ISHEPP XX

JINR, Dubna

Relativistic Description Of Particle Production and Acceleration by Ion and Laser Beams

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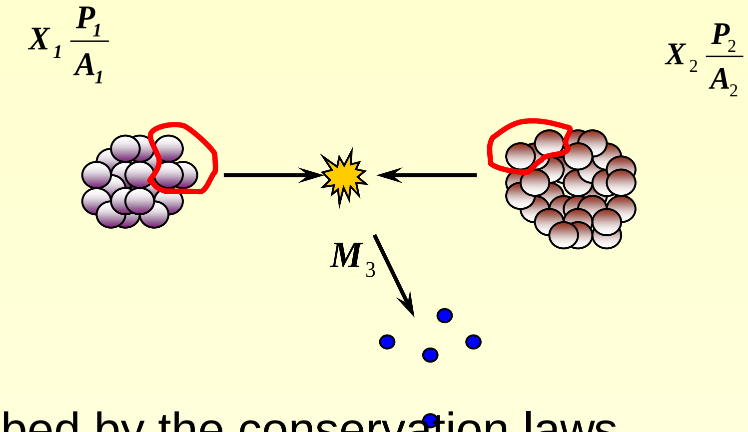
Scope

- Relativistically invariant self-similarity solution for particle production in nuclear reactions;
- Generation of particle beams by ultrashort laser pulses;
- Ion beam conversion anisotropy in NRT

Self-similarity solution for relativistic interacting particles



$$X_1P_1 + X_2P_2 = P_1' + \sum P_i'$$

The relationship between X_1 and X_2 is described by the conservation laws written in the form

$$\left(X_1M_1u_1 + X_2M_2u_2 - M_3u_3\right)^2 = \left(M_nX_1u_1' + M_nX_2u_2' + \sum_{k=4} M_ku_k\right)^2$$

Essentially, we are using the correlation depletion principle in the relative four-velocity space which enables us to neglect the relative motion of not detected particles, namely the quantity $2\sum_{k>1}(\gamma_{kl} - 1)M_kM_l$ in the right-hand side of the above equation.

Self-similarity solution for relativistic interacting particles

$$X_1X_2(\gamma_{12}-1)-X_1\left(\frac{M_3}{M_p}\gamma_{13}+\frac{M_4}{M_p}\right)-X_2\left(\frac{M_3}{M_p}\gamma_{23}+\frac{M_4}{M_p}\right)=\frac{M_4^2-M_3^2}{2M_p}$$

In the case of production of antiparticle with mass M_3, the mass M_4 is equal to M_3 as a consequence of conservation of quantum numbers. In studying the production of protons and nuclear fragments

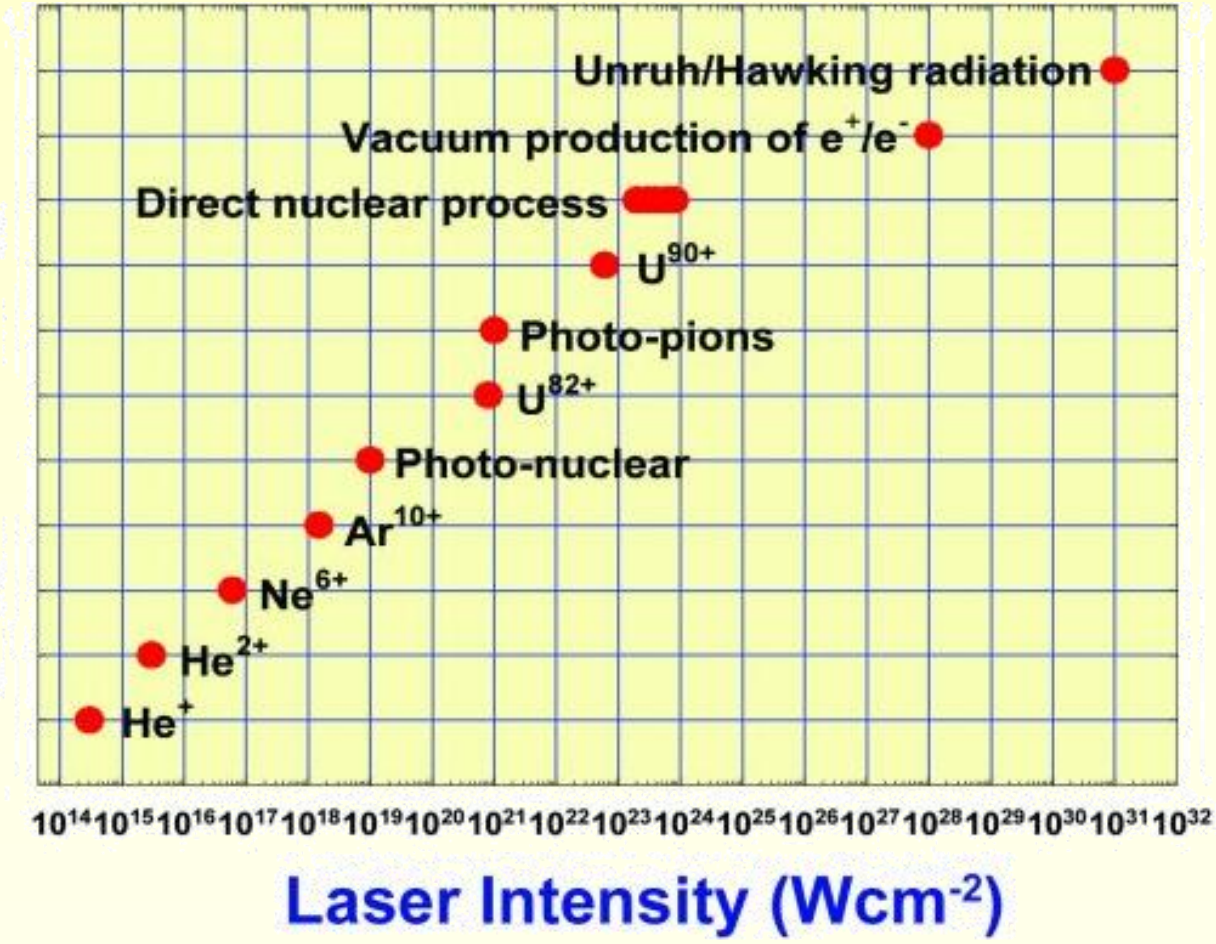
$M_4 = -M_3$ as far as the minimum value of Π corresponds to the case that no other additional particles are produced. The values of X_1 and X_2 obtained from the minimum Π are used to construct a universal description of the A-dependencies.

$$\Pi=\frac{1}{2}\left(X_1^2+X_2^2+2X_1X_2\gamma_{12}\right)^{1/2}$$

$$S=\left(P_1+P_2\right)^2$$

$$E\frac{d^3\sigma}{d^3p}=C_1A_1^{\alpha\,(X_1)}A_2^{\alpha\,(X_2)}f(\Pi)$$

Nuclear Physics with Lasers



Maximum achieved laser power ~10^{21} W/cm^2.

Near future – an increase in power by a factor of 100.

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Fundamental short time-scale relativistic physics: new collective phenomena

- Laser powers >10^{19}-10^{20} W/cm^2;
- Times <100 fs;
- Electron densities >10^{20} cm^{-1};

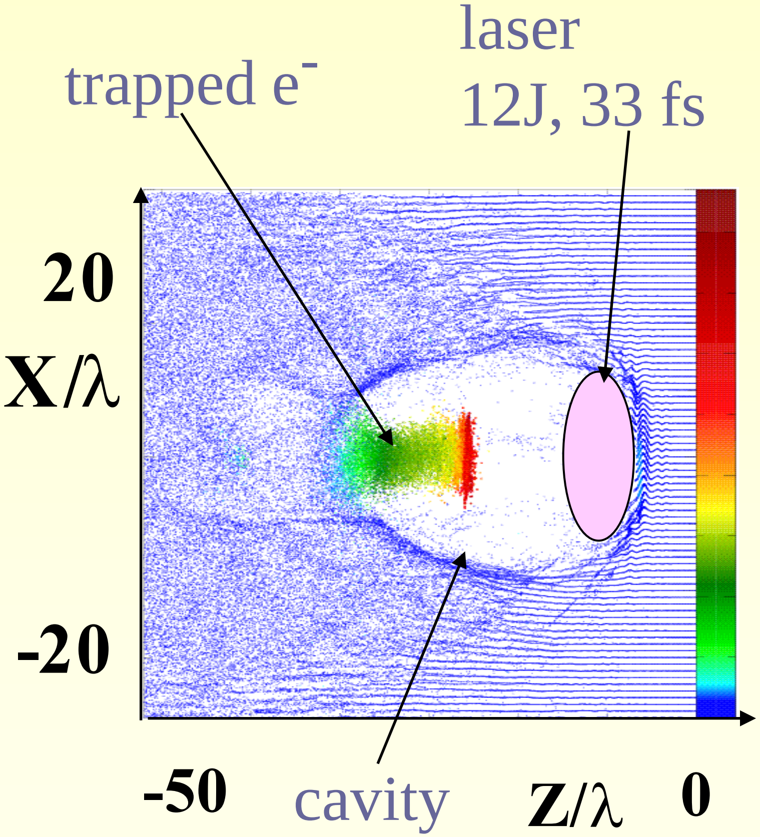
Particle production by ultrashort laser pulses

- Great Britain [1]: TiSa laser (800 nm, 40 fs), supersonic He target (2 mm). Pulse intensity 2.5×10^{18} W/cm^2. Plasma density 3×10^{17} cm^{-3} ÷ 5×10^{19} cm^{-3} . Monoenergetic electron spectrum, 70 MeV, energy spread 3 %. About 10^8 electrons (20 pC) per bunch.
- USA [2]: TiSa laser (810 nm, 60 fs), gas target. Driver-preinitiated plasma channel. Optimal gas density 4×10^{19} cm^{-3} . Pulse intensity 1.1×10^{19} W/cm^2. A 10 fs bunch with 3×10^9 80 MeV electrons. Energy spread 2 %.
- France, Germany [3]: TiSa laser (820 nm, 33 fs), He target density 6×10^{18} cm^{-3} . Pulse intensity 3.2×10^{18} W/cm^2. A < 30 fs bunch with 10^9 170 MeV electrons. Energy spread 24 % (due to spectrometer resolution).

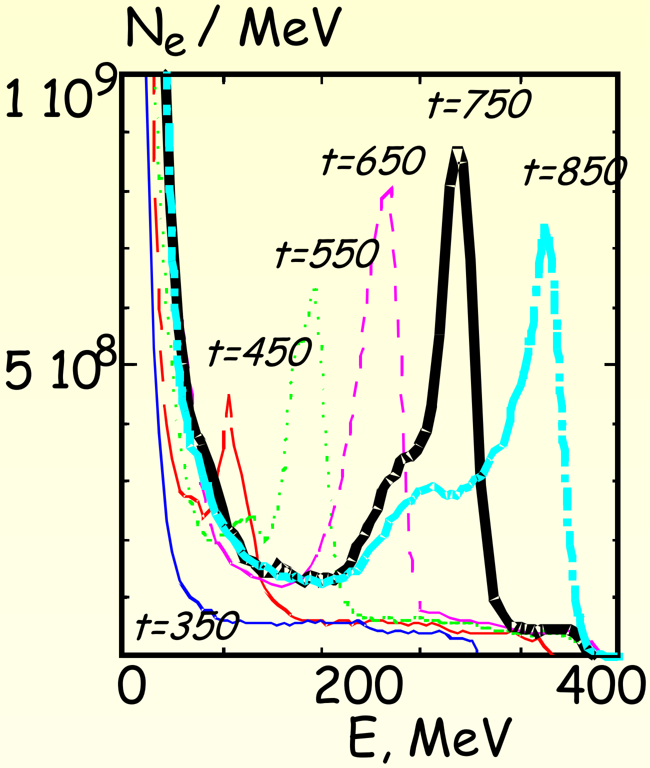
1. Mangles, et al. Nature vol.43 30 September 2004 pp.535-538
2. Geddes, Esarey, et al. Nature vol.43 30 September 2004 pp.538-541
3. Pukhov, Malka, et al. Nature vol.43 30 September 2004 pp.541-544

Ultra-relativistic case, I=10^{20} W/cm^2: Bubble formation

A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B, **74,** *p.*355 (2002)



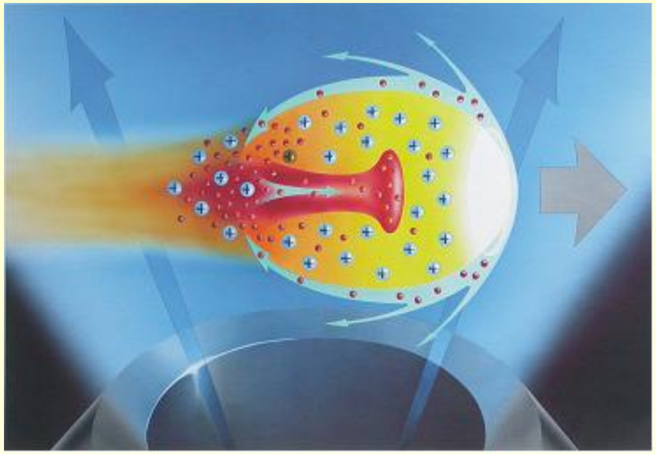
Time evolution of electron spectrum

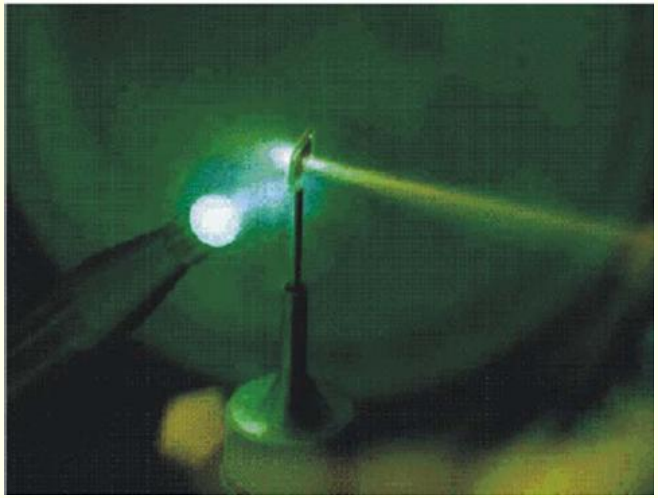


Particle production by ultrashort laser pulses

10TW - 100TW, 5 - 50 fs, driving laser pulse

- High conversion efficiency (≥20 %)
- Quasi-monochromatic electron spectrum (70, 80, and 170 MeV).
- Low emittance
- Extremely short acceleration distance (100 μm ÷ 1 mm)
  Beam current ~ 10 kA.

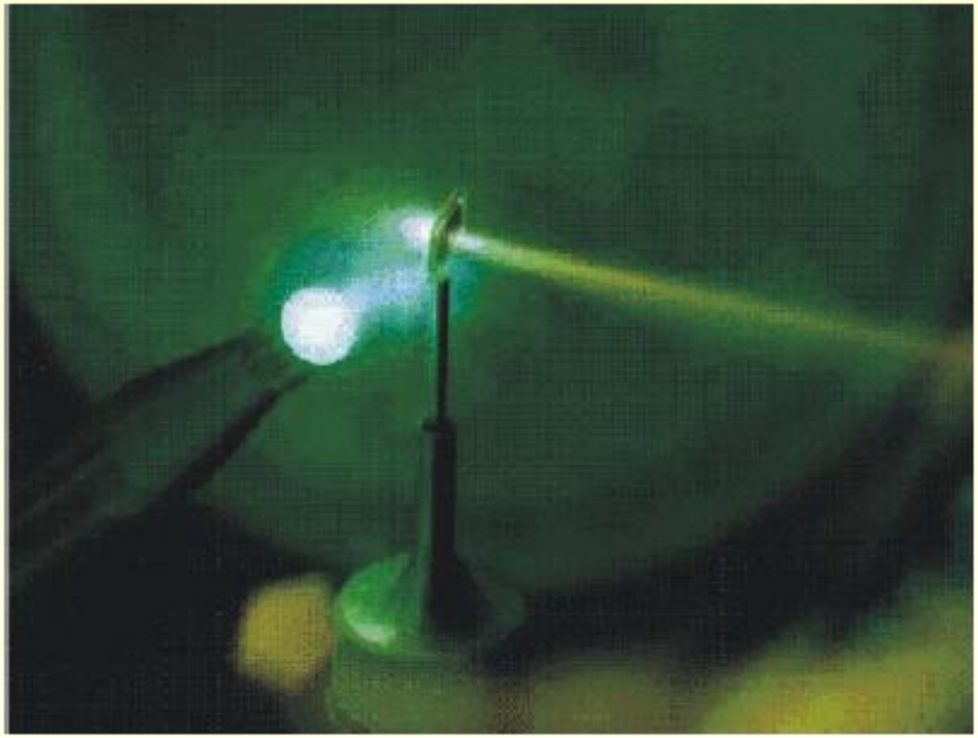




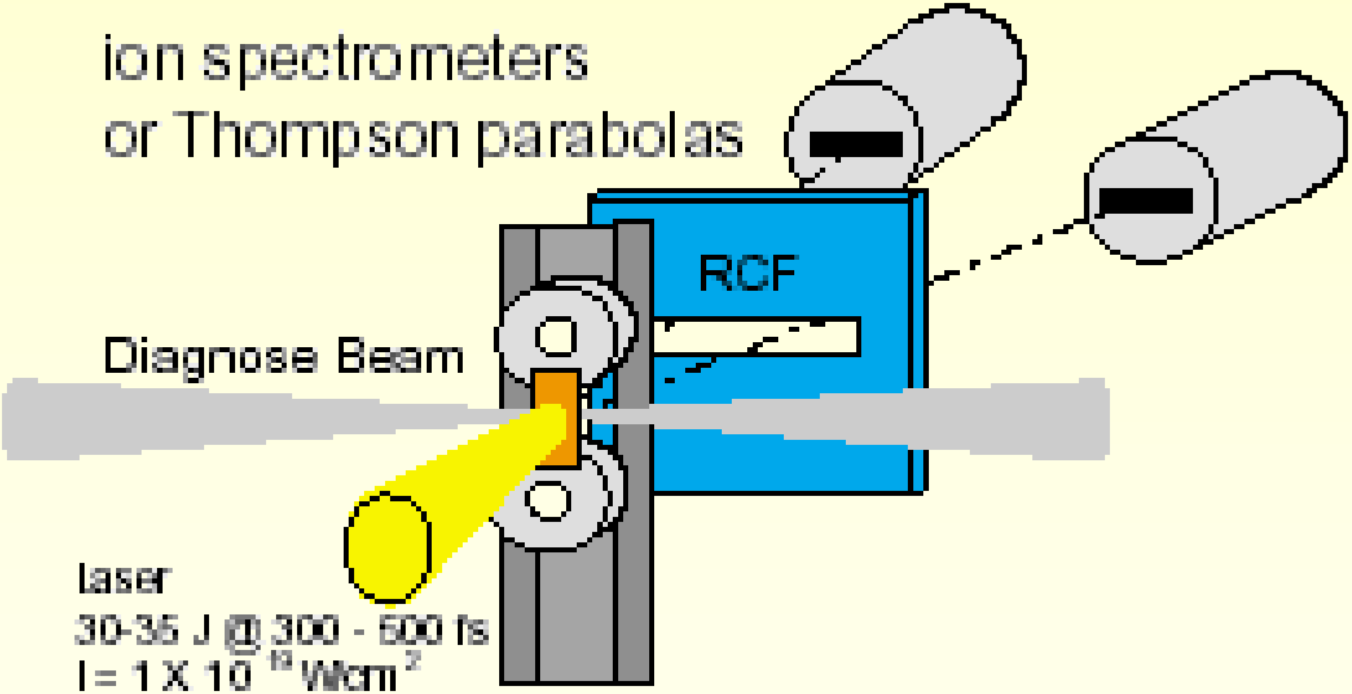
An advance towards table-top charged particle accelerators for radiography, biology, medicine.
There is a hope to obtain >1 GeV electron beams in near future.

Discovery of intense Proton beams at the Petawatt Laser

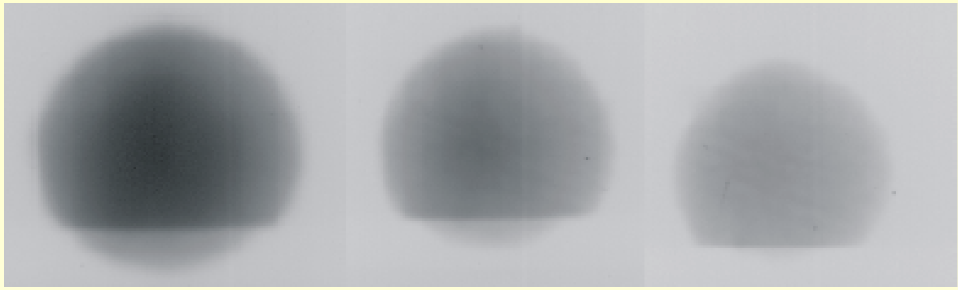
10^{13} Protons per shot
Energy up to 50 MeV
Time < 10 ps
I >50 MA



Experimental setup

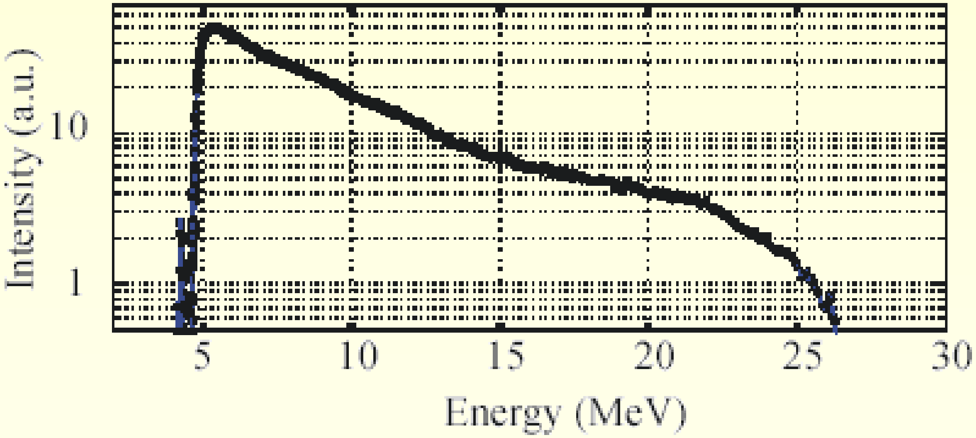


Beam parameters



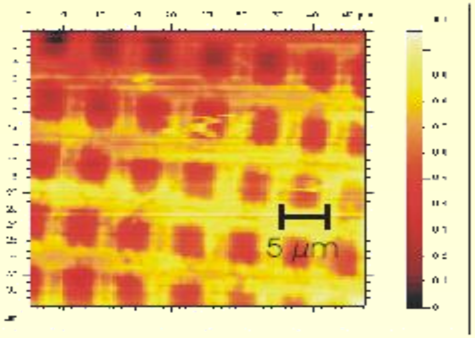
RCFs placed behind the target show homogenous spatial distribution and energies > 25 MeV

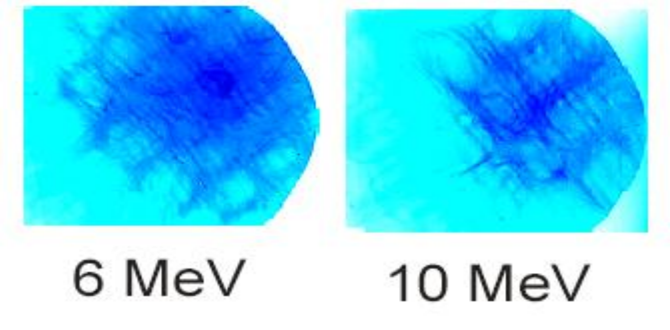
10^{12} Protons
Time < 10 ps
Energy > 25 MeV



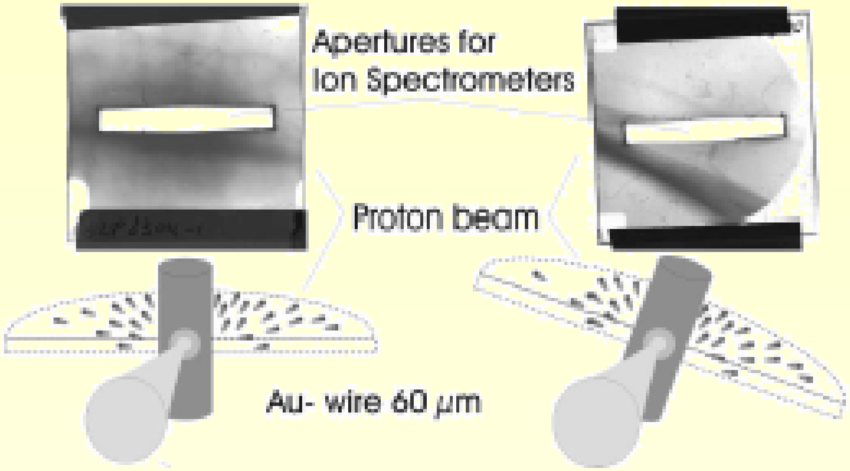
Beam shaping

Structured targets




6 MeV

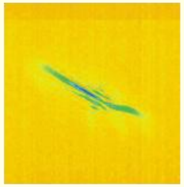
10 MeV

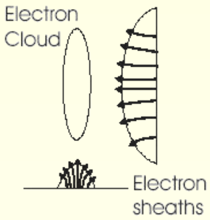


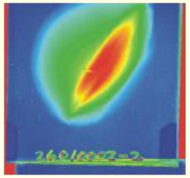
Influence of the laser focus

Asymmetric laser focus produces an asymmetric proton beam

Laser focus





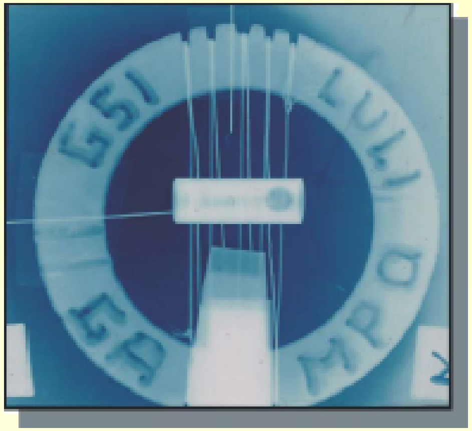


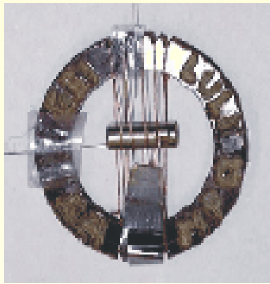
Ion distribution

☞Proton beam shaping possible with a suitable laser focus

Proton radiography

Due to the proton-matter interaction proton radiography can shadowgraph light ions in an enviroment of heavy material
⇨Complementary diagnostic to x-ray radiography

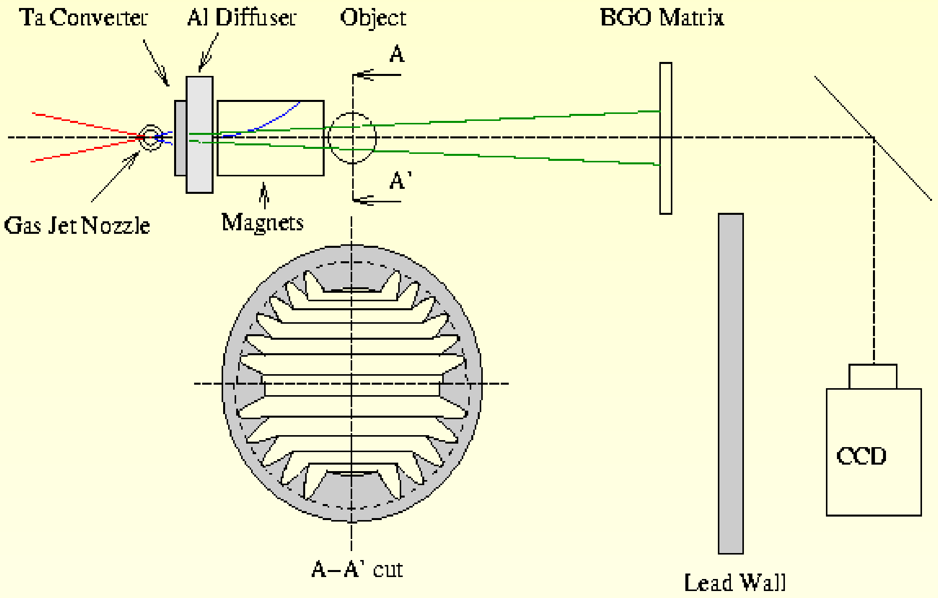




Cu-wires 250μm
Steel Hohlraum
300 μm wall thickness
Ti - layers 100μm
Epoxy-ring 1.5mm
Glass semi - spheres
900 μm dia., 20 μm wall

Laser accelerated protons with their excellent beam quality offer radiography with high spatial and temporal resolution

High resolution γ radiography



2.5mm tantalum at 3mm of the nozzle center

Aluminium 7.5mm thick to scatter electrons

BGO screen at 1.6m from the nozzle, 600 μm pixels size

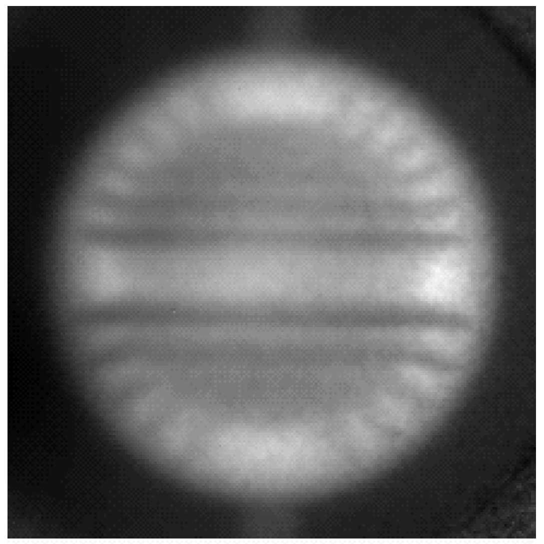
17cm magnet length (B of 0.1T)

20 mm diameter object in Tungsten,
at 35cm of the nozzle

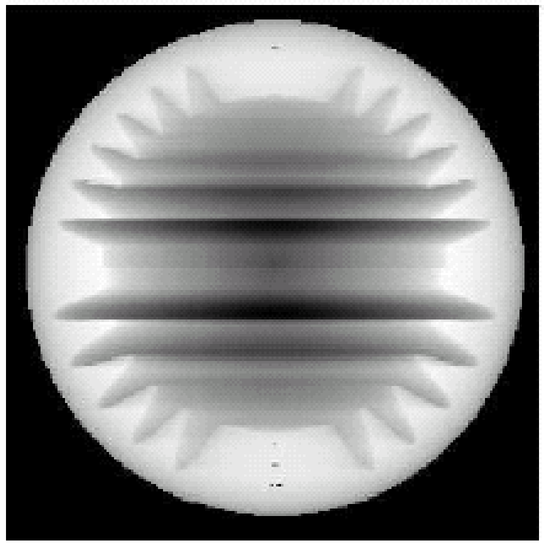
Victor Malka, Laboratoire LOA, ENSTA – CNRS - École Polytechnique,
91761 Palaiseau cedex, France

γ-radiography results

Resolution of the order of 400 μm

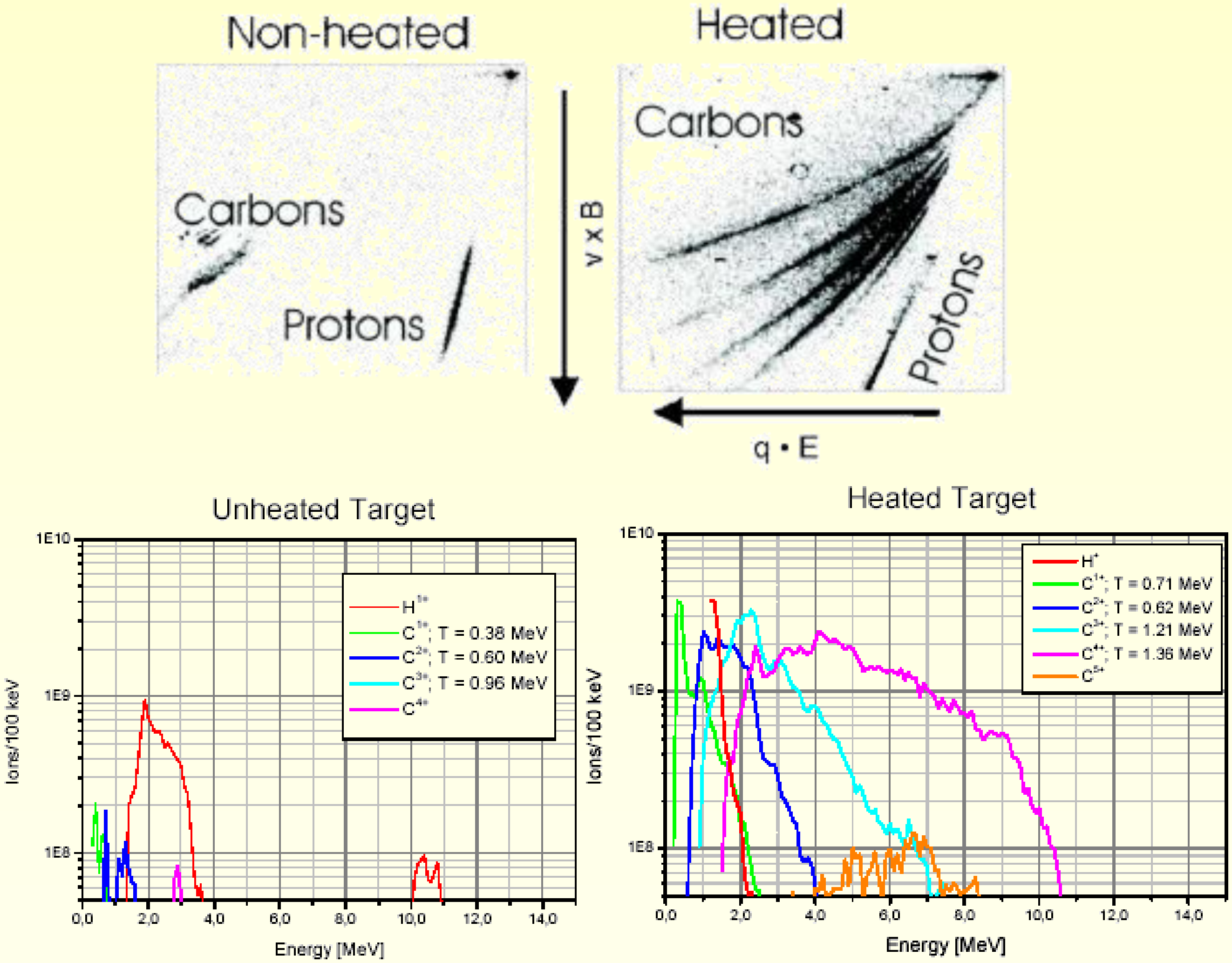


measured



calculated

Acceleration of ions



Injector for accelerators

Laser accelerated ions could be an alternative for classical ion sources and injectors

Advantages:

- Beam parameters and quality are comparable or better
- Smaller size and easier to operate

Open questions:

- Phase space matching
- Low repetition rate

Relativistic e+e- pair production: three steps

- Generation of MeV electrons in subcritical laser plasma

10^{18} W/cm^2; $n_e = n_c \exp(-x/\Delta)$; $n_c = 10^{21} 1/cm^3$; $\Delta = 30\, mkm$

$$\frac{dN_e}{dE} \approx 3 \cdot 10^{10} \cdot E \cdot \exp(-1.2 \cdot E)$$

- Bremsstrahlung conversion of MeV electron energy into MeV photons in a high-Z solid target

$8 \cdot 10^7$ photons with an energy higher than 1 MeV

- e+e- pair production (photonuclear reactions)

Electron – positron pair production

Appl. Phys. Lett., Vol. 77, No. 17, 23 October 2000

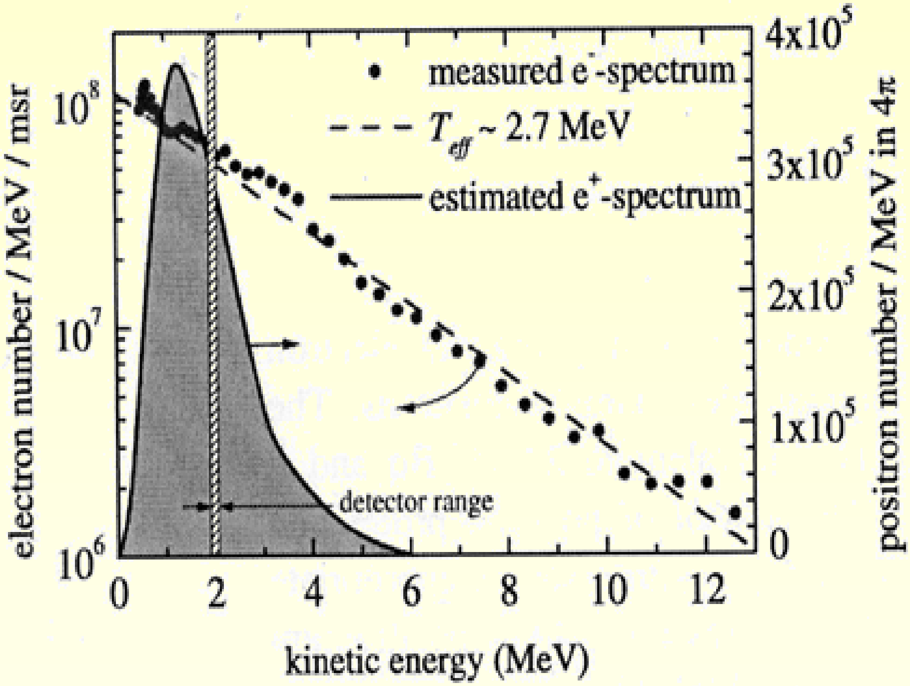


FIG. 1. Measured energy distribution of the primary electrons (closed-circles, exponential fit as dashed line) used to produce positrons (expected spectrum as solid line). The line-shaded stripe gives the energy range covered by the detector. It encompasses ~5% of the total number of positrons.

Self-similarity solution for particle production by ultrahigh intensity electromagnetic fields

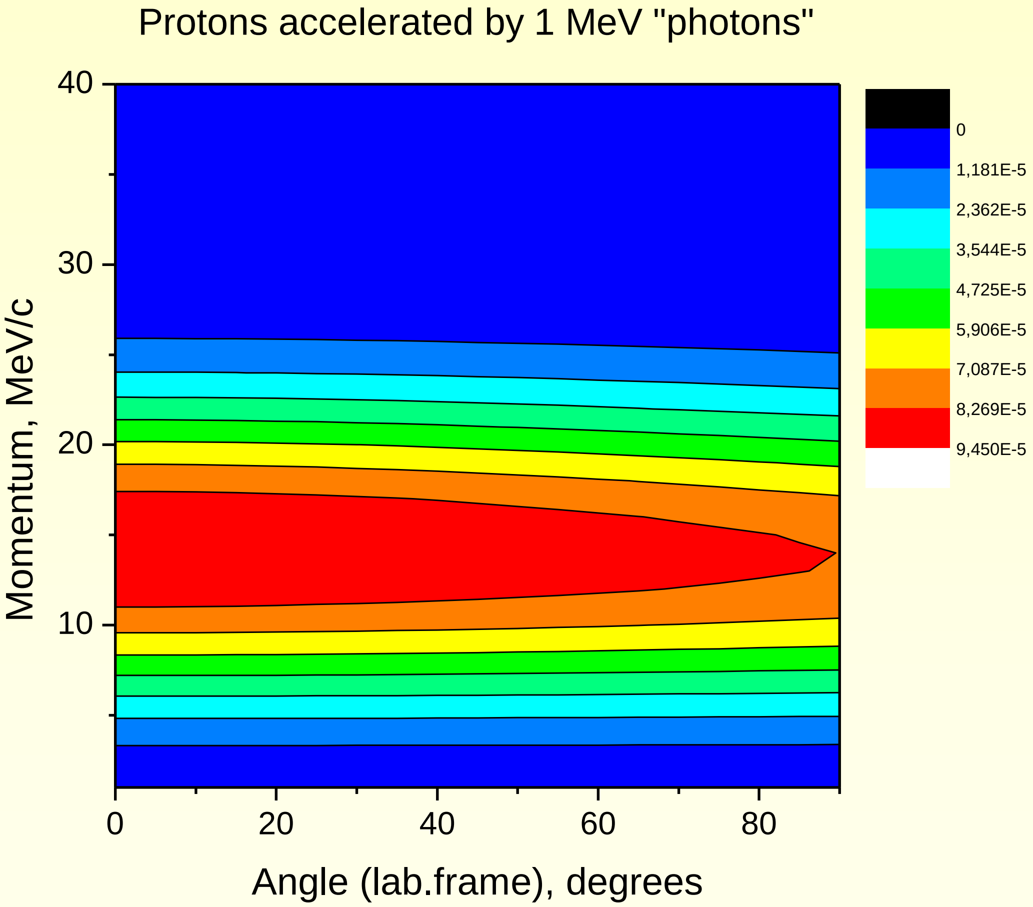
$$\sigma_{inv} = C_1 \exp\left(-\frac{\Pi}{C_2}\right)$$

$$\sigma_{inv} = C_1 \exp\left(-\frac{X}{C_2}\right)$$

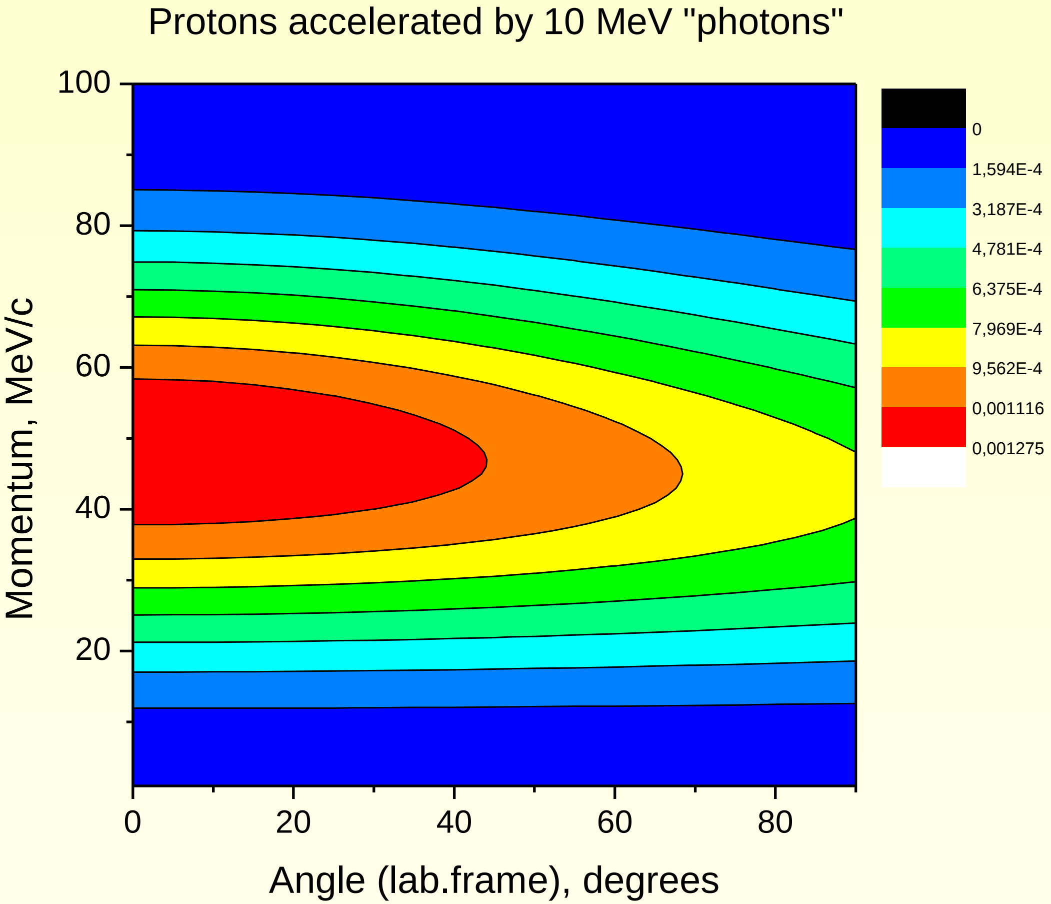
$$E_\gamma + xP_1 = xP_1' + P_3 + P_4$$

$$x = \frac{E_\gamma\left(E_3 - P_3\cos\alpha_3\right)}{M_1\left(E_\gamma - E_3 - M_4\right)}$$

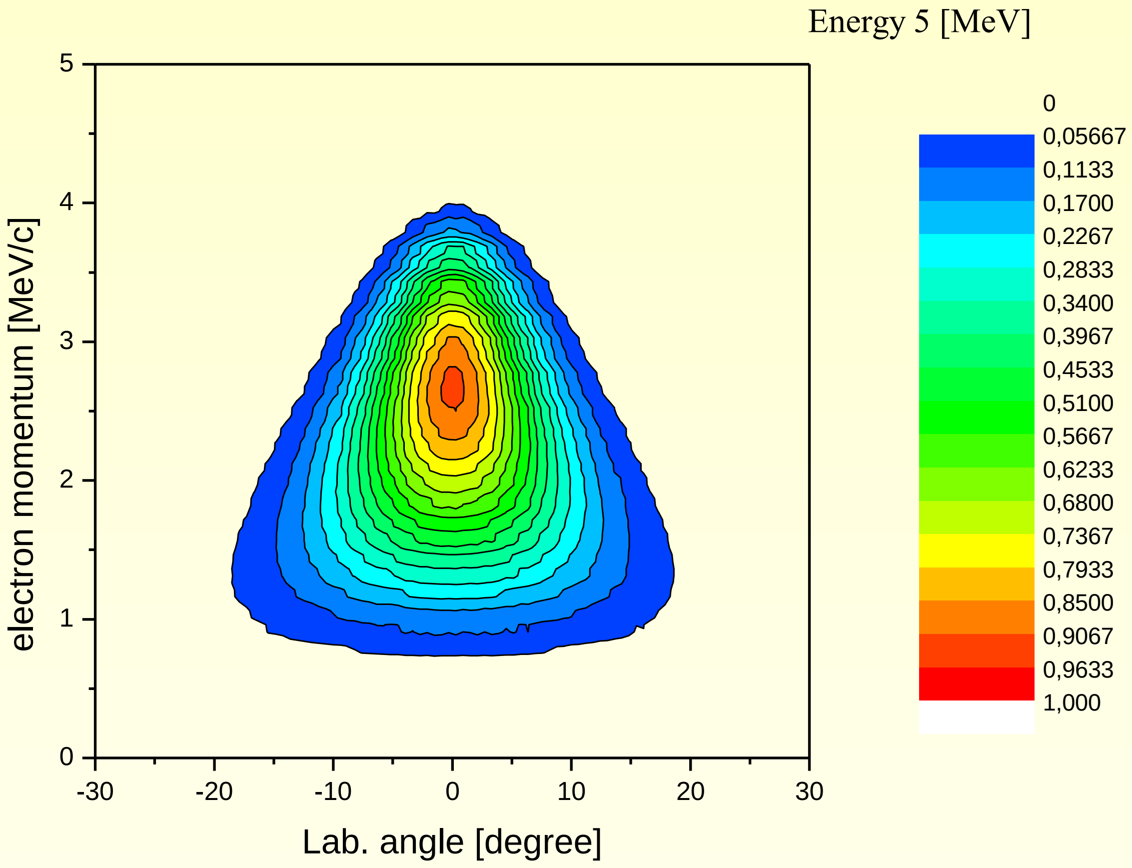
Proton beam acceleration



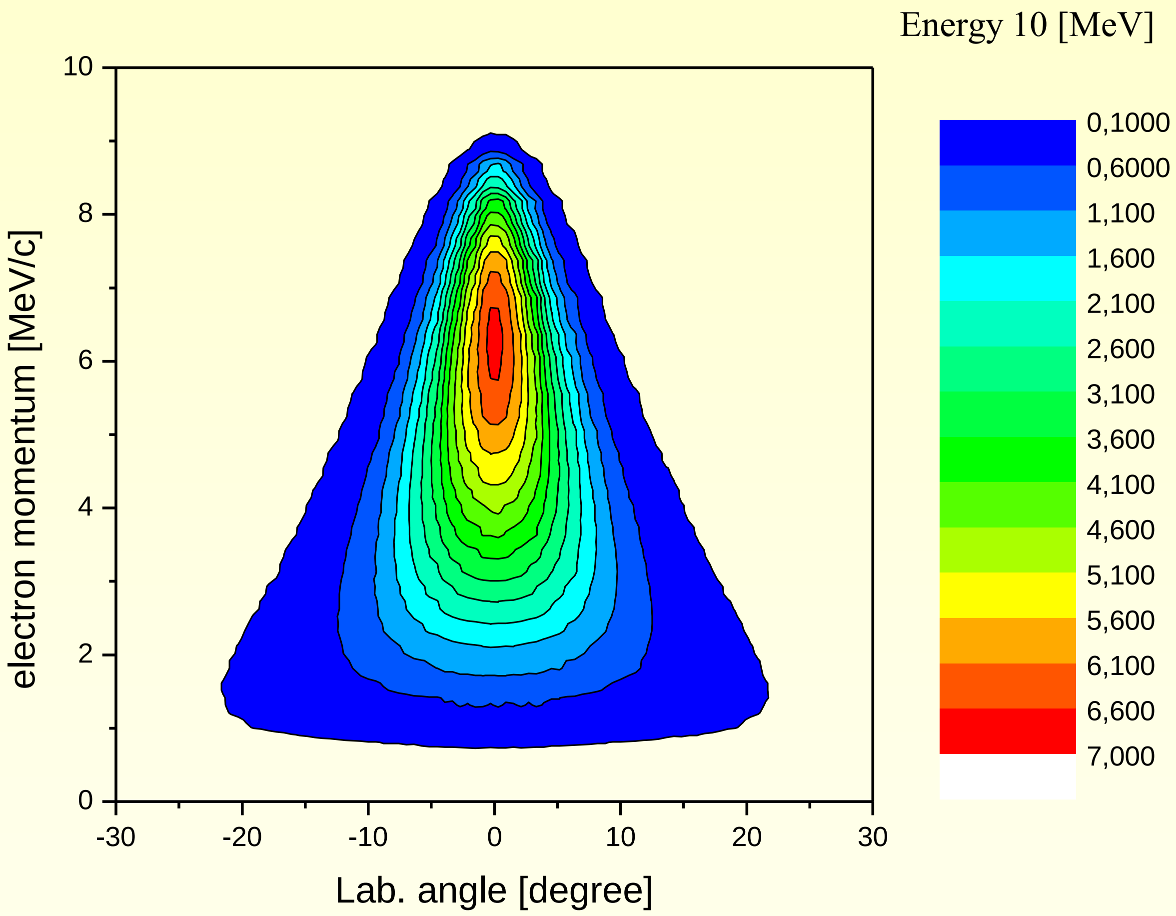
Proton beam acceleration


Protons accelerated by 10 MeV "photons"

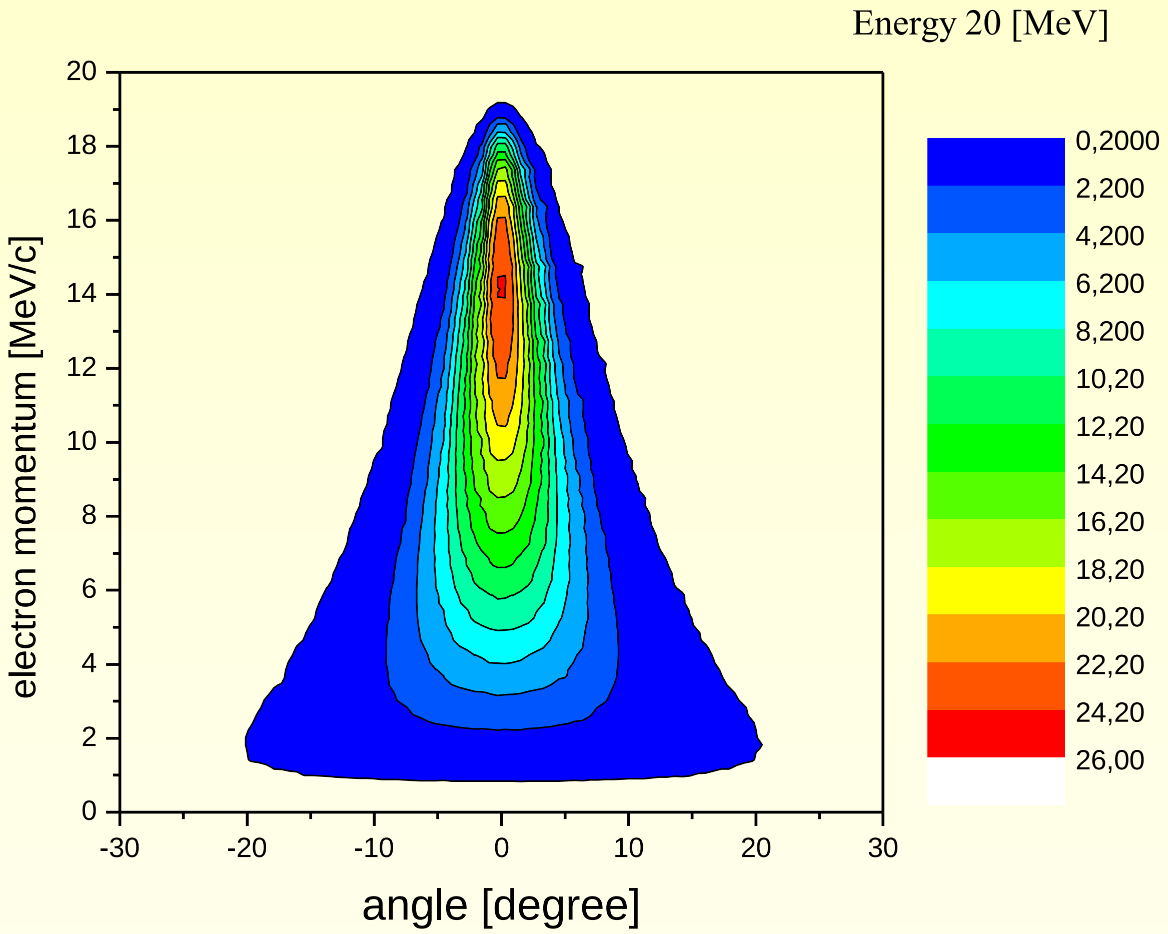
Electron beam production



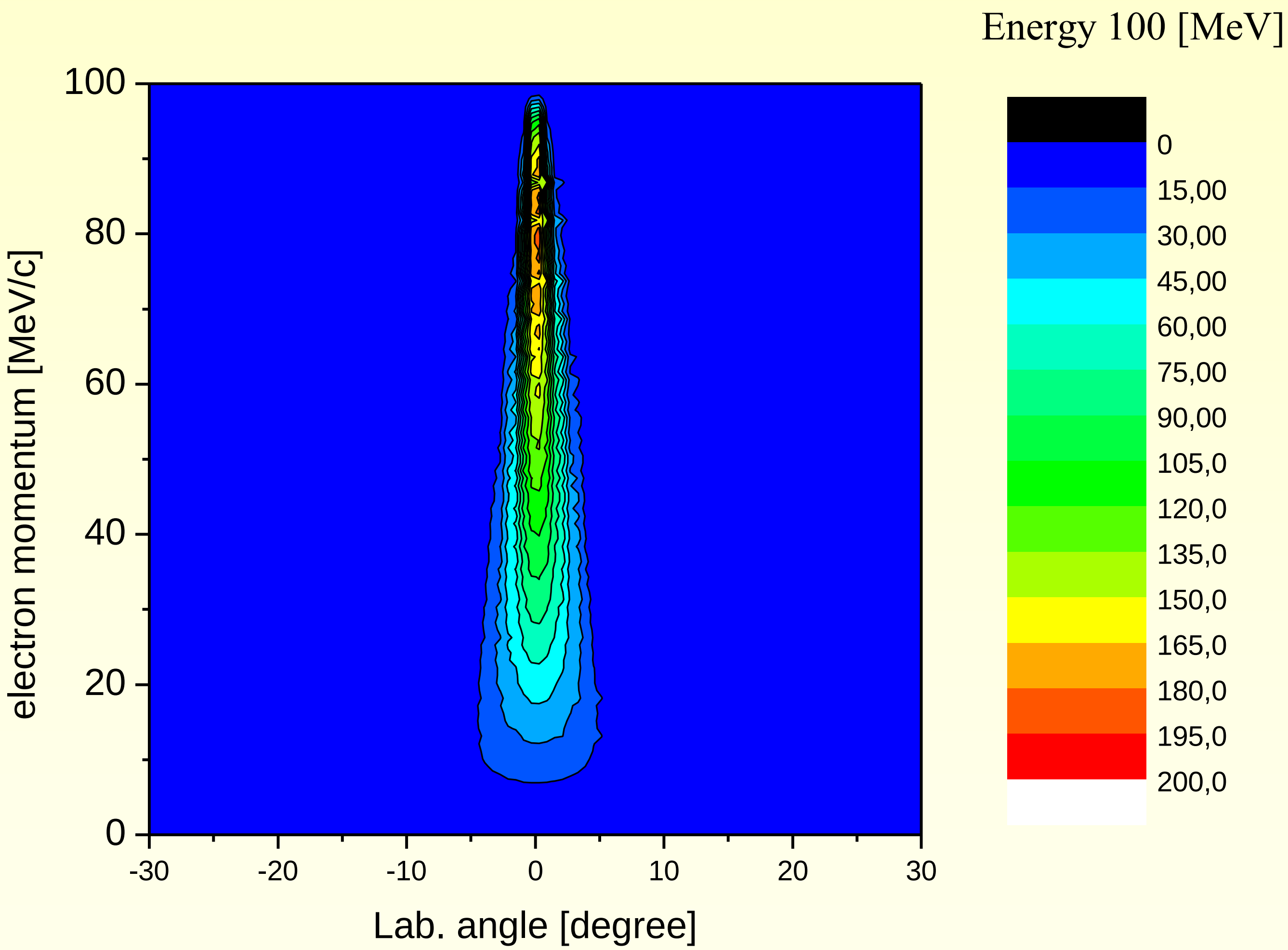
Electron beam production



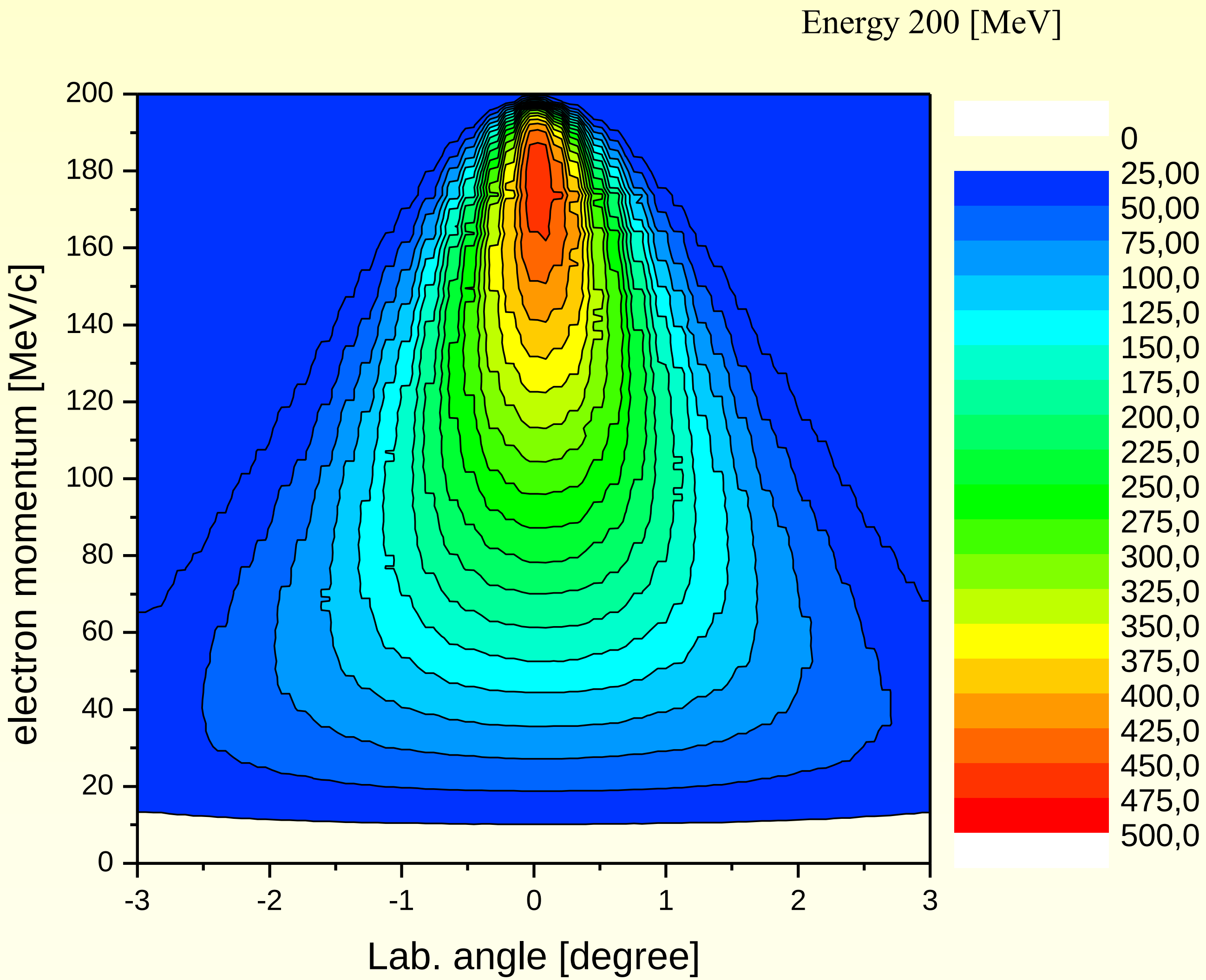
Electron beam production



Electron beam production

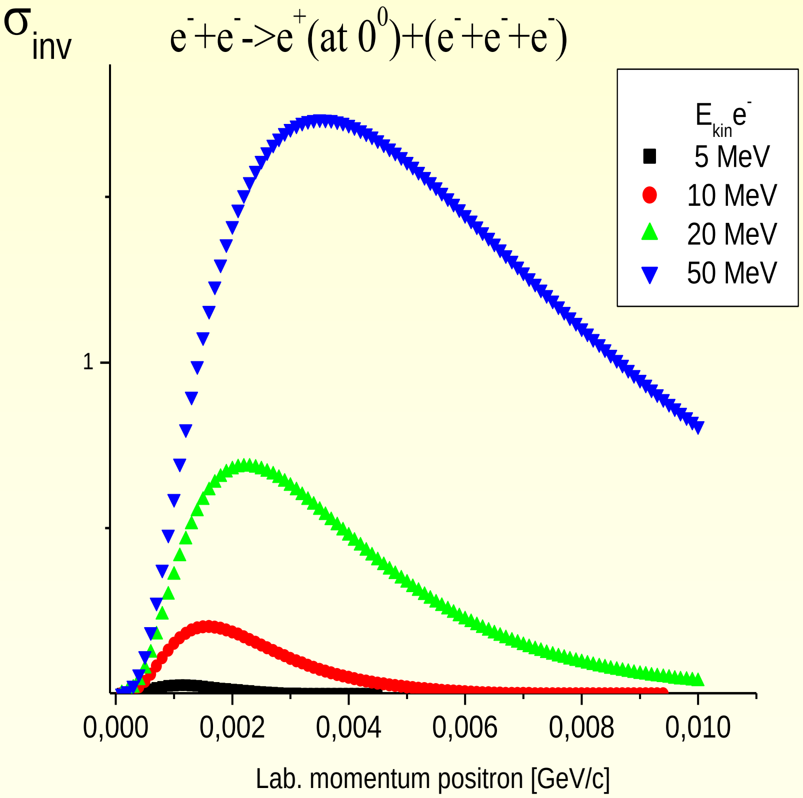


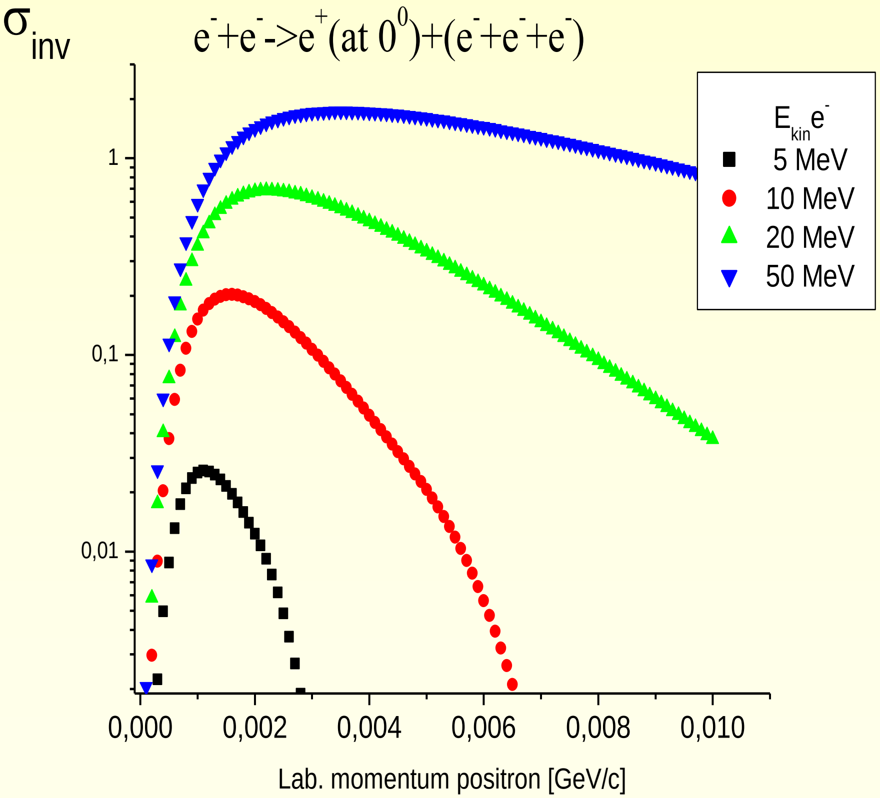
Electron beam production



Self-similar solution in electron – positron pair production

$$\sigma_{inv} = C_1 \exp\left(-\frac{\Pi}{C_2}\right)$$

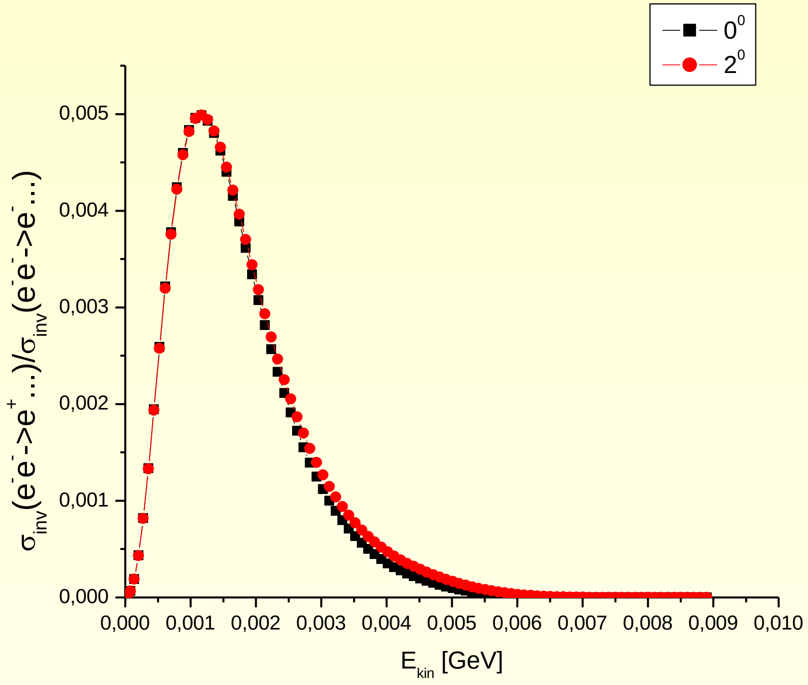


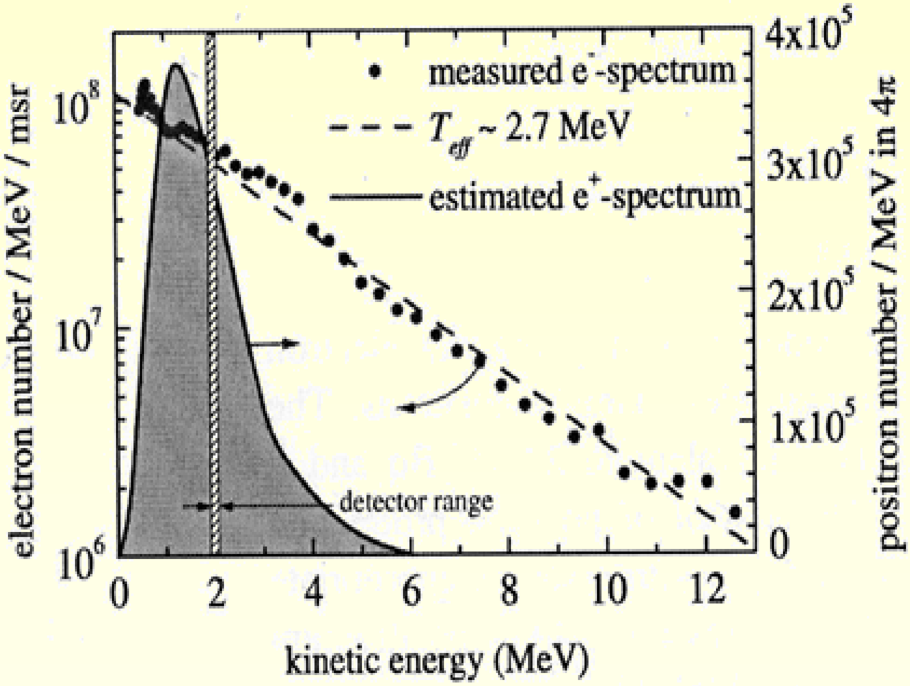


Electron – positron pair production. Comparison with experiment

$10\ MeV \quad e^- + e^- \rightarrow e^+ + 3e^-$

Appl. Phys. Lett., Vol. 77, No. 17, 23 October 2000





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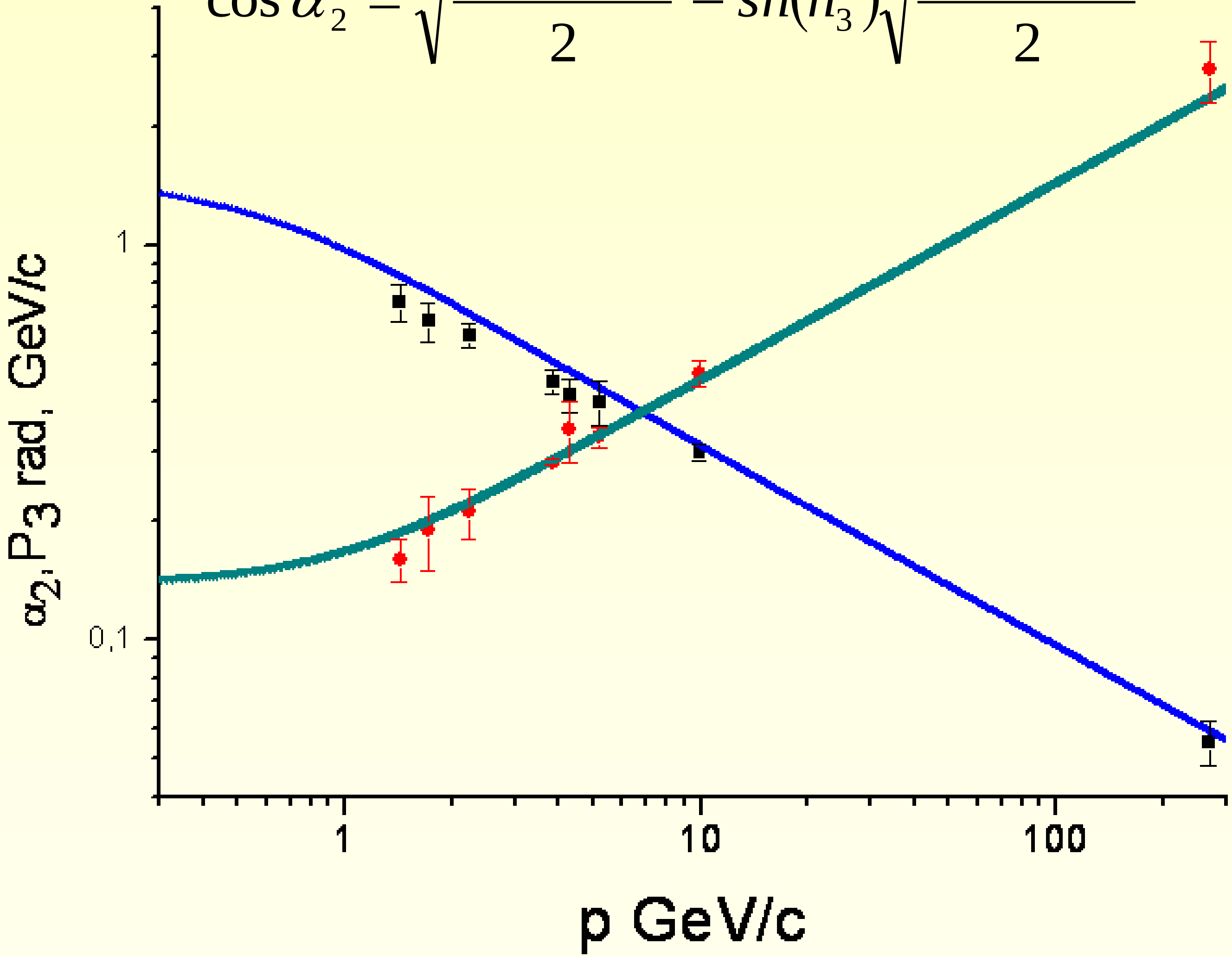
Directed Nuclear Radiation

$$\cos\alpha_2 = \sqrt{\frac{1+th(\rho_1)}{2}} - sh(h_3)\sqrt{\frac{1-th(\rho_1)}{2}}$$



Conclusions

- The new field of fundamental research, ultrashort laser beam-matter interaction, couples laser physics and relativistic nuclear physics
- Multiple applications:
    - gamma and proton radiography
    - precise material processing (new generation electronics etc.)
    - ion sources for accelerators
    - positron beams for PET
- Self-similarity solution provides a unified description of particle production by ultrashort laser pulses. This solution can be used “as is” and built in other codes for account of particle and laser beam conversion
- Experiments on e+e- production by femtosecond laser are under preparation in collaboration with Joint Institute for High Temperatures, RAS (Moscow)