

Beschleunigen mit Licht

Ia. Wie wird ein Elektron beschleunigt ?

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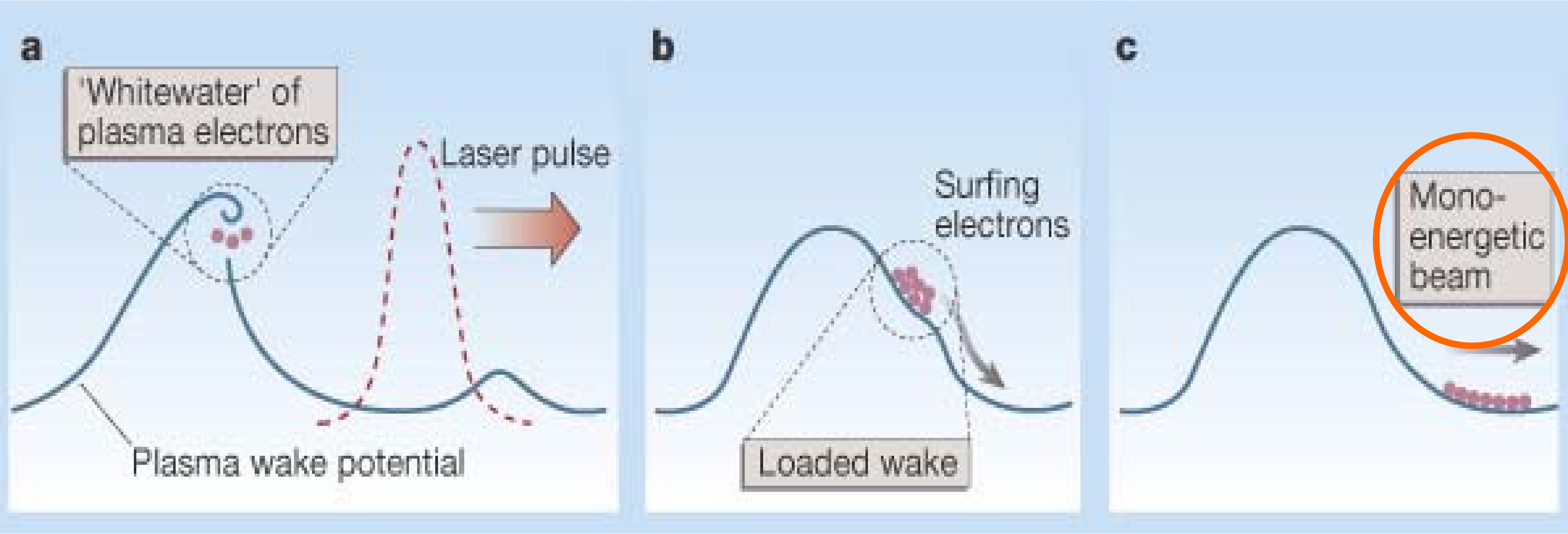
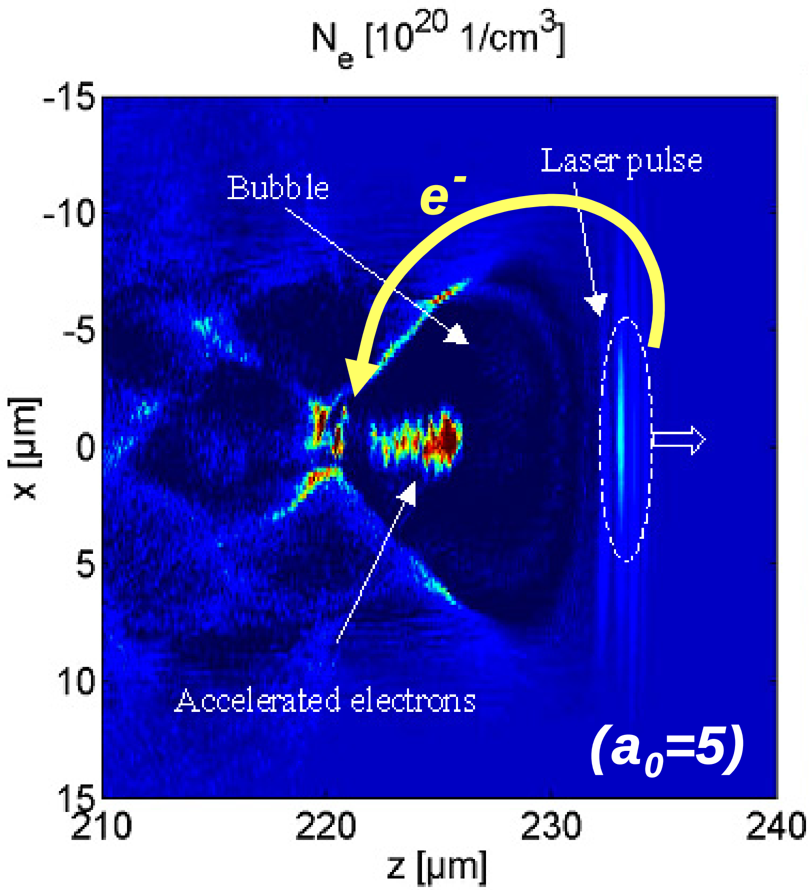
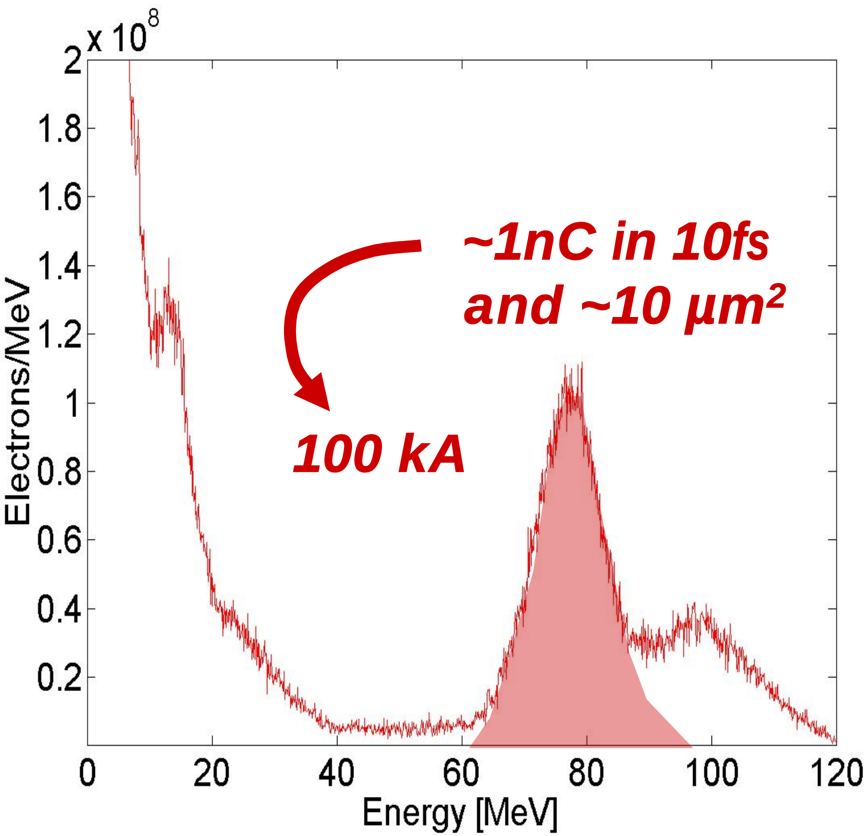
strongly idealized...



T. Katsouleas, Nature 431, 515 (2004)

… and yet surprisingly „real“ in the highly nonlinear broken wave – blow-out – bubble regime …

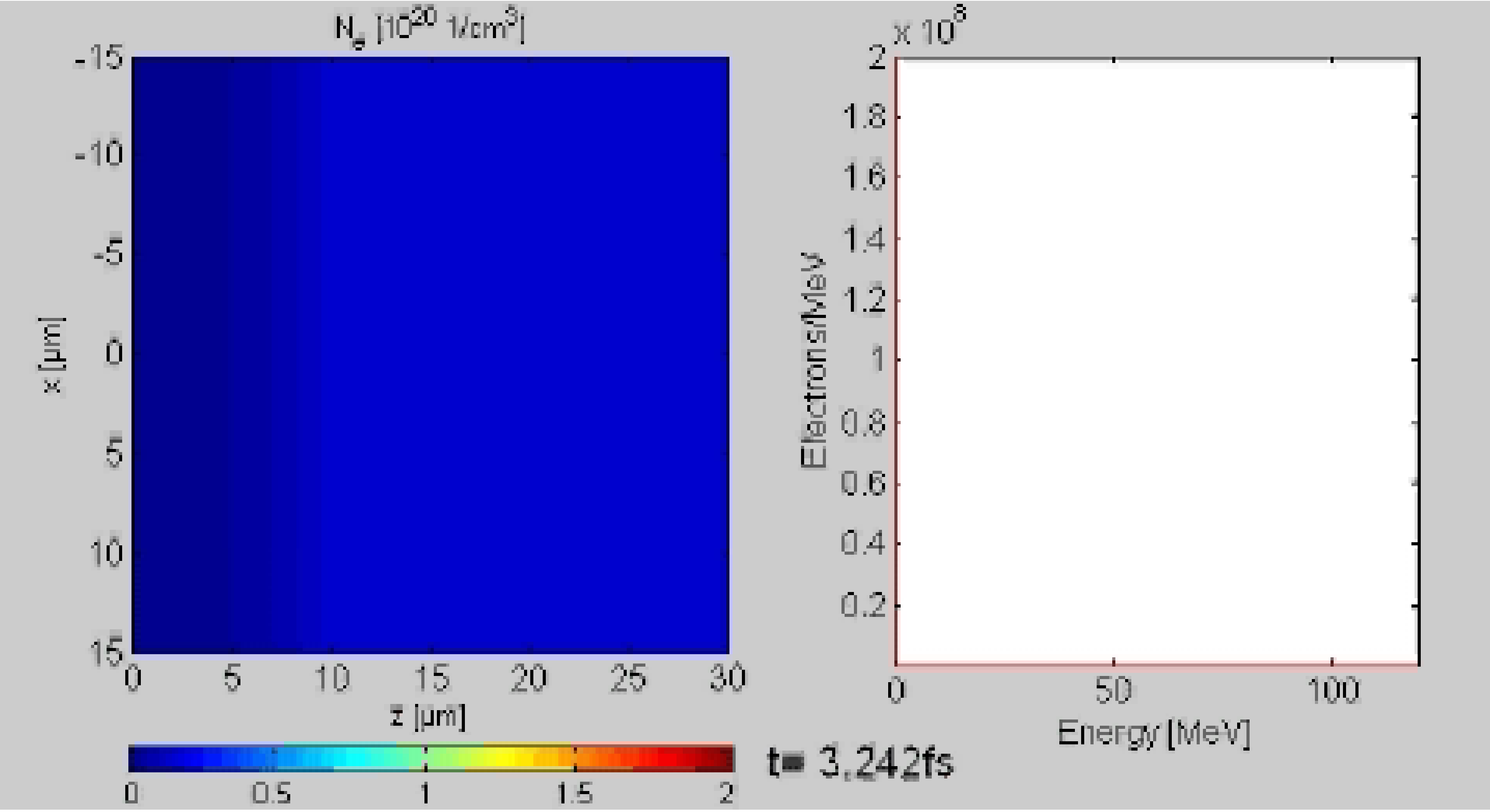




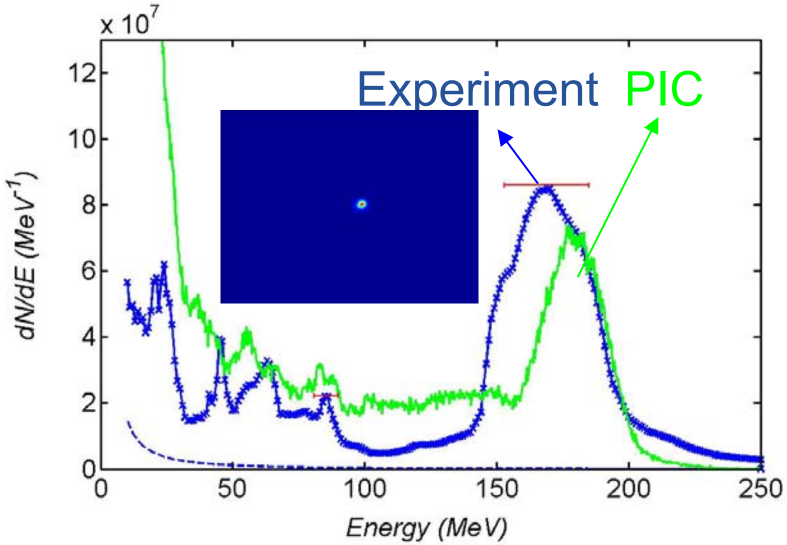
plasma wavelength* < *pulse length

[M. Geissler, NJP 8 (2006) 186]

bubble acceleration

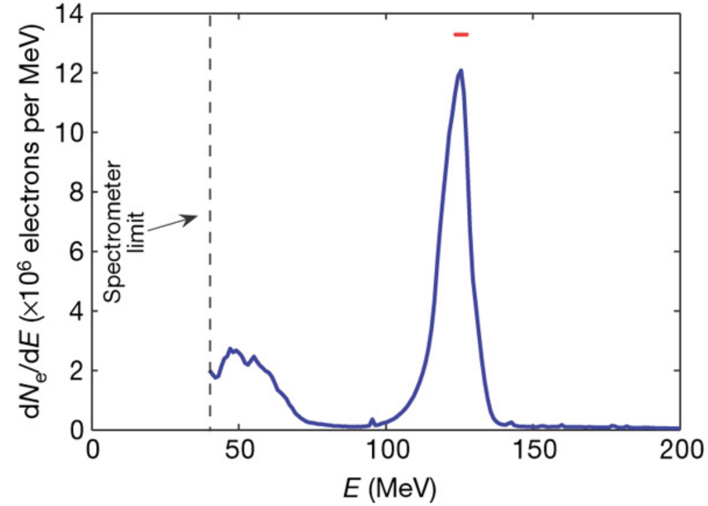


[M. Geissler, NJP 8 (2006) 186



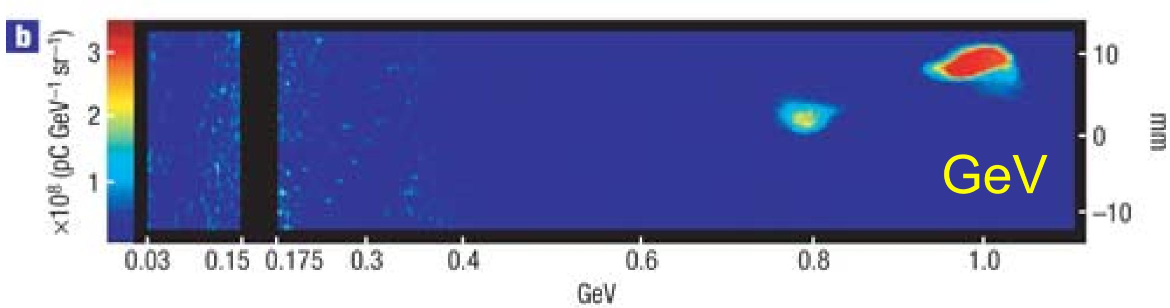
S. Mangles et al., C. Geddes et al., J. Faure et al.,
in Nature 431 (2004)

controlled injection



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

matched discharge capillary



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

Features of laser accelerated beams

high charge (up to nC)
short pulses (down to 10fs)

high peak current
(up to 100kA)

space charge

„compact" accelerators (up to GeV electrons)

low rep-rate (<10Hz)

excellent emittance, yet poor divergence

Features of laser accelerated beams

high charge (up to nC)
short pulses (down to 10fs)

high peak current
(up to 100kA)

space charge

„compact“ accelerators - local machines

low rep-rate (<10Hz) - restrict to low average
yet high peak dose

excellent emittance, yet poor divergence

Beschleunigen mit Licht

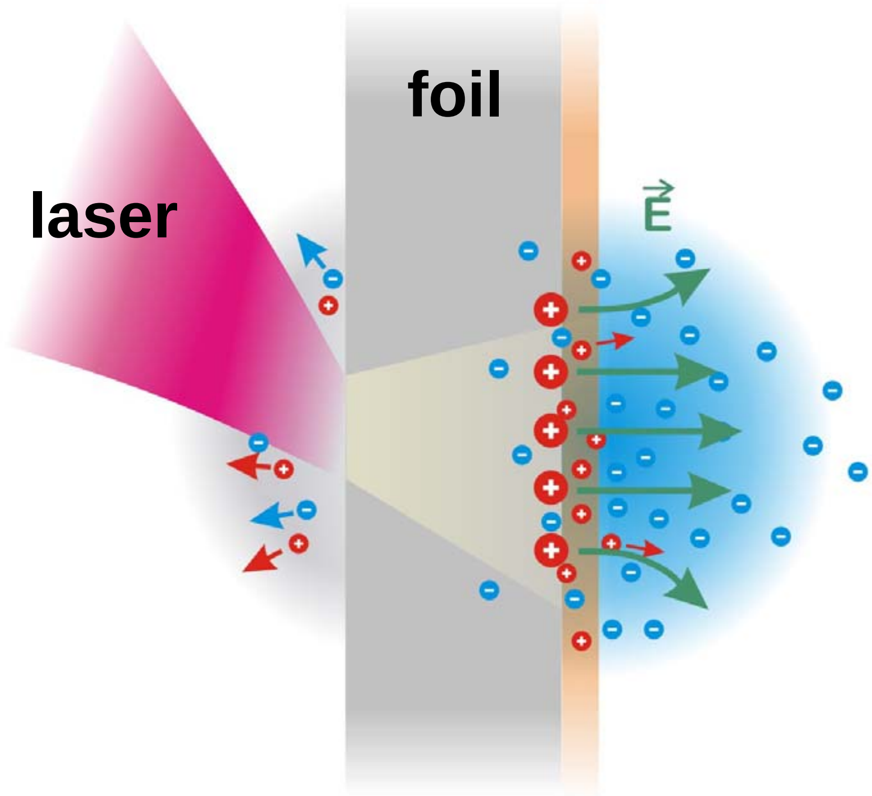
II. Wie erreicht man die viel schwereren Ionen ?

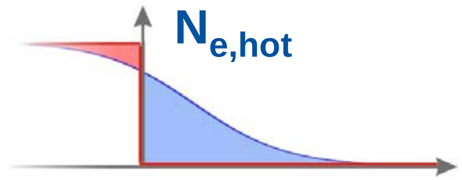
… immer nur über die Elektronen …

III. Mögliche medizinische Anwendungen

Ion acceleration – TNSA regime

- electron acceleration
- hot (MeV) electrons penetrate the (μm) foil
- quasi static field forms normal to target surface, source size >> laser spot





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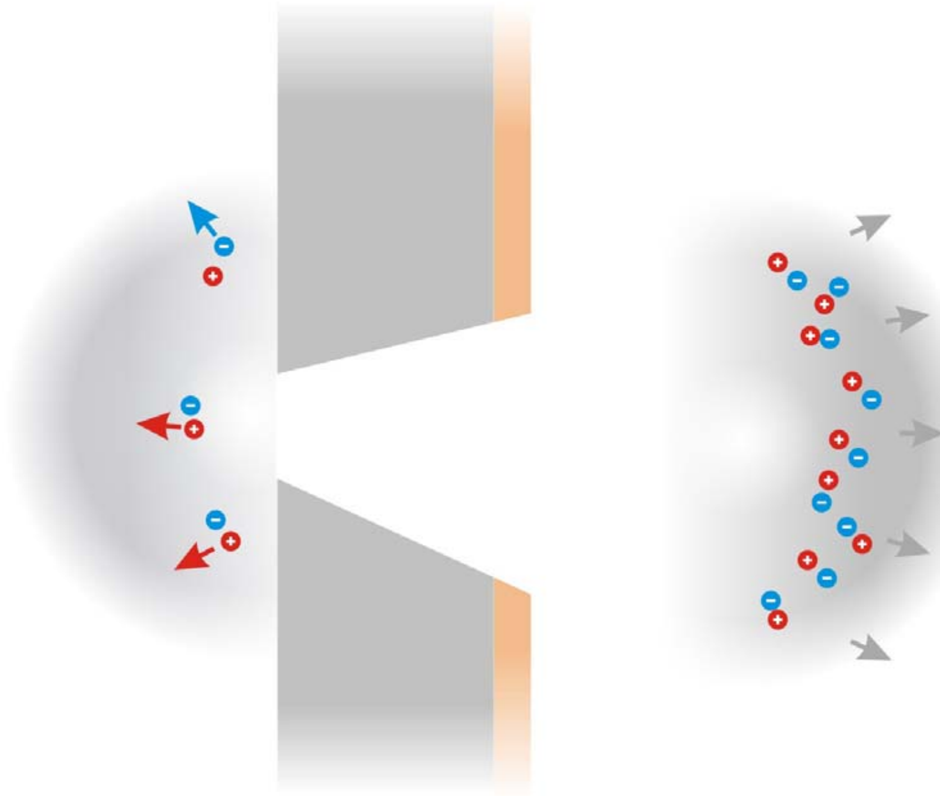
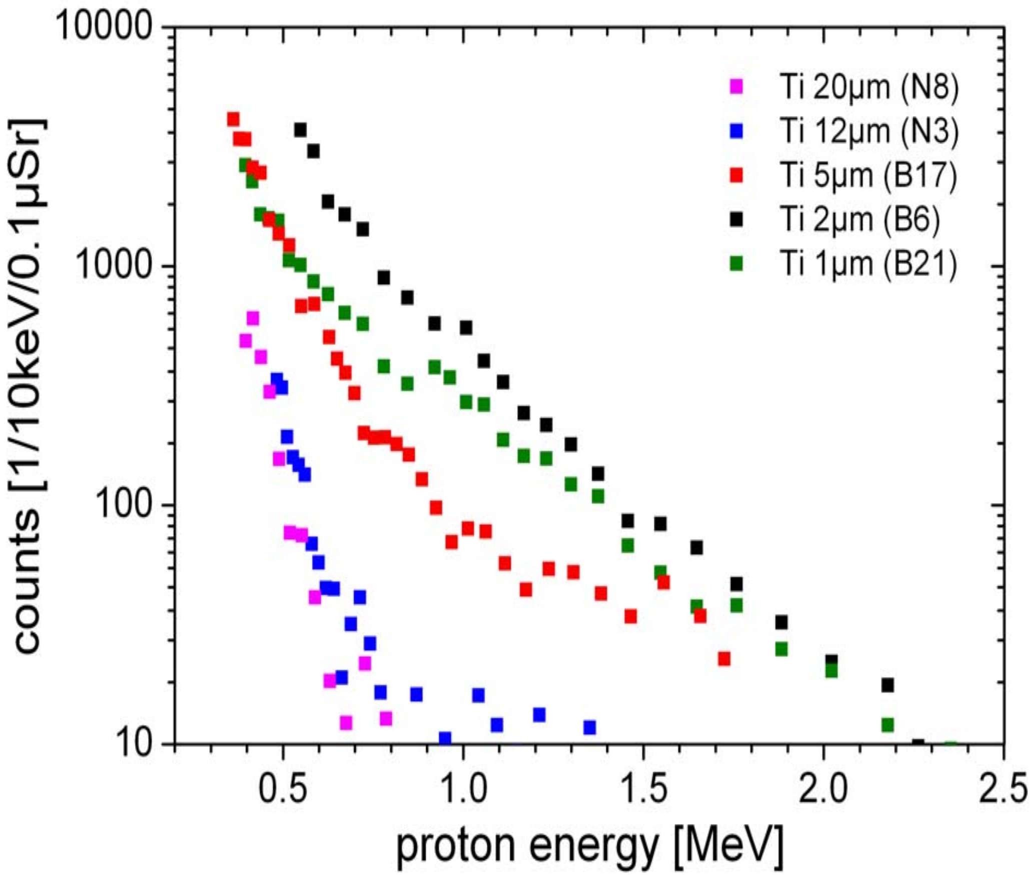


quasi-neutral pulse with exponential energy distribution (with max. energy depending on laser pulse duration, energy, and target thickness)

Ion acceleration – TNSA regime



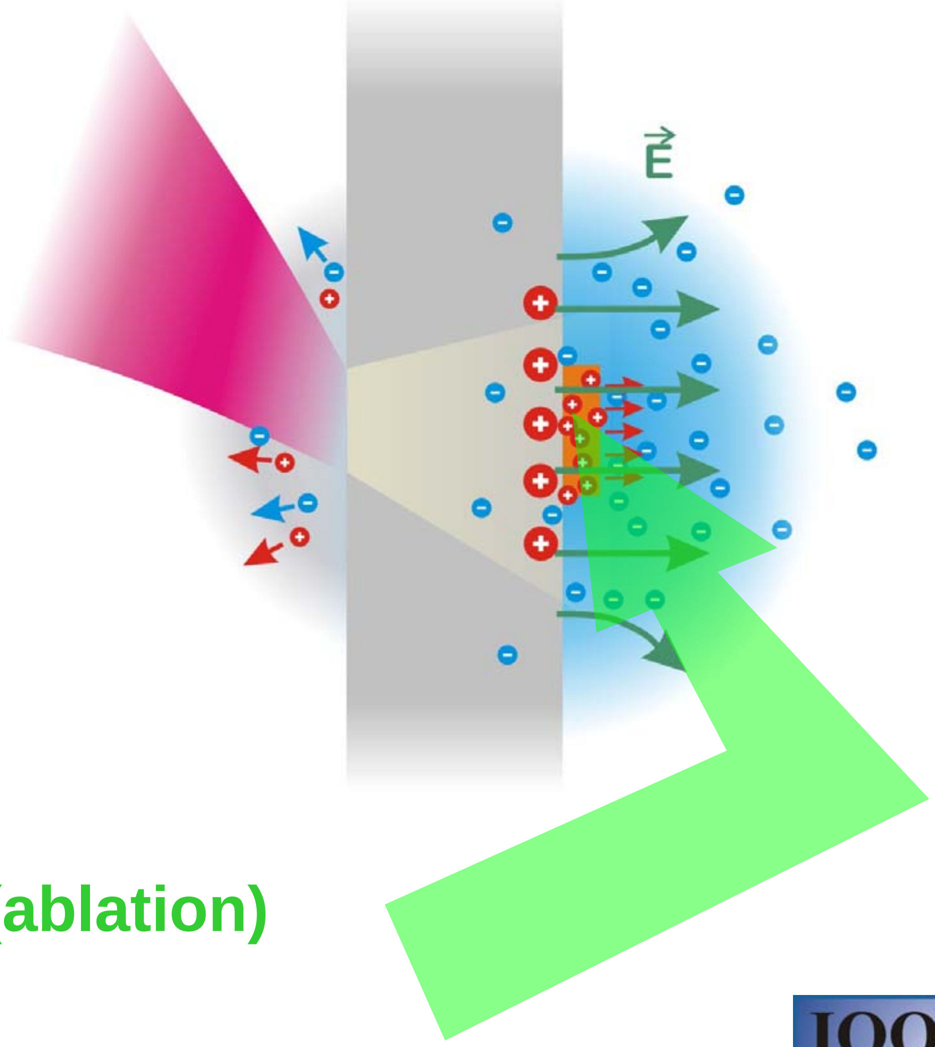
quasi-neutral pulse with exponential energy distribution (with max. energy depending on laser pulse duration, energy, and target thickness)

IOQ Jena

Ion acceleration – TNSA monoenergetic

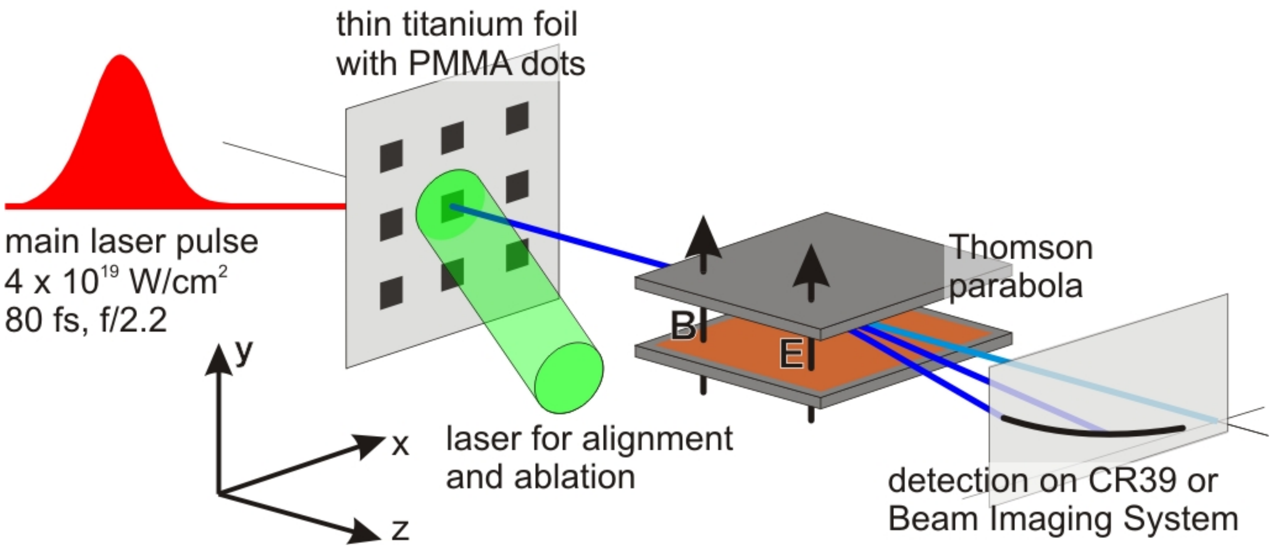
- enhance yield in the central, homogeneous region by applying a proton rich „dot“

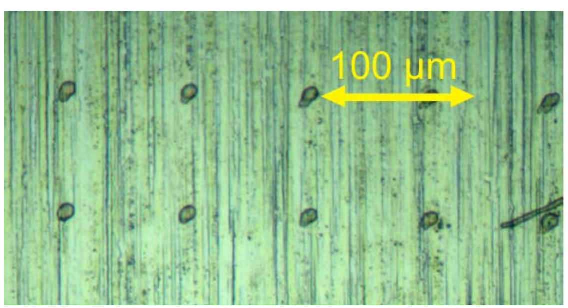
- use thin dot (to avoid temporal field depletion and shielding)



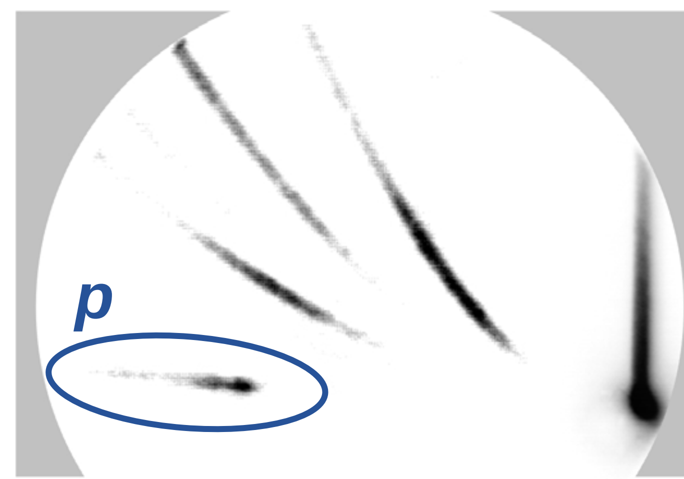
- Careful backside cleaning (ablation) increases the fidelity

exp. status in Jena (2006)



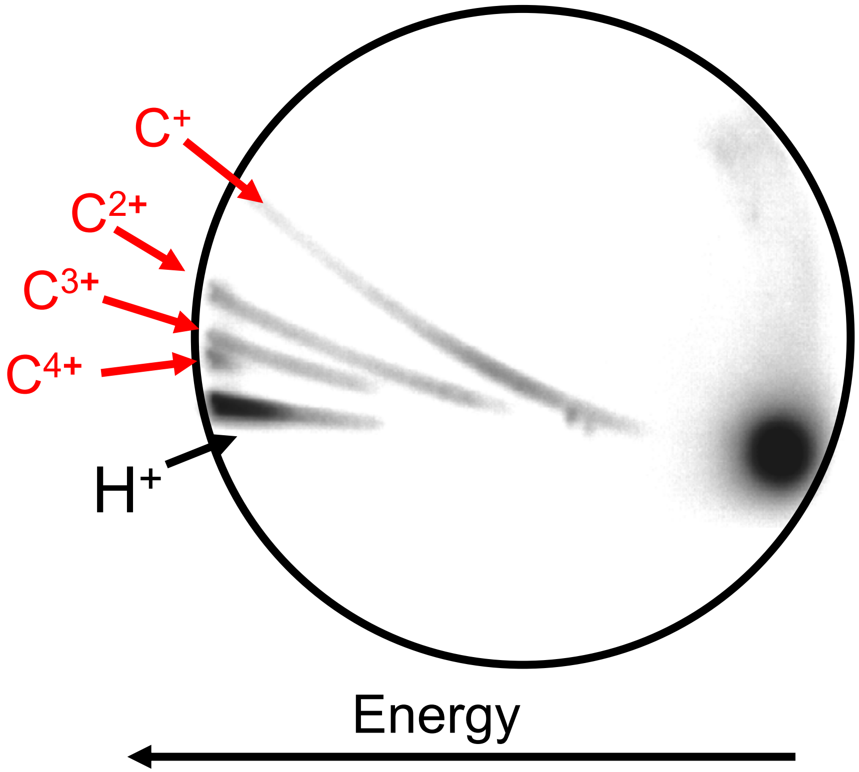


Lith. polymer coating on Ti-foil
8 x 8 – 20 x 20 µm^2 base area
0.15 – 1.0 µm height



IOQ Jena

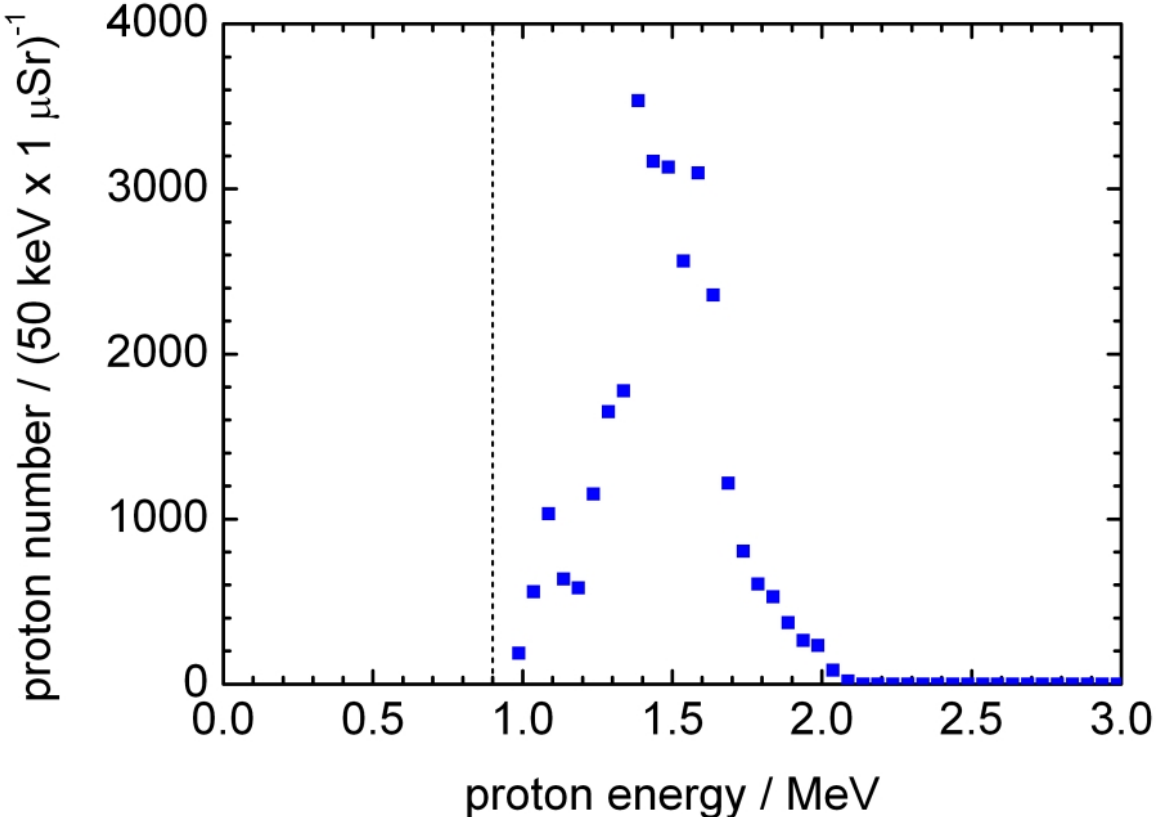
Different ion species



Ions are seperated by a mass and energy selective spectrometer and hit a position sensitive detector.

All species of ions located at the backside of the foil can be accelerated

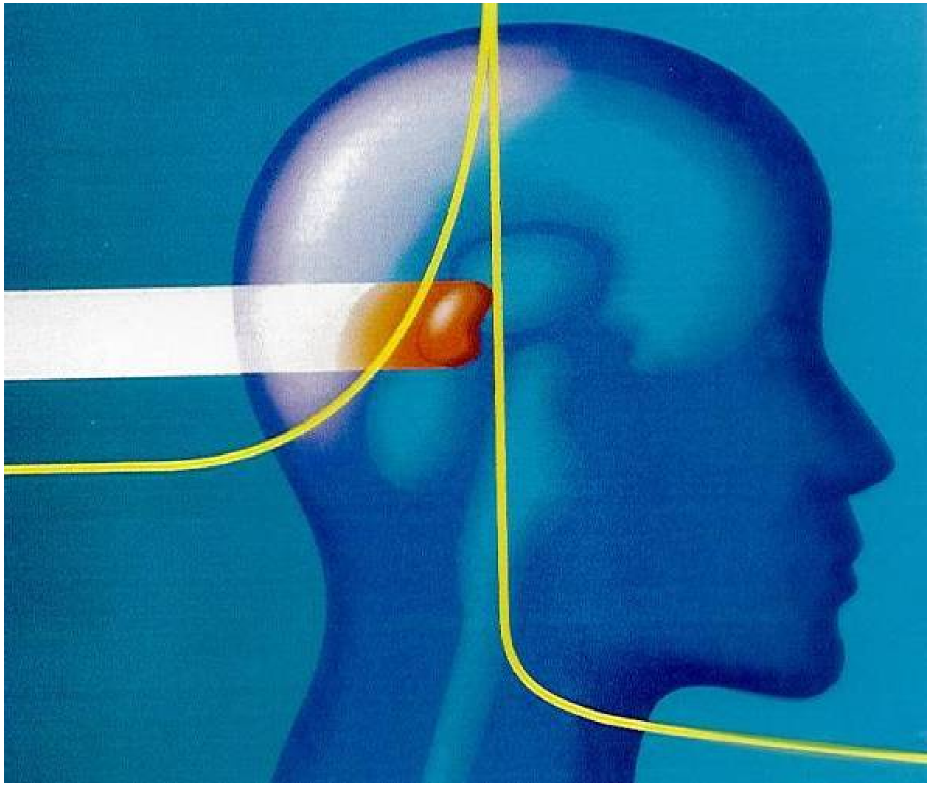
Ion acceleration – TNSA monoenergetic



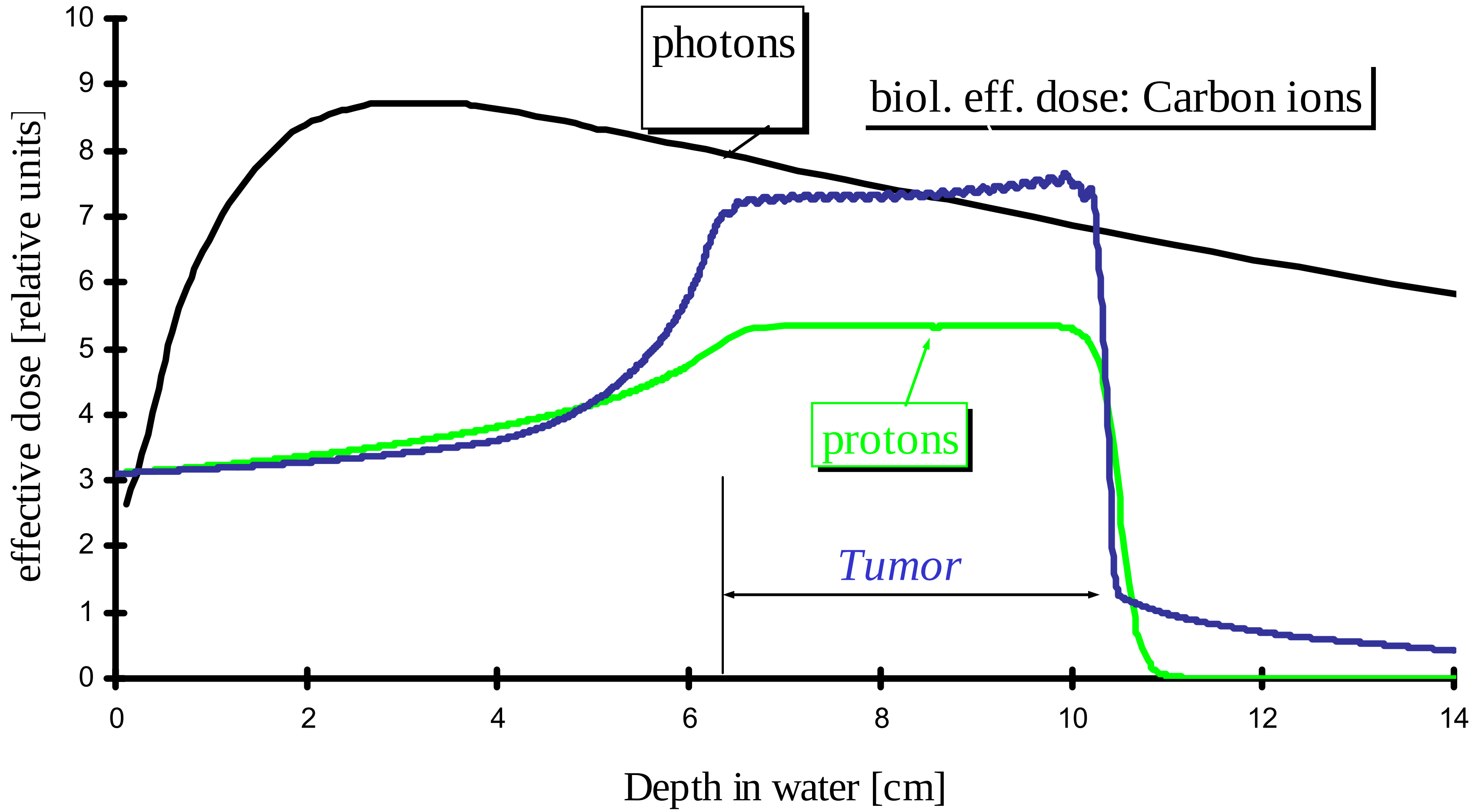
- **overall number of ions about 10^8 in 20msr**
- **80% fidelity with online target cleaning (ablation)**

[H. Schwoerer et al., Nature 439 (2006) 445]

Laserbeschleuniger für die Ionenstrahl Tumortherapie ?

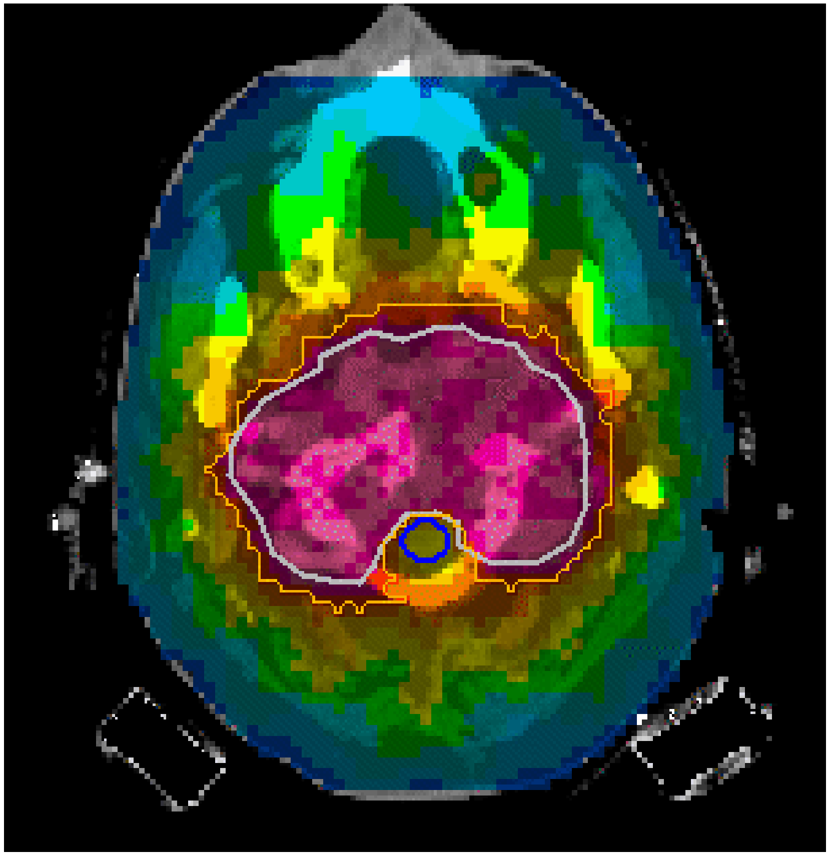


Ion beam therapy – the idea

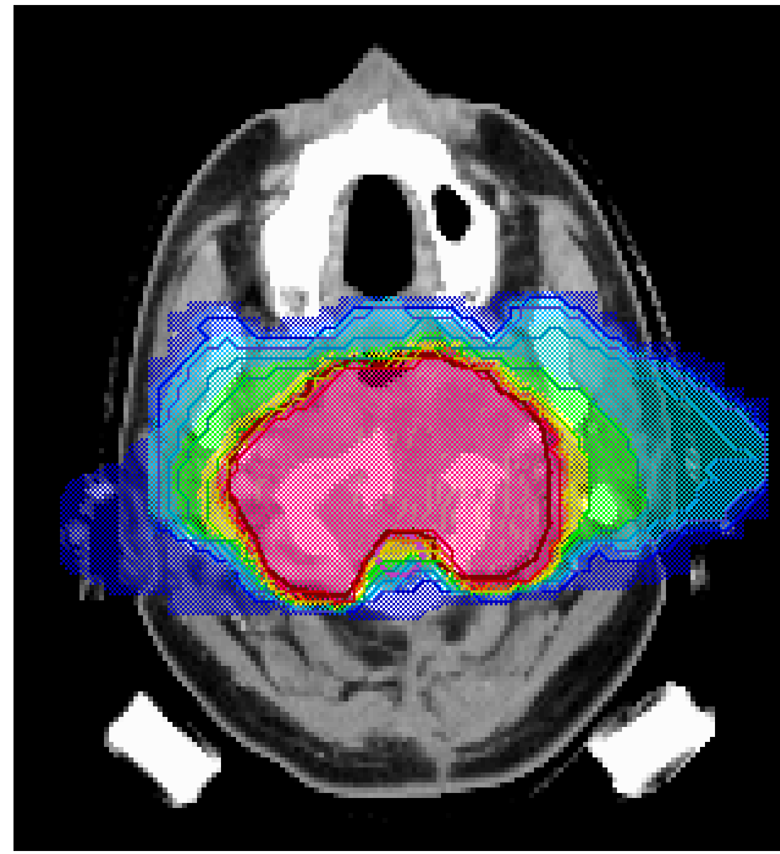


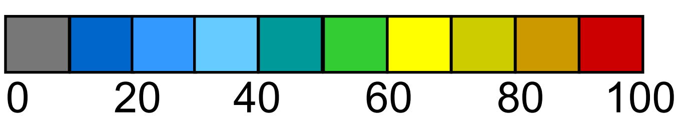
Ion beam therapy – treatment planning

Photons: 9 fields



carbon-ions: 2 fields

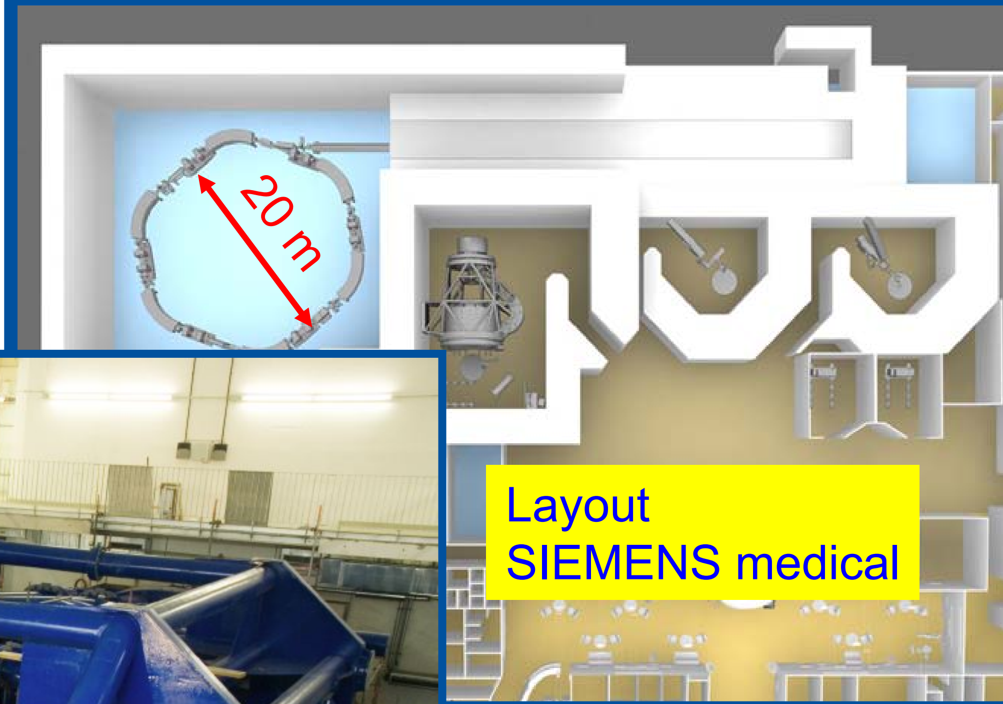




dose in % of the maximum dose

Courtesy O. Jäkel, DKFZ Heidelberg

The GSI / HIT approach



Pictures by courtesy of T. Haberer HIT Heidelberg

requirements for ion beam therapy

Dose: ***40-80 Gray distributed over 10-20 fractions***

-> 10^9-10^{10} ions per fraction and few minutes

Spatial control: ***mm-scale @ 20cm depth***

-> 200 MeV @ percent level control
-> mm pointing (contour shaping)

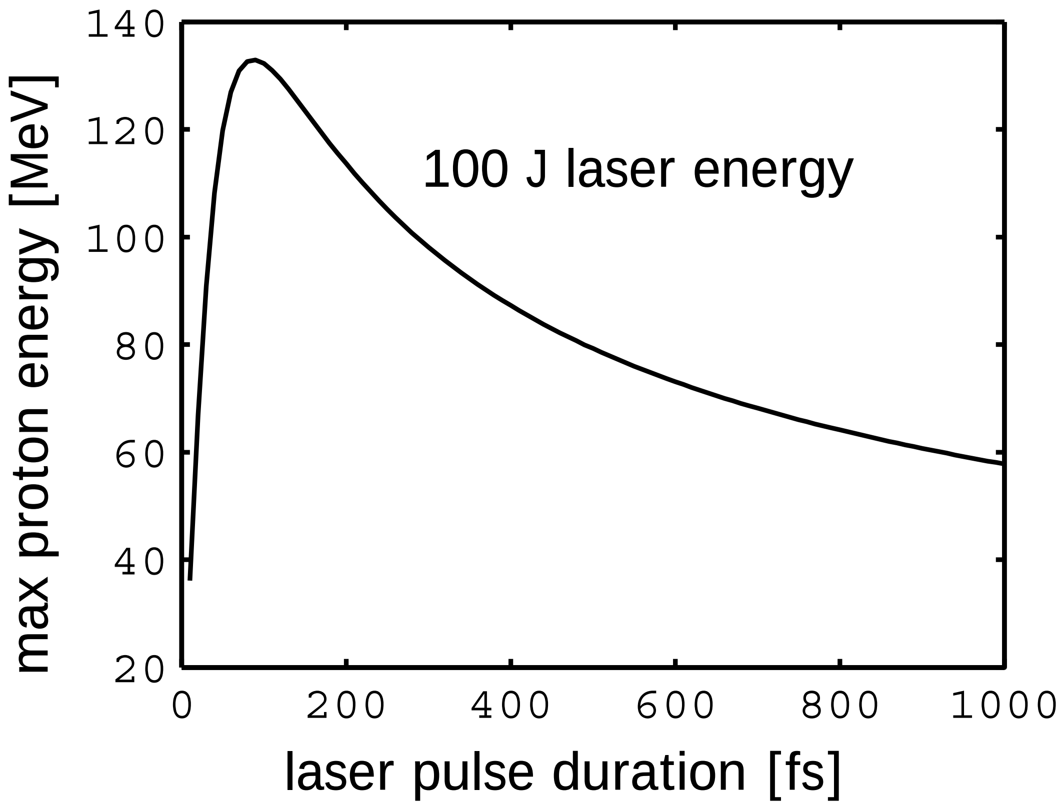
Complete (nondestructive shot-to-shot) monitoring

Clean beam

-> 5% position dependent dose control

TNSA – increasing the energy

For each laser system there is an optimal pulse duration for TNSA ion acceleration, which is not necessarily the shortest

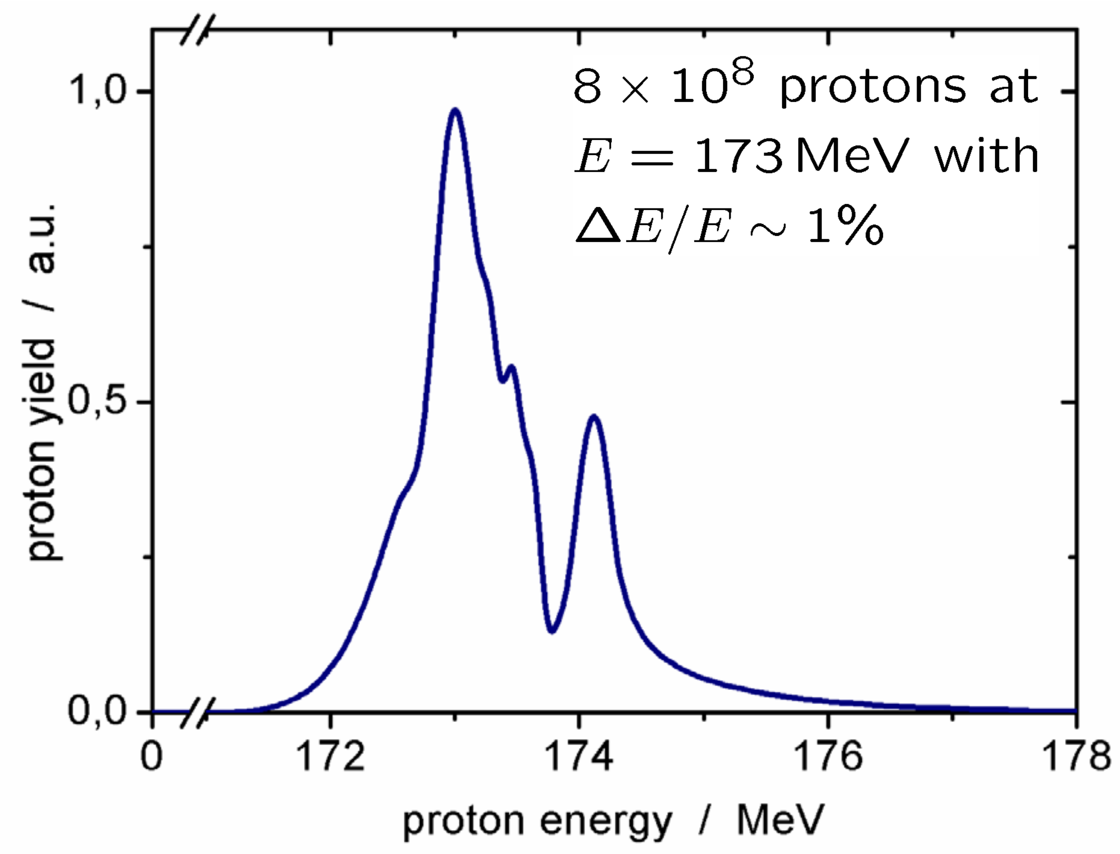


[J. Schreiber, et al, PRL 97 (2006) 045005]

POLARIS simulation

2D-PIC simulation by T. Esirkepov for next laser generation (POLARIS):

100 J in 100 fs, $I_L = 10^{21}$ W/cm^2, 5 µm Ti-foil + 0.1 µm PMMA dot (Ø 2.5 µm)



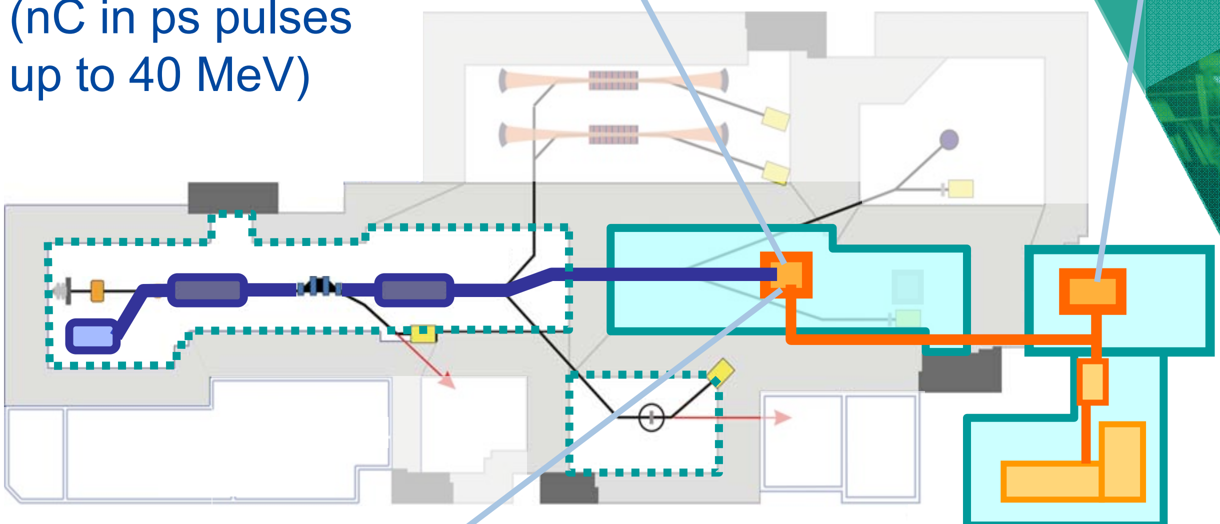
Aktuelle Situation am FZD

Present situation at FZD

Electron acceleration

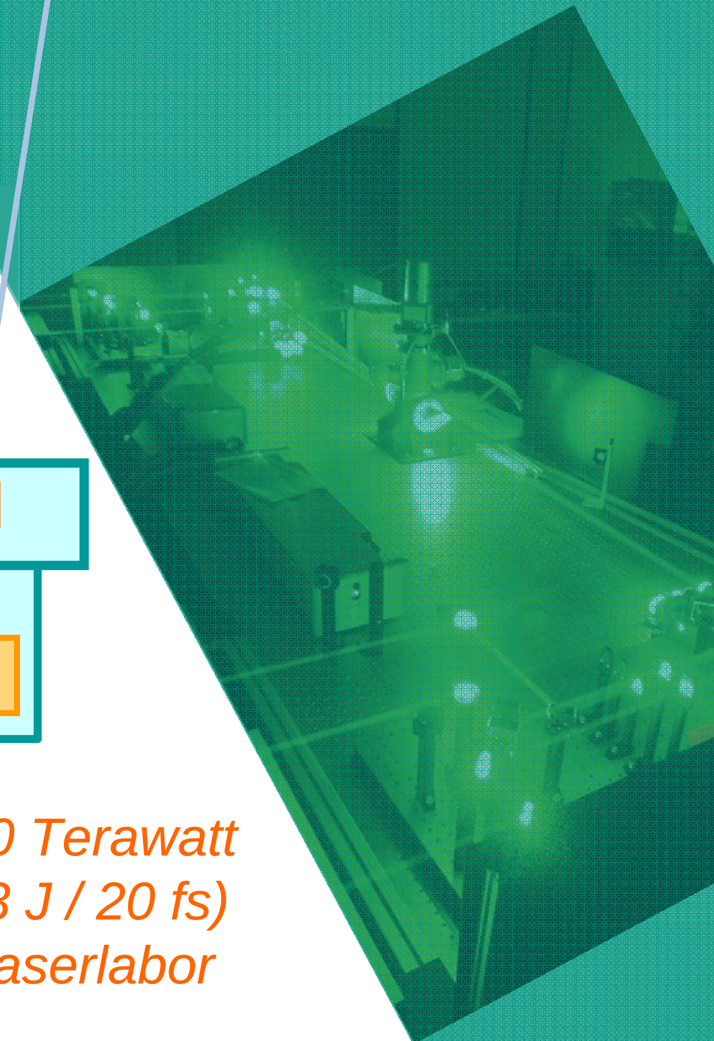
Ion acceleration

ELBE
SC RF accelerator
(nC in ps pulses
up to 40 MeV)



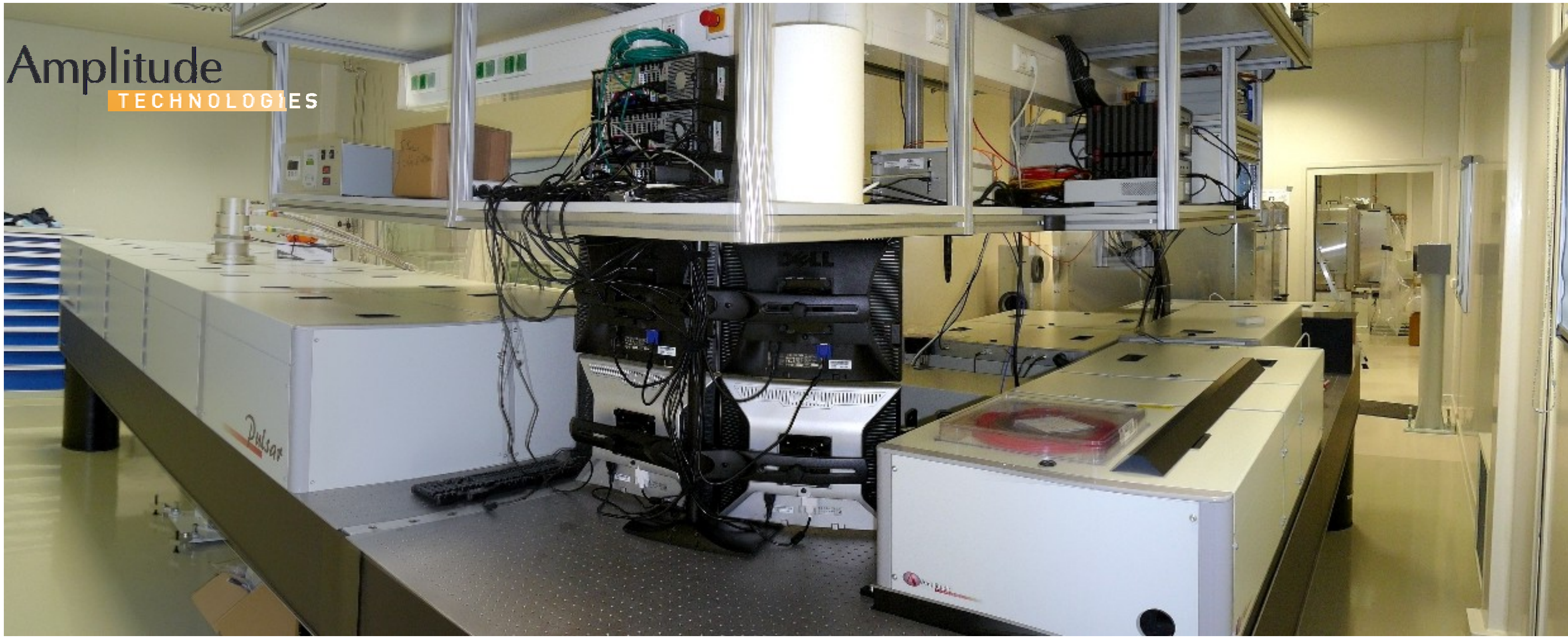
Thomson scattering

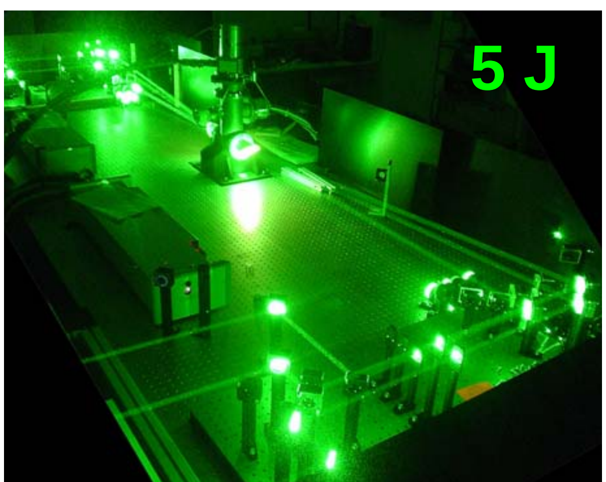
150 Terawatt
(3 J / 20 fs)
Laserlabor

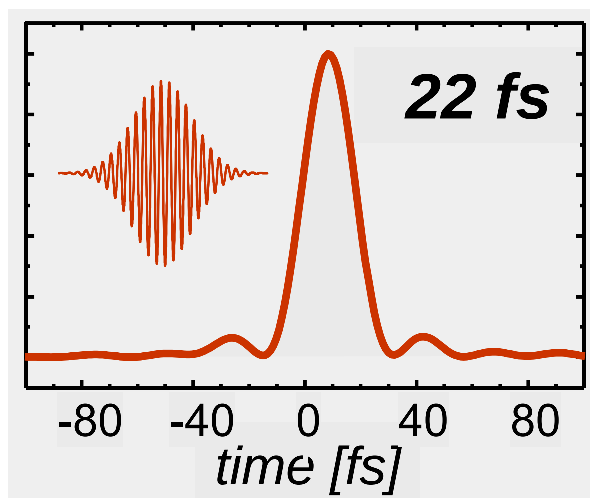


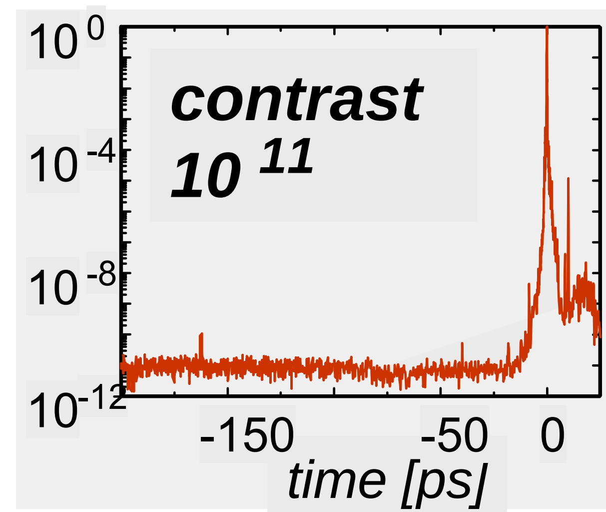
August 2007

Amplitude TECHNOLOGIES









thanks to

T. Kluge, S. Kraft, K. Zeil, S. Bock, (A. Debus, M. Bussmann, M. Siebold)

K. Ledingham

S. Karsch, J. Osterhoff, A. Popp, Zs. Major, M. Fuchs, B. Marx, R. Hörlein, K. Schmid, L. Veisz, S. Becker, D. Habs, F. Grüner, F. Krausz, (T.P. Rowlands-Rees, S.M. Hooker), M. Geissler

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

B. Hidding, G. Pretzler