Advanced Acceleration Schemes

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Indore 452 013, India

Second International Particle

Accelerator Conference

(IPAC-2011)

5-9 Sept. 2011, San Sebastian, Spain

Raja Ramanna Centre for Advanced Technology

(Started in 1986)

Accelerators

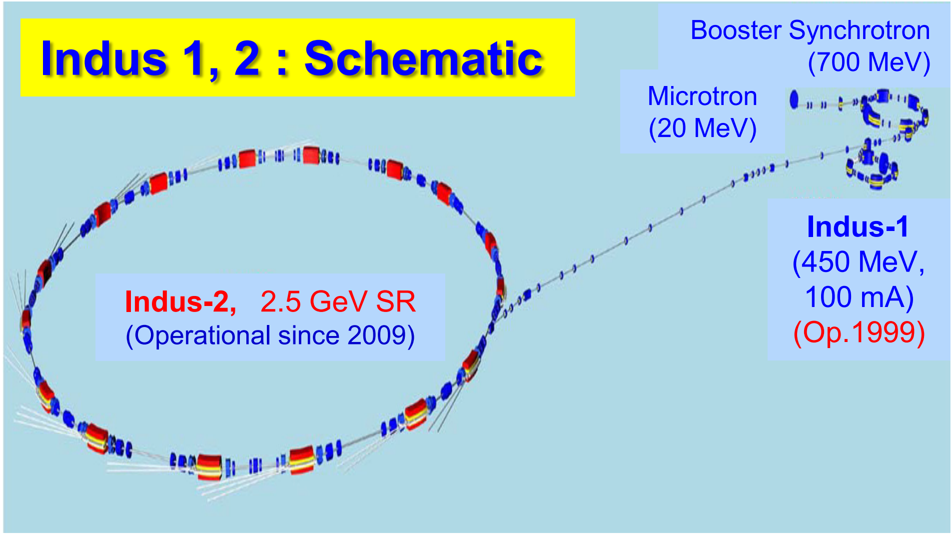
- Indus-1 : 450 MeV SRS
- Indus-2 : 2.5 GeV SRS
- 750 MeV DC accelerator
- Proton Accelerator : Planned
- Applications : Basic science and industrial

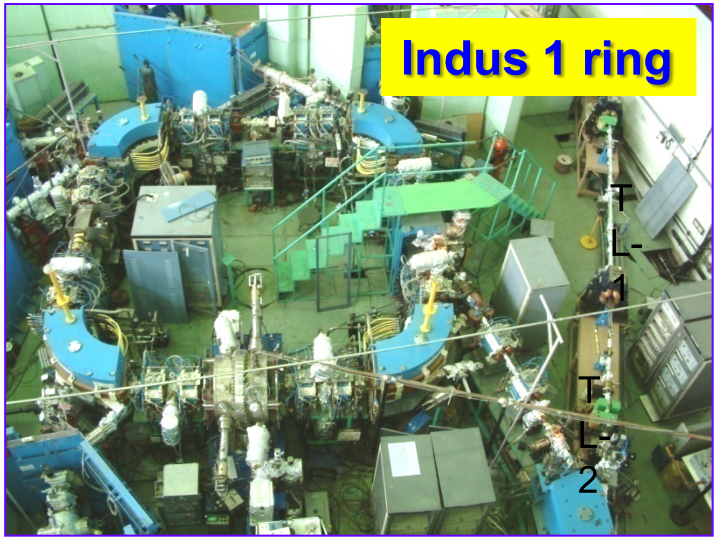
Lasers

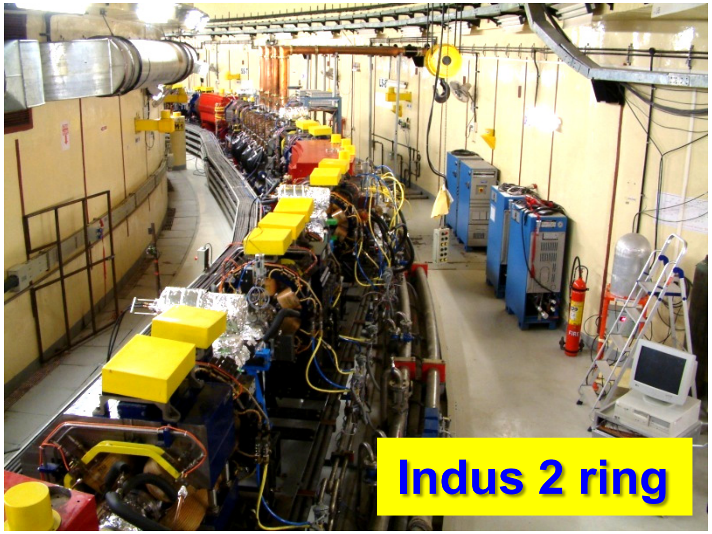
- CO_2 lasers, Copper Vapour Lasers, Nd:YAG lasers, KrF laser, Iodine laser, Semiconductor lasers, and Nd:glass high power lasers
- Applications : Industrial, medical and basic sciences

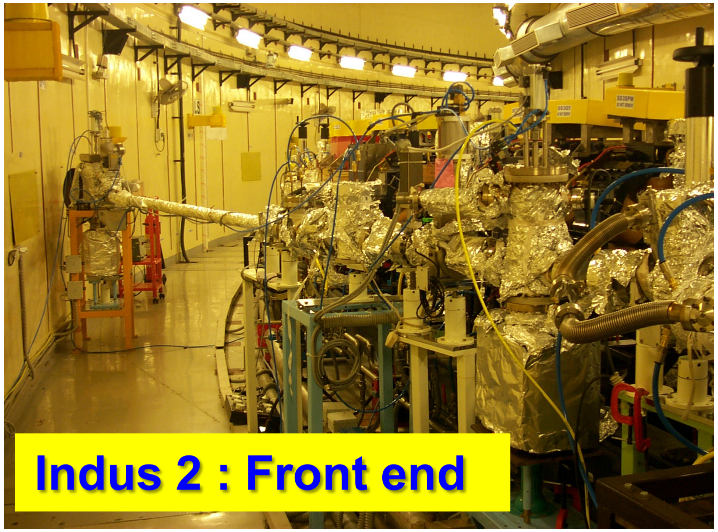
Total staff : About 1,400 (500 Scientists & Engineers)

Accelerators built at RRCAT



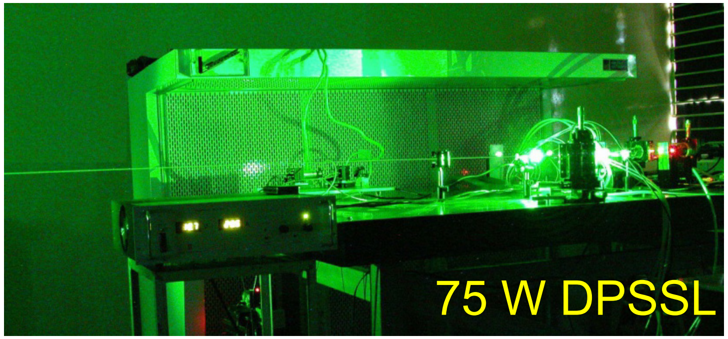






Lasers built at RRCAT

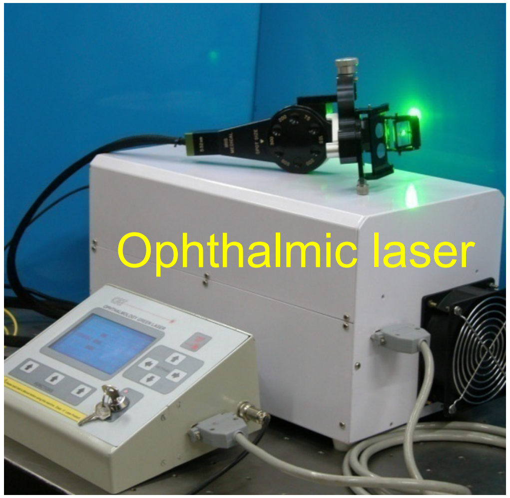
30W Copper Vapor Laser



75 W DPSSL

Mini N_2 Laser

400 J, 1 ns Nd:glass high power laser chain



Ophthalmic laser

Outline of the talk

- Acceleration of electrons using light
- Problems associated with acceleration
- Schemes of acceleration using light
- Plasma based electron acceleration schemes
- Status of these schemes
- Future outlook

Charge Particle acceleration using light

Lawson–Woodward Theorem : The net energy gain by charged particles from the electromagnetic waves is zero

under the following conditions:

i. The region of interaction is *infinite*,

ii. The e.m. fields are in *vacuum with no walls or boundaries,*

iii. The electron beam is highly *relativistic* (v≈c),

iv. No *static electric or magnetic* fields are present,

v. *Ponderomotive* (non-linear) *effects* are neglected.

(J.D. Lawson, *IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)*

In order to achieve a non-zero net energy gain, *one or more* of the assumptions of LW theorem must be violated. (....... not difficult)

Violation of the Lawson –Woodward Theorem

1) **Introduce a *gas medium***
   - Inverse Cherenkov Accelerator

2) **Introduce *magnetic field***
   - Inverse Free Electron Laser Accelerator

3) **Introduce *boundaries***
   - Inverse Transition Radiation Accelerator

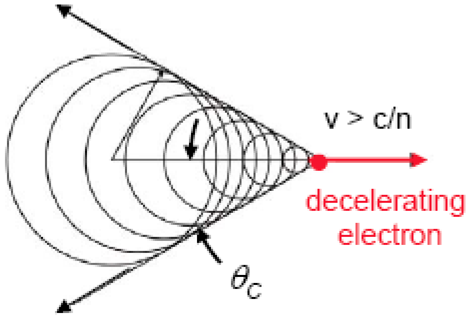
4) **Introduce *plasma***
   - Beat Wave Accelerator
   - Wakefield Accelerator
     a) Plasma Wakefield Accelerator
     b) Laser Wakefield Accelerator

Electron acceleration with EM wave

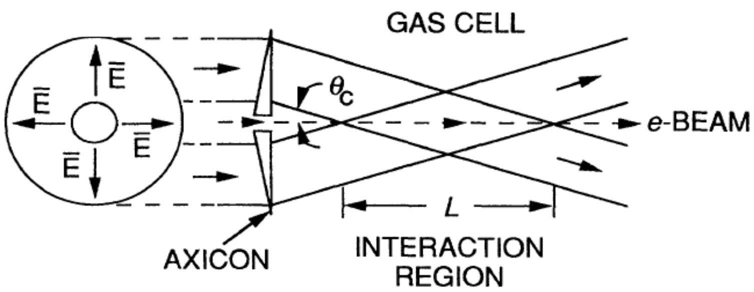
- If a process makes free electrons emit light, in principle, its inverse process can be used to accelerate the electrons using light. (e.g. Inverse Cherenkov Acc., Inverse FEL Acc., Inverse Transition Radiation Acc. etc)

- The phase velocity of the e.m. wave has to be lowered to match the electron velocity (use a loaded structure, gas, plasma) or restrict the acceleration length.

Inverse Cherenkov Accelerator (ICA)

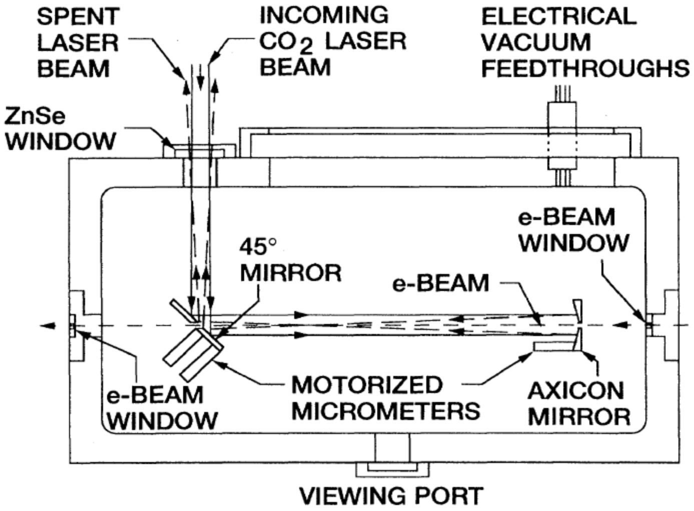


Phase matching achieved at the Cherenkov angle defined by
$\theta_C = \cos^{-1}(1/n\beta)$



First demonstration by J.A.Edighoffer *et al*, PRA 23, 1848, 1981 (Stanford, USA)

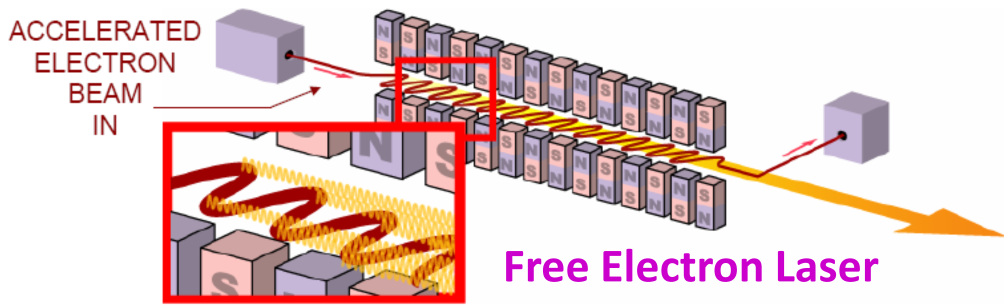
Kimura *et al*., PRL **74**, 546 (1995); Campbell *et al*., IEEE TPS **28**, 1094 (2000)



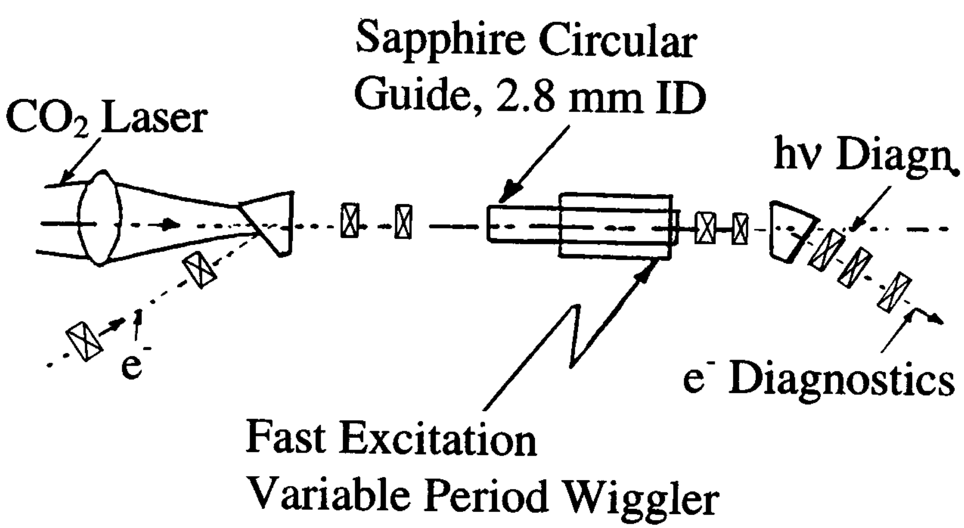
H_2 gas used to slow down the phase velocity of the CO_2 laser light to match it with the Cherenkov angle

Few percent broadening of the beam energy spectrum observed in presence of the laser beam.

Inverse FEL Accelerator (IFELA)



Injection at energy **above** resonance: FEL
Injection at energy **below** resonance : IFELA



R.B. Palmer JAP 43, 3014, 1972 (BNL)

- Concept of IFEL acceleration

I. Wernick *et al*, PRA 46, 3566, 1992

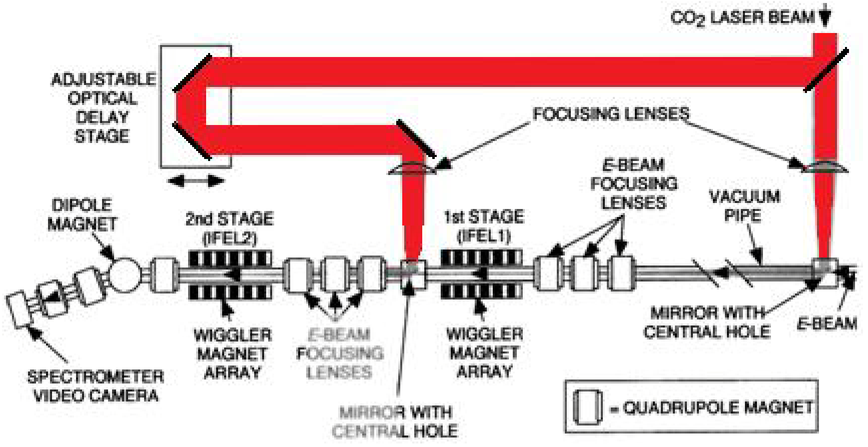
- First demonstration of IFELA
- Acceleration of 9% of 750 keV electrons to 1 MeV energy (Columbia Univ.)
- FEL used as light source

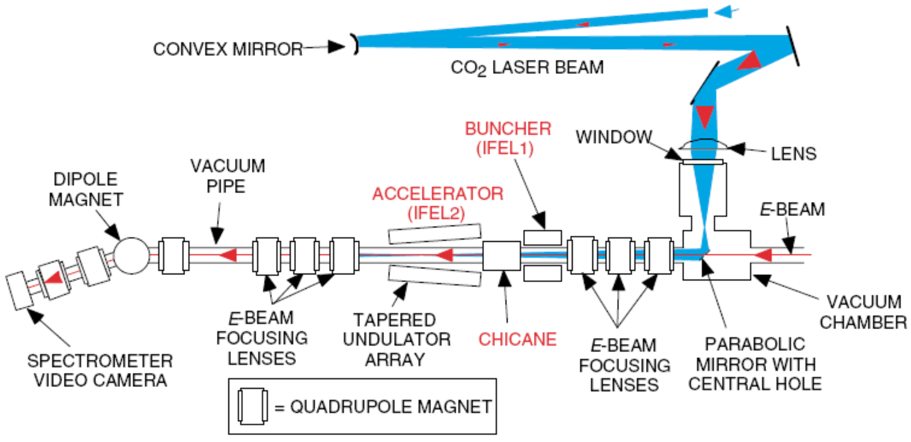
← A. van Steenbergen *et al*, PRL 77, 260, 1995 (ATF, BNL, USA)

- 2.5% gain in energy by 40 MeV electrons

Two Stage IFEL Acceleration

Staged Electron Laser Accelerator (STELLA) [ATF-BNL]





First demonstration of two stage acceleration based on IFELA

W.D. Kimura et al, PRL 86, 4041 (2001)

First demonstration of electron trapping and acceleration.

W.D. Kimura et al, PRL 92, 054801(2004)

In these experiments, like in Inverse Cherenkov experiments, only a few percent shift in energy was observed.

At UCLA's Neptune laboratory, with a more powerful CO_2 laser with a strongly tapered undulator, a 15 MeV electron beam was accelerated to about 30 MeV , with a peak gradient of 70 MeV/m P.Musumeci *et al*, PRL 94, 154801 (2005)

Vacuum Acceleration

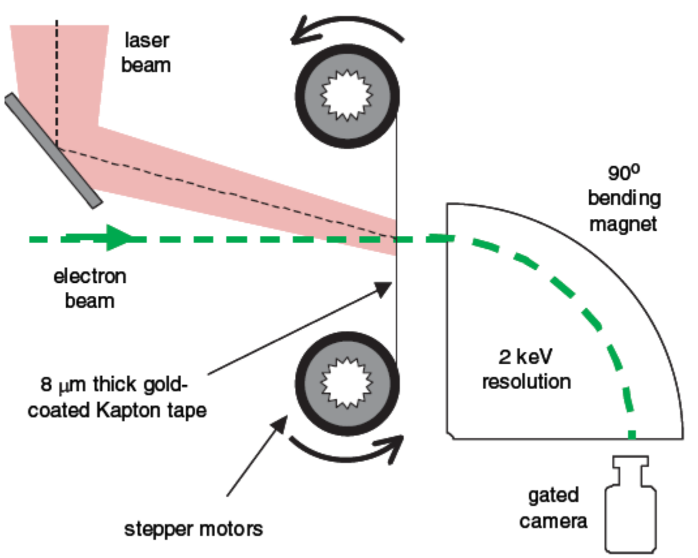
A number of schemes have been proposed, using different concepts.

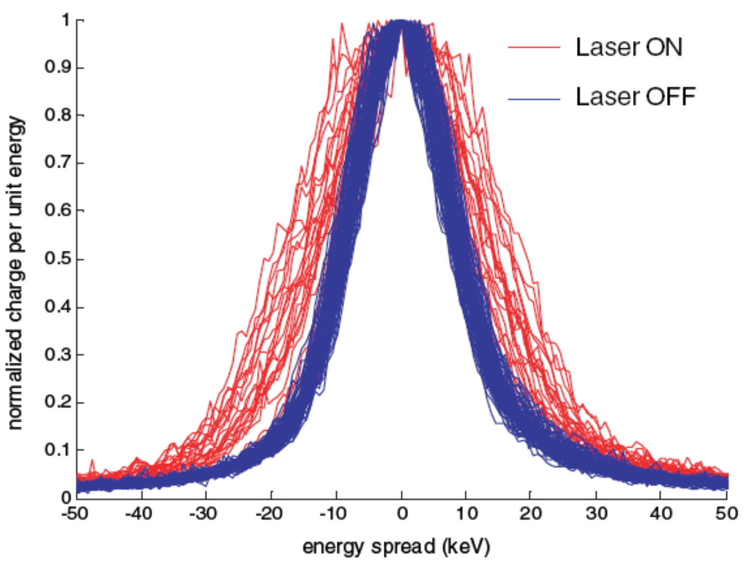
No substantial experimental validation for most.

Inverse Transition Radiation Acceleration

- 8 micron thick, 0.9 micron gold coated Kapton foil used as target.
- With laser on, the energy of the e-beam shows a large spread.
- Laser on, no foil, no energy spread.
- The result is referred to as “Proof of Lawson-Woodward Theorem”

T. Plettner et al, PRL 95, 134801, 2005 (Stanford)



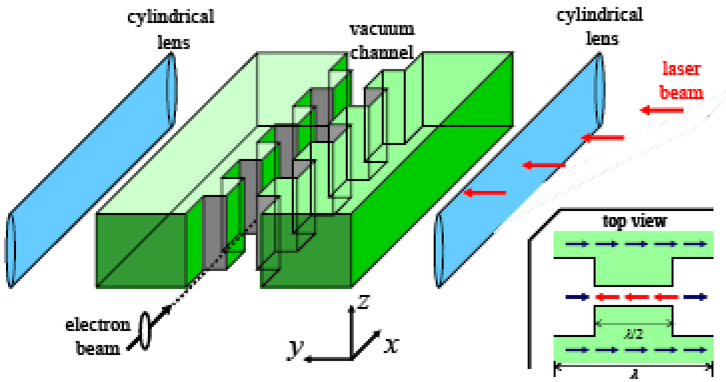


Dielectric Accelerator

A number of dielectric structures have been proposed

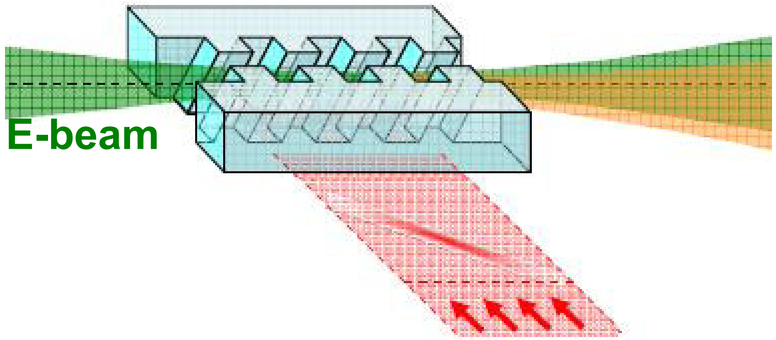
Work mostly at ANL, SLAC, and EuclidTechlabs

One proposal : E-163 experiment at SLAC on Optical Dielectric Structure



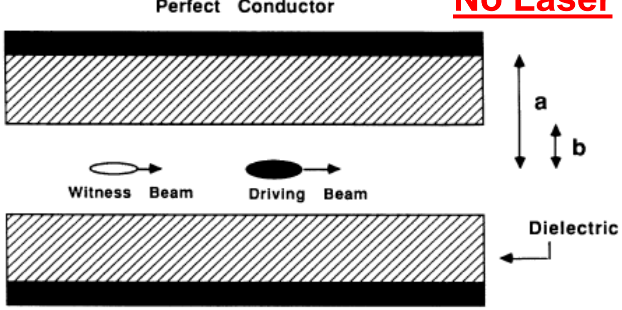
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Dielectric structure



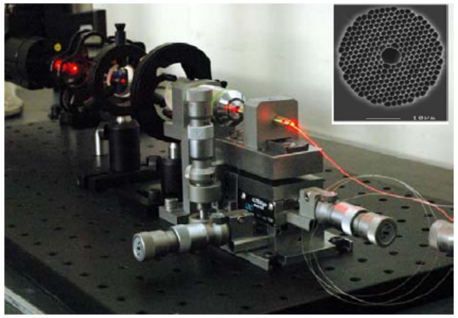
Dielectric wakefield accelerator

No Laser



W.Gai et al, PRL 61,2756, 1988 (ANL)

Photonic Fiber accelerator

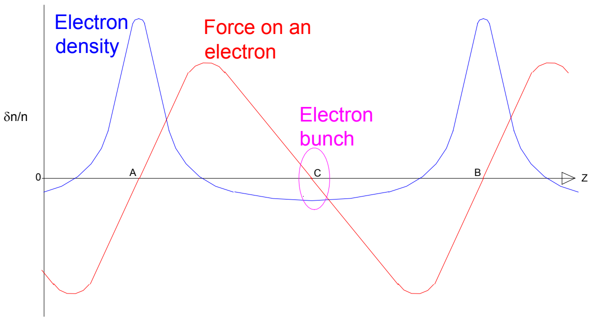


X.E. Lin, PR STAB. 4, 051301, 2001 (SLAC)

Plasma based accelerators

Basic idea :

- ➢ Use laser to excite electron plasma wave (Langmuir waves) in the plasma by ponderomotive force (F_p α –▼Intensity)
- ➢ The plasma wave travels with a phase velocity equal to the group velocity of the laser pulse (< c)
- ➢ A bunch of electrons at right phase will get accelerated.



Advantage of plasma as an accelerating medium

- ❖ Plasma consists of electrons and ions
  - → No problem of break down unlike any other material medium
  - → Can sustain very high fields
- ❖ E (V/cm) ~ √ n_0 (cm^{-3}) : $n_0 \sim 10^{19}$ cm^{-3} → E = 300 GV/m
  - → Three orders of magnitude larger than that possible by other methods
  - → Offers possibility of achieving TeV energy within few meters

Plasma based accelerators

- **Beat Wave Accelerator**

  Use of two laser beams of diff. frequencies

- **Wakefield Accelerator**

  a) Plasma Wakefield Accelerator

  Electron beam creates the wakefield

  b) Laser Wakefield Accelerator

  Ultra-short (fs) laser pulse creates the wakefield

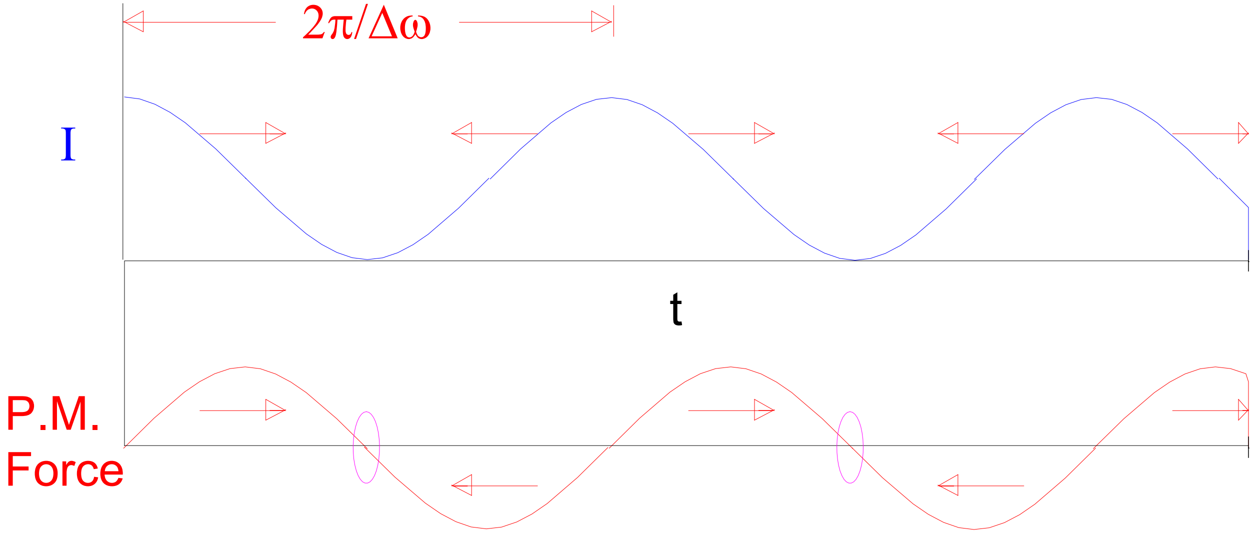
Laser Beat Wave Acceleration

C. Joshi et al, Nature 311, 525 (1984)

- Two laser waves of frequency ω_1 and ω_2 will beat at a frequency

  $\Delta\omega = \omega_1 - \omega_2$

- If this frequency difference is exactly equal to the plasma frequency (i.e. $\Delta\omega = \omega_1 - \omega_2 = \omega_p$), then strong Langmuir waves will be excited in the plasma by the longitudinal ponderomotive force of the beat wave.



Laser Beat Wave Acceleration

- Lasers : Nd: YAG Laser : $\lambda = 1.064\ \mu m$ and Nd: YLF Laser : $\lambda = 1.054\ \mu m$
- Two CO_2 lasers operating at $\lambda = 10.6\ \mu m$ and $9.6\ \mu m$ respectively

- $N_e = (\omega_1 - \omega_2)^2 e_o\, m / e^2$ is the required density
- For CO_2 as well as Neodymium lasers, $N_e \sim 10^{17}\ cm^{-3}$

- $E_{max} = 0.511\ \varepsilon\ [\ \omega_p/c\ ]$ MeV/cm $\sim \varepsilon \sqrt{n_e(cm^{-3})}$ V/cm $(\varepsilon = \Delta n/n_e)$
- $n_e \sim 10^{17}\ cm^{--3}$, $\varepsilon \sim 0.1$ → $E_{max} \sim 3$ GV/m

- Long pulse lasers preferred to excite plasma waves for longer time
- Here one needs to have a *preformed* plasma of *uniform density*

- Lasers of shorted duration (<100 ps) do not need preformed plasma as they form plasma themselves, but going for ultrashort pulses (< 1 ps) , the number of beats becomes small (beat separation ~100 fs)

Some results on Laser Beat Wave Accelerator

First results : C.E. Clayton et al, PRL 70, 37 (1993)
(UCLA Group of C. Joshi)

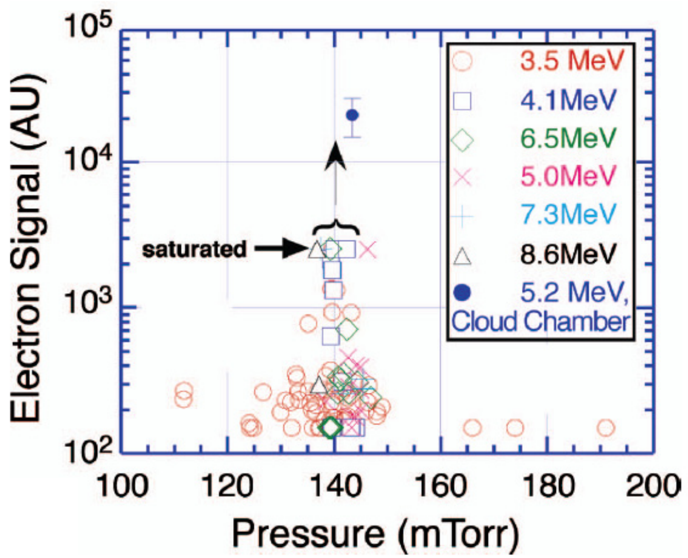
Injected e-beam at 2.1 MeV,

Observed accel .electrons up to 8.6 MeV

Gradient of 0.7 GeV/m inferred.

In 1994, the same group reported accelerated electrons to 30 MeV (from 2 MeV) over 1 cm (E = 2.8 GV/m)

CO_2 laser used



Ecole Polytechnique, France

Two synchronized Neodymium lasers

Nd: YLF : 1.053 µm : 90 ps, 12 J, **Nd: YAG** :1.064 µm : 200 ps, 4.4 J

Deuterium gas at 2.27 mb (background pressure) $N_e \sim 10^{17}$ cm^{-3}

Electron source : 2.5 to 3.3 MeV electrons [400 µs duration, I =200 µA]

3.3. MeV electrons accelerated to 4.7 MeV (Field : 1.2 GV/m) **(1994)**

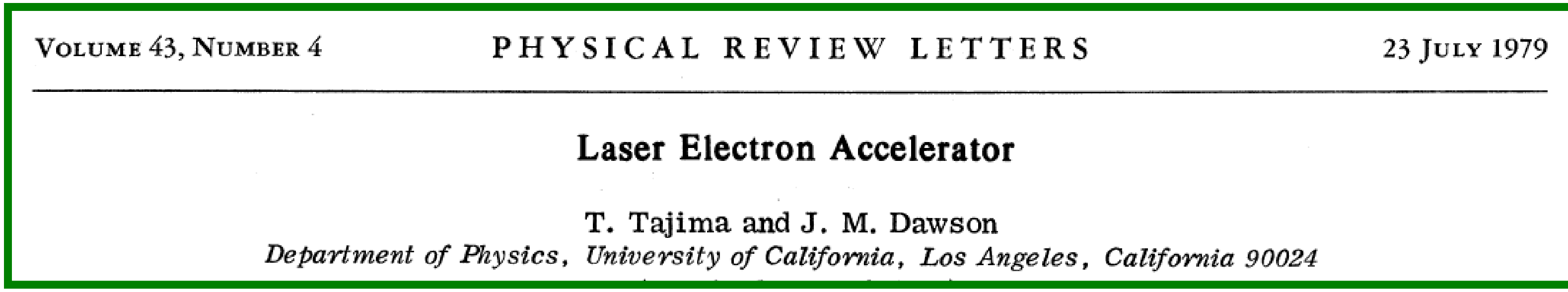
Other labs:

Univ. of Osaka (Japan)

Imperial College (UK)

Chalk River Lab. Canada

Wakefield Accelerators

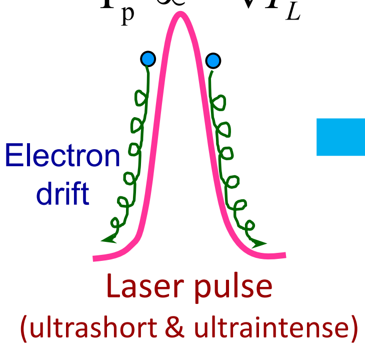

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

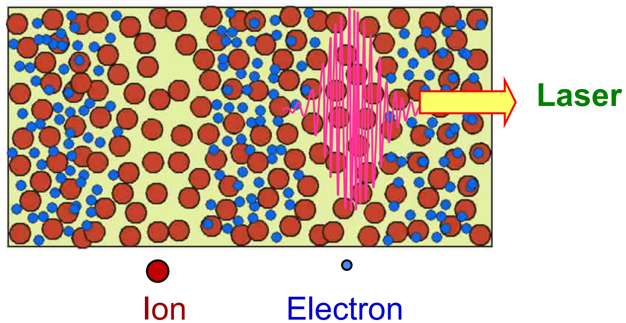
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

Ponderomotive force

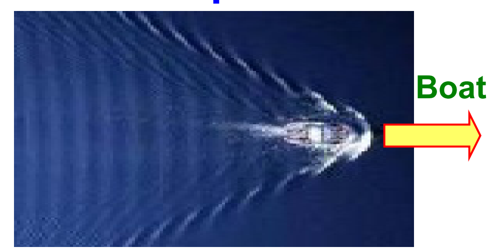
$F_p \propto -\nabla I_L$

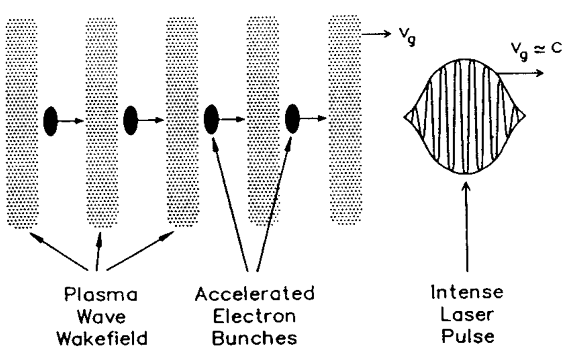


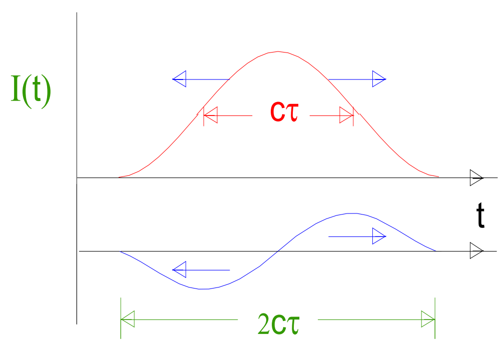
Plasma wave behind a laser / e-beam



Water wakefield wave behind a speed boat







For resonant excitation of the plasma wave :

$$c\tau_{laser} \approx \lambda_p / 2$$

➔ultrashort laser pulse (~ few 10 fs)

Initial results of Laser Wakefield experiment

Ecole Polytechnique Experiment

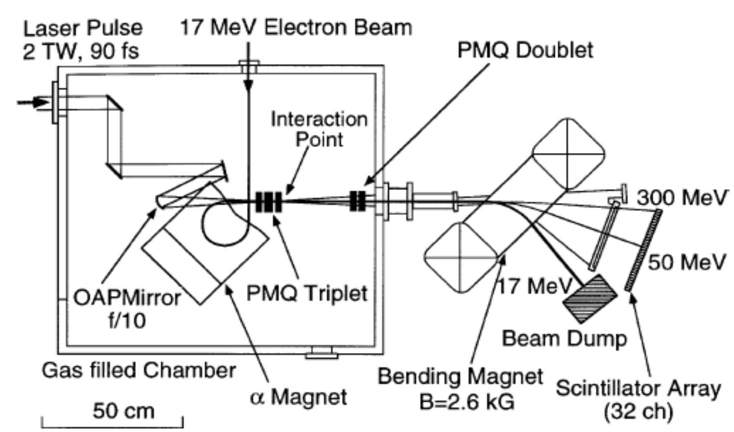
(F.Amiranoff et al, PRL, 3, 1998)

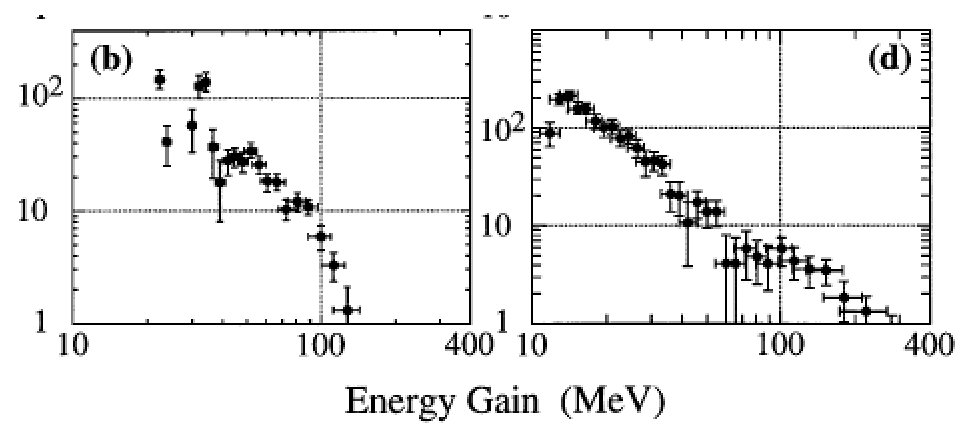
- Laser : Nd:Glass laser : 400fs, 1.057mm (LULI)
  $P = 3.5$ TW , $I = 4 \times 10^{17}$ W/cm^2
- E beam : CW e beam from Van de Graaff generator
  Total energy = 3 MeV
- Plasma density : $N_e \sim 2 \times 10^{16}$ cm^{-3}
- Maximum energy gain of 1.6 MeV
- $E_{max} = 1.5$ GV/m

KEK – U. Tokyo – JAERI Experiment

(H.Dewa et al, NIMPR A 410,357, 1998)

- Laser used : 2TW, 90 fs Ti:sapphire
  Focussed in He gas to 13μm radius spot
  $\pi Z_R \sim 700\mu$m
- E-beam : 17 MeV, single bunch from an RF Linac
- Bunch size : 10ps , focussed dia. = 800μm
- Plasma density : 4×10^{17} cm^{-3}
- Energy gain : More than 200 MeV
- $E_{max} = 2$ GV/m





Self- modulated Laser Wakefield Acceleration

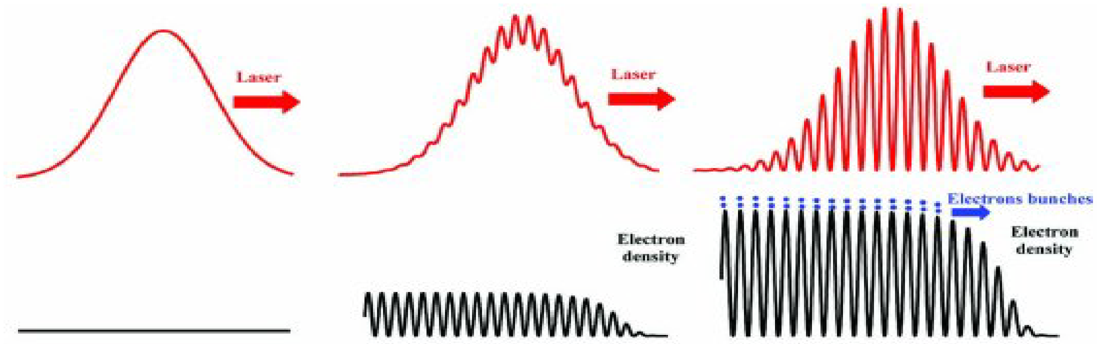
$c\tau_{laser} >> \lambda_p/2$ and $P_L > P_c\,(GW) = 17\,(n_c / n_e)$: the relativistic self-focusing threshold

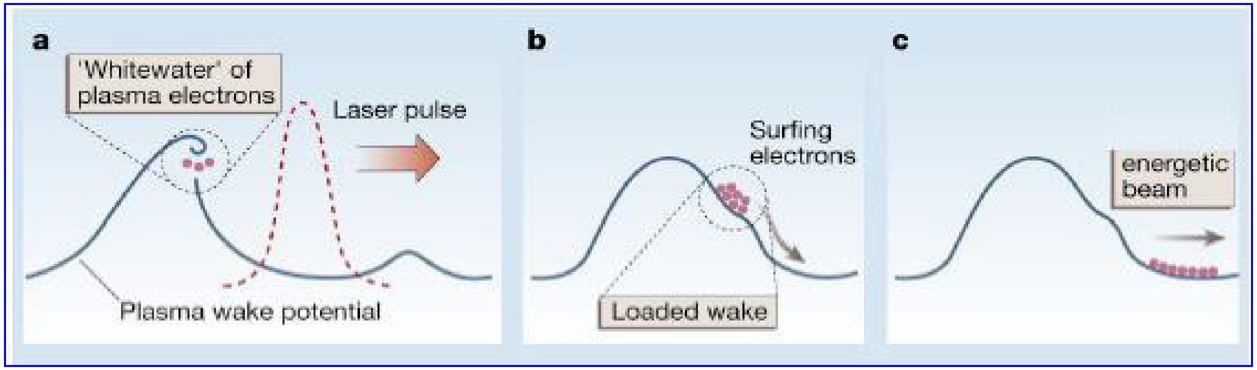
- Laser pulse → Forward Raman Scattering instability → excitation of Langmuir waves.
- The modulation in density due to Langmuir wave → redistribution of the laser light leading to photon bunches at plasma wavelength (self-modulation of the laser pulse)
- The ponderomotive force of the modulated light strongly excites Langmuir waves

  → Wave-breaking takes place → Self-injected electrons get accelerated.

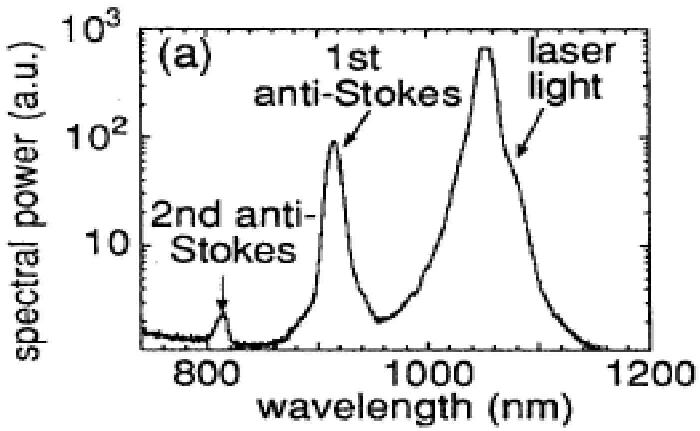
Self - modulation of the laser pulse

Excitation of strong plasma waves





Wave-breaking in Sm-LWFA experiments

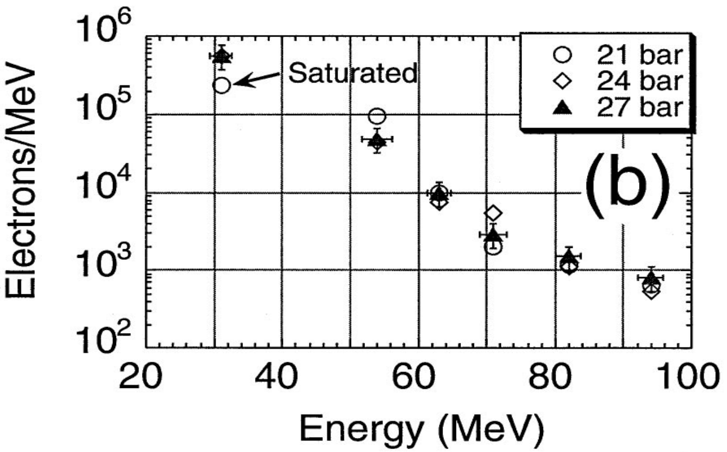


C.A. Coverdale et al, PRL 74, 4659, 1995 [LLNL+UCLA]

First correlation of self injected electrons with forward Raman scattering by plasma waves

Laser : Nd:glass 1053 nm, 3 J, 600 fs;

Helium gas jet



D. Gordon et al, PRL 80, 2133, 1998 [RAL+ IC + EP + UCLA]

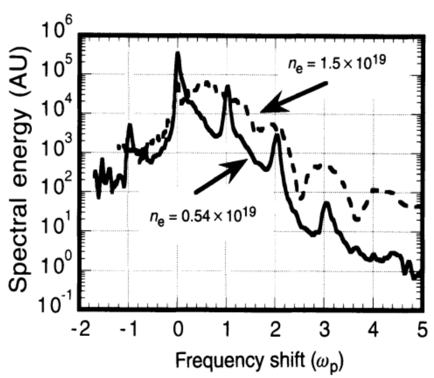
Electrons upto 94 MeV (continuous)

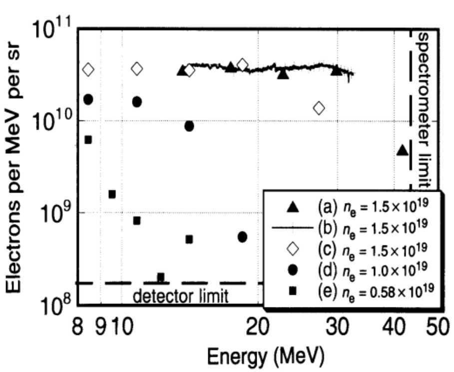
Acceleration gradient : **160 GV/m**

Laser : Vulcan @ RAL

Nd:glass, 1053 nm, 20 J, 1 ps;

Helium gas jet





A. Modena et al, Nature (Letters) 377, 606, 1995 [RAL+ IC + EP + UCLA]

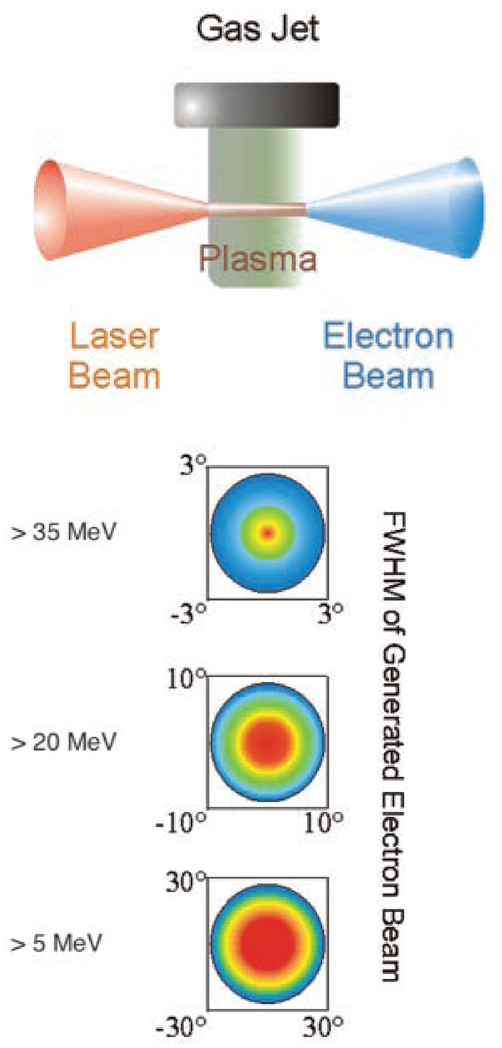
Electrons upto 44 MeV (continuous)

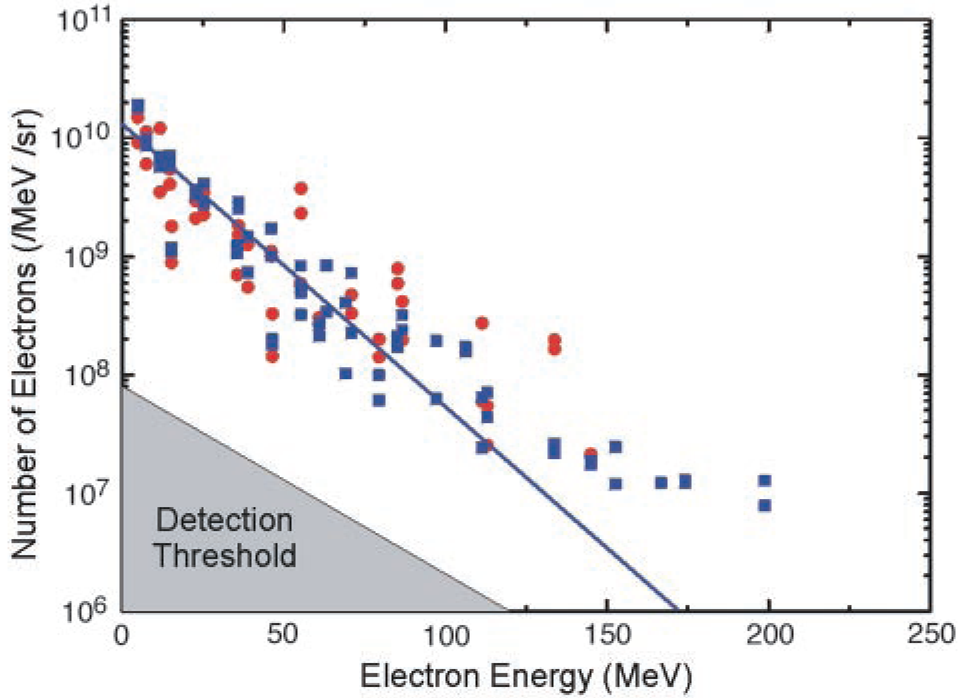
FRS by plasma waves also seen

Laser : Vulcan @ RAL, Nd:glass, 1053 nm, 20 J, 1 ps; Helium gas jet

LWFA of self-injected electrons

V. Malka et al, Science 298, 1596, 2002 (France+U.K.)





Ti:sapphire laser, 10 Hz, 1J in 30 fs (33 TW)

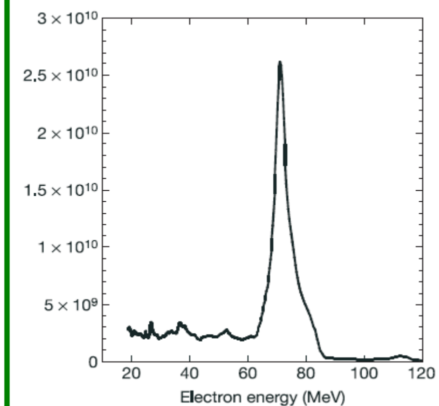
Focused intensity I~ $3x10^{18}$ W/cm^2

He gas jet, N_e ~ 2-6 x 10^{19} cm^{-3}

Beam energy continuous, upto 200 MeV

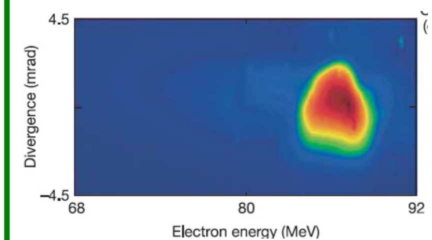
Generation of quasi-mono-energetic electron beams

Nature 431
Sept. 2004



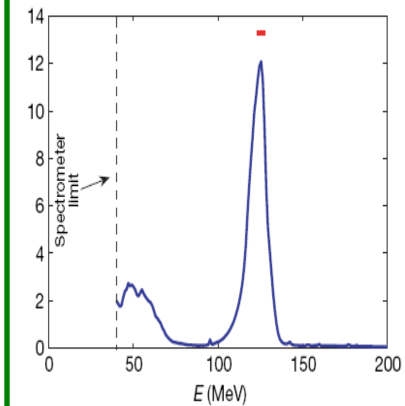
70 MeV

S. P. D. Mangles *et al*,
Nature 431,**535**, 2004
RAL, ICL, USG (U.K.)
and UCLA (USA)



86 MeV

C.G.R.Geddes *et al*,
Nature 431,**538**, 2004
LBNL, UCB, UCol.B
(USA)



170 MeV

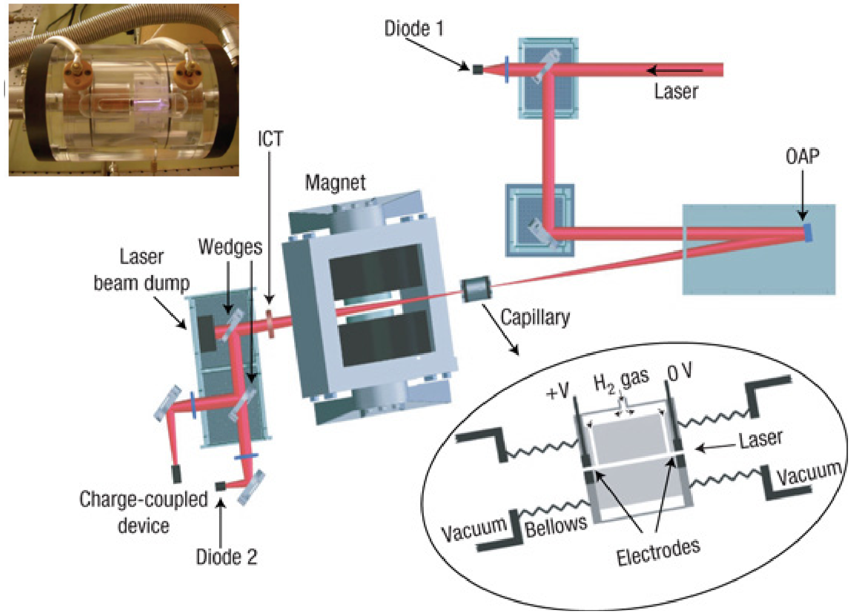
J. Faure *et al*,
Nature 431, **541**, 2004
LOA (France)

Subsequent to above experiments, many laboratories all over the world reported quasi-mono-energetic electron beam generation of few tens of MeV to GeV energy, within few years.

GeV electron beam : Capillary discharge channel

W. P. Leemans *et al*, Nature Physics 2, 696, 2006
K. Nakamura *et al*, Phys. Plasmas 14, 054708, 2007

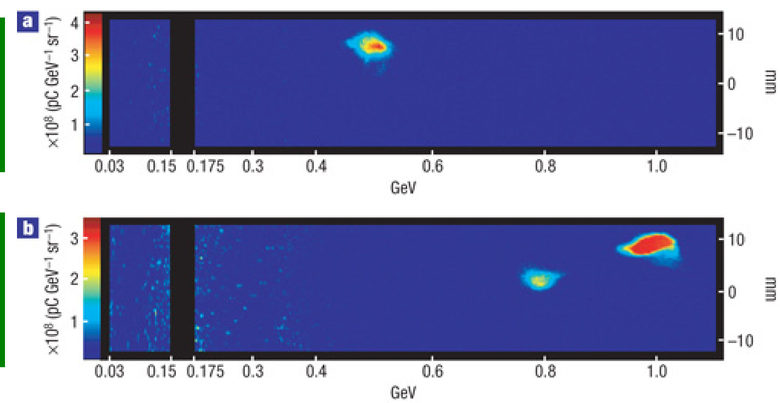
LBNL (USA) and Univ. Oxford (UK)



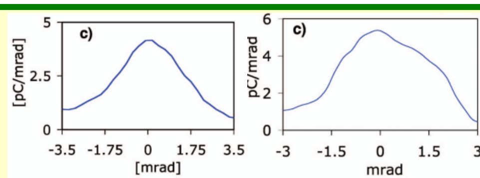
Laser pulse length : ~ 40 fs
Peak power : ~40 TW
Focal spot radius : 25 μm
Hydrogen filled capillaries (20 kV)
Diameter : 190, 225, 310 μm
Length : ~ 33 mm

Electron energy : 0.5 GeV
225 micron capillary, N_e ~3.5×10^{18} cm^{-3}, 12 TW

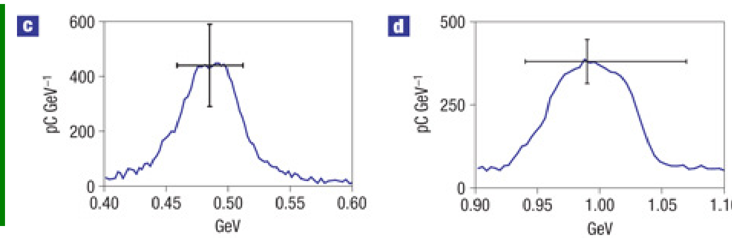
Electron energy : 1 GeV
310 micron capillary, N_e ~4.3×10^{18} cm^{-3}, 40 TW



Divergence: 2mrad
Energy spread: 2.5%
Beam charge : > 30pc

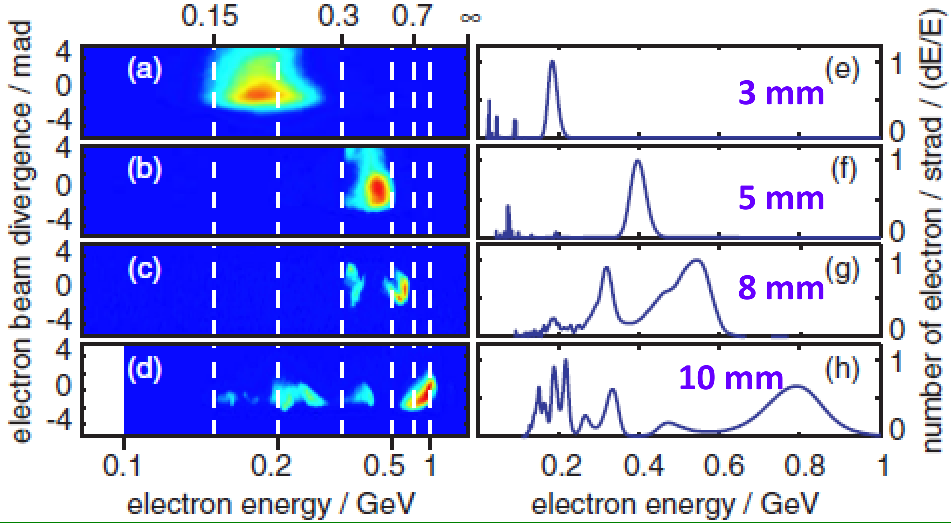


0.5 GeV 1 GeV



Near-GeV electron acceleration in self-guided channel

S. Kneip *et al*, PRL 103, 035002 , 2009; [RAL based work]



Laser pulse energy : 10 J

Laser pulse duration : 55±5 fs

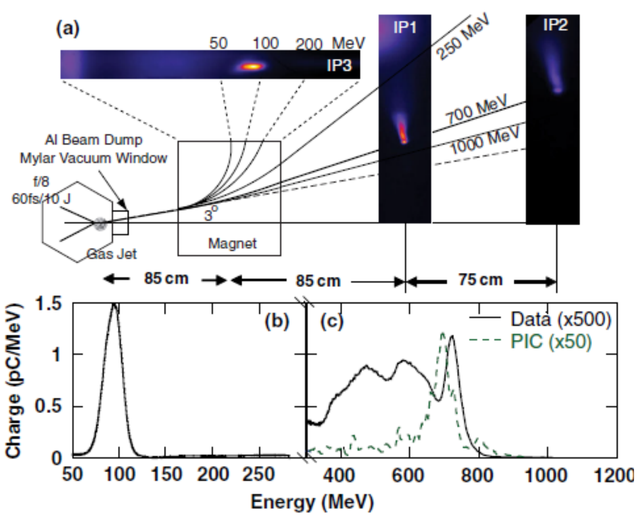
Peak power : ~ 200 TW

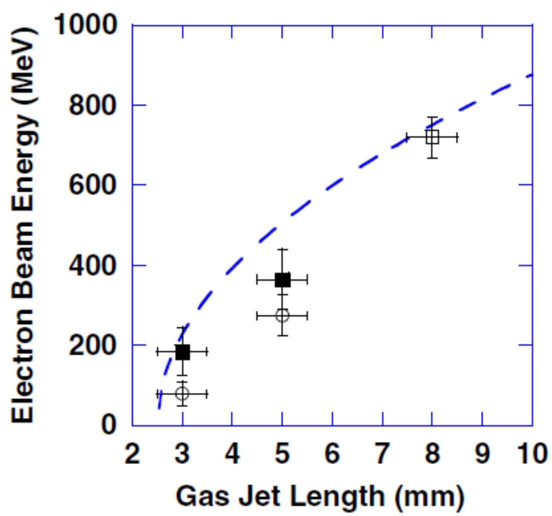
Focal spot (FWHM) : 22 μm

Gas-jet width : 3,5,8,10 mm (He)

Ele. density : 5.7 x10^{18} cm^{-3}

D. H. Froula et al. PRL 103, 215006, 2009; LLNL, UCLA (USA)





Laser pulse ~ 60 fs,

Peak power ~ 200TW

Focal spot : 18 μm

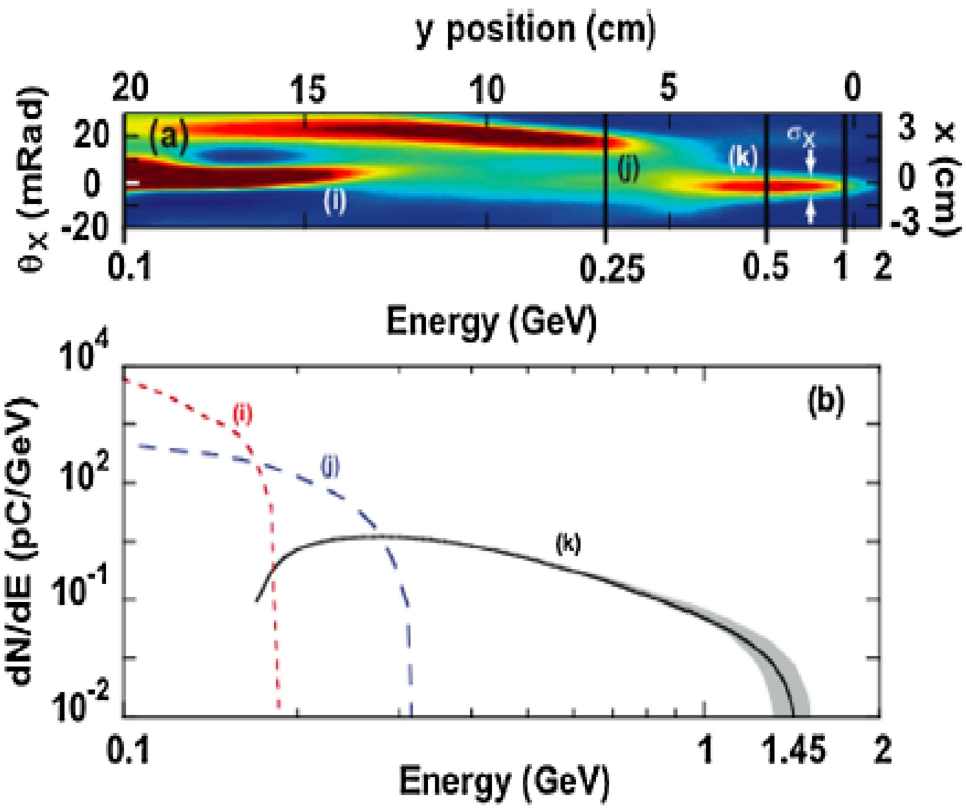
Gas-jet (L): 3,5,8 mm

Gas used : Helium

Density : 5x10^{18} cm^{-3}

Beyond 1 GeV electron acceleration in self-guided channel

C. E. Clayton *et al*, PRL 105, 105003 (2010);
LLNL, UC (USA)



Laser pulse duration : 60 fs

Peak power : 110 TW

Focal spot (FWHM) : 18 μm

Gas-cell length : 1.3 cm

Gas : 97% He + 3% CO_2

Ele. density : 1.3 x 10^{18} cm^{-3}.

GeV electrons *only with CO_2*

Not mono-energetic

Accn. Gradient : ~100 GV/m

Highest energy acceleration

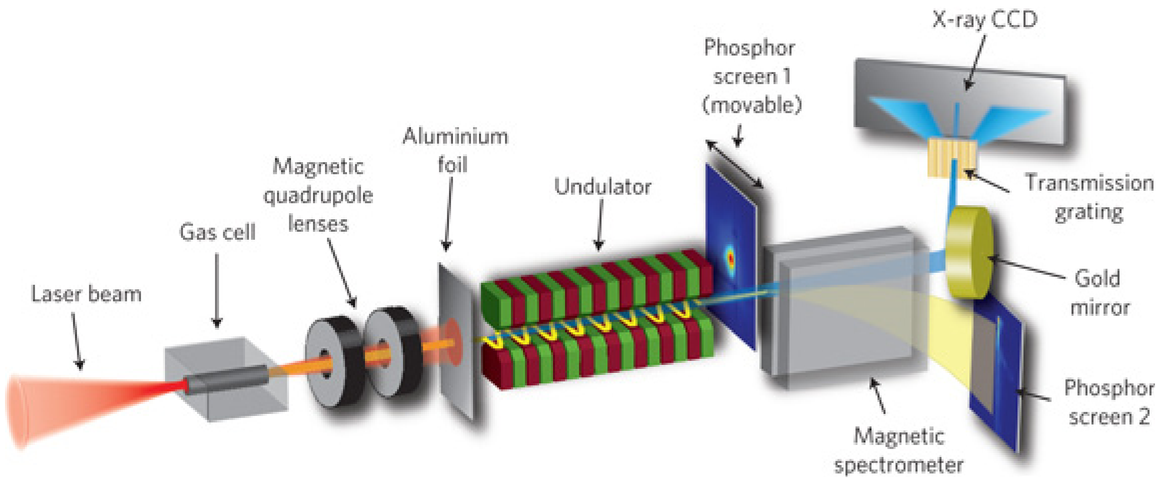
with laser beams

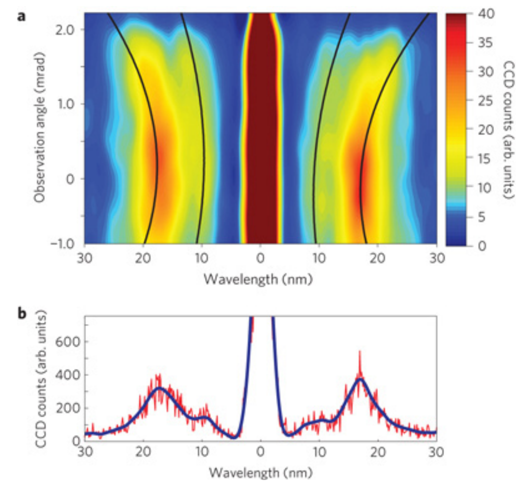
Current status of laser wake-field acceleration
in the regime of stable acceleration of e-beams

❖ **Divergence, θ_d :**	**~ 1 mrad**	(e.g. J. Osterhoff *et al.*, PRL-2008)
❖ **Norm. emittance, ε_γ :**	**~ 1 π mm.mrad**	(S. M. Wiggins *et al.*, PPCF -2010)
❖ **Pointing variation, Δθ :**	**~ 1 mrad**	(e.g. J. Osterhoff *et al.*, PRL-2008)
❖ **Energy, E_{pk} :**	**~ up to 500 MeV**	(e.g. W. P. Leemans *et al.*, Nature-2006)
❖ **Energy stability :**	**~ 2 %**	(e.g. J. Osterhoff *et al.*, PRL-2008)
❖ **Energy spread, $\Delta E/E_{pk}$:**	**< 1%**	(S. M. Wiggins *et al.*, PPCF -2010)
❖ **Beam charge, Q :**	**~ few10 pC**	(e.g. J. Faure *et al.*, Nature - 2006)
❖ **Bunch duration, τ_b :**	**< 2 fs**	(e.g. J. Faure *et al.*, Nature - 2011)
❖ **Energy tuning :**	**~ 50 – 250 MeV**	(J. Faure *et al.*, Nature - 2006)

X-ray FEL with laser driven accelerator

M. Fuchs *et al*, Nature Physics 5, 826 (2009) [MPIQ, Germany, UO, UK]





ATLAS Ti:sapphire laser : 850 mJ with 37 fs pulse duration.

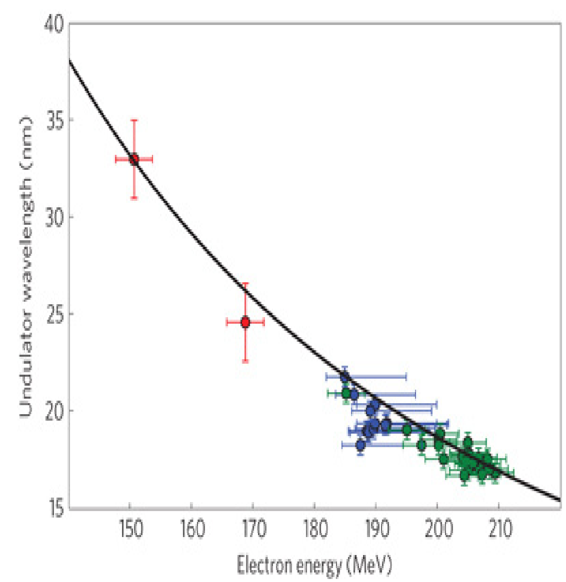
15 mm long hydrogen-filled gas cell of 200 micron diameter.

At n_e=8 x 10^{18} cm^{-3}, electron accelerated up to 210 MeV.

The average beam divergence after collimation with the magnetic lenses is 0.7 mrad

The permanent-magnet (NdFeB) undulator of length 30 cm with 5 mm-long periods.

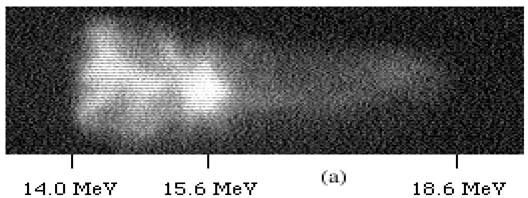
At a gap of 1.2 mm between the poles, it has *K*=0.55.



Plasma wake-field acceleration (PWFA)

First experimental demonstration : **J.B. Rosenzweig *et al*, PRL 61, 98 1988**

Main beam : 21 MeV, witness beam : 15 MeV, N_e ~ 10^{13} cm^{-3} : **~35 keV shift**



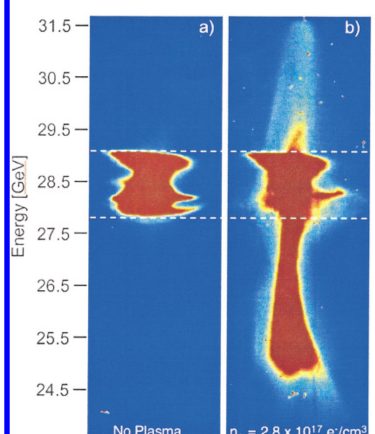
N.Barov et al, PR ST-AB 3, 011301, 2000

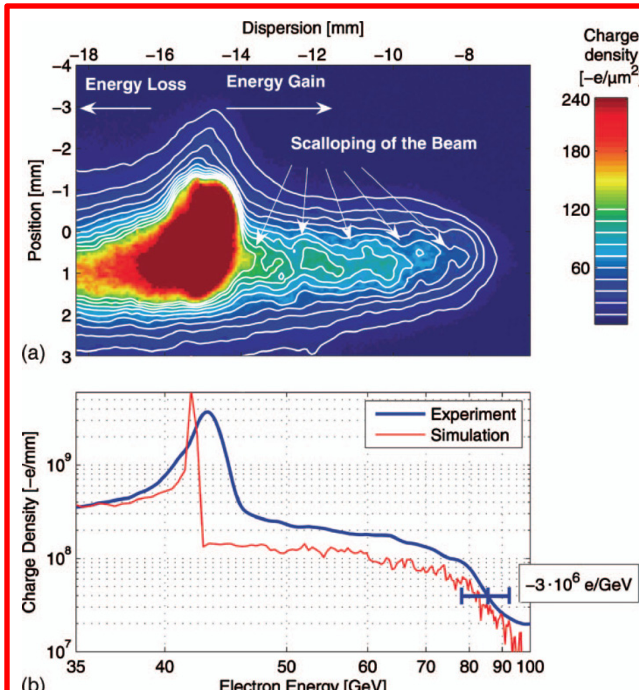
Peak acceleration gradient of 62 MeV/m

(ANL-WFAF)

M. Hogan *et al.*, Phys. Rev. Lett., 95, 054802, 2005.

3 GeV acceleration





Energy doubler

I. Blumenfeld *et al*, Nature 445, 741, 2007

85 cm long, 2.7x10^{17} cm^{-3} lithium plasma

42 GeV ebeam

Accelerating field : 52GV/m

PWFA method can be used to accelerate e^+ beam also.

Future Outlook

- Plasma based acceleration will continue to be the most promising technology for next generation compact high energy electron accelerators.
- LWFA based compact and low cost next generation free electron x-ray lasers are on the horizon.
- Two international committees, the International Committee for Future Accelerators **(ICFA)** and the International Committee for Ultra Intense Lasers **(ICUIL)** have formed a Joint Task Force for exploring future applications of intense lasers in accelerators, including colliders, light sources, and medical accelerators.
- Second Joint ICFA-ICUIL Workshop on Sept 20-22, 2011 at the Lawrence Berkeley National Laboratory, California, USA

Future Outlook

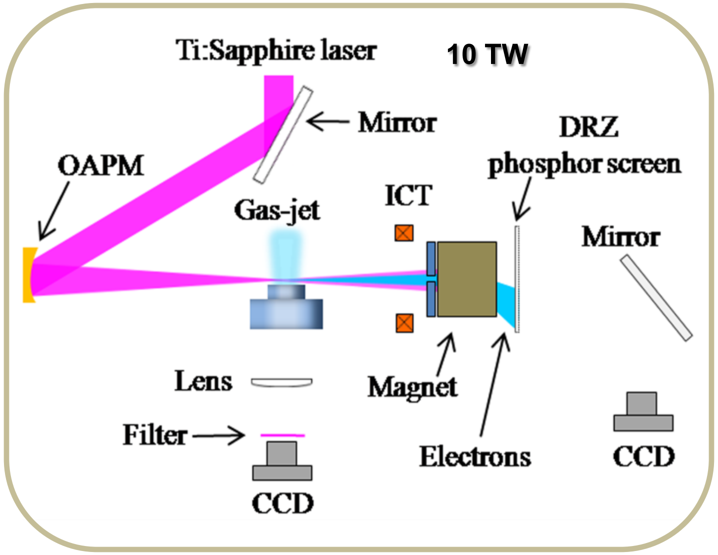
- Demonstration of 10 GeV beam is expected with a couple of years from LWFA in several cm-long capillary waveguides, with the presently available technology and knowledge (**BE**rkeley **L**ab **L**aser **A**ccelerator : **BELLA**)

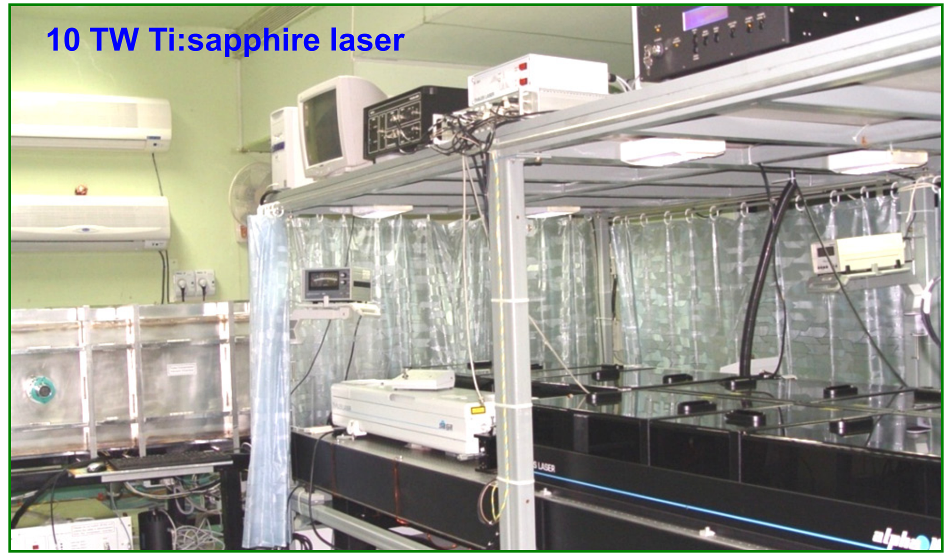
- Demonstration of high gain acceleration of electron / positron bunches with high quality from plasma wake-field acceleration in a single stage is expected in near future. (**F**acility for **A**dvanced a**C**celerator **E**xperimental **T**ests, **FACET**)

- Ongoing efforts towards GeV range compact IFEL accelerators would lead to compact high brightness sources of ultra-short duration radiation.

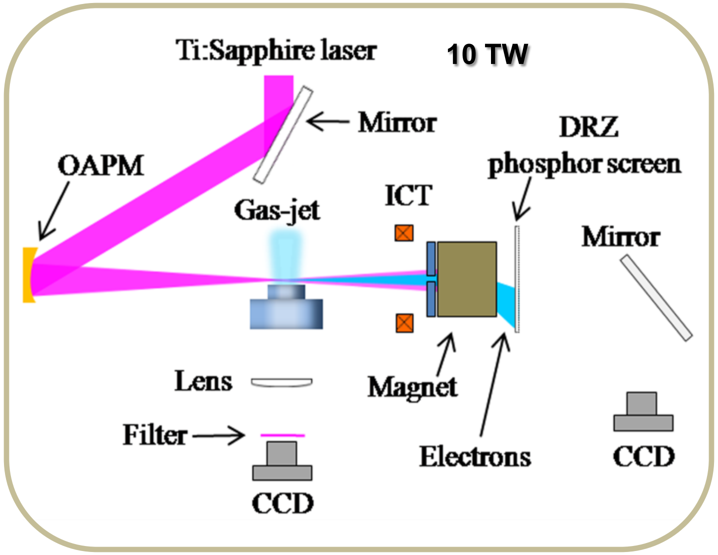
  (**R**adiabeam-**U**CLA-**B**NL **I**FEL **CO**llaboratio**N** : **RUBICON**)

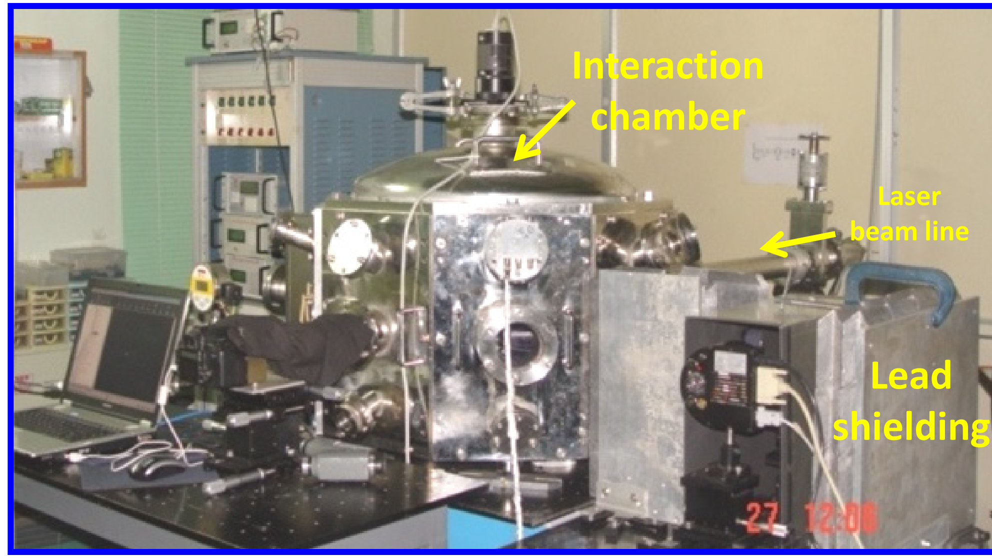
Laser based electron acceleration work in India



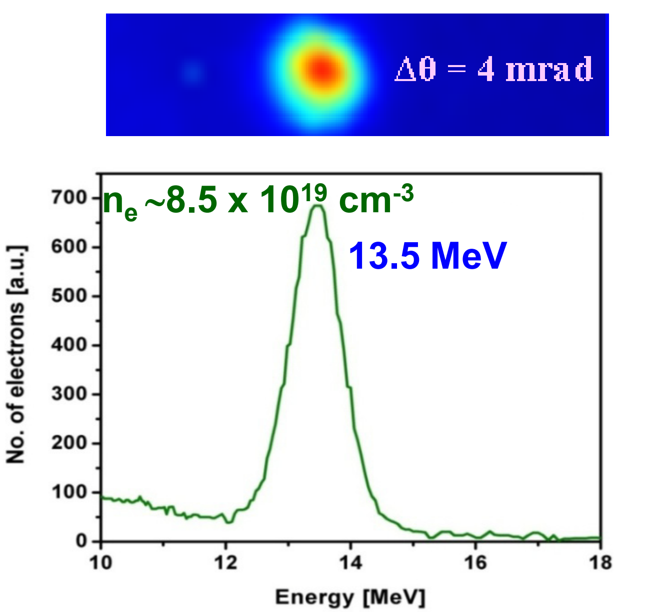


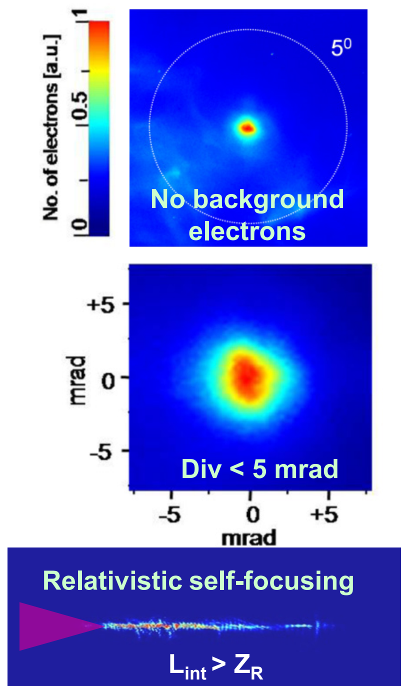
Laser based electron acceleration work in India

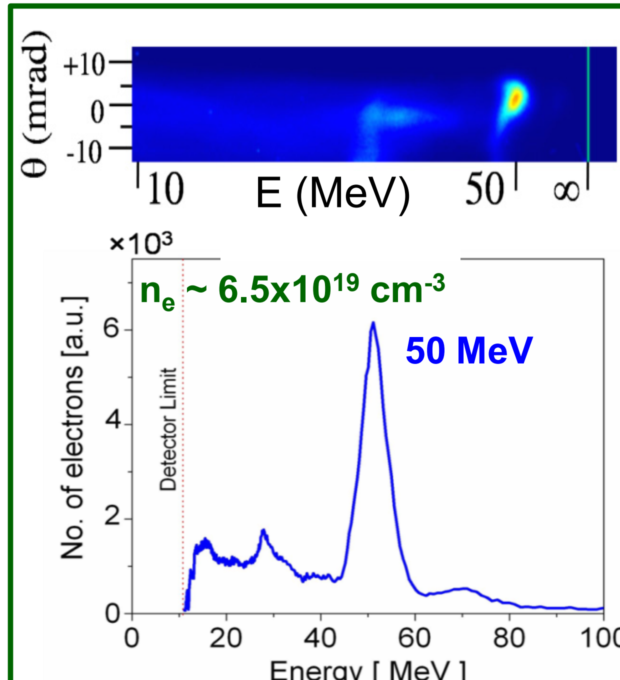




Mono-energetic spectrum



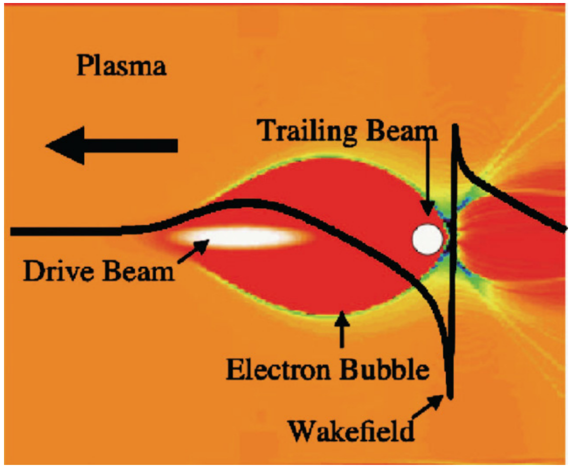




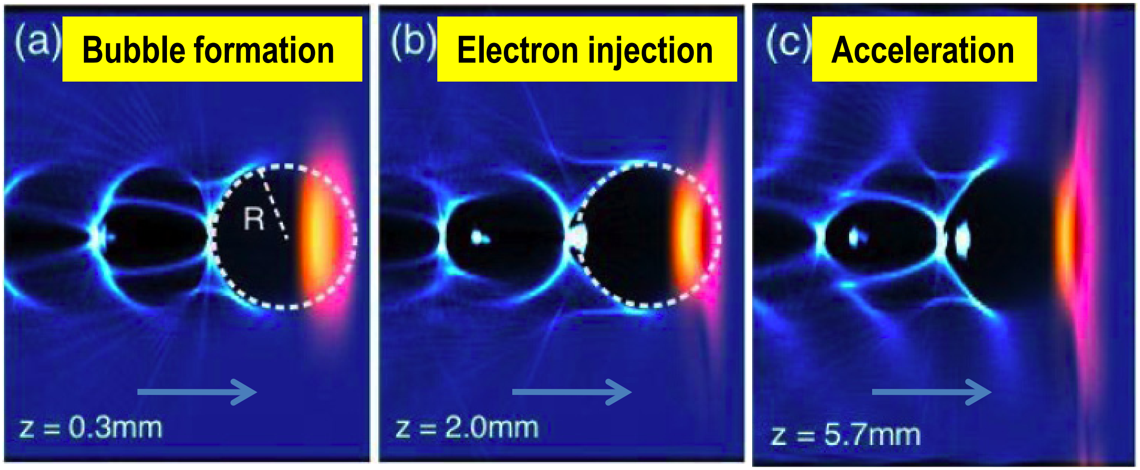
Thank You for your attention !!!

The Bubble Regime (Blowout)

- Theoretical work based on 3D PIC simulations indicated that under resonant conditions a scheme called the "Bubble Regime" can be achieved ($c\tau_L < \lambda_p$ and $a_o > 2$).
- In this regime, the laser ponderomotive force blows out the plasma electrons radially and leaves a cavitated (blowout) region behind the laser pulse, surrounded by high electron density region.
- At the back of the bubble, electrons are trapped and are accelerated along the laser axis.
- Equally applicable to wake-field created by e-beams, when $n_b > n_e$



QuickPIC simulation



A. Pukhov *et al,* Appl. Phys. B. 74, 355, 2002