A challenge of Laser-Plasma Accelerators toward High Energy Frontier

Kazuhisa NAKAJIMA
KEK

at

U.S. - Japan Workshop on Heavy Ion Fusion and High Energy Density Physics

Utsunomiya University, September 28 -30, 2005

OUTLINE

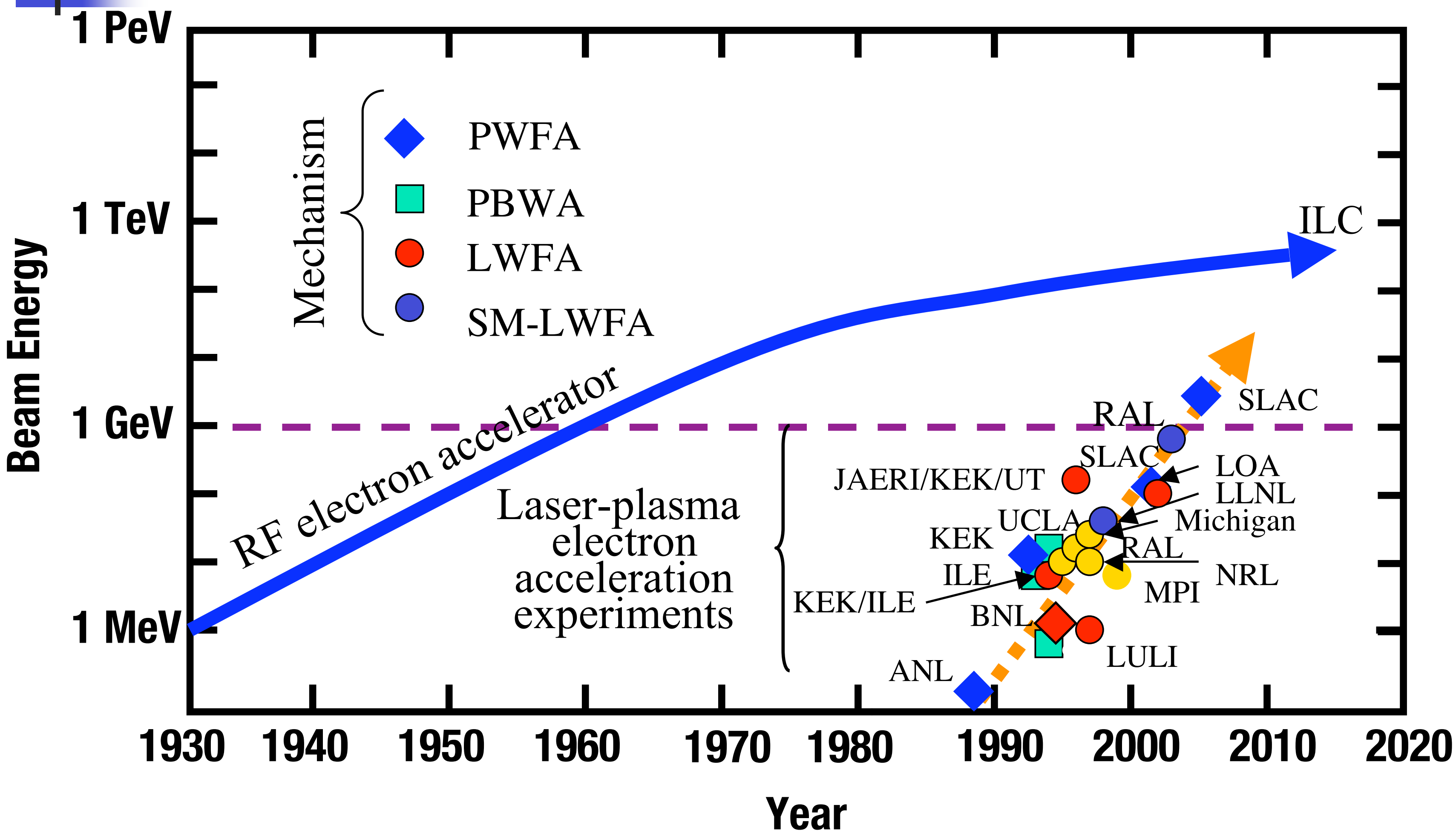
- Recent progress of laser & plasma acceleration

- High energy acceleration mechanism
with self-injection

- Super high average power laser driver for
Multi-TeV laser collider

- Capillary plasma channel development

Laser Plasma Accelerators challenge high-energy frontier with low-cost, high-quality beams



Super-high fields of lasers promise high-quality, high-energy beams

Higher electric fields without breakdown

The state-of-the-art laser field ~ $1x10^{12}$ V/cm

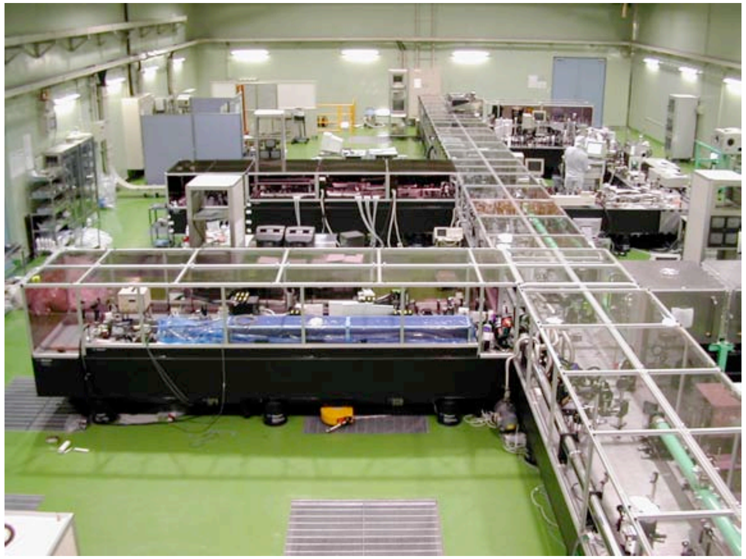
Vacuum breakdown of laser fields to e^+e^- generation

$1.6x10^{16}$ V/cm

Very short wavelength
Very short pulse
Very good coherency

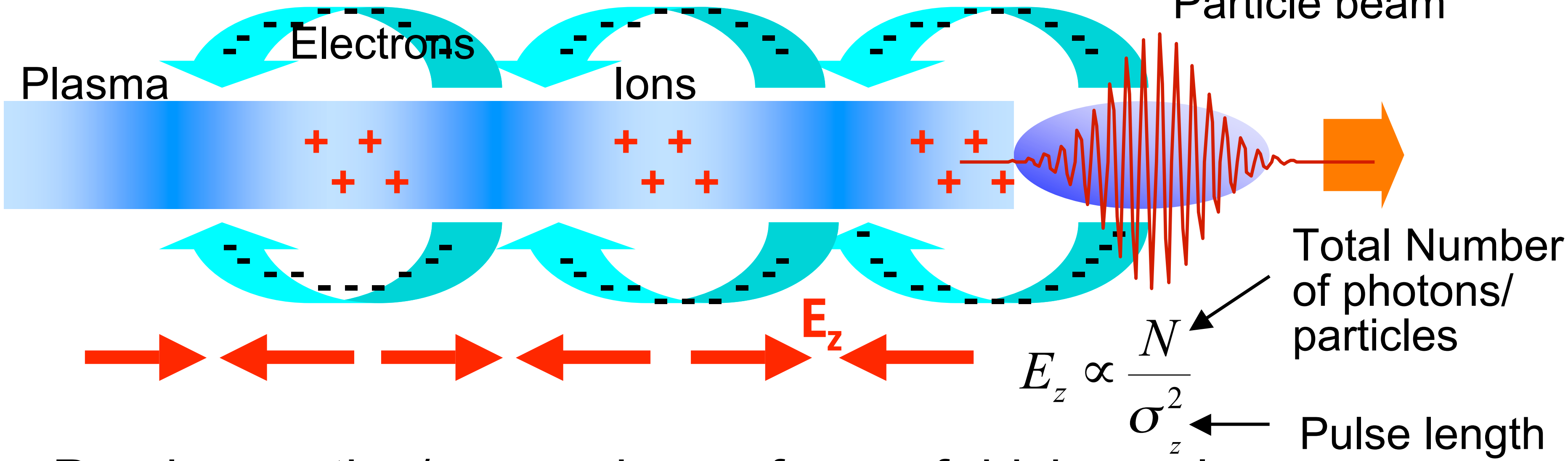
Femto-, Atto- high quality beams

JAERI-APRC PW laser



Laser/Plasma Wake Field Accelerator concept

T. Tajima, J.M. Dawson, PRL 43, 267, 1979
P. Chen, Part. Accel. 20, 171, 1985

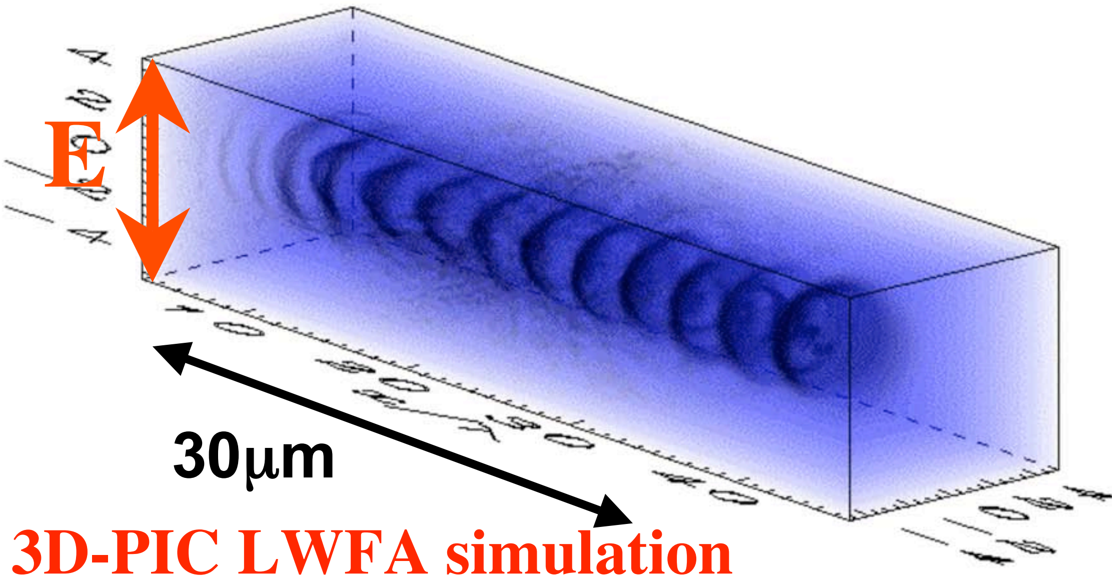


- Ponderomotive/space charge force of driving pulse expels plasma electrons.
- Plasma ions exert restoring force.
- Space charge oscillations are excited.

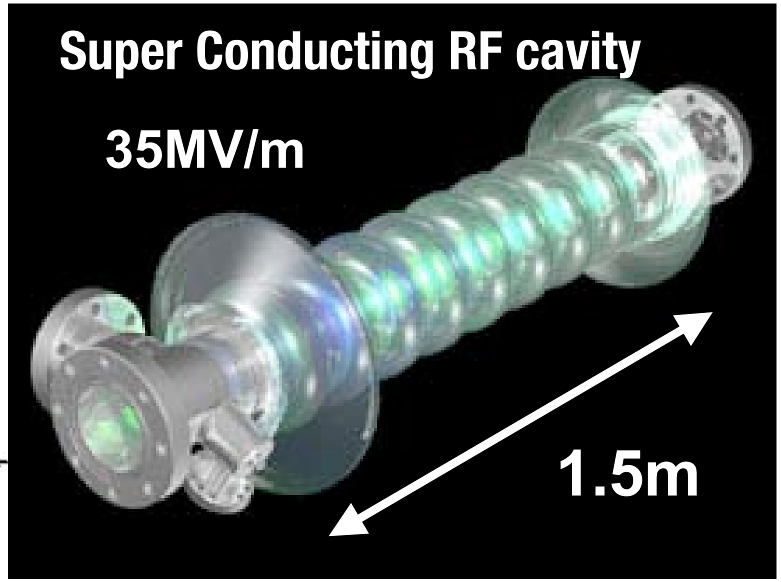
Plasma accelerators can generate more than 100 GV/m

The wave breaking amplitude

E_{max} [V/cm] ~ $n_e^{1/2}$ [cm^{-3}]
e.g. E_{max} ~ 100 GV/m
for $n_e = 10^{18}$ cm^{-3}



3D-PIC LWFA simulation
by Timur Esirkepov, JAERI



First proof-of-principle LWFA experiment at KEK/ILE 1993

30 GeV/m Self-Modulated Laser Wakefield was observed.

"Observation of Ultrahigh Gradient Electron Acceleration by a Self-Modulated Intense Short Laser Pulse"
K. Nakajima et al., Physical Review Letters, 74, pp. 4428-4431 (1995)

1 ps 30TW laser

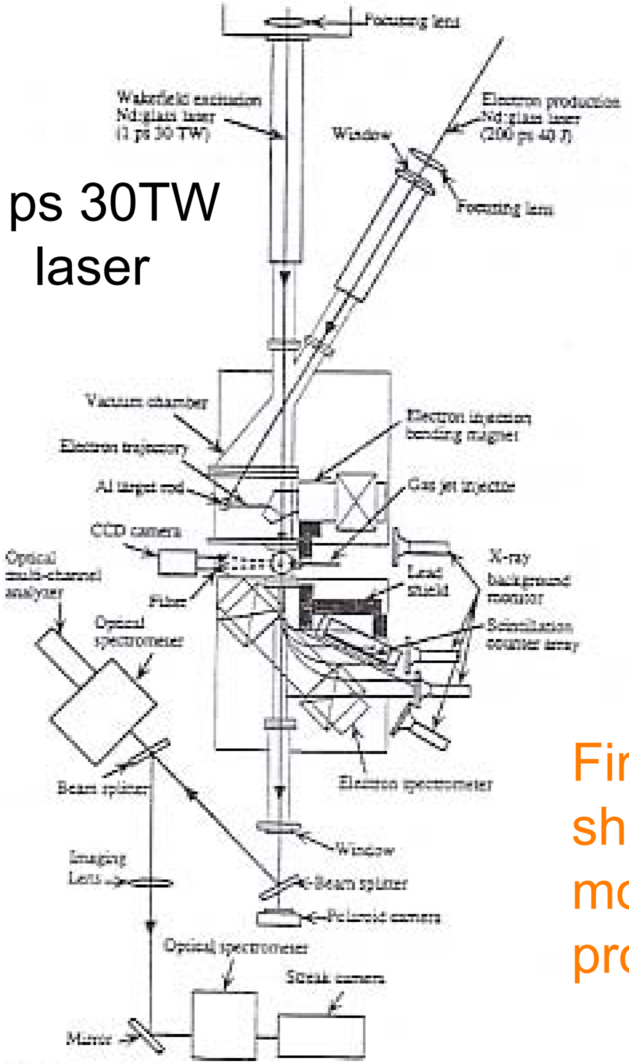


Fig. 2. Schematic of the experimental setup.

First experiment showed monoenergetic property.

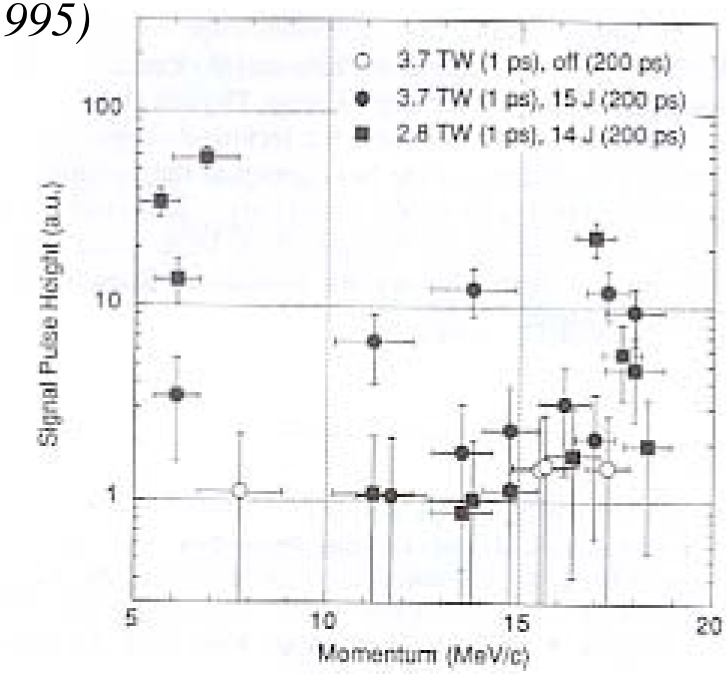
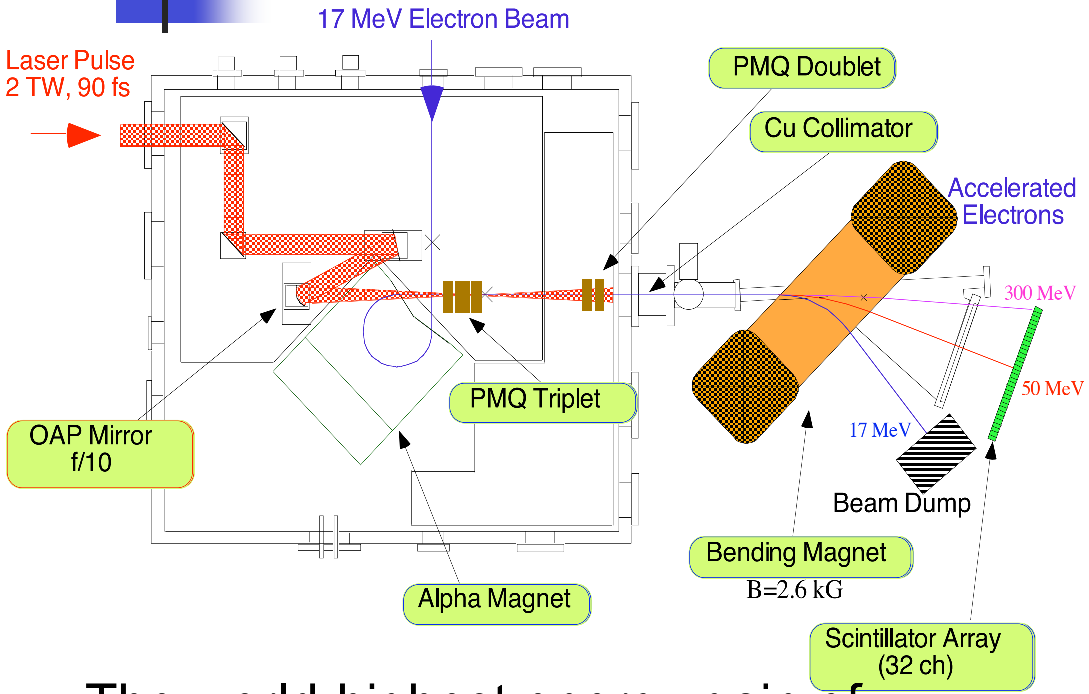


FIG. 2. Observed momentum spectra of accelerated electrons for a He gas jet at the back pressure 7.8 atm.

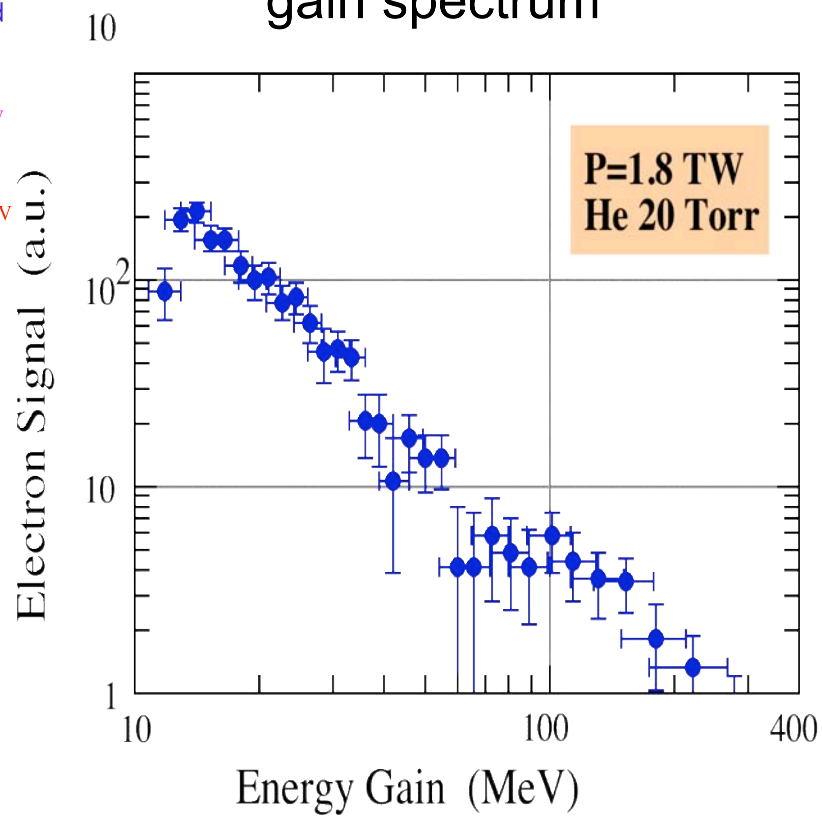
High-energy gain standard-LWFA experiment at JAERI-KEK-U. Tokyo, 1996

H. Dewa et al., NIM A410, 357, 1998
M. Kando et al., JJAP, 38, L967, 1999



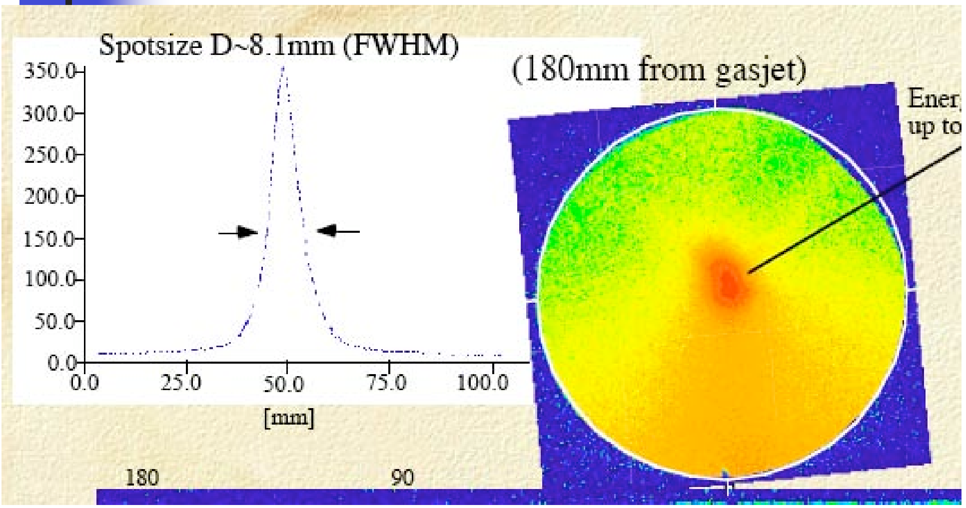
The world-highest energy gain of >250 MeV has been achieved by LWFA experiments using 2TW, 90fs T^3 laser and 17 MeV electron linac.

Measured energy gain spectrum



High quality electron beam generation experiment at U. Tokyo-JAERI

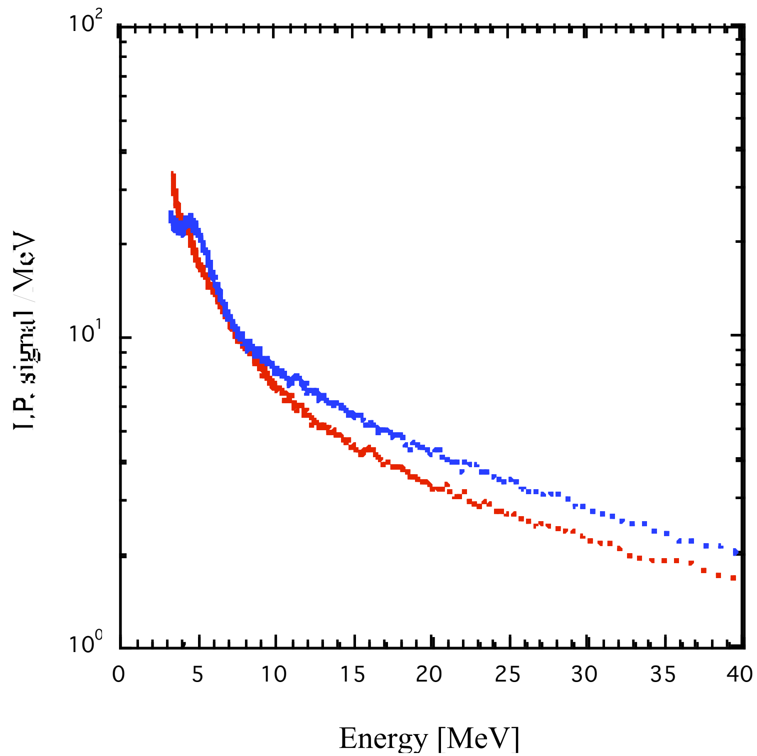
T. Hosokai et al., Phys. Rev. E 67, 036407, 2003



He 2.8×10^{19} cm^{-3},
Laser~4.8 TW, a_0 ~2.0

Energy of e-beam up to 40 MeV
Emittance ~ 0.1π mm mrad
Charge ~ 100 pC
Duration ~ 40 fs

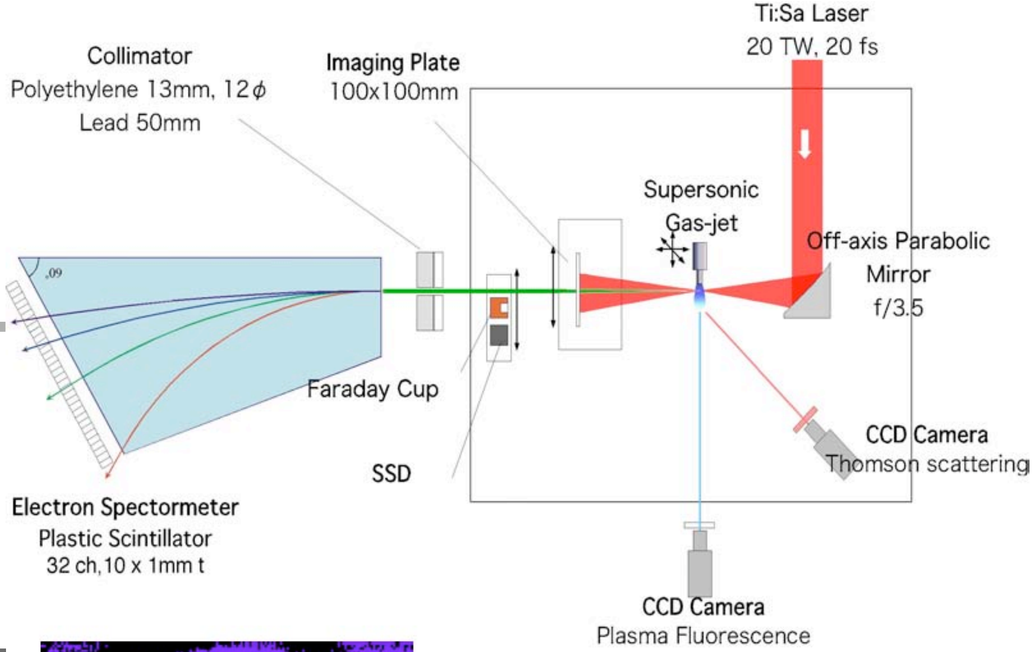
Energy spectrum

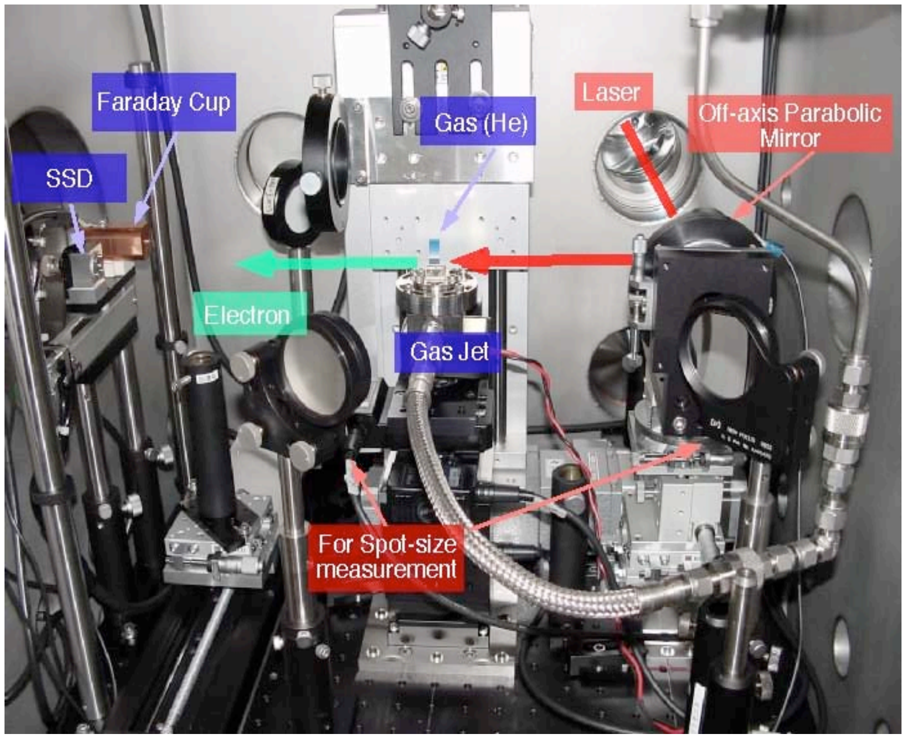


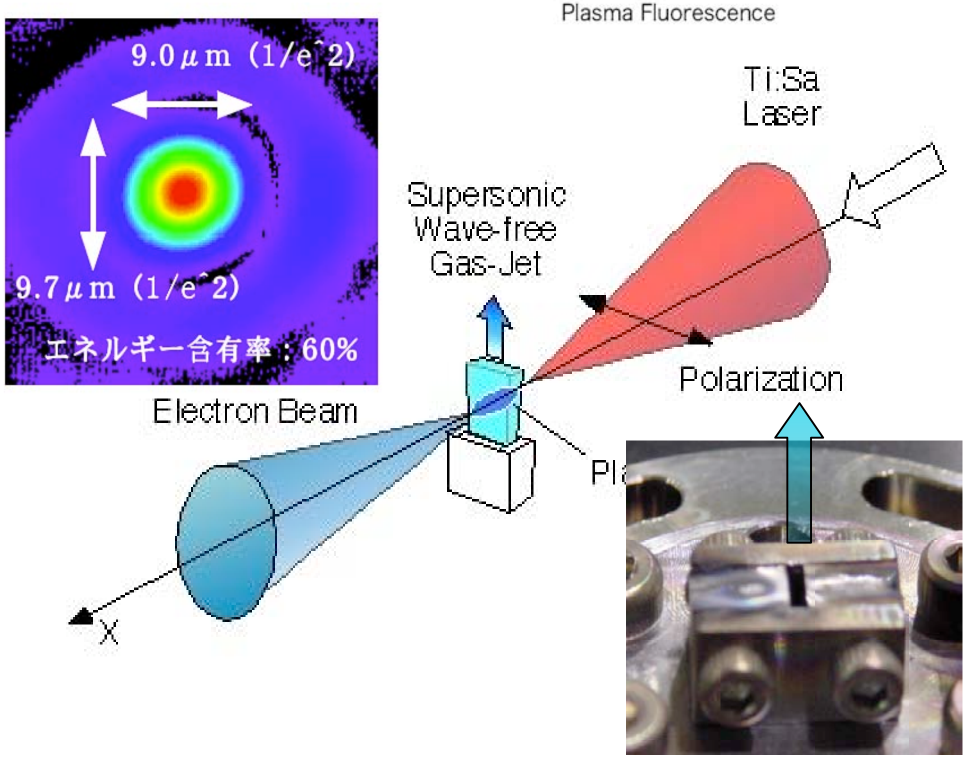
Laser plasma acceleration setup at JAERI-APRC

Laser
Pulse Energy: 420 mJ
Pulse duration: 23 fs
Contrast: ~10^{-6}

Plasma
Gas:Helium
Plasma density: ~1.4×10^{20} cm^{-3}
Slit dimension: 1.3 x 4.0 mm

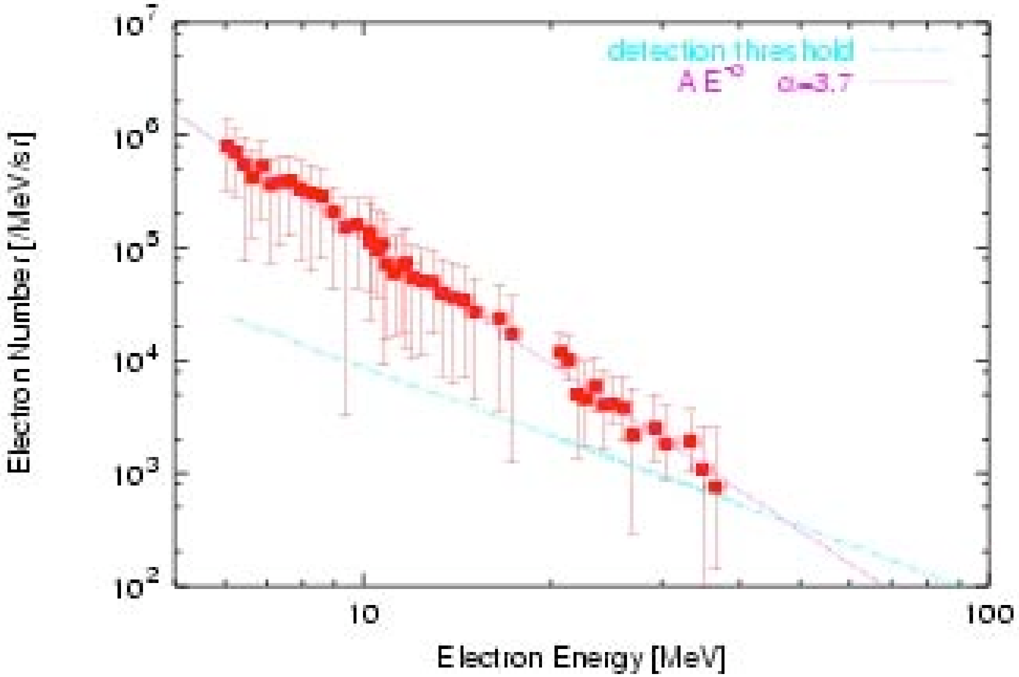




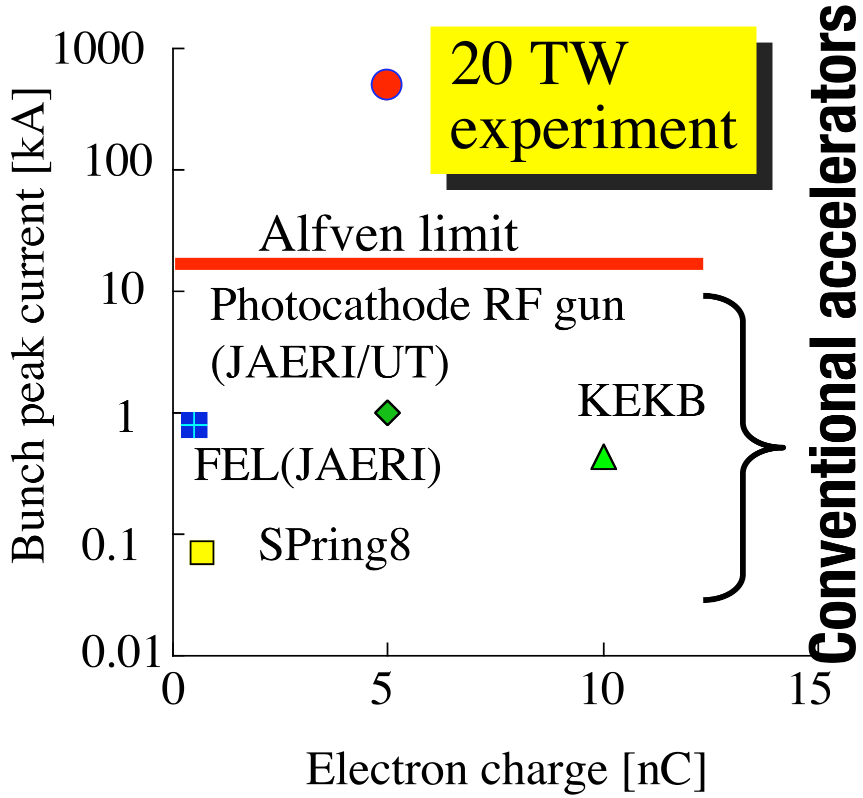


Ultrahigh current electron production experiments at JAERI-APRC, 2003

Energy spectra of laser-plasma electron acceleration at 2.3 x10^{19} W/cm^2 (a_0=3.3), n_e ~ 10^{20} cm^{-3}. Maximum Energy 40 MeV/ mm



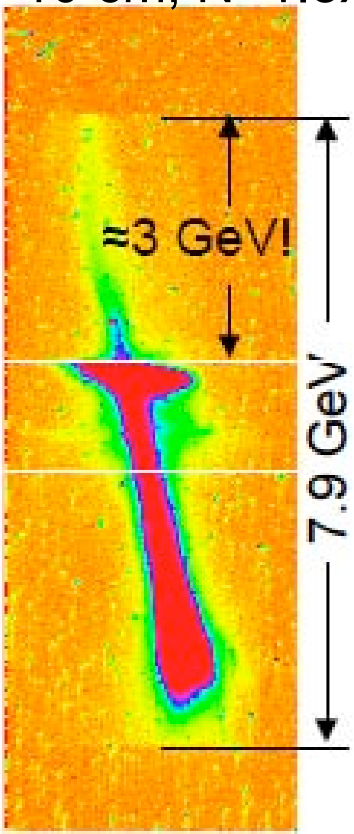
5nC/shot corresponding to Mega Ampere relativistic electron beams per shot

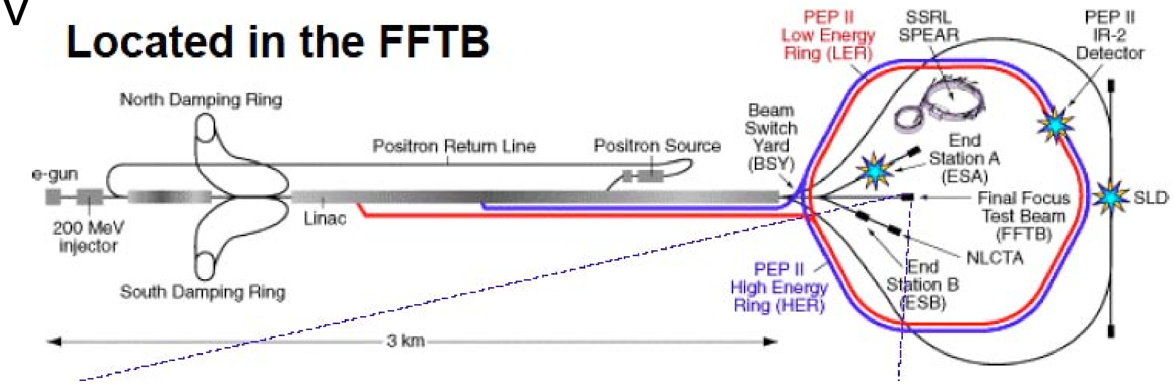


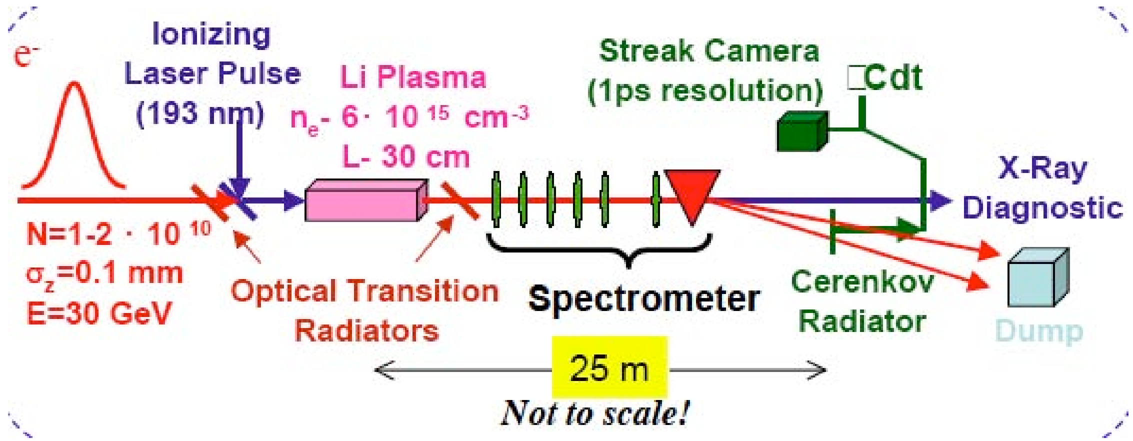
Plasma Wakefield Accelerators break through GeV Barrier in 10cm

PWFA experiments at SLAC FFTB, 2004

Energy gain reaches ~ 4 GeV
at n_e~2.55x10^{17} cm^{-3}
for L=10 cm, N=1.8x10^{10}







C. Joshi (UCLA) , AAC2004

Laser plasma accelerators produce a "Dream beam" sensation, 2004

ICL/RAL, UK

"Monoenergetic beams of relativistic electrons
from intense laser-plasma interactions"
S. P. D. Mangles et al., NATURE, 431, 535, 2004.

LBNL, US

"High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding"
C. G. R. Geddes et al., NATURE, 431, 538, 2004.

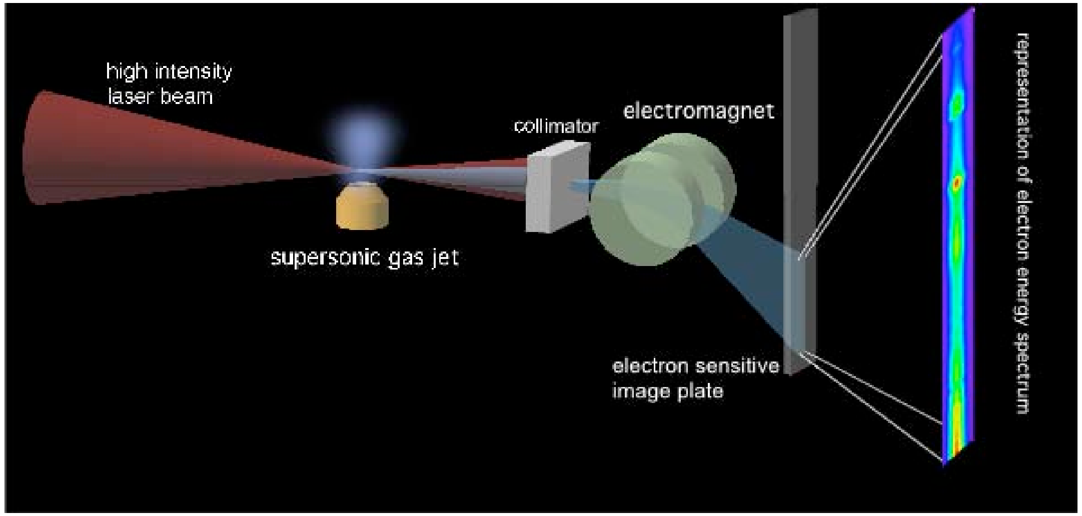
LOA, France

"A laser-plasma accelerator producing monoenergetic electron beams"
J. Faure et al., NATURE, 431, 541, 2004.

Thomas Katsouleas, NATURE, 431, 515, 2004

Monoenergetic beams of relativistic electrons from intense laser-plasma interactions

ILC/RAL, ALPHA-X group, UK



by the courtesy of S. Mangles, Imperial Colledge London

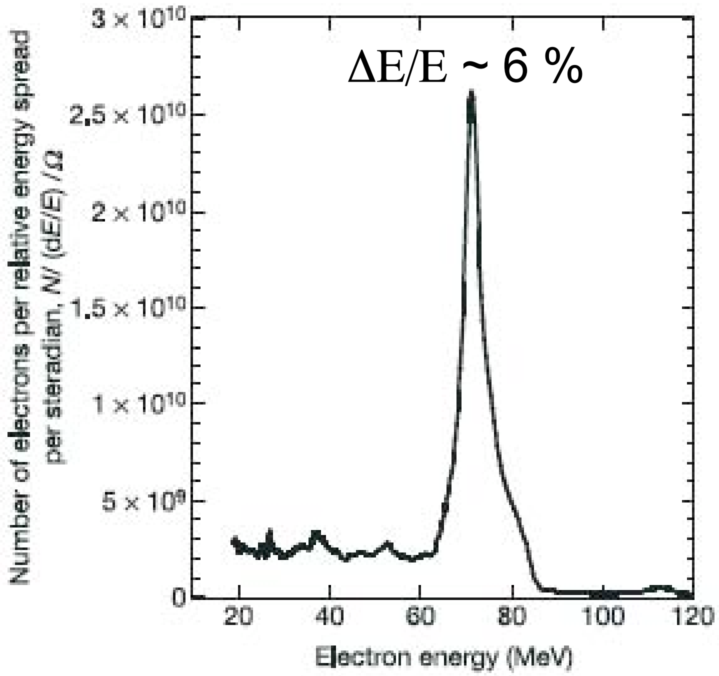


Figure 3 Measured electron spectrum at a density of 2×10^{19} cm^{-3}. Laser parameters: $E = 500$ mJ, $\tau = 40$ fs, $I \approx 2.5 \times 10^{18}$ W cm^{-2}. The energy spread is ±3%. The energy of this monoenergetic beam fluctuated by ~30%, owing to variations in the laser parameters.

•Laser parameters:

Exp. 1 360 mJ 45 fs (8 TW)

Exp. 2 500 mJ 45 fs (11 TW)

•Focusing optic f/20

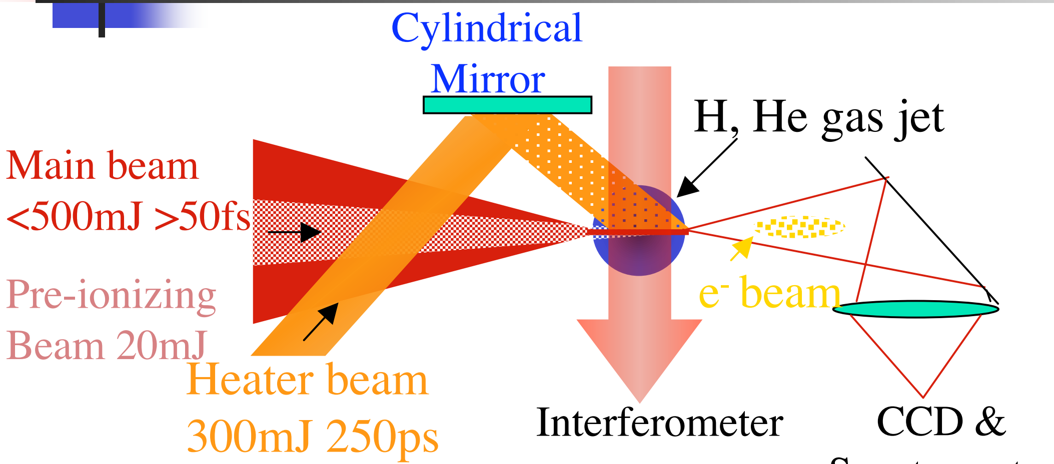
• focal spot 25 μm FWHM

$n_e = 2 \times 10^{19}$ cm^{-3}

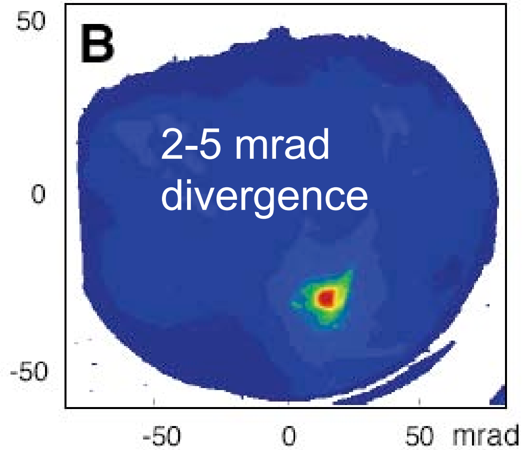
High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

L'OASIS Group at LBNL, UC Berkeley, USA

by the courtesy of W. Leemans, LBNL

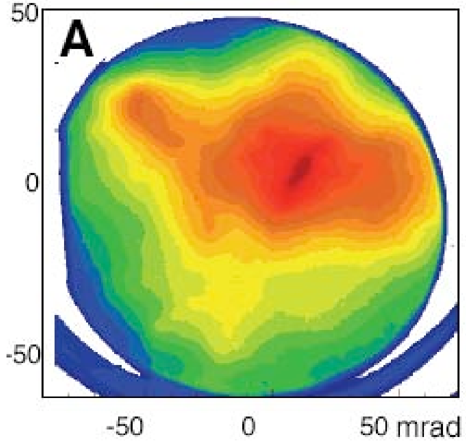


Guided

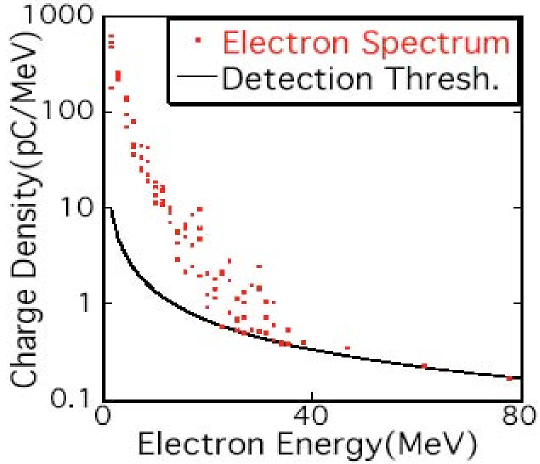


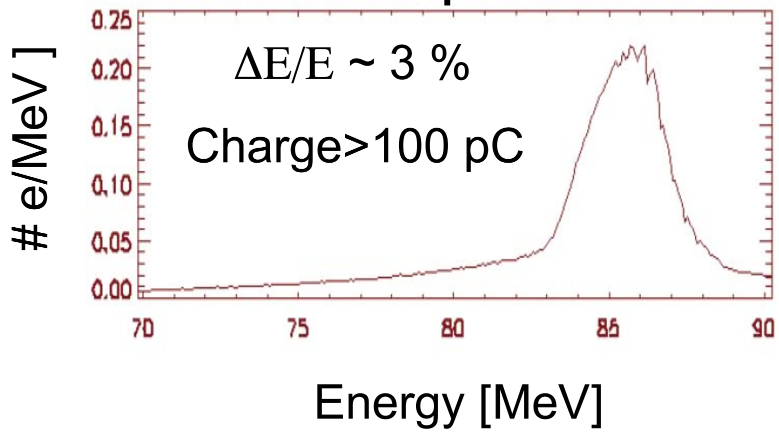
Beam profile

Unguided



Beam profile



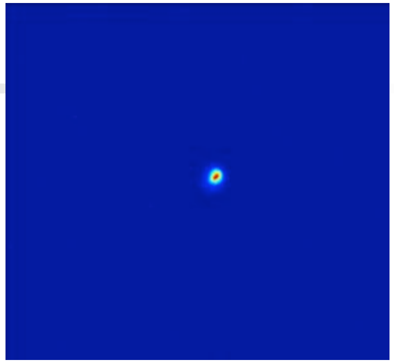


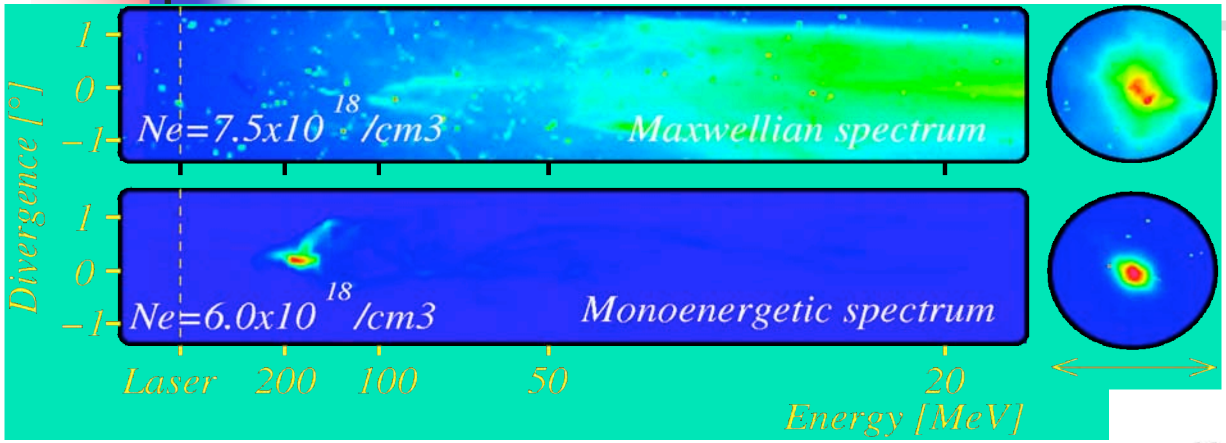
A laser-plasma accelerator producing monoenergetic electron beams

LOA Group, France

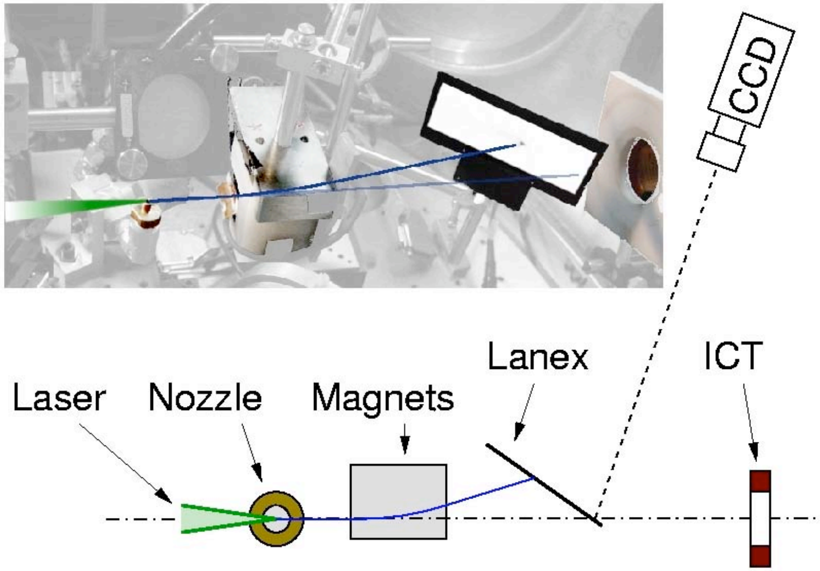
by the courtesy of V. Malka, LOA

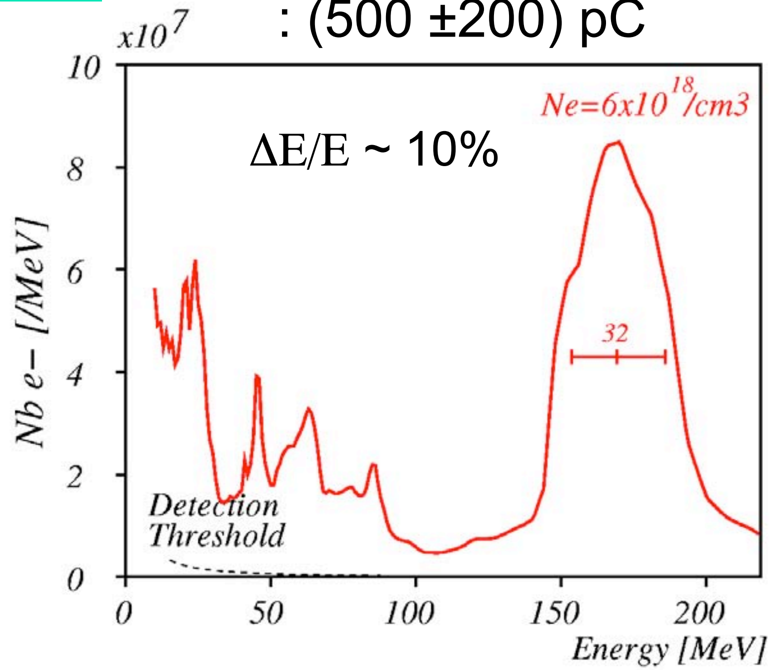
30TW, 30fs
$3x10^{18}$ W/cm^2





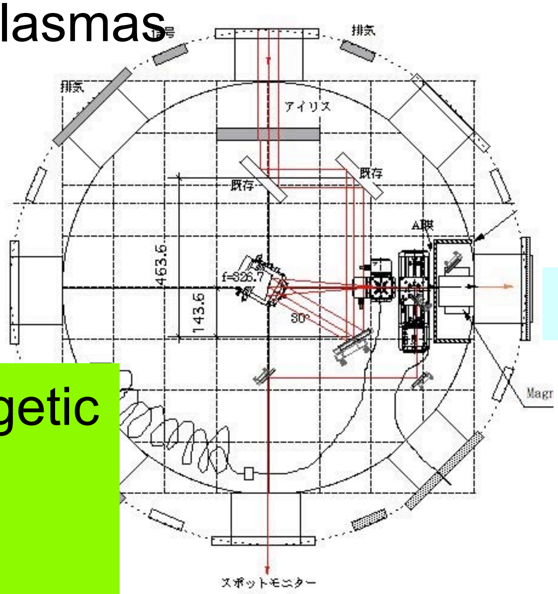
Charge in [150-190] MeV : (500 ±200) pC

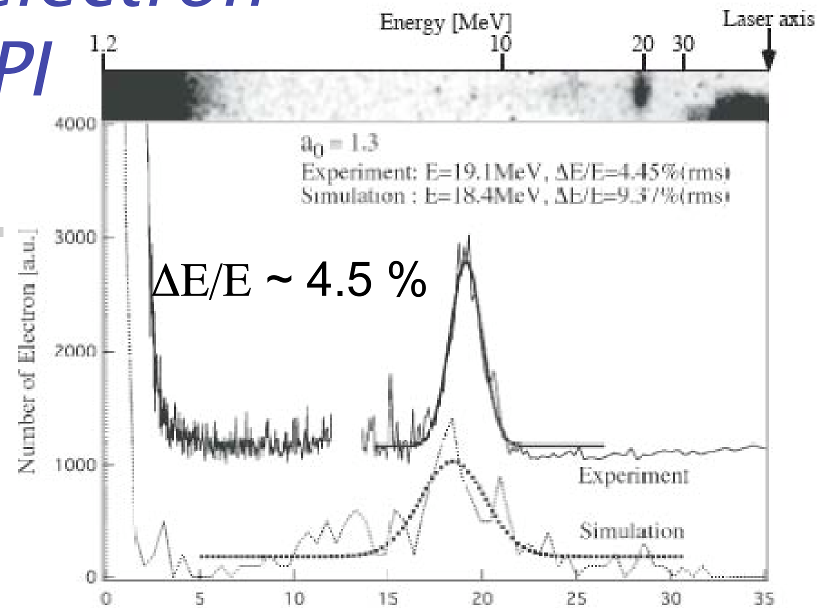




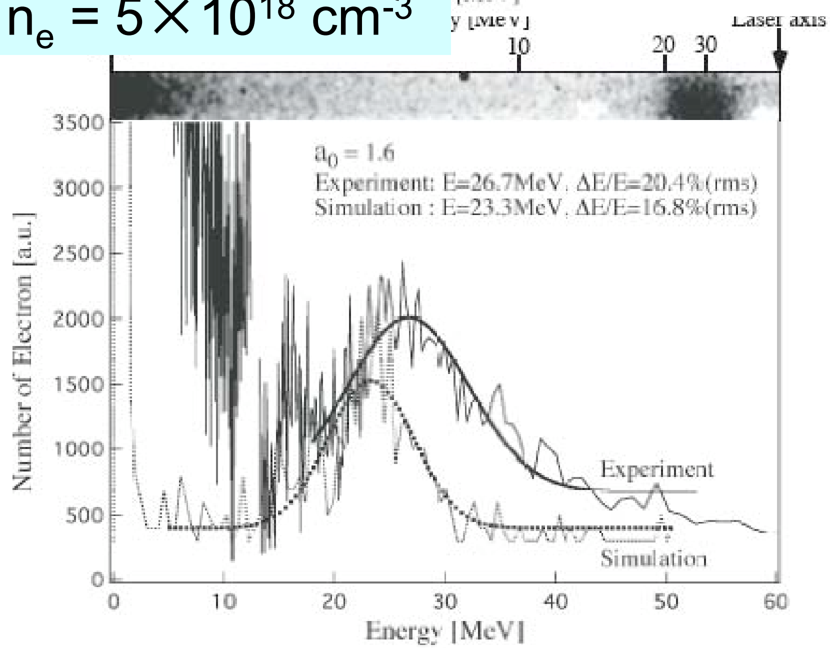
Stable monoenergetic electron generation, JAERI-CRIEPI Group, 2004

A. Yamazaki et al.,to be published in Physics of Plasmas





$n_e = 5\times10^{18}$ cm^{-3}



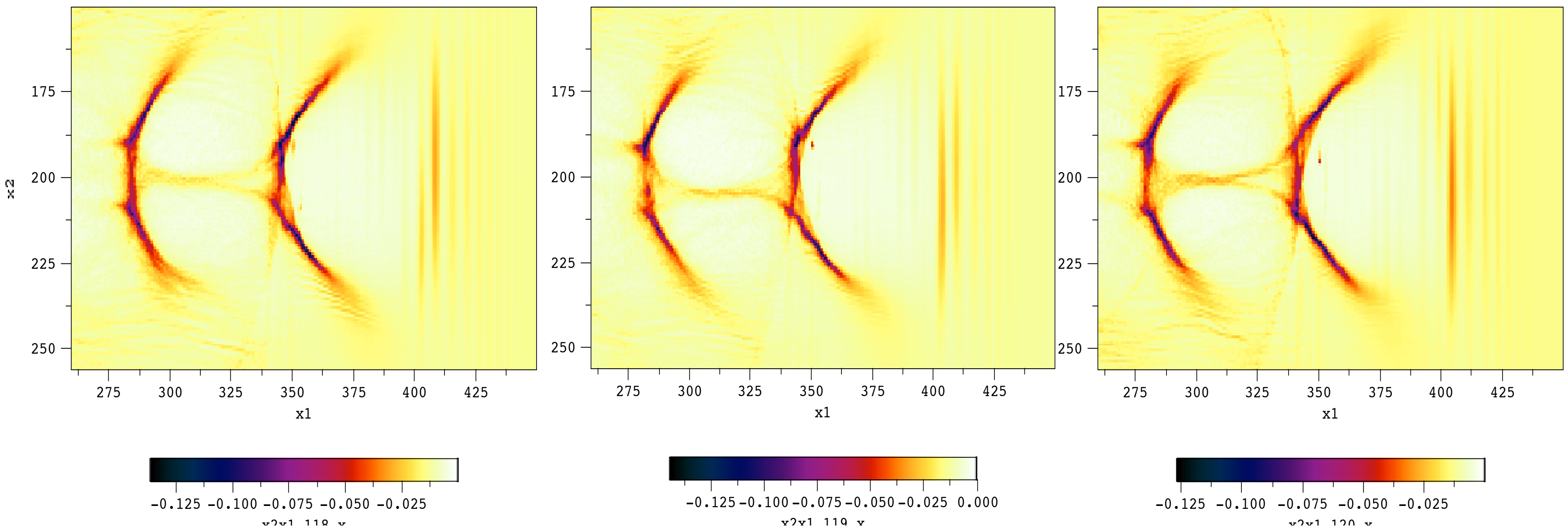
Many new monoenergetic electron acceleration experiments:
AIST,
U. Tokyo,
JAERI,
KERI (Korea)
MPQ (Germany)

Laser pulse:
P = 7TW,
t_L = 70fs,
λ_0 = 800nm

Proposed monoenergetic mechanism:

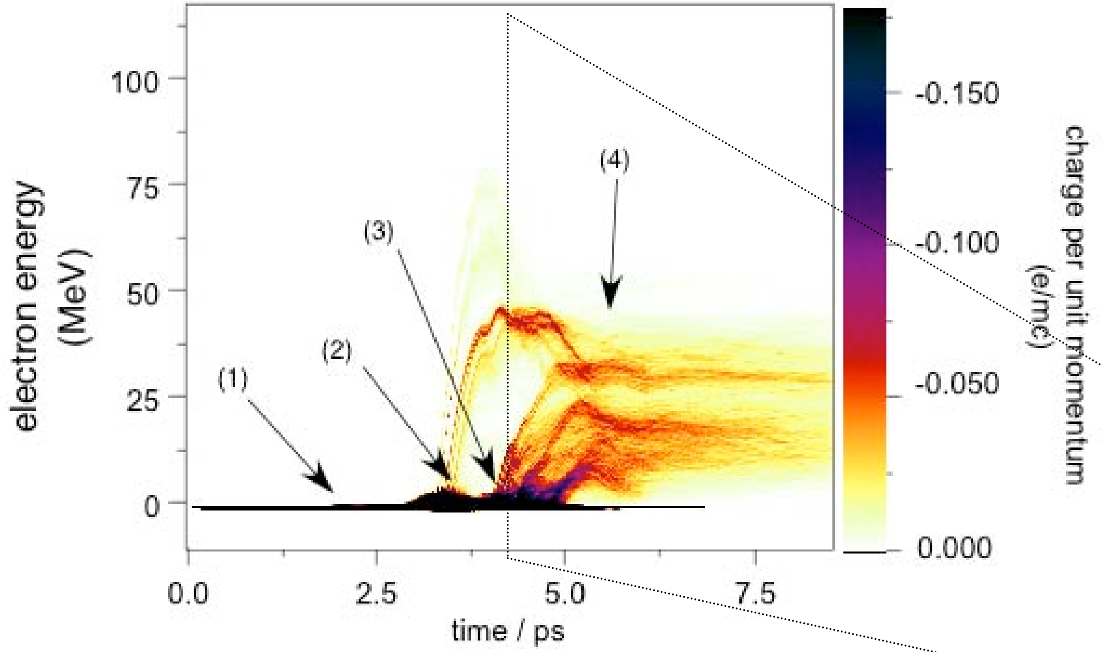
Transverse Wave breaking

by S. Mangles, Imperial Colledge London

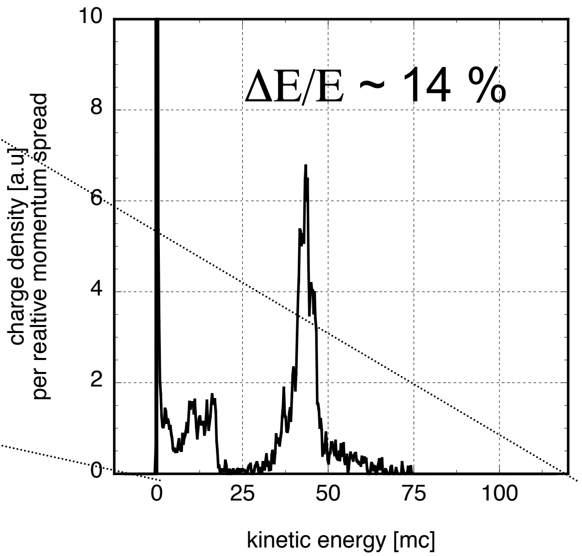


- Wave front is curved due to transverse profile of laser
- Injection happens from sides in these 2D3V simulations
- Very similar to "transverse wake wave breaking" described by Bulanov et al, PRL **78** 4205 (1997)

How to make a monoenergetic spectrum
Interaction length < Dephasing length



Electron spectrum at 4.3 ps



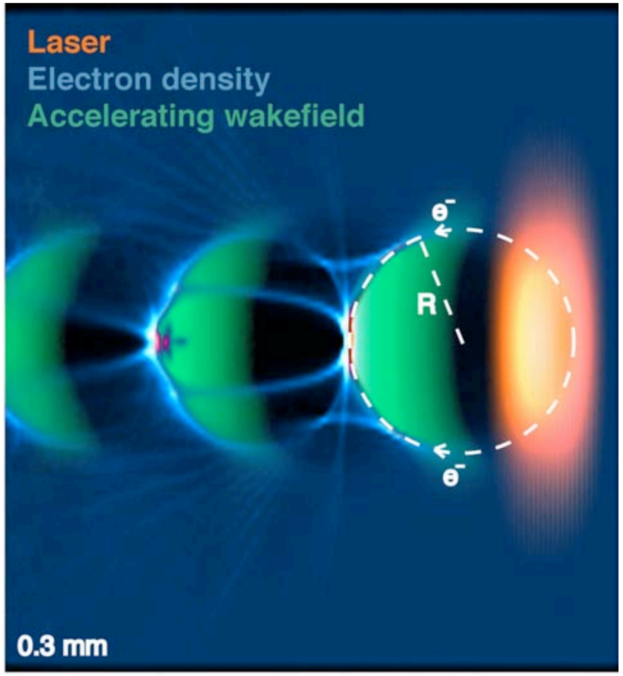
1) Plasma wave becomes non-linear
2) Transverse wave breaking takes place - particles injected into wave
3) Further wave periods also break
4) Dephasing has occurred and energy spread is increased

Fine plasma density control is essential.

Proposed monoenergetic mechanism: Bubble acceleration in the ultra-relativistic blowout regime

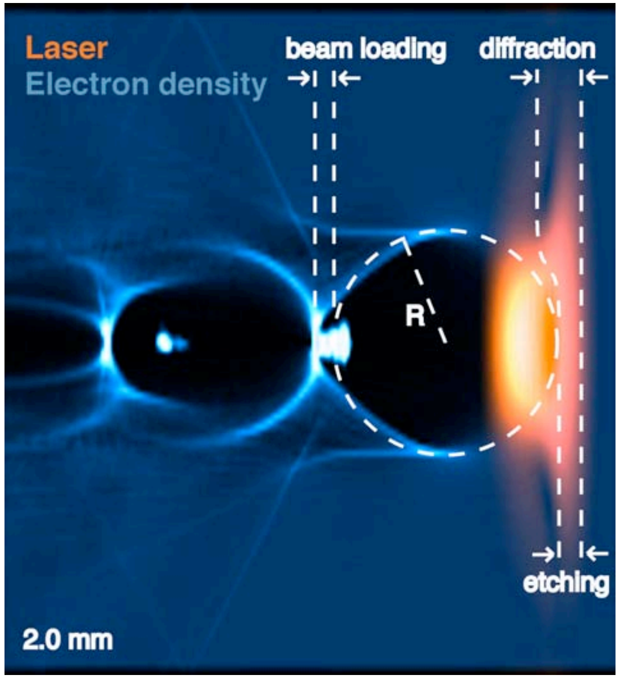
by W. Lu, UCLA, HEEAUP2005

Cavity formation



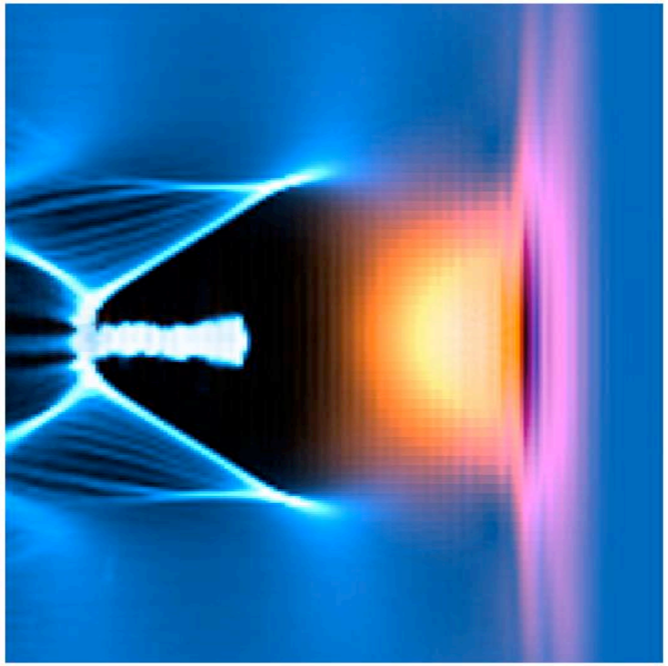
Electron void (ion channel) formation behind the pulse

Self-injection



Electron self-injection into ion channel

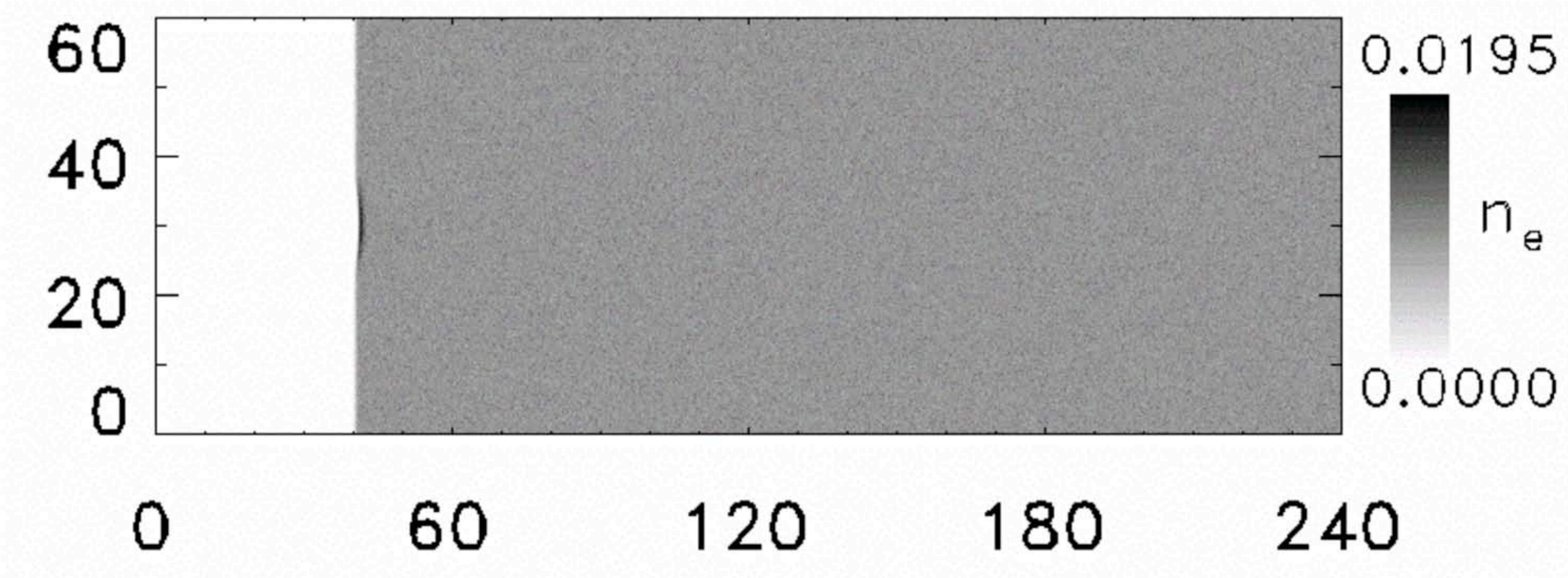
Acceleration



Shutdown of self injection due to beam loading

Bubble Acceleration simulation

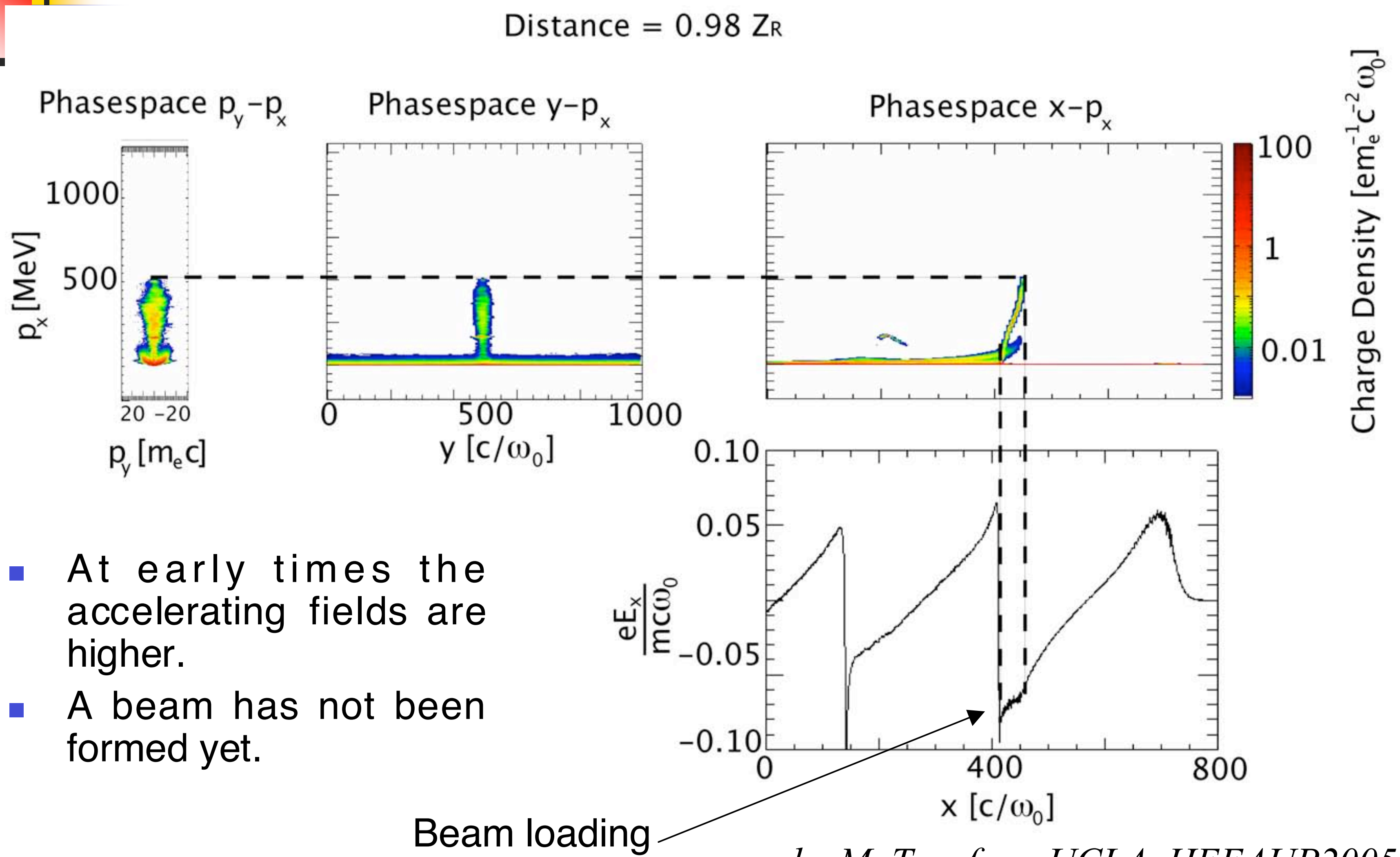
2D example 1: a_L=10, t_L=10, with a sharp plasma boundary. A sharp density peak over 20 times of the initial density found starting at t=50



By the courtesy of Z-M Sheng, IOP China

Simulations of electron acceleration

for 200TW, 30fs, $n_p = 1.5\times10^{18}cm^{-3}$, $a_0=4$, $w_0=20\mu m$

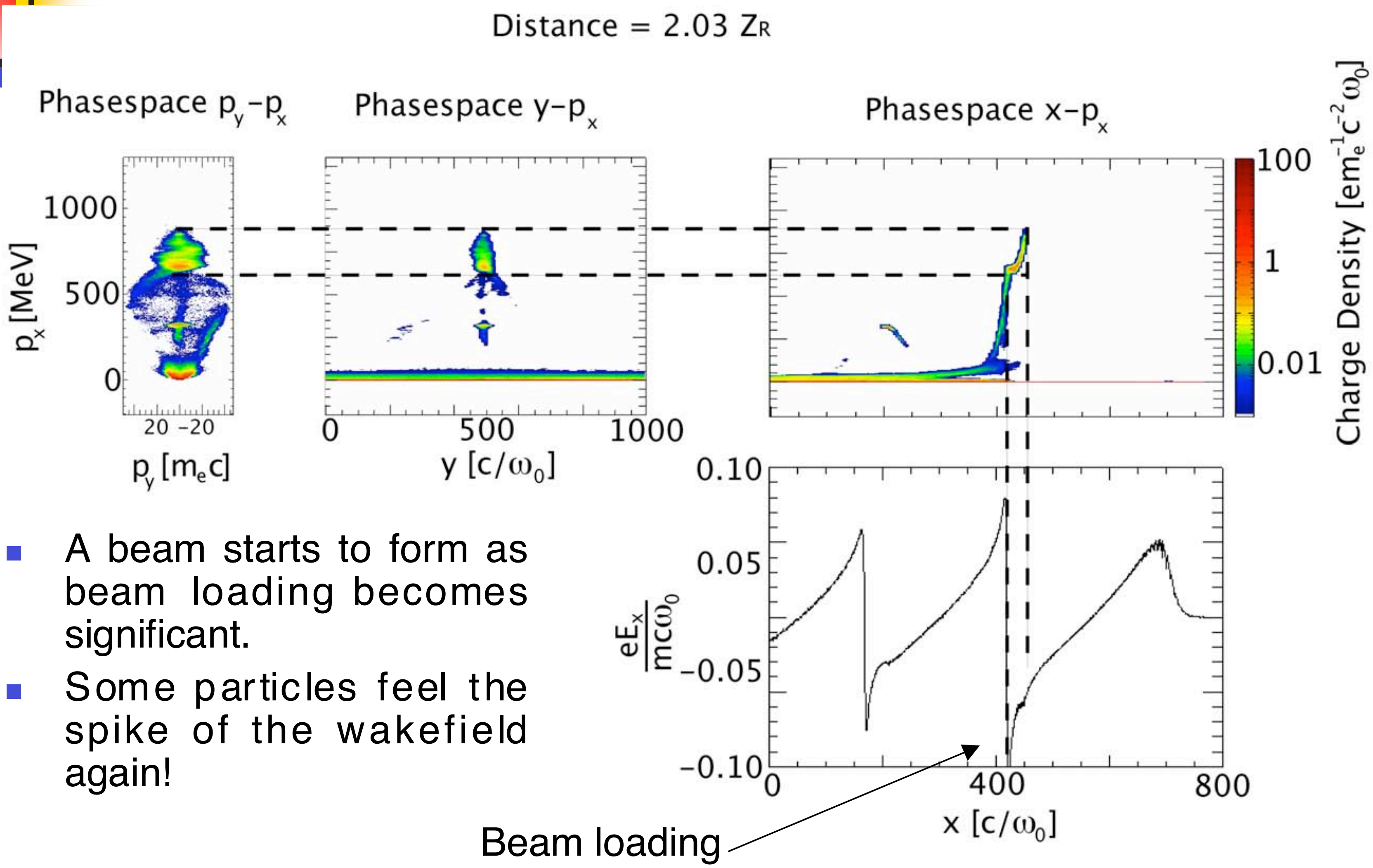


- At early times the accelerating fields are higher.
- A beam has not been formed yet.

by M. Tzoufras, UCLA, HEEAUP2005

Simulations of electron acceleration

for 200TW, 30fs, n_p =1.5x10^{18}cm^{-3}, a_0=4, w_0=20μm

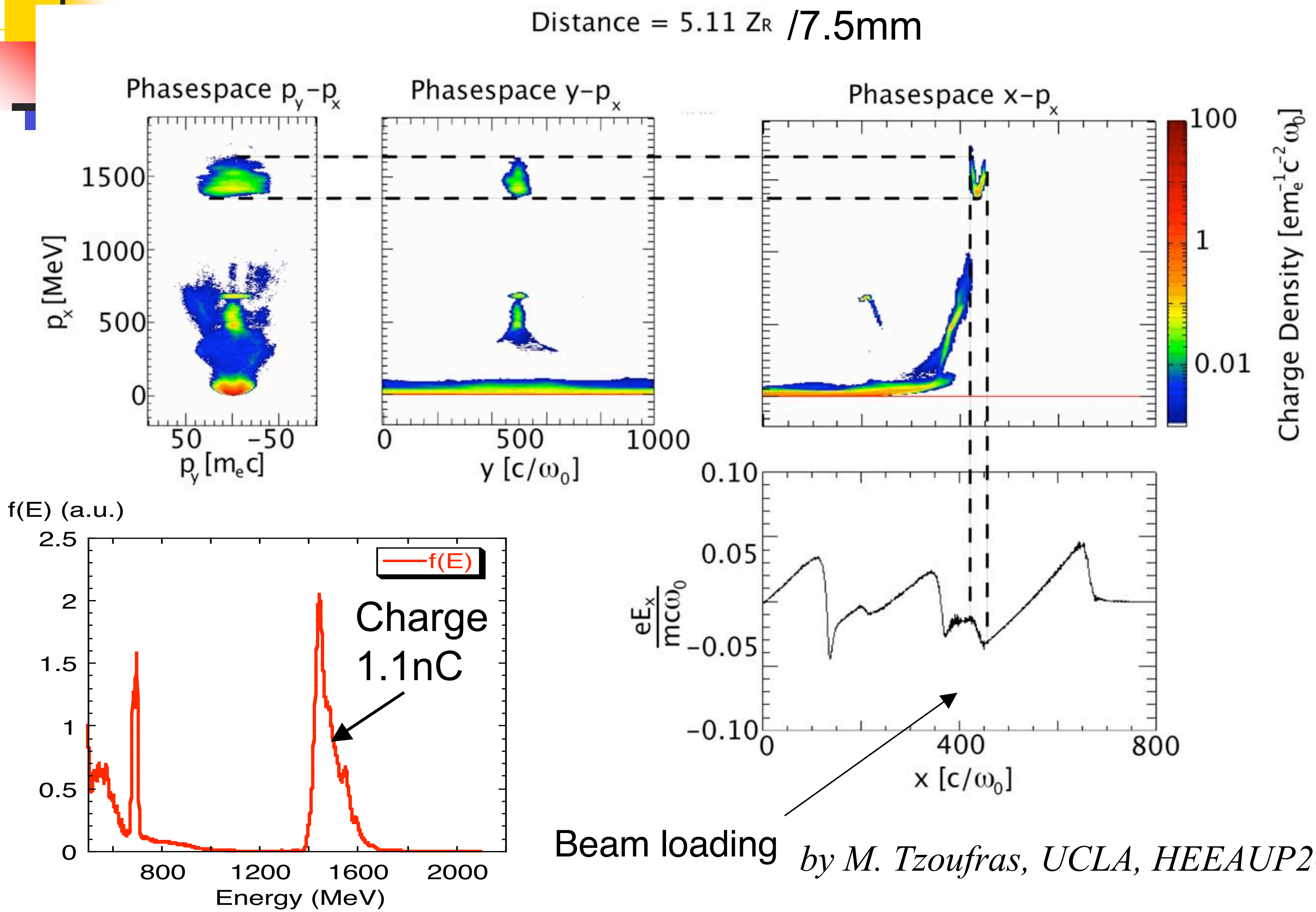


- A beam starts to form as beam loading becomes significant.
- Some particles feel the spike of the wakefield again!

by M. Tzoufras, UCLA, HEEAUP2005

Simulations of electron acceleration

for 200TW, 30fs, n_p =1.5x10^{18}cm^{-3}, a_0=4, w_0=20μm



by M. Tzoufras, UCLA, HEEAUP2005

Matched Blowout Acceleration

Wake amplitudes in the ultra-relativistic blowout regime (k_pR_b ~ 4-5).

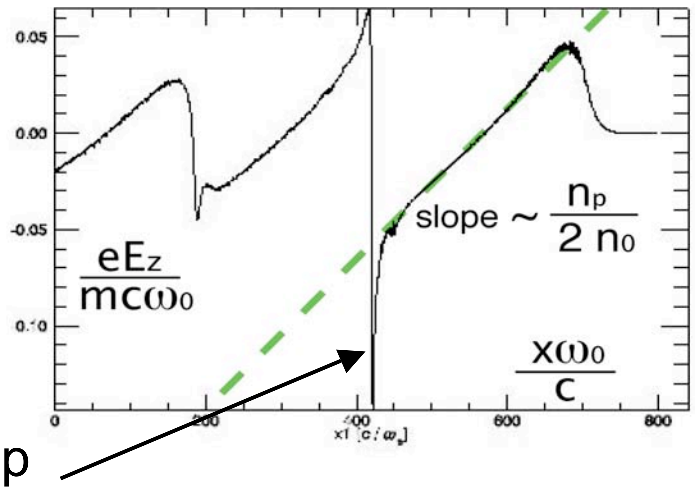
$$\frac{eE_z}{mc\omega_p} \approx \frac{1}{2}\xi, \quad \frac{eE_M}{mc\omega_p} \approx \frac{1}{2}k_pR_b$$

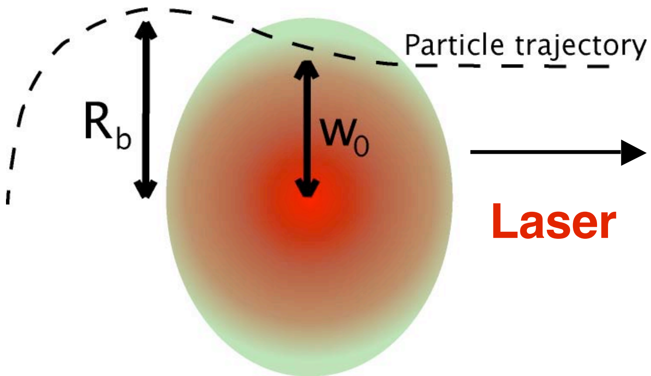
Matched laser spot size is given by balance of ponderomotive and ion channel forces as approximately

$$k_pR_b \approx k_pW_0 \approx 2\sqrt{a_0}$$

For **given laser power P and given plasma density n_p, this matching condition gives:**

$$a_0 \approx 2\left(\frac{P}{P_c}\right)^{1/3}$$





by W. Lu, UCLA, HEEAUP2005

Scaling formula for matched blowout acceleration

Self-injection condition: $a_0 \approx 4 \sim 5 \Rightarrow \begin{cases} \dfrac{P}{P_c} \approx 8 \sim 16 >> 1 \\ k_p R_b \approx 4 \sim 5 >> 1 \end{cases}$

For self-guiding: $a_0 > a_c \approx \left(\dfrac{n_c}{n_e} \right)^{1/5}$

Dephasing length: $L_{dp} \approx \dfrac{2}{3} \left(\dfrac{k_0}{k_p} \right)^2 R_b \approx \dfrac{4}{3} \left(\dfrac{k_0}{k_p} \right)^3 \sqrt{a_0} k_0^{-1}$

Pump depletion length: $L_{pd} \approx \left(\dfrac{k_0}{k_p} \right)^2 c\tau \approx 2 \left(\dfrac{c\tau}{R_b} \right) \left(\dfrac{k_0}{k_p} \right)^3 \sqrt{a_0} k_0^{-1}$

Energy gain: $\Delta E \approx \dfrac{2}{3} mc^2 \left(\dfrac{k_0}{k_p} \right)^2 a_0$ or $\Delta E \approx mc^2 \left(\dfrac{P}{P_r} \right)^{\frac{1}{3}} \left(\dfrac{n_c}{n_p} \right)^{\frac{2}{3}}$

Total charge: $N_b \approx \dfrac{3\lambda_0}{4\pi r_e} a_0^{3/2} \left(\dfrac{n_c}{n_e} \right)^{1/2} \approx 5.1 \dfrac{\lambda_0}{r_e} \sqrt{P}$

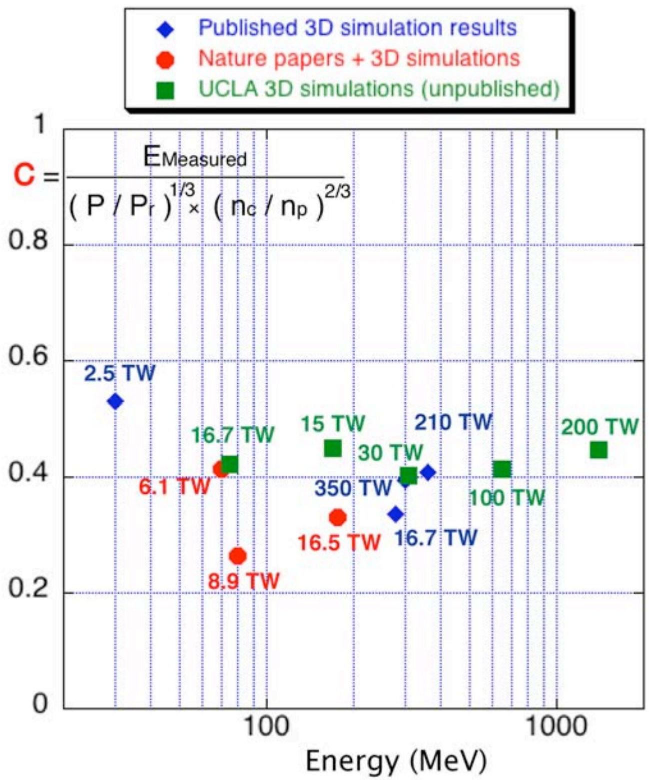
Scaling laws

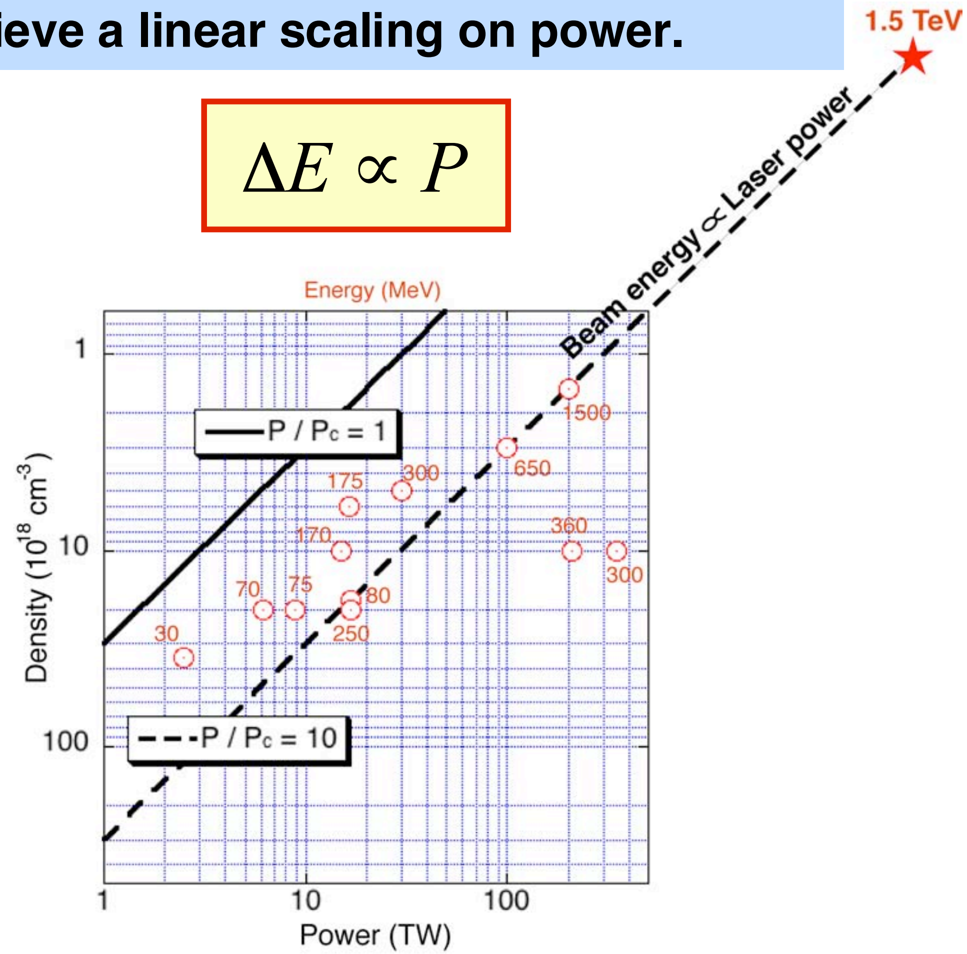
by W. Lu, UCLA, HEEAUP2005

Verification of the scaling through simulations

As long as the laser can be guided (either by itself or using shallow plasma density channel), one can increase the laser power and decrease the plasma density to achieve a linear scaling on power.

$$\Delta E \propto P$$





Schemes for TeV energy frontier

Multi-staging scheme

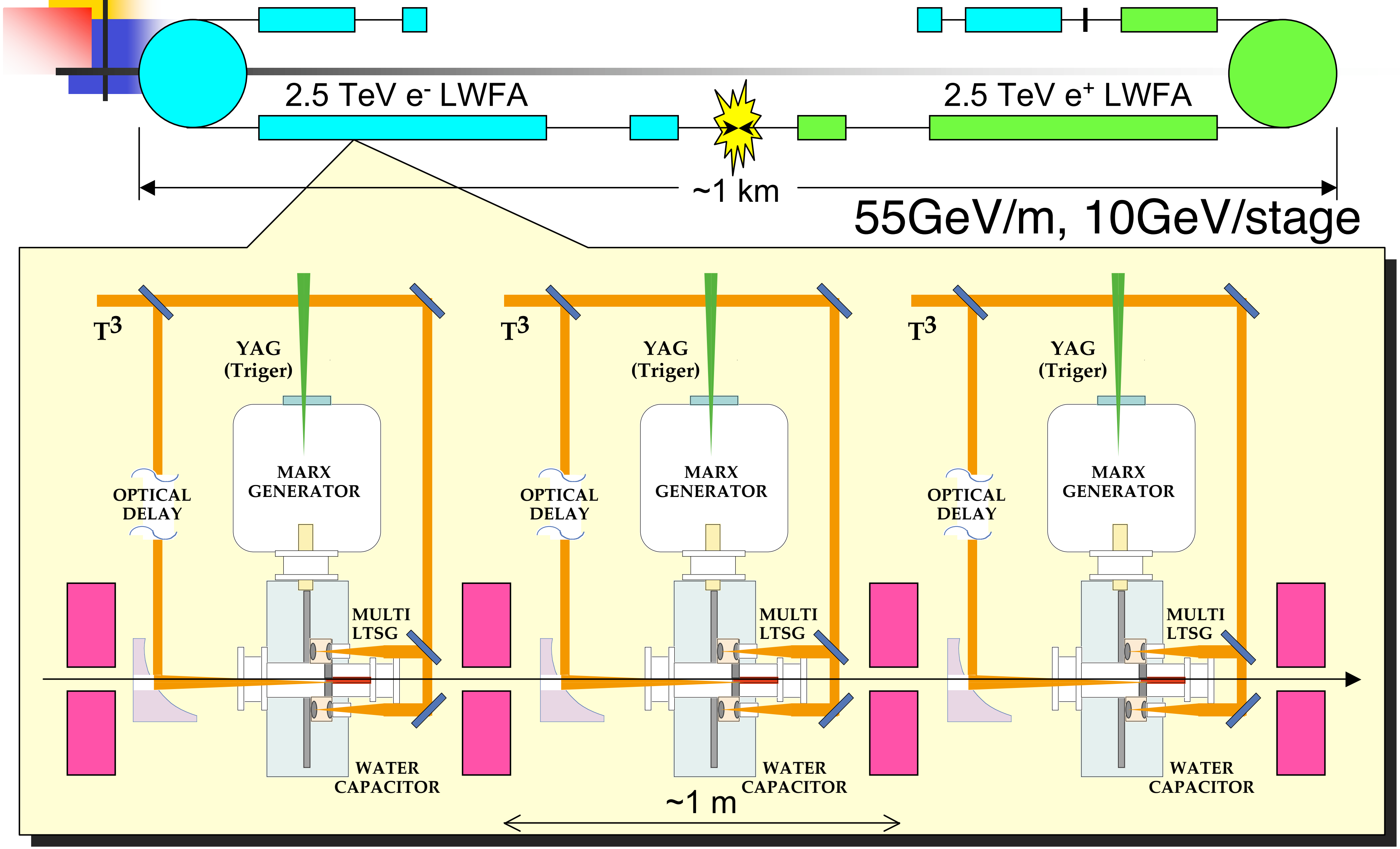
- Successive acceleration of 10 GeV/cell energy gain over the length limited by dephasing or pump depletion.
- Matching between cell to cell ➡ Spatial alignment
- Pumping power to each cell ➡ Temporal synchronization

Single-staging scheme

- Single cell acceleration up to TeV energy
- Extremely high peak power pump laser

Both schemes need optical guiding through plasma channel

5 TeV e^+e^- LWFA Linear Collider consisting of staged plasma channels



Parameters of 5TeV e^+e^- Linear Collider based on LWFA

Collider parameters

CM Energy	E_{cm}	**5 TeV**
Luminosity	L_g	**10^{35} cm^{-2}s^{-1}**
Emittance	E_y	2.2 nm
Beta at IP	β_y	22 μm
Beam size at IP	σ_y	0.1 nm
Bunch length	σ_z	0.32 μm
Number of particles	**N**	**5×10^7/ bunch**
Collision frequency	f_c	**50 kHz**
Average beam power	P_b	2 MW
Disruption parameter	D_y	0.93
Beamstrahlung parameter	Υ	3485

LWFA parameters

Plasma density	n_e	3.5×10^{17}cm^{-3}
Acceleraion length	L_{ac}	20 cm
Accelerating gradient	E_z	**55GV/m**
Energy gain/ stage	W	**10 GeV**
Laser power/ stage	P_{av}	**100 kW**
Laser pulse energy	E_L	2 J
Laser pulse duration	τ	100 fs
Laser peak power	P	**20 TW**
Number of stages		**500**
Total laser power		**50 MW**
Total length		**~ 1 km**

(M. Xie et al.,AIP CP398,AAC96,233,1997)

Single-stage TeV accelerator

by W. Lu, UCLA, HEEAUP2005

	Uniform plasma	20% deep plasma channel
Peak Power, P	1000 PW	120 PW
Pulse duration, τ	1 ps	1 ps
Plasma density, n_p	6.5×10^{15} cm^{-3}	2×10^{15} cm^{-3}
Spot radius, W_0	450 μm	470 μm
Acceleration length, L	80 m	280 m
a_0	12.1	4
Total charge, Q	120 nC	40 nC
Energy gain, ΔE	1012 GeV	1120 GeV

$a_0 = 6.8\sqrt{P[TW]}\frac{\lambda_0}{W_0}$; Normalized vector potential of laser field

Two Beam Accelerator–CLIC project

Compact LInear Collider

150MV/m, 38 km, 3 TeV CM Collider

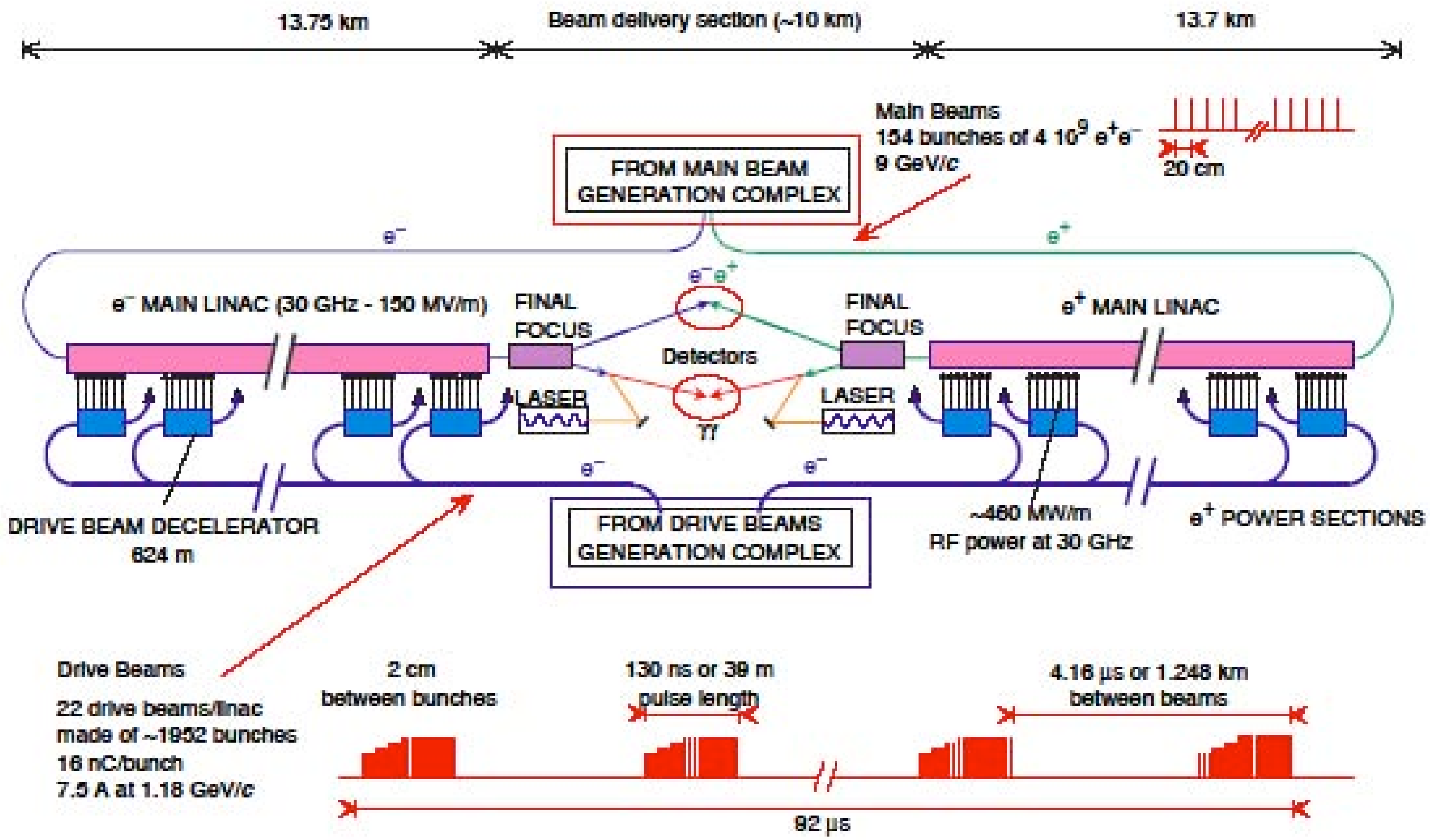


Fig. 1.1: Overall layout of CLIC for a centre-of-mass energy of 3 TeV.

Laser for Multi-TeV collider

Power requirement for 3 TeV CLIC with luminosity 10^{35} $cm^{-2}s^{-1}$

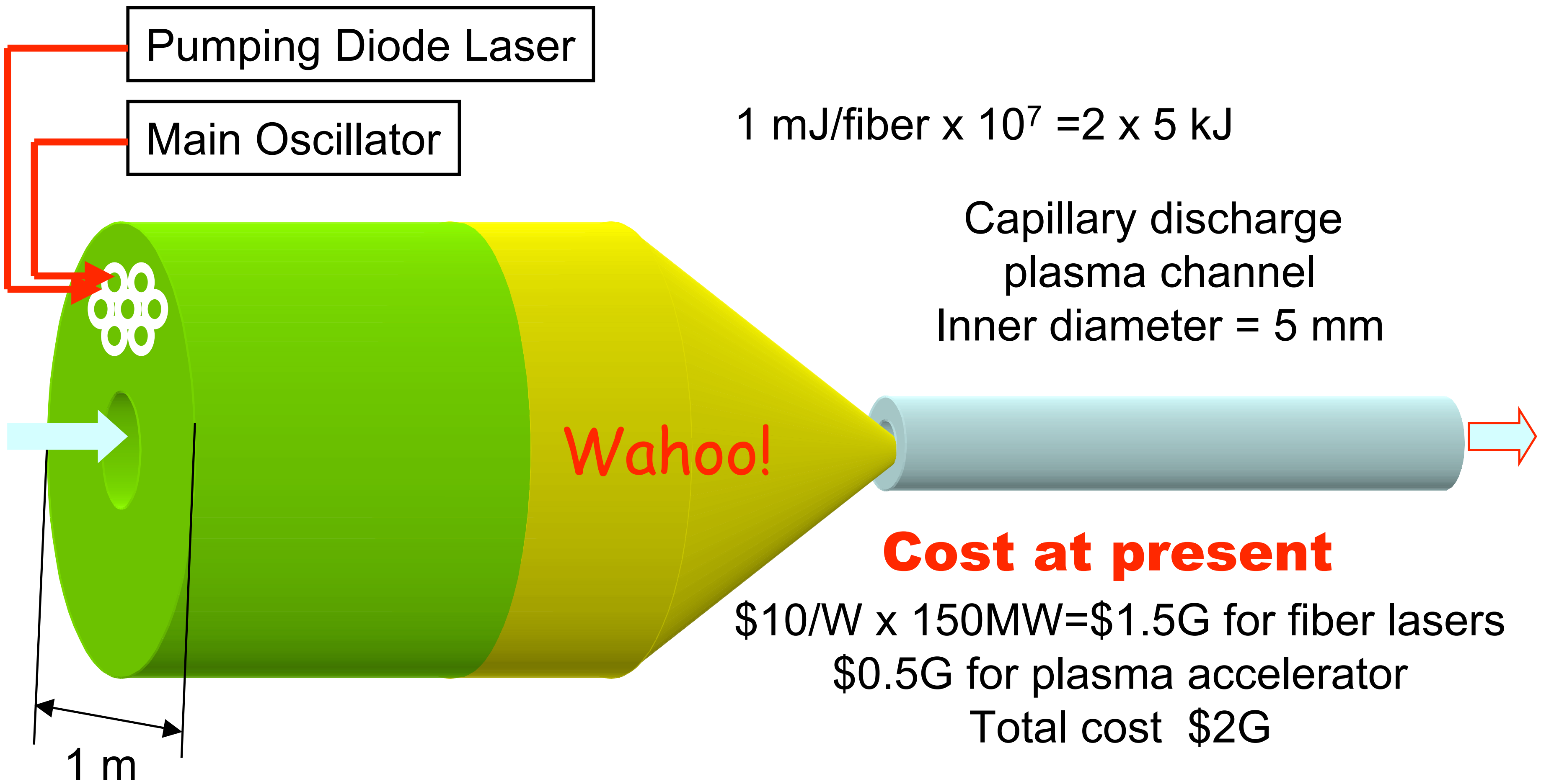
Number of charge/bunch	$4x10^9$
Beam energy/bunch	0.96 kJ
Number of bunches/pulse	154
Linac repetition rate	100 Hz
Beam power/beam	14.8 MW
Total AC power	410 MW

Power requirement for 3 TeV LWFA collider

Wakefield acceleration efficiency	20%
Laser energy/pulse	5 kJ
Peak power of 100 fs laser pulse	50 PW
Repetition rate of LWFA linac	15 kHz
Average driving power for two LWFA	150 MW
Total AC power of fiber lasers with 30%	500 MW

Proposed 150MW average power laser for LWFA collider

suggested by G. Mourou, HEEAUP2005

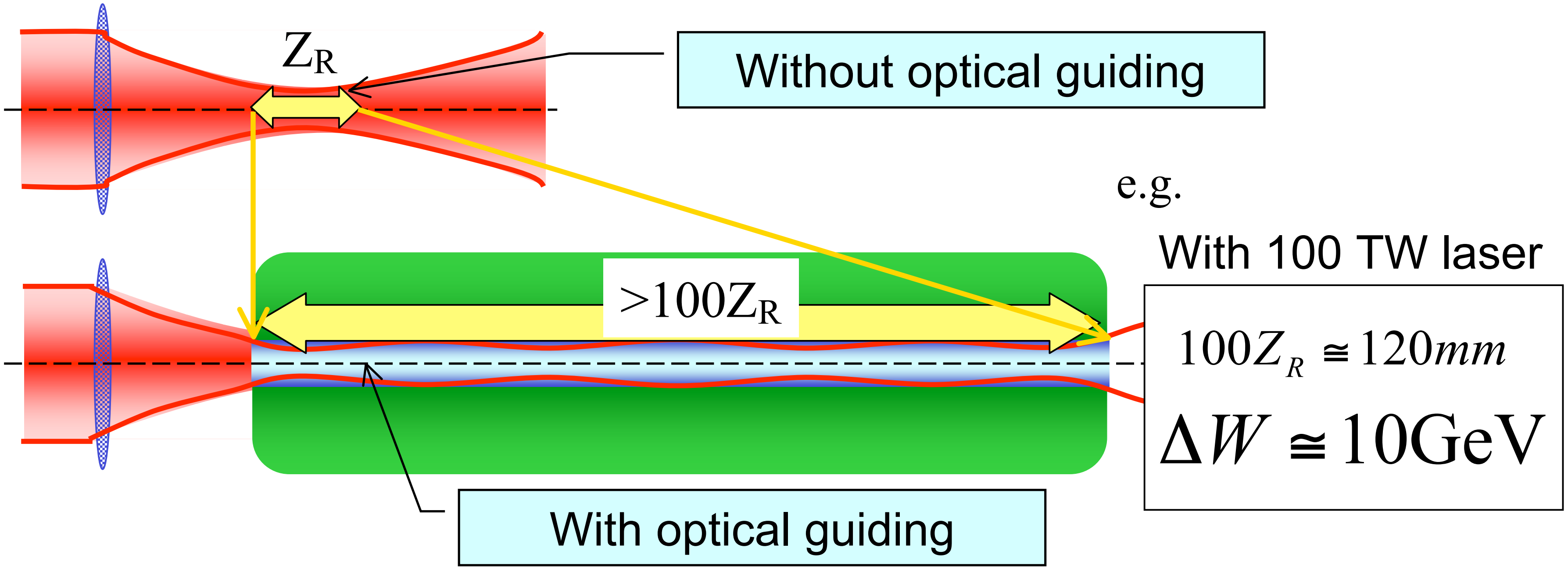


Cost at present

$10/W x 150MW=$1.5G for fiber lasers
$0.5G for plasma accelerator
Total cost $2G

High energy acceleration more than 1 GeV

necessary to increase acceleration length over many Rayleigh lengths.



$$100Z_R \cong 120mm$$

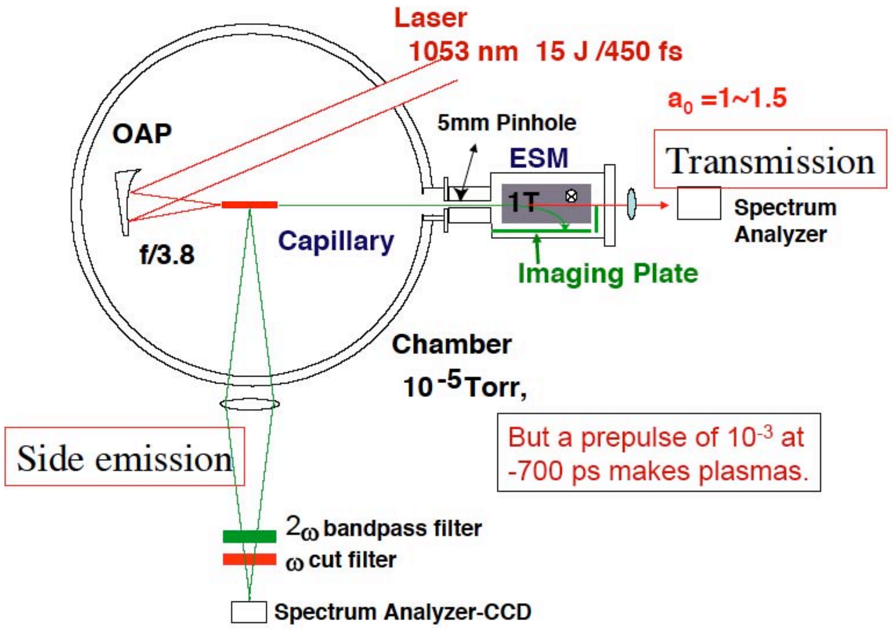
$$\Delta W \cong 10\text{GeV}$$

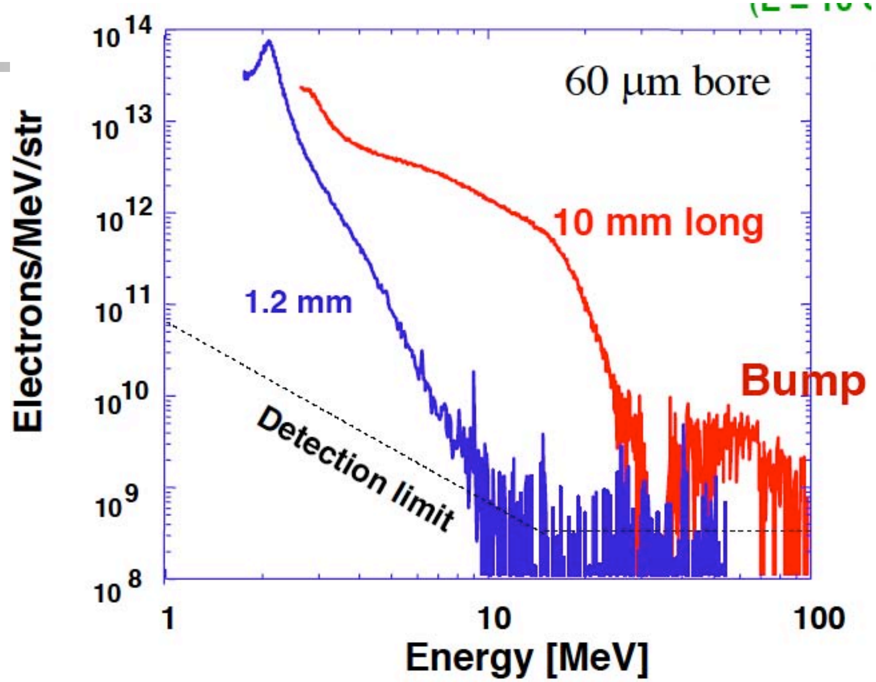
Optical guiding technology in plasmas

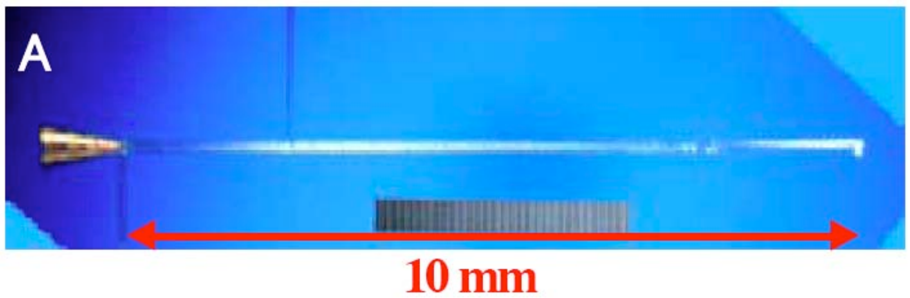
- Relativistic self-guiding
- Ionization induced self-channeling
- Laser-produced plasma waveguide
- Capillary discharge plasma waveguide
- Capillary optical guide

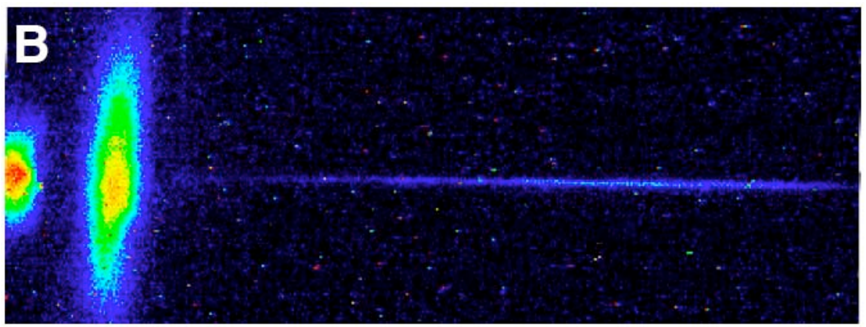
Capillary Accelerator -Electron generation through capillary at Osaka Univ.

Y. Kitagawa et al., Phys. Rev. Lett. 92, 205002, 2004

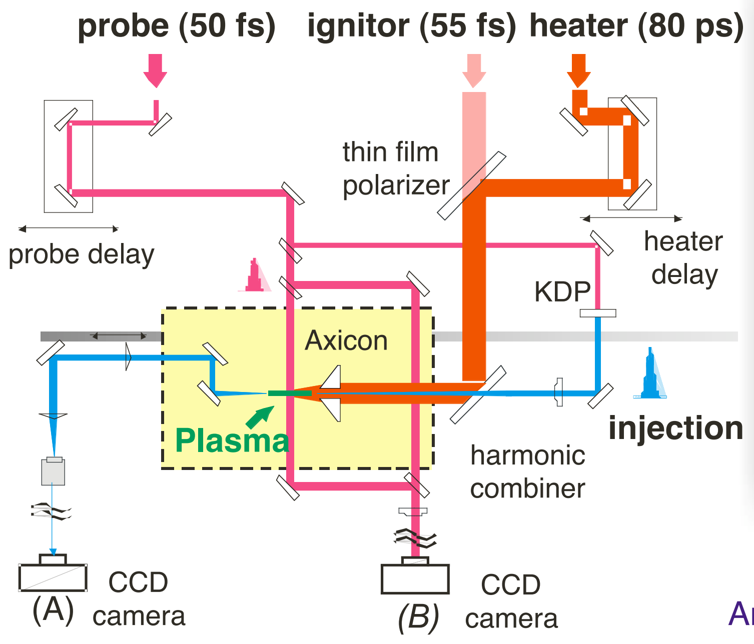


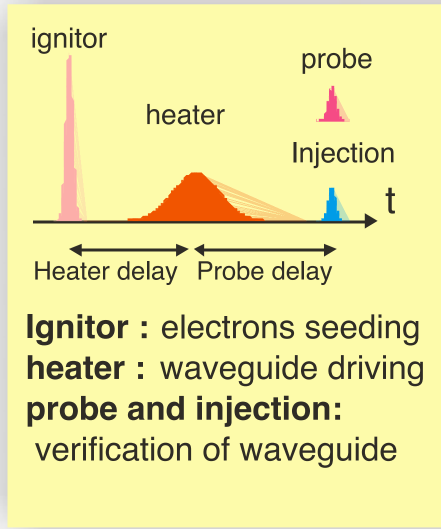




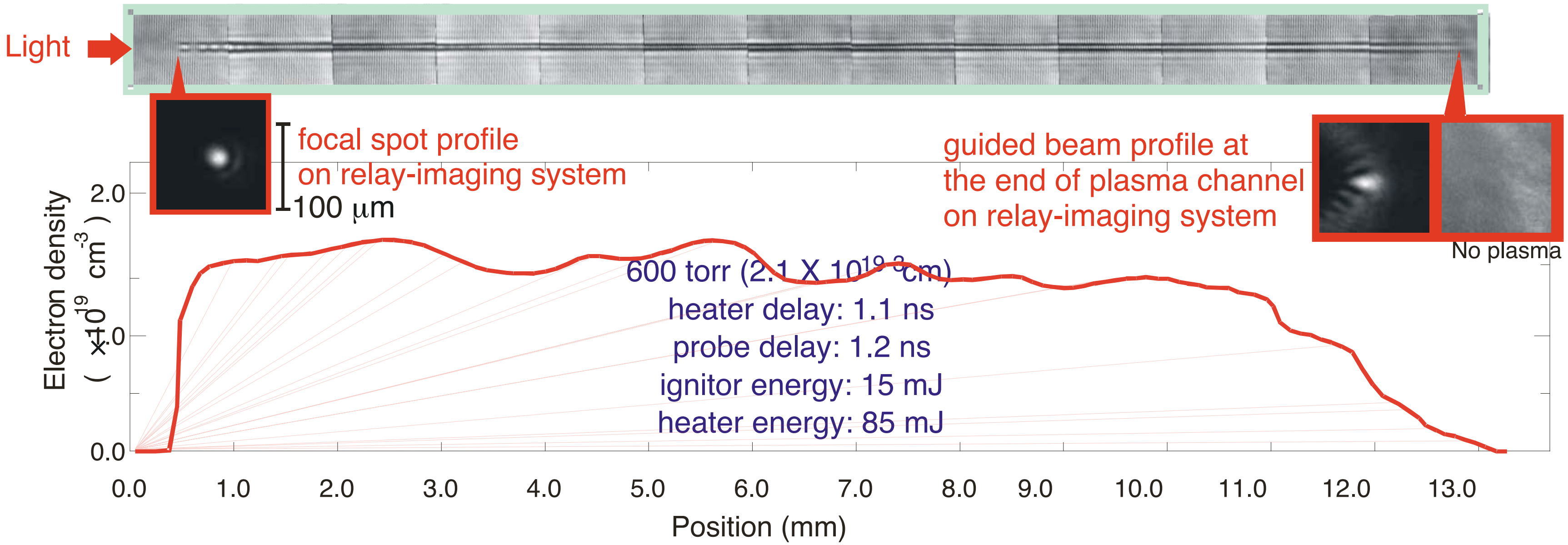


Generation of a uniform plasma waveguide extending over 1.2 cm at IAMS, TAIWAN





chamber pressure :
Ar 600 torr (2.1 X 10 19-3cm)

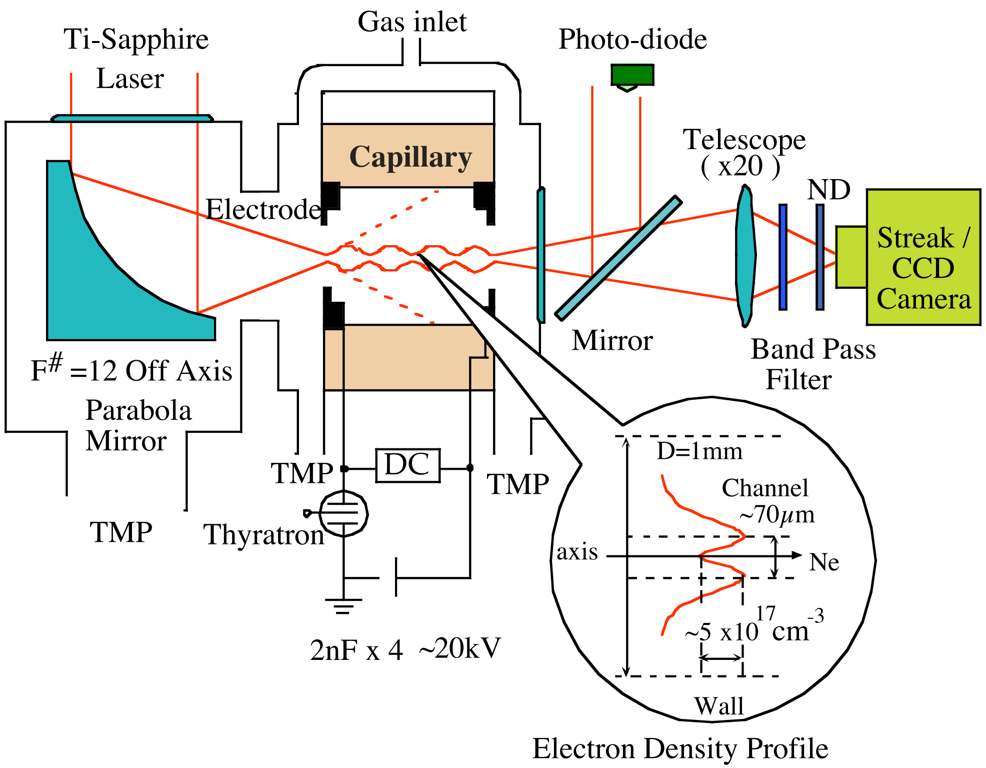


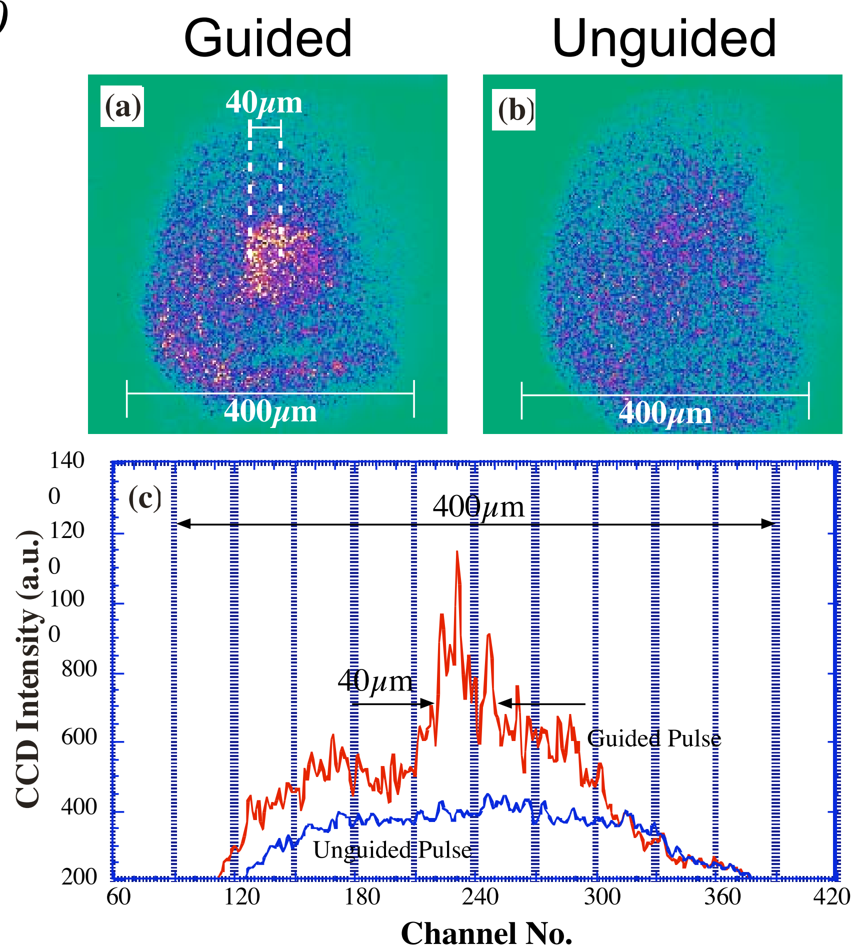
by the courtesy of Szu-yuan Chen,IAMS

2-cm fast Z-pinch capillary optical guiding at JAERI-APRC 1998

2TW, 90fs laser pulses (> 1×10^{17} W/cm^2) has been guided over 2 cm in a Z-pinch capillary discharge plasma.

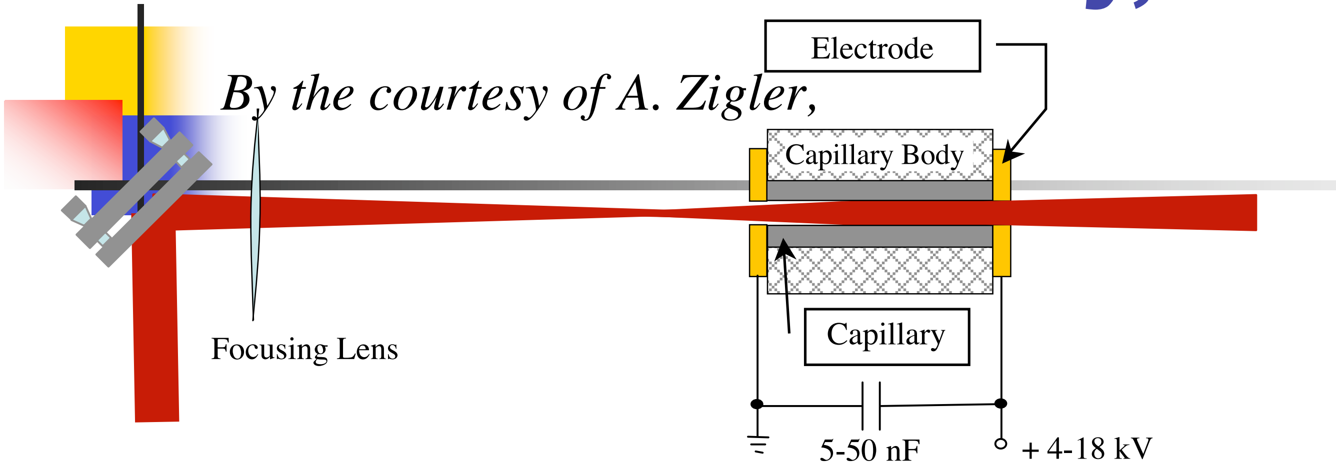
T. Hosokai et al., Opt. Lett. 25,10, 2000

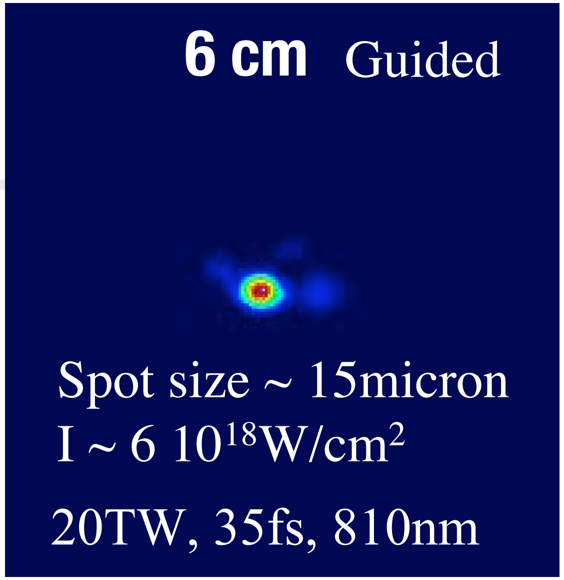




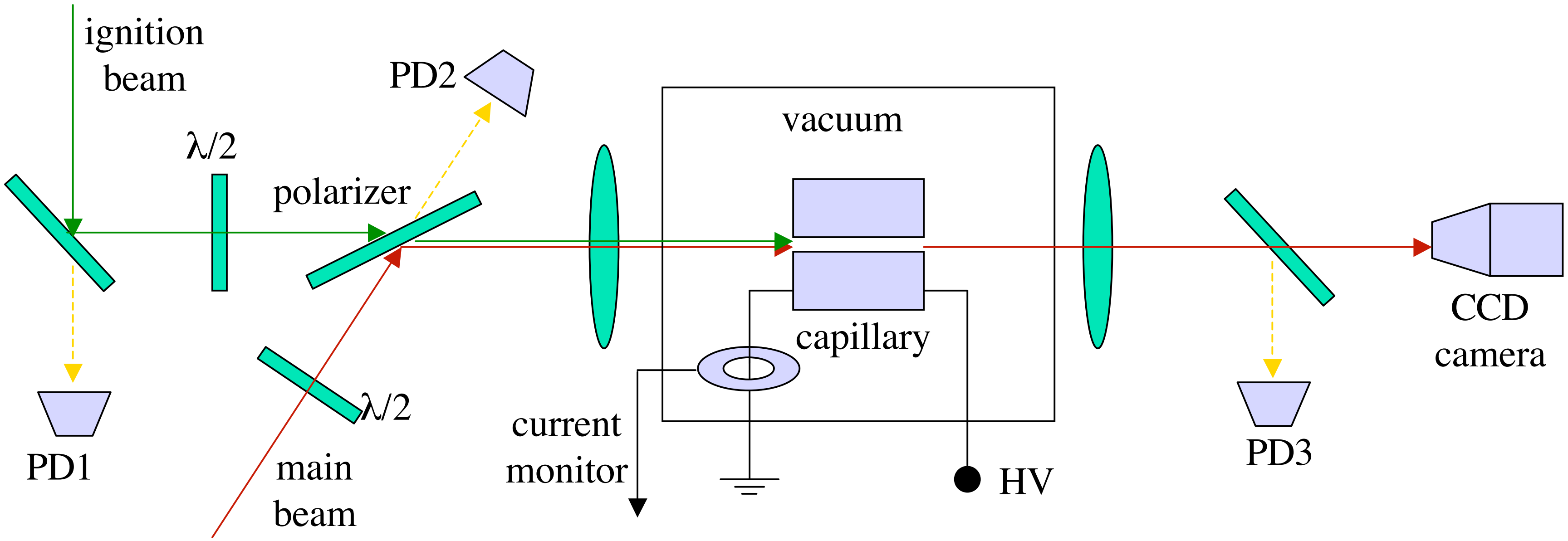
Capillary discharge plasma channel at Hebrew University, Israel

By the courtesy of A. Zigler,



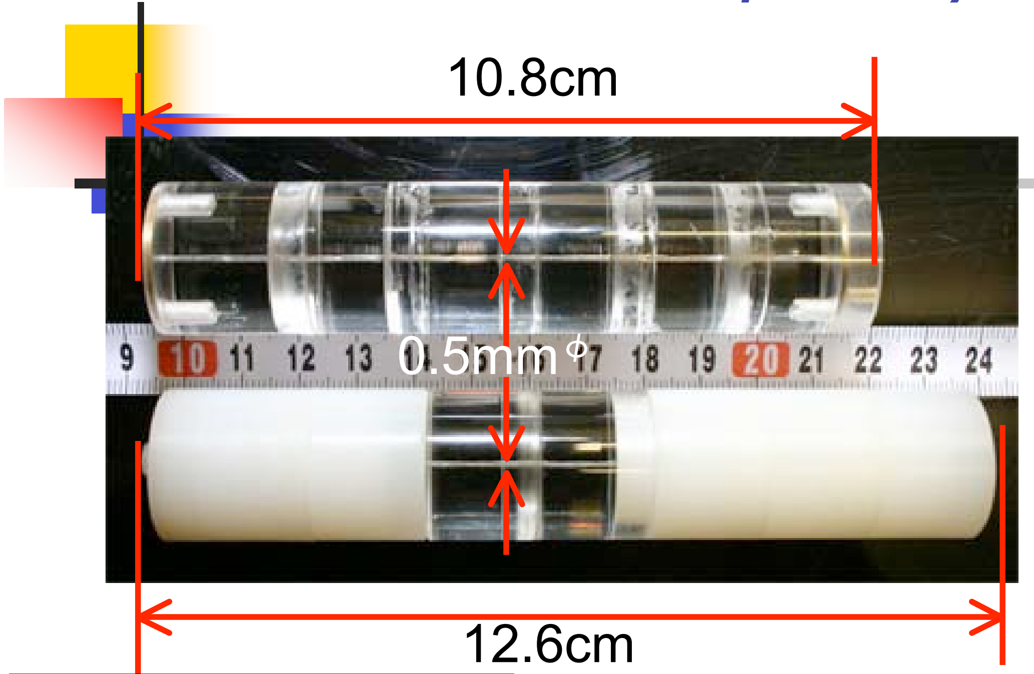


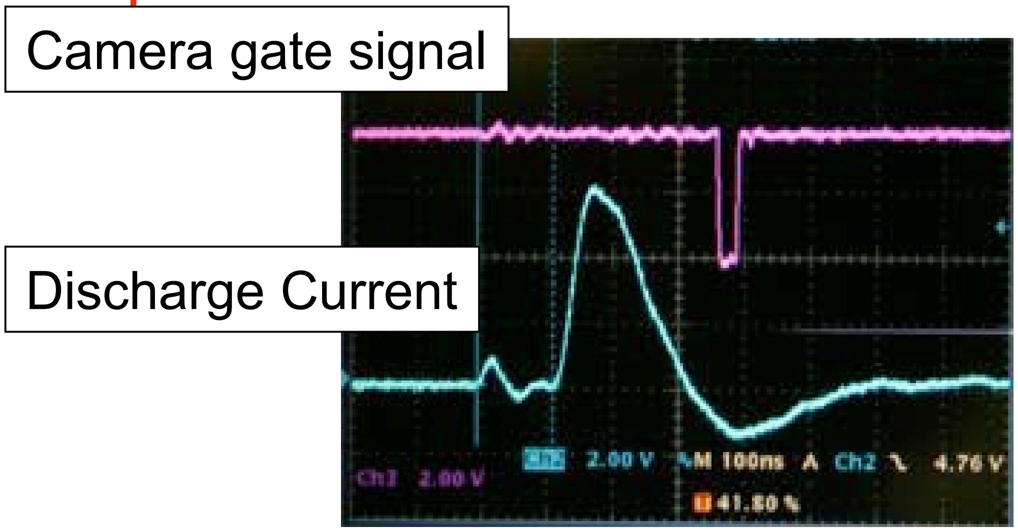
Experimental setup: BN capillaries, d = 0.3 – 0.4 mm, l = 10 – 15 mm;
C = 50 nF, U = 4 – 18 kV, L ≈ 1 μH ; (I_m = 500 – 2500 A,)
Laser ~ 10-20mJ, 10 ns, 1.064 μm



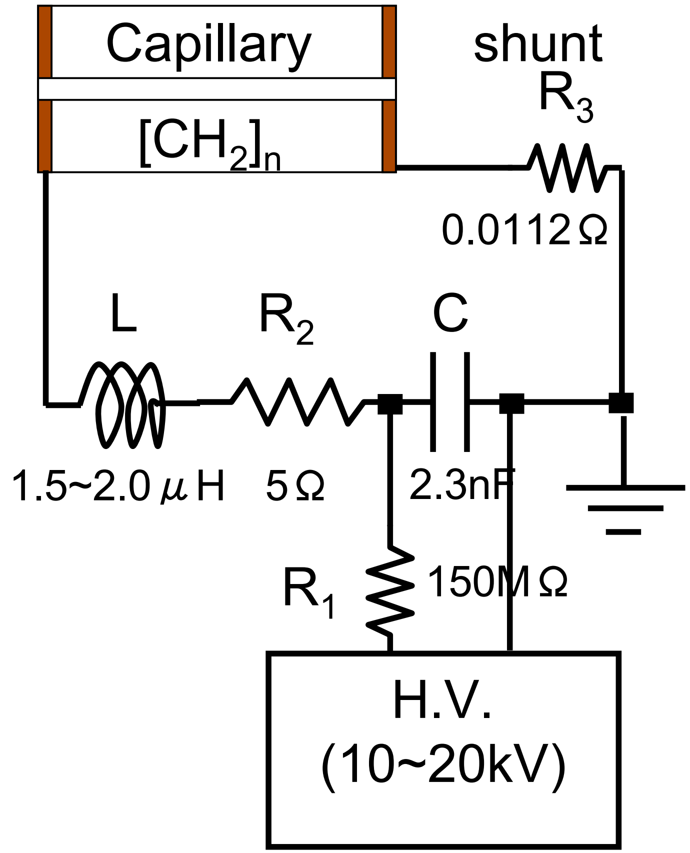
10cm Capillary discharge plasma channel developed by Hebrew Univ. , Israel

Under Hebrew Univ. & Soken-dai collaboration



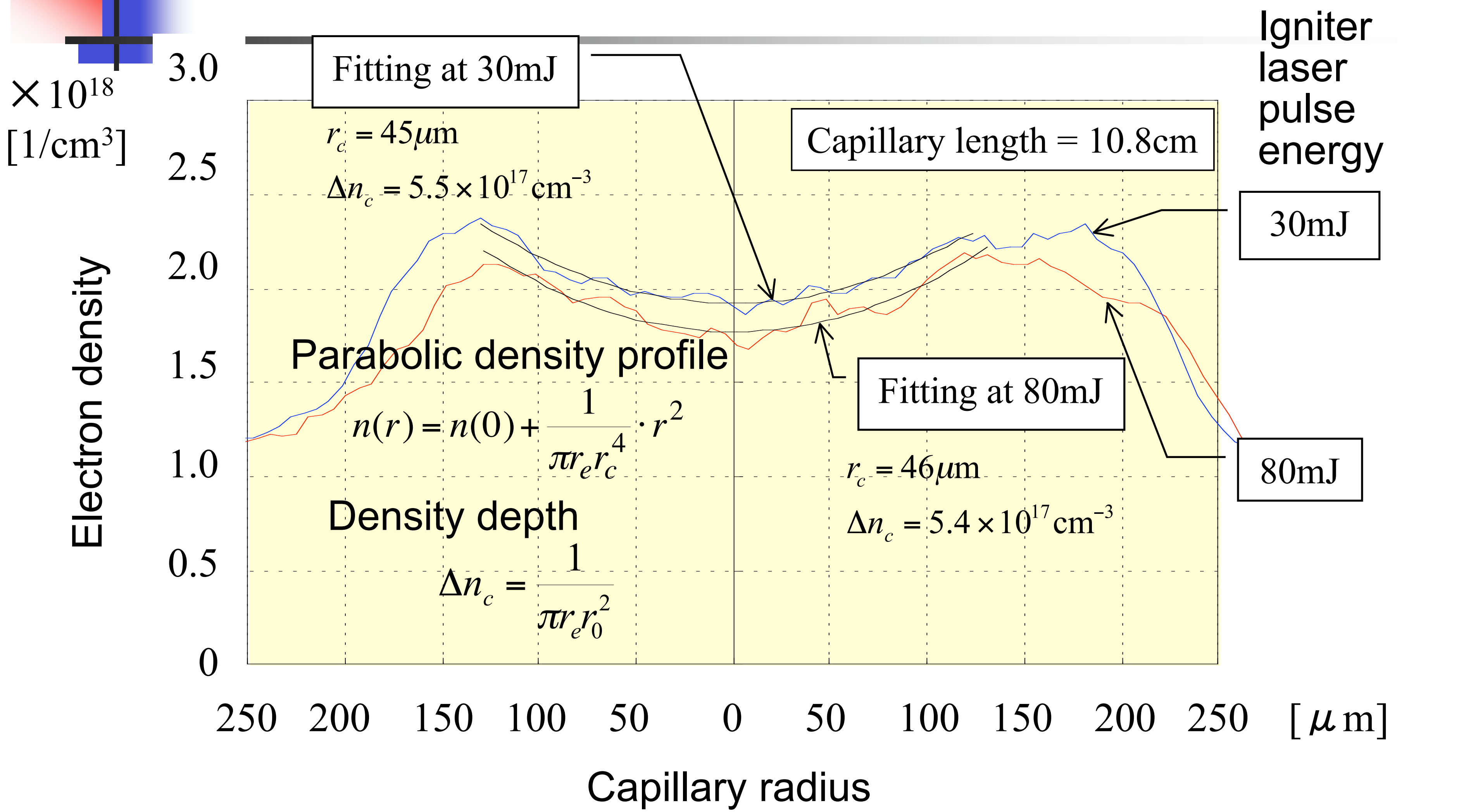


Discharge circuit

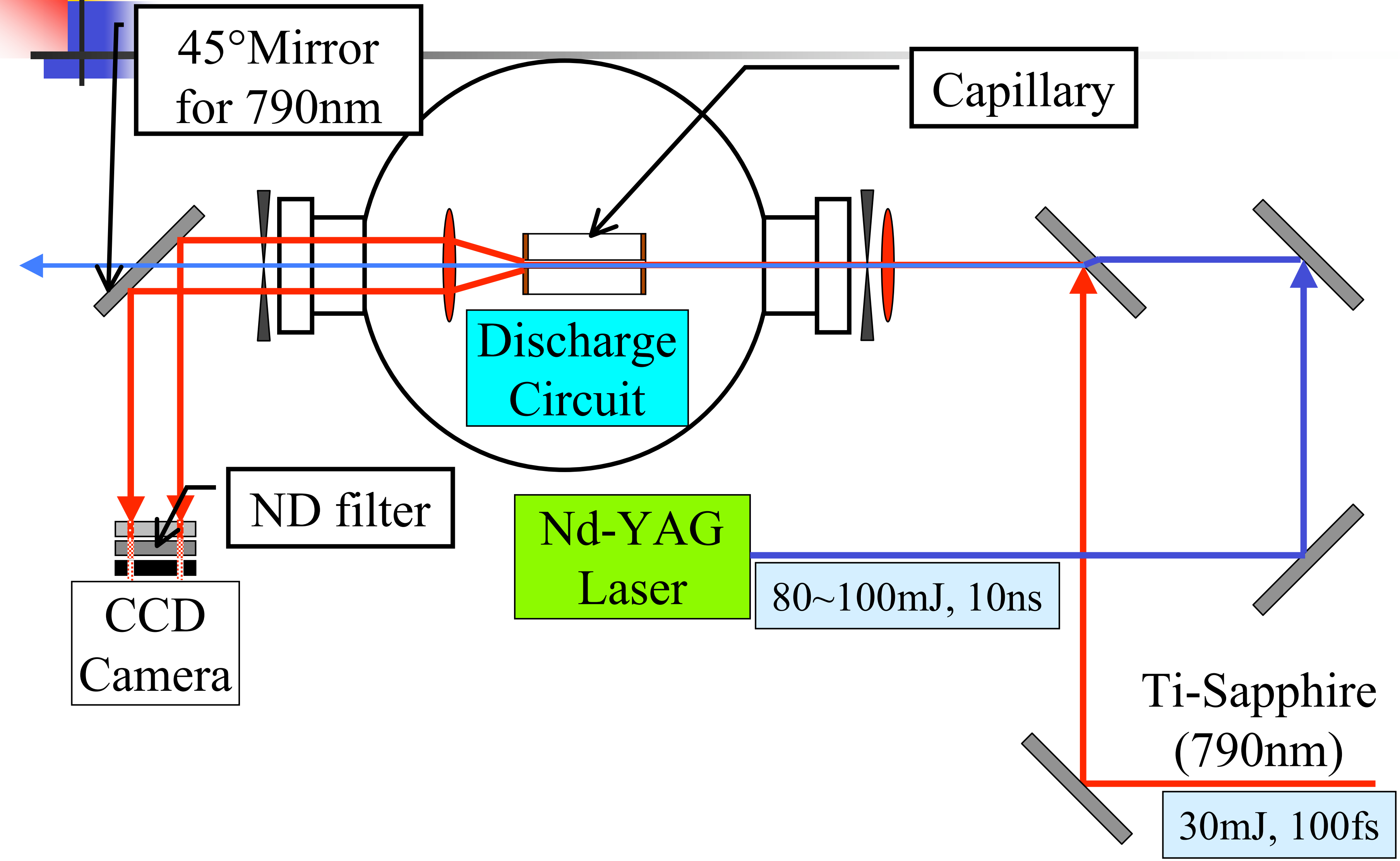


Density profile of Plasma Channel

well fitted to be parabolic density distribution



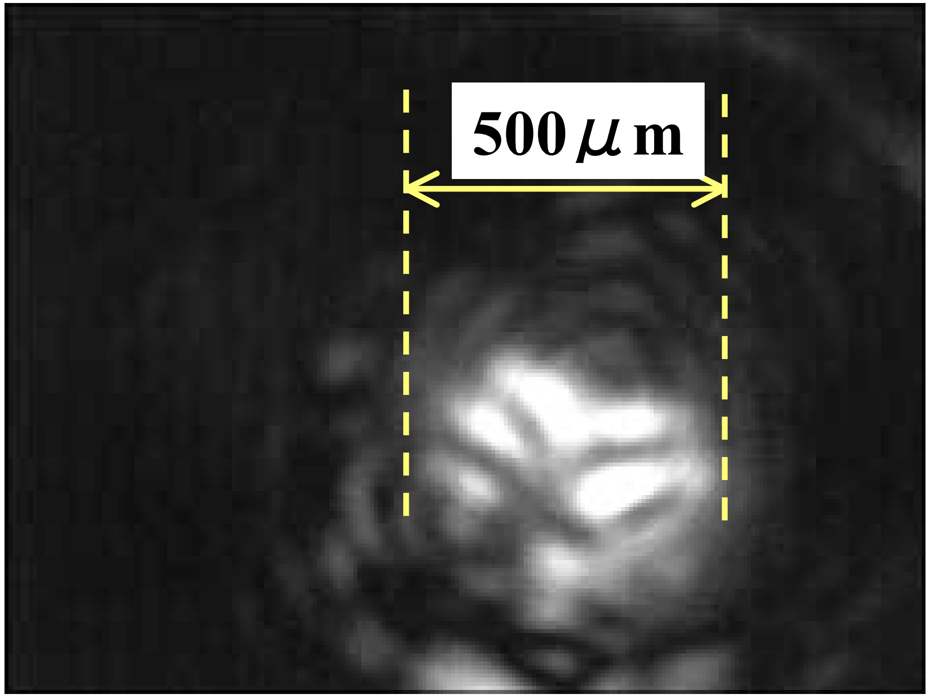
Optical guiding of 0.3 TW femtosecond laser pulse



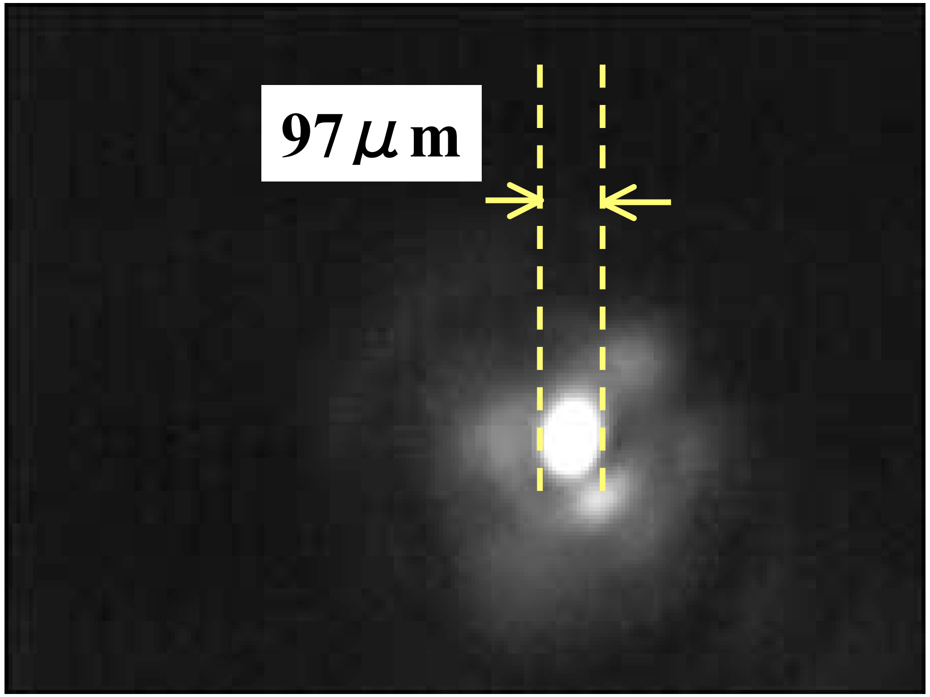
Transmission profile through a 12.6cm capillary

The world-first 10cm optical guiding

Unguided



Guided



(0.5mm = capillary diameter)

After digital filtering

Capillary is operated over less than **one hundred shots** of discharges.

实验结果讨论

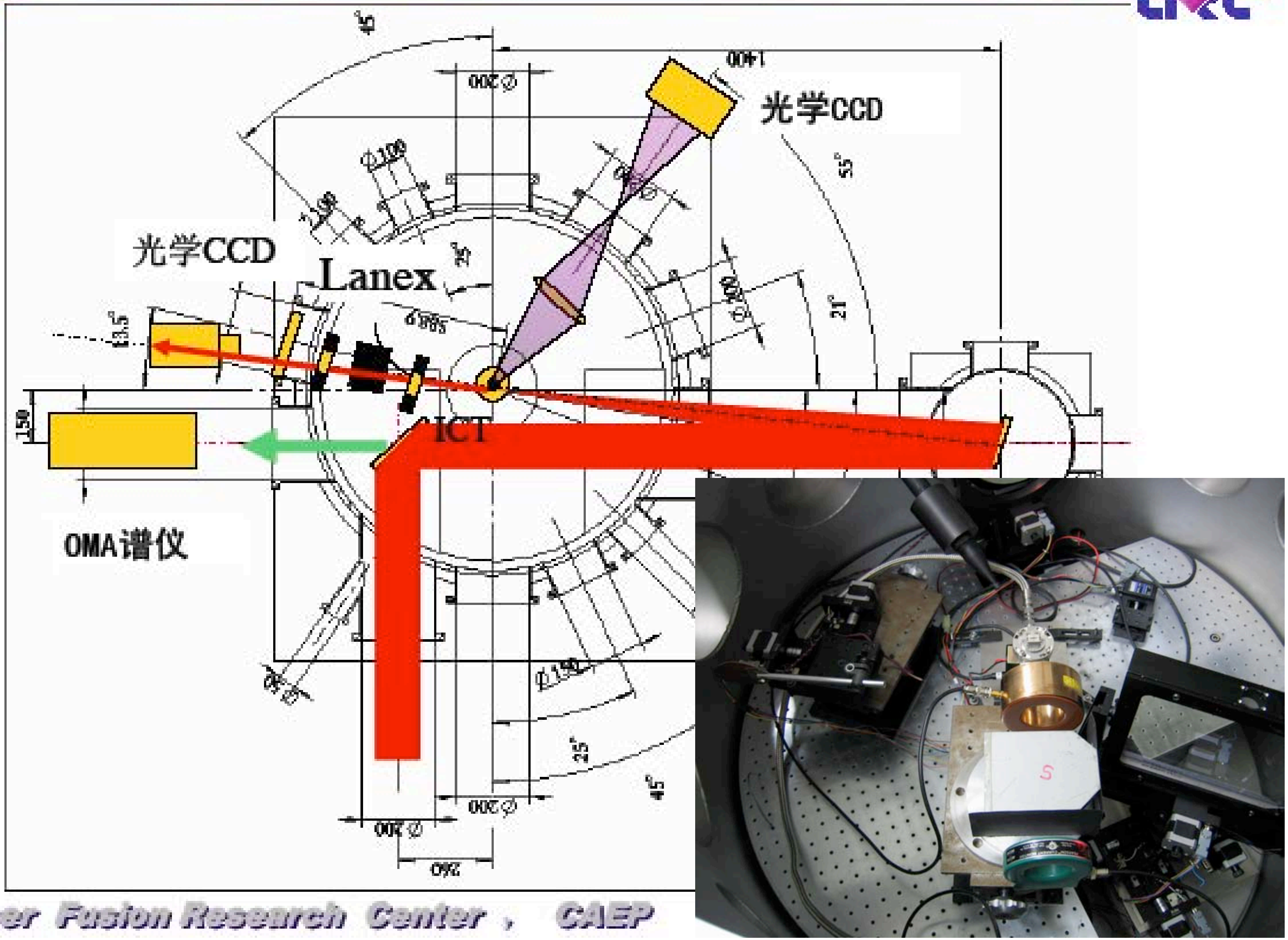
Joint experiment of electron acceleration at CAEP, Mian-Yang, Sichuan, China

超短超强激光电子加速
实验小结

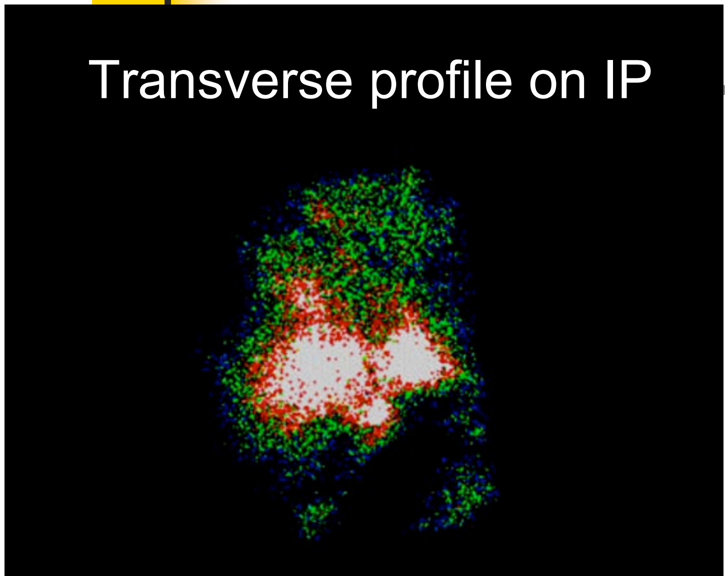
by International Collaboration of
CAEP, Tsinghua Univ. (CHINA)
JAERI, KEK (JAPAN)
LOA (FRANCE)
UCLA, USC, NRL (USA)
Hebrew Univ. (ISRAEL)

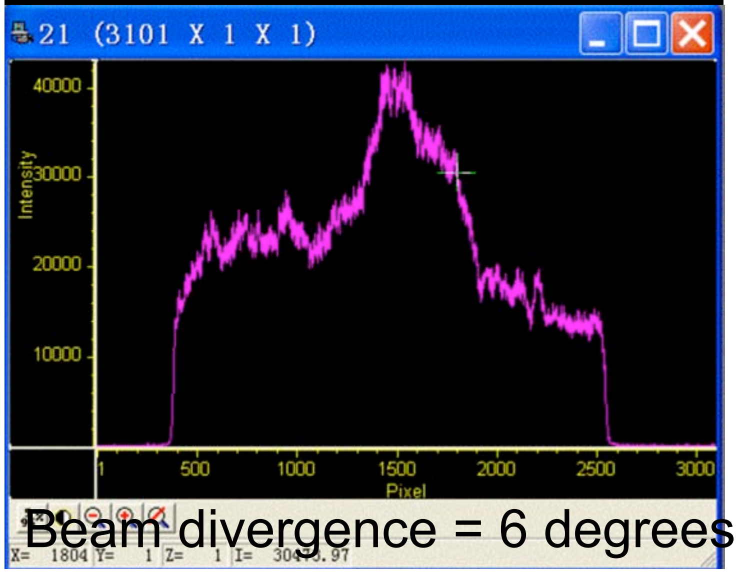
First laser acceleration experiment in China was carried out using CAEP SILEX-1 laser in July by the collaboration of CAEP, Tsinghua Univ., JAERI and KEK.

Experimental setup based on SILEX－I

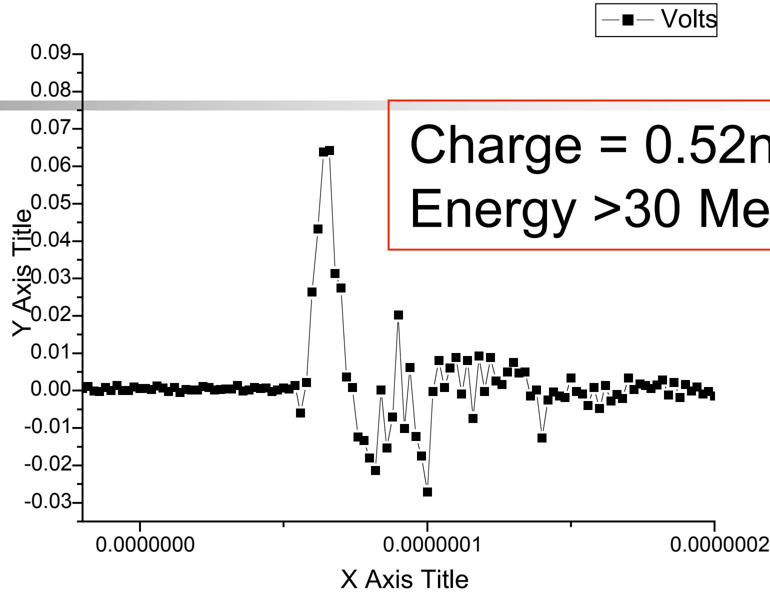


Electron beam images on Imaging plate and Beam Current Transformer





Beam divergence = 6 degrees in FWHM

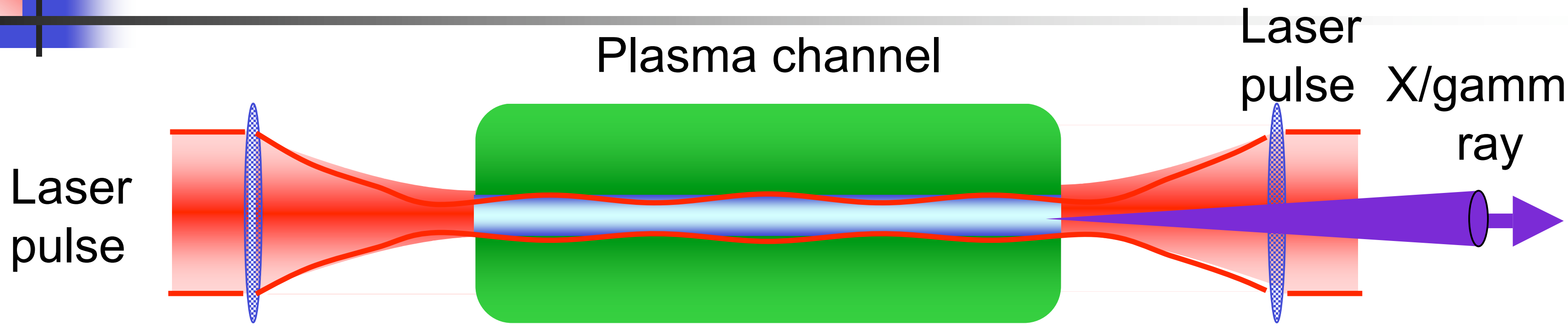


Charge = 0.52nC
Energy >30 MeV

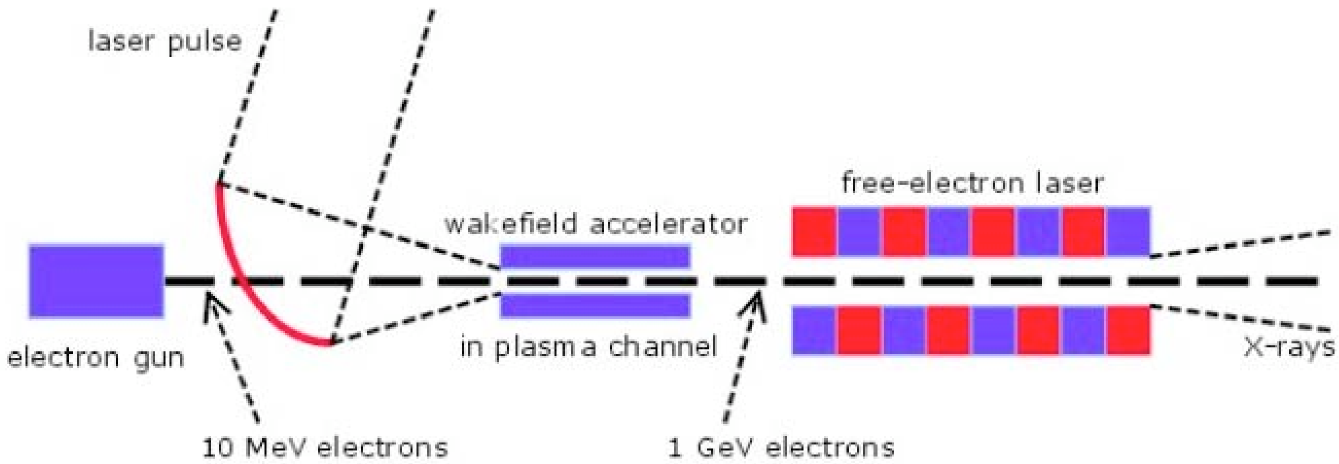
5mm Self-plasma channeling plays

an important role for electron acceleration.

Near term applications of high energy laser-plasma accelerator

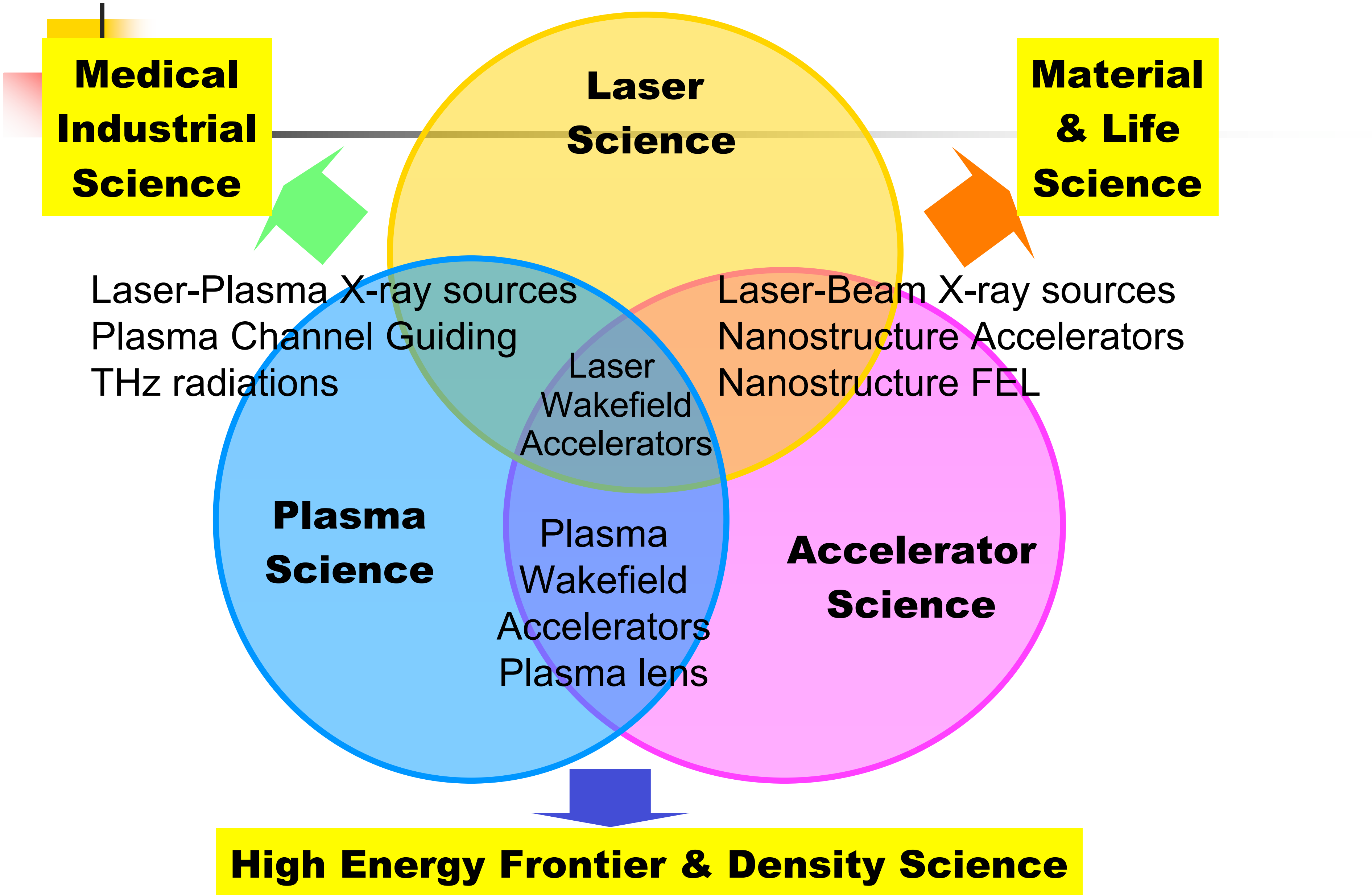


Compact Femtosecond X/gamma-ray source

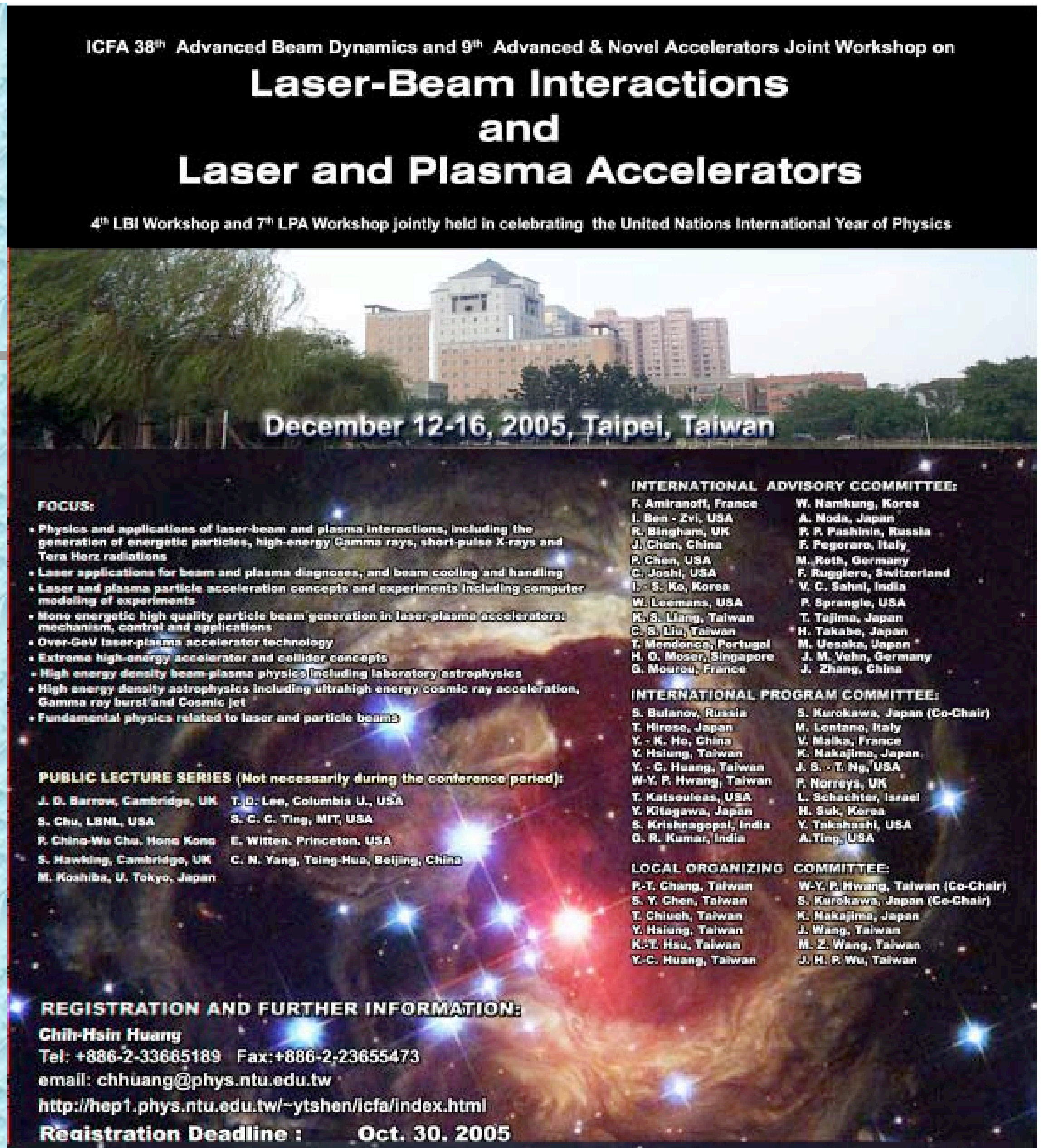


Compact Coherent X-ray source

Scope of laser-plasma acceleration



ICFA joint workshop on Laser-Beam Interactions and Laser and Plasma Accelerators in Taipei, Taiwan Dec. 12-16, 2005



http://hep1.phys.ntu.edu.tw/~ytshen/icfa/index.html