Particle Accelerators:
The Next Generation

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Major parameters

- Beam energy
- Beam energy-spread
- Beam current
- Beam emittance
- Beam stability
- Beam repetition-rate

Industrial Market for Accelerators

The development of state of the art accelerators for HEP has lead to :
research accelerators for other field of science (light source spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting&welding...)

Application	Total systems (2007) approx.	System sold/yr	Sales/yr (M$)	System price (M$)
Cancer Therapy	9100	500	1800	2.0 - 5.0
Ion Implantation	9500	500	1400	1.5 - 2.5
Electron cutting and welding	4500	100	150	0.5 - 2.5
Electron beam and X rays irradiators	2000	75	130	0.2 - 8.0
Radio-isotope production (incl. PET)	550	50	70	1.0 - 30
Non destructive testing (incl. Security)	650	100	70	0.3 - 2.0
Ion beam analysis (incl.AMS)	200	25	30	0.4 - 1.5
Neutron generators (incl. sealed tubes)	1000	50	30	0.1 - 3.0
Total	**27500**	**1400**	**3680**	

Total accelerators sales increasing more than 10% per year

Energy-ranges for LWFA accelerators

- **Low energies (10s of MeV)** – well established industrial base with a well-established technology. Not much advantage for LWFA

- **High energies (many hundreds of GeV).** Colliders. Many issues about staging, stability, acceleration of positrons, repetition rate and luminosity. Important efforts on at SLAC (FACET, PWFA) and LBL (BELLA, LWFA), but will take time.

- **Medium energies (~ 1 GeV).** Most likely applications of plasma-based accelerators, particularly LWFA. Main applications here would be for light sources – especially free-electron lasers.

XFELs around the world

	LCLS (USA)	XFEL (Europe)	SACLA (Japan)	*FLASH*	FERMI	ARC-EN-CIEL
Wavelength (nm)	0.15	0.1	0.1	6.4	1.2	1
Energy (GeV)	14	17.5	6.1	1	3	1
Norm. emit. (mm-mrad)	1.2	1.4	0.4	2	2	2
Undulator Period (mm)	30	35.6	15	27.3	32.6	30
Undulator Length (m)	113	133	23	27	32	12
Undulator Parameter 'K'	3.7	3.3	1.3	1.17	1.24	??
Peak Current (kA)	3.4	5	3	6.25	2.5	5
Pulse Structure (fs @ Hz)	77 @ 120	67 @ 32,500	500 @ 60	160 @ 72,000	160 @ 50	200 @
Accelerator Technology	Normal; S-band	S/C; L-band	Normal; C-band	S/C; L-band	Normal; S-band	S/C; L-band

Quasi-energetic beams

These experiements marked the beginning of the consideration of laser wakefield **ACCELERATORS**, rather than just acceleration.

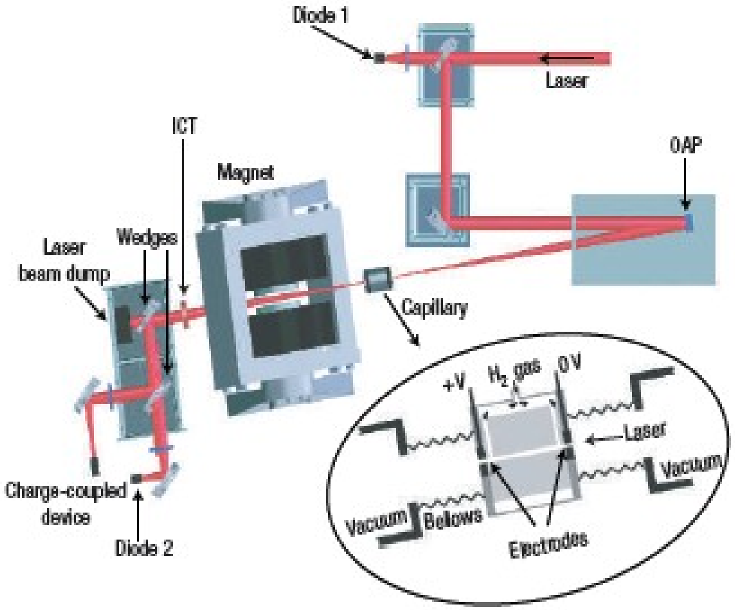
For the first time bunched beams (in energy) were obtained, though the energy-spread (~few %) was still too high for most accelerator applications.

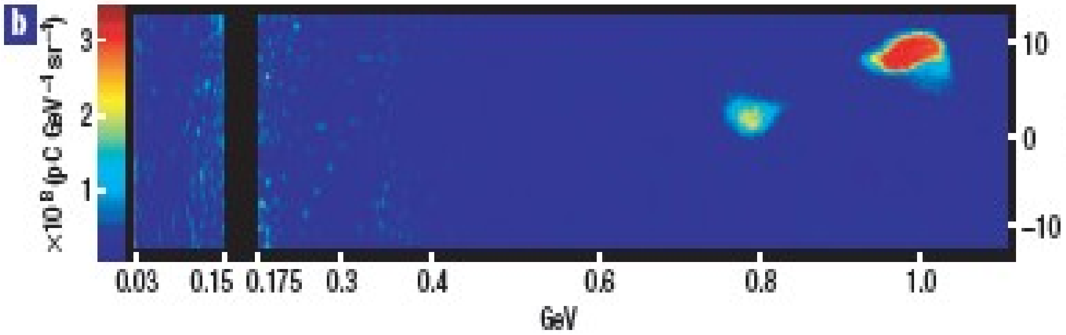
- S.P.D. Mangles *et al.*, Nature, **431**, 535 (2004),
- J. Faure *et al.*, Nature, **431**, 541 (2004),
- C.G.R. Geedes *et al.*, Nature, **431**, 538 (2004)

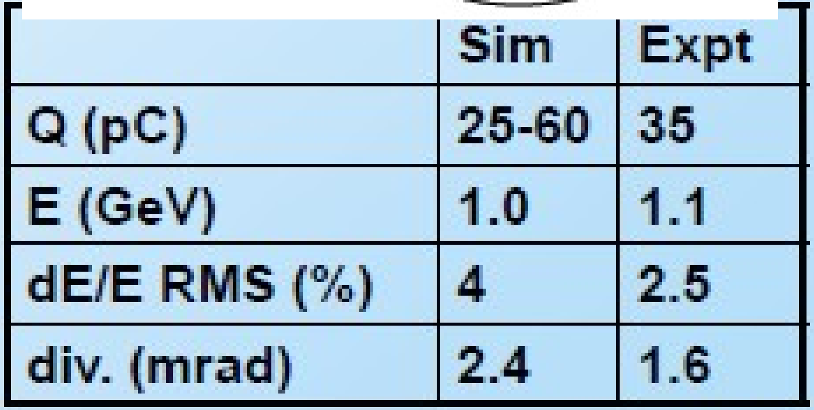
GeV beams

W. P. Leemans *et al.*, Nature Physics **2**, 696 (2006)

The 1.0 GeV beam shown was obtained in the 310 μm capillary with a density of 4.3×10^{18} cm^{-3} and input laser power of 40 TW, 37 fs ($a_0 = 1.46$). 1.0 GeV, 2.5% r.m.s. energy spread, 1.6 mrad divergence r.m.s., ~30 pC.







	Sim	Expt
Q (pC)	25-60	35
E (GeV)	1.0	1.1
dE/E RMS (%)	4	2.5
div. (mrad)	2.4	1.6

How to improve beam quality?

Certain things are well-established:

- Use lower laser intensity – below self-injection threshold
- Use lower plasma density – higher energy, better stabillty
- Match laser spot-size - slightly larger than plasma wavelength, better propagation

How to control injection?

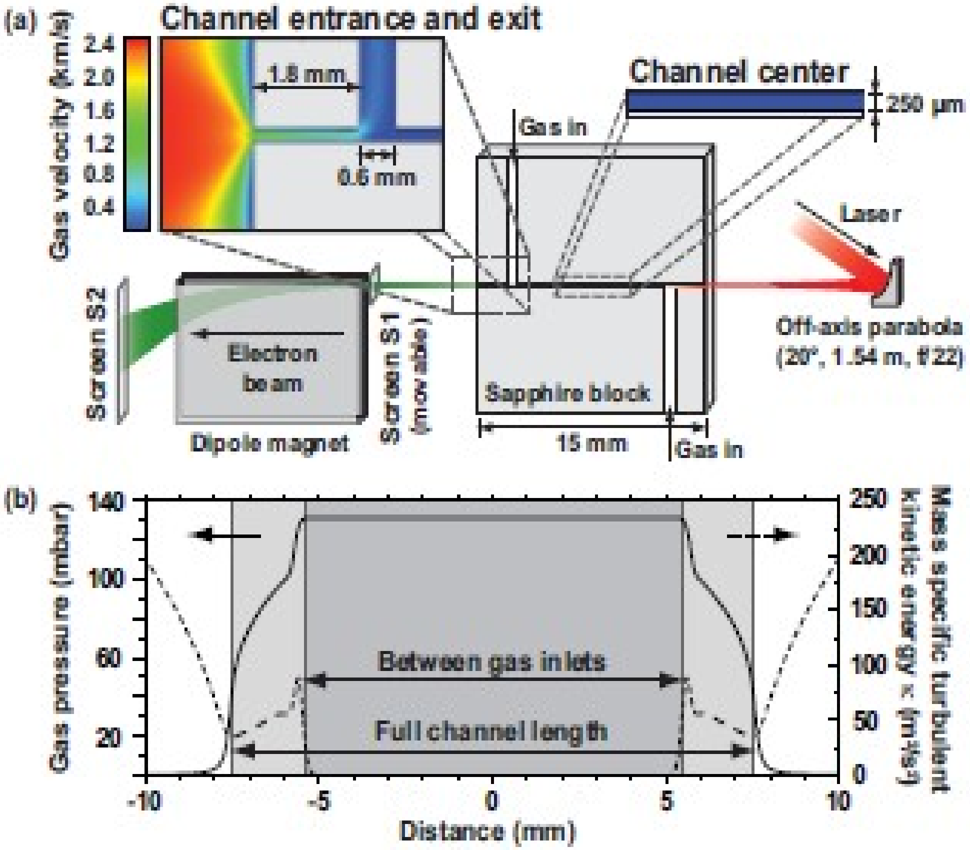
- Near-threshold injection
- Density transition
- Colliding pulses
- Ionization injection

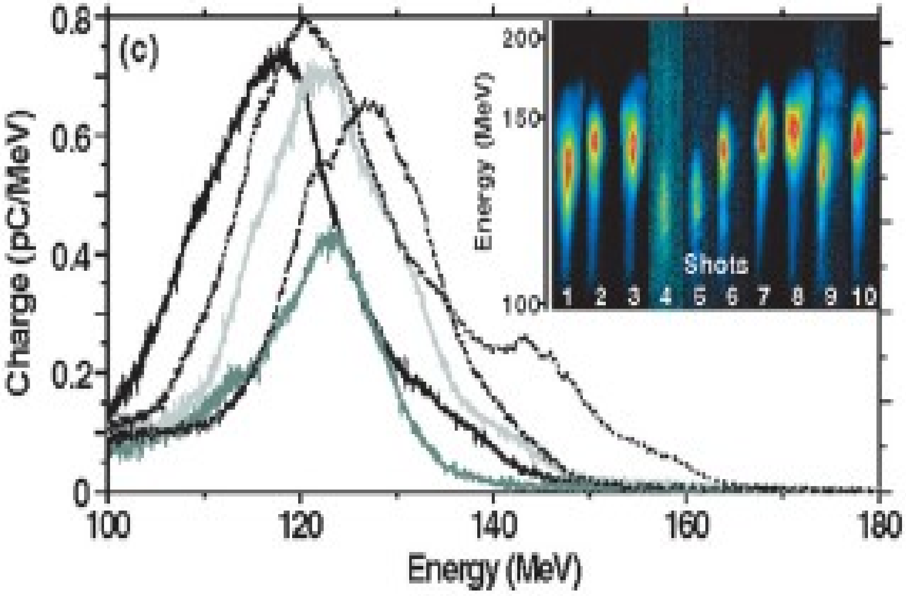
1: Near-Threshold Injection

*Generation of **stable** low-divergence electron beams by LWFA in a steady-stage flow gas cell. Laser causes ionization, not electrical discharge. The gas cell reduces target density fluctuations threefold compared to supersonicgas jets.*

J. Osterhoff *et al.*, PRL **101**, 085002 (2008)

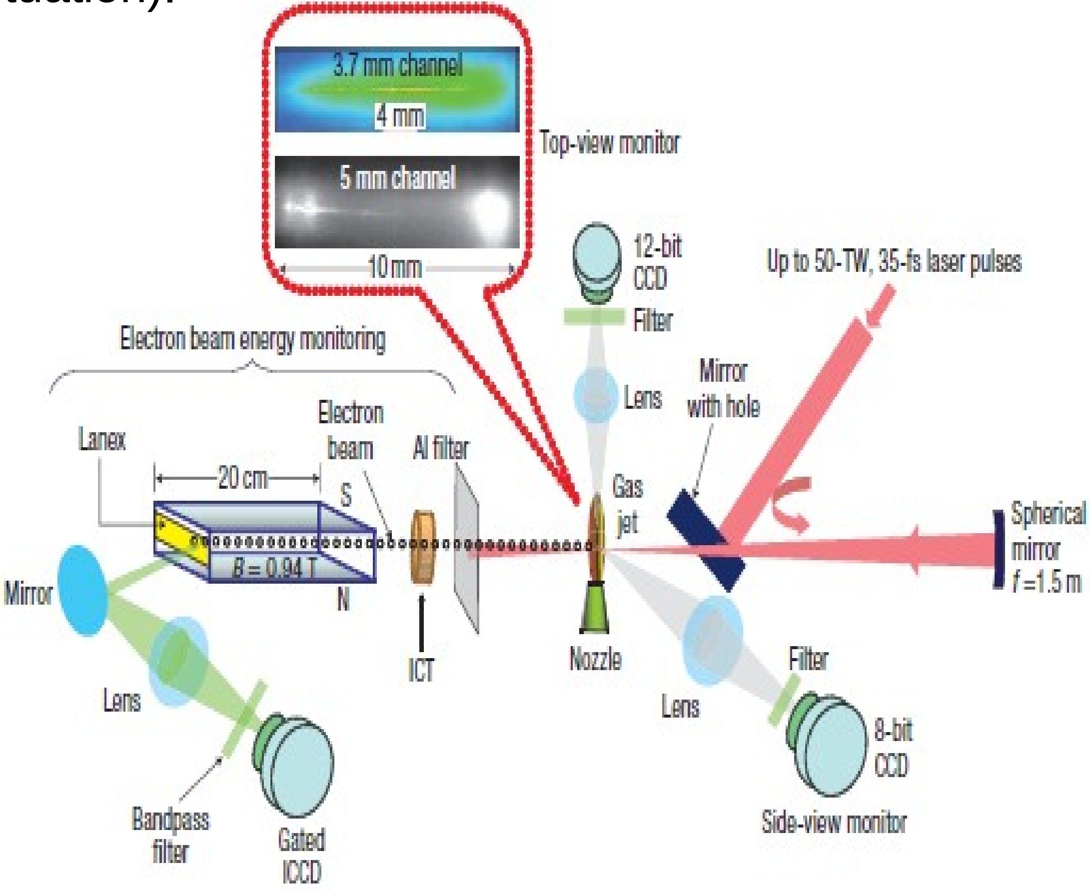
Laser : 20 TW
1cm gas cell target
0.8J, 40 fs, a_0=0.9
$n_e=7\times10^{18}\,\mathrm{cm}^{-3}$
Stable e-beam :
10 pC
220 MeV
Div = 2 mrad
DE/E = 8%

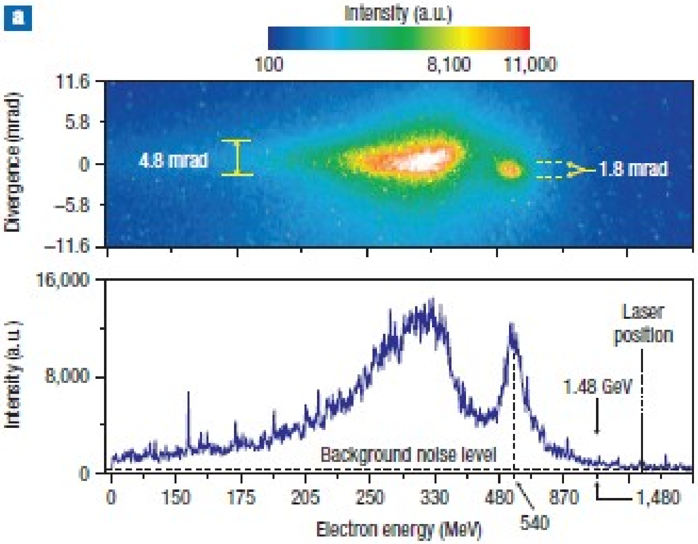


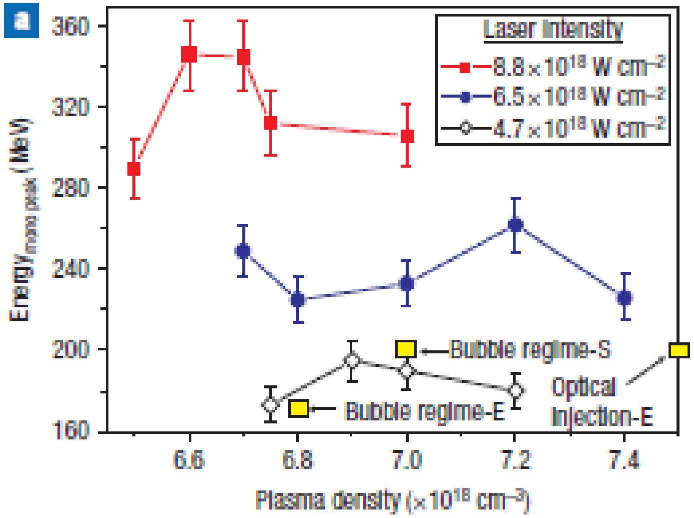


N. A. M. Hafz *et al.*, Nature Photonics **2**, 571 (2008)

100 TW, 32 fs, 22 micron,
Density 7×10^{18} cm^{-3}, 237 MeV
Energy stability 4.5% (coming from laser fluctuation).



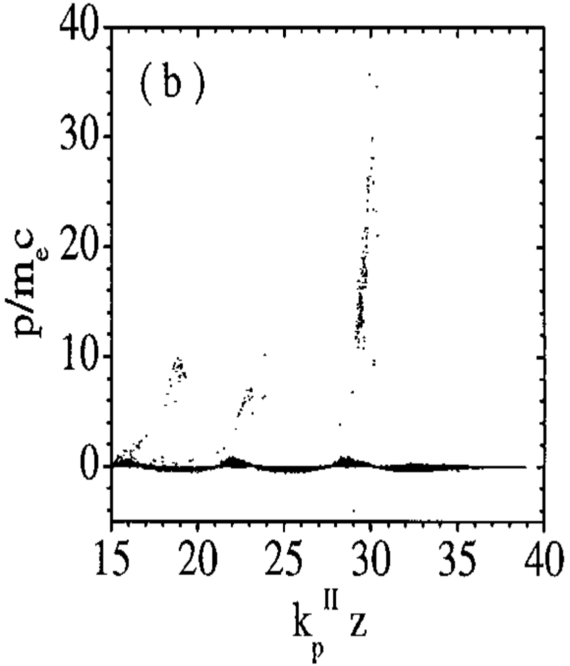


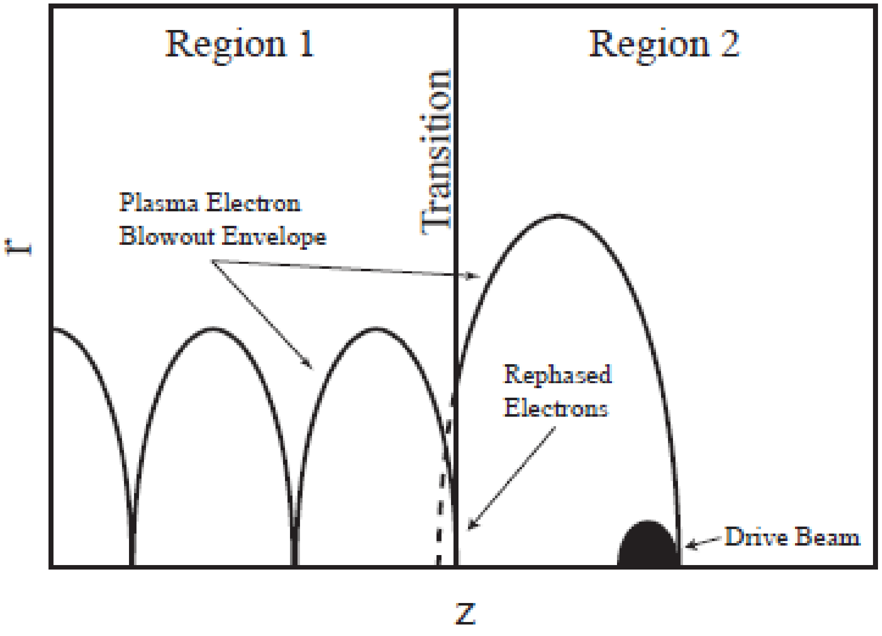


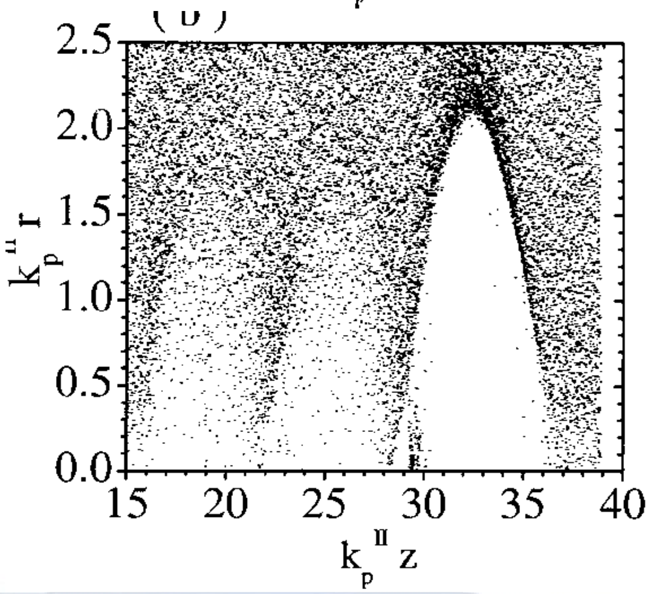
Sharp Density Transition

H. Suk *et al.*, PRL **86**, 1011 (2001)

Acoss the sharp density transition (~plasma period), the plasma wavelength suddenly increases. Intial electrons in Region 2, when they move backwards, enter Region 1, with shorter plasma wavelength. When they reenter Region 2 they are rephased, to be in the accelerating phase.

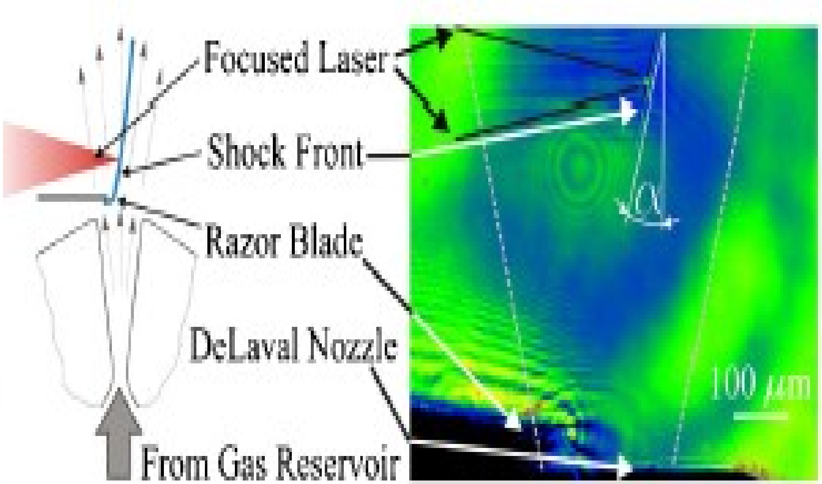


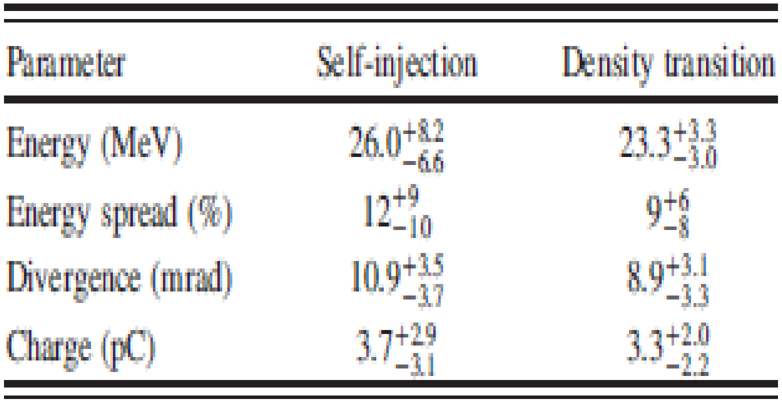




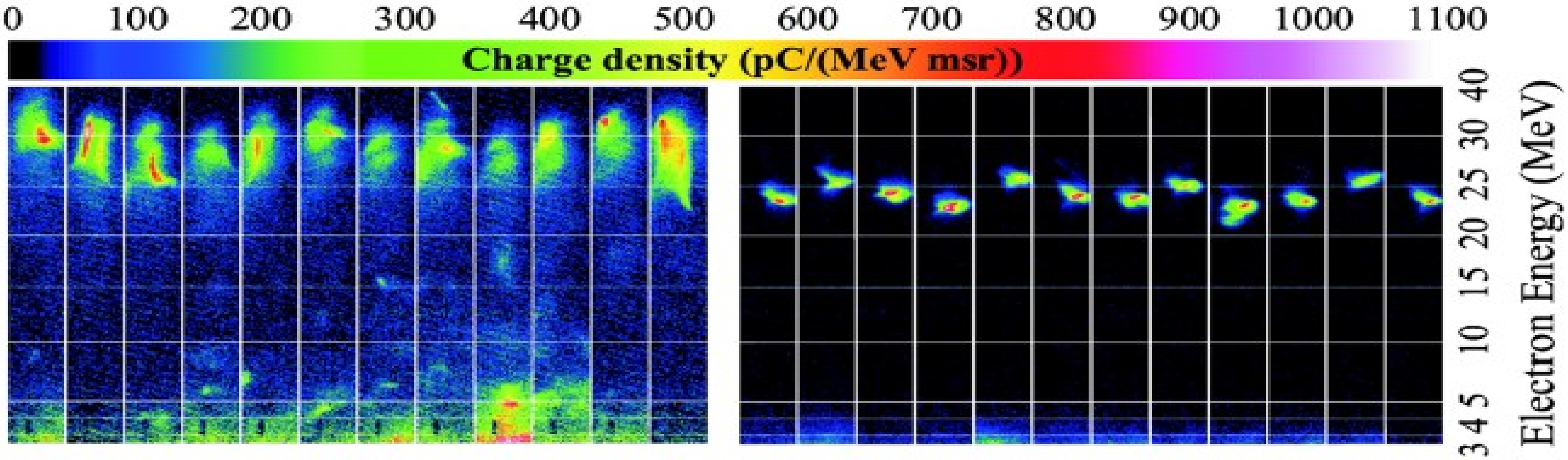
Density transition – experiment

K. Schmid *et al.*, PRSTAB, **13**, 091301 (2010)





Parameter	Self-injection	Density transition
Energy (MeV)	$26.0^{+8.2}_{-6.6}$	$23.3^{+3.3}_{-3.0}$
Energy spread (%)	12^{+9}_{-10}	9^{+6}_{-8}
Divergence (mrad)	$10.9^{+3.5}_{-3.7}$	$8.9^{+3.1}_{-3.3}$
Charge (pC)	$3.7^{+2.9}_{-3.1}$	$3.3^{+2.0}_{-2.2}$



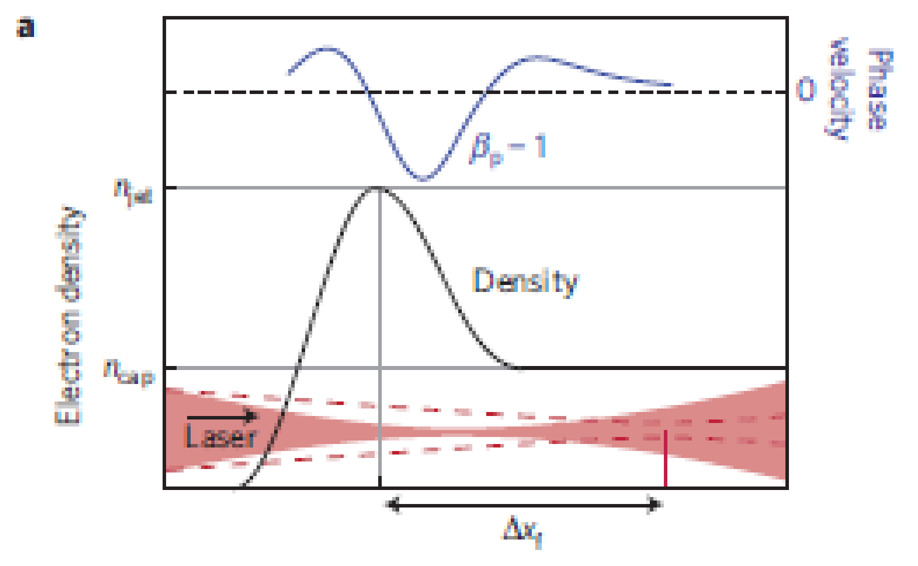
(a) Self injection

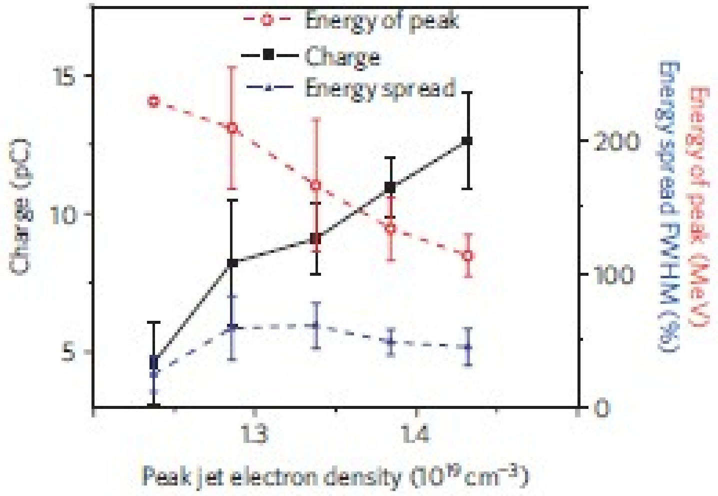
(b) Injection at density transition

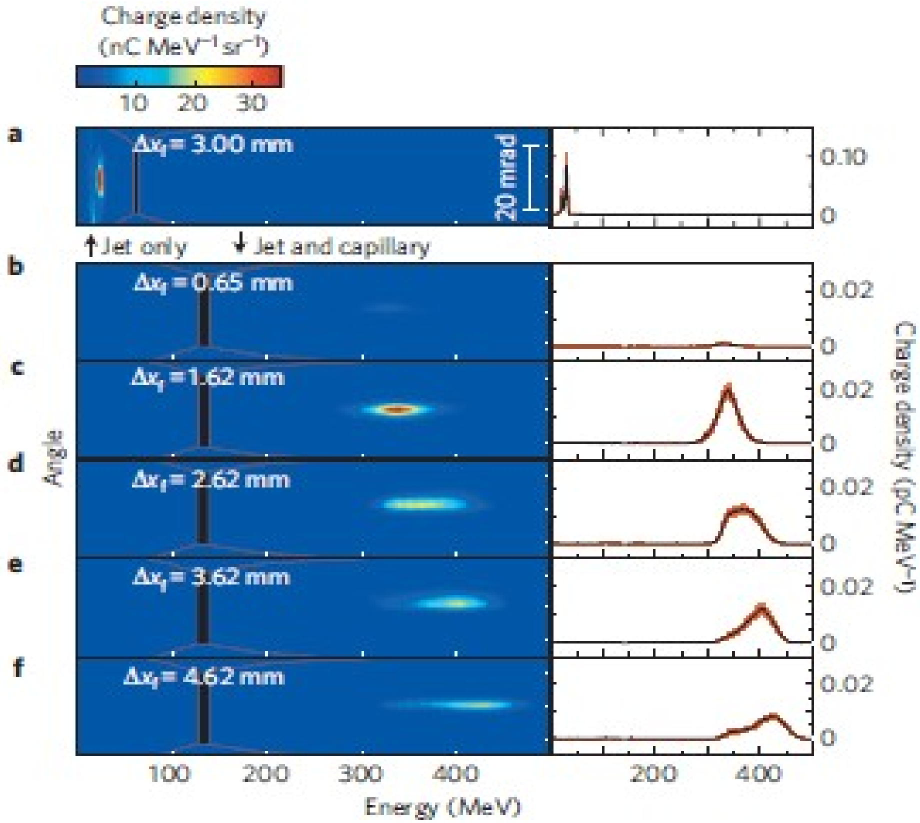
Density ramp and phase control

A. J. Gonsalves *et al.*, Nature Physics, August 2011

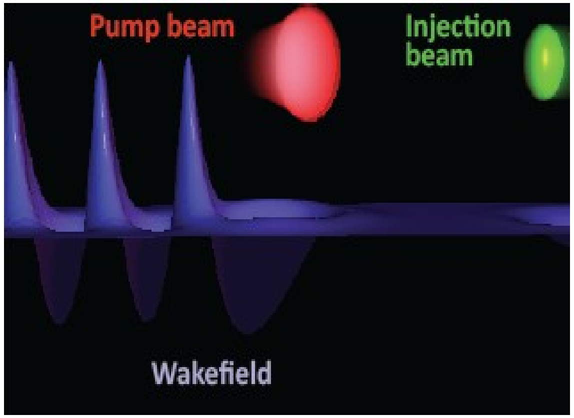
Laser 20 TW, 40 fs, a0 = 0.9,
Plasma 7 & 1.8 x10^{18} cm^{-3}.
Energy 100-400 MeV, charge 1-10
pC, energy-spread > 11%.
But, stable beam ***at low density***

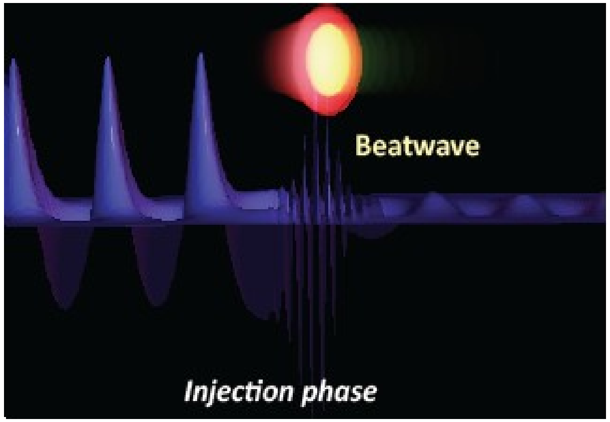


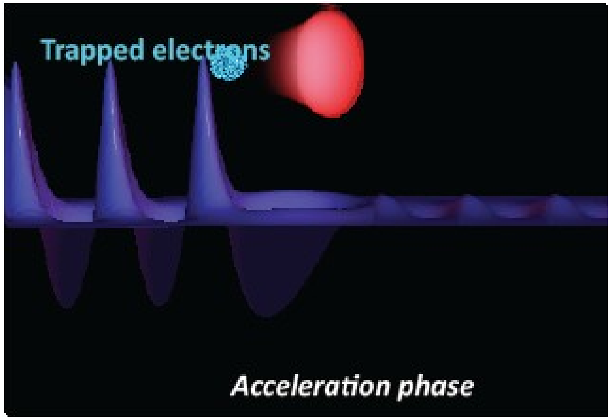




Colliding Laser Pulse







The drive laser creates an accelerating structure. The second heats the electrons and causes injection, into the first bucket.

E. Esarey et al., PRL **79**, 2682 (1997)
H. Kotaki et al., Physics of Plasmas, 11 (2004)

J. Faure *et al.*, Nature **444**, 737 (2006)

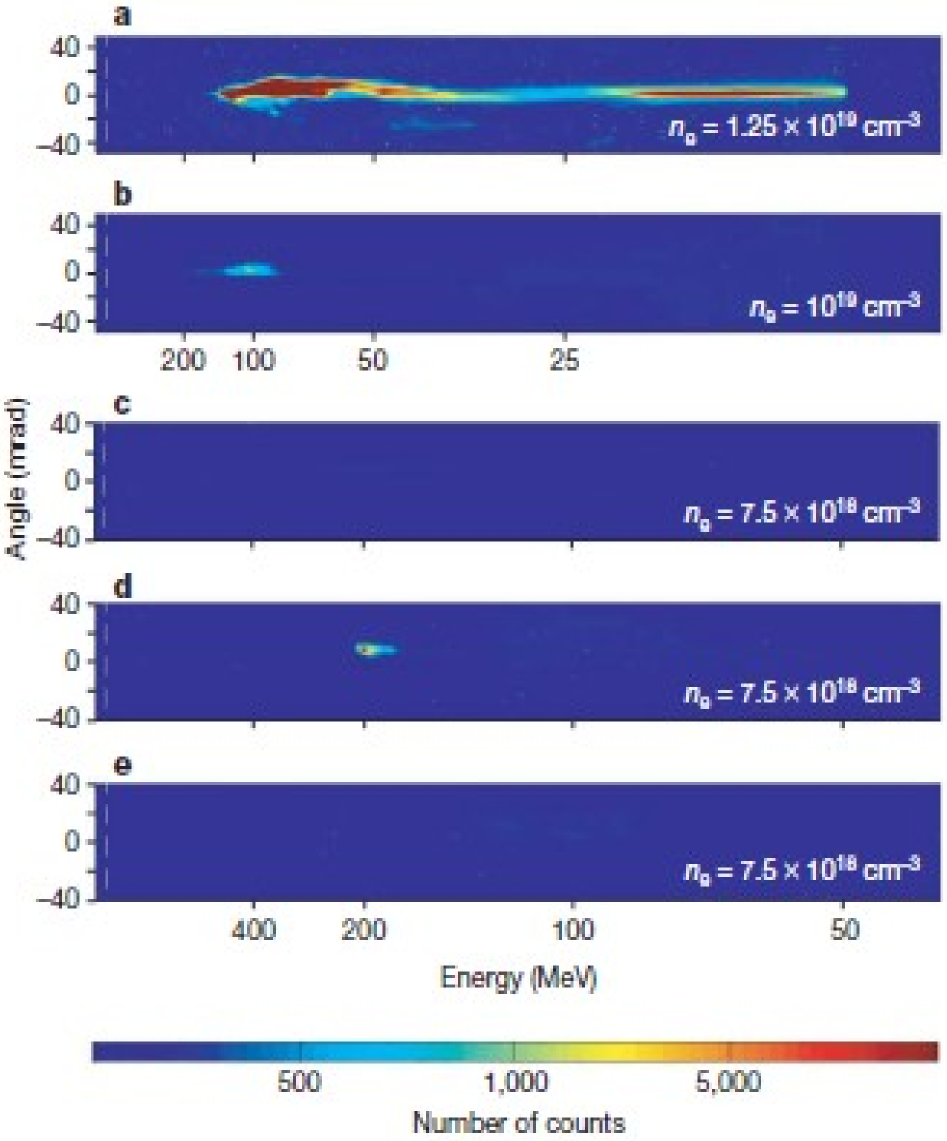
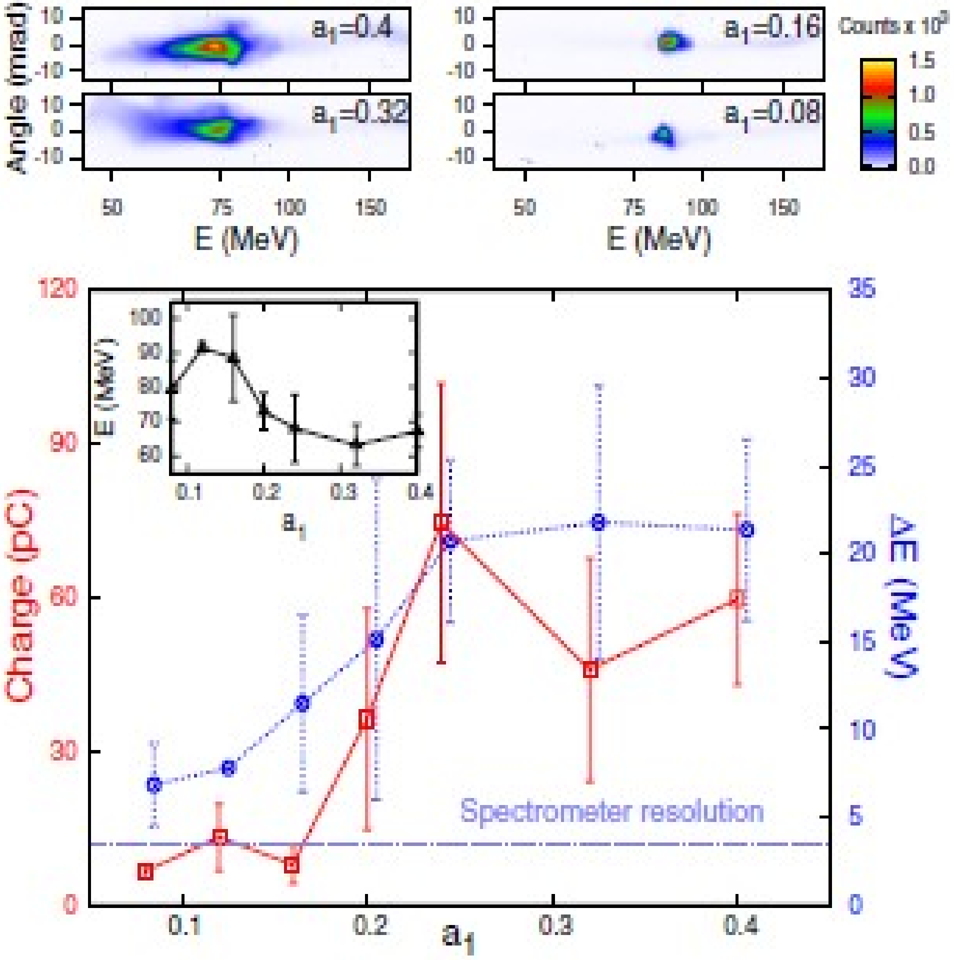


Figure 1 | Raw images of the electron beam obtained with the electron spectrometer. Horizontal axis, electron energy; vertical axis, angular divergence. The colour scale reflects the number of counts which gives an indication of the beam charge. **a–c** were obtained with the pump laser pulse only. **a**, The image shows an intense self-injected electron beam with a broad energy distribution ($n_e = 1.25 \times 10^{19}$ cm^{-3}). In **b** the self-injected electron beam has less charge but a quasi-monoenergetic distribution ($n_e = 10^{19}$ cm^{-3}). In **c** there is no electron beam, because the density is below the threshold for self-injection ($n_e = 7.5 \times 10^{18}$ cm^{-3}). **d** was obtained by colliding the pump with the injection pulse with parallel polarizations, at the same plasma density ($n_e = 7.5 \times 10^{18}$ cm^{-3}). A high-quality monoenergetic electron beam at 200 MeV is produced. **e**, When the polarizations of the laser beams are crossed, no injection occurs.

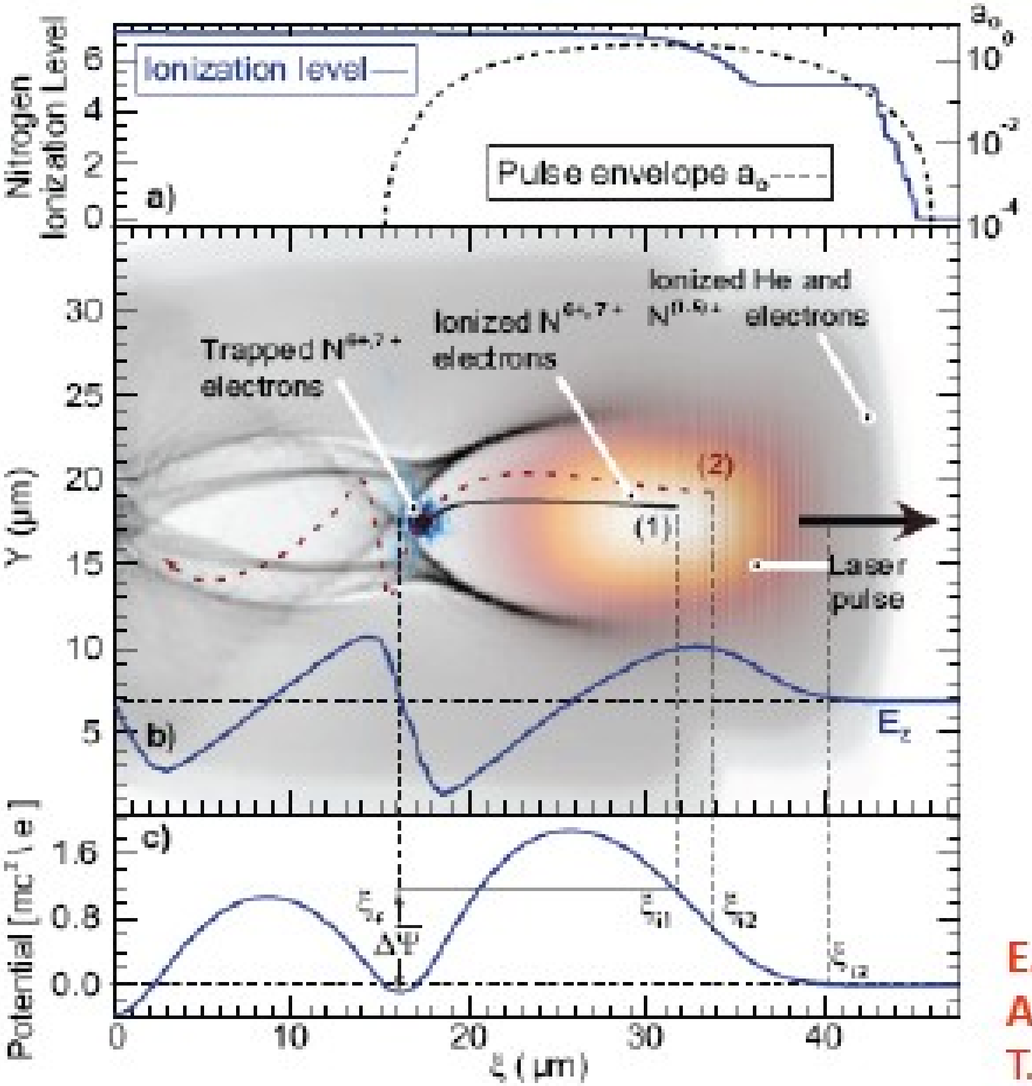
C. Rechatin *et al.*, PRL **102**, 164801 (2009)



With this method, the production of a laser accelerated electron beam of 10 pC at the 200 MeV level with a 1% relative energy spread FWHM was demonstrated.

UCLA

Ionization Induced Trapping in Laser-Produced Wakes



Use trace atoms with a large step in ionization potential

We use 9:1 He : Nitrogen mix.

The two He electrons and the first 5 (L-shell) N electrons form the wake

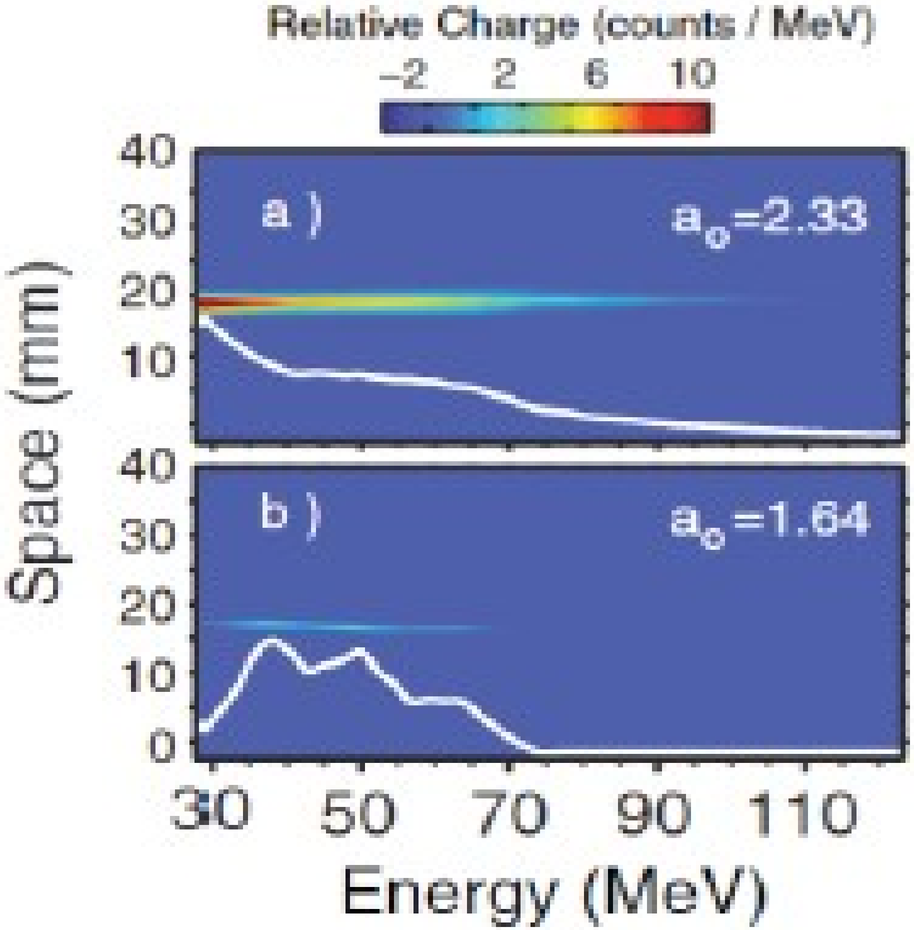
The 6th (K shell) nitrogen electron is ionized in the wake and trapped more easily by the wake potential than the electrons that support the wake.

Ionization trapping reduces the wake amplitude and therefore the laser power needed to trap electrons.

E.Oz et al PRL 2007

A . Pak et al submitted Phys Rev Lett (2009)

T.R. Rpwland -Rees et al PRL (2006)



Laser: 10 TW, 0.8J, 45 fs, $a_0 \approx 2$, $n_e = 1.4 \times 10^{19}$ cm^{-3}

Improve the energy spread at low laser intensity
Improve the stability
Increase the charge

C. McGuffey et al Phys. Rev. Lett. 104, 025004 (2010)

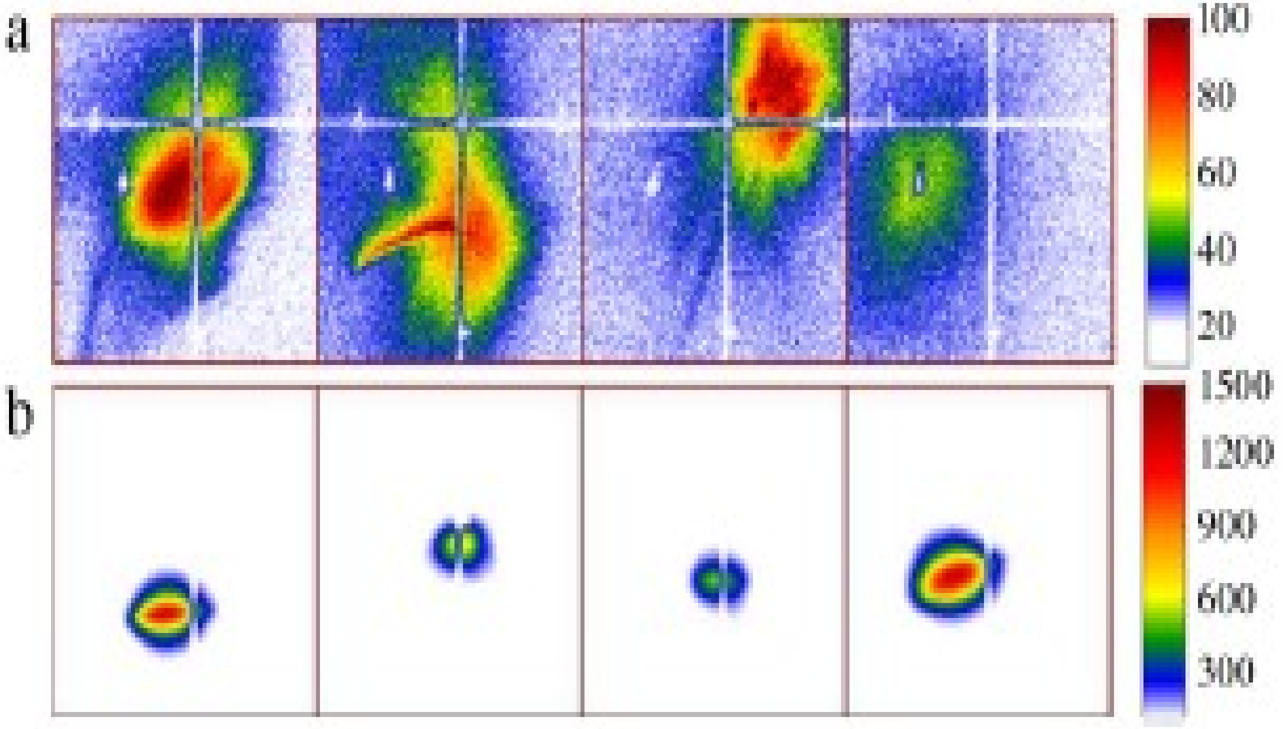
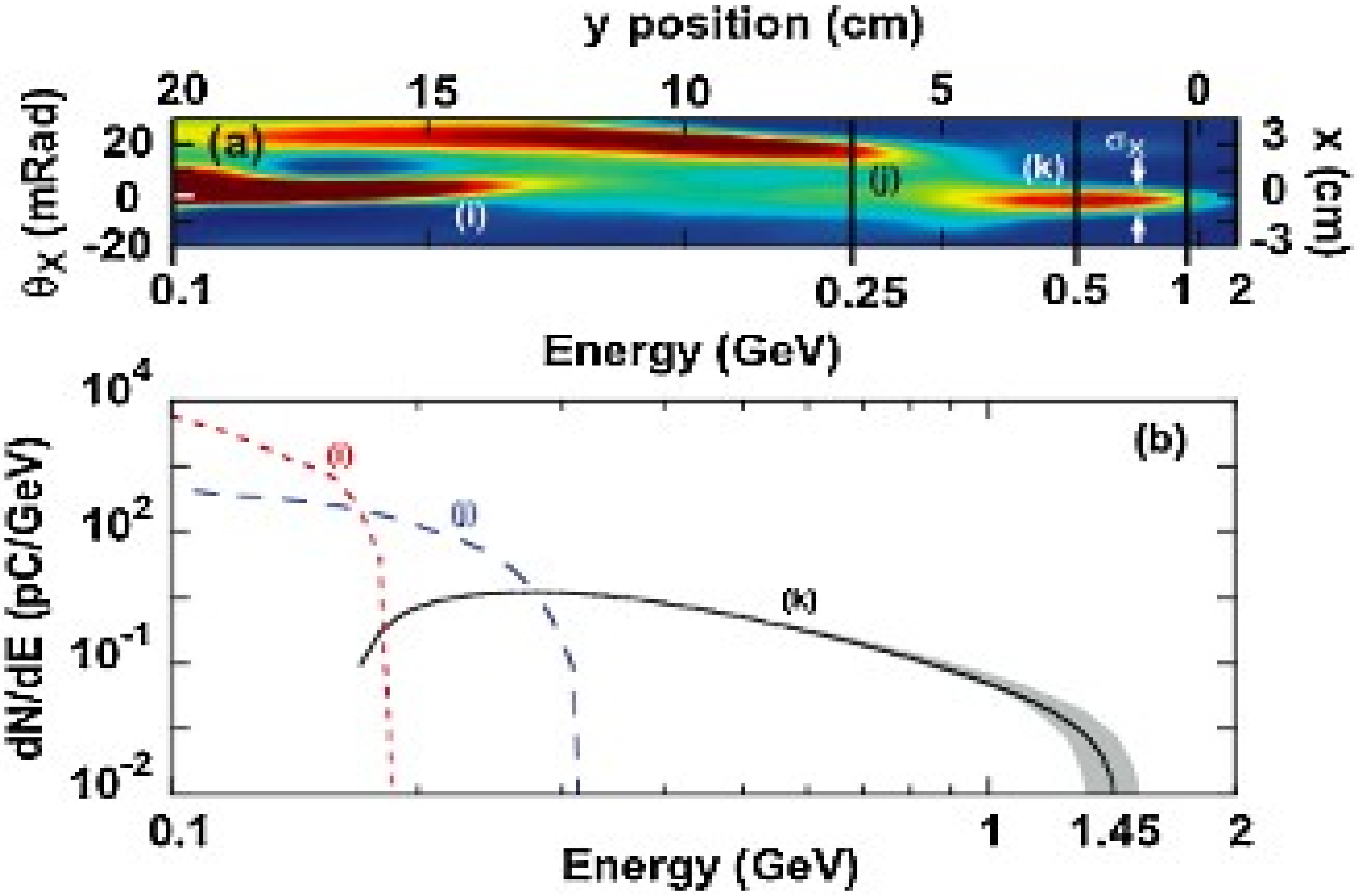


FIG. 3 (color online). Electron beam profiles measured on a Lanex screen 1 m from the target. The top four images, (a), are from shots with pure helium and the bottom four, (b), are from shots with a 1% argon additive, both at equal electron number density $n_e = 2 \times 10^{19}$ cm^{-3}. Note the difference in color scale, which represents electron signal [arb] per pixel.

1.4 GeV in 13 mm through ionization trapping

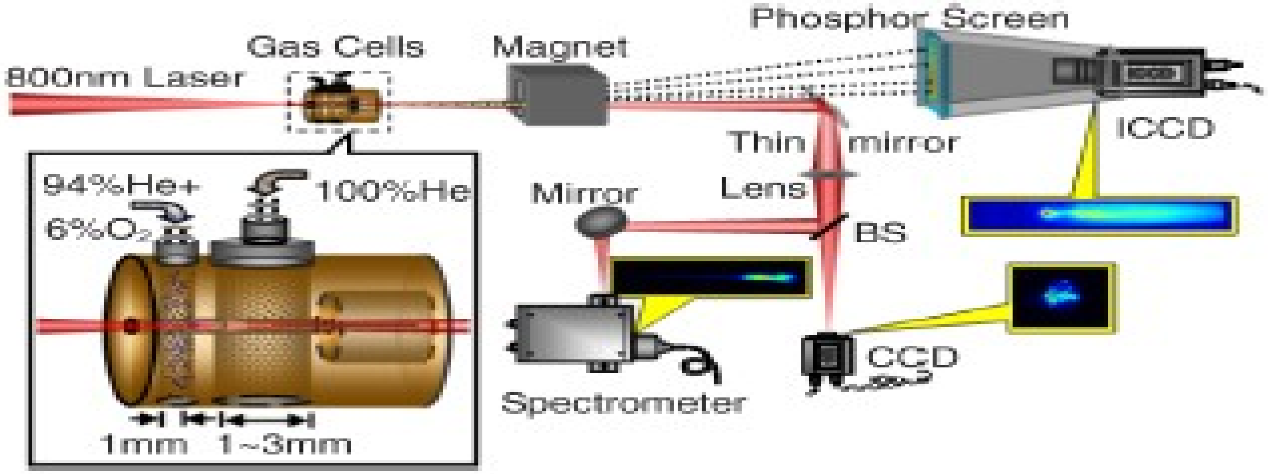
C E Clayton *et al.*, Phys. Rev. Lett. 105, 105003 (2010)

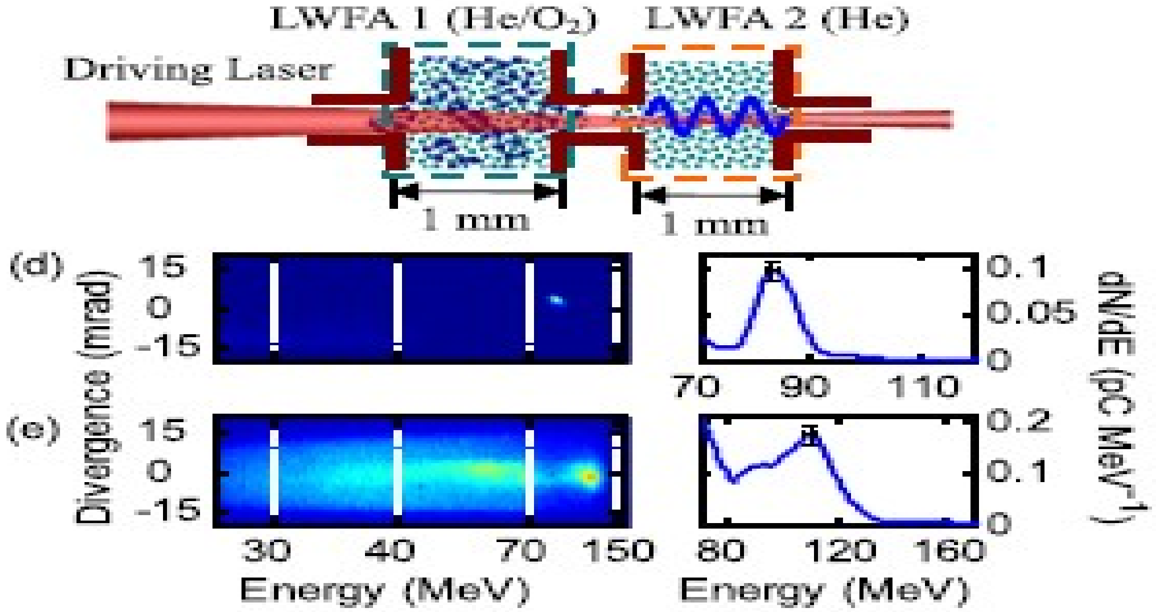


110 TW, 60 fs, He(97%)+CO2(3%), 1.3 cm length, density $1.3\text{x}10^{18}$ $\text{cm}^{-3.}$
Self-guiding has been demonstrated at the cm-lscale.

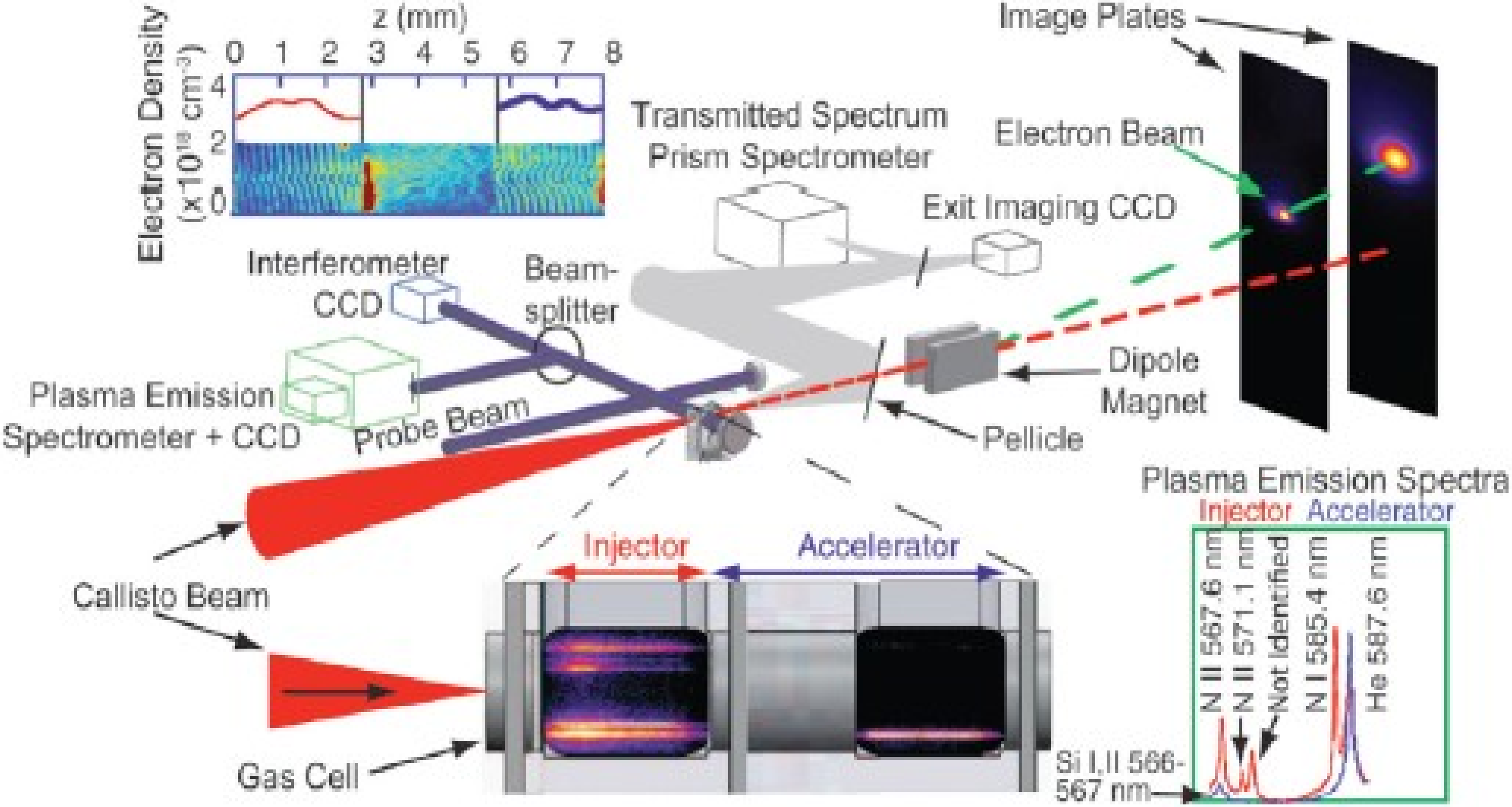
Ionization-trapping – double stage

J. S. Liu *et al.*, PRL 107 035001 (2011)





Ionization Induced Trapping : two stage plasma accelerators



Laser : 30-60 TW, 60 fs, a_0=2-2.8, n_e=3x10^{18}cm^{-3}

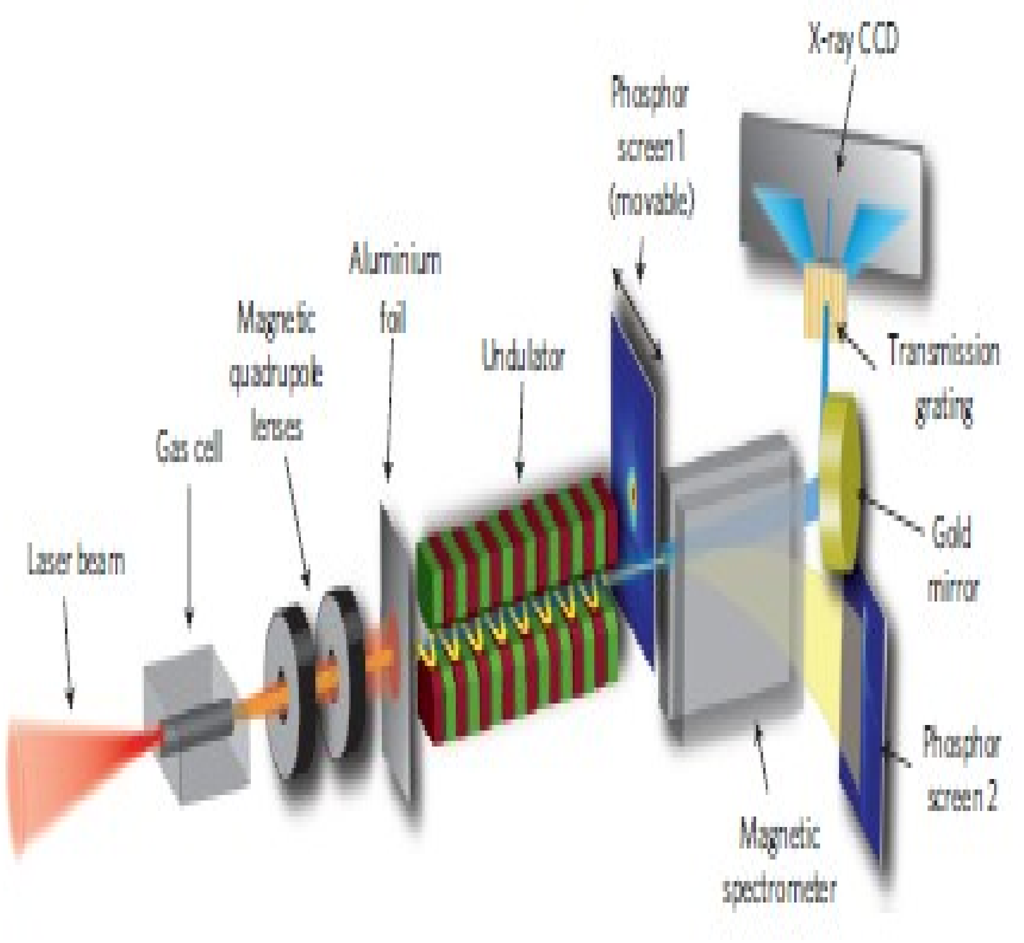
35 pC, 460 MeV, div = 2 mrad, DE/E>5%

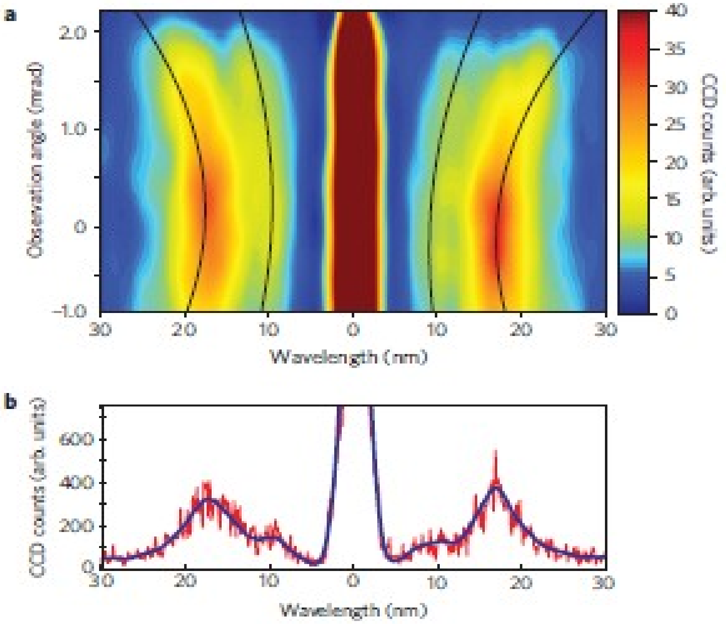
B. B. Pollock et al., PRL 107, 045001 (2011)

Applications to Radiation Sources

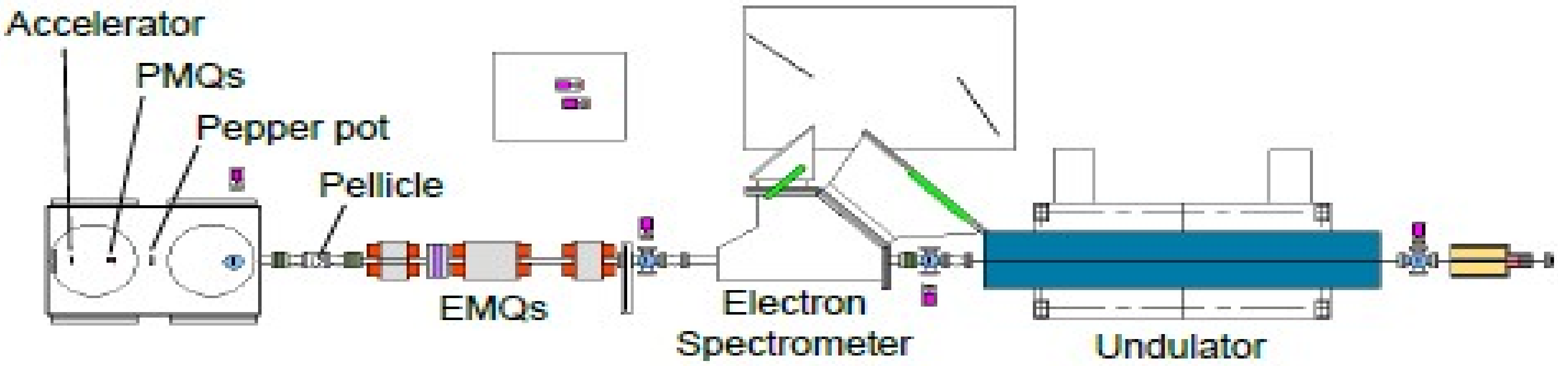
Laser-driven soft X-ray undulator source

M. Fuchs *et al.*, Nature Physics, 5, 826 (2009)

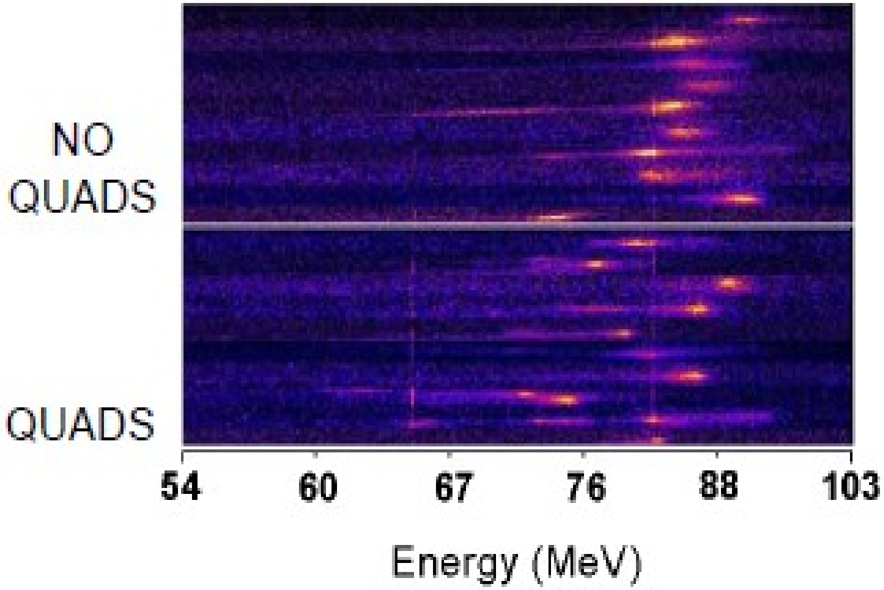


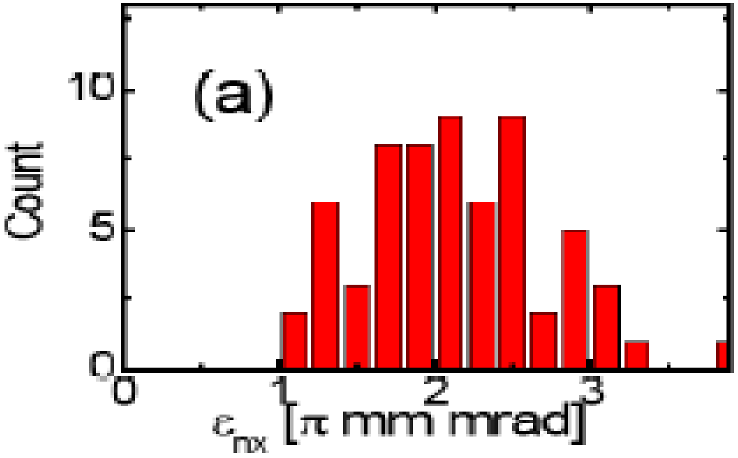


ALPHA-X Beam Line

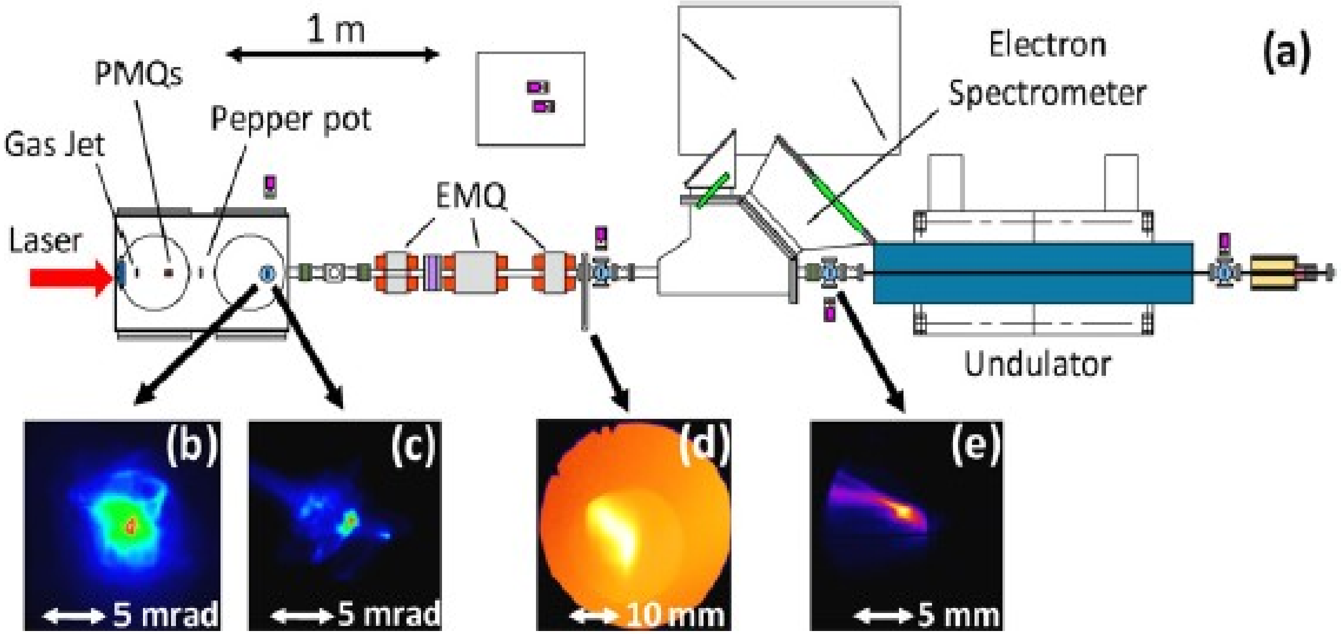


- Laser: λ_0 = 800 nm, E = 900 mJ, τ = 35 fs, P = 26 TW, $I = 2 \times 10^{18}$ Wcm^{-2}, initial a_0 = 1.0
- Gas Jet: helium, 2 mm nozzle, $n_e \approx 1 - 5 \times 10^{19}$ cm^{-3}





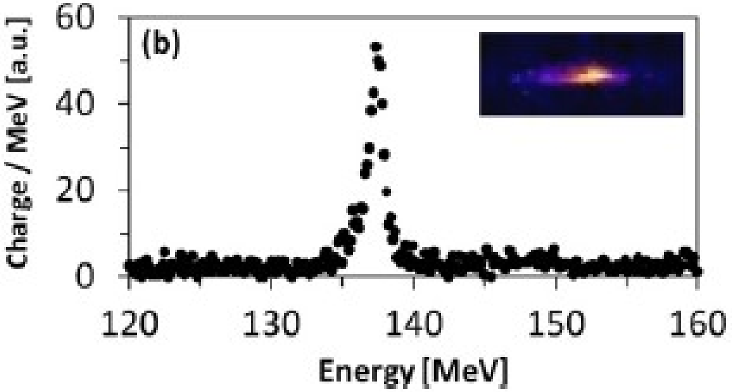
ALPHAX experiment

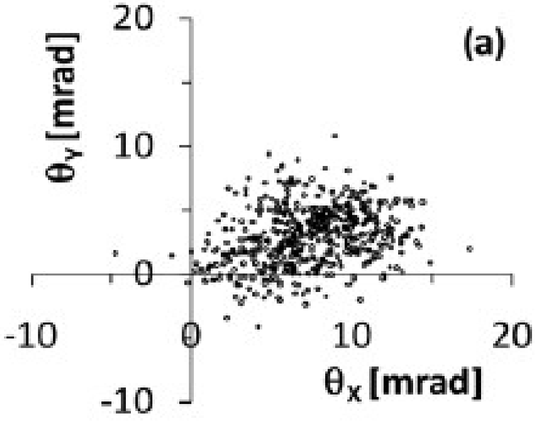


Energy-spread < 1%

Emittance 1.25 mm-mrad for 125 MeV beam.

(However, emittance will increase with distance/energy.)





Summary

No problem in getting GeV beams. Still to get ~ 10 Gev beam

No problem getting kA beams, because of the fs pulse-length. However, may have to worry about pulse-stretching in transporting the beam.

Energy-spread < 1% still only achieved by ALPHAX. May be OK for soft X-ray FEL.

Normalized emittance of 1 pi mm-mrad achieved only by ALPHAX. Consistent with size, divergence and energy?

Stability still needs to be improved.

Repetition rate needs to improve only slightly (say 50 Hz).

Must remember that best numbers have been demonstrated in different situations, especially at different energies. Things will get worse with greater acceleration.

Need to study injection mechanism in greater detail – transevrse position and momentum of injected particles.

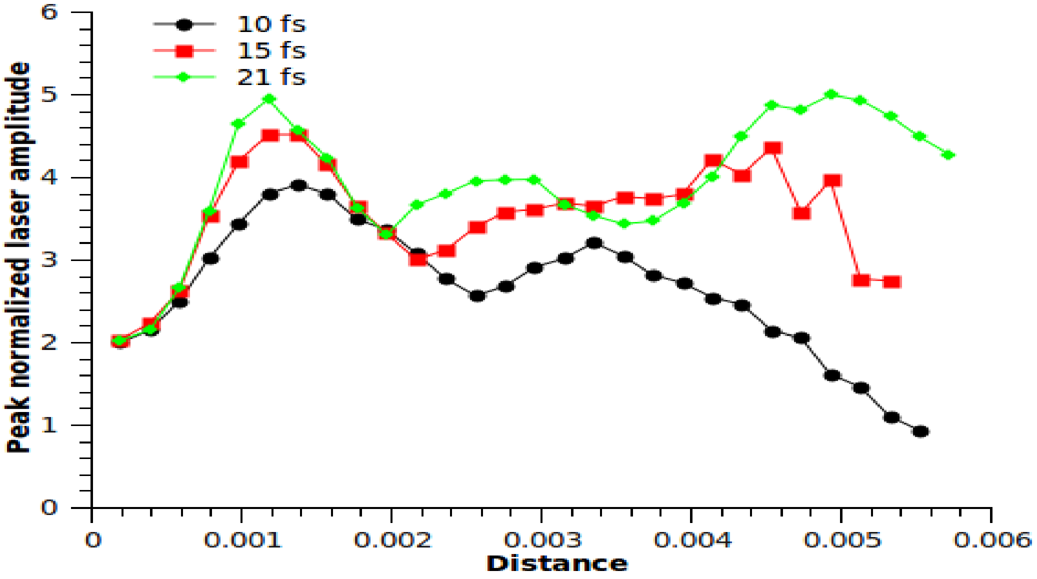
Work done at Centre for Excellence in Basic Sciences (CBS), Mumbai

Evolution Dynamics of laser pulse in near injection threshold regime

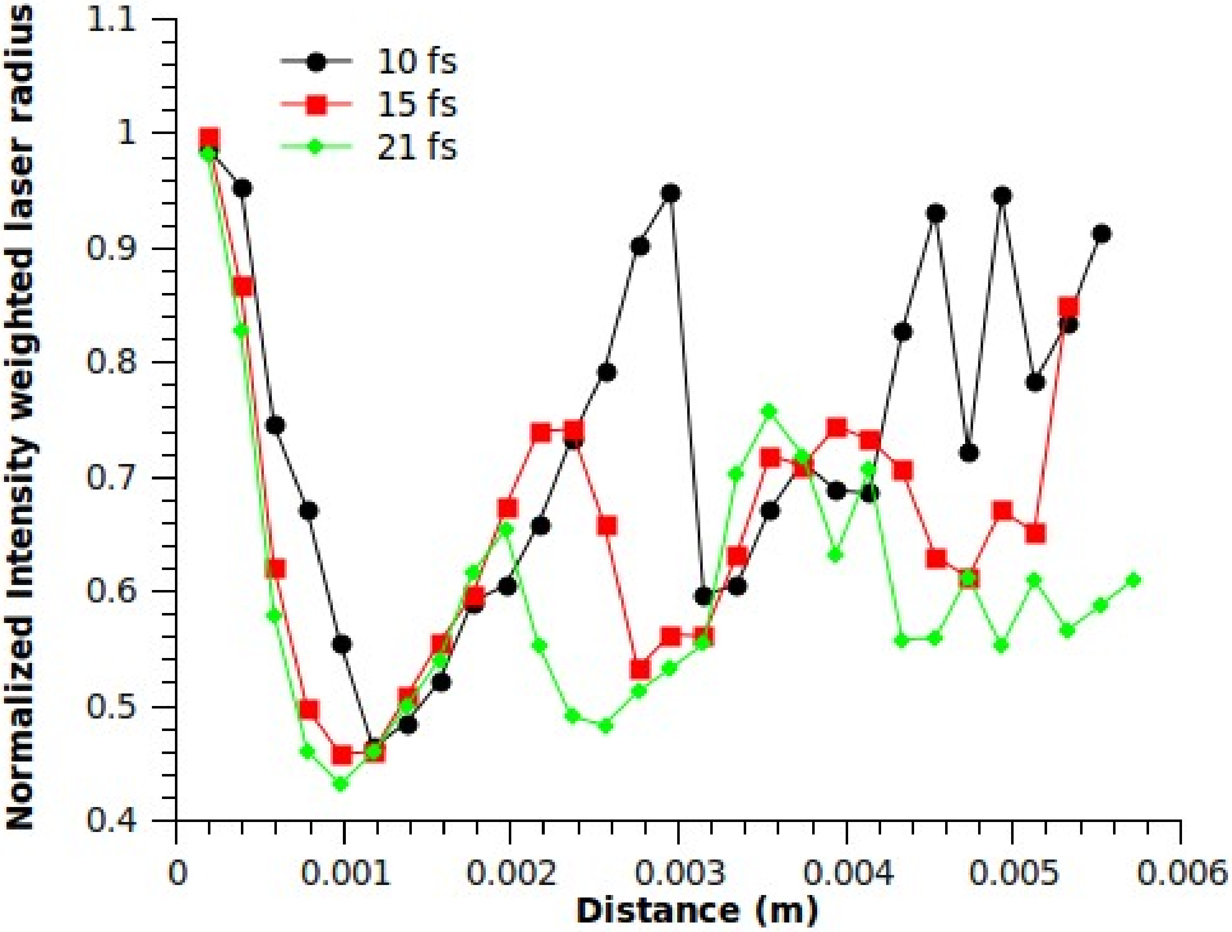
Ajay K. Upadhyay, Sushil A Samant, Deepangkar Sarkar, Pallavi Jha,
Srinivas Krishnagopal,
Physics of Plasmas ***18****, 033109 (2011)*

- Laser wavelength = 800 nm
- Laser intensity (a0) ~ 1.5 - 2
- Laser pulse-width = varied from 10 – 25 fs
- Laser spot-size = varied (> plasma wavelength; ~ 20 μ m)
- Plasma wavelength = 18 μm (3.4 x 10^{18} cm^{-3}
- Homogenous plasma
- Simulations using VORPAL

Evolution of normalized laser pulse peak amplitude

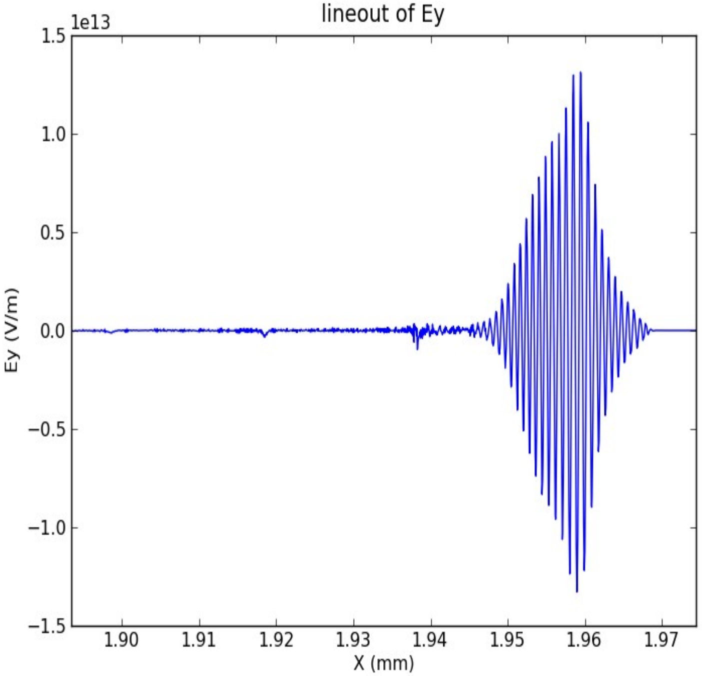


Evolution of spot size

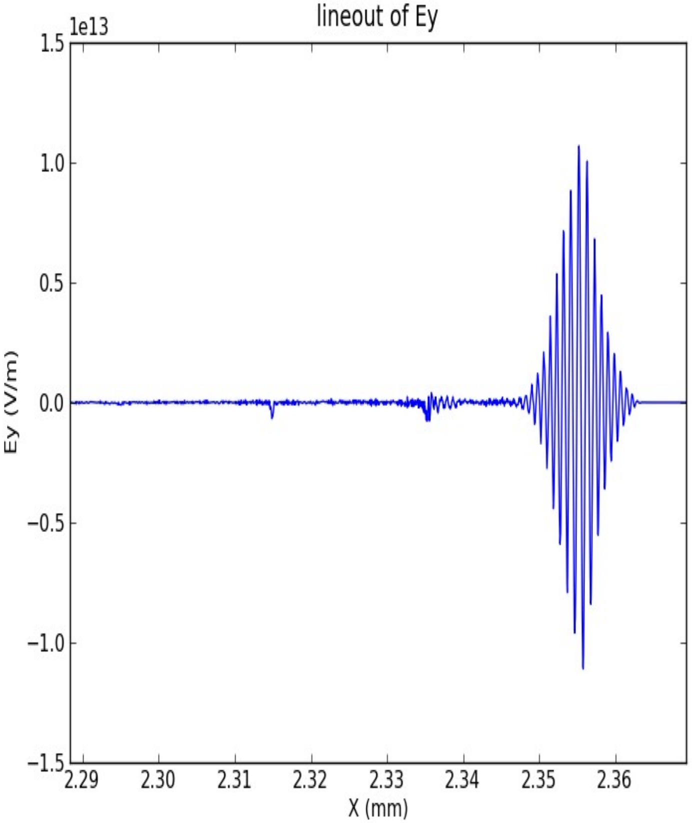


Pulse steepening

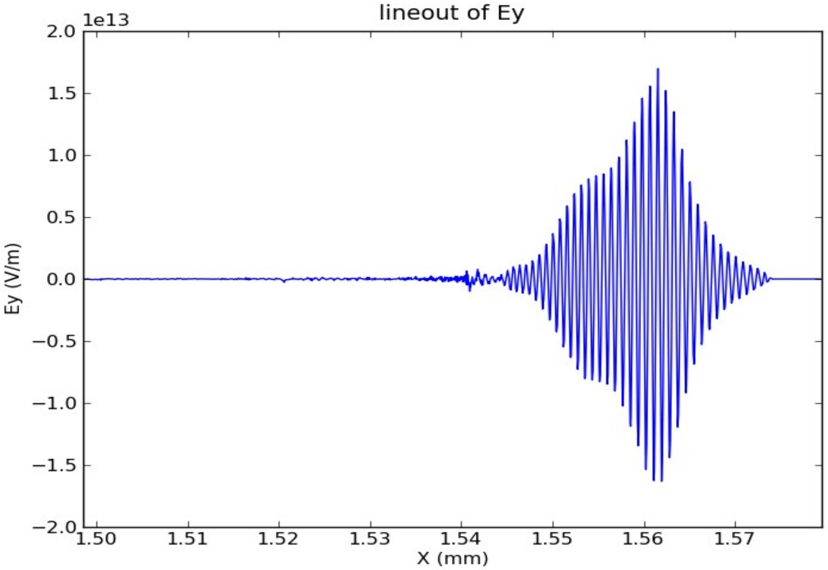
15 fs



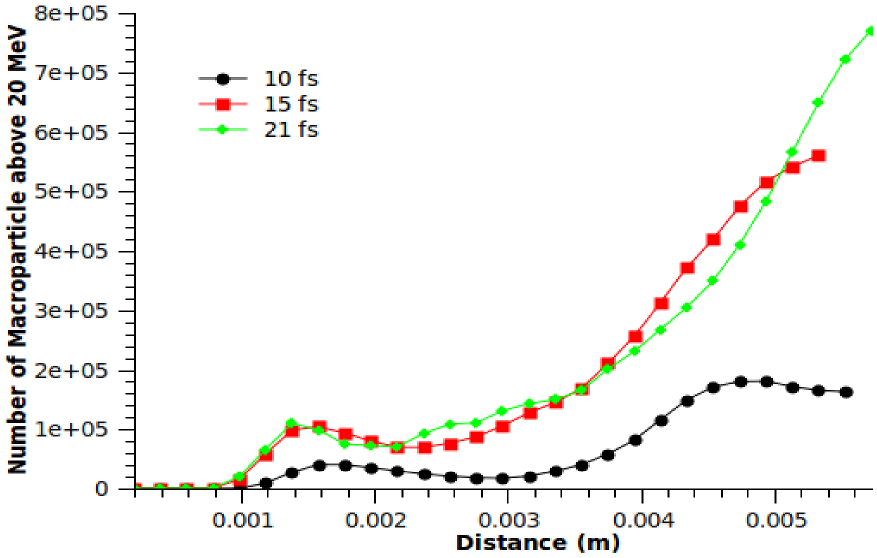
10 fs

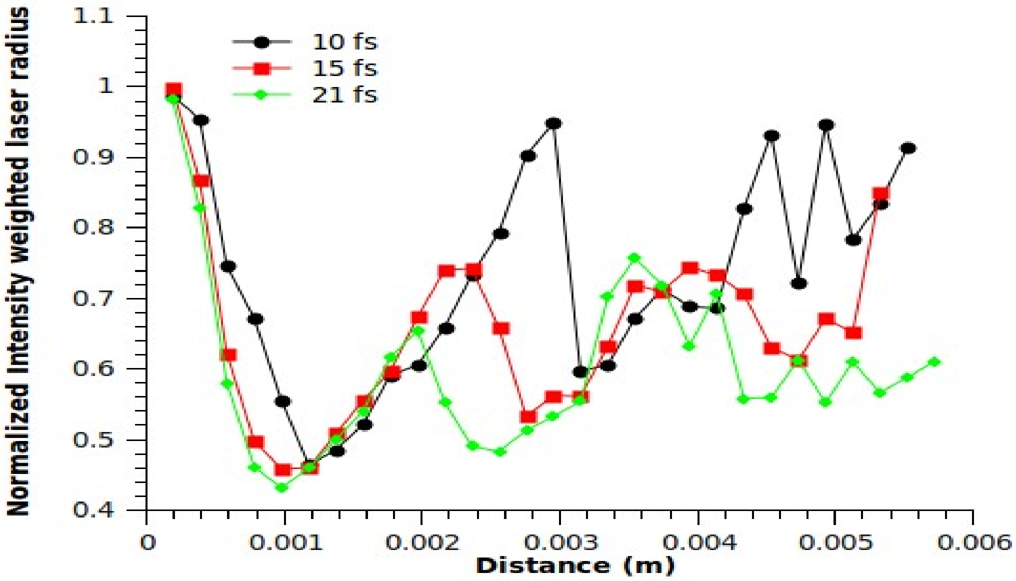


21 fs

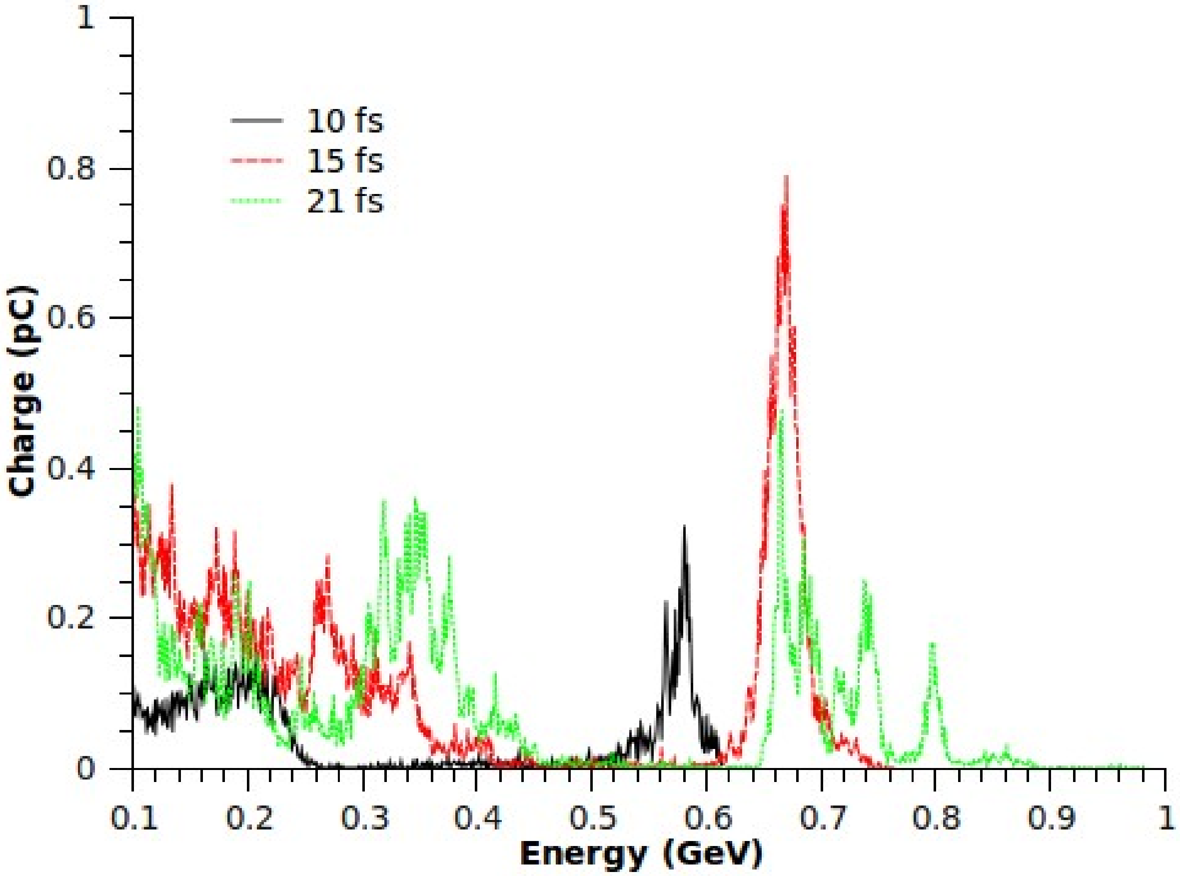


Self injection of electrons due to laser pulse evolution





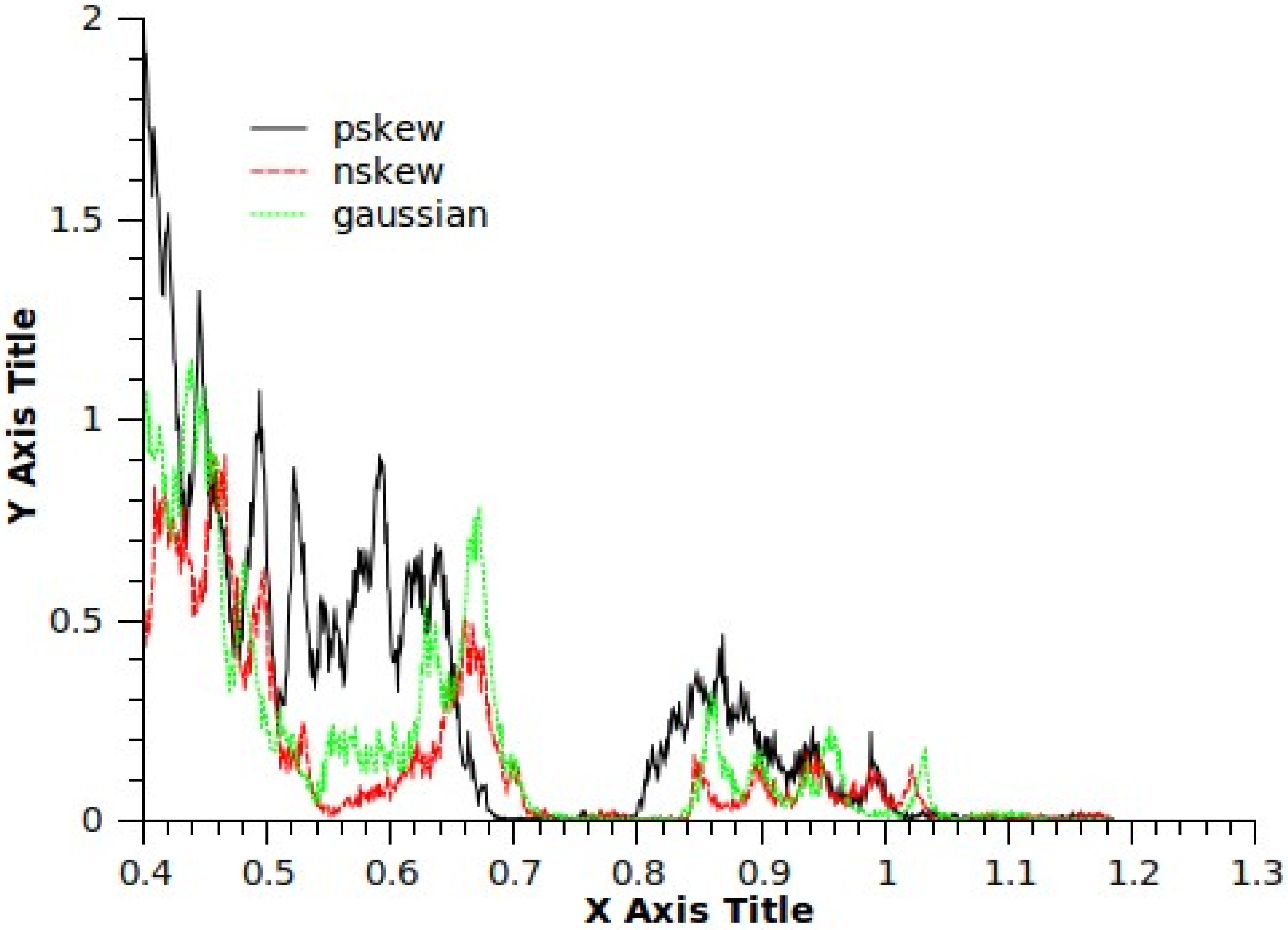
Histogram after propgating a distance 3.12 mm



parameters	L=10fs	L=15 fs	L=21fs
Mean energy (GeV)	0.57	0.67	0.71
Normalized Emittance (mm-mrad)	5.9 (y) 2.38 (z)	7.63 (y) 4.09 (z)	7.96 (y) 4.17 (z)
Rms Energy spread (%)	3.59	2.84	7.04
Charge (pC)	7.25	24.0	18.0
Current (kA)	0.98	2.5	2.83
Rms Beam length (fs)	1.23	1.6	1.06
Plasma length (mm)	3.12	3.12	3.12

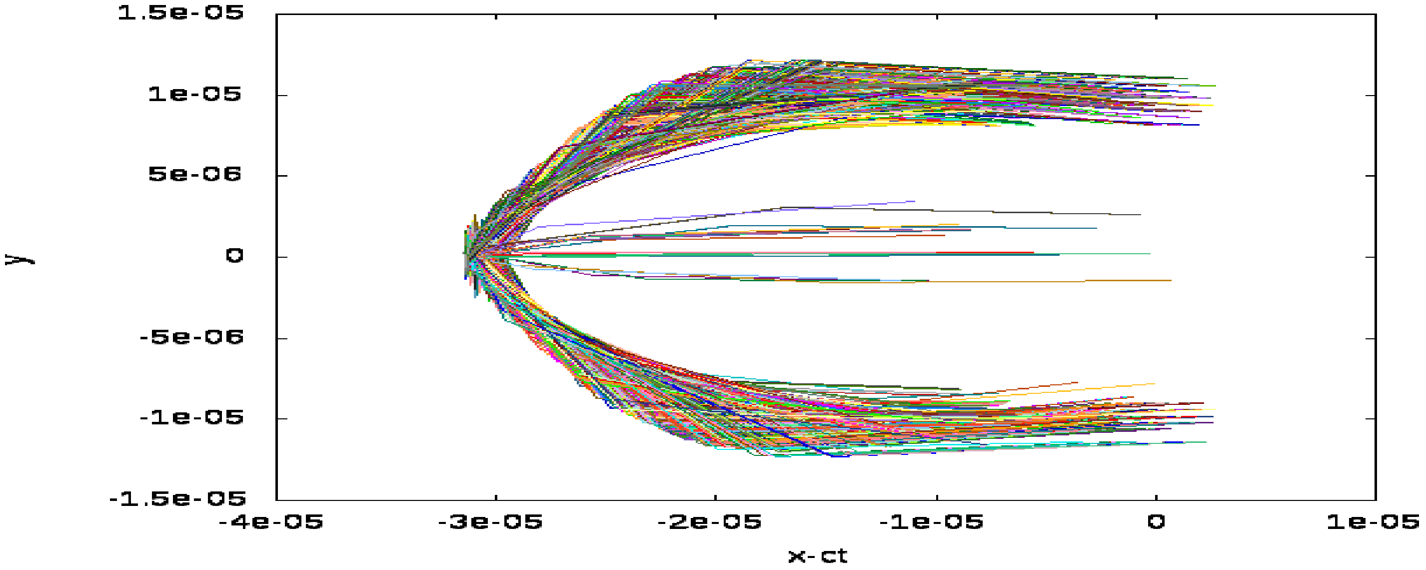
Use of skew-Gaussian pulses

Histogram after propgating a distance 5.07 mm

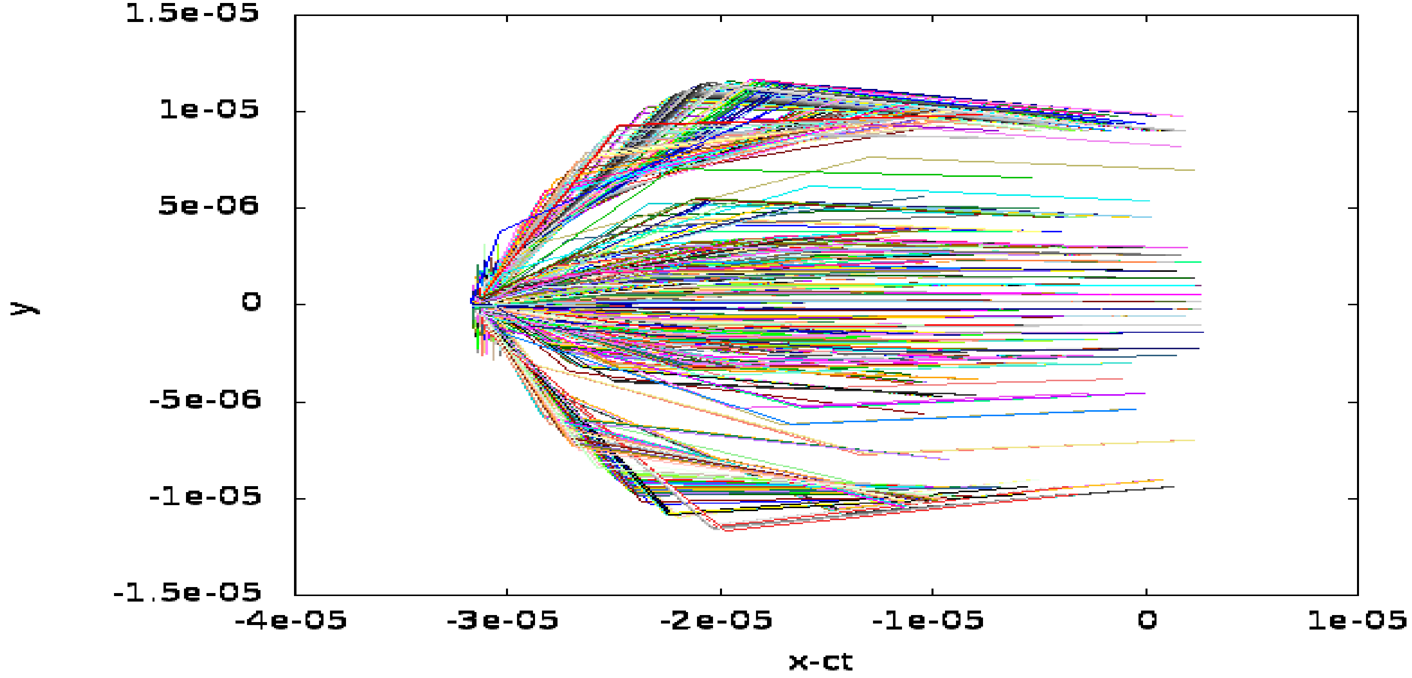


Pulseshape	Gaussian	Positive skew	NegativeSkew
Mean energy (GeV)	0.93	0.89	0.95
Normalized Emittance (mm-mrad)	15.45 (y) 5.9 (z)	37.5 (y) 9.4 (z)	21 (y) 6.89 (z)
Rms Energy spread (%)	7.0	6.6	7.07
Charge (pC)	18.34	36.7	14.7
peakcurrent (kA)	2.34	1.99	1.92
Rms Beam length (fs)	1.3	3.07	1.27
Plasma length (mm)	5.07	5.07	5.07

Injection of plasma electron in laser driven plasma cavity

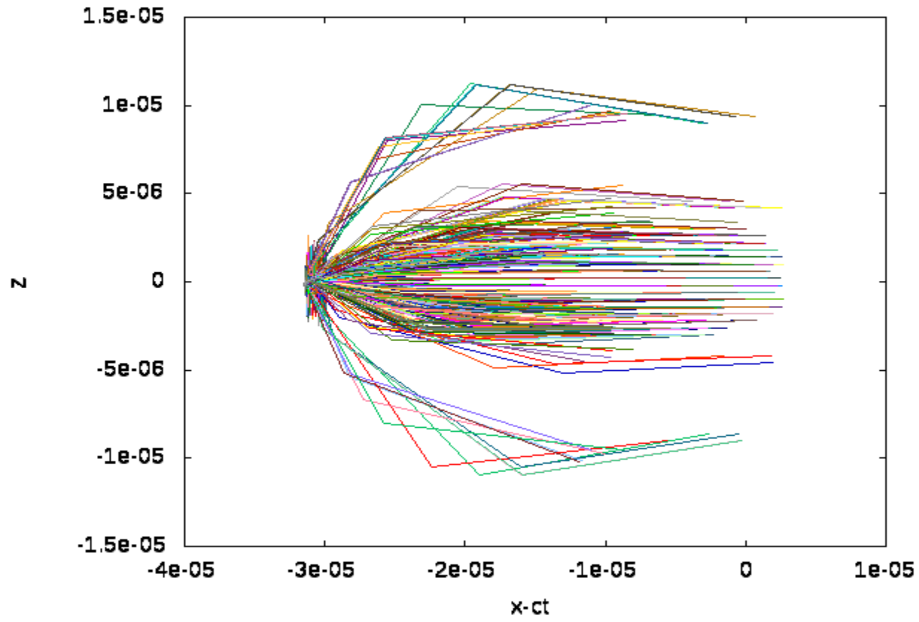


Y Polarized laser pulse

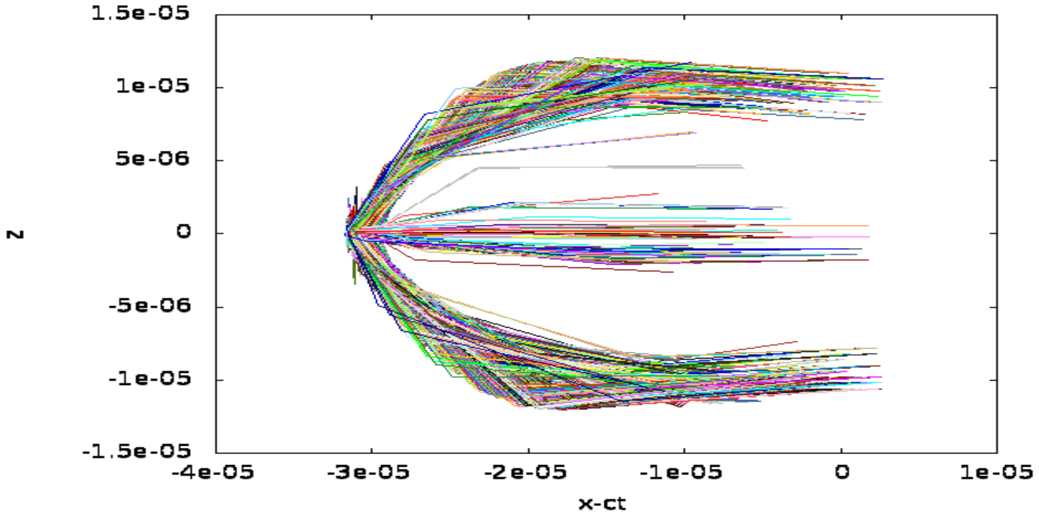


Z polarized laser pulse

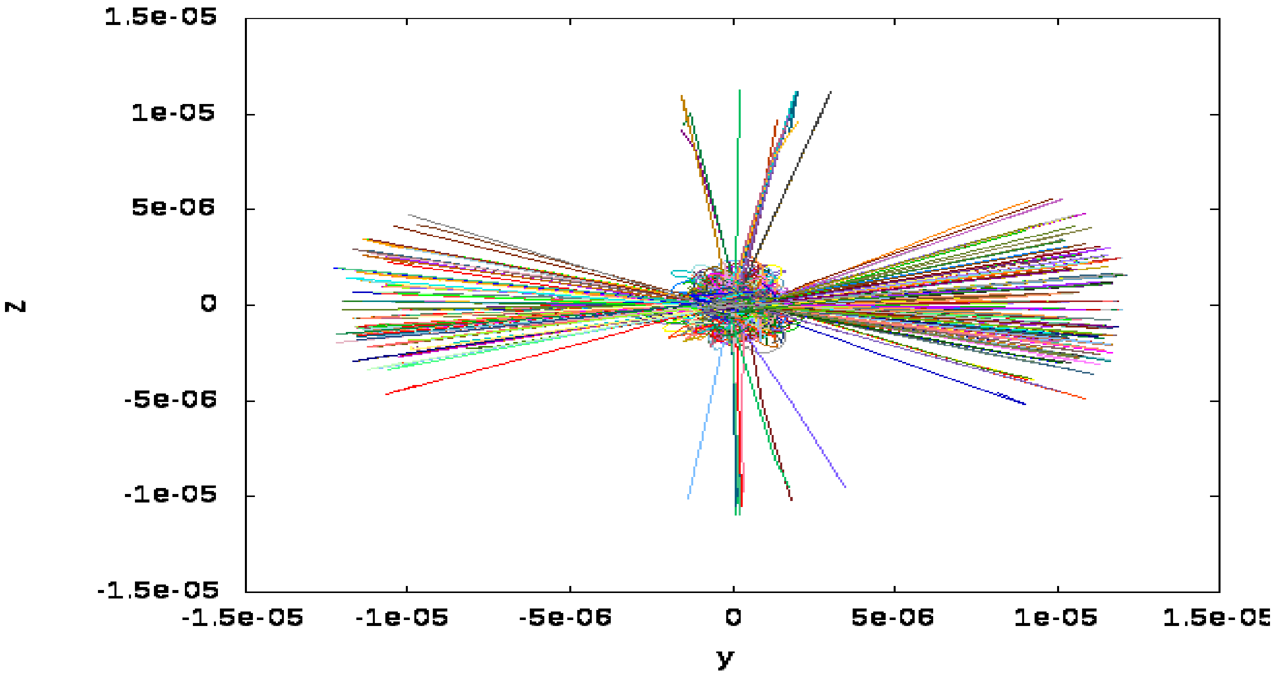
Y Polarized laser pulse



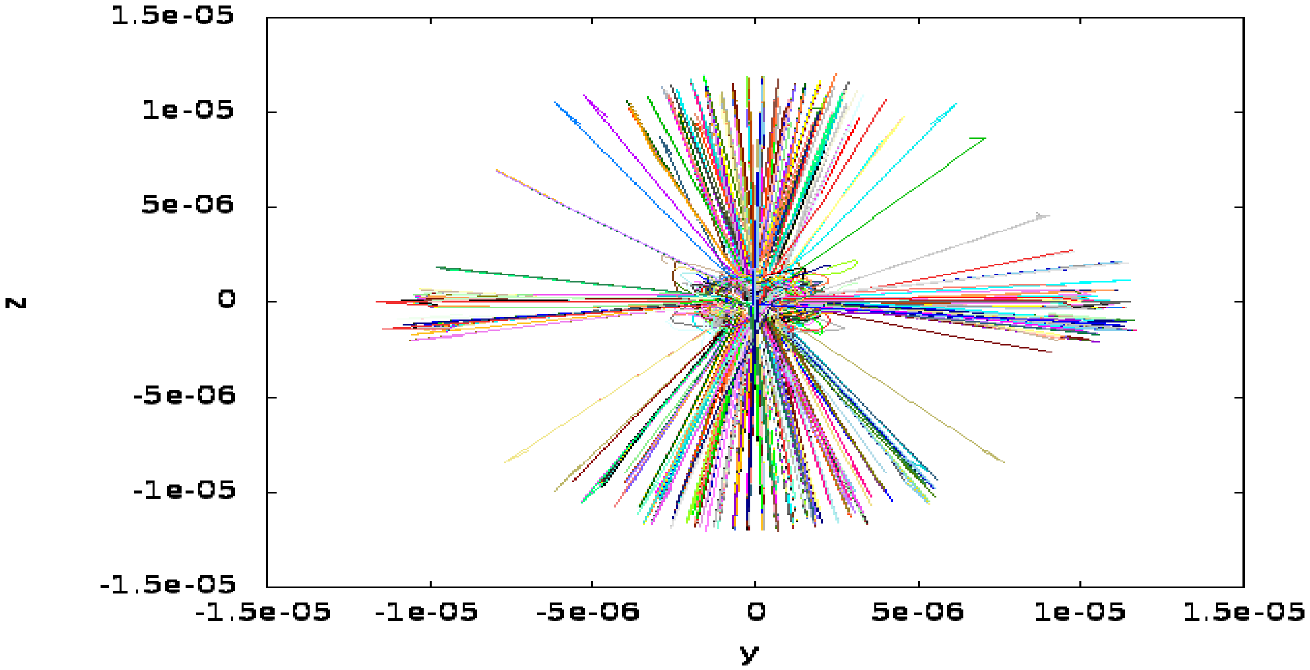
Z Polarized laser pulse



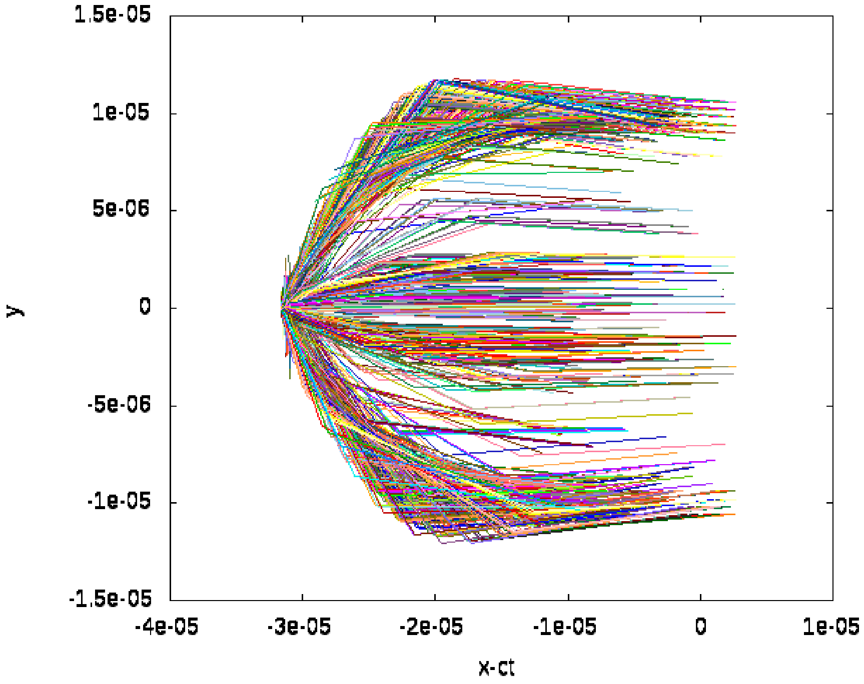
Ypolarized laser pulse

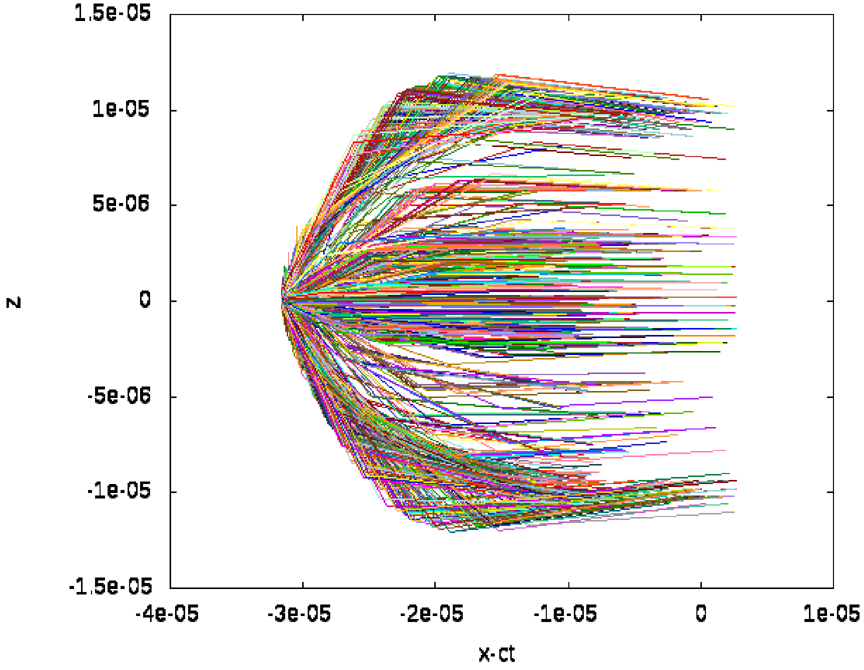


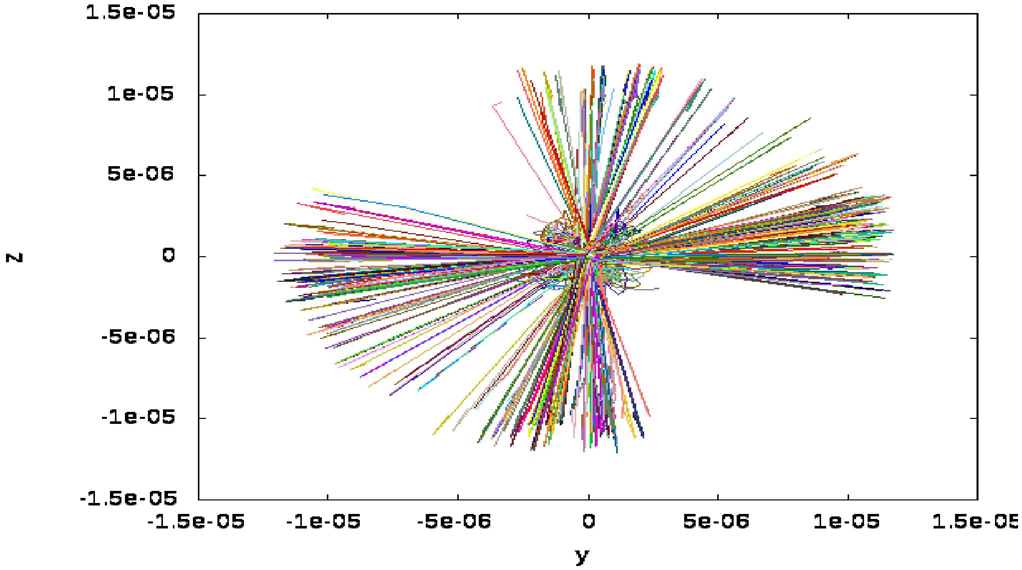
Z polarized laser pulse



Circular polarized laser pulse







Conclusion from injection study

1. The trajectory of high energy electrons show particles which are injected, their initial co-ordinate is asymmetric. If particle is coming from large y its z co-ordinate is small.

2. The number of particle coming from large y is larger in y polarized case, and a reversal of this behavior is observed in z polarized light.

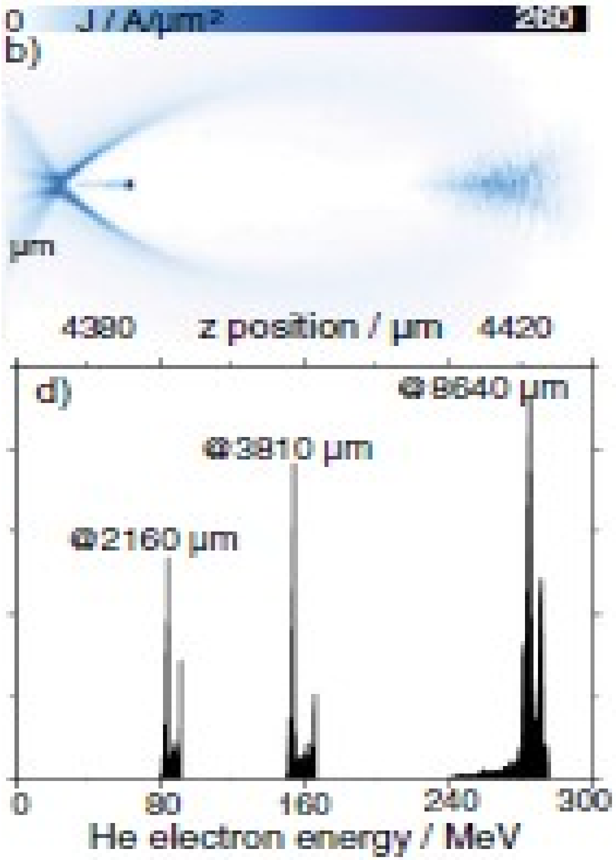
3. The asymmetry in injected particle coordinate is also found for circular polarized laser pulse, but number of particle coming from large y and large z is nearly equal.

4. Injected particles start with more transverse momentum than longitudinal momentum, and drift directly towards the axis. After a time equal to around one plasma period, the longitudinal momentum becomes roughly equal to the transverse momentum. At this time the beam is already relativistic.

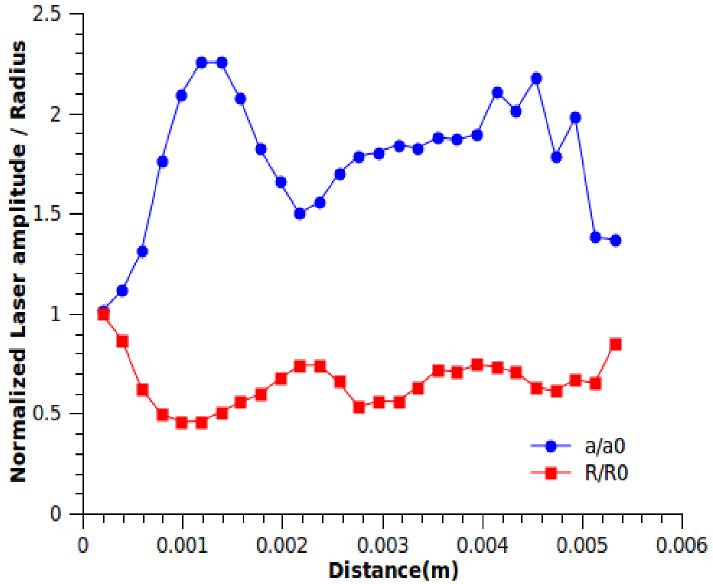
5. Need to understand details of injection better to improve emittance and energy-spread.

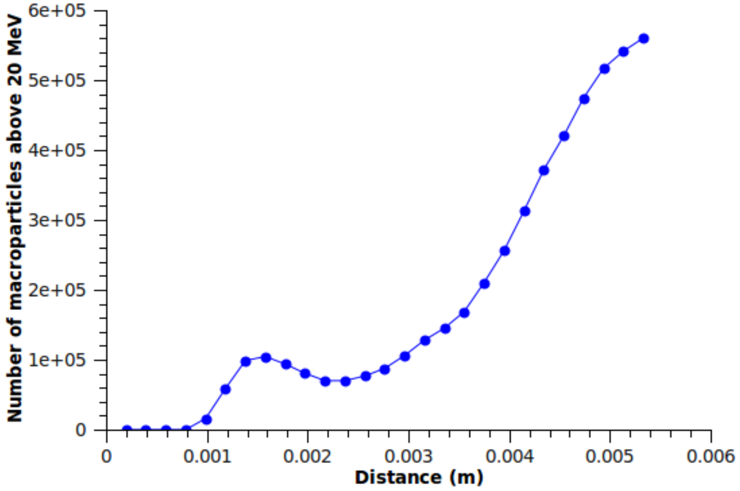
THANK YOU!

Beam-plasma accel

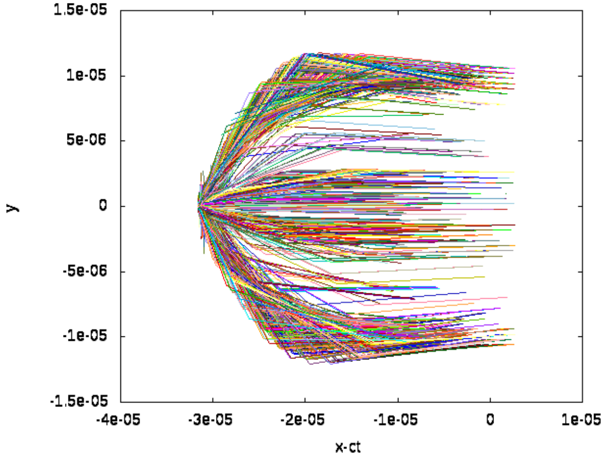


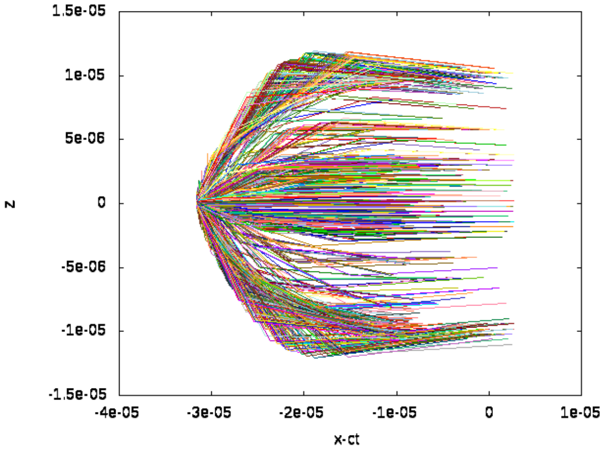
Self-injection of electrons due to laser evolution

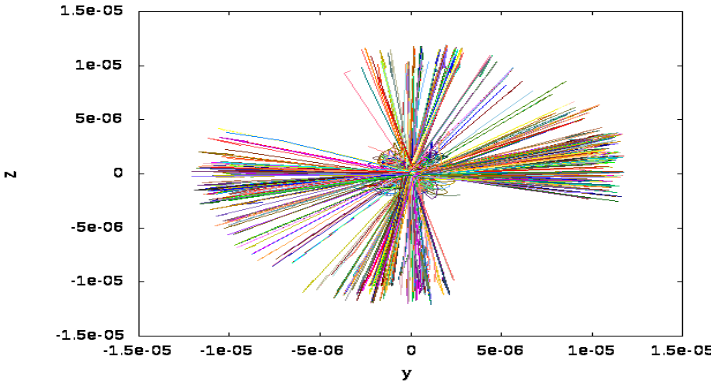




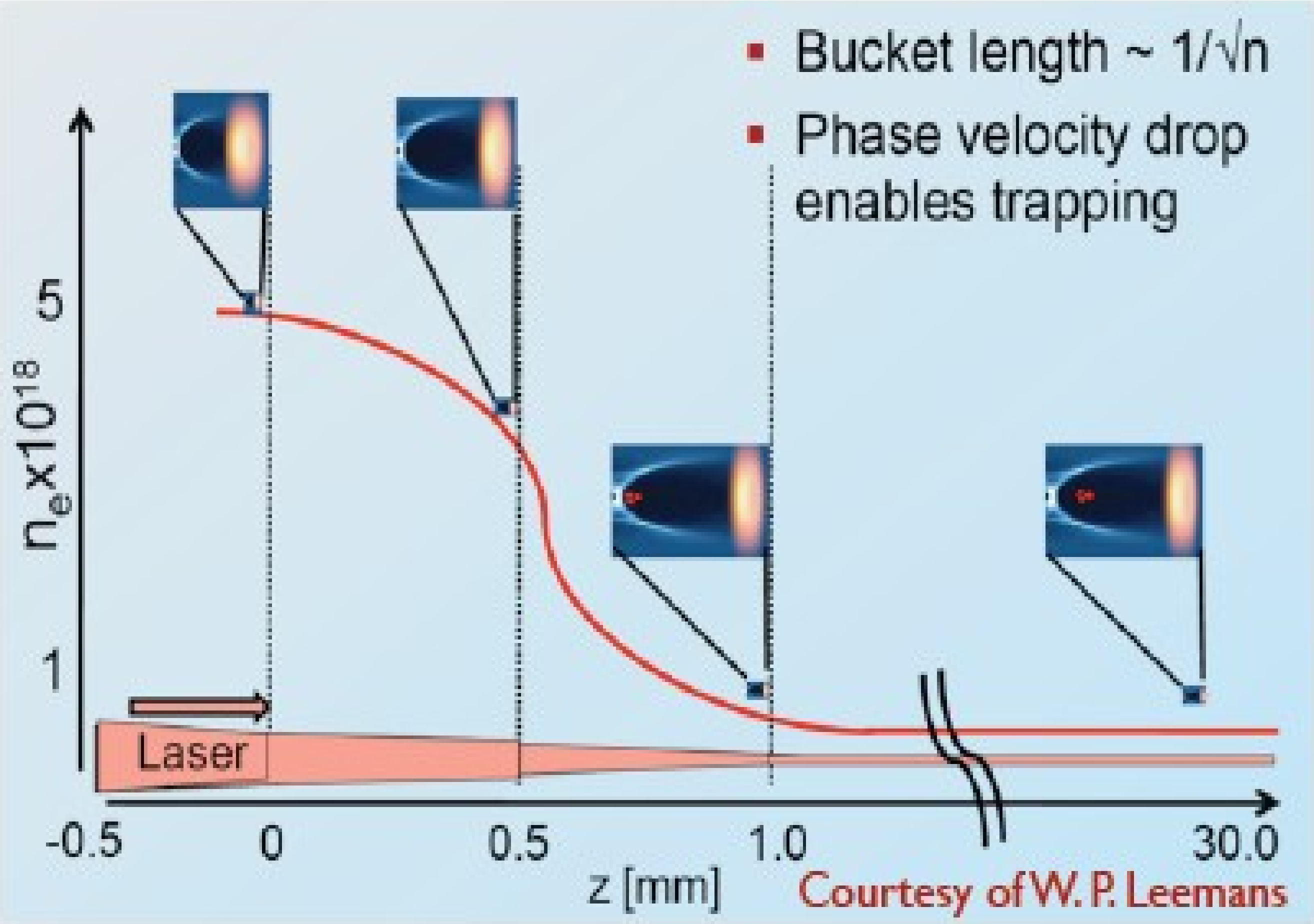
Circular polarized laser pulse







Density ramp injection : principle



- Bucket length ~ 1/√n
- Phase velocity drop enables trapping

Courtesy of W. P. Leemans

$$v_p/c = (1 + \frac{\zeta}{k_p}\frac{dk_p}{dz})^{-1}$$

where, $\zeta = z - ct$ and $k_p(z)$

which depends on z through en density

$$\frac{k_p}{dz} = \frac{k_p}{2n_e}\frac{dn_e}{dz}$$

For a downward density, the wake phase velocity slow dow facilitating electrons trapping

S. Bulanov *et al.*, PRE **58**, R5257 (1998), H. Suk *et al.*, PRL **86**, 1011 (2001), T.-Y Chien *et al.*, PRL **94**, 115003 (2005), T. Hosokai *et al.*, PRL **97**, 075004 (2006), C. G. R. Geddes *et al.* PRL **100**, 215004 (2008), J. Faure *et al.*, Phys. of Plasma **17**, 083107 (2011)