Laboratorio FLAME, stato del *commissioning* e primi esperimenti

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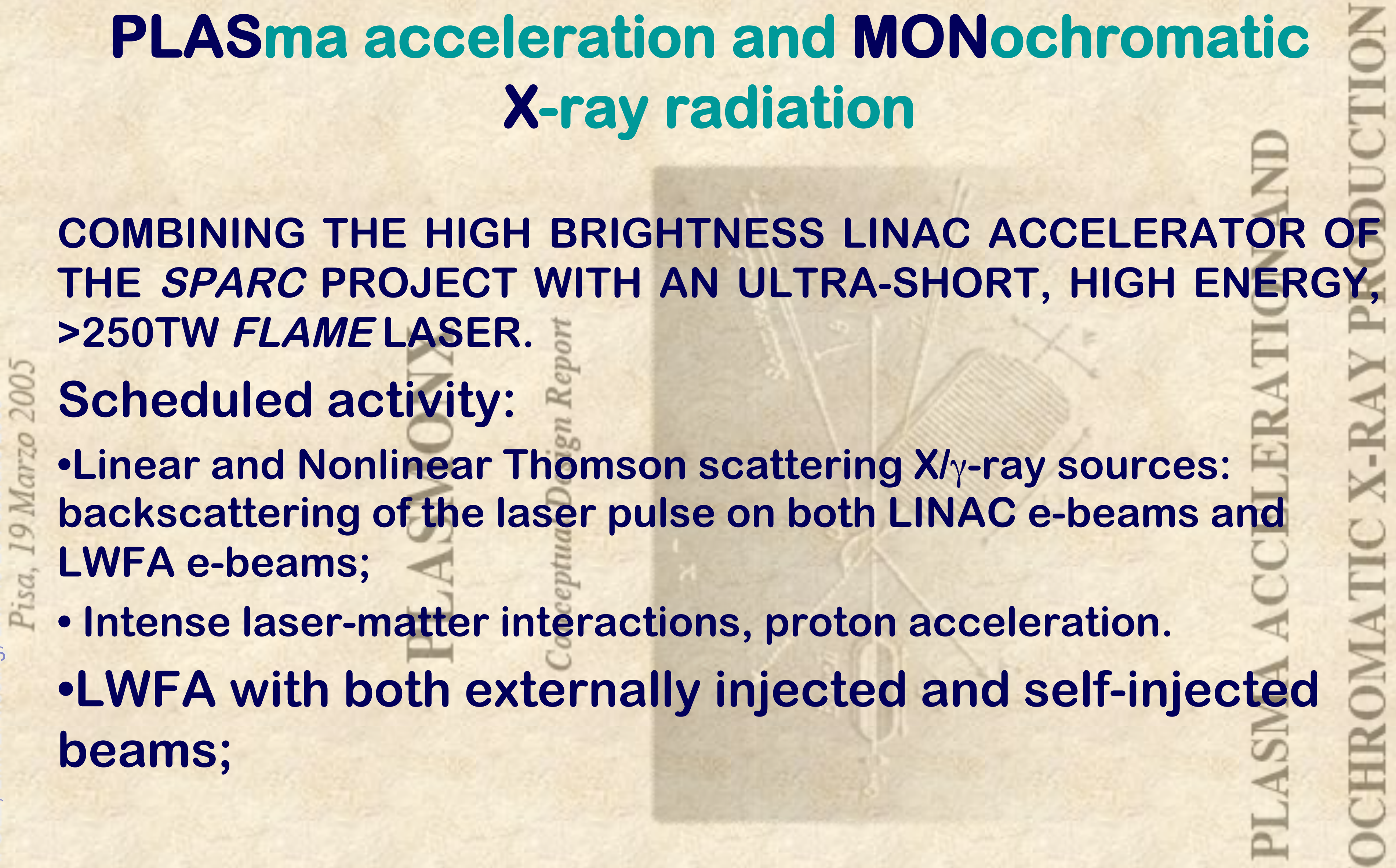
On behalf of the FLAME Team

Contents

- Motivations: the PLASMON-X project;
- FLAME lab general layout;
- An overview of the laser system;
- FLAME target area for laser-only experiments;
- First commissioning experiments on self-injection;
- The team
- Conclusions and pending issues

PLASma acceleration and **MON**ochromatic **X**-ray radiation



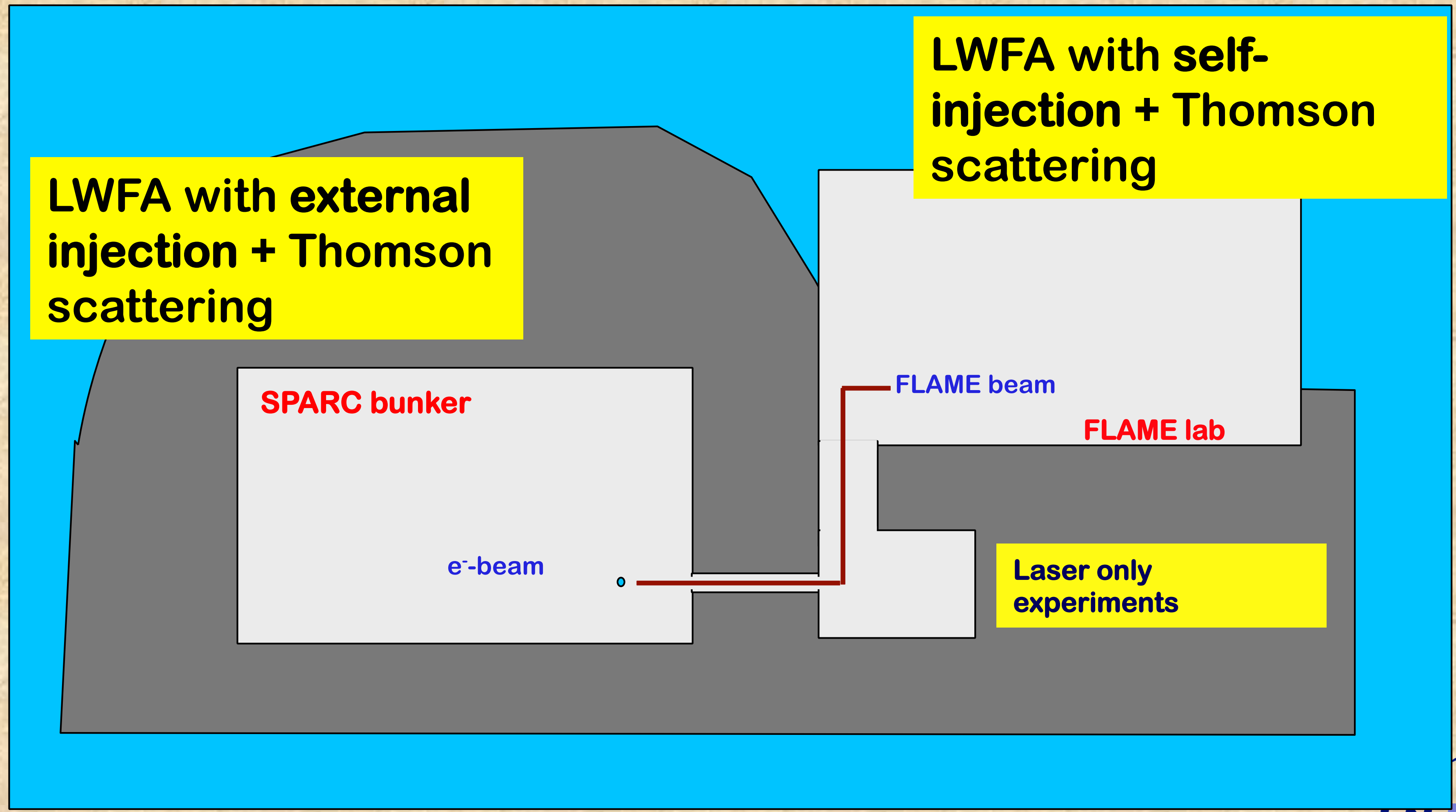
COMBINING THE HIGH BRIGHTNESS LINAC ACCELERATOR OF THE *SPARC* PROJECT WITH AN ULTRA-SHORT, HIGH ENERGY, >250TW *FLAME* LASER.

Scheduled activity:

- **Linear and Nonlinear Thomson scattering X/γ-ray sources: backscattering of the laser pulse on both LINAC e-beams and LWFA e-beams;**
- **Intense laser-matter interactions, proton acceleration.**
- **LWFA with both externally injected and self-injected beams;**

FLAME Layout

Underground tunnel to transport FLAME laser pulses to SPARC



LWFA with self-injection + Thomson scattering

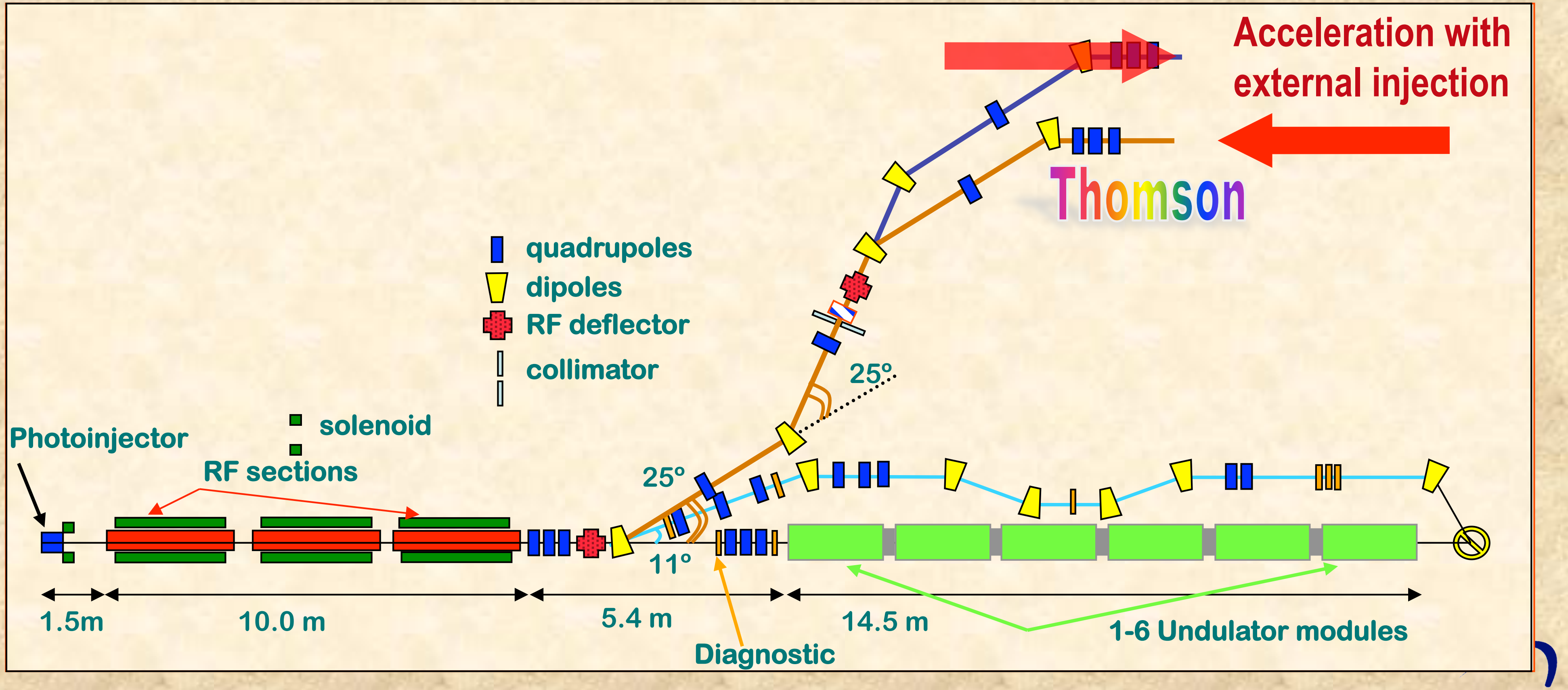
LWFA with external injection + Thomson scattering

Laser only experiments

LINAC layout

Features:

- High brightness e-beam
- Very low emittance

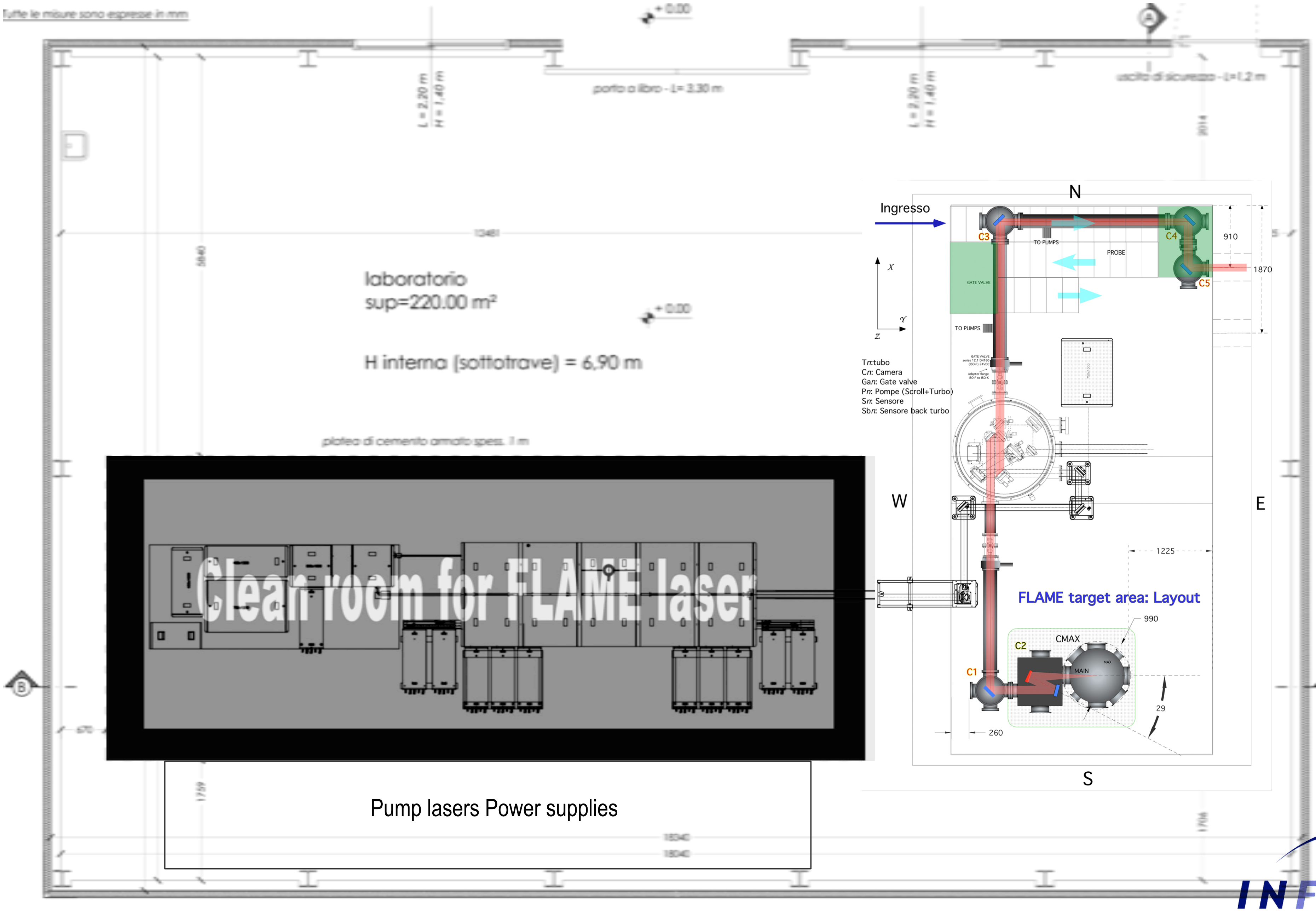


The FLAME laboratory

27th March 2007 –
beginning of construction

23rd June 2008 –
Building completed

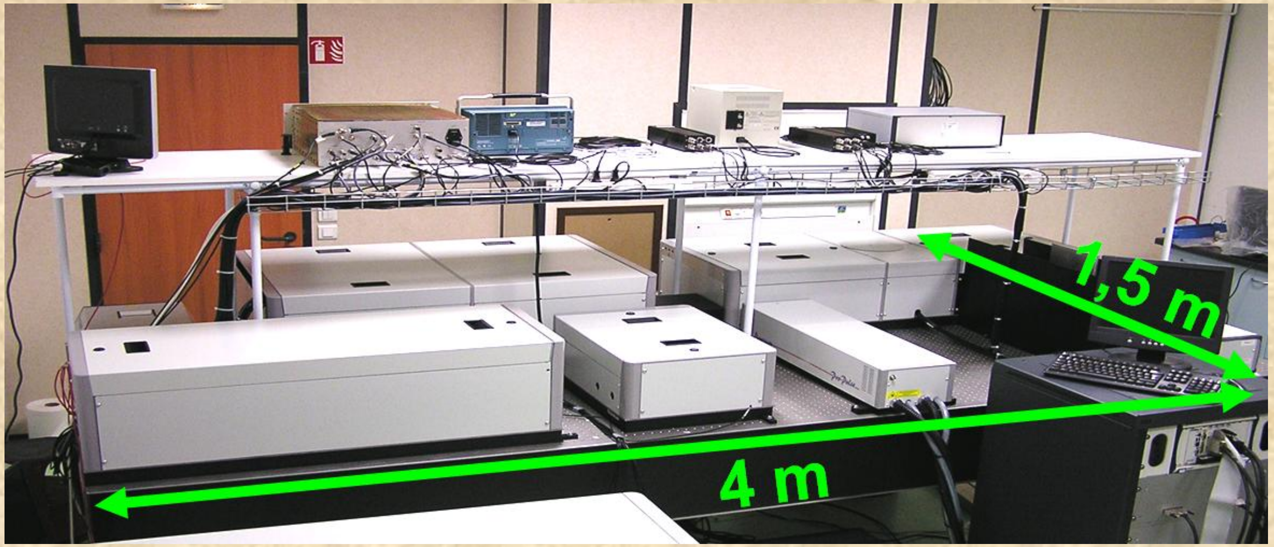
The FLAME laboratory



FLAME LASER

FLAME laser: specifications

Repetition Rate	10 Hz
Energy (after compression)	up to 6 J (typ. exp. 5.6J)
Wavelength	800 nm
Pulse duration	down to 20 fs (typ.23 fs)
Peak power	up to 300 TW
ASE contrast	$< 10^{10}$
Pre-pulse contrast	$< 10^{-8}$

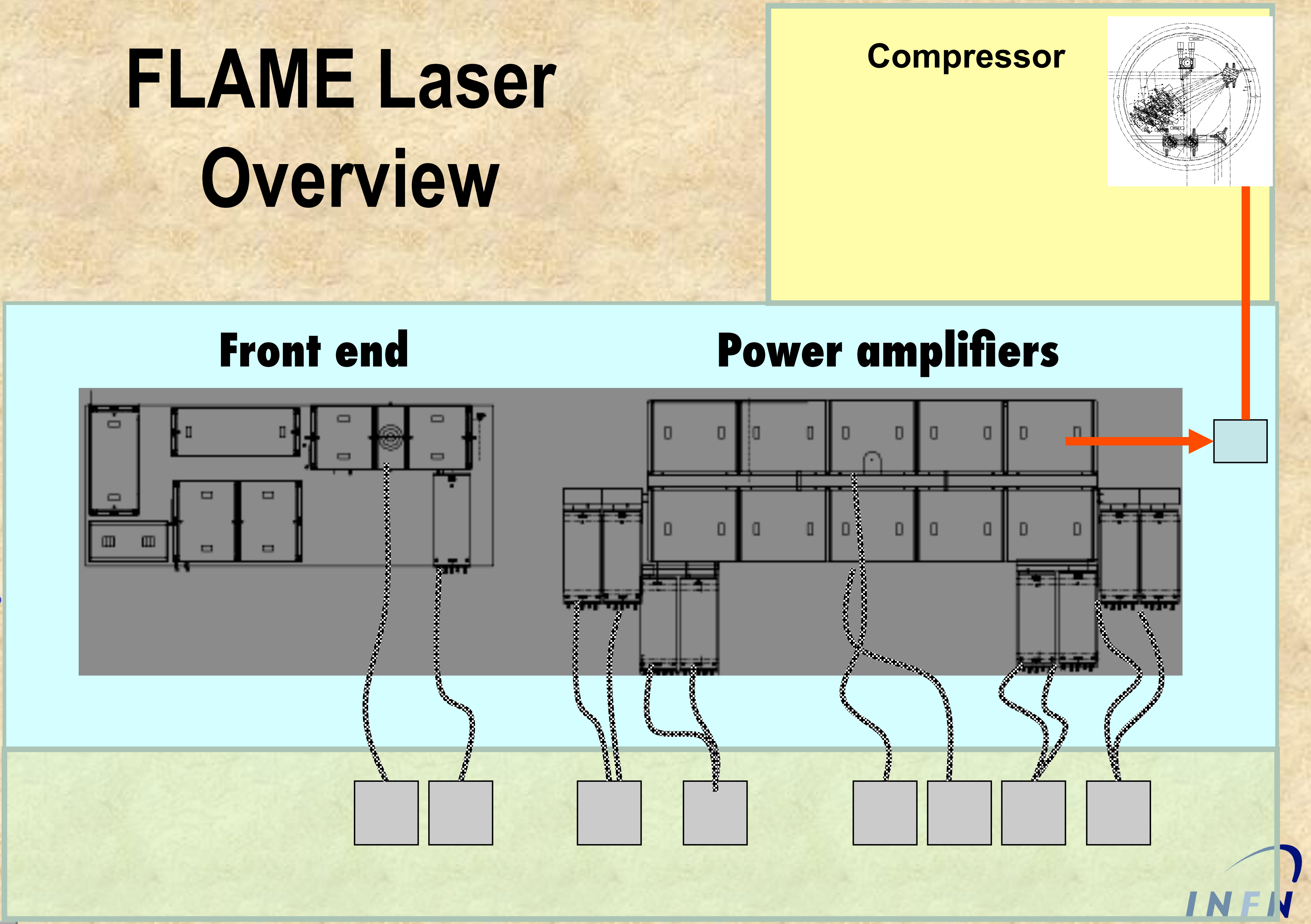


Front end @

Amplitude TECHNOLOGIES

INFN

FLAME Laser Overview



Compressor

Front end

Power amplifiers

THE OSCILLATOR

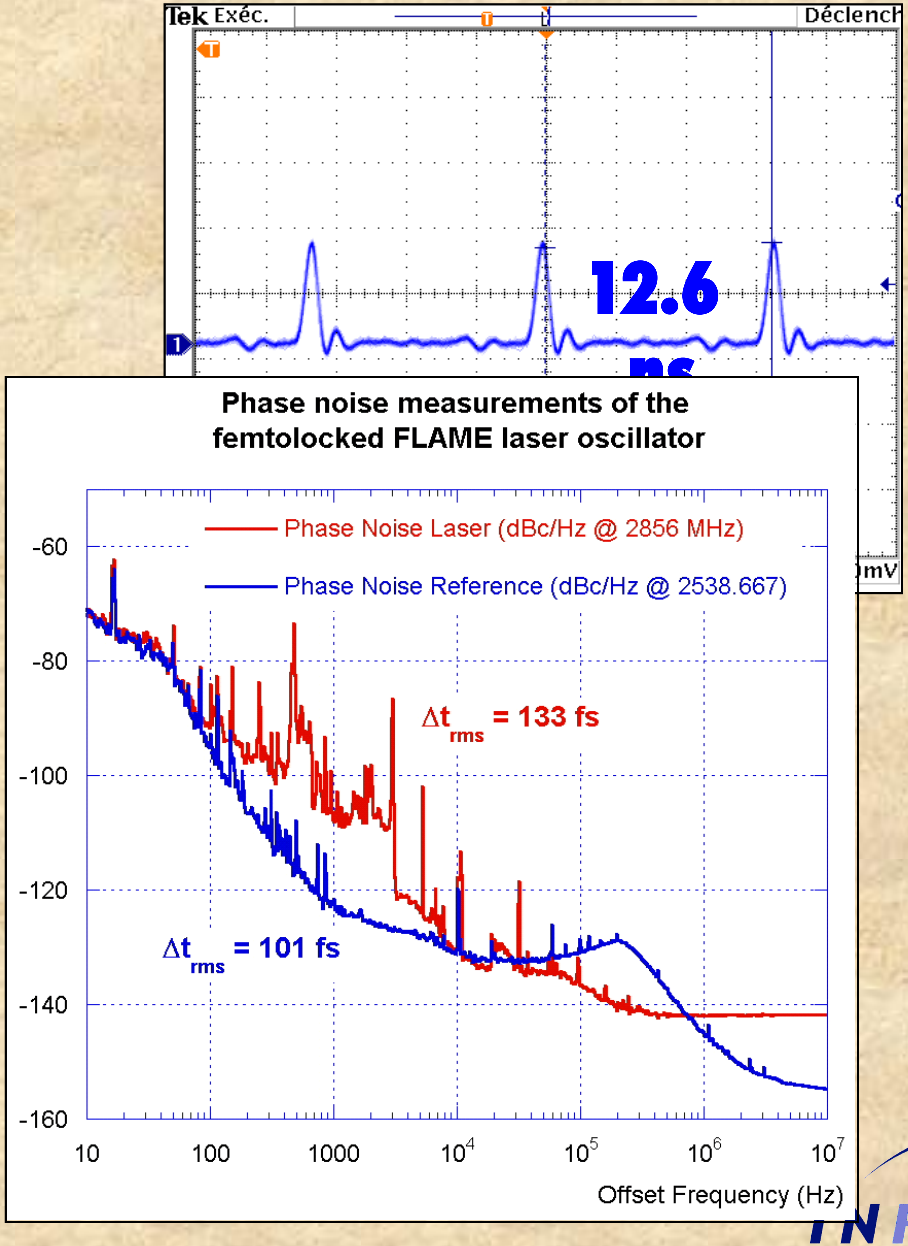
Oscillator Femtosource Synergy Pro

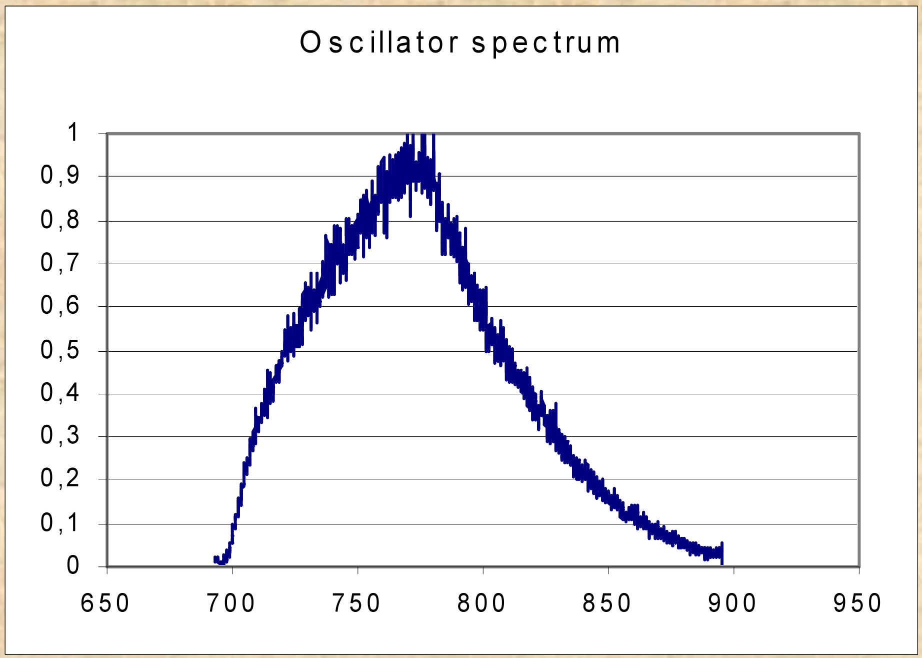
Pump = Finesse 532 from Laser Quantum

Pulse train measured @ 79.333 MHz

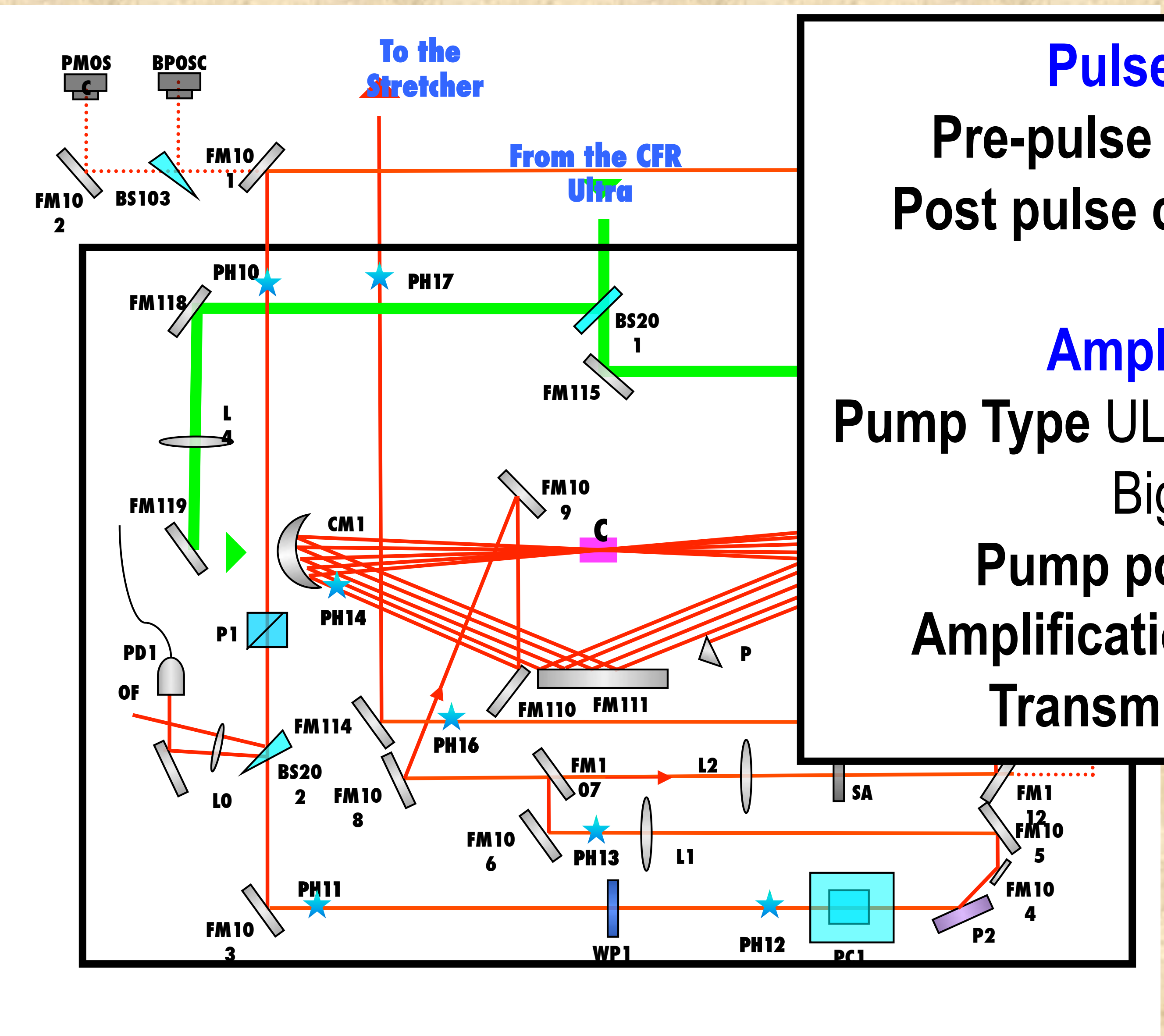
Spectrum FWHM > 80 nm

Femtolock option ➔ jitter < 150 fs





THE «BOOSTER»



Pulse Seletor

Pre-pulse contrast <1%

Post pulse contrast <10%

Amplification

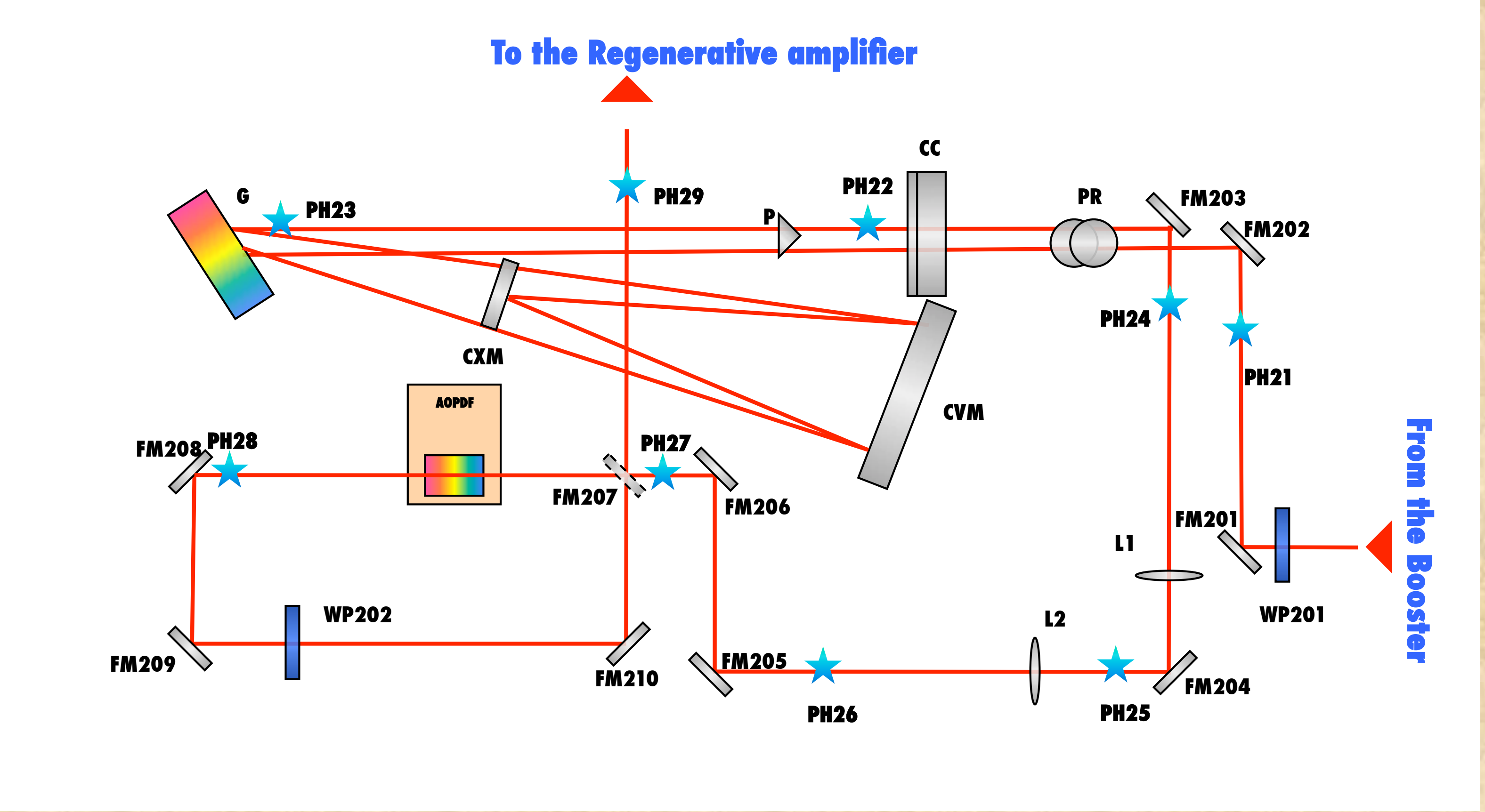
Pump Type ULTRA from Quantel-Big Sky

Pump power 5.5 mJ

Amplification Gain 10000

Transmission 30%

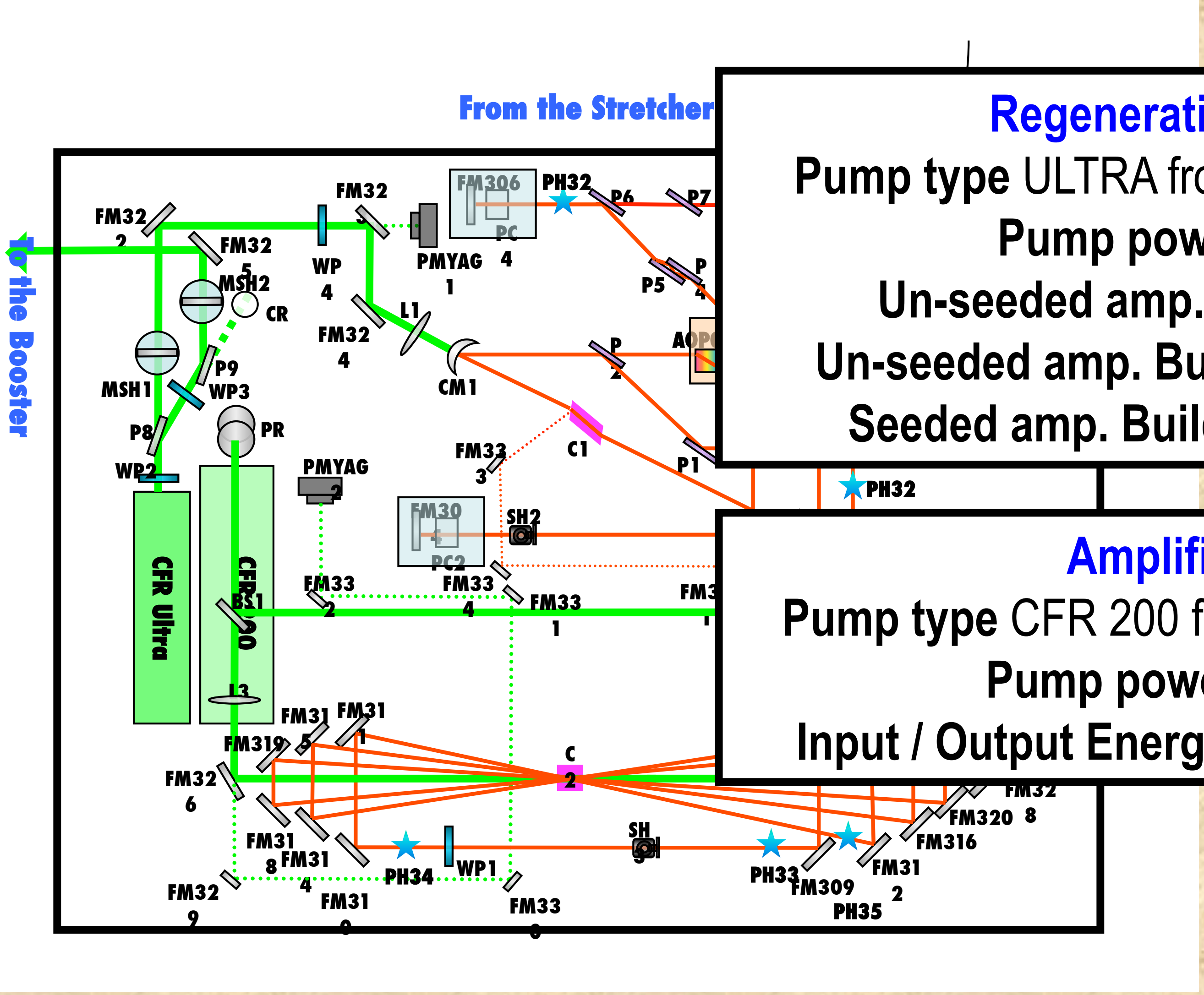
THE STRETCHER



Transmission of the stretcher 22%

Spectral Bandwidth 750-850 nm

THE REGENERATIVE CAVITY



Regenerative cavity

Pump type ULTRA from Quantel-Big Sky

Pump power 14 mJ

Un-seeded amp. Energy 1.1 mJ

Un-seeded amp. Build up time 310 ns

Seeded amp. Build up time 140 ns

Amplifier #1

Pump type CFR 200 from Quantel-Big Sky

Pump power 120 mJ

Input / Output Energy 0.7 mJ / 25-30 mJ

THE AMPLIFIER #1

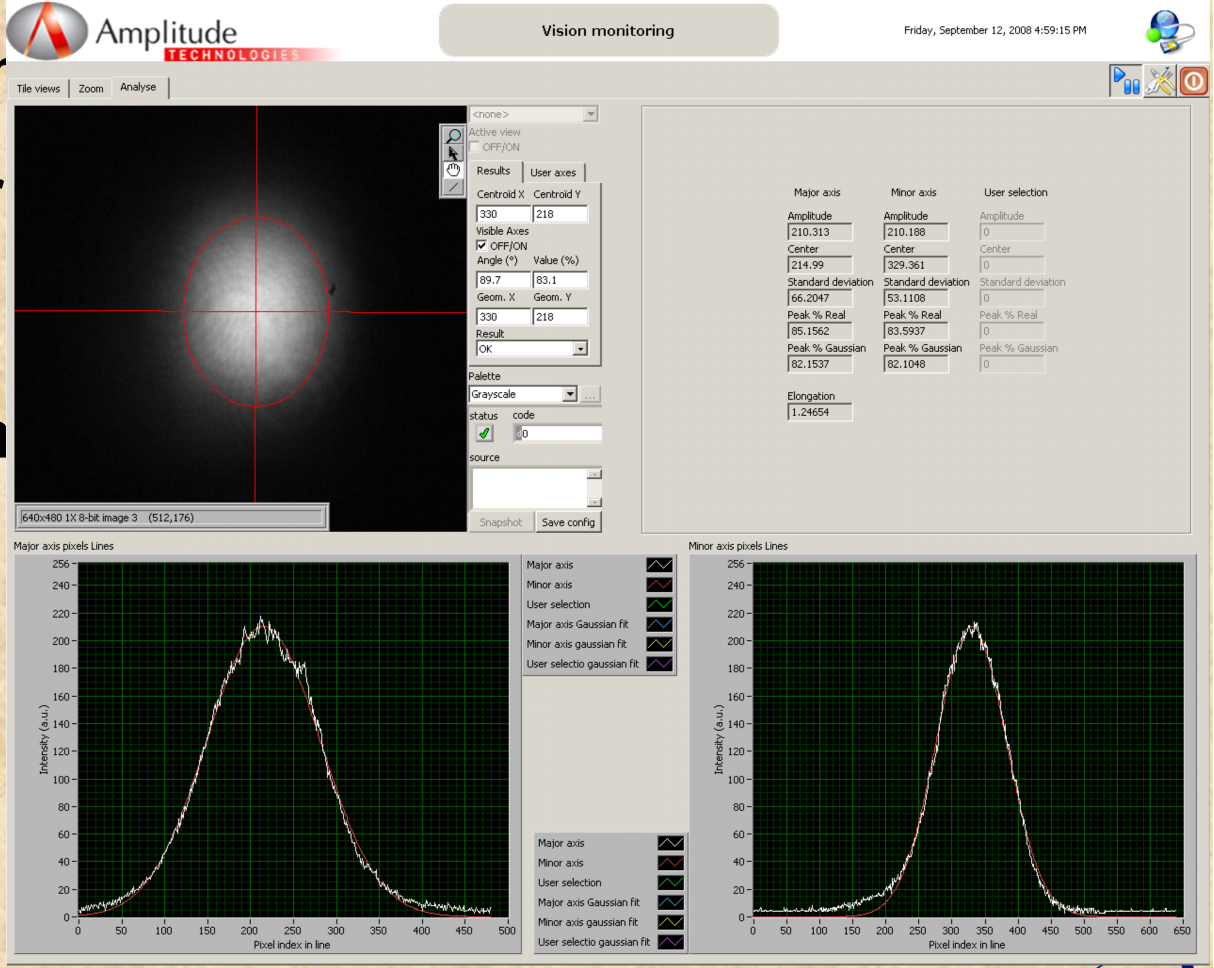
Spectral Characterization

With the natural spectrur

With the broadened spectr

Spatial Characterization

Regenerative cavity spectral characterization



Centroïd X	Centroïd Y
330	218

Visible Axes
☑ OFF/ON

Angle (°)	Value (%)
89.7	83.1

Geom. X	Geom. Y
330	218

Result: OK

status: ✓ code: 0

source

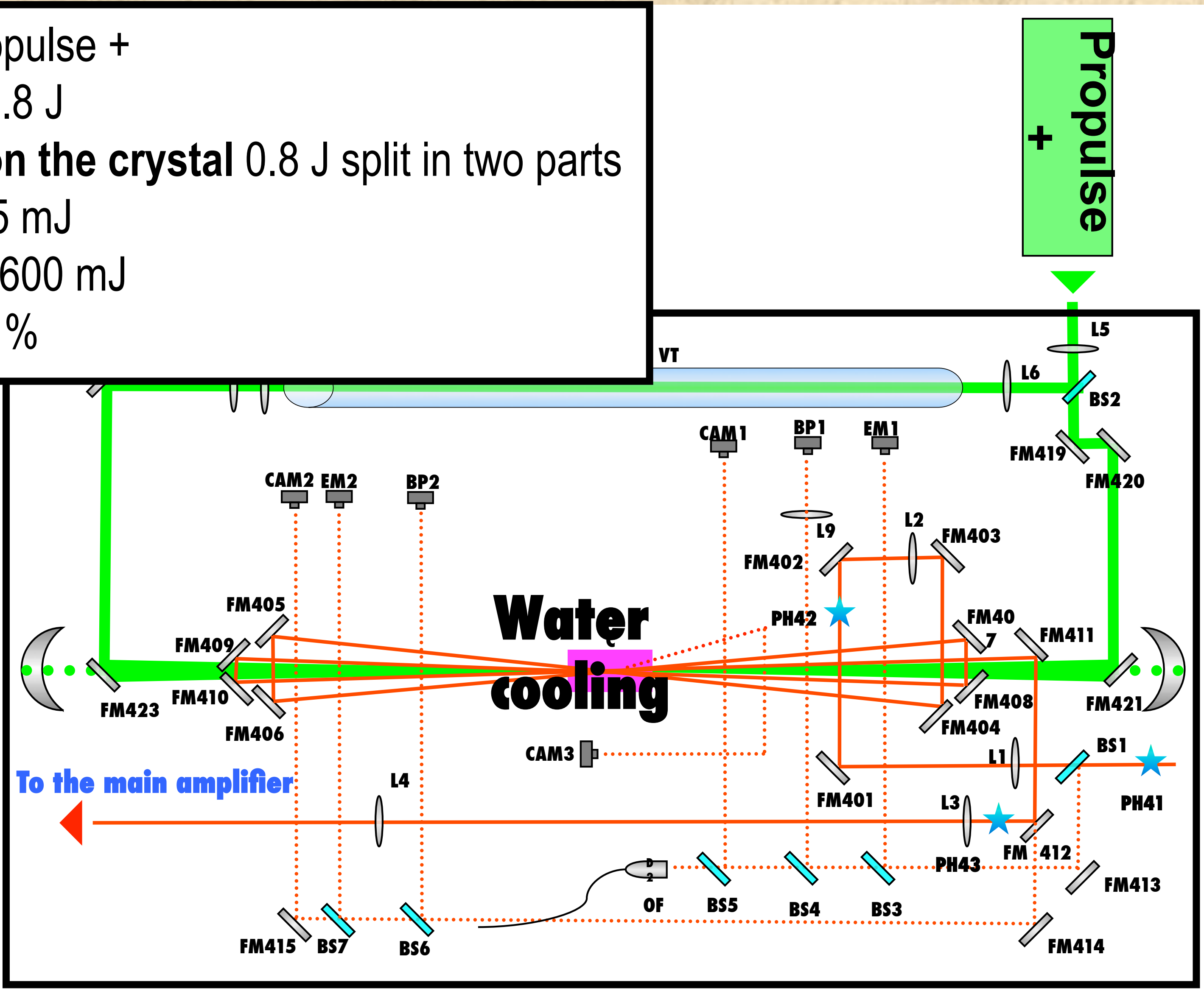
	Major axis	Minor axis	User selection
Amplitude	210.313	210.188	0
Center	214.99	329.361	0
Standard deviation	66.2047	53.1108	0
Peak % Real	85.1562	83.5937	0
Peak % Gaussian	82.1537	82.1048	0

Elongation: 1.24654

➔ Large spectrum
➔ Smooth Gaussian profile

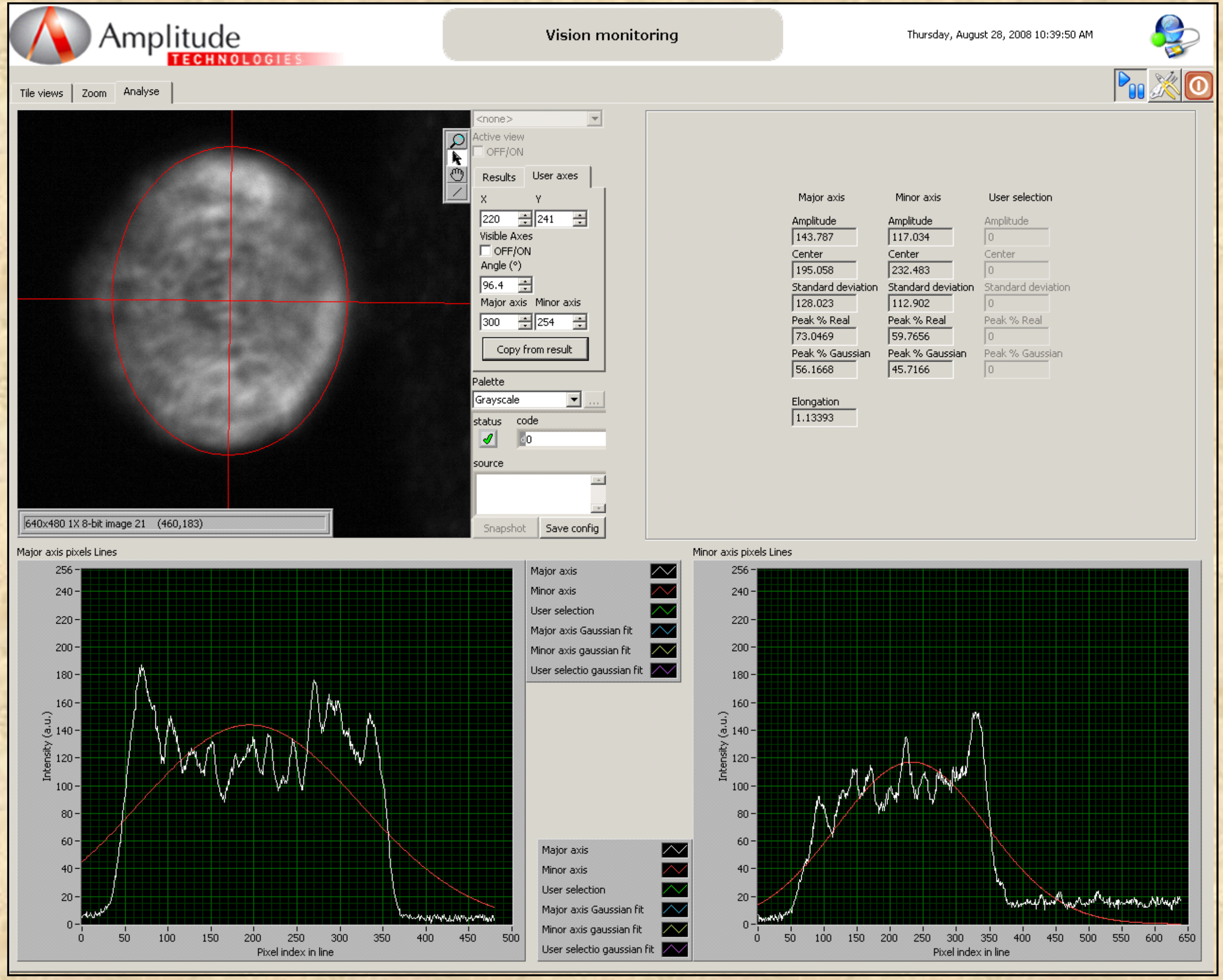
THE AMPLIFIER #2

Pump laser Propulse +
Pump energy 1.8 J
Pump energy on the crystal 0.8 J split in two parts
Input energy 25 mJ
Output energy 600 mJ
RMS factor < 2 %



THE AMPLIFIER #2

Intermediate field Beam Profile → Flat top



Thursday, August 28, 2008 10:39:50 AM

X 220 Y 241

Visible Axes ☐ OFF/ON

Angle (°) 96.4

Major axis 300 Minor axis 254

Palette Grayscale

status ✓ code 0

source

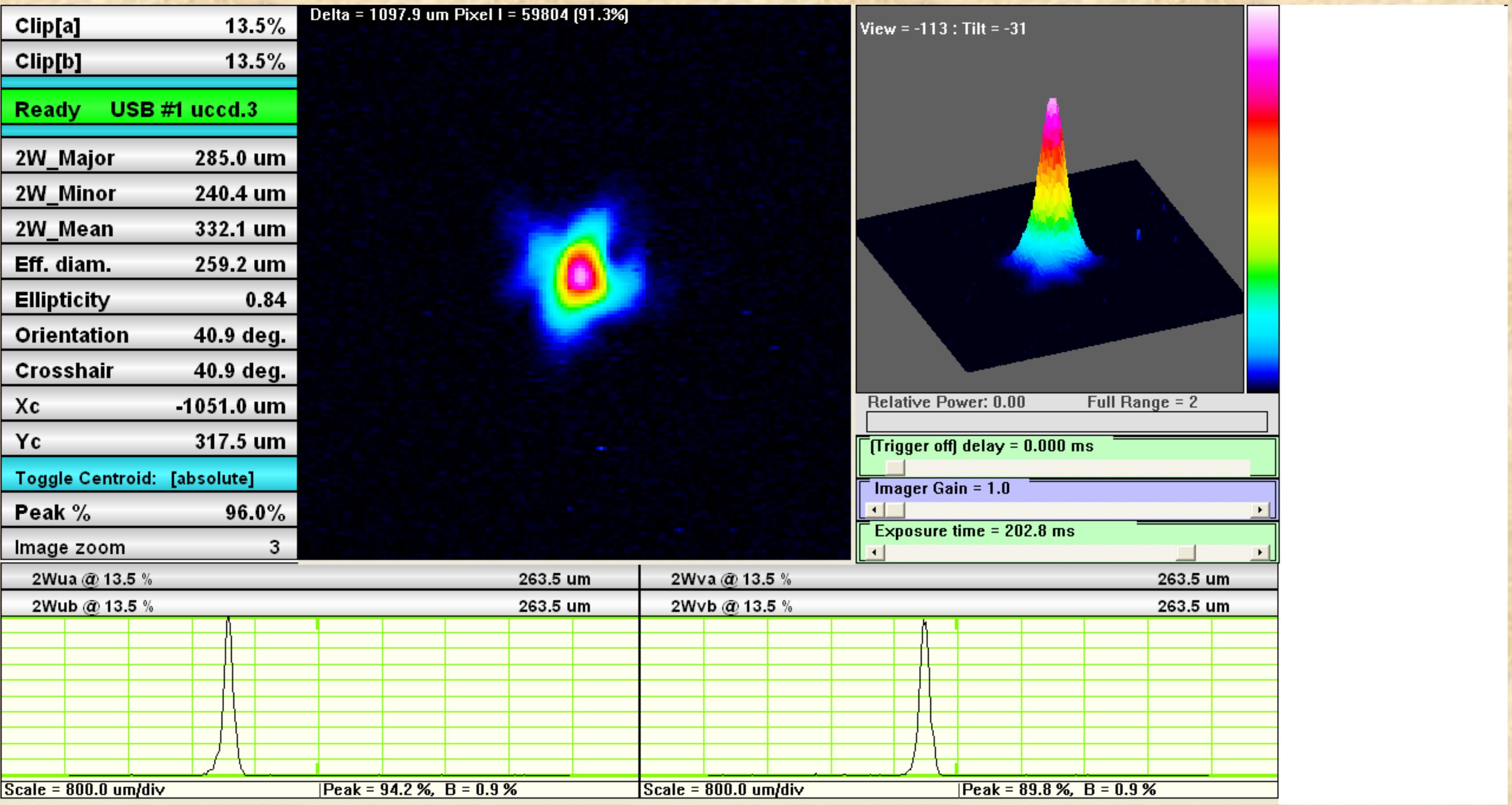
640x480 1X 8-bit image 21 (460,183)

	Major axis	Minor axis	User selection
Amplitude	143.787	117.034	0
Center	195.058	232.483	0
Standard deviation	128.023	112.902	0
Peak % Real	73.0469	59.7656	0
Peak % Gaussian	56.1668	45.7166	0

Elongation 1.13393

THE AMPLIFIER #2

Far field Beam Profile



Clip[a]	13.5%
Clip[b]	13.5%
Ready	USB #1 uccd.3
2W_Major	285.0 um
2W_Minor	240.4 um
2W_Mean	332.1 um
Eff. diam.	259.2 um
Ellipticity	0.84
Orientation	40.9 deg.
Crosshair	40.9 deg.
Xc	-1051.0 um
Yc	317.5 um
Toggle Centroid:	[absolute]
Peak %	96.0%
Image zoom	3

Delta = 1097.9 um Pixel I = 59804 (91.3%)

View = -113 : Tilt = -31

Relative Power: 0.00 Full Range = 2

(Trigger off) delay = 0.000 ms

Imager Gain = 1.0

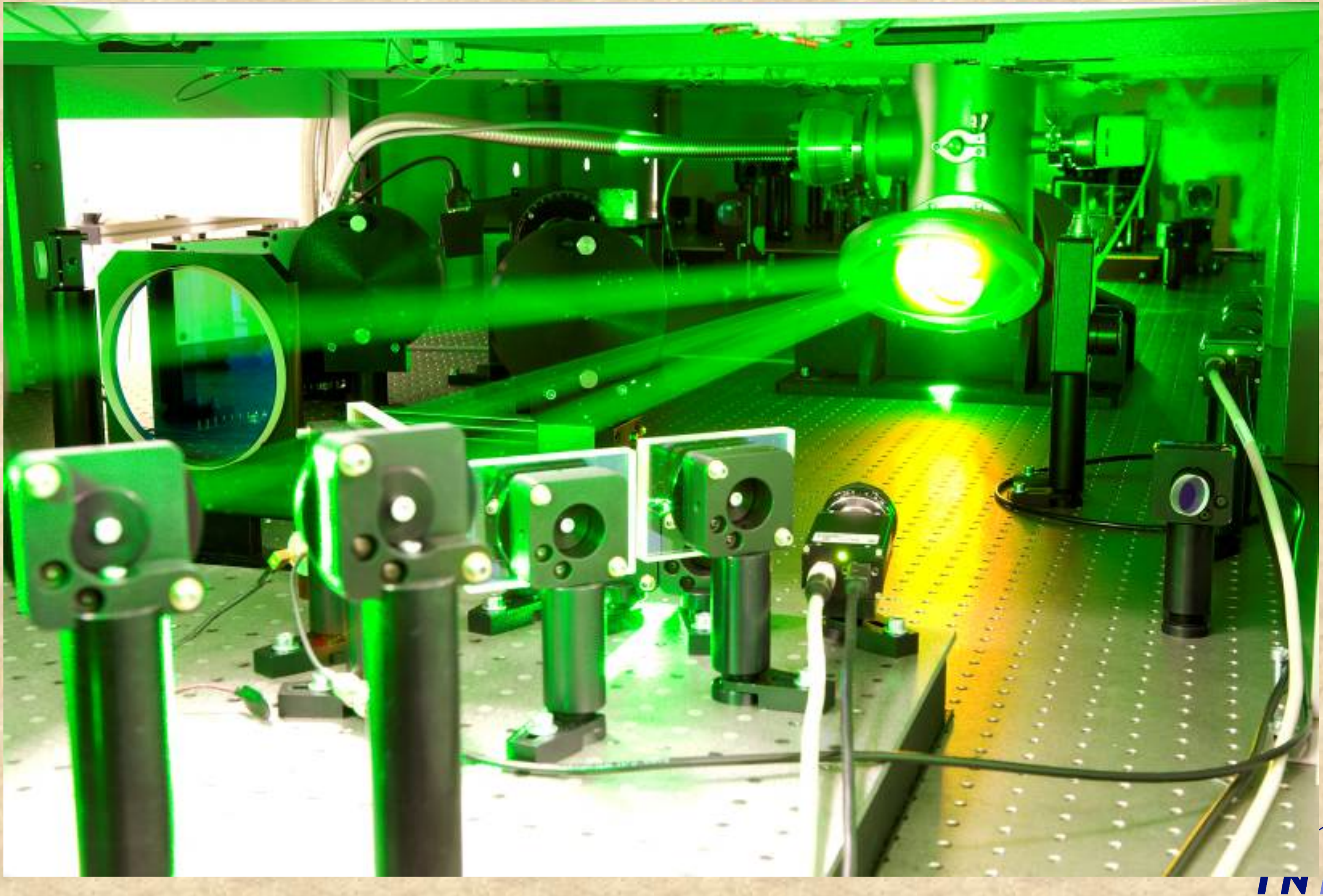
Exposure time = 202.8 ms

2Wua @ 13.5 %	263.5 um	2Wva @ 13.5 %	263.5 um
2Wub @ 13.5 %	263.5 um	2Wvb @ 13.5 %	263.5 um

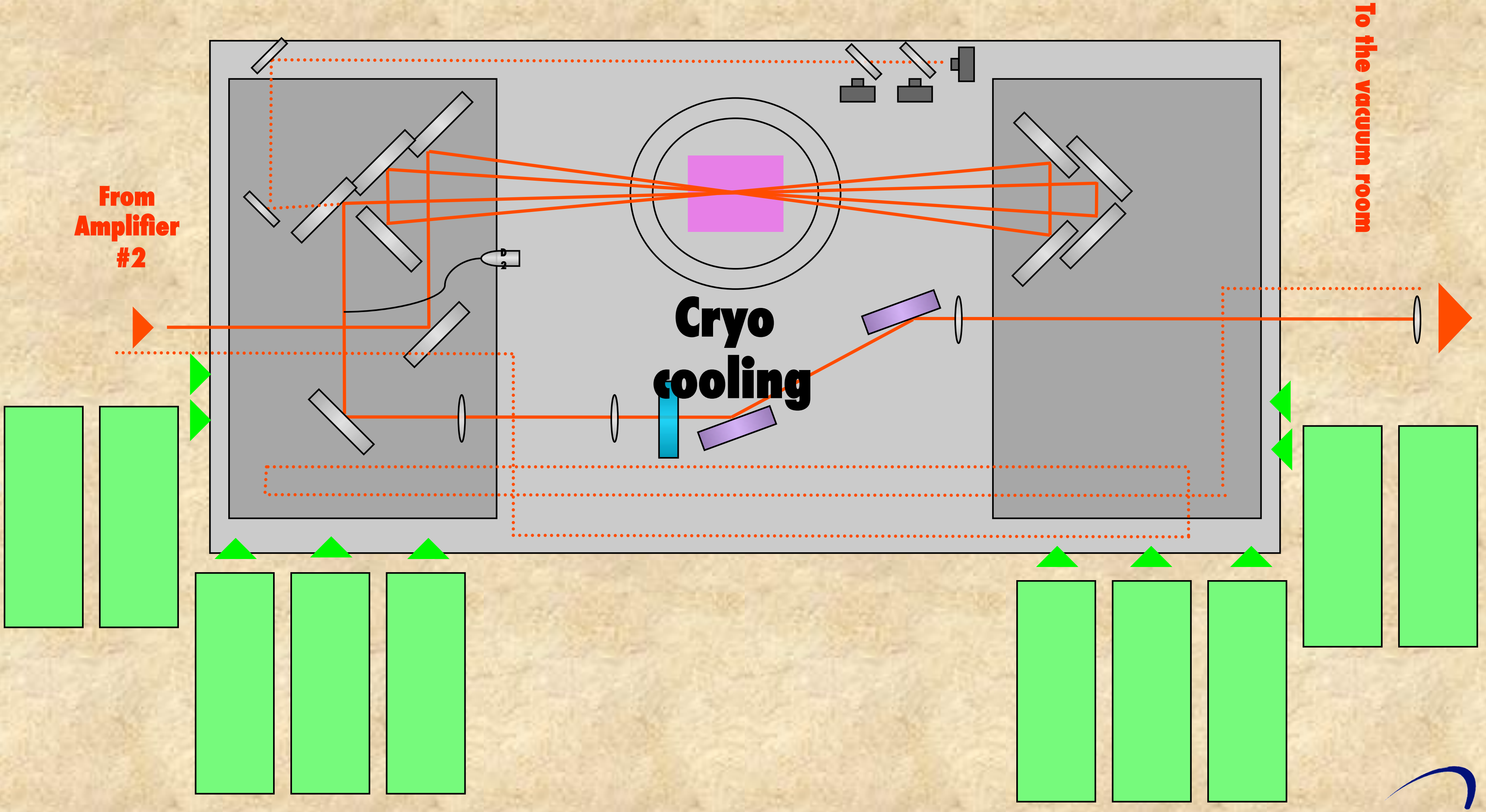
Scale = 800.0 um/div |Peak = 94.2 %, B = 0.9 %

Scale = 800.0 um/div |Peak = 89.8 %, B = 0.9 %

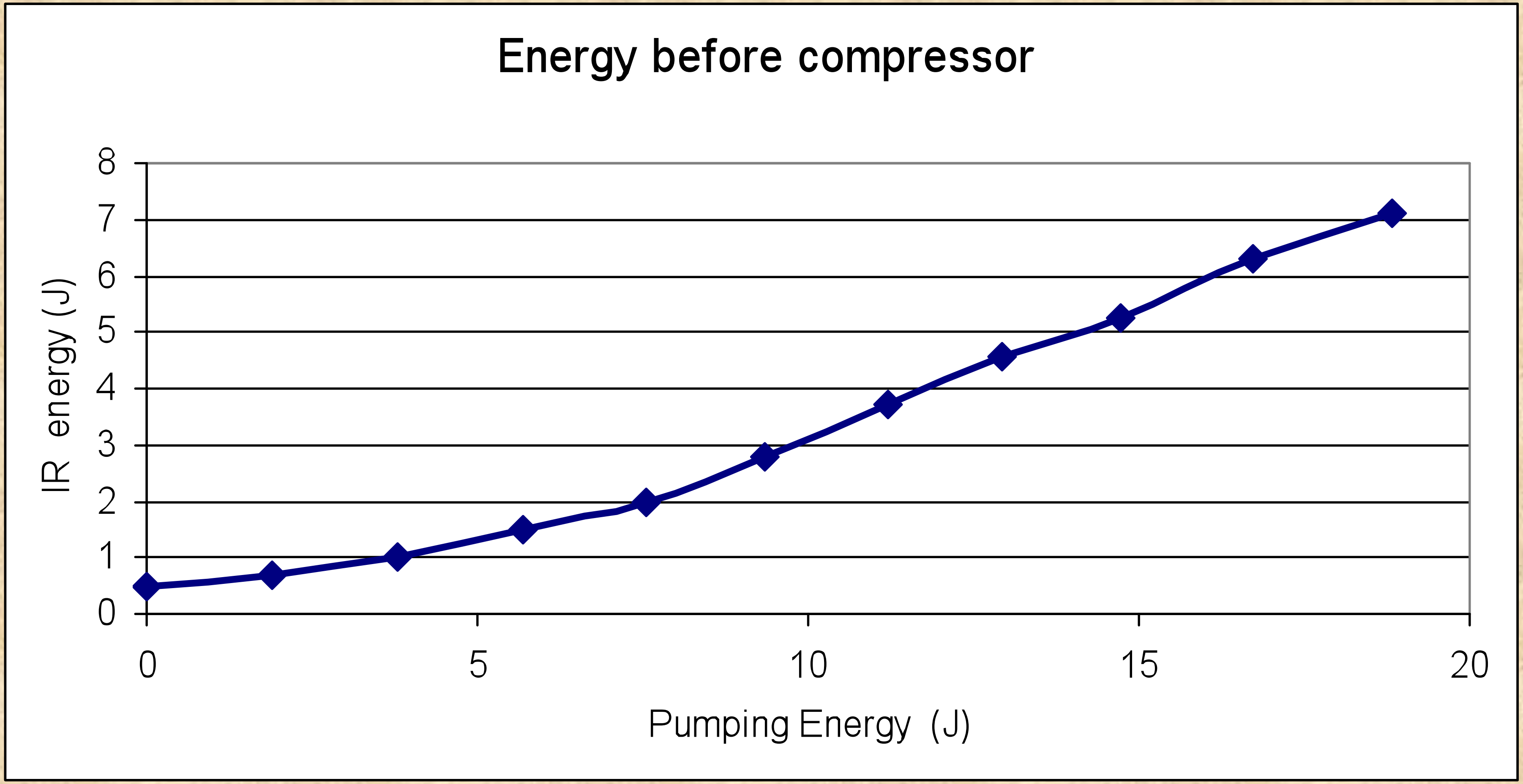
AMPLIFIER #3 – THE POWER AMPLIFIER



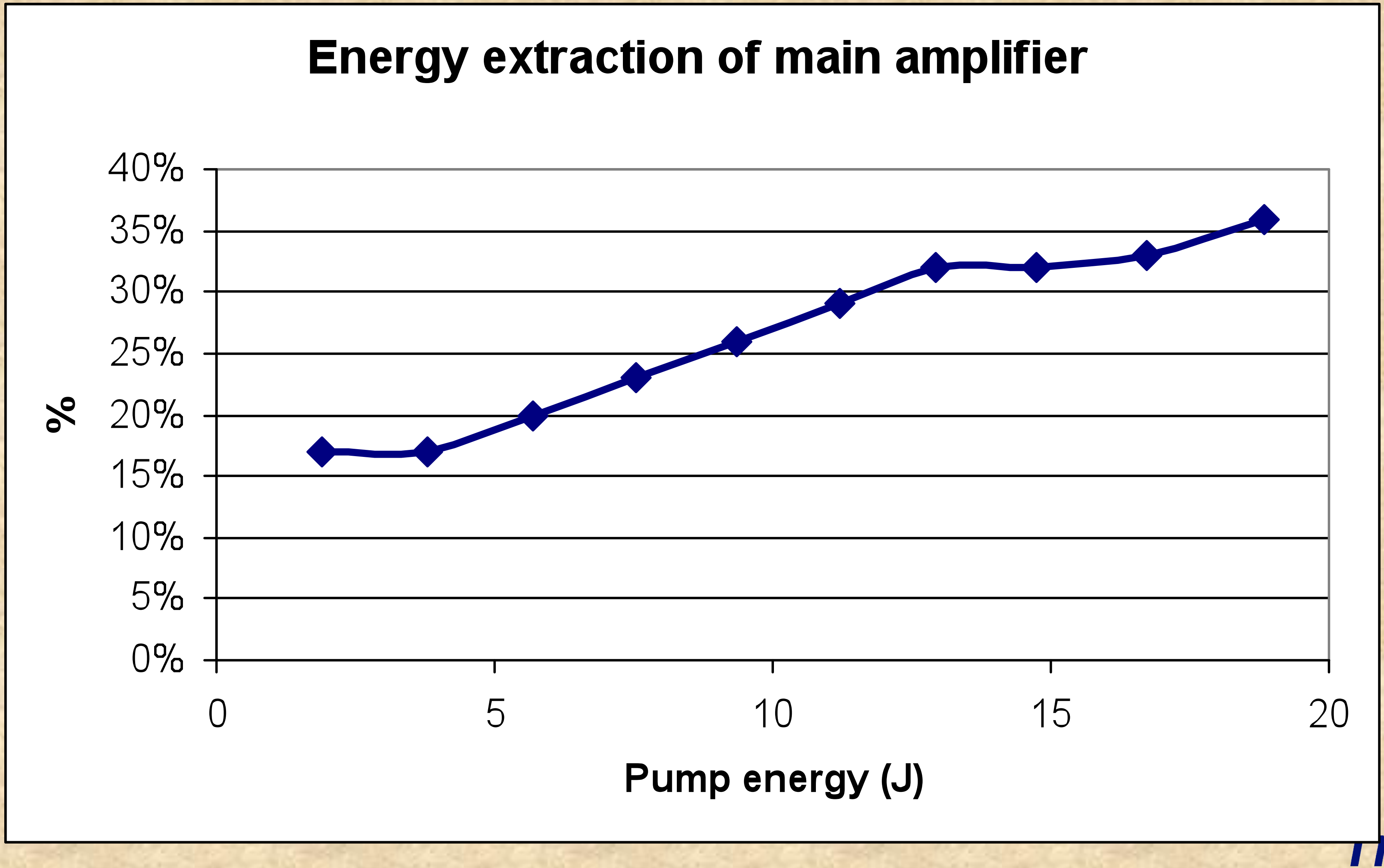
AMPLIFIER #3 – THE POWER AMPLIFIER



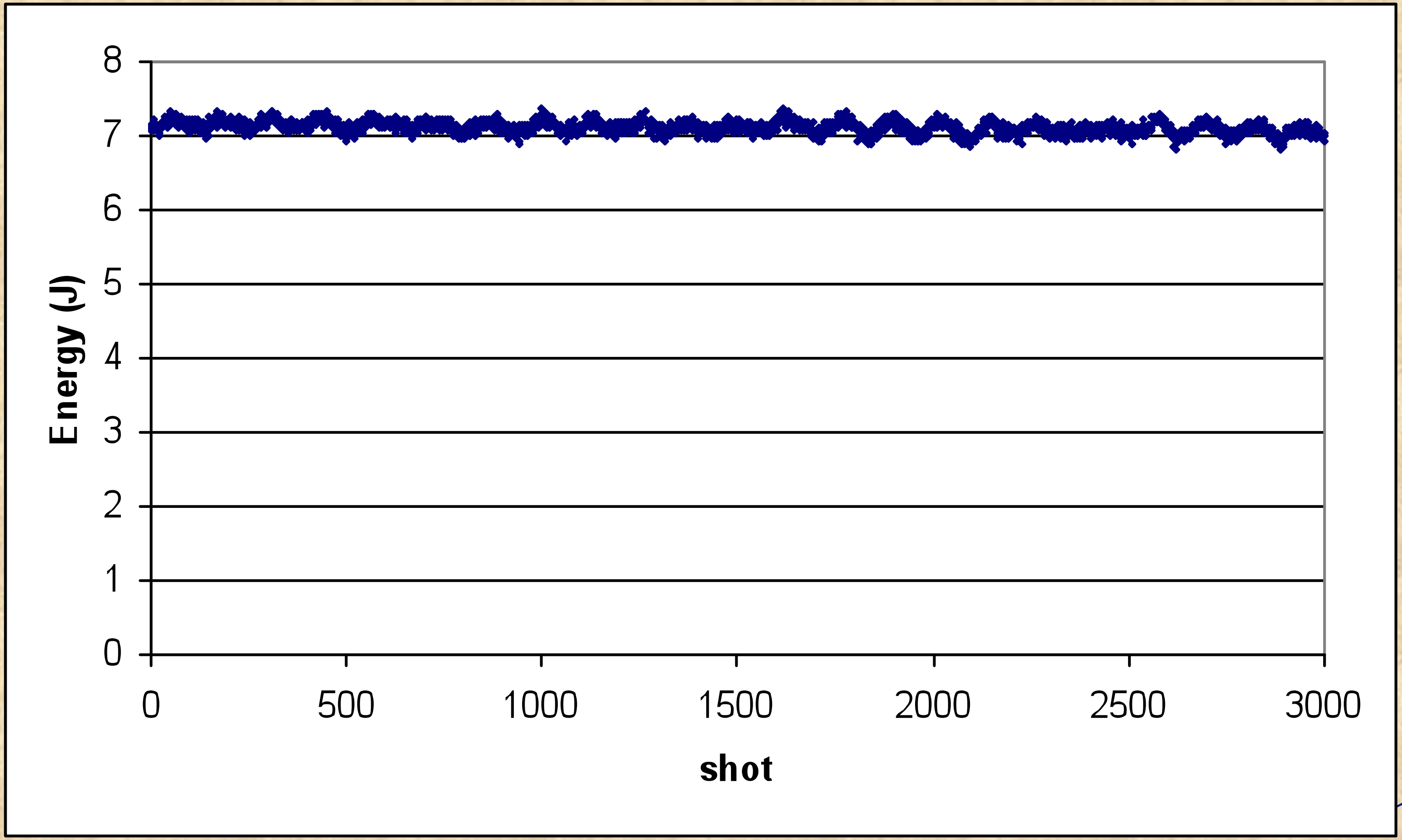
POWER AMPLIFIER – output energy



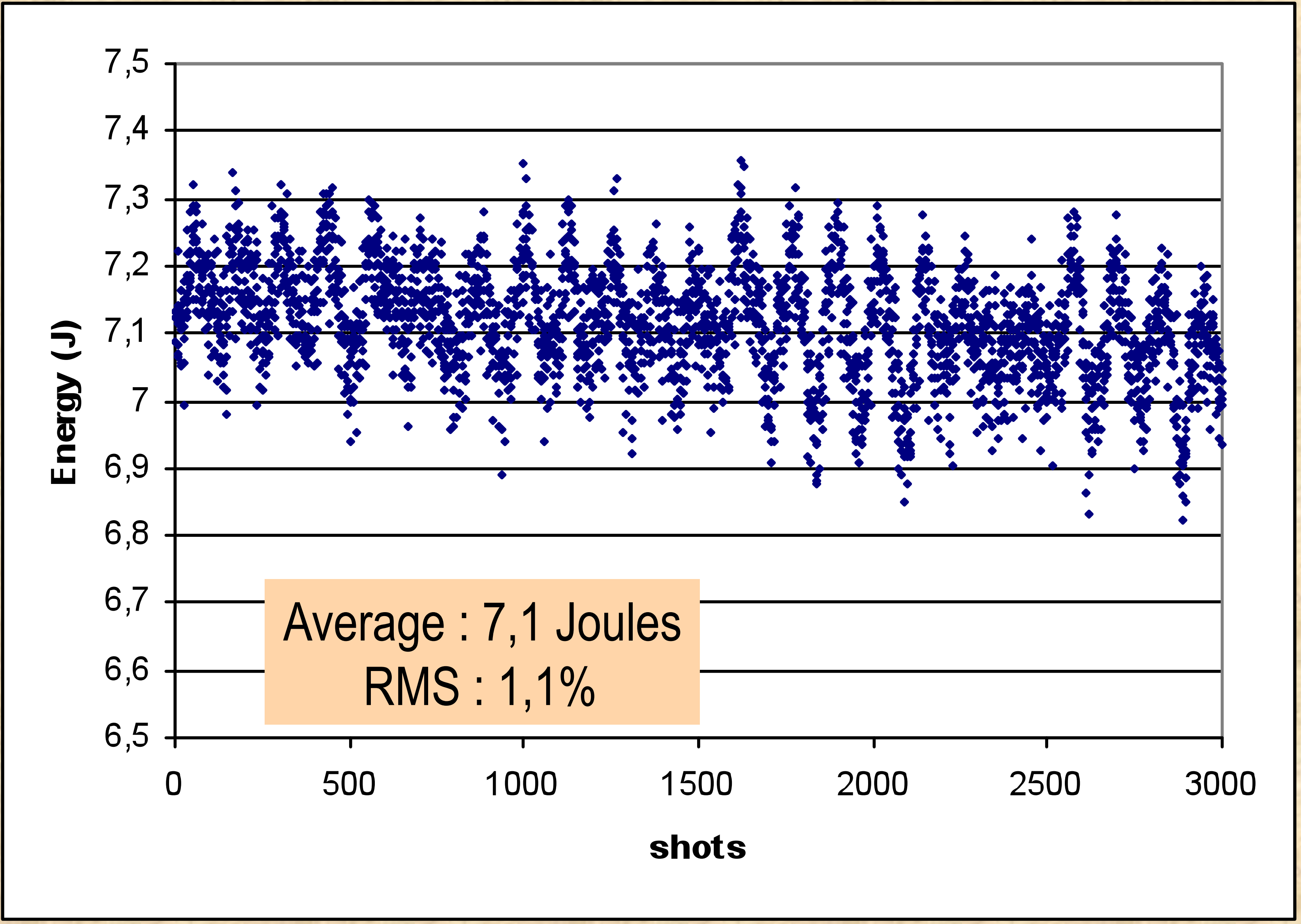
POWER AMPLIFIER – extraction efficiency



POWER AMPLIFIER- stability



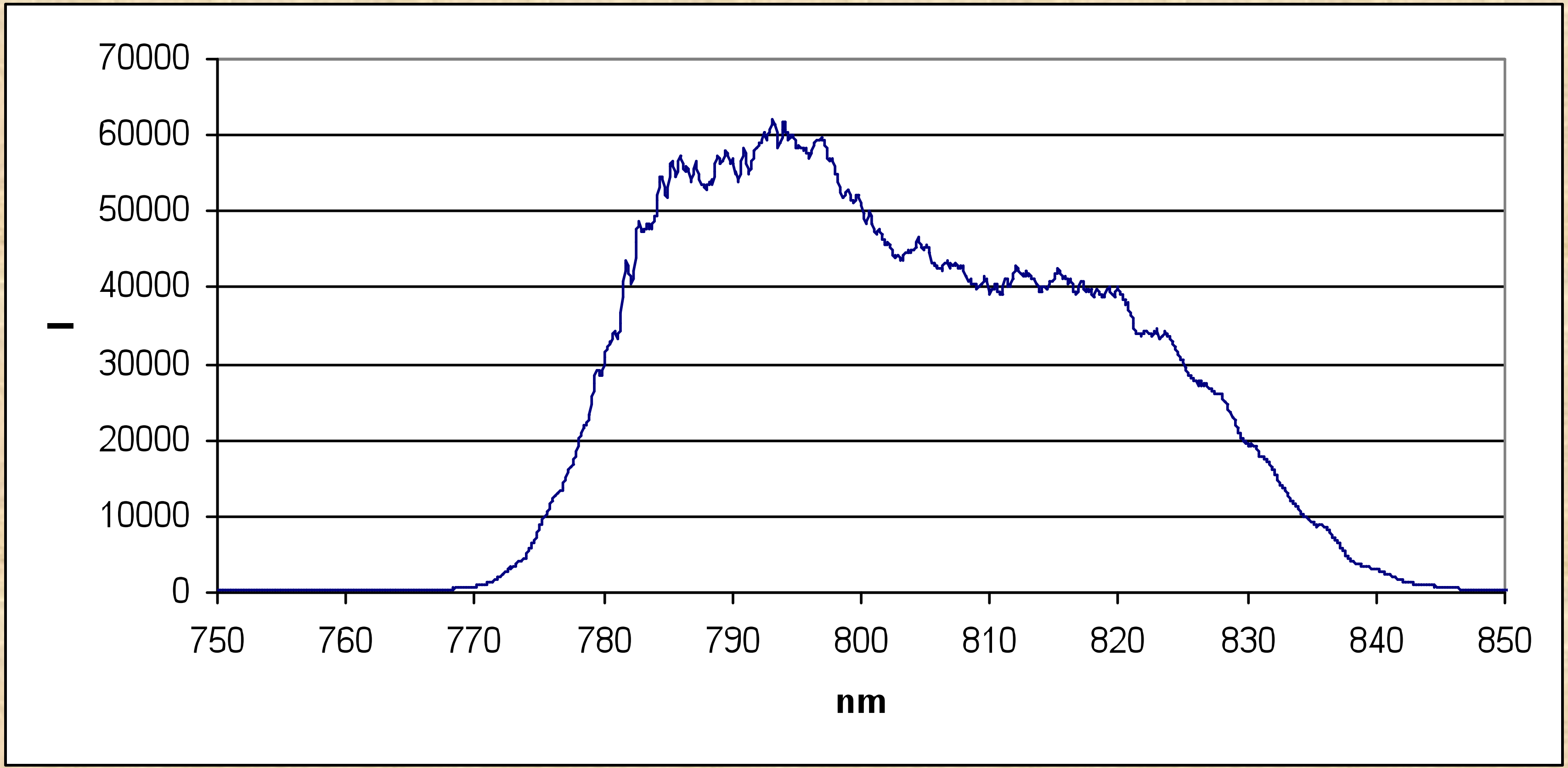
POWER AMPLIFIER- stability



Average : 7,1 Joules
RMS : 1,1%

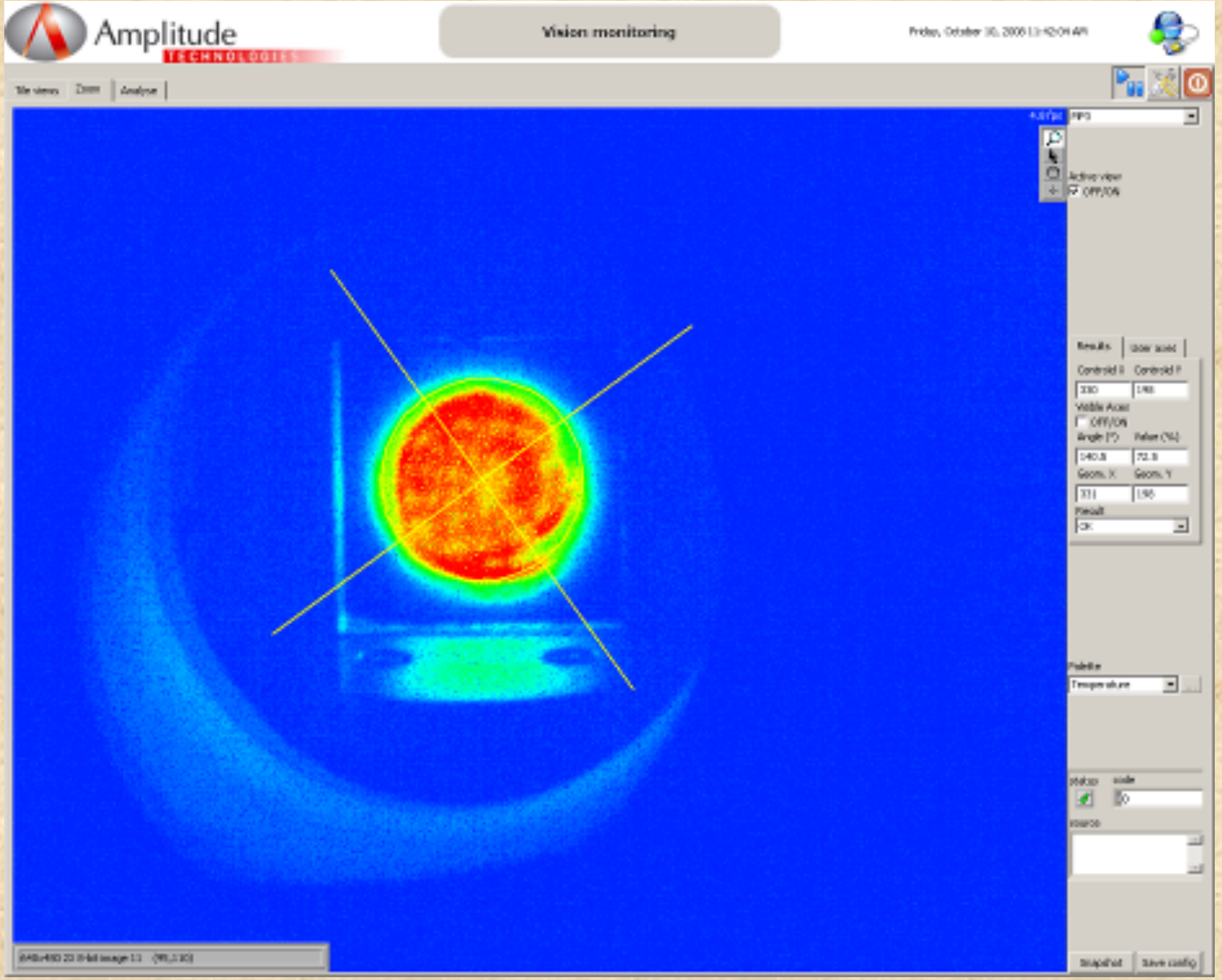
POWER AMPLIFIER - spectrum

7J spectrum



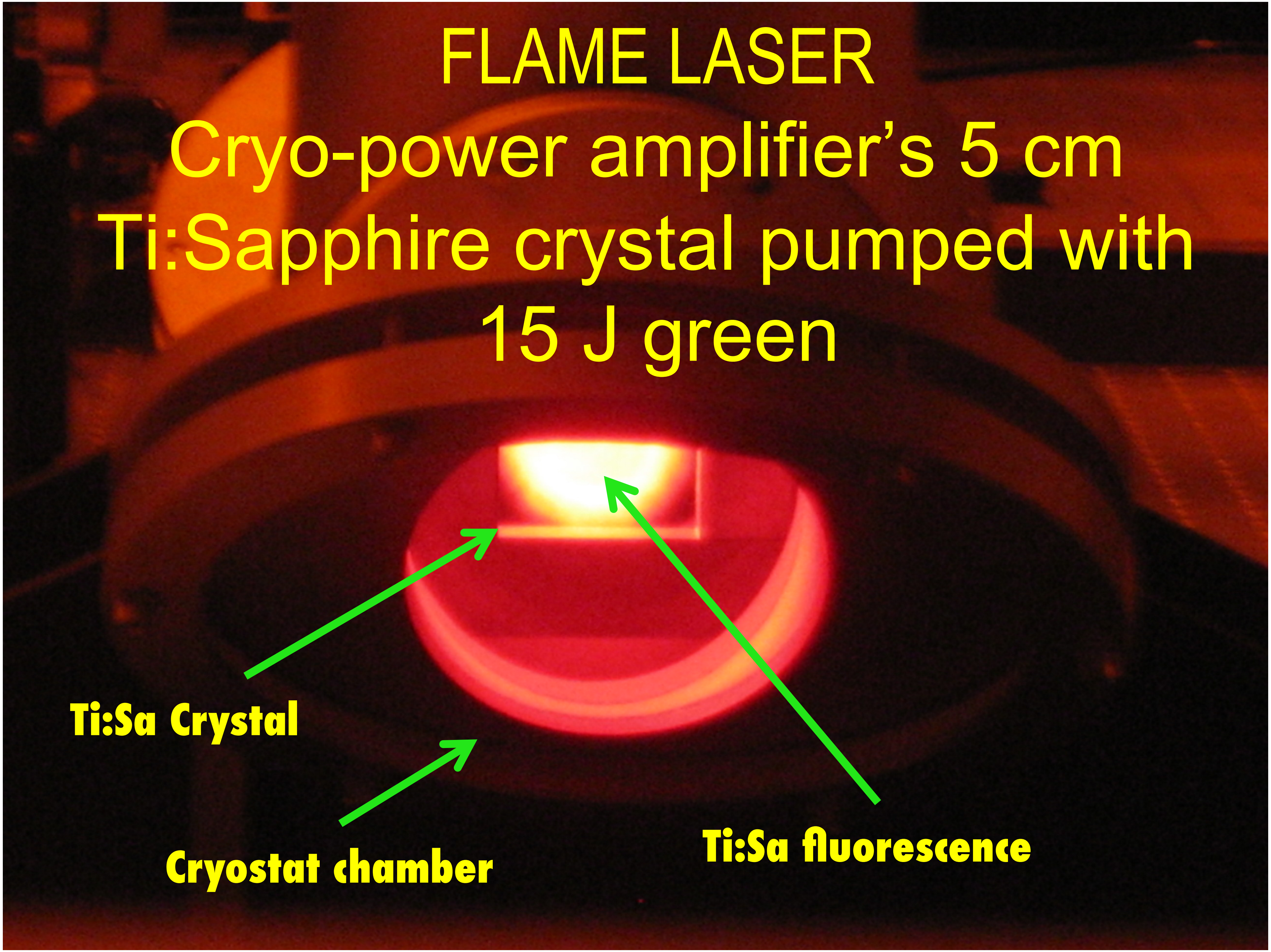
POWER AMPLIFIER

Pictures from the crystal fluorescence during amplification @ 6 J

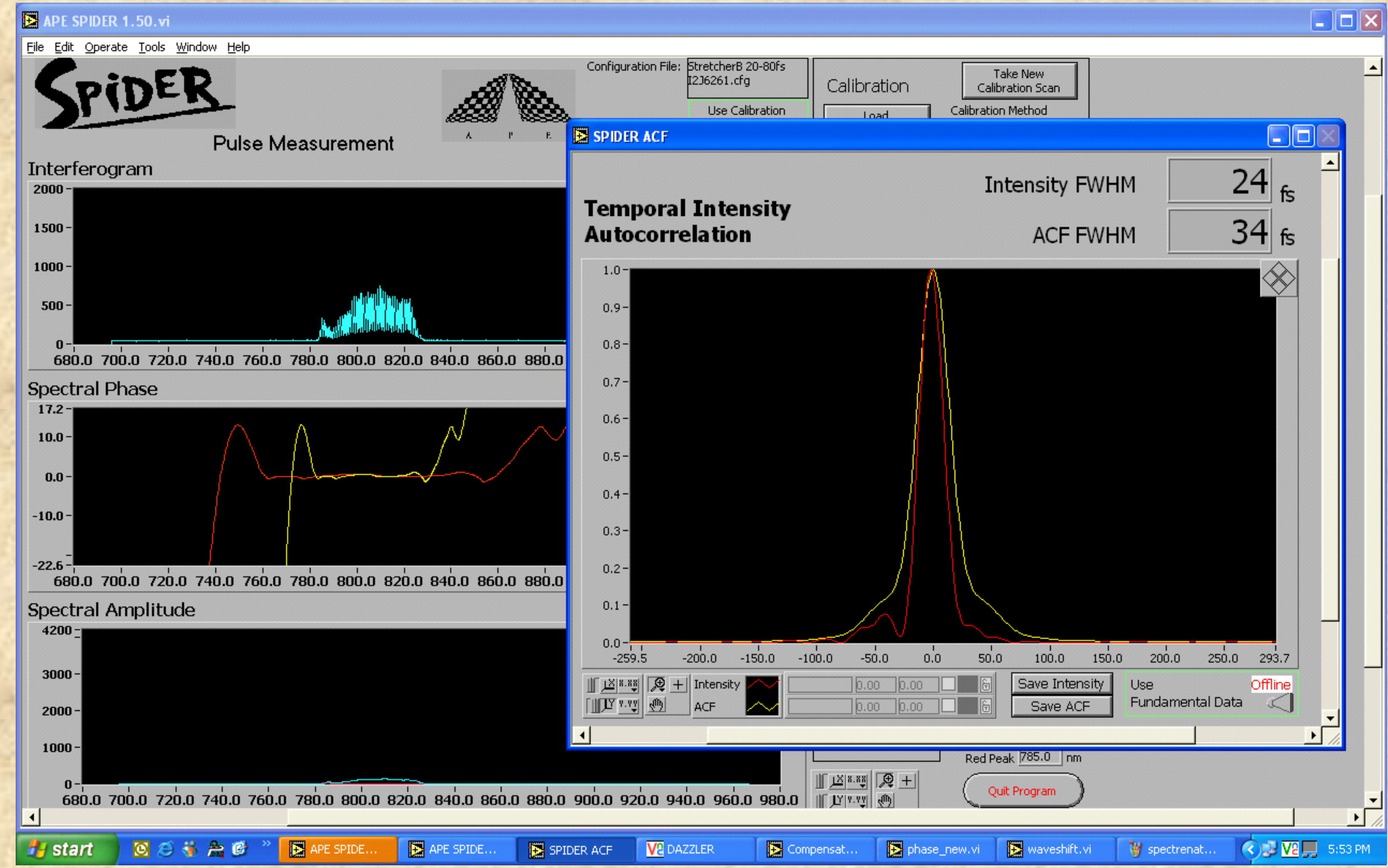


FLAME LASER

Cryo-power amplifier's 5 cm Ti:Sapphire crystal pumped with 15 J green



THE COMPRESSOR: spectral control



Configuration File: StretcherB 20-80fs I2J6261.cfg

Temporal Intensity Autocorrelation

Intensity FWHM 24 fs

ACF FWHM 34 fs

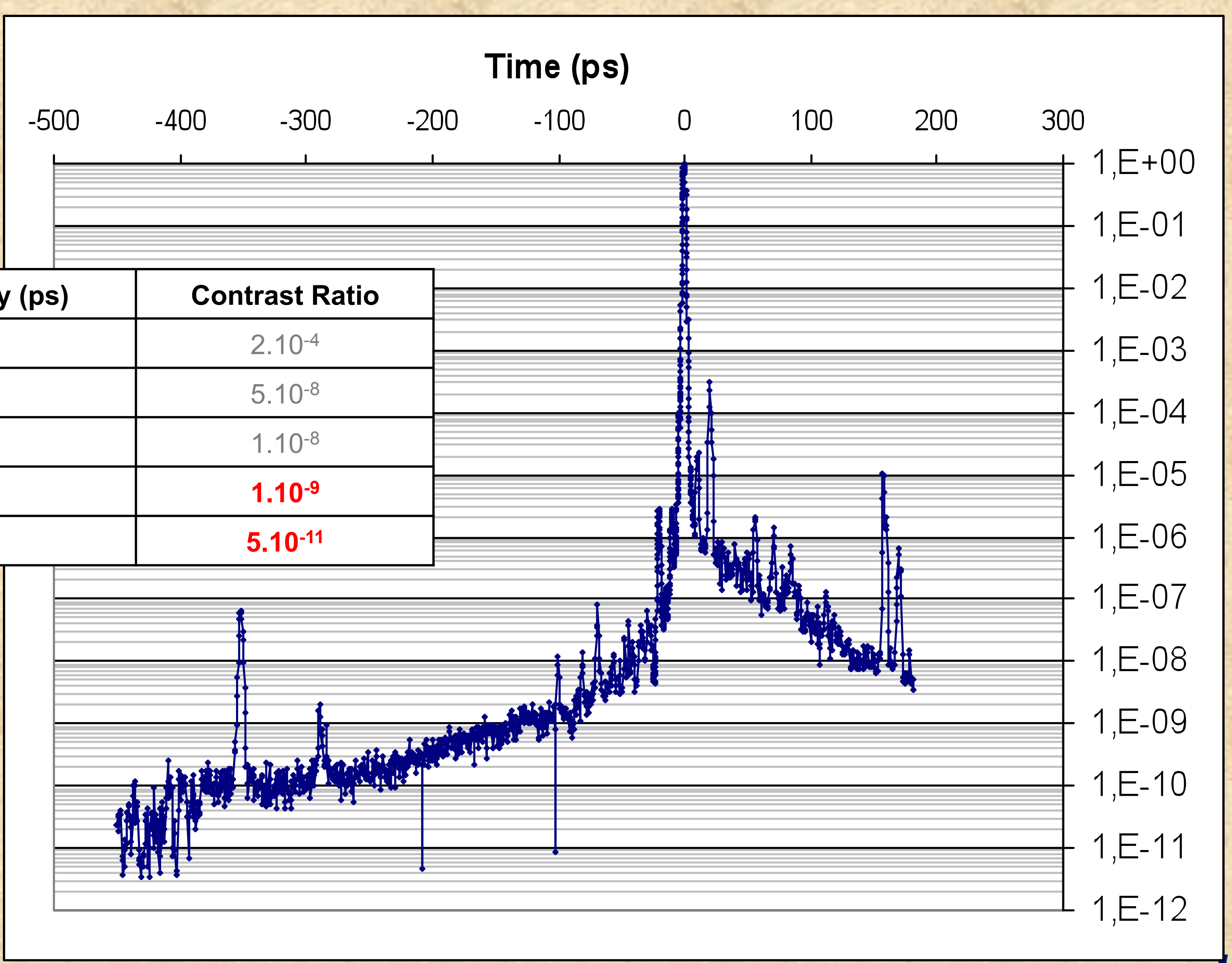
Red Peak 785.0 nm

Pulse duration with the test compressor

Spider measurments

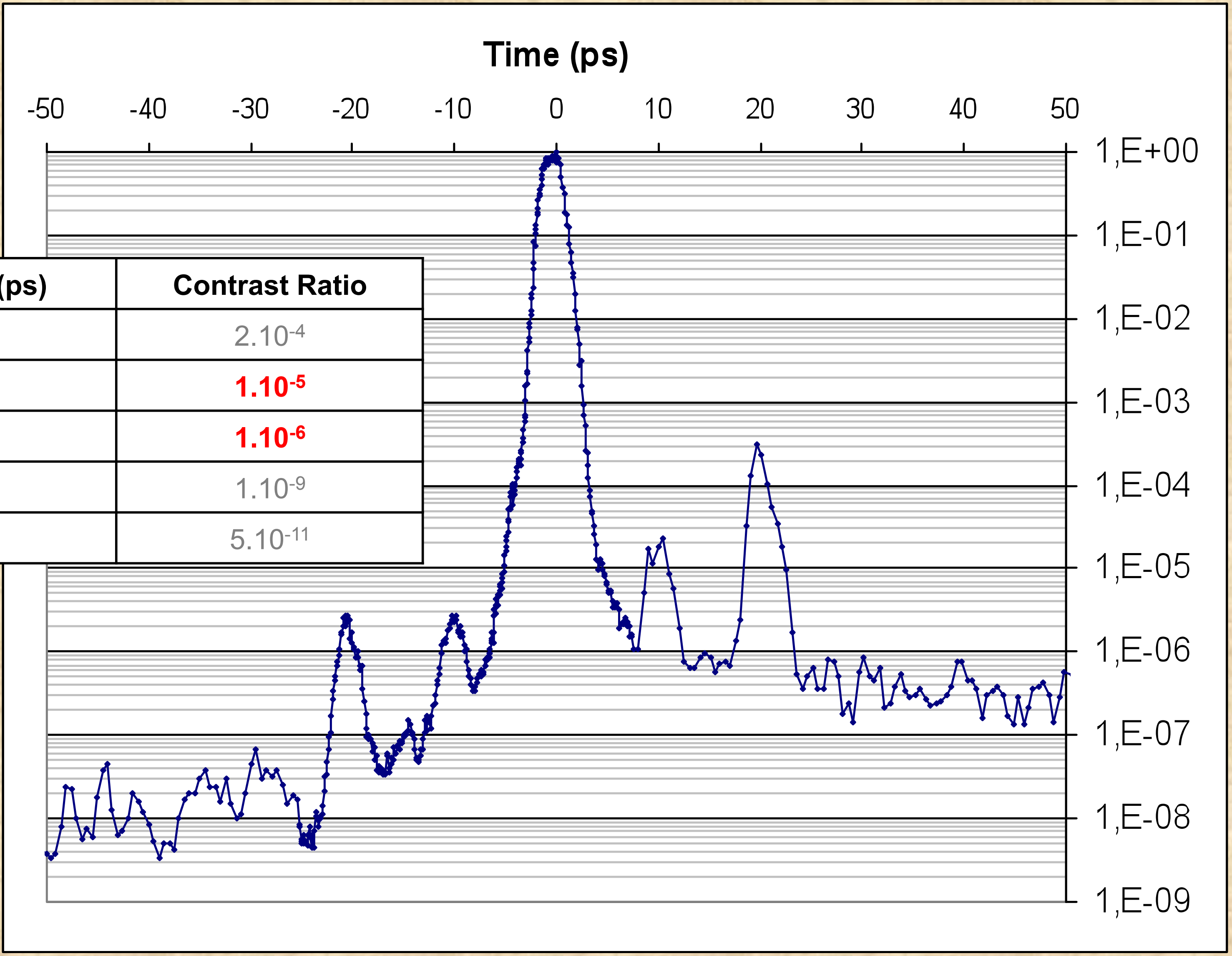
- natural duration < 55 fs
- corrected duration < 25 fs

THE COMPRESSOR sub-ns contrast



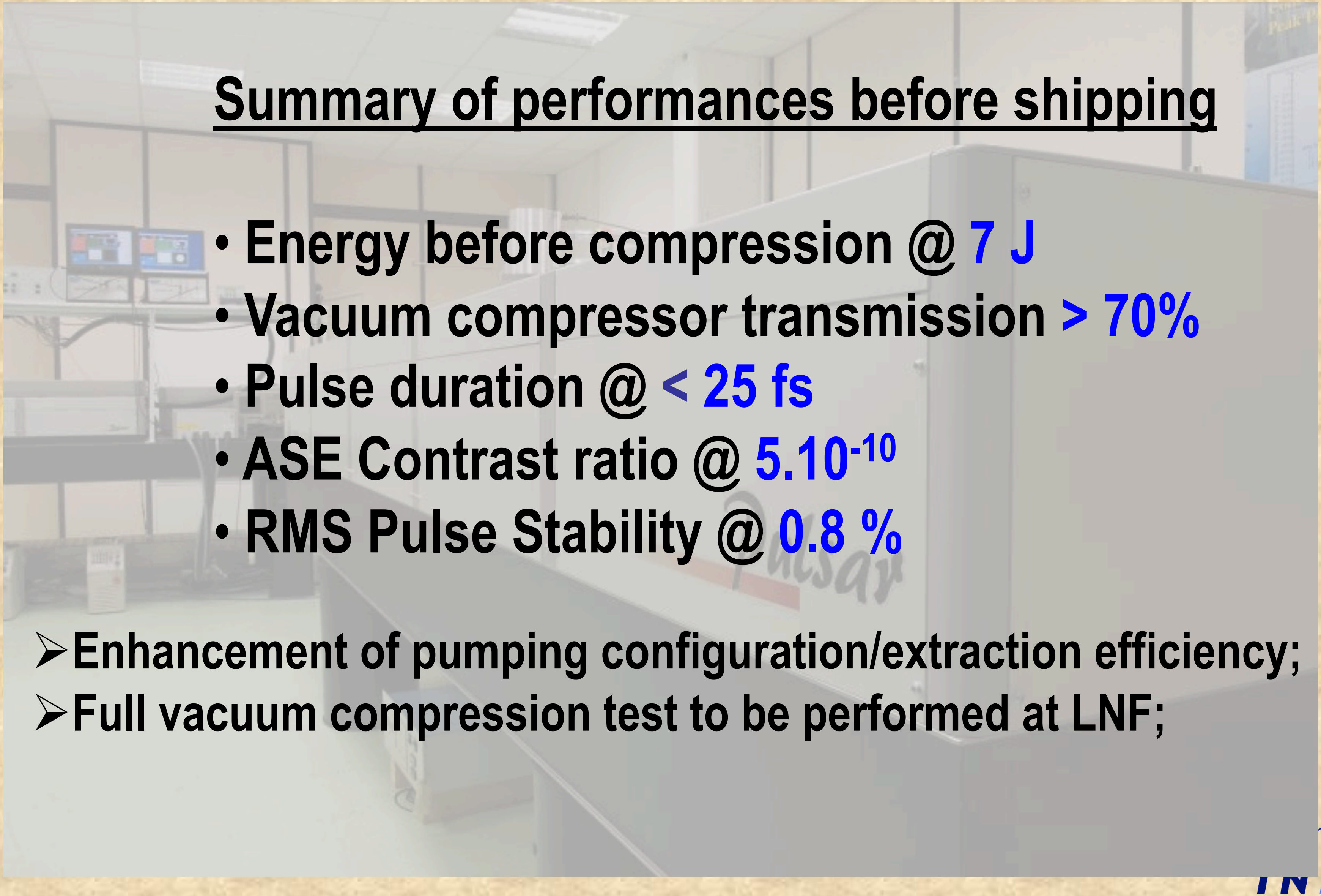
Time Delay (ps)	Contrast Ratio
-1	2.10^{-4}
-5	5.10^{-8}
-10	1.10^{-8}
-150	**1.10^{-9}**
-450	**5.10^{-11}**

THE COMPRESSOR: ps contrast



Time Delay (ps)	Contrast Ratio
-1	2.10^{-4}
-5	**1.10^{-5}**
-10	**1.10^{-6}**
-150	1.10^{-9}
-450	5.10^{-11}

SUMMARY OF FLAME LASER



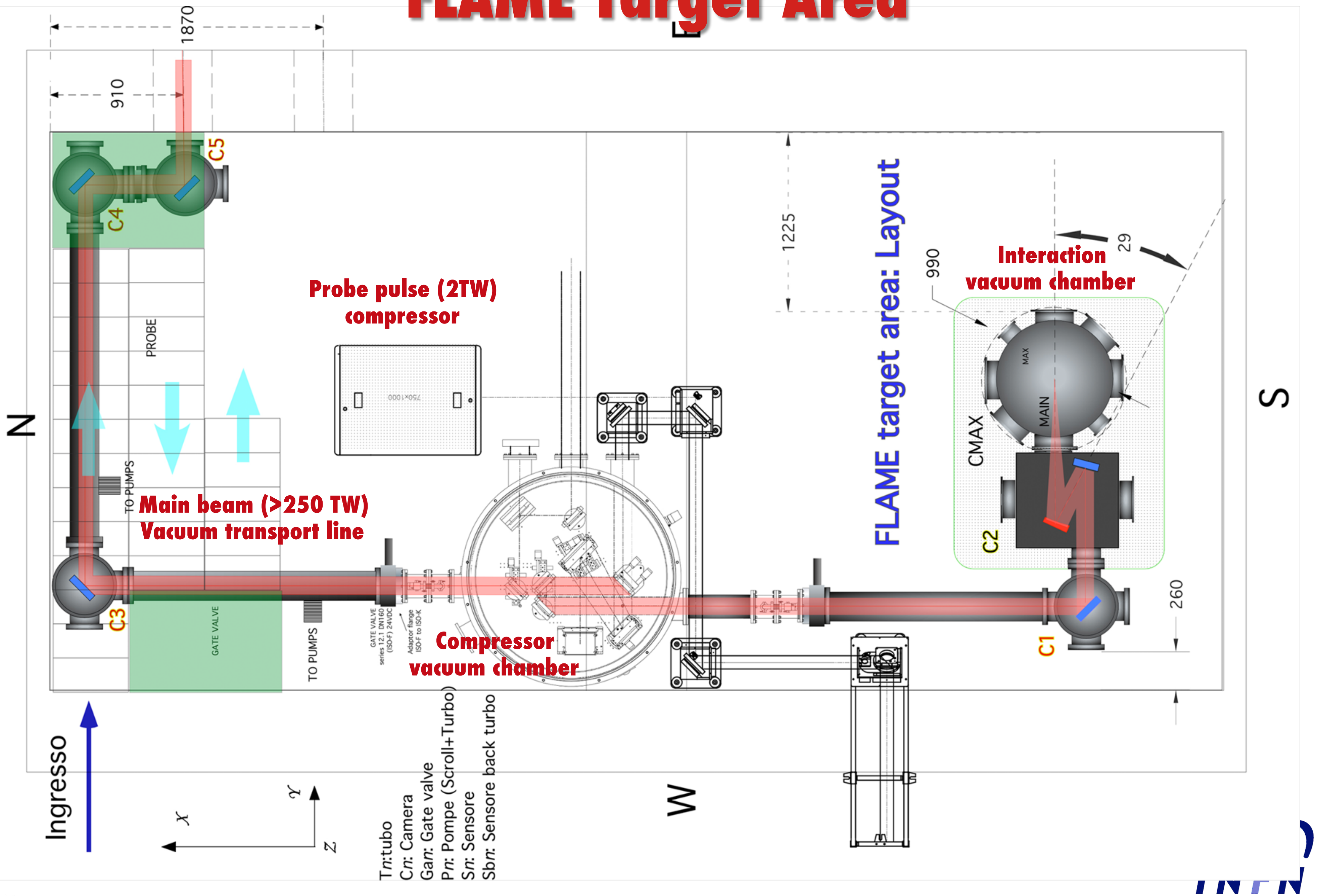
Summary of performances before shipping

- Energy before compression @ 7 J
- Vacuum compressor transmission > 70%
- Pulse duration @ < 25 fs
- ASE Contrast ratio @ 5.10^{-10}
- RMS Pulse Stability @ 0.8 %

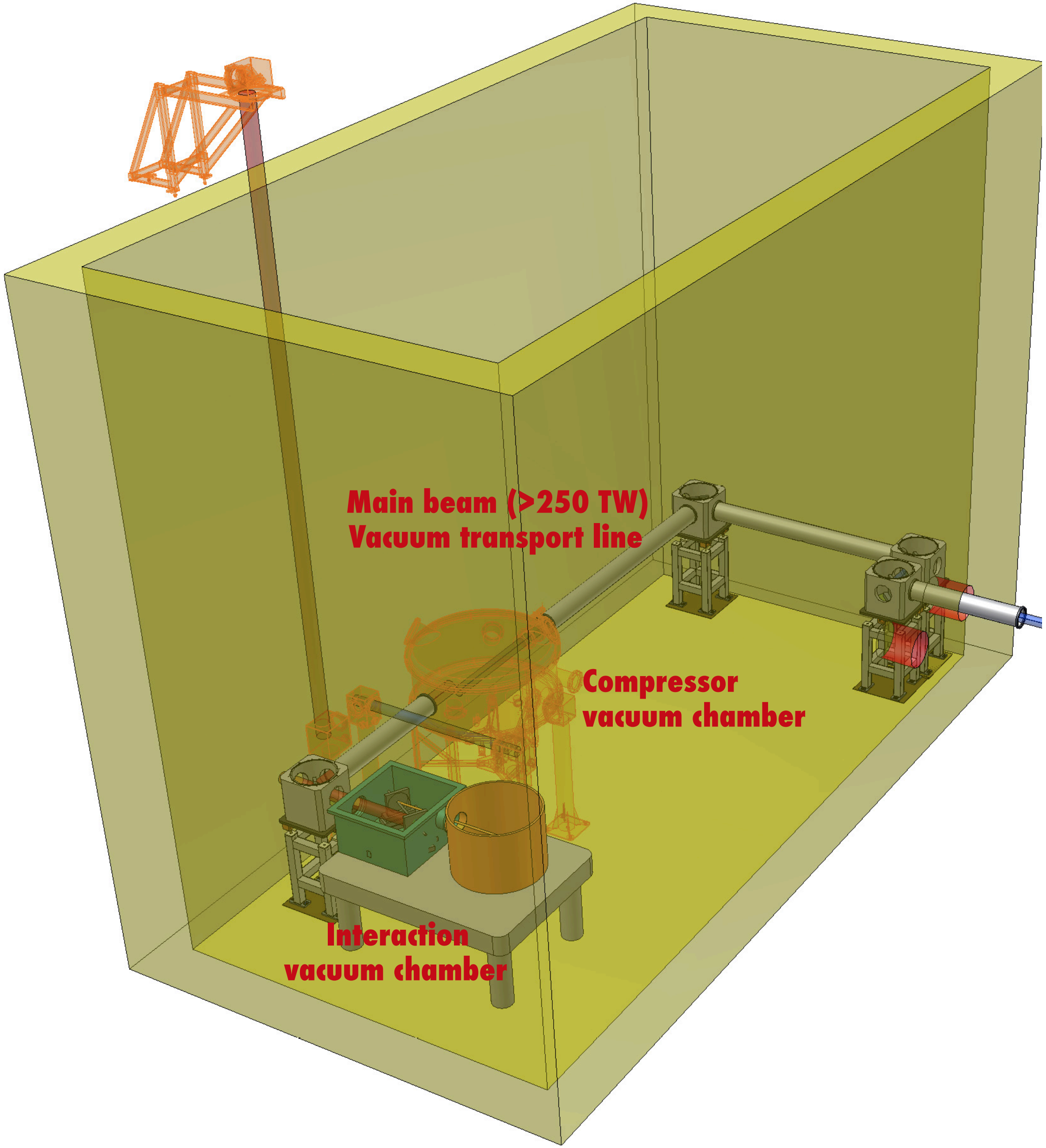
- ➢Enhancement of pumping configuration/extraction efficiency;
- ➢Full vacuum compression test to be performed at LNF;

FLAME target area

FLAME Target Area

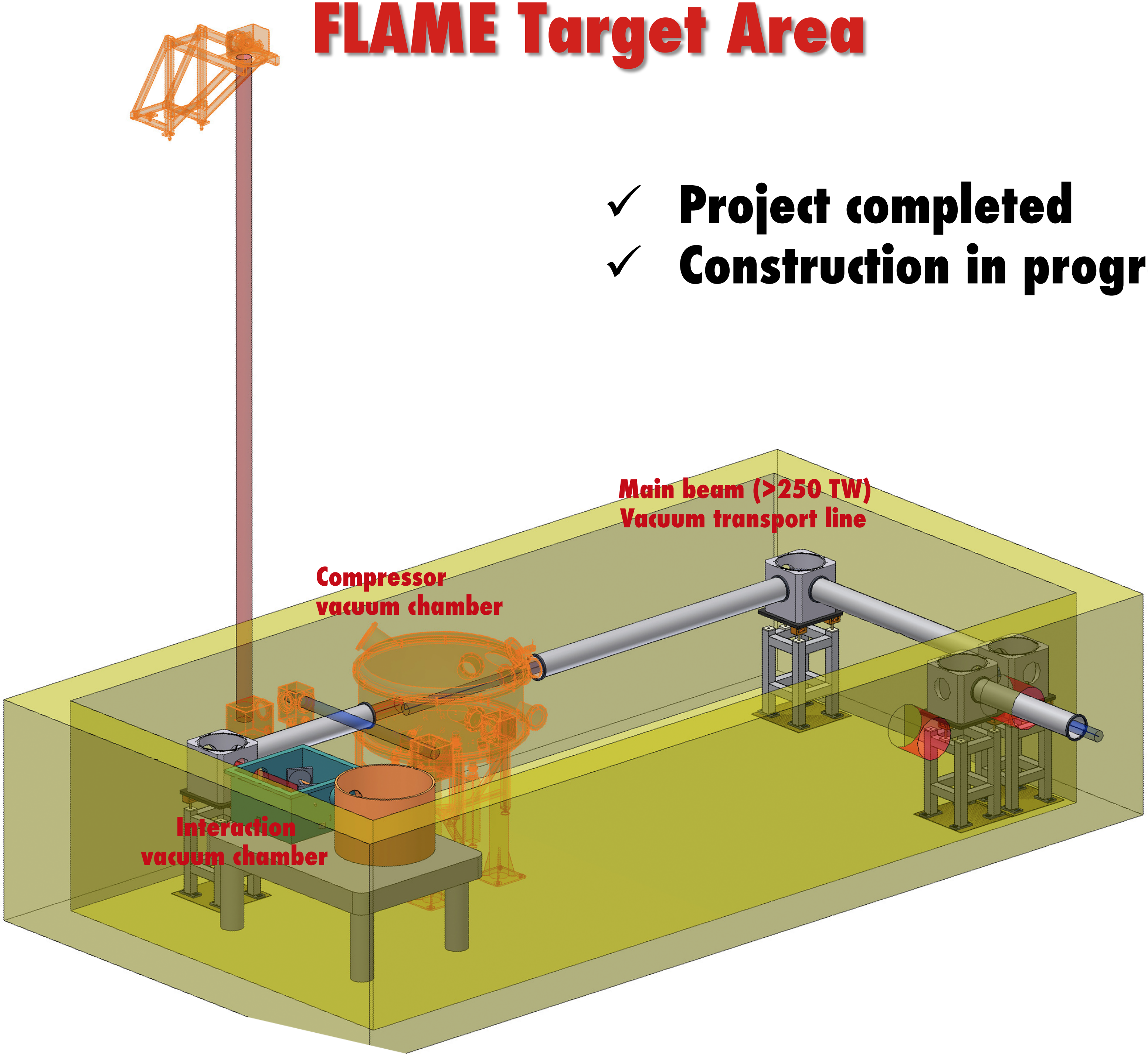


FLAME Target Area



FLAME Target Area

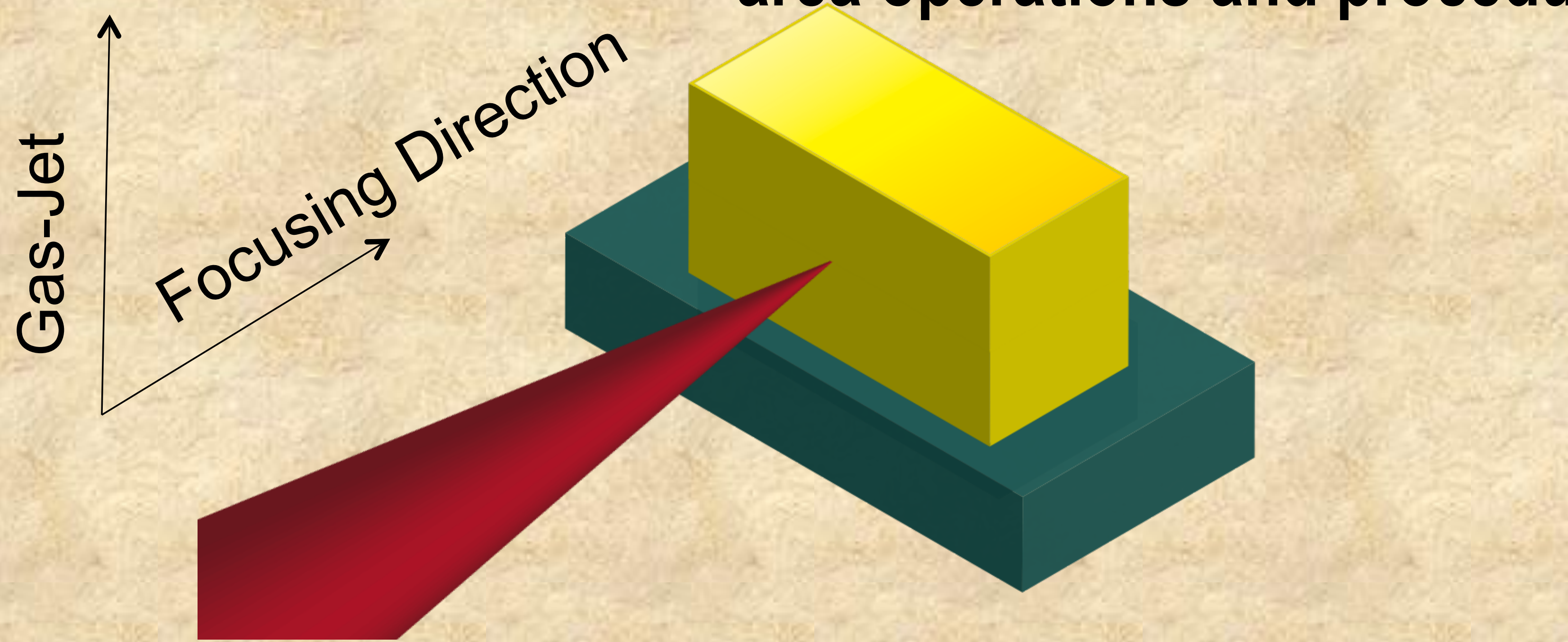
- ✓ **Project completed**
- ✓ **Construction in progress**



First “test” experiment

THE "TEST" SELF-INJECTION EXPERIMENT

MAIN TASK: establish performance of the FLAME laser system in real experimental conditions and test target area operations and procedures

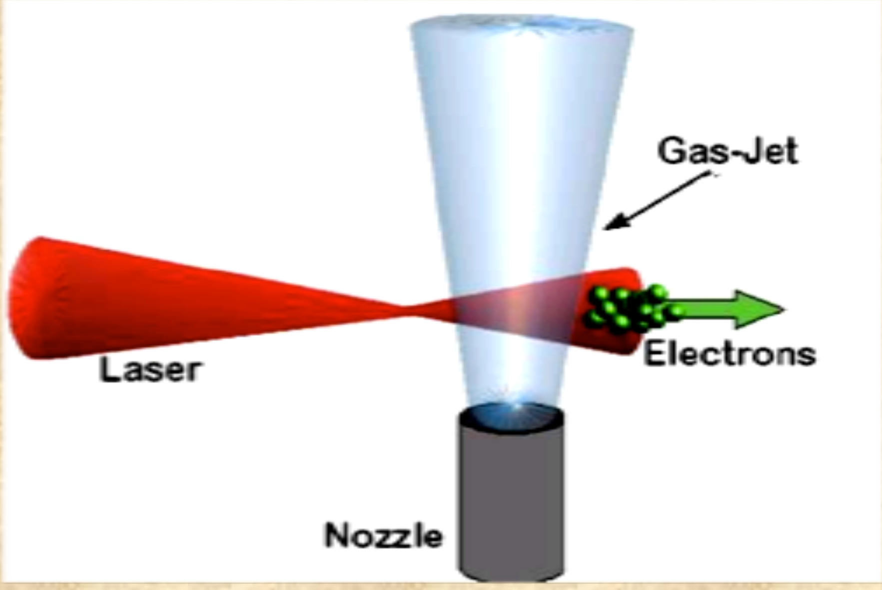


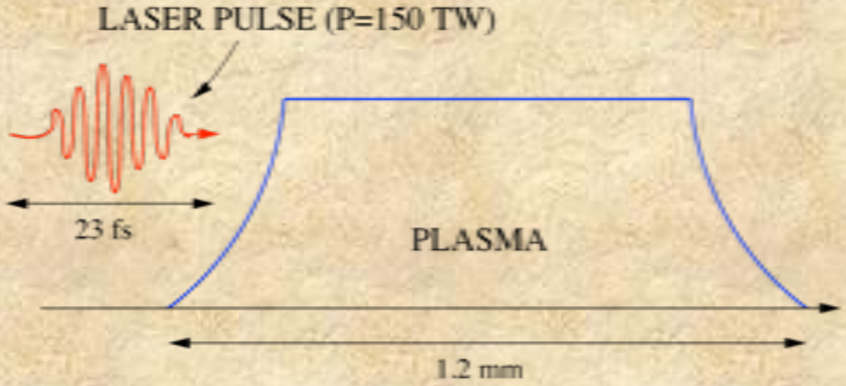
A supersonic gas–jet is used as a target. gas–jet targets have been successfully used and tested in the CEA-Saclay and "pilot| Pisa esperiment and offer ideal conditions for both self-injection measurements and laser pulse characterisation via optical probing

A.Giulietti et al. Phys.Rev.Lett, 105002, 2008.

Self-injection simulations
(di C. BENEDETTI ET AL.,)

- (Half power) FLAME laser
  - P =150 TW, $\tau_{fwhm} = 24$ fs
  - waist: $w_0 = 8 \div 40$ ($1/e^2$ radius of the laser intensity profile, $w_{fwhm} \simeq 1.2\, w_0$)
  - norm. vector potential $a_0 \equiv \frac{eA_{laser}}{mc^2} = 8.5 \cdot 10^{-10}\sqrt{I[\text{W/cm}^2](\lambda[\mu\text{m}])^2} \geq 2$



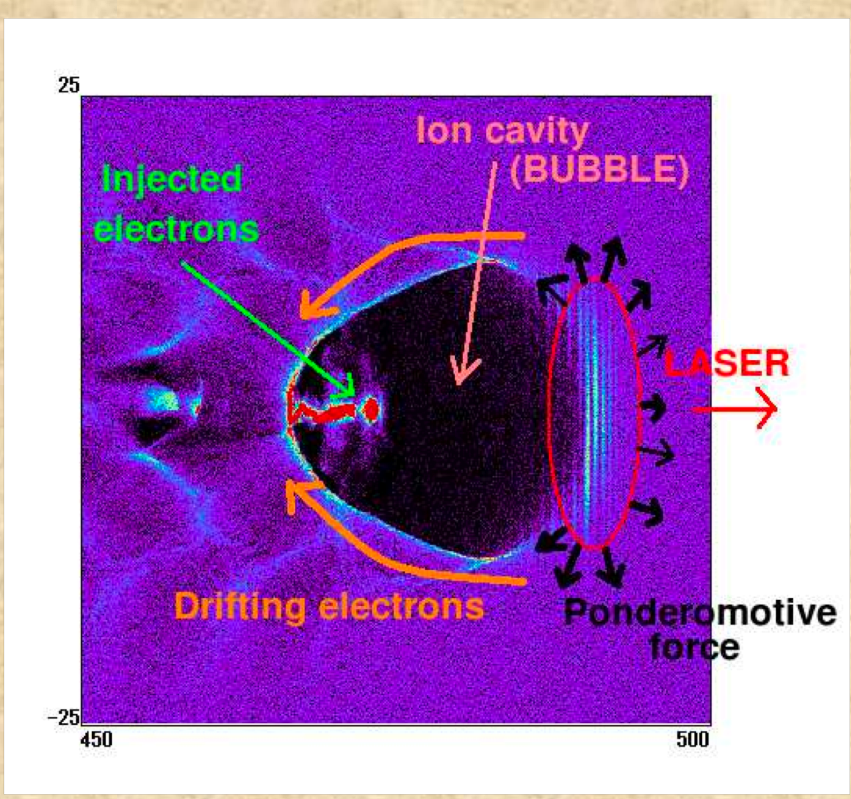


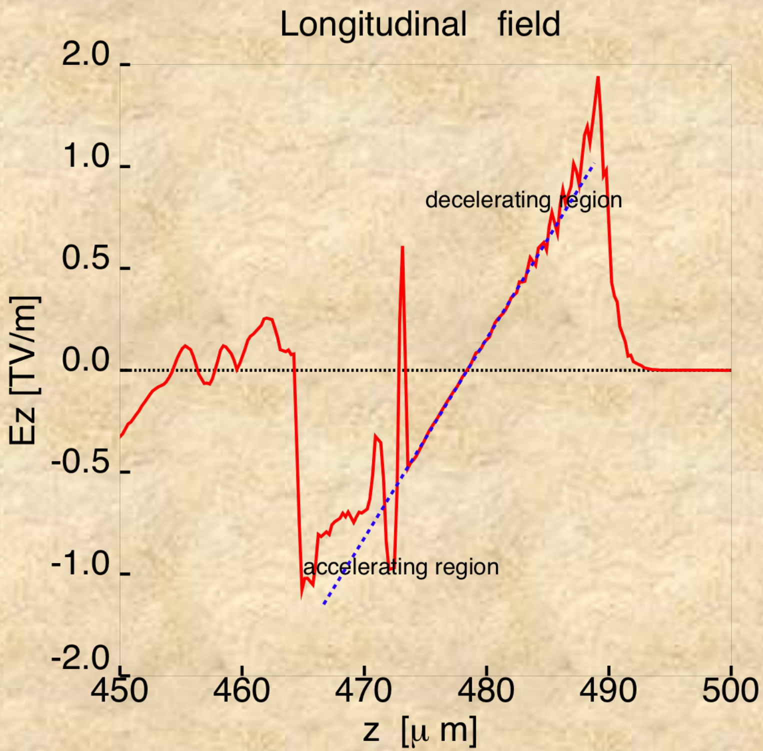
- Two regimes:

1. $w_0 < \lambda_p \Rightarrow$ **Nonlinear 3D regime (bubble)**
2. $w_0 > \lambda_p \Rightarrow$ **Nonlinear "1D-like" regime** (+ properly modulated gas-jet)

SIMULAZIONI self-injection
(di C. BENEDETTI ET AL.,)

- **Nonlinear 3D regime (bubble)** [a]





- $R_{bub} \simeq O(\lambda_p) \qquad E_z^{(max)} \simeq 100\sqrt{n_0[\mathrm{cm}^{-3}]} \times a_0 \quad [\mathrm{V/m}]$
- $\begin{cases} v_{elect} \simeq c \\ v_{bub} \simeq c(1 - 3\omega_p^2/(2\omega_0^2)) < v_{elect} \Rightarrow \text{acc. length is finite + monochromaticity} \end{cases}$

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[a] S. Gordienko and A. Pukhov, Phys. Plas. 12 (2005) / W. Lu *et al*. PRSTAB 10 (2007)

SIMULAZIONI ALADYN
(di C. BENEDETTI ET AL.,)

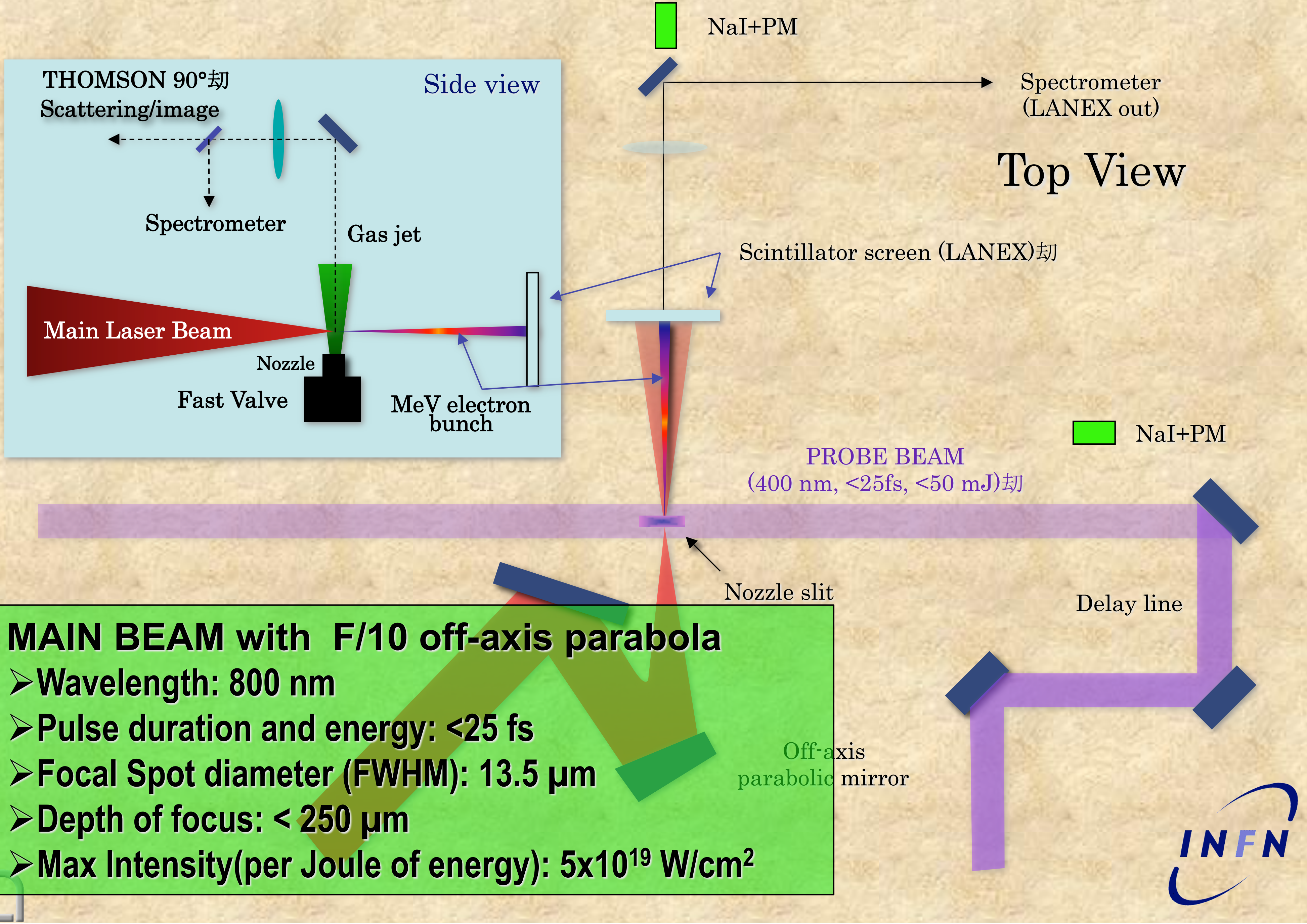
1. "best" (in terms of monochromaticity) bunch: $L_d \equiv L_{gasjet} \simeq 0.9 \div 1$ mm
   $w_0 \simeq R_{bub} \simeq 9$ μm, $I \simeq 1.2 \cdot 10^{20}$ W/cm^2, $a_0 = 7.4$
   $L_{pd} \simeq 1.2$ mm > L_{gasjet}, L_d
   $n_p \simeq 1 \cdot 10^{19}$ cm^{-3}
   $W \simeq 400$ MeV

2. highest energy for a given L_{gasjet} ($\simeq$ 1 mm): $\frac{\partial E}{\partial w_0}\Big|_{L_{gasjet}} = 0$
   $w_0 \simeq R_{bub} \simeq 10$ μm, $I \simeq 9.7 \cdot 10^{19}$ W/cm^2, $a_0 = 6.7$
   $L_d \simeq 1.5$ mm > L_{gasjet}, $L_{pd} \simeq 1.7$ mm > L_{gasjet}
   $n_p \simeq 7.7 \cdot 10^{18}$ cm^{-3}
   $W \simeq 450$ MeV (monochromaticity ???)

3. $W = 1$ GeV monochromatic electron beam (with gas jet):
   $w_0 \simeq R_{bub} \simeq 14$ μm, $I \simeq 5 \cdot 10^{19}$ W/cm^2, $a_0 = 4.8$
   $L_d \equiv L_{gasjet} \simeq$5.6 mm, $L_{pd} \simeq 4.4$ mm < L_{gasjet} (!!!)
   $n_p \simeq 3 \cdot 10^{18}$ cm^{-3}

4. Out of "bubble" regime: $a_0 \lesssim 3.5$
   $w_0 \gtrsim 19$ μm, $I < 2.6 \cdot 10^{19}$ W/cm^2

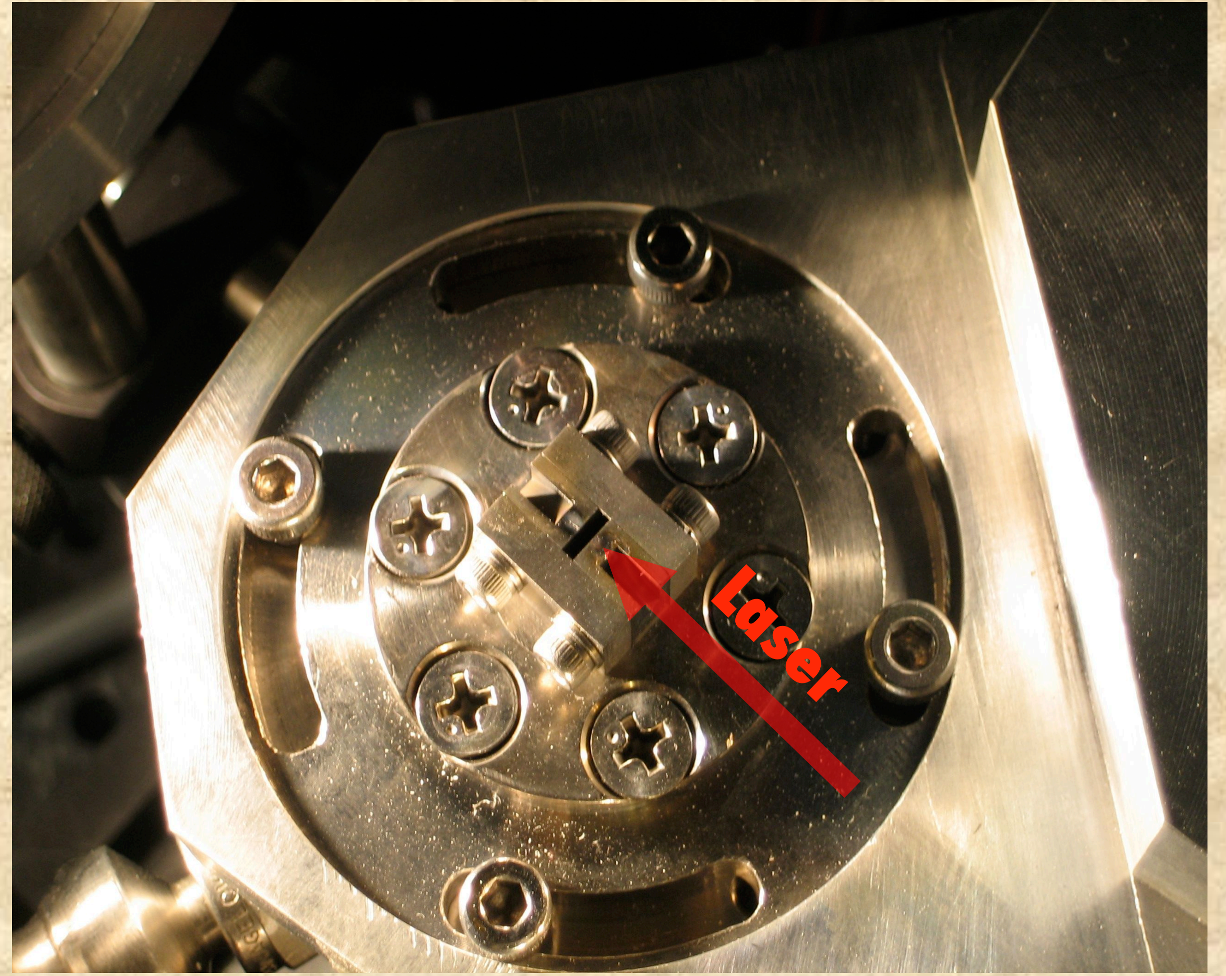
Planned experimental set up



MAIN BEAM with F/10 off-axis parabola

- ➢Wavelength: 800 nm
- ➢Pulse duration and energy: <25 fs
- ➢Focal Spot diameter (FWHM): 13.5 μm
- ➢Depth of focus: < 250 μm
- ➢Max Intensity(per Joule of energy): $5x10^{19}$ W/cm^2

Pulsed gas-Jet nozzle



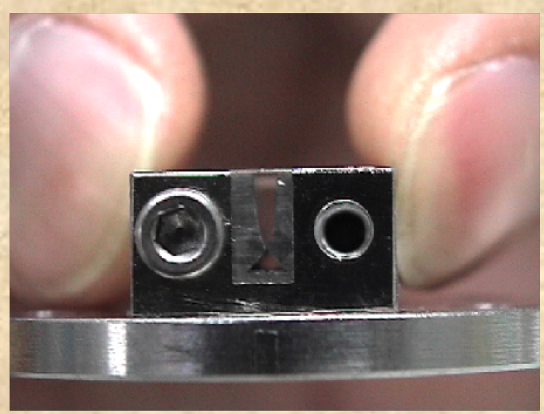
Nozzle size: 4mm x 1.2mm or 10 mm x 4 mm

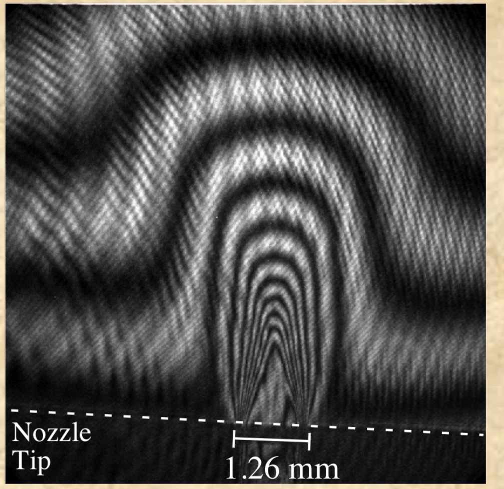
<u>Possible application of a continuous gas-jet under consideration (v. talk L. Gialanella, Ven 20. H.11.10)</u>

High-density well-defined gas jet (1)

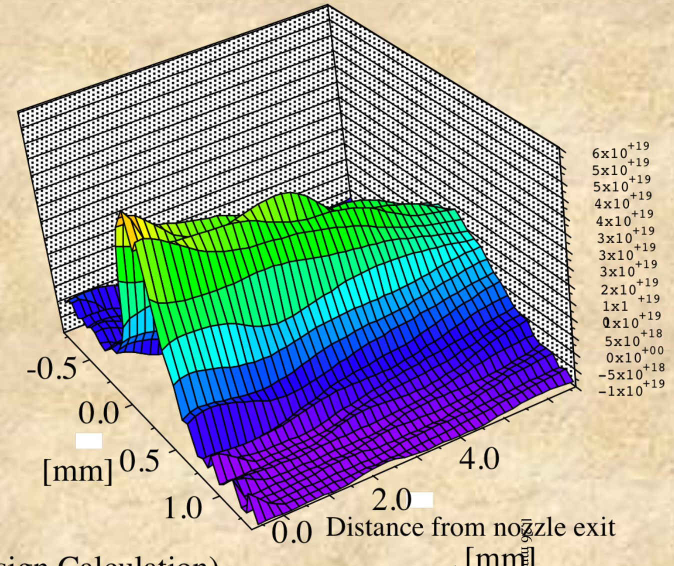
Shockwave free supersonic nozzle

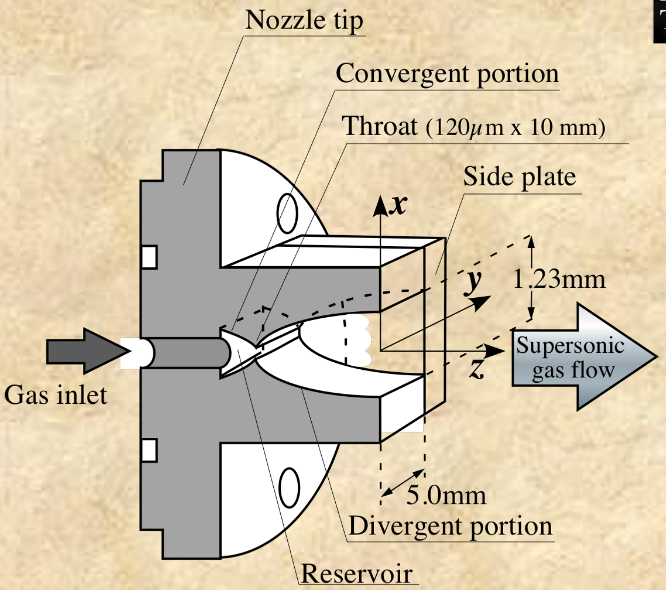
Nuclear Engineering Research Laboratory
Graduate School of Engineering
University of Tokyo

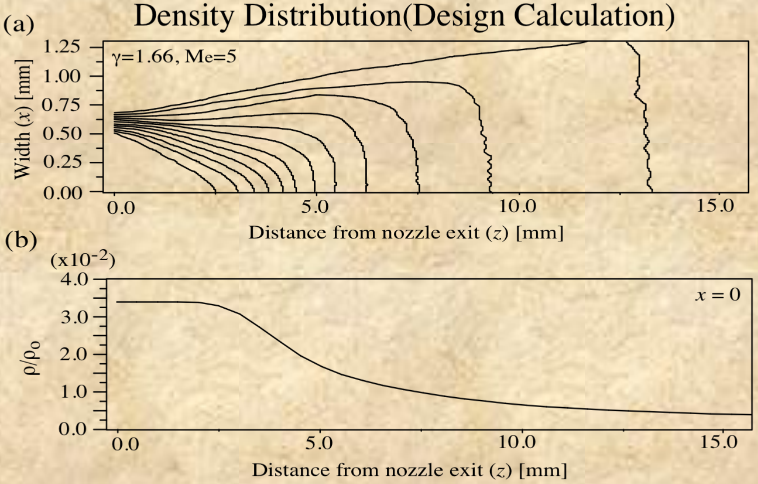


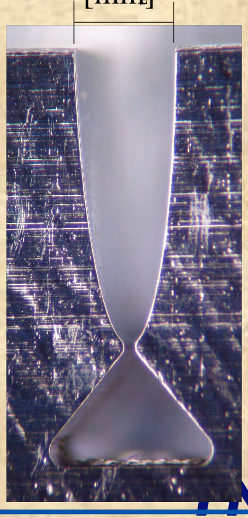


Measured Density Distribution









Courtesy of T. Hosokai, Tokyo Institute of Technology

“TEST” EXPERIMENT DIAGNOSTICS

OPTICAL DIAGNOSTICS FOR LASER PROPAGATION STUDIES

- Thomson scattering
- Femtosecond optical probing
- Transmitted and scattered beam spectroscopy

ELECTRON DIAGNOSTICS FOR ELECTRON ACCELERATION MEAS.

- Establish self-injection acceleration conditions
- Provide benchmarking for modelling

OPTICAL DIAGNOSTICS: THOMSON SCATTERING

In the classical picture of Thomson scattering, the electrons oscillate in the laser field and, in turn, emit radiation. The properties of this scattered radiation are thus related to the properties of the medium. The particle will move mainly along the direction of the oscillating electric field, resulting in electromagnetic dipole radiation. The scattering can be described in terms of the emission coefficient defined as ε where:

$$\epsilon dt dV \, d\Omega d\lambda$$

is the energy scattered by a volume element dV in time dt into the solid angle dW between wavelengths λ and λ + Δλ.

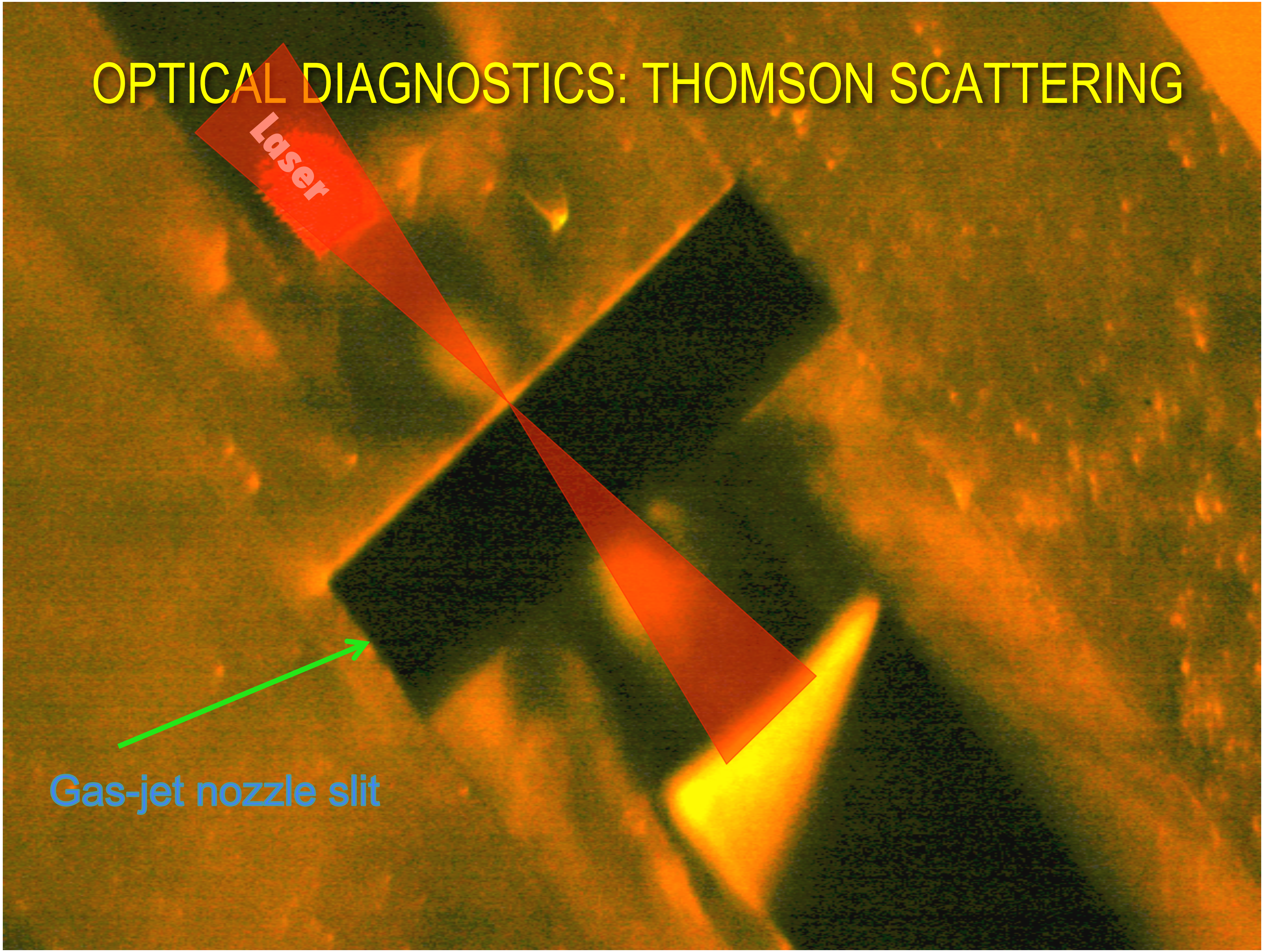
In our case, with the diagnostic placed perpendicularly to the plane in which the laser field oscillates, the emission coefficient is:

$$\epsilon = \frac{\pi\sigma}{2} I n_e$$

where s is the Thomson differential cross section, n_e is the electron density, and I is the incident flux.

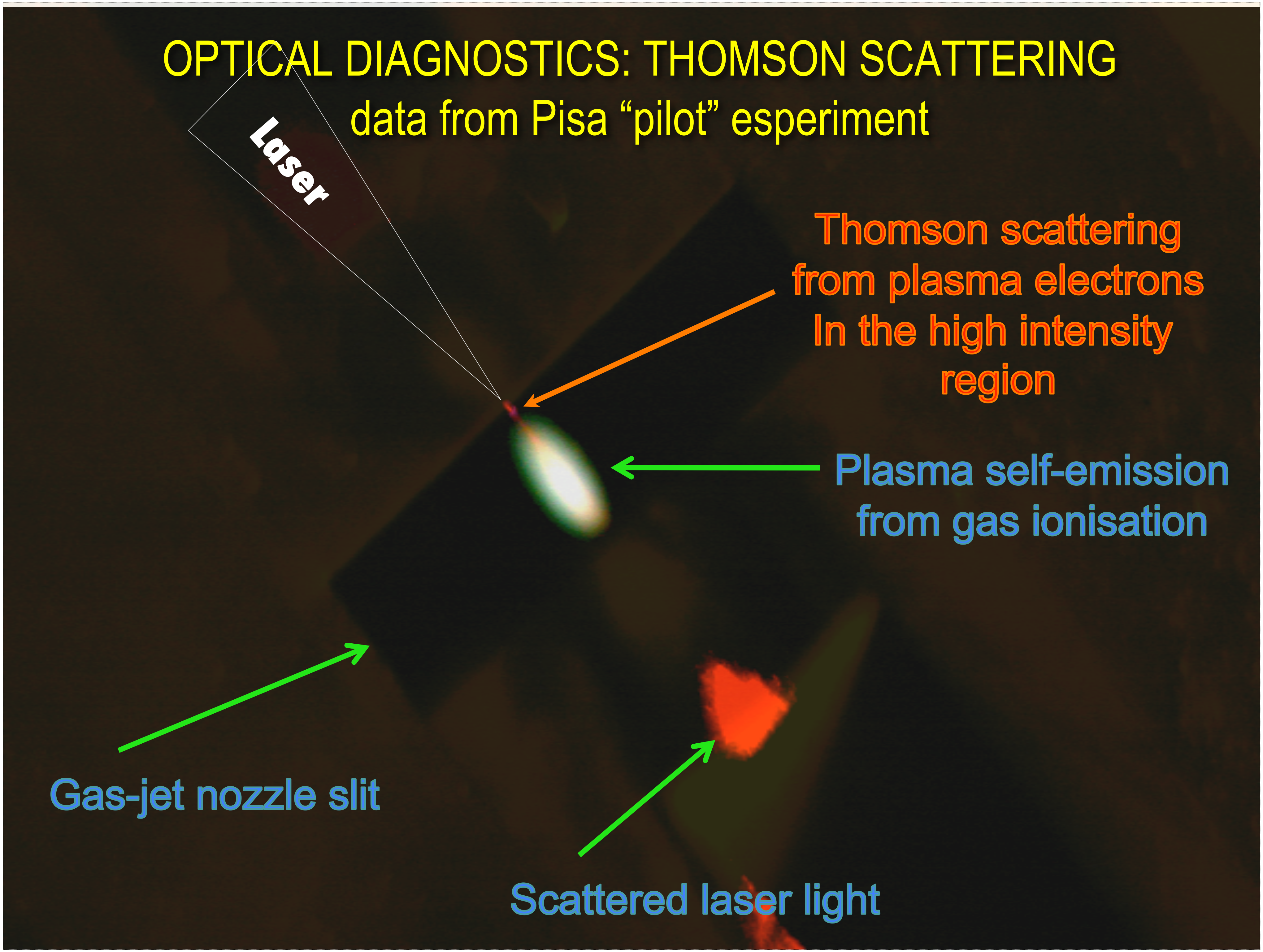
This result simply shows that the Thomson scattering provides combined information on the laser intensity and electron density.

OPTICAL DIAGNOSTICS: THOMSON SCATTERING



OPTICAL DIAGNOSTICS: THOMSON SCATTERING

data from Pisa “pilot” esperiment



Thomson scattering from plasma electrons In the high intensity region

Plasma self-emission from gas ionisation

Gas-jet nozzle slit

Scattered laser light

OPTICAL DIAGNOSTICS: THOMSON SCATTERING

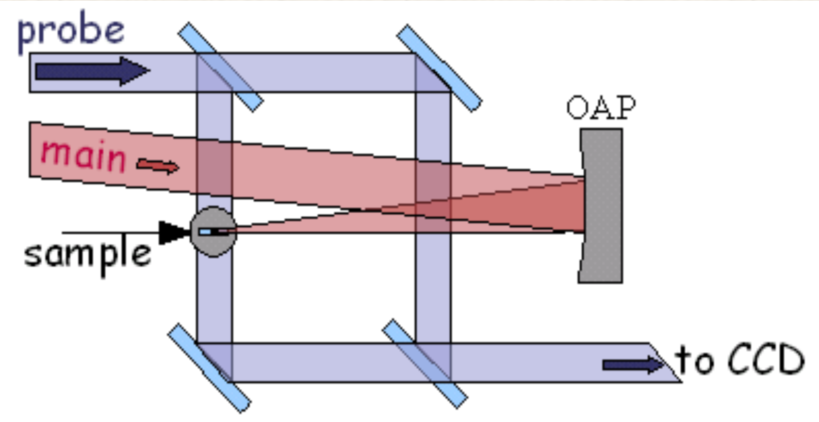
data from Pisa “pilot” esperiment

OPTICAL DIAGNOSTICS: THOMSON SCATTERING

data from Pisa “pilot” esperiment

OPTICAL DIAGNOSTICS: FEMTOSECOND INTERFEROMETRY

- All-optical way to retrieve the electron density map of the accelerating medium
- Exploit a laser beam to probe the plasma via its refractive index effect on the interference fringe pattern
- Use of ultrashort laser pulse enables femtosecond resolution measurements



i.e. : Mach-Zehnder interferometer

- From the refractive index we can get to n_e…

OPTICAL DIAGNOSTICS: FEMTOSECOND INTERFEROMETRY

The total phase shift in the plasma arm (WKBJ approx.) is:

$$\phi = \int k \cdot dl = \int N \frac{\omega}{c} dl$$

Comparing the phase difference between the two arms:

$$\Delta\phi = \int (k_{plasma} - k_0) dl = \int (N-1) \frac{\omega}{c} dl$$

The plasma refractive index is

$$N = \sqrt{1 - \frac{n_e}{n_c}} \approx 1 - \frac{n_e}{2n_c}$$

n_c (0.4 μm) ≈ $6.9 \cdot 10^{21}$ cm^{-3}

$$\Delta\phi \simeq \frac{\pi}{\lambda \cdot n_c} \int n_e dl$$

that can be inverted to obtain $n_e(x,y,z)$

Abel inversion

(under suitable geometrical symmetry, i.e. cylindrical)

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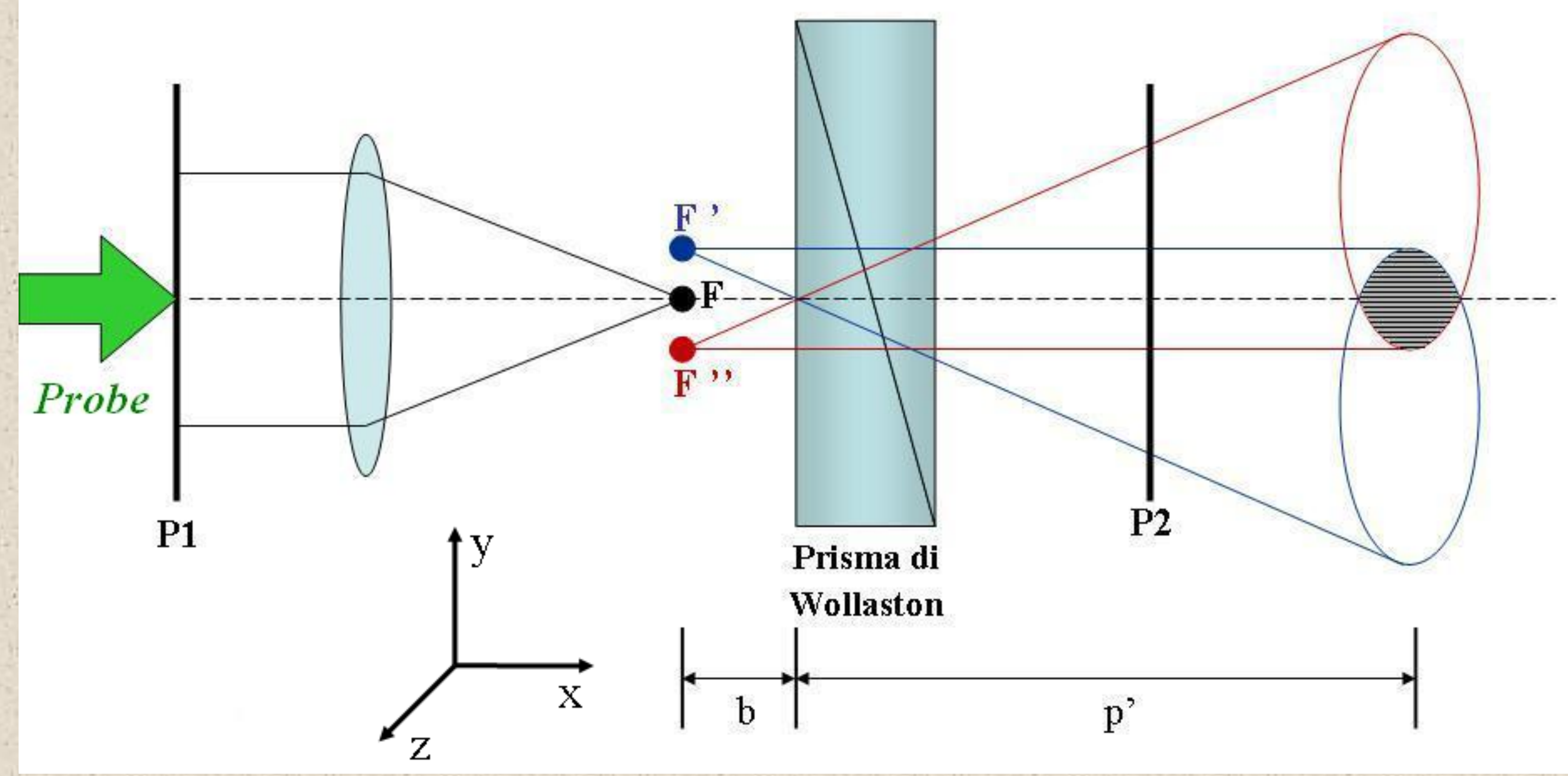
P. Tomassini et al., Appl.Opt., 40(35):6561, (2001).

THE NOMARSKI INTERFEROMETER



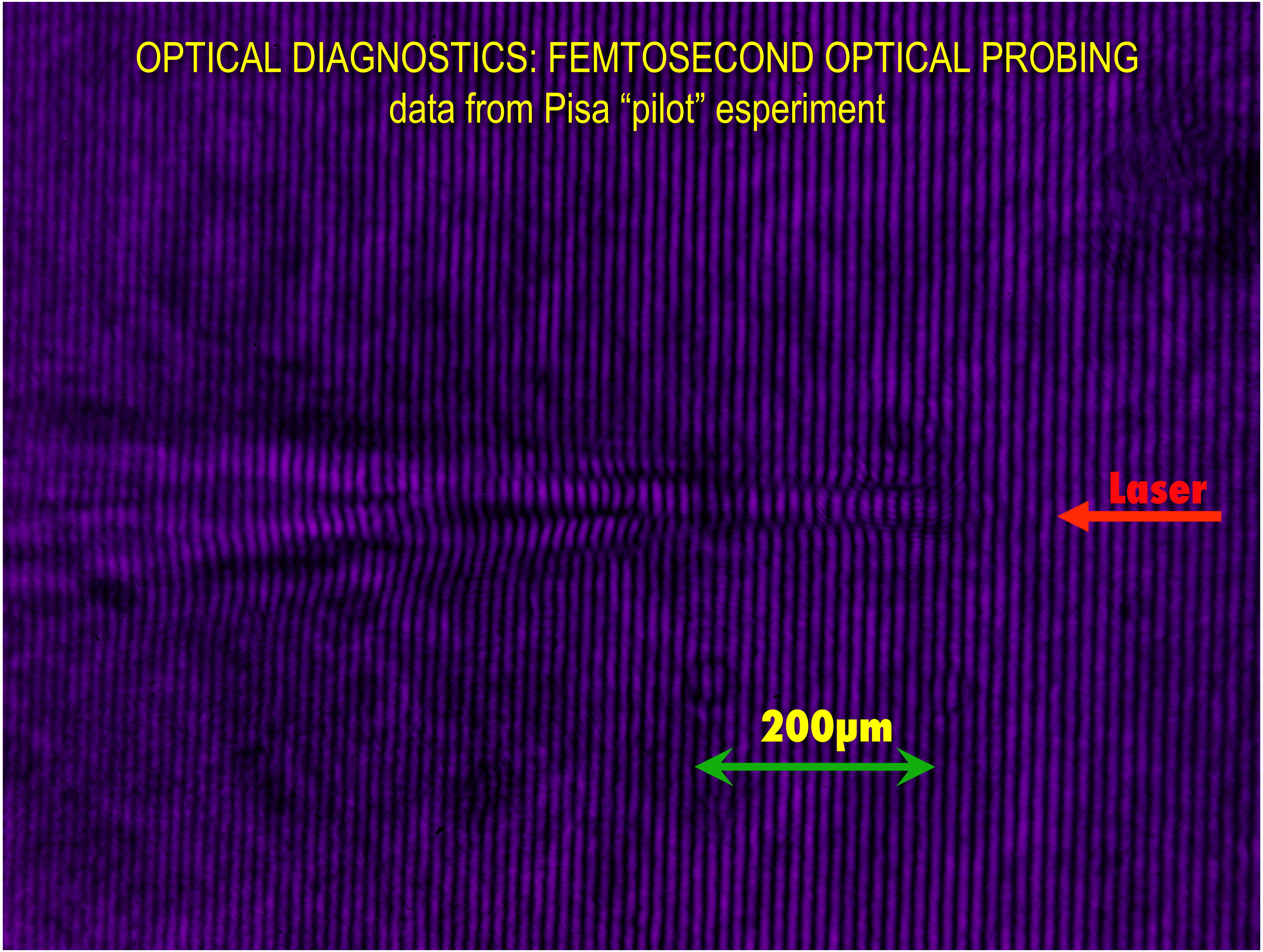
R.Benattar et al, Rev.Sci.Inst. **50**(12),1583 (1979)

- ✓ **It's an in-line set-up**
- ✓ **Enables control of imaging parameters (resolution, f.o.v …)**

- O.Willi, in Laser-Plasma Interactions 4, Proceedings of the XXXV SUSSP, St. Andrews, 1988, edited by M.B. Hooper (SUSSP, Edinburgh, 1989).
- L.A.Gizzi et al. Phys. Rev. E **49**, 5628 (1994); M.Borghesi et al., Phys. Rev. E **54** , 6769 (1996).

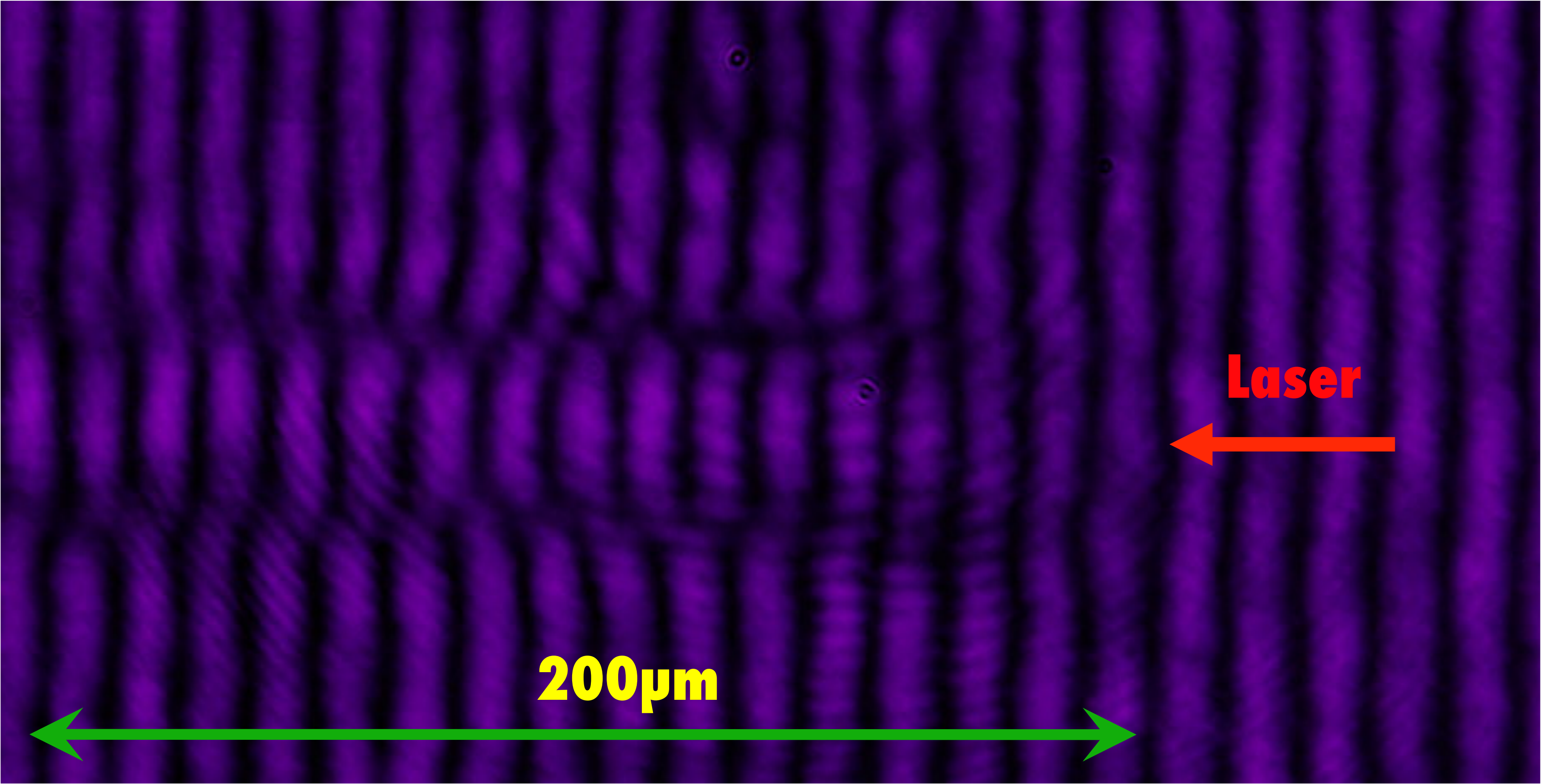
OPTICAL DIAGNOSTICS: FEMTOSECOND OPTICAL PROBING

data from Pisa “pilot” esperiment



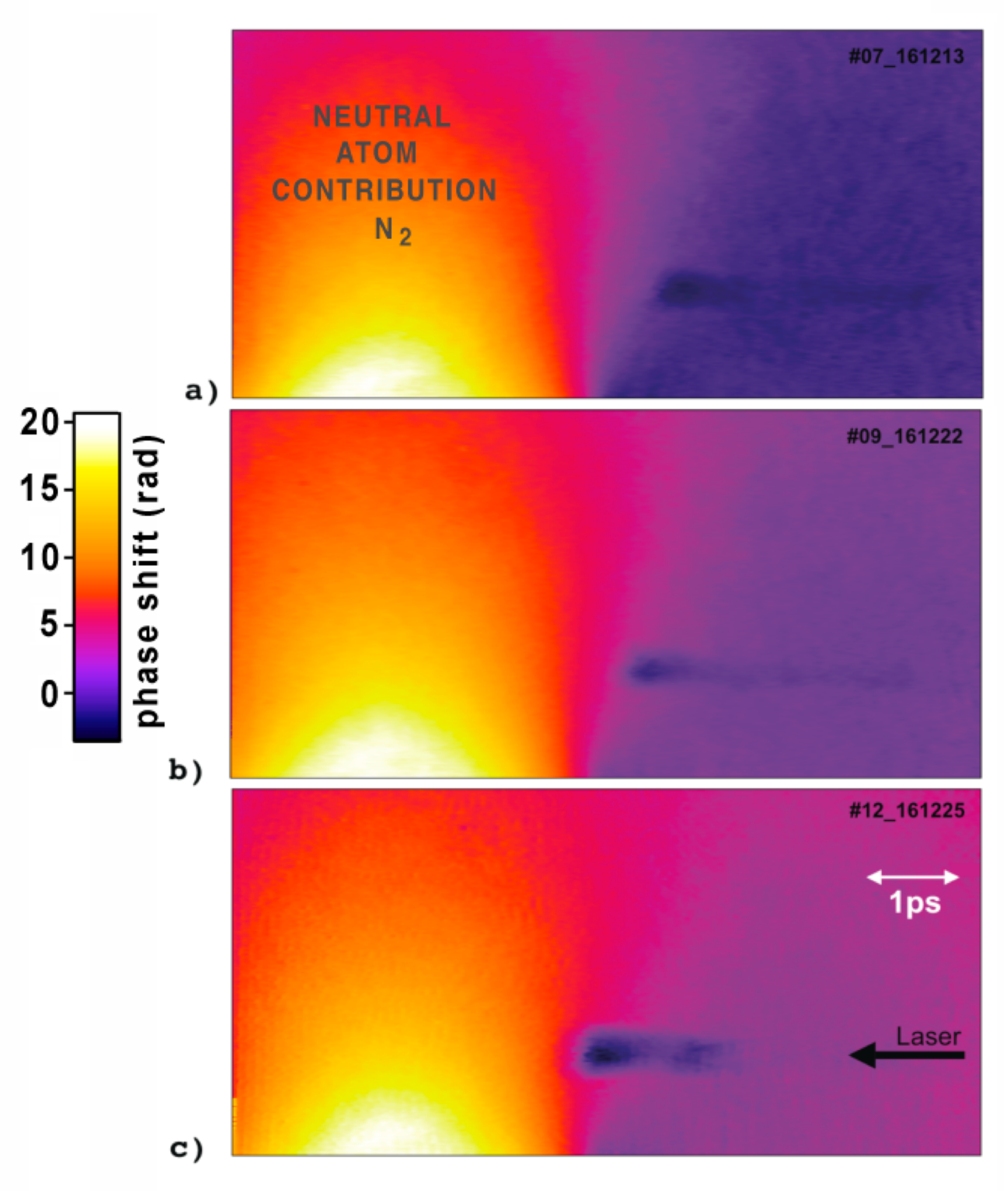
OPTICAL DIAGNOSTICS: FEMTOSECOND OPTICAL PROBING

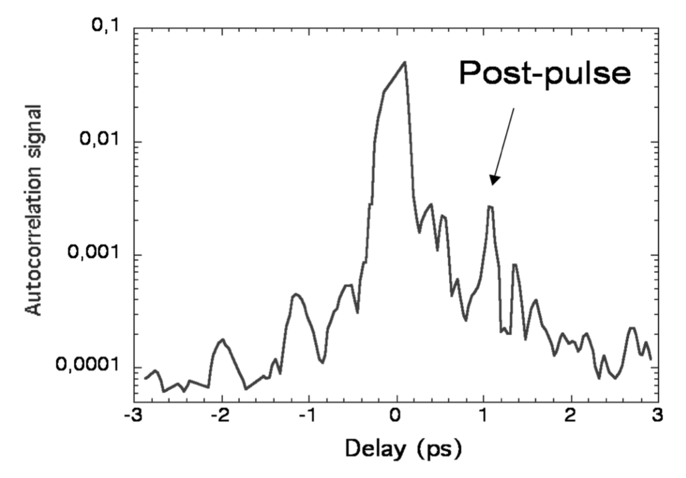
data from Pisa “pilot” esperiment



L.A.Gizzi et al., Channeling ‘09

OPTICAL PROBING: TRACKING FEMTOSECOND PULSES
data from CEA-Saclay esperiment





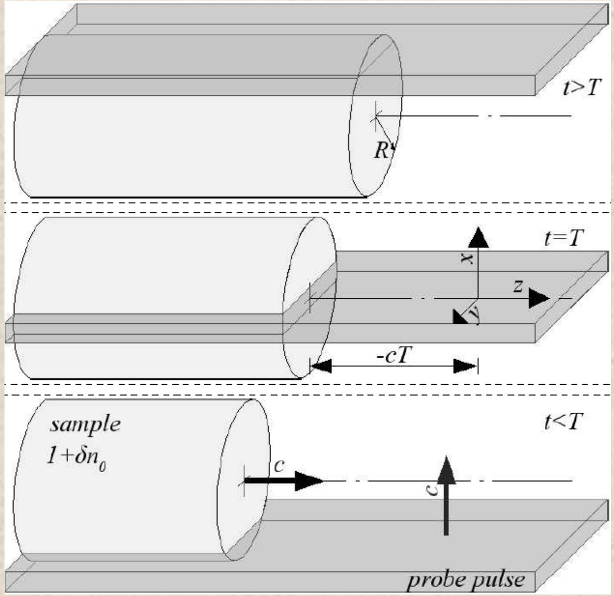
- L.A. Gizzi et al., AIP Conf. Proc. Vol. **827**, 3 Editors M. Lontano et al., Melville, N.Y. (2006).
- L.A.Gizzi et al., submitted to PRE

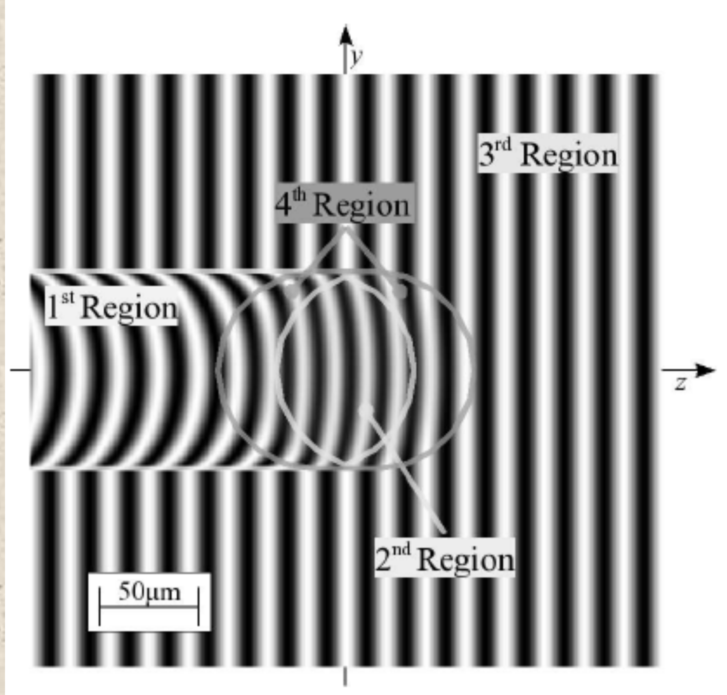
FEMTOSECOND PROBING: ADDITIONAL EFFECTS

Fringe Visibility depletion and probe transit time: the model*

Probe length ($c\,\tau$) < Transit time (cR) & $\delta\mu\, c\,\tau \approx \lambda_p$

$$\Delta\varphi(x,y,T) = \frac{2\pi}{\lambda_p}\int_{-\infty}^{+\infty} \delta\mu\left(x,y,z,T+\frac{z}{c}\right)\,dz$$





$$V = V_o \frac{\sin(\mathrm{A})}{\mathrm{A}}$$

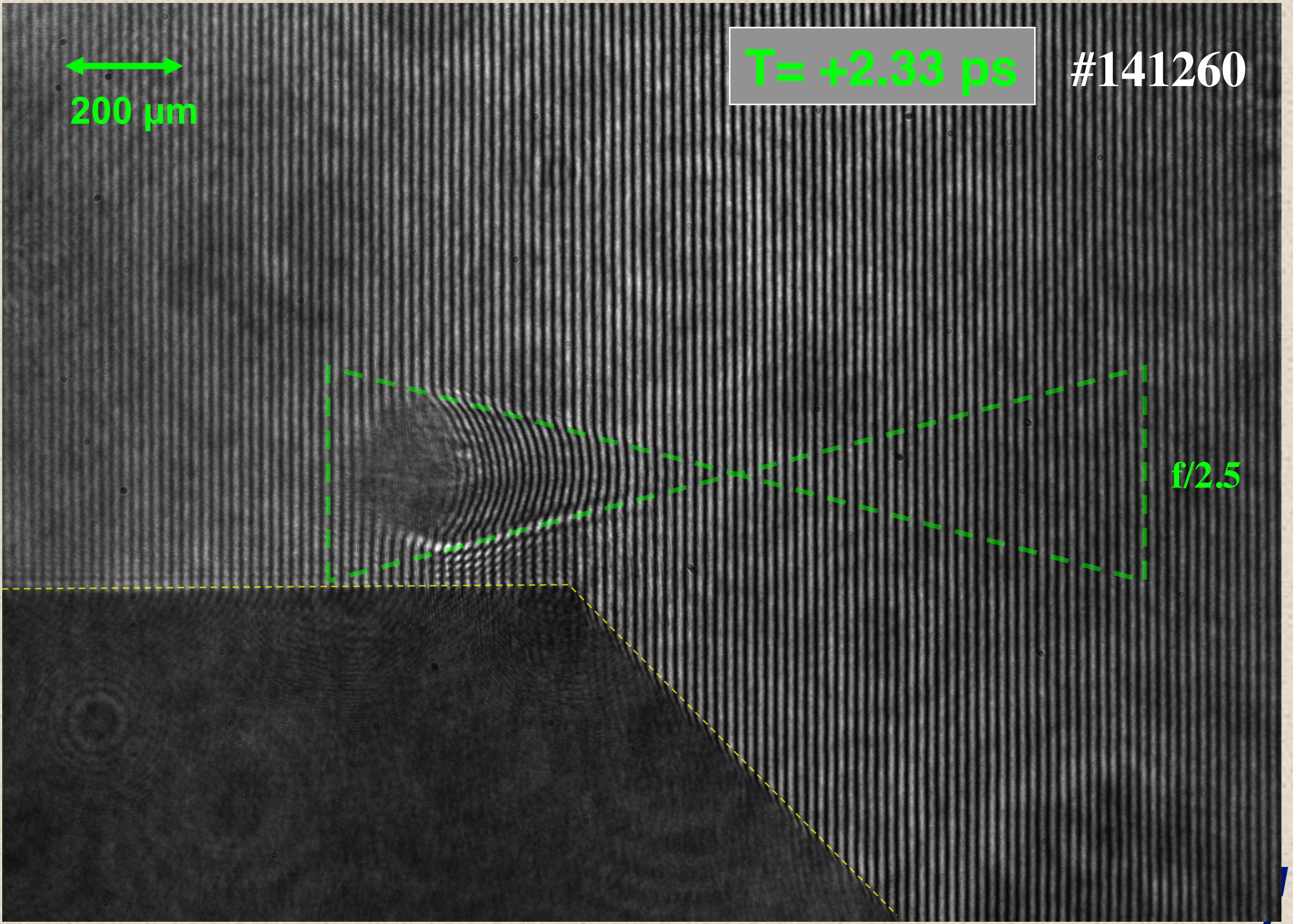
$$\mathrm{A} = \pi\delta\mu c\tau / \lambda_p$$

M. Galimberti, J. Opt. Soc. Am. A (2006).

L.A. Gizzi et al., Phys. Rev. E, **74**, 036403 (2006).

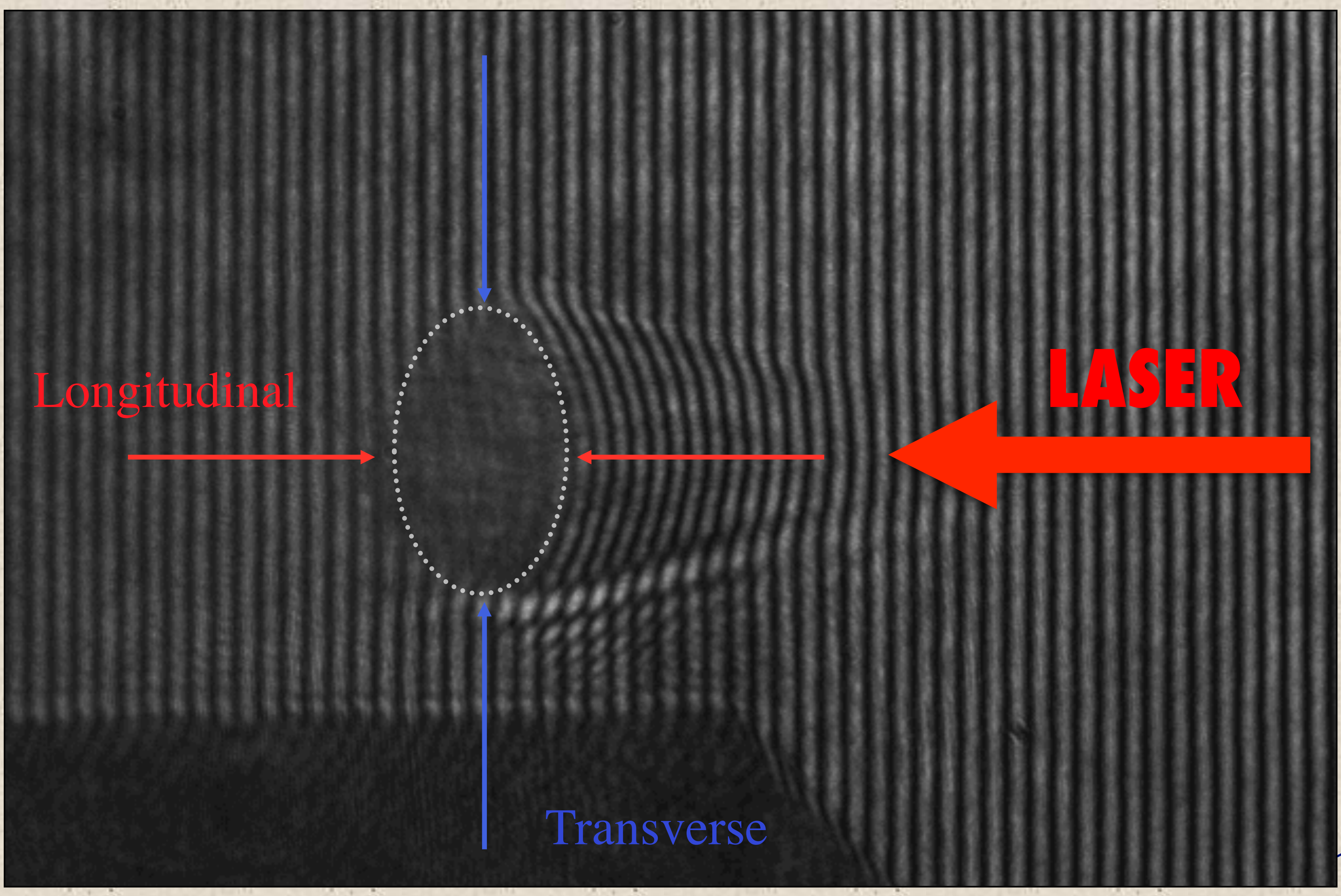
FEMTOSECOND PROBING OF LASER-PLASMA FORMATION IN A GAS

data from CEA-Saclay experiment



LASER PULSE FRONT: LOSS OF FRINGE VISIBILITY

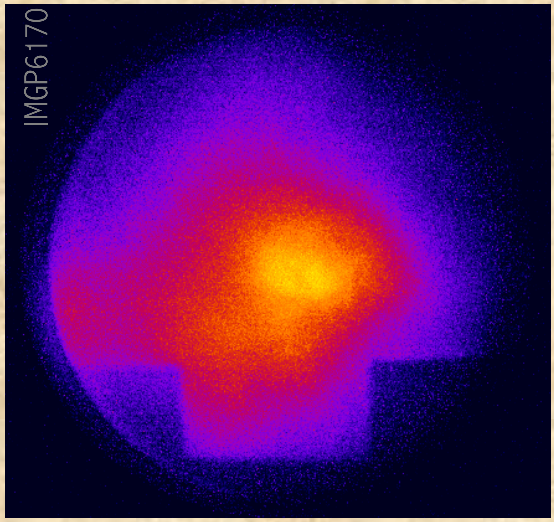
data from CEA-Saclay experiment

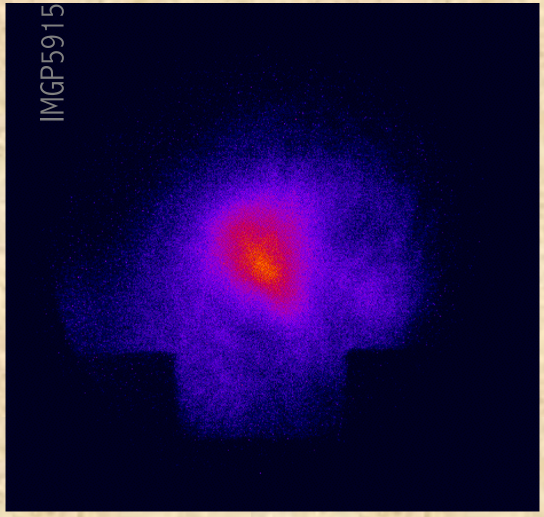


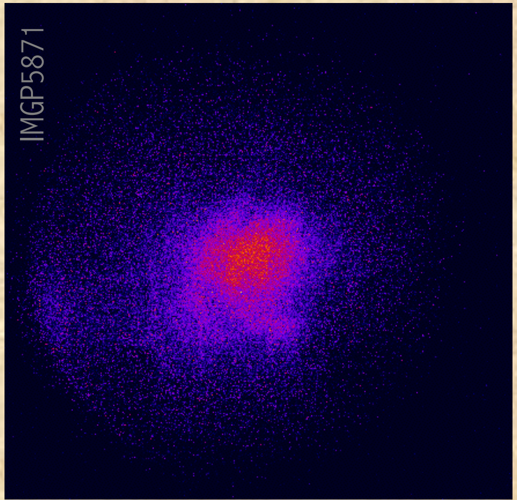
ELECTRON DIAGNOSTICS: **PHOSPHOR SCREENS**

data from Pisa "pilot" esperiment

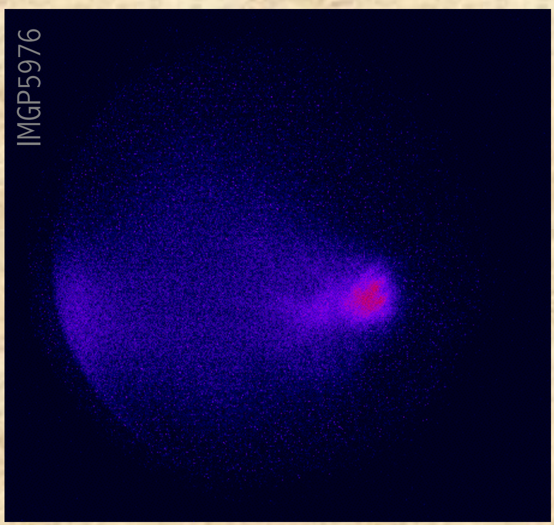
Tipo A
bassa collimazione

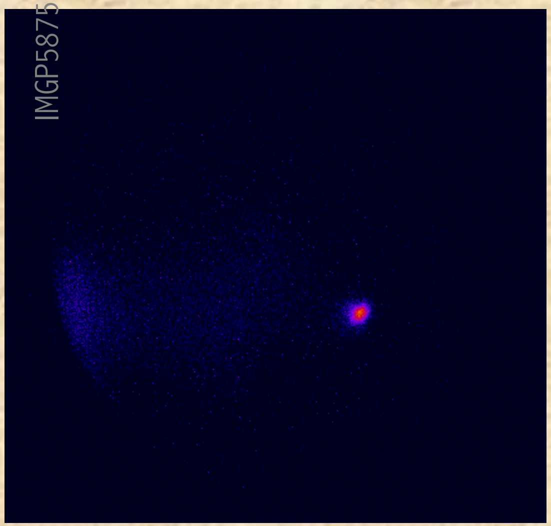


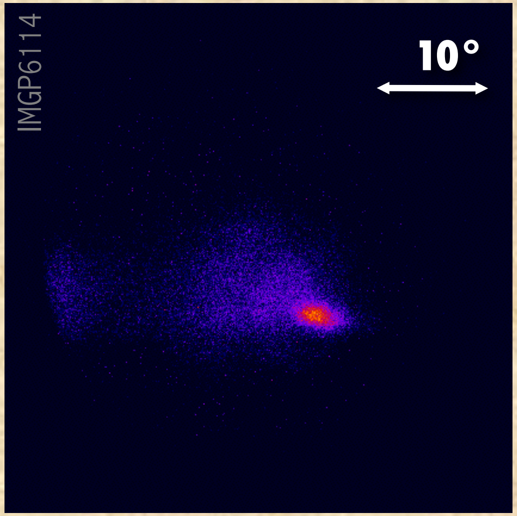




Tipo B
alta collimazione

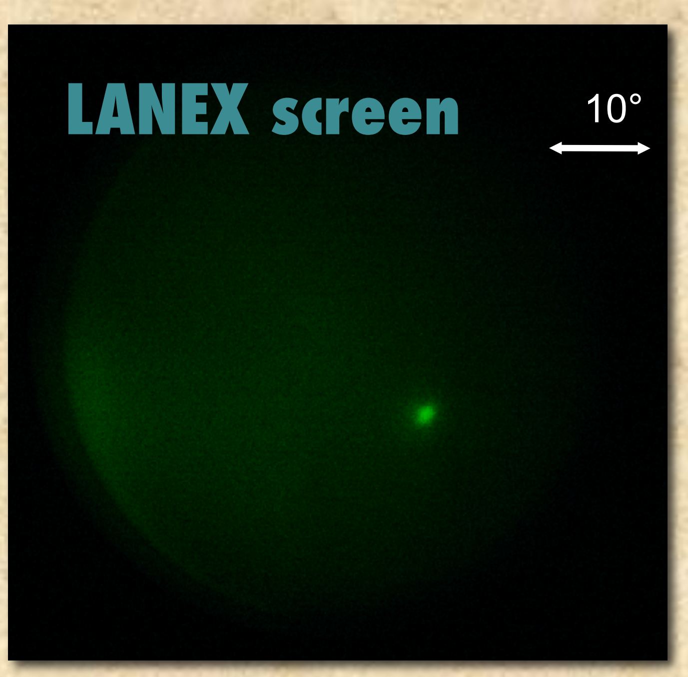


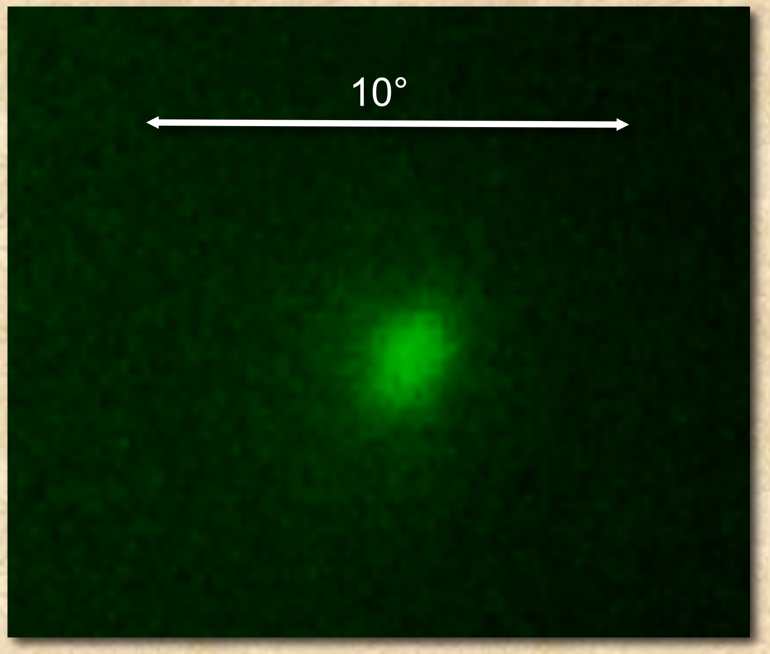




ELECTRON DIAGNOSTICS: PHOSPHOR SCREENS

data from Pisa "pilot" experiment



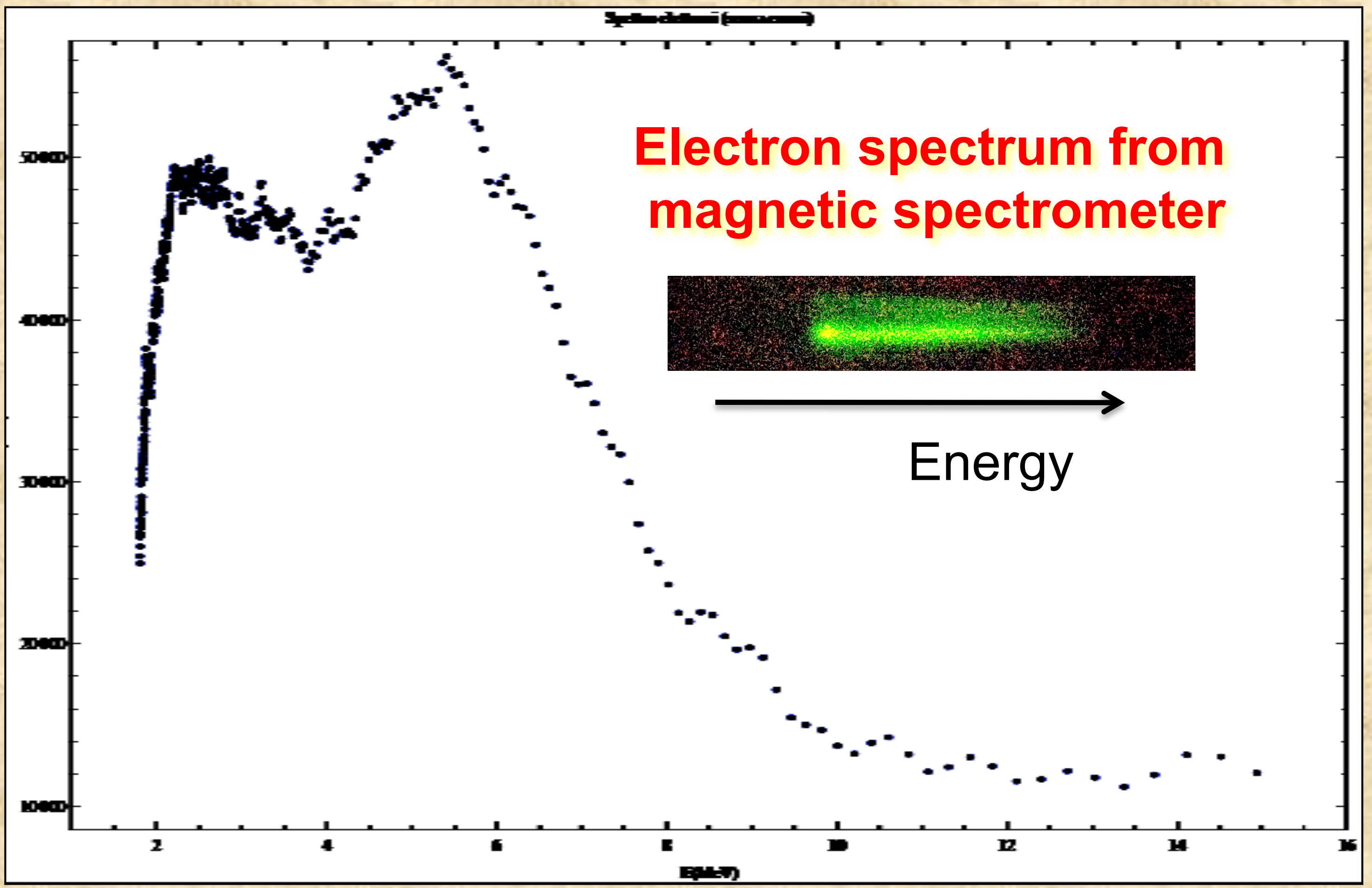


ELECTRON BEAM PATTERN

He@50 bar

ELECTRON DIAGNOSTICS: MAGNETIC SPECTROMETER

data from Pisa “pilot” experiment



Electron spectrum from magnetic spectrometer

New sub-GeV magnetic spectrometer under development
Collaboration with U. Roma1 (vedi talk R. Faccini)

FLAME team

FLAME TEAM

FLAME COMMISSIONING TEAM: SUBSYSTEMS AND RESPONSABILITIES

1/3

- LASER INSTALLATION and Control-Command
  <u>Leonida A. GIZZI</u> & <u>Danilo GIULIETTI</u>

- FLAME software interfaces, utilities and resources
  <u>Giampiero DI PIRRO</u>

- FLAME-SPARC interfaces
  <u>Carlo VICARIO</u> (LNF)

FLAME COMMISSIONING TEAM: SUBSYSTEMS AND RESPONSABILITIES

2/3

- BEAM TRANSPORT AIR+ VACUUM

Valerio LOLLO, Alberto CLOZZA & Andrea GAMUCCI

- SAFETY

Adolfo ESPOSITO

- FLAME TaRGET AREA, laser focusing & diagnostics

Luca LABATE

FLAME COMMISSIONING TEAM: SUBSYSTEMS AND RESPONSABILITIES

3/3

- FLAME Target Area - test experiments diagnostics

<u>Carlo A. CECCHETTI</u>

- FLAME web site and outreach

<u>Leonida A. GIZZI</u> & <u>Luca LABATE &...</u>

- LOGISTICS

<u>Oreste CERAFOGLI</u>

- TECHNICAL AND ENGINEERING support

<u>Luciano CACCIOTTI</u>

INFN

Conclusions and pending issues

- Flame building completed in record time;
- Beam transport line design, completed and under construction;
- Laser Acceptance tests at Amplitude successfully completed with recommendations;
- Laser installation awaiting clean room completion;
- Test experiment designed and under implementation.