Impressions from the Dream Beams Symposium

26.2-28.2
Max-Planck-Institut fuer Quantenoptik (MPQ)

Winni Decking
The Munich Center for Advanced Photonics (MAP)
MAP Research Goals

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

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

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

D. Advanced photonics for medicine
   D.1 Laser-based photon and particle beams for medicine
# Dream Beams Symposium - Program

**Dream Beams Symposium, MPQ Garching, programme**

**Sunday, Feb. 26**
- 9:00: Krausz (Meyer-Meislab) (MPQ): Welcome, Dream Beams (*?)
- 9:45: Malikov (LOA Paris): Experimental demonstration of controlled electron injection

**Monday, Feb. 27**
- 9:00: Zee (Queen's Univ., Belfast): KeV surface harmonics
- 9:45: Esarey (BNL, Berkeley): GeV electrons from guided acceleration

**Tuesday, Feb. 28**
- 9:00: Santoku (UNR Reno): Advanced Particle-in-Cell simulation for high energy density physics
- 9:45: Hajdu (Uni. Upasala): Beams needed for biomolecule imaging

**Wednesday, Feb. 28**
- 10:00: Coffee
- 11:00: Bulanov (JAERI, Kyoto): Prospects and limits of laser particle acceleration
- 11:45: Wei Lu (UCLA): Possible path towards a 100 GeV leva stage
- 12:15: Kemp (LLNL): Collisional relaxation of super-thermal electrons in dense plasma
- **Lunch at IPP Cafeteria**

**March 26, 2024**
- 14:00: Mendonca (IST, Lisbon): Non-linear relativistic optics
- 14:30: Gibbon (KFA,-Julich): Mesh-free particle simulation
- 15:00: Schroder (BNL, Berkeley): THz and fs x-ray pulses
- 15:30: Coffee
- 16:00: Sheng (CAS Beijing): THz radiation and mono-energetic electrons from surface acceleration
- 16:30: Kostyukov (RAS): Radiative processes in plasma-based accelerators in ultrahigh energy regime

**ARRIVAL, transfer to Hotel Maria Garching**
- 17:00: Leaving for Munich

**March 27, 2024**
- 18:00: Visit at Arnold-Sommerfeld-Center (ASC)
- 18:00: Bavarian Buffet at MPQ

**March 28, 2024**
- 8:00: Gasthof Neuwirt in Garching, Welcome
- 9:00: Dinner in Munich near ASC
- 10:00: Posts, Discussion Time
- 10:00: Talks: 30 (+15) min and 20 (+10) min

**Seeding of FELs with Higher Harmonics**
- 14:00: Maseck (BESSY Berlin)

**GEO, nuclear and high-energy processes**
- 14:30: Jentschura (MPK Heidelberg)

**Conditions for detecting Unruh radiation**
- 15:00: Schutzhold (Uni. Dresden)

**Theory of surface harmonics**
- 16:00: Baeva (Uni. Dusseldorf)

**Simulation of surface harmonics**
- 16:30: Rykovoyanov (MPQ)

**Scaling of laser driven proton acceleration**
- 17:00: Leftereye (CEA, Bruyères-le-Château)

**Acceleration of narrow bunch proton lasers**
- 17:30: Schwoerer (Uni Jena)
Classical accelerator limitations

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

Courtesy of W. Mori & L. da Silva

LOA

Plasma cavity

RF cavity

1 m

100 \mu m

Courtesy of V. Malka (LOA)
Mid 90's - 2003: lasers generate electron beams with 100% energy spread

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

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

A. Pukhov\textsuperscript{1,2},
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12 J, 33 fs pulse

Courtesy of W. Leemans (LBL)
Recent results on e-beam:
From maxwellian to mono spectra

Electron density scan

Monoenergetic with Low Charge
\(N_e = 3.5 \times 10^{18} \text{ cm}^{-3}\)

Maxwellian (\(T = 25 \text{ MeV}\))
\(N_e = 1.5 \times 10^{19} \text{ cm}^{-3}\)

Monoenergetic with High Charge
\(N_e = 6.0 \times 10^{18} \text{ cm}^{-3}\)

Maxwellian (\(T = 11 \text{ MeV}\))
\(N_e = 2.0 \times 10^{19} \text{ cm}^{-3}\)

Monoenergetic + Maxwellian
\(N_e = 7.5 \times 10^{18} \text{ cm}^{-3}\)

Maxwellian (\(T = 15 \text{ MeV}\))
\(N_e = 3.0 \times 10^{19} \text{ cm}^{-3}\)

Monoenergetic + Maxwellian (\(T = 23 \text{ MeV}\))
\(N_e = 1.0 \times 10^{19} \text{ cm}^{-3}\)

Maxwellian (\(T = 11 \text{ MeV}\))
\(N_e = 5.0 \times 10^{19} \text{ cm}^{-3}\)

Courtesy of V. Malka (LOA)

V. Malka, et al., PoP 2005
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 \( L \sim \) dephasing length: monoenergetic

T. Katsouleas, Nature 2004
Plasma channel production: ignitor-heater method

- Two step process for channel formation (in H₂ gas jet):
  1. Ionization: co-linear ultrashort ‘ignitor’ pulse \((I > 10^{14} \text{ W/cm}^2)\)
  2. Inverse Bremsstrahlung heating: 250 ps ‘heater’ pulse with \(I \sim 10^{13}\text{W/cm}^2\)

- Shock formation leads to on-axis density depletion on axis


Courtesy of E. Esarey (LBL)
86 MeV electron beam with %-level energy spread

Beam profile

Unguided

Guided

Spectrum

- Electron Spectrum
- Detection Thresh.


9 TW
50 fs
2e19 cm⁻³
300 pC
3 mrad
ΔE < 4 MeV

300 pC
Divergence~1 mrad

86 MeV, ΔE/E=2%
2004 Results: High-Quality Bunches

Approach 1: bigger spot
- RAL/IC⁺ (12.5 TW -> ~20 pC, 80 MeV)
- LOA⁻ (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

GeV: channeling over cm-scale

- Increasing beam energy requires increased dephasing length and power:

\[ \Delta W[\text{GeV}] \sim \frac{I[\text{W/cm}^2]}{n[\text{cm}^3]} \]

- 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

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**Laser:** 40-100 TW, 40 fs 10 Hz

**Plasma channel technology:** Capillary

1 GeV

Courtesy of E. Esarey (LBL)
0.5 GeV Beam Generation

Density: $3.2-3.8 \times 10^{18}/cm^3$

Laser: $950(\pm 15\%)$ mJ/pulse (compression scan)

**Injection threshold:** $a_0 \sim 0.65$ ($\sim 9$ TW, 105 fs)

Less injection at higher power

- Relativistic effects
- Self modulation

Stable operation

500 MeV Mono-energetic beams:

$a_0 \sim 0.75$ ($11$ 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

312 μm diameter and 33 mm length capillary

Laser: 1500(±15%) mJ/pulse
Density: 4x10^{18}/cm³
Injection threshold: a₀ ~ 1.35 (~35TW, 38fs)
Less injection at higher power
Relativistic effect, self-modulation

1 GeV beam: a₀ ~ 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

Courtesy of E. Esarey (LBL)
Laser wakefield accelerator (LWFA)-driven FEL

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


Schematic of LBNL LWFA-driven FEL:

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

**LBNL-LWFA**

- 1 J/pulse, $10^{19}$ W/cm$^2$
- 10 Hz
- Laser beam
- Plasma channel: $10^{18}$ cm$^{-3}$
- Single-pass, high-gain SASE FEL
  - 0.5 GeV, 5 kA electron beam
  - Undulator: 5 m
    - 2.18 cm period, 220 periods, $K=1.85$
- FEL output:
  - $\lambda=31$ nm
  - $10^{13}$ photons/pulse
  - XUV radiation

**LBNL laser system**

Plasma capillary technology

Stable 0.5 GeV beams demonstrated

conventional undulator

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

K. Robinson et al., IEEE QE (1987)
HHG-seeded LWFA-driven FEL

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

**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

**HHG seed**
- Laser beam
- hollow gas-filled waveguide
- ~3 cm plasma channel
- 0.5 GeV electron beam
- Single-pass, high-gain FEL
- Undulator
- ~3 m

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

**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

Gain length vs. energy spread

Exponential Gain Length vs. Energy Spread

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

for parameters:
- $\varepsilon_N = 1 \text{ mm-mrad}$
- $E = 0.5 \text{ GeV}$
- $\lambda_0 = 2.18 \text{ cm}$
- $K = 1.85$
- $\beta = 3.6 \text{ m}$

Courtesy of C. Schroeder (LBL)
FEL Radiation Characteristics

[GiNGER' calculation]

5-kA seeded GiNGER Results:

- Photons/pulse: $3 \times 10^{13}$
- RMS Norm.Inverse Bandwidth: 500
- Peak Brightness: $6 \times 10^{16}$ (photons/pulse/mm²/μrad²/0.1% BW)
- Output Divergence Angle: 72 μrad
- 3rd Harmonic Power/Fundamental: 0.4%

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

• not only table-top size, but sufficient output power:
  ~ 1 µm only!!
  ~ nC charge
  ~ 100 kA

Typical length scale = plasma wavelength

\(\frac{\lambda}{\varepsilon_n} \approx 6 \text{ mm·mrad}\)
\(\Delta E/E \approx 0.04\%\) (rms)

\(\text{saturated length (Xie Ming)}\)
\(\Lambda (Xie Ming)\)
\(\lambda_u = 5 \text{ mm (150 MeV)}\)
\(\varepsilon_n = 1 \text{ mm·mrad}\)
\(\Delta E/E = 0.5\%\) (rms)

\(\frac{\lambda}{\varepsilon_n} \approx 6 \text{ mm·mrad}\)
\(\Delta E/E \approx 0.04\%\) (rms)

\(\text{DESY FLASH (fs mode):}\)
\(\lambda_u = 27 \text{ mm (462 MeV)}\)
\(\varepsilon_n = 6 \text{ mm·mrad}\)
\(\Delta E/E \approx 0.04\%\) (rms)

\(\frac{\lambda}{\varepsilon_n} \approx 6 \text{ mm·mrad}\)
\(\Delta E/E \approx 0.04\%\) (rms)

Courtesy of F. Gruener (MPQ)
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,
    \( \leq 0.5 \text{ mm}\cdot\text{mrad} \) norm. emittance, \( \geq 1 \text{ nC} \) 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
- mini-quadrupoles: 530 T/m

Courtesy of F. Gruener (MPQ)
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)
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 straightforward 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
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