4th EMMI workshop on Plasma Physics with Intense Heavy Ion and Laser Beams

2-4th May at GSI Darmstadt

Can laser-driven protons be used as diagnostic in ICF experiments ?

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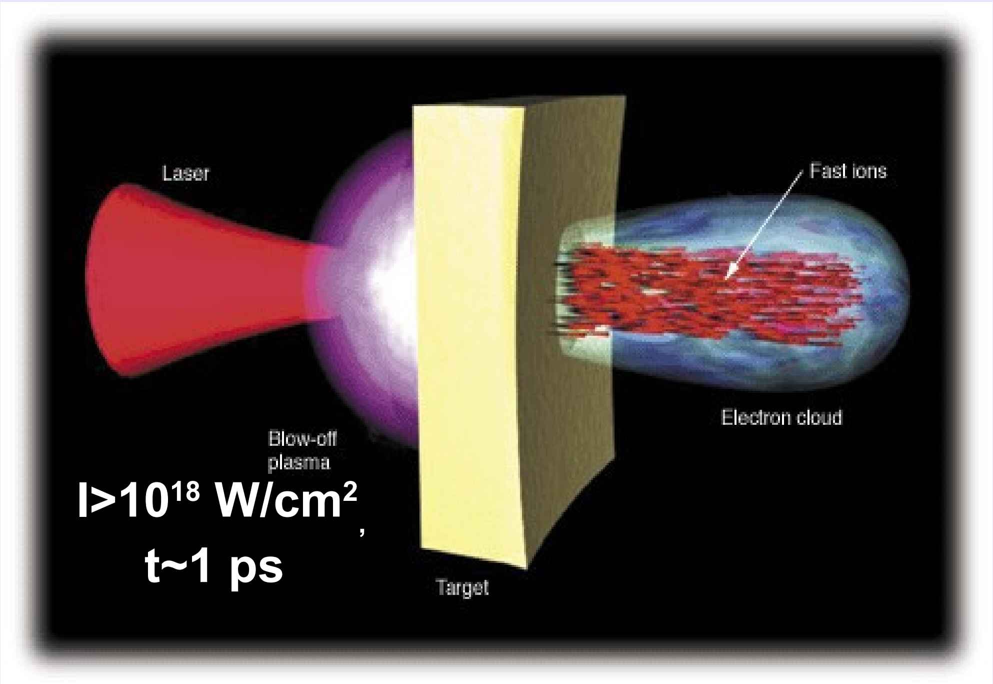
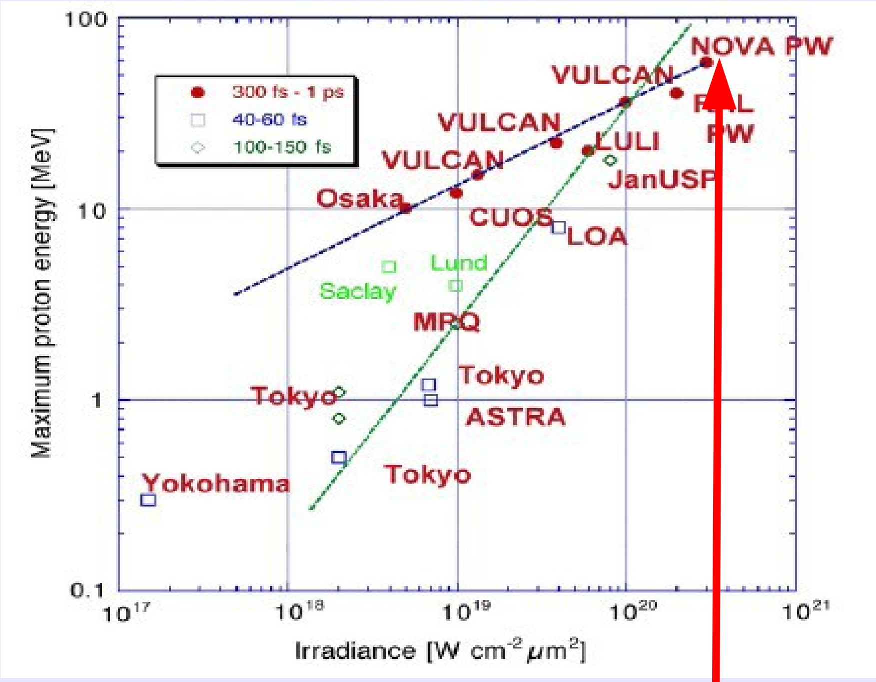
OUTLOOK

- Laser-driven proton acceleration
- Inertial Confinement Fusion & Hiper project
- Hiper related Experiments
- Scheme of Proton Radiography
- A criterion for PR resolution
- Validation with Monte Carlo simulations
- Conclusions

Proton acceleration mechanism





R. Snavely et al. Phys. Rev. Lett. 85, 2945 (2000)
E. L. Clark et al. ibid. 84, 670 (2000)

M. Borghesi et al.,Plasma Phys. Contr. Fus. 50, 024140 (2008)

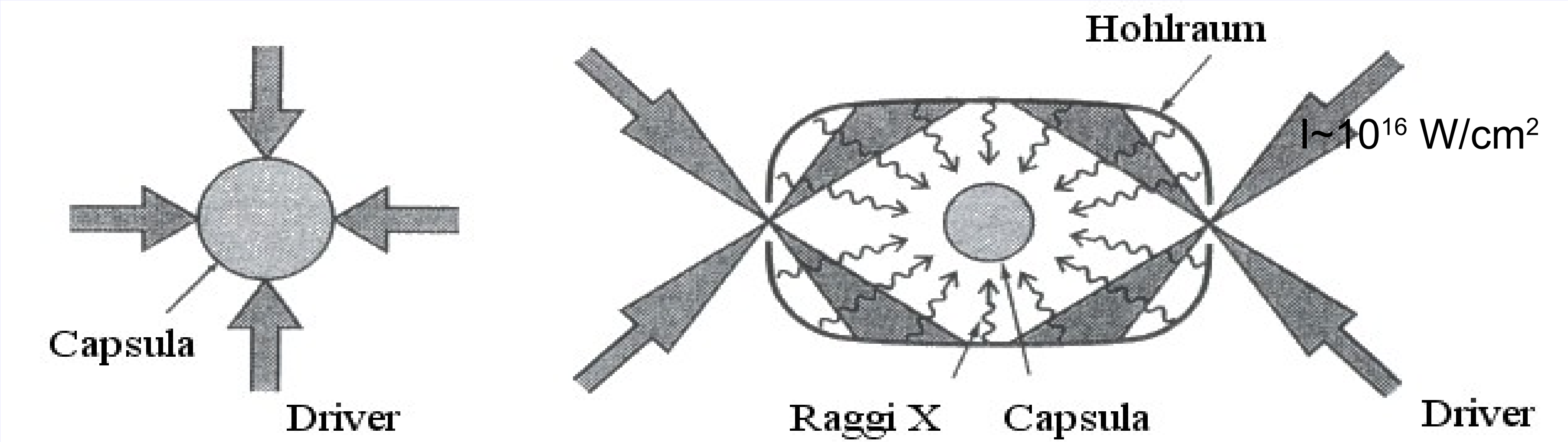
- TNSA → **I~10^{21} W/cm^2 E$_{max}$~60 MeV (multi-energy)**

  [Wilks, et al., POP 8, 542 (2001)]

- RPA → **I>10$^{21\text{-}23}$ W/cm^2 E$_{max}$~ 200 MeV (mono energetic)**

[S.C.Esirkepov, et al., PRL 92, 175003 (2004)]

Mechanism of Inertial Confinement Fusion



$I \sim 10^{14}$ W/cm^2
$t \sim 1$ ns

<u>Subjects involved in ICF approach to nuclear fusion</u>

<u>(indirect drive approach)</u>
--> National Ignition Facility (Livermore USA)

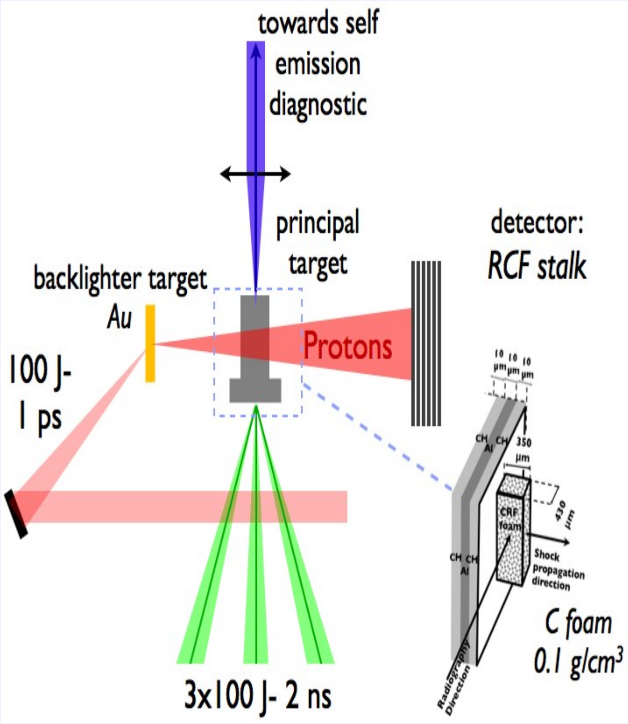
<u>(direct drive approach)</u>
--> Hiper project (Europe)
(*) fast ignition or (*) shock ignition

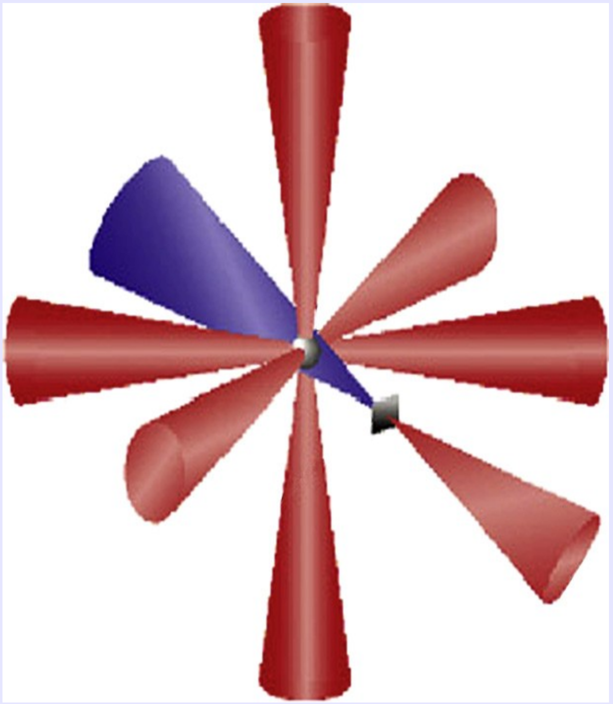
Hiper-relevant Experiments

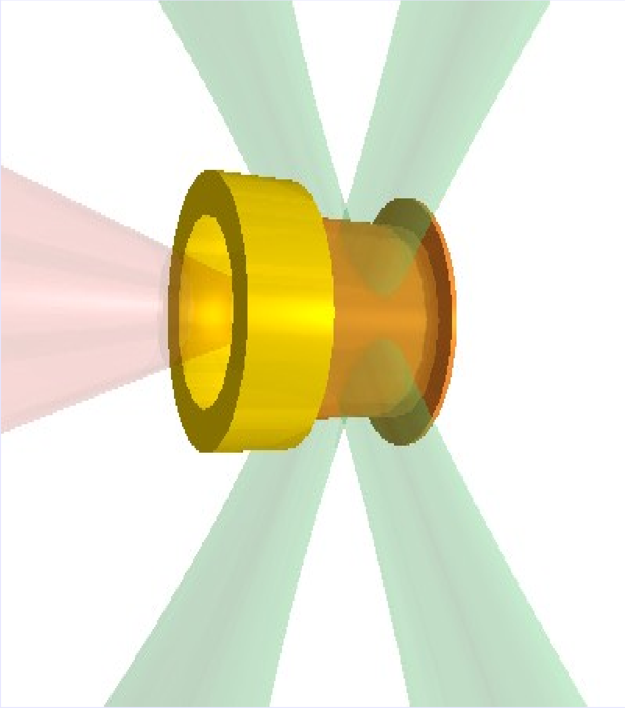
RAL-07 planar compression

RAL-06 spherical compression

RAL-08 cylindrical compression







A. Ravasio et al, PRE 82, 016407 (2010)

Mac Kinnon et al, PRL 97, 045001 (2006)

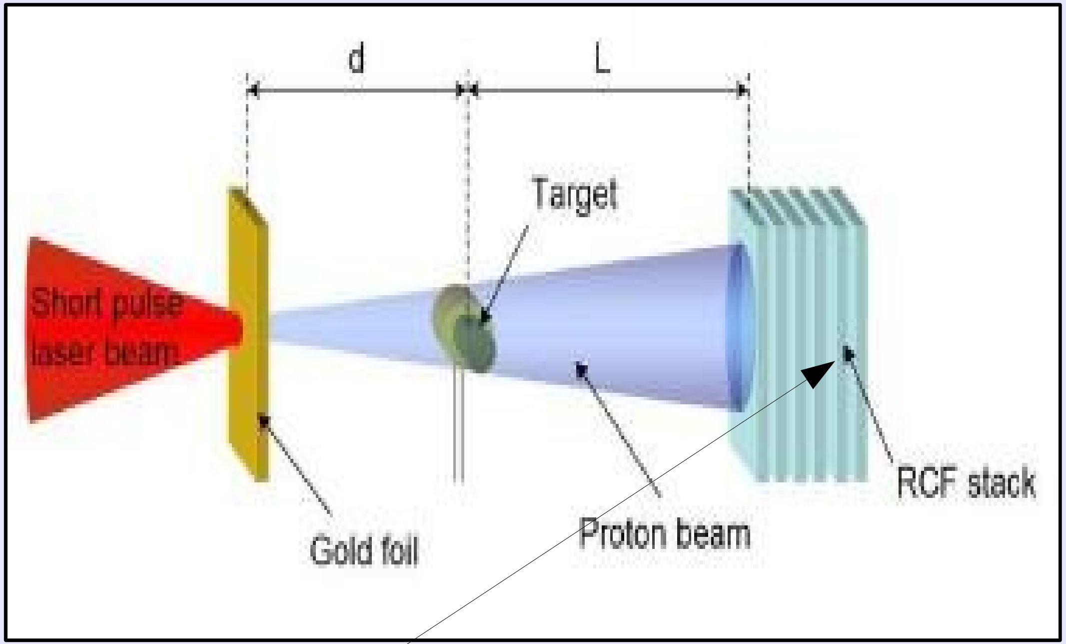
L. Volpe et al, POP 18, 006101 (2011) PPCF 53 (2011) 032003

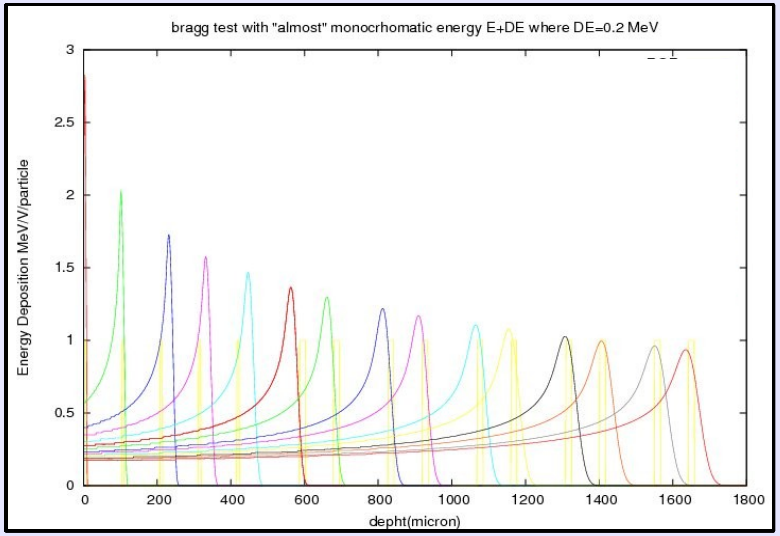
Principles of Proton radiography

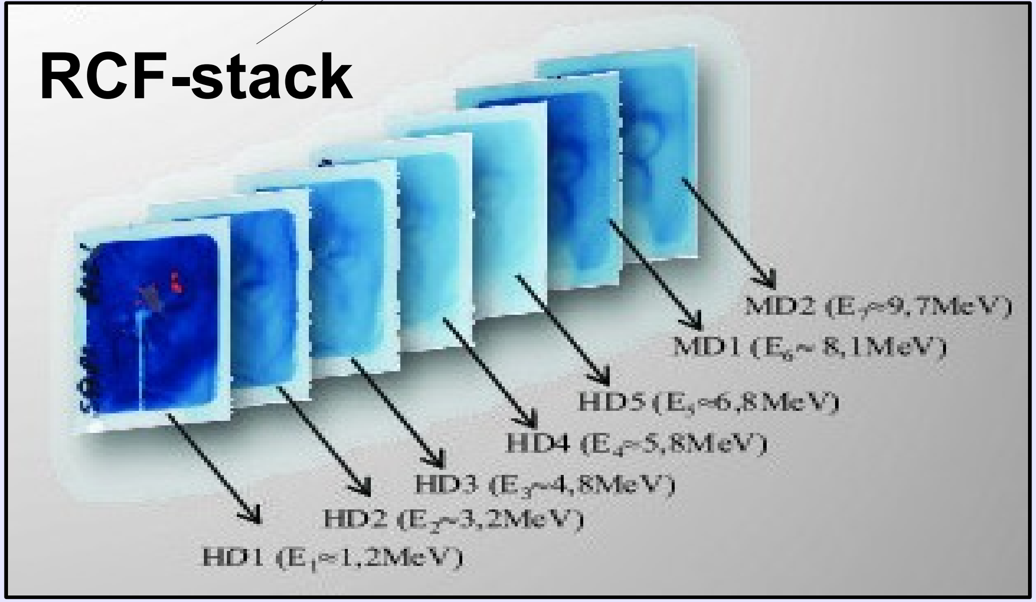
- **Bragg peak**

$$\Delta E \rightarrow \Delta t \rightarrow \Delta X$$

- **one shot ~0.6 ns**
- **Different time delay for each shot**





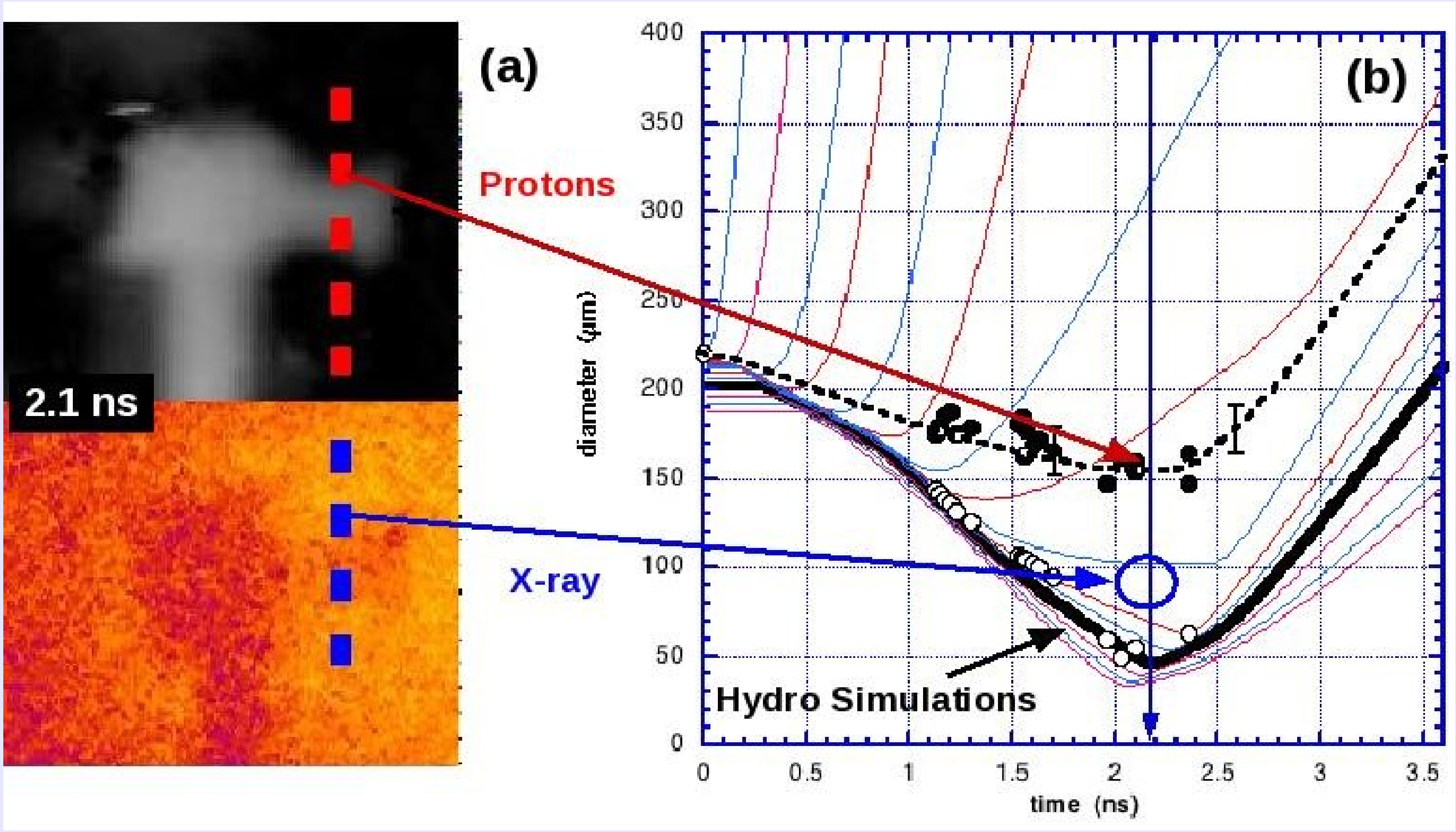


detection of electric and magnetic fields in plasmas

--M. Borghesi, et al., Phys. Rev. Lett. 82 1529 (2003)

--D. Batani, et al., Phys. Plasmas 16 1 (2009)

RAL-08 cylindrical implosion experimental results



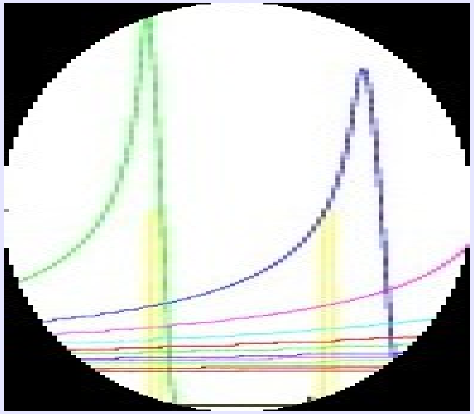
- **Stagnation time ~2.1 ns (good agreement)**
- **Cylinder Images appears enlarged with respect to the theoretical ones**
- **Protons seem not to be able to probe the dense region.**

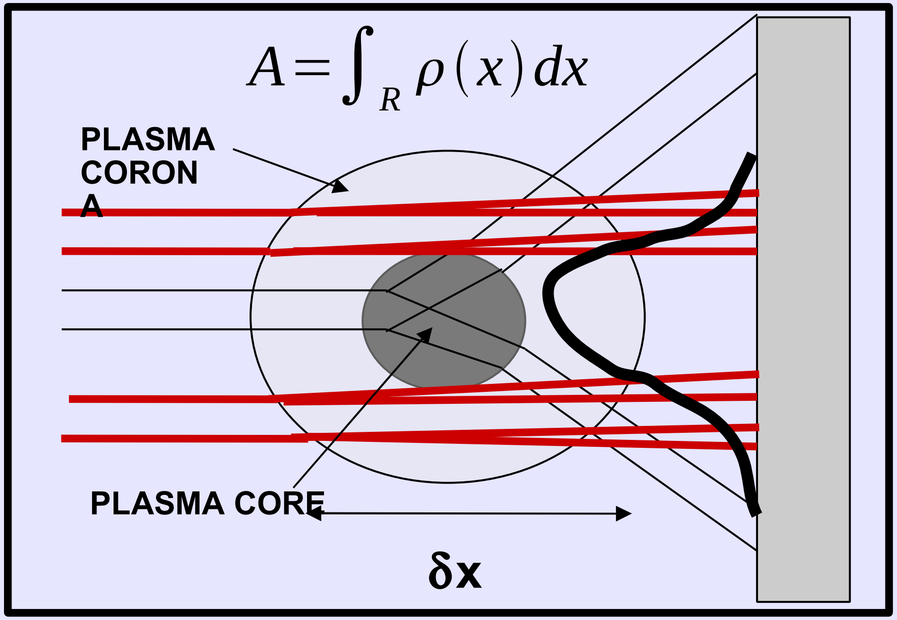
Due to the large number of collisions occurring in our case many physical effects become important :

- **Multiple Coulomb scattering**
- **Energy loss**
- **Modification of the spectrum**
- **Mixing effects on layers**

$$\theta = \frac{E_s}{2}\sqrt{\frac{1}{L_r}}\frac{\sqrt{A[g/cm^2]}}{E[MeV]}$$

$$\frac{dE}{dx} \propto \rho$$





Could be Other physical effects (electric and magnetic field)

$\theta_E/\theta_{MS} < 1\%$

dE/dx(plasma) ≠ dE/dx(matter)

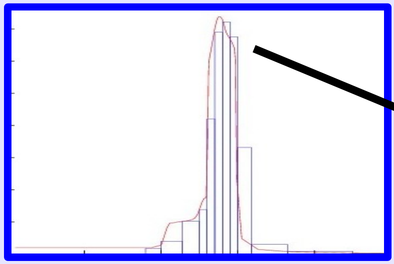
$$\left[\frac{dE}{dx}\right]_p \propto \rho \ln\left(\frac{1}{\sqrt{\rho}}\right)$$

$$(7c)\quad \vartheta_E/\vartheta_{MS} = 0.5\times 10^{-6} E[V/cm]\sqrt{\frac{L[cm]}{\rho[g/cm^2]}}$$

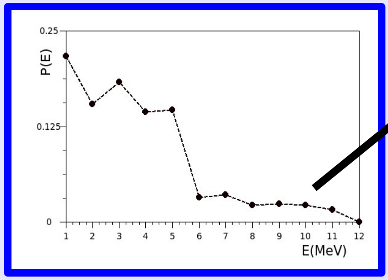
F.C. Young, et al., Phys. Rev. Lett., **49**, 549 (1982)
T. Peter, J. Meyer-ter-Vehn, Phys. Rev. A, **43**, 4, 1998 (1991)

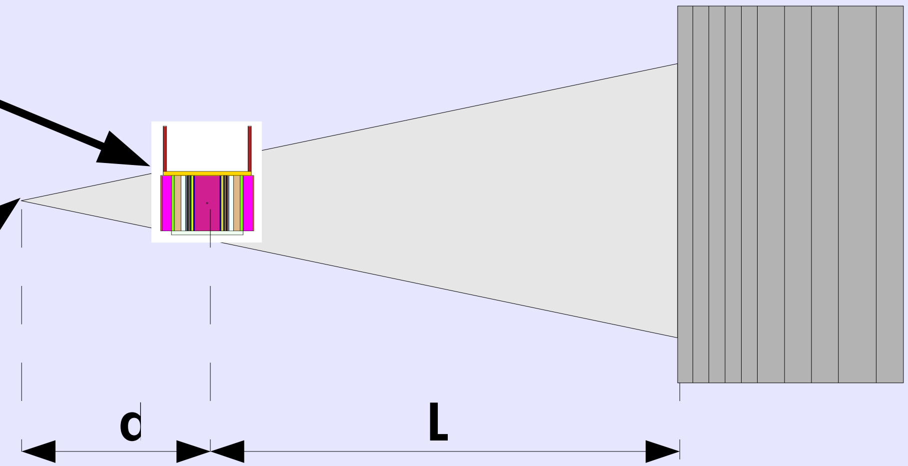
Monte Carlo simulations: mcnpx inputs

Hydro simulations (CHIC)



Initial spectrum source from experimental data analysis

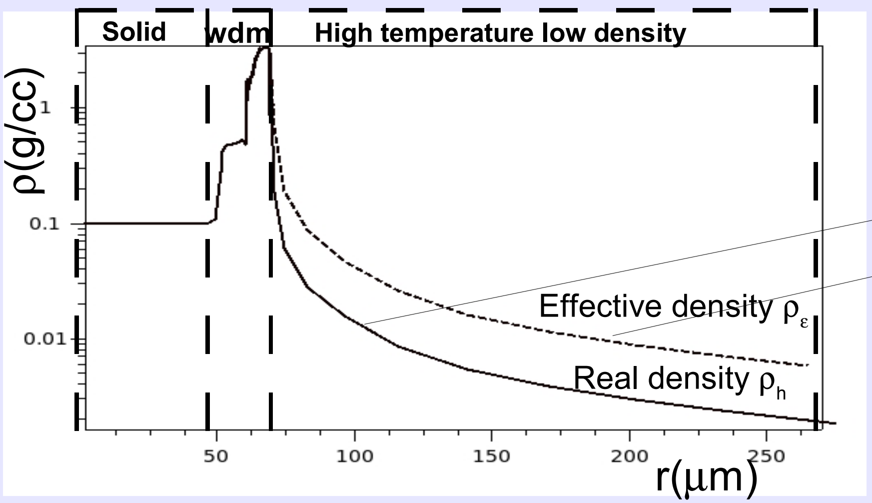


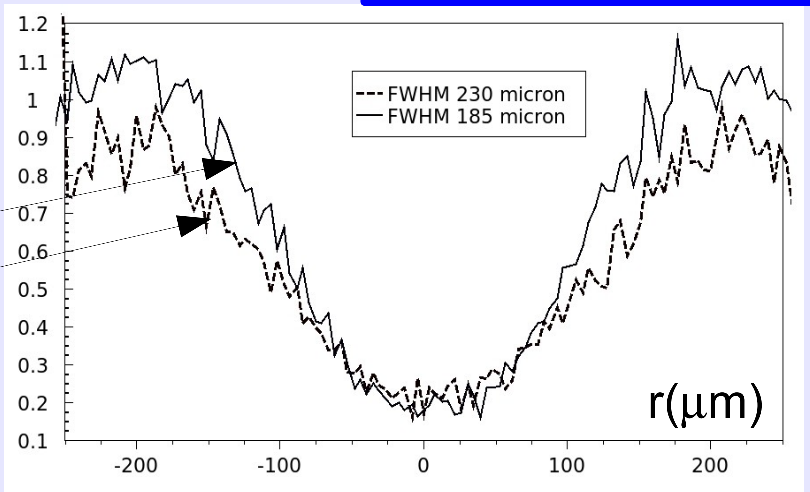


$$\left[\frac{dE}{dx}(\rho_e, T, q_t, A, Z)\right]_{\text{cold}} = \left[\frac{dE}{dx}(\rho_p, T, q_t, A, Z)\right]_{\text{plasma}}$$

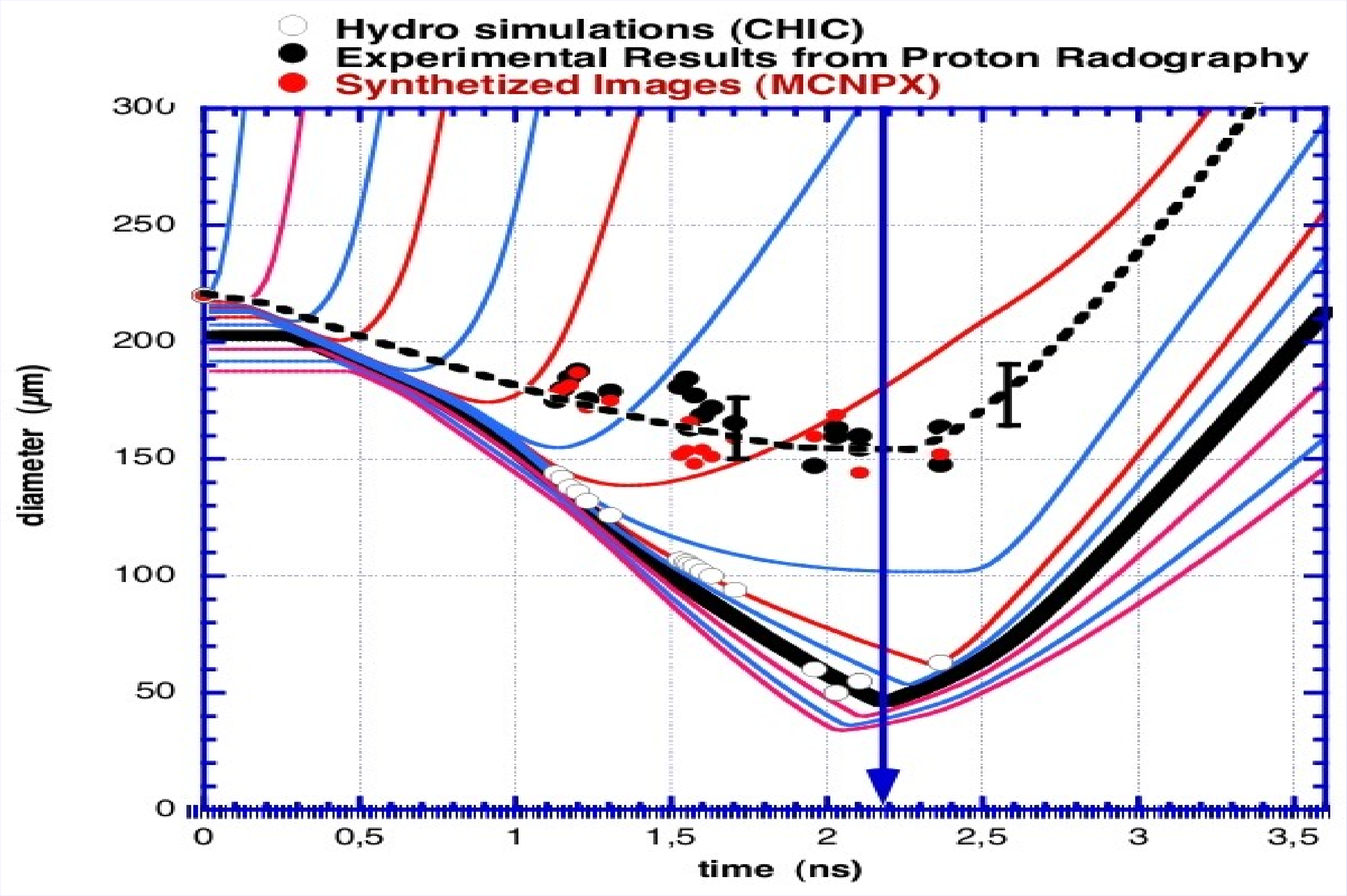
$$\rho_e = \eta \rho_p$$

$$\eta = \frac{q_t}{Z}\left\{\frac{L_f}{L_b} + \frac{Z - q_t}{q_t}\right\}$$





FINAL RESULT



L.Volpe, et al, Physics of Plasmas 18, 012704 (2011);
L. Volpe et al, Plasma Phys. Control. Fusion 53 (2011) 032003

Proton radiography resolution

i.e.

Quantitative estimation of PR resolution as a function of the experimental parameters

Strong condition I

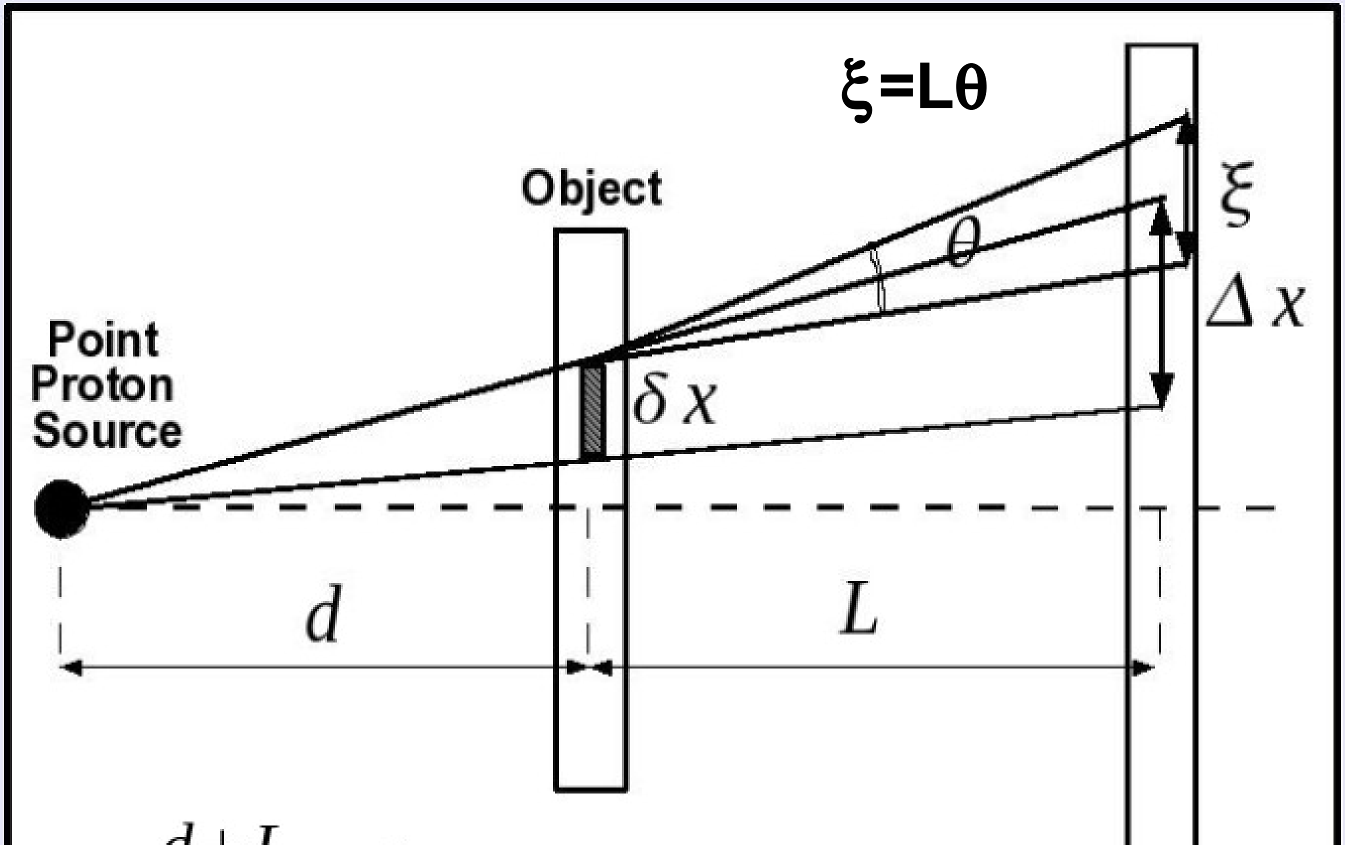
$$\Delta x \sim M \delta x \qquad I \sim \mu \Delta x \sim \mu M \delta x \sim \sqrt{\Delta x^2 + \xi^2}$$

$$\mu = \sqrt{1 + \left(\frac{\tilde{\xi}}{\delta x}\right)^2}$$

Criterion for PR

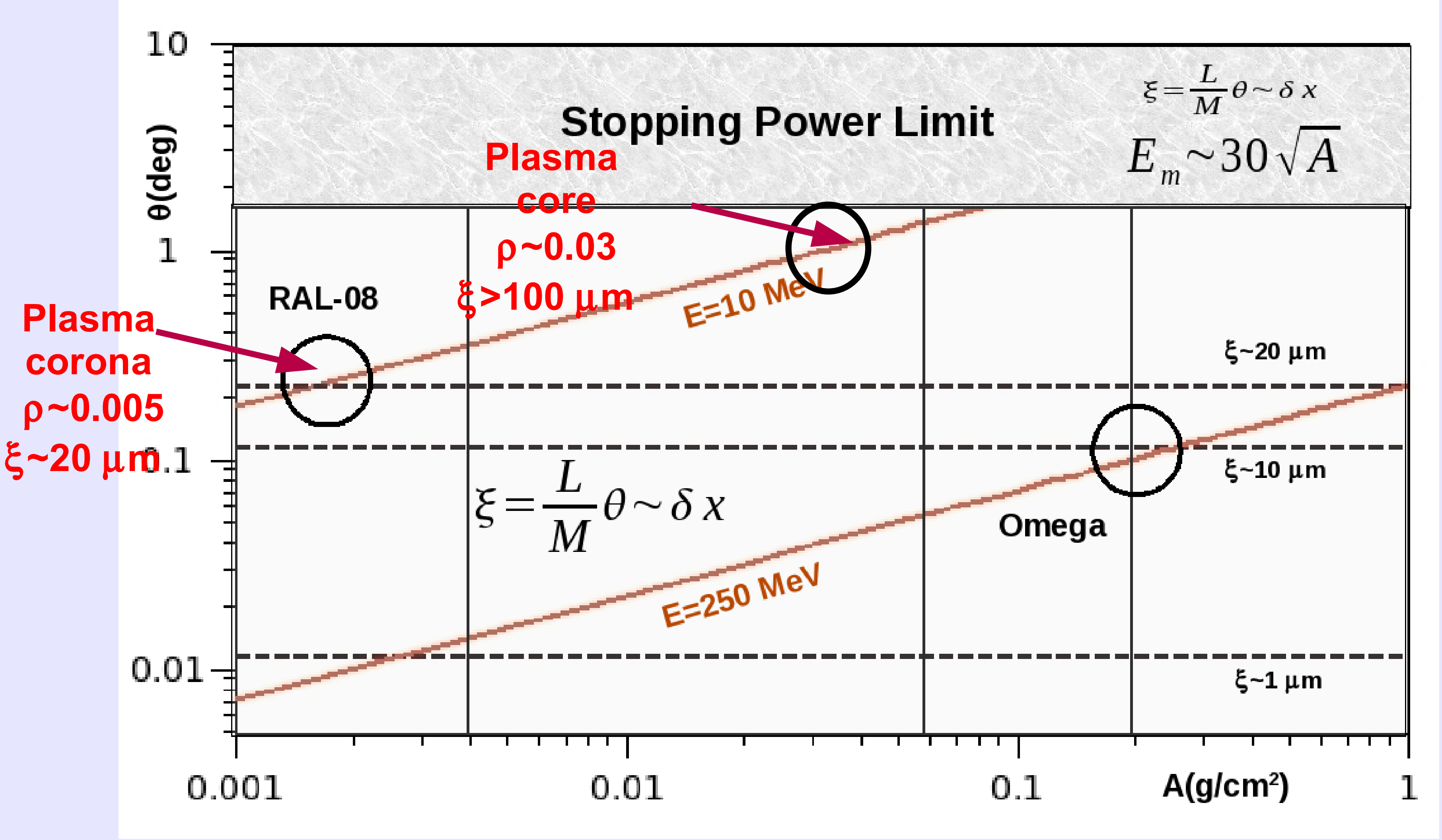
$$0 \le \tilde{\xi} \le \delta x$$

$$1 \le \mu \le \sqrt{2}$$

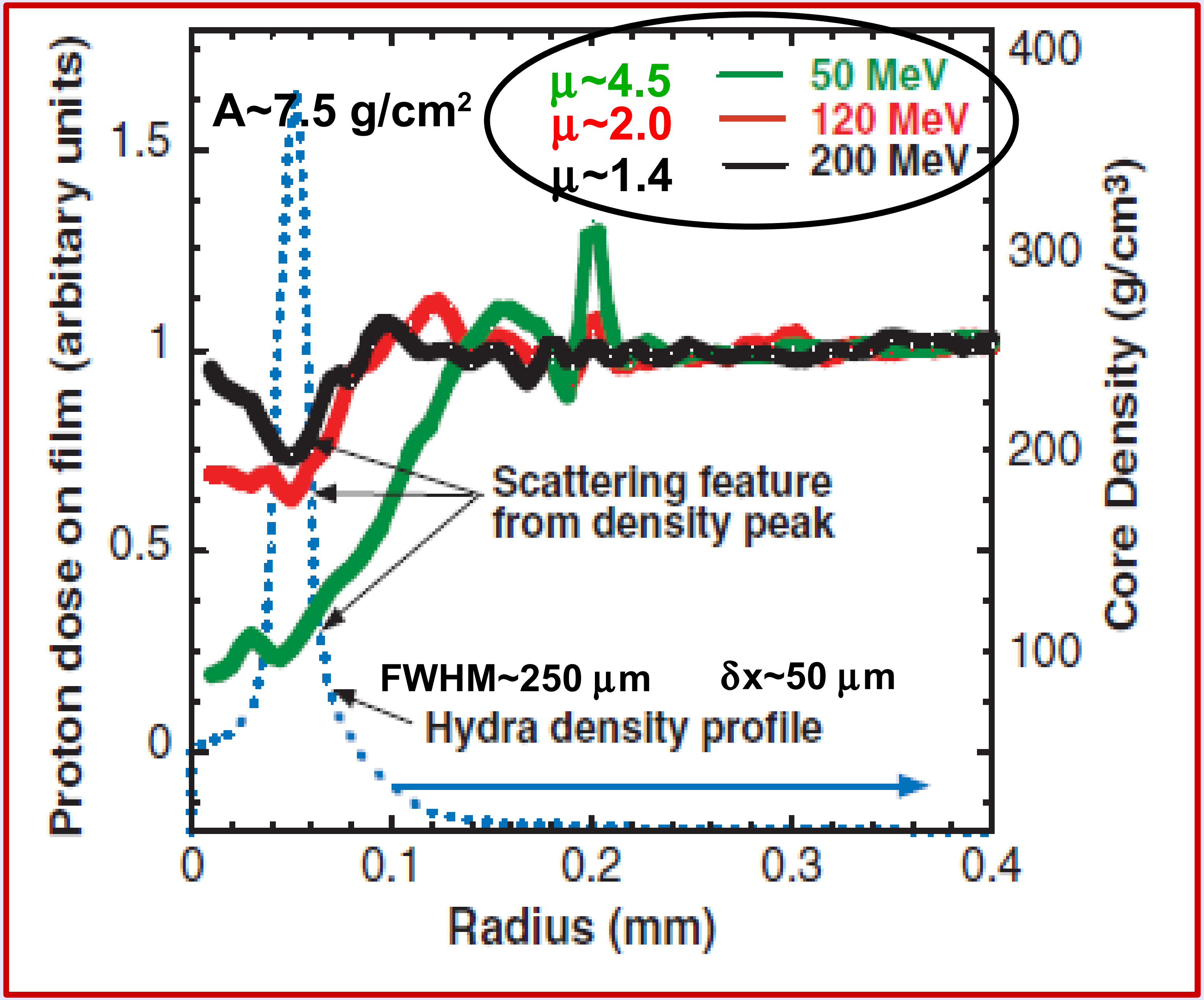


$$M = \frac{d+L}{d} \qquad \tilde{\xi} = \xi / M$$

Strong condition II



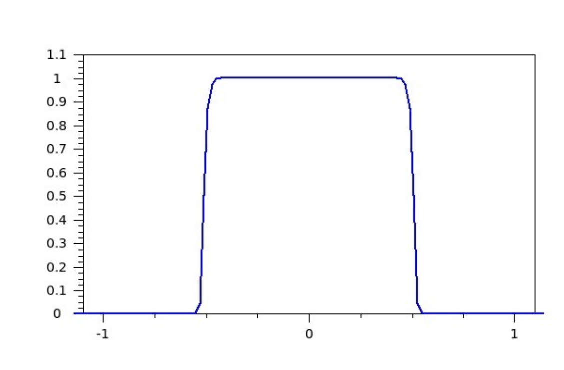
Minimum energy required to overcome certain area density



A.J. MacKinnon, et al., Phys. Rev. lett. 97, 045001 (2006)

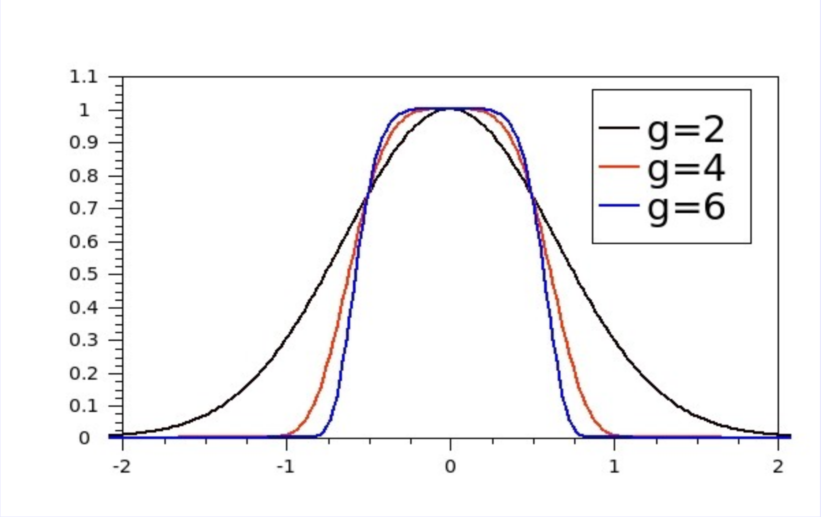
“weak” condition I

- Strong condition is impracticable at the moment
- What we would like to know about imploding shell ?
- PR should give us information about:
  - Peak density of the imploding shell
  - Size of the imploding shell
  - Time dependent (x-ray no !)



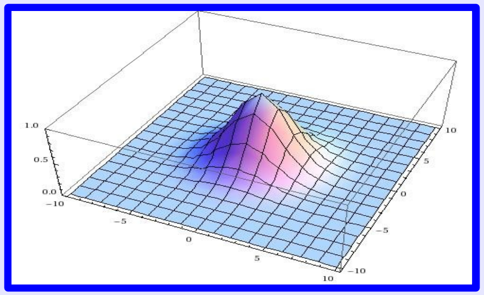
- There exist some condition in which low energy proton beam works giving us informations about cylinder size only

- PR is almost energy independent for sharp density profile objects (similar to neutral particles)
- Smooth profiles decrease PR resolution due to the MS



“weak” condition II

$$A_{x,y}(\gamma) = \rho_p \exp\left[-\ln 2\left(\frac{x^\gamma + y^\gamma}{w^\gamma}\right)\right] \quad A_y(\gamma) = \int_R A_{x,y}(\gamma)dx = A_x(\gamma)\exp\left[-\ln 2\left(\frac{y}{w}\right)^\gamma\right]; \quad A_x(\gamma) = \rho_p \int_R \exp\left[-\ln 2\left(\frac{x}{w}\right)^\gamma\right]dx$$

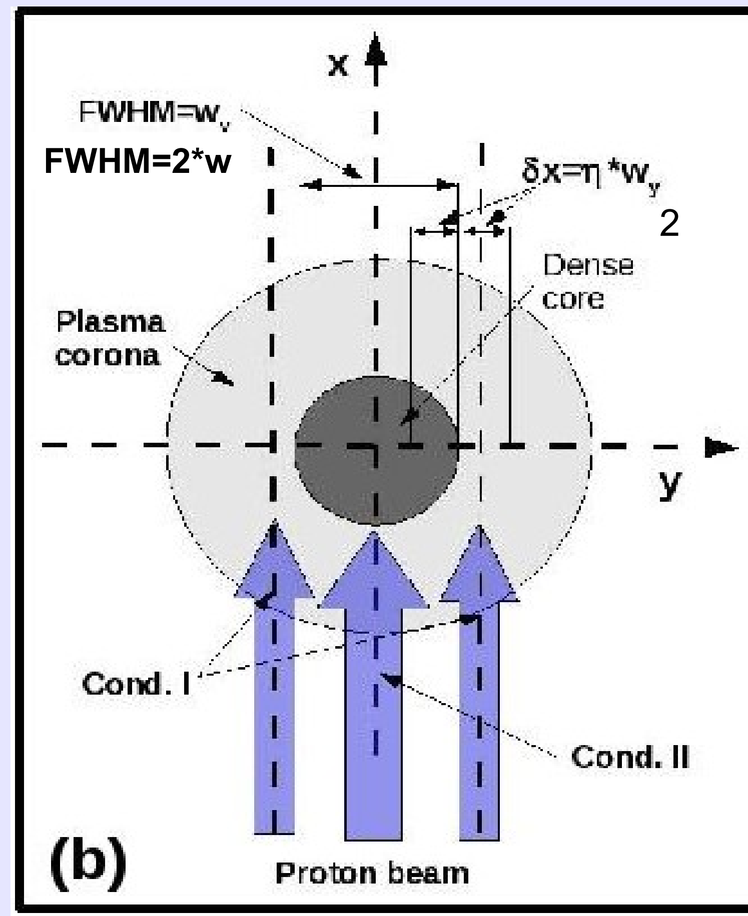


;

$$\xi_y(\gamma) = \frac{\Gamma c\sqrt{A_y(\gamma)}}{E_p} = \frac{\Gamma c\sqrt{A_x(\gamma)}}{E_p}\exp\left[-\frac{\ln 2}{2}\left(\frac{y}{w}\right)^\gamma\right]; \quad \Gamma = \frac{L}{M} = \frac{Ld}{L+d}; \quad c = \frac{E_s}{2\sqrt{L_R}}$$

I CONDITION (ξ(w+2ηw)<2ηw):

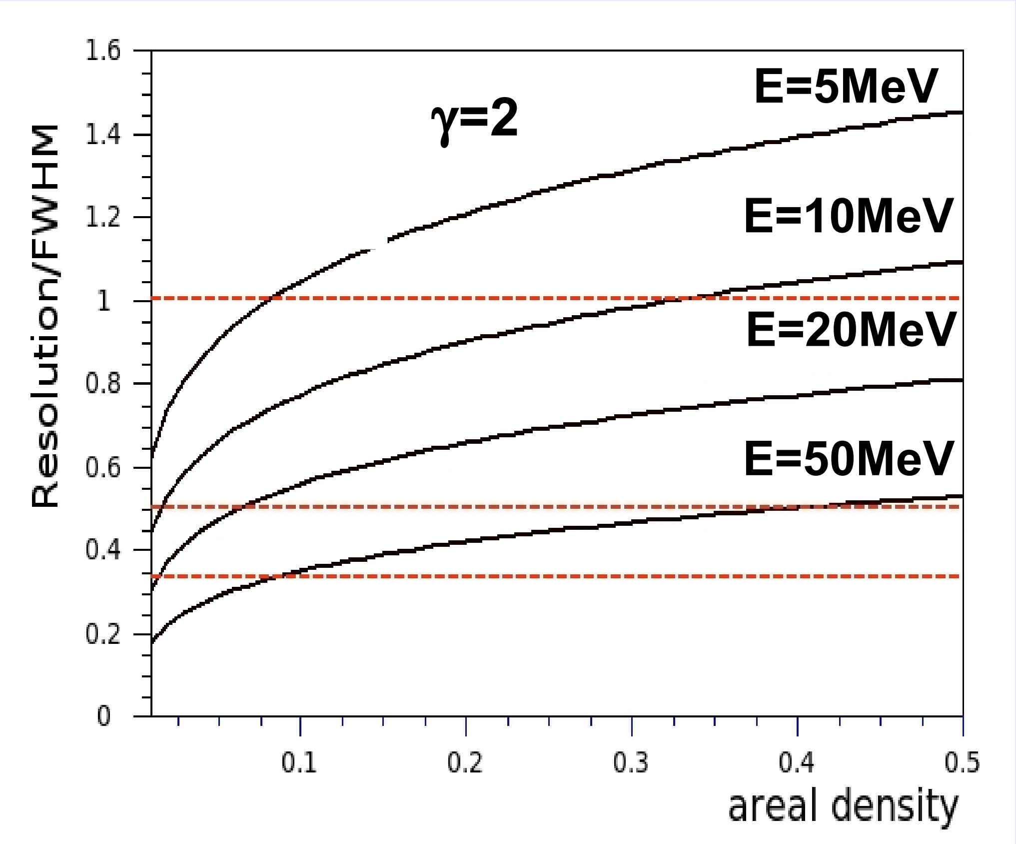
The blurring ξ(w+2ηw) occurring by protons passing through the plasma corona (region of the density distribution outside the FWHM must be of the same order of the resolution (δx=2ηw) which we would like to obtain (the resolution must be a fraction of the FWHM).

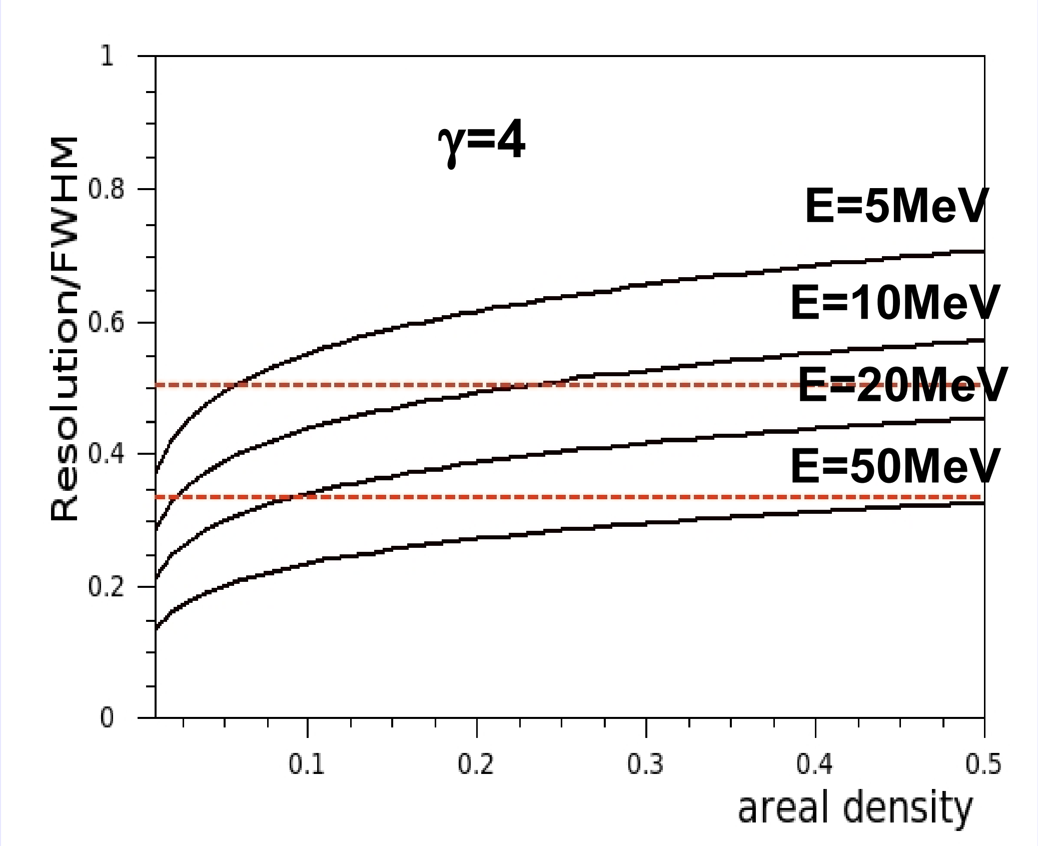


II CONDITION(ξ(w-2ηw)>4w):

The blurring ξ(w-2ηw) occurring by protons passing through the plasma corona (region of the density distribution outside the FWHM (see right fig.) must be larger than 2 FWHM of the target density profiles (this condition is related to the geometry of the target density profile only and does not depend on the proton energy).

“weak” condition III





I CONDITION: PR resolution as a function of the areal density for different energy values (E= 5, 10, 20, 50 MeV) assuming supergaussian density profiles:, γ=2 (left) γ=4 (right).

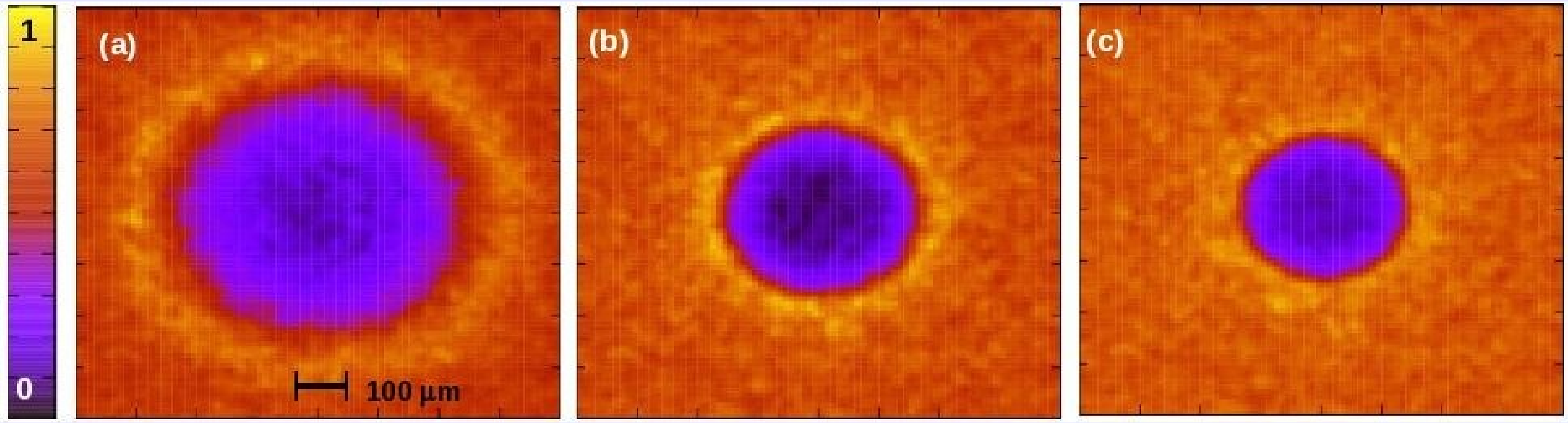
Two examples:

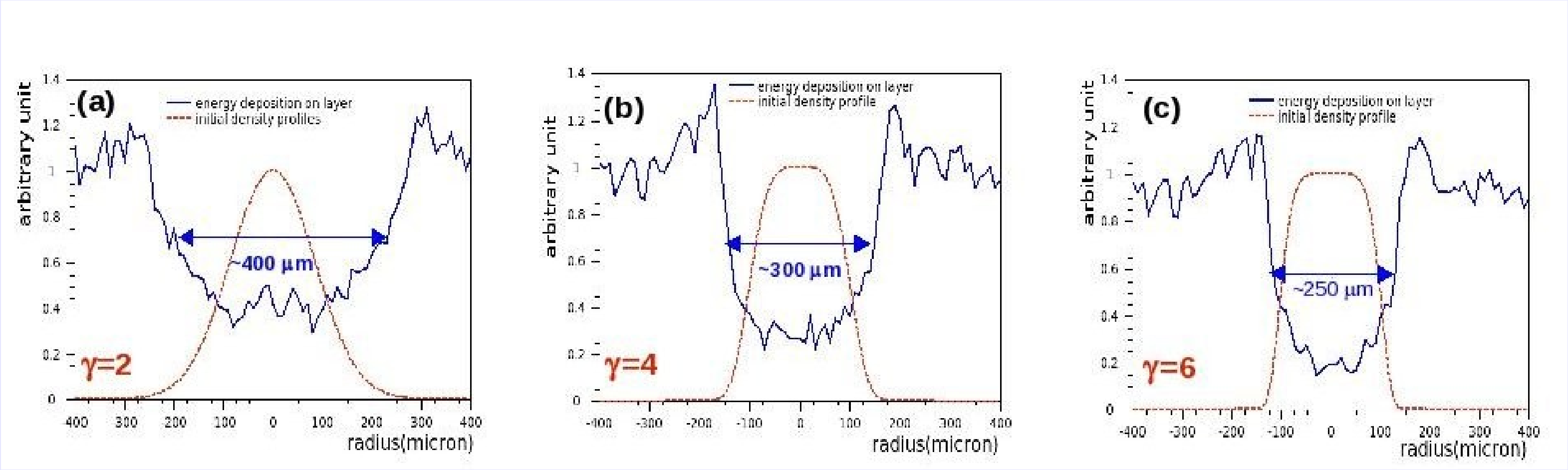
-RAL-08 (A~0.05g/cm^2 and E=10 MeV) gives Resolution ~0.7 and 0.4 FWHM for γ=2 and γ=4

-Omega (A~0.2 g/cm^2 E~1.5 MeV) gives Resolution ~1 and 0.4 FWHM for γ=2 and γ=4

"weak" condition III

Analytical predictions Vs Monte Carlo simulations performed using the program MCNPX





MC Simulations are performed assuming 10 MeV proton beam probing a spherical target with variable (γ=2 (a); γ=4 (b) ; γ=6 (c)) gaussian density profiles (ρ=6g/cm^2; w=FWHM/2= 100 µm) which correspond to a peak areal density A(y=0) ~0.12 g/cm^2 .
Simulation results showed in left figure confirm the analytical prediction giving resolution values close to those obtained analytically. Resolution= ((a) ~ 1 FWHM, (b) ~ 0.4 FWHM, (c) ~ 0.2 FWHM)

Conclusions and Remarks

- Systematic study of PR performance in ICF experiments
- Performance as a function of experimental parameters
- Two conditions to be satisfied
- “Strong” condition not available at the moment
- “weak” condition
  - Less stringent ; geometrical dependent
  - Only target size information (no peak density)