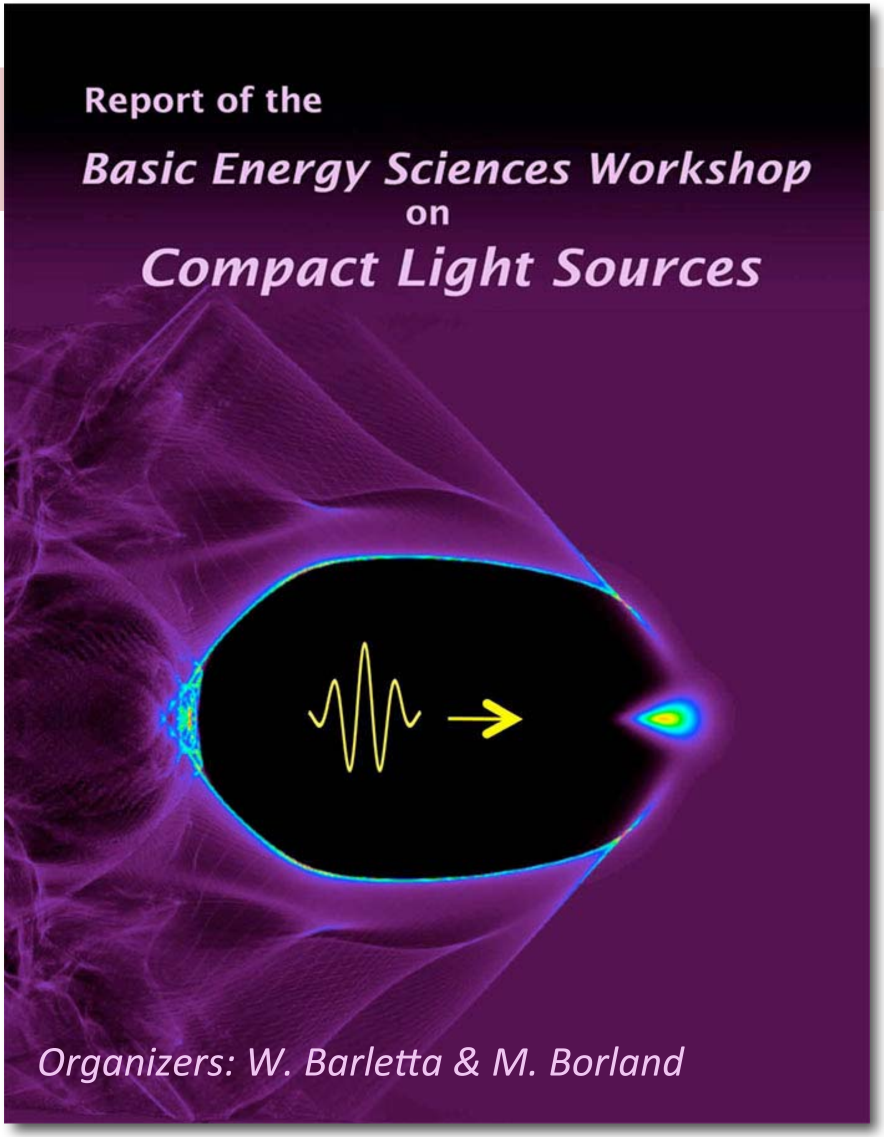

Report of the

Basic Energy Sciences Workshop

on

Compact Light Sources

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Charge to the workshop

- Evaluate alternatives to canonical light sources that are becoming increasingly costly
- Examine the state of the technology for compact light sources (CLS) & expected progress in emerging technologies
- Identify advantages & disadvantages of CLS relative to third generation storage rings and FELs

Evaluate Compact Light Source

Cost effectiveness, User access & availability, Reliability

- We did not try to rank or directly compare approaches

What do we mean by a compact light source?

- Size: “University-scale” < few hundred m^2
- Capital cost: < few tens of M$
- Operating cost: few M$/year
- Possibly modular or easily expanded

Advances in accelerator, laser, & nanotechnology
offer opportunities to build high performance X-ray sources
of the scale of a university laboratory

Overarching conclusions

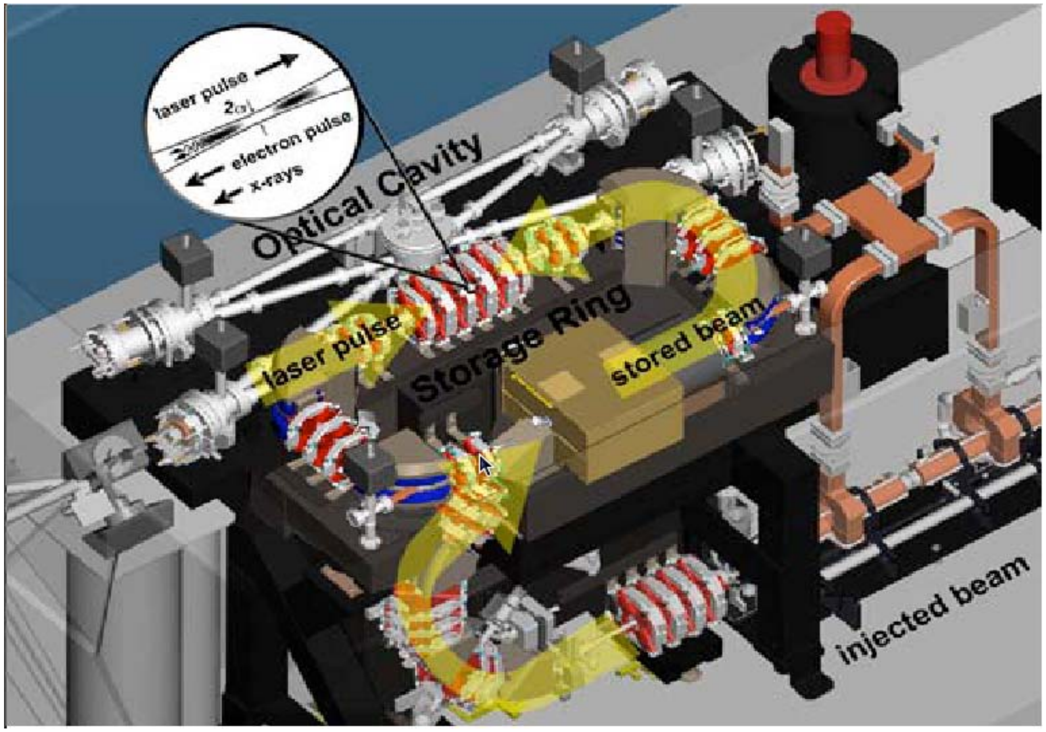
- Compact light sources are ***not a substitute*** for large, synchrotrons & FELs that typically incorporate extensive user support facilities
- Scientific & technological vitality of X-ray science depends on access
- Compact light sources offer attractive, *complementary capabilities*
  - Small fraction of the cost & size of large national user facilities
  - Rapid turn around for high risk research, often unexpected breakthroughs
  - Rapid advance in source technologies
  - Impact on broad range of science & technology, even medicine
  - Personnel (i.e. students, scientists) with versatile capabilities
  - Potential for technological and commercial application
  - Take source to application
- On a 10 year plus timescale, they offer the potential for a new paradigm national user facility

R&D that would enhance performance potential of both compact & large sources

- IR laser systems delivering kW-class average power with femtosecond pulses at kHz repetition rates.
  - Application to ICS sources, plasma sources, & HHG sources, & seeding sources for conventional FELs
- Laser cavities for storage of 10 mJ, ps & fs pulses focused to µm beam sizes
- High-brightness, high-repetition-rate electron sources
- CW superconducting rf-linacs operating at 4 K, while not essential, would reduce capital and operating costs

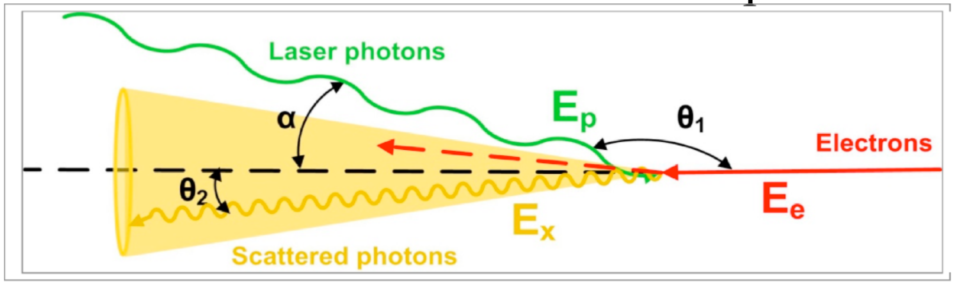
These items could be developed on a 5 year time scale assuming adequate funding

Inverse Compton Scattering Sources (ICS)



With ICS *X-ray flux ~ laser pulse energy*

- Collision between a relativistic electron & a photon



- In normal Compton scattering the $E_\gamma > E_e$
- Inverse process has the Thomson cross-section when $\hbar\omega < \gamma$
- Scattered photon satisfies the undulator equation with period $\boldsymbol{\lambda_L/2}$ for head-on collisions

$$\lambda_x = \lambda_L \frac{1+\gamma^2\theta^2}{4\gamma^2}$$

- ==> X-ray energy decreases by a factor of 2 at an angle of $1/\boldsymbol{\gamma}$
- Photon energy reach into hard gamma rays

Challenge is matching laser & e-beam pulses in time & space

Present & near term planned performance: CW machines

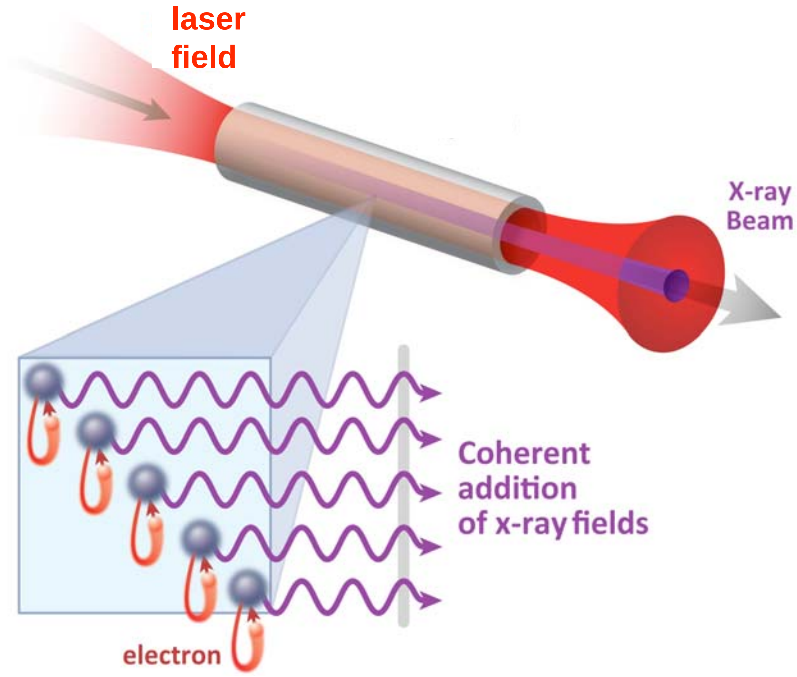
Machine	Range (keV)	Average Brightness	Peak Brightness	Flux (0.1% BW)	Pulse width (ps)	Rep Rat (MHz)
JLAB	7-50 100-3k	10^8	10^12	10^9	0.3	75
KEK	0.1 - 50	10^16	CW	10^13	5	163
Lyncean	7-70	10^12	CW	10^11	100	65
MIT (proposed)	0.8 - 50	10^15	10^19	10^12	0.3	100
THOMX	50-90	10^11	CW	10^11	20	25

Coherent Compton scattering would increase brightness several orders of magnitude

Present & near term planned performance: Timing mode pulsed machines

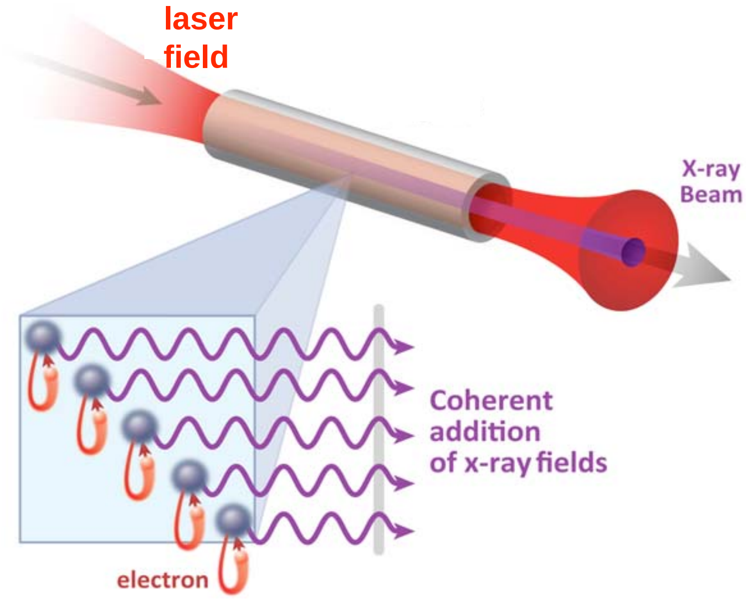
Machine	Range (keV)	Peak Brightness	Photons/shot (0.1%)	Pulse width (ps)	Rep Rat (Hz)
BNL	1-30		10^8	4	10
LBNL-LPA	10-10k	10^{22}	10^4	.003	10
LLNL (planned)	600 400-5k	10^{16} 10^{21}	10^6	1	10 >>100
MIT (proposed)	0.8 - 50	10^{23}	10^8	0.5	10

High-Harmonic Generation (HHG) in gases



HHG driven by femtosecond lasers

- Low cost, stand-alone, table-top-scale, tunable EUV/XUV source
  - ➙ Full spatial and temporal coherence & ultrafast pulse duration



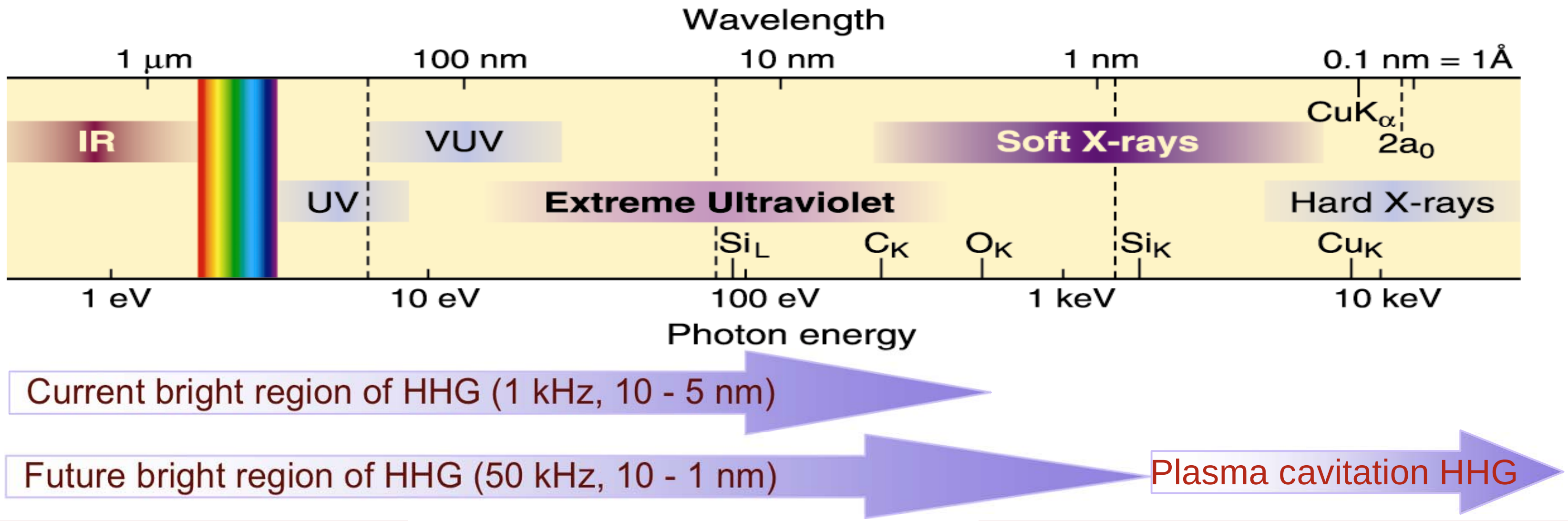
Semi-classical picture:

1. Atom is tunnel ionized by the laser’s intense EM field
2. Emitted electron accelerates in the laser field, gaining energy
3. Electron energy is released as harmonics of the fundamental laser when electron recombines with the ion

Phase match the HHG process by equalizing laser and x-ray phase velocities

Characteristics of HHG sources

- Laser pulse energy required for HHG is < 5mJ
  - ➞ Repetition rate can scale to 100's of kHz or higher
- Efficiency from laser to harmonics ~ $10^{-7} - 10^{-5}$
  - ➞ ≈ µJ /harmonic/ pulse)
- Ultrafast (fs to as)
- High rep rate, pump-probe and coincidence imaging
- Broad band: from VUV to SXR



Current bright region of HHG (1 kHz, 10 - 5 nm)

Future bright region of HHG (50 kHz, 10 - 1 nm)

Plasma cavitation HHG

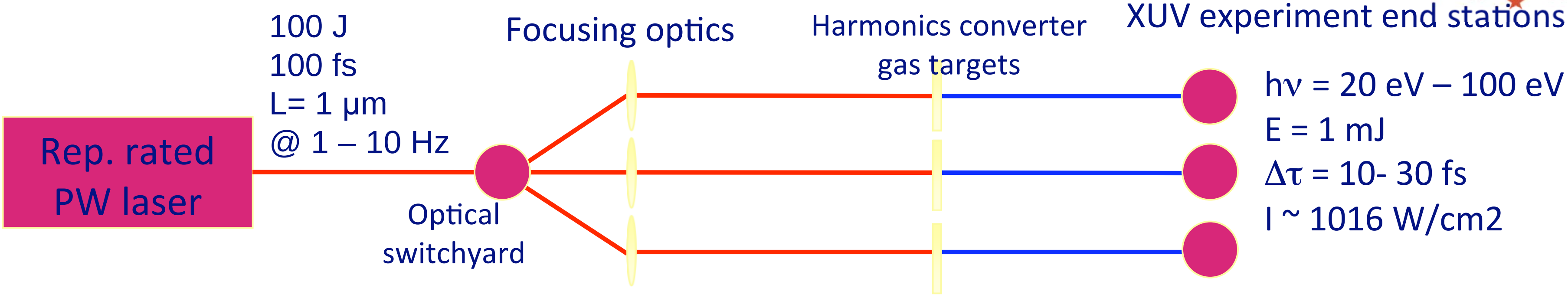
High average power EUV/Soft X-ray facilities

Status and outlook	
Present status	Ti:sapphire based pump lasers ~μW average power
2 year goal	Sub-100 W average power Yb/OPA systems at 1.5 μm and 3 μm > 400 W 1μm Yb-doped femtosecond lasers Recirculating cavities for HHG up to 100 eV
5 year goal	Sub-M$, 0.1-1 mW coherent soft x-ray sources Fully coherent hard x-rays

Investments required	
Initial R&D (2 yr)	$2M - $4M (equipment plus labor)
Facility construction	Existing labs

Operations Considerations	
Staffing levels required	1FTE
Annual operations cost	$0.5M
User access	2 teams at one time, access every other week

High peak power XUV facility: repetition rated PW laser HHG source



Rep. rated PW laser

100 J
100 fs
L= 1 μm
@ 1 – 10 Hz

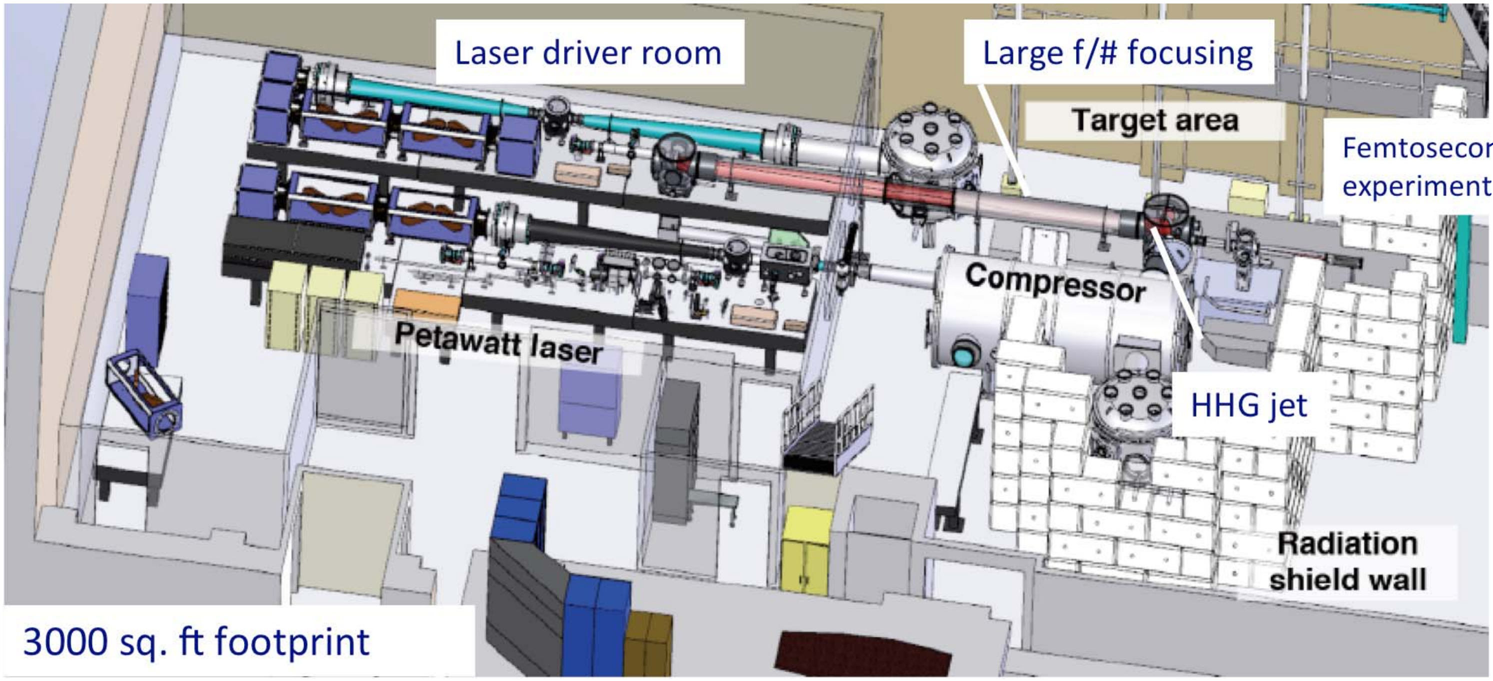
Optical switchyard

Focusing optics

Harmonics converter gas targets

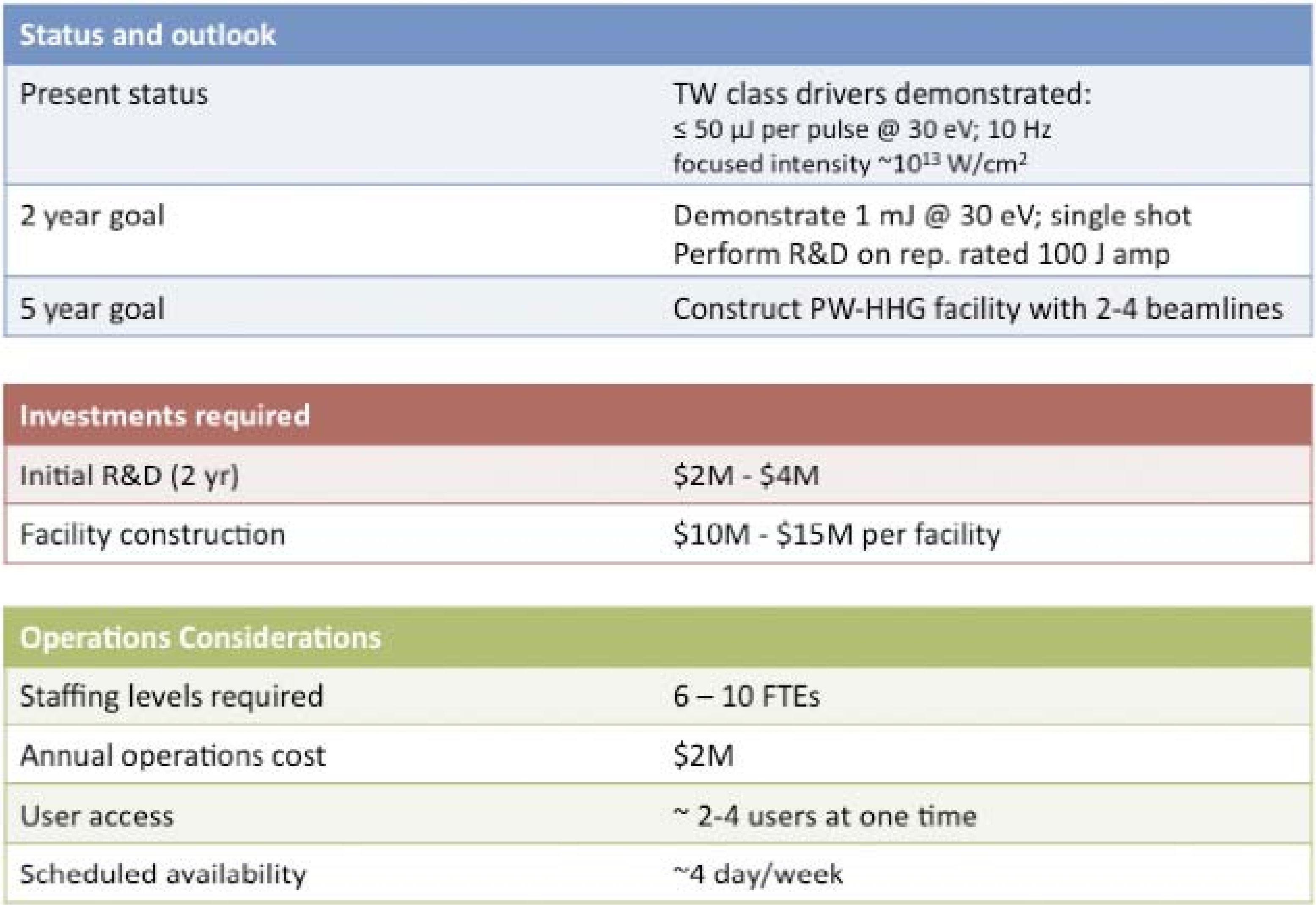
XUV experiment end stations

hν = 20 eV – 100 eV
E = 1 mJ
Δτ = 10- 30 fs
I ~ 1016 W/cm2



A PW HHG facility would deliver pulses in the XUV with parameters very similar to the FLASH FEL at DESY for a very modest investment

High peak power XUV facility:
Rep. rated PW laser HHG source – Costs & status

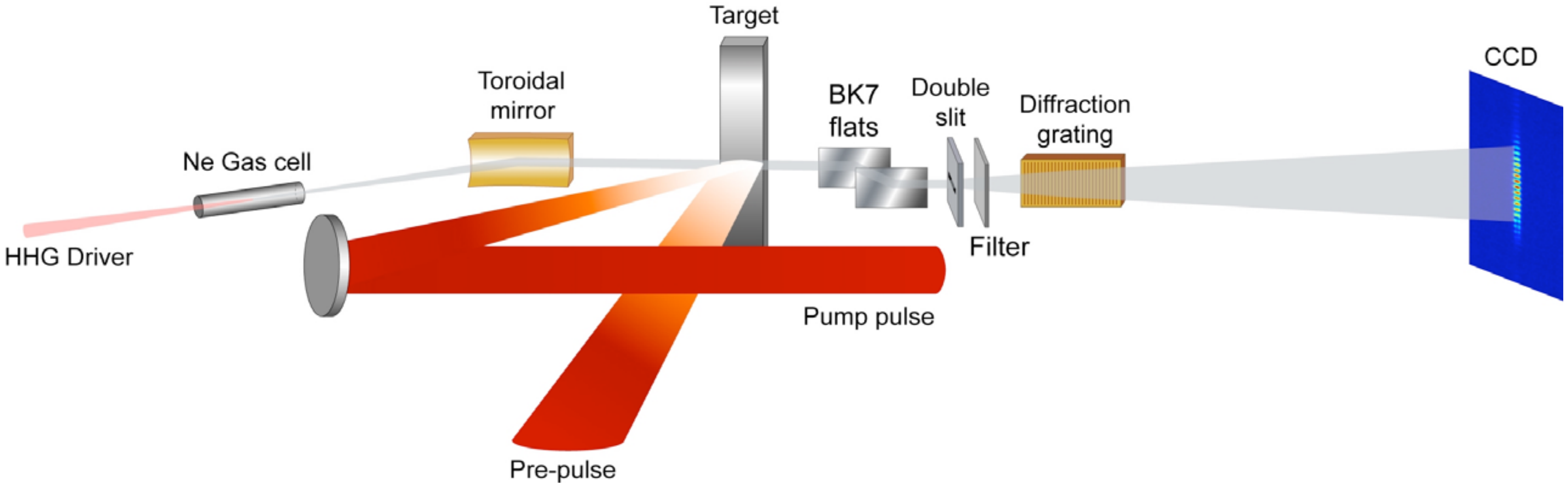


Status and outlook	
Present status	TW class drivers demonstrated: ≤ 50 µJ per pulse @ 30 eV; 10 Hz focused intensity ~10^{13} W/cm^2
2 year goal	Demonstrate 1 mJ @ 30 eV; single shot Perform R&D on rep. rated 100 J amp
5 year goal	Construct PW-HHG facility with 2-4 beamlines

Investments required	
Initial R&D (2 yr)	\$2M - \$4M
Facility construction	\$10M - \$15M per facility

Operations Considerations	
Staffing levels required	6 – 10 FTEs
Annual operations cost	\$2M
User access	~ 2-4 users at one time
Scheduled availability	~4 day/week

Laser-driven plasma sources

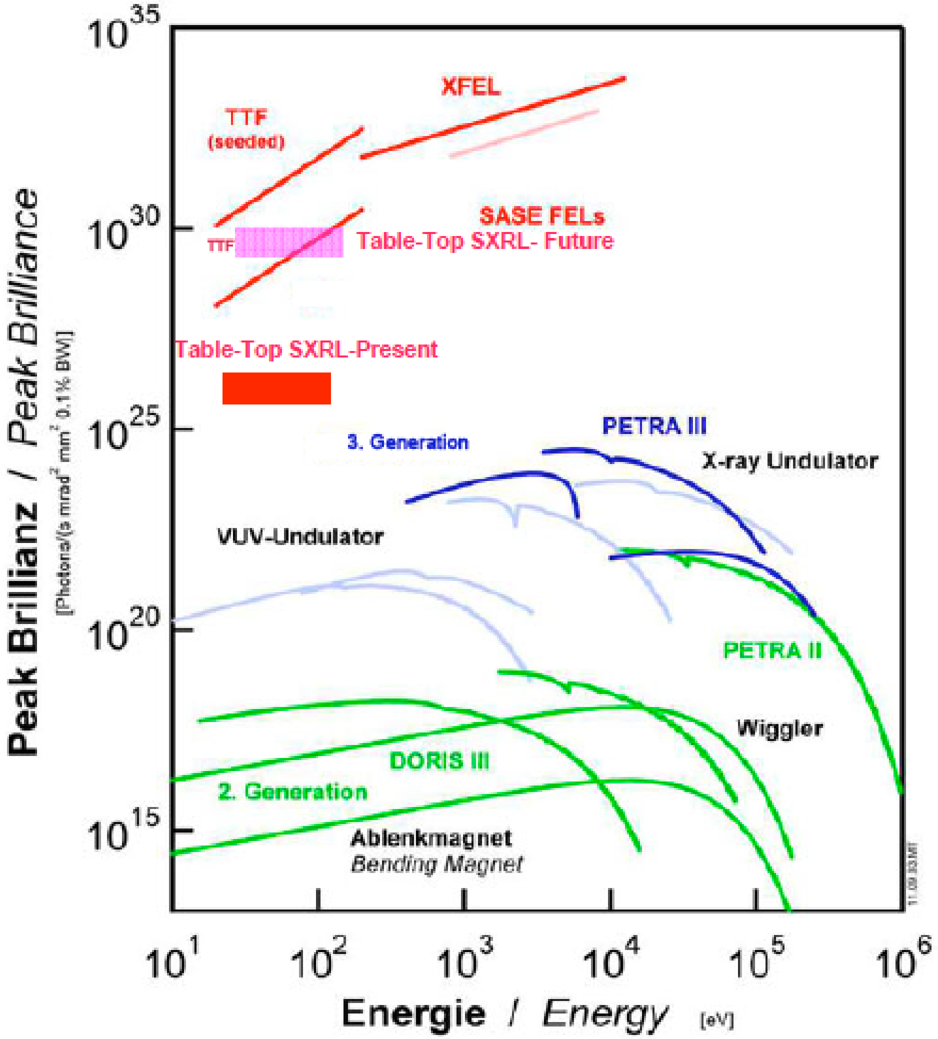


. Schematic diagram of injection-seeded soft x-ray laser amplifier that produces a high brightness phase-coherent soft x-ray laser beam by seeding a dense laser-created plasma amplifier with high harmonic pulses.

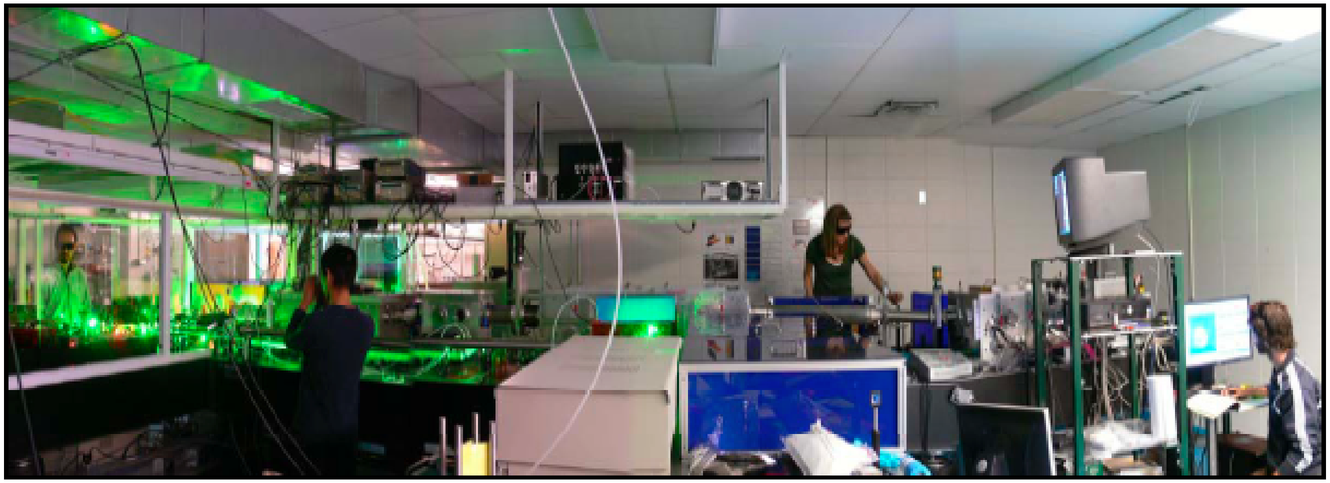
Table-top soft x-ray lasers

- **Advantages:**
  - **High pulse energy**: Highest pulse energy available from a coherent table-top source. (> 6 x 10^{11} photons/pulse @ 100 eV in 13-33 nm region.
    - Extremely compact capillary discharge lasers already produce > 1 x 10^{14} photons per pulse at 26.5 eV).
  - ***High average flux.*** (eg. 20 μW demonstrated at ~ 100 eV, with 1 mW potentially resulting from further development).
    - > 1 mWaverage power currently available at λ= 46.9 nm from capillary discharge lasers.
  - ***Compact*** (1-3 optical tables). Capillary discharge-pumped lasers are as small as desk-top size.
  - **Full Phase coherent for seeded SXRL** (plasma-based lasers are presently the only soft x-ray lasers with full temporal coherence)
  - **Short pulse** duration (1-5 ps). Potential for 50-100 fswith further development.
- **Limitations:** Line-tunable, numerous lines accessible but not continuously tunable.

Brightness of table-top SXR lasers



Compact repetitive laser-pumped plasma Soft X-Ray Lasers

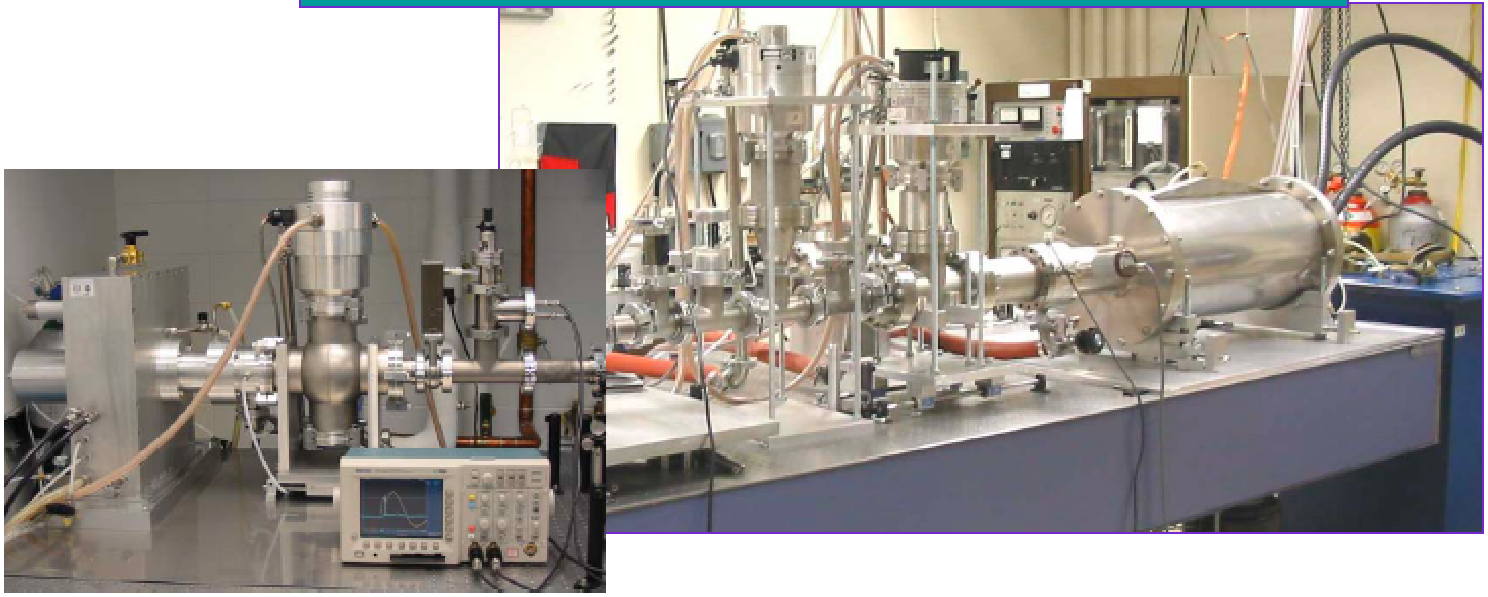


- Wavelength range coverage: 10 nm- 50 nm (present)- sub 10 nm (future)
- Average power: up to 20 μW (present), > 1 mW (future)
- Pulse energy: up to 10 μJ (present), > 0.1 mJ (future)
- Narrow spectral bandwidth: $\Delta\lambda/\lambda < 10^{-4}$
- Repetition rate: 1-10 Hz (present), > 100 Hz (future)
- Pulsewidth: 1-5 ps (present), < 100 fs (future)
- Size: 1-3 optical tables
- Coherence: full coherence (seeded mode), partial coherence (ASE mode)
- Facility cost: $ 2-4 M

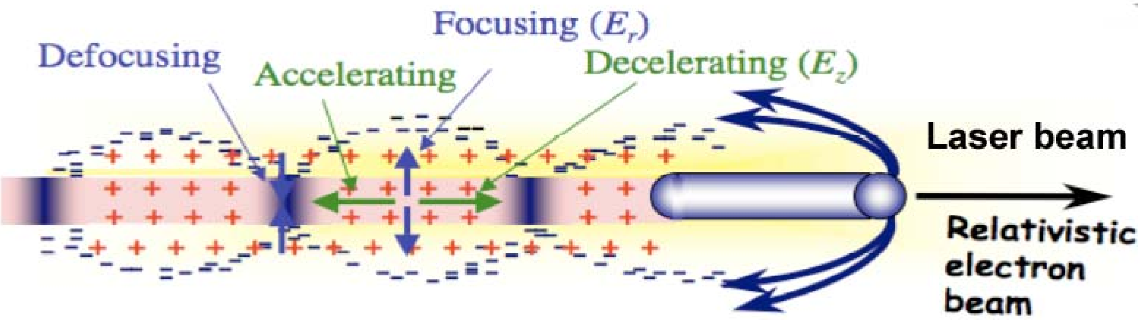
Discharge-pumped lasers produce coherent average power @ 46.9 nm similar to synchrotron beam line

Ne-like Ar Capillary discharge λ=46.9 nm laser

- Average power: > 1 mW
- Pulse energy: 0.01 mJ –0.5 mJ
- Narrow spectral bandwidth: $\Delta\lambda/\lambda = 10^{-4}$
- Repetition rate: up to 10 Hz
- Pulsewidth ~ 1ns
- Size: table-top to desk-top
- High spatial coherence
- Cost: $ 0.3 -0.4 M. Can be easily installed in any lab



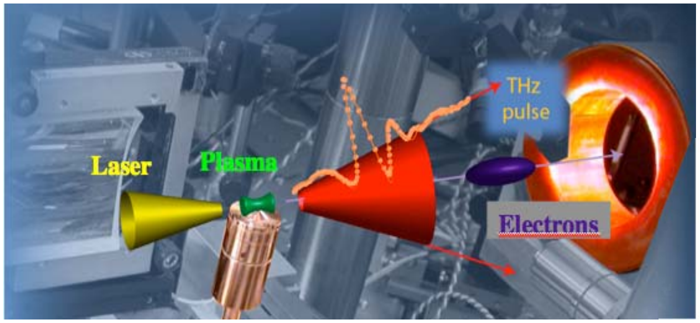
Sources based on plasma accelerators (10 - 100 GeV/m)



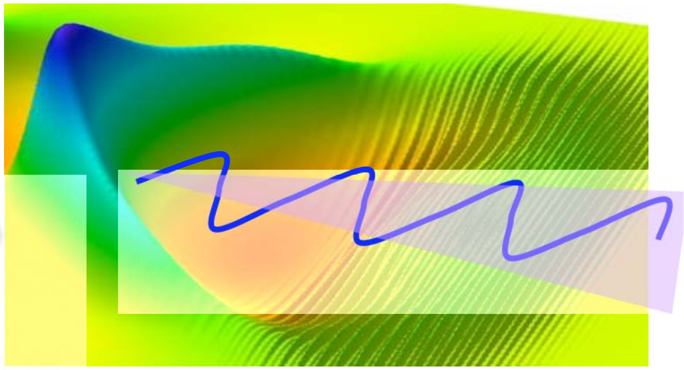
PWFA schematic, indicating plasma oscillations set up by drive electron bunch expelling plasma electrons from the path of the drive bunch

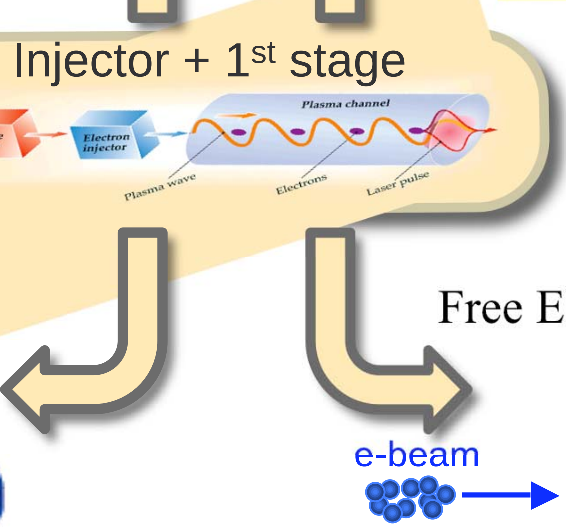
Multi-spectral radiation from THz to γ's fully synchronized, ultra-short

Transition radiation from beam exiting plasma – MV/cm THz



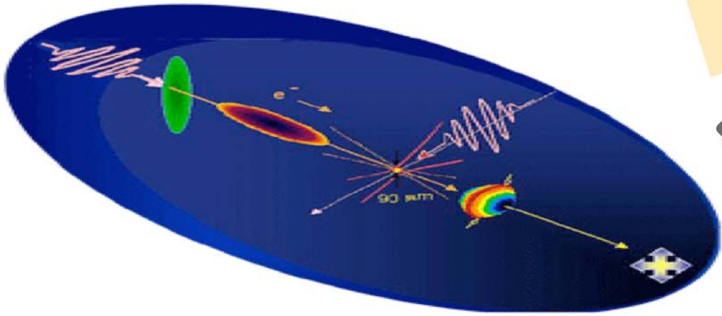
Betatron radiation during acceleration – Multi keV



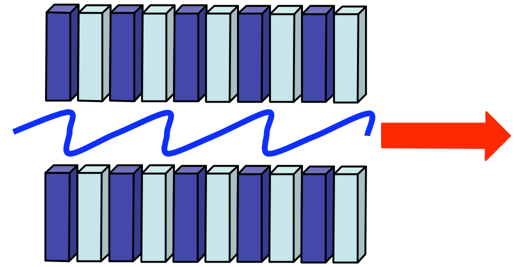


Injector + 1st stage

Thomson Scattering – Multi keV/MeV x-ray/gamma ray

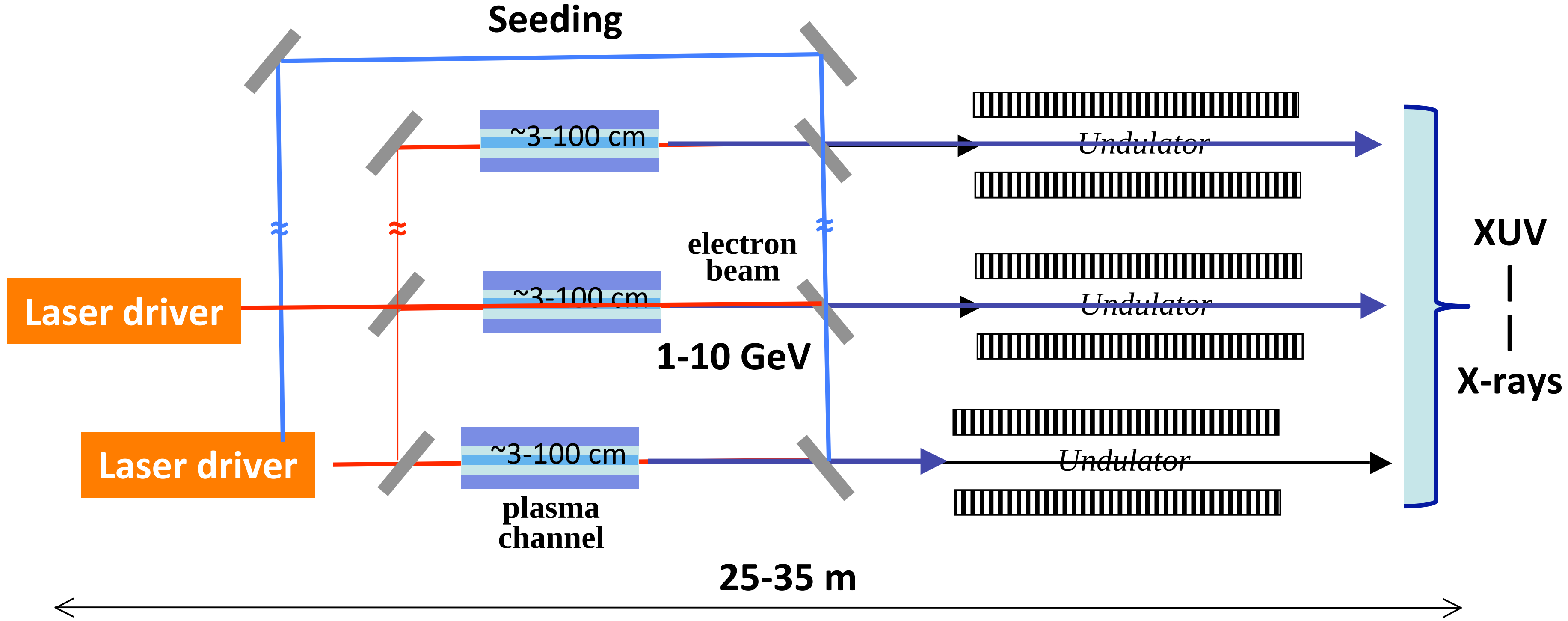


Free Electron Laser-> XUV, X-ray

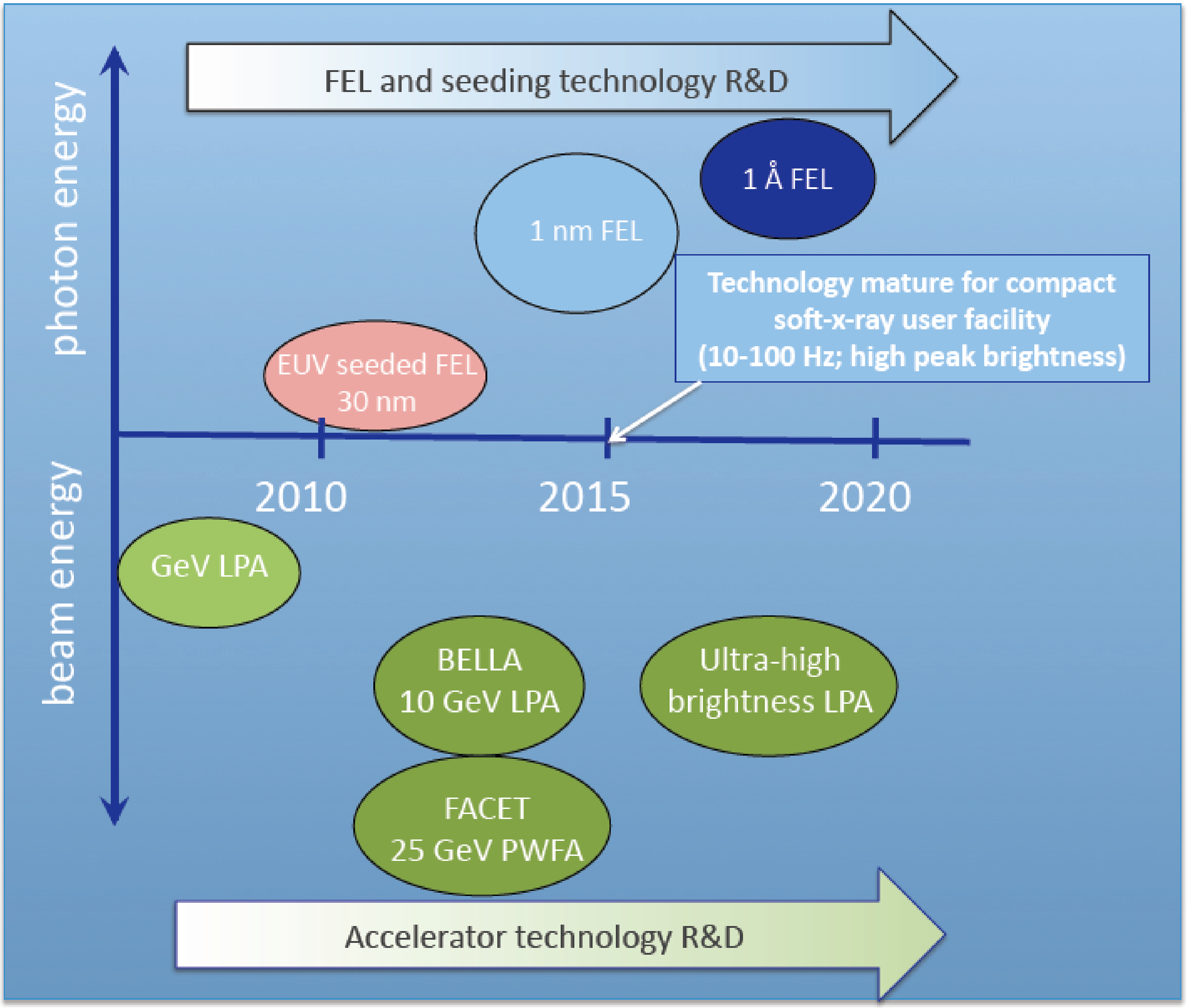


Laser Plasma Accelerator Facility

- Linac cost is minimal ==> build multiple linacs & beam lines driven by single laser or multiple lasers
- As laser cost decreases and performance increases: power each beam line with its own laser



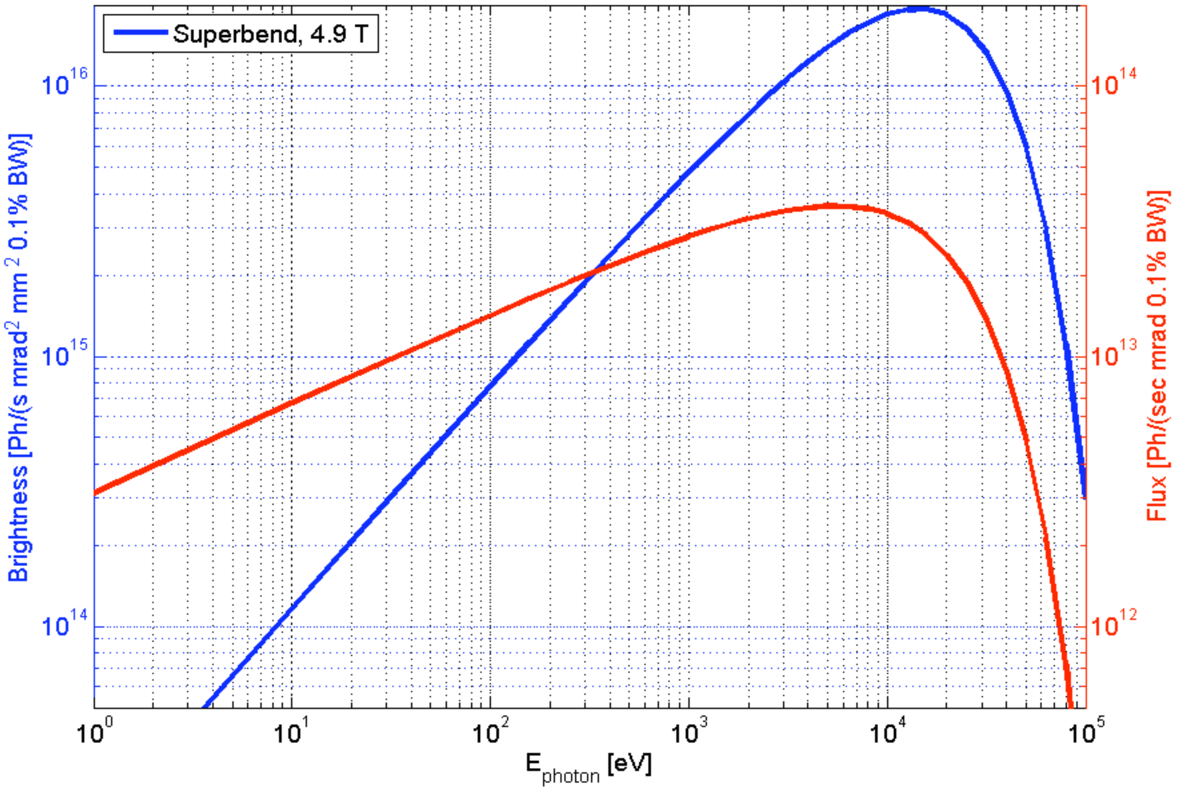
Progress in plasma- accelerators for future light sources



Technology mature for compact soft-x-ray user facility (10-100 Hz; high peak brightness)

Small storage rings

Possible brightness and flux with current technology



Ring charateristics:

1.5 – 2.0 GeV

60 – 80 m circumference

Several 5 T bend magnets

10 nm emittance

500 mA current

~ 40 bend magnet beamlines

(maybe 1/2 on s/c magnets)

Same as productive Superbend beamlines on ALS

Pro’s and Con’s of small rings

- Pros:
  - High Flux, Moderate Brightness, Many Beamlines, Reasonable Cost per Beamline, High Stability, Option for (partial) circular polarization out of plane, If desired could provide round beams (with lower brightness)
- Cons:
  - Facility is smaller but not tabletop, Moderate total cost, Very limited potential for short pulses
- Future R+D
  - On axis injection for lower emittance lattices
- Other potential
  - Ring of this size but lower beam energy could be optimized as source for stable, broadband, coherent THz radiation

Small ring summary

- Storage rings are
  - Cost effective for large numbers of beamlines
  - Providing large average flux and average brightness
- New lattice designs & more compact magnets enable
  - Reduced size (to 60-75 m circumference)
  - Lower cost (to 50 M$)
  - Facility that could offer 20-40 beamlines with same flux & same brightness as bend magnet beamlines at 3rd generation rings

Very cost effective per beamline

Thanks to all the participants

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