Laser Plasma Wakefield Acceleration : Concepts, Tests and Premises

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Summary

Part 1 : Laser plasma accelerator : motivation

Part 2 : Laser plasma accelerator as booster

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Part 4 : New scheme of injection : toward a stable, tuneable and quasi monoenergetic electron beam.

Part 5 : Conclusion and perspectives

Classical accelerator limitations

E-field$_{max}$ ≈ few 10 MeV /meter (Breakdown)
R>R$_{min}$ Synchrotron radiation

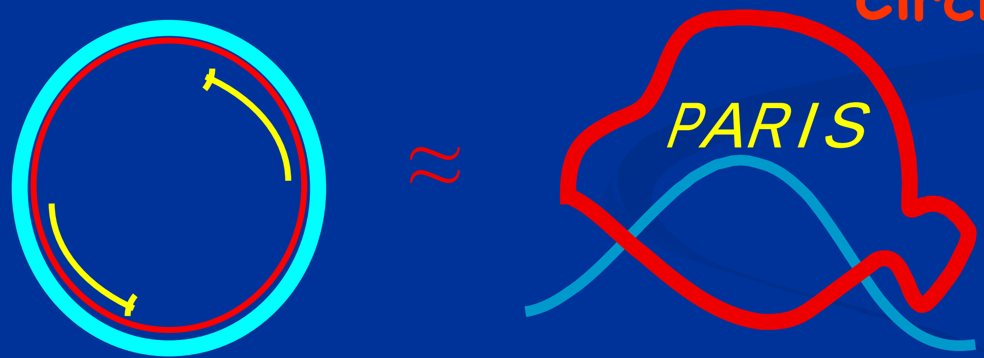
→ Energy ↗ = Length ↗ = $$$ ↗

LEP at CERN

27 km

Circle road

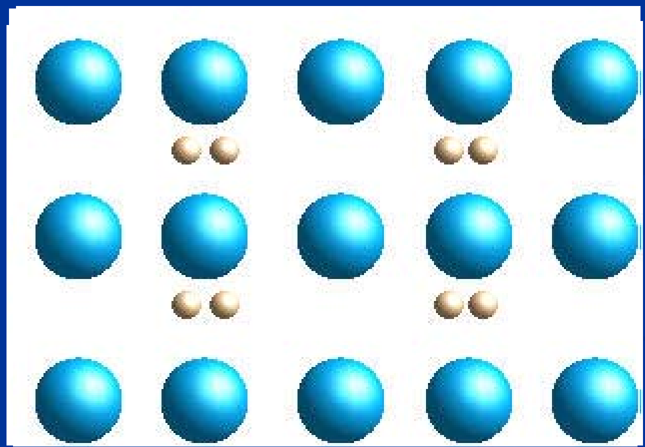
31 km



→ New medium : the plasma

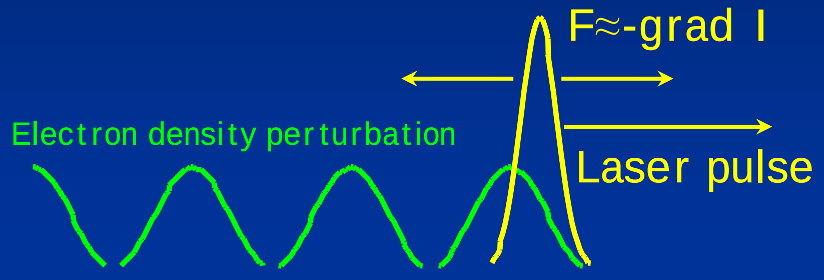
Why is a Plasma useful ?

- Superconducting RF-Cavities : $E_z = 55$ MV/m
- Plasma is an Ionized Medium → High Electric Fields



How to excite Relativistic Plasma waves?

The laser wake field



$\tau_{laser} \approx T_p / 2$
=>Short laser pulse

Phase velocity $v_{\phi epw} = v_{g^{laser}}$ => close to c
Analogy with a boat

Are Relativistic Plasma waves efficient ?

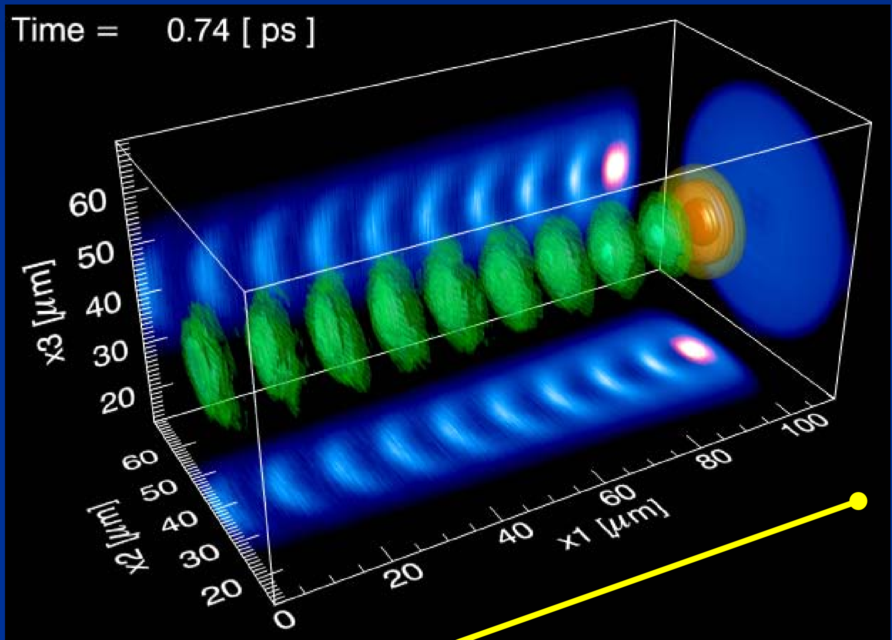
$$E_z \sim \sqrt{n_e}$$

E_z = 0.3 GV/m for 1 % Density Perturbation at 10^{17} cc^{-1}

E_z = 300 GV/m for 100 % Density Perturbation at 10^{19} cc^{-1}

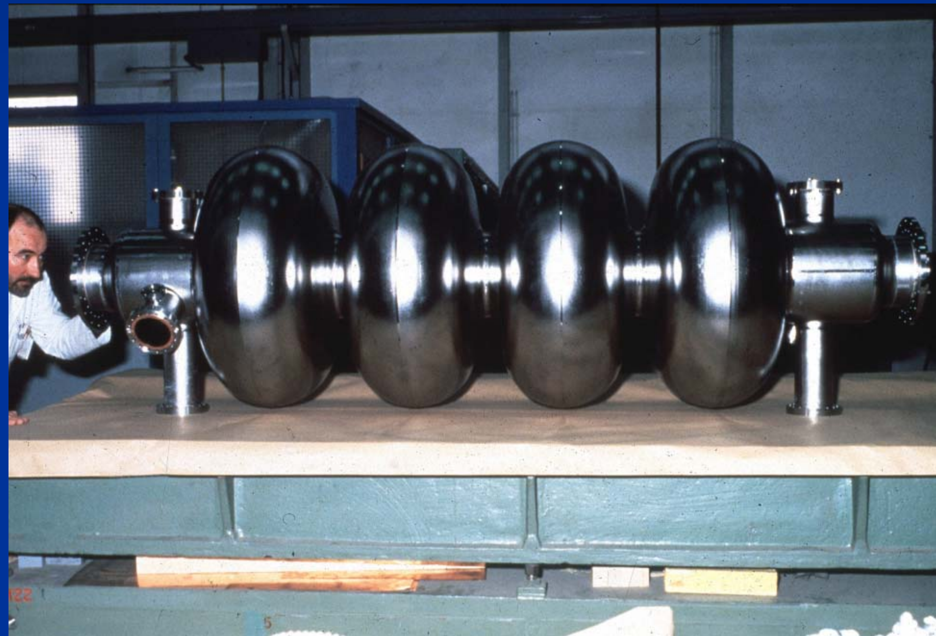
Relativistics microelectronic devices

Courtesy of W. Mori & L. da Silva



100 μm

Plasma cavity



1 m

RF cavity

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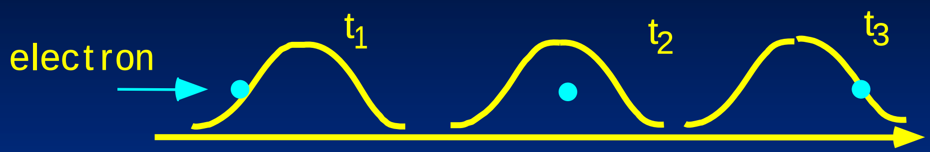
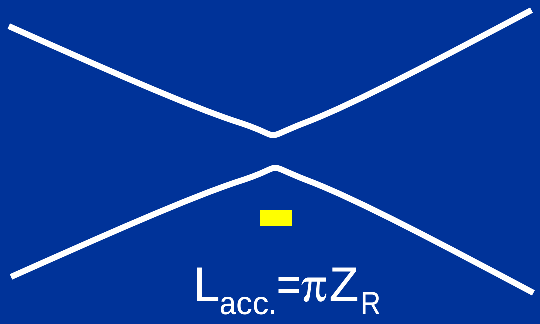
Interaction and dephasing lenghts



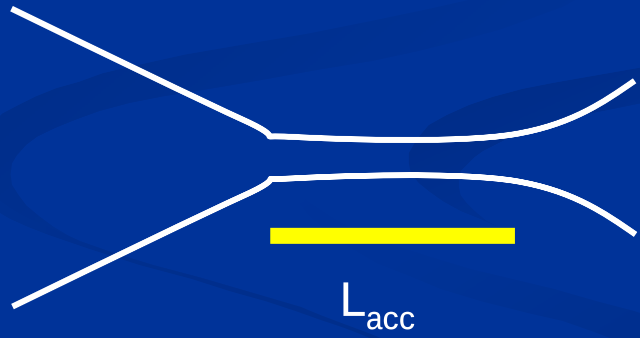
$\gamma_e >> \gamma_\phi >> 1$

$L_{\text{Deph.}} = \lambda_p \gamma_\phi^{\,2}$ $\qquad$ $\Rightarrow L_{\text{deph.}} = (\lambda_0/2)(n_c/n_e)^{3/2}$

Diffraction limited



Guiding : channel or relativistic



$\Delta W_{diff.}$ [MeV] $\approx 580\,(\lambda/\lambda_p)/(1+a_0^{\,2}/2)^{1/2}$ P [TW]

ΔW_{ch} [MeV] $\approx 60\,(\lambda_p/w_0)$ P [TW]

W. P. Leemans et al., IEEE 24, 2 (1996)

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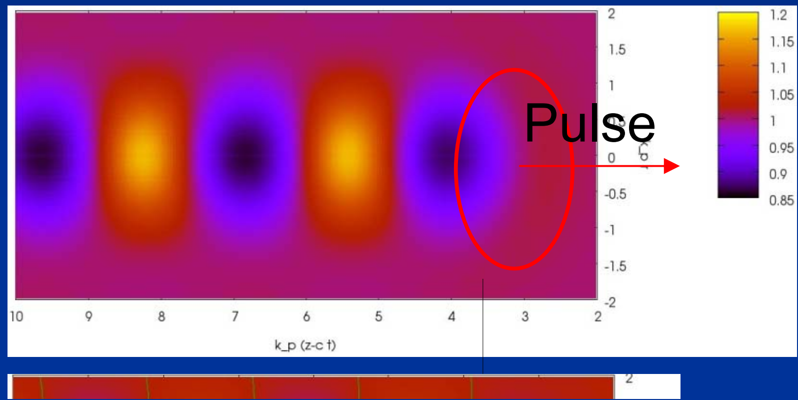
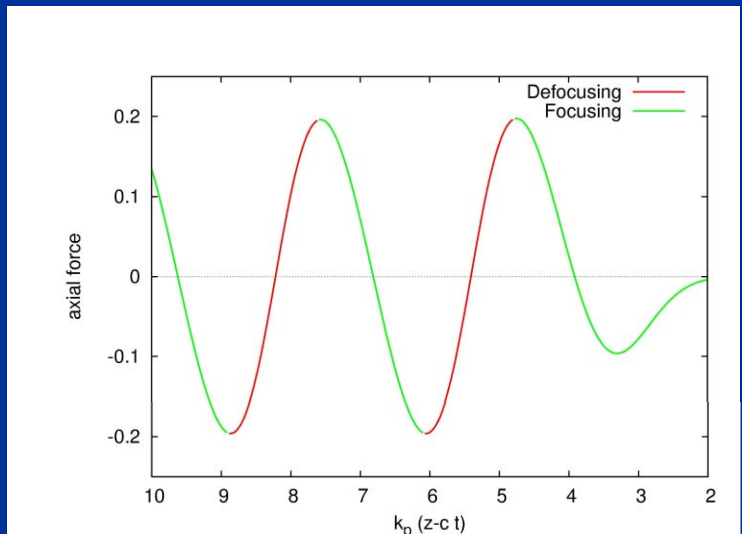
Accelerating & focusing fields in Linear RPW

- Small Laser amplitude a_0=0.5
- Homogeneous plasma



Electron density



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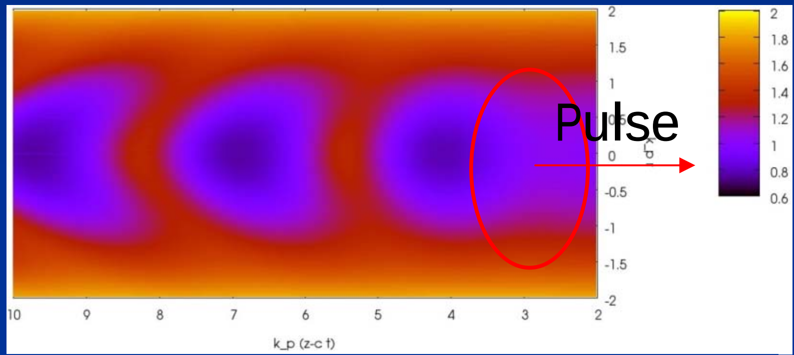
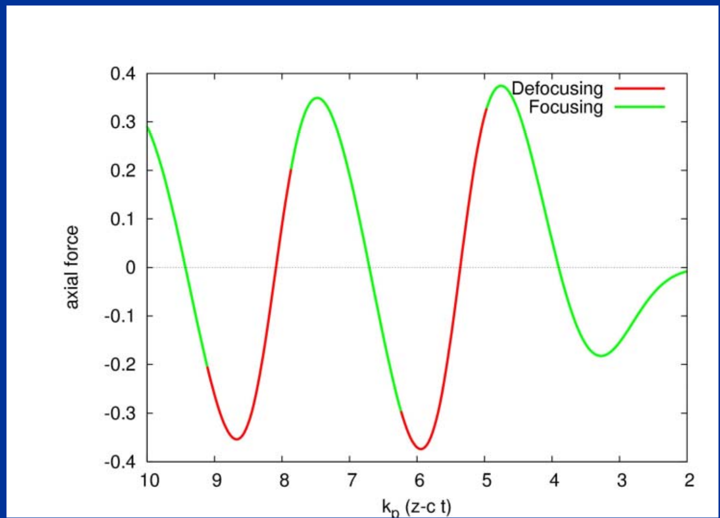
Accelerating & focusing fields in plasma channel

- Small Laser amplitude a_0=0.5
- Parabolic plasma channel



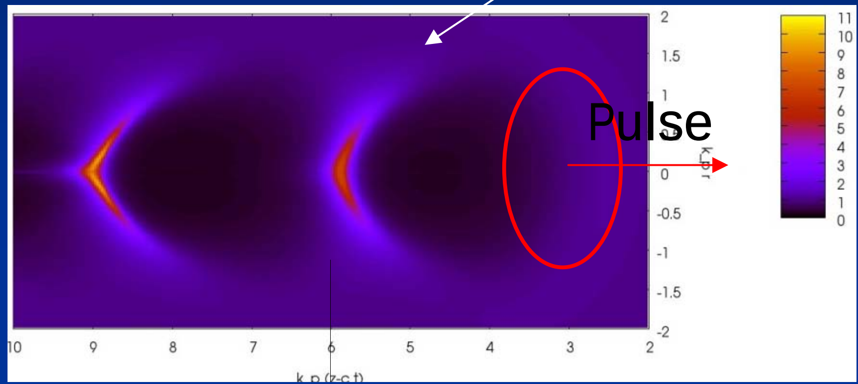
Electron density



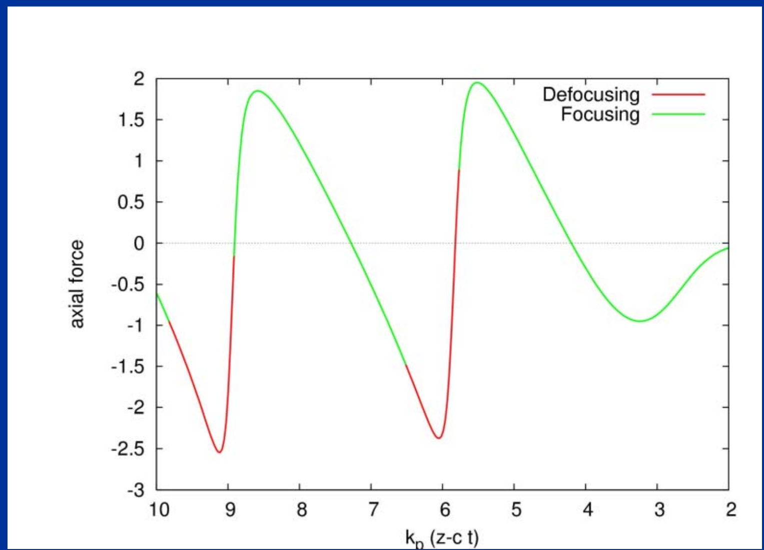
Accelerating & focusing fields in NL RPW

- Large Laser amplitude a_0=2
- Homogeneous plasma

relativistic shift of ω_p

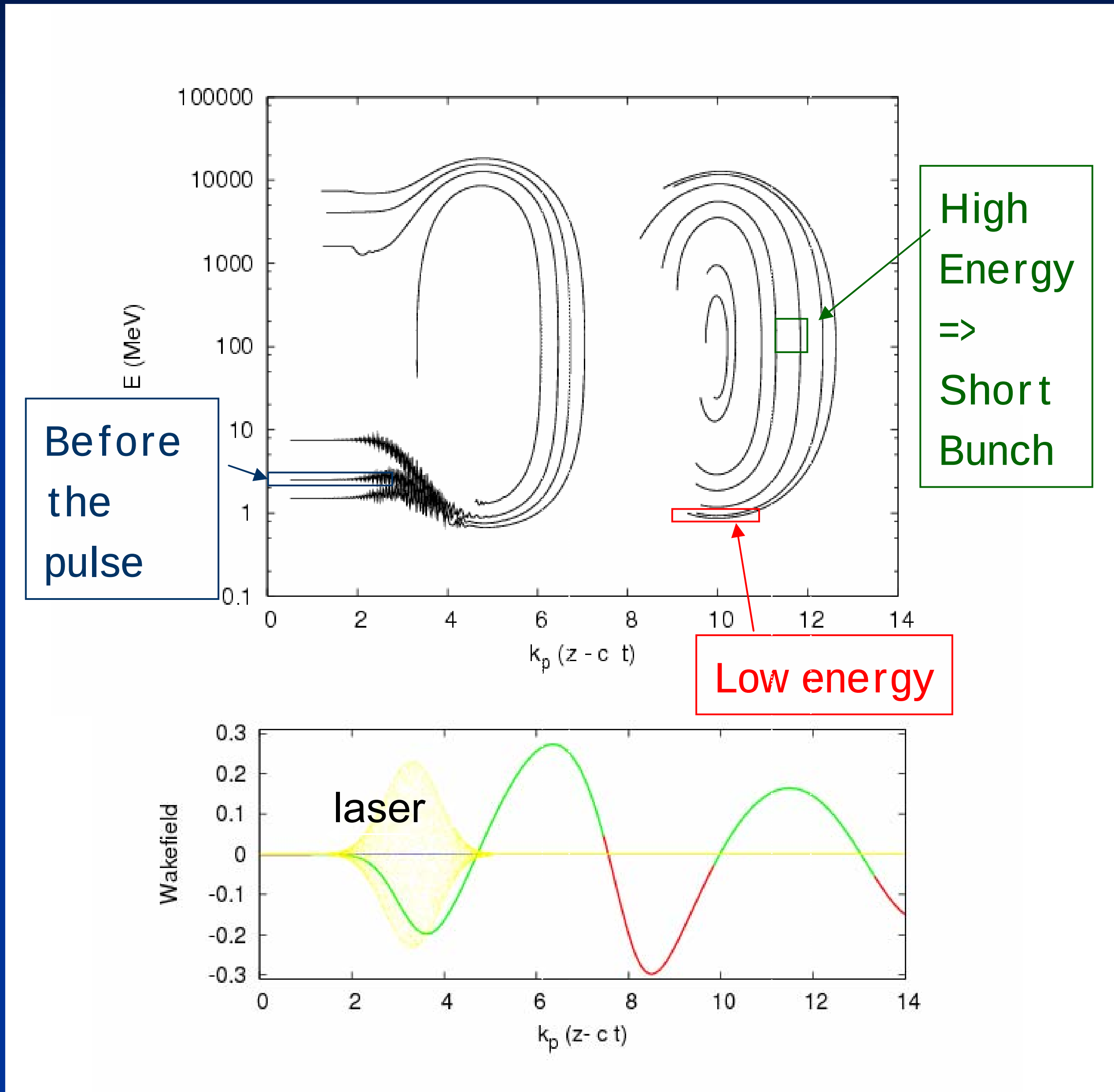


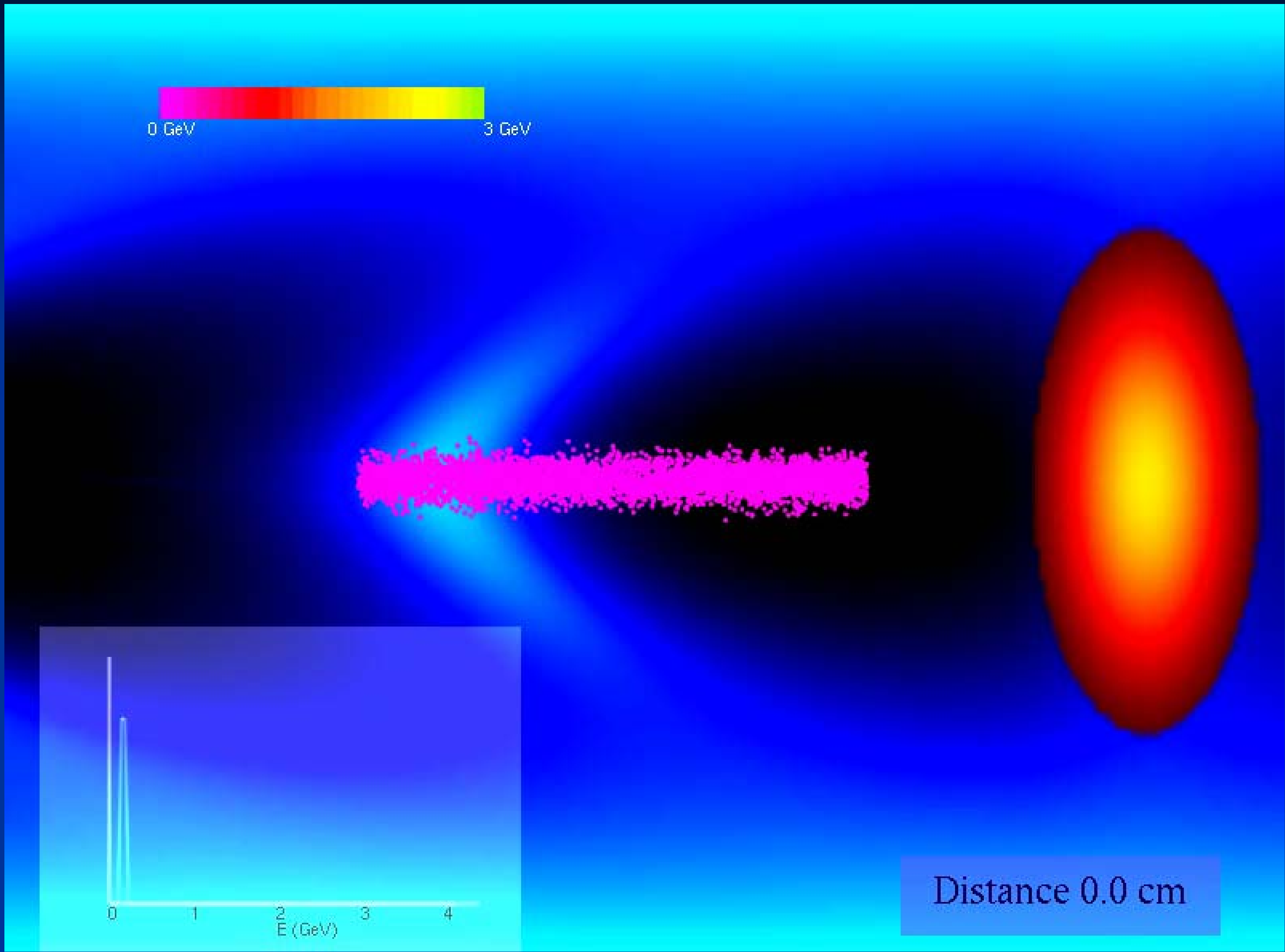
Electron density



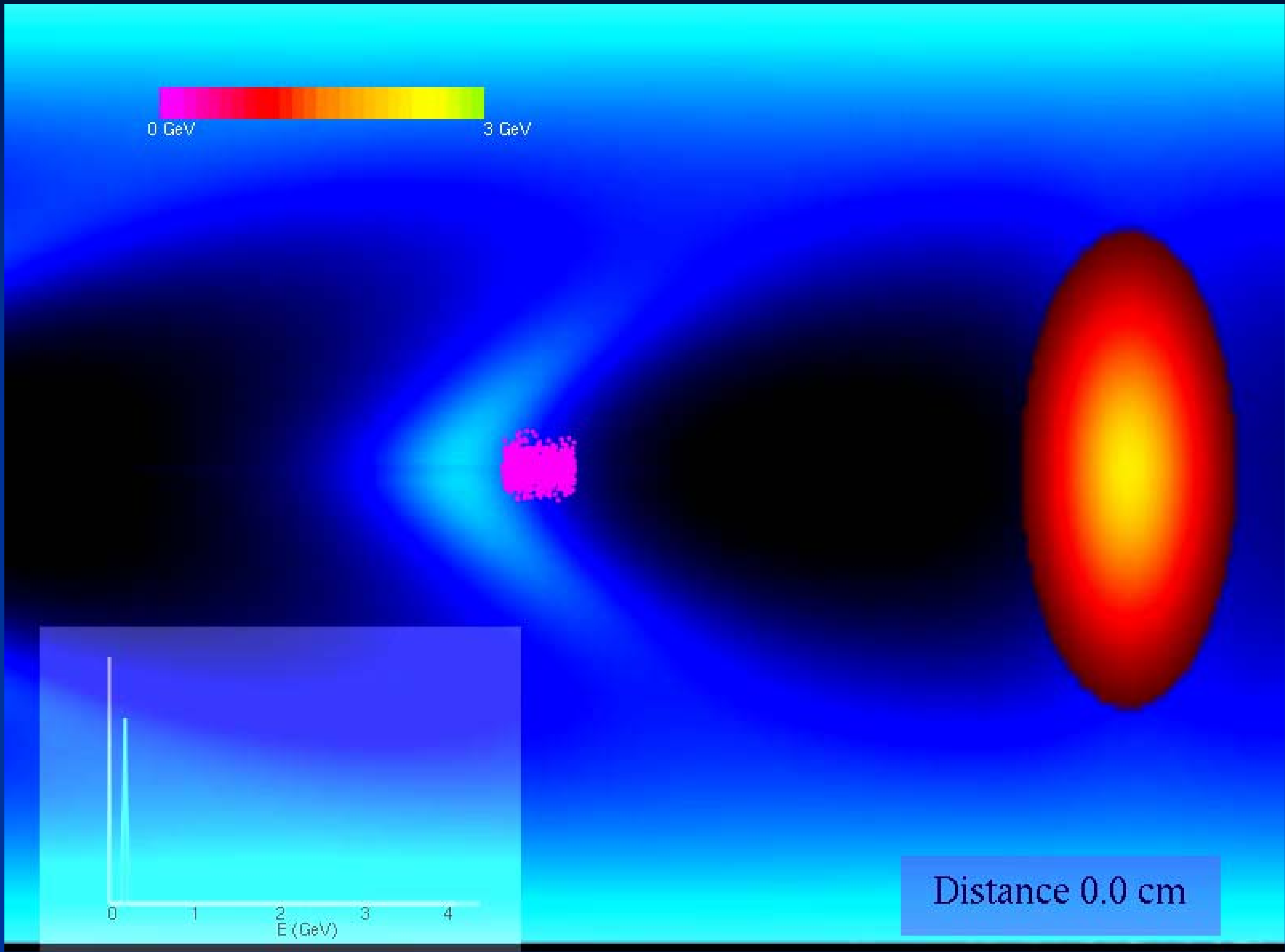
Three Injection schemes

Low energy =>
Low charge





τ_{bunch} = 200 fs



Injecting the LOA e-beam @ τ_{bunch} = 30 fs, 170 MeV

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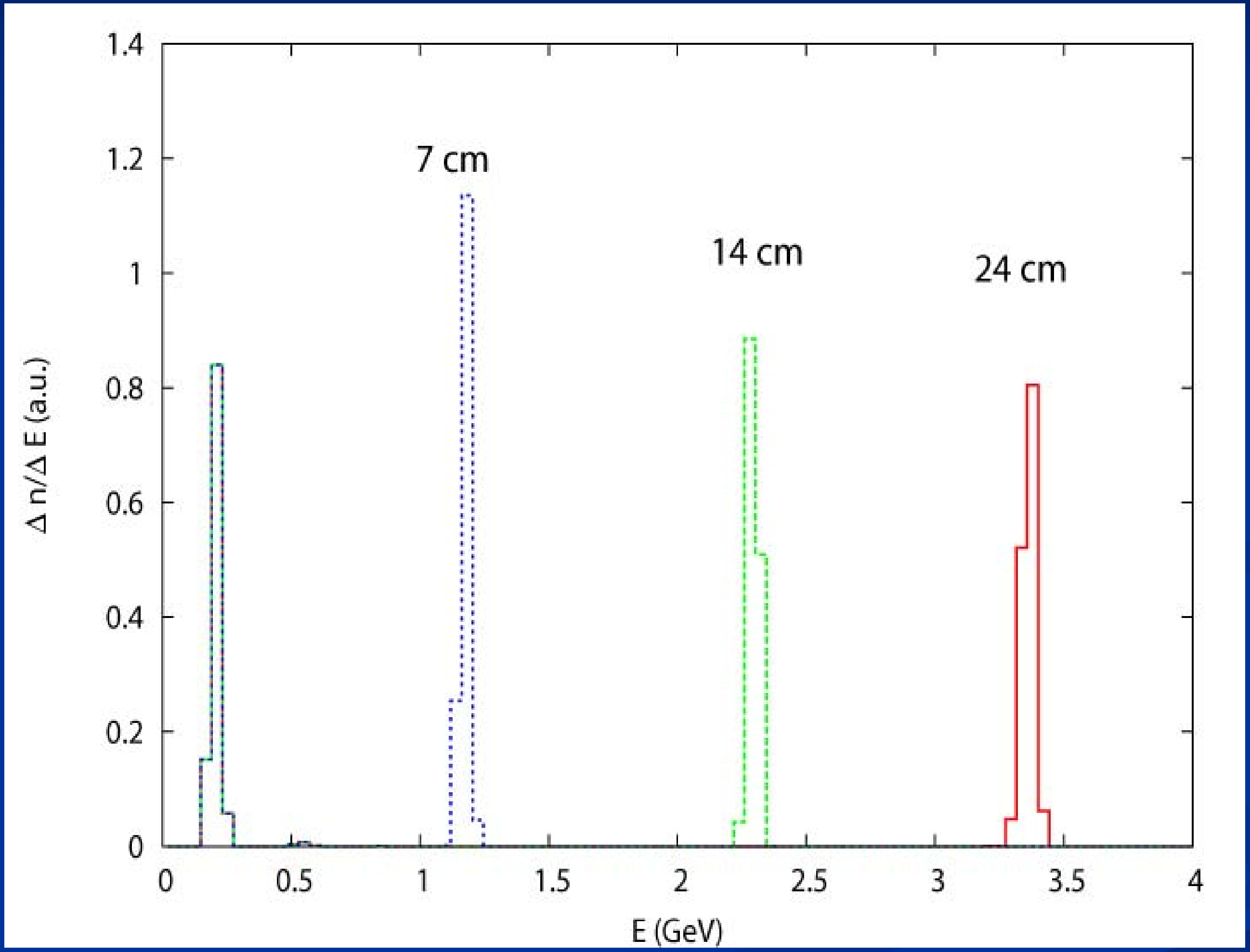
3 GeV, 1% energy spread e-beam

- E=9 J
- P= 0.15 PW
- a_0=1.5
- Parabolic channel:
- r_0=47 μm,
- $n(r)=n_0\ (1+0.585\ r/r_0)$
- $n_0 = 1.1\times10^{17}\ cm^{-3}$



3.5 GeV, with a relative energy spread FWHM of 1% and an unnormalized emittance of 0.006 mm.

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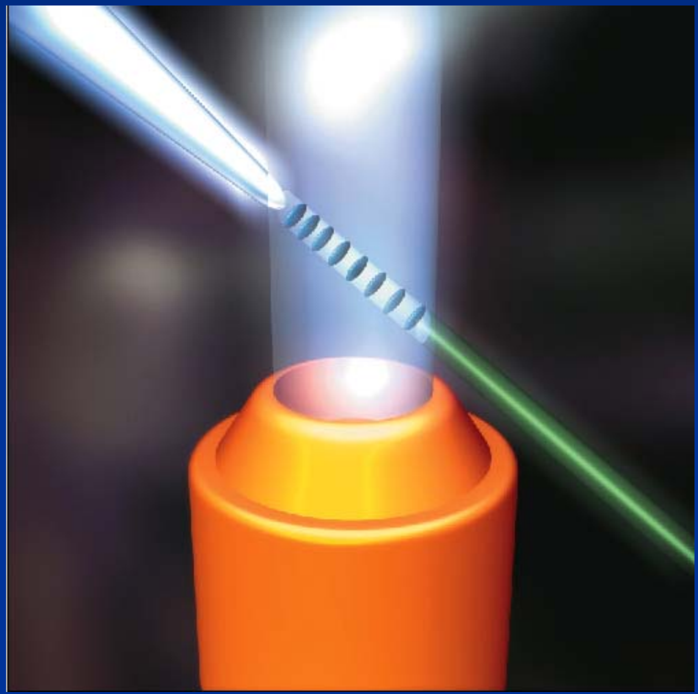
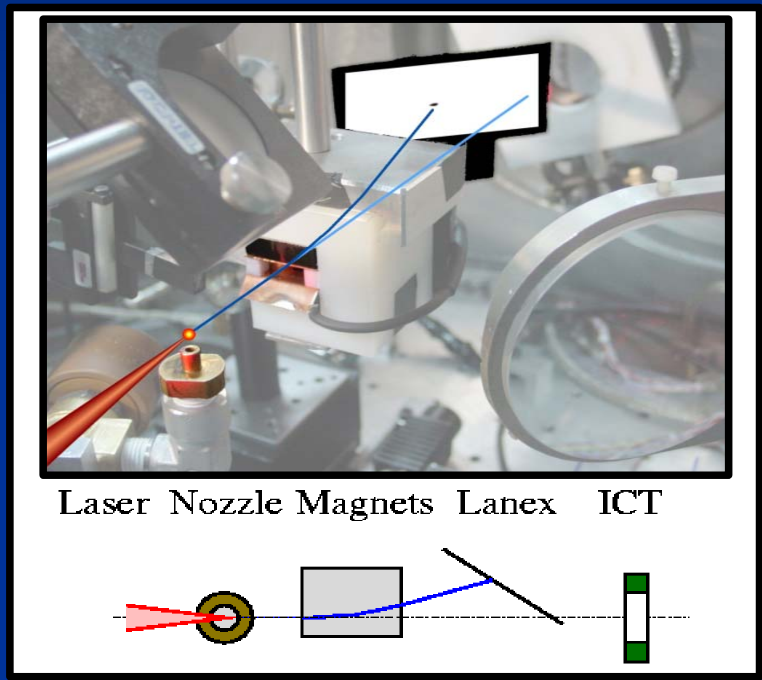
Laser plasma injector

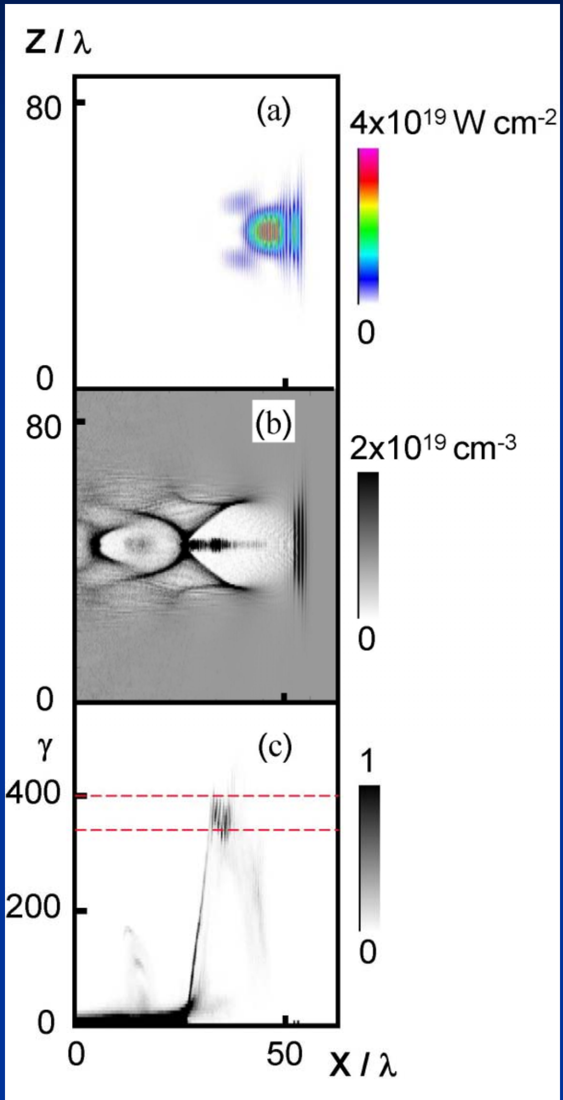


Scheme of principle



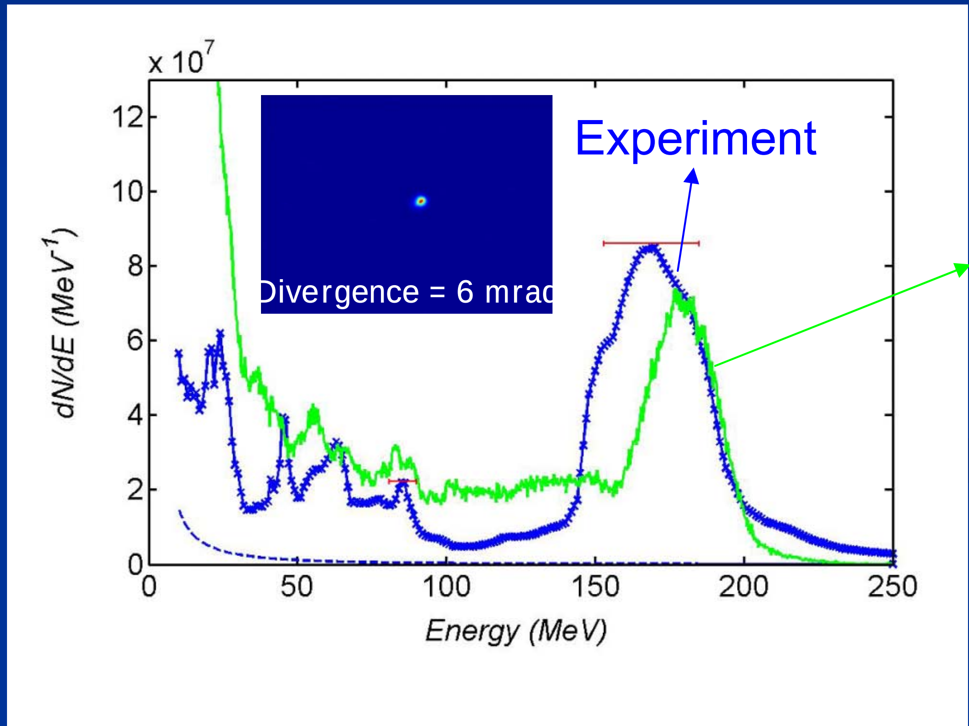
Experimental set up

Energy distribution improvements: The Bubble regime



Charge in the peak : few 100 pC

According to absolute calibration of scintillator*



At LOA

J. Faure et al. Nature (2004)

Several groups have obtained quasi monoenergetic e beam but at higher density ($\tau_L > \tau_p$)

**Y. Glinec et al., in preparation, NB*

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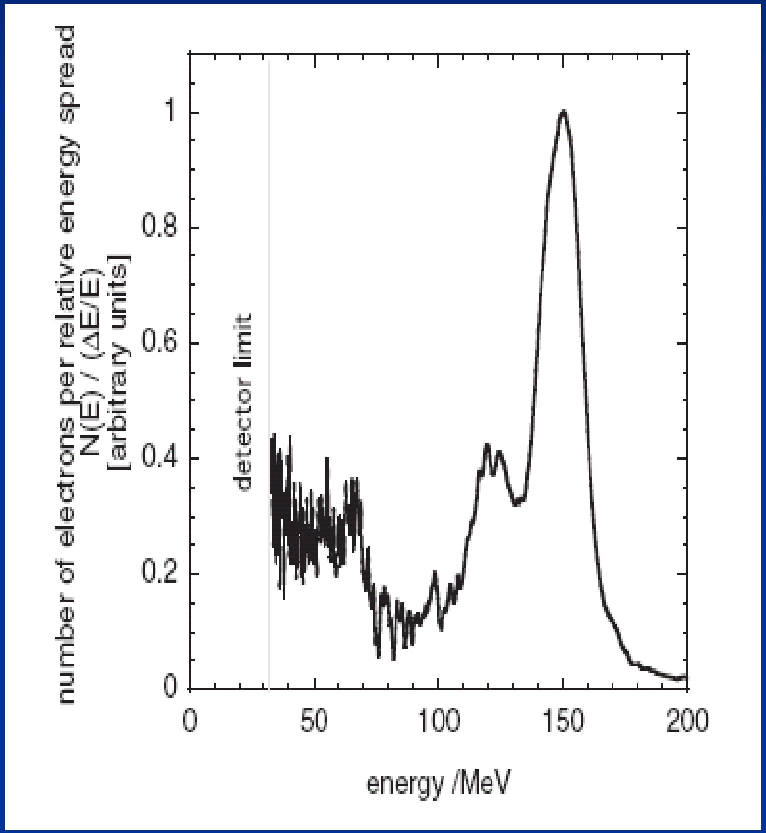
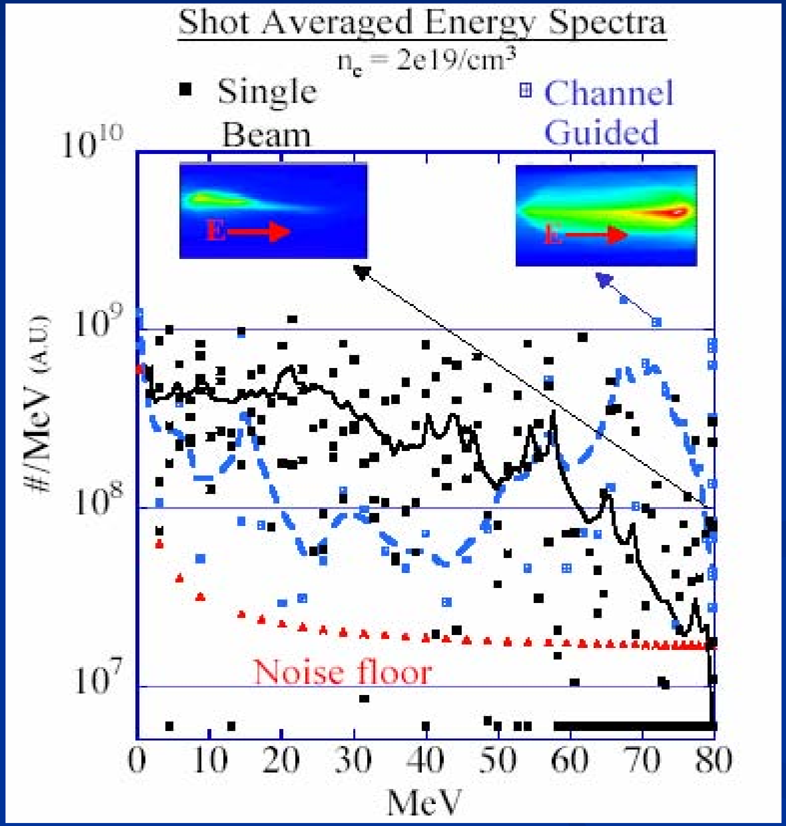
Quasi monoenergetic e-beam :14 groups





At Lundt
Mangles et al. PRL (2006)

At LBNL
Geddes et al. Nature (2004)

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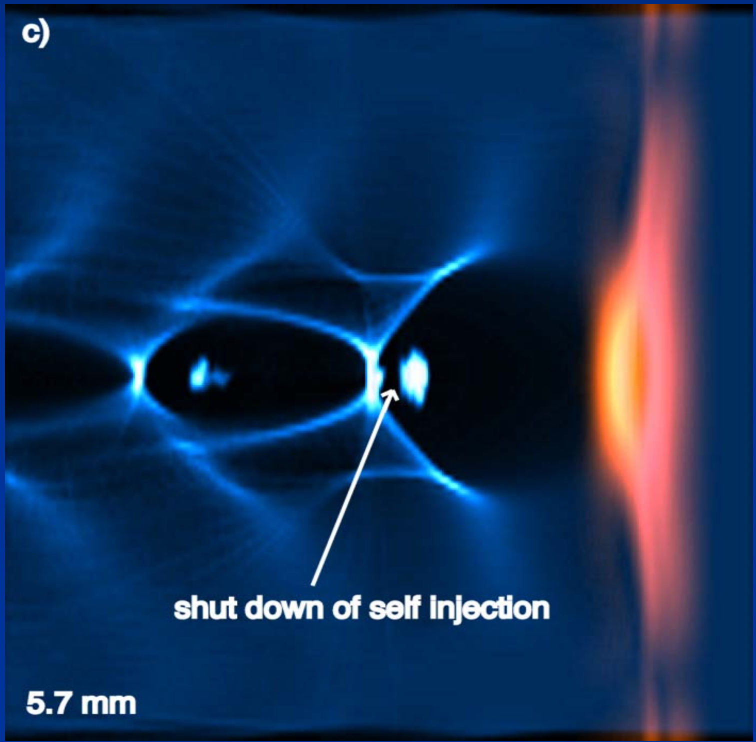
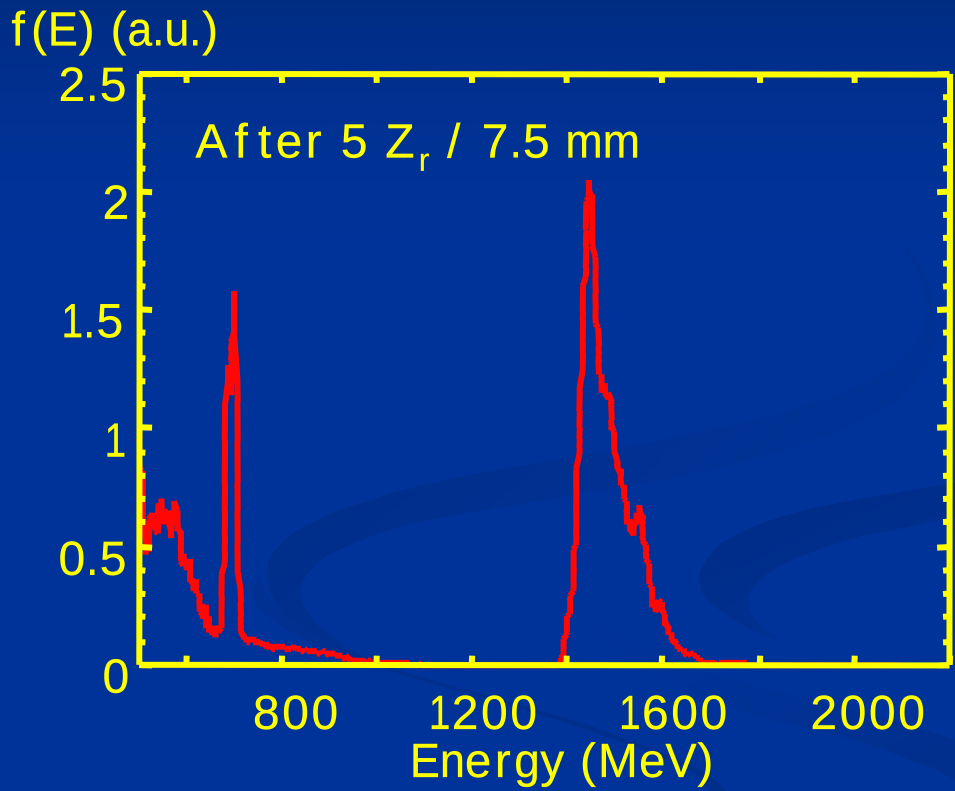
Laser plasma injector : GeV electron beams

$$w_0 = 20\,\mu m \quad \tau = 30\,fs \quad P = 200\,TW \quad \lambda = 0.8\,\mu m \quad a_0 = 4 \quad n_p = 1.5\times 10^{18}\,cm^{-3}$$





Courtesy of UCLA& Golp groups

Laser plasma injector :

+ good efficiency : $E_{e\text{-}beam}/E_{laser} \approx 10\ \%$

+ simple device

+ sub 30 fs duration : ideal as injector

+ with channel : GeV range is obtained[1] with moderate laser power*

*But since the efficiency is conserved a compromise between charge and energy must be found

-Stability not yet demonstrated !

- Energy spread still too large for some applications : $\delta E/E \approx$ few %

** Courtesy of S. Hoocker or F. S. Tzung PRL (2004)*

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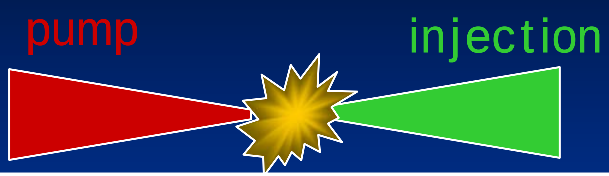
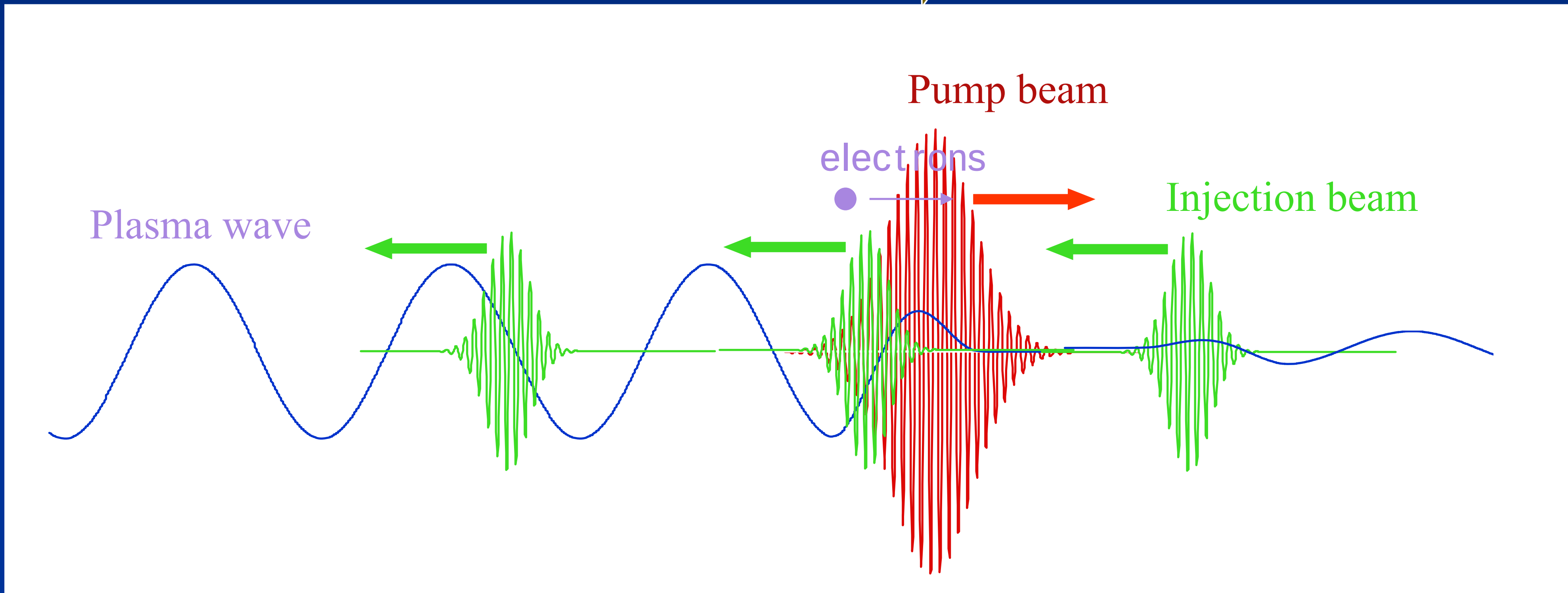
External injection using another laser pulse

Counter-propagating geometry:





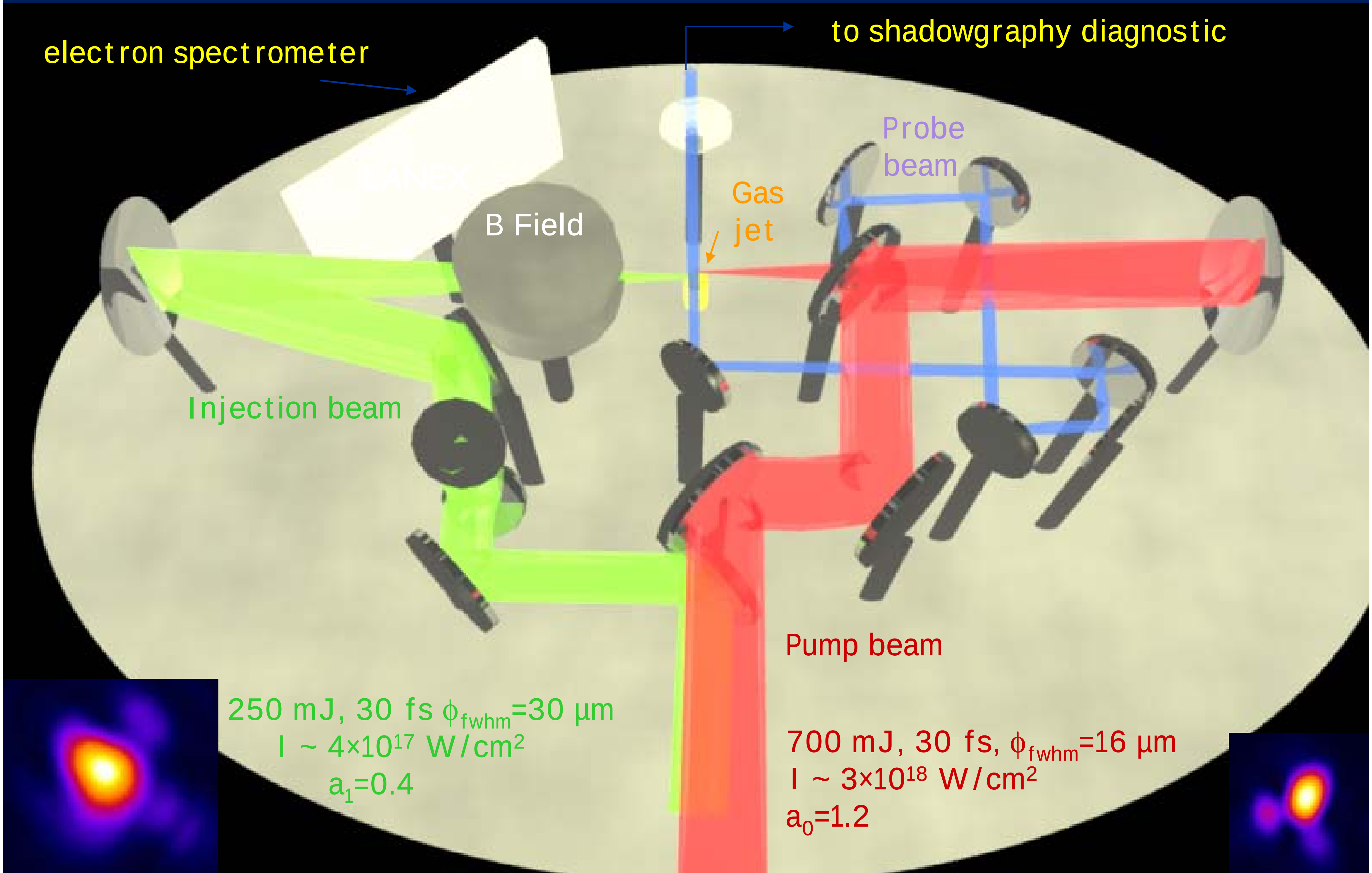
Ponderomotive force of beatwave: $F_p \sim 2a_0a_1/\lambda_0$ (a_0 et a_1 can be “weak”)

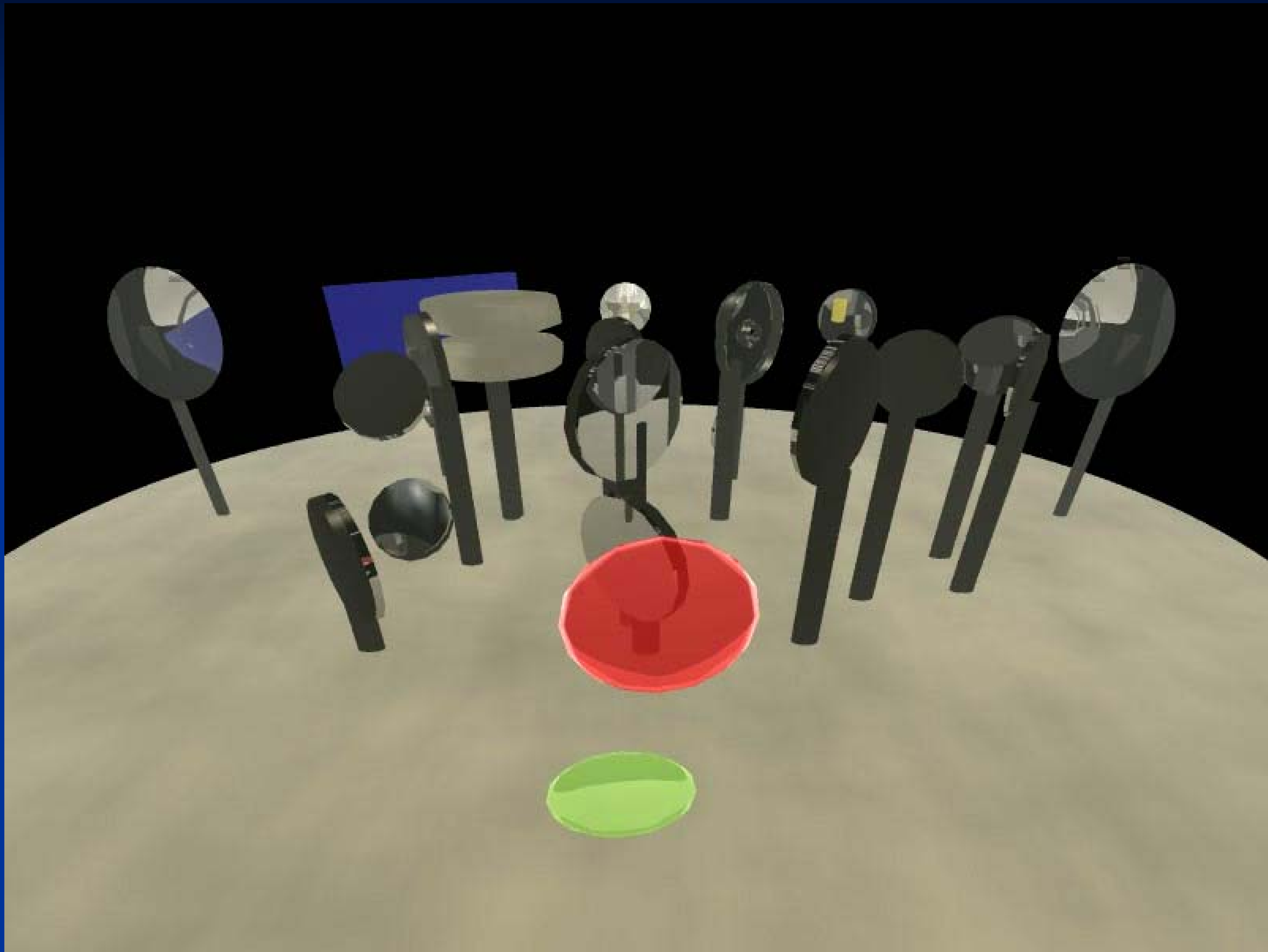
Boost electrons locally and injects them:

INJECTION IS LOCAL IN FIRST BUCKET

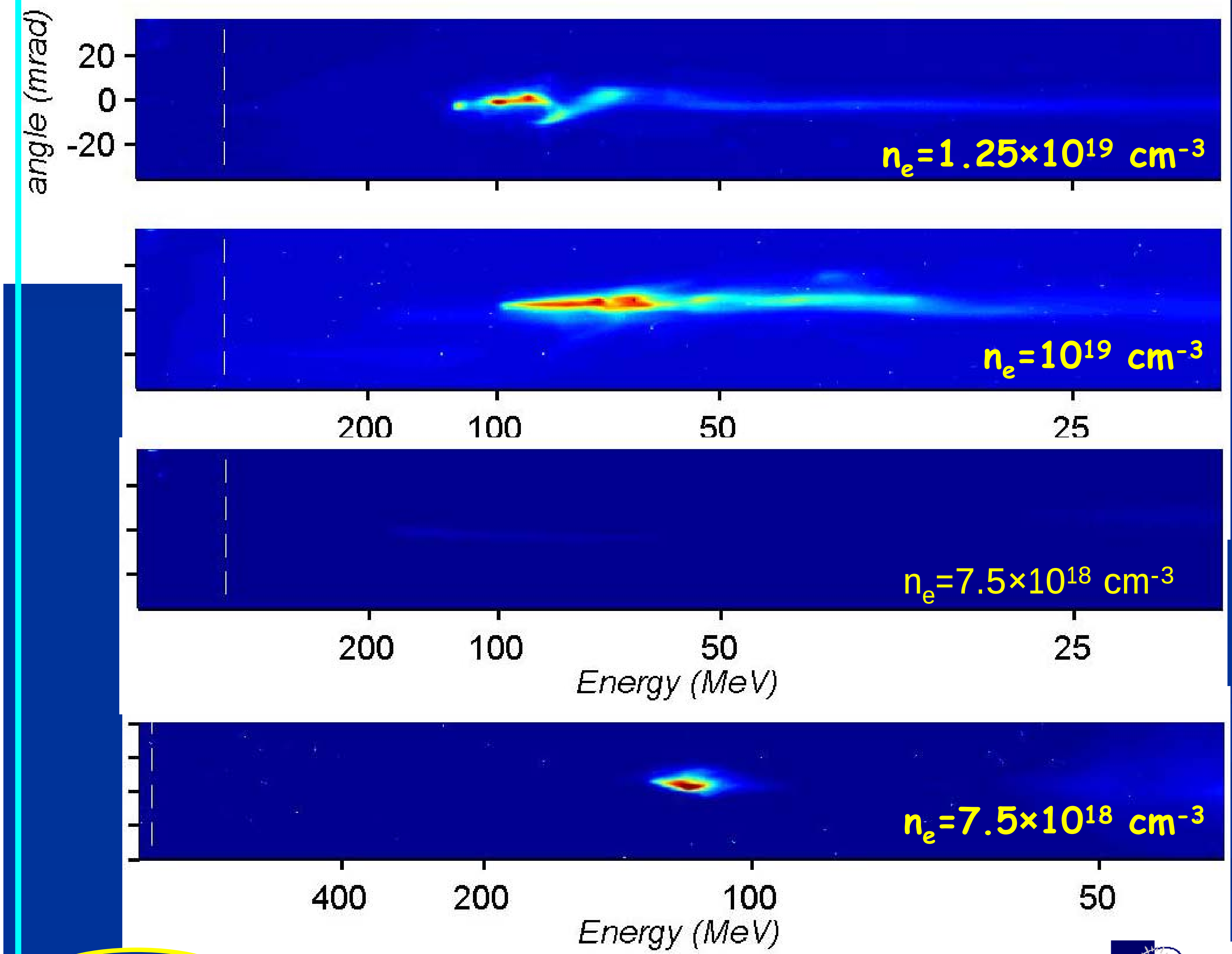
E. Esarey et al, PRL 79, 2682 (1997), G. Fubbiani et al. (PRE 2004)

Experimental set-up

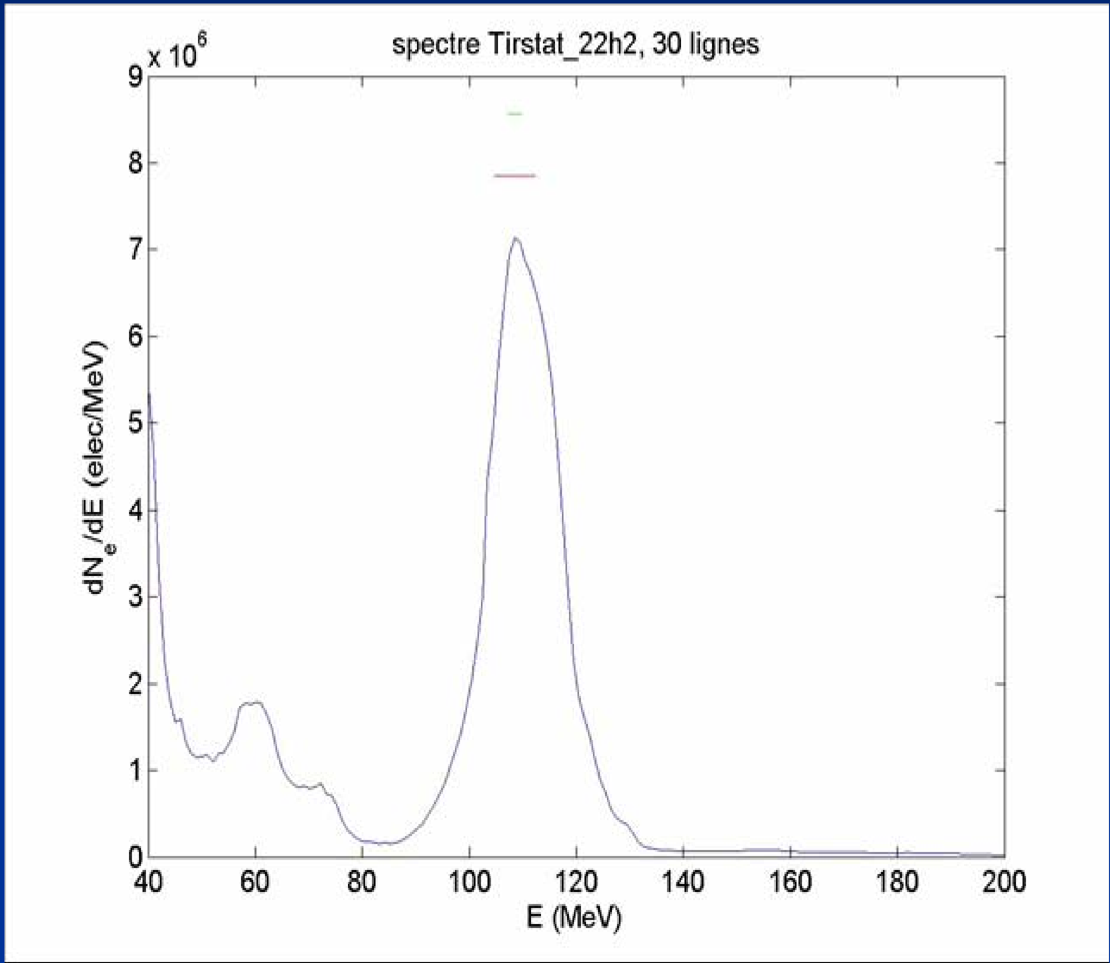




From self-injection to external injection



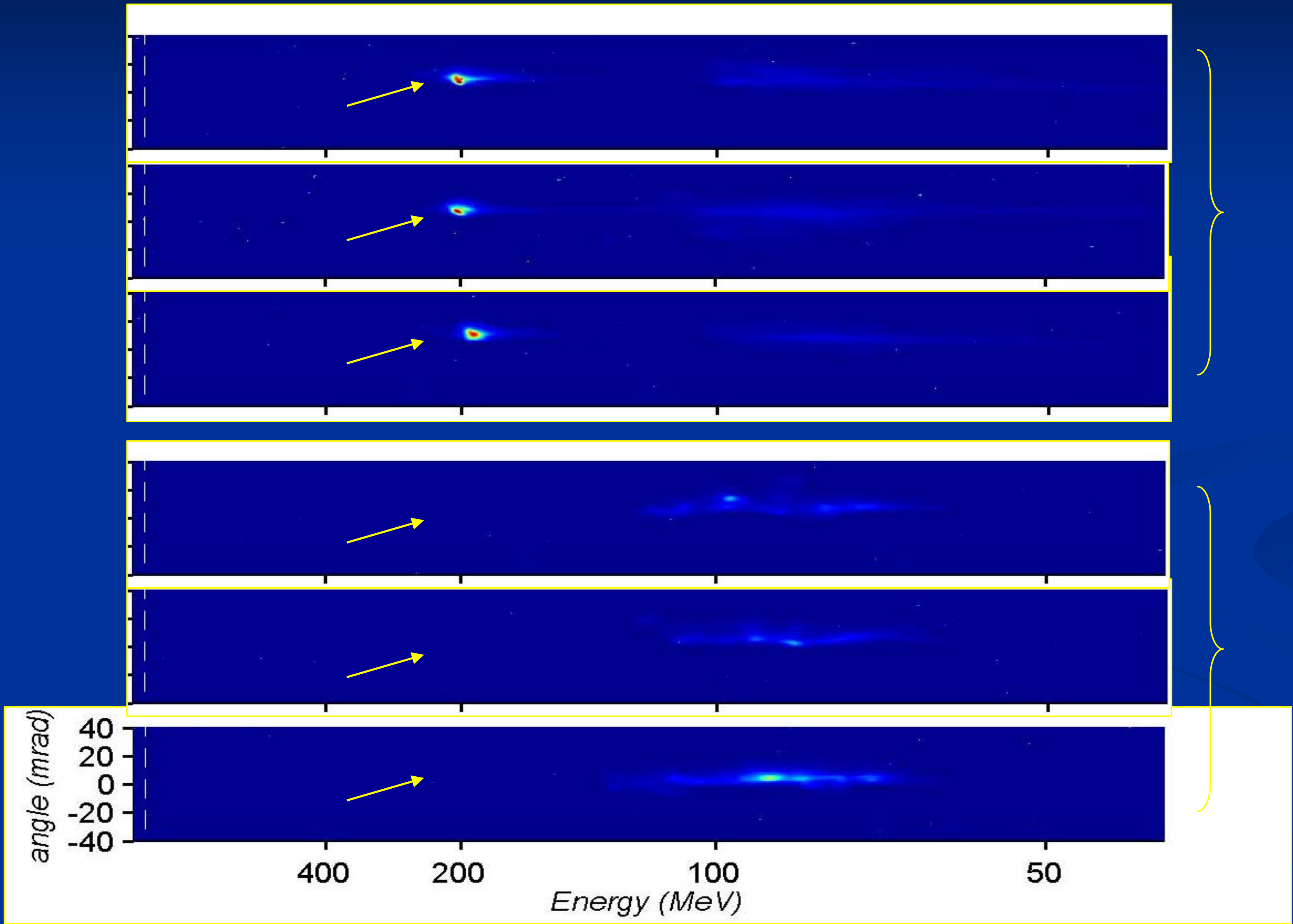
Optical injection by colliding pulses leads to stable monoenergetic beams



STATISTICS

Bunch charge= 15 +/- 5 pC
Peak energy= 118 +/- 7 MeV
ΔE= 13 +/- 2.5 MeV
ΔE/E= 11 %
Divergence= 5.7 +/- 2 mrad
Pointing stability= 2 mrad

Monoenergetic bunch comes from colliding pulses: polarization test



Parallel polarization

Crossed polarization

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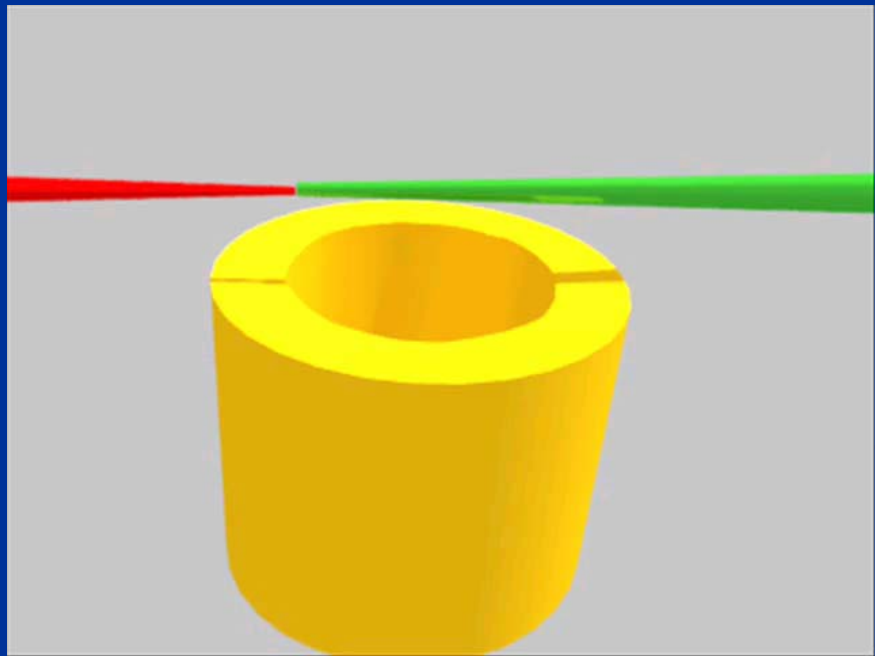
Controlling the bunch energy by controlling the acceleration length

By changing delay between pulses:
- Change collision point
- Change effective acceleration length
- Tune bunch energy

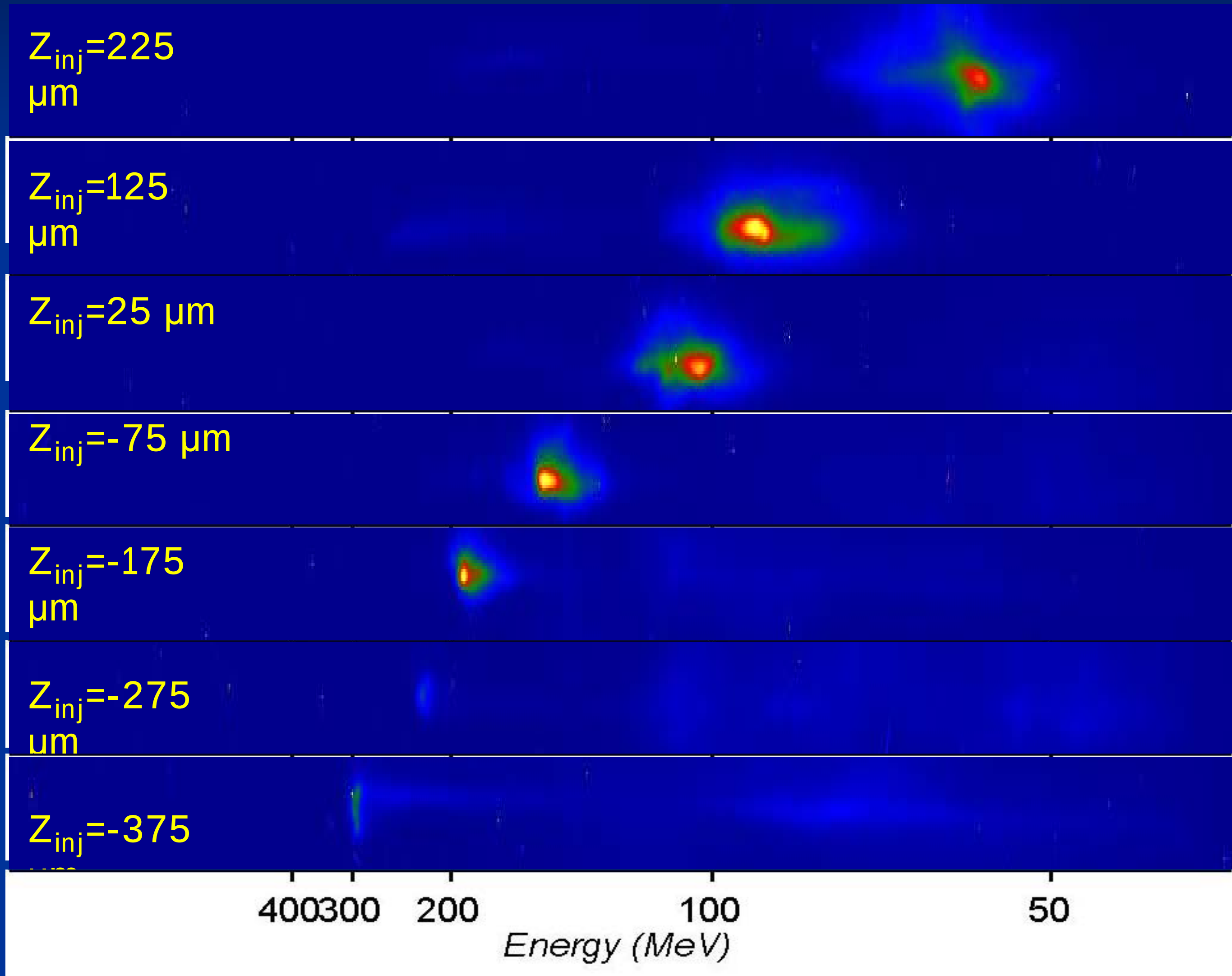
Pump beam

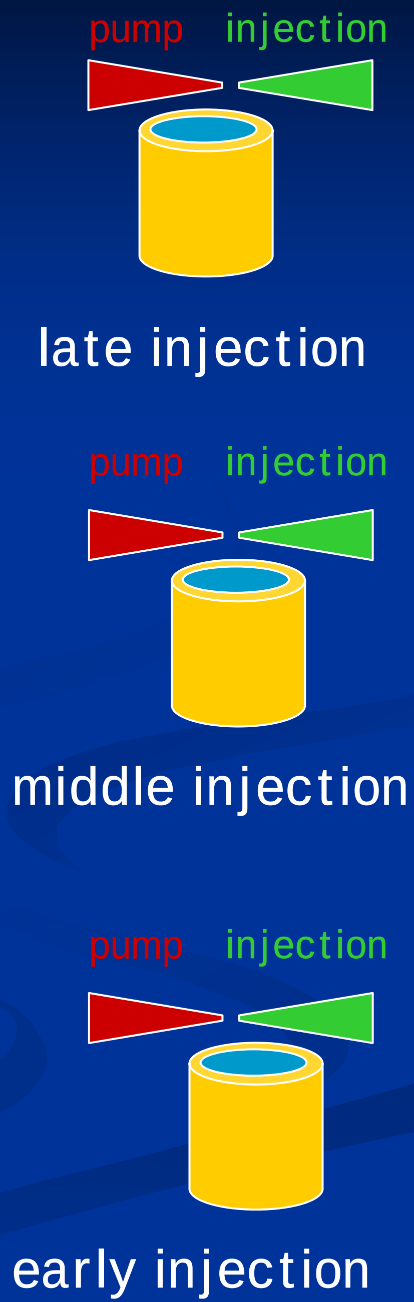


Injection beam

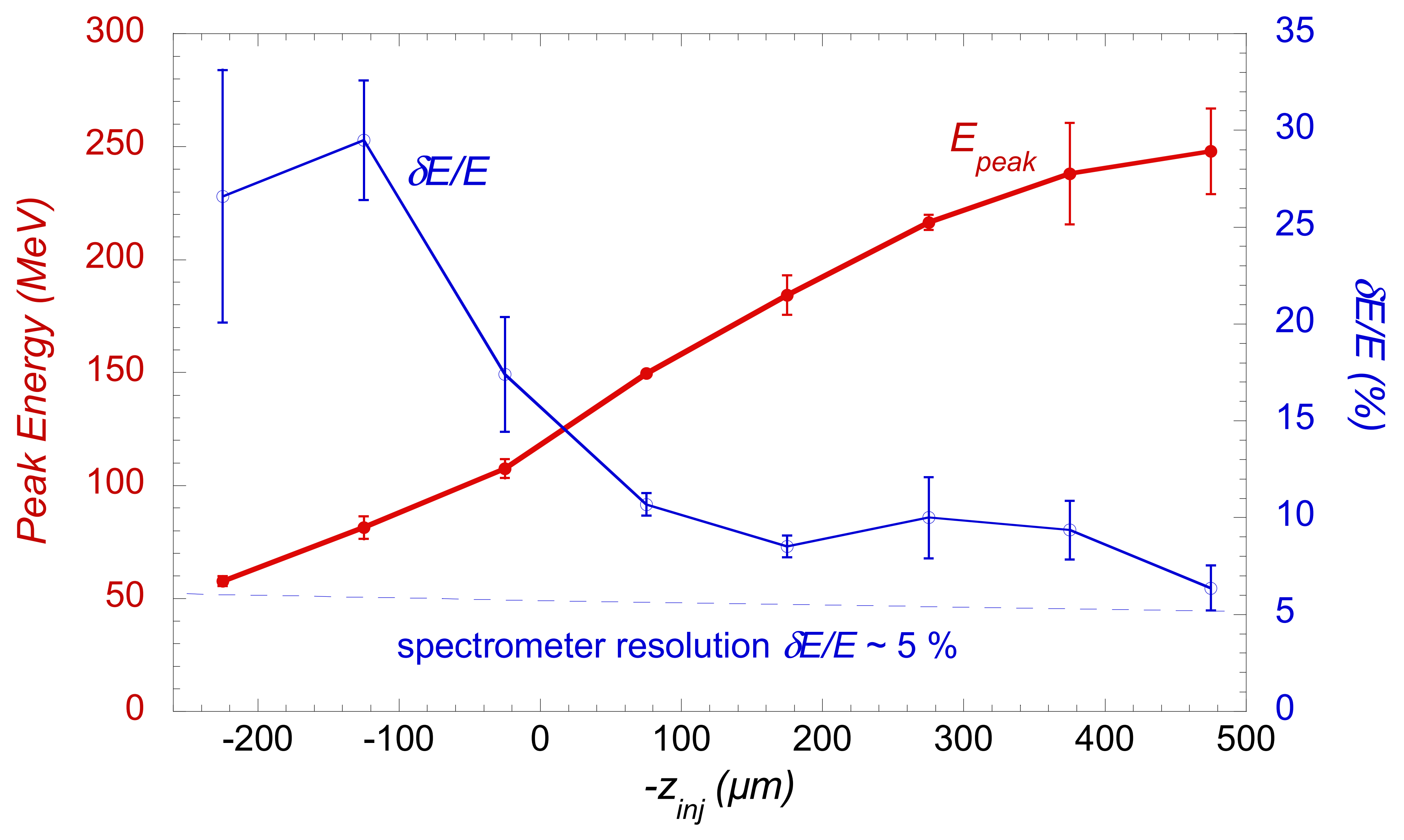
Gas jet

Tunable monoenergetic bunches





Tunable monoenergetic electrons bunches:



190 MeV gain in 700 µm: E=270 GV/m

Compare with $E_{max}=mc\omega_p/e=250$ GV/m at $n_e=7.5\times10^{18}$ cm^{-3}

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Conclusions / perspectives

SUMMARY

- Optical injection by colliding pulse: it works !
- Monoenergetic beams trapped in first bucket
- Enhances dramatically stability
- Energy is tunable: 20-300 MeV
- Charge up to 50 pC in monoenergetic bunch
- $\delta E/E$ down to 5 % (spectrometer resolution), δE ~ 10-20 MeV

PERSPECTIVES

- Combine with waveguide: tunable up to few GeV with $\delta E/E$ ~ 1 %
- Multi/single stage accelerators
- Stable source:

    extremely important

    accelerator development

    light source development

    Applications (material science, radiotherapy, chemistry etc…)

Parameter designs Laser Plasma Accelerators

ELI : > 100 GeV

$a_0=4$

P(PW)	τ (fs)	$n_e(cm^{-3})$	W_0 (μm)	L(m)	E(J)	Q(nC)	E(Gev)
0.12	30	2e18	15	0.009	3.6	1.3	**1.12**
1.2	100	2e17	47	0.28	120	4	**11.2**
12	300	2e16	150	9	3.6k	13	**112**
120	1000	2e15	470	280	120k	40	**1120**

Golp and UCLA Group

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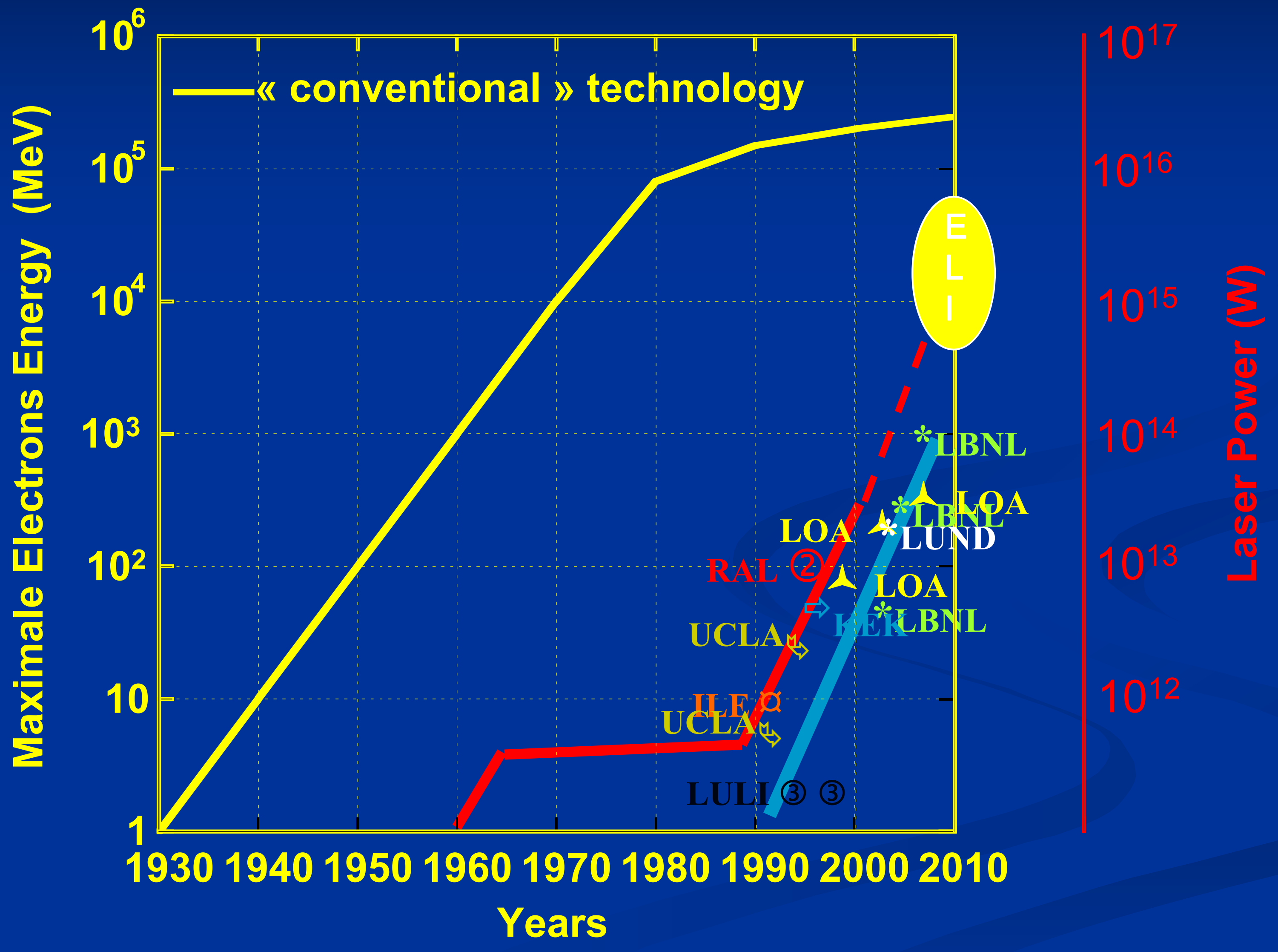
Electron beam energy and laser power evolution



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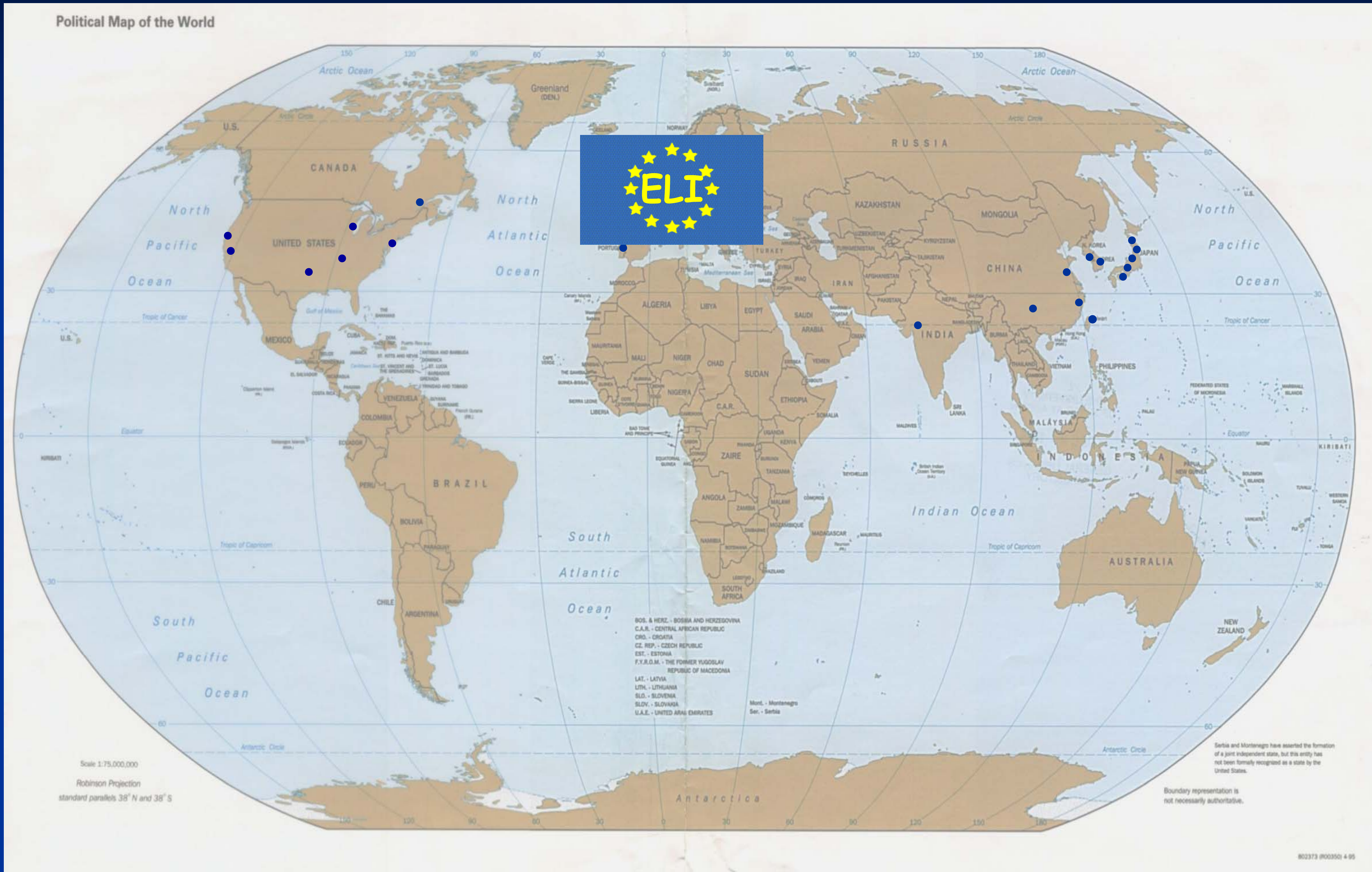
Towards an Integrated Scientific Project for European Researcher : ELI



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