# The Physics of the Laser-Plasma Accelerators: Challenges & Limits

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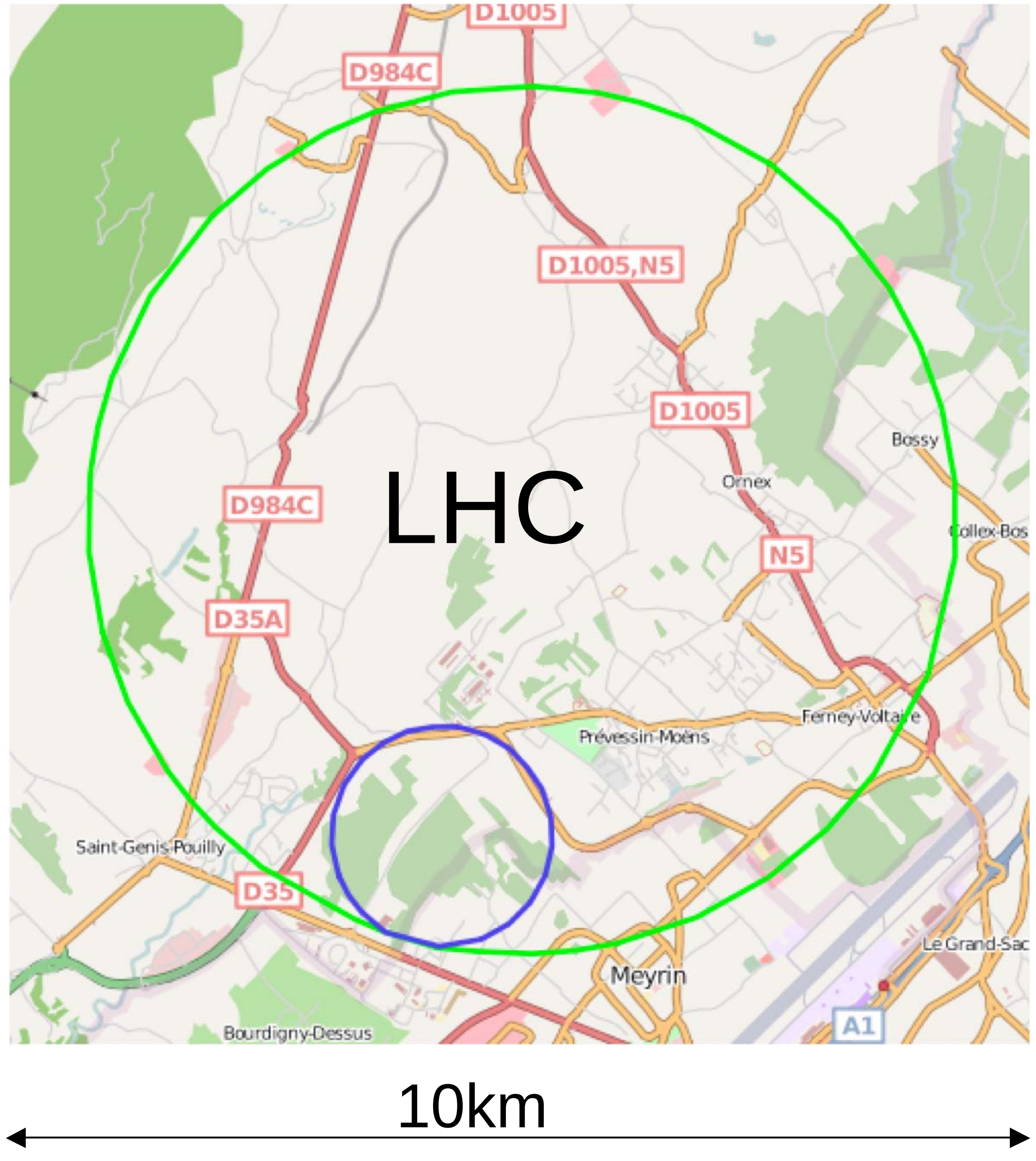
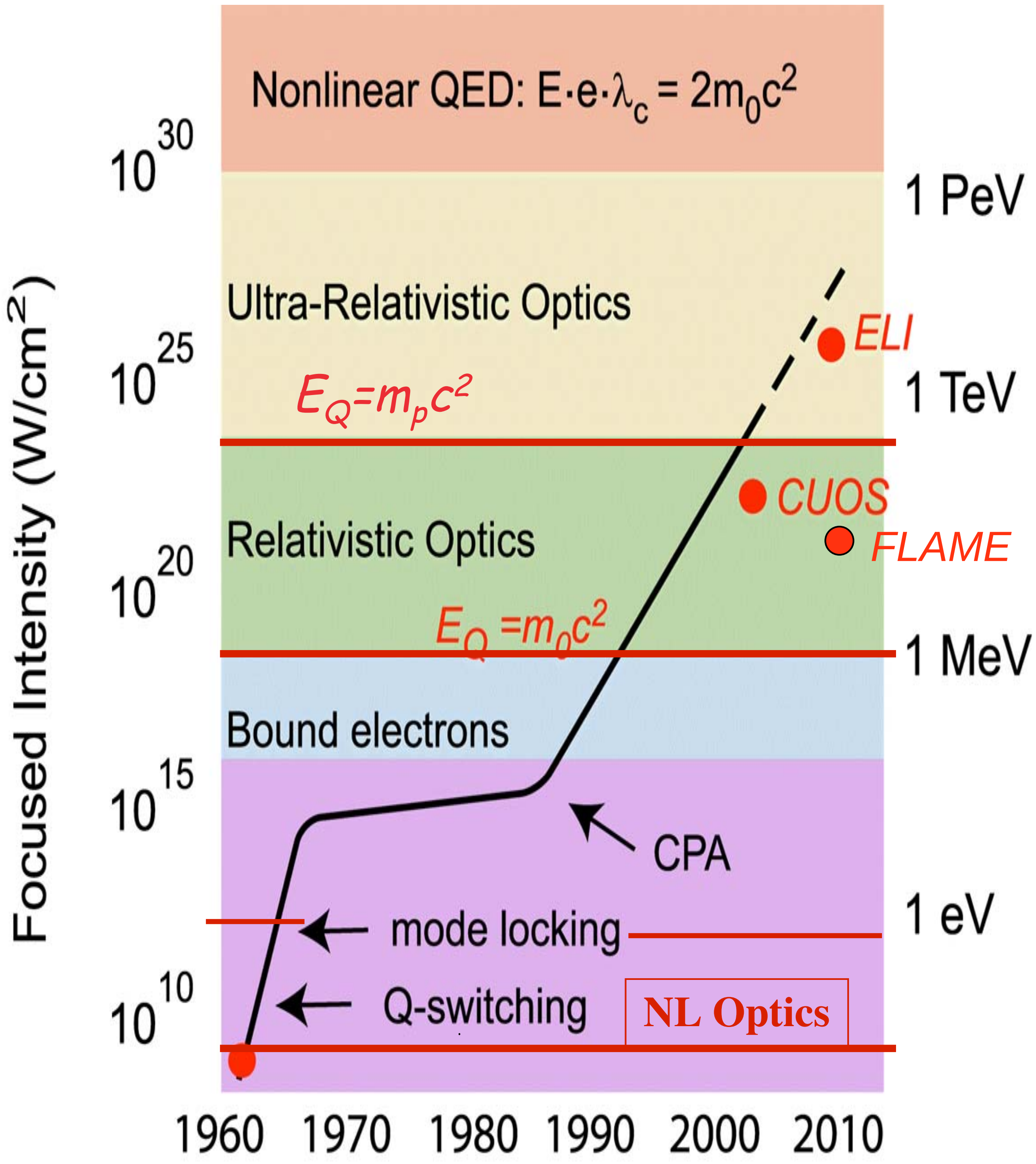
# The gigantism of conventional accelerators



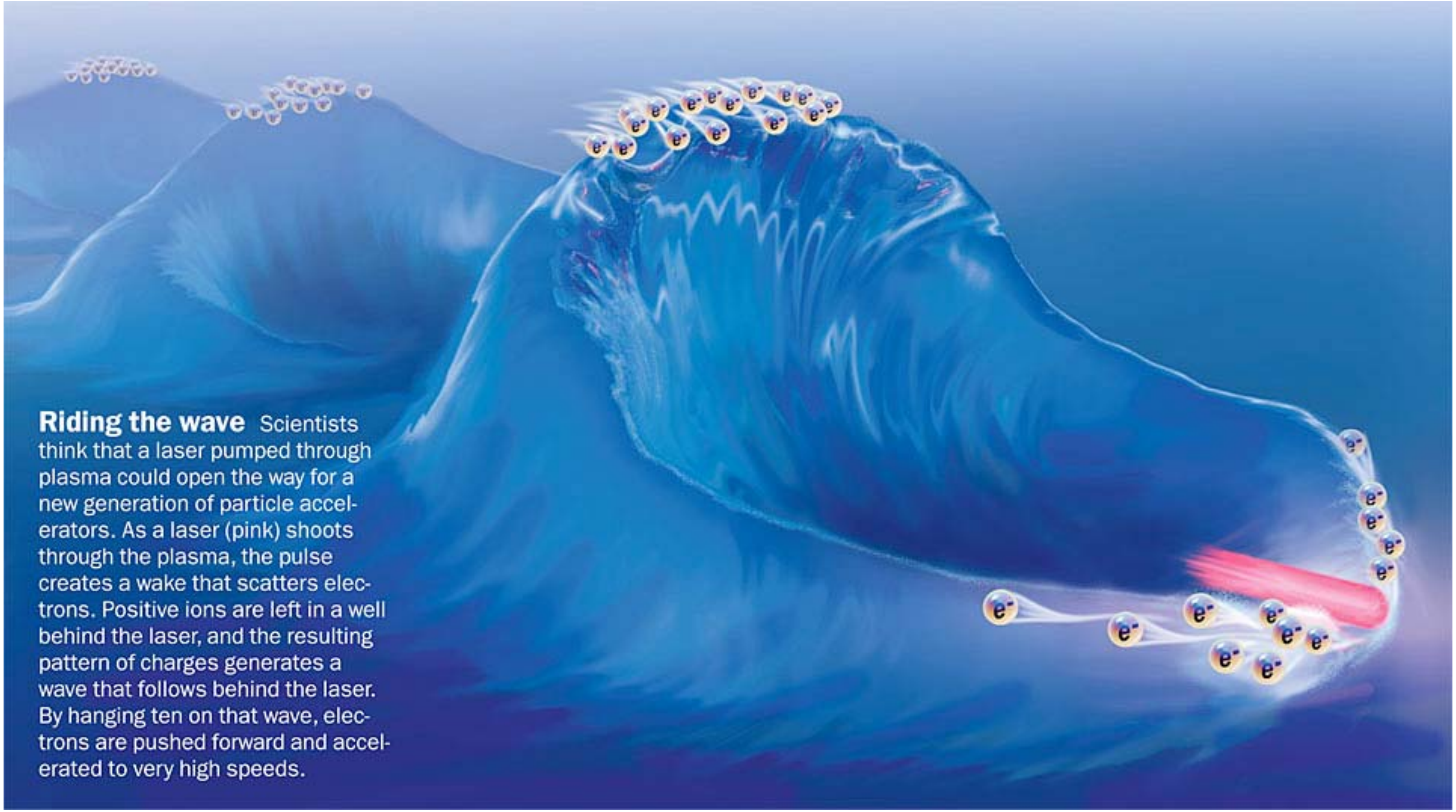



***The evolution of the pulsed laser amplification techniques:***

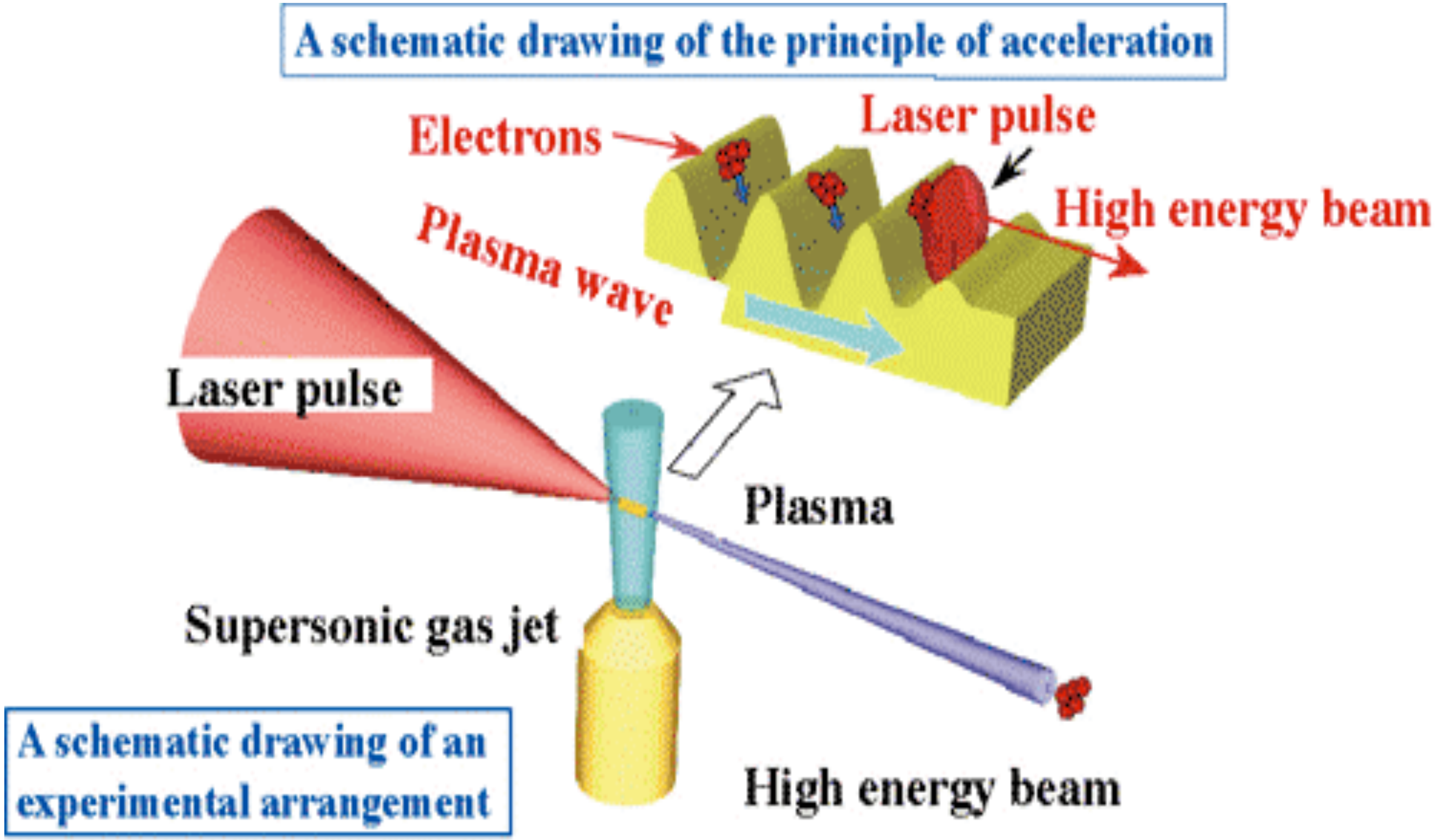
**from ns to fs**

**from MW to PW**

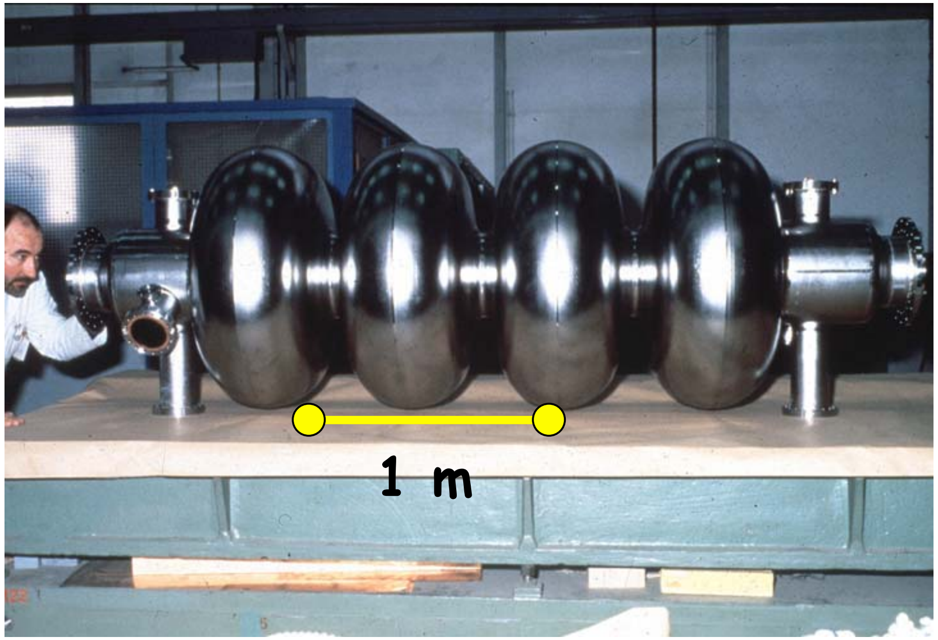
# Ultra-short & super-intense laser pulse in a plasma



**The ponderomotive force related to the laser pulse produces the Wake Field and the Coulomb force related to the Electron Plasma Wave accelerates the electrons**

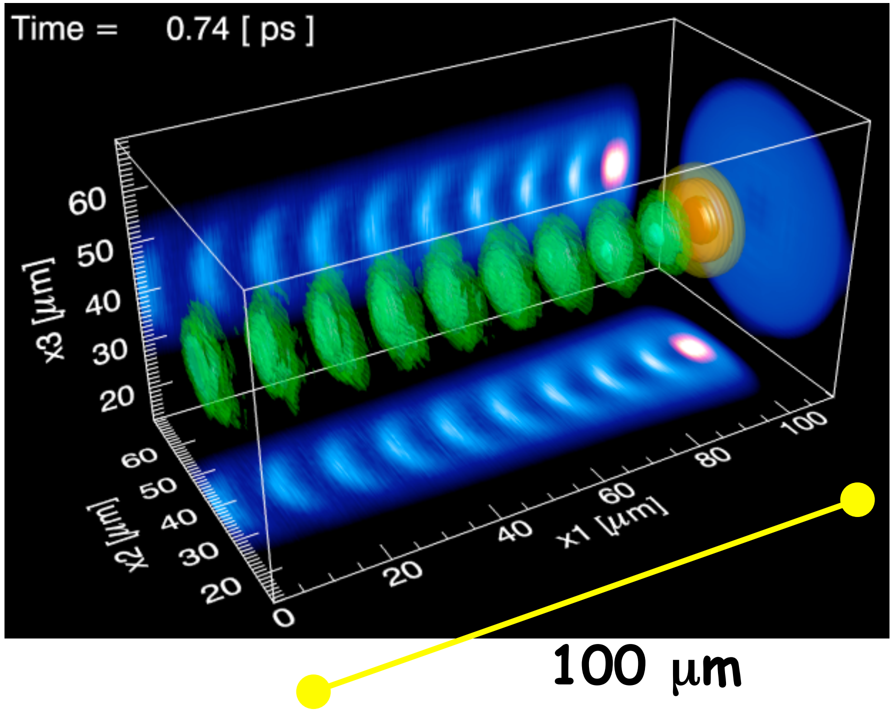


# RF CAVITY versus "PLASMA CAVITY"




RF cavity

*Courtesy of W. Mori & L. da Silva*




Plasma cavity

$E_{max} \approx 20 MV/m$

$E_{max} > 100 GV/m$

## Why a plasma to accelerate electrons ?

* no limits to the accelerating electric fields

* electron plasma waves fit requirements for particle acceleration:

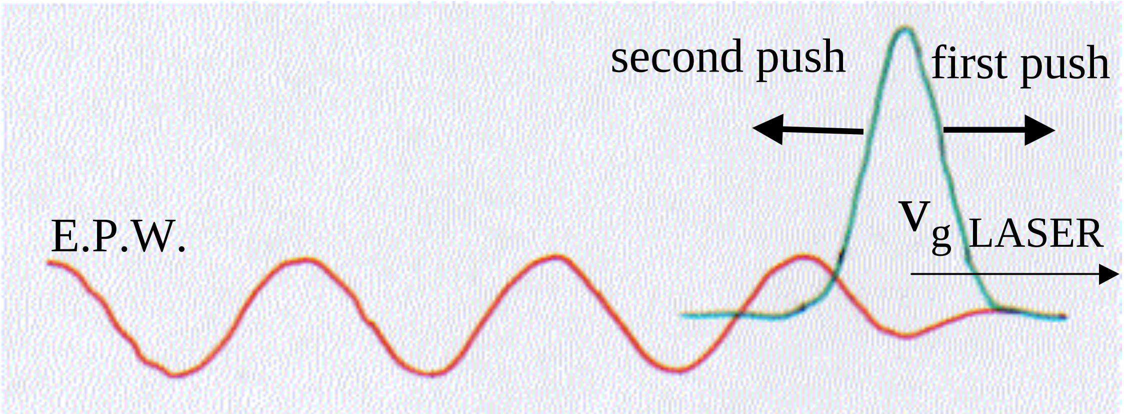
- *intense longitudinal electric fields:* $E_{V/cm} \approx (n_{cm-3})^{0.5}$
- *phase velocity very close to the speed of light c*

## Why high intensity fs laser pulses ?

* the ponderomotive force is proportional to $-\nabla I$

* the plasma resonance can be excited at higher density $2c\tau_{laser} \approx \lambda_p$

# LASER WAKE FIELD



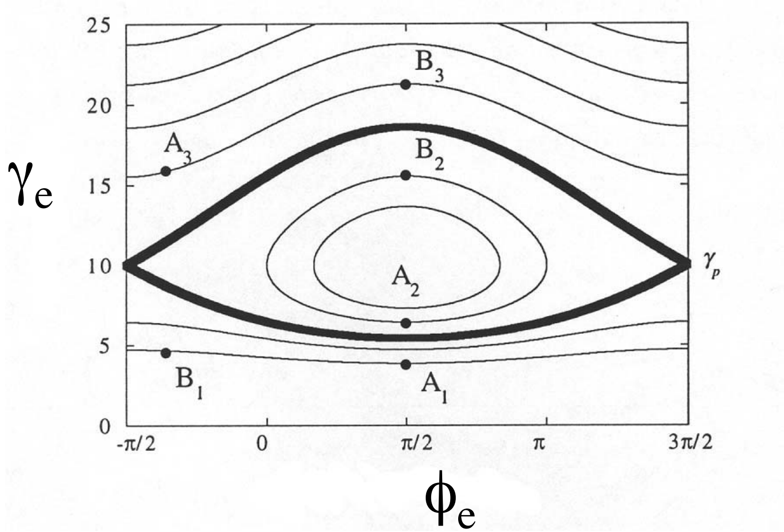

$$\tau \cdot c \approx \frac{\lambda_p}{2} \iff \tau \approx \frac{T_p}{2} \Rightarrow n_e\left(cm^{-3}\right) \approx \frac{3 \cdot 10^{-9}}{\tau_{(s)}^2}$$

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

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

# ELECTRON ACCELERATION IN E.P.W.

## 1D MODEL




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

$$along \;\; a \;\; distance \;\; L_{deph} \approx \gamma_p^2 \lambda_p = \lambda_0 \left( \frac{n_c}{n_e} \right)^{\frac{3}{2}} \qquad \lambda_p \approx \frac{2\pi c}{\omega_{pe}}$$

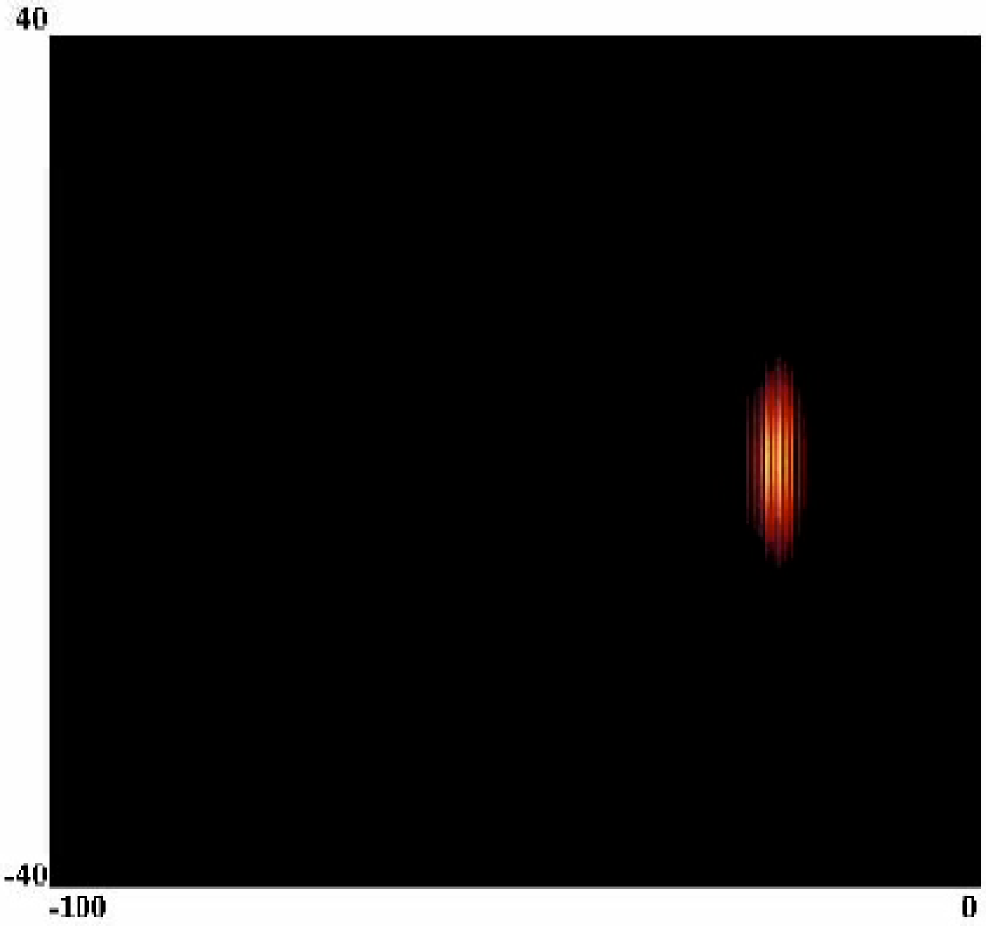
$$\Delta W_{\max} \approx eE_{\max} \cdot L_{deph} \propto n_e^{\frac{1}{2}} \cdot \frac{1}{n_e} \cdot n_e^{-\frac{1}{2}} = \frac{1}{n_e}$$

# Typical underdense plasmas for Ti:Sa laser

$$n_e = 10^{20} cm^{-3} \quad \gamma_p = 3.16 \quad E_{\max} \approx 10^{10} Vcm^{-1} \quad \Delta W_{\max} \approx 20 MeV \quad L_{deph} \approx 30 \mu m$$

$$n_e = 10^{18} cm^{-3} \quad \gamma_p = 31.6 \quad E_{\max} \approx 10^{9} Vcm^{-1} \quad \Delta W_{\max} \approx 2 GeV \quad L_{deph} \approx 3 cm$$

# LASER PLASMA ACCELERATION




PIC simulation by Carlo Benedetti, INFN-BO

$N_e = 10^{19} cm^{-3}$

L=1mm

T=20fs

$W = 9\mu m$

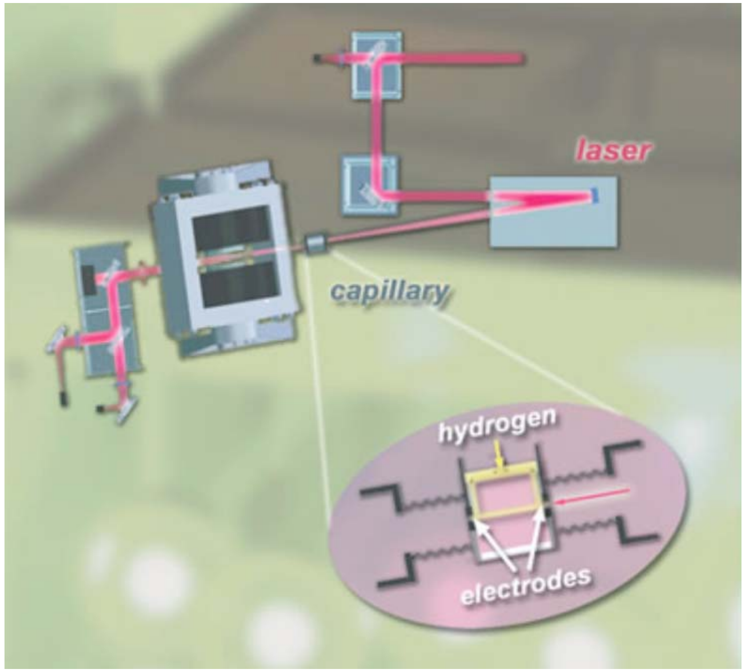
$I = 1.5\ 10^{20} W/cm^2$

$U_{el} \approx 400 MeV$

# LASER GUIDING

- Hollow fiber
- Gas cell
- Relativistic Self-Focusing P(GW) >17 $n_c/n_e$
- Pre-formed channel

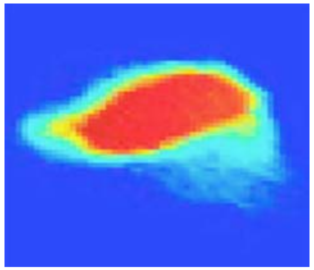
# 1GeV in 3.3 cm capillary




40 TW Ti:Sa laser focused on a Ti:Sa capillary 3.3 cm long, filled with Hydrogen.

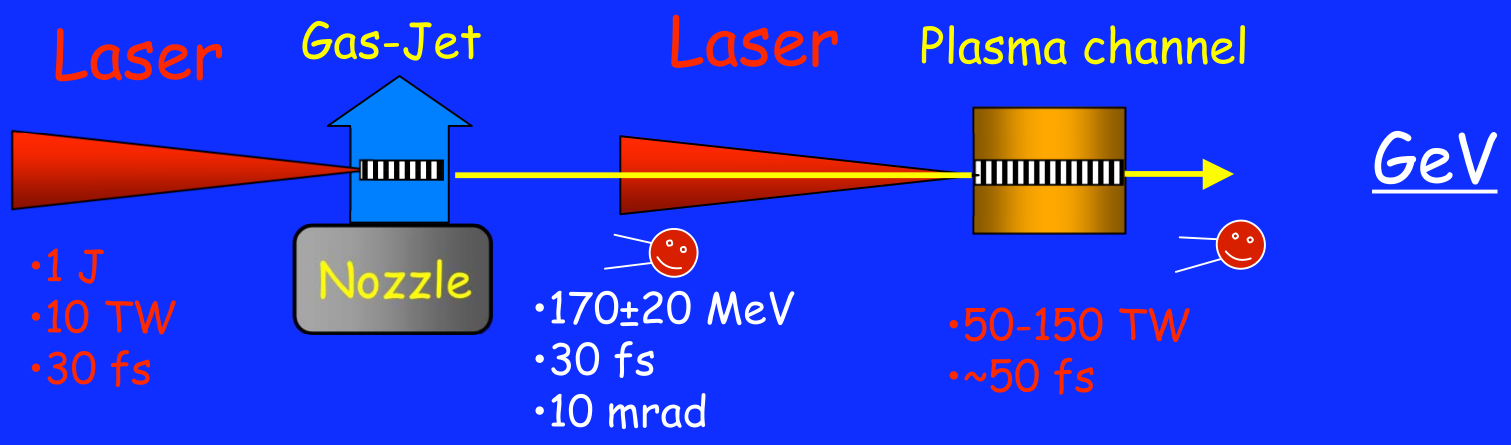
Electrical discharge produces a $10^{18}$ cm-3 plasma

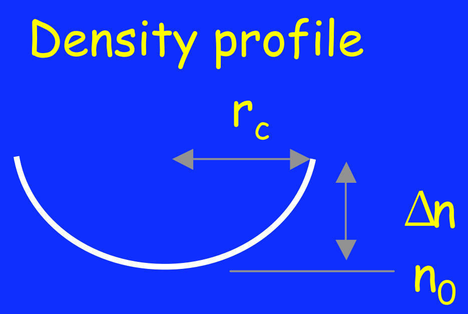
2.5% energy spread of accelerated electron



W.P. Leemans, S. Hooker et al Nature **2**, 629, 2006

# GeV acceleration in two-stages




- Pulse guiding condition : $\Delta n > 1/\pi r_e r_c^2$
- Weak nonlinear effects ⇒ more control : $a_0 \sim 1\text{-}2$
- High quality beams : $L_b < \lambda_p \Rightarrow n_0 < 10^{18}\ cm^{-3}$

*Courtesy V. Malka*

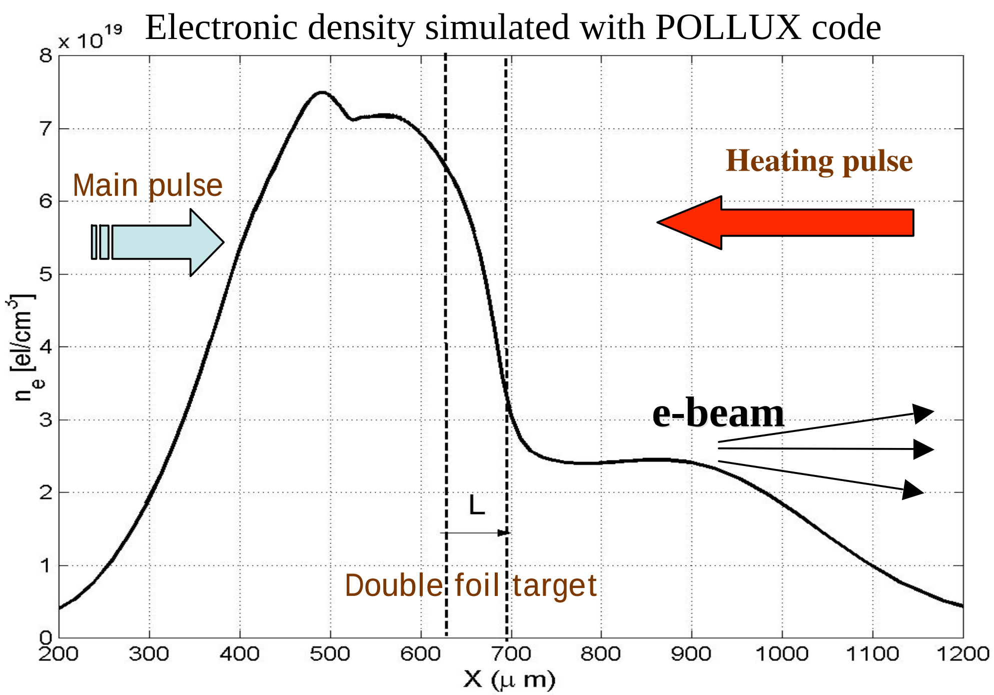
# IMPROVING THE ENERGY SPREAD

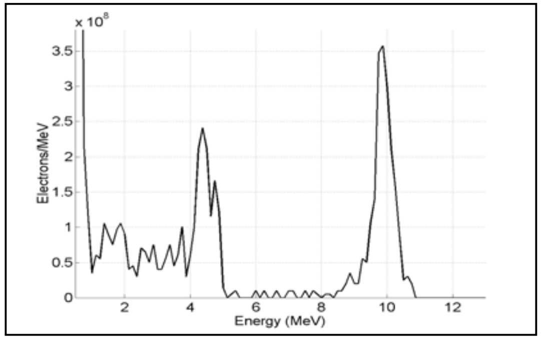
- Controlled injection

- 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)***

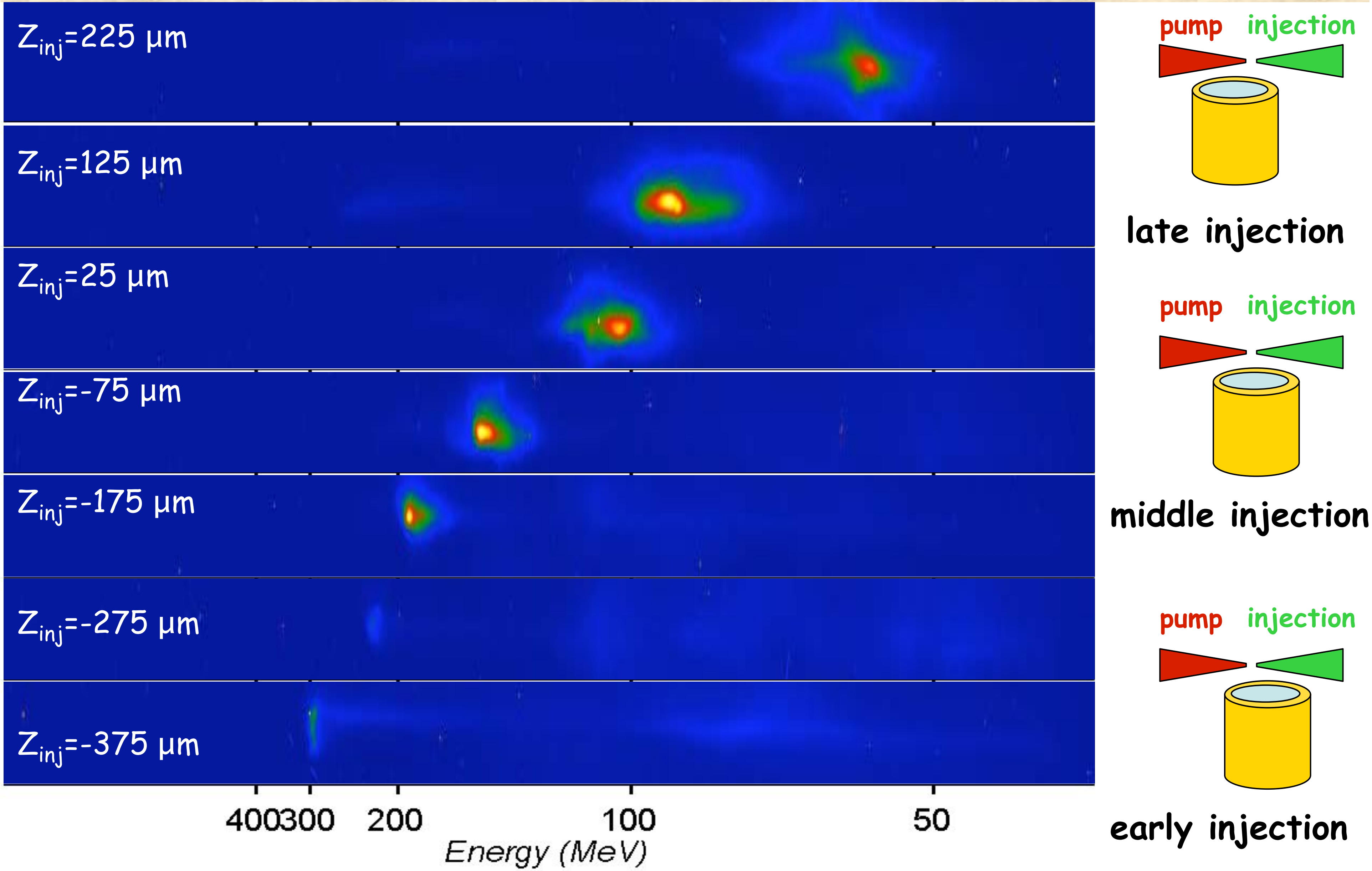



P. Tomassini, M. Galimberti, A.Giulietti, D. Giulietti, L.A.Gizzi, L.Labate, F. Pegoraro, *Production oh high quality* ...PRST, 6, 121301 (2003).

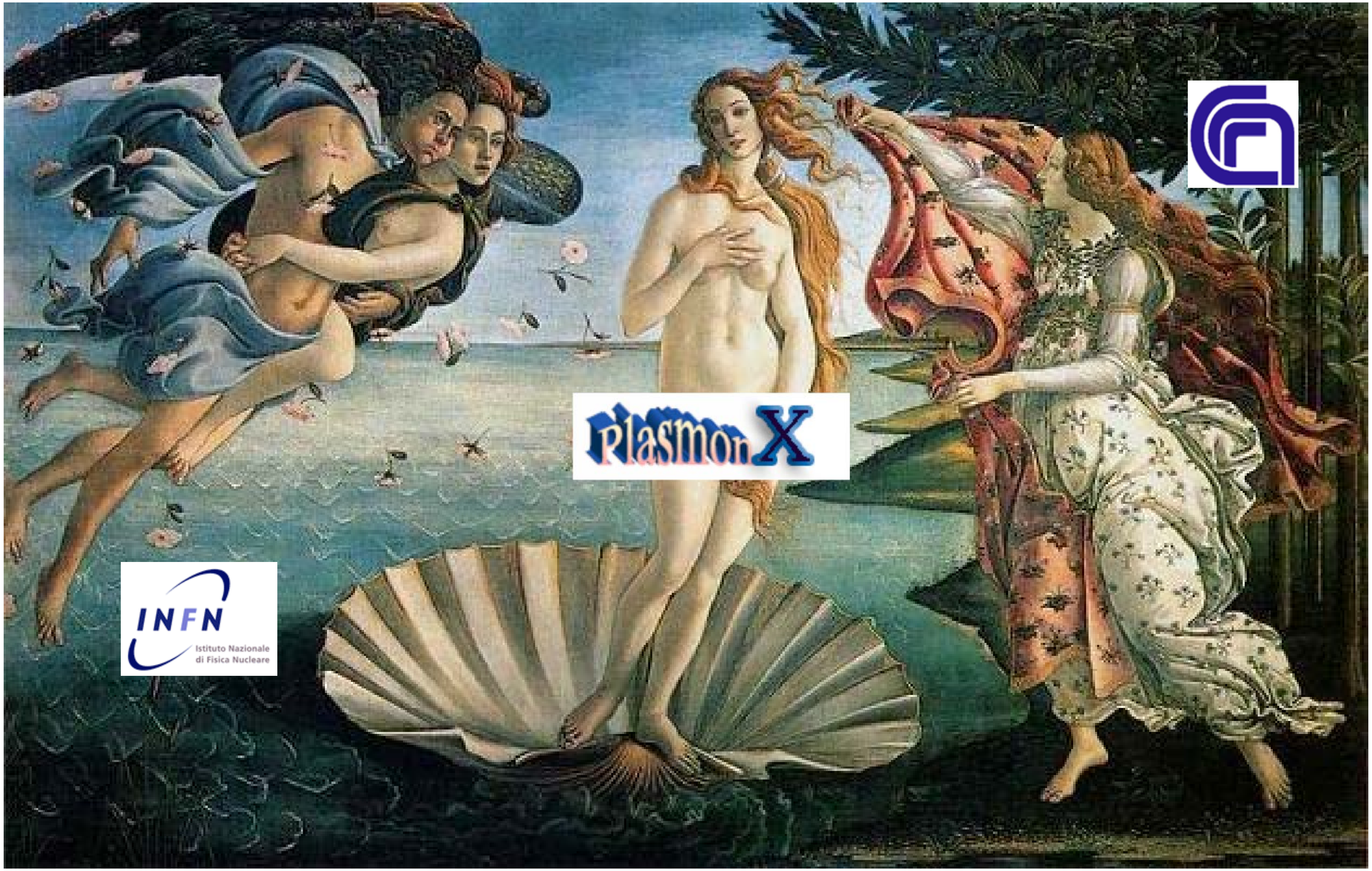
# Tunable monoenergetic bunches

V. Malka and J. Faure



2005

# The birth of.... PlasmonX

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*Conceptual Design Report*

# PLASMA ACCELERATION AND MONOCHROMATIC X-RAY PRODUCTION

Acronym: PLASMONX

2005


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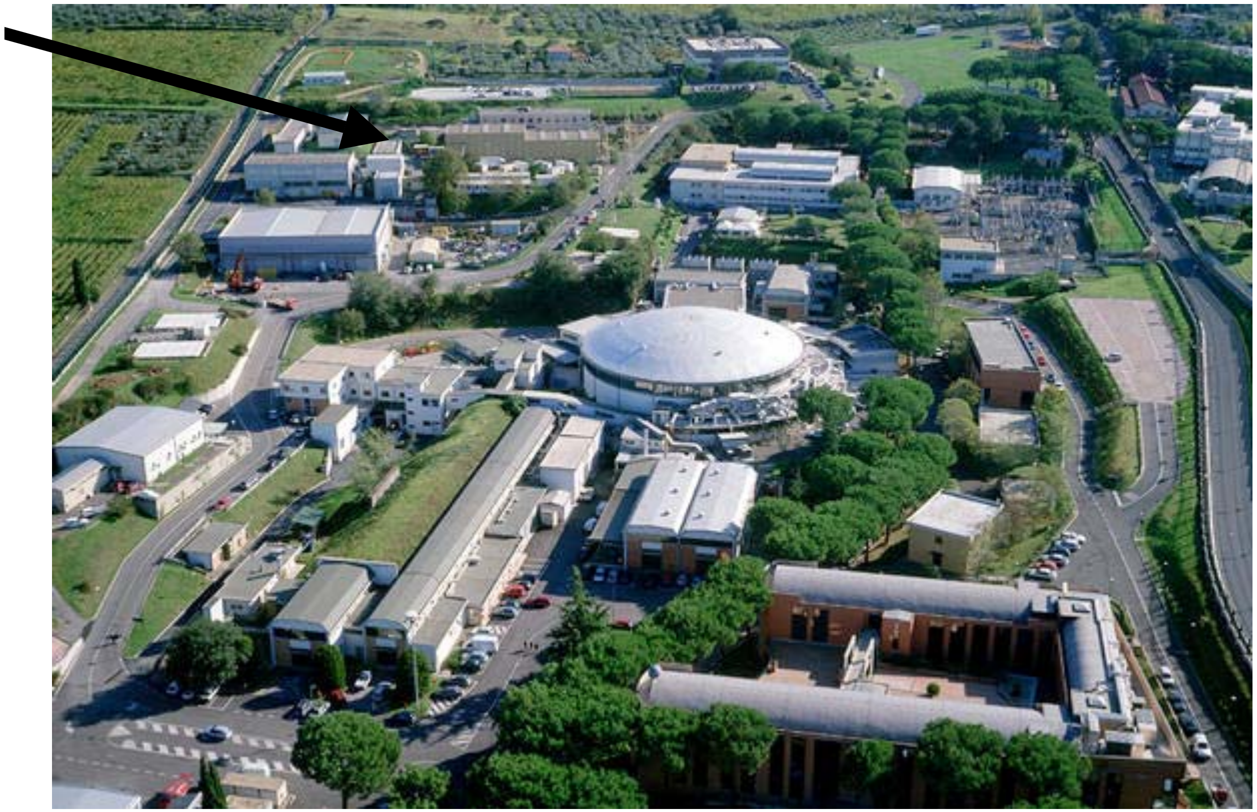
**PLA**sma acceleration and **MON**ochromatic **X**-ray production

**@ LNF-INFN**



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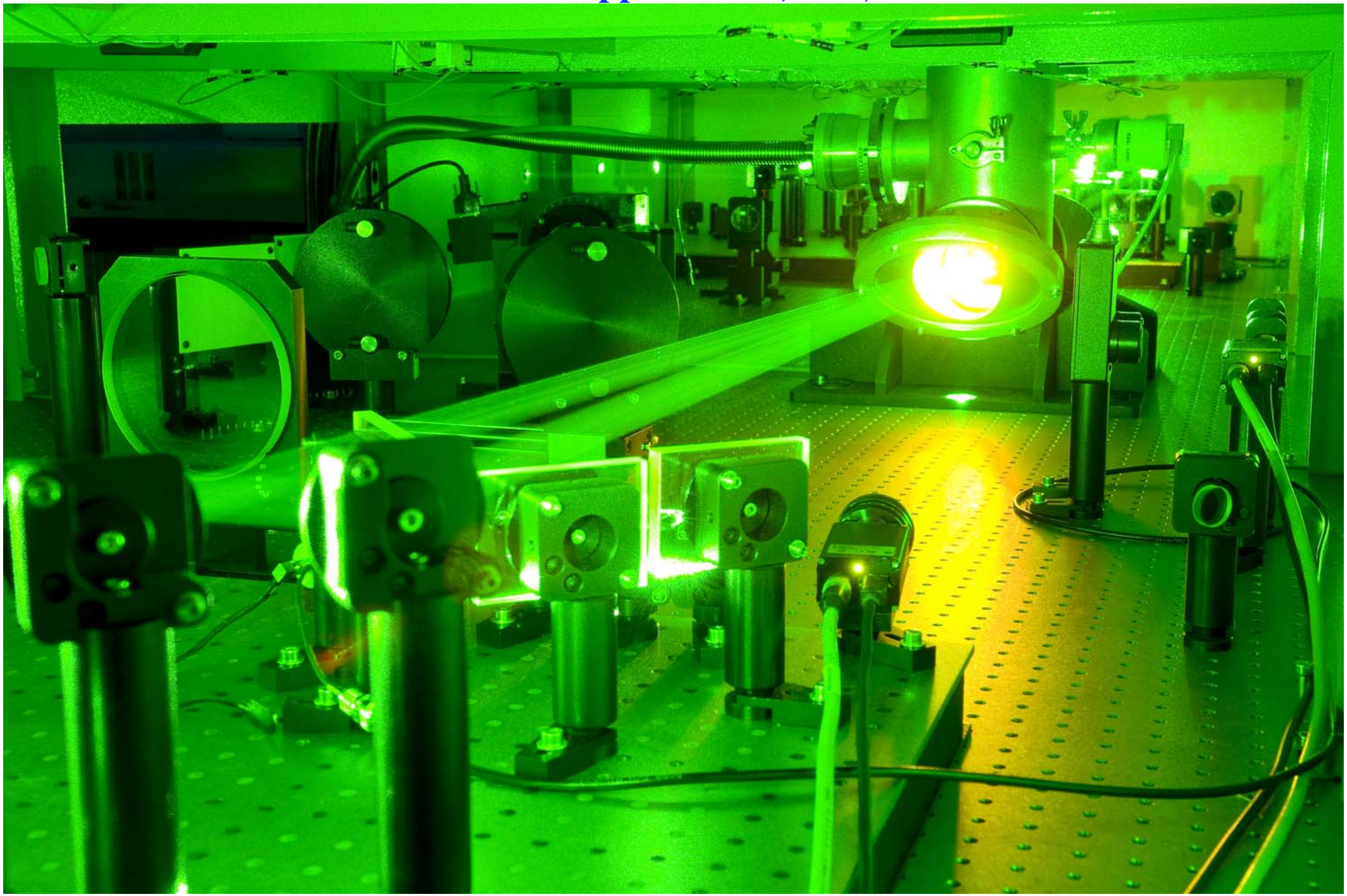
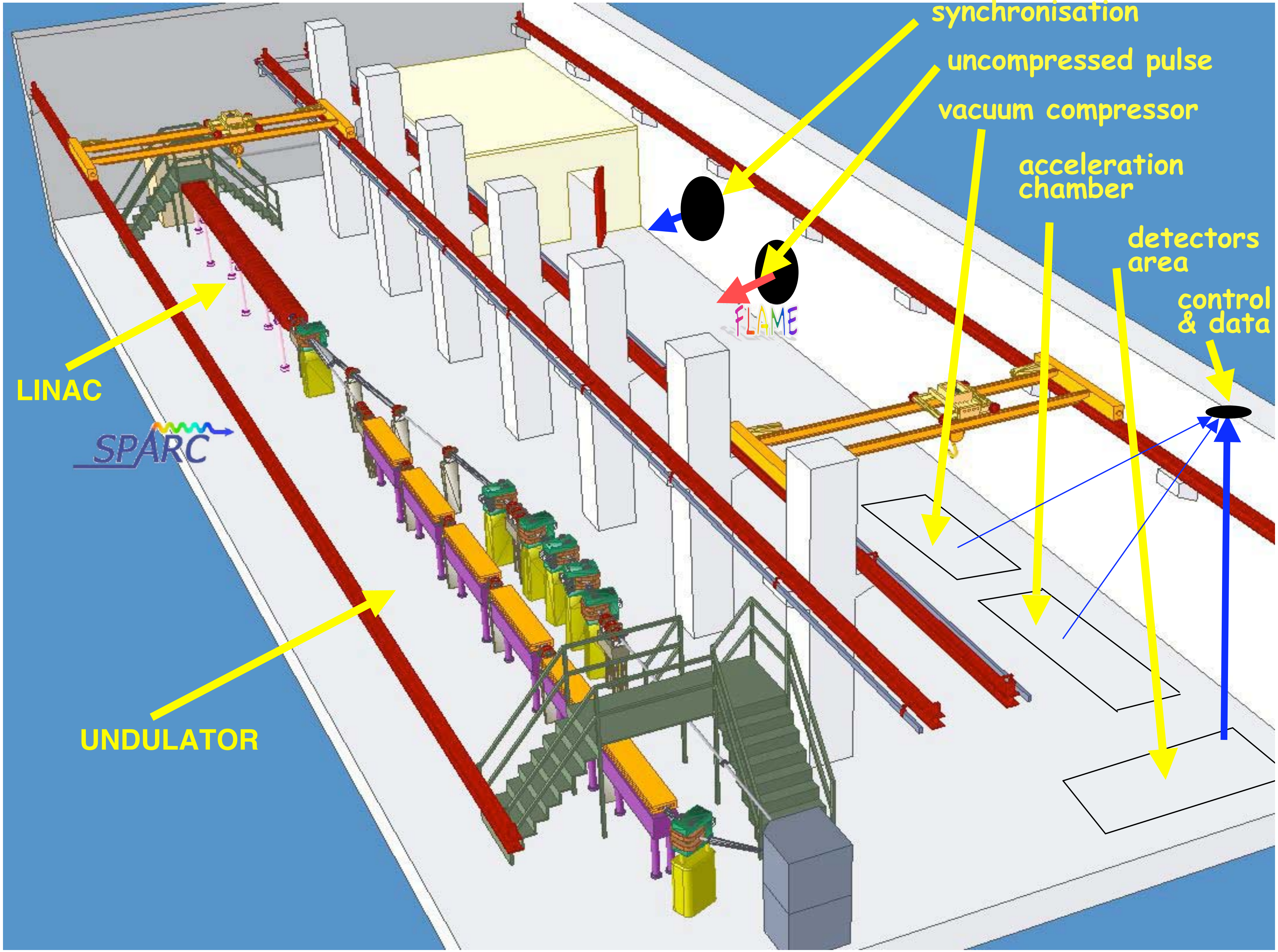
# FLAME: Frascati Laser for Acceleration and Multidisciplinary Experiments

## 300TW Ti:Sapphire 6J, 20fs, 10Hz



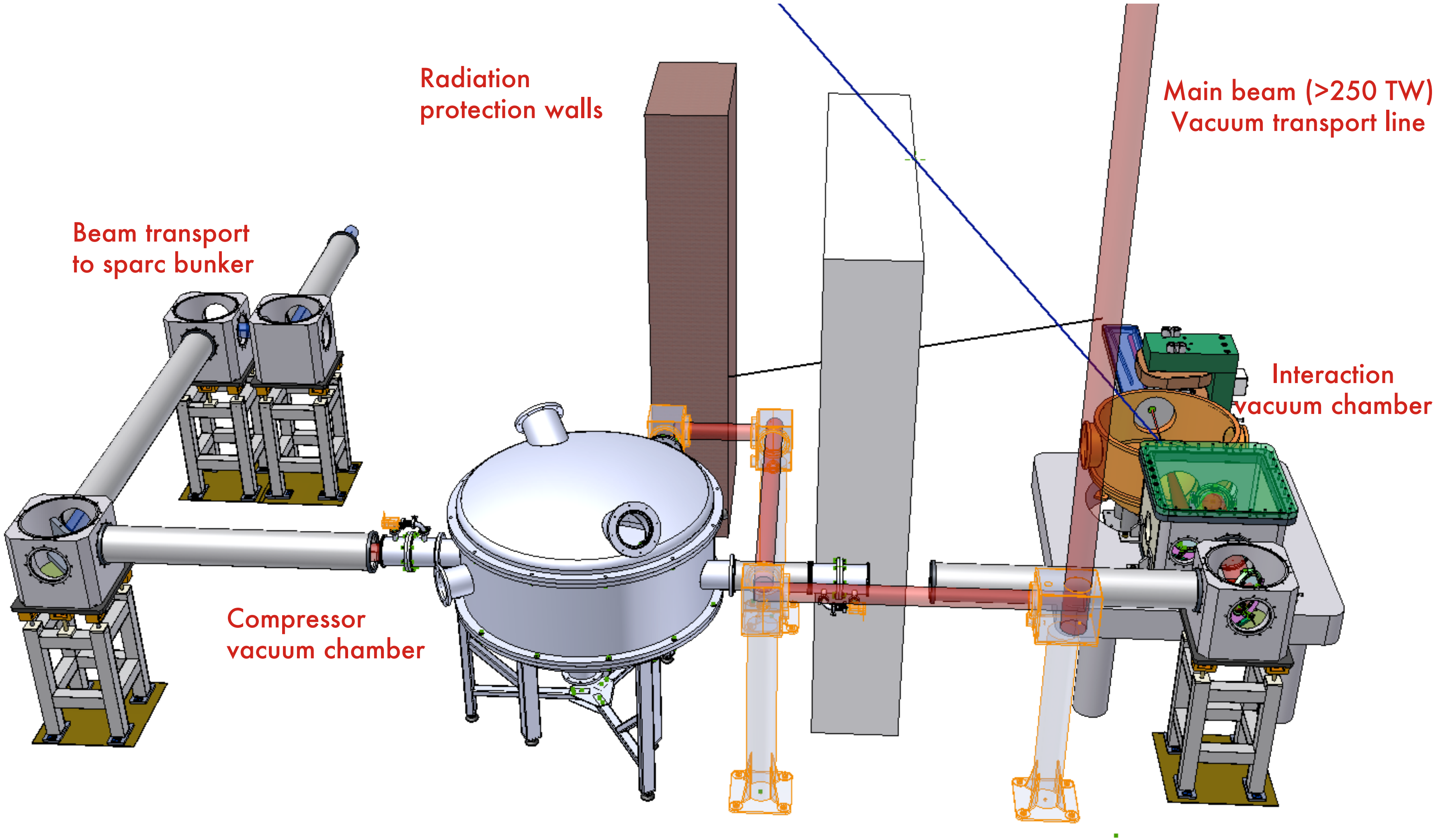

SPARC: the 200MeV LINAC
and the UNDULATORS



synchronisation
uncompressed pulse
vacuum compressor
acceleration chamber
detectors area
control & data
FLAME
LINAC
SPARC
UNDULATOR

# The FLAME laboratory


# FLAME Target Area

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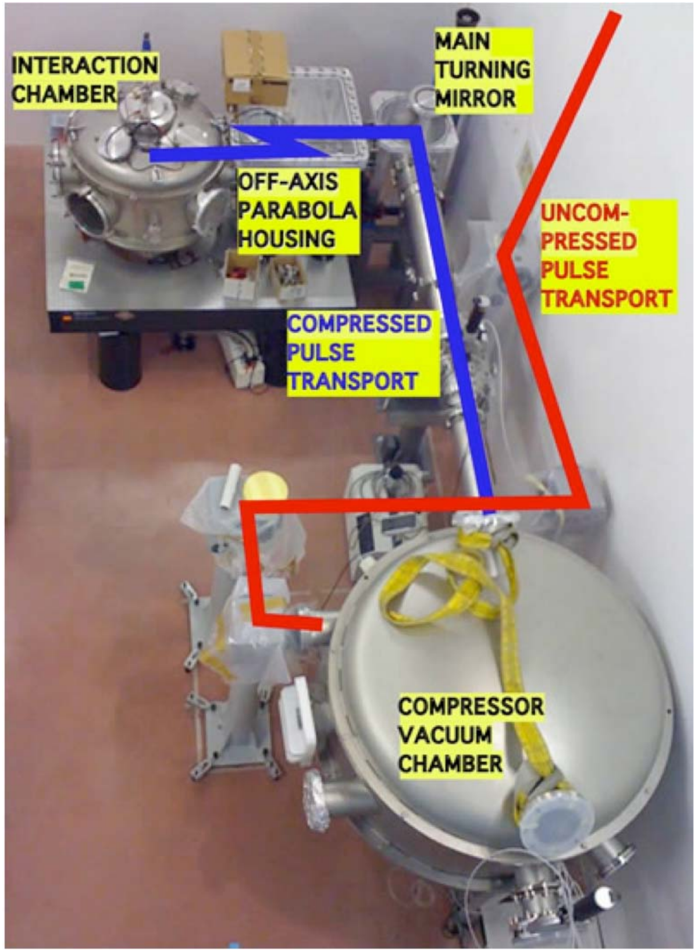
# FLAME TARGET AREA



# Interaction chamber

# VERT. AND HORIZ. SHIELDING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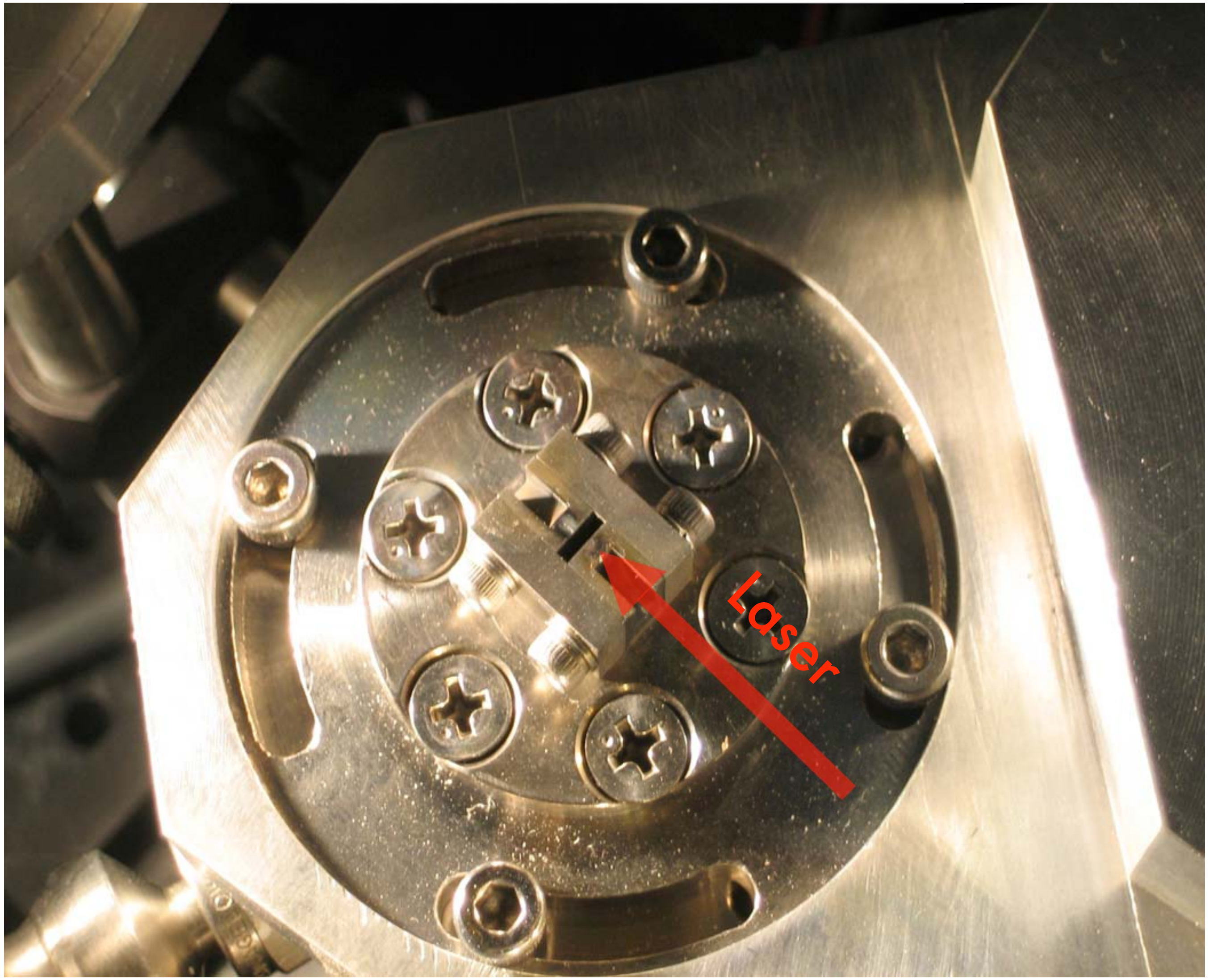
# MAIN BEAM OPTICS IN PLACE

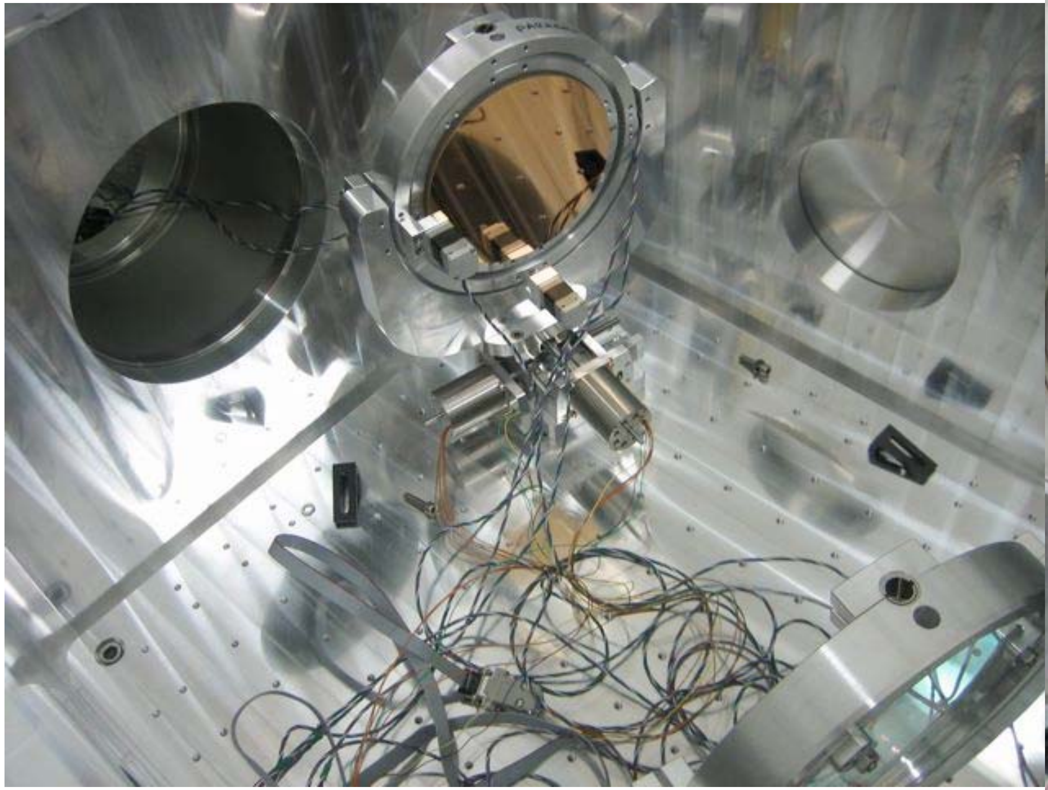
45 AND 15° TURNING MIRROR MOUNTED

# Gas-Jet nozzle



# FOCUSING LASER

1 m focal length, 7”, 15° Off Axis Parabola (SORL)

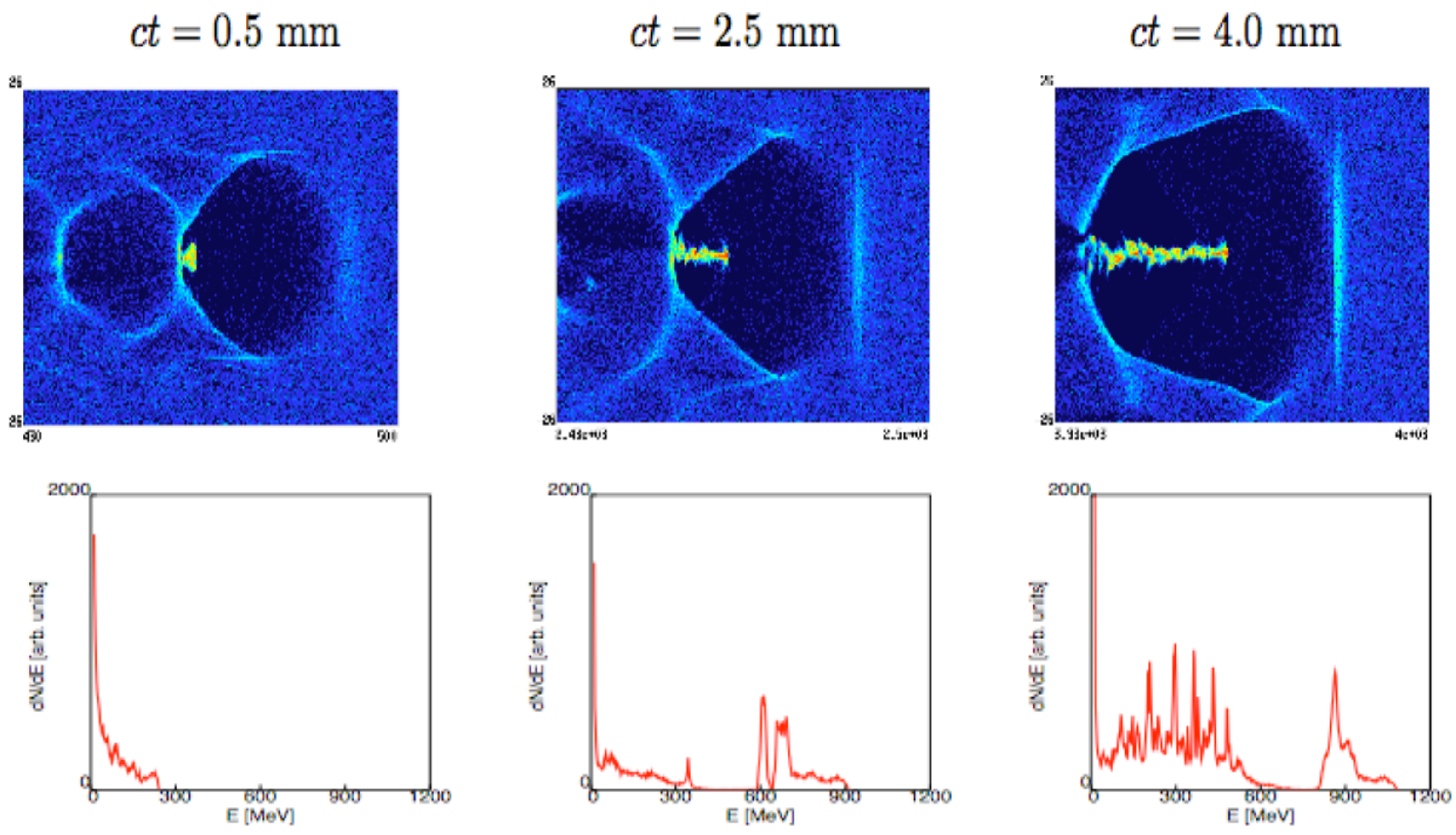


# SIMULAZIONI ALADYN

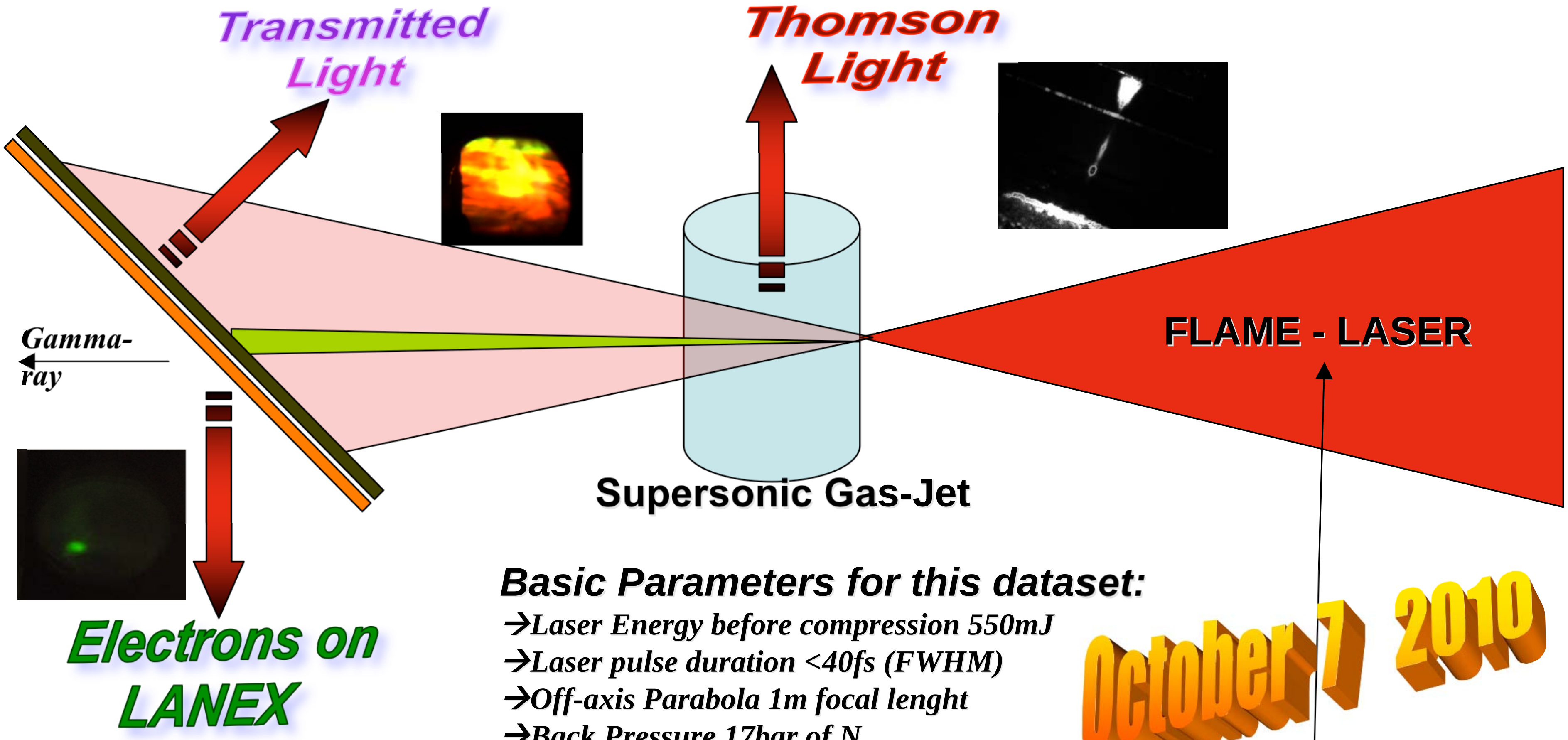
(di C. BENEDETTI ET AL.,)

## Studies for the SITE

- 3D sim. "GeV-class" ($L_{gasjet} = 4$ mm)



# *S.I.T.E., basic setup and first electrons data at* FLAME - LNF




***Basic Parameters for this dataset:***

- →*Laser Energy before compression 550mJ*
- →*Laser pulse duration <40fs (FWHM)*
- →*Off-axis Parabola 1m focal lenght*
- →*Back Pressure 17bar of $N_2$*

**Only 1 over 10 pump laser are used in this case!**

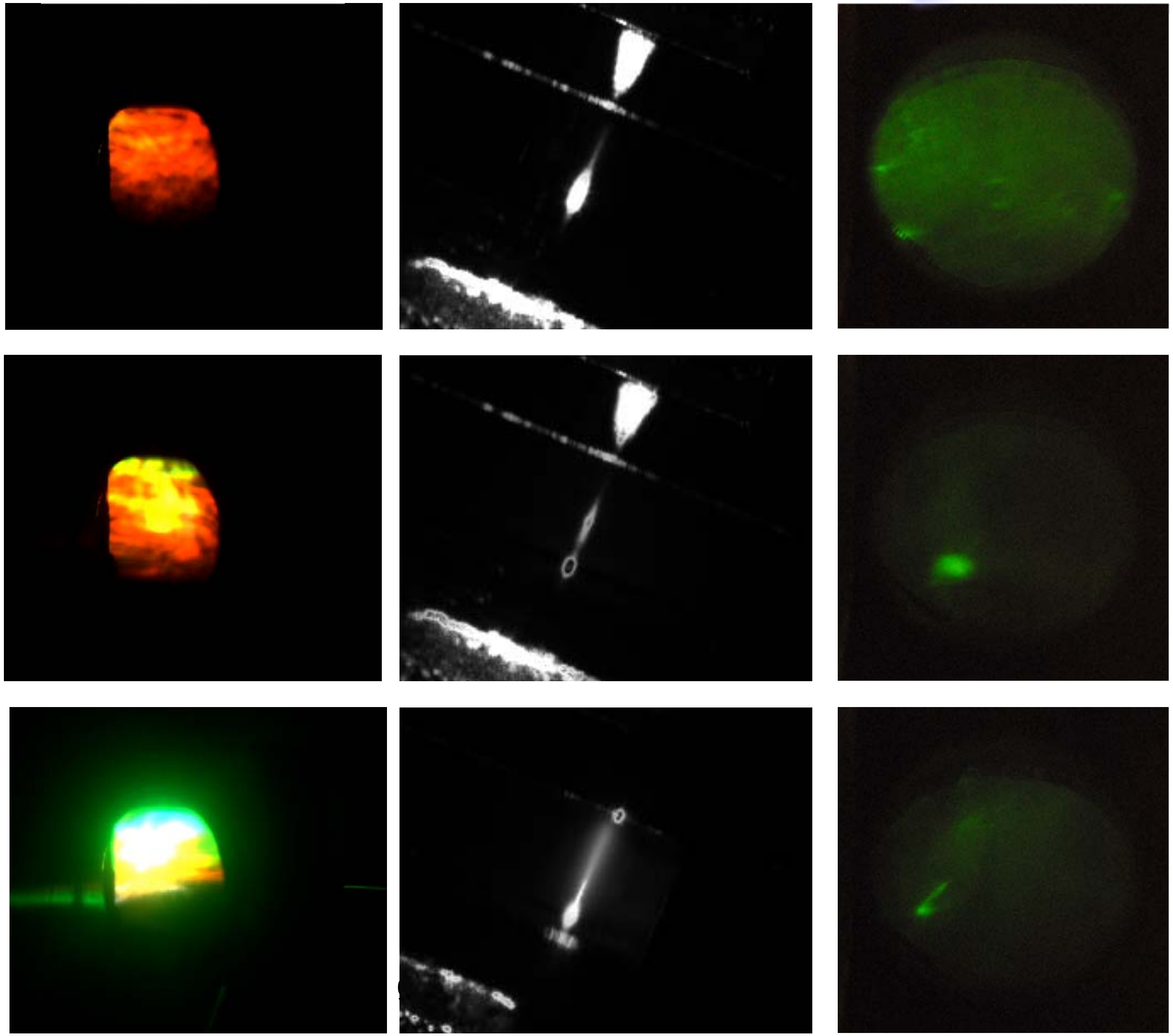
## FLAME - S.I.T.E. Preliminary DATA

Transmitted Light | Thomson Light | Electrons on LANEX

***No***
electrons collimation

***Medium***
electrons collimation

***HIGH***
electrons collimation



# The laser plasma accelerators status

demonstrated

- Energy gains up to 1 GeV
- E-fields of 1 GV/m to 1000 GV/m
- Good e-beam quality : Emittance $< 3\pi$mm.mrad
- charge at high energy
- Quasi monoenergetic
- Generate a tunable e-beam
- Very high peak current : 100 kA

TO DO

- enhance stability
- electron sources up to several GeV (nC, $<1$ ps):
  - *Guiding or PW class laser systems
  - *Multi Stages
- applications of the secondary sources
- Compact XFEL

# CONCLUSIONS

- National and international facilities based on ultra-intense and ultra-short pulse Ti:Sa laser systems will open unique opportunities for:

- New Acceleration Techniques
- High brightness sources of electrons, protons, ions, neutrons, positrons, X & $\gamma$-rays, …
- Applications in HEP, medicine, ICF, material science, astrophysics, femtochemistry, attosecond science, …

# Riding the wave

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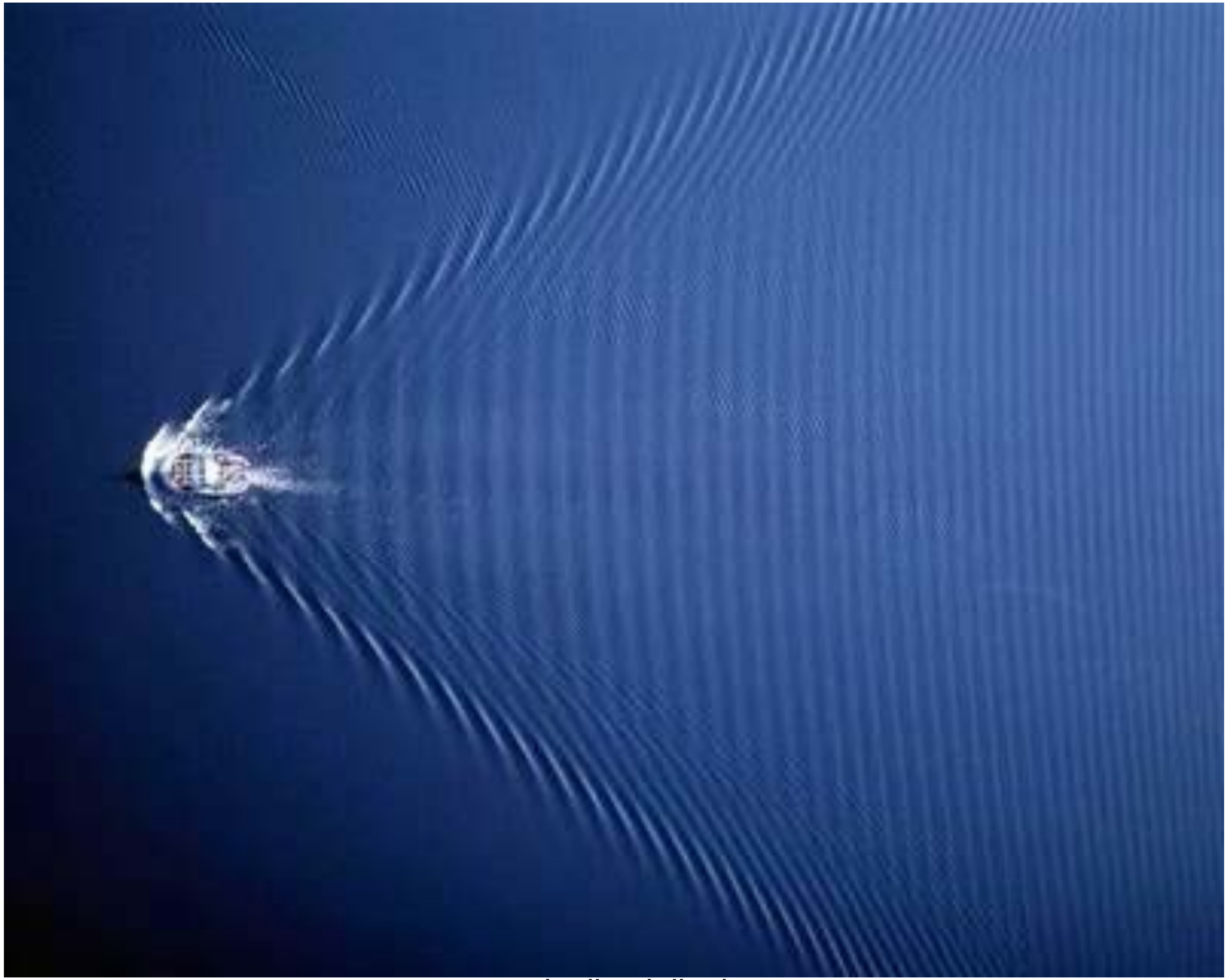
# Force of Gravity:WAVE WAKE



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# Force of Gravity: SURFER

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# EXTEDINNG THE ACCELERATION LENGTH

*in the most LWFA experiments*

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

*for LWFA to be effective*

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

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

For $E_L \approx 10J$, $\tau \approx 20fs$, $\lambda \approx 1\mu m$, $I_0 \approx 10^{20} W/cm^2$

$L_{acc} \approx 1mm$

# First “test” experiment
# @
# LNF

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# SIMULAZIONI ALADYN

(di C. BENEDETTI ET AL.,)

## Studies for the SITE

- **Nonlinear 3D regime (bubble)**: phenomenological theory [*W. Lu & al., PRSTAB 10 (2006)*]
  - "stability" of the bubble: $k_p R_{bub} \simeq k_p w_0 \simeq 2\sqrt{a_0}$
  - dephasing length: $L_d = \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} R_{bub}$
  - pump depletion: $L_{pd} = \frac{\omega_0^2}{\omega_p^2} c\tau_{fwhm}$, shuld be $L_{pd}$> min($L_{gasjet}, L_d$)

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

Taking the waist $w_0$ as a free parameter ($R_{bub} \simeq w_0$), we have

- $n_p$ [cm$^{-3}$] $\simeq 8.7 \cdot 10^{21}/(w_0[\mu\text{m}])^3$
- $L_d[\mu\text{m}] \simeq 0.13 \times (w_0[\mu\text{m}])^4$
- $L_{pd}[\mu\text{m}] \simeq 1.8 \times (w_0[\mu\text{m}])^3$
- $\boxed{W[\text{MeV}] \simeq 79 \times \frac{L_{gasjet}[\mu\text{m}]}{(w_0[\mu\text{m}])^2}\left(1 - \frac{3.75\times(L_{gasjet}[\mu\text{m}])}{(w_0[\mu\text{m}])^4}\right)}$ (for $L_d \geq L_{gasjet}/2$)
- $Q \simeq 0.5 \div 0.6$ nC