Secondary sources generated by short intense laser pulses: high energy particles and radiation

N. Andreev, M. Agranat, S. Ashitkov, A. Emelianov, A. Eremin, V. Fortov, A. Frolov, E. Gurentsov, K. Khishchenko, O. Kostenko, P. Levashov, S. Kuznetsov, A.Ovchinnikov, O. Rosmej [1], A. Shevelko, D. Sitnikov, M. Veysman

IHED JIHT RAS

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 14 - 15, 2009, JIHT, Moscow, Russia

Organized by JIHT RAS and EMMI

EMMI

Outline

- **Introduction**
  - *What can we do with PW lasers and where we are?*
- **Laser wakefield electron acceleration by PHELIX**
  - *in guiding structures*
  - *In gas jets*
- **Ion sources by optical field ionization**
  - *residual ion energy*
  - *ponderomotive acceleration*
- **X-ray radiation using solid and nano-structured targets**
  - *mechanisms of hot electrons production*
  - *optimization of K_α x-ray yield*
- **Powerful sources of terahertz radiation**
  - *terahertz radiation in magnetized plasma*
  - *low-frequency transition radiation*
- **Mega-gauss magnetic fields in laser plasmas**

➢*What can we do with PW lasers…?*

from the **Summary**

of the Franco-Russian ISTC Workshop on the physics with PETAL,

March 9 - 11, 2009, Le Barp, France

(**PETAL is a 3.5 kJ, 0.5 – 10 ps, PetaWatt-class laser** which is under construction in the Aquitaine)

Fundamental physics:

- **nuclear physics with lasers** (*production of isomeric nuclei),*
- **physics of high intensity laser plasma interaction** (*strong magnetic and electric fields, nonlocal energy transport),*
- **high energy density physics** (*development of new, more detailed equations of state, studies of transport and optical properties of non ideal plasma, modeling of atomic transitions and opacities),*
- **laser driven melting and ablation** (*especially with sub-ps laser pulses).*

It was mutually acknowledged that the collaboration in the domain of development of

secondary sources

of energetic charged particles, neutrons and radiation

is absolutely necessary for all envisioned applications of PETAL

➢*What can we do with PW lasers…?*

secondary sources

of high energy particles and radiation

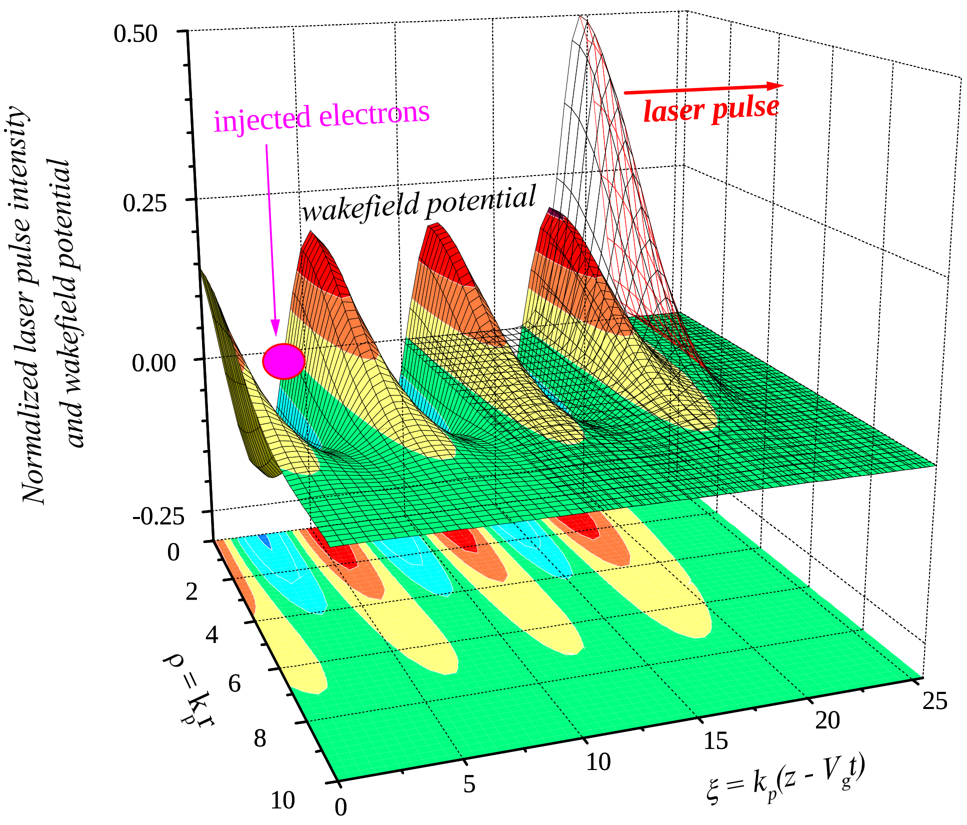
The particular subjects could be:

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

➢laser wake field electron acceleration

IHED
JIHT RAS

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

JIHT RAS

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

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

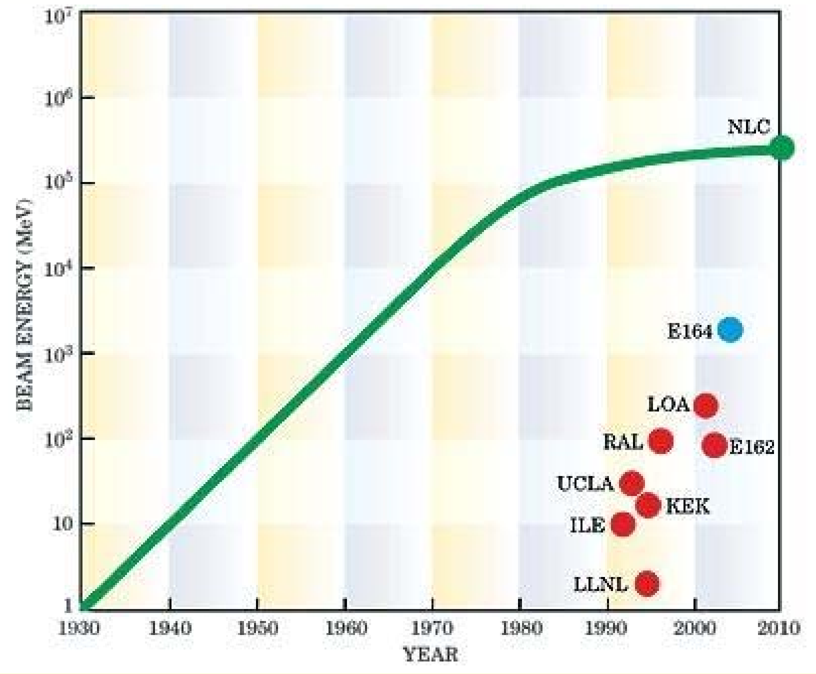
$\alpha = \delta n / n_0$ – ***plasma wave amplitude; at*** α = 0.3÷1.0, $n_e = 10^{17} \div 10^{18}$ cm^{-3}:

$$E_P = 10 \div 100\ GV/m$$

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

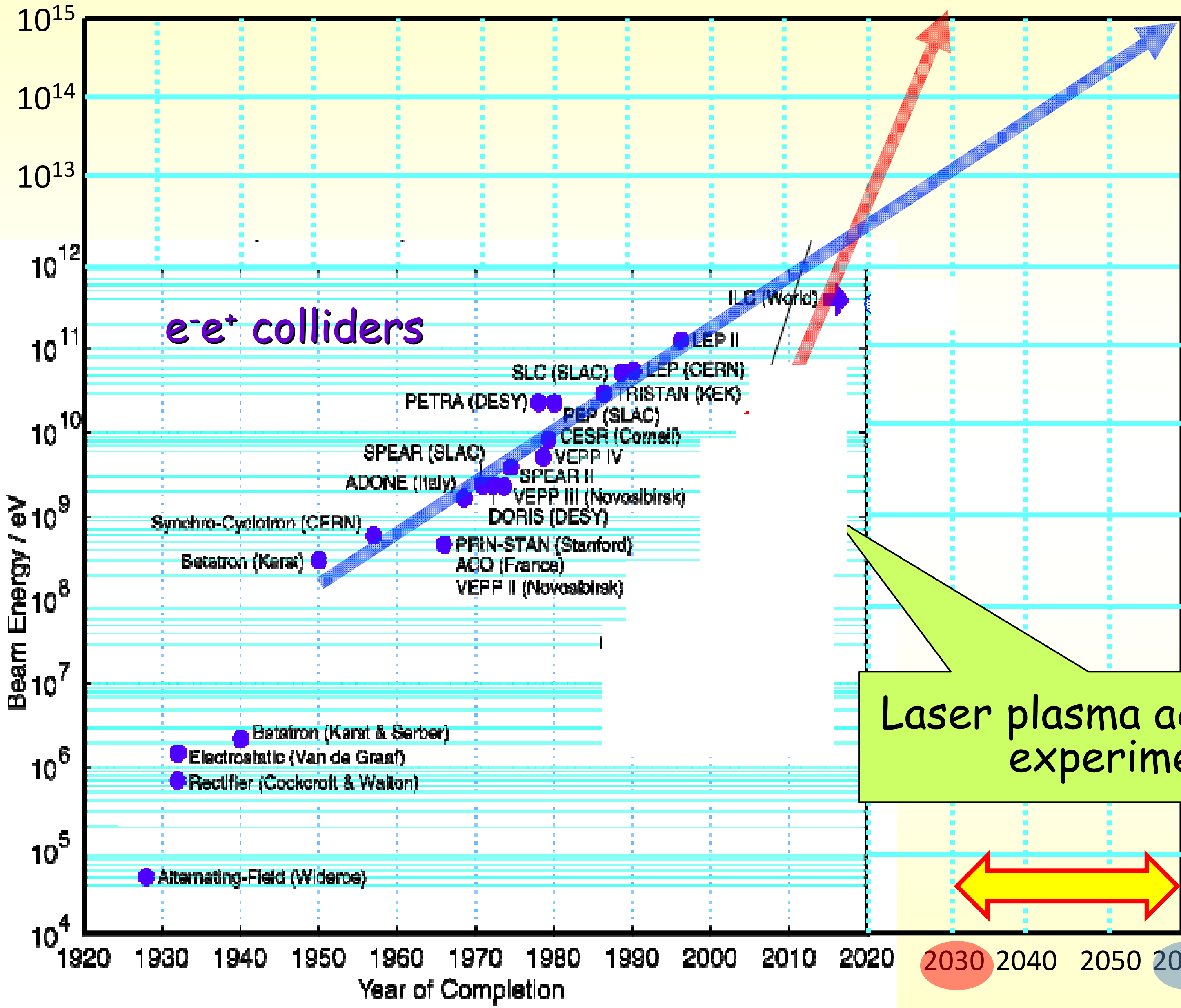
E_{RF} ~ 10 - 100 MV/m

Exponential growth of “the Livingston curve” began tapering off around 1980



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

(Suzuki,2009)



Toshi Tajima

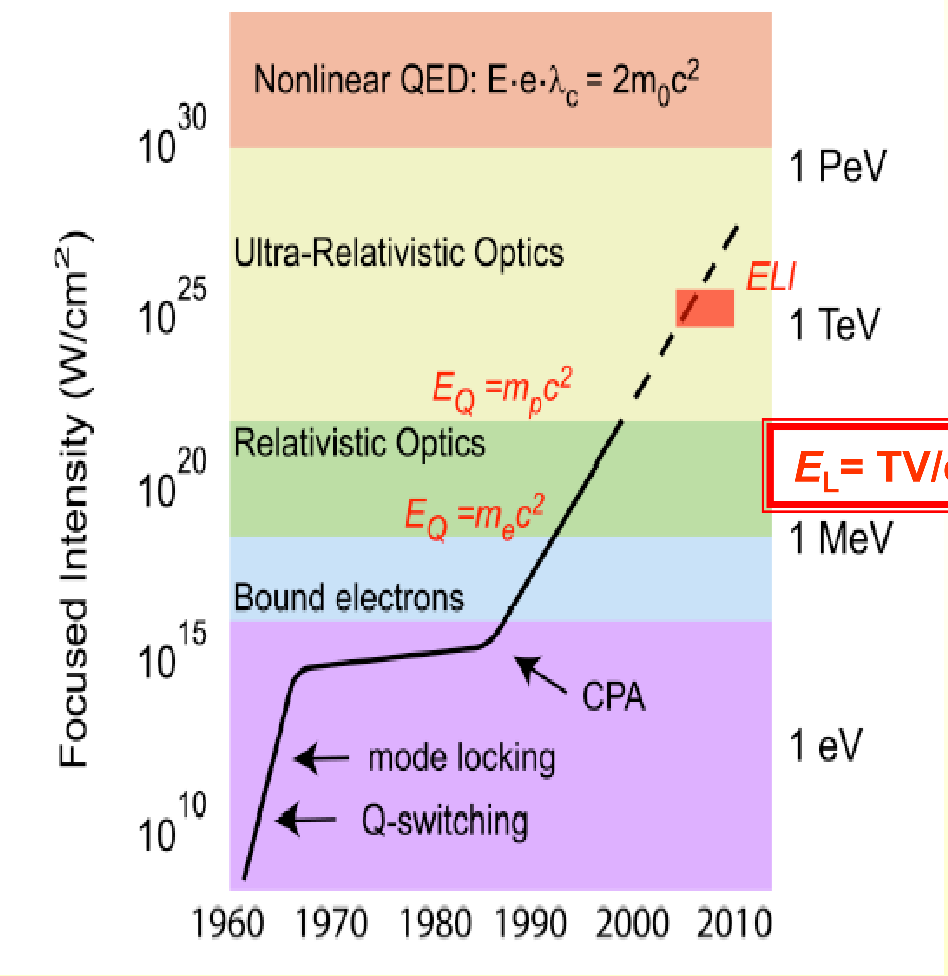
extreme light infrastructure

ELI Grand Challenges

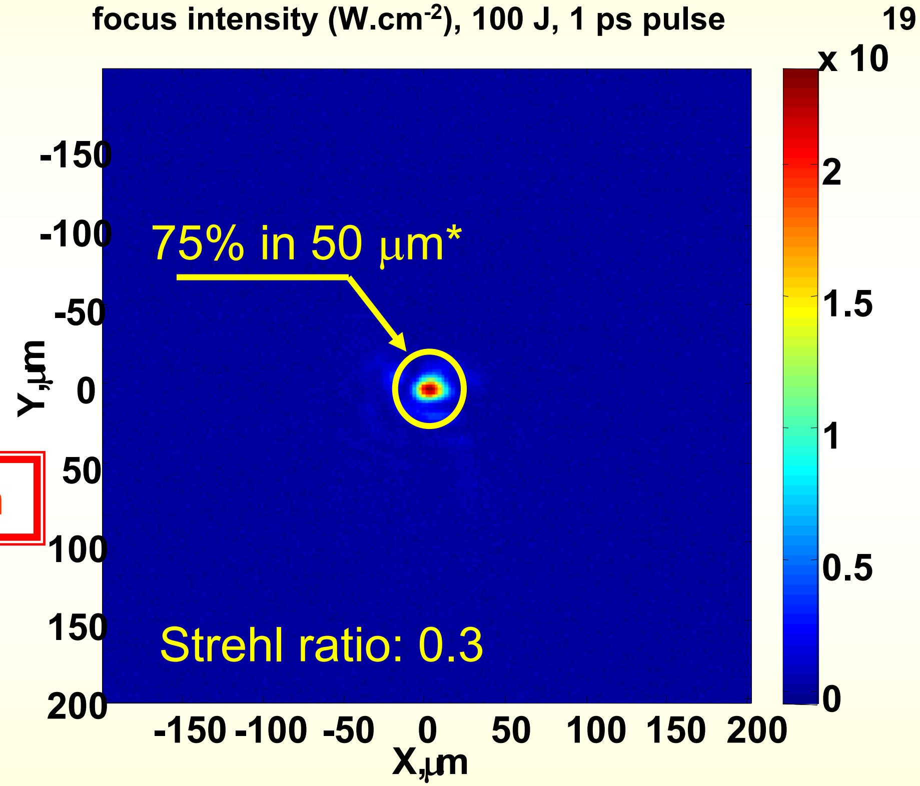
Paris, April 27th-28th 2009

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

where we are with PHELIX intensity



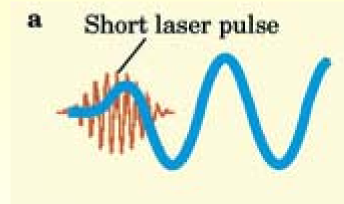
E_L= TV/cm

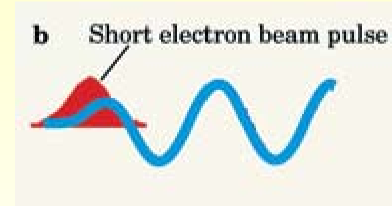


PHELIX
Petawatt High-Energy Laser for Heavy Ion Experiments

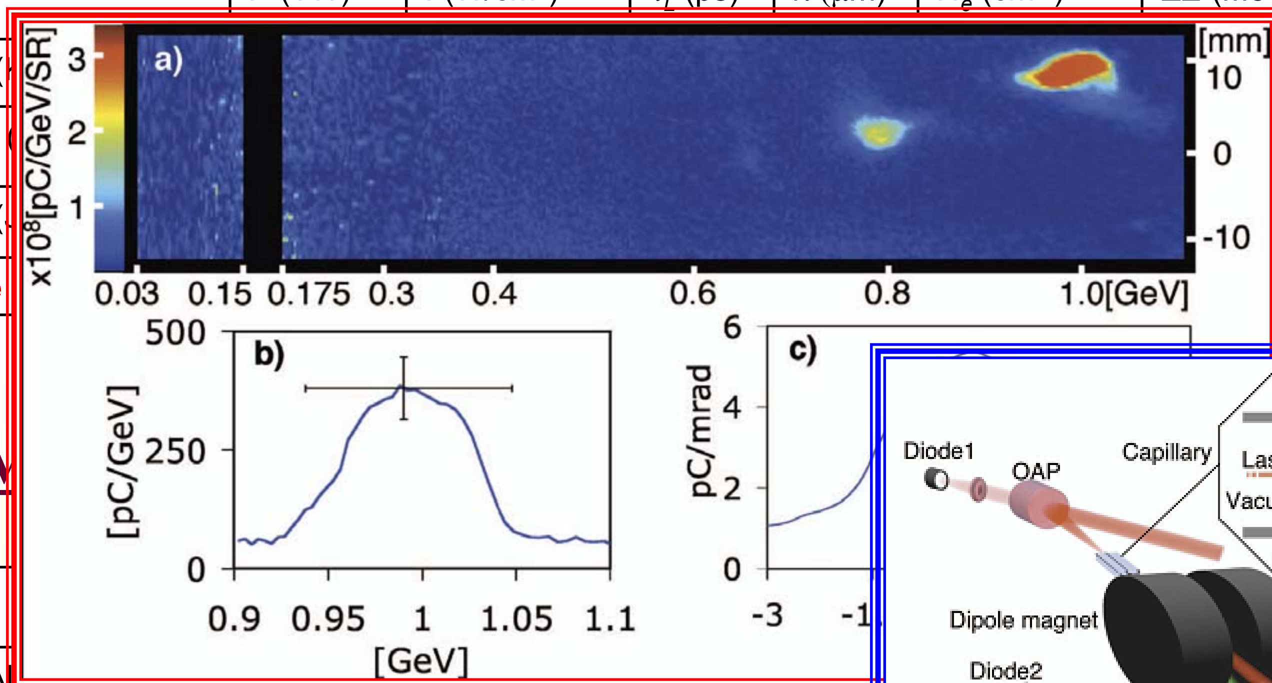
Parameters and results of some experiments

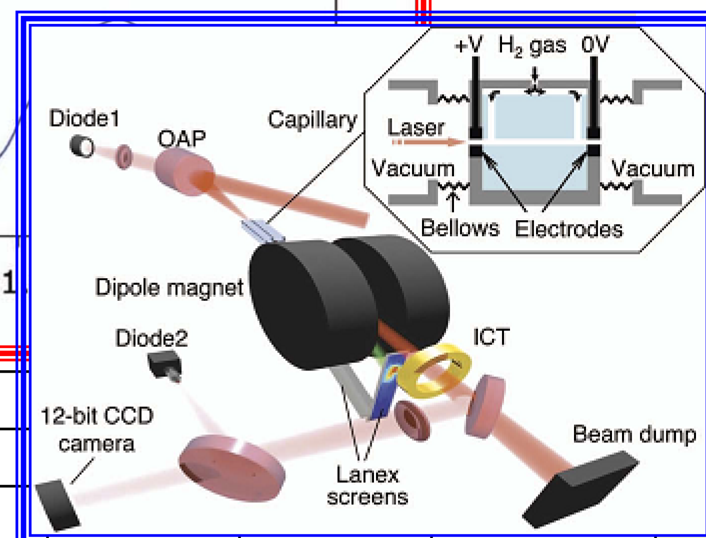
for **standard LWFA** scheme $c\tau_L \approx \lambda_p/2$





	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**

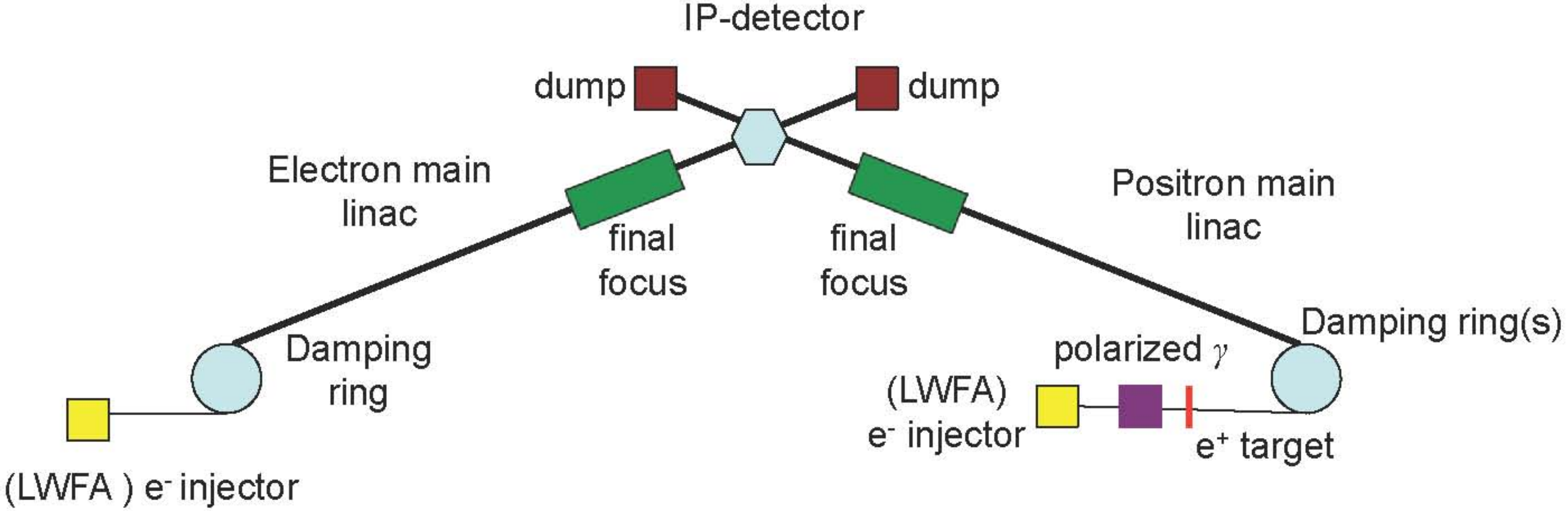




for **Self-M**

UK (RAL)							
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

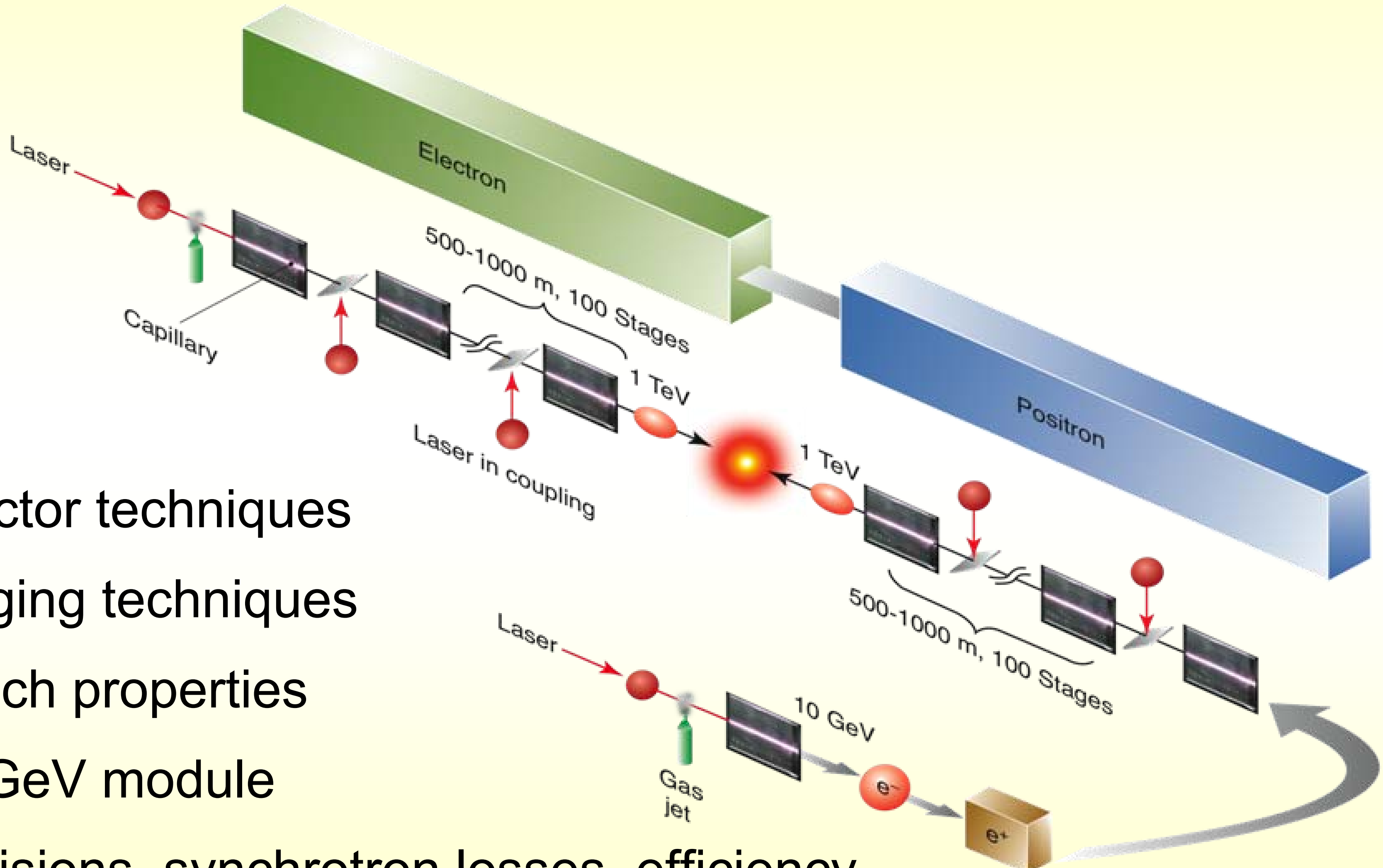
Electron-Positron Linear Collider



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

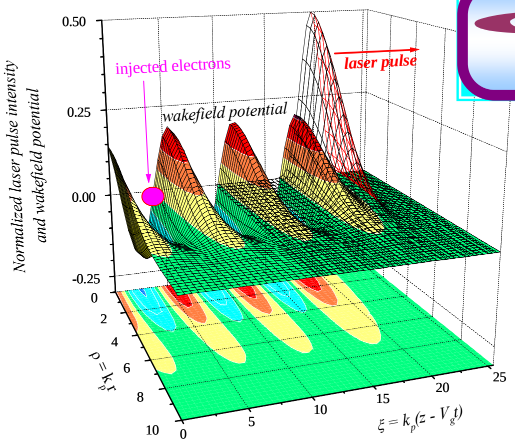
Laser plasma accelerator based concept for a Laser Plasma Linear Collider



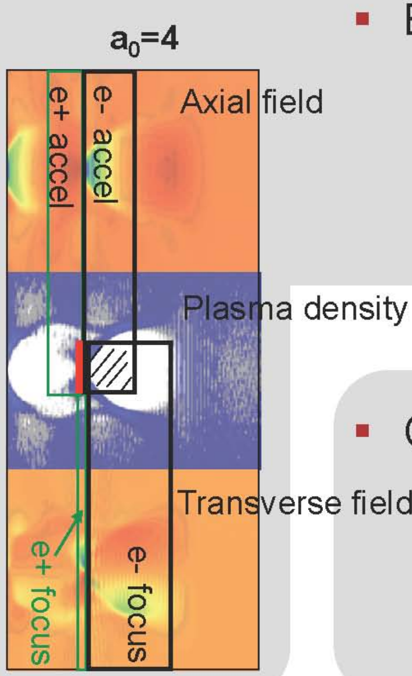
- Injector techniques
- Staging techniques
- Bunch properties
- 10 GeV module
- Collisions, synchrotron losses, efficiency

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

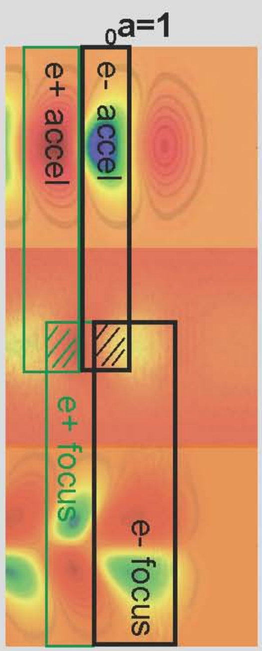
Laser-Plasma Acceleration of electrons with record gradients ~ 10 GV/m



Linear & blowout regimes: e+/e- acceleration



- Blowout regime
  - high field
  - very asymmetric
    - focuses e-
    - defocuses e+
- Quasilinear
  - linear: symmetric e+/e-
  - high a0 desired for gradient
    - too high enters bubble: e+
  - a_0 ~1-2 good compromise



E. Esarey

Physical Restrictions on the Monoenergetic Acceleration of Electrons/Positrons in Laser-Plasma Accelerators

- *Dephasing of electron/positron bunches;*
- *Diffraction of the laser pulse;*
- *Depletion of the laser pulse;*
- *Electron/positron bunches loading effect*
- *Focusing/defocusing of electron/positron bunches*
- *Nonlinear laser pulse distortions*

IHED JIHT RAS

Physical Restrictions on the Energy of Accelerated Electrons in Laser-Plasma Accelerators

Dephasing of electron/positron bunches

Maximum length of acceleration:

$$l_a \le L_{deph} = \frac{\lambda_p}{2(c - v_{ph})} c = \gamma_g^2 \lambda_p, \quad \gamma_g = \frac{\omega_0}{\omega_p} = \sqrt{\frac{n_c}{n_e}}$$

Energy gain: $$\Delta W_e = eE_a l_a \cong \frac{e\Delta\varphi}{\lambda_p / 2} l_a = 2mc^2 \gamma_g^2 \alpha$$

Laser Pulse Diffraction:

$$L_{diff} = \pi Z_R = \frac{2\pi^2 r_L^2}{\lambda}, \quad a_0^2 \propto P_L / r_L^2 \qquad \alpha \propto a_0^2$$

for LWFA $$\Delta W_{diff} [\mathrm{MeV}] = 960 \frac{\kappa \lambda [\mu\mathrm{m}]}{\tau [\mathrm{fs}]} P[\mathrm{TW}]$$

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

IHED
JIHT RAS

Typical parameters

Laser pulse:

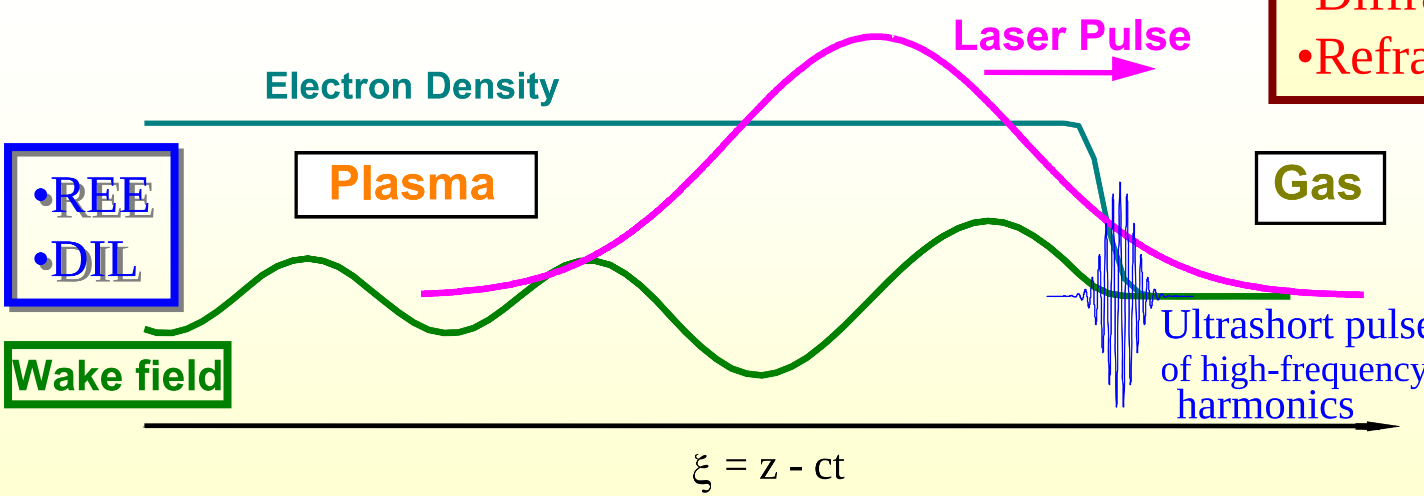
I_{max}>10^{15}W/cm^2 , FWHM < 1 ps, λ ≈ 1 mkm

Gas:

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

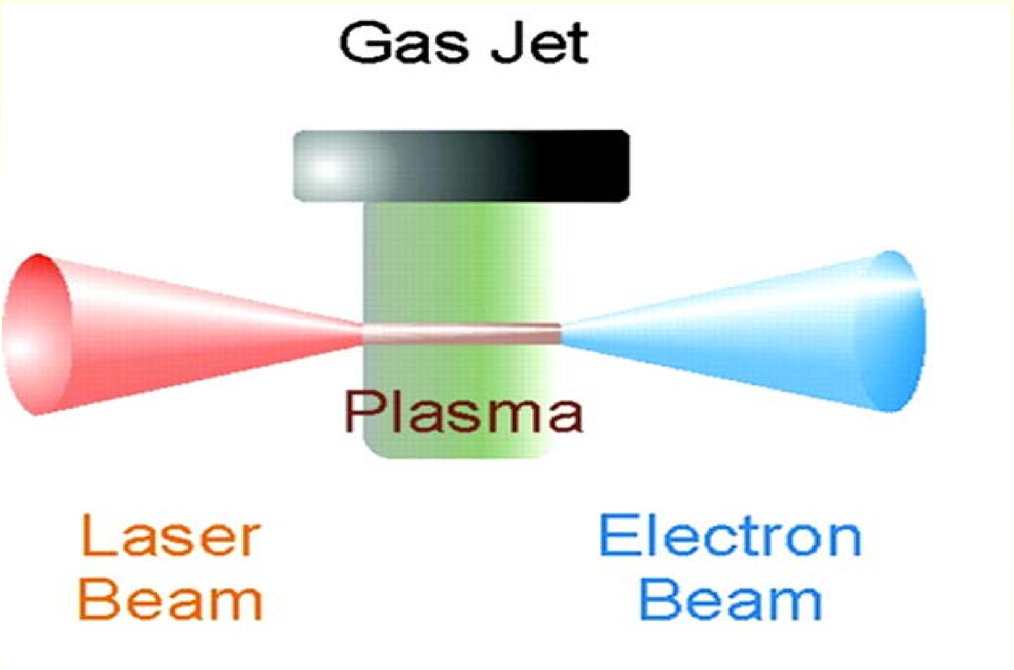
Laser Pulse Distortions:

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



Electron Acceleration in the PHELIX Focus

Petawatt High-Energy Laser for Heavy Ion Experiments



Laser Parameters:

λ_0=1.053 τ_{FWHM}=300 fsec
w_0=100 µm
I_L=$2x10^{18}$W/cm^2, E_L=190 j

Plasma Density:

n_e=2.5 $10^{16}cm^{-3}$
γ_g=200

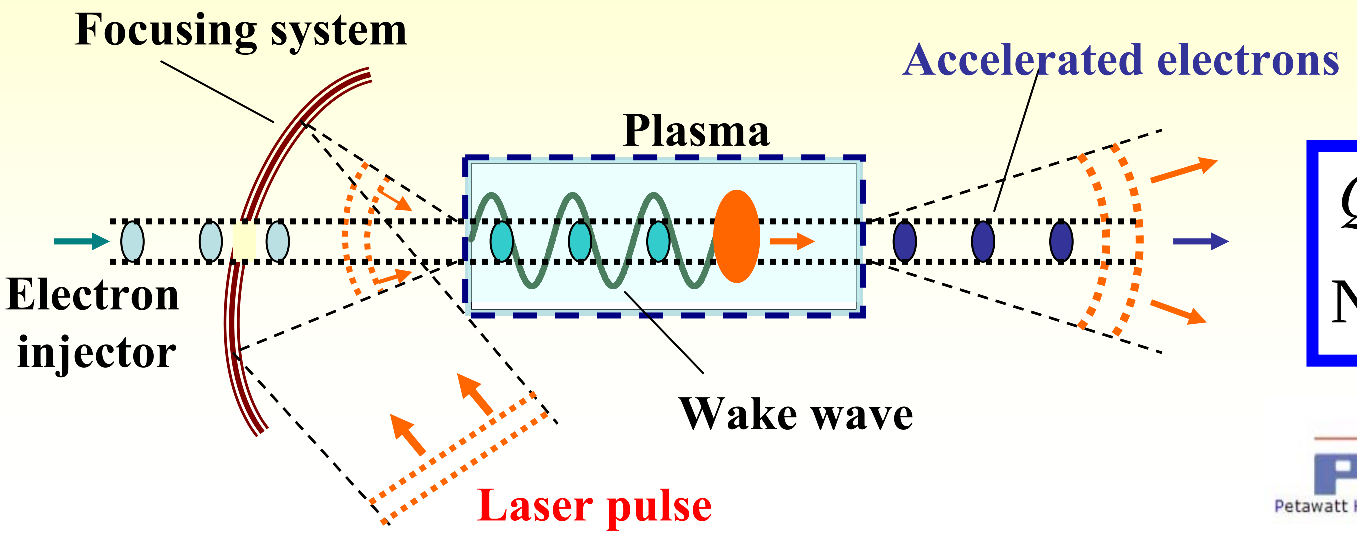
$N_{e\text{-}bunch} \approx 10^9$
$Q_b \approx$ 200 pC

Injected Electrons with $E_{inj}=\gamma_g\ mc^2$ are accelerated to E~0.8 GeV,
Length of acceleration $l_a \sim L_{diff} \sim 10$ cm

EMMI

GSI

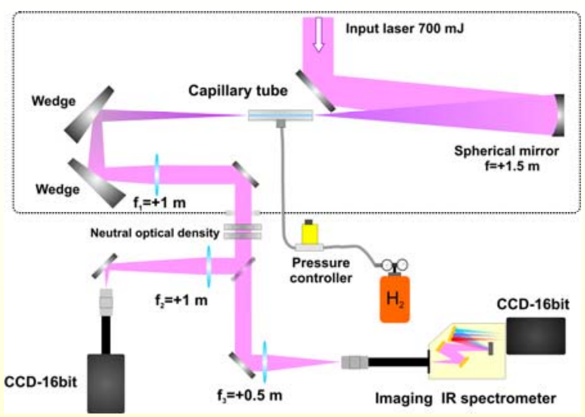
Laser Wakefield Electron Acceleration



$Q_b \leq 100\text{pC}$

$N_{\text{e-bunch}} \approx 10^9$

Petawatt High-Energy Laser for Heavy Ion Experiments



B. Cros, et al. Schematic view of the experiment
at the Lund Laser Center

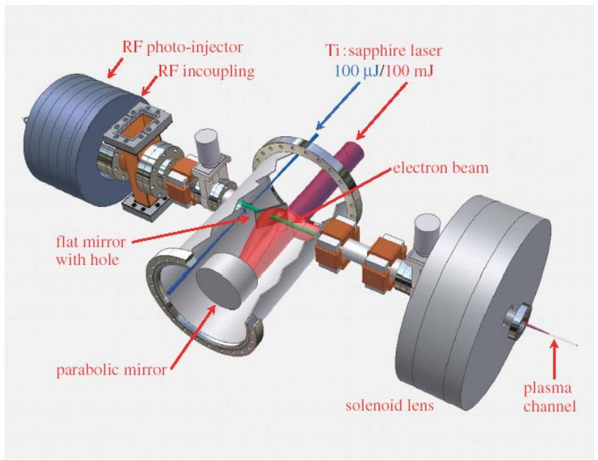


Figure 1. Layout of experiment planned at TU-Eindhoven on LWA with external injection.

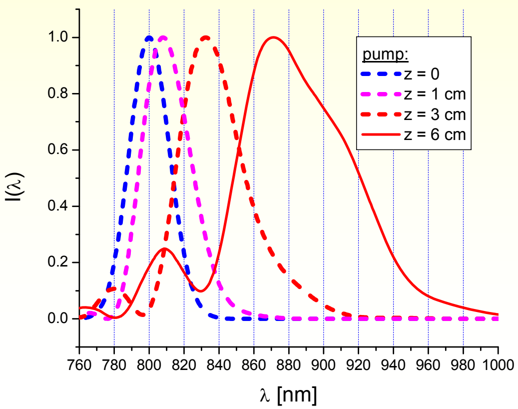
λ_0 = 1.053μm
τ_{FWHM} = 300 fs
w_0=200 μm
E_L=150 j
n_e=1.7·10^{16} cm^{-3}
***E* ~ 2.7 GV/м**
L_{trap}~10 cm, L_{acc}~ 1 m

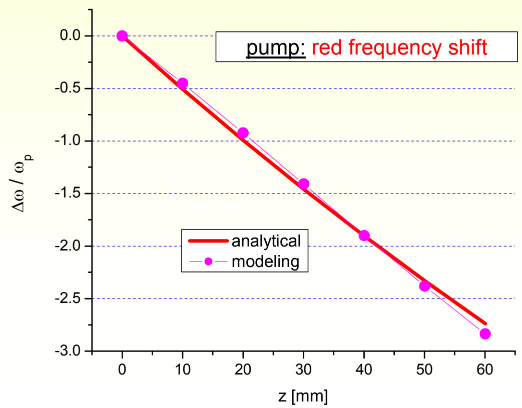
Wakefield generation by guided laser pulses

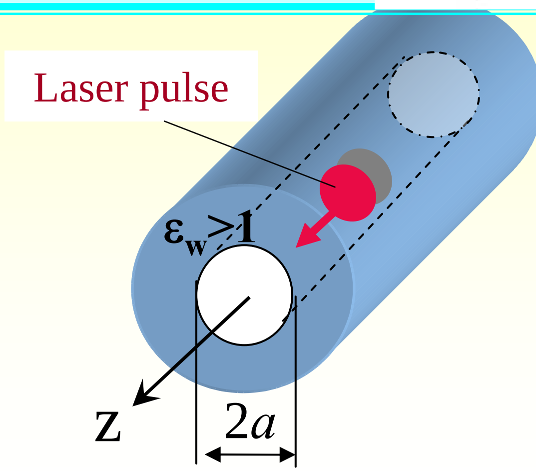
➢ *spectroscopic diagnostics of the wakefield*

IHED JIHT RAS

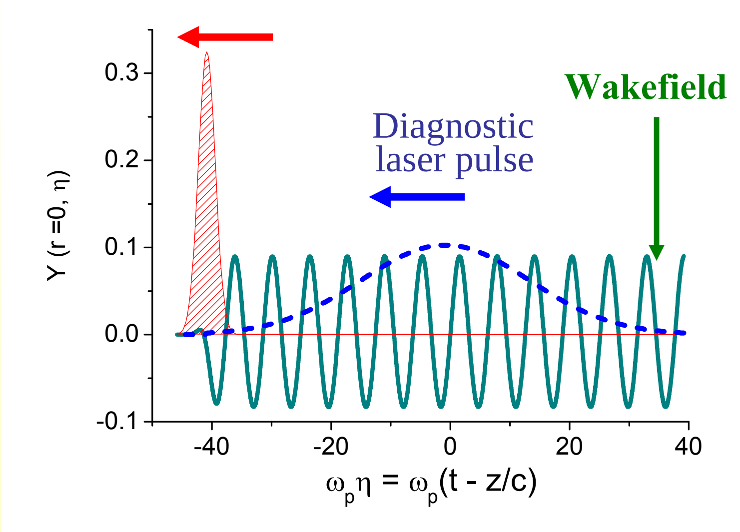
Frequency Shift of the Pump Pulse



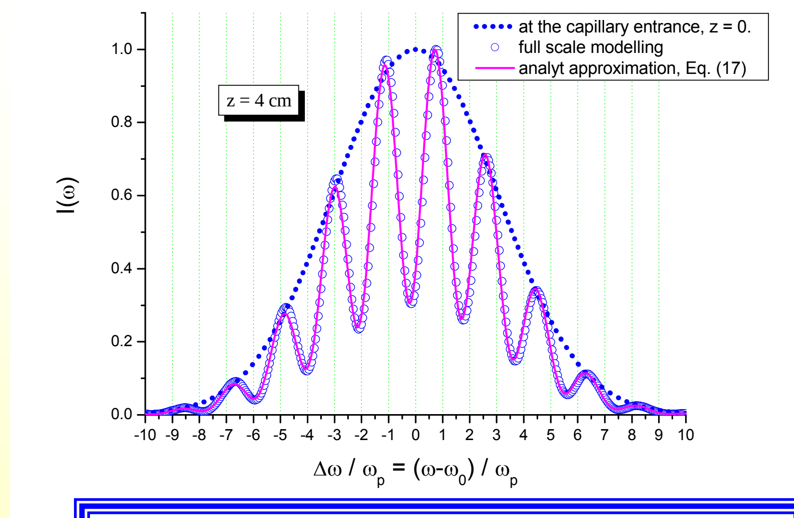




Short intense laser pulse

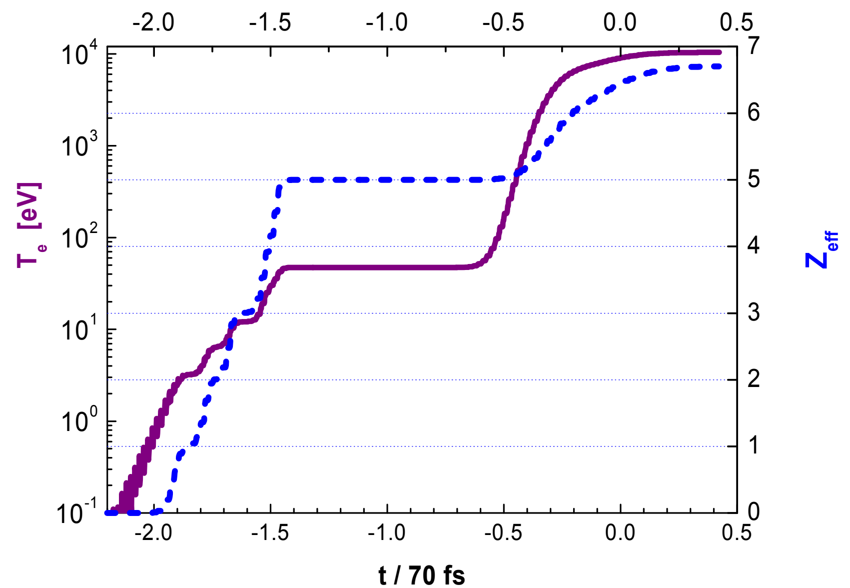


Spectrum Modulation of the Probe Pulse



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

Multi-group Residual Electron Energy Distribution of many-electron atoms



laser pulse parameters:
I_L=10^{19} W/cm^2, τ_L = 70 fs,
λ=0.78μm
Nitrogen gas

Energy of electron groups and relaxation times (N_2=1.5×10^{19} W/cm^2)

k	1	2	3	4	5	6	7
$Q_{e,k}$ [eV]	3.3	9.7	23.4	79.5	120.	39×10^3	39×10^3
$t_{ee,k}$	60 fs	150 fs	380 fs	1.8 ps	2.6 ps	13 ns	13 ns

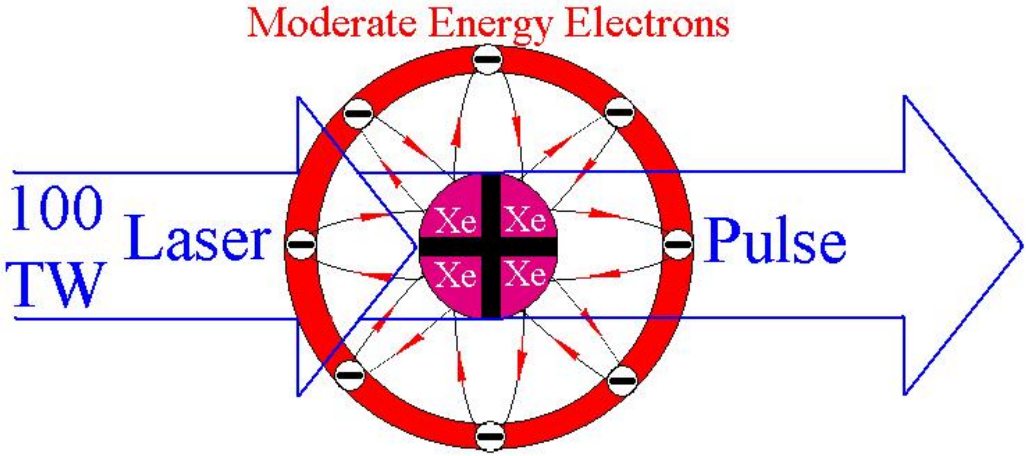
Ion sources by optical field ionization produced by PHELIX

Petawatt High-Energy Laser for Heavy Ion Experiments

A large amount of ions with low temperature (less than 100 eV), low momentum spread and narrowed charge state distribution can be produced by petawatt-class short-pulse laser

Low Temperature Xe^{+26} Ions Laser Source

Residual ion energy is the least unavoidable ion energy after ionization of gases by a short intense laser pulse



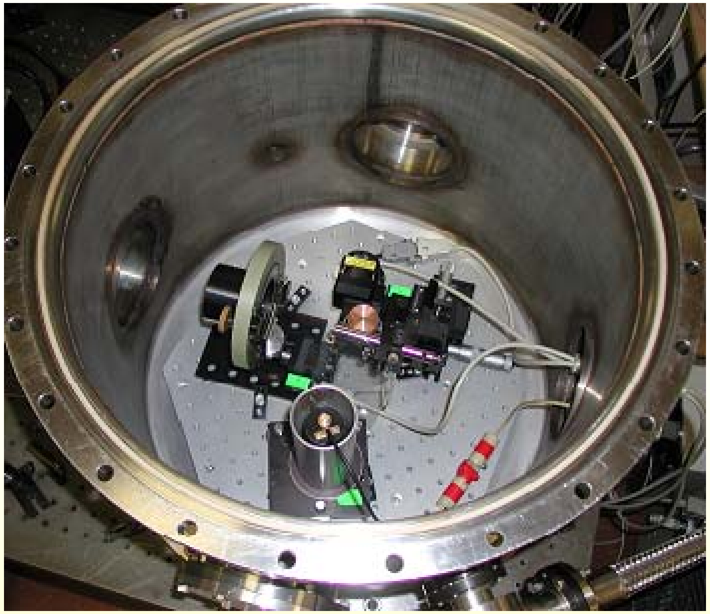
Moderate and Low Energy Ionization Electrons are Caught by Ambipolar Electric Field and Produce Undesirable:

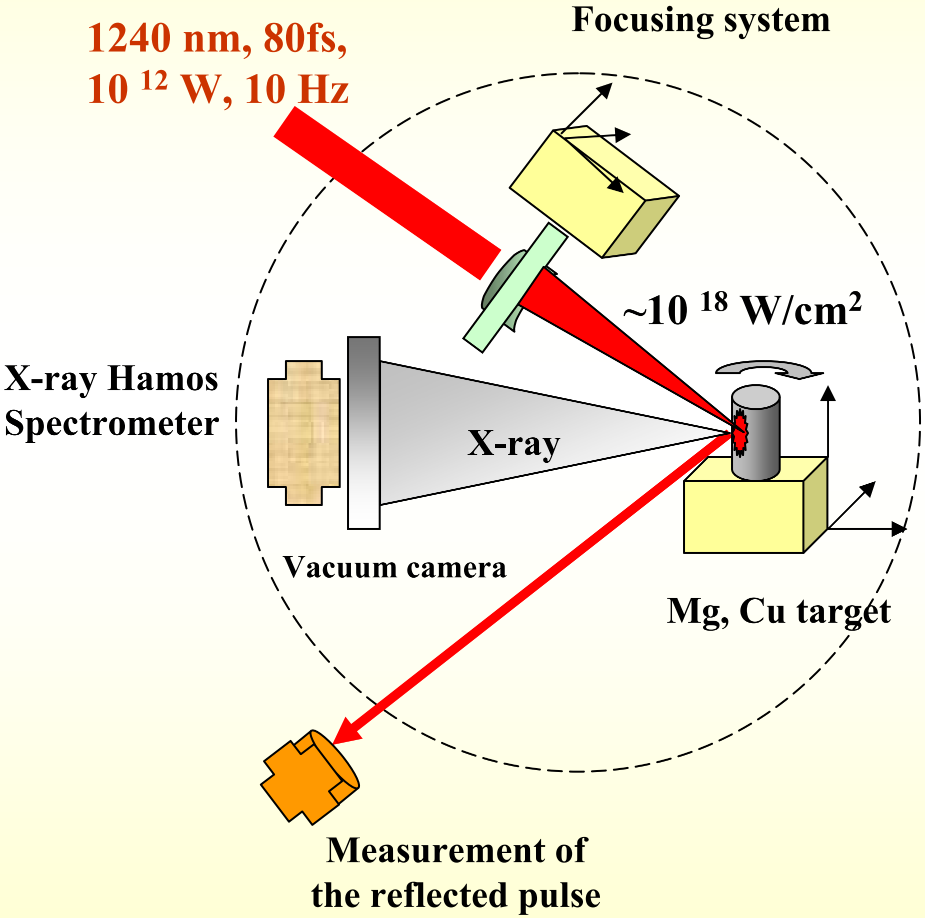
1) Ion Heating, 2) Collisional Ionization, 3) Recombination

and ponderomotive acceleration of ions by laser pulse

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

X-ray radiation of laser plasma



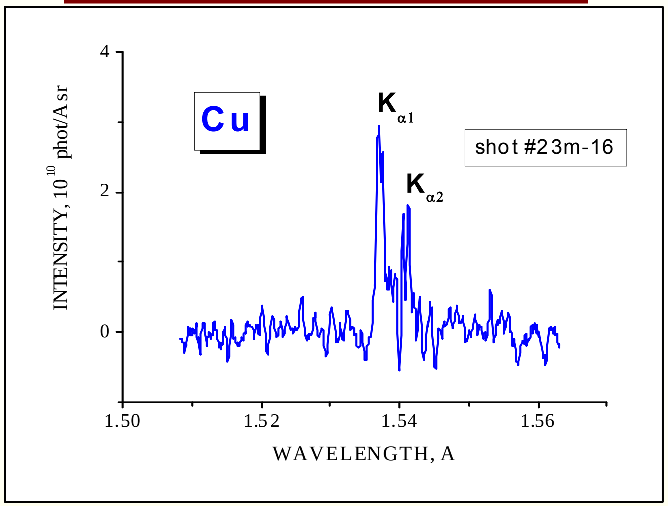


IHED JIHT RAS

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/cm²

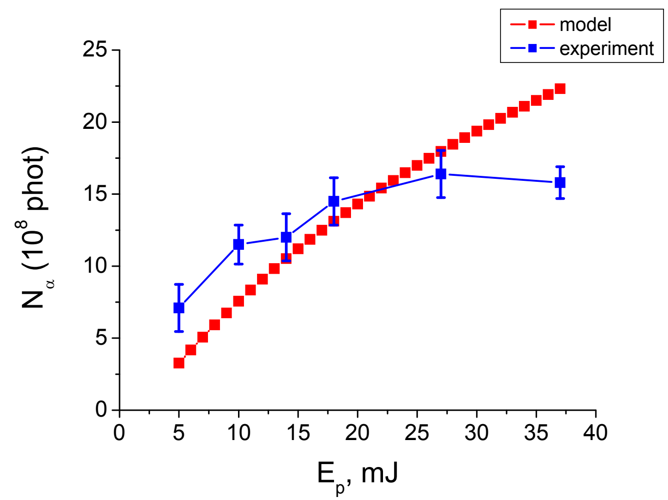
Single laser short experiment



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

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

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

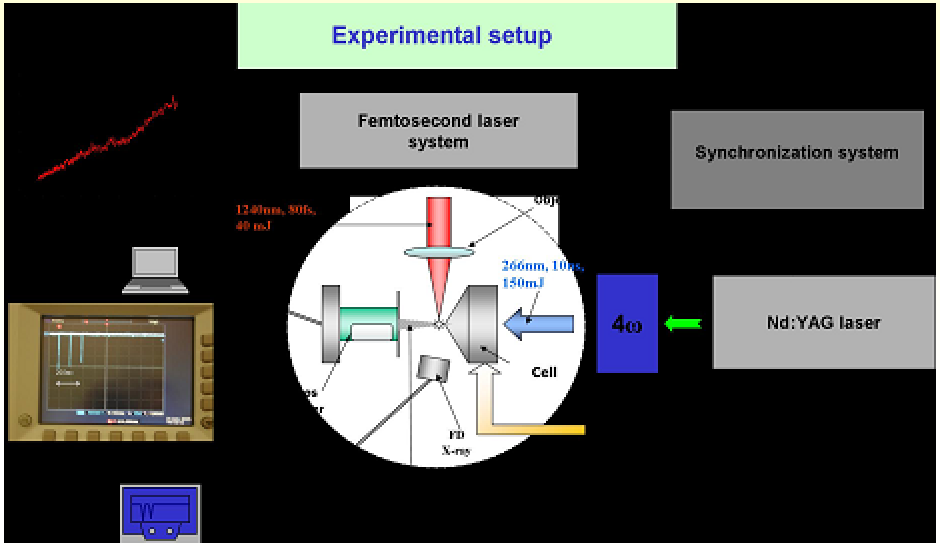
E_0 – driving, E_L – laser field, f –absorption, η = 1.57, $I_{L,16} = I_L/10^{16}$ W/cm² – laser intensity

РОССИЙСКАЯ АКАДЕМИЯ НАУК
Физический институт имени П.Н.Лебедева
ФИАН

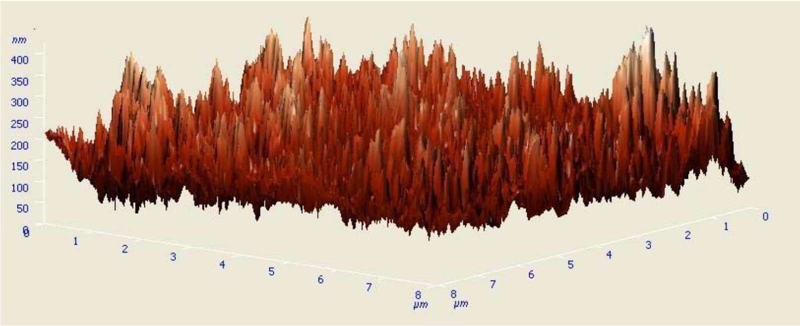
117924, ГСП-1, Москва, В-333
Ленинский просп. 53,
Для телеграмм: Москва В-333 ФИАН
Телекс: Москва 113308 НЕОДИМ
Факс: (095) 938 22 51
Tel.: (095) 135 14 29

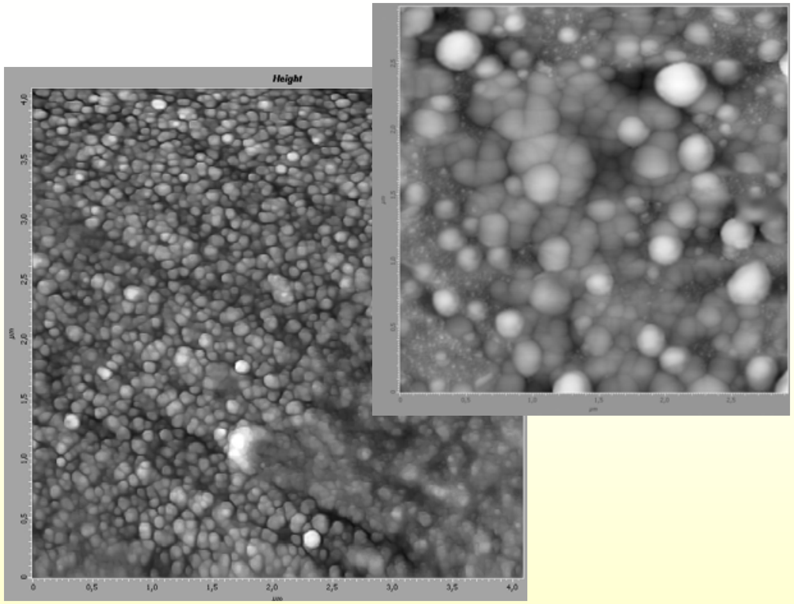
There is a range of laser pulse parameters in which K_α yield may be described by vacuum heating mechanism

nano-structured targets



Fe clusters on Cu target





A.V. Eremin Laboratory

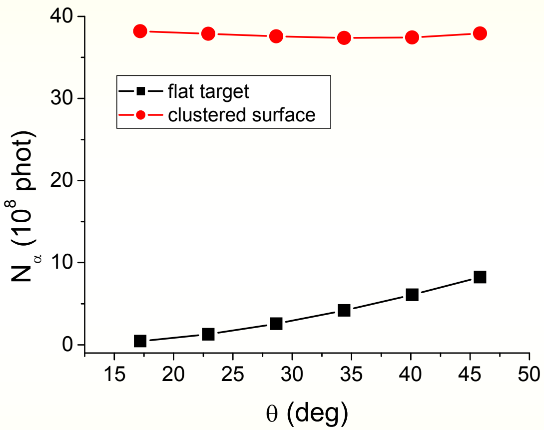
X-ray radiation using solid and nano-structured targets irradiated by PHELIX and 10 TW LS of JIHT

IHED
JIHT RAS

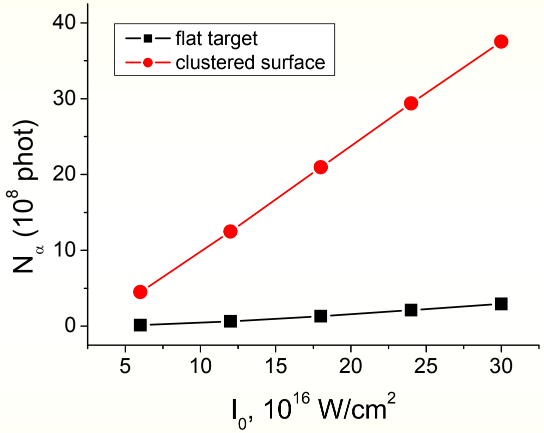
PHELIX
Petawatt High-Energy Laser for Heavy Ion Experiments

Fe clusters on Cu target

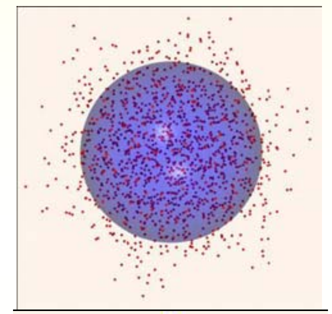
$$E_0 = 3E_L \cos\theta_1$$

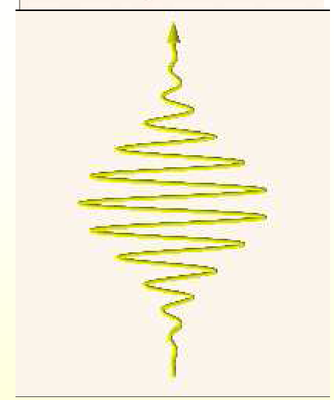


Dependence of K_α yield on angle of incidence for peak intensity 3×10^{17} W/cm^2



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





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

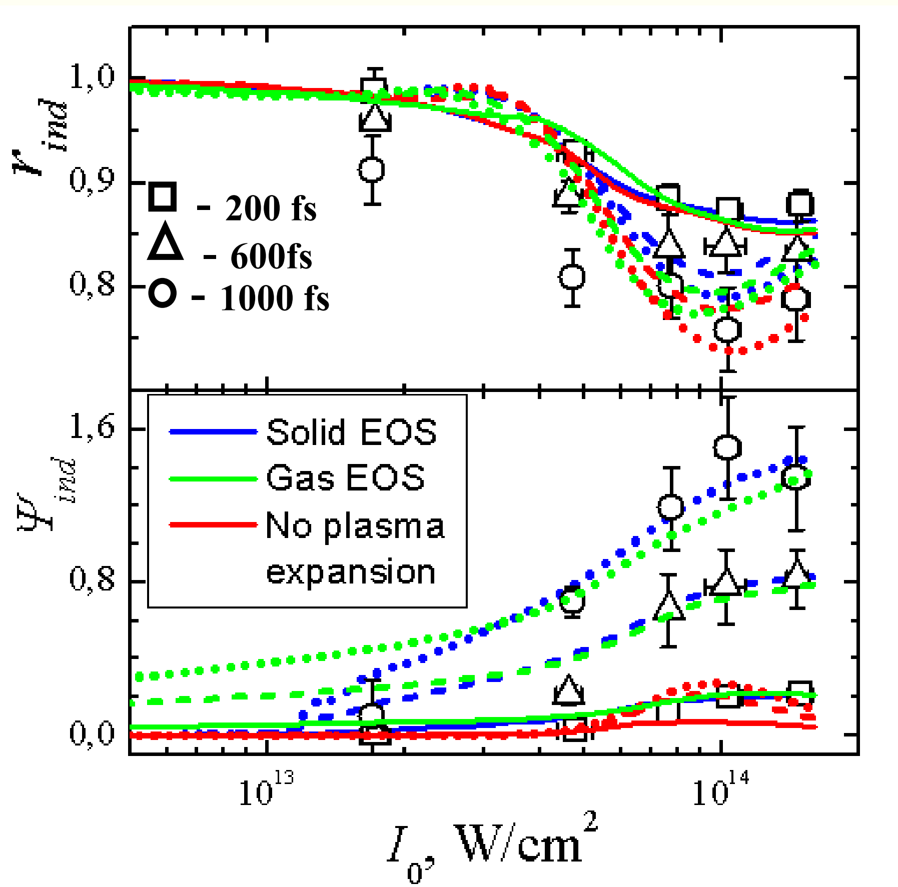
EMMI

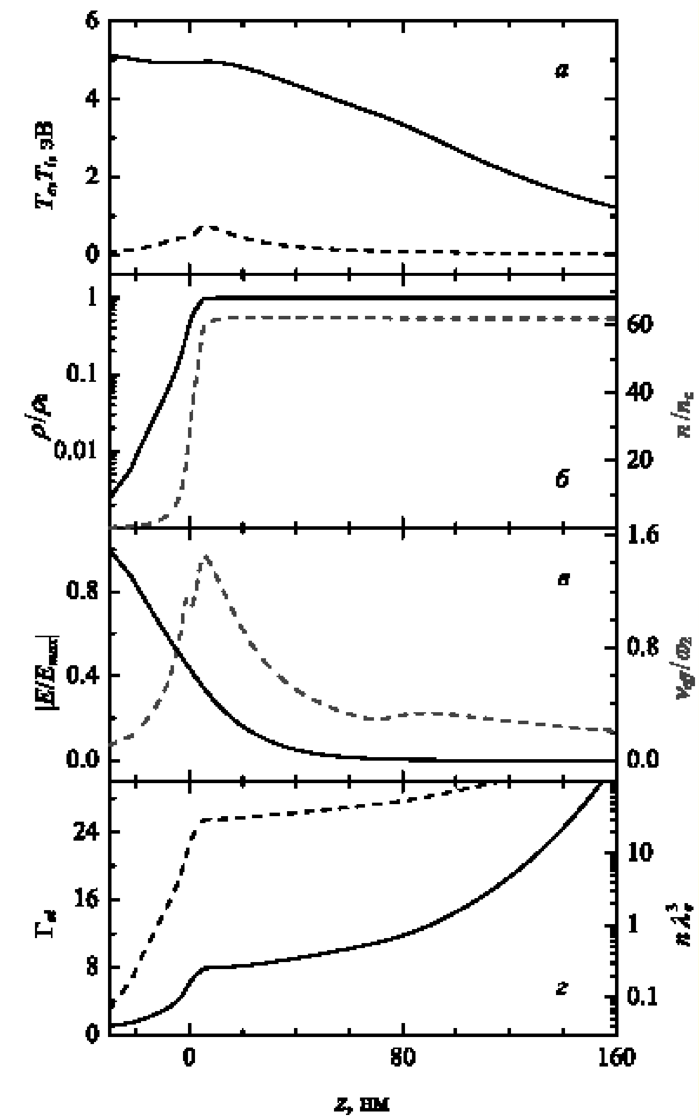
Enhancement of driving electric field at a cluster surface and favorable conditions for K_α photons to escape from the wafer lead to considerable enhancement of K_α yield

GSI

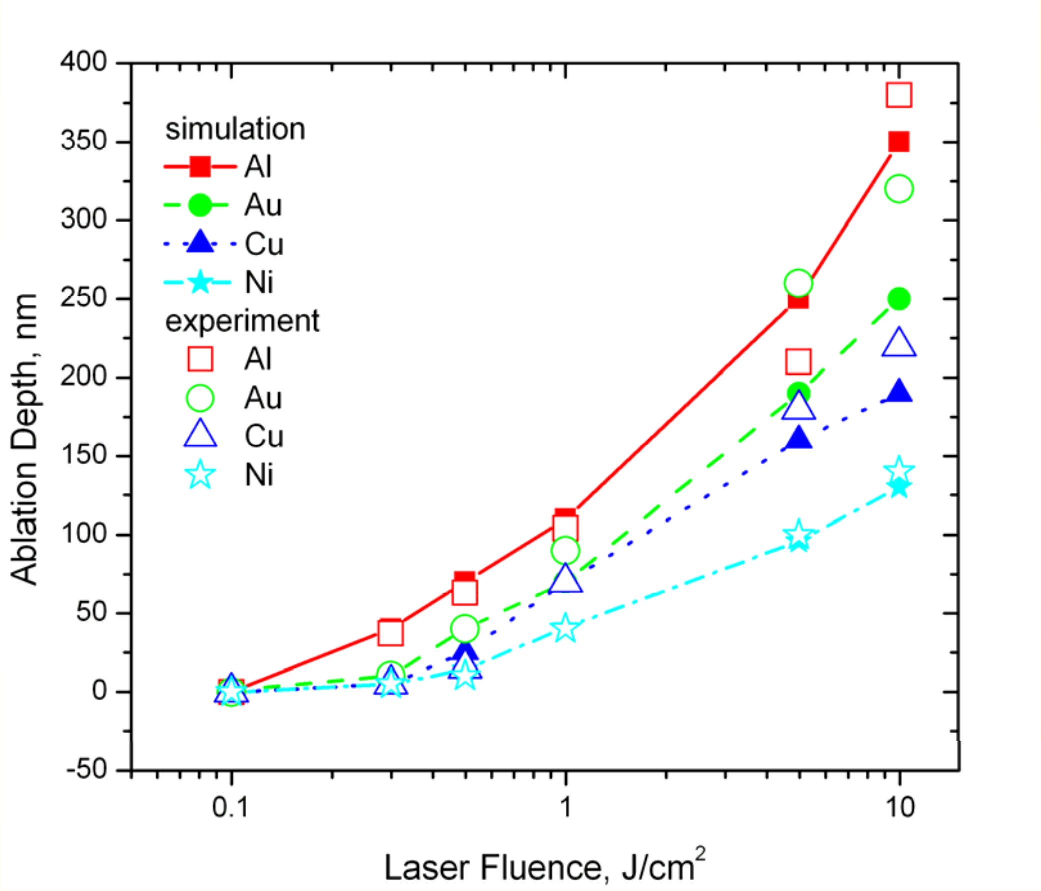
Femtosecond optical diagnostics and hydrodynamic simulation of Al plasma

Laser pulse: $\tau_L = 100$ fs; $I < 2 \cdot 10^{14}$ W/cm^2



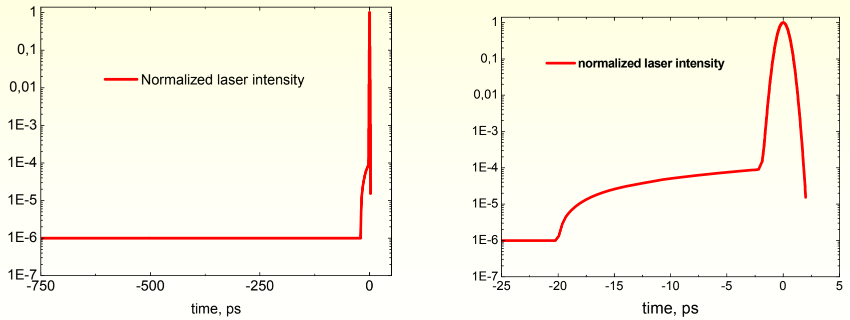


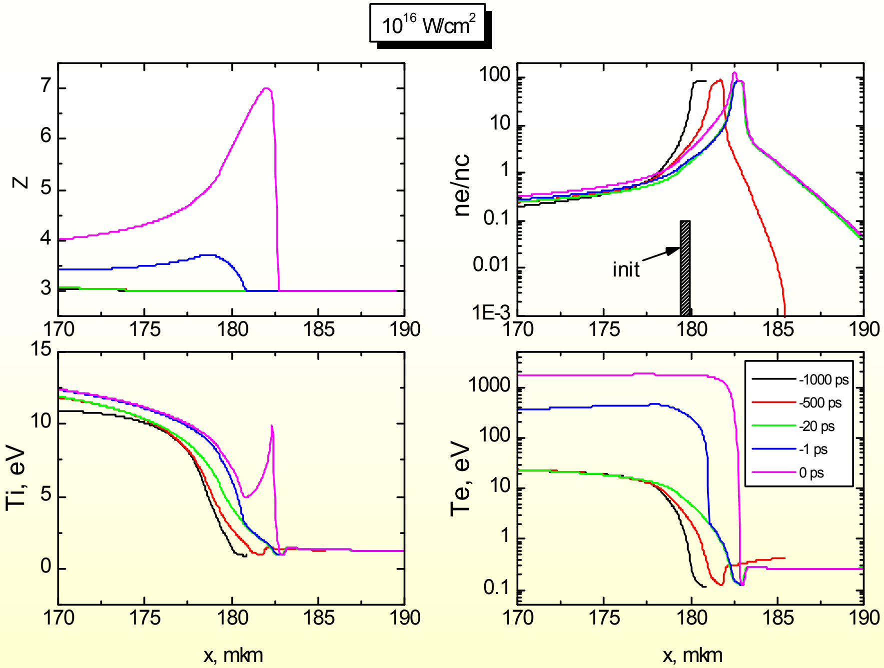
Ablation of metal targets by fs pulses



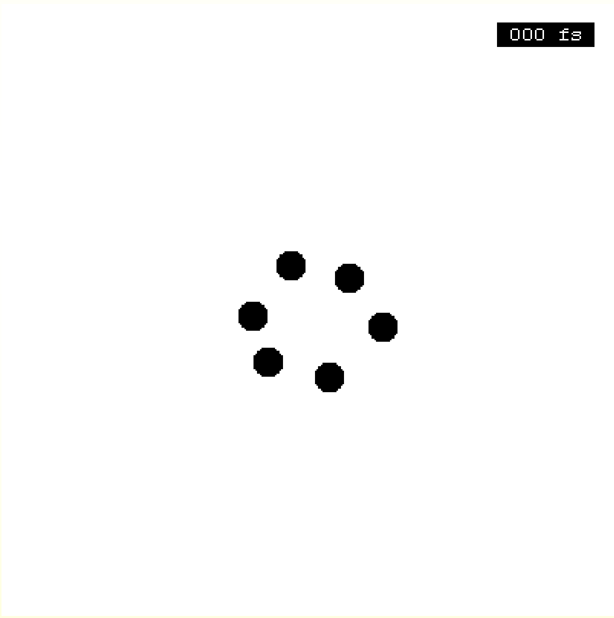
M. E. Povarnitsyn *et al.* // PRB **75**, 235414 (2007).
M. E. Povarnitsyn *et al.* // Appl. Surf. Sci. **253**, 6343 (2007)
M. E. Povarnitsyn *et al.* // Appl. Surf. Sci. (in press, 2008)

Pilot modeling of the nanostructure dynamics





Interaction with Cu wires (n_e/n_{cr})



λ = 1.053 mkm, $I_0 = 10^{17}$, W/cm^2, τ = 500 fs

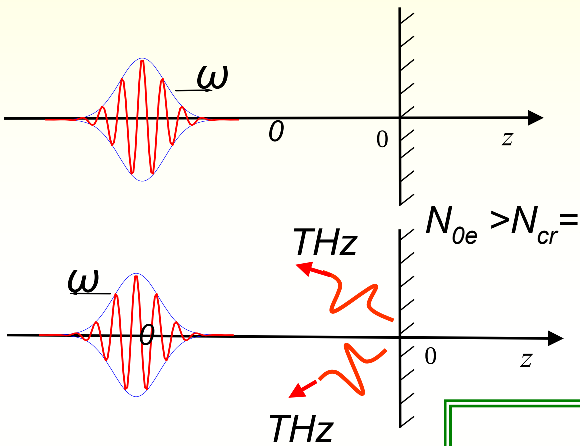
produced plasma with the density of order critical one will expand **over distances of the order of 5 μm before the main pulse**.

Powerful sources of terahertz radiation produced by PHELIX

Petawatt High-Energy Laser for Heavy Ion Experiments

JIHT RAS

SiO_2 aerogel, ρ=0.02 g/cm-3

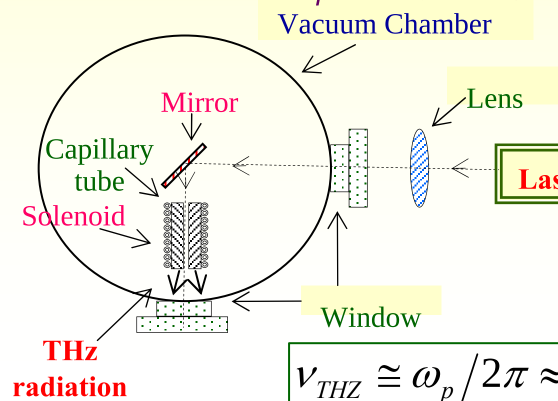


$N_{0e} > N_{cr} = m_e \omega_0^2 / 4\pi e^2$

$\nu_{THZ} \cong 1/\pi\tau \approx 1\text{THz}$

$$W_{THz} \cong \frac{\omega_0^2}{\omega_p^2}\frac{V_E^2}{c^2}\frac{W_L}{\omega_p^2\tau^2}$$

Magnetic field ($\omega_p >> \Omega_e = eB_0/m_e c$)



$\nu_{THZ} \cong \omega_p / 2\pi \approx 1\text{THz}$

$$\frac{dW_{THz}}{dz} = \frac{0.5}{\omega_0^2\tau^2}\left(1 + \frac{2}{k_p^2 R_L^2}\right)\frac{V_E^2}{4c^2}\frac{W_L}{L}$$

Laser: λ_0=1.053μm; τ_{FWHM}=0.5ps; I_L=2·10^{18} W/cm^2; R_L=50 μm (W_L=100J)

Plasma: N_{0e}=6·10^{21} cm^{-3}; $\omega_p\tau$=1200

THz: $P_{THz} \approx$ 30 MW; $W_{THz} \approx$ 10μJ;
$W_{THz}/W_L \approx 10^{-7}$

Plasma: N_{0e}=1.4·10^{16} cm^{-3}; ω_p =6.7 ·10^{12} s^{-1}

THz: $W_{THz}/W_L \approx 3\cdot10^{-4}$z[см]; z=10см :

P_{THz}≈10GW; W_{THz}≈0.3J; $W_{THz}/W_L \approx 3\cdot10^{-3}$

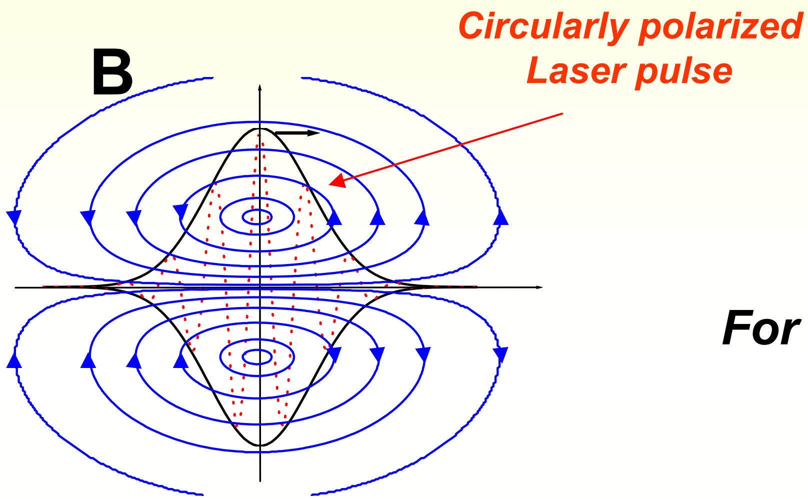
EMMI

GSI

IHED
JIHT RAS

Mega-gauss magnetic fields in plasmas produced by PHELIX

Petawatt High-Energy Laser for Heavy Ion Experiments



$$\frac{eB_z}{m_e c\omega_0} = \frac{\omega_p^2}{2\omega_0^2}\frac{V_E^2/c^2}{\left(1+V_E^2/c^2\right)}$$

For relativistic laser intensities, $V_E/c > 1$
at critical density, $\omega_p \approx \omega_0$

$$\Omega_e \approx \omega_0$$

Laser: λ_0=1.053μm; τ_{FWHM}=0.5ps (τ=0.3ps); I_L=3·10[19]W/cm[2] ; R_L=15 μm
(W_L=100 J; P_L= 300 TW)

gas: N_{0e}=3·10[19]cm[-3] → ***B***

$\Omega = 1.8\cdot 10^7 B_0[G]s^{-1} \quad \omega_p = 6.7\cdot 10^{12} s^{-1} \quad \Omega = 0.1\omega_p \Rightarrow B_0 = 3.7\cdot 10^4 G$

EMMI

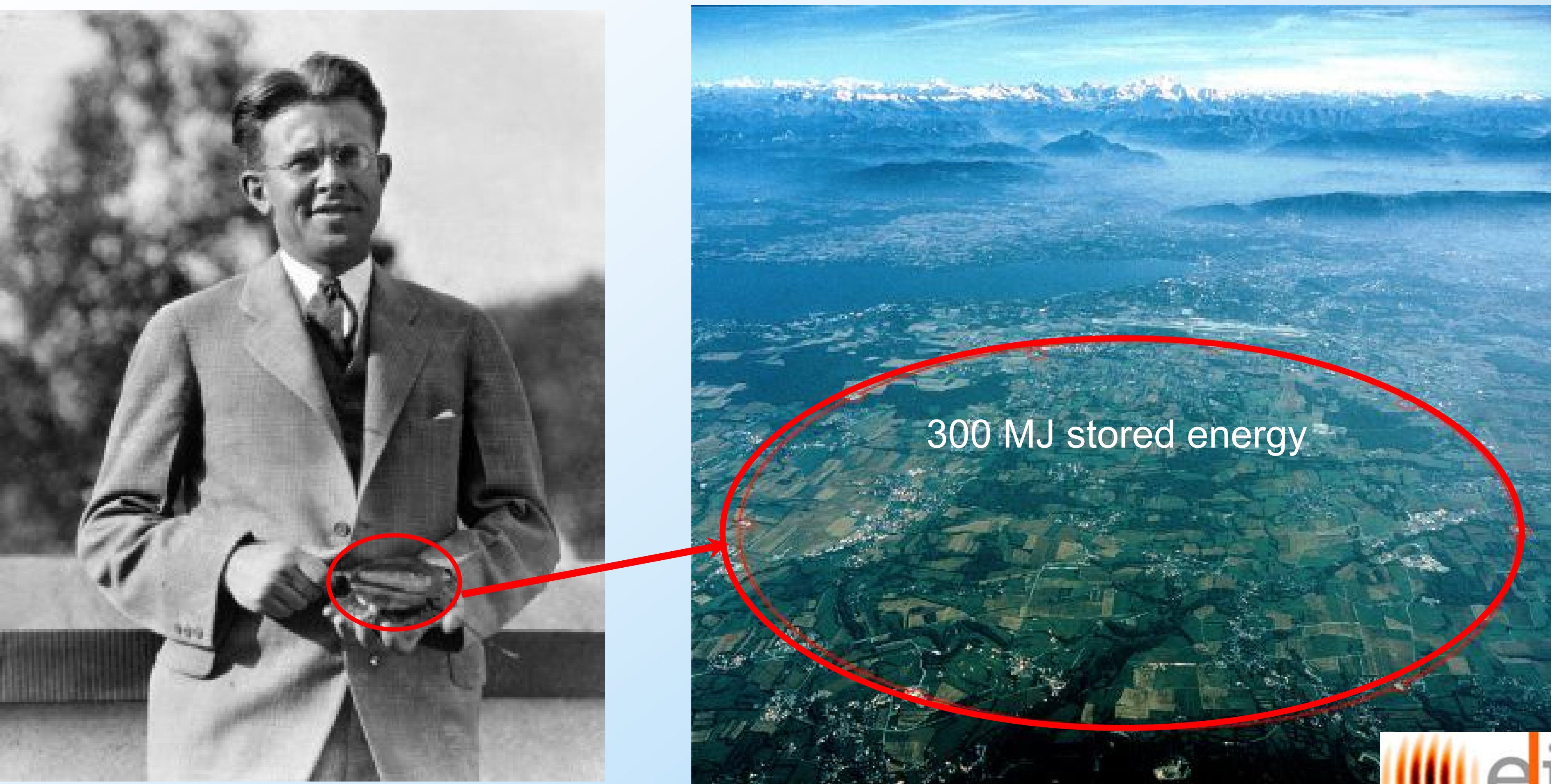
GSI

People who say it cannot be done should not interrupt those who are doing it.

George Bernard Shaw

1929

LHC, 2009



Size x 10^5 Energy x 10^9

W. Leemans

Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

ExtreMe Matter Institute EMMI

Workshop on Plasma Physics with Intense Laser and Heavy Ion Beams

May 14 - 15, 2009, JIHT, Moscow, Russia

Thank You for attention!

Organized by:
Joint Institute for High Temperature, Russia and
ExtreMe Matter InsituteEMMI, Germany

Conference Chairman
Vladimir E. Fortov, JIHT, Moscow
Thomas Stoehlker, GSI, Darmstadt

Organizing Committee
Nikolay Andreev
Rudolf Bock
Carlo Ewerz
Konstantin Khishchenko
Pavel Levashov
Mikhail Povarnitsyn
Olga Rosmej

With thanks for collaboration to

B. Cros *- CNRS-Universitè Paris XI, France*
E. Esarey *- LLNL, USA*
W. Leemans *- University of Nevada, USA*
G. Maynard *- CNRS-Universitè Paris XI, France*
P. Mora *- CPHT, CNRS- Ecole Polytechnique, France*
A. Pogosova *- Institute for High Temperatures RAS, Russia*
E. Tcirlina *- Institute for High Temperatures RAS, Russia*