UPPSALA UNIVERSITET

Towards a femtosecond 100-kHz Compton source at Uppsala University

I. Project in a nutshell
II. X-ray technology evolution & Compton sources
III. Layout & ideas behind the project

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2023, UU

Uppsala University

Oldest university in Scandinavia (1477)

- **Sweden**
  - 11 million (pop.), 450'000 km^2, 600 GEur (GDP)
- **Uppsala**
  - 25'000 students, 9'000 staff, 900 MEur annual budget
  - faculties of theology, law, medicin, pharmacy, arts, social sciences, languages, educational sciences, science and technology
  - university library and hospital
- **Science and technology**
  - 10'000 students, 1'800 staff
  - historical profiles: Linnaeus, Rudbeck, Celsius, Ångström, Siegbahn, Svedberg
  - **R&D areas**
    - physics, chemistry, biology, earth sciences, engineering, mathematics, IT

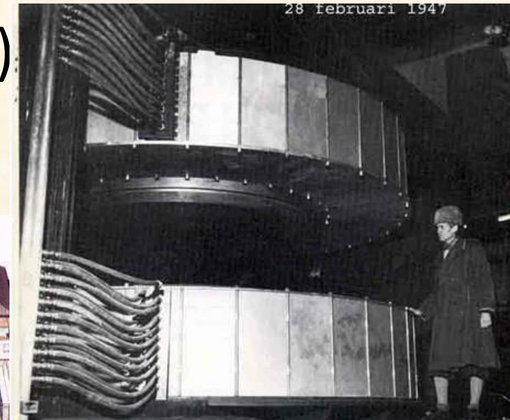
Uppsala Accelerator History

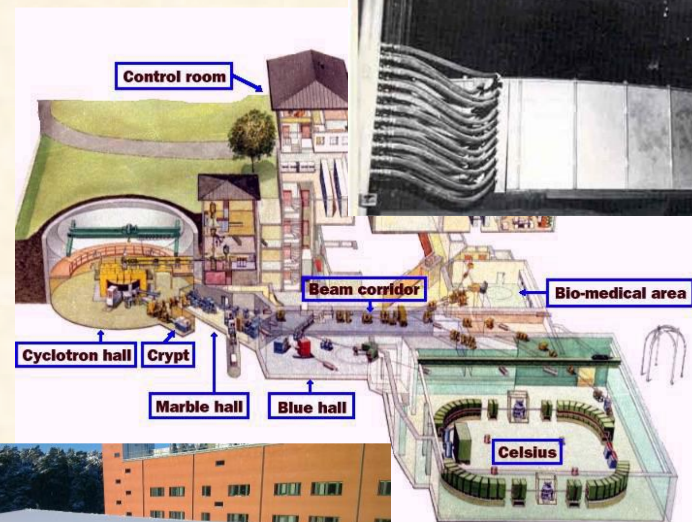
1940's: The(odore) Svedberg proposes to build a cyclotron

- Gustaf Werner synchro-cyclotron (1947 - 2015)
  - nuclear physics & cancer treatment
- CELSIUS ring (1984 - 2005)
  - nuclear physics

- CTF3/CLIC (since 2005)
- FLASH/XFEL (since 2008)
- ESS (since 2009)

- FREIA laboratory (since 2011)
- Skandion clinic (2015)
  - cancer treatment

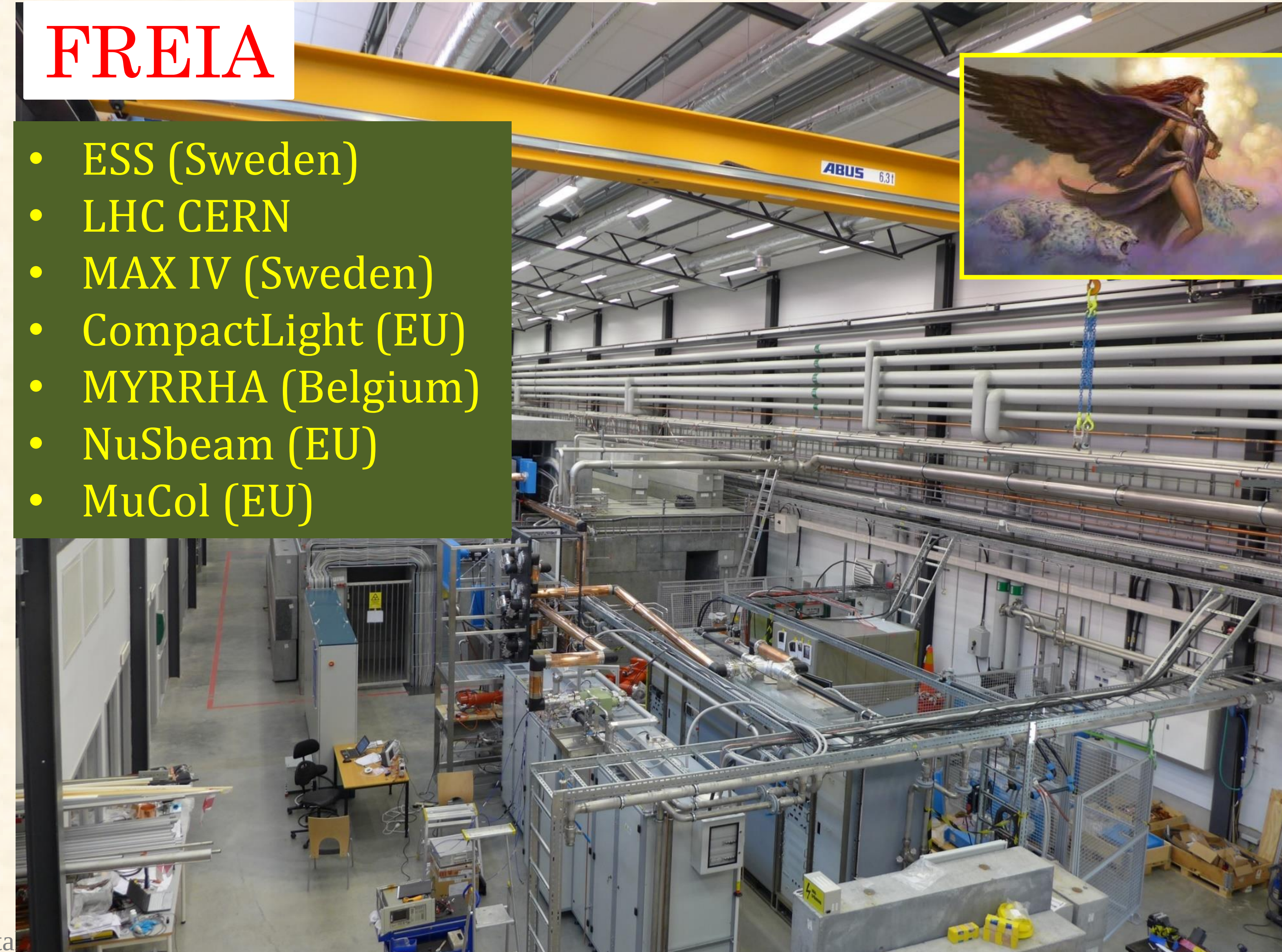




Accelerator physics at FREIA in Ångström

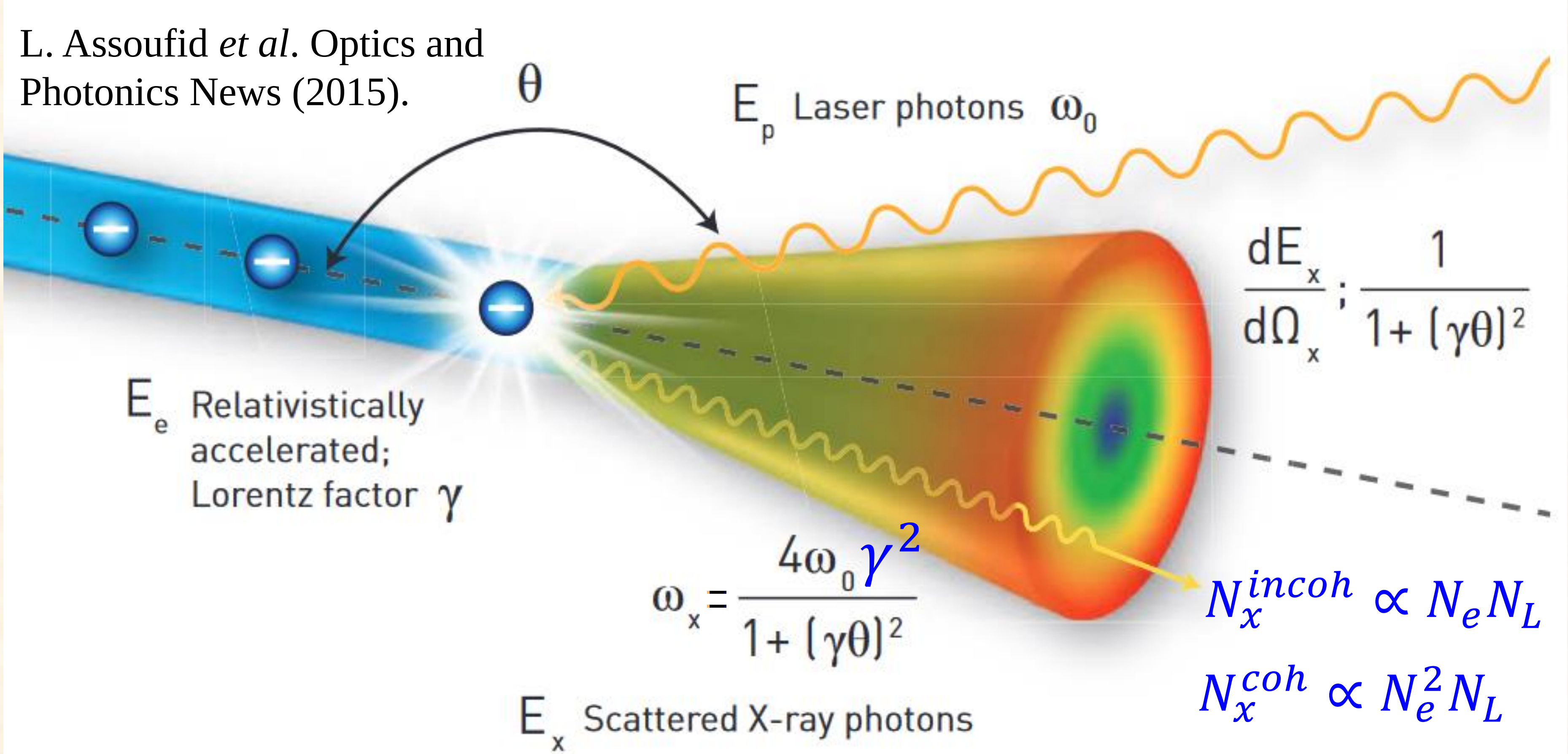
FREIA

- ESS (Sweden)
- LHC CERN
- MAX IV (Sweden)
- CompactLight (EU)
- MYRRHA (Belgium)
- NuSbeam (EU)
- MuCol (EU)



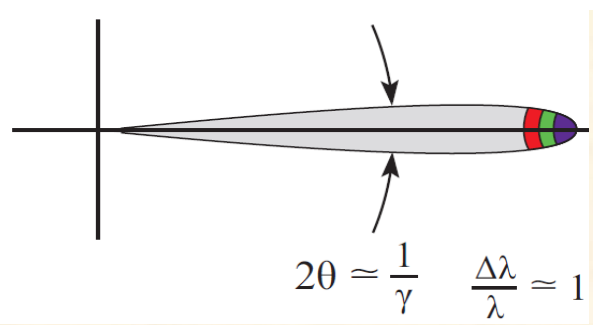
Inverse Compton scattering source

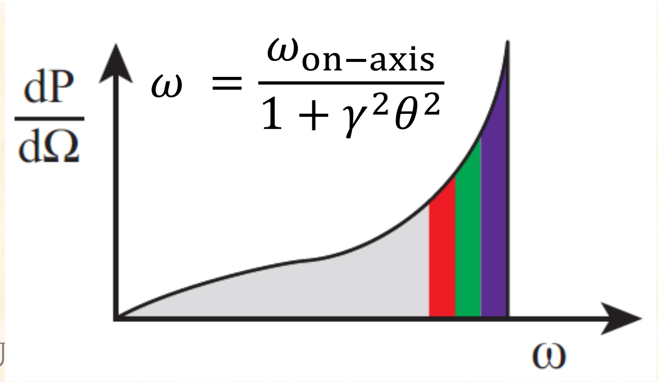
L. Assoufid *et al*. Optics and Photonics News (2015).



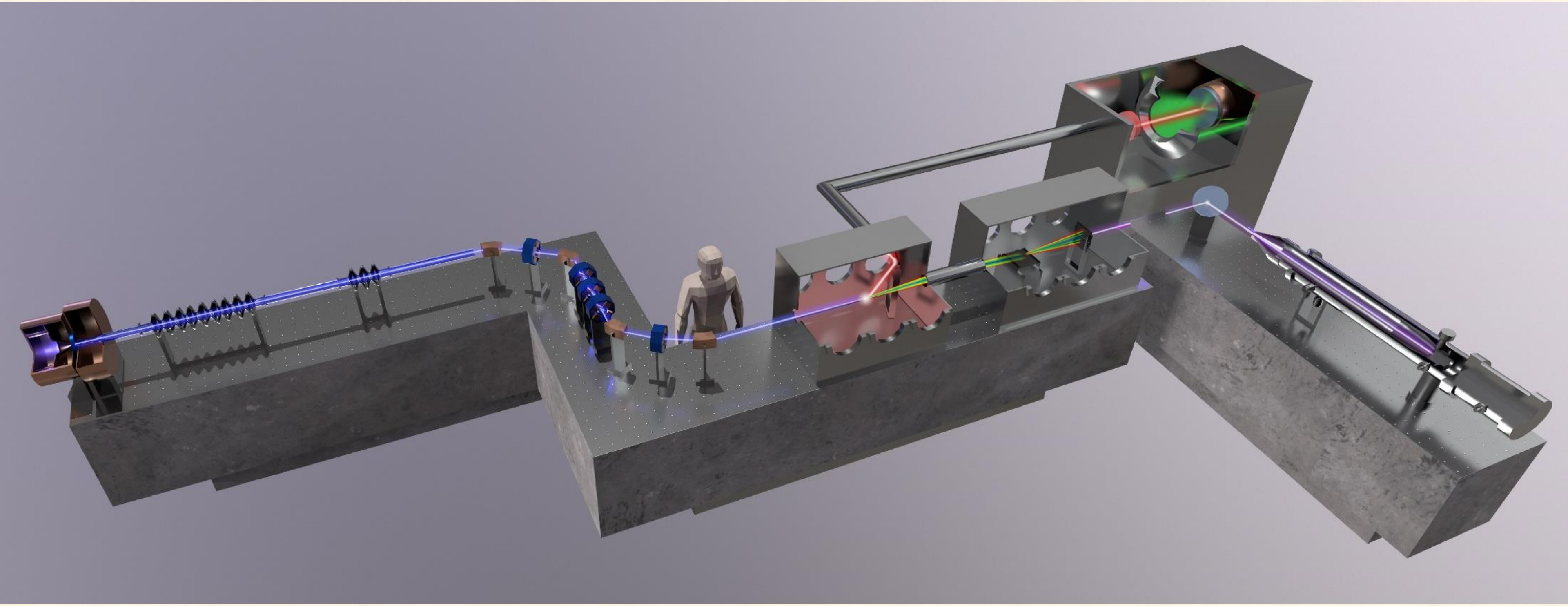
$N_x^{incoh} \propto N_e N_L$

$N_x^{coh} \propto N_e^2 N_L$



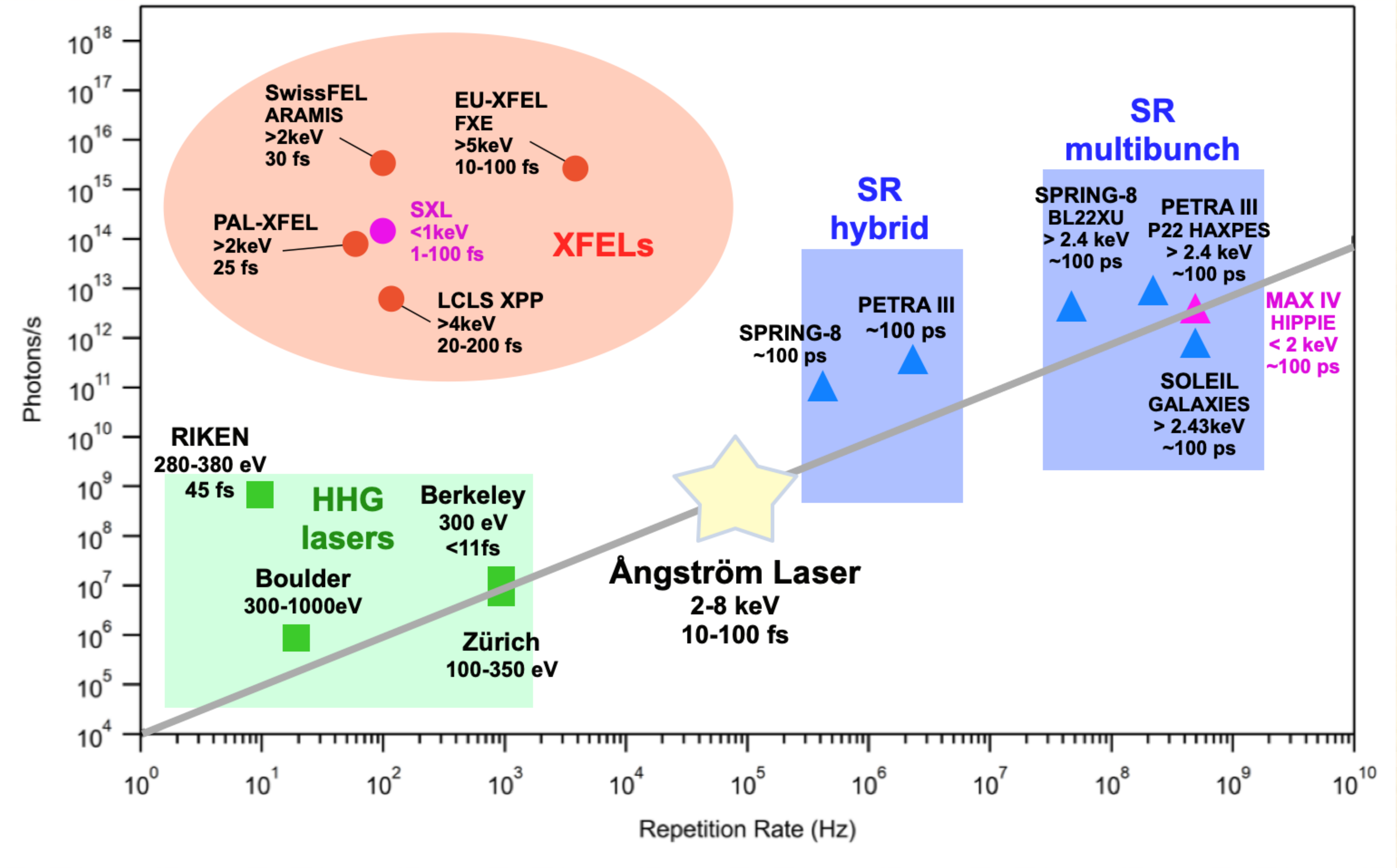


Ångström laser – a SC-linac based fs X-ray source



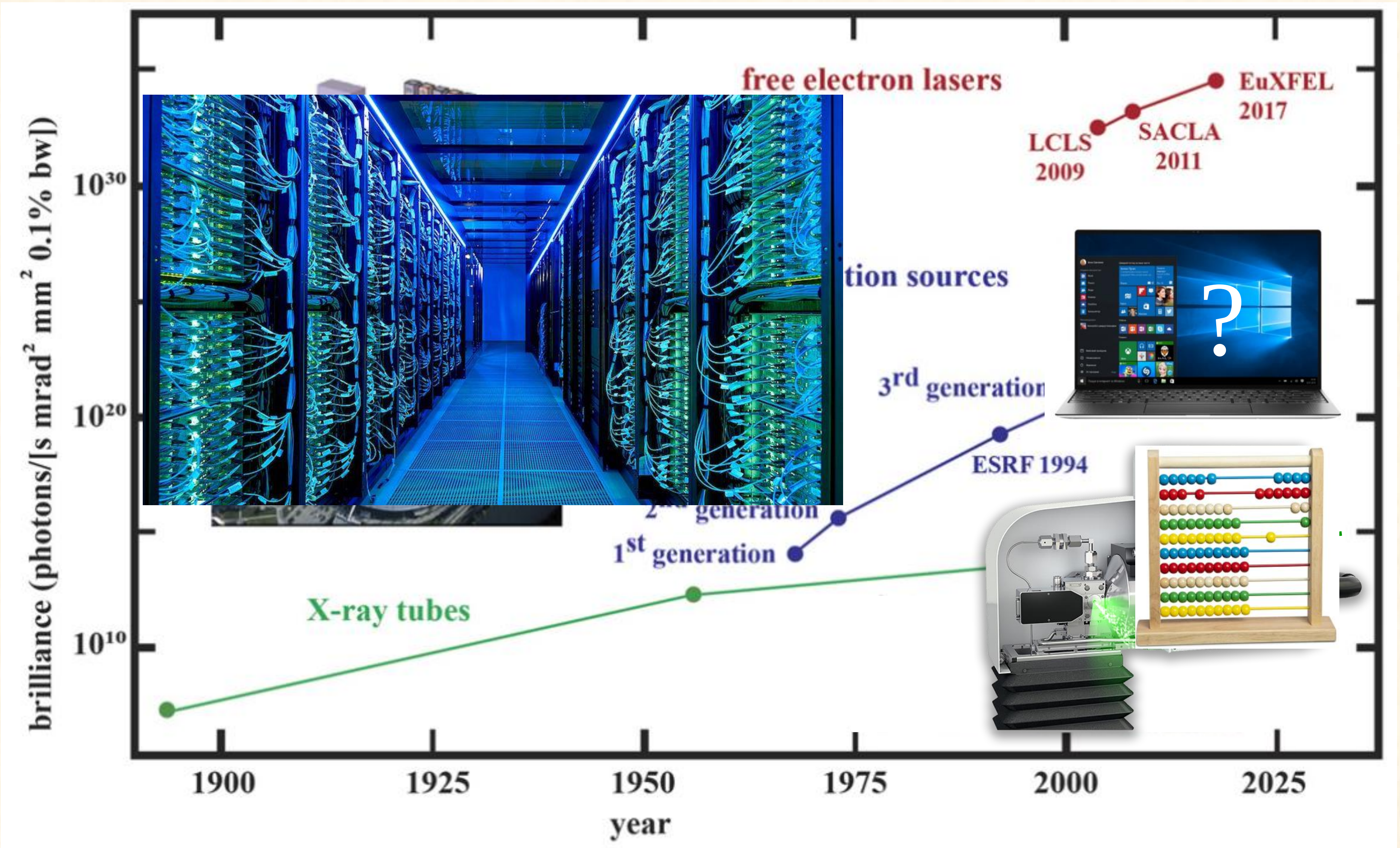
X-ray output parameters	Optical undulator	Broadband beamline (at the sample)	Mono-beamline (at the sample)
X-ray energy range	2-13 keV	2-13 keV	2-8 keV
X-ray energy bandwidth	1 %	1 %	~0.02 %
X-ray pulse duration (FWHM)	< 200 fs	< 200 fs	< 200 fs
Flux (s^{-1}) at 100 kHz repetition rate	10^{10}	10^{9}	10^{7}-10^{8}
X-ray spot size (FWHM)	8.0 μm	35 μm	41 μm

Ångström laser – a discovery tool for material science



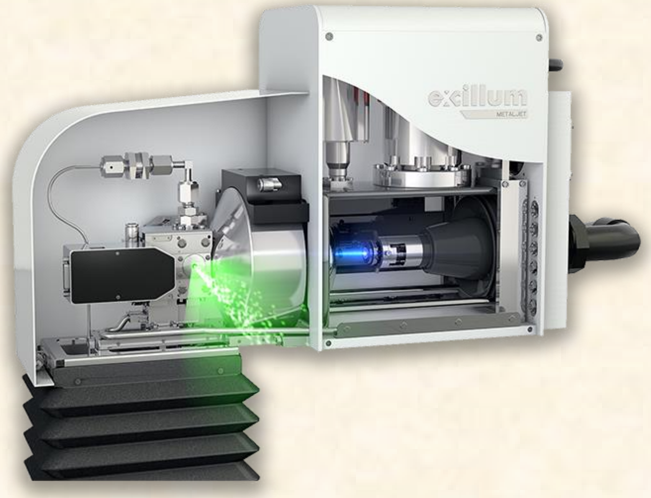
X-ray technology evolution & Compton sources

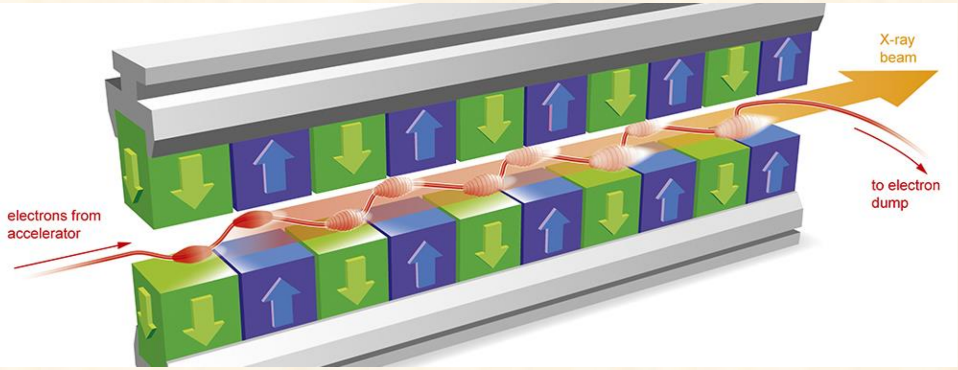
Technological evolution of X-ray generation



Valerio Cerantola et al 2021 J. Phys.: Condens. Matter 33 274003

Synchrotrons & FELs vs X-ray tubes





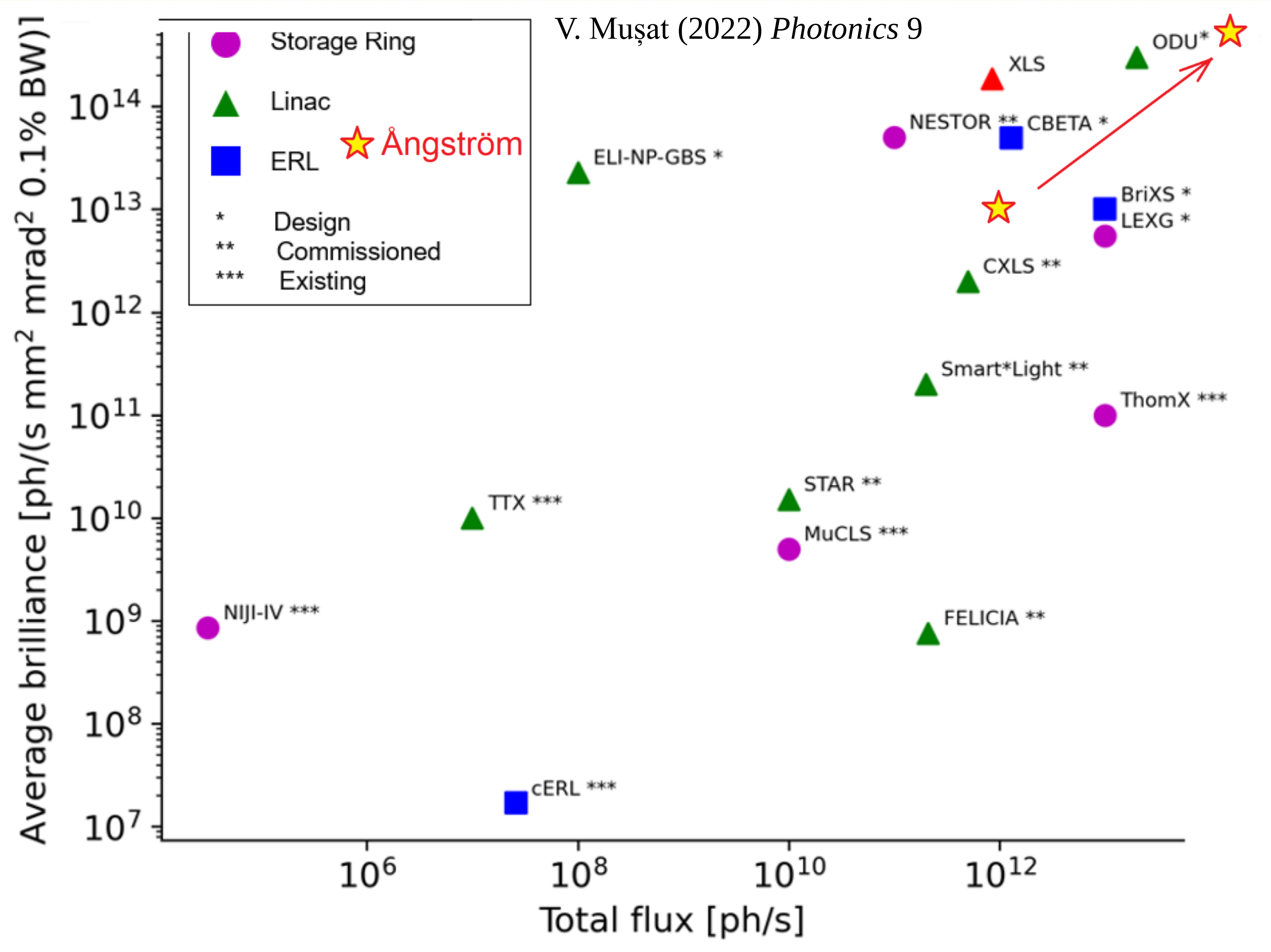
X-ray tube

- wide availability & ease of use
- next-door sample analysis
- capability to test new ideas without the barriers of schedule, travel and expenses

Synchrotrons & FELs are a fantastic tool but a high access price…

Our objective is a femtosecond laboratory X-ray source based on inverse Compton scattering

The landscape of Inverse Compton Sources



Compact synchrotron technology

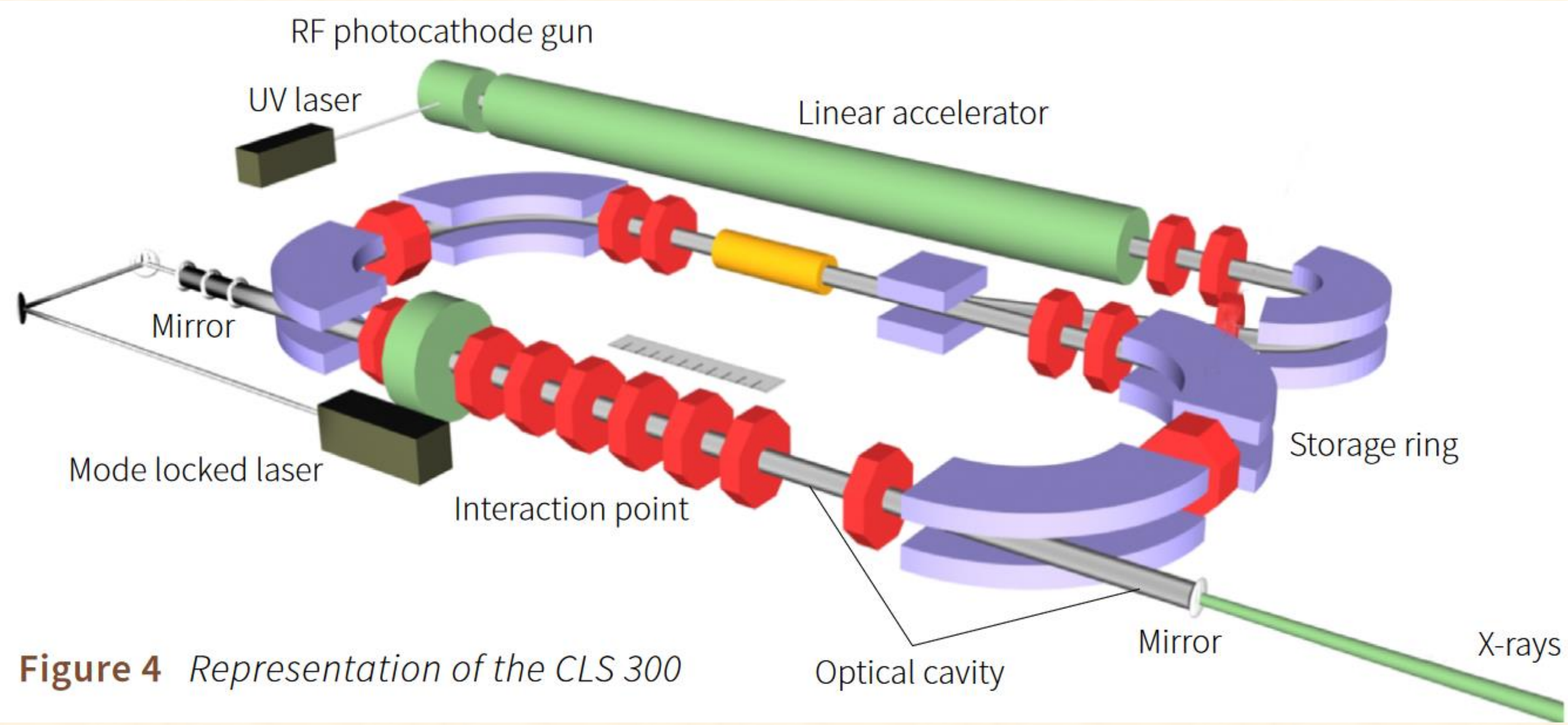
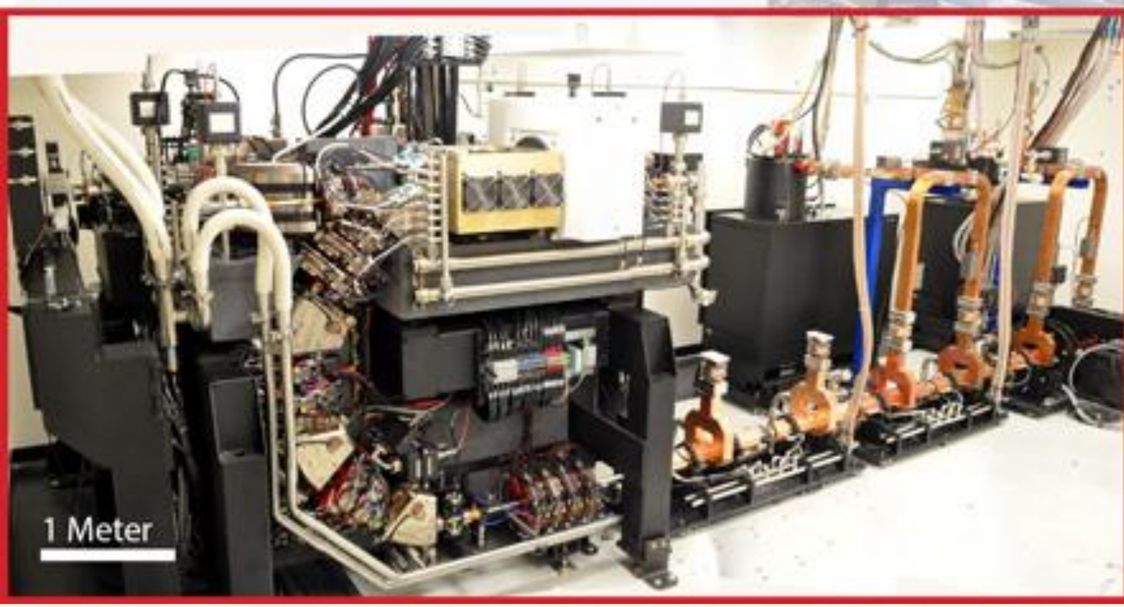


Figure 4 *Representation of the CLS 300*

Courtesy Lyncean Technology

Commercial compact synchrotron: Lyncean Tech.

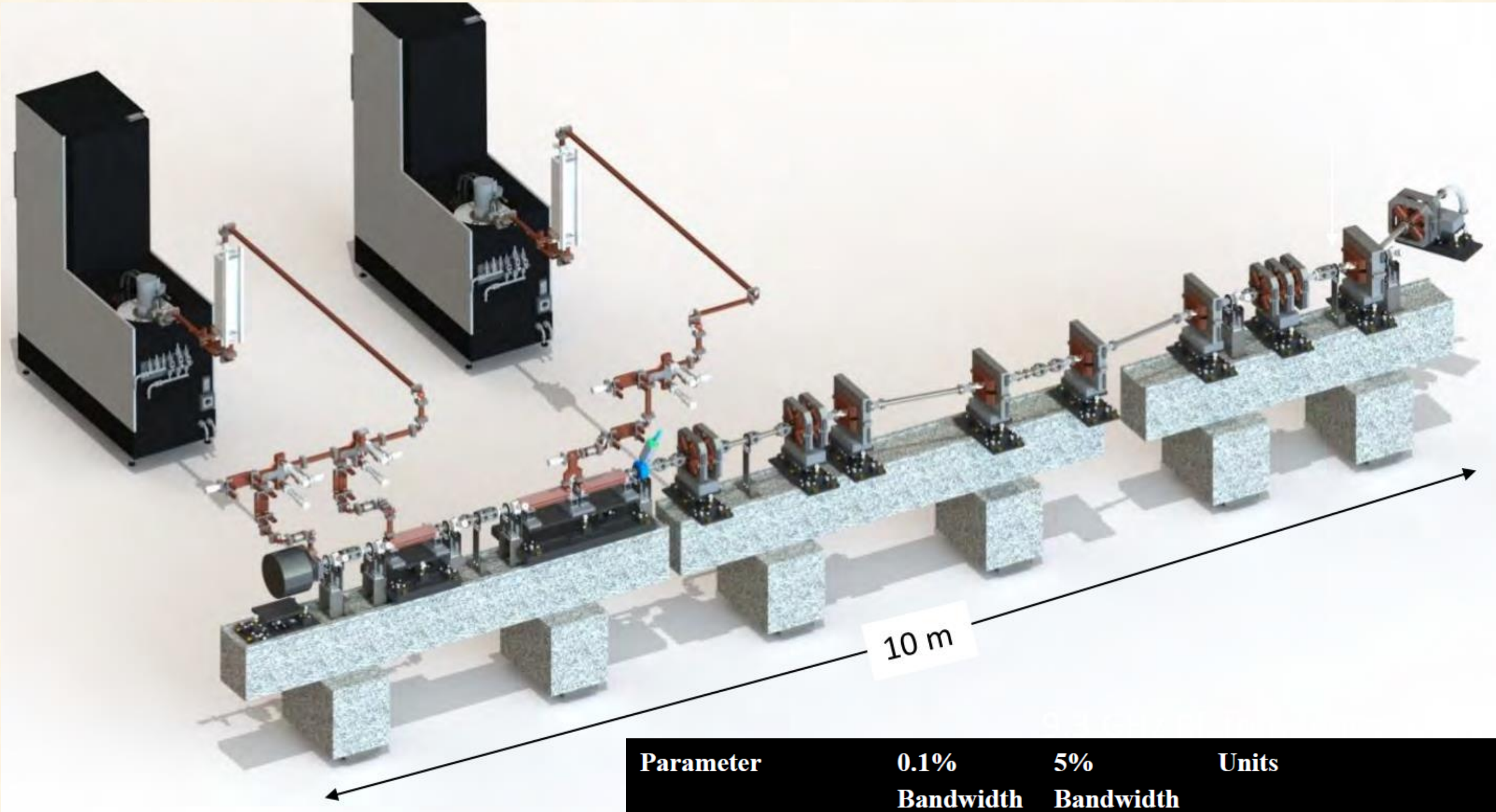
Source parameter	Value
Source size	~ 50 um
Bandwidth	3-5 %
Flux, 0.1%BW @15keV	5 10^8 ph/s
X-ray energy	15 – 35 keV
X-ray pulse length	60 ps
Repetition rate	65 MHz



Operated at Munich university

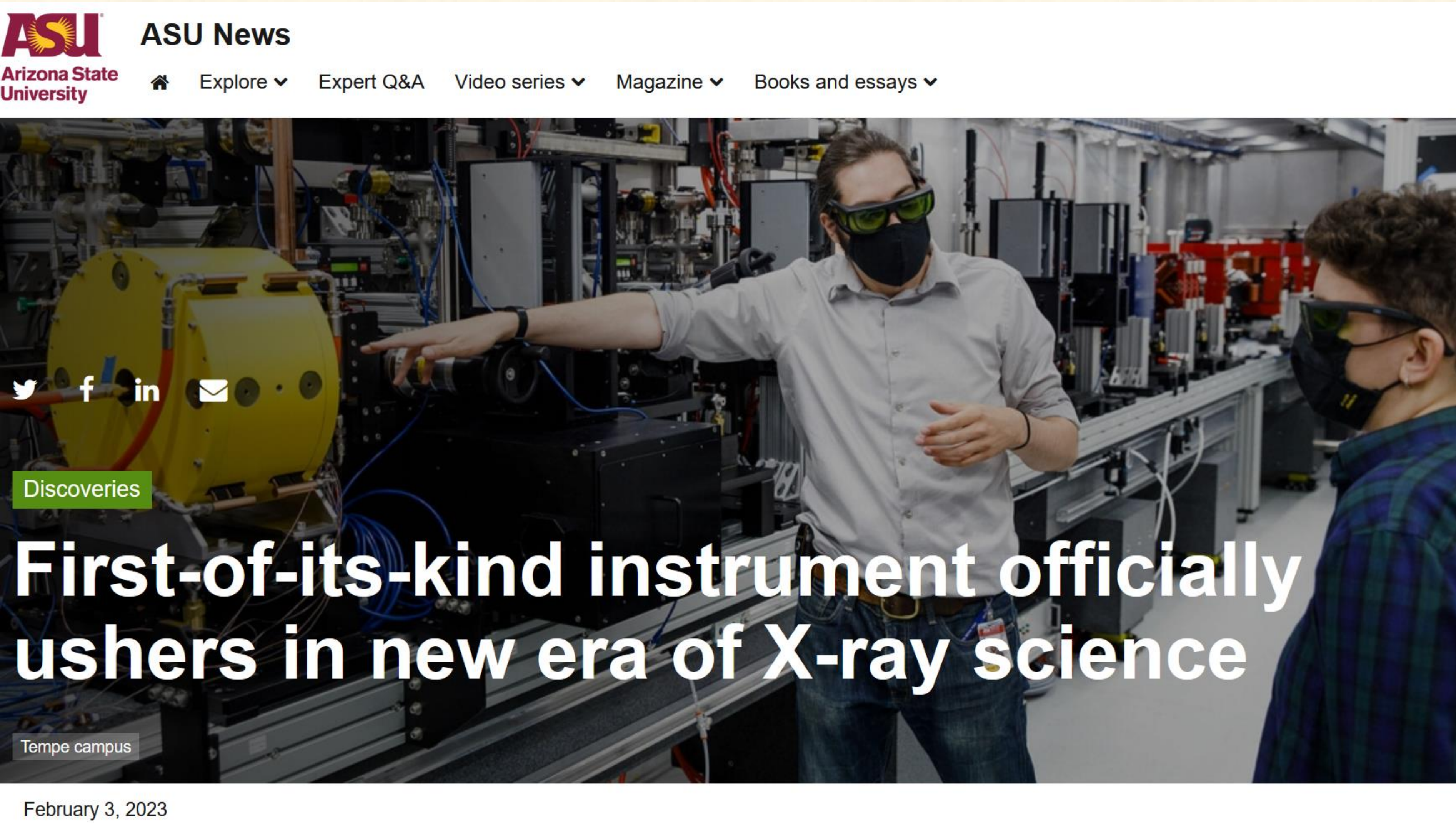
X-ray pulse length ~ 60 ps

Project at Arizona State University

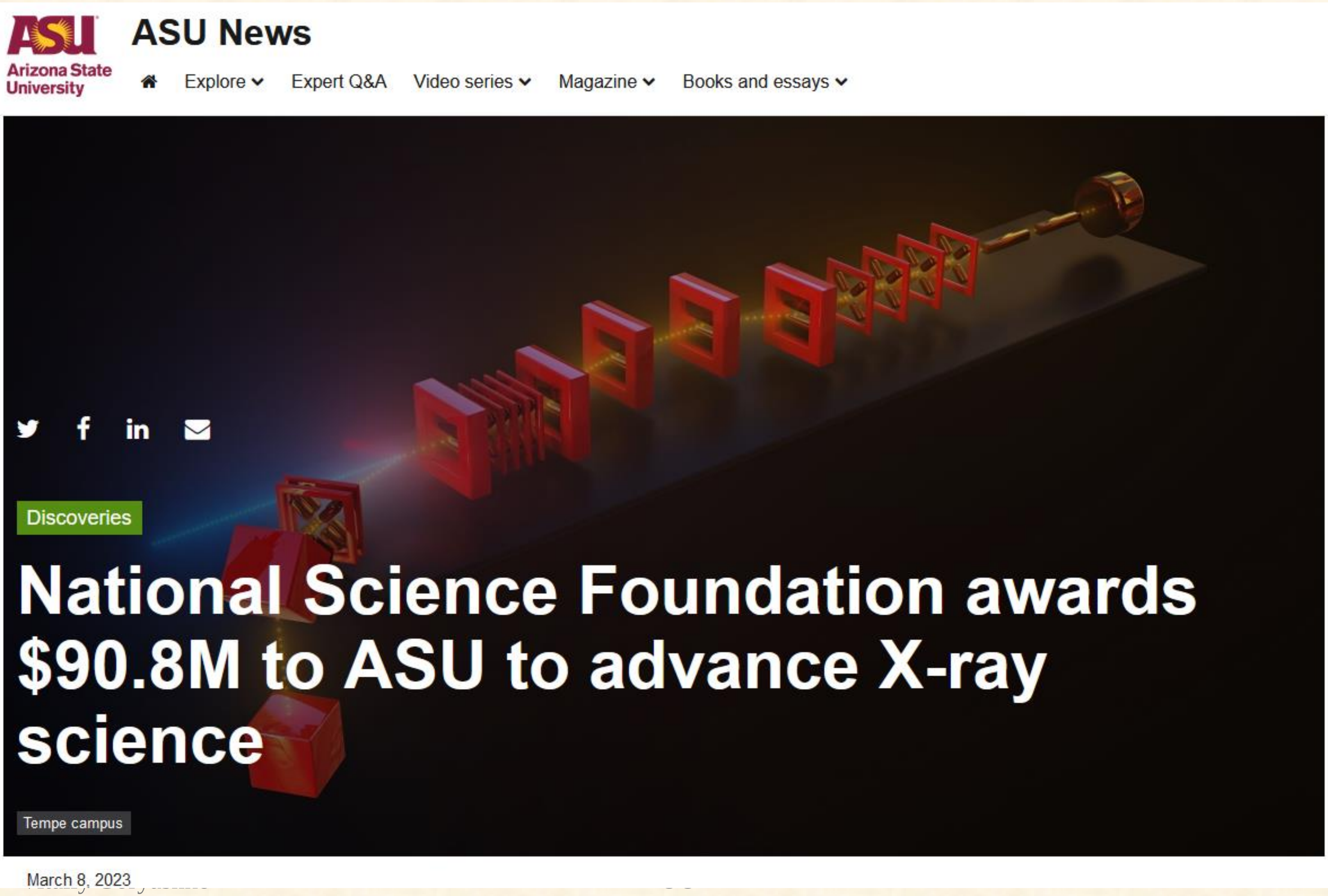


Parameter	0.1% Bandwidth	5% Bandwidth	Units
Average flux	5×10^{9}	1×10^{11}	photons/s
Average brilliance	2×10^{12}	5×10^{12}	photons/(s .1% mm²mrad²)
Peak brilliance	3×10^{19}	9×10^{18}	photons/(s .1% mm²mrad²)
Photons per pulse	5×10^{6}	1×10^{8}	
RMS pulse length	<500	<500	fs
Repetition rate	1	1	kHz

ASU’s instrument makes its first X-rays

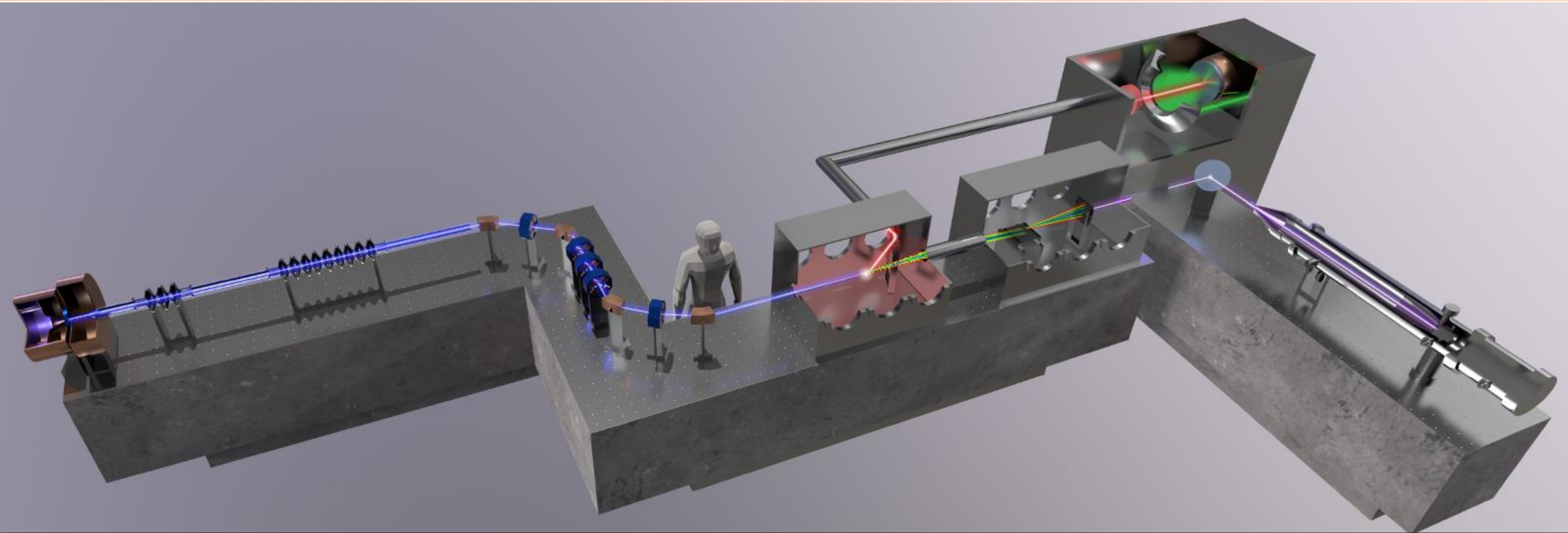


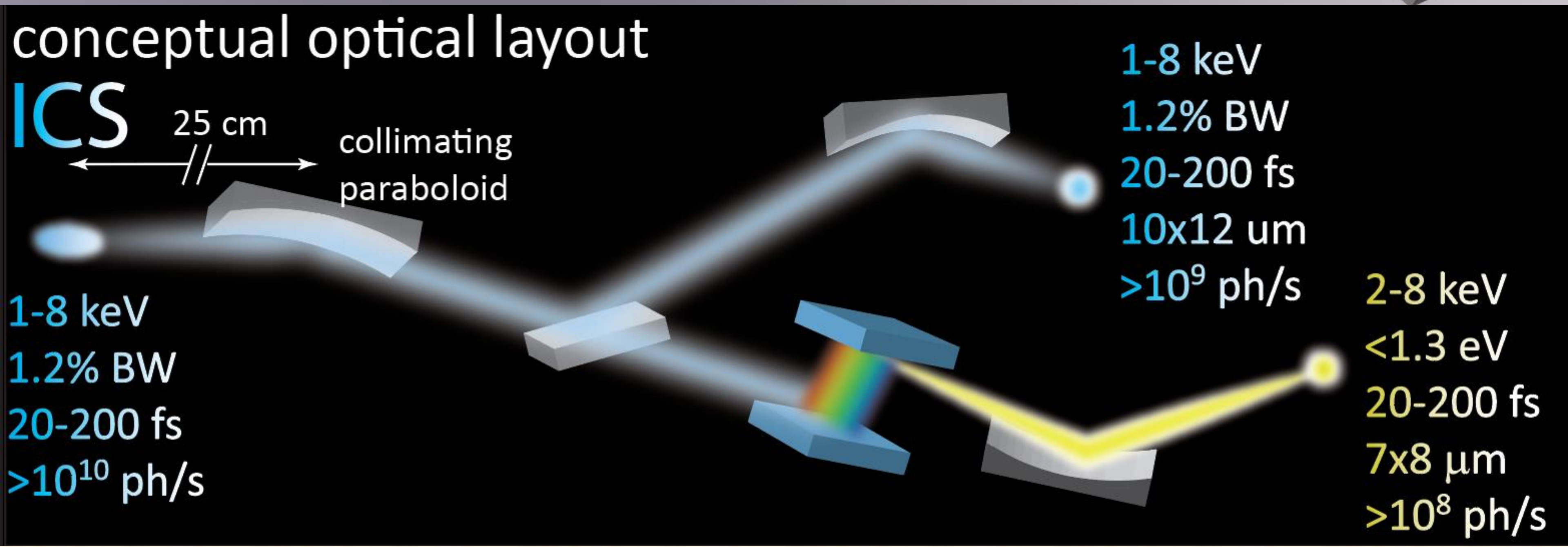
ASU’s compact coherent FEL



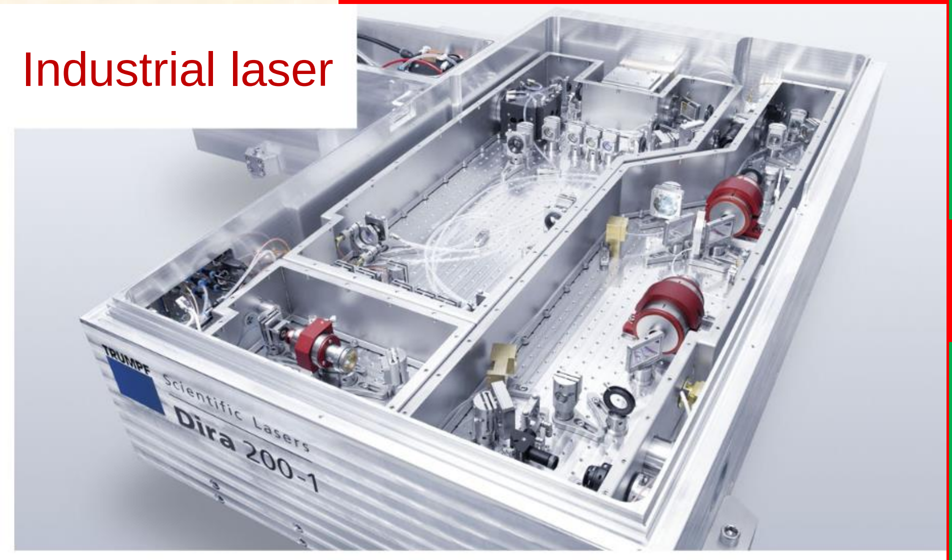
Ångström Laser in Uppsala: layout and ideas behind

Ångström Laser @ FREIA

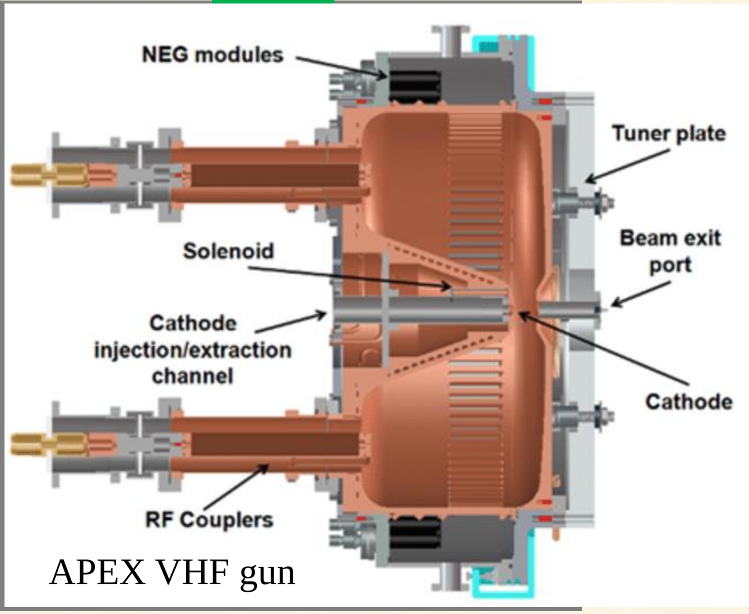




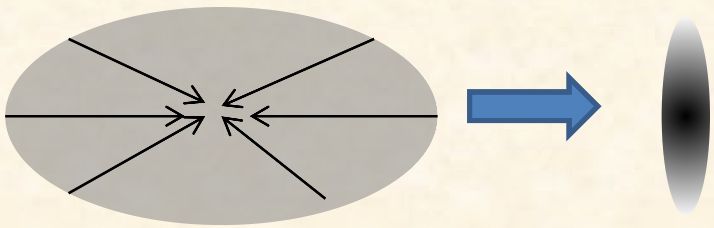
Enabling technologies for a compact X-ray laser

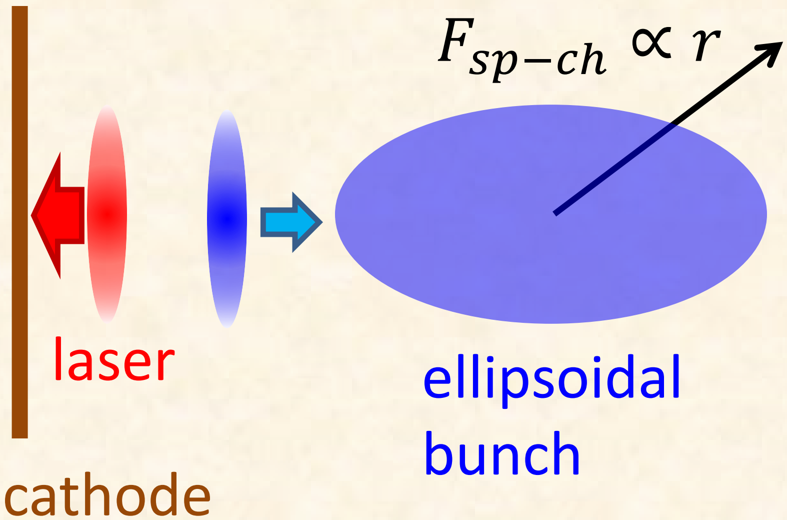


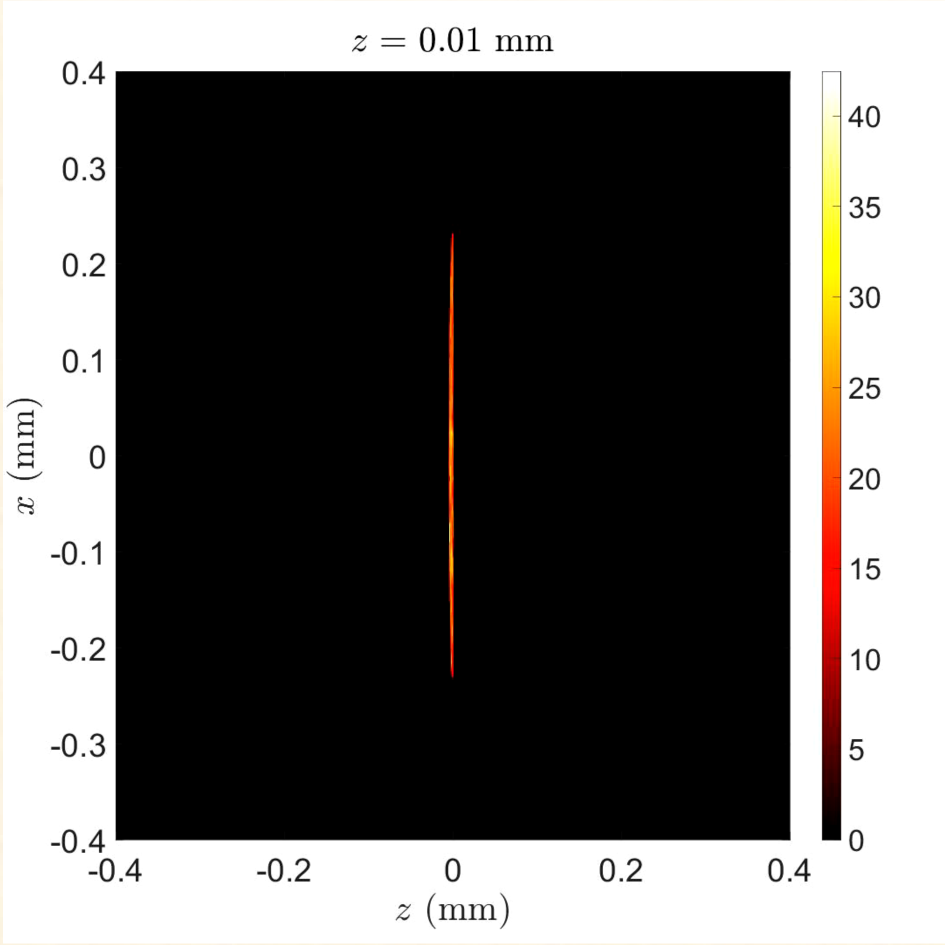
ARTOF @ momentum microscope



Blow-out bunch generation

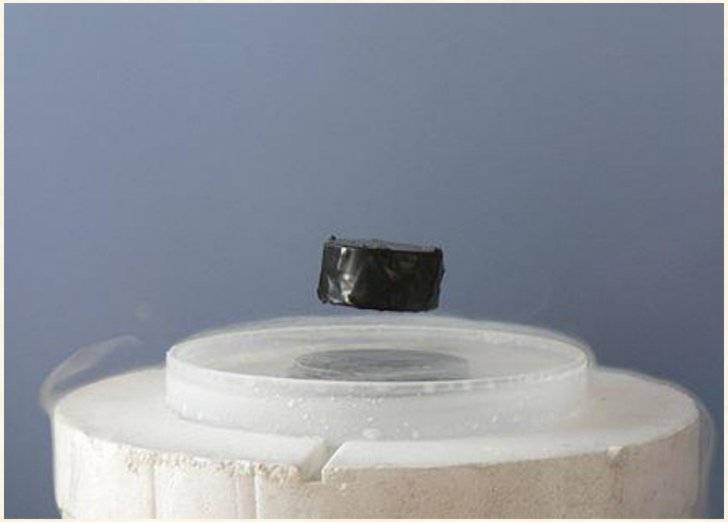






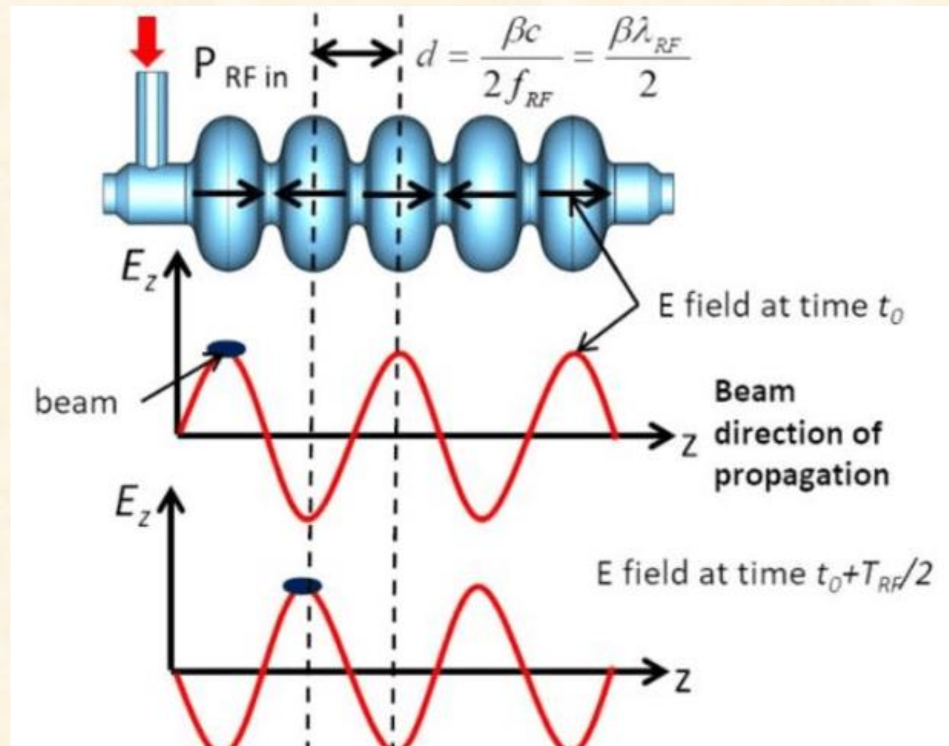
- $\rho(r,z) = \sigma_0\sqrt{1-(r/R)^2}\,\delta(z)$
- A flat charged disk can blow out into a fully fledged ellipsoidal bunch, O.J. Luiten, PRL 094802 (2004).

Superconducting RF technology



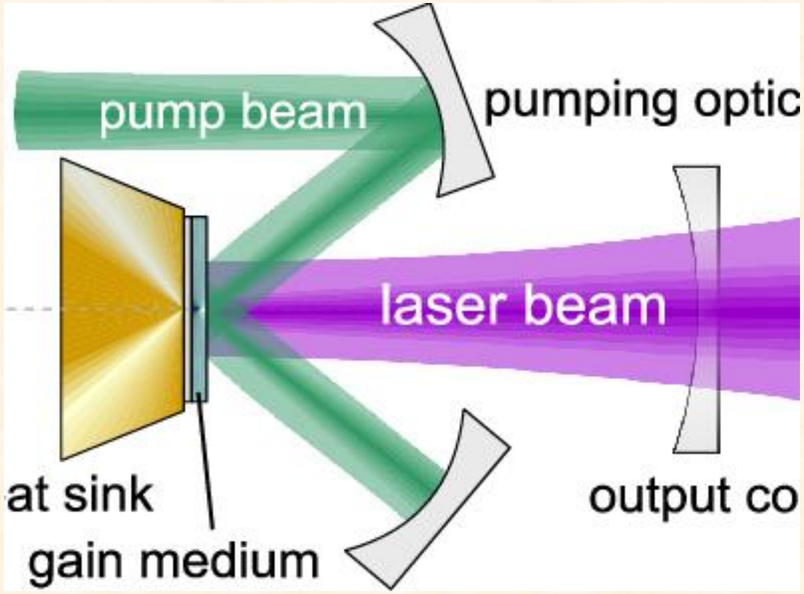
30 million electron x volts

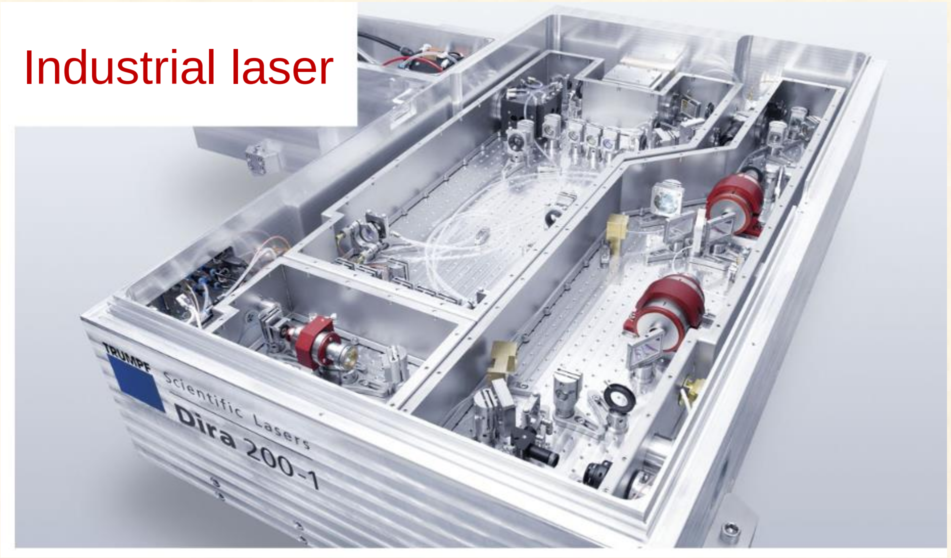
D. Alesini, CERN school, 2021

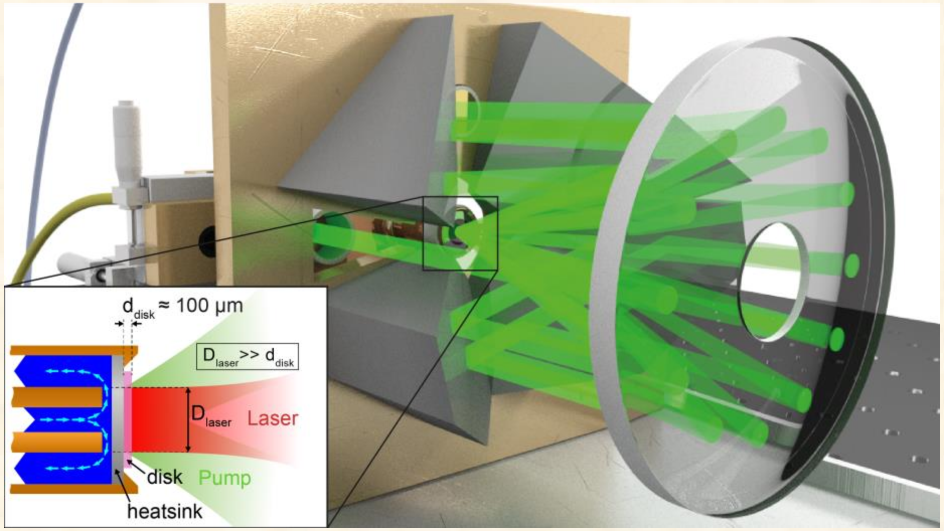


Vitaliy Goryashko

kW-class IR laser: thin-disk Yb:YAG technology





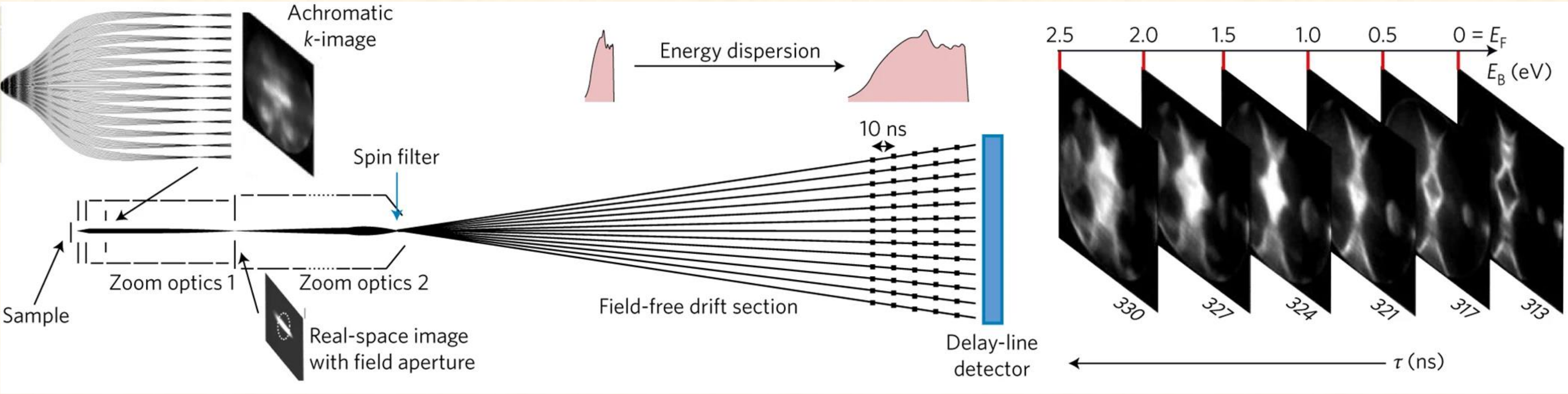


Courtesy of M. Saraceno, martin@saraceno.info

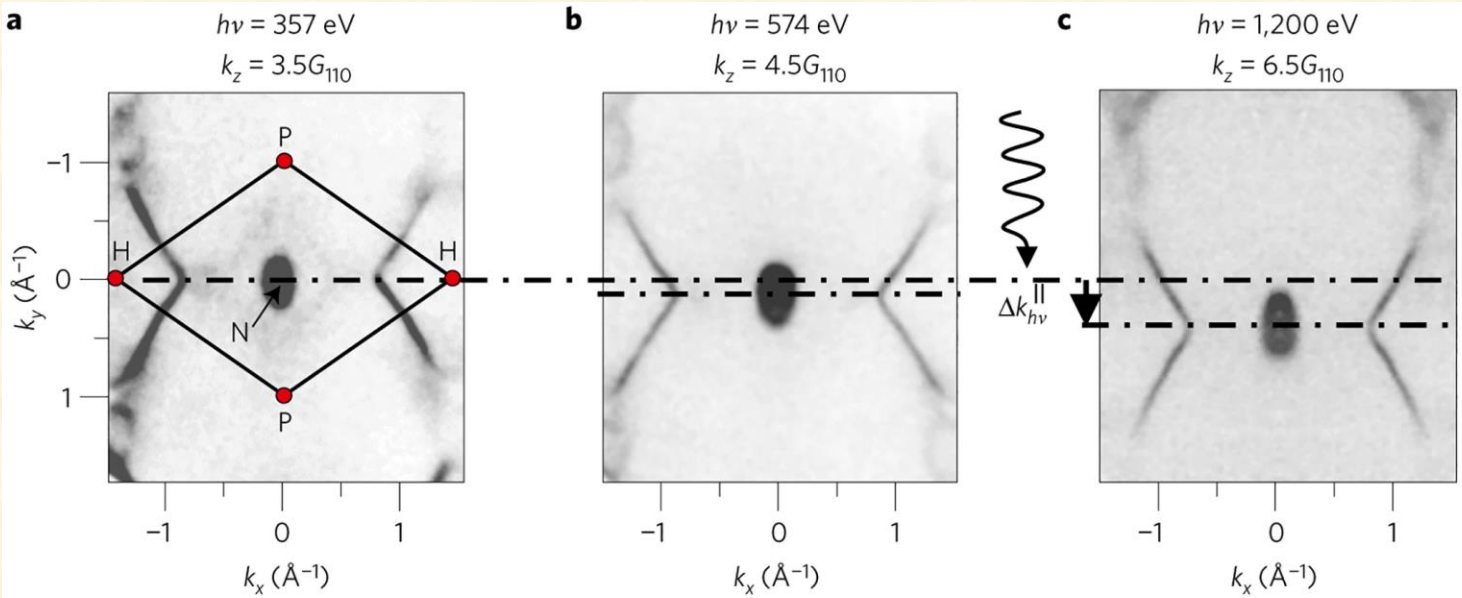
Thin-disk Yb:YAG lasers from TRUMPF at 1 um:

- Off-the-shelf: 0.75 kW, 20-100 kHz, up to 150 mJ, < 1 ps
- Demonstrated: 1.9 kW, 20 kHz, up to 95 mJ, < 1 ps
- On special order: 5 kW, 100 kHz, 50 mJ, < 1 ps

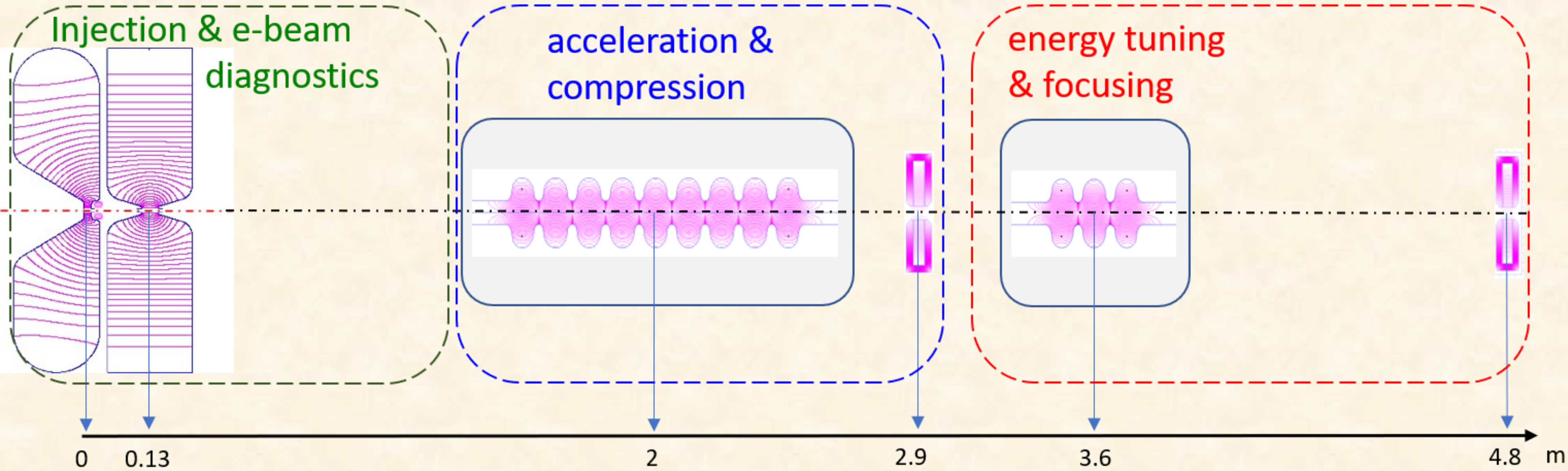
Detection of photo-electrons



[Nature Mat. 16, 615 (2017)]



Accelerator



Injector: **16 pC**

- energy: 1 MeV
- energy spread: 9.7 keV
- x-beam size: 240 um
- z-beam size: 770 um
- duration: 2.66 ps
- x-emittance: 65 nm
- z-emittance: 0.4 keV mm

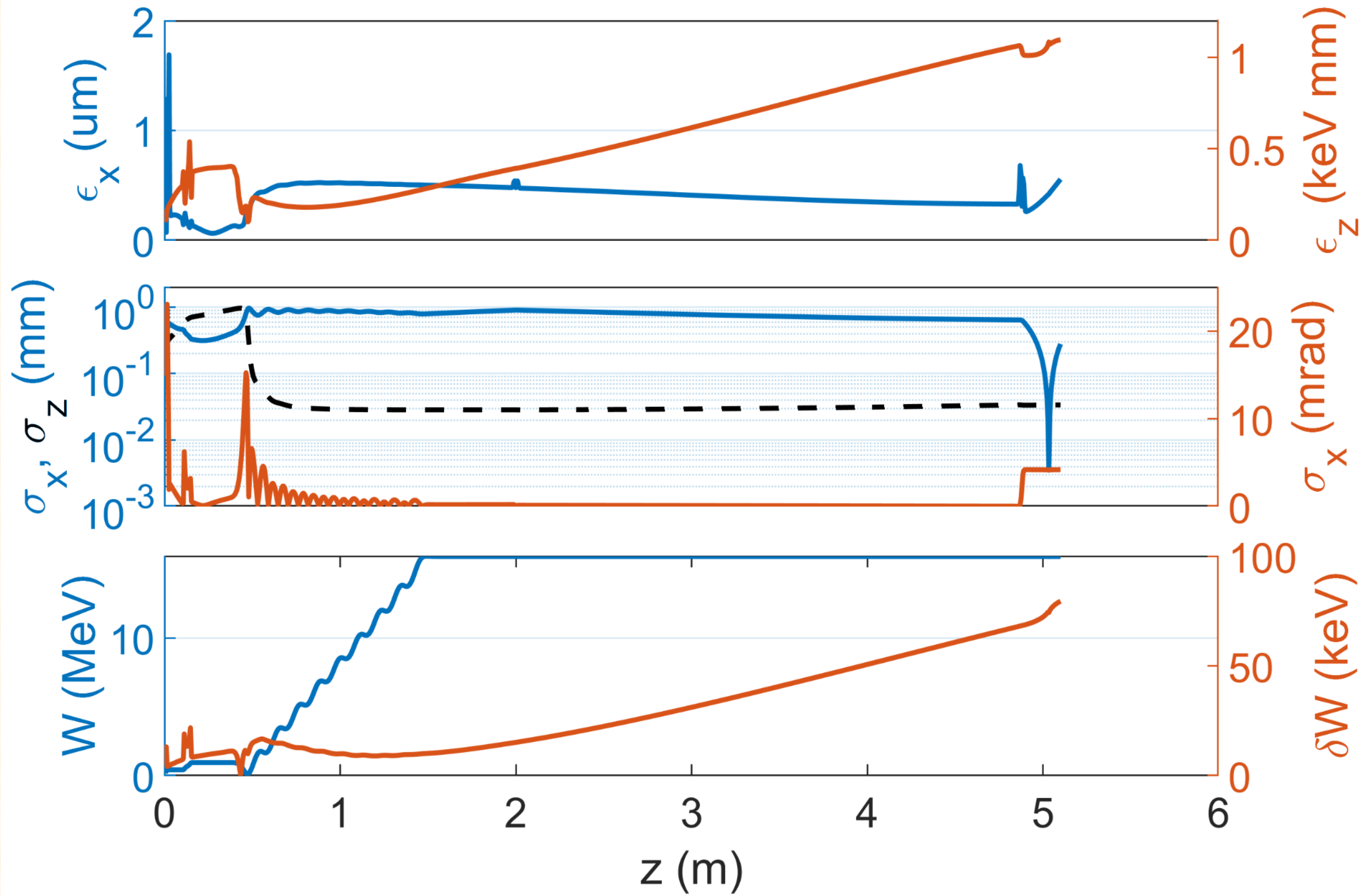
TESLA module:

- 16 MeV
- 30 keV
- 1000 um
- 70 um
- 0.23 ps
- 230 nm
- 0.4 keV mm

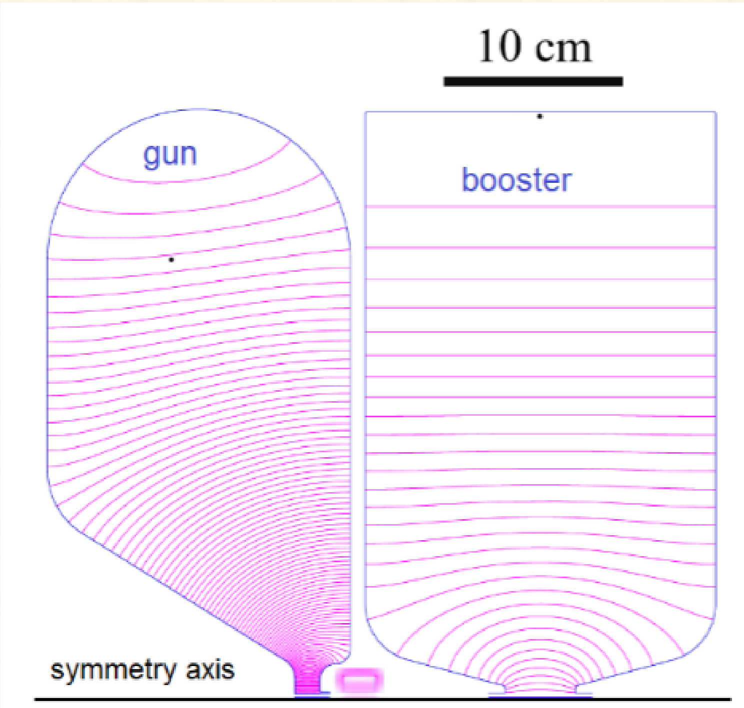
Tuning & focusing:

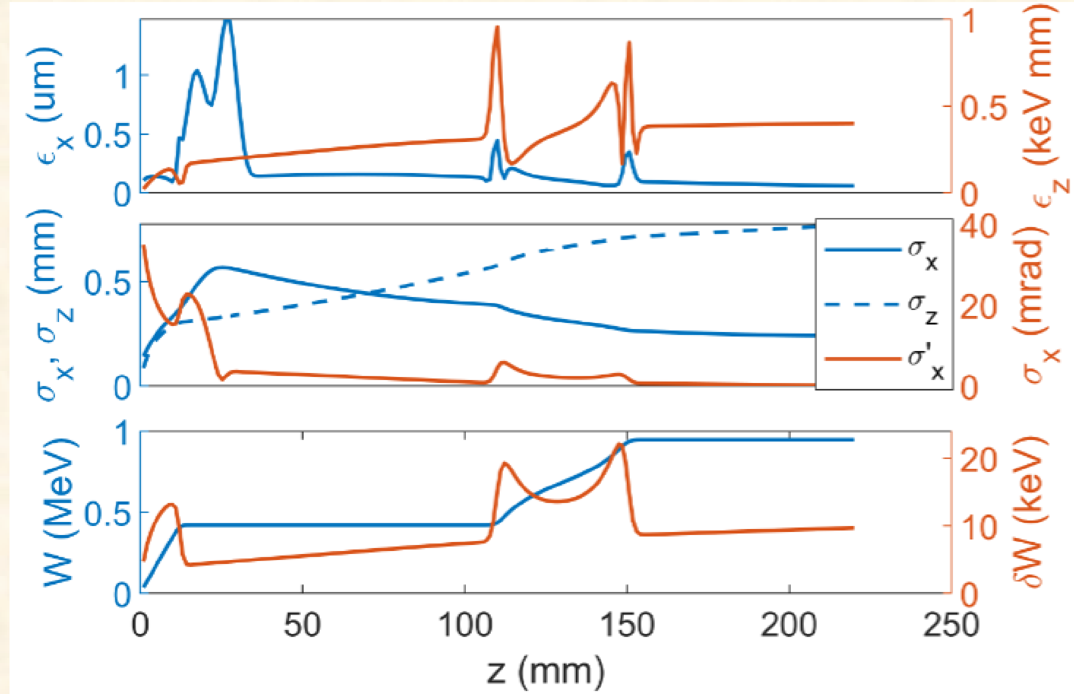
- 10-22 MeV
- 30-80 keV
- 3-5 um
- 50 um
- 0.1-0.2 ps
- 100-200 nm
- 0.8-1 keV mm

Beam evolution along the accelerator



Gun + booster

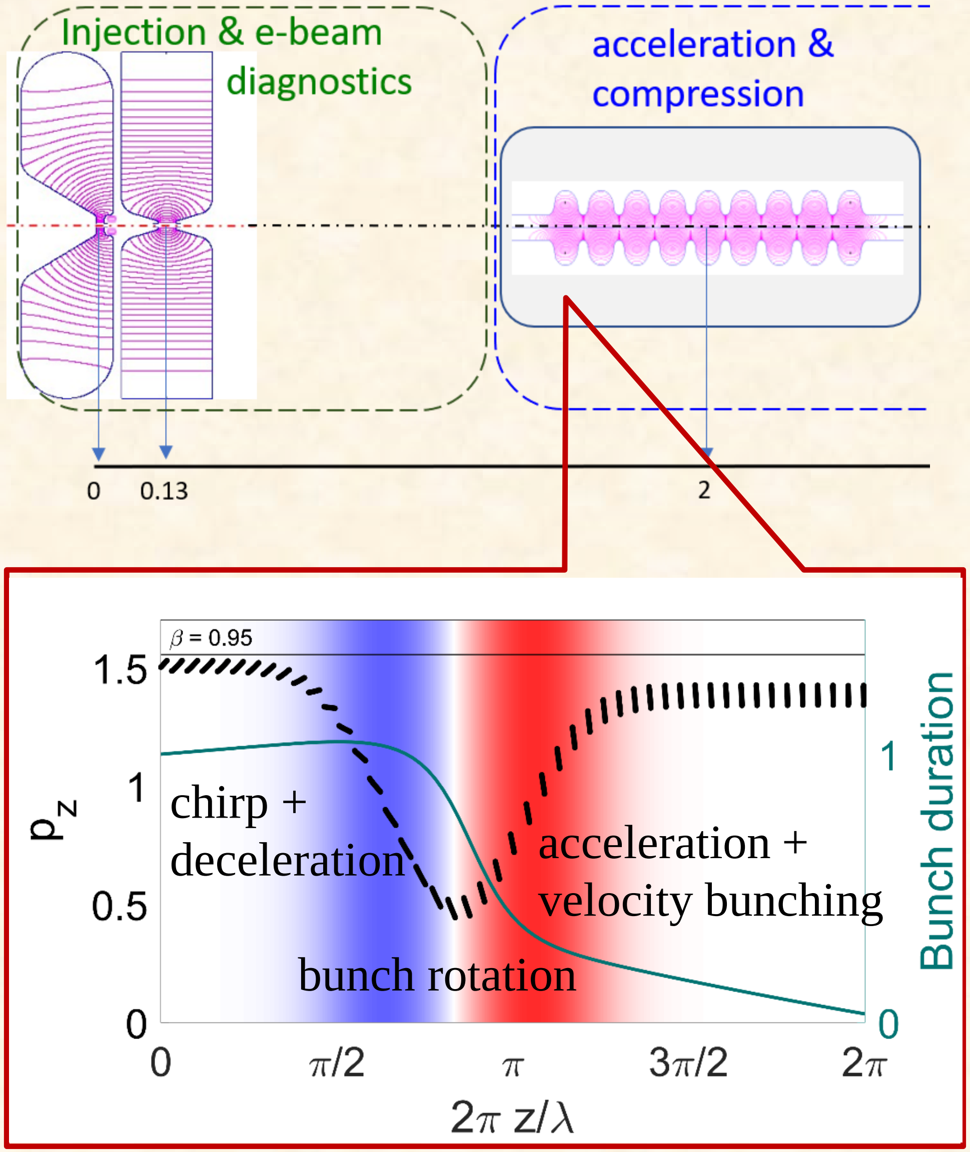


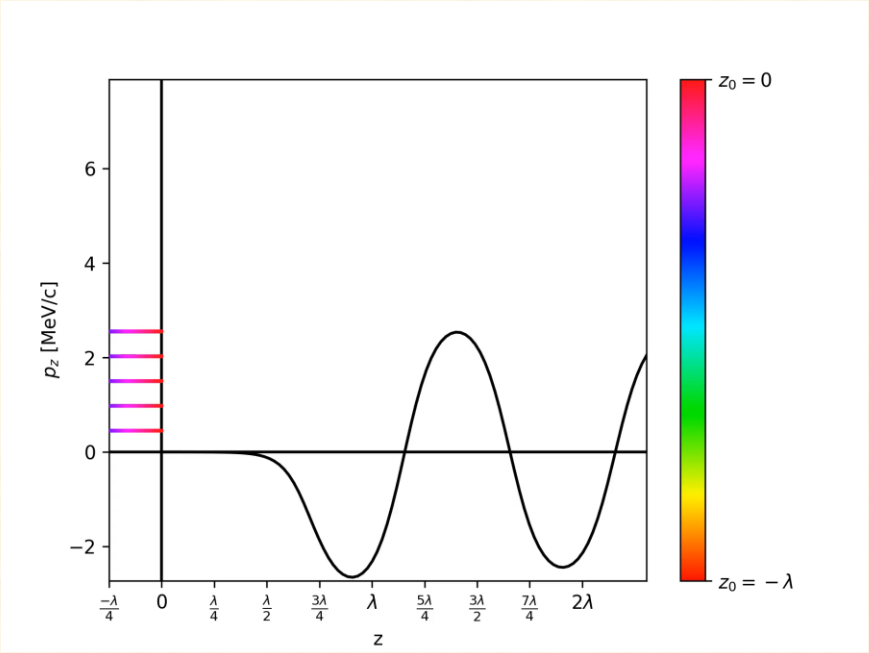


Parameter	Symbol	Value	Units
Peak accelerating field	E_{acc}	35	MV/m
Emission phase	-	0	degrees
Charge	Q	16	pC
Energy	W	130	meV
Energy spread	δW	80	meV
rms x-bunch size	σ_x	107	μm
rms bunch duration	σ_t	30	fs
rms x-beam divergence	σ'_x	2.47	mrad
rms thermal x-emittance	ε_x	44	nm

Parameter	Symbol	Value	Units
Charge	Q	16	pC
Energy	W	420	keV
Correlated energy spread	δW	5.3	keV
rms x-beam size	σ_x	2	mm
rms z-beam size	σ_z	0.46	mm
rms x-beam divergence	σ'_x	24.4	mrad
rms normalised x-emittance	ε_x	57	nm
rms normalised z-emittance	ε_z	0.24	keV mm
ratio of x and y emittances		0.99	

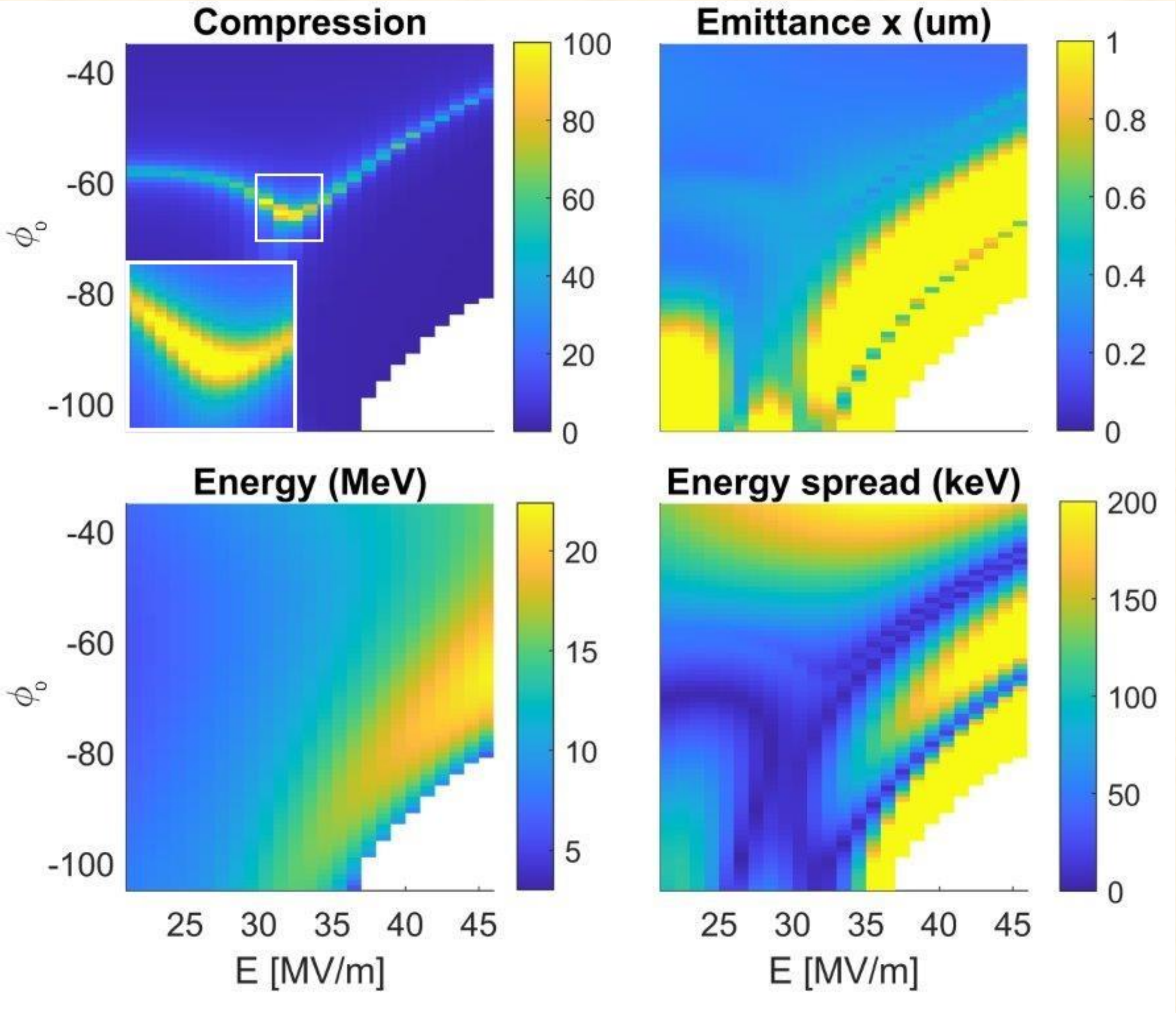
Half-wavelength bunching



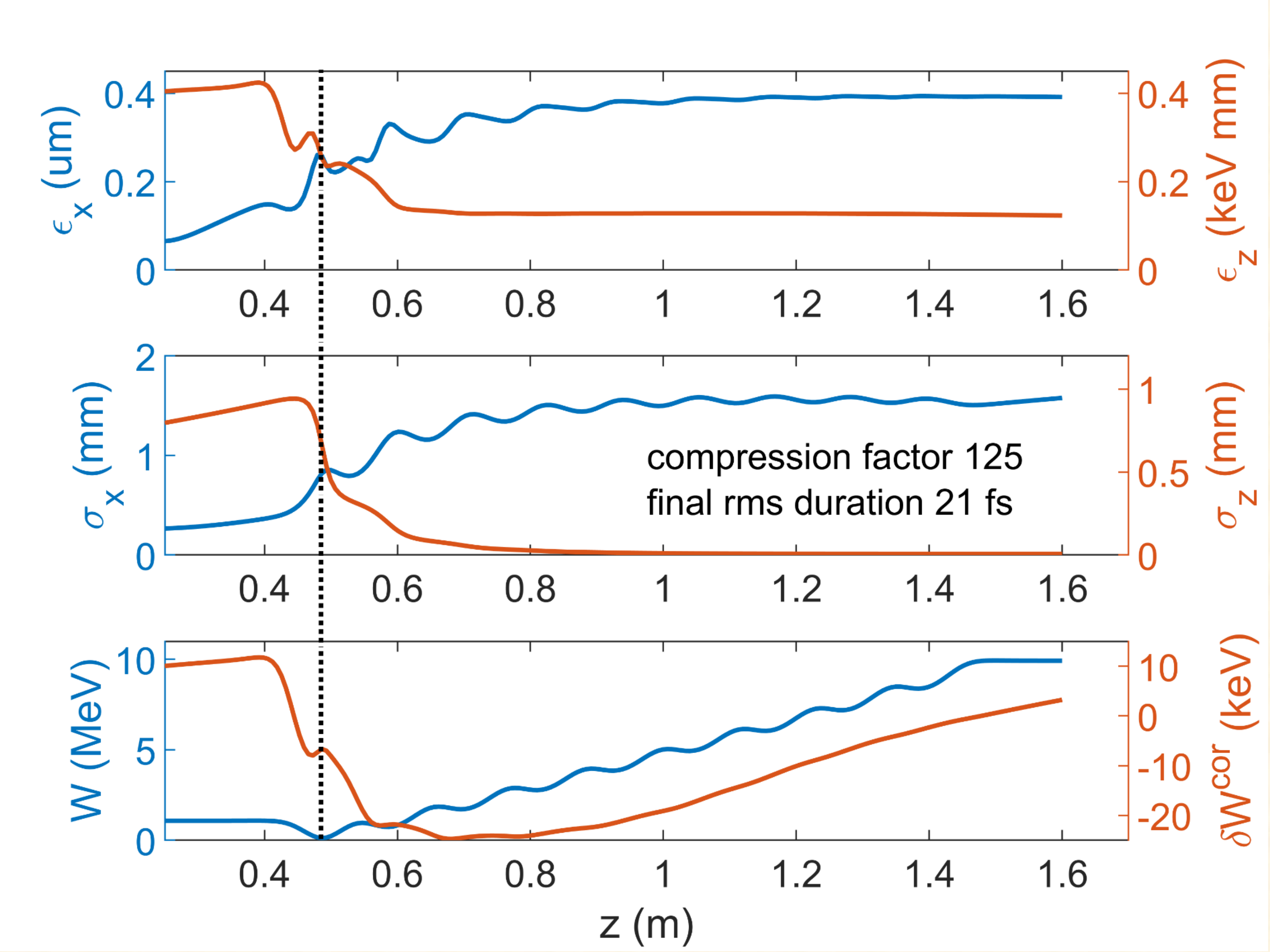


- very short compression length $\lambda/2$
- strong compression
- compression and acceleration occur in the same structure
- quite immune to the amplitude and phase jitter of the field
- compatible with classical velocity bunching

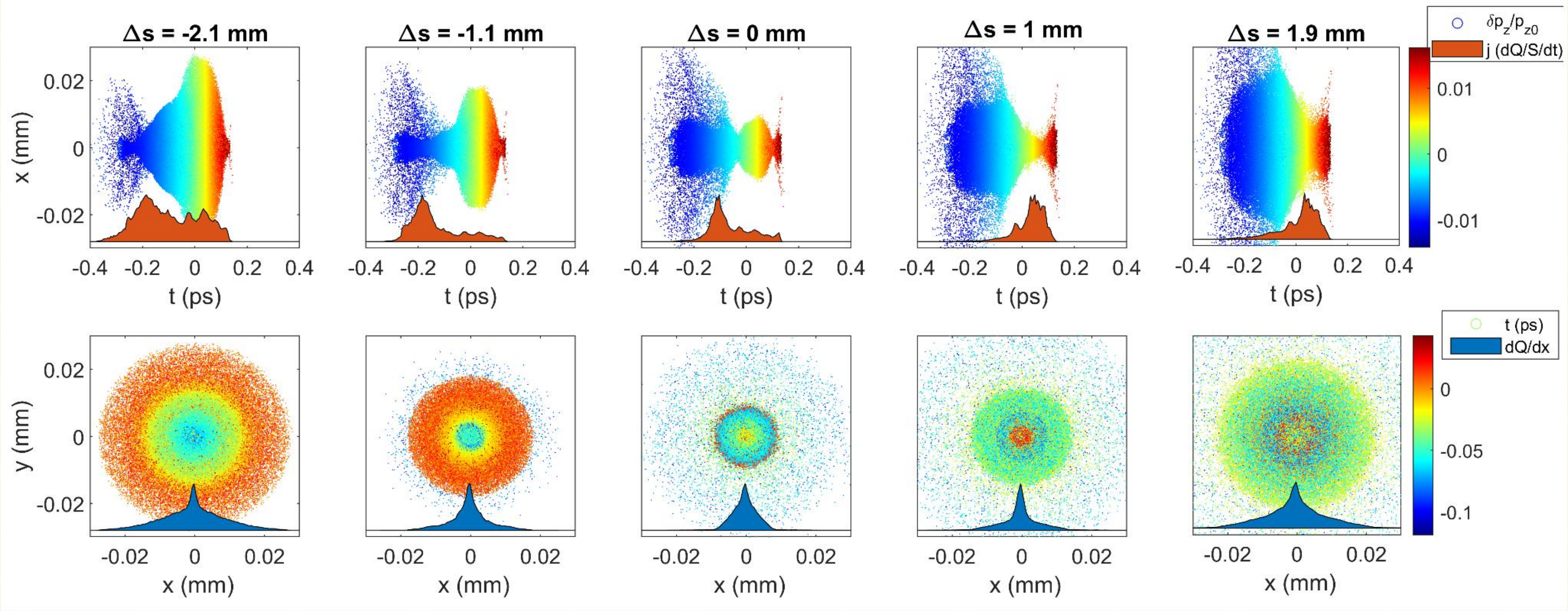
Scan over cavity parameters



Beam evolution during compression



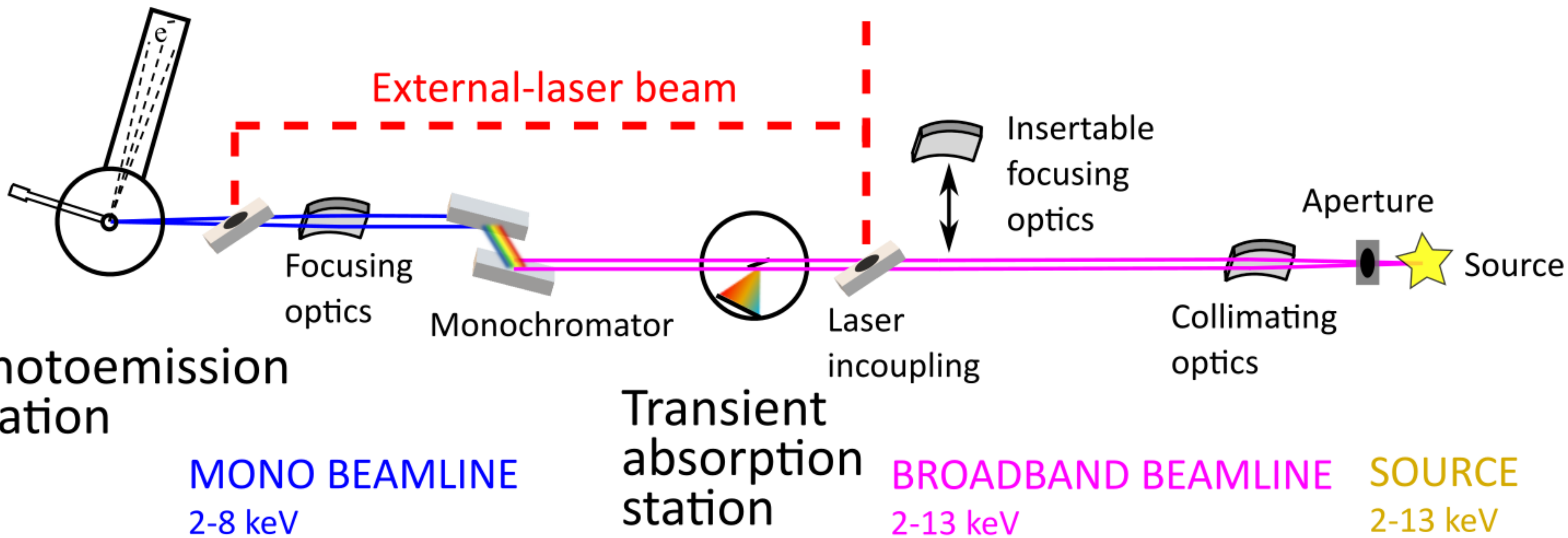
Beam at the interaction point



Target parameters of our incoherent X-ray source

Electron beam parameters	electron bunch charge	Q_b	16	pC
	number of electrons	N_b	10^8	
	bunch energy	U_b	16	MeV
	relative energy spread	δ_γ	0.5%	
	fwhm bunch duration	τ_b	<200	fs
	bunch emittance	ϵ_n	0.4	mm mrad
	rms bunch size	σ_b	3.5	um
	geometrical beta-function	β_g	~2	mm
Laser beam parameters	laser wavelength	λ_L	1.0	um
	rms laser pulse duration	τ_L	1	ps
	rms laser beam size	σ_L	4.9	um
	Rayleigh length	z_R	0.3	mm
	laser pulse energy	$\mathcal{E}_L$	50	mJ
	undulator parameter	$\mathcal{K}$	0.14	
	laser rep. rate	f_L	100	kHz
1.2X-ray yield	radiation wavelength	λ_r	0.25	nm
	photon energy	E_{ph}	4.8	keV
	rms X-ray pulse duration	τ_X	<200	fs
	rms X-ray beam size	σ_X	3.7	um
	opening angle of radiation cone	θ	1.75	mrad
	BW of acceptance cone, **rms**	BW_{cone}	1%	
	X-ray photons/shot	N_{ph}	2.2 10^4	
	X-ray photons/second/0.1%BW	$\mathcal{F}_{0.1\%}$	7 .4 10^8	
	average spectral density within θ	D	1.5 10^9	ph/sec/eV

X-ray beamline

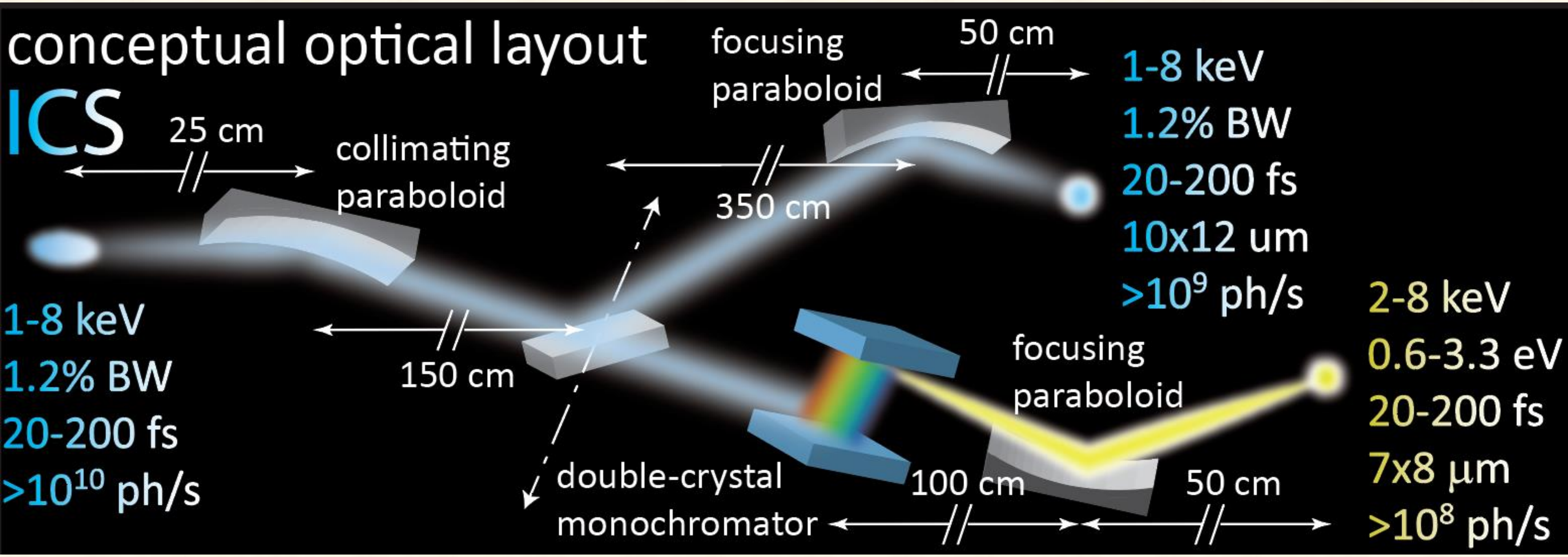


MONO BEAMLINE
- 2-8 keV
- <200 fs
- 0.02% BW
- 18 μm at sample
- 10^7-10^8 ph/s

BROADBAND BEAMLINE
- 2-13 keV
- <200 fs
- 1% BW
- 15 μm at sample
- >10^9 ph/s

SOURCE
- 2-13 keV
- <200 fs
- 1% BW
- 3 μm source size
- >10^{10} ph/s

X-ray beamline



Staged approach to short-pulse generation:

- < 200 fs FWHM
- < 50 fs FWHM
- train of attosecond pulses