Plasma Wake Acceleration

New Accelerator Concepts for Particle Therapy (Laser-electron, Laser-ion.. etc)

Markus Roth

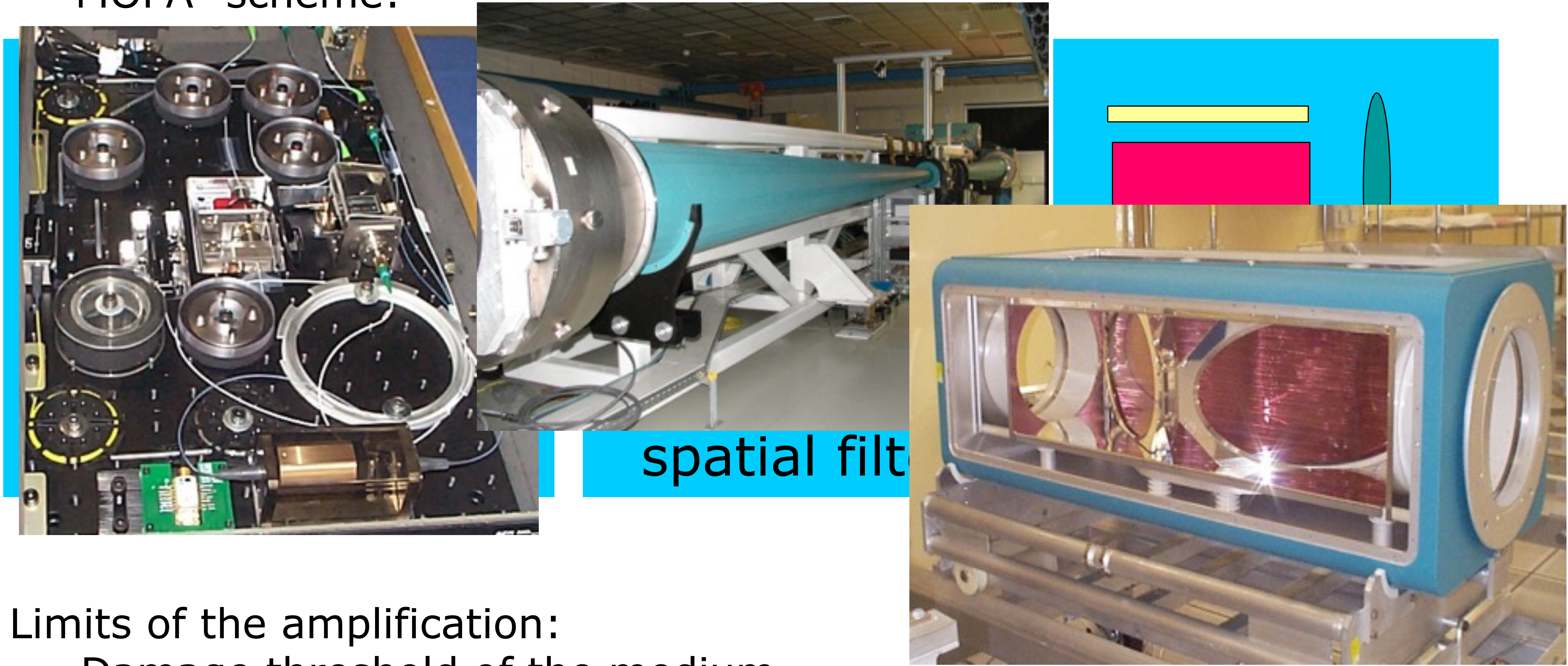
Institute for Nuclear Physics
TU Darmstadt

Outline

- Ultra-Intense-Lasers
- Laser-driven electrons
  - Potential for Applications in Therapy
  - Use of secondary Radiation
- Laser-driven Ion Beams
  - Properties and Mechanism
  - Experiments
- Applications as Sources for Therapy
  - Transport of laser-accelerated protons
- Summary

How to do A LOT of laser light

MOPA- scheme:



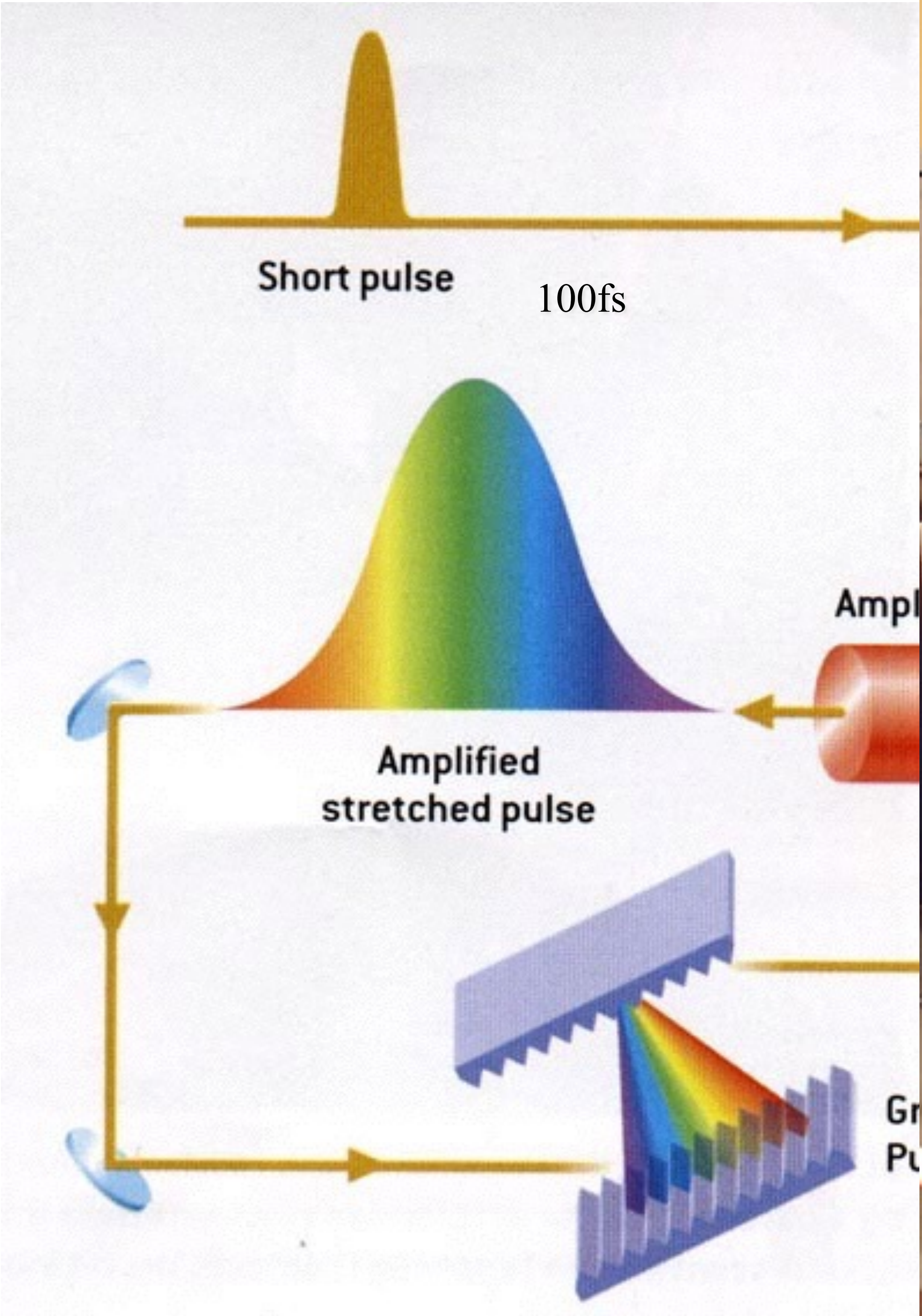
Limits of the amplification:

Damage threshold of the medium
non-linear refraction index

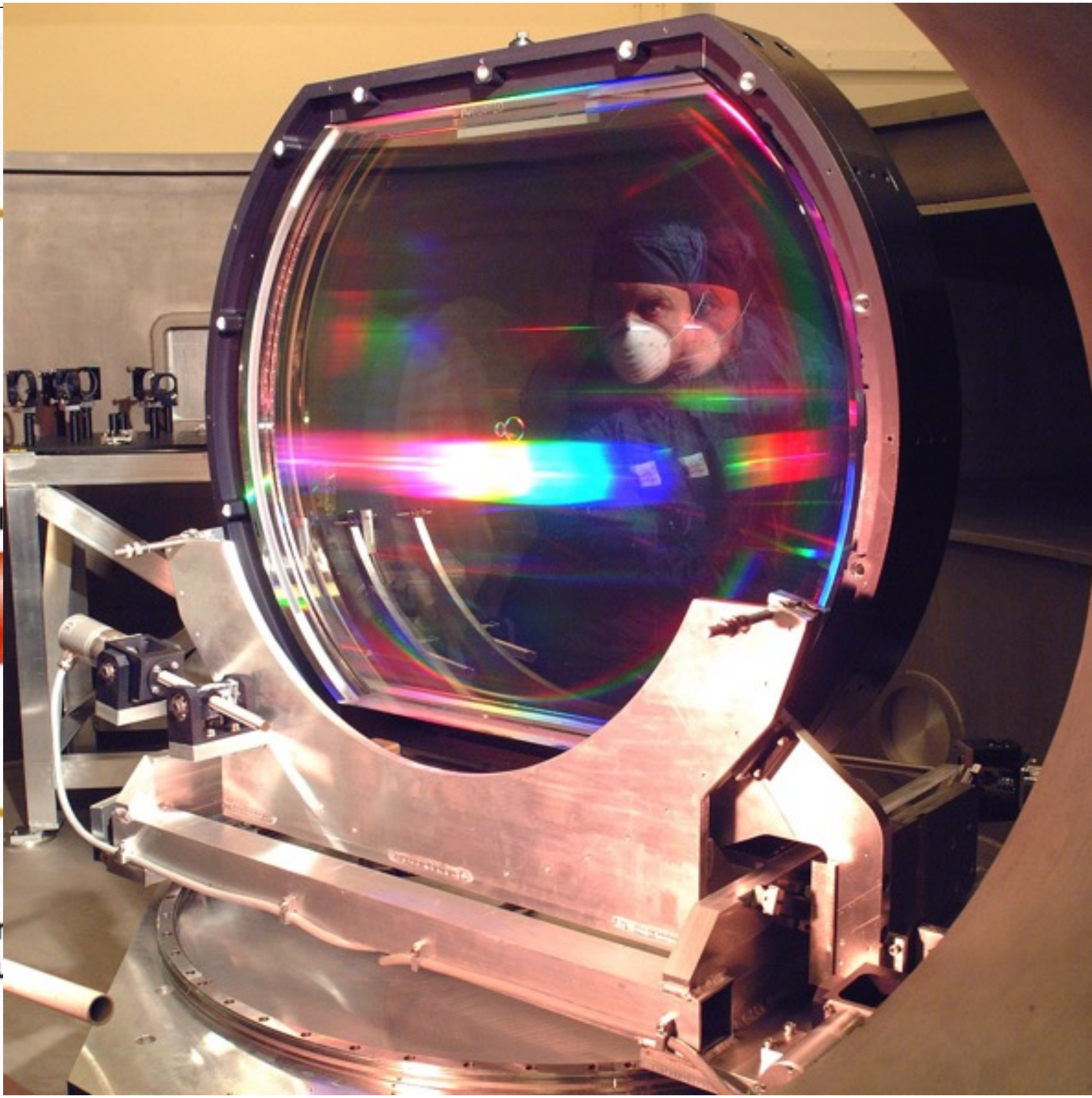
$$B = \Delta\Phi = \frac{2\pi}{\lambda}\int I(l)\, n_{nl}\, dl$$

self- filamentation
beam quality

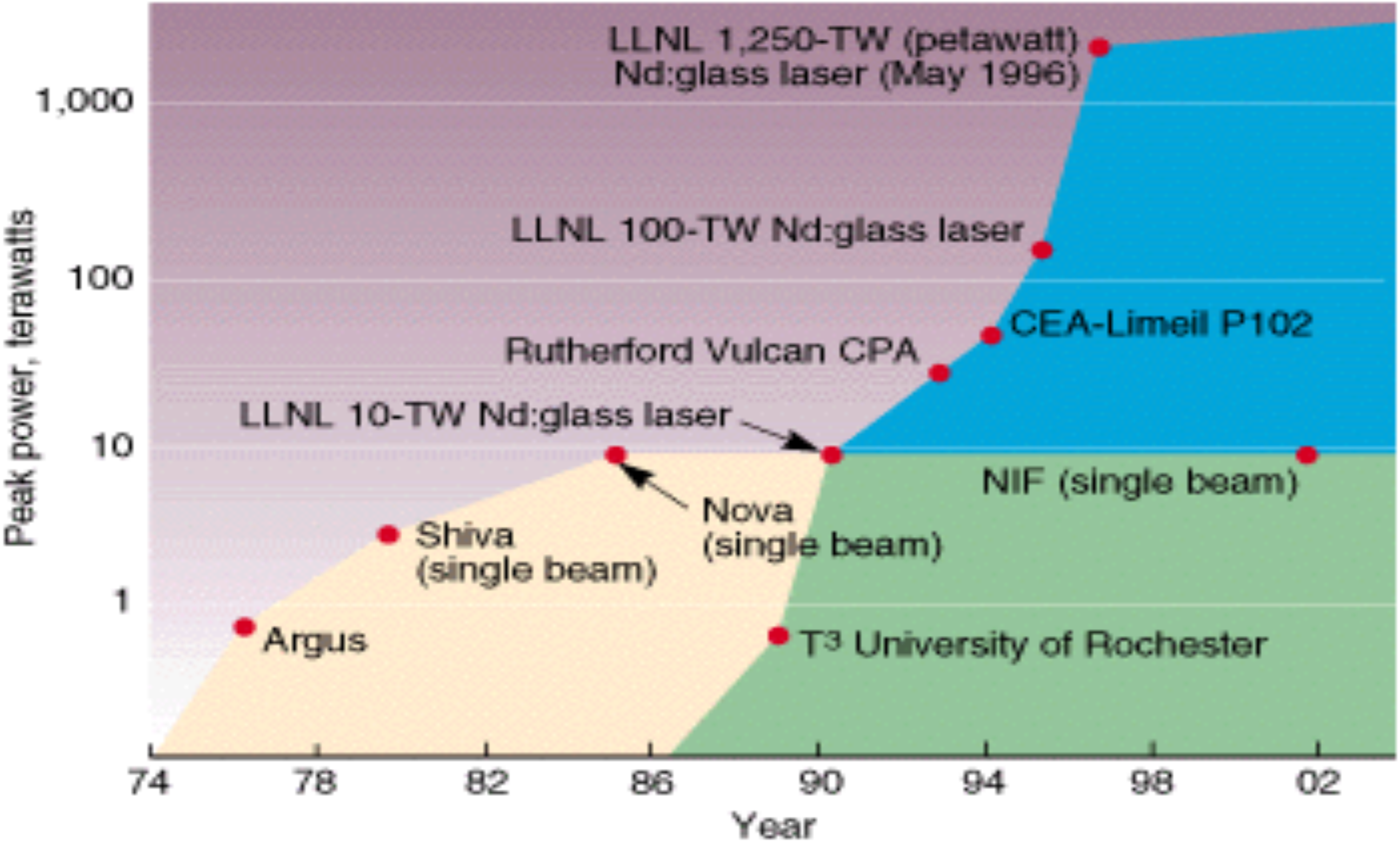
CPA technique



100fs



CPA


LLNL 1,250-TW (petawatt)
Nd:glass laser (May 1996)
LLNL 100-TW Nd:glass laser
CEA-Limeil P102
Rutherford Vulcan CPA
LLNL 10-TW Nd:glass laser
NIF (single beam)
Nova
(single beam)
Shiva
(single beam)
Argus
T3 University of Rochester
Peak power, terawatts
1,000
100
10
1
74
78
82
86
90
94
98
02
Year

The Petawatt opens a new regime of ultra-relativistic laser-matter interactions

Enormous EM fields

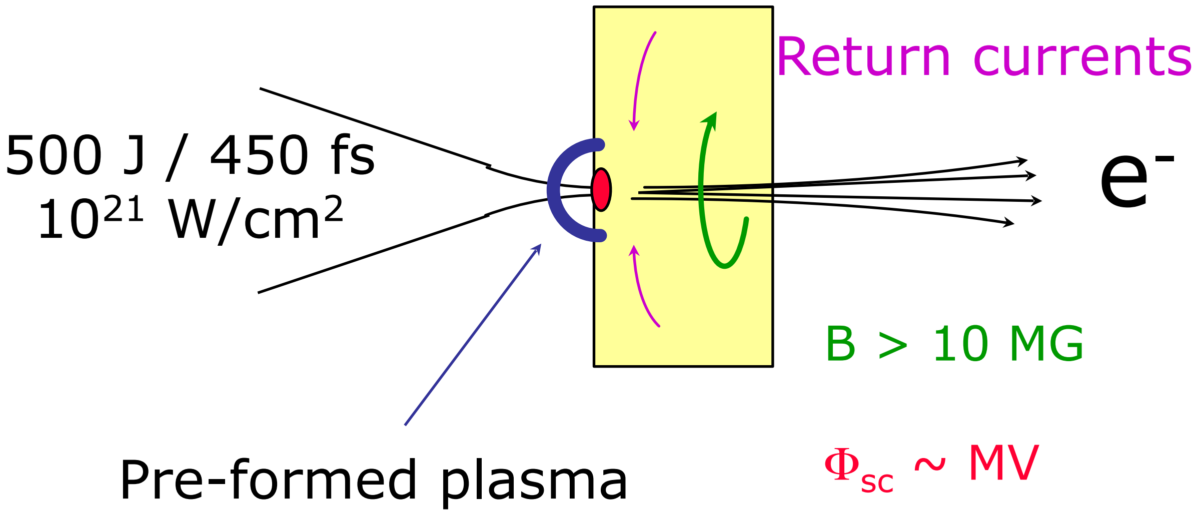
at $I = 10^{21}$ W/cm^2 :

$E \sim I^{1/2}\,\lambda = 10^{14}\ V/m$

$B = E/c = 3x10^{5}\ Tesla$

$P_{rad} = I/c = 3x10^{10}\ J/cm^{3}$

$= 300\ GBar$



Laser-plasma effects

- filamentation
- self-focusing
- plasma acceleration
- » dependence on pre-pulse

Relativistic Electron Motion

Cycle-averaged oscillation energy:

$E_{avg} = mc^2[1+ a_o^{\,2}/2]^{1/2}$

$a_o = eA/mc^2 = [I/(1.37x10^{18})]^{1/2}\lambda(\mu m)$

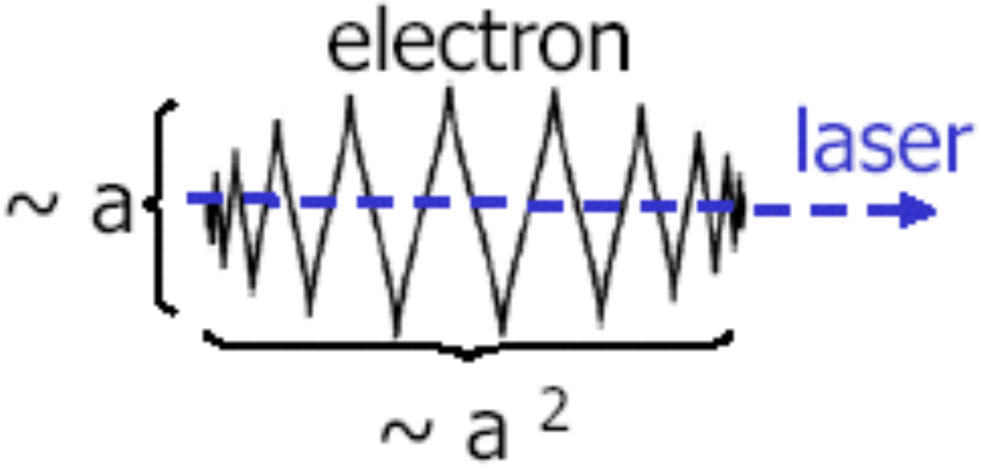
at 10^{21} W/cm^2, $a_o \sim 27$, $E_{avg} > 10$ MeV

Electron & bremsstrahlung energies can greatly exceed nuclear excitation & pair-creation thresholds

Lawson Woodward theorem….

Electron trajectory in plane laser pulse

$$\vec{F} = -e\Big[\underbrace{\vec{E}}_{\sim a} + \underbrace{(\vec{v}/c)\times\vec{B}}_{\sim a^2}\Big]$$

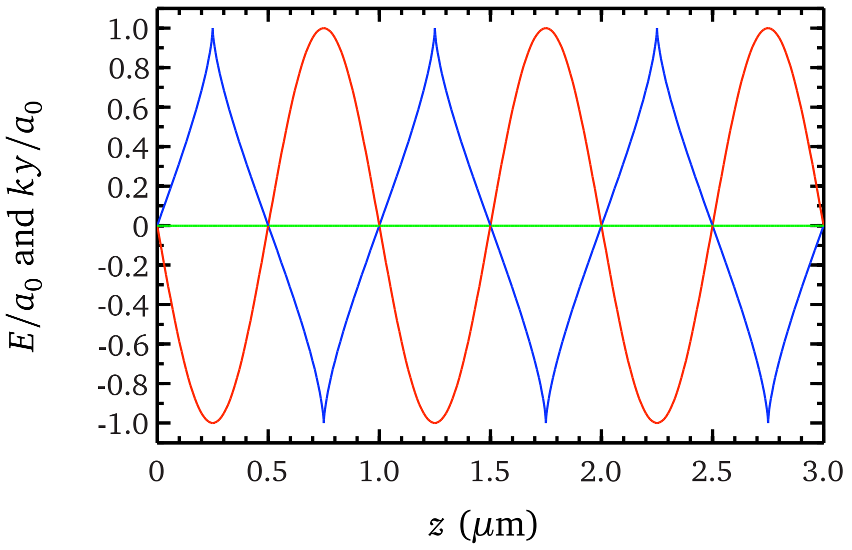


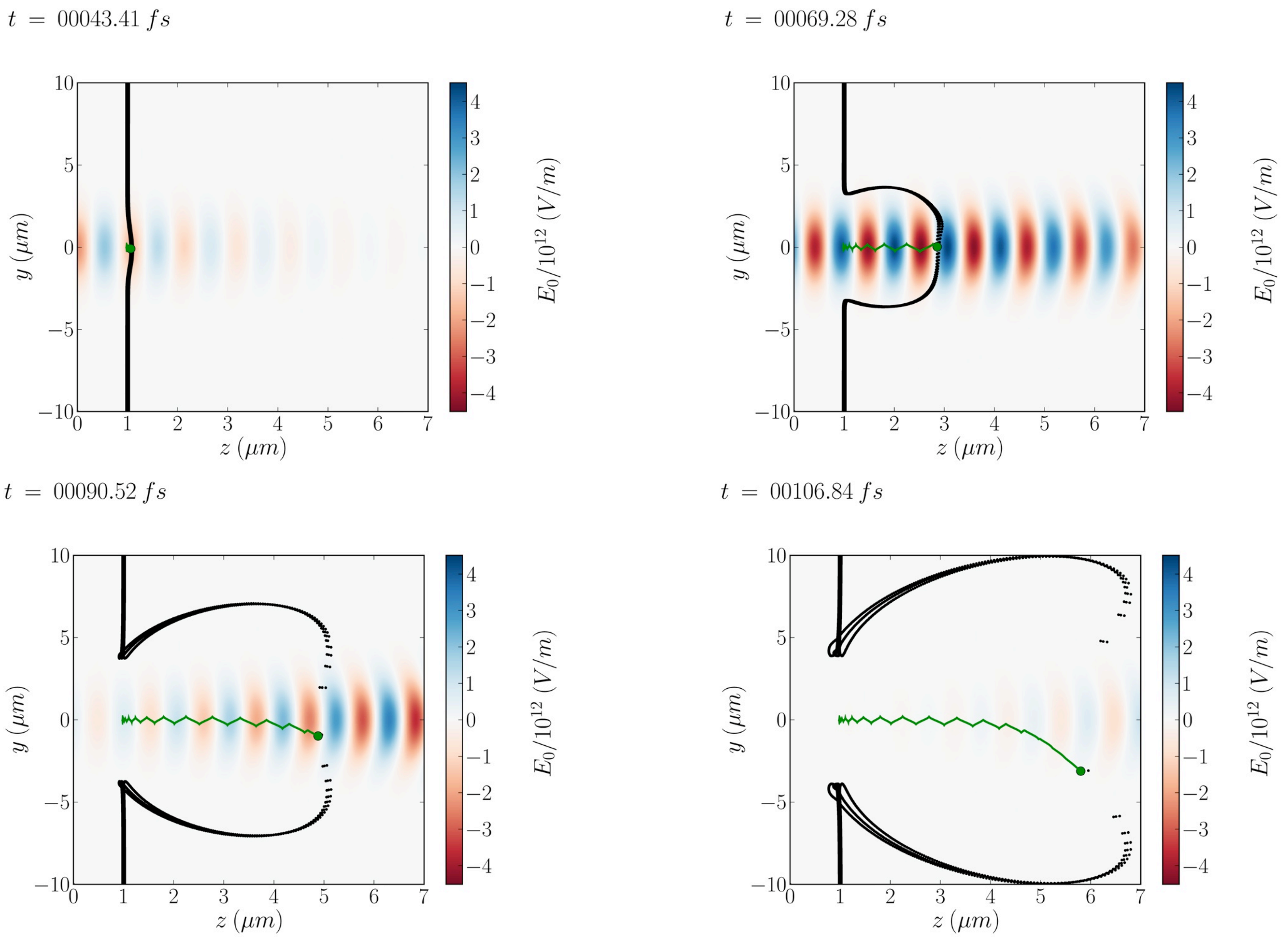
$a = eA/mc^2$

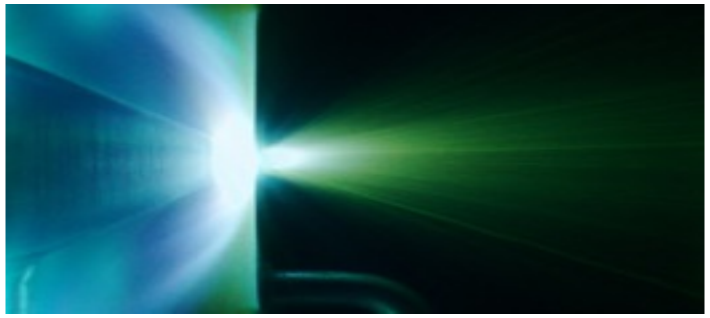
laser amplitude

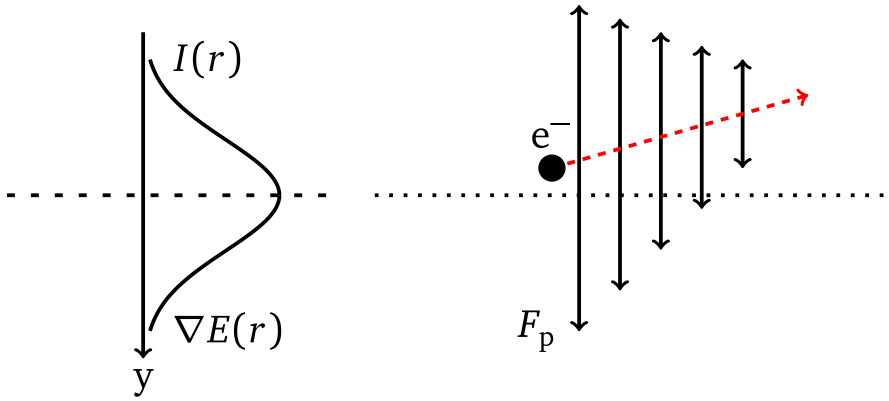
an electron cannot gain energy from a plane wave

But in reality.....





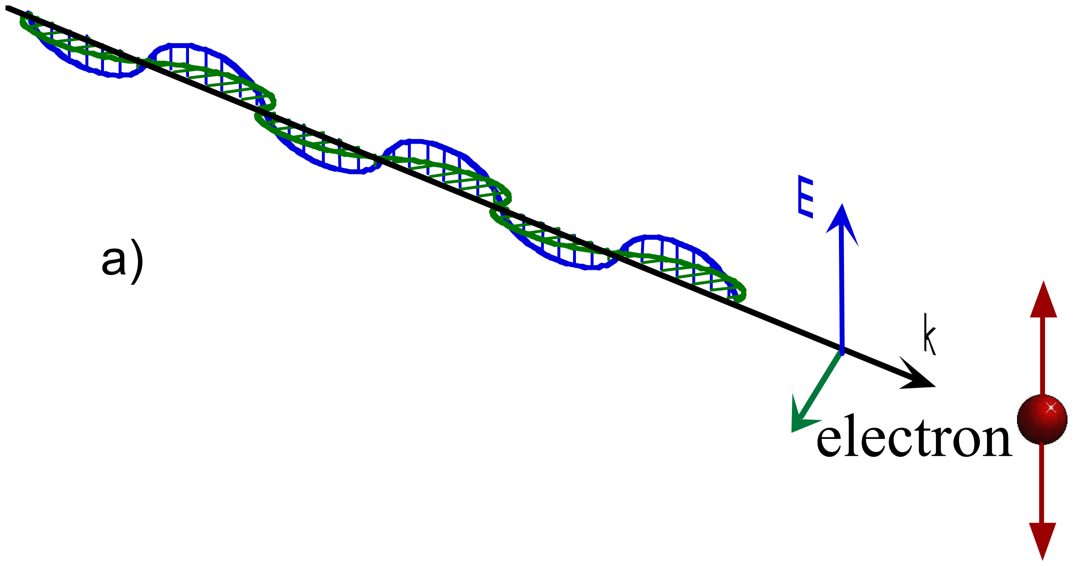




$$f_p = -\frac{e^2}{4m_e\omega_L^2}\nabla(\boldsymbol{E}\cdot\boldsymbol{E}^*). \qquad f_p = -\frac{c^2}{\gamma}\left[\nabla m_{\text{eff}} + \frac{\gamma-1}{v_0^2}\left(\boldsymbol{v}_0\cdot\nabla m_{\text{eff}}\right)\boldsymbol{v}_0\right] \qquad m_{\text{eff}} = \left(1+\frac{e^2\boldsymbol{A}\cdot\boldsymbol{A}^*}{2m_e^2c^2}\right)^{1/2} = \bar{\gamma},$$

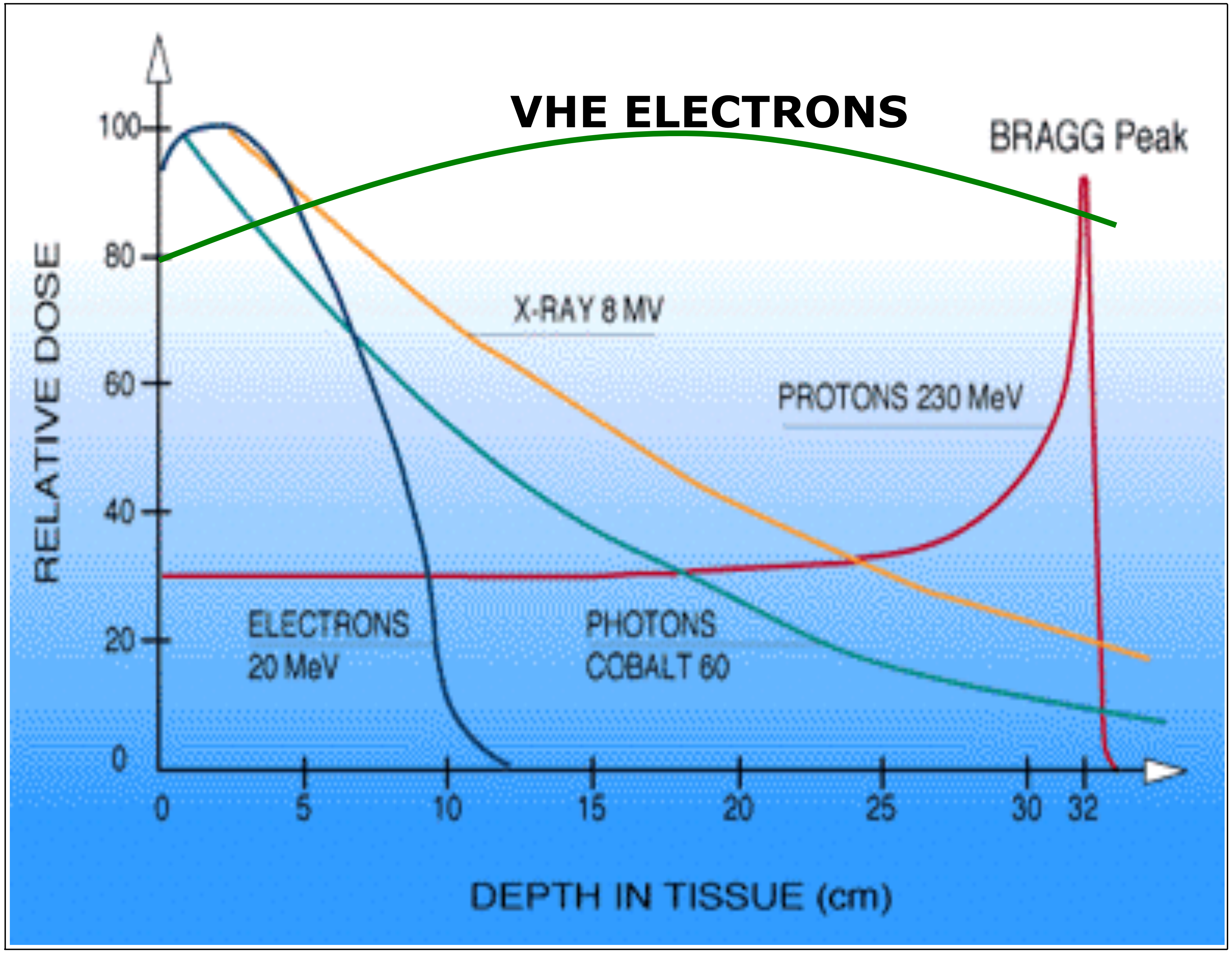
Relativistic Effects (e-m rectification)

classical Optics



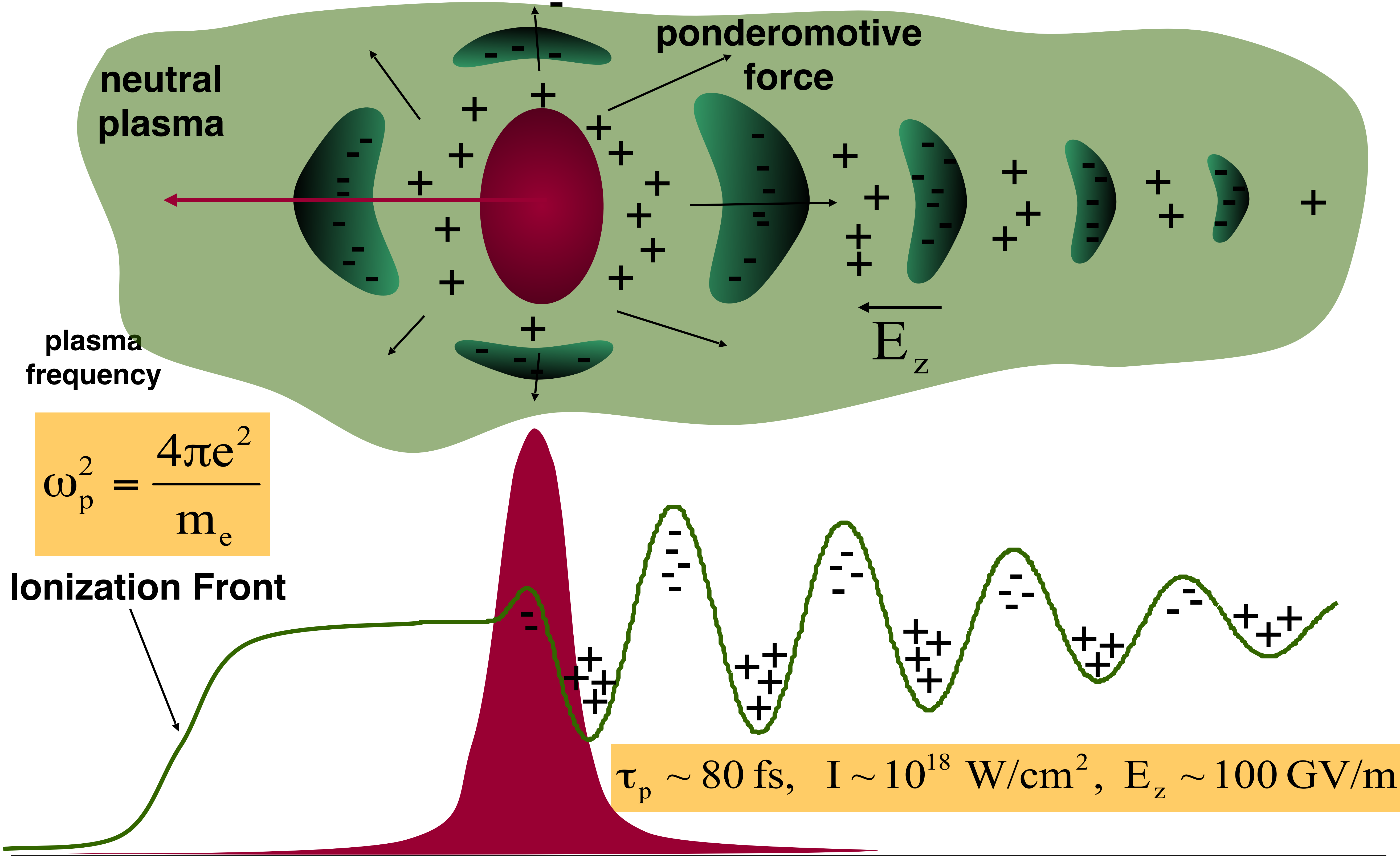
Ultra-Intense Lasers will push large amounts of electrons in FORWARD direction!

Dose deposition : Photon X, electrons VHE (very high energy) electrons, & ions



„Surfing“ on plasma waves – Wake Field Acceleration

Resonant Laser Wakefield Generation:

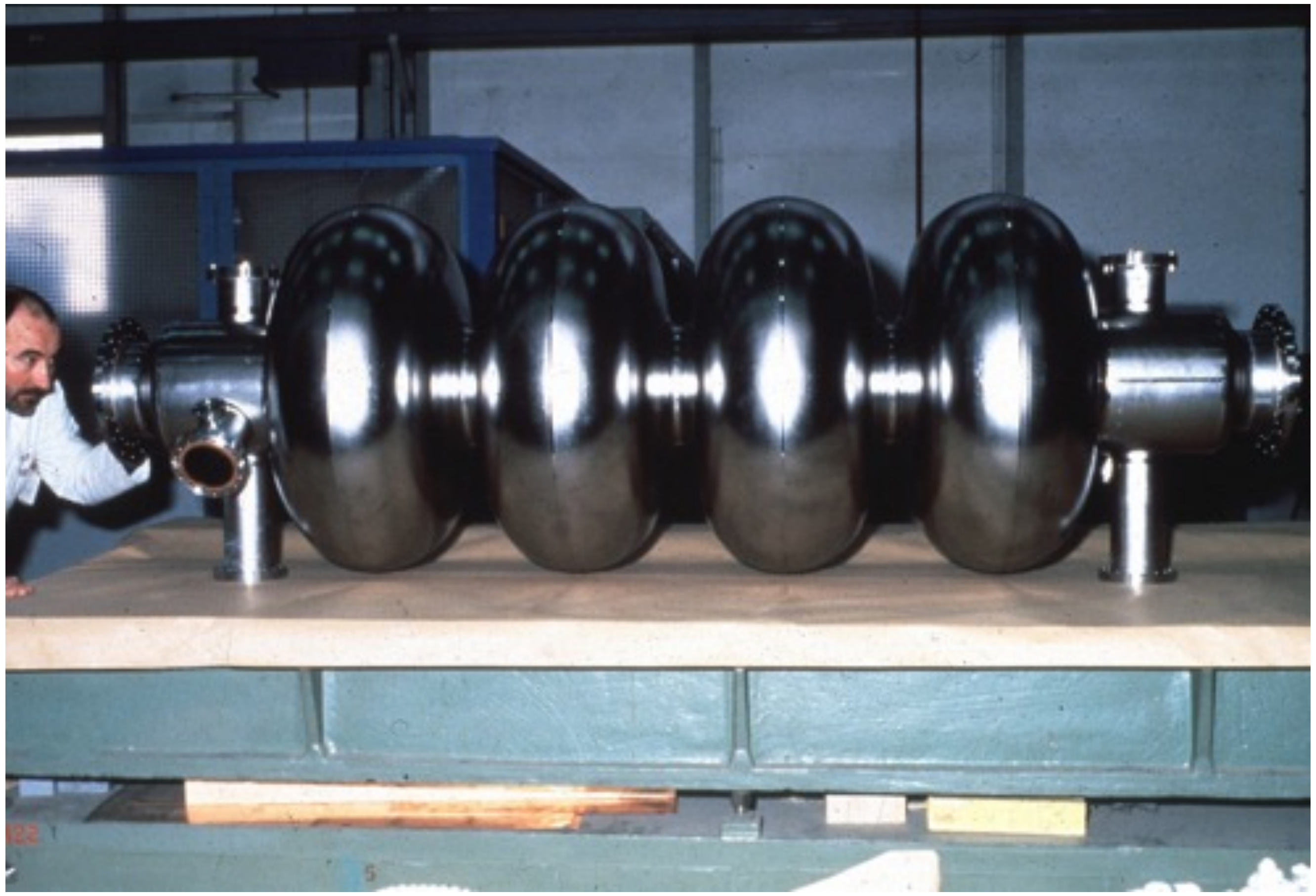


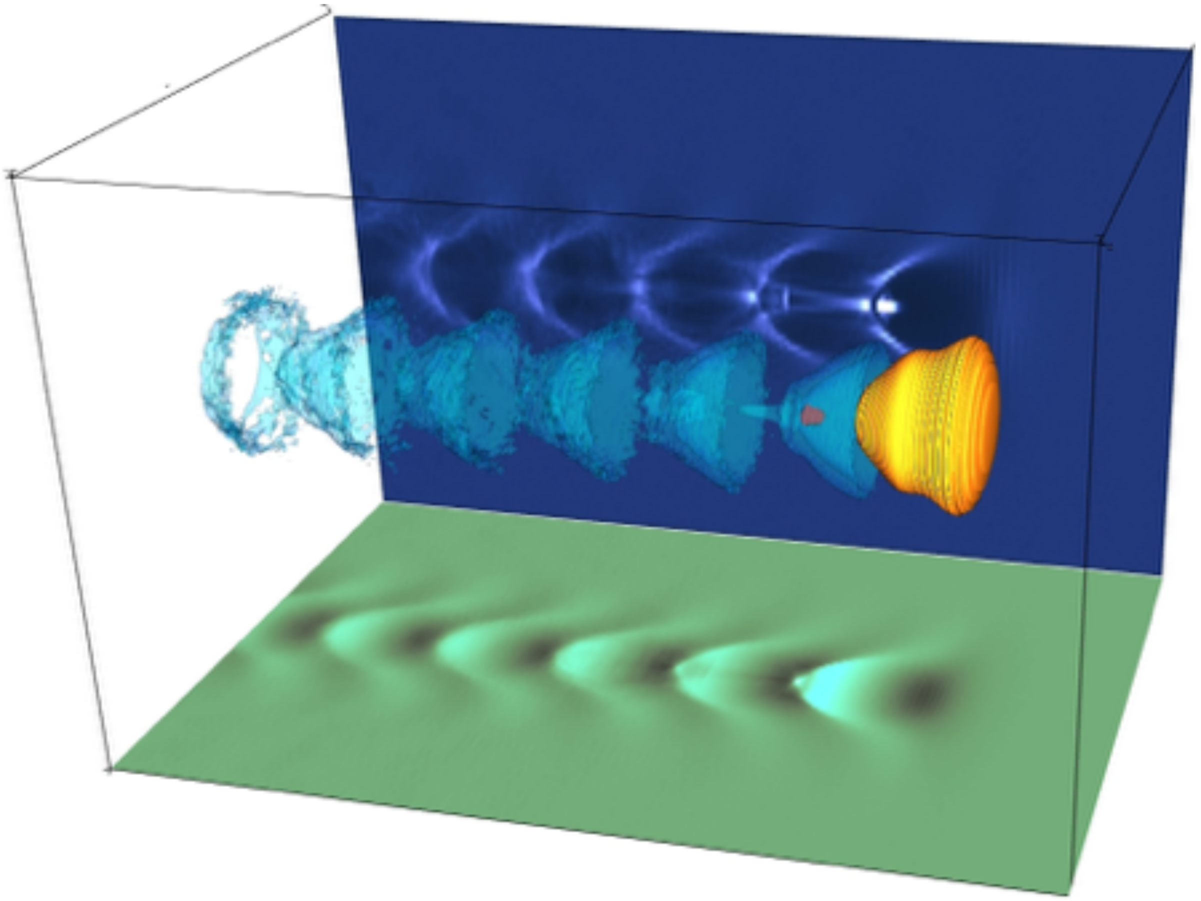
$$\omega_p^2 = \frac{4\pi e^2}{m_e}$$

$$\tau_p \sim 80\text{ fs},\quad I \sim 10^{18}\text{ W/cm}^2,\quad E_z \sim 100\text{ GV/m}$$

Efficient acceleration in plasmas = compact accelerator ?

RF cavity : 1 m **Plasma cavity : 1 mm**





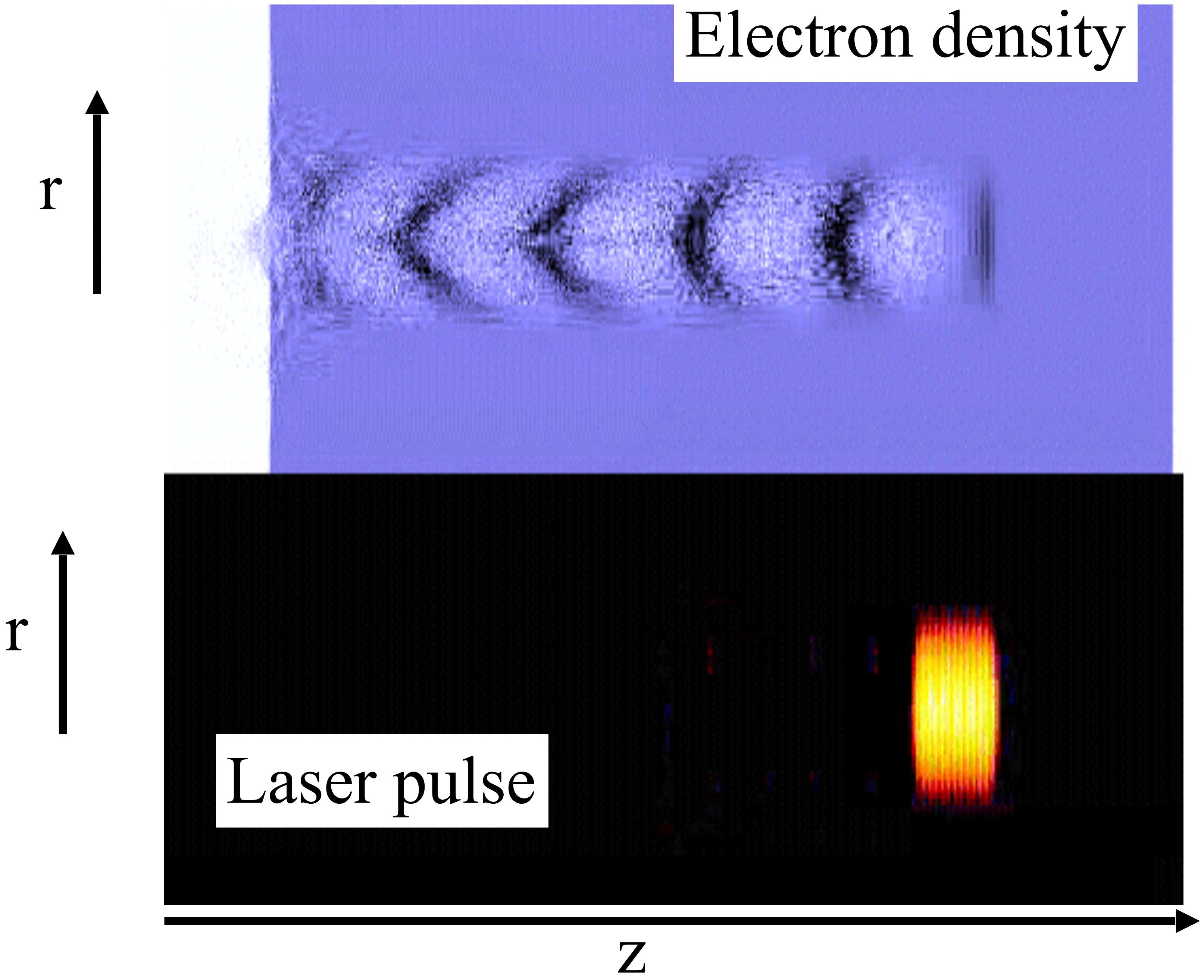
E = 10-100 MeV/m **E = 100-1000 GeV/m**

courtesy of **V. Malka *et al.*, Science 2002**

2D PIC Resonant LWFA Simulation

A. Pukov et al, MPI - Quantenoptic, Germany

$I=4 \times 10^{18}$ W/cm^2, $t=70$ fs, $ne=3 \times 10^{17}$ cm^{-3}



Limits of the electron acceleration

For the optimum plasma condition, $\lambda_p = \pi\sigma_z$

Diffraction limitation:

$$L_{diff} = \pi Z_R = \frac{\pi^2 r_0^2}{\lambda_0}$$

$$\Delta W_{dif}[\mathrm{GeV}] \cong 0.85 P[\mathrm{TW}]\lambda_0[\mu\mathrm{m}]/(\gamma_0 \tau_L[\mathrm{fs}])$$

Dephasing limitation:

$$L_d[\mathrm{cm}] = 0.18 \times 10^{-4} \tau_L^3[fs]\gamma_0/\lambda_0^2[\mu\mathrm{m}]$$

$$\Delta W_d[\mathrm{GeV}] \cong 0.01 P[\mathrm{TW}]\tau_L^2[\mathrm{fs}]/r_0^2[\mu\mathrm{m}]$$

Pump depletion:

$$L_{pd}[\mathrm{cm}] = 1.06 \times 10^{-6} \tau_L^3[\mathrm{fs}] r_0^2[\mu\mathrm{m}]\gamma_0^3/(\lambda_0^4[\mu\mathrm{m}] P[\mathrm{TW}])$$

$$\Delta W_{pd}[\mathrm{GeV}] = 0.91 \times 10^{-3} \tau_L^2[\mathrm{fs}]\gamma_0^2/\lambda_0^2[\mu\mathrm{m}]$$

e.g.

$\lambda_0 = 0.8\mu\mathrm{m}$,

$P = 2\mathrm{TW}$,

$\tau = 100\mathrm{fs}$,

$r_0 = 10\,\mu\mathrm{m}$

$Z_R \cong 0.4\mathrm{mm}$

$a_0 = 0.77\ (\gamma_0 = 1.14)$

$n_0 \cong 3.5 \times 10^{17}\,\mathrm{cm}^{-3}$

$\lambda_p \cong 60\mu\mathrm{m}$

Diffraction limit:

$L_{diff} \cong 1.2\mathrm{mm}$

$\Delta W_{dif} \cong 12\ \mathrm{MeV}$

Dephasing limit:

$L_d \cong 32\mathrm{cm}$

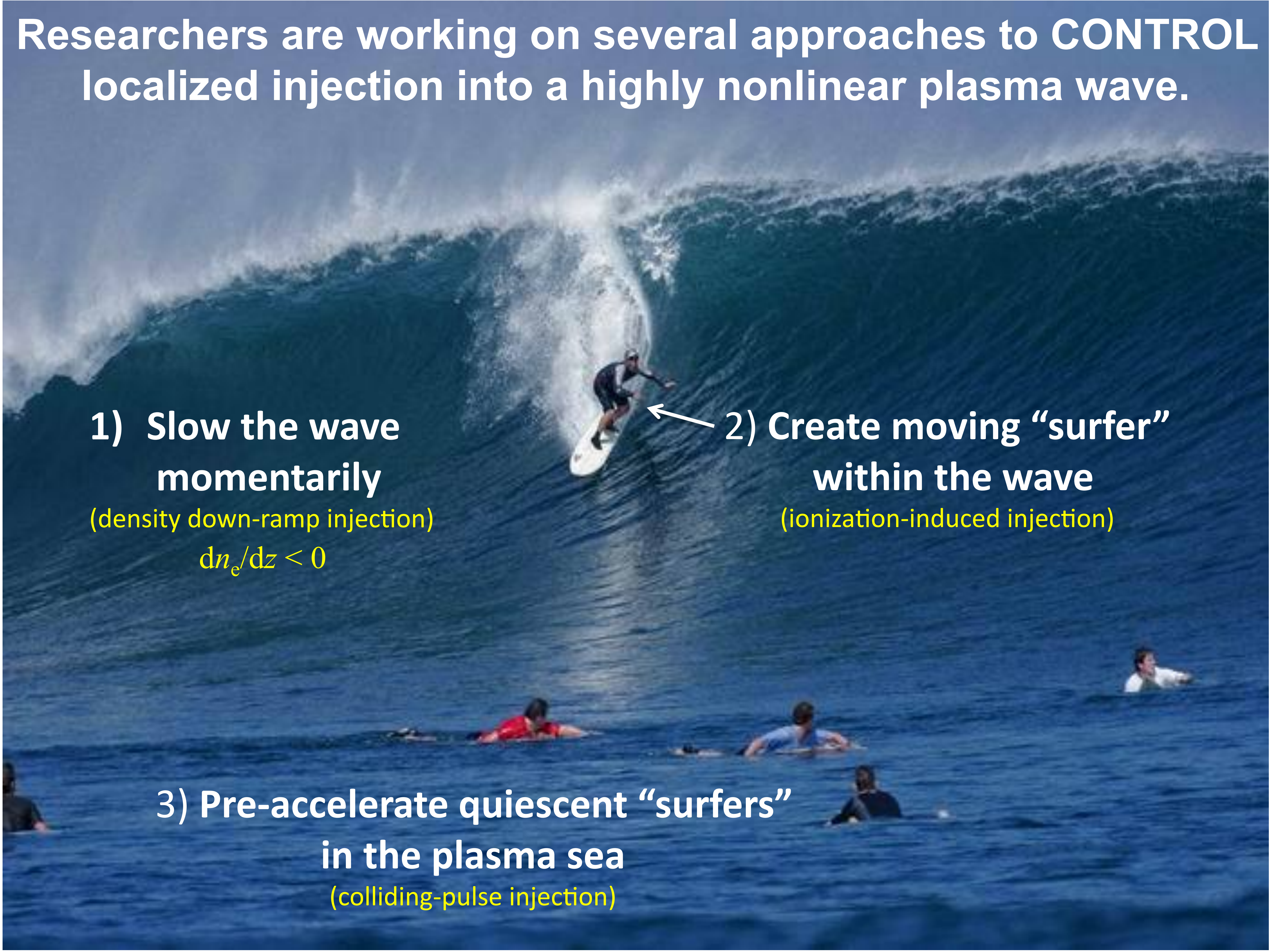
$\Delta W_d \cong 2\ \mathrm{GeV}$

Pump depletion limit:

$L_{pd} \cong 192\mathrm{cm}$

$\Delta W_{pd} \cong 18.5\ \mathrm{GeV}$

Researchers are working on several approaches to CONTROL localized injection into a highly nonlinear plasma wave.



1) **Slow the wave momentarily**

(density down-ramp injection)

$\mathrm{d}n_e/\mathrm{d}z < 0$

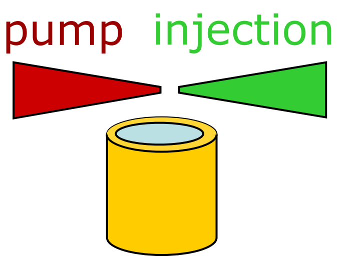
2) **Create moving “surfer” within the wave**

(ionization-induced injection)

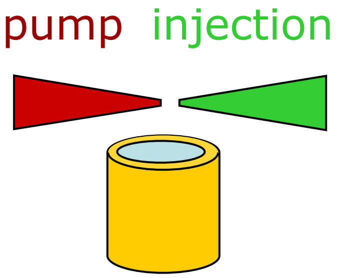
3) **Pre-accelerate quiescent “surfers” in the plasma sea**

(colliding-pulse injection)

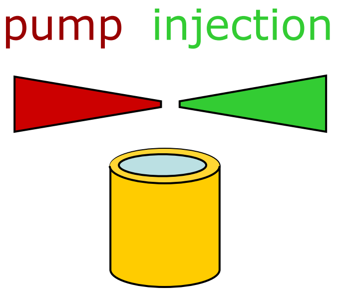
Use of a two laser scheme:
Mono energetic e-beam :1% energy spread



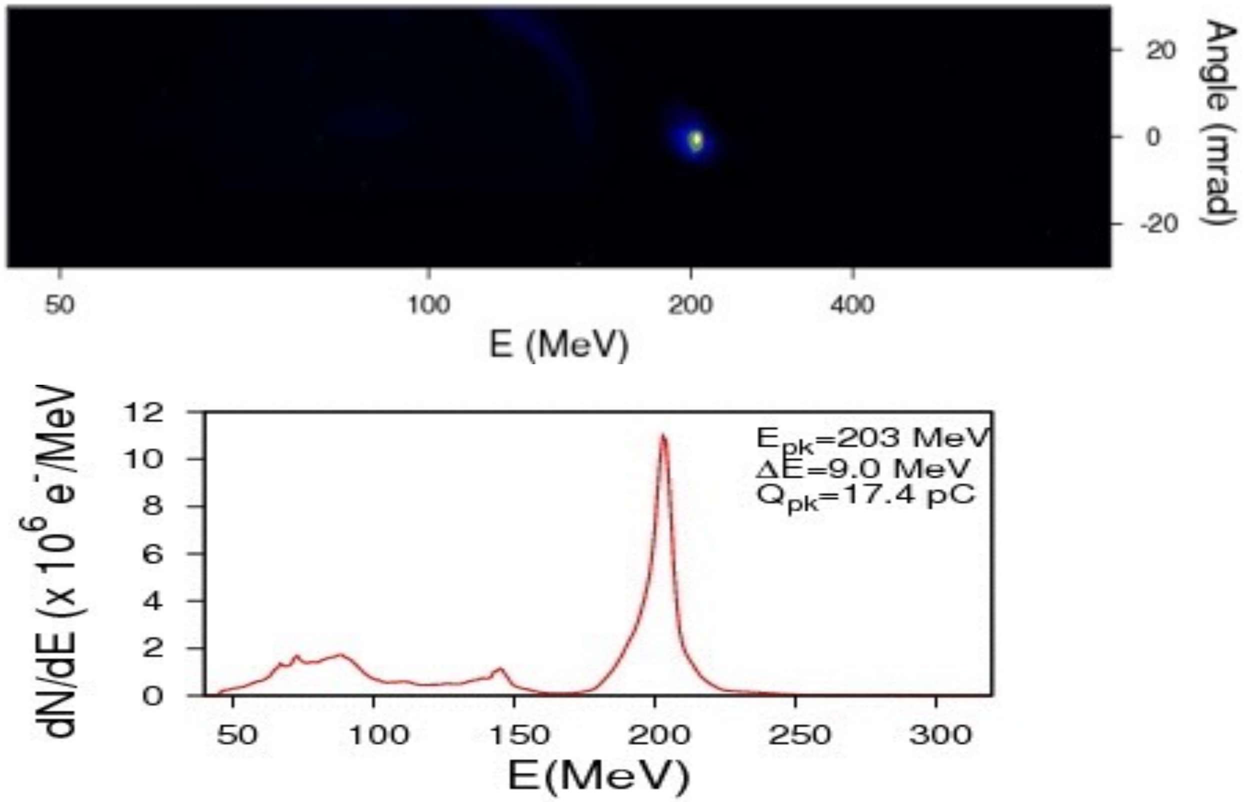
Late Injection

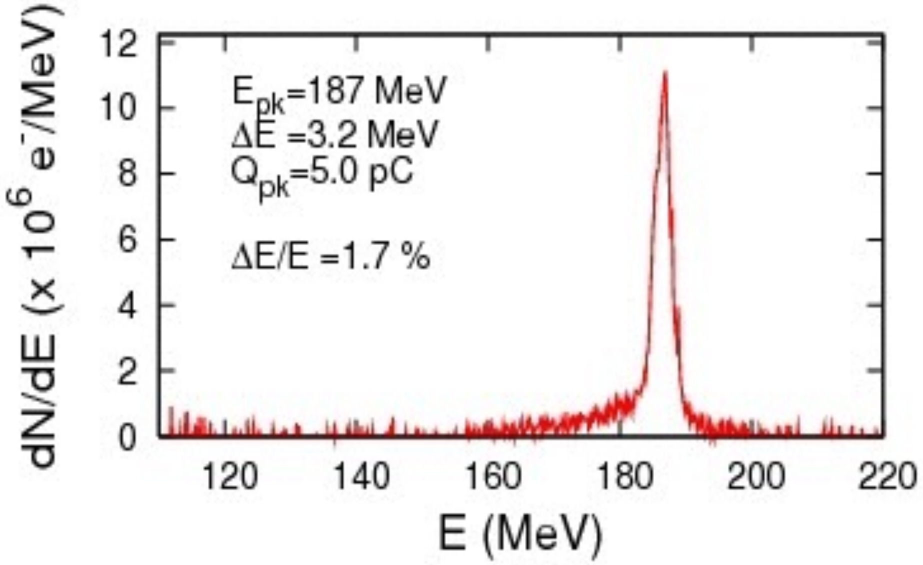


Injection at center



Early Injection





J. Faure et al., Nature 2006

Courtesy of Victor Malka

Application to radiotherapy: Improvement of some cancer treatments

TECHNISCHE
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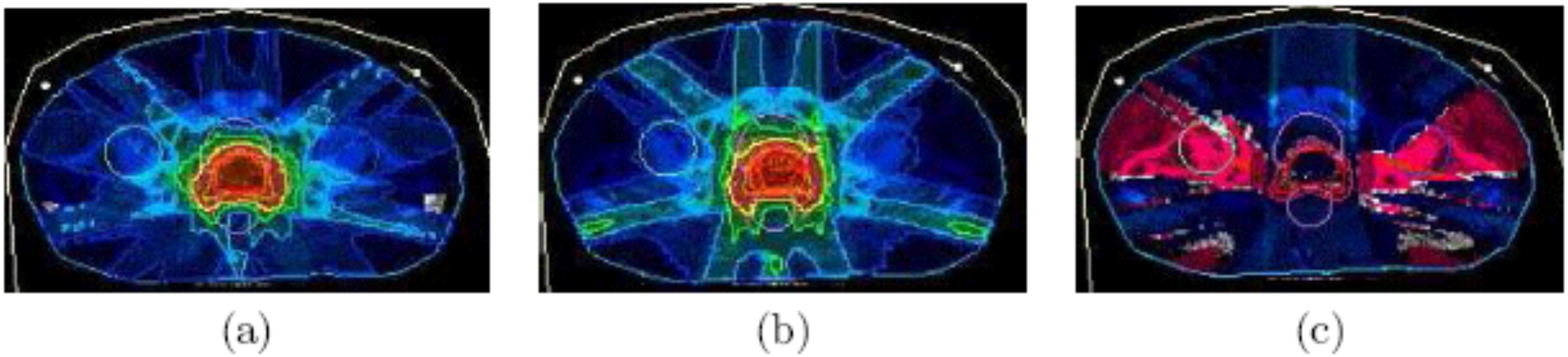
DARMSTADT

A typical transversal dose distribution with 7 beams.

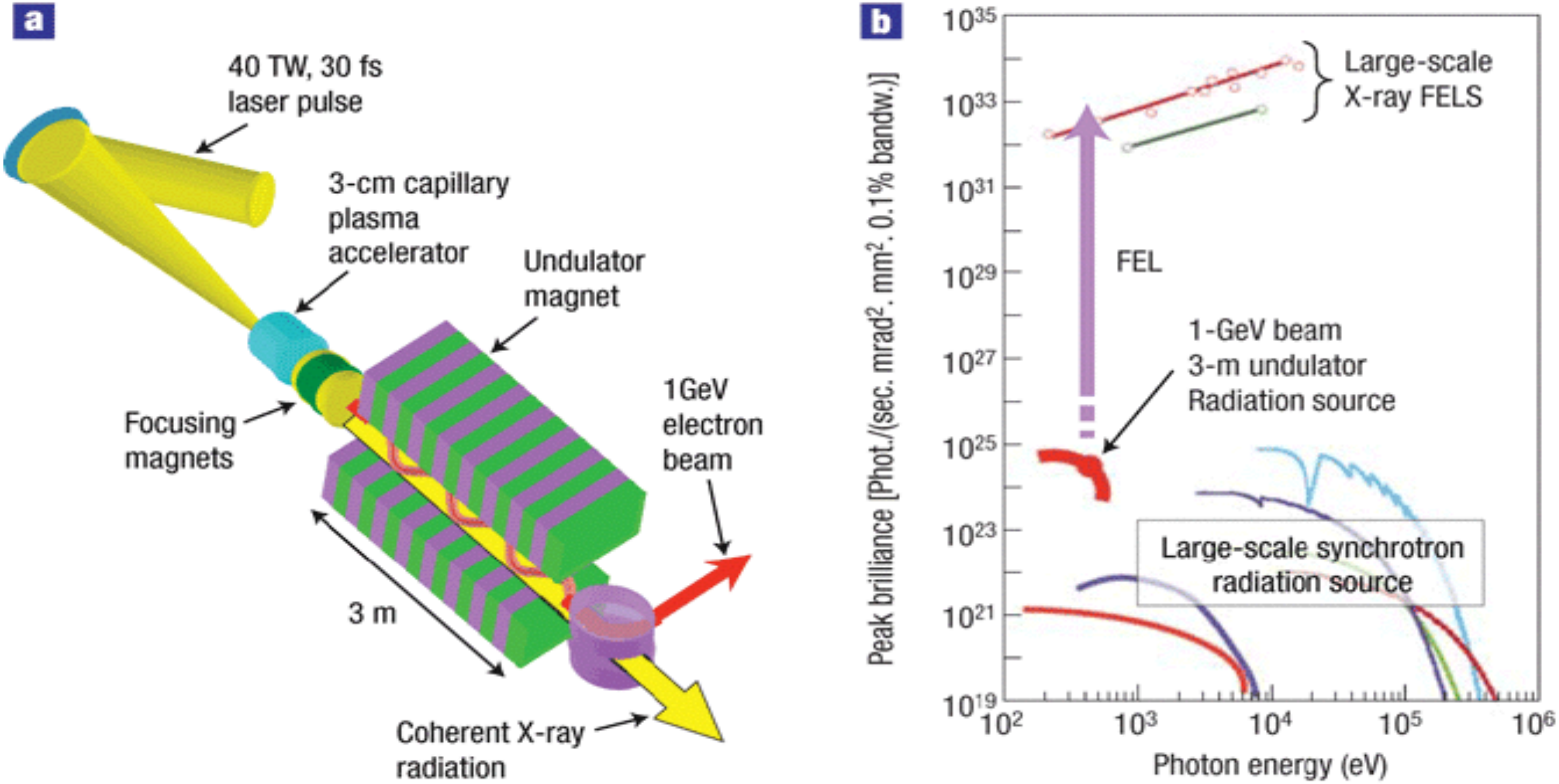

(a) (b) (c)

Electrons **Photons X** **Différence**

A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved **up to 19%.**

Use of secondary radiation

Cc



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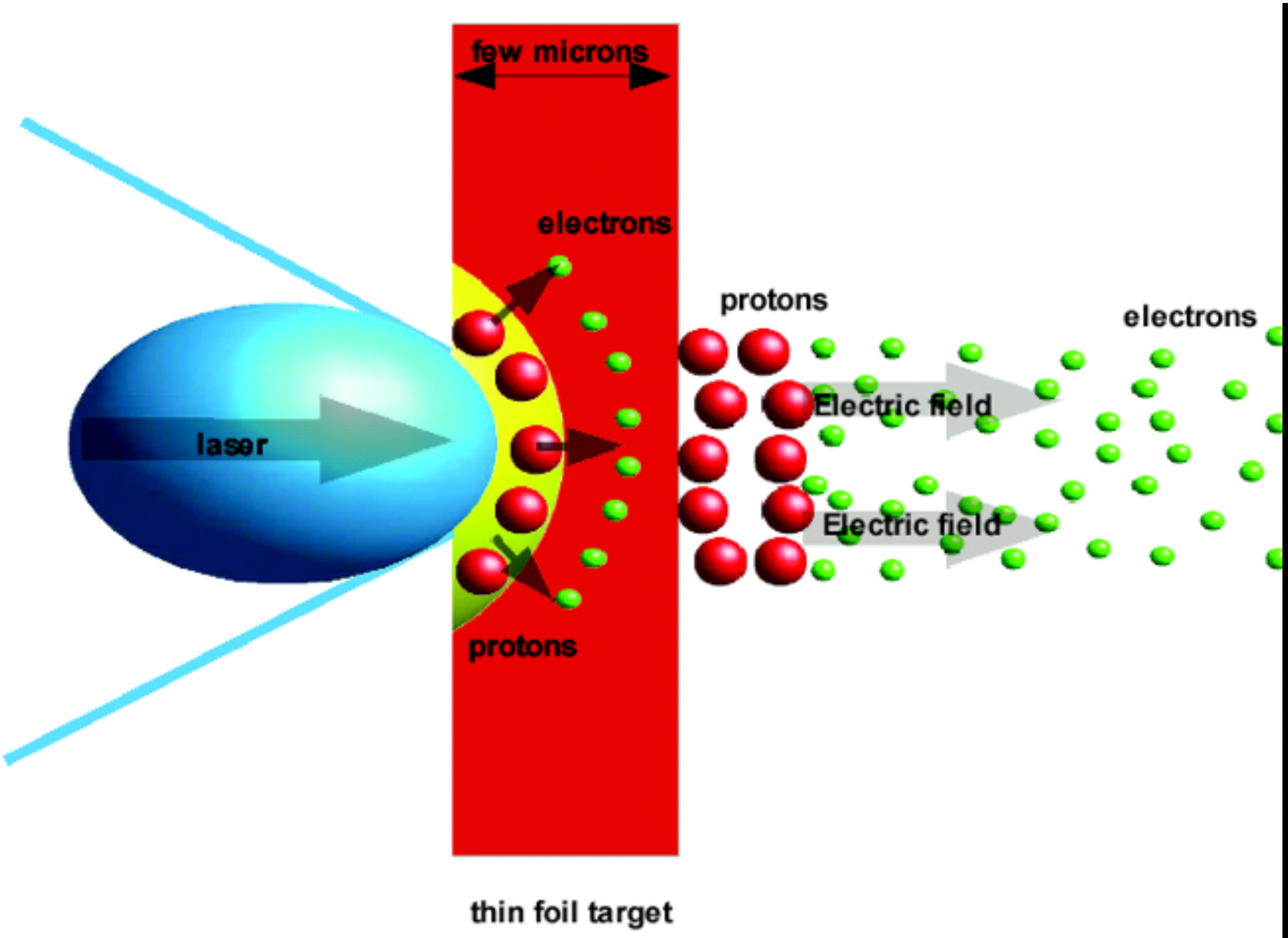
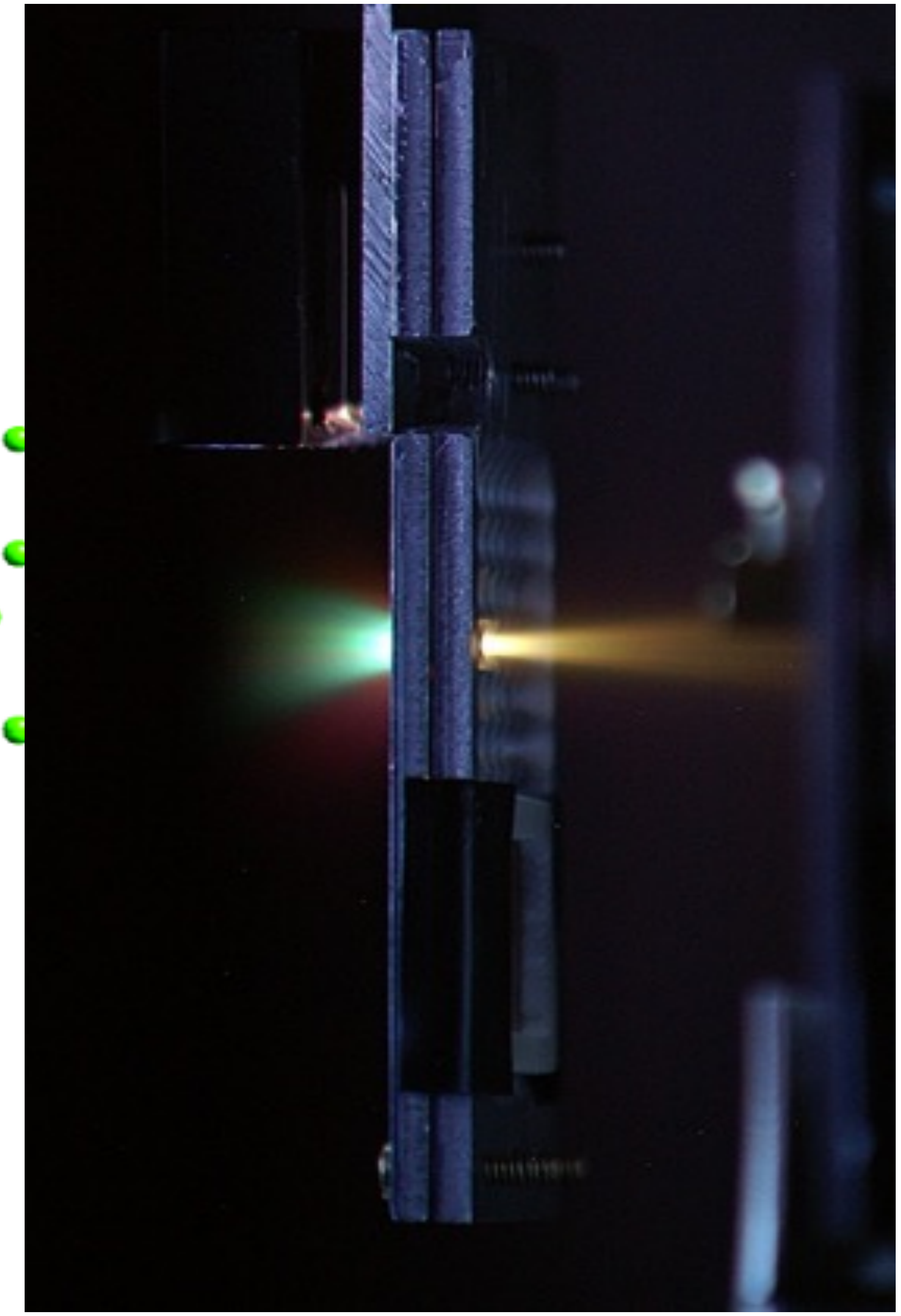
***Kazuhisa Nakajima* ,*Nature Physics* 4**, 92 - 93 (20

C. B. Schroeder, W. M. Fawley, E. Esarey, W. P. Leemans
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Proton acceleration with lasers : Static electric fields





Requirements for ion acceleration

The requirements strongly depend on the application: a few examples

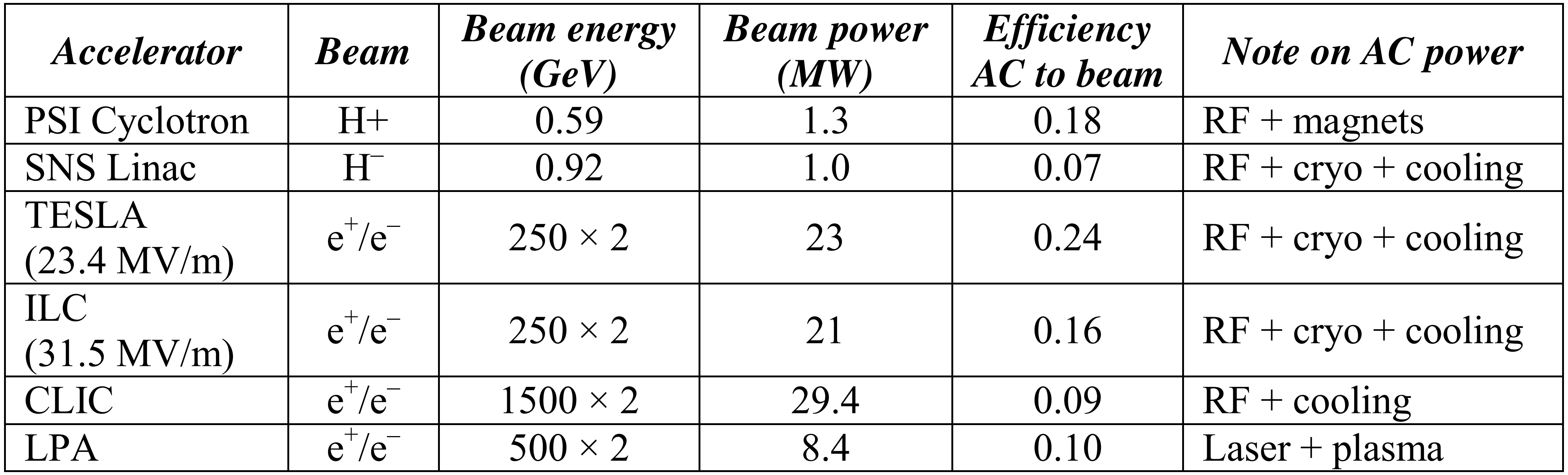
- Ion source as a new injector:
  - Rep rate matched to conventional accelerator structures (e.g. 50 Hz)
  - Ion energy a few tens of MeV
  - Radial beam shaping for divergence optimization
  - Ion species selectable
  - Energy matched to particle number acceptable to acc structure
- Medical Application:
  - Ion energy >250 MeV for protons and >400 MeV/u for e.g. Carbon (prob. no TNSA)
  - High contrast
  - Rep rate 10 to 30 Hz
  - Energy stability better 3%
  - Relatively low particle numbers required (10^{11} or 10^{9} per patient)
  - Uniform ion beam --> Laser beam shaping

General remark

- For most applications high particle numbers are required
- Energy conservation asks for laser energy, not only intensity
- High contrast is key as most applications cannot rely on TNSA
- Wall plug efficiency becomes important

ICFA/ICUIL Meeting

Table 1: Comparison of wall-plug efficiency of various accelerators.



Accelerator	*Beam*	*Beam energy (GeV)*	*Beam power (MW)*	*Efficiency AC to beam*	*Note on AC power*
PSI Cyclotron	H+	0.59	1.3	0.18	RF + magnets
SNS Linac	H^-	0.92	1.0	0.07	RF + cryo + cooling
TESLA (23.4 MV/m)	e^+/e^-	250 × 2	23	0.24	RF + cryo + cooling
ILC (31.5 MV/m)	e^+/e^-	250 × 2	21	0.16	RF + cryo + cooling
CLIC	e^+/e^-	1500 × 2	29.4	0.09	RF + cooling
LPA	e^+/e^-	500 × 2	8.4	0.10	Laser + plasma

Example: Medical:

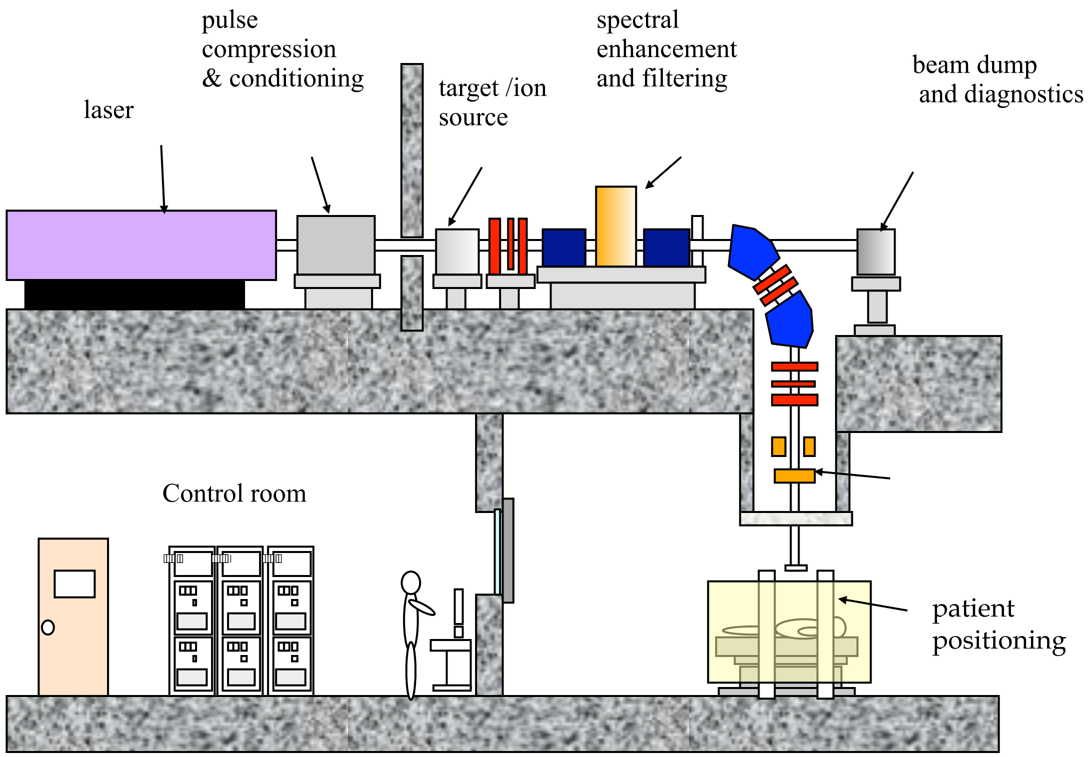
	Experiments	Status	Theory	Relevance to Therapy
TNSA	> 1999	$>10^{13}$ ions, robust, reproducible	Analytical + 2D/3D simulations	+
TNSA/BOA (Break-out-afterburner)	> 2011	experimental evidence	2 D / 3D simulations	++(+)
RPA	>2008	experimental evidence not conclusive	2 D / 3D simulations >GeV	++
Coulomb explosion	-	-	2 D simulation	+
Gas Jet - RPA	> 2009	2 MeV observed	2D	++

Direct Treatment
Particle Selection and Beam Collimation

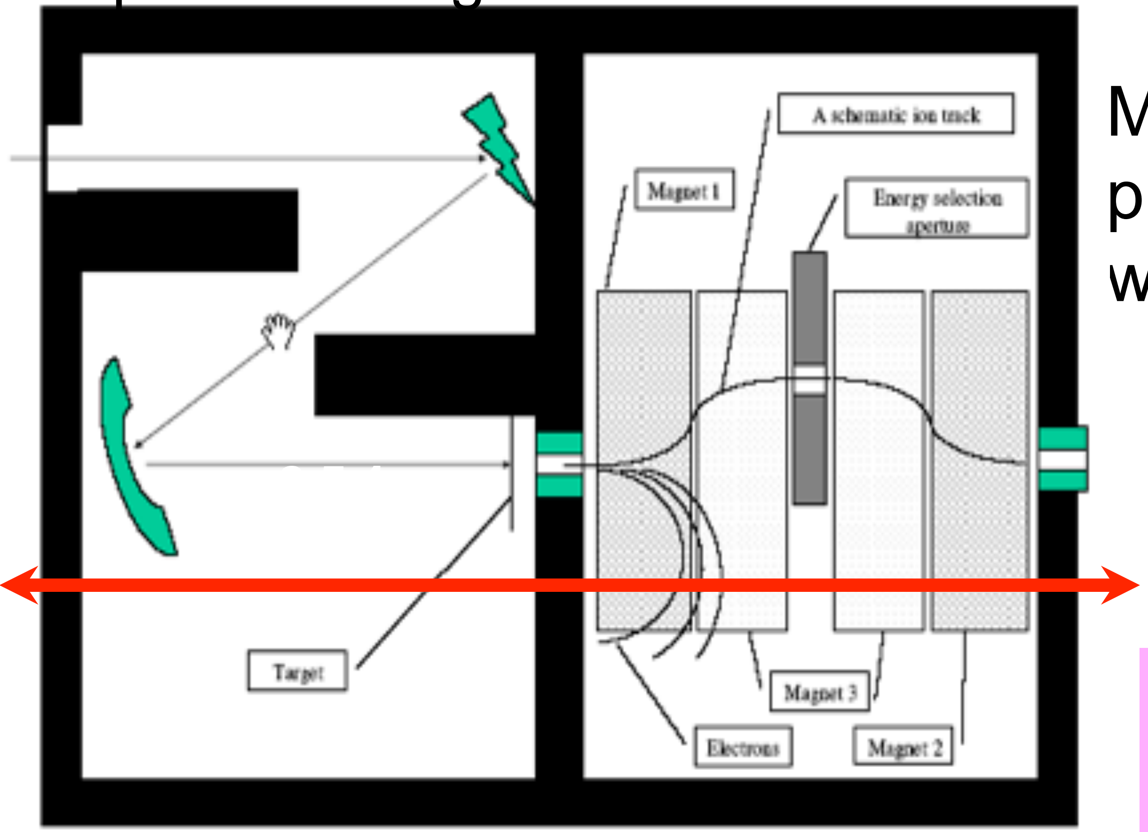
The Idea of direct laser treatment:

Laser must deliver 250 MeV Protons
(400 MeV/u Carbon)

Non- Maxwellian Distribution
Shielding Essential (gamma's, Neutrons)
(Might require 10's of PW Laser Power
@ high rep rate)



Spot Scanning???

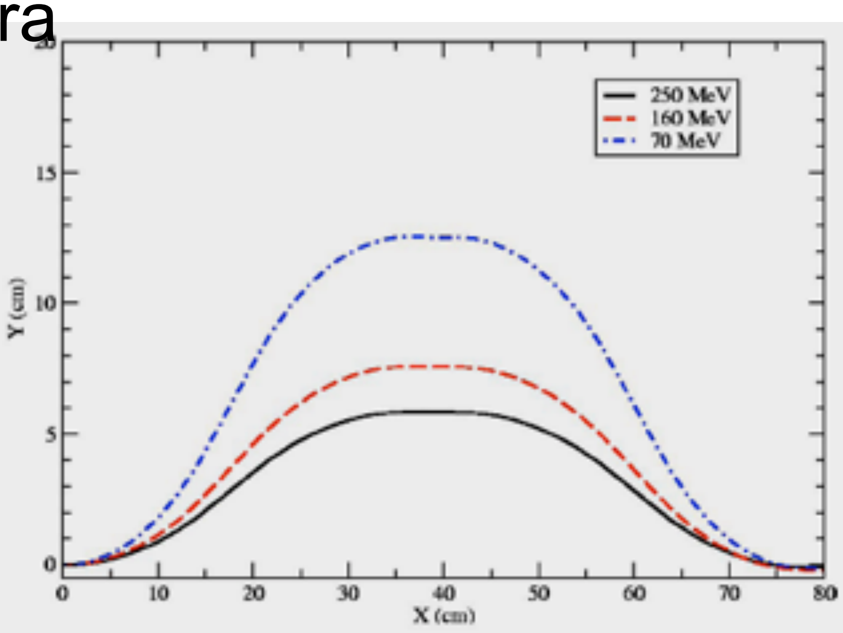


Movable aperture to select protons of desired energy with sharp beam penumbra

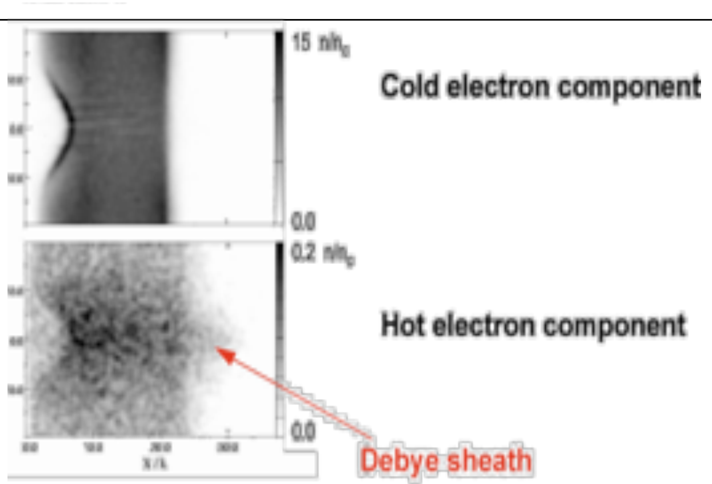
Nb_3Ti superconducting coils can provide I = 85 A per loop with magnetic field to 4.4 Tesla by Biot-Savart law:

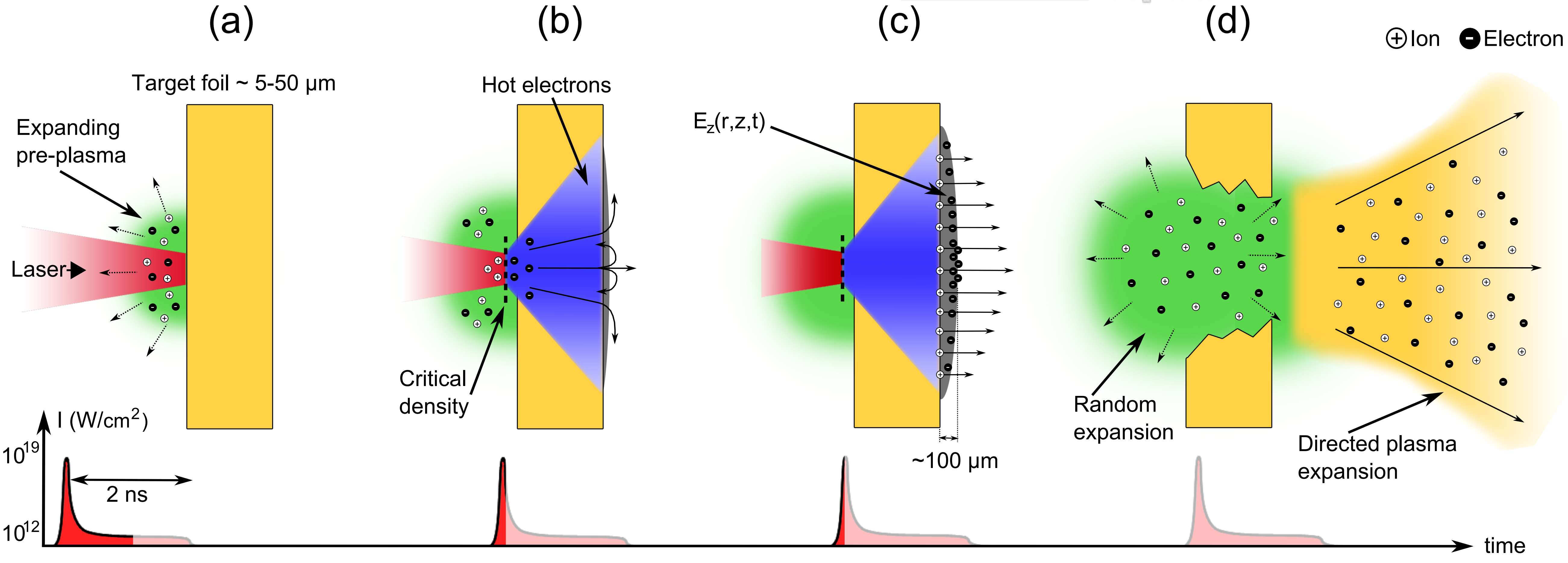
$$B = \oint \frac{\mu_0 I dl \times r}{4\pi r^3} = \sum_i^4 \int \frac{\mu_0 I dl \times r_i}{4\pi r_i^3}$$

C. Ma
(Fox Chase Cancer Center)



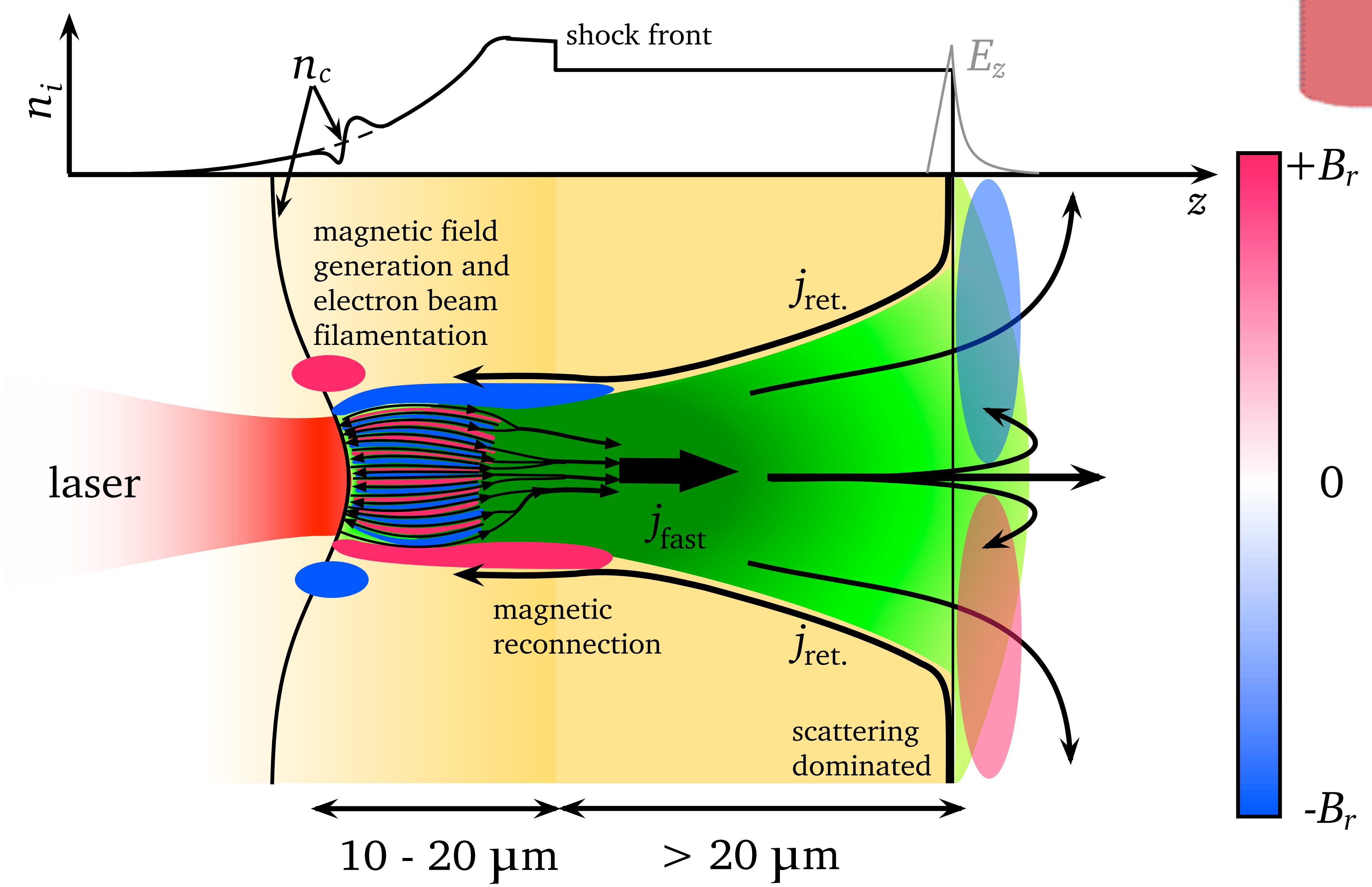
Overview

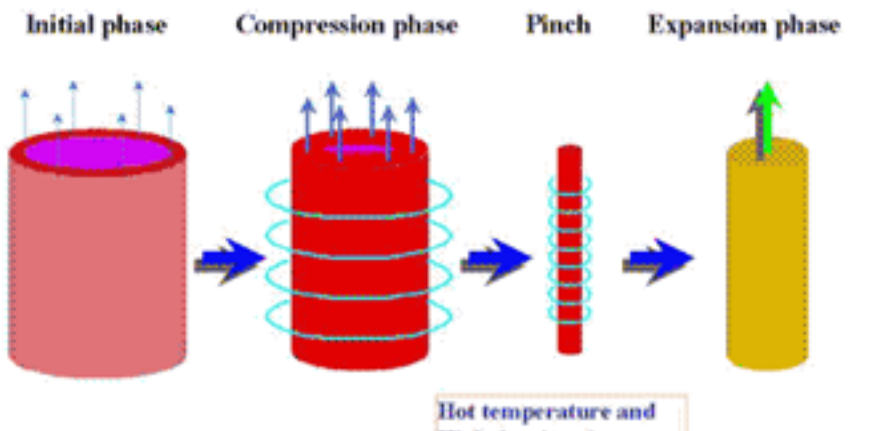

15 n/n_c
Cold electron component
0.0
0.2 n/n_c
Hot electron component
0.0
Debye sheath


(a)
(b)
(c)
(d)
⊕ Ion
● Electron
Target foil ~ 5-50 µm
Expanding pre-plasma
Laser
Hot electrons
Critical density
E_z(r,z,t)
~100 µm
Random expansion
Directed plasma expansion
I (W/cm²)
10^19
10^12
2 ns
time

Electron driver III

$$I_{\text{Alfvén}} \approx 17\,\beta\gamma\;\text{kA}$$





Hot temperature and High density plasma

Super-cooled plasma by rapid expansion

TNSA

- Electrons escape into vacuum at the rear side
- Charge separation: Potential $$\varepsilon_0 \frac{\partial^2 \Phi}{\partial z^2} = e n_e .$$
- if one half space perfectly compensates the potential (target) and for z →∞ it goes to infinity the field can be obtained analytically

$$n_e = n_{e,0} \exp\left(\frac{e\Phi}{k_B T_{hot}}\right) \qquad \text{Ansatz } e\Phi / k_B T_{hot} = 2\ln(\lambda z + 1)$$

the potential is $$\Phi(z) = -\frac{2k_B T_{hot}}{e} \ln\left(1 + \frac{z}{\sqrt{2}\lambda_D}\right)$$

- and the field $$E(z) = \frac{2k_B T_{hot}}{e} \frac{1}{z + \sqrt{2}\lambda_D} .$$

TNSA II

- if one takes the electron density and the spreading into account the Debye length is:

$$\lambda_D = \left(\frac{\varepsilon_0 k_B T_{hot}}{e^2 n_{e,0}}\right)^{1/2} \approx 1.37\mu m \frac{r_0 + d\tan\theta/2}{r_0} \frac{\sqrt{1+0.73 I_{18}\lambda^2} - 1}{I_{18}^{7/8}}$$

the Debye length: very short (0.6 µm in the example), depends on laser intensity and target thickness

$$E_{max}(z=0) = \frac{\sqrt{2}k_B T_{hot}}{e\lambda_D}$$

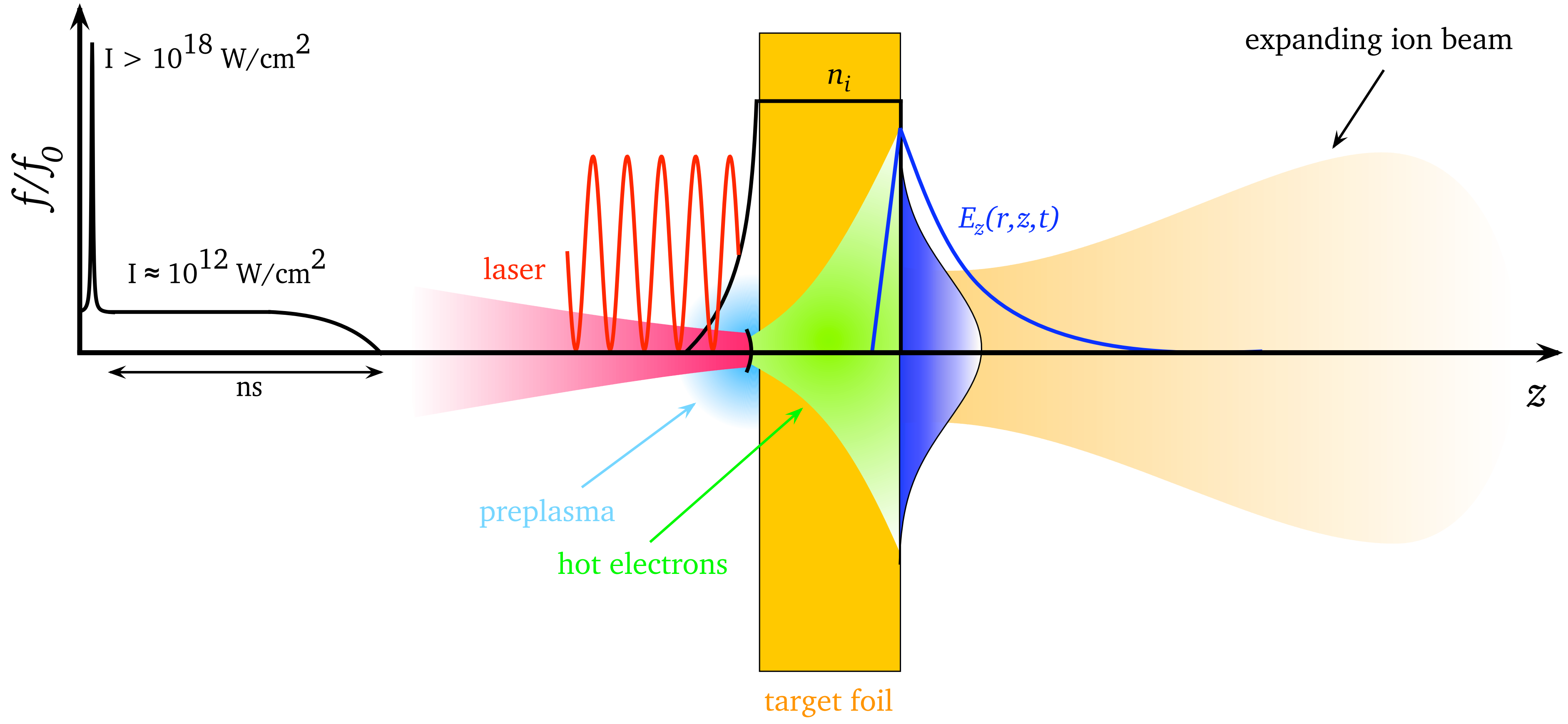
$$\approx 5.2 \times 10^{11} V/m \frac{r_0}{r_0 + d\tan\theta/2} I_{18}^{7/8}$$

$$= 9 \times 10^{10} V/m \frac{r_0}{r_0 + d\tan\theta/2} E_{12} E_{12}^{3/4}.$$

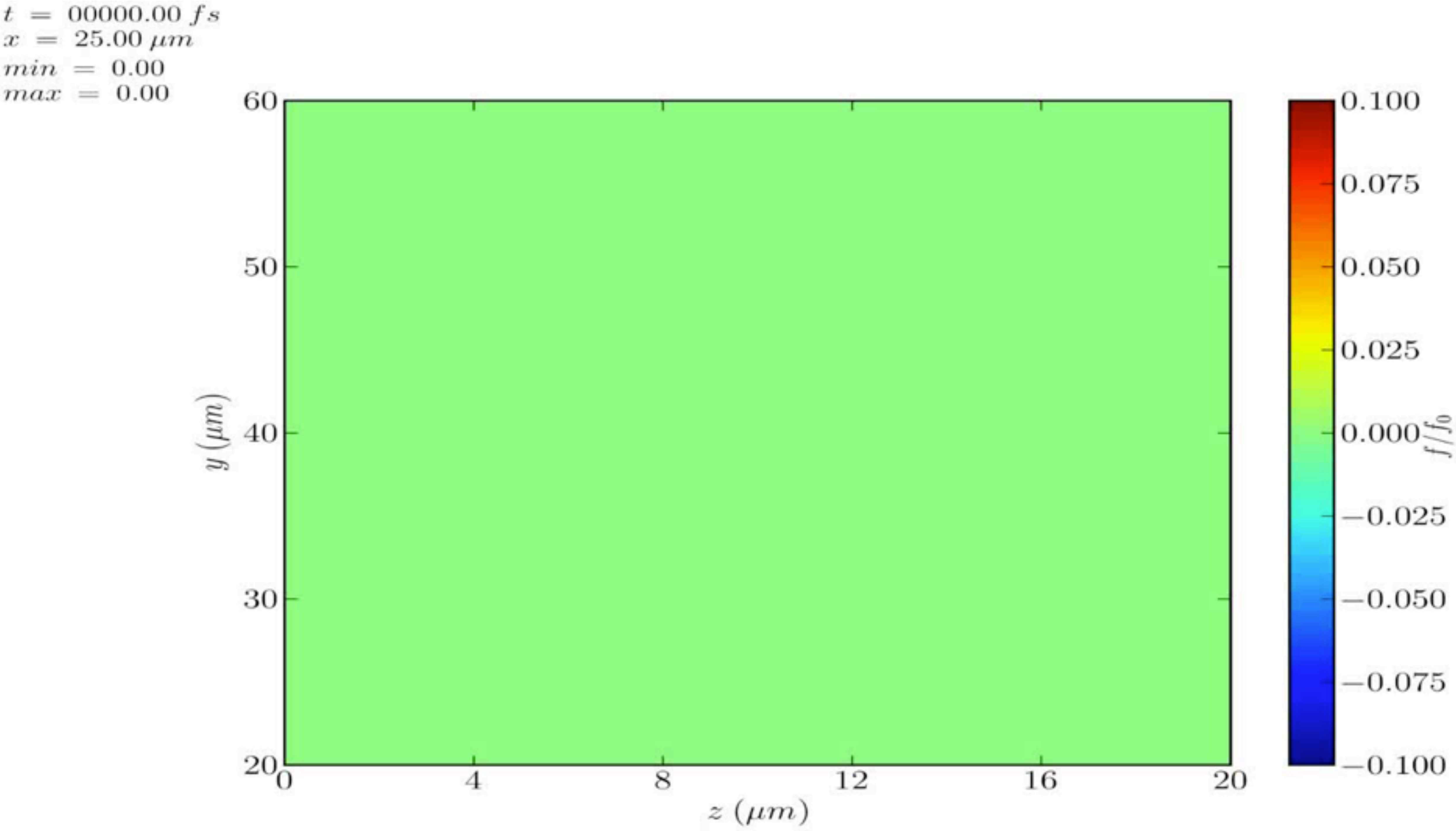
Field can easily exceed several 10^{12} V/m

Immediate field ionization of the atoms at the rear surface

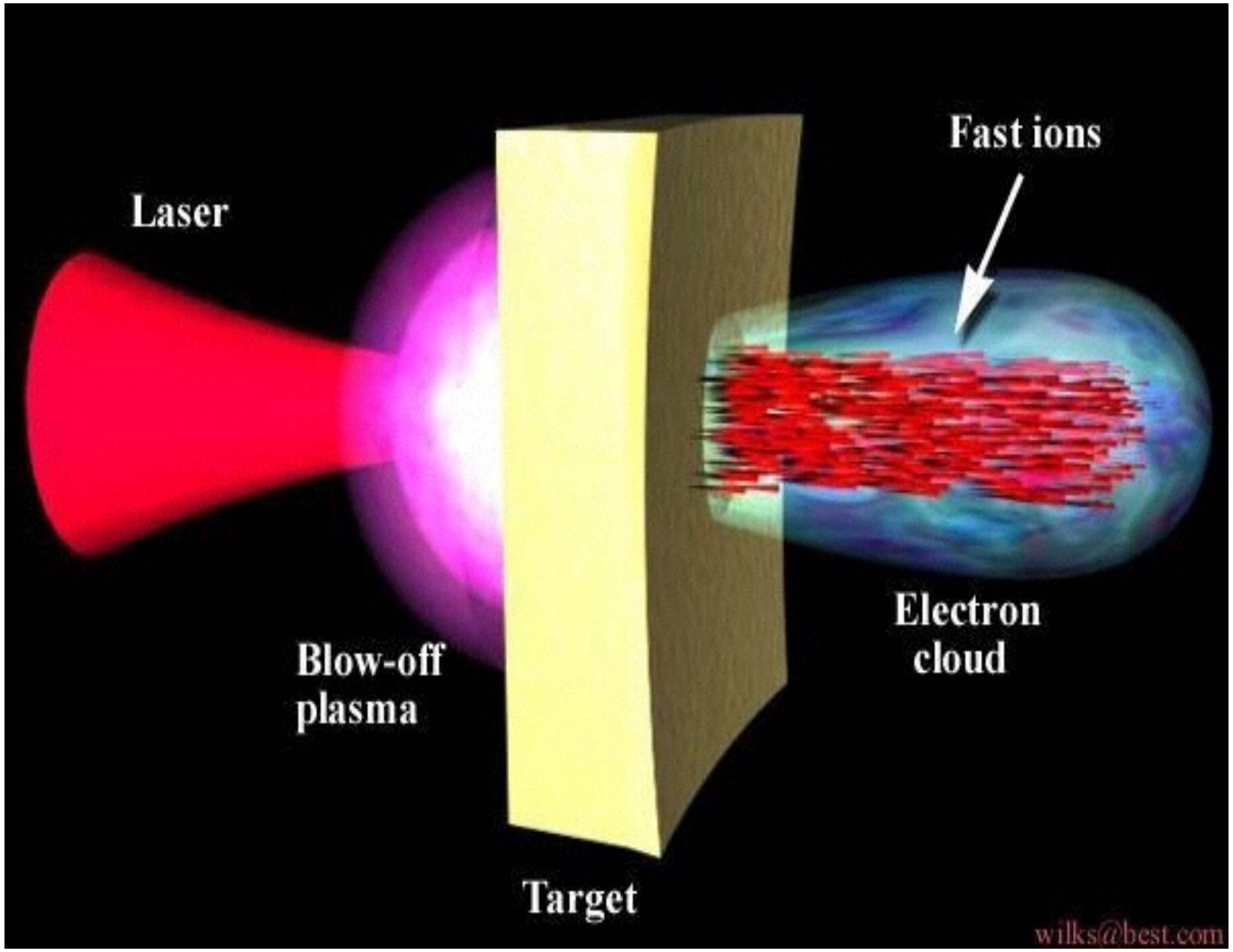
TNSA III


$I > 10^{18}$ W/cm^2
f/f_0
$I \approx 10^{12}$ W/cm^2
ns
laser
n_i
expanding ion beam
$E_z(r,z,t)$
z
preplasma
hot electrons
target foil

to summarize... a TNSA simulation



Ion Beam Properties



Number of Protons:
10^{14} (LLNL- Petawatt)

Pulse duration:
few Picoseconds

Maximum Energy:
60 MeV (LLNL Petawatt)

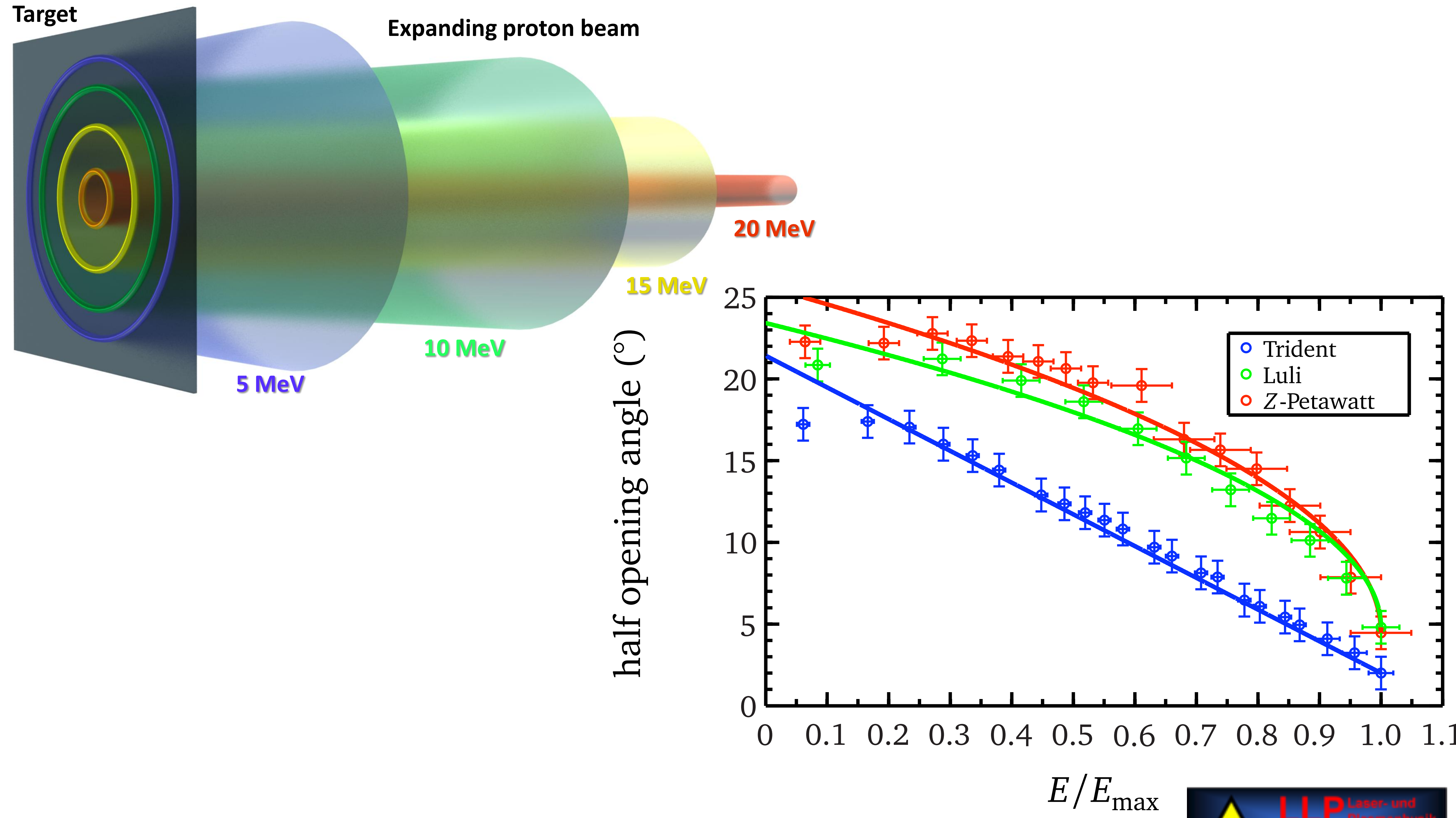
Divergency:
<10° for highest energies

Always normal to the rear

Origin of Protons: Surface Contaminants

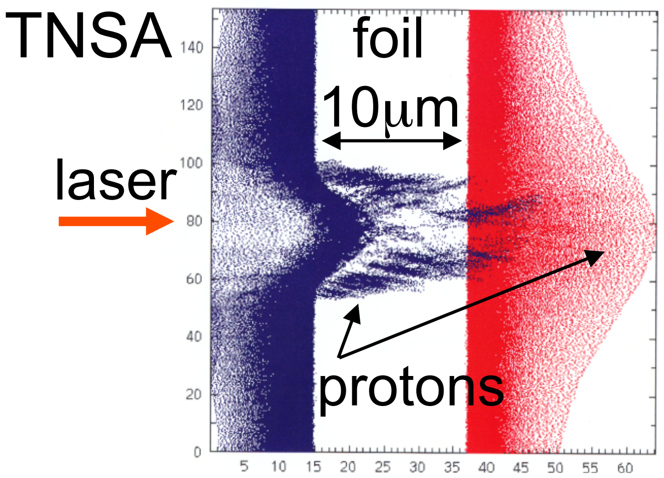
Petawatt experiments 3/99

Spatial Particle Distribution



Ion Acceleration Mechanisms

Ion acceleration mechanism	**Acronym**	**Ion Accel. process**
Target-Normal Sheath Acceleration S. Hatchett *et al.*, Phys. Plas. **7**, 2076 (2000)	TNSA	Charge separation GeV protons? X



TNSA vs. BOA

Accessible with moderate contrast lasers
Micrometer sized targets
Spectrum limited to 70 MeV
Surface acceleration

High contrast lasers needed
Sub-Micrometer sized targets
Ion energies exceeding 120 MeV/u
Volume acceleration
Heavy ions (deuterons) at same speed as protons
Lower EMP and less debris

High contrast Lasers (PHELIX)

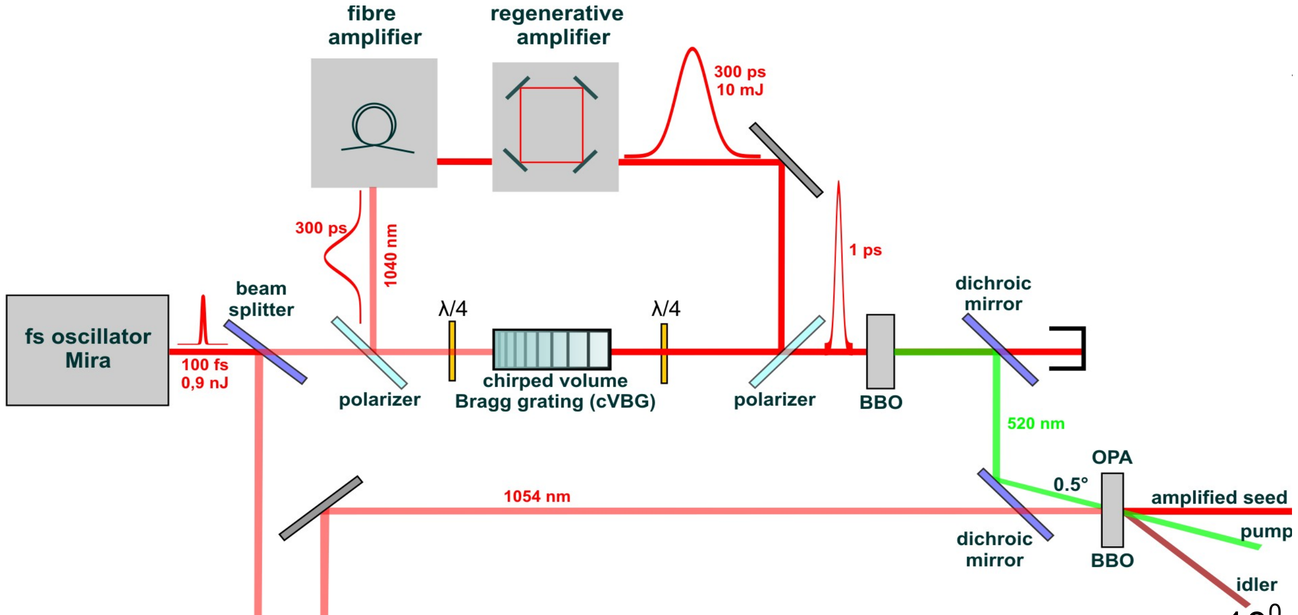
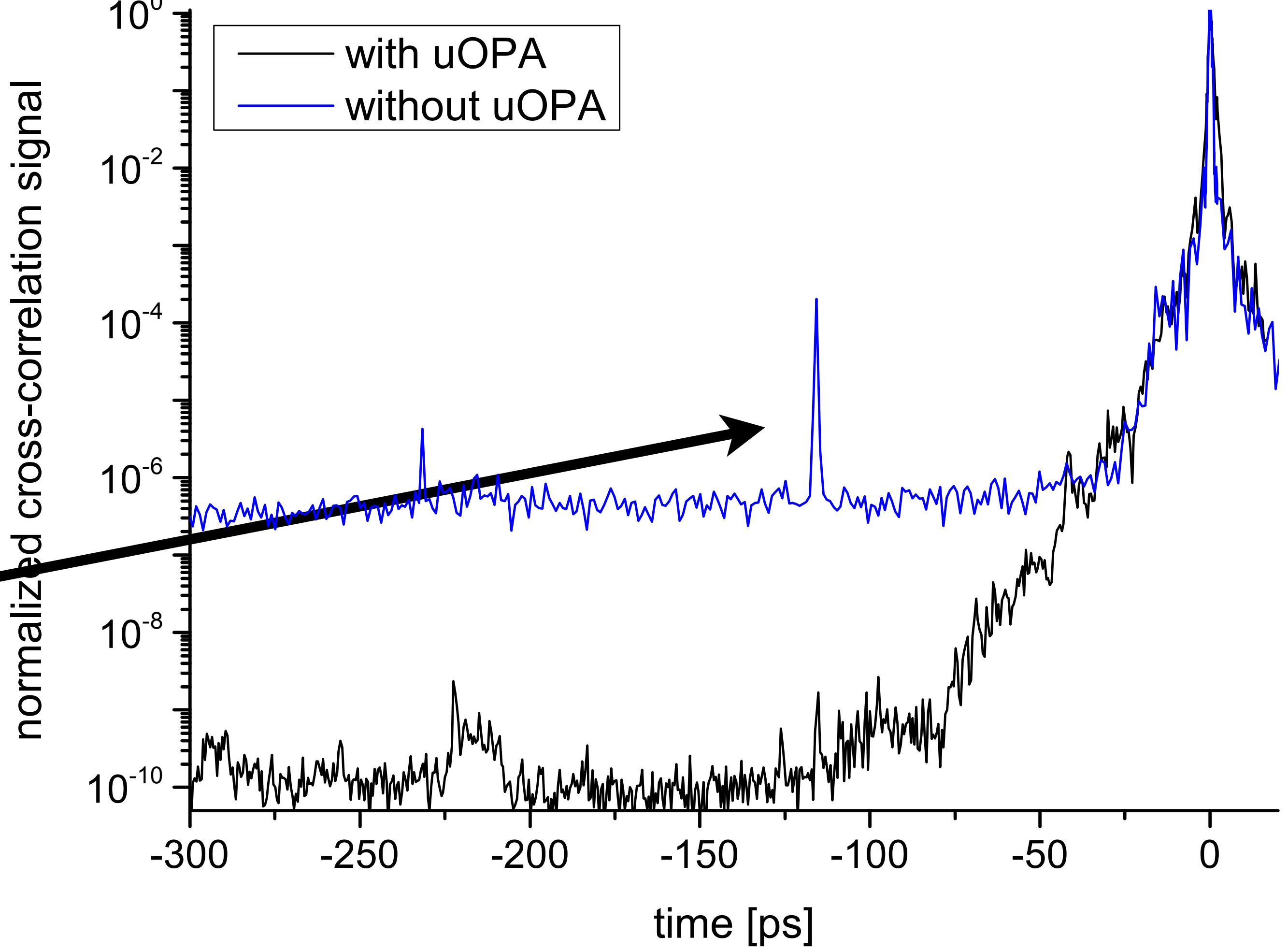


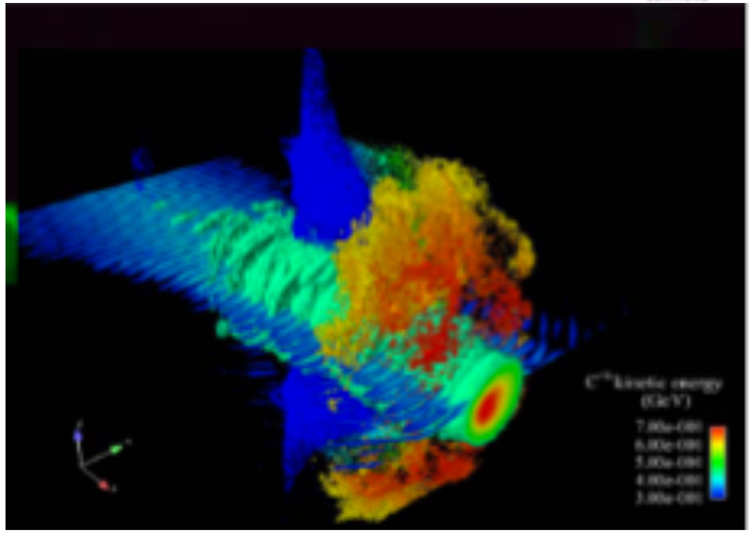
Fig. 2: Setup of the contrast-boosting module



Prepulse from the oscillator

F. Wagner et al., Applied Physics B (2013)

Break out Afterburner (BOA)

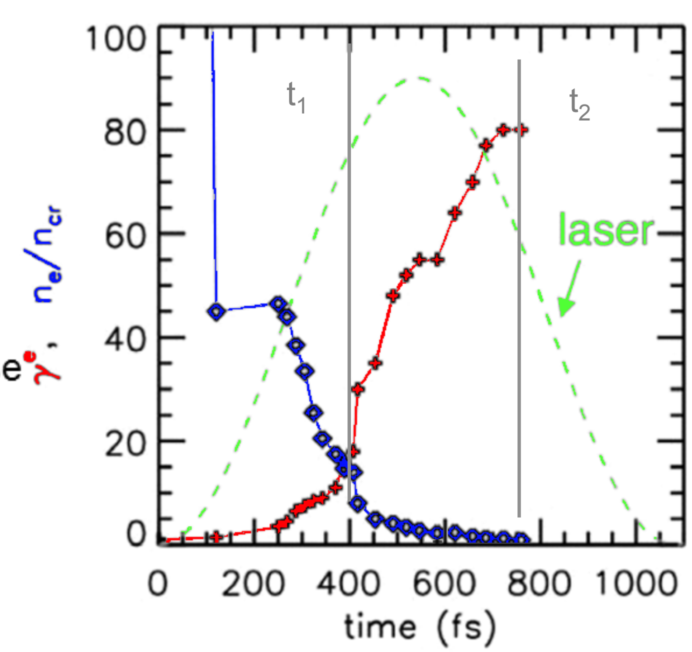


t_1: relativistic transparent

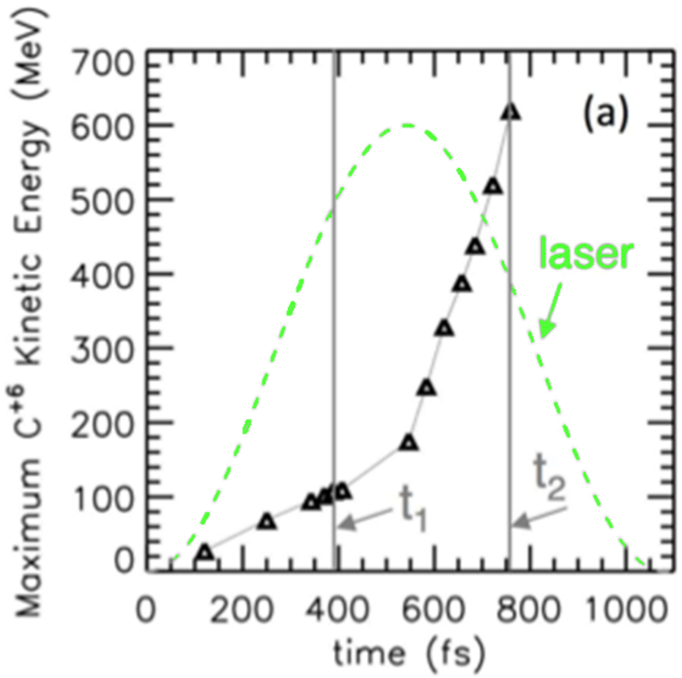
$$n' > 1 \geq n'/\gamma$$

t_2: classically underdense

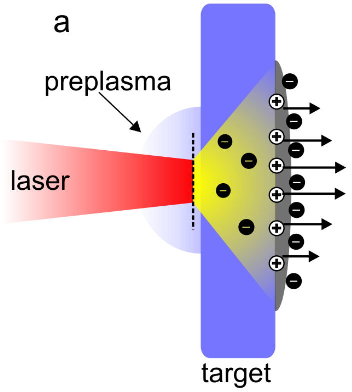
$$n' < 1$$



Yin, et al., Laser and Particle Beams 24 (2006), 1–8
Yin, et al., Phys. Plasmas 14, 056706, (2007)
Yin, et al., Phys. Plasmas 18, 063103 (2011)



Albright, et al., Phys. Plasmas 14, 094502 (2007)
Yin, et al., Phys. Rev. Lett. 107, 045003 (20011)



a) Target Normal Sheath Acceleration (TNSA) phase
b) Intermediate phase
c) Laser Breakout Afterburner (BOA) phase

$$\eta = \sqrt{1 - \frac{n_e}{\gamma n_c}} = \sqrt{1 - \frac{\omega_p^2}{\gamma \omega_L^2}} \qquad \omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

VPIC: 100nm CH2 target & Trident laser with 2x10^{20}W/cm^2

Max. energy	proton	carbon
Ideal laser	132 MeV	450 MeV
Real laser	121 MeV	447 MeV

First BOA experimental results TRIDENT/ PHELIX

High contrast beam

thin targets 200-900nm

cryo targets

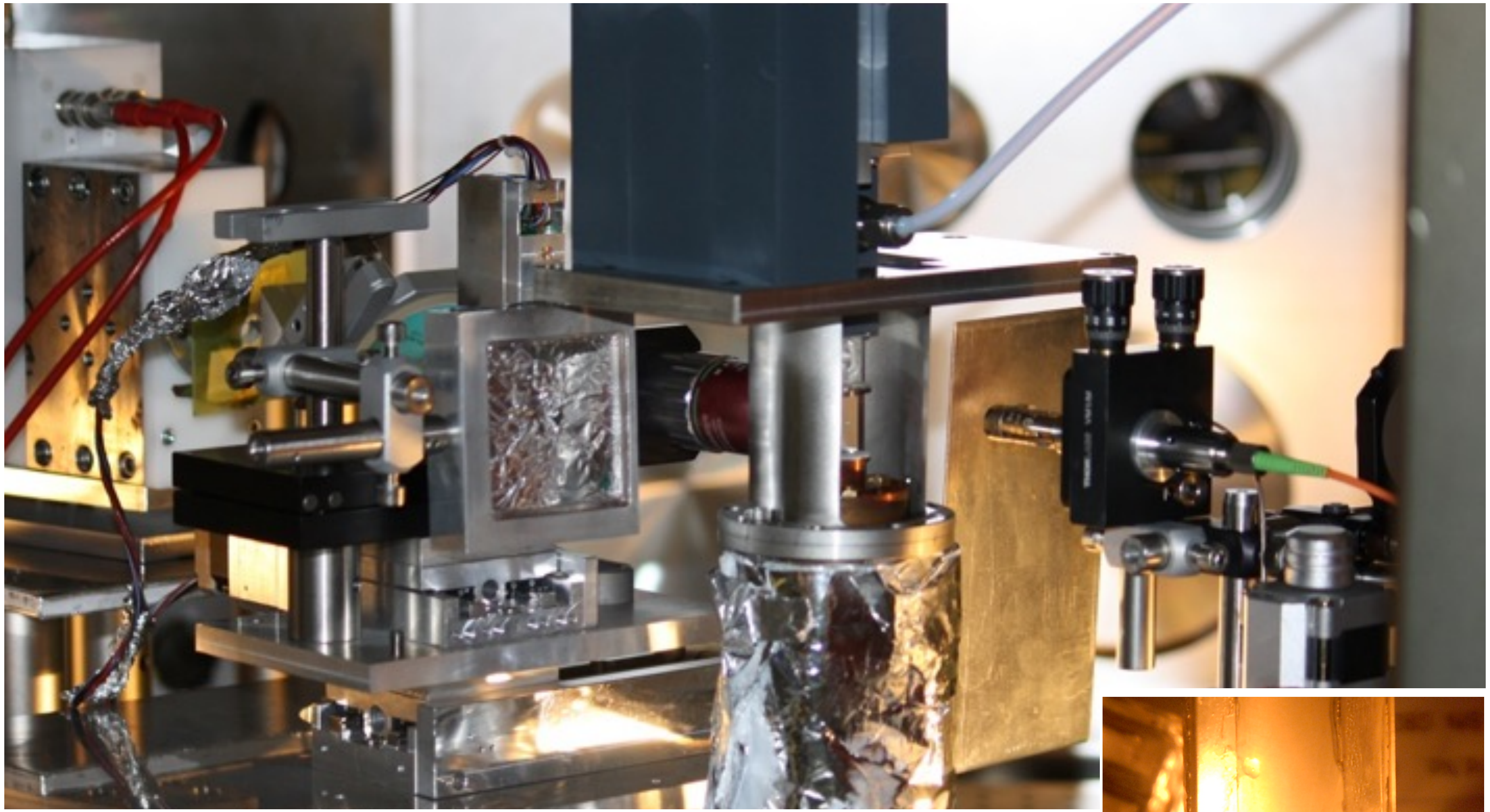
short f# parabola

About 80 J on Target

Using CH foils around
100 MeV protons

First test on Cryo target
55 MeV protons

Pure deuteron beam



Tailoring and transport of ion beams
- the LIGHT project -

TECHNISCHE UNIVERSITÄT DARMSTADT

TECHNISCHE UNIVERSITÄT DARMSTADT

TECHNISCHE UNIVERSITÄT DRESDEN

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

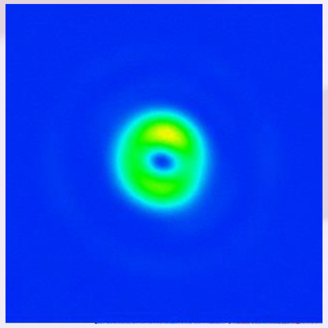
LIGHT

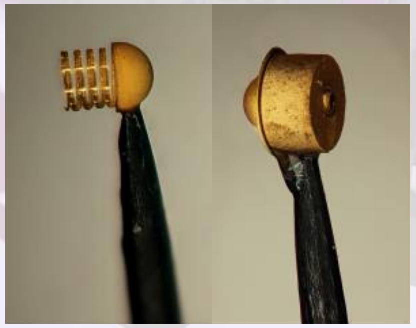
Laser Ion Generation, Handling and Transport

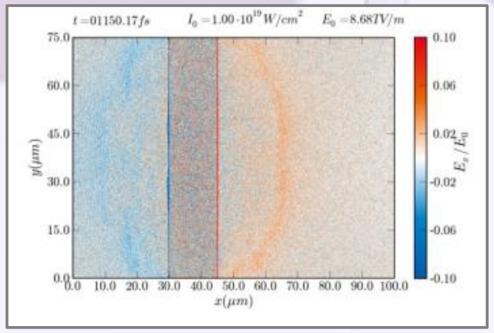
GSI
PP PHELIX Accelerator

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

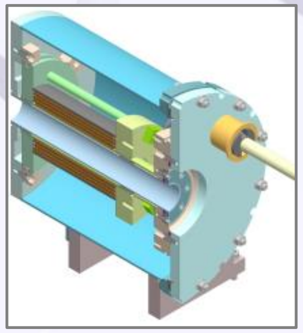
HI Jena
Helmholtz-Institut Jena

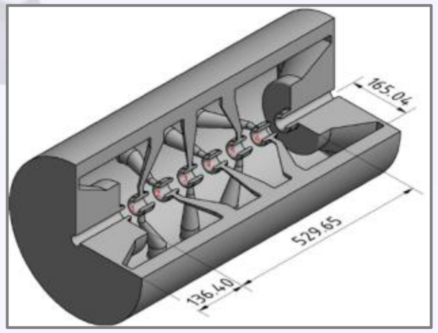

laser shaping


target shaping



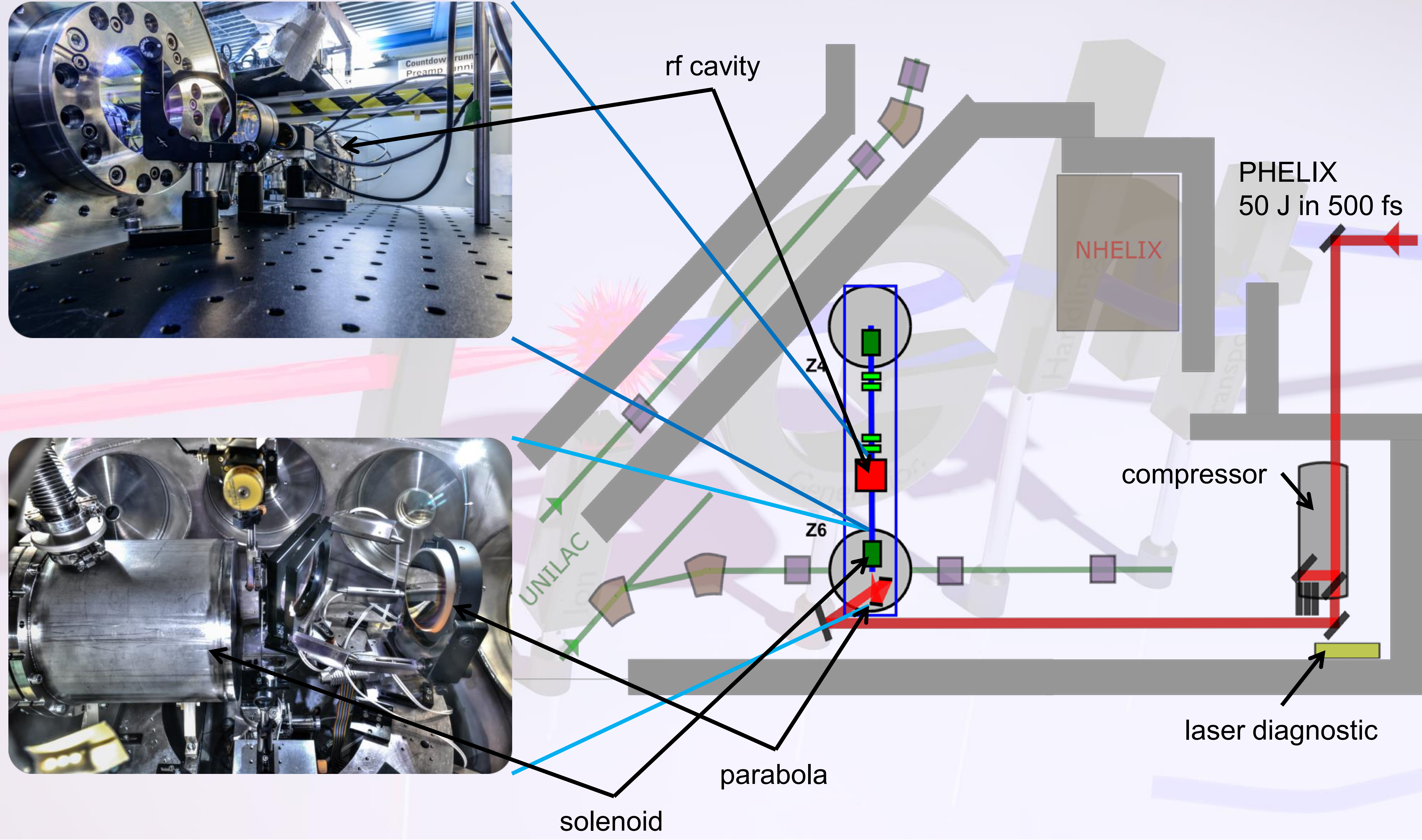
simulation


transport



post acceleration

The LIGHT Beamline



rf cavity

PHELIX
50 J in 500 fs

compressor

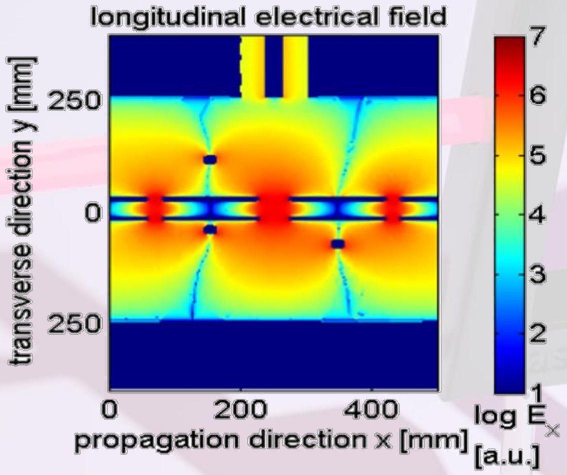
laser diagnostic

parabola

solenoid

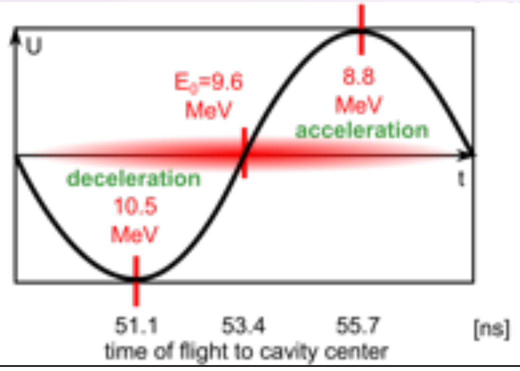
phase rotation

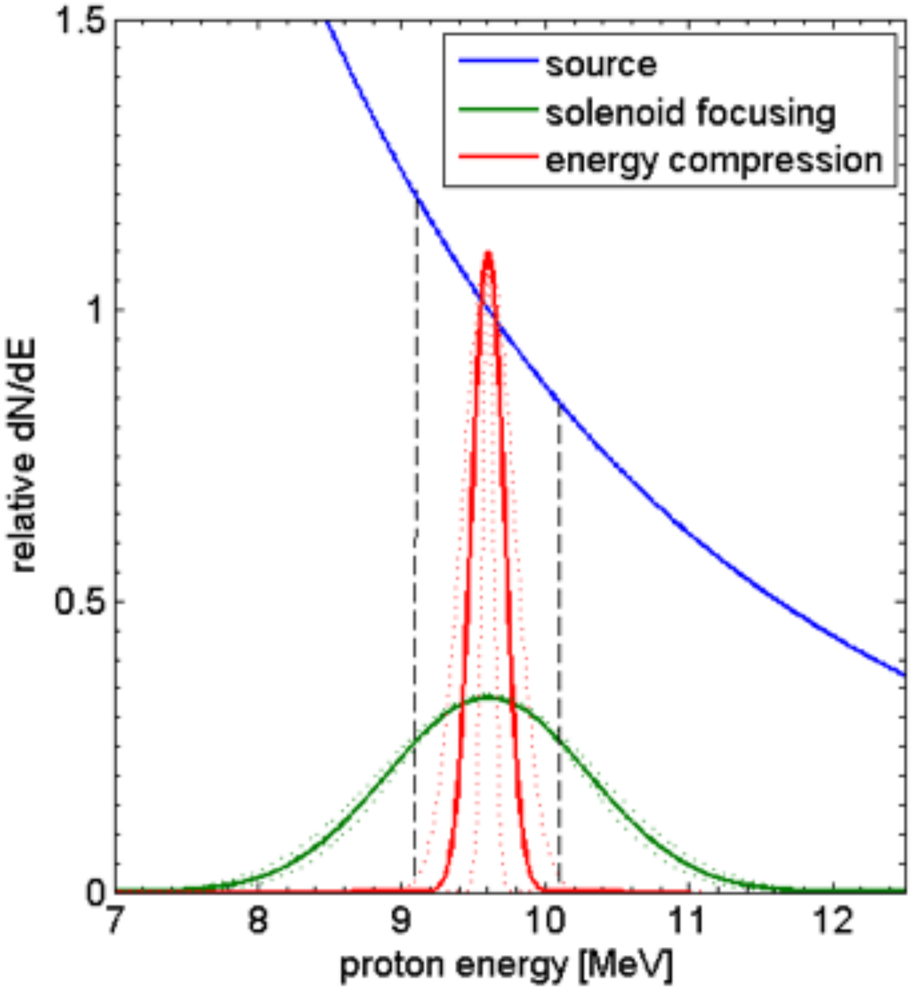
S. Busold et al., PR-STAB 17, 031302 (2014)



double spiral resonator

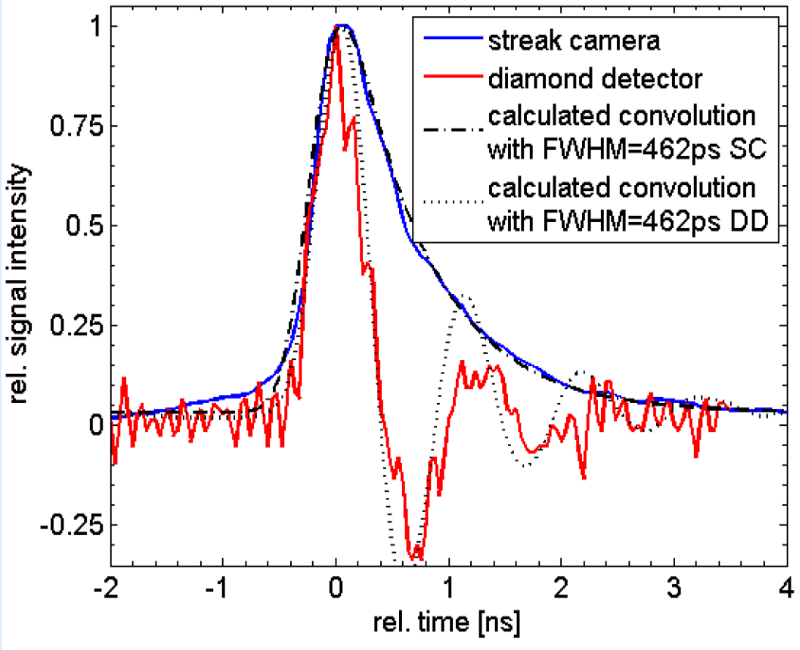
- > 100 kW rf power
- 3 gaps
- ±1 MV acc. voltage
- 108.4 MHz





Energy selection and width for 9.6 MeV :
18.0 ± 3.0 % due to chromatic focusing of the solenoid
2.7 ± 1.7 % using the cavity

n_p = 5 x 10^8
t = (462 ± 40) ps
I = 100 mA



shortest measured pulse length:

- FWHM: 462 ps ± 40 ps

F. Nürnberg et al., RSI 80, 033301 (2009)

Laser Ion Parameter for Treatment

	Spot scanning	Passive formation	Comments
Protons / laser shot	2x10^7	2x10^8	reach 2 Gy by accumulation
# transverse	10x10 spots	10 reps for lateral uniformity	
Energy steps	10	10	$\Delta E/E=\pm 5\%$
Reps → dose spec. (~30% intensity jitter)	40	40	10 reps 4 gantry directions
Total # shots per fraction	10000	1000	¼ applied
Duration of fraction **Laser rep rate**	5 min 30 Hz	1.5 min 10 Hz	

Laser requirements for medical applications:

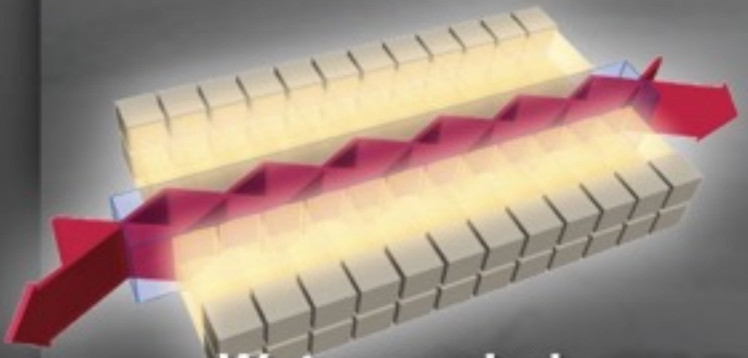
- Based on the need for RPA or BOA acceleration to reach the required particle energy:

	laser proton	**laser carbon**
Rep rate (spot/passive)	30 Hz / 10 Hz	
Laser intensity (W/cm^2)	1-3 10^{21}	1-3 10^{22}
Pulse duration (fs)	50-150	
Rise time (fs)	<20	
Contrast (5 ps / 500 ps)	$<10^{-8}$ / 10^{-12}	$<10^{-9}$ / 10^{-13}
Laser energy stability	1-5%	
Spot radius (μm)	5	
Peak power (PW)	1-3	10-30
Pulse energy (J)	50-150	500-1500
Average power (kW) 10 Hz (30 Hz)	0.5-1.5 (1.5-4.5)	5-15 (15-45)
Laser cost assumption	<10 M€	~15 M€
Laser wavelength (nm)	800-1054	
Efficiency	1-10%	
Polarization	lp/cp	
Laser beam quality	diffraction limit	
Pulse stability	0.01	
Laser pointing (μrad)	1-10	
Laser availability	12 h/day (50% duty factor)	
Failure rate	<2%	

Architectures for rep-rated 100 J systems

HALNA – Japan

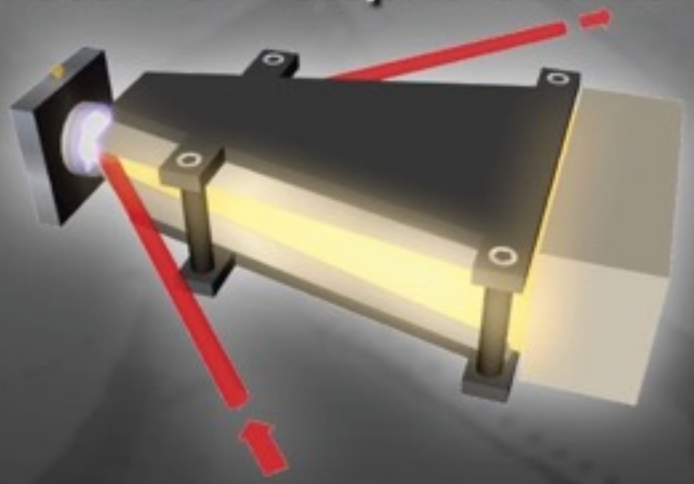
Dr. Toshiyuki Kawashima



Water cooled,
side pumped
Nd:Phosphate slab

Lucia – France

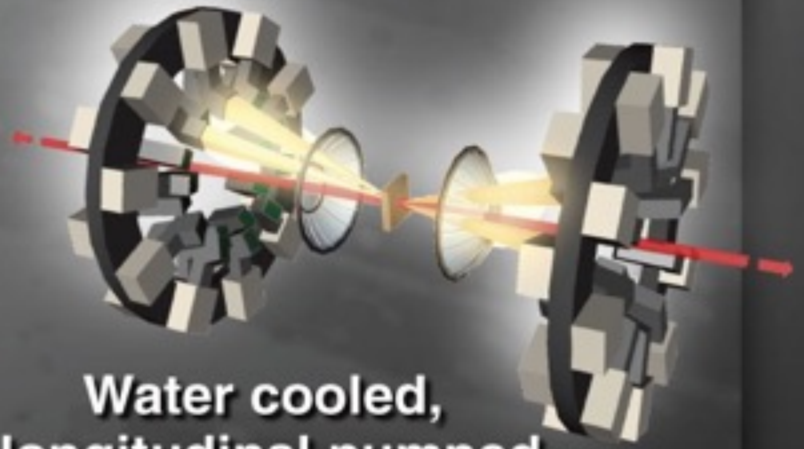
Dr. Jean-Christophe Chanteloup



Water cooled,
longitudinal pumped
Yb:YAG disk

Polaris – Germany

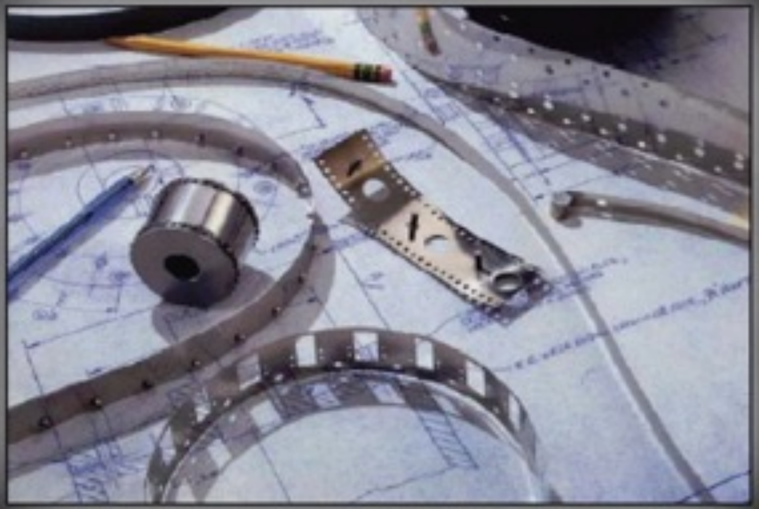
Dr. Joachim Hein



Water cooled,
longitudinal pumped
Yb: Flurophosphate disk

LALTI – Ohio

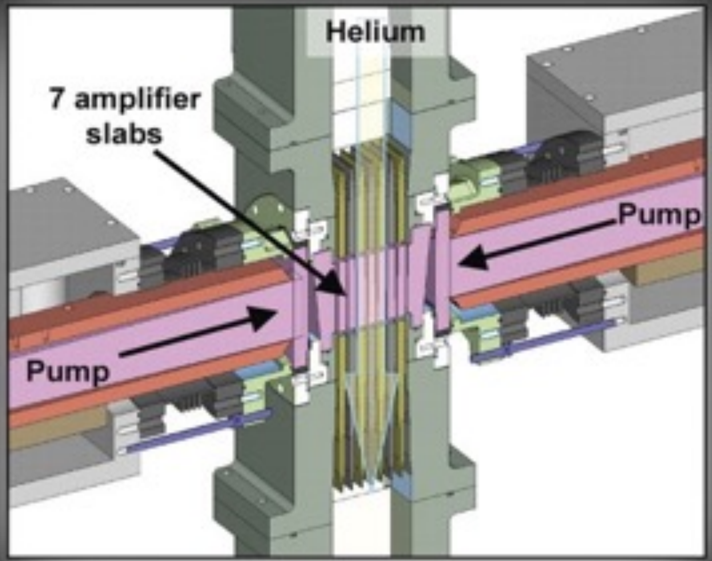
Dr. Linn Van Woerkom



Short pulse system
with rep-rated targets

Mercury – USA

Dr. Andy Bayramian



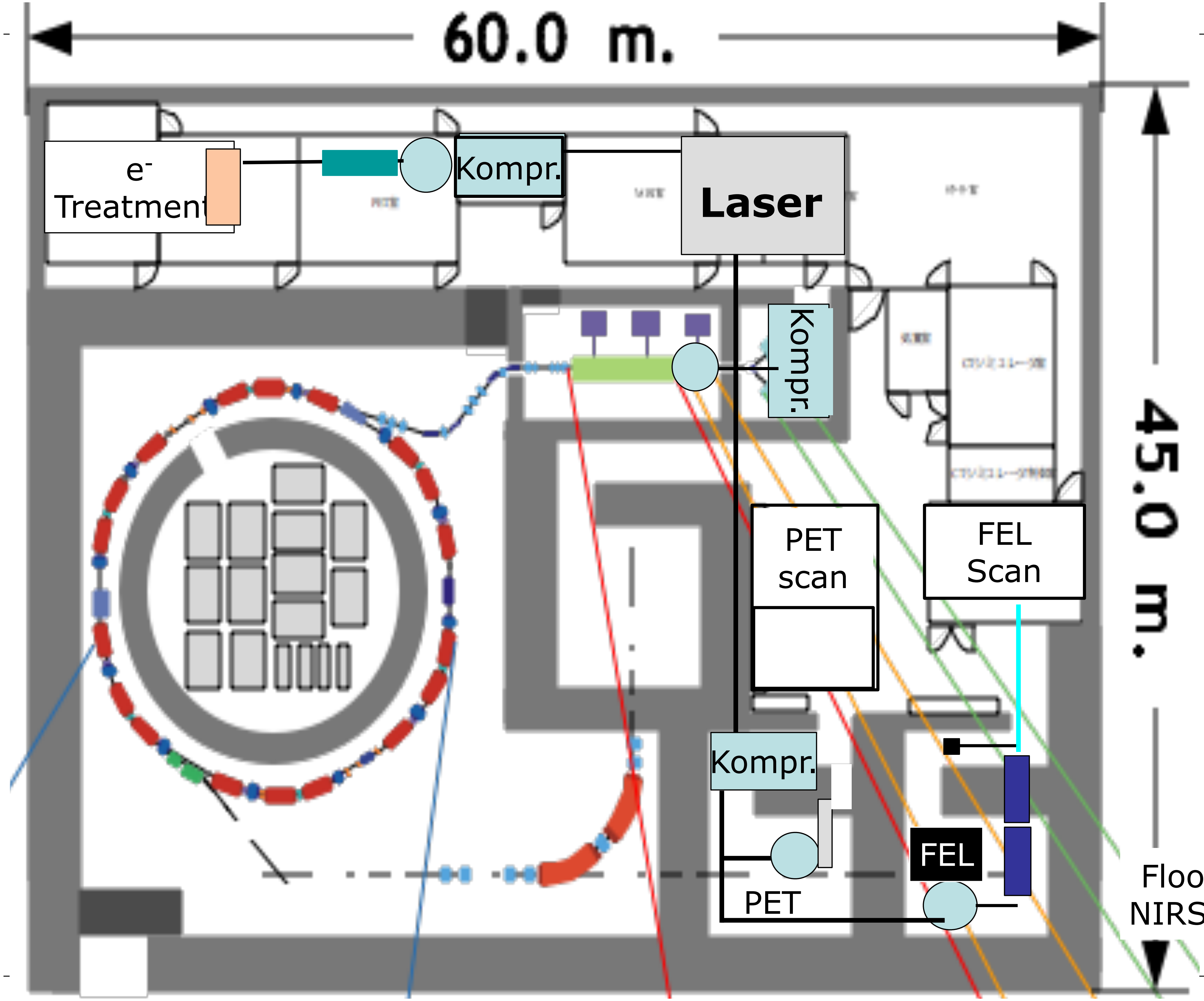
Gas cooled, face pumped
Yb:S-FAP slab

Prospects

- At an energy level of a few tens of Joules high-rep rate, DPSSL‘s are supposed to be available in a few Jears
  (Mercury, JAERI, POLARIS, LOA)
  you can buy 100 TW table top systems @ 10 Hz already
- „monochromatic“ ion beams have been observed for the first time
- Excellent beam emittance would allow for smaller apertures, higher gradients, smaller accelerators
  (PET Production, tumor therapy)
- the driving laser system could also be used for
  e-beam generation, PET-isotope production and coherent x-ray diagnostics at the same time

Summary

Vision for a UHI Laser in Medicine



Floorplan: Carbon Facility
NIRS HIMAC, Dr. Koji Noda

Summary

Summary

- As of today laser acceleration has a theoretical potential to compete with conventional drivers for therapy

- Extremely high beam quality. How to preserve during transport?

- Laser injector into synchrotron
  - „good“ parameter match (based on PHELIX data)
  - 10 Hz Petawatt laser in reach
  - hard to compete with linac technology, space charge?!!

- „full energy laser“ scenario lacks data
  - small cones (~2-3°), smaller production $\Delta E/E$(~10-20%)
  - > 100 Hz laser systems, nm foils (feasible?)
  - reproducibility, precision unknown

Thank You !

- Feasibility Experiment next step – GSI „best“ place to do it!

I. Hofmann (GSI)

High intense and energetic X-ray beams for phase contrast imaging in medical diagnostics: technical requirements and applications

Paola Coan

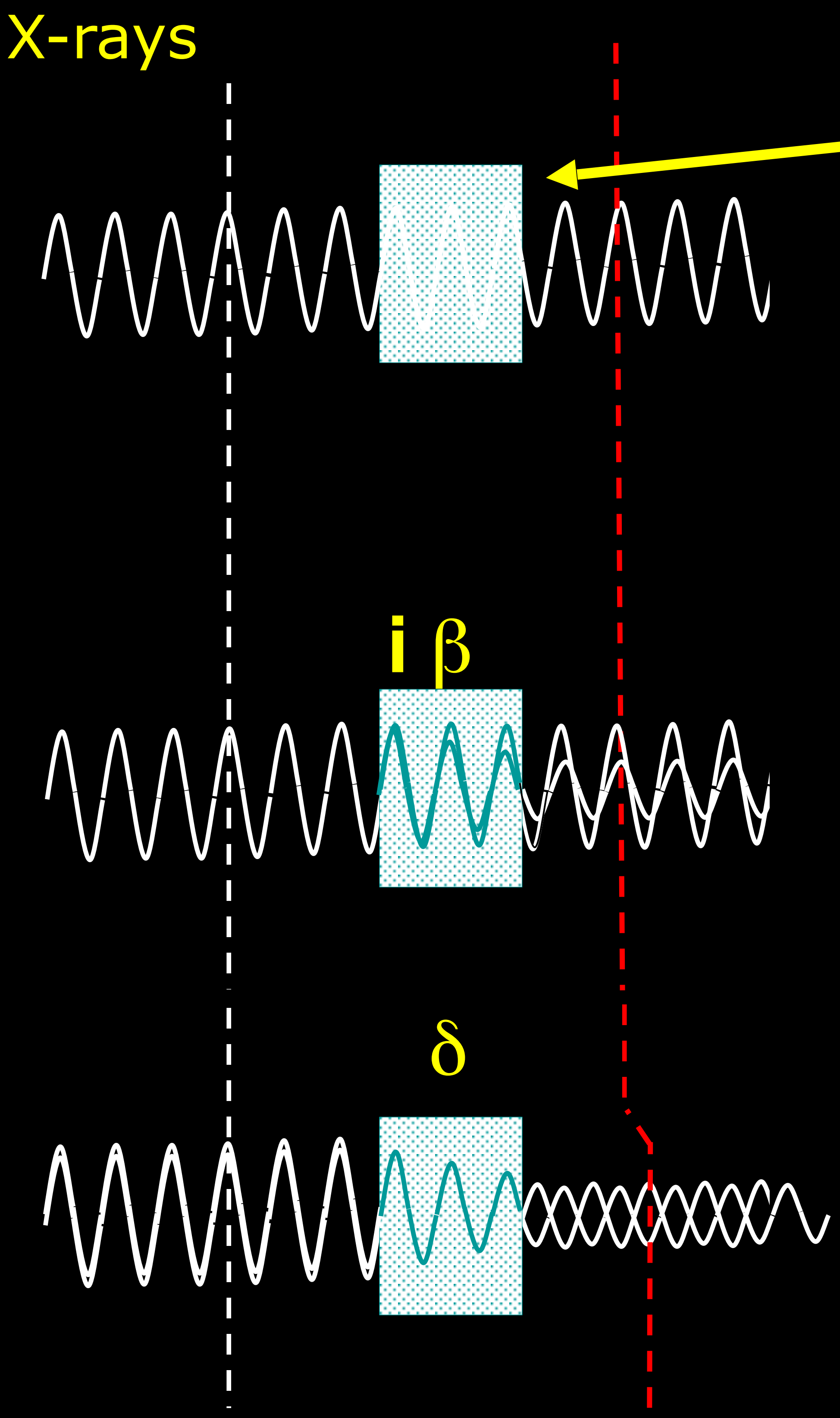
C. GLASER, T. SCHNEIDER, A. BRAVIN, P. C. DIEMOZ, M. REISER, D. HABS

Munich-Centre for Advanced Photonics (MAP)
Munich, LMU, Germany

Biomedical Beamline
European Synchrotron Radiation Facility
Granoble, France

II International Symposium on Laser-Driven Relativistic Plasmas Applied to Science, Industry and Medicine - 23rd January 2009

X-rays through the matter



$$n = 1 - \delta + i\,\beta$$

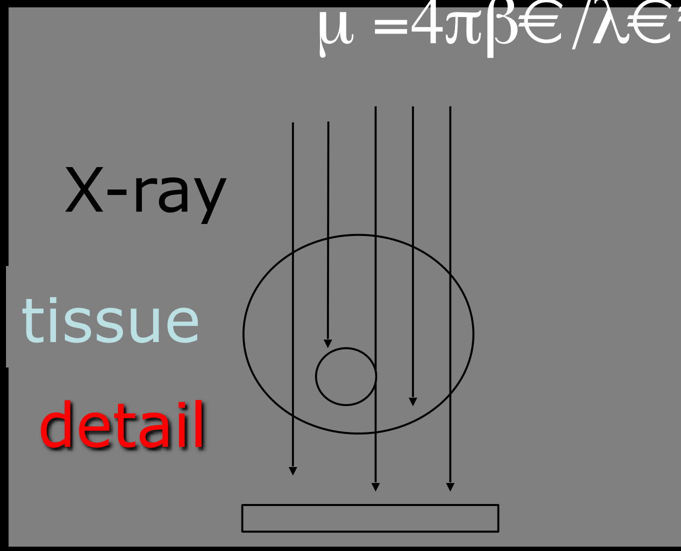
complex-valued index of refraction

In the diagnostic X-ray energy range:

àAmplitude modulation

- Photoelectric effect
(+ Incoherent scattering)

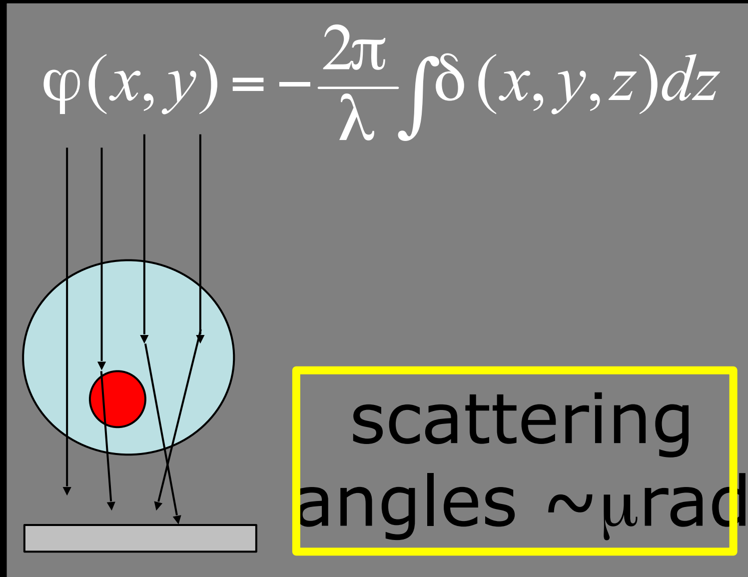
ABSORPTION-based RADIOLOGY



→ Phase shifts

- Elastic (“coherent”) scattering

PHASE CONTRAST IMAGING



$$\varphi(x,y) = -\frac{2\pi}{\lambda}\int \delta(x,y,z)\,dz$$

scattering angles ~μrad

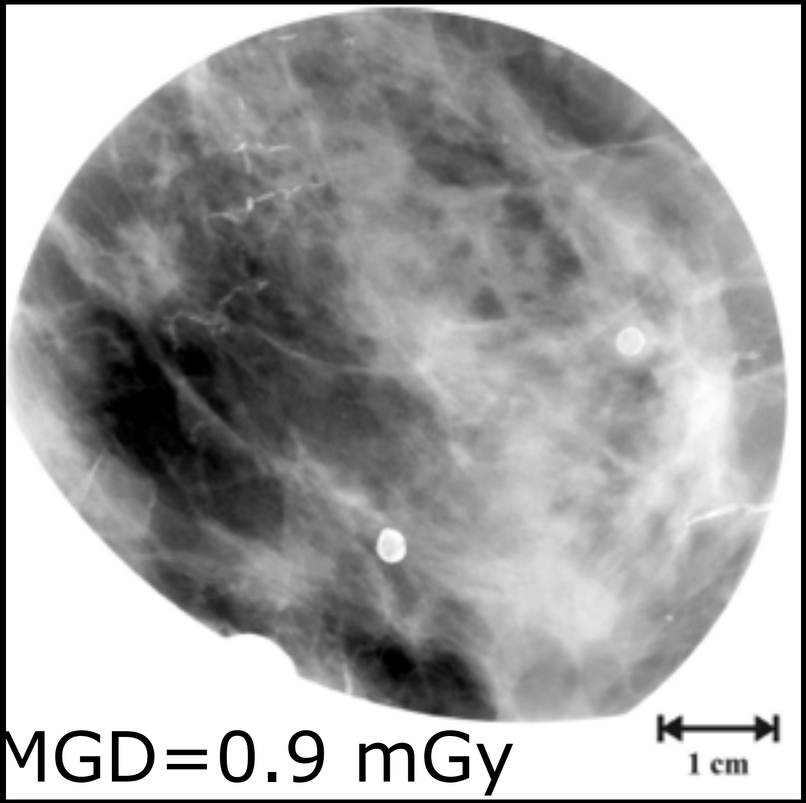
Keyriläinen et al. *Radiology*, 2008

conventional

Analyzer-based

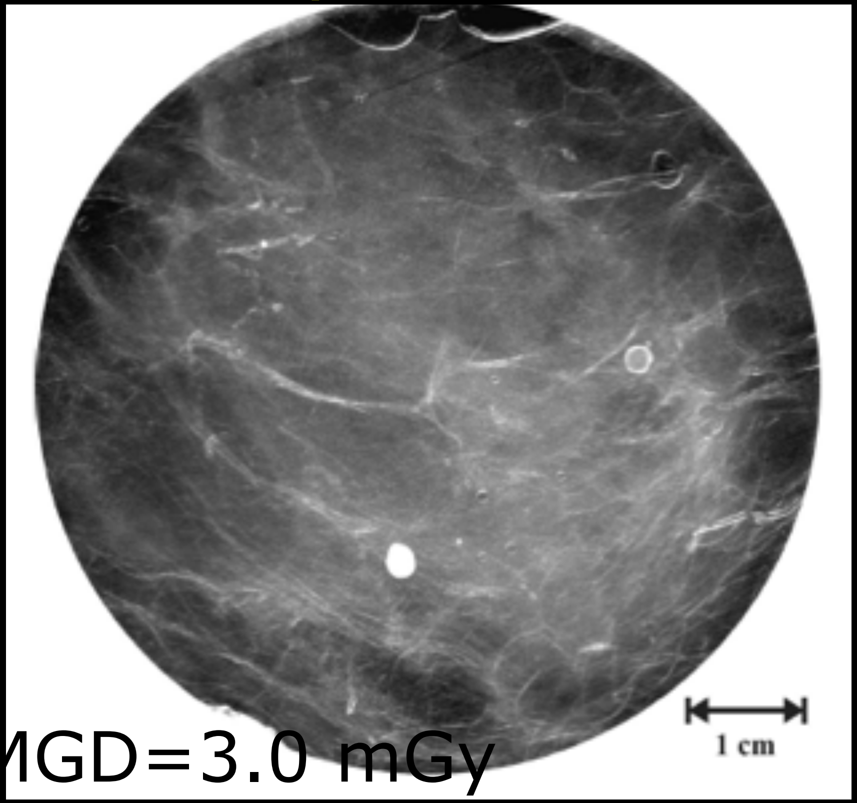
Planar radiograph

Multifocal lobular carcinoma



MGD=0.9 mGy

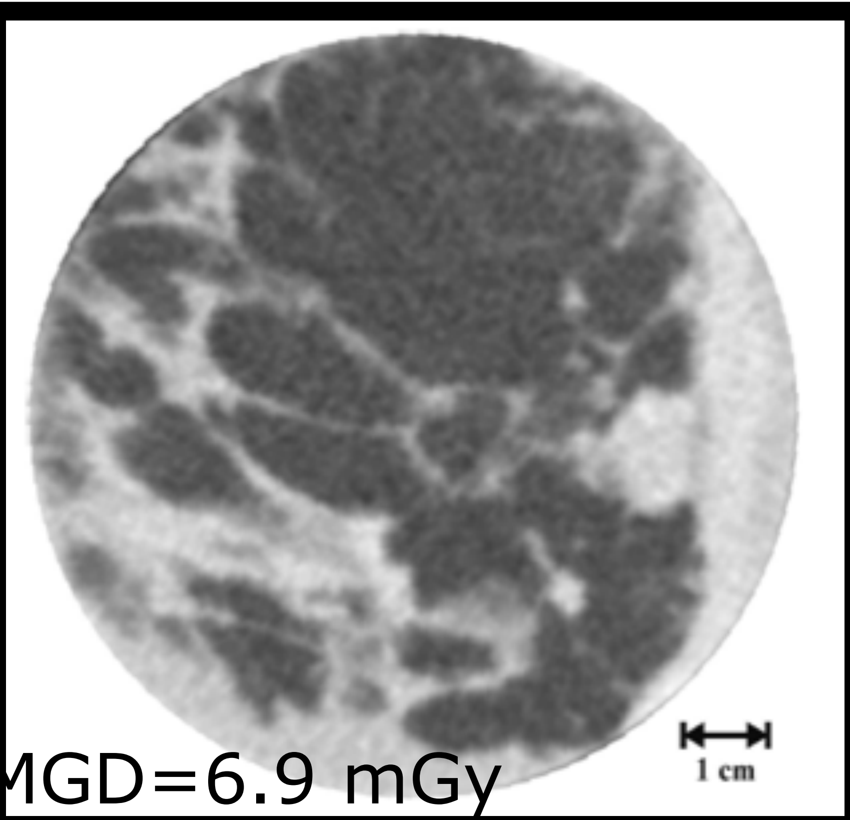
26 kVp and 9 mAs



MGD=3.0 mGy

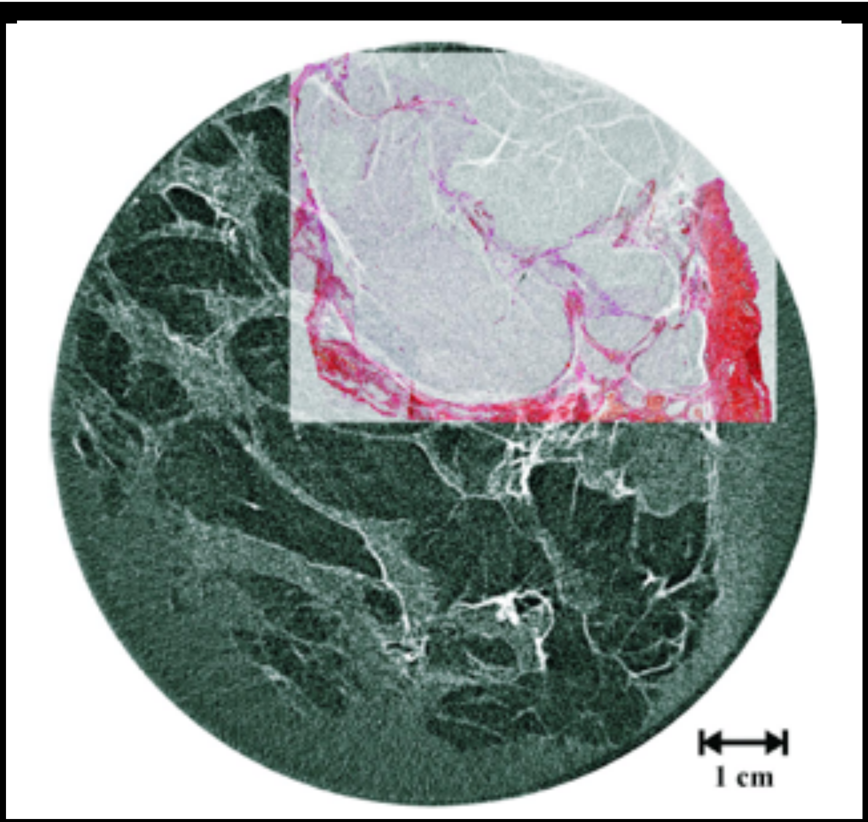
30 keV

CT radiograph



MGD=6.9 mGy

80 kVp and 50 mAs



30 keV