Future Light Sources

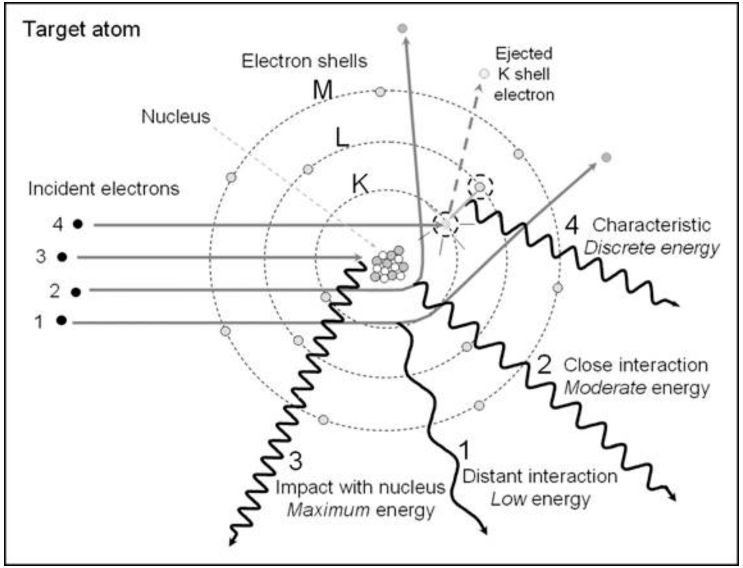
Mark Boland

AOF Synchrotron School

29 May 2017

CREATING RADIATION

Electrons interacting with atoms to make x-rays

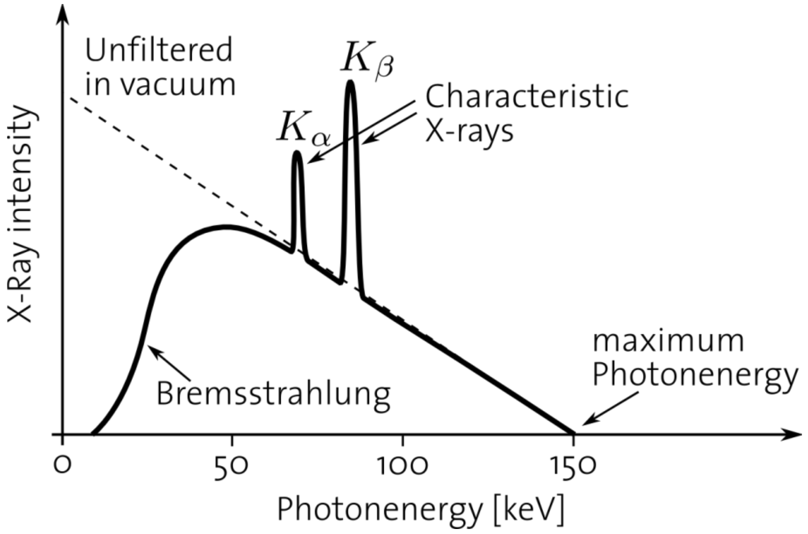


JNMT Journal of NUCLEAR MEDICINE TECHNOLOGY

X-ray production by energy conversion. J. Anthony Seibert J. Nucl. Med. Technol. 2004;32:139-147

- Traditionally x-rays are created using energetic electrons interacting with atomic electrons

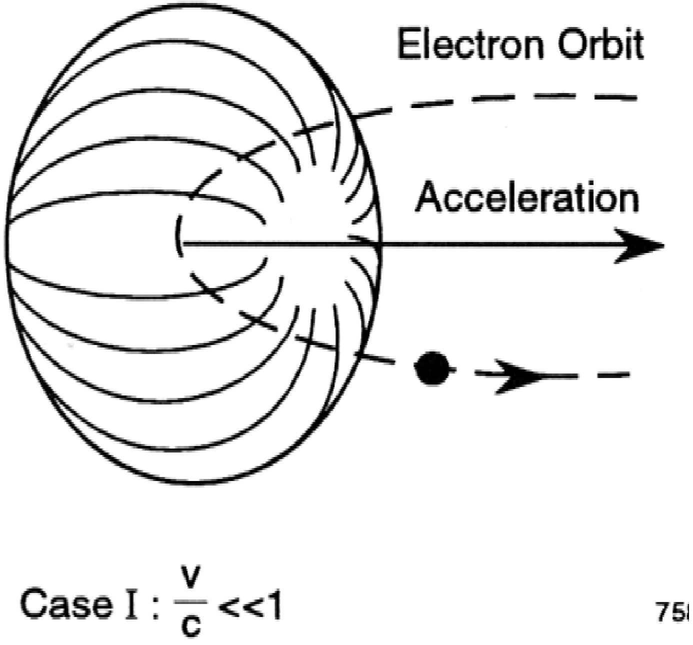
X-ray tube spectrum

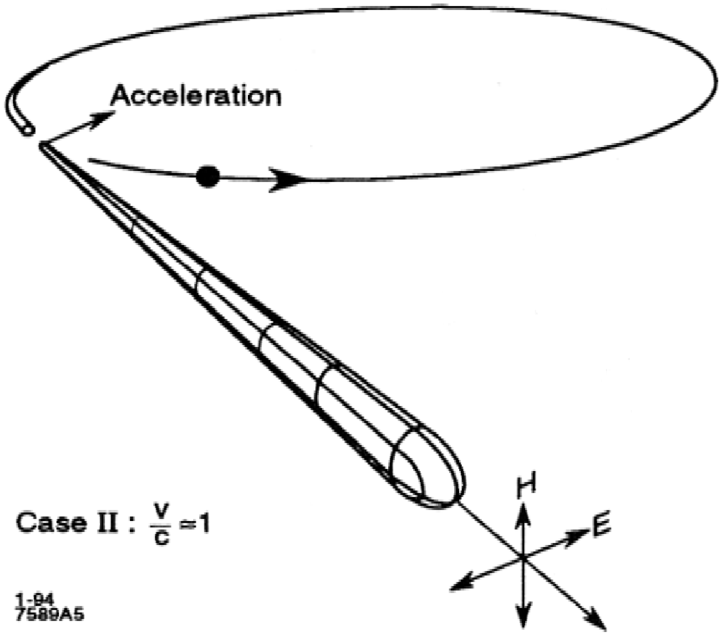


- Not tunable, x-ray lines characteristic of the material
- Broad angular and spectral distribution
- Low Coherence

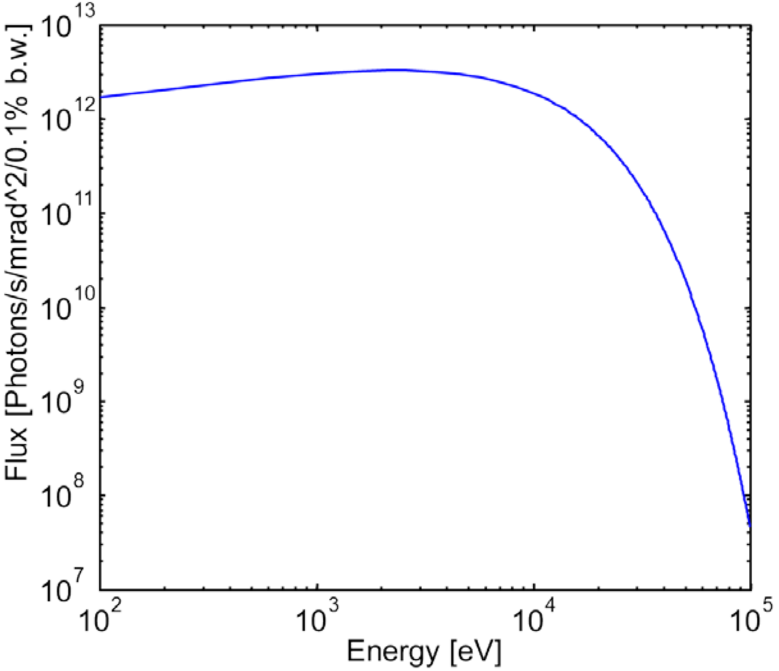
https://miac.unibas.ch/PMI/01-BasicsOfXray.html

Relativistic Lorentz Boost

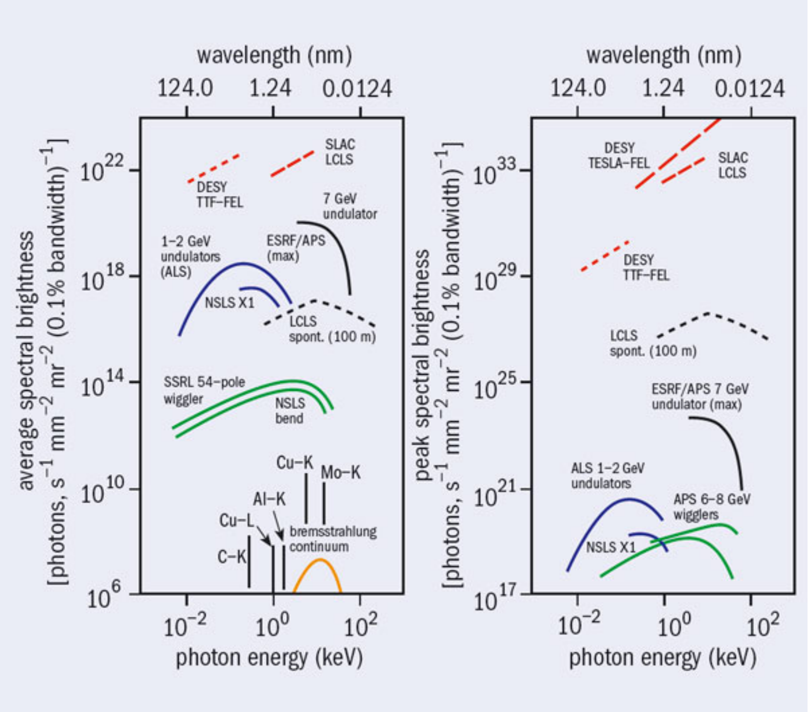




Dipole Magnet Synchrotron Radiation



Radiation from Relativistic electrons



CERN Courier
Nov 30, 2010
Making X-rays: bright times ahead for FELs

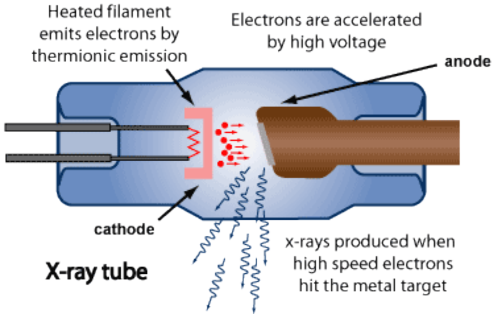
- Store relativistic electrons in a magnetic trap called a storage ring
- Achieve high currents (~500 mA) and fast repetition rates (~500 MHz)
- Tunable in energy and time

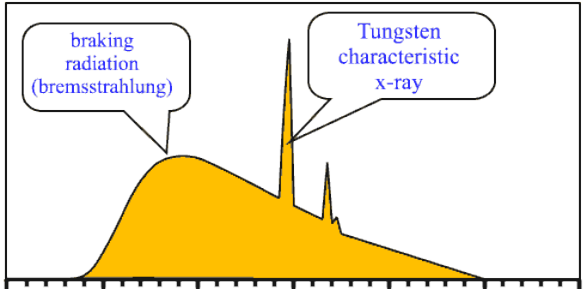
GENERATIONS OF LIGHT SOURCES

Current lab X-ray Laboratory Sources

X-ray tubes:

- Broadband with few characteristic lines
- Reasonable photon flux but limited brilliance

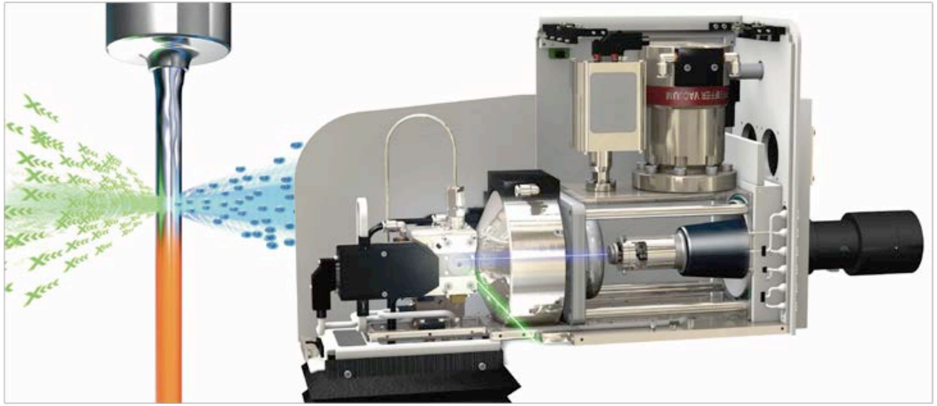




<u>Exciting development:</u>

Liquid Ga source:

- 9.2 keV line (Ga K_{α})
- Very good brilliance
- Unfortunately no wavelength tunability



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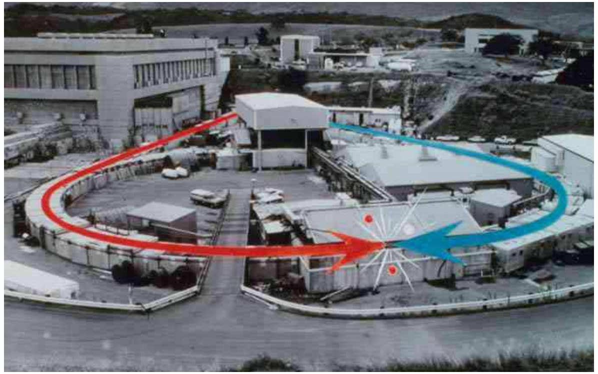
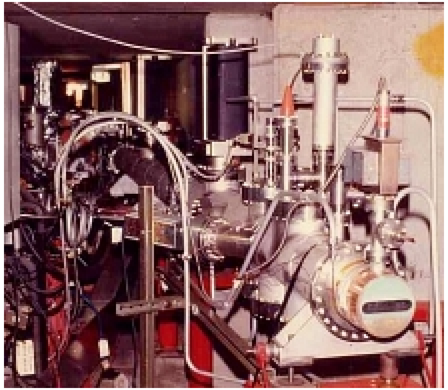
REDEFINING THE X-RAY TUBE

First Generation Storage Rings

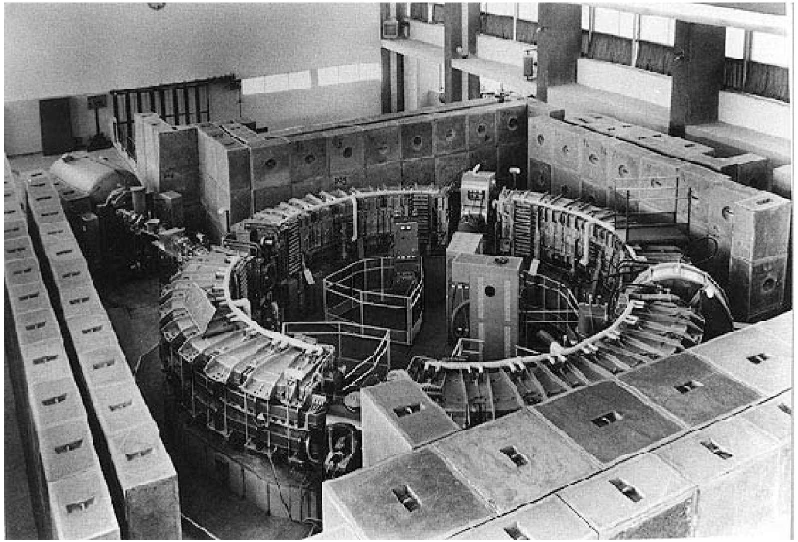




Stanford Synchrotron Radiation Project pilot project beamline inside SPEAR, 07/06/1973. (SLAC Archives)

- Rings build for colliding beams
- Photon beamlines operated parasitically
- Machines built and run primarily for High Energy Physics

Second Generation Storage Rings



Febbraio 1959: L'elettrosincrotrone in funzione; in alto a sinistra l'iniettore

- Dedicated machines
- Large emittance
- Bending magnet radiation
- Low energy x-rays

Third Generation Storage Rings

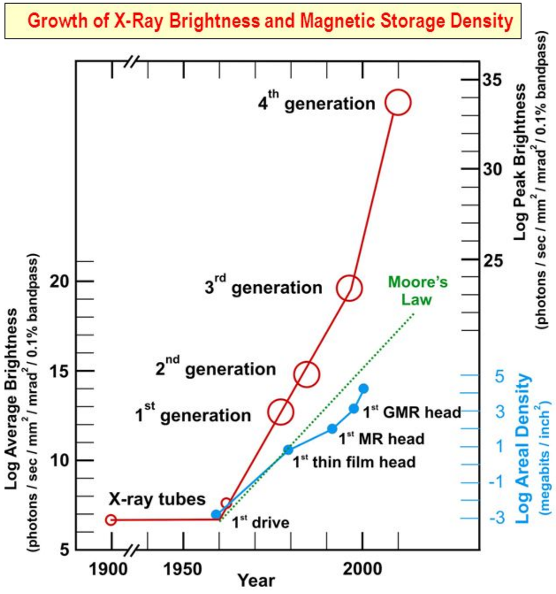
- Dedicated user facilities for photon sources
- Addition of straight sections for Insertion Devices (IDs)
- Pictured are two pioneers:
  - Herman Winick pioneer of the use of IDs and
  - Toshiyuki Mitsuhashi pioneer of the measurement of Synchrotron Radiation properties

Fourth Generation Storage Rings

MAX IV, Lund University, Sweden

- Ultra low emittance
- Improved design and technology
- High quality insertion devices

Rapid Development in Brightness



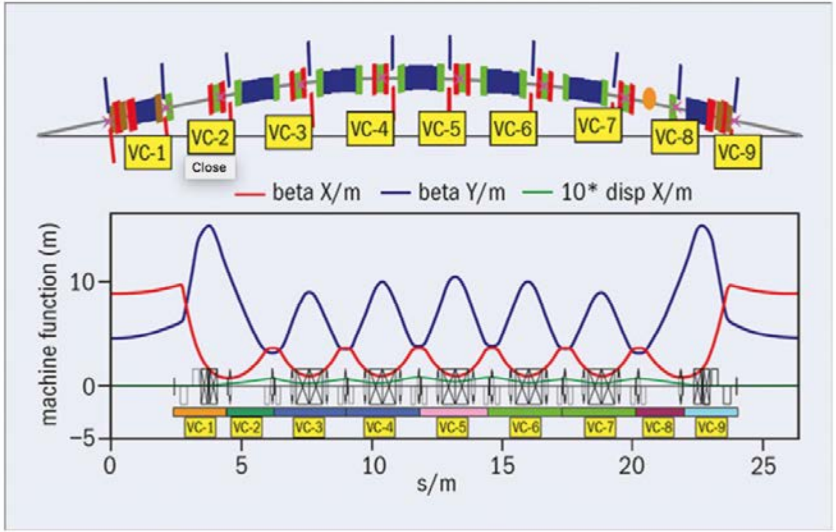
- Constantly improving design and technology
- High quality magnets
- Feedback systems to stabilise high current electron beams

Storage Ring World Map

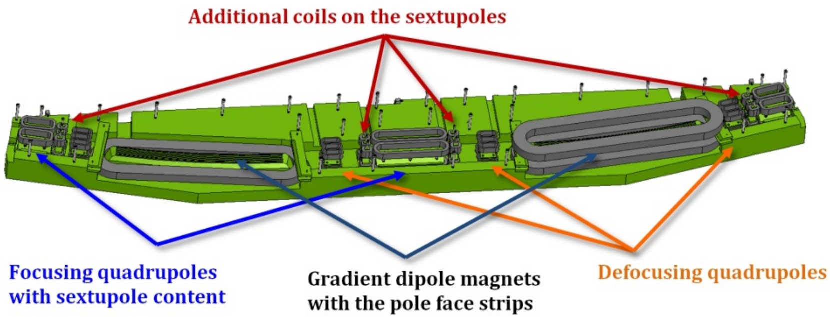
Fig. 4. Synchrotron radiation sources around the world.

M.E. Couprie
New generation of light sources: Present and future ☆
Journal of Electron Spectroscopy and Related Phenomena, Volume 196, 2014, 3–13
http://dx.doi.org/10.1016/j.elspec.2013.12.007

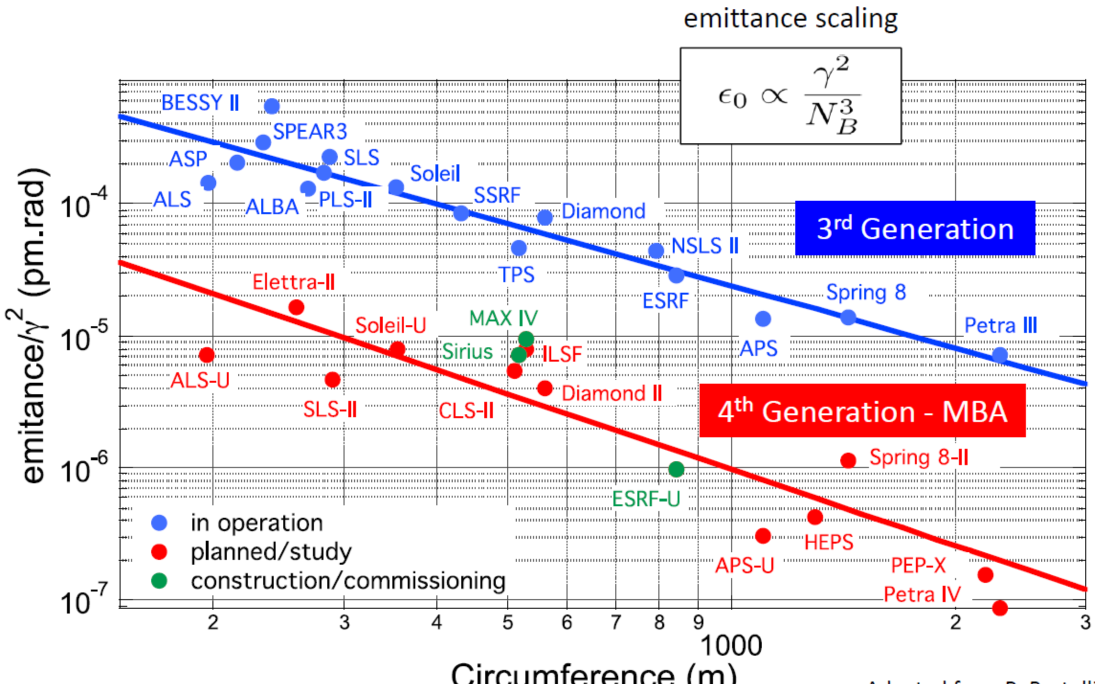
Enabling Technology



- Compact magnets with high gradients
- Vacuum technology for small pipes



Evolution of Storage Rings



Adapted from R. Bartollini

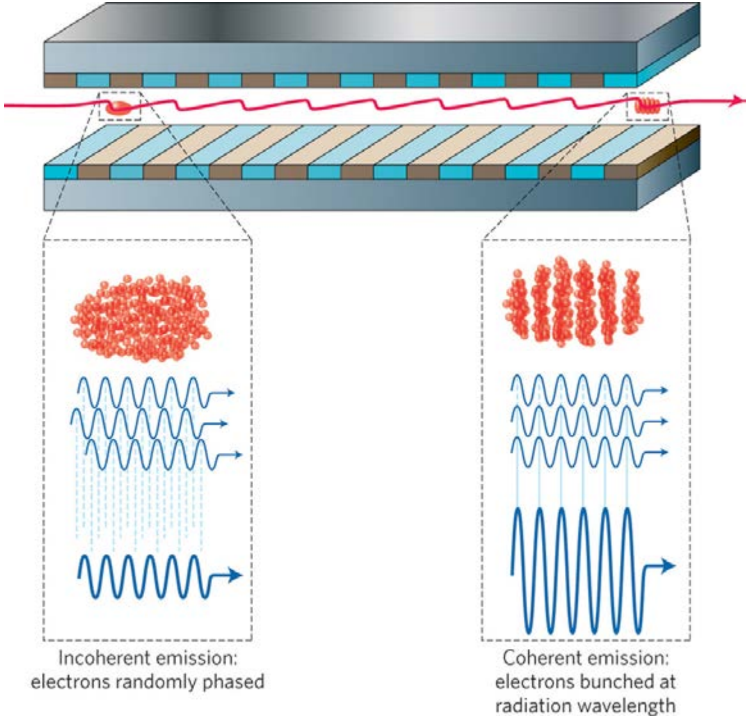
Liu Lin, IPAC'17

New Storage Rings and Upgrade Plans

Machine	Energy [GeV]	Circum. [m]	Emit. [pm]	N_B	Status	
MAX-IV	3	528	140	330	operation,	new
Sirius	3	518	100	250	construction,	new
ESRF-U	6	844	224	135	construction,	upgrade
ALS-U	2	196	108	109	planned,	upgrade
APS-U	6	1104	280	42	planned,	upgrade
CLS-II	3	510	147	186	planned,	new
Diamond-II	3	561	144	140	planned,	upgrade
Elettra-II	2	259	72	250	planned,	upgrade
HEPS	6	1296	336	59	planned,	new
ILSF	3	528	100	275	planned,	new
PEP-X	4.5	2199	12		planned,	upgrade
PETRA-IV	6	2304	504	12	planned,	upgrade
SLS-II	2.4	290	84	103	planned,	upgrade
Soleil-II	2.75	354	104	230	planned,	upgrade

ALTERNATIVES TO STORAGE RINGS

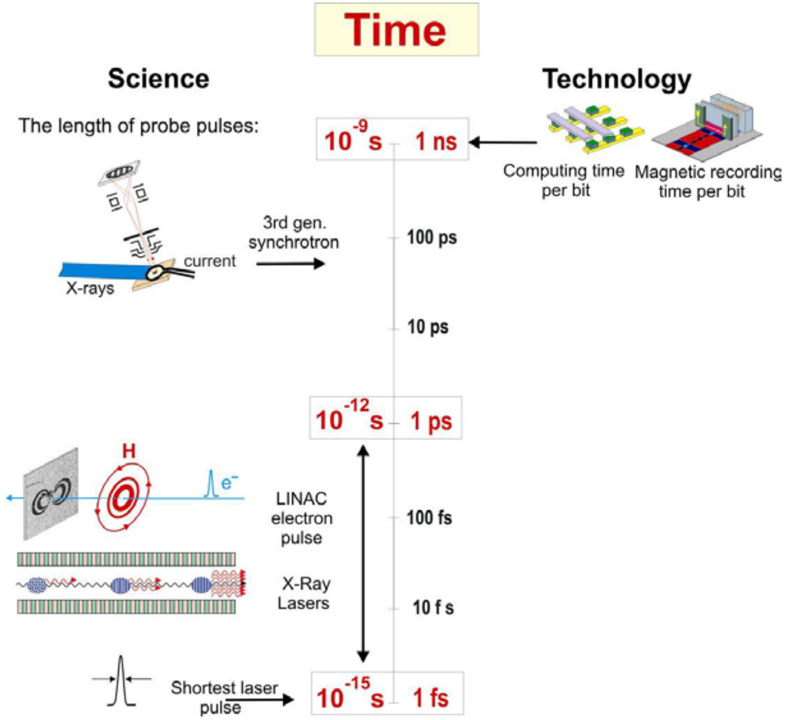
Free Electrons Lasers



- Bunches of electrons from a linac pass into an undulator
- Over time microbunches form enhancing the coherence
- Radiation emission coherent, N^2 with the number of electrons (c.f. N for a storage ring)
- 10^{33} instantaneous brightness on femtosecond time scale

X-ray free-electron lasers
Brian W. J. McNeil
Neil R. Thompson
Nature Photonics 4, 814–821 (2010) doi:10.1038/nphoton.2010.239

Radiation Time Structure



- Storage Ring time structure ~10 ps every ~1 ns
- FEL time structure ~10 fs every ~1 ms
- Fast time structure allows pump-probe experiments:
  - Excite sample with one photon source
  - Measure relaxation of sample with varying time delay

FEL World Map

Fig. 6. Map of FELs: in project in italic, in red for VUV soft X ray, in blue for hard X-ray. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

M.E. Couprie
New generation of light sources: Present and future ☆
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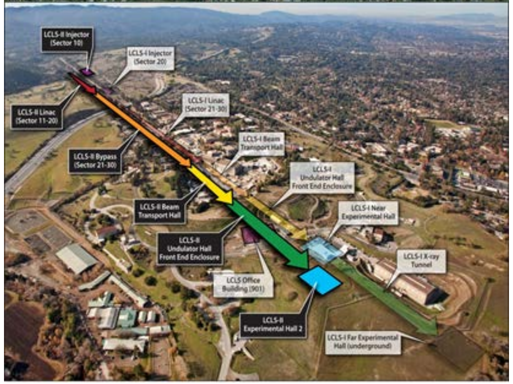
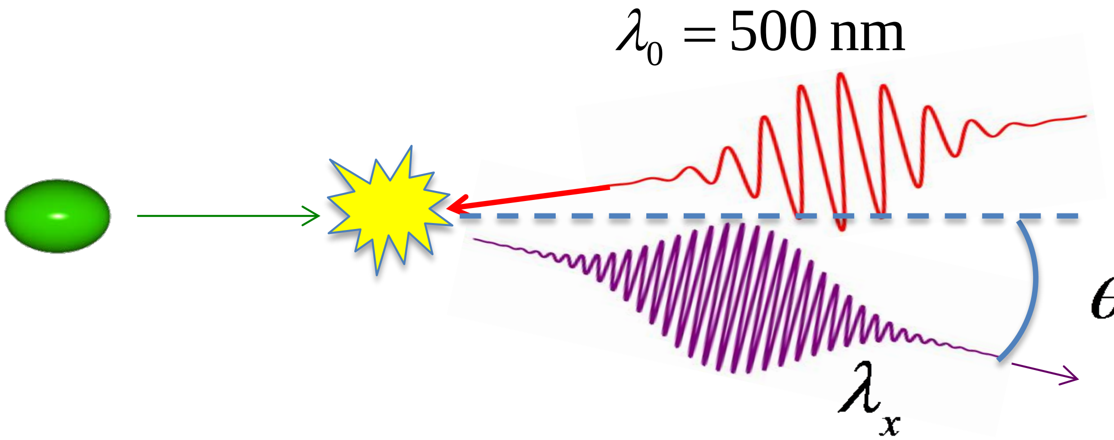
http://dx.doi.org/10.1016/j.elspec.2013.12.007

Limitations of XFELs



- Very large and expensive
- Only 1-2 beamlines can operate at a time

Inverse Compton Scattering (ICS):head on collision

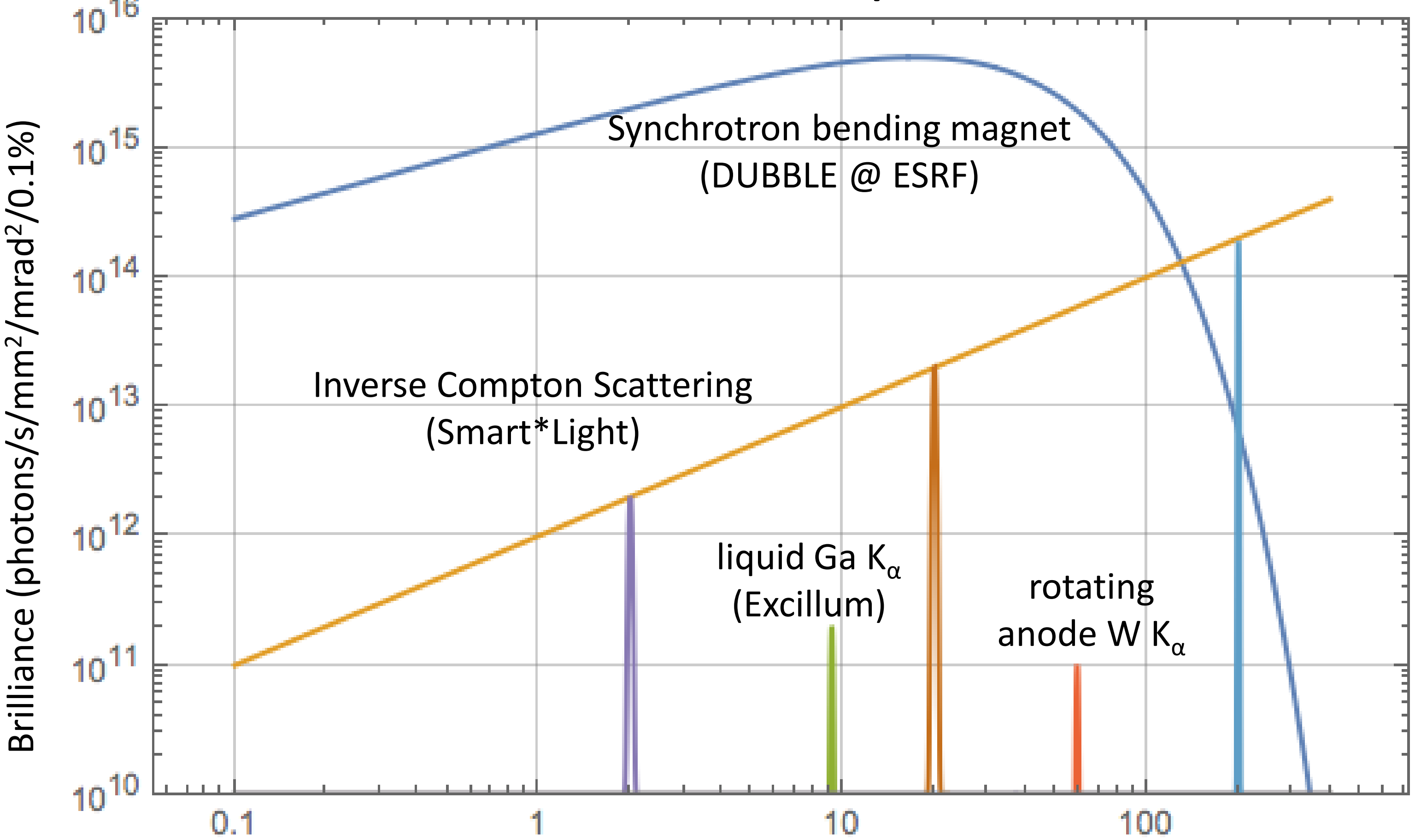


$$\lambda_x = \frac{\lambda_0}{4\gamma^2}(1+\gamma^2\theta^2)$$

- X-rays emitted in narrow cone, half angle γ^{-1}
- X-ray energy dependent on emission angle
- 1% energy spread if $\theta < 0.1\ \gamma^{-1}$

Electron energy	Lorentz factor γ	X-ray Wavelength	X-ray energy	Emission angle 0.1 γ^{-1}
5 MeV	11	10.8 Å	1.2 keV	9 mrad
15 MeV	30	1.4 Å	9.1 keV	3 mrad
25 MeV	50	0.50 Å	24.7 keV	2 mrad
50 MeV	99	0.13 Å	96.7 keV	1 mrad

Brilliance Comparison



Lyncean TECHNOLOGIES, INC.

ICS sources: Lyncean

first commercial ICS source

- Limited in energy
- Poor tunability
- Long pulses

Journal of
Synchrotron Radiation
ISSN 0909-0495

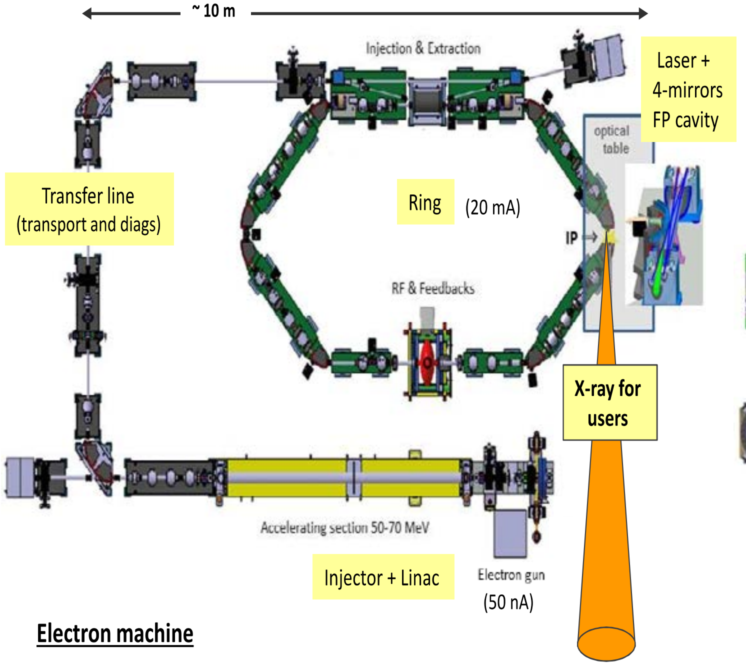
Received 6 September 2008
Accepted 23 October 2008

Hard X-ray phase-contrast imaging with the Compact Light Source based on inverse Compton X-rays

Martin Bech,[a]* Oliver Bunk,[b] Christian David,[b] Ronald Ruth,[c,d] Jeff Rifkin,[c] Rod Loewen,[c] Robert Feidenhans'l[a] and Franz Pfeiffer[b,e]*

ICS sources: ThomX

under construction

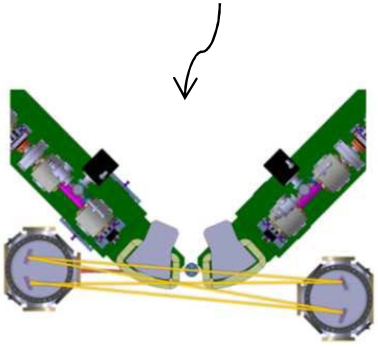


Electron machine

- 1 nC / bunch , 50 Hz inj. freq.
- **50-70 MeV**
- Ring, 20 MHz frep.
- **σ_e ~ 70 µm**
- **ε_N ~ 4 mm.mrad**
- τ_e ~ 10-20 ps

X-ray beam

Flux	10^{13}
Brigthness	10^{11}
Transv. size	70 µm
E_X	20-90 KeV

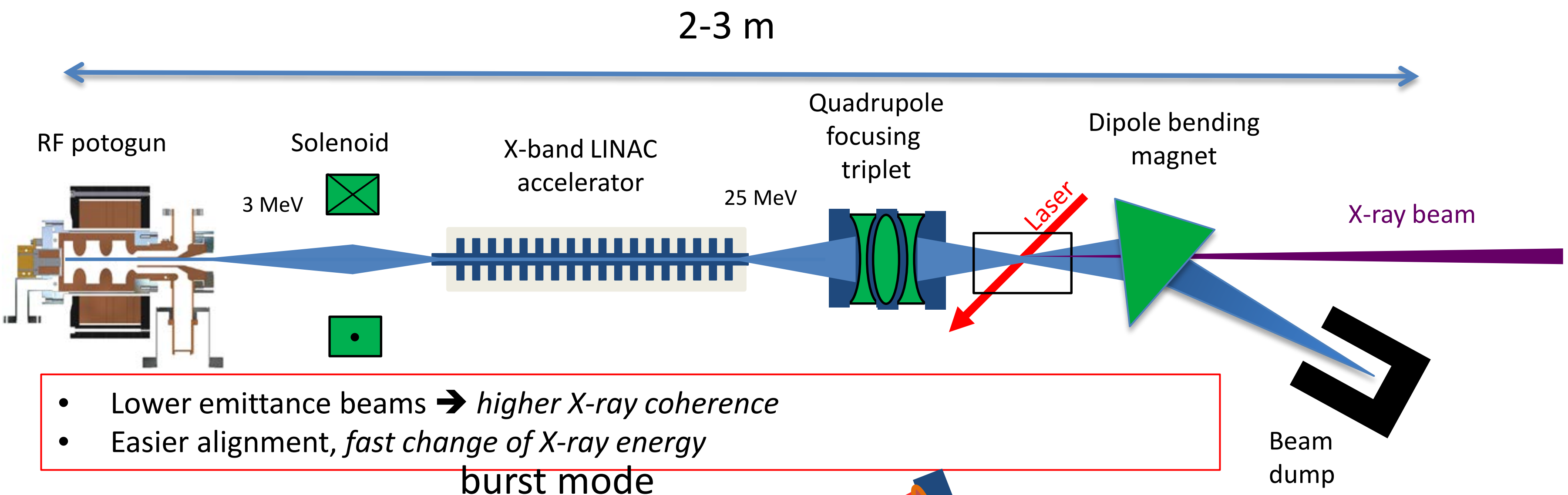


Laser /Cavity system

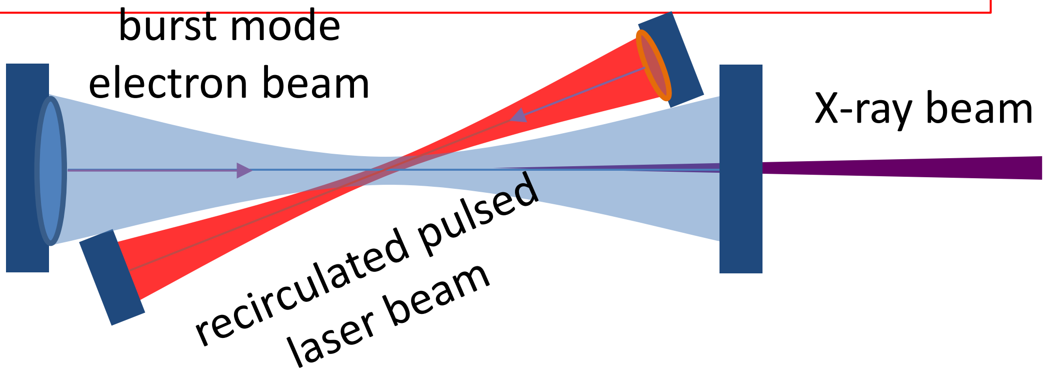
- Pulsed laser : ps , ~ 1W average
- Optical fiber amplification
  → (100 W) 2-3 µJ/pulse
- Optical FP cavity amplification
  → (gain 10000)

→ **1 MW stored inside the cavity**
→ (20-30 mJ/pulse)

LINAC-based ICS sources: why?

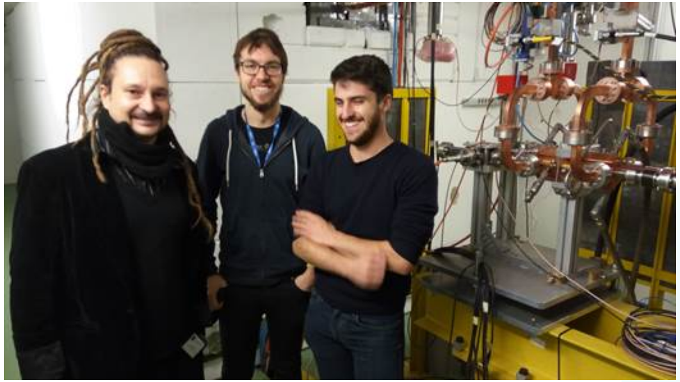


- Lower emittance beams ➔ *higher X-ray coherence*
- Easier alignment, *fast change of X-ray energy*

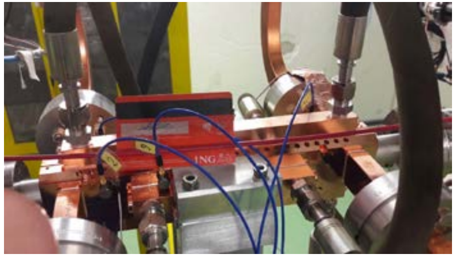


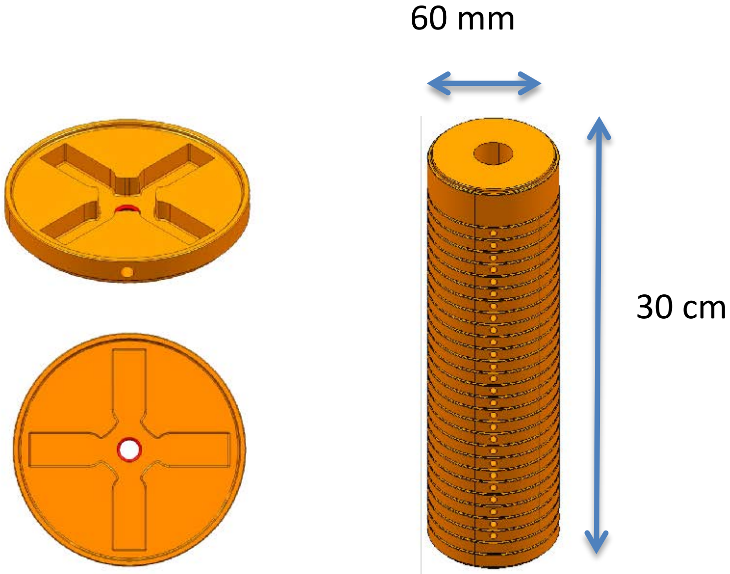
Enabling technology: compact 12 GHz X-band LINAC

Developed by CERN, PSI and VDL-ETG collaboration



X-band test facility @ CERN





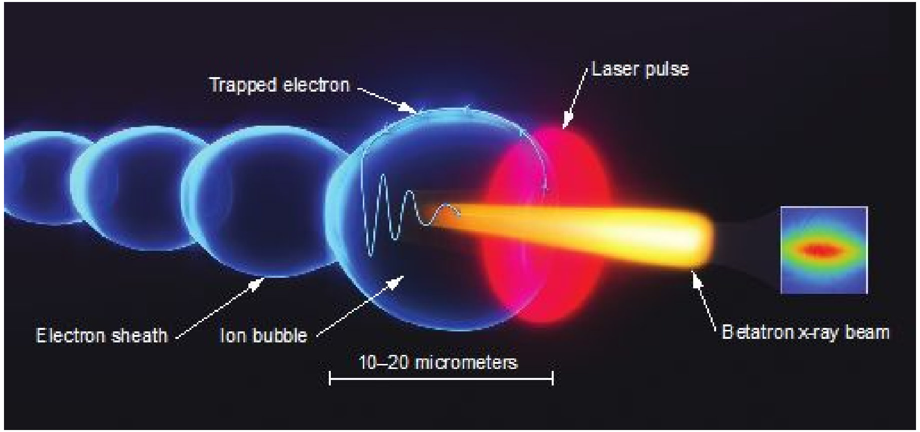
24 disks

- 12 GHz accelerator structure
- 50 MV/m average operating gradient
  (Max average gradient 100 MV/m)

1 m long accelerator structure sufficient for generating up to ~100 keV monochromatic X-ray beams

NOVEL ACCELERATOR CONCEPTS

Laser Plasma Accelerator



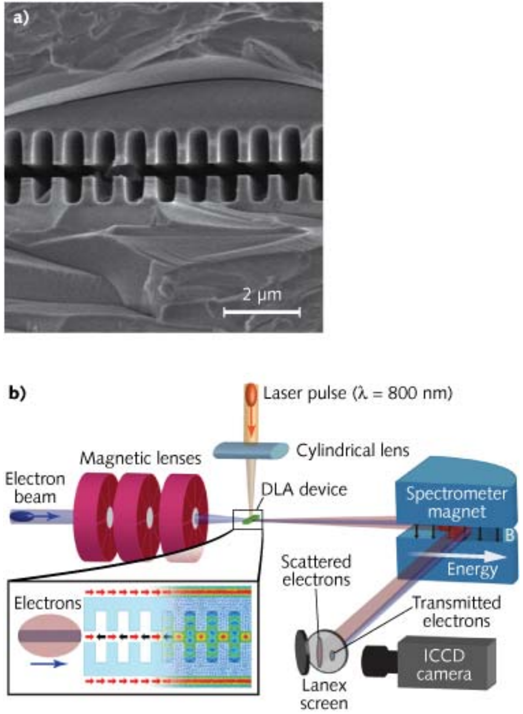
- Extremely high gradients
- Low efficiency
- Shot-to-shot unstable

Laser wakefield accelerator based light sources: potential applications and requirements

F Albert1, A G R Thomas2, S P D Mangles3, S Banerjee4, S Corde5, A Flacco6, M Litos5, D Neely7, J Vieira8, Z Najmudin3Show full author list

Published 22 July 2014 • © 2014 IOP Publishing Ltd
Plasma Physics and Controlled Fusion, Volume 56, Number 8

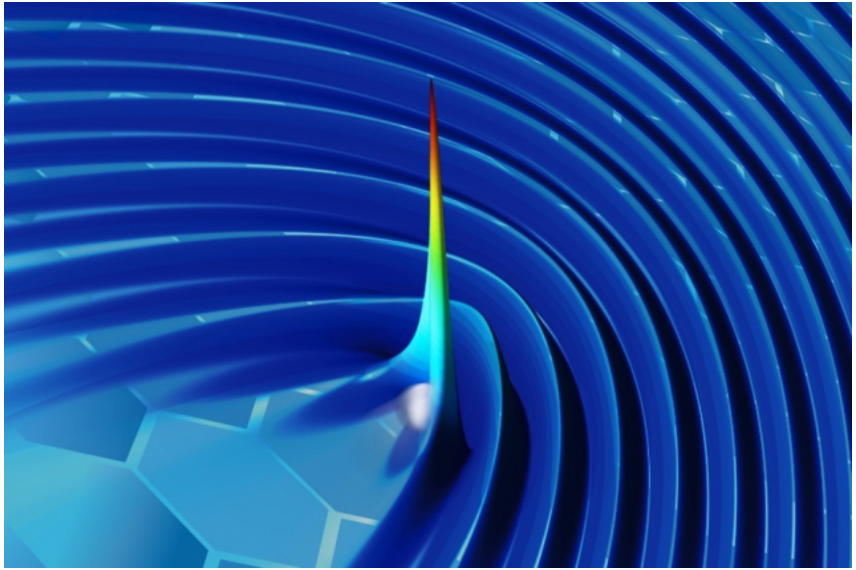
Laser Dielectric Accelerator



- High gradient
- Hard to align
- Still requires relatively high injection energy

Demonstration of electron acceleration in a laser-driven dielectric microstructure
E. A. Peralta et. al. Nature 503, 91–94 (07 November 2013) doi:10.1038/nature12664

Extreme Ideas



Towards graphene plasmon-based free-electron infrared to X-ray sources
Liang Jie Wong et. al. Nature Photonics 10, 46–52 (2016)
doi:10.1038/nphoton.2015.223
http://nature.com/articles/doi:10.1038/nphoton.2015.223

- Use graphine and atomic lattice structures to achieve electron accelerator