Impressions from the Dream Beams Symposium

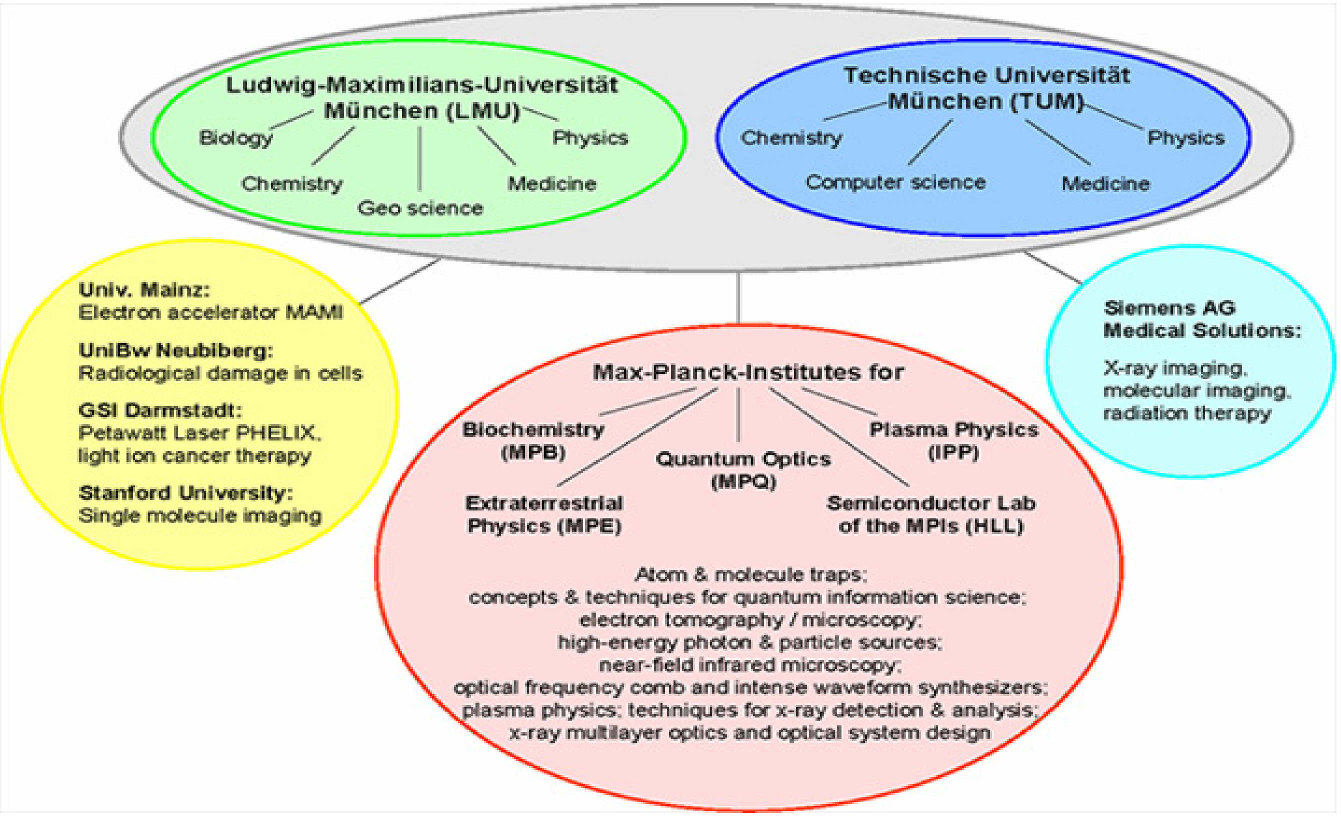
26.2-28.2

Max-Planck-Institut fuer Quantenoptik (MPQ)

Winni Decking

The Munich Center for Advanced

cs (MAP)



Ludwig-Maximilians-Universität München (LMU)
- Biology
- Chemistry
- Geo science
- Medicine
- Physics

Technische Universität München (TUM)
- Chemistry
- Computer science
- Medicine
- Physics

Univ. Mainz:
Electron accelerator MAMI

UniBw Neubiberg:
Radiological damage in cells

GSI Darmstadt:
Petawatt Laser PHELIX,
light ion cancer therapy

Stanford University:
Single molecule imaging

Max-Planck-Institutes for
- **Biochemistry (MPB)**
- **Extraterrestrial Physics (MPE)**
- **Quantum Optics (MPQ)**
- **Semiconductor Lab of the MPIs (HLL)**
- **Plasma Physics (IPP)**

Atom & molecule traps;
concepts & techniques for quantum information science;
electron tomography / microscopy;
high-energy photon & particle sources;
near-field infrared microscopy;
optical frequency comb and intense waveform synthesizers;
plasma physics; techniques for x-ray detection & analysis;
x-ray multilayer optics and optical system design

Siemens AG Medical Solutions:

X-ray imaging,
molecular imaging,
radiation therapy

MAP Research Goals

A. Photon and particle beams
  - A.1 Next-generation light sources
  - A.2Brilliant particle and photon sources

B. Fundamental interactions and quantum engineering
  - B.1Fundamental physics and nuclear transitions
  - B.2Optical transitions and quantum engineering

C. Structure and dynamics of matter
  - C.1Electron dynamics in atoms, molecules, solids and plasmas
  - C.2Molecular dynamics and elementary chemical reactions
  - C.3Biomolecules and nano-assemblies

D. Advanced photonics for medicine
  - D.1Laser-based photon and particle beams for medicine

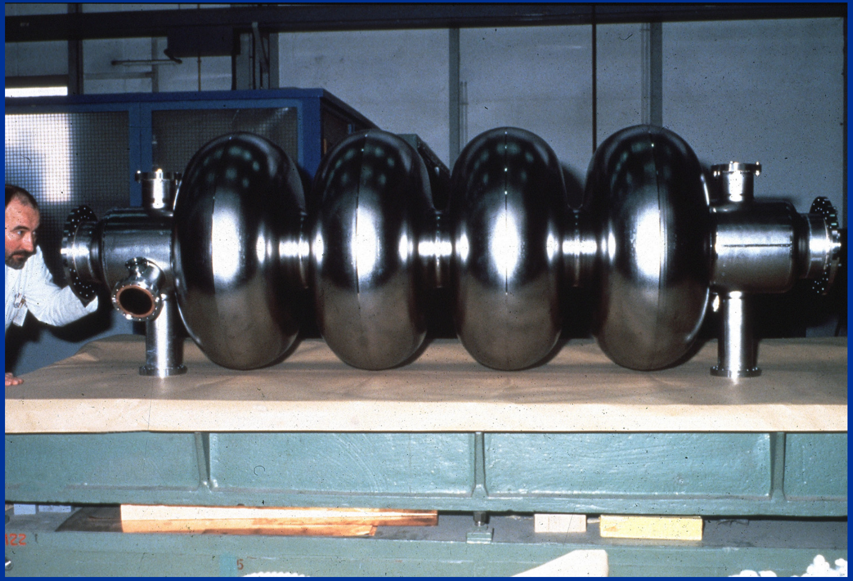
Dream Beams Symposium - Program

Dream Beams Symposium, MPQ Garching, programme

Sunday, Feb. 25	Monday, Feb. 26	Tuesday, Feb. 27	Wednesday, Feb. 28
	9:00 Krausz / Meyer-ter-Vehn (MPQ): Welcome, Dream Beams (?)	9:00 Zepf (Queens Uni. Belfast): KeV surface harmonics	9:00 Sentoku (UNR Reno): Advanced Particle-in-Cell simulation for high energy density physics
	9:45 Malka (LOA Paris): Experimental demonstration of controlled electron injection	9:45 Esarey (LBNL Berkeley): GeV electrons from guided acceleration	9:45 Hajdu (Uni. Uppsala): Beams needed for biomolecule imaging
	10:30 Coffee	10:30 Coffee	10:30 Coffee
	11:00 Bulanov (JAERI Kyoto): Prospects and limits of laser particle acceleration	11:00 Pukhov (Uni. Düsseldorf): Theory and simulations of relativistic laser plasmas	11:00 Grüner (LMU Munich): Laser-driven Table-Top FEL
	11:45 Wei Lu (UCLA): possible path towards a 100 gev lwfa stage	11:45 Geissler (MPQ): Simulating electron acceleration in channels	11:45 Habs (LMU München): MAP Dream Beams: From probing the vacuum to medical applications
	12:15 Kemp (LLNL) Collisional Relaxation of Super Thermal Electrons in Dense Plasma	12:15 Karsch (MPQ): First MPQ channel electrons and PW-Field-Synthesizer(PFS) project	
	Lunch at IPP Cafeteria	Lunch at IPP Cafeteria	Lunch at IPP cafeteria
	14:00 Mendonca (IST, Lisbon): Non-linear relativistic optics	14:00 Tour MPQ	14:00 Meseck (BESSY Berlin) Seeding of FELs with Higher Harmonics
	14:30 Gibbon (KFZ Jülich): Mesh-free particle simulation		14:30 Jentschura (MPK Heidelberg): QED, nuclear and high-energy processes
	15:00 Schroeder (LBNL Berkeley): THz and fs x-ray pulses	15:00 Silva (IST Lisbon): Control of the explosions of nanoplasmas	15:00 Schützhold (Uni. Dresden): Conditions for detecting Unruh radiation
	15:30 coffee	15:30 Mora (CPhT, EP, Palaiseau): Theory of ion acceleration by lasers	15:30 coffee
	16:00 Sheng (CAS Beijing): THz radiation and mono-energetic electrons from surface acceleration	16:00 coffee	16:00 Baeva (Uni. Düsweldorf): Theory of surface harmonics
	16:30 Kostyukov (RAS): Radiative processes in plasma-based accelerators in ultrahigh energy regime	16:30 Ruhl (Uni. Bochum): Advanced PIC Simulations: Energy deposition, target heating and ionization	16:30 Rykovanov (MPQ): Simulation of surface harmonics
ARRIVAL, transfer to Hotel Maria Garching	17:00 Leaving for Munich	17:00 Lefebvre (CEA, Bruyeres-le-Chatel): Scaling of laser driven proton acceleration	17:00 end
		17:30 Schwoerer (Uni Jena): Acceleration of narrow band protons with lasers	
	18:00 Visit at Arnold-Sommerfeld-Center (ASC)	18:00 Bavarian Buffet at MPQ	
19:00 Gasthof Neuwirt in Garching, Welcome	19:00 Dinner in Munich near ASC	19:00 Posters, Discussion Time	talks: 30 (+15) min and 20 (+10) min

Classical accelerator limitations

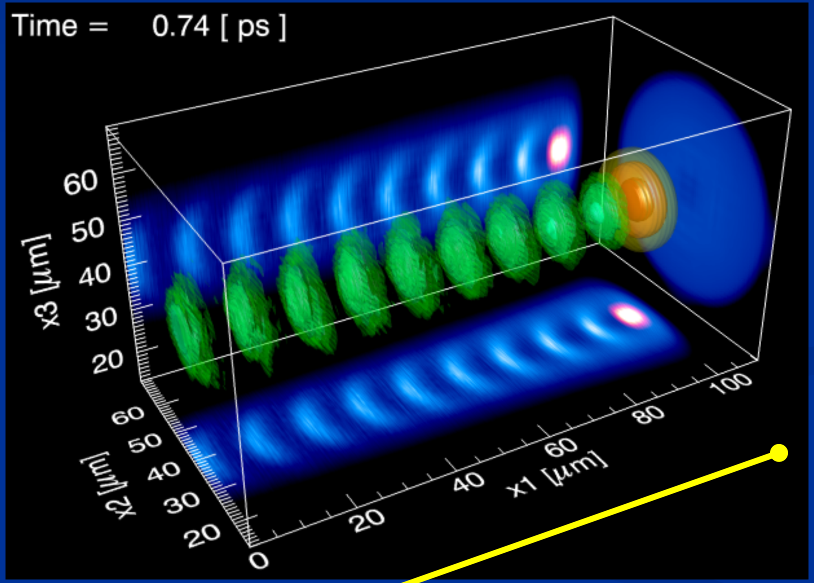
E-field$_{max}$ $\approx$ few 10 MeV /meter (Breakdown)
$R > R_{min}$ Synchrotron radiation



1 m

RF cavity

Courtesy of W. Mori & L. da Silva



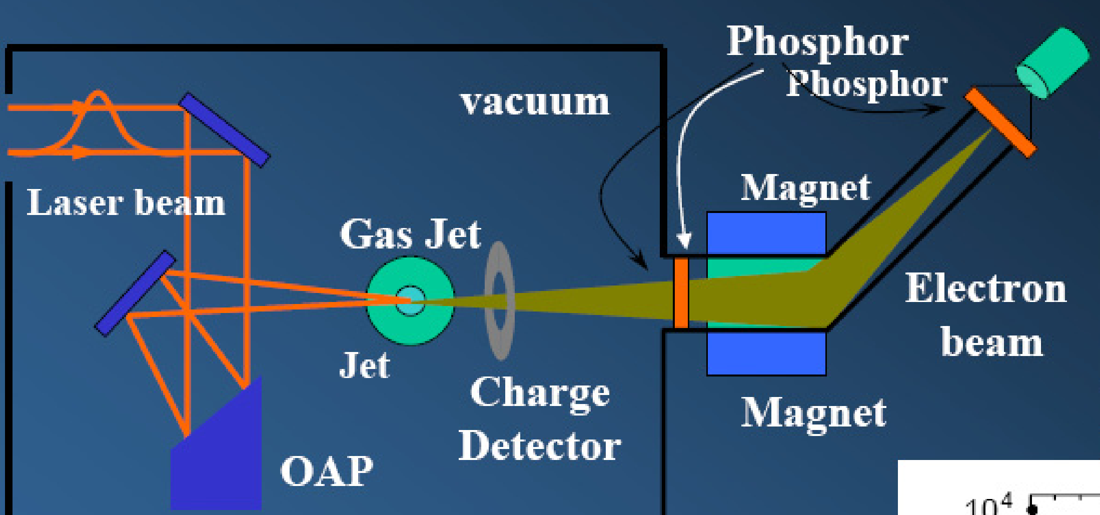
100 µm

Plasma cavity

Courtesy of V. Malka (LOA)

Mid 90's -2003: lasers generate electron beams with 100 % energy spread

Courtesy of W. Leemans (LBL)

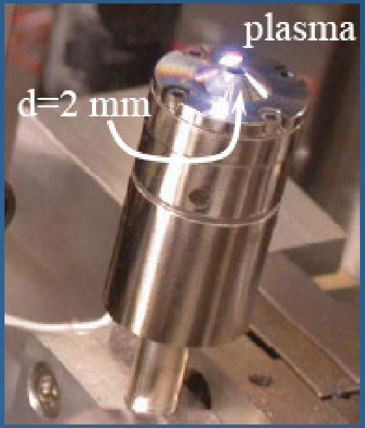


Ebeams:

1-100 MeV, nC

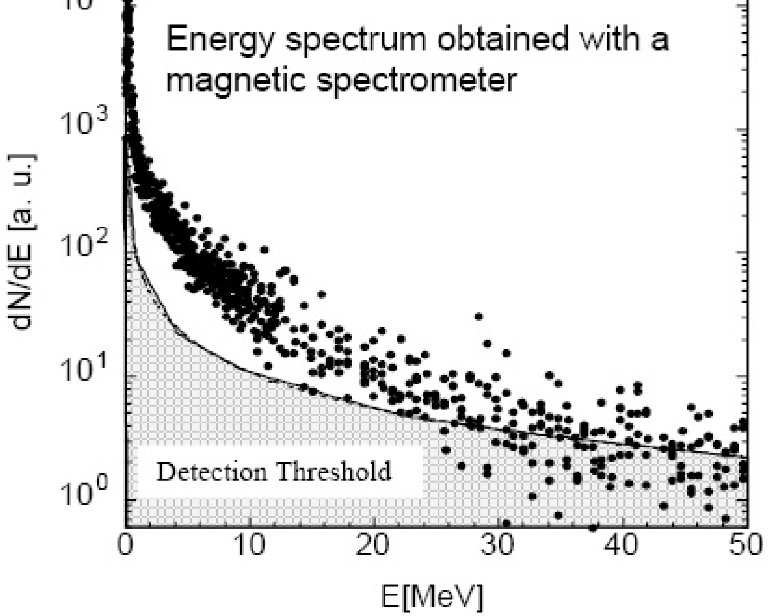
<100 fs,

~10-100 mrad divergence

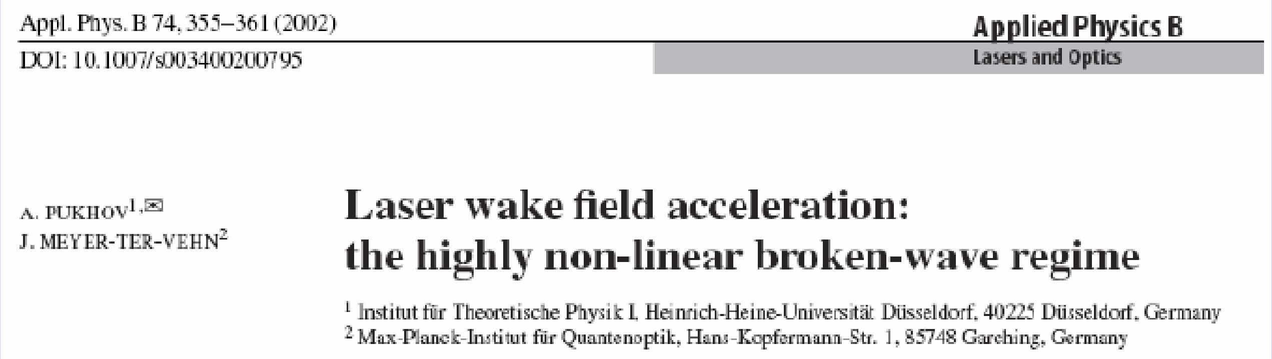


Modena *et al.* (95); Nakajima *et al.* (95); Umstadter *et al.* (96); Ting *et al.* (97); Gahn *et al.* (99); Leemans *et al.* (01); Malka *et al.* (02)

e-beam spectrum



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



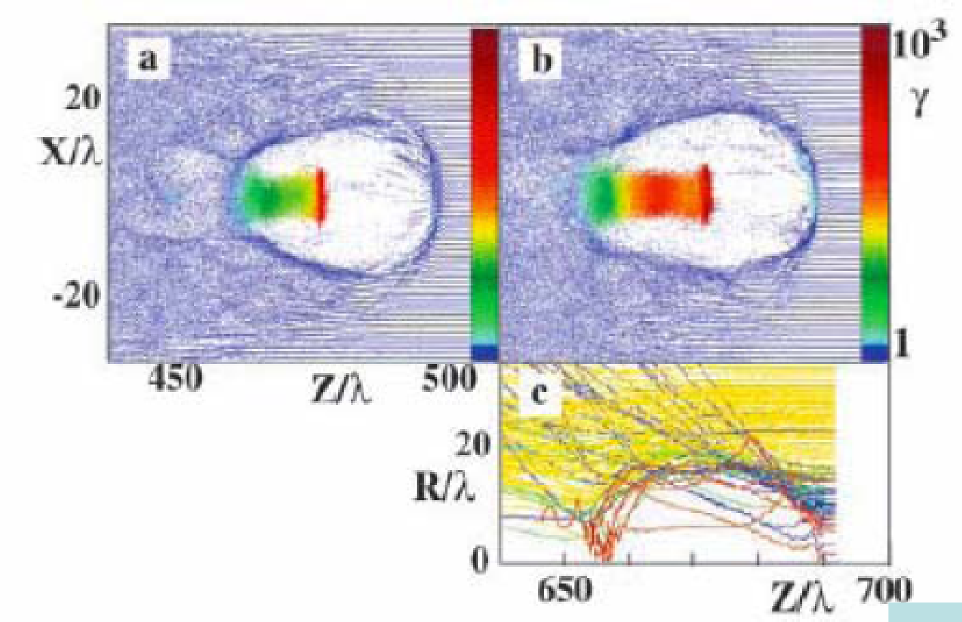
Appl. Phys. B 74, 355–361 (2002)
DOI: 10.1007/s003400200795

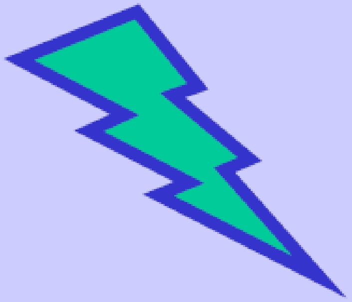
Applied Physics B
Lasers and Optics

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





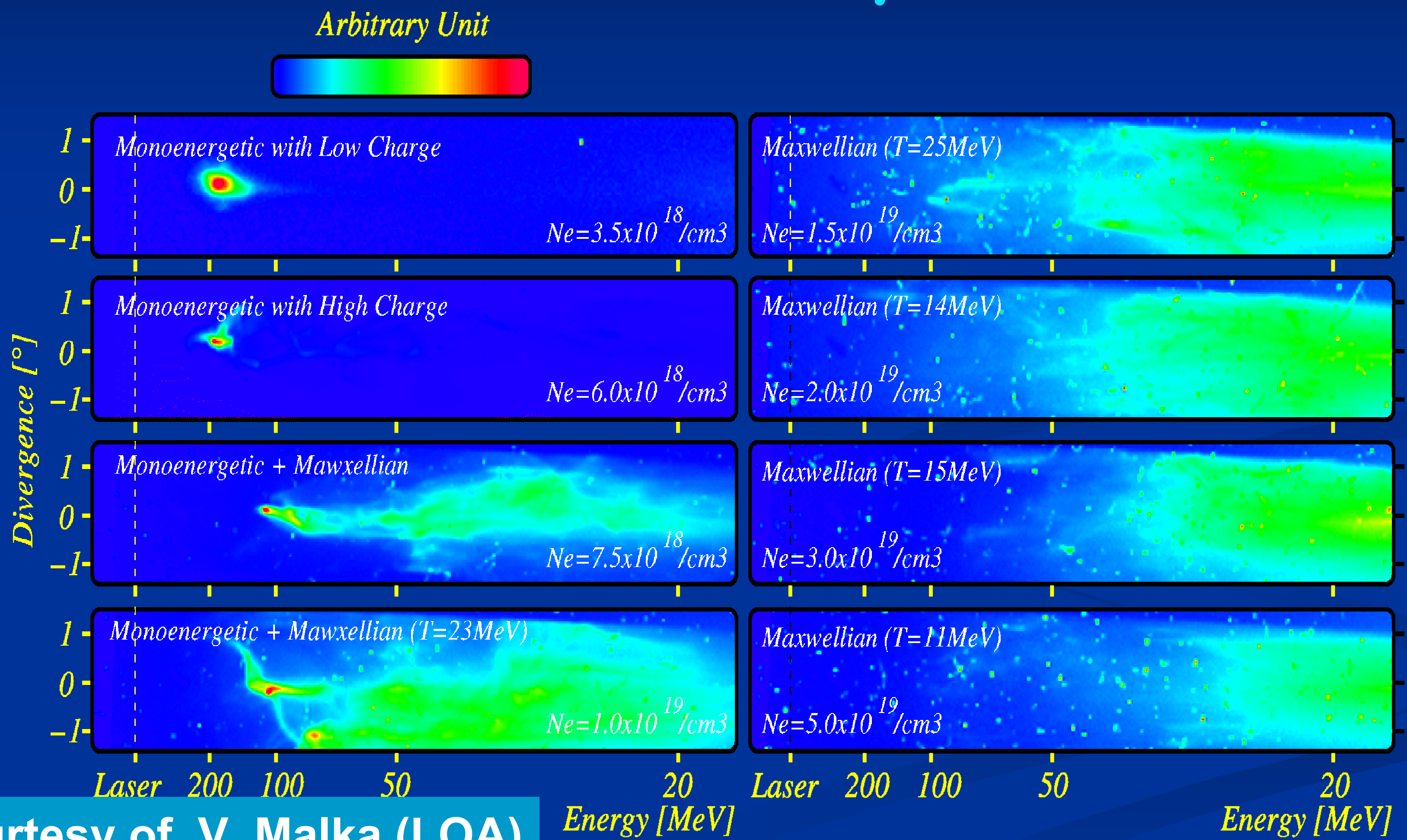
12 J, 33 fs pulse

Courtesy of W. Leemans (LBL)

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

Recent results on e-beam : From maxwellian to mono spectra

Electron density scan



Courtesy of V. Malka (LOA)

V. Malka, et al., PoP 2005

LOA

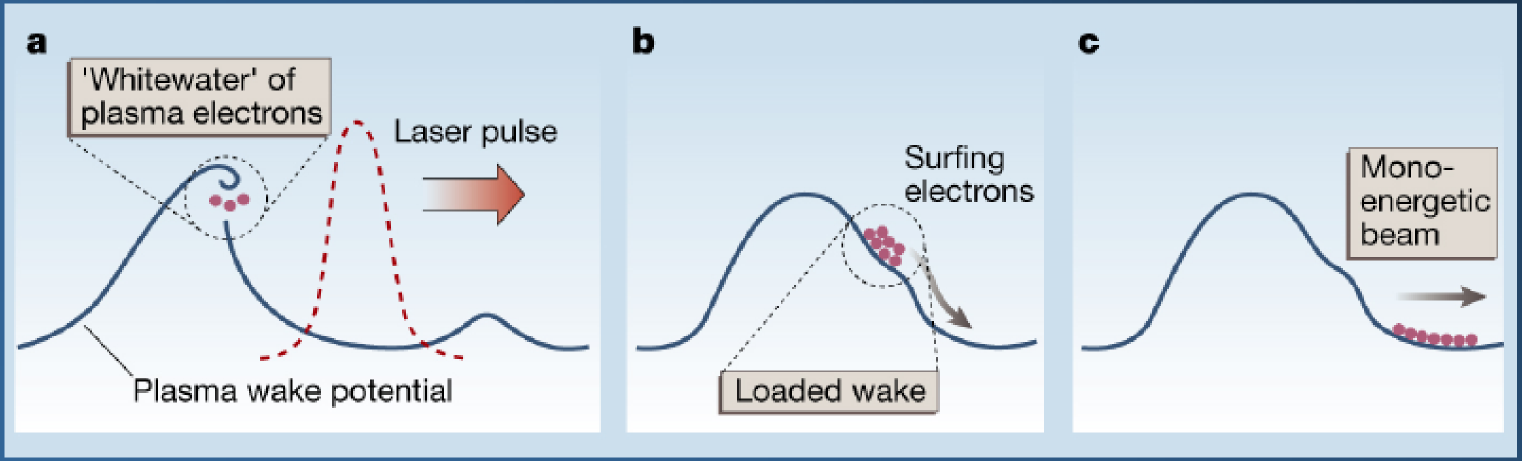
Recipe for a Monoenergetic Beam

a. Excitation of wake (self-modulation of laser)
   Onset of self-trapping (wavebreaking)

b. Termination of trapping (beam loading)
   Acceleration

c. Dephasing
   - If L > or < dephasing length: large energy spread
   - If L ~ dephasing length: monoenergetic

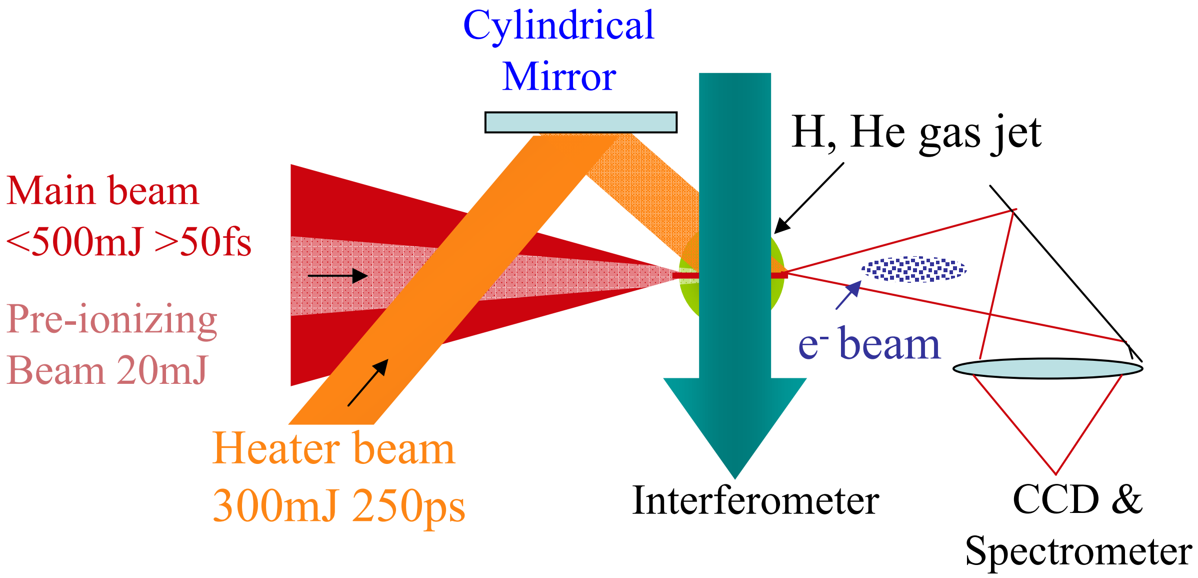
**Courtesy of
W. Leemans (LBL)**

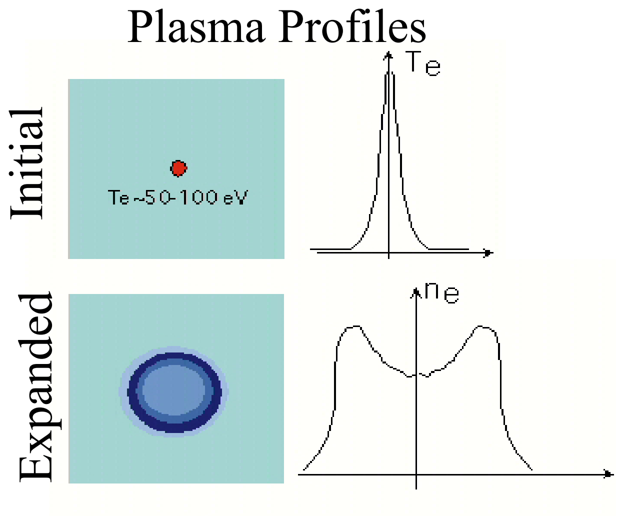


T. Katsouleas, Nature 2004

Plasma channel production: ignitor-heater method

- Two step process for channel formation (in H_2 gas jet) :
  1. Ionization: co-linear ultrashort ‘ignitor’ pulse (I > 10^{14} W/cm^2)
  2. Inverse Bremsstrahlung heating: 250 ps ‘heater’ pulse with I ~ 10^{13}W/cm^2
- Shock formation leads to on-axis density depletion on axis



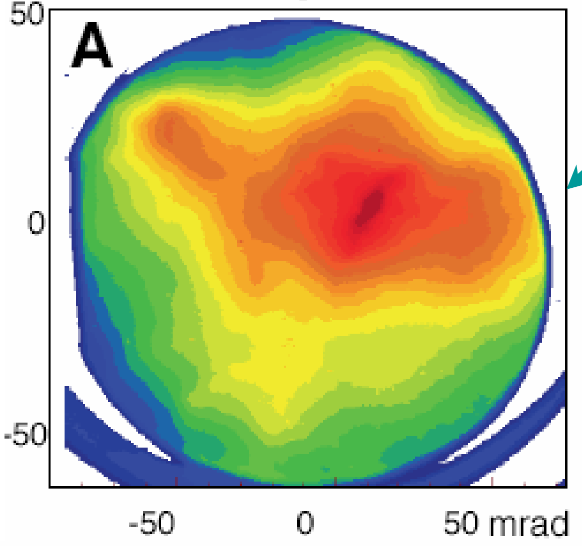

Plasma Profiles

P. Volfbeyn, et al., Phys. Plasmas (1999)

**Courtesy of
E. Esarey (LBL)**

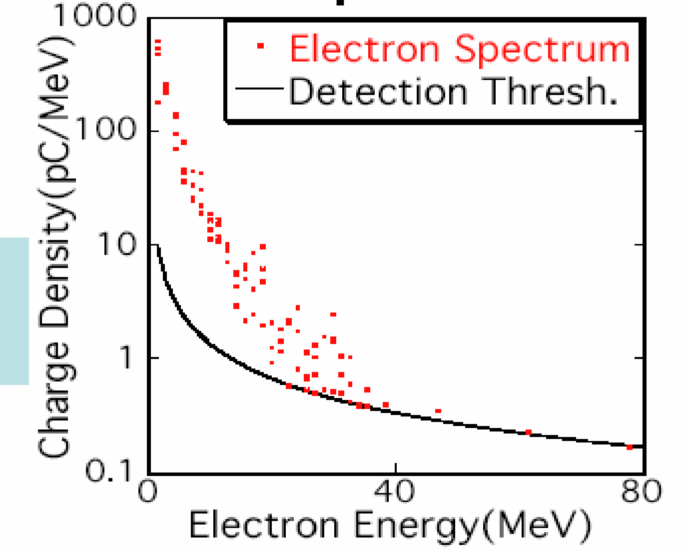
86 MeV electron beam with %-level energy spread

Beam profile



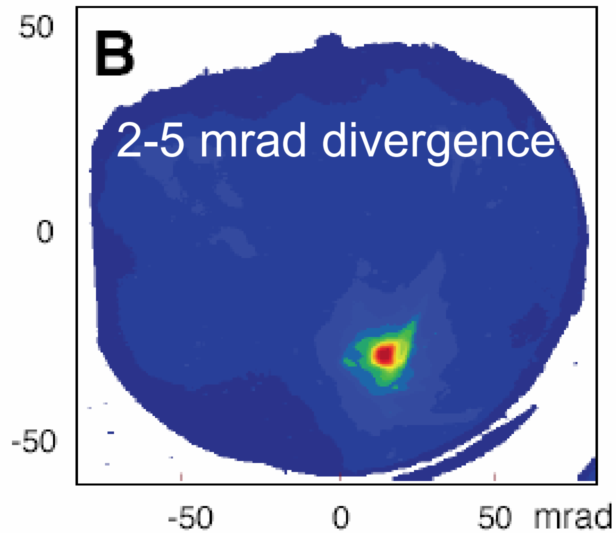
Unguided

Spectrum

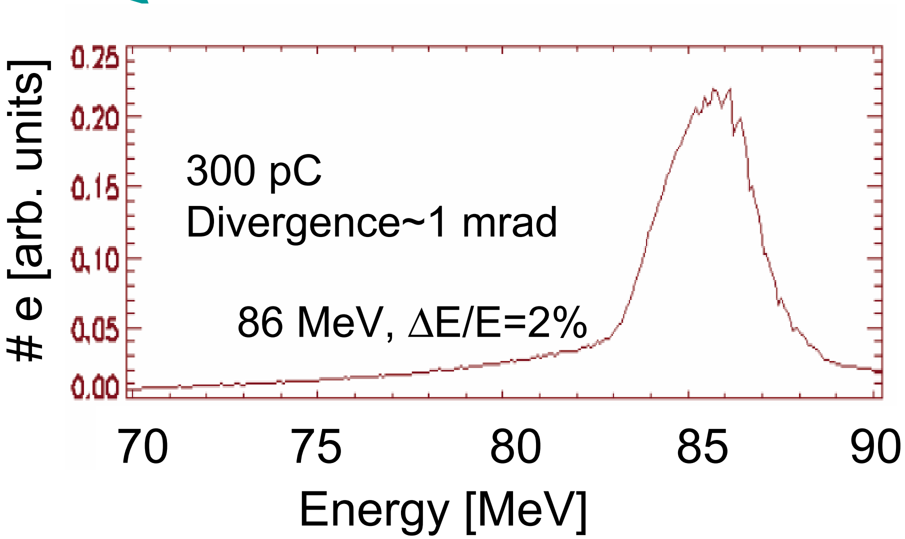


Courtesy of
E. Esarey (LBL)

Guided



9 TW
50 fs
2e19 cm^{-3}
300 pC
3 mrad
ΔE < 4 MeV



C.G.R Geddes *et al*, Nature, Sept 30 2004

2004 Results: High-Quality Bunches

- **Approach 1: bigger spot**
  - RAL/IC$^+$ (12.5 TW -> ~20 pC, 80 MeV)
  - LOA$^\wedge$ (33 TW -> ~500 pC, 170 MeV)
  - **For GeV -> 1 PW class laser**
- **Approach 2: preformed channel guided**
  - LBNL* (9TW, 2mm channel -> ~300 pC, 86 MeV)
  - **For GeV -> ~10-50 TW class laser$^\$$, longer guiding structure**

30 September 2004

International weekly journal of science

nature

$10.00

www.nature.com/nature

Dream beam

The dawn of compact particle accelerators

Offshore tuna ranches
A threat to US waters?

The Earth's hum
Sounds of air and sea

Protein folding
Escape from the ribosome

Human ancestry
One from all and all from one

technology feature RNA interference

Courtesy of W. Leemans (LBL)

$^+$S. Mangles et al, *Nature* **431**(2004) 535; ^J. Faure et al, *Nature* **431**(2004) 541
*C.G.R. Geddes et al, *Nature* **431** (2004) 538; $^\$$W.P. Leemans et al, *IEEE Trans. Plasmas* Sci. **24** (1996) 331.

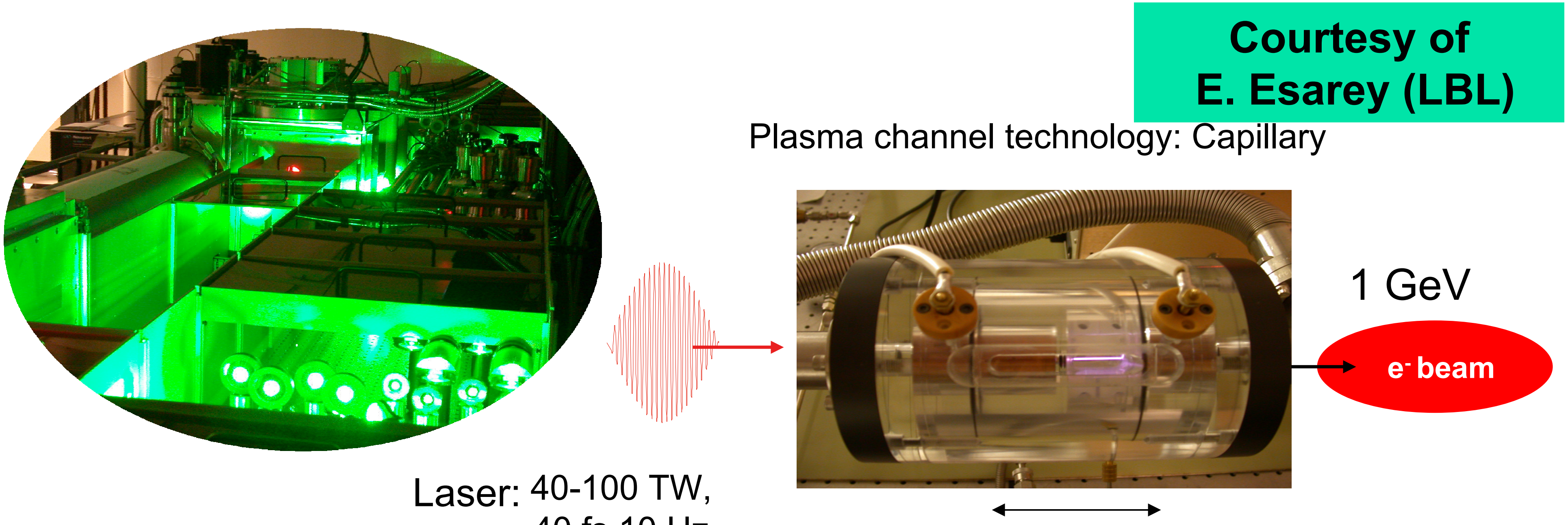
GeV: channeling over cm-scale

- Increasing beam energy requires increased dephasing length and power:

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

- Scalings indicate cm-scale channel at ~ 10^{18} cm^{-3} and ~50 TW laser for GeV
- Laser heated plasma channel formation is inefficient at low density
- Use capillary plasma channels for cm-scale, low density plasma channels

Courtesy of
E. Esarey (LBL)



Plasma channel technology: Capillary

1 GeV

e^- beam

Laser: 40-100 TW,
40 fs 10 Hz

3 cm

0.5 GeV Beam Generation

Courtesy of
E. Esarey (LBL)

225 μm diameter and 33 mm length capillary

Density: 3.2-3.8x10^{18}/cm^3

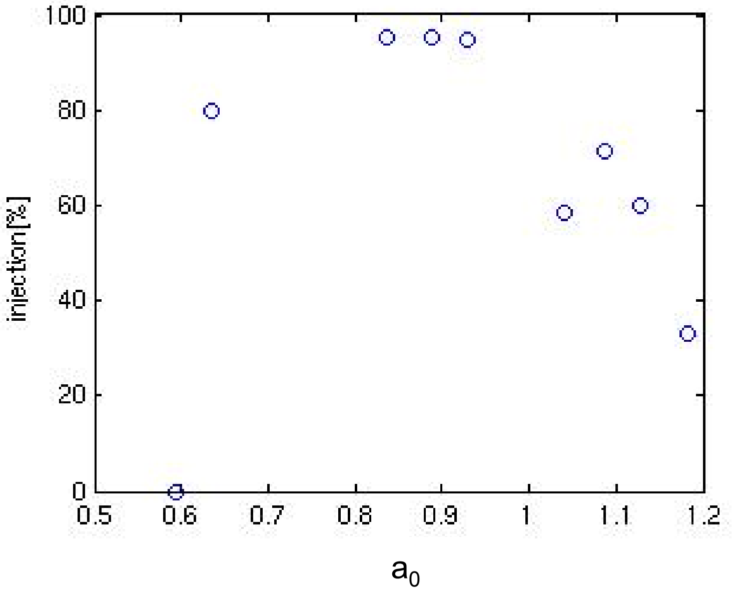
Laser: 950(±15%) mJ/pulse (compression scan)

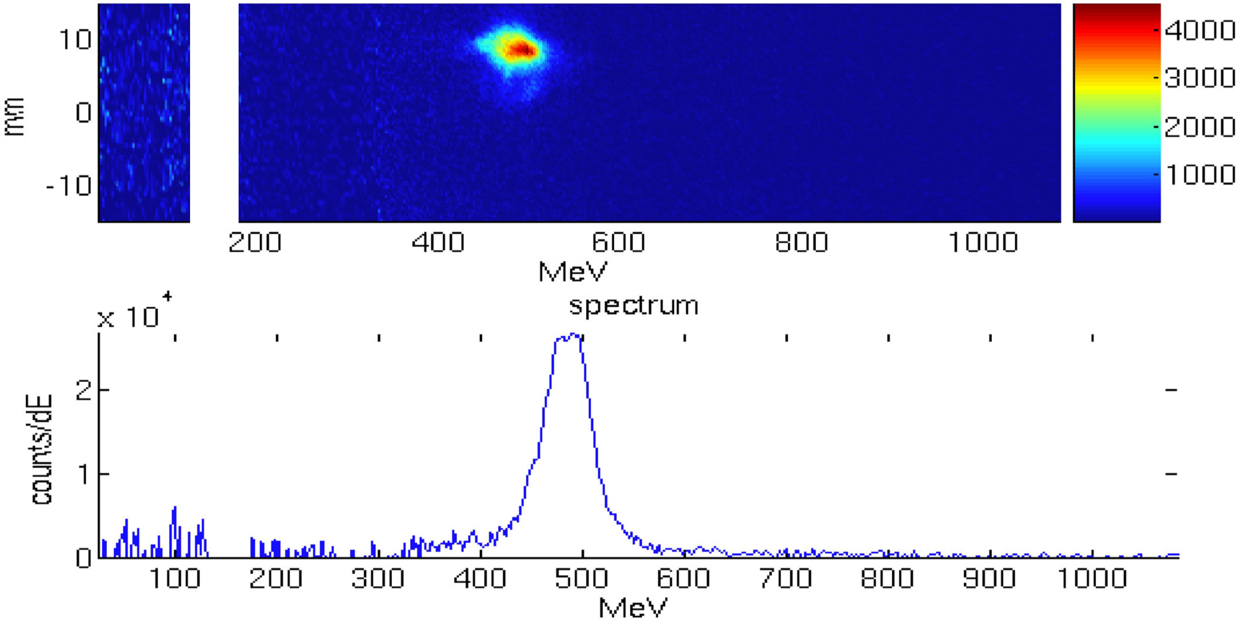
Injection threshold: a_0 ~ 0.65 (~9TW, 105fs)

Less injection at higher power

-Relativistic effects

-Self modulation





Stable operation

500 MeV Mono-energetic beams:

a_0 ~ 0.75 (11 TW, 75 fs)

Peak energy: 490 MeV
Divergence(rms): 1.6 mrad
Energy spread (rms): 5.6%
Resolution: 1.1%
Charge: ~50 pC

1.0 GeV Beam Generation

Courtesy of
E. Esarey (LBL)

312 μm diameter and 33 mm length capillary

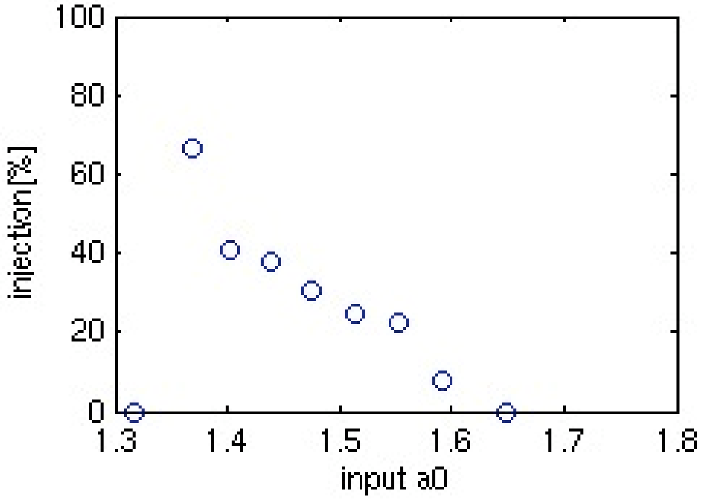
Laser: 1500(±15%) mJ/pulse

Density: $4 \times 10^{18}/cm^3$

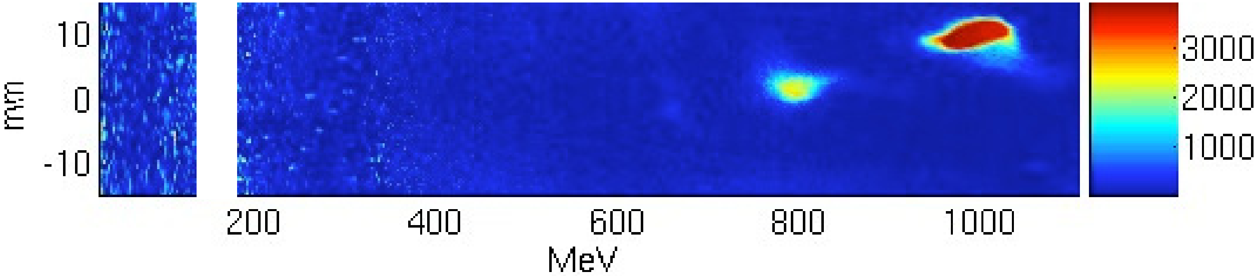
Injection threshold: a_0 ~ 1.35 (~35TW, 38fs)

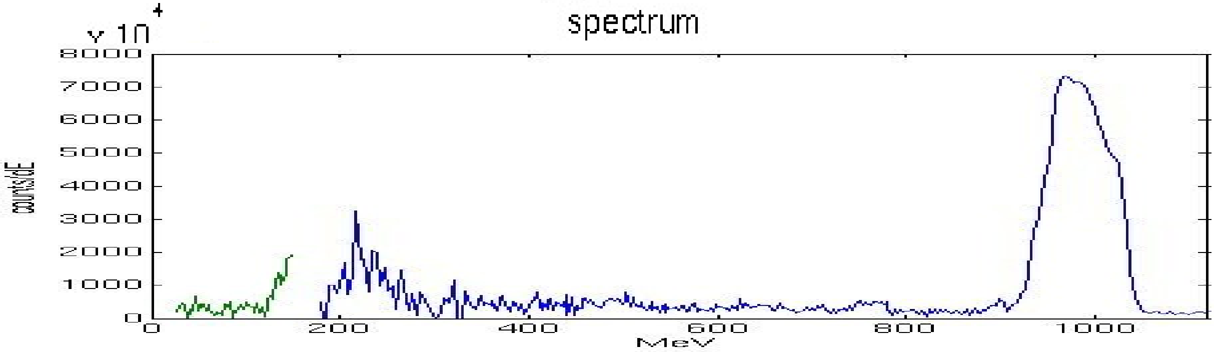
Less injection at higher power

Relativistic effect, self-modulation



1 GeV beam: a_0 ~ 1.46 (40 TW, 37 fs)





Peak energy: 1000 MeV
Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%
Charge: > 30.0 pC

Less stable operation

Laser power fluctuation, discharge timing, pointing stability

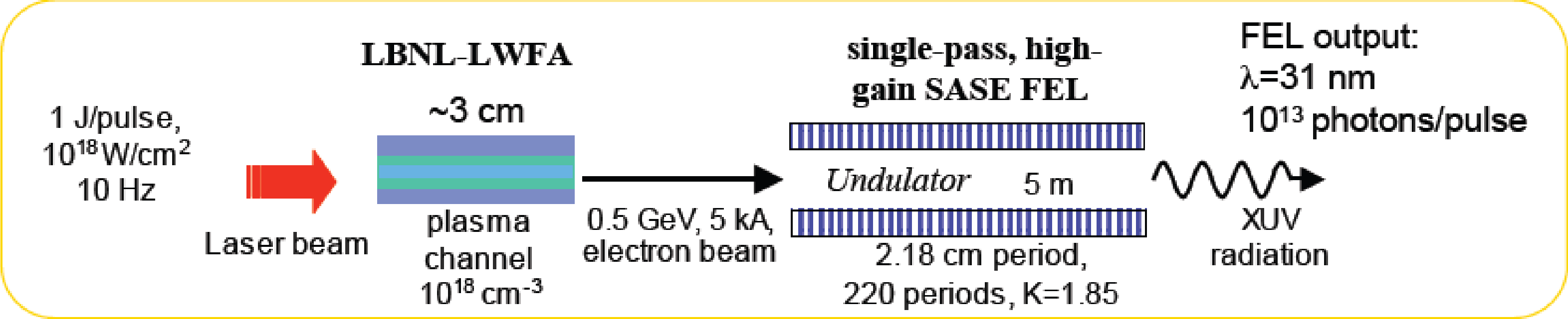
Laser wakefield accelerator (LWFA)-driven FEL

High-gain FEL natural application for LWFA (ultra-short, high peak current) beams

[F. Grüner et al., Appl. Phys. B (2007); D. Jaroszynski et al., Philos. Trans. R. Soc., Ser. A (2006)]

Schematic of LBNL LWFA-driven FEL:

C. B. Schroeder et al., in Proc. of FEL06 (www.jacow.org/) (2006).



1 J/pulse,
10^{18} W/cm^2
10 Hz

Laser beam

LBNL-LWFA

~3 cm

plasma
channel
10^{18} cm^{-3}

0.5 GeV, 5 kA,
electron beam

single-pass, high-gain SASE FEL

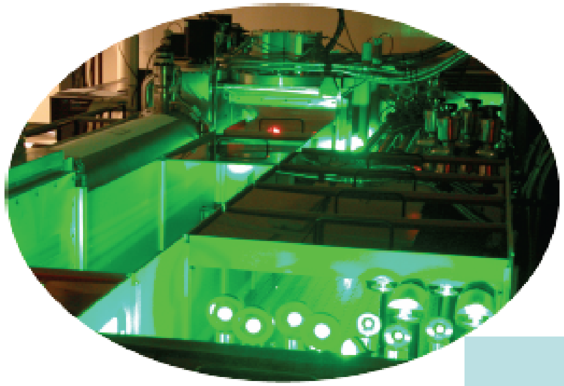
Undulator 5 m

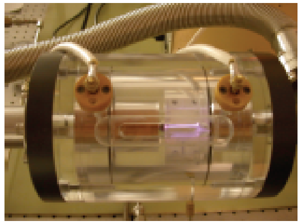
2.18 cm period,
220 periods, K=1.85

FEL output:
λ=31 nm
10^{13} photons/pulse

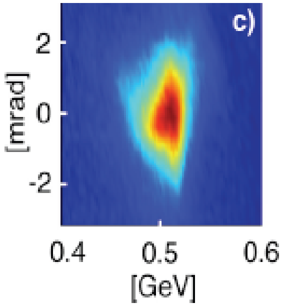
XUV
radiation

LBNL laser system





Plasma capillary technology



Stable 0.5 GeV beams demonstrated

conventional undulator

K. Robinson et al., IEEE QE (1987)

**Courtesy of
C. Schroeder (LBL)**

HHG-seeded LWFA-driven FEL

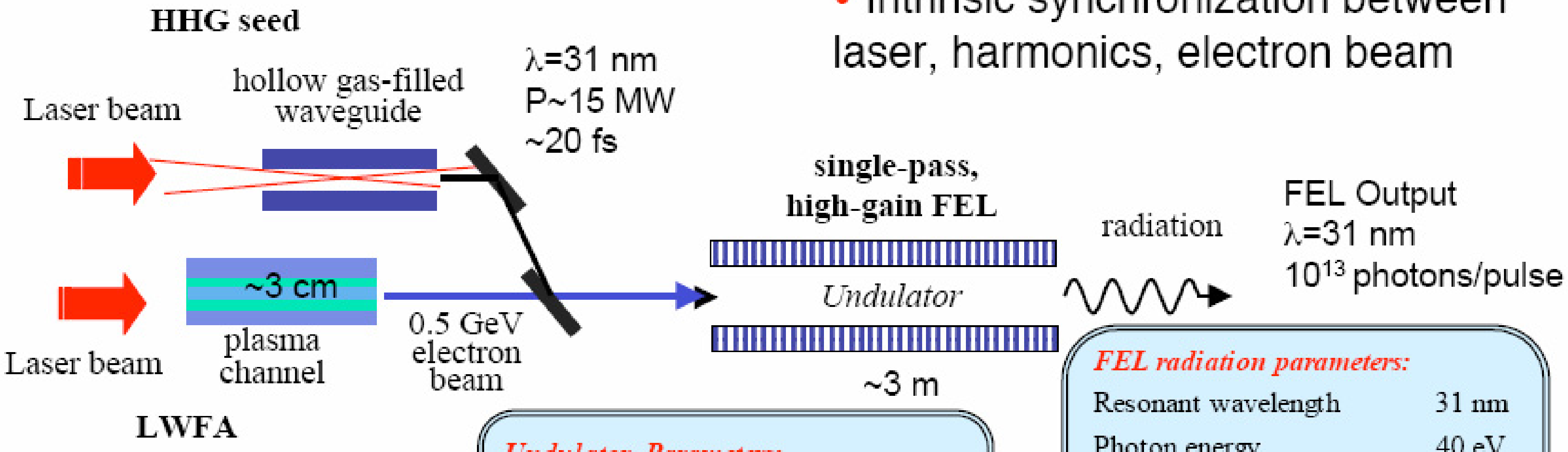
Courtesy of
C. Schroeder (LBL)

Schematic of HHG-seeded, LWFA-driven FEL:

[C.B.Schroeder et al., in Proc. of FEL06 (2006).]

HHG[*] *seed:*	
Harmonic wavelength	31 nm
Power	15 MW
Duration, FWHM	20 fs

- Reduced undulator length
- Reduced power fluctuations
- Improved coherence
- Intrinsic synchronization between laser, harmonics, electron beam



HHG seed

Laser beam

hollow gas-filled waveguide

λ=31 nm
P~15 MW
~20 fs

Laser beam

~3 cm

plasma channel

0.5 GeV electron beam

LWFA

single-pass, high-gain FEL

Undulator

~3 m

radiation

FEL Output
λ=31 nm
10^{13} photons/pulse

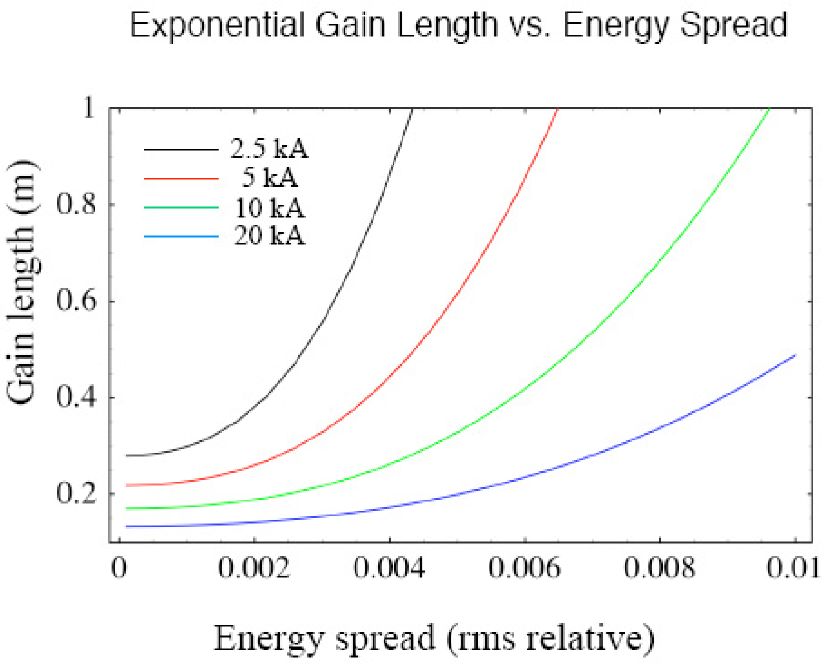
LWFA Electron Beam:	
Beam Energy	0.5 GeV
Peak current	5 kA
Charge	0.1 nC
Bunch duration, FWHM	20 fs
Energy spread (slice)	0.25 %
Norm. Emittance	1 mm-mrad

Undulator Parameters:	
Undulator type	planar
Undulator period	2.18 cm
Number of periods	220
Peak Field	1.02 T
Undulator parameter, K	1.85
Beta function	3.6 m

FEL radiation parameters:	
Resonant wavelength	31 nm
Photon energy	40 eV
FEL parameter	5×10^{-3}
1D Gain length	0.19 m
3D Gain length	0.31 m
Steady-state sat. power	12 GW
Spontaneous rad. Power	4 kW
Slippage length	7 μm

[*] E. Takahashi et al., Phys. Rev. E 66, 021802 (2002).

Gain length vs. energy spread



$L_g < 0.5$ m requires $\sigma_\gamma/\gamma < 0.45\% \times (I/5\ \mathrm{kA})^{2/3}$

for parameters:

ε_N =1 mm-mrad

E=0.5 GeV

λ_u=2.18 cm

K=1.85

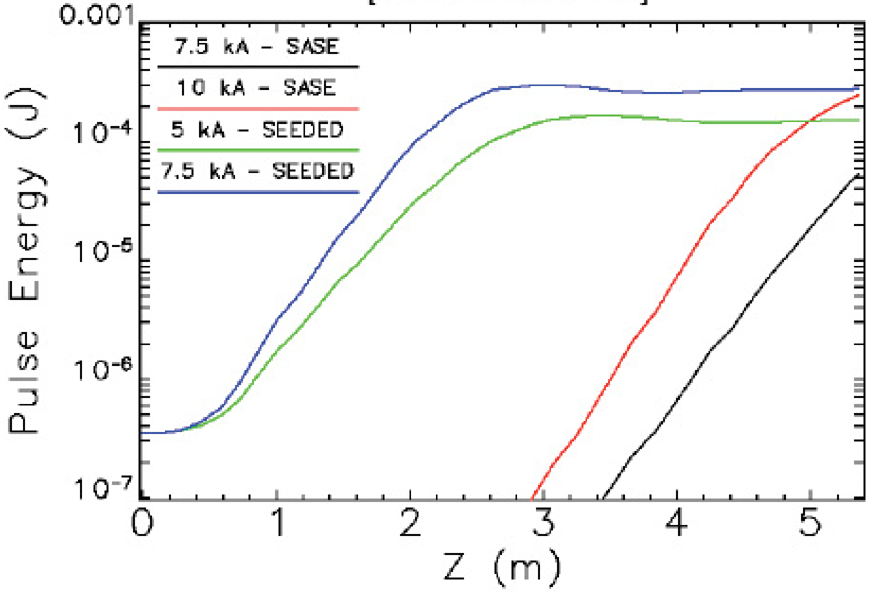
β=3.6 m

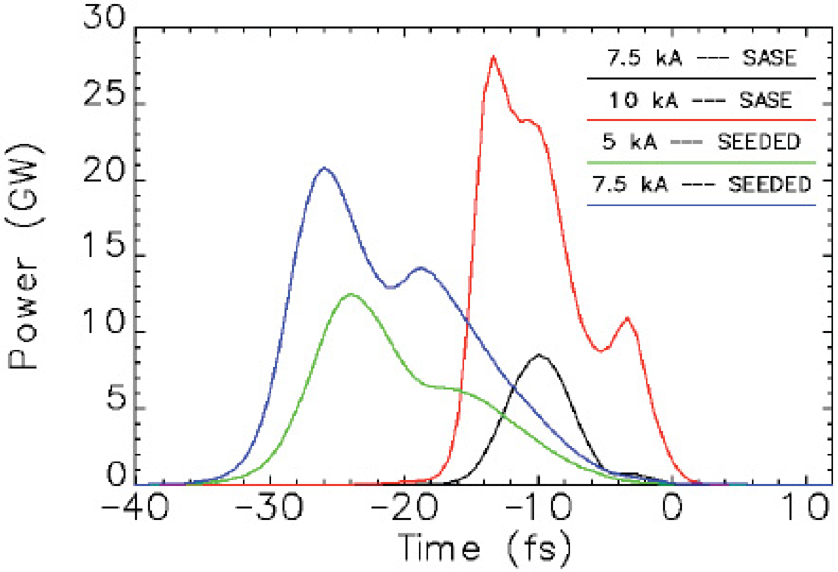
Courtesy of C. Schroeder (LBL)

Courtesy of C. Schroeder (LBL)

FEL Radiation Charateristics

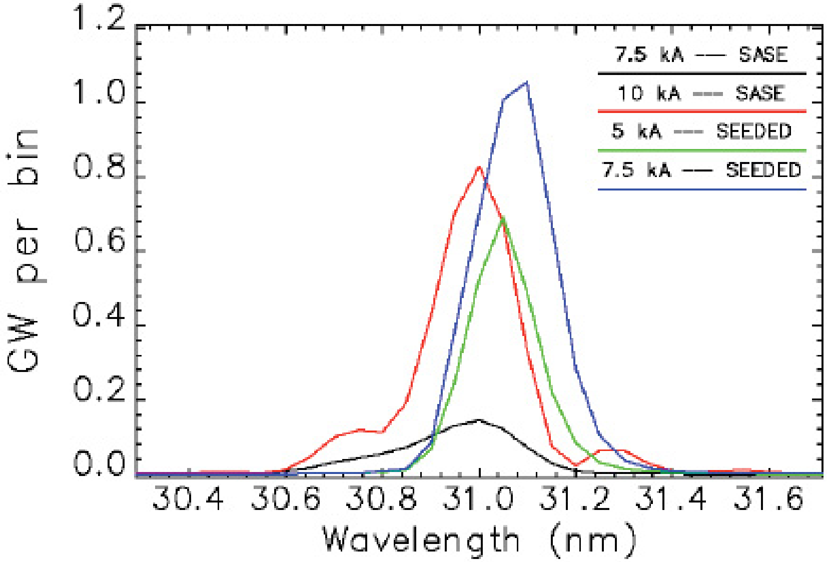
[GINGER[*] calculation]





5-kA seeded GINGER Results:

Photons/pulse	3×10^{13}
RMS Norm.Inverse Bandwidth	500
Peak Brightness (photons/pulse/mm^2/mrad^2/0.1% BW)	6×10^{16}
Output Divergence Angle	72 μrad
3rd Harmonic Power/Fundamental	0.4%



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[*] W.M.Fawley, LBNL Tech. Report No. LBNL-49625 (2002)

Why XFELs?

- time scale of chemical reactions: fs
- X-ray: wavelength of atomic scale
- fs-X-ray pulse → “4D imaging with atomic resolution”

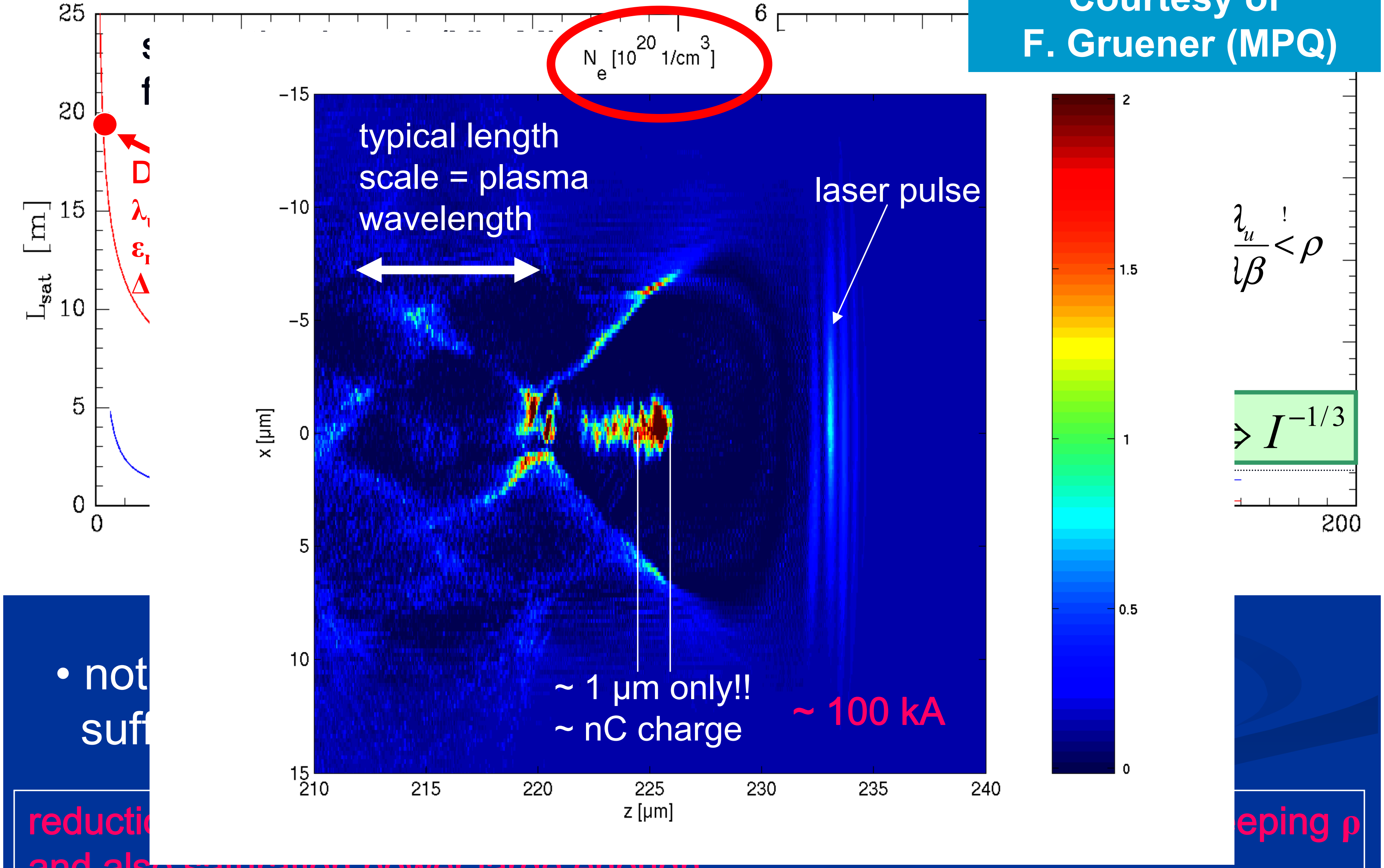
- **single molecule imaging → ultrahigh brilliance!**

- medical application for table-top XFEL: SAXS, PCI
  → direct cancer diagnostics

Courtesy of
F. Gruener (MPQ)

Constraints for *table-top* FELs

Courtesy of F. Gruener (MPQ)



- not suff

reducti... eping ρ and also saturation power large enough

Demands on “Bubble Physics”

- we need new ideas for reaching the demanding parameters
  - proof-of-principle cases relaxed
  - TT-XFEL for 5 keV
  - med-XFEL for 50 keV:
    ~7 GeV electrons, 0.1% energy spread,
    ≤ 0.5 mm·mrad norm. emittance, ≥ 1 nC charge

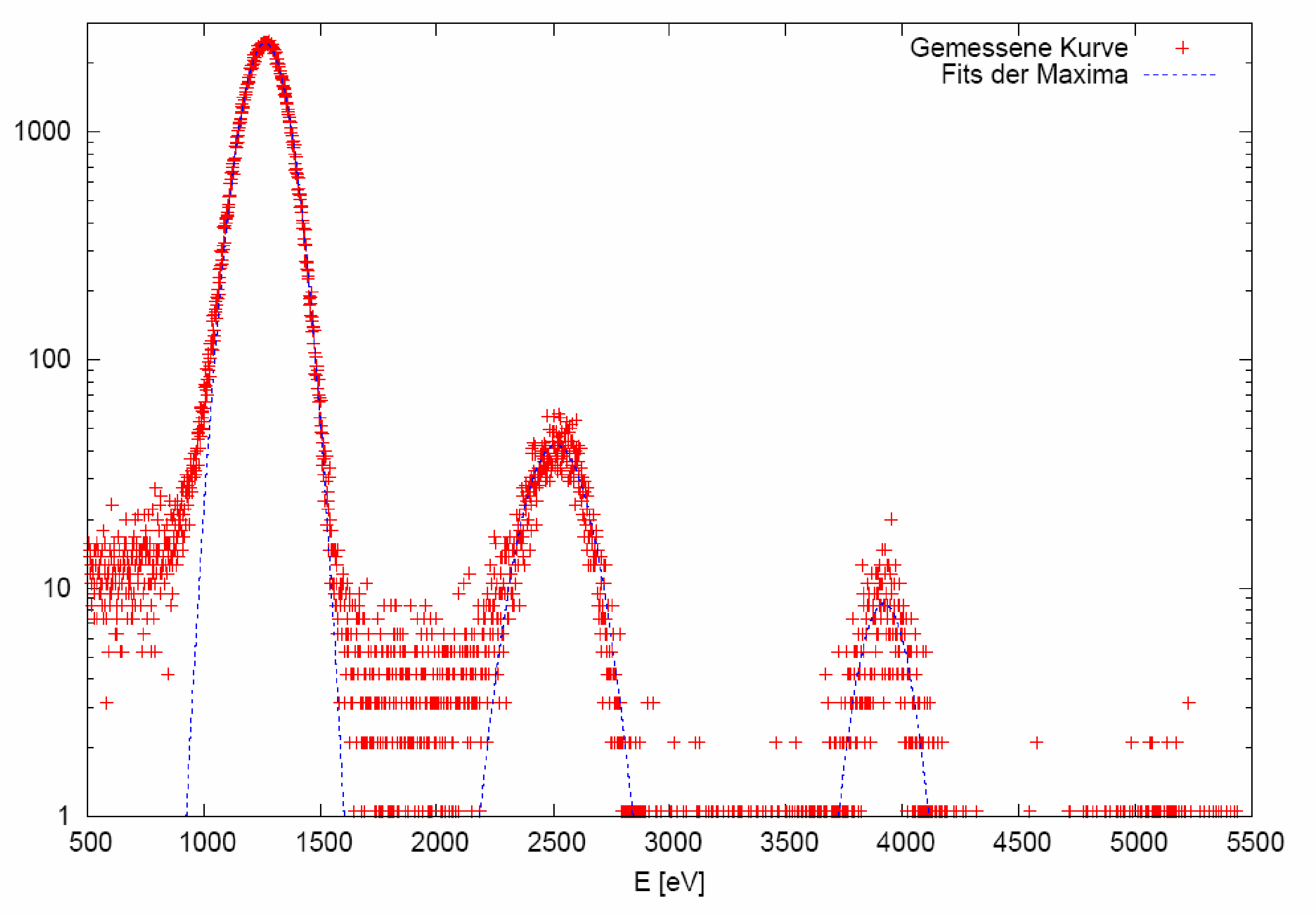
- we need models/designs for capillary scenarios:
  - bubble to blowout transition?
  - density gradients?
  - staged capillaries?

- we need understanding of the amount of energy spread, emittance
  - make use of dephasing?
  - is absolute energy spread frozen after injection?
  - emittance reduction?

Courtesy of
F. Gruener (MPQ)

Experimental Status

- undulator: hybrid, 5 mm period, 0.9 T peak field
- r



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F. Gru

Conclusion

- key feature of laser-plasma accelerators:
  high currents, up to 100 kA
- thus, short-period undulators are feasible for SASE
- hence, **table-top** FELs are possible

- discussion
  - huge demand on **theory** of laser-accelerators
  - feedback from experiments (e.g. bunch length)
  - need desperately input distributions for FEL simulations

Courtesy of
F. Gruener (MPQ)

Summary (1)

Laser Plasma Acceleration is an exciting and dynamic field due to recent advances in

- Theory (bubble regime)
- Simulations (PIC and grid free codes)
- Experiments
- Laser technology (TW lasers with fs pulse length)

Application for TT FEL seems to be straight forward and obvious, especially as excitement at the moment is high and the road is paved

But: energy spread, emittance, current, space charge transport, wake fields are all very challenging problems

Summary (2)

We should work together and thus propose a

Joint DESY-MPQ-BESSY Workshop on

- Space Charge simulations
- Wakefield simulations
- Laser-Beam interactions
- SASE FEL simulations
- HGHG FEL simulations

Planned date: May 9-11, 2007
Where: MPQ Garching