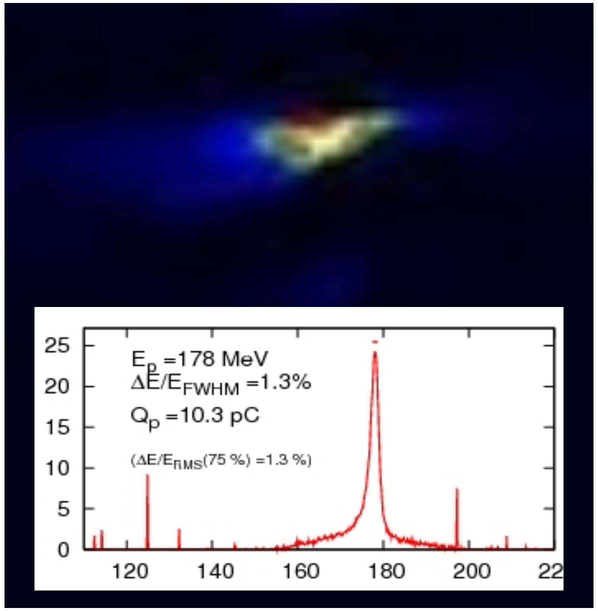
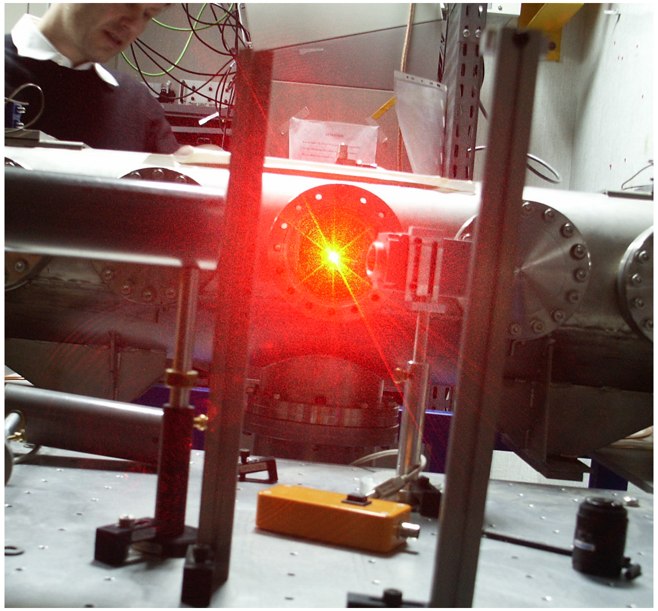
Laboratoire Leprince-Ringuet

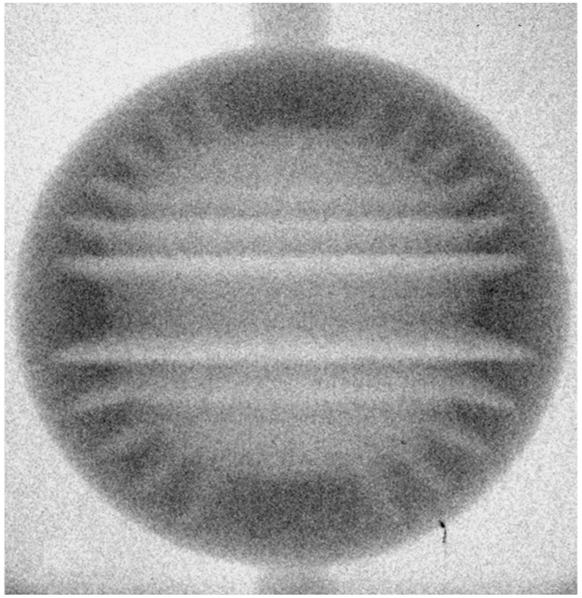
Visite Master APIM 27/10/2010

Groupe d'Accélération par Laser et Ondes Plasma

Nouvelles techniques d'accélération de particules

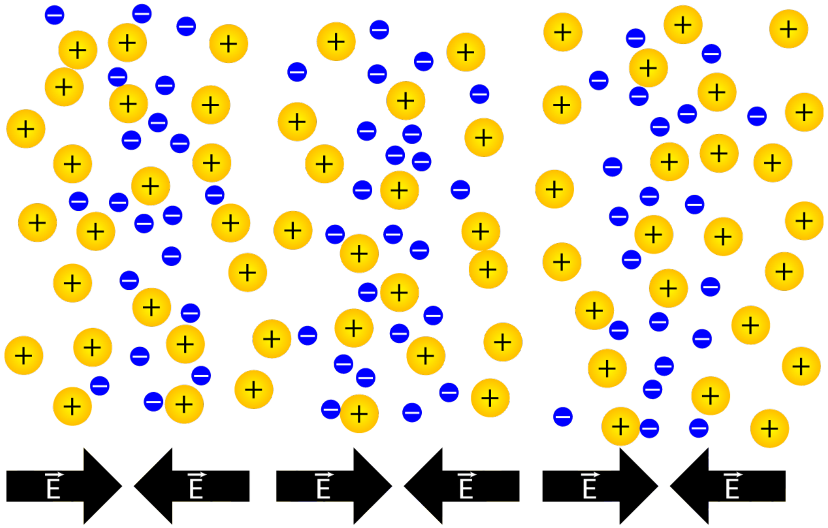






Accélération de particules par ondes plasma

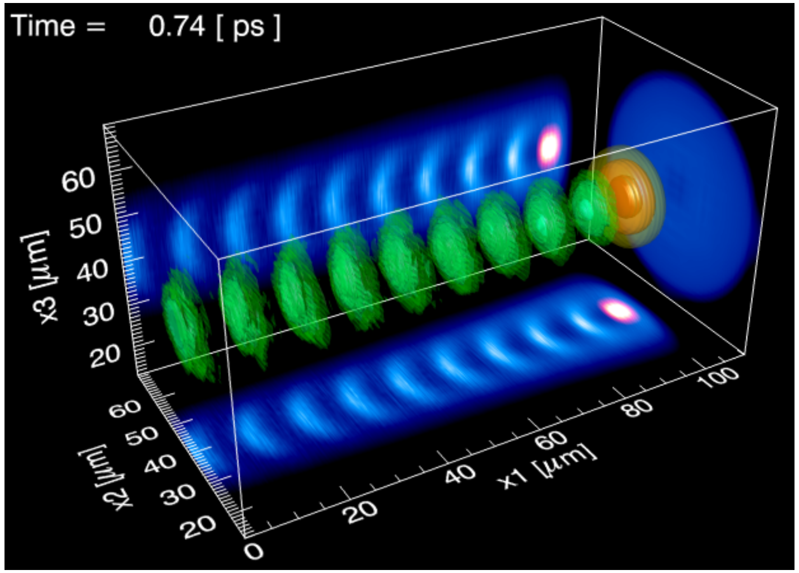
onde plasma



gaz d'électrons et d'ions (plasma) :
attraction/repulsion électrostatique

fréquence plasma: $\omega_P \propto \sqrt{n_e}$

résonateur = plasma



$$E_z = \frac{m_e c \omega_p}{e} \approx 300000\,\mathrm{MV/m}$$

(pour $n_e = 10^{19}$ cm^{-3}) $\omega_p \propto n_e^{1/2}$

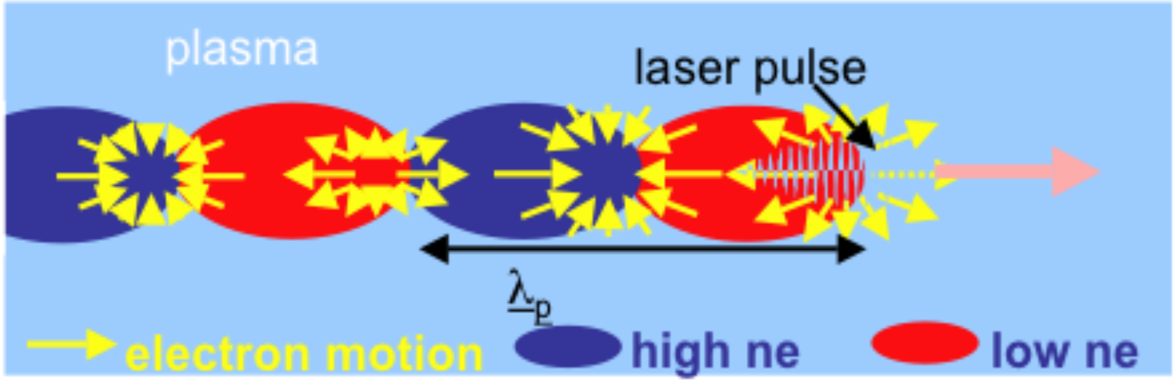
Onde plasma accompagnée d'un champ E longitudinal très intense!

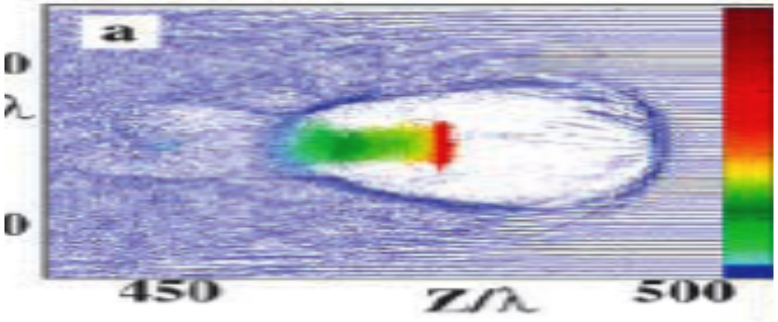
excitation de l'onde plasma par champs électriques intenses :

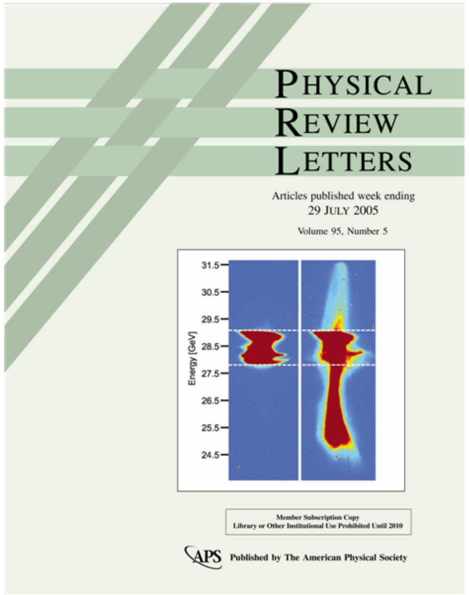
- ➤ faisceaux d'électrons
- ➤ impulsions laser ultra-intenses

2004: Une percée majeure

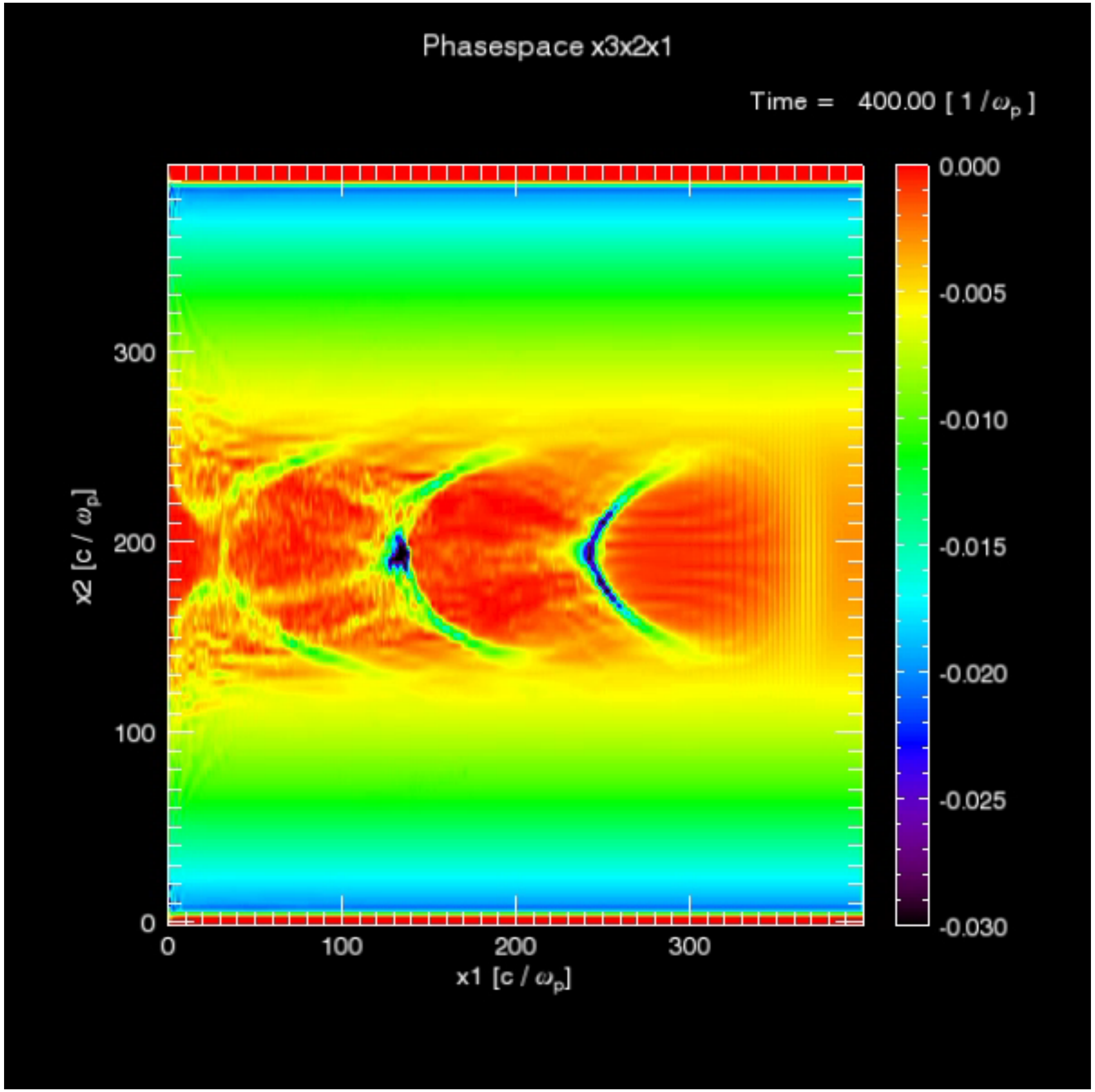
- ❍ réalisation du «régime de la bulle»:
  expulsion totale des électrons du plasma
- ❍ **faisceaux d'e⁻«monochromatiques»**
  et fortement collimés







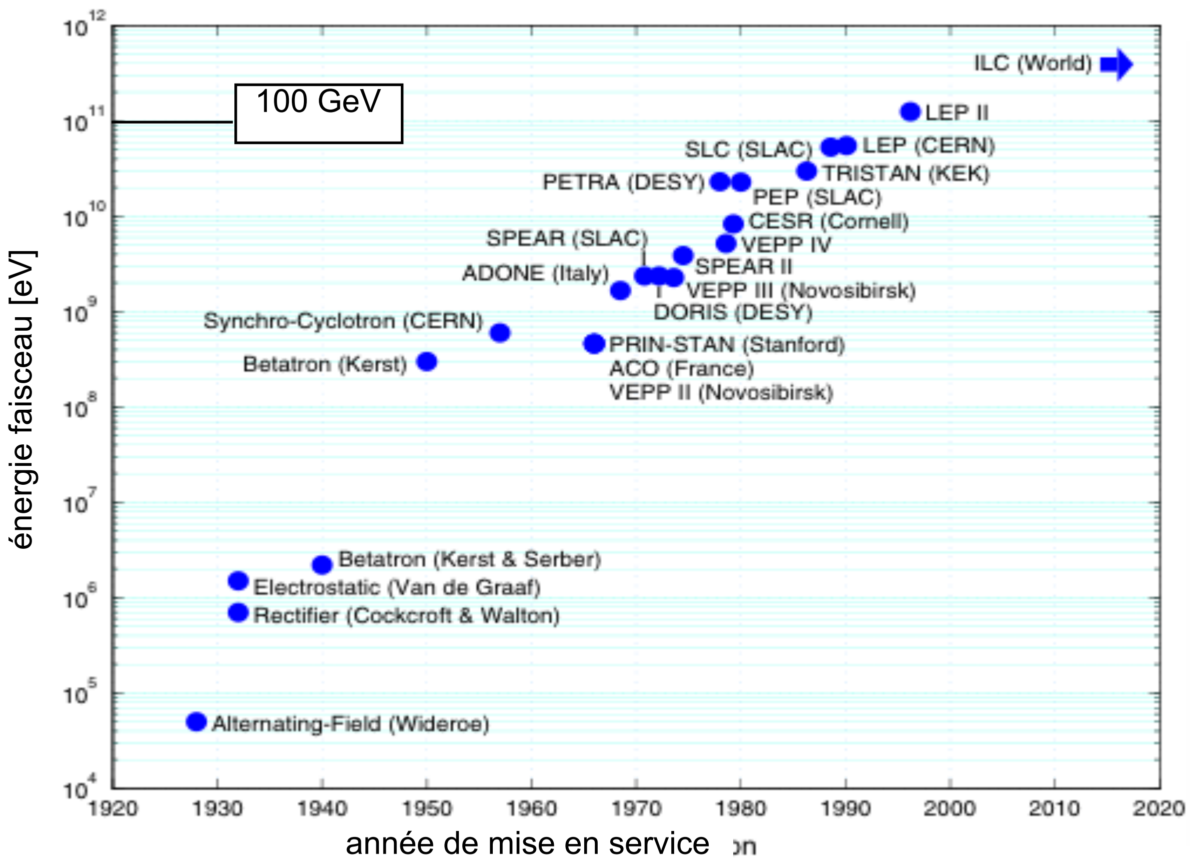
particle-in-cell (PIC) simulation of self-injection into bubble



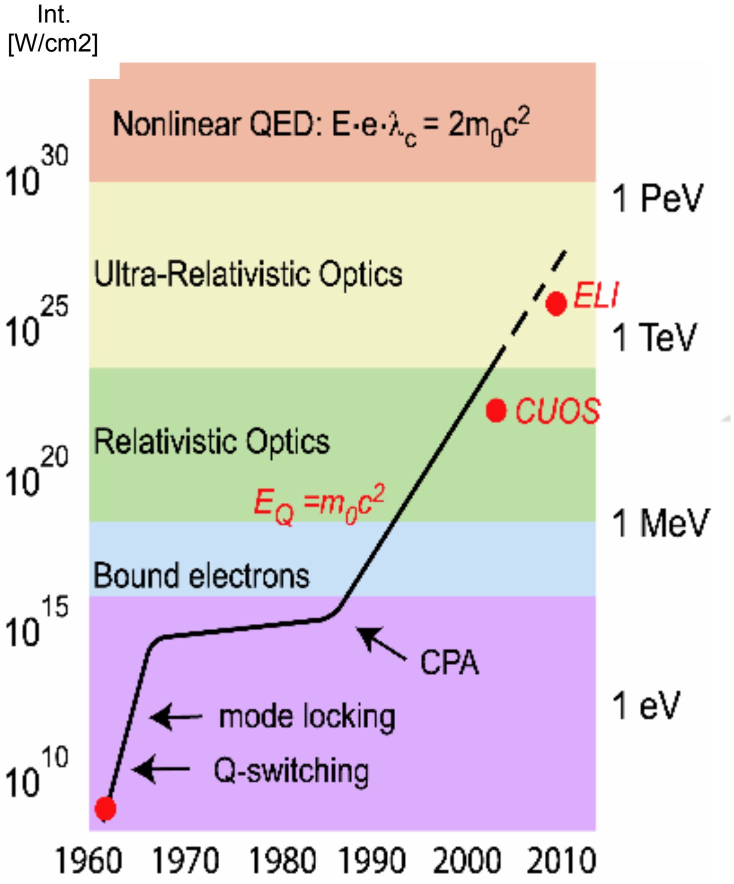
Wei Lu (UCLA), AAC2006, Lake Geneva (USA)

why get interested in laser acceleration?

RF accelerators (e^-/e^+)



LASERS

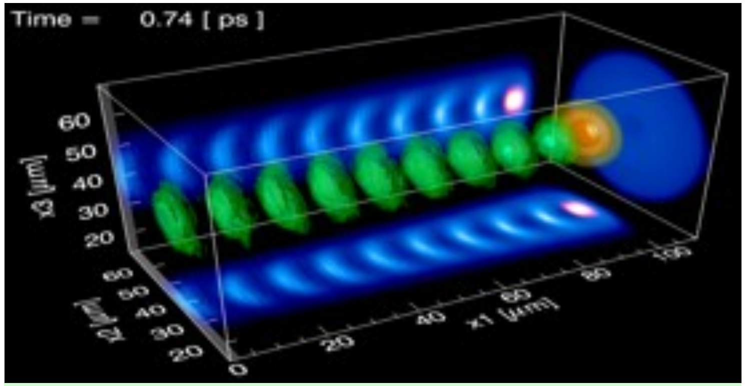


- LINACS: energy = gradient × length ➔ long machines
- LASERS: progression in intensity ➔ technology breakthrough

increase the accelerating gradient: form RF to plasma waves

→ decrease size of « accelerating structure »

$$E_z < 100\,\mathrm{MV/m}$$



$$E_z = m_e c\omega_p / e \approx 100\,\mathrm{GV/m}$$

klystron → **high power laser (ultra-short pulse)** **E=O(10J), τ=O(10fs) ⇒P=O(10PW)**

✖ **repetition rate 0.1-1Hz** → 10-100 kHz

✖ **wall-plug efficiency few %** → few 10%

RF cavity → **gas jet, gas cell, gas-filled capillary, capillary discharge** (n ≈10^{17}-10^{19}cm^{-3})

- **stability** : → maîtrisé ✔ (contre-propagatif)
- **laser guiding** : *beam-loading, pump-depletion*
- **laser coupling** at capillary entry

RF wave → **plasma wave** ($\lambda_P \approx$10-100µm)

- **régime:** linear, wave-breaking, bubble (*blow-out*)
- **transverse emittance:** focussing

✔ **longitudinal emittance:** energy dispersion ΔE/E, $\varepsilon_{T,}$

- **stability:** ion movement, useful plasma wave buckets

Les défis présents et futurs pour l’accélération par laser

paramètres d’un paquet d’un faisceau de particules :

charge, ⟨position⟩, ⟨angle⟩, ⟨énergie⟩, dispersion en E, émittance transverse, longueur

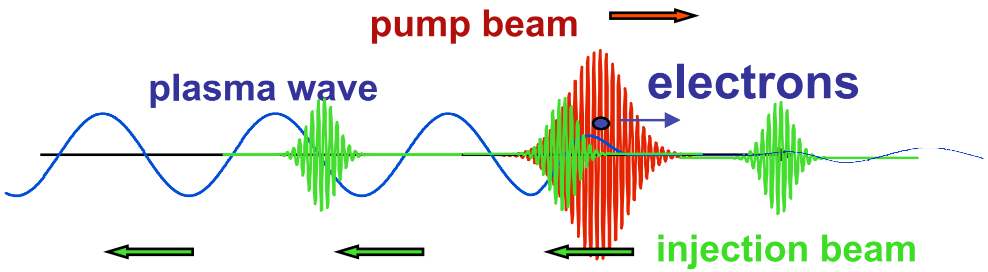
	LWFA	**ILC**	unit
❍ **augmenter l’énergie**	0.2–1	250	GeV
➤allonger la distance d’accélération			
❍ **augmenter la charge**	0.01–0.1	3	nC
➤haute densité de gaz? injection externe?			
❍ réduire l’espacement des paquets	0.1–10	370.10^{-9}	s
➤laser rep. rate: “10Hz”, multi plasma-wave buckets?			
❍ **dispersion en énergie (“monochromaticité”)**	1%	0.1%	
❍ **longueur (ou durée) des paquets**	<3 (?)	300	µm
➤«*bane or blessing?*», **mesure difficile**			
❍ **émittance transverse (“concentrabilité”)**	<3 (?)	19/0.07	mm.mrad

❍ **stabilité et contrôle des faisceaux** (“reproductibilité”)

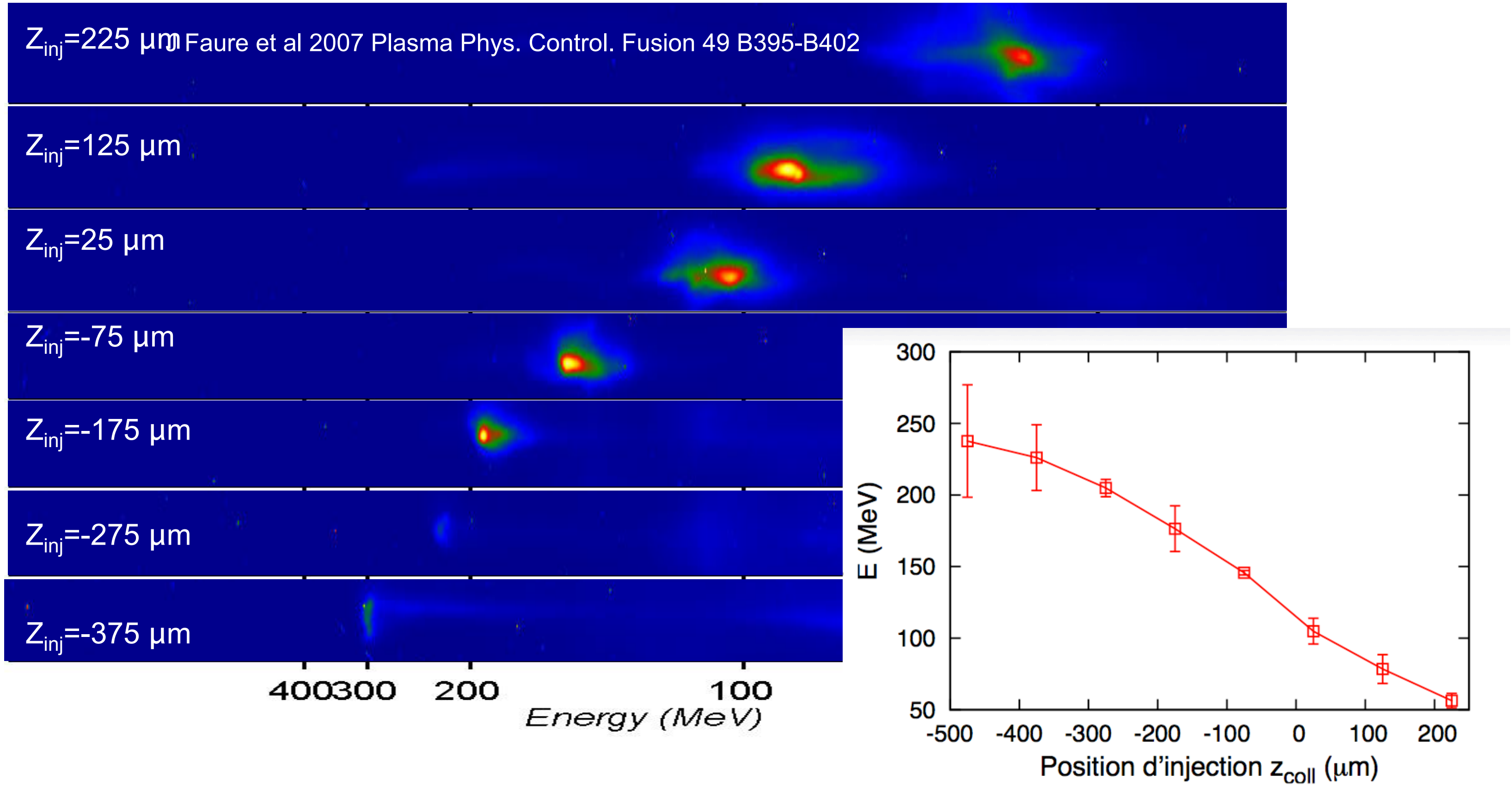
charge, angle (pointé), énergie

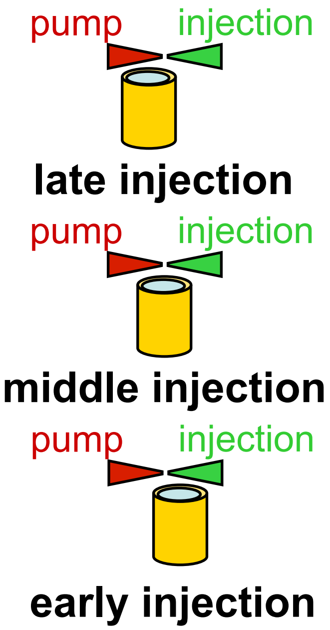
Maîtrise de l'énergie du faisceau: Injection contrôlée (LOA,2006)

- **2 impulsions contra-propagatives**
  laser existant: 30fs, ~1J, ~30TW
  faisceau pompe: 700mJ
  faisceau injection: 250mJ


pump beam
plasma wave
electrons
injection beam

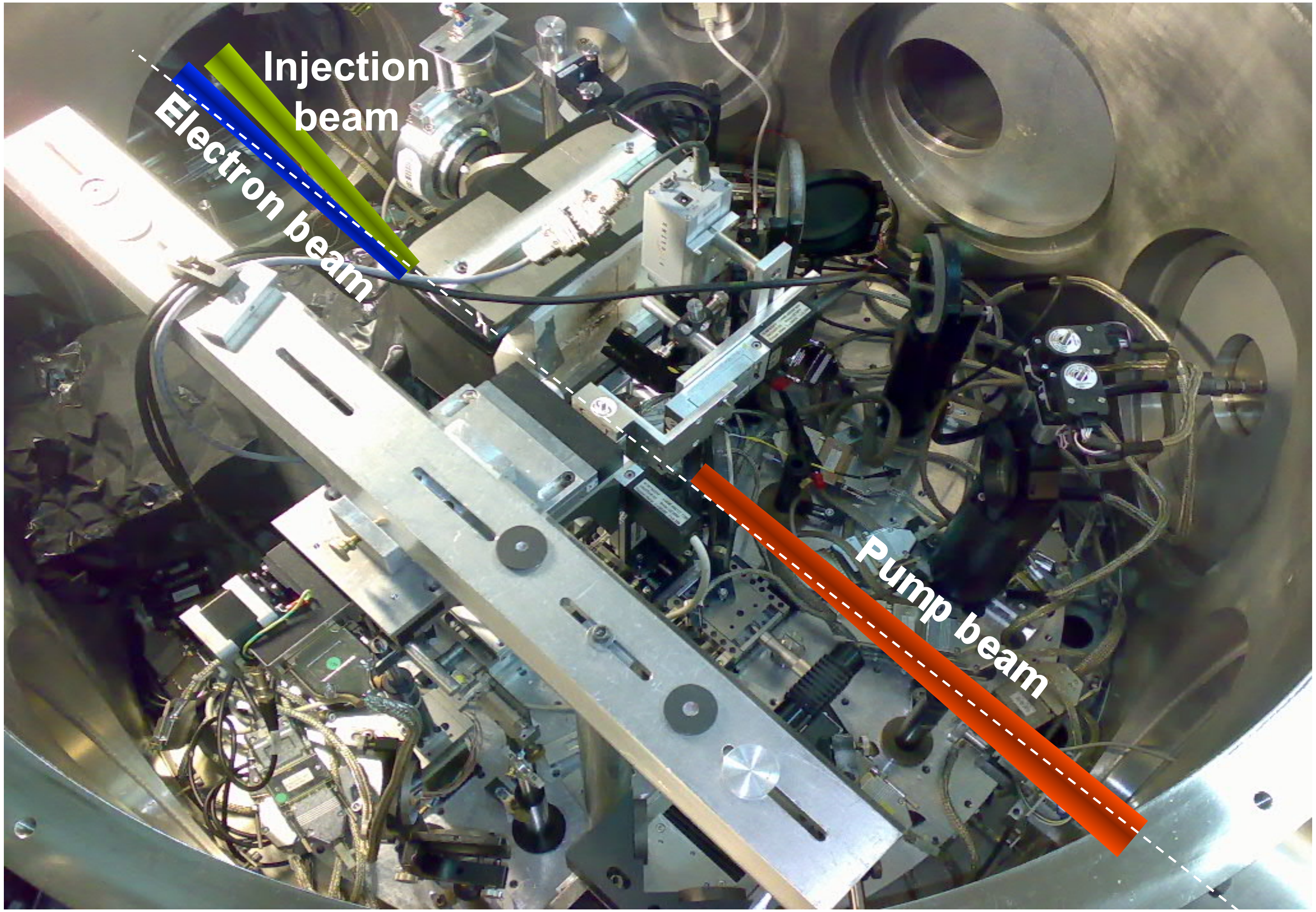
- **injection contrôlée d'e- dans plasma: ajustement de l'énergie**


Faure et al 2007 Plasma Phys. Control. Fusion 49 B395-B402

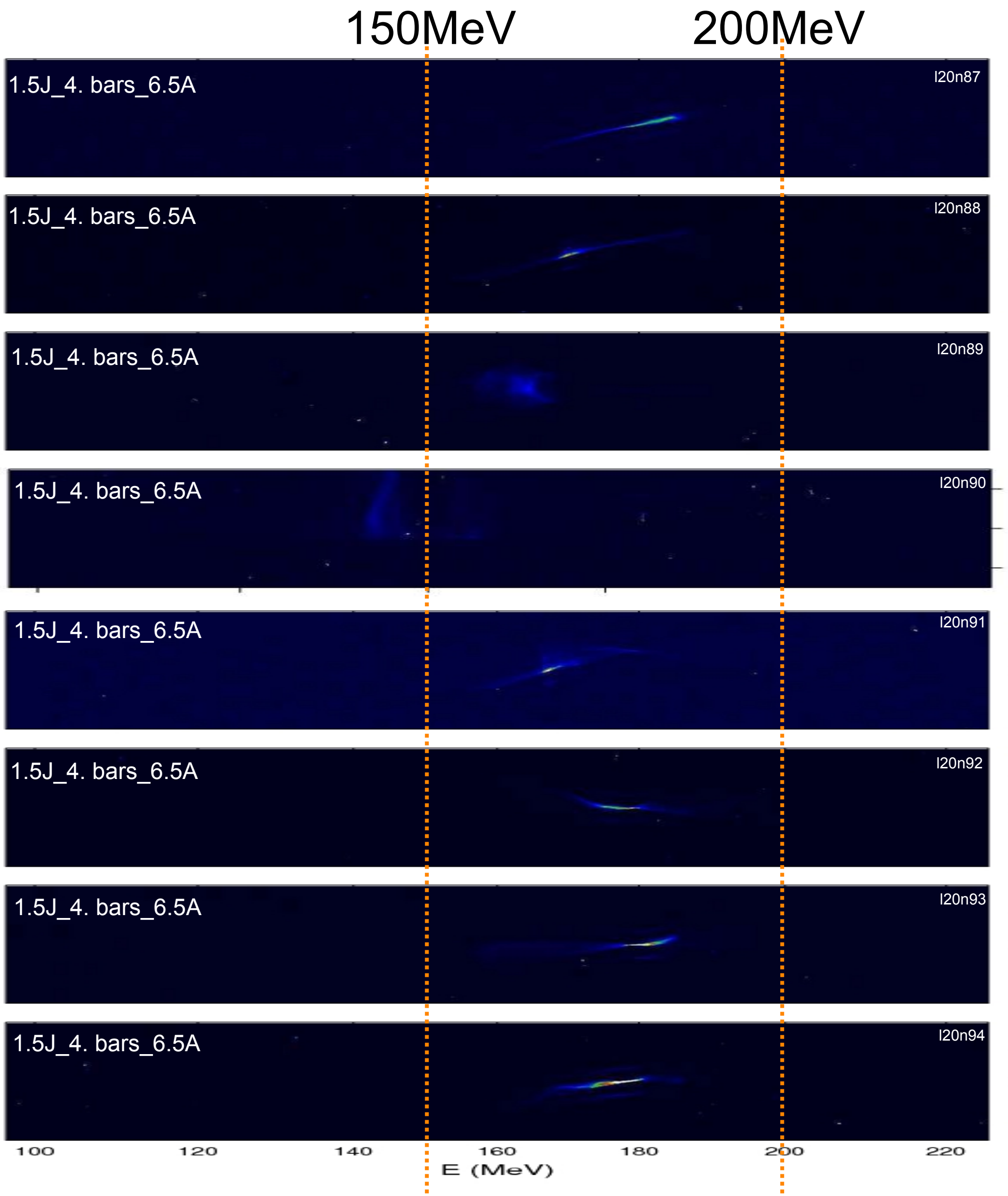

pump injection
late injection
pump injection
middle injection
pump injection
early injection

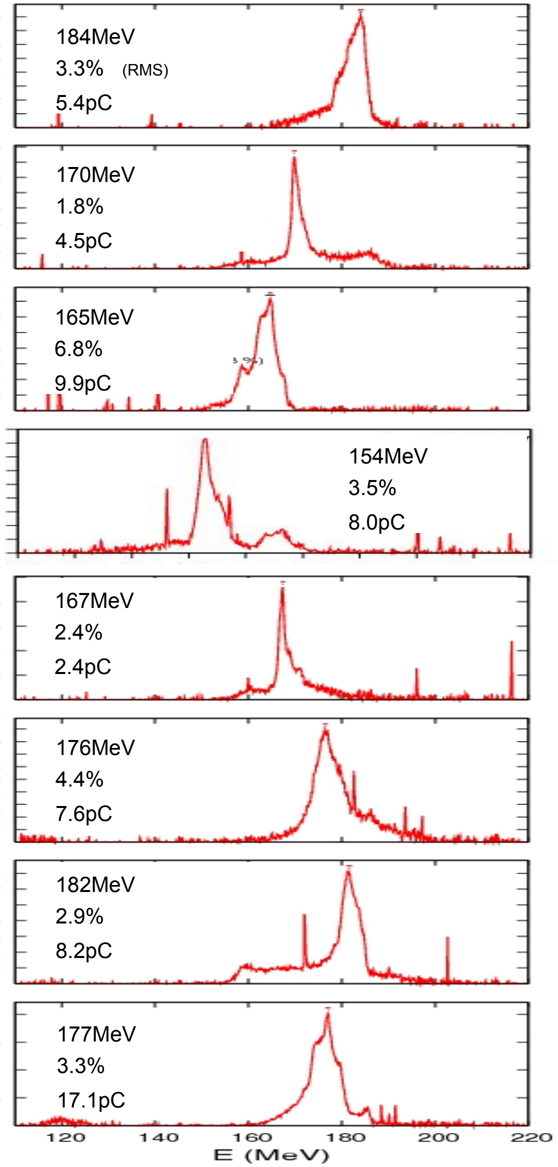
colliding pulse injection: experimental setup (2008)

- LASER
  - TiSaph: 50TW 30fs
  - 2 beams
    a_0=1.3 a_1=0.6
  - non-collinear
    angle=7º
  - <1 shot/ 10sec
- gas jet
  - length = 3mm
  - e^- density
    $n_e = 3.10^{18}$–$2.10^{19}\mathrm{cm}^{-3}$
    (via pressure)



Stabilité du faisceau : 8 tirs consécutifs (AAC08, A.B.)



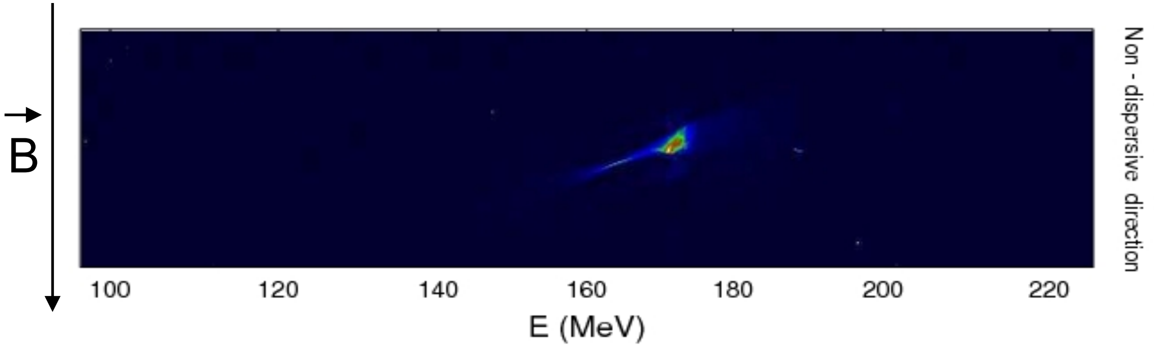


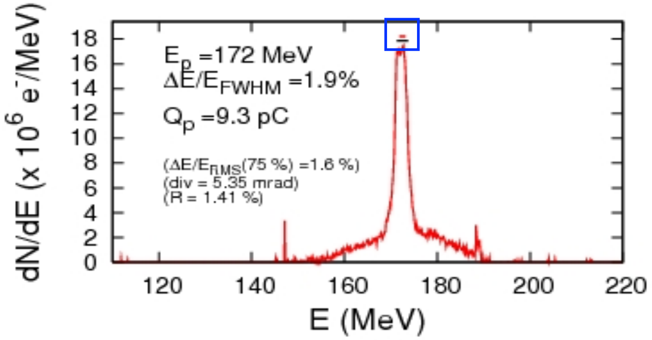
Monochromaticité : observatº de spectres étroits (AAC08, A.B.)

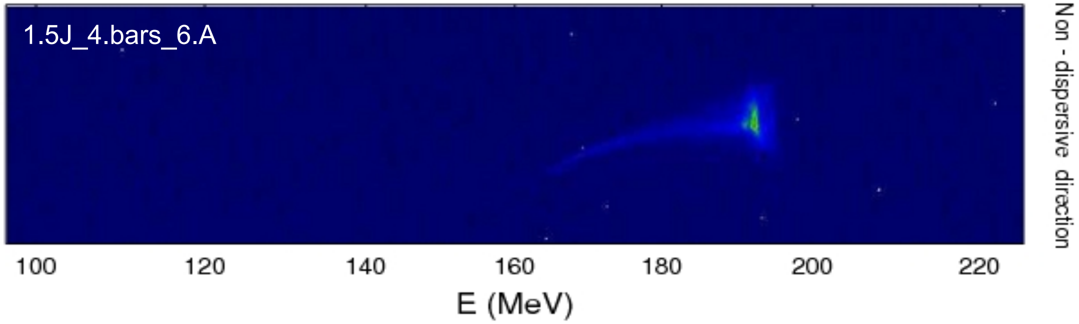
- assuming 3mrad divergence

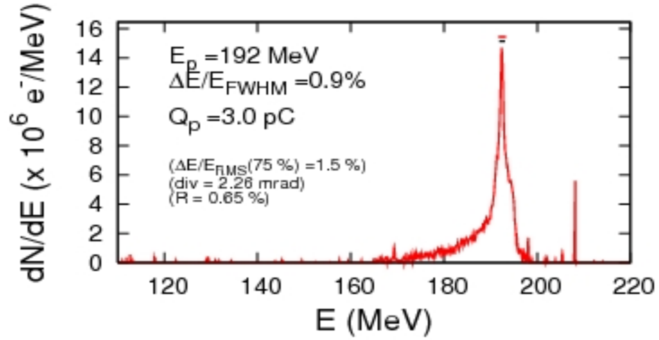
- deduced from direct measurements on the screen

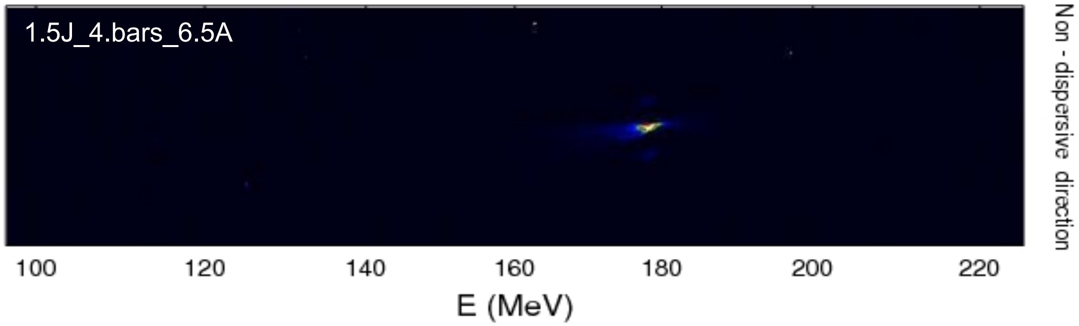
Error bars

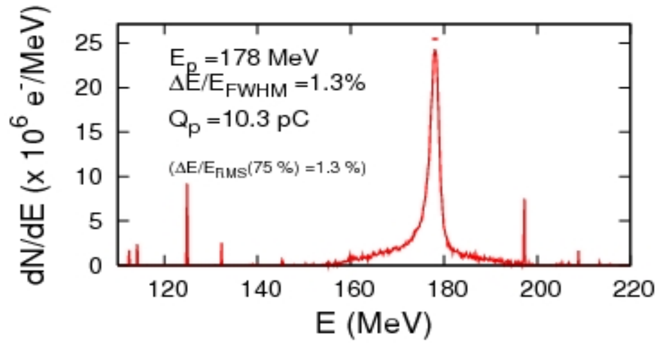






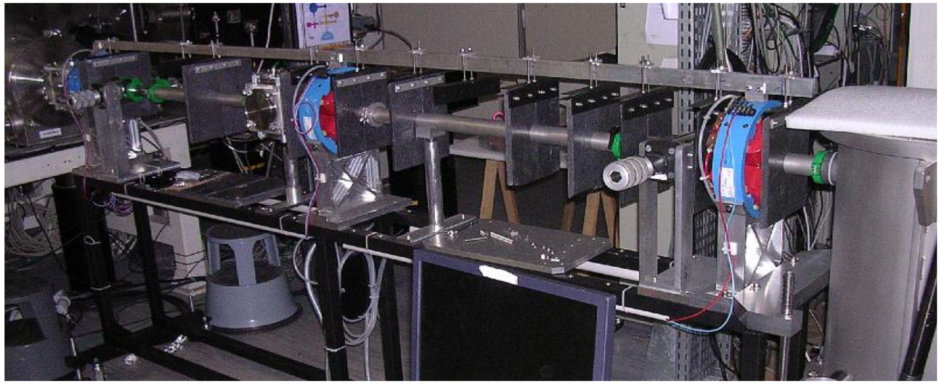


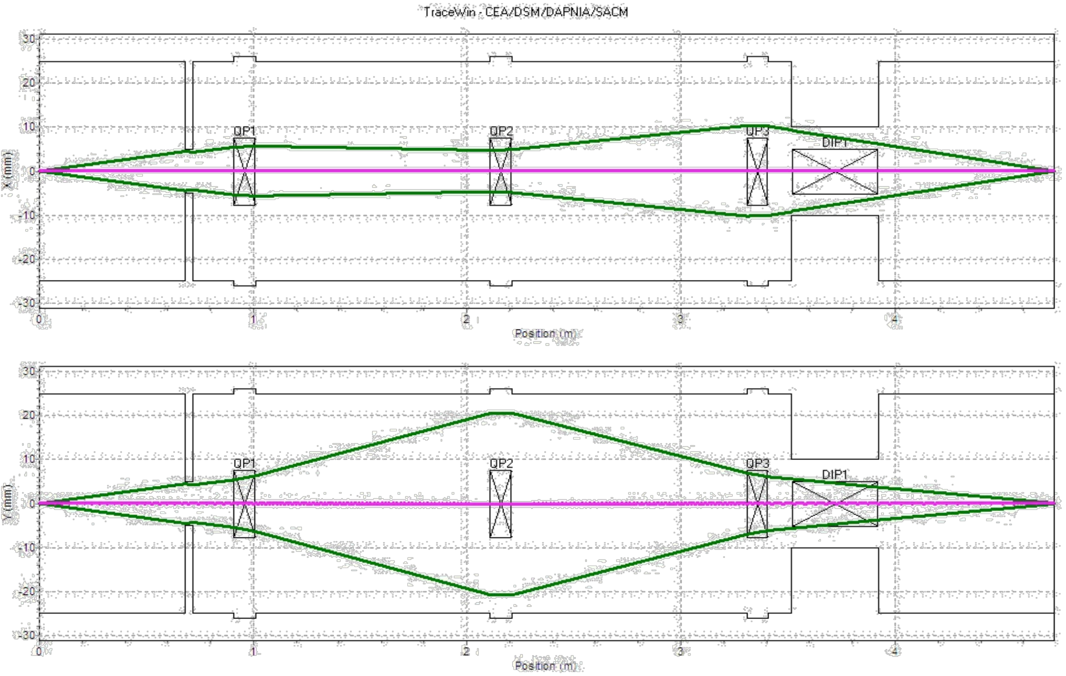




design of a high resolution magnetic spectrometer

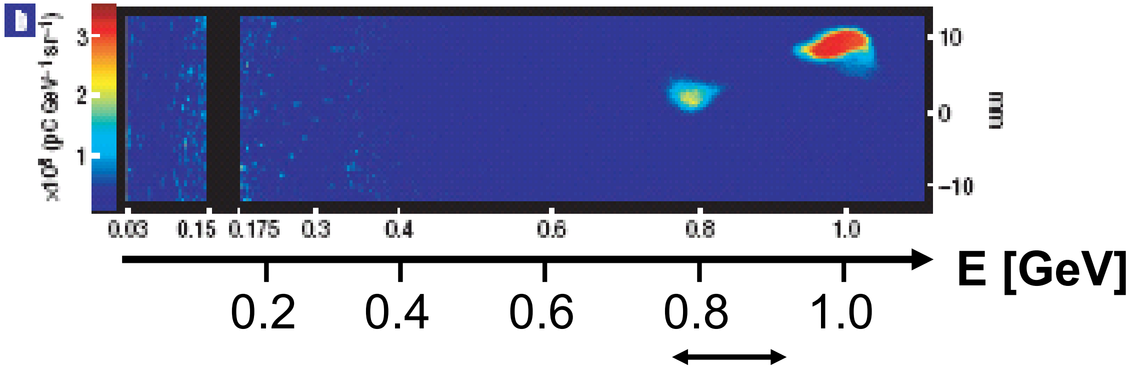
- quadrupole triplet (FODOF, ∫|dB/dx|dz = 1.2T) + permanent dipole (∫Bdz = 0.36T Tm)
- E resolution <1% over 100-150 MeV over 100-400MeV range
- 2 energy ranges: 100-220 MeV, 220-1200MeV ⇒ 2 phosphor screens
- avoid resolution degradation by multiple scattering ⇒ transport in vacuum
- stigmatic imaging for particular energy values
- in general: astigmatic ⇒ divergence estimation ⇒ **E resolution** shot to shot



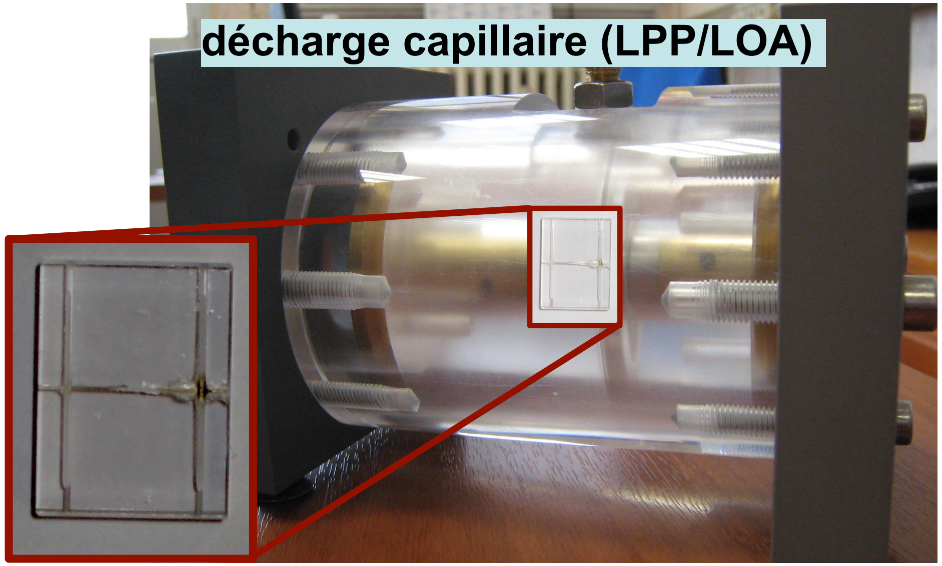


Frontière de l’énergie : augmenter la longueur d’accélération

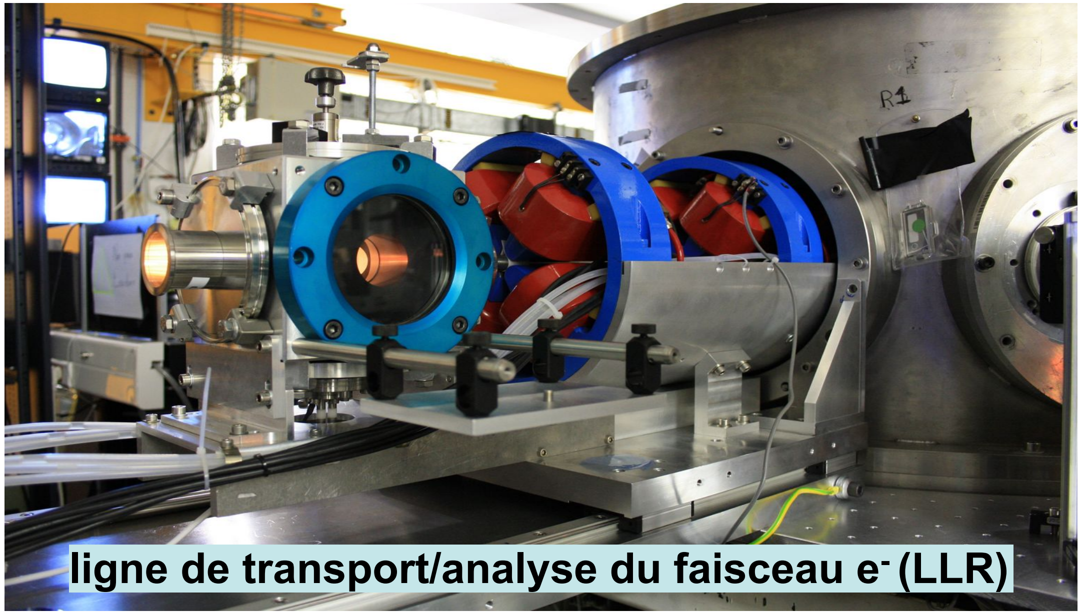
- guidage de l’onde plasma (et du laser):
  - auto-focalisation dans une cellule de gaz
  - canaux plasma créés par laser
  - capillaires « passifs »
  - **décharge dans un capillaire**
- régime d’auto-injection (= bulle plasma = *blowout*)
- opération stable à 450 MeV
- **décharge capillaire dévéloppé par LOA & LPP, manip en cours**



W.P. Leemans, et al., Nature Phys. 2, 696-699

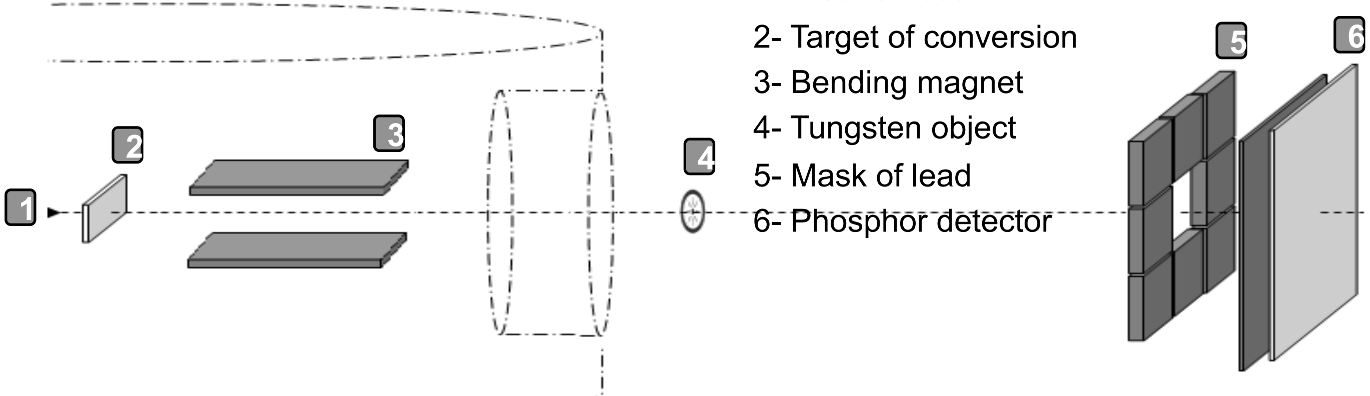


décharge capillaire (LPP/LOA)



ligne de transport/analyse du faisceau e^- (LLR)

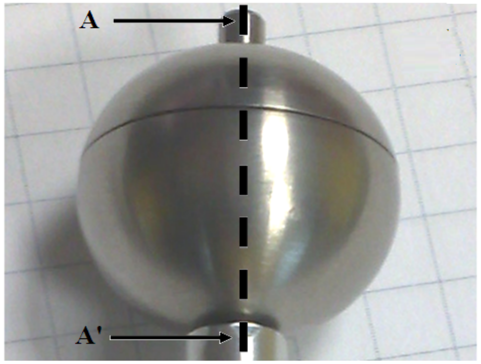
Une application : la radiographie gamma

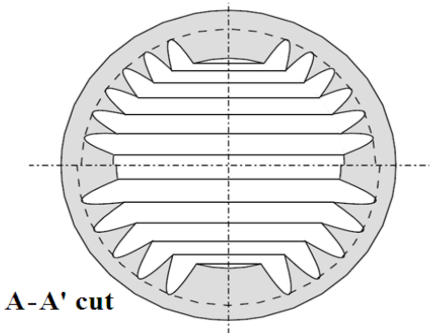


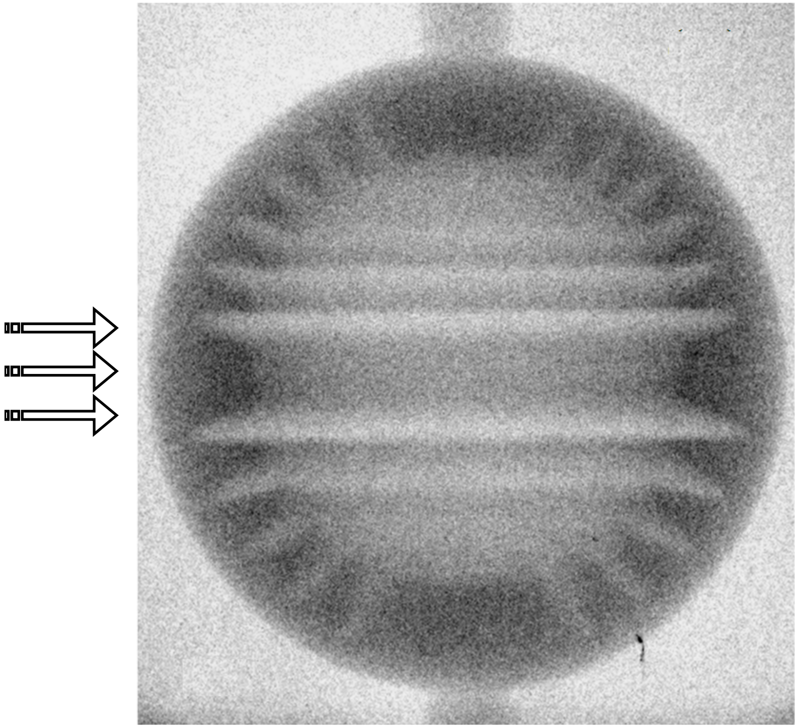
1- Electron beam
2- Target of conversion
3- Bending magnet
4- Tungsten object
5- Mask of lead
6- Phosphor detector

LOA & LLR

Ahmed BEN ISMAIL, 13th Asia-Pacific Conference on Non-Destructive Testing (APCNDT 09)

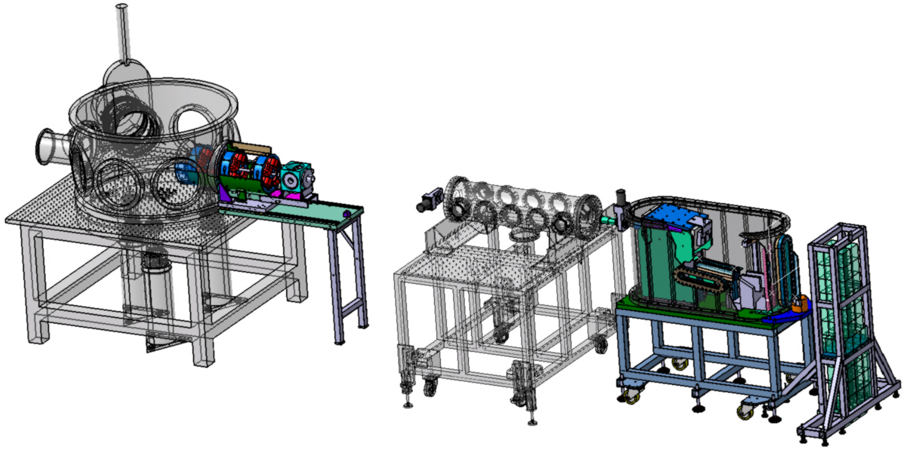


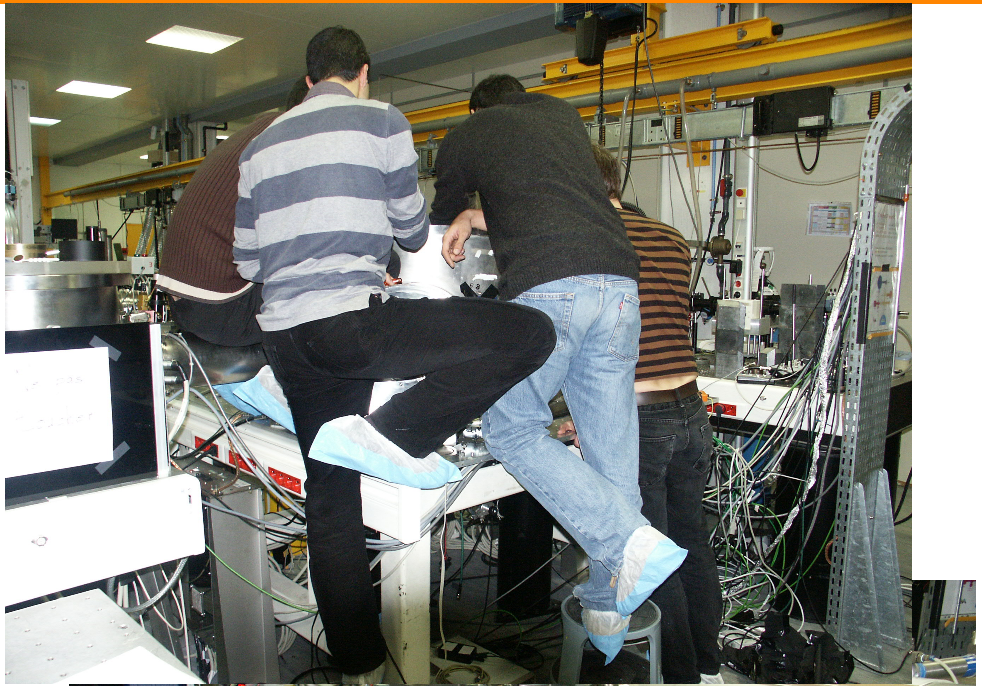


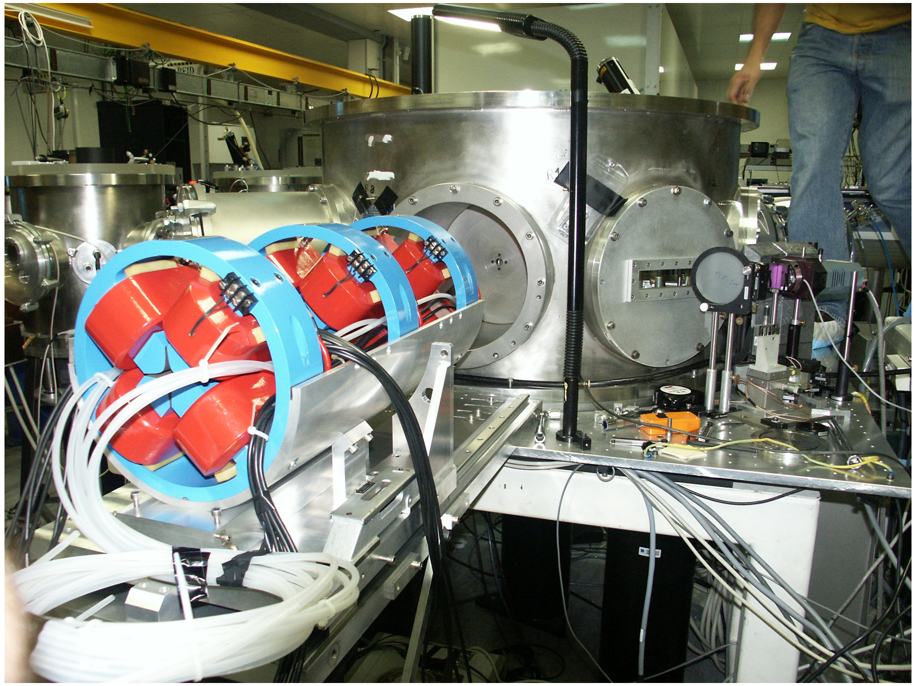


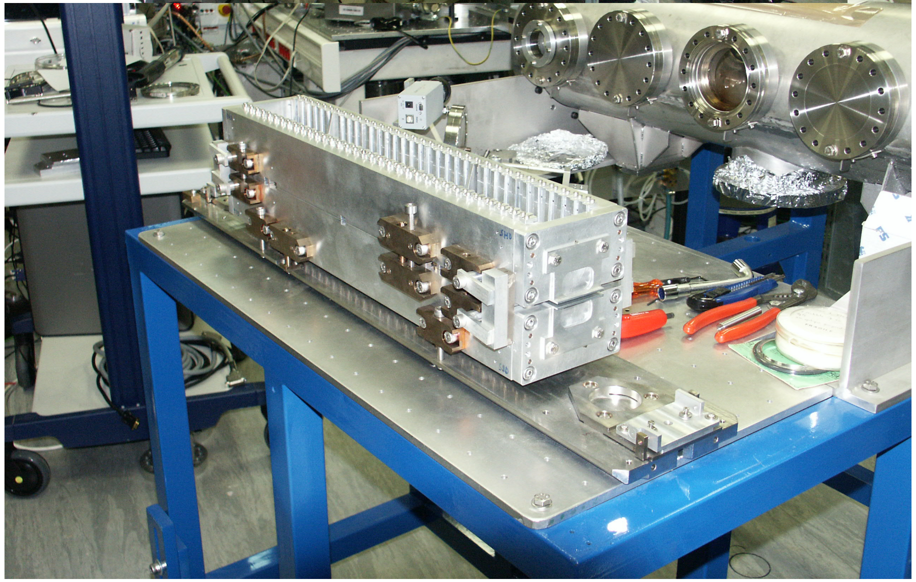
undulator experiment at LOA (2009/2010)

compactified beam transport line

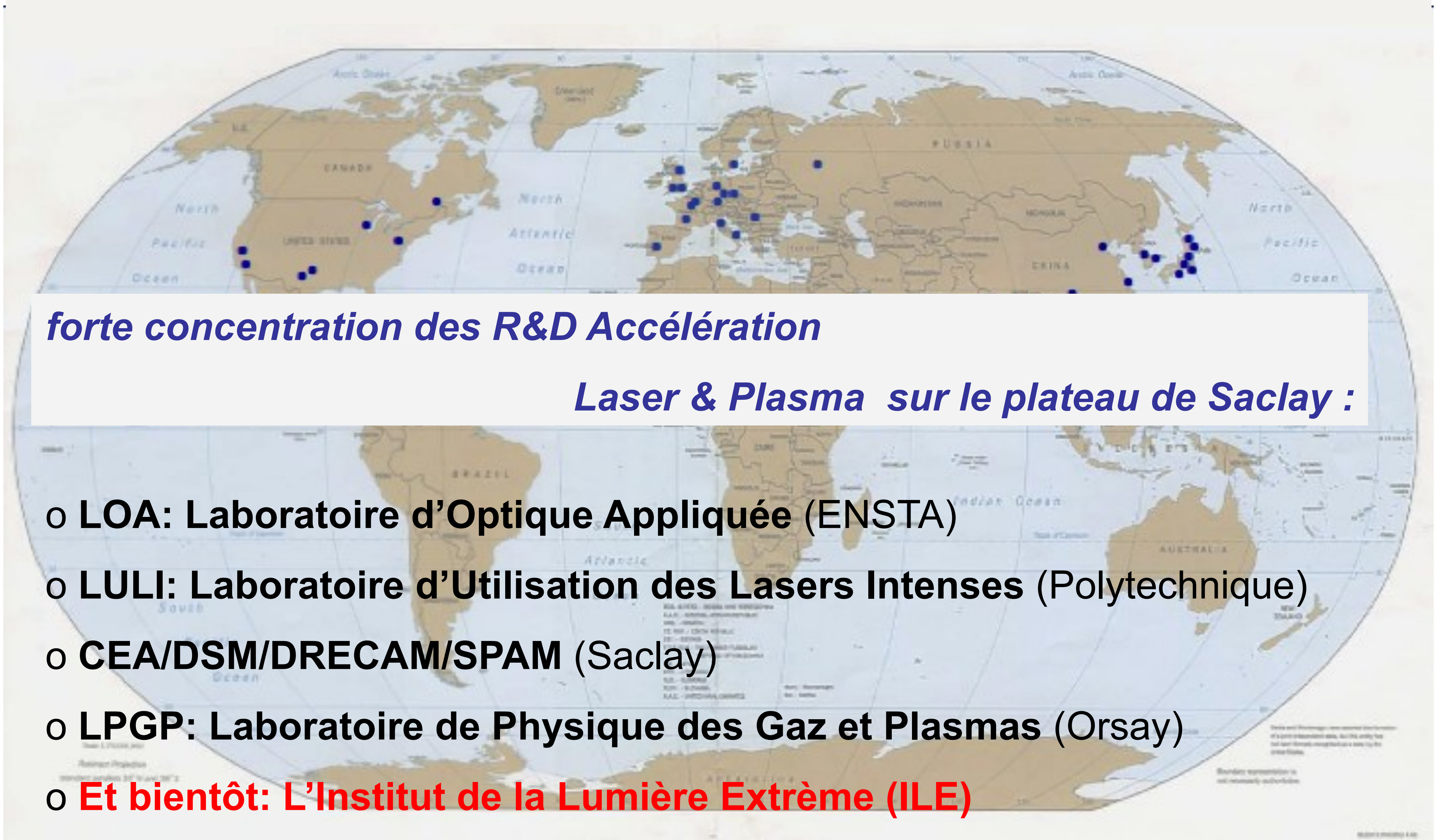








Accélération Laser & Plasma partout dans le monde



forte concentration des R&D Accélération

Laser & Plasma sur le plateau de Saclay :

o **LOA: Laboratoire d'Optique Appliquée** (ENSTA)

o **LULI: Laboratoire d'Utilisation des Lasers Intenses** (Polytechnique)

o **CEA/DSM/DRECAM/SPAM** (Saclay)

o **LPGP: Laboratoire de Physique des Gaz et Plasmas** (Orsay)

o **Et bientôt: L'Institut de la Lumière Extrême (ILE)**

Contexte présent et futur

- **LOA** : laser de la salle jaune «salle jaune» 40TW, 30fs
  - injection dans un onduleur
  - guidage du laser dans une décharge capillaire (augmentation de l'énergie)
  - mesure de l'émittane du faisceau d'e^-
- **CEA** (SPAM) : IRAMIS UHI 100TW 25fs, 100TW, 2 salles
- **ILE** (Institut de la Lumière Extrême)
  - implantation au à partir de 2013
  - deux lasers: LUIRE: 1PW 15fs, début 2011 (installé à l'ENSTA)
    APOLLON:10 PW, 15fs 2014 (installat° au CEA Orme des Merisiers)
  - applications: e^-. p, XFEL compact, physique exotique
  - accélération d'électrons: O(10GeV), caractérisation complète, 2 étages
- **ELI** (Extreme Light Infrastructure)
  - 10 fois ILE (100PW)
  - projet européen
  - **LLR «membre » d'ELI**