Ion acceleration in nanostructured targets

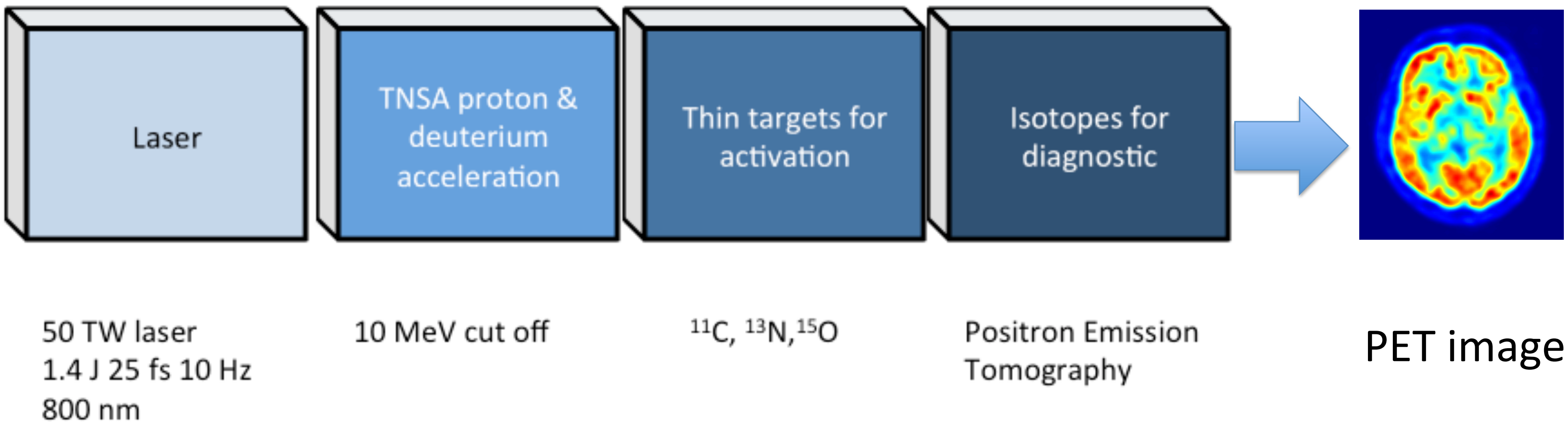
Camilo Ruiz
Instituto de Física Fundamental y Matemáticas
Universidad de Salamanca

Outline

- Motivation
- Initial question
- How to estimate the prospects for PET.
- Simulations on ion acceleration in nano structured targets
- Conclusions

L2A2: Laser Laboratory for Acceleration and Applications at the USC

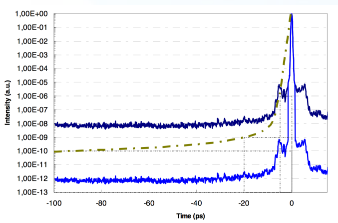
- Objectives:
  - Establish the new lab
  - Do basic science in laser plasma acceleration
  - Try to push new technology for radioisotope production from laser driven ions.
  - One of the important applications of laser driven plasma accelerators is the use of protons to produce radioisotopes.
  - The production of short-lived isotopes such as ^{11}C or ^{18}F is important in medicine for positron-emission tomography (PET).



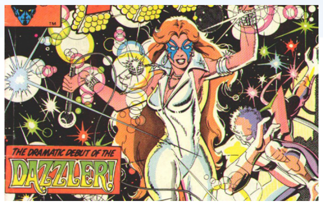
Laser system @ L2A2

Peak power	45 TW	30 GW
Nominal Energy	1.4 J	1 mJ
Pulse duration	<25 fs	<35 fs
Central wavelength	800 nm +- 10 nm	800 nm+-10 nm
Repetition rate	10 Hz	1 Khz

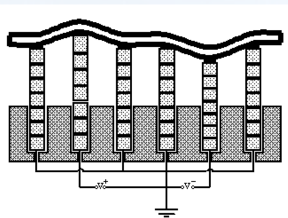
XPW: 10^{11} ps contrast



Dazzler: Spectral control



High power Adaptive Mirror



Beam pointing stability for underdense experiments

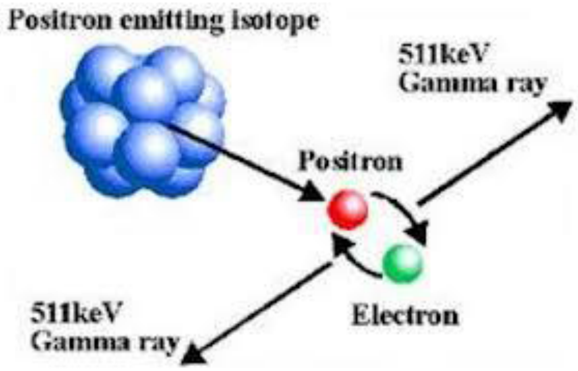
5μrad rms 500shots

Energy stability < 1.5 % rms
Strehl radio >0.6
Divergence 15 urad

Motivation: Positron Emission Tomography (PET)

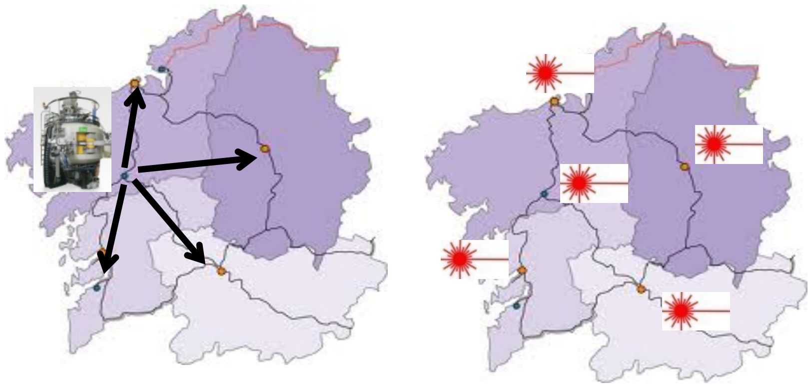
PET is considered the most sensitive 3D imaging technique:
-Positrons emitted by specific β^+ radionuclides annihilate producing two photons

-The back-to-back emission of pairs of photons from a given volume made it possible its reconstruction using appropriate image reconstruction algorithms



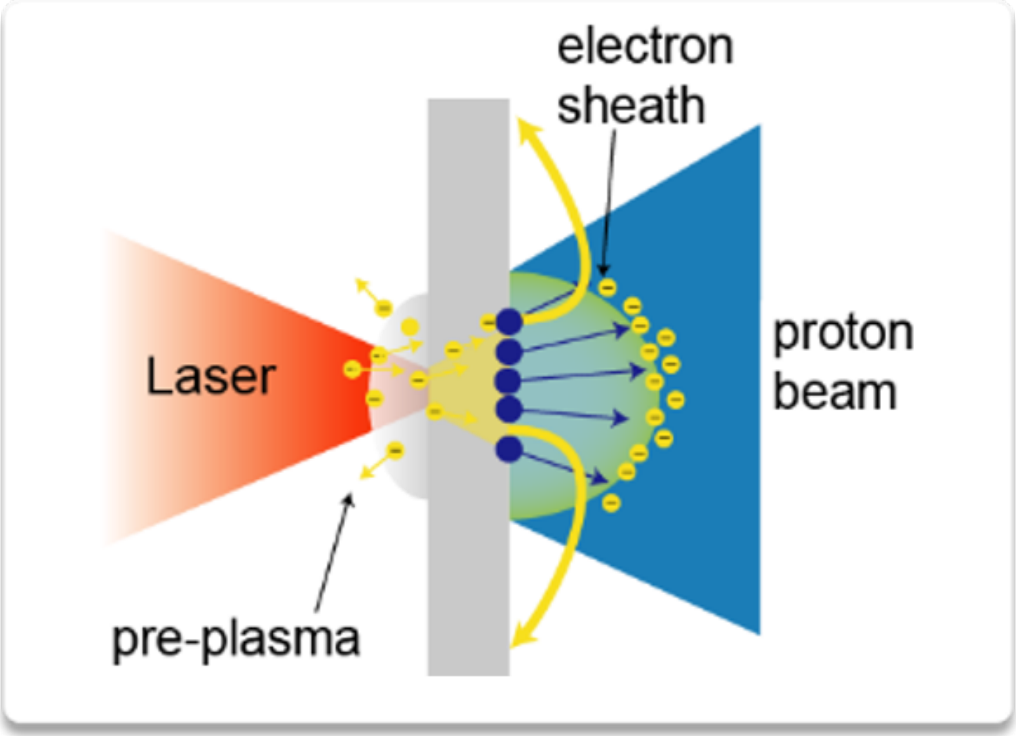
The production of radionuclides requires an accelerator with a complex infrastructure :
-The production strategy is based on a regional production center and distribution.

-Short-lived emitters can only be used close to the production center
Laser accelerators may represent an option:
Simpler and cheaper infrastructure.
Compact device that could be installed in any hospital for the production of short-lived radioisotopes



^{11}C	^{13}N	^{15}O	^{18}F
20 min.	10 min.	2 min.	110 min.

Target Normal Sheath Acceleration (TNSA)



Characteristics
- Broad spectra
- High number of protons: 10^{10}-10^{13}
- Low emittance: $4x10^{-3}$ mm/mrad
- Divergence 10-20 degrees
- Ultrashort 0.1-10 ps

Snavely et al, PRL **85** (2000) 2945
Other observations:
Clark et al, PRL **84** (2000) 670
Maksimchuk et al, PRL **84** (2000) 4108

Ion acceleration by superintense laser-plasma interaction
Andrea Macchi, Marco Borghesi, and Matteo Passoni
Rev. Mod. Phys. 85, 751

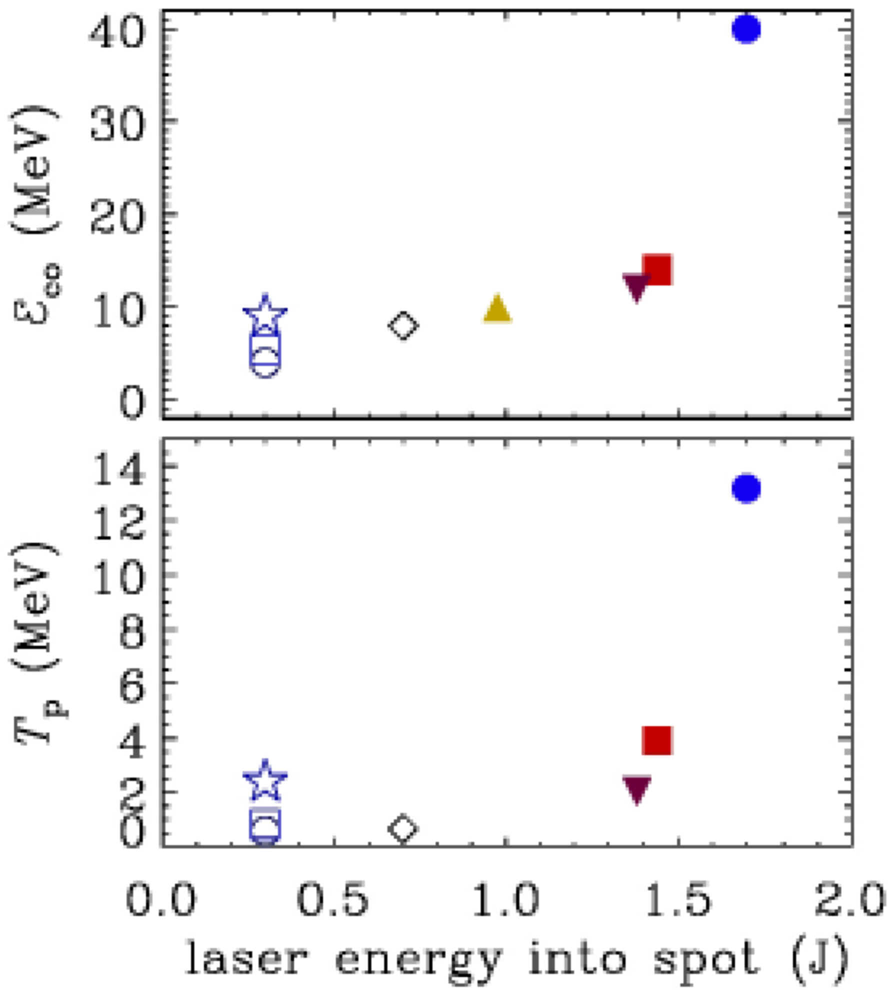
Why TNSA?

- The most studied phenomena
- Achievable with <2J per pulse
- Micron thick targets instead of nm thick targets
- Several routes for optimization described
- A broad spectrum is useful depending on the cross section

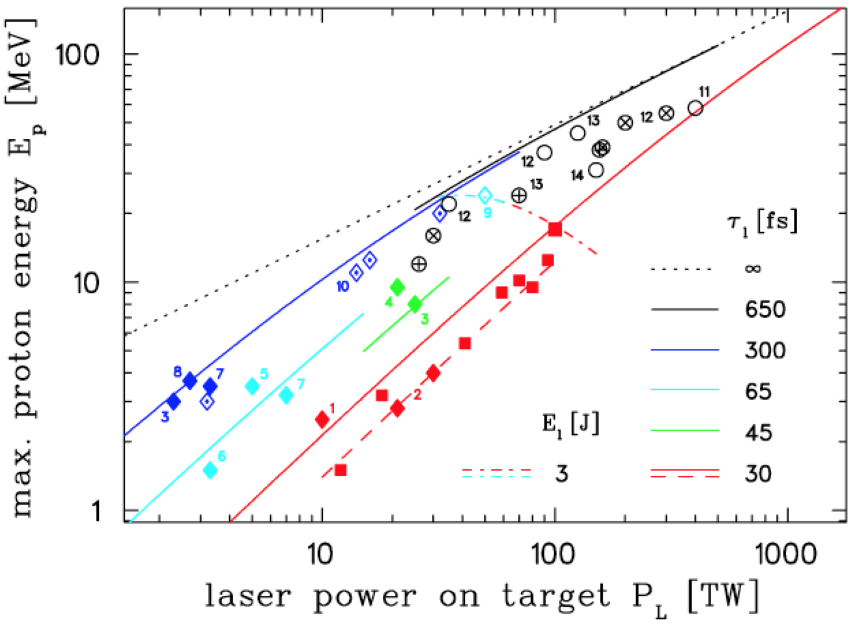
▸ progress should be monitored on small-scale lasers with potential for high repetition rate and cost-effective applications

A. Macchi

TNSA Protons: Laser energy below 2J



A. Macchi



K Zeil, et al, NJP 12 (2010) 045015 (16pp)

- **Overdense.**
- **TNSA**
- **10 um Al foils**
- **Single shot**
- **10 MeV protons**

Initial question.

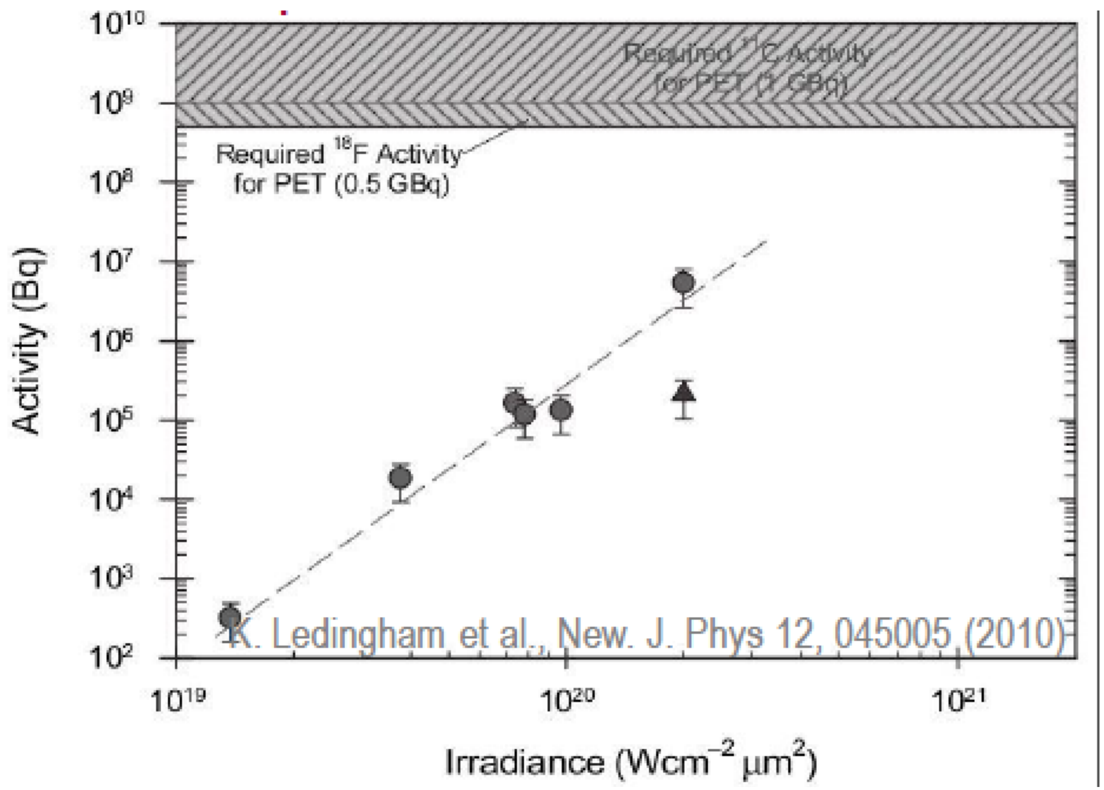
- Would it be possible to produce radioisotopes for medical imaging such as PET from laser driven ions?

The initial question:
Activation by laser produced protons

- 120 J, ~1 ps (10^{20} W/cm^2), CR ~10^6
  ^{11}C activity/shot ~ 200 kBq
  I. Spencer et al., NIMB 183, 449 (2001)

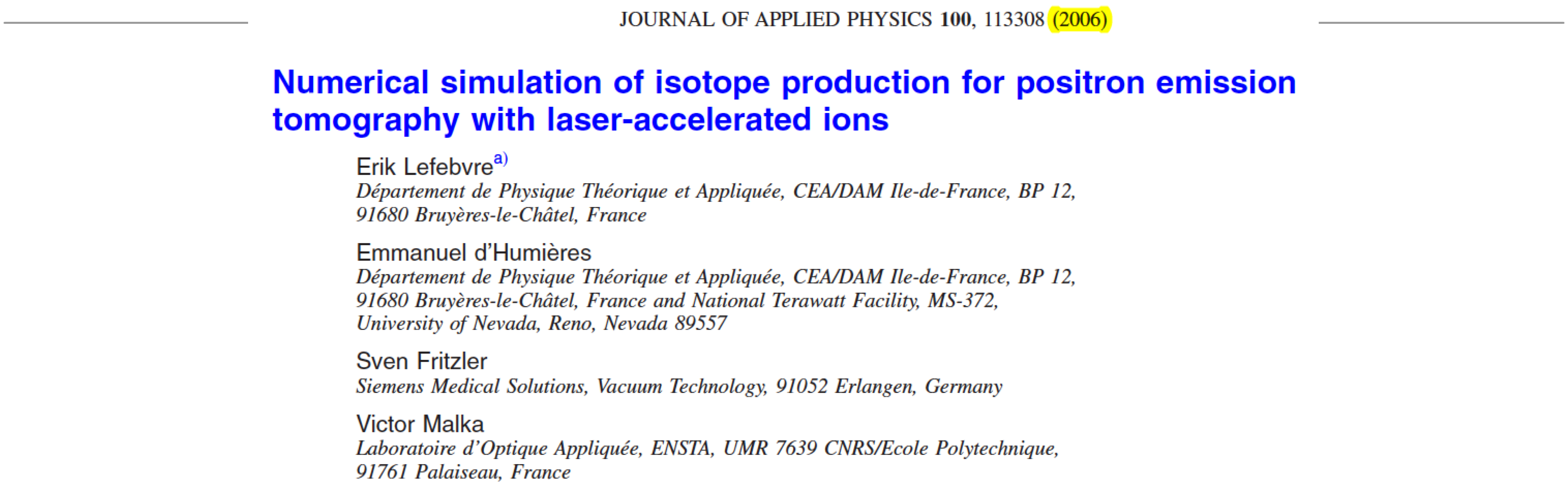
- 20-30 J, 0.3 – 0.8 ps (1-6 10^{19} W/cm^2), CR <10^6
  ^{11}C activity/shot ~ 1 MBq
  J. Fuchs et al., PRL 94, 045004 (2005)

- 0.8 J, 40 fs (6 10^{19} W/cm^2), CR <10^6
  ^{11}C activity/shot ~ 1.2 kBq
  S. Fritzler et al., App. Phys. Lett. 83, 3039 (2003)



I. Spencer, et al, Nuclear Instruments and
Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 183 (2001) 449.
S. Fritzler, et al, Appl. Phys. Lett. 83 (2003) 3039.
K. W. D. Ledingham, et al, J. Phys. D: Appl. Phys. 37 (2004) 2341.
L. Robson, et al, High-power laser production of pet isotopes, Lecture Note in Physics 694 (2006) 191.

One estimation from 2006


JOURNAL OF APPLIED PHYSICS **100**, 113308 (2006)

Numerical simulation of isotope production for positron emission tomography with laser-accelerated ions

Erik Lefebvre[a)]
Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, BP 12, 91680 Bruyères-le-Châtel, France

Emmanuel d'Humières
Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, BP 12, 91680 Bruyères-le-Châtel, France and National Terawatt Facility, MS-372, University of Nevada, Reno, Nevada 89557

Sven Fritzler
Siemens Medical Solutions, Vacuum Technology, 91052 Erlangen, Germany

Victor Malka
Laboratoire d'Optique Appliquée, ENSTA, UMR 7639 CNRS/Ecole Polytechnique, 91761 Palaiseau, France

$I = 10^{20} W/cm^2$

^{11}C	1.1×10^8	per shot	94.8 Gbq 1Khz 1hr
^{18}F	3.1×10^7	per shot	9.7 Gbq 1Khz 1hr

$I = 4 \times 10^{20} W/cm^2$

^{18}F	104 Gb (2.8 Ci) 1Khz 1hr

New estimation 2016

Study of the production yields of ^{18}F, ^{11}C, ^{13}N and ^{15}O positron emitters from plasma-laser proton sources at ELI-Beamlines for labeling of PET radiopharmaceuticals

Ernesto Amato [a], Antonio Italiano [b,*], Daniele Margarone [c], Benedetta Pagano [d], Sergio Baldari [a,d], Georg Korn [c]

[a] *Section of Radiological Sciences, Department of Biomedical and Dental Sciences and of Morphologic and Functional Imaging, University of Messina, Italy*
[b] *Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Messina, Italy*
[c] *Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*
[d] *Nuclear Medicine Unit, University Hospital "G. Martino", Messina, Italy*

Table 2
Total radionuclide activities produced at the end of bombardment (EOB), for different laser repetition rates and irradiation times, for the three proton spectra, according to Table 1.

Nuclide	$T_{1/2}$ (min)	A^{CYCL} (MBq)	T_{irr}^{CYCL} (min)	Rep. rate (Hz)	1			5			10		
				T_{irr} (min)	15	60	120	15	60	120	15	60	120
^{18}F	110	52000 (F^-)	60	**spectrum**	**Total Activity at EOB (MBq)**								
				low	1.8	6.4	10.8	9.1	31.9	53.8	18.3	63.8	107.5
				medium	11.4	39.6	66.8	56.8	198.2	333.9	113.5	396.3	667.8
				high	54.4	189.8	319.9	271.9	949.2	1599.6	543.9	1898.4	3199.1
^{11}C	20	36000 (CO)	50	**spectrum**	**Total Activity at EOB (MBq)**								
				low	2.0	4.4	5.0	10.2	22.1	24.8	20.4	44.1	49.6
				medium	32.1	69.4	78.1	160.7	346.9	390.3	321.4	693.8	780.5
				high	198.6	428.6	482.2	993.0	2143.2	2411.1	1985.9	4286.4	4822.2
^{13}N	10	4000 (NH_3)	10	**spectrum**	**Total Activity at EOB (MBq)**								
				low	0.1	0.1	0.1	0.4	0.6	0.6	0.7	1.1	1.1
				medium	44.3	67.5	68.6	221.6	337.5	342.8	443.3	675.0	685.5
				high	502.8	765.7	777.7	2514.2	3828.5	3888.3	5028.4	7657.0	7776.6
^{15}O	2	74000 (O_2)	10	**spectrum**	**Total Activity at EOB (MBq)**								
				low	5.7	5.7	5.7	28.5	28.7	28.7	57.0	57.3	57.3
				medium	7.5	7.6	7.6	37.5	37.8	37.8	75.1	75.5	75.5
				high	43.3	43.5	43.5	216.3	217.5	217.5	432.6	435.0	435.0

Diagram of the estimation

- Energy per shot.
- Intensity
- Average power

Laser

- Target
- Geometry
- electron energy distribution
- Current

Electrons

TNSA
- Proton energy distribution
- Number of ions

Protons

- Activation (p,n)
- Geometry
- Target
- Activation time

Activation

- Dose for PET

Dose

Diagram of the estimation.

- The estimation compare against the production of a cyclotrons.
- 2006. In order to compete with a regular cyclotron it is necessary to have **1PW, 1Khz**.
- 2016. "*In principle, the feasibility to produce* ***clinically relevant amounts of positron emitters, to be used for inline preparation of single doses of radiopharmaceuticals****,…, peak power* ***(PW)*** *and high repetition rate* **(10 Hz)"**.
- Consider a broader perspective.

Broader considerations for the estimation.

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

TNSA
- Proton energy dist
- Number of ions

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

Broader considerations for the estimation.

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

TNSA
- Proton energy dist
- Number of ions

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

Broader considerations for the estimation.

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

Broader considerations for the estimation.

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

Broader considerations for the estimation.

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

- Radiopharmacy cost

Broader considerations for the estimation.

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

- Radiopharmacy cost

- Advance imaging technique

Broader considerations for the estimation.

Overall cost & complexity

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

- Radiopharmacy cost

- Advance imaging technique

Broader considerations for the estimation.

Overall cost & complexity

New paradigm for radioisotope production

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

- Radiophar macy cost

- Advance imaging technique

Broader considerations for the estimation.

Overall cost & complexity

New paradigm for radioisotope production

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

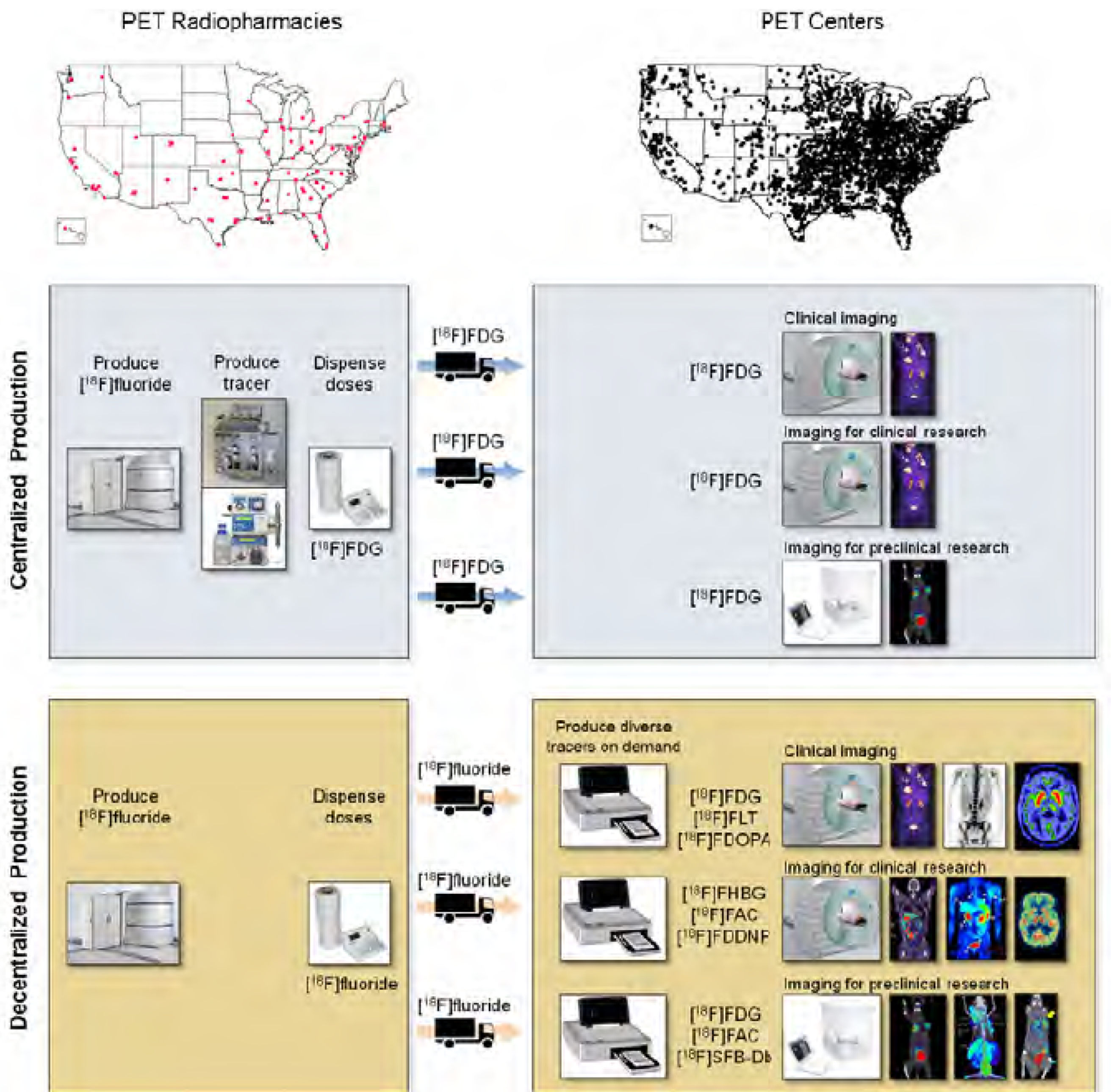
- Dose for PET

- Radiophar macy cost

- Advance imaging technique

High repetition rate

New paradigm for radio isotope production



Emerging Technologies for Decentralized Production of PET Tracers

Pei Yuin Keng[1], Melissa Esterby[1,2] and R. Michael van Dam[1]
[1]*Crump Institute for Molecular Imaging, Department of Molecular & Medical Pharmacology, David Geffen School of Medicine, University of California, Los Angeles*
[2]*Sofie Biosciences, Inc.*
USA

Overall cost & complexity

- **Large Cyclotrons**
- Commercial installations are large facilities
- A special building
- Designed to produce a large number of doses
- Cost effective use depend on number of PET scanners
- Strong restriction on research related to new pharmaceuticals in preclinical
- Short lifetime (110 min) implies dose will undergo multiple half life of decay before use
- Careful planning
- Only FDG

- **Laser**
- Not a special building, limited shielding
- Lowest possible energy
- Adjusted to single dose production
- Minimal down time
- Radiopharmacy tuned for single dose (Lab on chip)
- Fully automated extraction

Overall cost & complexity

- **Large Cyclotrons**
- Commercial installations are large facilities
- A special building

- Only FDG

- **Laser**
- Not a special building, limited shielding
- Lowest possible energy
- Adjusted to single dose production
- Minimal down time
- Radiopharmacy tuned for single dose (Lab on chip)
- Fully automated extraction

Overall cost & complexity

- **Large Cyclotrons**
- Commercial installations are large facilities
- A special building

- Only FDG

- **Laser**
- Not a special building, limited shielding

- Fully automated extraction

New diagram for the estimation.

Overall cost & complexity

New paradigm for radioisotope production

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

- Dose for PET

- Radiophar macy cost

- Advance imaging technique

High repetition rate

Nano and micro structured target

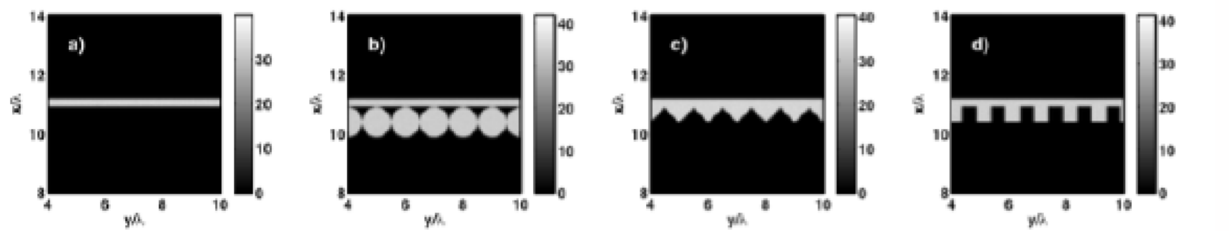
State of the art

Microstructuring the front of the target surface enhances energy absorption and improves ion acceleration [1-7].

The increased absorption creates more energy available for the particles to be accelerated.

[1] Phys. Plasmas 18(10) (2011)
[2] Contrib. Phys. Plasmas 53(2), 173-178 (2013)
[3] Plasma Phys. and Control. Fusion 58, 014038 (2016)
[4] New J. Phys. 13, 053028 (2011)
[5] Phys. Rev. Lett. 109, 234801 (2012)
[6] Phys. Rev. Lett., 110, 215004 (2013)
[7] Nature Lett. 439(26), 445-448 (2006)

5 IOP Institute of Physics DEUTSCHE PHYSIKALISCHE GESELLSCHAFT



Target (figure 1)	Electron temperature (MeV)	Electron divergence (°)	Laser absorption (%)
(a)	0.10	14.8	3.8
(b)	0.40	39.7	55.2
(c)	0.42	41.8	80.5
(d)	0.37	40.9	43.9

Image from [4]

Triangular shapes

Why a triangular shape?

Proton cutoff and energy absorption are enhanced compared to others [4].

There are prospects of using easier-to-make tilted triangles: possibly better for oblique incidence experiments.

Experimental limitations

Structure height below a wavelength and below bulk thickness

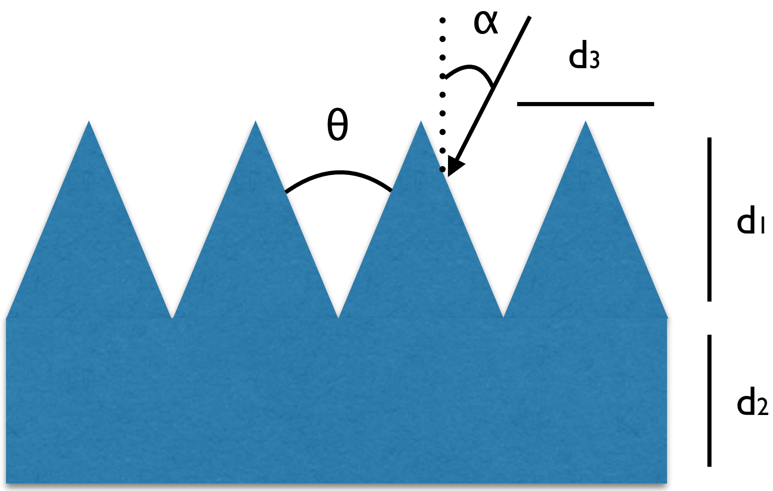
Parameters to vary

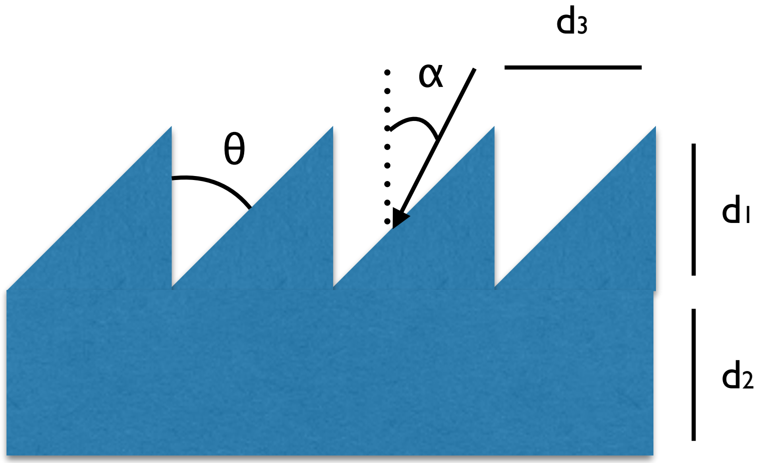
- The structure height
- The triangle width
- The bulk thickness
- The angle of incidence

[4] New J. Phys. 13, 053028 (2011)

Shapes

The angle of incidence of the laser is represented by α.





Triangular shapes

Why a triangular shape?

Proton cutoff and energy absorption are enhanced compared to others [4].

There are prospects of using easier-to-make tilted triangles: possibly better for oblique incidence experiments.

Experimental limitations

Structure height below a wavelength and below bulk thickness

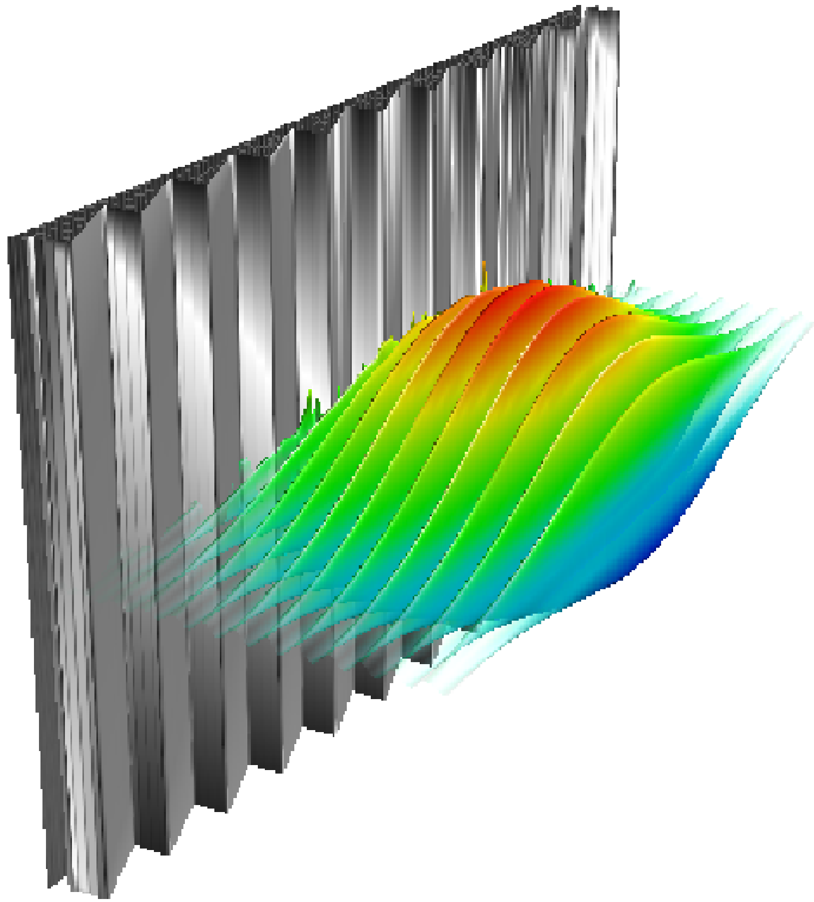
Parameters to vary

- The structure height
- The triangle width
- The bulk thickness
- The angle of incidence

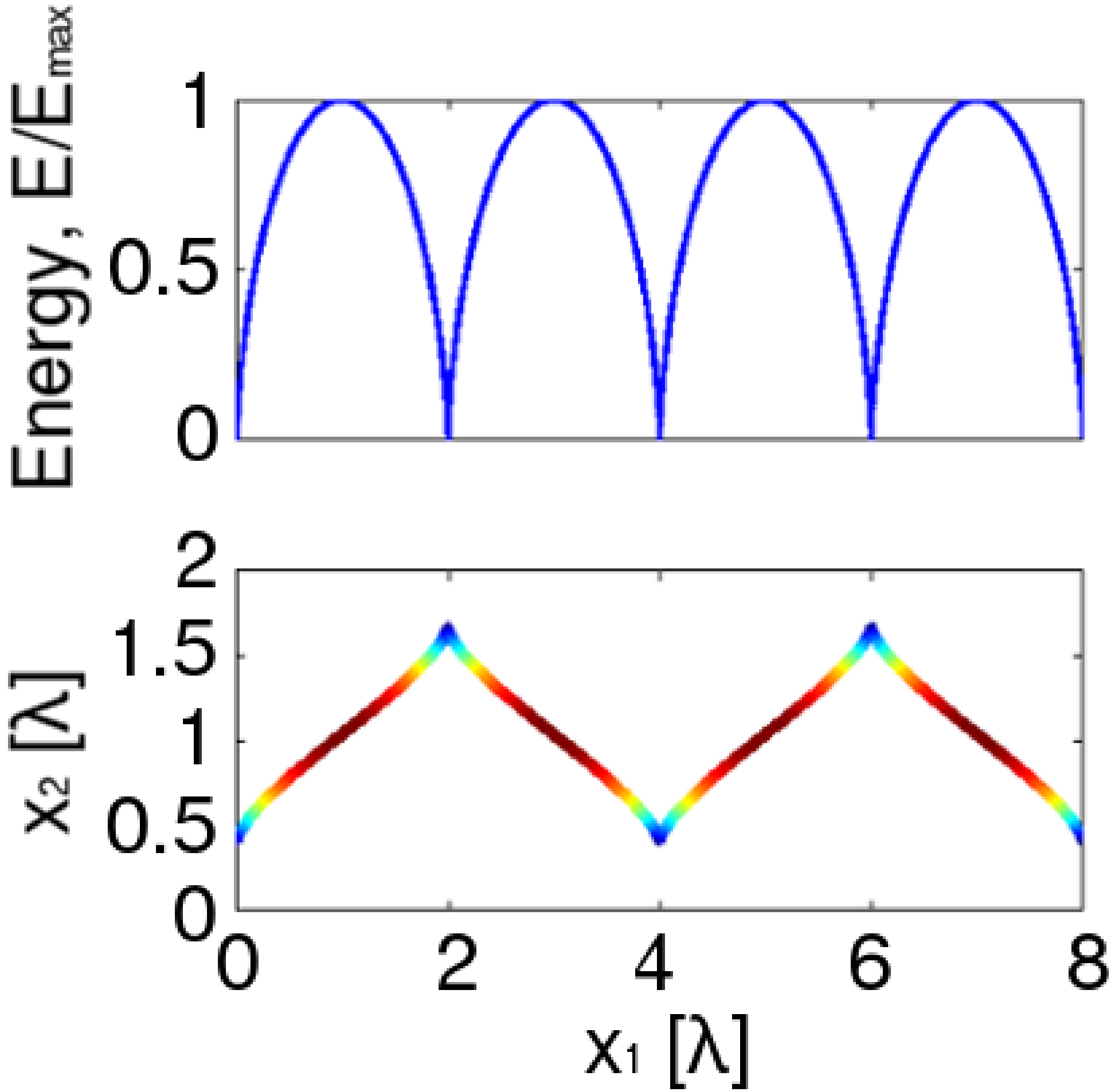
[4] New J. Phys. 13, 053028 (2011)

Shapes

The angle of incidence of the laser is represented by α.

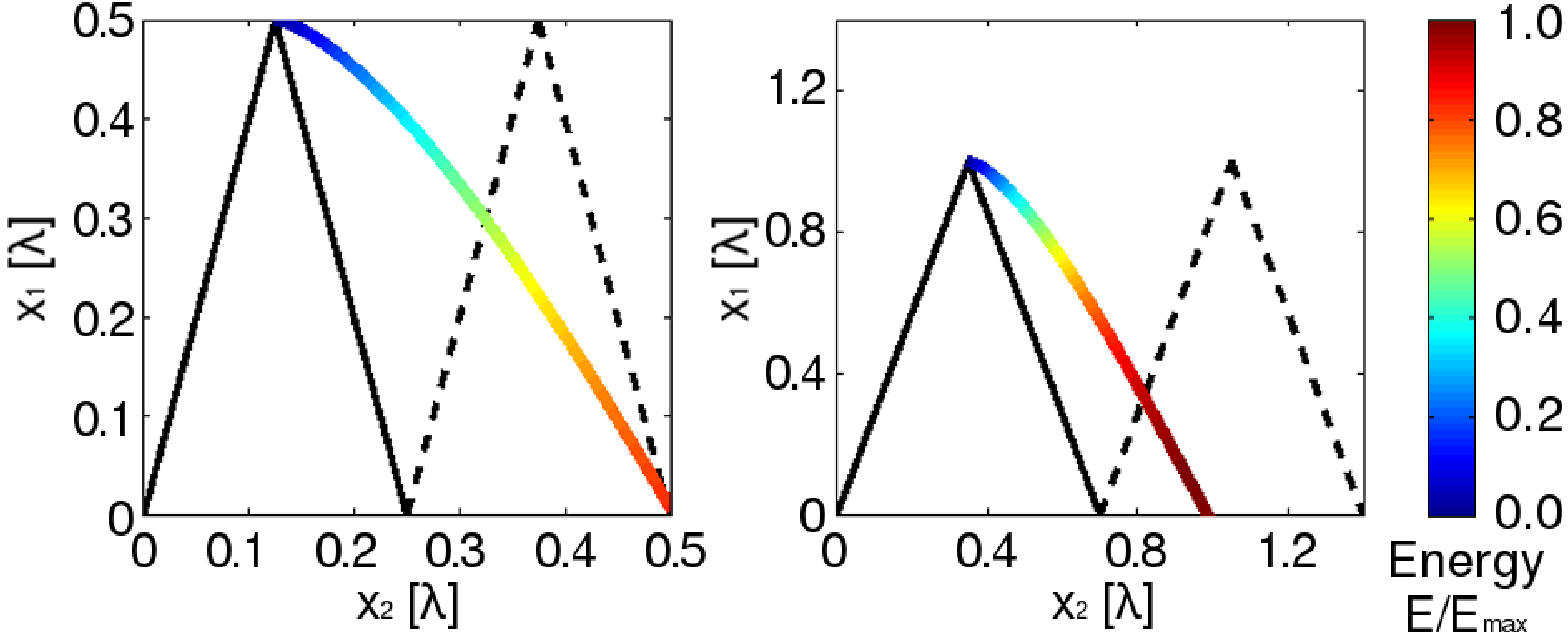


Simple idea



Simple idea

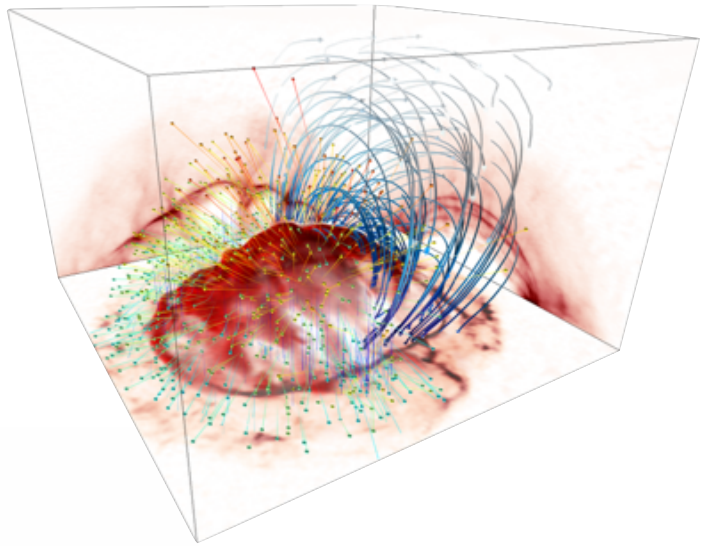
- Use the geometry of the target to optimize the energy delivered by the electron to the target

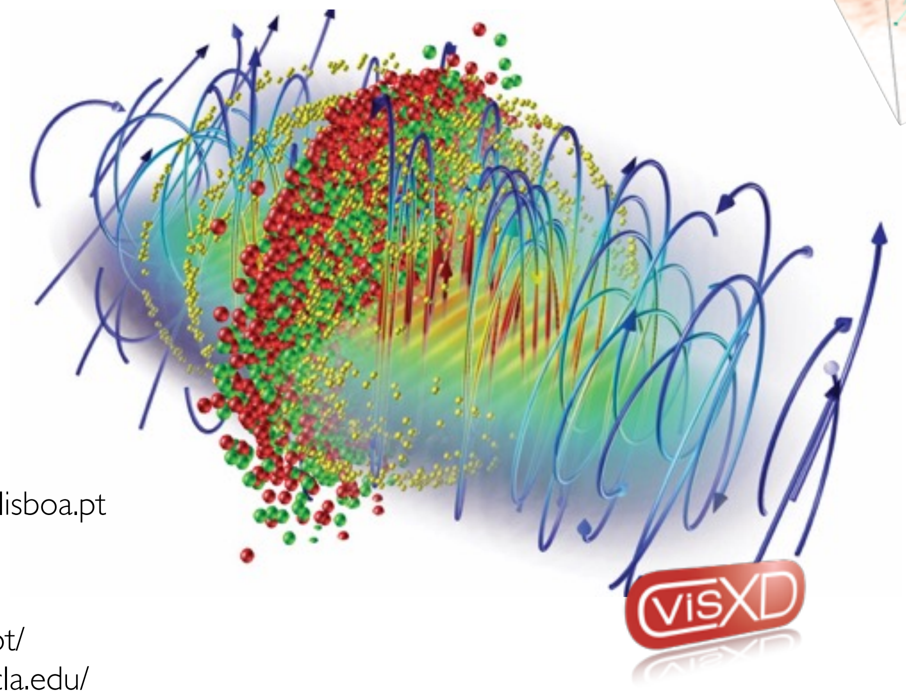


OSIRIS PIC code

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





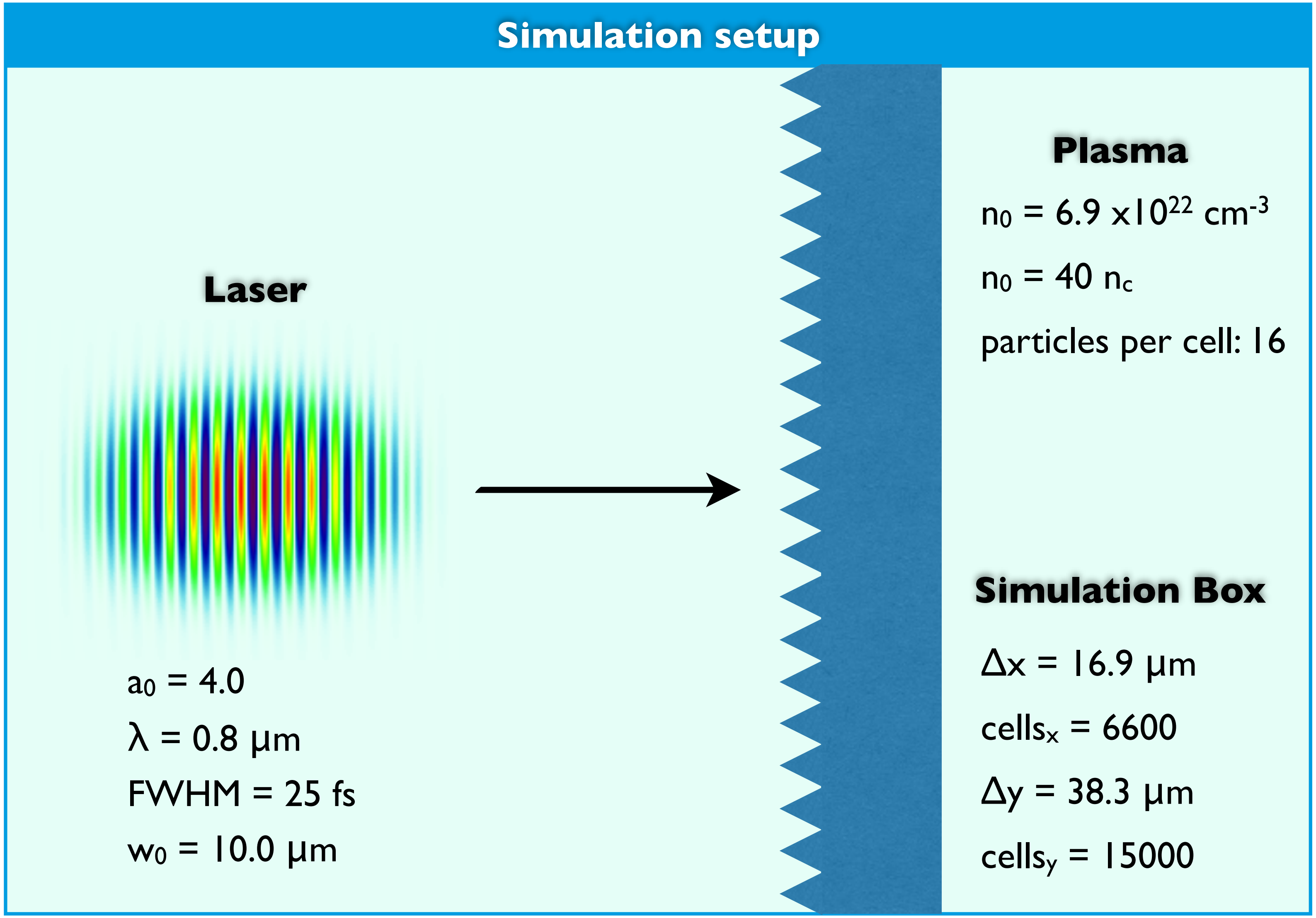
code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- Particle merging
- GPGPU support
- Xeon Phi support
- QED Module

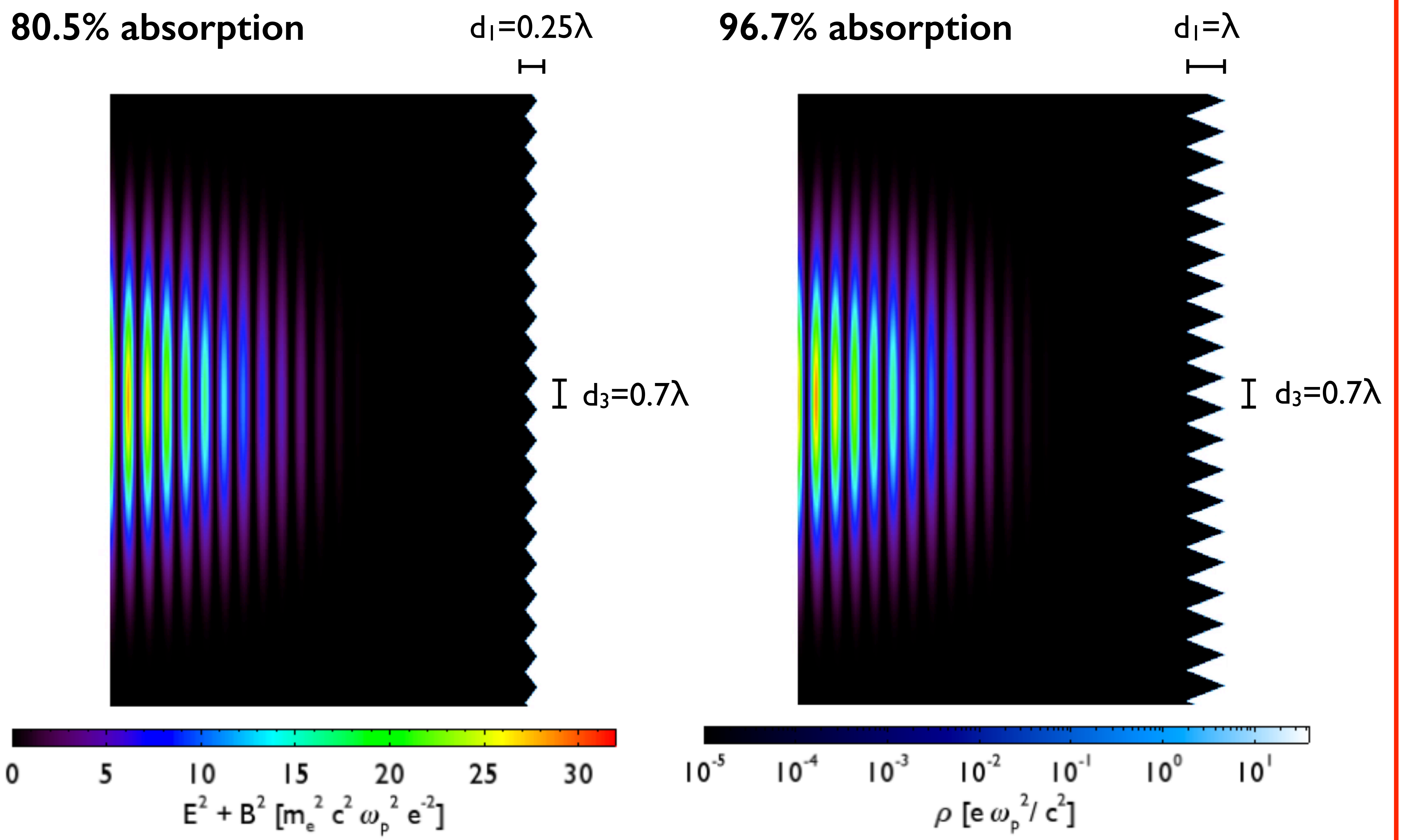
Ricardo Fonseca
ricardo.fonseca@tecnico.ulisboa.pt
Frank Tsung
tsung@physics.ucla.edu

http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/

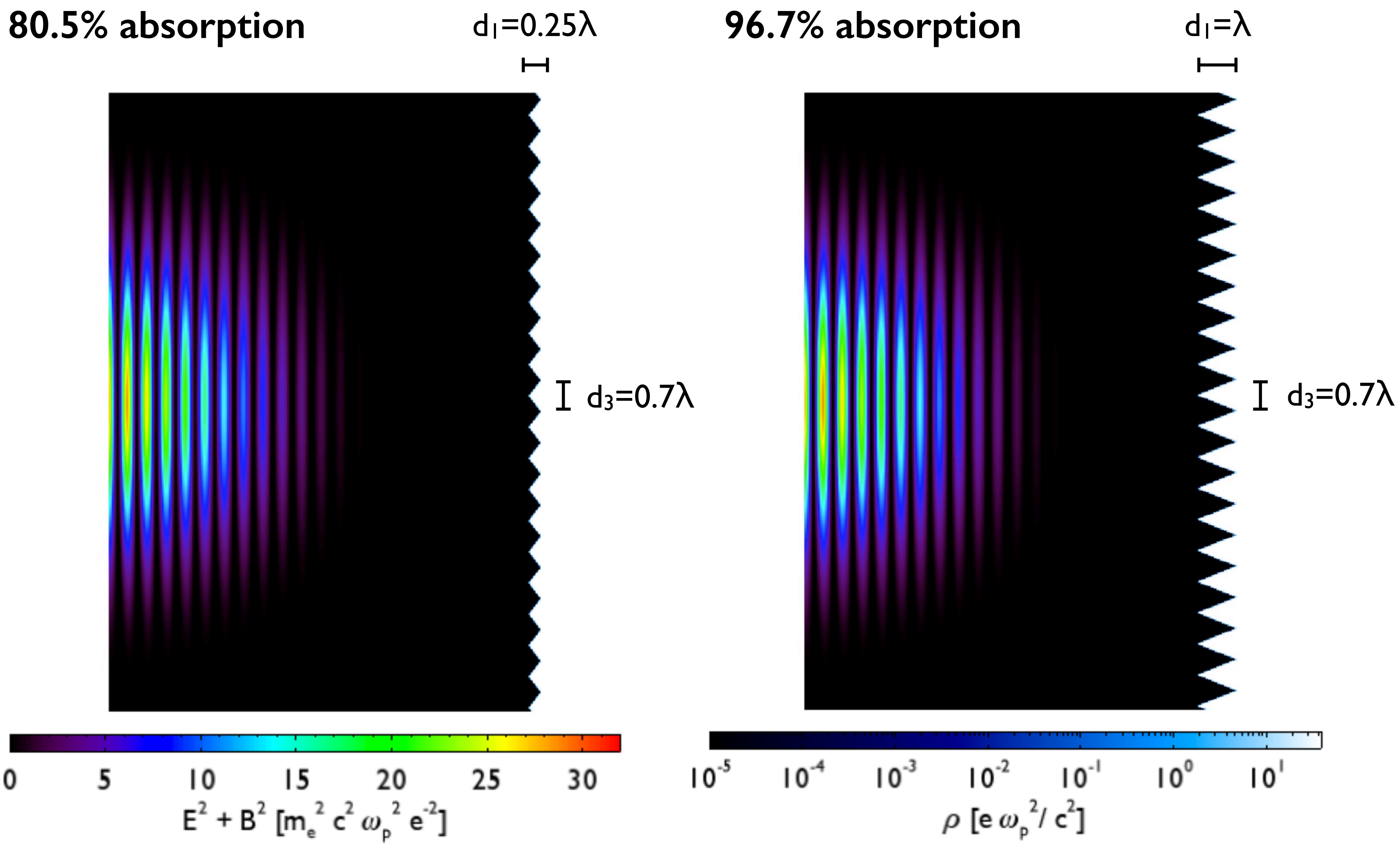
Simulations in 2D for parameter scan



Different structures mean different absorption

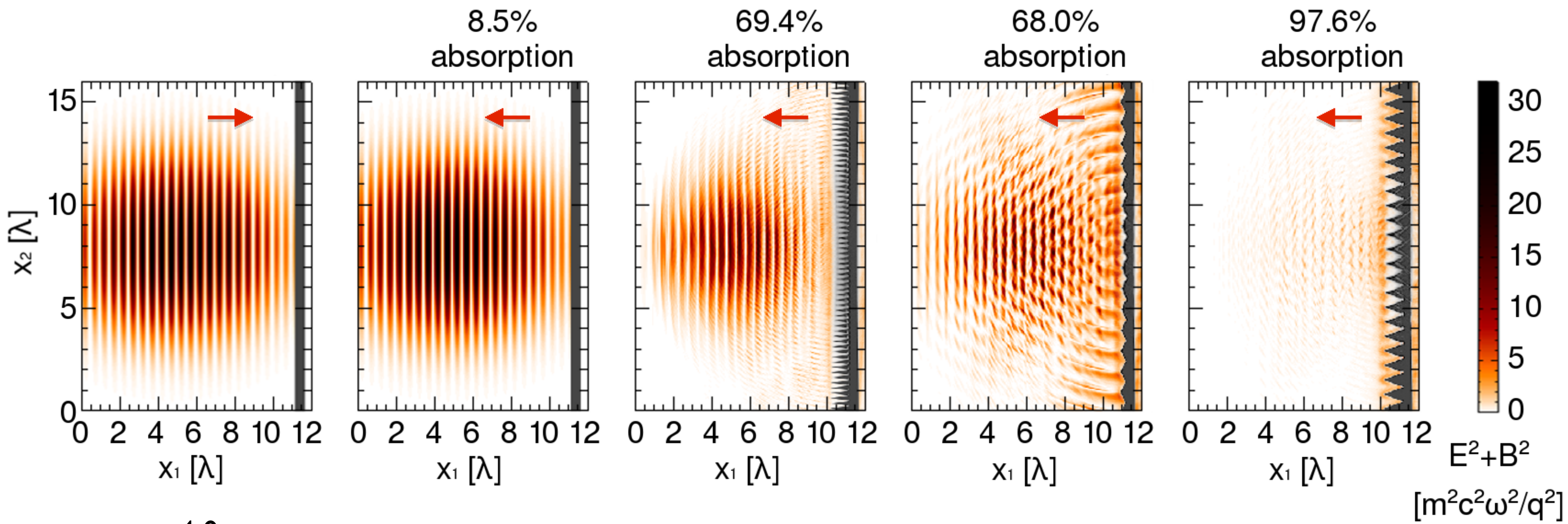


Different structures mean different absorption



Laser absorption

- Reflected field for different parameters of the structure



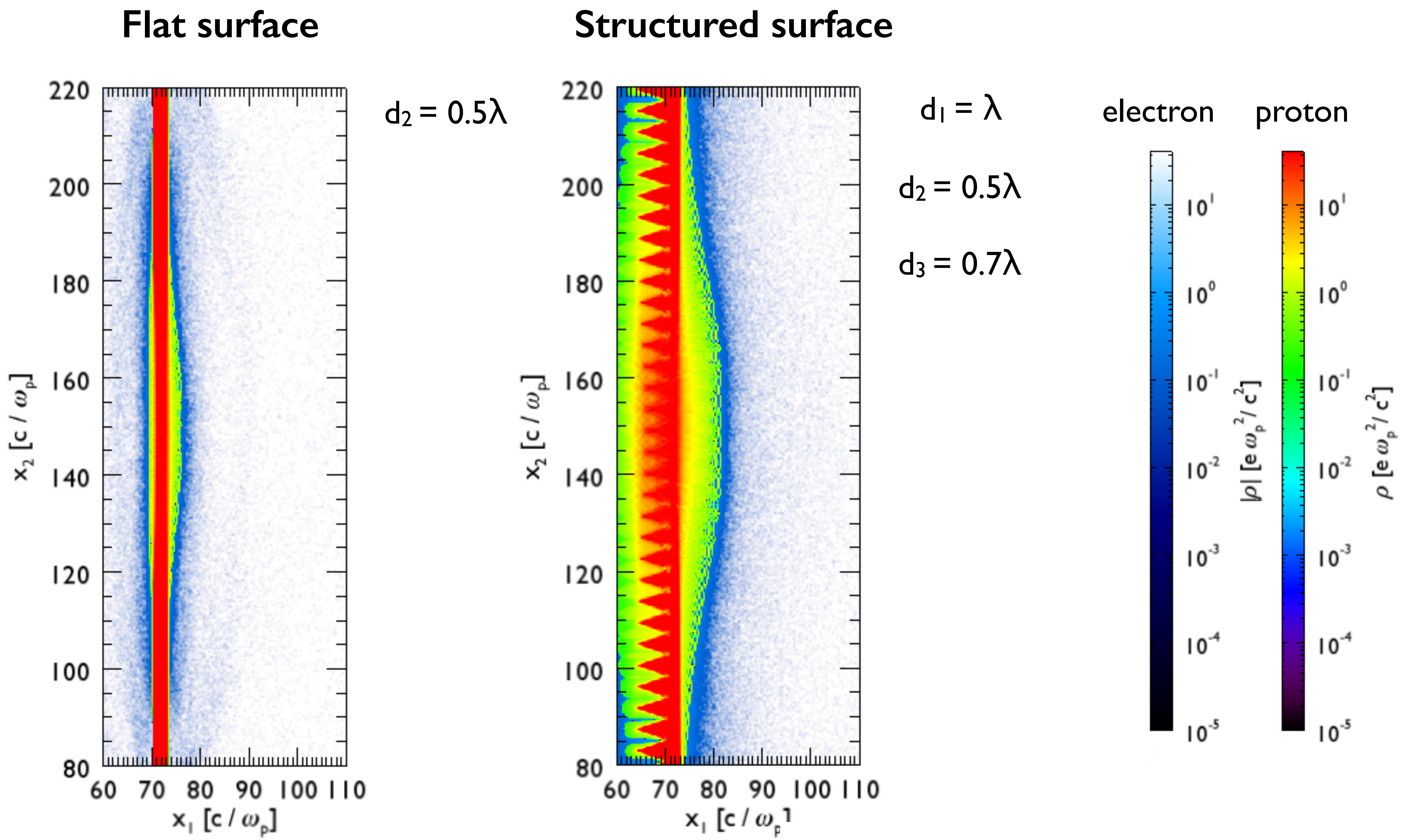
$a_0 = 4.0$

$\lambda = 0.8\ \mu m$

FWHM = 25 fs

$w_0 = 10.0\ \mu m$

Mechanism for proton acceleration



Effect of the width of the triangular structure

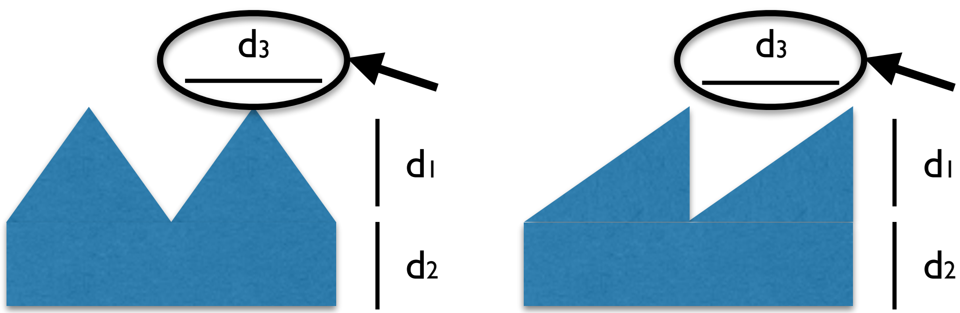
Effect of the width

- If $d_3 << \lambda$: The structures become invisible.
- If $d_3 >> \lambda$: The surface becomes flat.

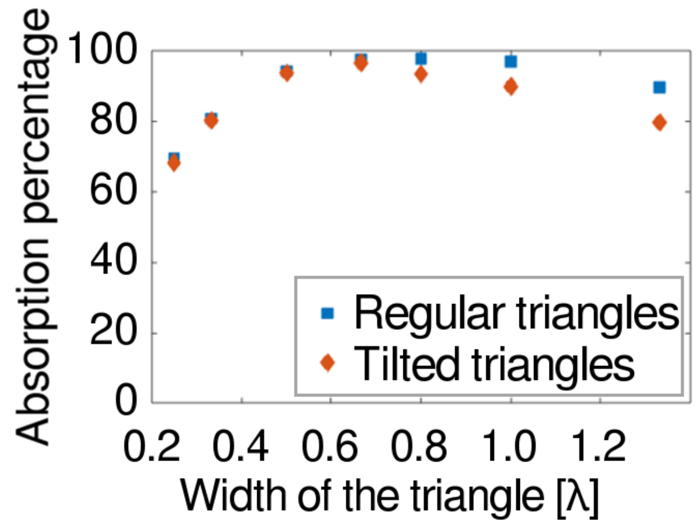
Model and data show maximum absorption for a width:

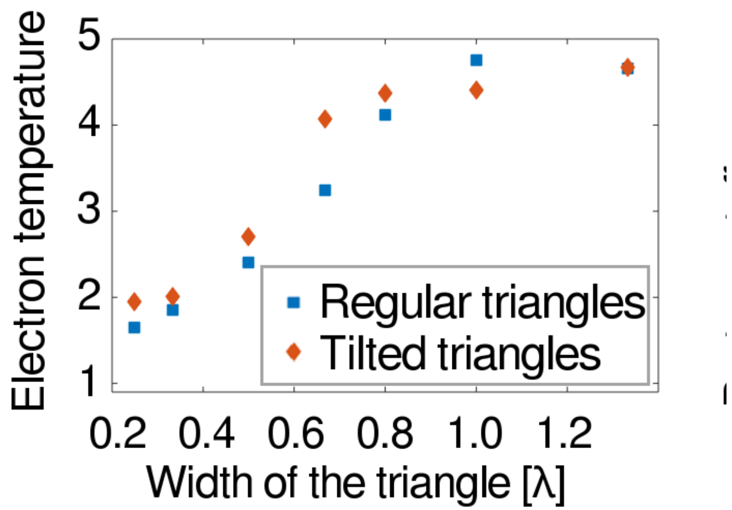
$$d_{3,max} = 2a_0\lambda(\pi n_e)^{-1/2} = 0.7\lambda$$

$d_2 = 0.5\lambda$



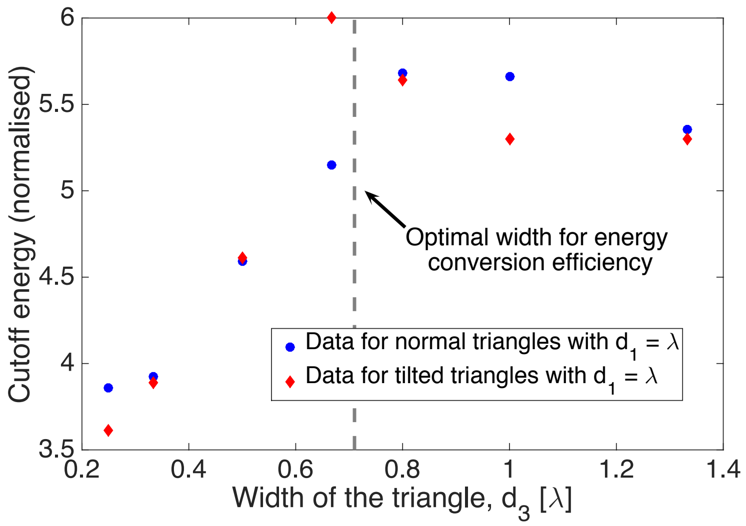
Absorption/Electron energy



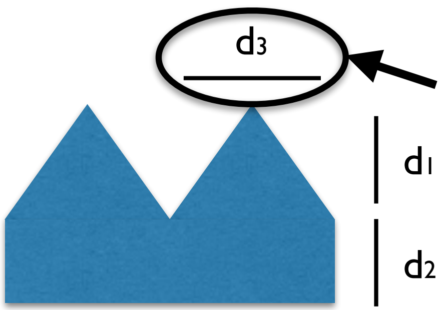


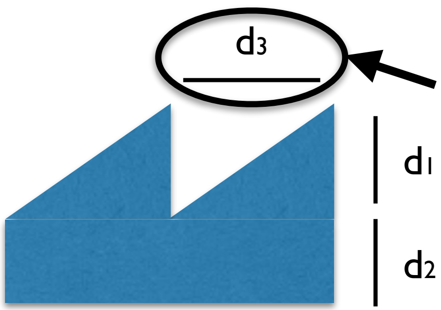
Effect of the width of the triangular structure

Proton cutoff energy (t=405/w)



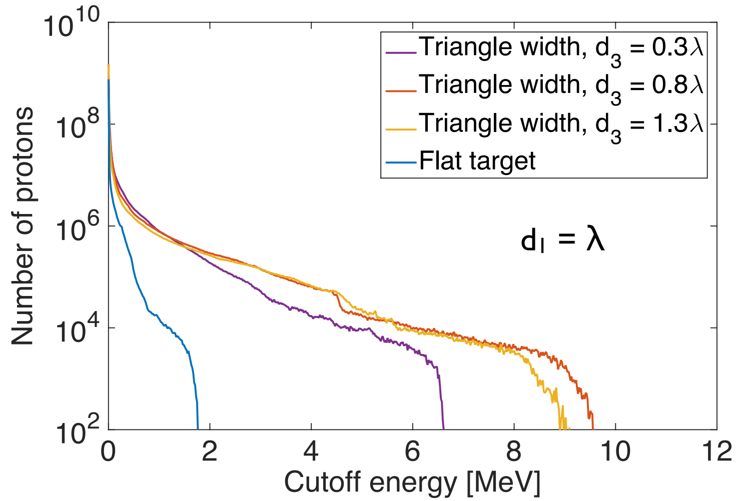
$d_2 = 0.5\lambda$



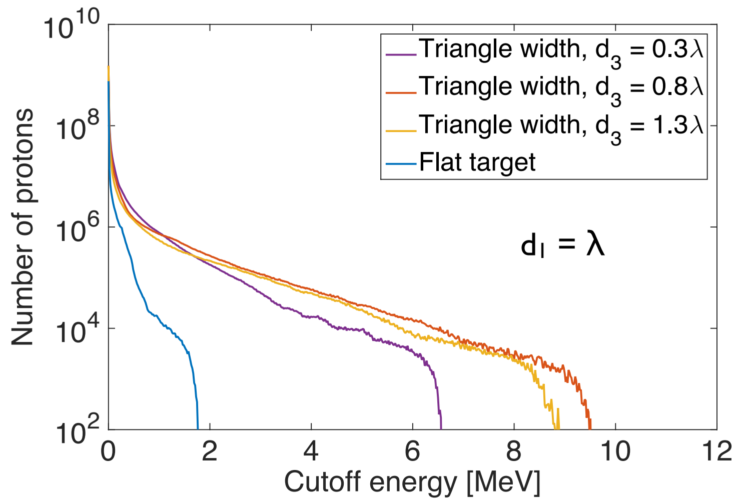


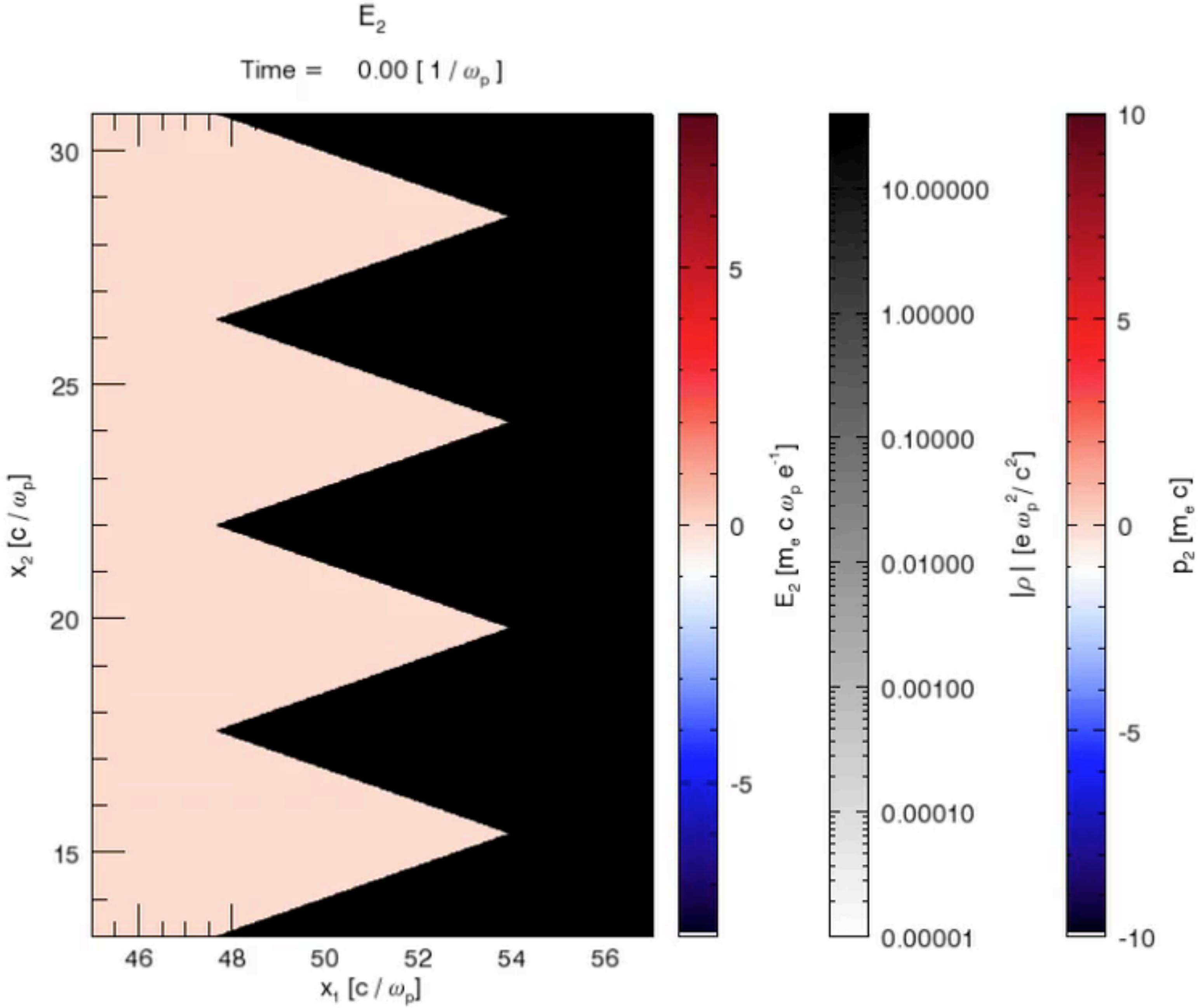
Proton spectra (t=405/w)

Normal triangles

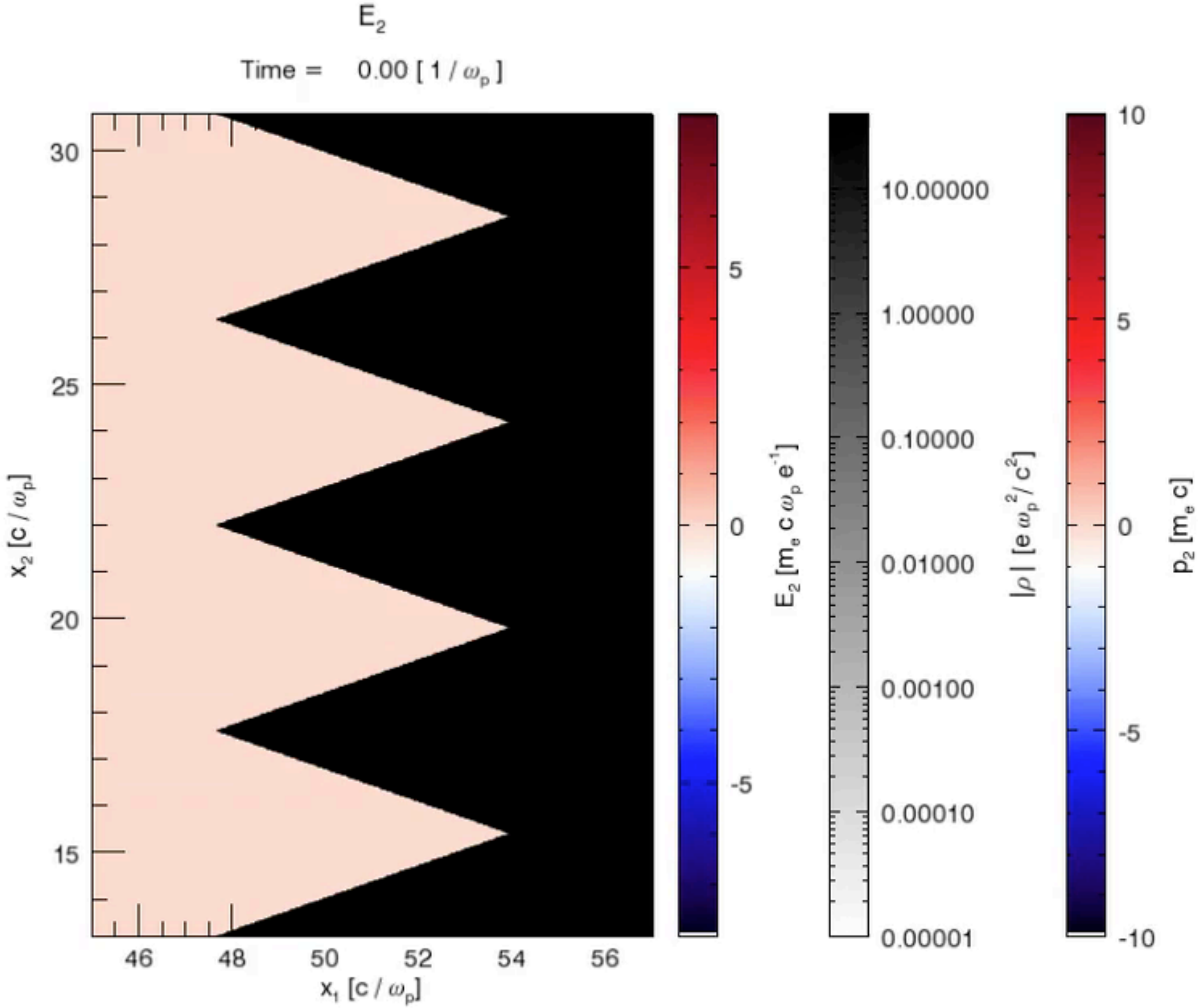


Tilted triangles



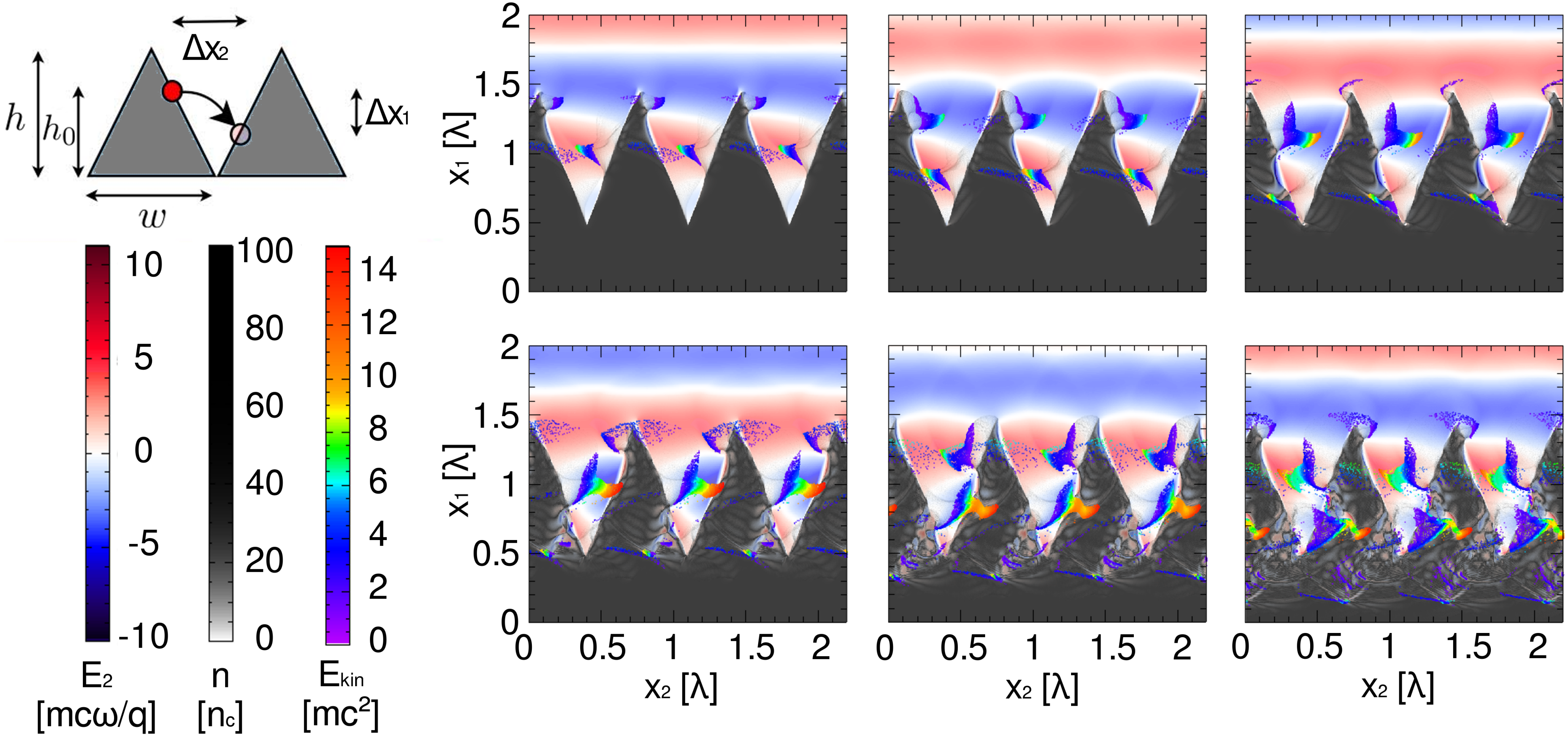


E2
Time = 0.00 [1 / ωp]
x2 [c / ωp]
x1 [c / ωp]
46
48
50
52
54
56
15
20
25
30
E2 [me c ωp e-1]
5
0
-5
|ρ| [e ωp2 / c2]
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001
p2 [me c]
10
5
0
-5
-10

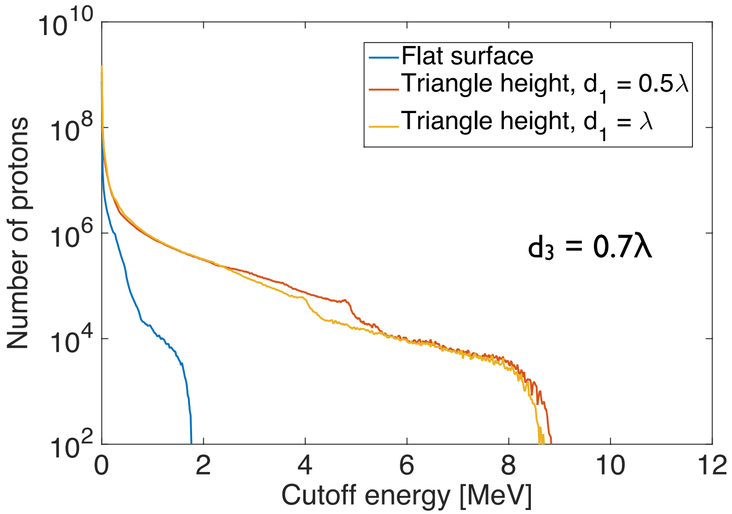


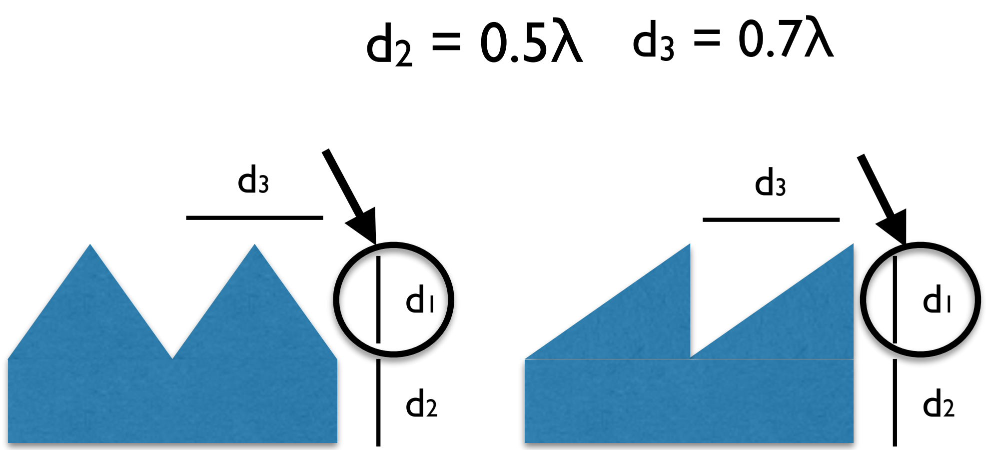
E2
Time = 0.00 [1 / ωp]
30
25
20
15
x2 [c / ωp]
46
48
50
52
54
56
x1 [c / ωp]
5
0
-5
E2 [me c ωp e-1]
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001
|ρ| [e ωp2 / c2]
10
5
0
-5
-10
p2 [me c]

Mechanism for efficient absorption

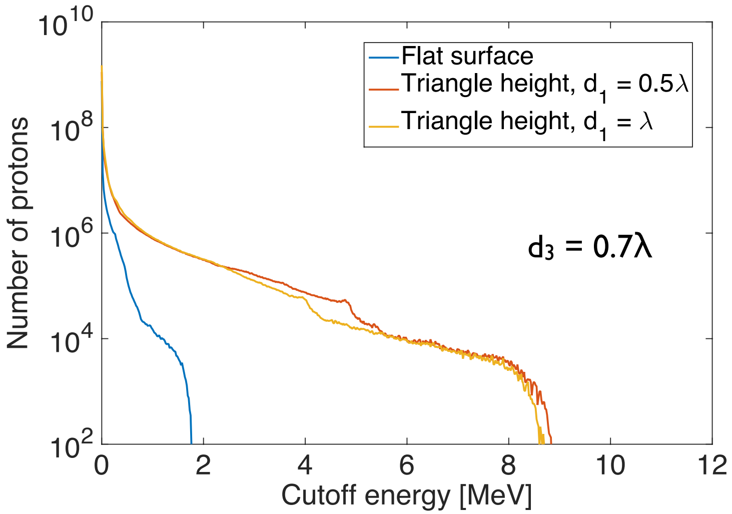


Dependence on the height of the structure

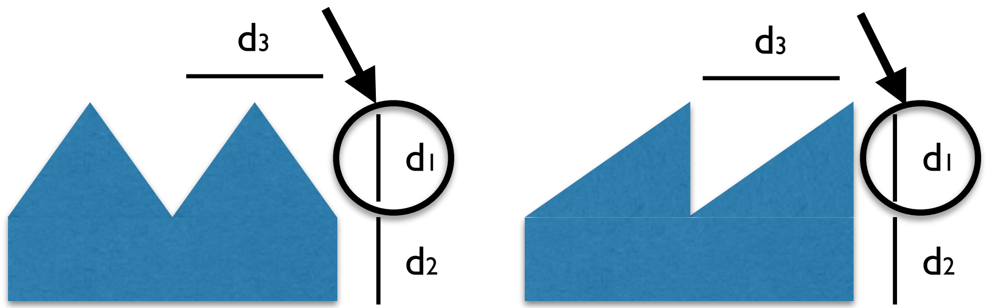


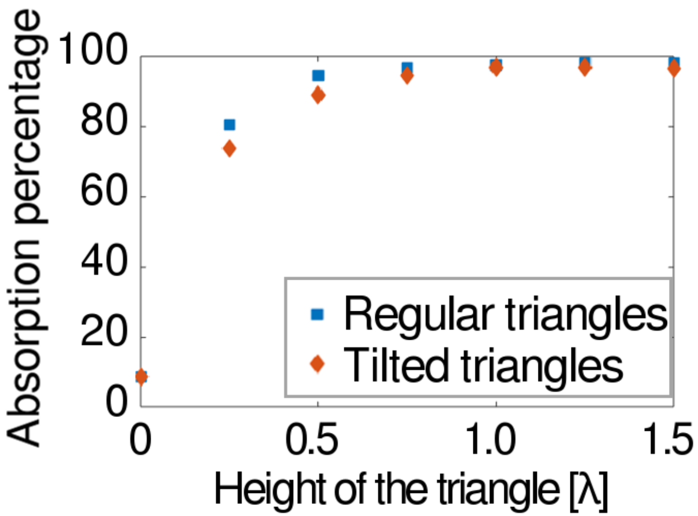


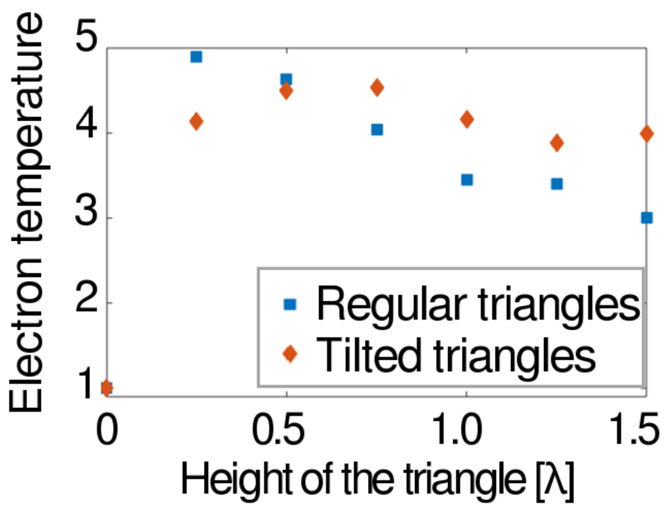
Dependence on the height of the structure

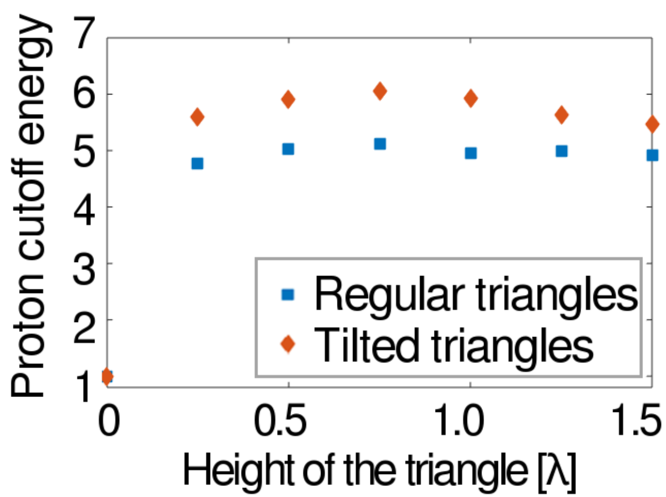


$d_2 = 0.5\lambda \quad d_3 = 0.7\lambda$







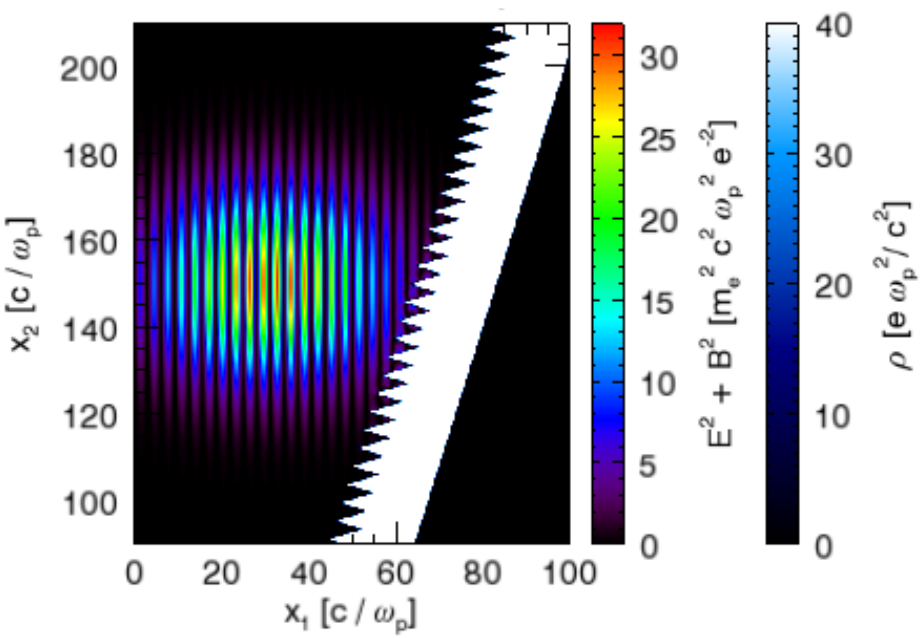


Angle of incidence

Main idea

Ion acceleration is optimized for a set of parameters, depending on the plasma density and laser peak intensity.

We want to obtain an estimate of the outcome in the most optimized situation for oblique incidence.

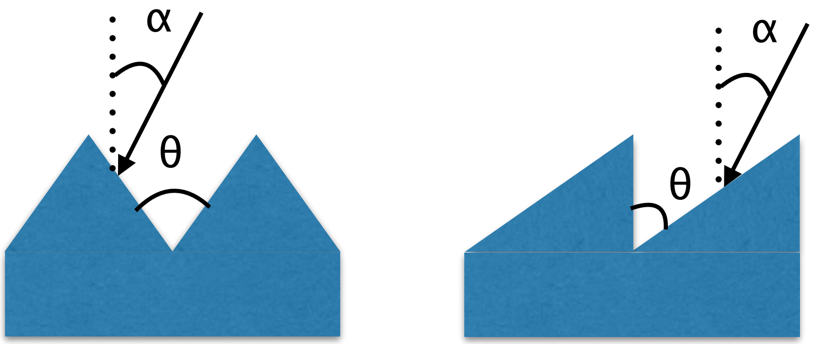


Optimal case

- **Incidence:** Oblique
- **Structure:** Tilted triangles
- **Optimal width:** $d_3=0.7\lambda$
- **Height with saturation:** $d_1=\lambda$
- **Realistic thickness:** $d_2=2\lambda$

Dependence with the incident angle

$d_2 = 0.5\lambda$ $d_3 = \lambda$



$d_1 = 1.2\lambda$ $d_1 = \lambda$

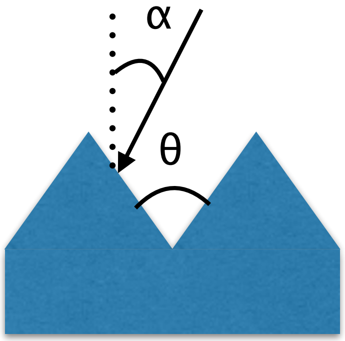
What we expect

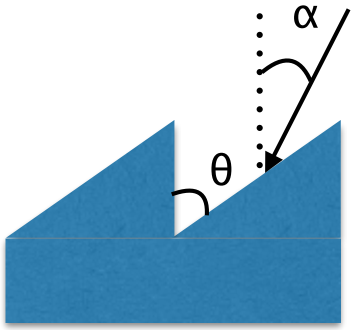
We expect an asymmetry for the tilted triangles for negative or positive angles.

We choose the sizes of the structures to have the same angle θ=45°.

Dependence with the incident angle

$d_2 = 0.5\lambda$ $d_3 = \lambda$



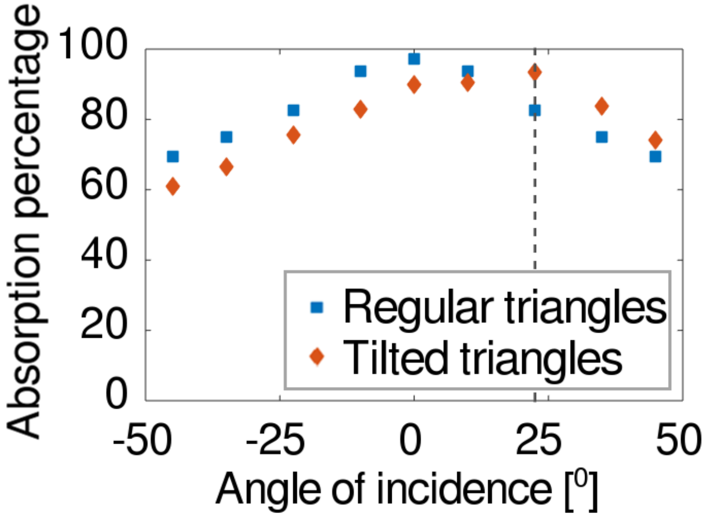


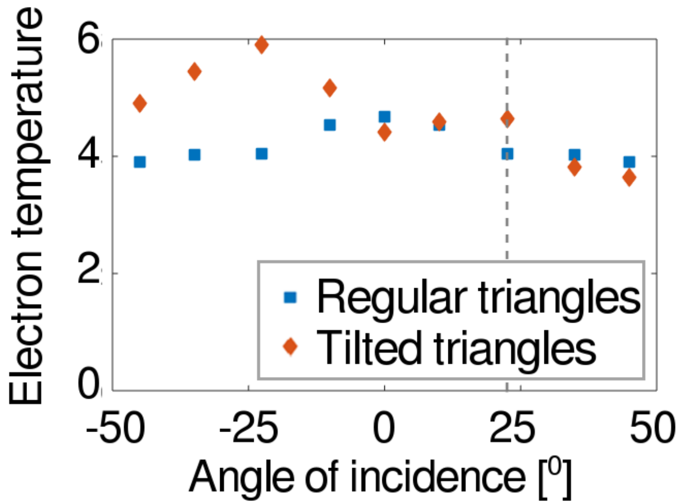
$d_1 = 1.2\lambda$ $d_1 = \lambda$

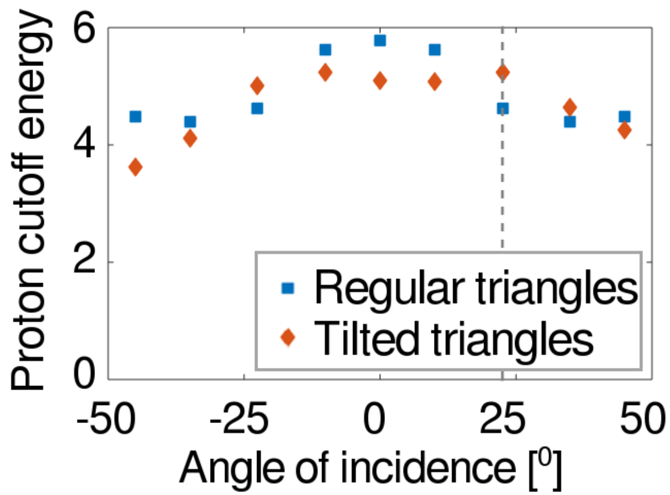
What we expect

We expect an asymmetry for the tilted triangles for negative or positive angles.

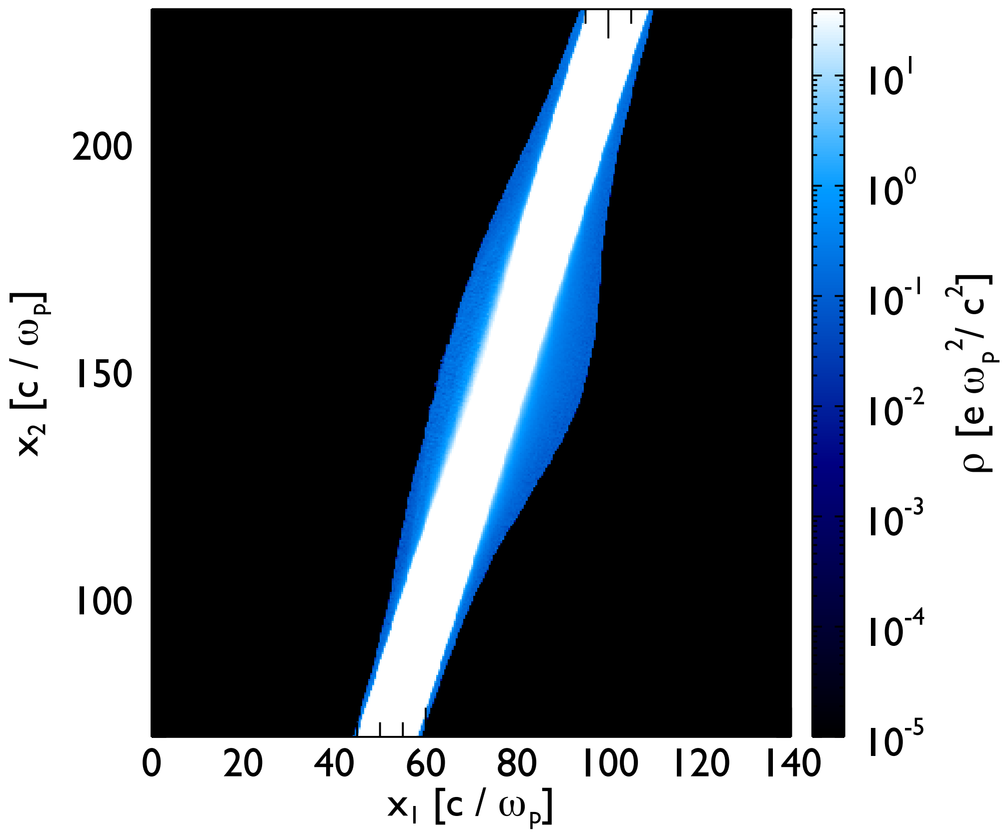
We choose the sizes of the structures to have the same angle θ=45°.





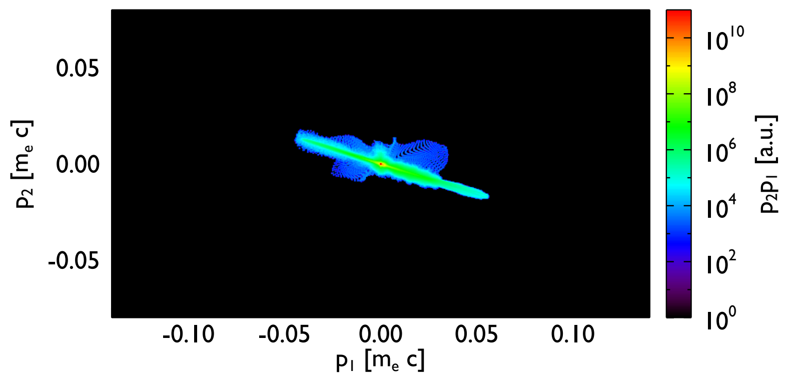


Proton charge density (t=405/w)



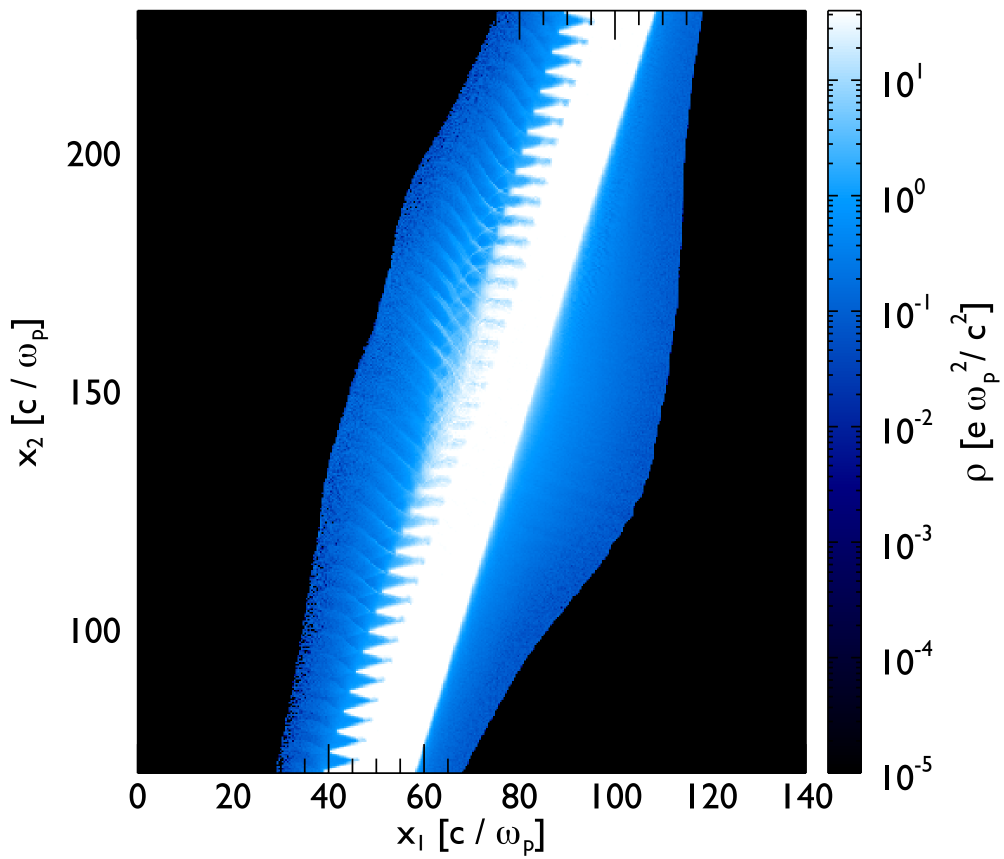
	Absorption	Proton cutoff
Flat	6,1 %	1,60 MeV
Structured	90,6 %	7,72 MeV
Ratio	*14,9*	*4,8*

Proton p_2p_1 phasespace (t=405/w)



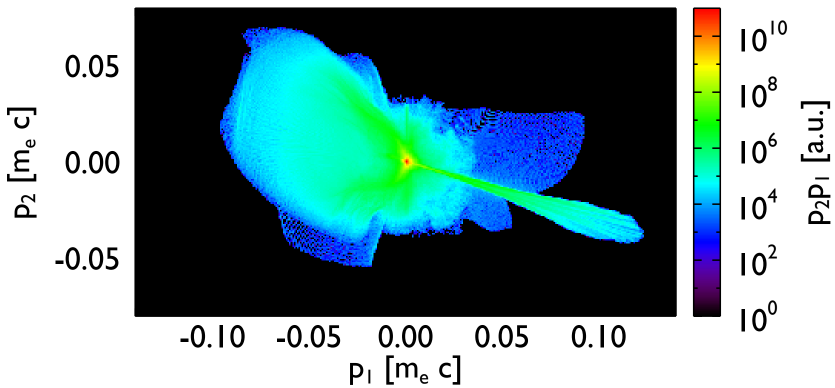
$\alpha = 17.5°\quad d_2 = 2\lambda$

Proton charge density (t=405/w)



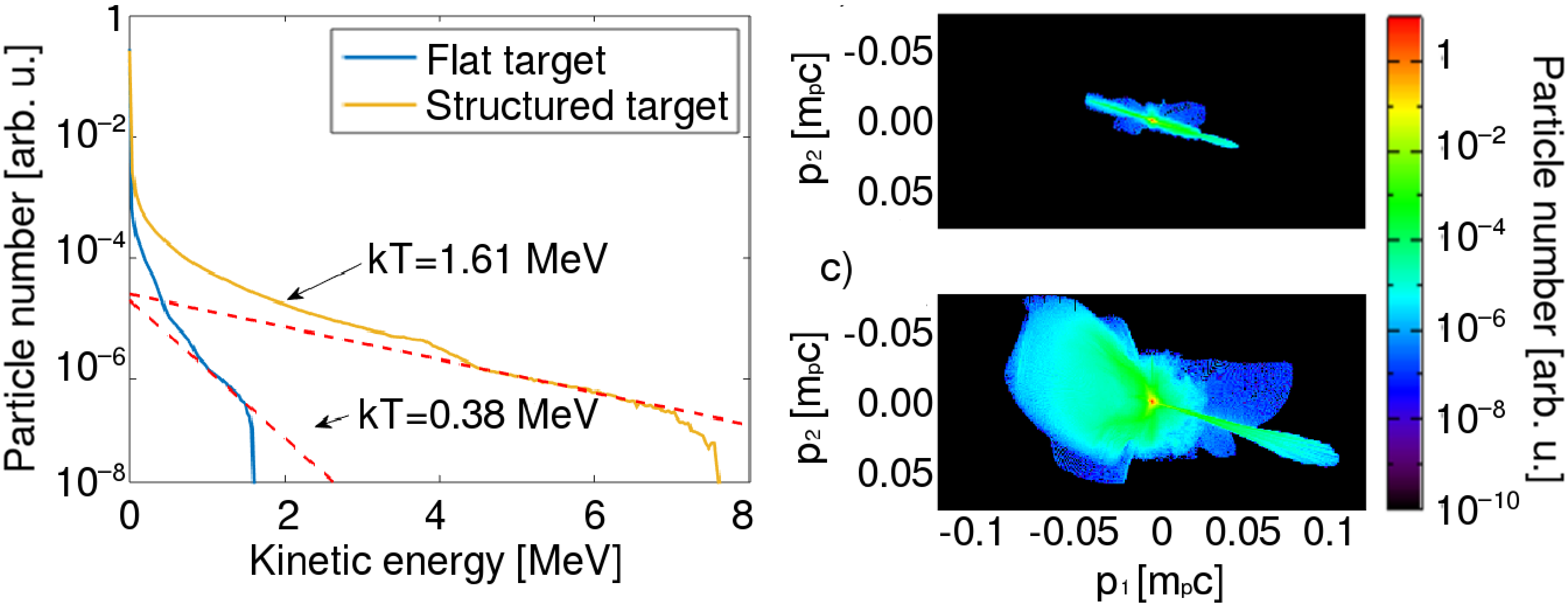
	Absorption	Proton cutoff
Flat	6,1 %	1,60 MeV
Structured	90,6 %	7,72 MeV
Ratio	*14,9*	*4,8*

Proton $p_2 p_1$ phasespace (t=405/w)



$\alpha = 17.5°$ $d_1 = \lambda$ $d_2 = 2\lambda$ $d_3 = 0.7\lambda$

Optimized proton beam



Comparison with 3D

Why comparing

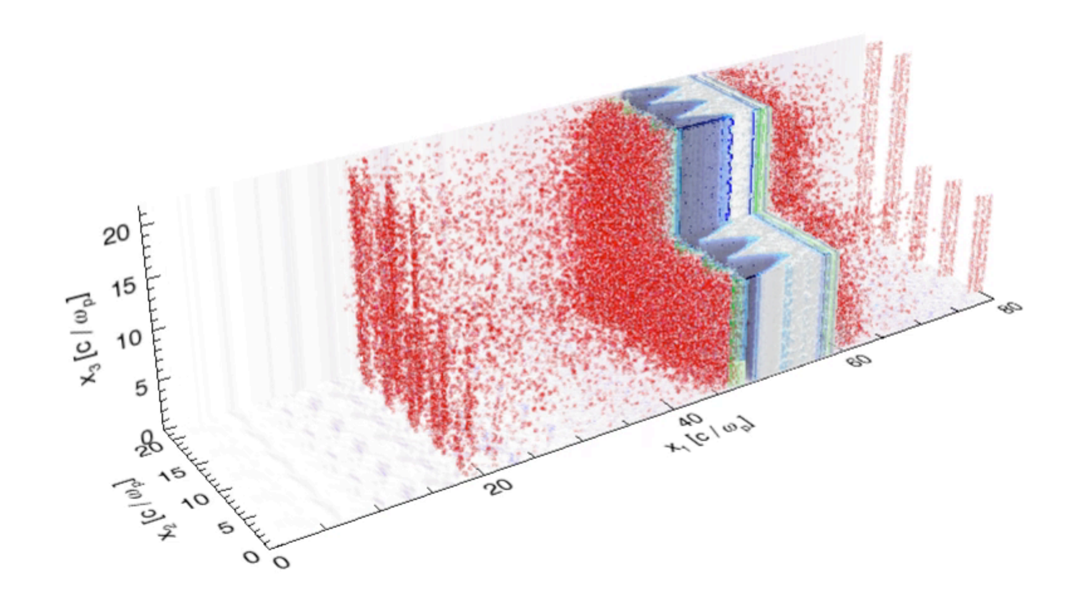
We need to know how the results scale from 2D to 3D to see how reliable they are.

We will use slab geometry to compare both cases.

Scaling of reflected energy and cutoff

	Regular triangles			Tilted triangles		
	2D	3D	3D/2D	2D	3D	3D/2D
Absorbed energy	95,4% ***No slab: 97,6 %***	91,5 %	***0,96***	92,3% ***No slab: 97,0 %***	89,5 %	***0,97***
Proton cutoff	4.29 MeV	4.28 MeV	***0,998***	4.50 MeV	4.21 MeV	***0,936***

Interaction



Simulation setup

Simulation:
x axis: 20.4 μm in 1600 cells
y/z axis: 2.8 μm in 220 cells
time step: 21.3 as

$d_1 = \lambda$
$d_2 = 0.5\lambda$
$d_3 = 0.7\lambda$

Laser:
$a_0 = 4.0$
$\lambda = 0.8$ μm
length = 18.8 fs

Plasma
$n_0 = 6.9 \times 10^{22}$ cm^{-3}
$n_0 = 40\ n_c$
particles per cell: 1x2x2

Comparison with 3D

Why comparing

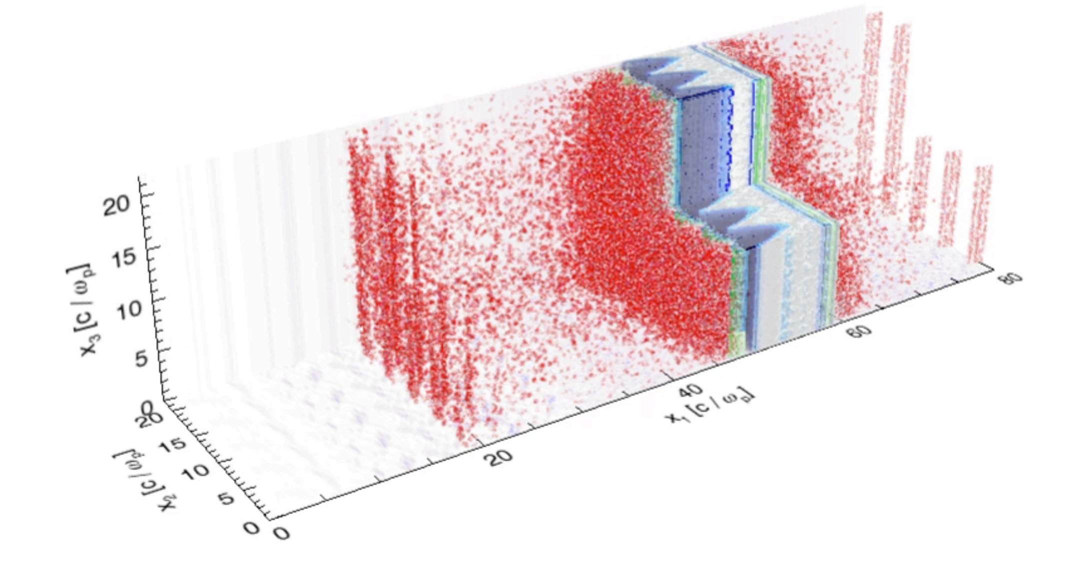
We need to know how the results scale from 2D to 3D to see how reliable they are.

We will use slab geometry to compare both cases.

Scaling of reflected energy and cutoff

	Regular triangles			Tilted triangles		
	2D	3D	3D/2D	2D	3D	3D/2D
Absorbed energy	95,4% ***No slab: 97,6 %***	91,5 %	***0,96***	92,3% ***No slab: 97,0 %***	89,5 %	***0,97***
Proton cutoff	4.29 MeV	4.28 MeV	***0,998***	4.50 MeV	4.21 MeV	***0,936***

Interaction



Simulation setup

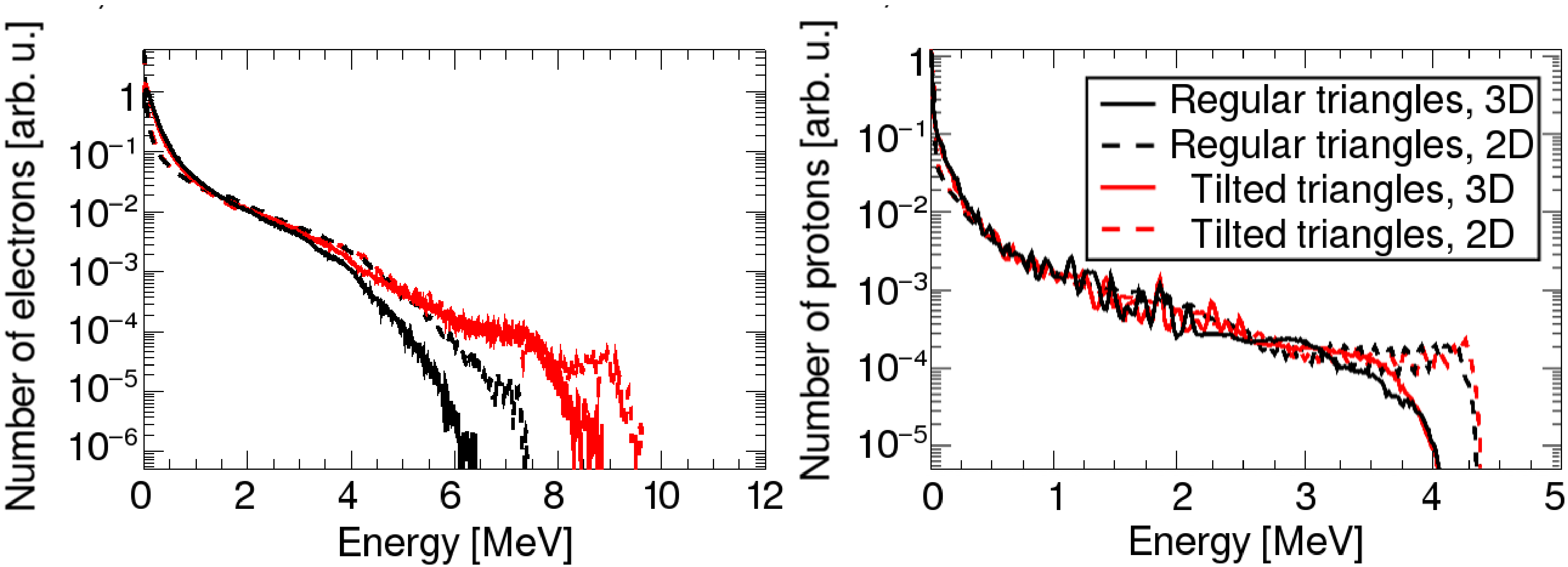
Simulation:
x axis: 20.4 μm in 1600 cells
y/z axis: 2.8 μm in 220 cells
time step: 21.3 as

$d_1 = \lambda$
$d_2 = 0.5\lambda$
$d_3 = 0.7\lambda$

Laser:
$a_0 = 4.0$
$\lambda = 0.8$ μm
length = 18.8 fs

Plasma
$n_0 = 6.9 \times 10^{22}\ cm^{-3}$
$n_0 = 40\ n_c$
particles per cell: 1x2x2

Comparison 2D vs 3D



3D: $3.1 \times 10^{11} p/shot$

New diagram for the estimation.

Overall cost & complexity

New paradigm for radioisotope production

- Installation cost
- Comple-xity

- Energy per shot.
- Intensity
- Average power

- Target
- Geometry
- electron energy dist
- Current

- Complex targets

TNSA
- Proton energy dist
- Number of ions

- Advance proton diag
- Online beam monitoring

- Activation (p,n)
- Geometry
- Target
- Activation time

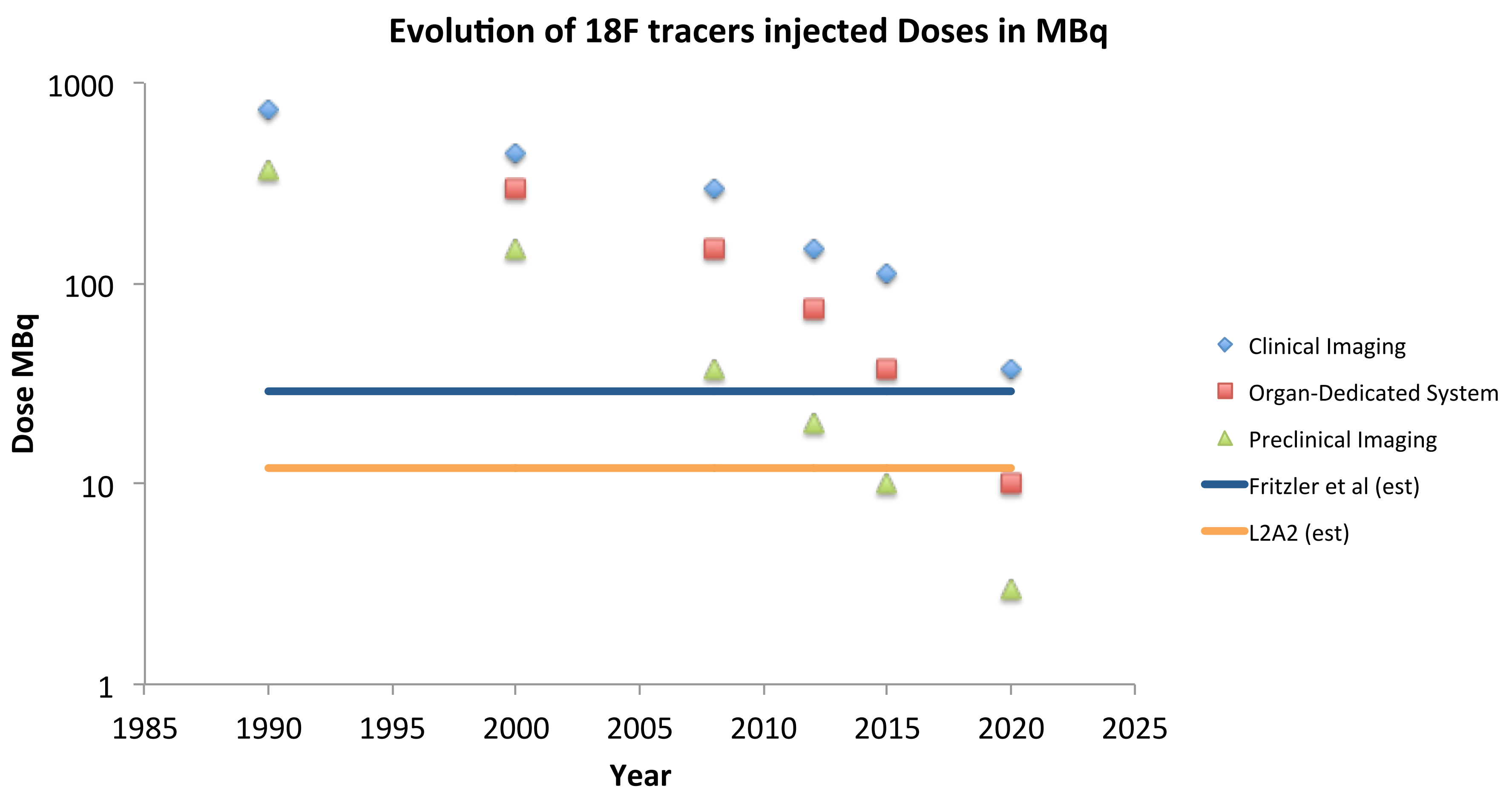
- Dose for PET

- Radiopharmacy cost

- Advance imaging technique

High repetition rate

The doses are continuously decreasing



RadioPharmacy efficiency not included

Fritzler, S. et al. Appl. Phys. Lett. 83, 3039-3041

New imaging techniques

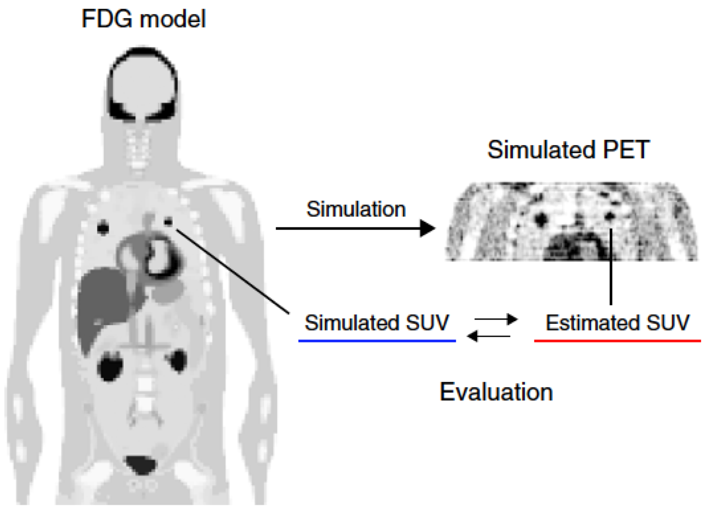
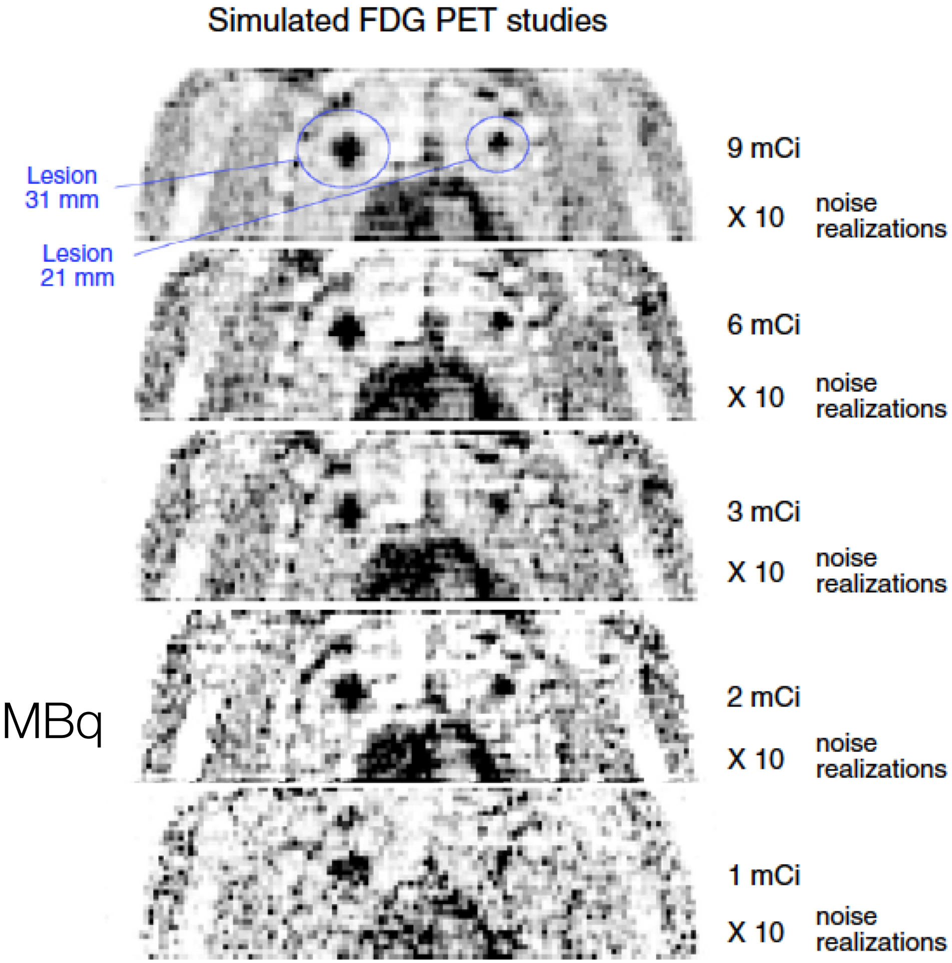


Fig. 1. Workflow was based on a realistic framework of multiple simulated FDG-PET studies.



74 MBq

Fig. 2. Coronal views of simulated FDG-PET studies of patients with solitary pulmonary nodules for different injected FDG doses ranging from 9 mCi to 1 mCi.

Silva-Rodríguez J, et al. Simulated FDG-PET studies for the assessment of SUV quantification methods.
Rev Esp Med Nucl Imagen Mol. 2014. http://dx.doi.org/10.1016/j.remn.2014.07.006

Acknowledge.

Laser physics

- J. Arines, C. Bao, M. Flores (USC)
- F. Cambronero, D. Nieto (L2A2)

Laser-matter interaction:

- C. Ruíz, A. Aragón (L2A2)
- A. Paredes (UVi)

Nuclear and medical Physics:

- H. Alvarez, J. Benlliure, D. Cortina (USC)
- A. Iglesias, J. Llerena, J. Silva (L2A2)

Sensors and computing:

- D. Cabello, V. Sánchez, J. Vidal (USC)
- B. Blanco, D. Castro (L2A2)

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
"Una manera de hacer Europa"

VNiVERSiDAD D SALAMANCA
CAMPUS DE EXCELENCIA INTERNACIONAL

Manuel Blanco

Marija Vranic

TÉCNICO LISBOA

Thanks