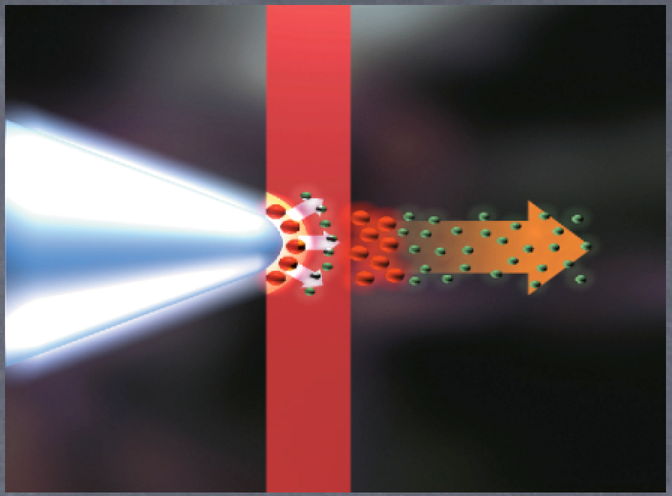
Proton acceleration with high intensity lasers: new developments in energy increase, focusing and energy selection



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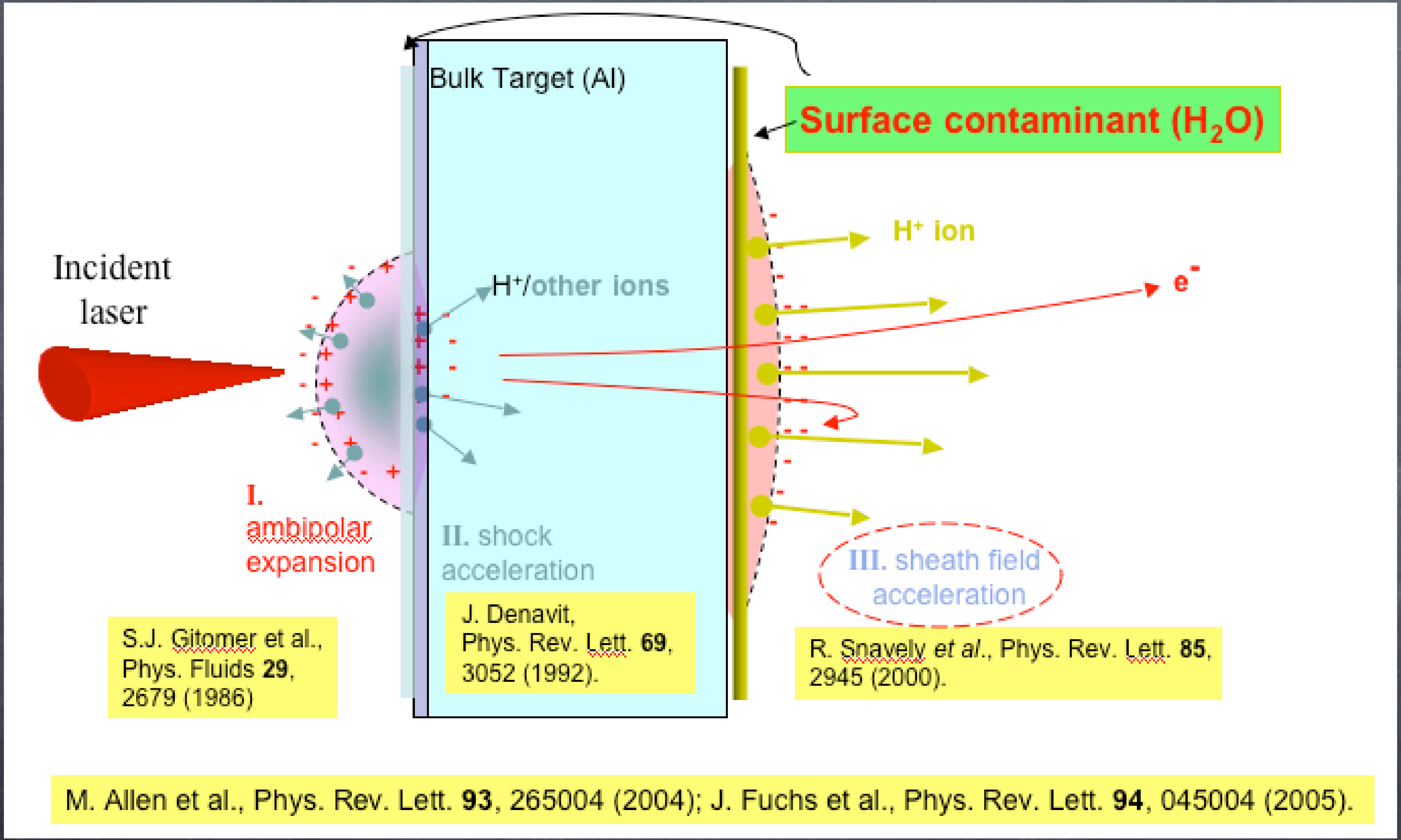
Proton acceleration in high intensity laser plasma interaction



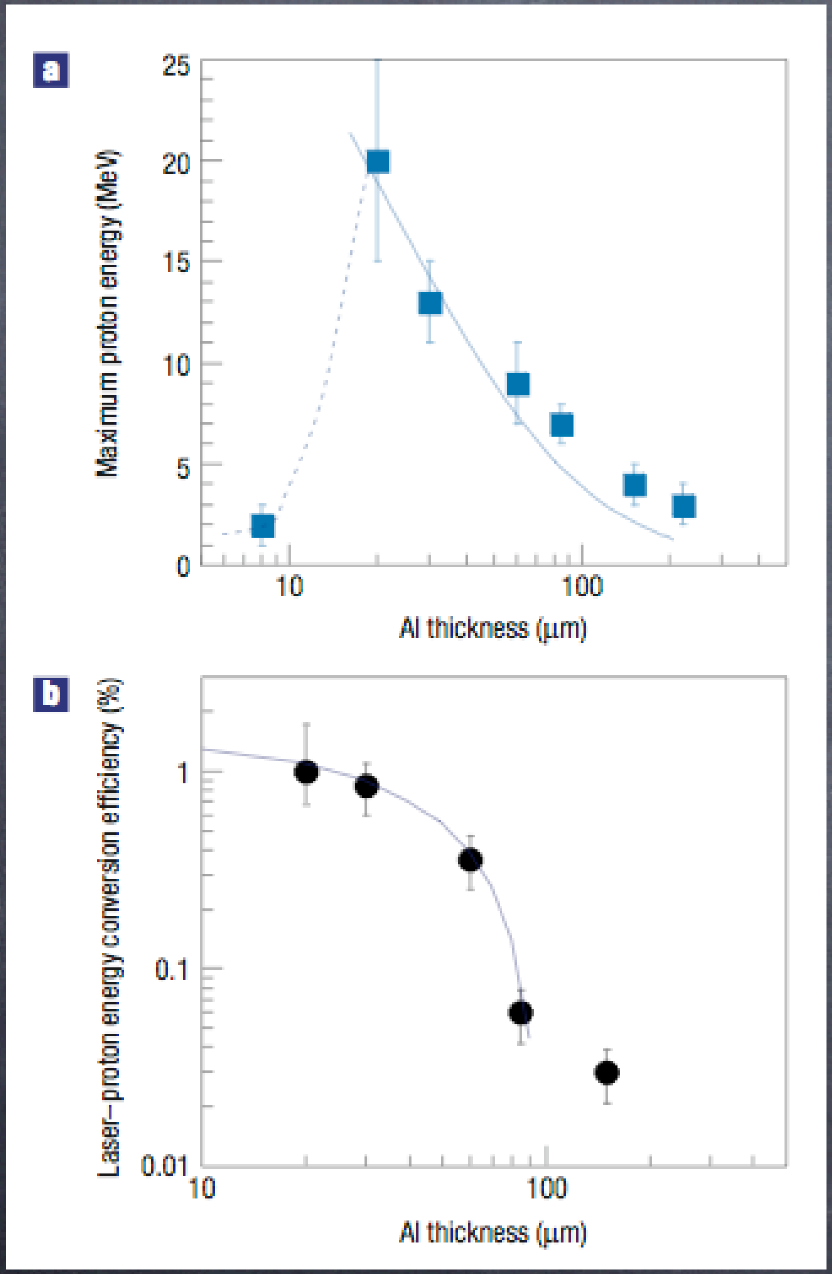
- <0.004 mm-mrad for the transverse emittance and <10^-4 eV-s for the longitudinal emittance
- Short duration (ps at the source)
- High spectral cut-off

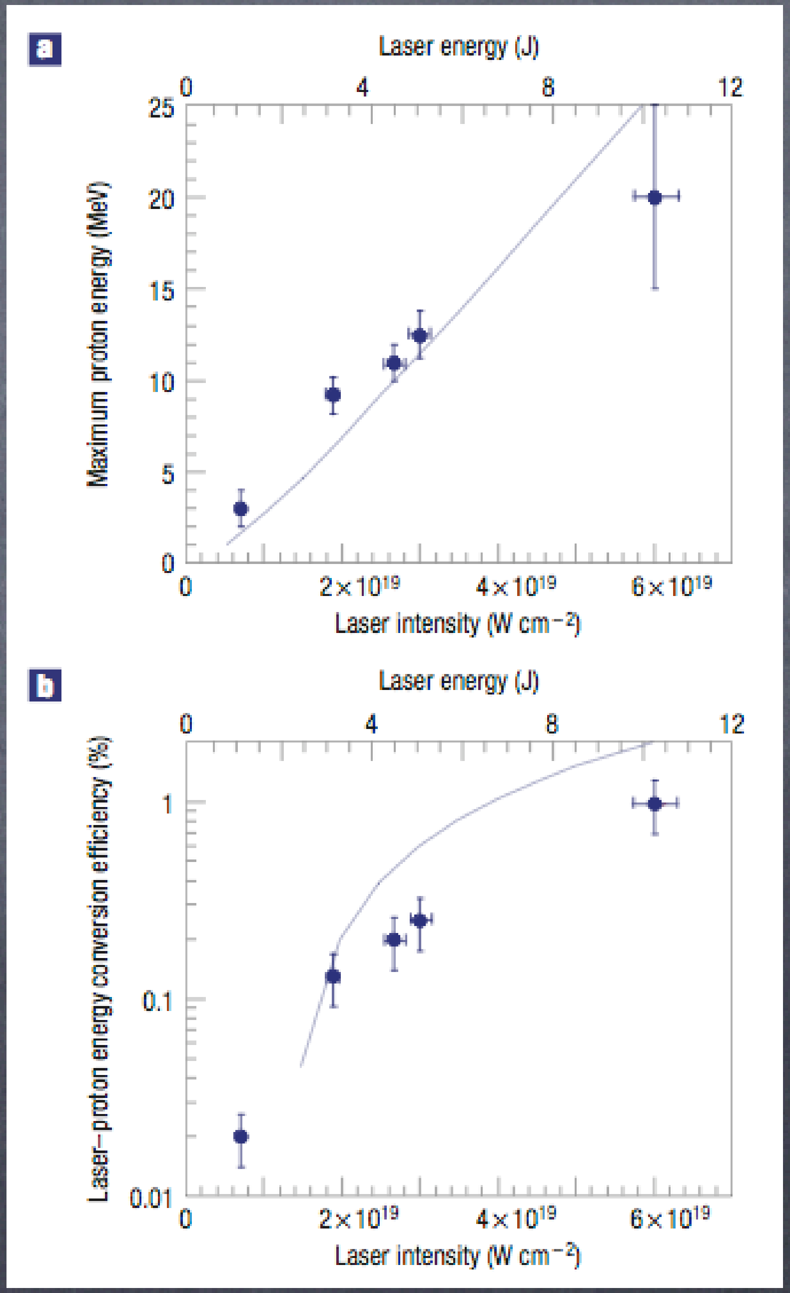
Outline

- Model of proton acceleration with high intensity lasers
  - Experimental results
  - Description of the model
  - Limits of the model
  - Implications on the optimum laser parameters needed for a given proton energy
- Proton beam collimation and energy selection using a cylinder irradiated by a high intensity laser
  - Experimental results
  - Mechanism
  - Application to high energy proton beams
  - Study of the symmetry of the deflecting field

Proton acceleration experiments at LULI

J. Fuchs et al., Nature Physics 2, 48 (2006).

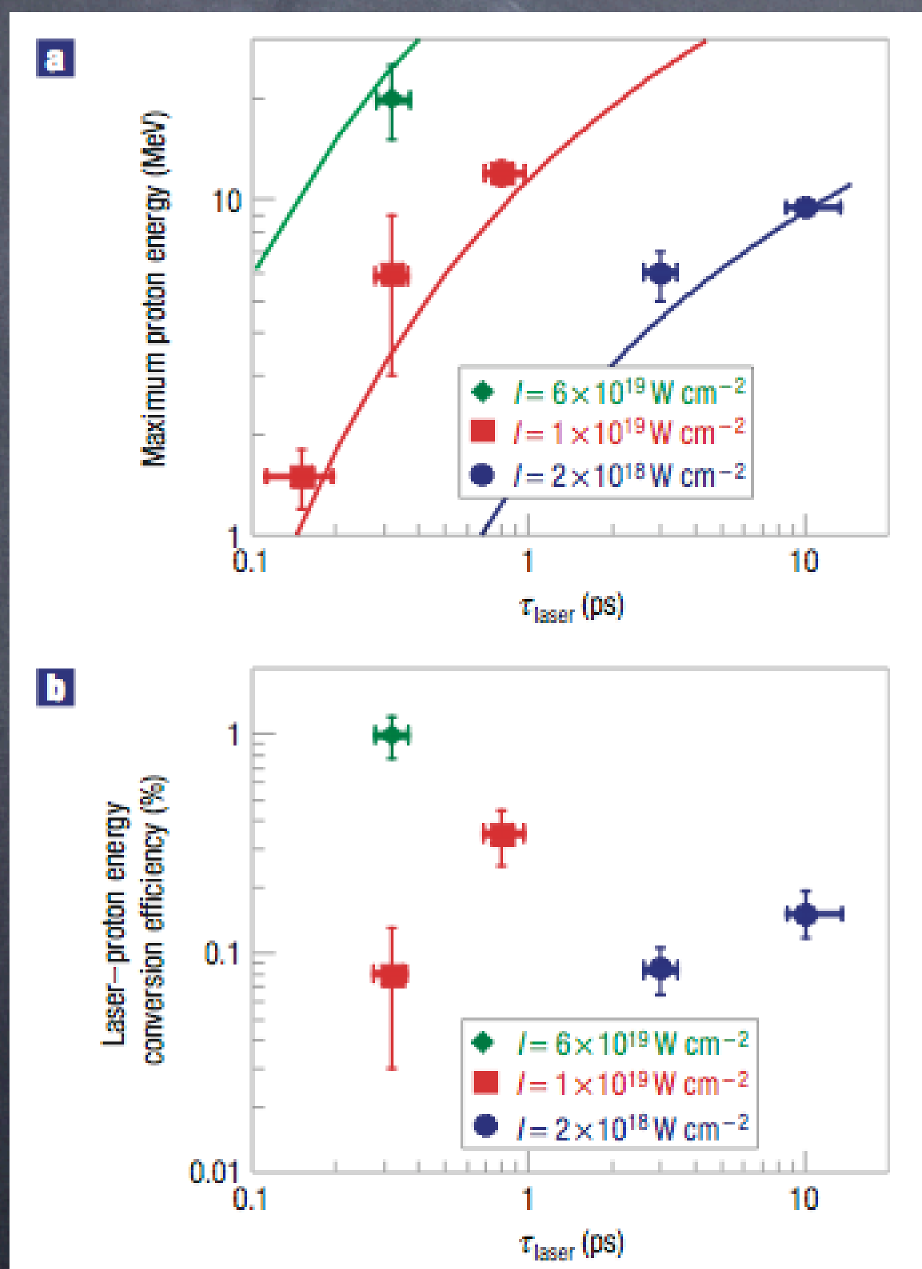


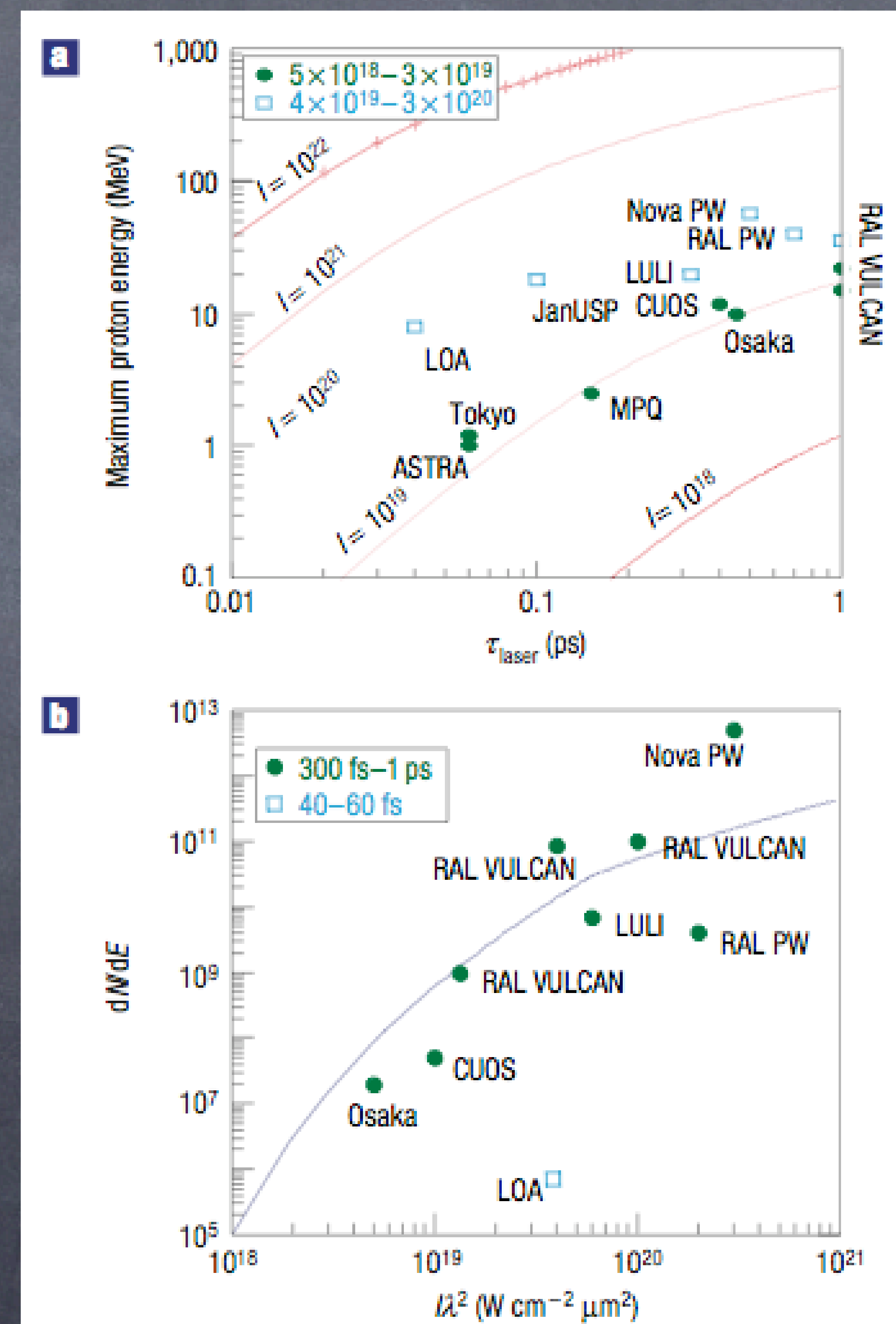


6 ! 10^{19} W/cm^2, 320 fs

20 microns target, 320 fs

Proton acceleration experiments at LULI





Model of proton acceleration with high intensity lasers

Hypothesis:
Maxwellian distribution for electrons
Isothermal expansion

$$n_e = n_{e0}\, e^{\frac{e\Phi}{k_B T_e}}$$

Self-similar solution: quasi-neutrality

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(n_i v_i) = 0$$

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial}{\partial x} v_i = -\frac{Ze}{m_i}\frac{\partial \Phi}{\partial x}$$

$$v_i = c_s + \frac{x}{t} \qquad : \lambda_D = c_s t$$

$$\Rightarrow v_{i,front} = 2 c_s \ln(\omega_{pi} t)$$

P. Mora and R. Pellat, Phys Fluid. **22**, 2300 (1979).

Lagrangian code:

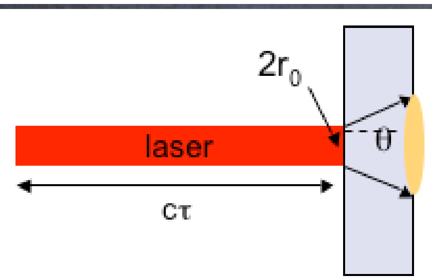
$$\varepsilon_0 \frac{\partial^2 \Phi}{\partial x^2} = e(n_e - Z n_i)$$

$$E_{max} = 2T_e \ln^2\left(t_p + \sqrt{t_p^2 + 1}\right)$$

$$\text{où } t_p = \frac{\omega_{pi} t_{acc}}{\sqrt{2e^3}}$$

$$\text{et } \omega_{pi} = \sqrt{\frac{q^2 n_{e0}}{m_i \varepsilon_0}}$$

P. Mora, Phys. Rev. Lett. **90**, 185002 (2003).

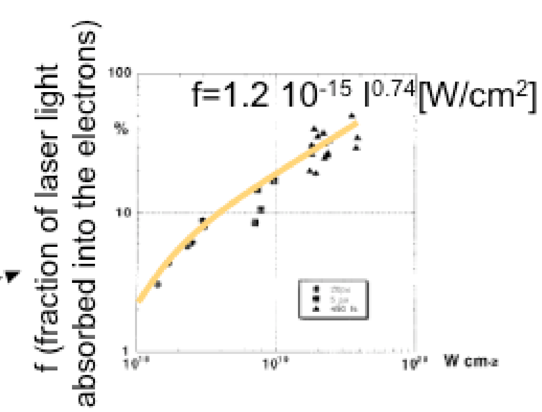


$$S_{sheath} = \pi\left(r_{laser} + d\tan\theta\right)^2$$

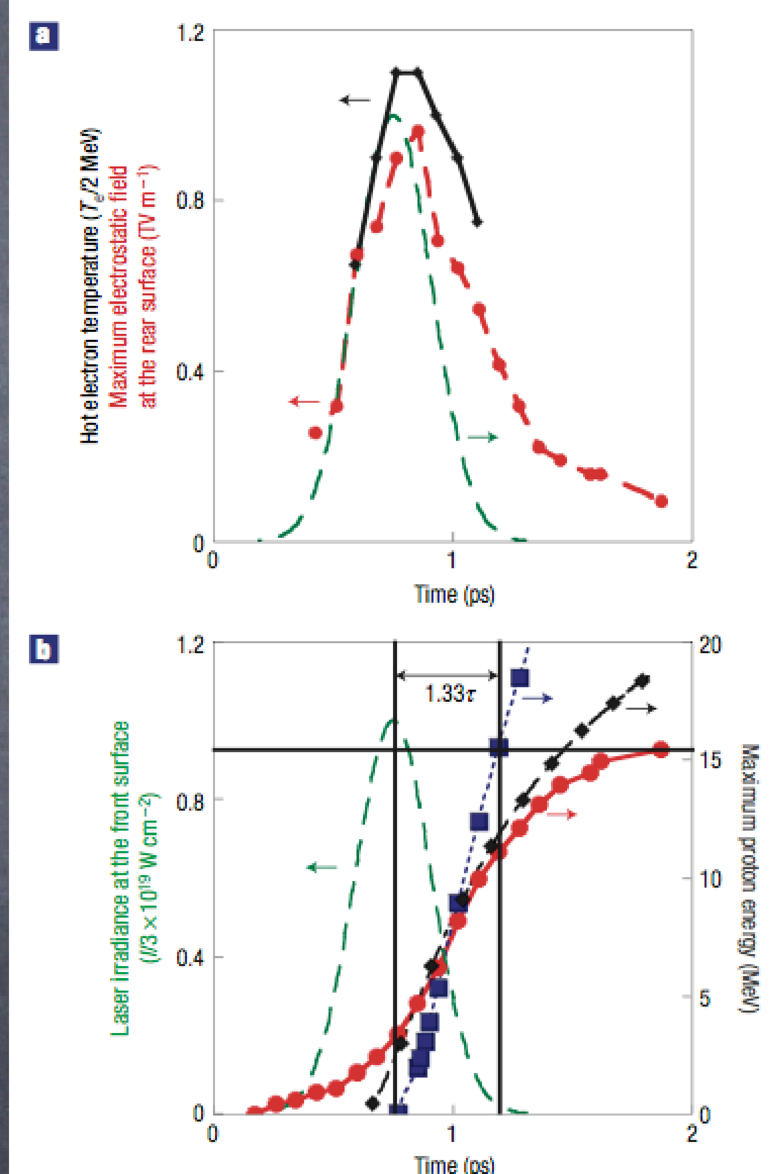
θ~25° (experiments+PIC)

$$n_{e0} = \frac{N_{total}}{c\tau_{laser} S_{sheath}}$$

N_{total}=(Total energy of e-)/<e- energy>
=fE_{laser}/T_{hot}



Key, M. *et al.*, *Phys. Plasmas* **5**, 1966 (1998).



$$E_{max}(MeV) = 2\times 0.511\cdot\left(\sqrt{1+\frac{I_{18}\lambda^2}{1.37}} - 1\right)\cdot \ln^2(\omega_{pi}\cdot 1.3\cdot \tau)$$

Comparison with PIC simulation results and other experimental results

Comparison with PIC simulations

I (W/cm²)	τ (fs)	FWHM (μm)	Thickness (μm)	E_PIC (MeV)	E_model (MeV)	ΔE/E_PIC
10^{22}	36	6	2	319	368	-15%
1.11×10^{22}	36	3	8	150	150	0
2×10^{21}	36	6	2	111	108	+3%
10^{21}	36	6	2	60	63	-5%
8×10^{20}	500	3	8	112	250	-123%
5×10^{20}	217	6	3	82	167	-104%
3×10^{20}	36	6	1	37	27	+27%
3×10^{20}	150	6	4	72	82	-14%
3×10^{19}	320	6	19	16	13	+19%

Comparison with short laser pulse duration experiments

Reference	Intensity ($W.cm^{-2}$)	Target thickness (μm)	t_{laser} (fs)	E_{max} RSA (MeV) 1.3×τ	E_{max} RSA (MeV) 2.×τ	E_{max} RSA (MeV) 3.×τ	Measured E_{max} (MeV)
RSI Mc Kenna+PRE Spencer	$6\ 10^{18}$	25	60	0.	0.40	0.82	0.8
RSI Mc Kenna	$6\ 10^{18}$	50	60	0.	0.	0.32	0.4
APL Fritzler	$6\ 10^{19}$	6	40	3.09	6.18	10.87	10
APL Fuji (acknowledge FSA !!!)	$7\ 10^{18}$	5	60	0.90	1.77	3.06	1.3
PoP Oishi	$6\ 10^{18}$	5	55	0.67	1.34	2.39	1.2
	$2\ 10^{18}$	5	55	0.23	0.47	0.87	0.5
	$2\ 10^{18}$	5	170	1.26	2.05	2.99	1.15
PoP Fukumi	$2.7\ 10^{18}$	3	70	0.58	1.10	1.84	0.88
PoP Schreiber	$2\ 10^{19}$	10	40	0.74	1.60	3.09	3

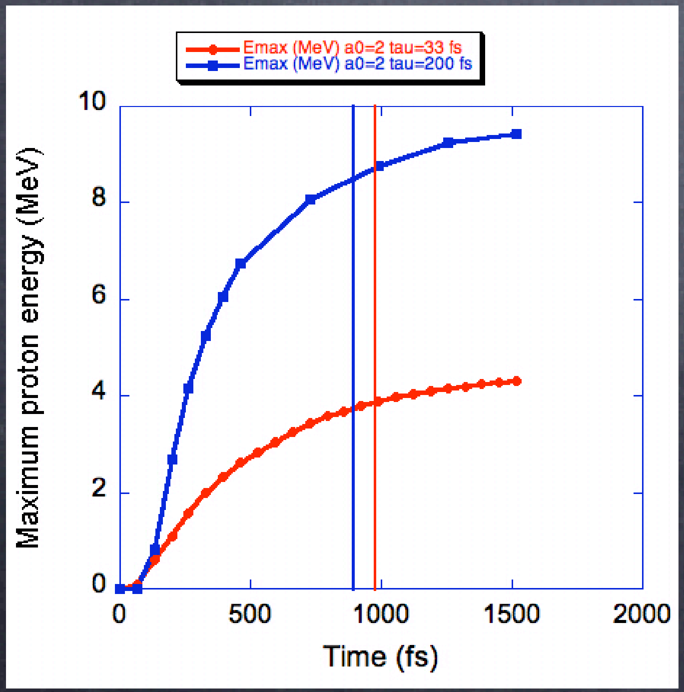
Model limitations

- Optimum laser parameters to get 200 MeV: 8 ! 10^{20} W/cm^2, 500 fs.
- But we have to enhance the model which does not work for short pulses at low laser energy and long pulses at high laser energy.

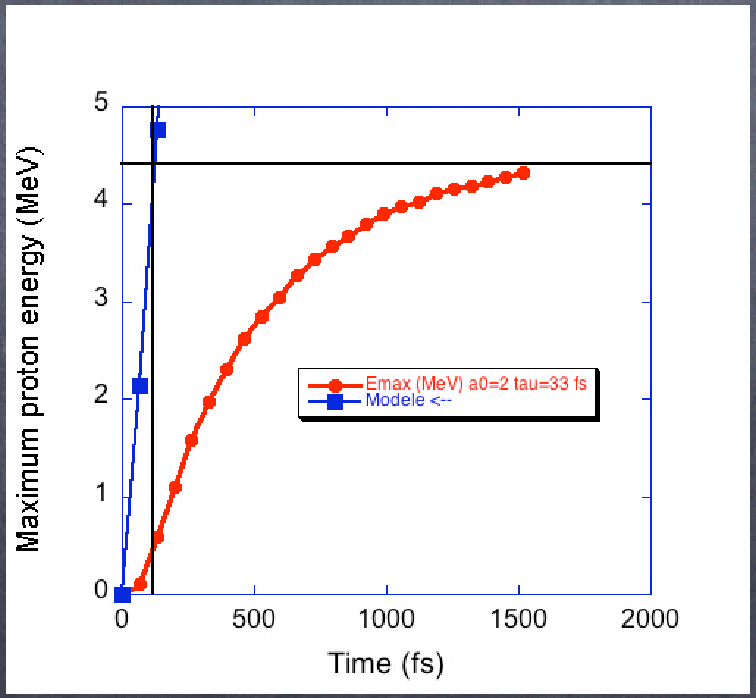
Vertical line: 90 % of the maximum proton energy is reached.

Characteristic times:

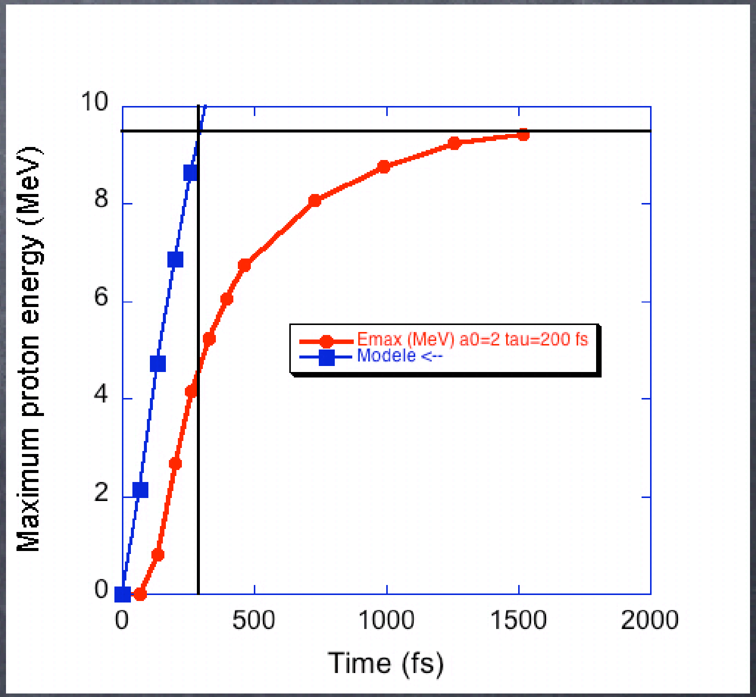
117 fs 289 fs



5.5 ! 10^{18} W/cm^2, 40 n_c target

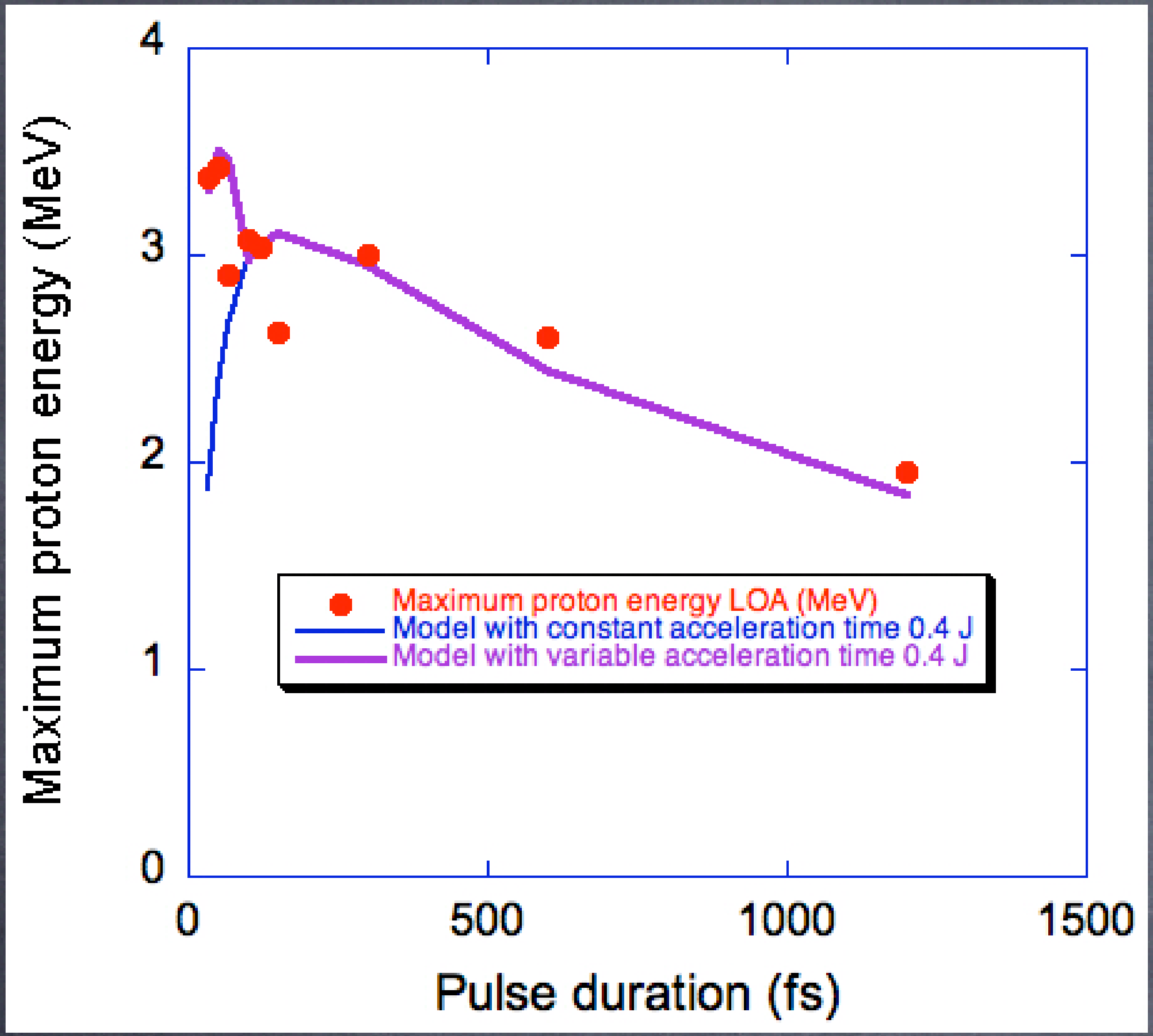


5.5 ! 10^{18} W/cm^2, 33 fs, 40 n_c target

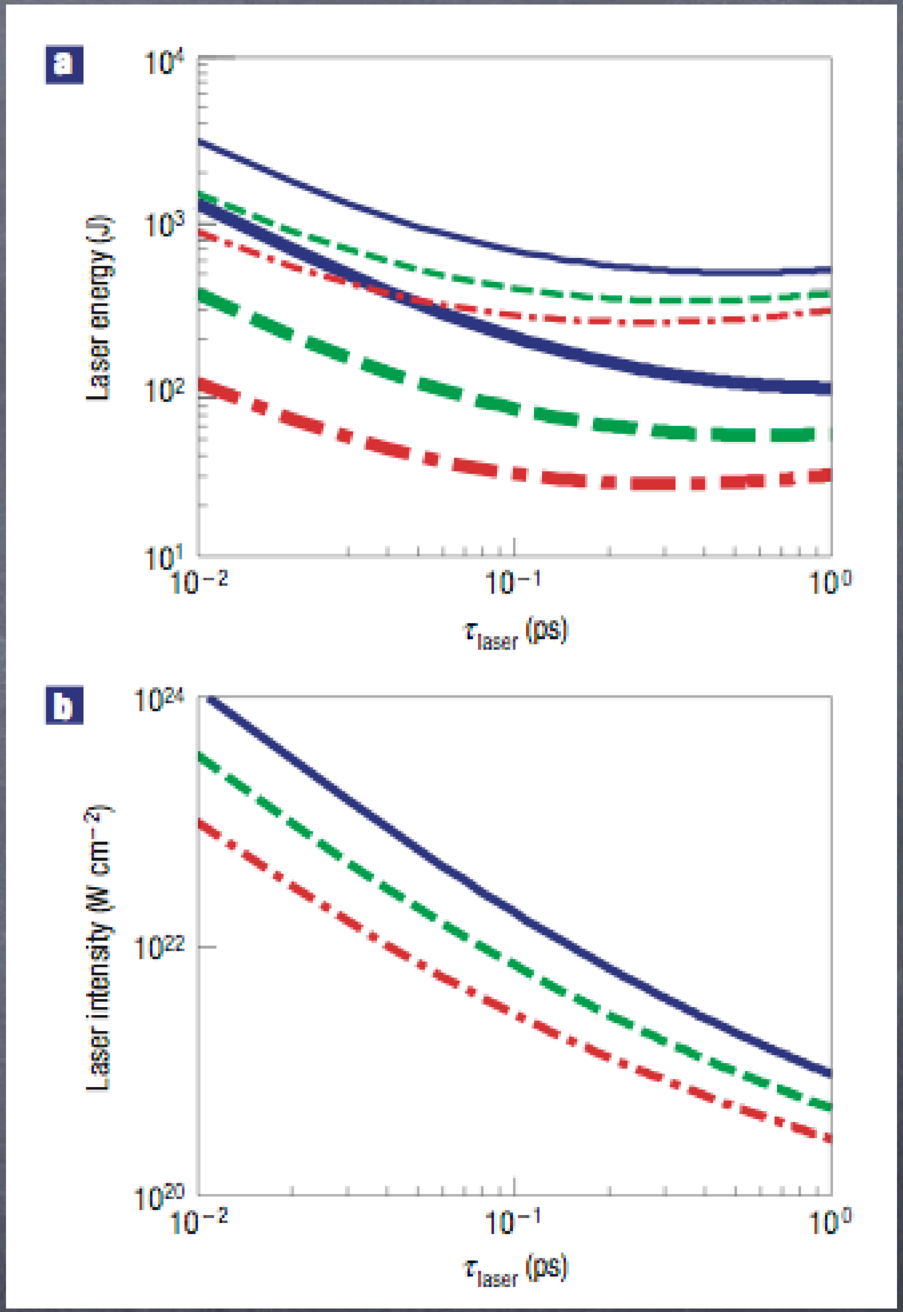


5.5 ! 10^{18} W/cm^2, 200 fs, 40 n_c target

Implications of these limitations

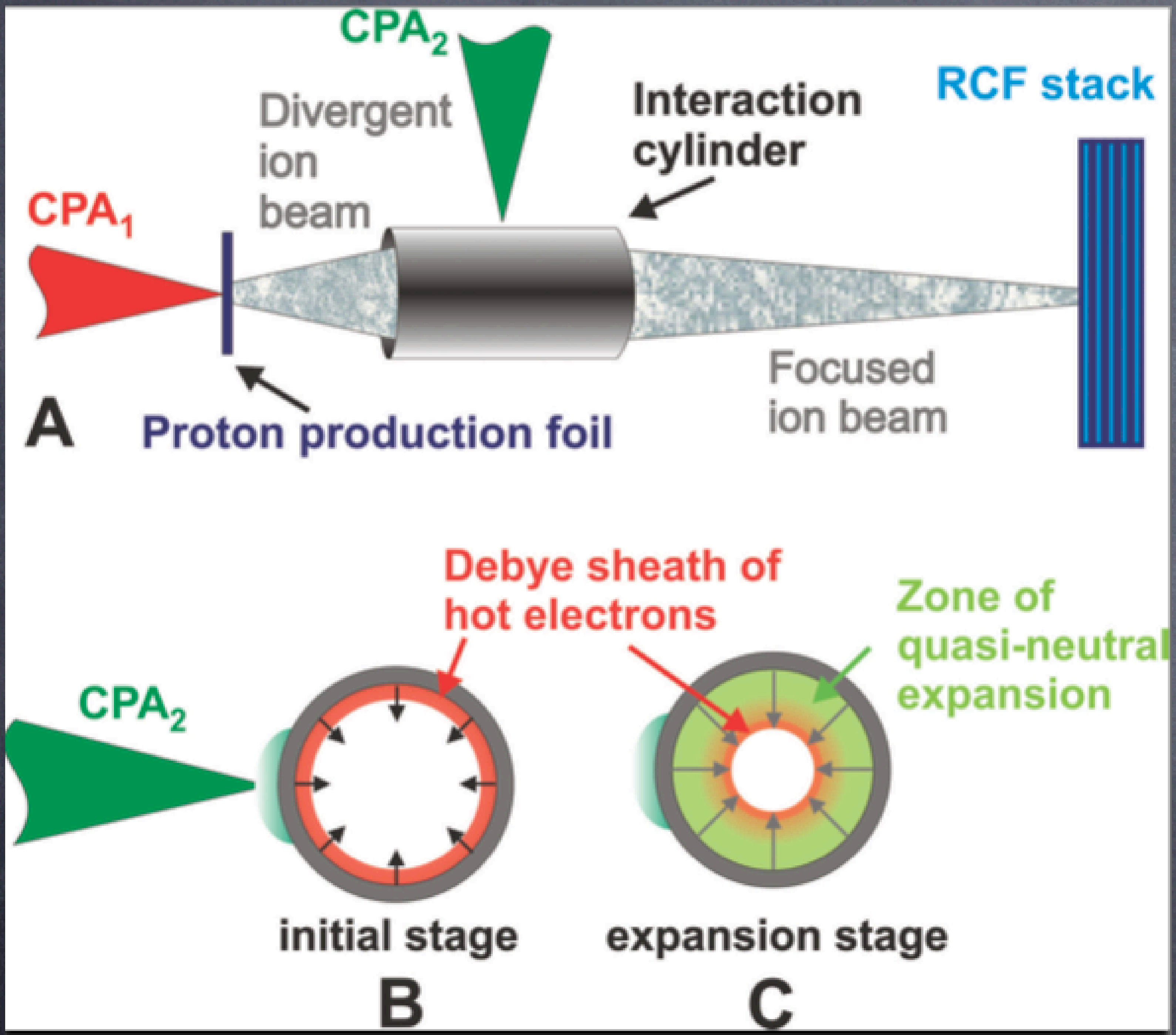


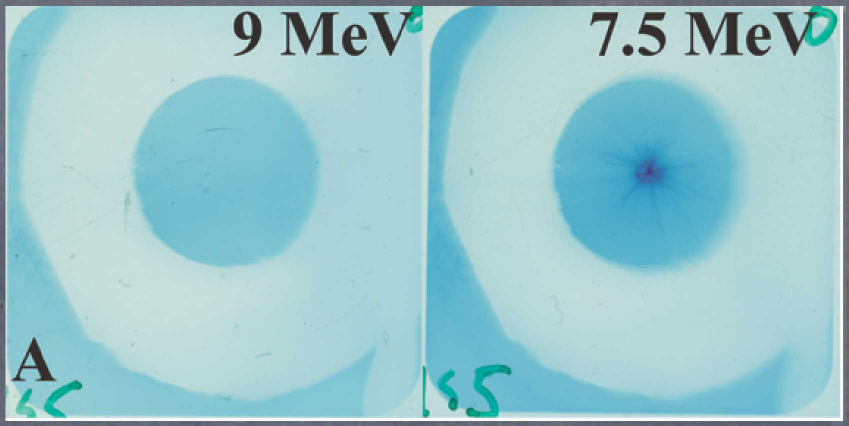
The model with a variable characteristic acceleration time works for a larger range of laser parameters. The optimum laser parameters to get a given proton energy are changed.



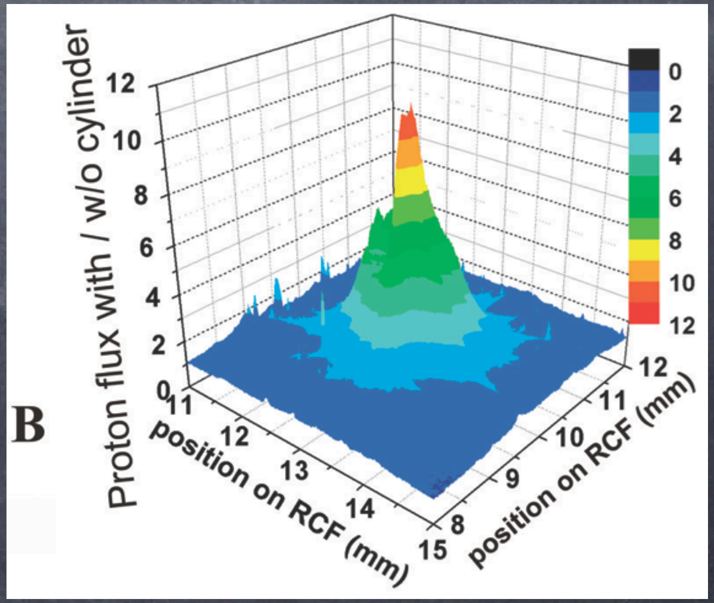
Laser energy needed as a function of pulse duration to obtain 200 MeV protons for various target thickness and laser focal spot size.

Focusing and energy selection using a cylinder irradiated by a secondary laser



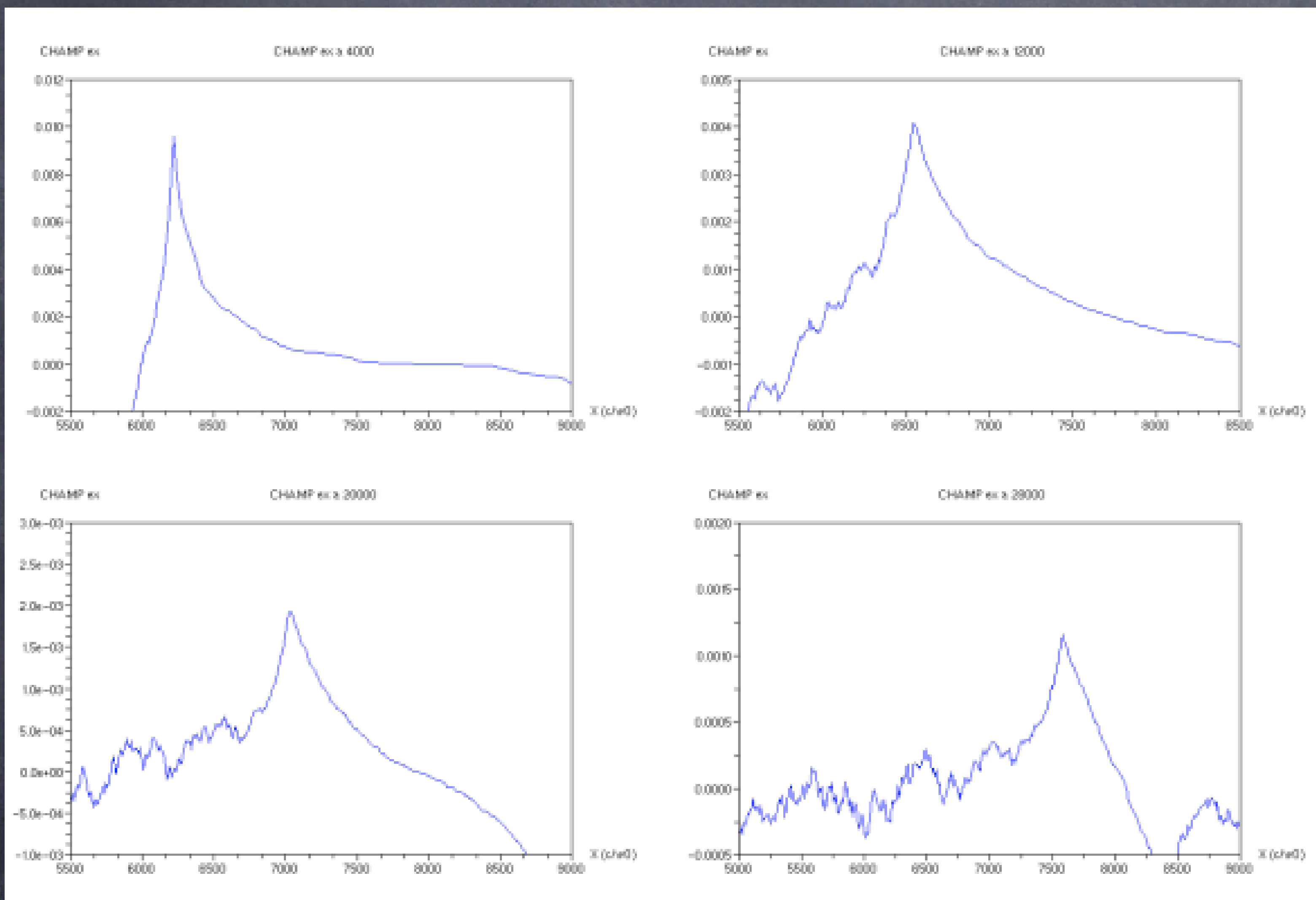


Secondary laser parameters: 3 ! 10^{18} W/cm^2, 350 fs. The Al cylinder is 3 mm long and its diameter is 650 "m. Its thickness is 50 "m.



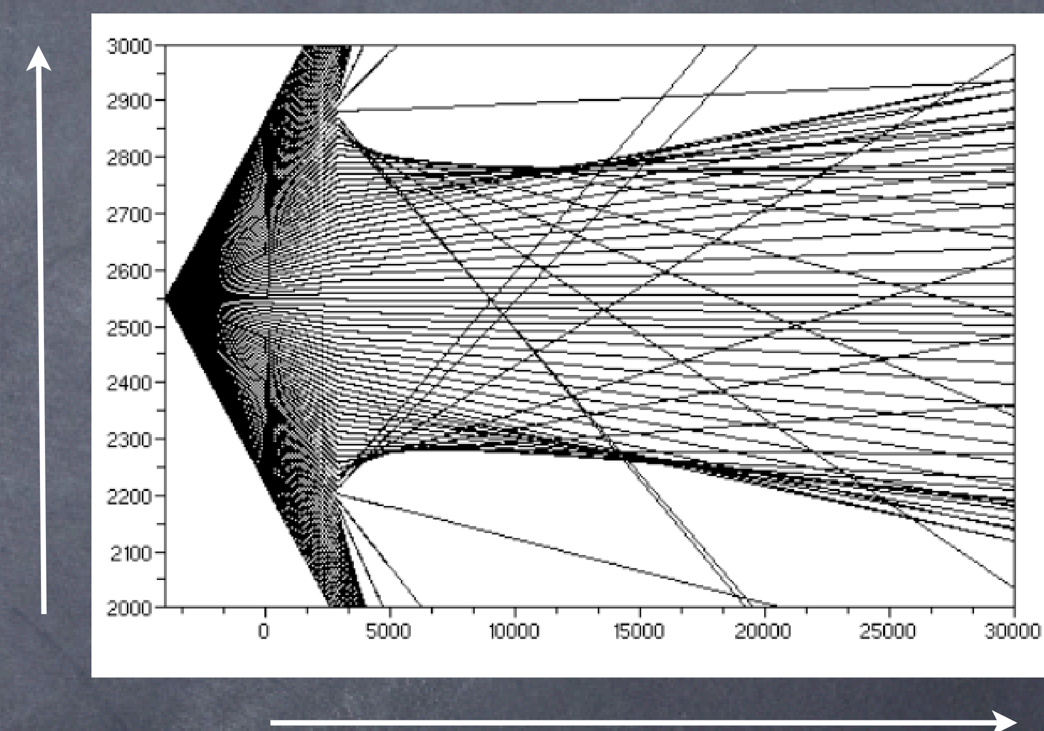
T.Toncian, M.Borghesi, J.Fuchs et al, Science Vol. 312, 21 April 2006, p.410 -413; www.sciencexpress.org / 16 February 2006 / 10.1126/science.1124412.

1D PIC simulation (CALDER) + raytracing



Evolution of the electrostatic field with time (max of 30 GV/m).
Secondary laser parameters: $3 ! 10^{18}$ W/cm^2, 320 fs.
(A 2D expanding cylinder leads to similar fields due to the size of the cylinder).

1 mm

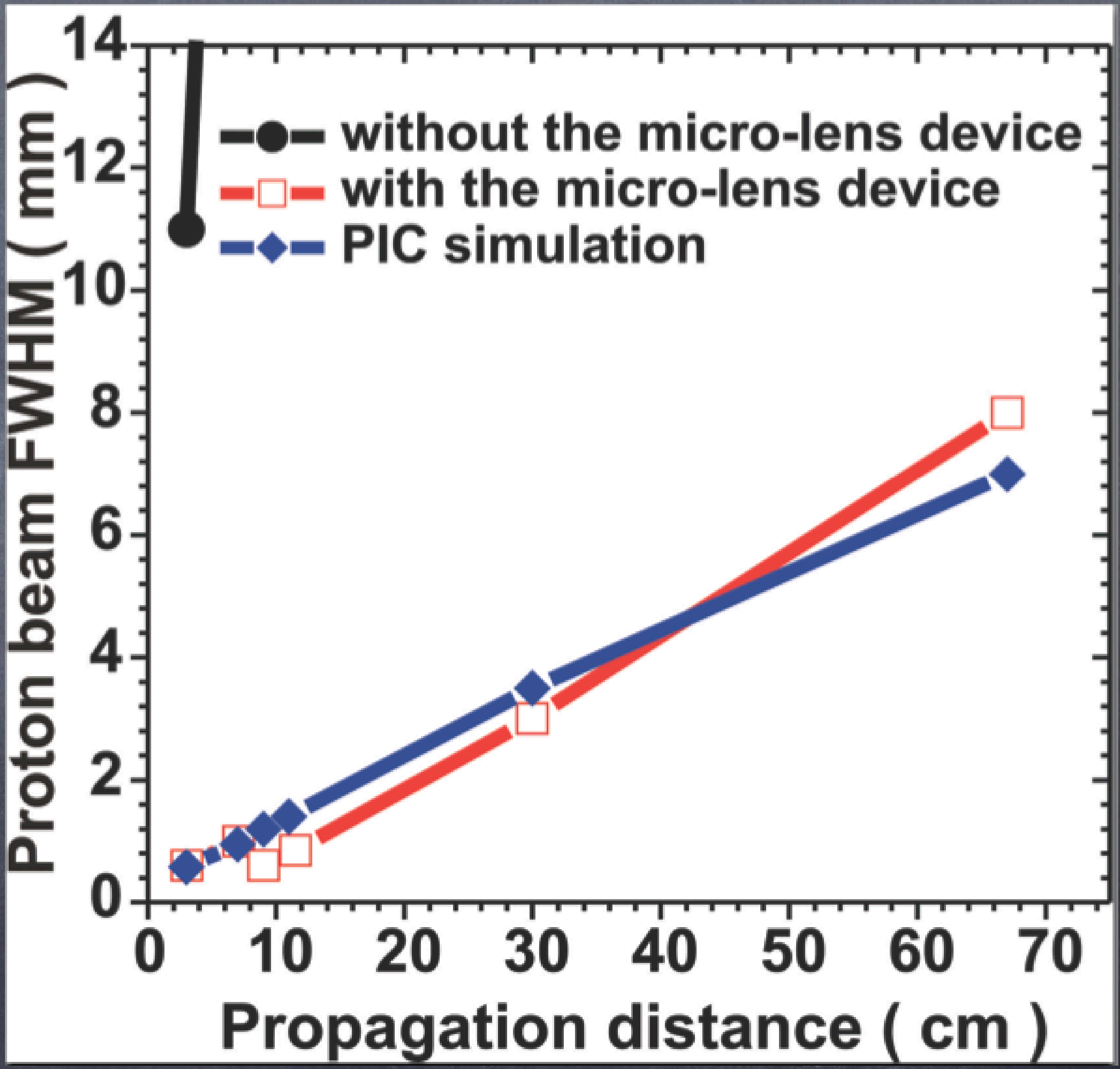


3 cm

Trajectories of 6.25 MeV protons passing trough the cylinder

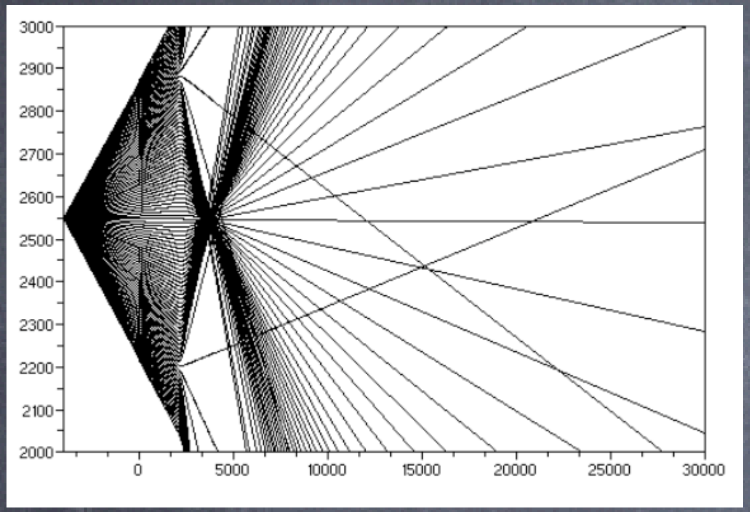
Comparison of the model with experimental results

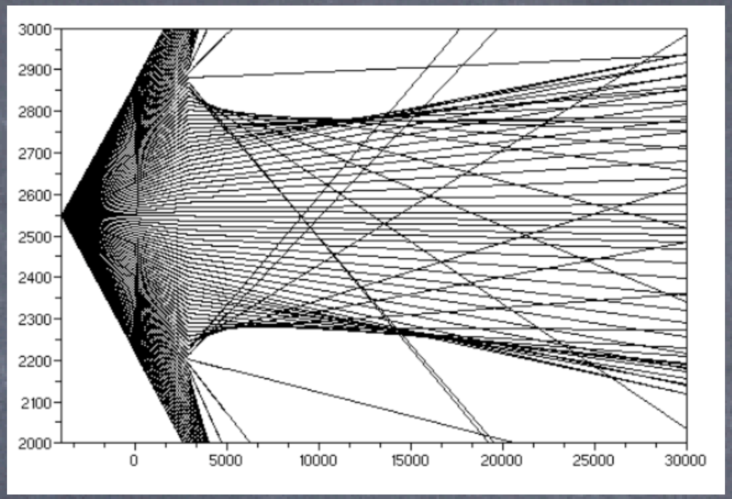
Comparison of the proton beam width in the model and in the experiments

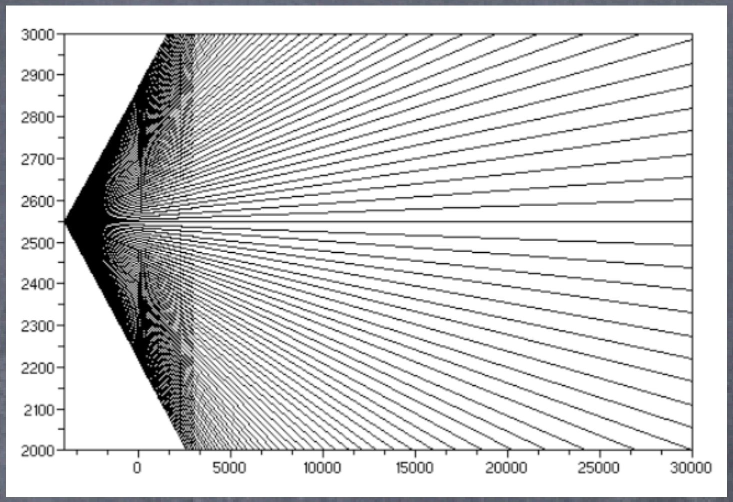


Spectrum of the proton beam that passed through the cylinder

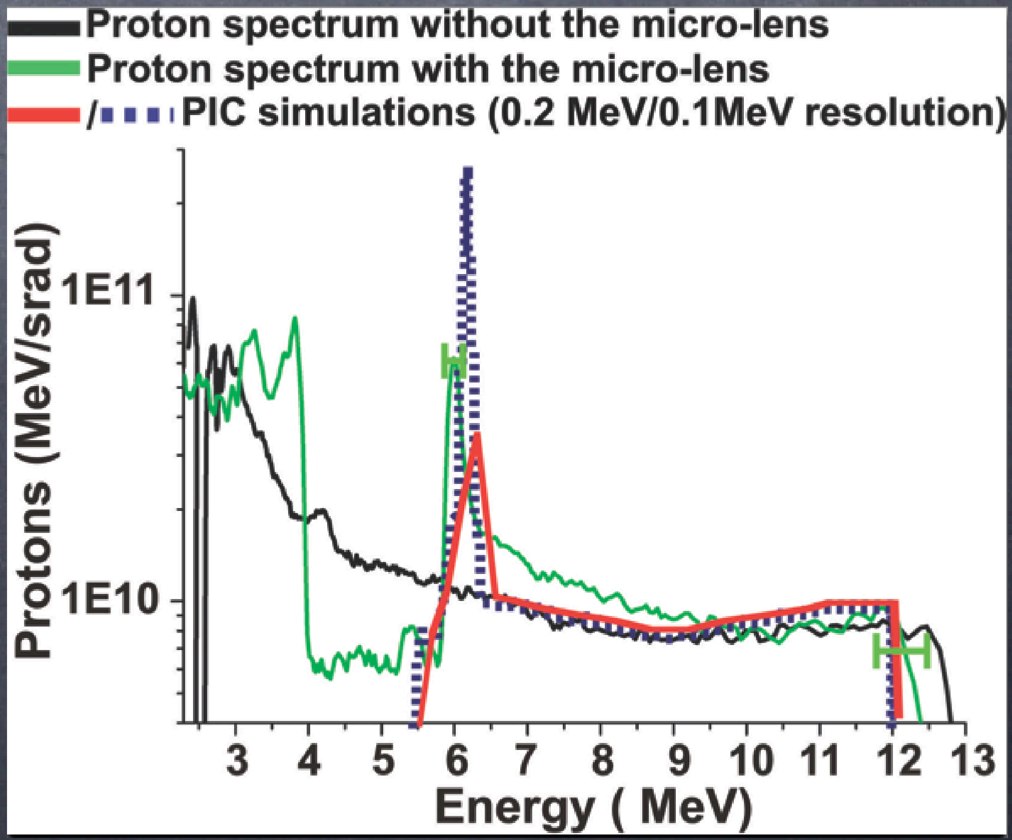
1 mm 4.9 MeV protons 6.25 MeV protons 7.5 MeV protons







3 cm

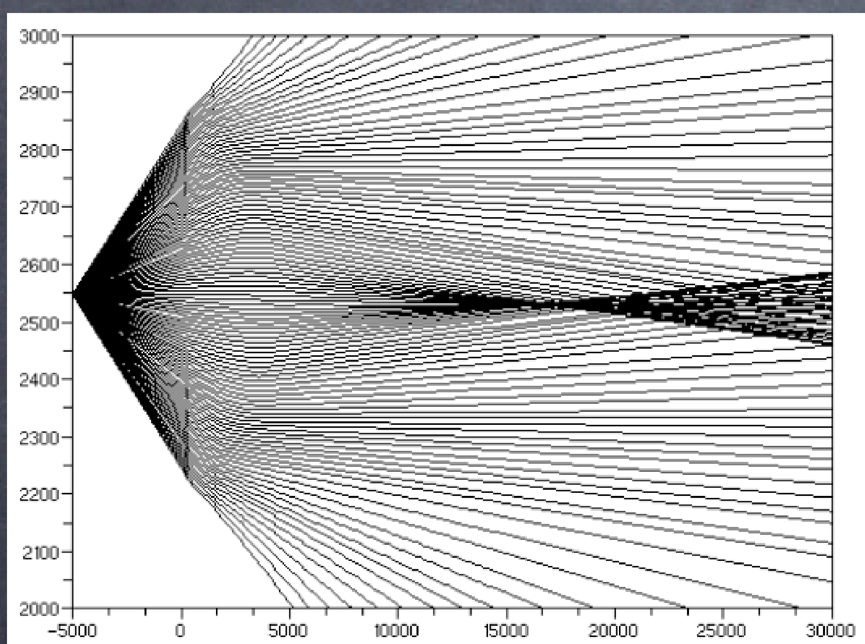


The experimental spectrum is well reproduced.
(Only protons passing trough a small slit are measured)

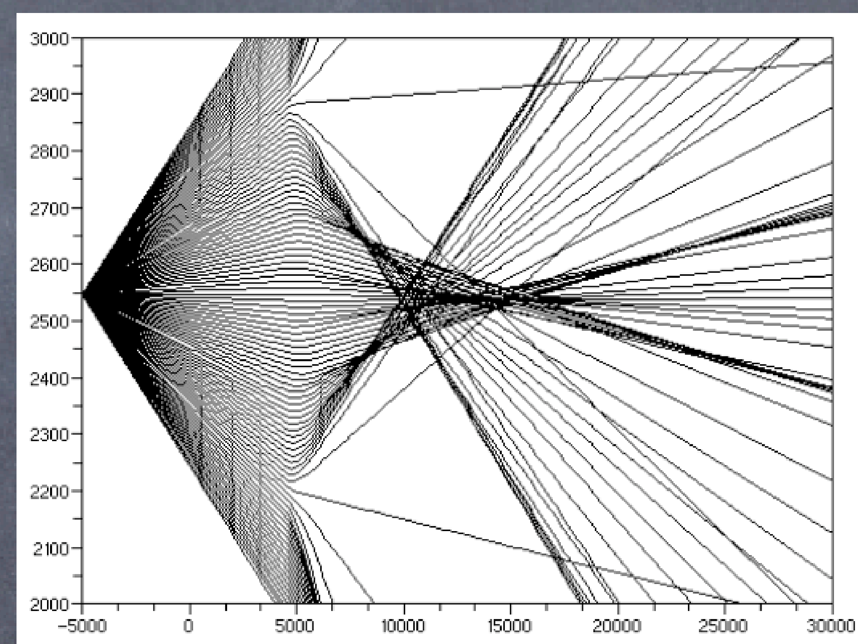
The cylinder micro-lens also works with high energy protons (270 MeV)

1 mm

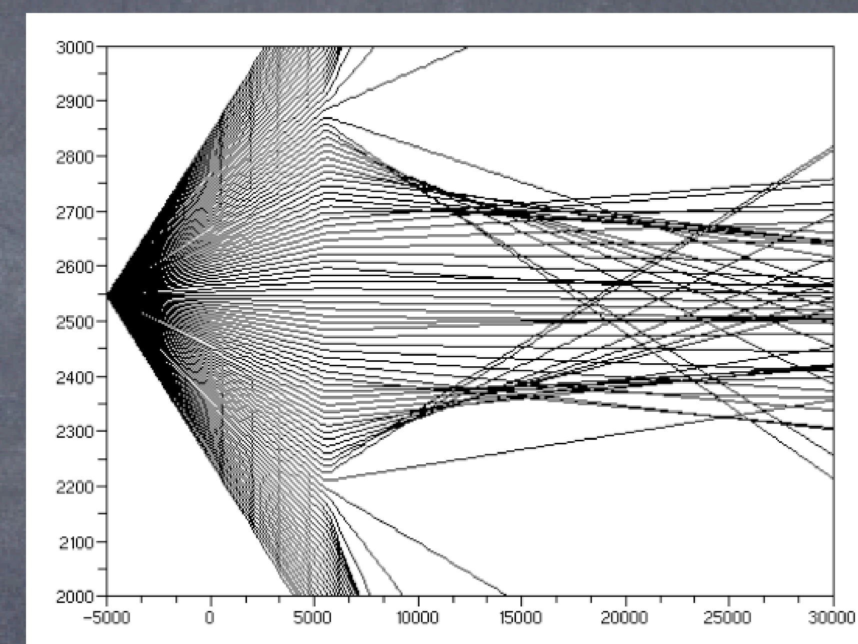
The protons enter when the laser is triggered.



The protons enter 19.1 ps before the laser is triggered.



The protons enter 22.9 ps before the laser is triggered.



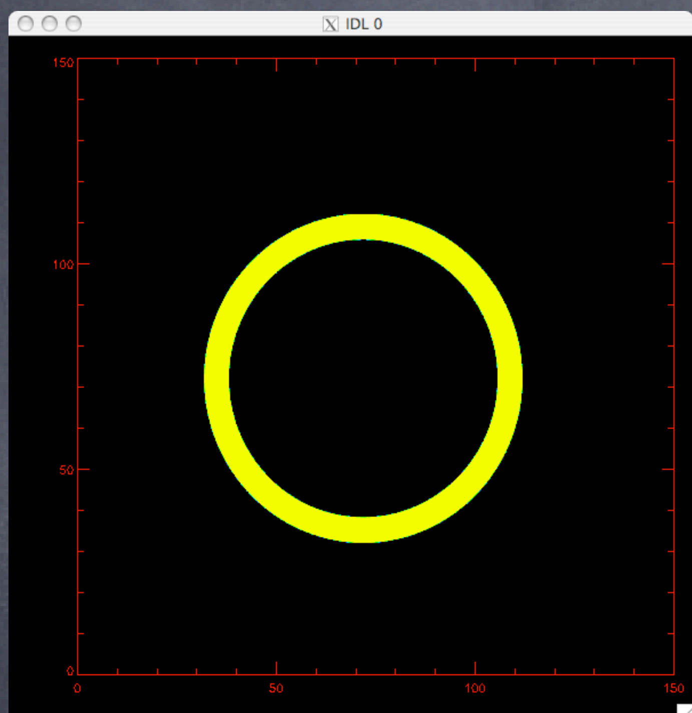
3 cm

Secondary laser parameters: 10^{19} W/cm^2, 700 fs. The cylinder is 6 mm long.

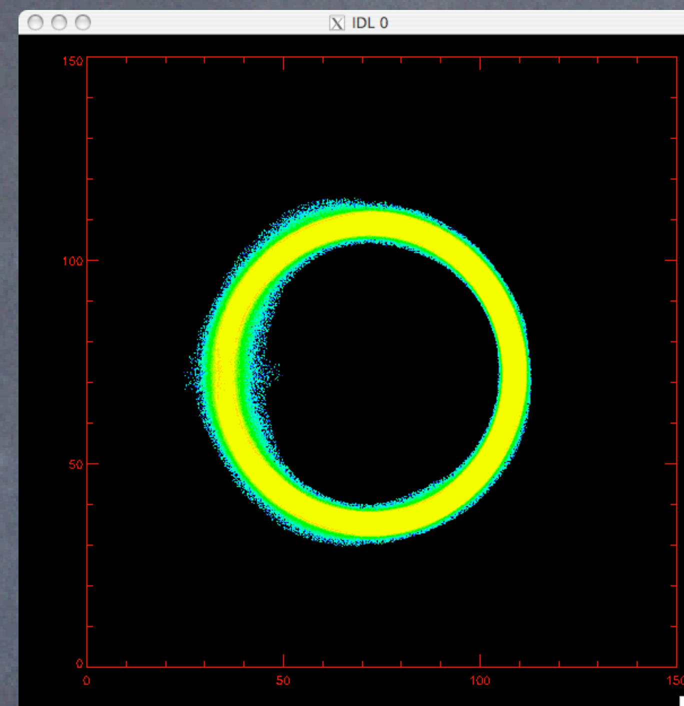
PIC Simulations of the interaction of a high intensity laser with a cylinder with PICLS2D

3 ! 10^{18} W/cm^2, 53 fs. The field reaches 150 GV/m. The cylinder size is 1/4th of the experiment size.

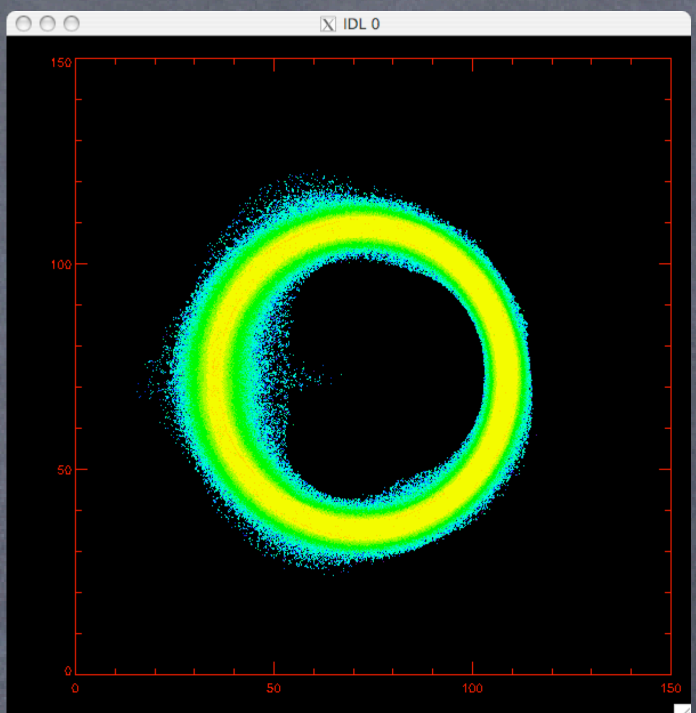
150 "m



6 ps



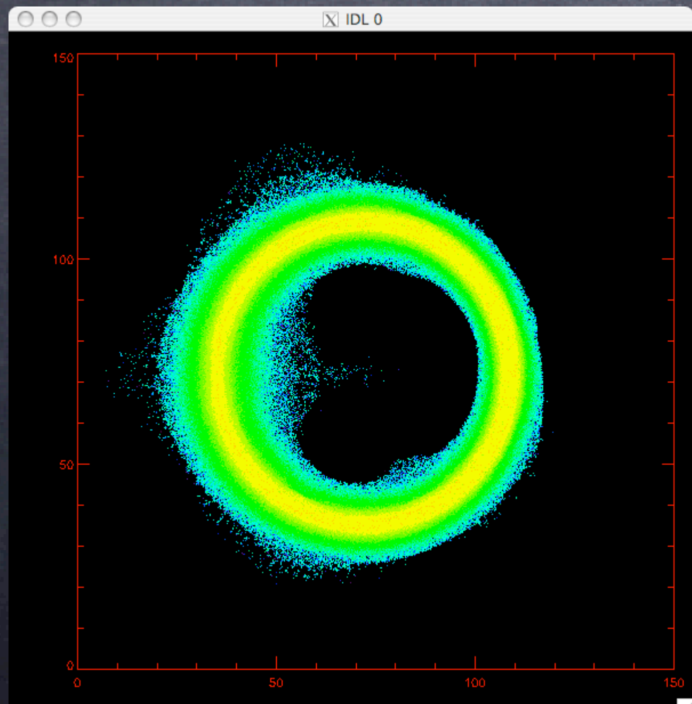
12 ps



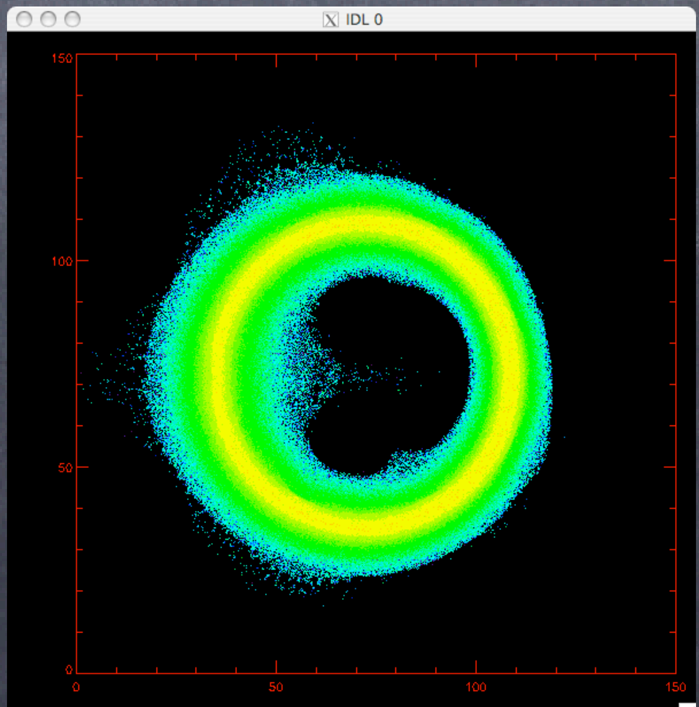
0 ps

150 "m

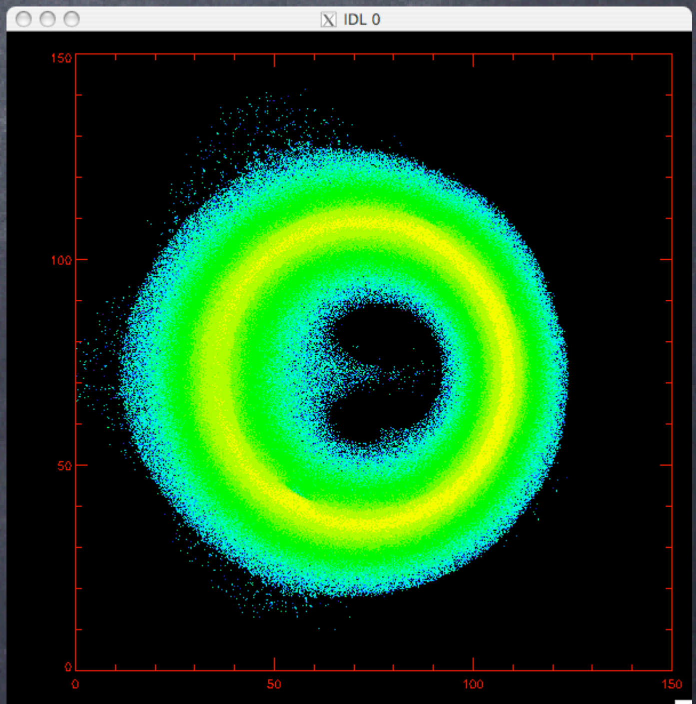
18 ps



24 ps



30 ps



Summary

- Proton beams produced by laser plasma interaction have unique properties.
- Recent progress in hot plasma expansion and laser proton acceleration dynamics support scaling laws useful to determine the best parameters for a given application.
- Propagating a laser accelerated proton beam trough a cylinder irradiated by a laser is a very original and efficient way to control the beam properties.