High Brightness Laser Induced Multi-MeV Electron/Proton Sources

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SUMMARY

- FROM Inertial Confinement Fusion STUDIES TO Laser Plasma Acceleration
- THE ILIL EXPERIMENTS
- CONTROLLING THE ELECTRON INJECTION
- EXTENDING THE ACCELERATION LENGTH
- APPLICATIONS
- CONCLUSIONS AND PERSPECTIVES

Super-intense laser pulse in a plasma (1)

$$I = uv_g = \varepsilon_0 E^2 c \cdot n$$

$$for \;\; n \approx 1 \qquad E_{V/cm} \approx \; 27.5 \; I_{W\cdot cm^{-2}}^{\frac{1}{2}}$$

$$n = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{\frac{1}{2}} \qquad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m \gamma}\right)^{\frac{1}{2}}$$

$$\gamma = \left(1 - \beta^2\right)^{-\frac{1}{2}} \qquad \beta = \frac{v}{c}$$

$$\gamma = \left(1 + \frac{\alpha a^2}{2}\right)^{\frac{1}{2}} \;\; \alpha = 1 \; (lin. \;\; p.) \;\; ; \;\; 2 \; (circ. \;\; pol.)$$

$$a = \frac{eE}{m\omega c} \approx 8.5 \cdot 10^{-10} \cdot I_{W\cdot cm^{-2}}^{1/2} \cdot \lambda_{\mu m}$$

Super-intense laser pulse in a plasma (2)

$$for\ \ 1J,\ \ 30\,fs\ \ \ @\ \ \lambda \approx 0.815\mu m\ \ \ laser\ \ \ pulse$$

$$focal\ \ spot\ \ \phi \approx 5\mu m$$

$$I \approx 10^{20} W \cdot cm^{-2}$$

$$E \approx 3 \cdot 10^{11}\, V/cm >> E_{at} \approx 5 \cdot 10^{9}\, V/cm$$

$$B \approx 1\ \ GGauss$$

$$P = \frac{I}{c} \approx 6.6 \cdot 10^{15}\, N/m^{2} \approx 66\ \ GBar$$

$$a \approx 7\ \ \Rightarrow\ \ \gamma \approx 5\ \ \Rightarrow\ \ E_{cin} = mc^{2}(\gamma - 1) \approx 2MeV$$

ELECTRON PLASMA WAVE EXCITATION BY PONDEROMOTIVE FORCES

$$\vec{F} = -\vec{\nabla} < U > = -\frac{e^2}{2\varepsilon_0 m c \omega^2} \vec{\nabla} I$$

non relativistic intensities

$$U = \frac{1}{2} m v_e^2 \qquad v_e = \frac{eE}{m\omega}$$

$$\vec{F} = -mc^2 \vec{\nabla} < \gamma >$$

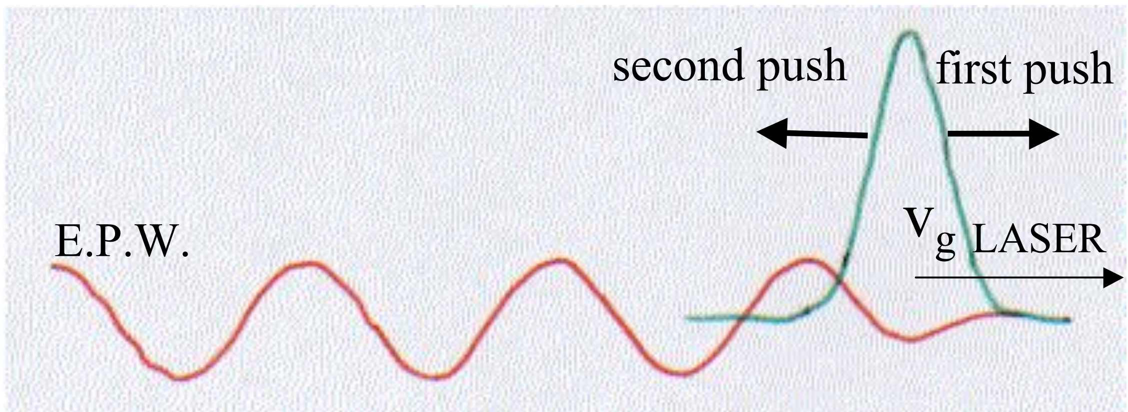
$$U = mc^2 (\gamma - 1)$$

relativistic intensities

$$v_{\phi,\ EPW} = v_{g,\ LASER}$$

the excited E.P.W. phase velocity equals the e.m. wave group velocity

E.P.W. EXCITATION BY LASER WAKE FIELD



$$\tau \cdot c \approx \frac{\lambda_p}{2} \Leftrightarrow \tau \approx \frac{T_p}{2} \Rightarrow n_e\left(cm^{-3}\right) \approx \frac{3 \cdot 10^{-9}}{\tau^2_{(s)}}$$

$$example: \ \tau = 30\,fs \Rightarrow n_e \approx 3.3 \cdot 10^{18}\,cm^{-3}$$

$$v_{\phi,epw} = v_{g,laser} = c\left(1 - \frac{\omega^2_{pe}}{\omega^2}\right)^{\frac{1}{2}}$$

ELECTRON PLASMA WAVE ELECTRIC FIELD

$$for \;\; \overline{\Delta n_e} \approx n_0 \quad and \;\; v_\phi \approx c$$

$$E_{\max} \approx \frac{n_0 e c}{\varepsilon_0 \omega_{pe}} \approx \left[n_0 \left(cm^{-3} \right) \right]^{\frac{1}{2}} \; \frac{V}{cm}$$

DAWSON LIMIT

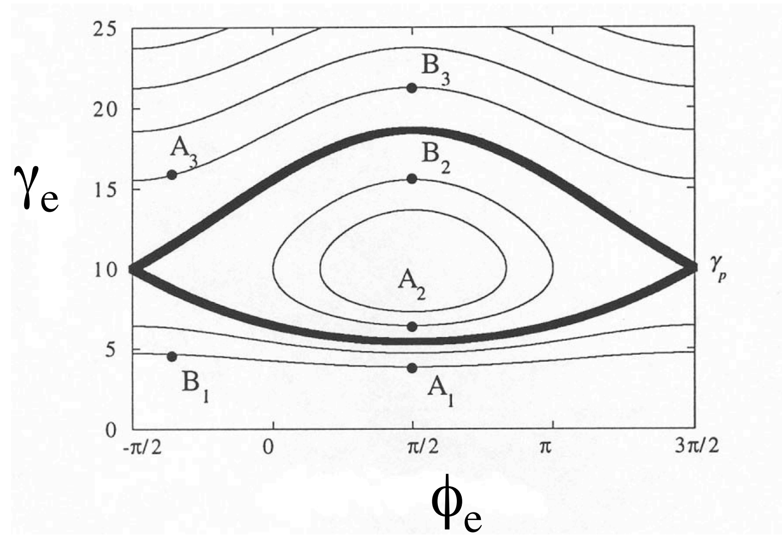
$Example:$

$$for \;\; n_0 = n_c(@1\mu m) \approx 1.1 \cdot 10^{21} cm^{-3} \quad \Rightarrow \quad E_{\max} \approx \; 3 \cdot 10^{10} \frac{V}{cm}$$

$$n_c = \frac{\varepsilon_0 m \omega^2}{e^2} \approx \frac{1.1 \cdot 10^{21}}{\lambda_{\mu m}^2} cm^{-3}$$

ELECTRON ACCELERATION IN E.P.W.

1D MODEL



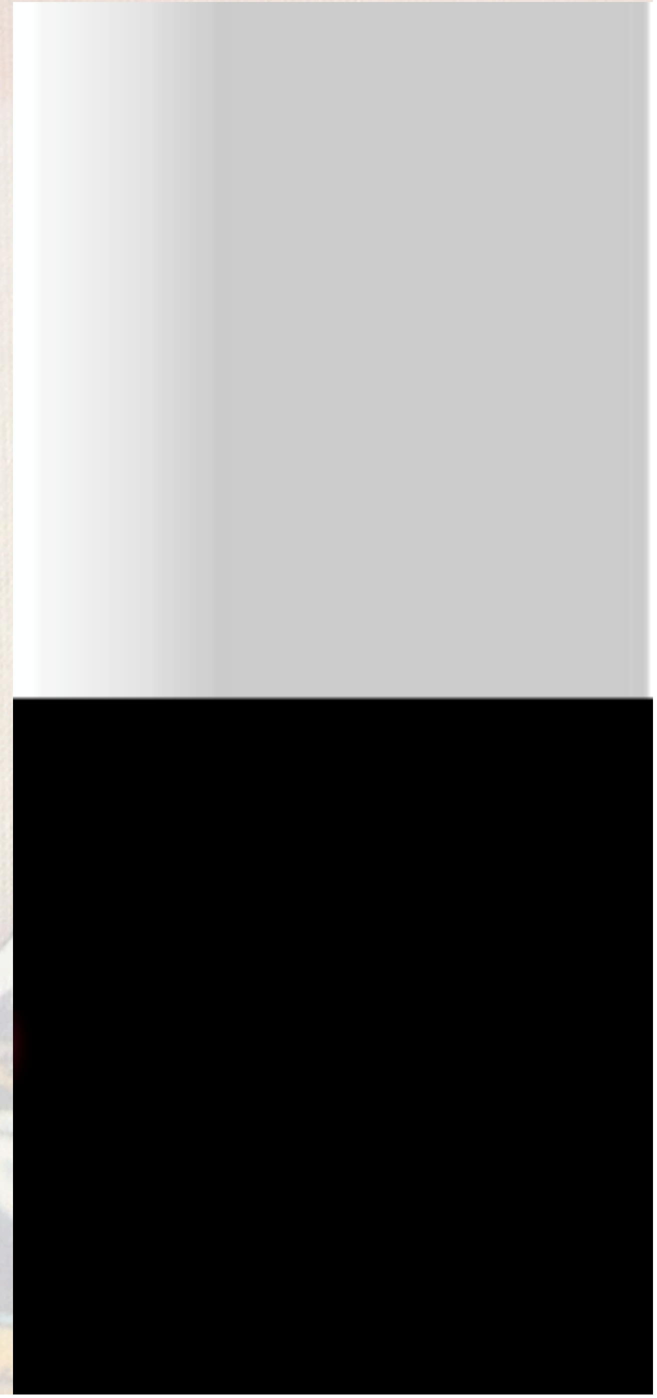
$$for\ \ \gamma_p \approx \frac{\omega}{\omega_{pe}} >> 1 \quad \Rightarrow \quad \Delta W_{\max} = 4\gamma_p^2 \frac{\delta n_e}{n_e} mc^2 \quad is\ \ the\ \ \max.\ energy\ \ gain$$

$$along\ \ a\ \ distance\ \ \ L_{deph} \approx \gamma_p^2 \lambda_p \qquad\qquad \lambda_p \approx \frac{2\pi c}{\omega_{pe}}$$

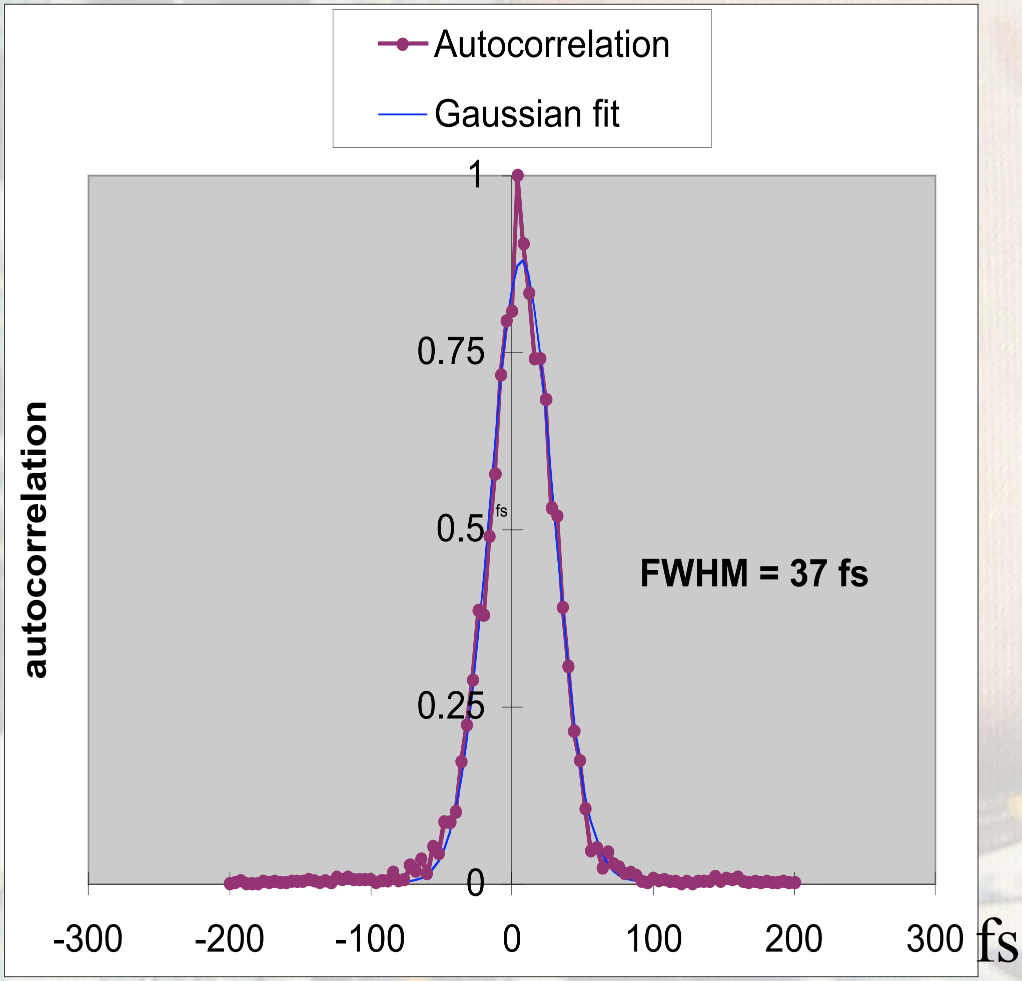
$$\Delta W_{\max} \approx eE_{\max} \cdot L_{deph} \propto n_e^{\frac{1}{2}} \cdot \frac{1}{n_e} \cdot n_e^{-\frac{1}{2}} = \frac{1}{n_e}$$

LWFA: 3D PIC SIMULATIO MOVIE

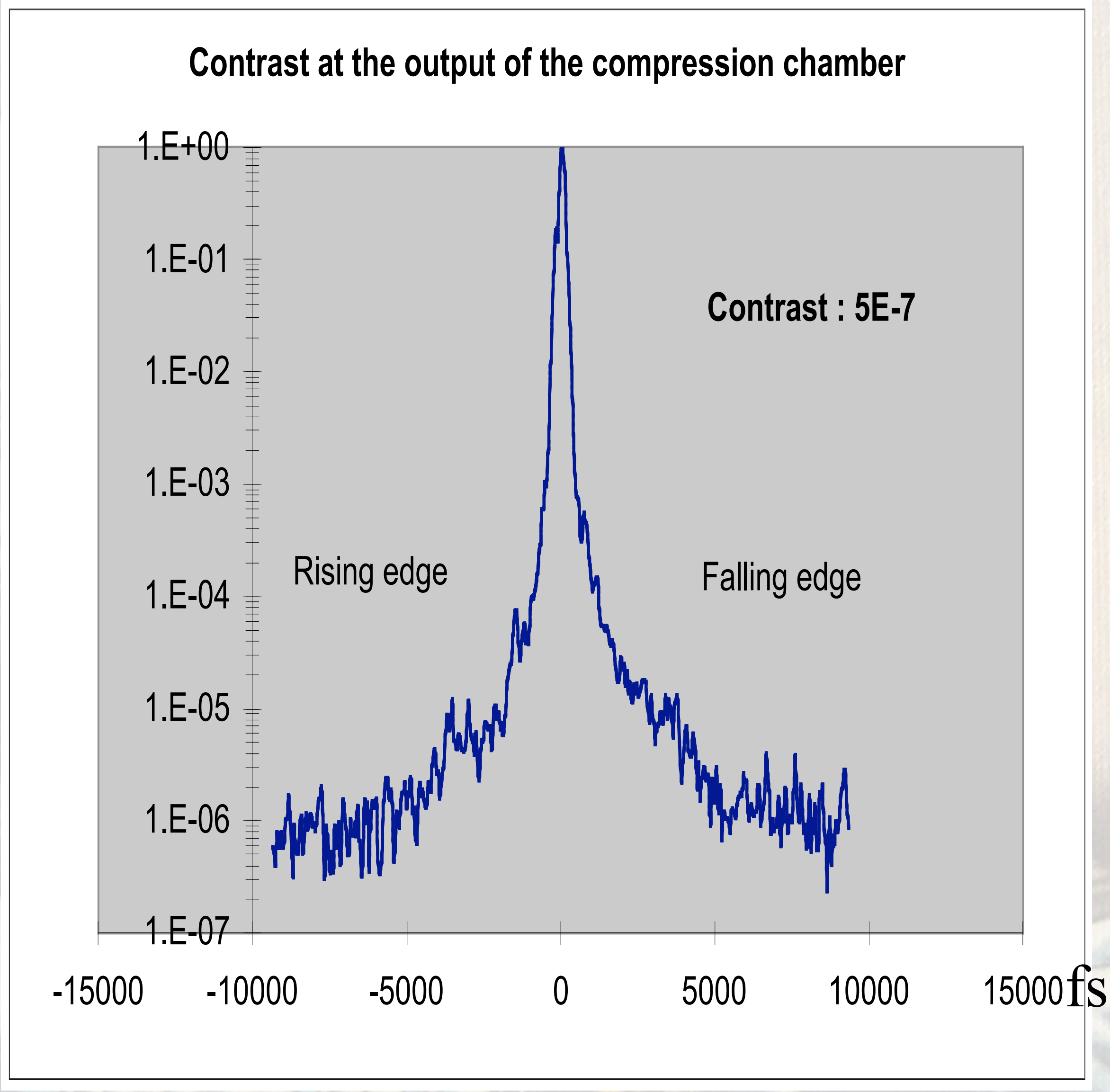
A "moving window" of a 30fs Ti:Sapphire laser pulse propagating in an unhomogeneous plasma (**40µm plateau** decreasing both sides with scale length of 10µm) whose maximum density is **4.3×10^{19}cm^{-3}**. The laser intensity **I=3.4×10^{19} W/cm^2** ($a \approx 4$) produces non-linear plasma waves of high amplitude $\delta n/n \approx a^2 >> 1$. A collimated beam of energetic electrons (up to 40MeV) is produced along the laser axis.



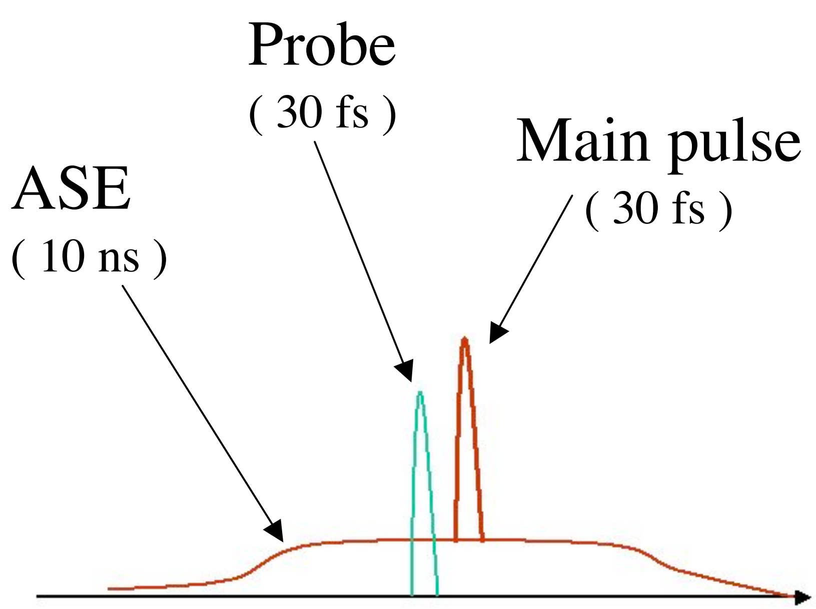
LOA Ti:Sapphire PULSE DURATION

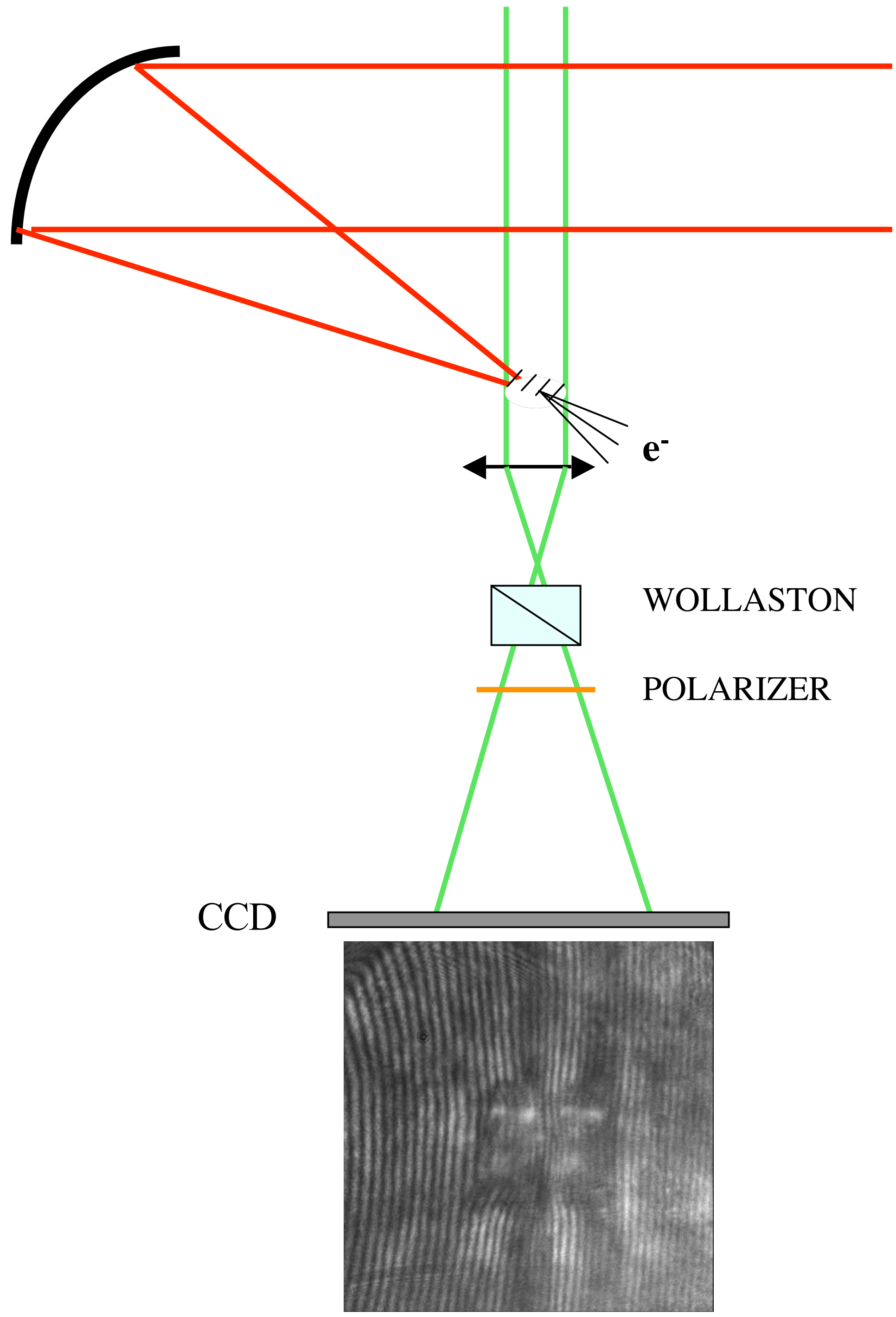


LOA Ti:Sapphire CONTRAST RATIO

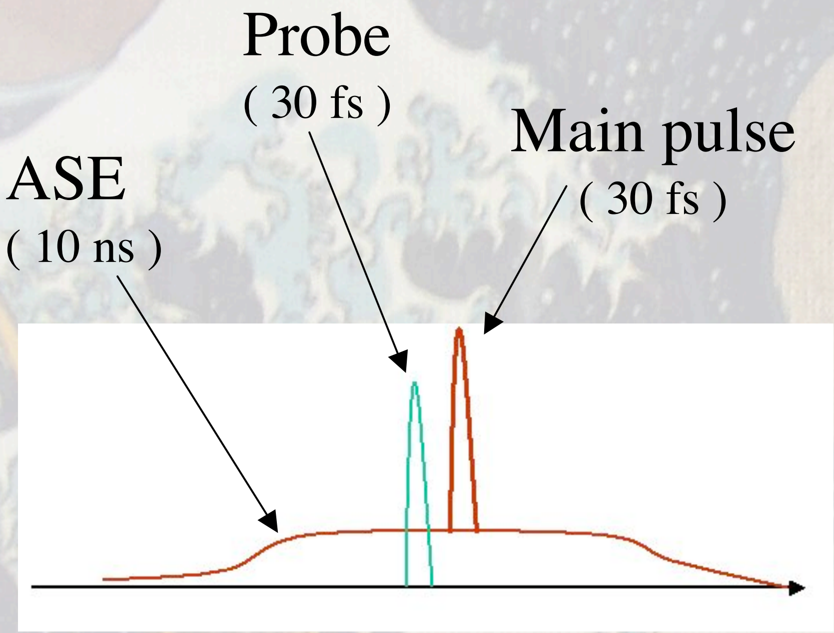


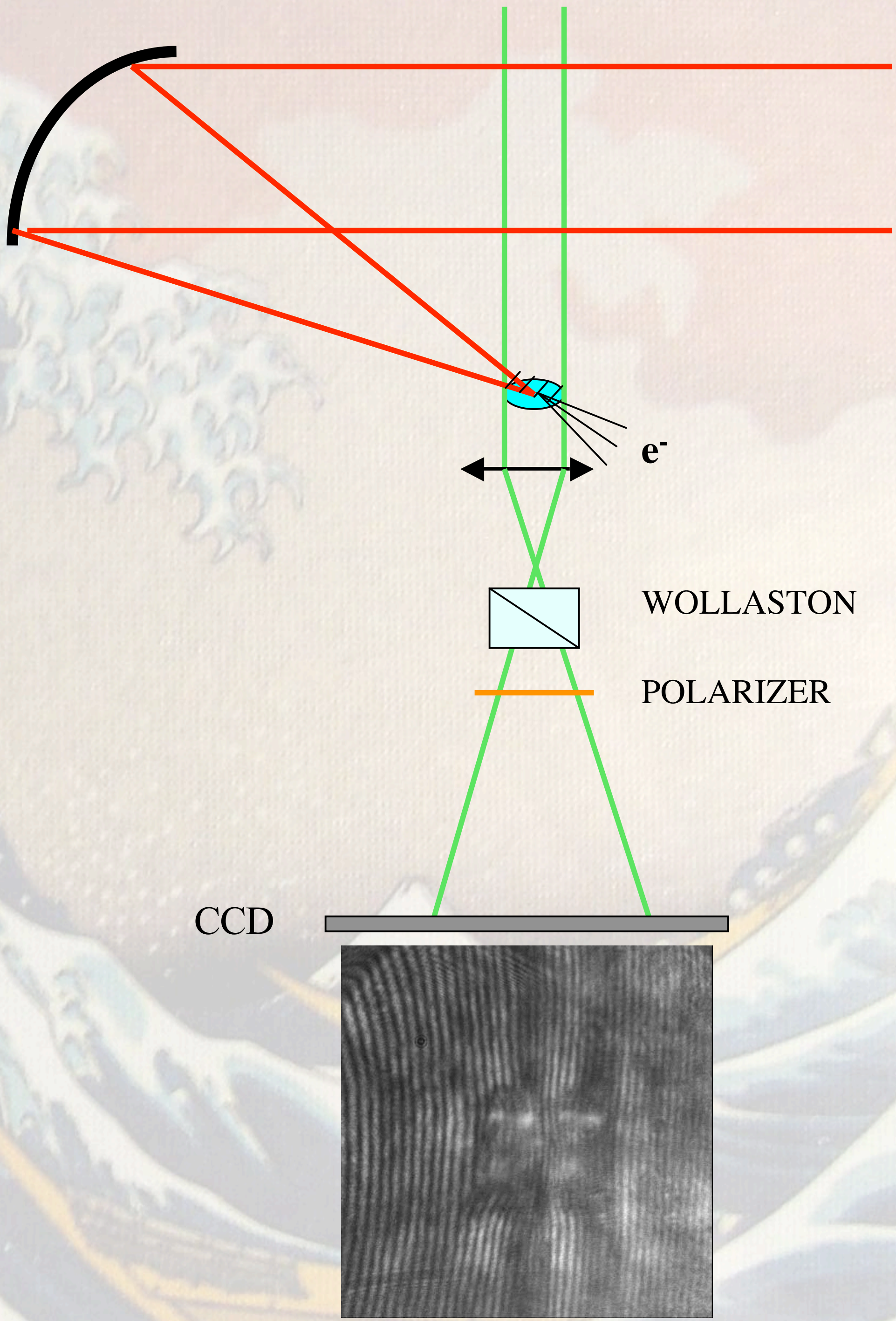
PULSE TIMING AND INTERFEROMETRY



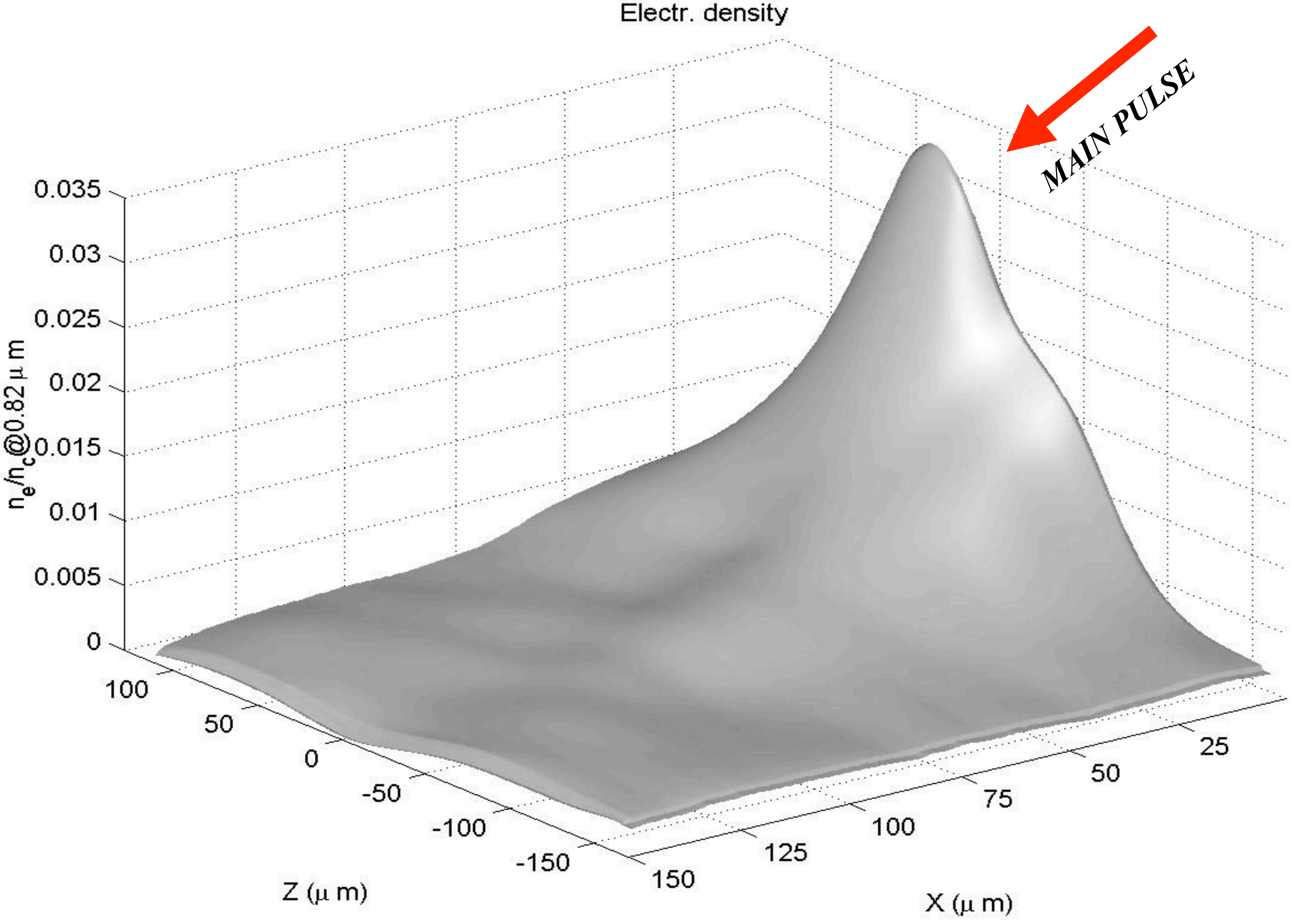


PULSE TIMING AND INTERFEROMETRY

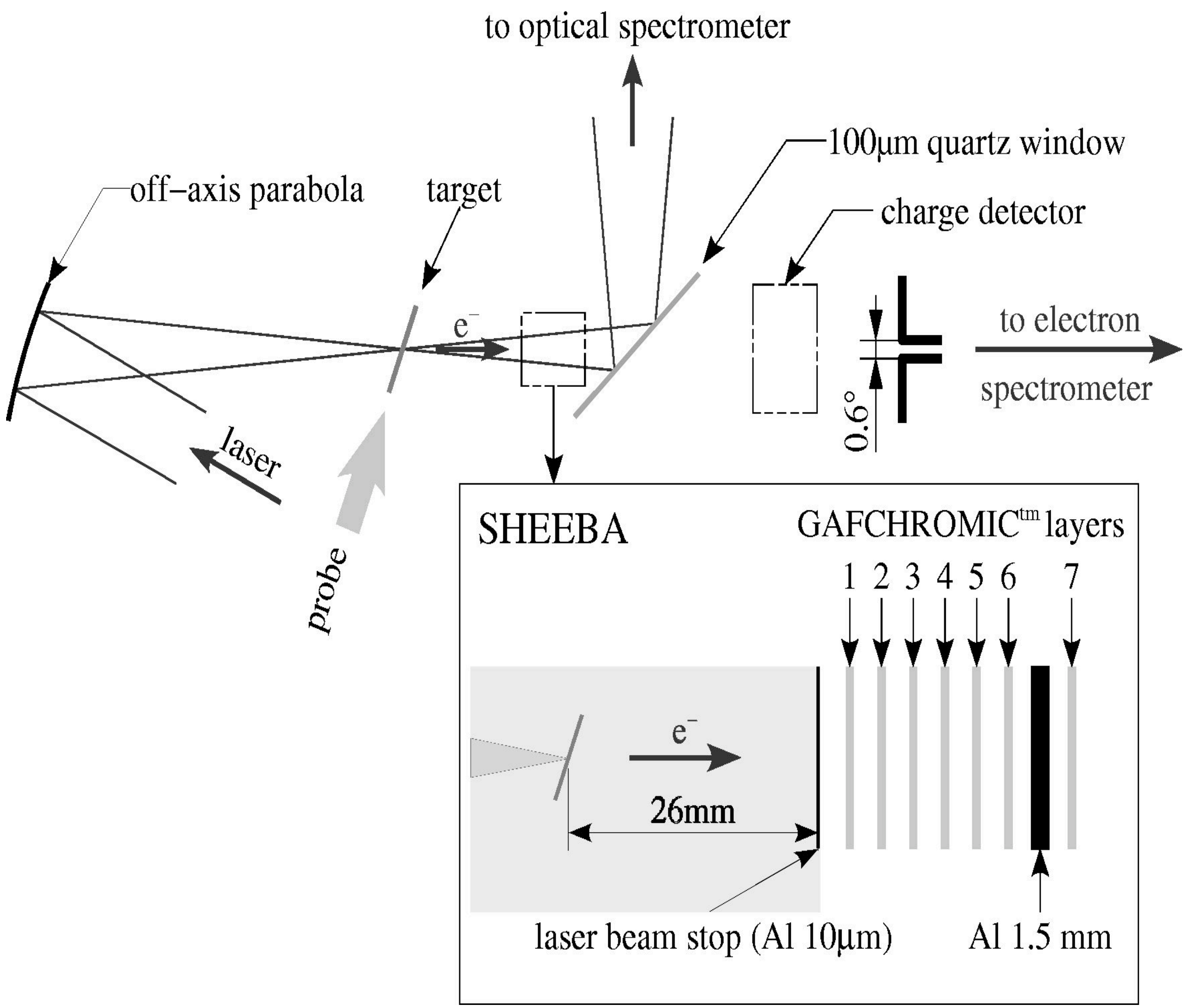




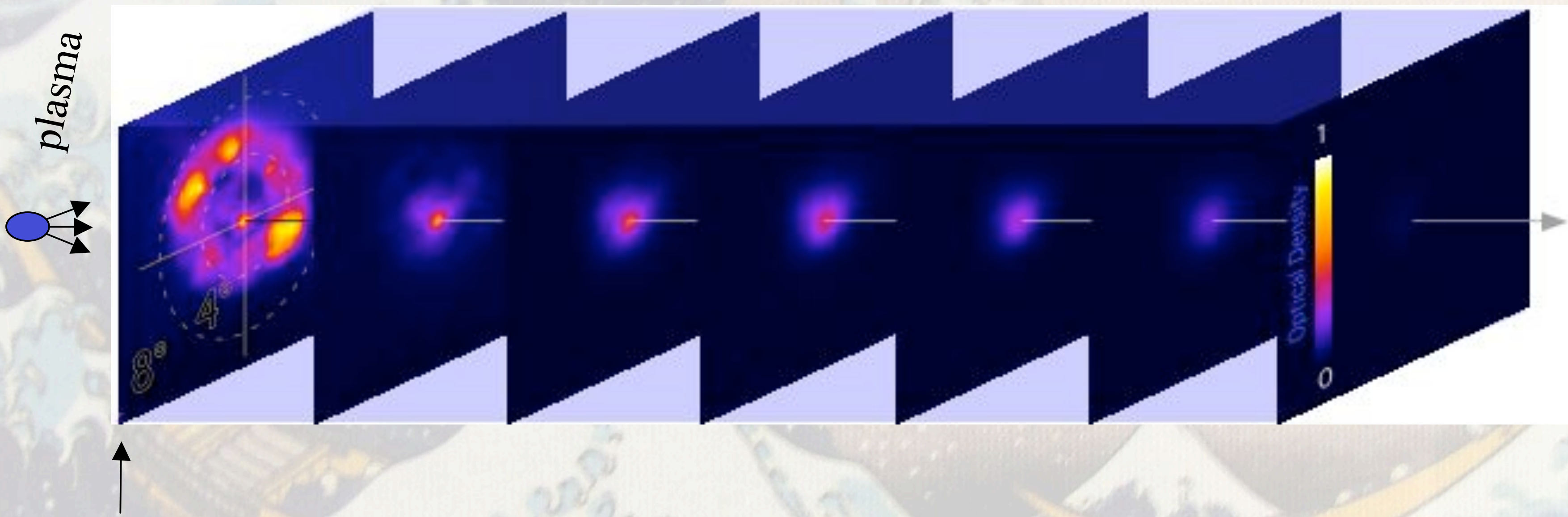
ELECTRON DENSITY PROFILE



Space Resolved Energy Spectrum of the Accelerated Electrons by Radiochromic Film Stack Detector



Angular distribution of accelerated electrons and a first estimation of their energy

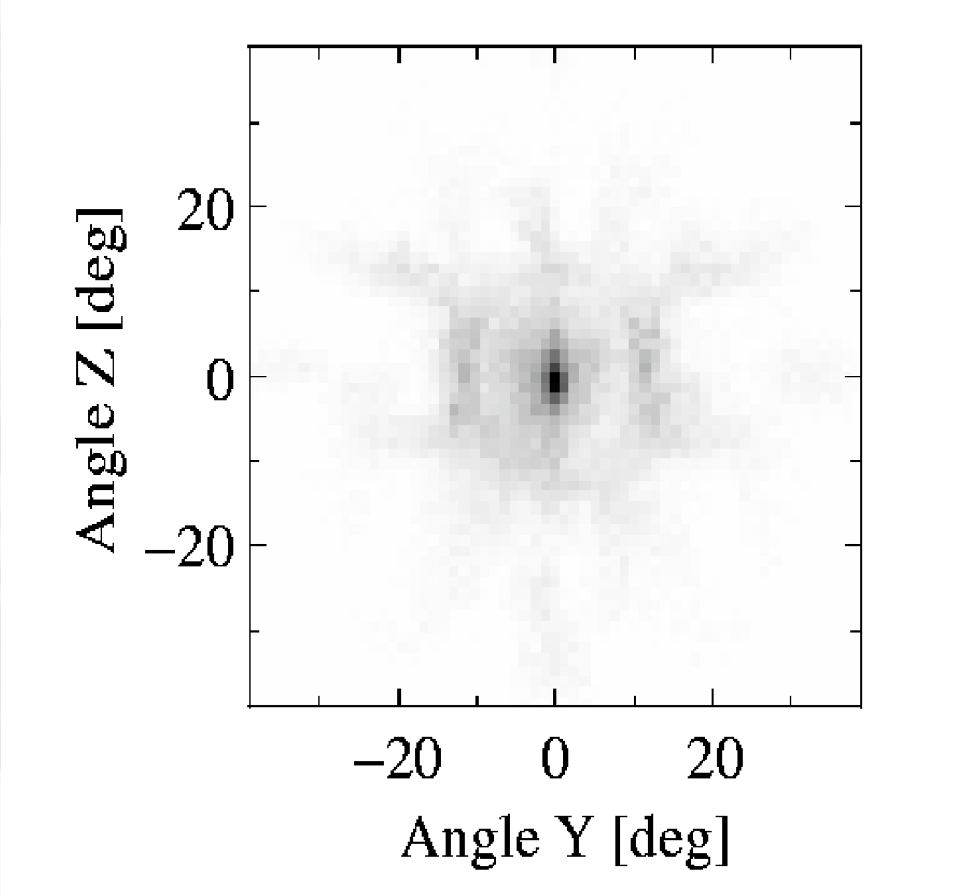


26 mm from the plasma

*This is **not** a simulation!*

Simulated angular distribution

This is a simulation!



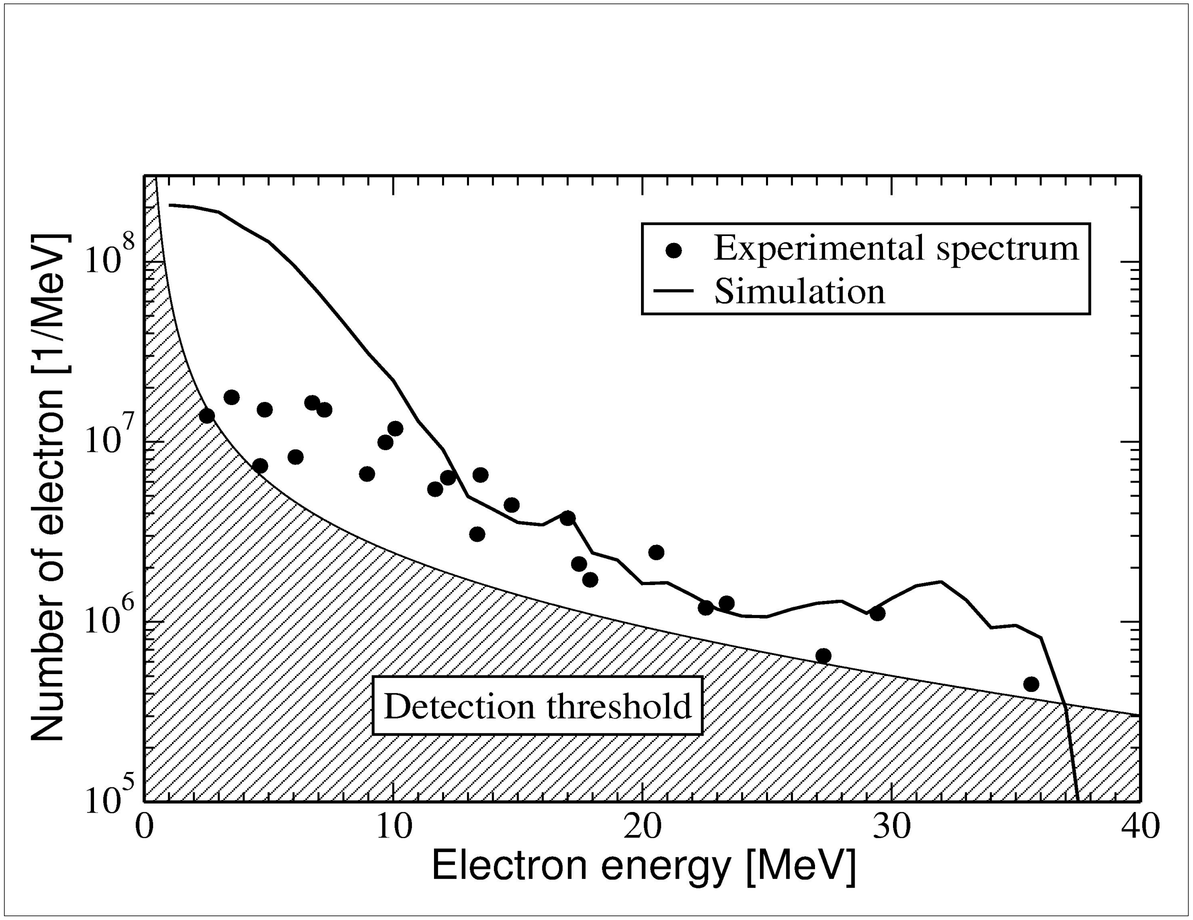
The pattern produced by the electrons accelerated forward on the first radiochromic film is simulated (3-D PIC) in the condition of our experiment (courtesy of Alexander Pukhov)

Total charge measurement

The number of high energy electrons emitted forward per shot was measured with a charge collector of aperture 7 degrees

0.2 nC per shot → 10^9 electrons/shot

High energy electron spectrum



The energy spectrum obtained with a specially designed electromagnet coupled with a set of four photodiodes is compared with the spectrum given by the 3D PIC code in the same conditions (Alexander Pukhov)

EXTENDING THE ACCELERATION LENGTH

in the most LWFA experiments

$$L_{acc} << L_{deph} \approx \gamma_p^2 \lambda_p$$

for LWFA to be effective

$$I = \frac{E_L}{\tau \pi w^2} \geq I_0 \Rightarrow w \leq \left(\frac{E_L}{\tau \pi I_0} \right)^{\frac{1}{2}} \Rightarrow L_{acc} = 2Z_R = \frac{2\pi w^2}{\lambda} \leq \frac{2E_L}{\tau \lambda I_0}$$

$$w = 1.22 \ \lambda \frac{f}{D} \ ; \ I_0 \ \textit{the intensity for which} \ \frac{\delta n_e}{n_e} \approx 1$$

LASER GUIDING

- Hollow fibers:

a few shots

- Relativistic Self-Focusing P(GW) > 17 n_c/n_e :

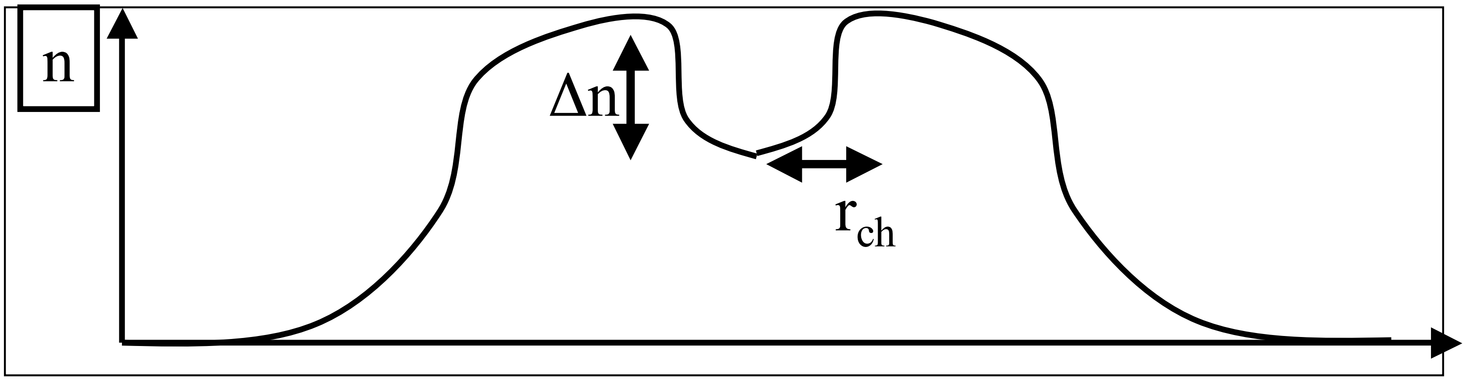
I, δn_e, L_{acc} increase, uncontrolled

- Pre-formed channel:

L_{acc} increase

PRE-FORMED CHANNEL (1)

- The laser pulse propagates in a plasma channel acting as a focusing lens that counter-balances the diffraction effects. For the optimal channel shape, laser pulses have been guided over distances exceeding $10Z_R$.



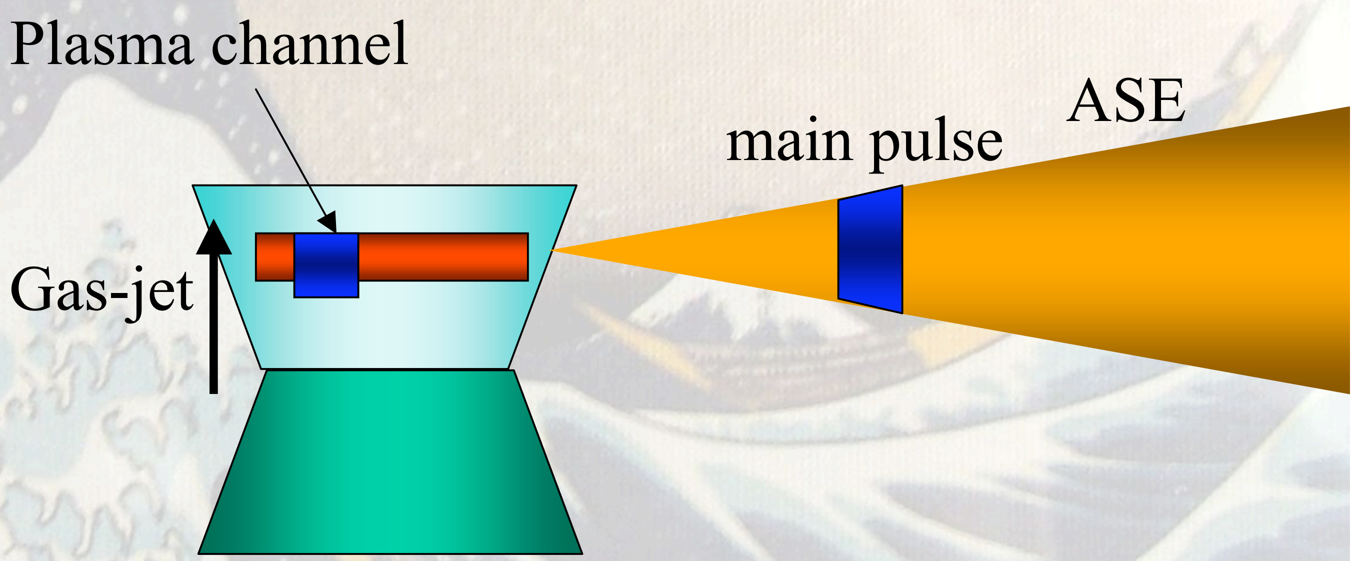
$$w_0 = \left[r_{ch}^2 / (\pi r_e \Delta n) \right]^{1/4} ; \quad r_e = e^2 / mc^2$$

- To pre-form the channel there are at least two experimental methods:

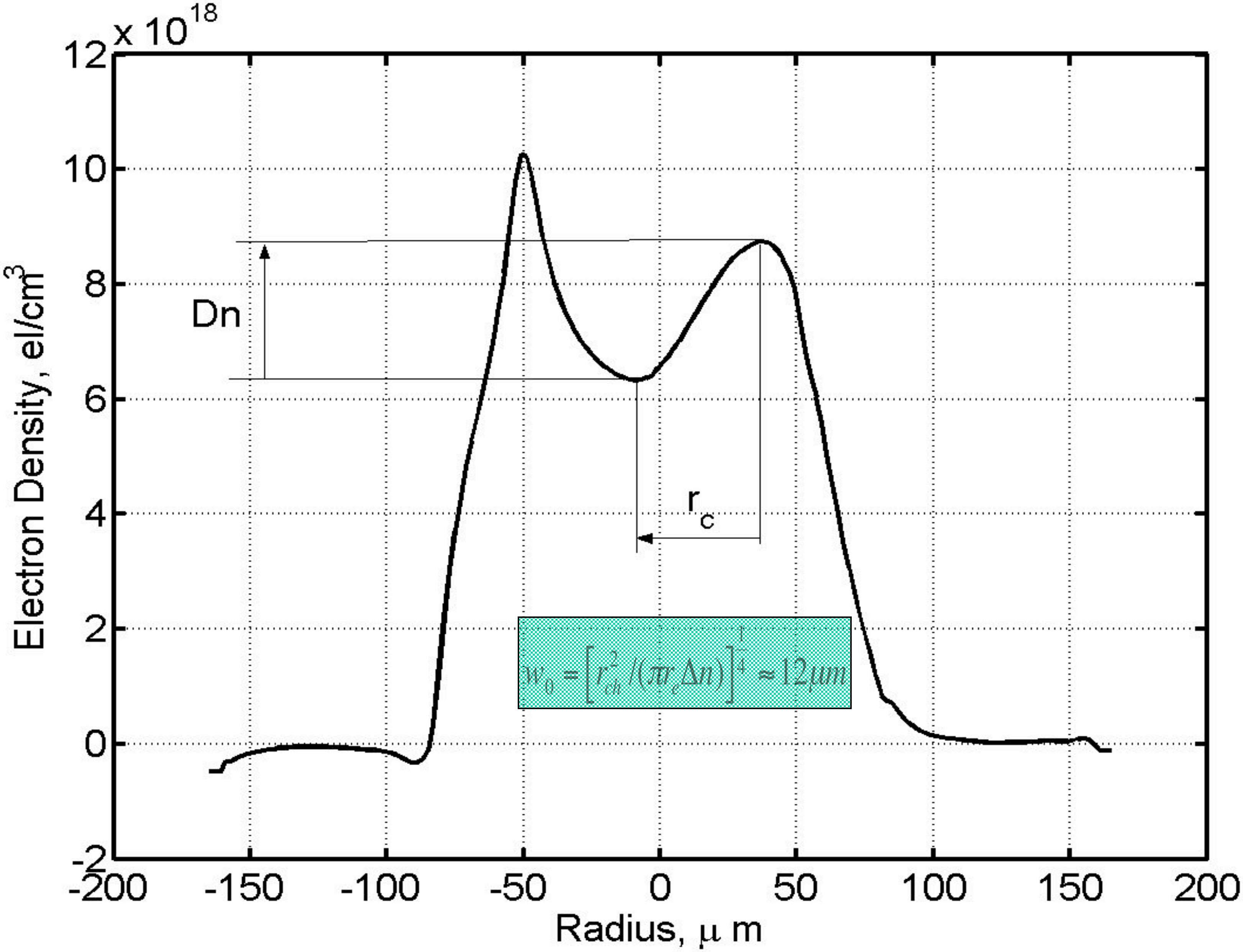
1. Gas discharge ; 2. Self focusing of nanosecond pulses in gas-jet

PRE-FORMED CHANNEL (2)

- A nanosecond pre-pulse (ASE of the Ti:Sapphire LASER) ionizes a gas-jet (He, Ar…) in the focal region. The pre-pulse self-focusing produces in the plasma a channel extending for several mm.



PRE-FORMED CHANNEL (3)



ELECTRON TRAPPING AND RELEASING IN THE ELECTRON PLASMA WAVE

The energy gain of the electrons depends on the conditions of their injection in the e.p.w. (v_{el}, ϕ_{el}) and those of their expulsion from the e.p.w.

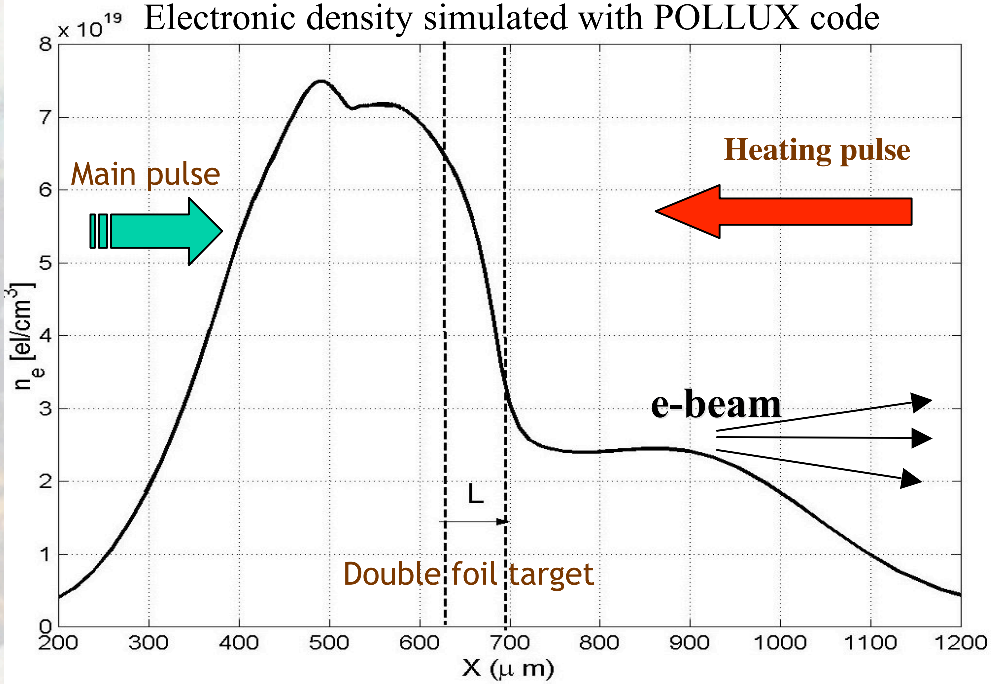
In the uncontrolled electron injection the energy spread of the accelerated electrons is $\approx 100\%$ ($\Delta W \approx 0 - \Delta W_{max}$)

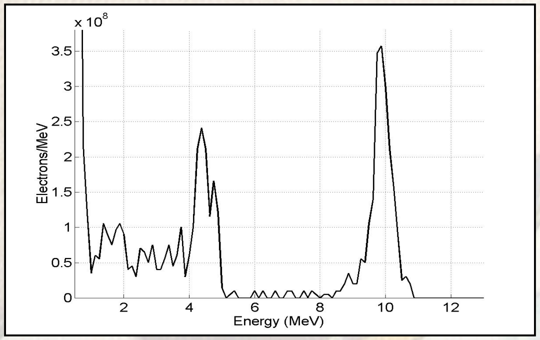
IMPROVING THE ENERGY SPREAD

- Controlled injection
- Injecting electron from a LINAC

Controlled injection

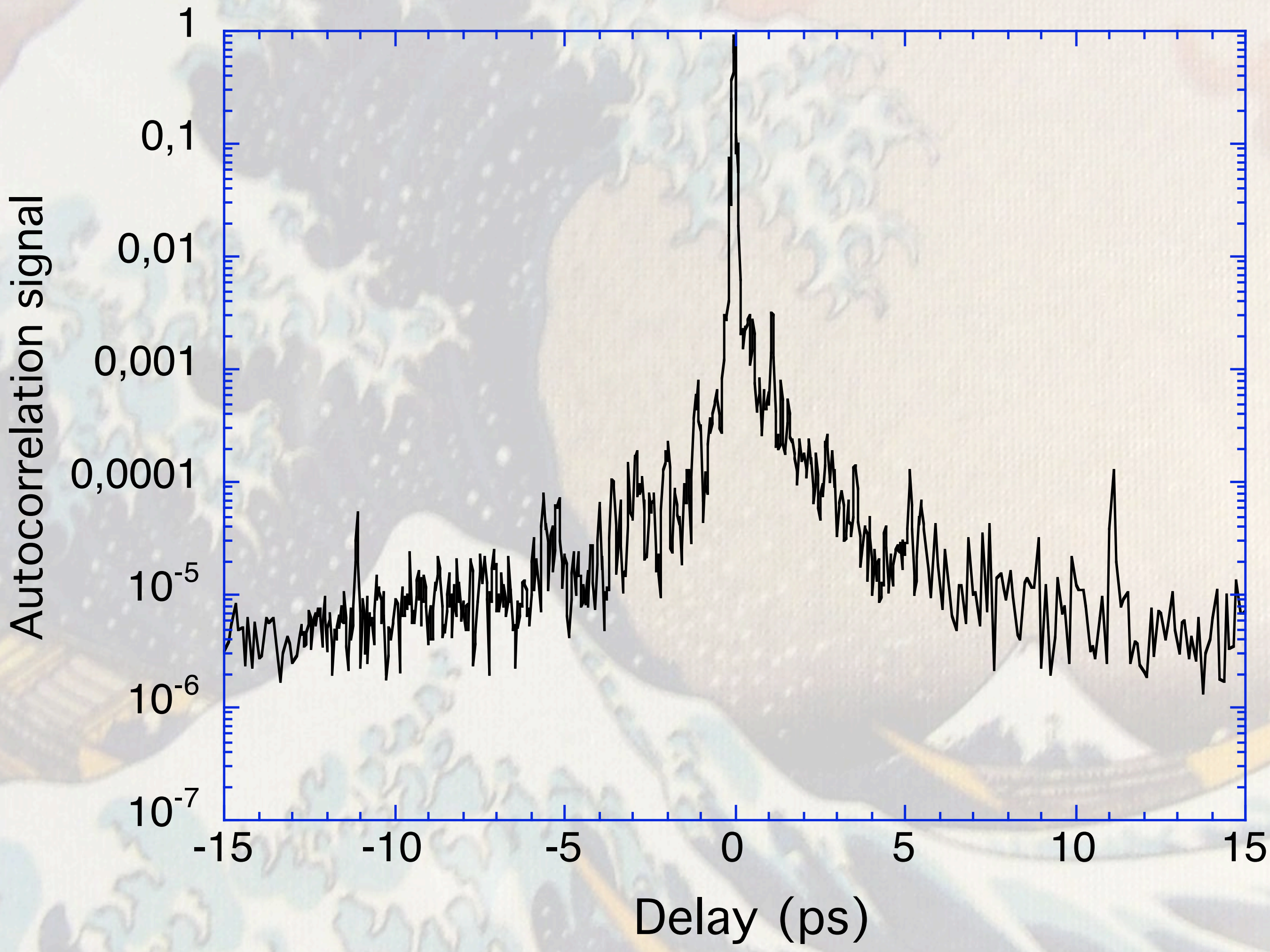
Controlled injection of electrons in Langmuir waves: a compact way of producing monoenergetic electron bunches (from an original idea of S. Bulanov et al PRL 1998)



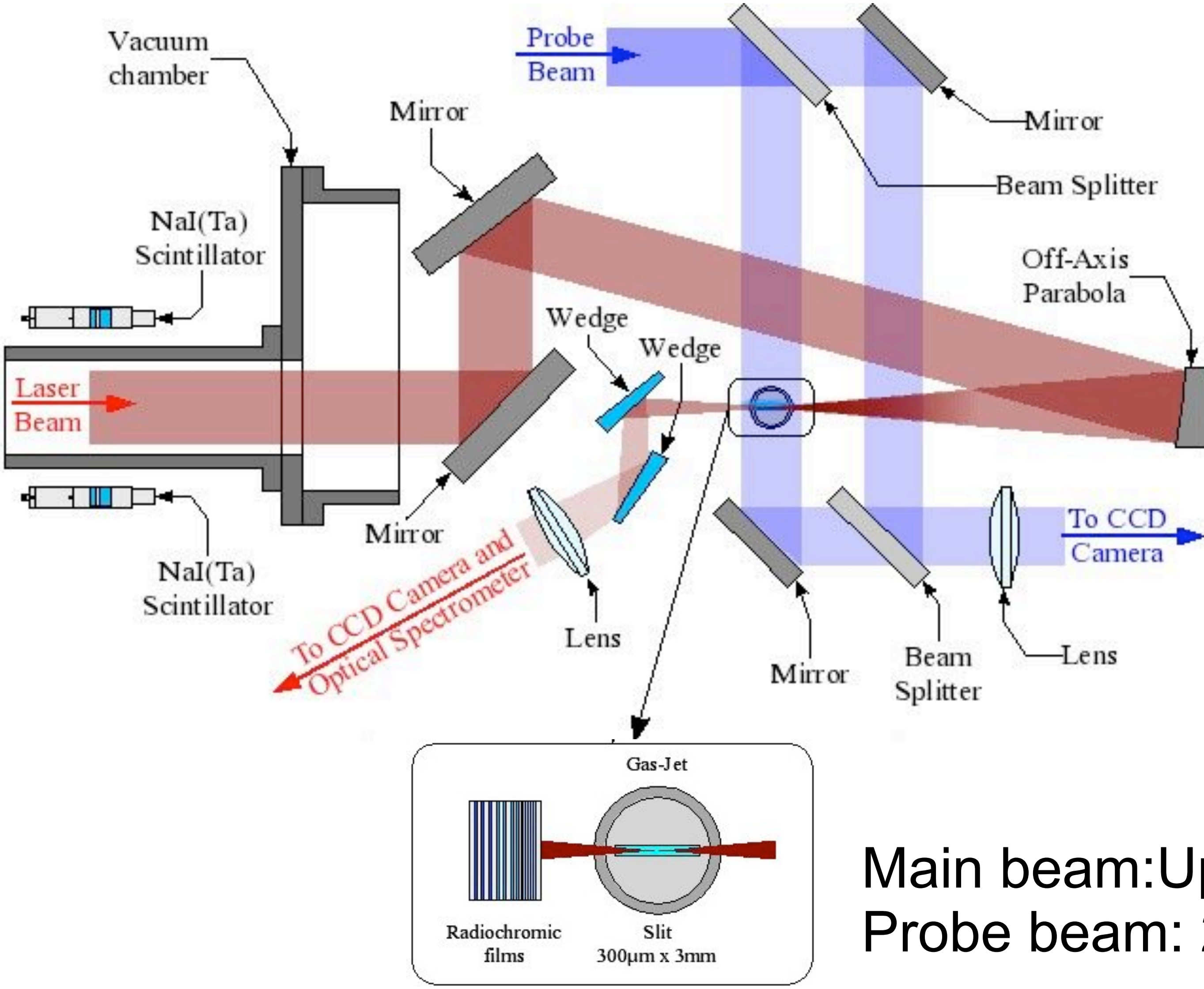


P. Tomassini, M. Galimberti, A.Giulietti, D. Giulietti, L.A.Gizzi, L.Labate, F. Pegoraro, *Production oh high quality* ...PRST, 6, 121301 (2003).

Third order autocorrelation of the SLIC laser pulse (CEA-Saclay)



An overview of the experiment (CEA-Saclay)



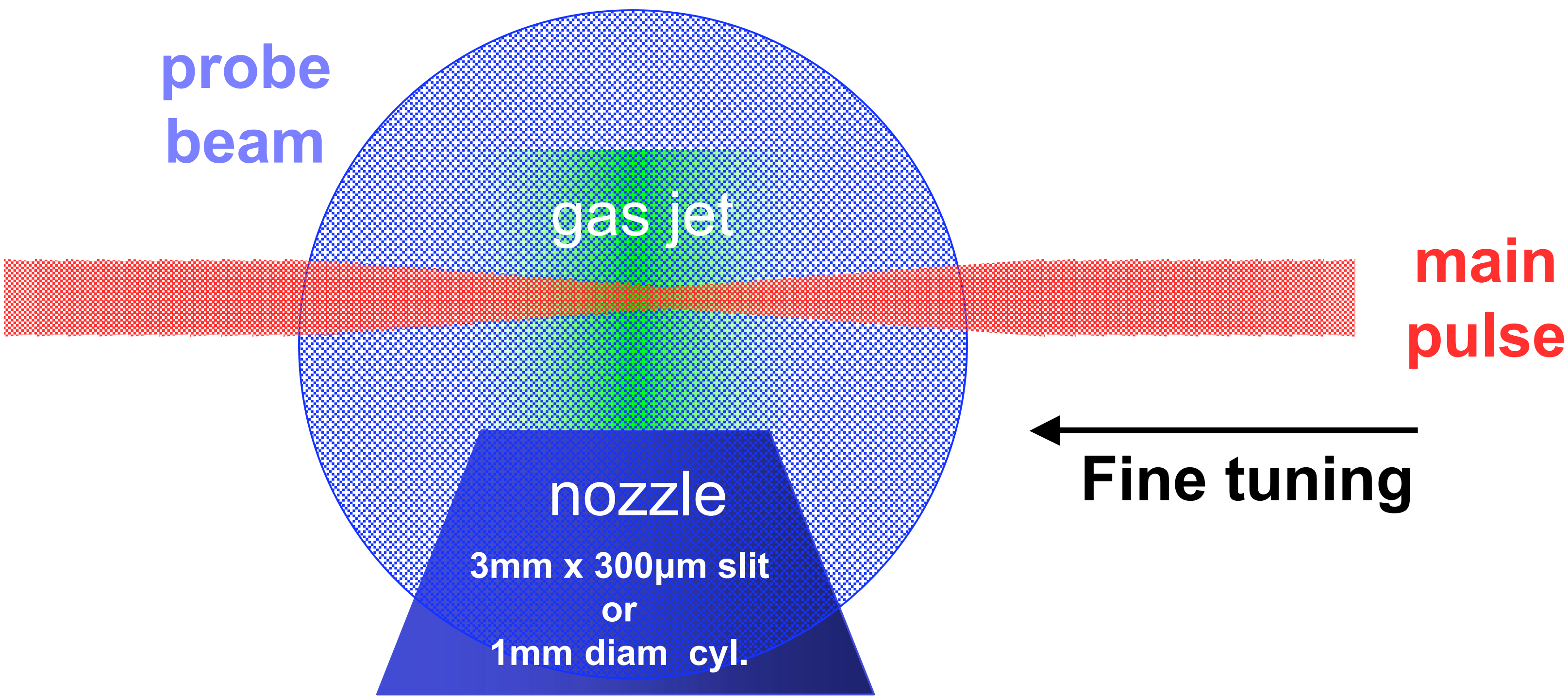
MAIN DIAGNOSTICS

- **Interferometer**
- **5,5μm/px and 1,64 μm/px**
- **Probe pulse duration (70-80 fs)**
- **Transmitted beam measurements (image and spectrum**
- **γ-ray detectors (NaI+PM)**
- **Radiochromic film detector (SHEEBA)**

Main beam:Up to 0.7 J, 65 fs
Probe beam: 2ω

The interaction geometry

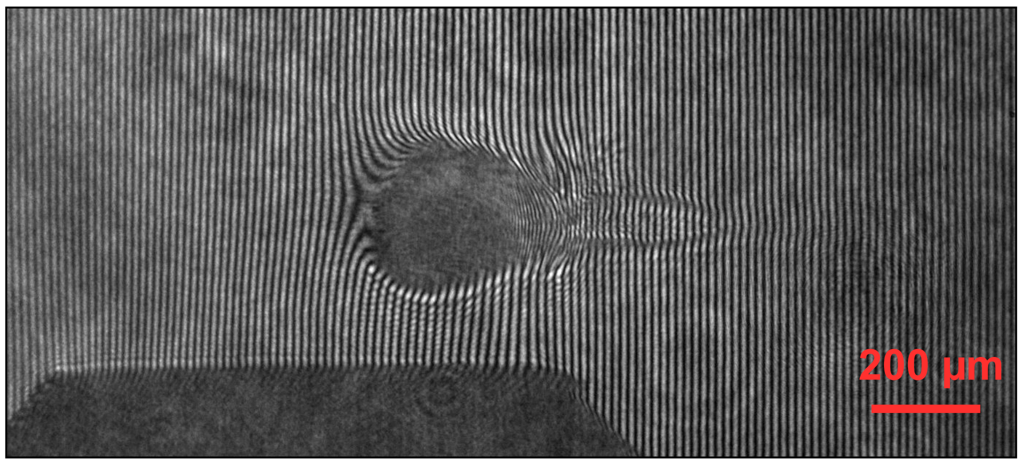
The position of the focus relative to the jet is a critical parameter



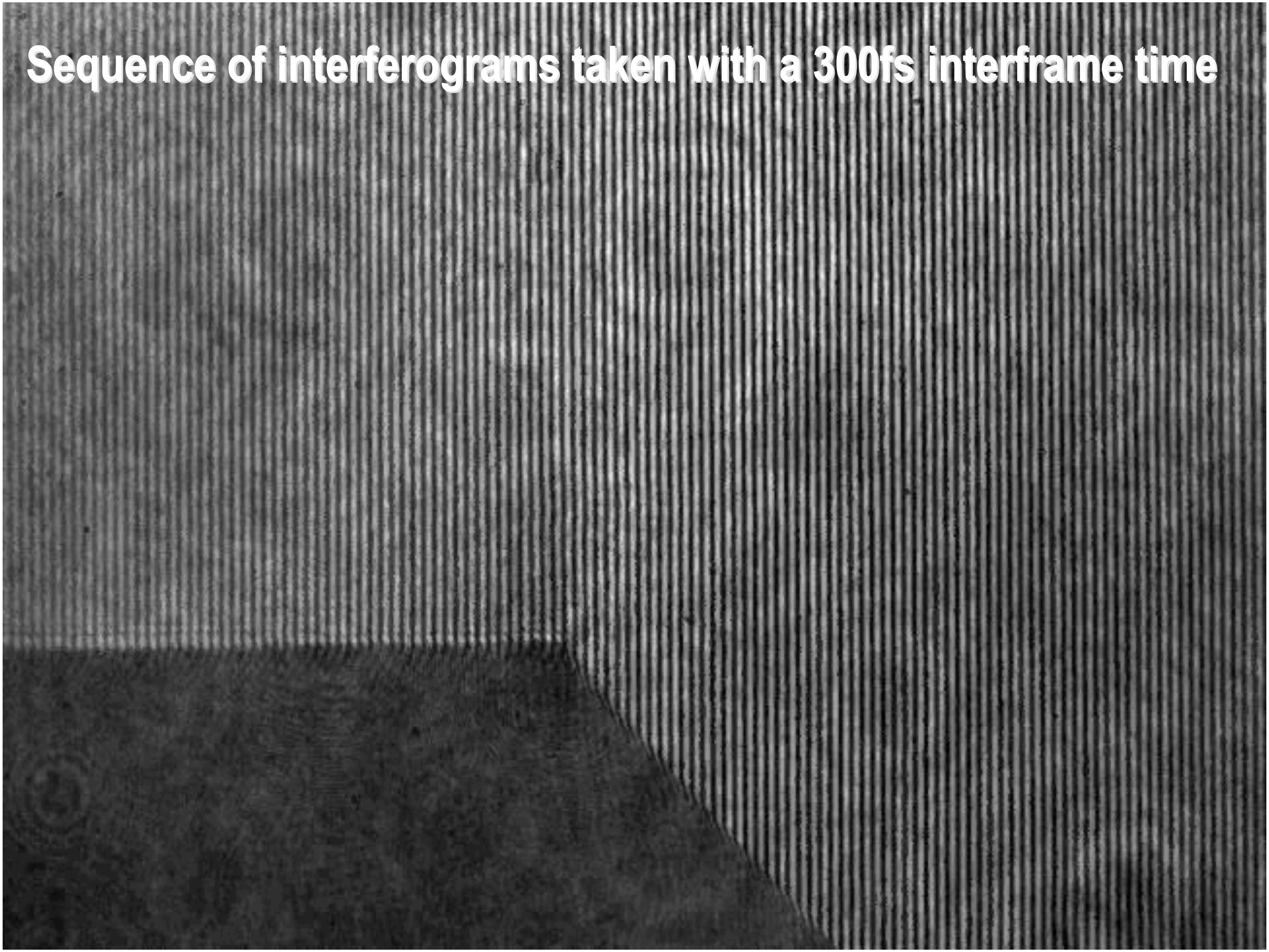
Energetic electron production

Correlation with plasma dynamics

Depending on the relative position of best focus and gas jet, early ionisation may take place due to Amplified Spontaneous Emission.

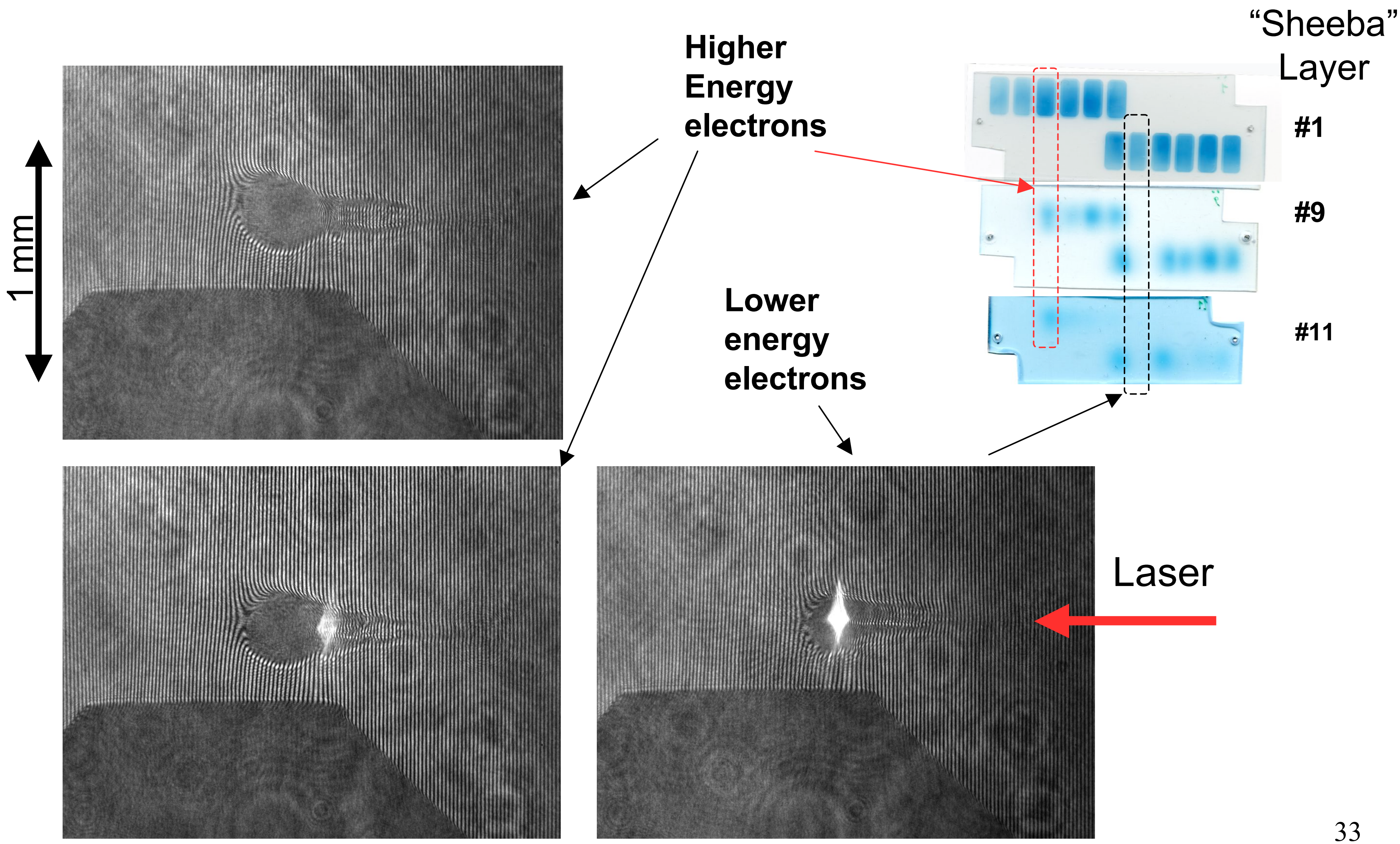


Simultaneous detection of electron energy spectrum and plasma interferometry enabled us to identify the role of ASE


Sequence of interferograms taken with a 300fs interframe time

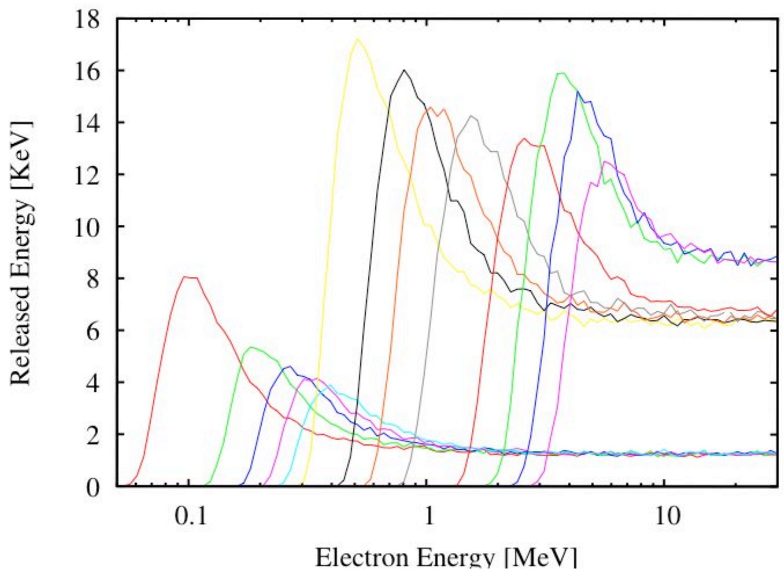
Energetic electron production

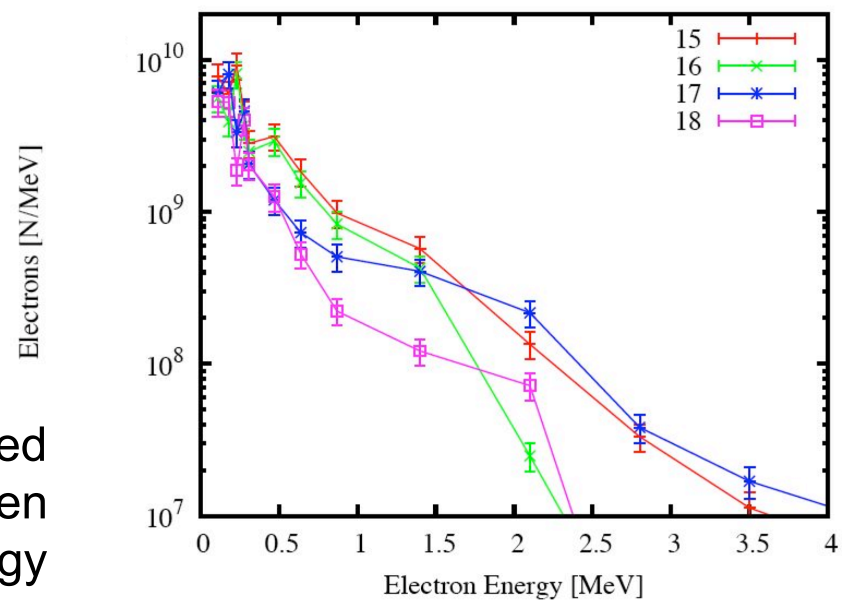
Correlation with plasma shape



Montecarlo Simulation of e-beam detector

A plot of the released energy as a function of the incident electron energy is calculated for each layer of the detector





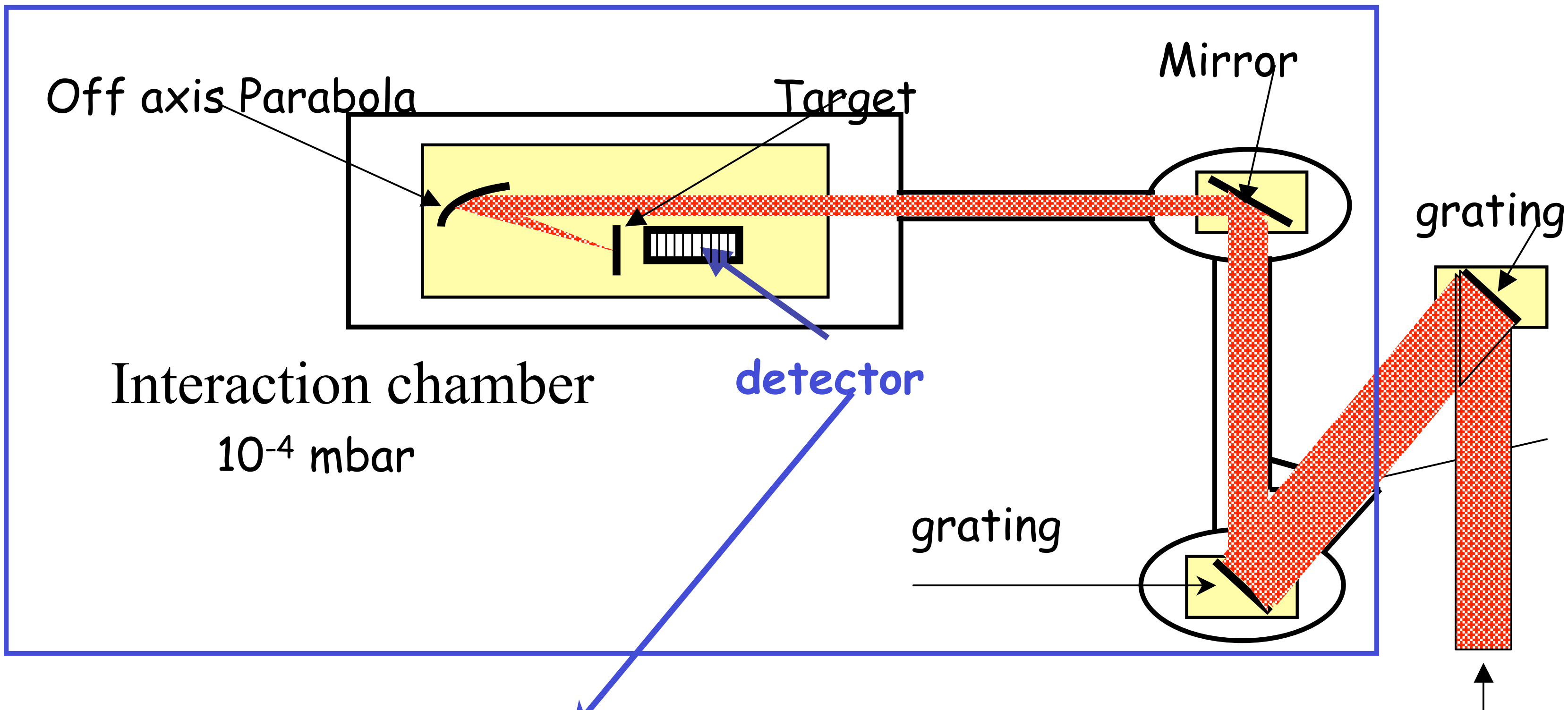
The measured dose (obtained scanning the films) is then converted into electron energy distribution.

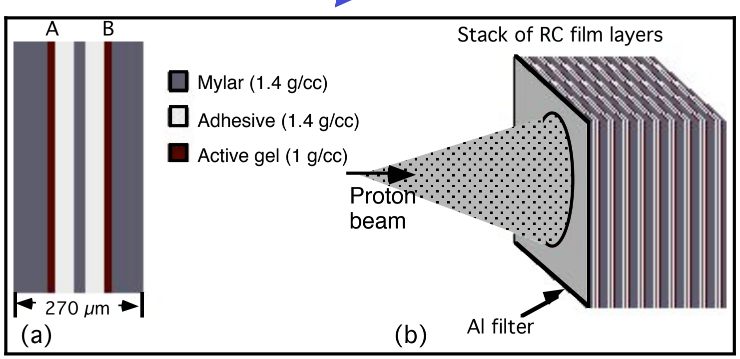
PROTON BEAMS IN LASER-MATTER INTERACTIONS

After the production of the energetic electron beam, the Coulomb force accelerates protons and ions up to energies of 10-50 MeV

Experimental set-up (CLF @ RAL)

in collaboration with Marco Borghesi Q.U. Belfast





laser

λ=1,053 μm

$I_L \sim 5 \times 10^{19}$ Wcm^{-2}

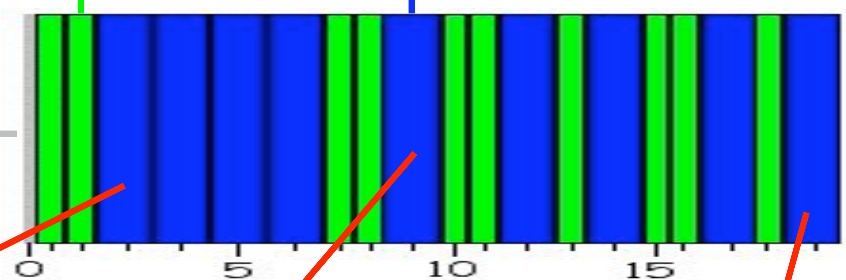
Raw data

Target ⇨ Al foil 250 μm thick

Detector

Mylar filter, ~ 175 μm

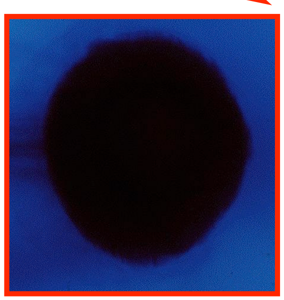
RCF film, ~ 270 μm



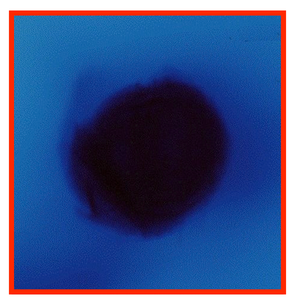
Al foil, ~ 25 μm;

filter for:

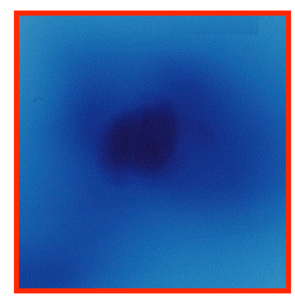
- X-ray emission
- Target fragments
- Ions emitted



Film n°3



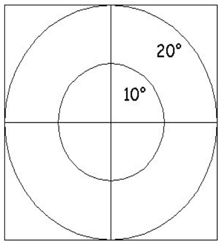
Film n°9

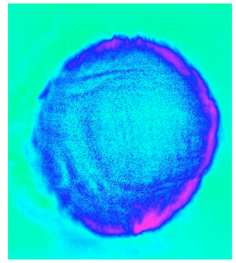


Film n°17

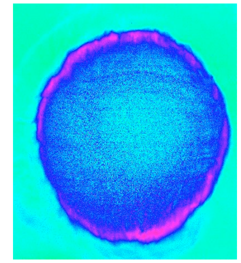
Spectral distributions

Typical anular structures

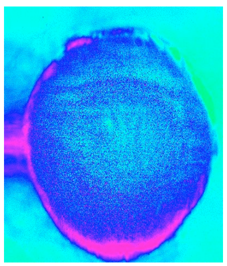




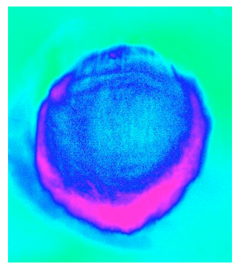
E_1 = 10.3 MeV



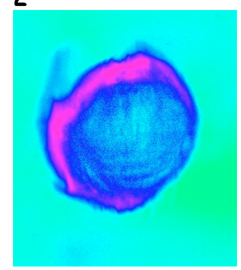
E_2 = 11.8 MeV



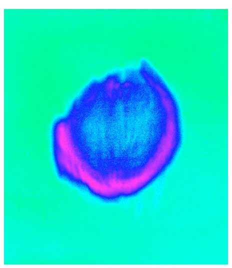
E_3 = 13.2 MeV



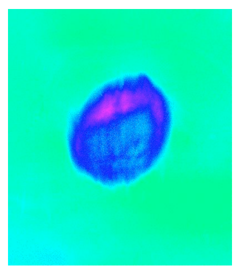
E_4 = 14.7 MeV



E_5 = 17.3 MeV



E_6 = 19.5 MeV



E_7 = 21.1 MeV

E_8 = 23 MeV

Angular divergence decreases as proton energy increases.

Applications [1]

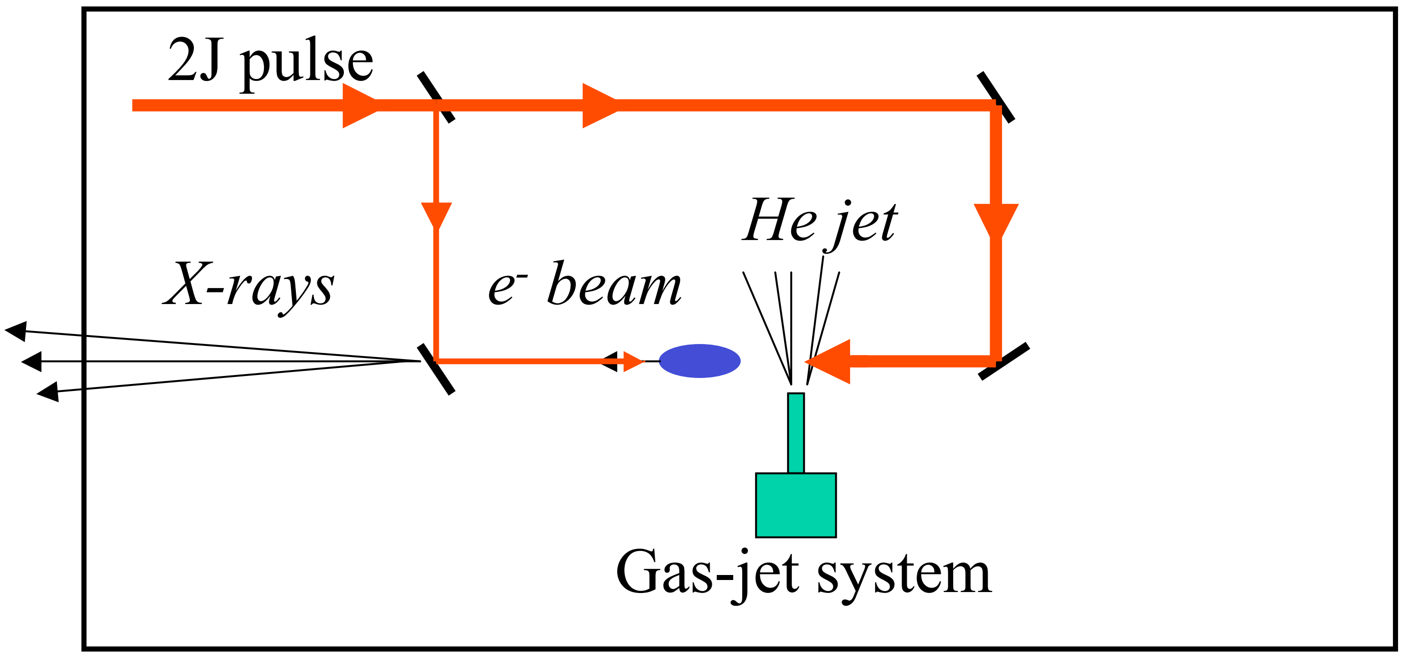
Table top pulsed source of energetic electrons, protons, ions:

➔ as injector for conventional accelerators

➔ for radio-nuclide activation

Applications [2]

- **TABLE-TOP** source of ***femtosecond X-rays*** via **Thomson back-scattering** of an ultrashort pulse on the accelerated electrons:



THE JOINT PROJECT INFN-CNR PLASMONX*

PlASma acceleration and **MON**ochromatic **X**-ray production

D. Giulietti, **Univ. di Pisa e INFN-Pisa**

ILIL team @ **CNR/IPCF - Pisa**

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P.Musumeci
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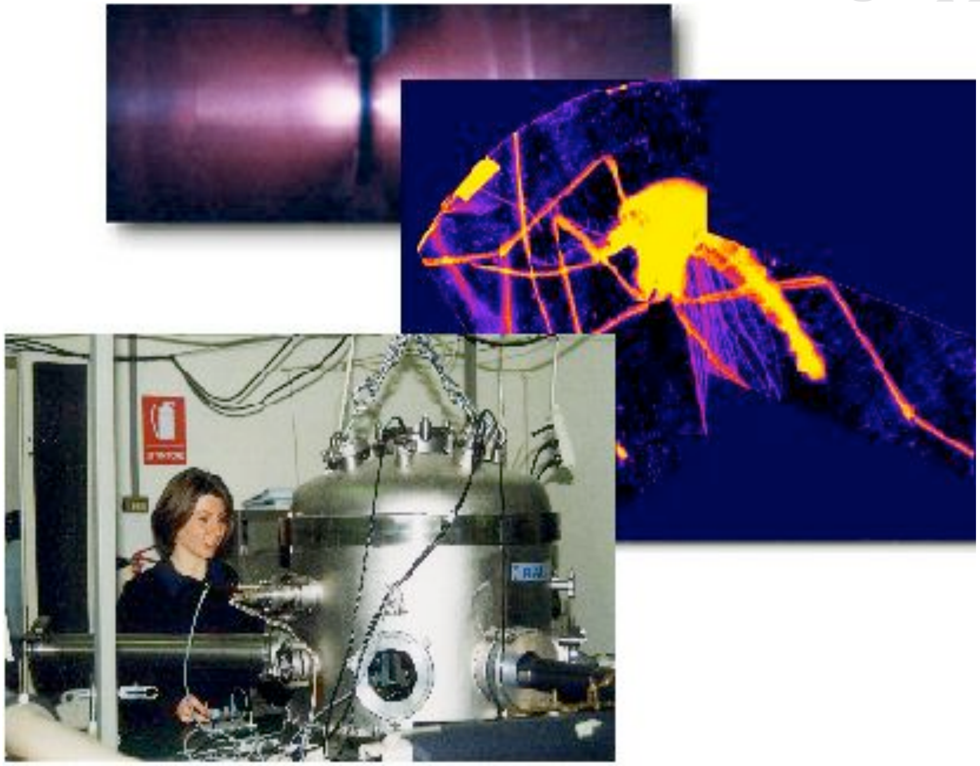
*FUNDED BY INFN IN THE FRAME OF THE PROGETTI SPECIALI: NUOVE TECNICHE DI ACCELERAZIONE

Il gruppo ILIL



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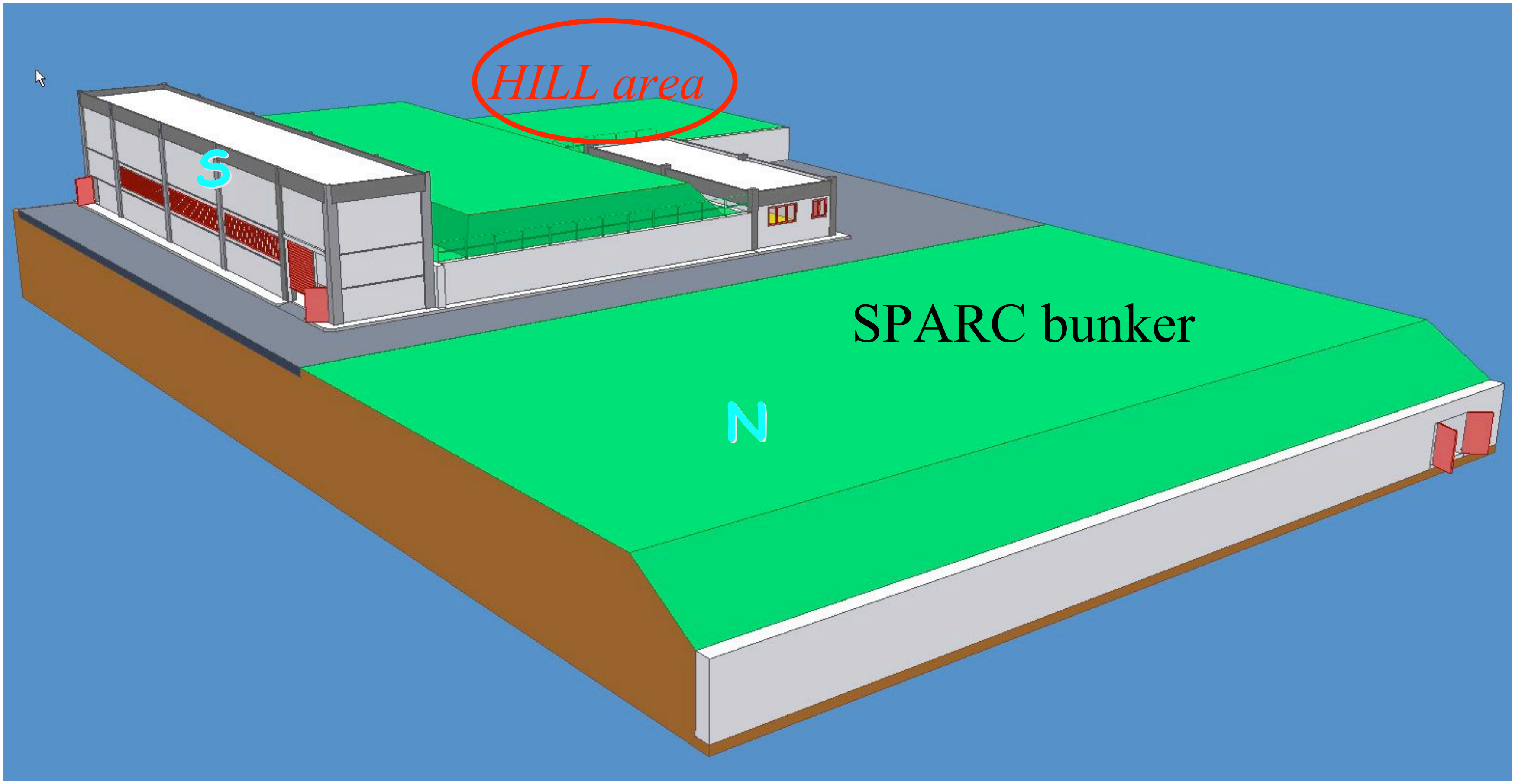
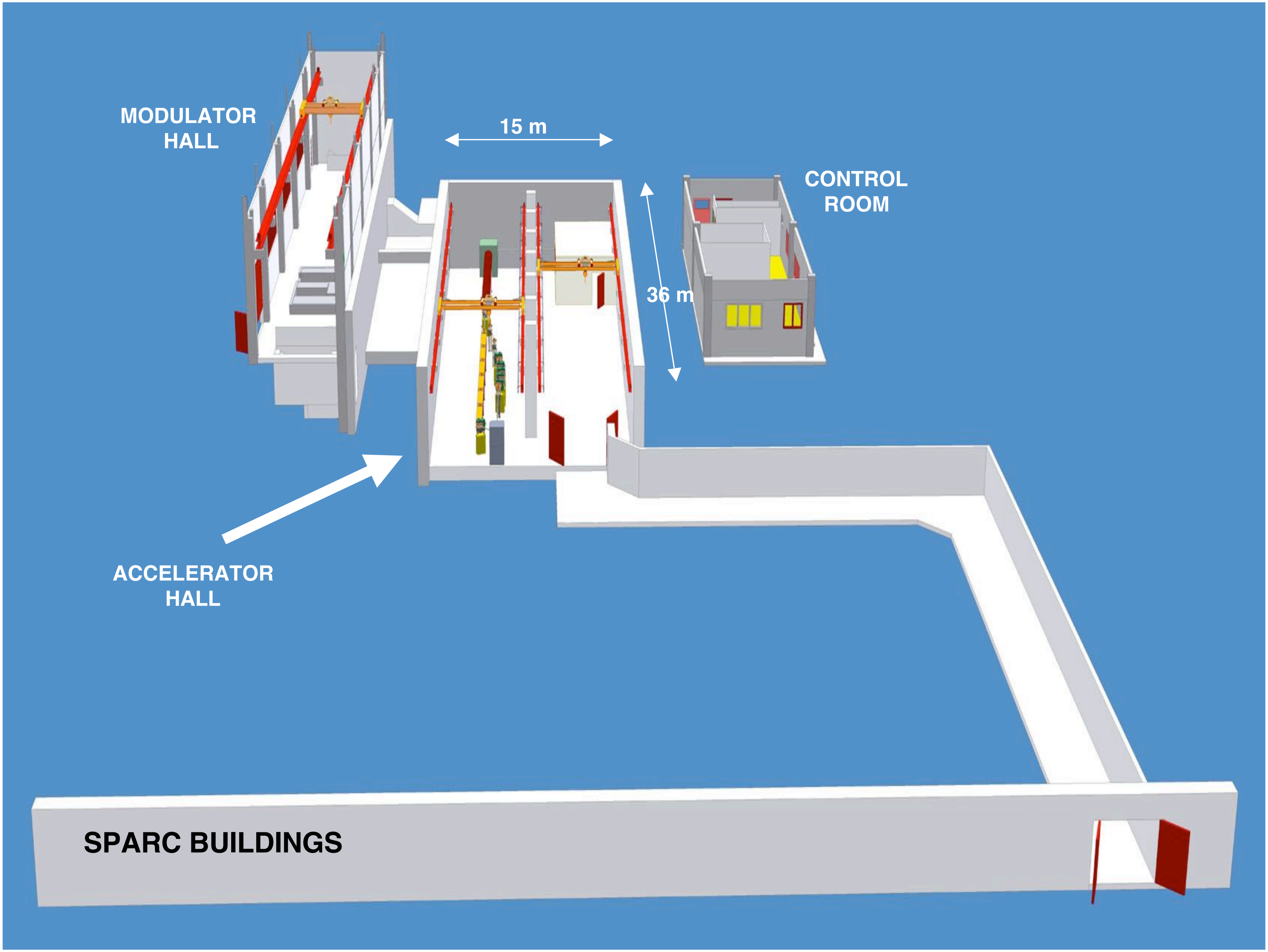
Laboratori Nazionali di Frascati

HILL@LNF

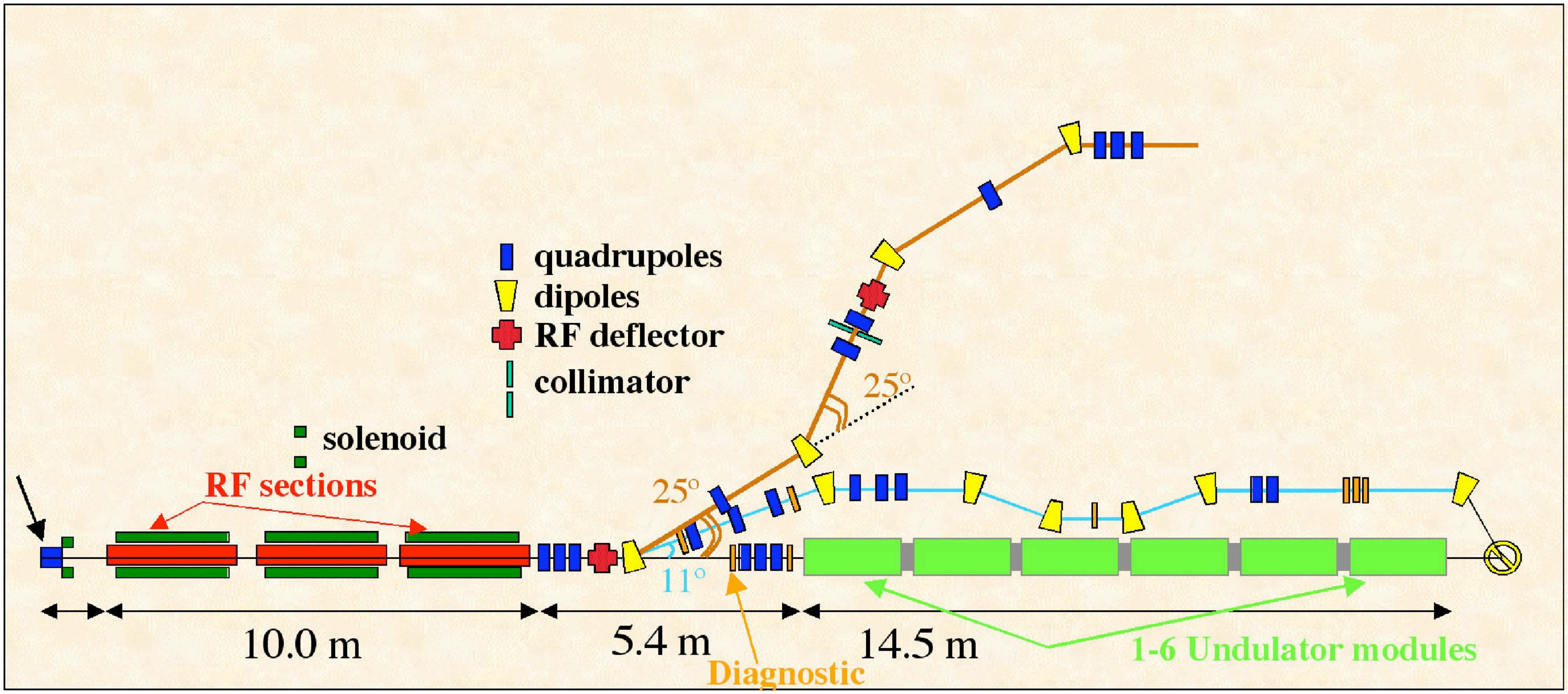
(High-Intensity Laser Laboratory @ LNF)



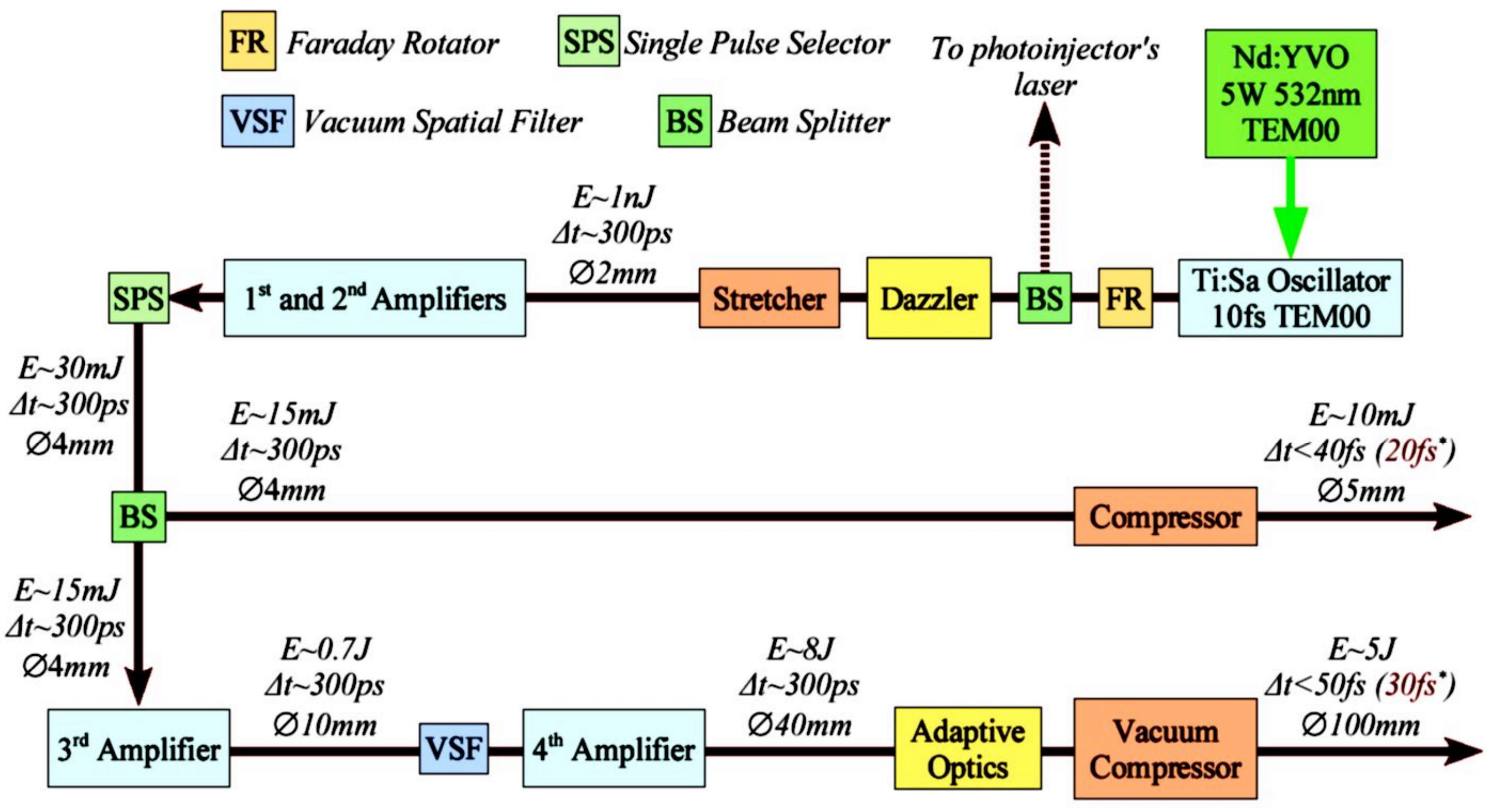
HILL location


MODULATOR
HALL
15 m
CONTROL
ROOM
36 m
ACCELERATOR
HALL
SPARC BUILDINGS

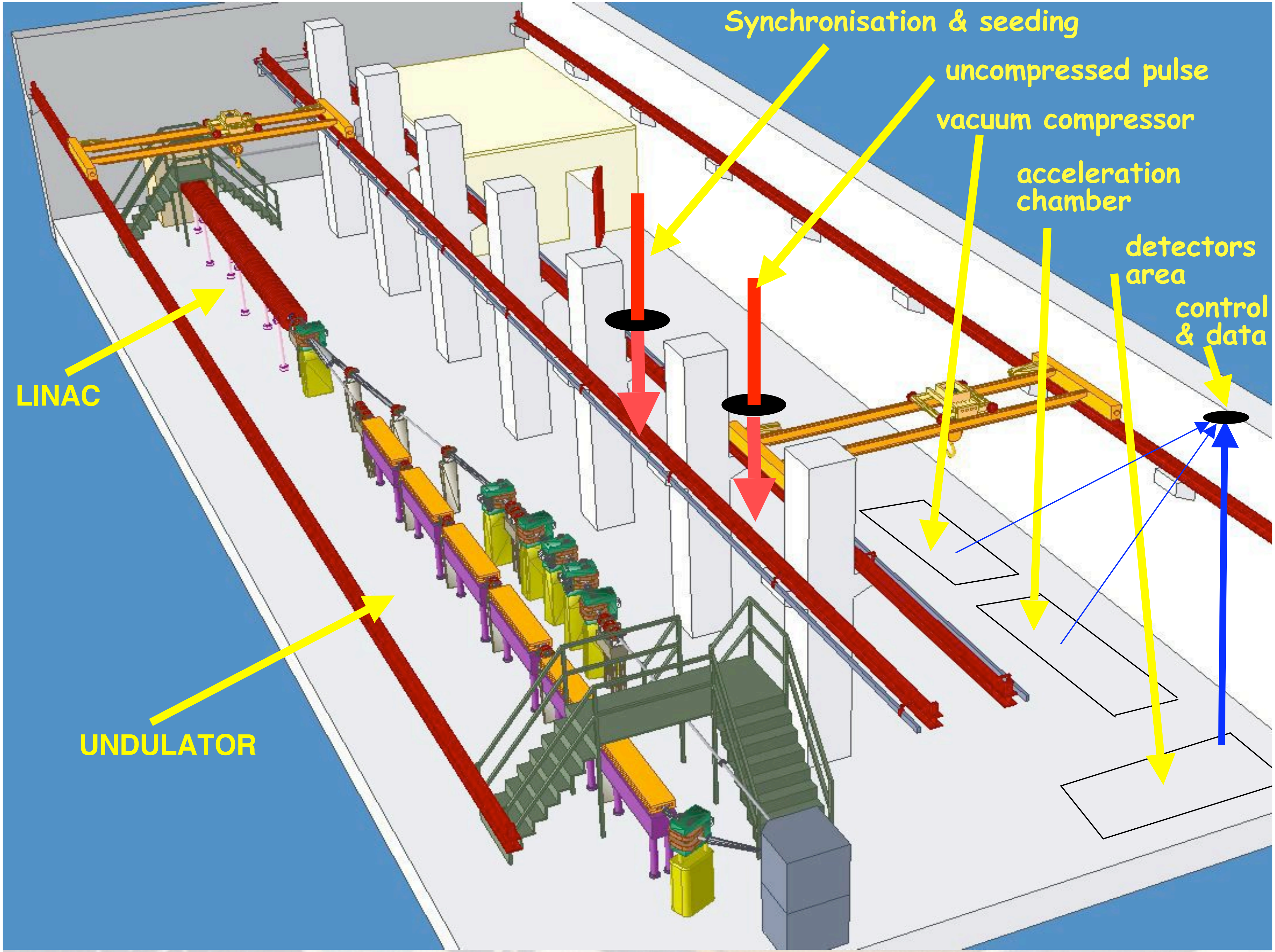
SPARC photo-injector and SASE-FEL experiment with additional double dog-leg beam line



The **F**rascati **L**aser for **A**cceleration and **M**ultidisciplinary **E**xperiments (**FLAME**)



FLAME Block Diagram


Synchronisation & seeding
uncompressed pulse
vacuum compressor
acceleration chamber
detectors area
control & data
LINAC
UNDULATOR

CONCLUSIONS

The femtosecond interaction with preformed plasmas from exploded thin foils or gas jet may provide suitable conditions for laser wakefield acceleration.

Very collimated bunches of 10^9 electrons accelerated forward up to 40 MeV have been produced with acceleration length below 0.1 mm.
This proves accelerating fields $E_P >> 10^{11}$ *V/m*.

The maximum electron energy is presently limited by both diffraction and plasma scale lengths, which are comparable.

The plasma wave formation and electron trapping mechanisms are both well depicted by 3-D PIC simulation, which also support the experimental measurements of angular distribution, total charge and energy spectrum of the accelerated electron bunches.

PERSPECTIVES

The plasma can be preformed with an independent, synchronised laser pulse, in order to better control its final scalelength, and eventually to preform a suitable channel.

The energy increase of the Ti:Sapphire laser pulses (in progress) would allow femtosecond interaction at the same relativistic intensity with a larger spot and diffraction length.

The method is suitable for optimisation in view of practical uses of the high energy electron bunches.

PLASMONX: combining high brightness photon and electron beams @ LNF

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(Siracusa)

thank you for attention

and ...

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