Generation of high energy electrons and x-rays under the action of short intense laser pulses: theory and experiment

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Joint Institute for High Temperatures
Russian Academy of Sciences, Moscow

PHELIX
Petawatt High-Energy Laser for Heavy Ion Experiments

GSI

[1]GSI- Darmstadt research center with ion and laser beams

ExtreMe Matter Institute EMMI

Workshop on Plasma Physics
with Intense Laser and Heavy Ion Beams

May 20 - 21, 2010 - Moscow, Russia

Organized by JIHT RAS and EMMI

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Outline

- **Introduction**
  - ***high energy electrons – the origin of secondary sources***
- **X-ray radiation using solid and nano-structured targets**
  - ***mechanisms of hot electrons production***
  - ***last experiments at JIHT laser complex***
  - ***optimization of K_{α} x-ray yield***
- **Laser wakefield electron acceleration**
  - ***predictions and perspectives***
  - ***last experimental and theoretical results***

➢*What can we do with PW lasers…?*

secondary sources

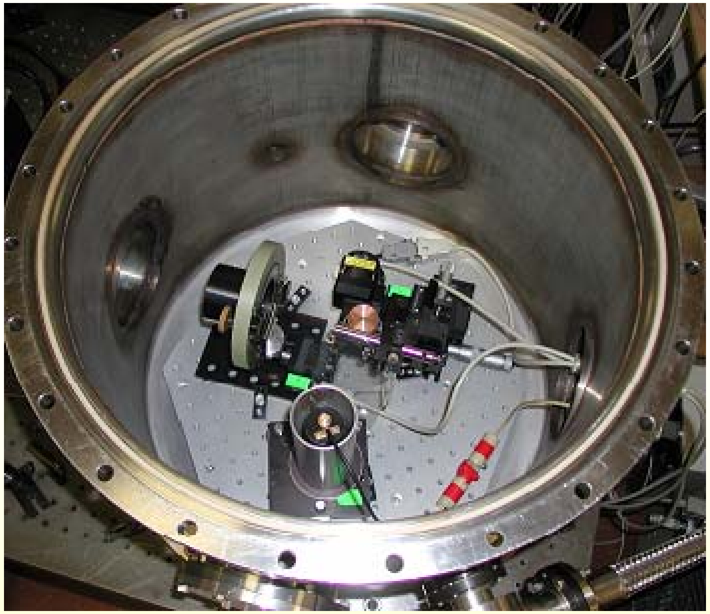
of high energy particles and radiation

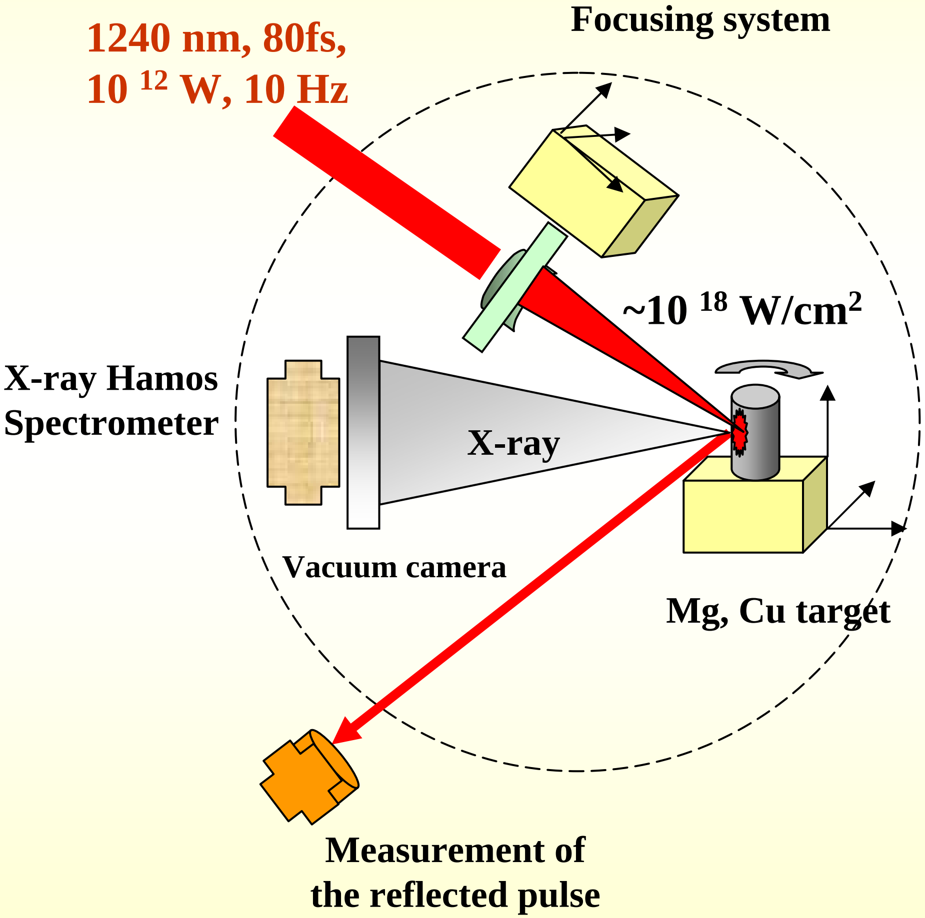
The particular subjects could be:

- **production of quasi-monoenergetic and stable source of protons** (*e.g., with the energy ~ 200 MeV for medical applications*),
- **new sources of X-ray radiation *using solid and nano-structured targets,***
- **laser wake field electron acceleration,**
- **powerful sources of THz radiation,**
- **laser-driven gamma-ray sources**

➢new sources of X-ray radiation *using solid and nano-structured targets*

X-ray radiation of laser plasma





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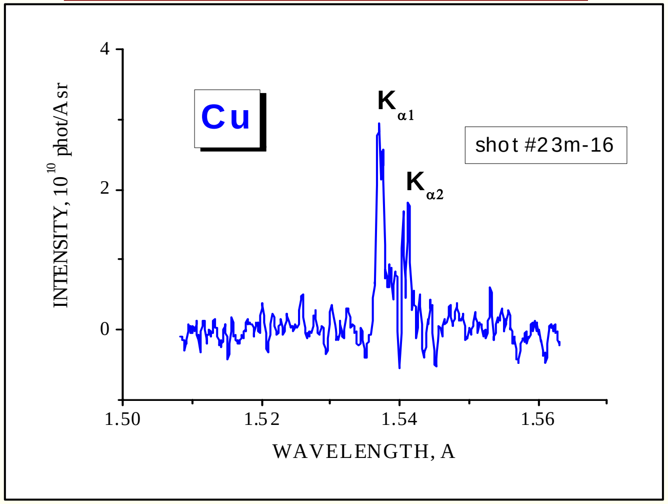
X-ray radiation using solid and nano-structured targets

K_α radiation from Cu laser-produced plasmas
Cr:Forsterite laser system, ω_0, *p-polarization*,
E_L=30 mJ, τ_L = 80 fs, $10^{16} \div 10^{17}$ W/cm^2

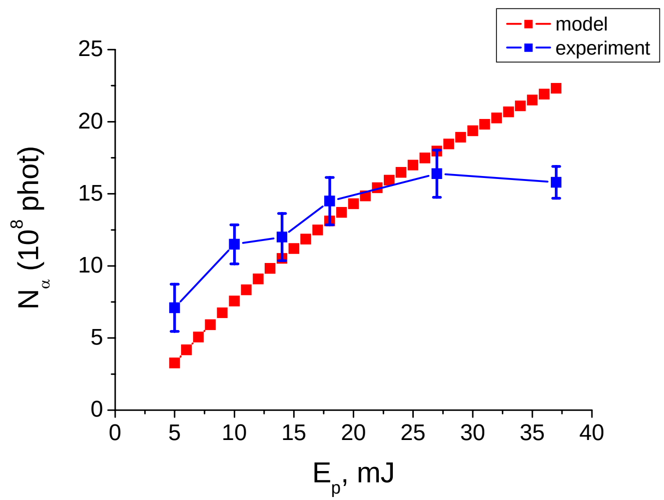
Single laser short experiment



$$E_0 = E_L\left[1 + (1 - f)^{1/2}\right]\sin\theta$$

$$T_{h,keV} = 7.6 I_{L,16}\lambda_{\mu m}^2\alpha^2\sin^2\theta$$

Optimization of K_α x-ray yield



The model calculation of K_α yield against pulse energy in comparison with experimental data received at IHED laser facility:
λ = 1.24 μm, τ_p = 80 fs,
d_f = 10 μm, θ = 45°, Fe target

E_0 – driving, E_L – laser field, f –absorption, η = 1.57, $I_{L,16} = I_L/10^{16}$ W/cm^2 – laser intensity

There is a range of laser pulse parameters in which K_α yield may be described by vacuum heating mechanism

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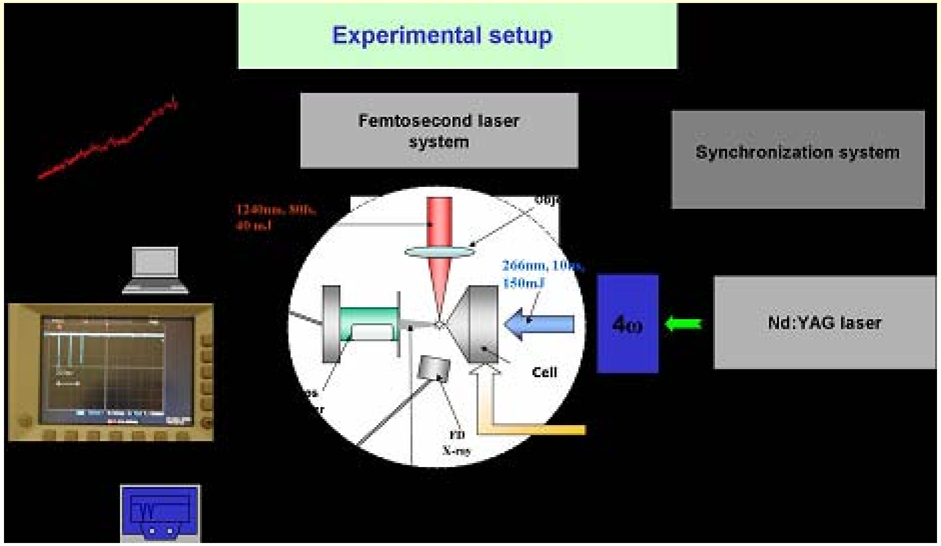
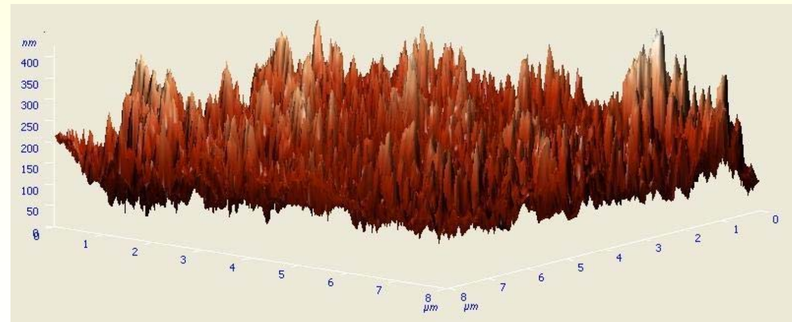
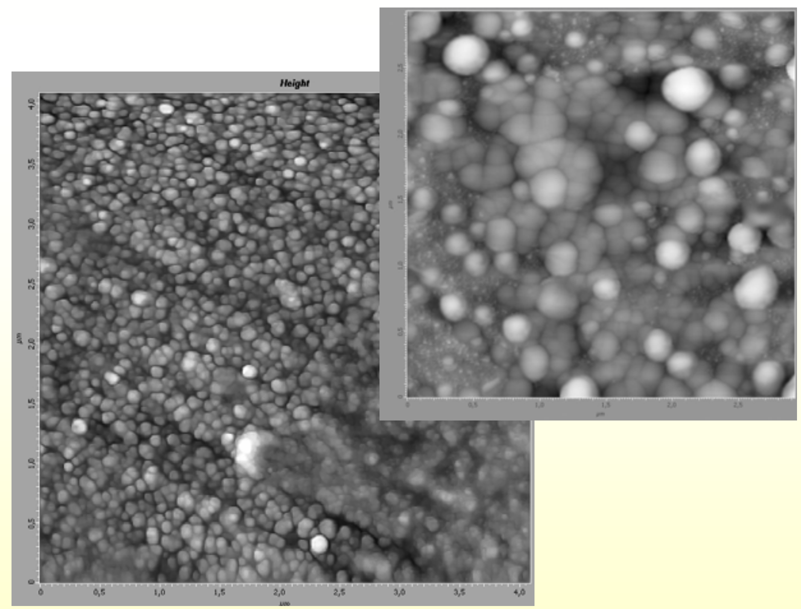
O. Kostenko, Friday, May 21st, 15:00

nano-structured targets



Fe clusters on Cu target





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X-ray radiation using solid and nano-structured targets irradiated by PHELIX and 10 TW LS of JIHT

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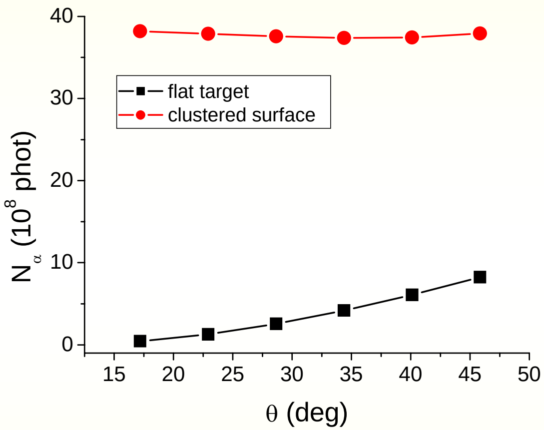
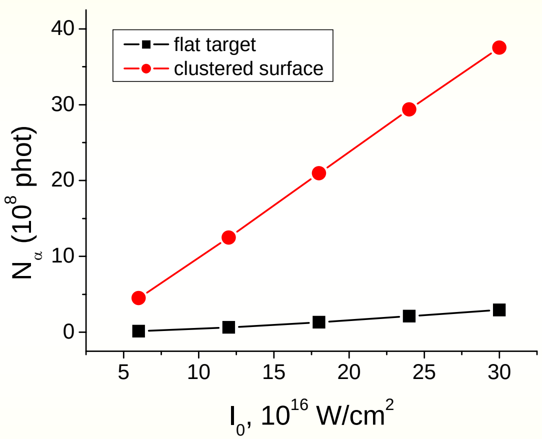
Fe clusters on Cu target

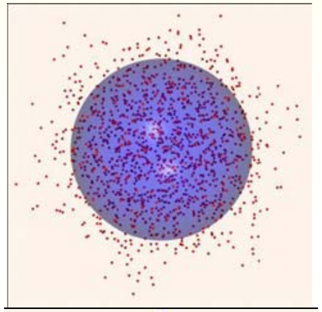


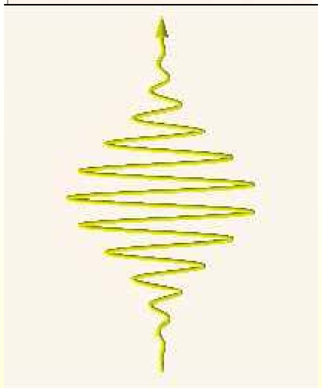
Dependence of K_α yield on angle of incidence for peak intensity 3×10^{17} W/cm^2



Dependence of K_α yield on peak intensity for angle of incidence 30°

$$E_0 = 3E_L \cos\theta_1$$





$$T_{h,keV} = 68.41\times I_{L,16}\lambda_{\mu m}^2 \cos^2\theta_1$$

Enhancement of driving electric field at a cluster surface and favorable conditions for K_α photons to escape from the wafer lead to considerable enhancement of K_α yield

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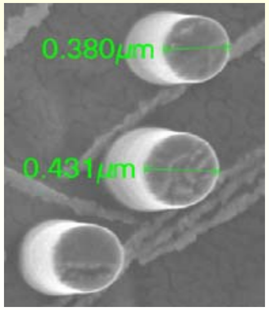
O. Kostenko, Friday, May 21[st], 15:00

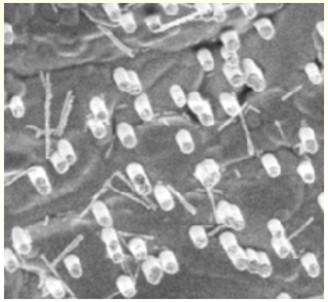
First Experiments with high Z- Nanostructures at PHELIX

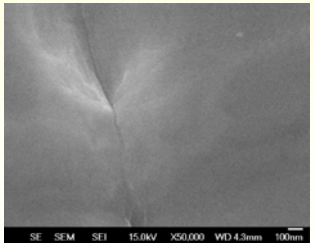
Petawatt High-Energy Laser for Heavy Ion Experiments

Cu-nano-hairs of 100-500nm, 1-5 μm high on the 8 μm Cu layer

GSI, Material Research; IMP, Lanzhou



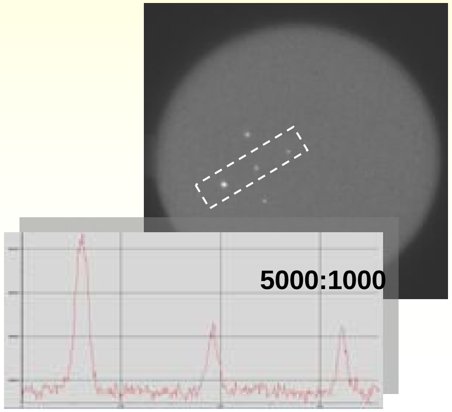




clean at the nanometer scale

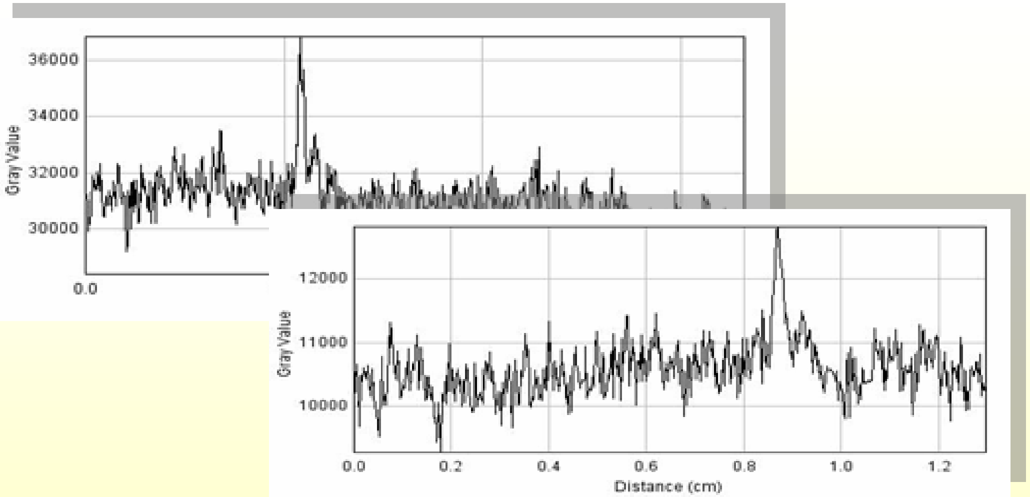
X-ray pin-hole camera images

16.12.08 2J, 5°,Cu-foil



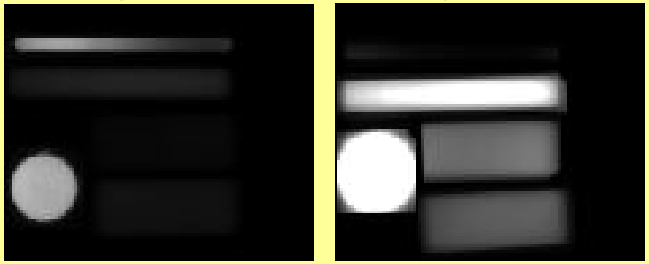
Cu-Ka obtained by laser irradiation of the Cu-foil

18.12.08, 20 J, 5°, Cu-foil 33 μm



Increased hard x-ray yield by irradiation of nanostructures

10J, Cu-foil **12J, Cu-nano**



experimental and theoretical study of the laser interaction with high Z nanostructures for generation of energetic x-ray pulses.

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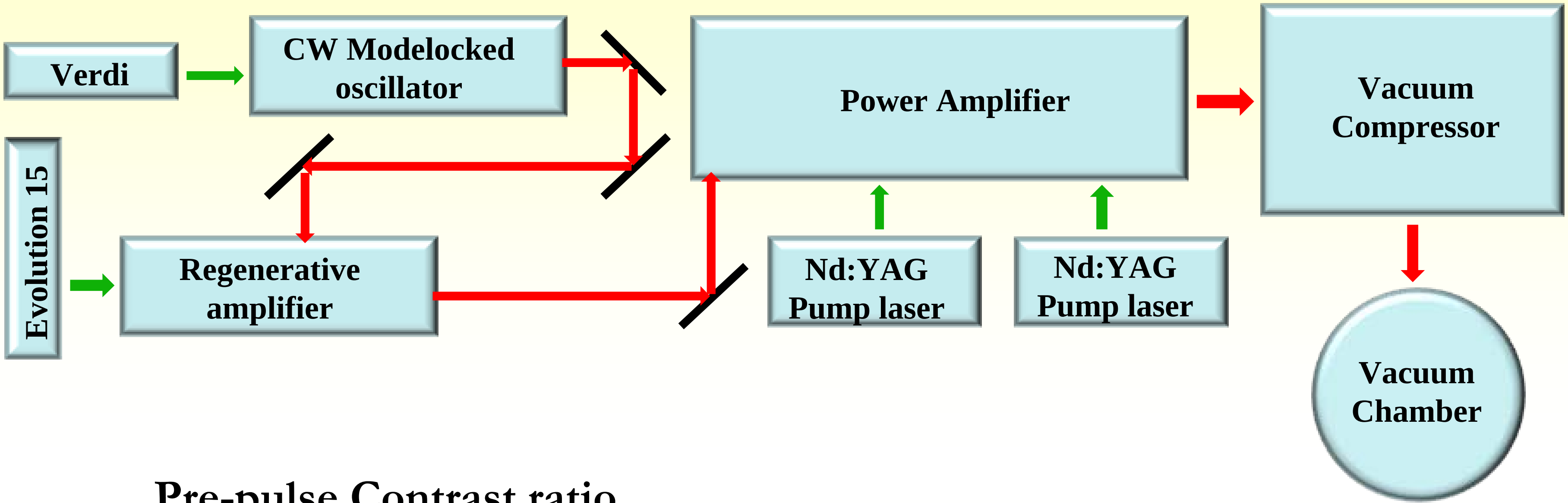
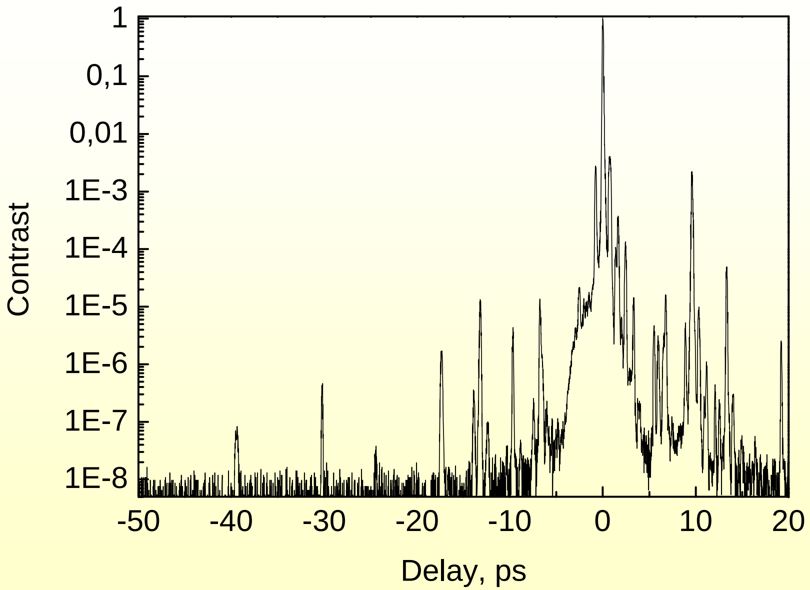
Femtosecond Laser System at JIHT

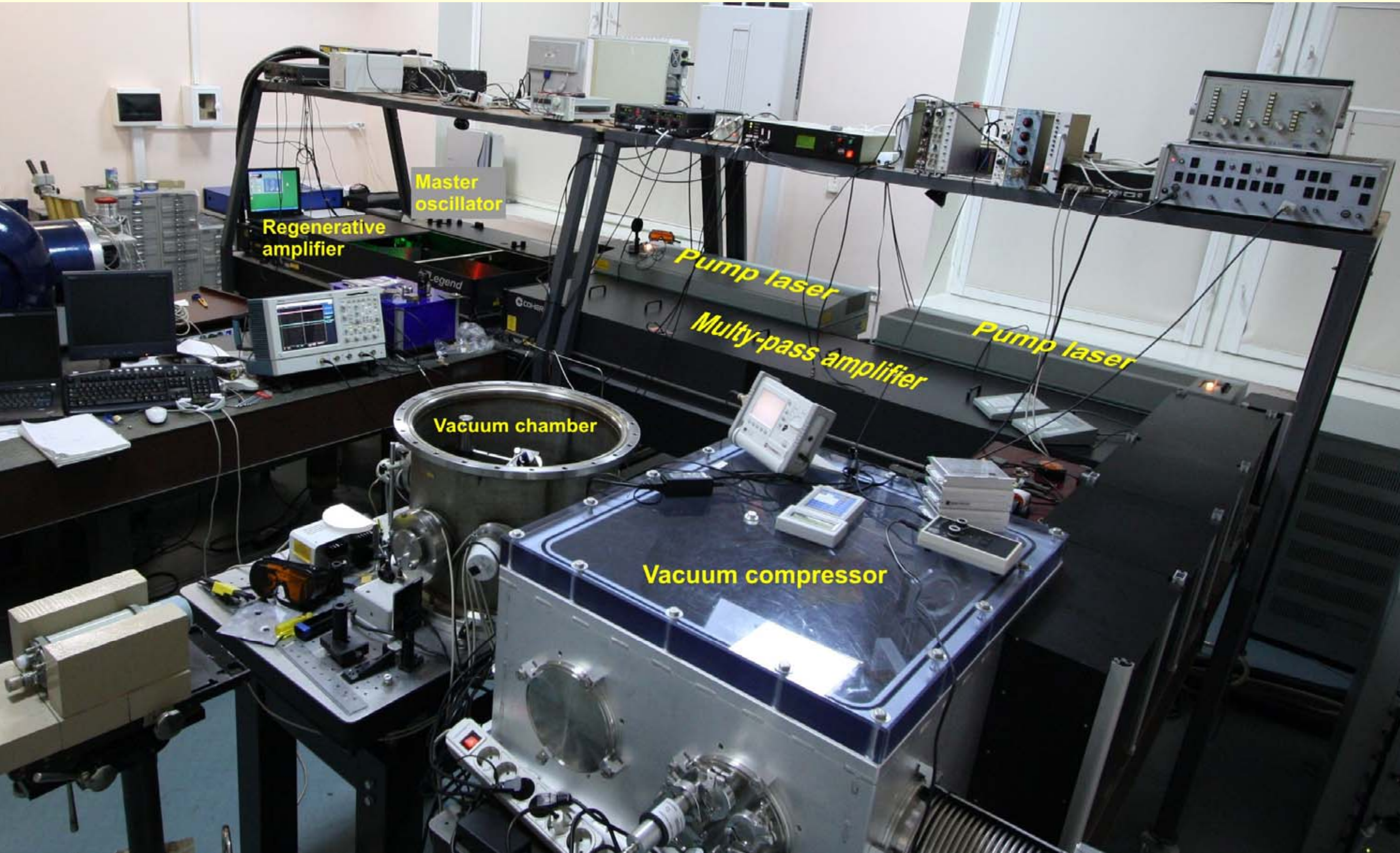


Pre-pulse Contrast ratio

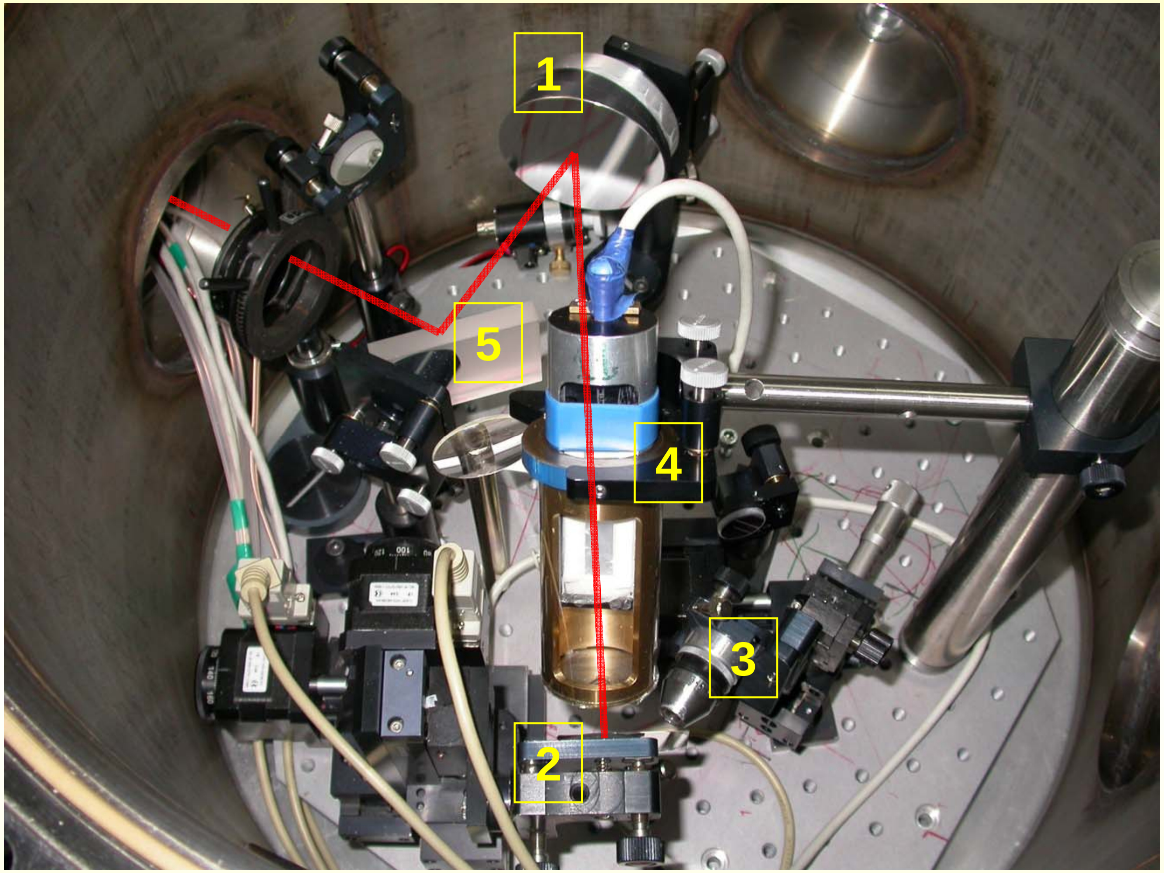


Laser parameters	
Center wavelength, nm	~ 800
Pulse duration (FWHM), fs	37 ± 5
Output energy	> 250 mJ
M^2 Figures	$M^2_x = 1.5$ $M^2_y = 1.35$
Bandwidth (nm)	~ 28 nm
Beam diameter ($1/e^2$)	30 mm

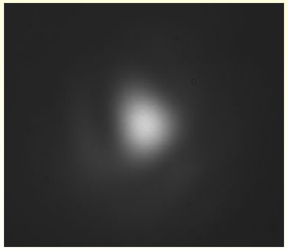
10 TW JIHT Femtosecond Laser System



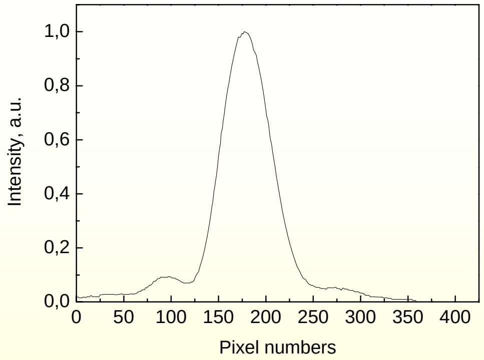
Experimental setup



Focal spot

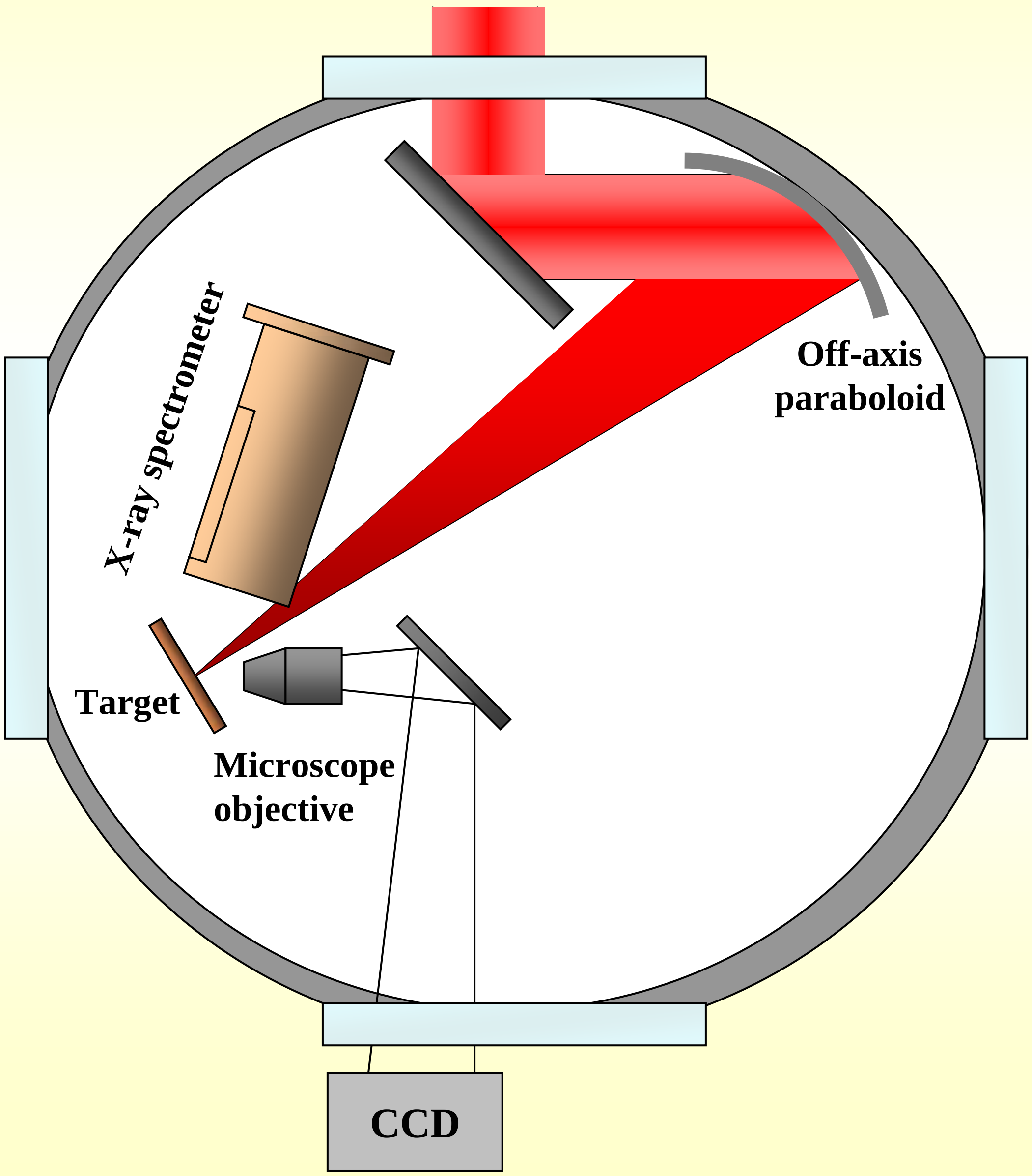


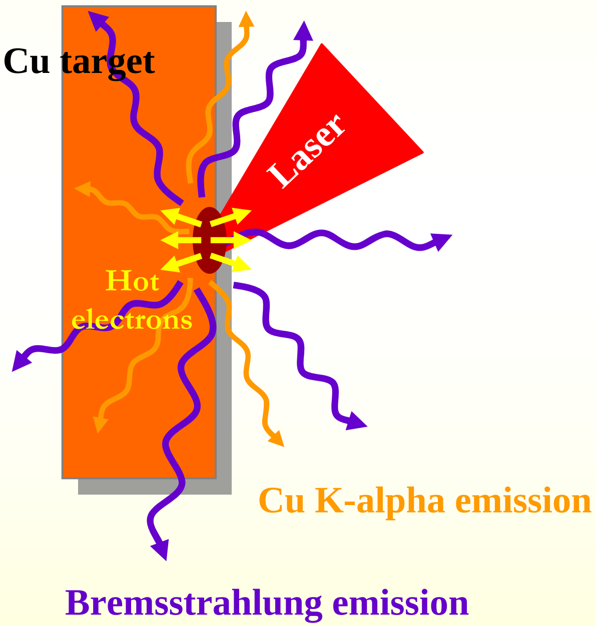
$D_{1/e}$=14μm



1 - Off-axis paraboloid (focal length 254mm).
2 - Motorized target unit with target holder.
3 - System for interactive control of focus spot.
4 – Von Hamos spectrometer
5 – Mirror (R=100%)

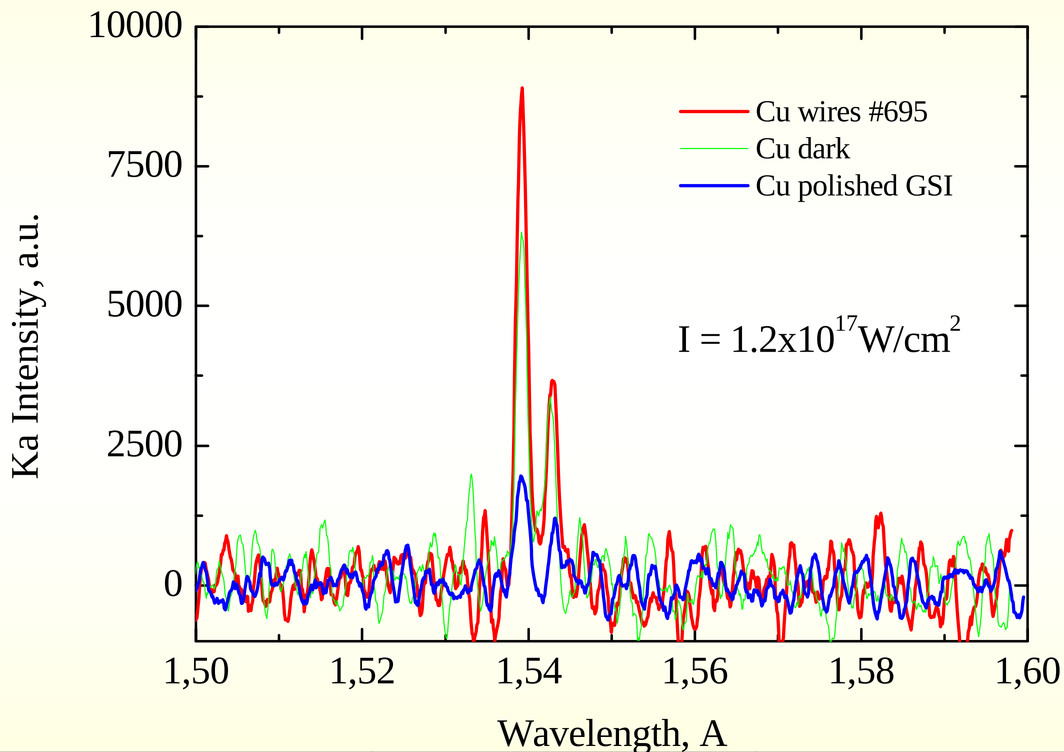
Experimental scheme





X-ray radiation using solid and nano-structured targets

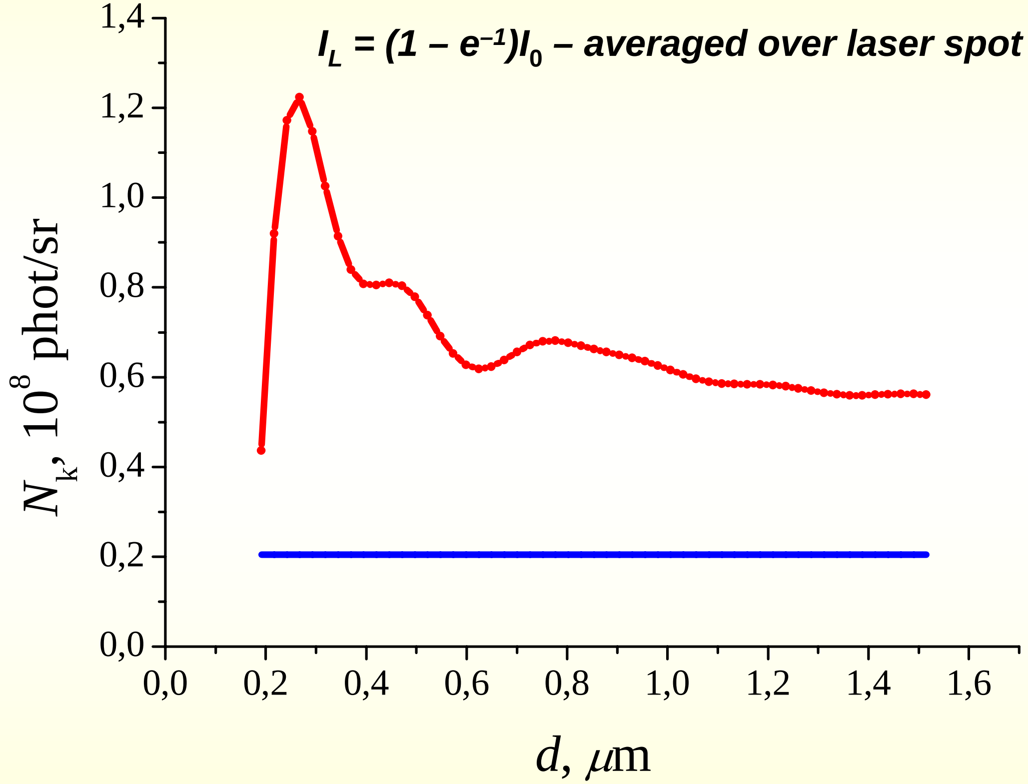
$I_0 = 1.2\times10^{17}$ W cm^{-2} (peak intensity), angle of incidence θ = 30º,
laser wavelength 0.8 μm, pulse duration 37 fs, P-polarization
focal spot diameter $2r_0$ = 14 *μm*

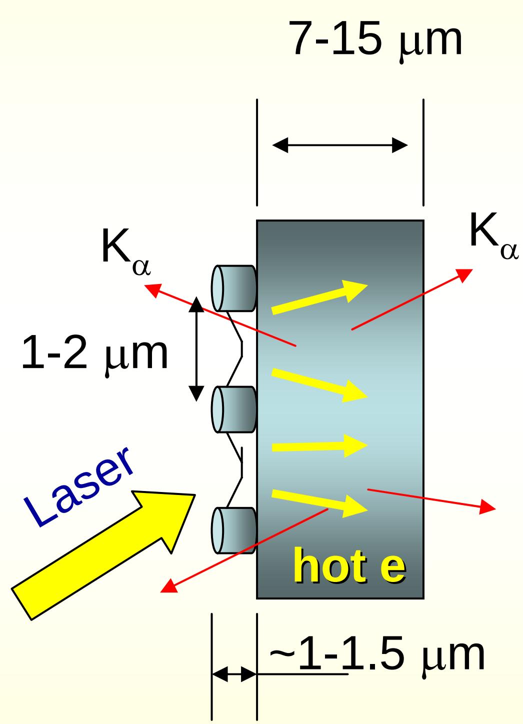


Target	X-Ray integral, a.u.	Abs yield of K_a, ph/(ster pulse)
Cu polished foil (GSI), 8um	5.98 $\times10^4$	**8.7×10^7**
Cu dark foil (GSI), 12.5 um	2.12 $\times10^5$	3.1×10^8
Cu foil with wires №695 (GSI)	2.26 $\times10^5$	**3.3×10^8**

K_α radiation using solid and nano-structured targets

$I_0 = 1.2\times10^{17}$ W cm^{-2} (peak intensity), angle of incidence $\theta = 30^o$,
laser wavelength 0.8 μm, pulse duration 37 fs, P-polarization
focal spot diameter $2r_0 = 14$ *μm*





@ d = 0.5 μm ***theoretical ratio nano wires / polished = 3.8***

experimental ratio = $3.3\times10^8/8.7\times10^7 = 3.8$

➢laser wake field electron acceleration

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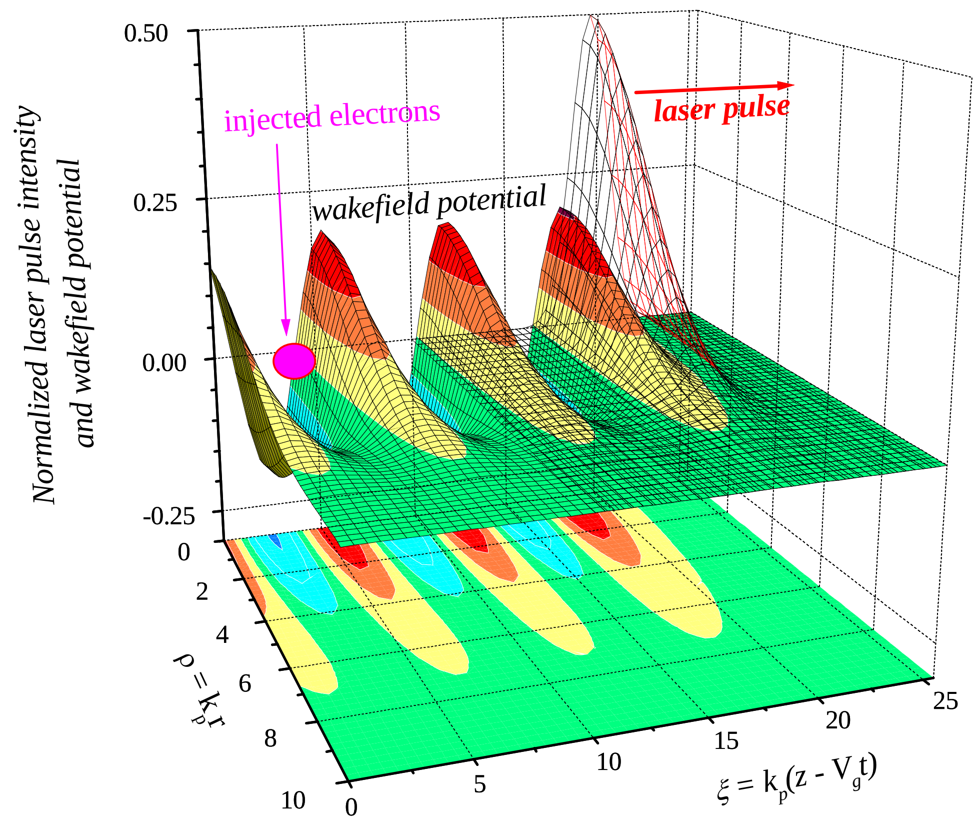
Laser-Plasma Acceleration of electrons with record gradients ~ 10 GV/m



The result of optimization of laser and plasma parameters for the monoenergetic acceleration of a short electron bunch in the wakefield generated by the 50 TW, 100 fs laser pulse in the plasma channel

Expected potential

of laser – plasma acceleration of electrons

Electric field of plasma wave (*with phase velocity ~ c,* $\lambda_p = 2\pi c/\omega_p$):

$$E_P\,[\mathrm{V/m}] \approx 10^2\,\alpha\,\left(n_e\,[\mathrm{cm}^3]\right)^{1/2} \propto \gamma_g^{-1} = \omega_p/\omega_0$$

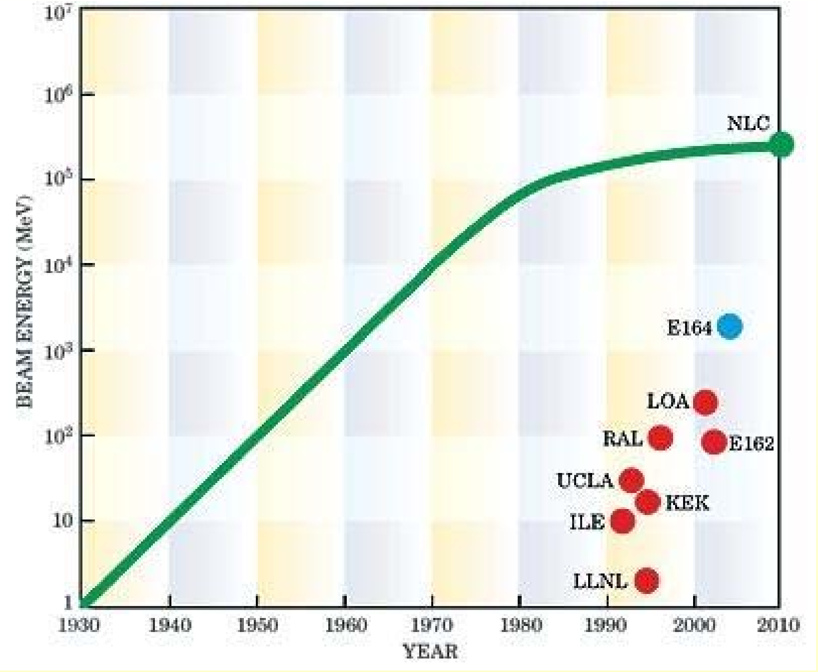
$\alpha = \delta n / n_0$ – *plasma wave amplitude; at* $\alpha = 0.3 \div 1.0$, $n_e = 10^{17} \div 10^{18}$ cm^{-3}:

$$E_P = 10 \div 100 \text{ GV/m}$$

maximum of accelerating gradient in traditional accelerators (RF linac):

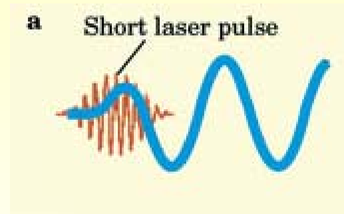
E_{RF} ~ 10 - 100 MV/m

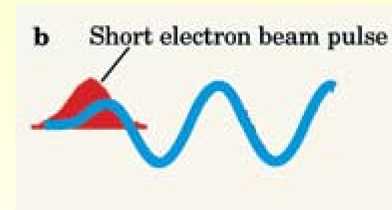
Exponential growth of "the Livingston curve" began tapering off around 1980



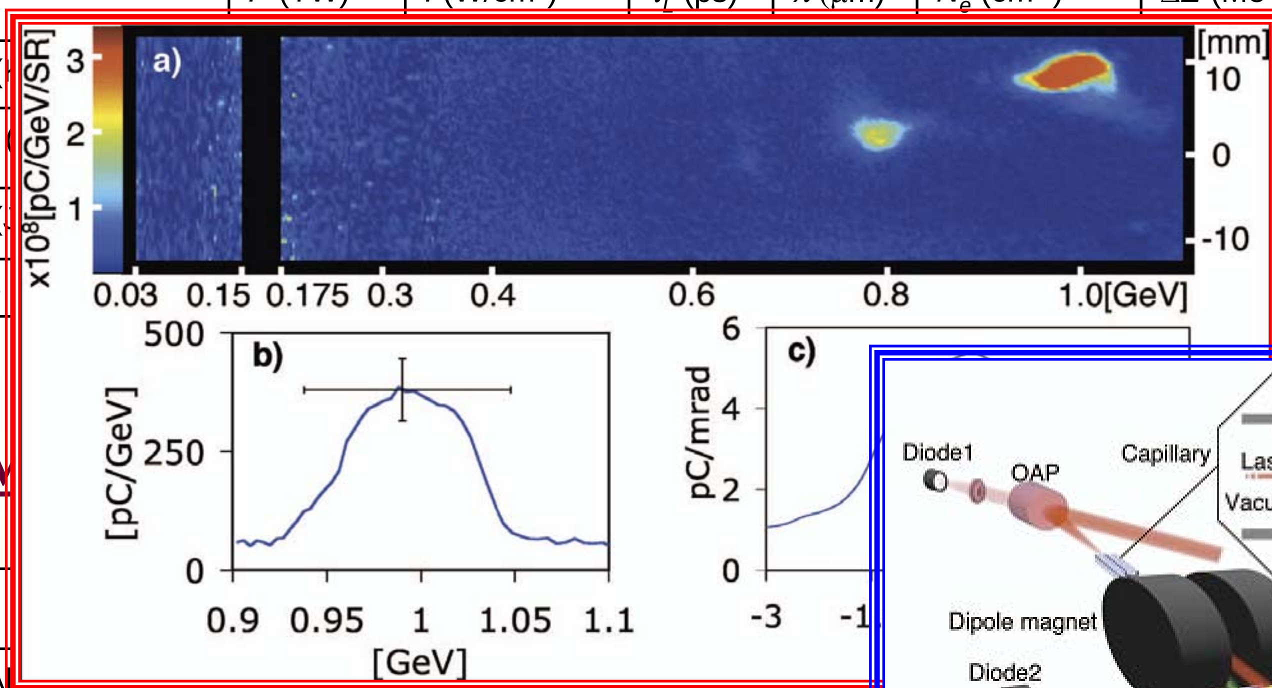
Parameters and results of some experiments

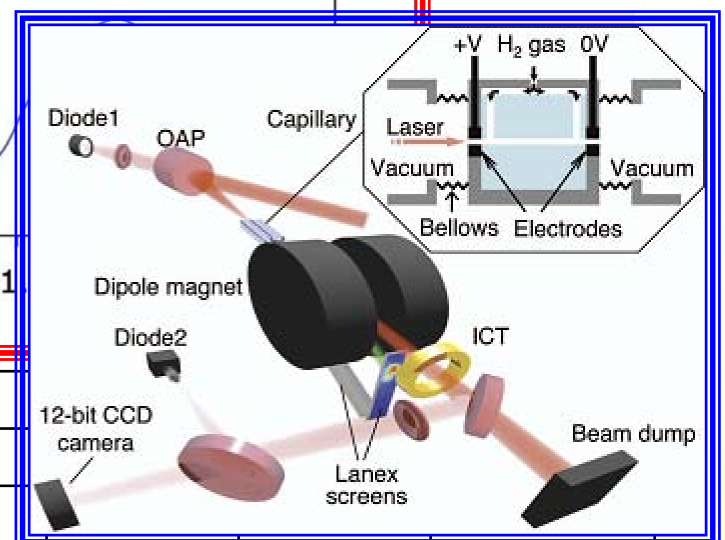
for **standard LWFA** scheme $c\tau_L \approx \lambda_p/2$





	P (TW)	I (W/cm^2)	τ_L (ps)	λ (μm)	N_e (cm^{-3})	ΔE (MeV)	E_{ac} (GV/m)
Japan (							0.7
France (							1.5
Japan (							20
France							**200**

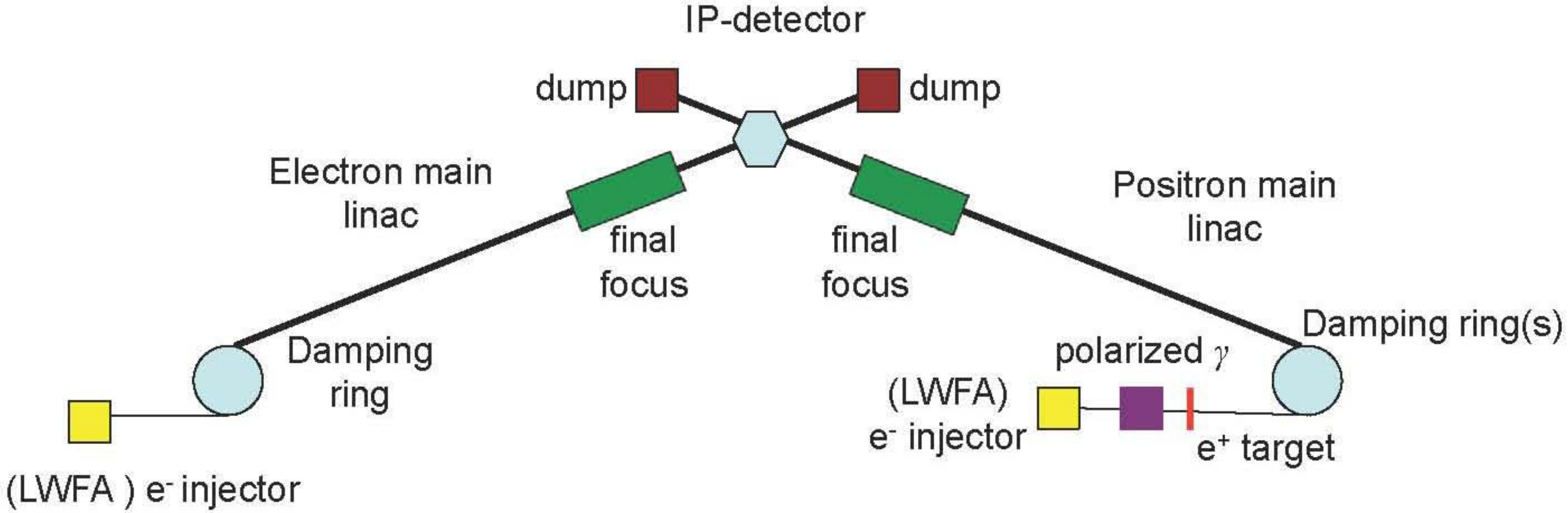




for **Self-M**

UK (RA							
France (CEA)	5	10^{19}	0.3	1.05			
USA (CUOS)	4.5	10^{18}	0.4	1.05			
USA (NRL)	2.5	4×10^{18}	0.4	1.05			
Japan (KEK)	3	10^{17}	1.0	1.05	10^{19}	17	30

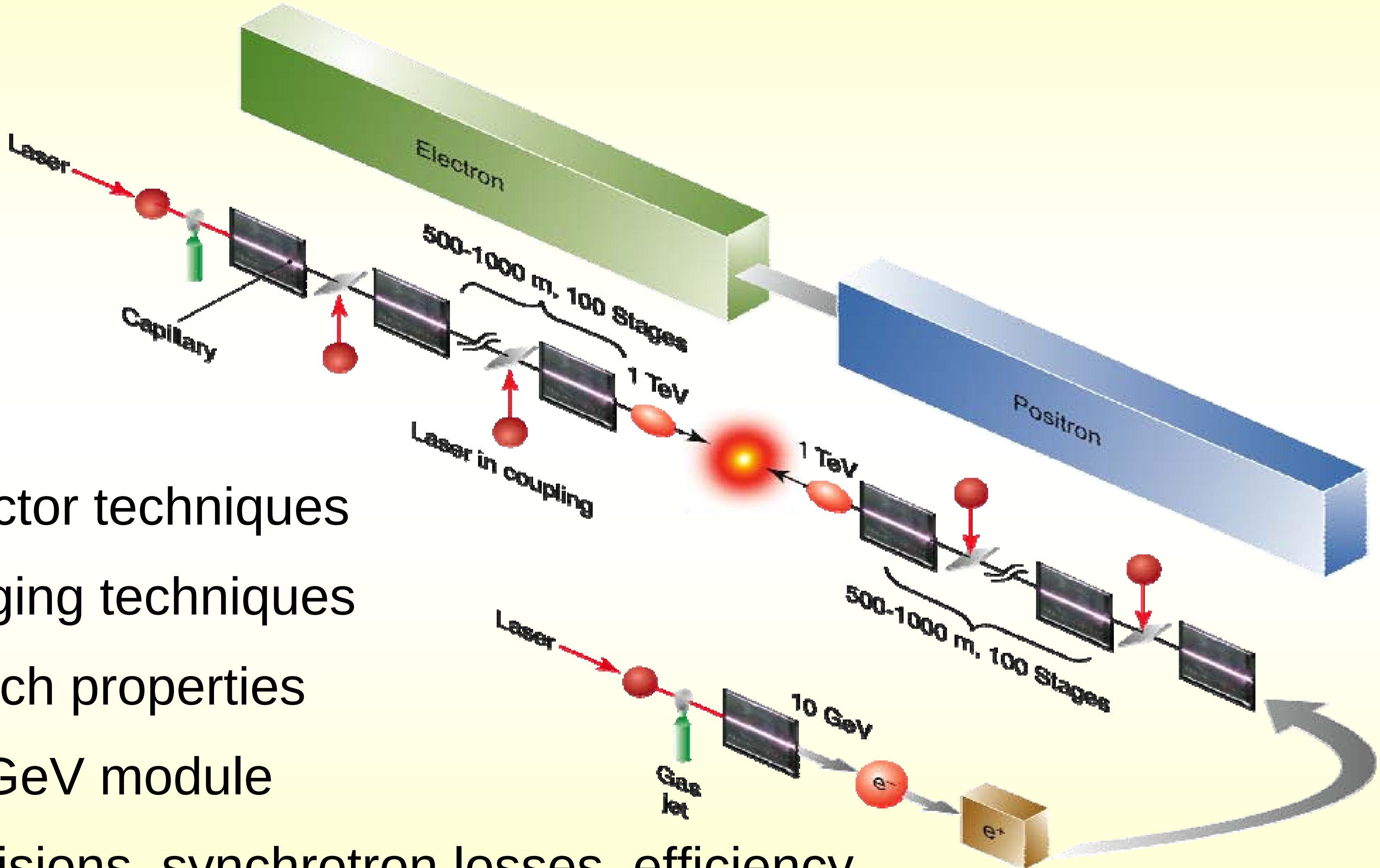
Electron-Positron Linear Collider



Conventional technology:

- Current generation of future linear collider designs based on existing technology (e.g., ILC): E_{cm}~ 0.5 TeV; gradient ~ 0.03 GV/m; ~30 km (~multi-$B).
- Higher energy collider with existing technology: 5 TeV ➔ >100 km, > tens of $B

Laser plasma accelerator based concept for a Laser Plasma Linear Collider



- Injector techniques
- Staging techniques
- Bunch properties
- 10 GeV module
- Collisions, synchrotron losses, efficiency

C.B. Schroeder et al., AAC Proceedings 2008: Leemans & Esarey, Physics Today, March 2009 ***W. Leemans***

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Main Processes Accompanying the Propagation of Short Intense Laser Pulses in Gases

Typical parameters

Laser pulse:

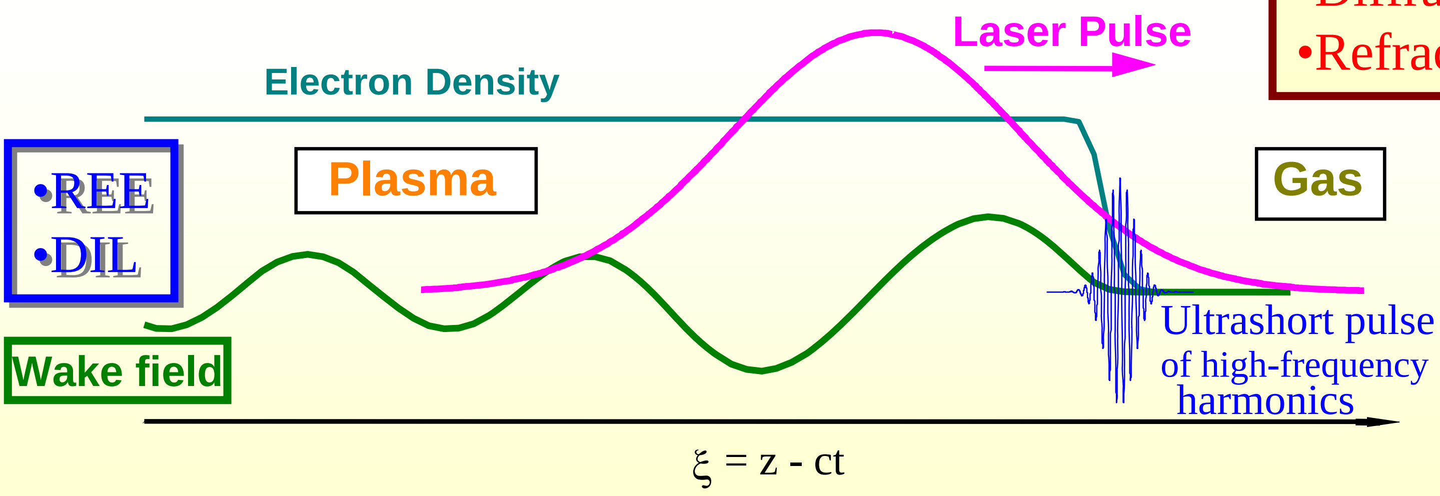
I_{max}>10^{17}W/cm^2 , FWHM < 1 ps, λ ≈ 1 mkm

Gas:

comparatively light atoms Z ≈ 1, n_{at}<10^{19}cm^{-3}

Laser Pulse Distortions:

- LASRS
- RS-F & S-M
- Filamentation
- Diffraction
- Refraction



Wakefield generation by guided laser pulses

➢*spectroscopic diagnostics of the wakefield*

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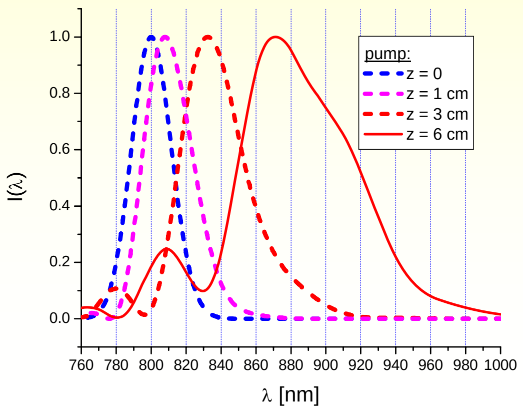
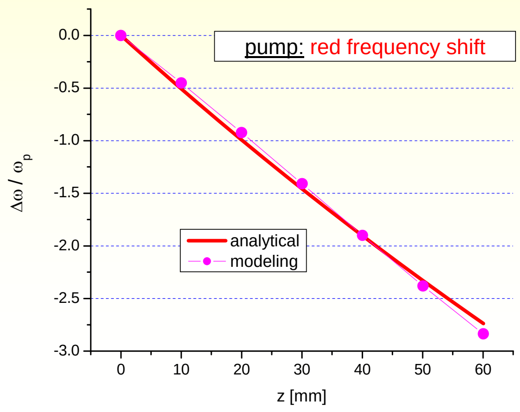
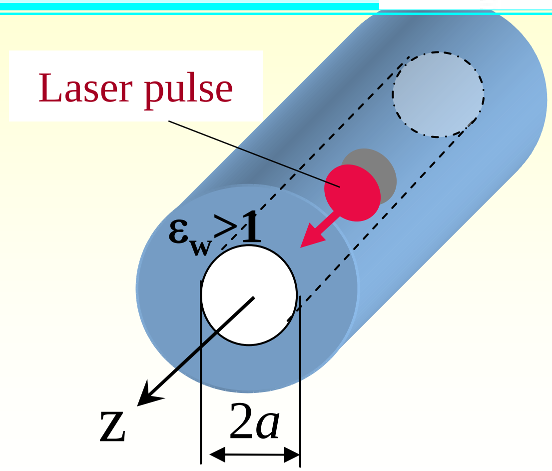
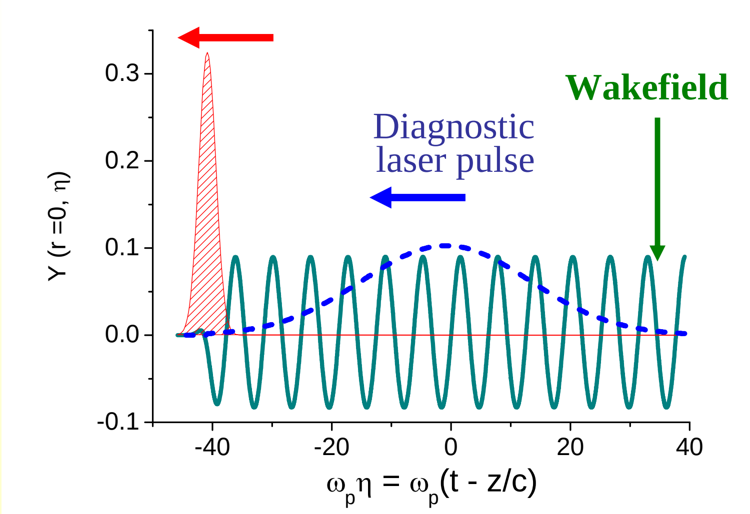
Frequency Shift of the Pump Pulse



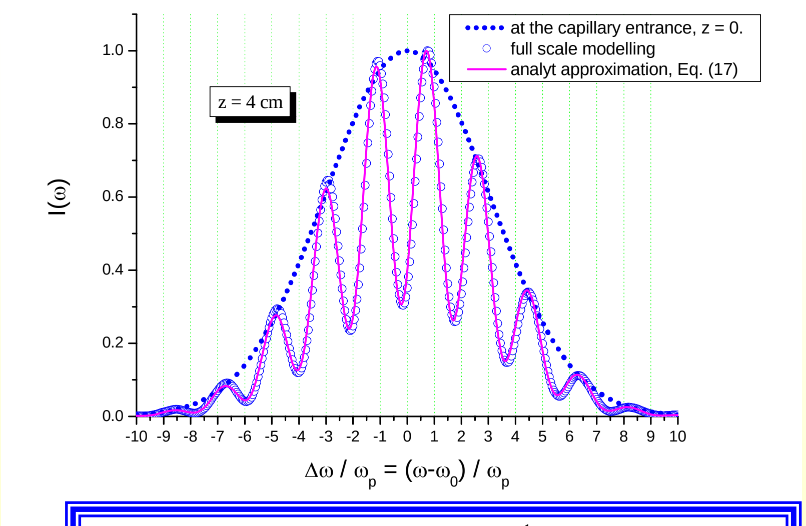




Short intense laser pulse



Spectrum Modulation of the Probe Pulse



$$\bar{A}(z) = C_r \frac{k_0}{k_p^2 z}\left[\sin\left(\frac{1}{4}\frac{\Omega^2\beta}{1+\beta^2}\right)\right]^{-1}\left[\delta\bar{I}(z)-\delta\bar{I}(z=0)\right]$$

N.E. Andreev, M.V. Chegotov, B. Cros, P. Mora, G. Vienx, Spectral diagnostics of laser wakefield in capillary tubes, Phys. Plasmas, **13, 053109 (2006).**

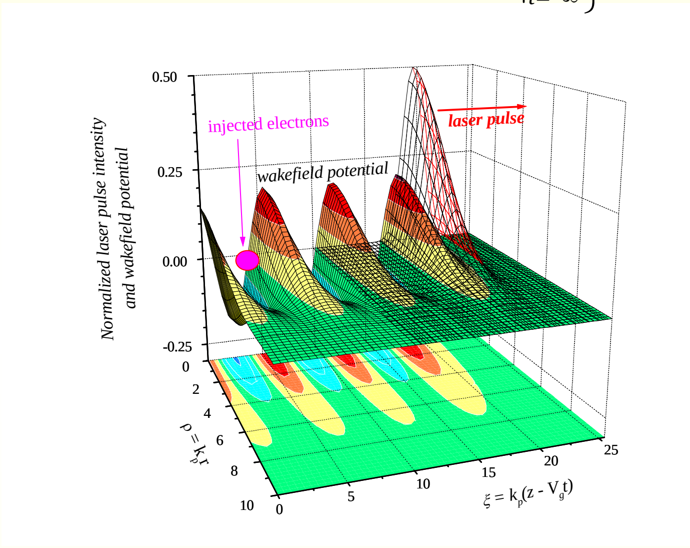
Spectroscopic Diagnostics of the Plasma Wakefield

$$\left\langle \omega^2 \right\rangle_{out} - \omega_0^2 = \frac{1}{\varepsilon_{out}} \left\{ \int_V d^3\mathbf{r} \int_{-\infty}^{+\infty} dt \left[\omega_0^2\, \mathbf{E}\,\mathbf{j} - \frac{\partial \mathbf{E}}{\partial t}\frac{\partial \mathbf{j}}{\partial t}\right] + \frac{1}{8\pi}\int_V d^3\mathbf{r} \left[\omega_0^2\left(\mathbf{E}^2+\mathbf{B}^2\right) - \left(\left(\frac{\partial \mathbf{E}}{\partial t}\right)^2 + \left(\frac{\partial \mathbf{B}}{\partial t}\right)^2\right)\right]\Bigg|_{t=-\infty}^{t=+\infty}\right\}$$

$$\left\langle\omega^2\right\rangle_\alpha = \oint_S \int_0^{+\infty} \omega^2 I_\alpha(\omega,\mathbf{R})\, d\omega\, \mathbf{n}\, ds \left[\oint_S\int_0^{+\infty} I_\alpha(\omega,\mathbf{R})\, d\omega\, \mathbf{n}\, ds\right]^{-1}$$

$\delta\overline{n}_e$ – Wakefield Amplitude

$I(\mathbf{r}, t)$ – Laser Pulse Intensity



$$\left\langle\omega^2\right\rangle_{out} - \left\langle\omega^2\right\rangle_{in} = -\frac{6\pi e^2}{m_e c\, \varepsilon_{out}} \int_V \int_{-\infty}^{+\infty} \delta\overline{n}_e \frac{\partial I(\mathbf{r},t)}{\partial t}\, dt\, d^3\mathbf{r} + \frac{\omega_0^2}{8\pi\varepsilon_{out}}\int_V\left(1-\frac{n_0(\mathbf{r})}{n_c}\right)\mathbf{E}^2_{p,\max}(\mathbf{r})\, d\mathbf{r}$$

$$\left\langle\omega^2\right\rangle_{out} - \omega_0^2 = -\frac{\omega_0^2}{4\pi\varepsilon_{out}}\int_V \mathbf{E}^2_{p,\max}\, d^3\mathbf{r}$$

$$\mathbf{E}^2_{p,\max} = \frac{m^2c^4}{e^2}\frac{\omega_p^2}{16}\left\{k_p^2\left|\int_{-\infty}^{\infty} dt\, e^{i\omega_p t}\, |\vec a|^2\right|^2 + \left|\frac{\partial}{\partial r}\int_{-\infty}^{\infty} dt\, e^{i\omega_p t}\, |\vec a|^2\right|^2\right\}$$

Spectroscopic Diagnostics of the Plasma Wakefield …

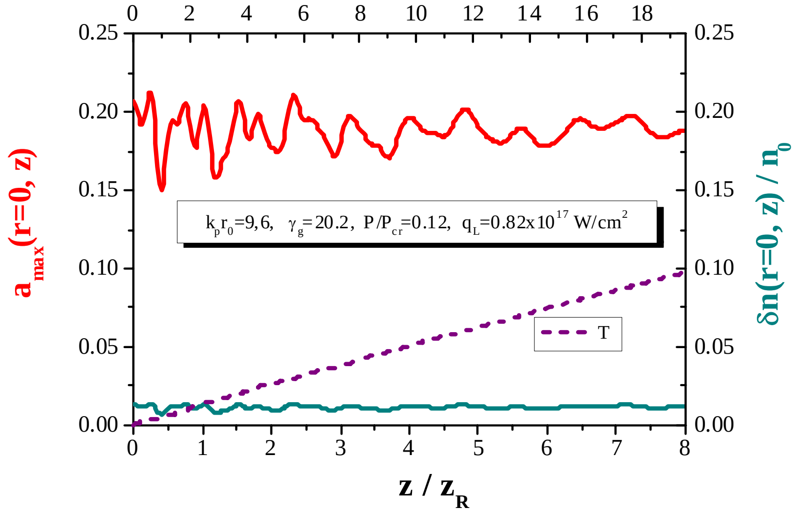
Nonlinear laser pulse propagation in a gas-filled capillary

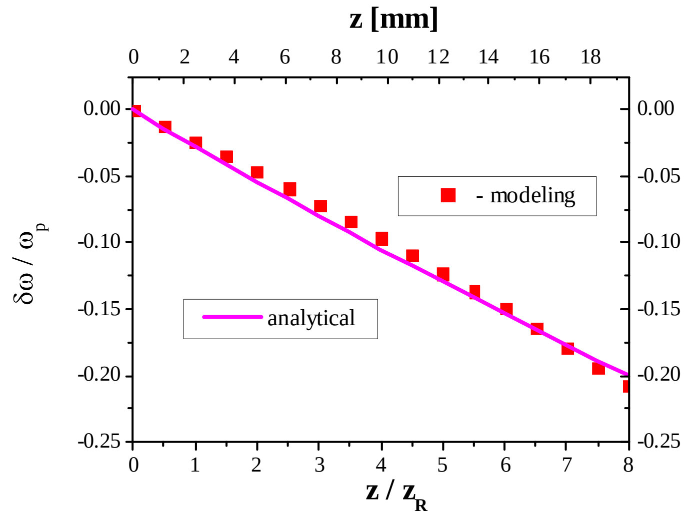
$$I(t,z,\mathbf{r}_\perp) = I_{\max} \exp\left(-2\frac{(t-z/c)^2}{\tau^2}\right) f(r)$$

$$f(r) \cong J_0^2\left(\frac{u_1 r}{R_{cap}}\right), \quad J_0(u_1)=0$$

$$\frac{\langle \omega^2 \rangle_{out} - \omega_0^2}{2\omega_0\omega_p} = \frac{\delta\omega}{\omega_p} = -\frac{1}{64}\left(\frac{\pi}{2}\right)^{1/2}\left(1.13k_p^2 r_0^2 + 8.72\right) a_0^2 \Omega \exp\left(-\frac{\Omega^2}{4}\right) z/z_R, \quad \Omega = \omega_p \tau$$

Hydrogen: N_a=4.1×10^{18}cm^{-3}, P_L=0.8 TW, $k_p r_0$=9.5, D_{cap}=75 mkm, P_L/P_{cr}=0.12

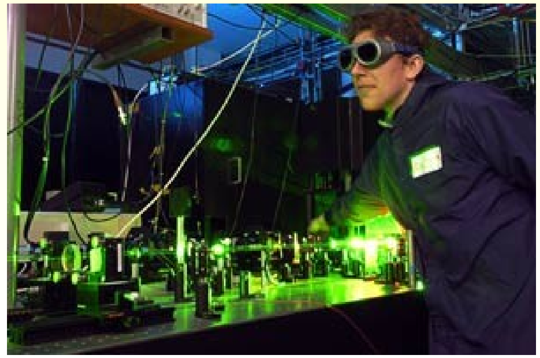


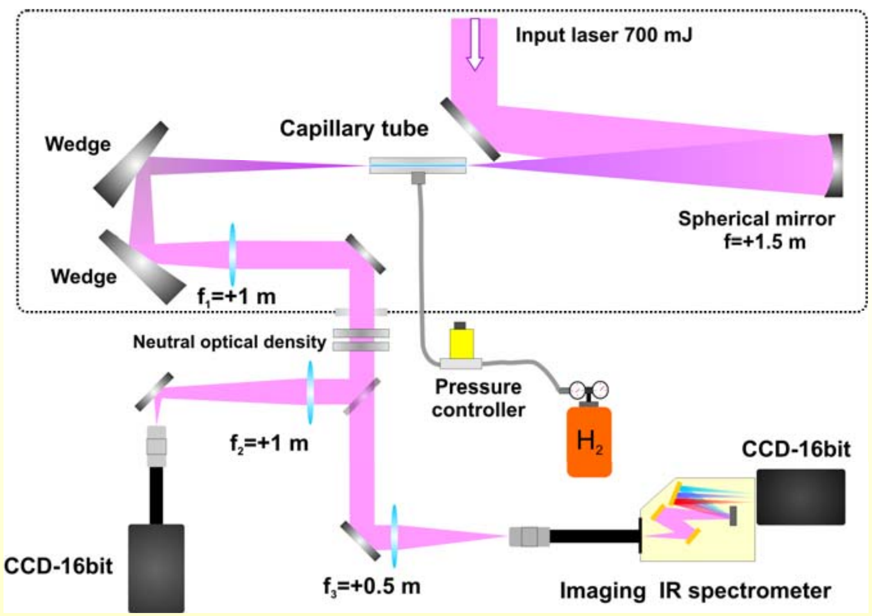


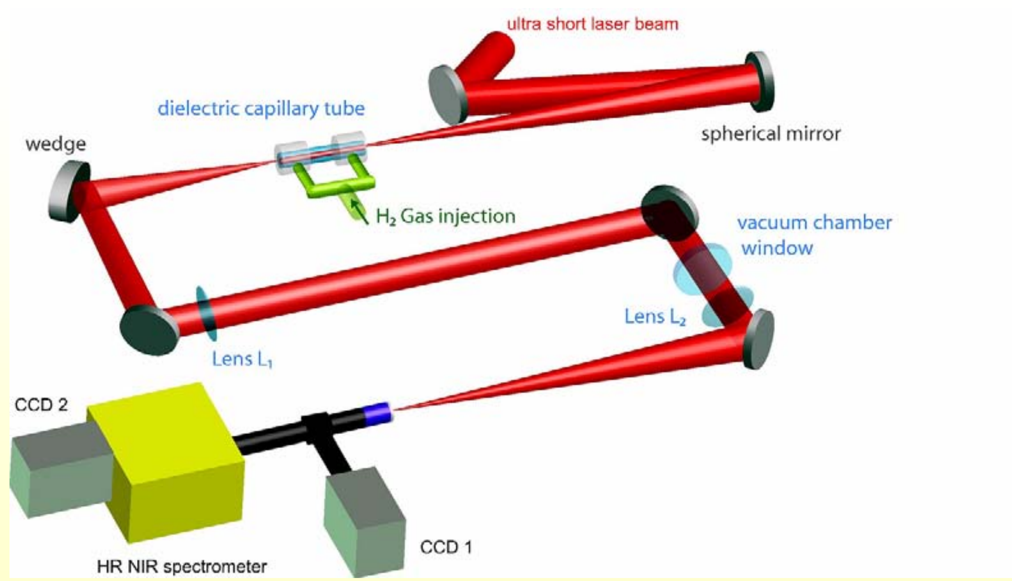
N.E. Andreev, M.V. Chegotov, Sov. Phys. JETP 101, pp. 56-63 (2005).

Laser plasma electron acceleration experiments - 2009

Lund Laser Centre



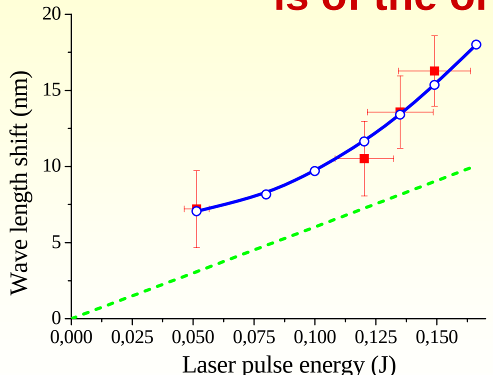


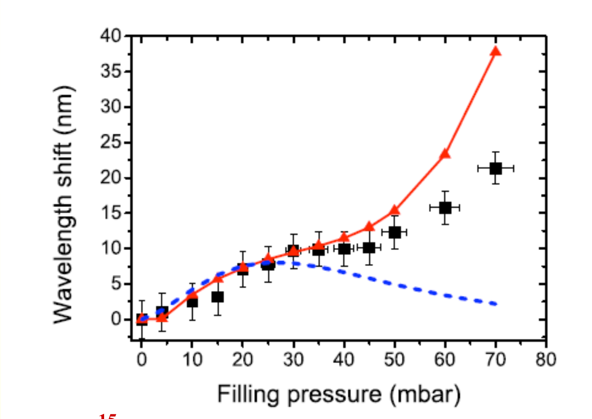


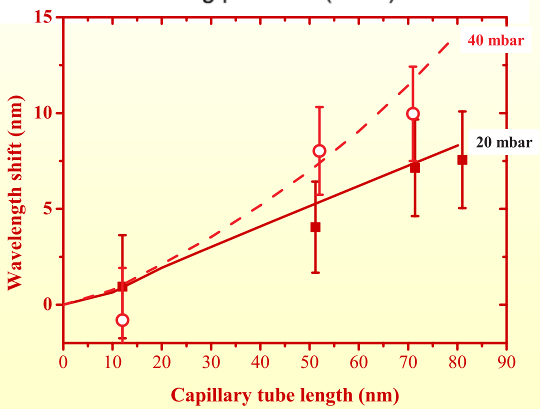
Phys. Rev. E 80, 066403 (2009)

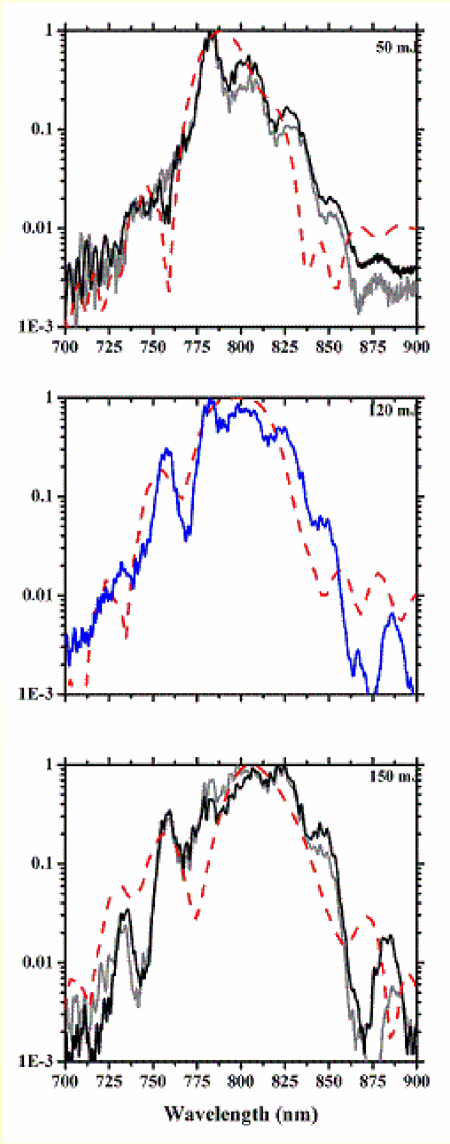
Spectral diagnostics of the laser wake fields in capillary tubes

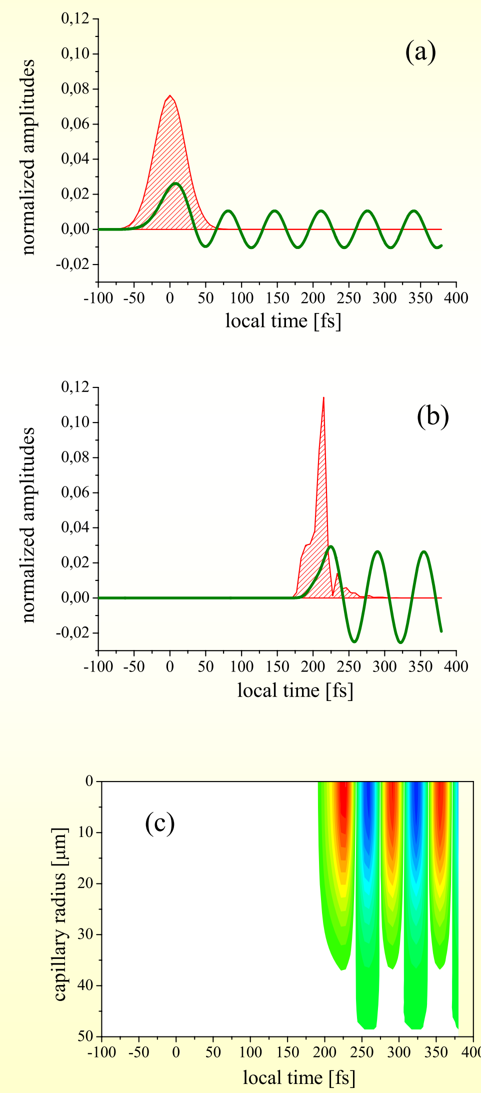
The average product of gradient and length achieved in this experiment
is of the order of 0.4 GV at a pressure of 50 mbar











N.E. Andreev, et al, NJP, 12, 045024 (2010)

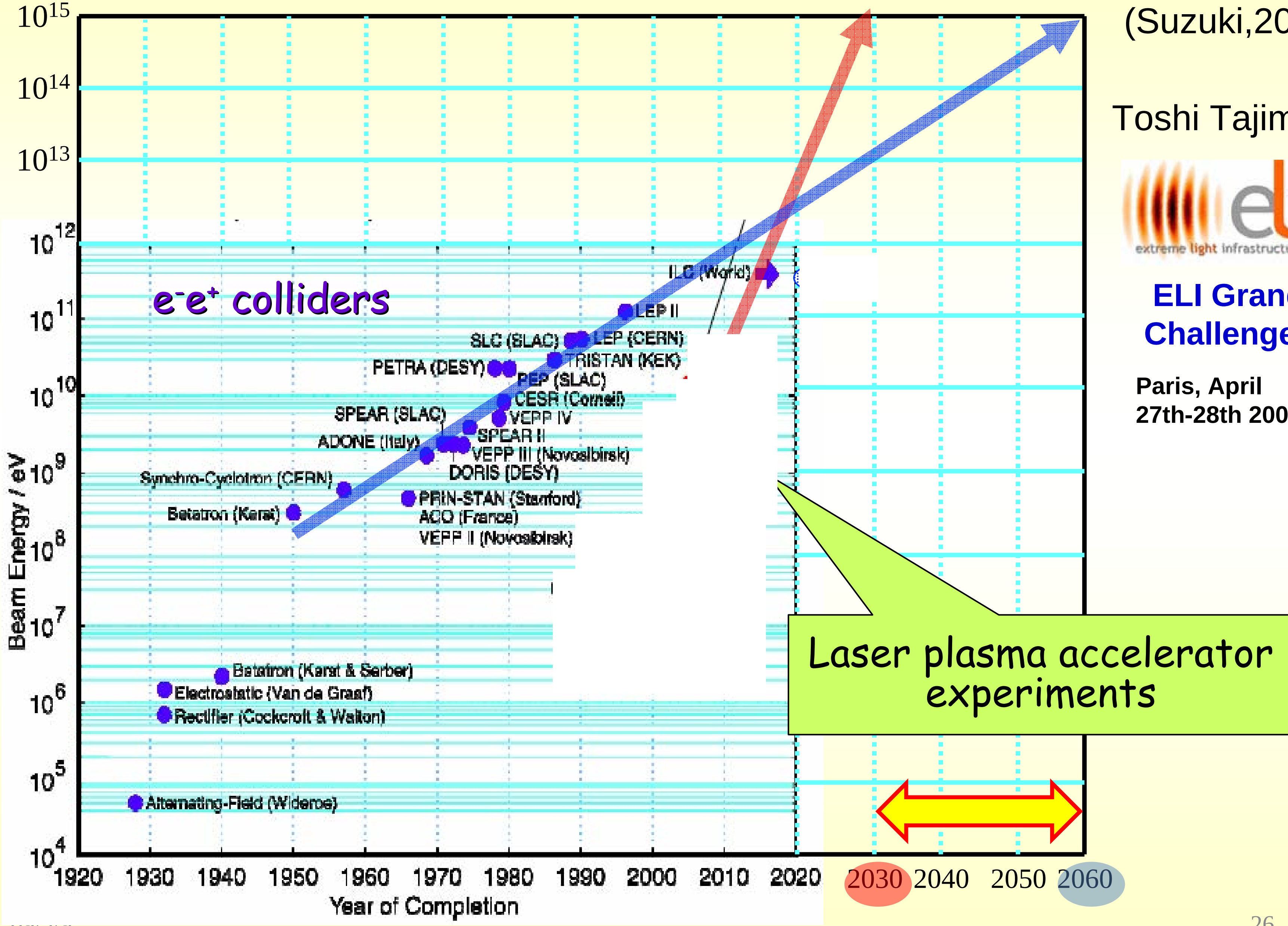
When can we reach 1 PeV ?: Suzuki Challenge(2)

(Suzuki,2009)

Toshi Tajima

ELI Grand Challenges

Paris, April 27th-28th 2009



V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4

ExtreMe Matter Institute EMMI

Workshop on Plasma Physics with Intense Laser and Heavy Ion Beams

May 20 - 21, 2010 - Moscow, Russia

Organized by Joint Institute for High Temperatures RAS, Russia, and ExtreMe Matter Institute EMMI, Germany

Conference Chairmen
Vladimir E. Fortov, JIHT RAS, Moscow
Thomas Stöhlker, GSI, Darmstadt

Main Topics
Physics of laser-matter inter[illegible]n, experiments [illegible]d theory
Interaction of heavy ions wit[illegible]ry
Scientific activities and pers[illegible]
Scientific activities and perspectives at TWAC, S[illegible]18 and perspectives for FAIR
Target development for laser and heavy ion experiments

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Thank You for attention!