Laser-Ion Acceleration

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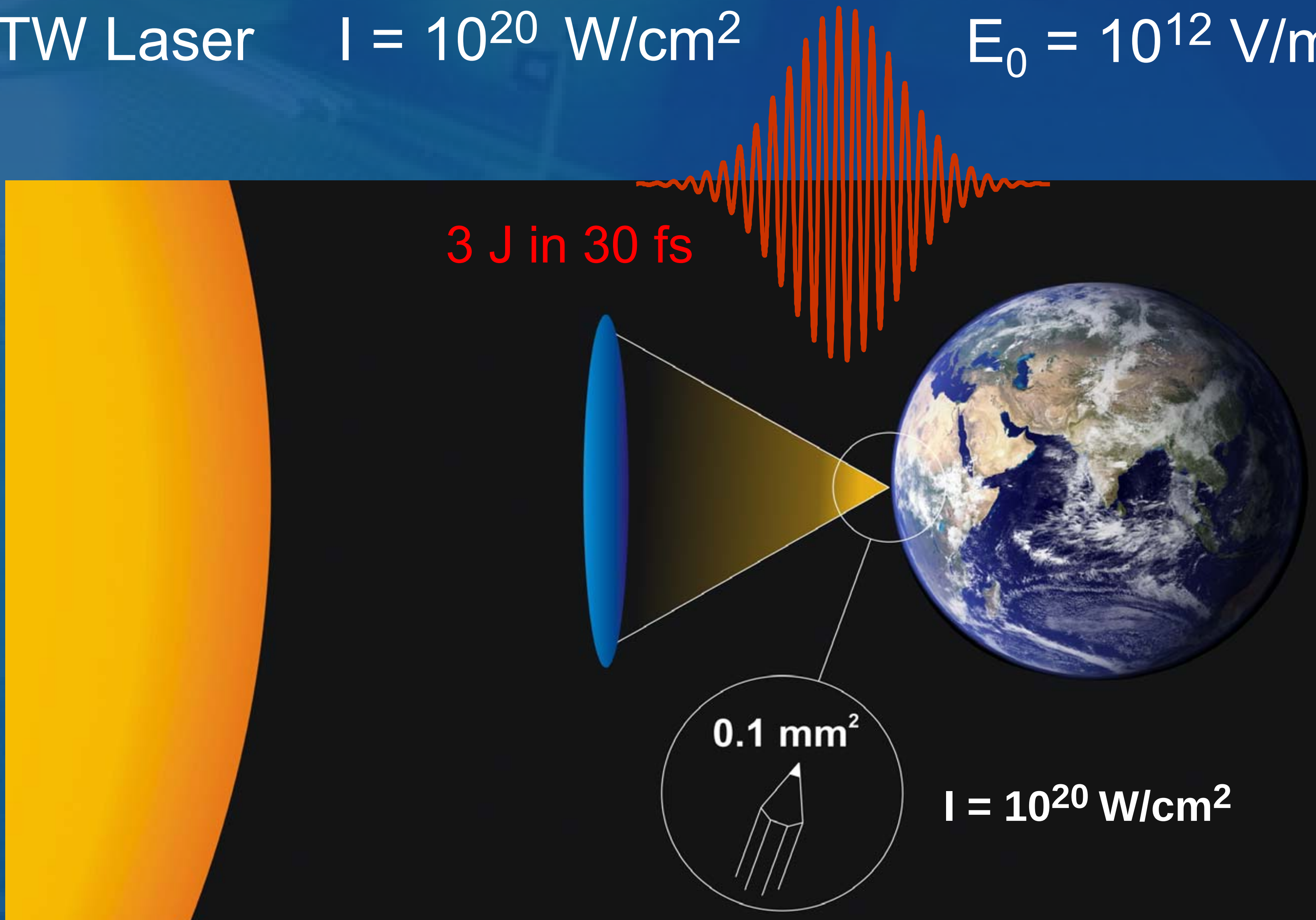
Laser-Particle-Acceleration

R. Sauerbrey

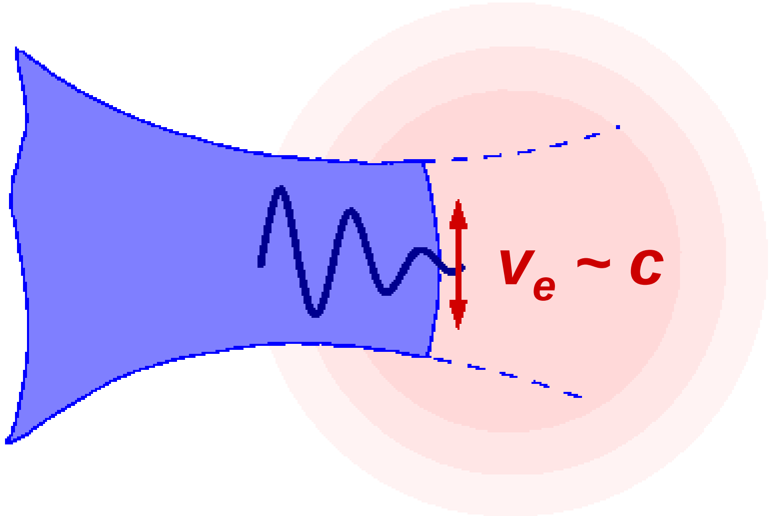
- What happens to one electron in the laser field ?
- Laser electron acceleration
- Laser ion acceleration
- Applications

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



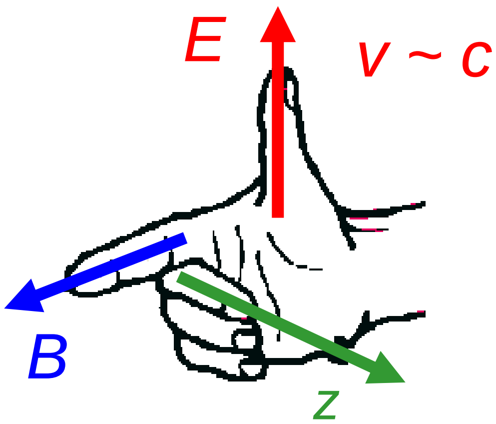
For laser intensities exceeding $I \sim 10^{18}\ W/cm^2$, the electron quiver motion becomes relativistic within half a period

target: one electron

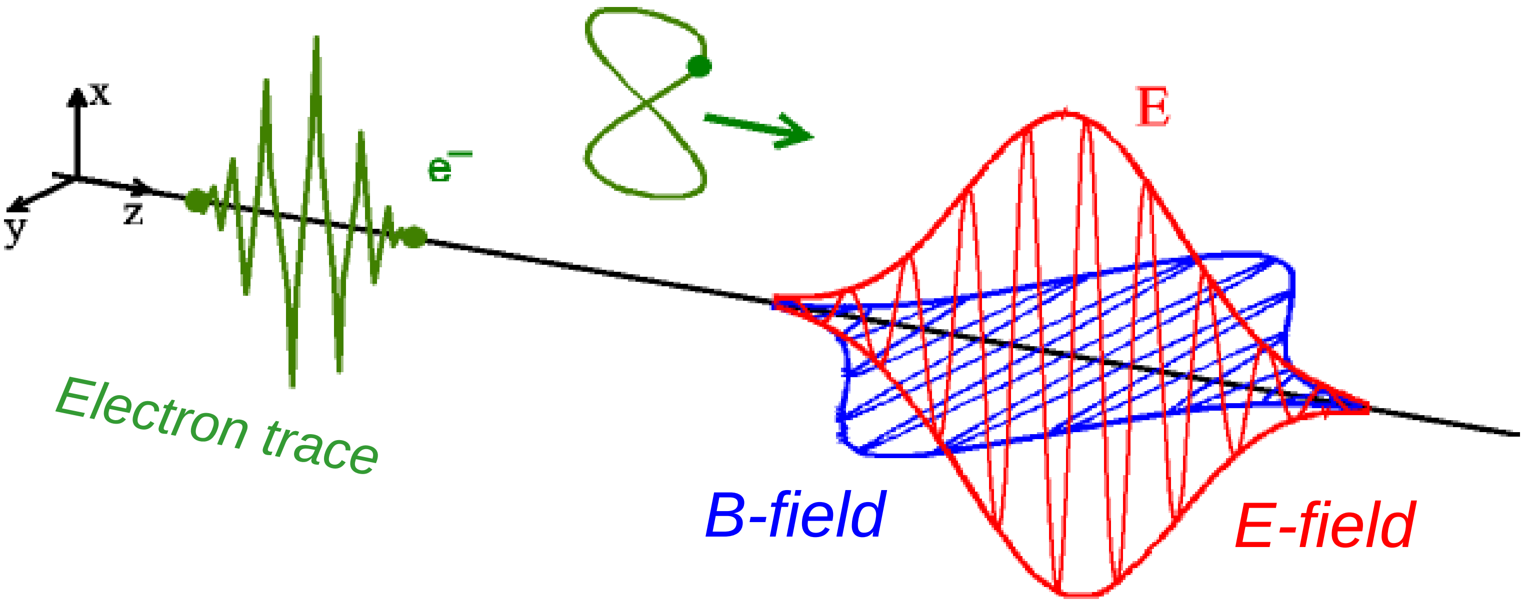


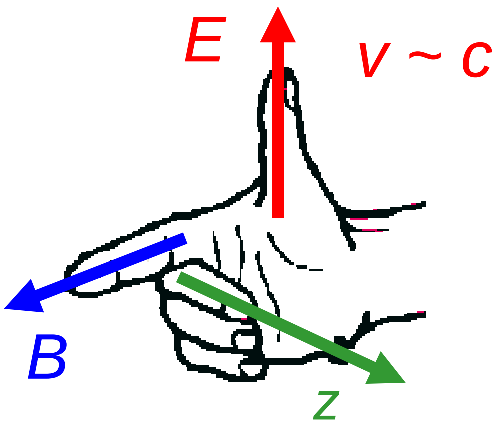
- *mass increase*
- *forward acceleration due to Lorentz force*
- *anharmonic osc.*

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

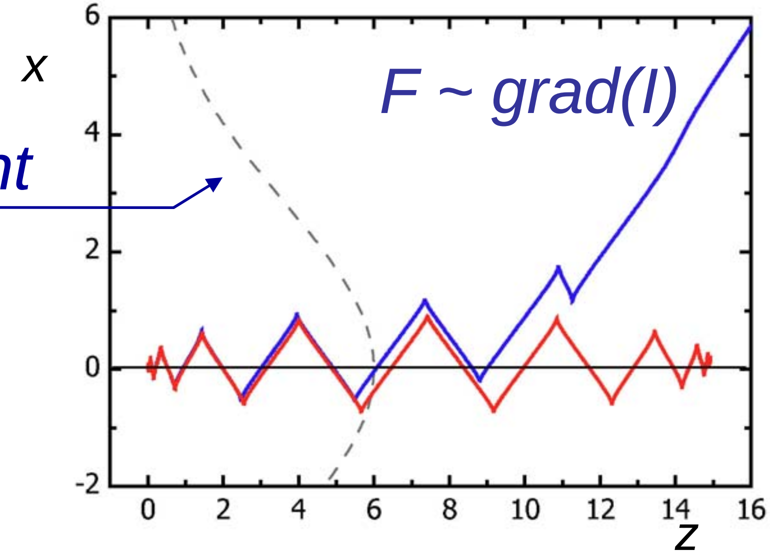


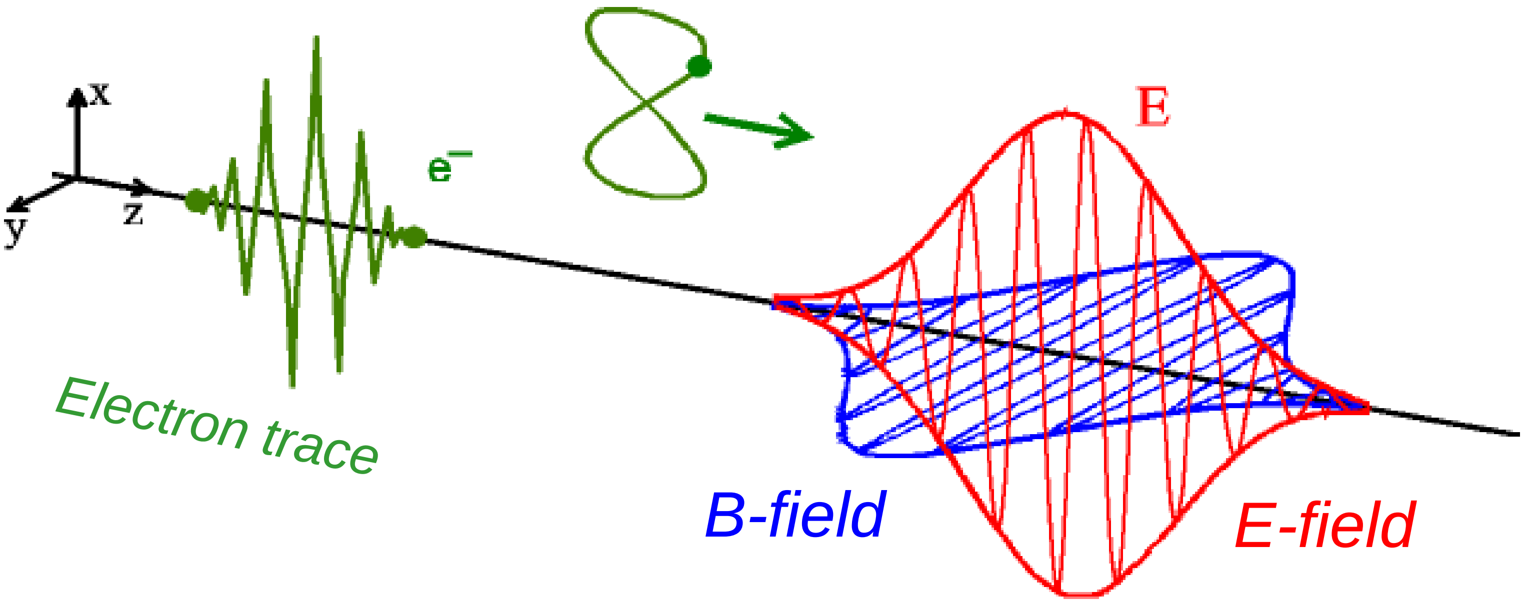
$$\vec{F} = e\vec{E} + e\,\vec{v} \times \vec{B} \qquad \left(B_0 = E_0/c\right)$$

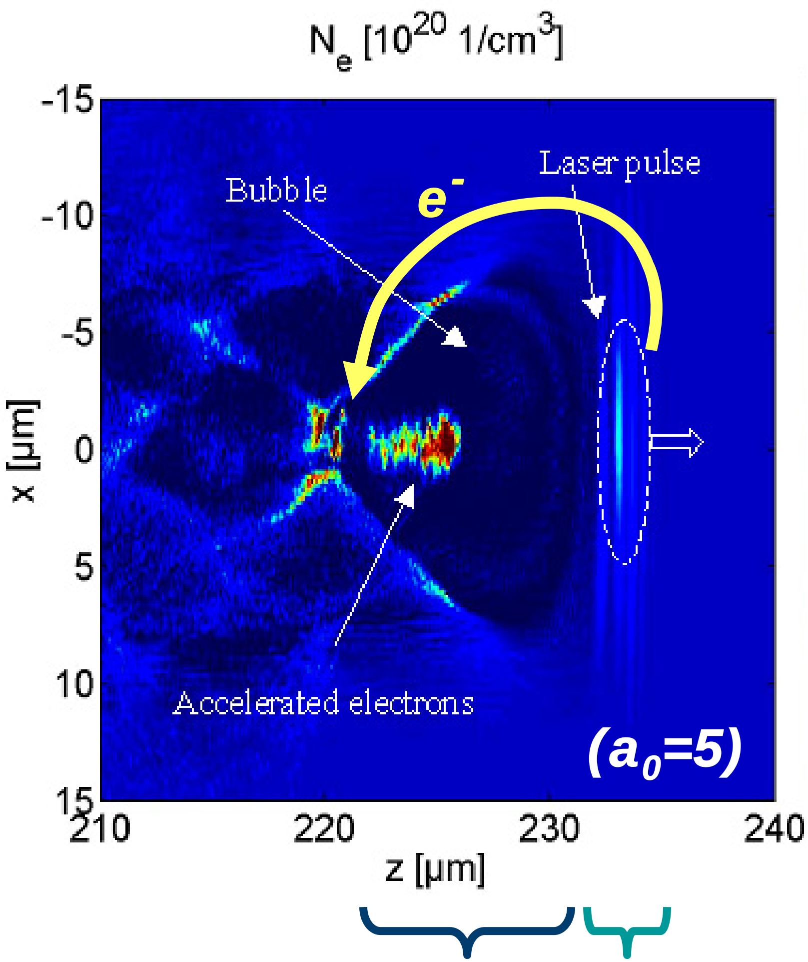




intensity gradient
ponderomotive
acceleration



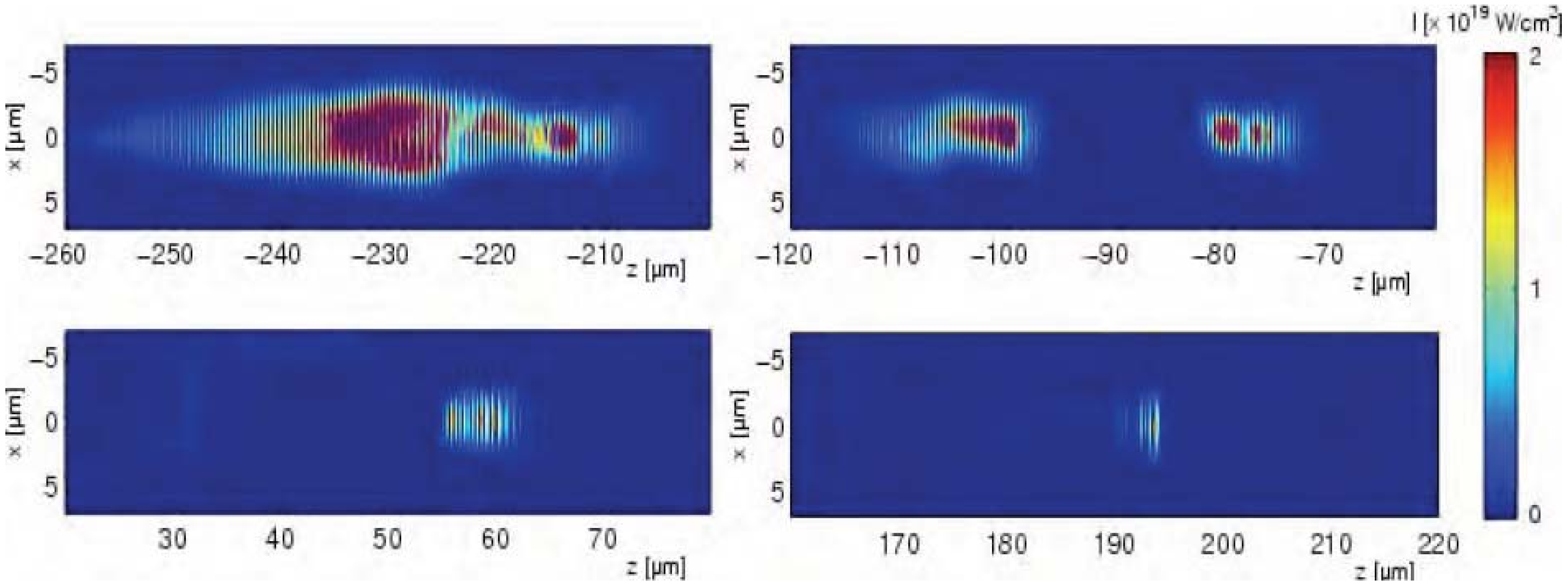




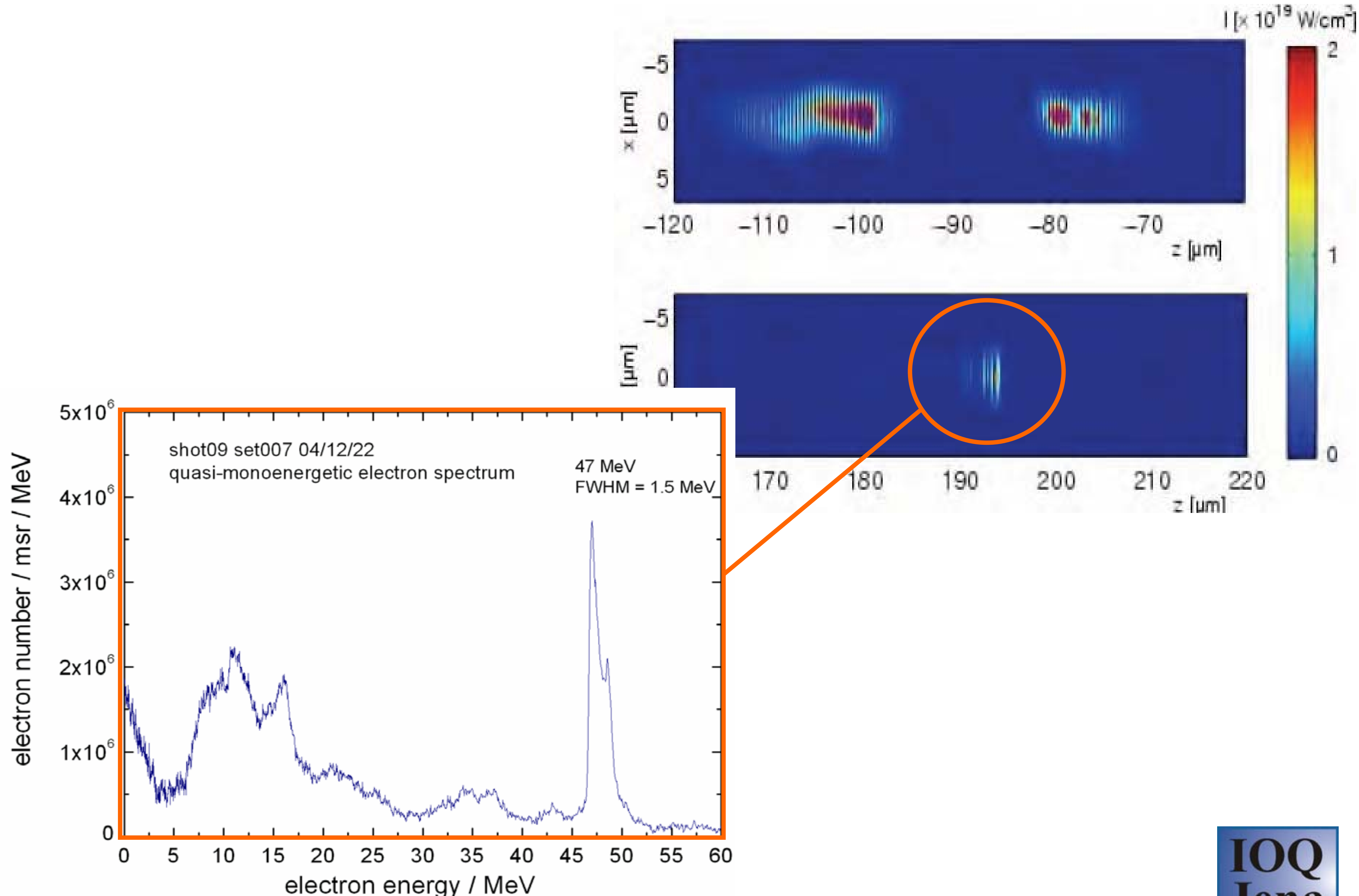
plasma wavelength < pulse length

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

relativistic pulse shortening ...



relativistic pulse shortening ...



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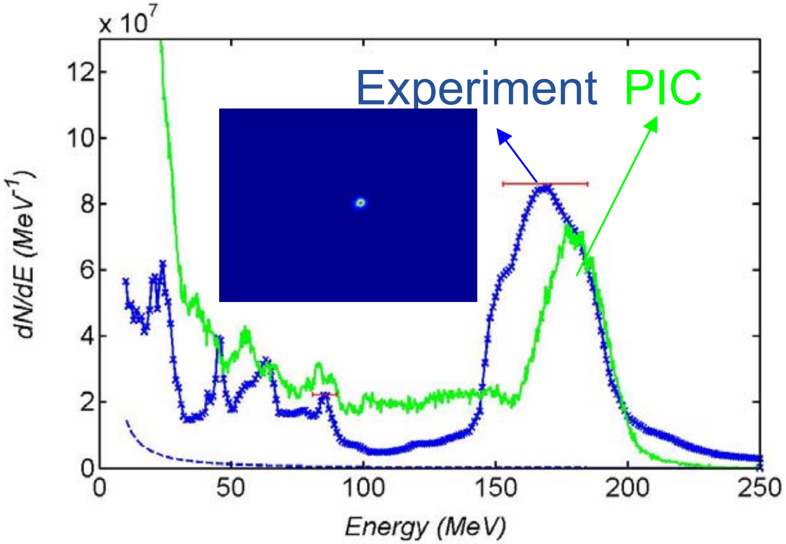
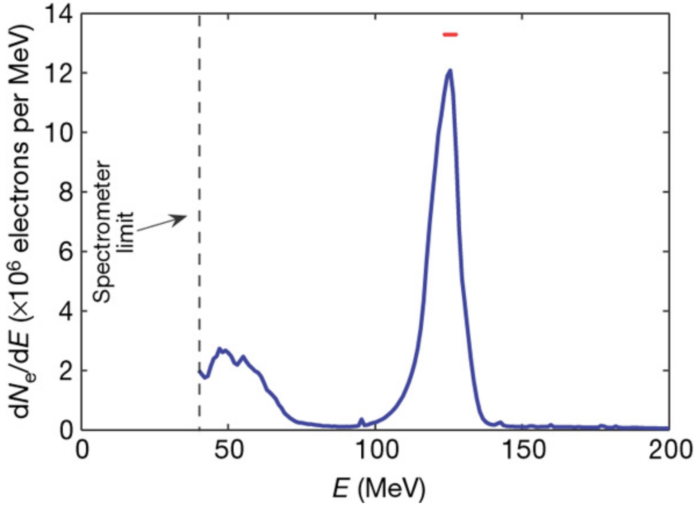
recent developments



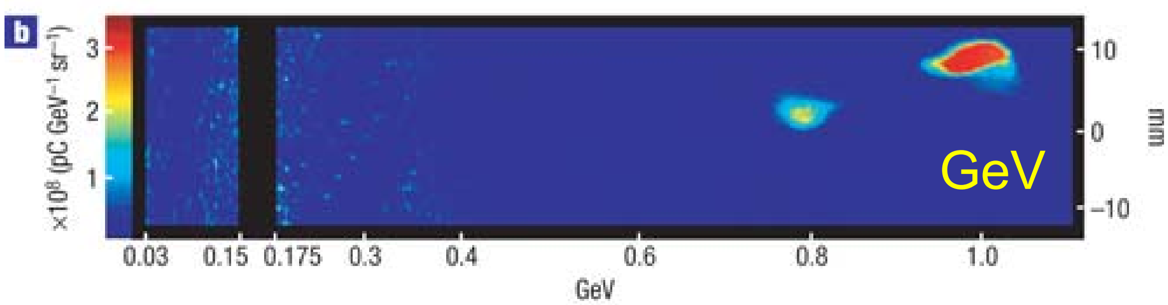
S. Mangles et al., C. Geddes et al., J. Faure et al.,
in Nature 431 (2004)

controlled injection



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

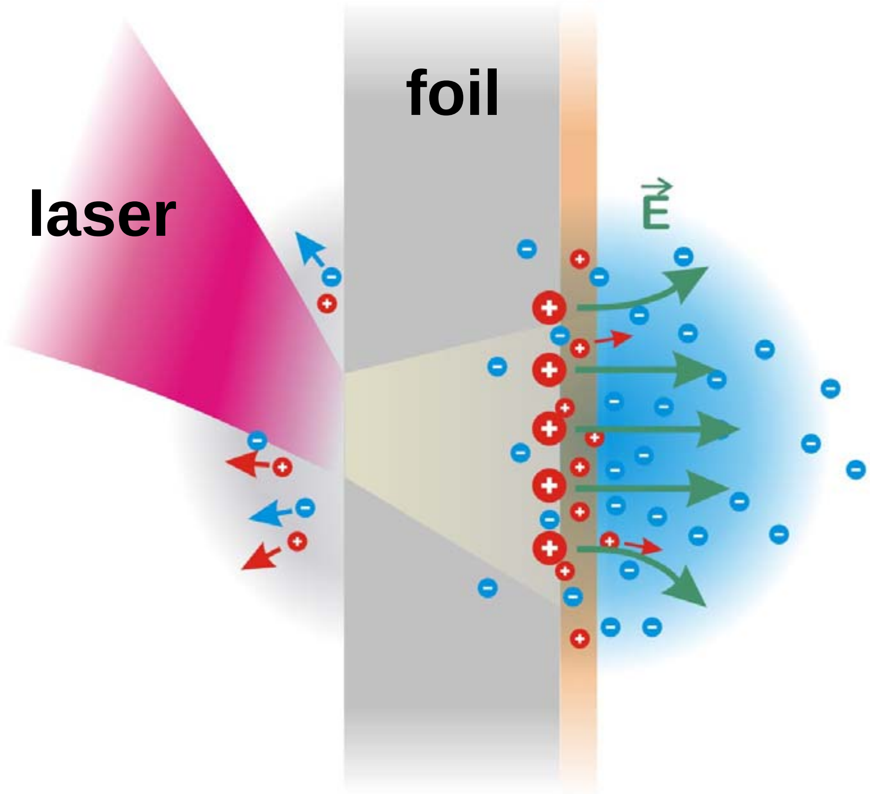
matched discharge capillary

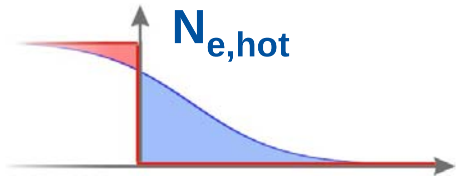


W. Leemans, et al.,
Nature physics 2 (2006) 696

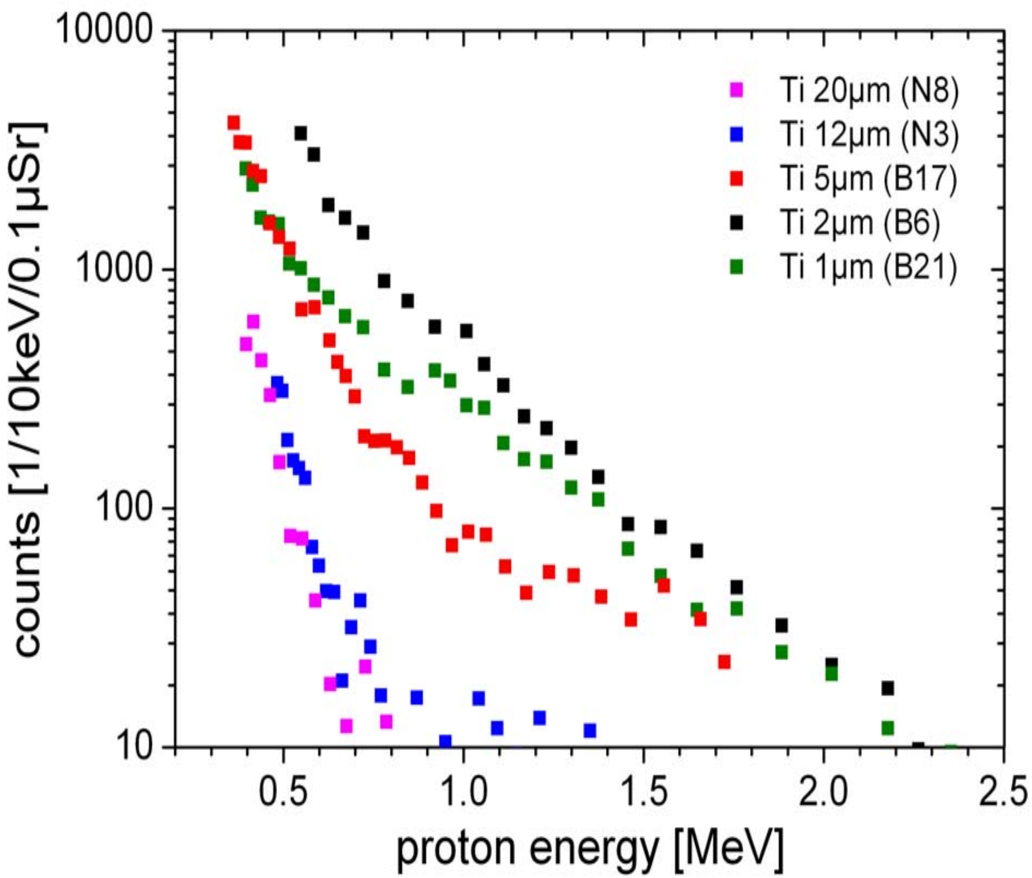
Ion acceleration – TNSA regime

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





Ion acceleration – TNSA regime

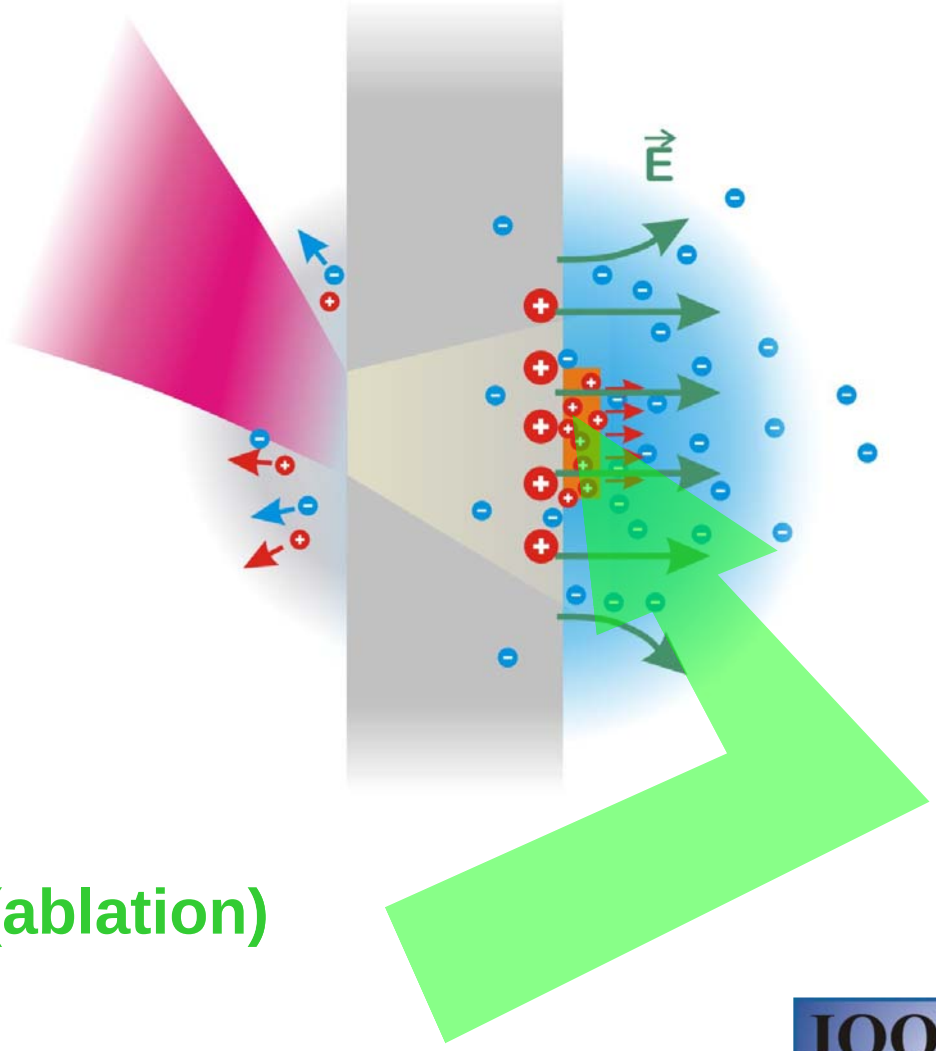


quasi-neutral pulse with exponential energy distribution (with max. energy depending on laser pulse duration, energy, and target thickness)

Ion acceleration – TNSA monoenergetic

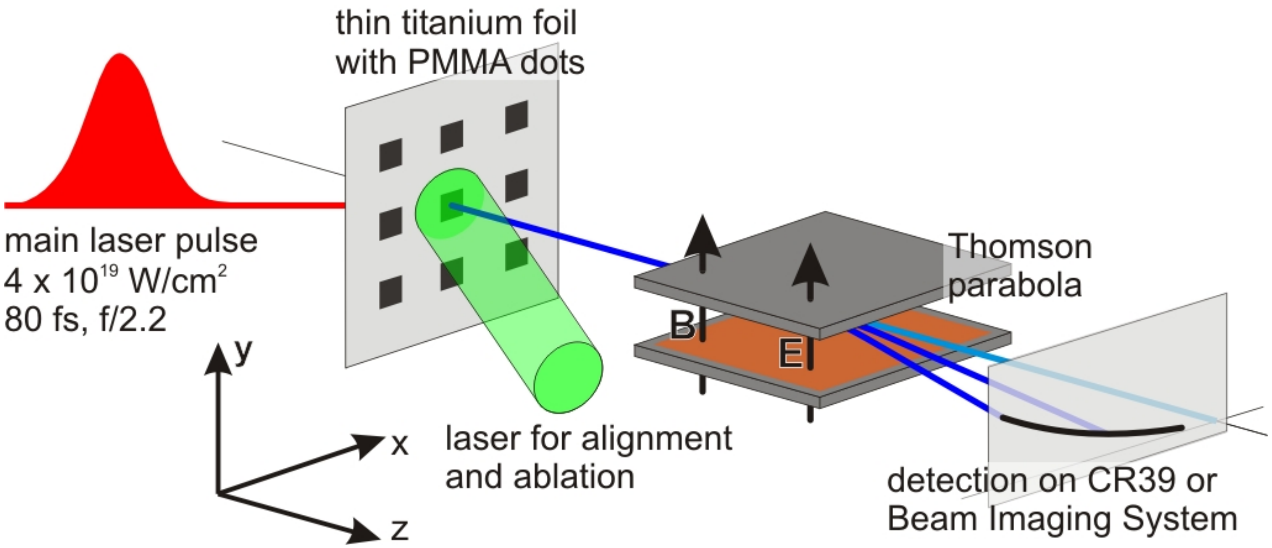
- enhance yield in the central, homogeneous region by applying a proton rich „dot“

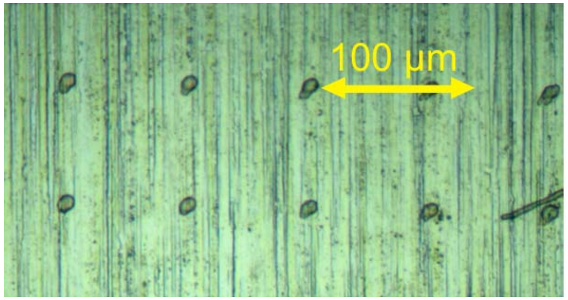
- use thin dot (to avoid temporal field depletion and shielding)

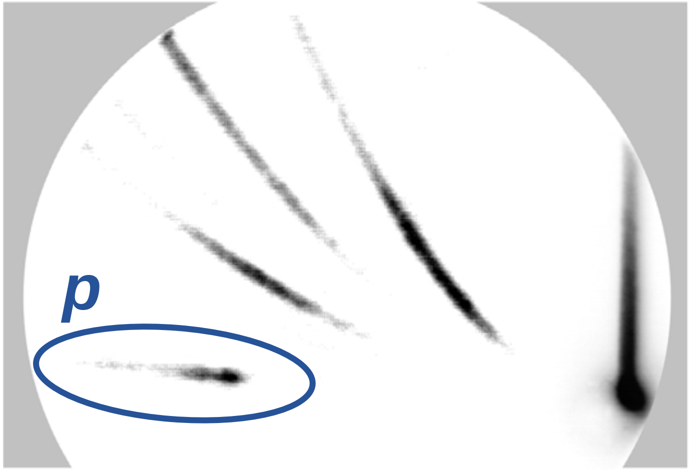


- Careful backside cleaning (ablation) increases the fidelity

Experiments







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

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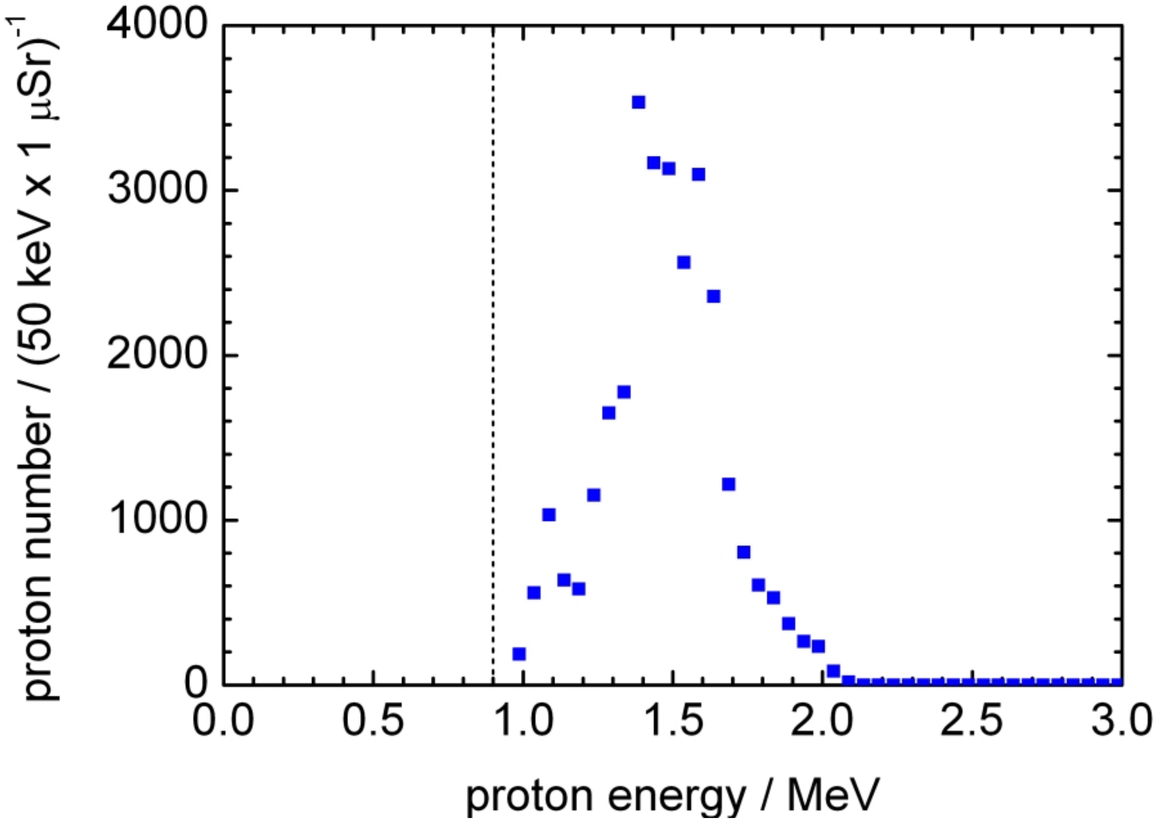
Ion acceleration – TNSA monoenergetic



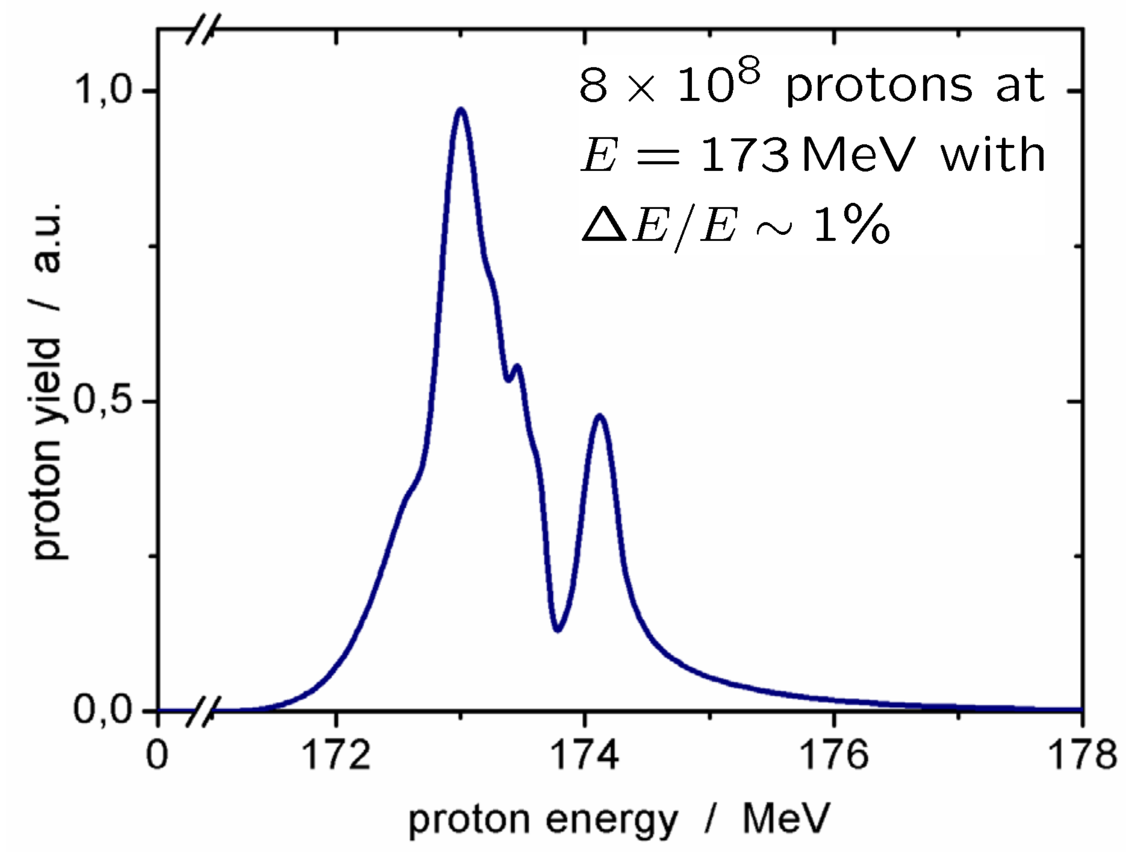
- **overall number of ions about 10^8 in 20msr**
- **80% fidelity with online target cleaning (ablation)**

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

POLARIS simulation

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

100 J in 100 fs, $I_L = 10^{21}$ W/cm², 5 µm Ti-foil + 0.1 µm PMMA dot (Ø 2.5 µm)



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

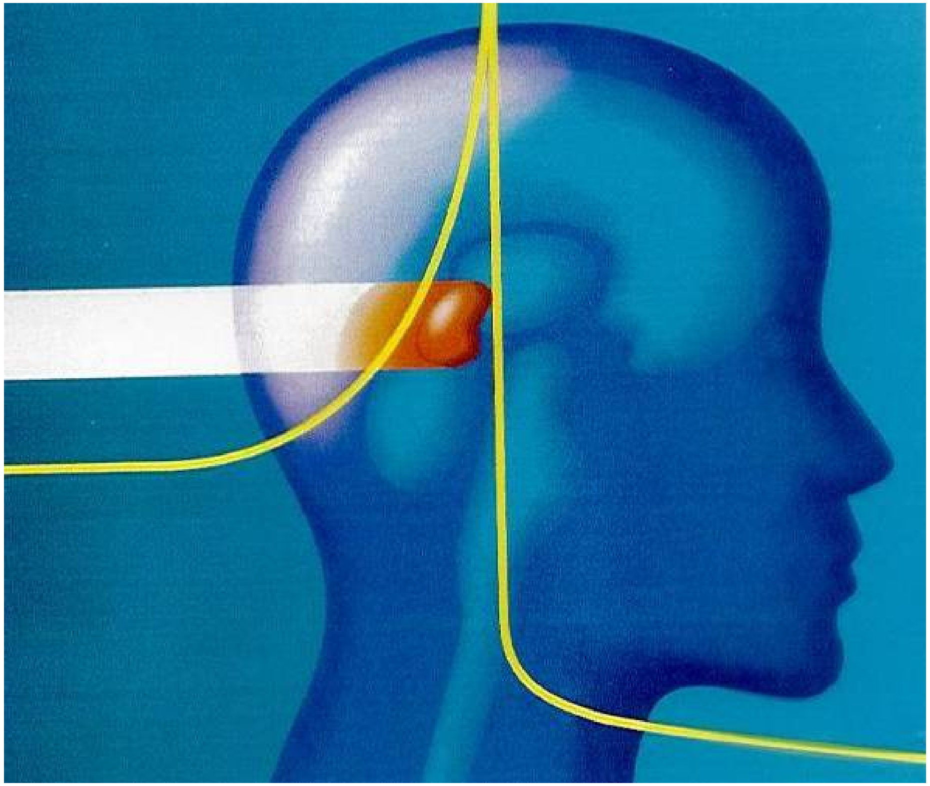
Applications of laser-accelerated particle beams

- Ultra-short X-ray pulses
  Free electron lasers, Thomson back scattering
- Nuclear and particle physics
- Everything you can do with conventional accelerators ?
- Medical applications
  Radiation therapy and imaging

Laser accelerators vs conventional accelerators

Available av. laser power	Average power (on target / stored)
CO_2 100 kW	*ELBE 10 kW (40 MeV e)*
fs PW class 100 W	*SNS 1.4 MW (GeV p)*
Diode pumped PW …few kW	
	LHC 350 MJ (7 TeV p)
Acc. Efficiency ~10%	*SIS100 50 MJ (20 AGeV U)*

Laser driven
ion (proton) beam therapy ?



requirements for ion beam therapy

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

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

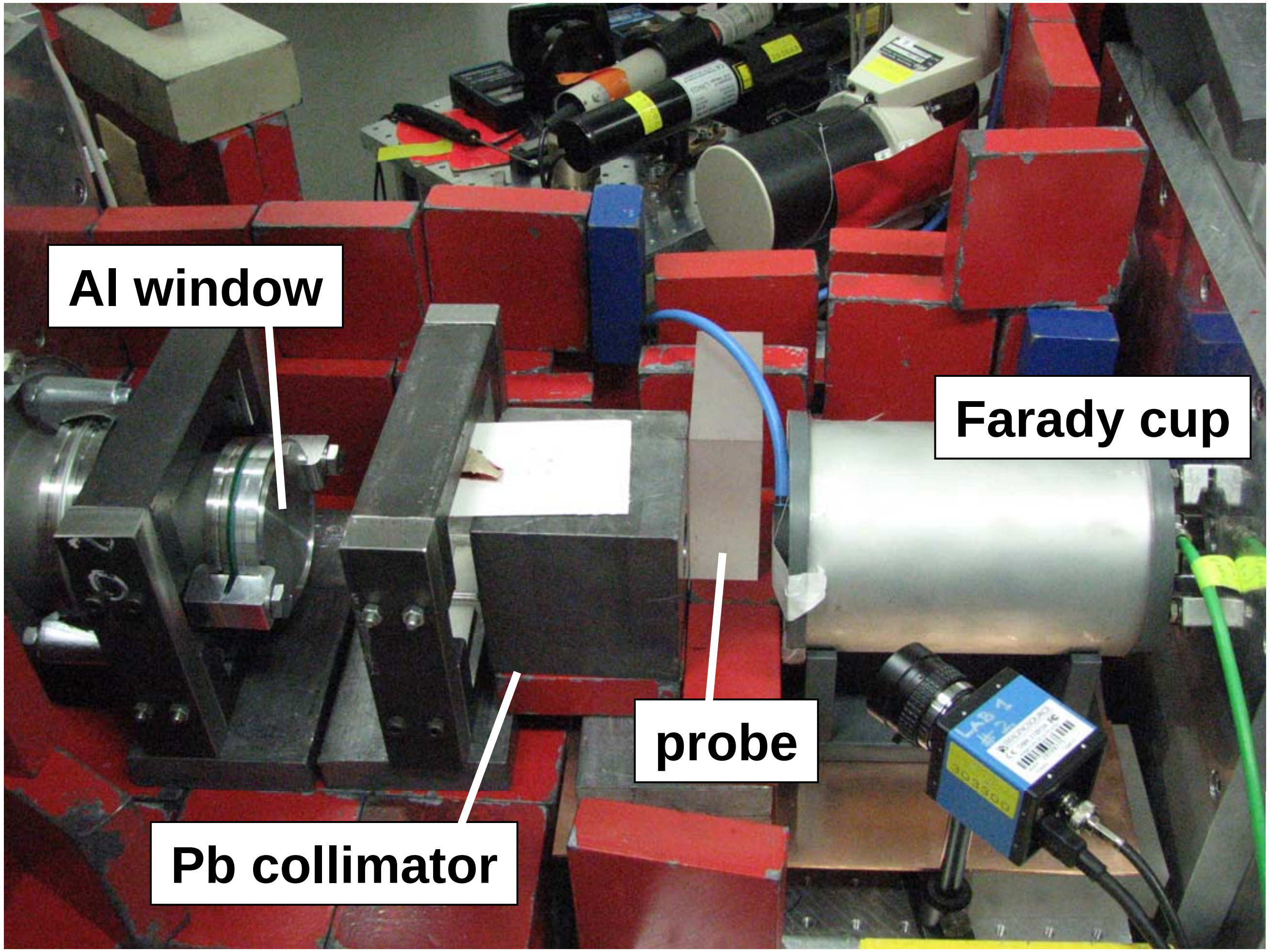
Spatial control: ***mm-scale @ 20cm depth***

-> 200 MeV @ percent level control
-> mm pointing (contour shaping)
-> 5% position dependent dose control

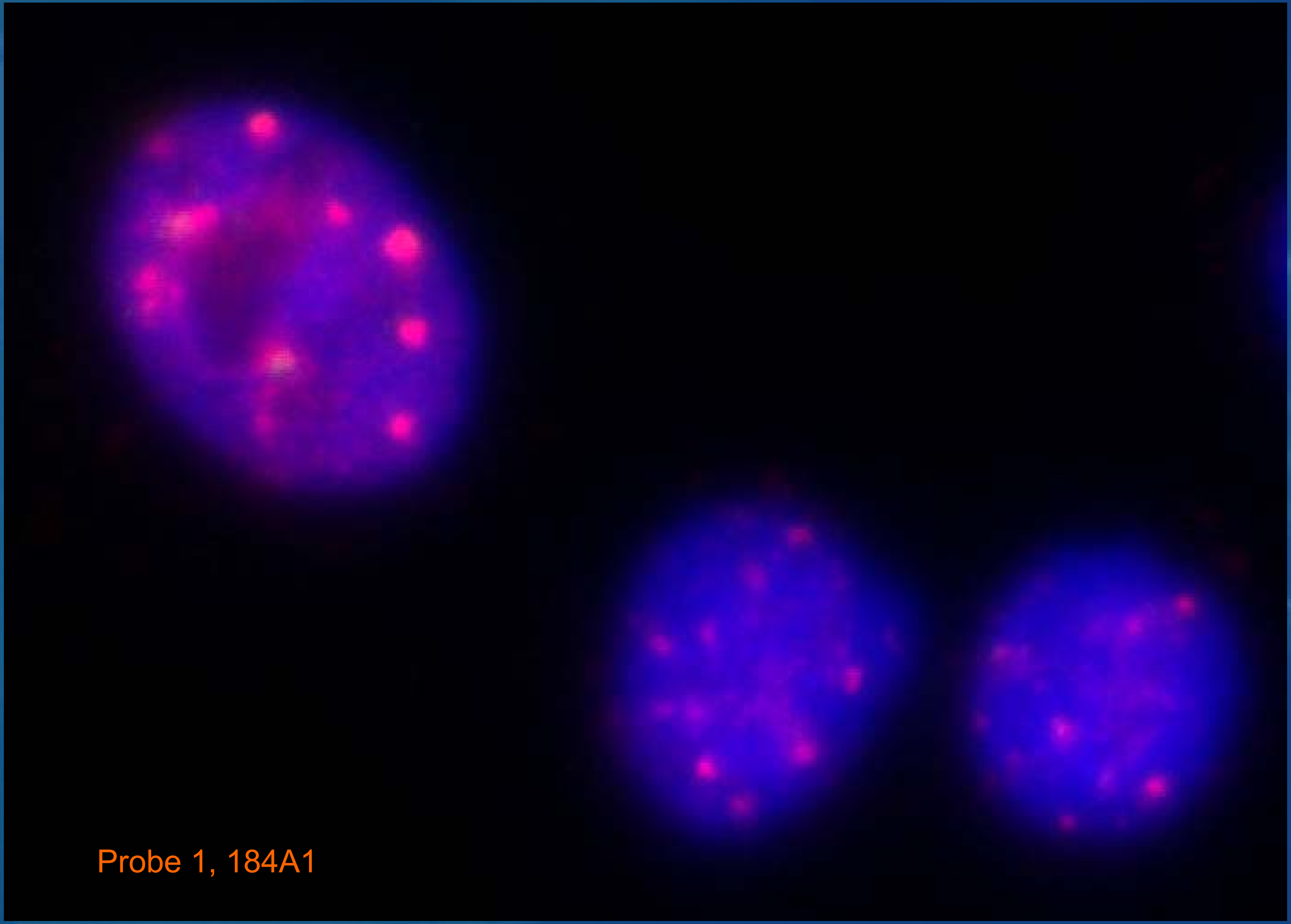
Complete (nondestructive shot-to-shot) monitoring

Clean beam (no other species, X-rays…)

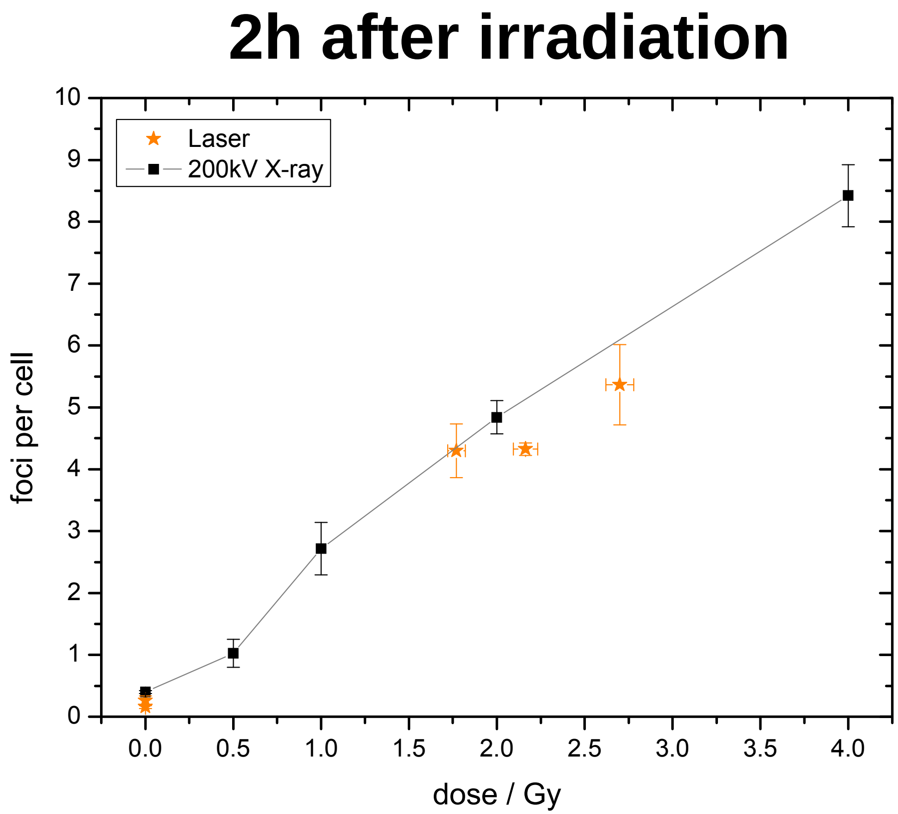
Two cell lines were irradiated with doses of ~3 Gy of laser accelerated electrons (undefined spectrum…)

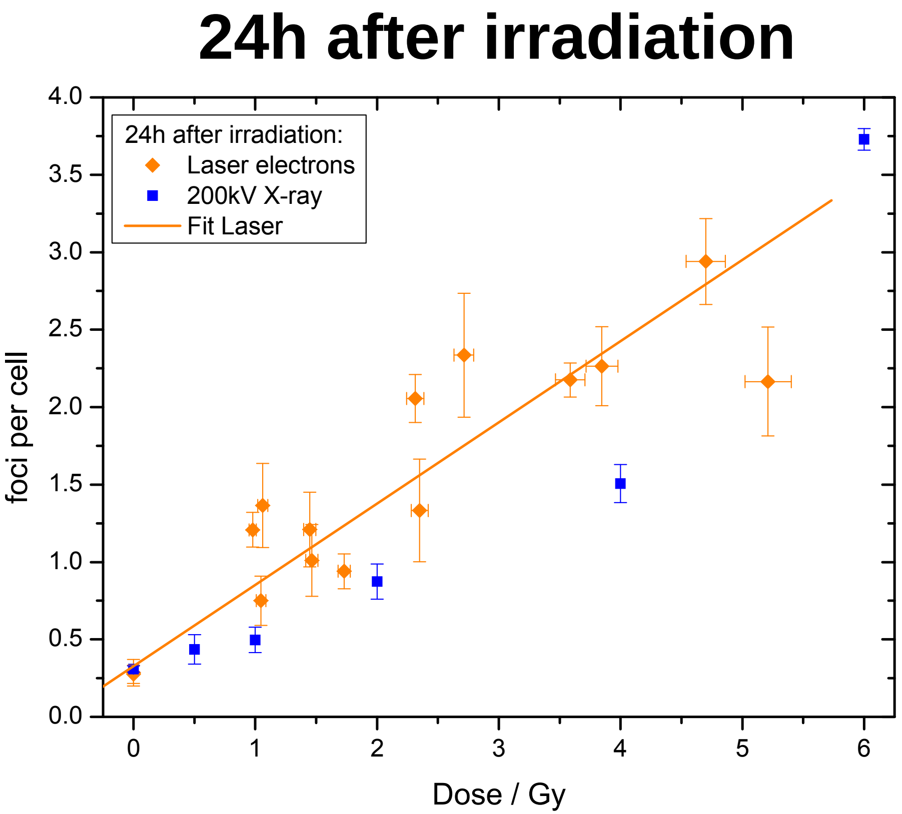


Detection of DNA damage (off line)



Preliminary results





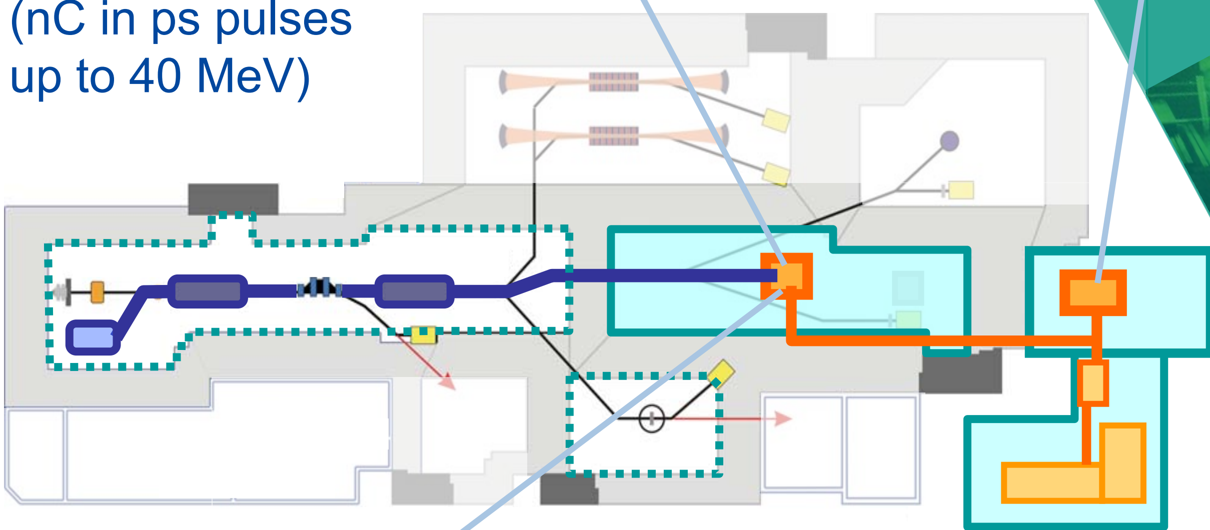
184A1 (humane Brustdrüsenepithelzellen, normal)

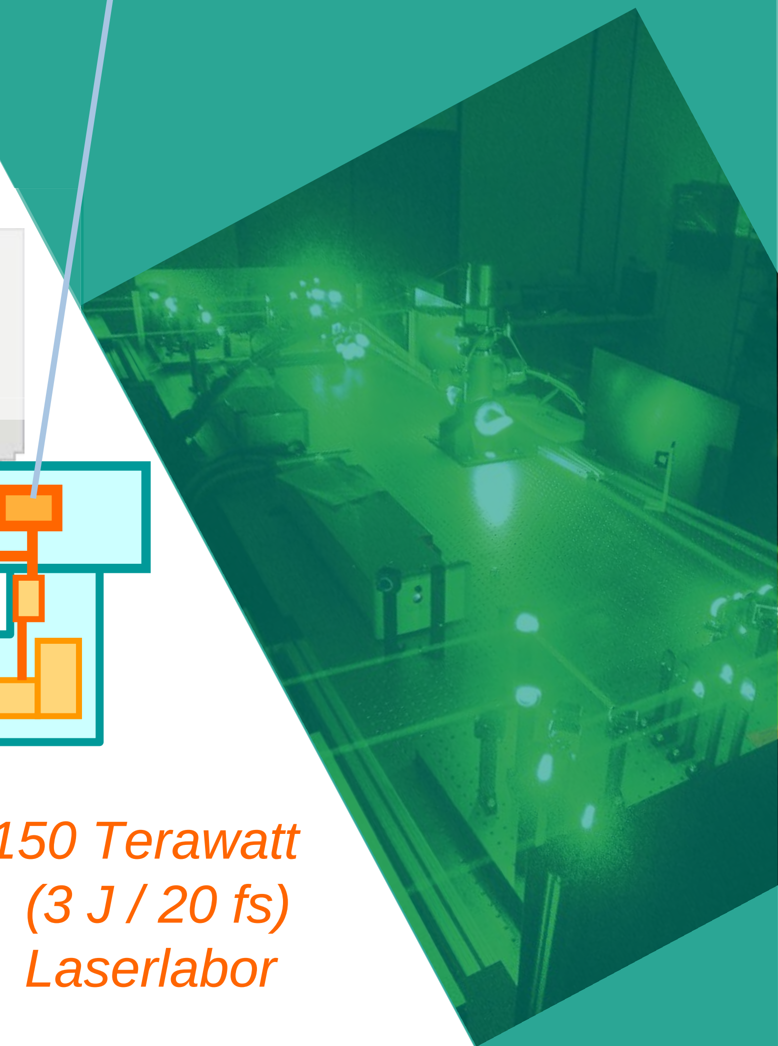
Present and future situation at FZD

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

thanks to

U. Schramm, A. Debus, T. Kluge, S. Kraft, K. Zeil, S. Bock

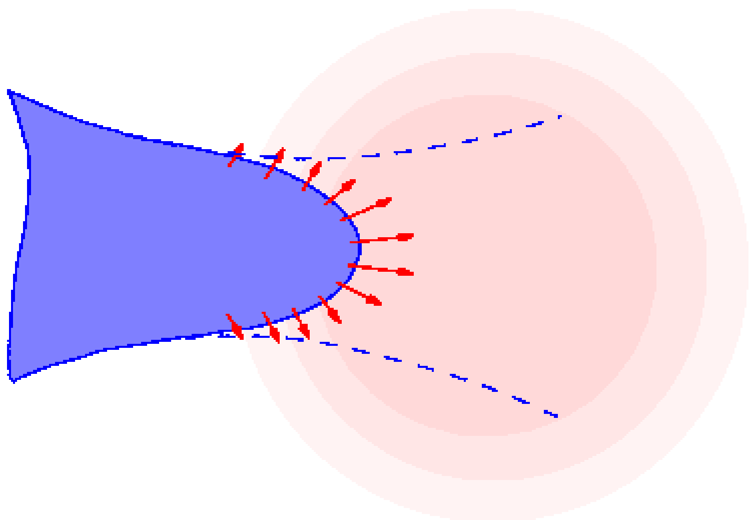
K. Ledingham

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

E. Beyreuther, L. Karsch, J. Pawelke, W. Enghardt, M. Baumann

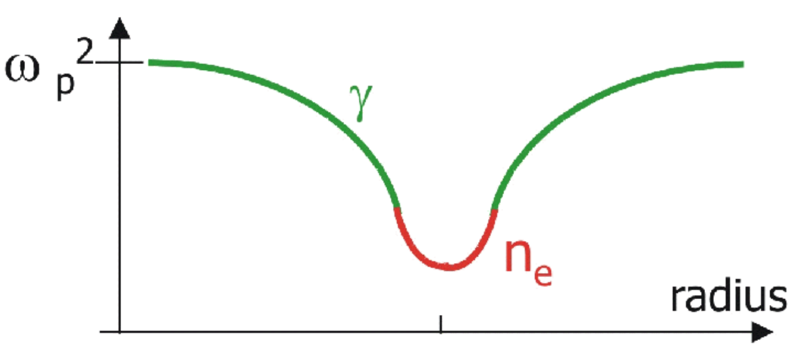
Forschungszentrum Dresden Rossendorf

target: underdense (=transparent) plasma



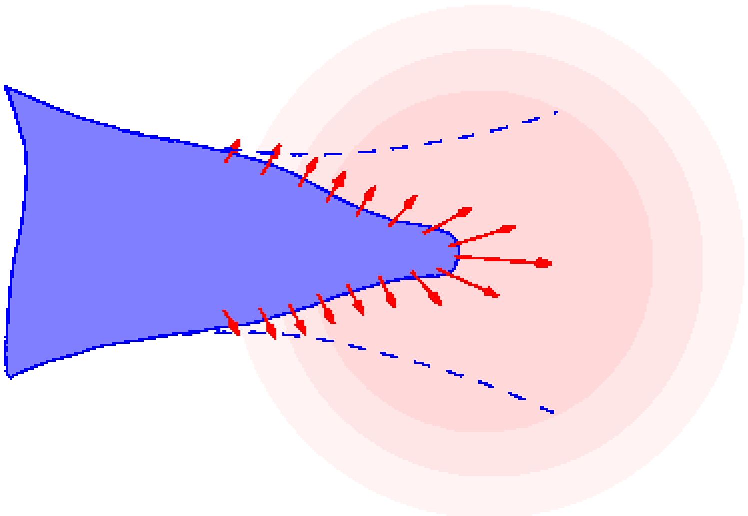
plasma frequency

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

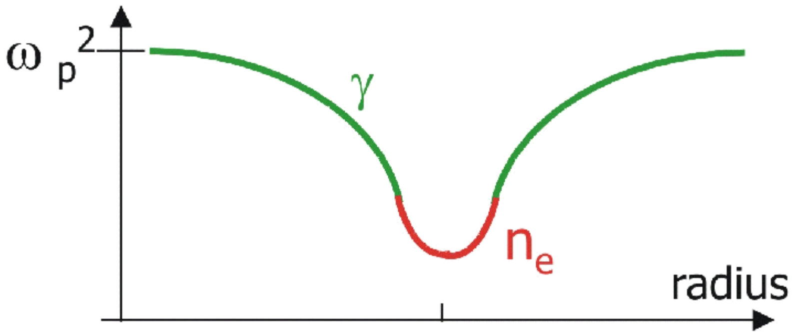


- mass increase
- density reduction

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

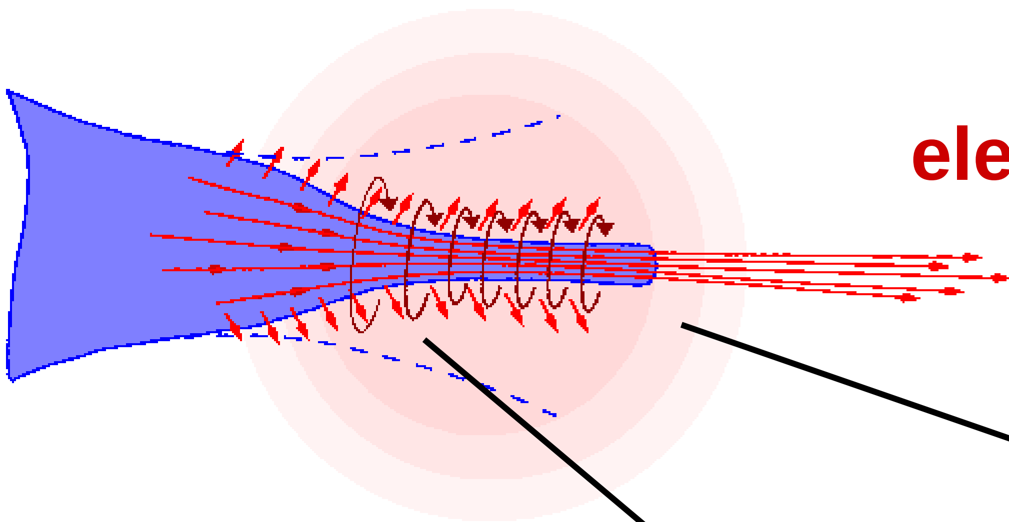


$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$



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

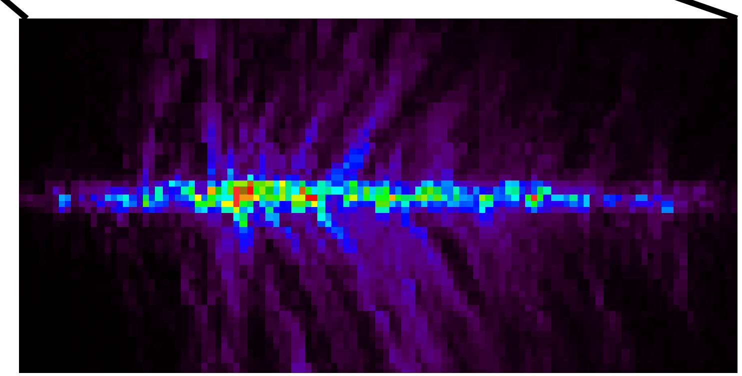
channel formation



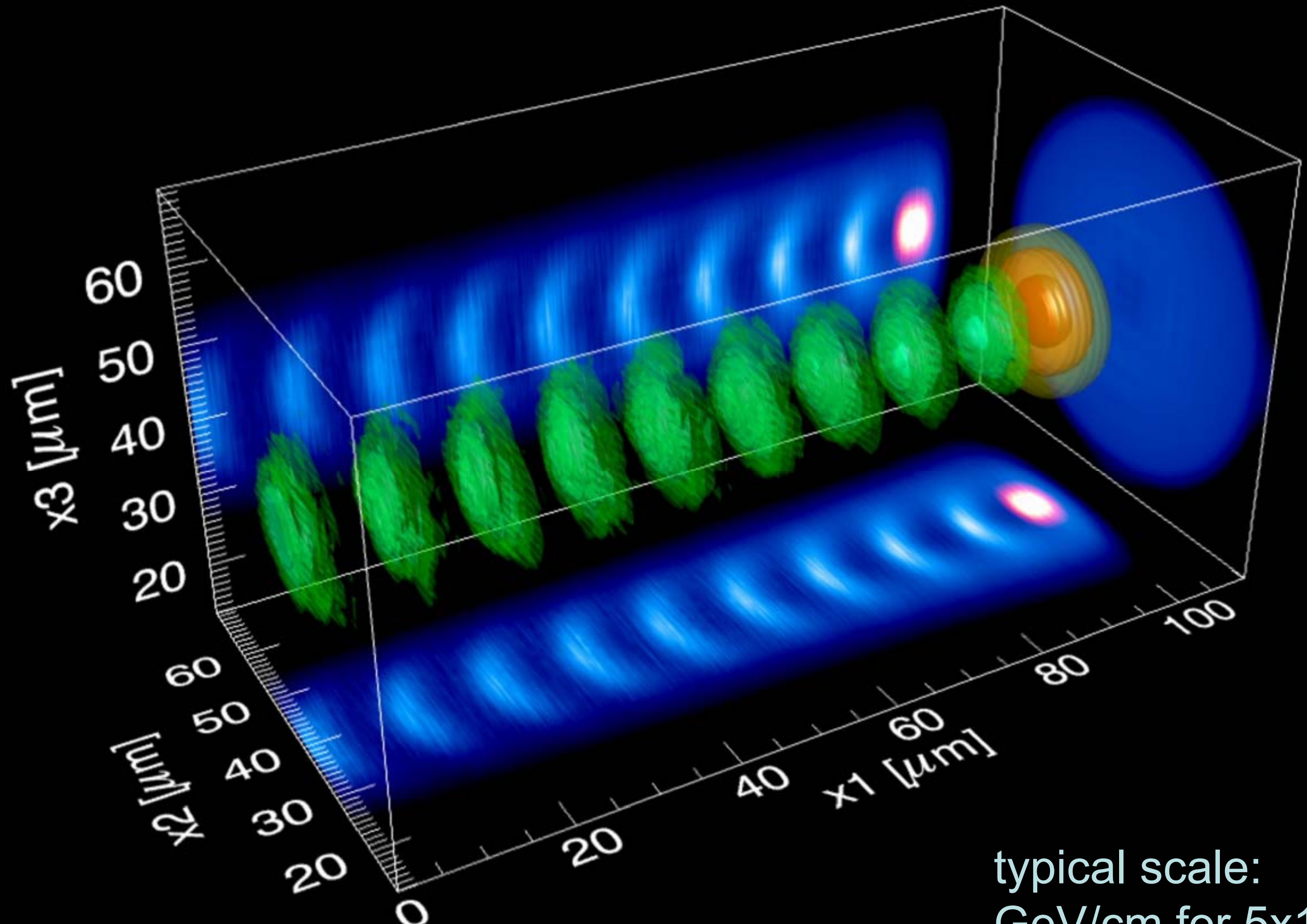
electron jet

Thomson scattering @ 2ω

(length 0.4mm = 400 λ)



wakefield formation



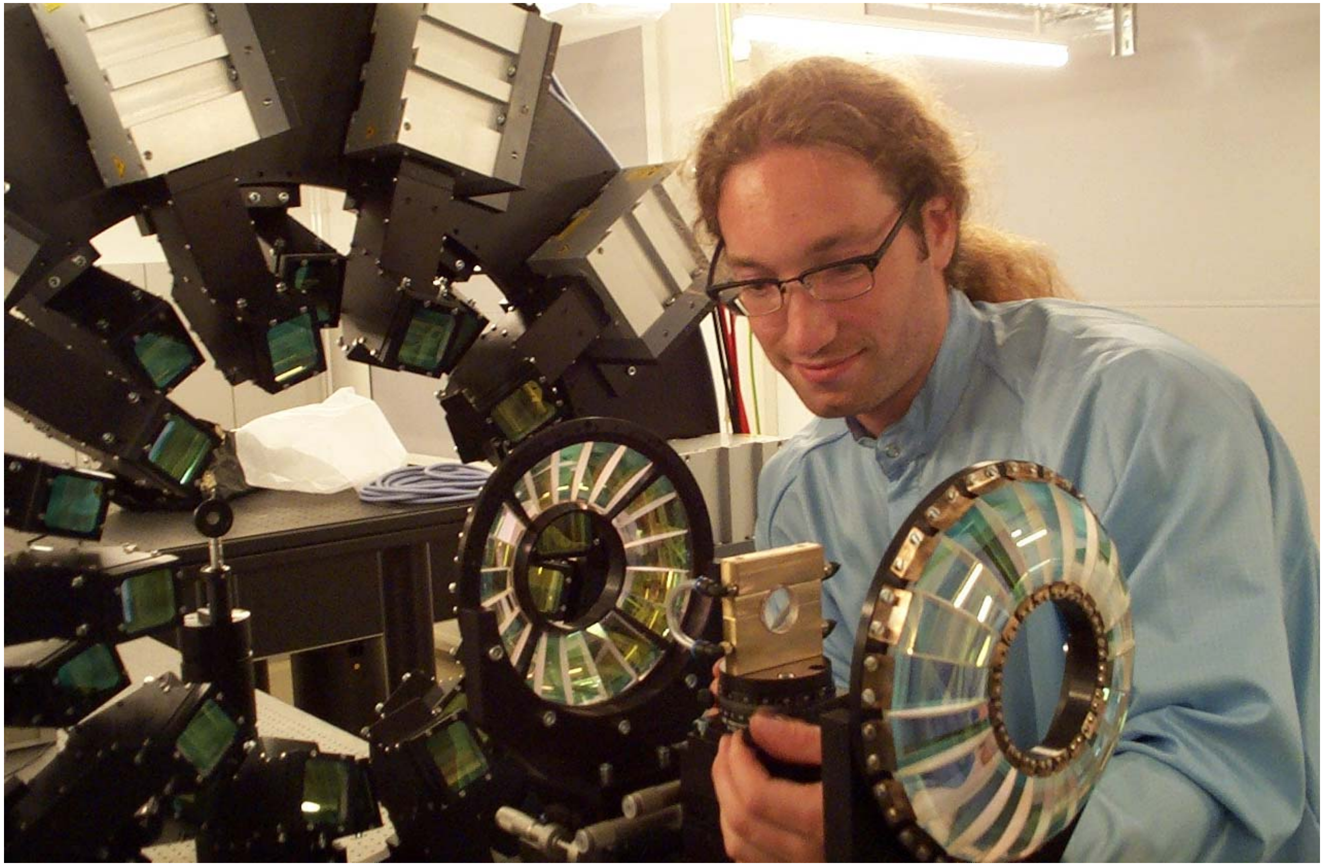
typical scale:
GeV/cm for 5×10^{18} e/cm^3

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

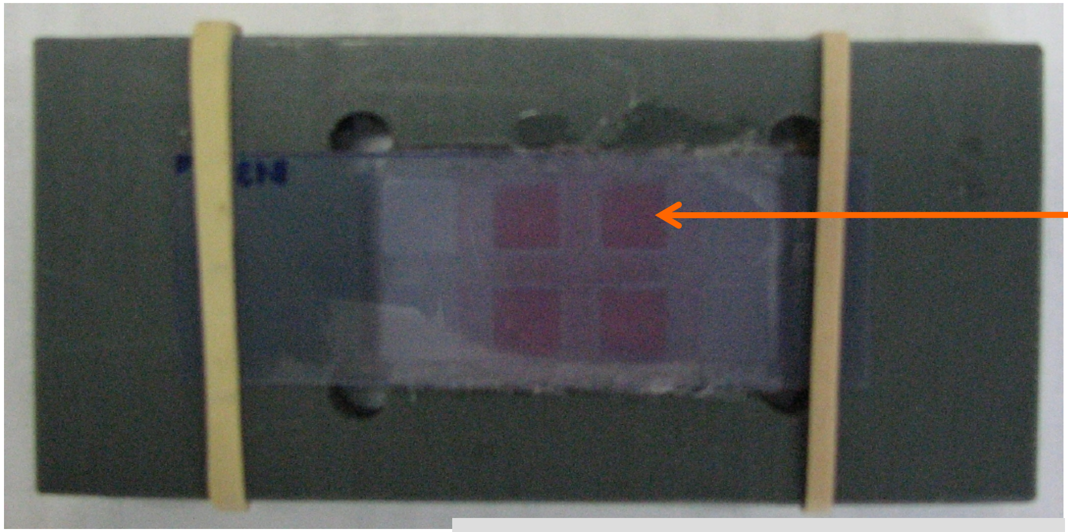
POLARIS simulation

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

100 J in 100 fs, I_L= 10^{21} W/cm², 5 µm Ti-foil + 0.1 µm PMMA dot (Ø 2.5 µm)

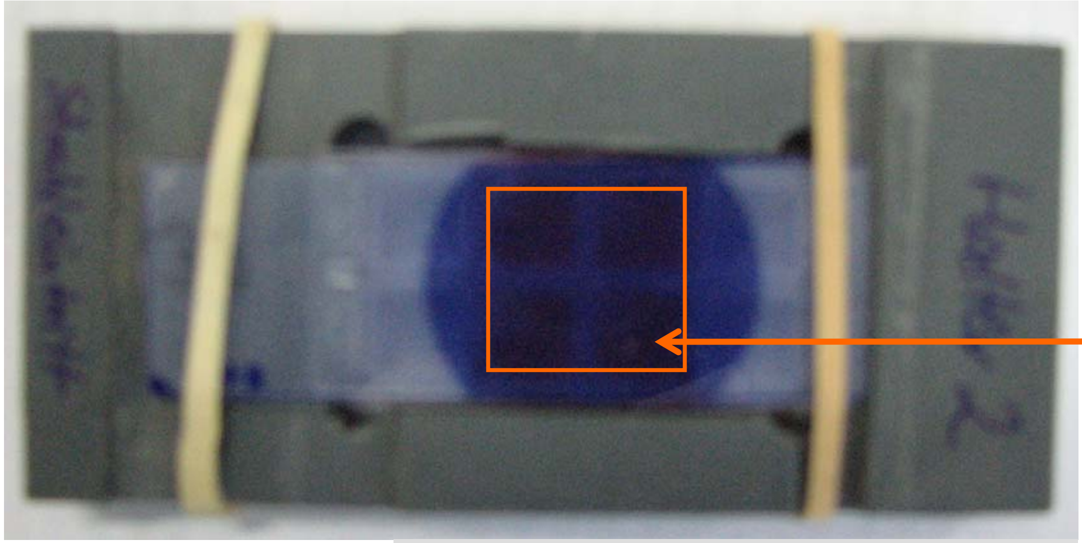


Irradiation geometry



Rückseite, vor Bestrahlung

Mittlere 4 Kammern des Objektträgers mit Zellen bedeckt



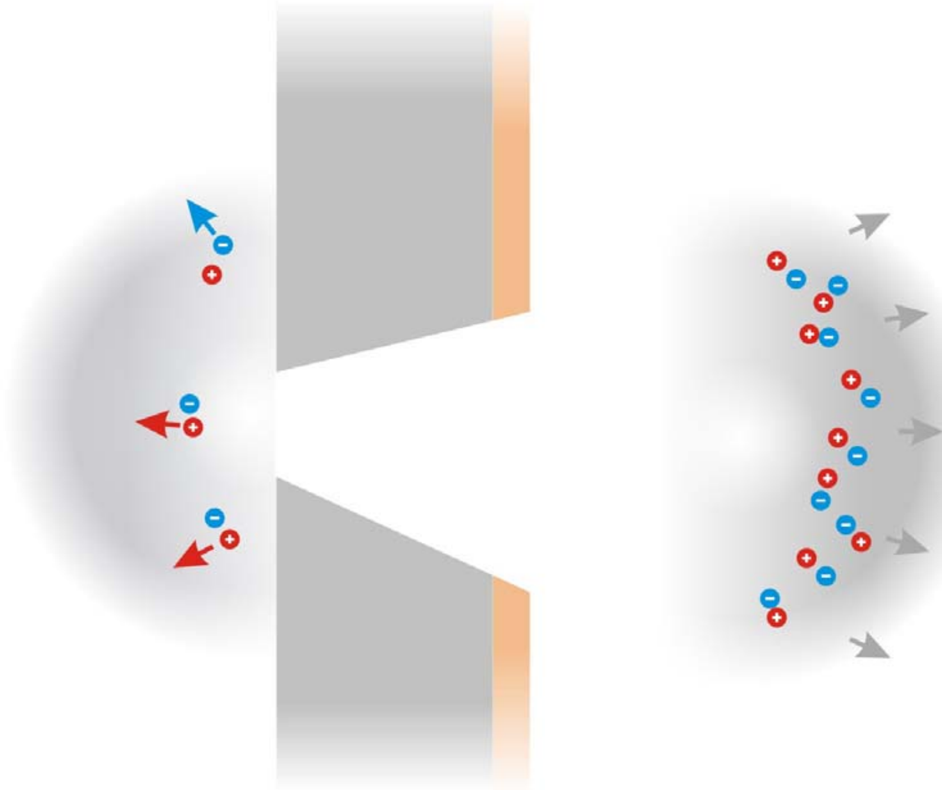
Vorderseite, nach Bestrahlung

Strahlfleck: 35mm

Ausgewerteter Bereich:
4 Kammern à 50 Zellen

Ion acceleration – TNSA regime

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



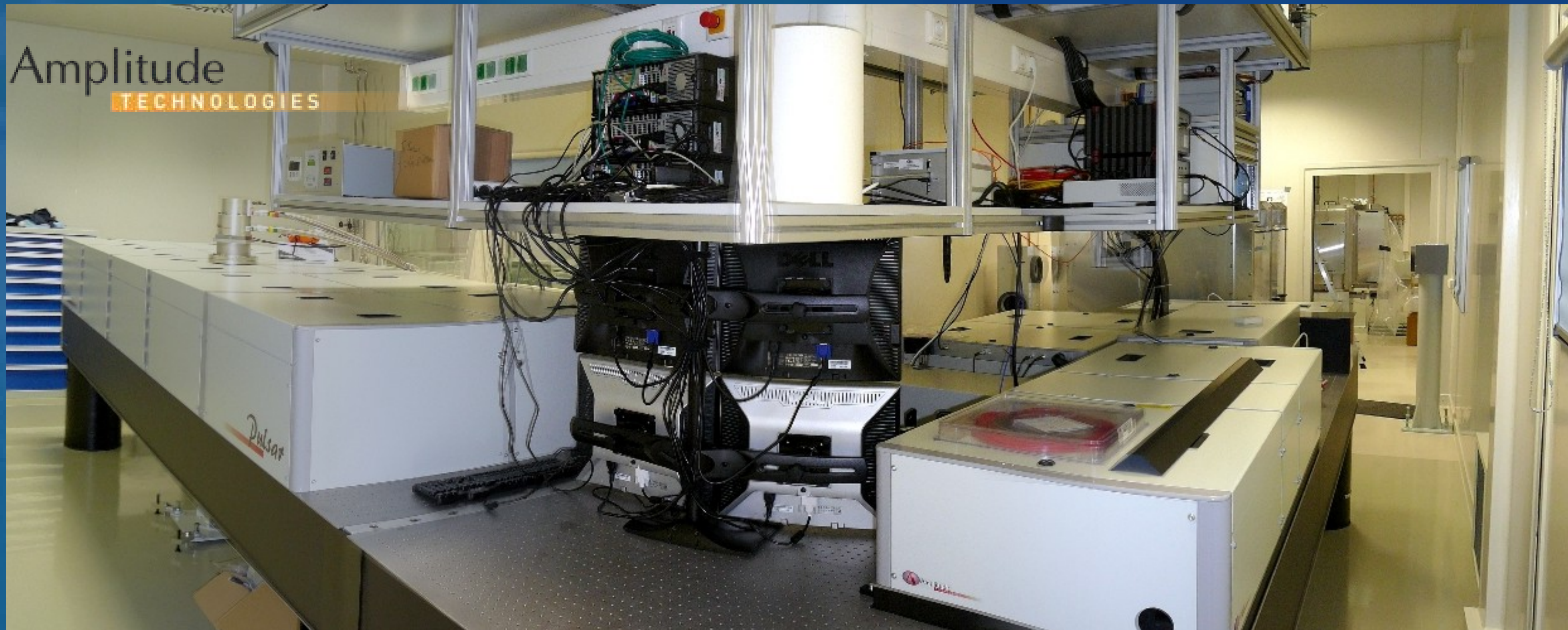
quasi-neutral pulse with exponential energy distribution (with max. energy depending on laser pulse duration, energy, and target thickness)

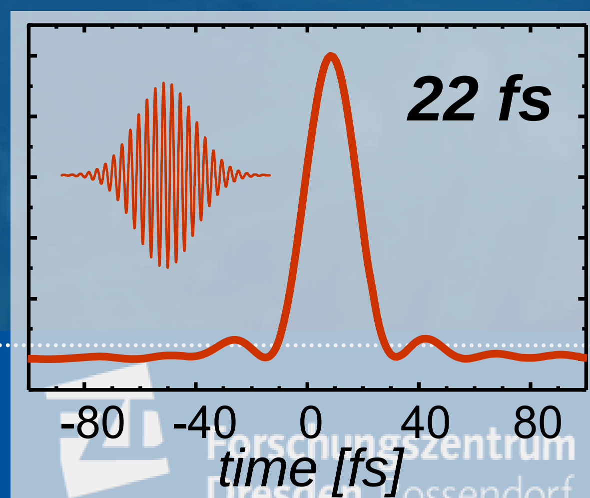
August 2007

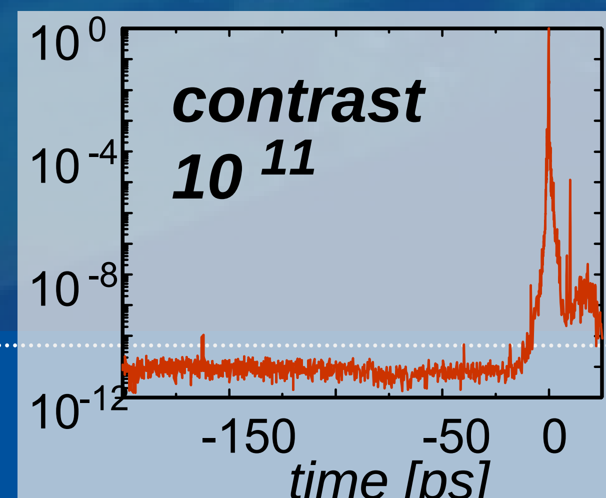
September 2007

December 2007

Amplitude TECHNOLOGIES





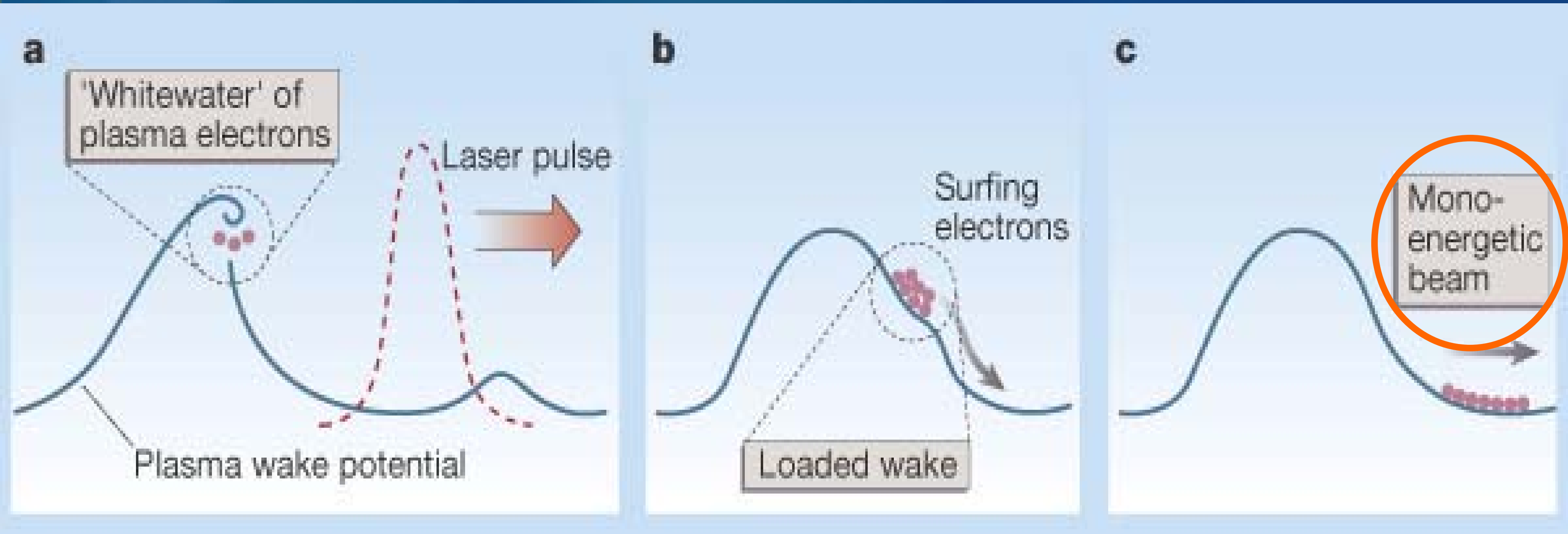


the FZD group (FWT)

R. Sauerbrey, U. Schramm

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

strongly idealized…



T. Katsouleas, Nature 431, 515 (2004)

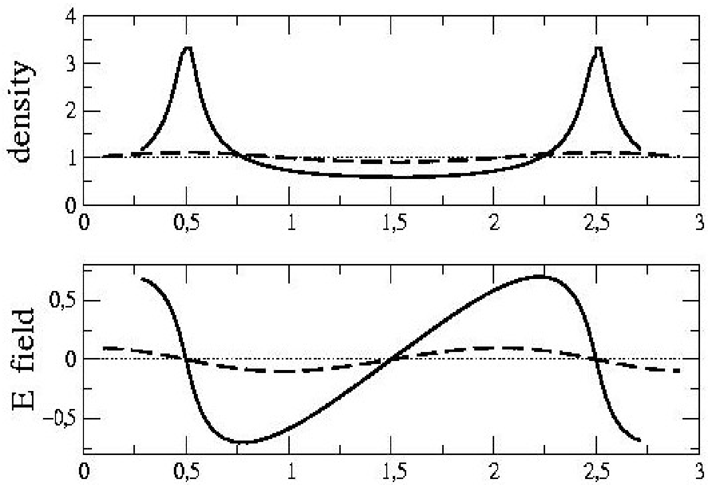
… and yet surprisingly „real“ in the highly nonlinear broken wave – blow-out – bubble regime …

wakefield formation – short driver

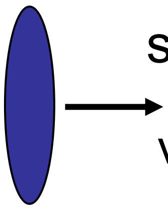
In a transparent plasma a relativistic laser pulse with $L < \lambda_p = c/\omega_p$ drives a longitudinal plasma wave

n/n_0

E_x/E_0



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



short laser pulse

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

non-linear plasma wave for relativistic intensities

acceleration of particles in (traveling) waves

-> matched external injection or self-injection

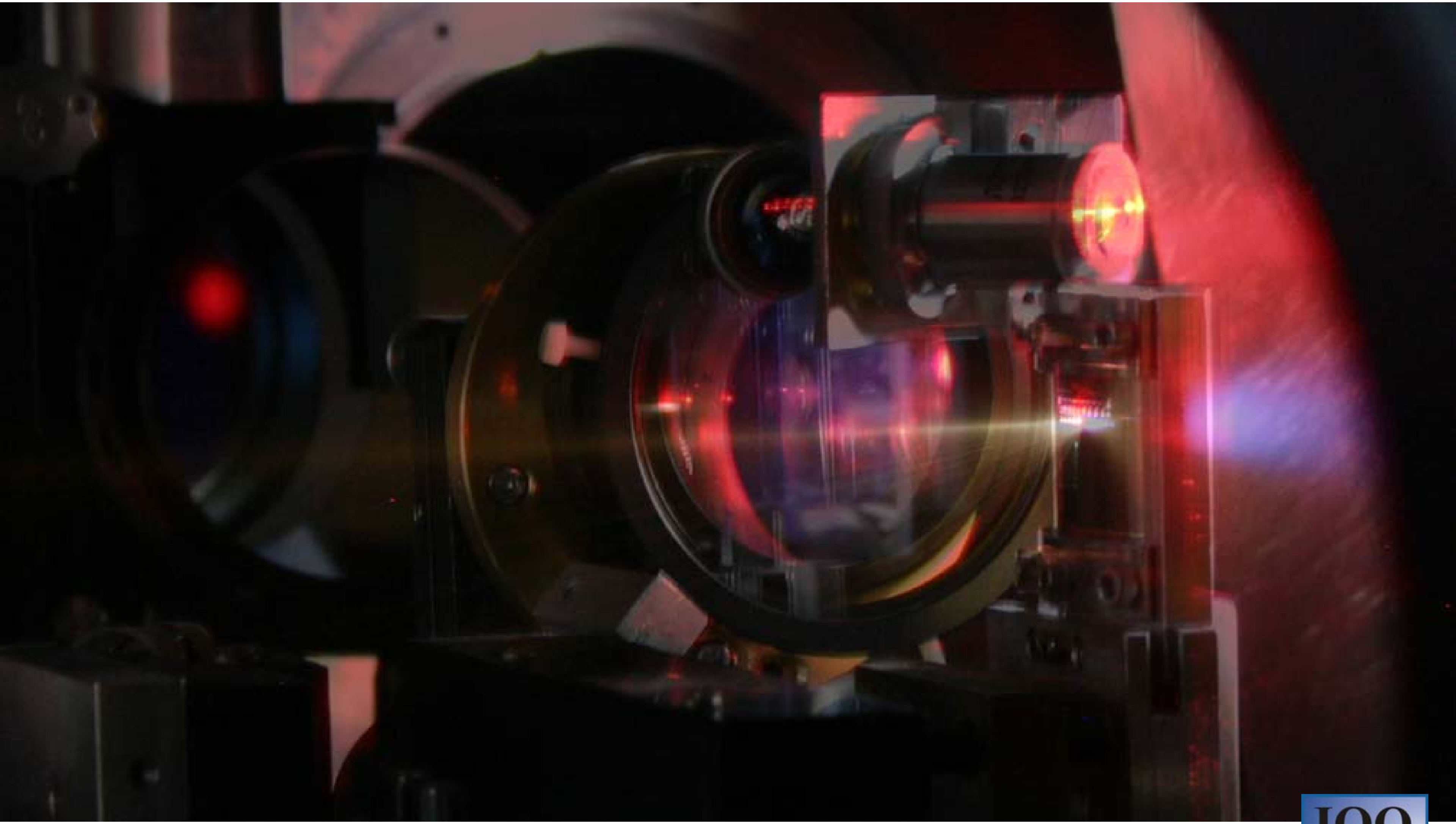
Typical (10TW) laser parameters are 1J in 40-80fs

- too long for high density (underdense) plasma
- too weak to use much less density
  (as threshold scales as $\omega_p^{-4/3}$ or $n_e^{-2/3}$ and
  including the larger spot size as $n_e^{-13/6}$)

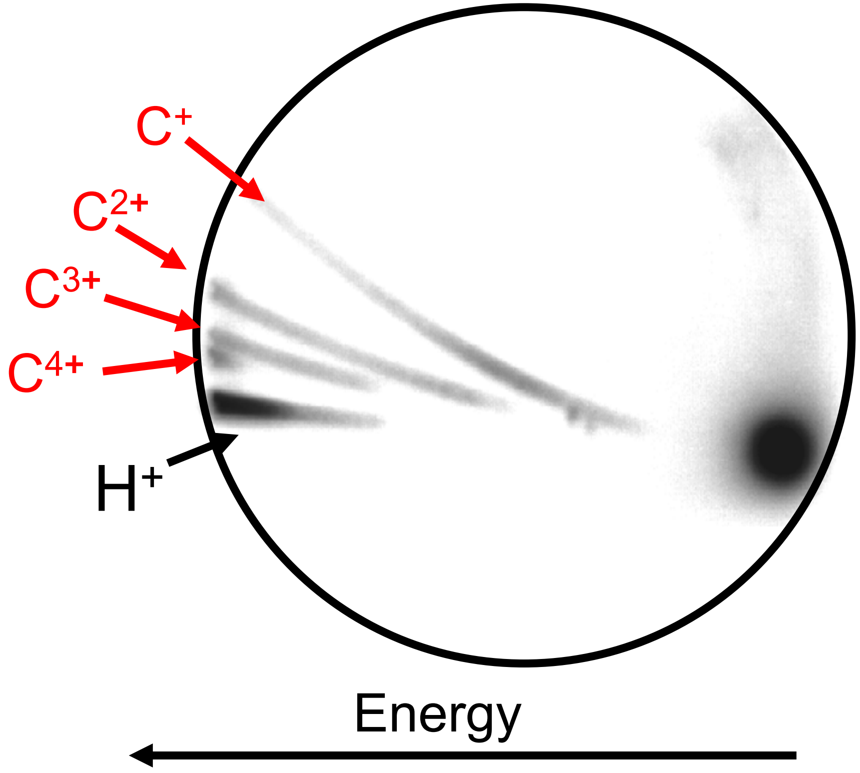
► one might use capillary guiding for an increased acceleration distance, where lower densities are favourable and

► rely on self-compression and -focusing (with all its instability problems)

exp. status in Jena (2006)



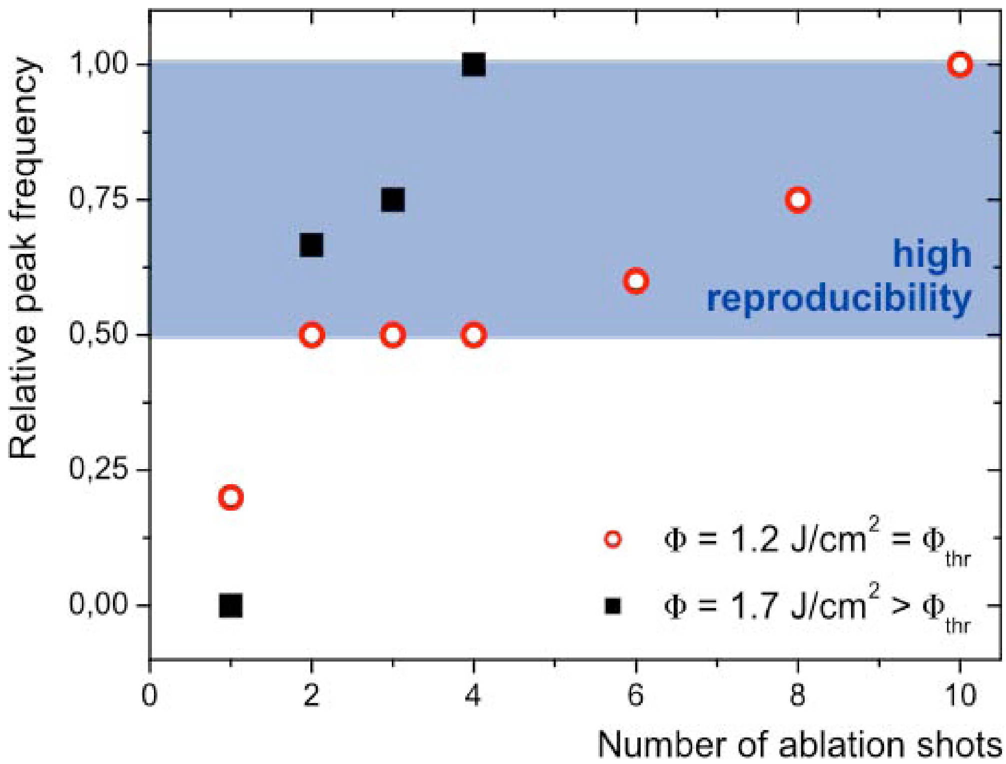
Different ion species



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

Reproducibility (IOQ Jena)



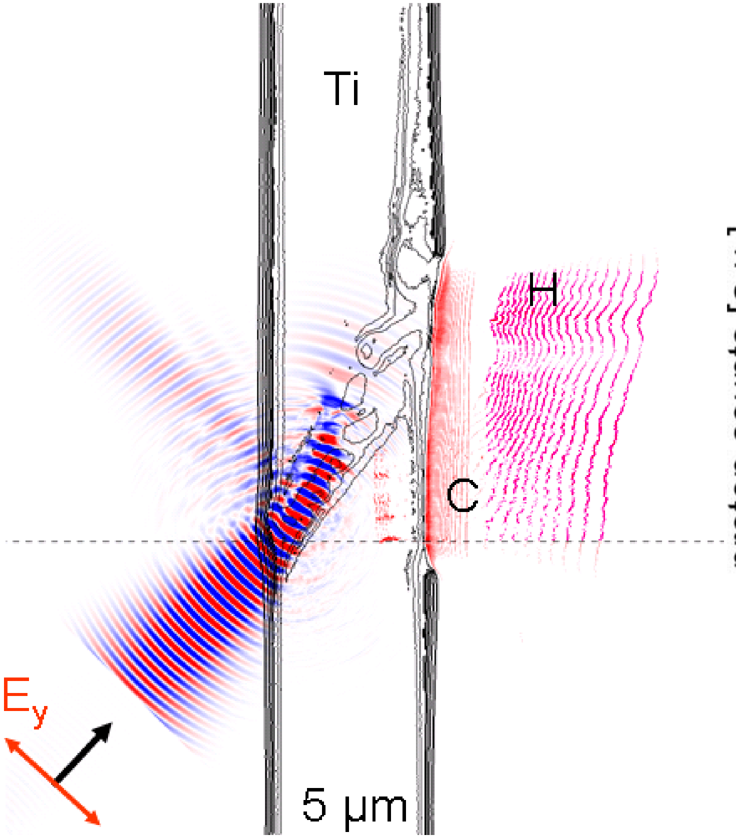
80% fidelity

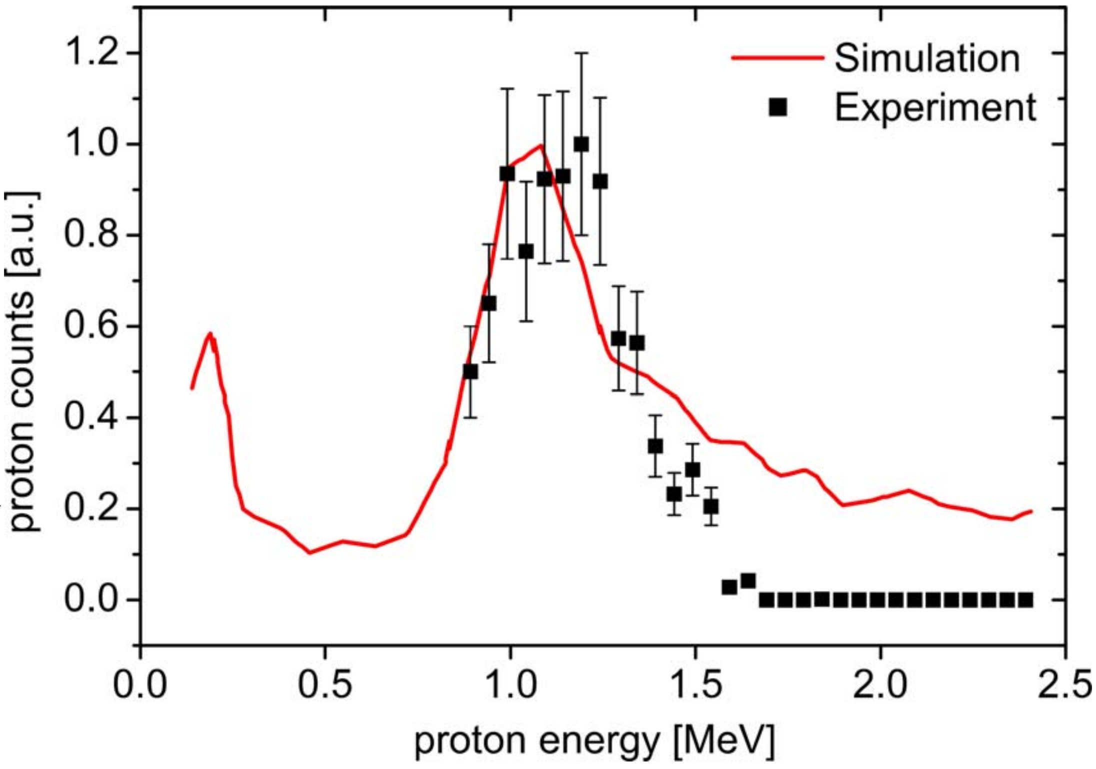
- Existence of threshold fluence » 1,2 J / cm2 @ tpulse » 5 ns, l = 532 nm
- Observations of initial incubation effects
- Recombination time for adsorbants > 5s at given chamber pressure of p » 10-5 mbar

Simulation of Jena results (2006)

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

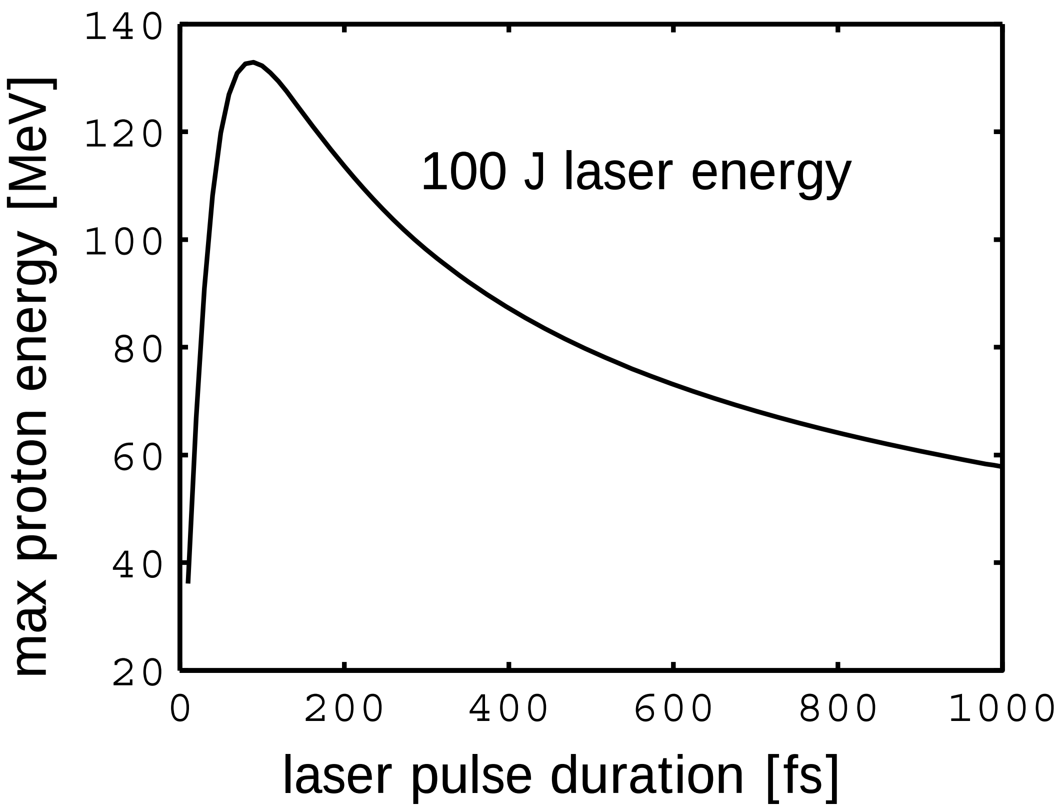
$I_L = 3 \times 10^{19}$ W/cm², 5 µm Ti-foil + 0.5 µm PMMA dot (20×20) µm²





TNSA – increasing the energy

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



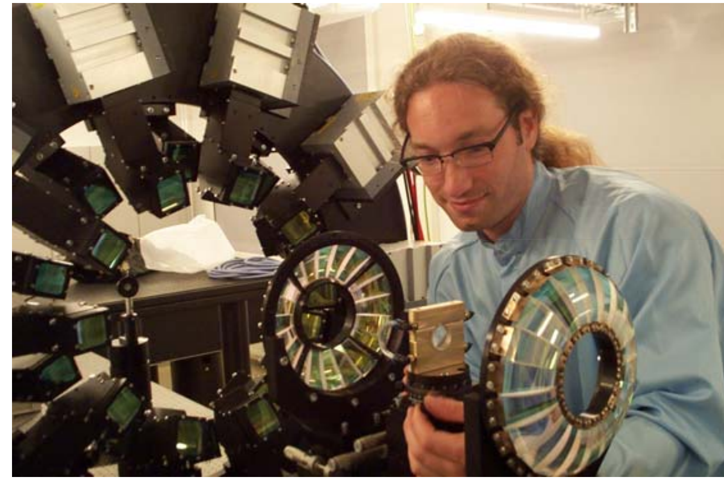
[J. Schreiber, et al, PRL 97 (2006) 045005]

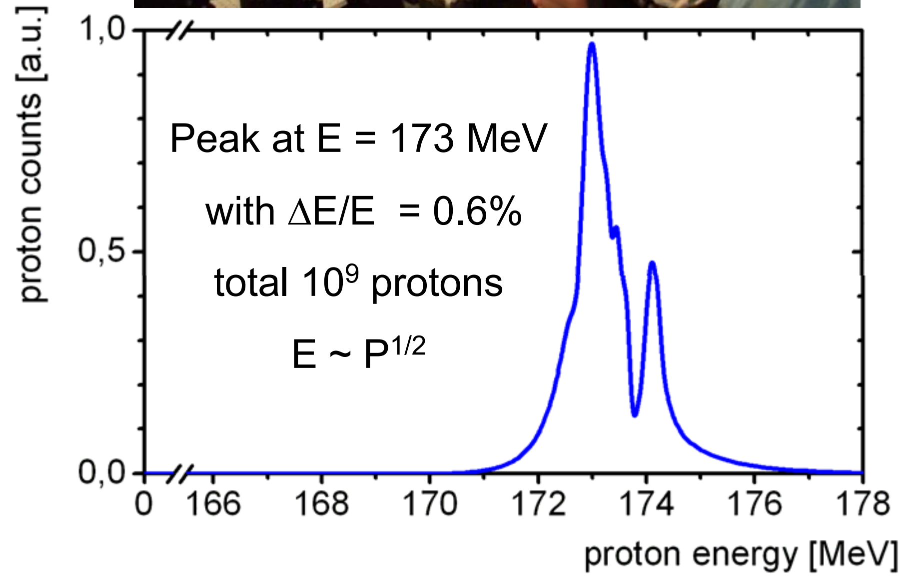
POLARIS laser system:

- 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)

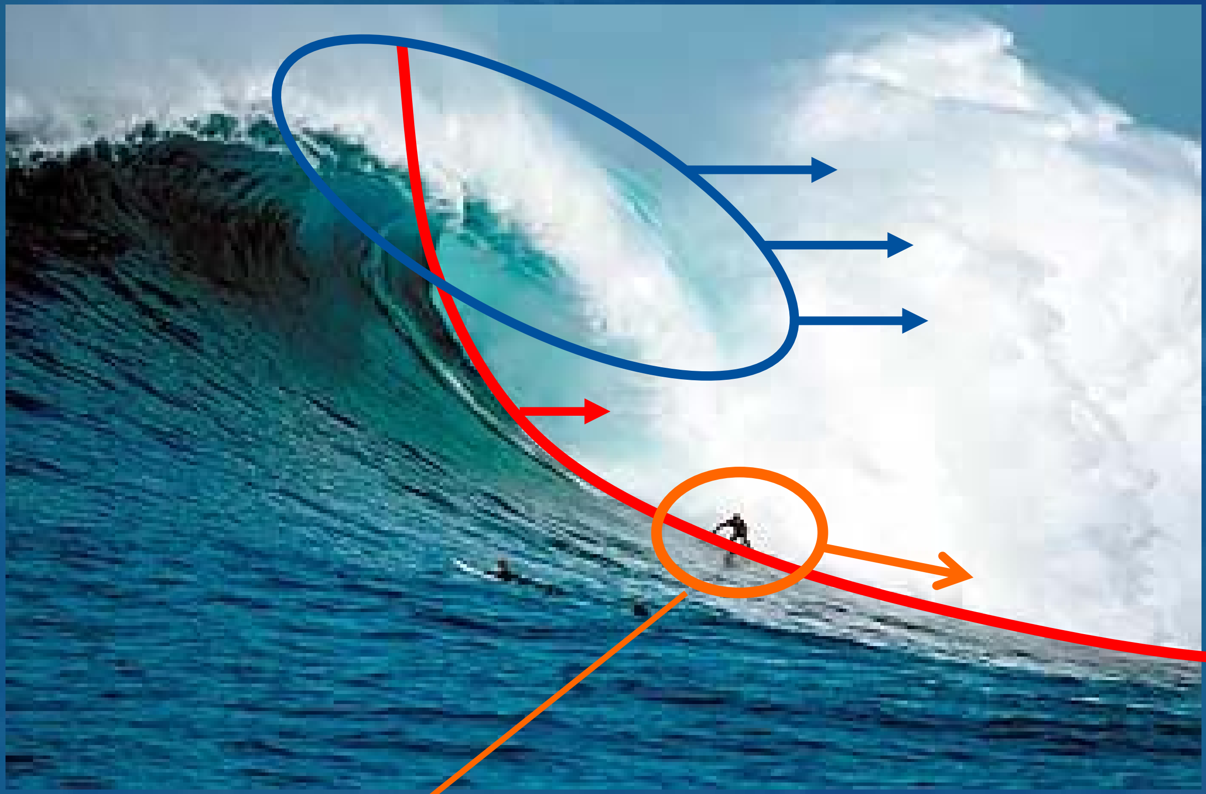
$I_{POLARIS} = 10^{21}\ W/cm^2$

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

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

wakefield acceleration

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

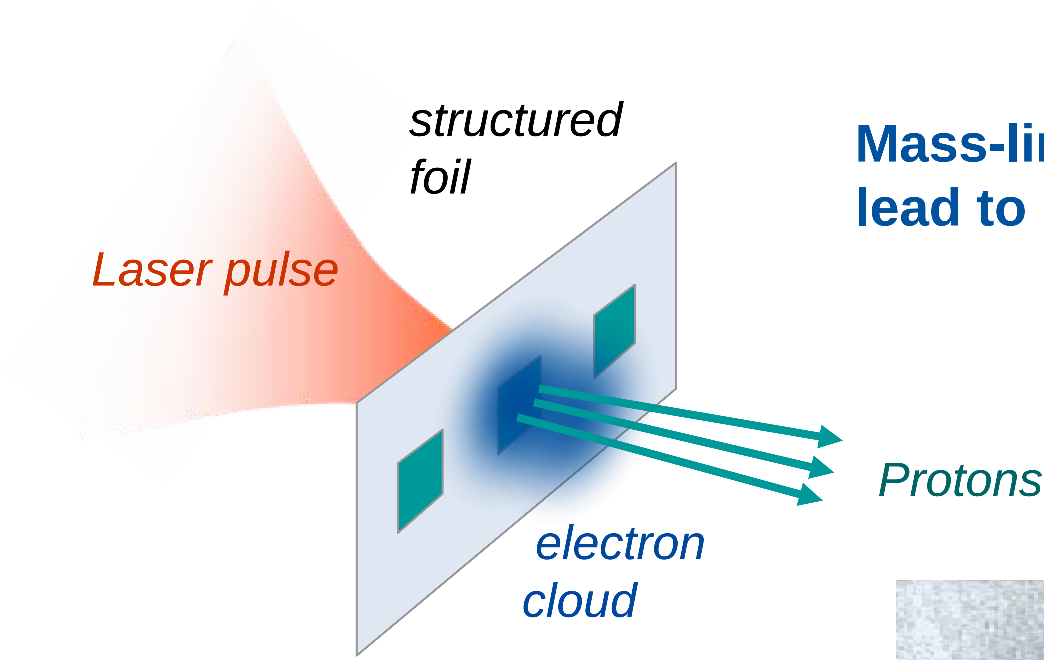


dephasing

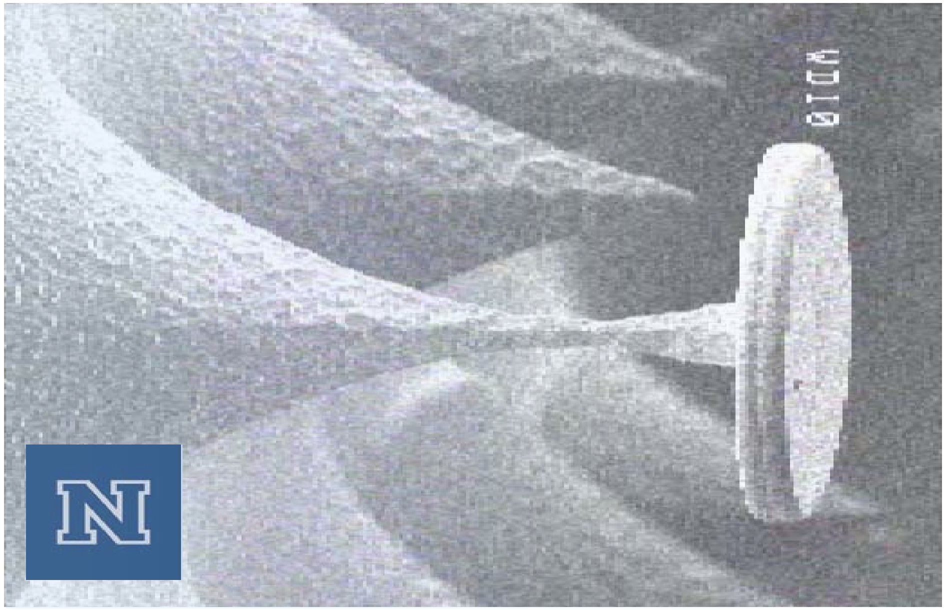
test particle $v_e > v_{ph}$
(external injection)

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

shaping the target



Mass-limited localized target (areas) lead to monoenergetic features



**More complex shapes might help
In guiding electrons …**

Features of laser accelerated beams

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

high peak current
(up to 100kA)

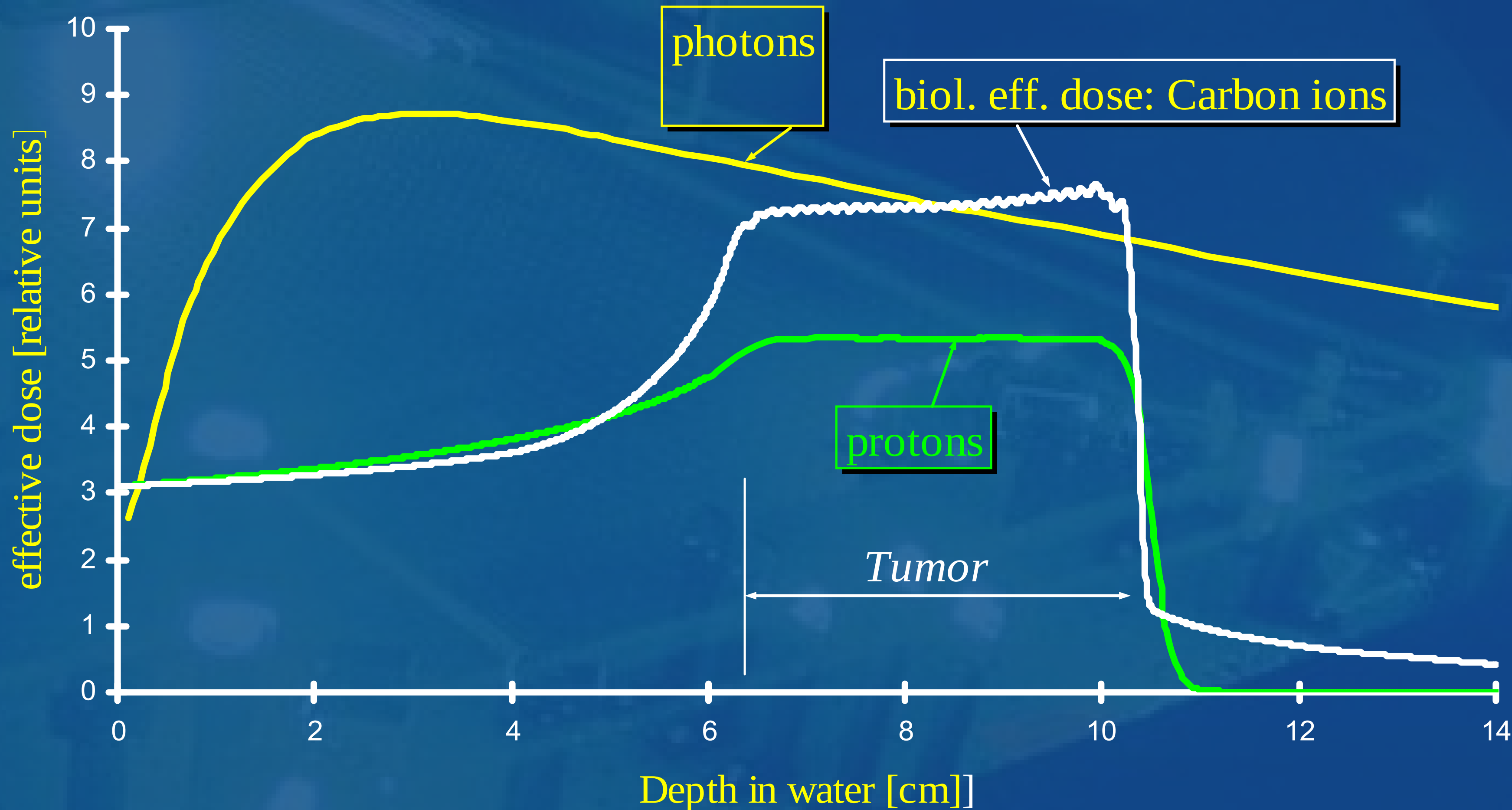
space charge

„compact“ accelerators - local machines

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

excellent emittance, yet poor divergence

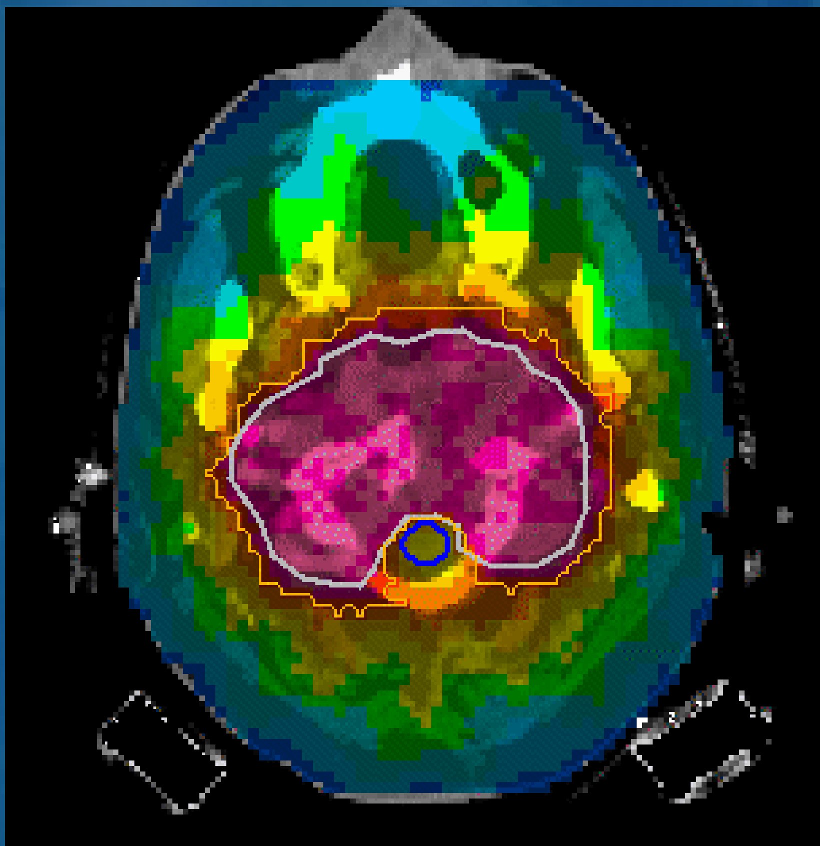
Ion beam therapy – the idea



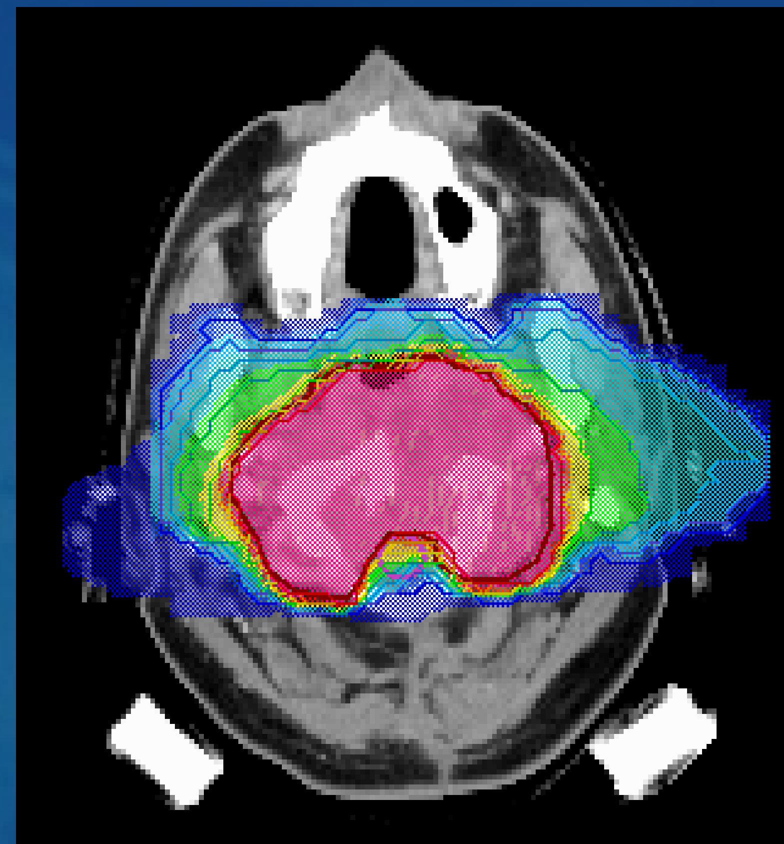
excitation of a longitudinal wave (wake)

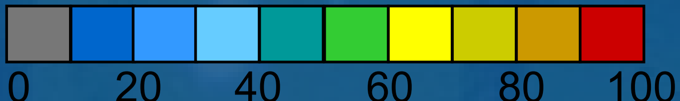
Ion beam therapy – treatment planning

Photons: 9 fields



carbon-ions: 2 fields

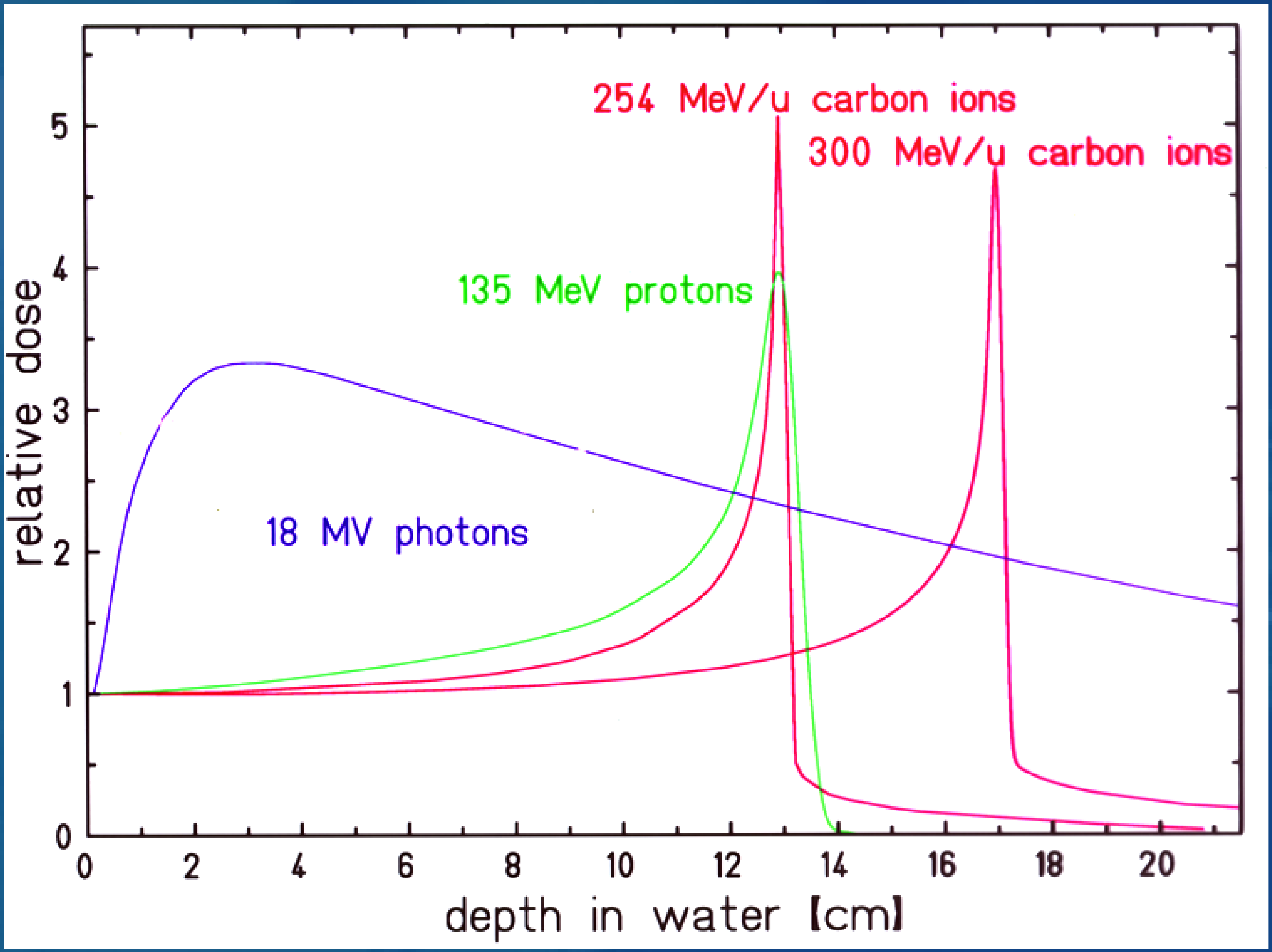




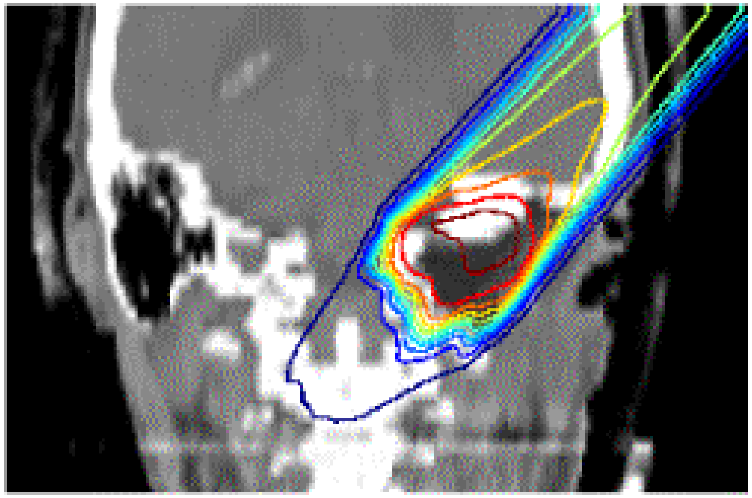
dose in % of the maximum dose

Courtesy O. Jäkel, DKFZ Heidelberg

Ion beam therapy – required energies

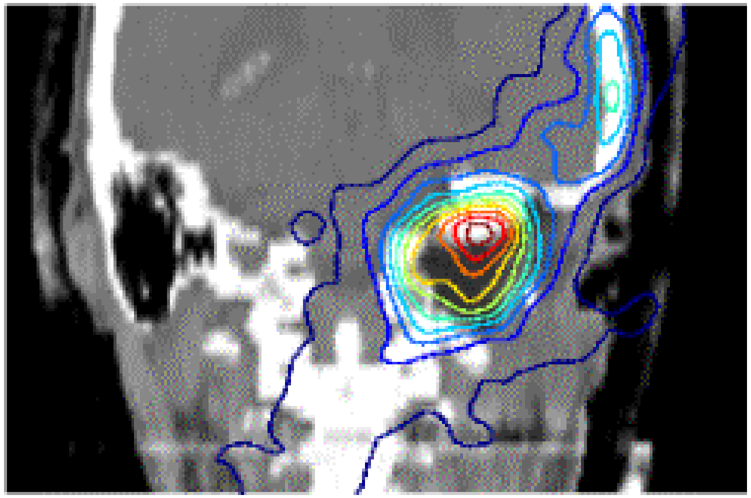


Verification by PET

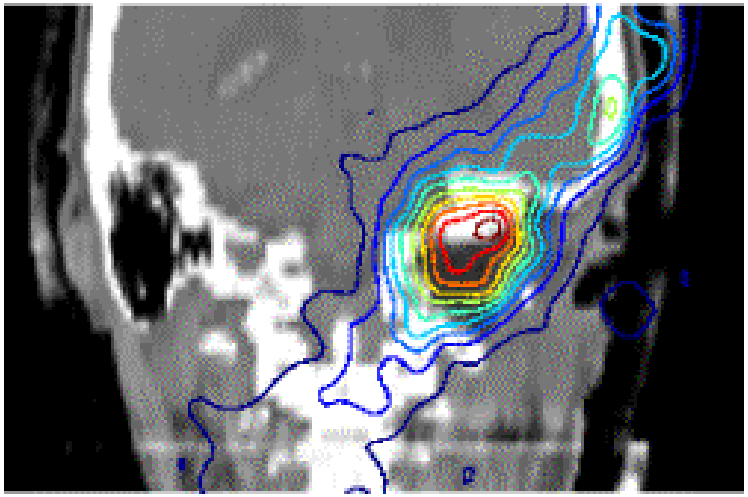


dose plan

W.Enghardt et al. ,
FZD Dresden



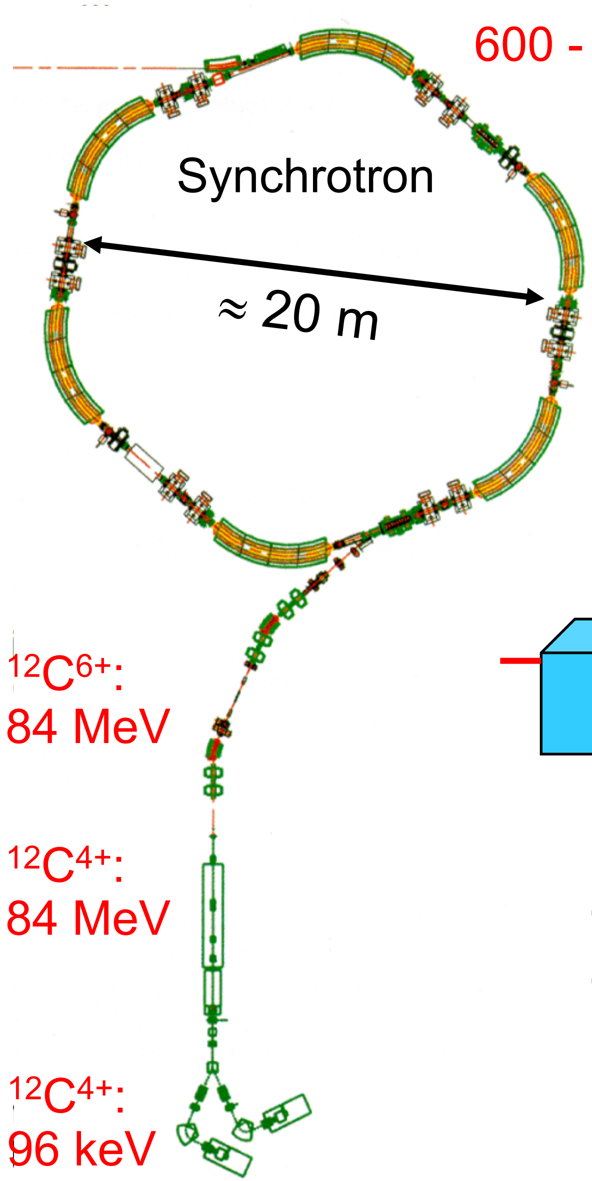
measured



simulated

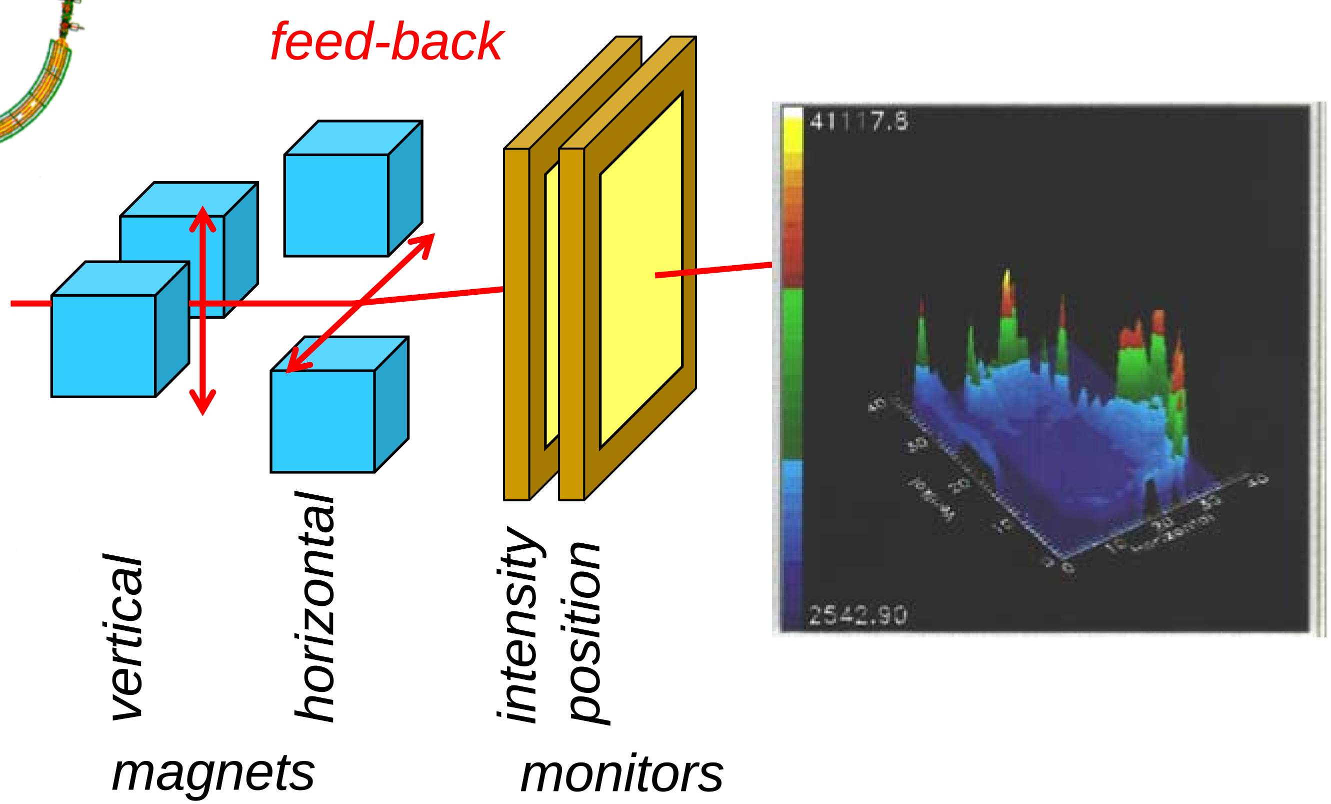
The GSI / HIT approach

600 - 5200 MeV, 10^6 - 10^8 Ionen/s, d = 5 - 10 mm

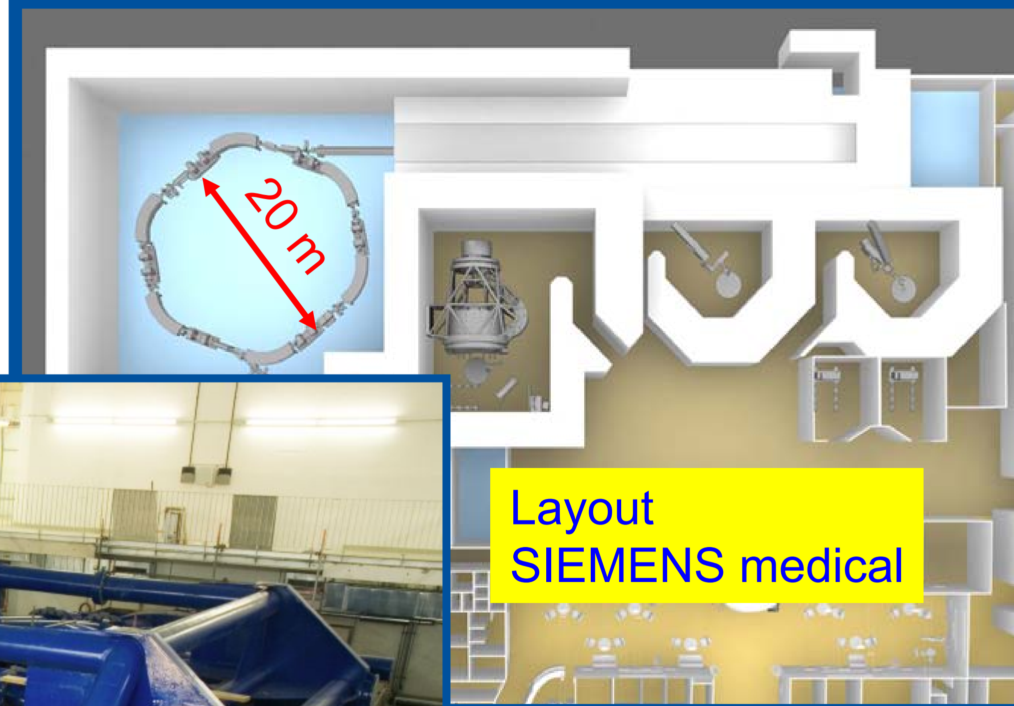


Intensity controlled position scan

T. Haberer et al.: Nucl. Instrum. Meth. A330 (1993) 296

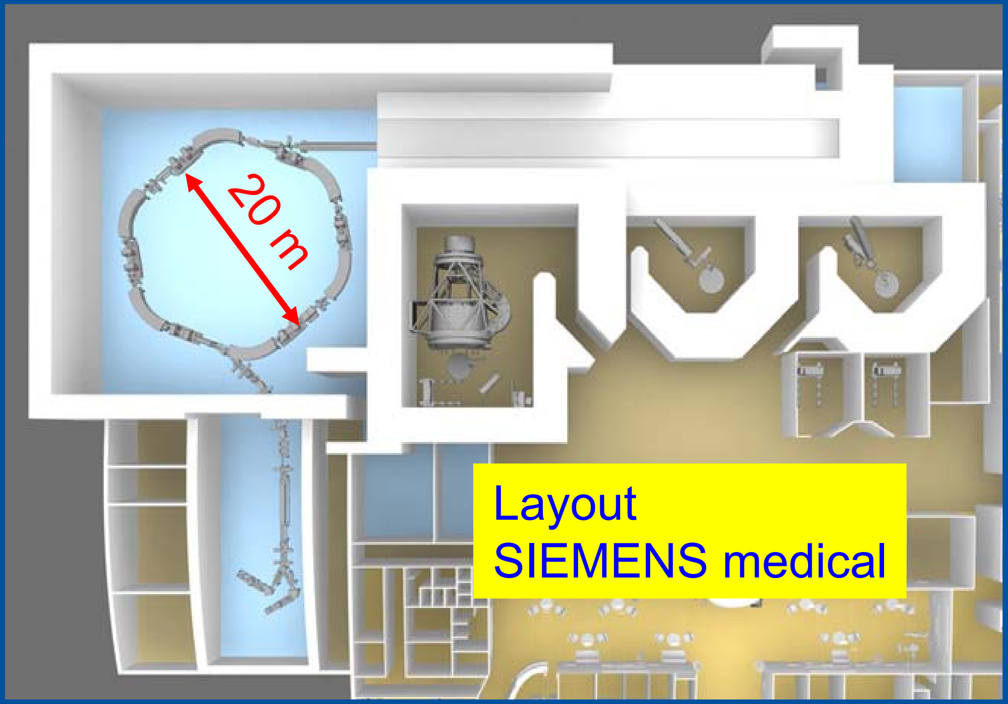


The GSI / HIT approach

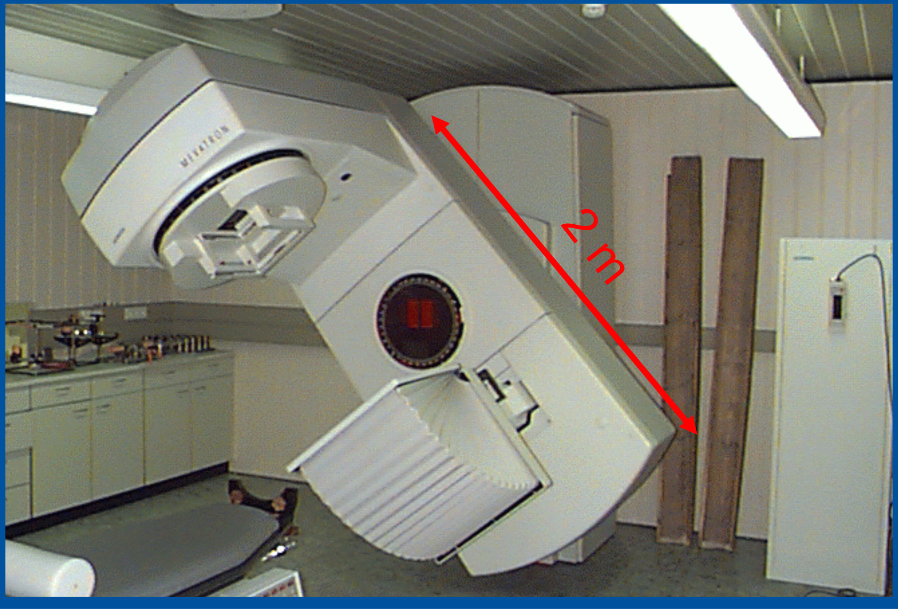


Pictures by courtesy of T. Haberer HIT Heidelberg

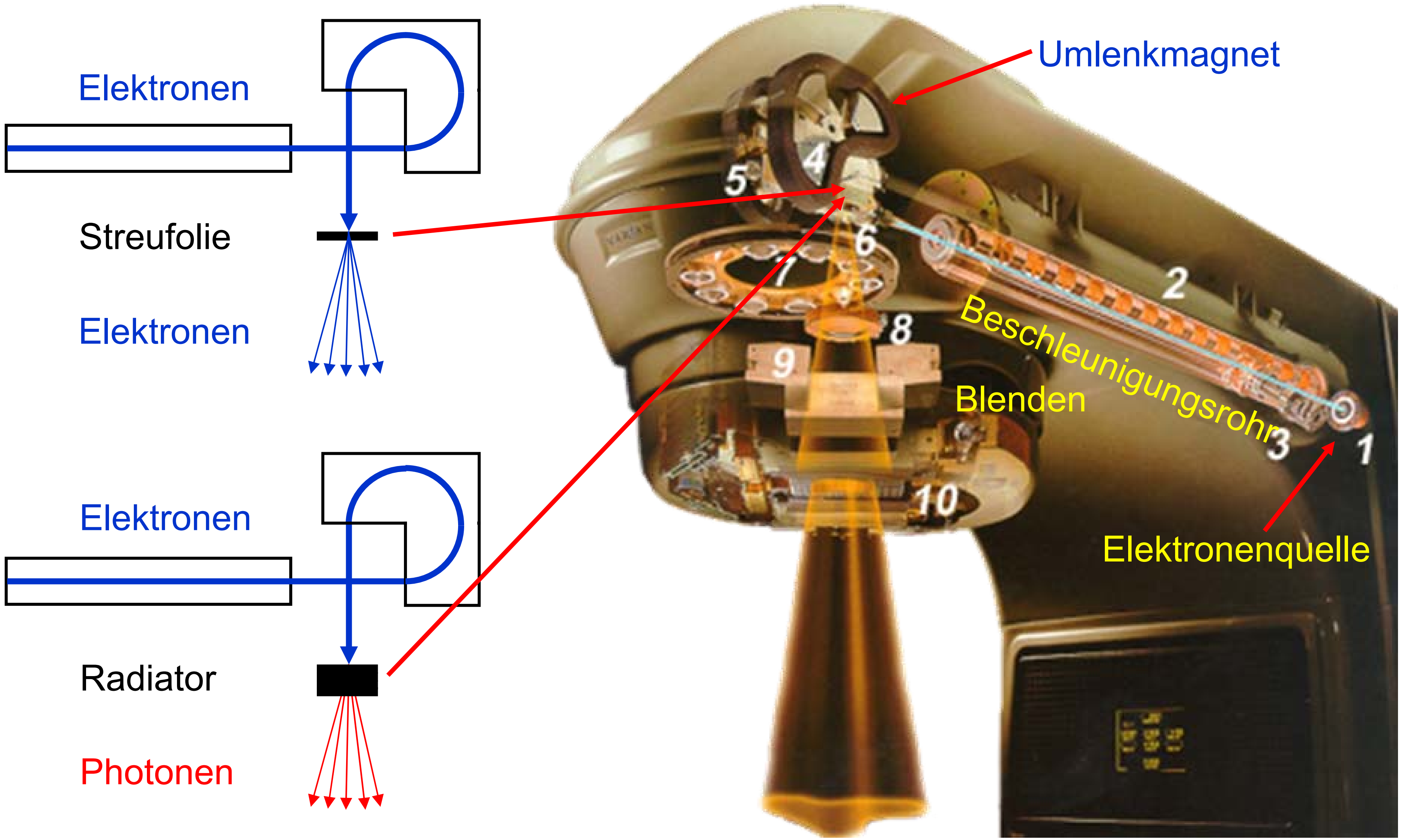
Conventional vs HIT

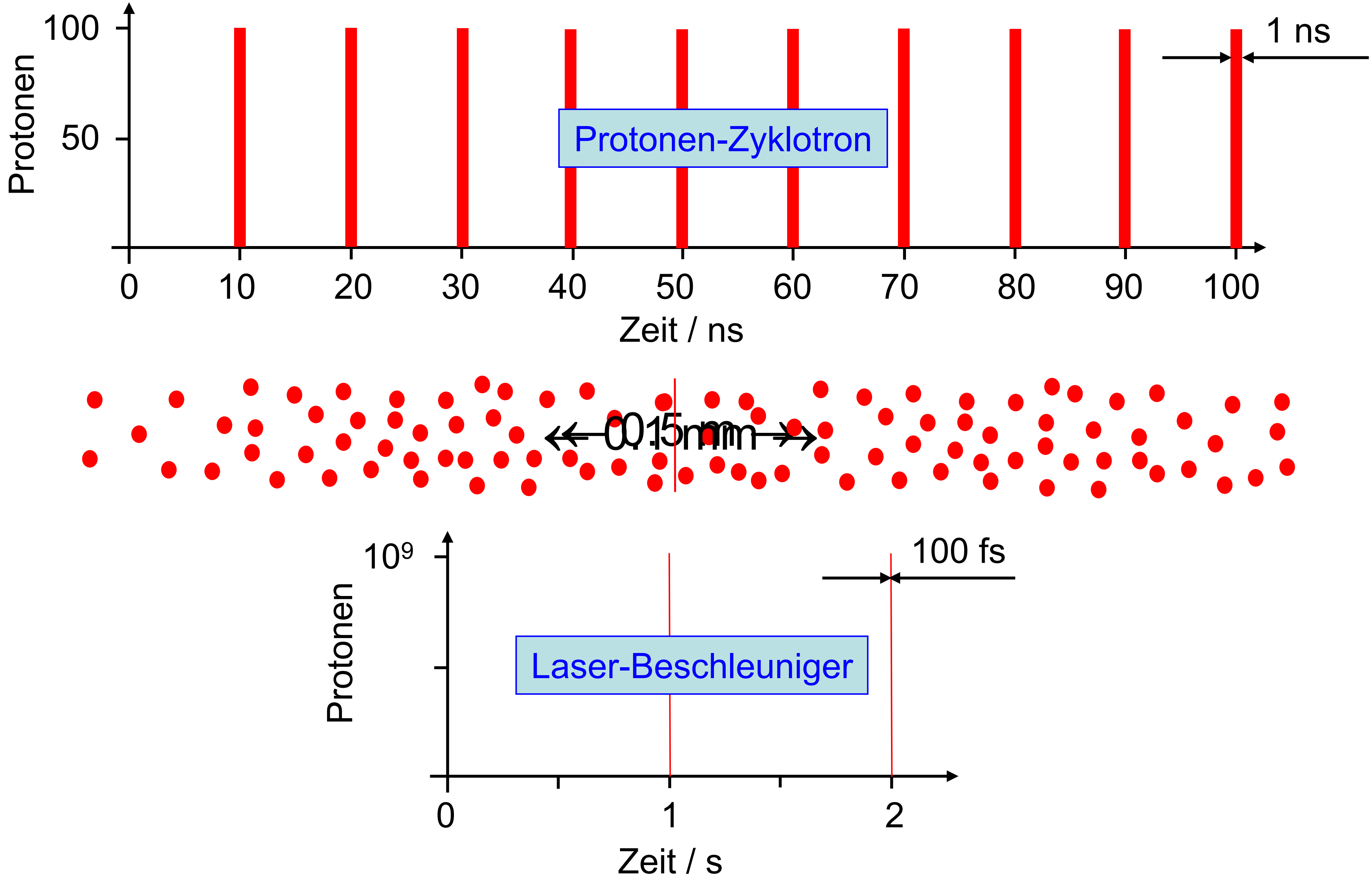


Conventional electron / photon therapy device



10x cheaper …


Elektronen
Streufolie
Elektronen
Elektronen
Radiator
Photonen
Umlenkmagnet
Beschleunigungsrohr
Blenden
Elektronenquelle
1
2
3
4
5
6
7
8
9
10



Protonen
100
50
1 ns
Protonen-Zyklotron
0
10
20
30
40
50
60
70
80
90
100
Zeit / ns
10^9
100 fs
Protonen
Laser-Beschleuniger
0
1
2
Zeit / s

1. Experimentparameter

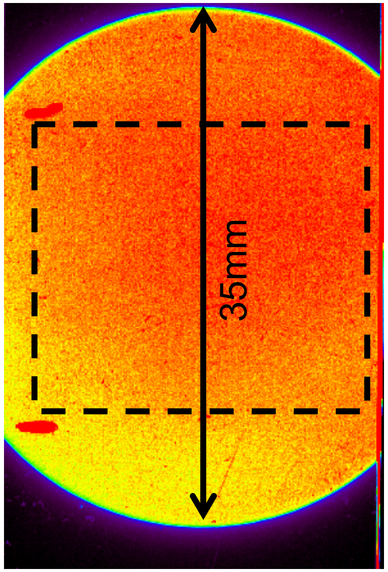
JETI: $P \sim 1.2$ J
$f = 2.5$ Hz

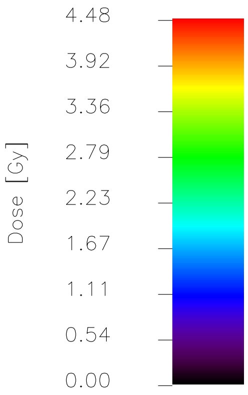
17.10.2007
Zelllinie: $FaDu_{DD}$ (Plattenepithelkarzinom, Kopf/Hals)
N_{Pulse}: 150 … 3000
Dosis: 0.263 Gy … 4.17 Gy
$t_{Bestrahlung}$: 60 s … 21 min
Probenanzahl: 31 (Doppelbestimmung)

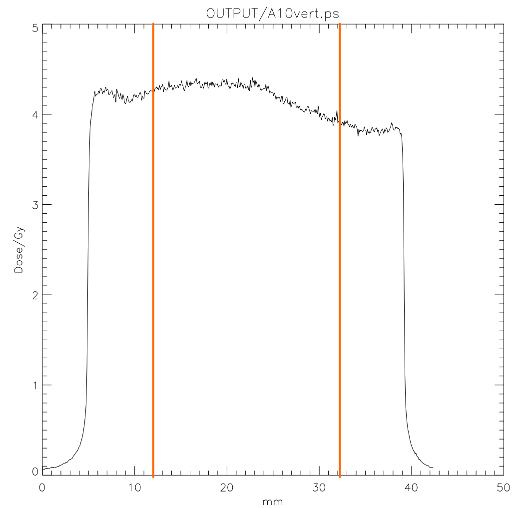
18.10.2007
Zelllinie: 184A1 (humane Brustdrüsenepithelzellen, normal)
N_{Pulse}: 450 … 2400
Dosis: 0.978 Gy … 5.210 Gy
$t_{Bestrahlung}$: ~3 min … ~ 16 min
Probenanzahl: 16 (Einfach- und Doppelbestimmung)

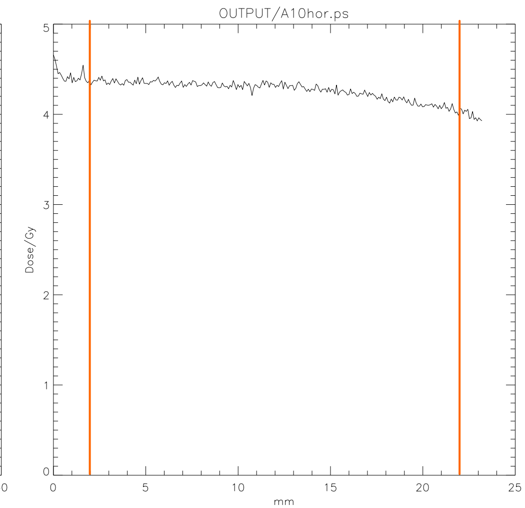
Biologischer Endpunkt: DNA Doppelstrangbrüche
(γH2AX + 53BP1, 2h + 24h nach Bestrahlung)

Dose distriution

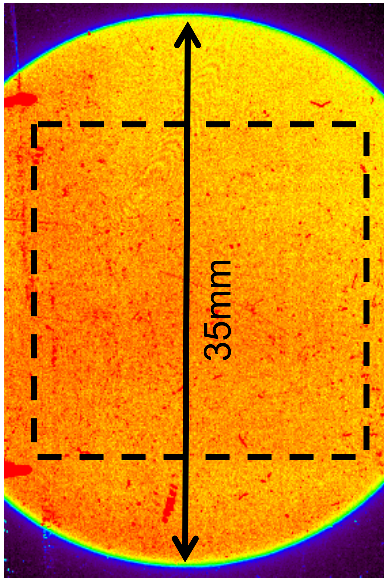


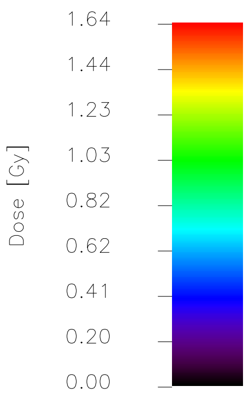


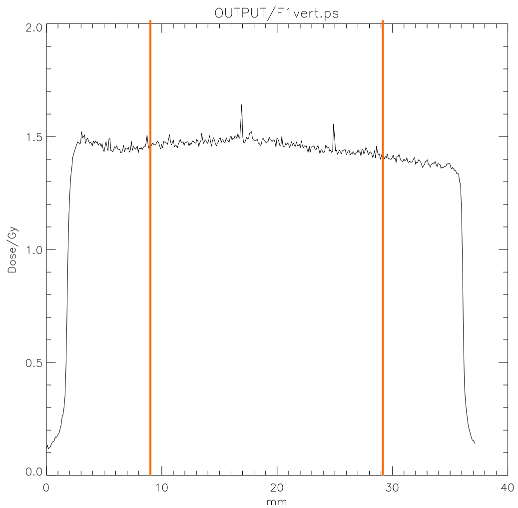


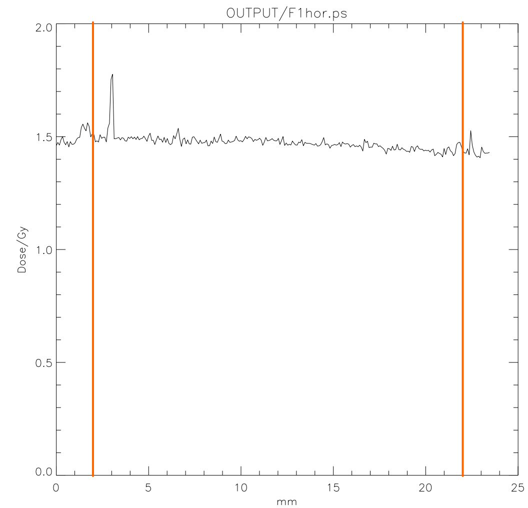


Film A10: 2000 Pulse, mittl. Dosis 4.128 Gy, 17.10.07



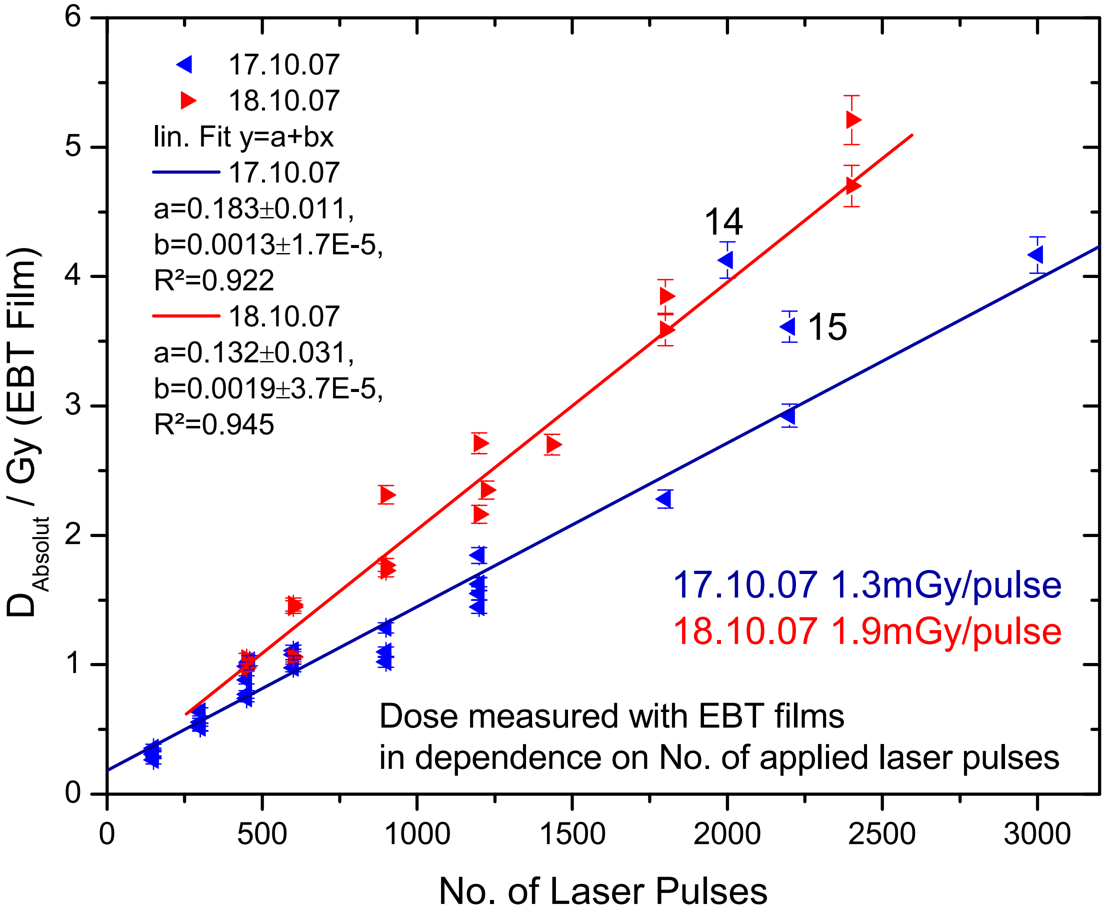






Film F1: 600 Pulse, mittl. Dosis 1.465 Gy, 18.10.07

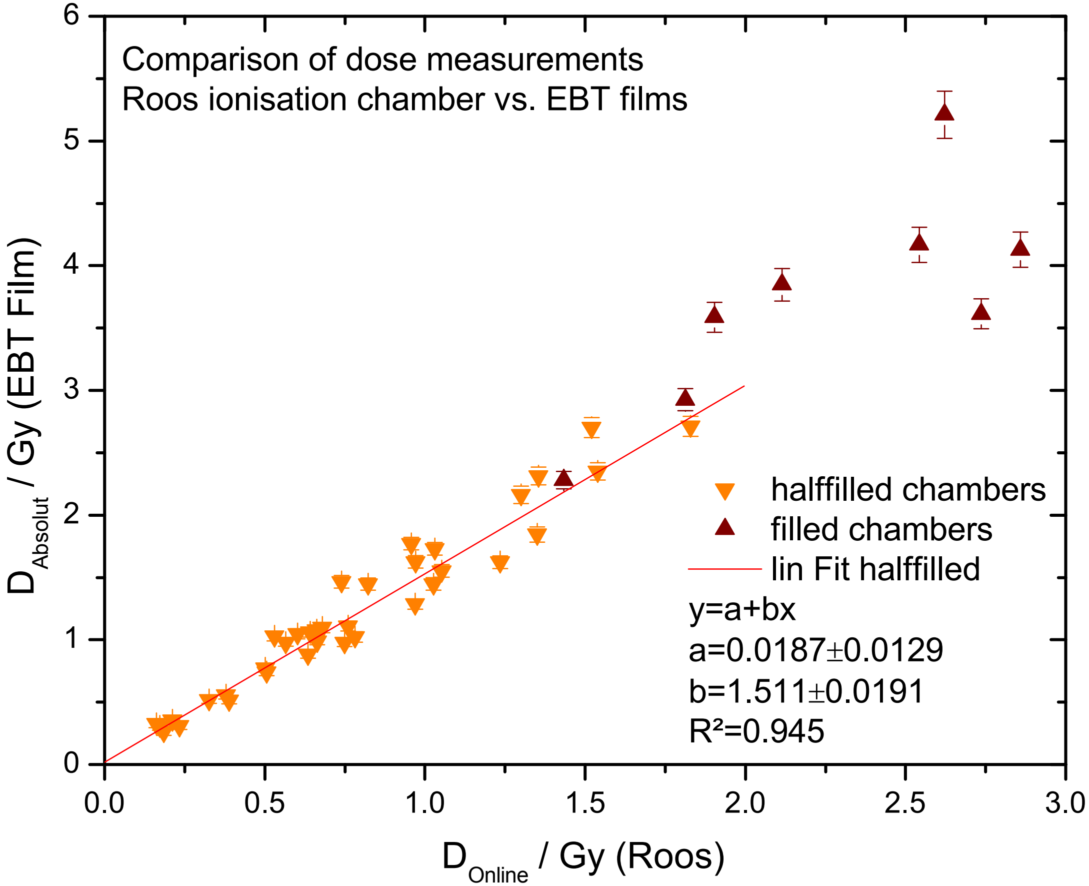
Vergleich der Anzahl applizierter Laserpulse mit der erreichten Absolutdosis in der Zellprobe



⇨ Stabile Pulsdosisleistung innerhalb eines Bestrahlungstages

⇨ Probe 14/15: Bestrahlung nach Mittagspause, Abkühlung der Vakuumpumpen

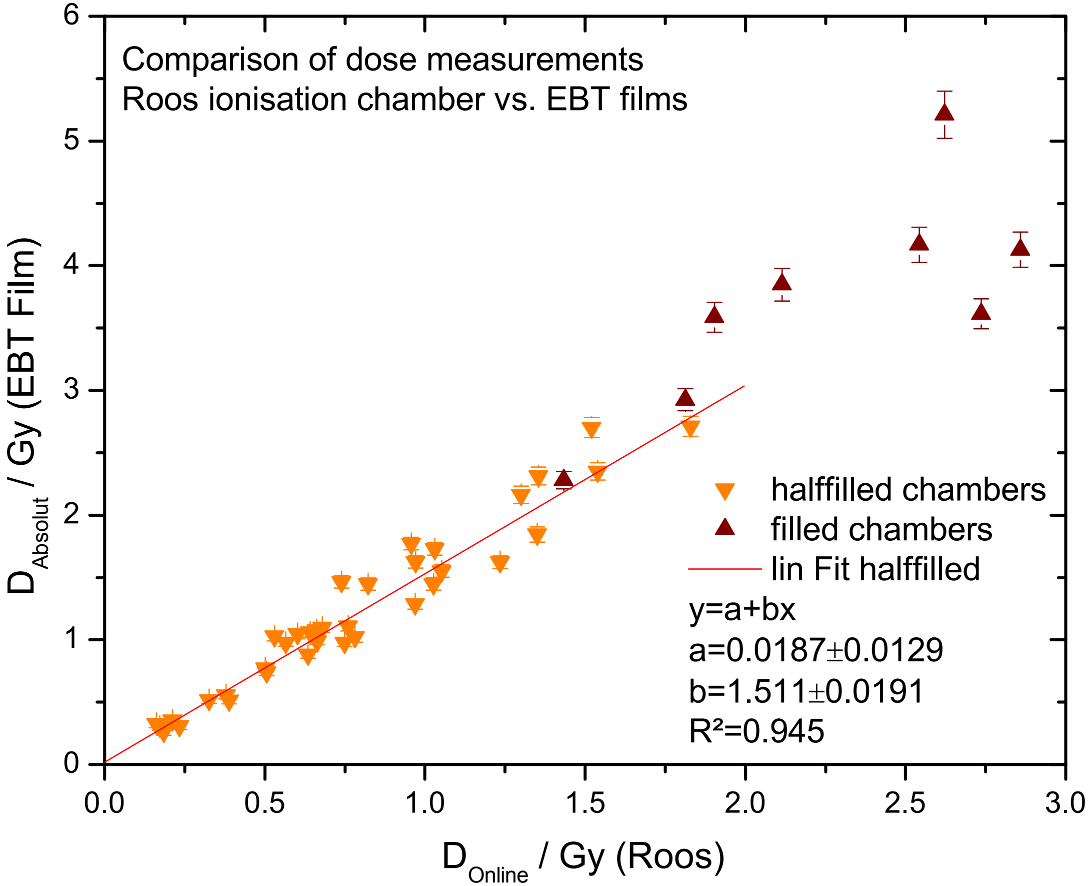
Vergleich der gemessenen Dosen mit EBT Filmen und Roos-Kammer



$D_{Absolut}/D_{Online} \approx 1.5$ (mit Zellen)

- ⇨ Gute Korrelation für „halbvolle“ Probenkammern → definiertes Probenvolumen
- ⇨ Starke Streuung für „volle“ Probenkammern → Schwankung des Volumens, Luftblasen, …
- ⇨ Füllung der Probenkammern wegen Gefahr der Austrocknung bei $t_{Bestrahlung}$ > 10 min

Vergleich der gemessenen Dosen mit EBT Filmen und Roos-Kammer



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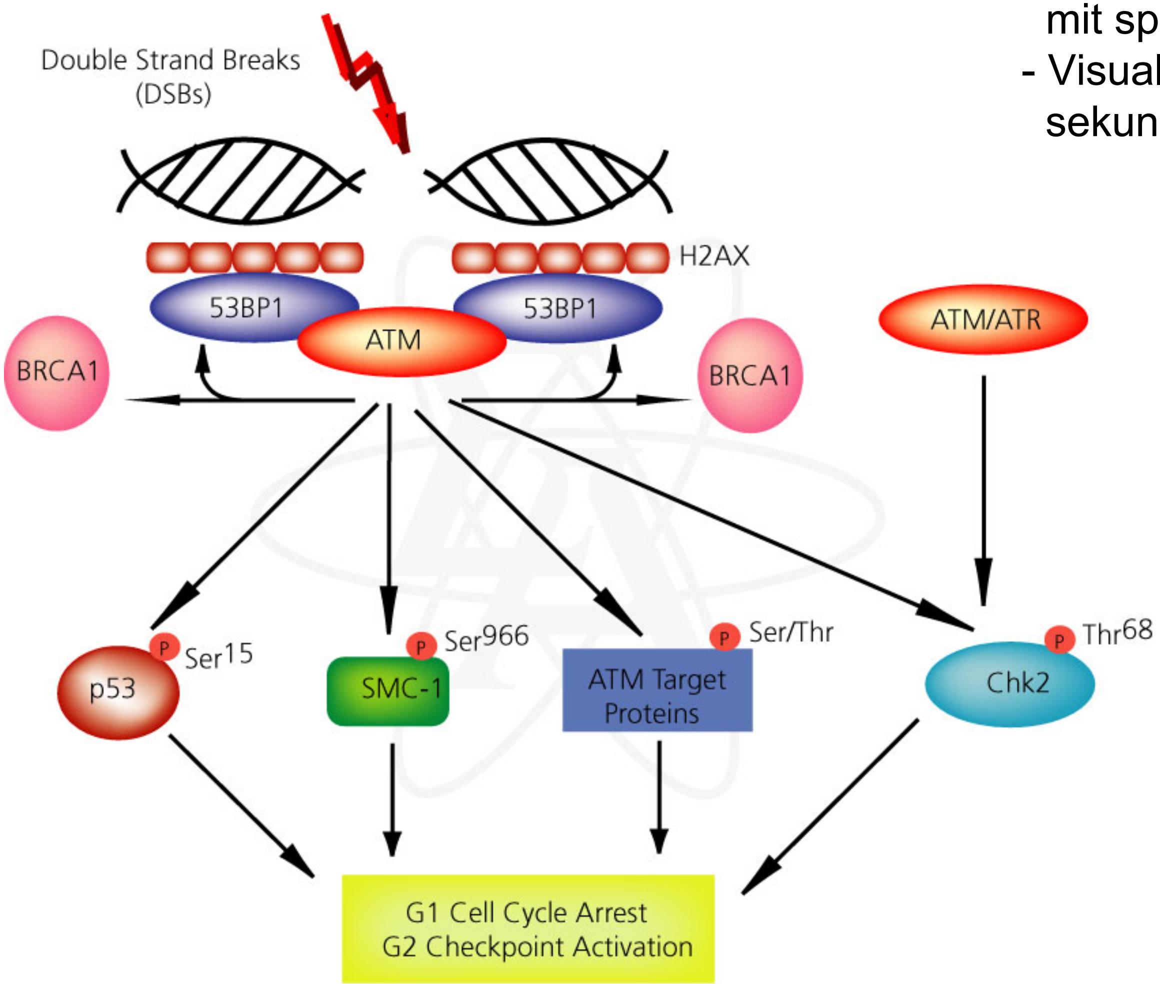
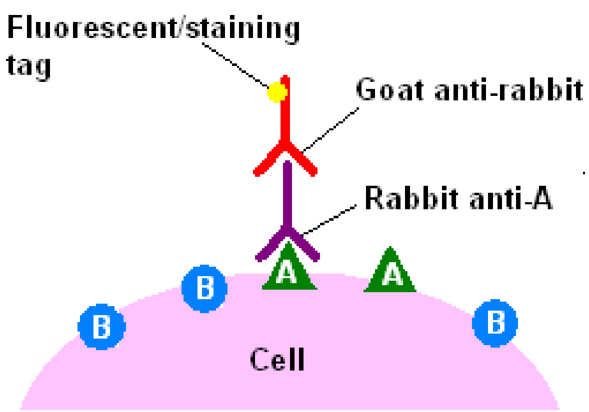
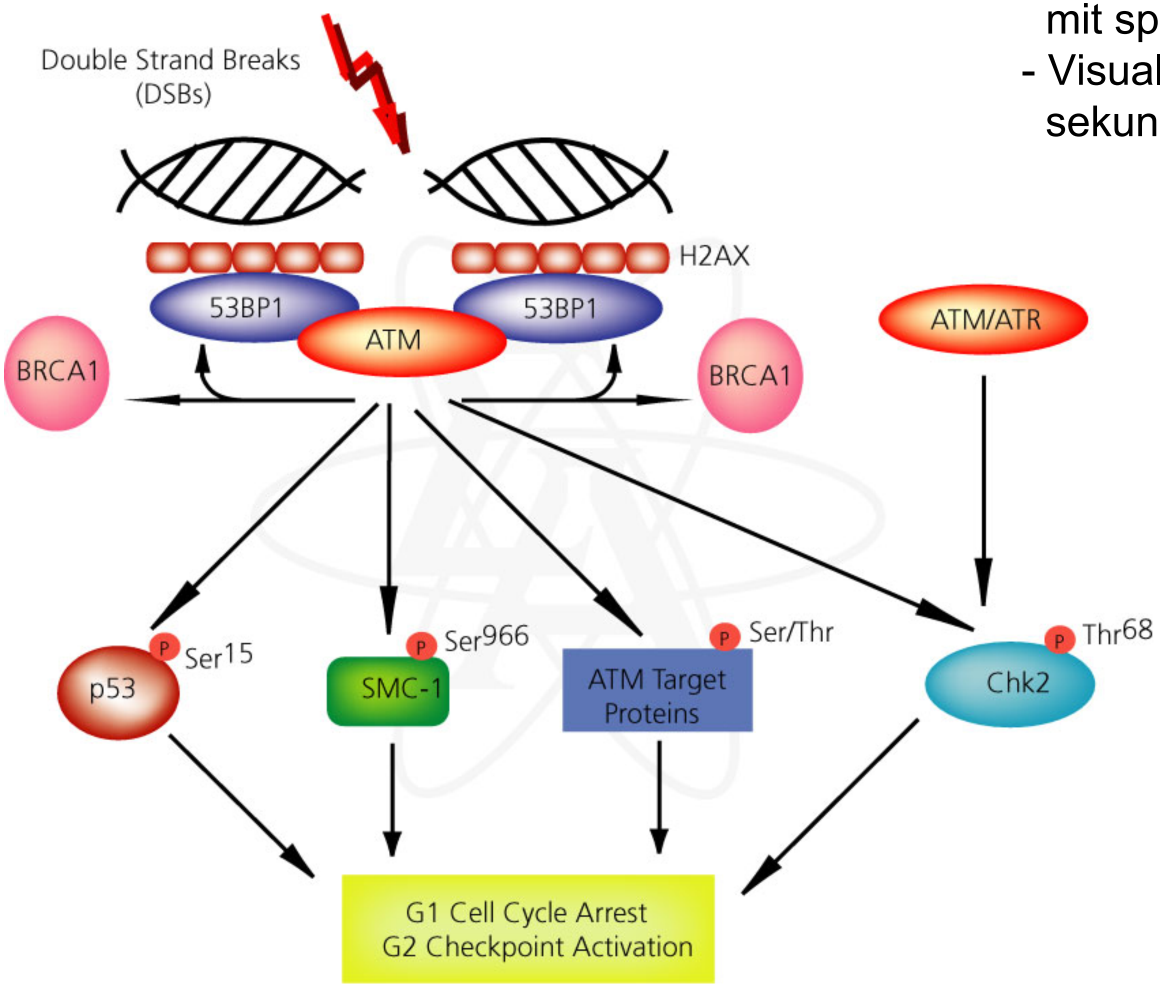
Nachweis der Doppelstrangbrüche:

- Detektion von γ–H2AX und 53BP1 mit spezifischen Antikörpern
- Visualisierung mit fluoreszenzmarkierten sekundären AK





Nature Cell Biology 4, E277, 2002



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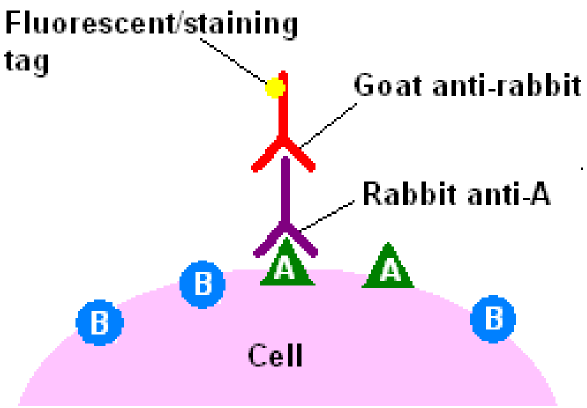
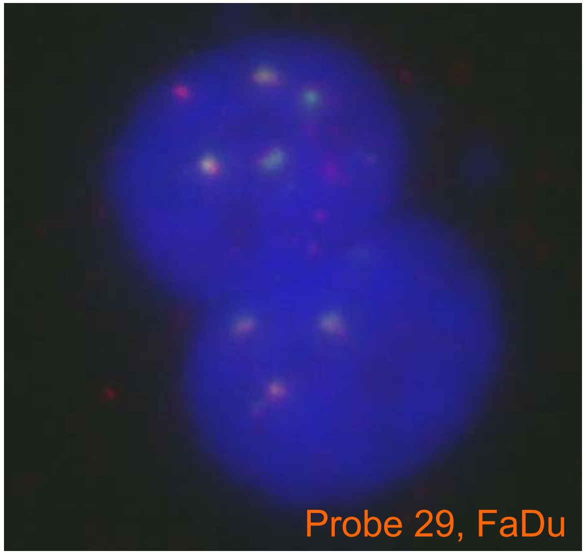
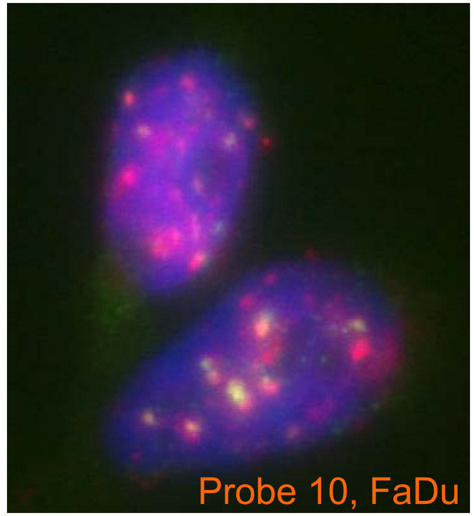
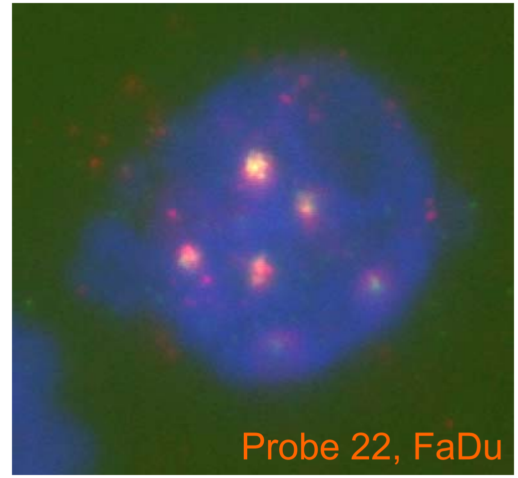


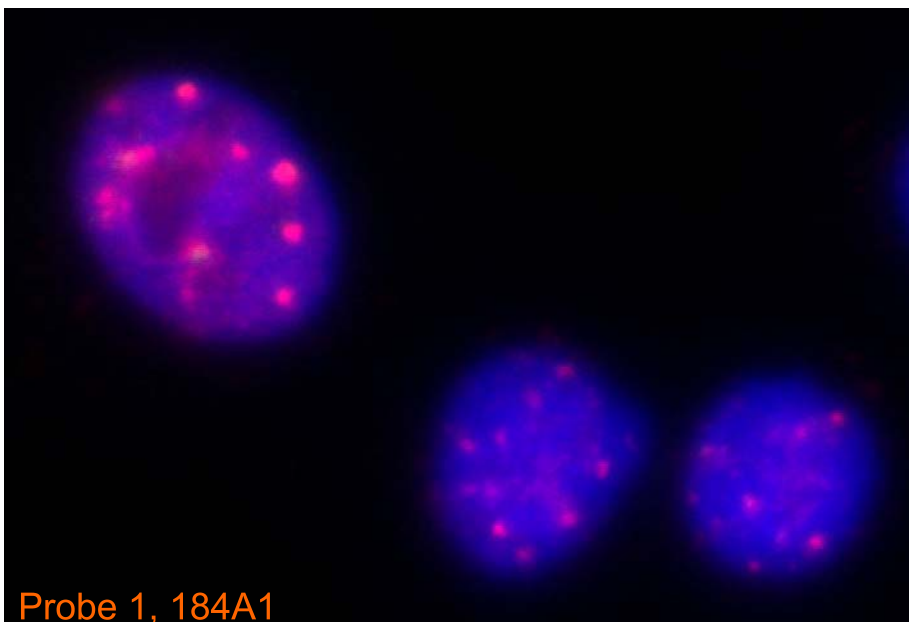
Nature Cell Biology 4, E277, 2002

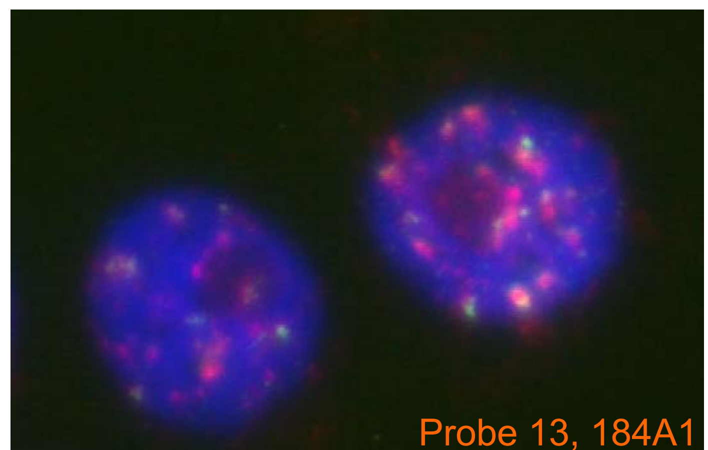
Detection of DNA damage

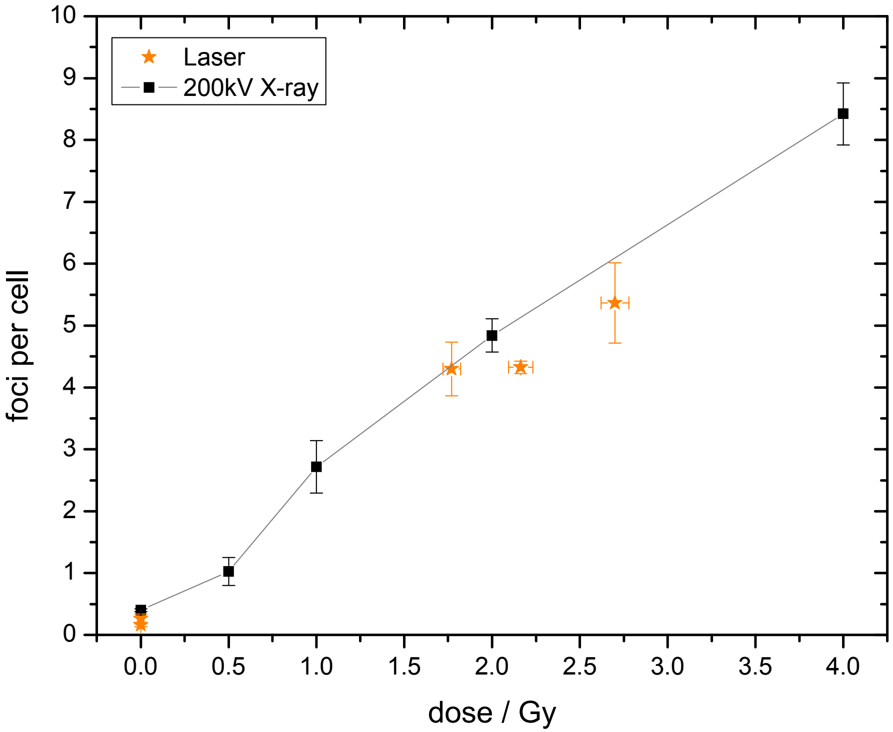


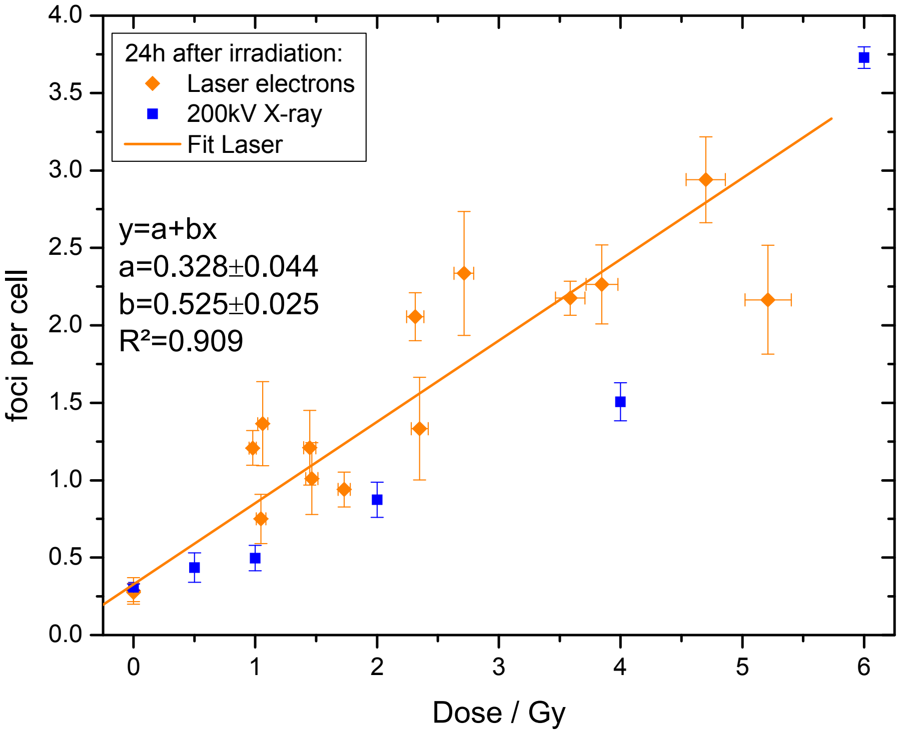




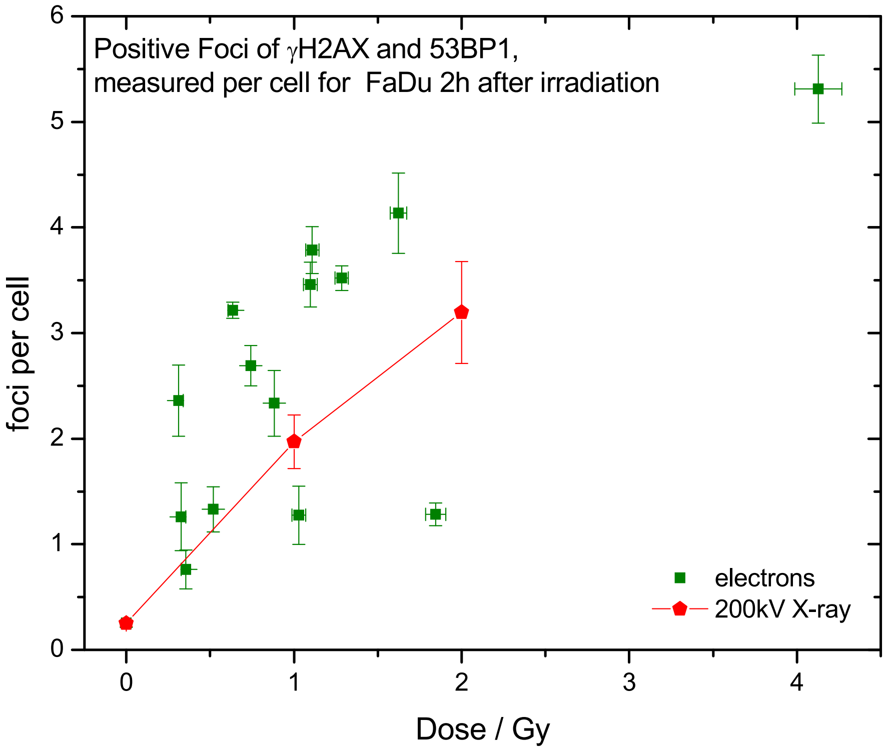


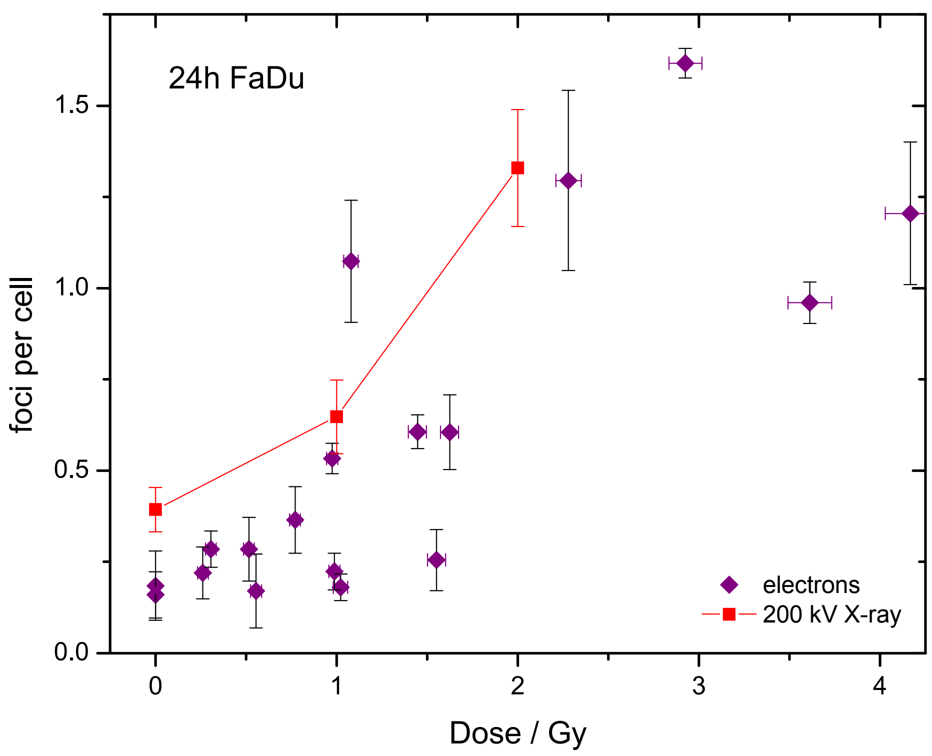






- 2h Daten: ~ Übereinstimmung bzw. leicht verringert für MeV Elektronen
- 24h Daten: - höhere Anzahl verbleibende DSB für MeV Elektronen
  → LET? Energiespektrum?
  → Verändertes Reparaturverhalten?





- Vergleich der Werte: 2h MeV e^- < 200kV X ⇔ 24h MeV e^- > 200kV X… Erklärung?
- Erwartung: Schädigung MeV Elektronen < 200 kV Photonen (LET)

Aber: Statistik 200 kV Daten unzureichend; 2 Experimente mit je 3 Dosispunkten
→ Wiederholung notwendig!

Bestrahlungen in Jena erfolgreicher als gedacht:

- Laser im „Dauereinsatz“ eingesetzt (Ausfall am 18.10.07)
- Stabile Pulsdosisleistung innerhalb eines Bestrahlungstages
- 47 bestrahlte Zellproben

Unklarheiten/nächste Schritte:

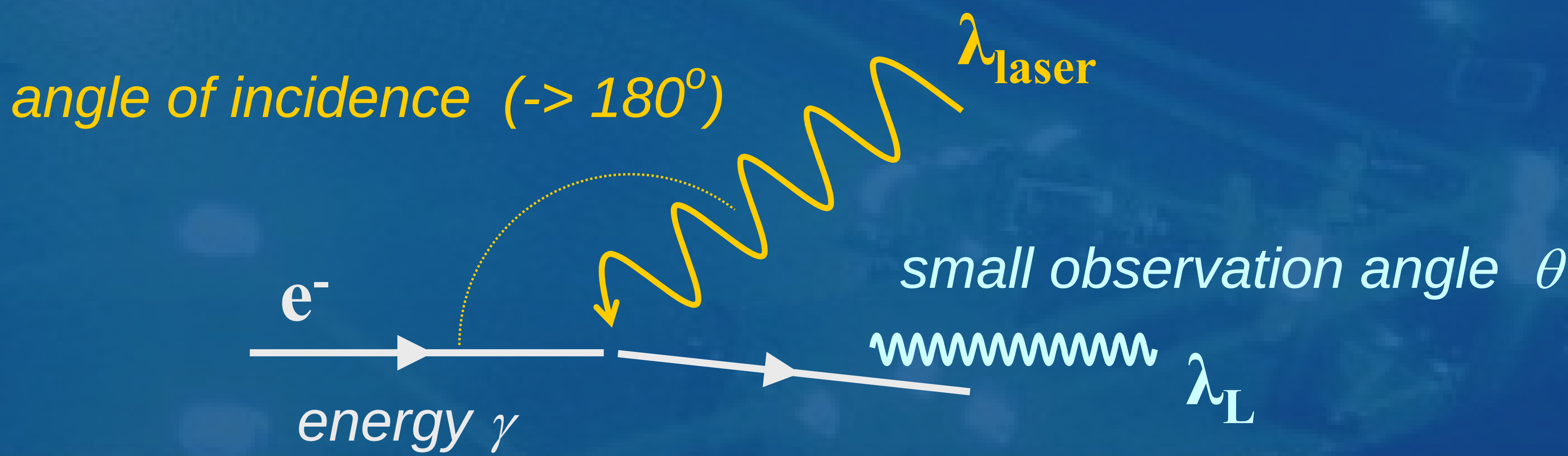
- Energiespektrum der Elektronen nicht ausreichend genau bekannt
  ⇨ Einfluss?, Messung?, Dosimetrie?

- Interpretation der gemessenen Daten schwierig, fehlende/zu wenige Referenzdaten
  ⇨„Zeitnahe“ Bestimmung von Referenzwerten für FaDu notwendig
  (an 200kV Röhre, parallel zu JeTi-Bestrahlungen)

- Referenzbestrahlungen:
  - Therapiebeschleuniger mit versch. Absorptionsmedien
  - Monoenergetische Elektronenstrahlung (ELBE)
  - 200 kV Röntgenröhre → bisher nur für 184A1

- Etablierung einer zweiten Tumorzelllinie + Referenzbestrahlungen

Thomson scattering – basic idea



photon energy, distribution, efficiency, coherence …

Thomson scattering – head on

$$\lambda_L = \frac{\lambda_{laser}}{4\gamma^2}\left(1+\frac{a^2}{2}+\gamma^2\theta^2\right)$$

Forschungszentrum Dresden Rossendorf

Resonance conditions (undulator and `optical undulator´):

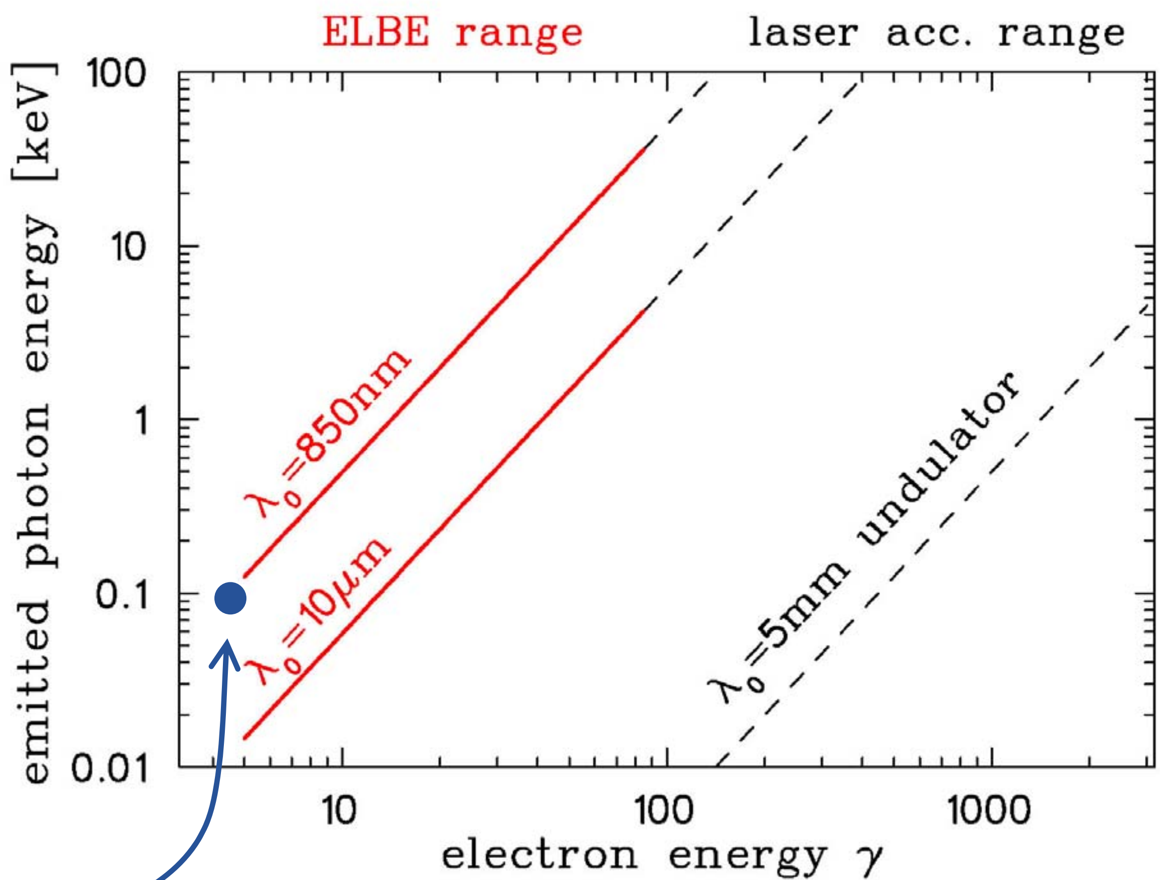
- ***Thomson scattering:***

$$\lambda_L = \frac{\lambda_{laser}}{4\gamma^2}\left(1 + \frac{a^2}{2} + \gamma^2\theta^2\right)$$

- ***Undulator radiation:***

$$\lambda_L = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

for 13.5 nm (92eV)
γ=4.4 (or 1.7 MeV)

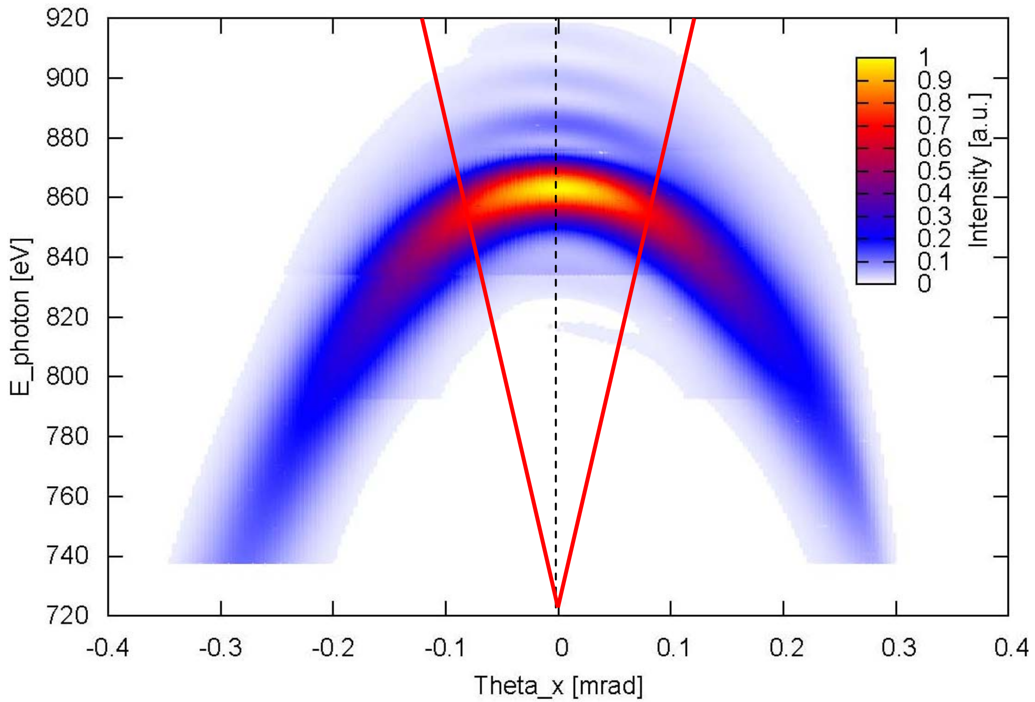


Thomson scattering (divergence and linewidth)

(treated as a counterpropagating undulator)

$$\lambda_L = \frac{\lambda_{laser}}{4\gamma^2}\left(1 + \frac{a^2}{2} + \gamma^2\theta_{obs}^2\right)$$

$$\theta_{emission,rms} \sim \frac{1}{\gamma\sqrt{N_{laser}}}$$



Thomson scattering (divergence and linewidth)

Wavelength @ rms emission angle:

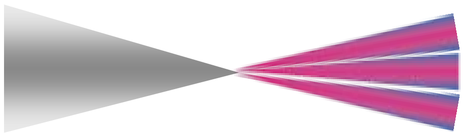
$$\lambda_L = \frac{\lambda_{laser}}{4\gamma^2}\left(1 + 1/N_l\right)$$

Relative width @ zero angle:

$$\Delta\lambda_L / \lambda_L \sim 1/N_l$$

For a reasonable number of oscillation periods of N_{laser} ~ 100 (i.e. 300fs for Ti:Sapphire laser)

► e-beam divergence defines radiation properties



Thomson scattering rate

yield limited by small cross-section (~r_e^2)

$$dN_{emission} / d\Omega \sim \alpha \cdot \gamma^2 \cdot a_0^2 \cdot N_e \cdot N^2{}_{laser}$$

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

1 nC, few ps
ε_n= 1 mm mrad

~100-300 fs (bandwidth, divergence)

1 (J-class) -> 10^8 photons / pulse @ 10Hz = 10^9/s
few mrad cone and % bandwidth (~10nW)