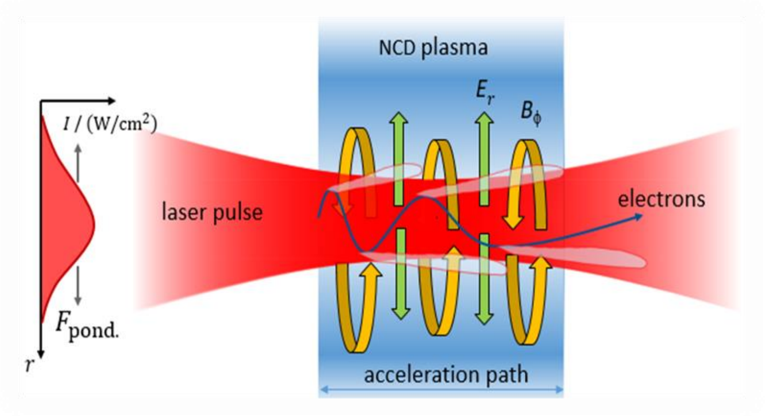
«Ускорение частиц в плазме и лазерно-плазменная физика экстремального света»

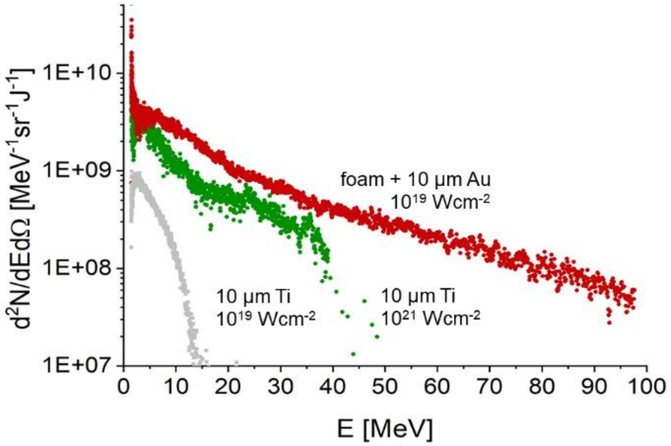
Онлайн-семинар, 08.04.2021

Strong improvement of diagnostic potential of high energy PW-class laser facilitates by application of low density polymer foams



Olga Rosmej

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



In collaboration with: N. E. Andreev, V. Popov (JIHT), X. Shen, A. Pukhov (HHU, Düsseldorf), N. G. Borisenko (LPI), M. M. Günther, S. Zähter, A. Sokolov (GSI), M. Gyrdymov, P. Tavana N. Zahn (GU) , A. Kantzyrev, A. Skobliakov, V. Panyshkin, A. Bogdanov (ITEP, Moscow), F. Consoli, M. Salvadori, M. Scisciò (ENEA, Frascati)

PW-class lasers: MJ in nanosecond pulses: 10^6 J / 10^{-9} s = 10^{15} W

NIF is the world's largest and most energetic laser: 2.0 MJ, 192 beams

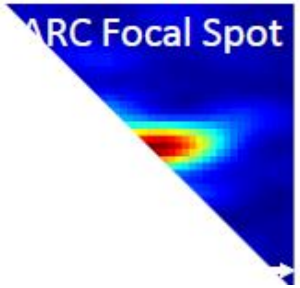
Laser Mégajoule plans to deliver about 1.8 MJ of laser energy, 240 beams

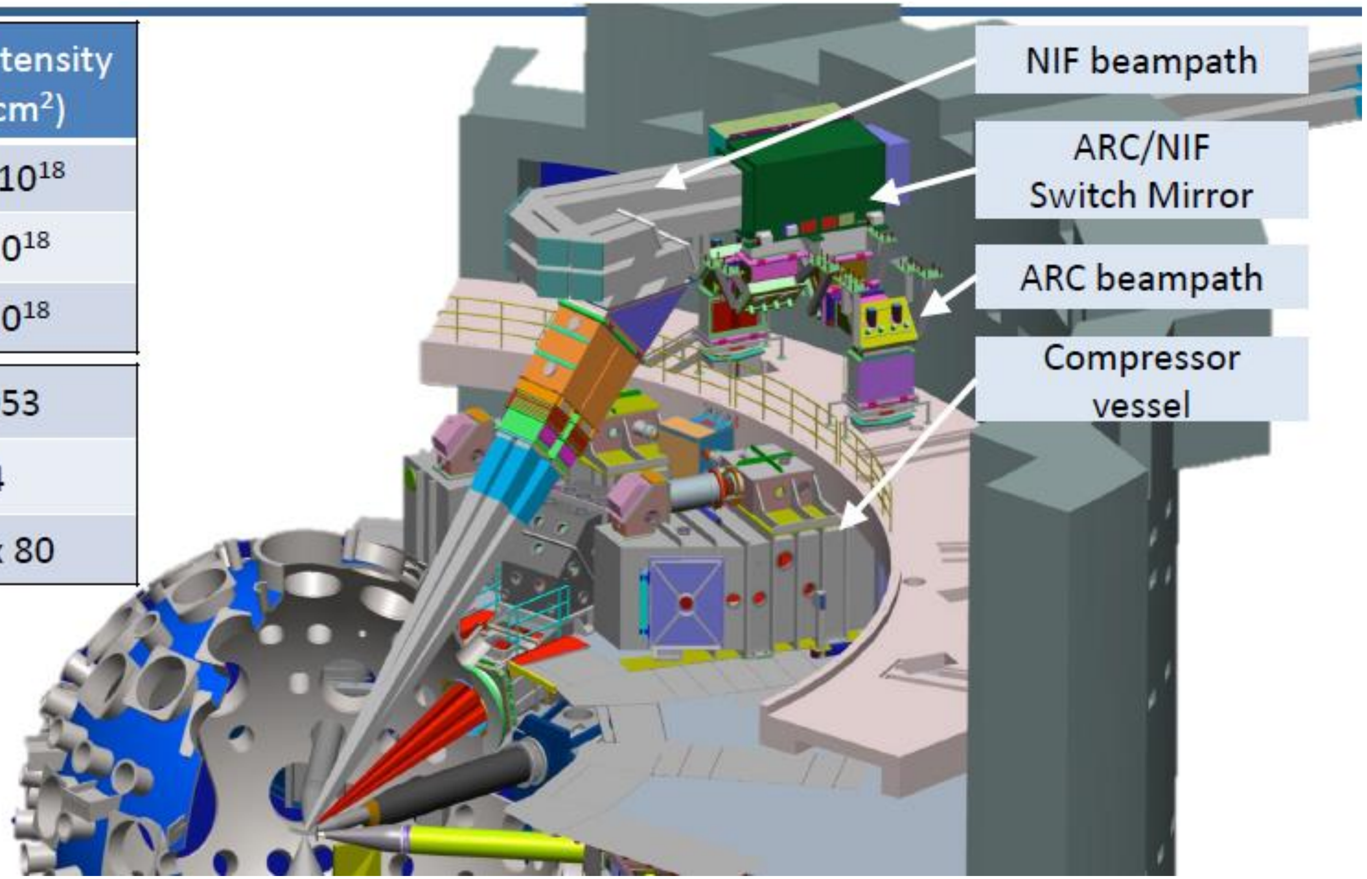
NIF’s short pulse laser, the advanced radiographic capability (ARC)

Largest amount of available short pulse energy in the world (up to 4 kJ)
but is delivered at quasi-relativistic intensities ($I_L < =10^{18}$ W/cm^2)

Energy/ beamlet (kJ)	Pulse Duration (ps)	Peak Intensity (W/cm^2)
1.0	30	0.3×10^{18}
0.6	10	1×10^{18}
0.25	1	2×10^{18}

Wavelength (um)	1.053
Number of beams	4
Spot Size Radius (um^2)	40 x 80





ARC (NIF): compound parabolic concentrator

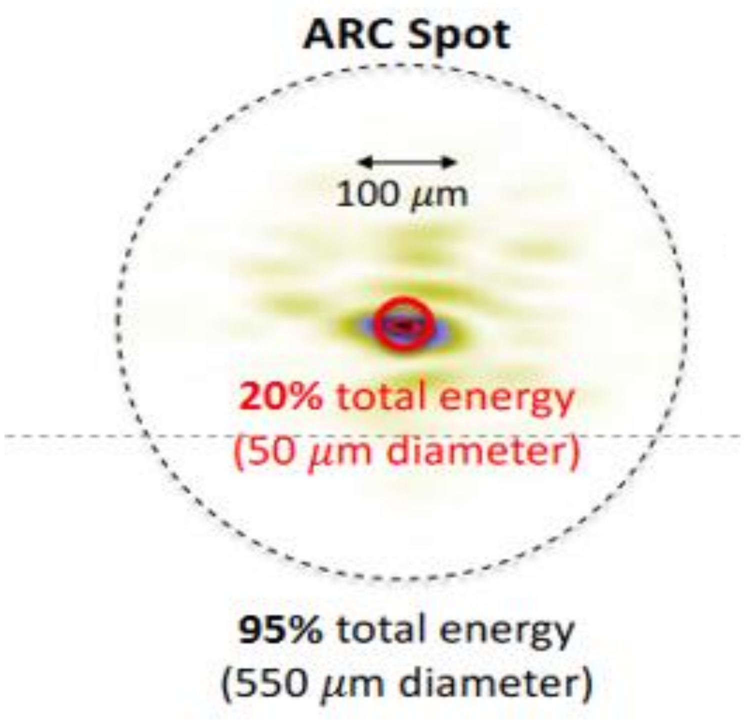
2020 NIF User Group Meeting

Rick Heredia

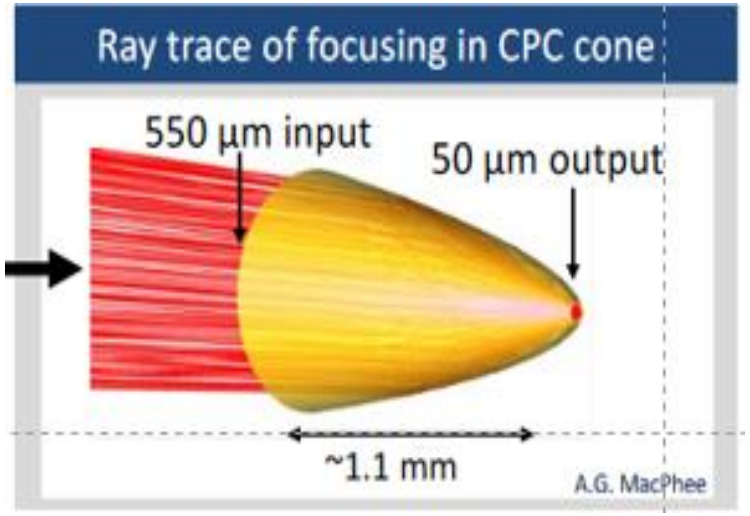
MECHANICAL & MOTION SYSTEMS

Special Targets Boost Intensity of Lasers

ARC- Advanced Radiographic Capabilities
but is delivered at quasi-relativistic intensities ($I_L <= 10^{18}$ W/cm^2)



CPC: large fraction of energy contained in the wings of the beam (80%) could be repointed towards the central beam spot

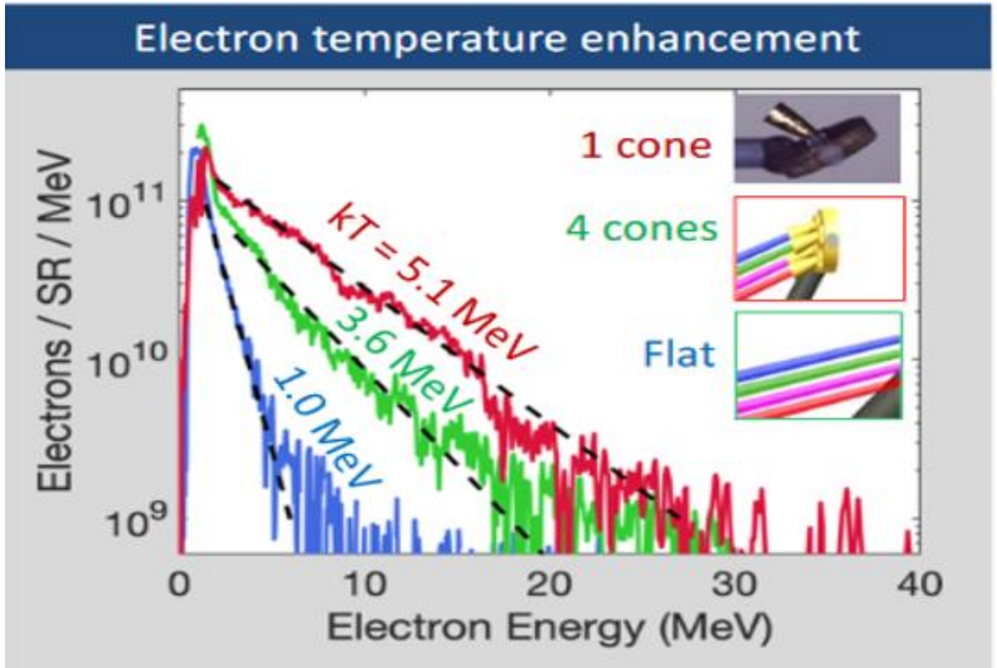


G. MacPhee *et al*, Optica **7**, 2 (2020)

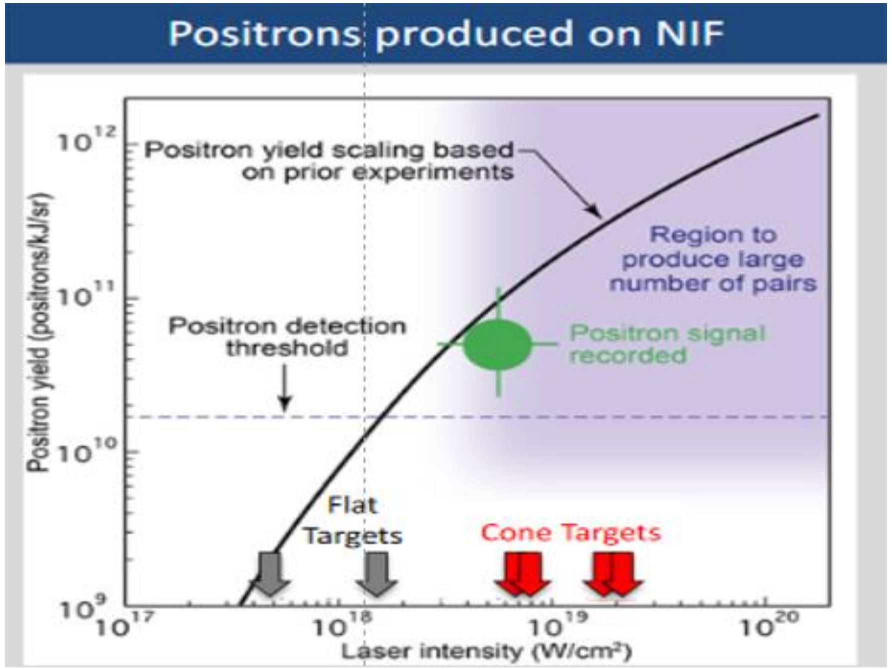
10x increase in laser-target coupling at near-relativistic intensities using **compound parabolic concentrators**

ARC (NIF) compound parabolic concentrators

(3-5)x higher effective electron temperature



10x more MeV positrons



0.3% conversion efficiency of the laser energy into gamma-rays

The increased performance is primarily due to the presence of **turbulent laser fields** from light reflecting from the cone walls as well as **increased NCD plasma volume** confined in the cone-> conditions for generation of **super-ponderomotive electrons**.

G. J. Williams *et al*,
arXiv:2012.11563v1 21 Dec 2020

Development of a Self-Modulated Laser Wakefield Accelerator Platform with a 10 keV to 1 MeV Hyper Spectral Photon Source for HEDS **PI:** C. Joshi, NIF

Titan, LLNL

OMEGA-EP, LLE

NIF – ARC, LLNL

LMJ – PETAL, CEA

2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

Titan
SMLWFA electrons
Betatron radiation

Titan
Compton scattering/Bremsstahlung

Titan
Radiography

Titan
Shock Compression

OMEGA-EP
SMLWFA electrons

OMEGA-EP
X-ray sources

OMEGA-EP
Radiography + shocks

NIF - ARC
SMLWFA electrons

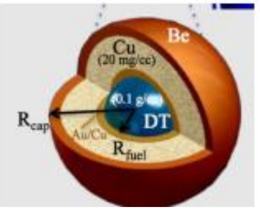
NIF - ARC
X-ray sources

LMJ – PETAL
SMLWFA electrons

MeV radiography:

- **Double shell capsule at NIF, 1800 g/cm^3, 10 µm radius**

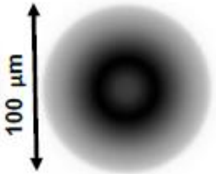
NIF capsule



0.2 MeV radiography

R. Tipton, LLNL

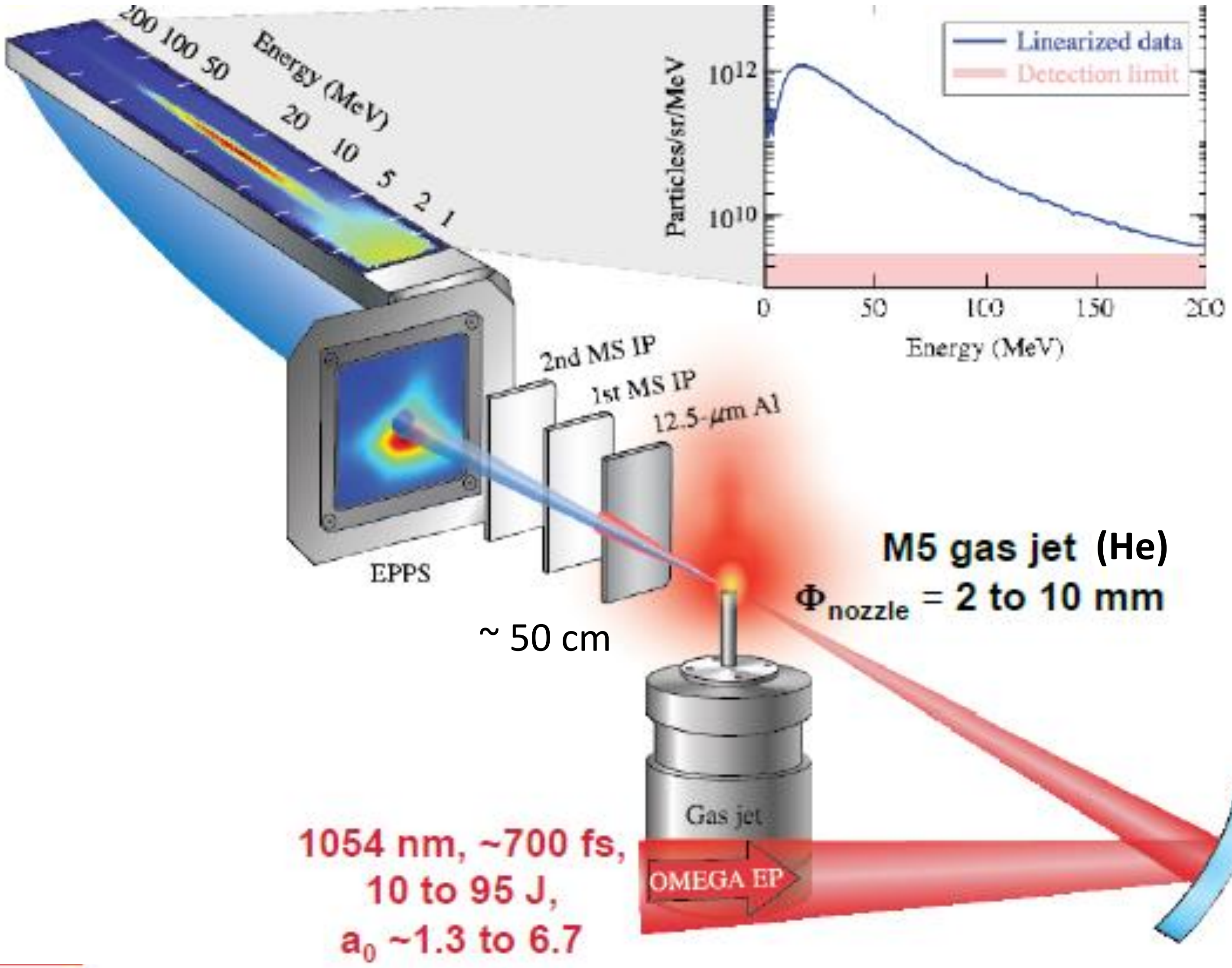
1 MeV radiography



New Developments in Laser Wakefield Acceleration at the Laboratory for Laser Energetics

OMEGA EP

SM-LWFA-based LPA



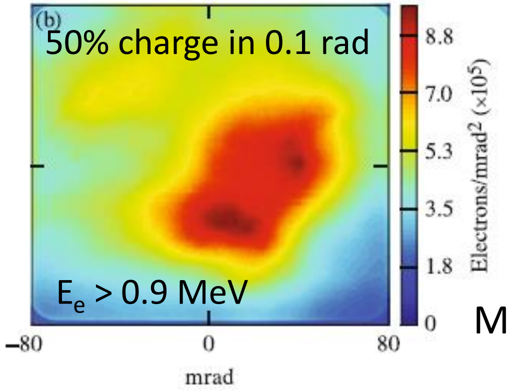
M5 gas jet (He)

Φ_{nozzle} = 2 to 10 mm

~ 50 cm

1054 nm, ~700 fs,
10 to 95 J,
a_0 ~1.3 to 6.7

f/2 OAP
apodized to
f/5 to f/10



MS IP after 37 μm Al

Results for a_o= 6.6

n_e=8x10^{18} cm^{-3}, Φ_{nozzle}= 6 mm

P/P_c= 3-4

Charge 700±420 nC (1-200 MeV)
conversion efficiency (18 MeV) ~ 11%

J. Shaw *et al*,
Sci. Reports 2021

Problems of reproducibility

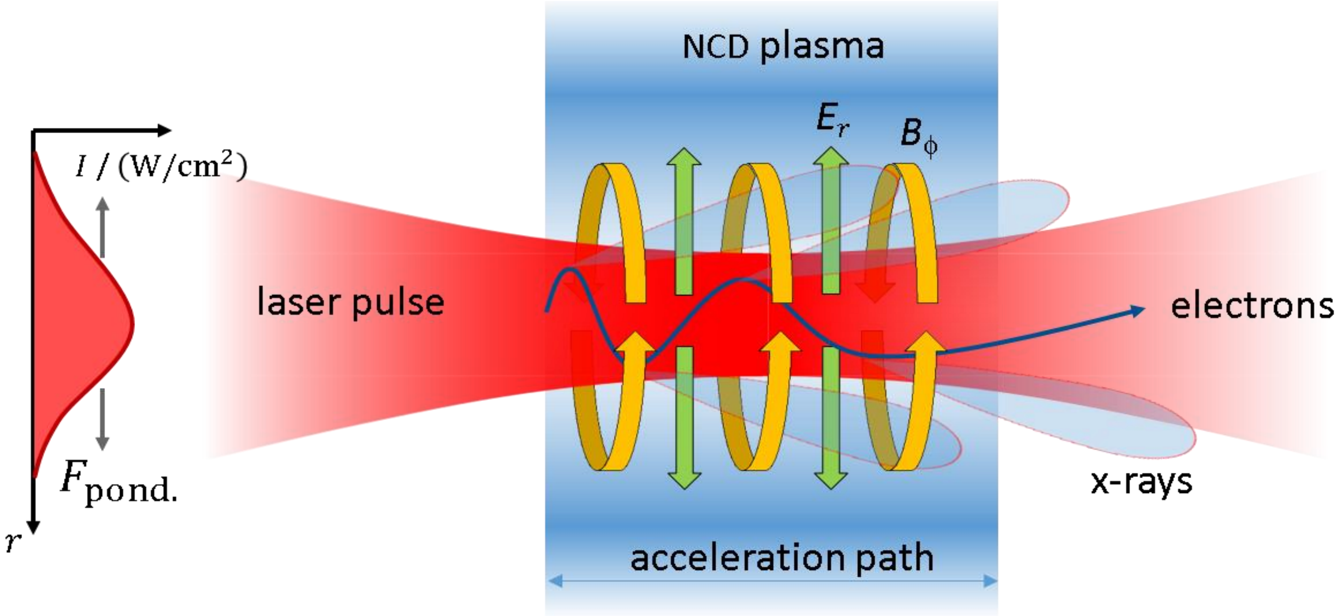
- The nature of SMLWFA means that there is variation in the reproducibility of the electron beam quality.
- The divergence of the electron beams will be affected by the plasma density profile and uniformity, the laser focal spot quality and size, the phase front of the laser, and the interaction between the laser and the plasma, including the coupling of the laser into the plasma and the subsequent laser evolution (modulation and self-focusing).
- **For all but three of the 23 high-plasma-density** (ne > 1.9 × 1019 cm−3) shots in this experiment, the **produced electrons did not form a defined beam**, and instead, the transverse charge profile was distributed across the entire solid angle collected by the EPPS.
- **For those three shots, all were produced in 10-mm nozzles**, which suggests that having longer plasmas, and therefore longer distances for laser evolution, may help maintain the transverse beam profile.
- For the remainder of the **49 shots with charge ≥ 50 nC**, the shots were either single-peaked with higher

divergence or **had multiple peaks**.

Direct Laser Acceleration in NCD Plasmas

to boost parameters of laser-driven sources of MeV particles and radiation

> 100x higher plasma density than for LWFA and SM-LWFA ->
-> higher charge of super-ponderomotive electrons but with lower energies

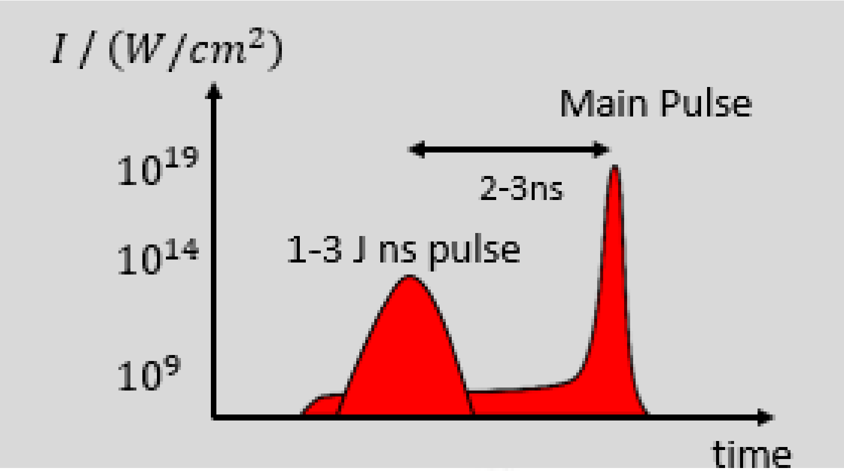


$$\omega_\beta = \left(1 - \frac{v_x}{v_{ph}}\right)\omega_L$$

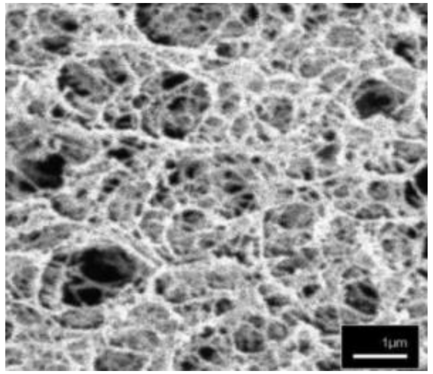
- self-focusing: $P_L > P_c = 17\ \mathrm{GW} \times n_c / n_e$
- ponderomotive force expels background plasma electrons from laser channel
- generation of quasi-static radial E-field that has a pinching polarity for electrons.
- self-generated quasi-static B azimuthal that traps electrons in the plasma channel.

Production of NCD plasma by supersonic ionization of polymer foams

can be triggered by well-defined ns-pulse (GSI) or by ns ASE (Omega EP)

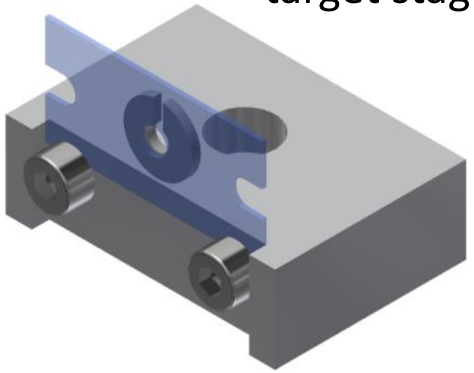


CHO 2 mg/cc



3D aerogel structure

target stage



N. Borisenko, LPI

500 µm thick NCD plasma "target" (Ne $\lesssim 0.7 \times 10^{21}$ cm^{-3}) is created by a **10^{14} W/cm^{2} ns prepulse**. **Supersonic ionization** (ionization is faster than HD-expansion) V= **500µm/2ns**

300 - 500µm foam thickness provides increased interaction length, restrictions given by the amount of laser energy

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

Experiment P176, PHELIX 2019

Set-up at the PHELIX laser-bay (P176, 2019)

PHELIX system:

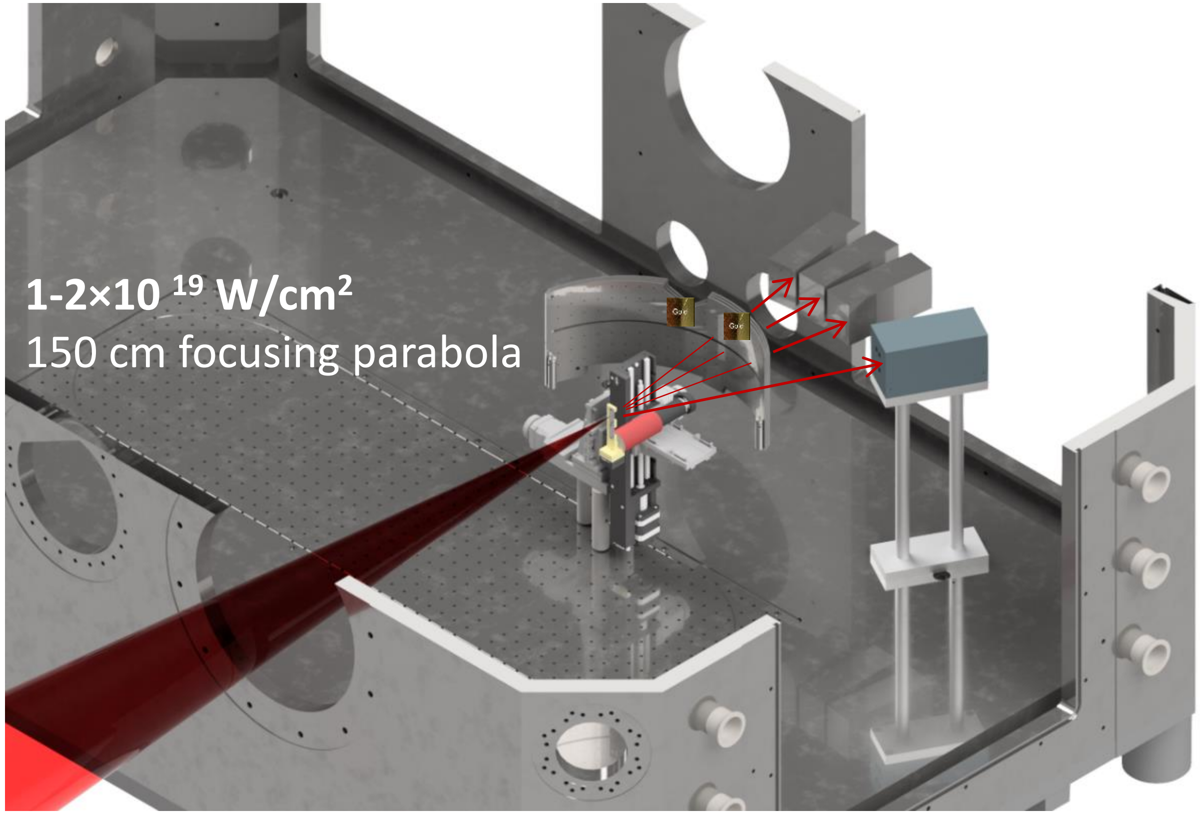
Nd:glass λ=1.053μm, s-polarized
main pulse:

- τ=700 fs
- 10^{19} W/cm^2 (20J , 15 μm)
- 10^{21} W/cm^2 (40J , 3 μm)
- ns contrast better than 10^{-11}

ns pulse: 1-3 J, 1.5 ns , Δt=2-3 ns

Targets:

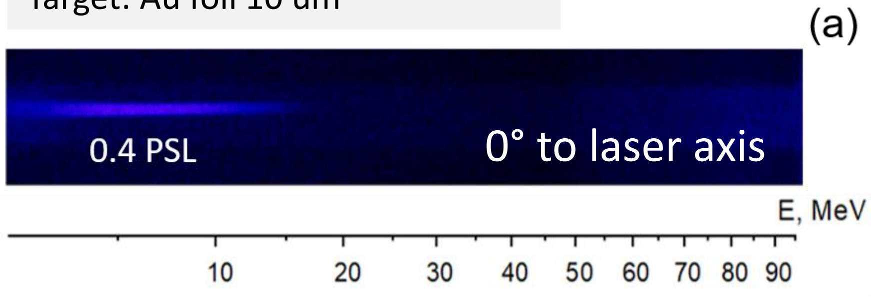
- 10 μm thin Ti, Au-foils
- mm-thick Au convertor
- low density polymer foams
  ρ=2 mg/cc (1.7 × 10^{20} at/cm^3)
- combination foam+foil

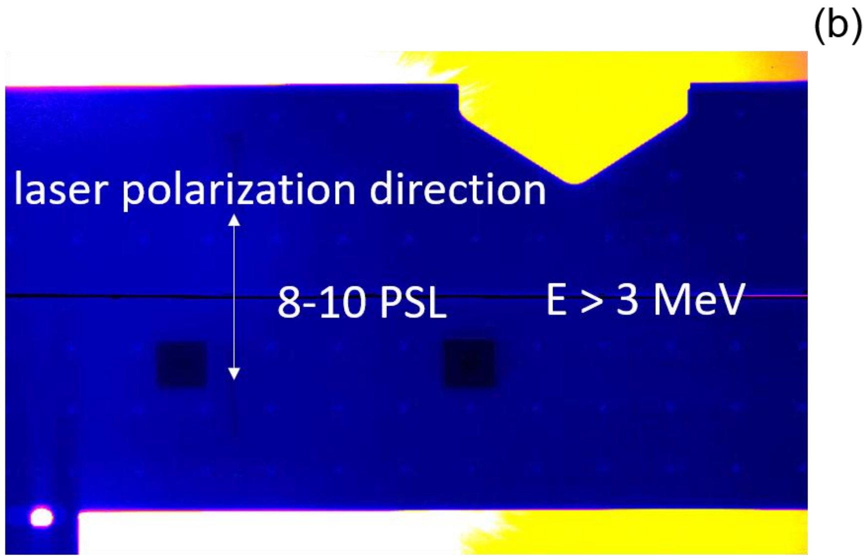


1-2×10 ^{19} W/cm^2
150 cm focusing parabola

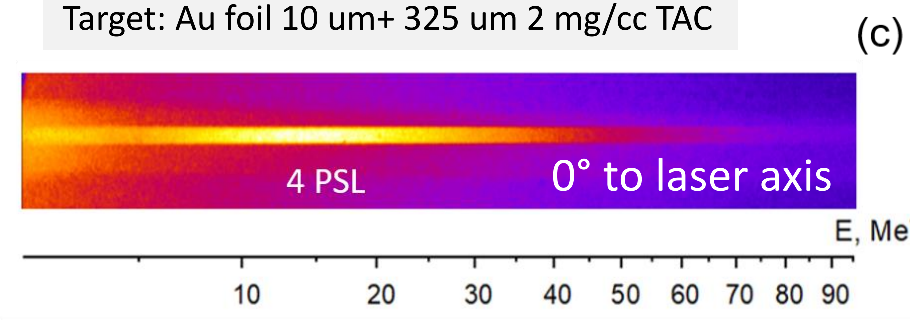
DLA in pre-ionized foam: raw electron spectra from PHELIX 20J, 10^{19}W/cm^2

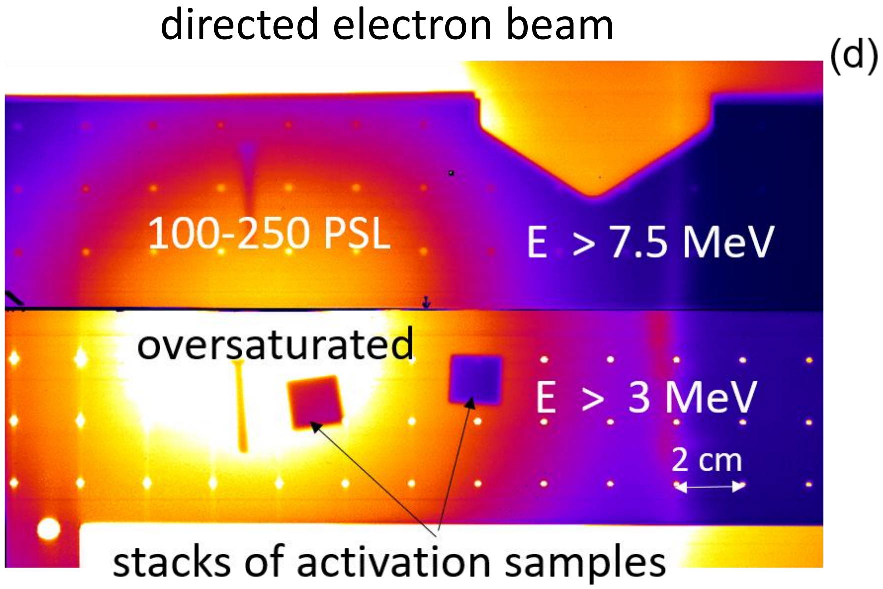
Shot 40: 700 fs, 10^{19} W/cm^2
Target: Au foil 10 um





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

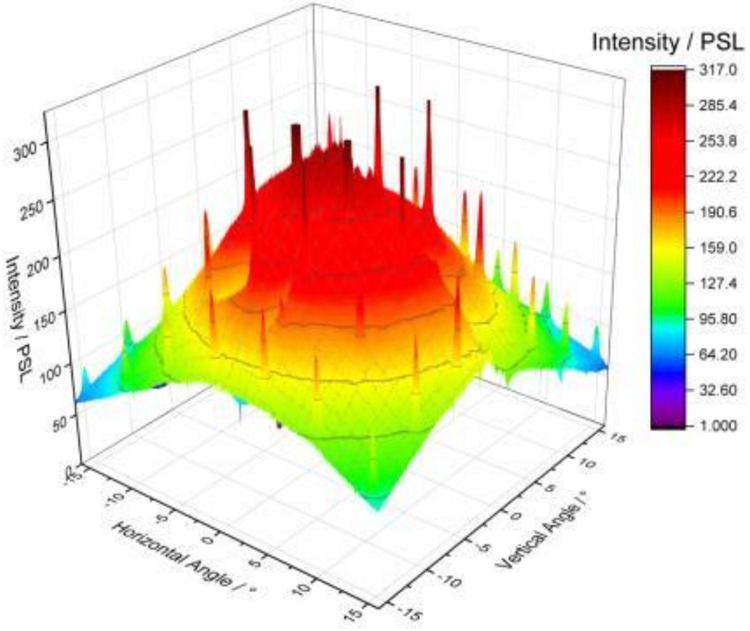


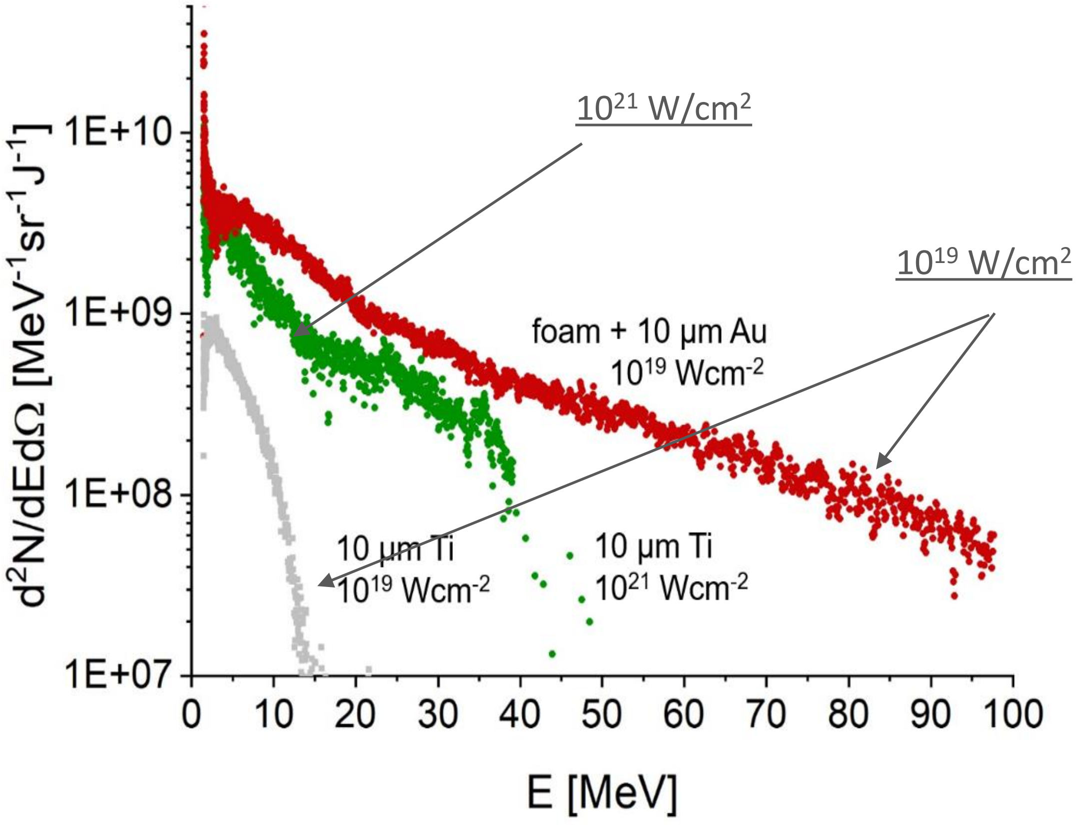


High-Current, Well-directed Beams of Super-Ponderomotive Electrons (PHELIX):

$T_{eff} \geq 11$ MeV, $E_{max} = 100$ MeV, $\theta_{½} = 13°$, 1 μC with E > 2 MeV

E > 3 MeV, $\theta_{FWHM} = 160$ msr



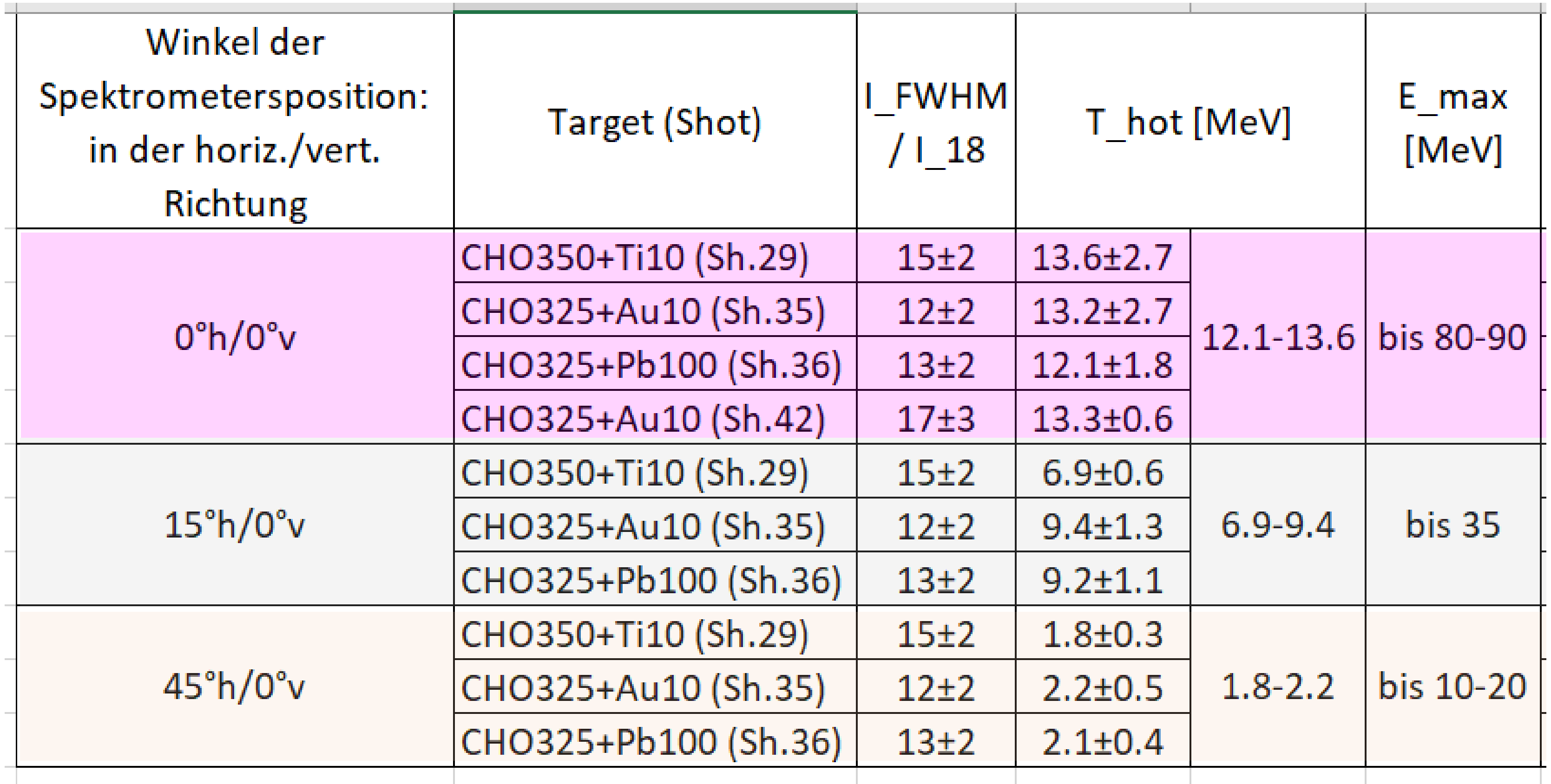


O. N. Rosmej et al, New J. Phys. **21**(2019) 043044

O. N. Rosmej et al Plasma Phys. Control. Fusion **62** (2020) 115024

Results M. Gyrdymov, GU-Frankfurt

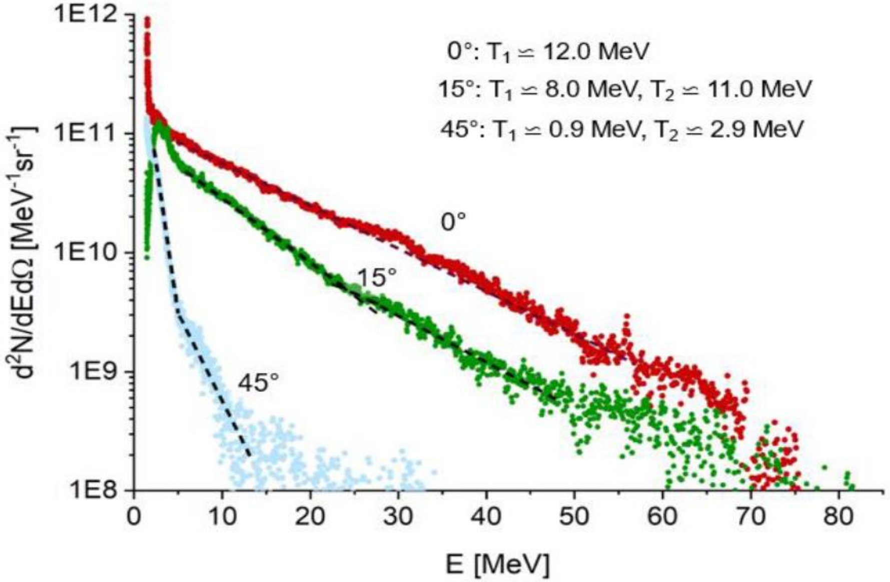
High Stability of DLA-Process



Winkel der Spektrometersposition: in der horiz./vert. Richtung	Target (Shot)	I_FWHM / I_18	T_hot [MeV]		E_max [MeV]
0°h/0°v	CHO350+Ti10 (Sh.29)	15±2	13.6±2.7	12.1-13.6	bis 80-90
	CHO325+Au10 (Sh.35)	12±2	13.2±2.7		
	CHO325+Pb100 (Sh.36)	13±2	12.1±1.8		
	CHO325+Au10 (Sh.42)	17±3	13.3±0.6		
15°h/0°v	CHO350+Ti10 (Sh.29)	15±2	6.9±0.6	6.9-9.4	bis 35
	CHO325+Au10 (Sh.35)	12±2	9.4±1.3		
	CHO325+Pb100 (Sh.36)	13±2	9.2±1.1		
45°h/0°v	CHO350+Ti10 (Sh.29)	15±2	1.8±0.3	1.8-2.2	bis 10-20
	CHO325+Au10 (Sh.35)	12±2	2.2±0.5		
	CHO325+Pb100 (Sh.36)	13±2	2.1±0.4		

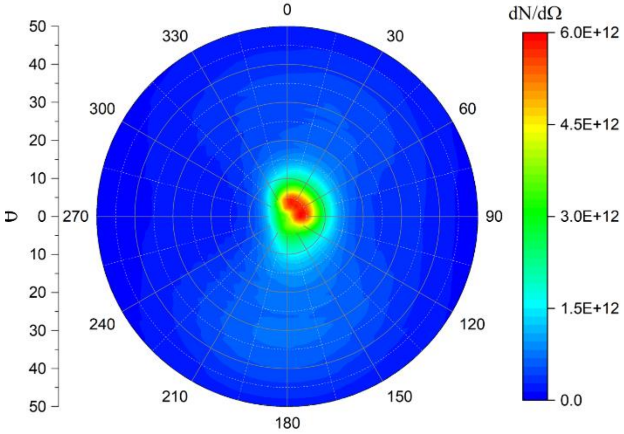
3D PIC Simulations for PHELIX and Comparison with Experiment

Measured angular dependent energy distributions



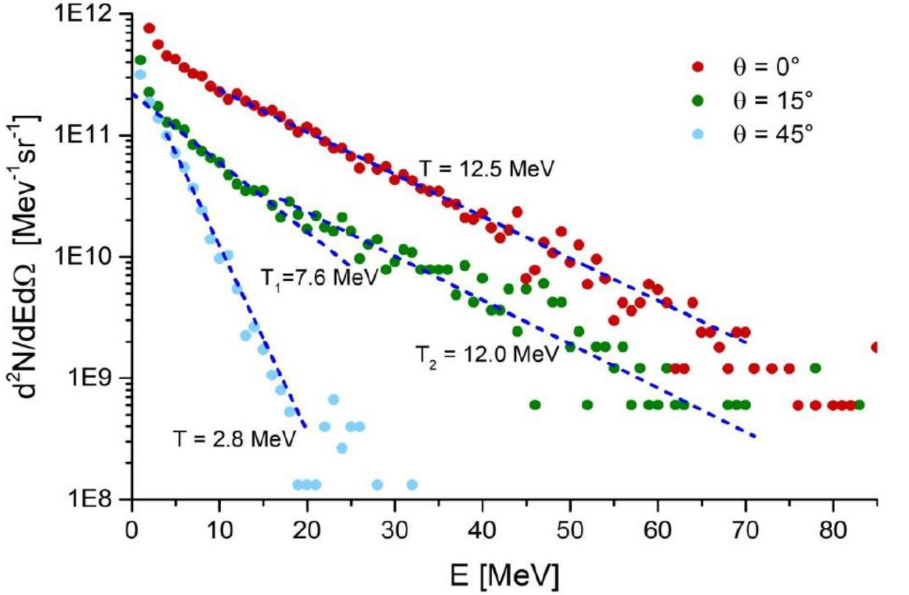
measured for a shot onto the pre-ionized foam layer at 2×10^19 Wcm^-2 laser intensity

Angular distribution of electrons with E > 7 MeV



½ θ at FWHM ~ 10°
(experiment ~ 13°)

Modeled angular dependent energy distributions



leave the simulation box at t = 2.5 ps

Summary: Super-Pondretomotive Electrons

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

- **Very robust acceleration mechanism**
- Effective temperature above 10 MeV (x10 of ponderomotive potential) (10^{21} W/cm^2 -> foil: 6 -7 MeV)
- Max energy up to 100 MeV (10^{21} W/cm^2-> foil: ~ 40 MeV)
- Electrons with E > 3 MeV propagate in ½ θ at FWHM ≤ 13°
- High charge: up to 1 μC at E > 2 MeV; > 50 nC (6%) E > 7.5 MeV

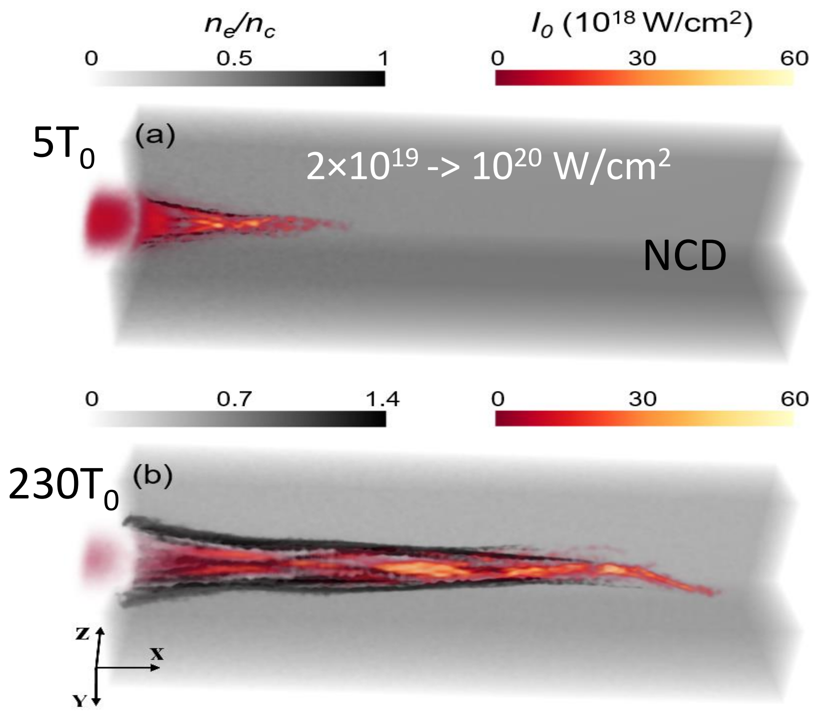
Secondary sources of particles and radiation:

- Bright betatron source in keV photon energy range
- Bright hard x-ray and positron sources

- Gamma and neutron sources
- High yield (p,xn), (γ,xn) nuclear reactions in Giant Dipole Resonance (GDR) region

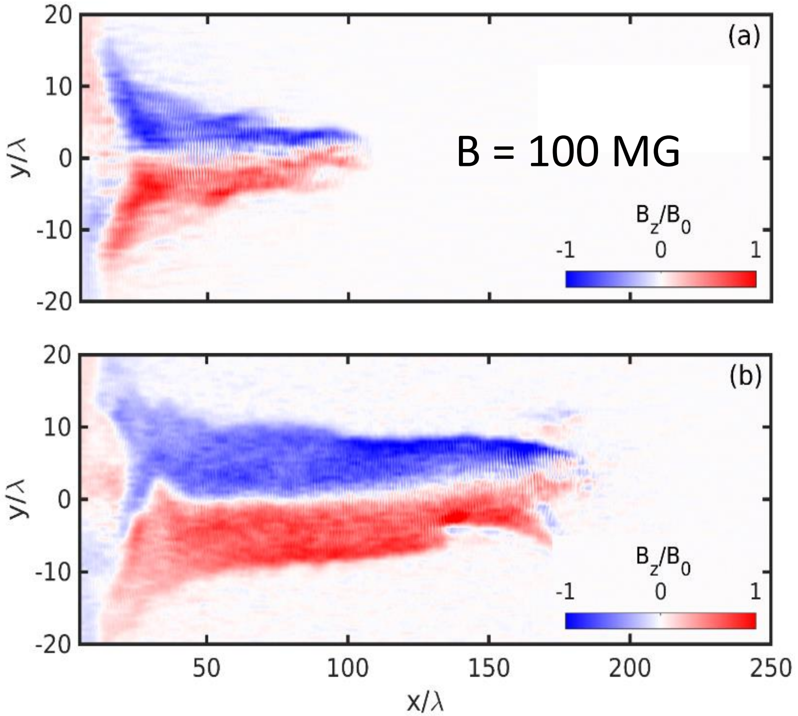
Betatron Radiation, 3D PIC (PHELIX: a_0=4.28, 700fs, E_{FWHM}= 20J)

laser intensity (red-yellow) and electron density (white-black)

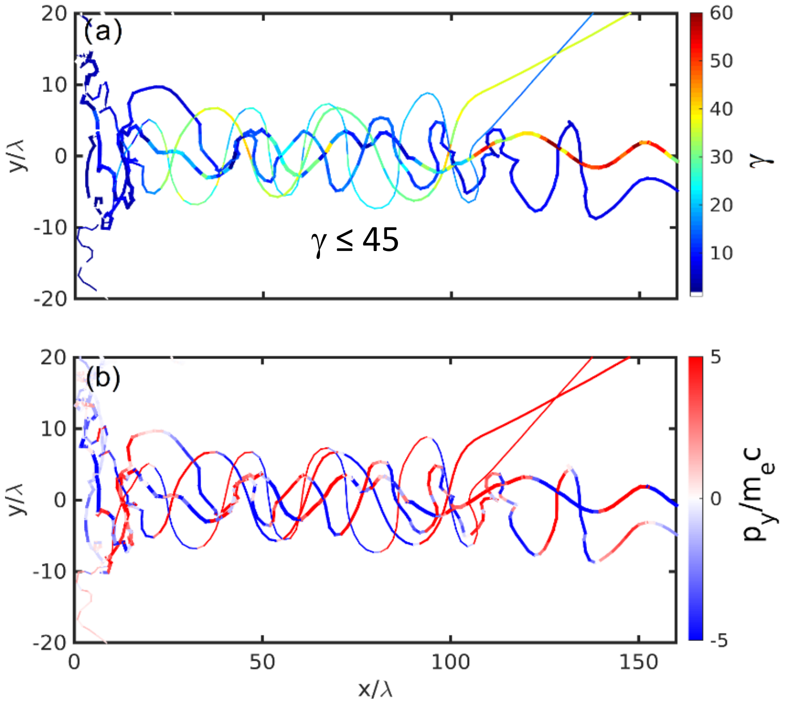


self-focusing up to 10^{20} W/cm²

azimuthal B-field



trajectories of selected electrons



X. Shen, A. Pukhov, HHU Düsseldorf

Betatron Radiation (PHELIX): Brilliance of 3×10^{20} photons/s/mm^2/$mrad^2$/0.1%BW.

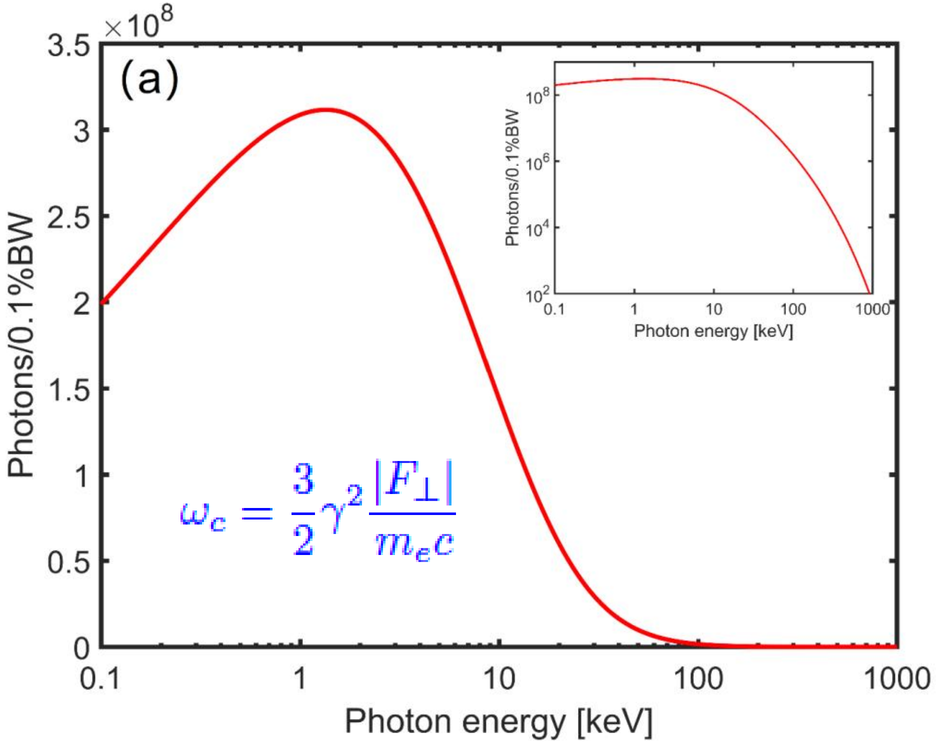
PETAL 1 kJ , SM-LWFA (a_0= 7.5, n_e= 10^{18} cm^{-3}, E_e~ 1 GeV) 7×10^{11} photons with E_c = 10 keV,

Ferri et al, PHYS. REV. ACCELERATORS AND BEAMS 19, 101301 (2016)

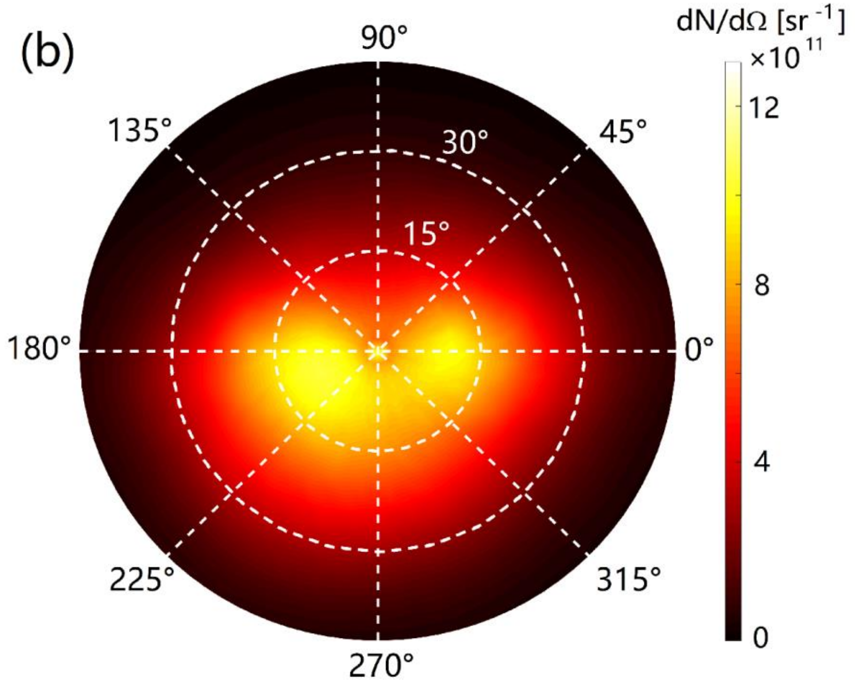
- Broad spectrum, large photon number:
- 6×10^{11} (1-10 keV), ~ 10^{11} (10-30 keV)

- opening angles: 360 mrad (y, laser polarization) and 270 mrad (z) RMS (root mean square)
- source radius: 4µm (RMS)

E_c = 5 keV



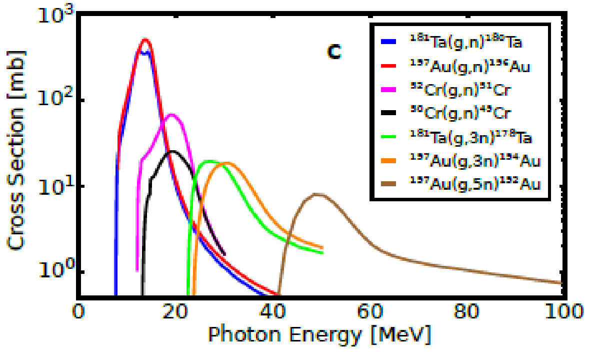
$$\omega_c = \frac{3}{2}\gamma^2 \frac{|F_\perp|}{m_e c}$$

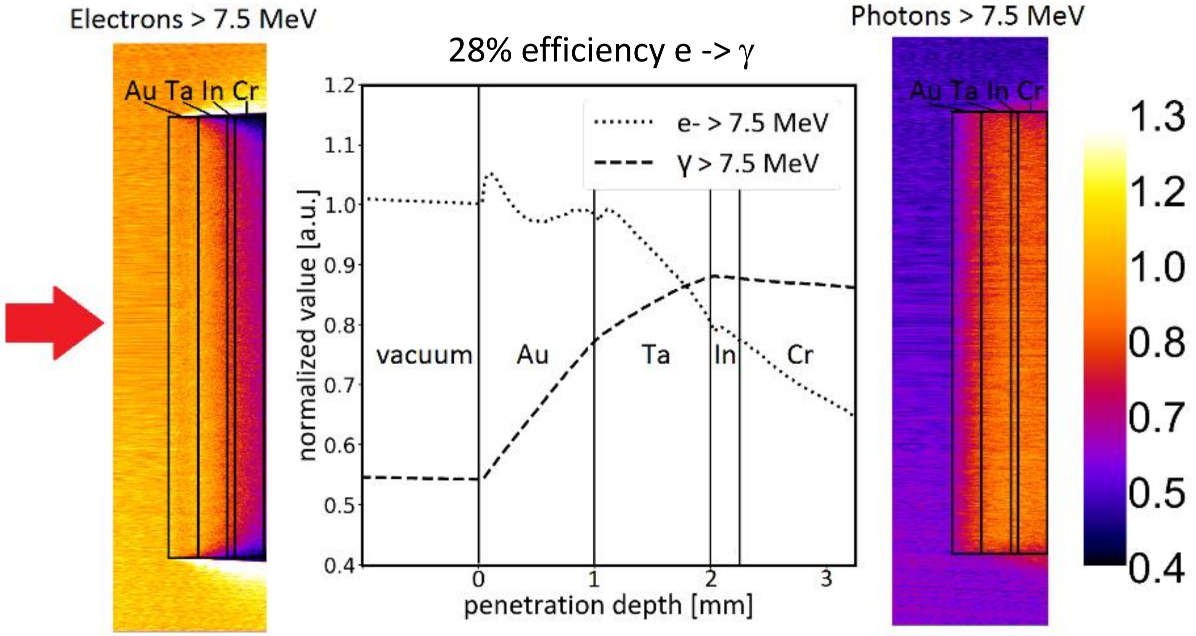


MeV Gammas: Well-directed, 10^{12}/sr photons with E > 7 MeV, Teff =10 -13 MeV

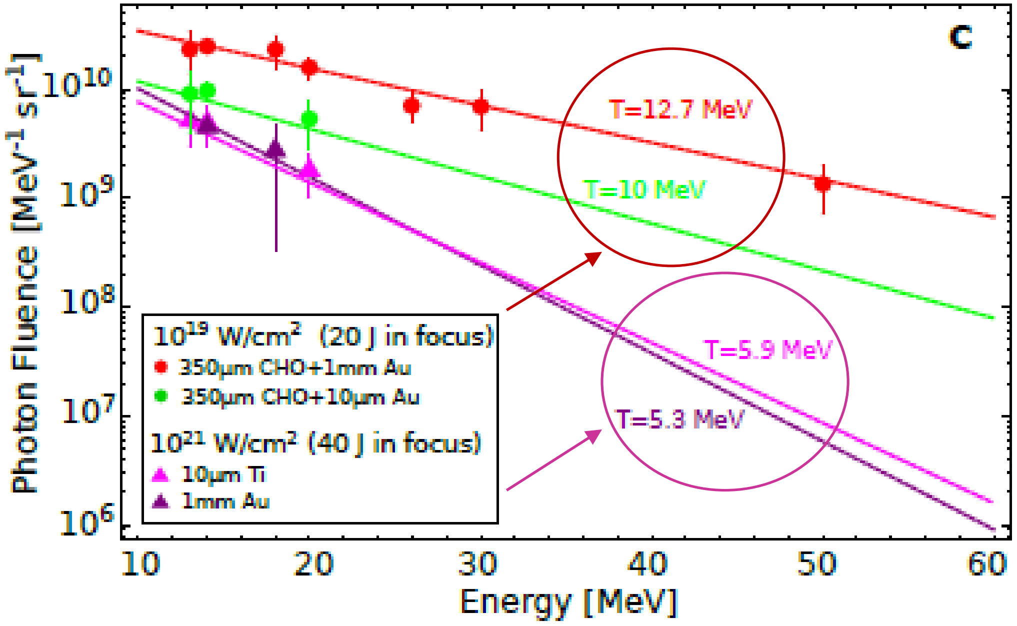
GDR energy region for γ,n reactions for isotopes production and for astrophysical applications

Nuclear activation-based diagnostics:
by M. Günther 2011, Plasma phys. **18** 083102





GEANT4, A. Skobliakov

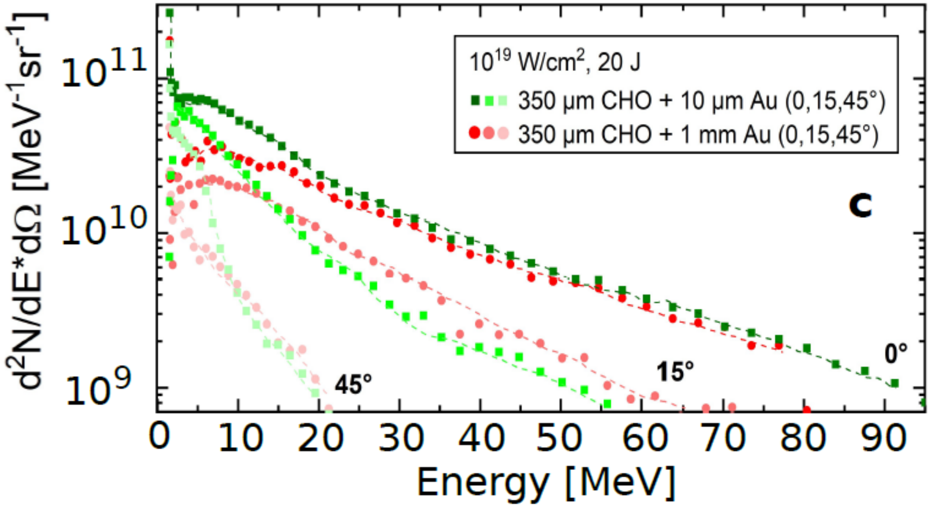


10^{19} W/cm² vs 10^{21} W/cm²: two times higher effective temperature and 10 times higher photon number (Eγ > 7 MeV)

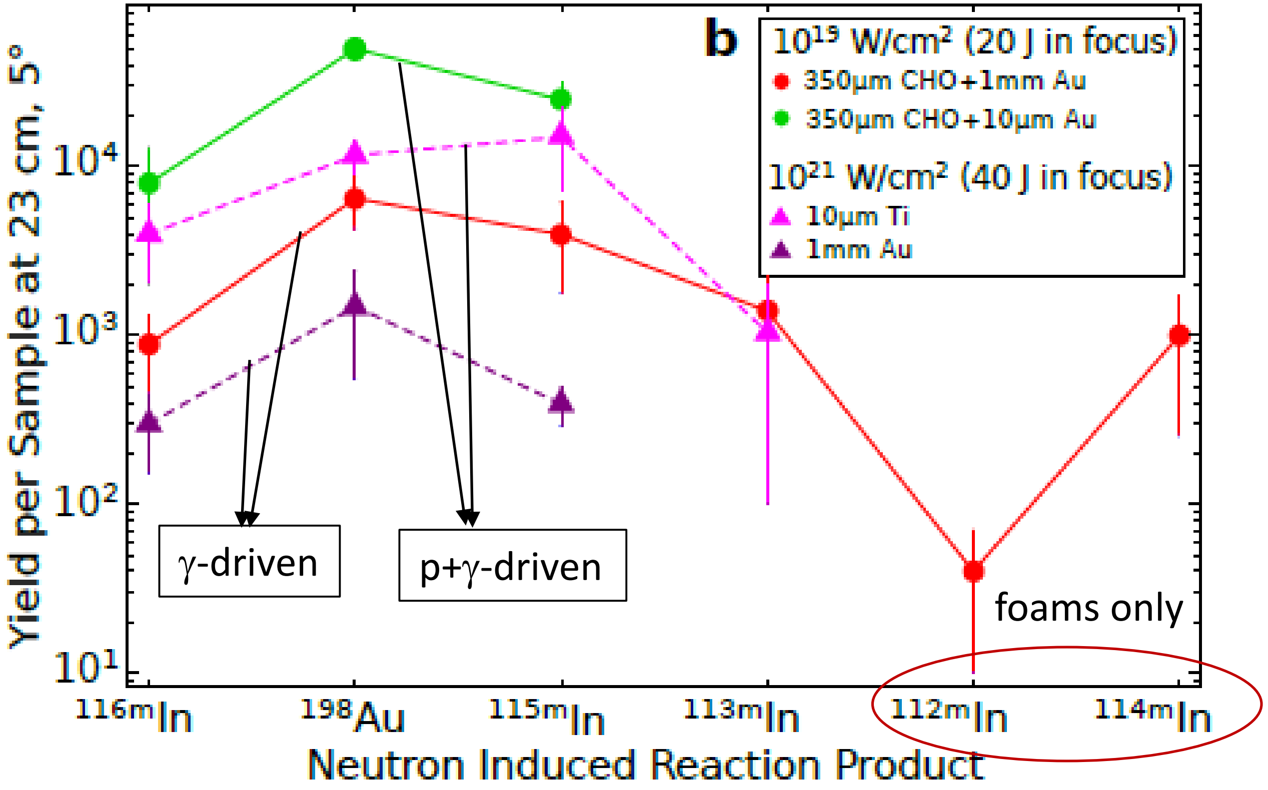
Neutrons: > 10^{10} n/4π/shot with T = 2.0 MeV in (γ,n) reactions

prompt transformation from gamma- to proton-driven : > 6×10^{10} n/4π with T= 0.5 MeV in (p,n) reactions

gamma driven NR -> high flux n-source
foam layers+ mm thick high Z foils
proton driven NR -> high fluence n-source
foam layers + µm thin foils
(no special conditions such as ultra-high contrast and ultra-relativiostic intensity)



reaction yield per In, Au-sample (15x15 mm², 23 cm distance, 5°)



E_p [MeV]

M. M. Günther et al, “New insights in laser-generated ultra-intense gamma-ray and neutron sources for nuclear applications and science”, **Nature Communications,** under review procedure

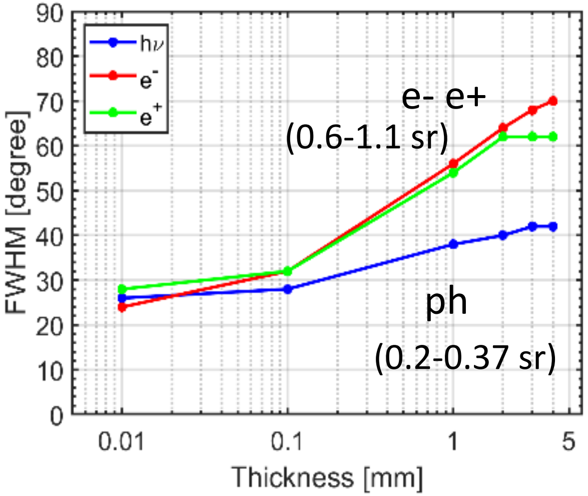
FLUKA (PHELIX): photons (0.1-1 MeV): 10^{13}/20 J, positrons (0.5 -10 MeV): 10^{10}@20 J

H. Chen, Phys. Rev. Lett. **102**, 105001: OMEGA ~ 10^{10} @ 400J

laser-driven x-ray radiography

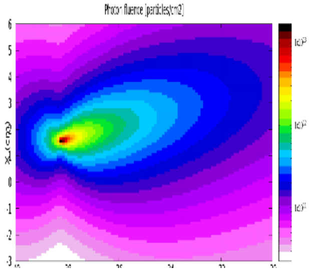
PHELIX

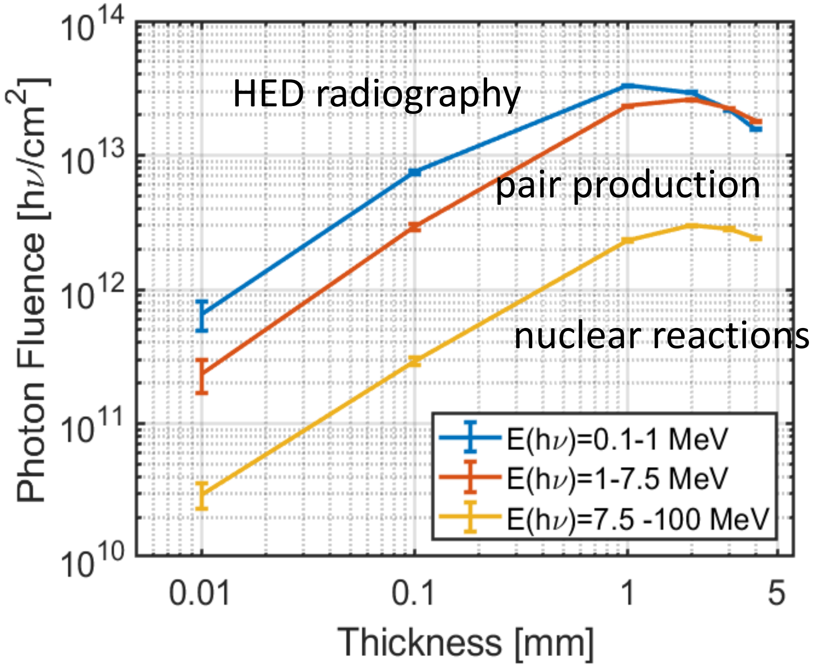
divergence angle



photons up to 100 MeV

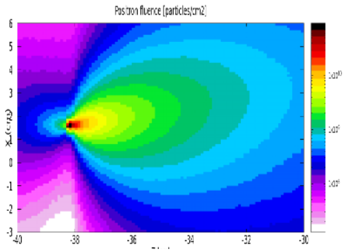
interaction of e-beam with 2 mm thick Au-convertor

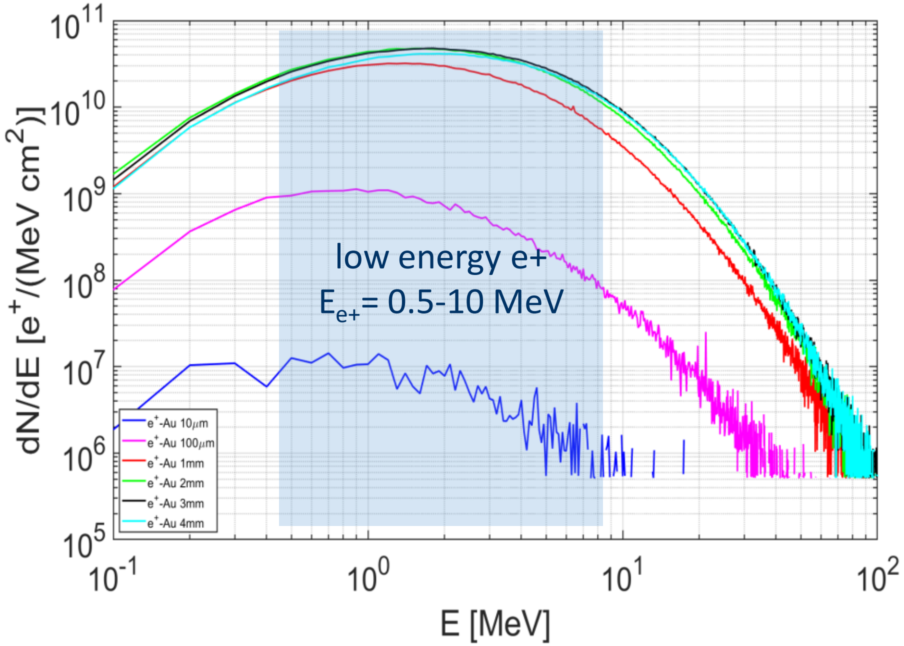




positrons up to 100 MeV

2-4 mm thick Au-convertor



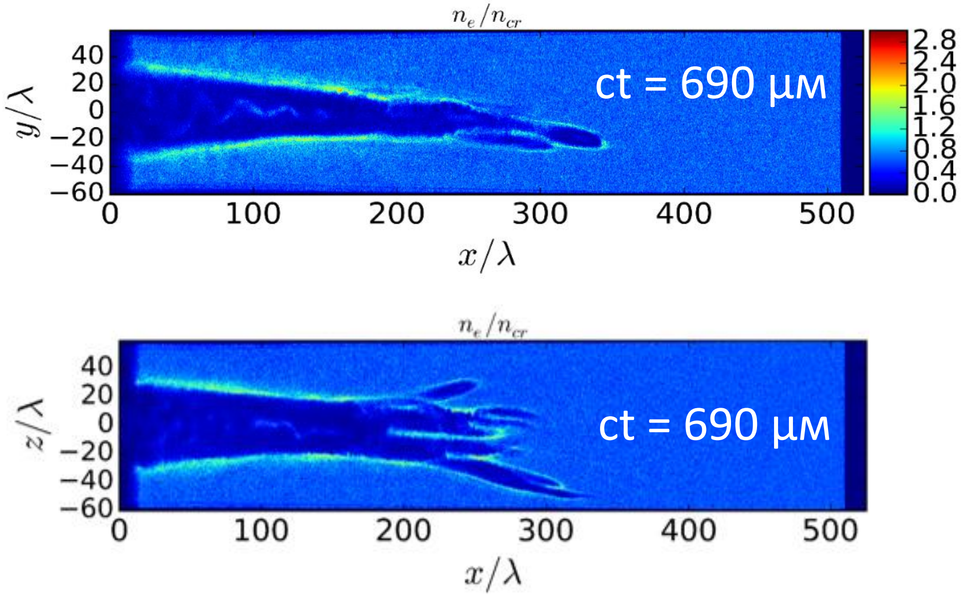


N. Zahn, GU

3D PIC Simulations for 200 J PHELIX up-grade

electron density in plasma channel,

XY and *XZ* -planes



filamentation and hosing of the laser pulse and electron current

λ=1 μм

700 fs

waist 25 μм (FWHM)

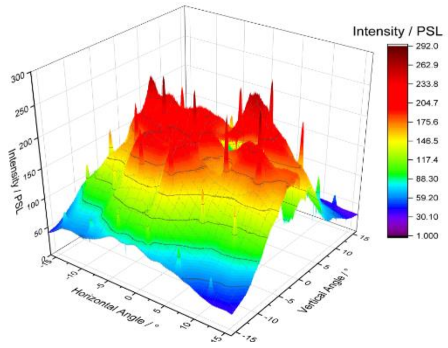
200 J (FWHM)

pulse length 178. μм

foam length 500 μm

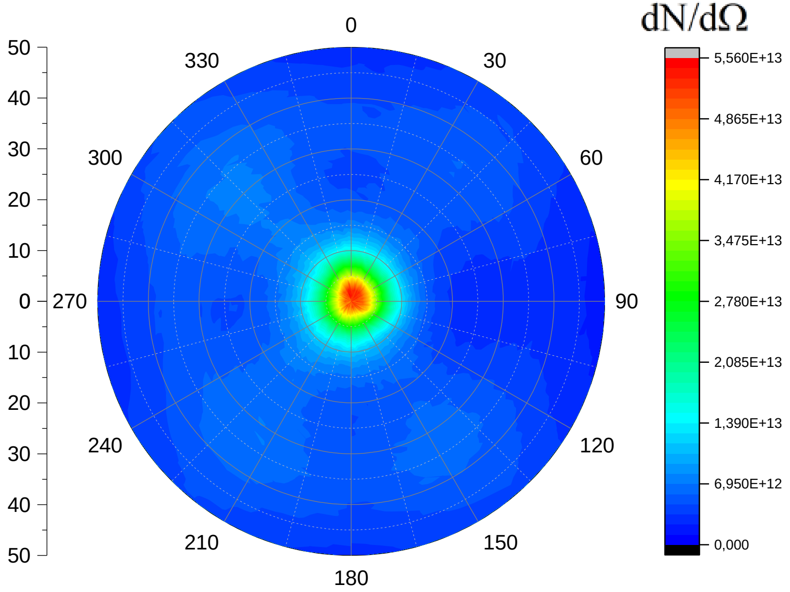
a_0=7.44

7.587×10^{19} W/cм²



Experiment, PHELIX 20 J:
5% of the current is in filaments

angular distribution of electrons
with *E* > 7.5 MeV



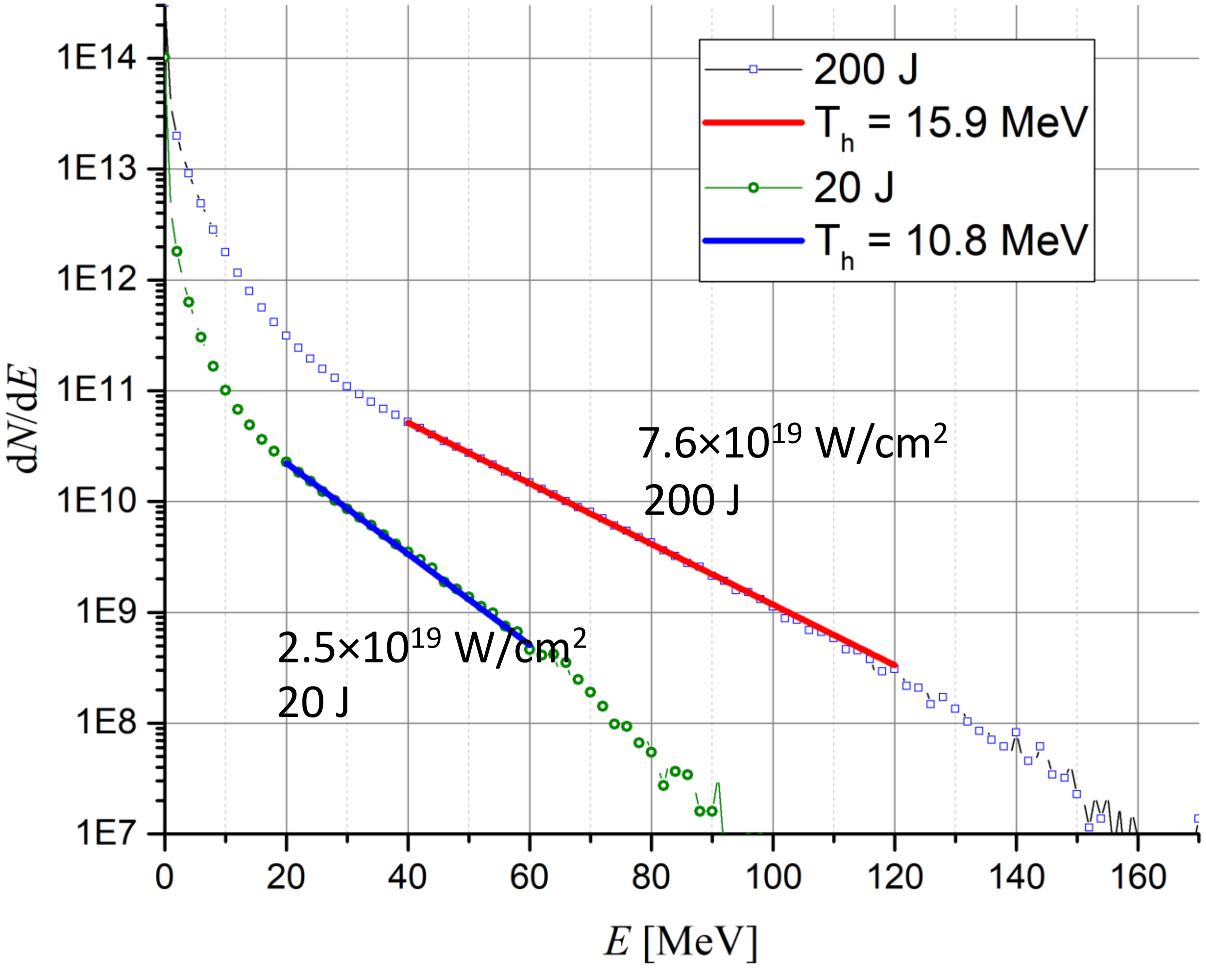
$$\frac{1}{2}\boldsymbol{\theta_{FWHM}} = 6.8^{\circ}$$

V. Popov, N. Andreev, JIHT, Moscow

Limitation on Effective Electron Temperature

T_{eff} – scaling with laser intensity: T_{eff}~ $\alpha(I/I_{18})^{1/2}$ with α = 1.5 MeV (A. Pukhov *et al.*, PoP **6**, N7 (1999))

Limitations due to filamentation of the laser pulse and electron current in NCD plasma at high laser energies



7.6×10^{19} W/cm^2
200 J

2.5×10^{19} W/cm^2
20 J

3D PIC 200 J:
expected T_{hot} ~ 21 MeV
simulated T_{hot} ~ 16 MeV

conversion efficiency (200J):
30% E> 2 MeV
10% E> 7.5 MeV

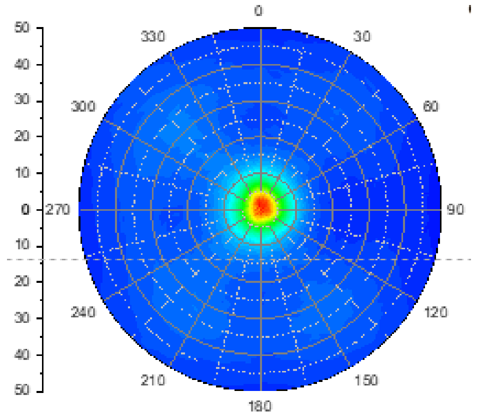
Limitation on measured electron number

$N_{super\text{-}pond}$ inside NCD plasma grows with E_{las} and I_{las}

Electron beam transport in vacuum is limited by the Alfven current: $\gamma \times 17.5$ kA, with $\gamma = E/mc^2$
Charge of electrons with ≥ 7.5 MeV ($\gamma \geq 15$) can not exceed 300 nC (1ps)

Electron spectrometer (40 cm from target) measures limited electron bunch charge

	E > 2 MeV		**E > 7 MeV**
20 J	4.5e+12/ **0.72 μC in 2π** **10% (100 nC) propagate in** $\theta_{1/2}=13^\circ$		1.2e+12/ **0.2 μC in 2π**
200 J	6.4e+13/**10 μC in 2π** **3%** propagate in $\theta_{1/2}=7^\circ$		1.9e+13/**3 μC in 2π** **10%** propagate in $\theta_{1/2}=7^\circ$

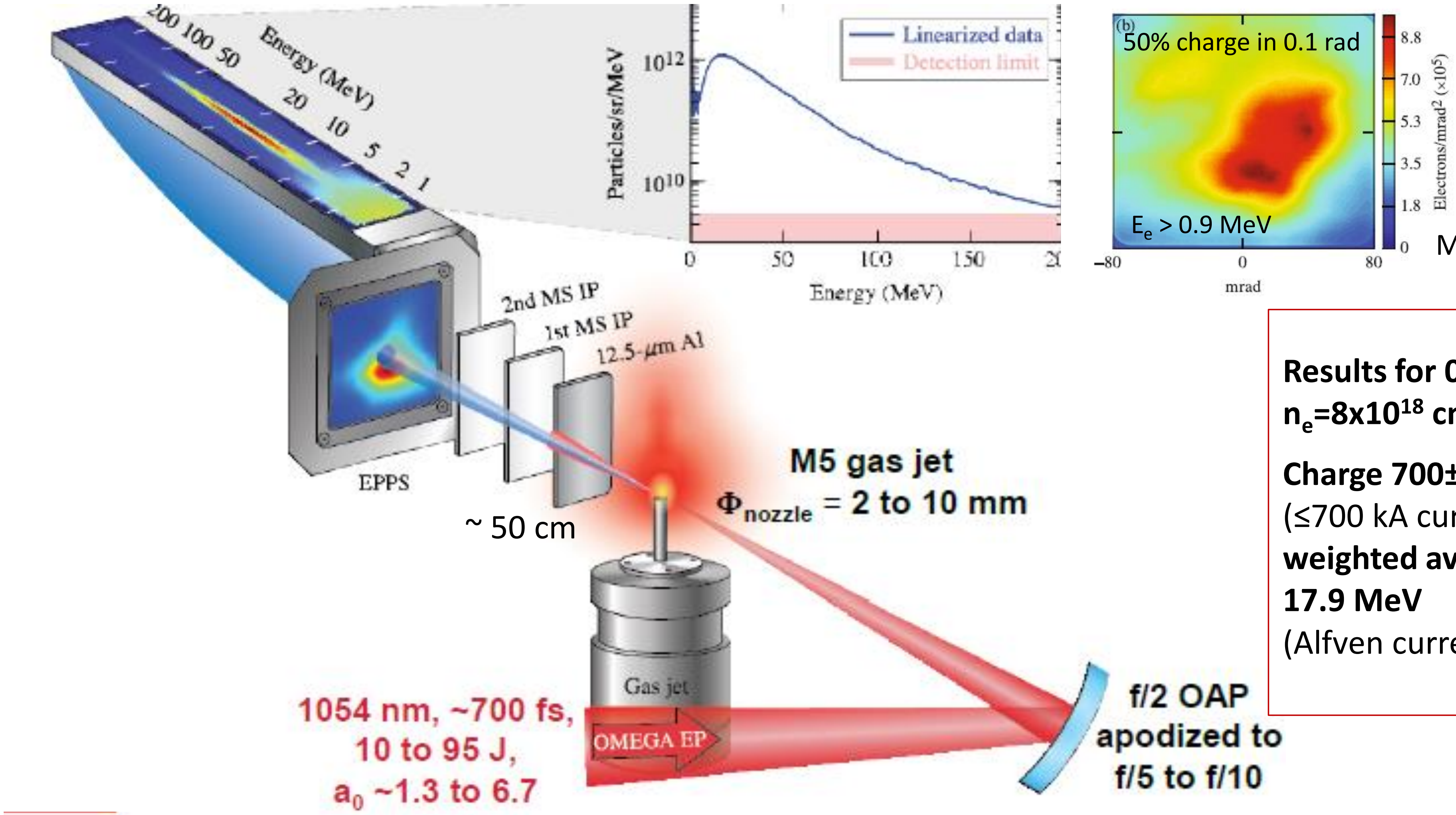


To make use of the total number of super-ponderomotive electrons for generation of gammas and neutrons:
vacuum-less contact between NCD plasma and foil/convertor

New Developments in Laser Wakefield Acceleration at the Laboratory for Laser Energetics

OMEGA EP

SM-LWFA-based LPA



MS IP after 37 µm Al

Results for 0.7 ps, a_o= 6.6
n_e=8x10^{18} cm^{-3}, Φ_{nozzle}= 6 mm

Charge 700±420 nC
(≤700 kA current)
weighted average electron energy 17.9 MeV
(Alfven current (γ=40) = 700 kA**)**

J. Shaw *et al*,
Sci. Reports 2021

Electron Charge as a Function of Plasma Density

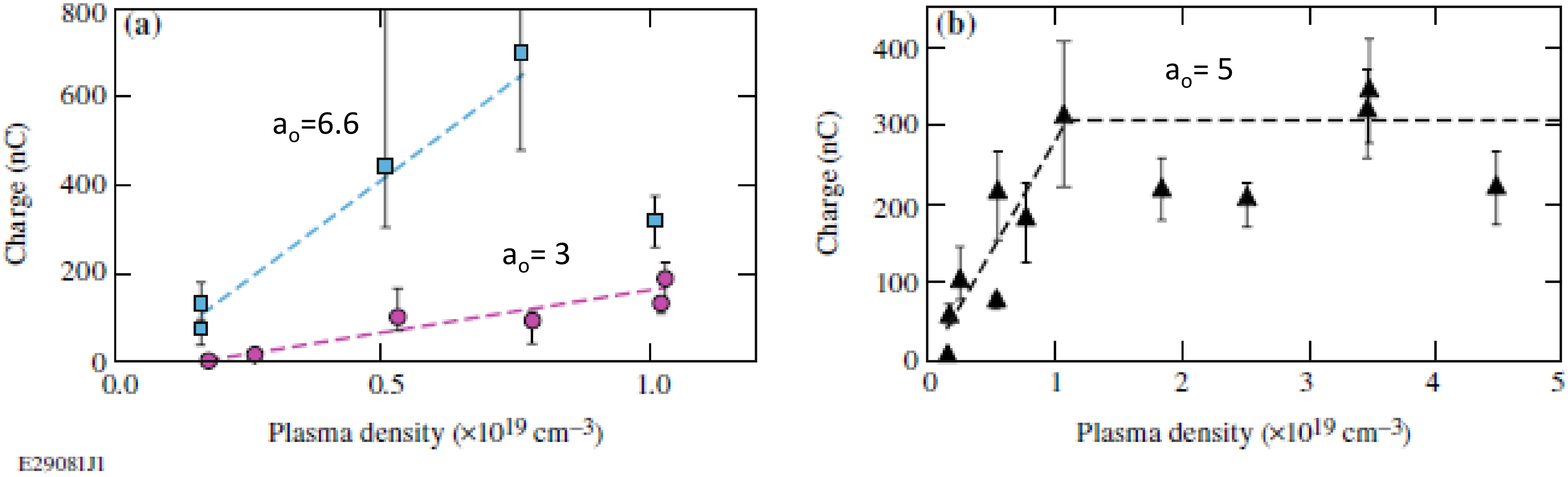
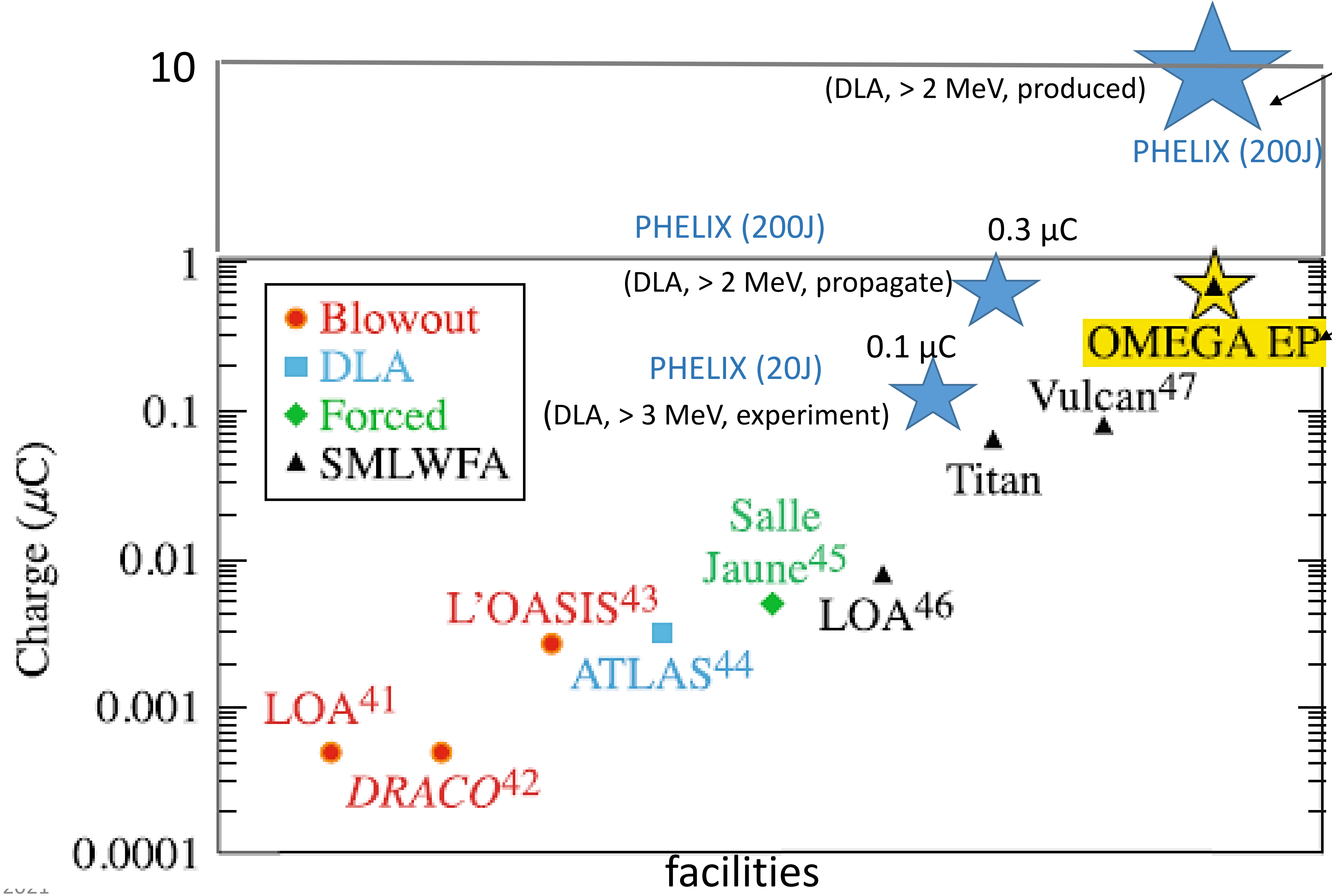


Figure 5. Electron beam charge as a function of plasma density (a) up to ~ 1 × 10^{19} cm^{-3} for a$_0$ ~ 3 (magenta circles) and a$_0$ $\gtrsim$ 6 (blue squares) for a 6-mm-diameter nozzle and (b) over the entire sampled plasma density range for a$_0$ ~ 5 and a 10-mm-diameter nozzle. The dashed lines are added to guide the eye.

Plot of the maximum charge of the electron beams produced by laser-plasma accelerators at different facilities

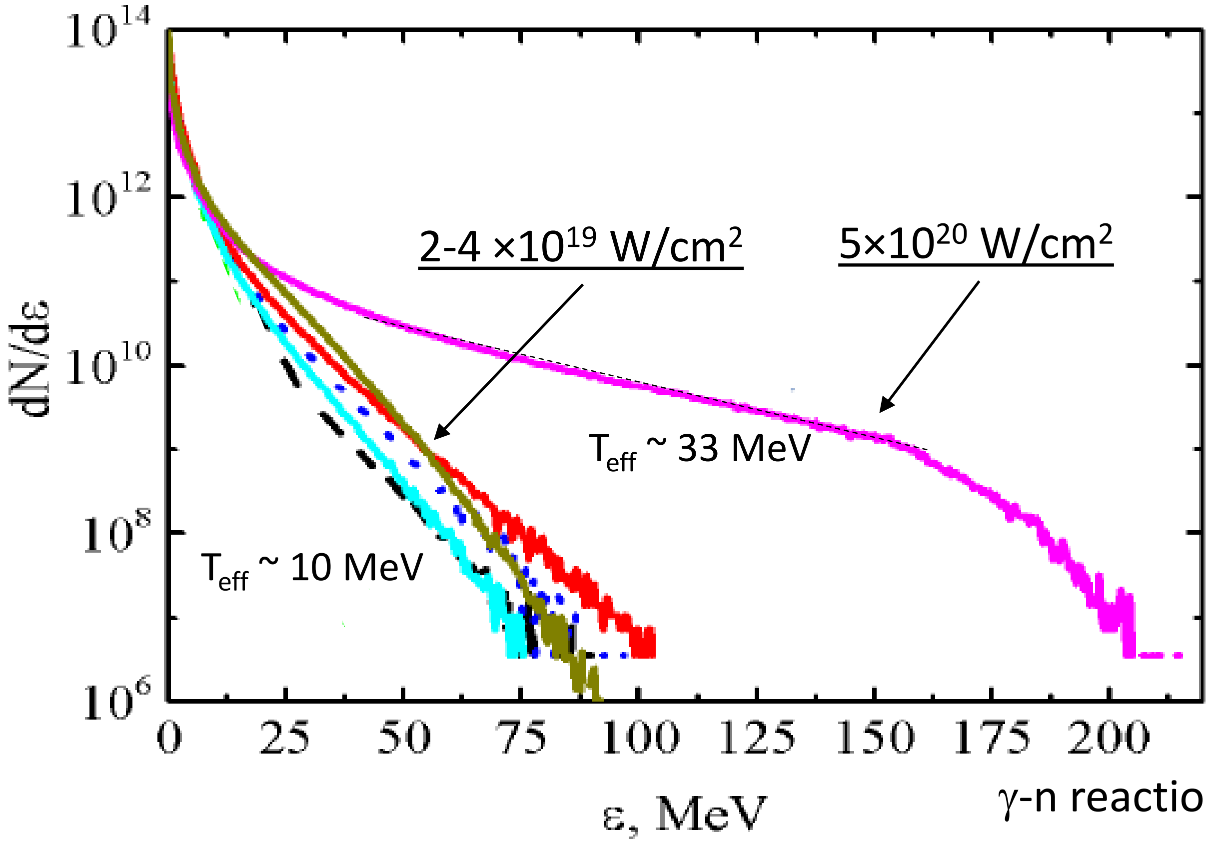


10 μC
E=2-120 MeV
30%

700 nC
E=1-200 MeV
11%

J. Shaw *et al*,
Sci. Reports 2021

Increase of Laser Intensity



E_{FWHM}= 56 J, 700fs, **5×10^{20} W/cm^2**

d=4 μm; 350 μm NCD-plasma

Pugachev L P and Andreev N E
2019 *J. Phys.: Conf. Ser.* **1147** 012080

1. More charge (up to 0.9 μC) can be transported
2. increase of the betatron $\omega_c \sim \gamma^2$.
3. higher energies of bremsstrahlung gammas
4. no win in the neutron production

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

GEANT4 , A. Skobliakov, ITEP

DLA-based Laser-driven Sources

Nature Communications 2021 M. Guenther *et al*:

Here, we present a novel concept for the efficient generation of gamma and neutron beams based on relativistic laser interactions with a **long-scale near critical density plasma at 10^{19} W/cm^2 intensity:**

Electrons: ≥100 nC are measured (2-100 MeV, T_{eff} =11-14 MeV) @ 20J

PIC predictions: 10 μC (2-100 MeV, Teff = 17 MeV) @ 200 J are produced inside NCD (0.7 μC @OMEGA 100 J)

Betatron:

7x10^{11} photons (1-30 KeV), E_c = 5 keV (PETAL 1.1 KJ, 7x10^{11} photons (1- 60 keV), E_c = 10 keV)

Gammas:

- directed (0.2 sr) gamma-beams (> 1 MeV) 10^{12} ph/sr with
- 1.7% laser-to-gamma conversion efficiency above 1 MeV (ARC-NIF, CPC, 0.3%)

Neutrons:

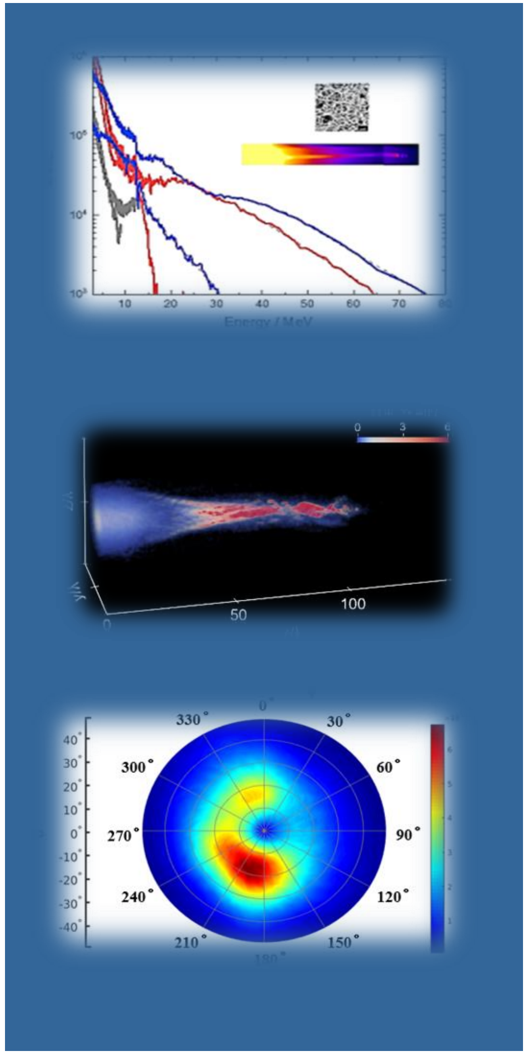
- ultra-high intense neutron source with > 6×10^{10} neutrons with
- 0.05% laser-to-neutron conversion efficiency
- record flux in optimized geometry: 10^{22} n/(cm^2 s)

Positrons:

- 10^{10} with 0.5-10 MeV (10^{10} @ OMEGA 400J)

Multidisciplinary Research with kJ, PW Laser Facilities

By using low density polymer foams for production of long-scale NCD plasmas, one **can strongly boost** parameters of laser driven sources of particles and radiation and use them for applications in **many research fields**.



Plasma Physics, HED-research:

foam and foam stacked with thin foil:

- Ultra-intense betatron and THz radiation,
- Well-directed electron and proton beams with high cut-off energies

Nuclear Physics:

foam stacked with thick high Z convertor:

- High fluence/ flux gamma and neutron sources
- High yield nuclear reactions in GDR region
- Production of theranostic relevant radio-isotopes

Biophysics:

- High flux ionizing radiation (e-, g) for investigation of the FLASH-effect: reduced impact of pulsed radiation (> 40 Gy/s) on normal tissue at ultra-high dose rates while supporting typical levels of tumor control.