Accelerating in the future: lasers start to produce quality high energy electron beams.

Wim Leemans

L'OASIS Group
LBNL

FNAL Colloquium, February 16, 2005

Outline

- The L'OASIS group
- Wakefield accelerators (from a historical perspective):
  - Concept
  - Wake excitation
  - Particle acceleration
  - Relativistic guiding
  - Unguided experiments
  - Preformed channel experiments
  - "New" regimes
- 1 GeV module and outlook

L'OASIS Group

- Staff: Wim Leemans (group leader), Csaba Toth, Eric Esarey (deputy group leader), Carl Schroeder, Brad Shadwick (1/2)
- Post-docs: Bob Nagler, Catalin Filip (Univ. Nevada Reno), Estelle Michel (Univ. Nevada Reno), Pierre Michel
- Graduates: Jeroen van Tilborg, Kei Nakamura (Univ. Tokyo), Cameron Geddes, Gwenael Fubiani (Univ. Orsay - Paris XI)
- Technicians: M. Dickinson, D. Syversrud, N. Ybarrolazza, J. Wallig
- Collaborations: Univ. Nevada Reno, LLNL, Oxford, Tech-X Corporation, Cornell, Univ. Colorado Boulder, AMAC (LBNL)

3	7	2	1	1	1	1	1

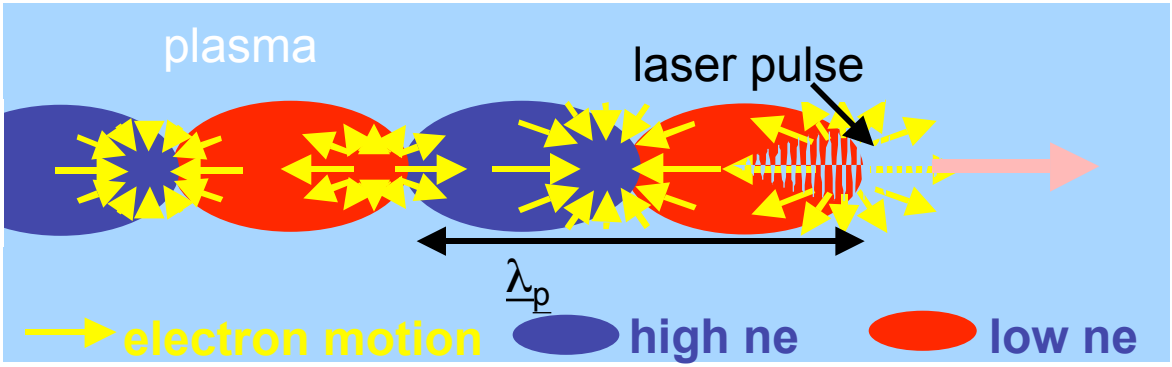
1979: Seminal paper by Tajima and Dawson

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

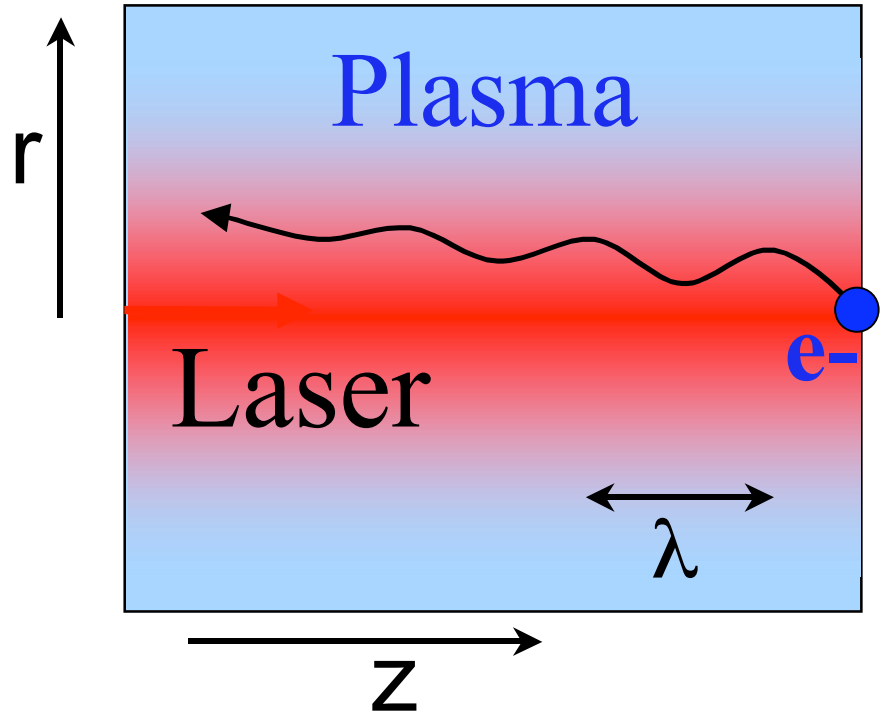
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.



Large longitudinal electric fields propagating near speed of light

How intense should the laser be ?



- Ponderomotive force

$$F_p = -mc^2 \nabla \frac{a^2}{2}$$

- Normalized vector potential

$$a_0 = \frac{eE_L \lambda}{2\pi mc^2} \cong 8.6 \times 10^{-10} \lambda[\mu m] I^{1/2} [W/cm^2]$$

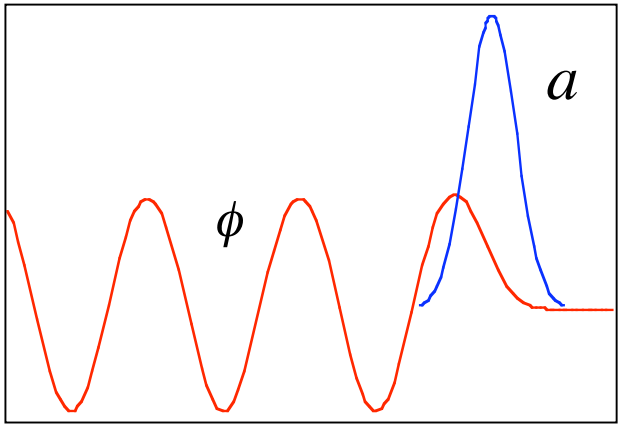
Example: for λ=0.8 μm, I_L= 10^{18} W/cm^2,

$a^2 \sim 0.5$

“Basic” Laser-driven plasma-based accelerators

Standard Laser wakefield accelerator (LWFA)

$L=\lambda_p$

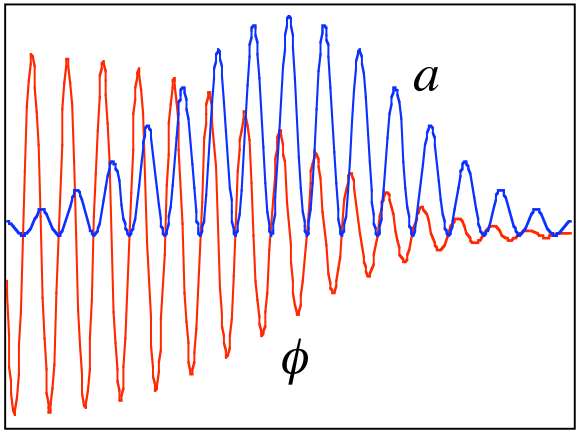


Plasma beat wave accelerator

Two beating pulses,

$L>>\lambda_p$,

$\omega_1 - \omega_2 = \omega_p$



Tajima and Dawson, PRL1979

Esarey et al., IEEE 1996

Field strengths can exceed 100 GV/m

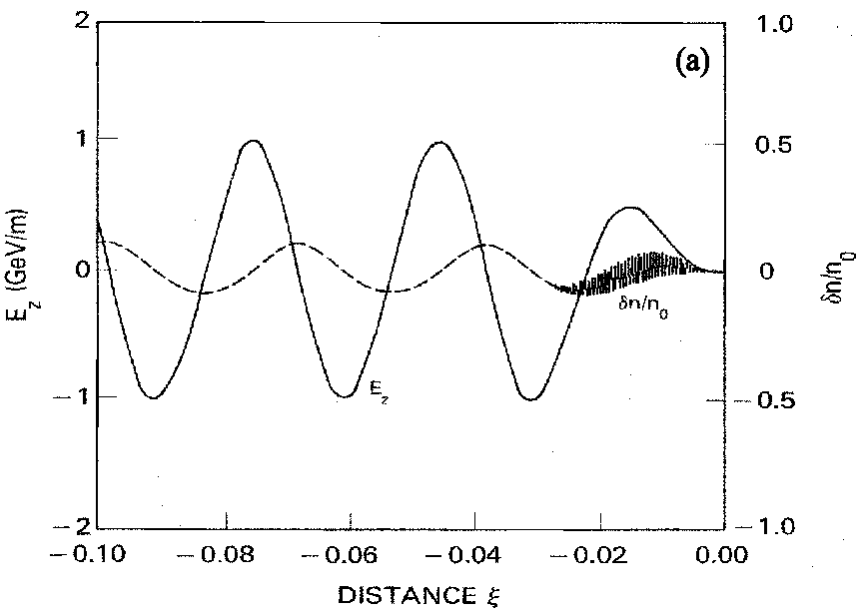
- Cold non-relativistic wavebreaking field:

$$E_0 = mc\omega_p / e \approx 96\left(n_0[\mathrm{cm}^{-3}]\right)^{1/2} \quad \text{V/m}$$

ex. $E_0 \approx$ 100 GV/m for n = 10^{18} cm^{-3},

Linear regime: a = 0.5

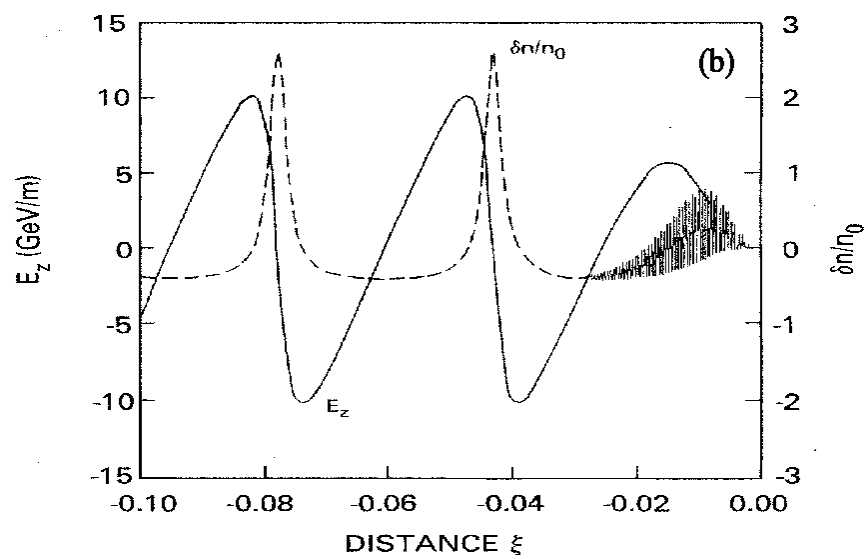
Sinusoidal wake



Nonlinear regime: a = 2.0

Wave steepening

Period lengthening



1985: Plasma wake excitation via frequency difference mixing

VOLUME 54, NUMBER 21 PHYSICAL REVIEW LETTERS 27 MAY 1985

Relativistic Plasma-Wave Excitation by Collinear Optical Mixing

C. E. Clayton, C. Joshi, C. Darrow, and D. Umstadter
Electrical Engineering Department, University of California, Los Angeles, California 90024
(Received 8 March 1985)

The relativistic plasma wave excited when the frequency difference between two copropagating CO_2 laser beams equals the plasma frequency is detected for the first time. The plasma-wave frequency, wave number, spatial extent, and saturation time are directly measured by use of 7-mrad, collective, ruby Thomson scattering and the forward-scattered ir spectrum. The wave amplitude $\tilde{n}/n_0$ is inferred to be (1–3)% which gives a longitudinal electric field of 0.3 to 1 GV/m at a laser intensity of 1.7×10^{13} W/cm^2, in reasonable agreement with theory.

PACS numbers: 52.35.Fp, 52.35.Mw, 52.40.Nk

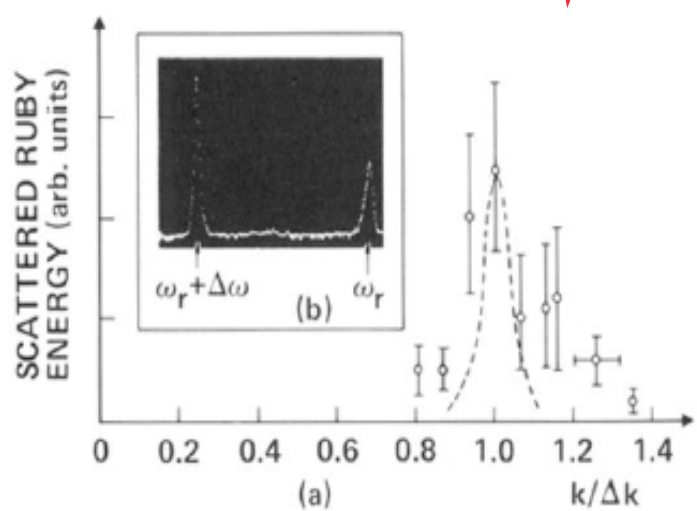
CO_2 laser

$$\omega_{scatt} = \omega_{probe} \pm \Delta\omega$$

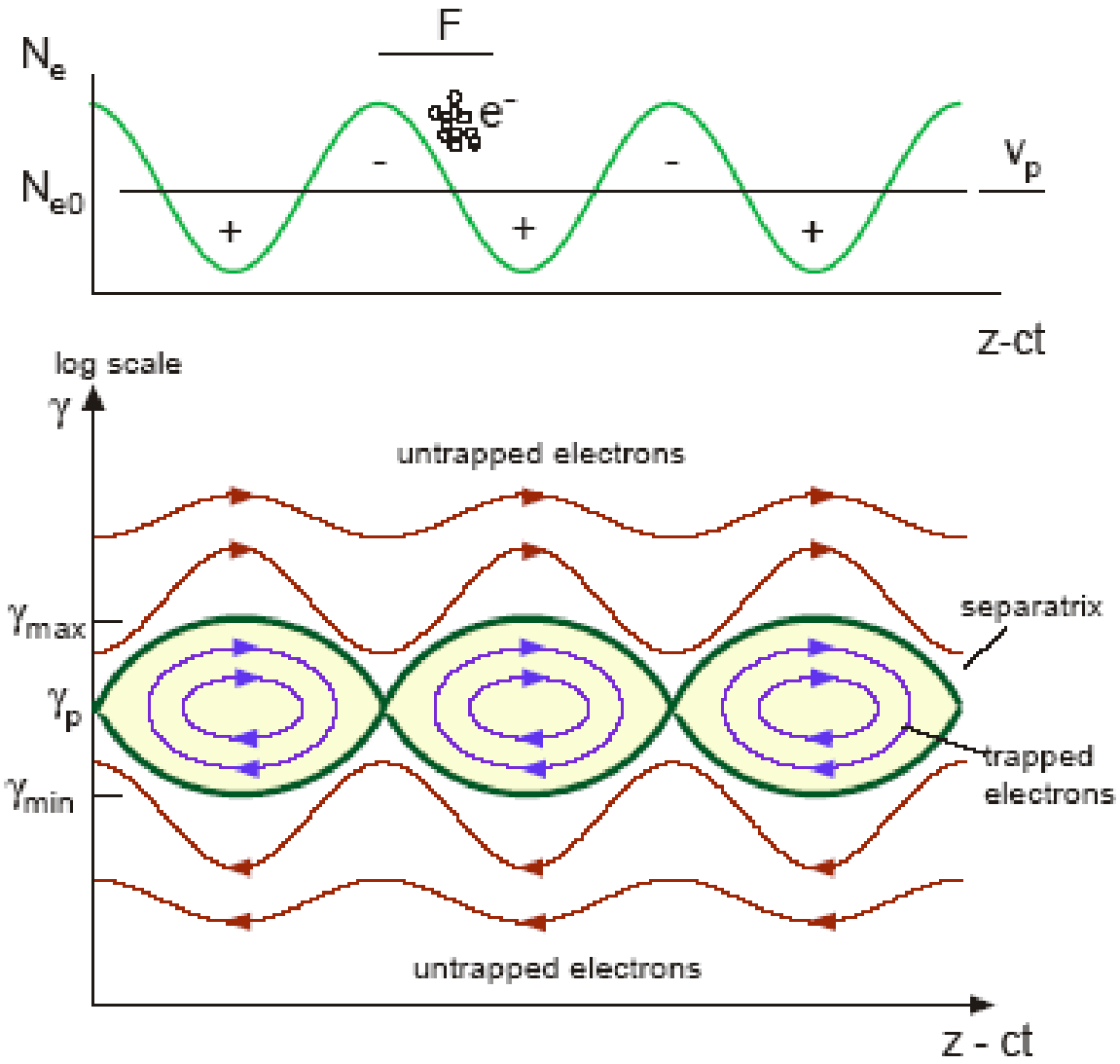
Scattered light

Ruby laser

Plasmon



Trapping in 1-D Wakefields



1993: Acceleration of externally injected electrons in beatwave

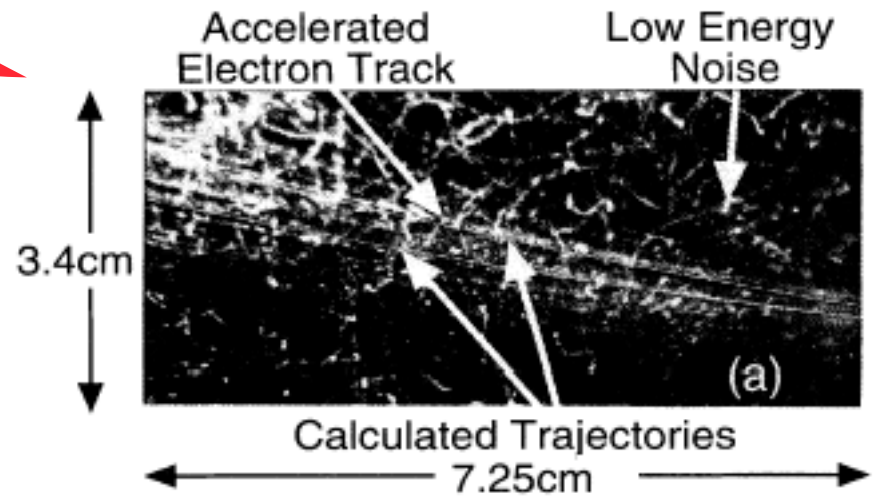
VOLUME 70, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JANUARY 1993

Ultrahigh-Gradient Acceleration of Injected Electrons by Laser-Excited Relativistic Electron Plasma Waves

C. E. Clayton, K. A. Marsh, A. Dyson, M. Everett, A. Lal, W. P. Leemans,[a] R. Williams,[b] and C. Joshi
Department of Electrical Engineering, University of California, Los Angeles, California 90024
(Received 14 September 1992)

High-gradient acceleration of externally injected 2.1-MeV electrons by a laser beat wave driven relativistic plasma wave has been demonstrated for the first time. Electrons with energies up to the detection limit of 9.1 MeV were detected when such a plasma wave was resonantly excited using a two-frequency laser. This implies a gradient of 0.7 GeV/m, corresponding to a plasma-wave amplitude of more than 8%. The electron signal was below detection threshold without injection or when the laser was operated on a single frequency.

CO_2 laser

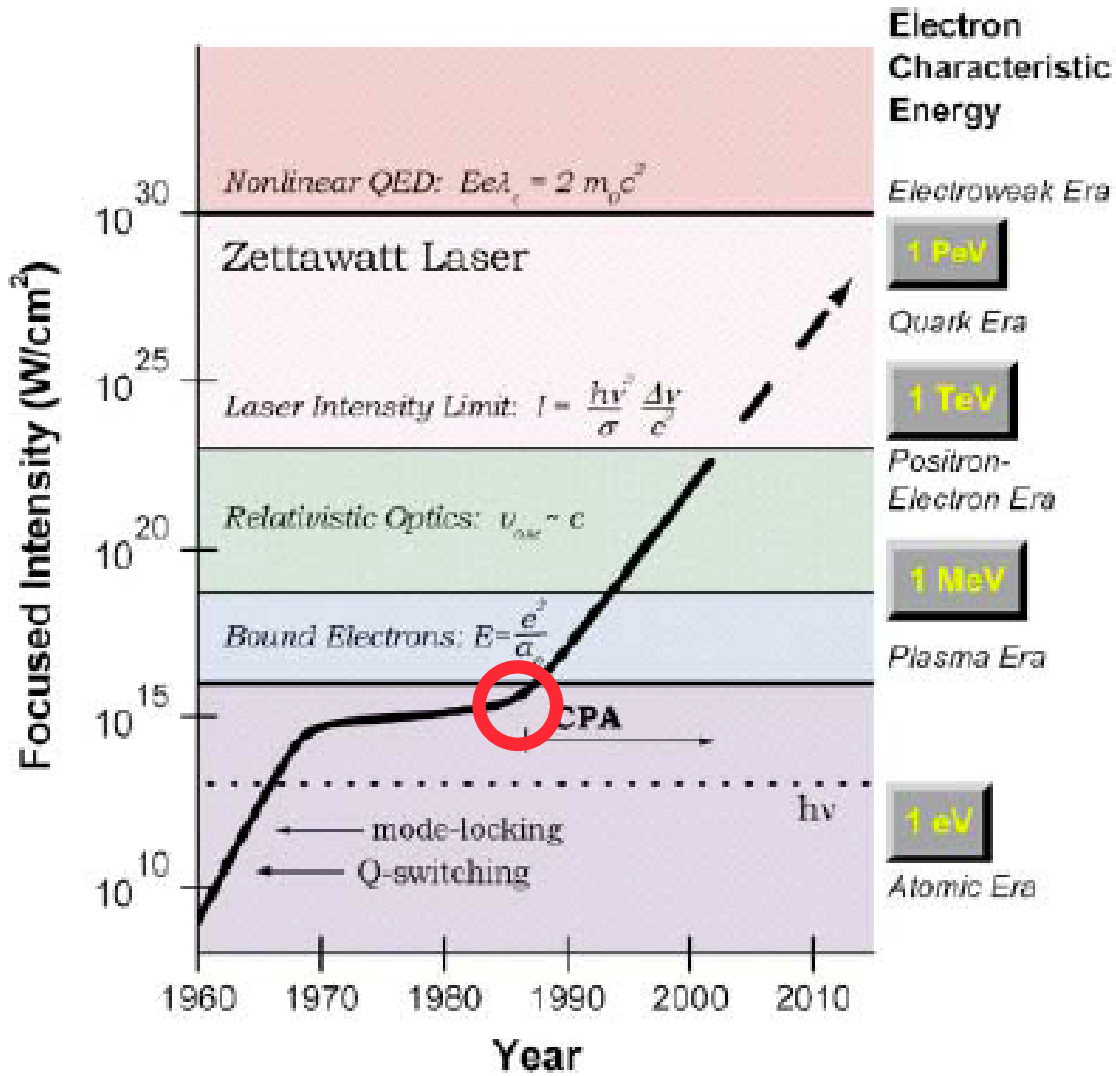


5.2 MeV tracks

10's of electrons

1985: Chirped Pulse Amplification Technology

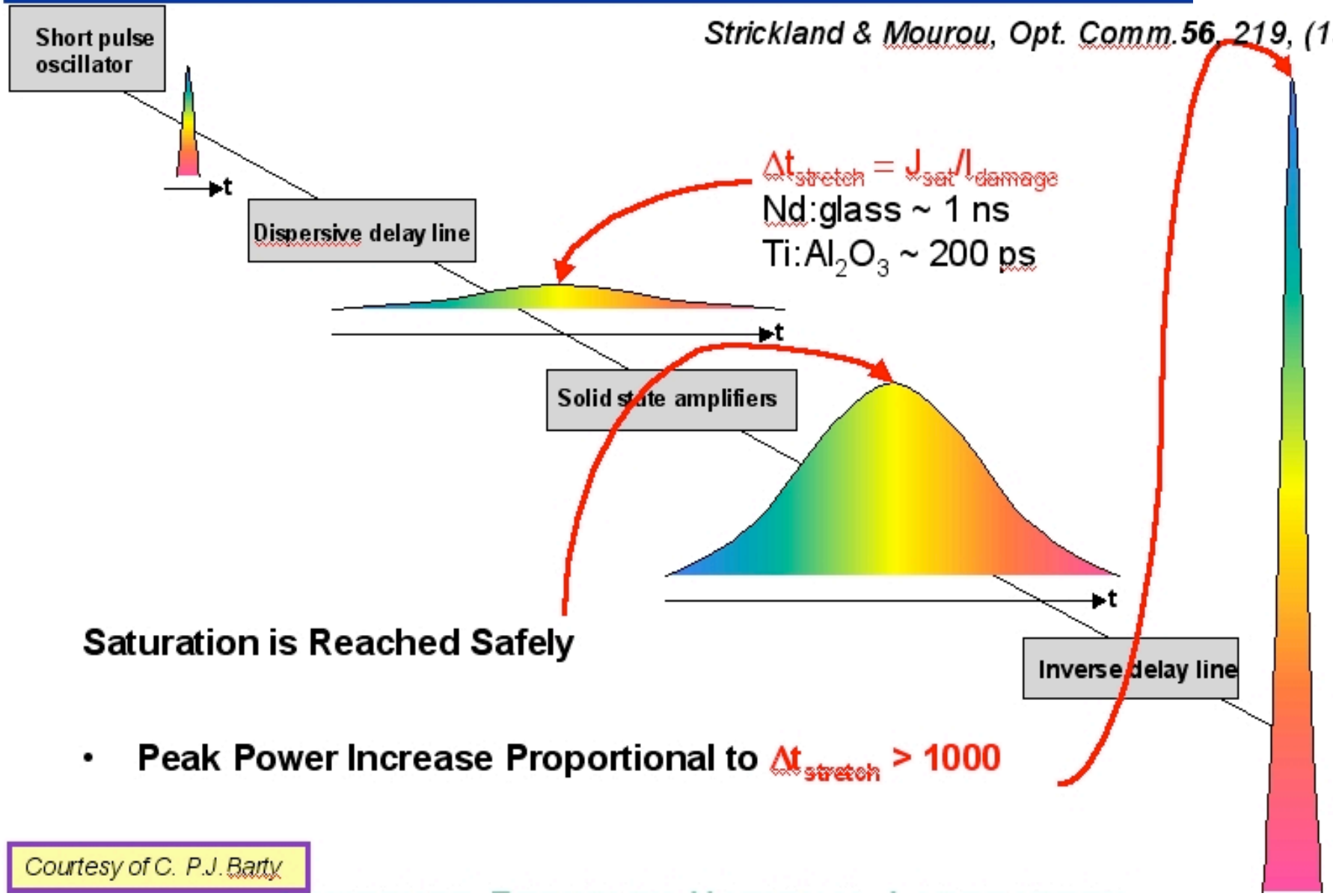
D. Strickland and G. Mourou, Optics Comm. 56 (1985)



Focused Intensity vs. Year
(after T. Tajima and G. Mourou, PRSTAB2002)

Generic Chirped Pulse Amplification

Strickland & Mourou, Opt. Comm. **56**, *219, (1985)*

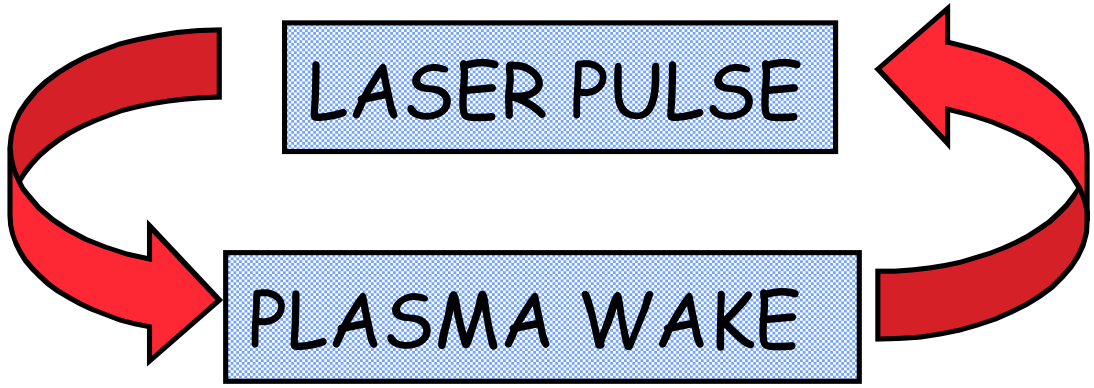


Saturation is Reached Safely

- **Peak Power Increase Proportional to $\Delta t_{stretch}$ > 1000**

Courtesy of C. P.J. Barty

"Photon acceleration/deceleration"



$$\omega_{Laser} = \omega_{Scatt} \pm \omega_p$$

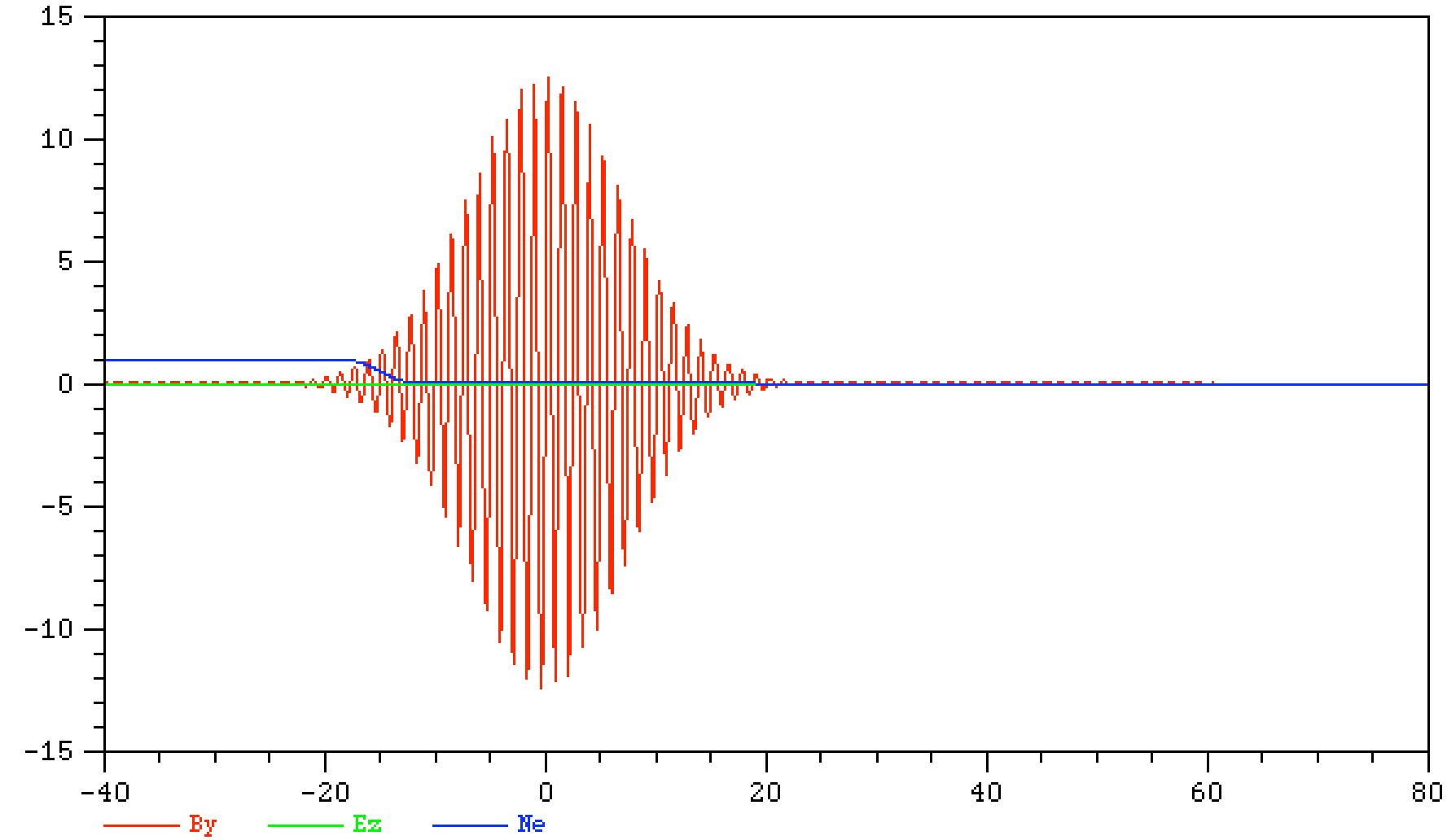
Red or blue shifted photon

"Raman forward scattering"

- Group velocity $\gamma_g \propto \dfrac{\omega}{\omega_p}$
- Normalized vector potential $a \propto \lambda I^{1/2}$

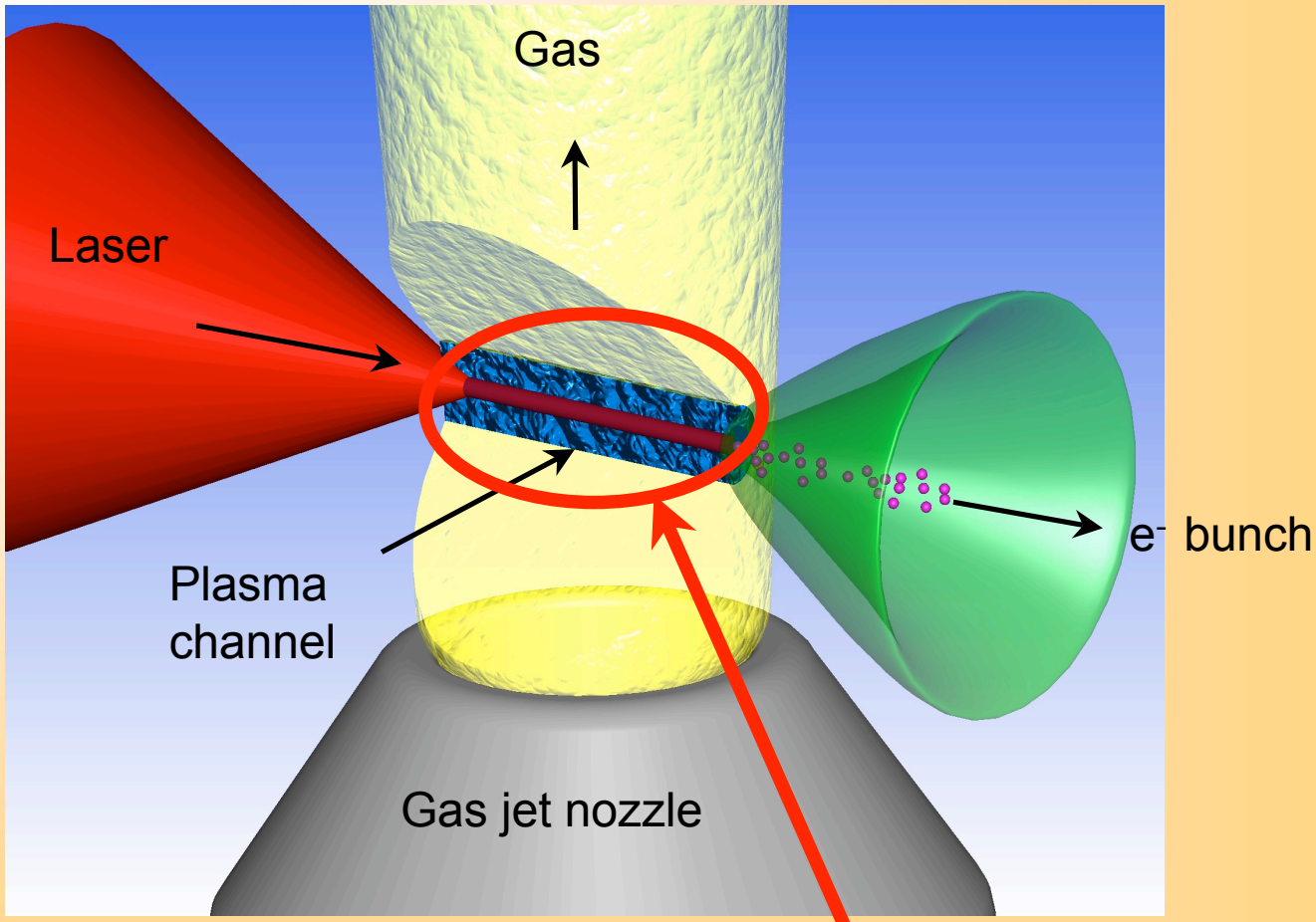
Pulse shape evolves

1-D Self-modulated laser wakefield: fluid simulation



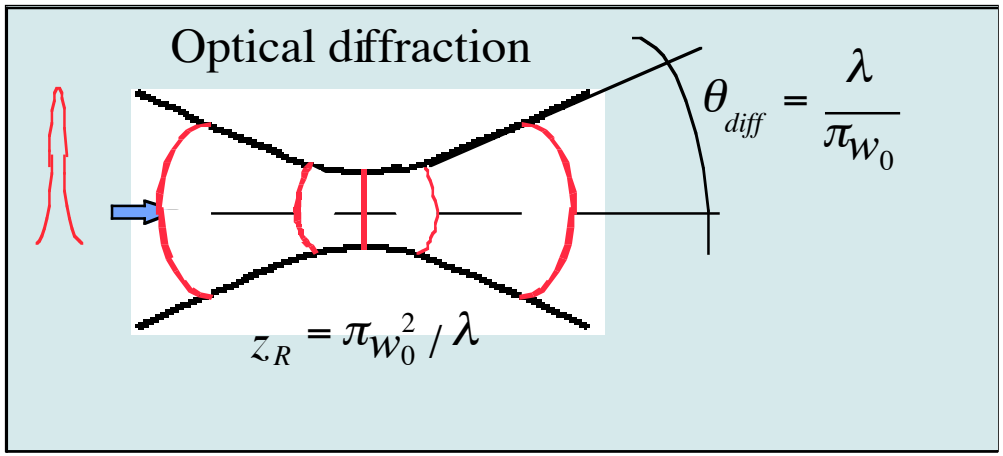
t = 0

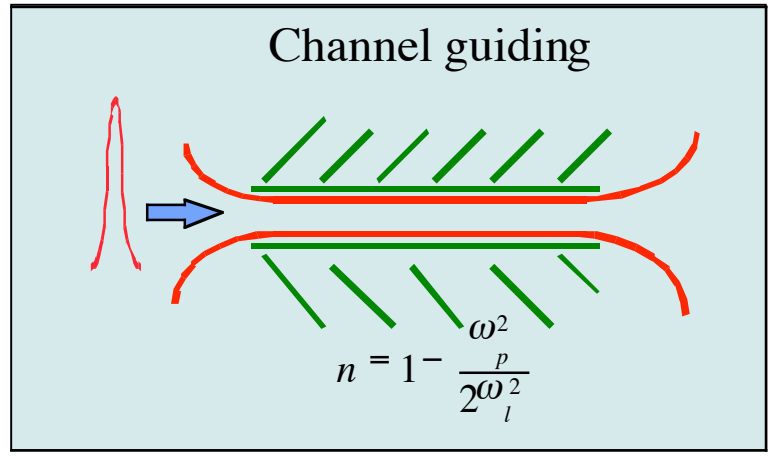
Laser wakefield experiments: single drive beam



How to make an intense laser beam propagate long distances?

Laser guiding: index of refraction varies radially





Guiding requires
$d\eta/dr<0$

Index of refraction $$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$

Wake

$$\eta \approx 1 - \frac{\omega_p^{\ 2}}{2\gamma_\perp \omega^2} = 1 - \frac{4\pi e^2 n_e(r)/m}{2(1+a^2)^{1/2}\omega^2} \approx 1 - \frac{\omega_{po}^{\ 2}}{2\omega^2}\left(1 - \frac{a^2}{2} + \frac{\delta n}{n} + \frac{\Delta n}{n}\right)$$

Relativistic

Channel

Relativistic self-guided experiments

$$\eta \approx 1 - \frac{\omega_{po}^{2}}{2\omega^{2}}\left(1 - \frac{a^{2}}{2} + \frac{\delta n}{n} + \frac{\Delta n}{n}\right)$$

Wake

Channel

Relativistic

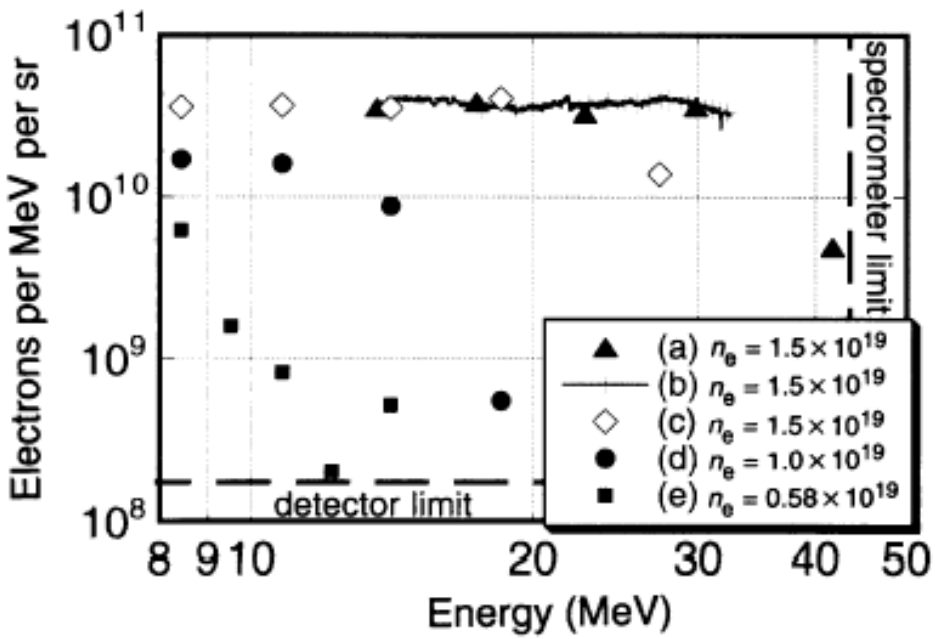
- Pulse long compared to plasma period
- $P > P_{crit} = 17\ (\omega/\omega_p)^2 = 17\ (n_c/n)$;
- E.g. P_{crit} = 1 TW for 1 micron laser in 10^{19} cm^{-3}
  - 1995 and 2004 Rutherford experiments with VULCAN
  - 1996 Univ. Michigan experiments

1995 : Self-modulated laser wakefield with CPA system

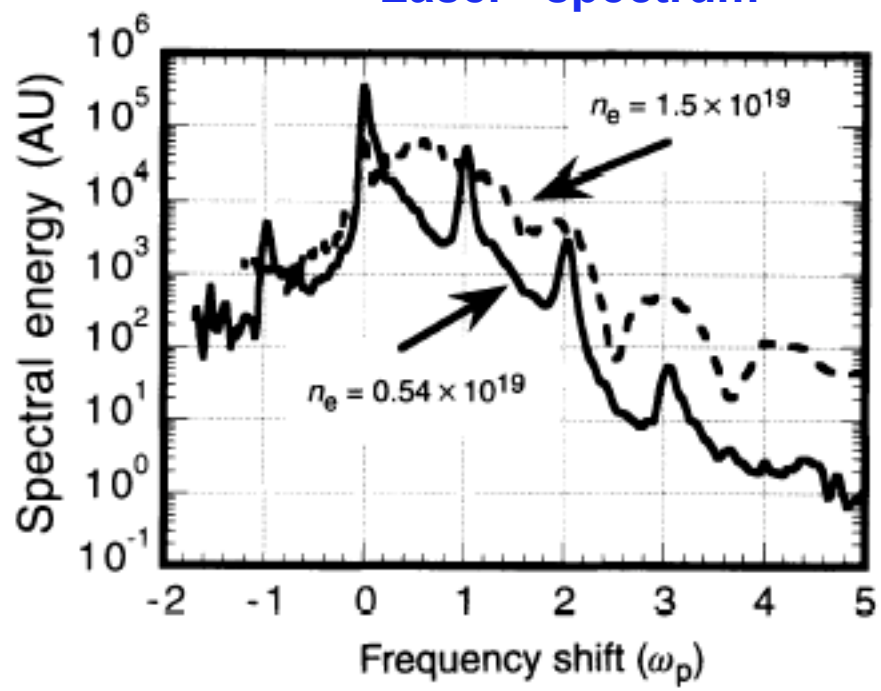
- Laser power P = 25 TW (VULCAN), 0.8 ps, 20 J
- F/60 solid angle= 16 mrad
- # e's/MeV= #e's/MeV/sr x 2.56E-4

$L_{laser} >> \lambda_p$

Electron spectrum



"Laser" spectrum

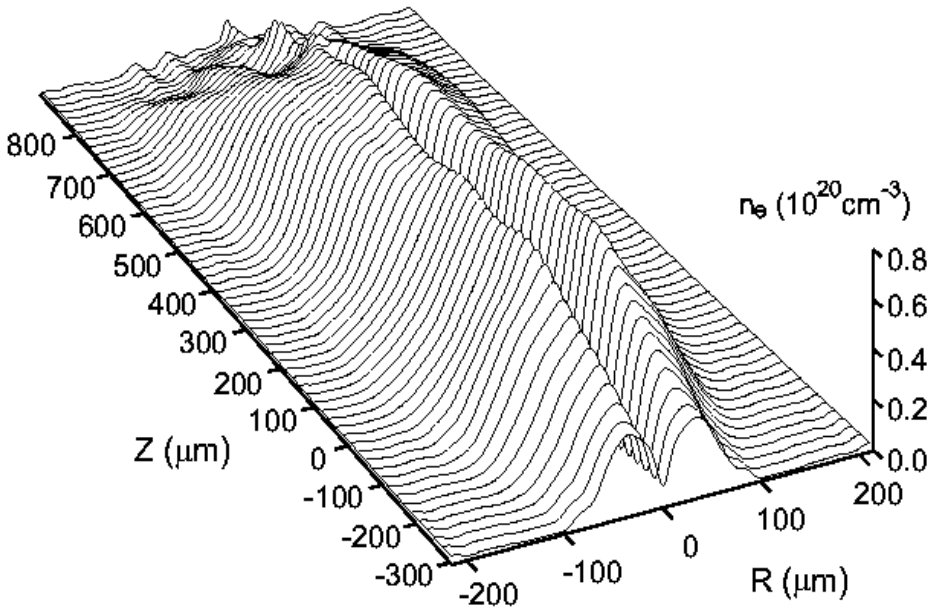


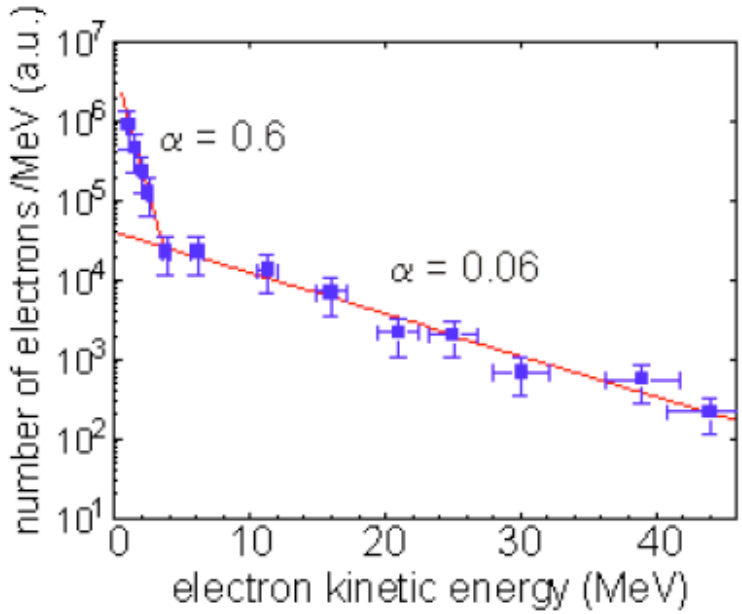
Nd:glass

A. Modena et al., Nature 377, 606 (1995)

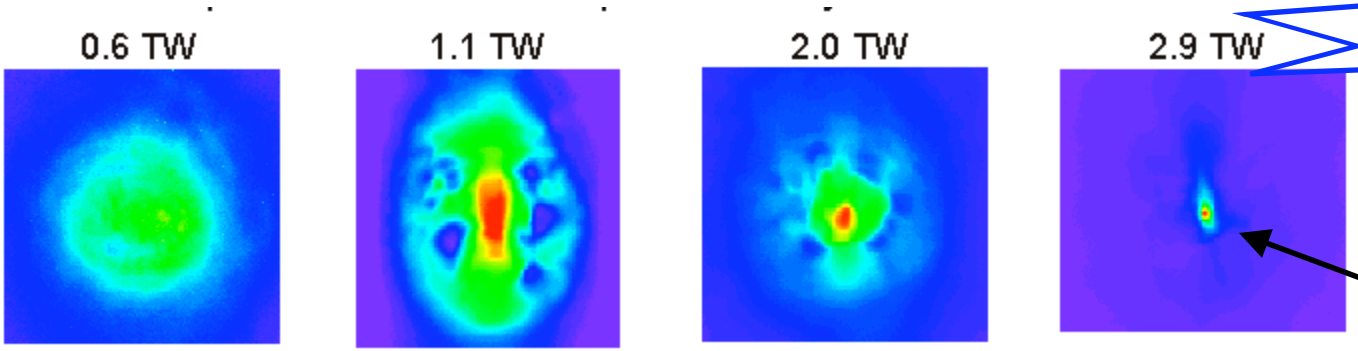
1996: relativistic guiding key for producing e-beam

D. Umstadter et al., Science 273, 472 (1996)





S.-Y. Chen *et al.*, *Phys. Plasmas*, 7, 403 (2000).



Nd:glass

τ_{laser} = 400 fs

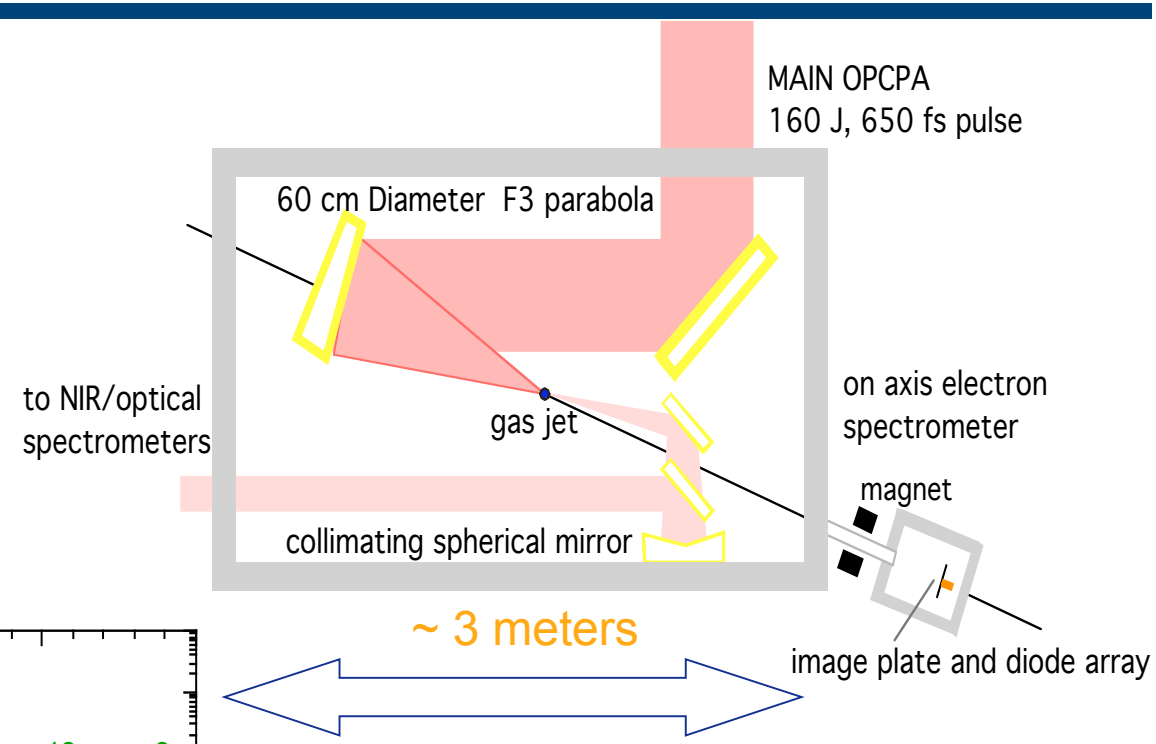
$\Delta\Theta$ = 1°

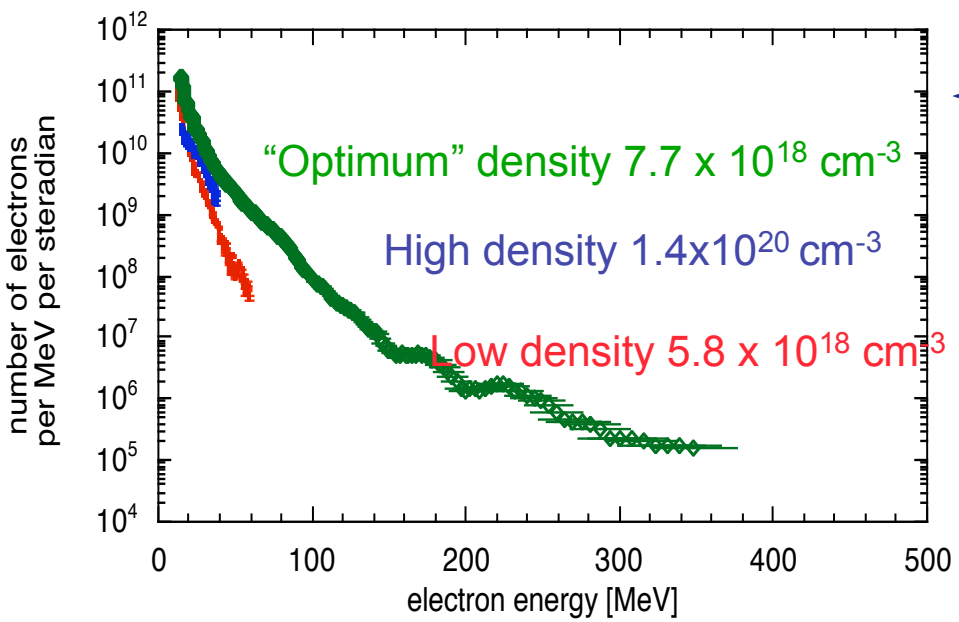
Imperial College London

Laser acceleration experiments using the VULCAN PetaWatt

Courtesy of K. Krushelnick et al.

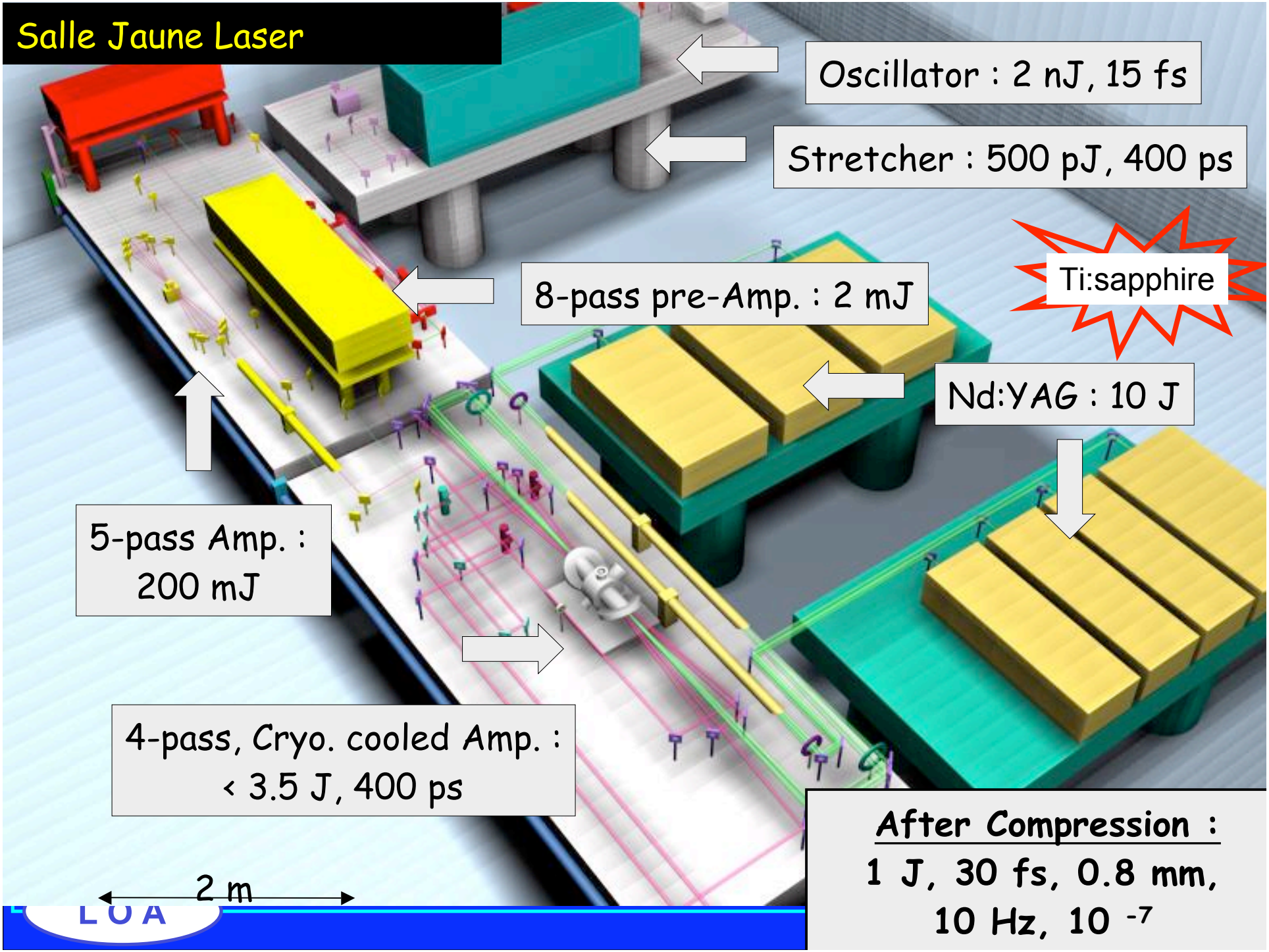
- Vulcan@RAL: 160 J in 650 fs
- Single shot laser



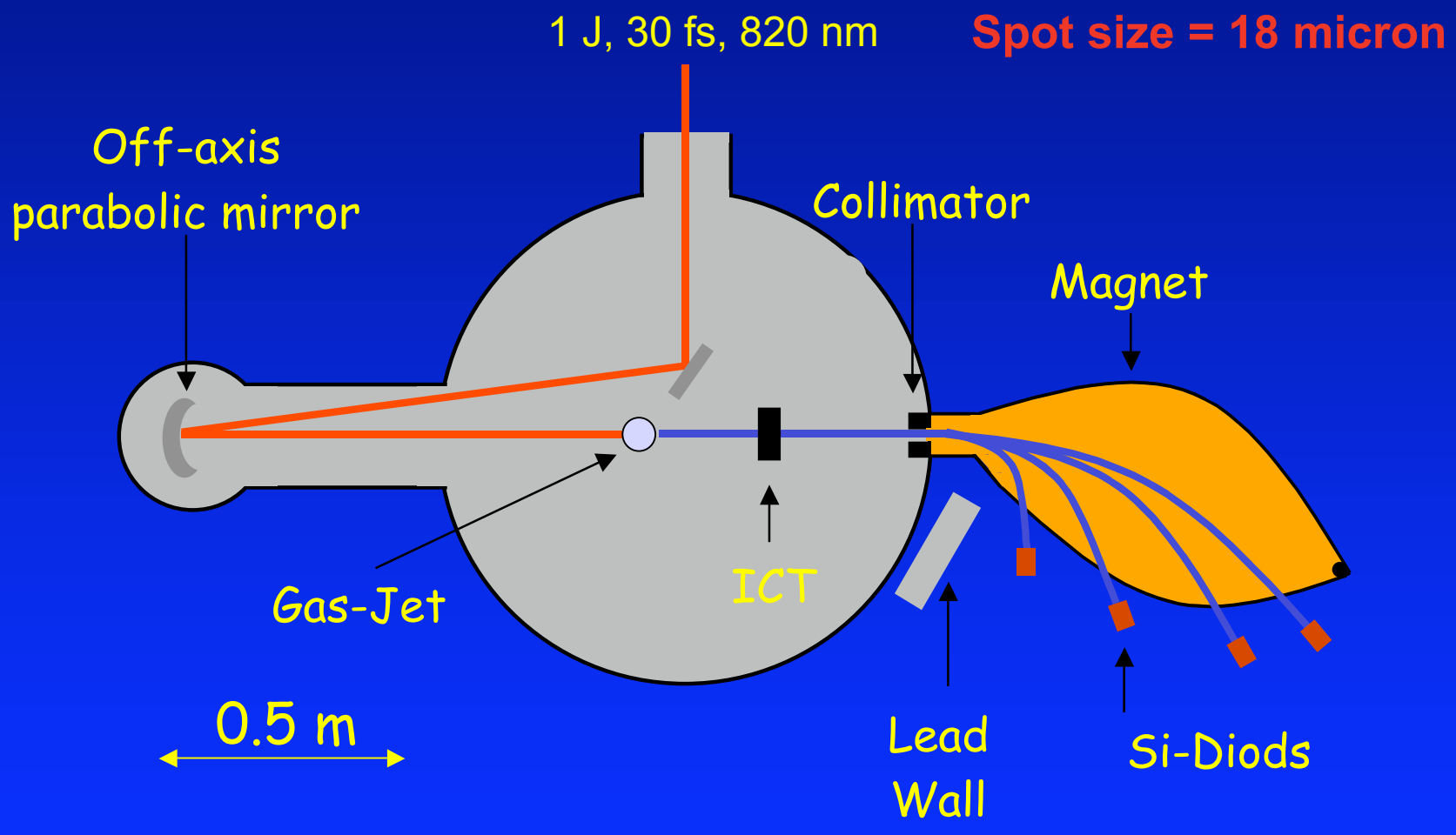


- 350 MeV electrons observed
- Energy spread large

Nd:glass

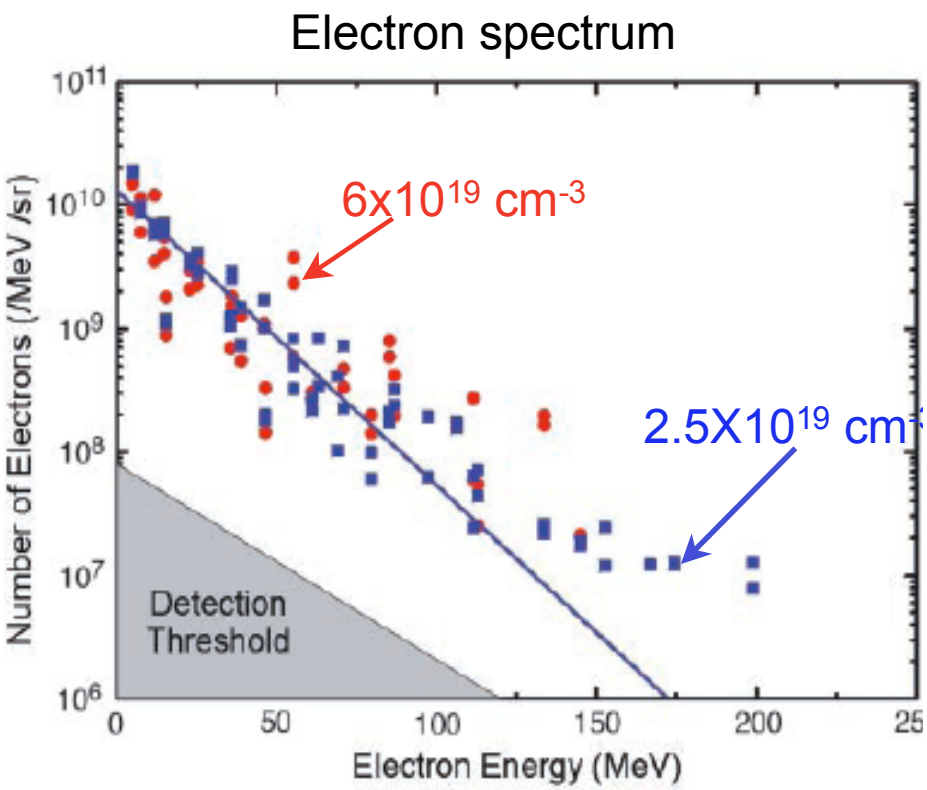

Salle Jaune Laser
Oscillator : 2 nJ, 15 fs
Stretcher : 500 pJ, 400 ps
Ti:sapphire
8-pass pre-Amp. : 2 mJ
Nd:YAG : 10 J
5-pass Amp. : 200 mJ
4-pass, Cryo. cooled Amp. : < 3.5 J, 400 ps
2 m
After Compression :
1 J, 30 fs, 0.8 mm,
10 Hz, 10 -7

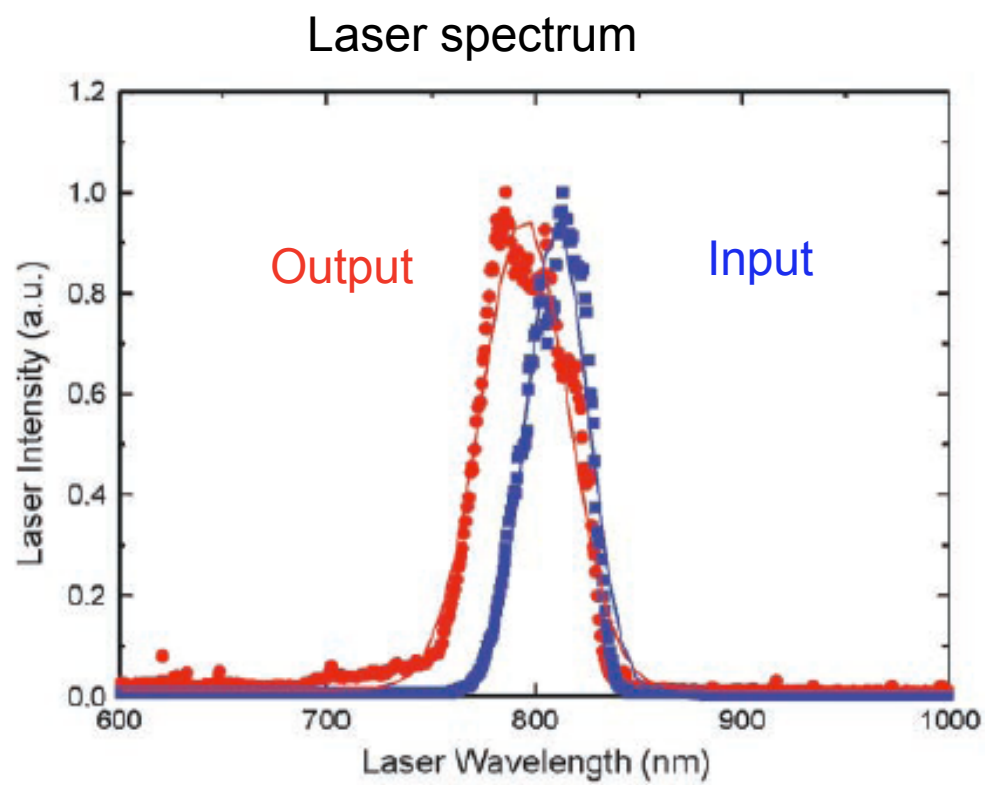
LOA Experimental Set-Up 2002



L O A

2002: "Forced Laser Wakefield" results





- "Forced laser wakefield" regime: short pulse self-modulation
- Need for guiding avoided by using "large" laser spot
- Note: Laser spectrum blueshifting does <u>not</u> agree with energy conservation argument

Ti:sapphire

V. Malka et al., Science 298. 1596 (2002)

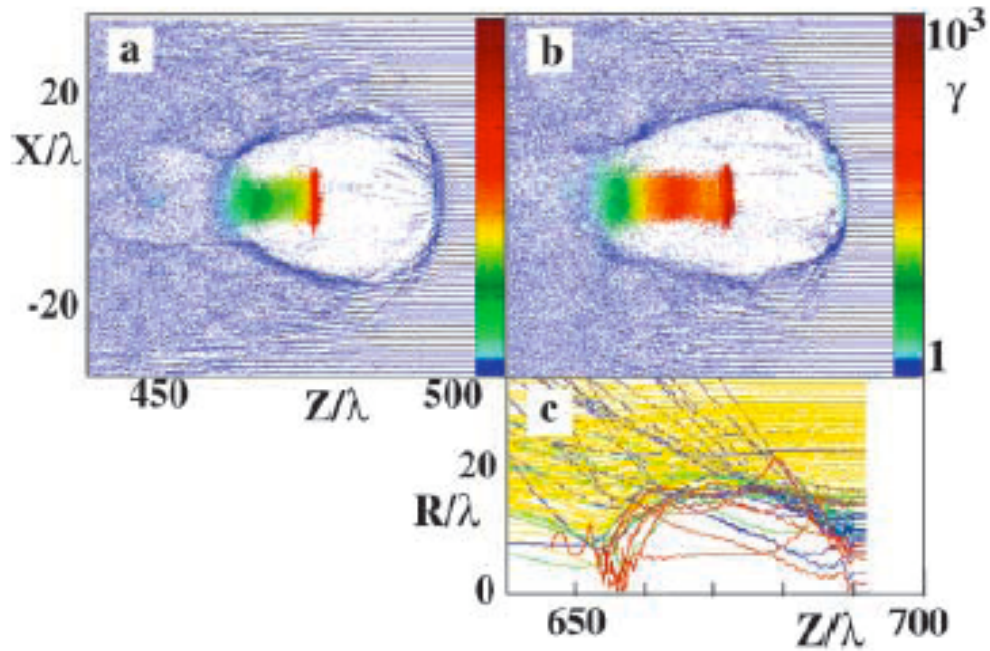
2002: Laser “bubble (or blow-out)” regime

Appl. Phys. B 74, 355–361 (2002)
DOI: 10.1007/s003400200795
Applied Physics B
Lasers and Optics

A. PUKHOV[1,✉]
J. MEYER-TER-VEHN[2]

Laser wake field acceleration: the highly non-linear broken-wave regime

[1] Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

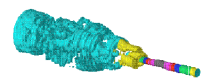


12 J, 33 fs pulse

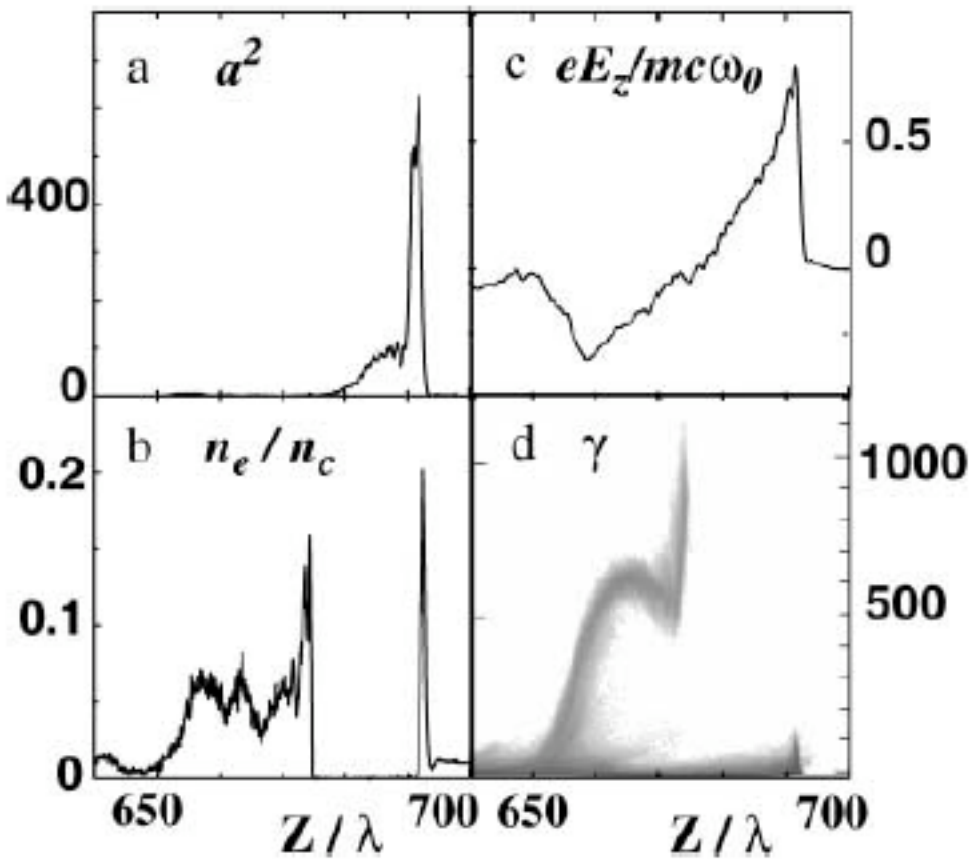
A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B, **74,** *p.*355 (2002)

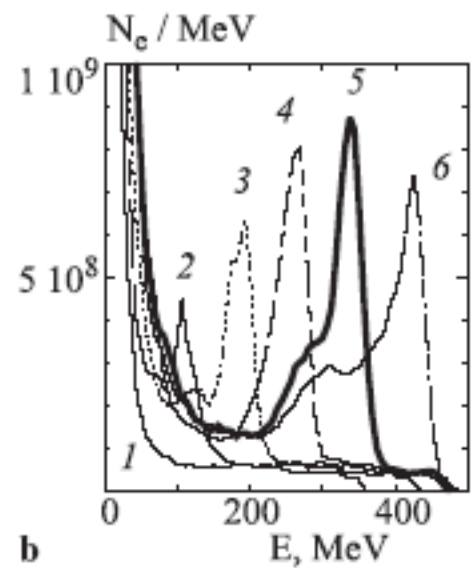
Laser pulse evolution leads to blow-out or bubble regime

A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B, **74,** *p.*355 (2002)



VLPL





But simulations use a_{in}=10: experimentally not doable…or is it?

In the mean time, back at the ranch…

controlled laser guiding

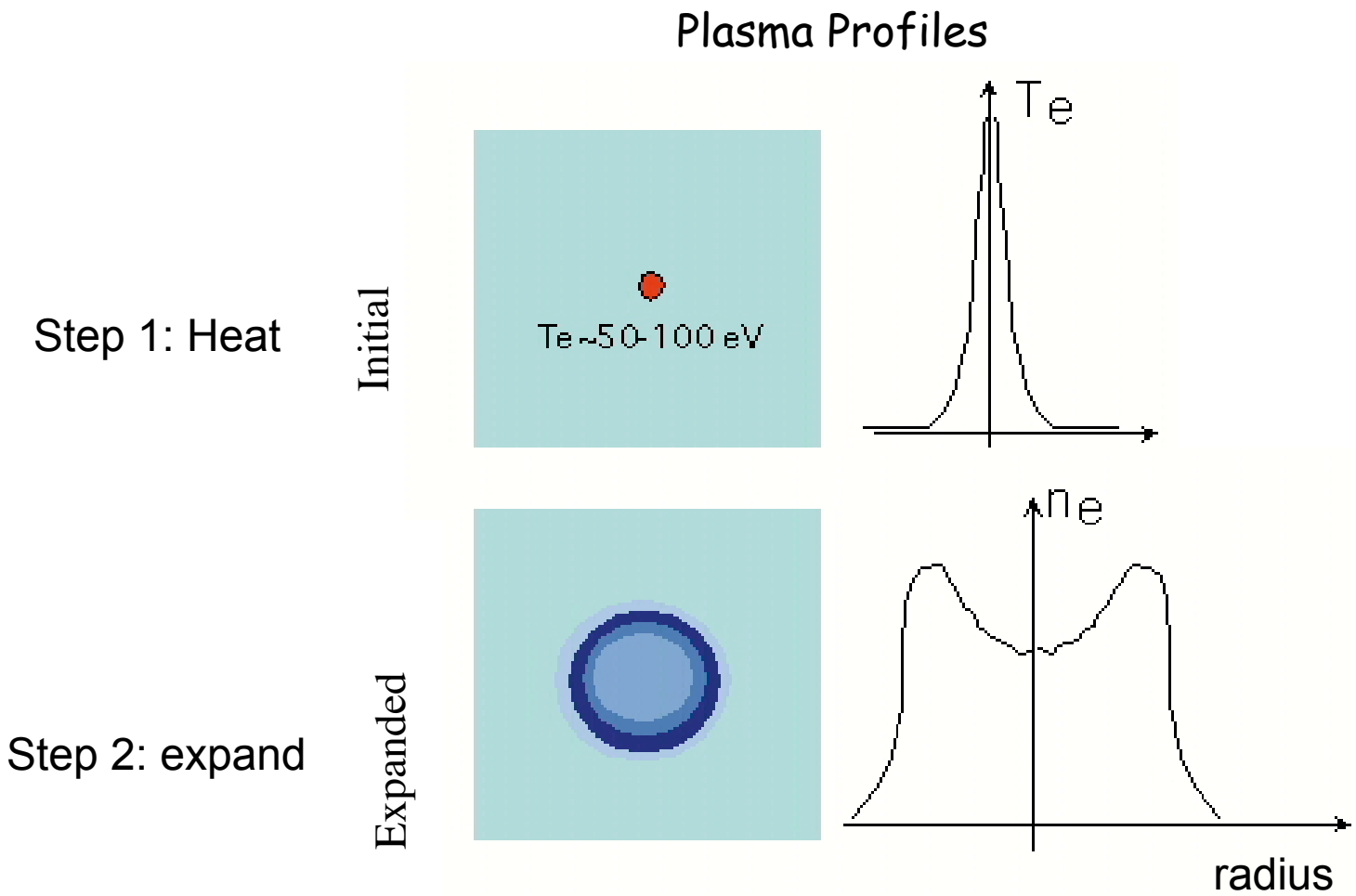
Wake

$$\eta \approx 1 - \frac{\omega_{po}^{2}}{2\omega^{2}}\left(1 - \frac{a^{2}}{2} + \frac{\delta n}{n} + \frac{\Delta n}{n}\right)$$

Channel

Relativistic

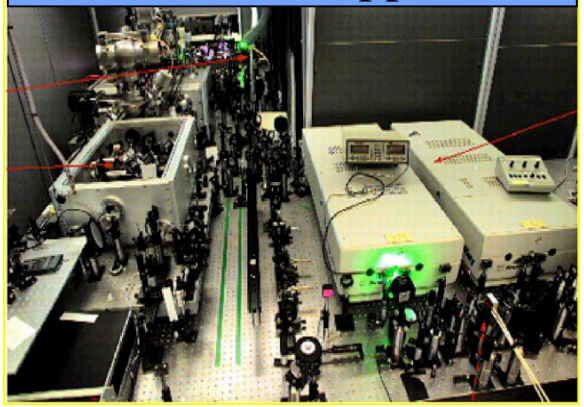
Plasma channel generation: hydro expansion



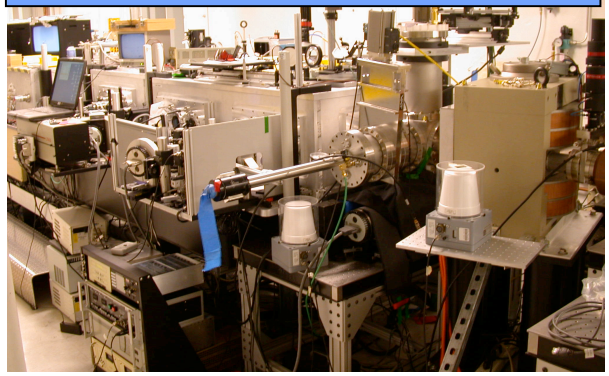
- On-axis axicon (C.G. Durfee and H. Milchberg, PRL 71 (1993))
- Ignitor-Heater (P. Volfbeyn et al., Phys. Plasmas 6 (1999))

L'OASIS facility: high rep rate, high peak power Ti:sapphire system

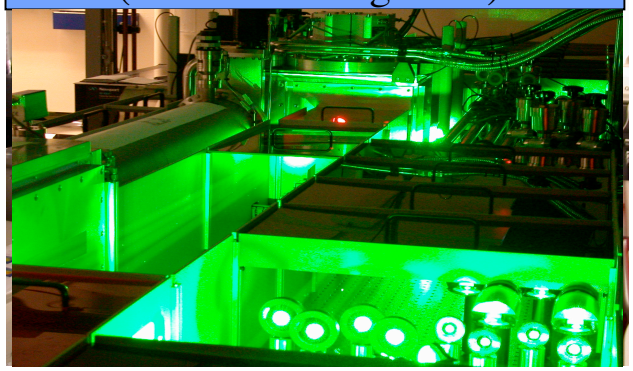
10 TW Ti:sapphire



Shielded target room



100 TW Ti:sapphire
(commissioning 2004)



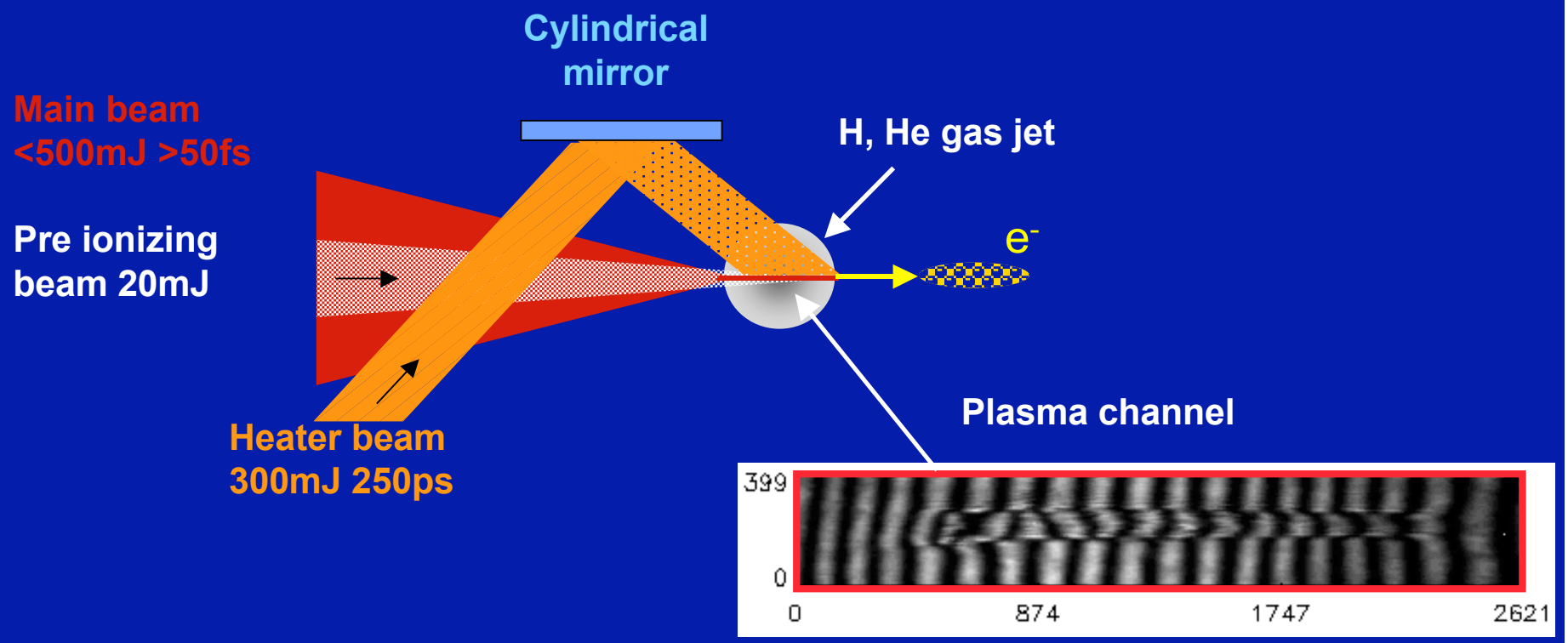
10 TW Ti:sapphire laser system:
500 mJ/pulse
t > 40 fs
10^{19} W/cm^2
10 Hz
6 μm spot size

Ti:sapphire

100 TW Ti: sapphire laser system:
3-4 J/pulse
t > 30 fs
10^{20} W/cm^2
10 Hz
6 μm spot size

L'OASIS: *Lasers, Optical Accelerator Systems Integrated Studies*

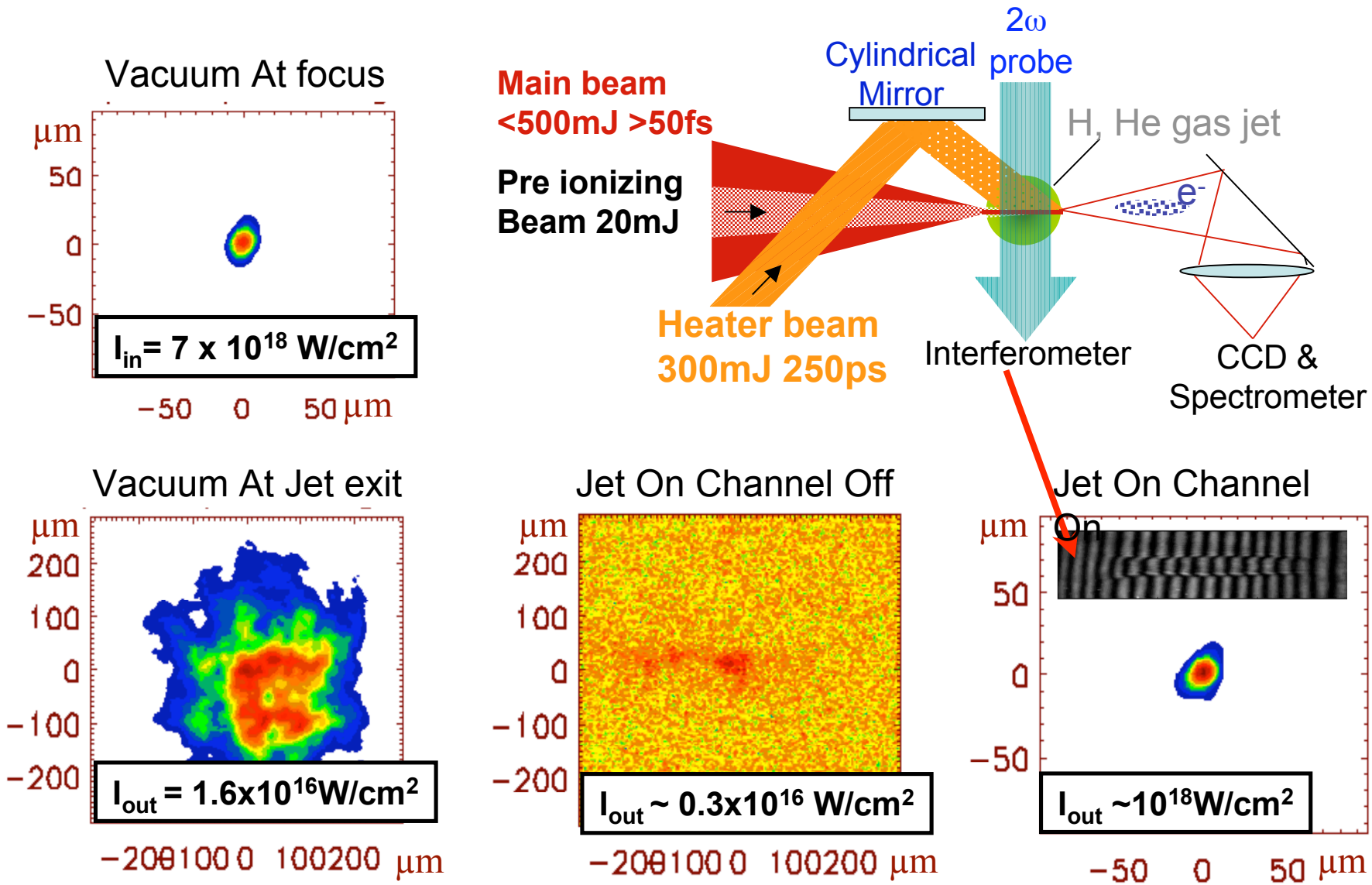
Plasma Channel Production: Hydrodynamic Ignitor-Heater in H_2 Gas Jet



Relativistic intensities (> 10^{18} W/cm_2) achieved in guided plasma

P. Volfbeyn, E. Esarey and W.P. Leemans, *Phys. Plasmas* 1999
C.G.R. Geddes et al., Nature 431, p. 543 (2004).

Relativistic intensities (> 10^{18} W/cm^2) guided at LBNL



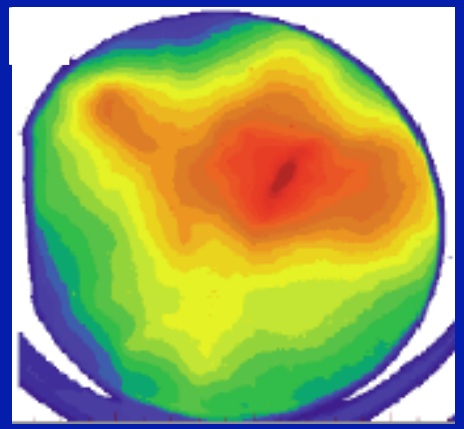
C. Geddes et al., Nature 431 (2004)

Effect on electron beam ?

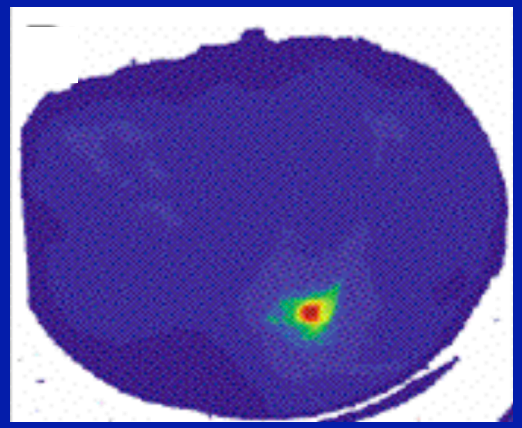
Millimeter Structure Delivers 85 MeV Electron Beam with Narrow Energy Spread

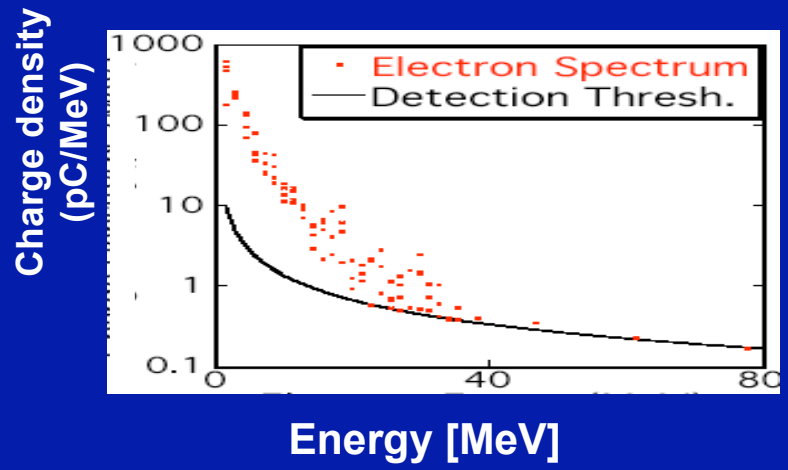
C.G.R. Geddes et al., Nature 431, 538, 2004

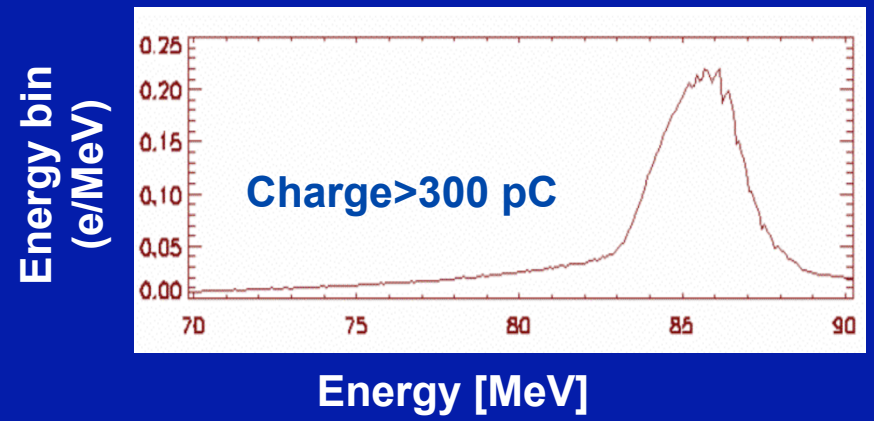
Unguided beam profile



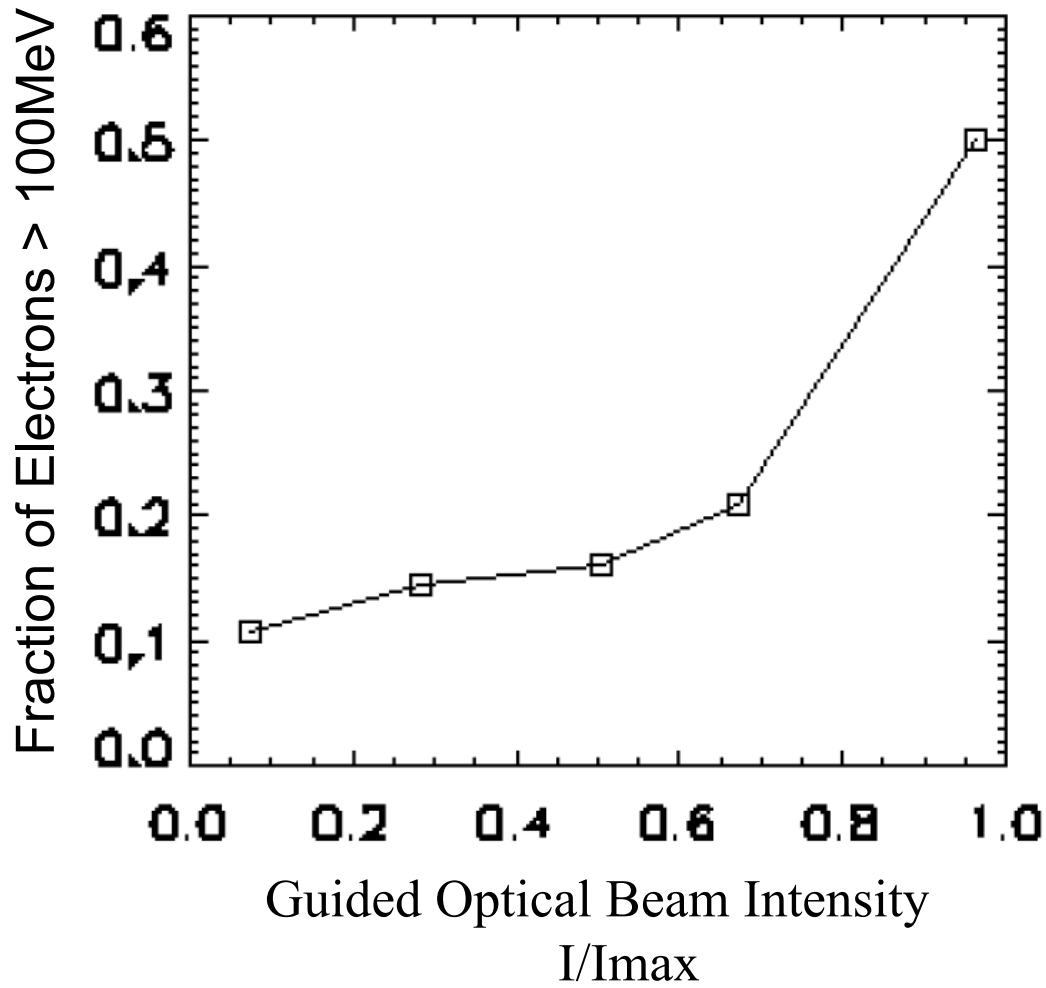
Guided beam profile





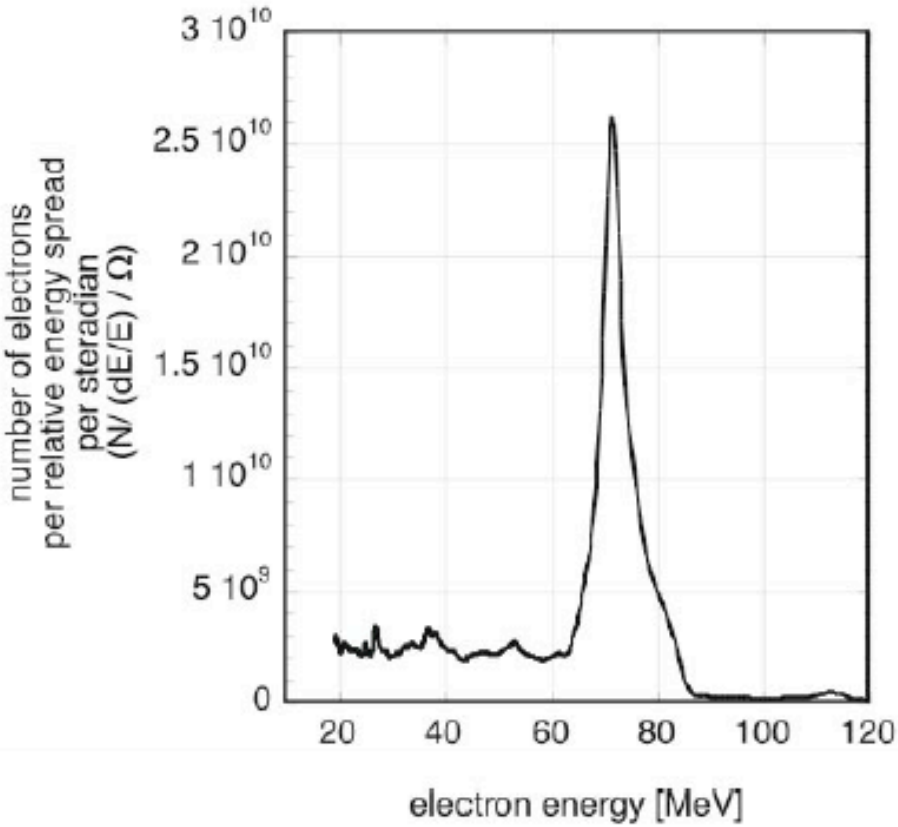


Highest Energy Electrons correlated with best guiding



Imperial College London

Mono-energetic spectra can be observed at higher power ($\Delta E/E$ = 6 %)



E ~ 500 mJ,
pulse duration ~ 40 fsec
Focal spot ~ 25 μm
Density ~ 2 x 10^{19} cm^{-3}

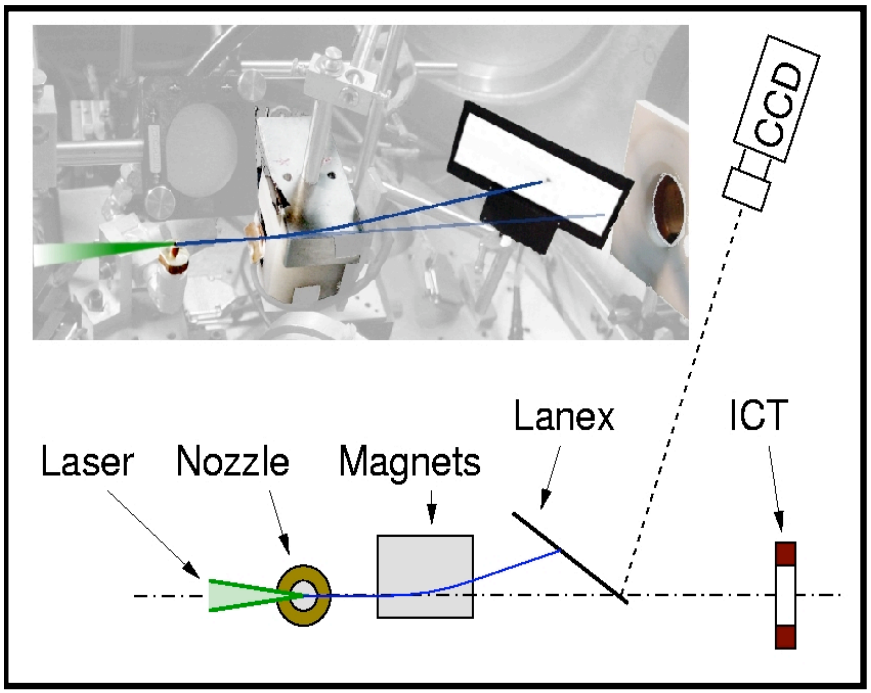
Significant shot-to-shot fluctuations in
a) energy spread
b) peak energy

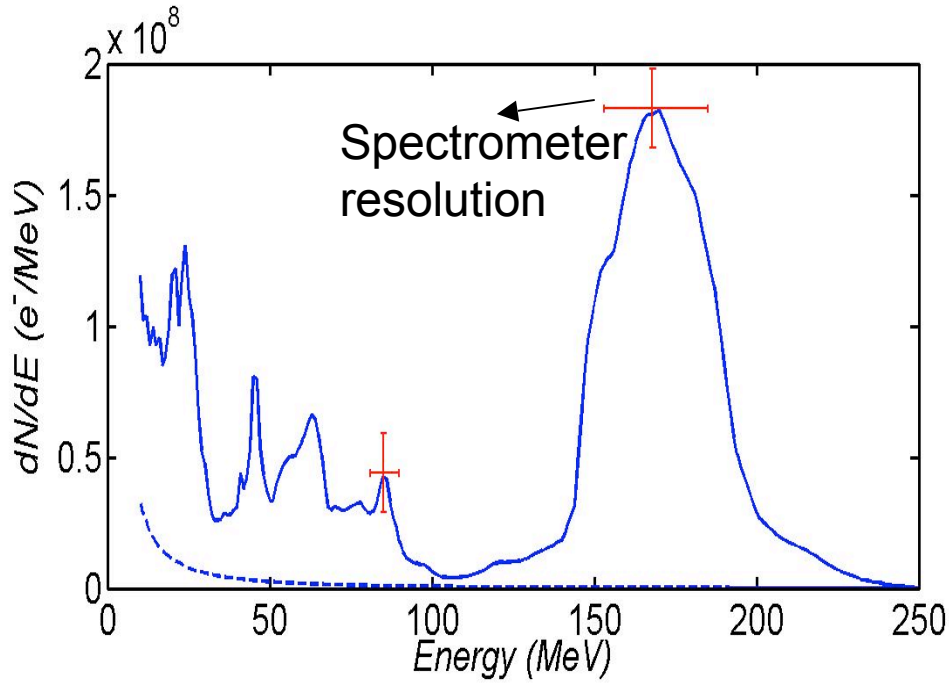
Careful control of laser and plasma conditions is necessary

Ti:sapphire

Courtesy: K. Krushelnick, RAL

2004 LOA Experiments





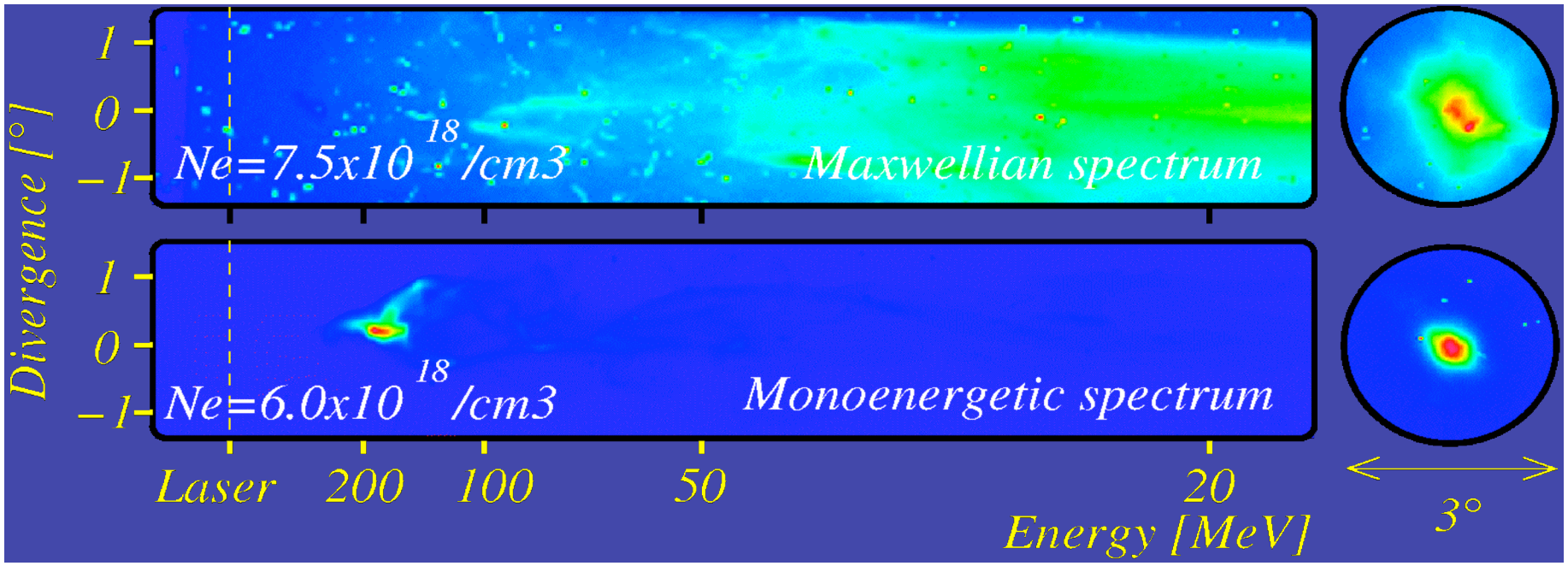
Charge in [150-190] MeV : (500 ±200) pC

- Same laser parameters as in 2002 exp'ts (*Malka et al., Science 2002*)
- Different diagnostic: single shot broad energy coverage
- Varying plasma density downward

Ti:sapphire

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

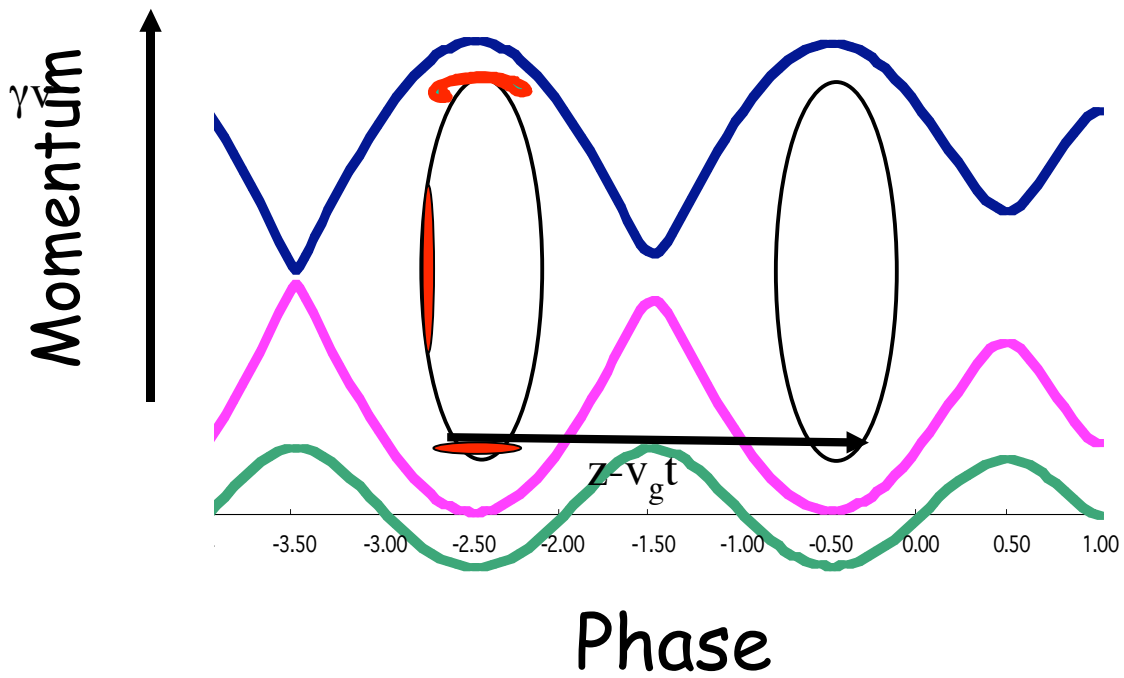
Energy distribution and spatial profile strongly dependent on plasma density



N.B. : color tables are different

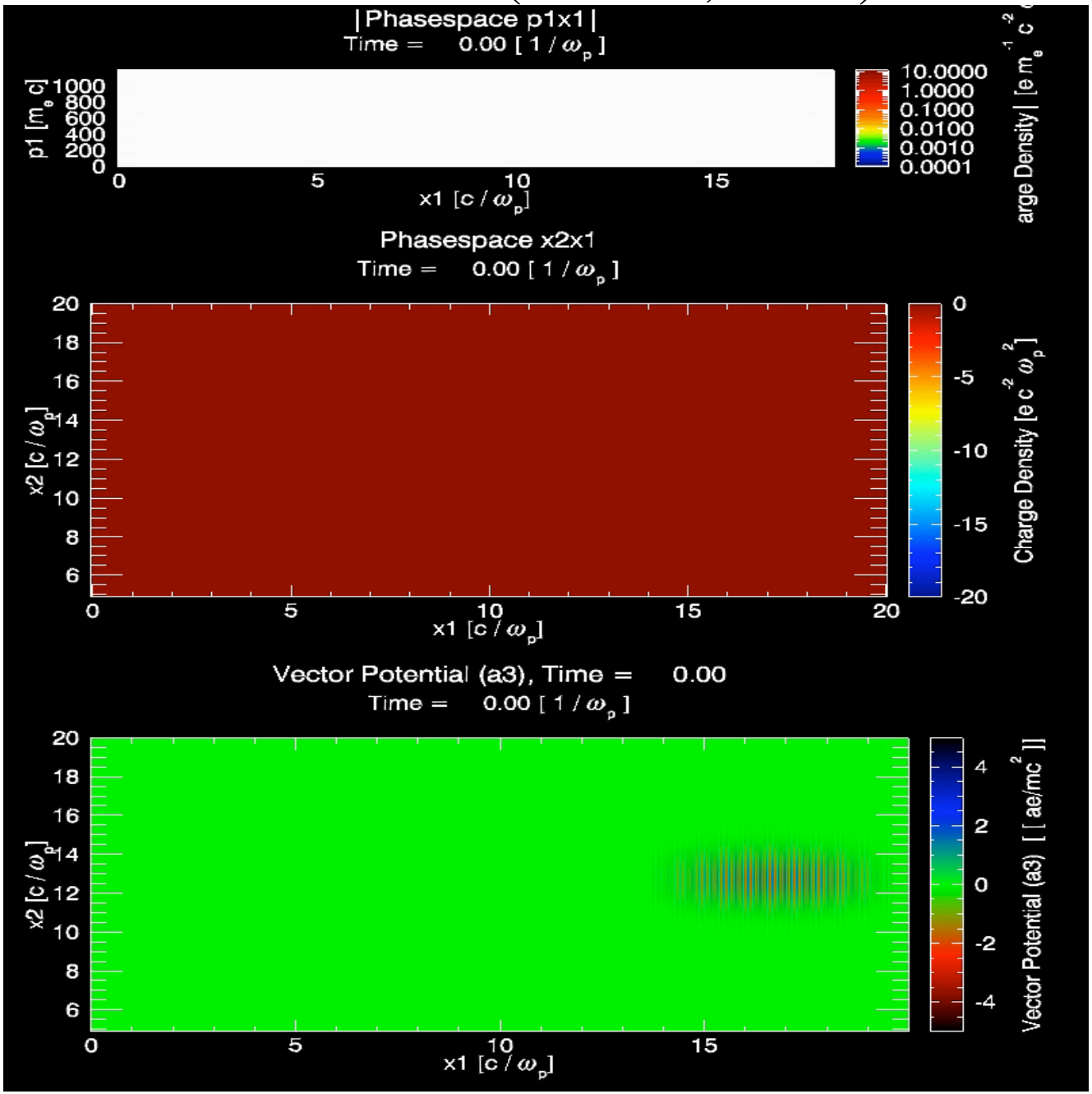
J. Faure et al., Nature 431, 541 (2004)

Group velocity of laser < speed of light causes particle dephasing



- Dephasing distance: $L_{dph} = (1/2)(\lambda_p^3/\lambda^2) \times \begin{cases} 1, & a_0^2 << 1 \\ (\sqrt{2}/\pi)a_0, & a_0^2 >> 1 \end{cases}$
  - Control via density and a_0: laser intensity
  - Optimum acceleration requires $L_{acc} = L_{deph}$: channel or large Z_R

2D PIC Code (W. Mori,UCLA)



"Recipe" for monoenergetic beam with self-trapped plasma electrons

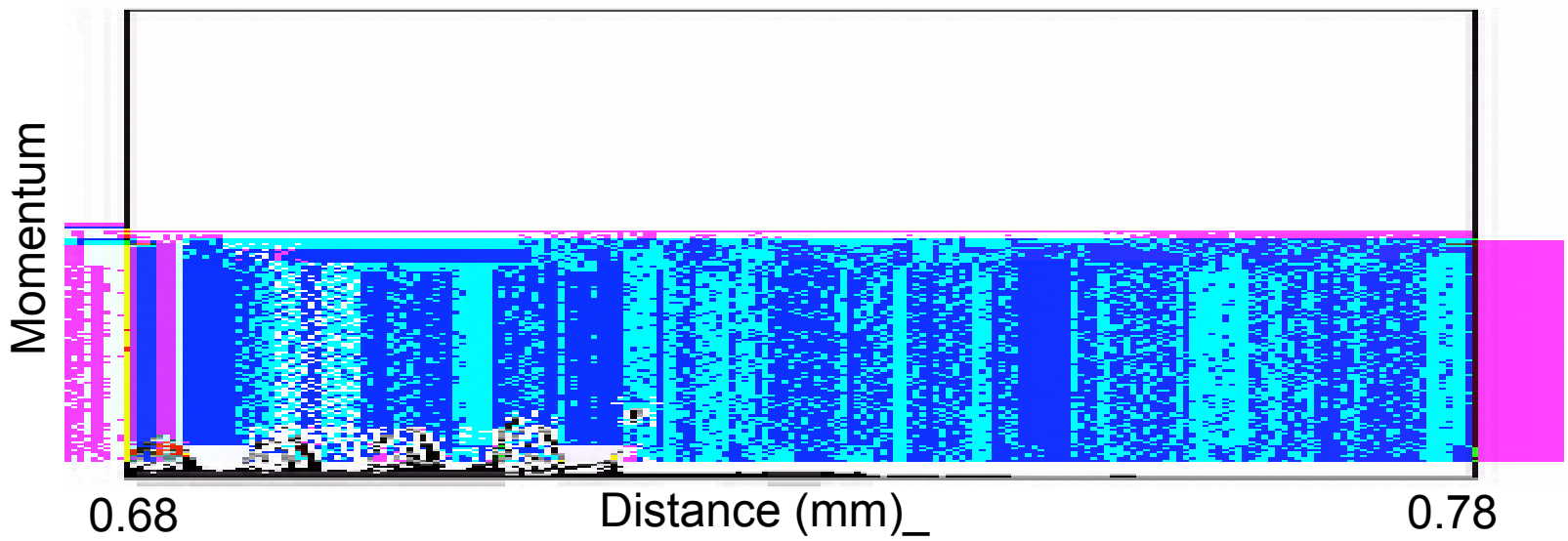
1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Termination of trapping (e.g., beam loading)
4. Acceleration

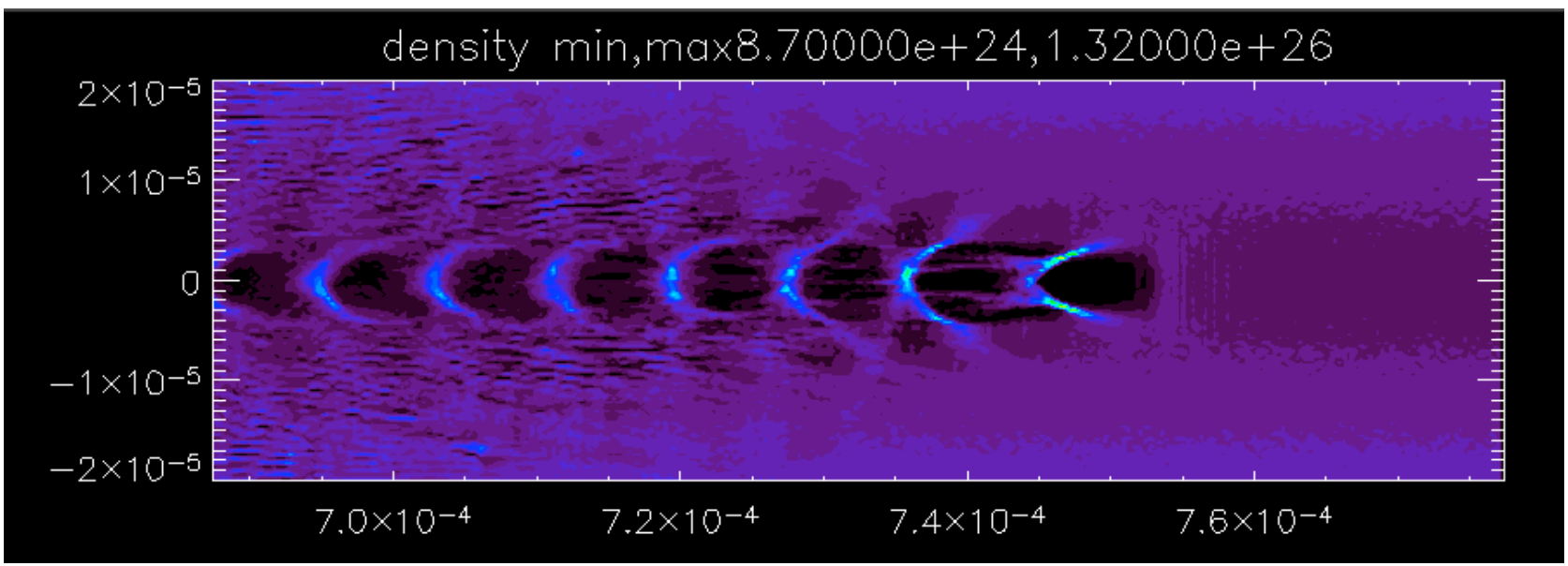
If L_{acc}> dephasing length: large energy spread

If L_{acc}< dephasing length: monoenergetic

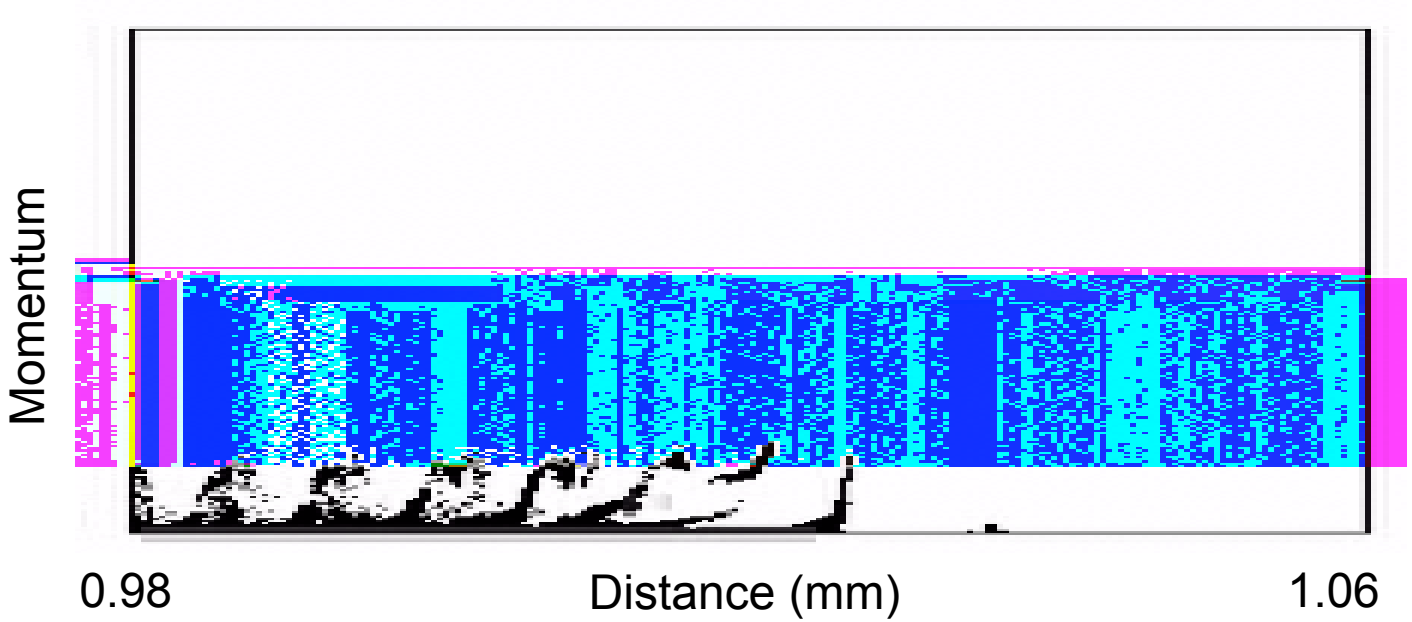
Optimal plasma density: lowest possible density to meet conditions 1 - 4

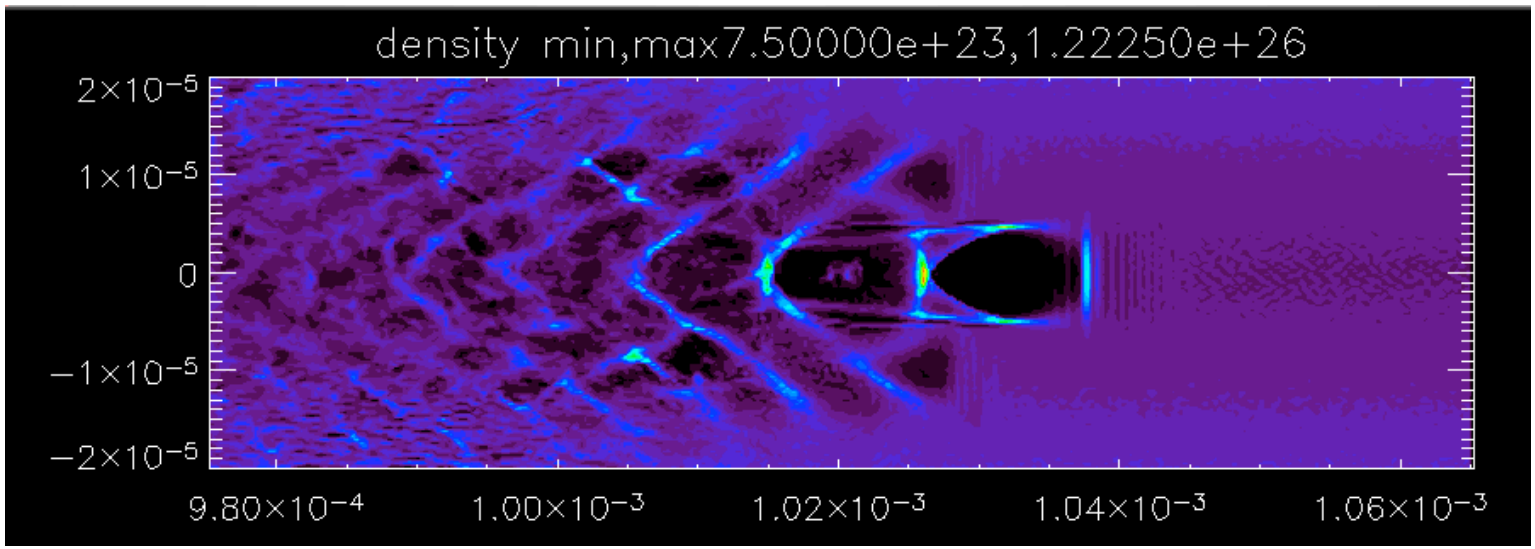
Formation of high quality beams by beam loading and dephasing



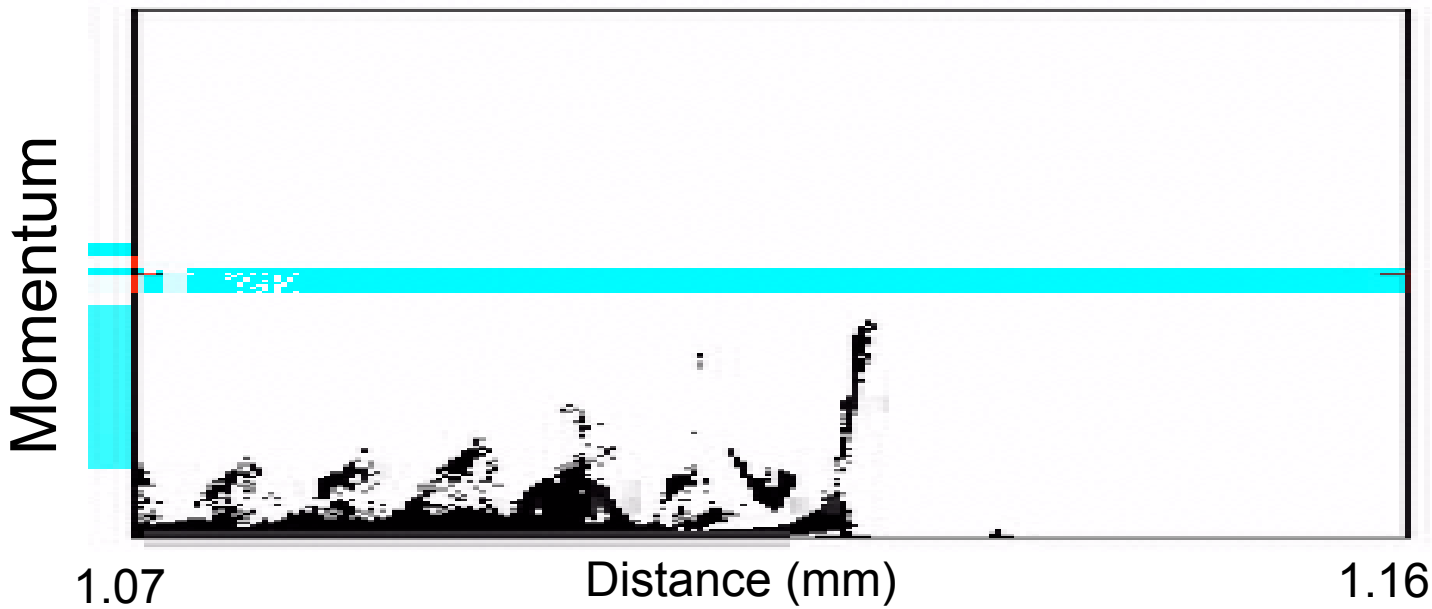


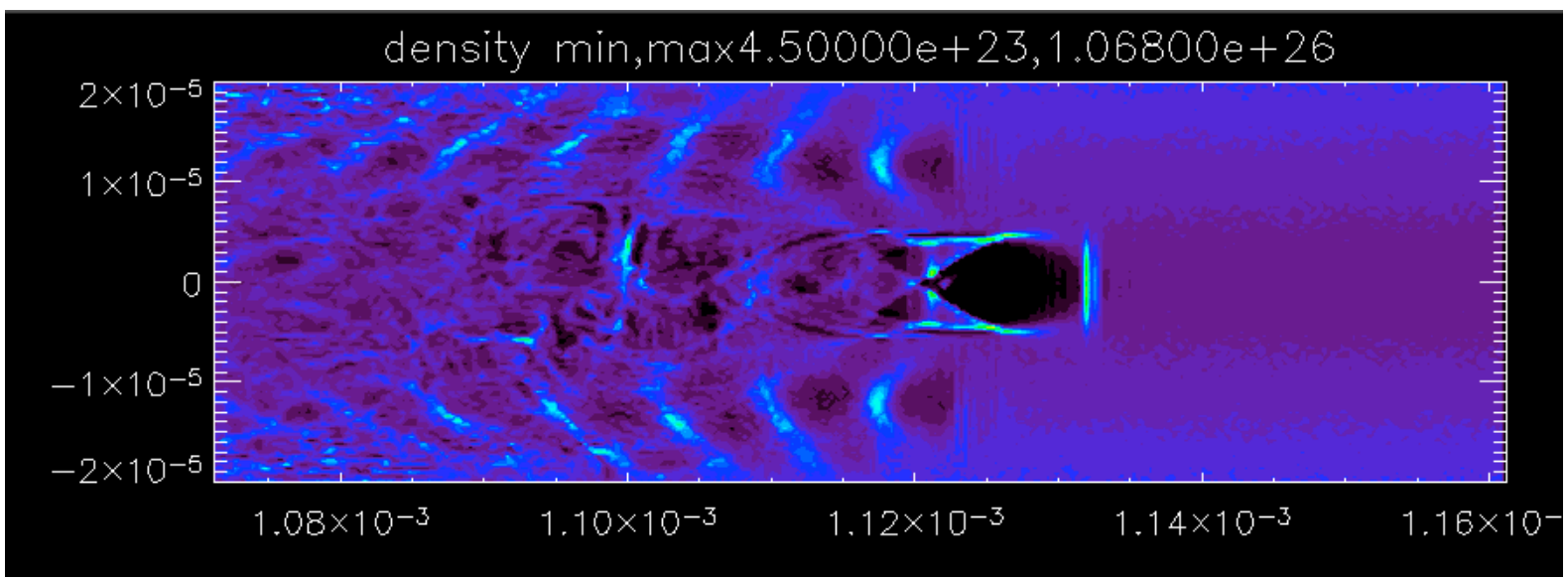
Injection phase



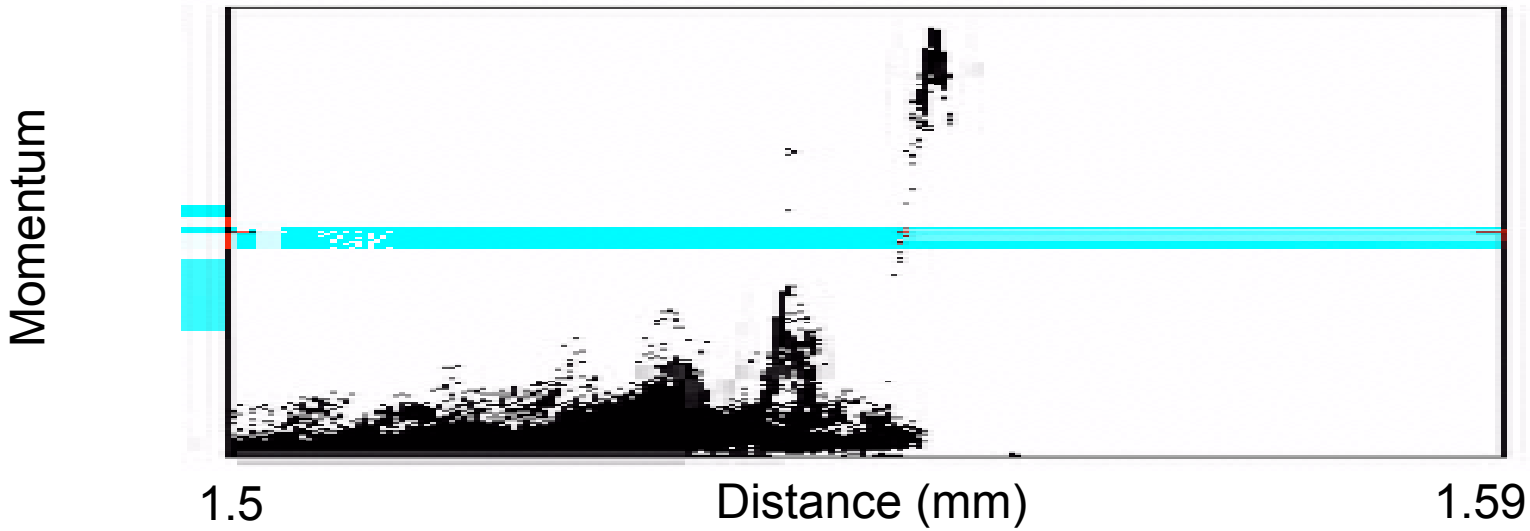


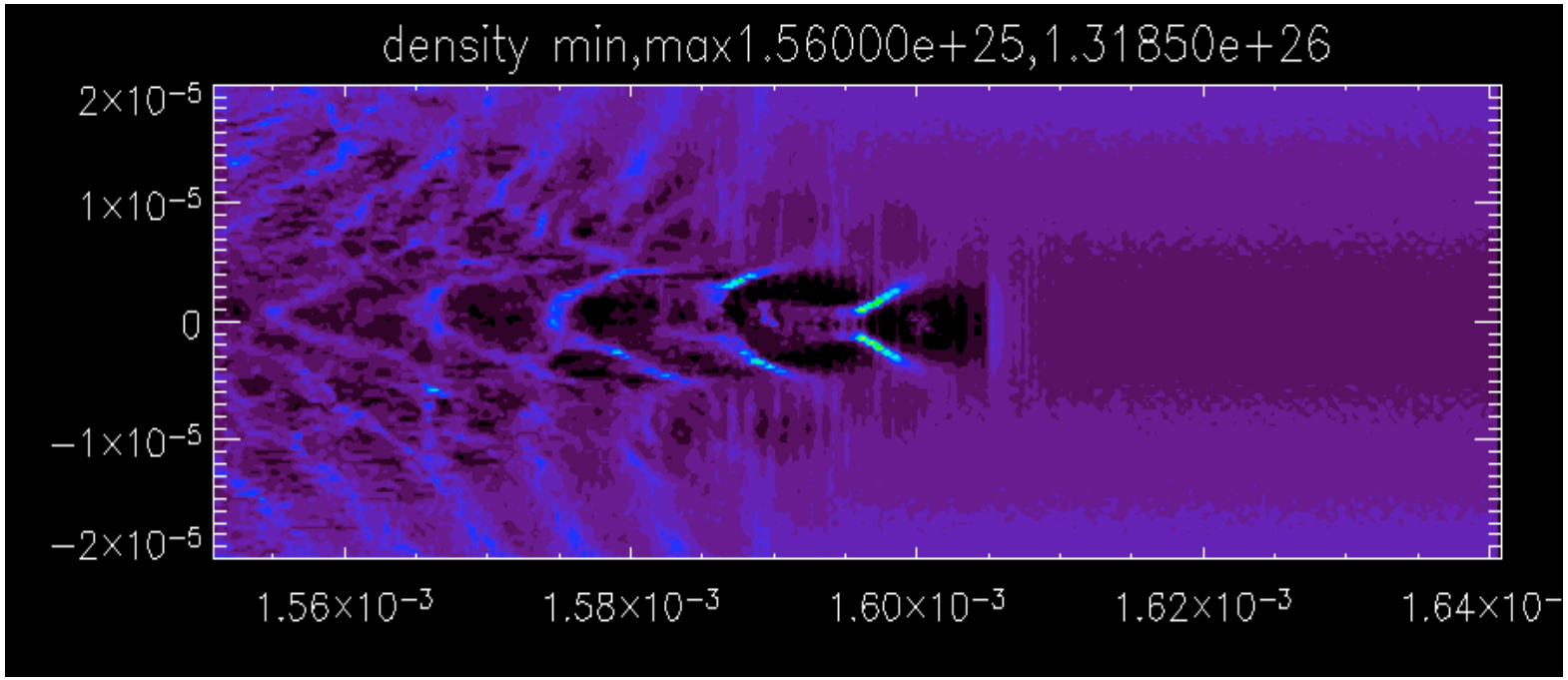
Large amount of trapped charge causes wake suppression





Dephasing: momentum bunching

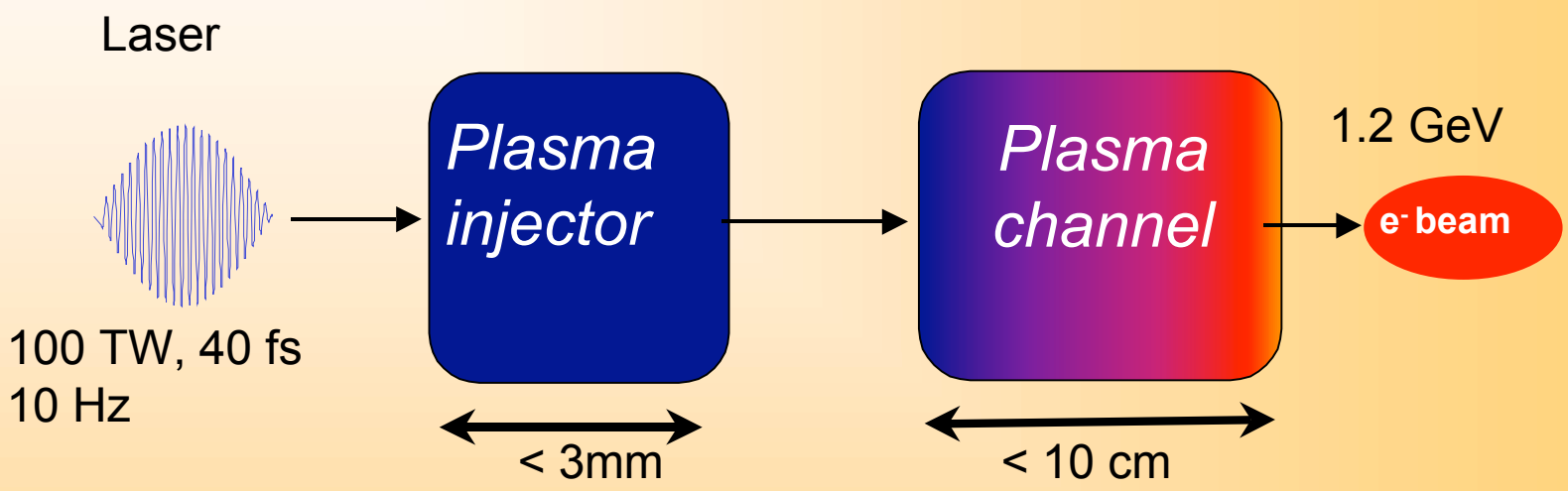




What's next ?

- Accelerator development
  - Controlling injection phase: colliding pulse
  - Increasing beam energy: capillary discharge
- Radiation source
  - Femtosecond x-rays
  - Terahertz radiation

Next step: 1 GeV compact module
100 TW laser + plasma channel



Energy Gain in a channel guided LWFA

Limited by electron dephasing: $L_d \approx \lambda_p^3 / \lambda^2$

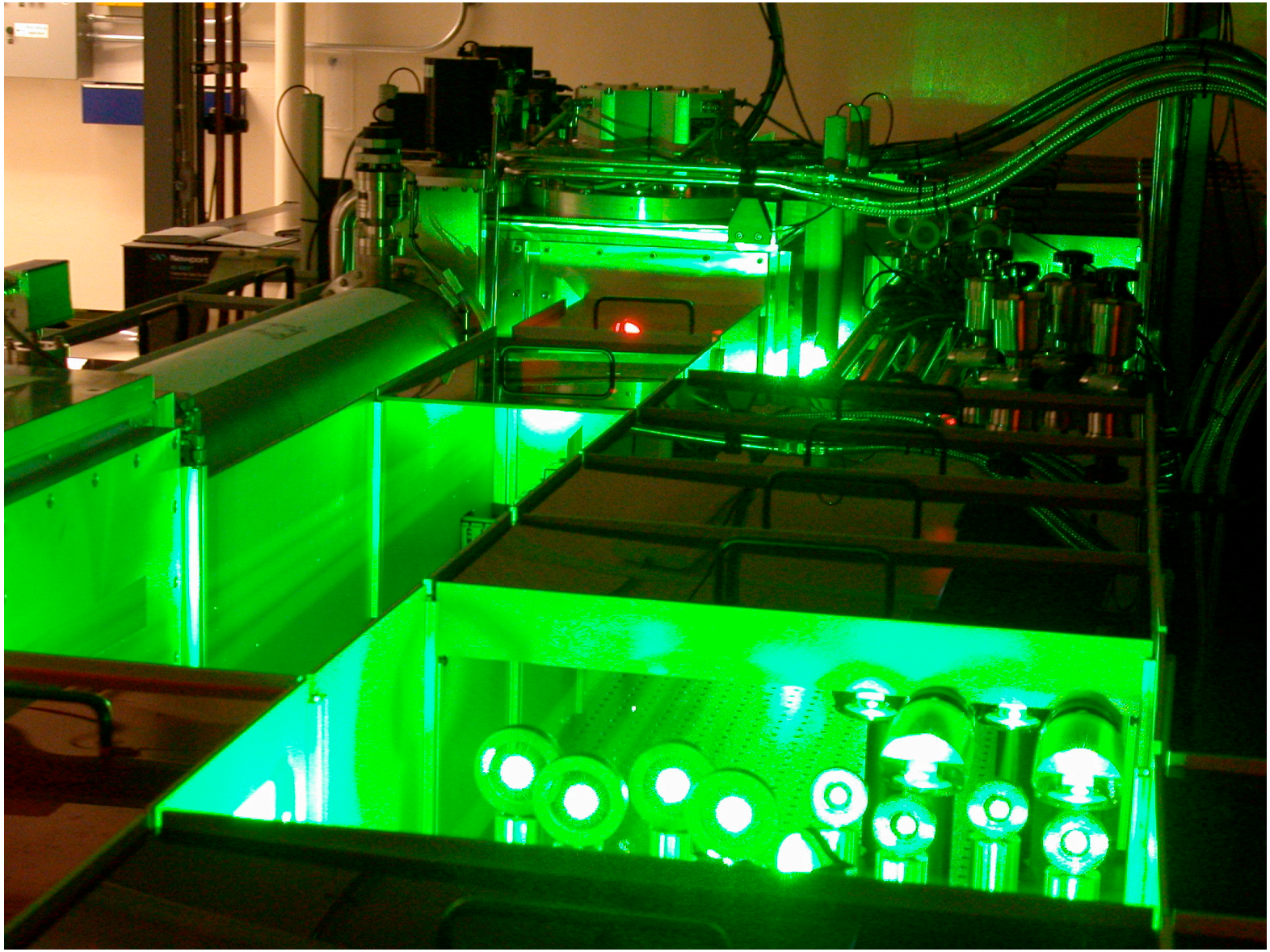
$$\Delta W_d[\mathrm{GeV}] \sim I[\mathrm{W/cm^2}] / n[\mathrm{cm^{-3}}]$$

$\lambda \approx 1\ \mu\mathrm{m}$, $L = \lambda_p \approx 100\ \mu\mathrm{m}$, $n = 10^{17}\ \mathrm{cm^{-3}}$, $I_L = 10^{18}\ \mathrm{W/cm^2}$, $P = 100$ TW

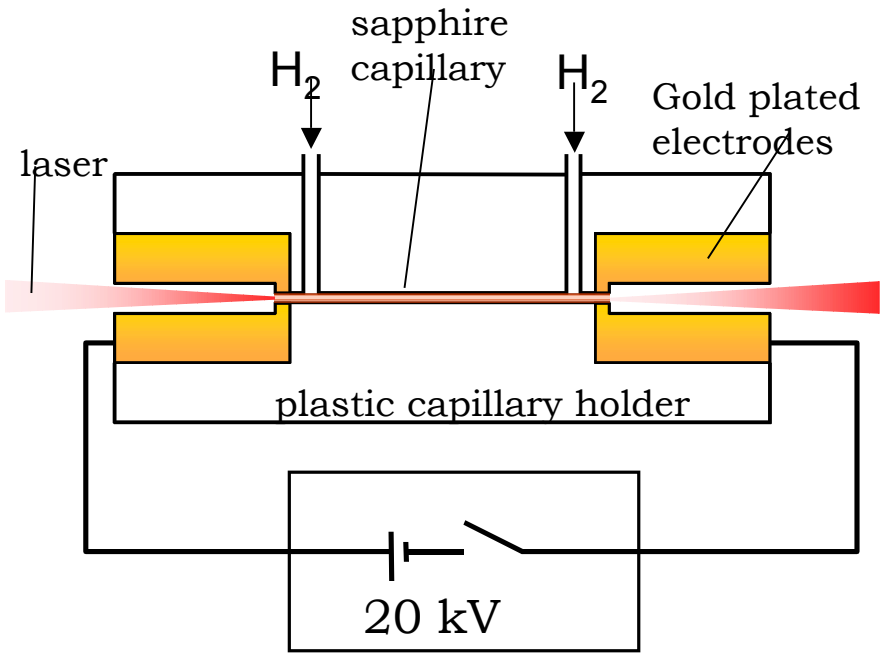
$\Delta W_d \sim 10$ GeV

W.P. Leemans et al., IEEE Trans. Plasma Science, v.24, p. 331, 1996

Relay imaged pumping of cryo-cooled amplifier system: presently 25 W, 10 Hz output



Hydrogen based discharge provides density profile suitable for guiding



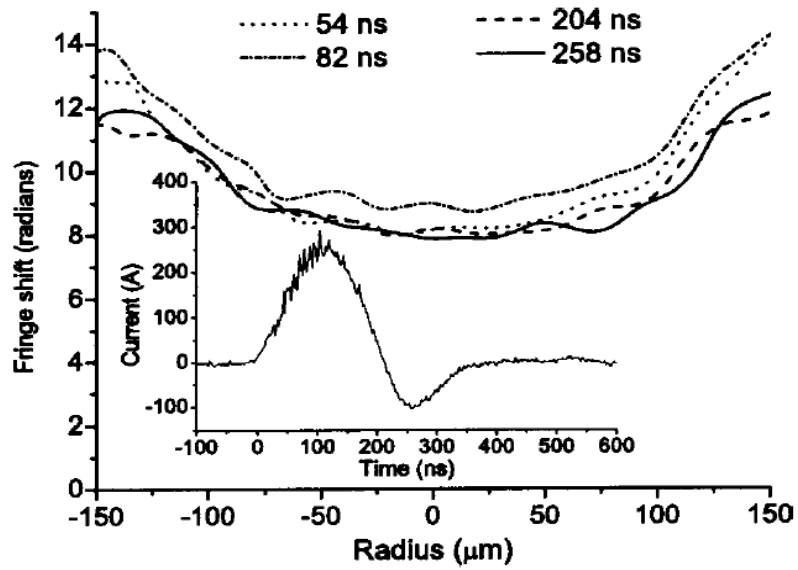
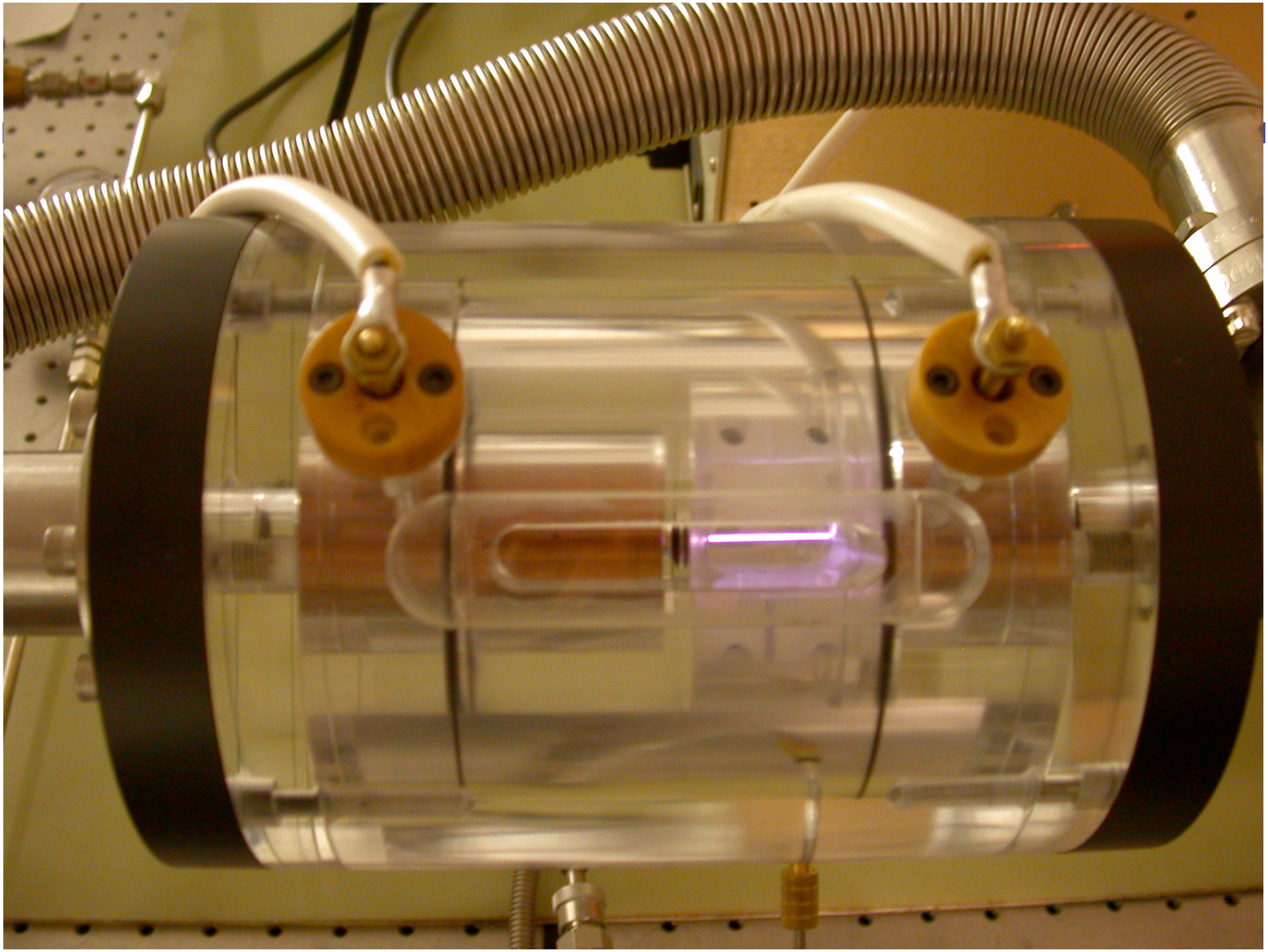


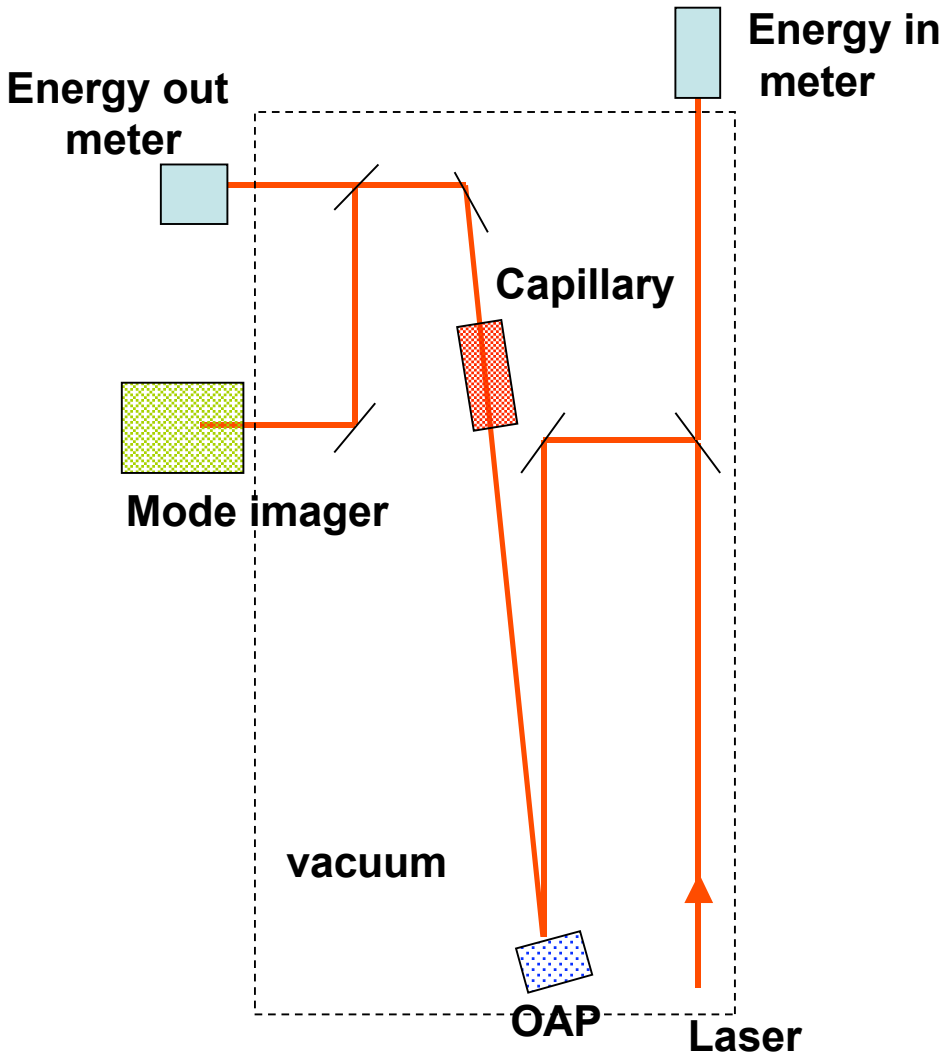
Figure taken from :
D. J. Spence, A. Butler, and S. M. Hooker, J. Opt. Soc. Am. B, **20**,p138, 2003

- Discharge allows lower density channels
- Lower density results in higher phase velocity
- Simulations indicate 3 cm, 10^{18} cm^{-3} optimal for 1 GeV



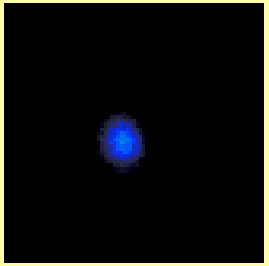
First results on guiding in capillary discharge using L'OASIS laser

- Collaboration with Oxford University and Alpha-X project

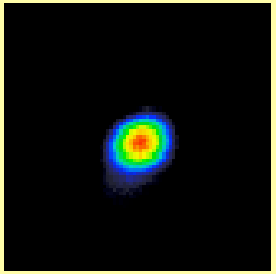


Exit of capillary

No discharge

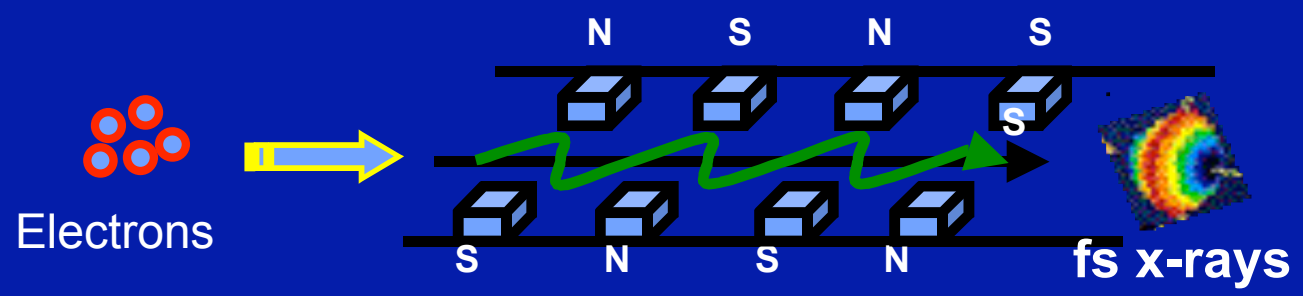


Discharge



- 0.1-0.3 TW
- 40 μm spot
- 70 % throughput

1 GeV laser accelerator will enable bright fs x-ray generation



- Channel guided LWFA with capillary:
  - GeV femtosecond beams*
  - Charge in femtosecond bunch order of 0.1-0.5 nC*
- Conventional undulator for fs x-ray generation

*A. Reitsma, Ph.D. dissertation 2002

Advanced Accelerator Facilities

:100TW, 10 Hz
:Laser driven
:Beam driven

– Beam driven: ATF-BNL, AWA-ANL, A0-FNAL, UCLA, SLAC-FFTB/NLCTA, U Tokyo, CLIC, TUE-NL

– Laser-driven ATF-BNL, UT Austin, UMaryland, NRL, UCLA-Neptune, Stanford, LBNL, RAL (UK), Strathclyde (UK), Oxford University (UK), Munich (D), Vienna (A), Lisbon (P), LOA (F)

A laser accelerator for HEP ?

- Front end injector (few GeV) : seems reachable in next 5 years
- Tool for diagnostic development and testing
- Luminosity?
- Issues:
  - Efficiency laser-> particle: 10 %
  - Wall plug -> laser: 10% diode, <1 % flash lamp
  - 1 GeV, 1 nC bunch = 1 J
  - Average laser power: < 100 W; need multi-kW…
  - Staging, stability

Summary

- Laser driven acceleration 25 year young
- New class of accelerators getting closer to reality
  - Channel guiding at relativistic intensities (up to 10^{19} W/cm^2)
  - High quality e-beams
- Next steps:
  - GeV module
  - Staging, stability, reproducibility: control !
- **Near future:** light sources based on GeV-class accelerator with fs x-ray pulses
- **Distant future:** collider physics relevant machines

Success of field intimately connected with progress in laser technology

The View that Pier is leaving behind…

Backup material