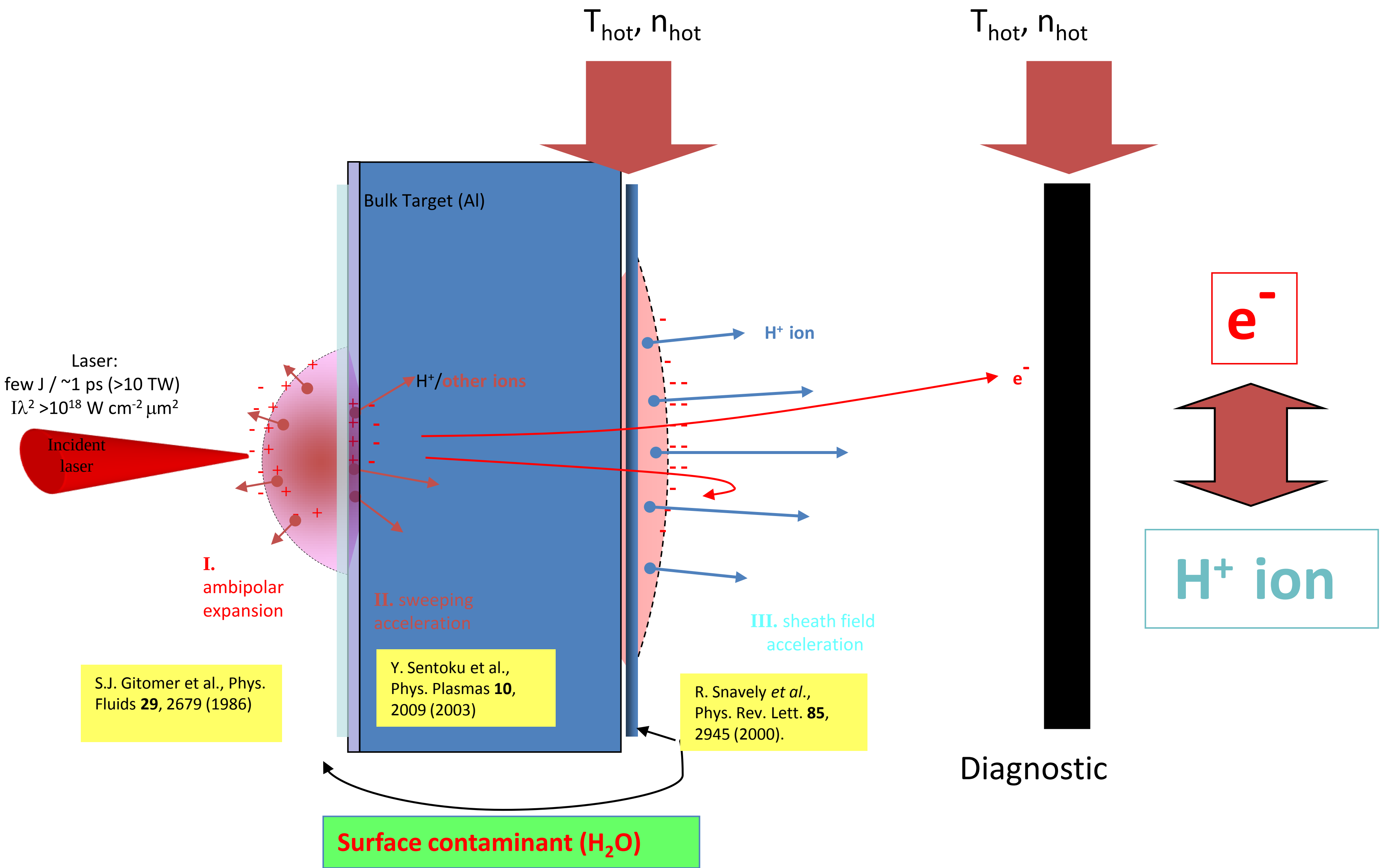
Measurement of electron and proton characteristics through calibrated diagnostics and correlation between their observables

J. Fuchs, P. Antici, S.Buffechoux,
A. Mancic, M. Nakatsutsumi, P. Audebert

Position of the problem



What are the possible observables?

Protons:

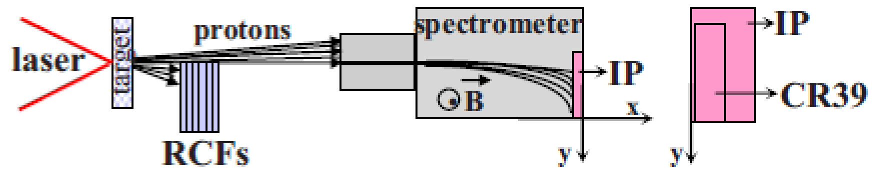
- Divergence → RCF
- Energy (spectrum) → Spectrometer+RCF
- Source size → RCF
- Emittance → RCF
- Duration → ???

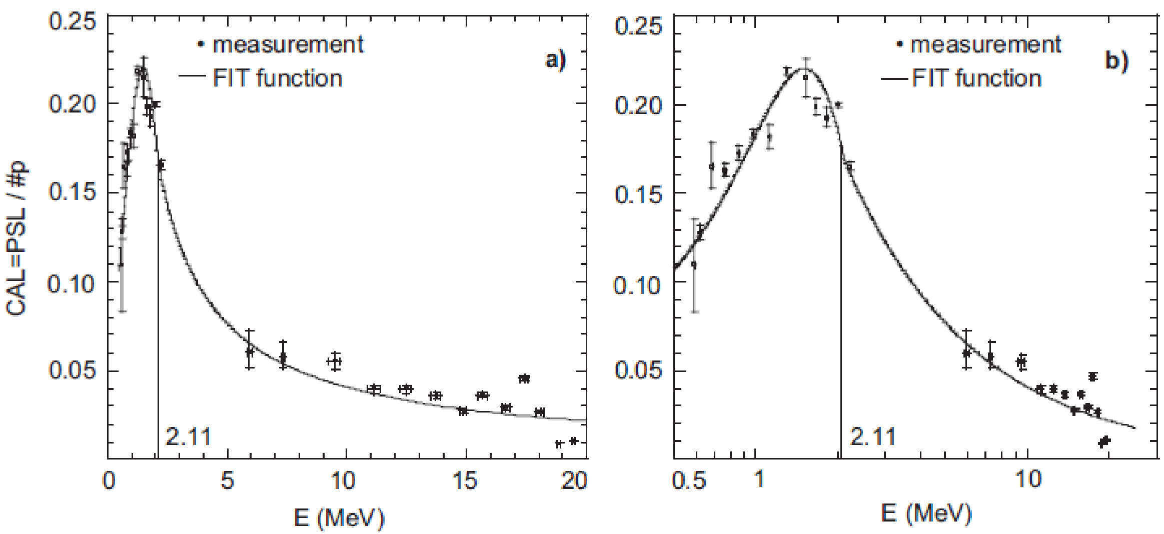
Electrons:

- Ne
- Te (spectrum)
- Divergence
- Spatial distribution

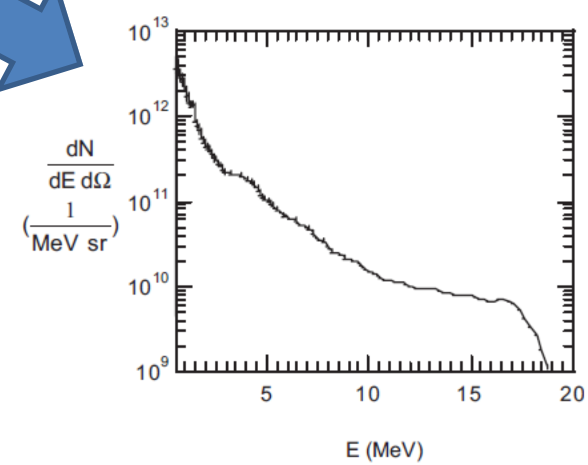
Magnetic spectrometer is a standard one equipped with calibrated IP as detector

For e-: see H. Chen RSI, K. Tanaka RSI
For protons:



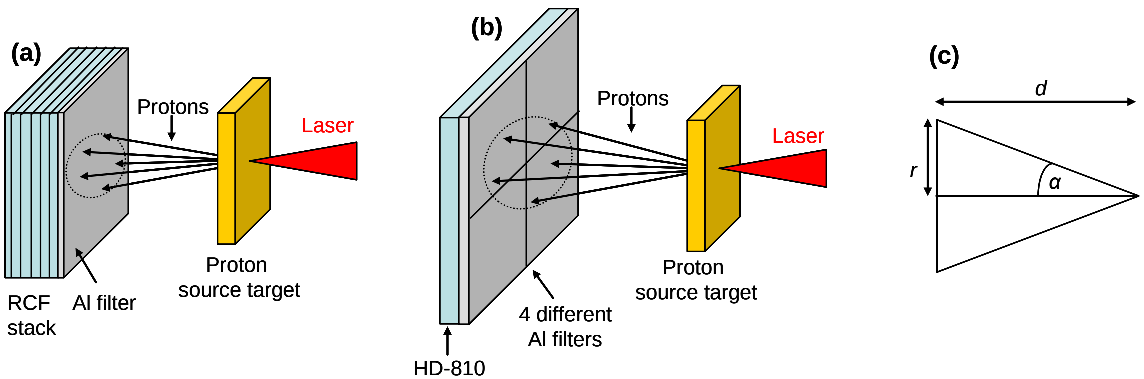


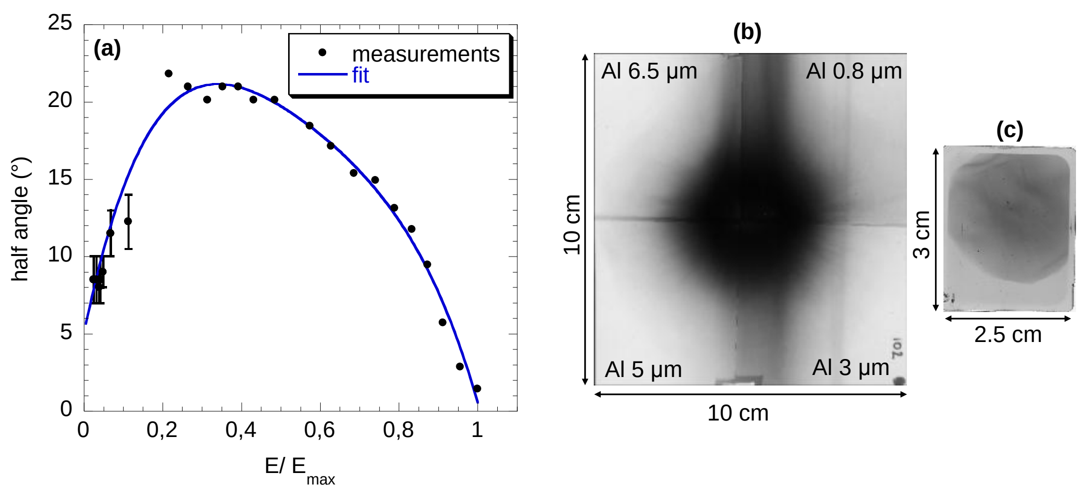
+ confirmed by activation of RCF with CENBG

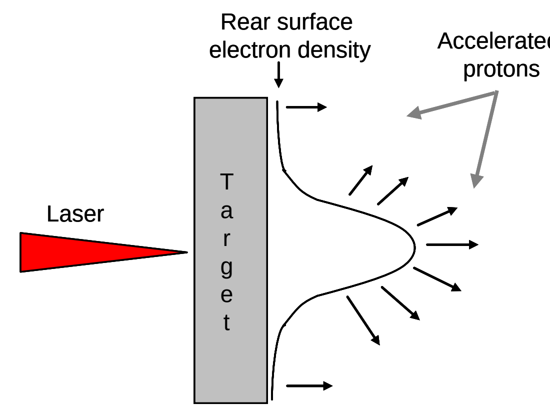


A. Mancic et al., Rev. Sci. Instrum. **79**, 073301 (2008)

Proton beam divergence

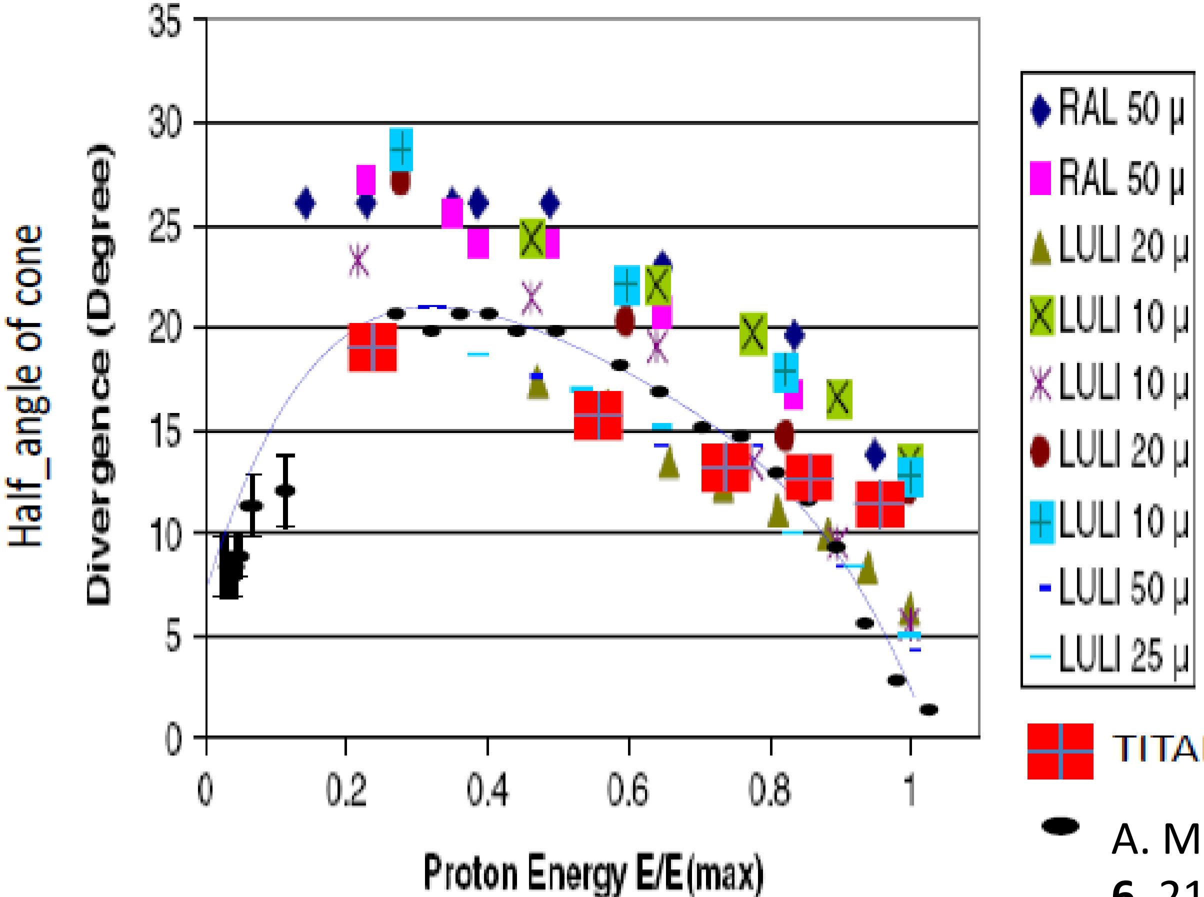






A. Mancic et al., HEDP **6**, 21-28 (2010)

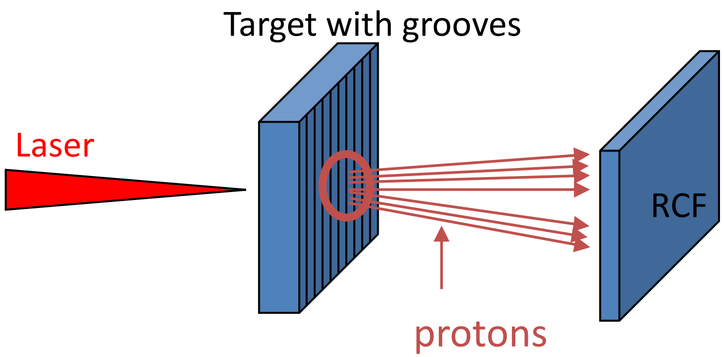
Consistent with measurements on other facilities

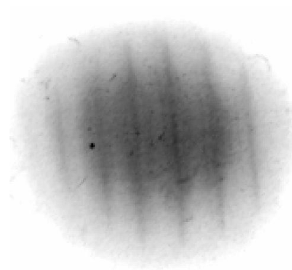


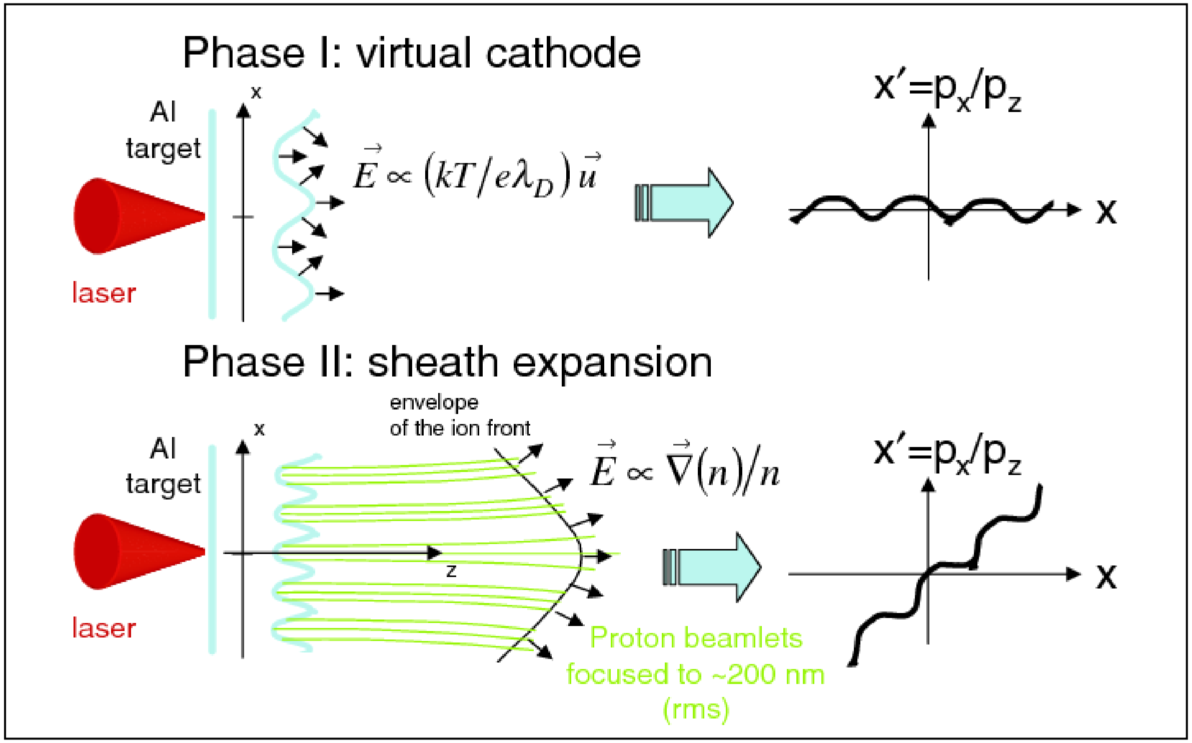
M. Roth's PPCF paper

A. Mancic et al., HEDP **6**, 21-28 (2010)

Emittance & source size measurements rely on using grooved targets

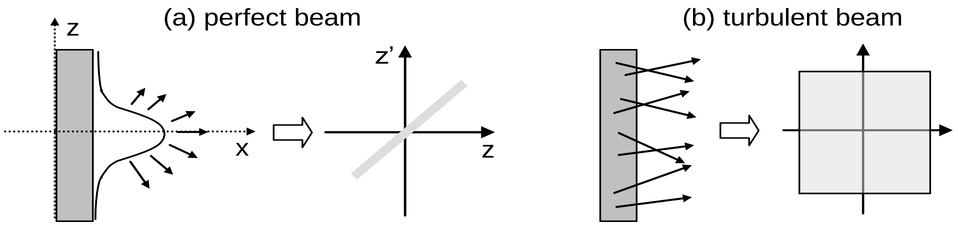


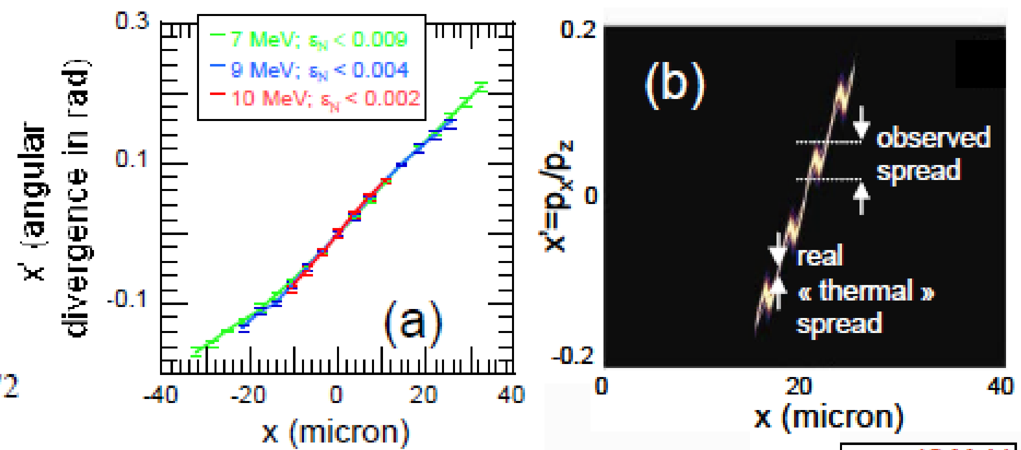




T. Cowan et al., PRL 2004

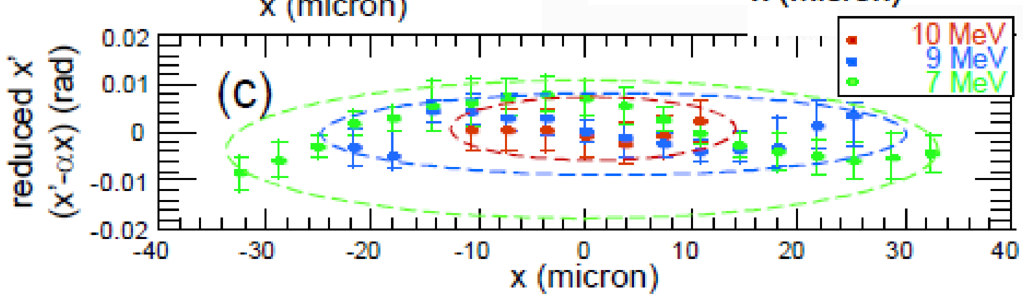
Transverse emittance measurement



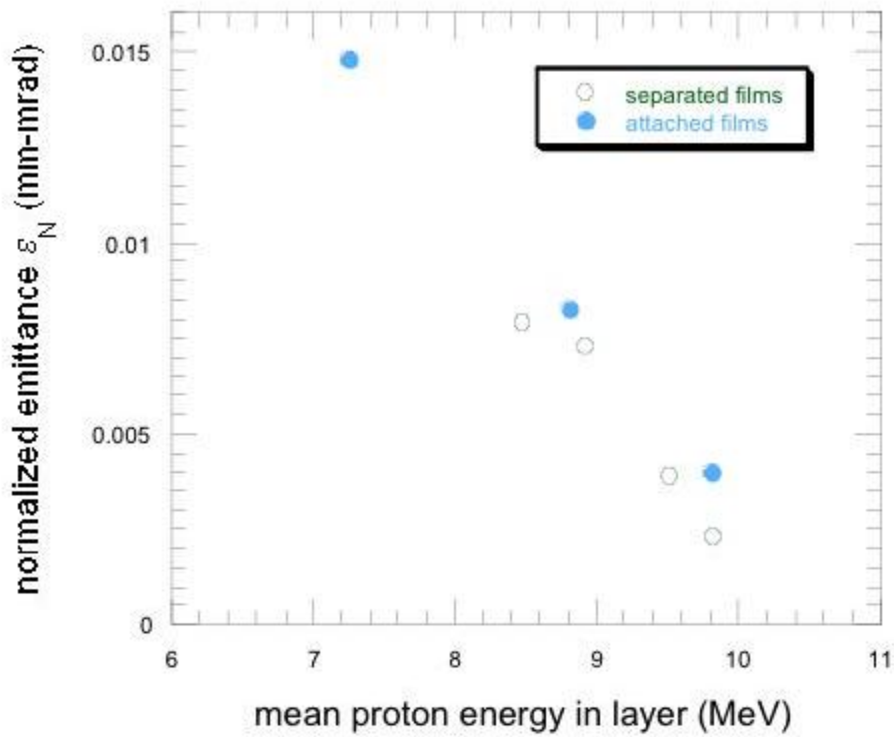


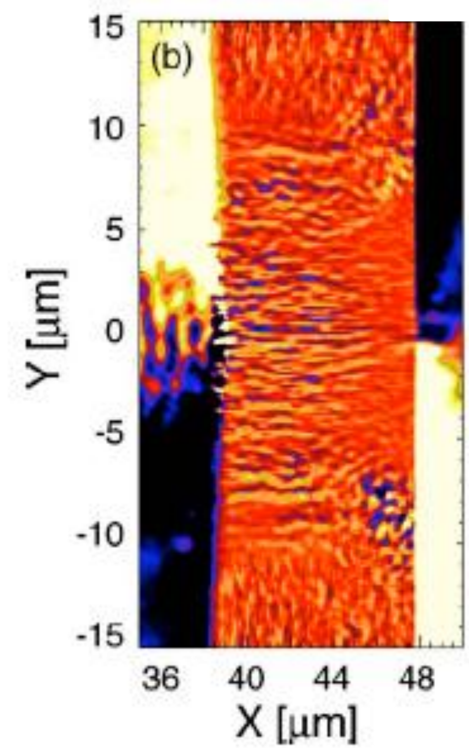
$$\varepsilon_N = (|\mathbf{p}|/mc)\,[\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2]^{1/2}$$

$$\varepsilon_N = \beta\gamma\,\sigma_x\,\sigma_{x'}$$



Record-low values, limited by magnetic instability

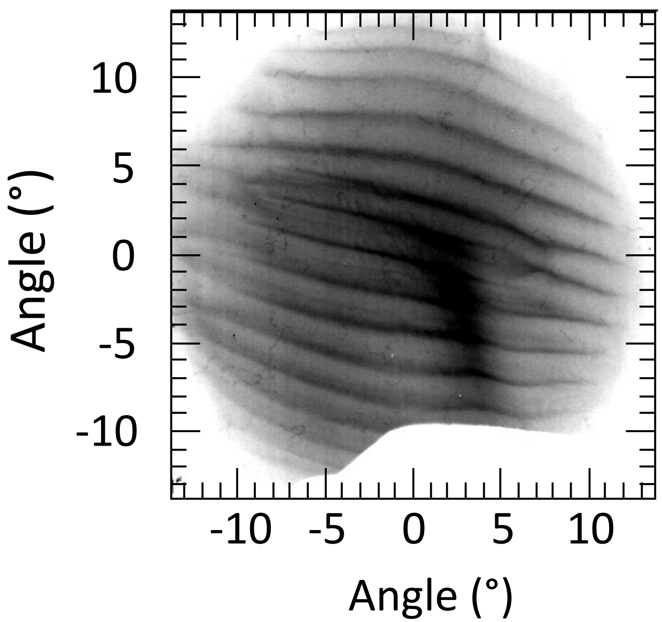


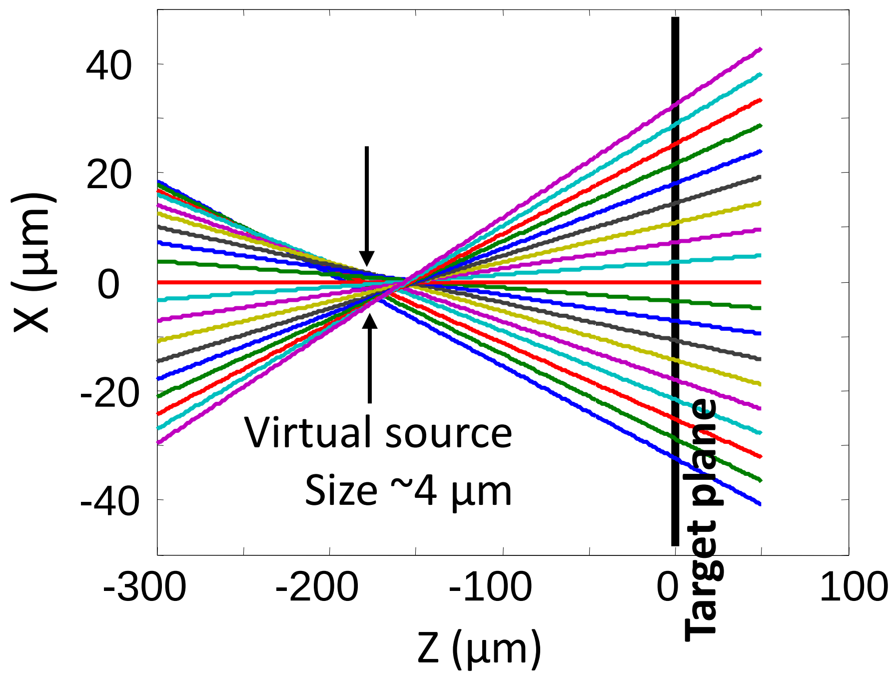


A. Kemp et al., PRE 2007

Allows also the measure the virtual source size

8 MeV layer





J. Fuchs et al., PoP 2007

What are the possible observables?

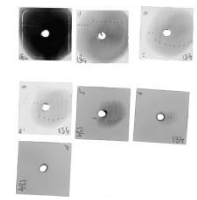
Protons:
- Divergence → RCF
- Energy (spectrum) → Spectrometer+RCF
- Source size → RCF
- Emittance → RCF
- Duration → ???

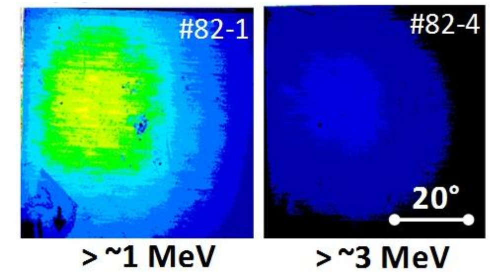
Electrons:
- Ne
- Te (spectrum) → Direct (e- measurements) or indirect (fitting of p+ measurements)
- Divergence
- Spatial distribution

The diagnostics used for electrons

Vacuum
Compressor
E=5-20 J
t_{laser}=0.3-5ps
Focal spot~5 μm
1ω: λ=1.053 μm
2ω: λ=0.527 μm

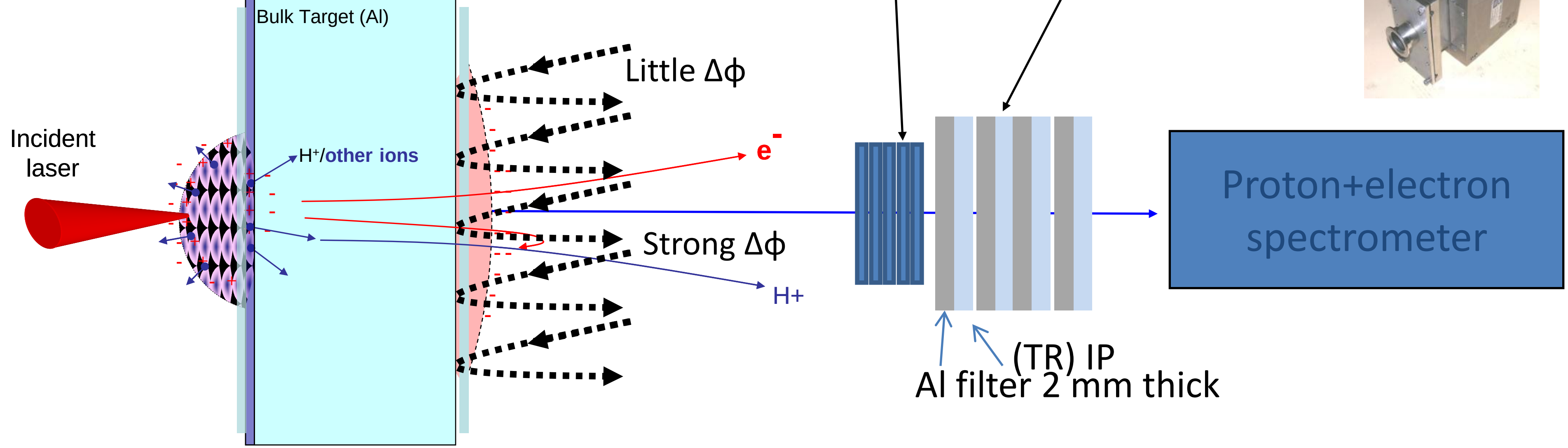
2) Radiochromic Films (RCF)



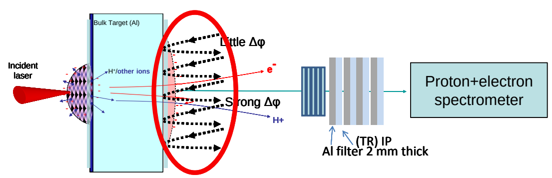
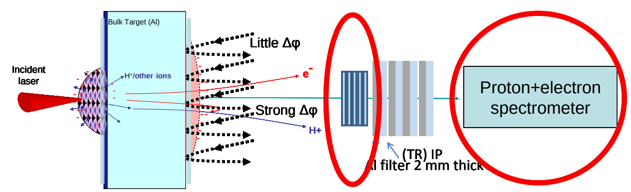
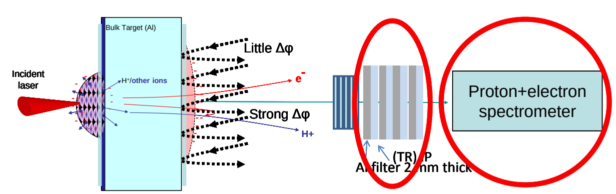


3) IP Stack

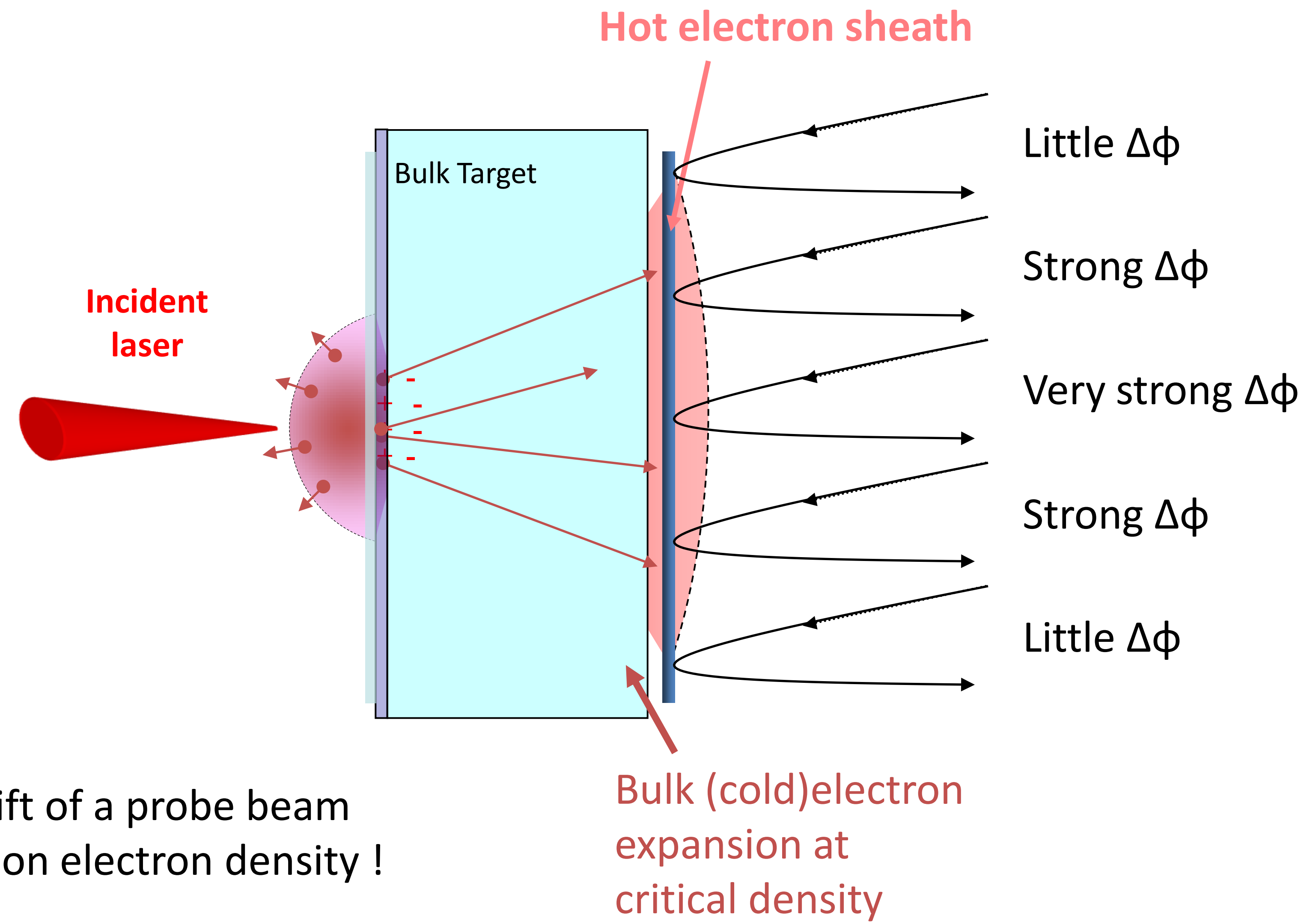
1) Time and space resolved interferometry (TASRI)



Overview

	Local	**Distant**
Direct	TASRI 	Electron spectrometer Image Plate (IP) 
Indirect		Proton spectrometer Radiochromic films 

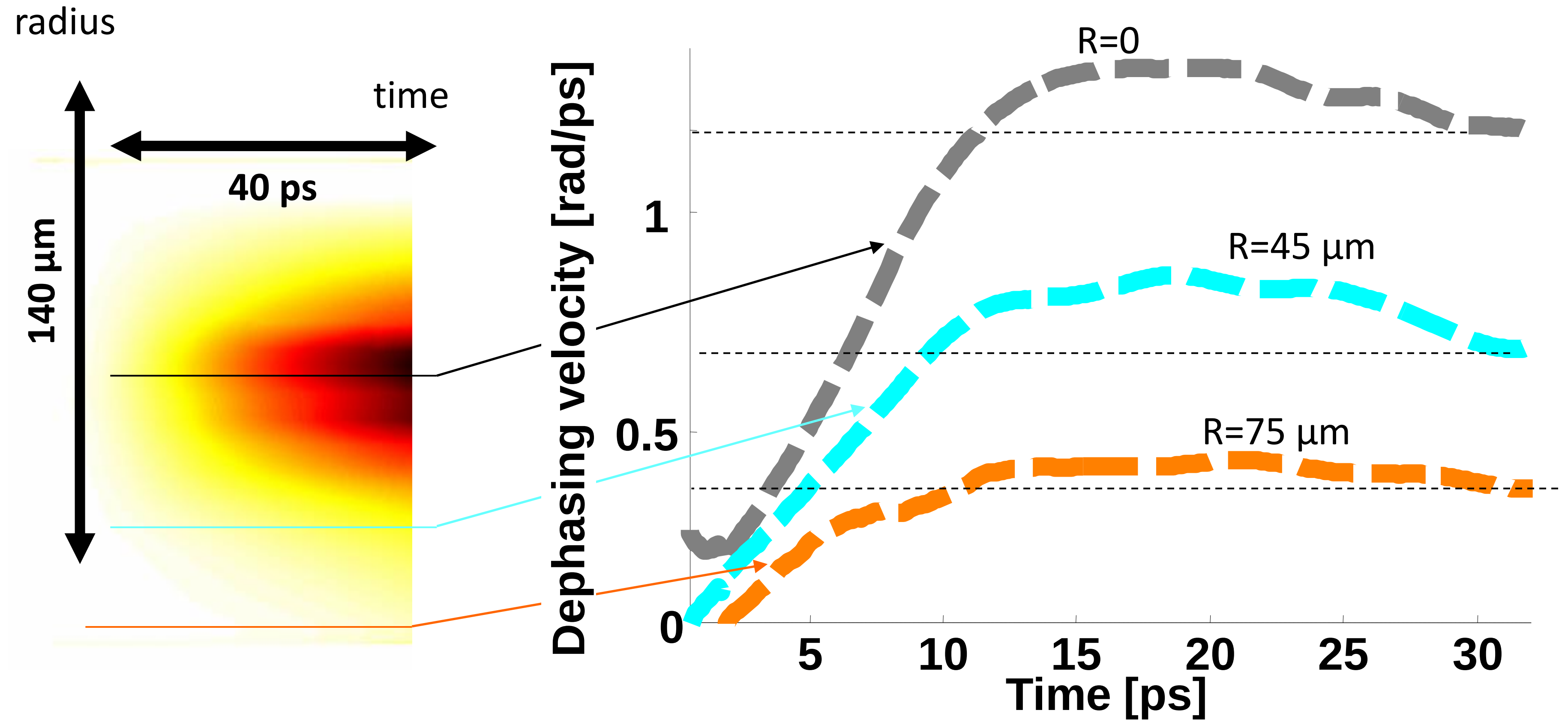
A **local** diagnostic of electron properties at the target rear (TASRI)



Phase shift of a probe beam depends on electron density !

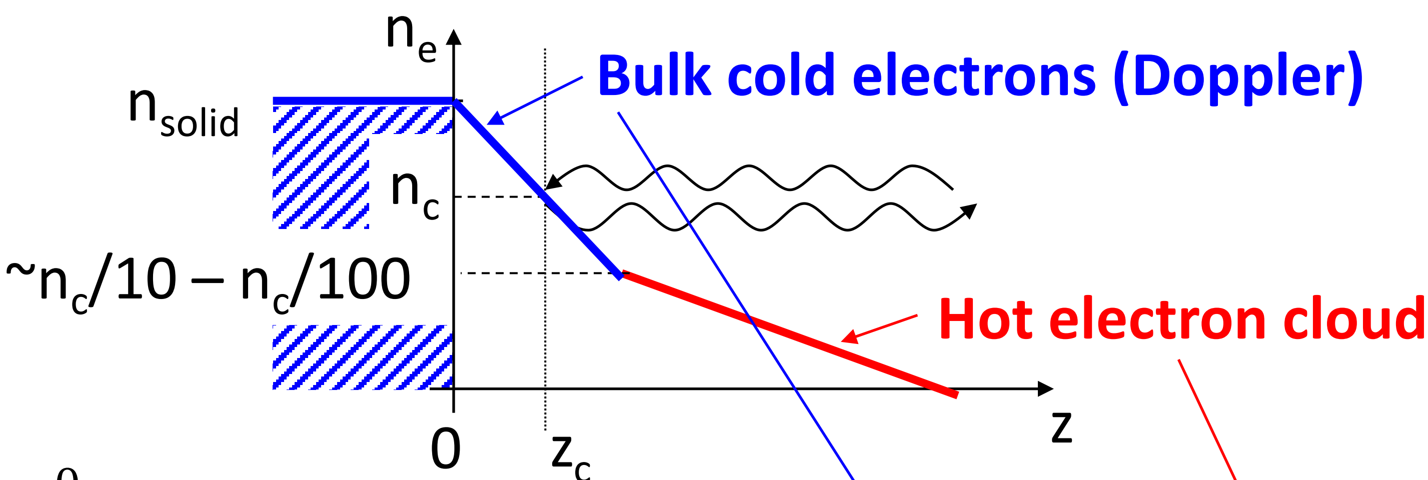
Profiles of [dφ/dt](t) change at different radii

Early overshoot decreases in amplitude as we go further outwards from the center of the irradiation zone



Linear phase shift due to Doppler target motion; early overshoot due to low-density hot electrons cloud

What we measure: $\Delta\varphi = \varphi(t) - \varphi_0$

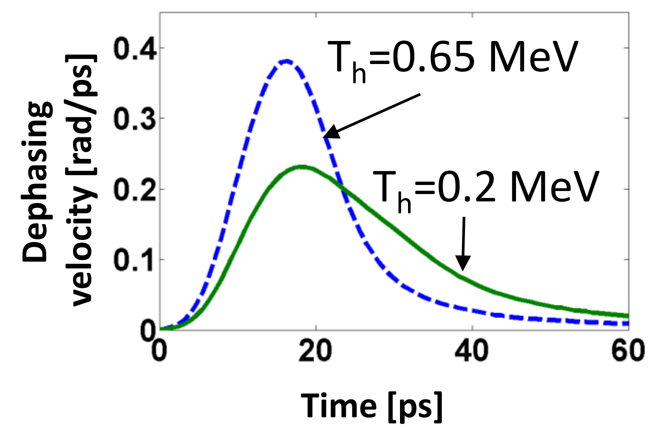


$$\varphi_0 = 2\int_{\infty}^{0} k(z)dz$$ = reference phase (from the unperturbed target)

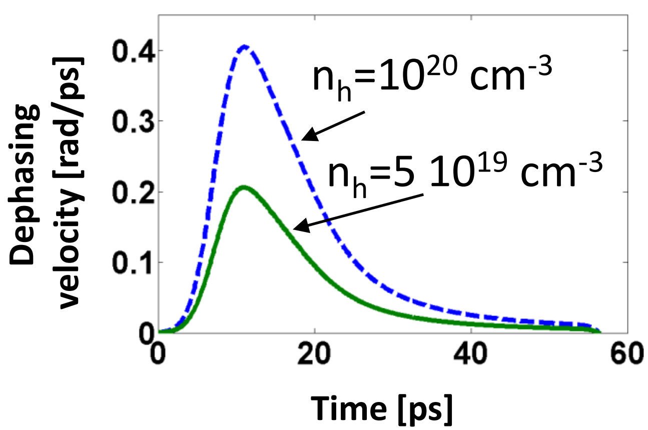
$$\varphi(t) = 2\int_{\infty}^{z_c(t)} k(z)dz = 2\int_{\infty}^{z_c(t)} \frac{\omega}{c}\sqrt{\varepsilon(z)}dz \sim \frac{2\omega}{c}\left(\int_{\infty}^{z_c(t)} dz - \frac{1}{2n_c}\int_{\infty}^{z_c(t)} n_e(z,t)dz\right)$$

Fitting both linear shift & early overshoot allows retrieving electron distribution parameters unambiguously

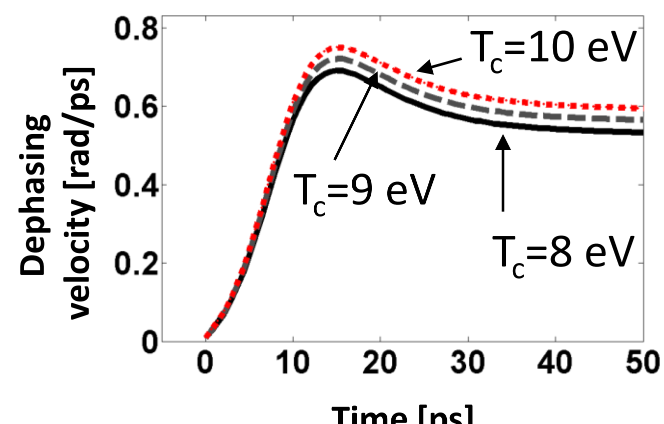
Sensitivity to initial hot electron **temperature**



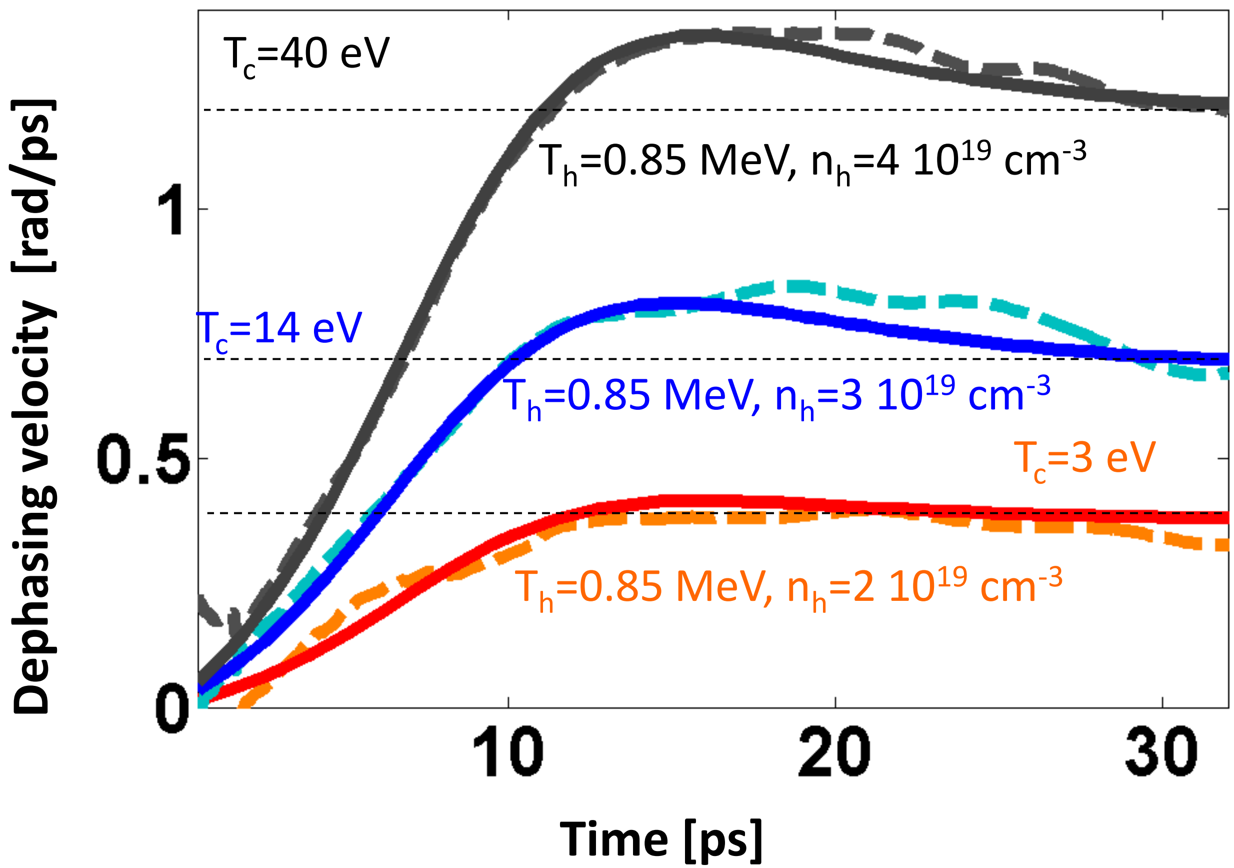
Sensitivity to initial hot electron **density**



Sensitivity to initial cold electron **temperature**



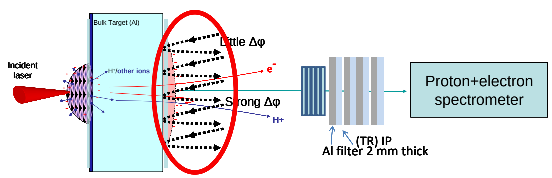
Example

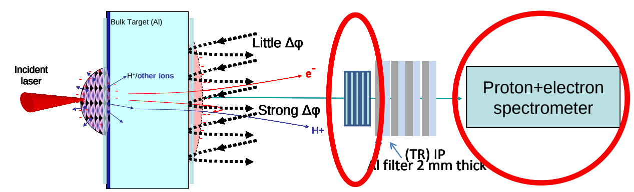


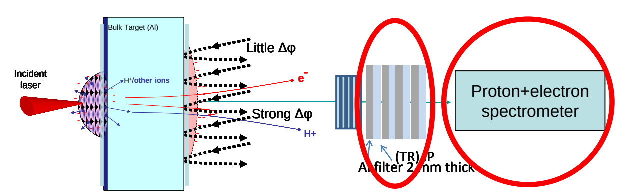
T_c=40 eV
T_h=0.85 MeV, n_h=4 10^19 cm^-3
T_c=14 eV
T_h=0.85 MeV, n_h=3 10^19 cm^-3
T_c=3 eV
T_h=0.85 MeV, n_h=2 10^19 cm^-3
Dephasing velocity [rad/ps]
1
0.5
0
10
20
30
Time [ps]

Overview

<table>
<tr><td></td><td>Local</td><td>Distant</td></tr>
<tr><td>Direct</td><td>TASRI


</td><td>Electron spectrometer
Image Plate (IP)


</td></tr>
<tr><td>Indirect</td><td></td><td>Proton spectrometer
Radiochromic films


</td></tr>
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Can we relate distant (escaping e-) & local diagnostics ?

→ Kinetic fluid simulations show that the tail of the e- distribution keeps a constant T

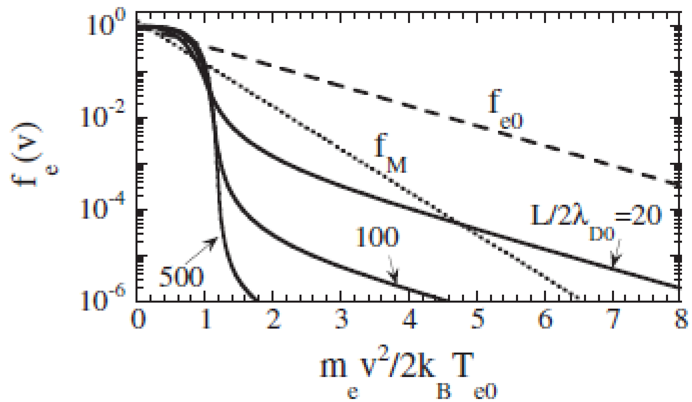


FIG. 1. Electron distribution function at $t = 0.44\tau$ for $L/2 = 20\lambda_{D0}$, $100\lambda_{D0}$, and $500\lambda_{D0}$. The distributions are normalized to $f_{e0}(0)$ and are taken at the center of the plasma foil, $x = 0$. The dashed line corresponds to the initial distribution function $f_{e0}(v)$. The dotted line corresponds to a Maxwellian distribution function $f_M(v)$ with the same density and energy content that the actual distribution, for $L/2 = 20\lambda_{D0}$ (the Maxwellian distribution functions corresponding to $L/2 = 100\lambda_{D0}$ and $500\lambda_{D0}$, not shown, are only slightly different).

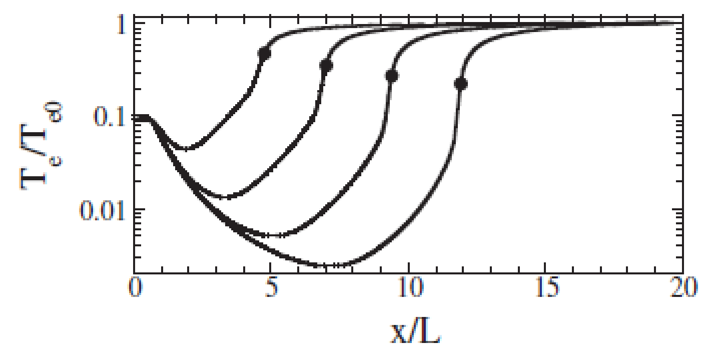


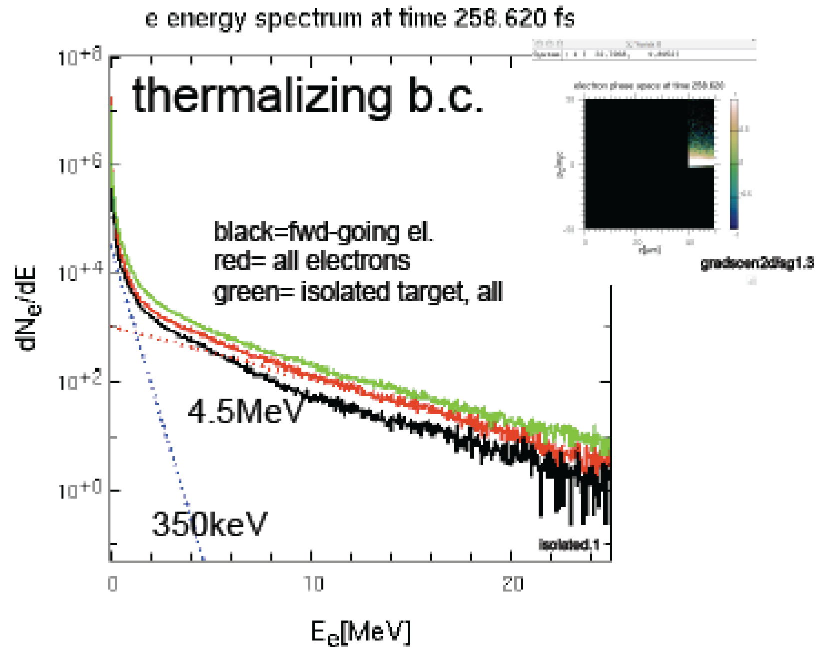
FIG. 3. Electron temperature as a function of space (only half the foil is shown) at $t = \tau$ for $L/2 = 20\lambda_{D0}$, $100\lambda_{D0}$, $500\lambda_{D0}$, and $2500\lambda_{D0}$ (from left curve to right curve). Space is normalized to L. The dots correspond to the position of the ion front at the far end of the expansion.

P. Mora & T. Grismayer, PRL 102, 145001 (2009)

This is confirmed by 2D PIC (A. Kemp, LLNL)

Spectrum of ‘escaping’ electrons resembles a spectrum in ‘thermalizing’ boundary simulation

early on, escaping electrons are not a bad representation of ‘input’ spectrum



AJ Kemp 2008

8

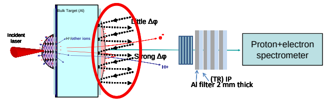
& also hybrid simulations (Ohio State U.)

Example of correlation regarding hot electron temperature

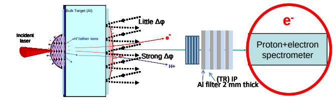
Exp @ 1ω / 10 μm Al

I=5 10^{19} W/cm² / t_{laser}=320 fs

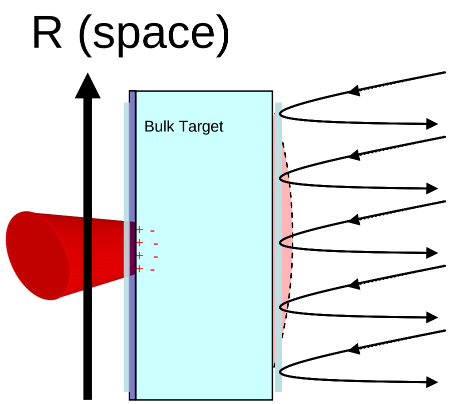
Determination of the hot electron temperature T_{hot}



DIRECT

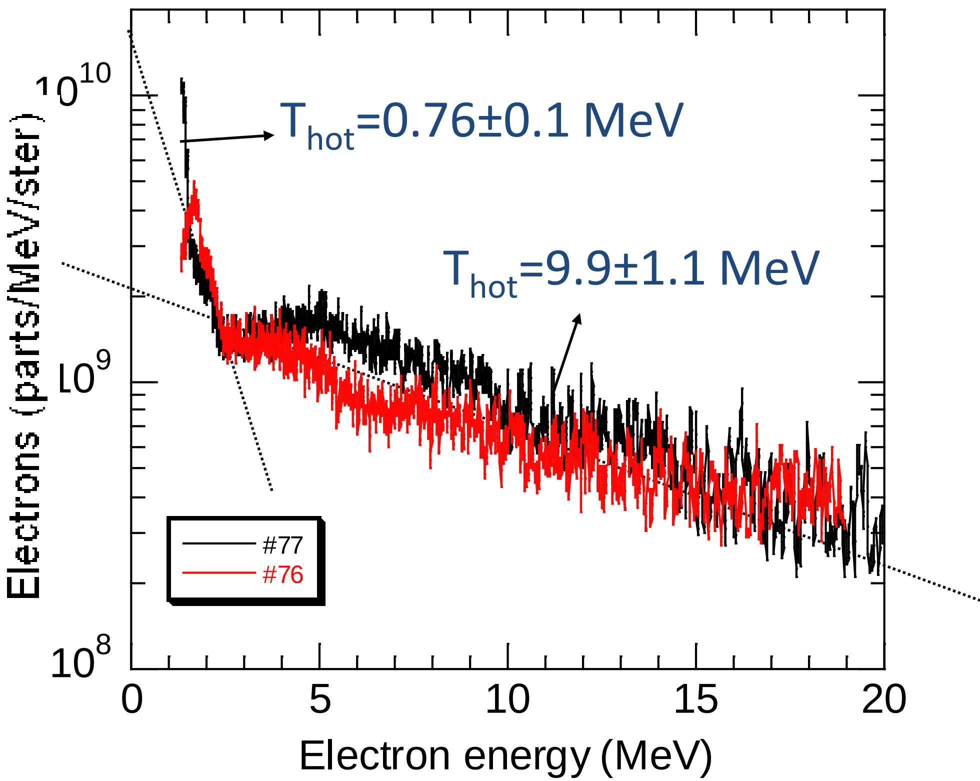


1) TASRI (expansion speed of hot electron cloud)



T_{hot}=0.85±0.2 MeV

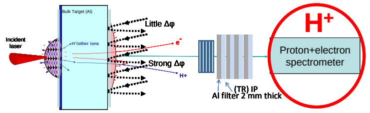
2) Electron spectrometer



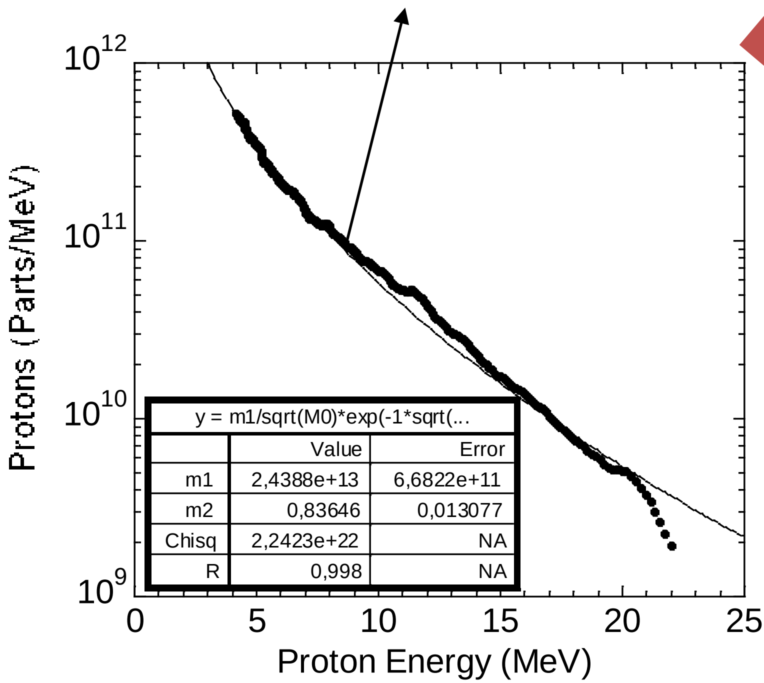
Exp @ 1ω / 10 μm Al
I=5 10^{19} W/cm² / t_{laser}=320 fs

P. Antici, PRL **101,** 105004 (2008)

Determination of the hot electron temperature T_{hot}
INDIRECT



Proton spectra
(using a model)



	Value	Error
m1	2,4388e+13	6,6822e+11
m2	0,83646	0,013077
Chisq	2,2423e+22	NA
R	0,998	NA

$$dN/dE=1.3N_{hot}c_s/[c(2Ek_BT_{hot})^{1/2}]\exp(-[2E/(k_BT_{hot})]^{1/2})$$

height — slope

T_{hot}=0.84±0.3 MeV

TASRI: T_{hot}=0.85±0.2 MeV
Electron Spectro: T_{hot}=0.76±0.1 MeV

Exp @ 1ω / 10 μm Al
I=5 10^{19} W/cm² / t_{laser}=320 fs

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

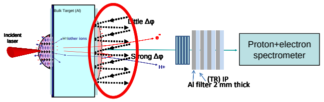
Example of correlation regarding hot electron number

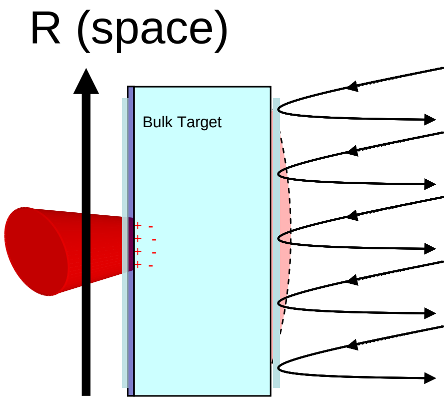
Exp @ 1ω / Al 25 µm

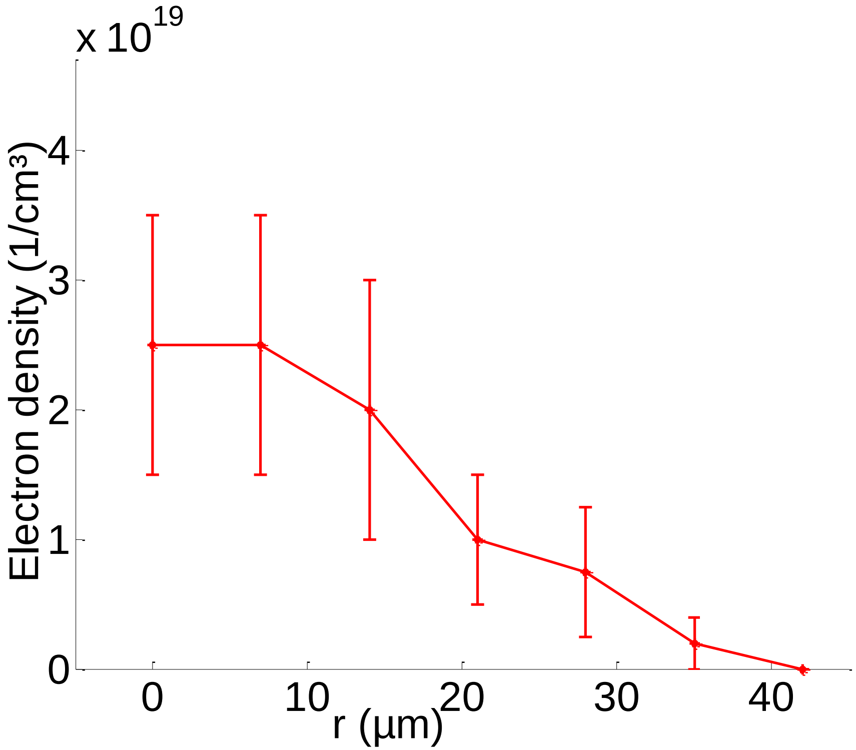
I~3e18 W/cm^2 / t_{laser}=5 ps

Determination of the hot electron density n_{hot} or total number N_{hot}

n_{hot} DIRECT



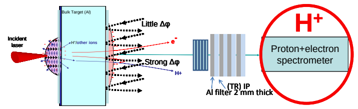




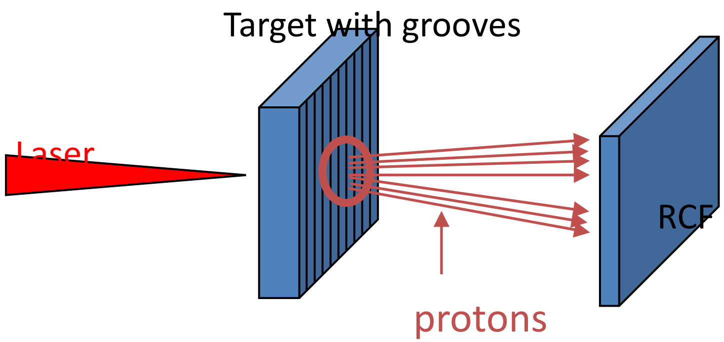
Exp @ 1ω / Al 25 µm

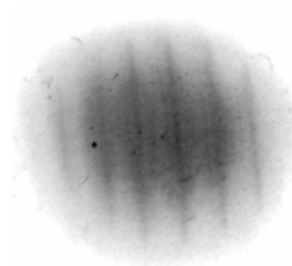
I~3e18 W/cm² / t_{laser}=5 ps

Determination of the hot electron density n_{hot} or total number N_{hot}



n_{hot} INDIRECT





$$E_{proton}=2*Z*k_b*T_h*(\ln(\tau+(\tau^2+1)^{0.5})^2$$

$$\tau=\omega_{pi}*t_{laser}/2.32$$

$$\omega_{pi}=(\mathbf{n_{hot}}Ze^2/m_i\varepsilon_0)^{0.5}$$

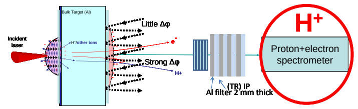
unknown

RCF using grooved target:

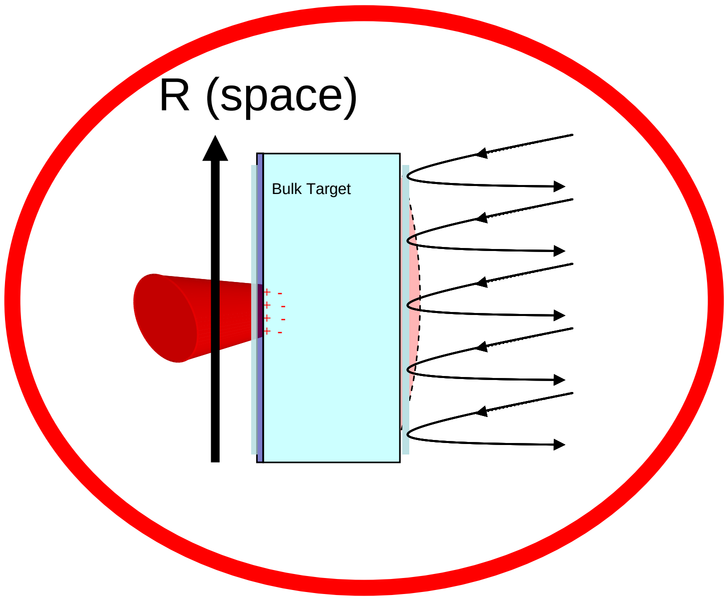
1) Every RCF is associated to one proton energy
2) Grooves on target allow retrieving the source diameter producing this energy
3) A model allows to associate proton energy to electron density:

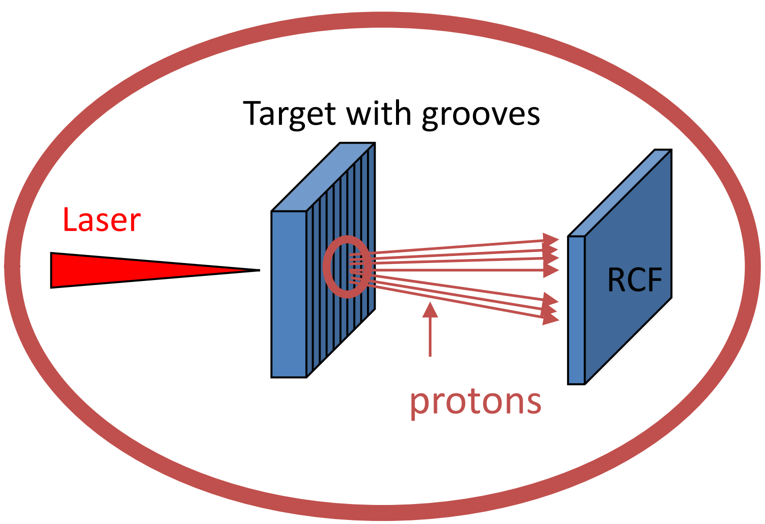
P.Mora, Phys. Rev. Lett. 90,185002 (2003)

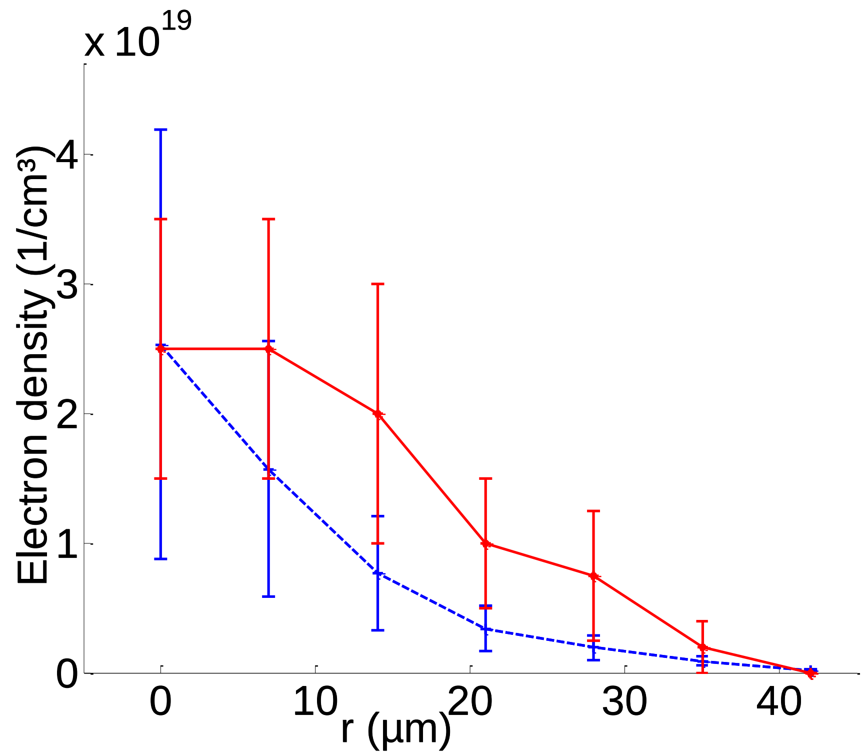
Determination of the hot electron density n_{hot} or total number N_{hot}



n_{hot} INDIRECT





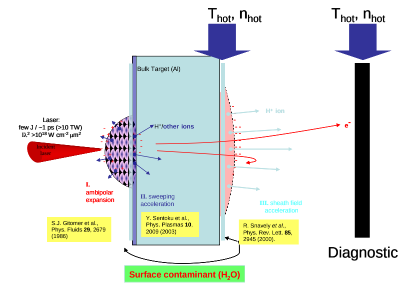


Exp @ 1ω / Al 25 µm

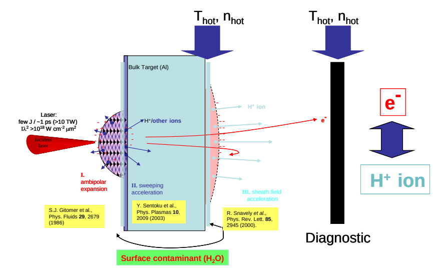
I~3e18 W/cm² / t_{laser}=5 ps

Conclusion

1) Local measurement are indicative of non local measurements



2) Indirect measurement (protons) can give information about electrons



3) This is valable for T_{hot} and n_{hot}

4) We have seen a variety of diagnostics valid in the range of present-day experiments…

Perspective