Лазерное ускорение частиц.

В. Ю. Быченков

Физический институт имени П.Н.Лебедева
FIAN

Третьи Черенковские чтения
«Новые методы в экспериментальной ядерной физике и физике частиц»
6 апреля 2010 г.
ФИАН

Research program has put ultra short-pulse laser and beam physics at the Forefront of Science

Acceleration, Radiation Sources, Nuclear Applications, Medical Applications

Ускорение электронов

Цели:

•Рекордные энергии. ГэВ-инжектор для стандартного ускорителя.

•Контролируемый источник высокоэнергичных электронов «на столе»

•ЛТС. Fast ignition

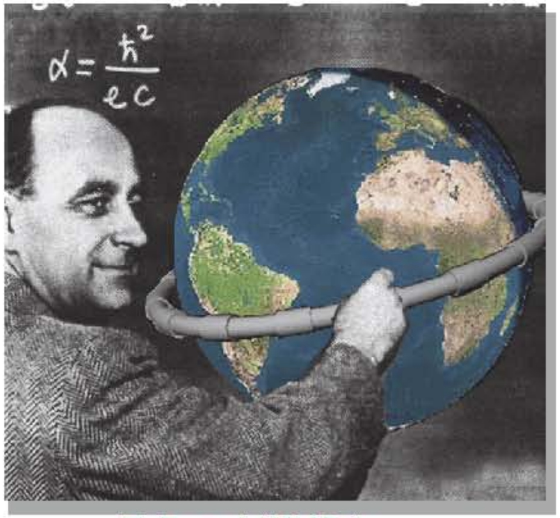
•Источники вторичного излучения (THz – gamma). ЛСВ «на столе»

•Электронная радиография

•Короткоживущие медицинские изотопы.

•Электронная терапия рака

Fermitron



E. Fermi (1940s)

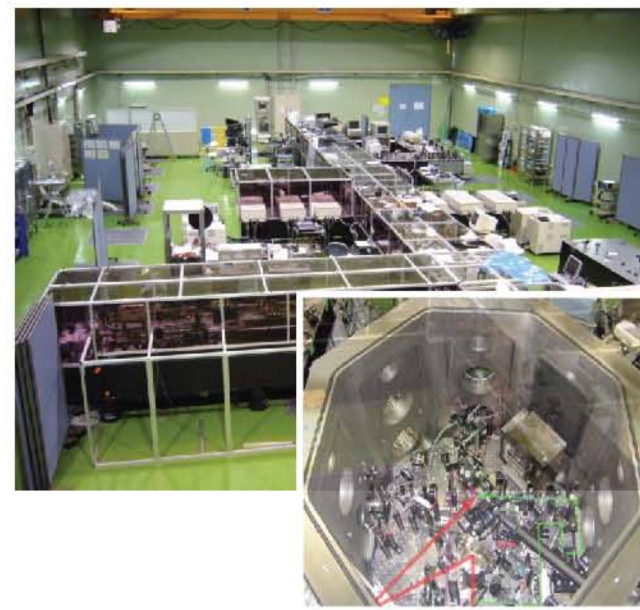
$$l_{acc} \approx 10^4 \, km$$

$$\mathcal{E}_e = 10^{15} \, eV$$

Лазерный ускоитель

~ 460 m

SPring8



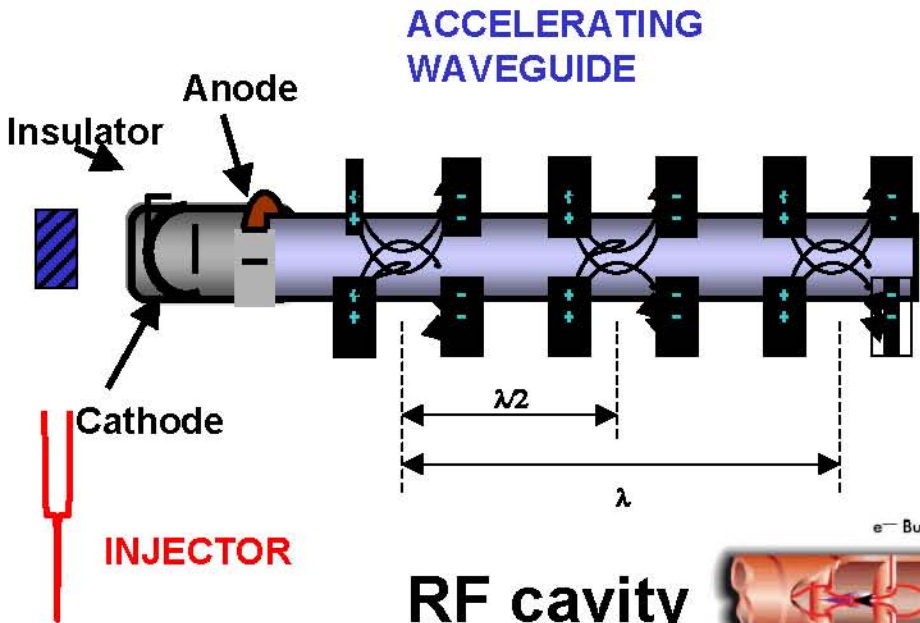
~ 1 m

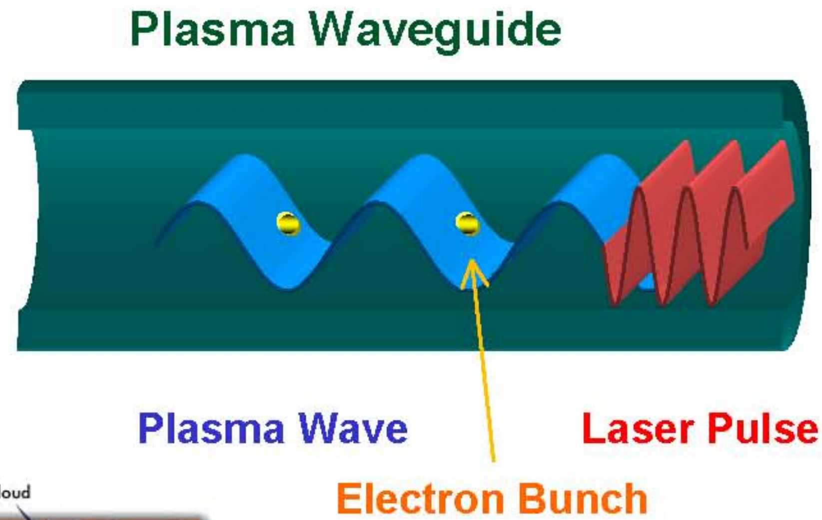
~ 1 cm

Classical and LWF Accelerators

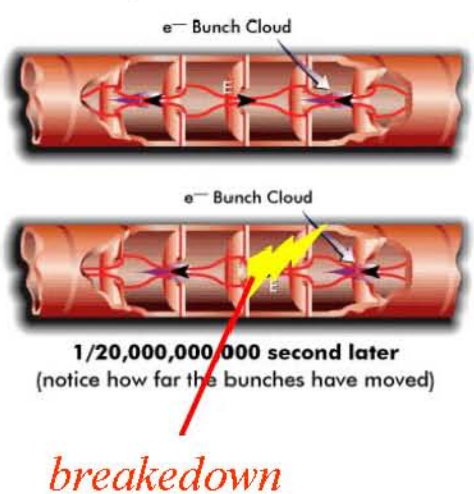
E-field $_{max}$ ≈ 10-100 MV/m
Material breakedown

E-field $_{max}$ ≈ 10-100 GV/m





RF cavity



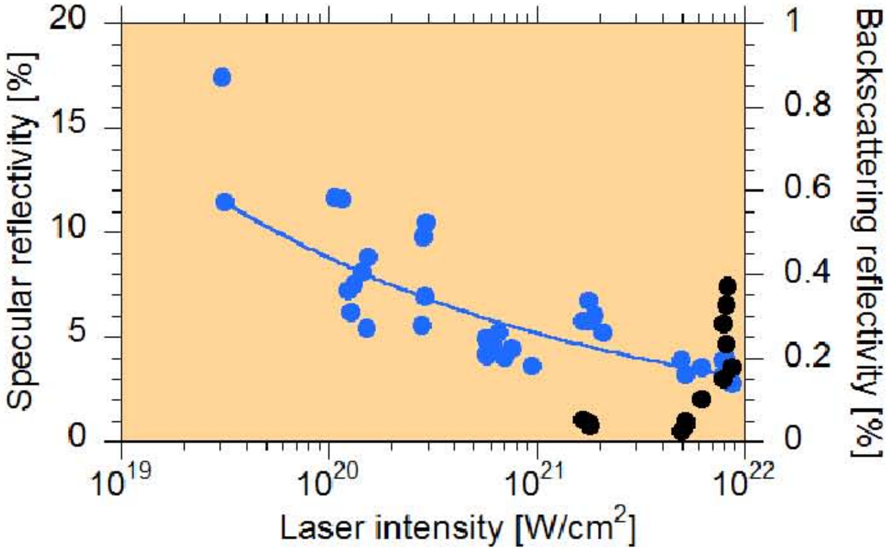
$1\ GeV \Rightarrow 0.1\ km$

$30\ GeV \Rightarrow \mathbf{3\ km}\ (SLAC)$

$1\ TeV \Rightarrow 100\ km$

Ultrahigh axial electric fields
Compact electron accelerators
Plasma wakefields:
fast waves
Plasma channel: Guides laser
Pulse and supports plasma wave

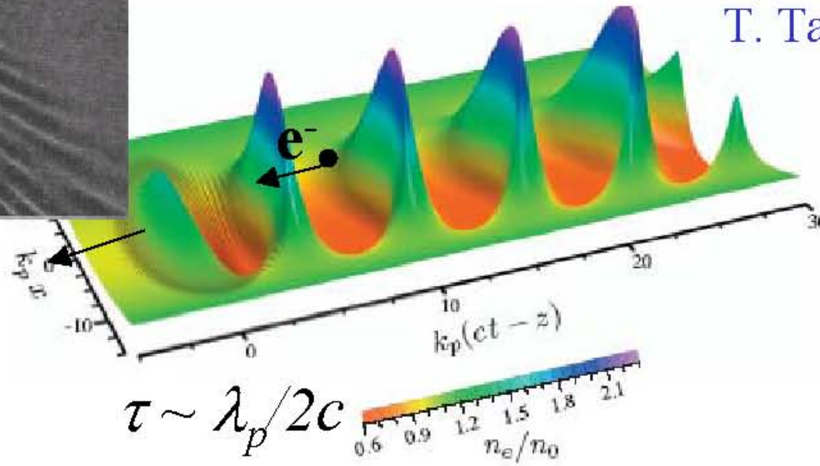
Center for Ultrafast Optical Science
CUOS
NSF Physics Frontier Center "Frontiers in Optical, Coherent, and Ultrafast Science"
FOCUS



HERCULES laser at University of Michigan (up to 500 TW 15 J, 30 fsec)

Experiments to intensities greater than 10^{22} W/cm^2 are being performed

LWA



T. Tajima and J. M. Dawson (1979)

FIG. 2. (Color) Plasma density perturbation excited by Gaussian laser pulse with $a_0=1.5$, $k_0/k_p=20$, $k_p L_{rms}=1$, and $k_p r_0=8$. Laser pulse is traveling to the left.

$\tau \sim \lambda_p/2c$

$\nabla \cdot E \sim (\omega_p/c)E \sim 4\pi e n$ $\qquad$ $\lambda_p(\mu m) = 2\pi c/\omega_p = 3.3\times 10^{10}\,[n_e\,(cm^{-3})]^{-1/2}$

$eE \geq \sqrt{n\,[cm^{-3}]}$ eV/cm

For $n=10^{18}$ cm^{-3}, $eE=100$ GeV/m $\rightarrow$ TeV collider in 10 m!

$V_p < c \quad V_e \rightarrow c$ расфазировка $\quad L_d$ – длина расфазировки

$L_d \sim \gamma_p^2 \lambda_p, \quad \epsilon_e \sim eE\,L_d \sim 2\pi\gamma_p^2 mc^2 \gg mc^2,$

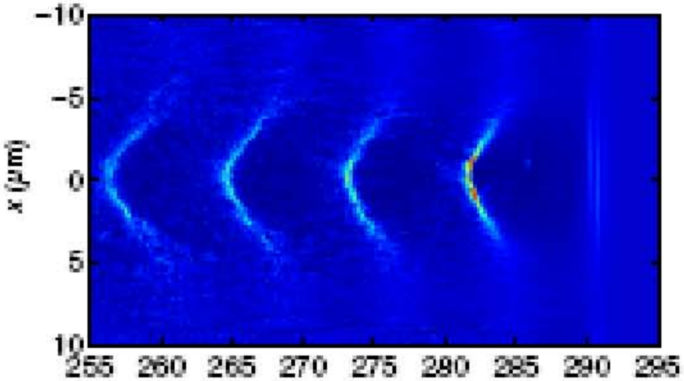
$\gamma_p = (1 - V_p^2/c^2)^{-1/2} \approx \omega/\omega_p \gg 1$

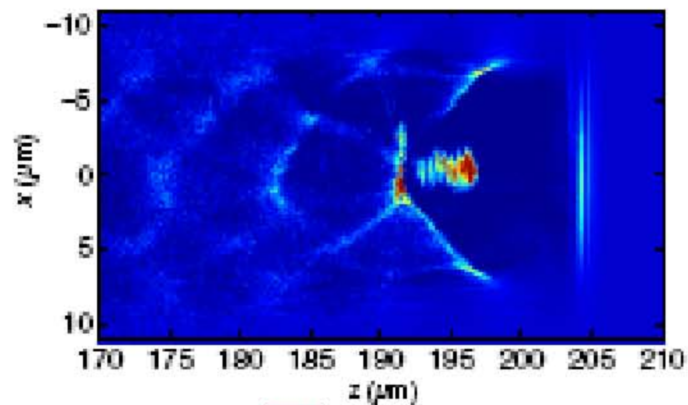
$E = E_0 \cdot f(a,n)$

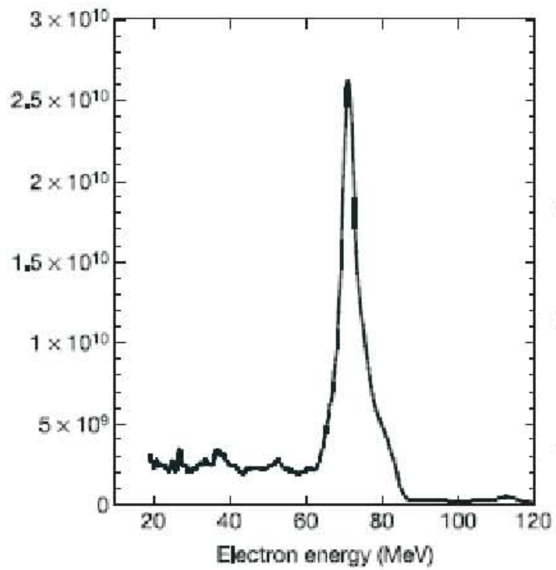
$a = eE_L/m\omega c$

$E_0 = (m/e)c\,\omega_p$ - Tajima-Dawson field

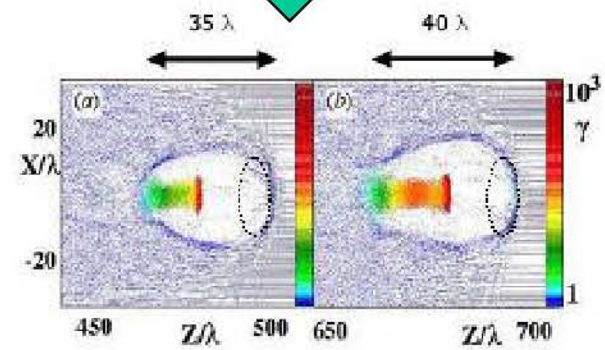
Solitary bubble regime

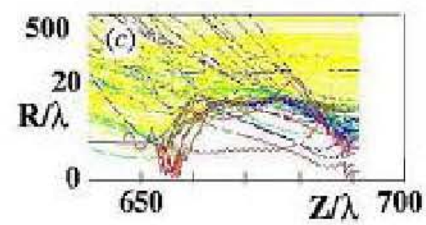






a=1.
40fs,
n=$2\cdot10^{19}$cm^{-3}
70 MeV
20-30 pC





Plasma density:

1.0×10^{19} /cm^3

Laser pulse :

33 fs
12 J
350 TW
a=10

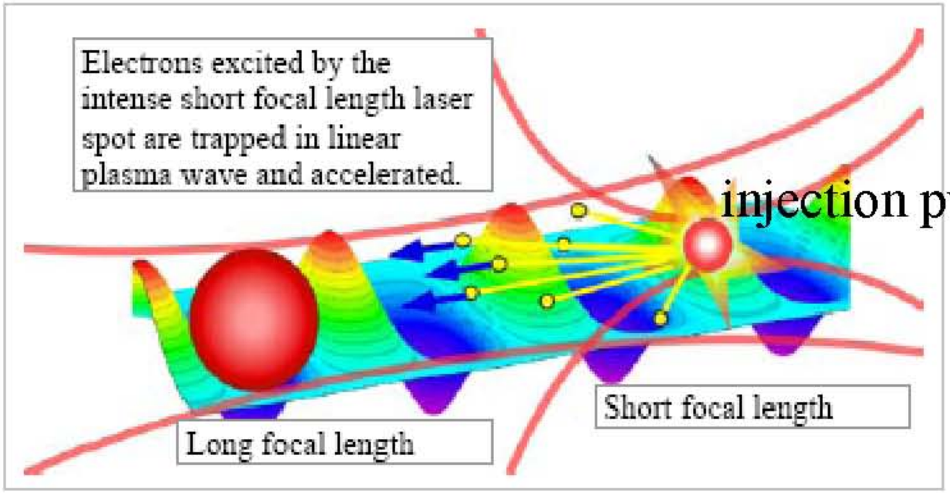
Инжекция

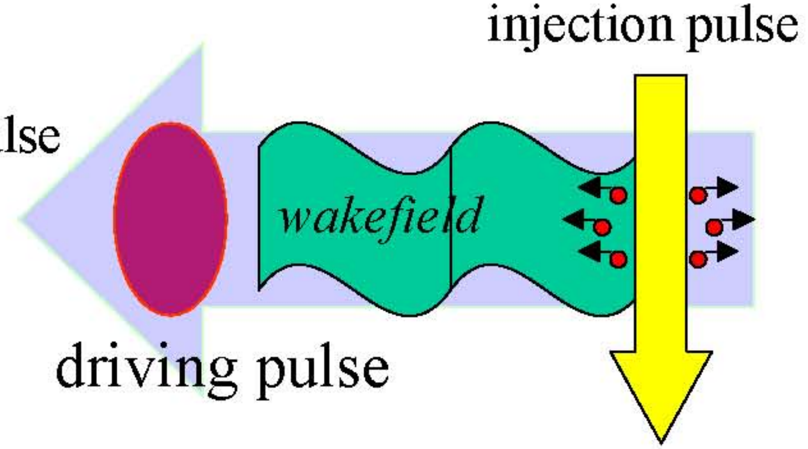
1. Внешняя инжекция пучка

2. Самоинжекция (опрокидывание, поперечные эффекты, деформация лазерного импульса, стохастический нагрев электронов, деформация плазменной волны захваченными частицами …) **неконтролируемая**

3. Самоинжекция контролируемая (профилирование плотности...)

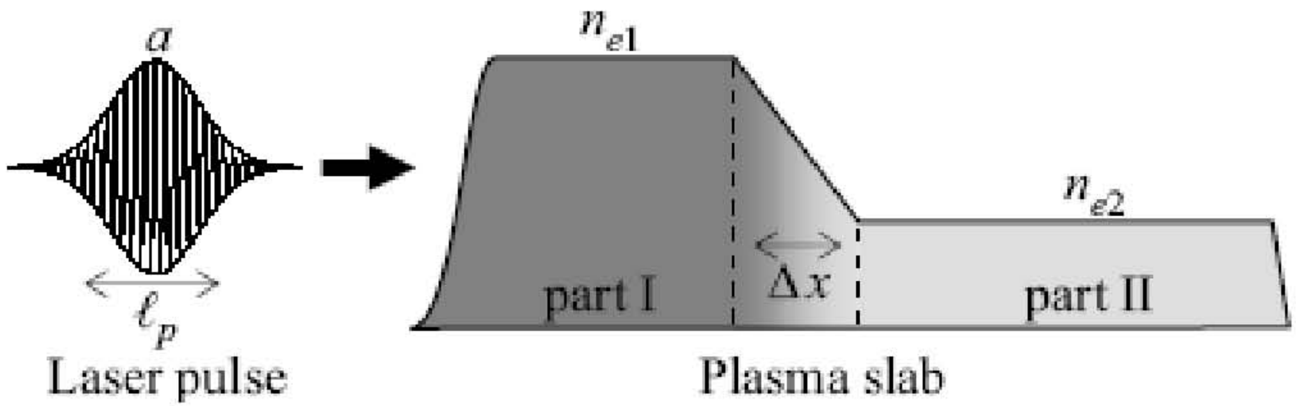
4. Оптическая инжекция контролируемая (пондеромоторная ‖ и ⊥ сталкивающиеся импульсы…)

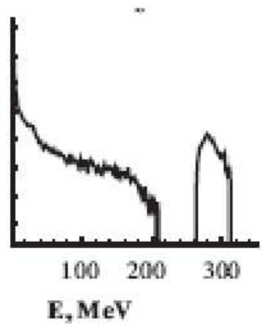




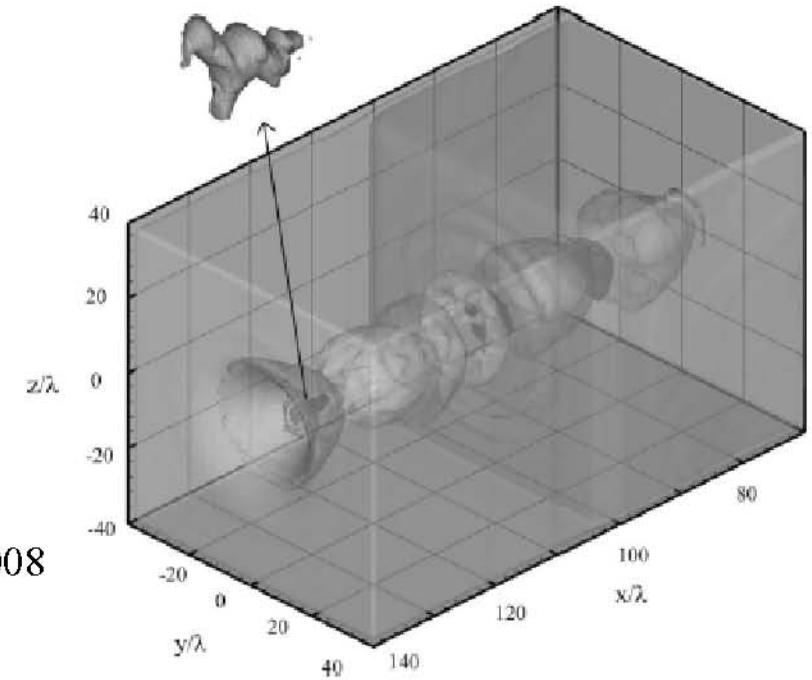
5. Ионизационная инжекция

Контролируемая инжекция за счет неоднородности



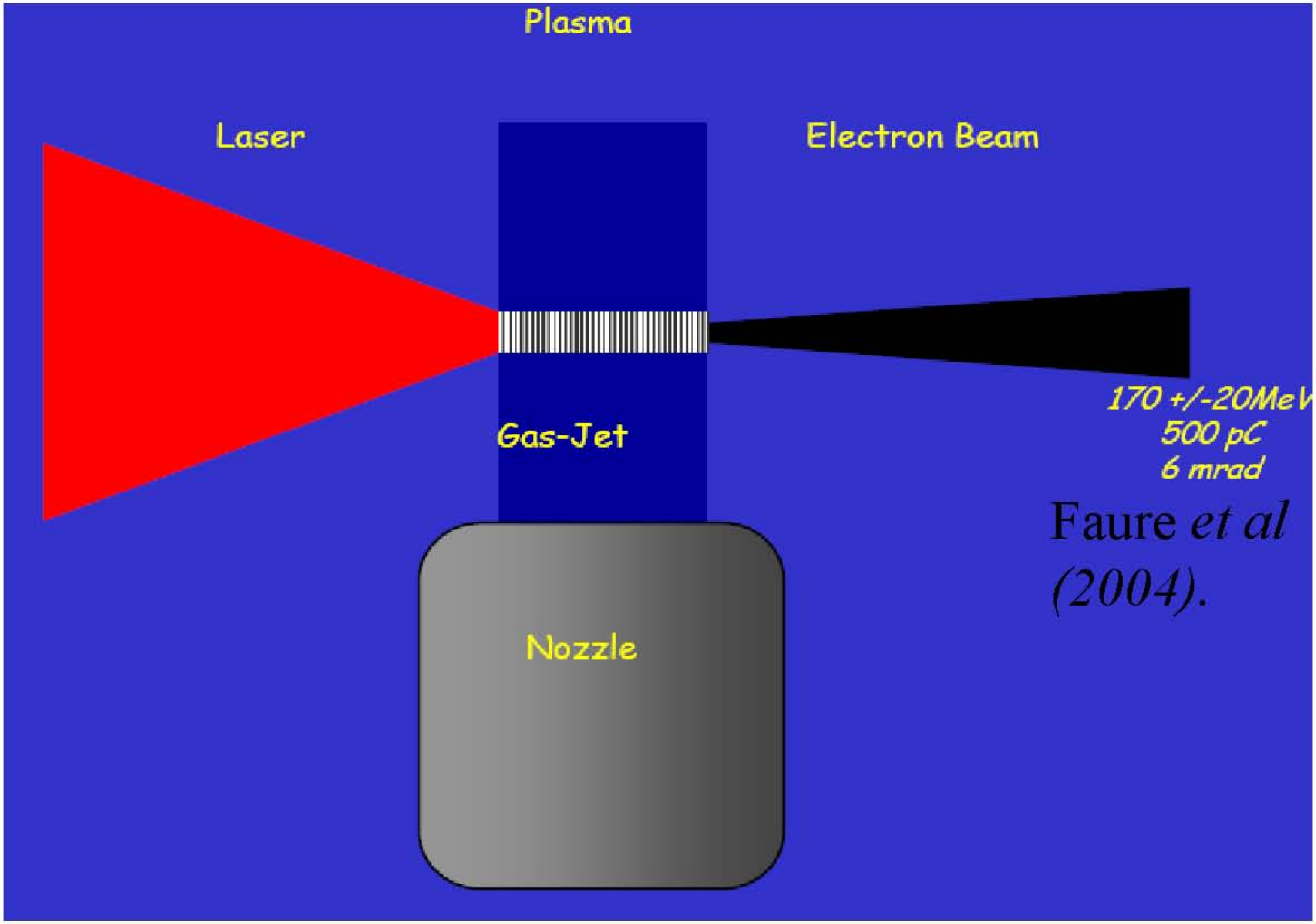


a=2
$l_{\parallel}=10.5\lambda$
$l_{\perp}=20\lambda$



A.V. Brantov et al.,
PHYSICS OF PLASMAS **15**, 073111 2008

Схема типичного эксперимента



Near-GeV electrons from gas jet

S. Kneip et al., PRL 103, 035002 (2009)

"Astra Gemini" RAL, λ=800nm, τ=55fs, I=2×10^{19}W/cm^2 (10J, a=4), D=22μm

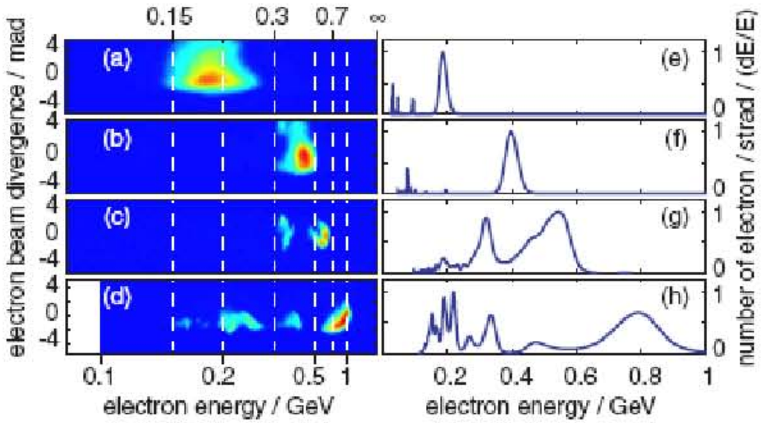
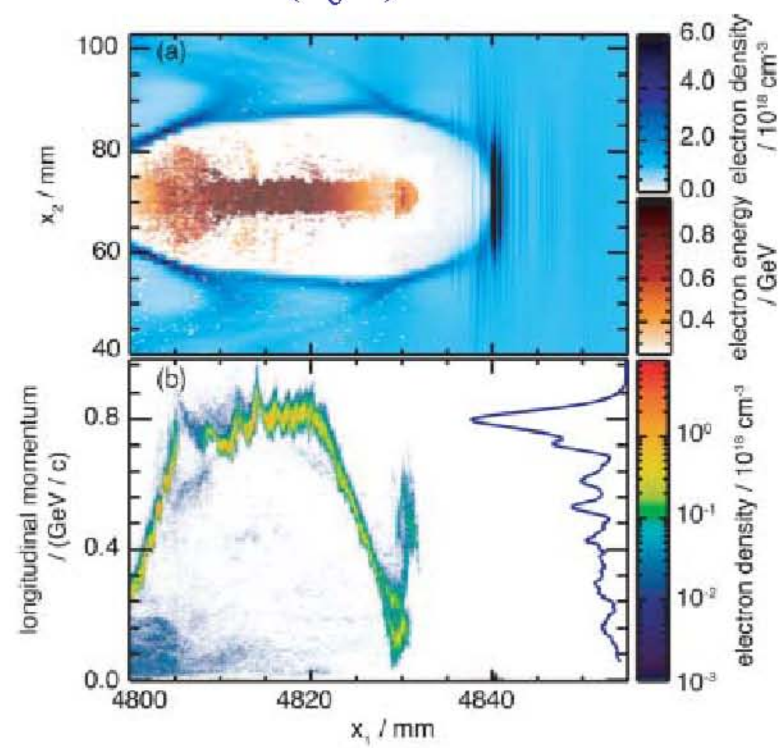


FIG. 1 (color online). Spectrally dispersed electron beams at the exit of the magnetic spectrometer for gas jet lengths (a) 3, (b) 5, (c) 8, and (d) 10 mm, at a plasma density of $n_e = (5.7 \pm 0.2) \times 10^{18}$ cm^{-3} with (10.0 ± 1.5) J of laser energy on target.

$\epsilon \approx a(n_c/n)$



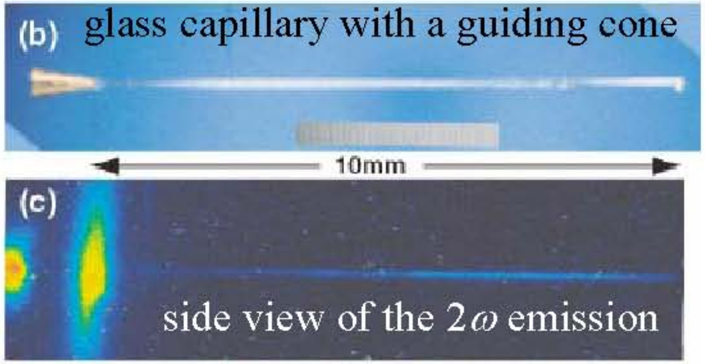
n=6×10^{18}cm^{-3} , L=1 cm

$\epsilon\approx$0.8GeV

Q=0.3-0.6 nC

Divergence=3.6mrad

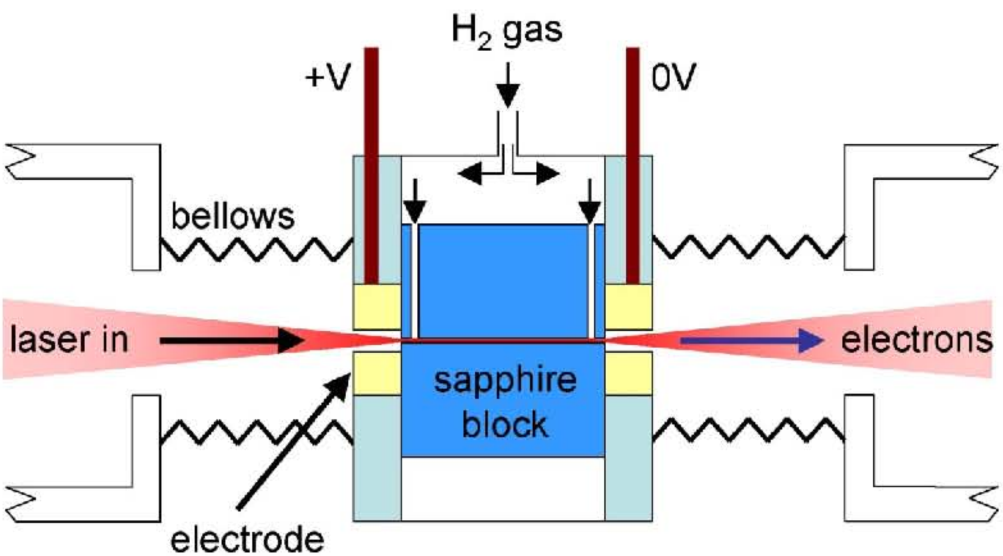
Эксперименты с капилляром



D=60 μm

two prepulses 0.7 and 6.3 ns

Kitagawa et al., **PRL Vol.92, No.20 (2004)**

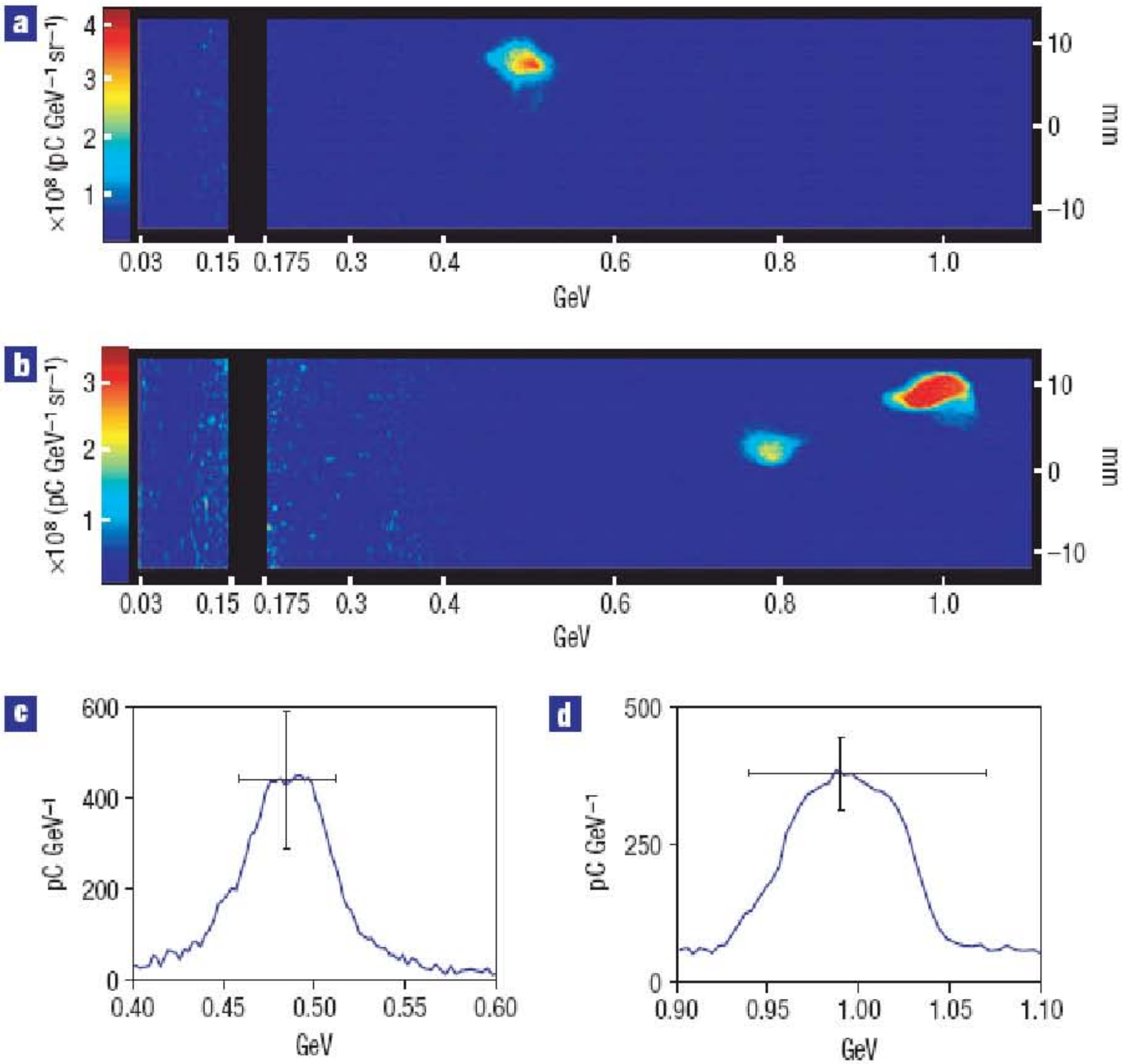


Gas-Discharge Capillary

laser-machined capillary into sapphire D=190-310 μm

W. P. LEEMANS et al., Nature Phys. 2, 696 (2006)

1 GeV bunches by channelling 40 TW laser pulse in a 3-cm-long gas-filled capillary discharge waveguide

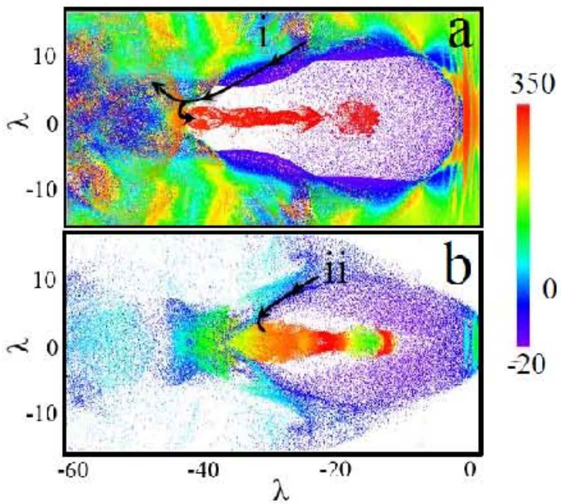


The horizontal axis is the beam energy and the vertical axis is the beam size. The 0.5 GeV (1.0 GeV) beam was obtained in the 225 (310) μm capillary with n= 3.5×10^{18} (4.3×10^{18}) cm^{-3} and laser power of 12 TW (40 TW).

W. P. LEEMANS et al., Nature Phys. 2, 696 (2006)

Ionization during the interaction

Experiment+simulation(theory) =CUOS(MICHIGAN)+VNIITF+FIAN
Phys.Rev.Lett. 104, 025004 (2010)

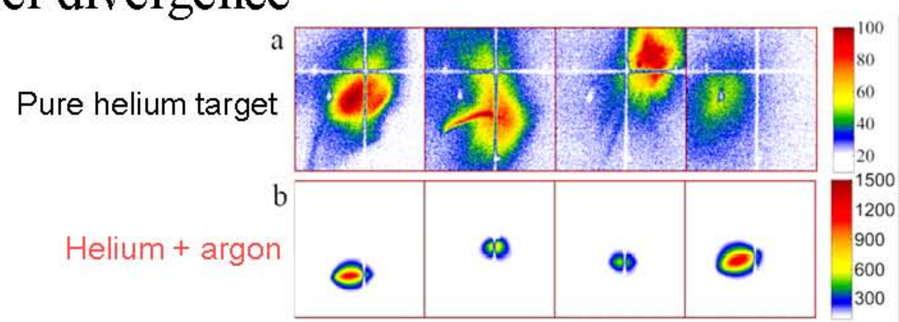


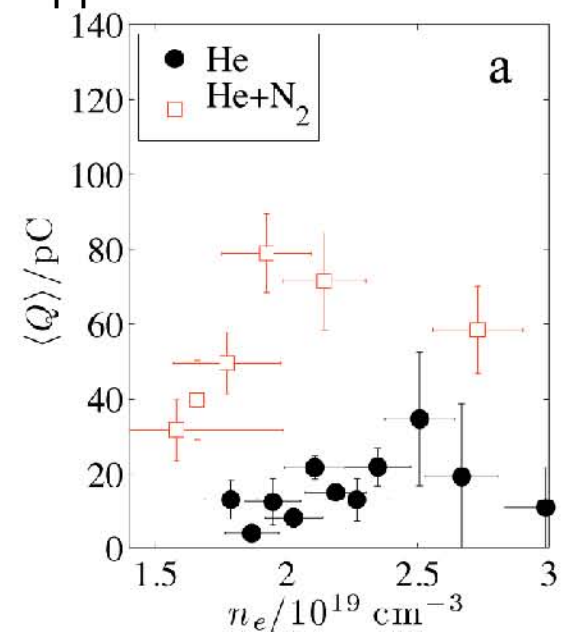
Simulation

a) Pre-ionized electrons are expelled by laser, most oscillate without trapping, few trapped

b) Electrons born near peak are more likely to become trapped

→ Better injection → increased charge
→ Lower divergence





How far can laser-plasma acceleration go?

Wei Lu, "Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D **nonlinear** regime," *Phys. Rev. Special Topics -Accelerators & Beams* **10**, 061301 (2007)

3D computer simulations increasingly guide development of future experiments

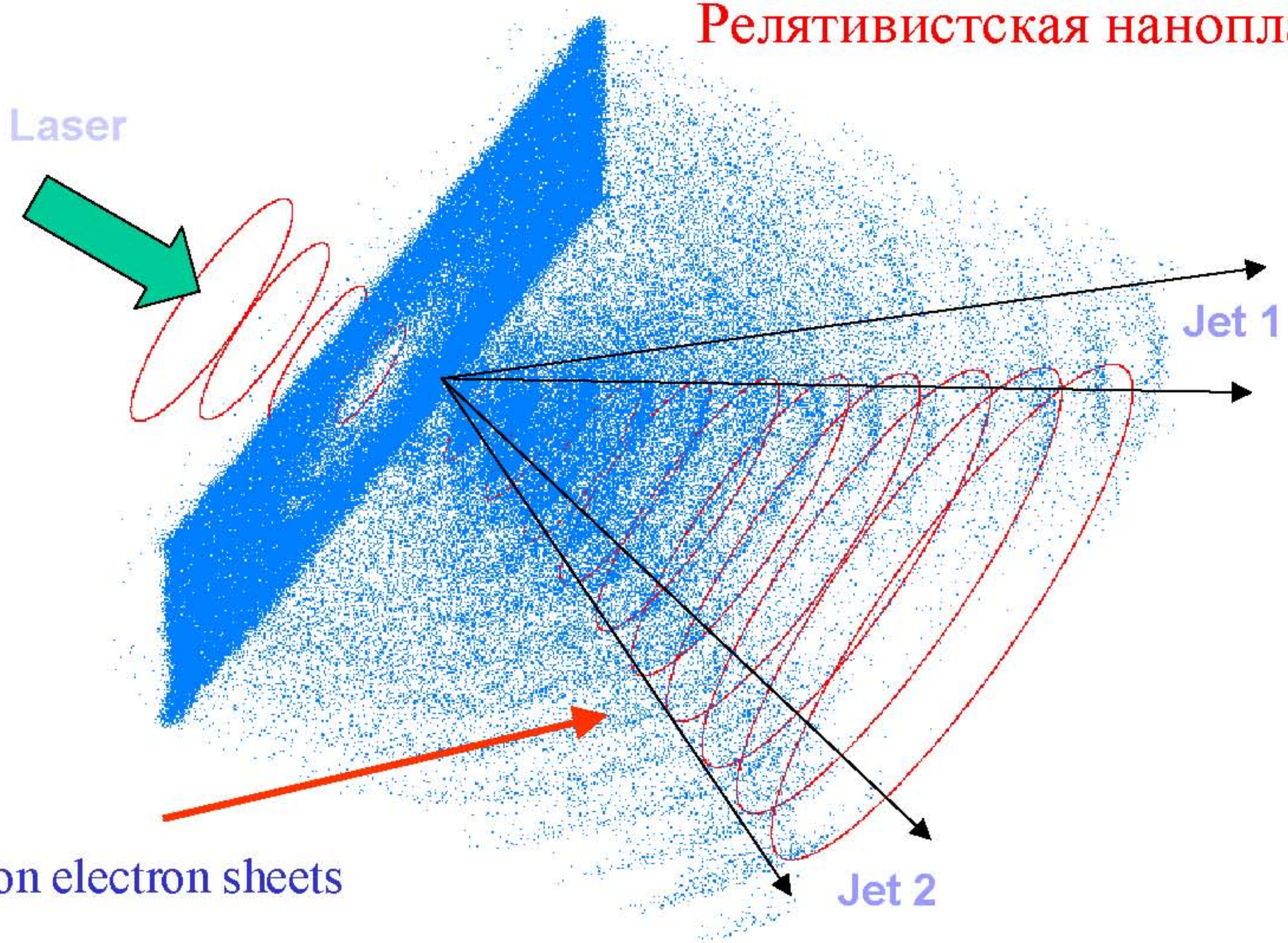
Laser Power [PW]	Pulse Duration [fs]	Plasma Density [cm^{-3}]	Spot Size [μm]	Int. Length [m]	e- charge [nC]	Energy Gain [GeV]	comments	
0.04	30	1.5×10^{18}	14	0.011	0.25	**0.95**	channel-guided, self-injected Leemans (2006)	
1.0	**80**	5×10^{17}	**34**	**0.08**	**1.3**	**5.7**	**self-guided, self-injected**	Texas Petawatt
2.0	100	3×10^{17}	47	0.18	1.8	10.2	self-guided, self-injected	
2.0	310	10^{16}	140	16.3	1.8	**99**	**channel-guided, externally injected**	
40	330	4×10^{16}	146	4.2	8	106	self-guided, self-injected	
20	1000	10^{15}	450	500	5.7	999	**channel-guided, externally-injected**	

Table entries feature:

1. *stable plasma structure*
2. $L_{dephasing} = L_{pump\ depletion}$
3. *balance between energy extraction & beam quality*

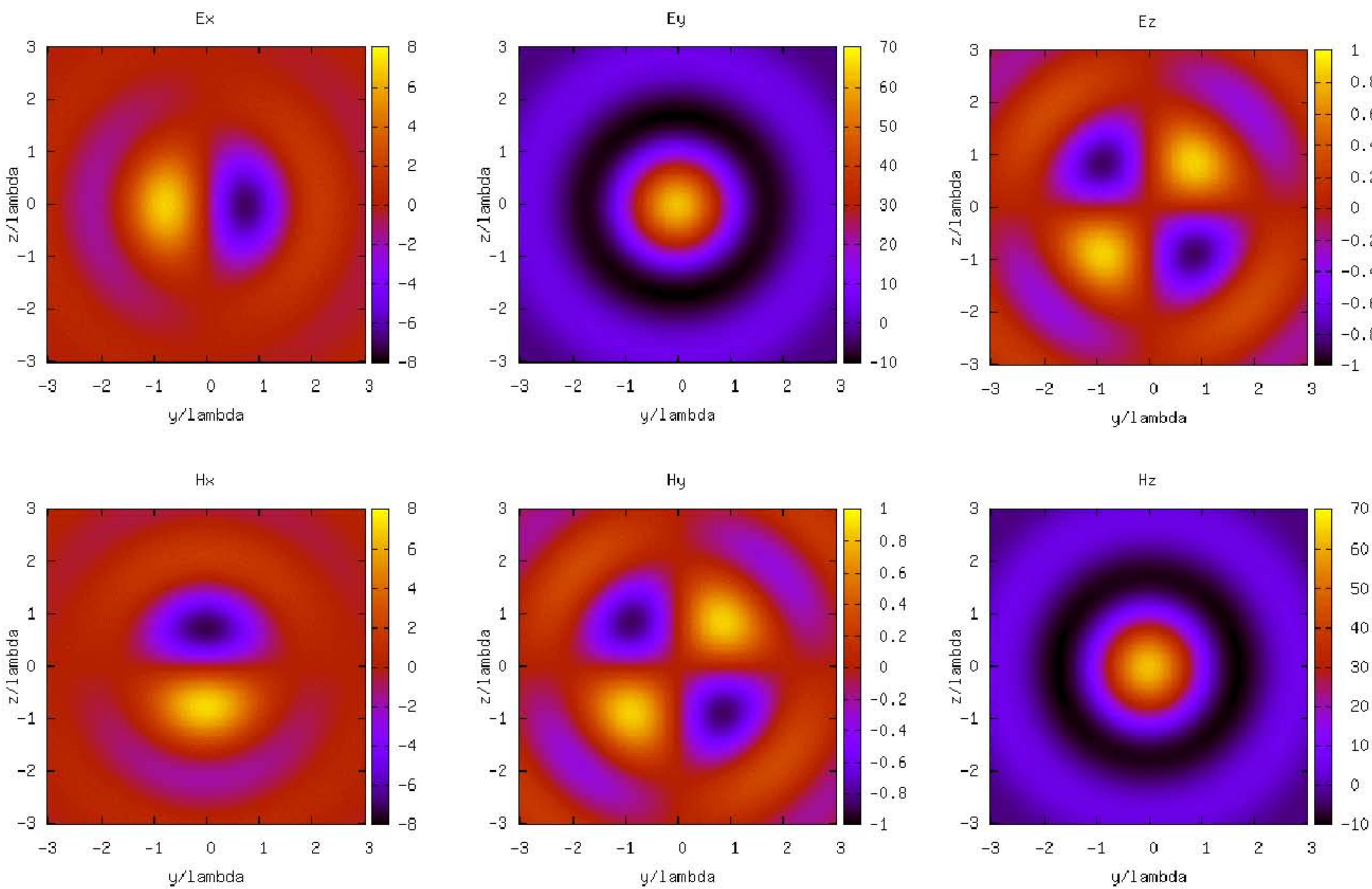
Interaction with an ultrathin foil

Релятивистская наноплазмоника



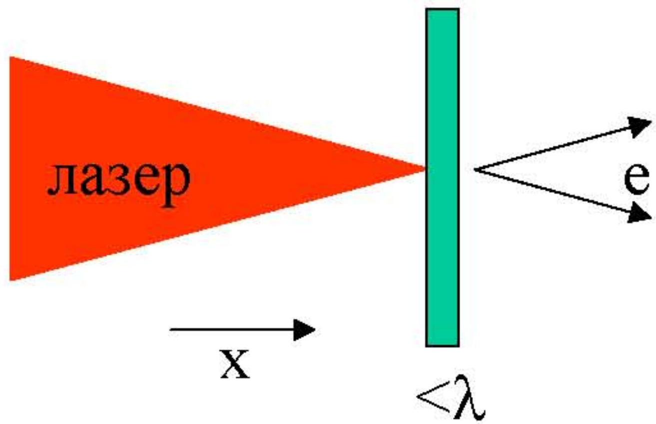
Typical foil parameters: $n = 50\ n_{cr}$, foil thickness $\delta \sim 80 - 120$ nm

Electromagnetic field in the focus

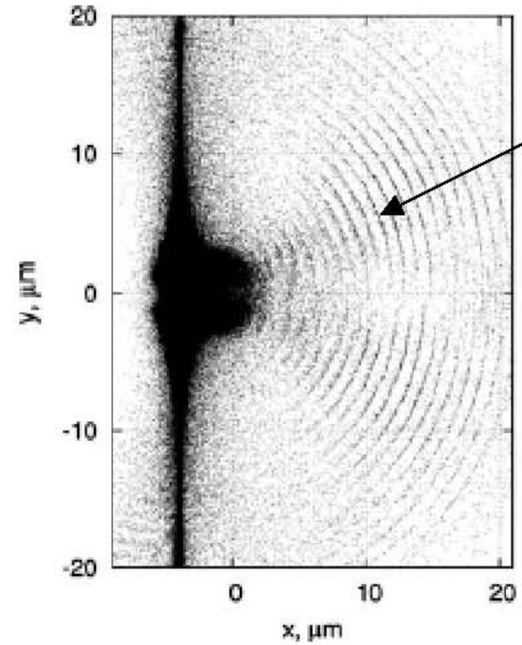


Фокусировка на дифакционном пределеб $D \sim \lambda$

Электроны «вперед» из ультра-тонких пленок

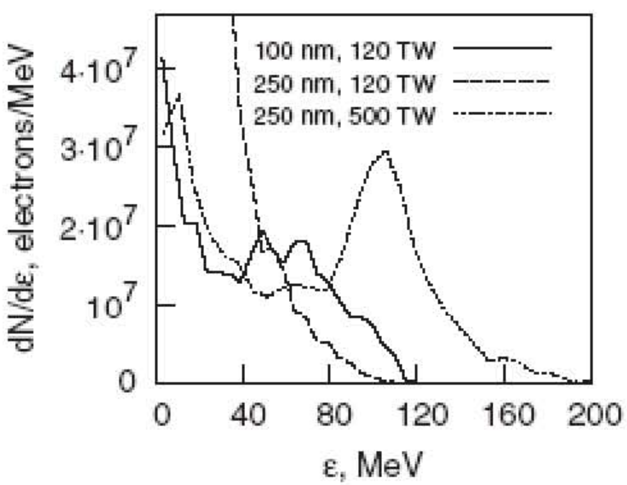


3D PIC



Субмикронные слои (релятивистские зеркала for tunable ultra-short X-ray source)

$n = 100n_{cr}$
~30 fs
120 TW
$f/1$



$$a(x,t) = a_0 \exp[-(x/c-t)^2/\Delta T^2]$$

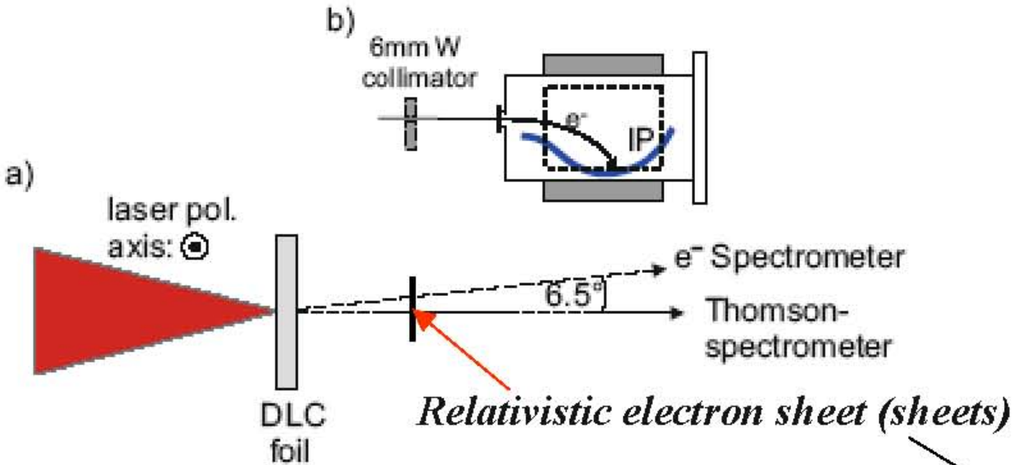
$$\delta t_n = \frac{T}{2\pi}\arccos\left(\frac{\exp[-(nT/\Delta T)^2]}{\exp[-((n-1)T/\Delta T)^2]}\right)$$

$$\Delta N \approx \frac{\Delta E_x R^2}{e} = \Delta a_x \frac{2\pi mc^2 R^2}{\lambda e^2}$$

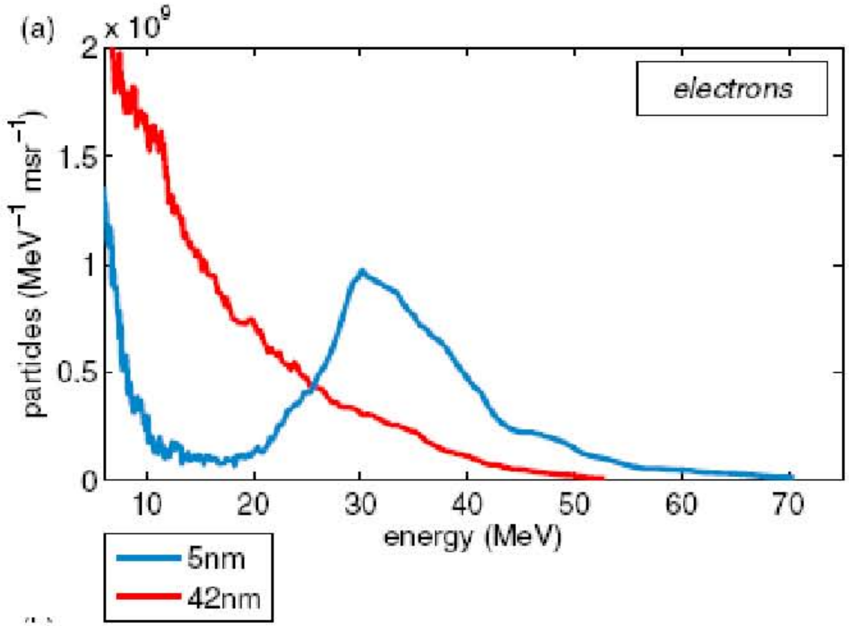
квазимоноэнегетичность только для достаточно тонких фольг

K. I. Popov et al., PHYS. PLASMAS 15, 013108 (2008)
K. I. Popov et al., PHYS. PLASMAS 16, 053106 (2009)

Электроны из ультра-тонких пленок (эксп.)



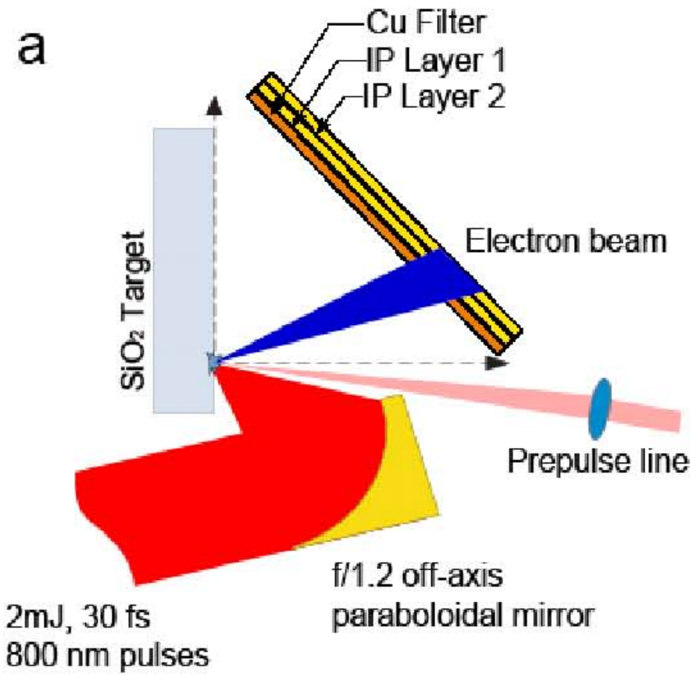
LANL, “Trident”,
90J, τ=500fs,
λ=1.053μm, D=9 μm,
I=$2\cdot10^{20}$W/cm^2, (a=12)
DLC targets

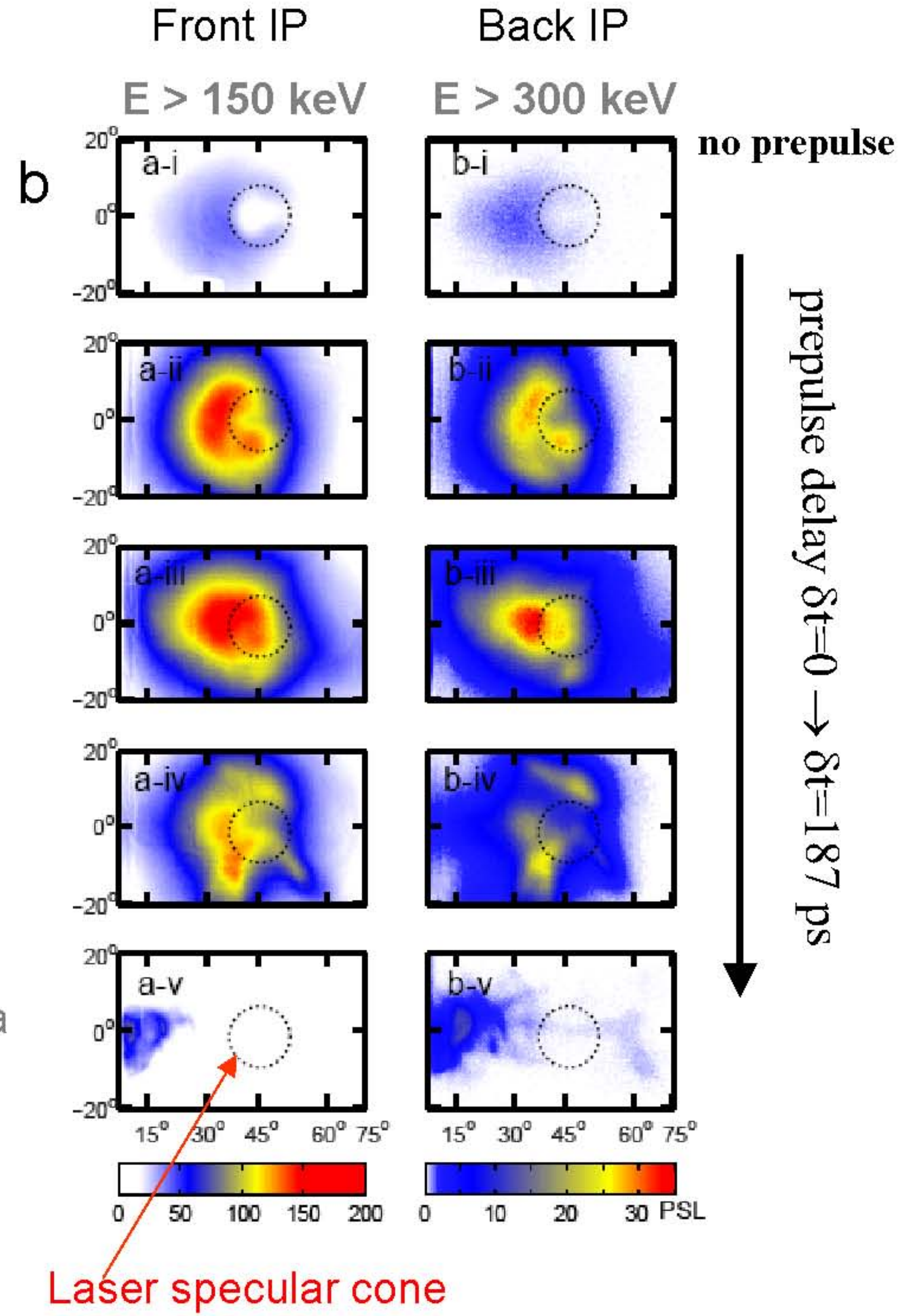


Tunable ultra-short
X-ray source

D. Kiefer1 *et al.*, Eur. Phys. J. D **55**, 427 (2009)

Толстая SiO_2 мишень, электроны «назад»





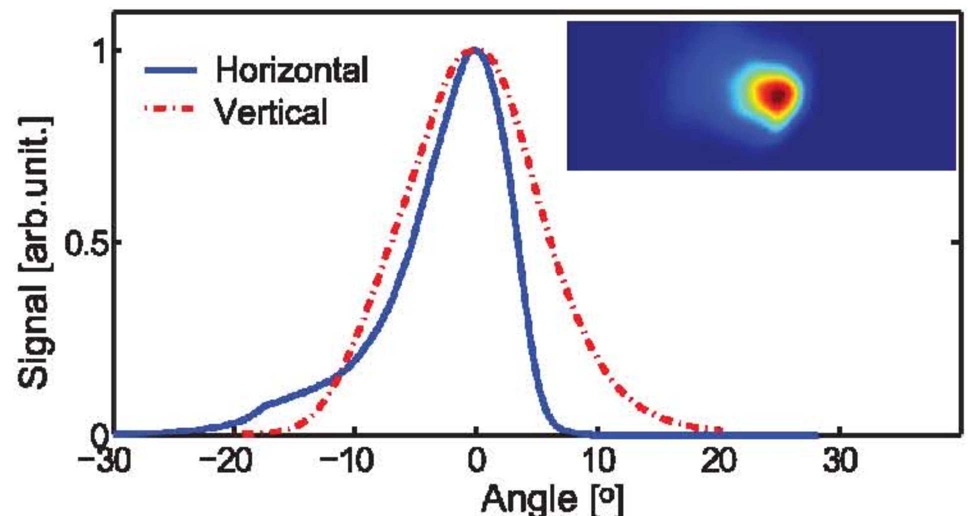
I. Well collimated e^- beam between specular and normal

II. Electron signal increases with δt to a max at ~ λ/2; For > λ/2 scale-length the beam broke up, toward normal

III. Electrons evacuated along the laser axis: direct acceleration of femtosecond e^- bunch

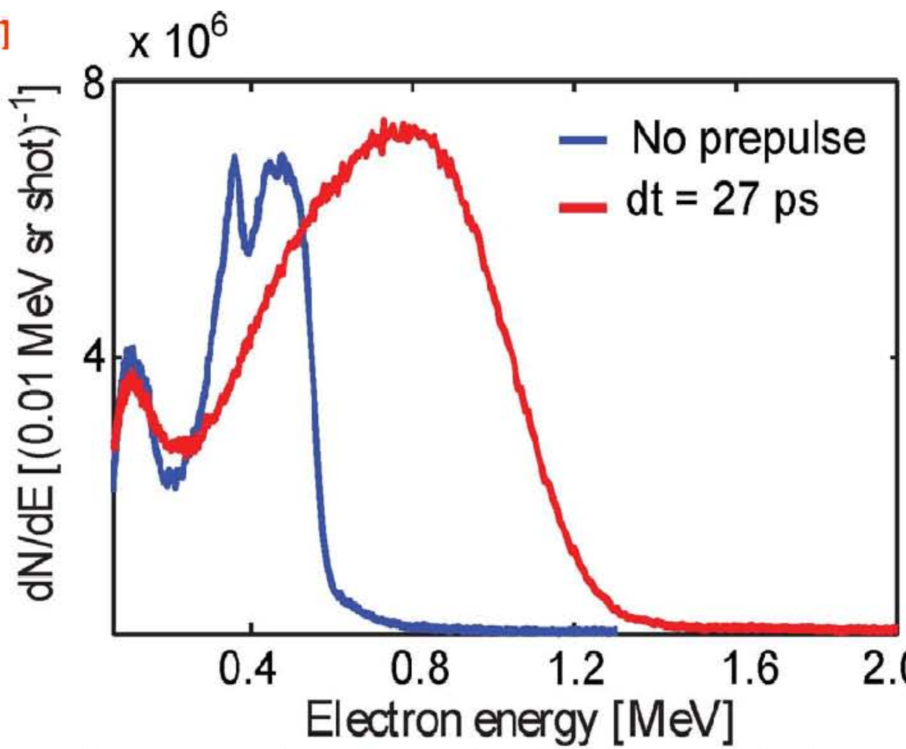
Beam Profile

- For E> 300 keV, FWHM intensity of the e- beam has a divergence of ~15°
- Total charge in the beam ~7pC



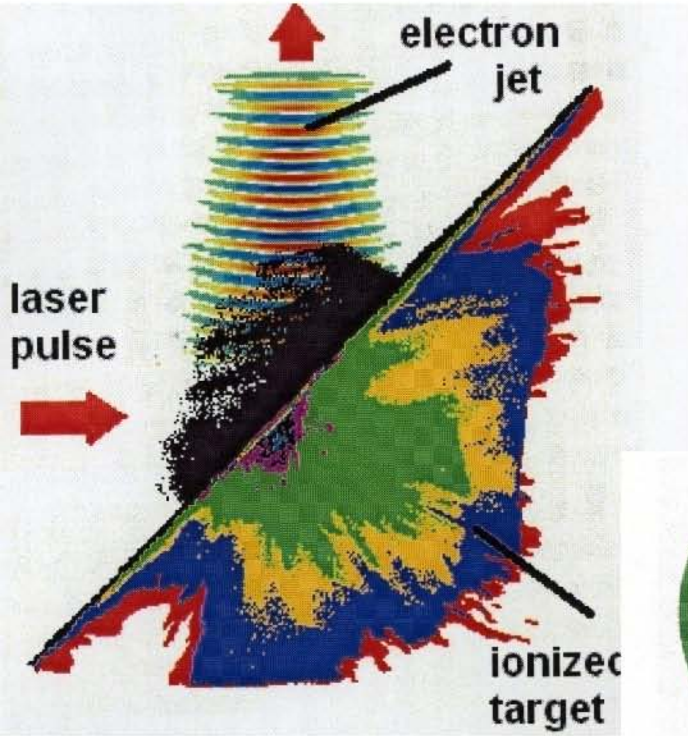
Energy Distribution and Scale-length: "*Quasimonoenergetic*" Bean

- Non-Maxwellian spectra with a double-peaked structure for short and intermediate scale-length
- High-energy peak becomes hotter with increasing scale-length to a max at λ/2
- At $L_n \approx \lambda/2$, E_{peak} = 780 keV
- For long scale-length, distribution is close to a Maxwellian



Averaged over up to 250 laser shots

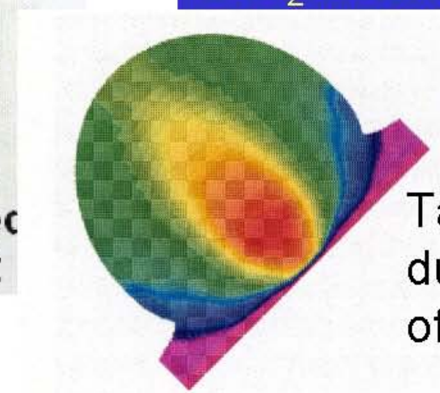
Collimated relativistic electron jets from field ionization



2D Hybrid Code PICNIC (RFNC-VNIITF, Russia, I. Glazyrin et al.)

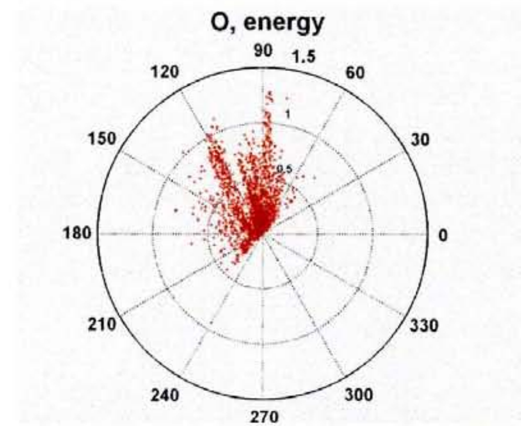
3 mJ, 32 fs pulse
R_f=1.2 μm
P-Polarization

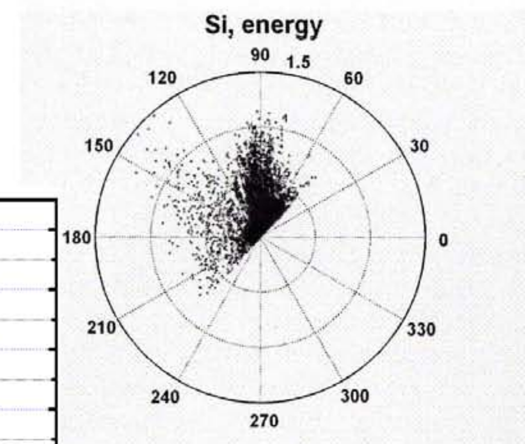
SiO_2 massive target

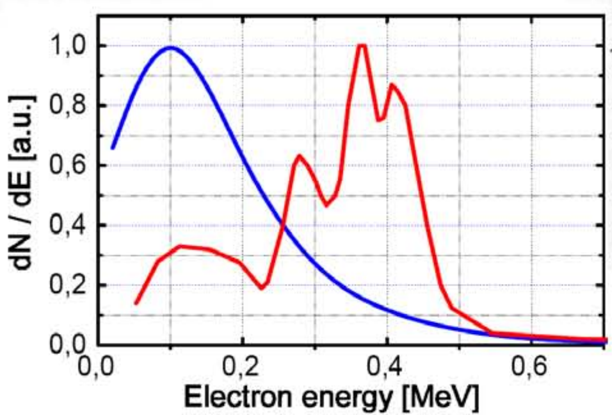


Target expansion during prepulse of 20 ps

e$^-$ bunches from O and Si

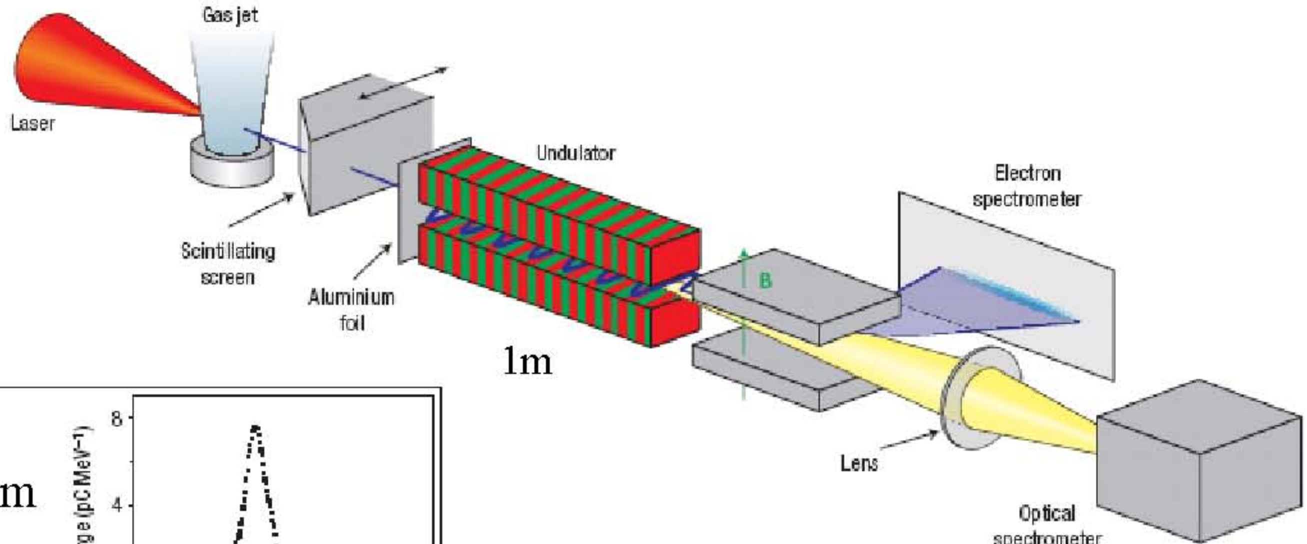


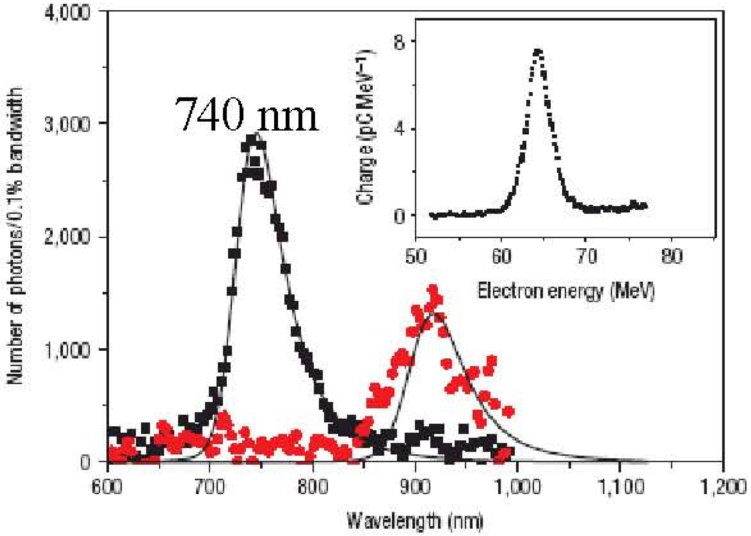




Experiment+simulation(theory)
CUOS(MICHIGAN)+VNIITF+FIAN
Phys.Rev.Lett. 235001 (2009)

Compact synchrotron radiation source





JETI (Jena), Ti:Sa ,

80 fs 5×10^{18} Wcm^{-2}

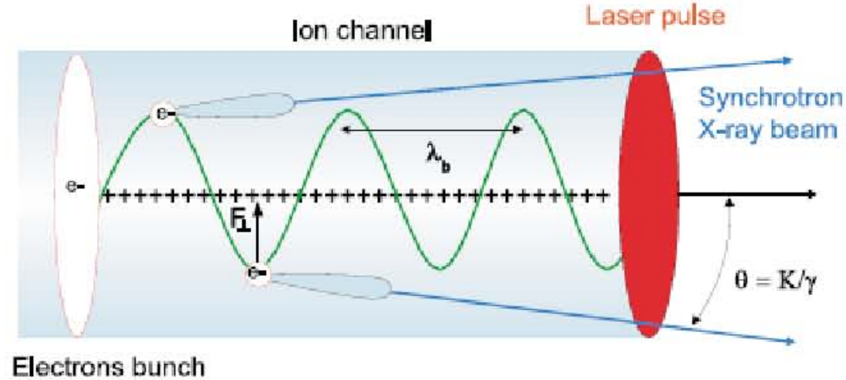
Undulator radiation spectrum and corresponding electron spectrum
Black – from 64 MeV, 28 pC electron bunch
Red – from 58 MeV, 14 pC electron bunch.

H.-P. SCHLENVOIGT et al., Nature physics **4** 130 (2008)

Betatron Motion in LWFA Plasma

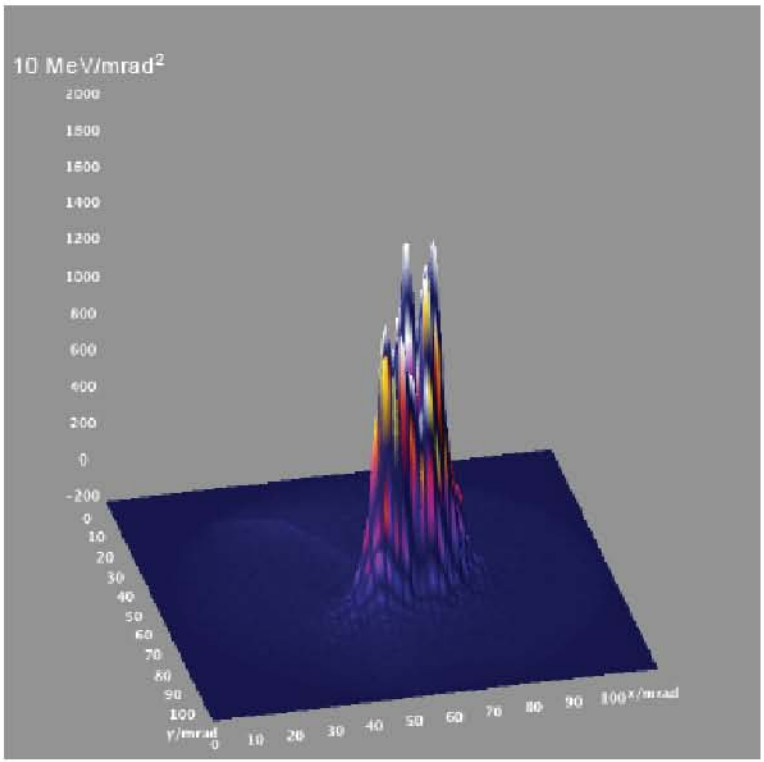
Kneip et al. Proc. SPIE 7359 73590T (2009)

Betatron motion in ion channel

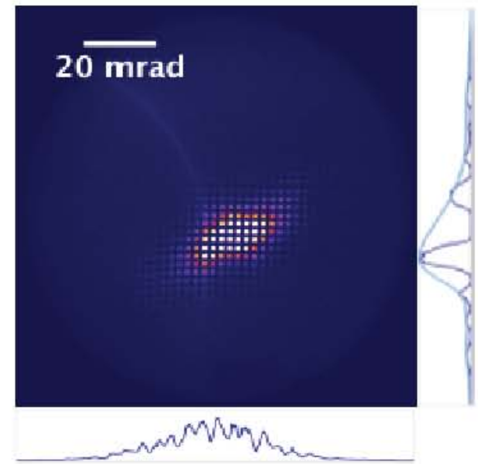


Significant size reduction can be achieved by using LWFA plasma as a source for x-ray beam

A narrow x-ray beam ($\theta_x < 4$ mrad) is observed.

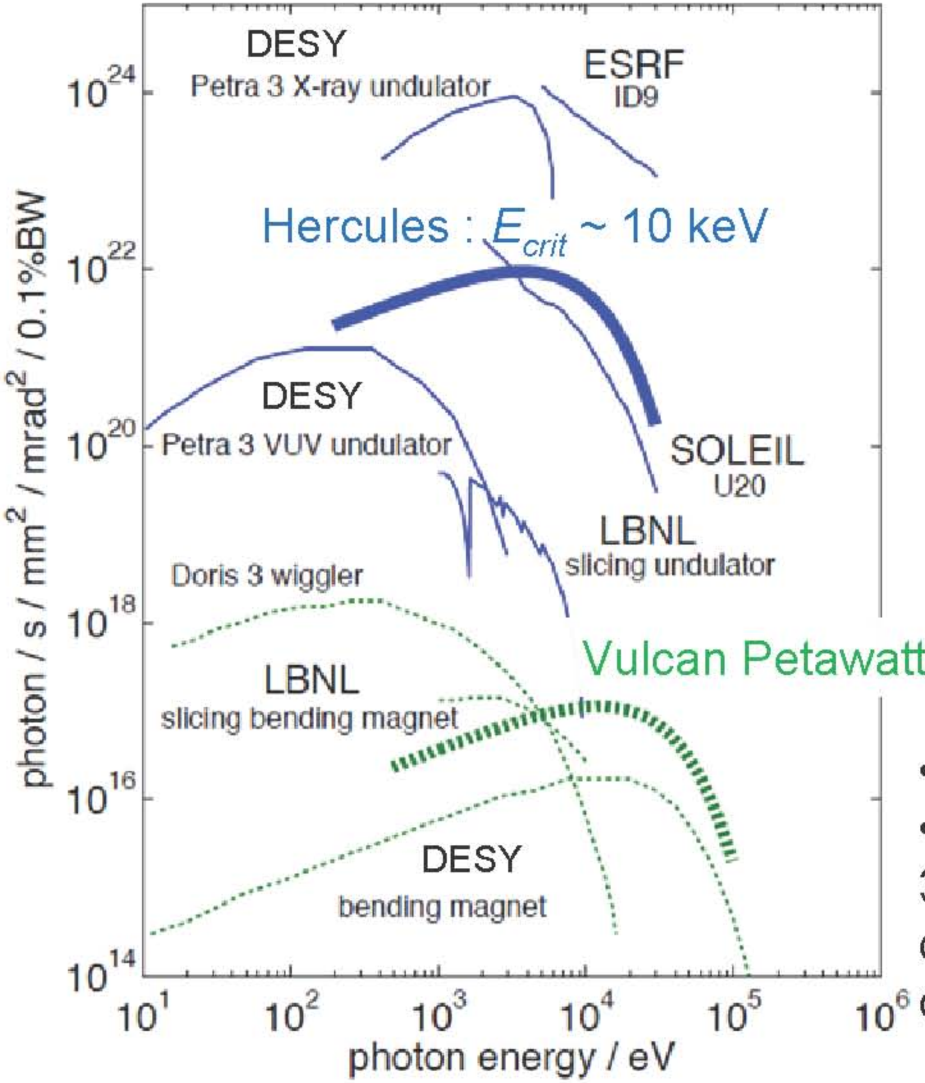


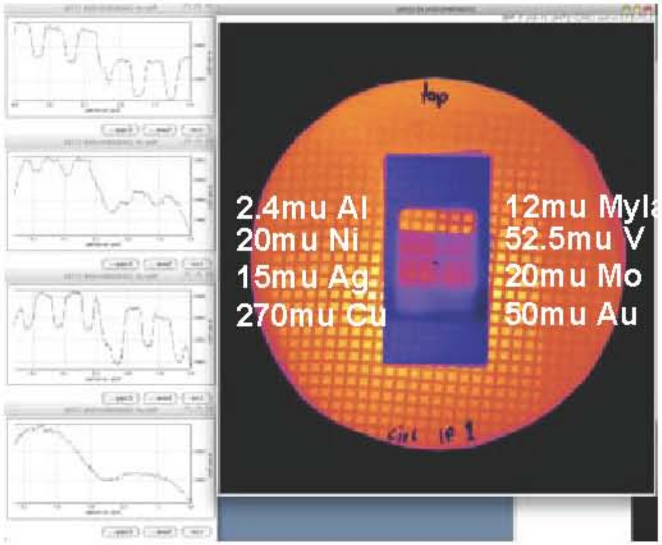
Nozzle dia. 5 mm
$N_e = 5\times10^{18}$ cm^{-3}
$a_0 \sim 5$



- $\theta_x = 12 mrad$
  $\theta_y = 4 mrad$
- Electrons: 220 MeV $\gamma = 440$
- $K = \gamma\theta$
- K_x=5, K_y=1.5
- ~10^9 photons at 1 keV

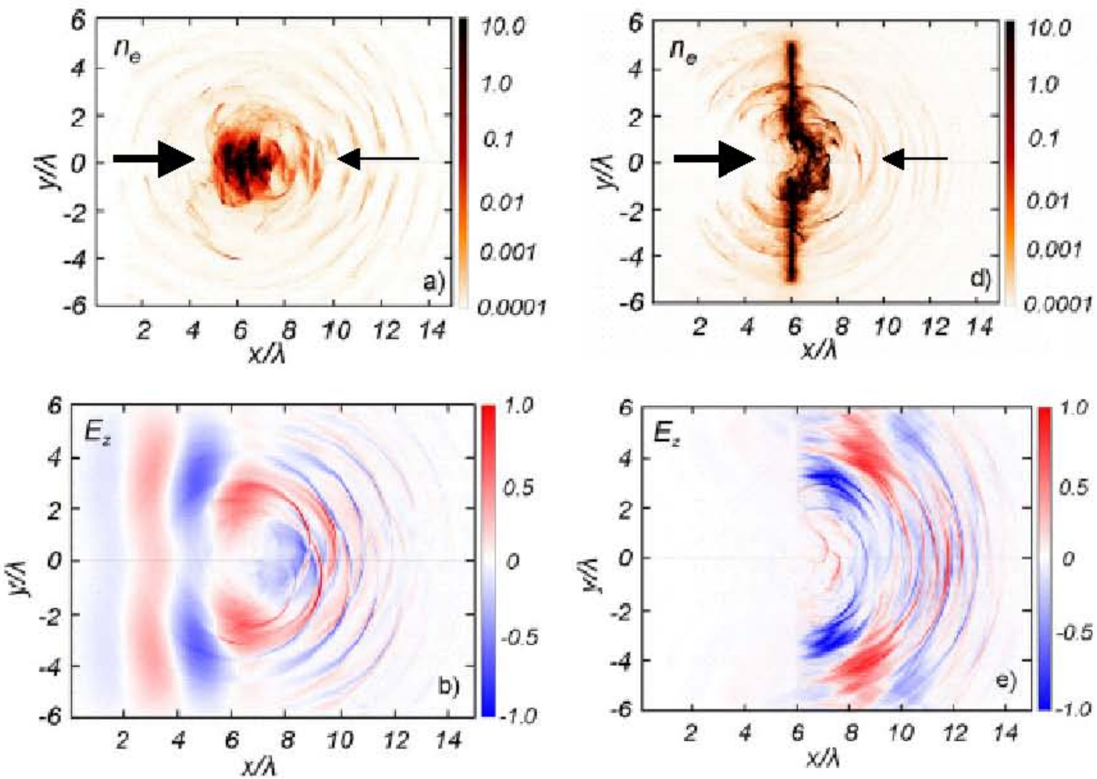
Peak brightness comparable to 3rd generation light sources.

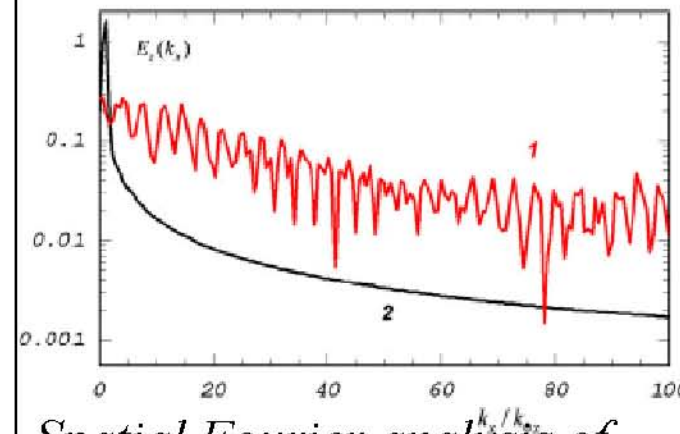




- Some shots shows E_{crit} ~ 40 keV
- The brightness is calculated by assuming 30 fs duration of x-ray pulse which is the duration of 400 MeV electron beam observed

X-ray source with relativistic mirrors



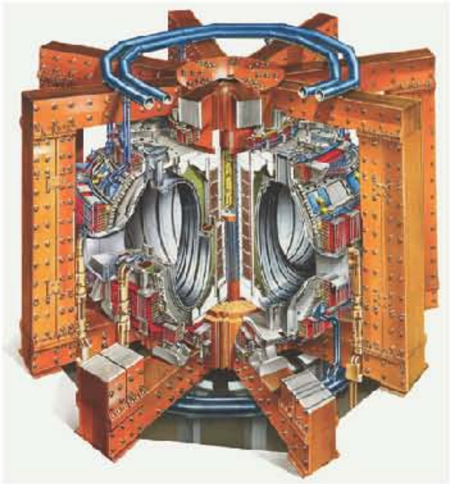
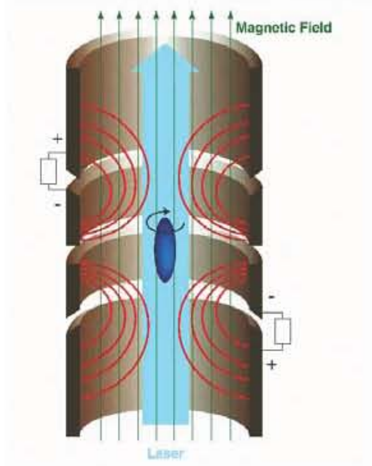
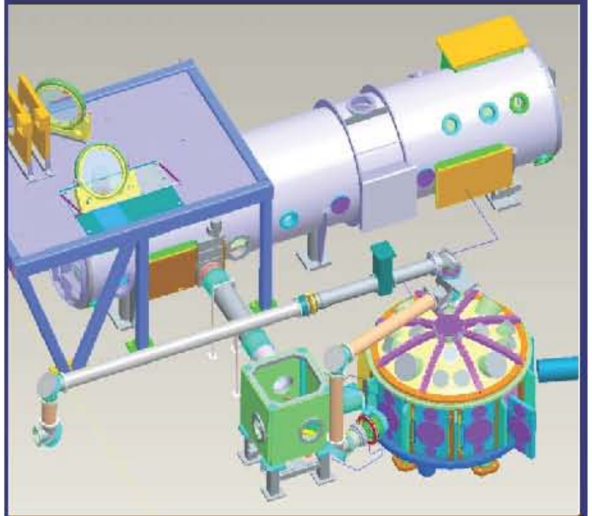


Spatial Fourier analysis of the reflected (red) and incident (black) pulses in the case of a mass limited target.

A mass limited target (a, b) and a thin foil (d, e). The electron density distribution and the distribution of counterpropagating pulse electric field after reflection.

S.S.Bulanov et al., Phys. Lett. A 374, 476 (2010)

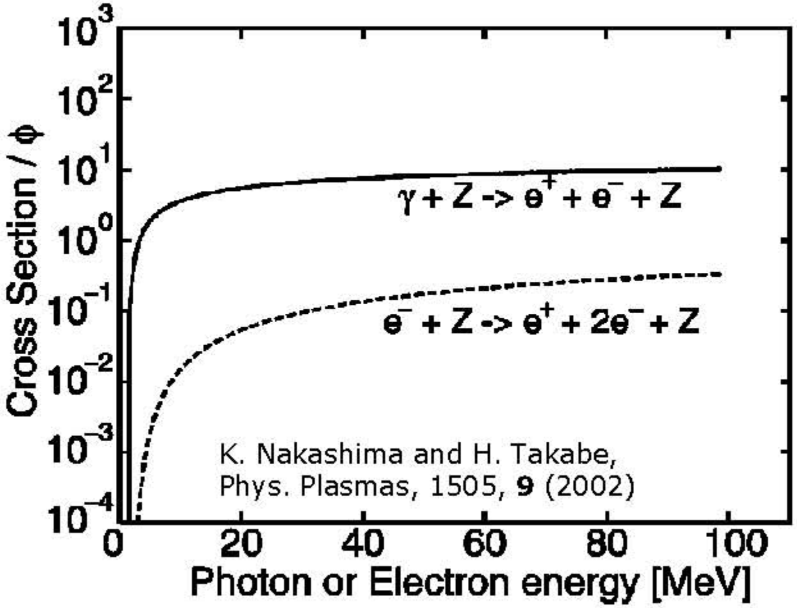
Positron Creation Using Ultra-intense Lasers

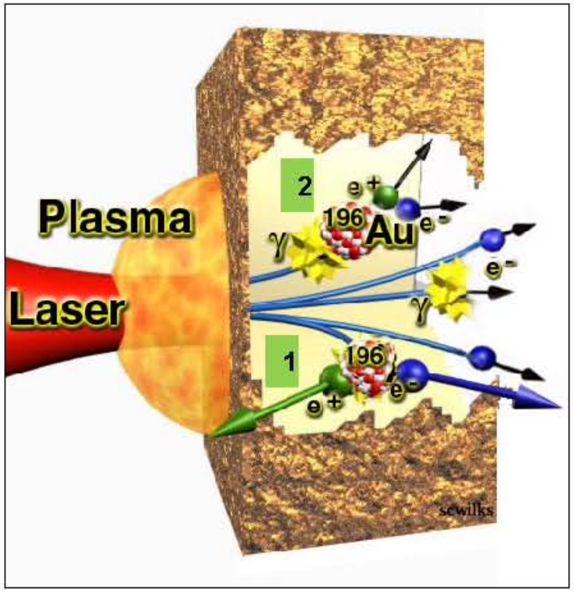
Tokamaks	Penning-Malmberg Traps	Ultra-intense Lasers
	 	
Theory only $N_{e+} \sim 8 \times 10^{14}$ $V \sim 2.7 \times 10^{7}\ cm^{3}$	Experimental $N_{e+} \sim 8 \times 10^{7}$ V ~ 6 cm x 1 mm(D.)	Titan laser $N_{e+} \sim 10^{11}$ V ~ 1 mm x 1 mm(D.)
$3.3 \times 10^{7}\ cm^{-3}$	$4 \times 10^{9}\ cm^{-3}$	$1 \times 10^{14-15}\ cm^{-3}$

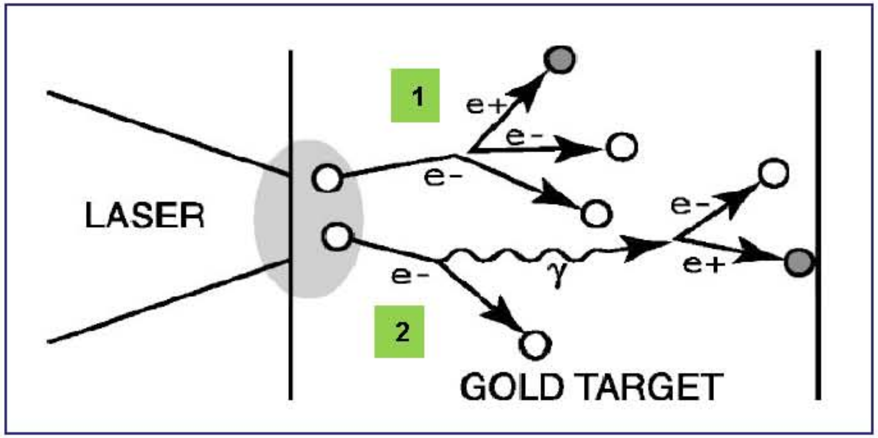
Could lasers create the highest density of positrons in the laboratory, by creating a large number in a short time (~ picosecond) ?

Two main processes involved in laser positron creation in the presence of high-Z nucleus

1. Direct (Trident) pair production
   $e^- + Z \rightarrow 2e^- + e^+ + Z$
   (Z: nucleus)
2. Indirect (Bethe-Heitler) pair production:
   $e^- + Z \rightarrow \gamma + e^- + Z$
   $\gamma + Z \rightarrow e^- + e^+ + Z$
   (γ: Bremsstrahlung)





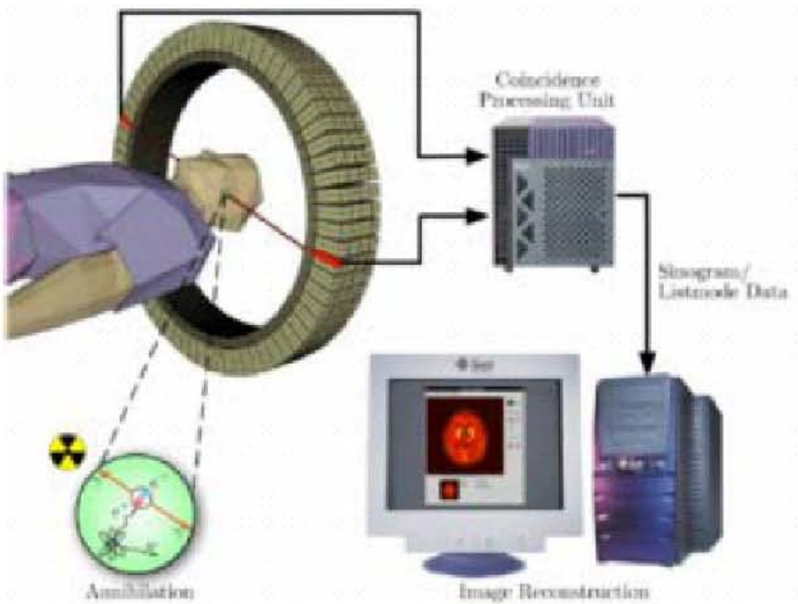


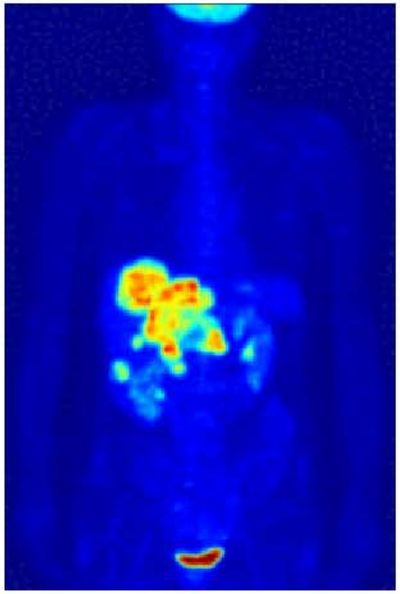
High energy (>MeV, relativistic) e^-s are the key to both processes

On-site production of short-lived isotopes for medical imaging

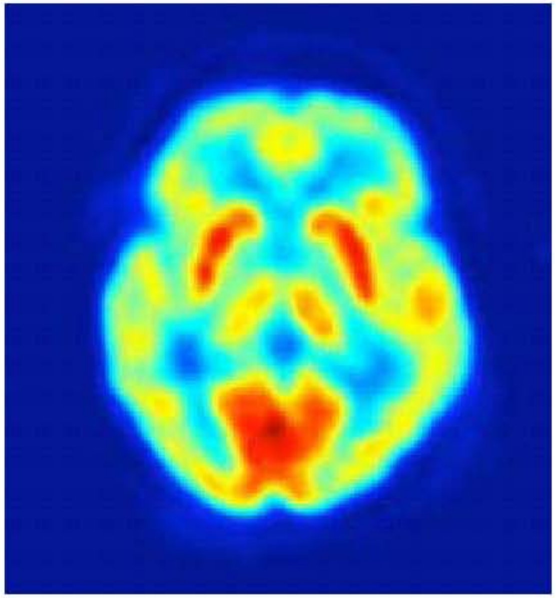
Limitations to the widespread use of PET arise from the high costs of cyclotrons needed to produce the short-lived radionucleotides for PET scanning .... Few hospitals and universities are capable of maintaining such systems ... *- Wikipedia -*

Positron Emission Tomography





^{18}F PET scan of tumor

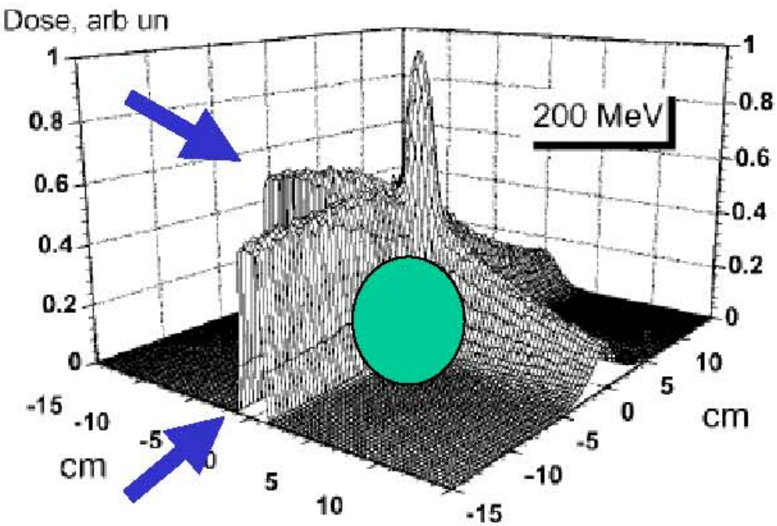


^{15}O PET scan of human brain

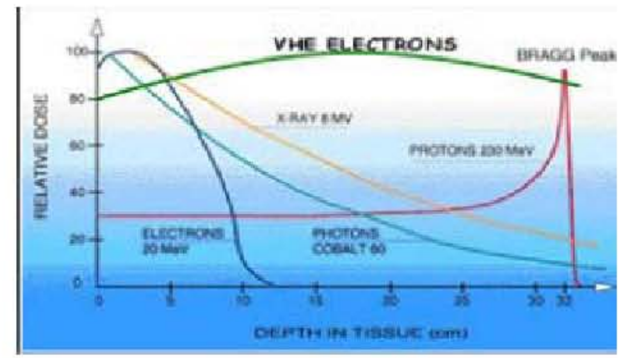
radiotracer	activation reaction	half-life	medical use
^{15}O	$^{16}O(\gamma,n)^{15}O$	2 minutes	neuro-imaging
^{11}C	$^{12}C(\gamma,n)^{11}C$	20 minutes	neuro-receptor-specific brain imaging
^{18}F	$^{19}F(\gamma,n)^{18}F$	110 minutes	clinical oncology

on-site production essential

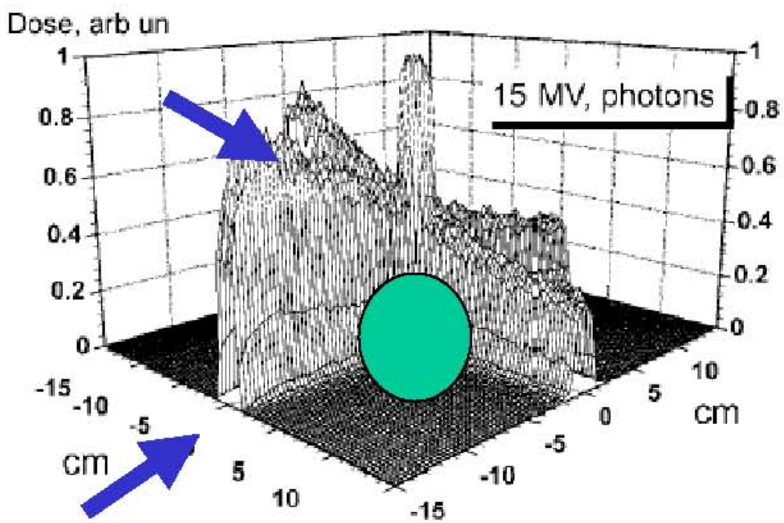
Electron beams in radiation therapy



Electron beam



Dose deposition



15 MV clinical accelerator

x-ray beam

C. DesRosierset al., Phys. Med. Biol. **45,** 1781 (2000)

Ускорение ионов

Цели:

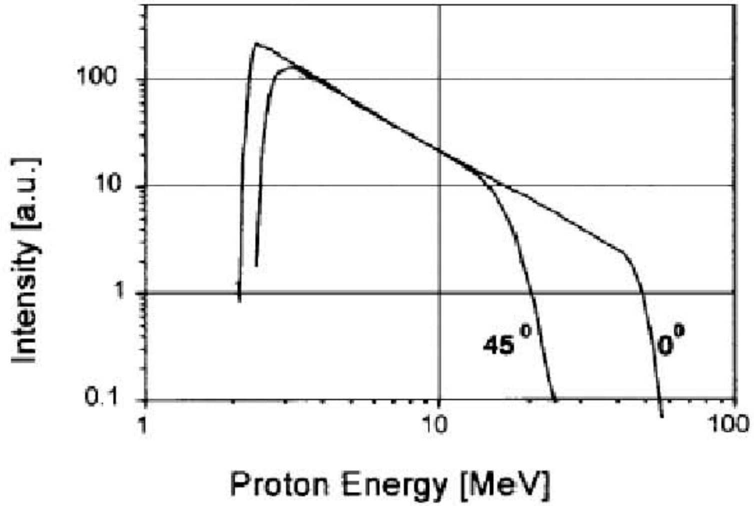
- Контролируемый источник высокоэнергичных ионов «на столе»
- ЛТС. Ion fast ignition
- Производство короткоживущих изотопов
- Вещество в экстремальных состояниях
- Радиография
- Инжектор для ионного ускорителя
- Адронная терапия
- Ядерная физика
- Астрофизика «на столе»
- Нейтронный источник
- Ионная имплантация

No significant increase in particle energies since first demonstrations

1 PW LLNL, 500 fs

450J, 3×10^{20} Wcm^{-2}

100-μm CH target

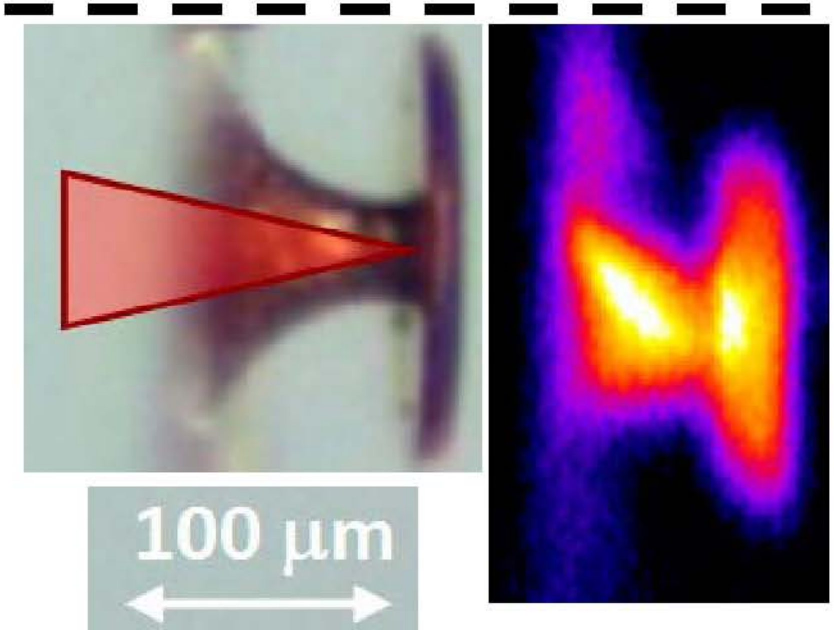


Protons with

E_{max}=58 MeV

R. A. Snavely et al., Phys. Rev. Lett. **85**, 2945 (2000)

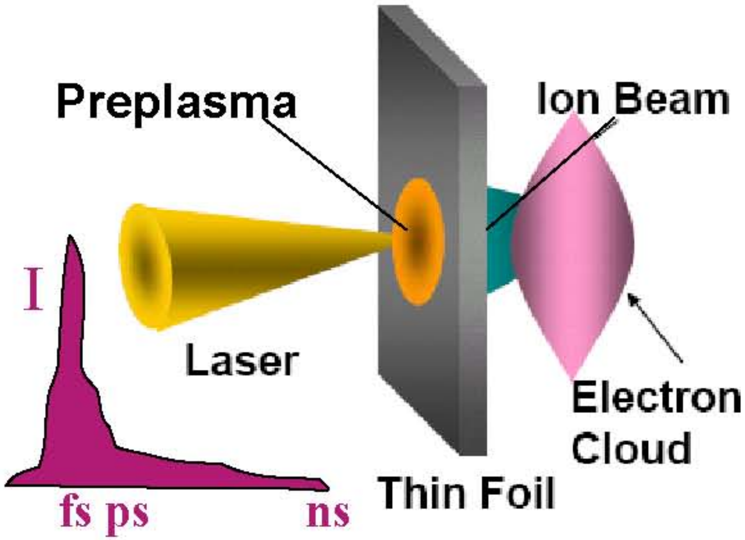
Newest result (APS DPP meeting 2009): "Trident", LLNL
150 TW, 500 fs
80J, 10^{20} Wcm^{-2}



Protons with

E_{max}=67 MeV

Электростатический механизм ускорения



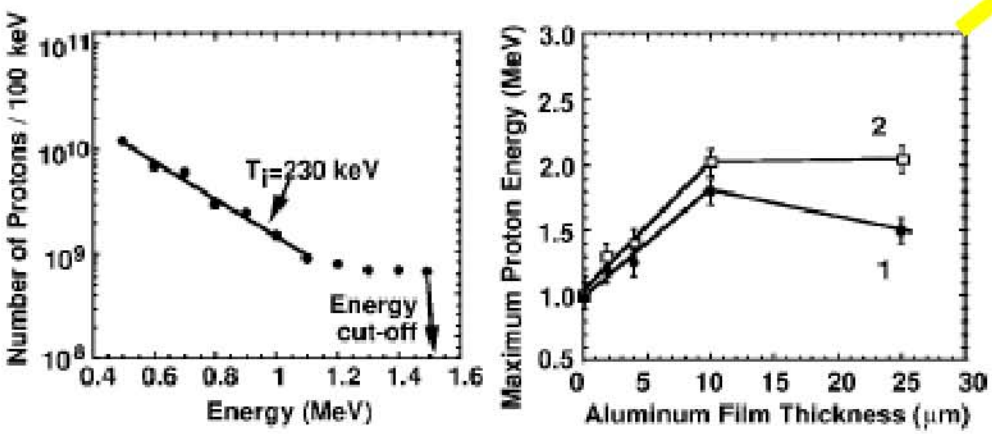
- Квазинейтальный разлет
- Двойной слой
- Кулоновский взрыв

I

Thin targets give higher ion energies but laser prepulse destroy the target!

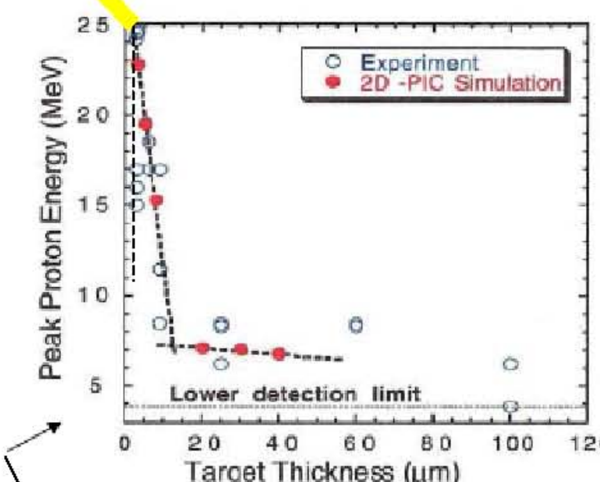
Типичный спект протонов «вперед» при невысоком контасте (<10 ^{8})

Улучшенный контраст



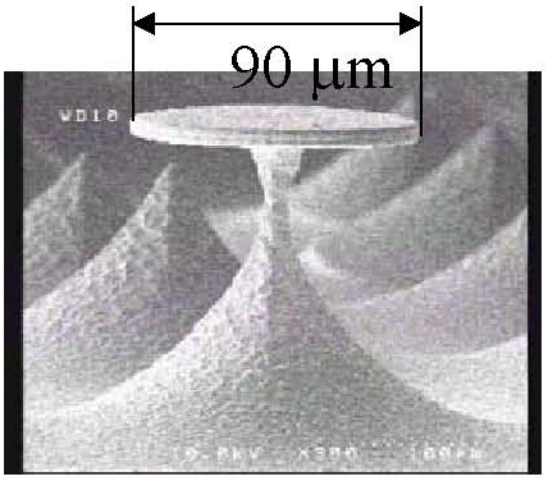
A.Maksimchuk et al., Phys.Rev.Lett 84, 4108 (2000)

The higher contrast the thinner target

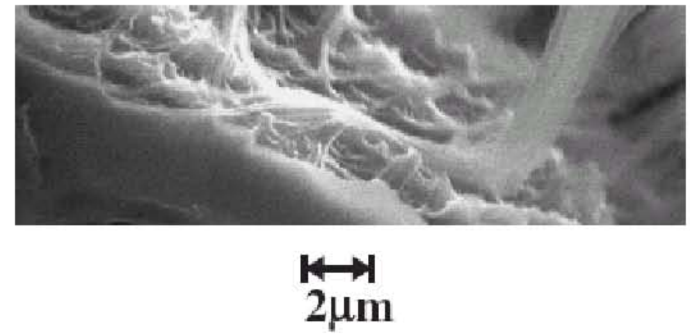


A.J. Mackinnon et al., Phys. Rev. Lett. 88, 215006 (2001)

Very sophisticated targets

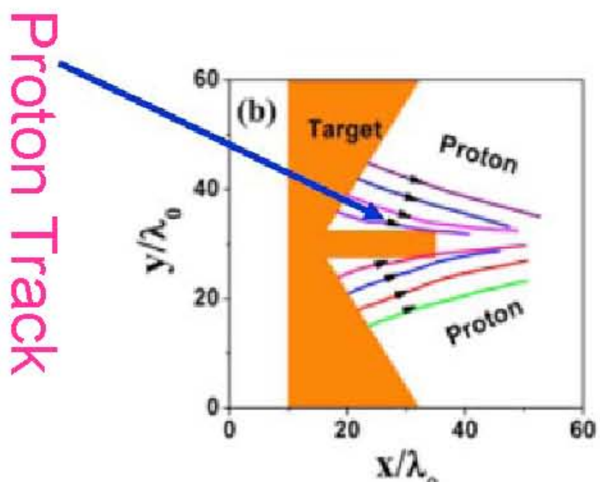


Pizza-Top Cone Target
«Trident» LLNL

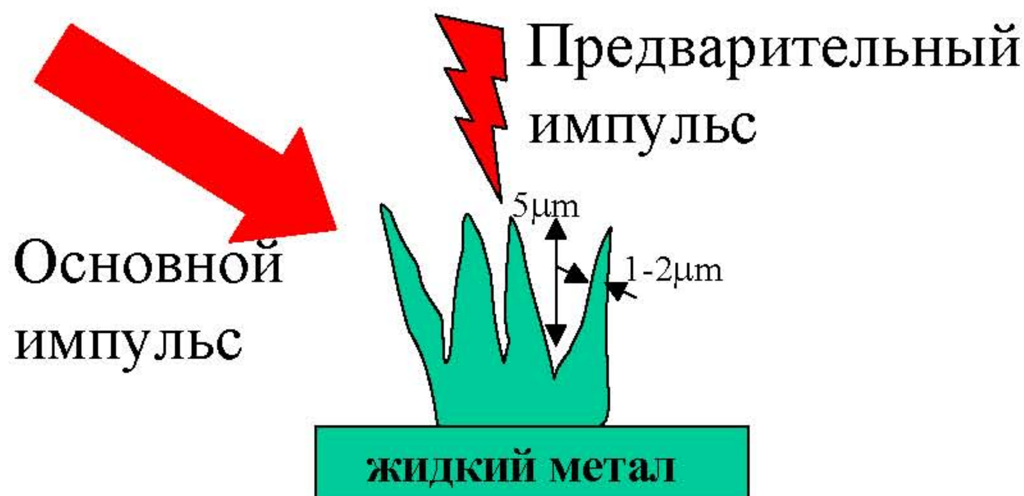


Poly tetra-fluoroethylene (PTFE) film with micro tips

Hamamatsu Photonics



Y. Y. Ma, et al., **Phys. Plasmas 16, 034502 (2009)**



МГУ

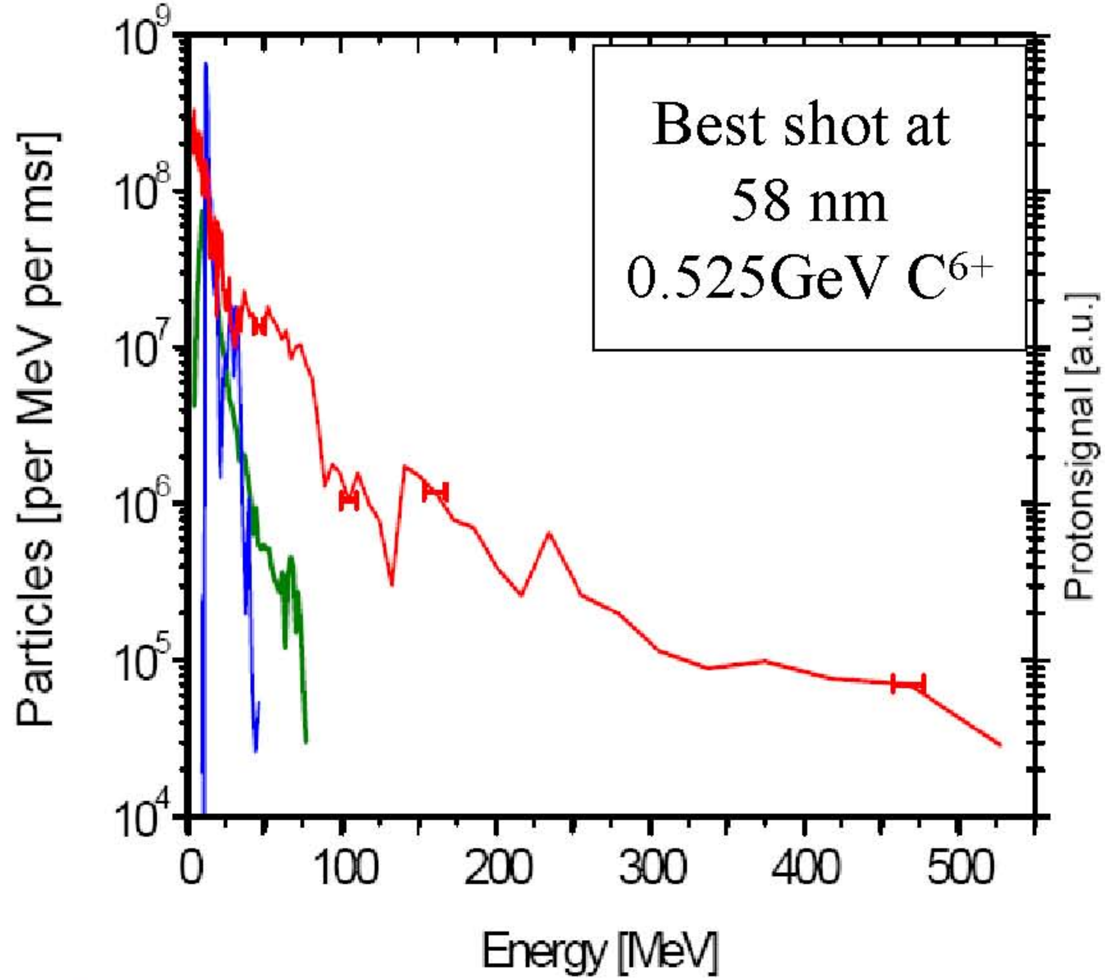
Most energetic ions from nm foils

Los Alamos NATIONAL LABORATORY Trident

2009

Surface cleaning

1. ***Heating***
2. ***Laser ablation***



E_{target} = 90.1J, t=540fs
I = 2x10 2x1020 20 W/cm²

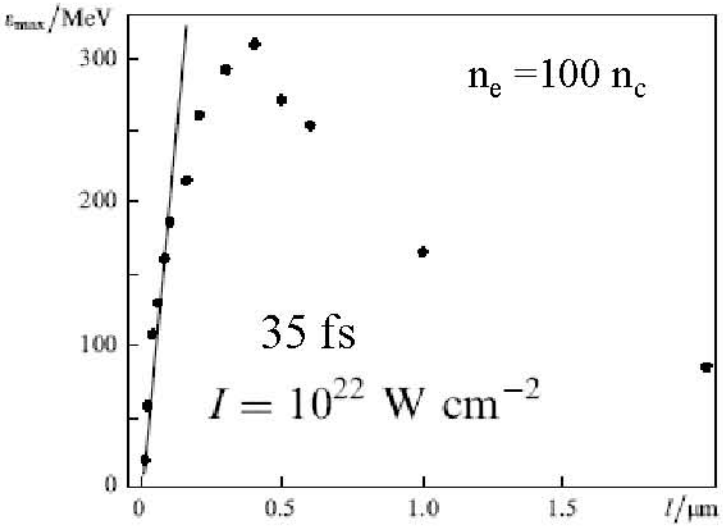
Short Prepulses ⇒ Contrast (I_{pp} / I_{ave}) < $5x10^{-10}$
Pedestal ⇒ Contrast (I_{ped} / I_{ave}) < $2x10^{-12}$

Optimal foil thickness

2D PIC simulation

Proton energy from H-foil target

There is an optimal thickness for given density and laser intensity



Brantov et al., Quantum Electronics **37** 863 (2007)

Relativistic transparency:

$$\frac{n_e l}{n_c \lambda} << a$$

$$\frac{n_e}{n_c}\frac{l}{\lambda} = 3 + 0.4a \qquad a = 0.85\sqrt{I\lambda^2 10^{-18}}$$

Esirkepov et al., PRL **96**, 105001 (2006)

$$a > \pi \frac{n_e}{n_c}\frac{l}{\lambda}$$

Condition of Coulomb explosion

$$E_{max} = \pi Z n_i e^2 l d$$

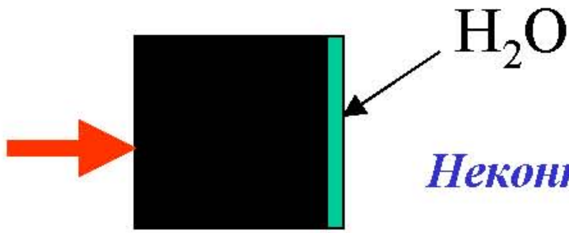
Maximum ion energy

Quasimonoenergetic ions.
Optimization of laser-target parameters

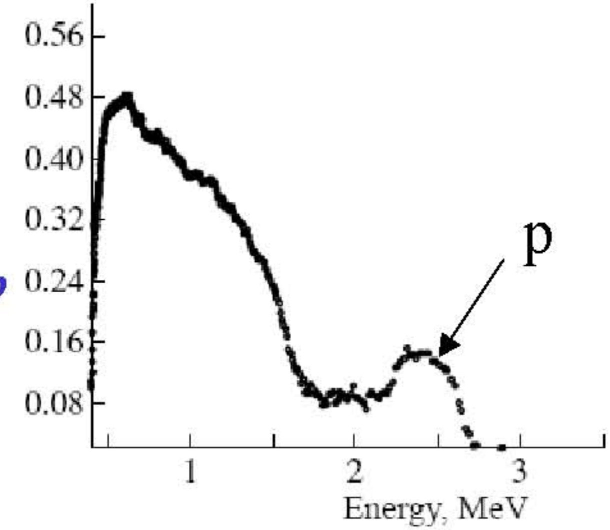
- Target thickness/density
- Target composition/design/shaping
- Mass limited target / foil
- Laser intensity/duration/polarization/focusing
- Laser hot sport Gaussian/Flat-top(super-Gaussian)

Двуслойные фольги

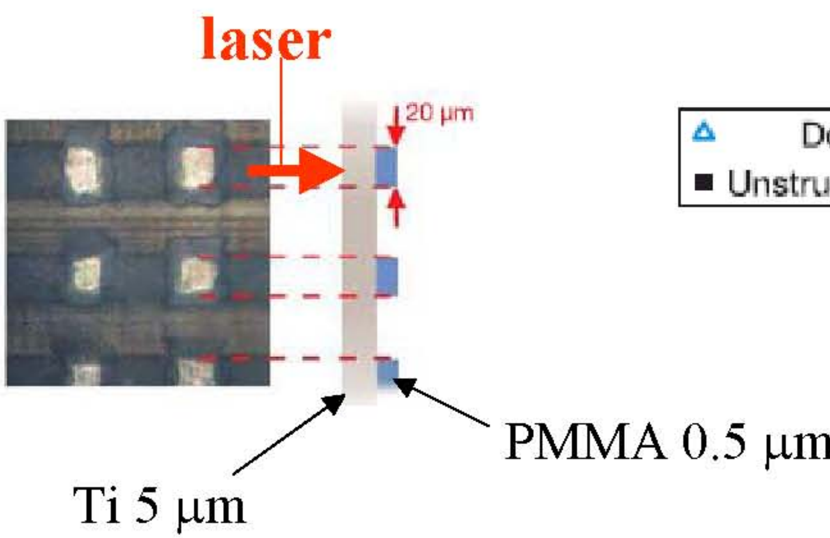
Естественное загрязнение

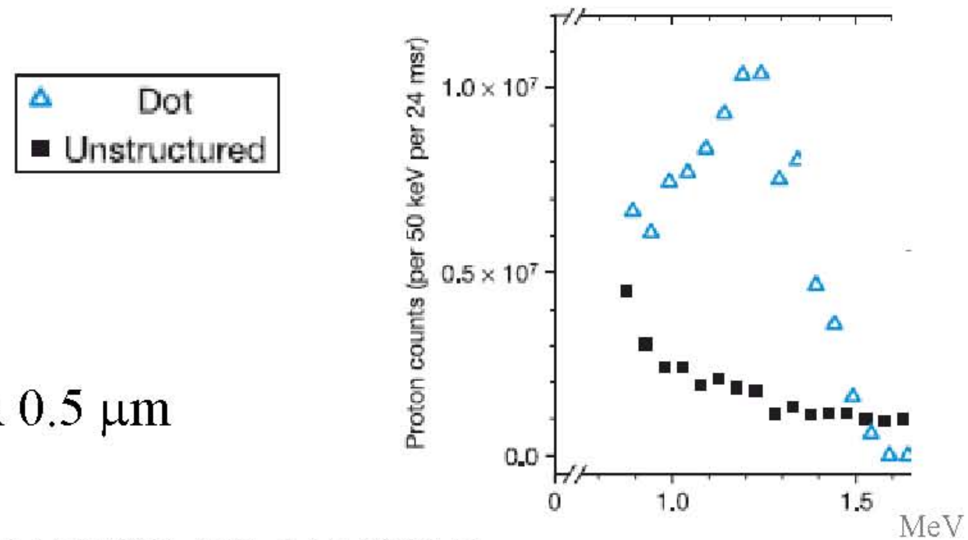


Неконтролиуемый спектр



Максимчук и др., Физика плазмы **30**, 514 (2004)

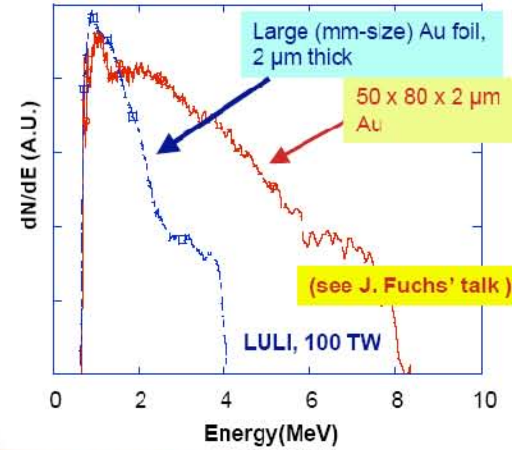


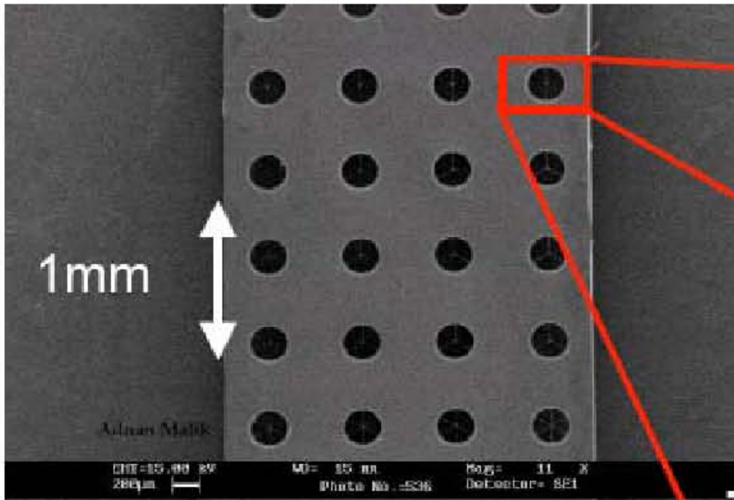


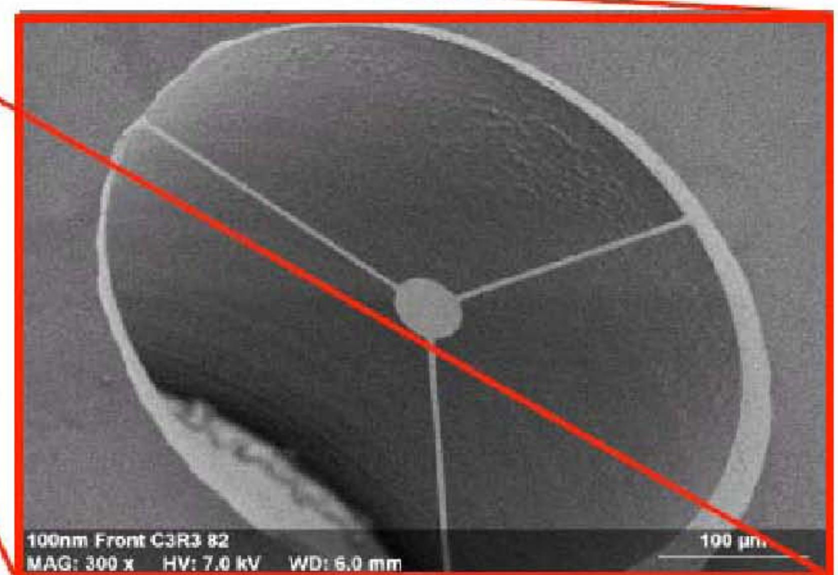
H. Schwoerer et al., NATURE **439**,445 (2006)

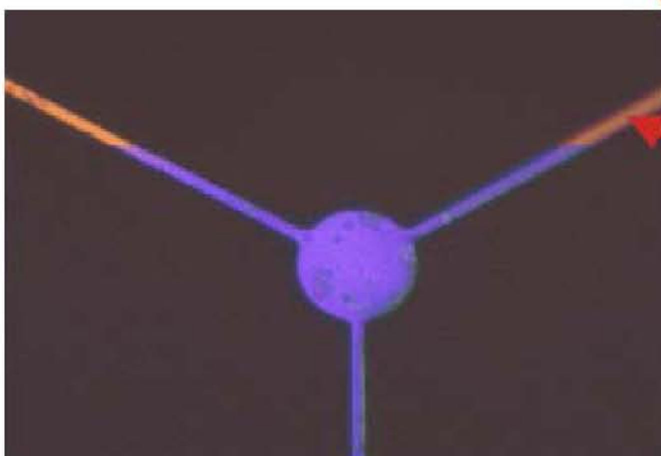
Mass-limited targets

RAL









Disks: 32um diameter, 40nm thick SiN membranes

Supporting wires: 1µm wide , 40 nm thick

Hole etched through 400µm thick Si.

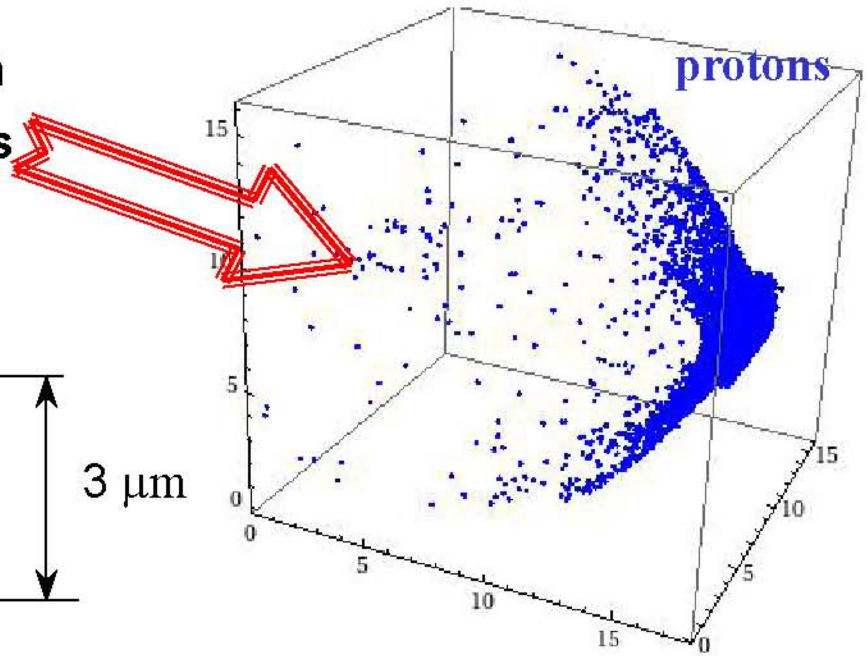
Potential for further miniaturization !

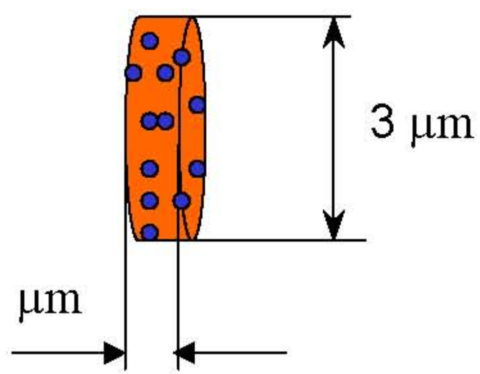
3D simulation of directed Coulomb explosion of mass-limited target

$I = 5\ 10^{21}$ W/cm^2

FWHM$_\perp$(D) = 4 μm

FWHM$_{||}(\tau)$ = 30 fs





Impurity (protons), Z=1, M=m_p, n

$\mu = ZM_1/Z_1M = 2,$

$n_1 = 10n = 20n_c$

Heavy ions Z_1,M_1, n_1

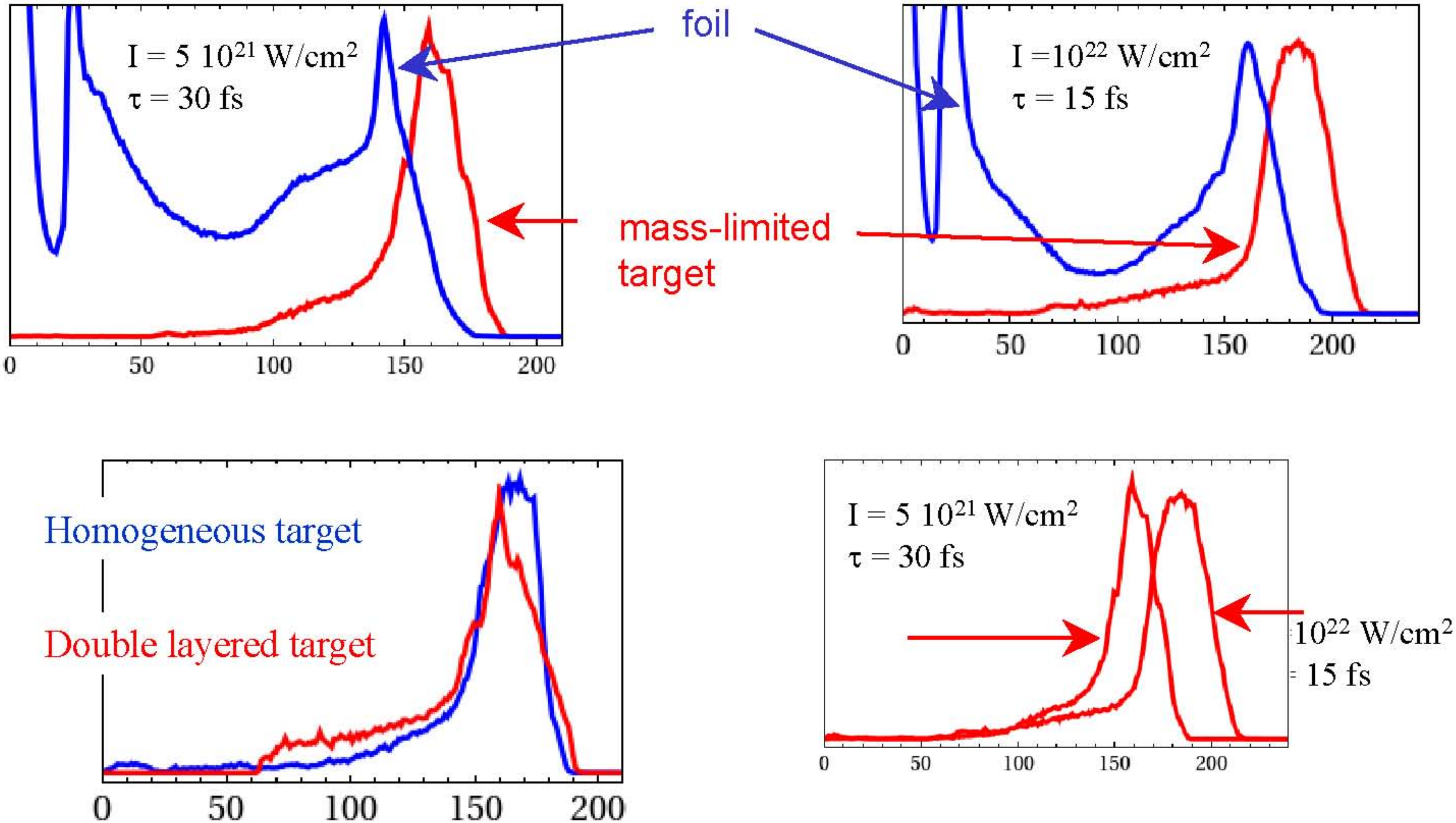
Моноэнергетичность
+
высокая энергия ионов
⇓

- **ультра-тонкая фольга**
- **ограниченная мишень**
- **легкая примесь**

- **высокий контраст**
- **радиальное сглаживание пучка**
- **радиальная поляризация**
- **ультракороткий импульс**

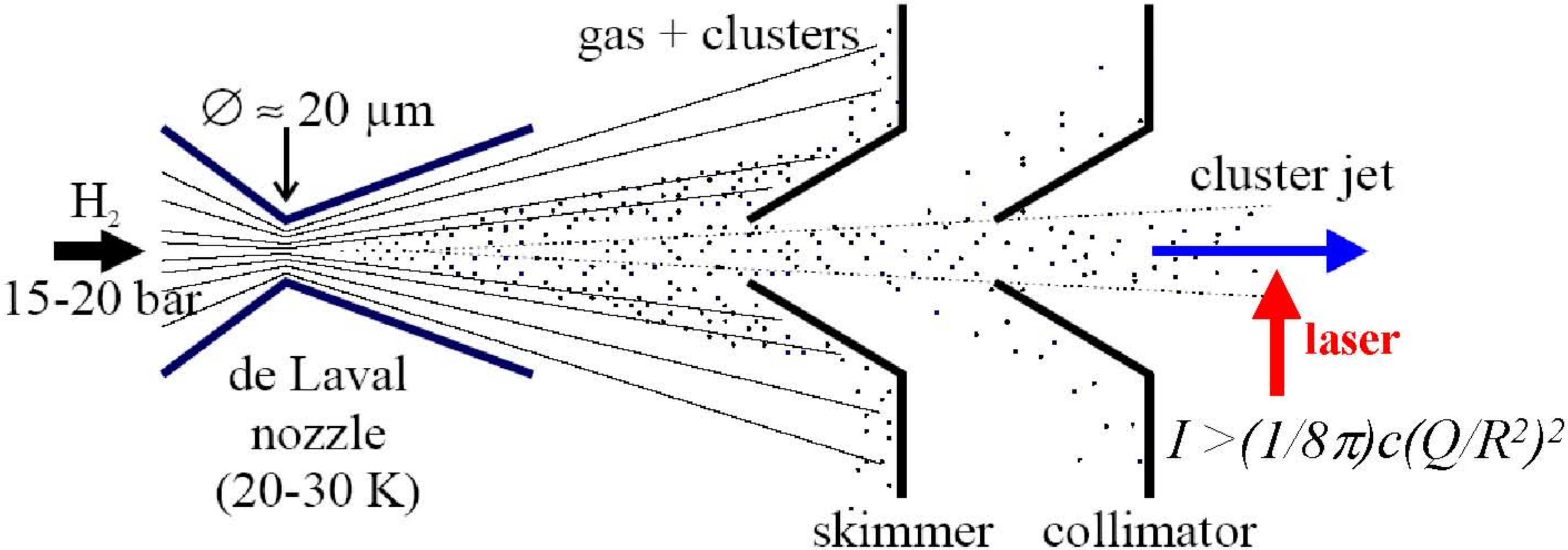
Brantov, Bychenkov,
Plasma Phys.Rep. **35**, N2 (2010)

Proton energy spectrum



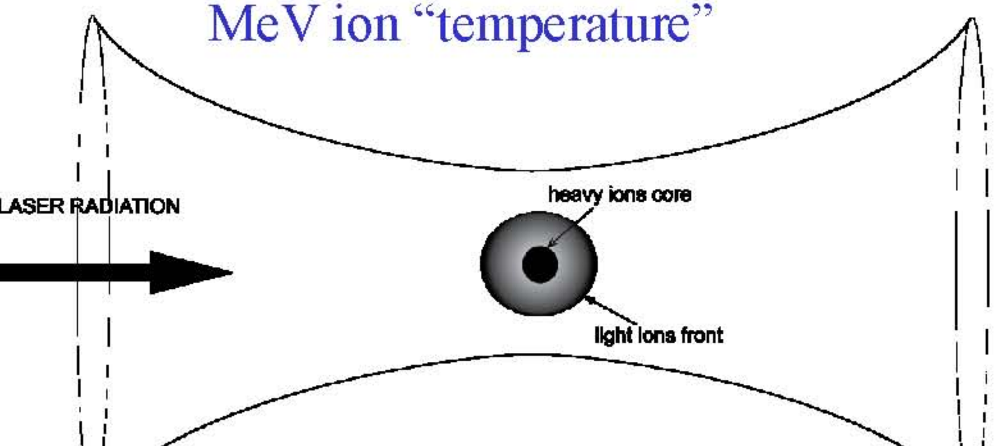
Нет преимущества от двуслойной мишени ! Более простая двух-компонентная однородная фольга работает не хуже !

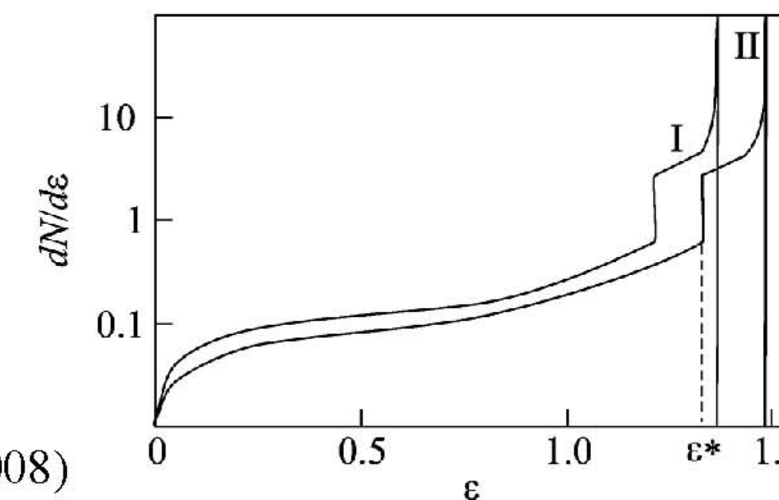
Кластерная плазма. Кулоновский взрыв



$$\varepsilon_{\max} = \frac{eQ_1}{2R}(3\mu - 1) \sim \frac{eQ_1}{R} \qquad \varepsilon^* = \frac{eQ_1}{R}\mu$$

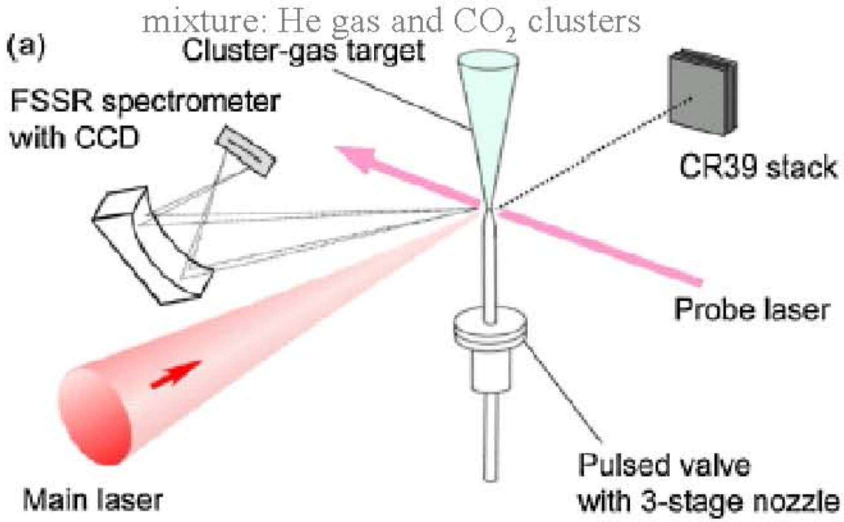
micro plasma with
MeV ion “temperature”





Андияш и др., Письма в ЖЭТФ **87**, 720 (2008)

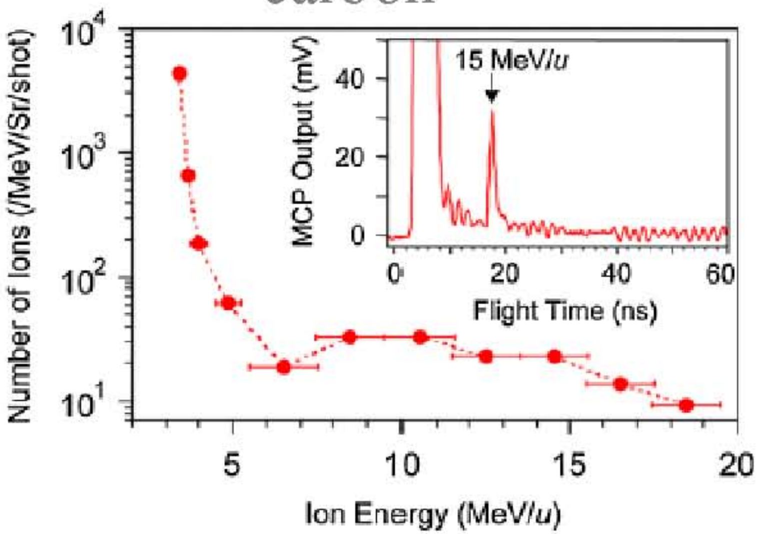
Ионы из газовой мишени



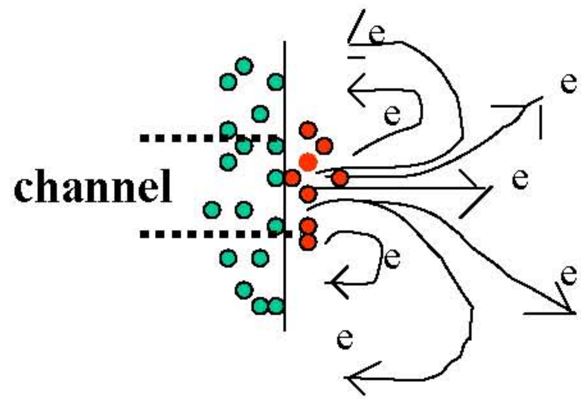
4-TW Ti:sapphire laser at JAEA-KPSI

n_e~$0.1n_c$, $I=7\times10^{17}Wcm^{-2}$ ⇒self-focusing

carbon



e



Record energy per nucl.

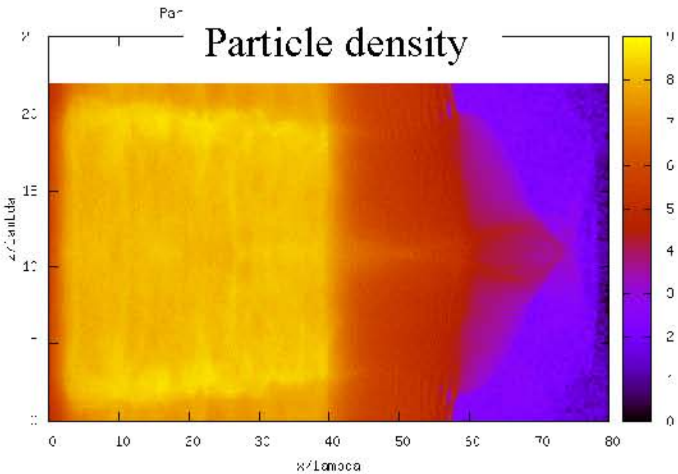
for so low laser intensity !

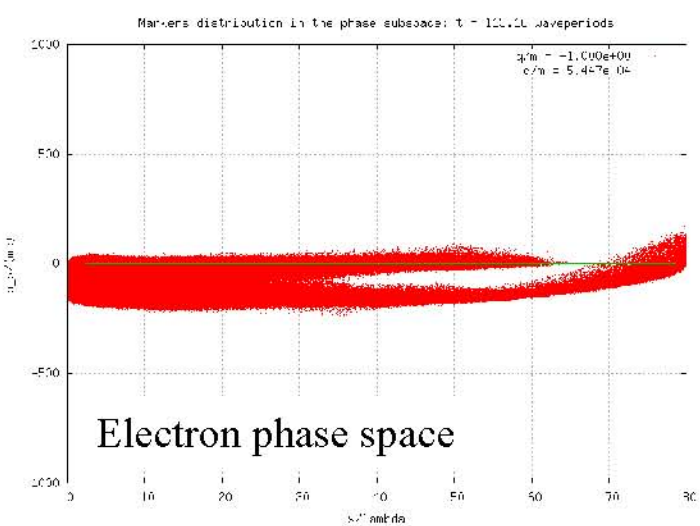
Y. Fukuda et al., Phys.Rev. Lett. **103**, 165002 (2009)

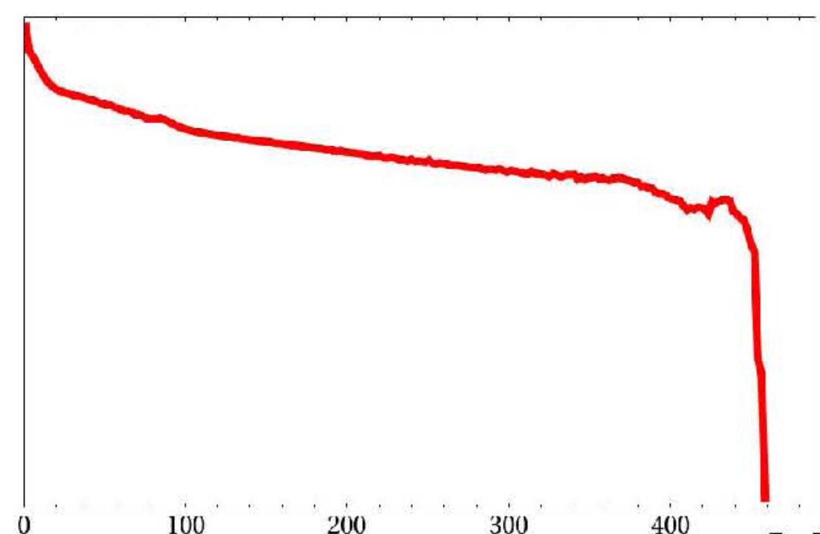
3D simulation of proton acceleration from dense gas

Laser - 10 fsec, 10^{22}W/cm^2, focus 5 μm
linear polarization

Target – dense gas plasma 40 μm
electrons + protons
density 10^{21} cm^{-3}





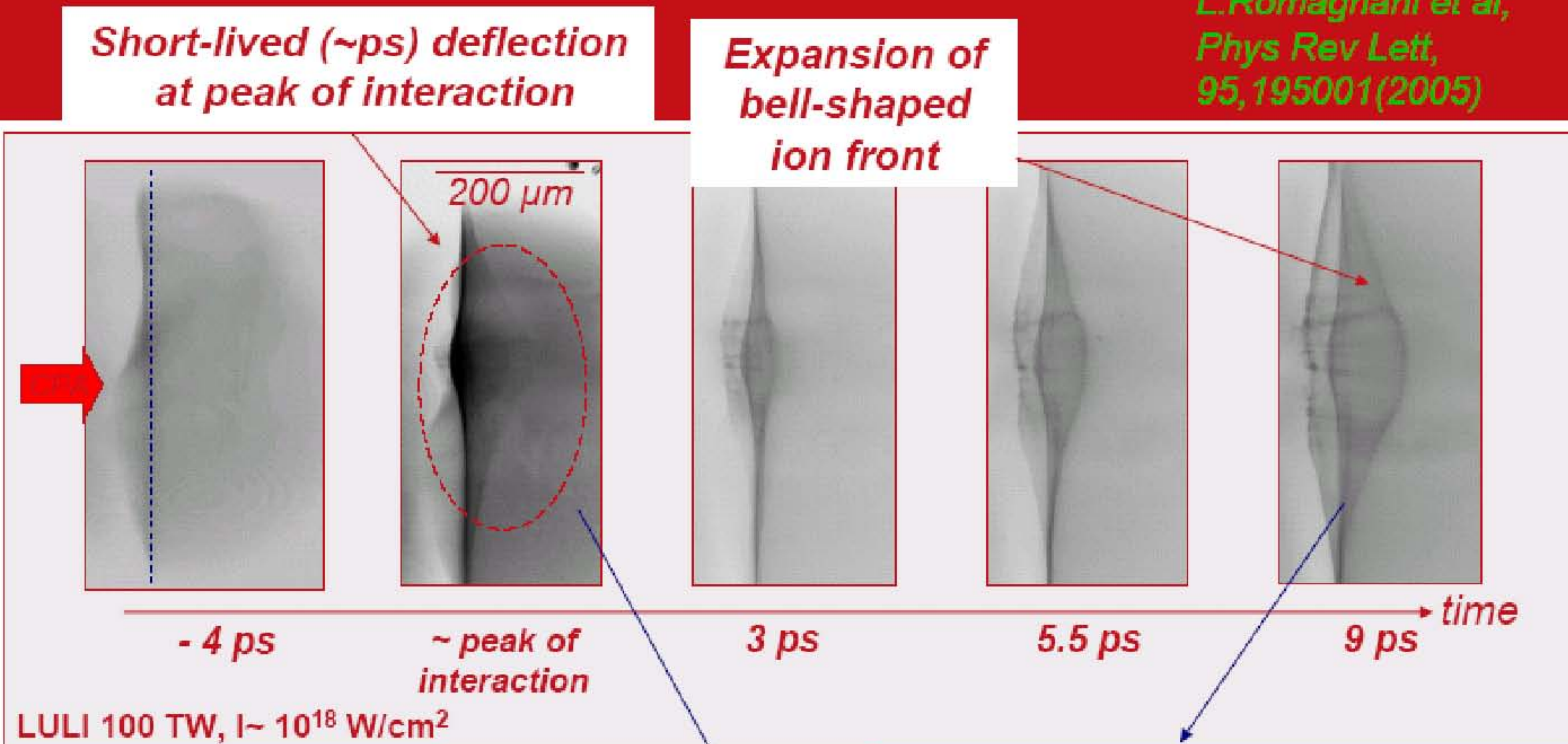


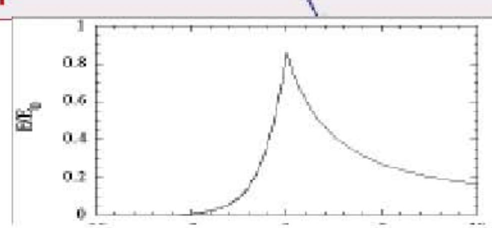
MeV

Proton spectra

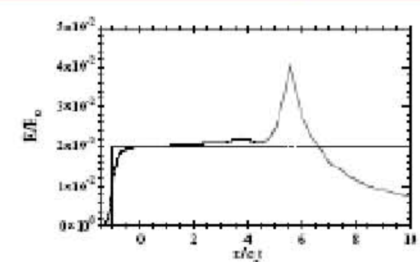
Detections of fields driving protons acceleration

L.Romagnani et al, Phys Rev Lett, 95,195001(2005)





Initial large(10^{11} V/m) E field



E field at Ion front

(Mora,PRL03)

Diagnosis of electron transport inside dense-matter (Weibel-driven filaments?)

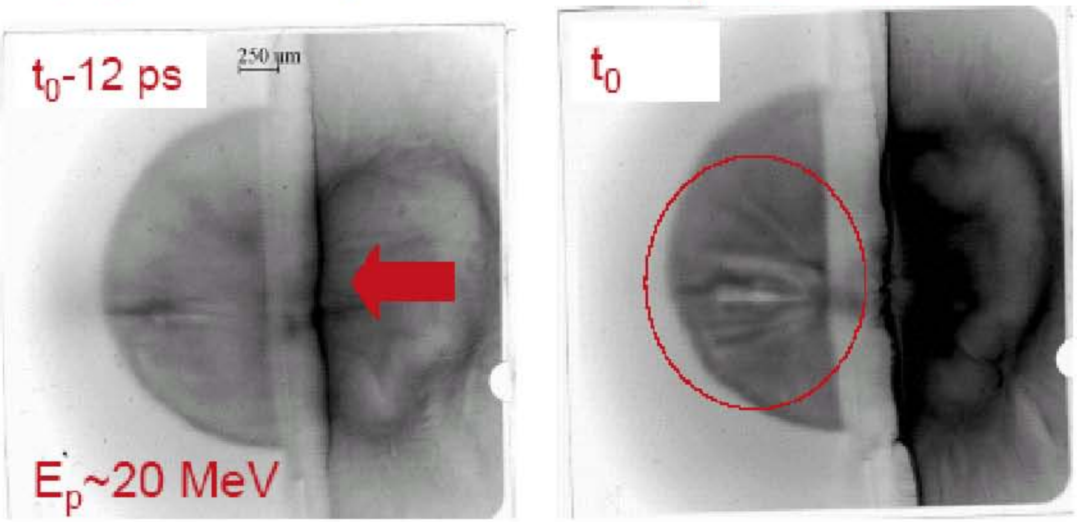
RAL PW

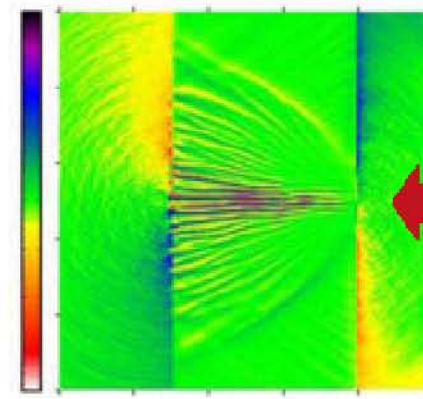
50mg/cc triacrylate foam, 30% Br doping, Au coating at front

$n_e = 10^{22}$-10^{23} cm^{-3}

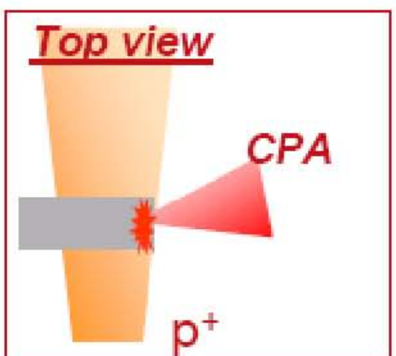
Interaction: 500 fs, ~10^{19} W/cm^2

Proton driver: ~ 500 fs, > 10^{20} W/cm^2.





B_z for CH density 250mg/cc



Filaments appear near the peak of irradiation pulses within a ~45º cone
Large MeV current (~100KA) is injected into target and is unstable to Weibel-like instabilities

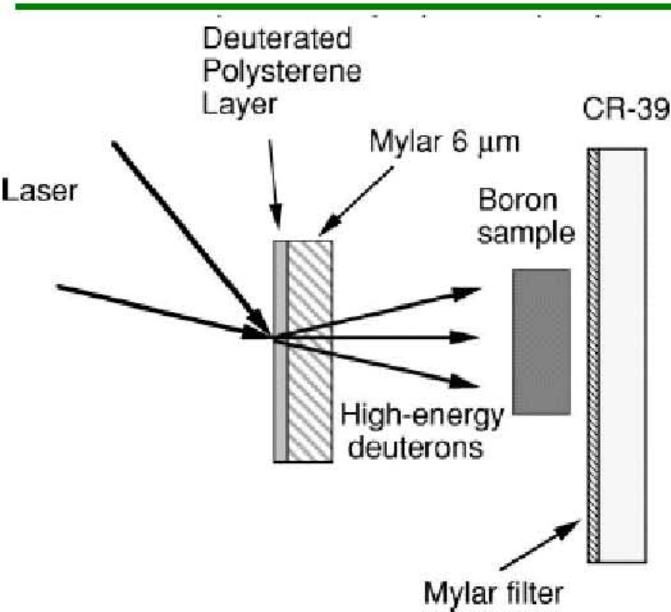
Medical Isotope Production using Proton Beams

позитронно-эмиссионная томография

Nuclear reaction	Half-life	Q (MeV)	Peak cross-section (mb)	Radiation measured
$^{11}B(p,n)^{11}C$	20.34 mins	2.76	430	β^+ 99%
$^{14}N(p,\alpha)^{11}C$	20.34 mins	2.92	250	β^+ 99%
$^{16}O(p,\alpha)^{13}N$	9.96 mins	5.22	140	β^+ 100%
$^{15}N(p,n)^{15}O$	123 seconds	3.53	200	β^+ 100%
$^{18}O(p,n)^{18}F$	109.7 mins	2.44	700	β^+ 97%

RAL, Vulcan
$5x10^{19}$ Wcm^{-2}
200 kBq per shot

Nucl.Instr.&Meth.Phys.Res. B183, 447 (2001)



CUOS, $^{10}B(d,n)^{11}C$
Nemoto et al.,
Appl.Phys.Lett.
78, 595 (2001)

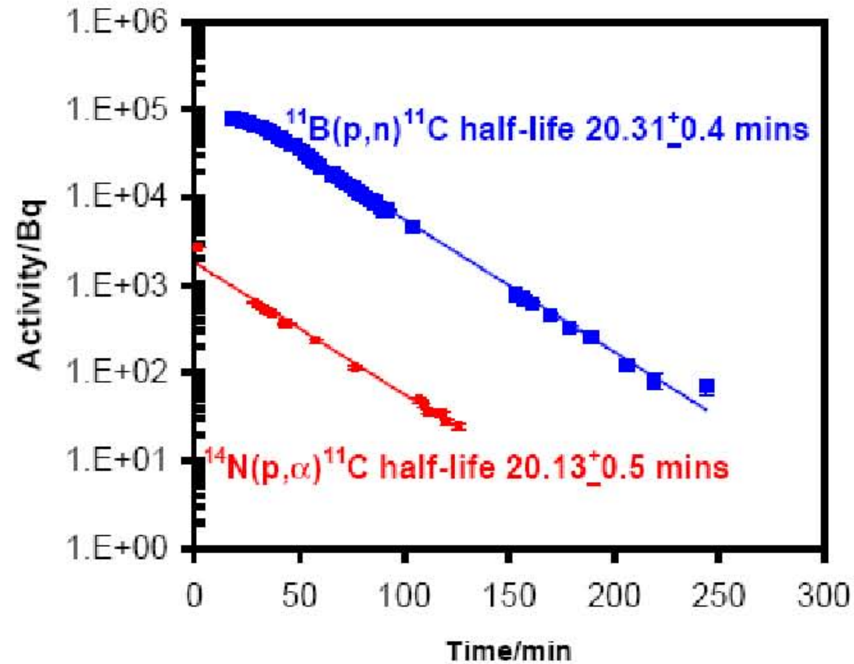
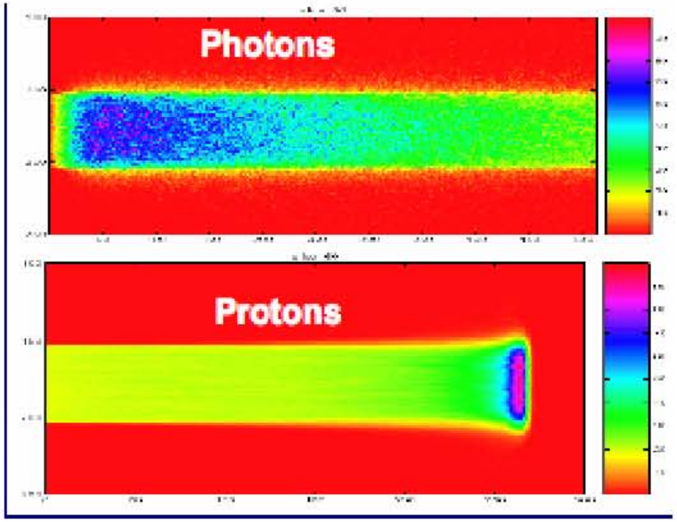


Figure 4. Decay curves for the activated boron and silicon nitride samples, showing that the isotope ^{11}C was produced via the reactions $^{11}B(p,n)^{11}C$ and $^{14}N(p,\alpha)^{11}C$.

Hadron therapy. Proton therapy



Photons don't stop

Protons Stop

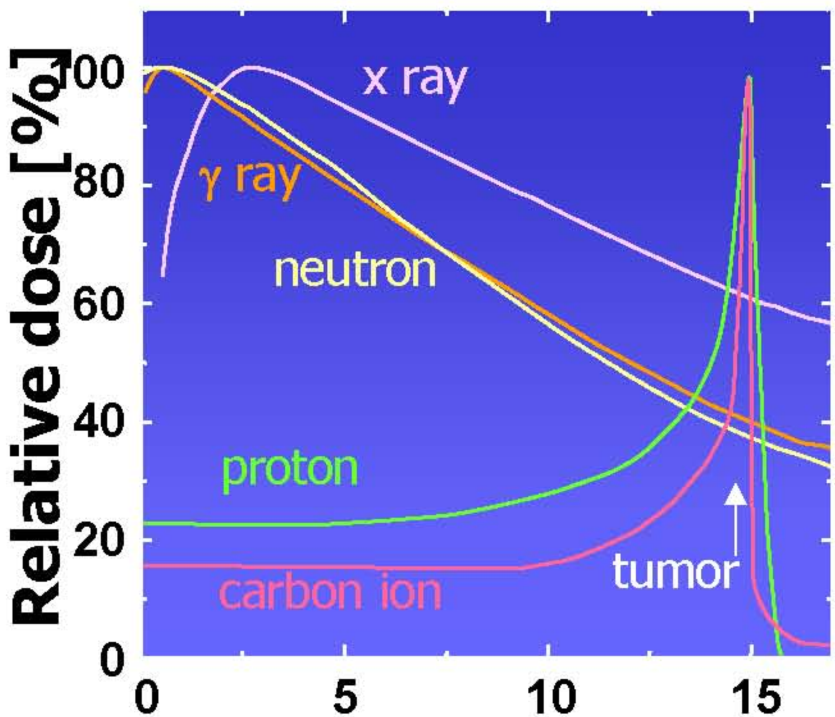
10^9-$10^{10}c^{-1}$

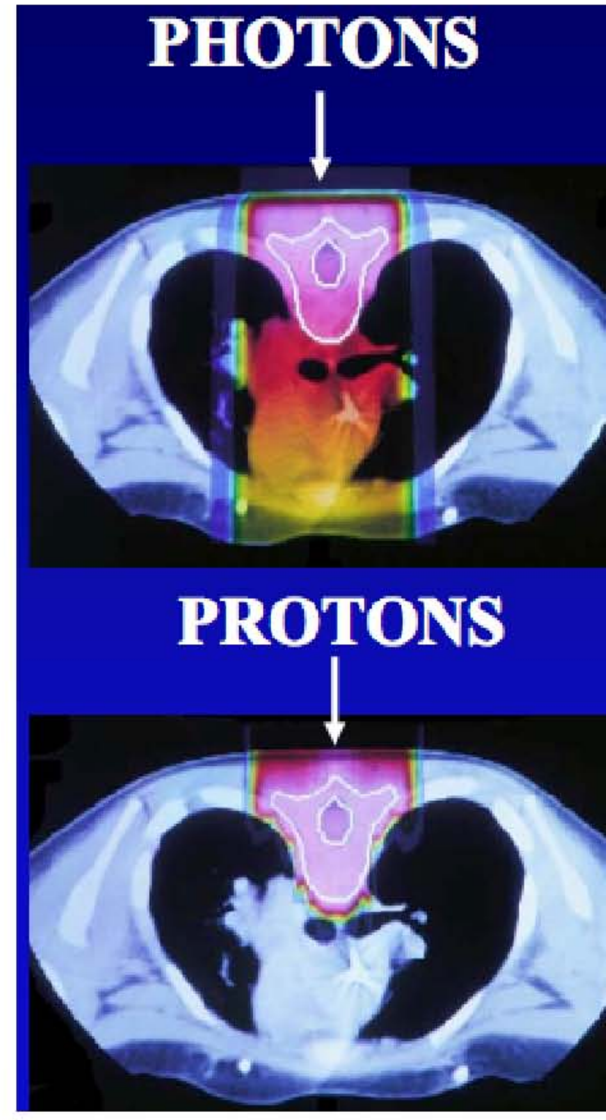
$\Delta\varepsilon/\varepsilon <$ few %

P: 200-250 MeV

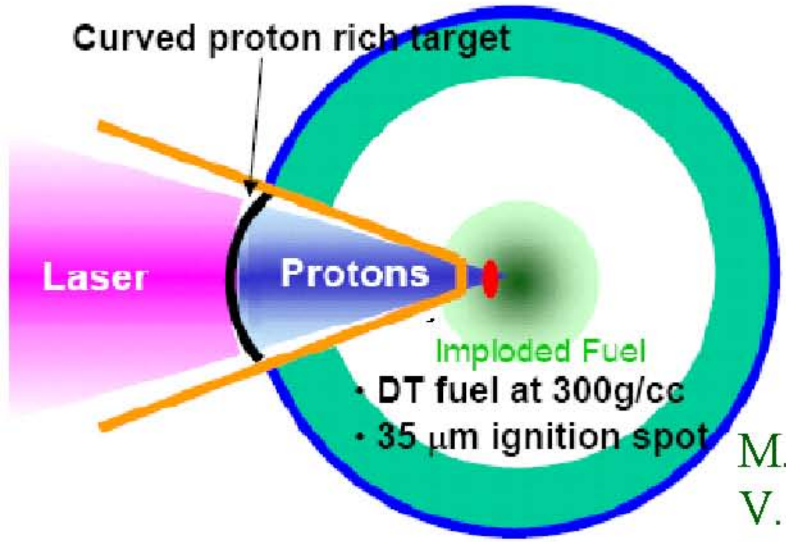
C: 300-350 MeV/n

The « optimum » dose distribution Delivers 100% dose to the tumour target and not to normal tissues. This should result in improved clinical outcomes when proton beams are used.





Fast Ignition using protons (ions)



Requirements:

$E_{protons}$ (3 to10 MeV) ~15 kJ

→ E_{Laser} ~100 kJ (for $\eta_{Laser \rightarrow proton}$ ~15%)

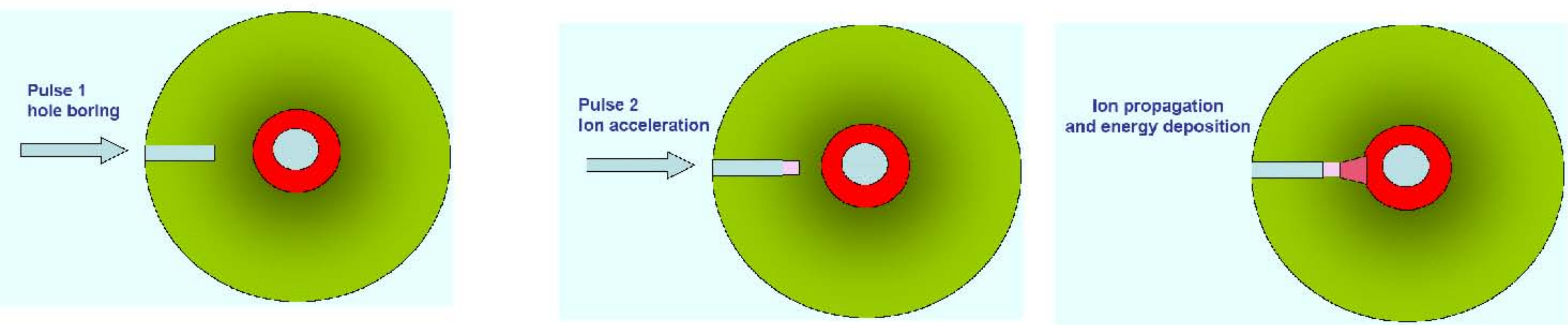
→ I_{Laser} ~10^{20} W.cm^{-2}

$t_{protons}$<20 ps

$\Phi_{protons}$~35 μm →focusing

M. Roth et al., Phys. Rev. Lett. **86**, 436 (2001)
V. Yu. Bychenkov et al., Plasma Phys. Rep. **27**, 1076 (2001)
M. Temporal et al., Phys. Plasmas **9**, 3098 (2002)

Fast ignition with hole boring



possibility of fuel ignition at the 30 PW & 100 kJ level

Соавторы

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Спасибо всем! The End!