GeV's Laser Plasma Accelerators Design Studies

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Summary

Part 1 : Laser plasma accelerator : motivation

Part 2 : Laser plasma accelerator as booster

Part 3 : Laser Plasma accelerator as injector : Production of monoenergetic electron beam

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

Part 5 : Conclusion and perspectives

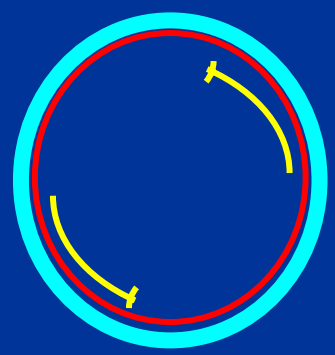
Classical accelerator limitations

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

→ Energy ↗ = Length ↗ = $$$ ↗

LEP at CERN

27 km



≈

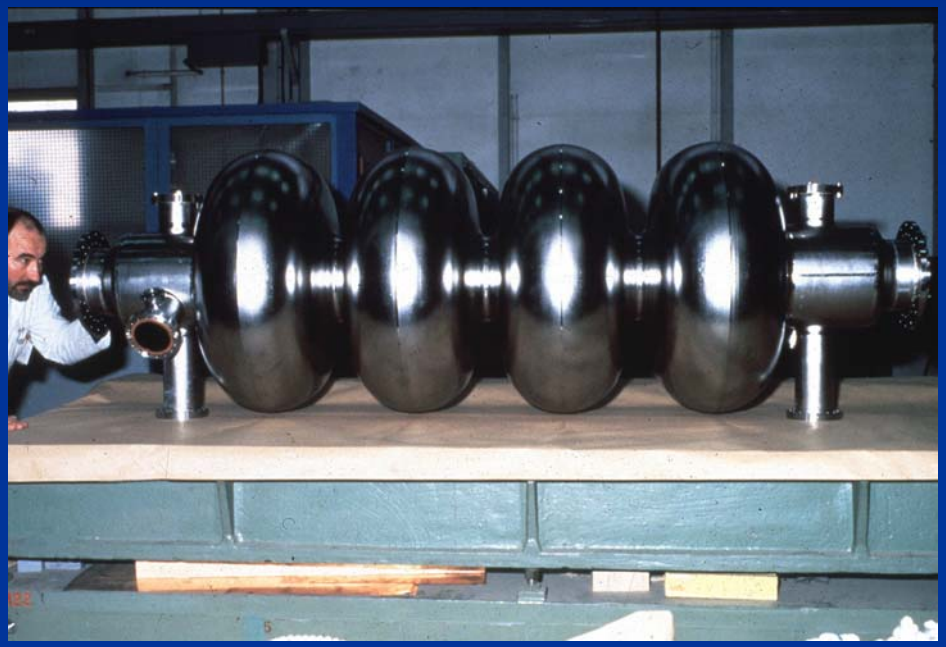
Circle road

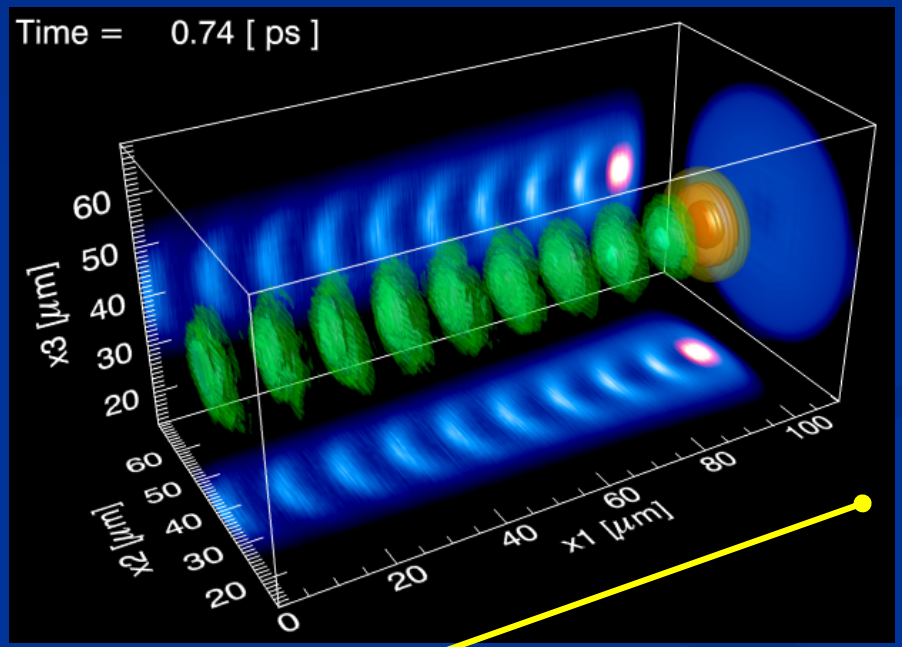
31 km

→ New medium : the plasma

Relativistics microelectronic devices

Courtesy of W. Mori & L. da Silva





1 m

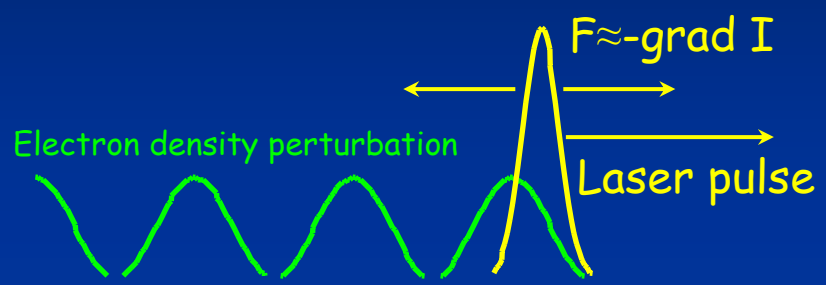
RF cavity

100 μm

Plasma cavity

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 ?

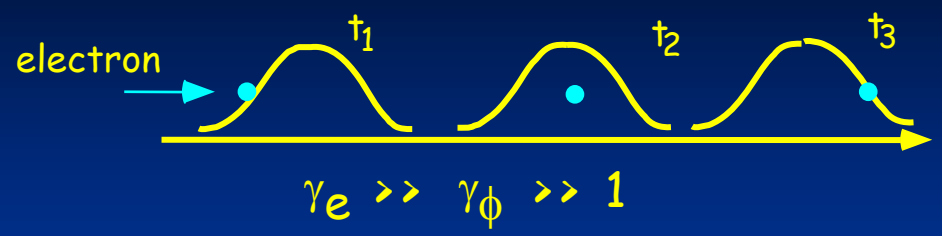
$$E_z \sim \sqrt{n_e}$$

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}

Tajima and Dawson, PRL (1979)

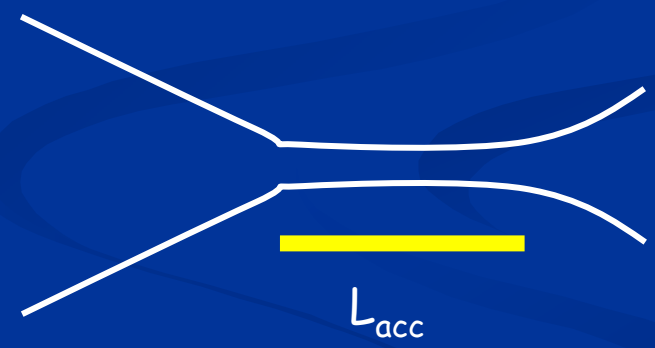
Interaction and dephasing lenghts



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

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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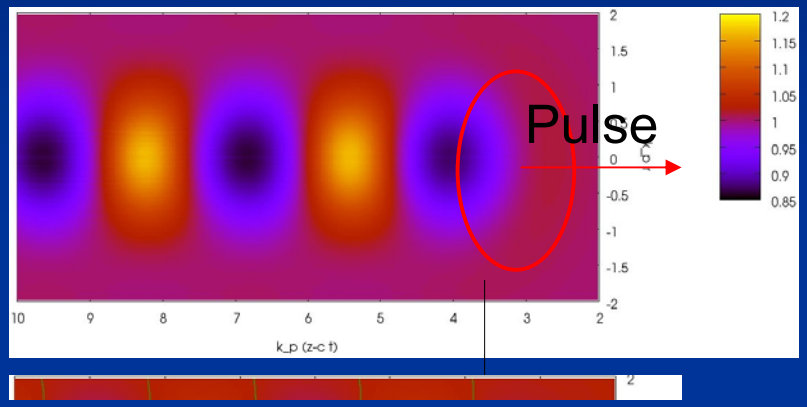
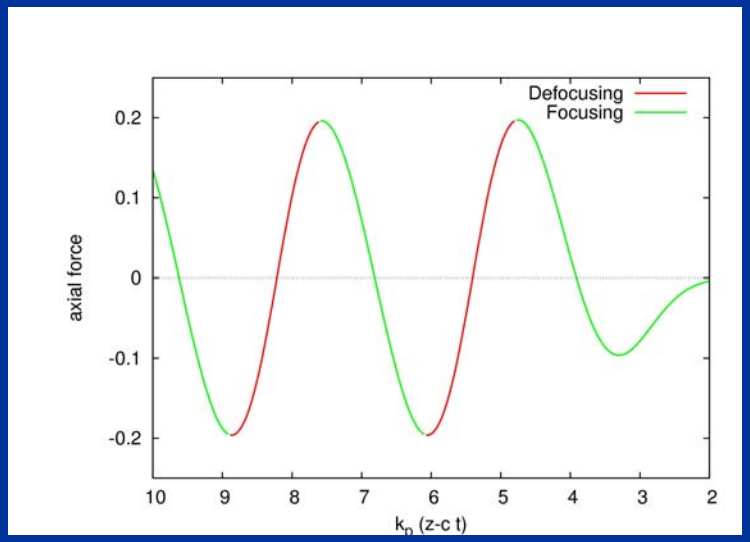
Accelerating & focusing fields in Linear RPW

- Small Laser amplitude a_0=0.5
- Homogeneous plasma

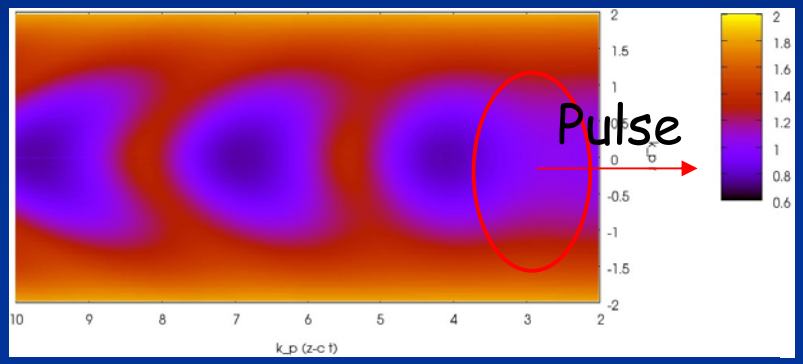


Electron density

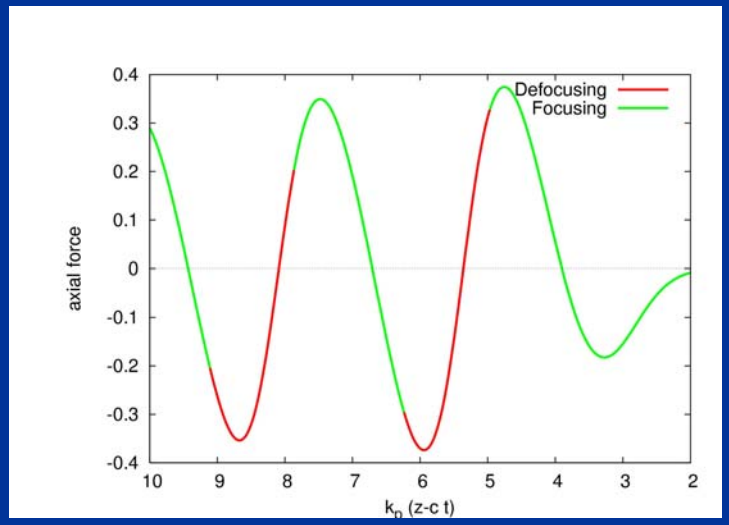


Accelerating & focusing fields in plasma channel

- Small Laser amplitude a_0=0.5
- Parabolic plasma channel



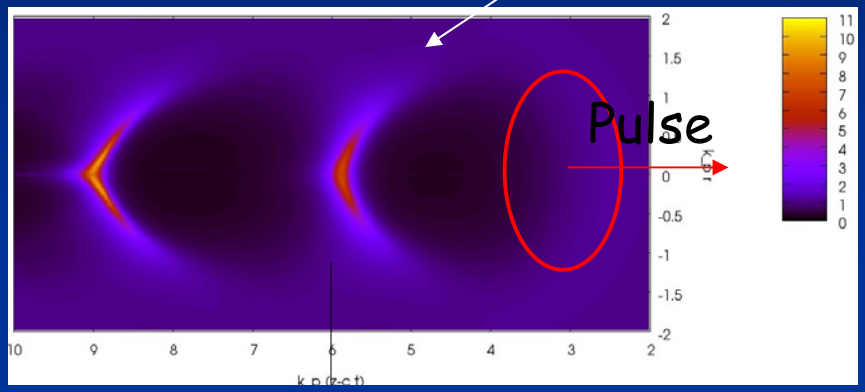
Electron density



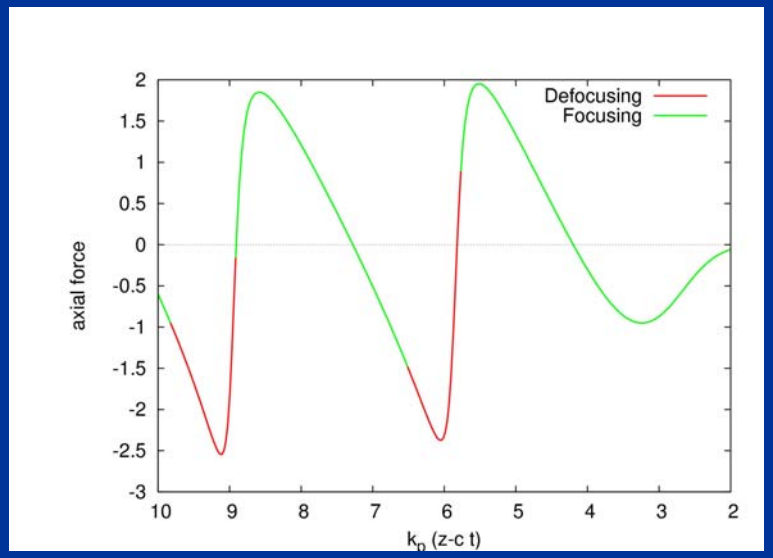
Accelerating & focusing fields in NL RPW

- Large Laser amplitude a_0=2
- Homogeneous plasma

relativistic shift of ω_p

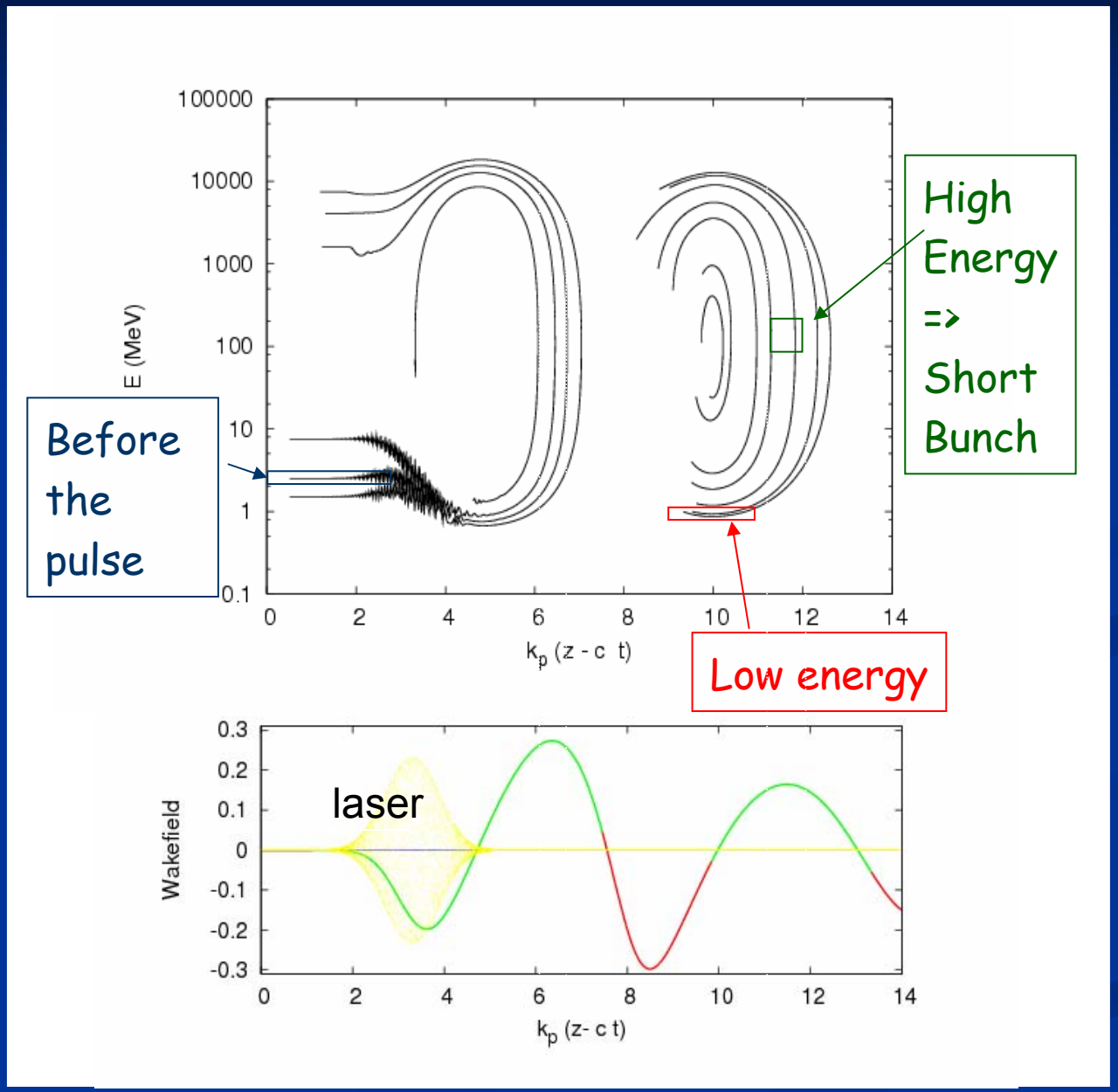


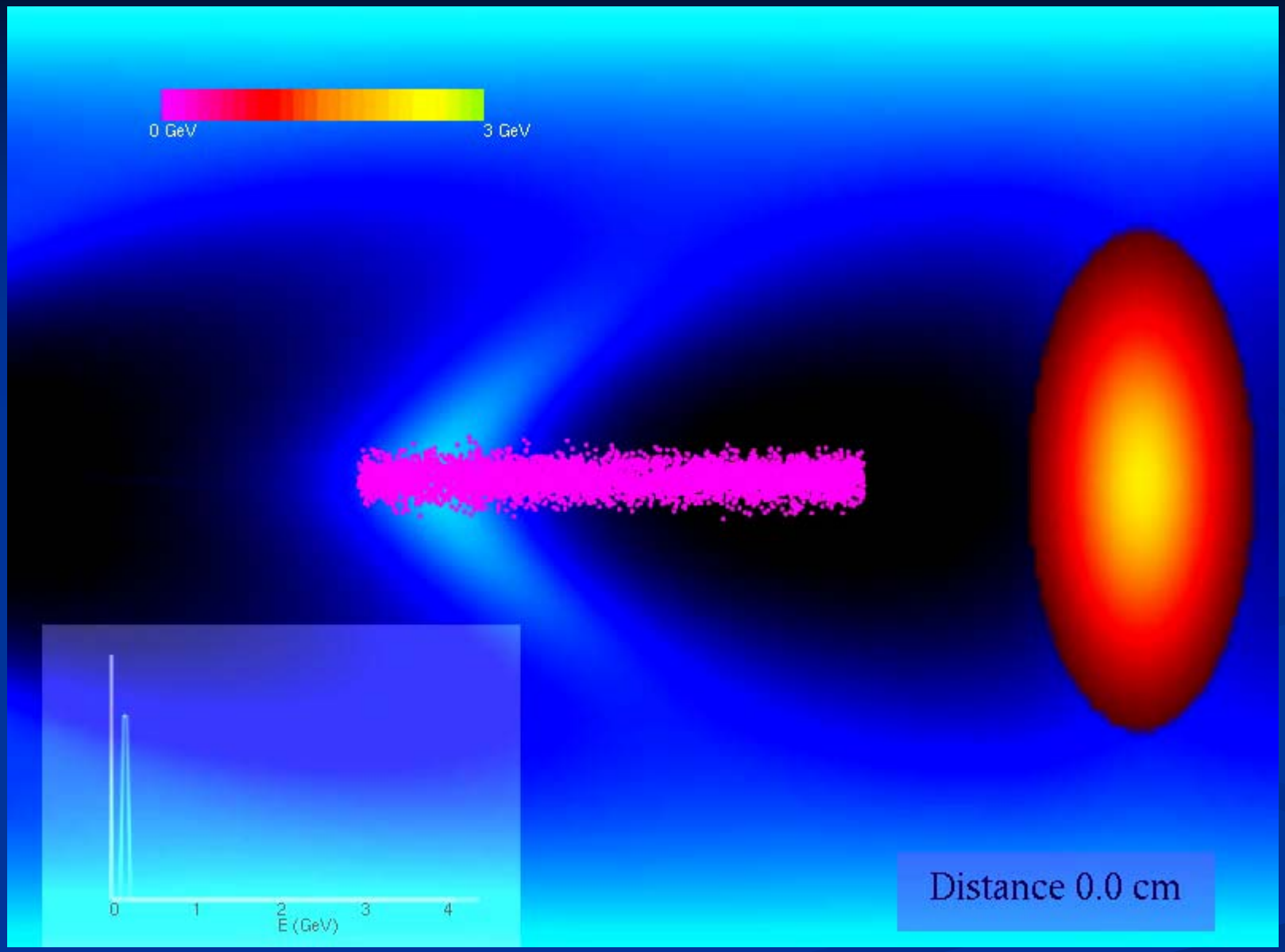
Electron density



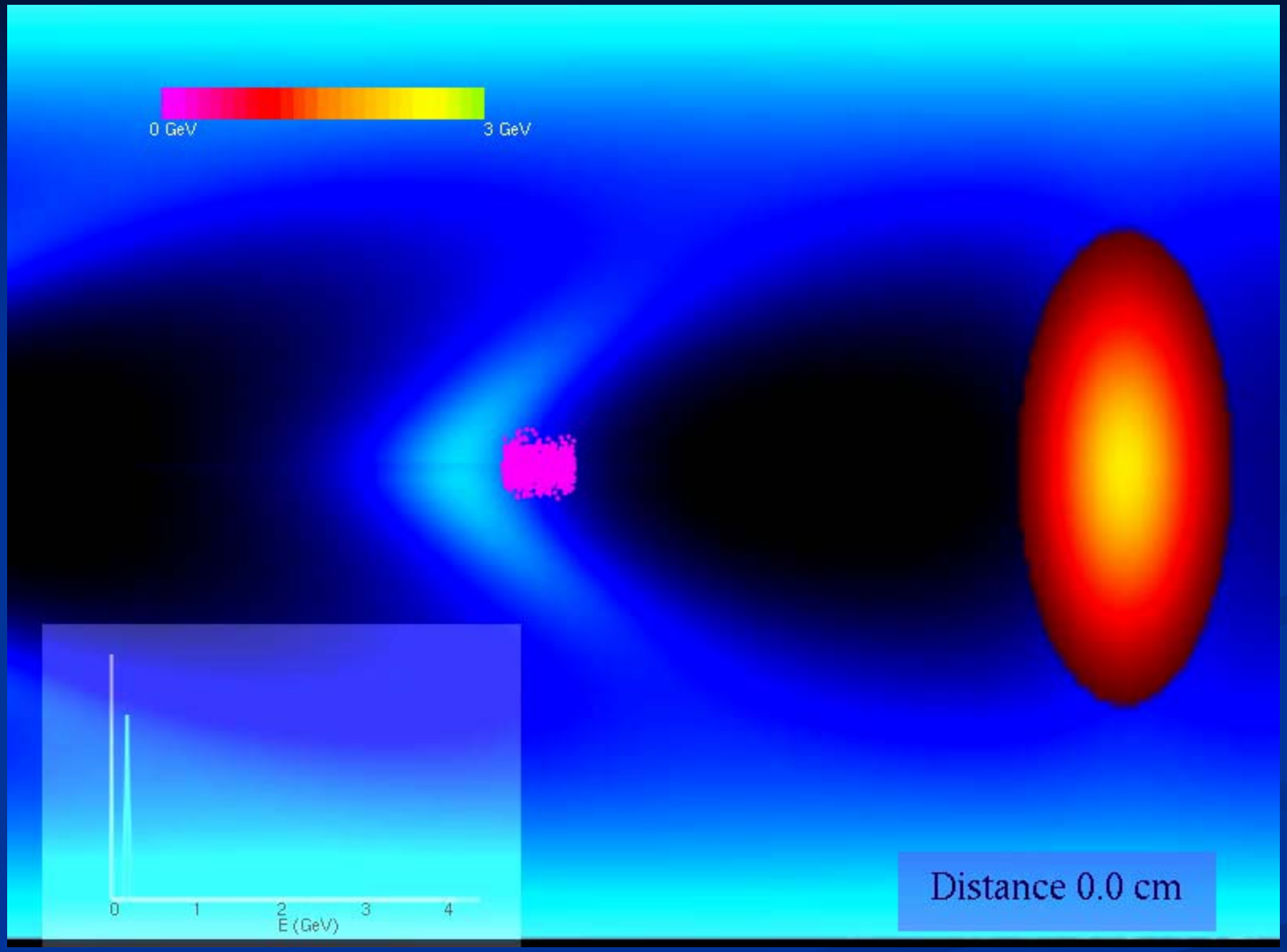
Three Injection schemes

Low energy =>
Low charge





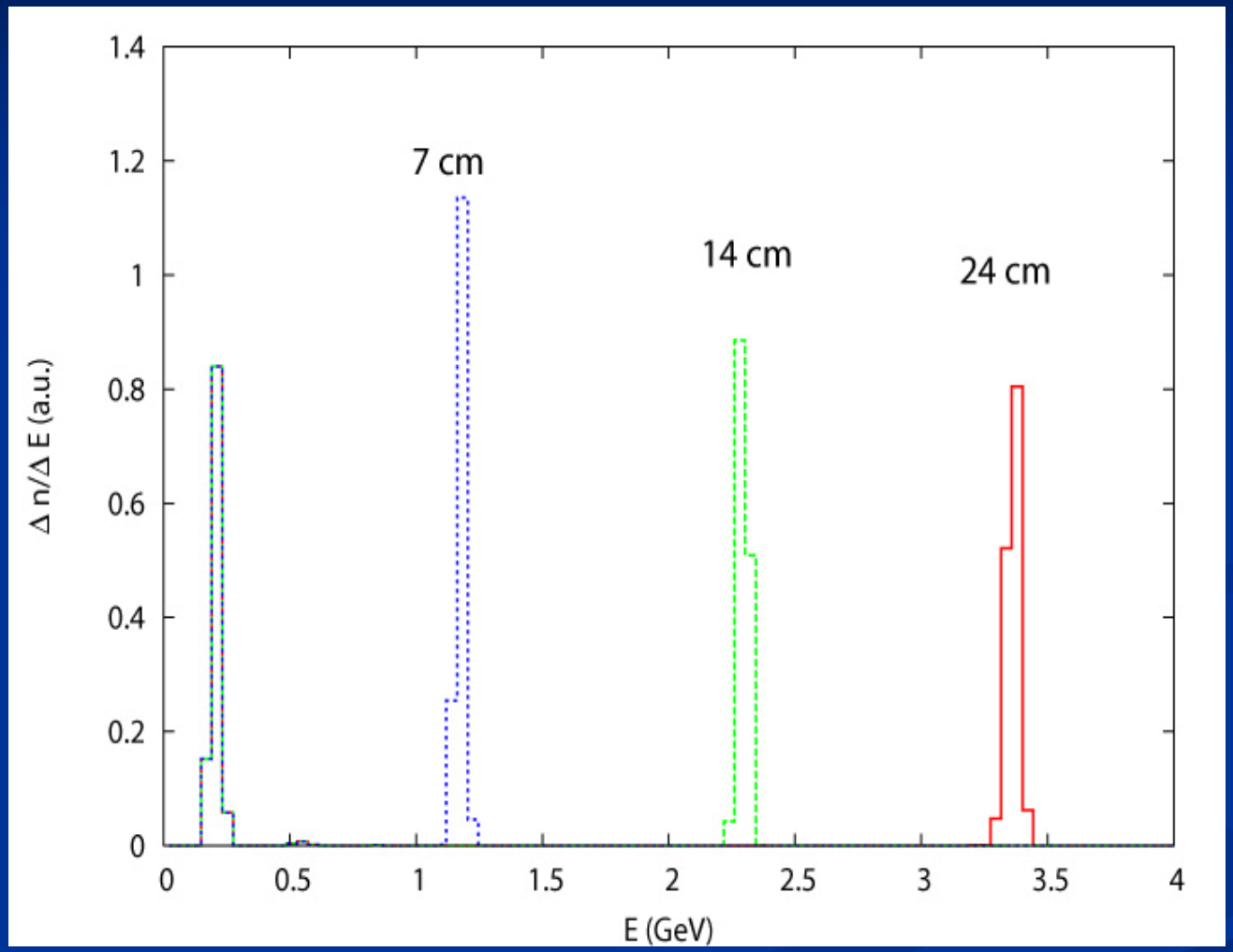
τ_{bunch} = 200 fs



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

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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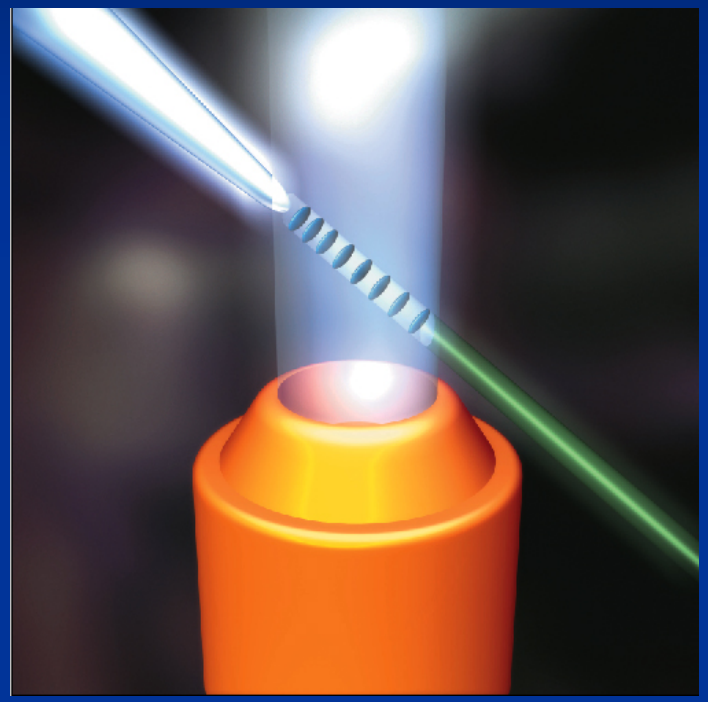
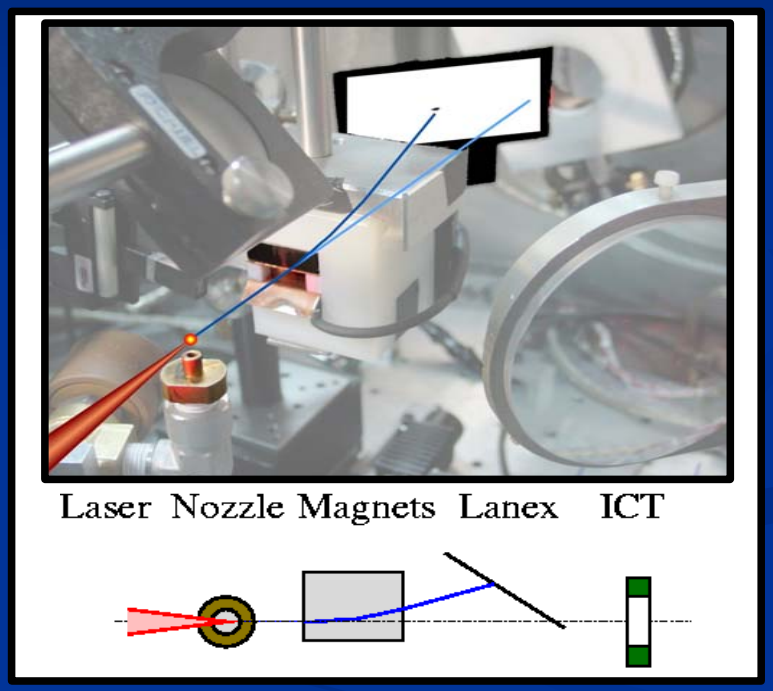
Laser plasma injector

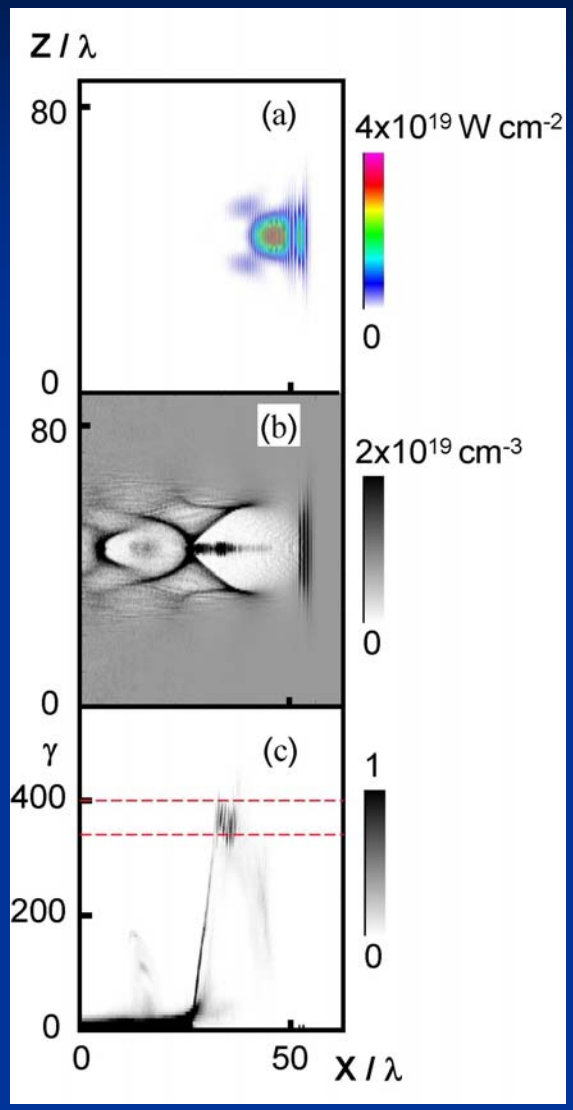


Scheme of principle

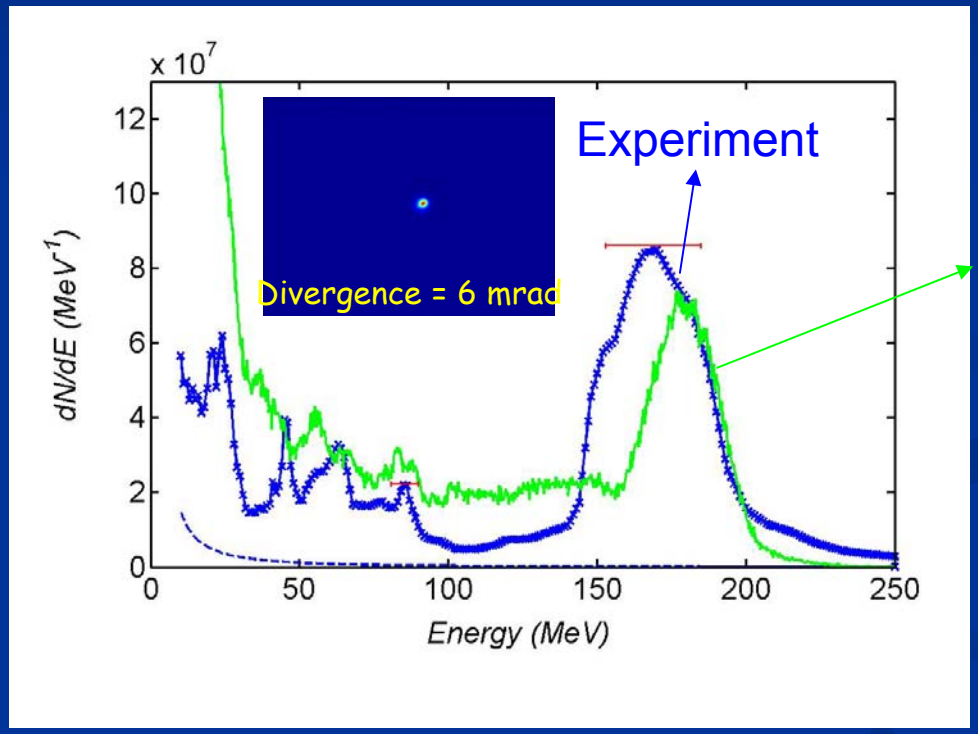


Experimental set up

Energy distribution improvements: The Bubble regime



Charge in the peak : 200-300 pC



At LOA
J. Faure et al. Nature (2004)

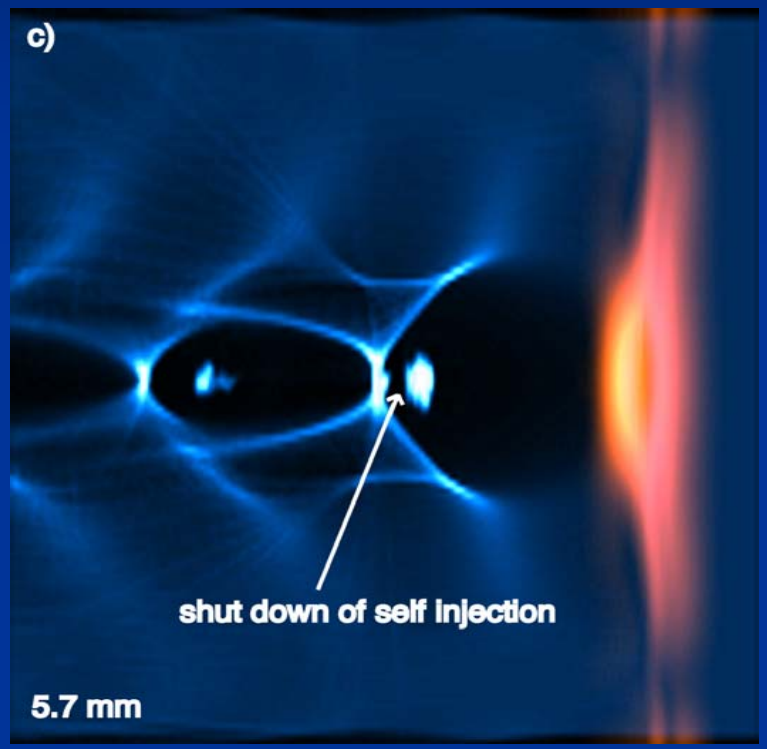
Quasi-monoenergetic beams reported in the litterature

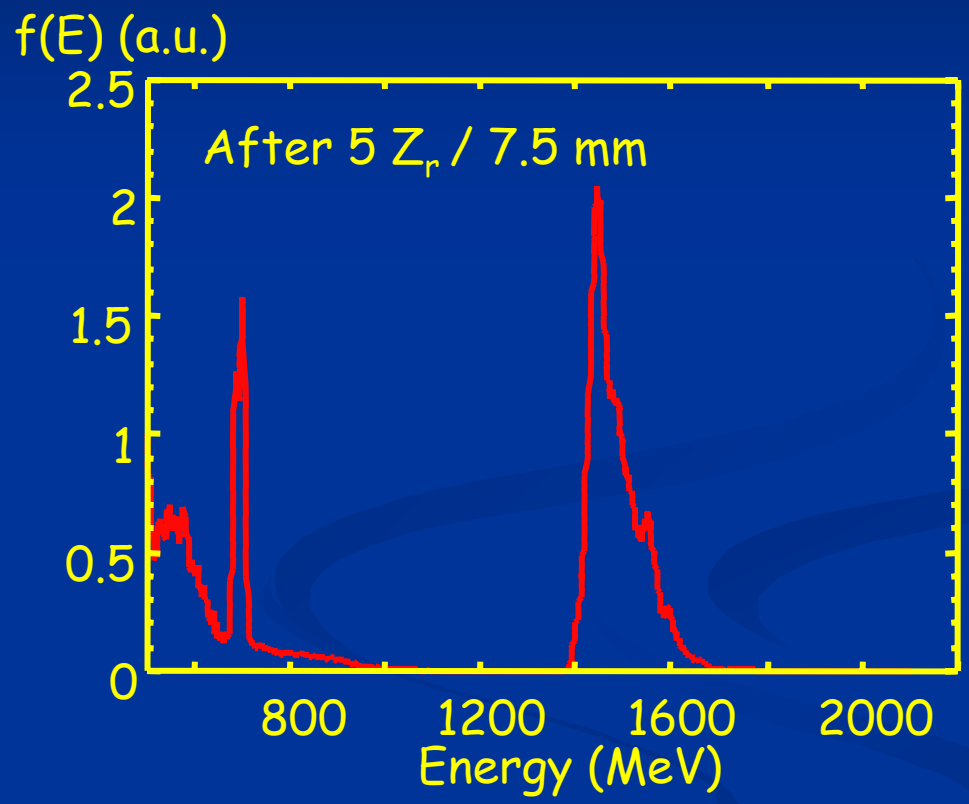
Name	Article	Lab	Energy [MeV]	dE/E [%]	Charge [pC]	Ne [x10^{18}/cm^3]	Intensity [x10^{18} W/cm^2]	τ_L/T_p	Remark
Mangles	Nature (2004)	RAL	73	6	22	20	2,5	**1,6**	
Geddes	Nature (2004)	L'OASIS	86	2	320	19	11	**2,2**	Channel
Faure	Nature (2004)	LOA	170	25	500	6	3	**0,7**	
Hidding	PRL (2006)	JETI	47	9	0,32	40	50	**4,6**	
Hsieh	PRL (2006)	IAMS	55		336	40		**2,6**	
Hosokai	PRE (2006)	U. Tokyo	11,5	10	10	80	22	**3,0**	Preplasma
Miura	APL (2005)	AIST	7	20	432E-6	130	5	**5,1**	
Hafz	PRE (2006)	KERI	4,3	93	200	28	1	**33,4**	
Mori	ArXiv (2006)	JAERI	20	24	0,8	50	0,9	**4,5**	
Mangles	PRL (2006)	Lund LC	150	20		20	5	**1,4**	

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

Laser plasma injector : GeV electron beams

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





Courtesy of UCLA& Golp groups

Laser plasma injector :

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

+ simple device

+ 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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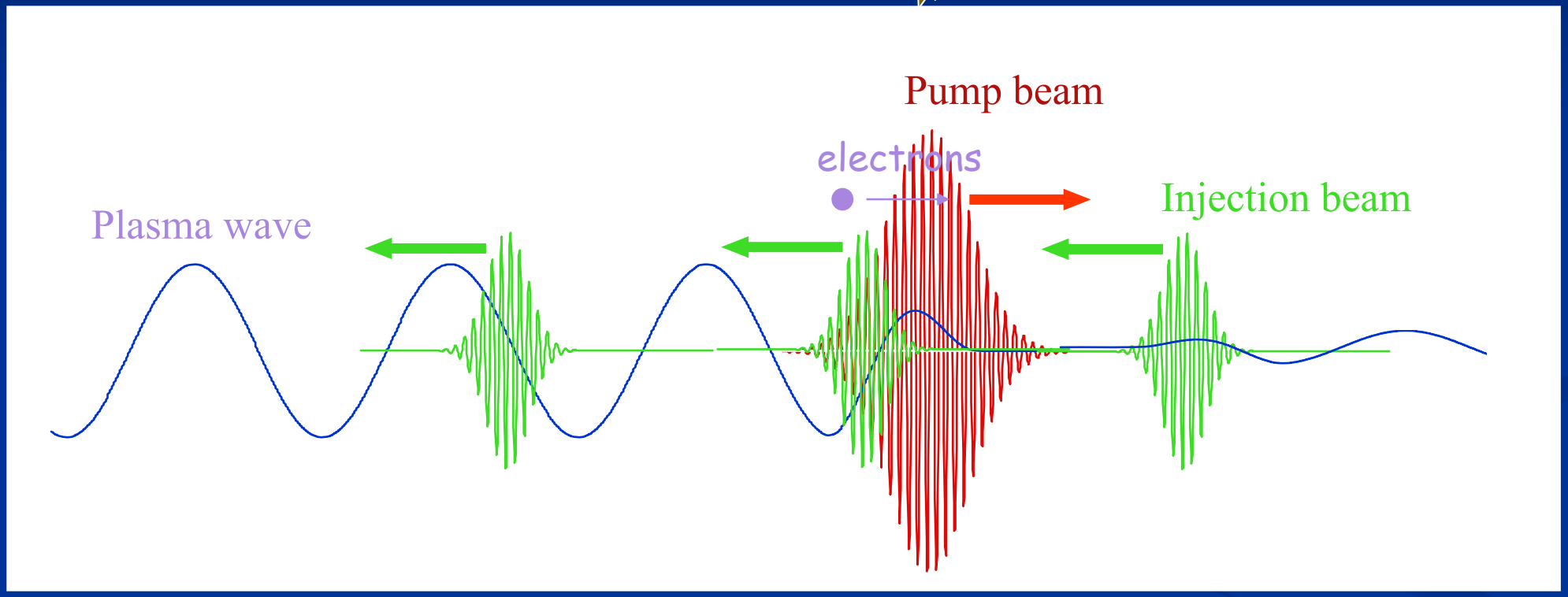
Controlling the injection

Counter-propagating geometry:



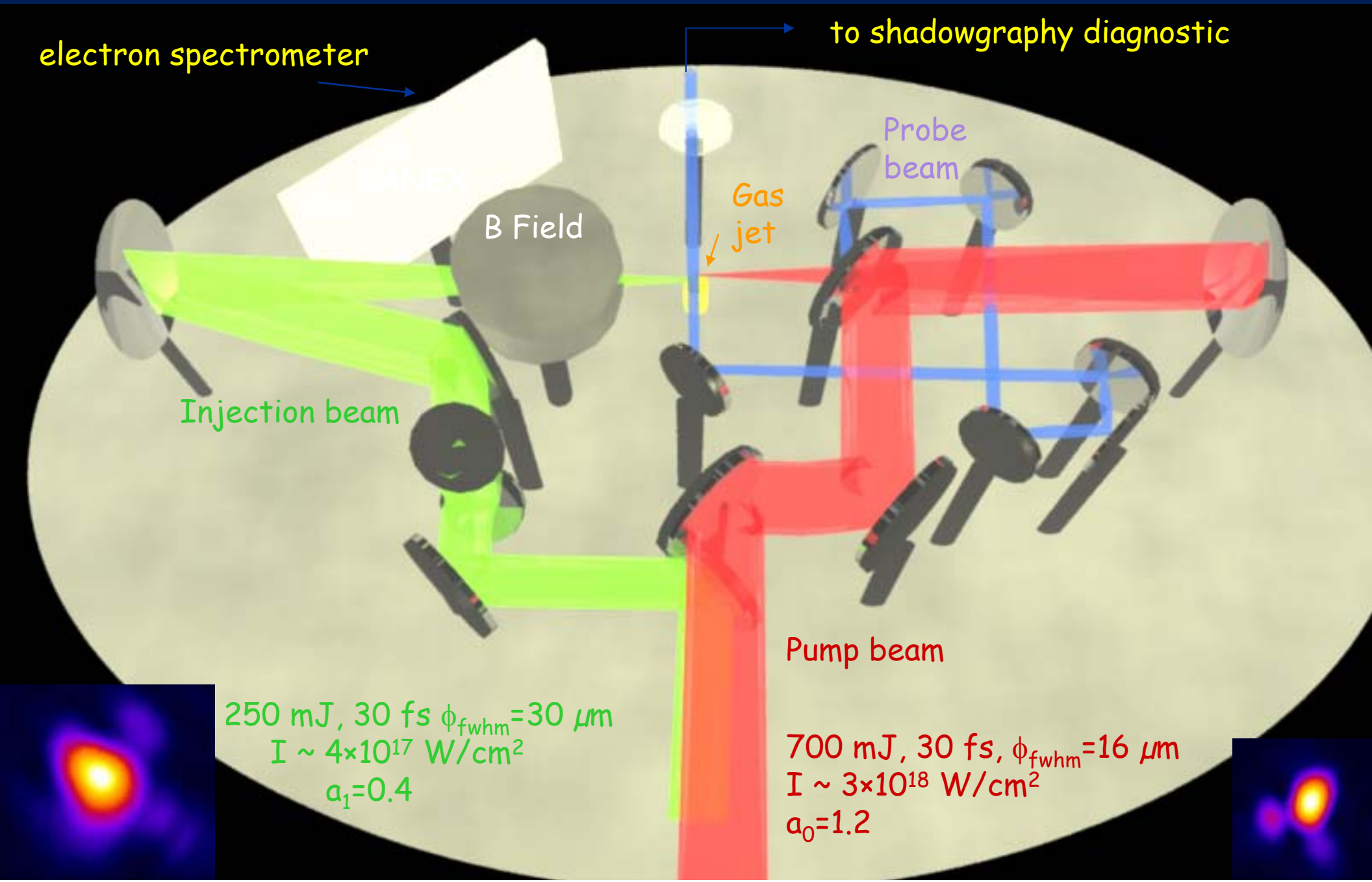
Ponderomotive force of beatwave: $F_p \sim 2a_0a_1/\lambda_0$ (a_0 et a_1 can be "weak")

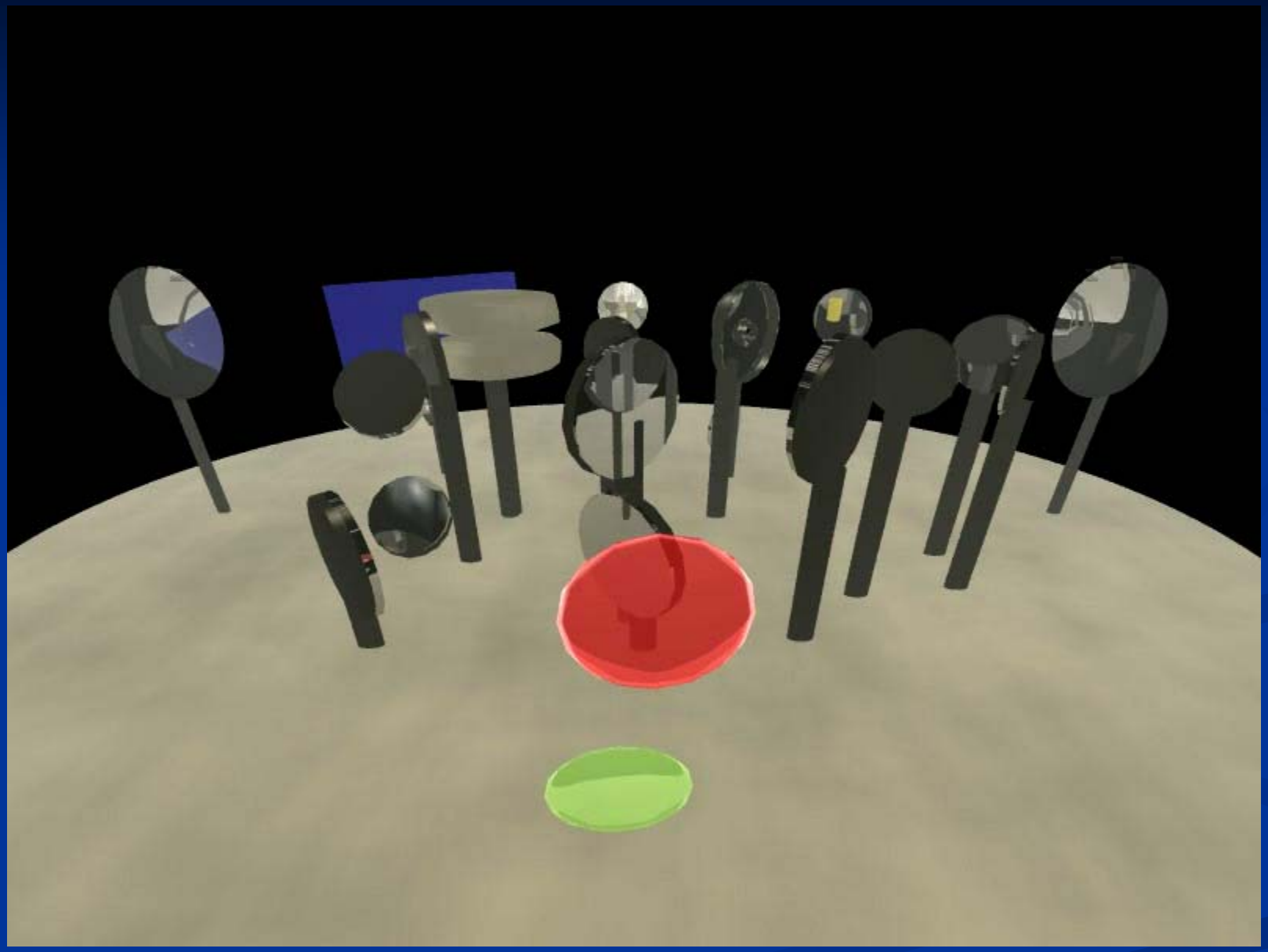
Boost electrons locally and injects them:

INJECTION IS LOCAL IN FIRST BUCKET

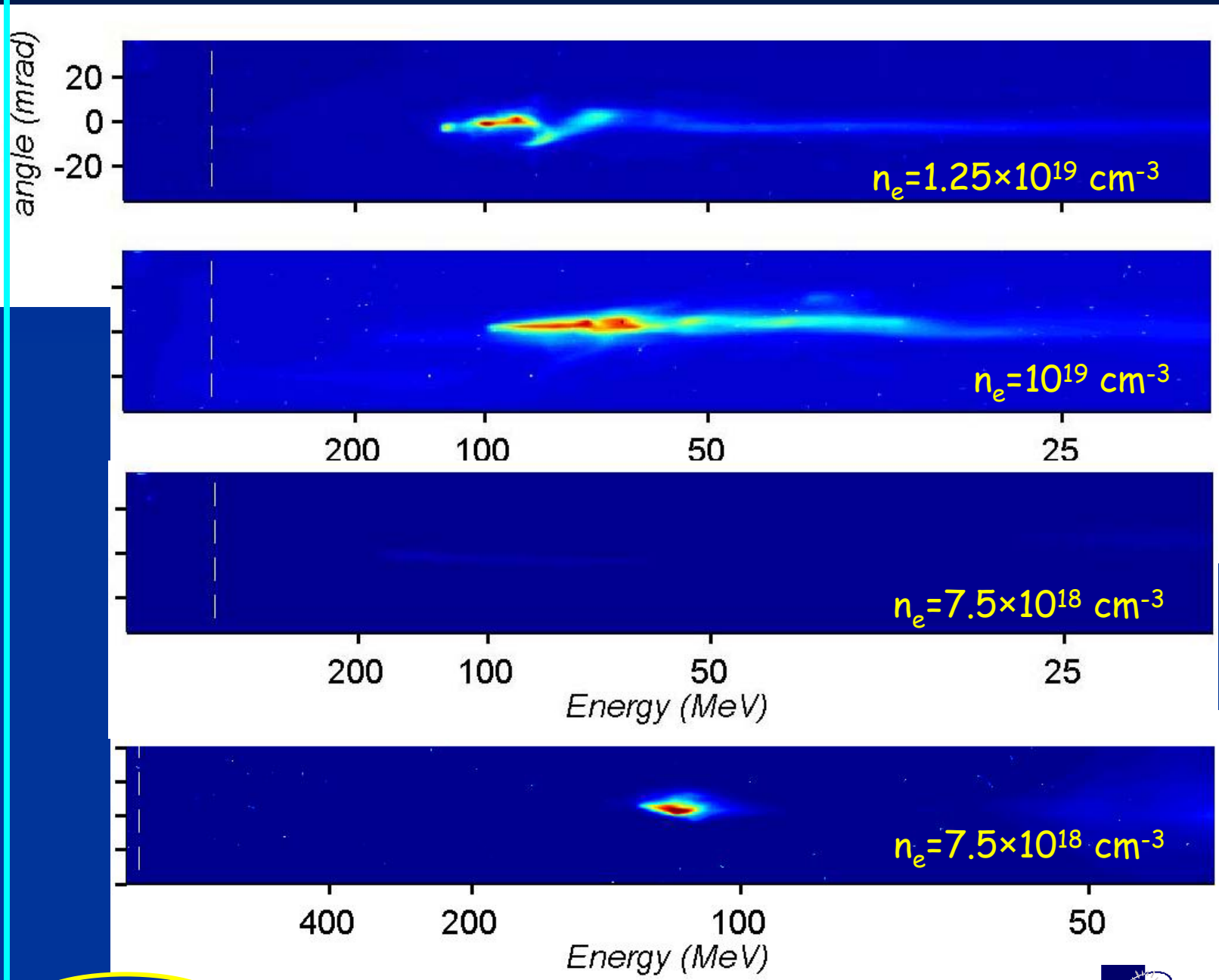
E. Esarey et al, PRL 79, 2682 (1997), G. Fubiani et al. (PRE 2004)

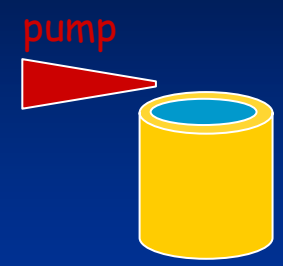
Experimental set-up





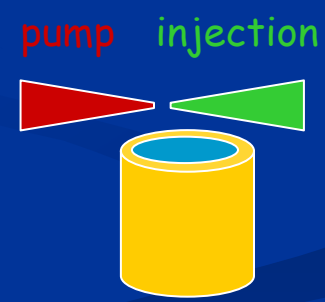
From self-injection to external injection





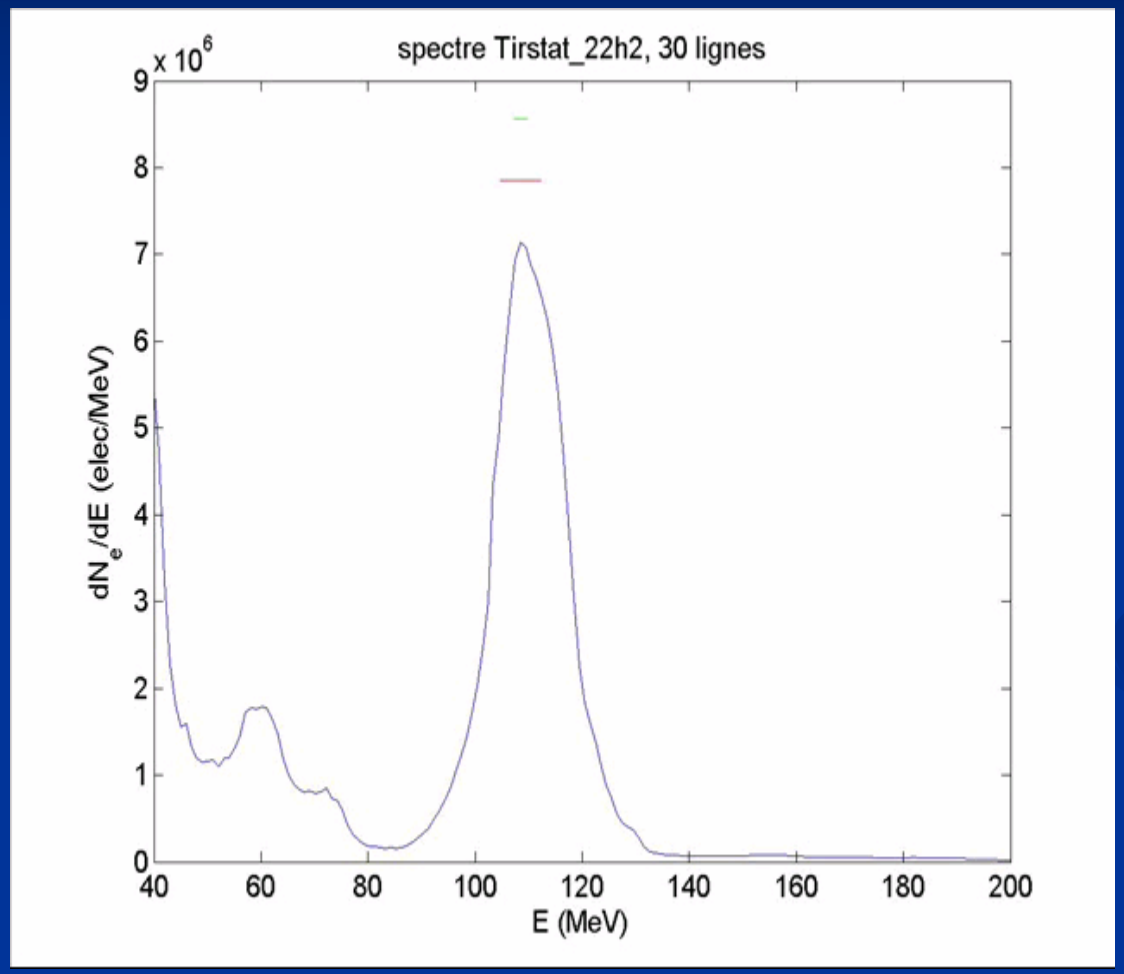
Single beam

Self-injection Threshold



2 beams

Optical injection by colliding pulses leads to stable monoenergetic beams

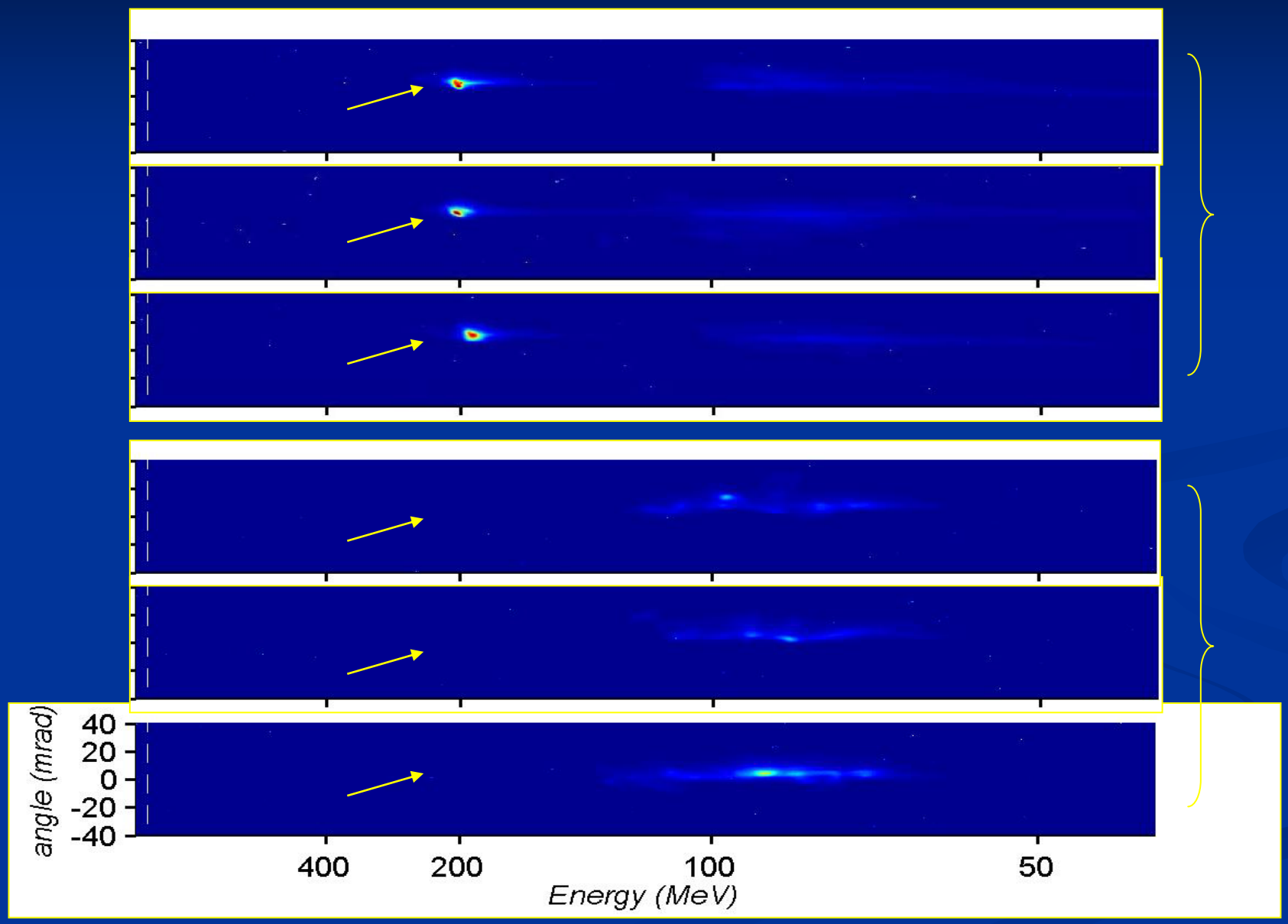


STATISTICS
value and standard deviation

Bunch charge= 19pC, σ = 6.8 pC
Peak energy= 117MeV, σ = 7 MeV
ΔE= 13MeV, σ = 2.5 MeV
ΔE/E= 11 %, σ = 2 %
Divergence= 5.7 mrad
Pointing stability= 1.8 mrad

*Charge measurements with absolute calibration of Lanex film (ICT gave a factor of 8 higher charge)

Monoenergetic bunch comes from colliding pulses: polarization test



Parallel polarization

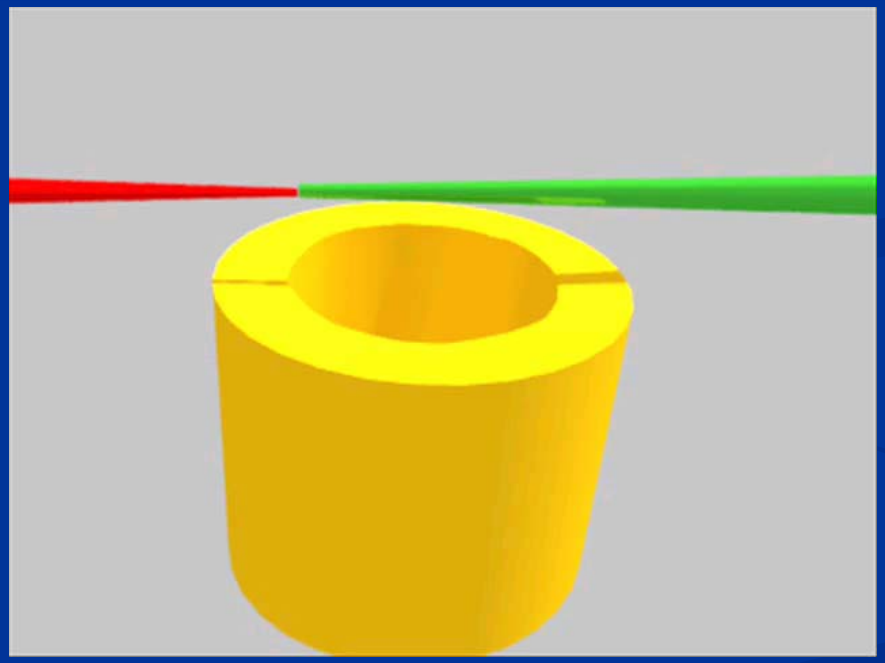
Crossed polarization

Controlling the bunch energy by controlling the acceleration length

By changing delay between pulses:

- Change collision point
- Change effective acceleration length
- Tune bunch energy

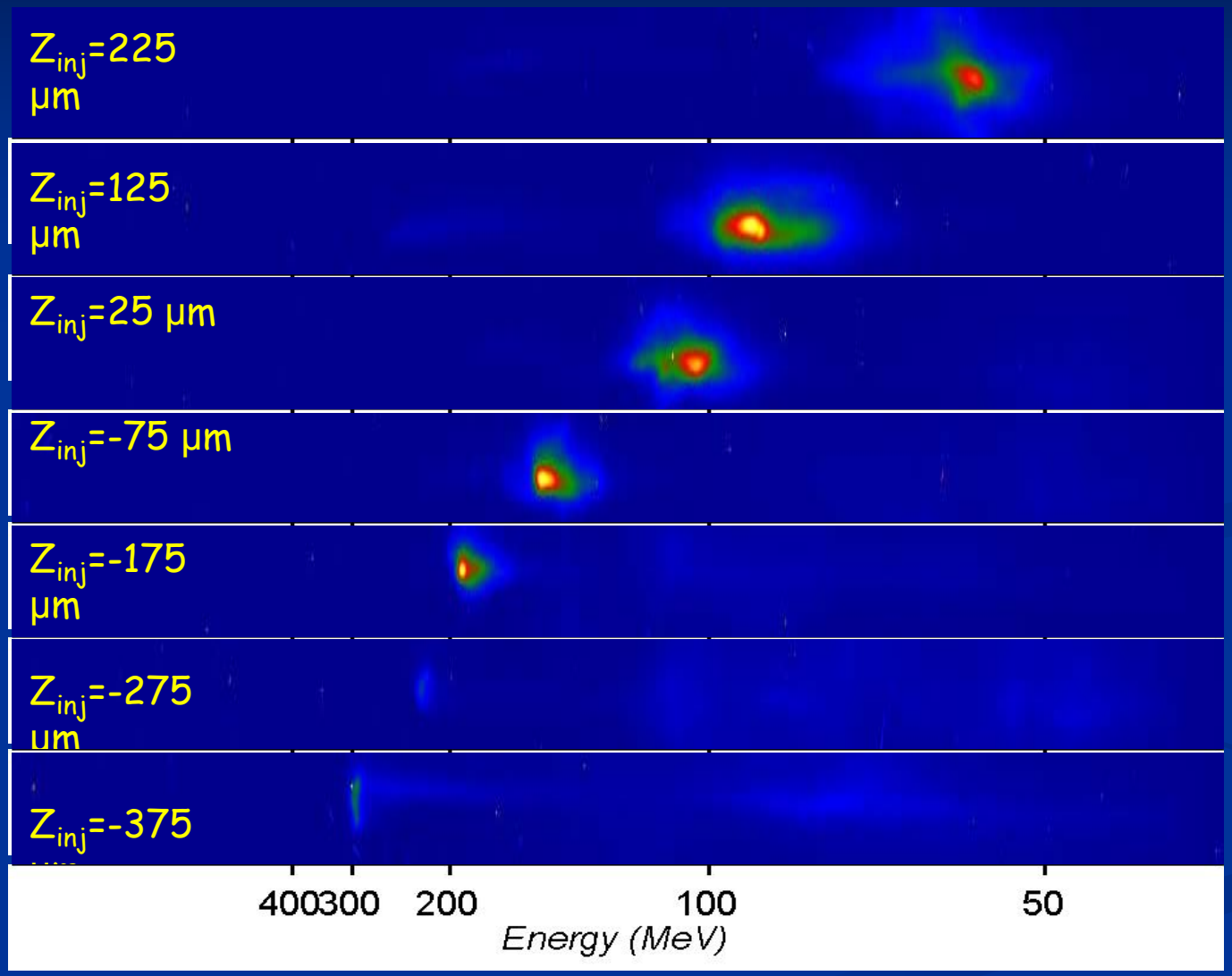
Pump beam

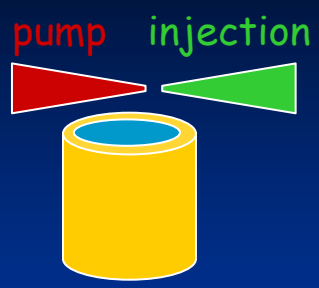


Injection beam

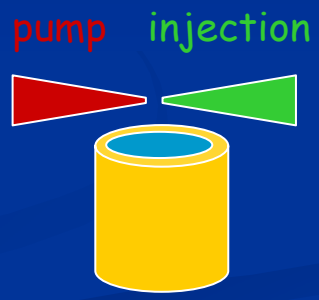
Gas jet

Tunable monoenergetic bunches

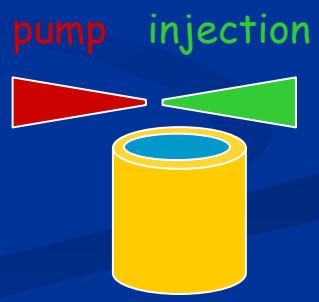




late injection

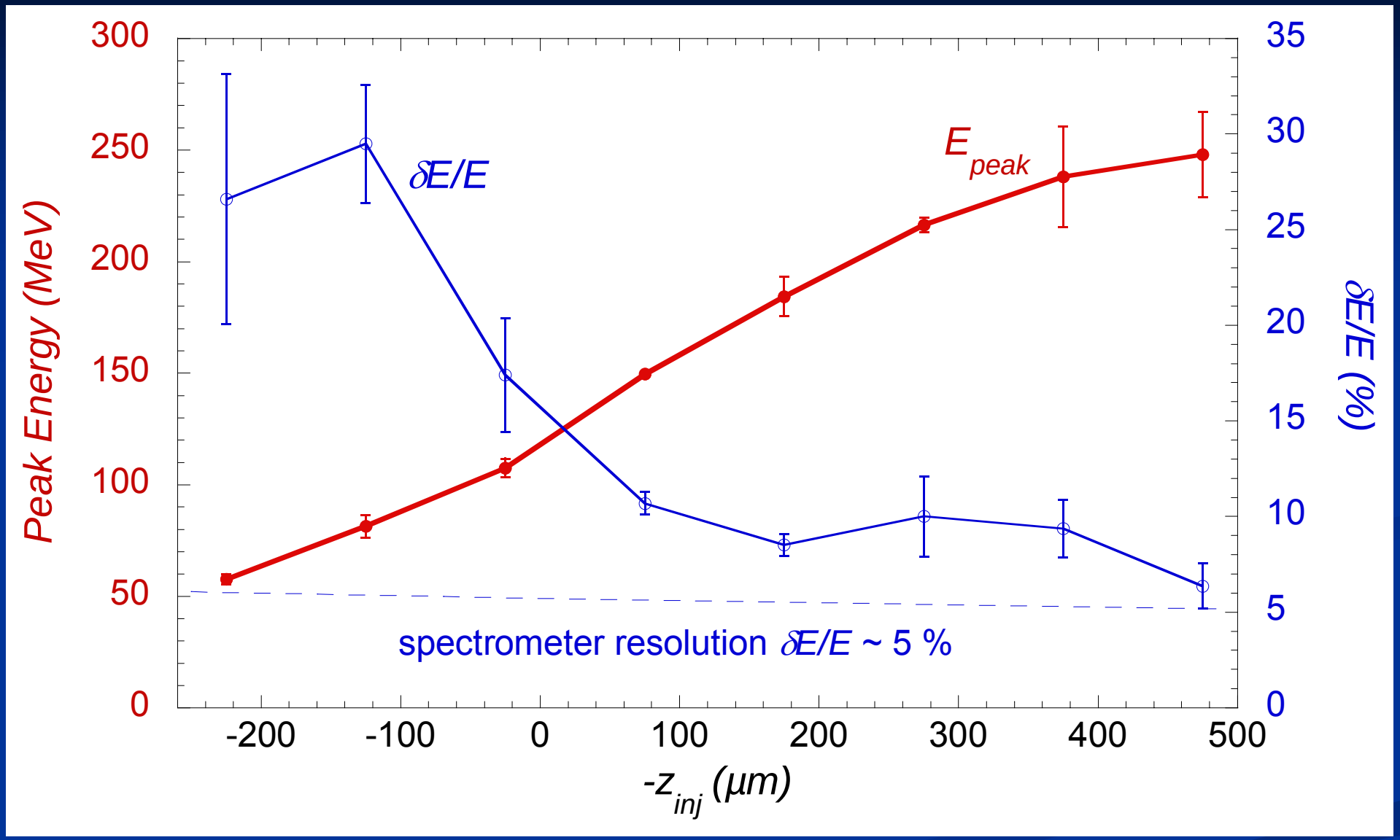


middle injection



early injection

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}

Conclusions / perspectives

SUMMARY

- Optical injection by colliding pulse: it works !
- Monoenergetic beams trapped in first bucket
- Enhances dramatically stability
- Energy is tunable: 15-300 MeV
- Charge up to 80 pC in monoenergetic bunch
- $\delta E/E$ down to 5 % (spectrometer resolution), δE ~ 10-20 MeV
- Duration shorter than 10 fs.

PERSPECTIVES

- Combine with waveguide: tunable up to few GeV's with $\delta E/E$ ~ 1 %
- Design future accelerators
- Model the problem for further optimization: higher charge
- Stable source:

  extremely important

  - accelerator development (laser based accelerator design)
  - light source development for XFEL
  - applications (chemistry, radiotherapy, material science)

A revolution is coming…one of the most evolving field in Science, a wonderful tool for academic formation

Thanks for your attention !