Optimization of gamma photon beams generation using ultra high intensity lasers to study the two- photon Breit-Wheeler pair generation process

E. d'Humières[1,2], X. Ribeyre[1], O. Jansen[1], G. Boutoux[1], J.L. Dubois[1], S. Hulin[1], S. Jequier[1], Y. Sentoku[2] and V. T. Tikhonchuk[1]

[1]Univ. Bordeaux-CNRS-CEA, 33405 Talence, France

[2]University of Nevada, Reno, USA

Outline

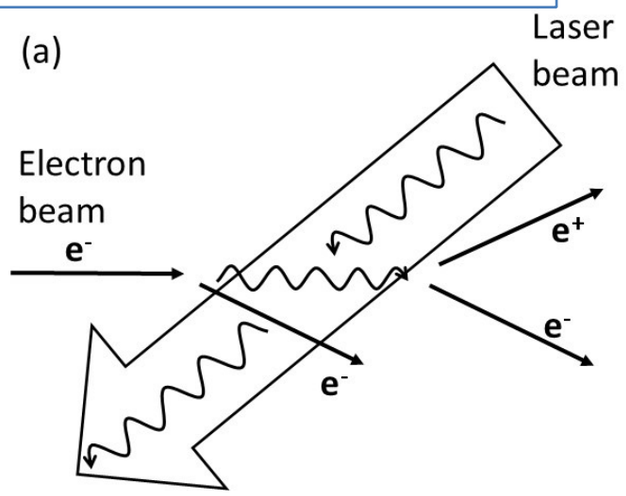
- Context: optimization of laser generated gamma sources to study the 2-photon Breit-Wheeler process
- Optimization of laser generated high energy photon sources in the Synchrotron dominated regime
- Optimization of laser generated high energy photon sources in the Bremsstrahlung dominated regime
- Calculations of the potential number of pairs created
- Conclusions and perspectives

Pair production in the lab

SLAC E144 experiment

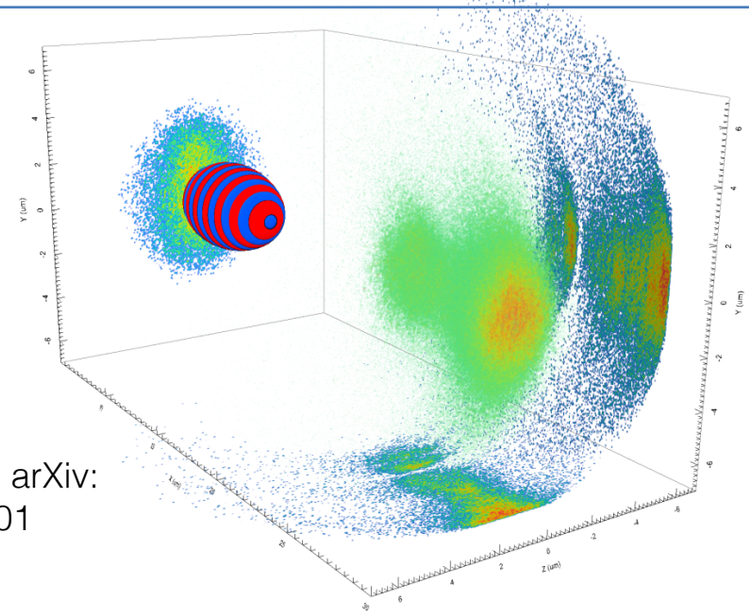
SLAC electrons
46.6 GeV

Laser ω
2.35 eV



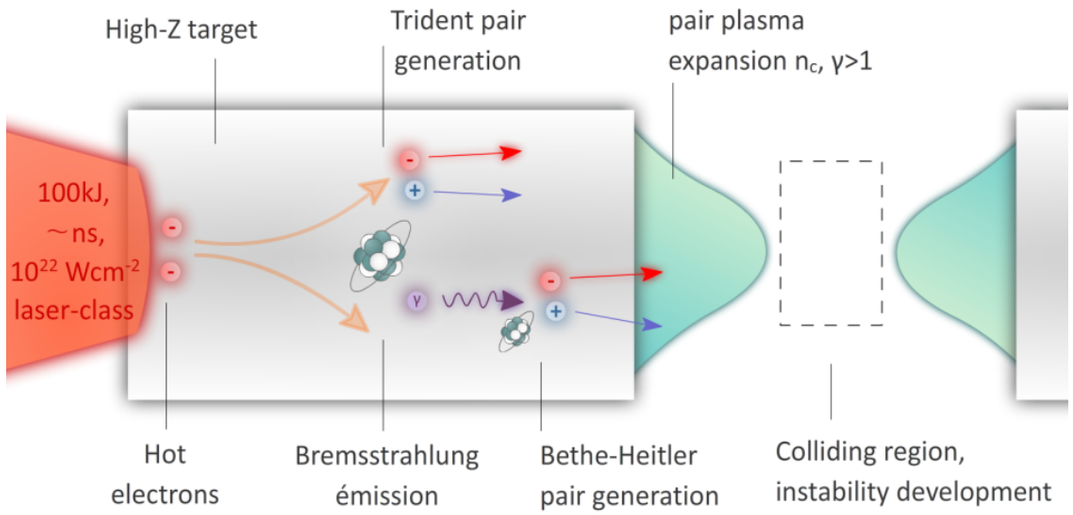
First observation of non-linear Breit-Wheeler pair production with real photons[2] (with n>4)

Multi photon BW using UHI lasers



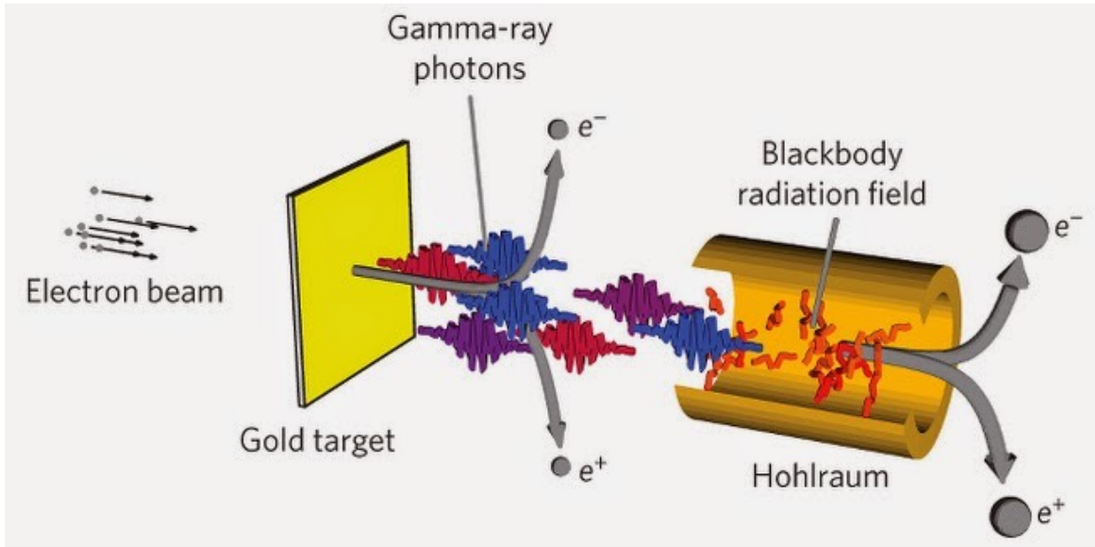
M. Lobet et al. arXiv: 1510.02301

Bethe Heitler using high intensity lasers



Myatt *et al.,* PRE **79**, 066409 (2009) ; Chen et *al.*, HEDP **7**, 225-229 (2011) ; G. Sarri et al. Nature Com. **6**, 6747 (2015)

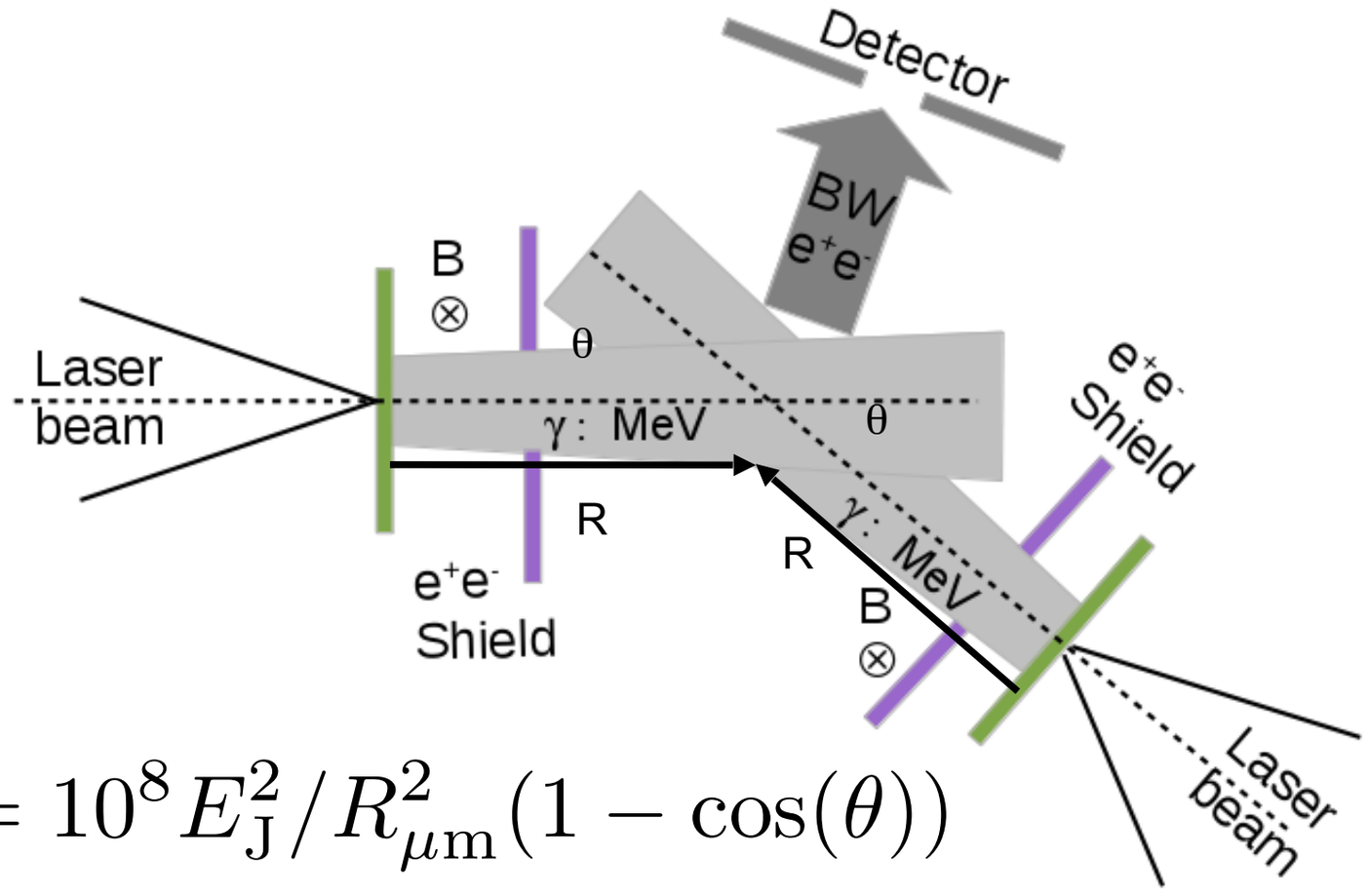
2 photon BW using NIF/LMJ class lasers



Pike, O. J. et al. Nature Photonics, 8, 434, (2014)

Collision of MeV-MeV photons in vacuum

Ribeyre X. et al. Phys. Rev. E 93, 013201 (2016)



$$N_p = 10^8 E_{\mathrm{J}}^2 / R_{\mu\mathrm{m}}^2 (1 - \cos(\theta))$$

θ : γ–beam divergence

R : distance between γ source and photons collision zone

MeV-MeV photons collision

$\mathrm{E_J} = 1 - 10\,\mathrm{J}$ and $\mathrm{R} = 500\,\mu\mathrm{m}$ $\theta = 30^\circ$

Pair production : per shot $\mathrm{N}_p = 3 \times 10^3 - 3 \times 10^5$

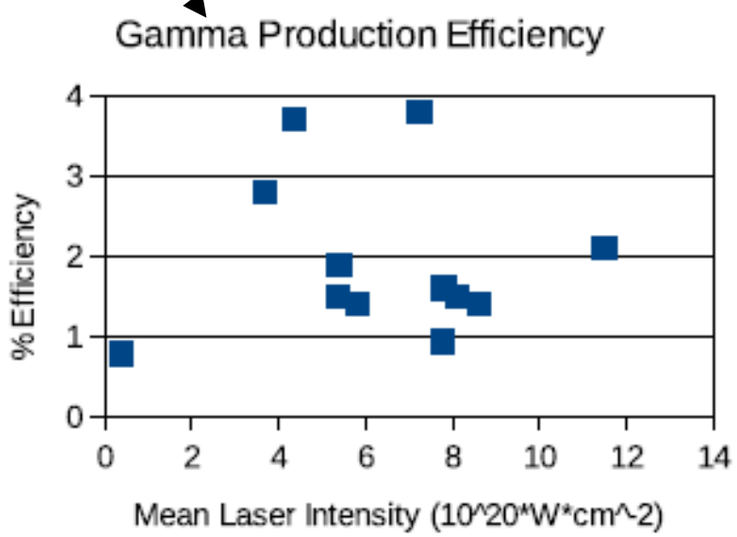
Possibility to study this process in the laboratory → **test new concepts of pair plasma production and explore this pair creation process in the ultra high field regime**
→ optimized gamma sources also have promising applications as radiography sources.

Need for high-intensity collimated MeV photon beams

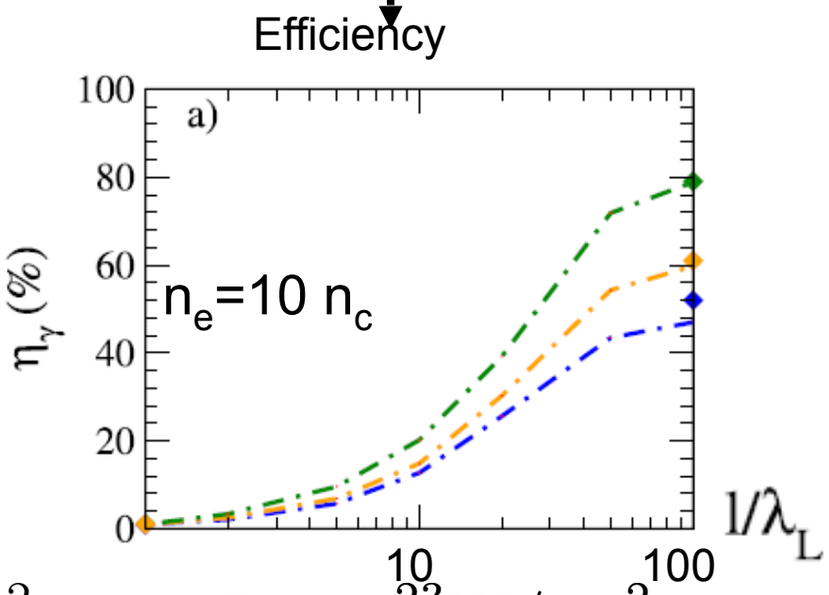
γ–ray sources in MeV range

Bremsstrahlung and Synchrotron sources are for now the most suitable for studies of BW

Source	Bremss.[1]	Betatron[2]	Compton[3]	Synchrotron[4]
Photon Energy	3-50 MeV	1-7 MeV	6-18 MeV	1-10 MeV
Beam Energy	1-24 J	1 μJ	1 μJ	1-10 J
Conv. Efficiency	1-2 %	10^{-6}	10^{-7}	10 %
Divergence	15°	0.1°	0.1°	30°
Pair Yield	10^{4}	10^{-3}	10^{-3}	10^{4}



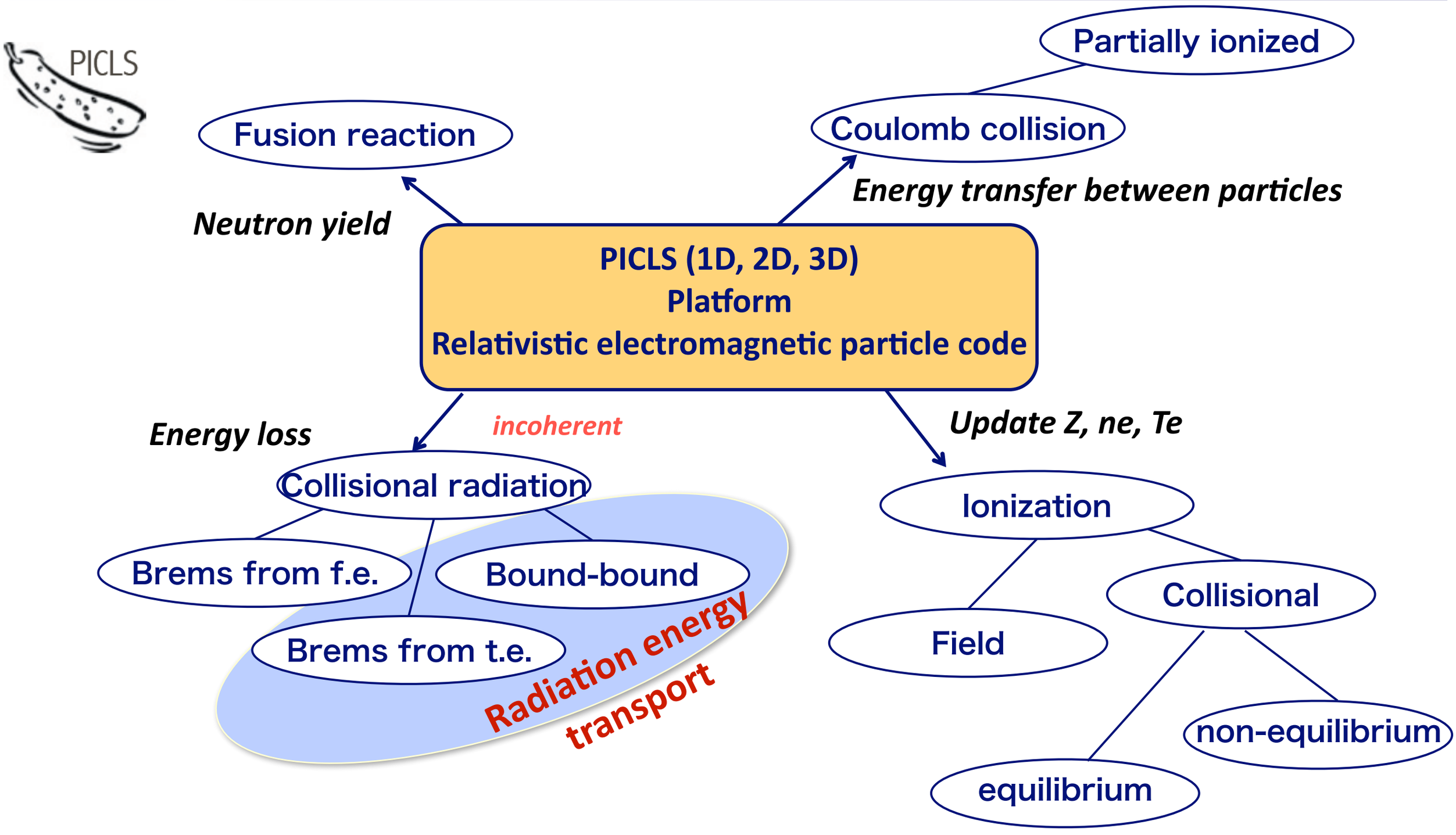
$I = 1 - 12 \times 10^{20}\mathrm{W/cm^2}$



$I > 10^{23}\mathrm{W/cm^2}$

[1]Henderson A. et al., HEDP **12**, 46 (2014)
[2]Cipiccia S. et al. Nature Physics **7**, 867 (2011)
[3]Sarri G. et al. PRL **113,** 224801 (2014)
[4]Capdessus, R. et al. PRL **110** (2013)

Structure of relativistic electromagnetic PIC code PICLS for HEDP



[1] Y. Sentoku, and A. J. Kemp J. Comput. Phys. 227, 6846 (2008)
[2] Y. Sentoku, E. d'Humières et al., PRL 107, 135001 (2011)
[3] R. Mishra, P. Leblanc, Y. Sentoku et al. Phys. Plasmas 20, 072704 (2013)

Visualization using IDL or Python

Optimization of laser generated high energy photon sources

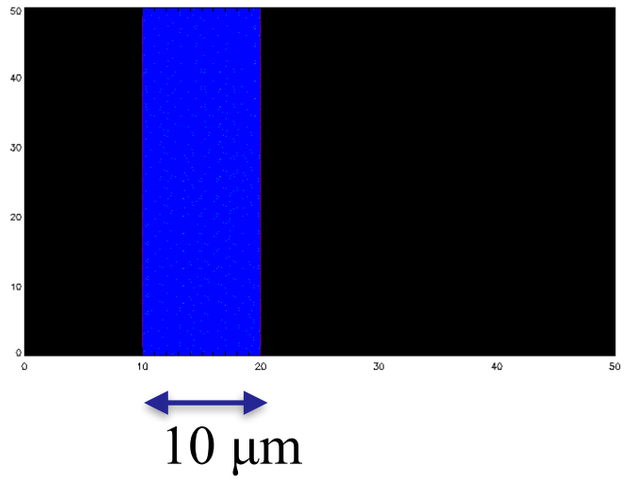
PICLS

Y. Sentoku and A. Kemp, J. Comput. Phys. **227**, 6846 (2008).

Solid foils

10 μm Al or Cu targets at solid density

23 fs pulse duration, 6 μm FWHM

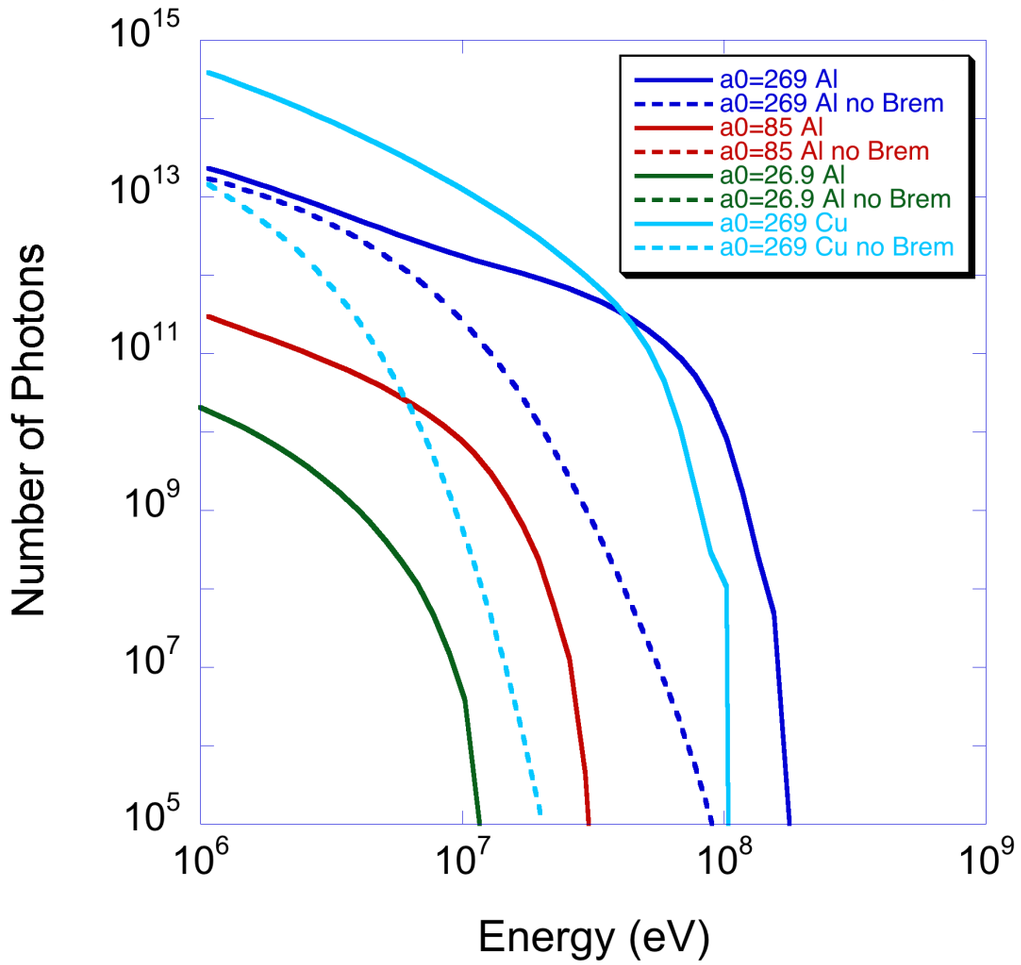


Radiative transfer equation

$$\left(\frac{1}{c}\frac{\partial}{\partial t}+\mathbf{n}\cdot\nabla\right)I=\eta-\chi I$$

- $I(\mathbf{r},\Omega,h\nu,t)$: intensity of radiation
- $\eta(\mathbf{r},h\nu,t)$: emissivity
- $\chi(\mathbf{r},h\nu,t)$: opacity

(a) **Multi-group method for photon energies**
(b) **S_N method for direction**
(c) **CIP (Constrained Interpolation Profile) scheme for advection**

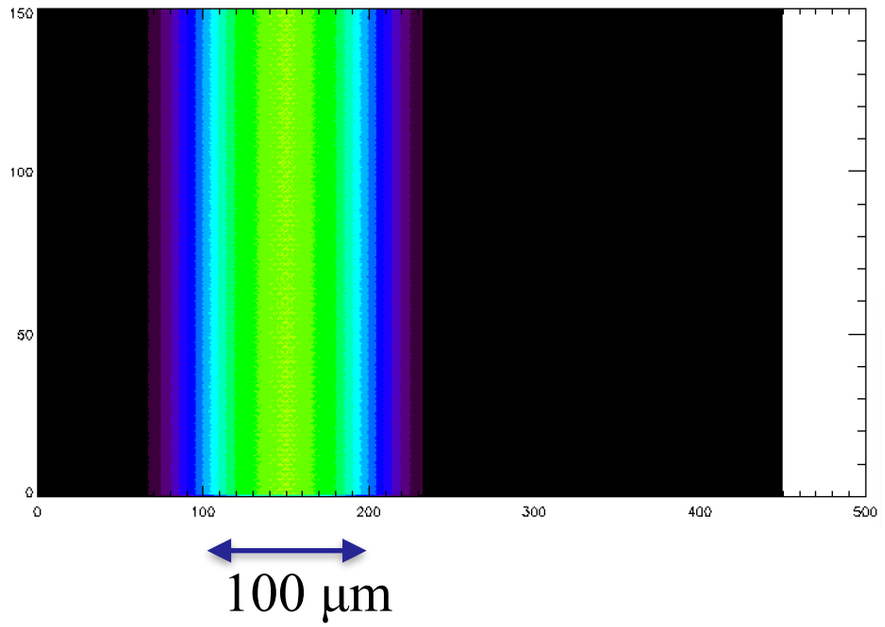


Optimization of laser generated high energy photon sources

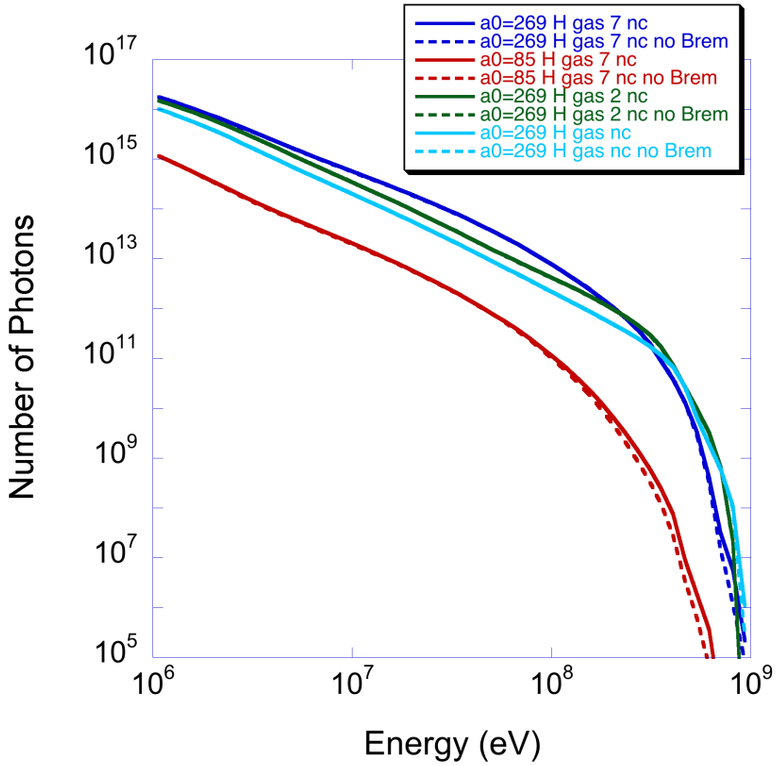
Y. Sentoku and A. Kemp, J. Comput. Phys. **227**, 6846 (2008).

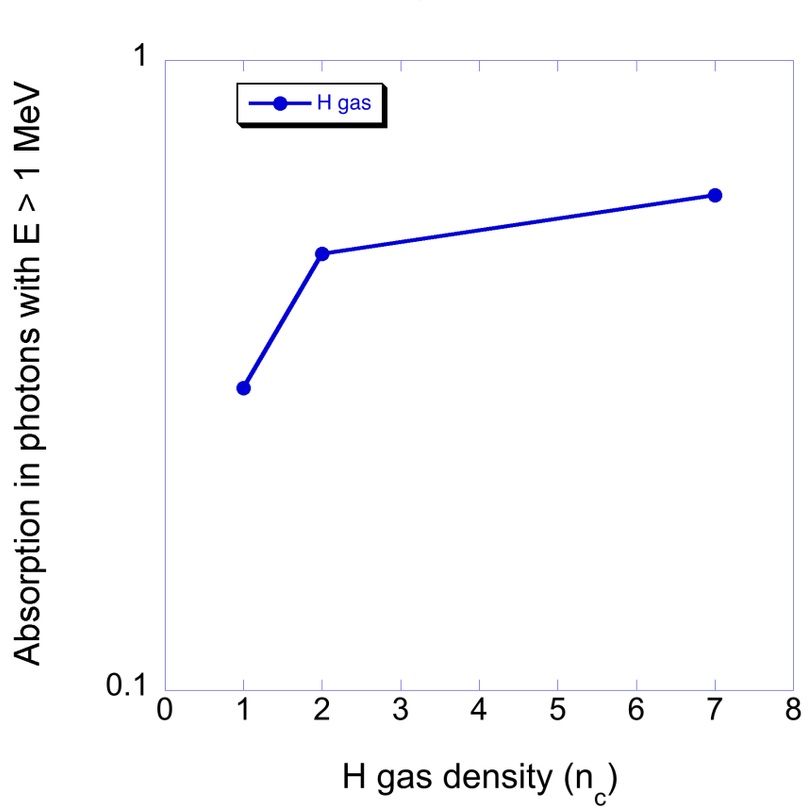
Gas jets: See recent developments by SourceLab and LULI

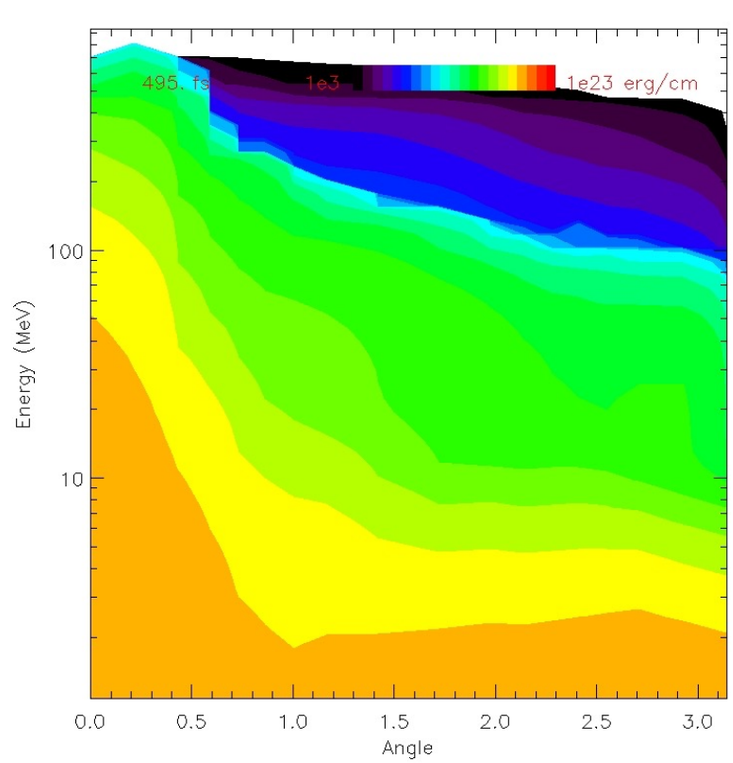
H, near critical density,
100 μm FWHM
23 fs pulse duration, 6 μm FWHM



Higher conversion efficiency in high energy photons using near-critical targets

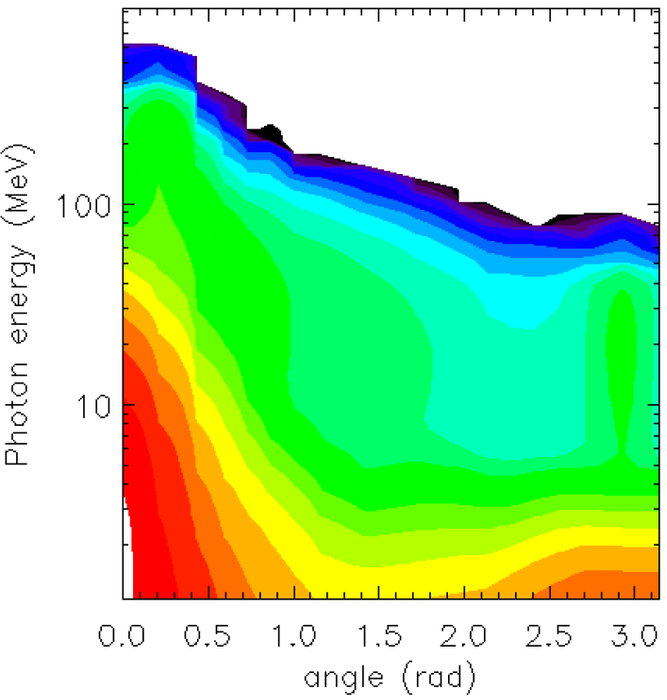




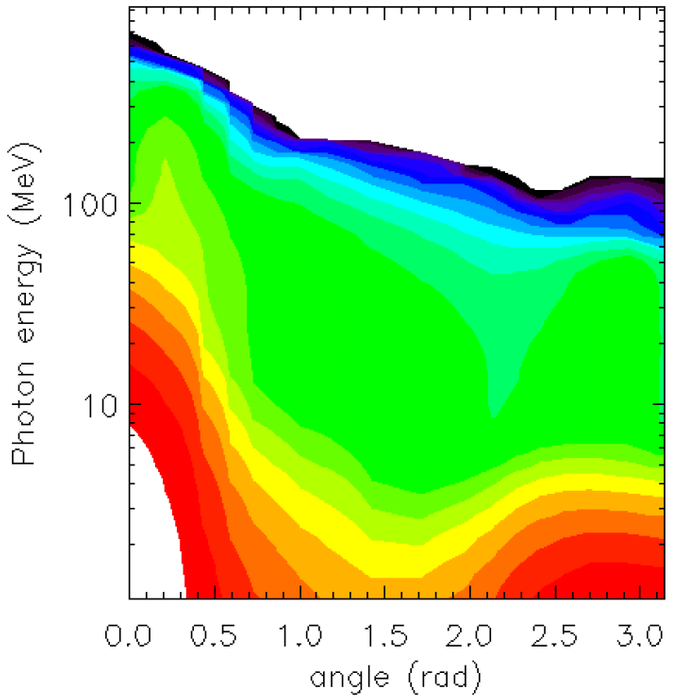


INRS parameters: energy and angle distribution of high energy photons

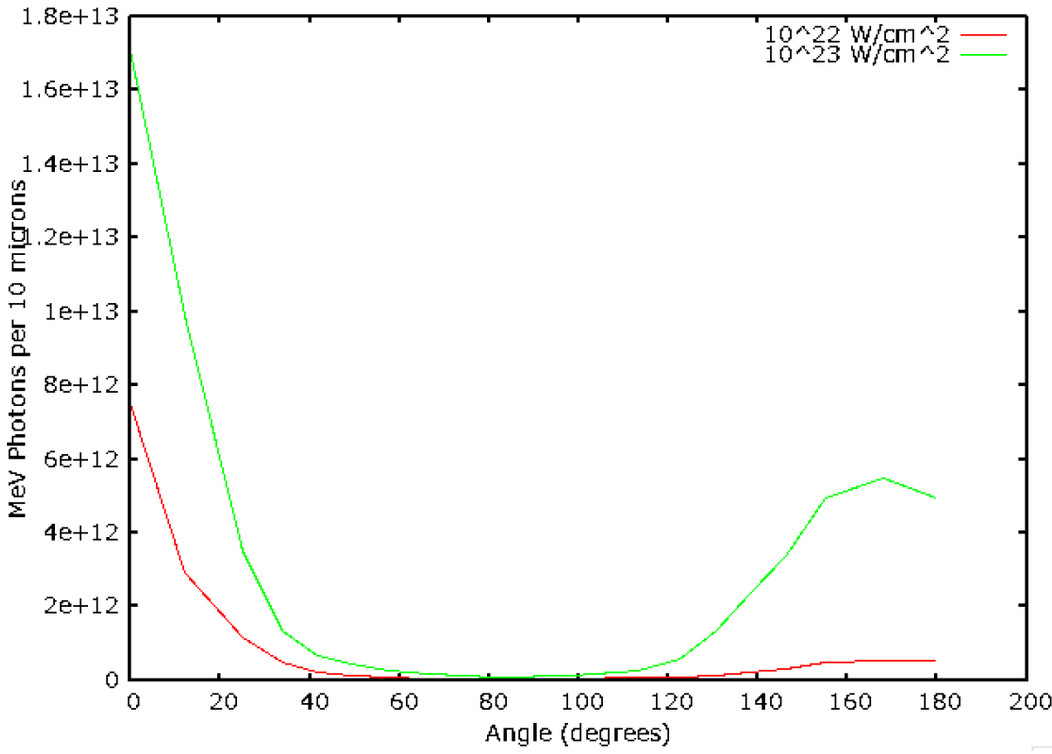
- The density profile used is a $\cos^2$, with a FWHM of 80 microns and a maximum density of 2 n_c.
- Protons and e^-
- Laser pulse duration ~ 16 fs, focal spot ~ 1-3 microns, intensity ~ $10^{22\text{-}23}$ W/cm^2.
- The laser is p-polarized and focused at the entrance of the plasma. λ=800 nm.



10^{22} W/cm^2, t= 1.716 ps



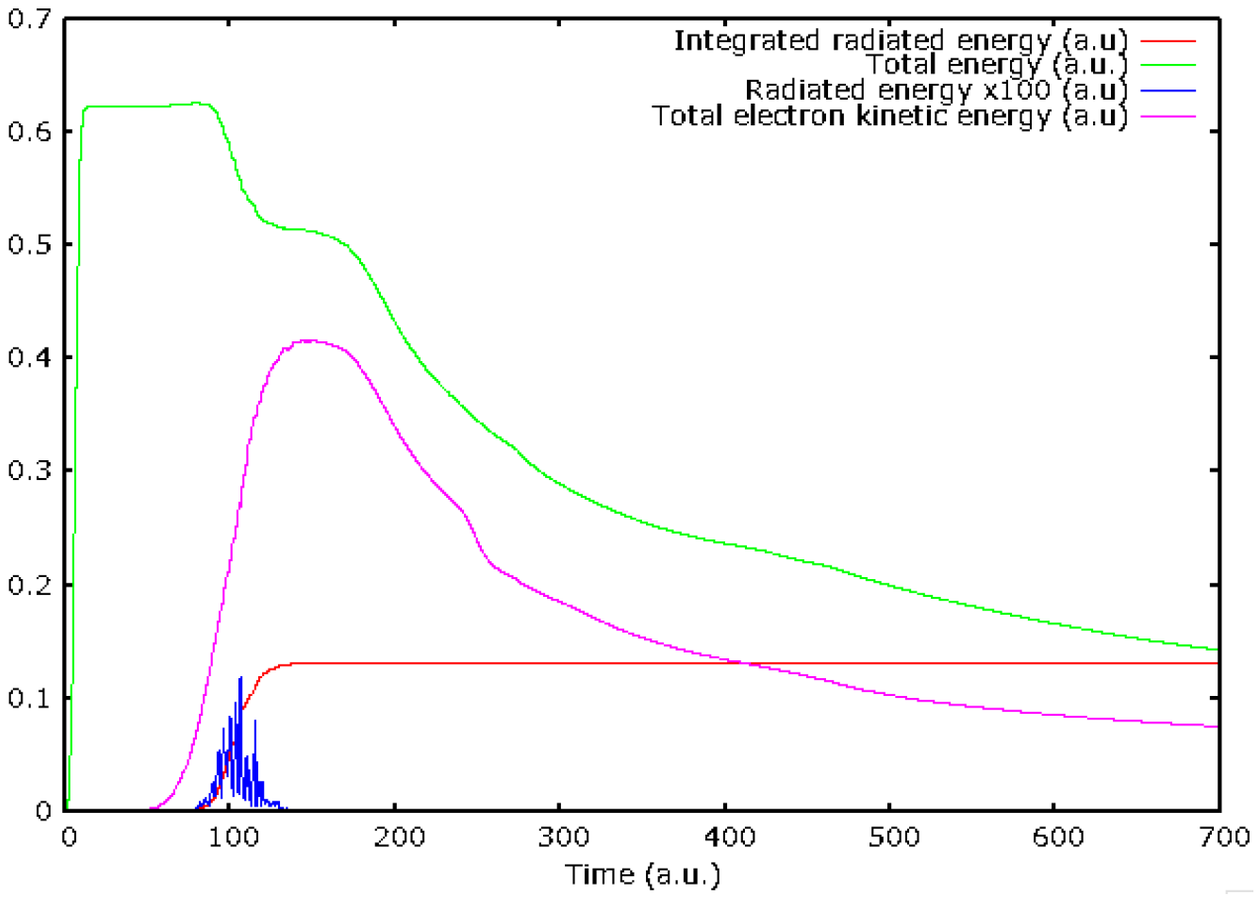
10^{23} W/cm^2, t= 1.584 ps



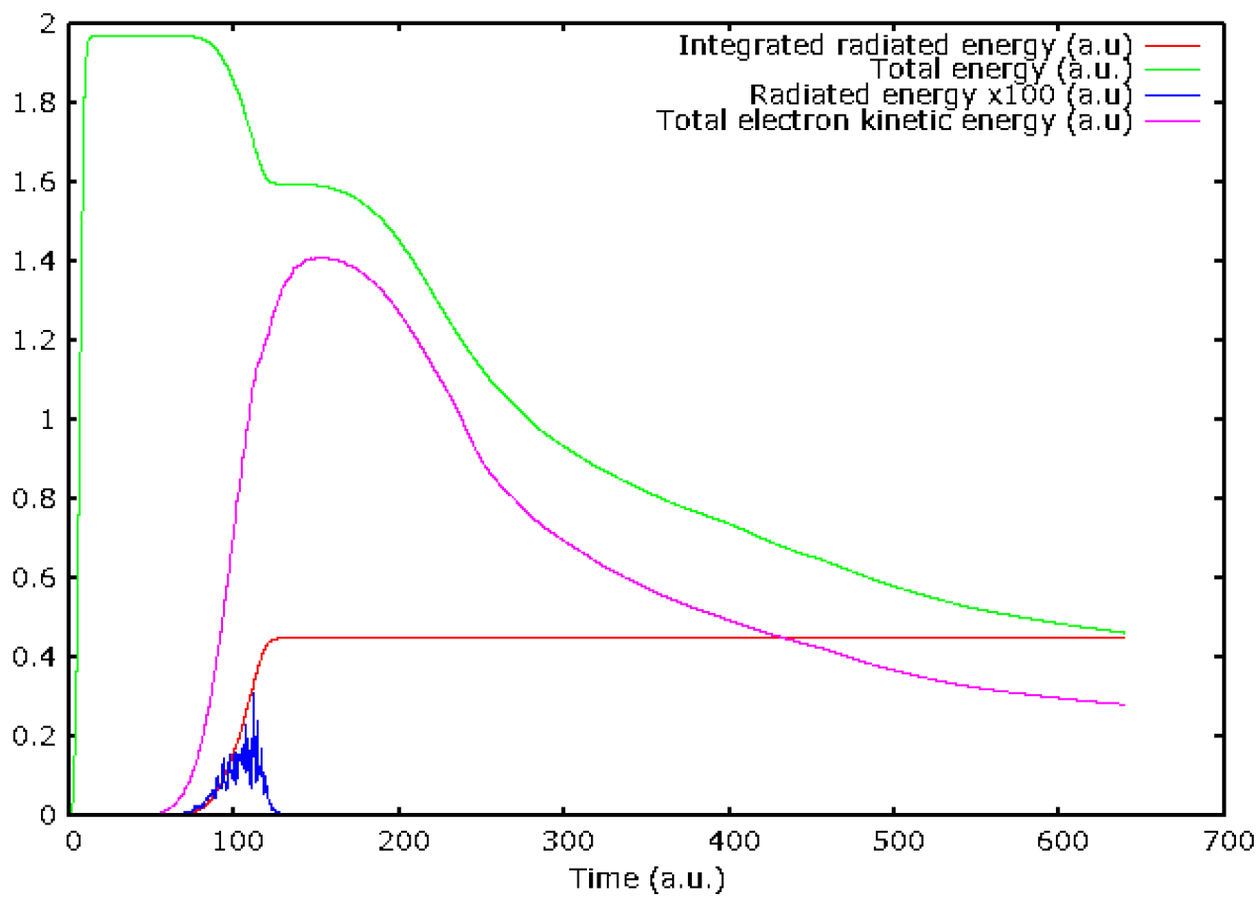
For 1 MeV photons

1 10^{10} erg/cm

Radiated energy

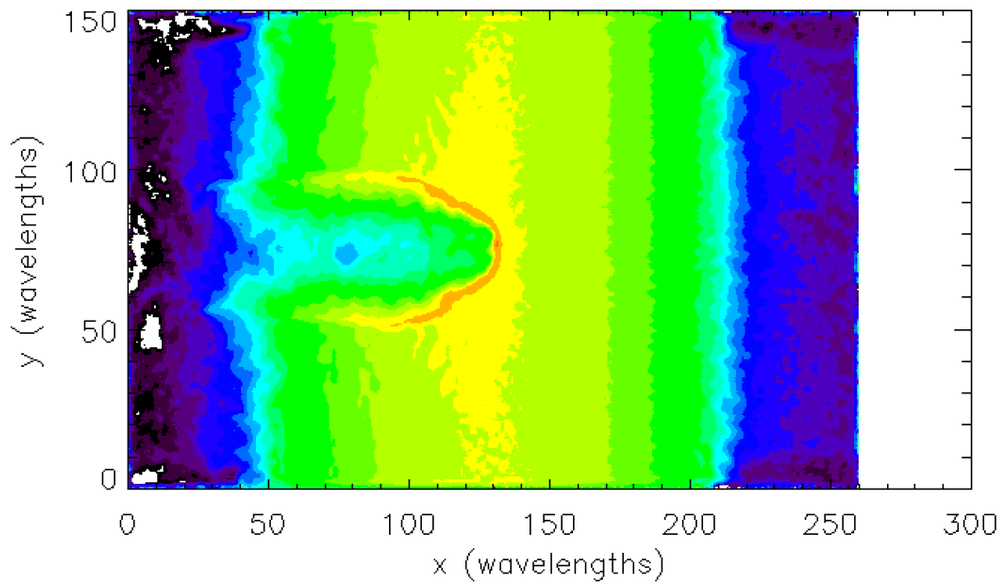


10^{22} W/cm^2, 21.3% absorption in photons with E > 1 MeV



10^{23} W/cm^2, 22.9% absorption in photons with E > 1 MeV

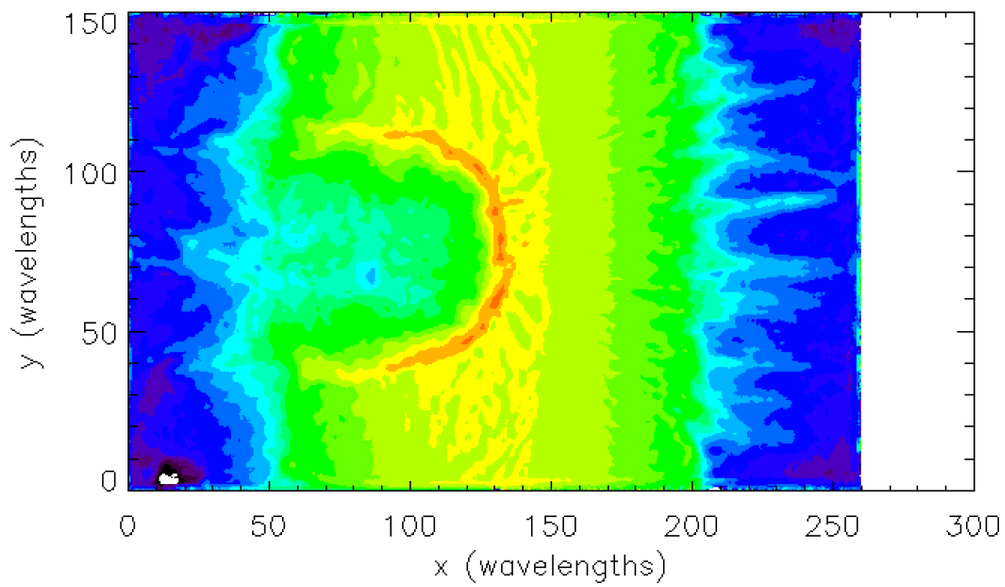
Density maps and magnetic field



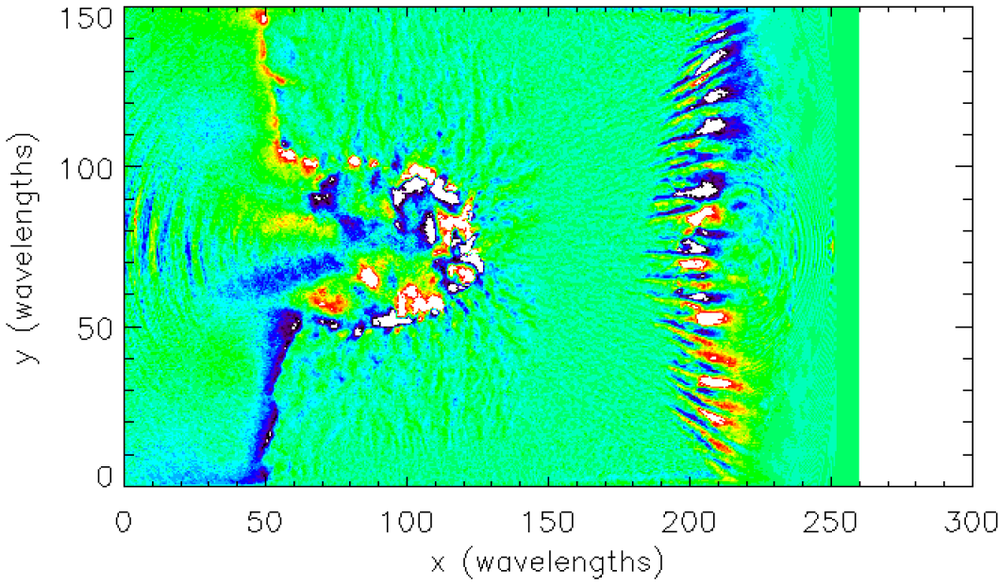
Electron density, t= 1.32 ps

B_z magnetic field, t= 0.66 ps

10^{22} W/cm^2



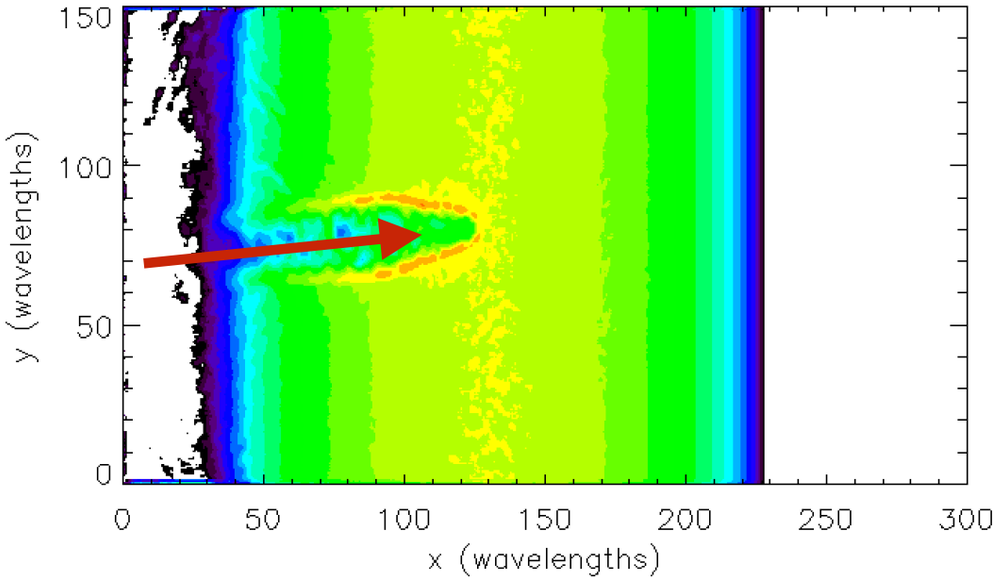
Electron density, t= 1.32 ps



B_z magnetic field, t= 0.66 ps

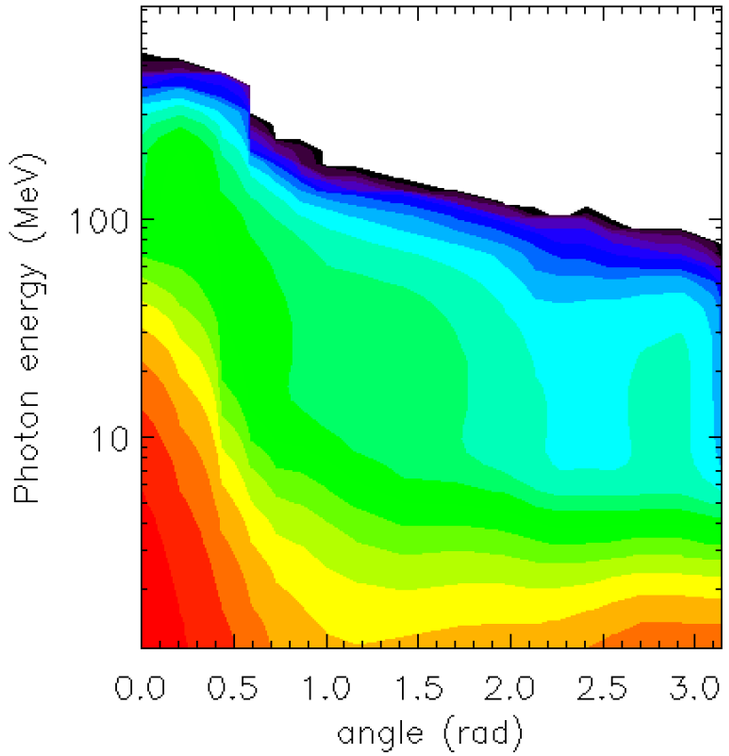
10^{23} W/cm^2

Case with a 5° incidence angle

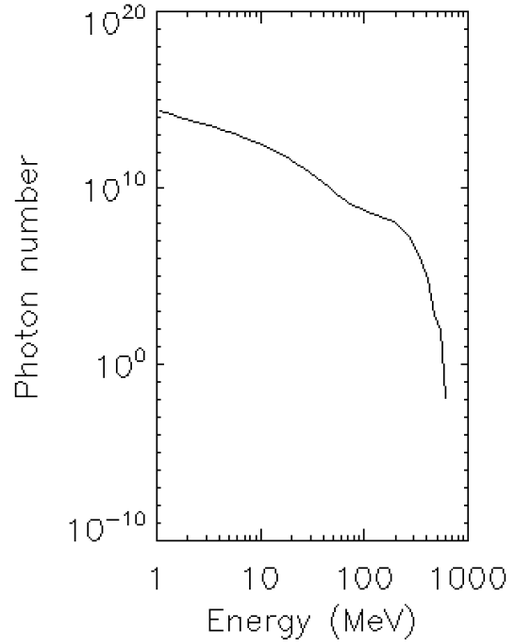


10^{22} W/cm²

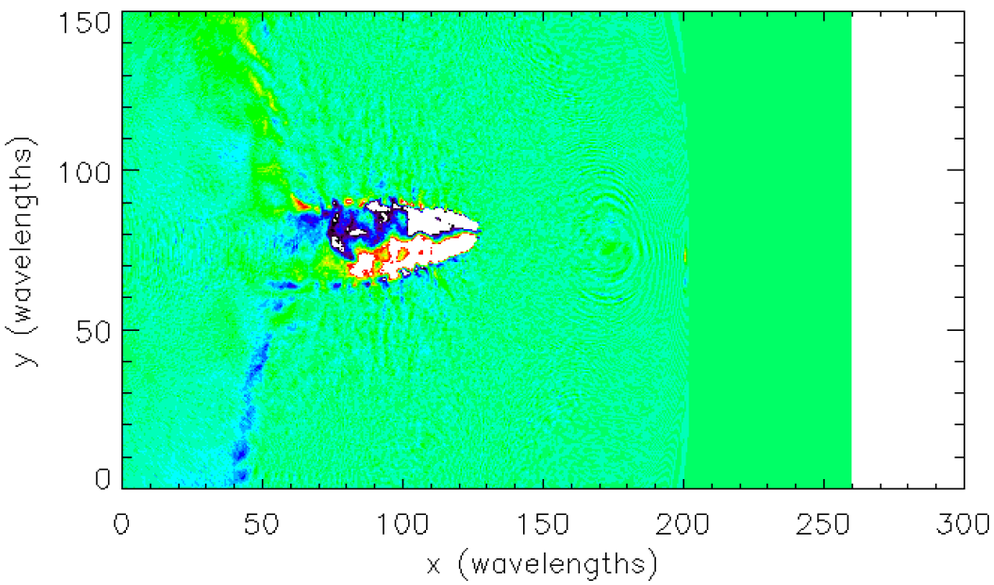
Photon angle and energy distribution, t=0.53 ps



Integrated photon spectrum, t= 0.53 ps



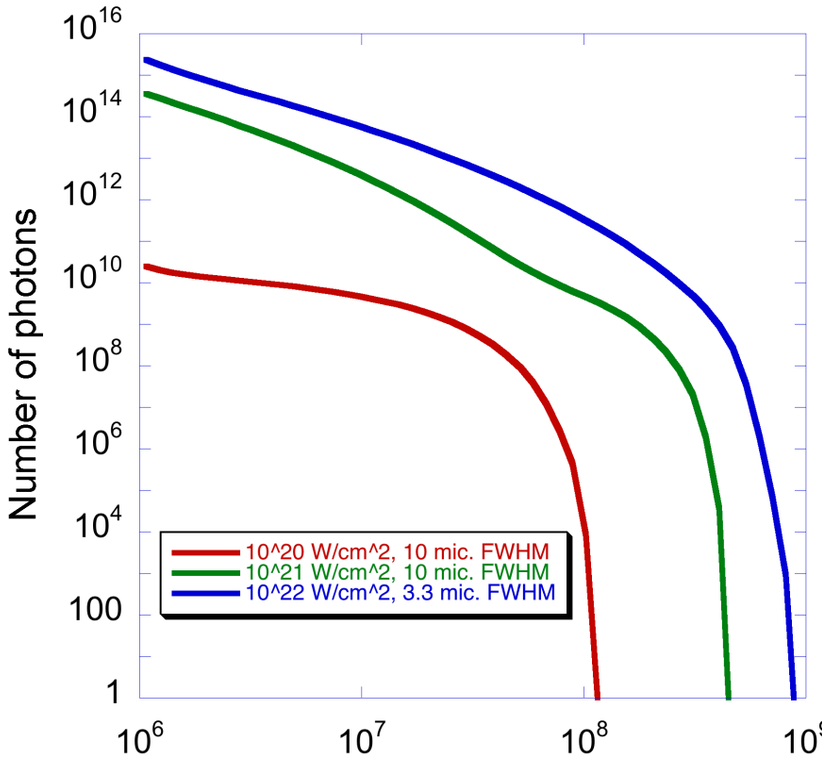
Electron density, t= 0.53 ps



B_z magnetic field, t= 0.53 ps

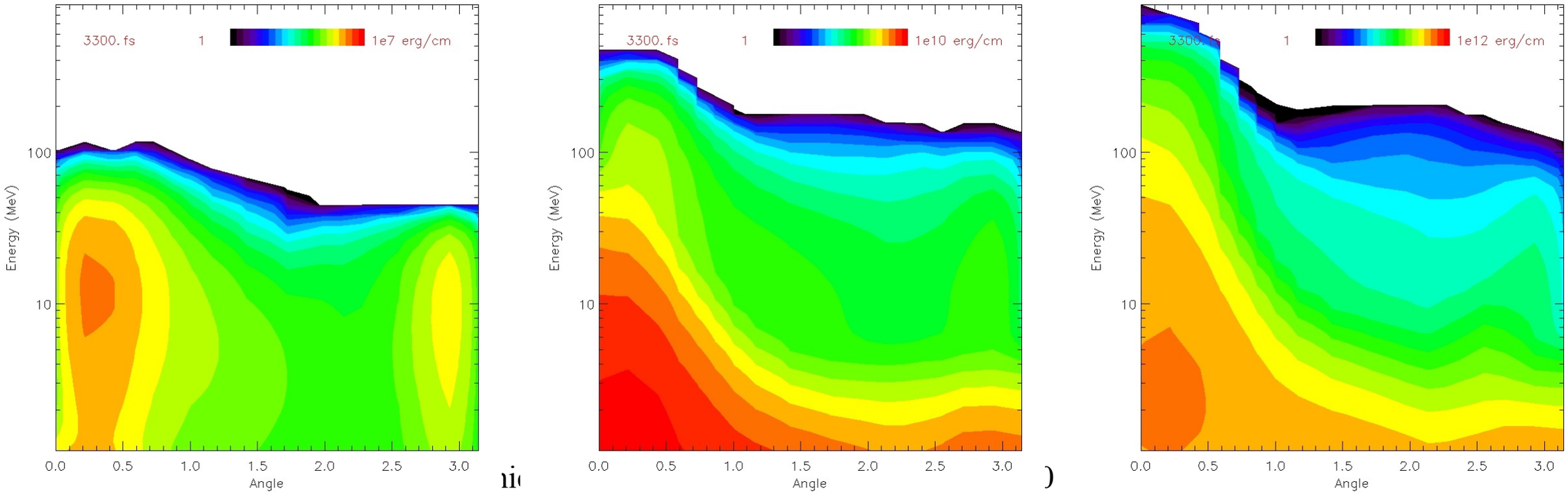
1 10^{10} erg/cm

Simulations with GSI parameters



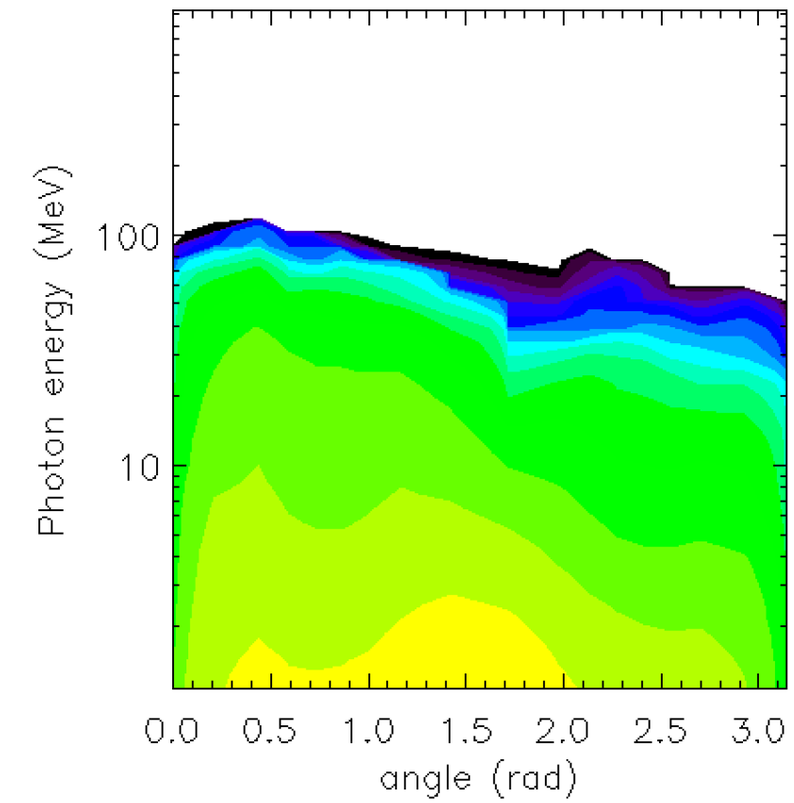
- 2D PICLS simulations with a helium plasma.
- The density profile used is a $\cos^2$, with a FWHM of 100 microns and a maximum density of 2 n_c.
- Laser pulse duration ~400 fs, focal spot ~ 3.3-10 microns, intensity ~ $10^{20\text{-}22}$ W/cm^2. The laser is p-polarized and focused at the entrance of the plasma.

10^{20} W/cm^2 10^{21} W/cm^2 10^{22} W/cm^2

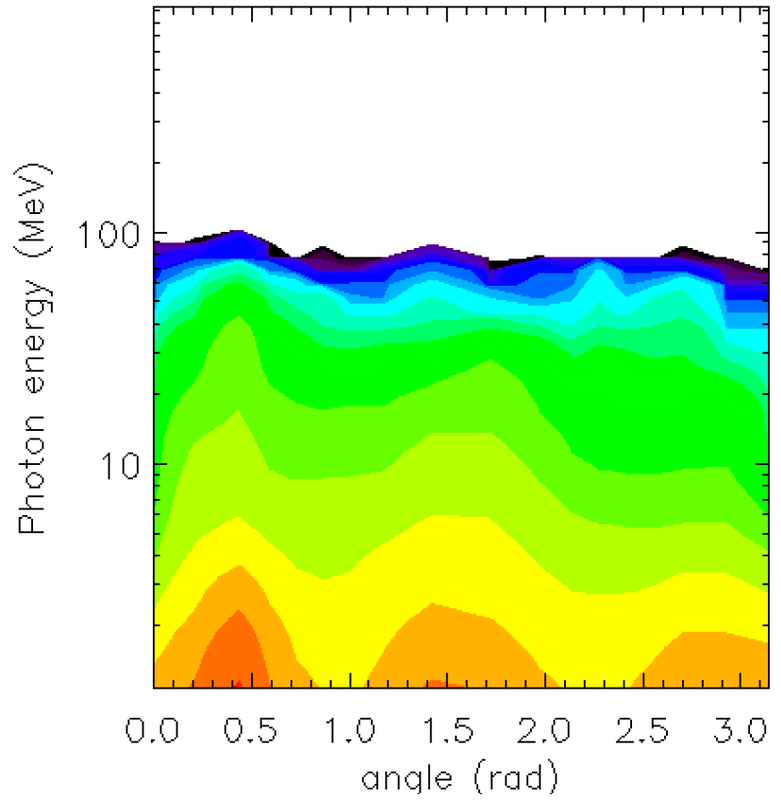


Simulations with PETAL parameters

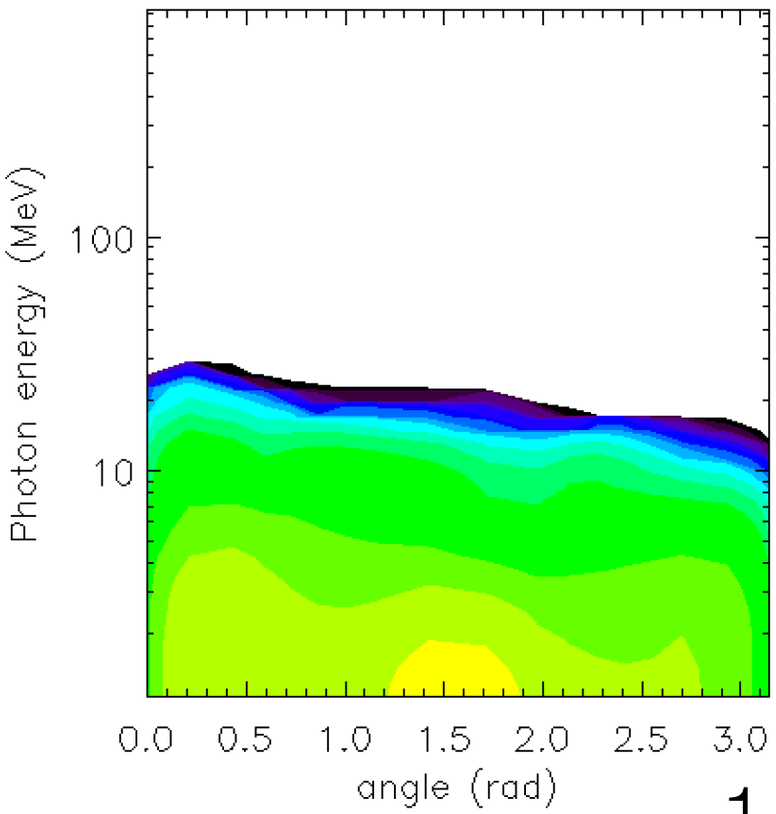
FWHM=50 μm



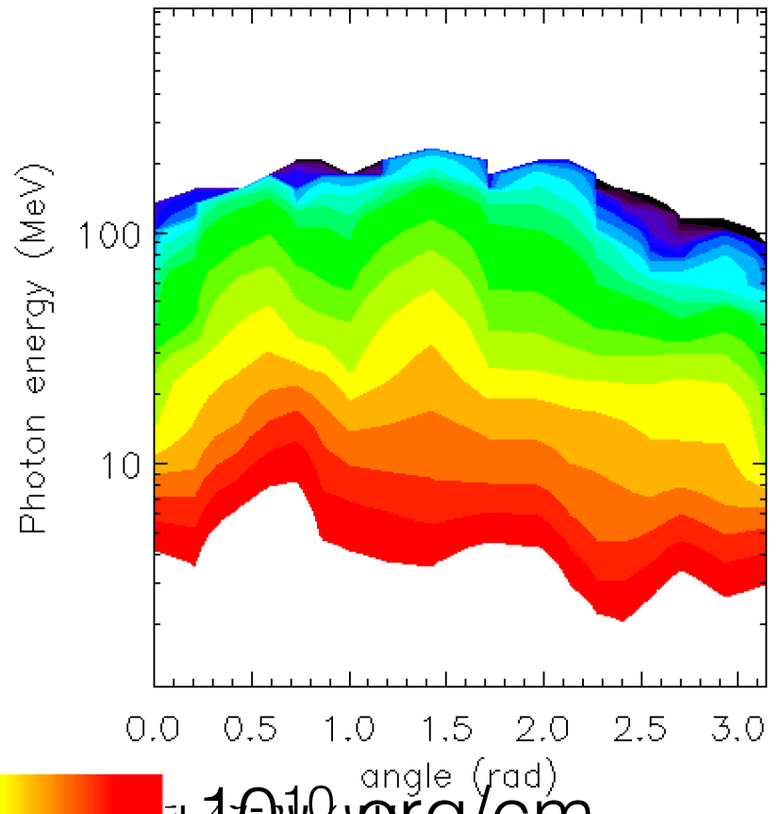
a_0= 6.584,
τ=0.5 ps
t= 1.32 ps



a_0= 9.311,
τ=0.25 ps
t= 1.32 ps



a_0= 13.168,
τ=0.125 ps
t= 1.32 ps



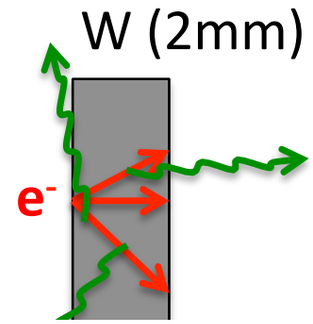
a_0= 4.6556,
τ=1 ps
t= 2 ps

1 [illegible] 10 erg/cm

Escaping particles spectra dN/(dEdθ) from GEANT4

→ Electron transport, ionisation and fluorescence

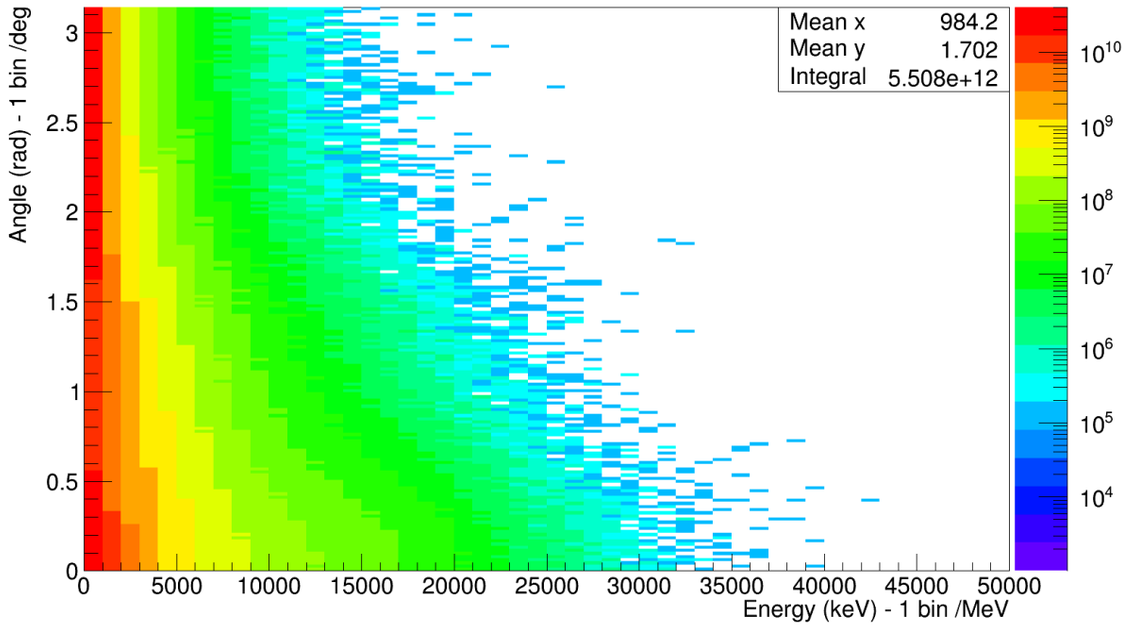
→ Secondary reactions involving e^-, e^+ and γ



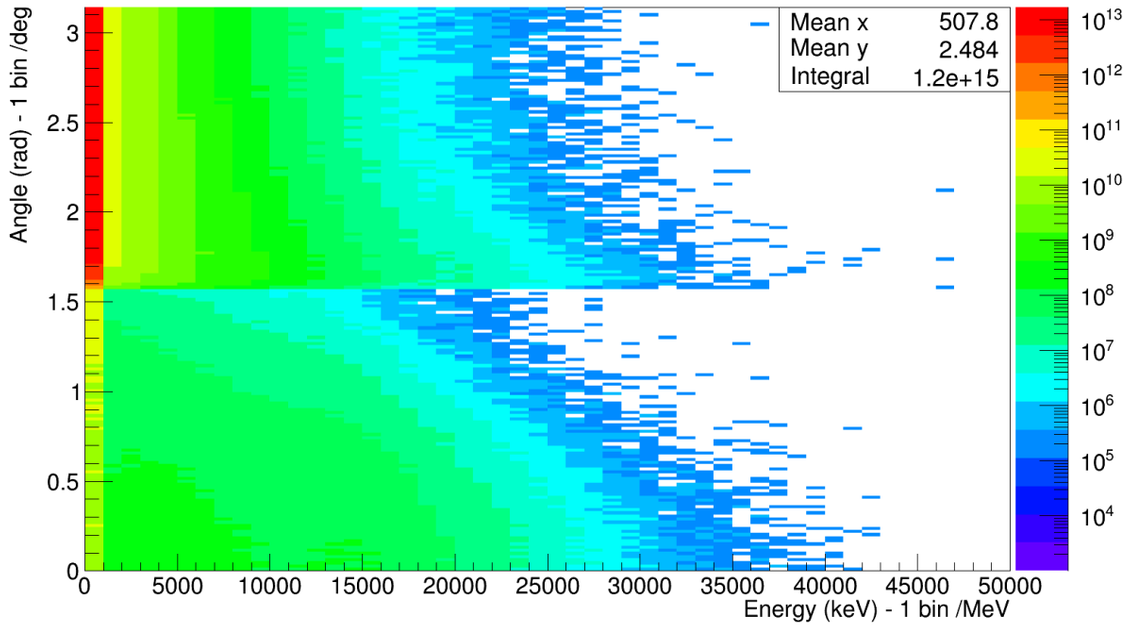
We compute the spectra with 1 keV energy bins and 0.035 radians angle bins (corresponding to 1° bin).

Spectra are here given in number of particles /MeV/ sr at a given angle.

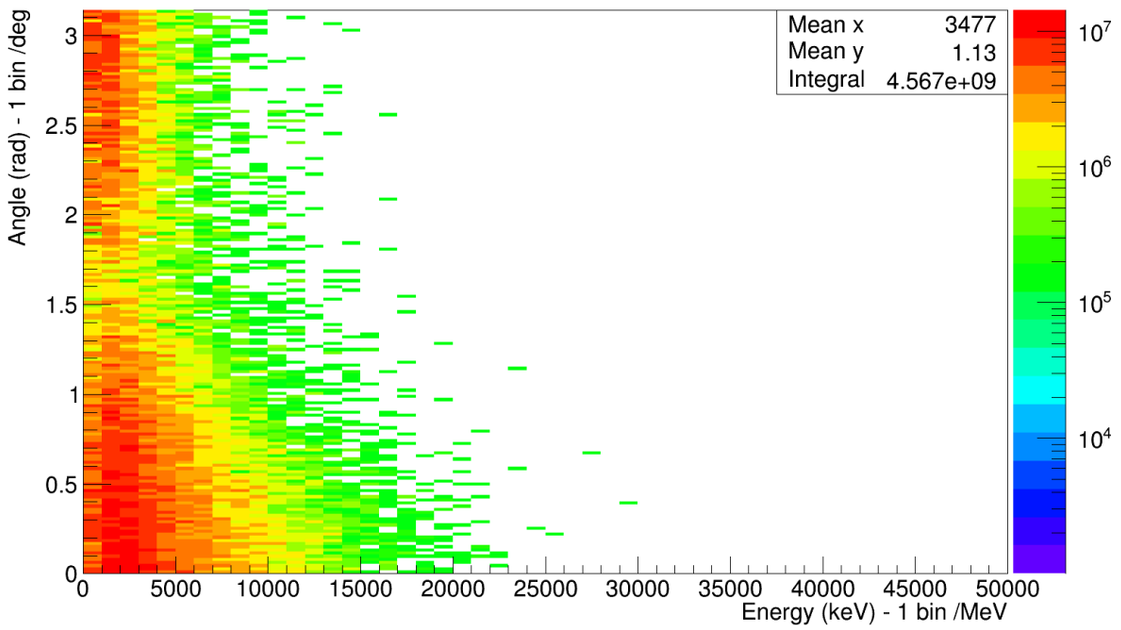
Photons /MeV /sr



Electrons /MeV /sr

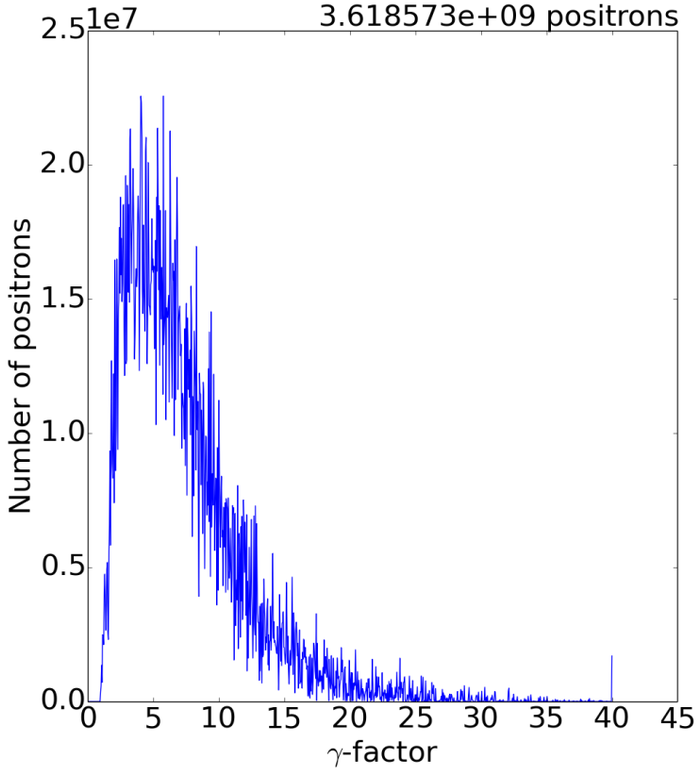


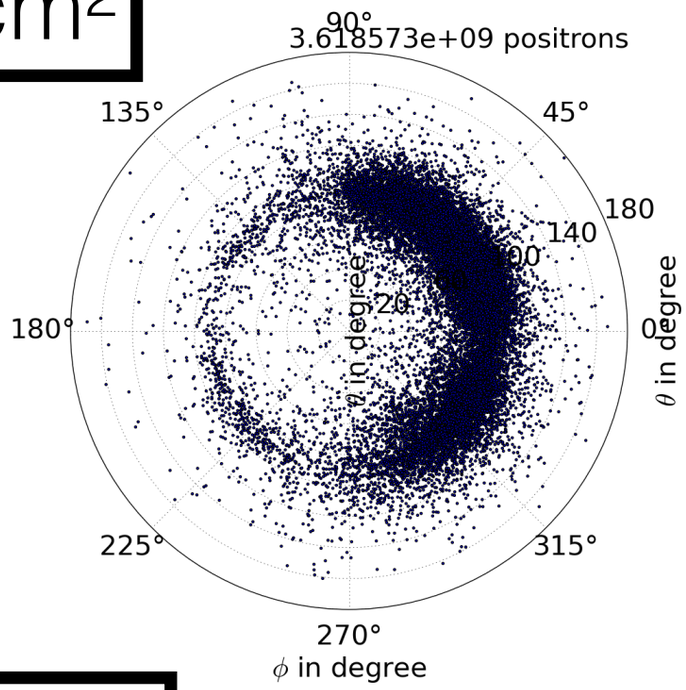
Positrons /MeV /sr

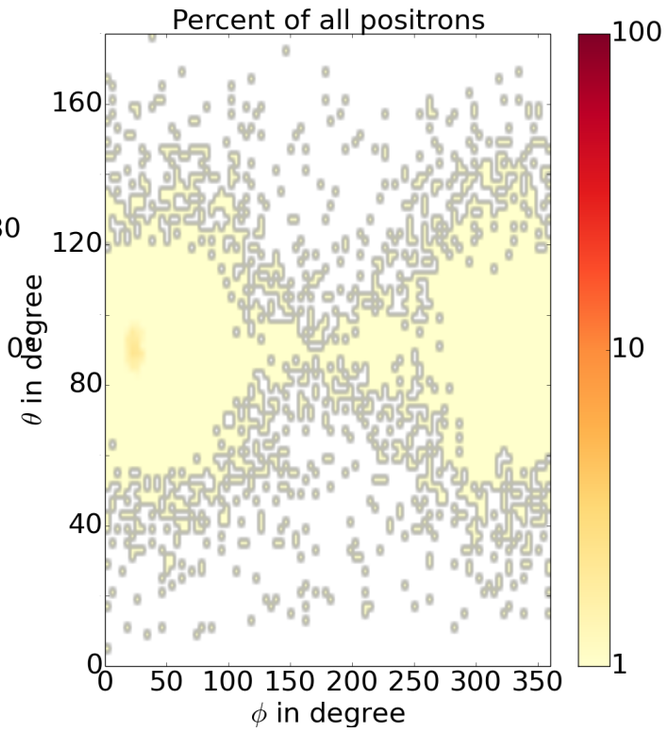


Photon collision and pair creation simulation results with INRS parameters

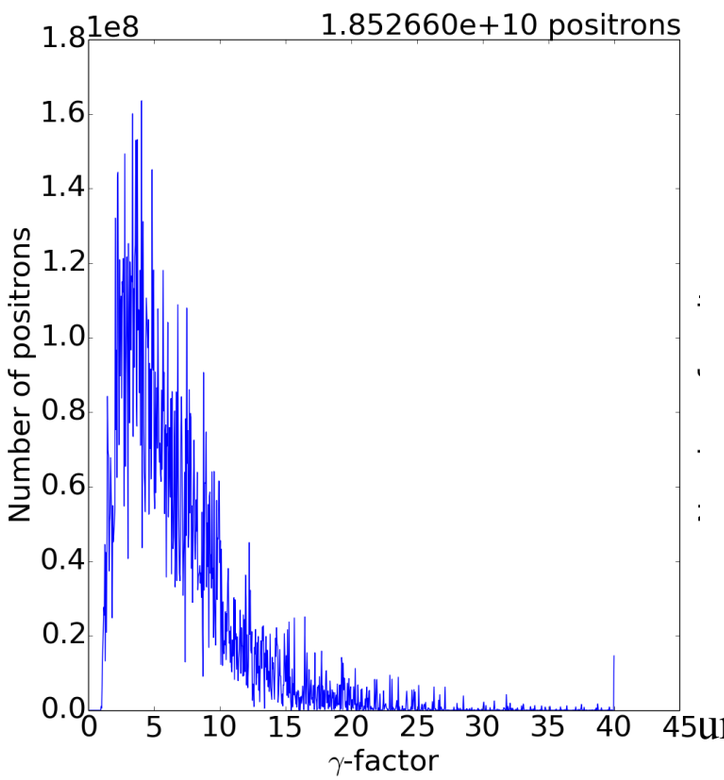
10^{22} W/cm²

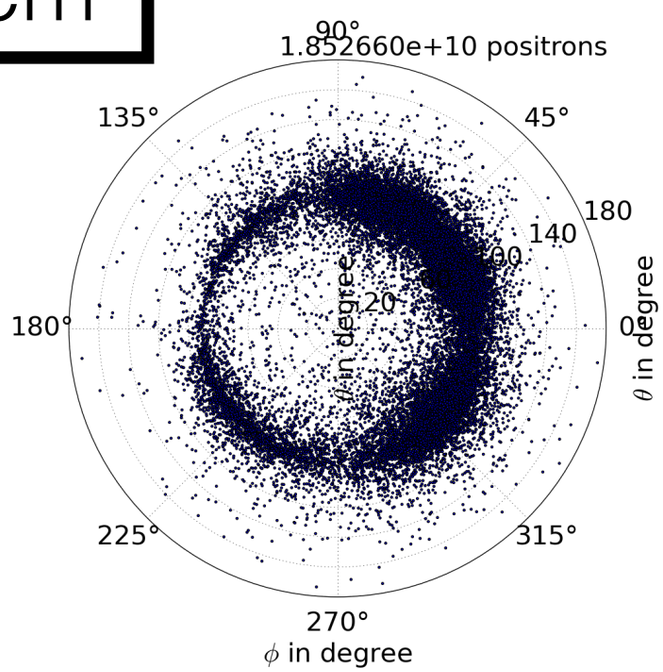


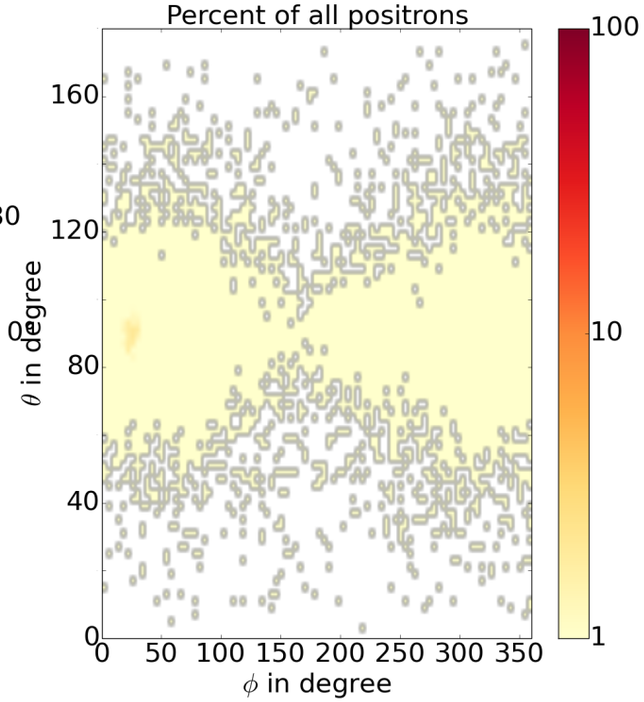




10^{23} W/cm²







Conclusions and perspectives

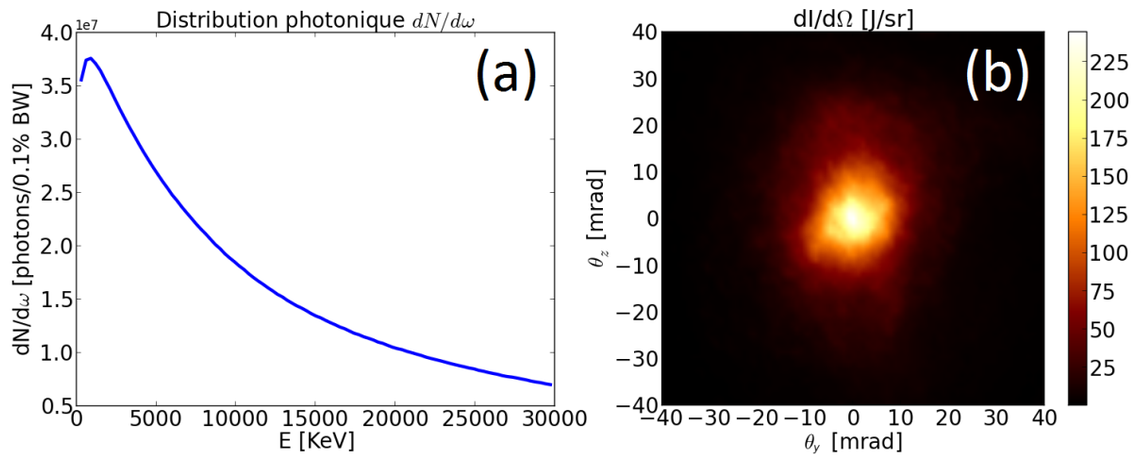
Pure Breit-Wheeler pairs creation :
- Never observed experimentally
- Great interest for fundamental physics and astrophysics
- Optimized gamma sources also have other promising applications

MeV - MeV Photons collider: **10^4** pair per shot[1]
(laser repetition rate > **1 shot per min**)
Possible experiment on ELI or Apollon facilities

[1] Ribeyre X. et al. Phys. Rev. E 93, 013201 (2016)

Optimization of the MeV-MeV setup
- Development of a photon collision tree code and study of beaming conditions
- PIC simulations to optimize gamma sources with solid and near critical targets

Perspectives:
- UHI laser installations will allow to revisit the standard model in high fields.
  → Next step: muons
- Coupling HED physics and particle physics



Betatron source on Apollon PhD Julien Ferri 2016

Further Studies:
- More source optimization: collaboration with UT using targets with channels (A. Arefiev, T. Toncian), and more sources (betatron)
- Apollon experimental proposal (optimization of the setup using simulations: PIC, tree code…, noise)