Ion emission from laser-generated plasma, $I\lambda^2$ dependence and FLAME facilities

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&

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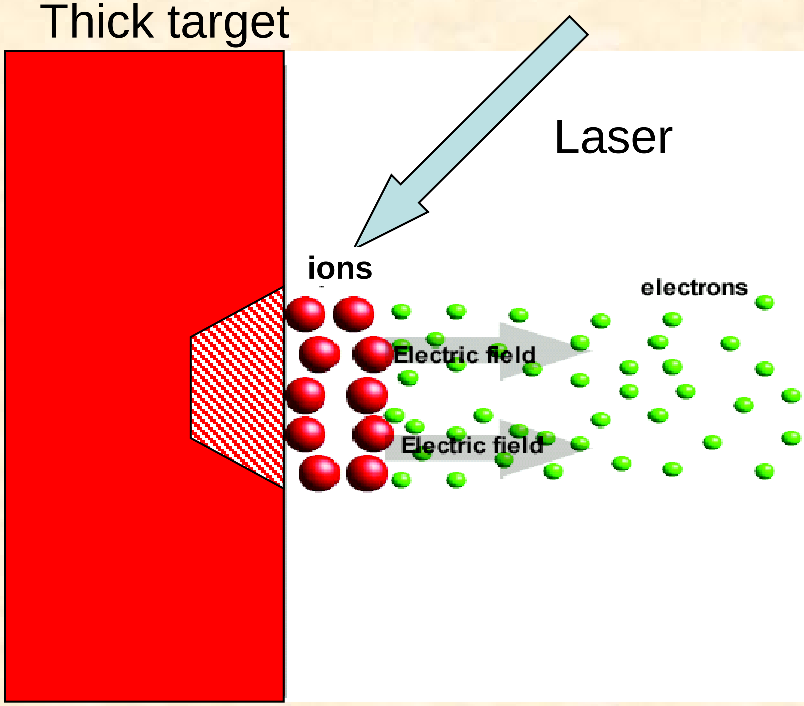
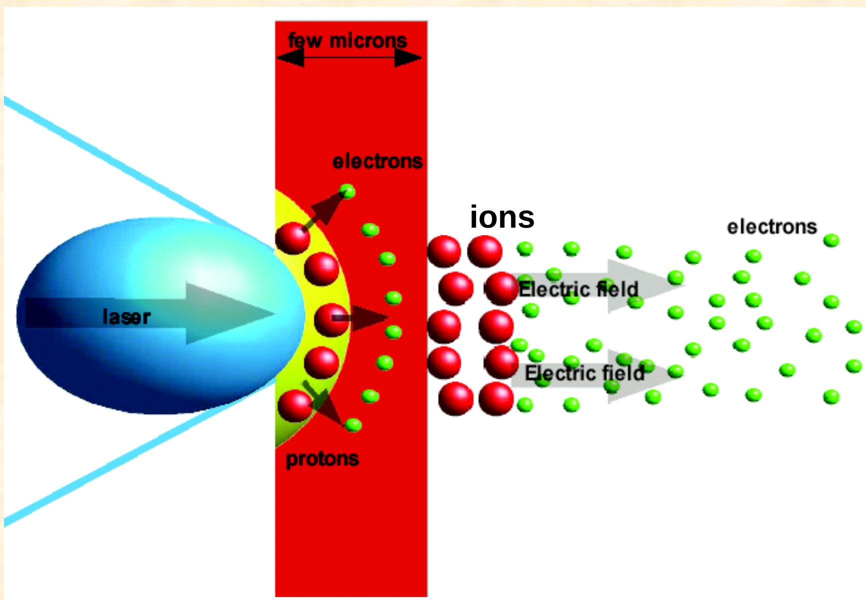
Agenda Terzo Meeting Generale Coll. LI^{2}FE**;** 12 Marzo 2010 0re 11.00, Frascati, INFN-LNF, Aula Touschek

Thick target





Thin target

Non-equilibrium Plasma

- Ablation yield
- Equivalent temperature (T_i, T_e, T_o)
- Equivalent density (n_{at}, n_i, n_e, n_0)
- Temperature and density gradients
- Equivalent acceleration voltage (V_0)
- Electric field ($E = V_0/\lambda_D$)
- Fractional ionization
- Angular distribution
- Ion energy distribution
- Charge state distribution
- X-ray distribution
- …

$\propto$ **$I = \varepsilon_L / S \Delta t$ (W/cm^2)**

Free electron abs ~ λ

f (target composition, geometry,…)

Know –how: INFN-Projects ECLISSE (2000-2002), PLAIA (2003-2005), PLATONE (2006-2008) and now **PLEIADI (Plasma Laser Energetic Ion Acceleration & DIagnostics:** 2009-2010). National Responsible: Prof. Lorenzo Torrisi

LECCE

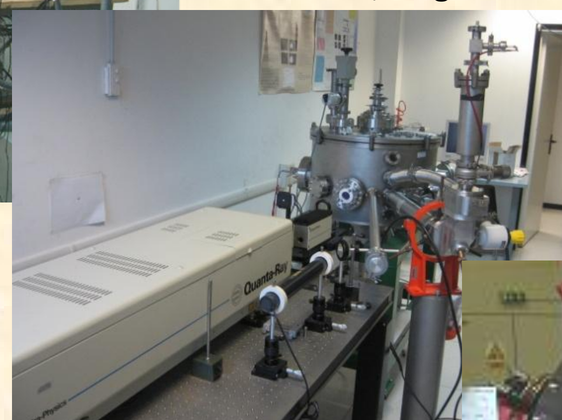
(XeCl-308 nm (20 ns), KrCl-222 nm (10 ns), 100mJ, single shot or 10 Hz r.r.) **10^8 W/cm^2**

MESSINA

(Nd:Yag, 532 nm, 3 ns, 400 mJ, single shot or 20 Hz r. r.) **10^{10} W/cm^2**

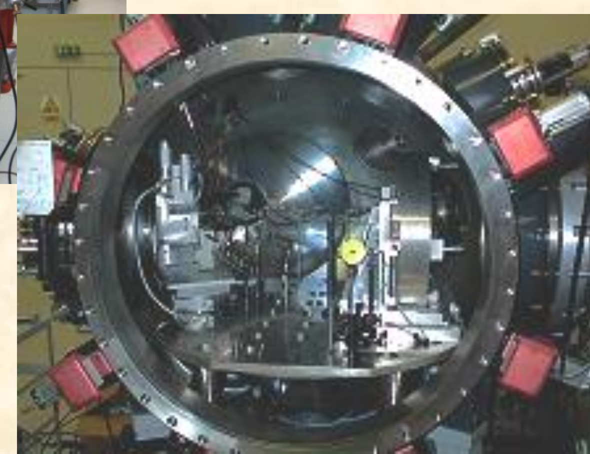
CATANIA

(Nd:Yag, 1064 nm, 532 nm, 355 nm, 9 ns, 1 J, single shot or 30 Hz r. r.) **10^{11} W/cm^2**



PALS, PRAGUE

(C_3F_7I, w_1=1315 nm, w_2=658 nm, w_3=438 nm, 300 ps, 1 KJ, single shot) **10^{16} W/cm^2**



kT≈ 5 eV - 50 keV

$$K_B T_i(eV) = 2 \cdot 10^{-5}\left[I_L\left(\frac{W}{cm^2}\right)\lambda^2(\mu m^2)\right]^{0.5}$$

kT

T, n, E_p, P_s, <q>, E_{field},… $\propto$ I λ^2

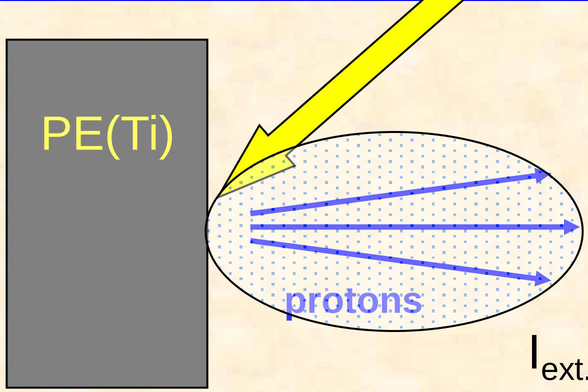
Low laser intensity → Thick target

(ns lasers, 1 J, >10^{10} W/cm^2):

kT ~ 100 eV + E ~ 1 MV/cm

~ 1 keV/charge state

$E_{protons}$~ 1 keV ; E_{carbon} ~ 6 keV

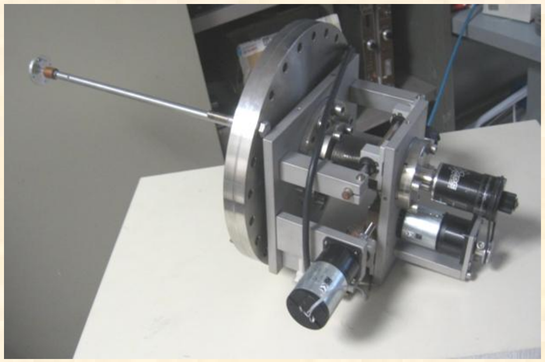


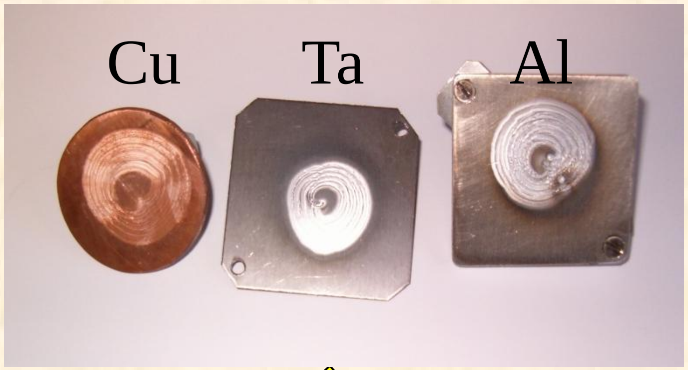
~ 10^{15} H^+/pulse

$I_{ext.}$ ~ 10 mA/cm^2(!)

(Underdensity phenomena: $n_e<n_c$)

Low ion energy, High current (high repetition rate and thick targets)





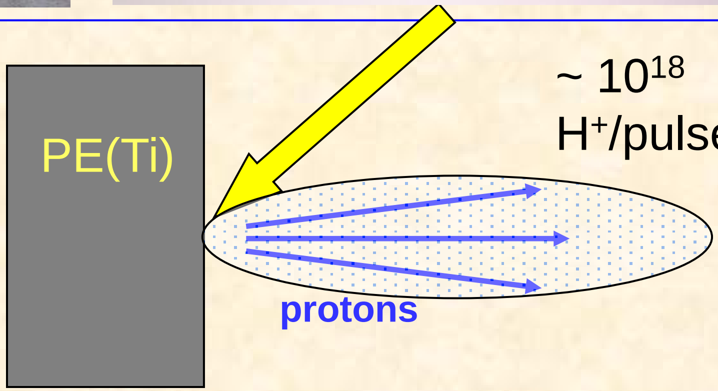
High laser intensity → Thick target

(ns lasers, 1 J, >10^{16} W/cm^2):

kT ~ 10 keV + E ~ 1 GV/cm

~ 500 keV/charge state

$E_{protons}$~ 500 keV ; E_{carbon} ~ 3 MeV



~ 10^{18} H^+/pulse

(near overdensity phenomena: n_e~n_c)

High ion energy, High current (is high repetition rate is possible)

Chirped Pulse Amplification (CPA) Technique

LASER	Type	Pulse Energy	Pulse duration	Rep. Rate	Power	Intensity	Use
FLAME LNF-Frascati-Italy	Ti:Sa	5 J	20 fs	10 Hz	250 TW	10^{21} W/cm^2	Electron Acceleration
POLARIS Jena-Rossendorf-Germany	Ti:Sa	150 J	150 fs	0.1 Hz	100 TW	10^{21} W/cm^2	Electrons & Ions acceleration X-rays Materials
LOASIS Berkeley USA	Ti:Sa	4 J	40 fs	10 Hz	100 TW	10^{20} W/cm^2	Ion Acceleration
JAERI Kansai, Japan	Ti:Sa	28 J	25 fs	10 Hz	100 TW	10^{21} W/cm^2	Electrons acceleration, Protontherapy
LULI Palaiseau-Parys, France	Ti:Sa	30 J	320 fs	10 Hz	100 TW	5×10^{19} W/cm^2	Ion acceleration
TRIDENT Los Alamos, USA	Nd:Glass	500 J	500 fs	5 Hz	200 TW	5×10^{19} W/cm^2	Ion Acceleration Protontherapy
VULCAN	Nd:Glass	500 J	300 fs-1 ps	10^{-3} Hz	100 TW	10^{20} W/cm^2	Electron & Ion acceleration-Astrophysics_Nuclear fusion
PHELIX	Ti:Sa-Nd:Glass	500 J	500 fs	10 Hz	500 TW	10^{20} W/cm^2	Ion acceleration, Plasma Physics
NIF (Lawrence Livermore National Laboratory) California USA	Nd:Glass	20 J	13 fs	10 Hz	500 TW	10^{20} W/cm^2	Multi LASER beams-Nuclear Fusion

Ultraintense lasers → Thin target

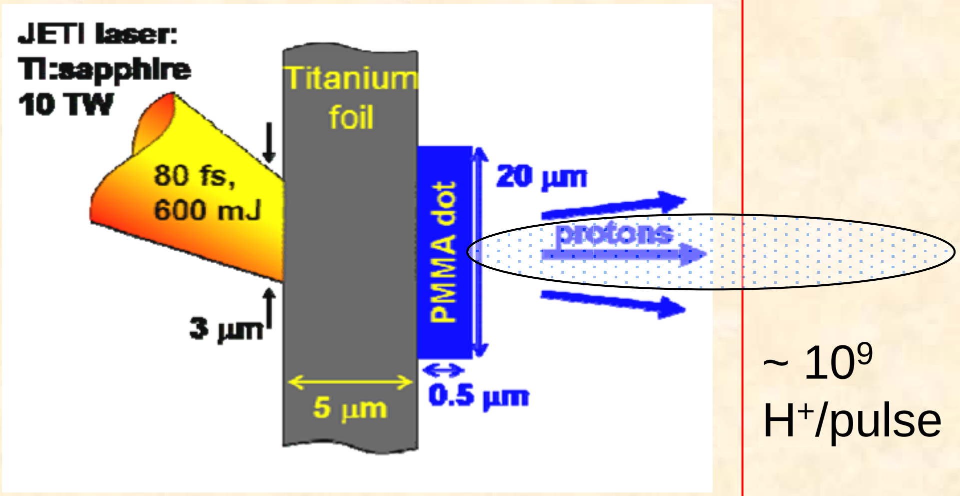
(fs lasers, 1 kJ, $>10^{18}$ W/cm^2);

kT ~ 100 keV + E ~ 1 GV/cm

~ 10 MeV/charge state

$E_{protons}$ ~ 10 MeV ;

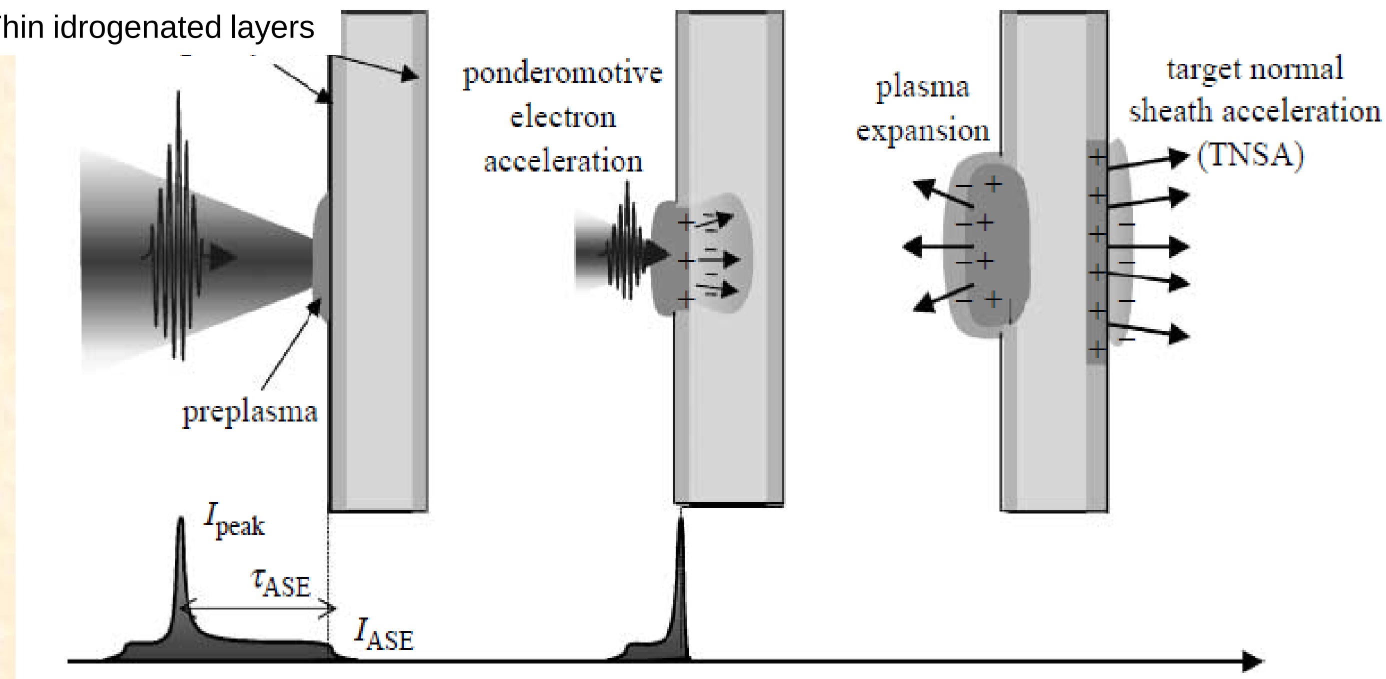
E_{carbon} ~ 60 MeV



~ 10^9 H^+/pulse

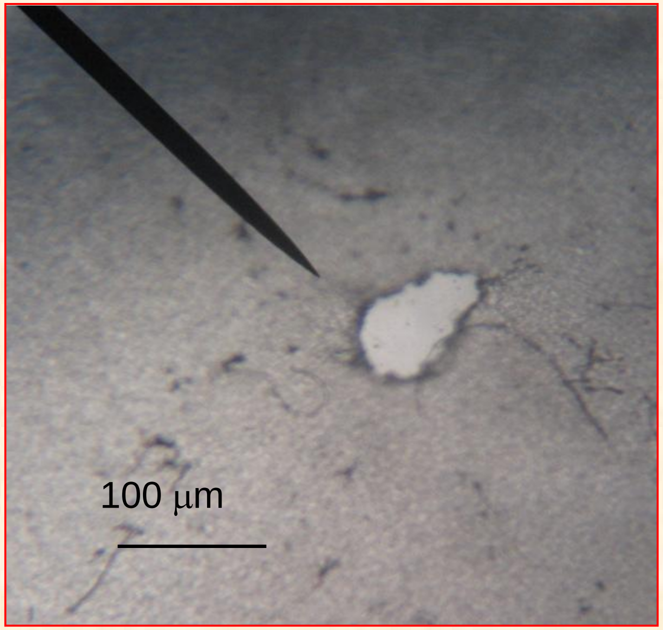
(Overdensity phenomena: $n_e > n_c$)

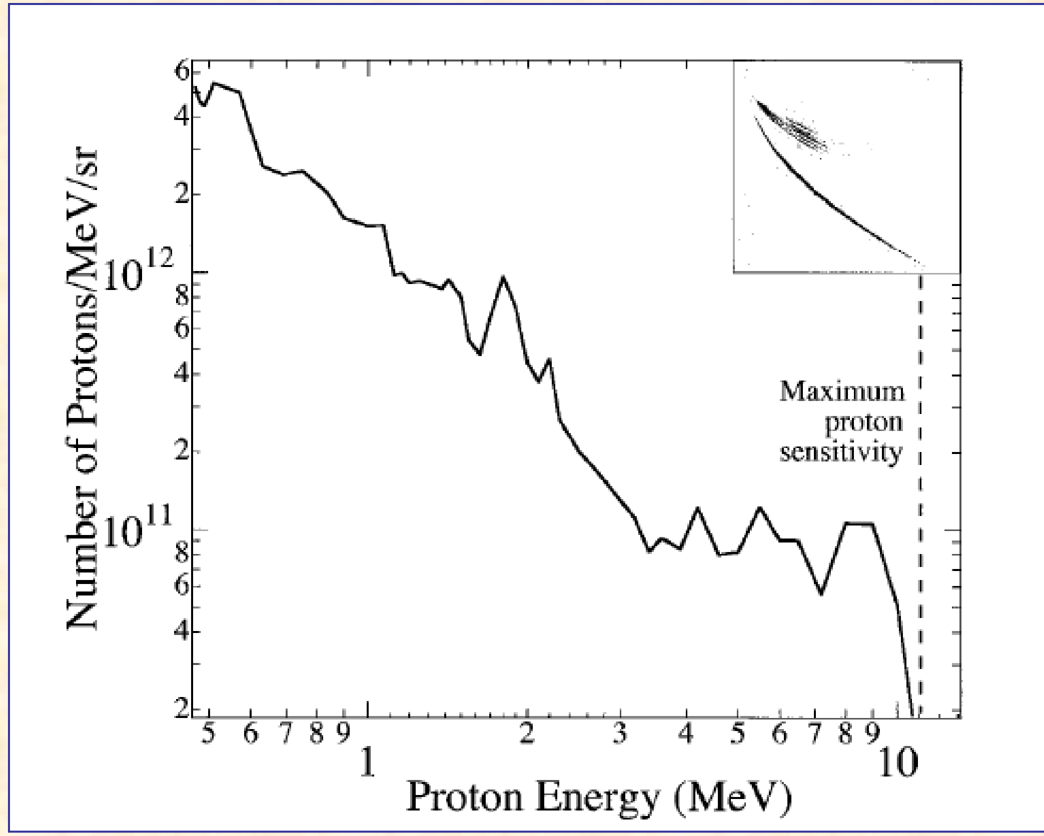
High ion energy, Low current (low rep. rate and thin targets).

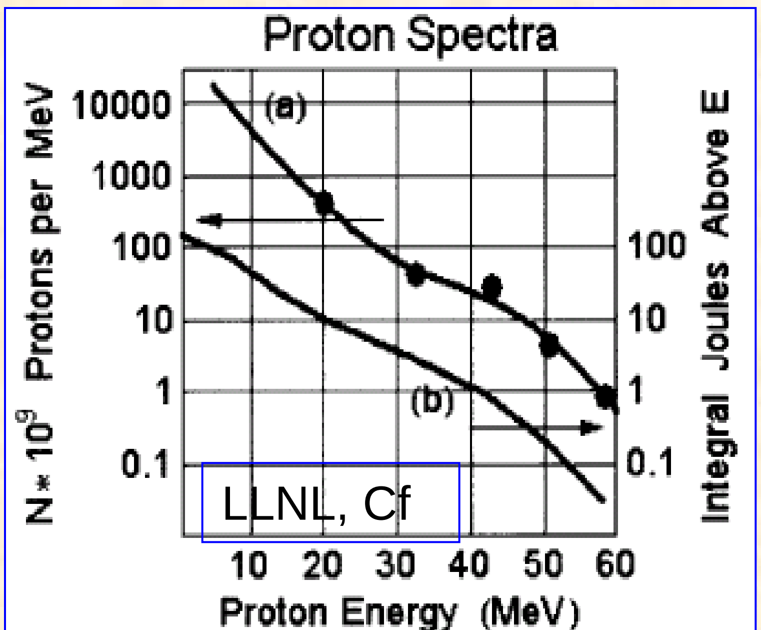


Acceleration mechanisms

- **Ponderomotive forces;**
- **Coulomb explosion;**
- **Resonant absorption;**
- **Self-focusing effects;**
- **Filamentation effects;**
- **Plasma outburst;**
- **Target normal sheath acceleration;**
- …







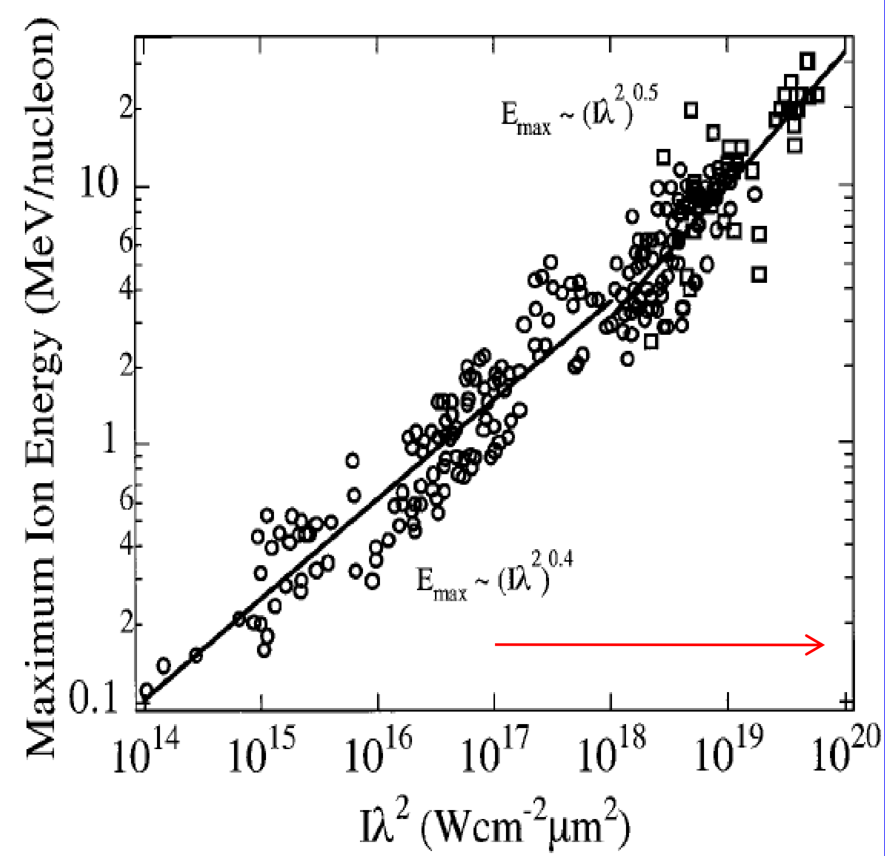
Beam multi-ions

H^{+}, C^{1+}-$^{6+}$, O^{1+}-$^{8+}$,

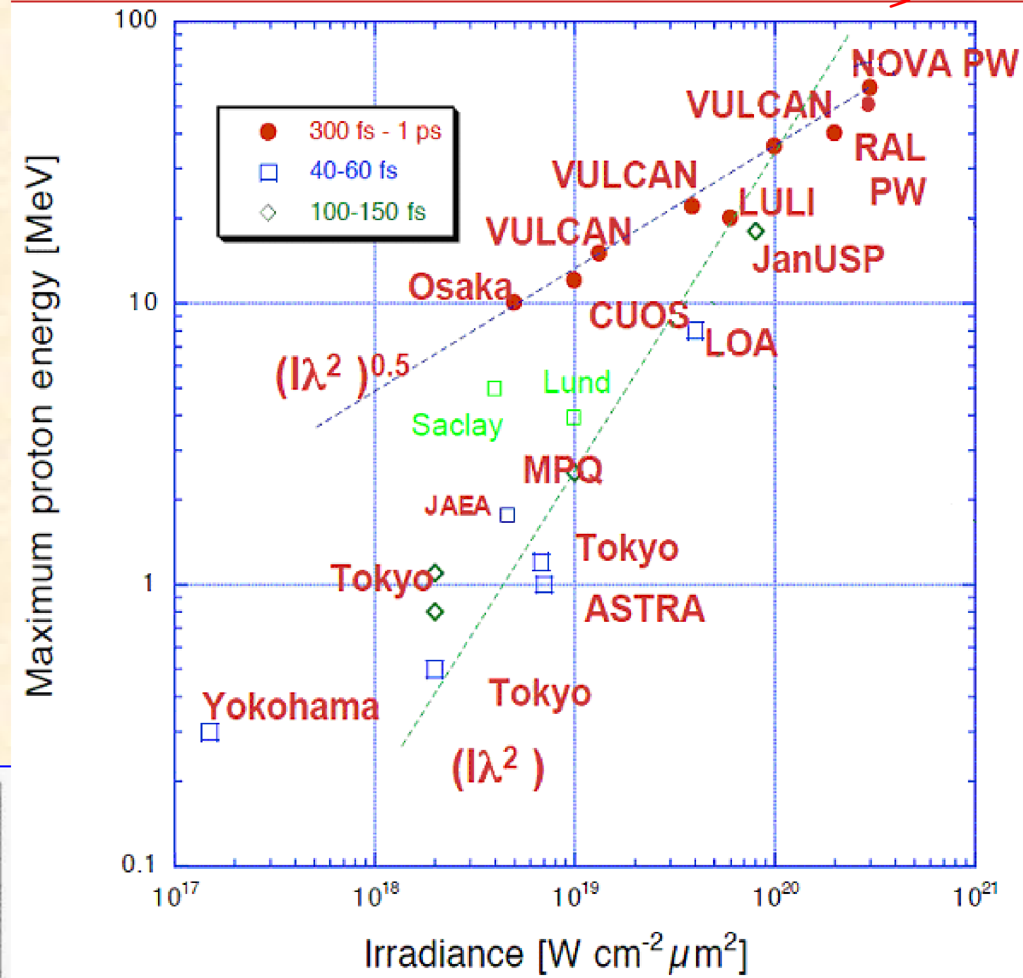
N^{1+}-$^{7+}$, Al^{1+}-$^{13+}$,…

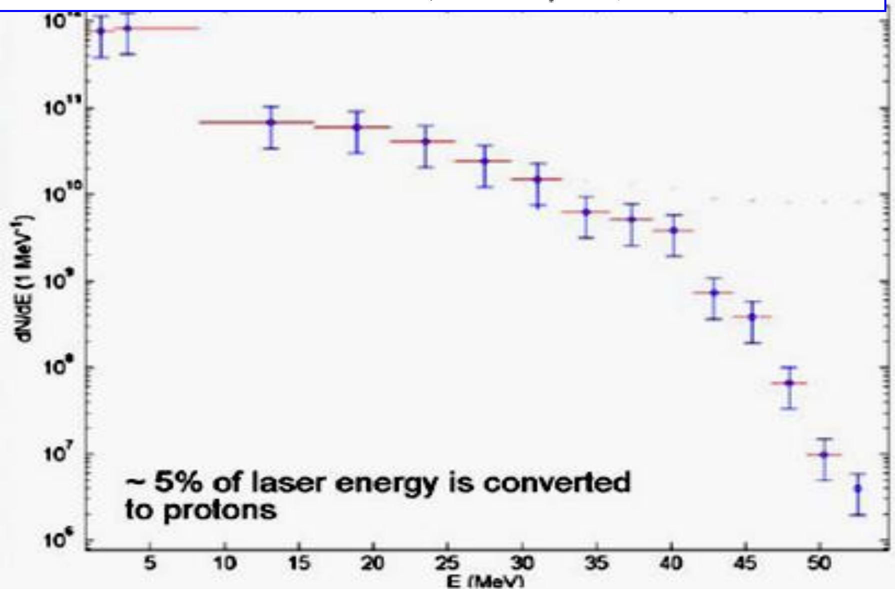
~ 1% - 5% laser energy converted in protons

R.A. Snavely et al., Phys. Rev. Lett. 85 (2000) 2945



Flame Facilities



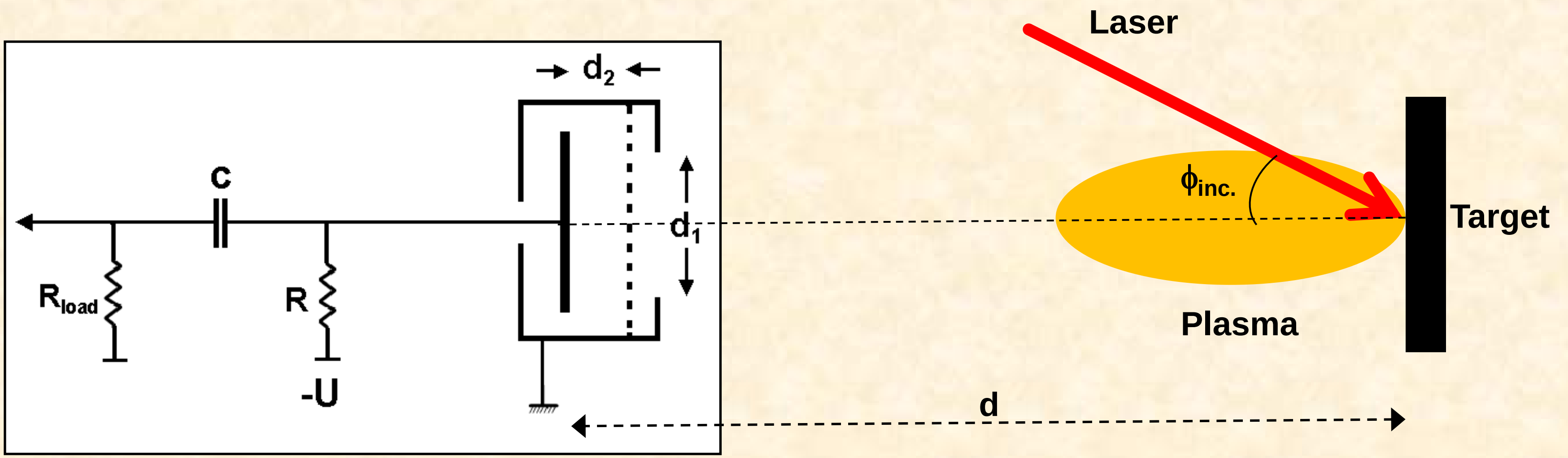


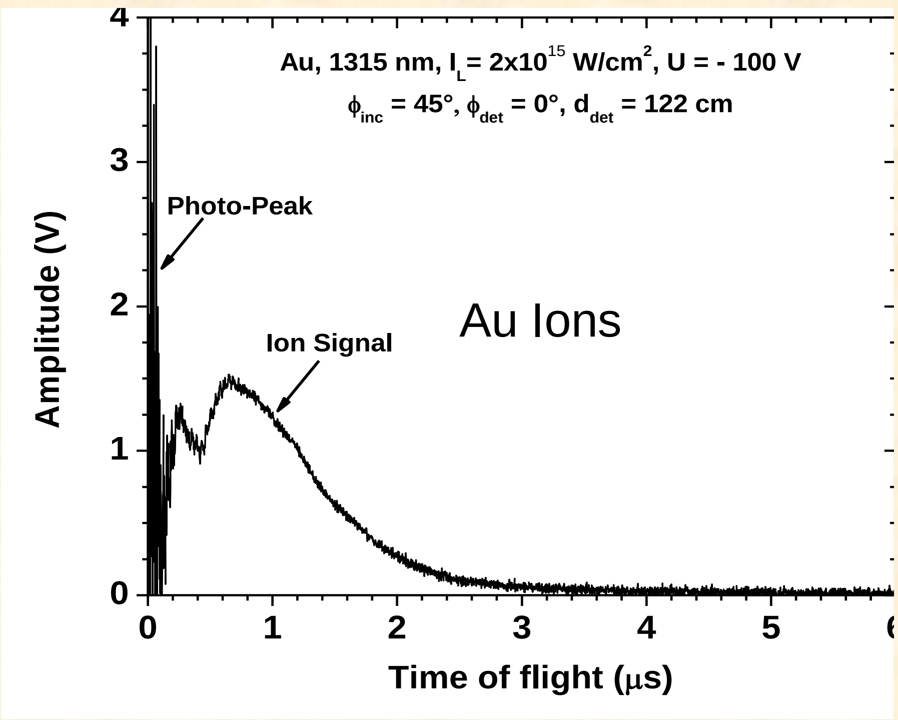
P. McKenna et Al.
Phil. Trans. R. Soc. A (2006) 364, 711

E. L. Clark et Al.,
Rev. Lett. 21(85-n.8), 1654, 2000

K. A. Flippo *et al.*
Rev. Sci. Instrum. **79**, 10E534 (2008);

Ion Collector (IC) Analysis in TOF

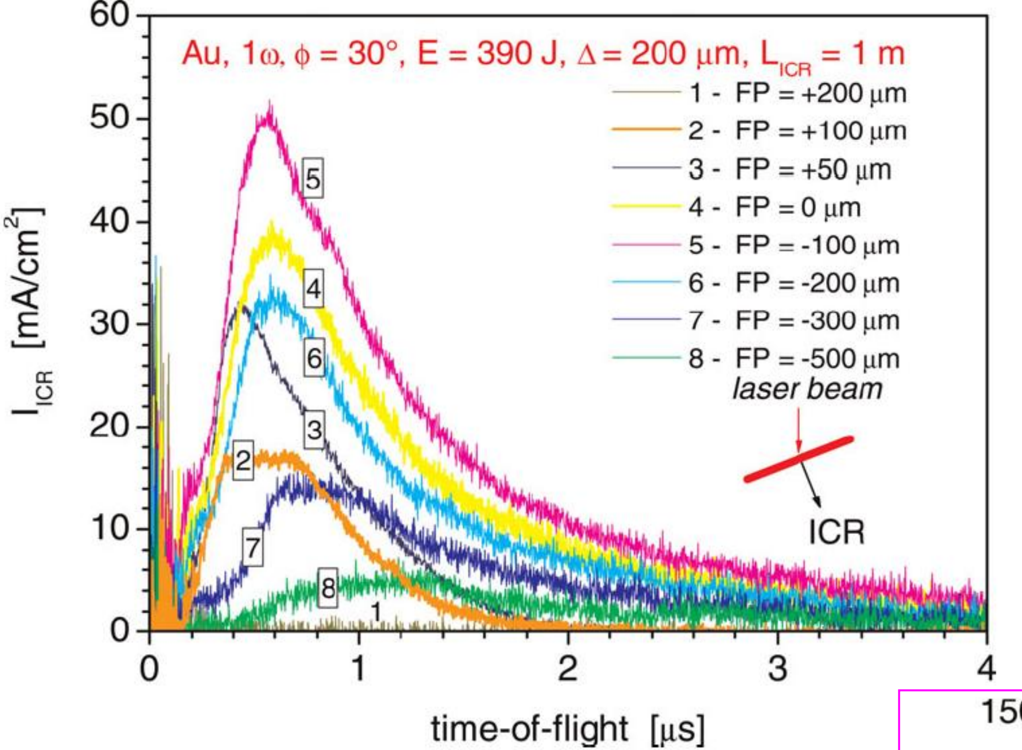


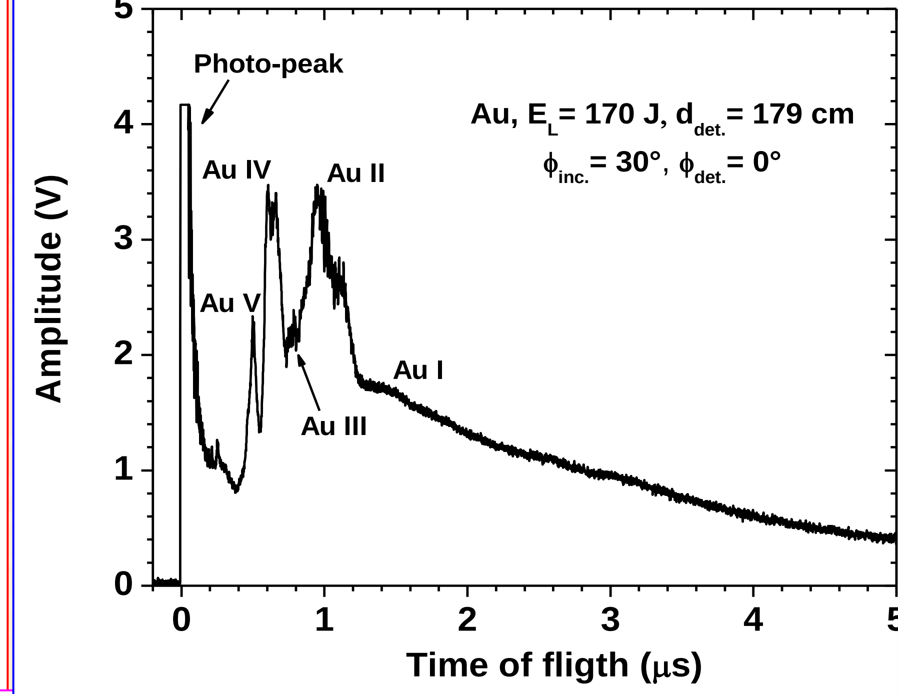


$$\bar{v}_p = \frac{d}{\bar{t}_p}$$ ⇒ $v_p = 2.5 \cdot 10^6$ m/s

$$\bar{E}_p = \frac{1}{2} m \bar{v}_p^2$$ ⇒ $E_{p1} \cong 4.3$ MeV

$E_{p2} \cong 35$ MeV

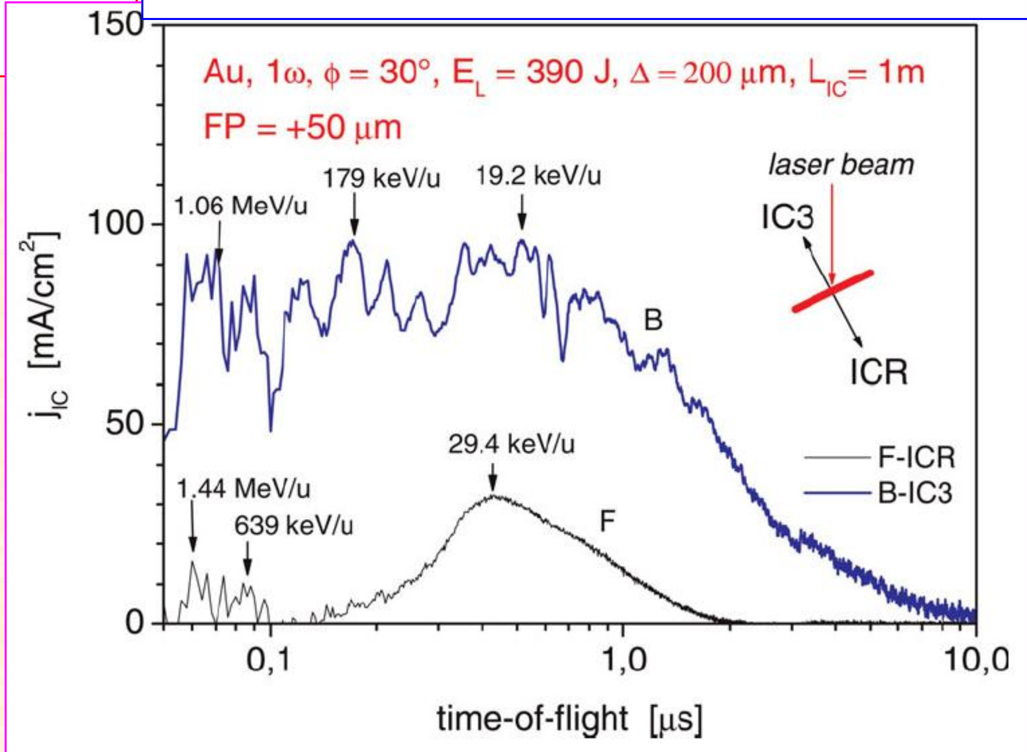




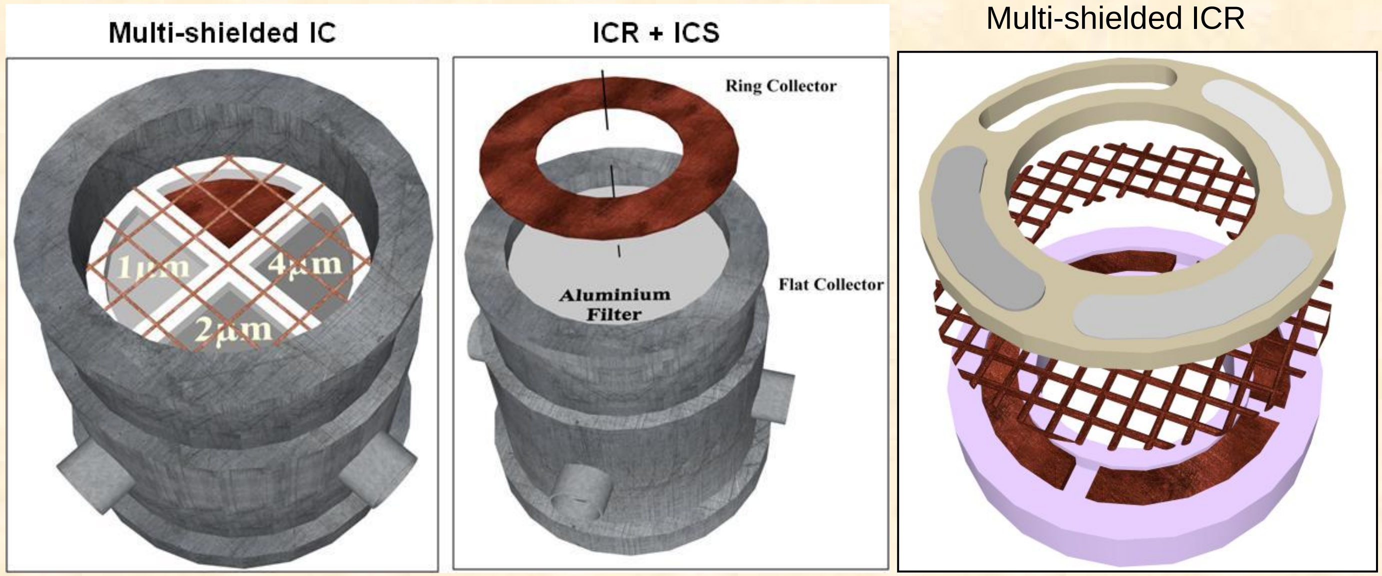
PALS Measurements

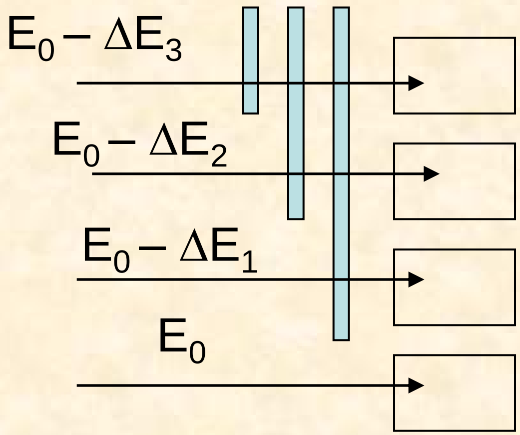
L. Láska, L. Torrisi et Al.
Rev. Sci. Instrum. 79, 02C715, 1-4, (2008)

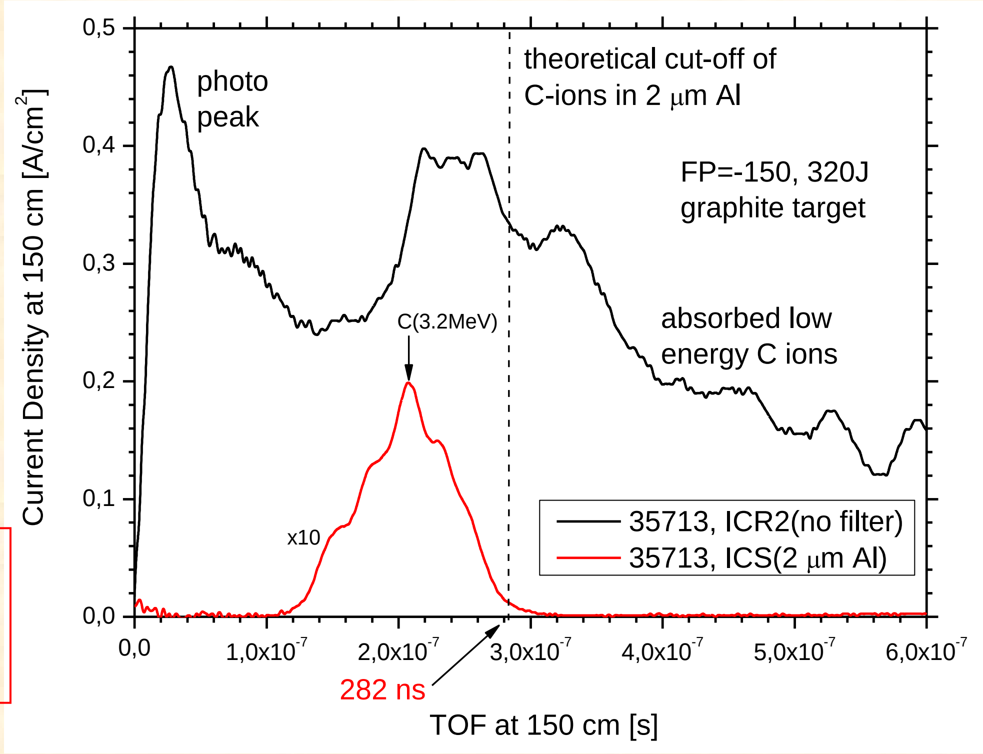
L. Laska, L. Torrisi et Al.
Laser and Particle Beams (2009), 27, 137



IC vs. ion species

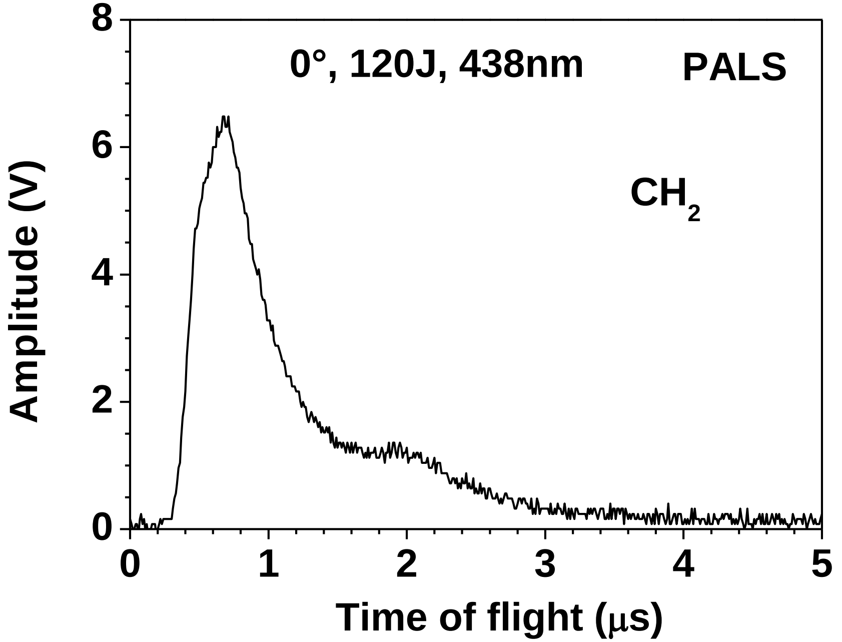






D. Margarone, J. Krasa, L. Laska, A. Velyhan, T. Mocek, J. Prokupek, E. Krousky, M. Pfeifer, S. Gammino, L. Torrisi, J. Ullschmied and B. Rus
Review of Scientific Instruments **81**, 02A506, 2010

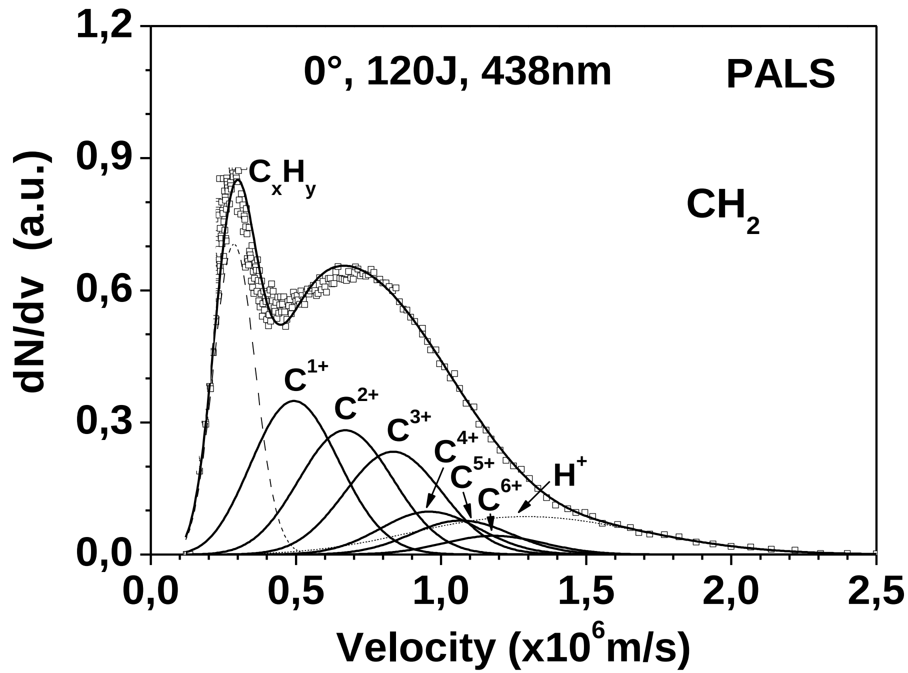
IC deconvolution method



Changes of variables:

$$v = \frac{d}{t}$$

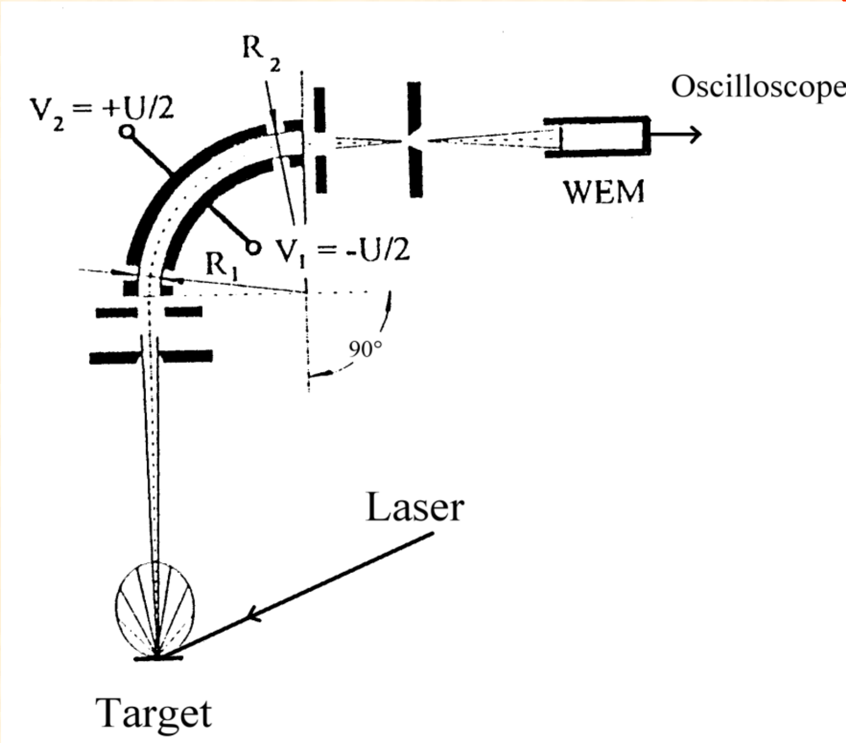
$$\frac{\partial N}{\partial v} = \frac{\partial N}{\partial t}\frac{\partial t}{\partial v} = \frac{\partial N}{\partial t}\frac{d}{v^2} = \frac{dU(t)}{eR_{load}v^2}$$

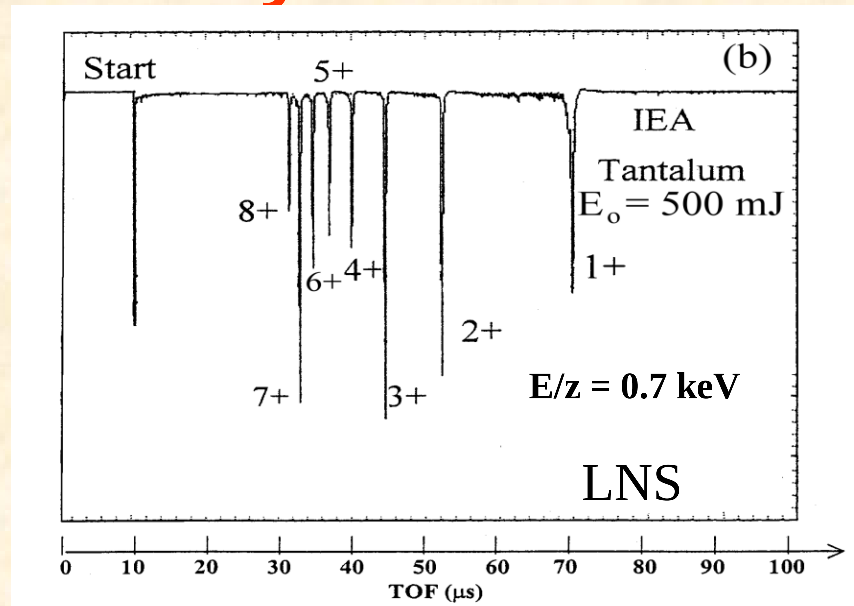


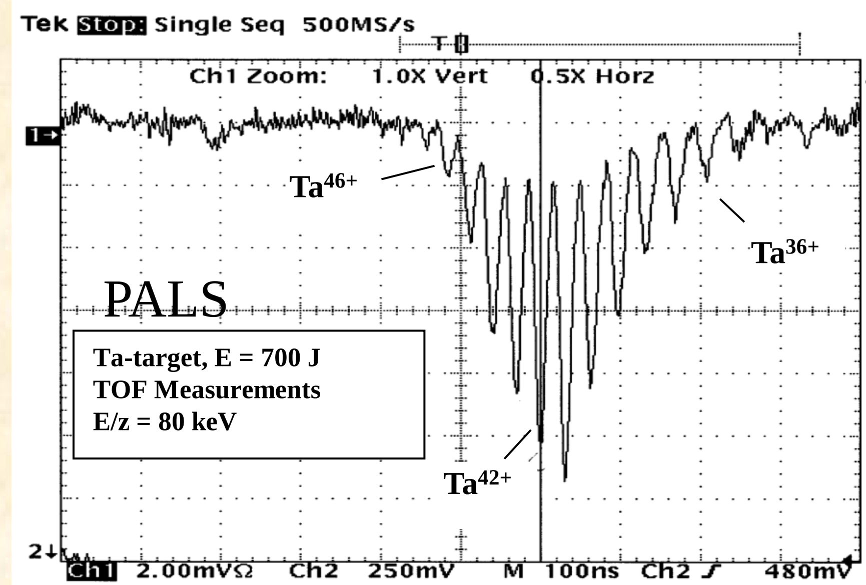
Ion	Velocity ($x10^6$ m/s)	Energy (keV)
C^{1+}	0.49	15
C^{2+}	0.67	28
C^{3+}	0.84	44
C^{4+}	0.96	57
C^{5+}	1.1	73
C^{6+}	1.2	90
H^{+}	1.3	17

A. Borrielli, L. Torrisi et Al.
Rad. Eff. and Def. in Solids, V. 163(4-6), 339, 2008

Ion Energy Analyzer





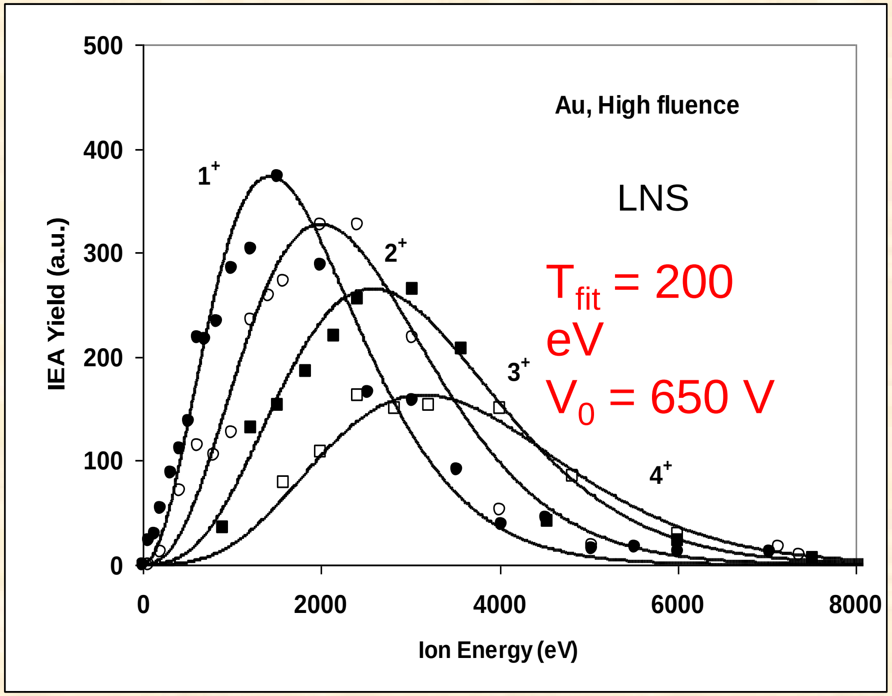


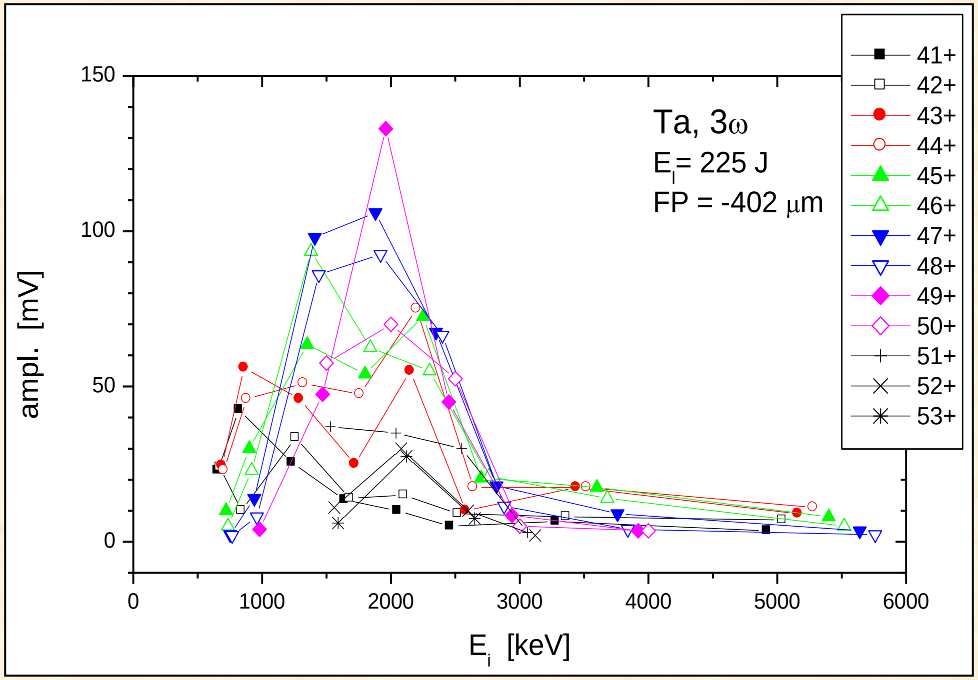
$E/z = (e\,U) / [2 \ln (R_2/R_1)] = K\,e\,U$

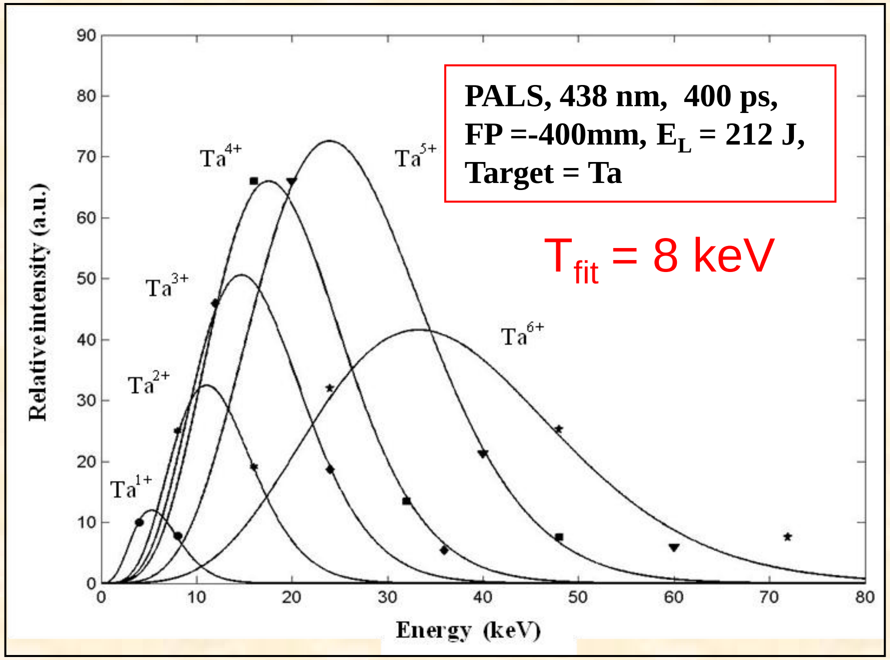
$$t = L\sqrt{\frac{M}{2ezkU}} = 0.72L(m)\sqrt{\frac{M(amu)}{E(eV)}}\frac{1}{\sqrt{z}}$$

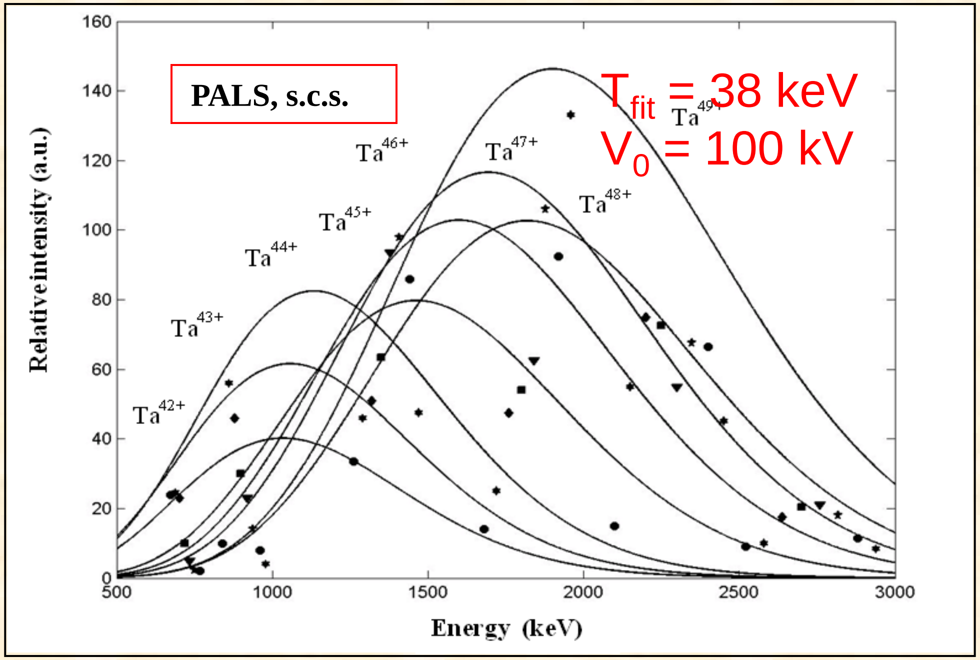
$$v = \frac{d}{t(TOF)} \qquad E = \frac{1}{2}mv^2$$

J. Wolowski, L. Torrisi et Al.; High Temperature Material processes 6, 521-528, 2002



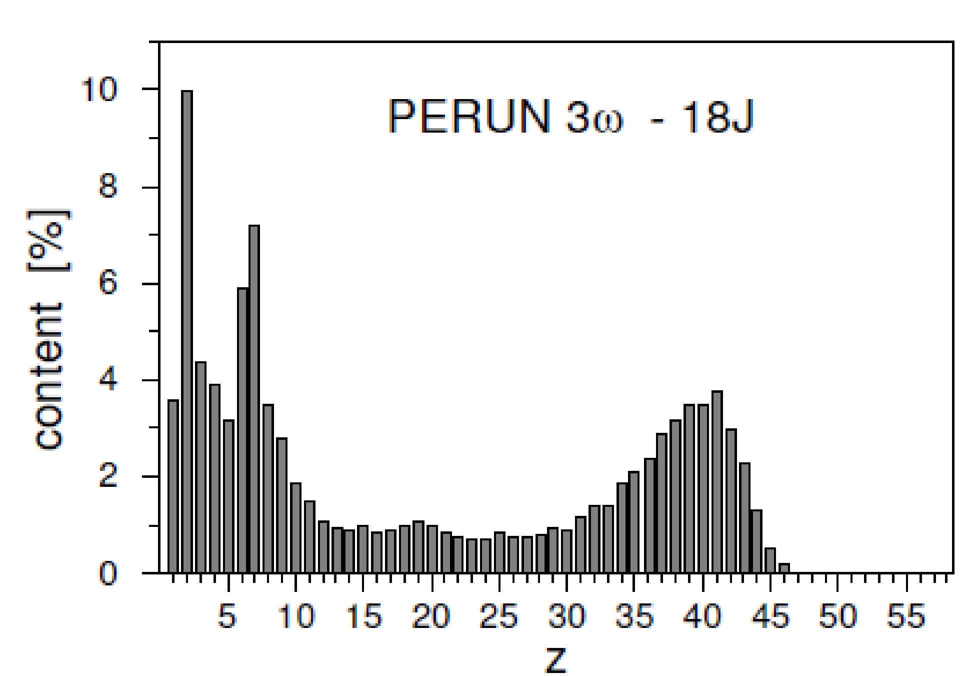


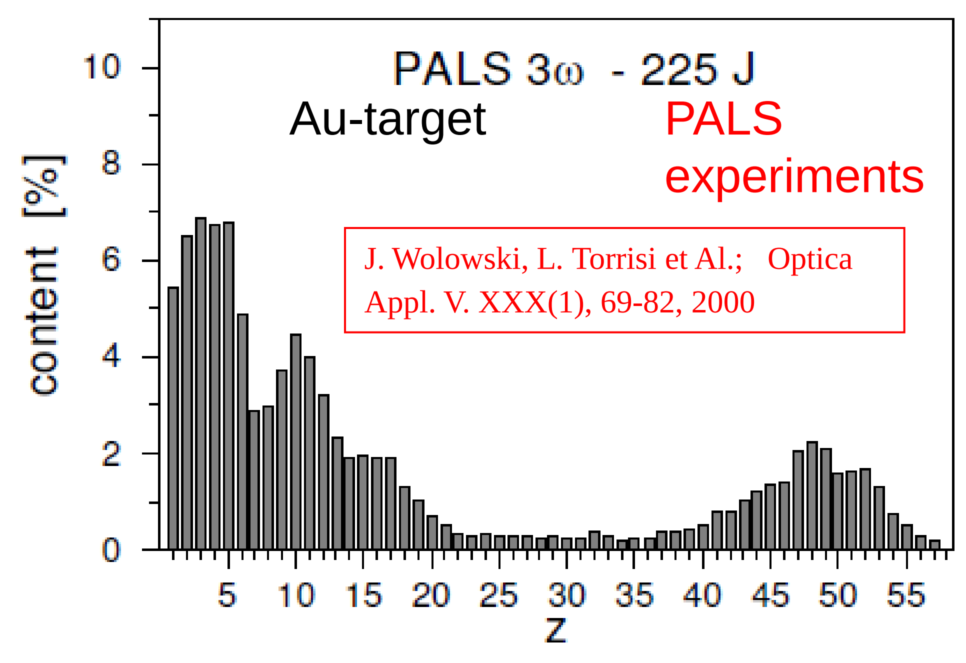


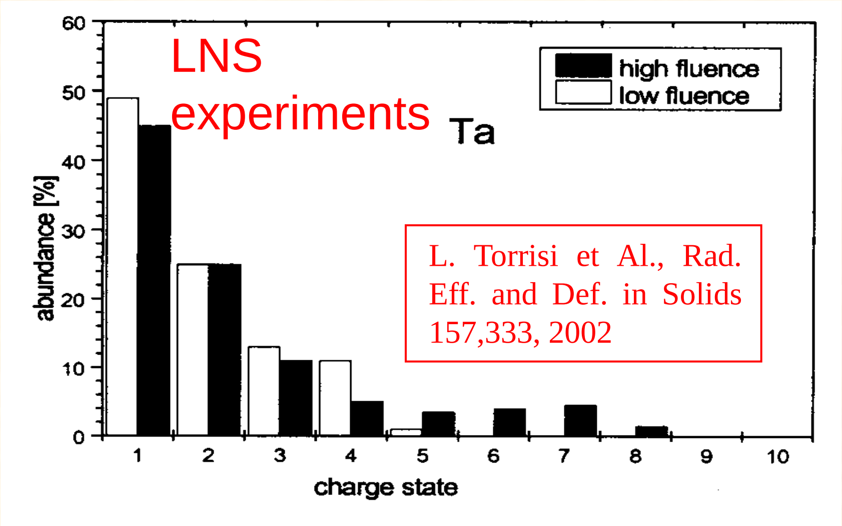


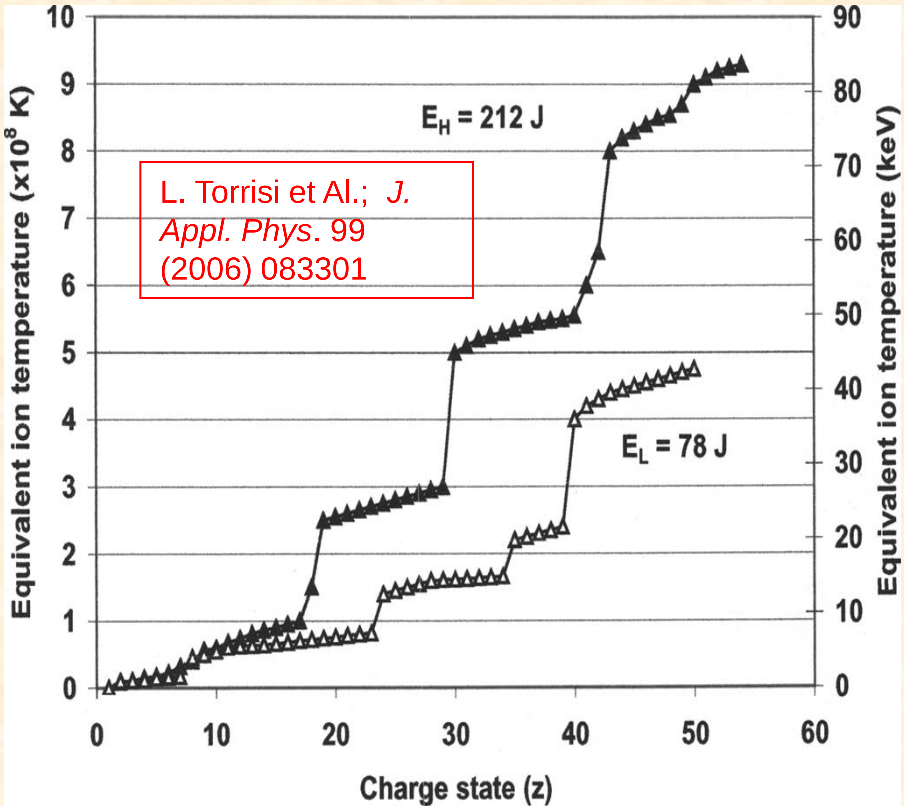
L. Torrisi, L. Andò, S. Gammino and L. Laska, J. Appl. Phys. 91(5), 18, 2002

Ion charge state distributions



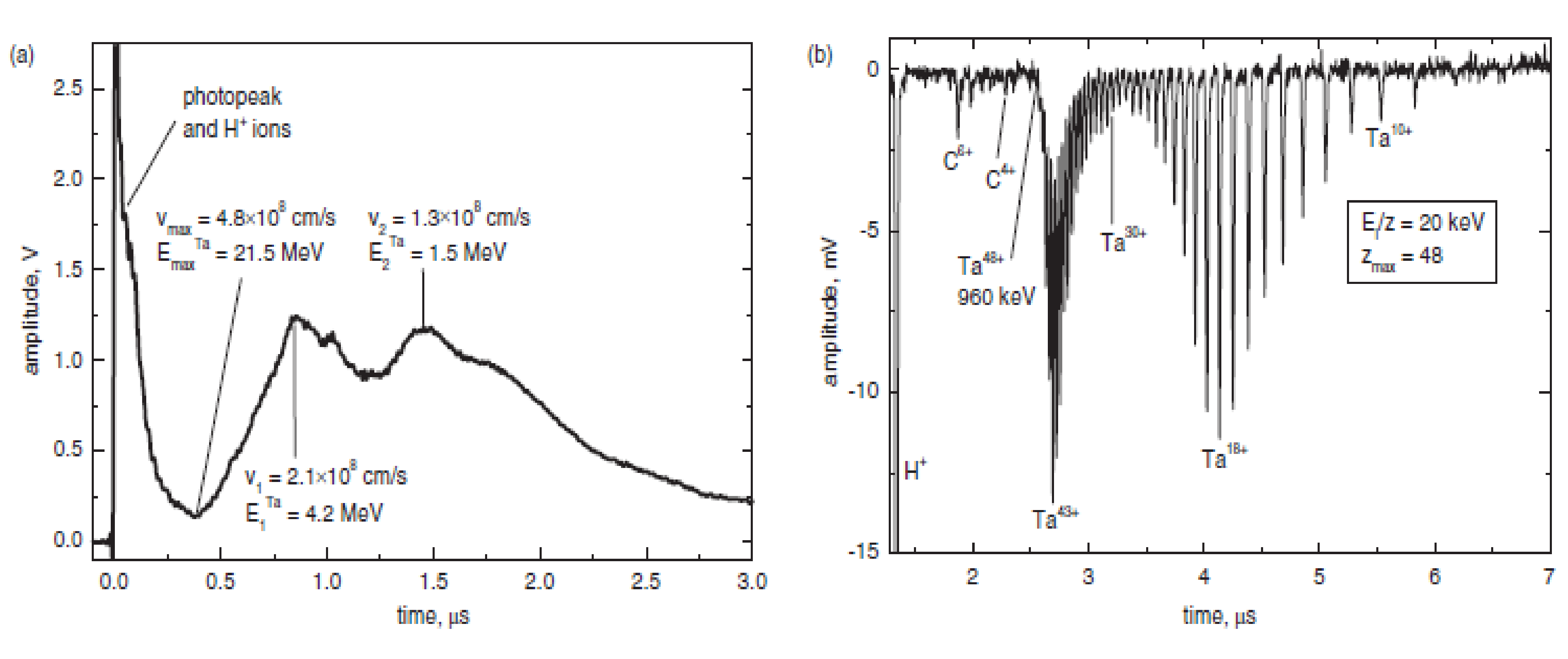






10^{16} W/cm^2 -PALS

IC-Detector IEA-Detector

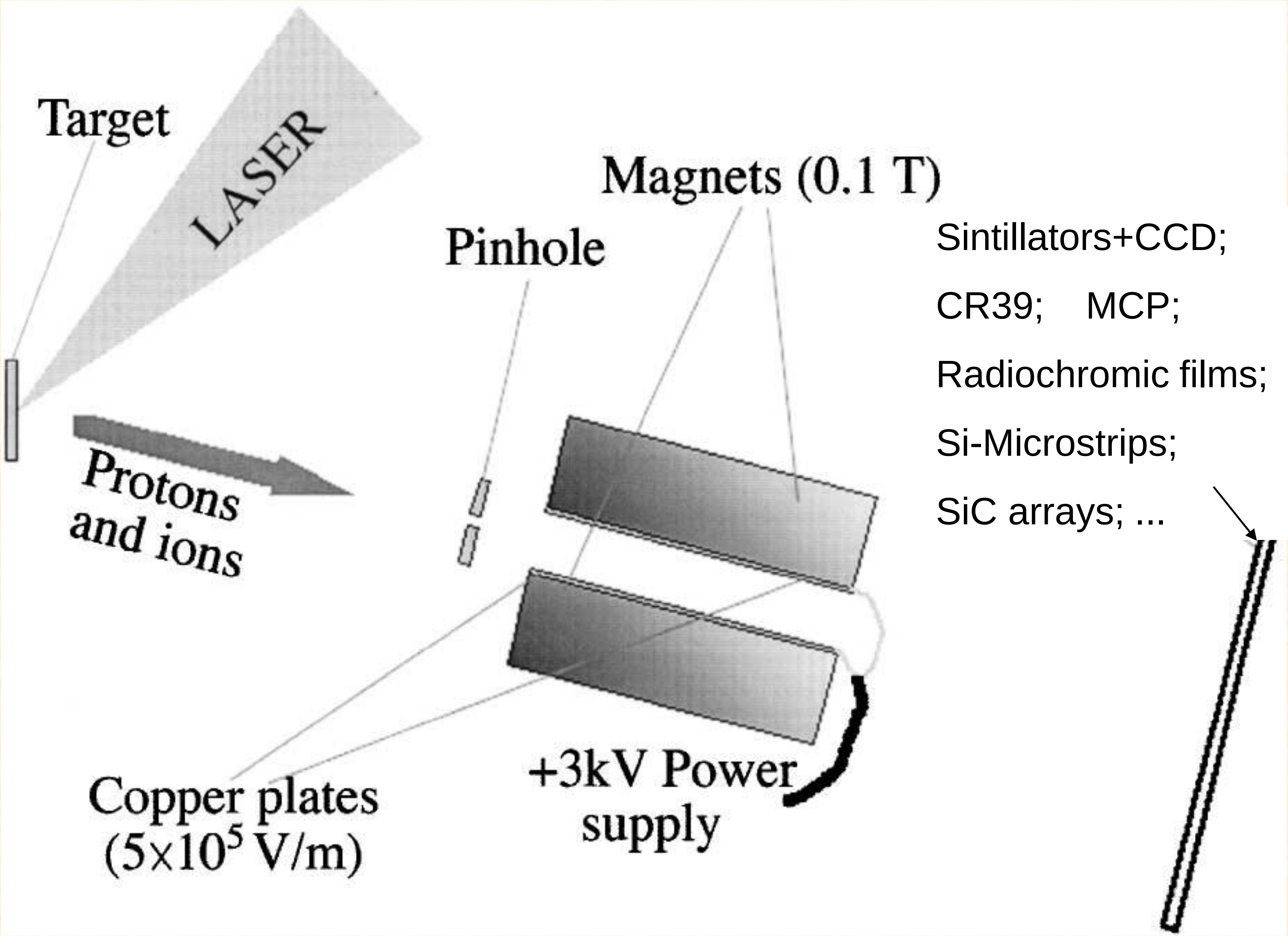


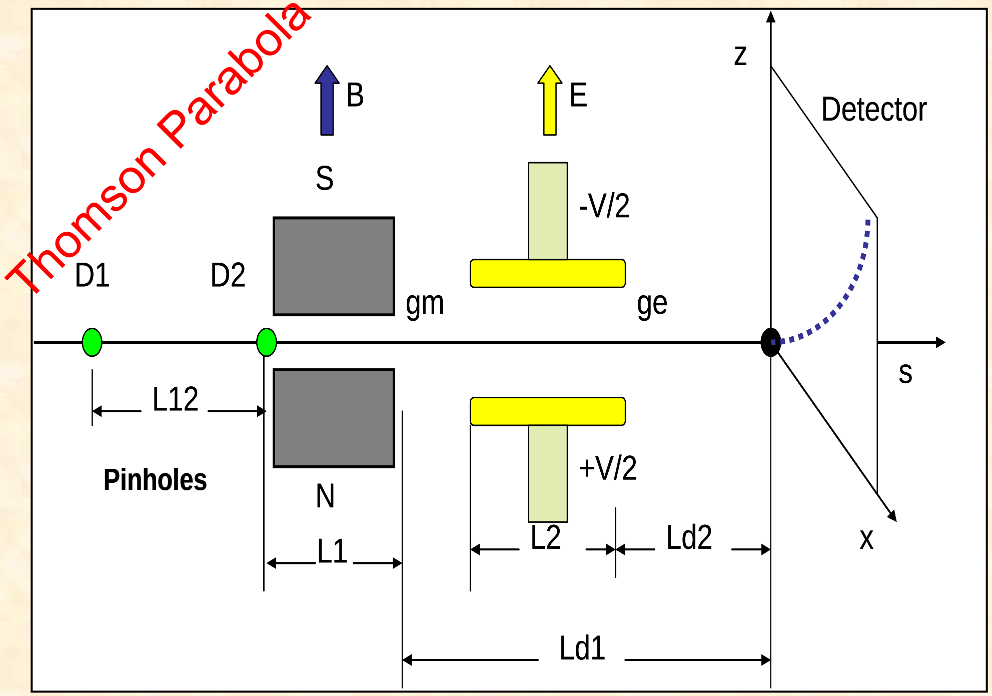
T, n, E_p, P_s, <q>, E_{field},… $\propto$ I λ^2

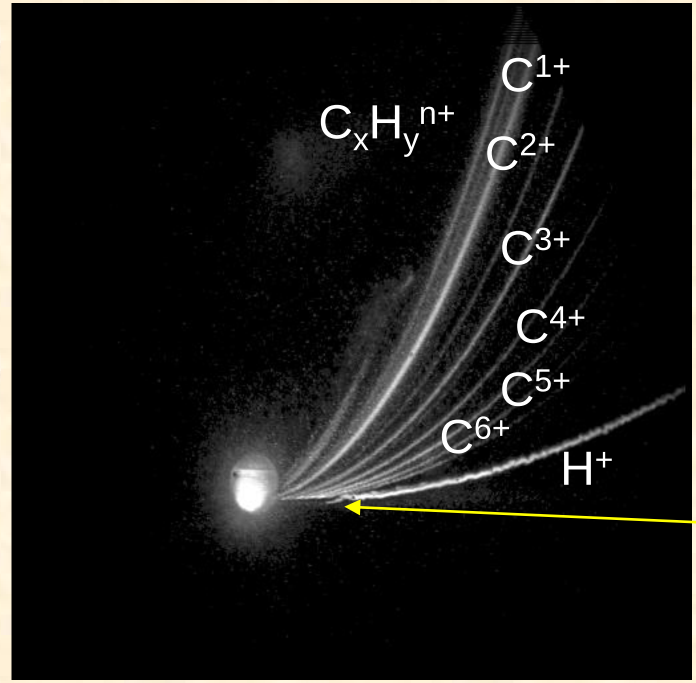
Non-equilibrium Plasma Physics

Non-linear phenomena investigations

A. Szydlowski, J. Badziak, P. Parys, J. Wolowski, E. Woryna, K. Jungwirth, B. Kralikova, J. Krasa, L. Laska, M. Pfeifer, K. Rohlena, J. Skala, J. Ullschmied, F.D. Boody, S. Gammino and L. Torrisi
Plasma Phys. Control. Fusion 45, 1417-1422, 2003

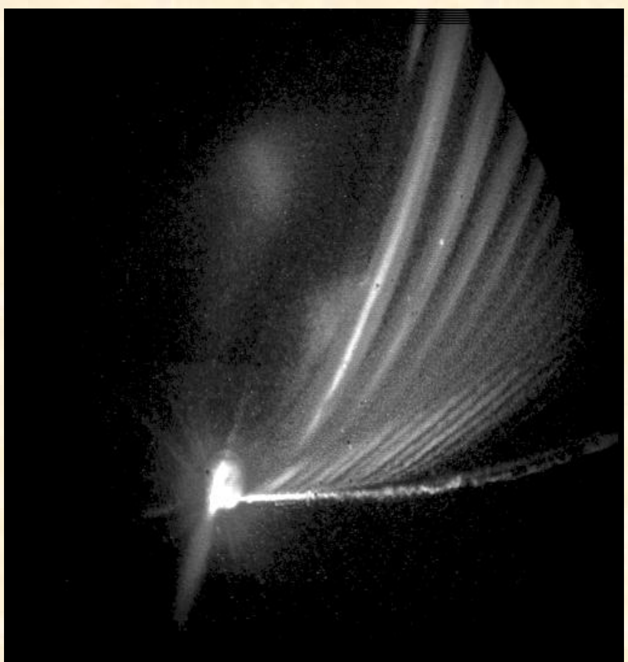

Target
LASER
Magnets (0.1 T)
Pinhole
Protons and ions
Copper plates (5×10^5 V/m)
+3kV Power supply
Sintillators+CCD;
CR39; MCP;
Radiochromic films;
Si-Microstrips;
SiC arrays; ...





0.5 MeV H^+

Polyethylene



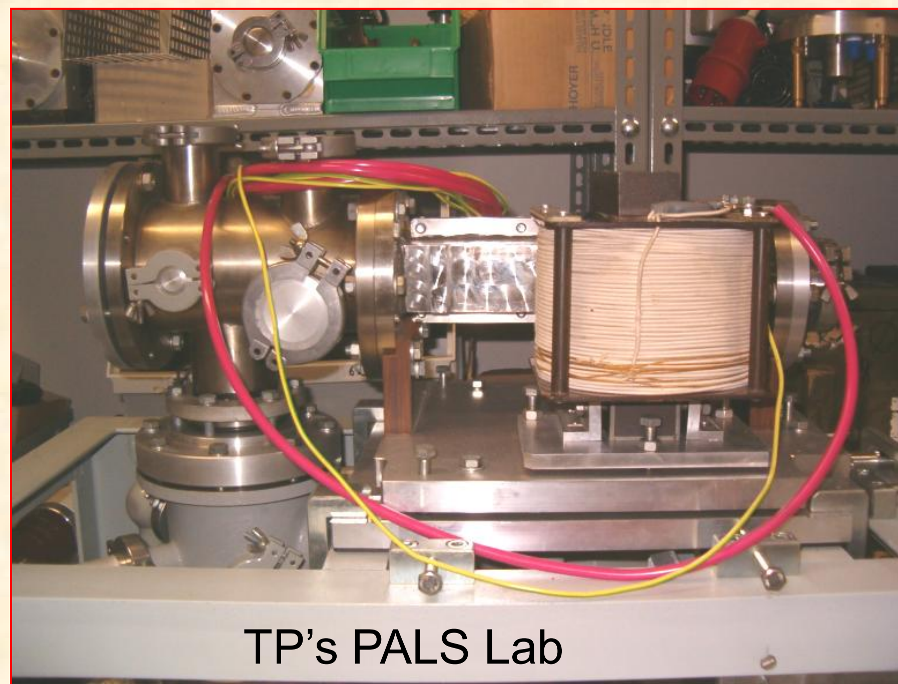
Al^{1+}

…

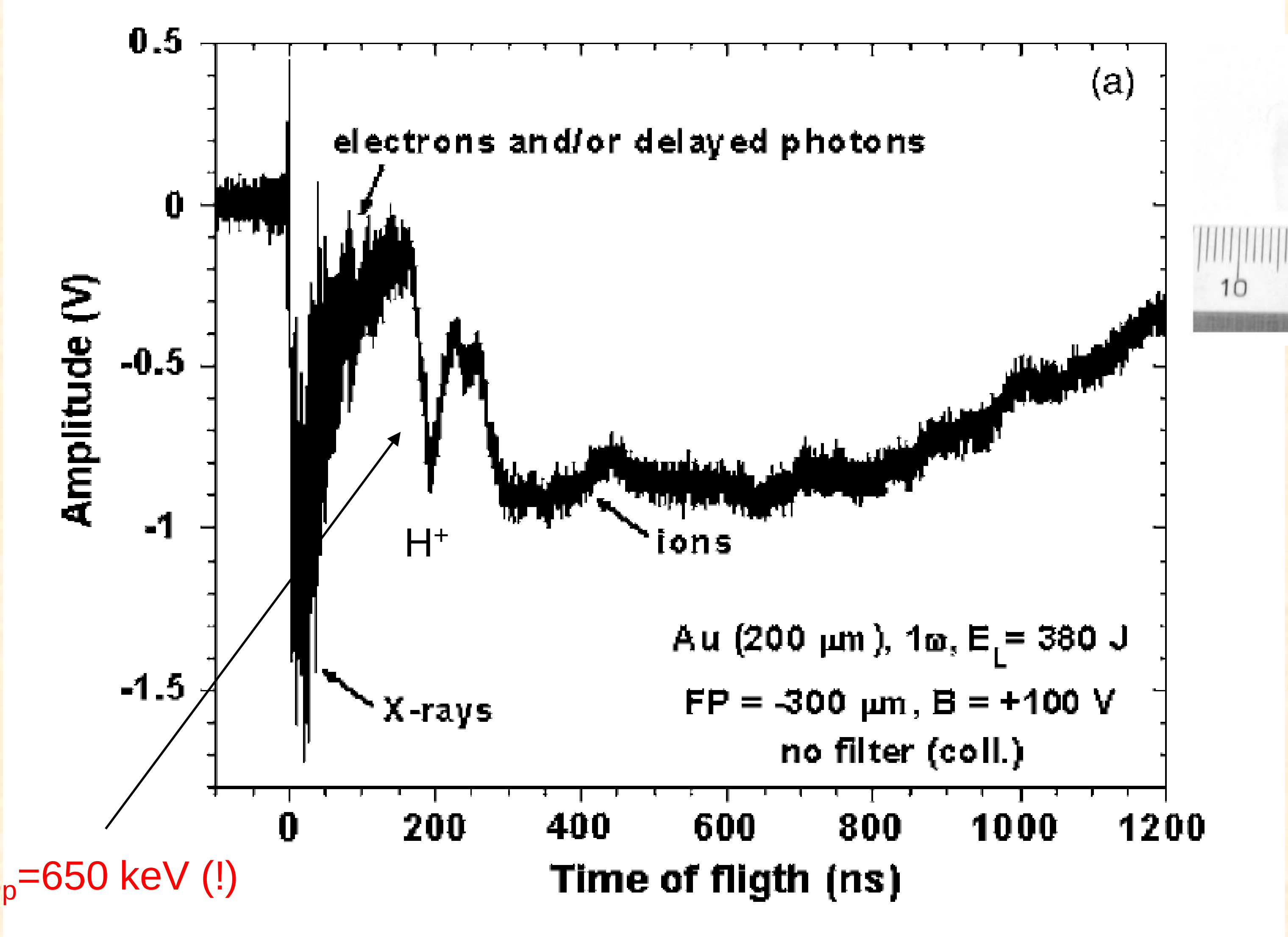
Al^{11+}

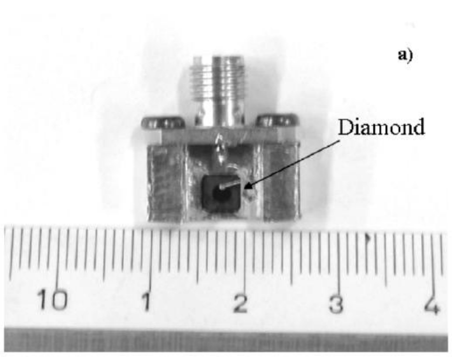
H^+

Aluminium



TOF-Monocrystalline Diamond detectors (PALS Experiment)

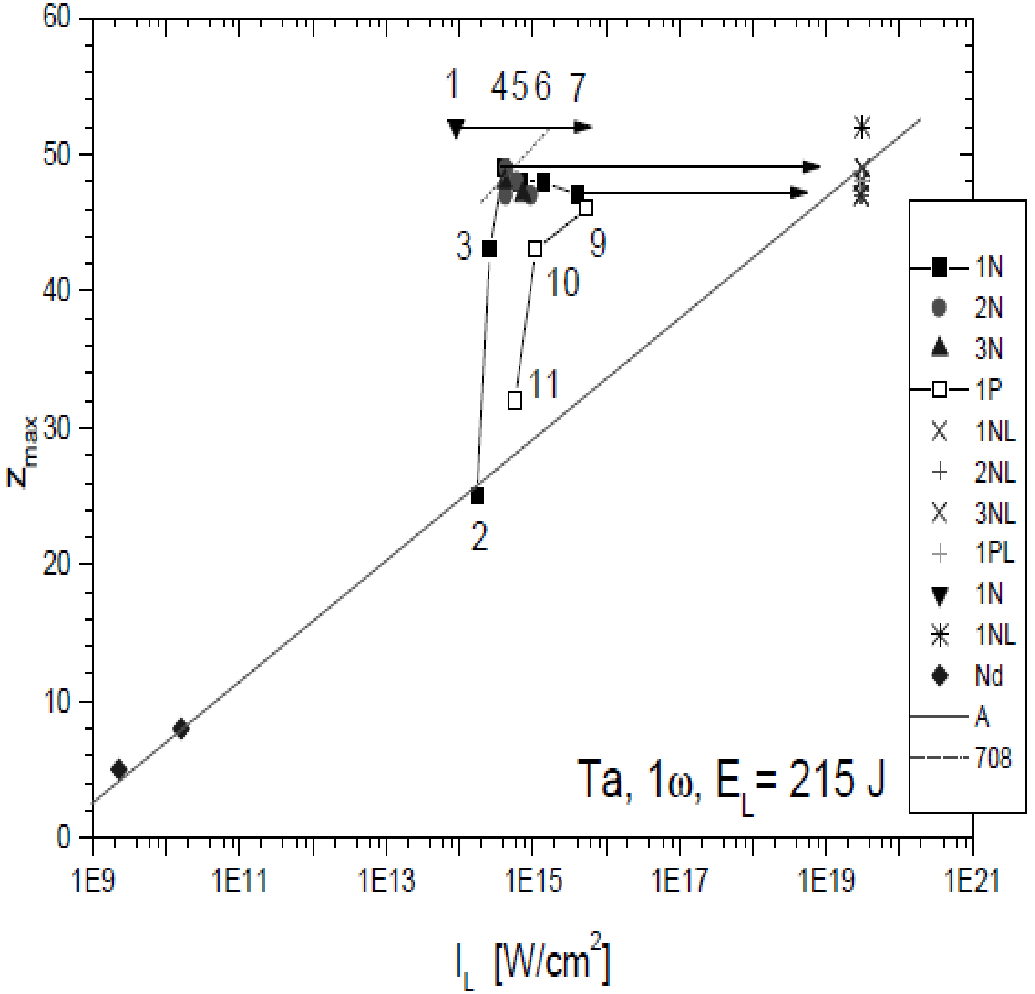


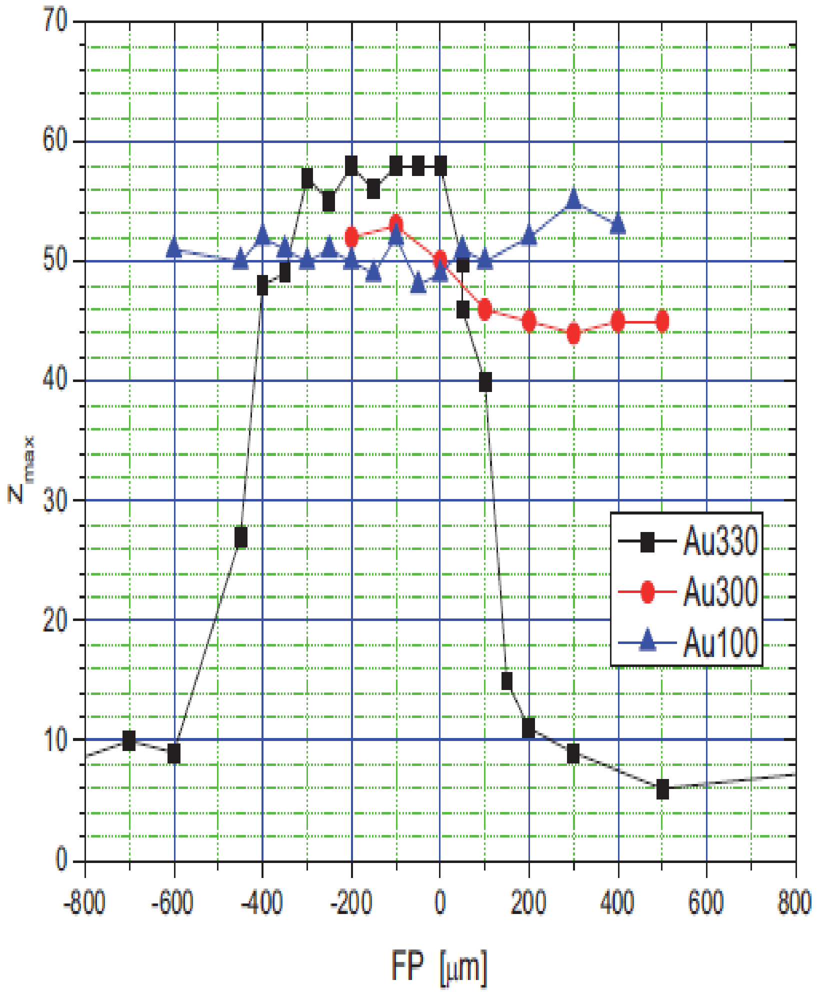


E_p=650 keV (!)

L. Torrisi, D. Margarone, L. Laska, M. Marinelli, E. Milani, G. Verona-Rinati, S. Cavallaro, L. Ryc, J. Krasa, K. Rohlena, J. Ullschmied
J. of Appl. Physics 103, 083106, 1-6, 2008

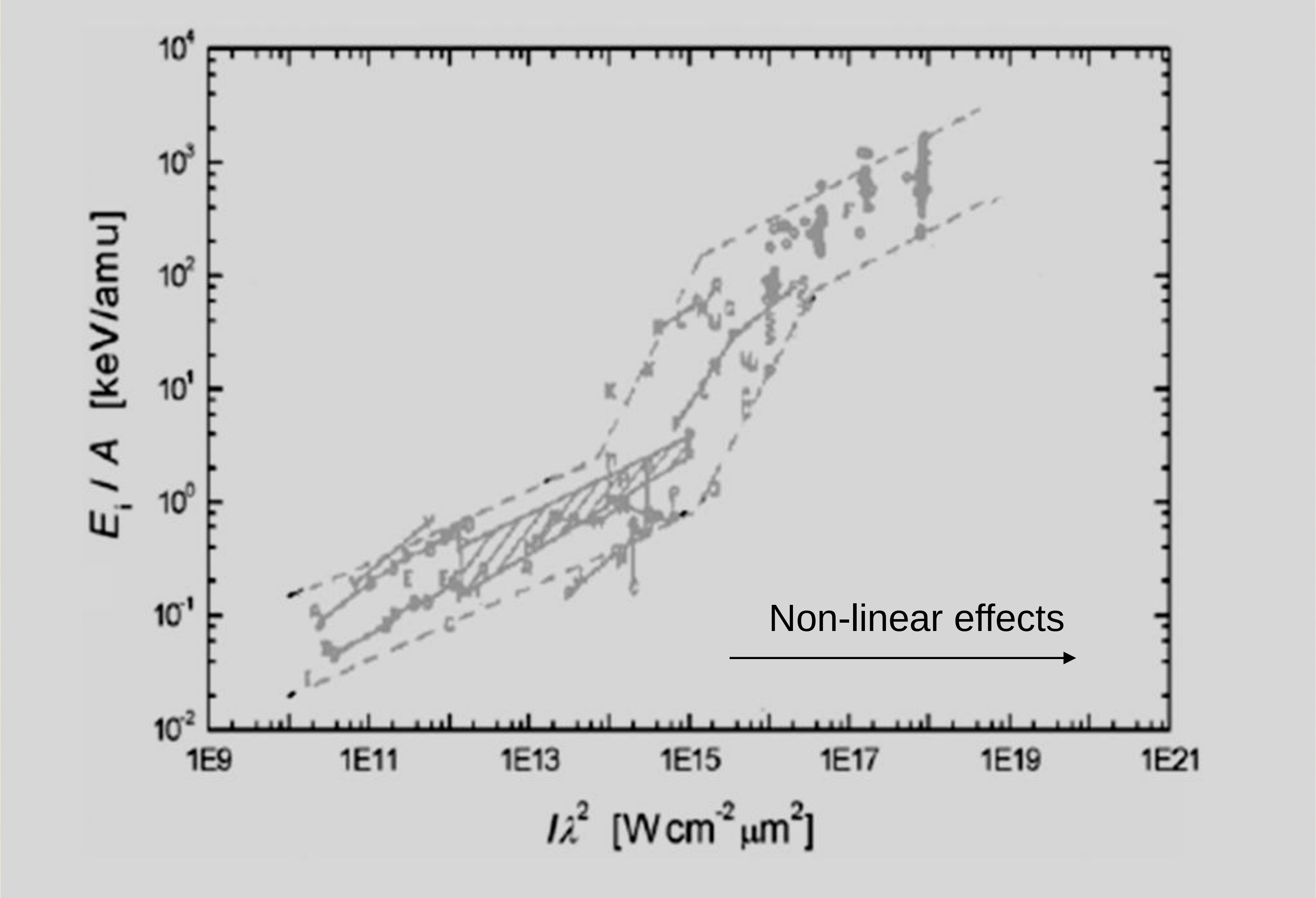
Self-focusing effect & $Z_{max} \propto I$ (PALS Experiments)





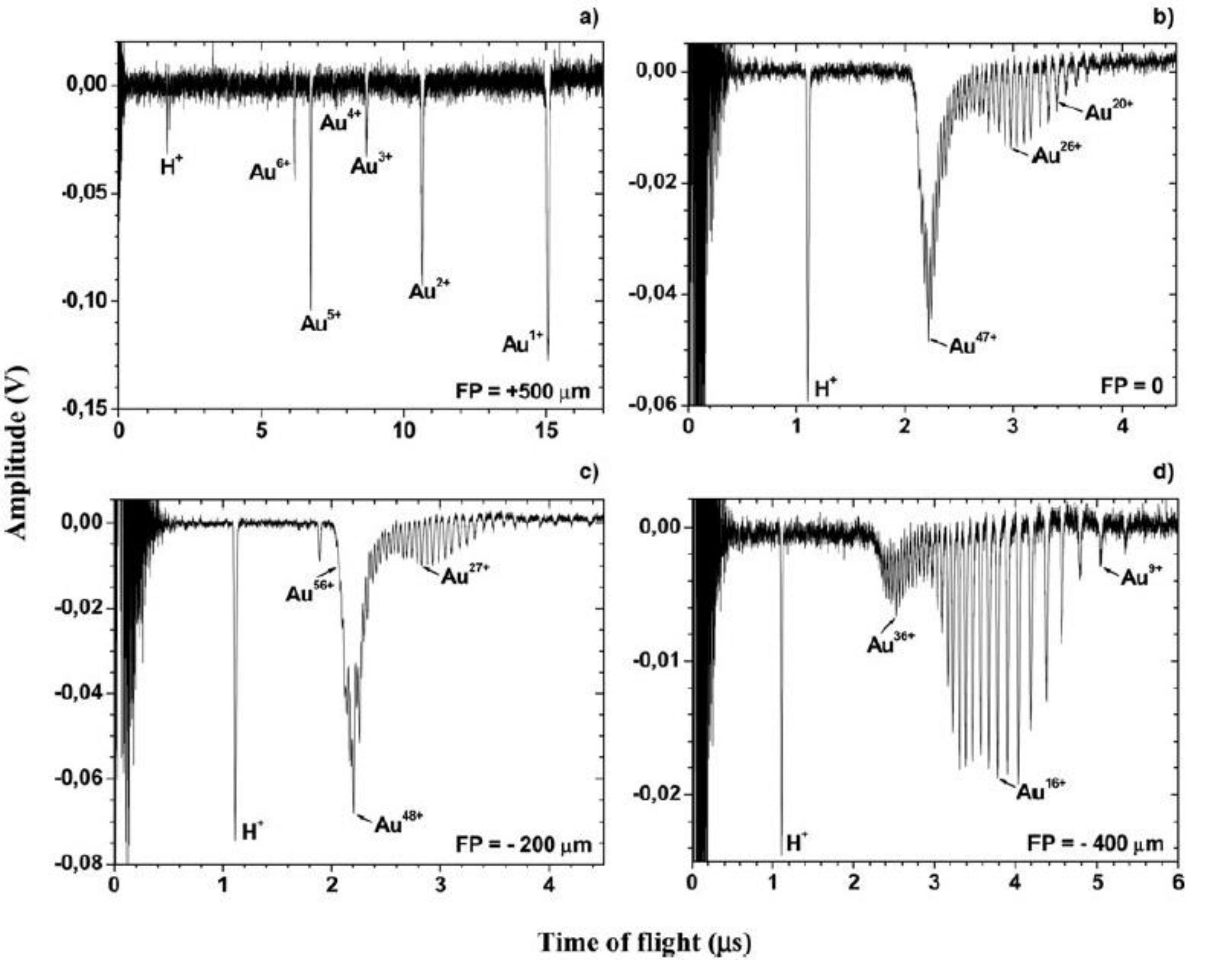
L. Laska, K. Jungwirth, J. Krása, M. Pfeifer, K. Rohlena, J. Ullschmied, J. Badziak, P. Parys, J. Wolowski, F.P. Boody, S. Gammino and L. Torrisi; *Czech. J. of Physics* 54, Suppl. C, C370-C377, 2004

PALS Experiments (E/A vs. $I\lambda^2$)



L. Laska, K. Jungwirth, J. Krasa, M. Pfeifer, K. Rohlena, J. Ullschmied, J. Badziak, P. Parys, J. Wolowski, S. Gammino., L. Torrisi and F.P. Boody; *Appl. Phys. Lett*. 86, 081502, 2005

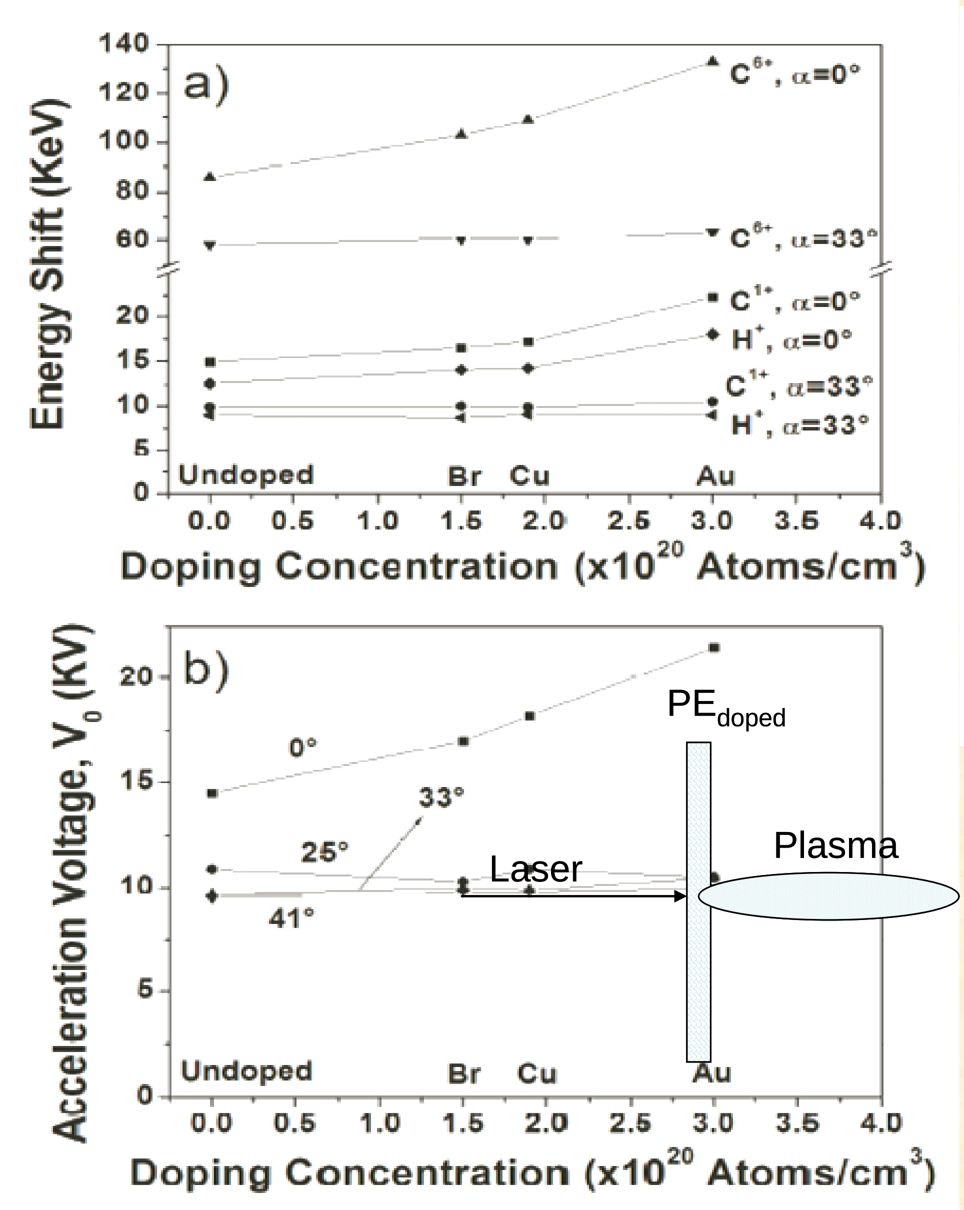
Self-focusing effects

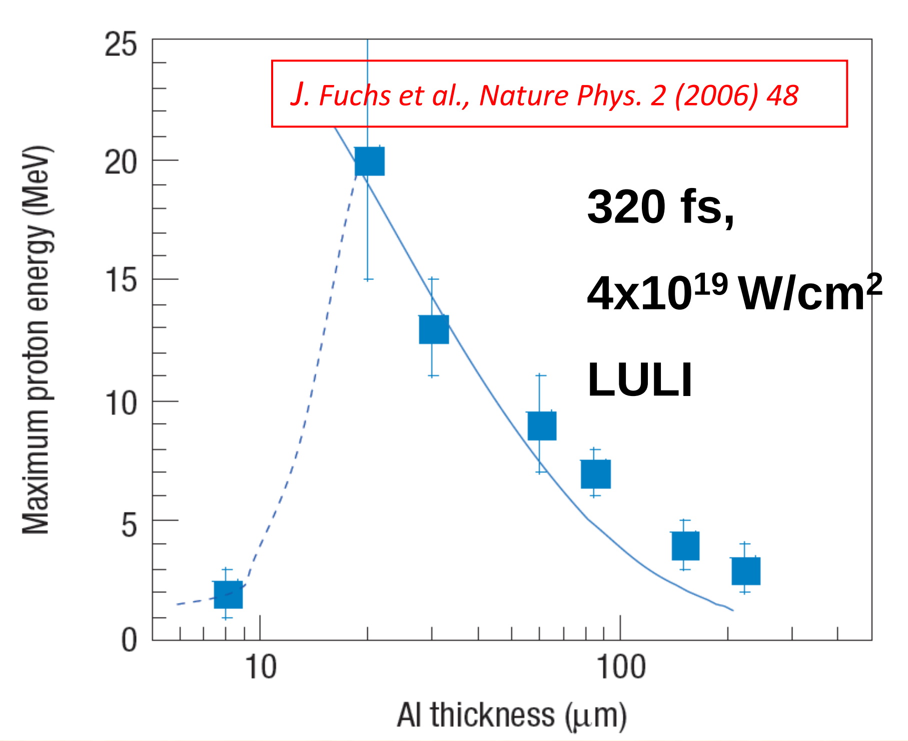


L. Torrisi, D. Margarone, L. Laska, J. Krasa, A. Velyhan, M. Pfeifer, J. Ullschmied, L. Ryc
Laser and Particle Beams 26, 379-387, 2008.

Dependence on the thin target :

Composition, Thickness, Geometry, Multilayers, Spot dimension,Focal position, Pulse duration, Pre-pulse, Doping, …





J. Badziak, L. Torrisi et Al.
Appl. Phys. Lett. 92, 211502 (2008);

L. Torrisi, A. Borrielli, F. Caridi and A.M. Mezzasalma
Atti Acc. Pelor. Dei Peric. V.LXXXVII, C1A0901003 (2009)

Problem to solve:

High beam energy (proton energy up to 100 MeV);

Ion selection

Mono-energy Beam (narrow energy distribution);

Ion dose/pulse (> 10^{10} particle/pulse)

Ion directivity (magnetic focalization)

High repetition rate (target moving)

High reproducibility (laser beam energy)

Plasma and Ion beam Detectors (TP, SiC and diamond detectors, Ion imaging diagnostics, detector arrays,…)

Thin target geometry and multi-composition to drive ion jet

…

FLAME Facilities for Ion acceleration Applications:

1. Ion detection for plasma diagnostics and understanding of base physics mechanisms
2. Investigations on Ion accelerator systems and LIS
3. Multi-energetic and multi-ionic ion beams useful for material treatments (Multiple ion implantation, doping, polymeric plasma ion irradiations,…)
4. Proton beams for use in medical Therapy (Protontherapy)
5. Ion beams useful for nuclear investigation (nuclear reactions, nuclear excitation and de-excitation,…)
6. Nuclear fusion ignition investigation
7. Astrophysical Field investigation
8. R & D of fast ion detectors (imaging, arrays,…)


Thank You
for the attention