Laser-plasma based electron accelerator

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Collaborators

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Simulations / theory

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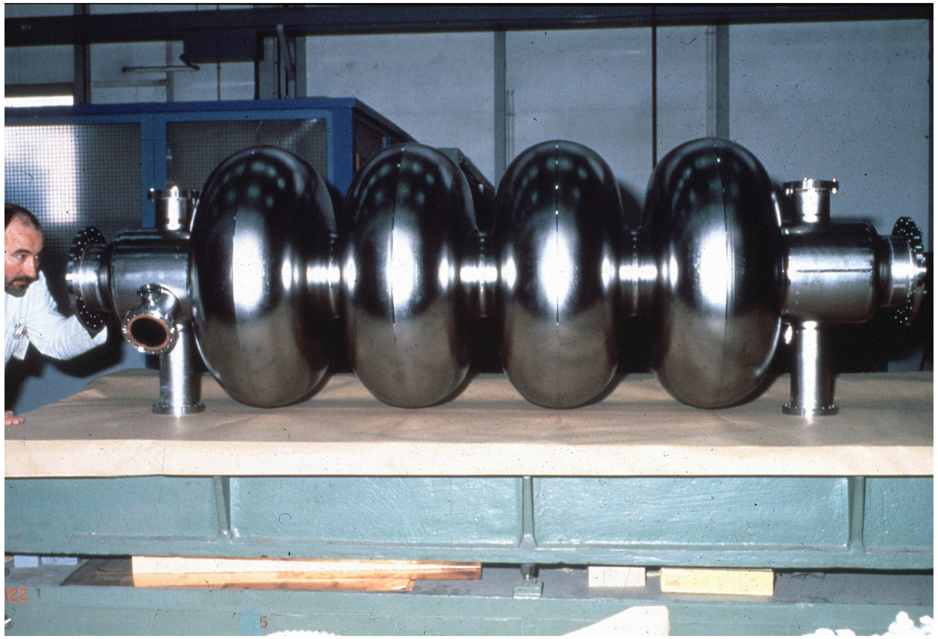
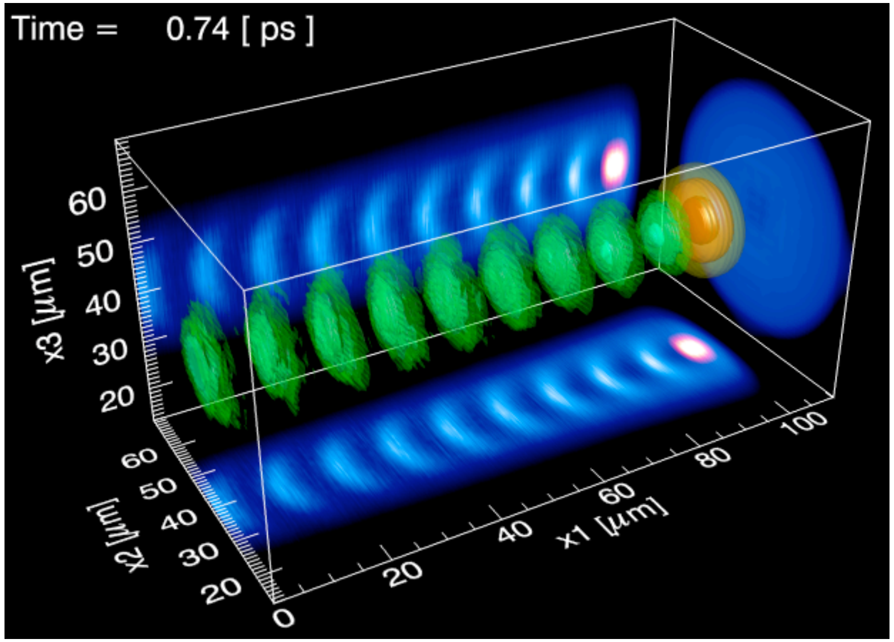
Main motivation: compactness

RF cavity: 1 m



E_z = 10-100 MV/m
Physical limit: breakdown

Plasma wave: 100 µm

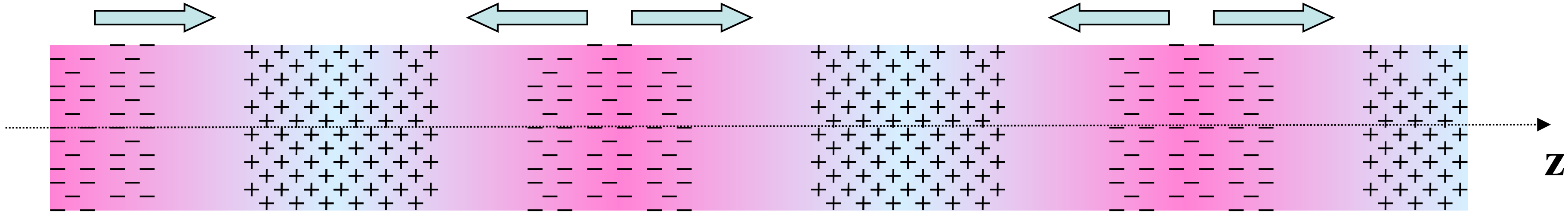


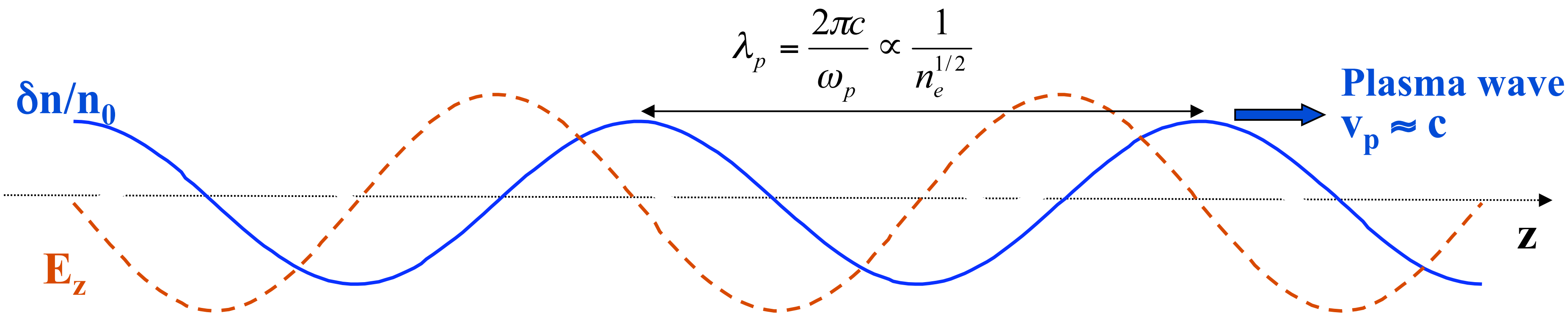
E_z = 10-100 GV/m
Physical limit: wavebreaking

\+ bunch length = a fraction of the wavelength of accelerating field
→ ultrashort electron bunches (10 fs)

Why plasmas ?

A plasma: free electrons and ions: already ionized



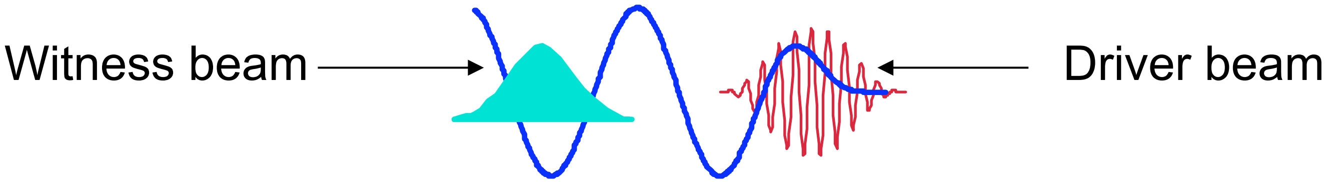


$E_z \propto \sqrt{n_e} \approx 300\ GV/m$ (for electron density $n_e=10^{19}$ cm^{-3})

E_Z is 10^4 greater than in a radio-frequency cavity
→ compact accelerators possible

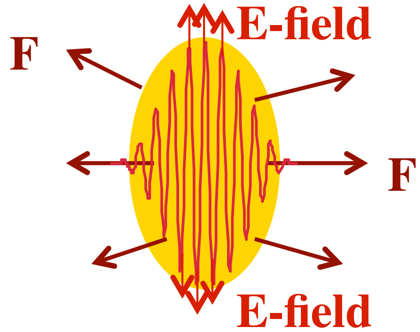
WAKEFIELDS

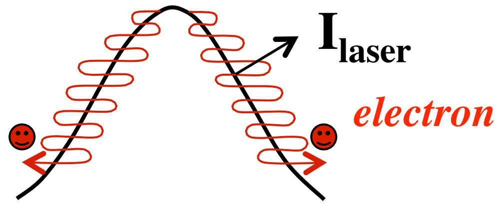
- Laser driver: an ultra-intense and ultra-short laser pulse



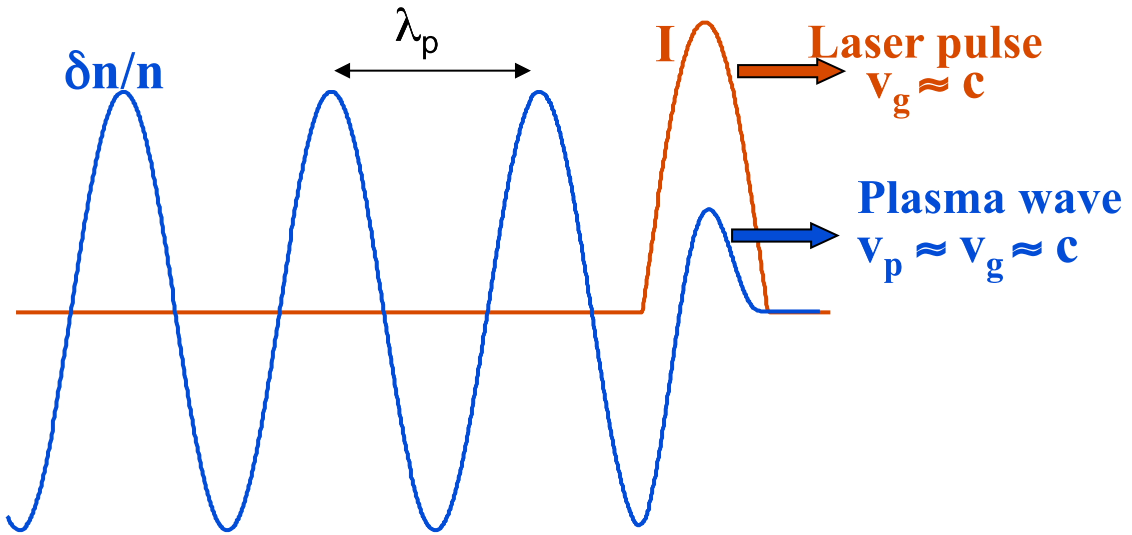
Tajima & Dawson, PRL (1979)

Laser driver: ponderomotive force





- Ponderomotive force: pushes electrons outward at high laser intensities ($I > 10^{18}$ W/cm^2) $F_p \sim -\nabla I_{laser}$



1D picture

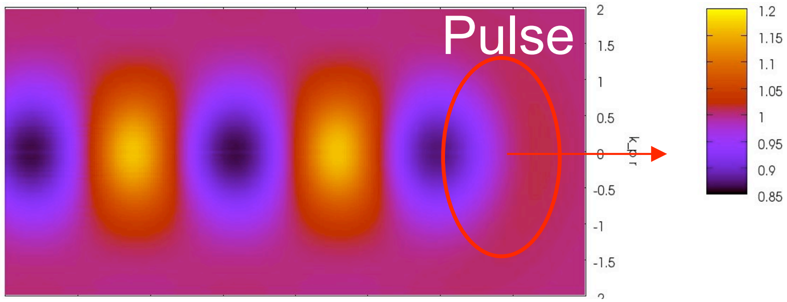
- Wakefield excitation is effective at resonance: $\tau_0 c \sim \lambda_p$

→ Short pulses are required ($\tau_0 < 100$ fs)

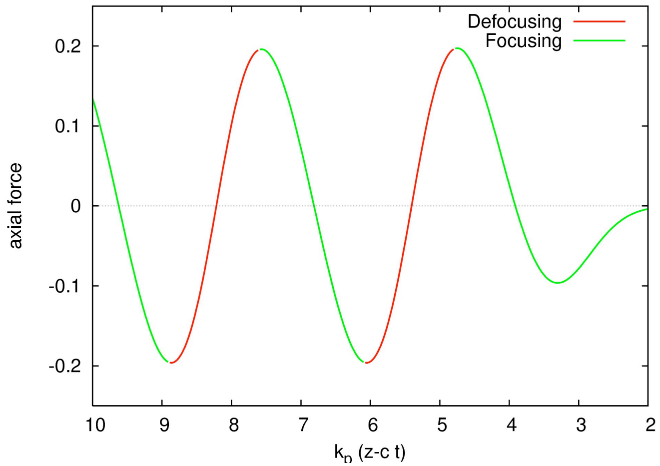
Accelerating and focusing fields

« weak laser intensity »: linear regime

a=0.5

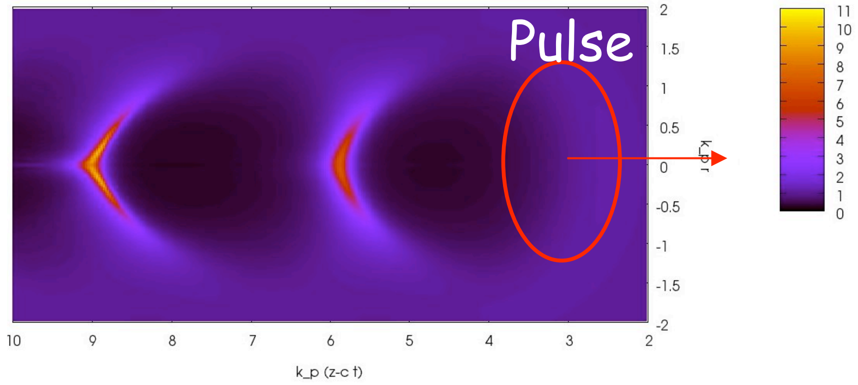


Electron density

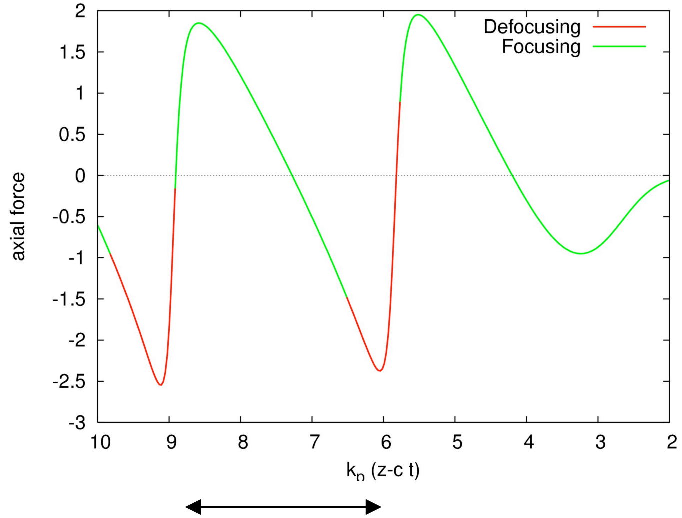


3D nonlinear wakefields

a_0=2



Electron density

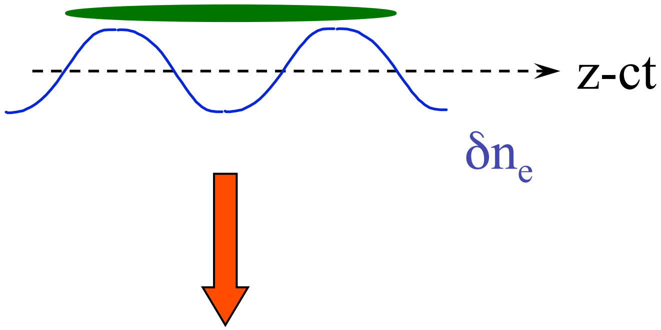


λ_p=10-30 μm

(depending on plasma electron density n_e)

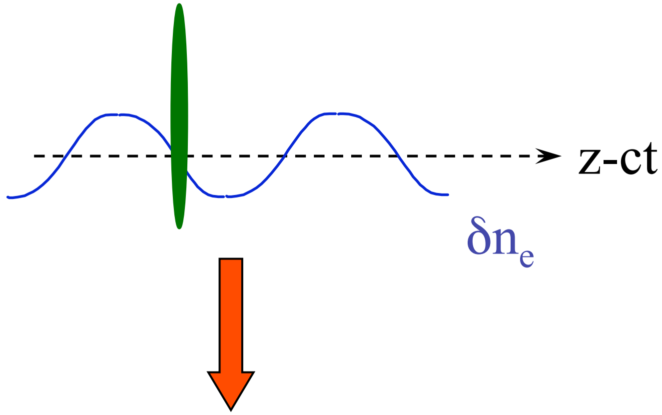
Injecting electrons in plasma wakefields

$L_{bunch} > \lambda_p$



Different phases
Different electric fields
100 % energy spread

$L_{bunch} < \lambda_p$



Electrons « in phase »
Monoenergetic acceleration

Challenge for RF technology: requires L_{bunch} < 100 fs

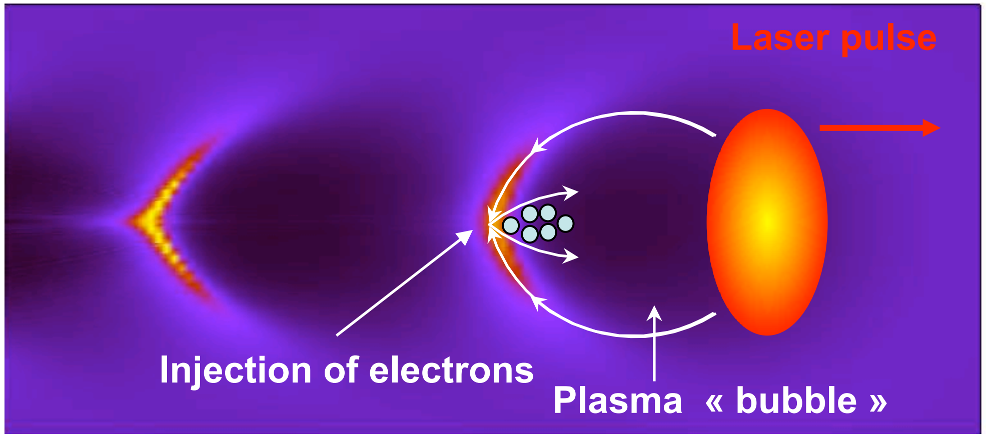
→Need to find ways to inject sub-100 fs electron bunches

→ Electron bunches accelerated in plasma waves are ultrashort (< 10 fs)

Self-injection in the nonlinear (bubble*) regime

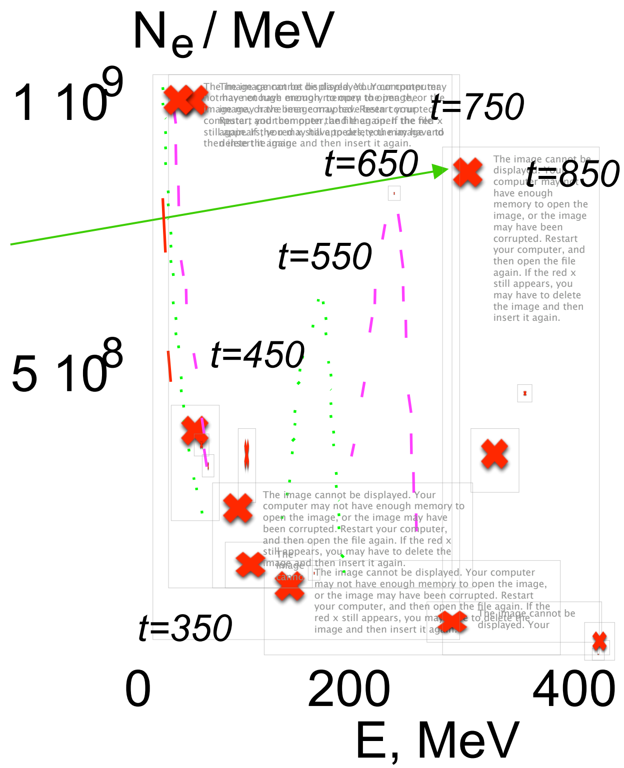
$c\tau \leq \lambda_p$ *and* $w_0 \leq \lambda_p$

$a > 3$

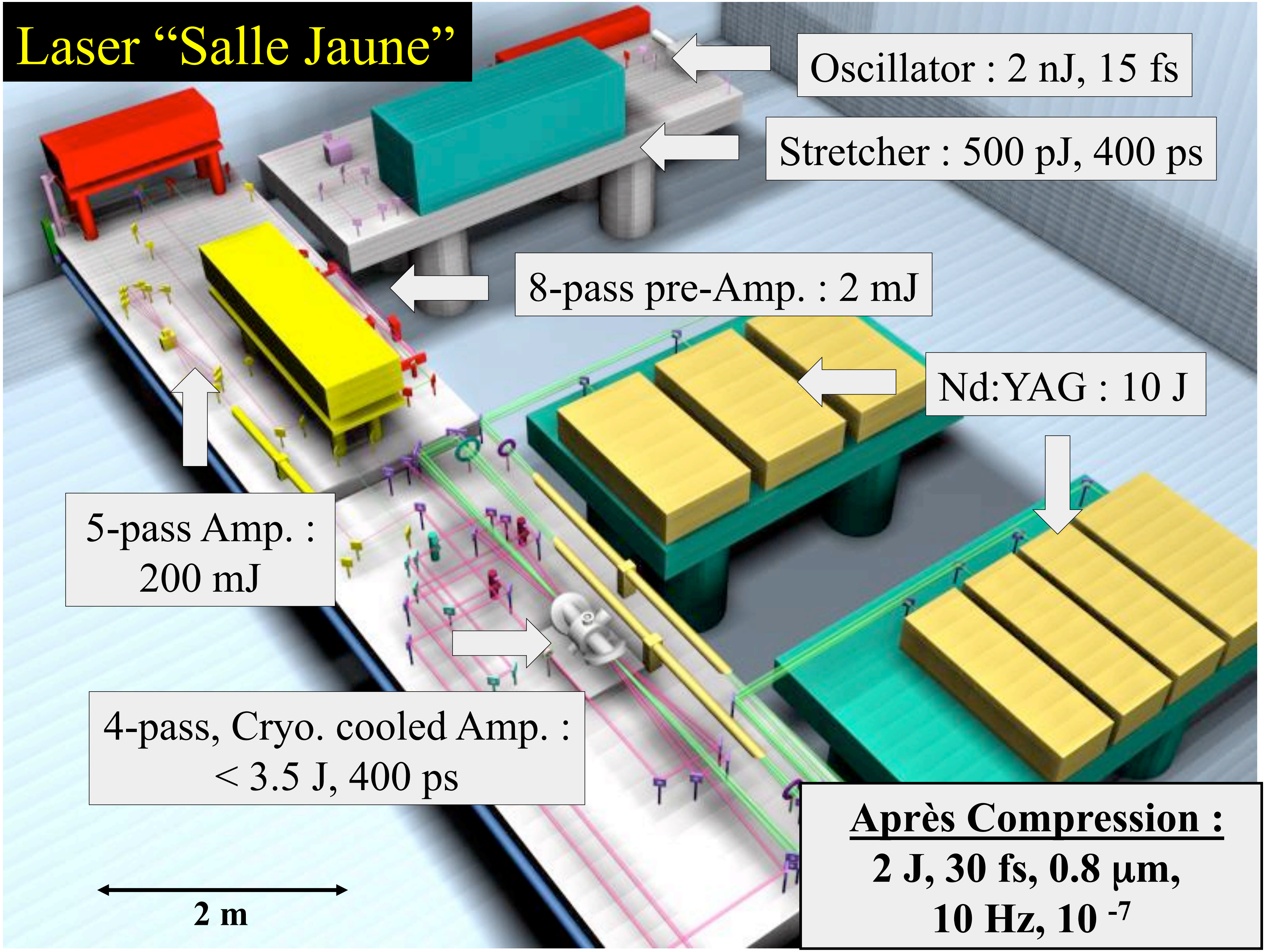


Time evolution of electron spectrum from PIC simulations

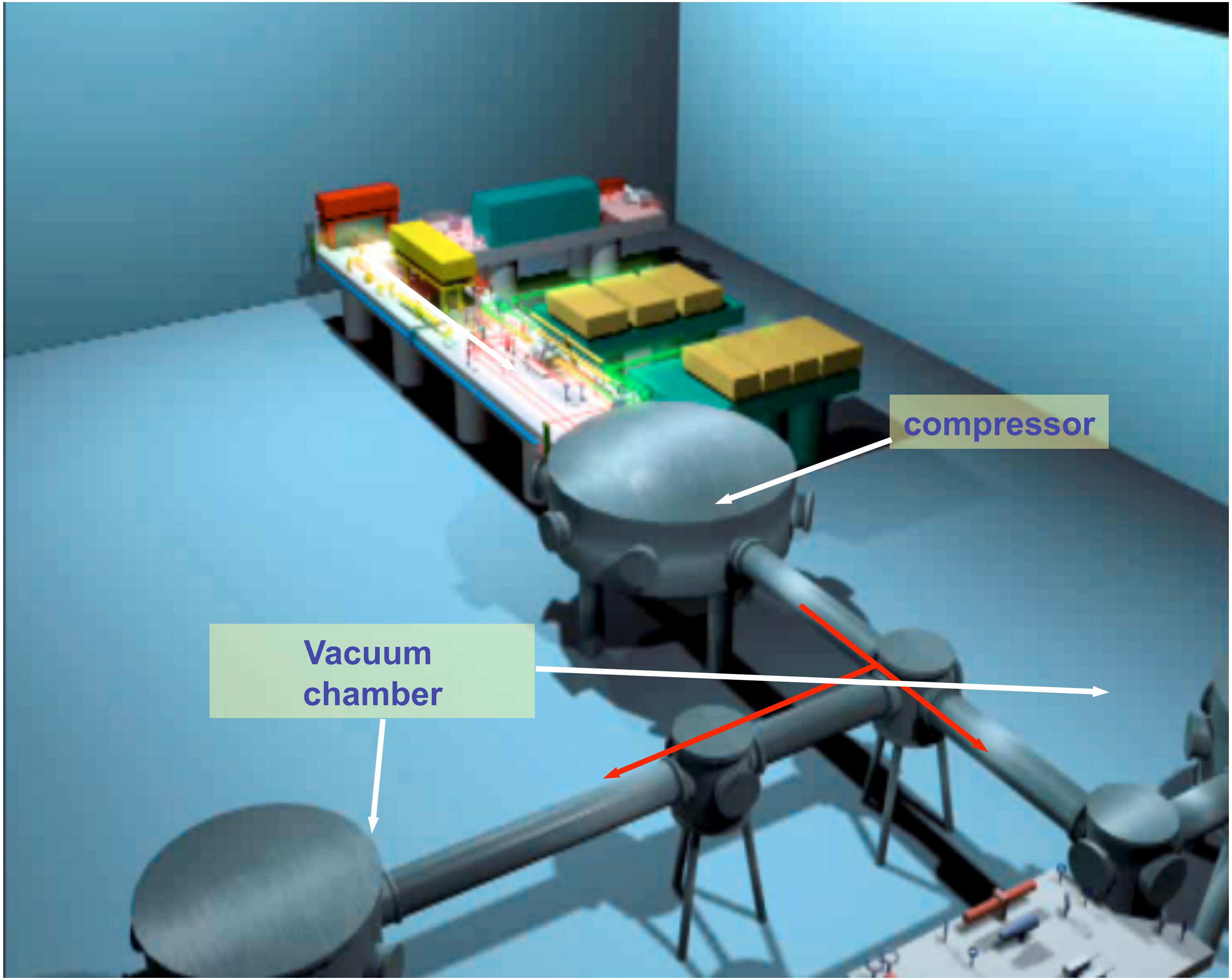
monoenergetic electron beam



*Pukhov & Meyer-ter-Vehn, Appl. Phys. B 2002

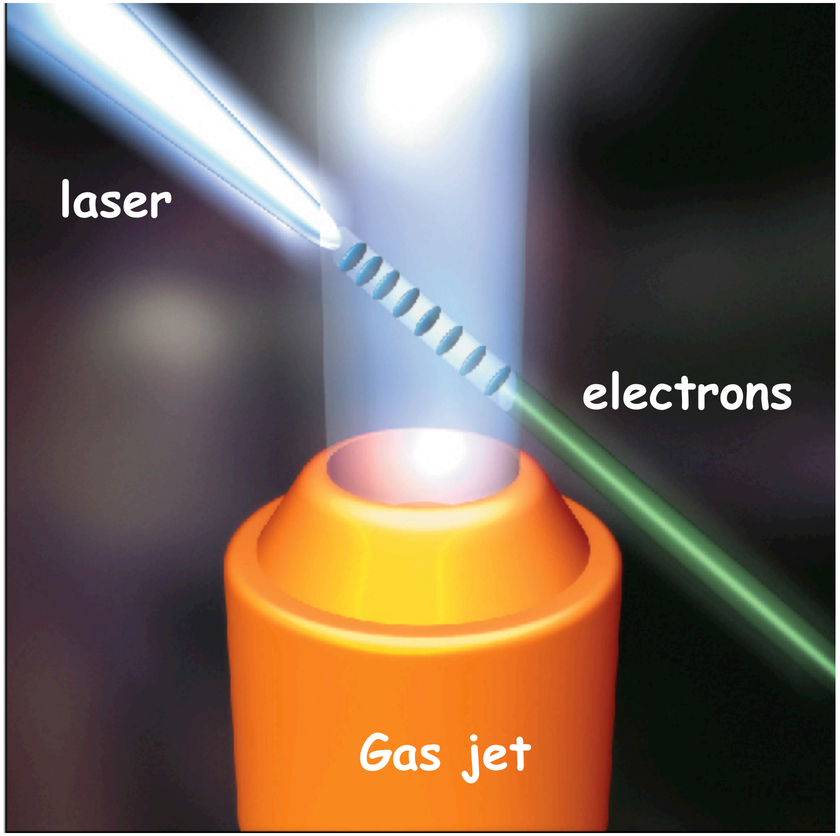


Laser "Salle Jaune"
Oscillator : 2 nJ, 15 fs
Stretcher : 500 pJ, 400 ps
8-pass pre-Amp. : 2 mJ
Nd:YAG : 10 J
5-pass Amp. : 200 mJ
4-pass, Cryo. cooled Amp. : < 3.5 J, 400 ps
2 m
Après Compression :
2 J, 30 fs, 0.8 µm, 10 Hz, 10 -7

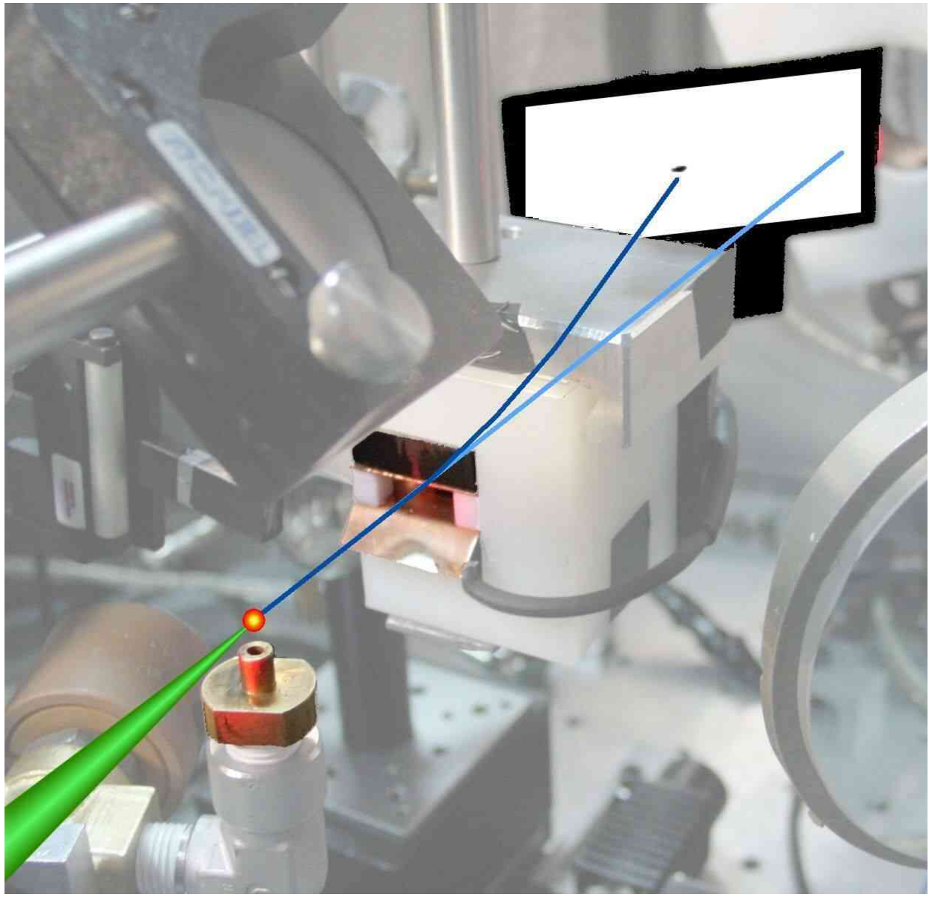

compressor
Vacuum chamber

Experiments

Scale: 100 MeV in 1 mm

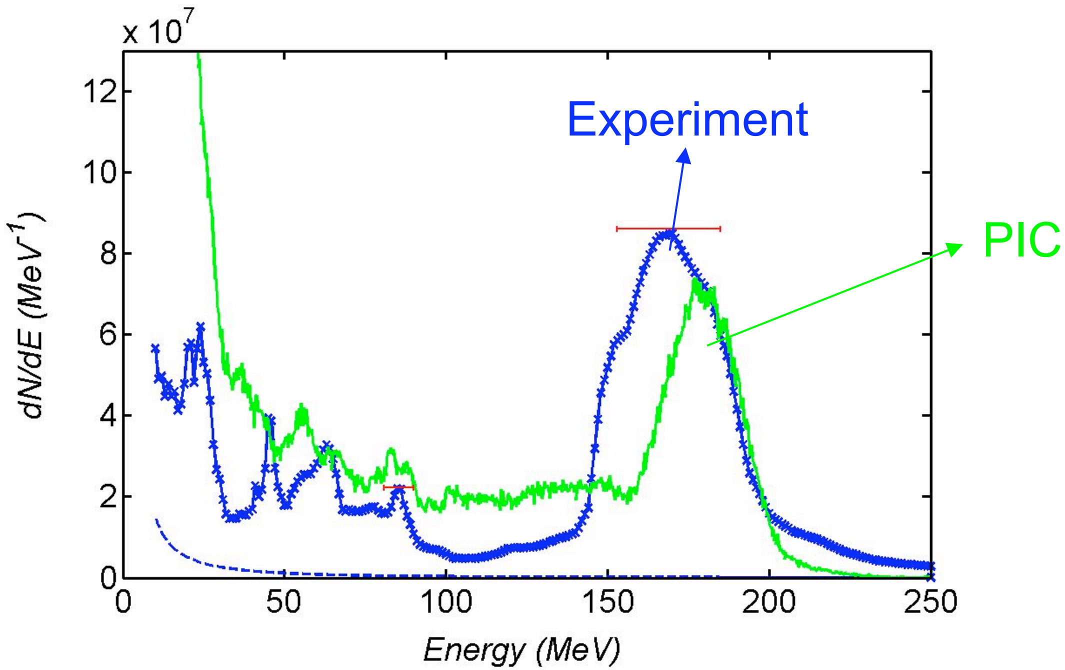


Schematic



Picture of experiment

First quasi-monoenergetic beams



J. Faure et al., Nature (2004)

Other quasi-monoenergetic results

• Berkeley experiment:
Used plasma channel for guiding
$n_e=2\times10^{19}$ cm^{-3}
$c\tau \sim 2.2\times\lambda_p$
85 MeV

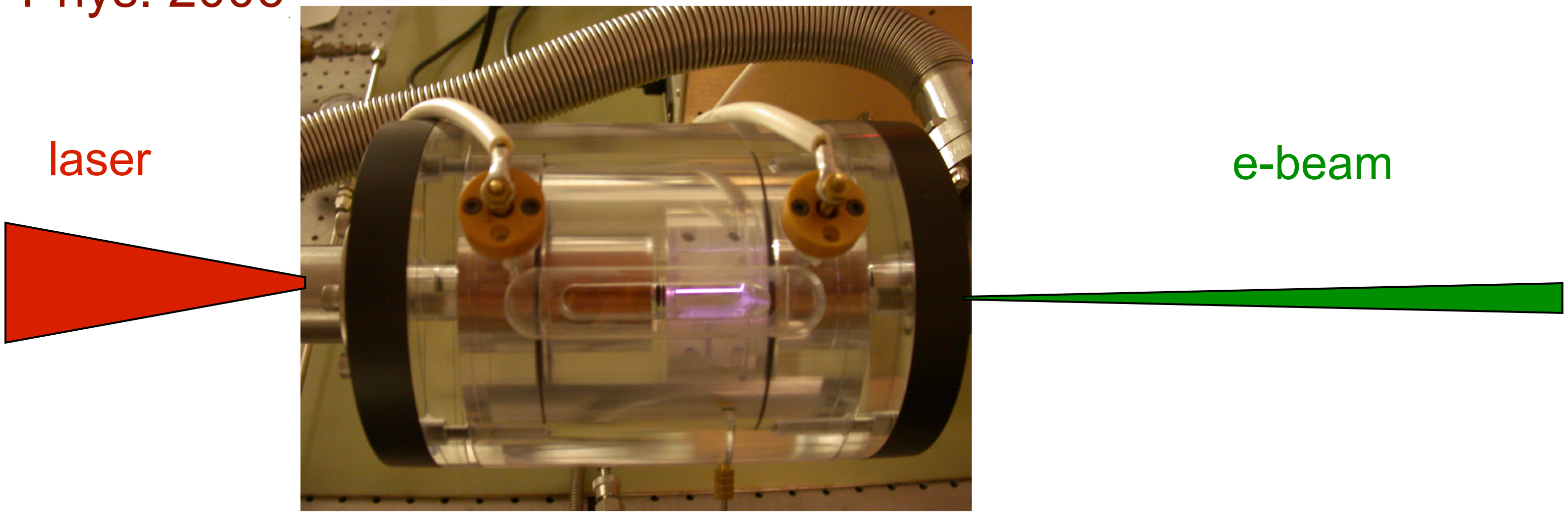
• Imperial college \ RAL
Long Rayleigh length
$n_e=2\times10^{19}$ cm^{-3}
$c\tau \sim 2\times\lambda_p$
75 MeV

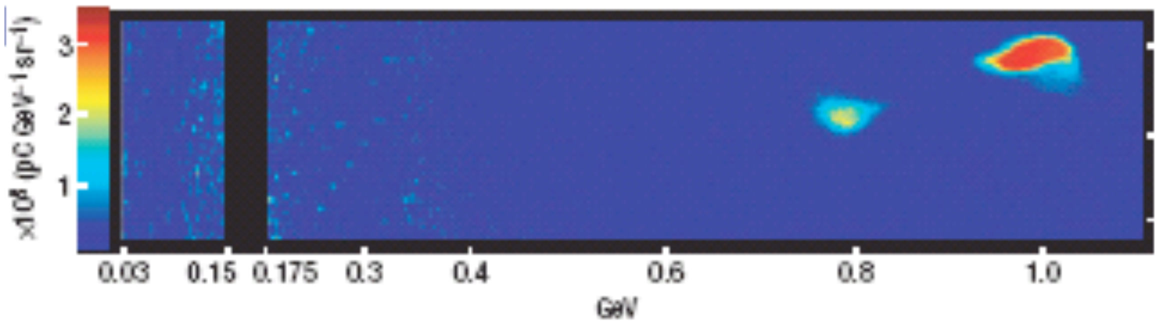
→ **Demonstrated by ~30 group around the world**

The path to higher energy

- Scale: 1 GeV in cm scale

- Berkeley experiment using plasma waveguide (Leemans et al., Nat. Phys. 2006)



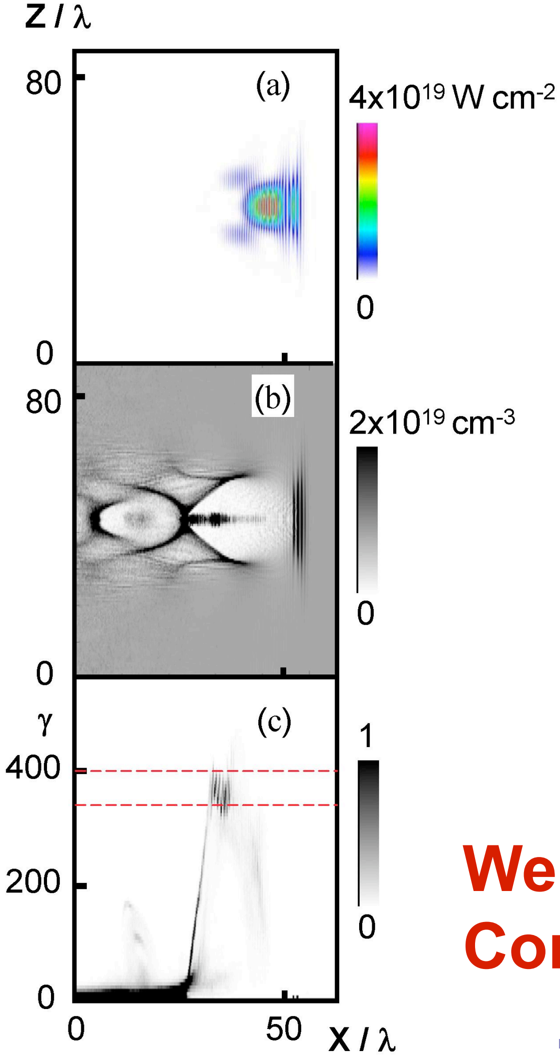


- Charge: ten's of pC
- δE/E=5 % (instrument limited)

Also GeV class beams at RAL (England), using a 500 TW laser

Physical picture of beam production

PIC simulation
2 mm propagation



Scenario:
nonlinear evolution of laser (self-focusing + pulse shortening)

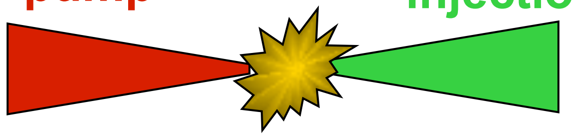
- → **Self-guiding of laser pulse**
- → **Increases laser intensity**
- → **Cause wave-breaking and electron injection**

Drawbacks:
- **Very nonlinear phenomena**
- **Injection is not controlled and depends on laser pulse evolution**

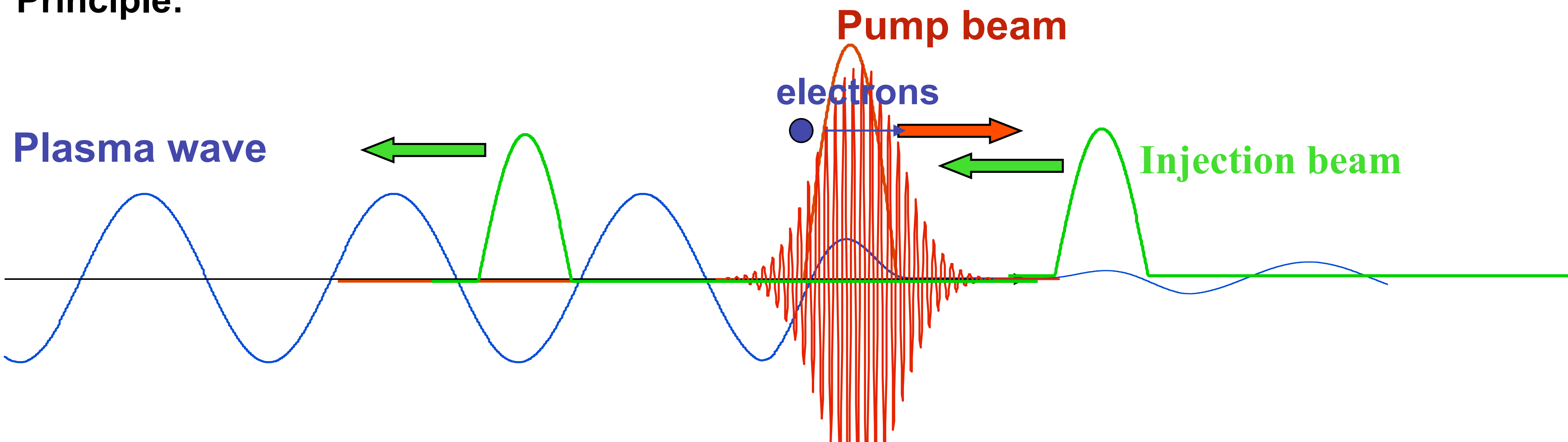
We want to develop a more controlled method
Control is important for higher beam quality

Control and stability: external injection using another laser pulse

Counter-propagating geometry:



Principle:



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

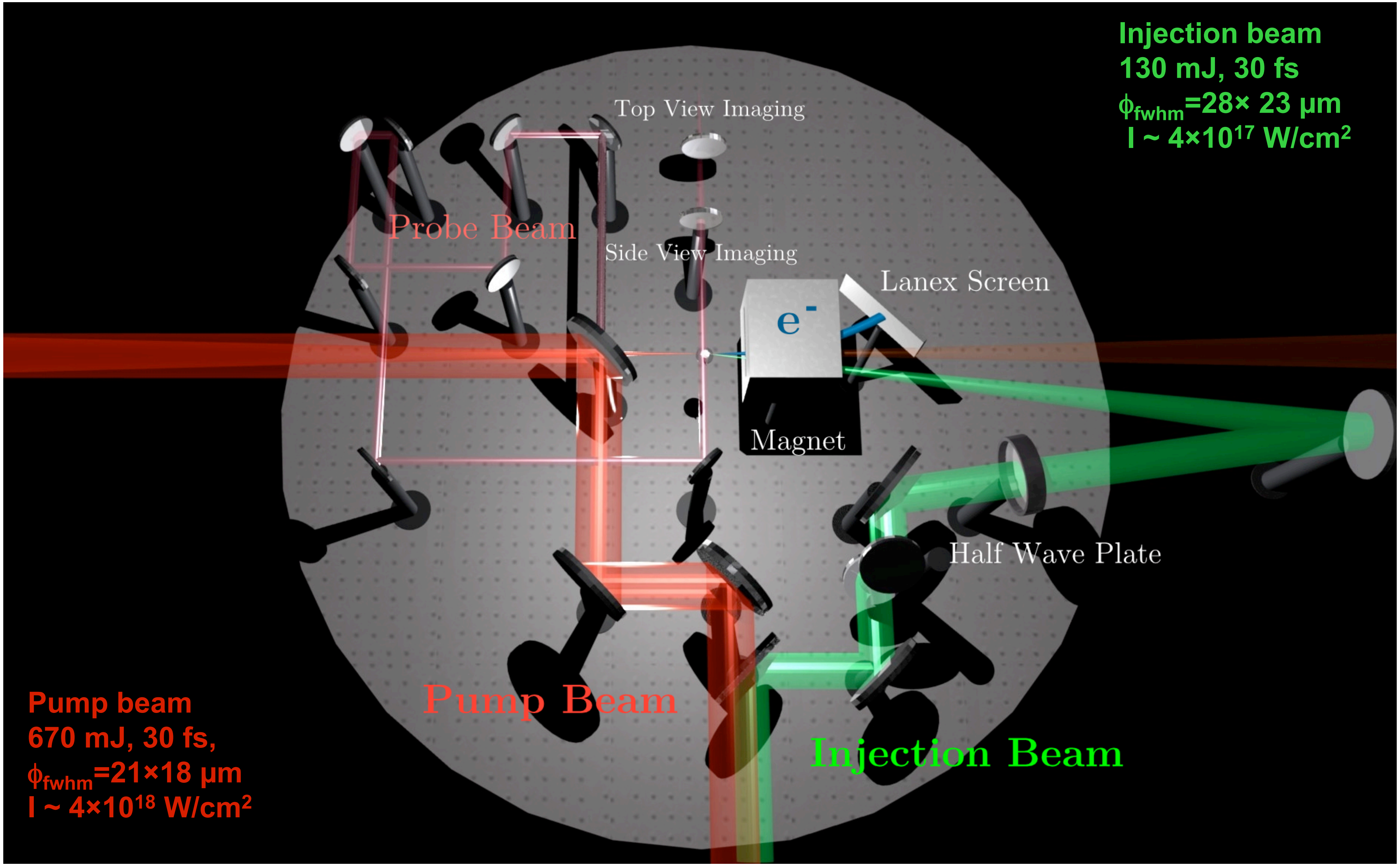
Boost electrons locally and injects them:

INJECTION IS LOCAL IN FIRST BUCKET

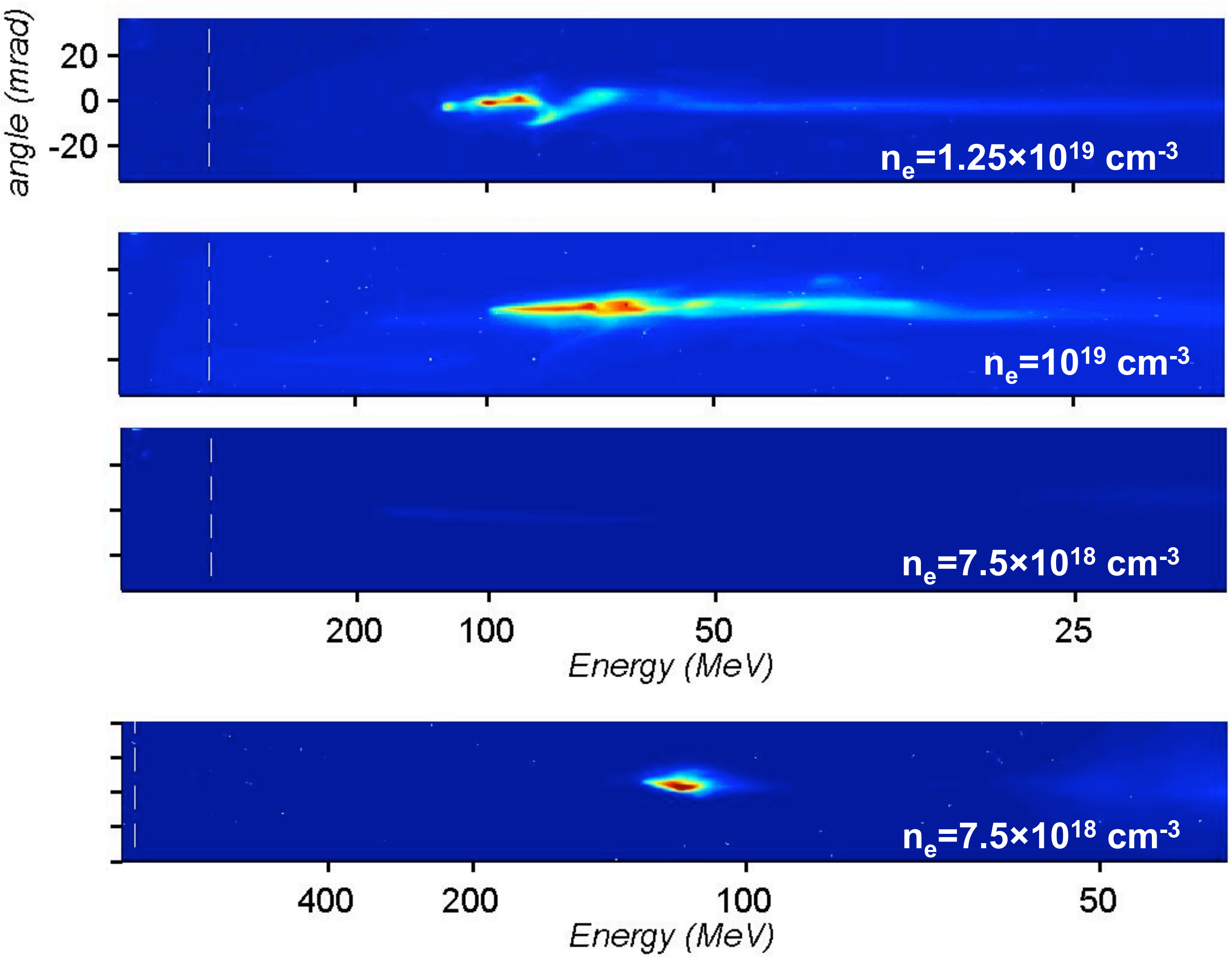
no need of self-focusing, no self-trapping

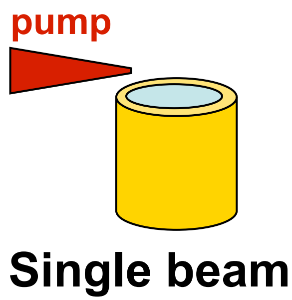
D. Umstadter et al, PRL 76, 2073 (1996); E. Esarey et al, PRL 79, 2682 (1997); Fubiani PRE 70, 016402 (2004)

Experimental setup

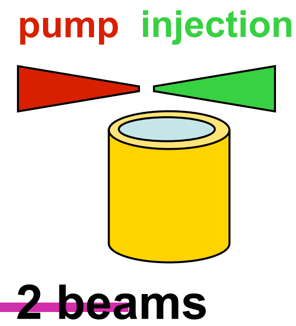


From self-injection to external injection





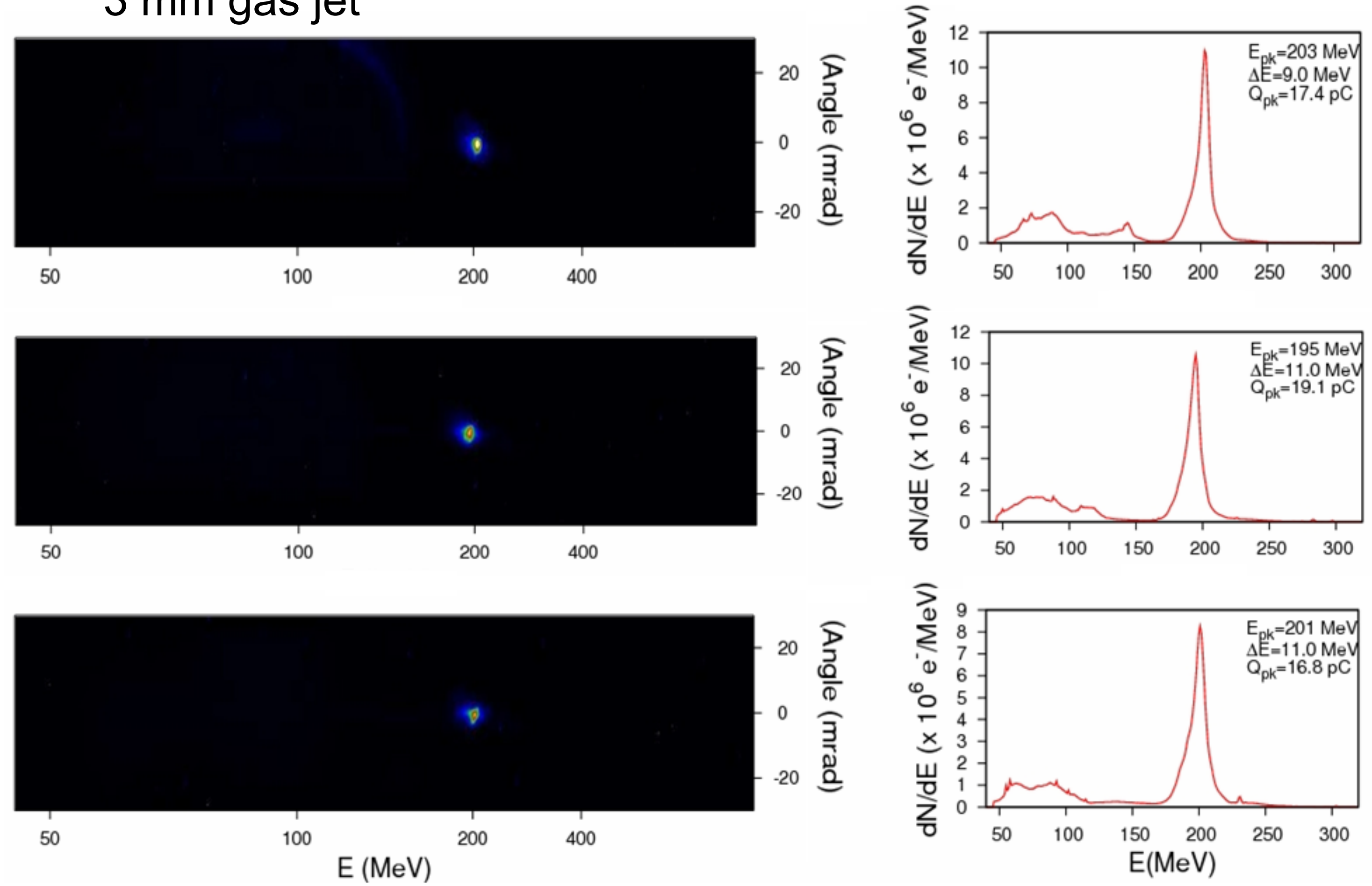
Self-injection Threshold



Faure et al. Nature 2006

Stable monoenergetic beams at 200 MeV

3 mm gas jet

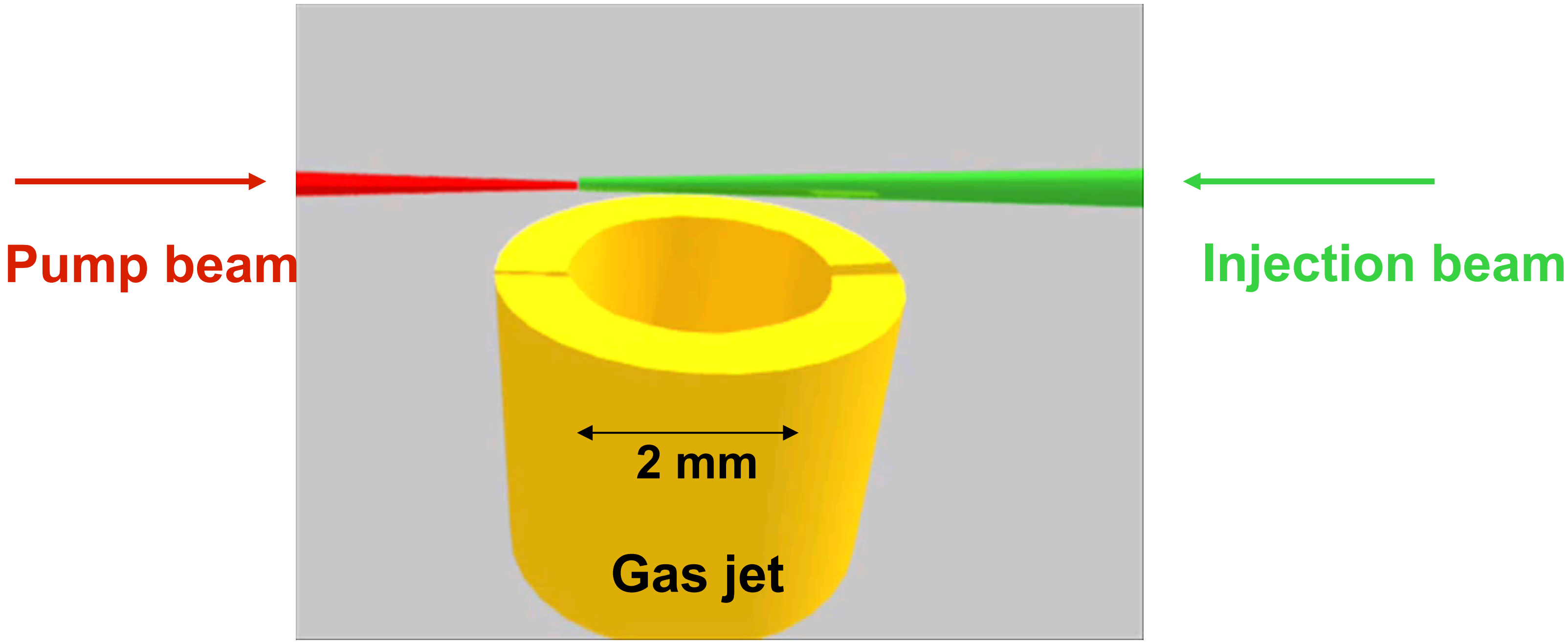


Statistics over 30 shots
E = 206 +/- 11 MeV (5 %)
Qpk = 13+/- 4 pC (30 %)
dE = 14 +/- 3 MeV (20 %)

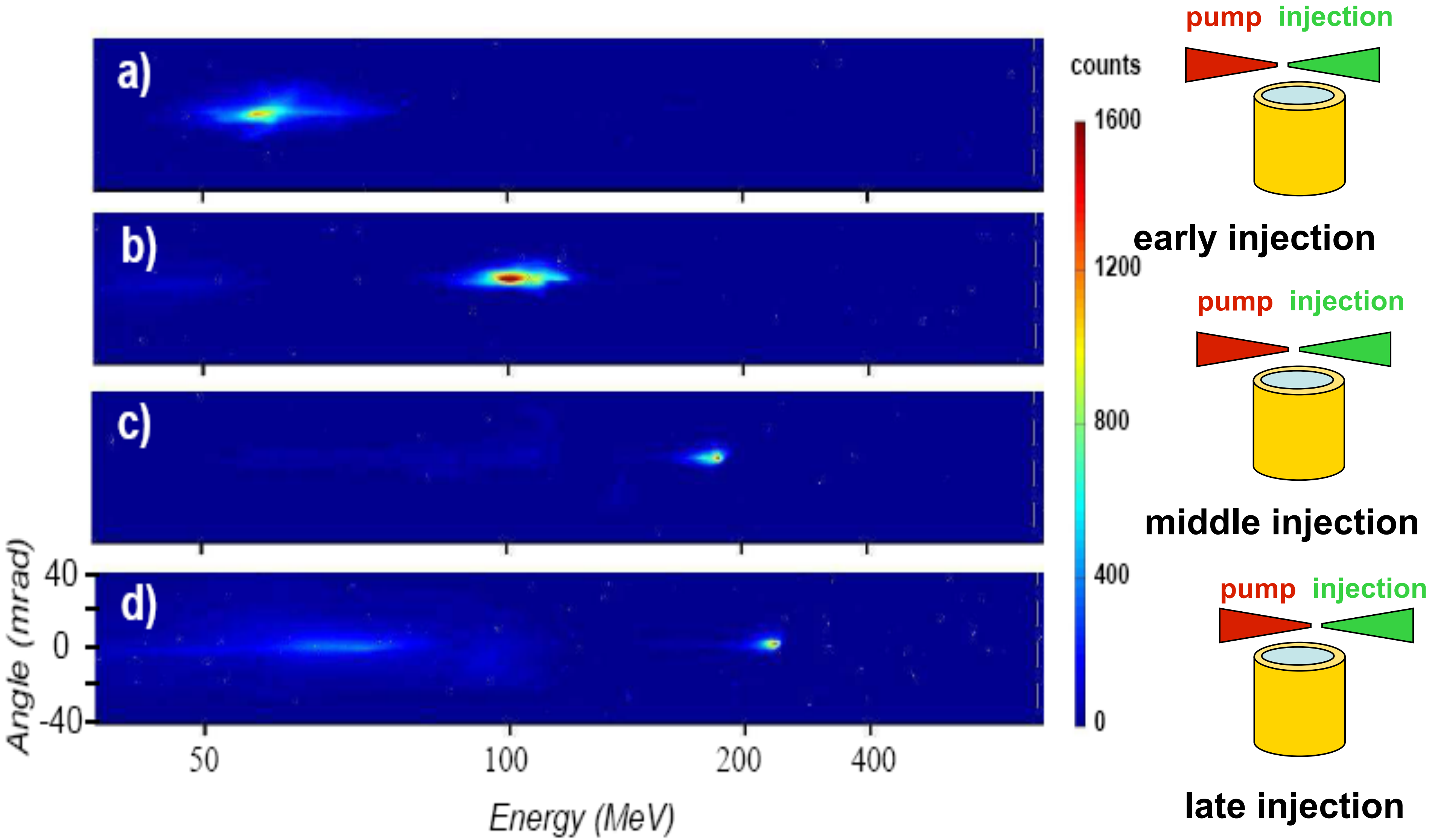
Very little electrons at low energy !!
dE/E=5% close to spectrometer resolution

Controlling the bunch energy by controlling the acceleration length

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

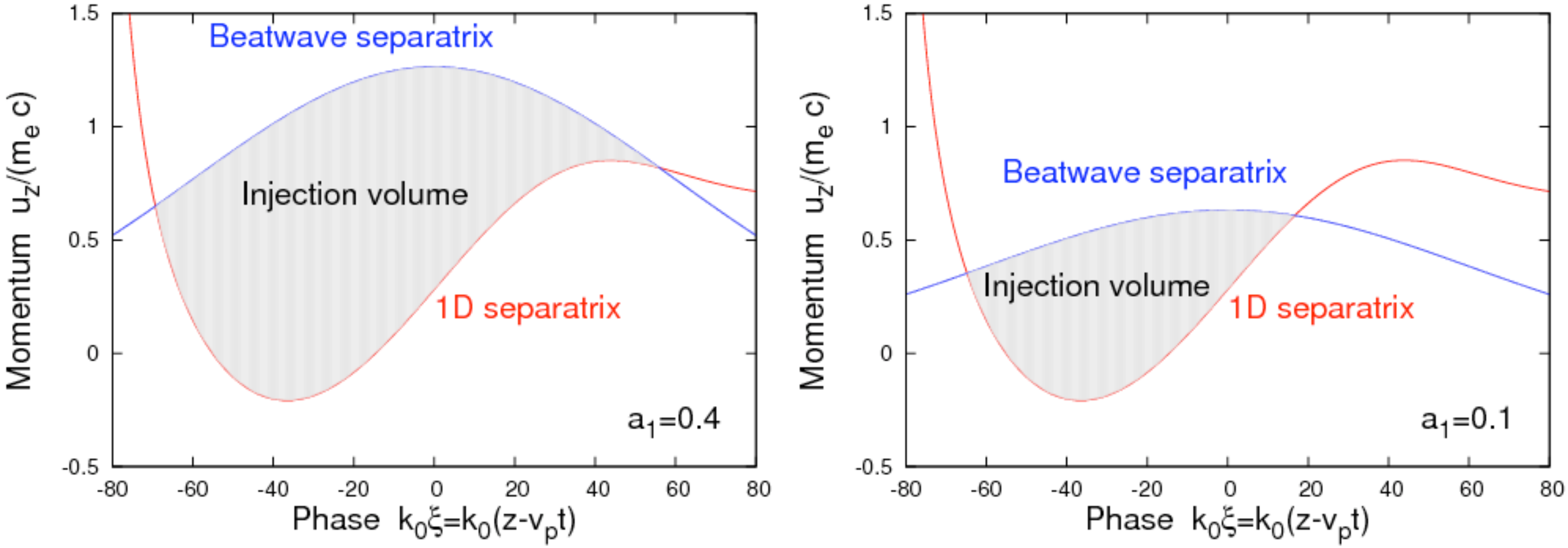


Tunable monoenergetic bunches



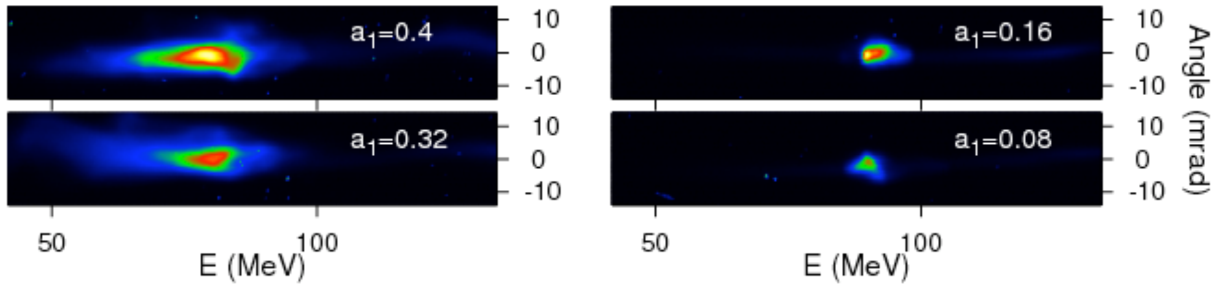
Tuning the charge and the energy spread

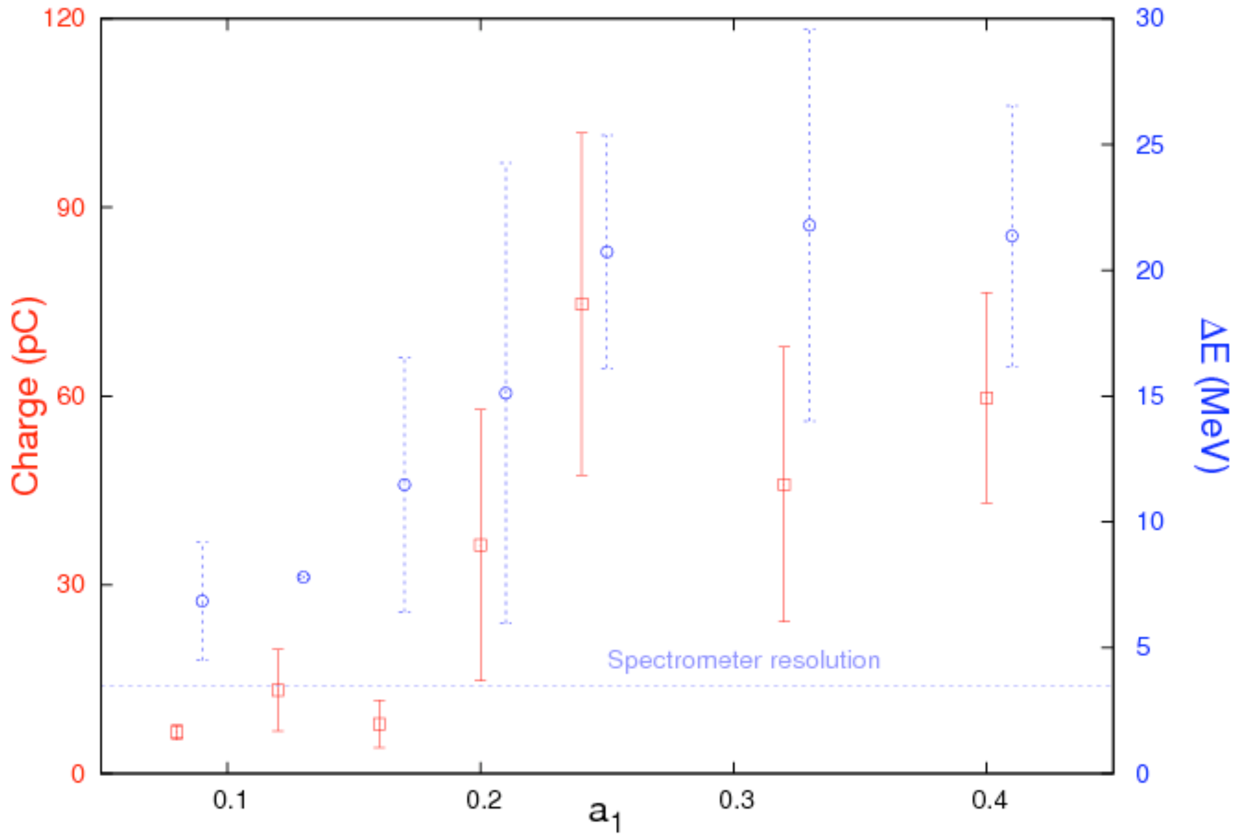
- Charge can be tuned by controlling the injection volume:
  → Changing intensity of injection beam: smaller I_{inj} means less heating and smaller injection volume



In pratice, energy spread and charge are correlated:
$\Delta V=\Delta p\Delta x$, conservation of ΔV +smaller injection volume also implies smaller Δp

Tuning the beam with injection beam intensity





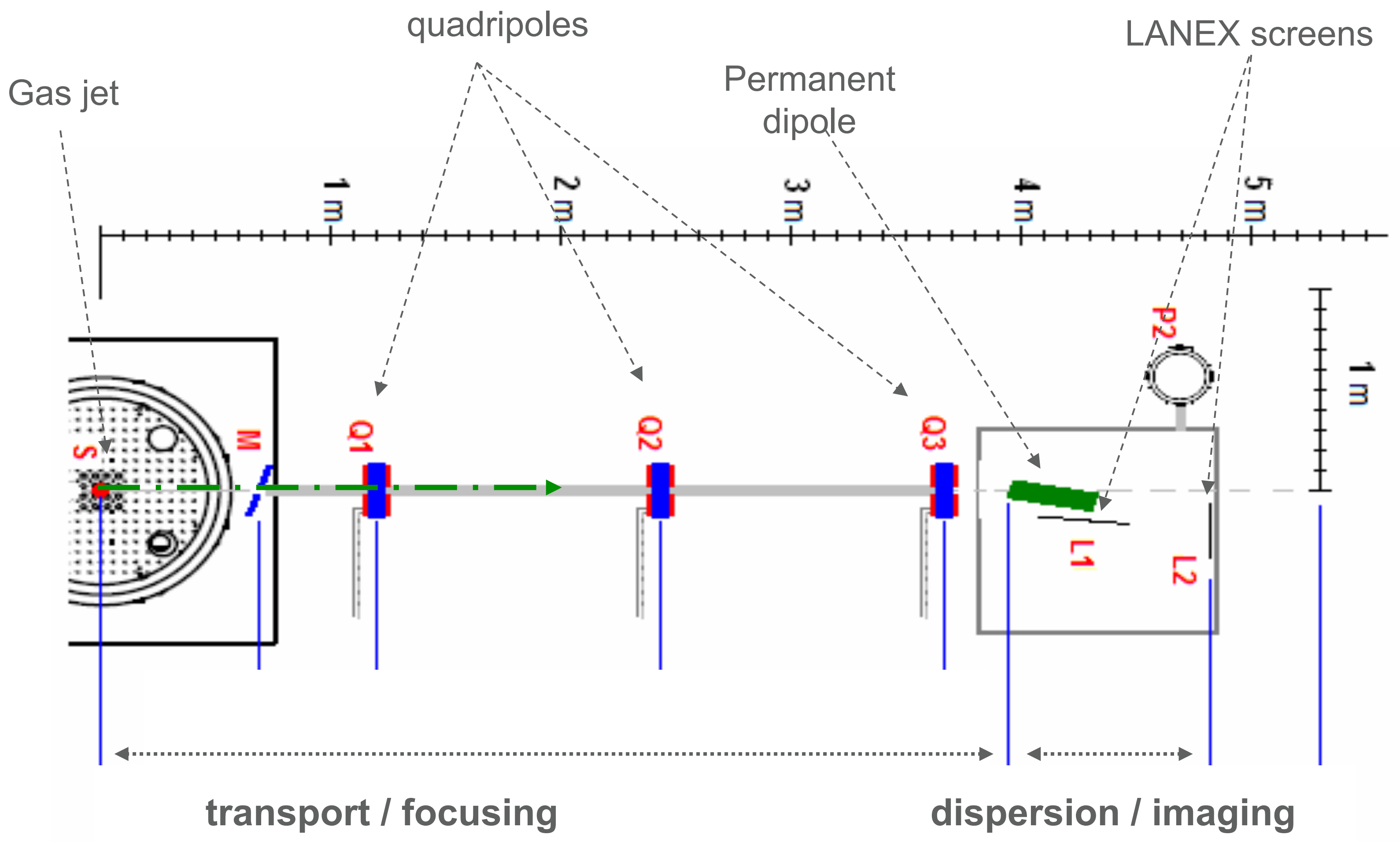
Energy @ 80 MeV stays similar

Charge from 60 to 5 pC

ΔE from 20 to 5 MeV (close to resolution)

Collaboration with LLR* for resolving small energy spread beams

Spectrometer was designed and built by Laboratoire Leprince Ringuet (LLR)

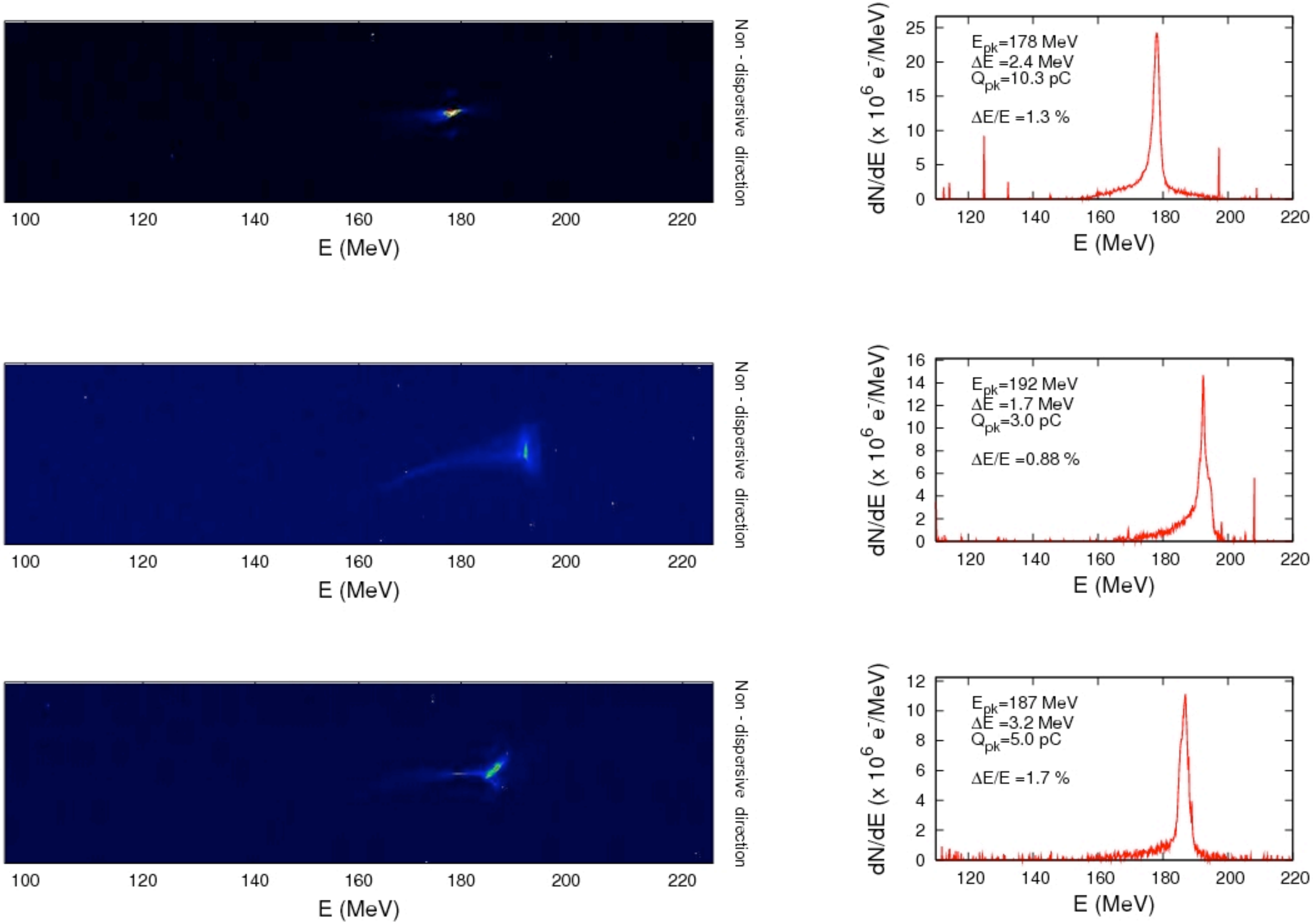


Resolution < 1 % expected

* A. Specka, H. Videau, A. Ben Ismail

Focusing spectrometer

1% energy spread beams



Conclusion

SUMMARY

- Quasi-monoenergetic beams produced at 100's MeV level
- Stability is improving (5 % rms in energy)
- Controlled injection provides
    - tunable energy: 20-300 MeV
    - tunable charge (in the 10's of pC range)
    - tunable energy spread (down to 1%)
- Simulations reproduce results
    - indicate < 10 fs electron bunches

PERSPECTIVES

- CONTINUE TO INVESTIGATE THIS TECHNIQUE:
    - Push energy limit: use wave guide to increase propagation distances. Goal: stable and tunable GeV class beams
- DIAGNOSE THESE BEAMS
    - Measure emittance
    - Measure bunch length
- USE THESE BEAMS (applications, science …)

Potential impact of laser-plasma accelerators

Moderate energy: 10 MeV-1GeV
Compact
Sub-50 fs bunch duration

X-rays:diffraction
γ-rays:radiography

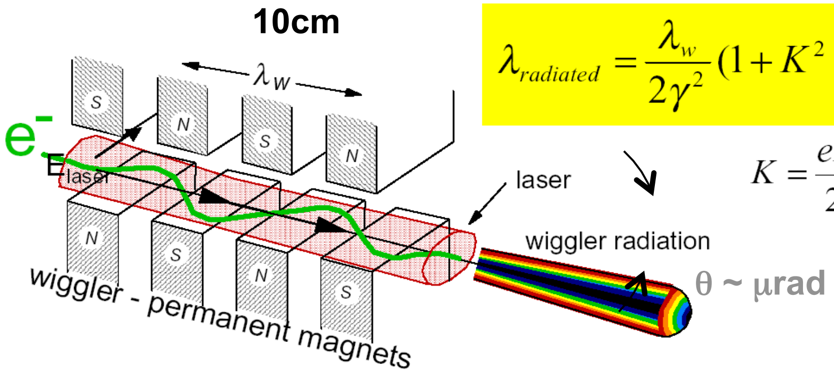
Medicine
Radiotherapy

Electrons generated by Laser-Plasma Interactions

Accelerator Physics
Injector

Chemistry & Radiobiology
Irradiation by short bunches

Compact XFEL: towards a bright X ray source



$$\lambda_{radiated} = \frac{\lambda_w}{2\gamma^2}(1 + K^2/2) = \lambda_{laser}$$

$$K = \frac{eB_o\lambda_W}{2\pi mc}$$

Advantage of laser-plasma accelerators:

- Short bunches → high peak current
- Seeding with perfectly synchronized harmonics of the laser

Challenges:

- Decrease energy spread (< 1% required for amplification)
- Increase charge

Applications: study of complex structures (X-ray diffraction, EXAFS) But fs time scale