Laser-driven X-ray FEL on a table top

Kazuhisa Nakajima

High Energy Accelerator Research Institute ***KEK****, Japan*

Yoshitomo Takahashi, Hitoshi Yoshitama, Takashi Kameshima

Graduate School for Advanced Studies ***SOKEN-DAI****, Japan*

Hideyuki Kotaki

J*apan* ***A****tomic* ***E****nergy* ***A****gency,* ***K****ansai* ***P****hoton* ***R****esearch* ***I****nstitute, Japan*

Shinichi Masuda

National Institute of ***A****dvanced* ***I****ndustrial* ***S****cience and* ***T****echnology, Japan*

Nasr A. M. Hafz

G*wangju* ***I****nstitute of* ***S****cience and* ***T****echnology,* ***A****dvanced* ***P****hotonics* ***R****esearch* ***I****nstitute, Korea*

International Conference on Ultrahigh Intensity Lasers

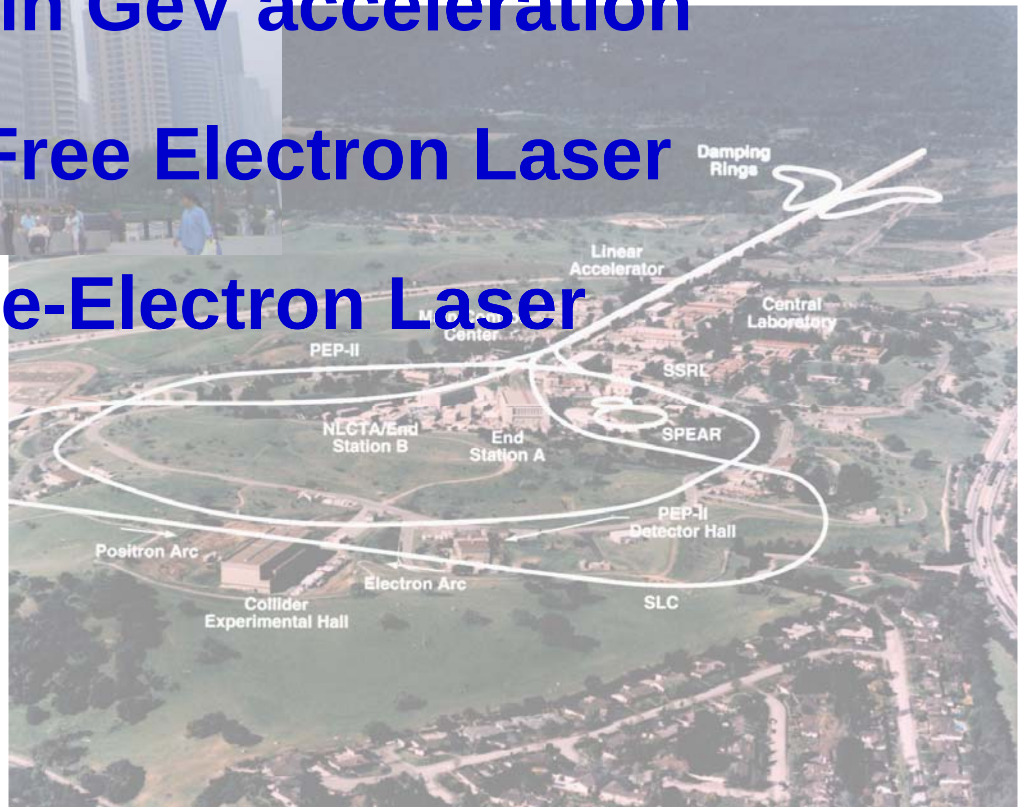
October 27-31, 2008, Tongli, China

Outline

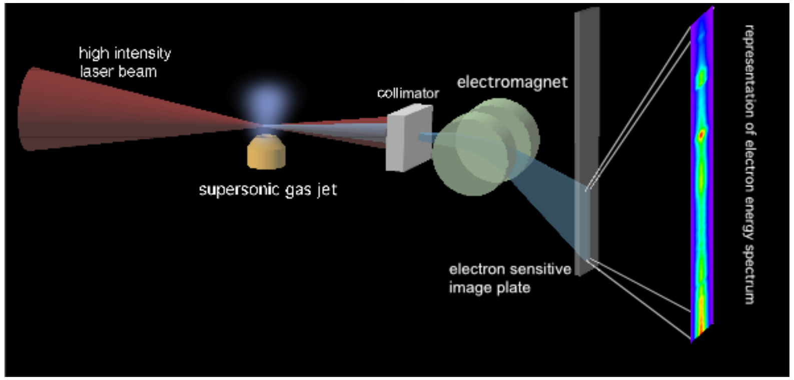
Recent progress in GeV acceleration

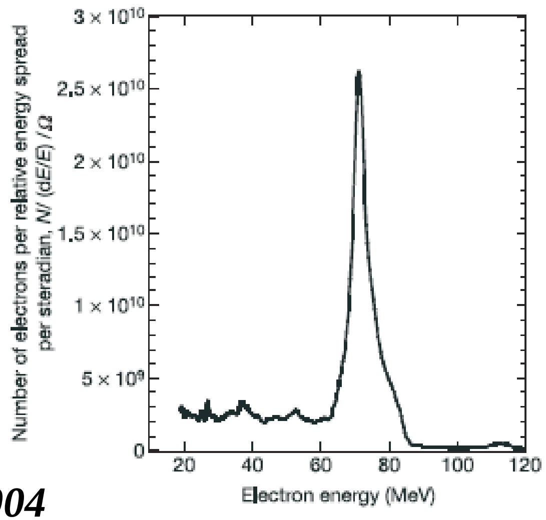
Table-top X-ray Free Electron Laser

All Optical Free-Electron Laser



Monoenergetic electron beams opened the way to applications

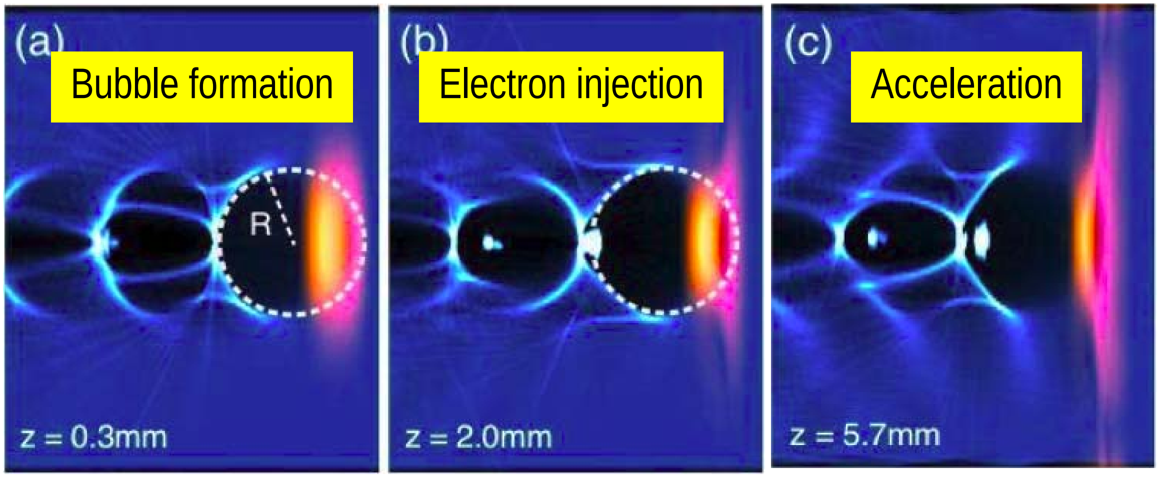


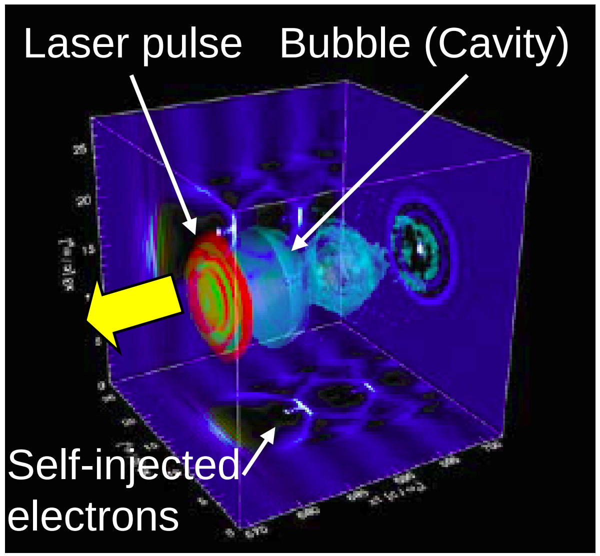


S. P. D. Mangles et al., NATURE, 431, 535, 2004

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

Laser-plasma acceleration in the bubble regime



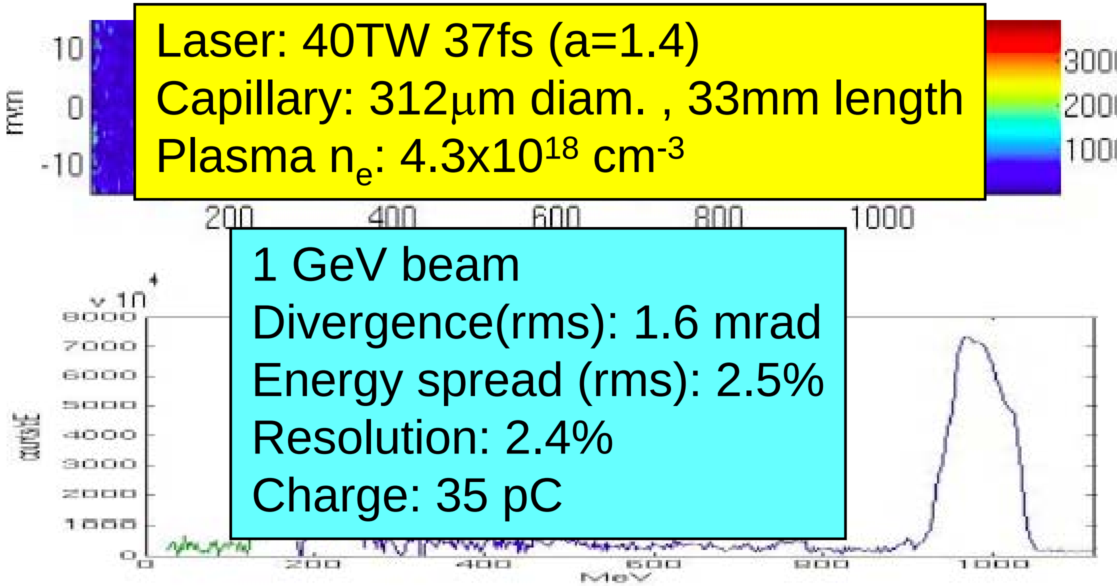


W. Lu, PRST-AB 10, 061301 (2007)

C. D. Murphy et al., Phys. Plasmas 13, 033108 (2006)

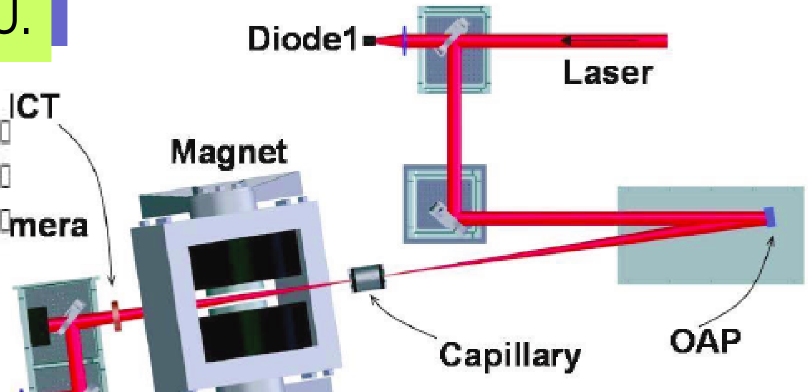
GeV laser-plasma acceleration achieved with cm-scale capillary

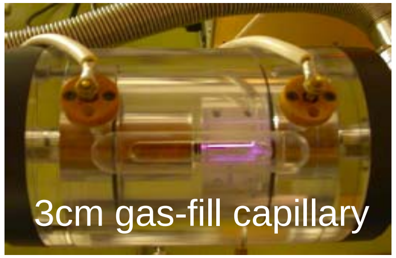
1 GeV capillary accelerator experiment at LBNL/Oxford U.



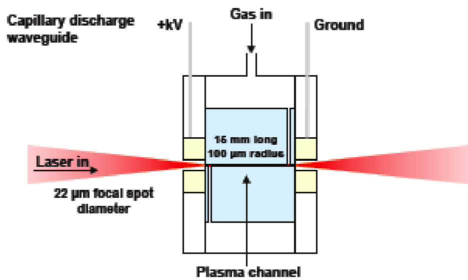
Laser: 40TW 37fs (a=1.4)
Capillary: 312μm diam. , 33mm length
Plasma n_e: 4.3×10^{18} cm^{-3}

1 GeV beam
Divergence(rms): 1.6 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%
Charge: 35 pC

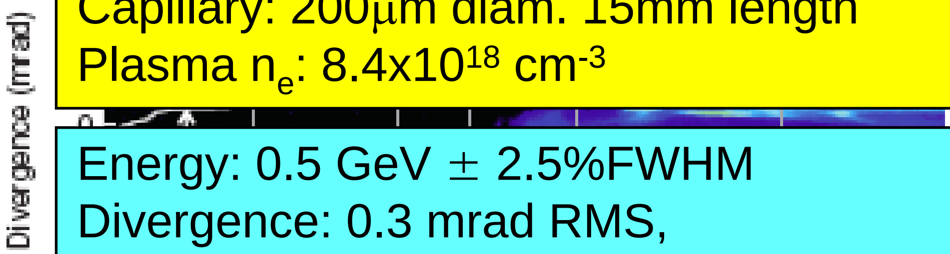




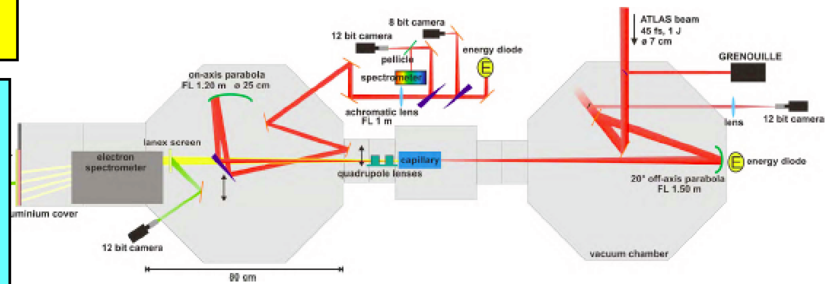
0.5 GeV capillary accelerator experiment at MPQ/Oxford U.



Laser: 18TW 42fs (1.5×10^{18} W/cm^2, a_0 =0.84)
f=1.5m d =23 μm FWHM
Capillary: 200μm diam. 15mm length
Plasma n_e: 8.4×10^{18} cm^{-3}

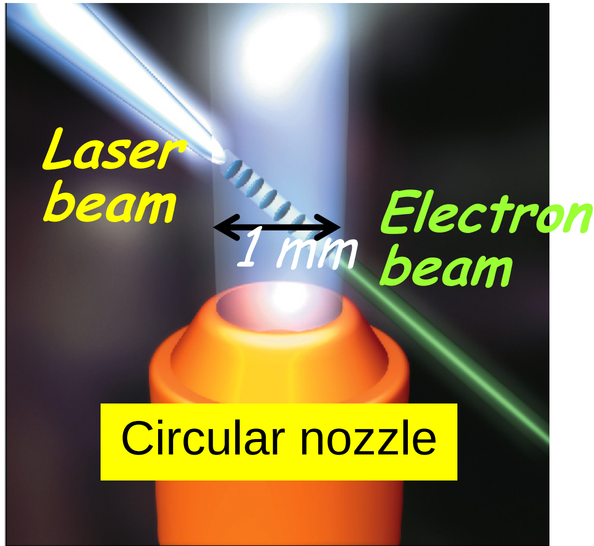


Energy: 0.5 GeV ± 2.5%FWHM
Divergence: 0.3 mrad RMS,
Charge: >0.3pC
Normalized emittance: < 2.4 mm mrad RMS

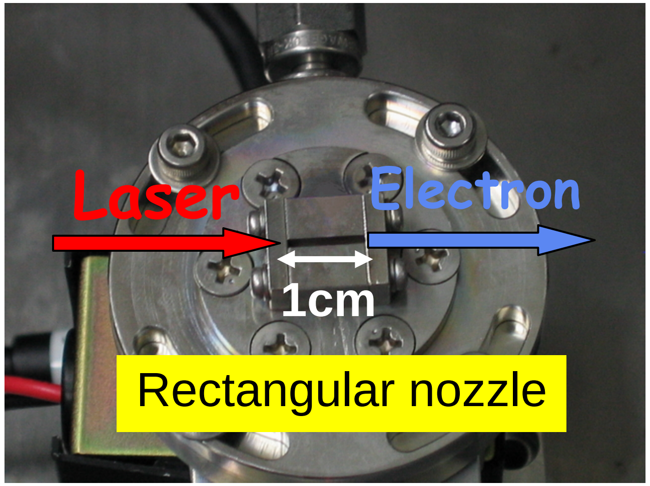


Plasma accelerators - inherent table-top

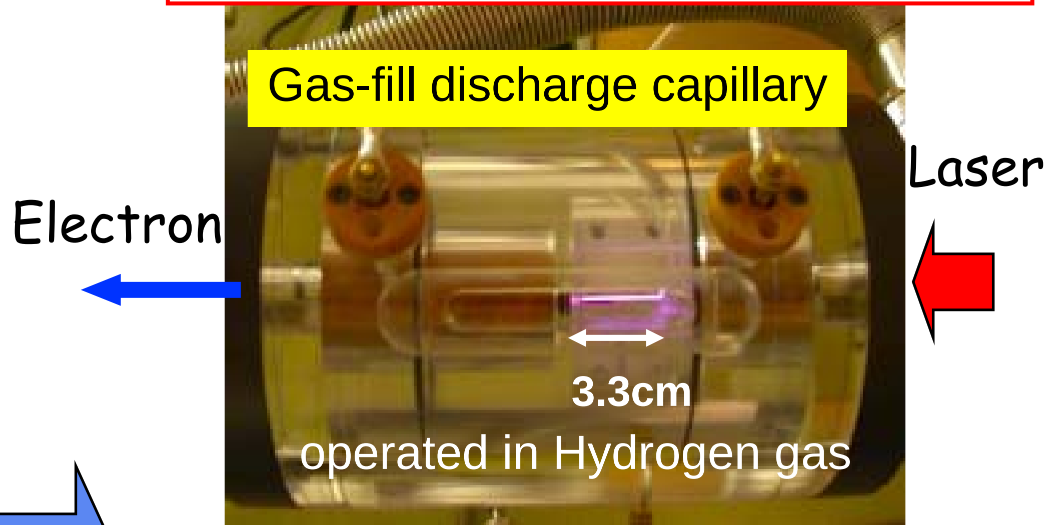
Millimeter-scale plasma channel



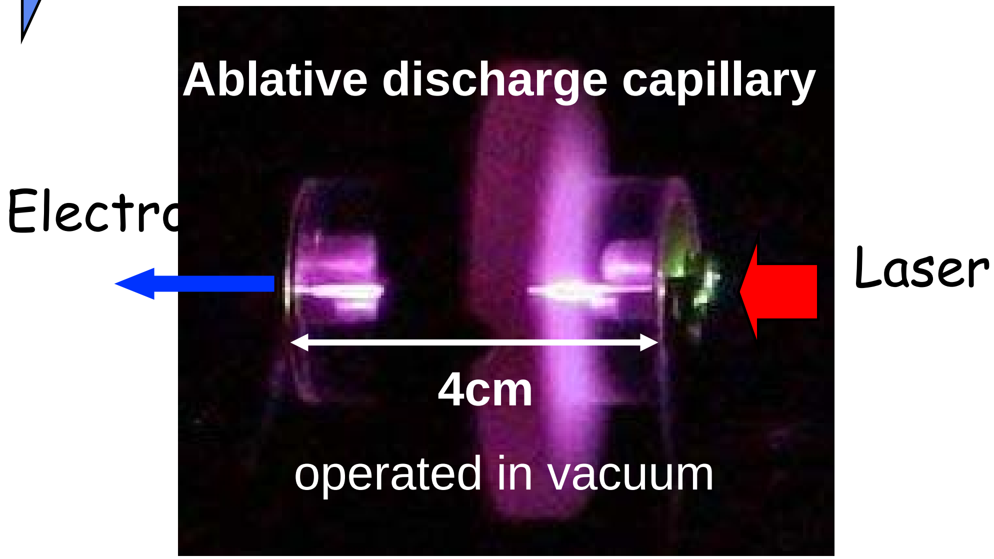
Super-sonic gas jet



Centimeter-scale plasma channel

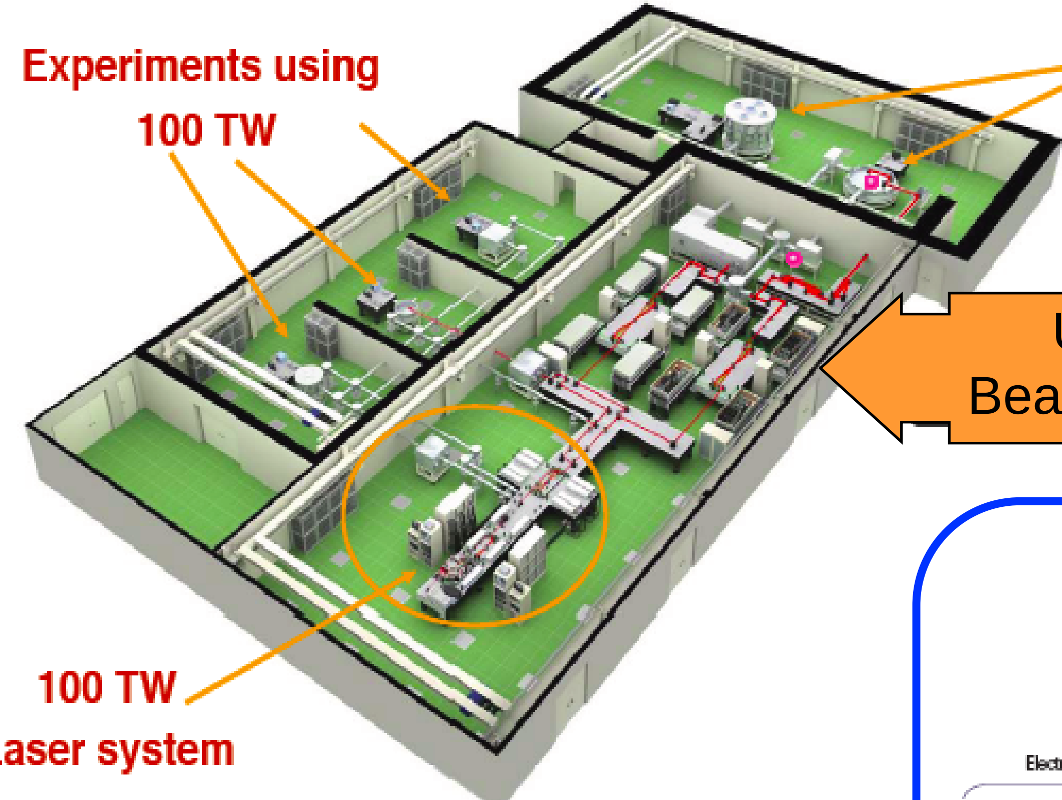


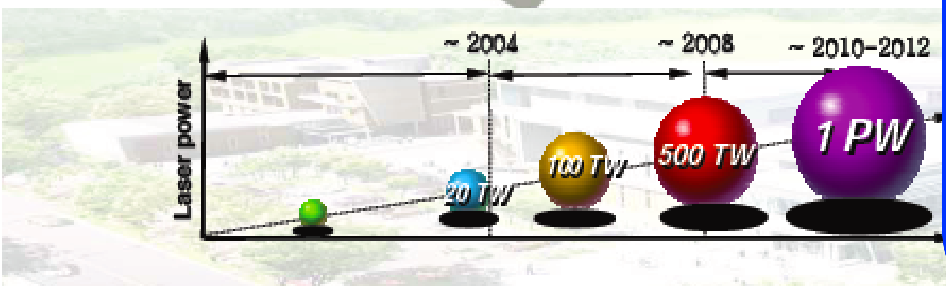
Capillary accelerator

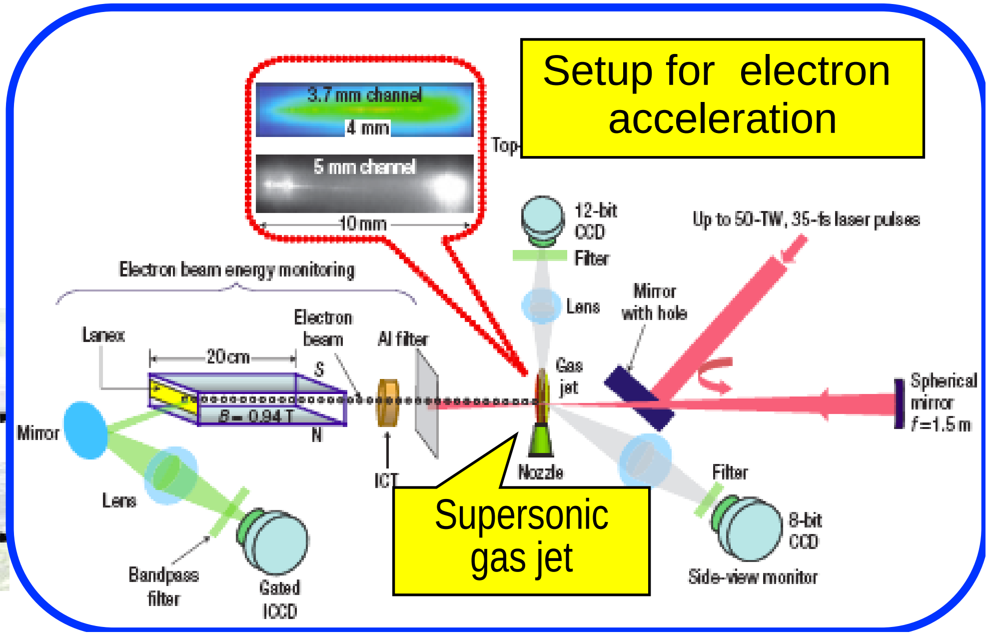


Progress in electron acceleration driven by laser at GIST-APRI, Korea

N. Hafz and J. M. Lee
in interview, nature photonics, 2, 580, 2008





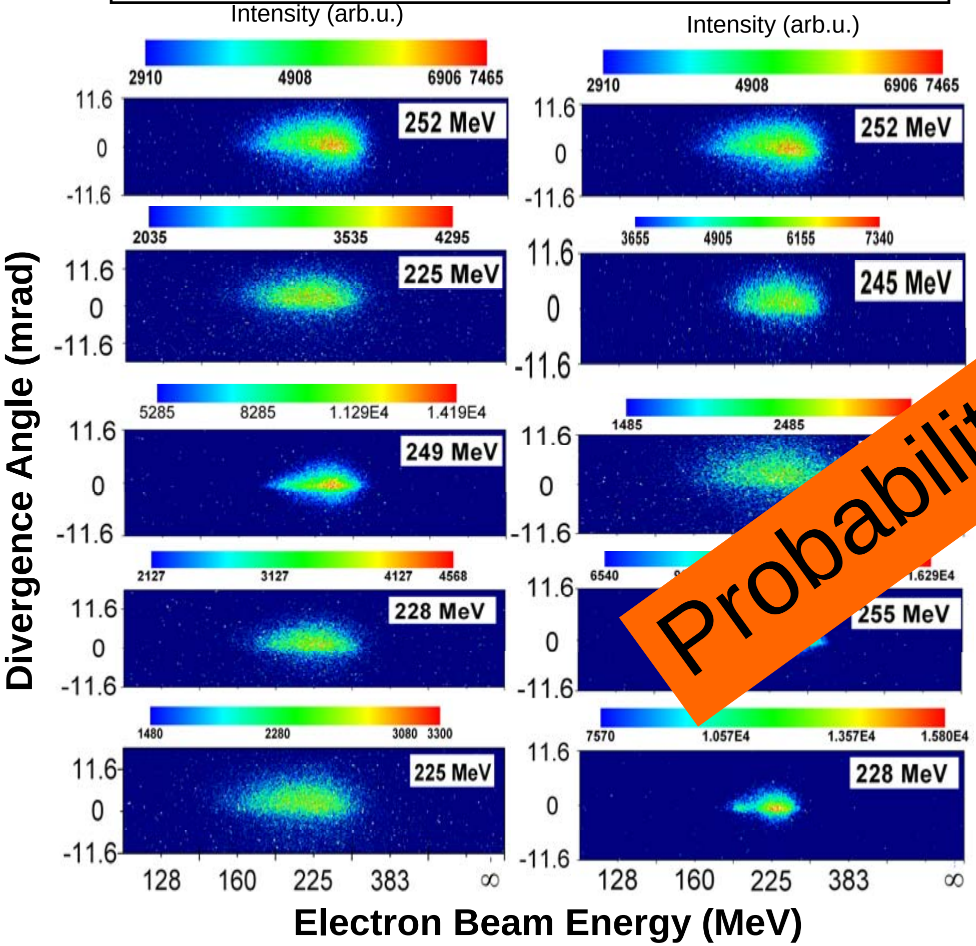


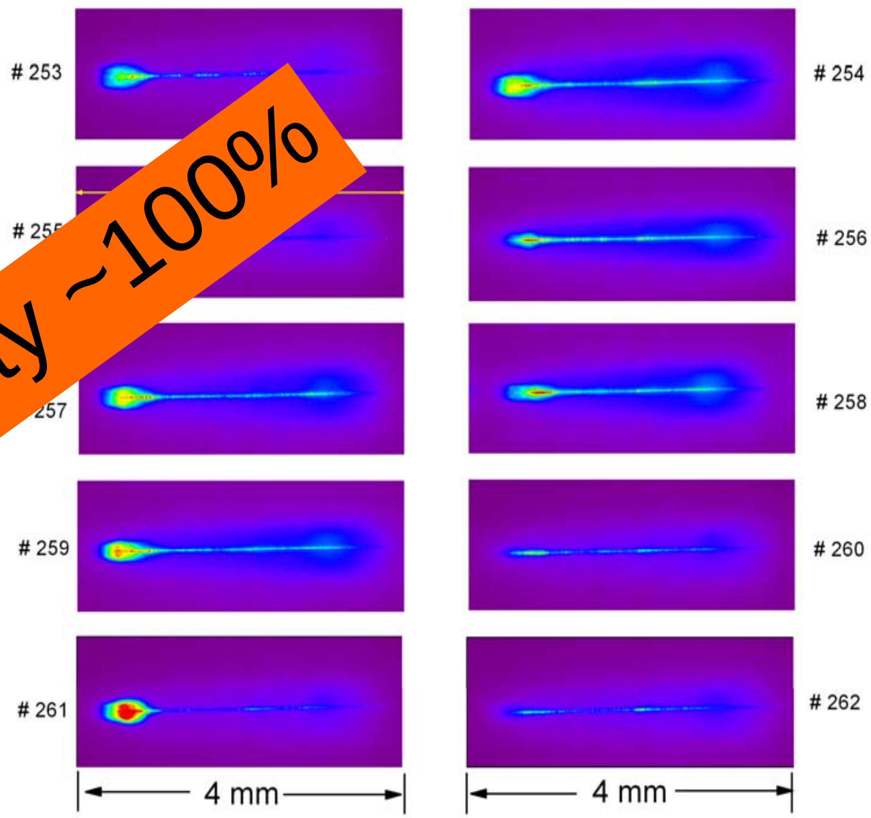
Stable Electron Beams with GIST laser

Mean electron energy = 236.9 MeV
SD/Mean E = 5 %
Charge: ~100pC
Divergence angle: ~a few mrad

F/22 (f=1.5 m)
1cm He gas jet

Mean laser power (J) = 36.8 TW
SD/Mean E = 4.6 %





Average Channel length ~ 3.5 mm

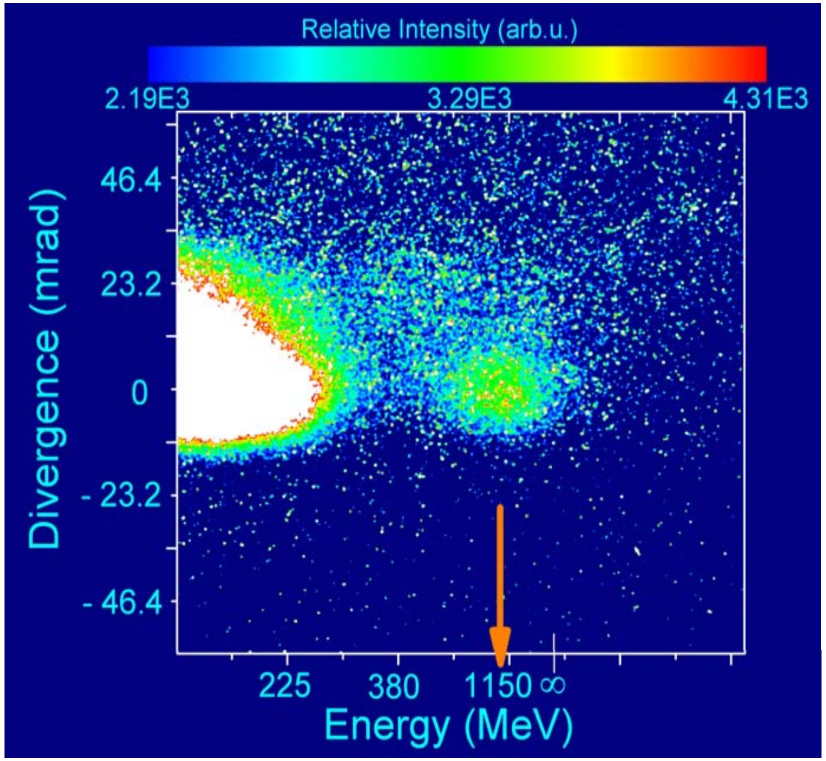
37 TW, 35 fs, $n_o \sim 7 \times 10^{18} cm^{-3}$, $L_d \sim 3.16$ mm

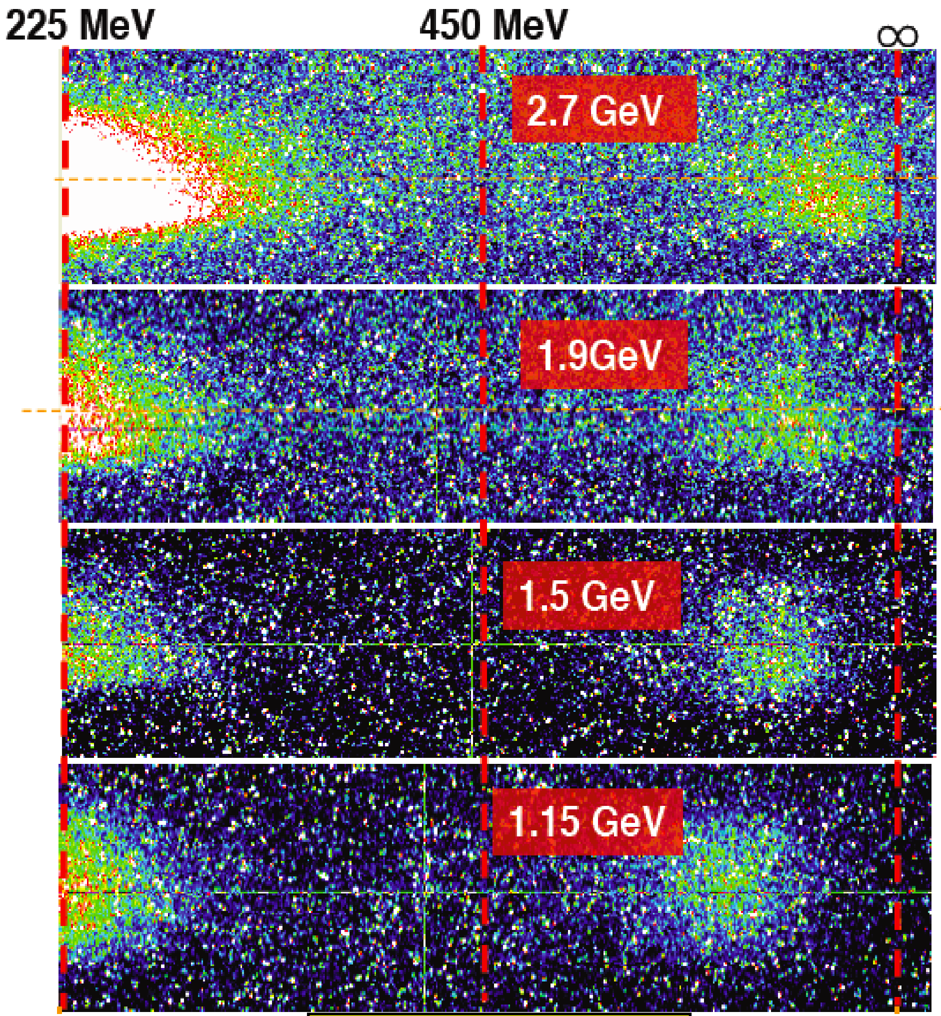
N. M. Hafz et al., Nature Photonics,2, 571 (2008)

GeV electron beams from 1cm gas jet at GIST

Laser: 50 TW, 35 fs
Plasma: 6.8 × 10^{18}cm^{-3}

Laser: 50 TW, 35 fs, 24 μm spot
Plasma: 2~3× 10^{18}cm^{-3}



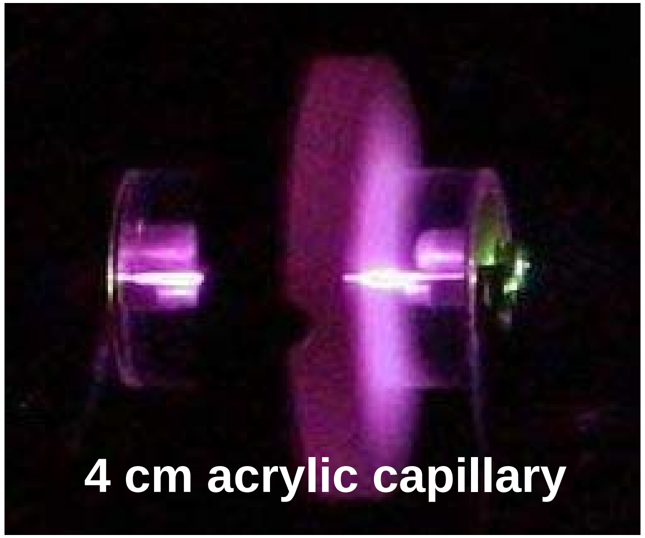


e-Beam:
E_{peak1}=1.15 GeV
E_{peak2}= 140 MeV
Q_{peak1}=10 pC
Q_{peak2}=500pC

Recent results

N. M. Hafz et al., Nature Photonics (2008)

Ablative capillary discharge plasma channel ignited with Nd:YAG laser

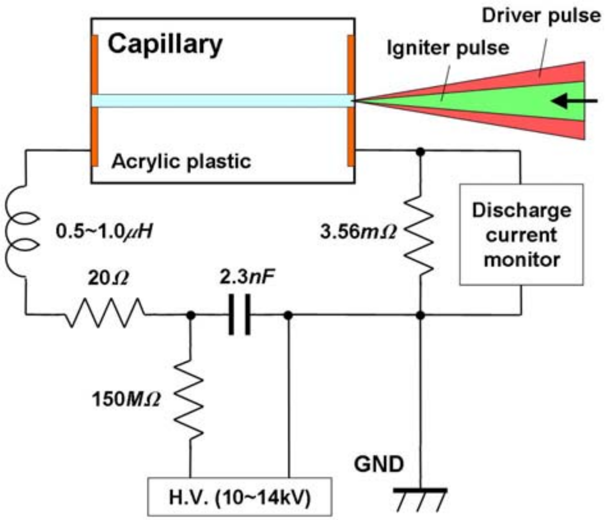


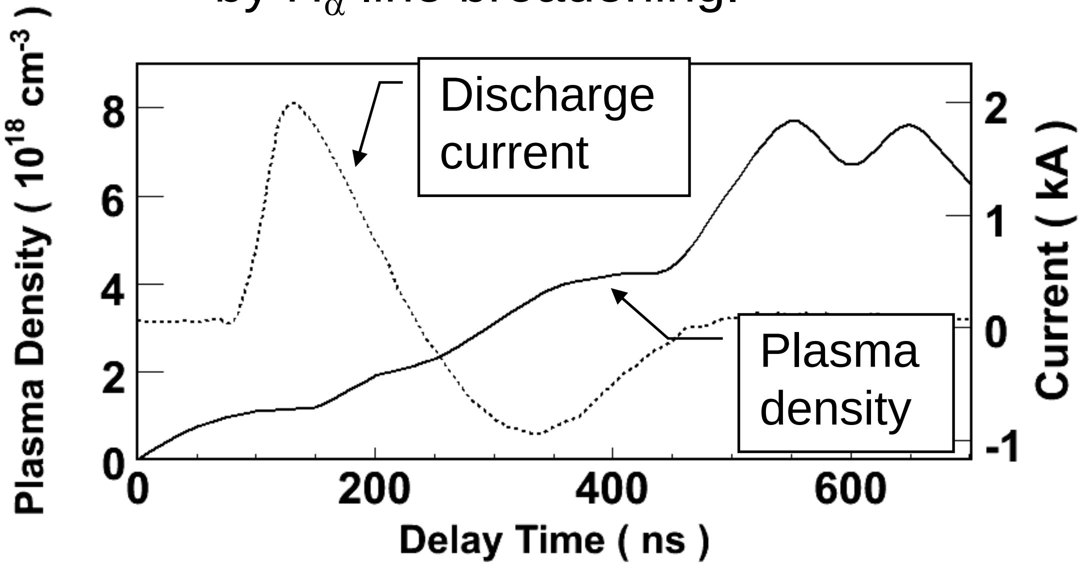
Stable operation in vacuum

Capillary was developed at KEK under the collaboration with Hebrew University.

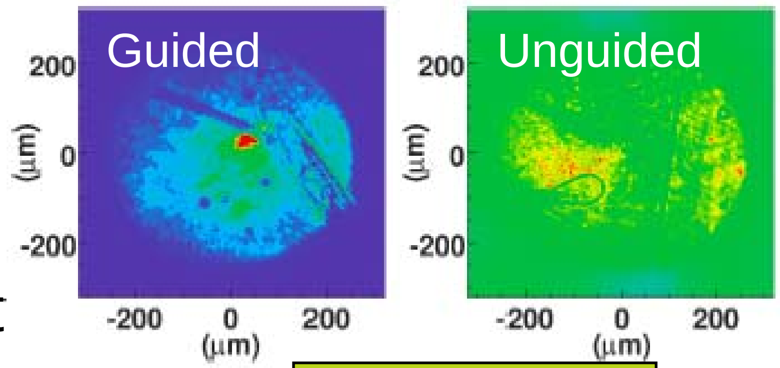
Discharge current and Plasma density

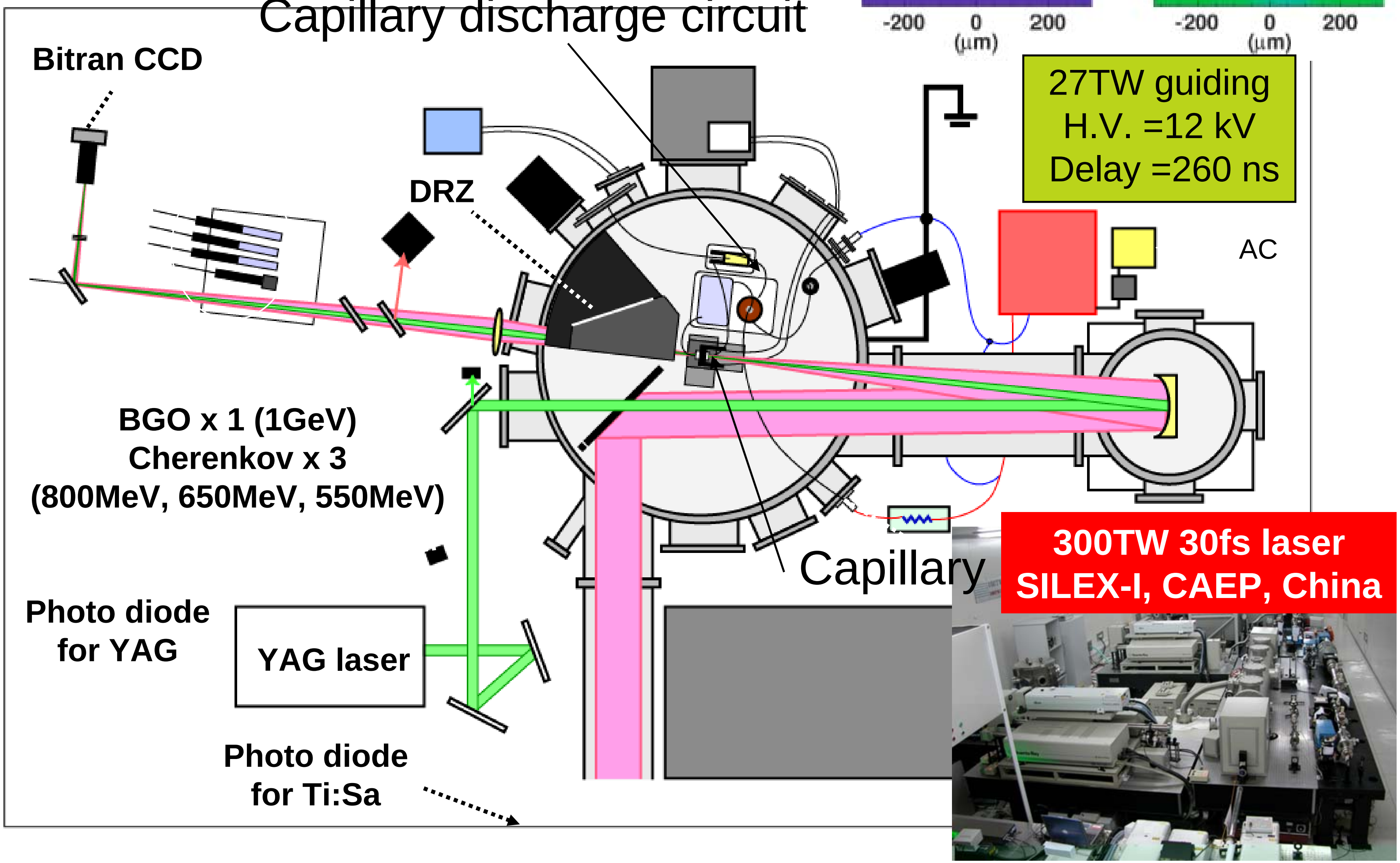
Plasma density was measured by H_α line broadening.





4 cm ablative capillary acceleration experiment at CAEP-SOKEN-KEK

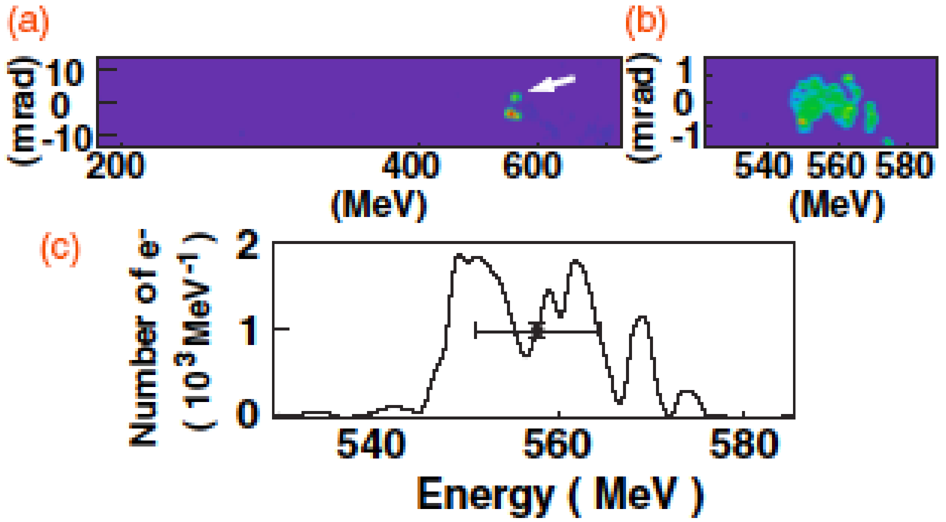




0.56 GeV, 1% energy spread beams from 4cm ablative capillary

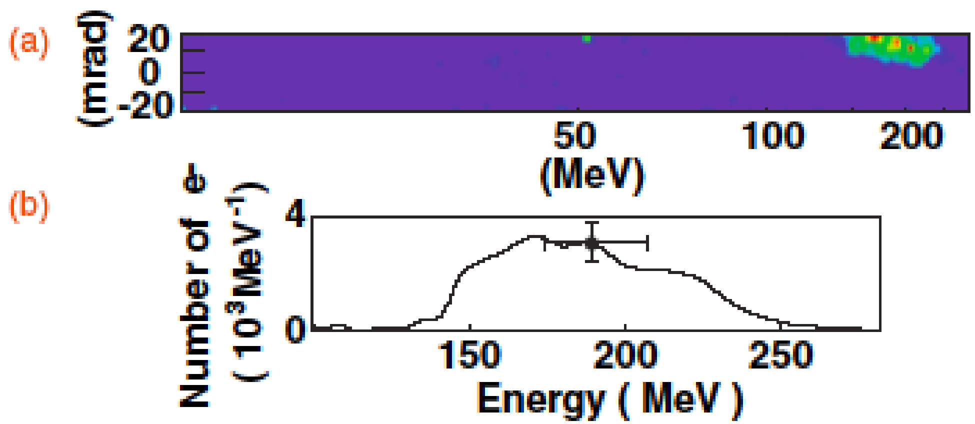
Laser: P = 24 TW 27fs (a_0 =1.7)
F/9.3 f=1.4m
Plasma: n_e = 1.9 x 10^{18} cm^{-3}

0.56 GeV beam
Divergence (rms): 0.59 mrad
Energy spread (rms): 1.2%
Charge: ~10fC

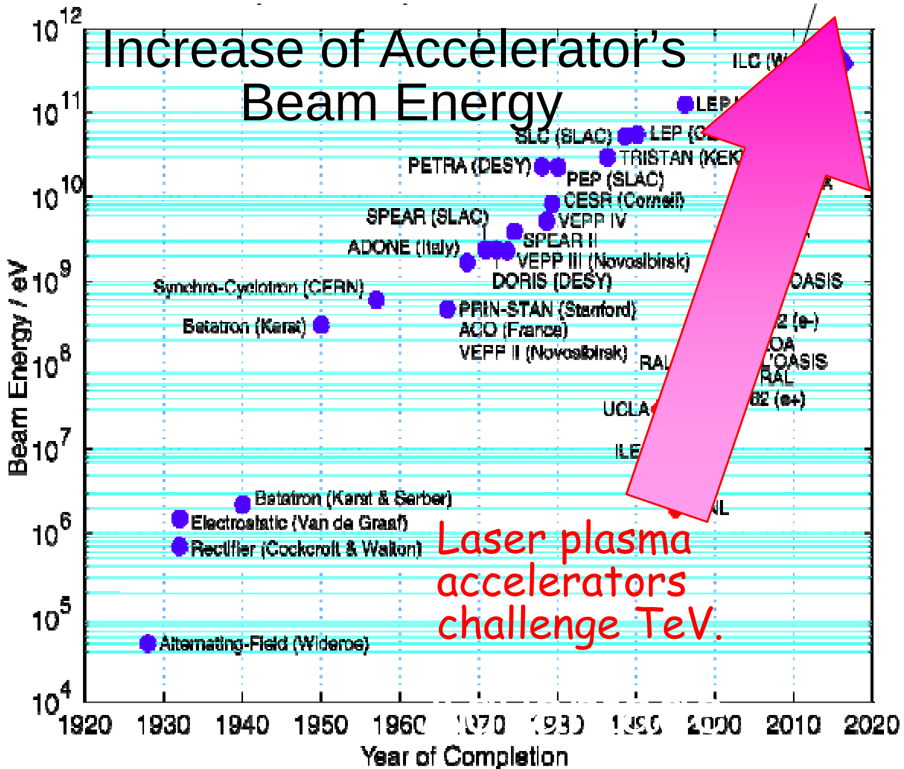


Laser: P = 16 TW 27 fs (a_0 =1.4)
Plasma: n_e = 2.7 x 10^{18} cm^{-3}

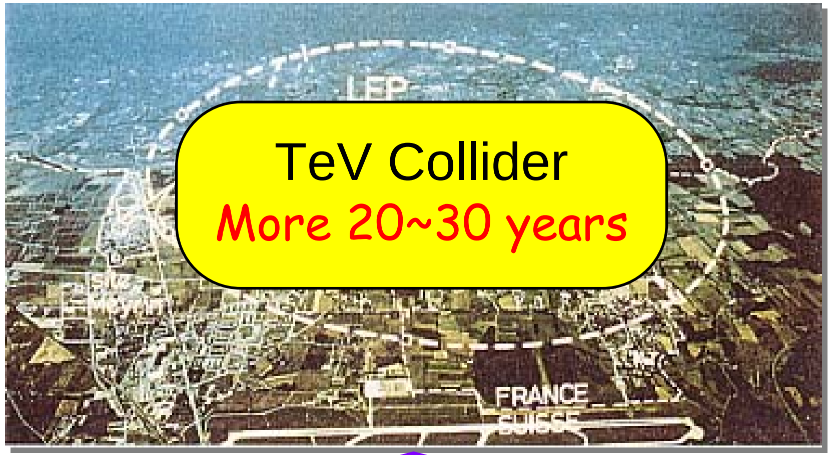
0.19 GeV beam
Divergence (rms): 11 mrad
Energy spread (rms): 15%
Charge: ~40fC



Kameshima et al., Applied Physics Express 1, 066001 (2008)

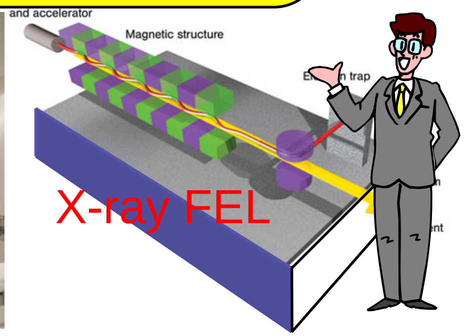


V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4



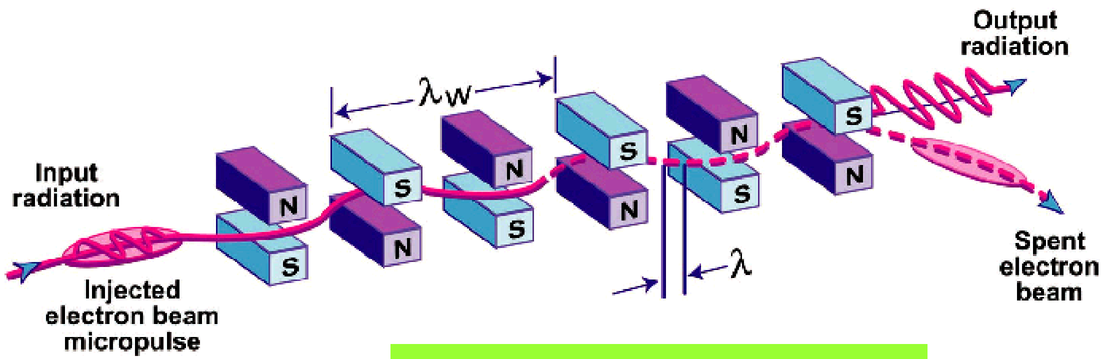
Applications to compact particle and radiation sources

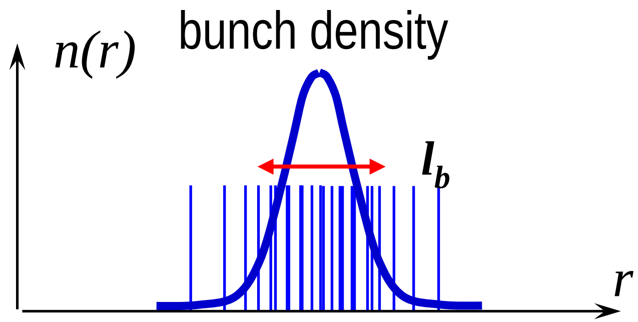
Now !

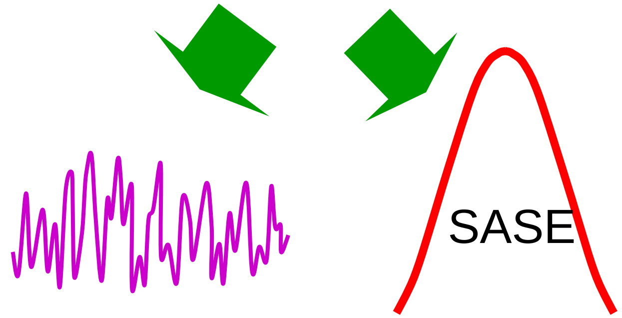


What is X-ray Free Electron Laser?

How to produce coherent radiation







$\lambda << l_b$ $E \sim N^{1/2}$; $I \sim N$	$\lambda >> l_b$; $E \sim N$; $I \sim N^2$
Spontaneous incoherent emission	Self-Amplified Spontaneous Emission

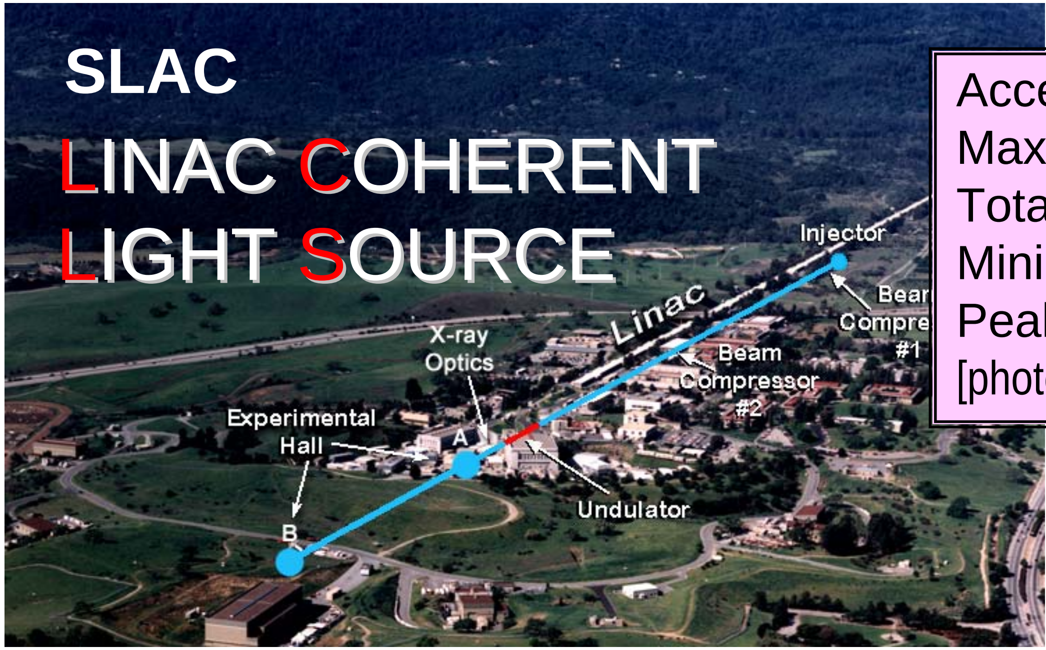
Resonance condition

FEL wavelength: $$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

Undulator parameter: $$K = 0.934 B_U[T]\lambda_U[cm]$$

Radiation Intensity: $$\frac{dI(\omega)}{d\omega} = \left[N + N(N-1)f(\omega)\right]\frac{dI(\omega)}{d\omega}$$

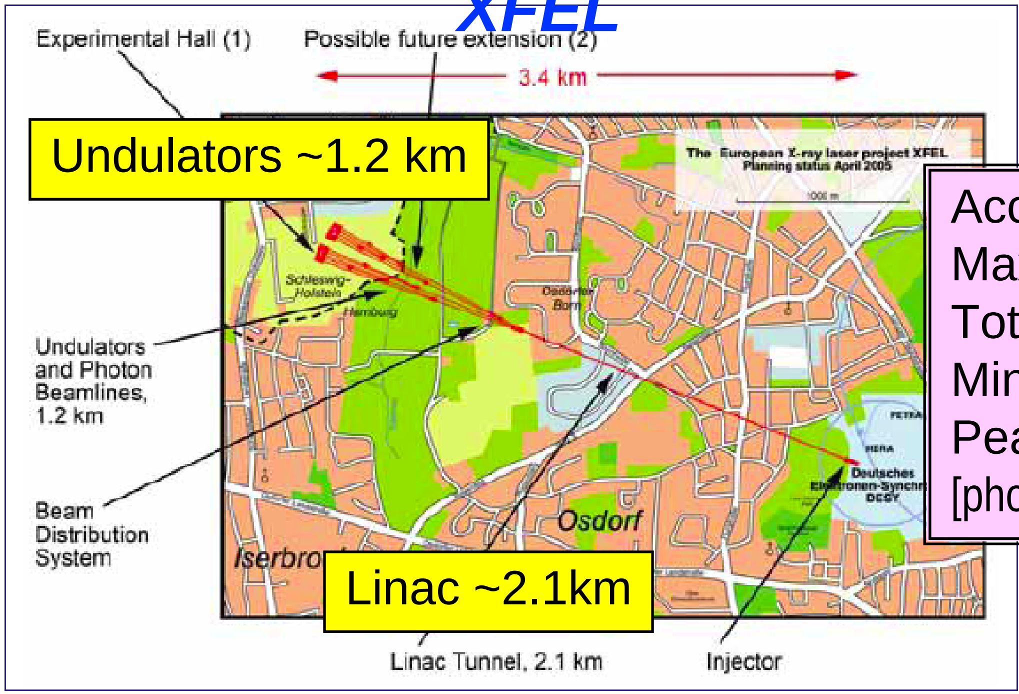
where $f(\omega) = \left|\int_{-\infty}^{\infty} e^{i\omega\hat{n}\cdot\vec{r}/c} S(r)dr\right|^2$ *(Nodvick & Saxon)*

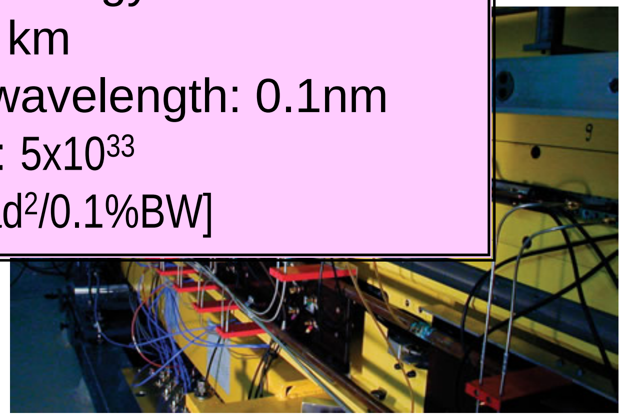


Accelerator: Normal conducting RF linac
Maximum beam energy: 14.3 GeV
Total length: 3 km
Minimum X-ray wavelength: 0.15nm
Peak brightness: 8.5×10^{32}
[photons/s/mm^2/mrad^2/0.1%BW]

European X-ray free-electron laser

XFEL

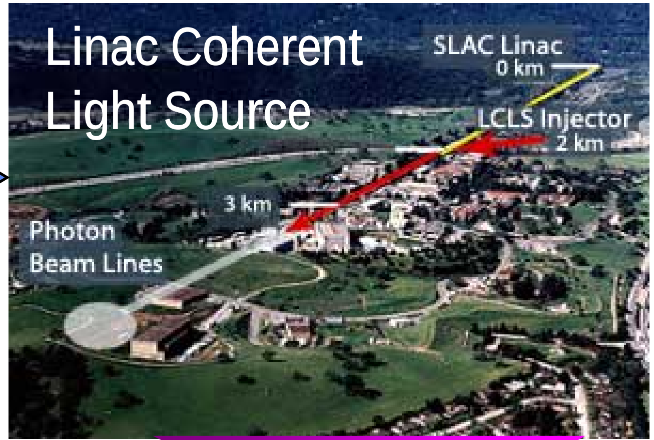




Accelerator: Superconducting RF linac
Maximum beam energy: 20 GeV
Total length: 3.4 km
Minimum X-ray wavelength: 0.1nm
Peak brightness: 5×10^{33}
[photons/s/mm^2/mrad^2/0.1%BW]

A table-top X-ray Free Electron Laser based on laser-plasma accelerated electron beams

Challenge to downsize kilometer-range X-ray FEL to a table-top scale

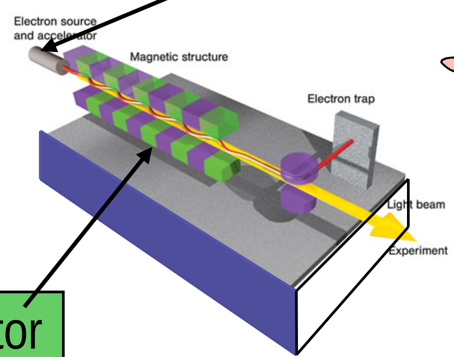


•Table-top size GeV-electron injectors including laser drivers and radiation shields.

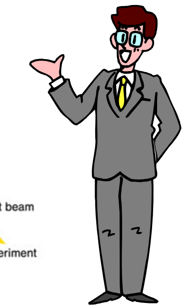
•Ultrashort electron bunch of the order of 10fs without bunch compressors, which produces very high beam current of the order of 100 kA for 1nC charge.

Shorter undulator length
Higher saturation FEL power

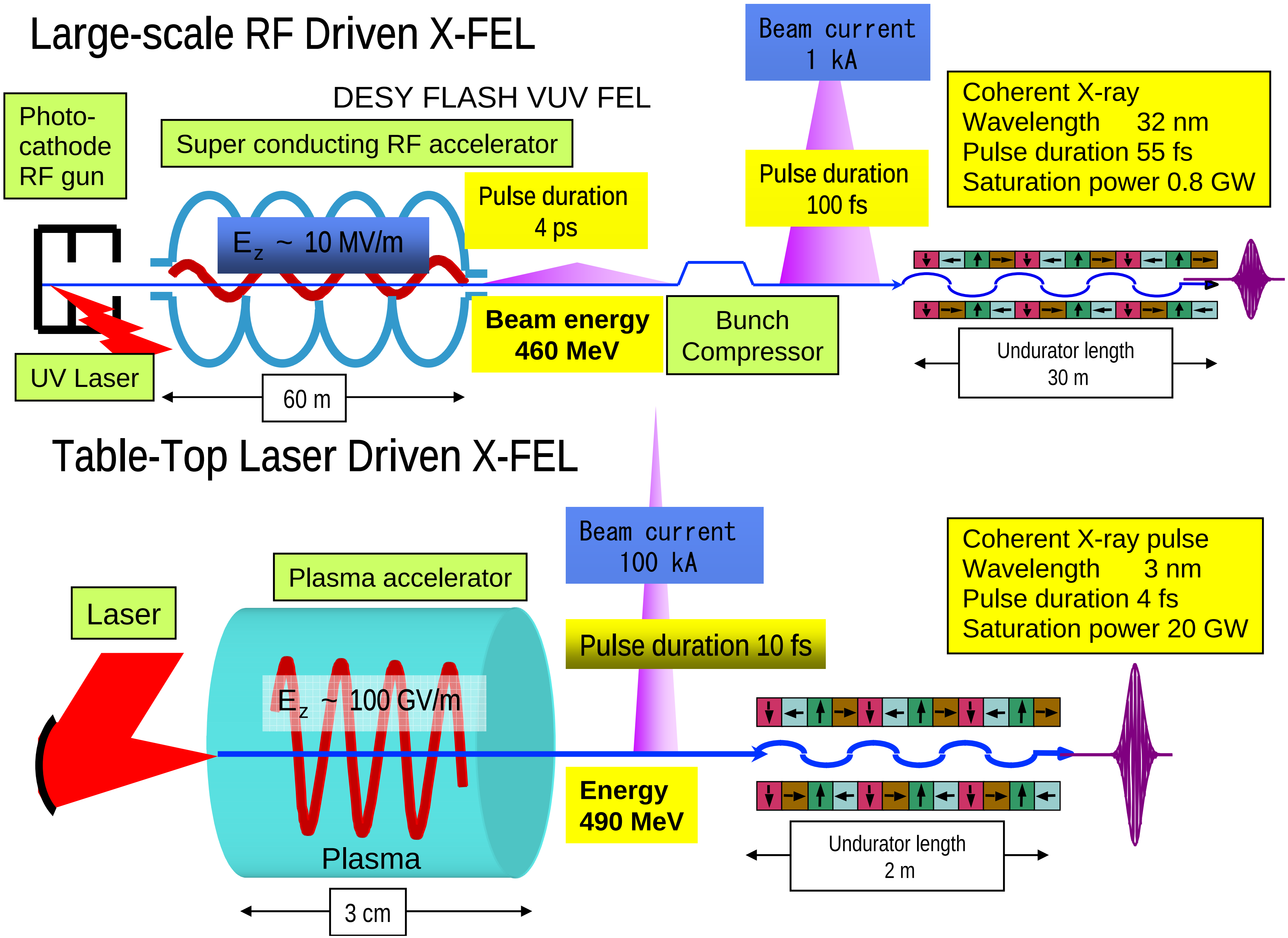
Electron linac



Undulator

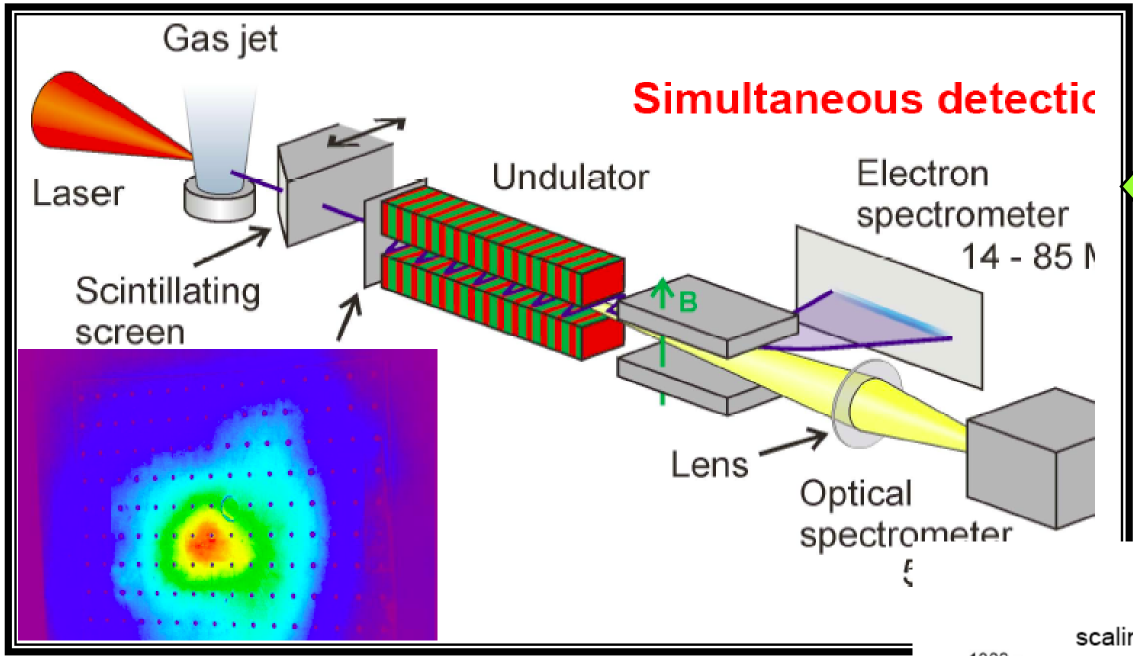


How to set up X-ray FEL on a table top



The first demonstration of undulator radiation from laser-accelerated electron beam

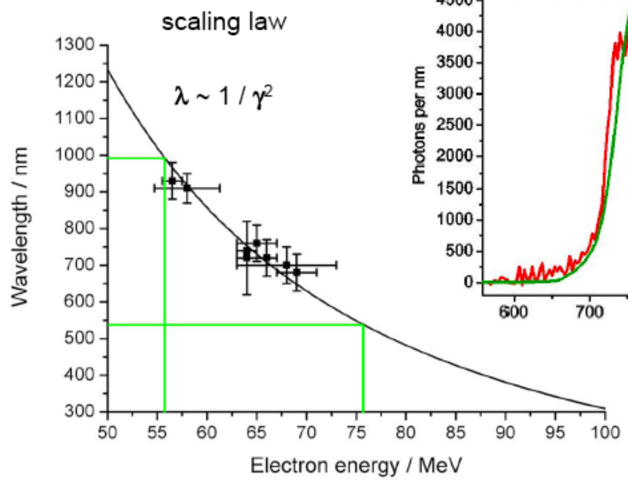
IOQ, JENA, Germany and University of Strathclyde, UK

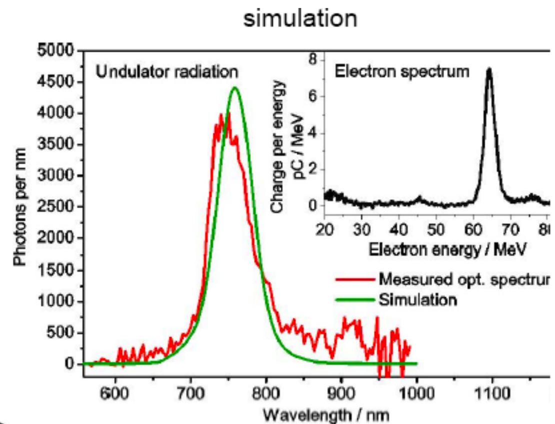


Simultaneous observation of electron and optical spectrum

Comparison of measurement with theory

Reasonable quality of laser accelerated electrons
in energy spread, divergence, pointing stability





Challenge to table-top X-ray FEL

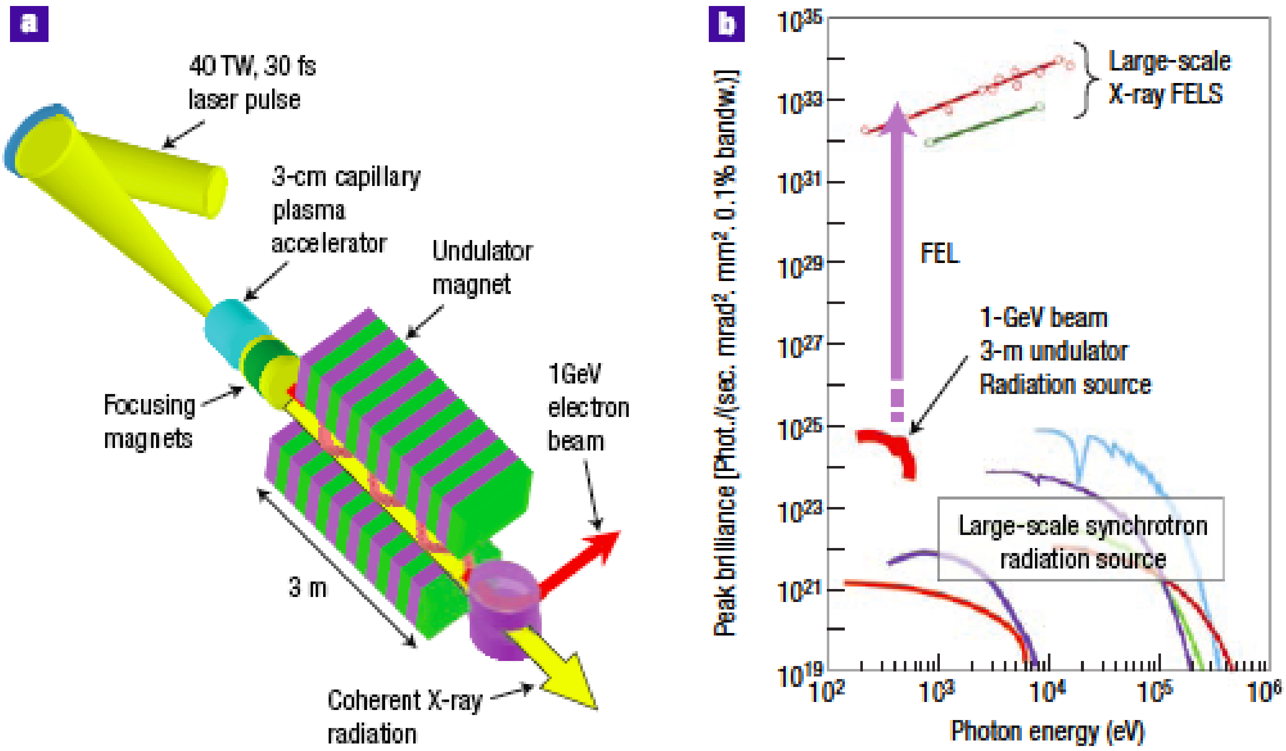


Figure 1 The path to X-rays on a table top. **a**, By combining the ability to produce 1-GeV electron beams from a 3-cm-long capillary laser wakefield accelerator recently demonstrated by Leemans *et al.*[7] with the synchrotron radiation scheme demonstrated by Schlenvoigt *et al.*[5], a compact, high-brilliance source of coherent X-rays could soon become a reality. **b**, Peak brilliance of undulator synchrotron radiation sources as a function of photon energy. Data from ref. 3. Taking the beam parameters reported by Leemans *et al.* (energy of 1 GeV, and an electron bunch length and charge of 10 fs and 30 pC), a high-brilliance source comparable to existing large-scale synchrotron radiation should be readily achievable. In the FEL regime, such radiation could be amplified by many orders of magnitude, to levels of brilliance similar to kilometre-scale FELs[2–4] currently under construction.

Kazuhisa Nakajima, nature physics, vol. 4, 93 (2008)

Design of Table-Top XFEL

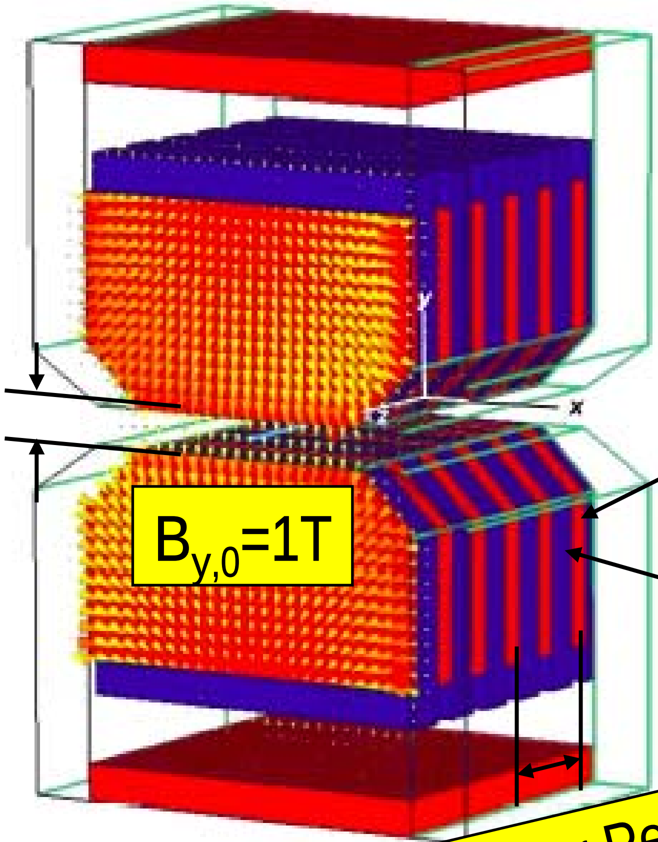
Parameter	FLASH VUV FEL	TABLE-TOP Soft-X-FEL	TABLE-TOP Hard-X-FEL
Current	1.3 kA	100 kA	160 kA
Norm. emitt.	6 mm mrad	1 mm mrad	1 mm mrad
Beam size	170 μm	30 μm	30 μm
Energy	461.5 MeV	491 MeV	1.74 GeV
Energy spread	0.04%	0.45%	0.1%
Undulator period	27.3 mm	5 mm	5 mm
Wavelength	30 nm (41.3 eV)	3 nm	0.25 nm
Saturation length	19 m	1.6 m	5 m
Pulse length	55 fs	10 fs	4 fs
Saturation power	0.8 GW	~20 GW	58 GW

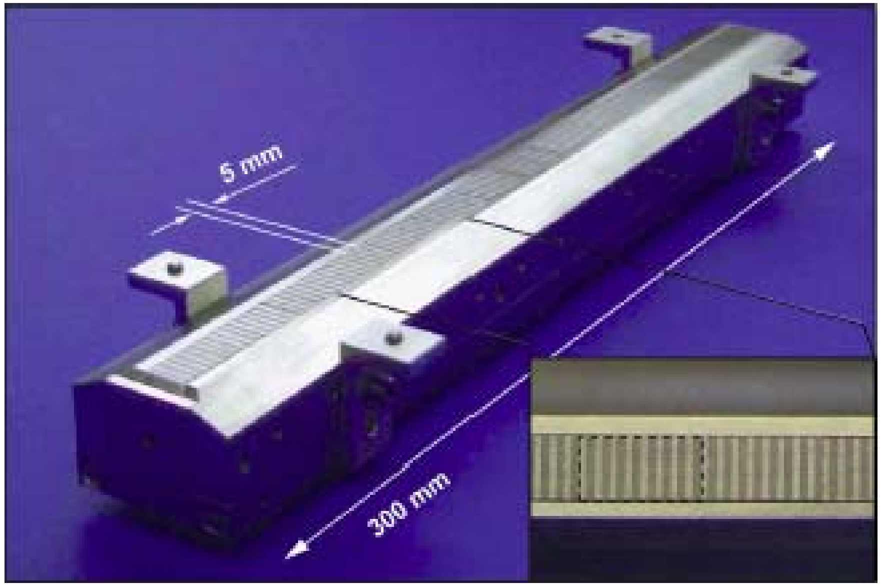
(F. Gruner et al., Appl.Phys. B 86 431, 2007)

Present laser-plasma accelerators are reachable to Table-Top Hard-X-FEL

Hybrid Miniature Undulator Magnet

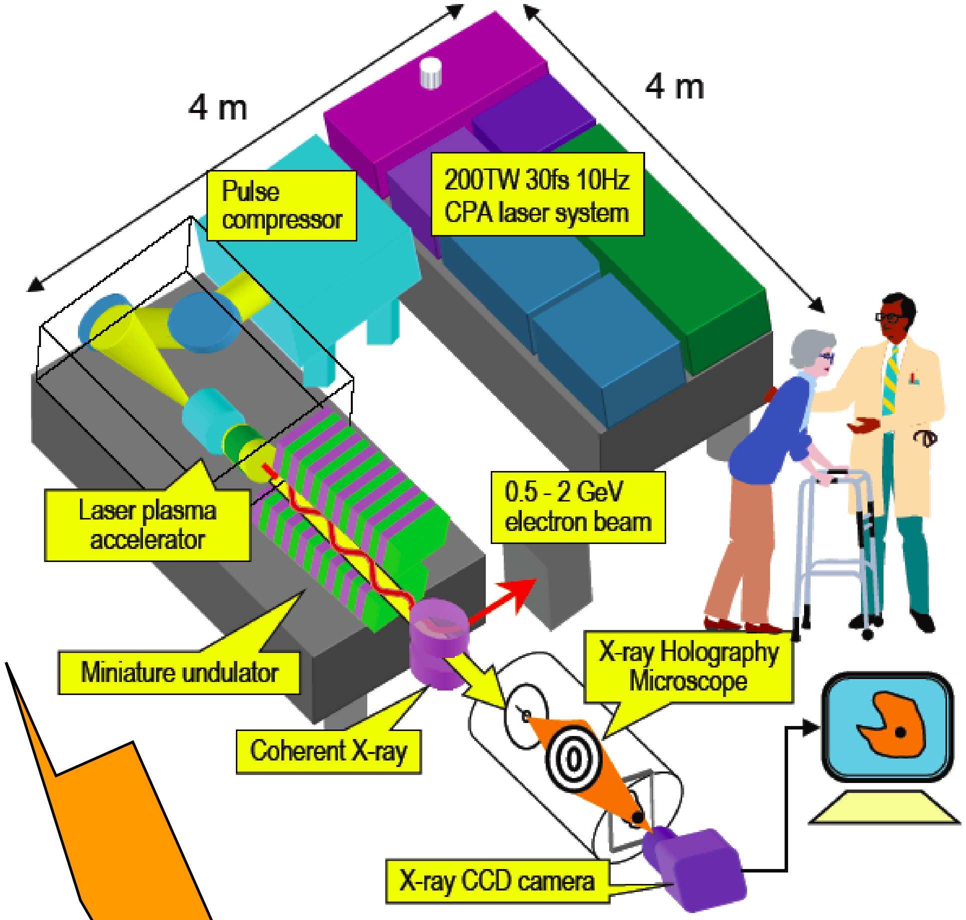
Undulator Parameter
$K=0.93\lambda_u[cm]B_0[T]=0.465$



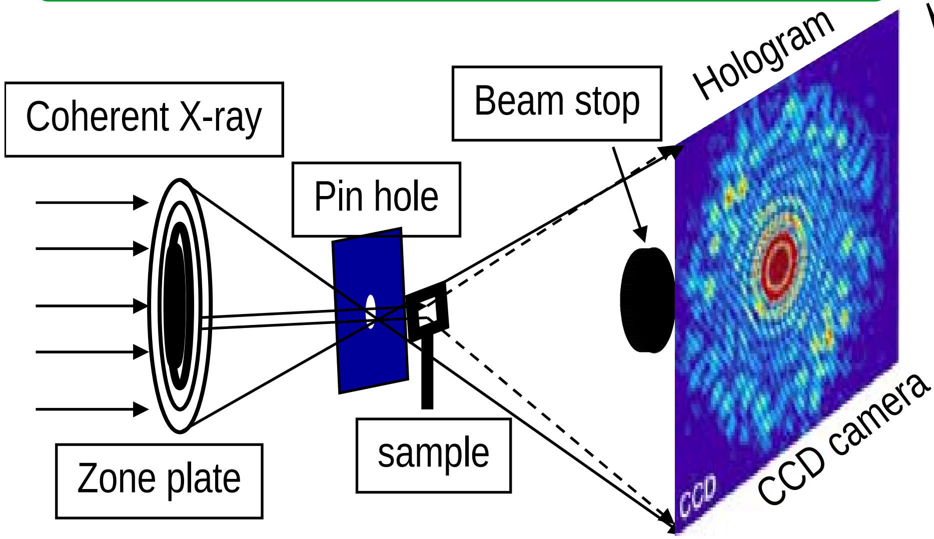


Miniature Undulator
(T. Eichner et al.,
PRST-AB, 10,
082401,2007)

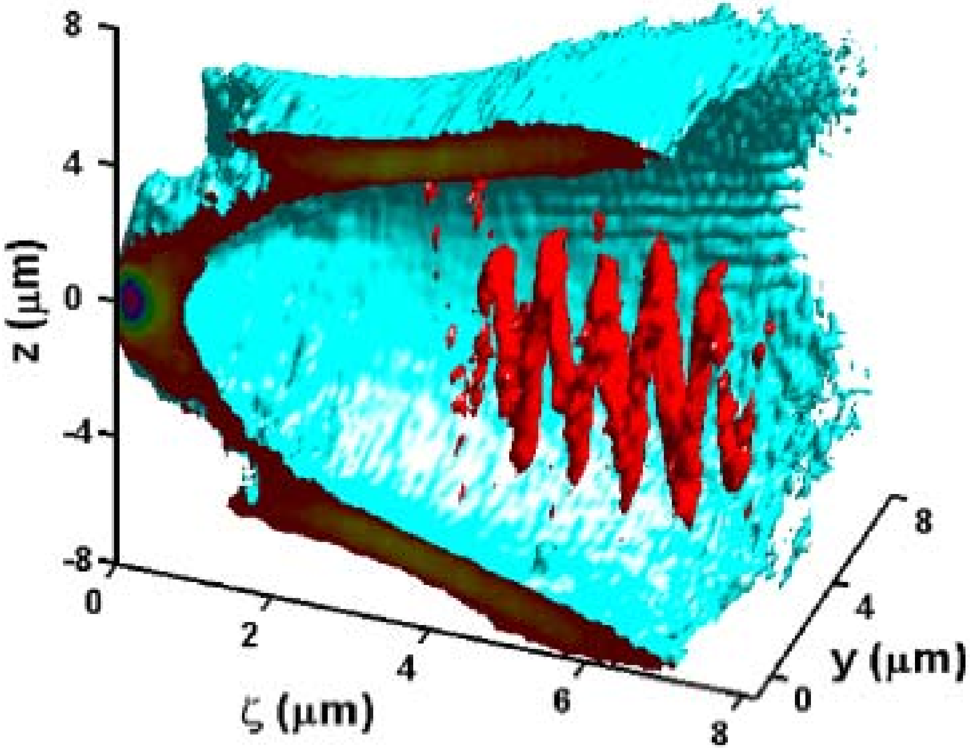
Laser-driven table-top X-ray free electron laser



X-ray Holography Microscope



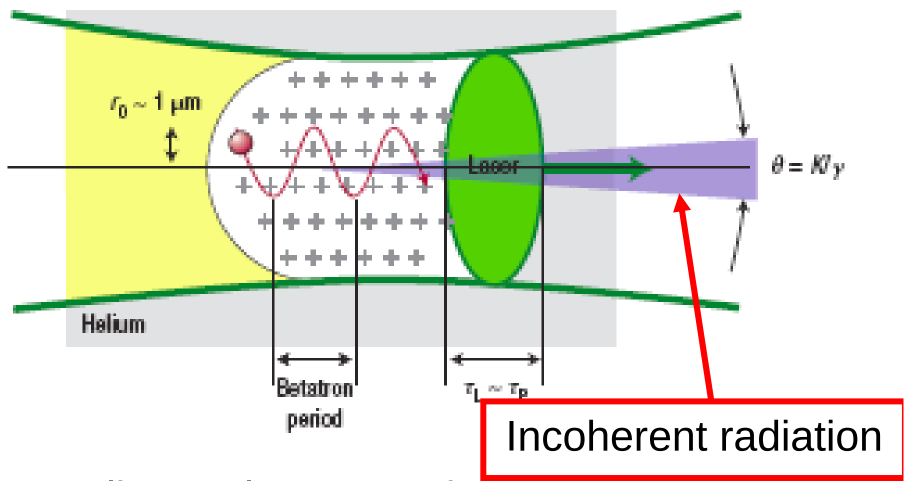
Laser-Driven Betatron X-ray radiation from plasma wiggler



Nemeth et al, PRL 100, 095002 (2008)

No external wiggler !

Plasma wiggler



V. Malka et al., nature physics 4, 447 (2008)

Betatron frequency: $\omega_b = \omega_p / (2\gamma)^{1/2}$

Wiggler strength parameter: $K = \omega_b \gamma r_0 / c$

Peak X-ray energy:

$$E(\text{eV}) = 1.45 \times 10^{-21} \gamma^2 n_e(\text{cm}^{-3}) r_0(\mu\text{m})$$

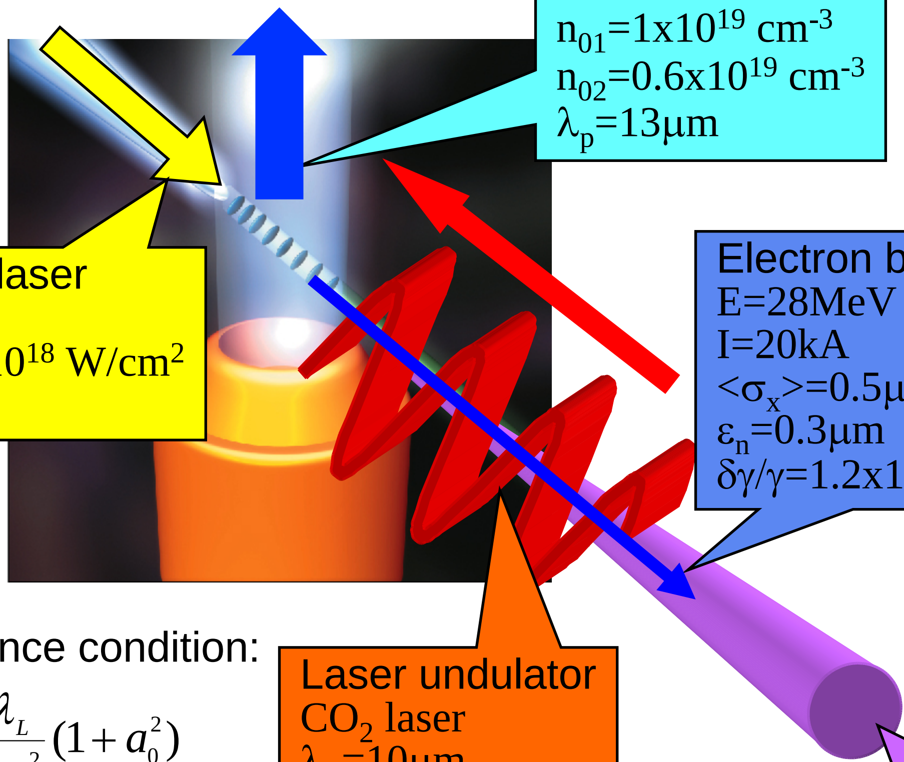
Divergence: $\theta = K/\gamma$

For a 1GeV electron beam with 1mrad divergence, 300 pC charge
10^8 photons/pulse/0.1%BW at 10keV within mrad

All Optical Free Electron Laser with optical undulator, replacing magnetostatic undulator

Plasma injector
$n_{01}=1x10^{19}\ cm^{-3}$
$n_{02}=0.6x10^{19}\ cm^{-3}$
$\lambda_p=13\mu m$

Drive laser
$E_L=2J$
$I_L=7x10^{18}\ W/cm^2$
$\tau=20fs$



Electron beam
$E=28MeV\ (\gamma=55.2)$
$I=20kA$
$\langle\sigma_x\rangle=0.5\mu m$
$\varepsilon_n=0.3\mu m$
$\delta\gamma/\gamma=1.2x10^{-2}$

Laser undulator
CO_2 laser
$\lambda_L=10\mu m$
$a_{0L}=0.8$

Coherent radiation
$\lambda_R=1.35nm$
$\delta\lambda_R/\lambda_R=0.8\%$
$P_{max}=200MW$
$L_R=0.1\mu m$
$L_{sat}=1mm$

Resonance condition:

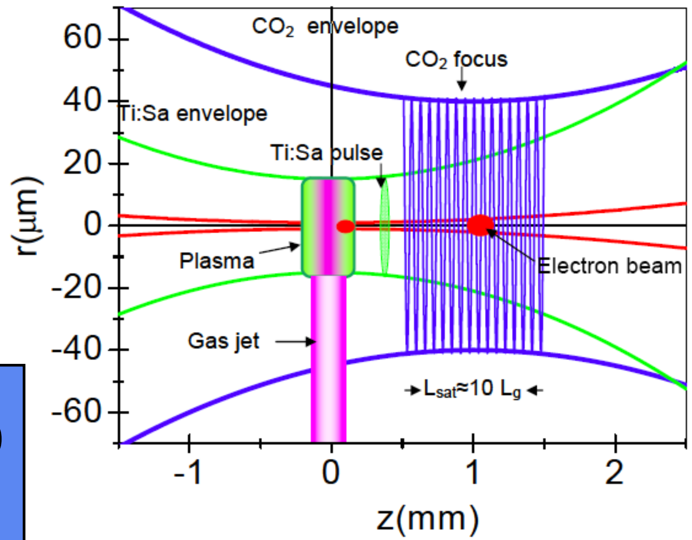
$$\lambda_R=\frac{\lambda_L}{4\gamma^2}(1+a_0^2)$$

Cooperation length:

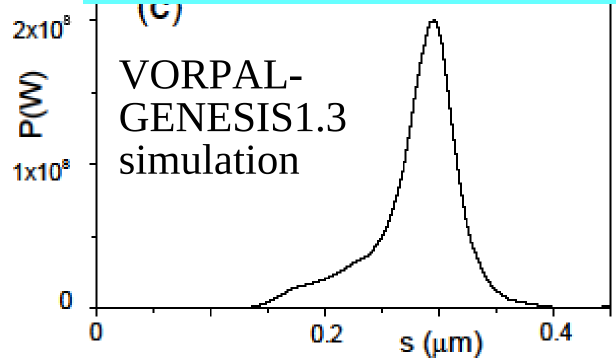
$$L_c=\frac{\lambda_R}{4\pi\sqrt{3}\rho}$$

Superradiant condition:

$$L_b/2\pi L_c<1$$



SASE superradiant FEL

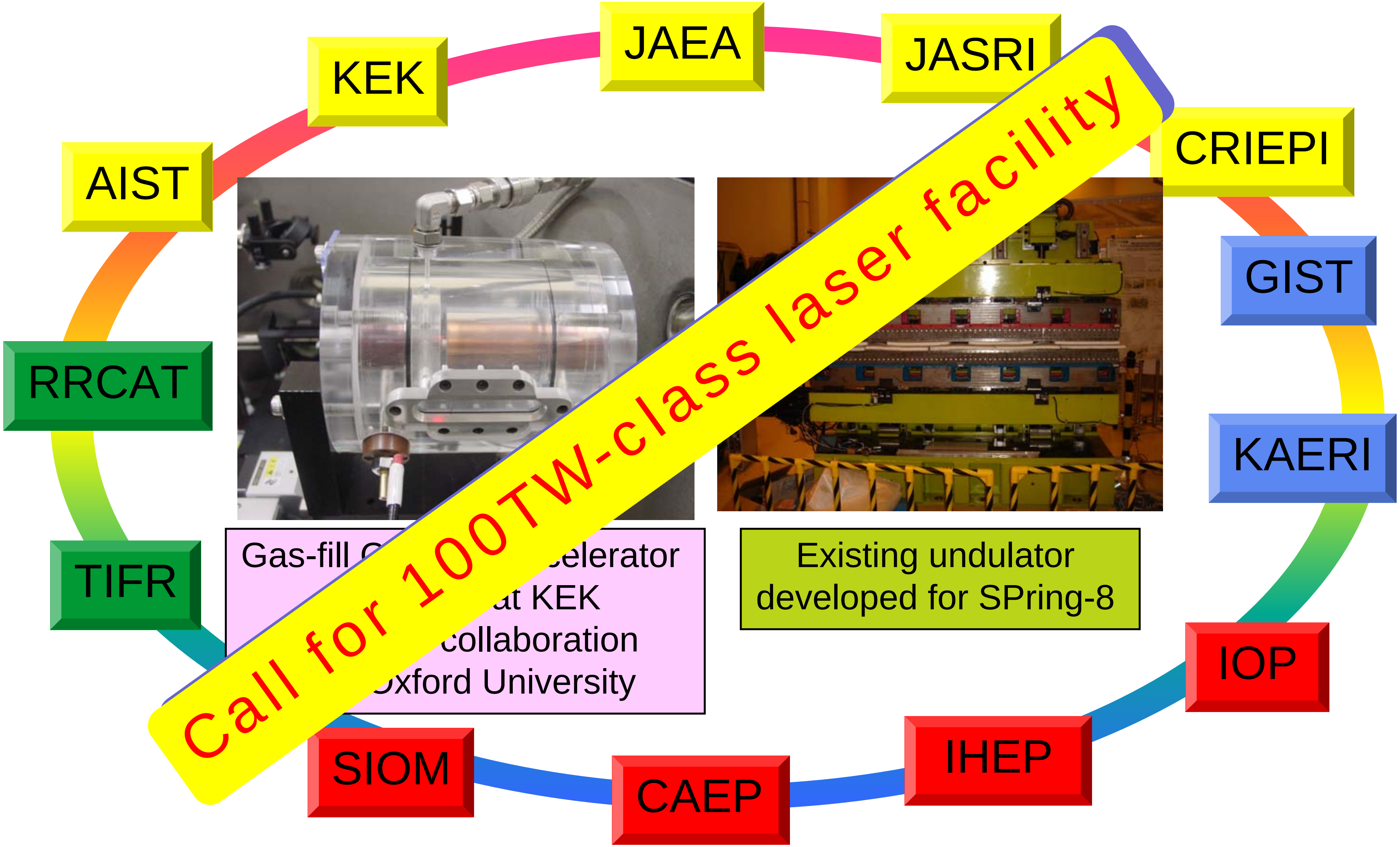


FEL parameter: $\rho=3x10^{-3}$
$L_c=0.14\mu m$
Beam length: $L_b=0.5\mu m$
$L_b/2\pi L_c=0.57$

Petrillo et al., PRST, 2008

Toward a table-top X-ray FEL

The first X-FEL application of laser plasma accelerators may be made by **A**sian **I**ntense **L**aser **N**etwork and **A**sian **C**ommittee for **F**uture **A**ccelerator.



Summary

- Laser plasma accelerators achieve the beam energy of multi-GeV with ~1% energy spread and ~1 mrad divergence.
- Laser-plasma accelerator makes it possible to build a km-scale X-ray free electron laser on a table top.
- All optical free electron laser with optical undulator makes a further compact X-ray FEL.

謝謝！！

Thank you for attention