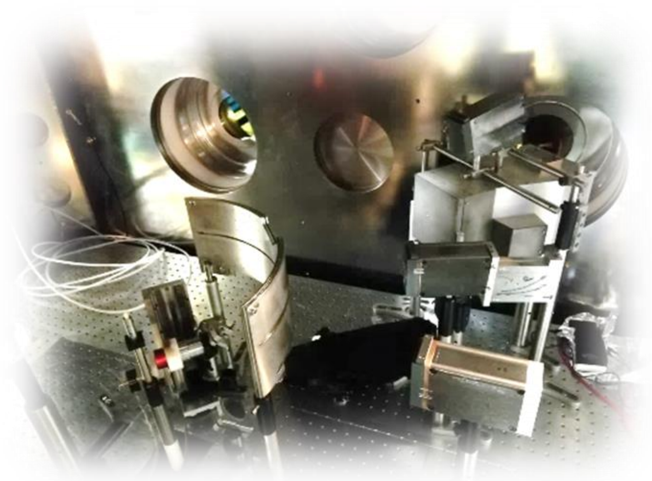
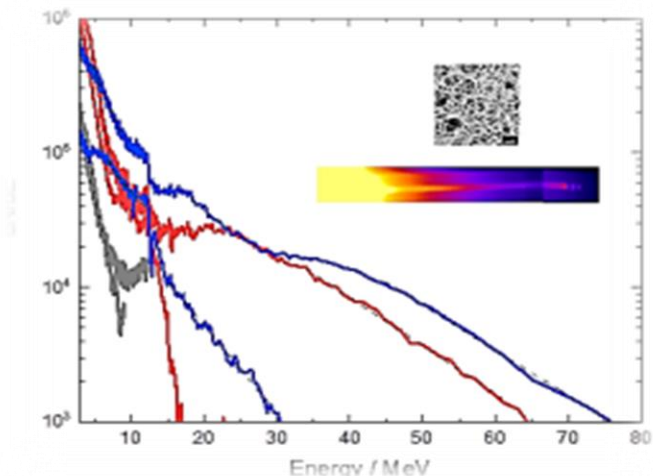
High current well-directed beams of super-ponderomotive electrons for laser driven nuclear physics applications.

«Ускорение частиц в плазме и лазерно-плазменная физика экстремального света»
онлайн-семинар, 16.10.2020





Olga Rosmej

GSI Darmstadt,
Plasma Physics Group, IAP, GU-Frankfurt
Helmholtz Research Academy Hessen for FAIR

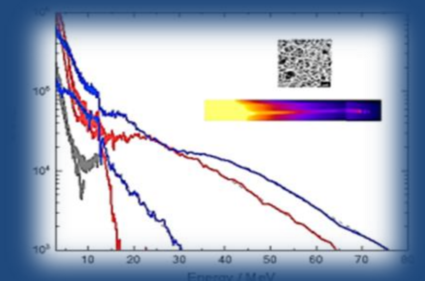
High-current well-directed relativistic electron beams for multidisciplinary research

Plasma Physics, HED-research:
ultra-intense betatron, THz and gamma-sources,

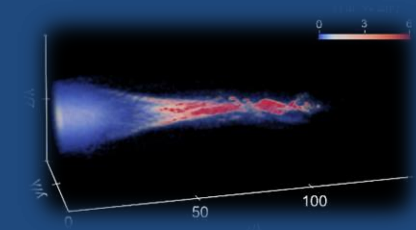
Nuclear Physics:
high fluence/ flux gamma and neutron sources,
high yield (p,xn), (g,xn) nuclear reactions in GDR region
theranostic relevant radio-isotopes.

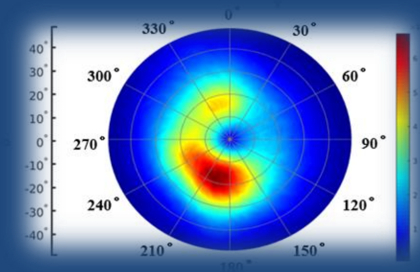
Biophysics:
high flux ionizing radiation (e-, γ) for investigation
of the FLASH-effect in the tumor therapy.

Collaboration: **Experiment-PIC-GEANT4**
GSI-Darmstadt (PP, BP); GU-Frankfurt;
HH-Düsseldorf; FS, HI-Jena; JIHT Moscow;
LPI-Moscow; ITEP-Moscow



Multi MeV electrons

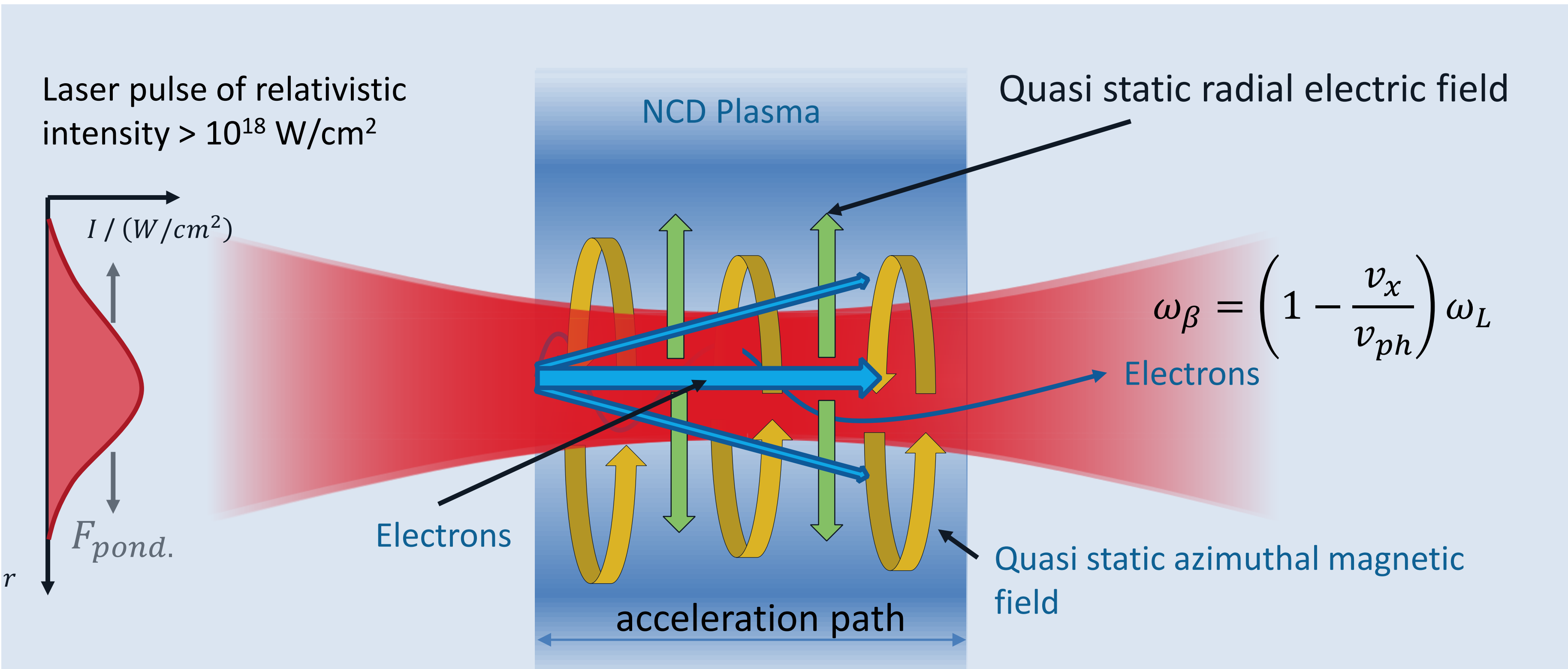




keV betatron

ACCELERATION OF ELECTRONS IN PLASMA OF NEAR CRITICAL DENSITY

Direct laser acceleration of relativistic electrons at betatron resonance
A. Pukhov, Z.- M. Sheng, and J. Meyer-ter-Vehn, V6, N7, PoP 1999



- self-focusing : $P_L > P_c = 17$ GW × n_c / n_e (high aspect ration channel)
- generation of quasi-static radial E-field that has a pinching polarity for electrons.
- self-generated quasi-static B azimuthal that traps electrons in the plasma channel.

PHASE SPASE OF ACCELERATED ELECTRONS

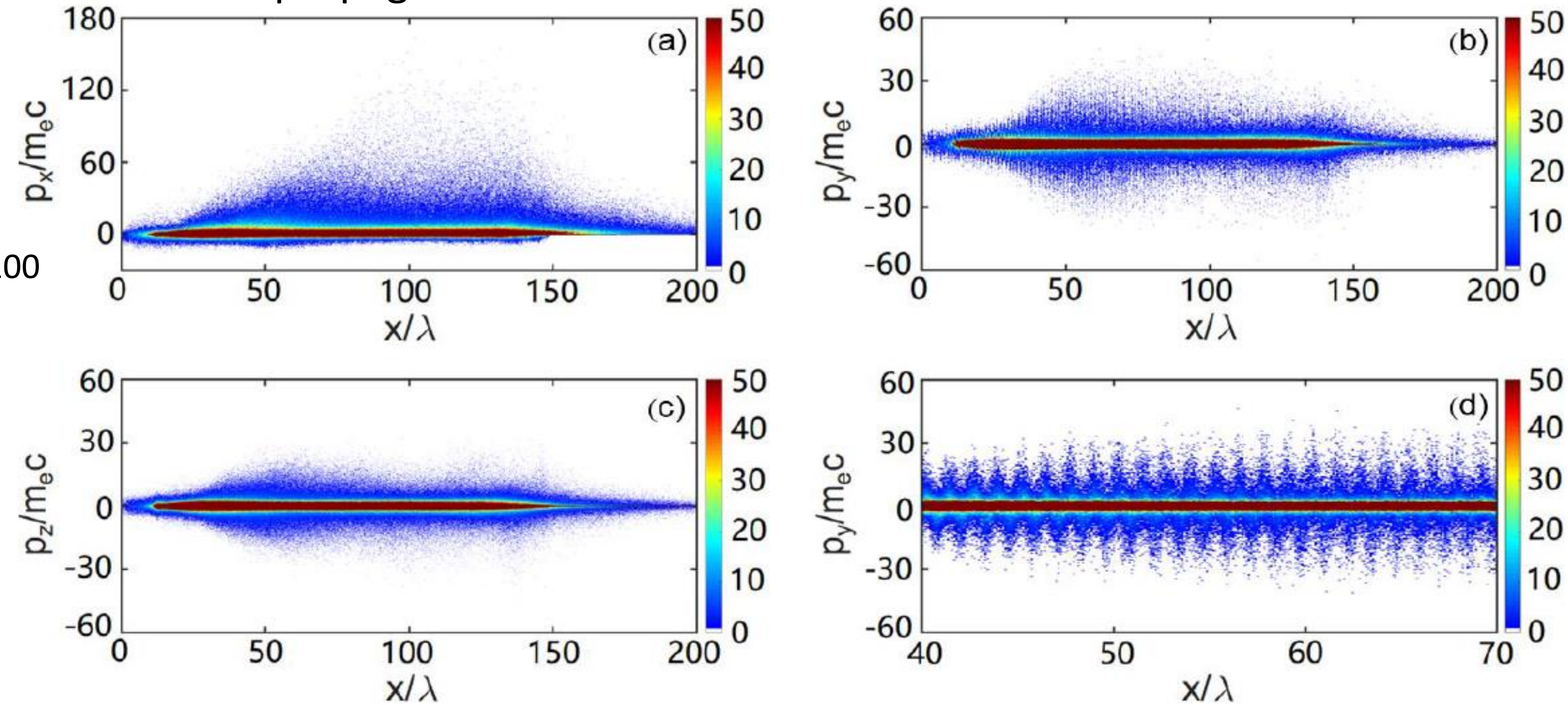
DLA

***ct*=100 μm**

X-laser propagation direction

Y-laser polarization direction

200



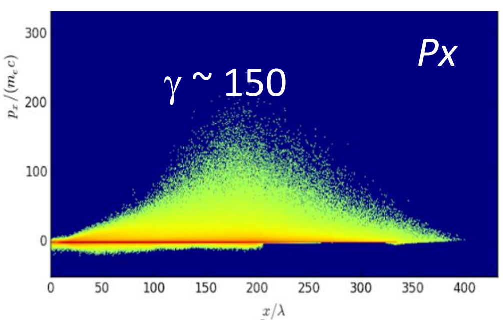
Snapshots of the electron phase space at ct=100μm after the laser pulse peak intensity arrived at the left plasma boundary: (a) momentum p_x vs x; (b) momentum p_y vs x; (c) momentum p_z vs x; (d) zoomed part of momentum p_y vs x in the range x/λ= [40, 70].

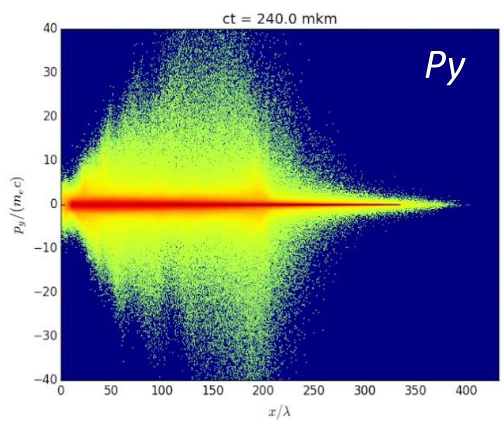
Color panels present a number of pseudo-electrons in simulations.

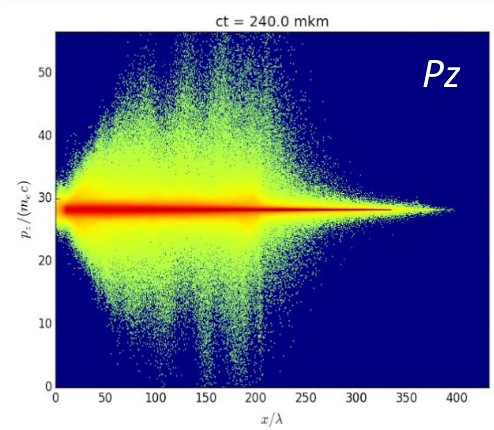
3D-PIC simulations X. Shen

At later times, stochastic heating starts to play a major role

***ct*=240 μm**







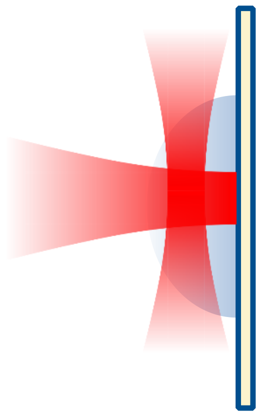
stochastic feature (*Pz* ~ *Py*)

3D-PIC simulations V. Popov

GENERATION OF PLASMA WITH NEAR CRITICAL ELECTRON DENSITY

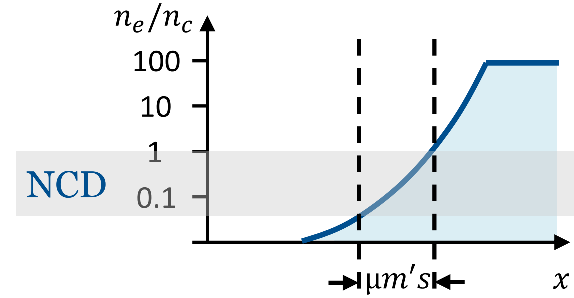
- Critical density $n_c(1054\ nm) = \frac{\varepsilon_0 m_e}{e^2}\omega_L^2 = 10^{21}\ cm^{-3}$

→ Foil target:

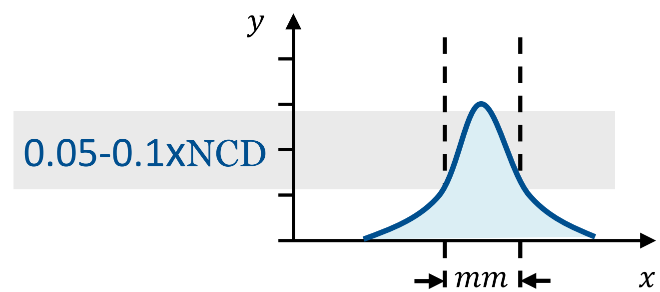


expanding plasma (longitudinal)

expanding plasma (transversal): longer electron acceleration path

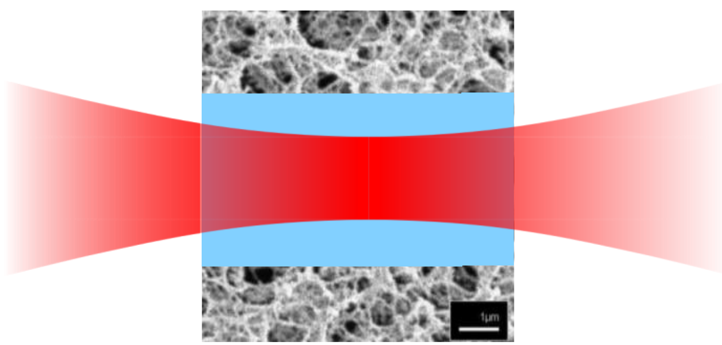


Pukhov, A., et al. *Physics of Plasmas* 6.7 (1999)

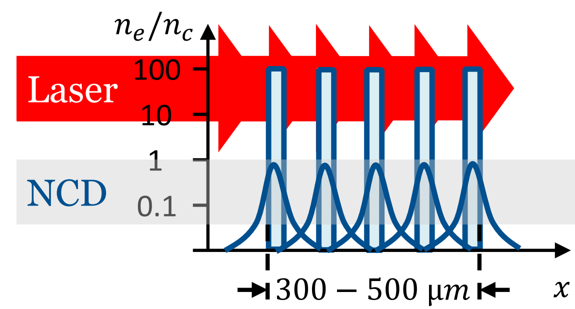


Willingale, L., et al. *New Journal of Physics* 15.2 (2013): 025023.

→ Foam target:



CHO-Foams (Triacetatecellulose: $C_{12}H_{16}O_8$): $300 - 500\ \mu m$, $2\ mg/cm^3$



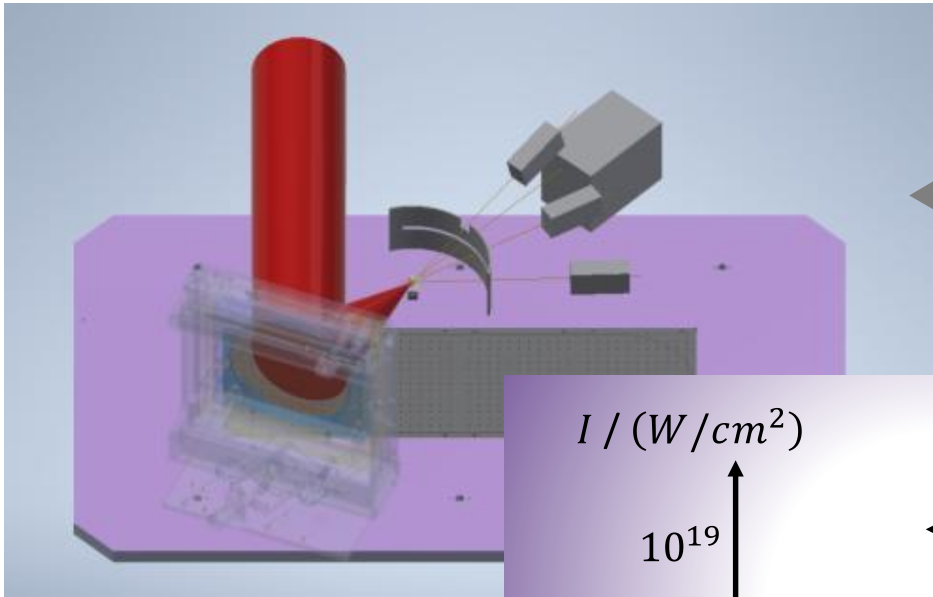
Rosmej, O et al 2019 *New J. Phys.* **21** 043044

supersonic ionization v = 500µm/2ns

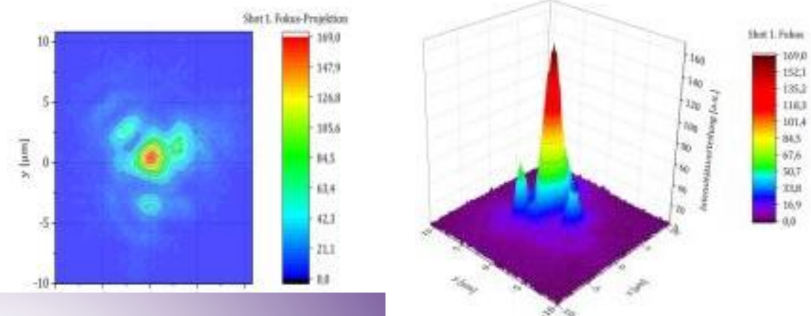
SET-UPS FOR DIFFERENT PHELIX-LASER INTENSITIES

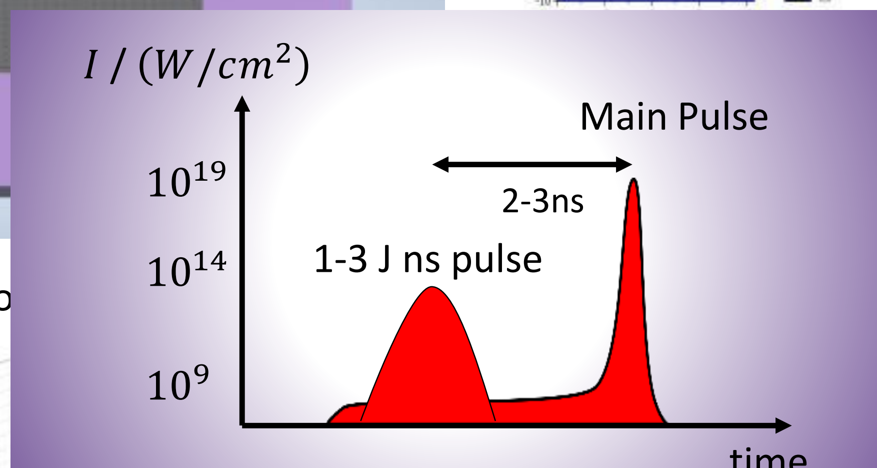
1ω Nd:glass

Experiments were performed at 10^{21}W/cm^2 and 10^{19}W/cm^2

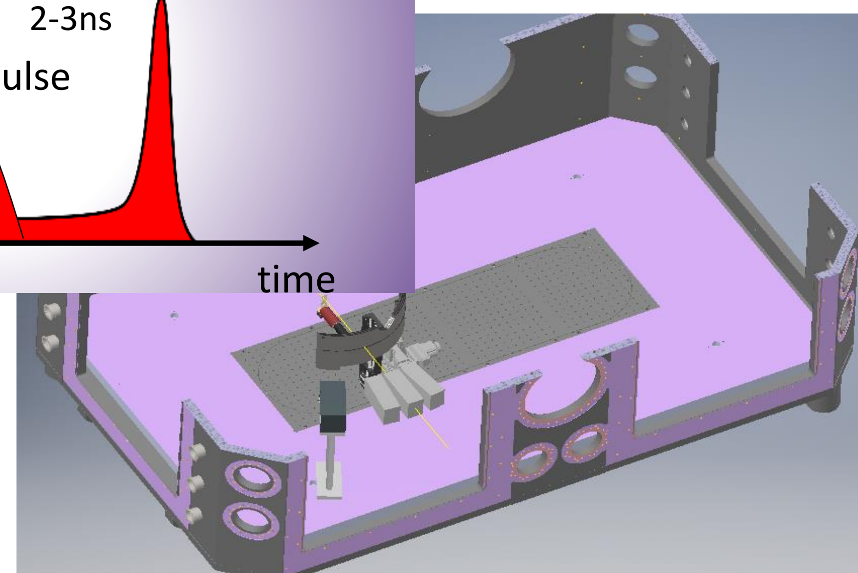


40 cm focusing parabola, **6-9×10^{20} W/cm^2**

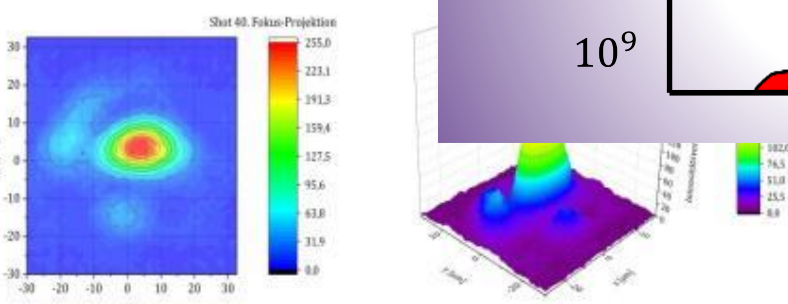




180 J,
X3.3 μm^2

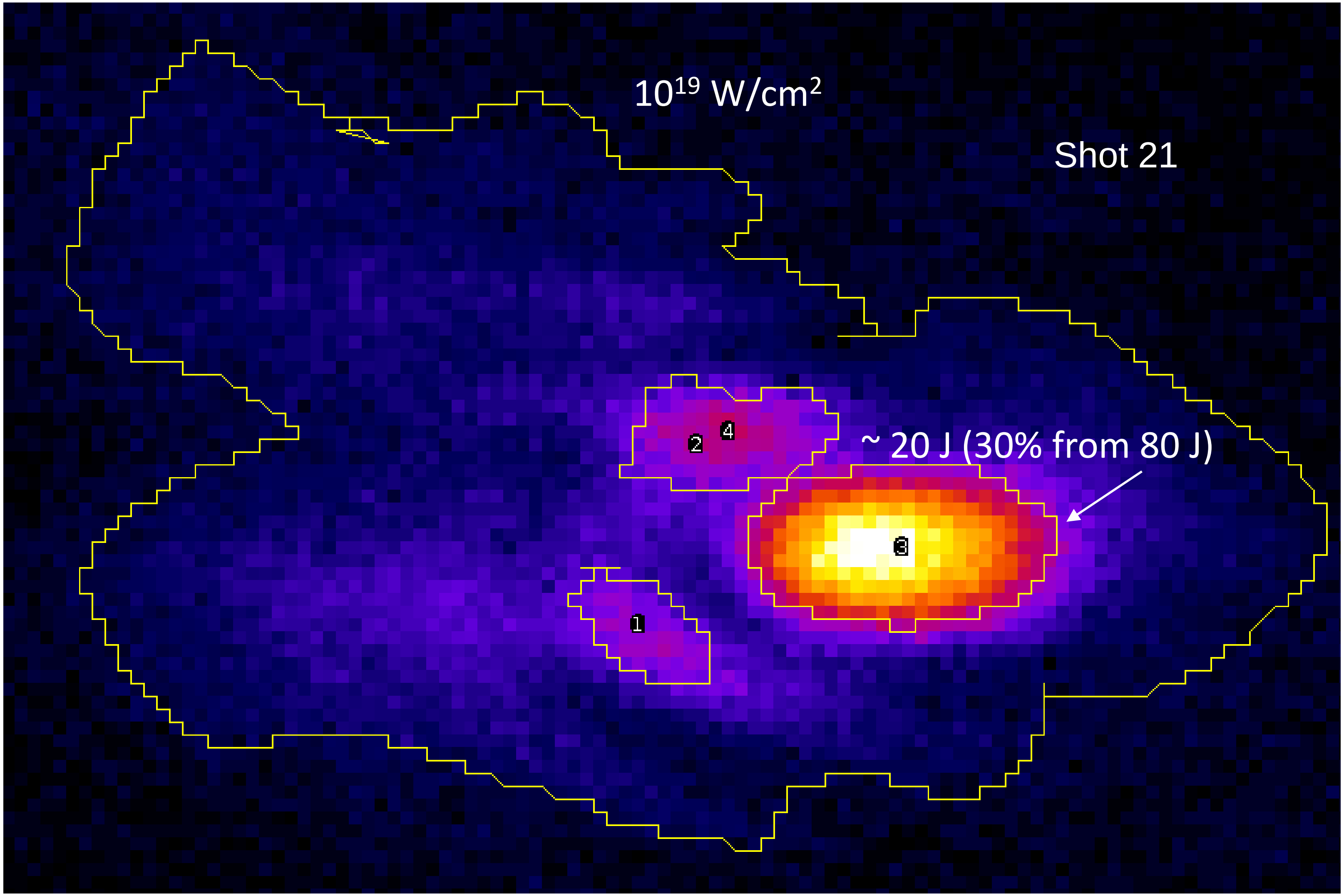


150 cm focusing parabo



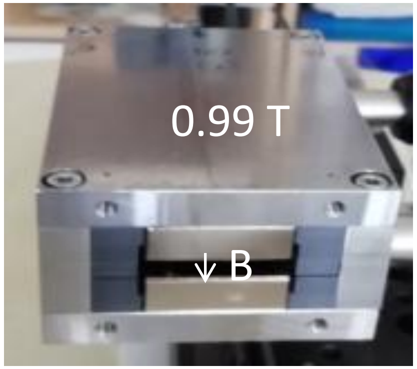
s-pol., 1ω, 700fs , E~100 J ,
20-30% in FWHM 10X19 μm^2,

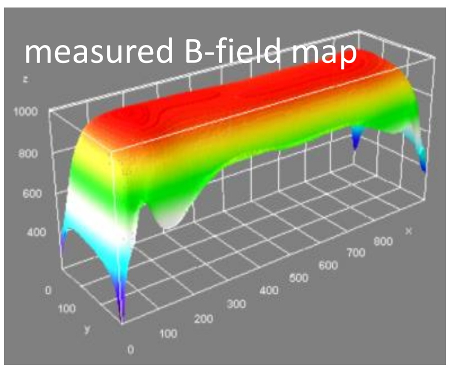
DISTRIBUTION OF LASER ENERGY IN THE FOCAL SPOT



DIAGNOSTIC SET-UP P176, PHELIX, September 2019

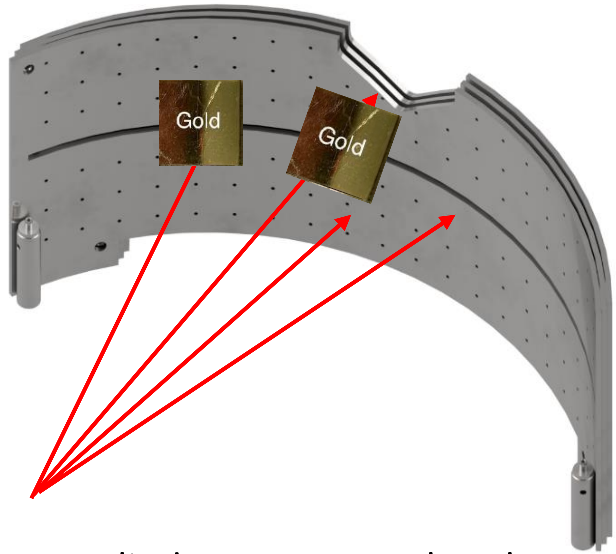
<u>Electron spectrometer:</u>
electron energy distribution





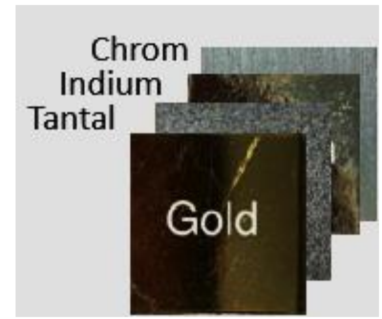
Static magnets, B=0.99T
2% energy resolution up to 100 MeV
Detector: calibrated imaging plates
-> <u>absolute number of electrons</u>

<u>Cylinder diagnostic:</u>
electron angular distribution

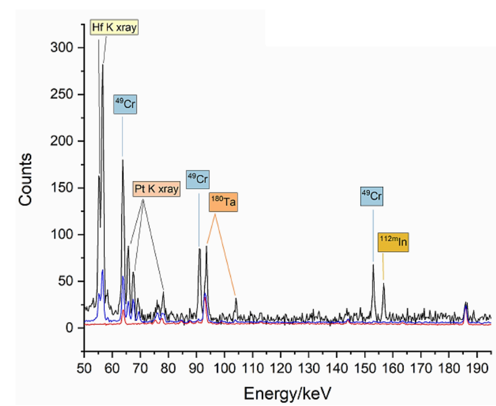


3 cylinders, 3mm steel each
R=200mm
Detector: imaging plates

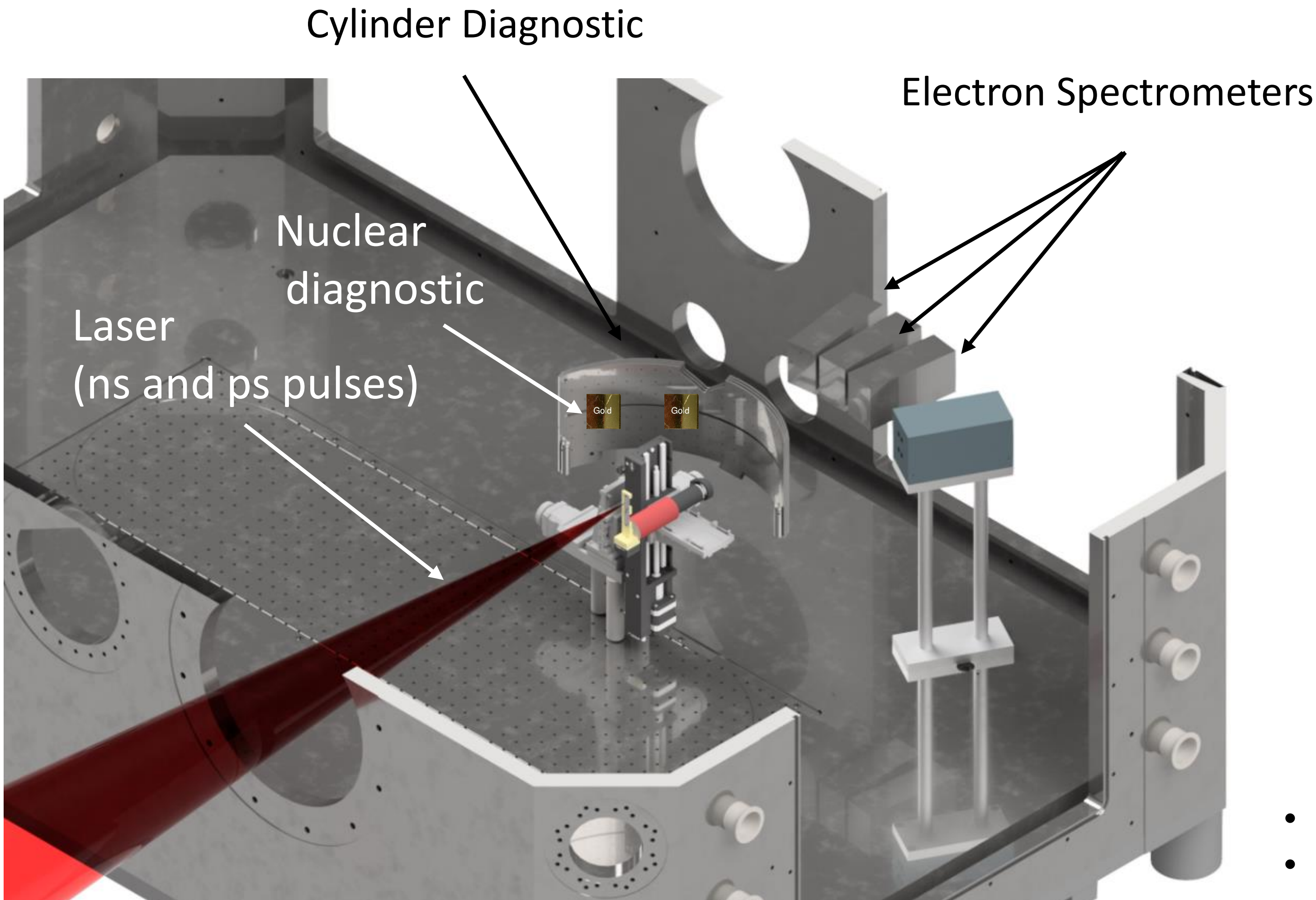
<u>Nuclear diagnostic:</u>
γ, neutron fluences



Ge-detector:
isotope type and number



EXPERIMANTAL SET-UP P176, PHELIX, September 2019



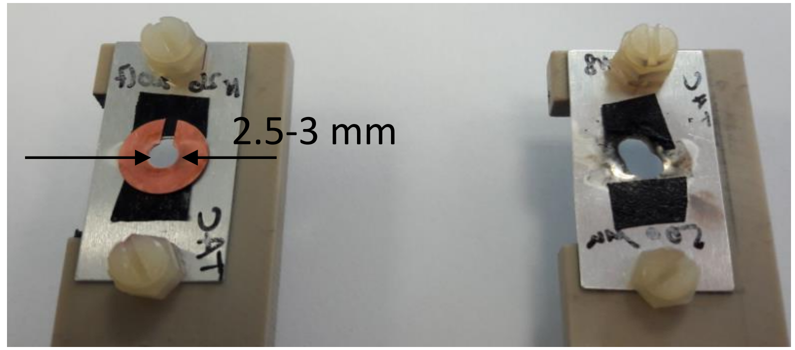
Target-Holder

- 10 μm Ti, Au-foils
- 1-2mm Au, W plates
- CHO- foams
- combination

NCD plasma: low density polymer foams ρ=2 mg/cc (1.7×10^{20} at/cm^3)
300-500 μm thickness, fully ionized (Z_{mean}= 4.2) -> $n_e = 0.65 \times 10^{21}$ cm^{-3}

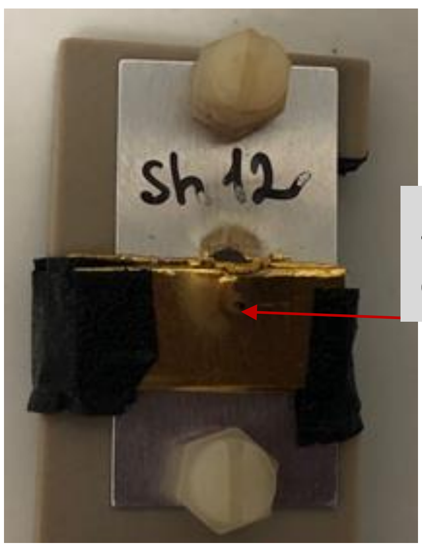
TARGETS AFTER INTERACTION

500 μm 2 mg/cc foam=
700 nm 1.4 g/cc polymer foil



Sh. 28
500 μm foam

shot 12:
10^{21}W/cm^2: 40J, d=3 μm
(1+1)mm Au-radiator



sub-mm crater

shot 21:
10^{19} W/cm^2: 20J d=15 μm
Foam+ 1mm Au

mms large hole

10 mm

shot 28:
10^{19} W/cm^2: 20J d=15 μm
Foam+ 0.1mm Pb

N. Borisenko, LPI

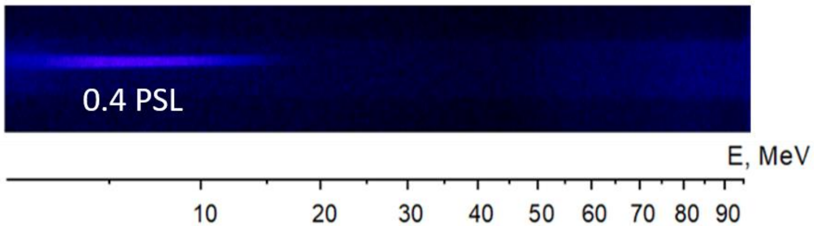
ENERGY AND ANGULAR DISTRIBUTION of MeV-ELECTRONS

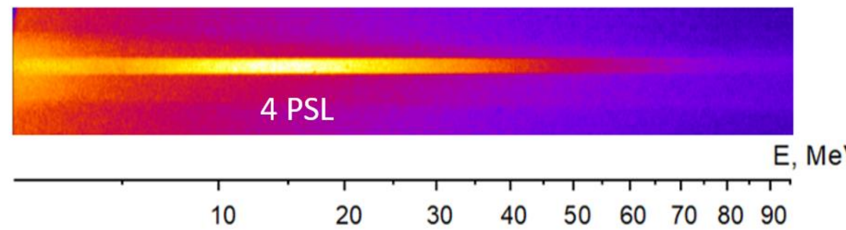
Highly energetic and well directed electron beam (γ>10) generated in NCD plasma

Shot 40: 700 fs, 10^{19} W/cm^2
Target: Au foil 10 um

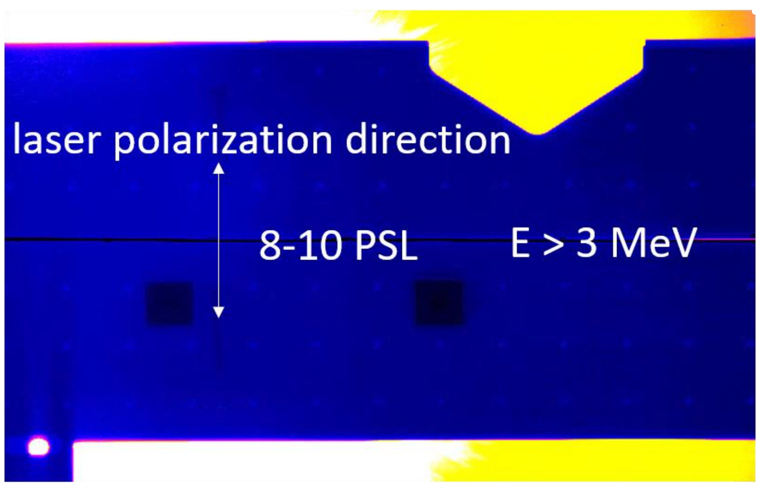
Shot 42: 700 fs, 10^{19} W/cm^2
Target: 325 um TAC + Au foil 10 um

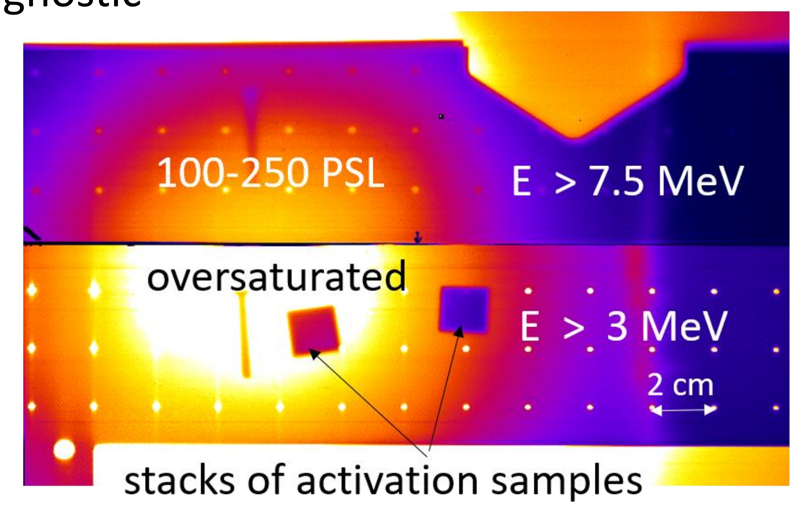
electron spectra at 0° to laser axis





cylinder diagnostic



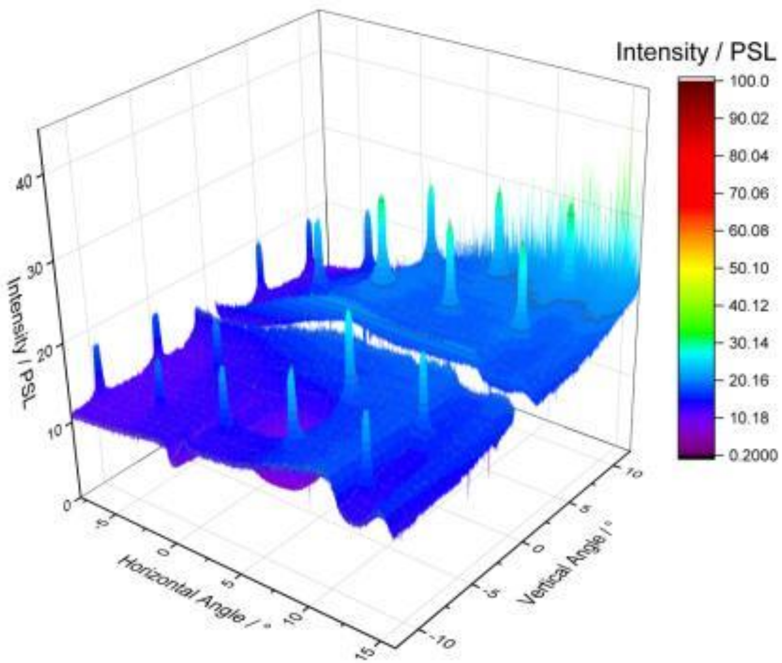


ANGULAR DISTRIBUTION OF RELATIVISTIC ELECTRONS

Well directed electron beam (γ>10) generated in foams

Shot 40: 700 fs, 10^{19} W/cm^2
Target: Au foil 10 um

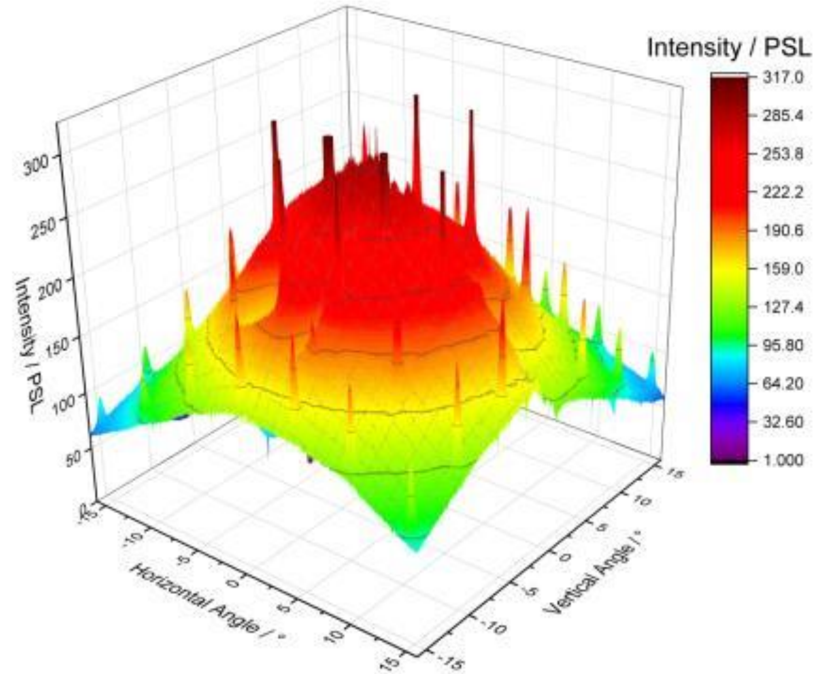
no directionality



low IP signal,

Shot 42: 700 fs, 10^{19} W/cm^2
Target: 325 um 2 mg/cc TAC+ Au foil 10 um

½ θ at FWHM ≤ 13°

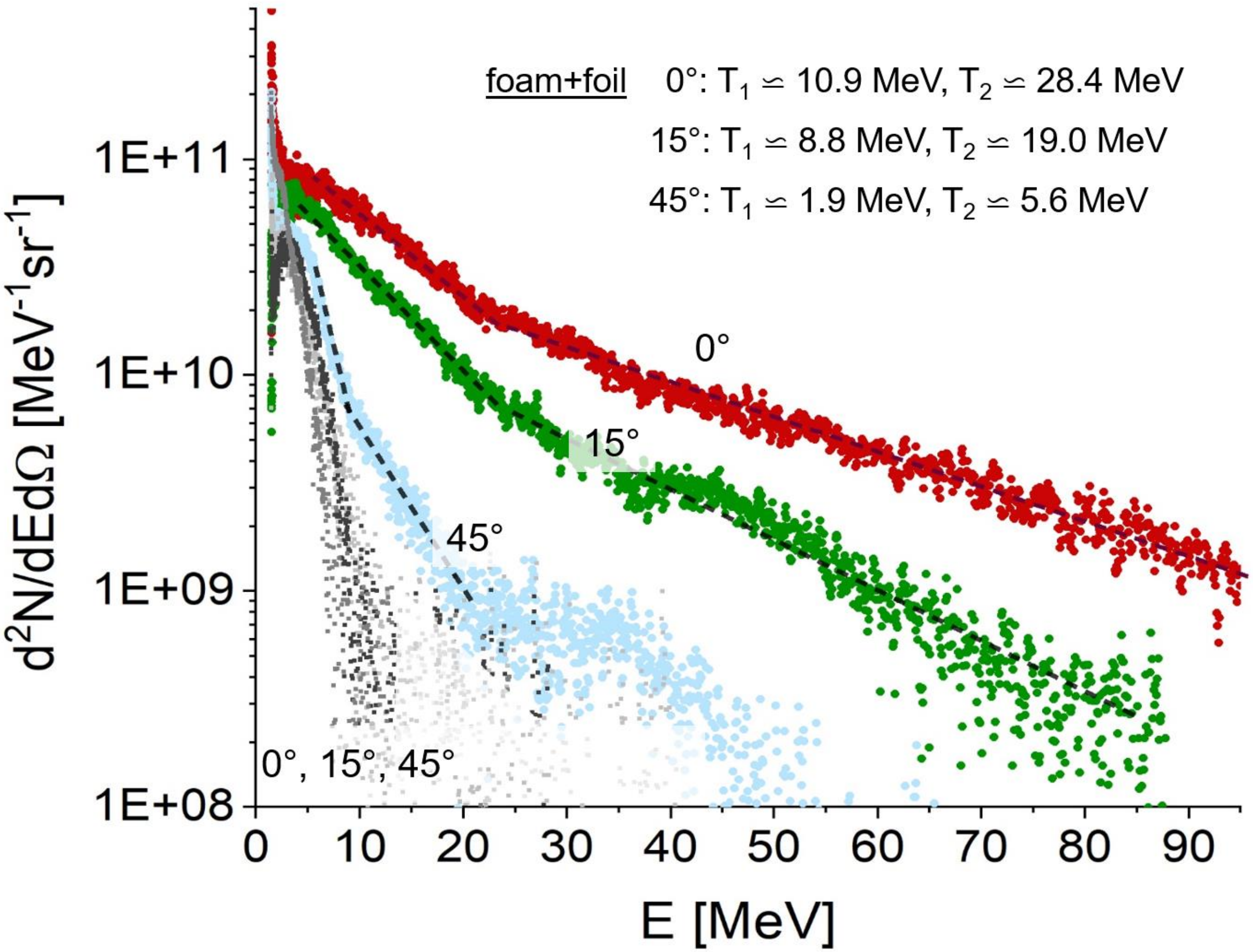


more than 30 times increase of the IP signal,

S. Zähter, GSI

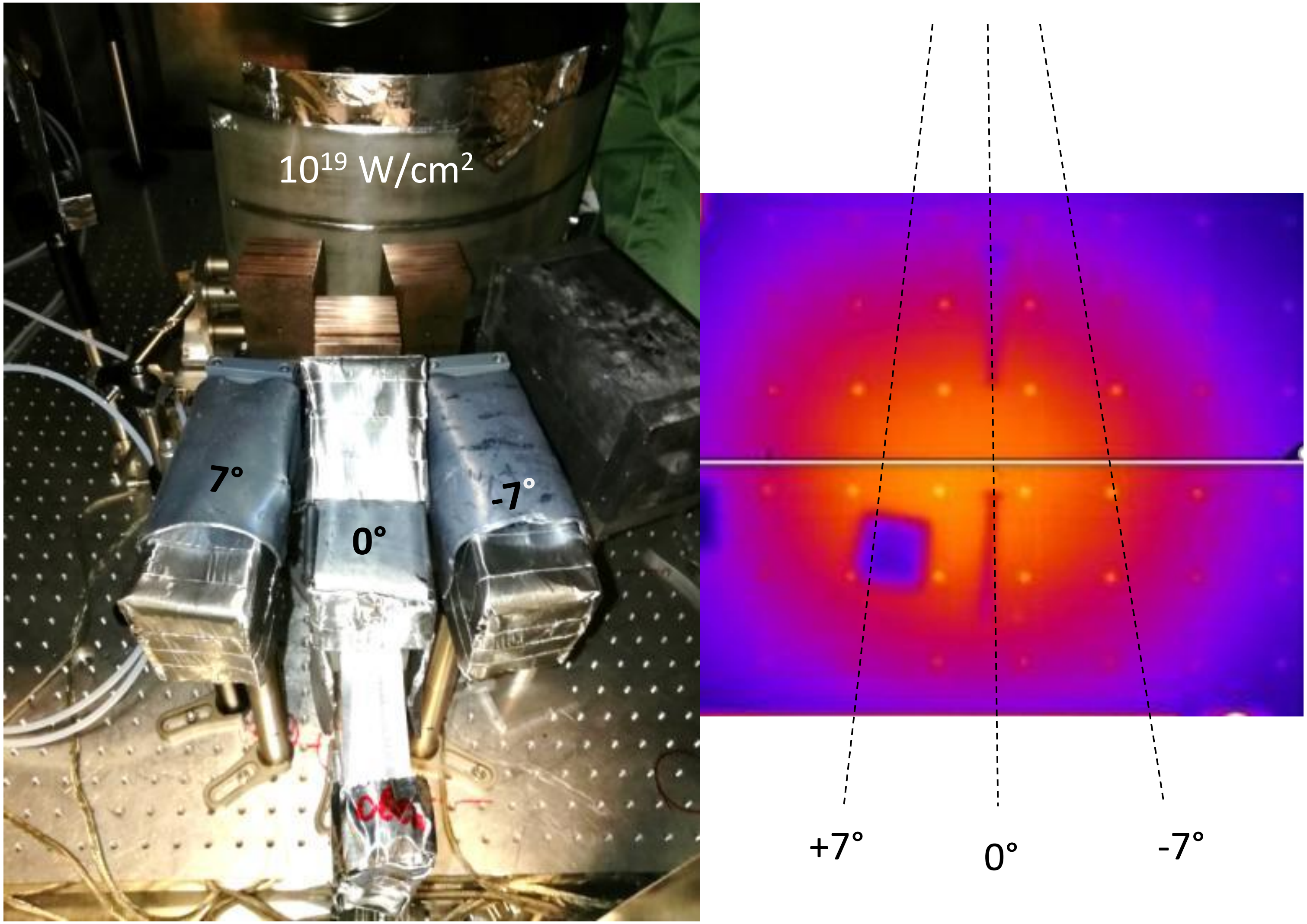
ENERGY DISTRIBUTION OF SUPER-PONDEROMOTIVE ELECTRONS

700 fs, E_{FWHM} = 20 J, 10^{19} W/cm^2
target: foam + foil



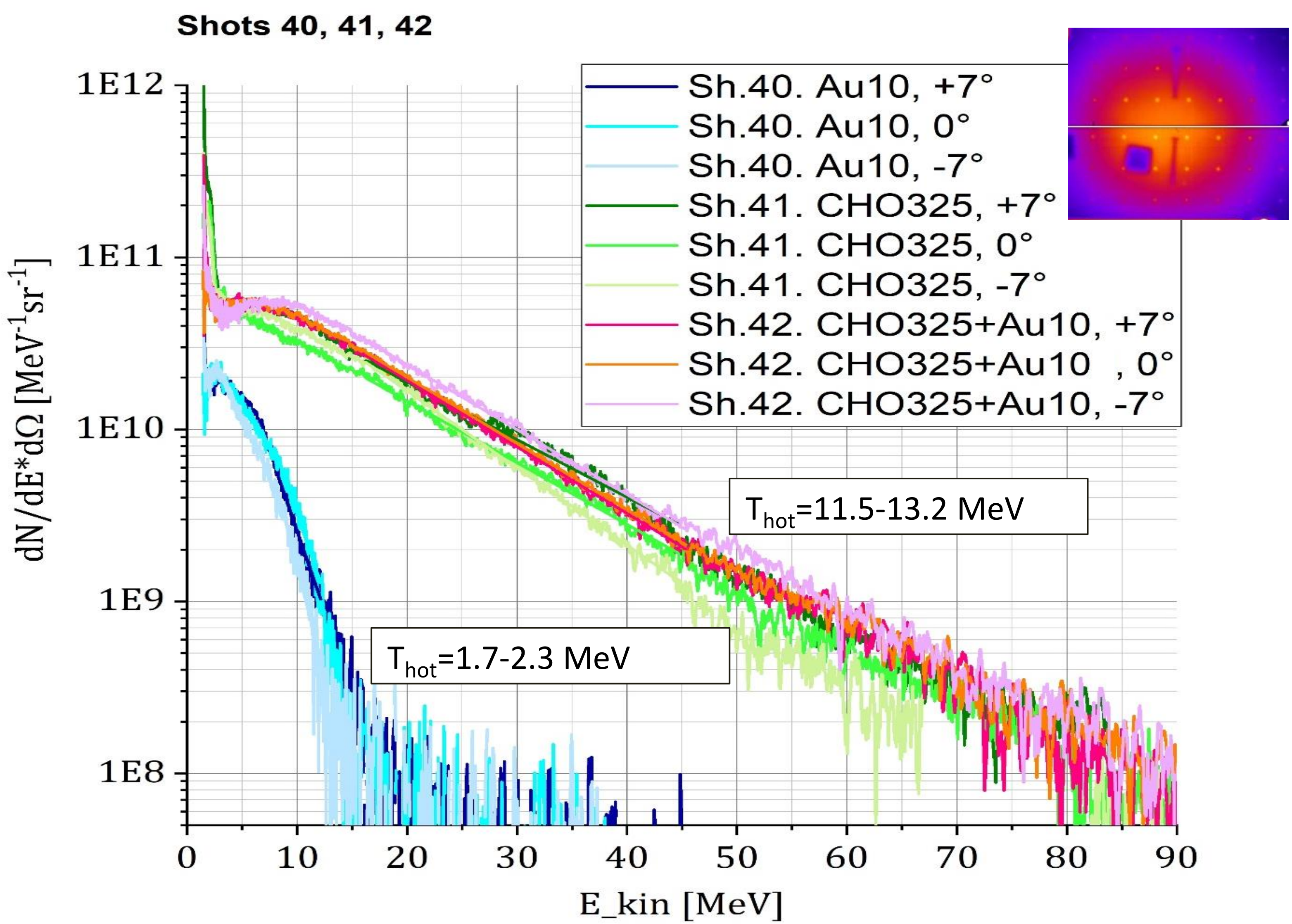
M. Gyrdymov, Frankfurt University

ENERGY AND NUMBER OF MeV-ELECTRONS INSIDE DIVERGENCE CONE



M. Gyrdymov, Frankfurt University

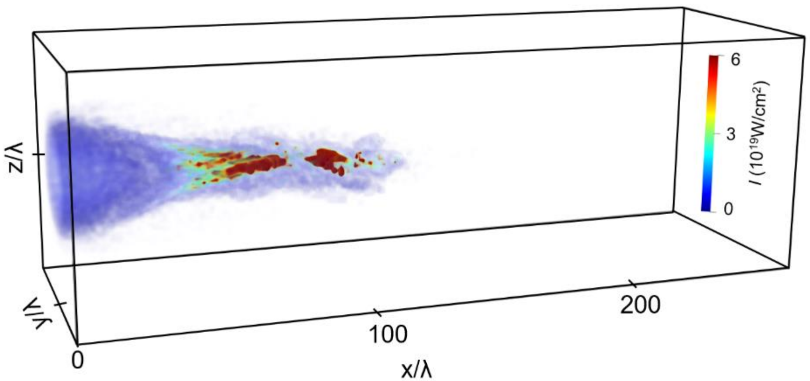
ENERGY AND NUMBER OF MeV-ELECTRONS INSIDE DIVERGENCE CONE



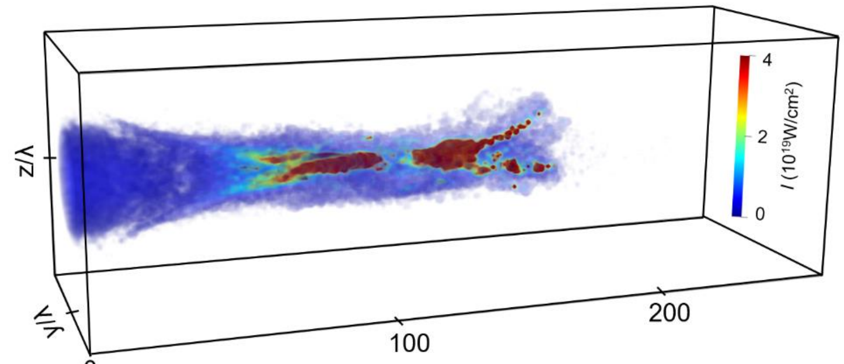
FULL 3D-PIC SIMULATIONS

3D view of the laser intensity distribution

t= 330 fs



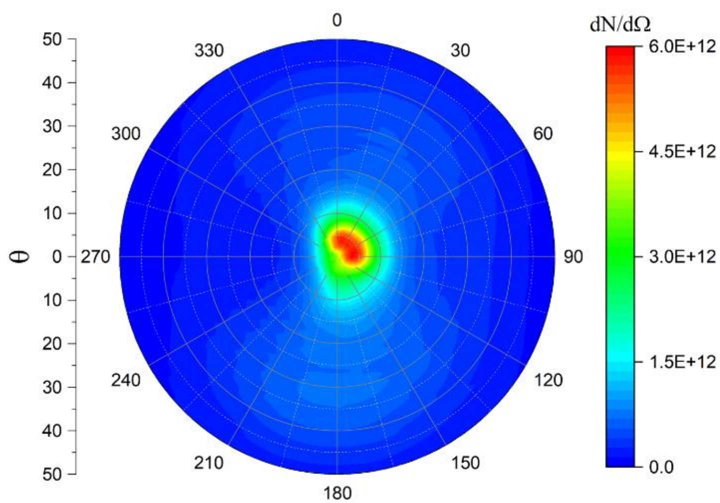
t=433 fs



laser pulse filamentation

Angular distribution
of electrons with E > 7 MeV

½ θ at FWHM ~ 10°
(experiment < 13°)

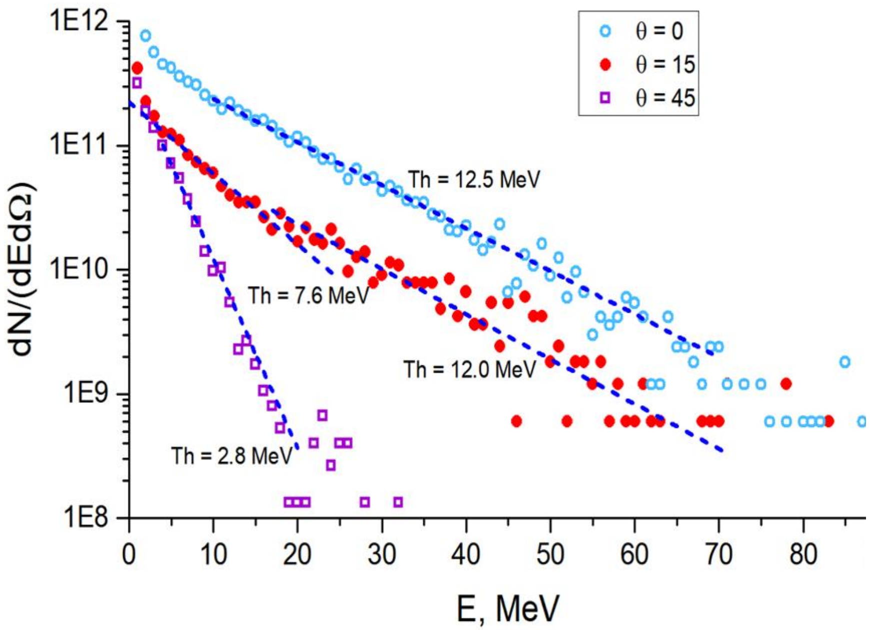


A. Pukhov, N. Andreev,
X. Shen, V. Popov

SIMULATED ANGLE DEPENDEND ELECTON ENERGY DISTRIBUTION

3D - PIC

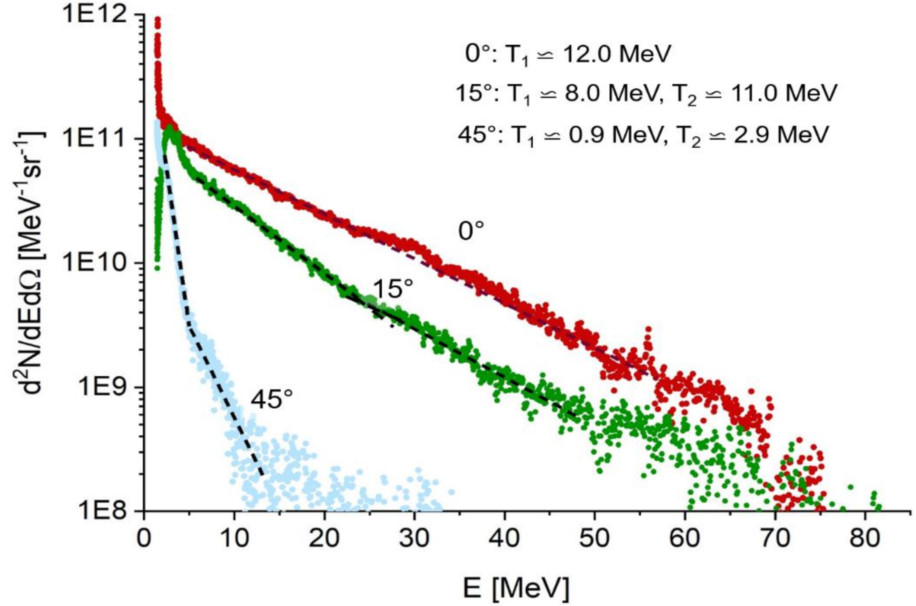
N_e (E > 7.5 MeV) = 3.3×10^{11} in 0.16 sr,



Laser:
2.5×10^{19} Wcm^{-2} ($a_L = 4.28$)
E_{FWHM}= 17.5 J
t_{FWHM}=0.7 ps

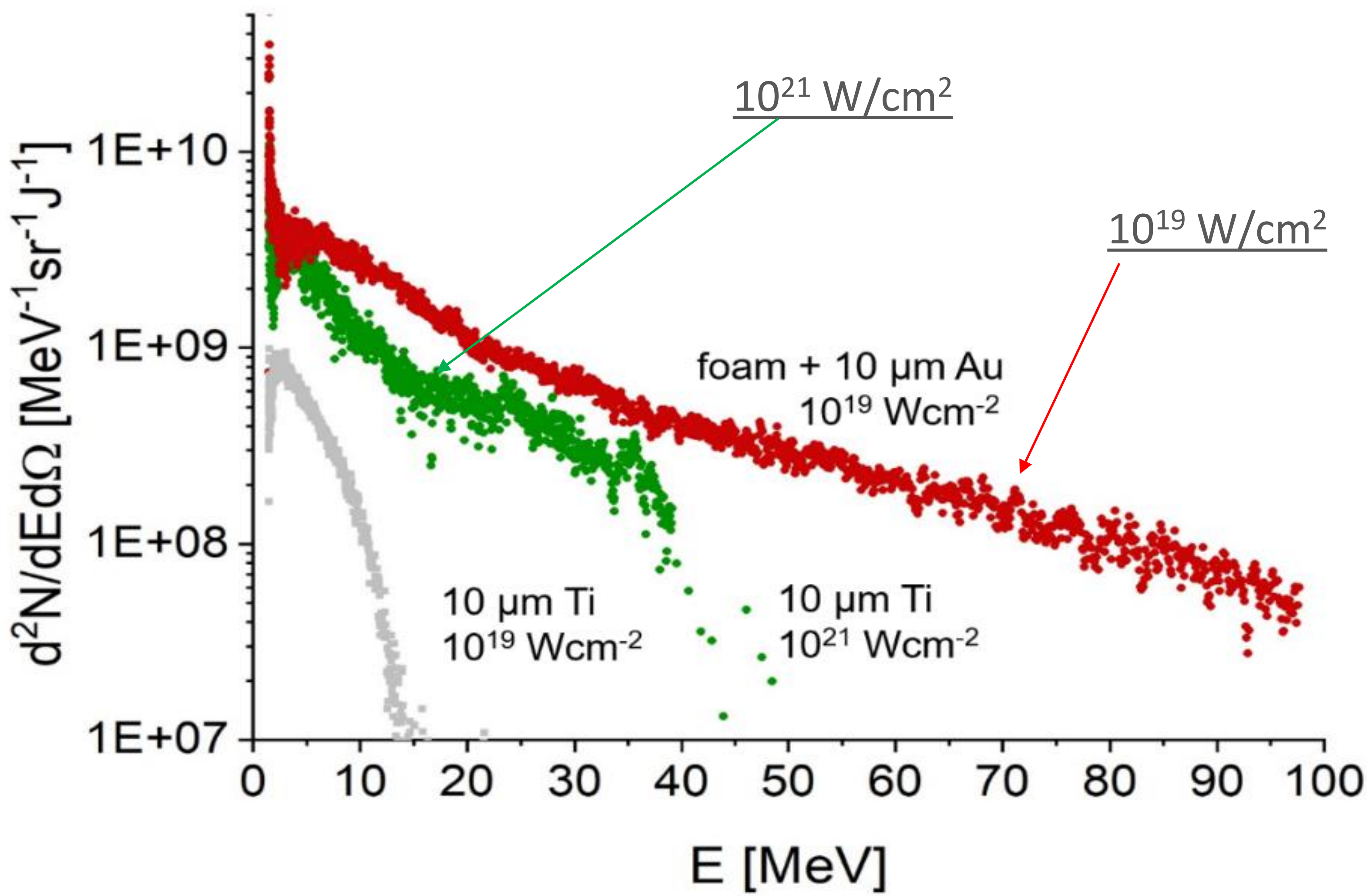
Experiment/ foam

N_e (E > 7.5 MeV) = 1.5×10^{11} in 0.16 sr,



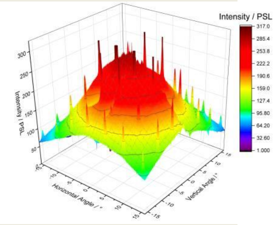
Target:
triacetate cellulose $C_{12}H_{16}O_8$
2 mg/cc x=300 μm
n_e= 0.65 n_{cr} (fully ionized)

ELECTRON ENERGY DISTRIBUTION FOR TWO LASER INTENSITITES



High current, well directed beams of multi-MeV electrons were generated in NCD-plasma at moderate relativistic laser intensities:

- Effective temperature above 10 MeV (10^{21} W/cm^2 -> foil: 6 -7 MeV)
- Max energy up to 100 MeV (10^{21} W/cm^2-> foi: ~ 40 MeV)
- E > 3 MeV propagate in ½ θ at FWHM ≤ 13°
- High current: up to 1 μC at E > 2 MeV; > 50 nC (6%) E > 7.5 MeV



Application in Nuclear Physics:

- high fluence/ flux gamma and neutron sources
- high yield (p,xn), (γ,xn) nuclear reactions in Giant Dipole Resonance (GDR) region
- theranostic relevant radio-isotopes.

PUBLICATIONS ON PHELIX BEAM-TIMES 2017, 2019

O N Rosmej et al, New J. Phys. **21**(2019) 043044

https://dx.doi.org/10.1088/1367-2630/ab1047

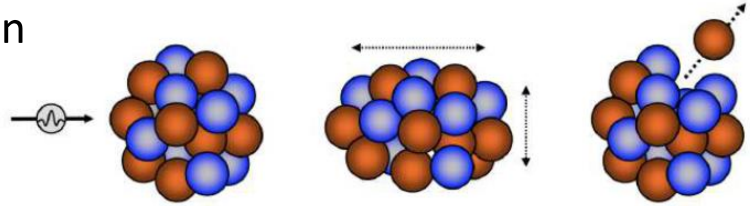
"Interaction of relativistically intense laser pulses with long-scale NCD plasmas for optimisation of laser based sources of MeV electrons and gamma-rays"

O. N. Rosmej et al, Plasma Phys. Control. Fusion **62** (2020) 115024
https://doi.org/10.1088/1361-6587/abb24e
"High-current laser-driven beams of relativistic electrons for high energy density research"

M. M. Guenther et al,
"New insights in laser-generated ultra-intense gamma-ray and neutron sources for nuclear applications and science"

submitted to **Nature Communications**

Application of nuclear diagnostics for characterization of MeV Gamma and neutron beams

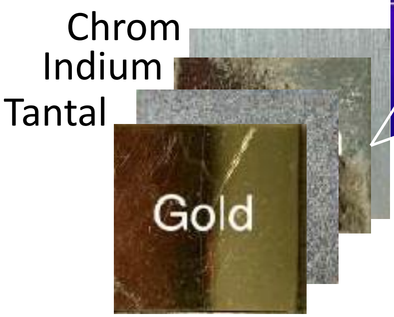


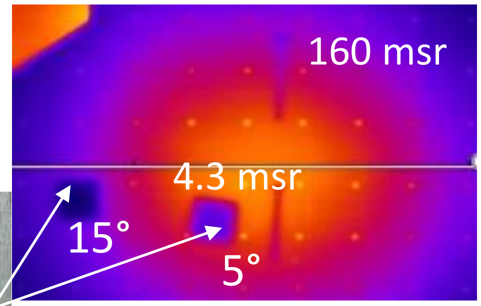
Photodisintegration reactions

Photonuclear Reaction	Treshhold Energy [MeV]	Giant Dipole Resonance (GDR) [MeV]	Half life
${}^{181}_{73}Ta(\gamma,n)^{180}_{73}Ta$	7,57	12	8,152 h
${}^{197}_{79}Au(\gamma,n)^{196}_{79}Au$	8,03	14	6,183 d
${}^{115}_{49}In(\gamma,n)^{114m}_{49}Au$	9,23	15,8	49,5 d
${}^{113}_{49}In(\gamma,n)^{112m}_{49}Au$	9,6	15,7	20,56 m
${}^{52}_{24}Cr(\gamma,n)^{51}_{24}Cr$	12,04	19	27,7025 d
${}^{50}_{24}Cr(\gamma,n)^{49}_{24}Cr$	13	20	42,3 min
${}^{115}_{49}In(\gamma,2n)^{113m}_{24}In$	16,7	19,4	1,6582 h
${}^{181}_{73}Ta(\gamma,3n)^{178m}_{73}Ta$	22,1	28	2,36 h
${}^{197}_{79}Au(\gamma,3n)^{194}_{79}Au$	23,03	32	38,02 h

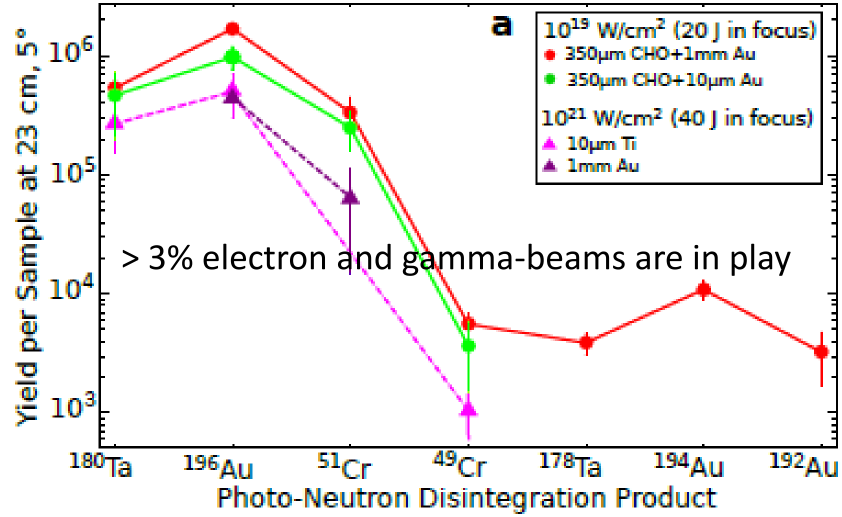
Günther M M *et al* 2011 *Phys. Plasmas* **18** 083102

HIGH YIELD OF PHOTO-NUCLEAR REACTIONS

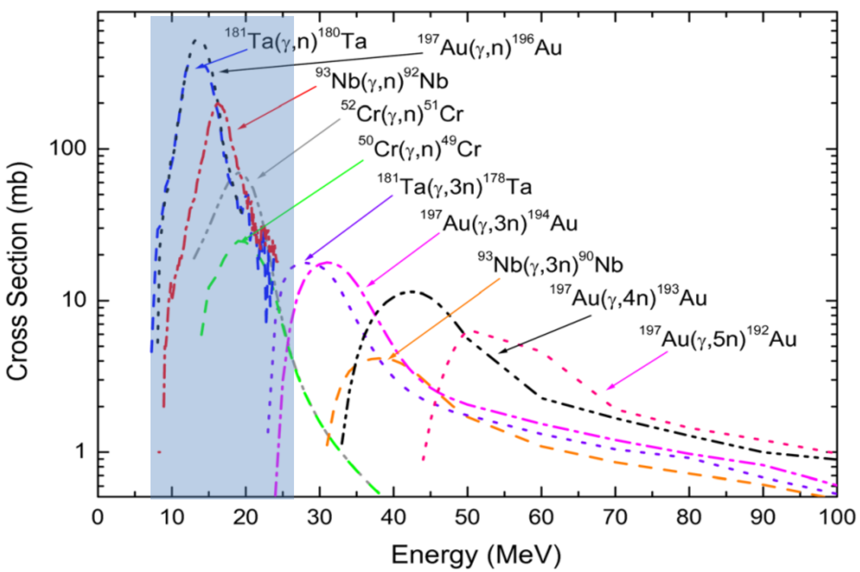


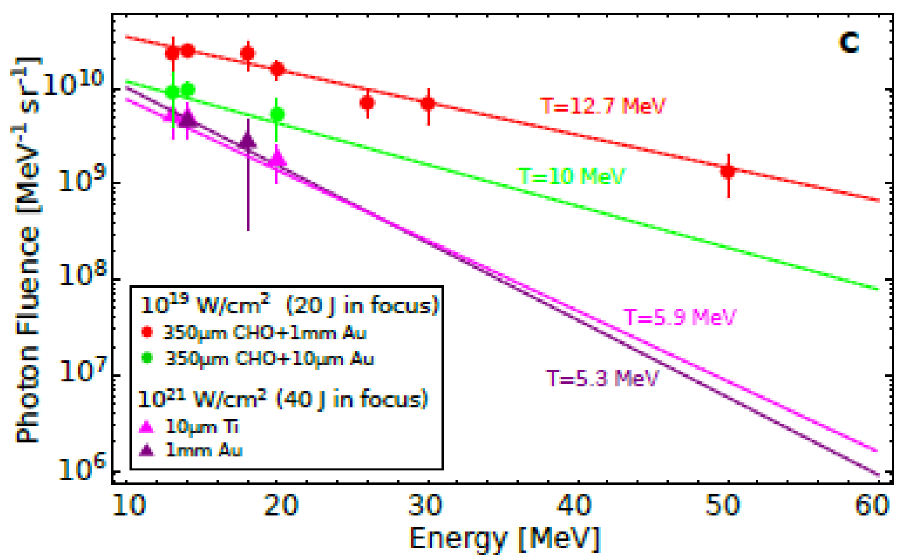


10-times higher reaction yield at 5° compared to 15°

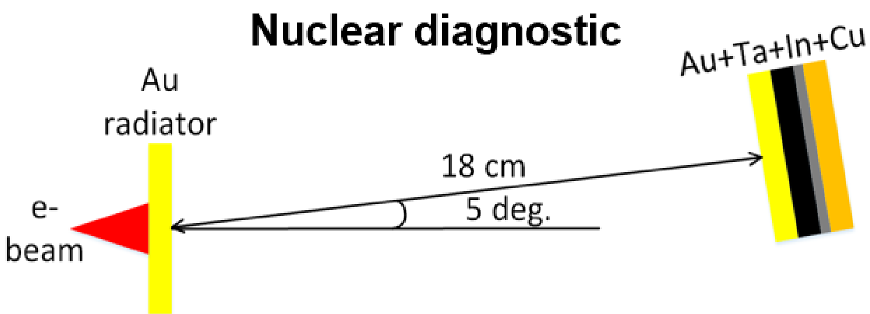


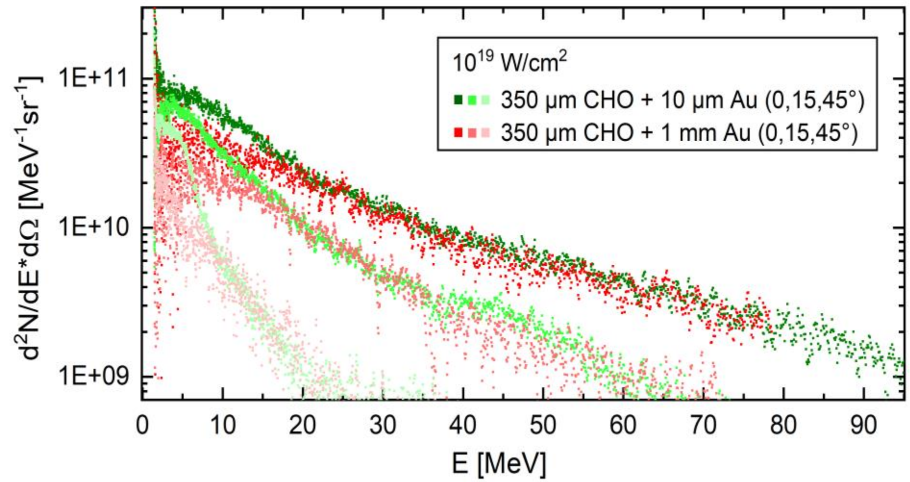
10^{12} ph/sr with E> 10 MeV and effective T=10-13 MeV

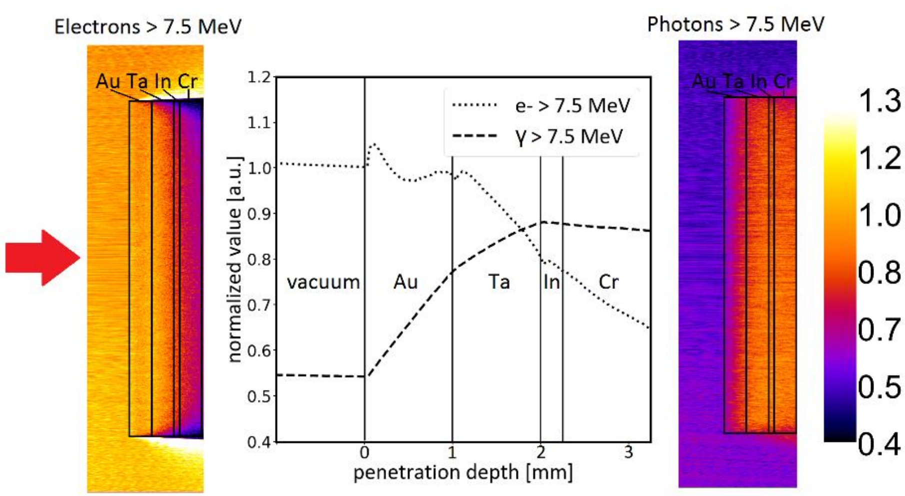


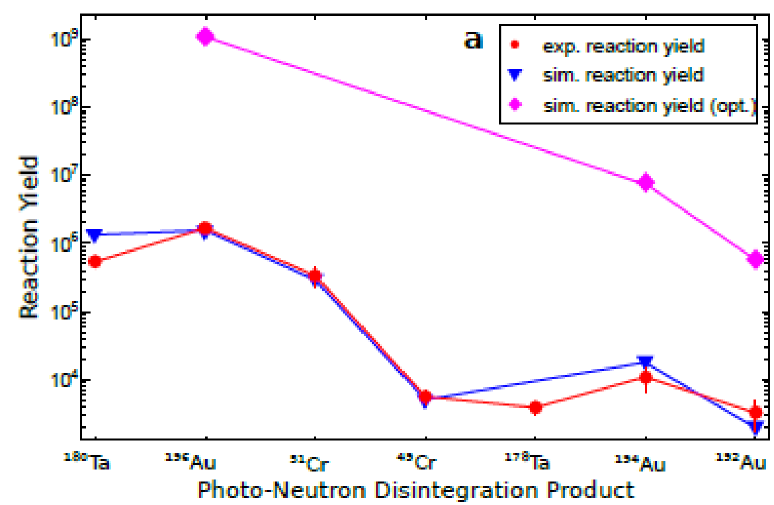


GEANT 4 SIMIULATIONS OF REACTION YIELDS









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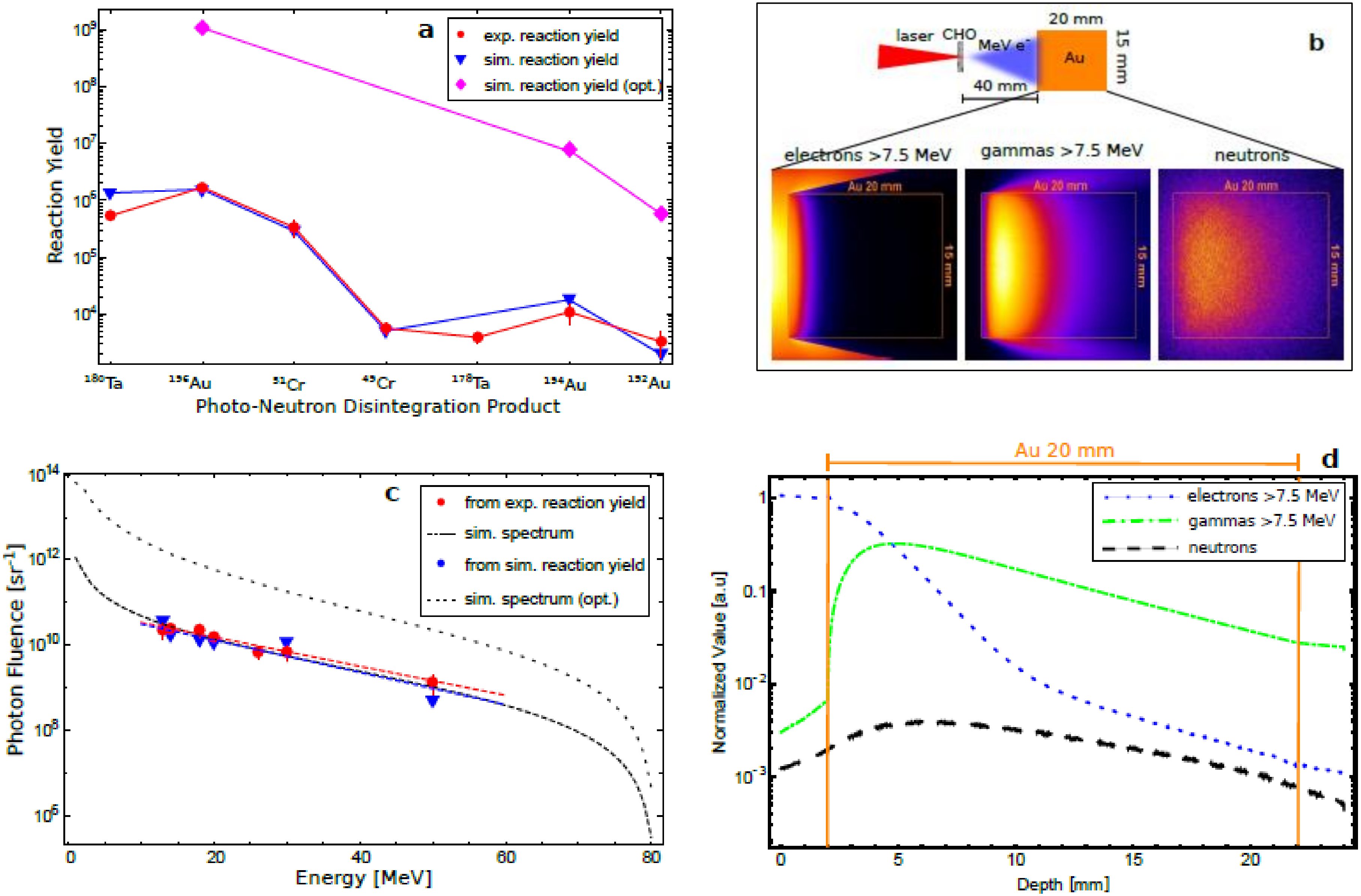
GEANT4 OPTIMIZATION OF GAMMA AND NEUTRONS PRODUCTION



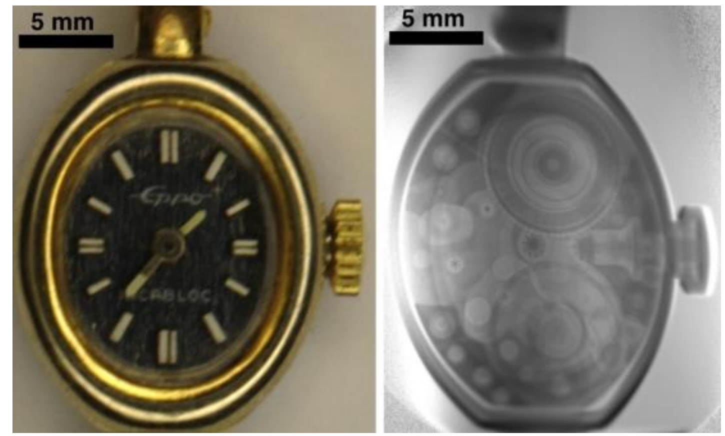
RADIOGRAPHIC APPLICATIONS

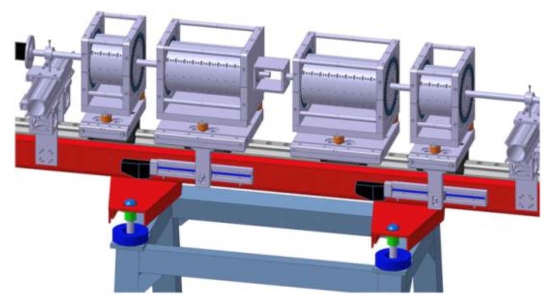
Laser driven X-ray radiography /PHELIX:

Laserpulse: E=30J, t=700 fs, FWHM=15 μm

Target: 10 μm Au-foil, P176 Sept. 2019

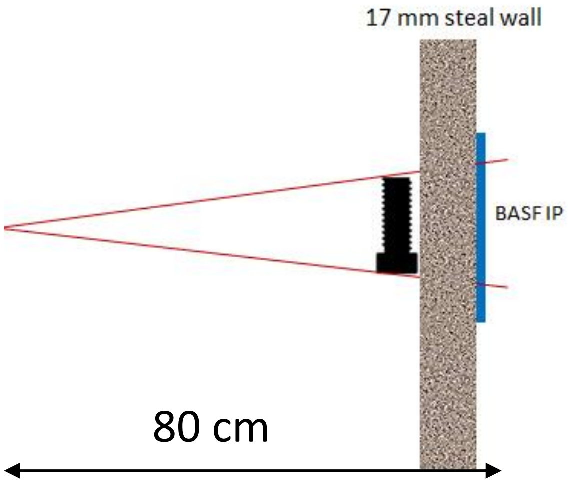
Proton radiography / SIS18

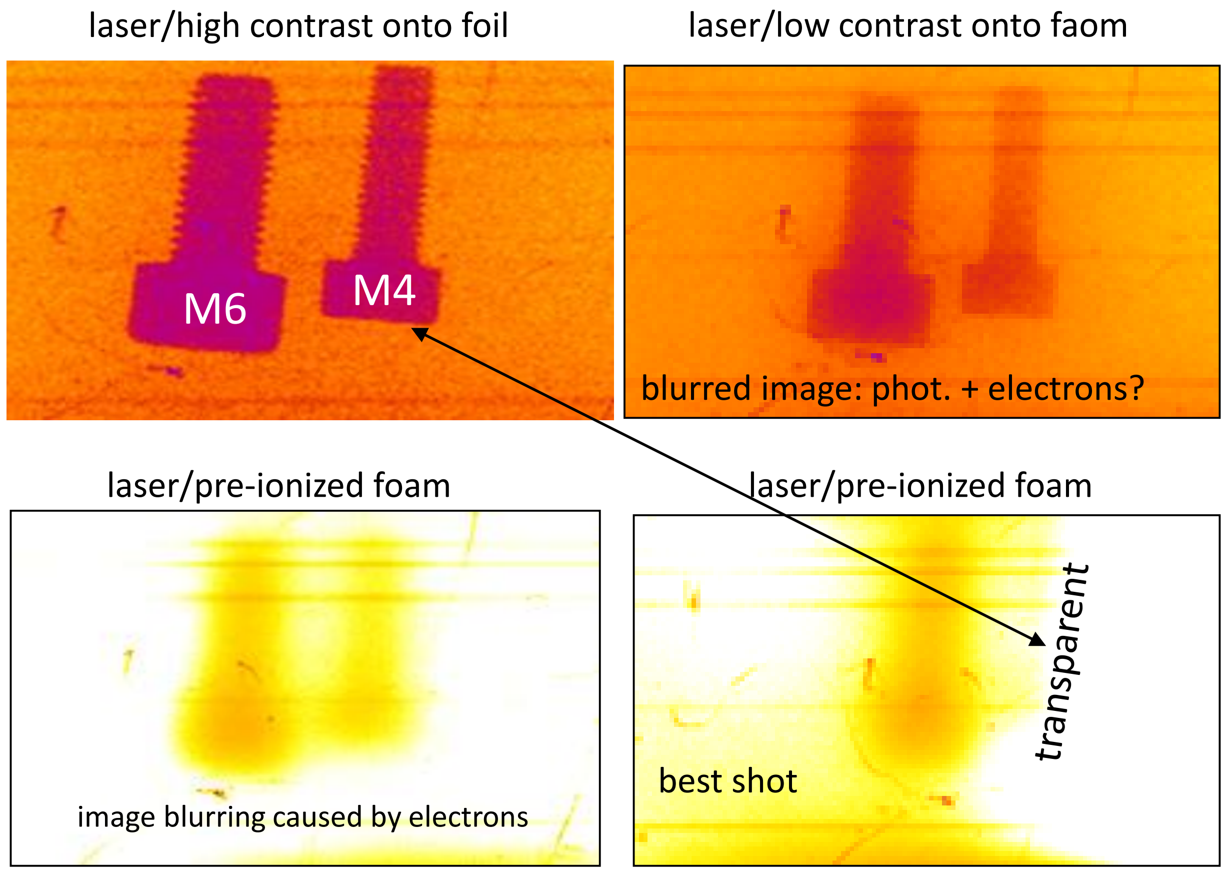




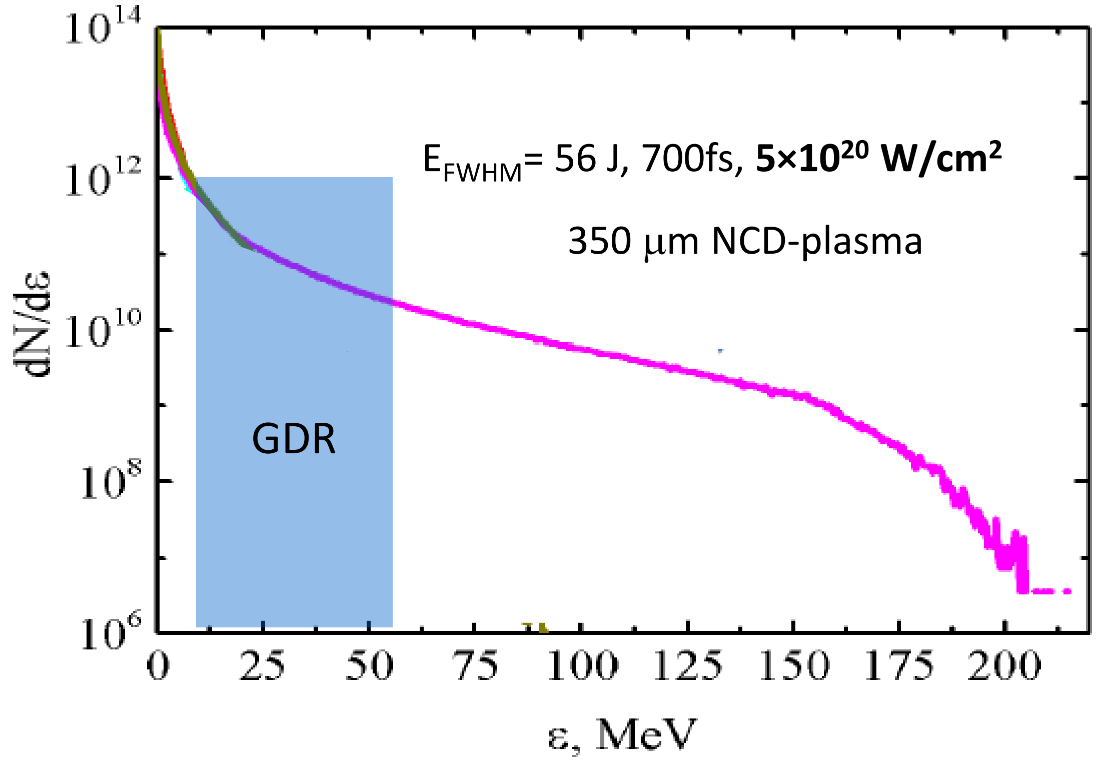
proton microscope for 4 GeV p

PHELIX Beam-time 2017





LASER ENERGY OR INTENSITY?



3D PIC,
L. Pugachev,
N. Andreev, JIHT

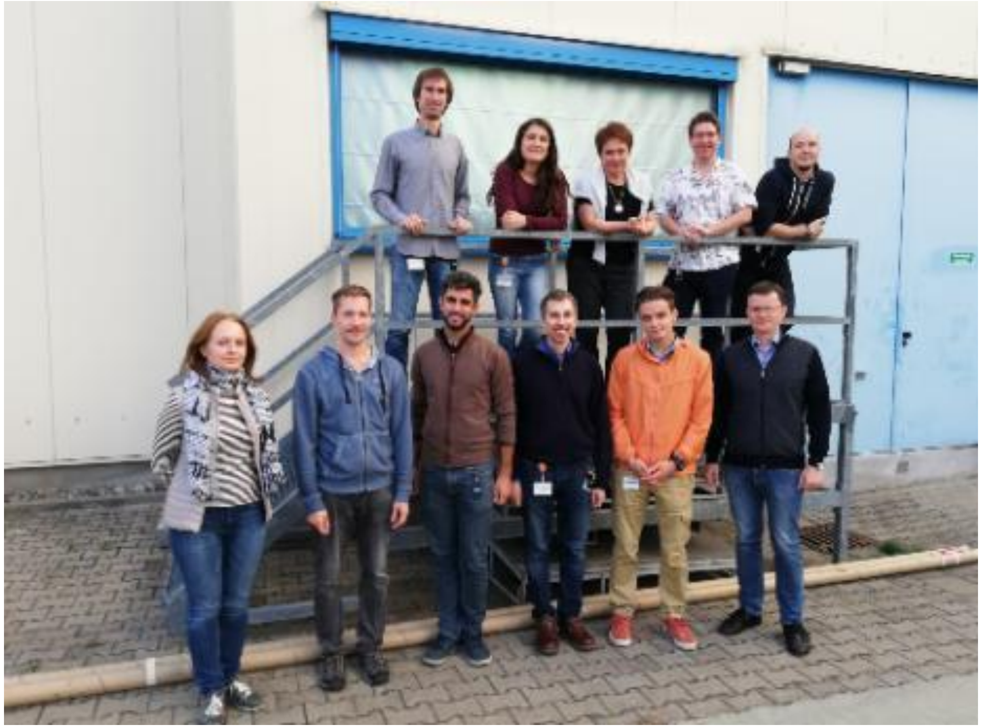
GEANT- 4 simulations,
A. Skobliakov, ITEP

γ-n reaction yield caused by electrons propagating in $1x1x1cm^3$ Au

Isotope (max GDR)	Yield, $5x10^{20}$ W/cm^2, 60 J	Yield, $2x10^{19}$ W/cm^2, 20J
196Au (14 MeV)	3,00E+09	1,10E+09
194Au (32 MeV)	4.62E+07	7,62E+06
192Au (50 MeV)	4.44E+06	5,80E+05

25-fold increase of the laser intensity does not lead to much higher reaction yields in the GDR region

INTERNATIONAL COLLABORATION



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A. Skobliakov (ITEP)

Targets: N. G. Borisenko (LPI)

Experiment: M. Guenther, M. Gyrdymov, P. Tavana, S. Zähter, N. Zahn, (GU-Frankfurt),
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F. Consoli, M. Salvadori, M. Sciscio (ENEA, Italy),