IL PROGETTO PLASMONX E LO STATO DEL *COMMISSIONING FLAME*

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On behalf of the PLASMONX/FLAME Team

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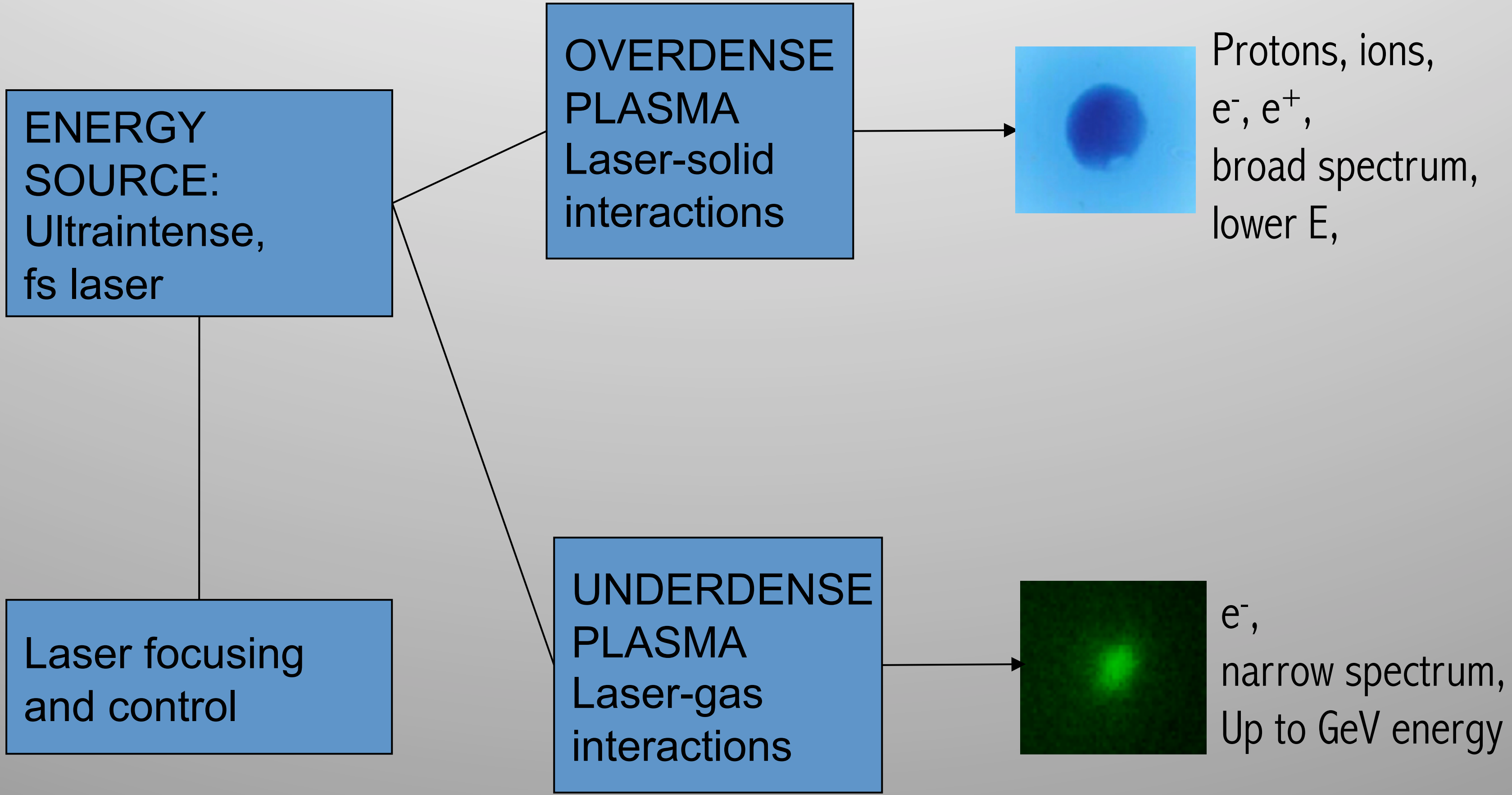
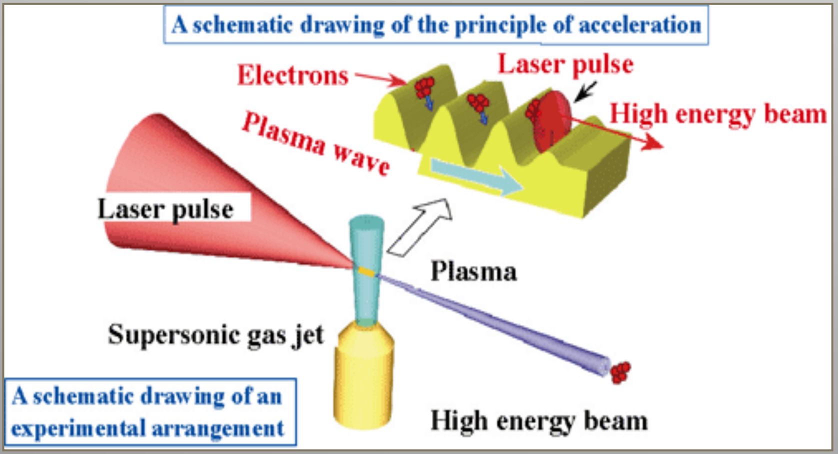
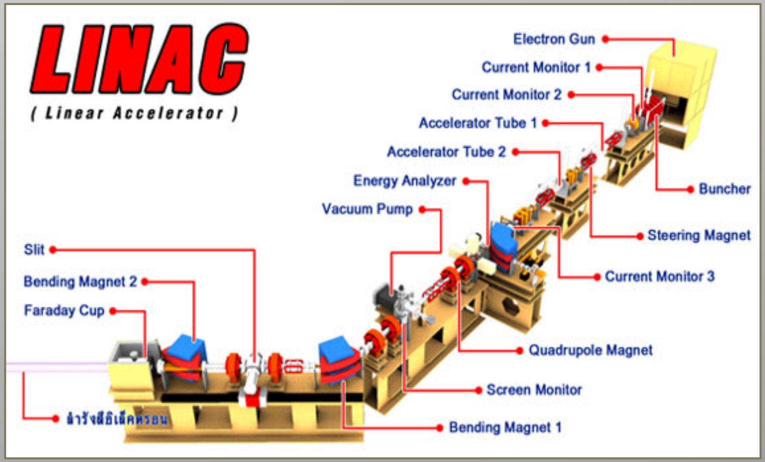
PARTICLE ACCELERATION WITH LASERS



TOWARDS MINIATURE ACCELERATORS?

- CONVENTIONAL ACCELERATORS:
  - ELECTRON GUN (LASER PHOTOCATHODE) + ACCELERATING CAVITIES (RF)
  - accelerating fields ≈ 15 MV/m
- LASER-PLASMA ACCELERATORS
  - PLASMA MEDIUM (GAS …) + ELECTRON PLASMA WAVES (INTENSE LASER)
  - Accelerating fields > tens of GV/m



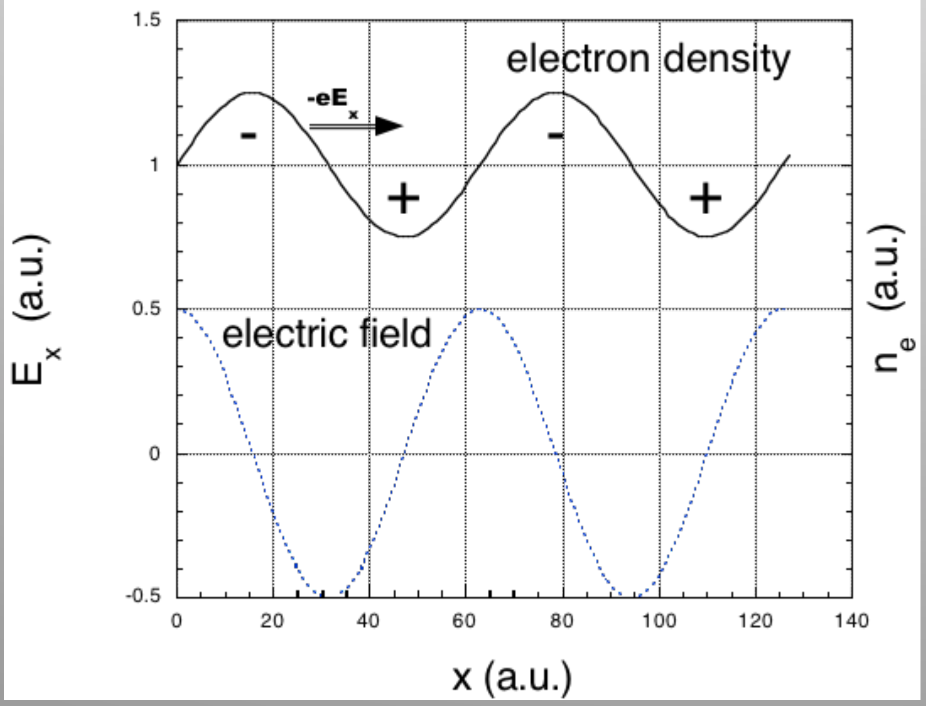


WHY A PLASMA?

- no structural limits to the accelerating electric fields;
- electron plasma waves (e.p.w) fit requirements for particle acceleration:

 - intense longitudinal electric fields;

 - phase velocity very close to the speed of light;

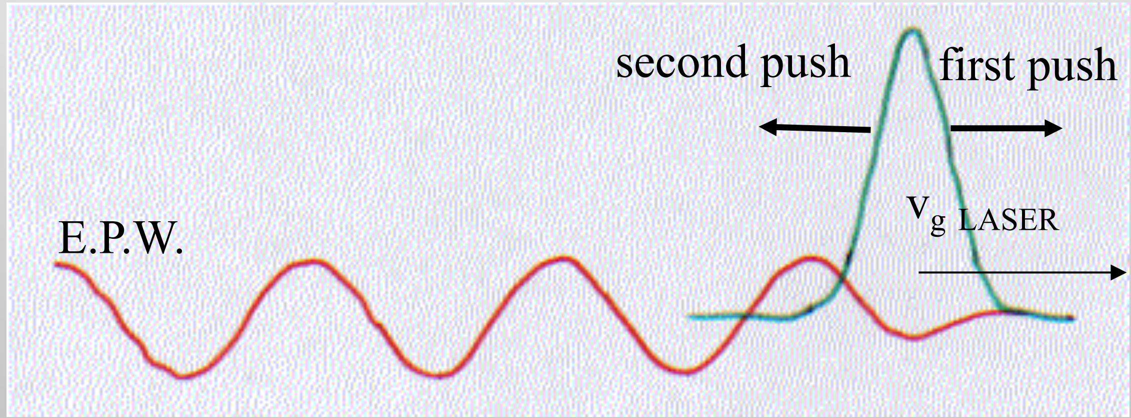


How to create high amplitude e.p.w. ?

- Ponderomotive force;
- Coulomb force;
- Use charged particles or laser pulses;

LASER WAKEFIELD

Electron plasma wave excitation by laser wakefield



electron plasma frequency $f_{pe} = \omega_{pe}/2\pi = 8.98 \times 10^3 n_e{}^{1/2}$ Hz

$$\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$$
$$= 5.64 \times 10^4 n_e{}^{1/2}\ \text{rad/sec}$$

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

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

$$v_{\phi,epw} = v_{g,laser} = c\left(1 - \frac{\omega^2_{pe}}{\omega^2}\right)^{\frac{1}{2}} = c\left(1 - \frac{n}{n_c}\right)^{\frac{1}{2}}; \ n_c(cm^{-3}) = 1.1 \times 10^{21} \left[\lambda(\mu m)\right]^{-2}$$

1T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43, 267 (1979).**

BEYOND CLASSICAL WF: SELF-INJECTION

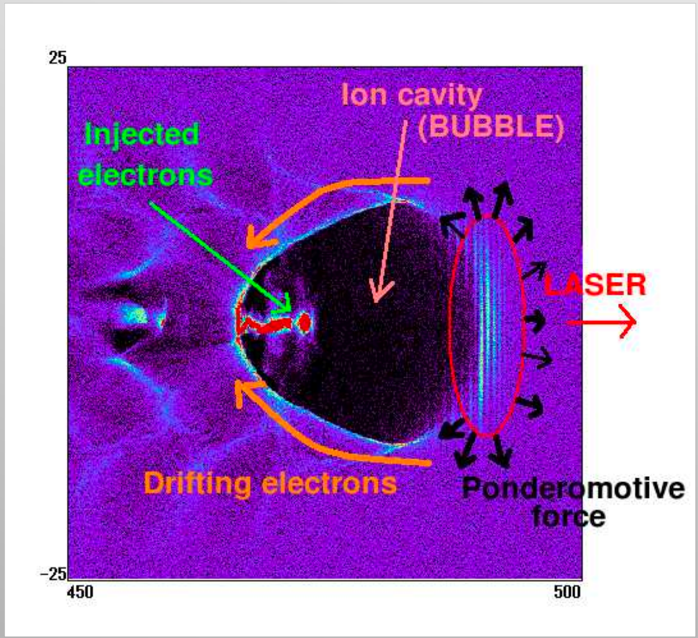
At ultra-short, ultra intense laser conditions:

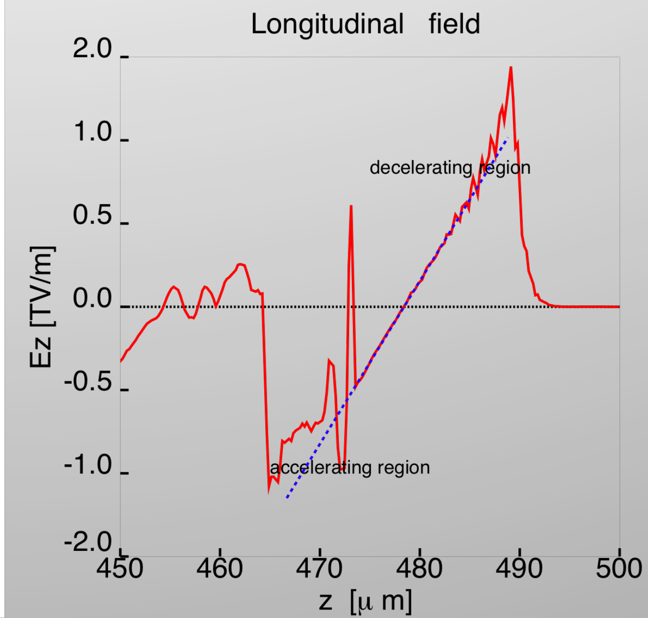
- Laser pulse self-focuses and self-compresses and creates an electron evacuated cavity (bubble)* surrounded by a high density wall of electrons;
- At sufficiently high density at the walls, electrons are driven at the back of the wall and injected in the bubble until the density of the injected electrons equals the wall density;
- The faster the process the higher the localisation of the injected electrons, with consequent reduction of energy spread.
- Self-injection, however, is non-linear and hard to control => reproducibility and energy stability is limited;
- All optical schemes** can be used to control injection to a significant degree;
- External injection using high-quality electron bunches can ultimately be used to boost energy while preserving quality (energy spread, emittance, charge etc. …)
- Deal with limiting **d-**factors: **d**iffraction, **d**ephasing, **d**epletion …

•Refs.: *A. Pukhov, Appl. Phys. B, **74**, 355 (2009), **J. Faure et al.,,Nature **444,** 737 (2006).

SELF-INJECTION DYNAMICS

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



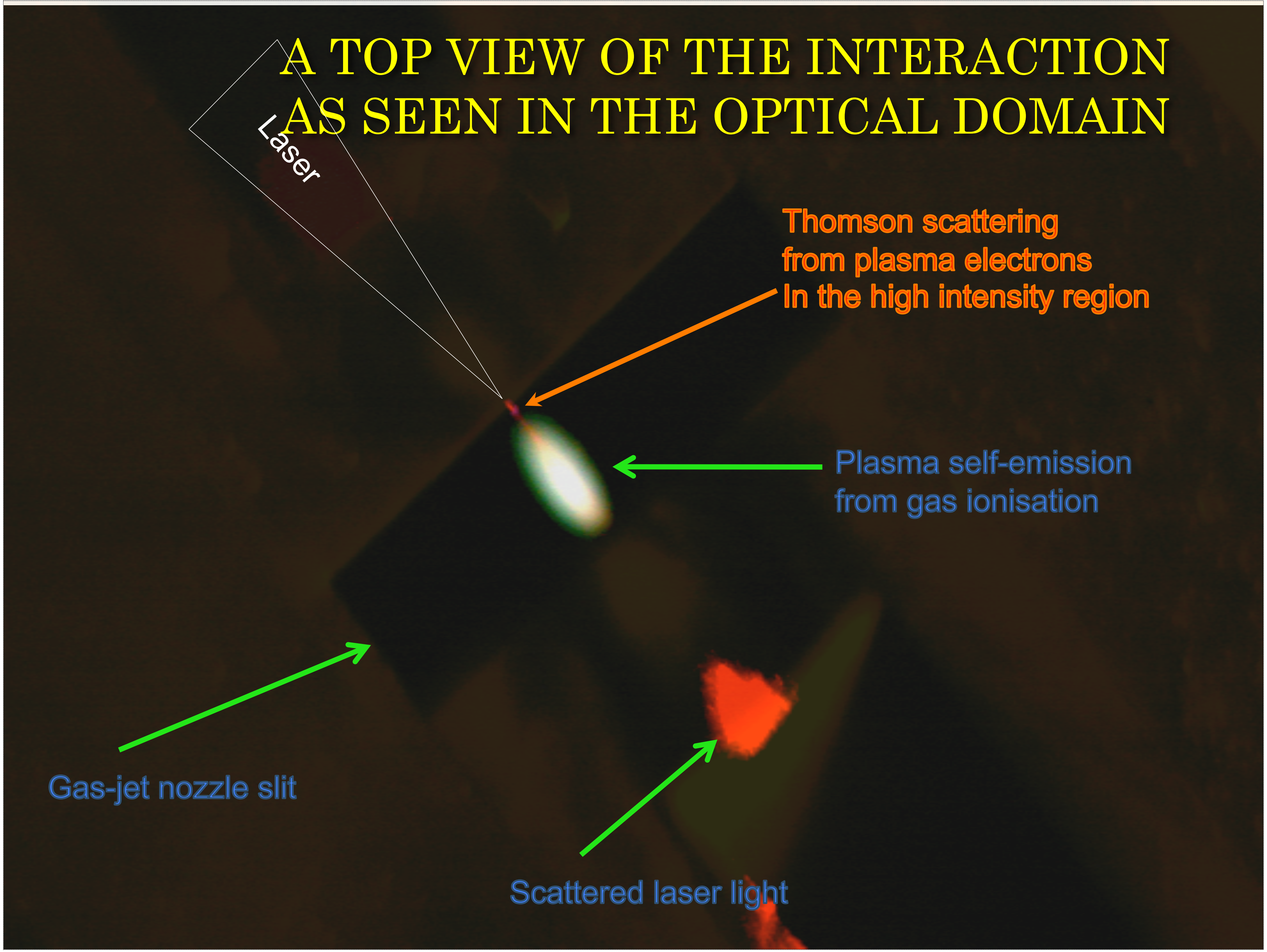


- $R_{bub} \simeq O(\lambda_p)$ $\quad E_z^{(max)} \simeq 100\sqrt{n_0[\text{cm}^{-3}]} \times a_0$ [V/m]
- $\begin{cases} v_{elect} \simeq c \\ v_{bub} \simeq c(1 - 3\omega_p^2/(2\omega_0^2)) < v_{elect} \Rightarrow \text{acc. length is finite + monochromaticity} \end{cases}$

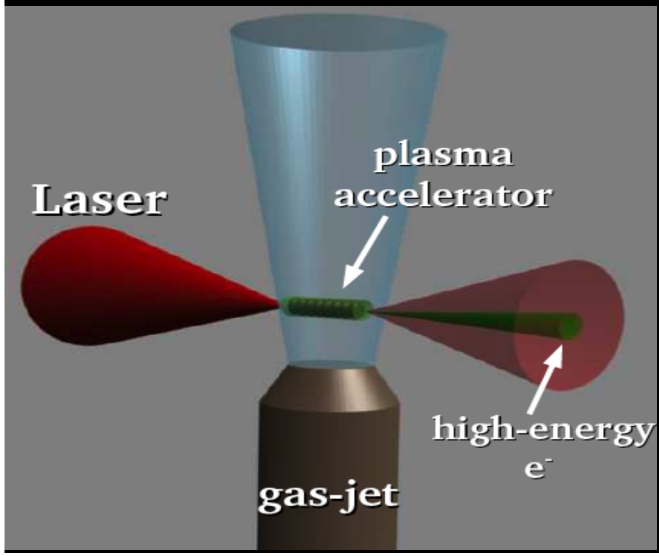
---

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

A TOP VIEW OF THE INTERACTION AS SEEN IN THE OPTICAL DOMAIN



THOMSON SCATTERING



TOWARDS HIGHER QUALITY BEAMS

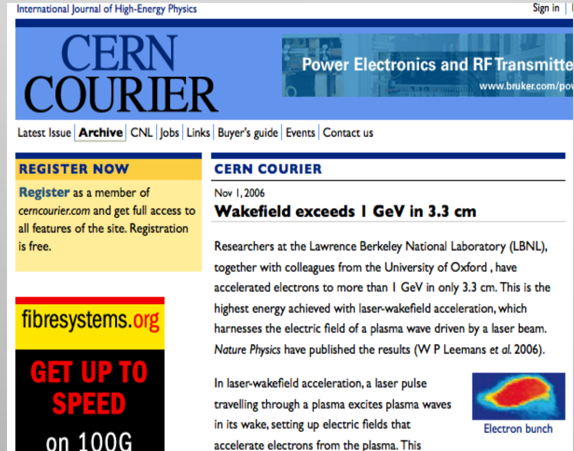
Ultrashort, ultraintense laser pulses can drive a new, highly non linear regime with a powerful injection mechanism that leads to a reduced energy spread.

S.P.D. Mangles et al., Nature, 431, 535 (2004); C.G.R. Geddes et al., Nature, 431, 538 (2004); J. Faure et al., Nature, 431, 541 (2004);

Since 2004, systematic production of electron bunches with energy in the hundreds of MeV range and moderate energy spread (5-10%):

- Miura, Appl. Phys. Lett. 86, 251501 (2005)
- Hsieh, Phys. Rev. Lett. 96, 095001 (2006)
- Hidding, Phys. Rev. Lett. 96, 105004 (2006)
- Hosokai, Phys. Rev. E 73, 036407 (2006)
- Giulietti et al., Phys. Rev. Lett. 101, 105002 (2008)

and many, many more …


International Journal of High-Energy Physics

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Nov 1, 2006

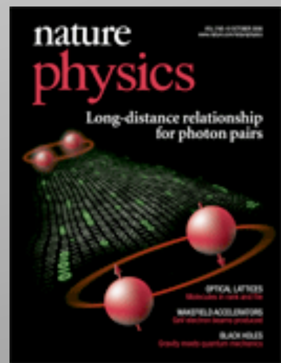
Wakefield exceeds 1 GeV in 3.3 cm

Researchers at the Lawrence Berkeley National Laboratory (LBNL), together with colleagues from the University of Oxford, have accelerated electrons to more than 1 GeV in only 3.3 cm. This is the highest energy achieved with laser-wakefield acceleration, which harnesses the electric field of a plasma wave driven by a laser beam. *Nature Physics* have published the results (W P Leemans *et al.* 2006).

In laser-wakefield acceleration, a laser pulse travelling through a plasma excites plasma waves in its wake, setting up electric fields that accelerate electrons from the plasma. This

Electron bunch

Most recent results from LBL LOASIS group: 1 GeV



"GeV electron beams from a cm-scale accelerator," by W. P. Leemans, B. Nagler, A. J. Gonsalves, Cs. Toth, K. Nakamura, C.G.R. Geddes, E. Esarey, C.B. Schroeder, and S.M. Hooker, October 2006 issue of Nature Physics.

PLASMONX PROJECT

PLASma acceleration and MONochromatic 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;**

Pisa, 19 Marzo 2005

PLASMA ACCELERATION AND
MONOCHROMATIC X-RAY PRODUCTION

INFN

PLASMONX PROJECT UNITS

PLASMONX PROJECT – TRENDS ...

POSITIVE …

- **Increasing scientific motivation among participants (INFN, CNR, University etc)**
- **Strong support from LNF;**
- **Speeding up, following latest achievements of FLAME commissioning phase;**

WORRIES …

Activity understaffed;

Need of established framework for collaboration between different participating bodies (INFN, CNR, UNIVERSITIES);

Pisa, 19 Marzo 2005

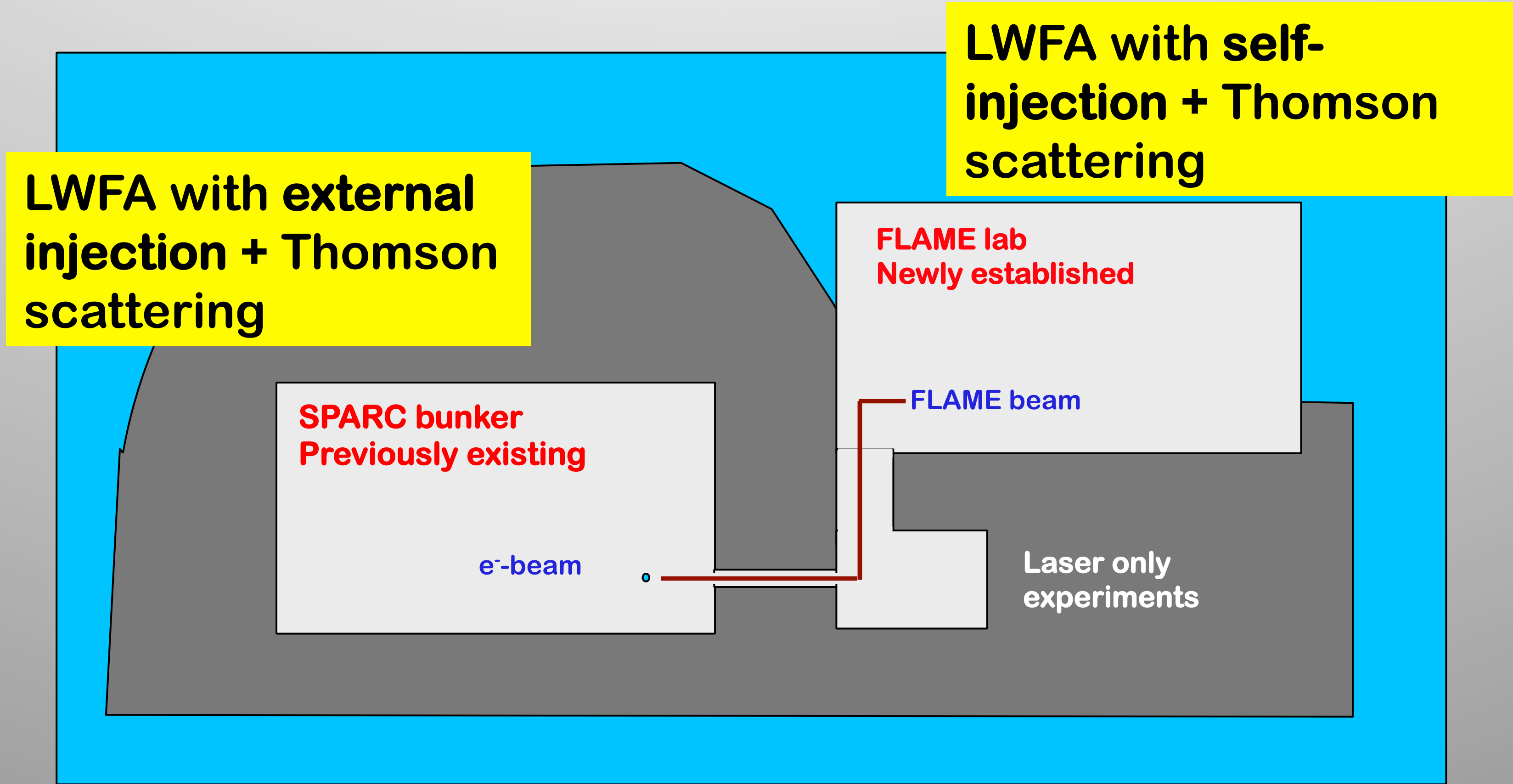
PLASMA ACCELERATION AND MONOCHROMATIC X-RAY PRODUCTION

INFN

FLAME: LASER AND LAB. STATUS

L.I.F.E. AREA AT LNF-FRASCATI

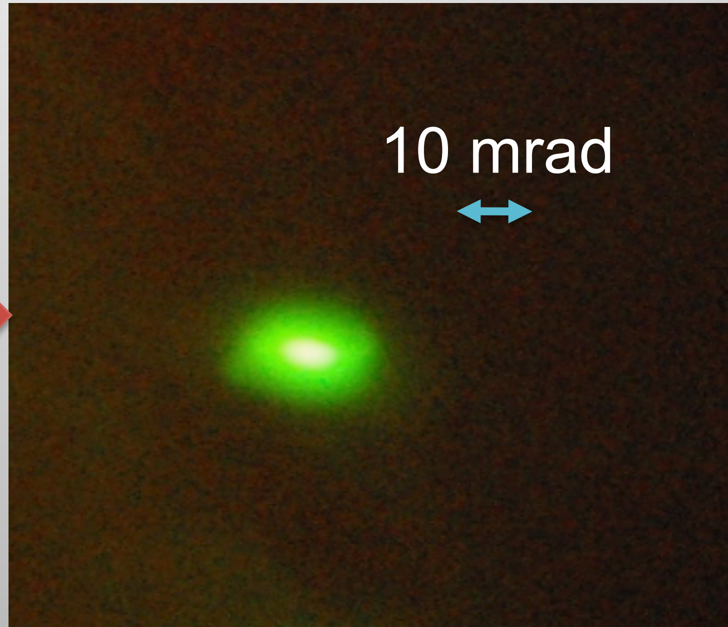
A dedicated area for LINAC and LASER combined operations



FLAME COMMISSIONING - STATUS

March 2007
Building construction starts

October 2010
First LPA electrons



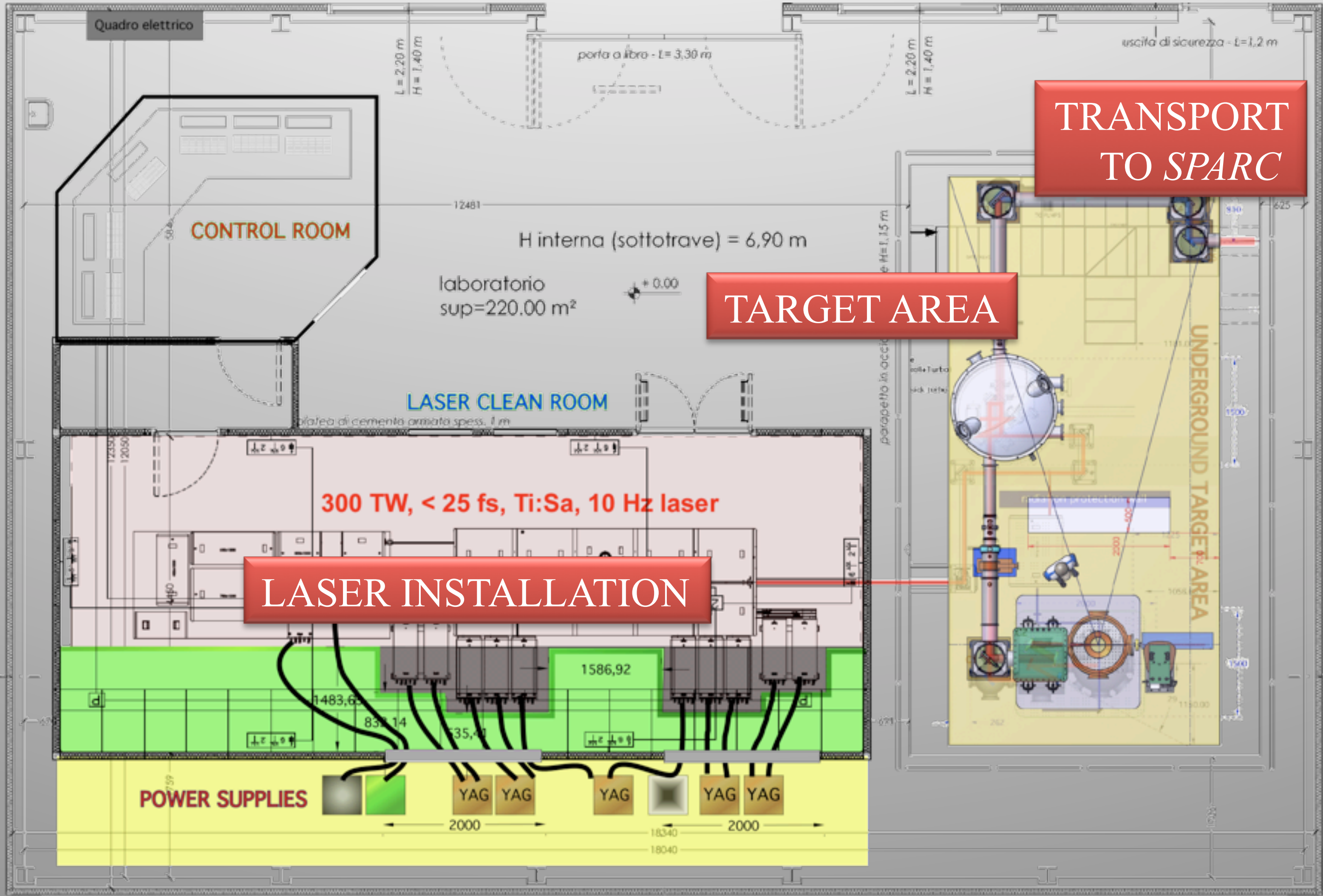
- *HARDWARE* COMPLETED
- LASER INSTALLATION COMPLETED
- TEST EXPERIMENT (SELF-INJECTION) STARTED

LASER: PROJECT REQUIREMENTS

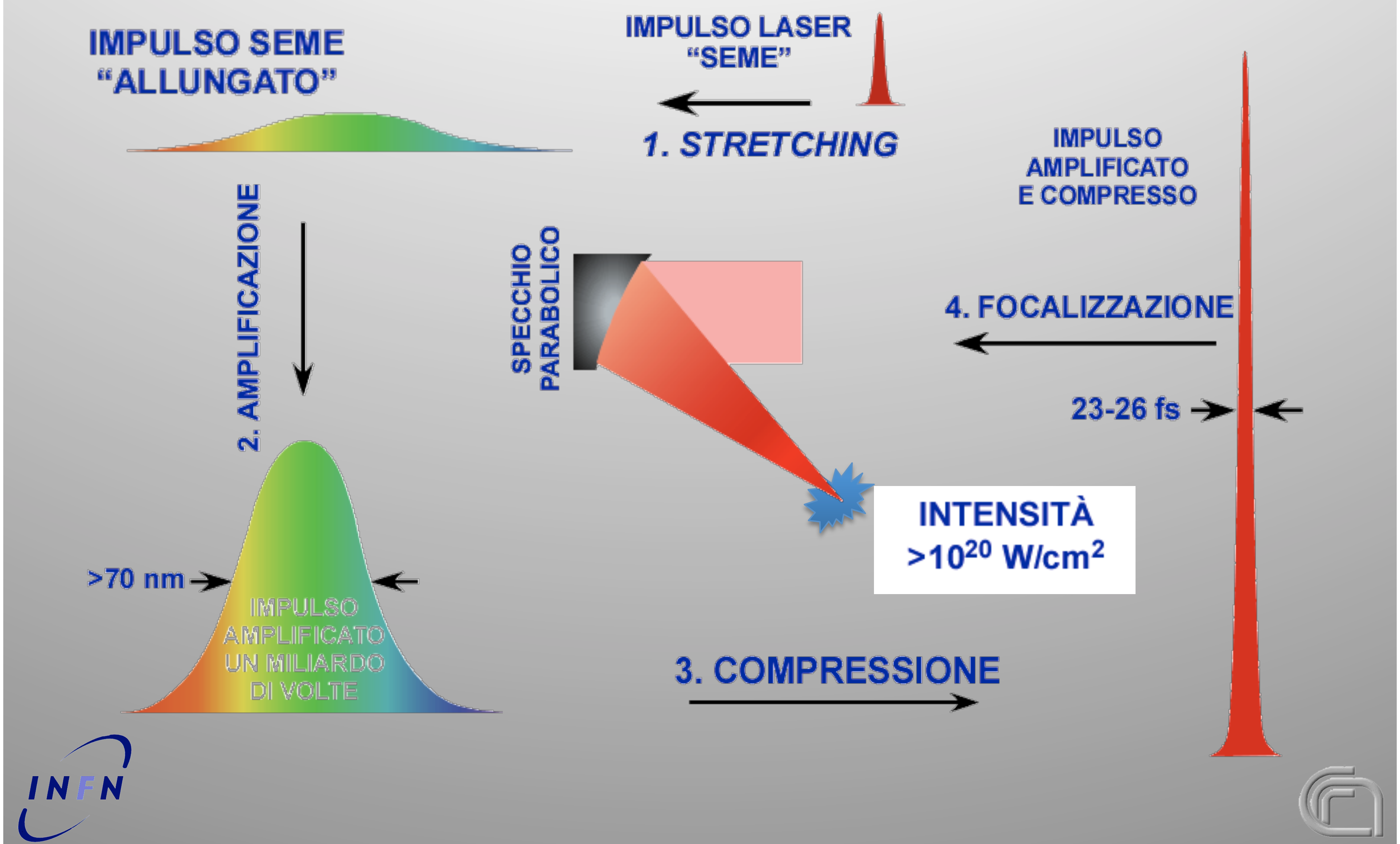
- FLAME to operate a 250 TW, 10 Hz system
- Basic issues/challenges (project driven):
  - Pulse contrast ($>10^{10}$)
  - Pulse duration (<30 fs)
  - Performance stability to compare with LINAC
  - Mechanical stability (2 μm at focal spot)
  - …

FLAME LAB: OVERVIEW

FLAME LAB INCLUDES *LASER INSTALLATION* AND RADIOPROTECTED *TARGET AREA* FOR LASER-TARGET EXPERIMENTS. TRANSPORT OF LASER TO SPARC FOR LASER-LINAC OPERATION IS ALSO IS INCLUDED

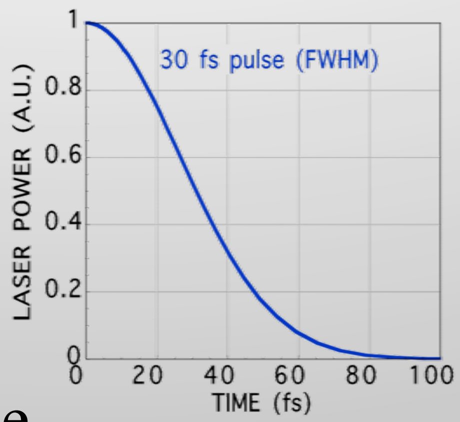


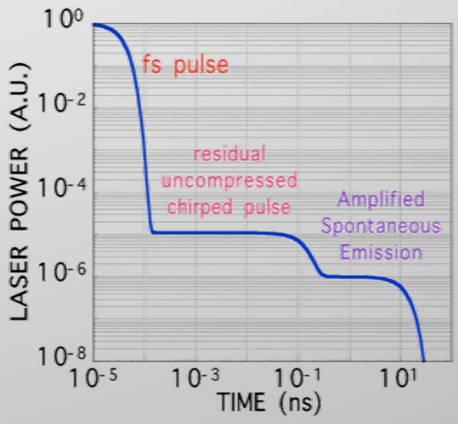
FLAME: DIAGRAMMA A BLOCCHI



LASER PULSE CONTRAST

Temporal contrast (ASE) in excess of 10 orders of mag. required for peak intensities on target of $>10^{22}$ W/cm^2.





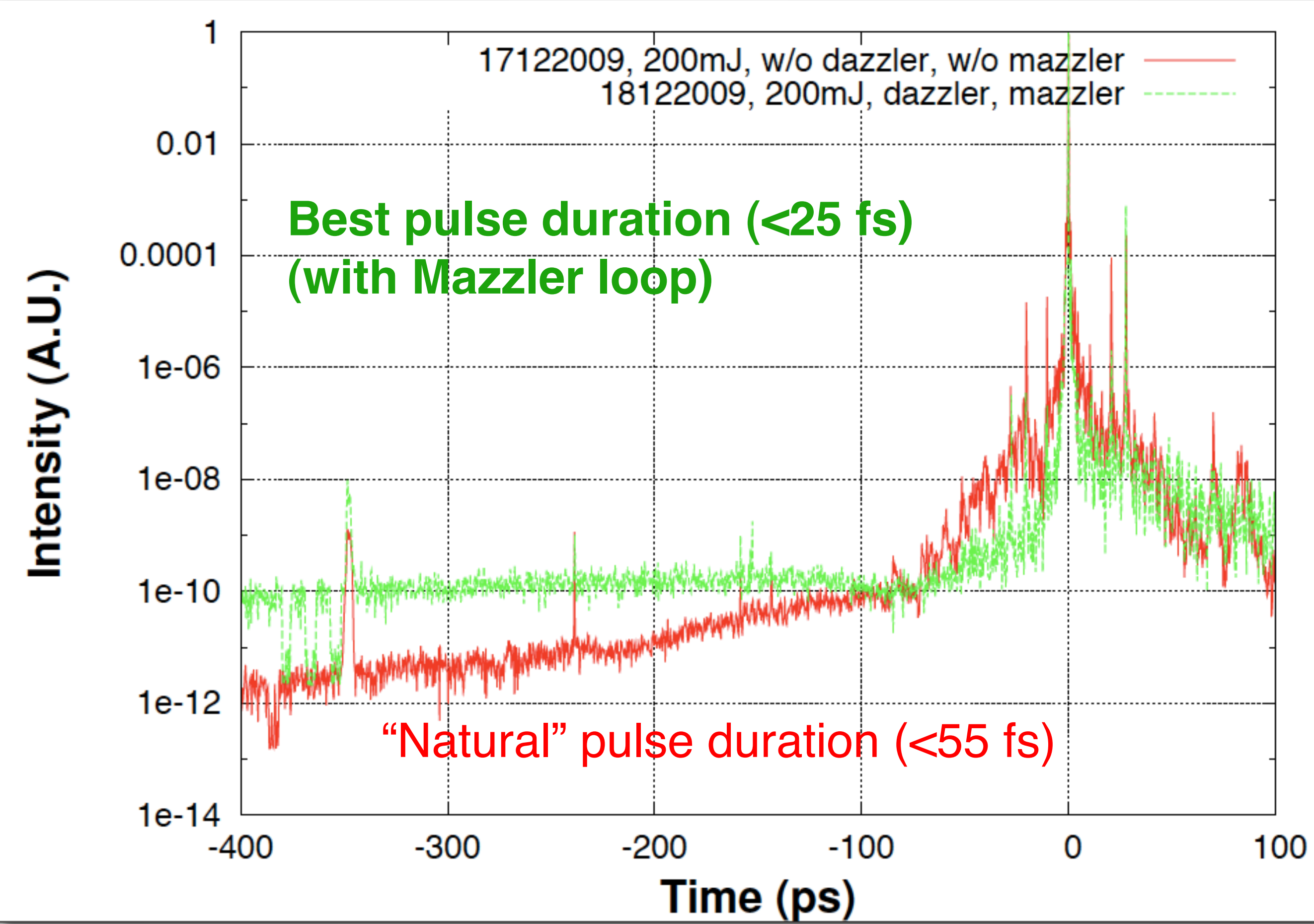
Established techniques include

• electro-optic devices (Pockel cells) for prepulse reduction;

• moderate gain in fromt end and saturable amplifier for ASE management;

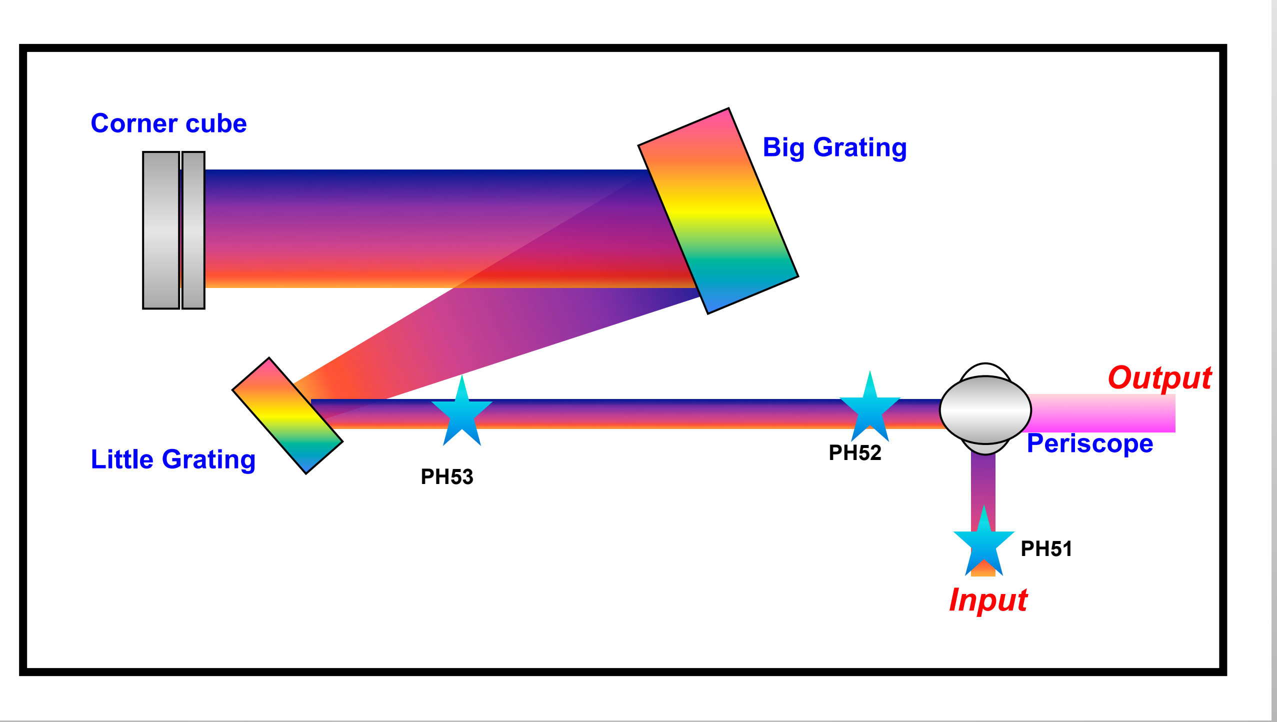
• Other advanced techniques (e.g cross polarized wave generation) again for front-end contrast enhancement;

LATEST CONTRAST MEASUREMENTS



- **Contrast level@200mJ well within specs;**

OPTICAL COMPRESSION



Efficiency of the vacuum compressor >70%

Pulse duration with the test compressor
Spider measurements

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

FINAL (POWER) AMPLIFIER

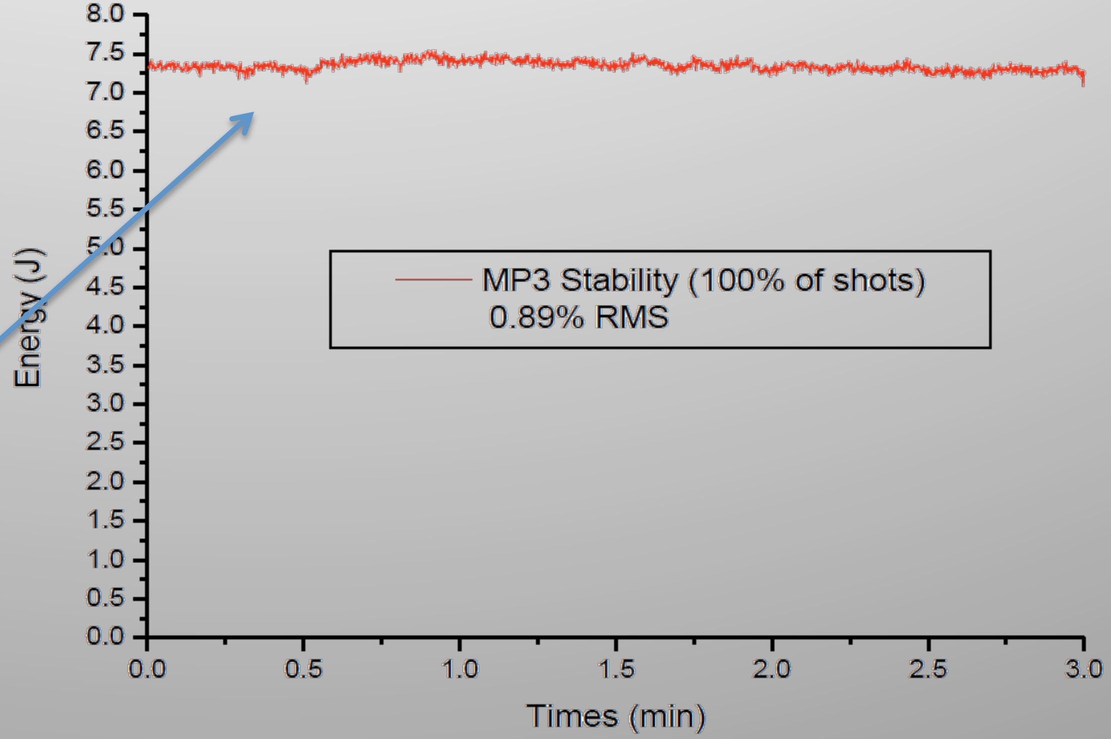
ALL (10) YAG PUMP LASER ALIGNED AND OPERATIONAL

	Voltage	Pump (J)	Total pump	IR (J)	Efficiency
Without				0.37	
Pump 10	1600/1750/1800	1.90	1.90	0.57	10.53%
Pump 2	1550/1600/1700	1.96	3.86	0.86	12.69%
Pump 3	1550/1600/1750	2.00	5.86	1.2	14.16%
Pump 11	1550/1650/1750	2.00	7.86	1.65	16.28%
Pump 4	1550/1650/1750	2.00	9.86	2.4	20.59%
Pump 9	1600/1700/1750	1.95	11.81	3.48	26.33%
Pump 5	1600/1650/1800	2.05	13.86	4.3	28.35%
Pump 8	1600/1700/1800	2.00	15.86	5.15	30.14%
Pump 6	1550/1600/1700	1.75	17.61	6.1	32.54%
Pump 7	1600/1650/1750	2.01	19.62	7.34	35.52%

FINAL AMPLIFIER: FULL ENERGY

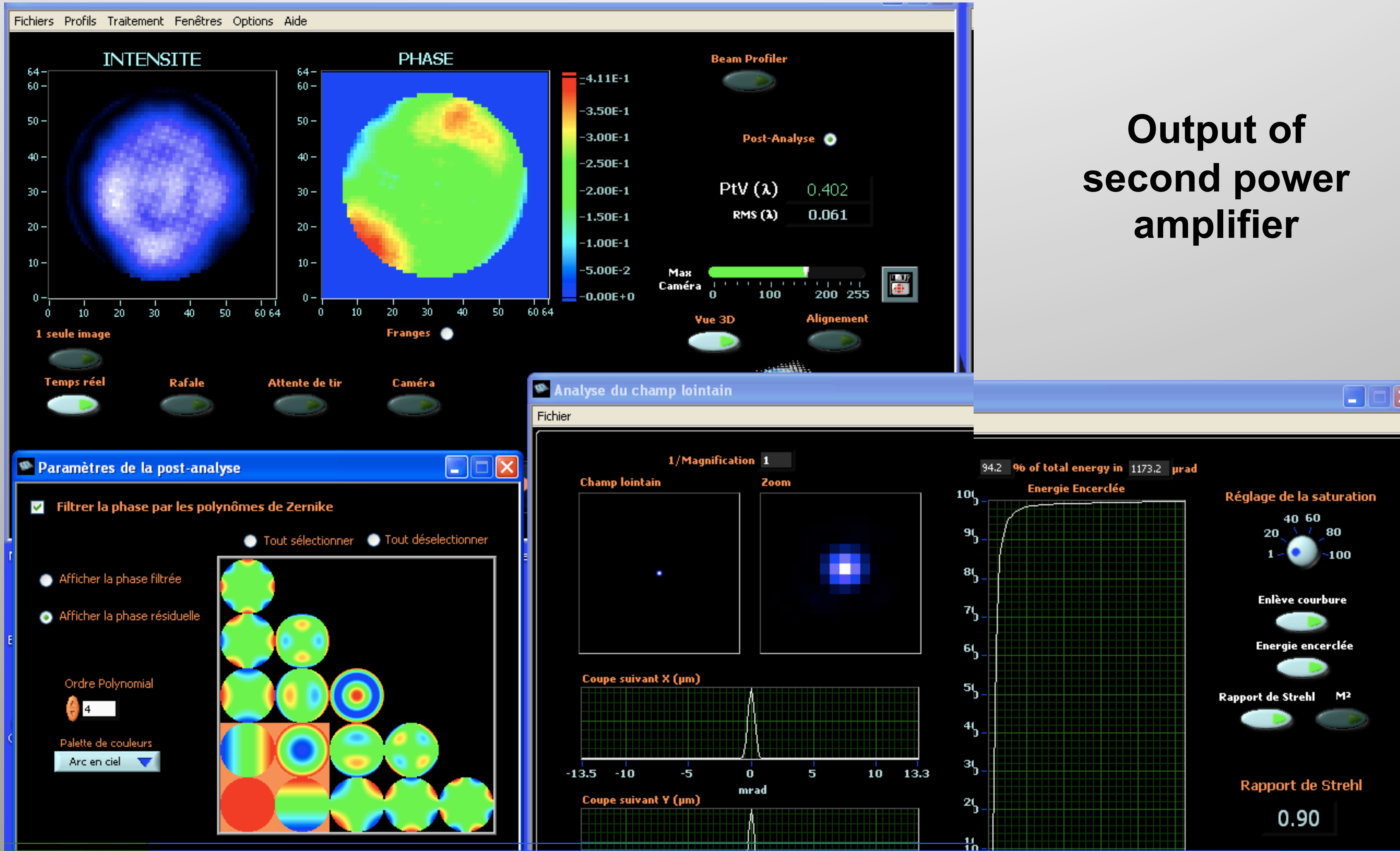
Final amplifier operational with all YAG pump lasers

Pulse energy: 7.34 J (before compression)



LASER PHASE FRONT CHARACTERIZATION

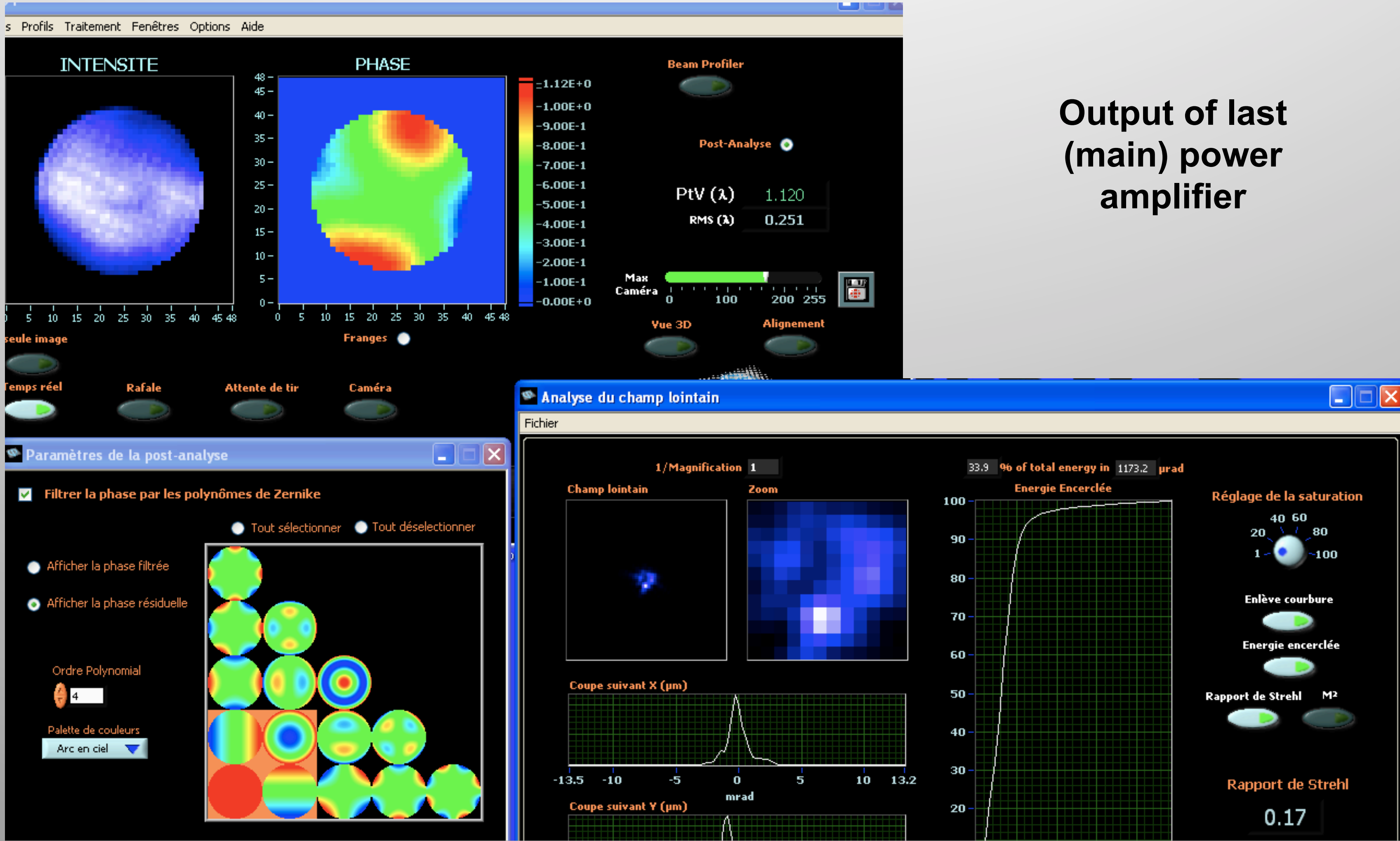
Front-end beam quality



Output of second power amplifier

LASER PHASE FRONT CHARACTERIZATION

Full output beam quality



Output of last (main) power amplifier

Correction required for optimum performance

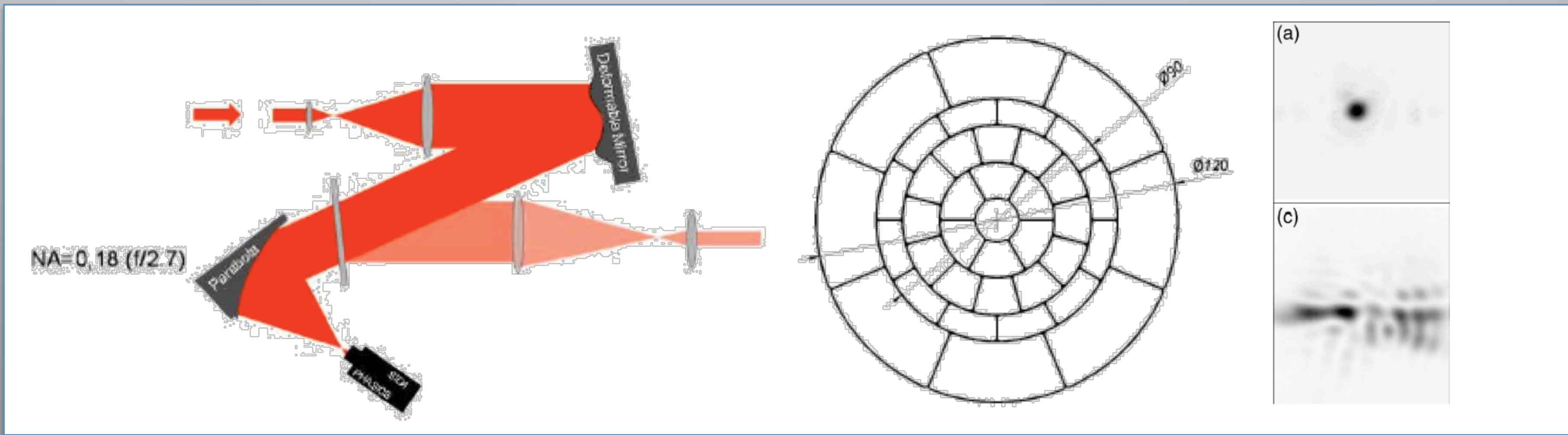
ADAPTIVE OPTICS

Installation planned 2011 – Funding secured

Active spatial phase control technique can be used to correct moderate distortions;

Sensors are used to measure intensity and phase map of the beam;

Deformable mirrors are used to correct the measured wave front distortions in a close loop;



S.-W. Bahk et al., Optics Letters **29**, 2837 (2004)

SUMMARY OF FLAME LASER

Summary of performance (to date)

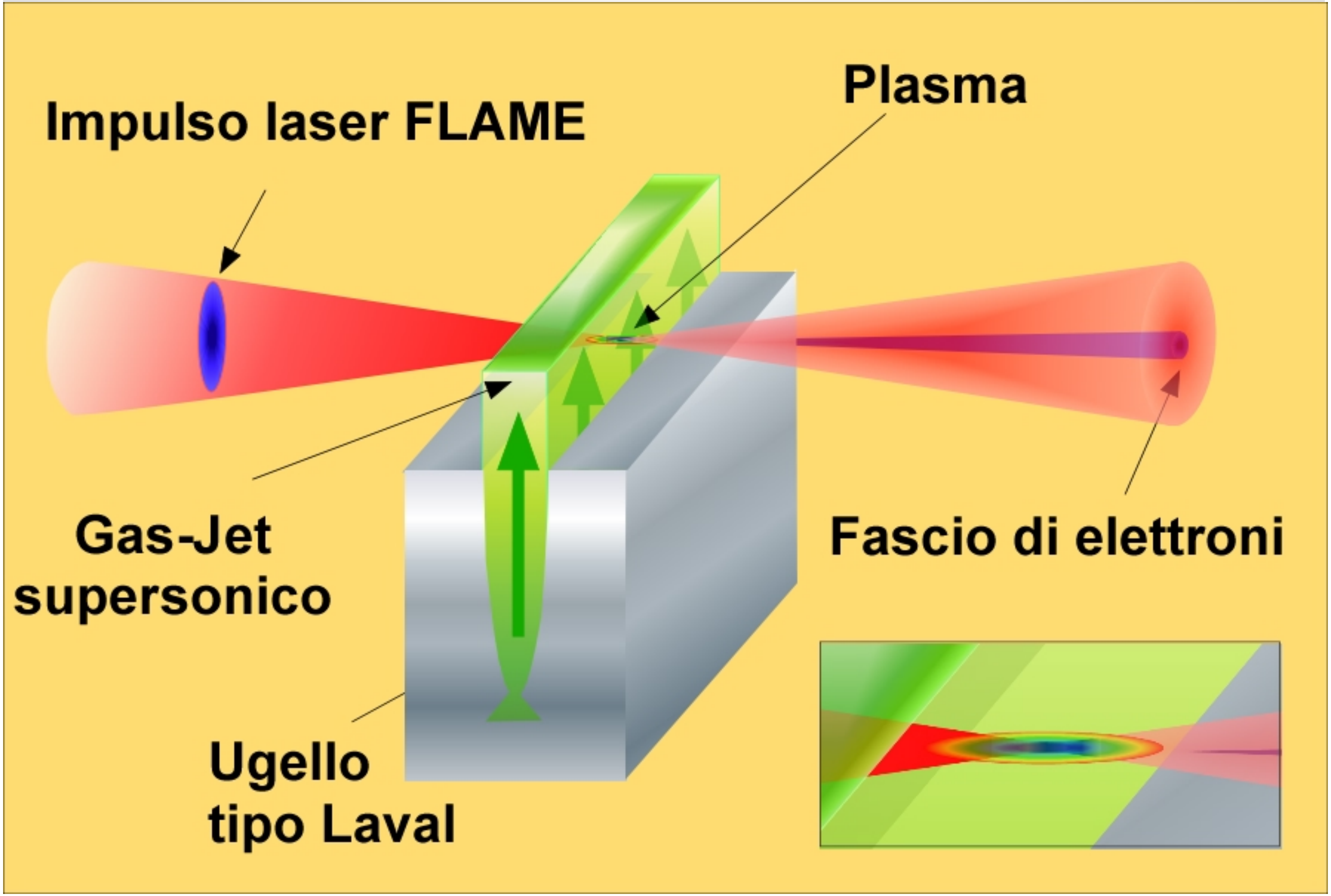
- Energy before compression @ 7.3 J
- Vacuum compressor transmission > 70%
- Pulse duration down to 23 fs
- ASE Contrast ratio: better than $2x10^9$
- Pre-Pulse Contrast better than 10^8
- RMS Pulse Stability @ 0.8 %
- Pointing Stability (incl. path) < 2μrad
- Phase front correction needed;

➢ Full vacuum compression planned before end of the year;

TEST EXPERIMENT:

LASER-PLASMA ACCELERATION WITH SELF-INJECTION A TEST EXPERIMENT (*S.I.T.E.*)

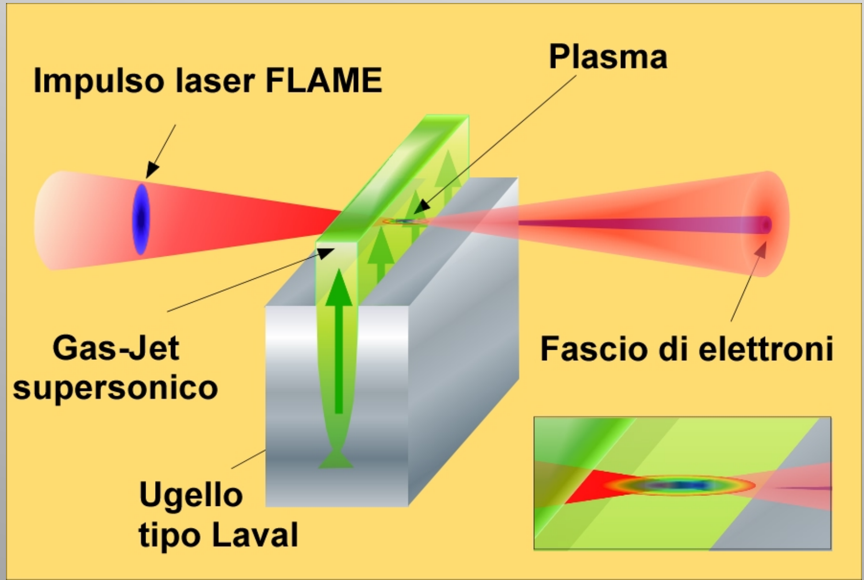
SELF-INJECTION – CONCEPT



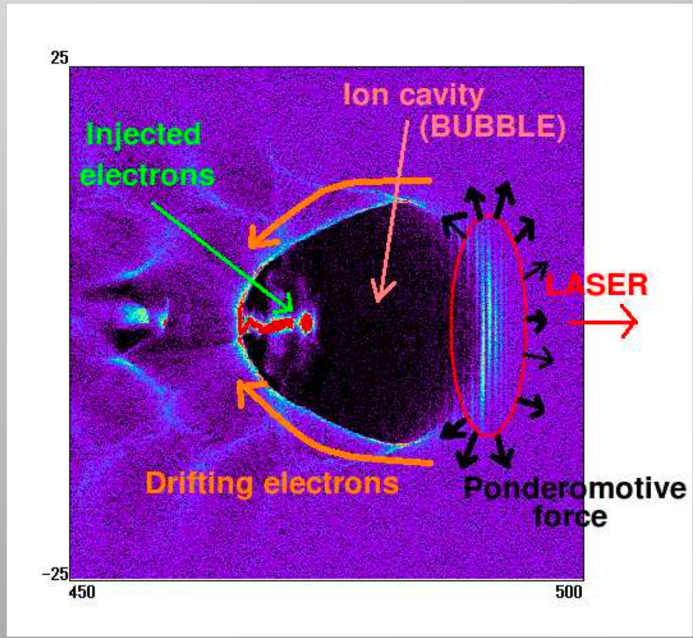
GeV ACCELERATION: PARAMETERS

Main set up parameters

$L_{gas\ jet}$ [mm]	n_e [e/cm^3]	τ [fs]	I_0 [W/cm^2]	w_0 [μm]
4	$3 \cdot 10^{18}$	30	$5.2 \cdot 10^{19}$	16

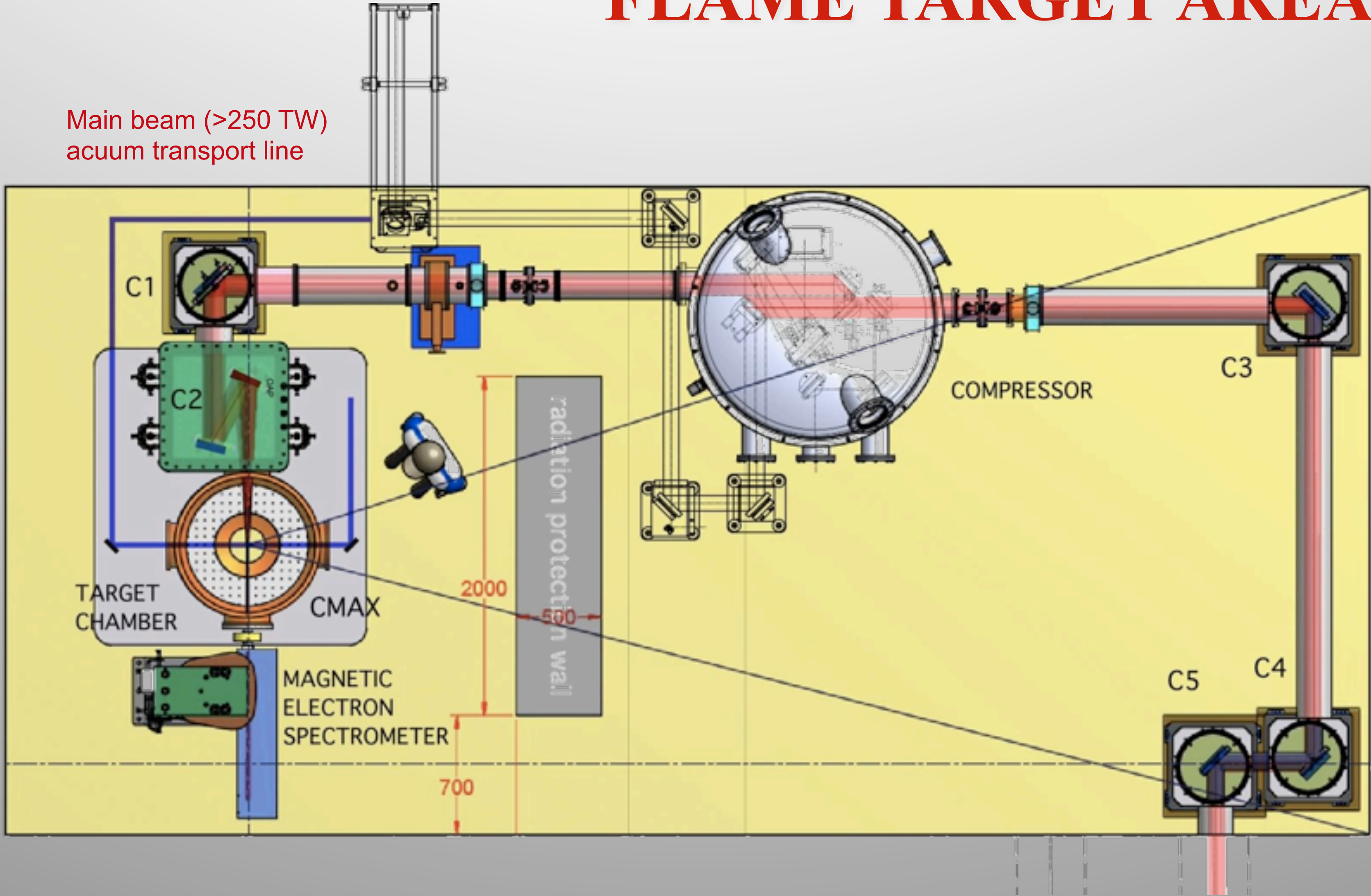


Nonlinear 3D regime (bubble) [a]



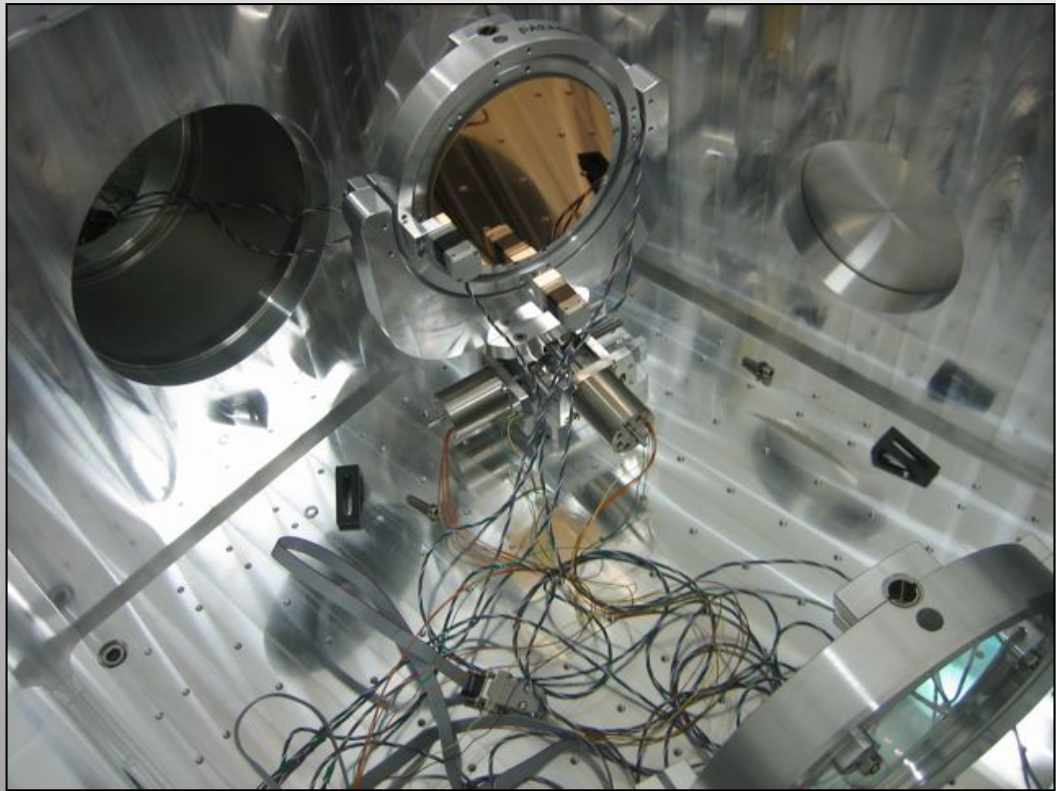
See: L.A. Gizzi et al., EPJ-ST, 175, 3-10 (2009)

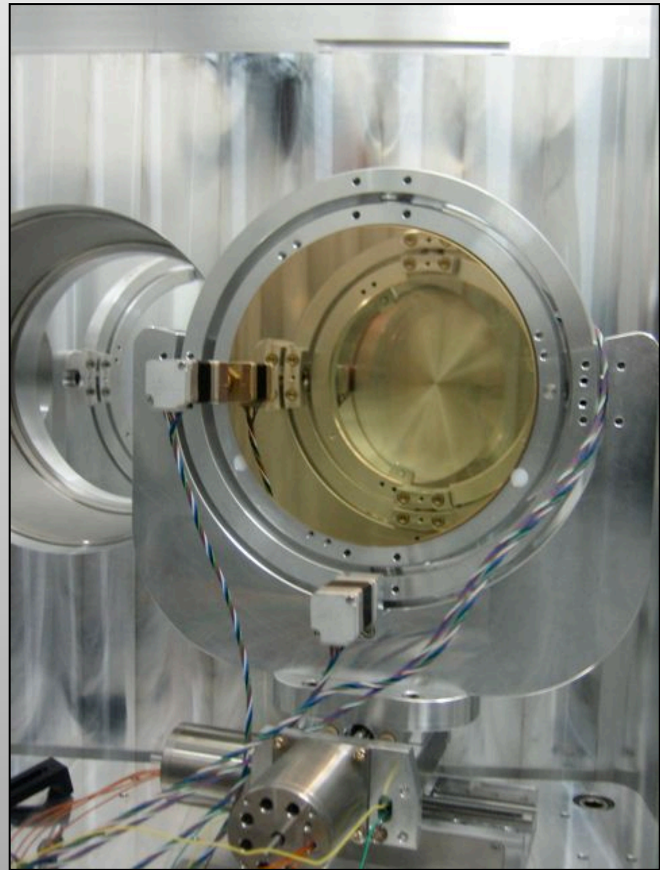
FLAME TARGET AREA



FOCUSING LASER

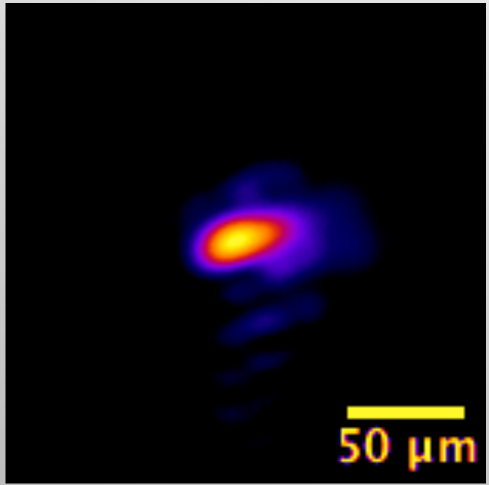
1 m focal length, 15° Off Axis Parabola (SORL)

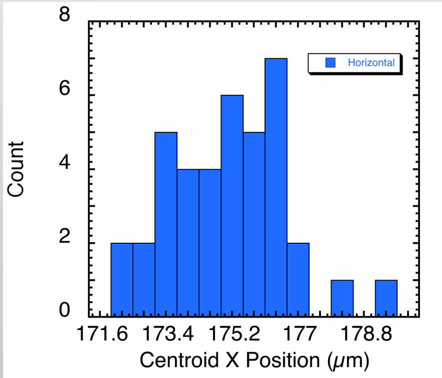


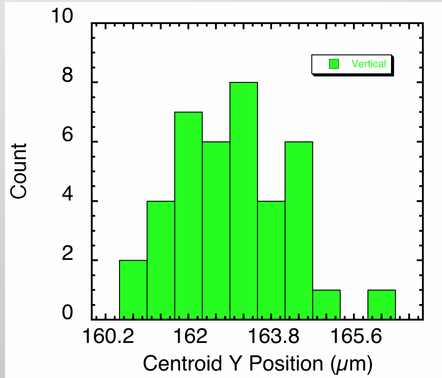


LASER AT TARGET CHAMBER CENTER

Pointing stability at TCC



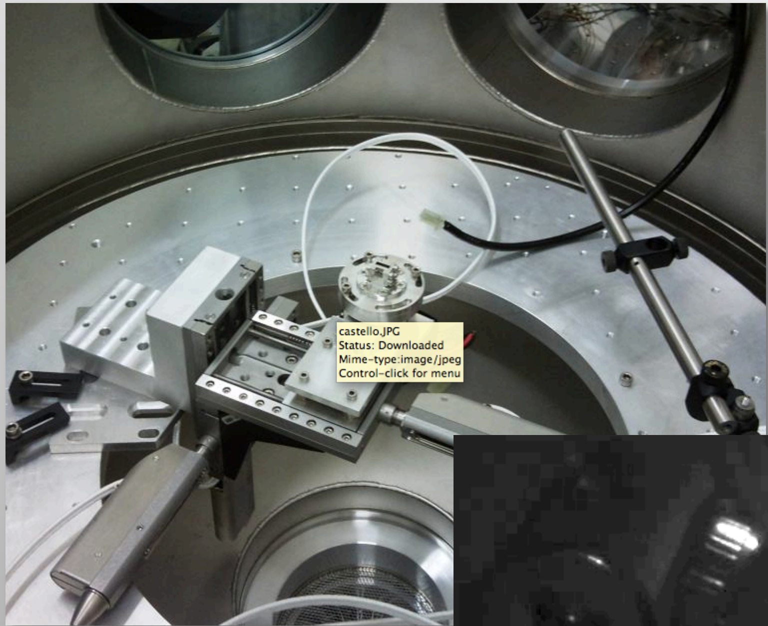


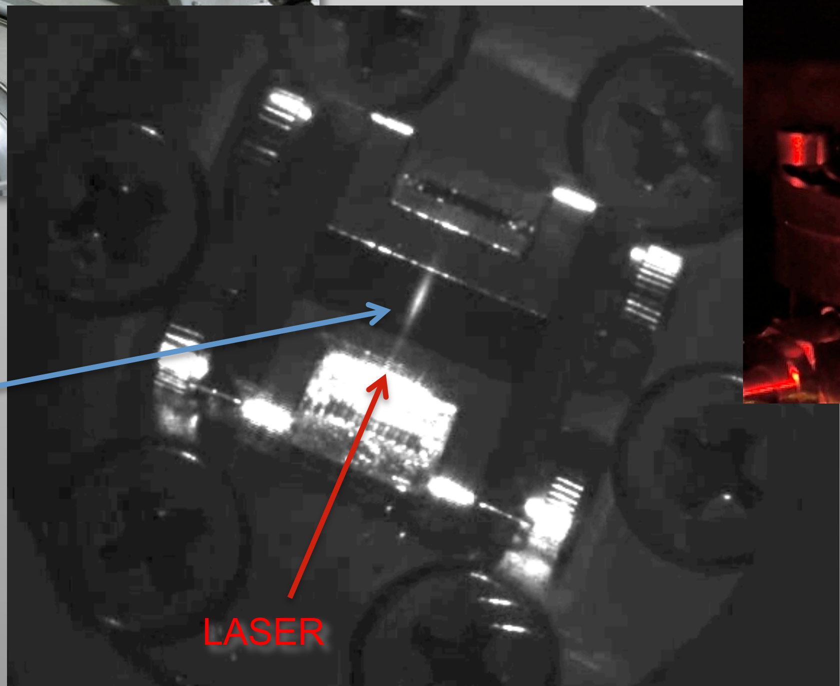


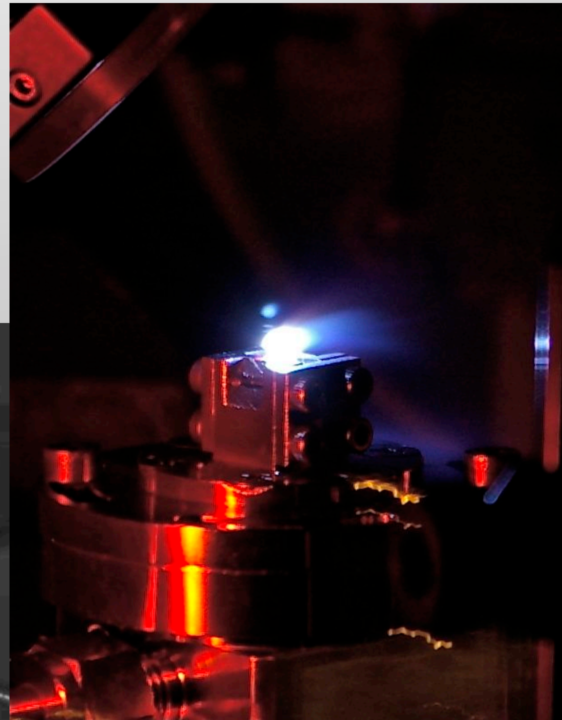
	Centroid Y	Centroid X
Minimum	160,89799	172,12
Maximum	166,22099	179,614
Points	39	39
Mean	162,9351	175,0372
Median	162,995	175,244
RMS	162,93927	175,04455
Std Deviation	1,18026	1,6241748
Variance	1,3930138	2,6379437
Std Error	0,18899286	0,26007611

LATEST: GAS-JET TARGET IN PLACE

August 2010: first plasma with f/10 OAP



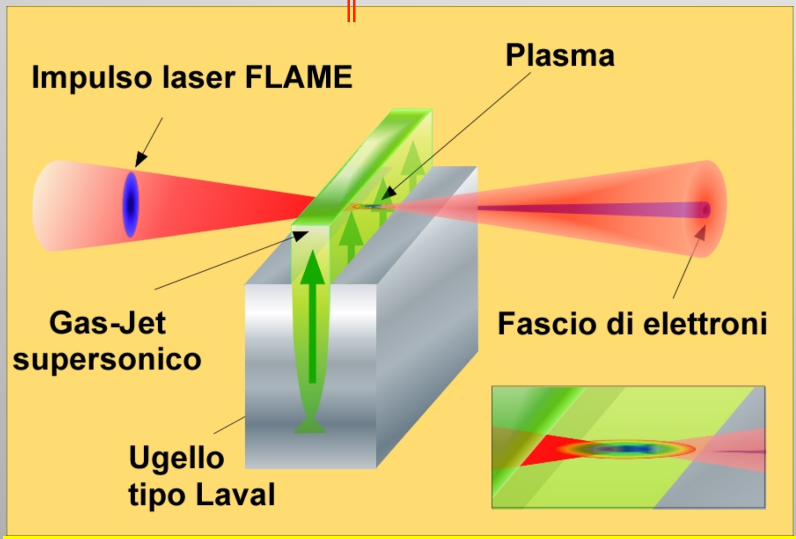




Wide-field top view image of the plasma (Thomson scattering imaging)

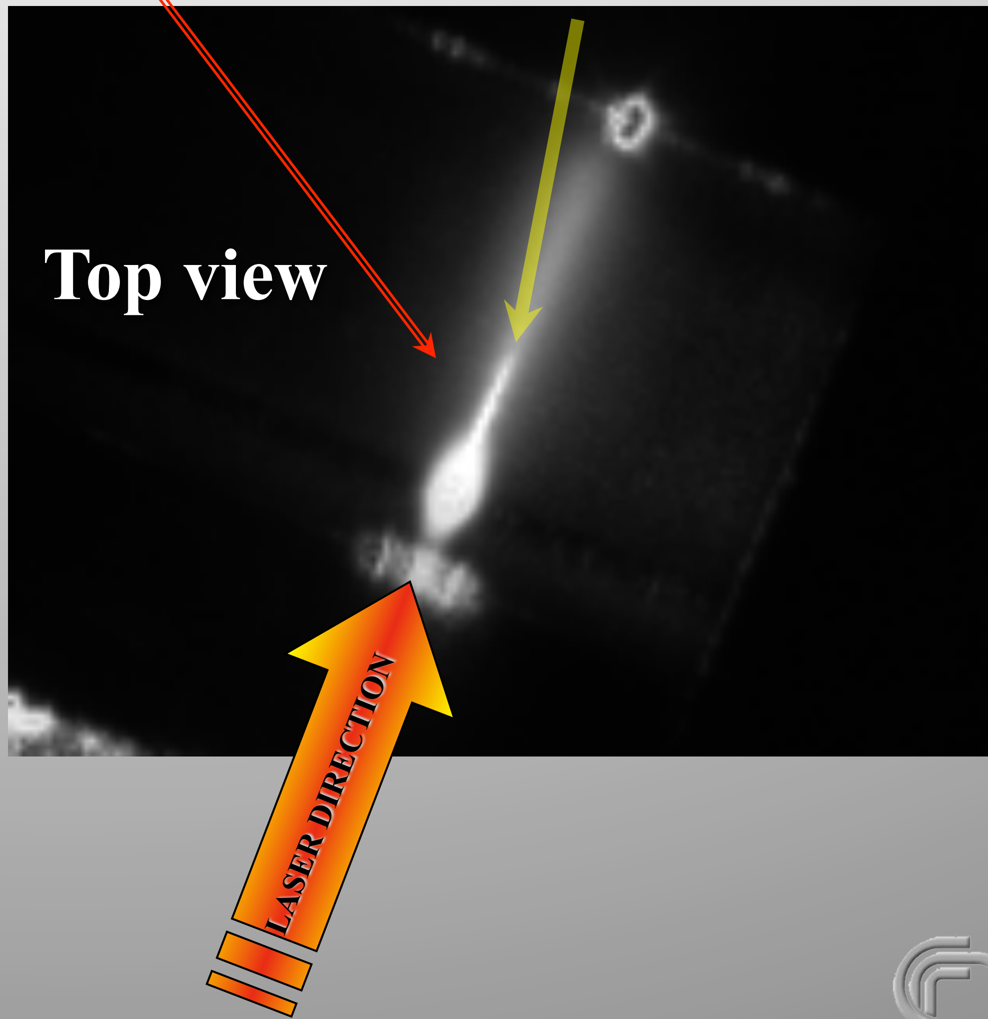
LNF-FLAME : first propagation test

September 2010: propagation control



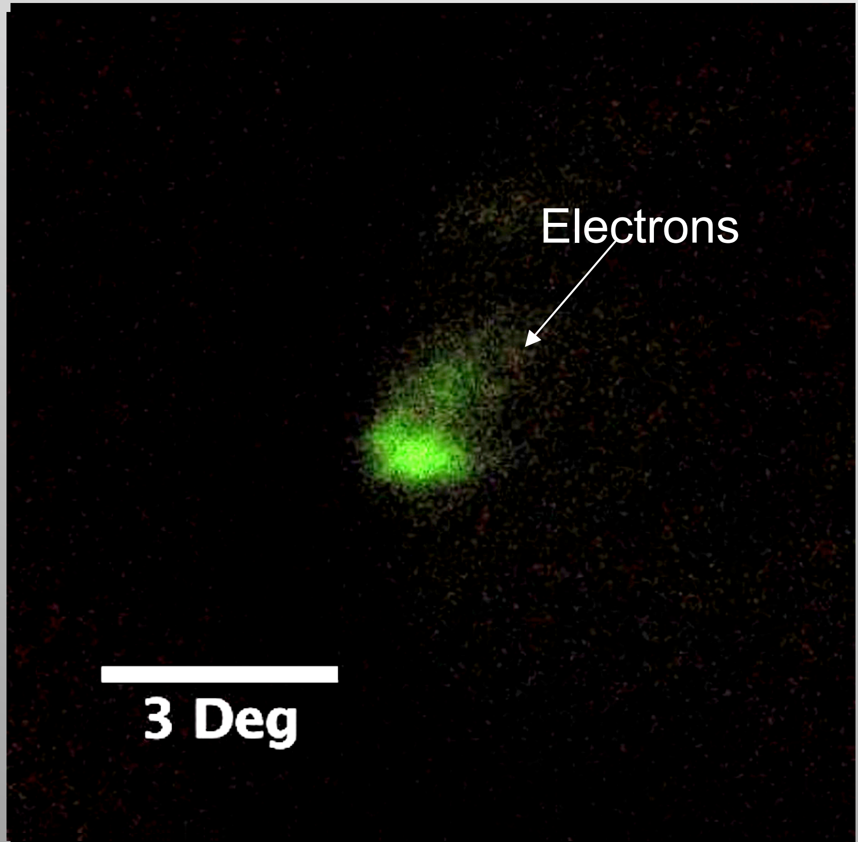
Set up

PLASMA - CHANNEL



LASER-PLASMA ACCELERATION at LNF
FIRST ELECTRONS FROM SELF-INJECTION

October 2010: first MeV e^- at low laser power



Basic Parameters for this dataset:

- →*Laser Energy before compression* ***550mJ***
- →*Laser pulse duration <40fs (FWHM)*
- →*Off-axis Parabola 1m focal length*
- →*Backing Pressure 17bar of N*
- → *4 mm length gas-jet*

LASER POWER ~ 7 TW

MAX LASER POWER will be~ 250 TW

Only 1 over 10 green pump laser are used in this case!
No focal spot and pulse duration optimization were performed!!

LASER-PLASMA ACCELERATION at LNF

FIRST ELECTRONS FROM SELF-INJECTION

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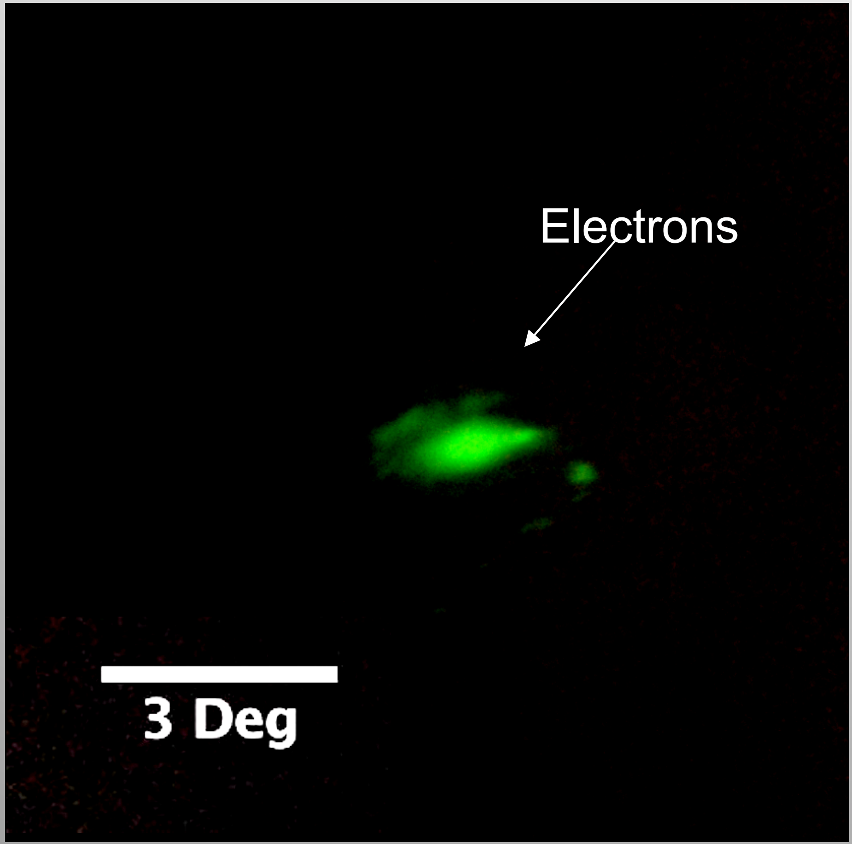

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LASER POWER ~ 7 TW

MAX LASER POWER will be~ 250 TW

Only 1 over 10 green pump laser are used in this case!
No focal spot and pulse duration optimization were performed!!

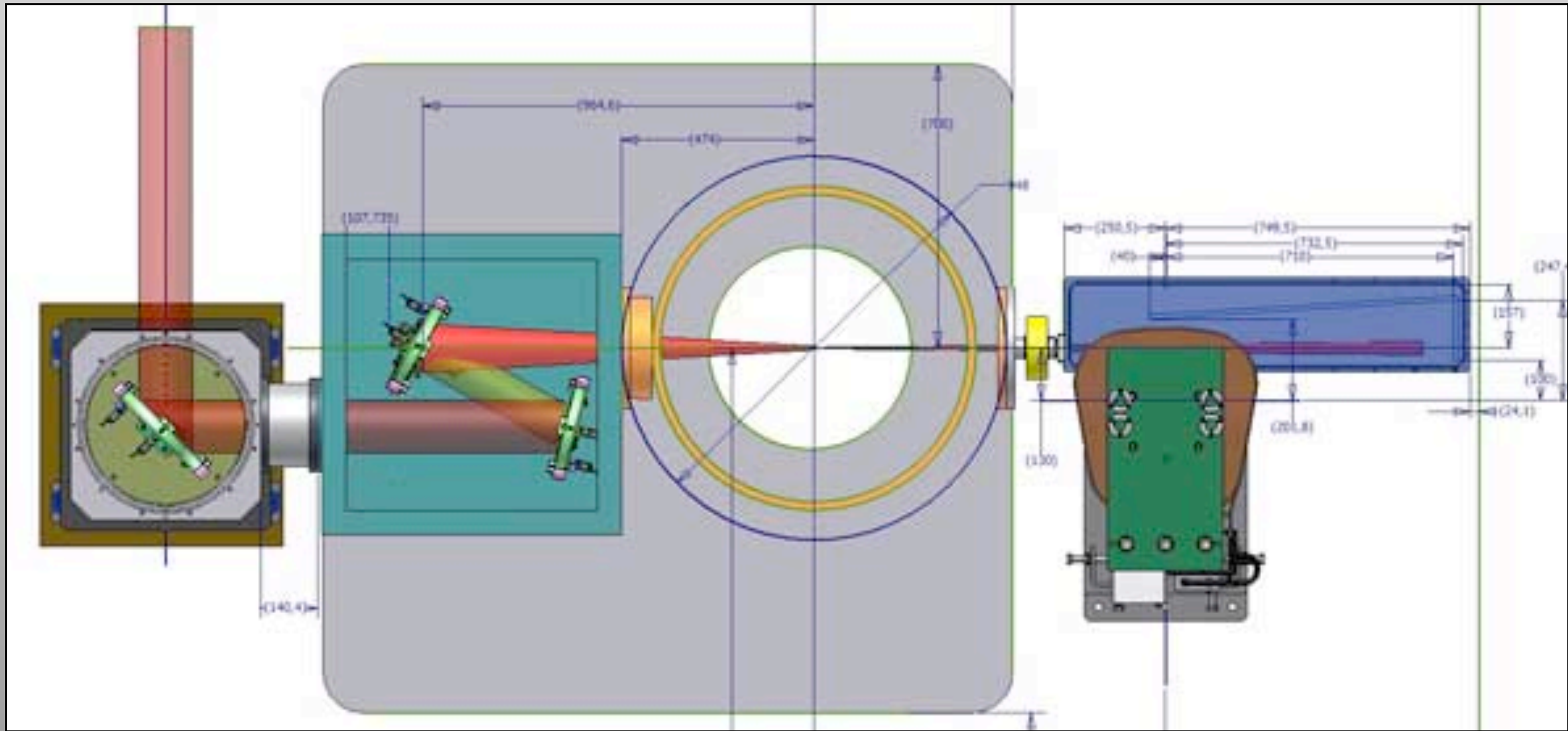
LPA Electron ENERGY

Preliminary energy measurements carried out with three different techniques

- Magnetic Spectrometer with electro-magnet and scintillating fibers;
- Radiochromic firm stack;
- Magnetic spectrometer with permanent magnet and LANEX screen.

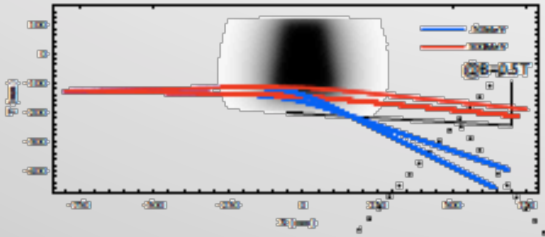
Electron ENERGY MEASUREMENTS

ELECTRON SPECTROMETER ON LINE – tests started

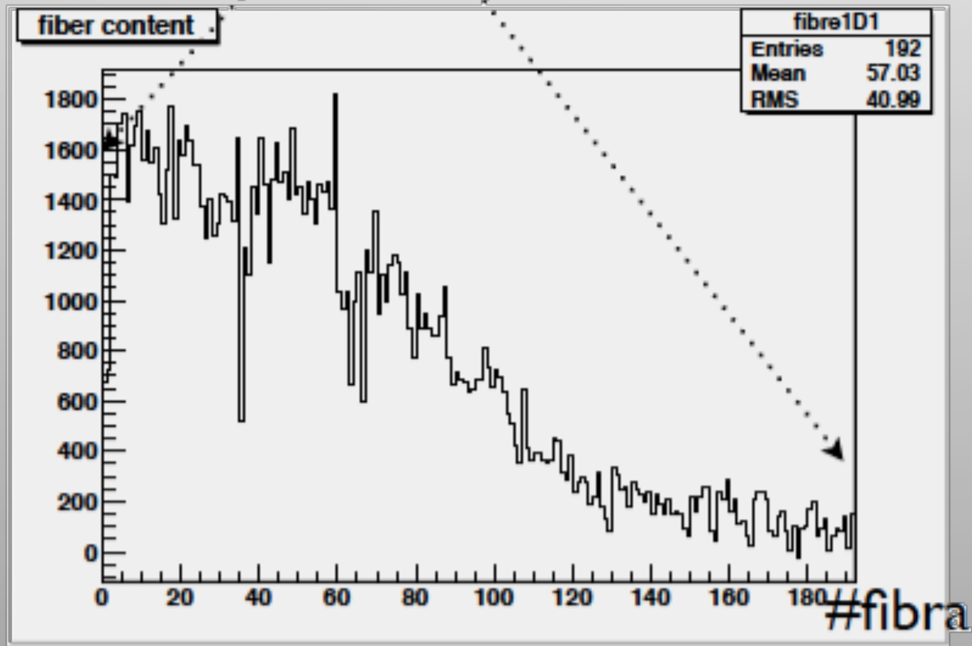


Preliminary data from Magnetic Electron Spectrometer

Uncollimated (no entrance slit), Laser energy range: 1J



B = 0



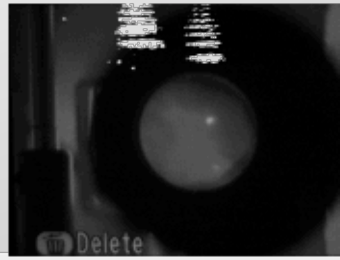
Immagini LANEX @ 30cm dal gas

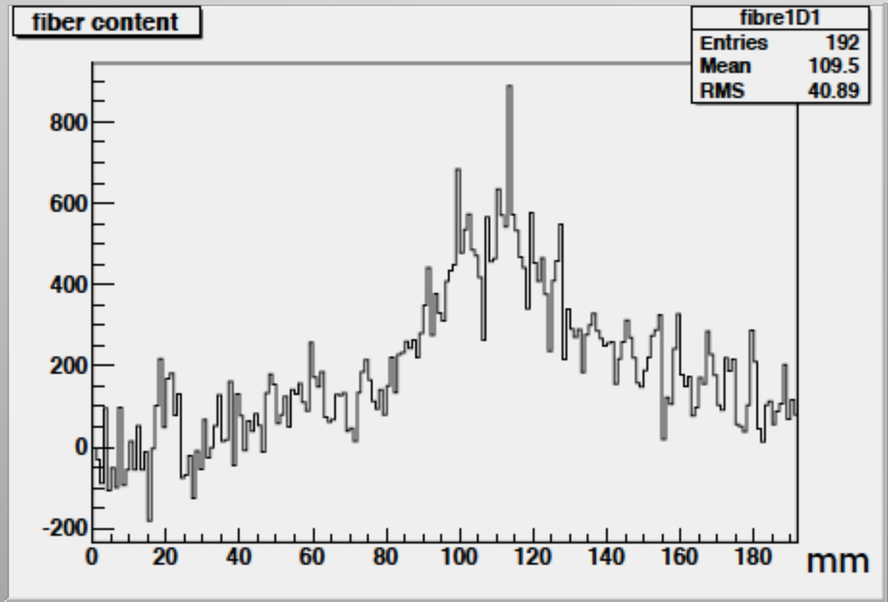
Particelle non collimate, spot di circa 7cm sul rivelatore in fondo allo spettrometro

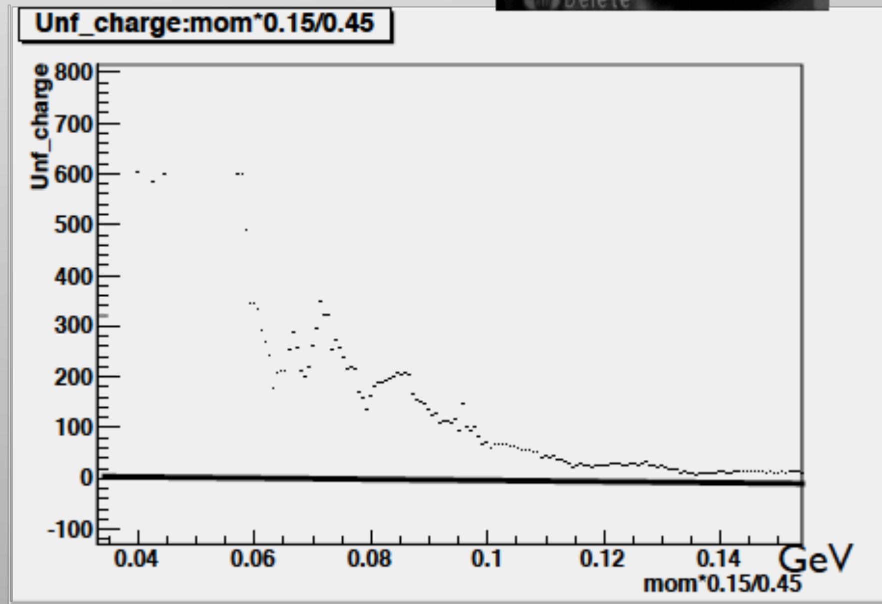
Preliminary data from Magnetic Electron Spectrometer

Laser energy range: 1J

B = 150mT



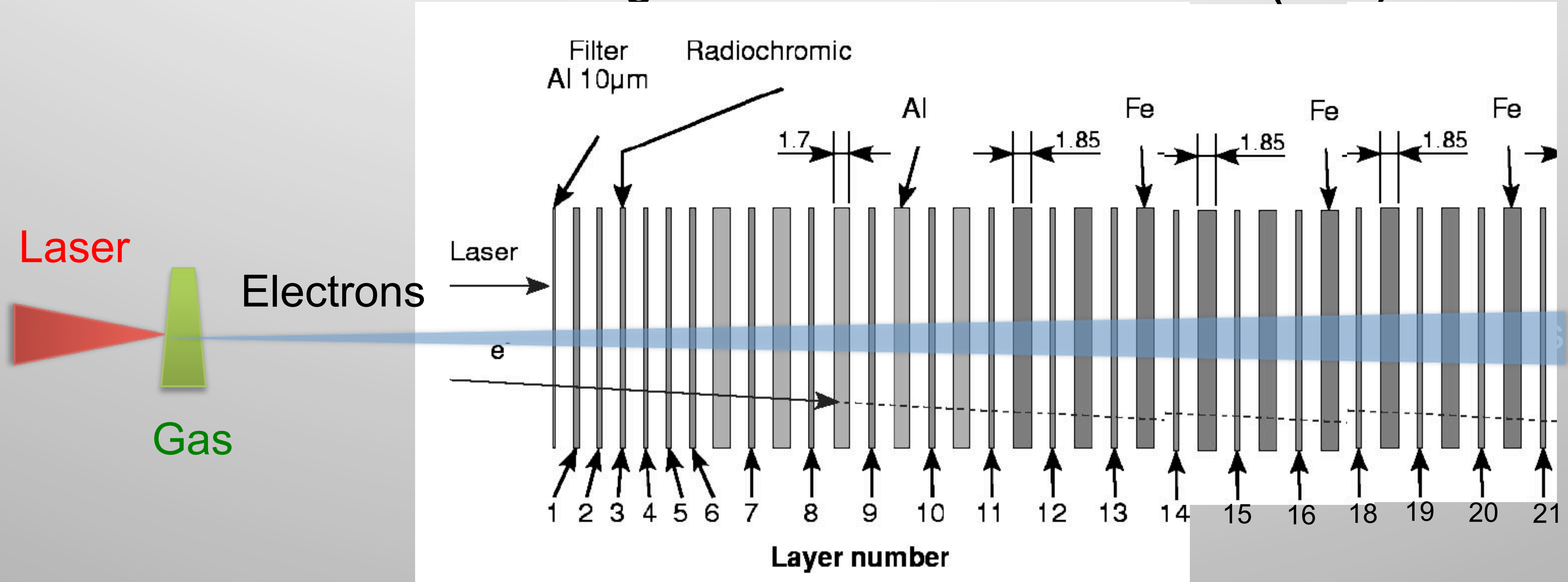




Data consistent with 100 MeV scale max electron energy

ENERGY ESTIMATE AT LOW LASER POWER

Performed using stack of Radiochromic films (RCF)



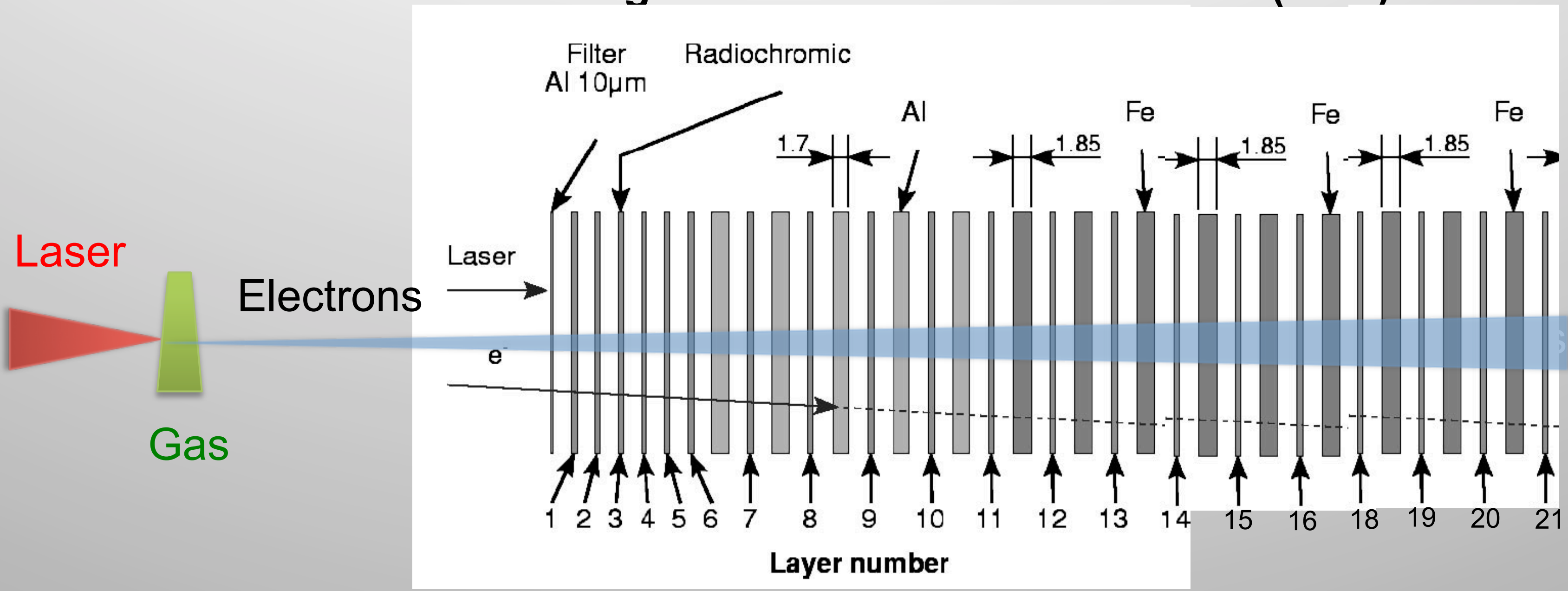
REVIEW OF SCIENTIFIC INSTRUMENTS **76**, 053303 (2005)

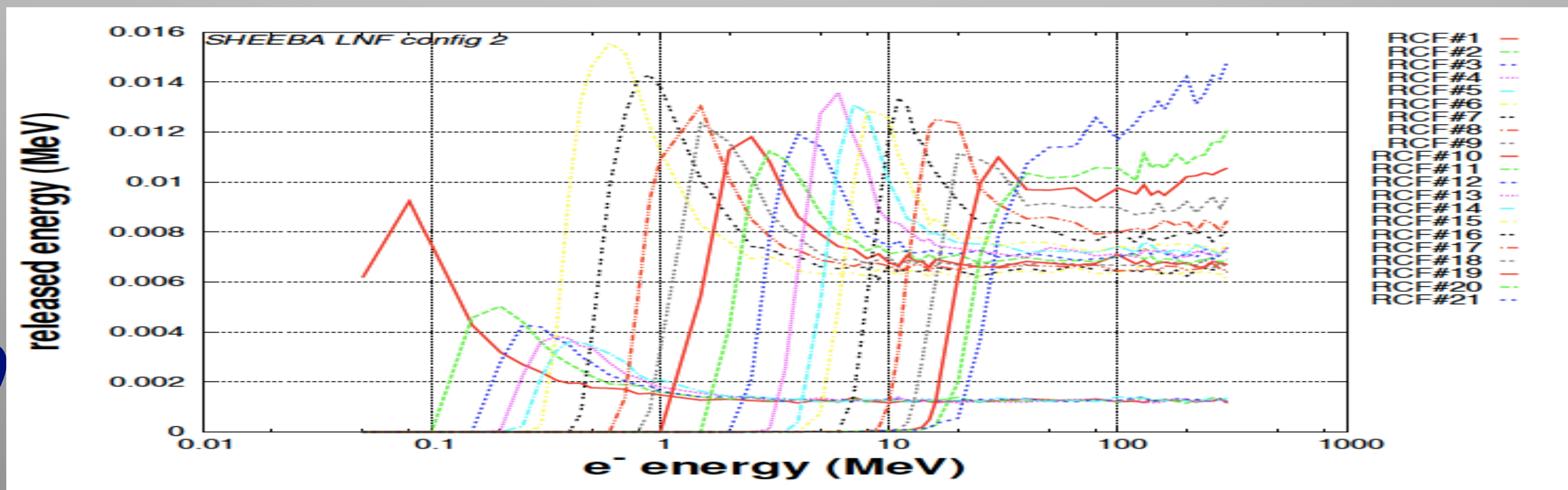
SHEEBA: A spatial high energy electron beam analyzer

Marco Galimberti,[a] Antonio Giulietti,[b] Danilo Giulietti,[c] and Leonida A. Gizzi[b]

ENERGY ESTIMATE AT LOW LASER POWER

Performed using stack of Radiochromic films (RCF)

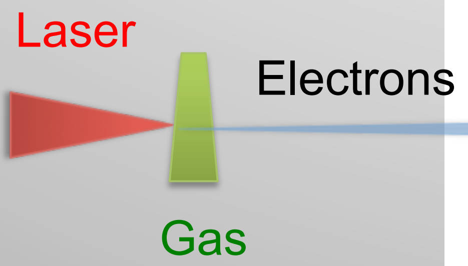


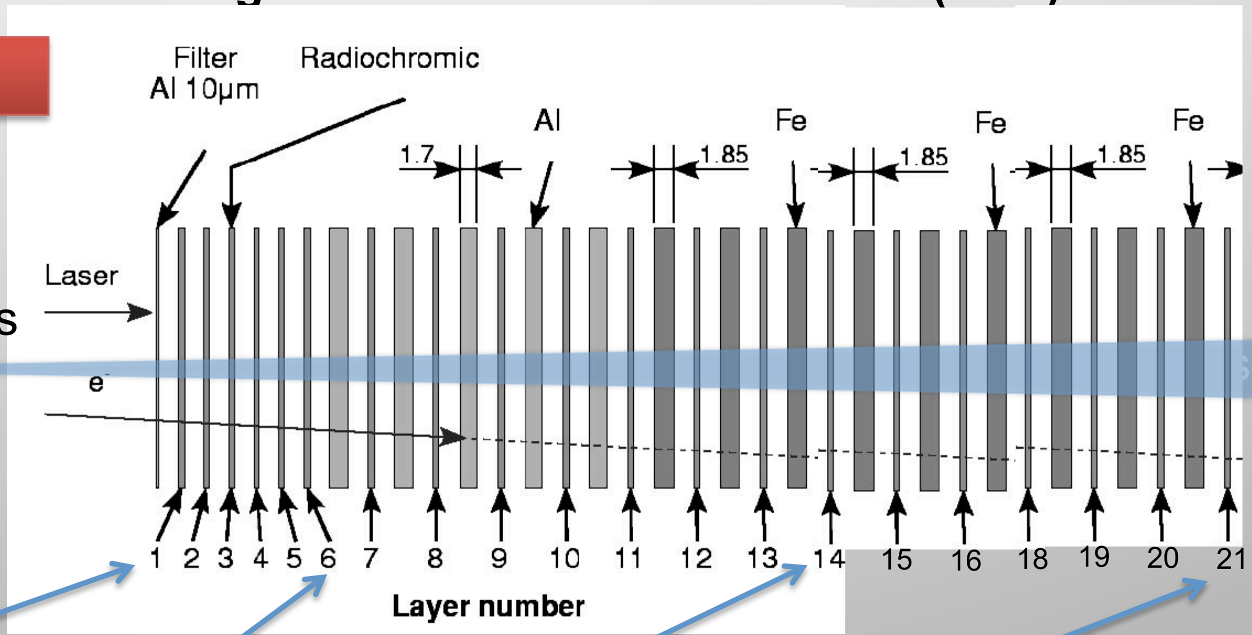


ENERGY ESTIMATE AT LOW LASER POWER

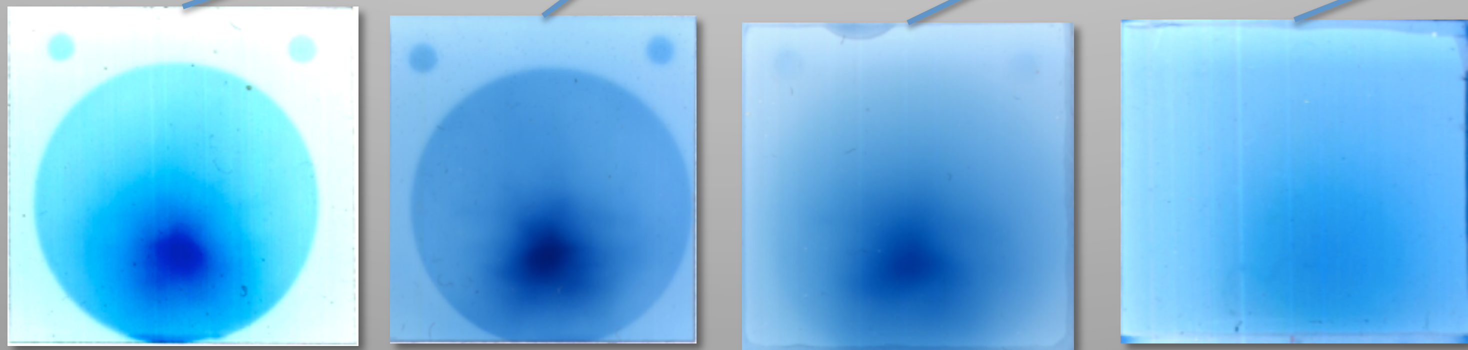
Performed using stack of Radiochromic films (RCF)

Laser energy range: 1J



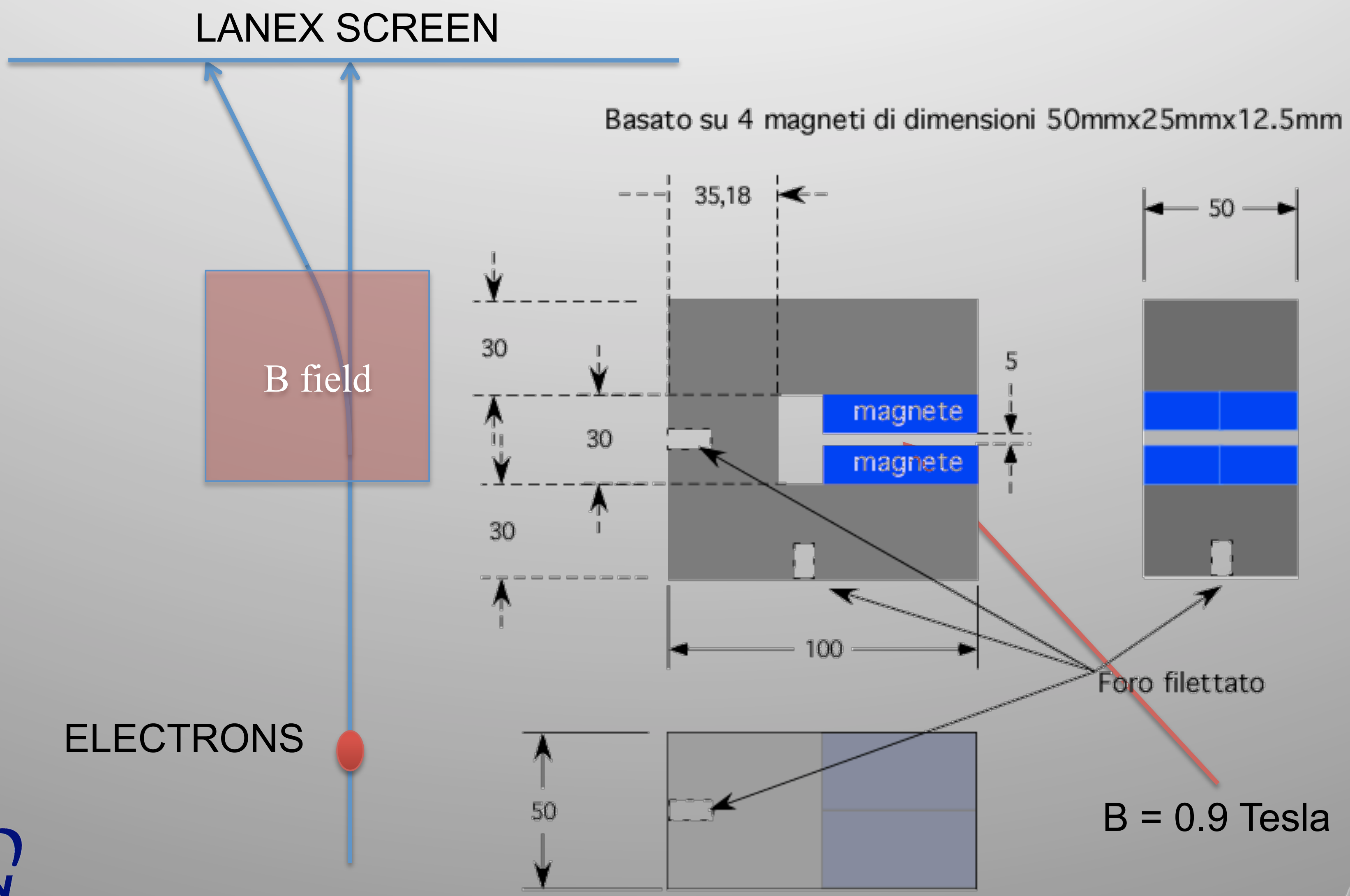


Data integrated over 31 shots



Signal well beyond layer 14 – new GEANT simulations in progress

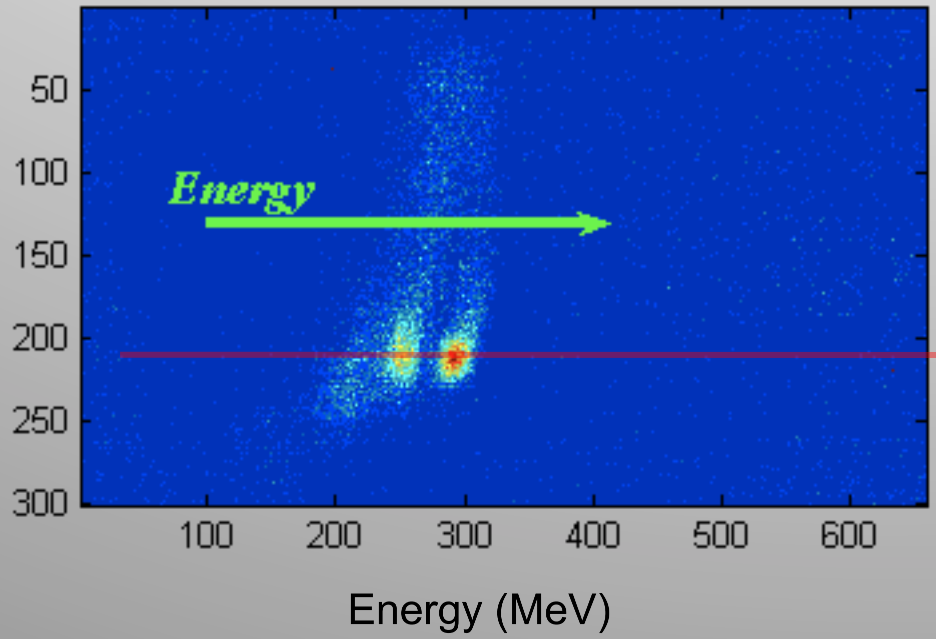
PERMANENT MAGNET SPECTROMETER



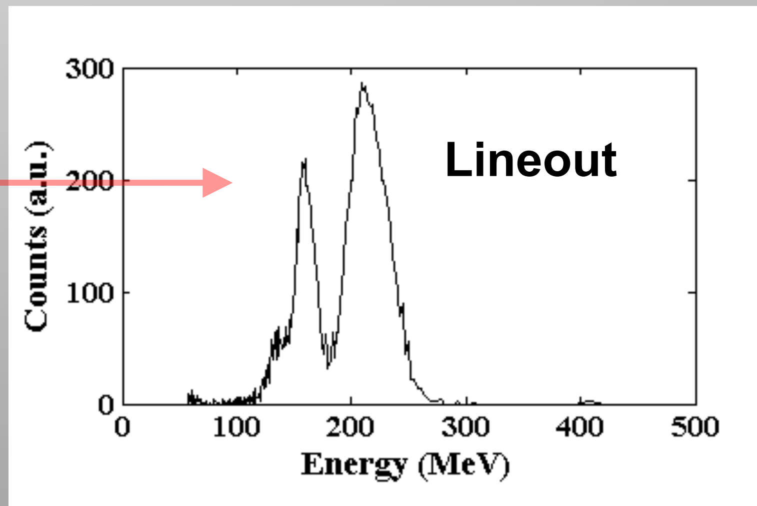
PRELIMINARY SPECTRUM

Recent spectra acquired at 2.5 J laser energy and 35 fs: expected intensity at focus: 7E18 W/cm2

Energy dispersion with a 0.9 T magnetic dipole



Electrons at lanex screen



Energy of LPA electrons entering the multi 100 MeV range

AGENDA FOR NEXT WEEKS

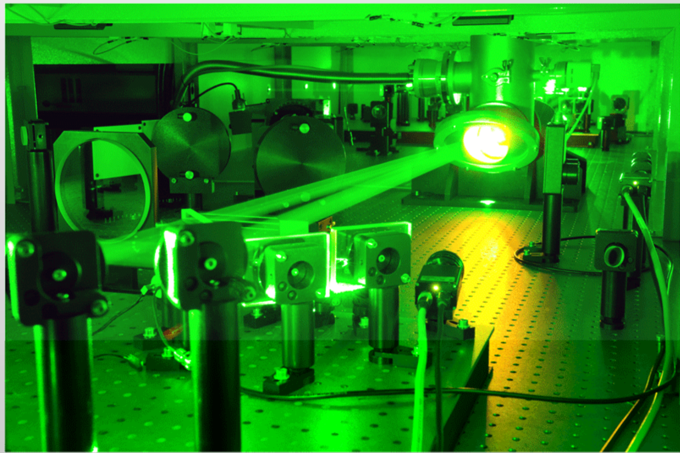
- **Finalize characterization of FLAME at full power:** transport, compression, OAP focusing (no target), far field, contrast, width, phase distortion, measurements … prepare for adaptive optics;
- **Complete set up** and test of HW and SW control and diagnostics for self-injection test experiment;
- **Complete registration** for radioprotection, safety and control of operations;
- **S.I.T.E. -** Laser on (gas-jet) target at >100 TW level – seek stable and mono-energetic bunch, measure energy, emittance, reproducibility. Extend plasma length.

INFN

PLANNED ACTIVITY

ATTIVITÀ COMMISSIONING FLAME E PLASMONX 2010-2011	LUG	AGO	SET	OTT	NOV	DIC	1° TRI '11	2° TRI '11	3° TRI '11	4° TRI '11
Acceleration with self-injection (SITE) - Laser Beam and Plasma Diagnstics	■									
Acceleration with self-injection (SITE) - Bunch production and characterisation with 1.2 mm gas-jet	■	■								
Acceleration with self-injection (SITE) - Bunch production and characterisation with 4.0 mm gas-jet,		■	■	■						
Acceleration with self-injection (SITE) - Bunch stability and control vs laser stability				■	■	■				
Commissioning FLAME: Assessment and validation of laser performance at interaction focus point					■	■	■			
Thomson Scattering: Installation of additional e-beam line and delivery of laser beamline							■			
FAST: Installation of laser-linac sync							■			
Thomson Scattering: integration of target chambre components and X-ray source optimisation								■	■	
Thomson Scattering: X-ray beam to users (BEATS)									■	■
FLAME target area Maintenance + set up and preliminary tests for solid target experiments							■	■		
Ion acceleration (LILIA) at FLAME target area									■	■

CONCLUSIONS



- PLASMONX progressing on schedule
- FLAME laser operational
- FLAME target area operational
- First multi-100MeV electrons from self-injection

CONTACT PERSONS FOR FLAME COMMISSIONING

TECHNICAL MANAGER
Giampiero DI PIRRO (LNF)
SUBSYSTEMS (Contact persons)
Laser Installation
Leonida A. GIZZIand Danilo GIULIETTI ((DIP. FIS. UNIPI, IPCF-CNR, INFN-PI, LNF)
Laser operations and control command
Tadzio LEVATO(LNF) and Luca LABATE (CNR & INFN-PI)
FLAME-SPARC interfaces – Laser, Optical, Electronics, Mechanics
Giancarlo GATTI
FLAME systems: clean room, water cooling and air conditioning
Luigi PELLEGRINO(LNF, Servizio Impianti a Fluido della DT)
Electricity network
Ruggero RICCI (LNF, Servizio Impianti Elettrici della DT)
Ethernet network
Massimo PISTONI (LNF)
FLAME software interfaces
Elisabetta PACE (LNF)
Beam Transport air+ vacuum - FLAME buildings
Valerio LOLLO (LNF), Alberto CLOZZA (LNF, Servizio Vuoto della DA) & Andrea GAMUCCI (CNR & INFN-PI)
SAFETY
Sandro VESCOVI (LNF), Tadzio LEVATO (LNF), Carlo VICARIO(LNF)
SAFETY (Radiation protection)
Adolfo ESPOSITO (LNF)
FLAME Target Area - laser beams (main and probe) control, focusing and diagnostics
Luca LABATE (CNR & INFN-PI)
FLAME Target Area - test experiments diagnostics and remote control
Carlo A. CECCHETTI (LNF & IPCF-CNR Pisa)
FLAME web site and outreach
Leonida A. GIZZI & Luca LABATE
Logistics
Oreste CERAFOGLI (LNF, Servizio Edilizia della DT)
Technical and Engineering support
Luciano CACCIOTTI (LNF)

INFN

S.I.T.E. - SELF-INJECTION test experiment: PEOPLE

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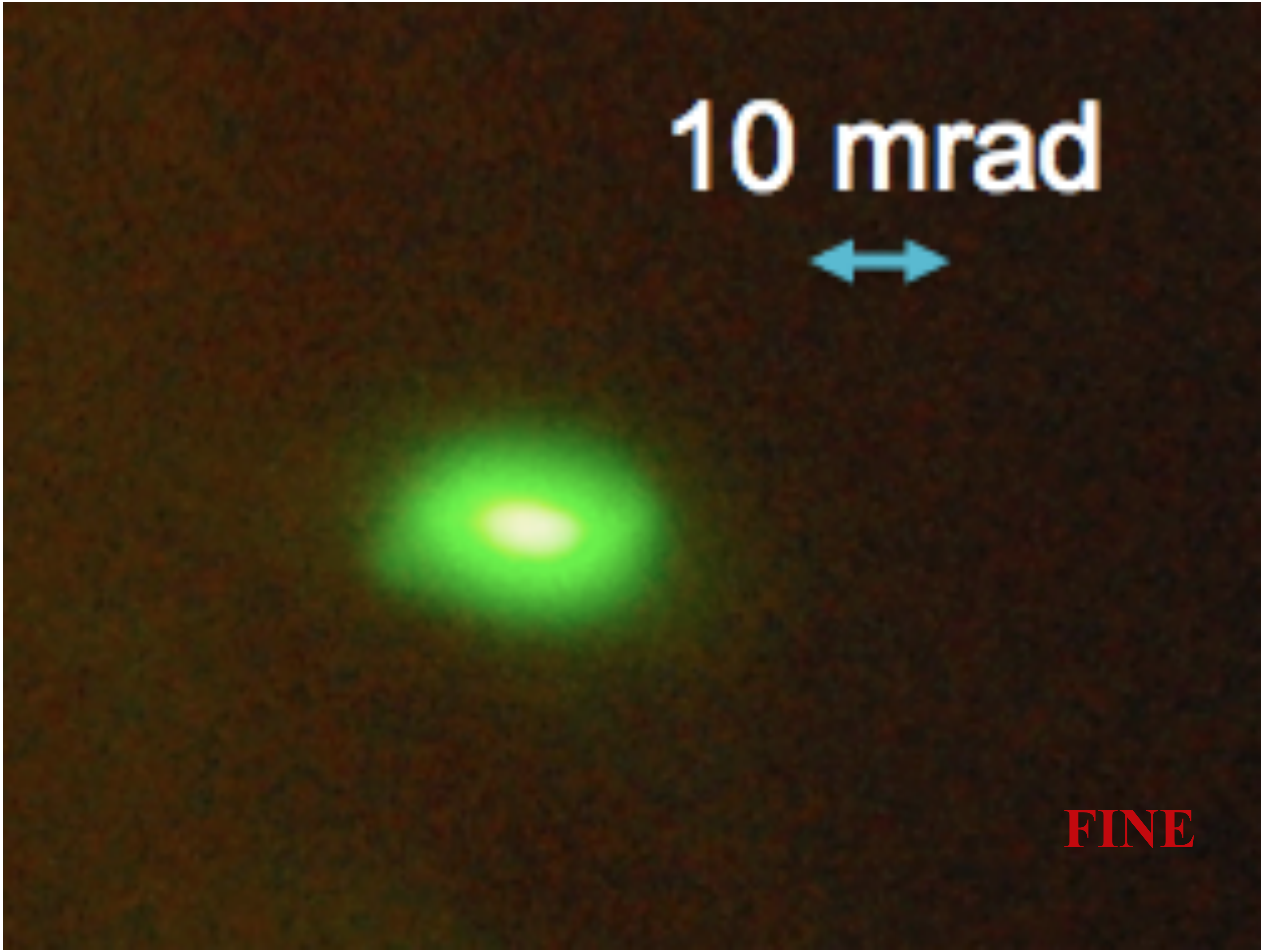
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