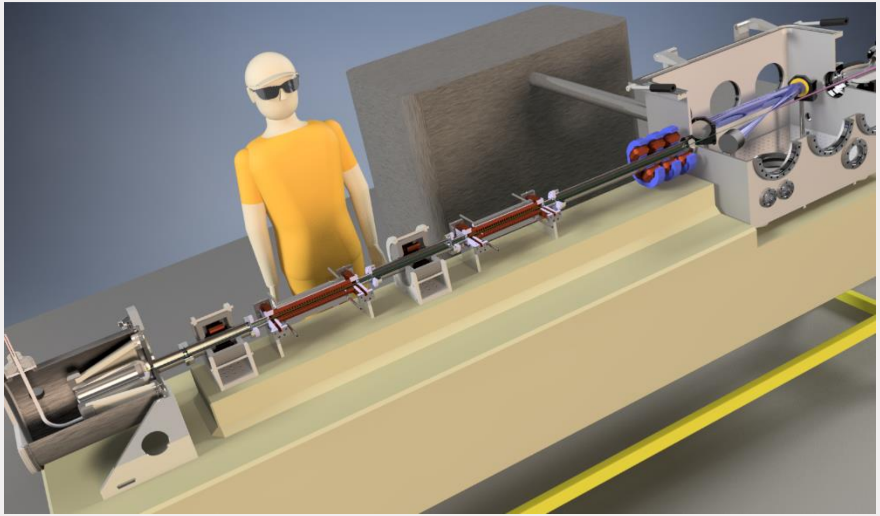
Cold and hot electron sources for the generation of coherent soft and hard X-rays by Compton scattering

Workshop on Science Opportunities with Table-Top Coherent X-Ray Sources, Uppsala, Sweden

Jim Franssen, Tim de Raadt, Daniel Nijhof, Brian Schaap, Xavier Stragier, Tom Lucas, Linda Stoel, Peter Mutsaers, Wiebe Toonen, Ali Rajabi, Marco van der Sluis, Eddy Rietman, Harry van Doorn,Frans van Setten, Jom Luiten

Department of Applied Physics



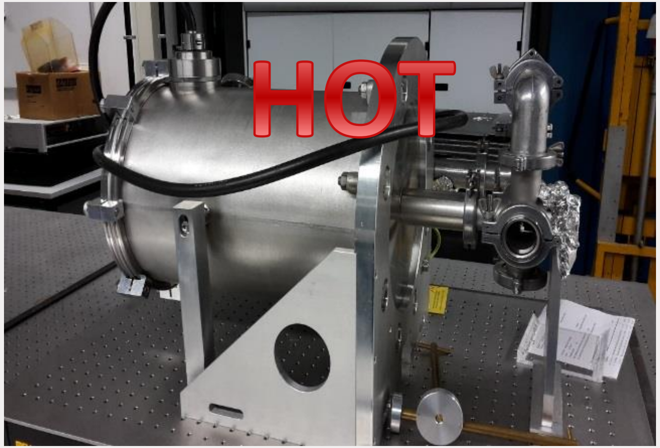
Interreg
EUROPESE UNIE
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

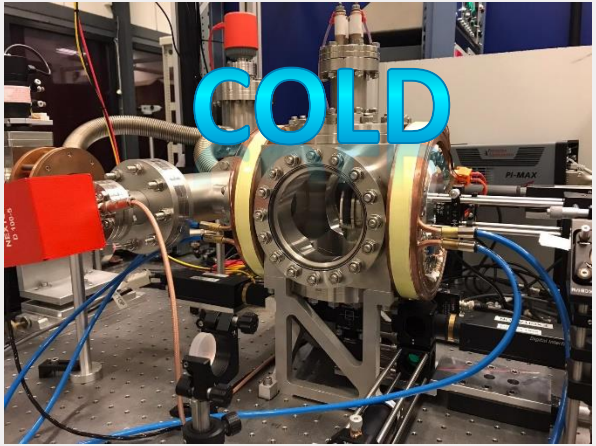
NWO

AccTec BV

TU/e

Smart*Light (*hard* X-rays) and ColdLight (*soft* X-rays)





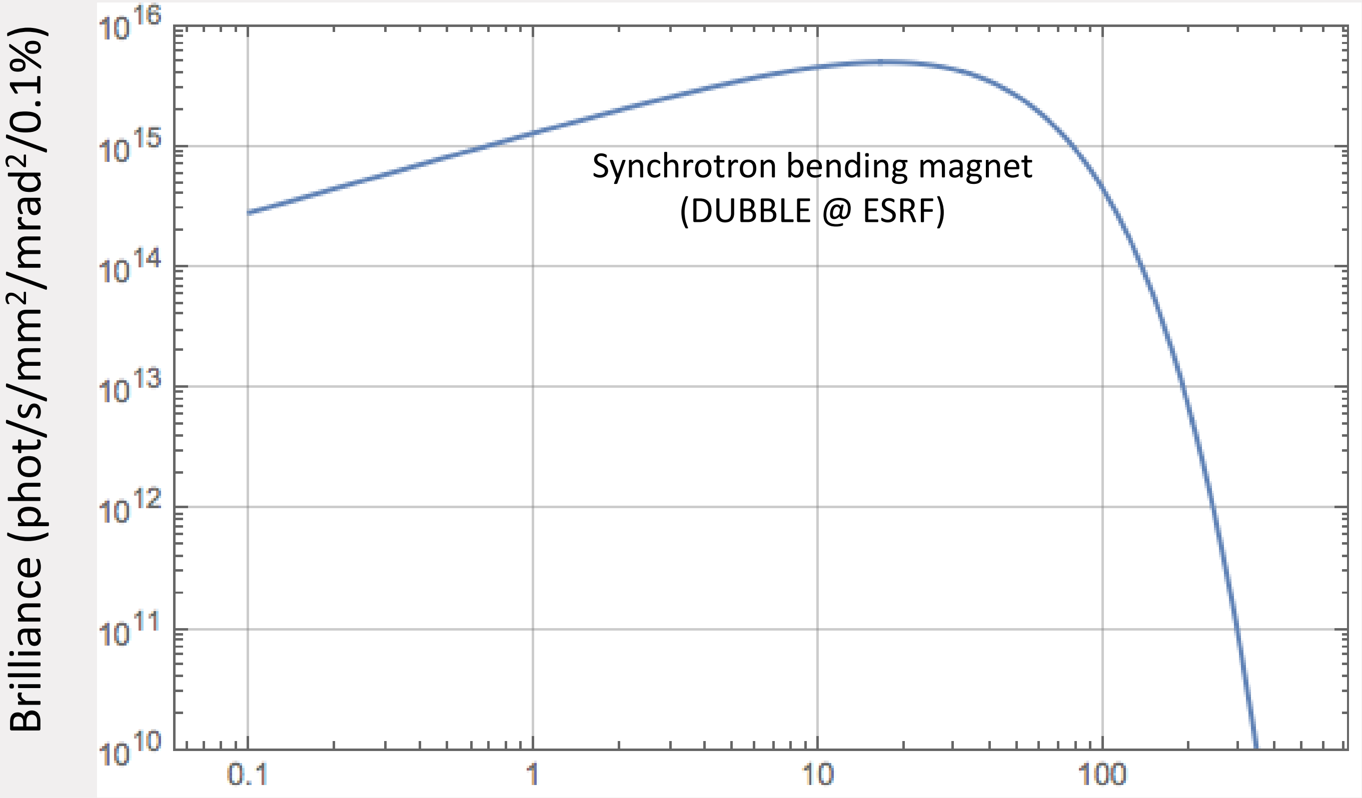
Interreg
EUROPESE UNIE
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

AccTec BV

ASML

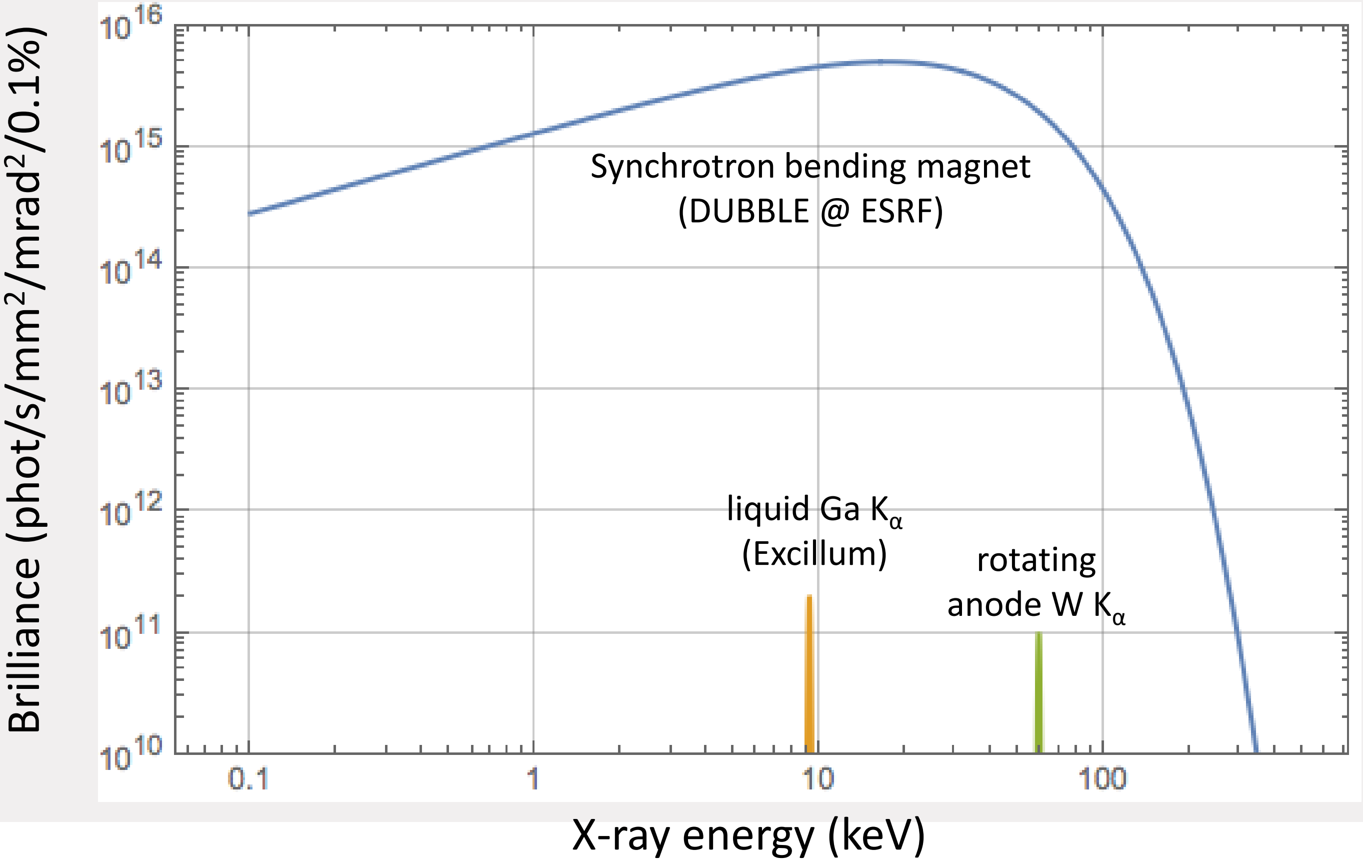
NWO

Brilliance



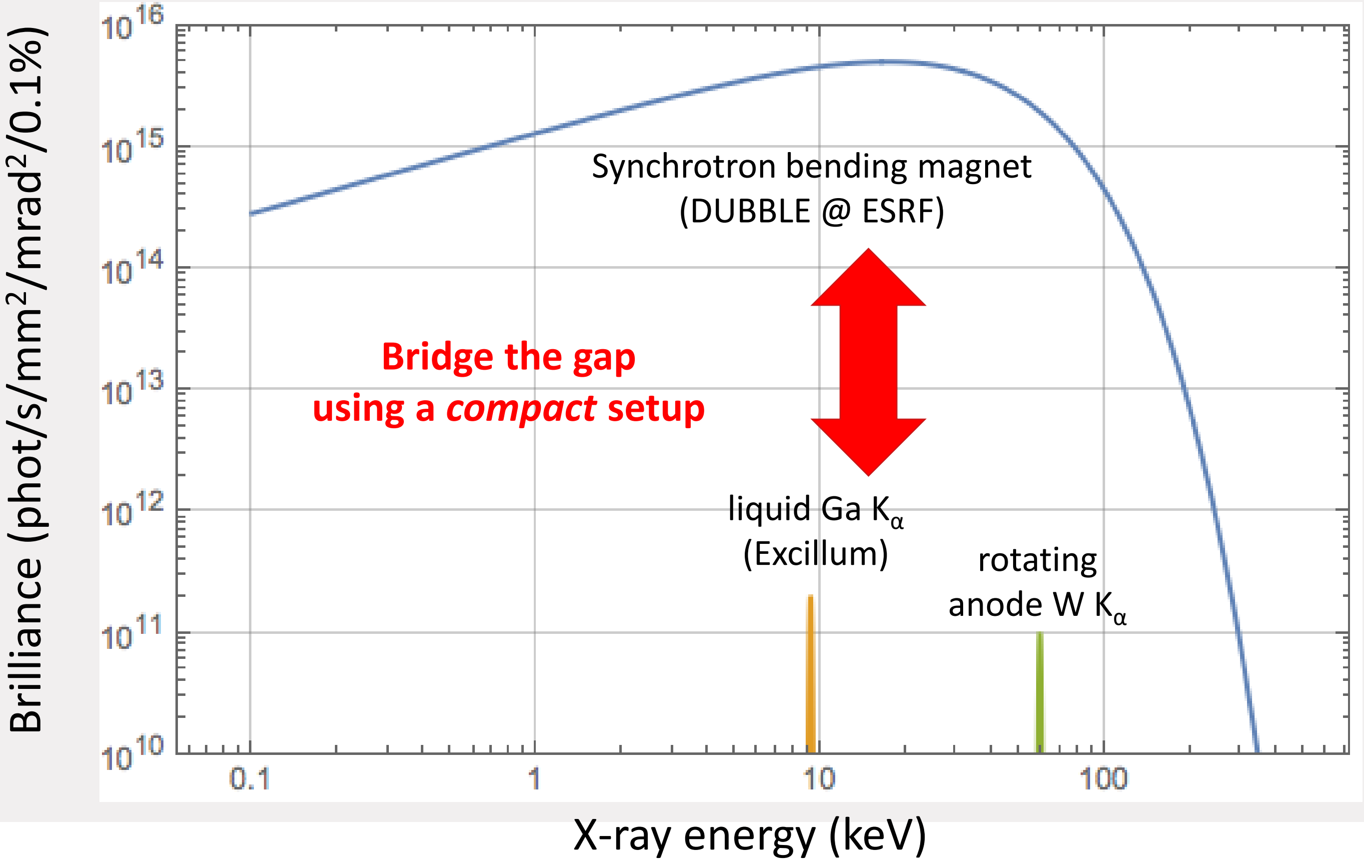
X-ray energy (keV)

Brilliance



Brilliance (phot/s/mm²/mrad²/0.1%)
10^16
10^15
10^14
10^13
10^12
10^11
10^10
Synchrotron bending magnet
(DUBBLE @ ESRF)
liquid Ga Kα
(Excillum)
rotating
anode W Kα
0.1
1
10
100
X-ray energy (keV)

Brilliance



Brilliance (phot/s/mm²/mrad²/0.1%)
10^16
10^15
10^14
10^13
10^12
10^11
10^10
0.1
1
10
100
Synchrotron bending magnet
(DUBBLE @ ESRF)
Bridge the gap
using a compact setup
liquid Ga Kα
(Excillum)
rotating
anode W Kα
X-ray energy (keV)

X-ray generation by Inverse Compton Scattering

$$I_x = \frac{I_0}{4\gamma^2}(1+\gamma^2\theta^2)$$

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

X-ray generation by Inverse Compton Scattering

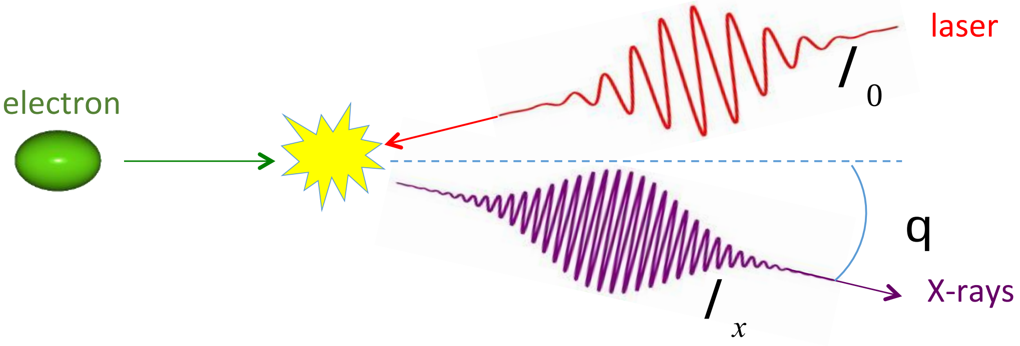
Laser wavelength $\lambda_0 = 500 \text{ nm}$

Electron energy	Lorentz factor	X-ray wavelength	X-ray energy	Half cone angle 1% energy spread
5 MeV	11	10 Å	1.2 keV	9.0 mrad
20 MeV	40	0.78 Å	16 keV	2.5 mrad
50 MeV	99	0.13 Å	95 keV	1.0 mrad

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

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

X-ray generation by Inverse Compton Scattering



X-ray photon number per pulse:

$$N_x = \frac{\sigma_T N_0 N_e}{2\pi(\sigma_e^2 + \sigma_0^2)}$$

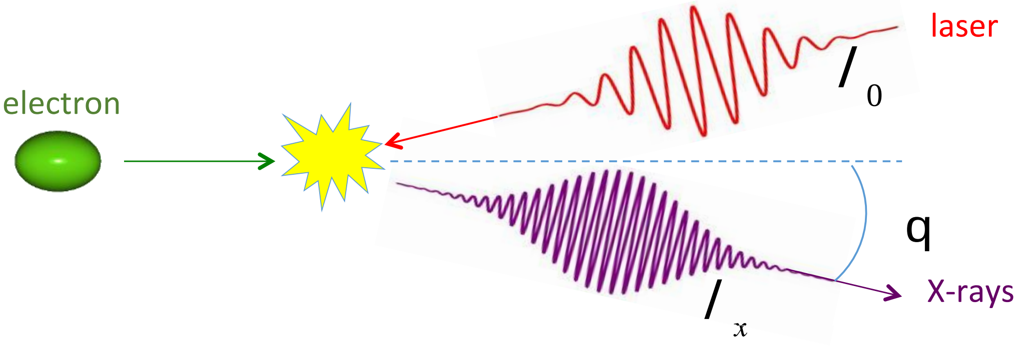
1030 nm, 200 mJ laser: $N_0 \approx 10^{18}$

laser spot size: $\sigma_0 \geq 5\mu\mathrm{m}$

$$\Rightarrow N_x \leq N_e \sim 10^8 - 10^9$$

≤1 X-ray photon per electron

ICS X-ray brilliance



X-ray photon flu :

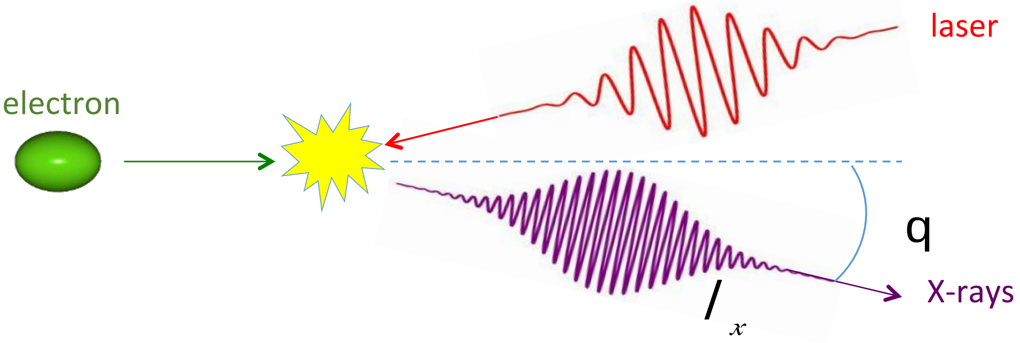
$$\Phi_x = \frac{\sigma_T N_0 N_e f_{rep}}{2\pi(\sigma_e^2 + \sigma_0)^2}$$

1030 nm, 200 mJ,1 kHz
100-bunch burst mode

$$f_{rep} = 10^5 \Rightarrow \Phi_x \sim 10^{13} - 10^{14} \text{ ph/s}$$

TU/e

ICS X-ray brilliance

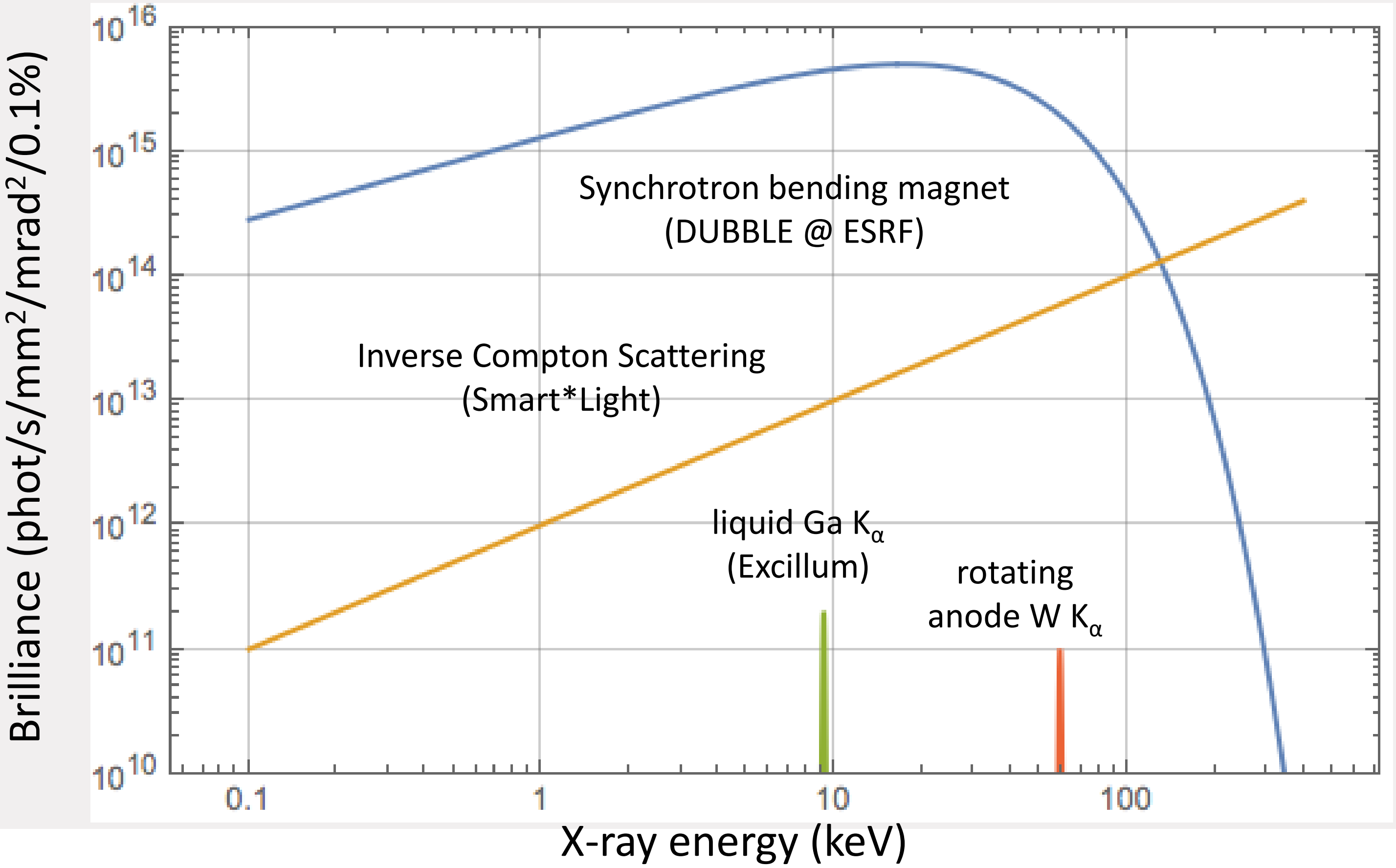


X-ray brilliance:

$$B_x = \frac{3}{2}\frac{\gamma^2 \sigma_T N_0 N_e f_{rep}}{(2\pi)^3 \varepsilon_n^2 (\sigma_e^2 + \sigma_0^2)}$$

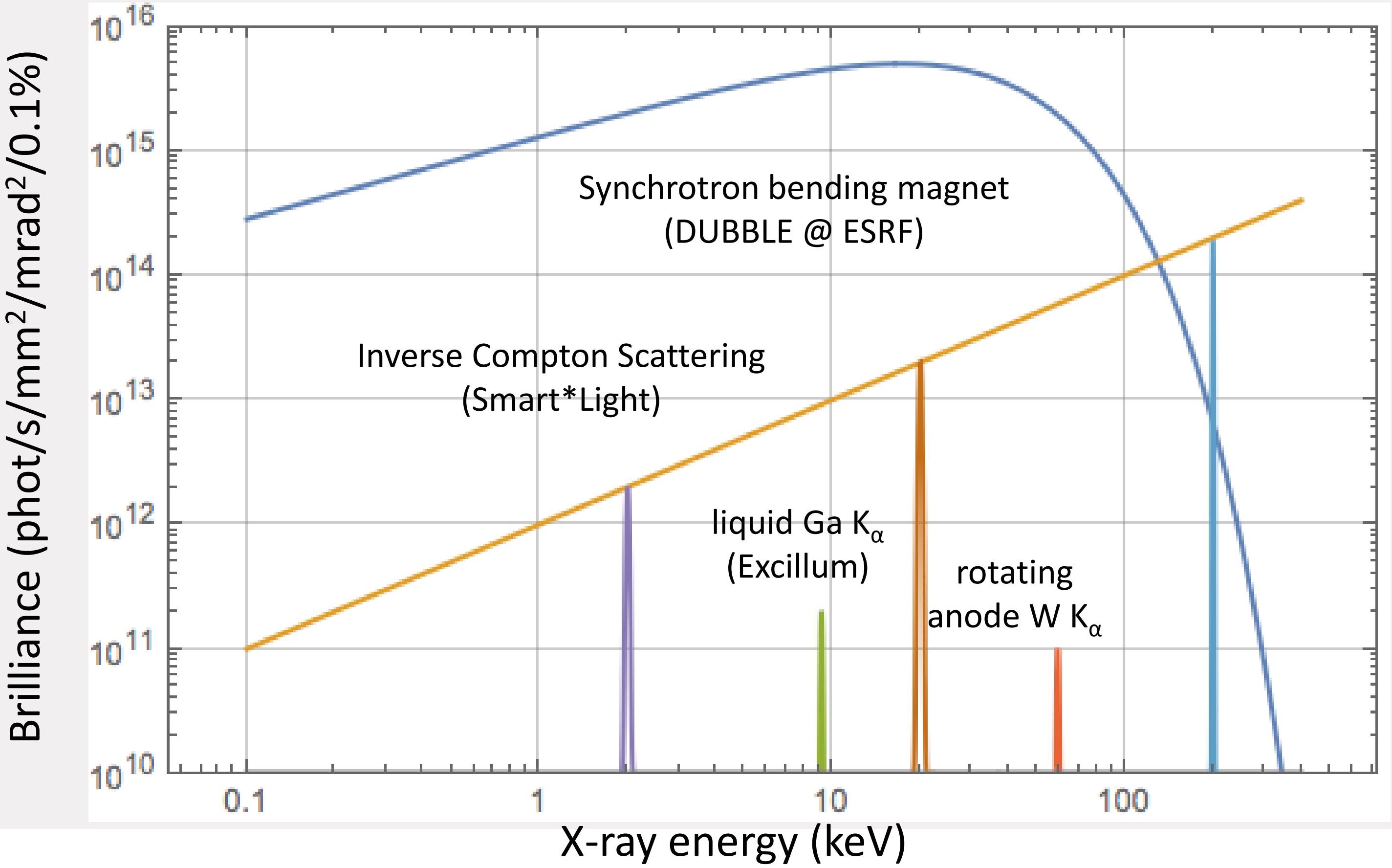
$$\left.\begin{array}{r} \varepsilon_n = 0.5\ \mu m \\ \gamma = 60 \end{array}\right\} \Rightarrow B_x = 1.2 \times 10^{13}\ \text{photons / s / mm}^2\text{ / mrad}^2\text{ / 0.1\% BW}$$

Brilliance



Brilliance (phot/s/mm²/mrad²/0.1%)
10^16
10^15
10^14
10^13
10^12
10^11
10^10
Synchrotron bending magnet
(DUBBLE @ ESRF)
Inverse Compton Scattering
(Smart*Light)
liquid Ga Kα
(Excillum)
rotating
anode W Kα
0.1
1
10
100
X-ray energy (keV)

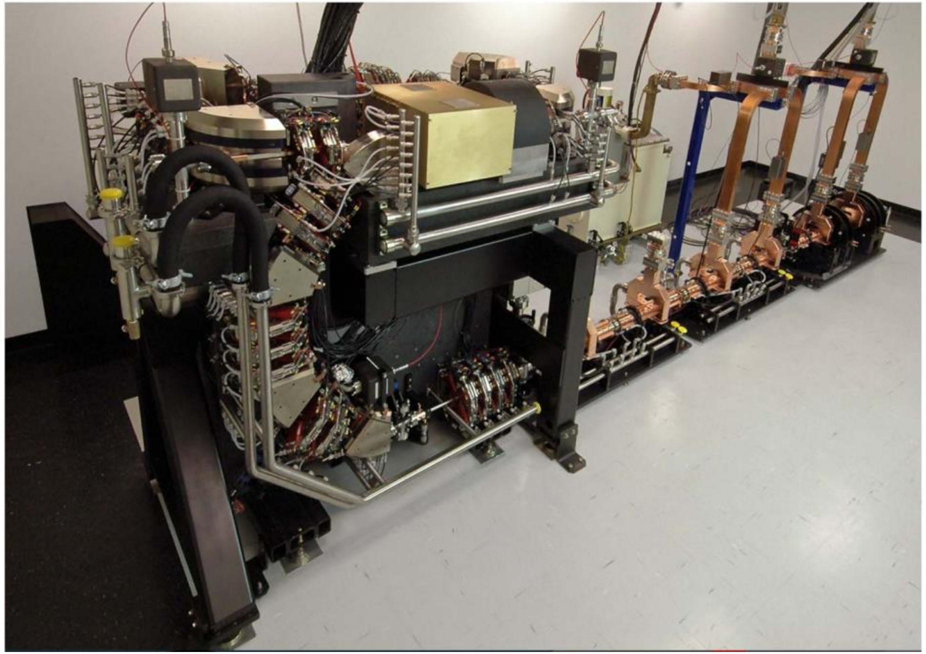
Brilliance

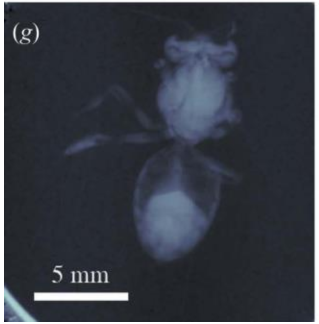


Brilliance (phot/s/mm²/mrad²/0.1%)
10^16
10^15
10^14
10^13
10^12
10^11
10^10
0.1
1
10
100
Synchrotron bending magnet
(DUBBLE @ ESRF)
Inverse Compton Scattering
(Smart*Light)
liquid Ga Kα
(Excillum)
rotating
anode W Kα
X-ray energy (keV)

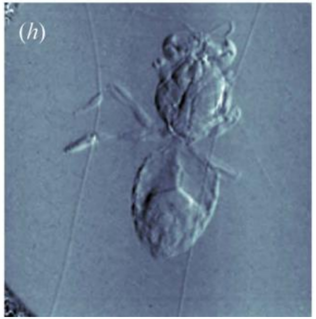
ICS sources: Lyncean

first commercial ICS source





absorption image



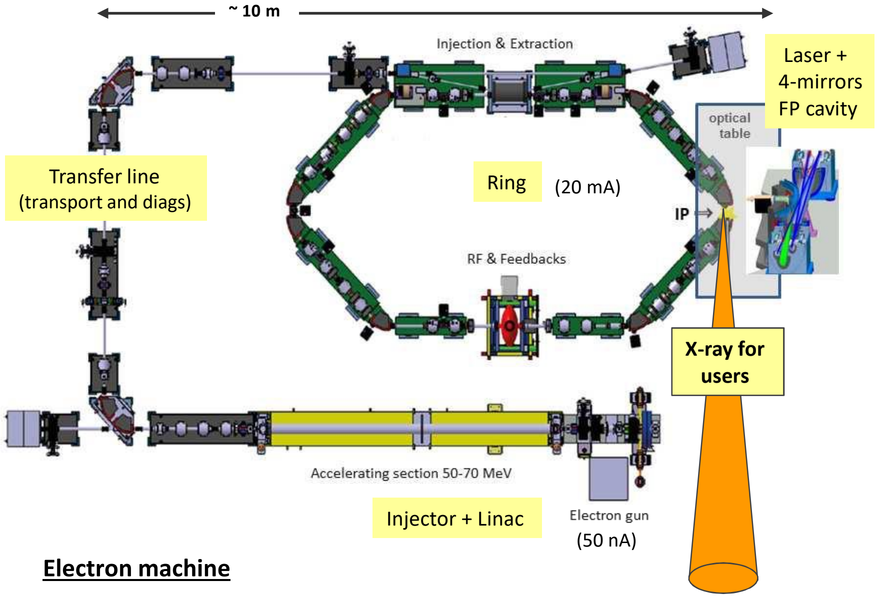
phase-contrast image

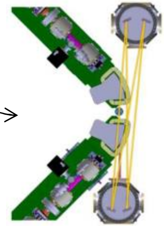
Journal of
Synchrotron Radiation
ISSN 0909-0495

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

ICS sources: ThomX

being commissioned





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)

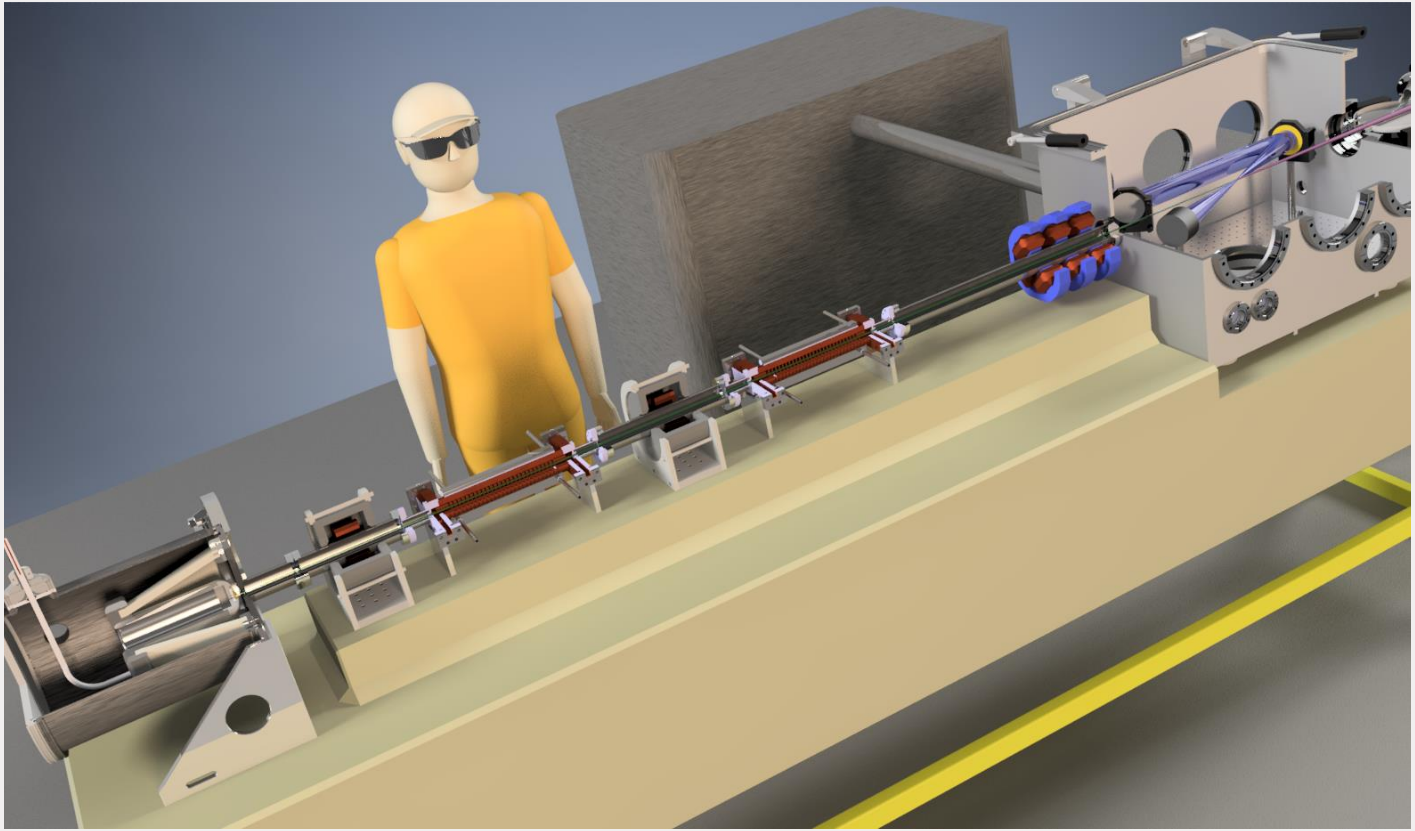
Electron machine

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

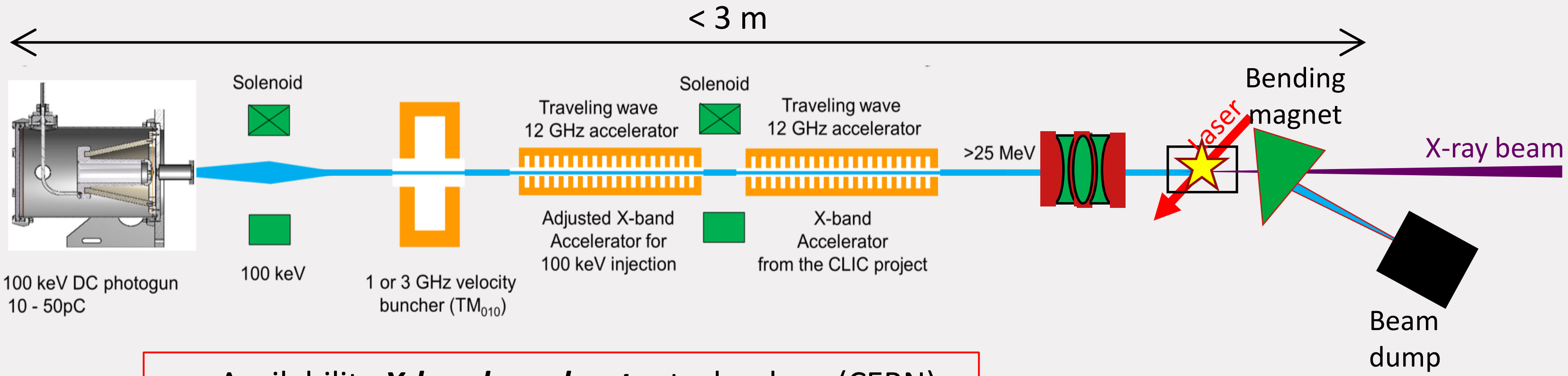
X-ray beam

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

Smart*Light: a LINAC-based ICS source



Smart*Light: a LINAC-based ICS source: *why?*

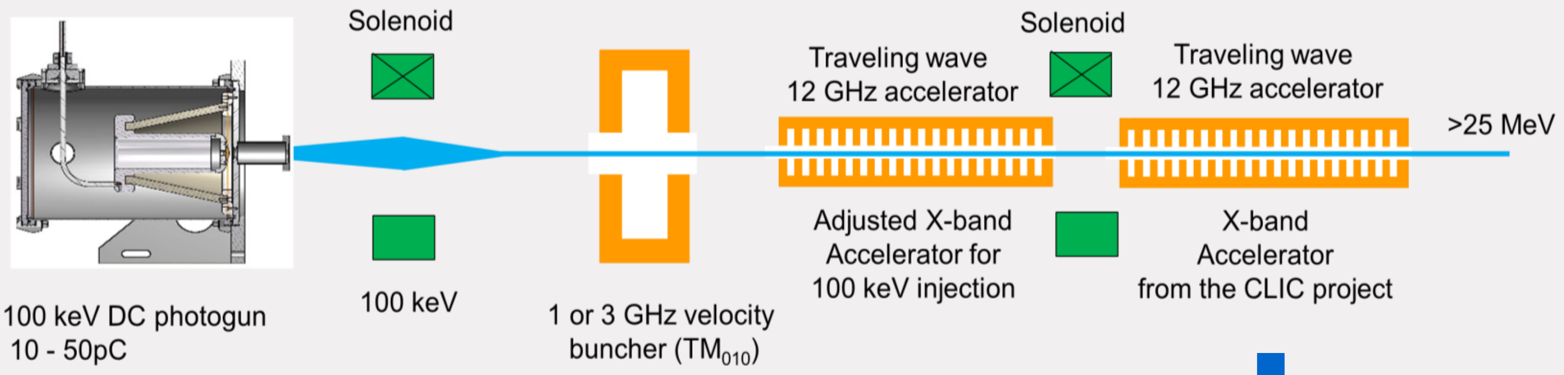


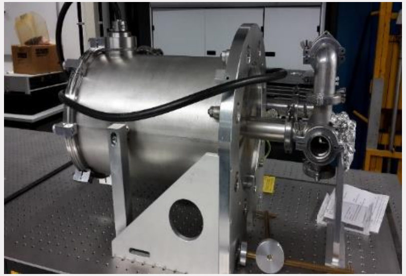
- Availability ***X-band accelerator*** technology (CERN)
- Lower emittance beams ➔ ***higher X-ray coherence***
- Easier alignment, ***fast change of X-ray energy***

- *Less radiation*
- *No bunker required*
- *Will fit into sea container*

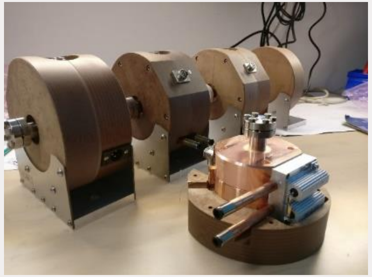
- *Proven technology, reliability & robustness*
- *Modular approach:* ***Swap Guns*** *&* ***Add LINACs***
- ***Upscaling of Photon Flux & X-ray Energy***

Available electron beam line components

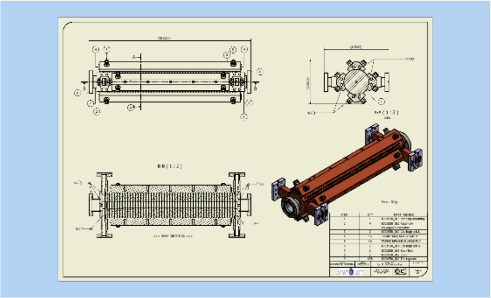




TU/e 100 kV DC photogun

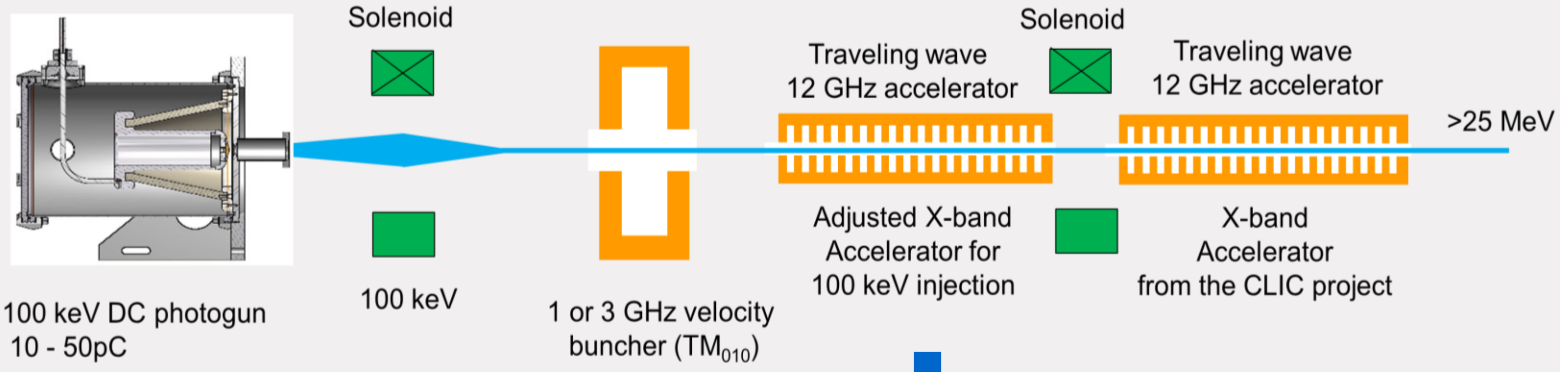


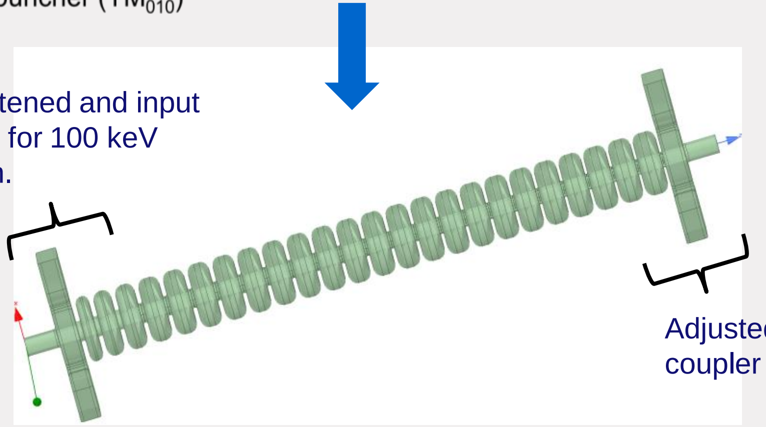
TU/e buncher cavity



modified CLIC accelerator section

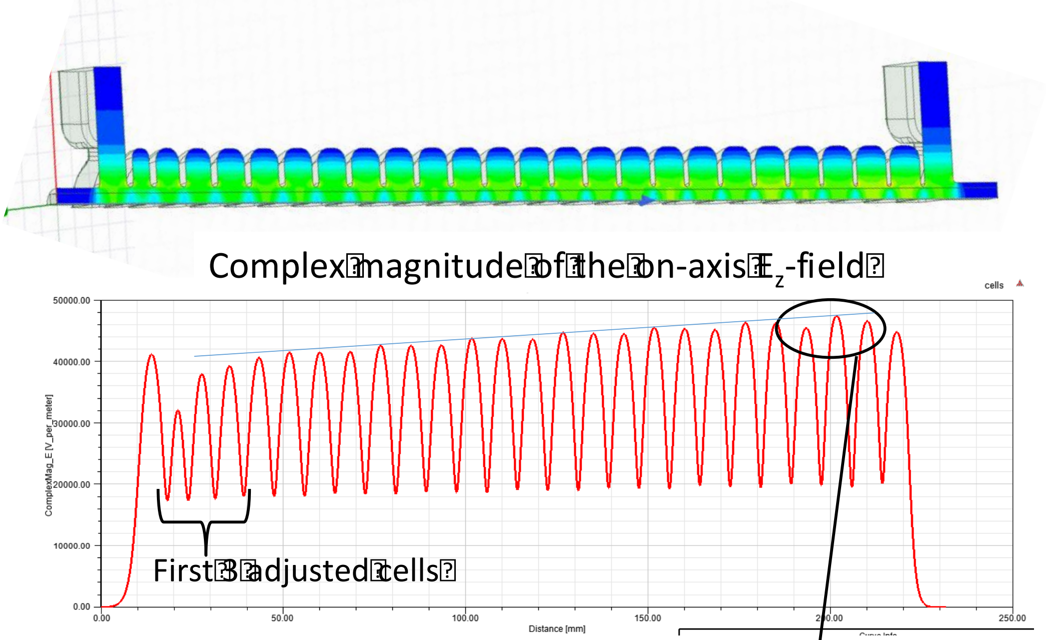
Smart*Light: a LINAC-based ICS source





First section being manufactured (50 cells now...)

Detailed design calculations with CLIC team CERN



Small standing wave component:
<2% reflected back in the
structure at output coupler

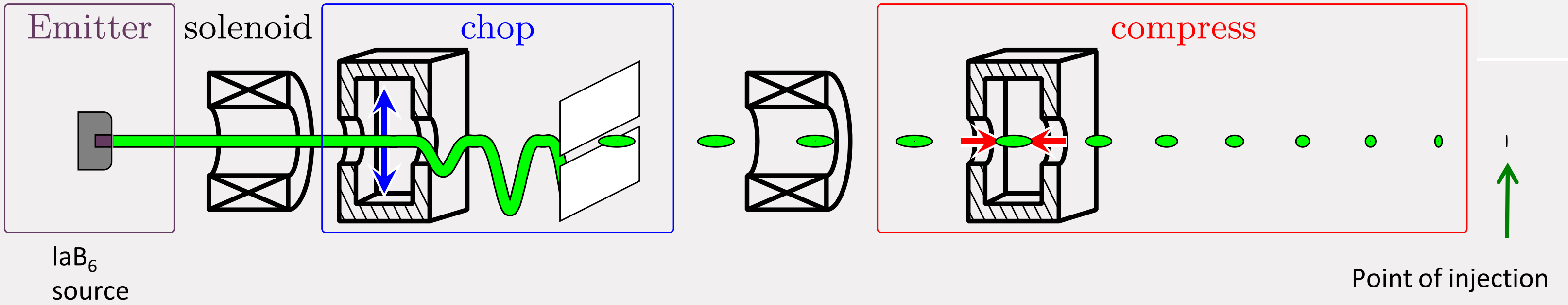
(Possible) Laser System

Trumpf Dira 200-1

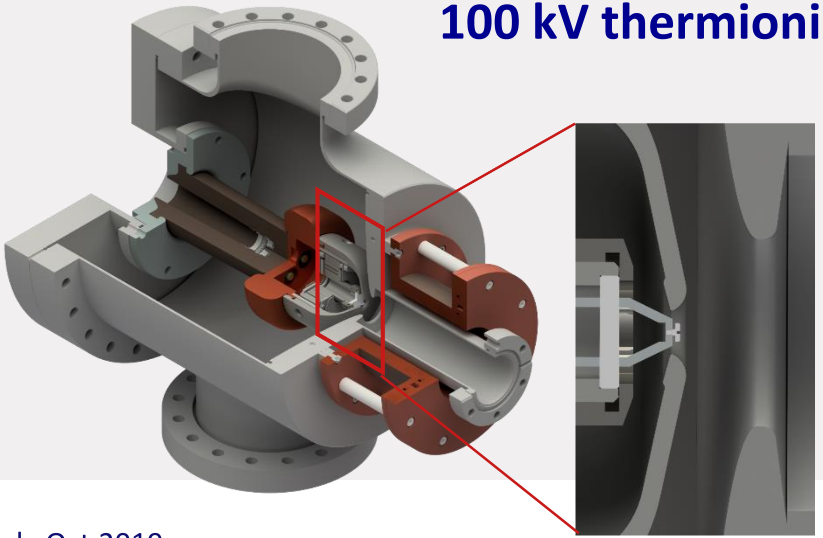
robust, reliable, turn-key industrial laser

- Commercially available, compact, high-power, sub-picosecond, 1030 nm, 200 mJ, @ 1 kHz
- With 2nd harmonic module: 515 nm, 100 mJ @ 1 kHz
- 100-bunch burst mode operation using Fabry-Pérot cavity?

Gun upgrade for 100-bunch burst mode



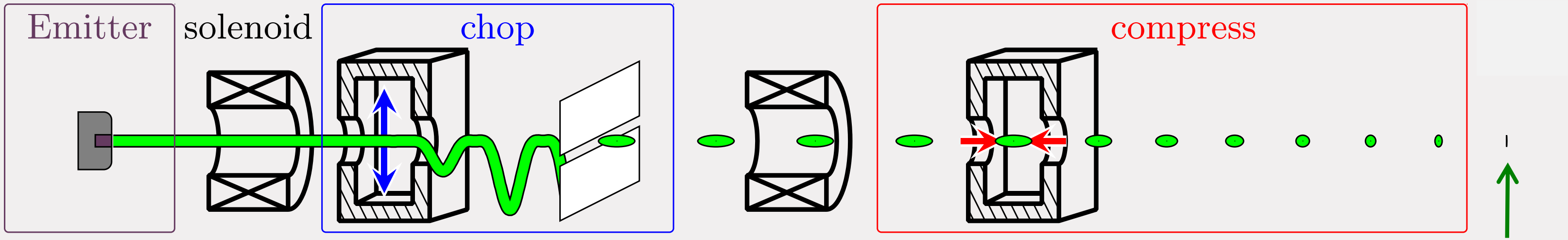
100 kV thermionic gun



- 1 mm LaB_6 crystal @ 1760 K
- 10 MV/m cathode field strength
- 100 mA continuous current
  - 70 nm rad thermal emittance

TU/e

Gun upgrade for 100-bunch burst mode

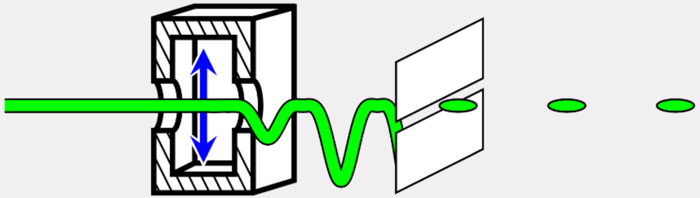


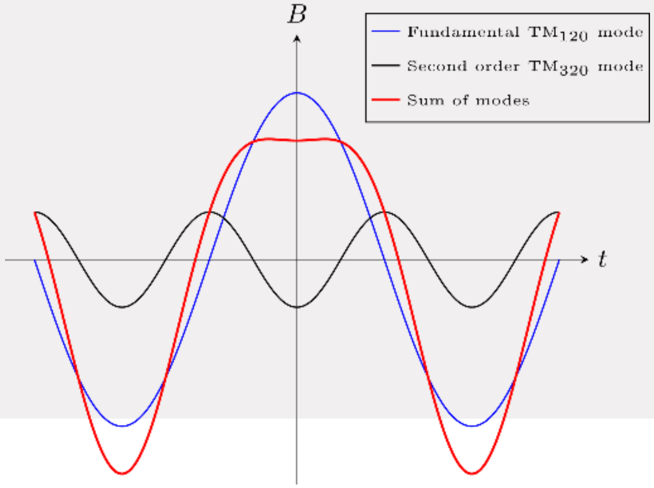
laB_6
source

Point of injection

Higher harmonic chopping (*and compression...*)

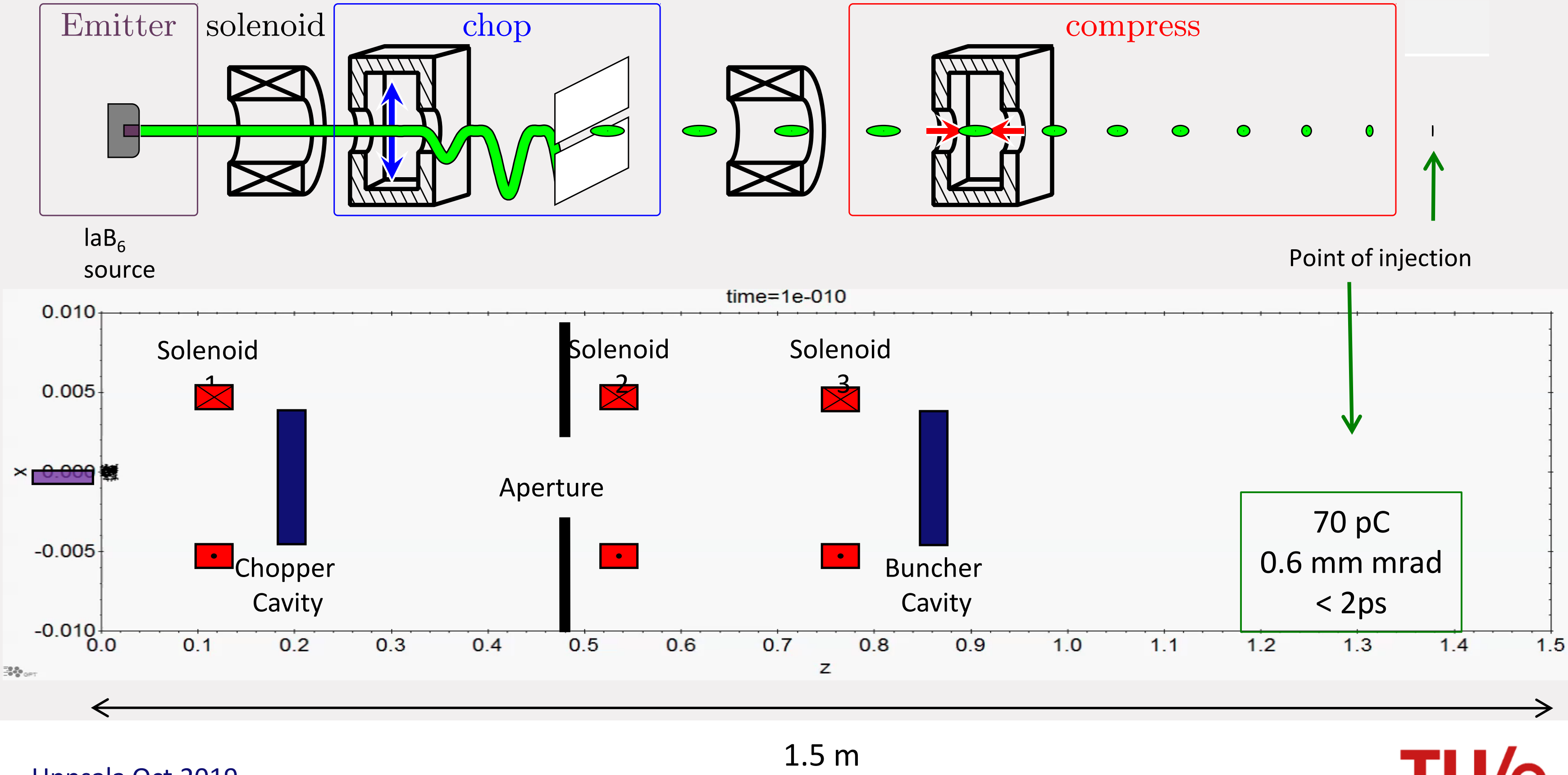
30% duty cycle: 70 pC/bunch @ 1.5 GHz





RF cavity:
Fundamental (1.5 GHz) and
second harmonic (3 GHz) mode

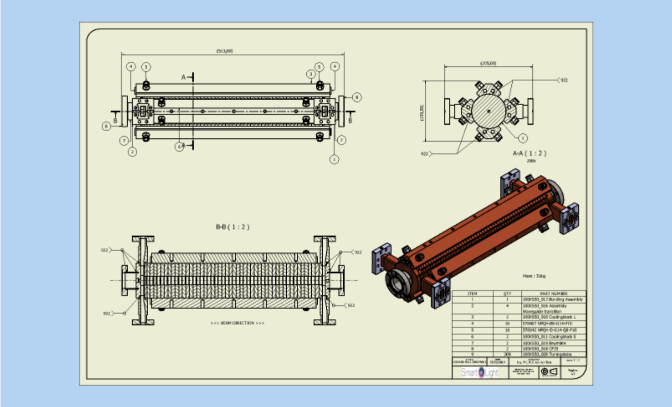
Gun upgrade for 100-bunch burst mode



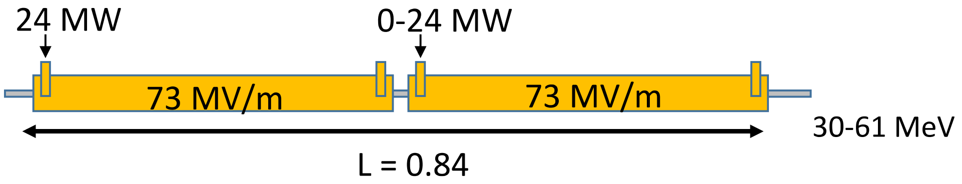
TU/e

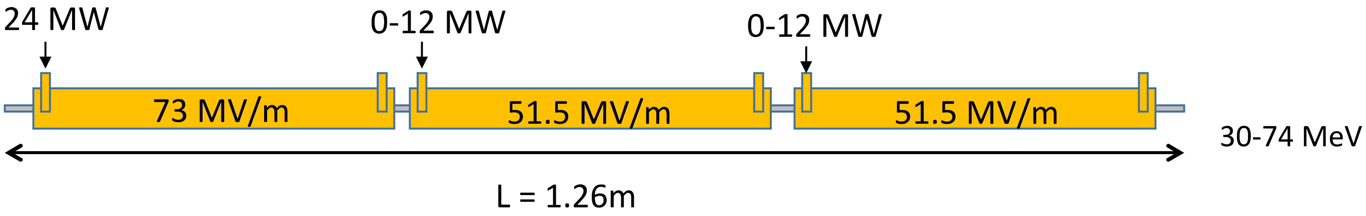
Upscaling to harder X-ray energies

Add 50-cell X-band sections; run with two klystrons.

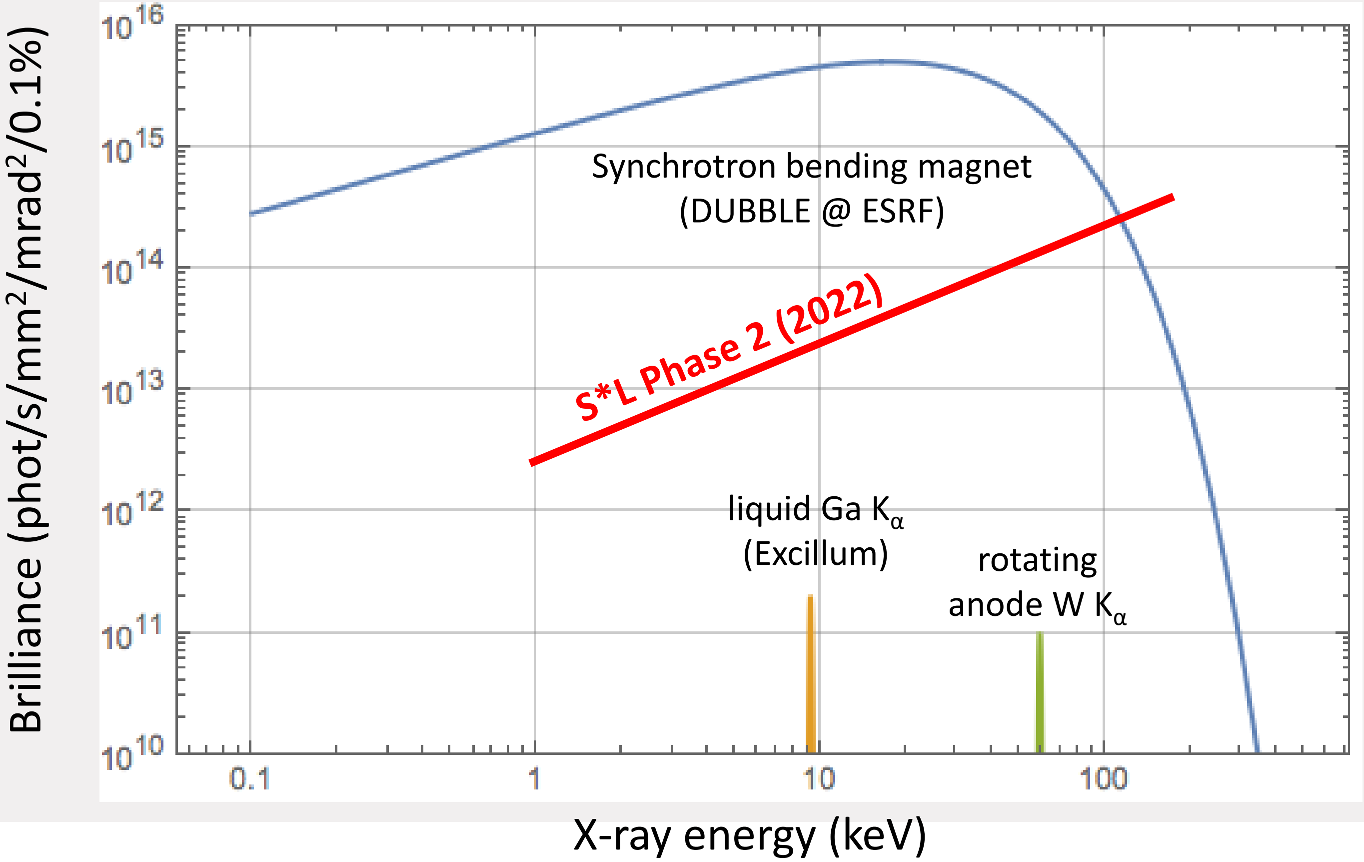


electron energy [MeV]	X-ray energy [keV] for a 515 nm laser
5	1,1
10	4,1
15	8,9
20	15,5
25	24,0
30	**34.3**
35	46,4
40	60,4
45	76,2
50	93,9
55	113,4
60	**134.8**
65	158,0
70	183,0
75	**209.9**

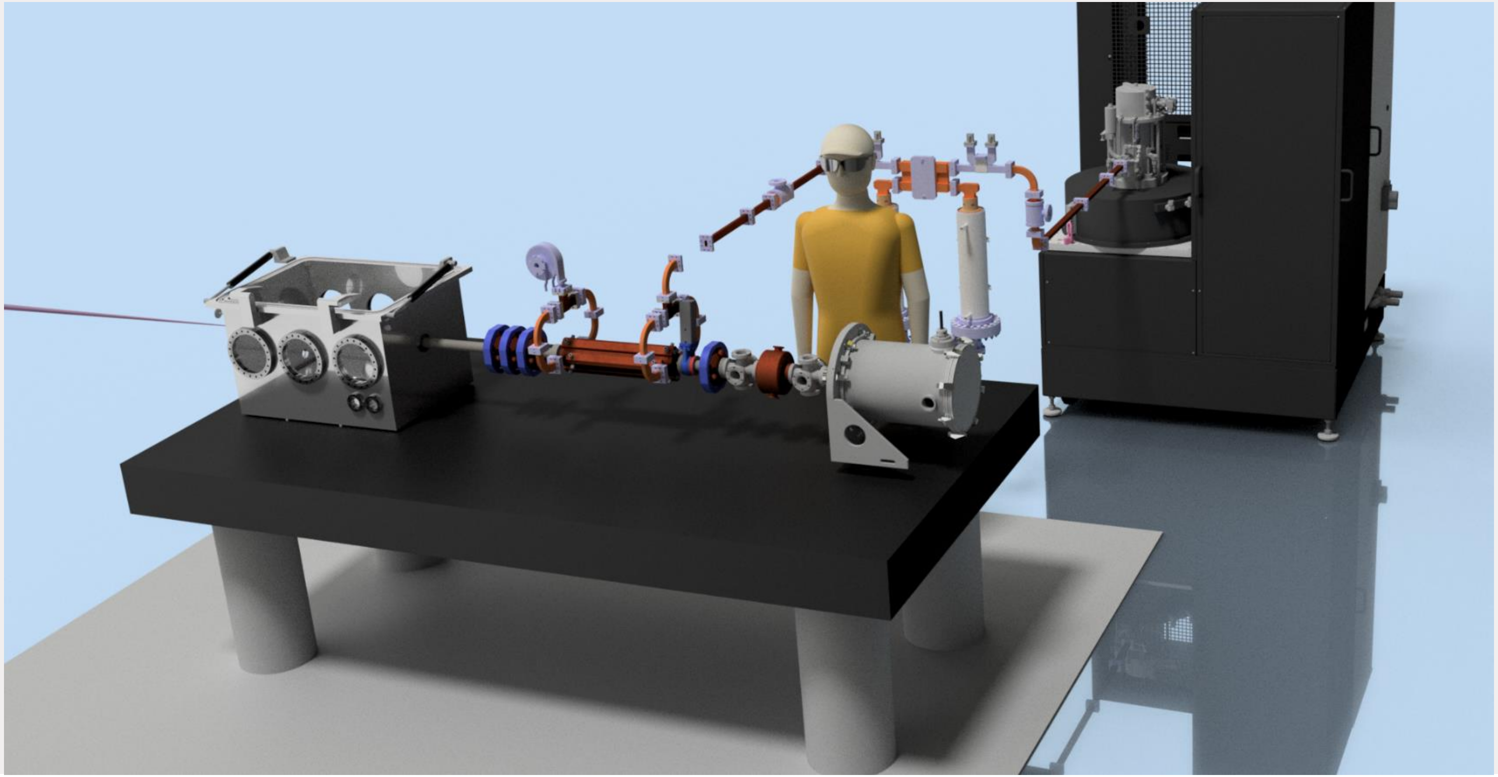




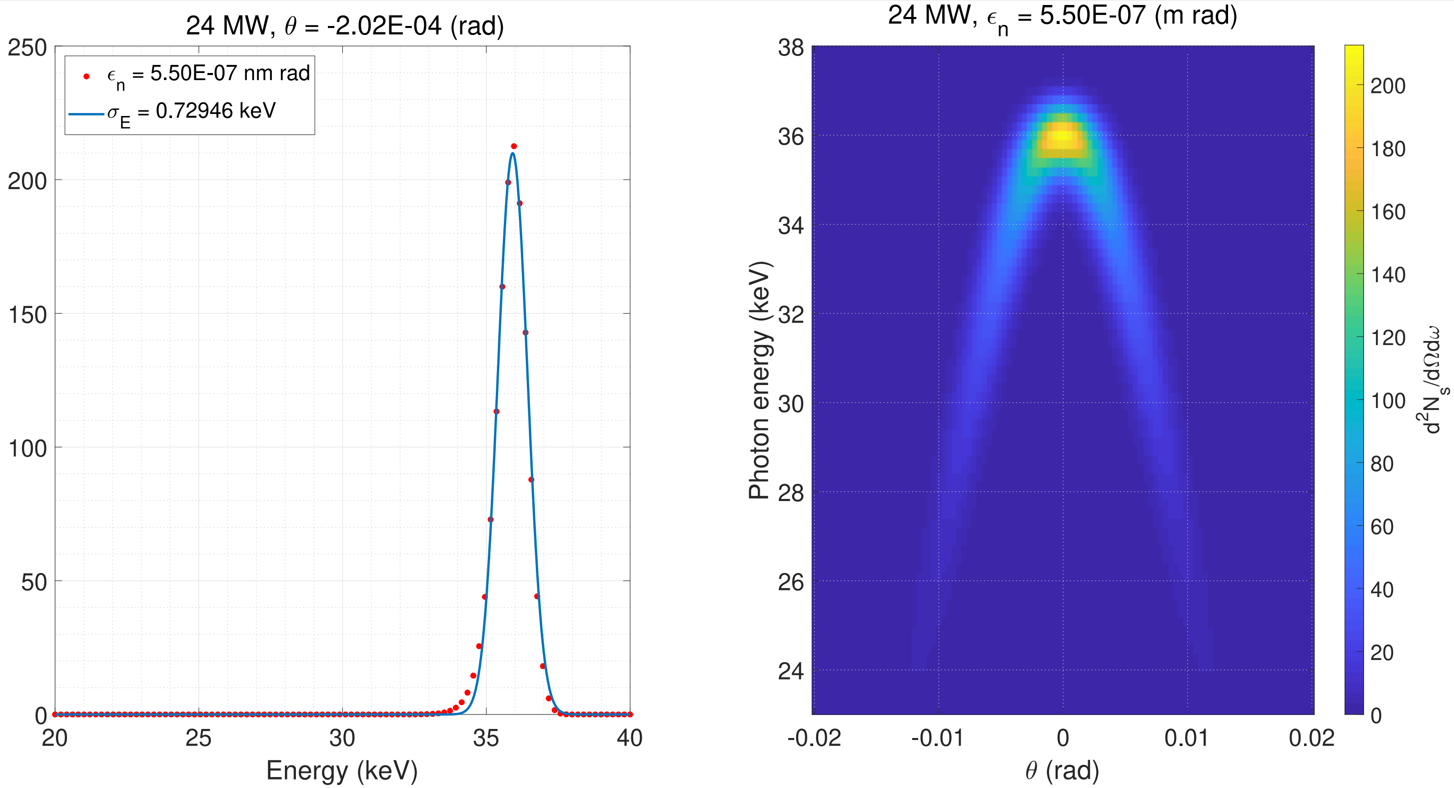
Smart*Light estimated performance



Smart*Light phase 1 in 2020

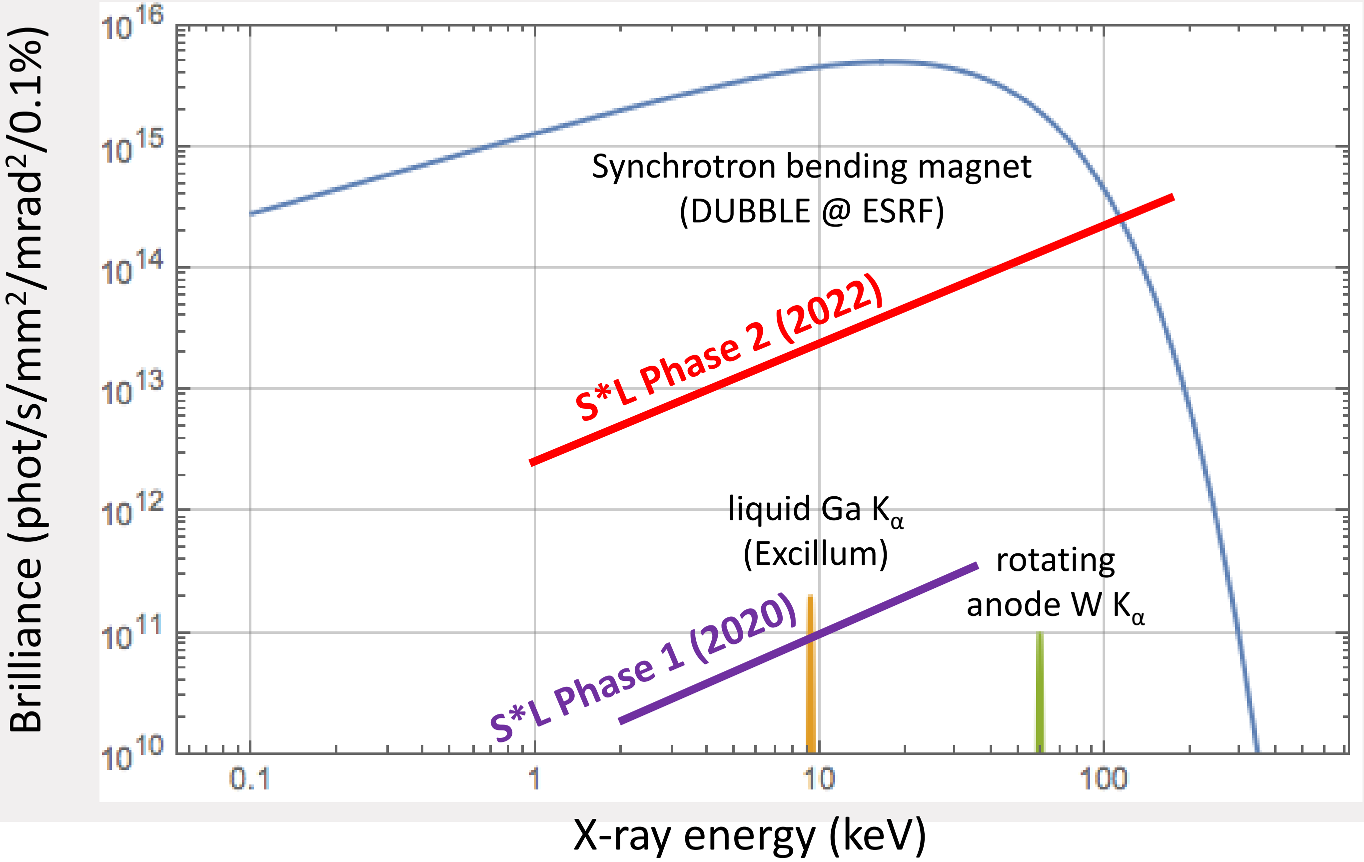


ICS calculations



31 MeV electron beam, 515 nm laser

Smart*Light estimated performance



Smart*Light summary

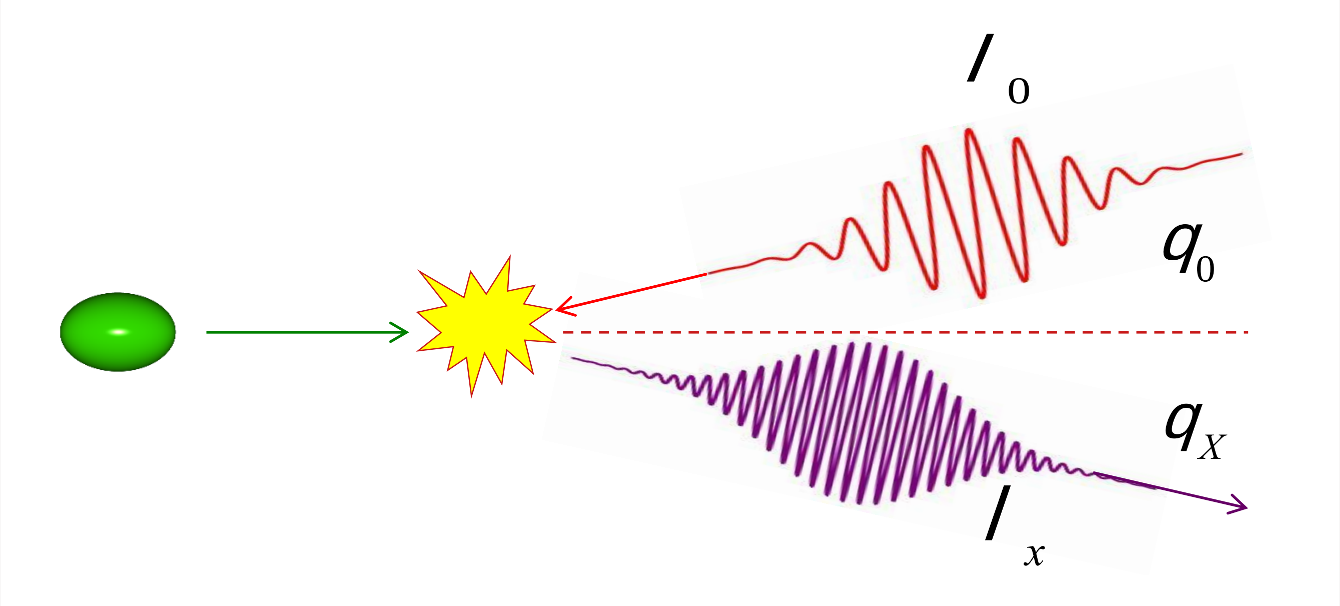
- Smart*Light: Inverse Compton Scattering Source for tunable, monochromatic hard X-ray beams in a compact setup
- Required accelerator and pulsed laser technology available
- Achievable hard X-ray brilliance several orders of magnitude higher than current lab sources
- Achievable hard X-ray brilliance at high energies comparable to synchrotron bending magnet radiation (DUBBLE @ ESRF)
- Construction started; first light expected in 2020, full performance in 2022.

Inverse Compton Scattering (ICS) soft X-ray source

EUV wavelength

$$l_X = l_0 \frac{1- b\cos q_X}{1+ b\cos q_0}$$

$$b = \frac{v}{c},\ g = \frac{1}{\sqrt{1- b^2}}$$

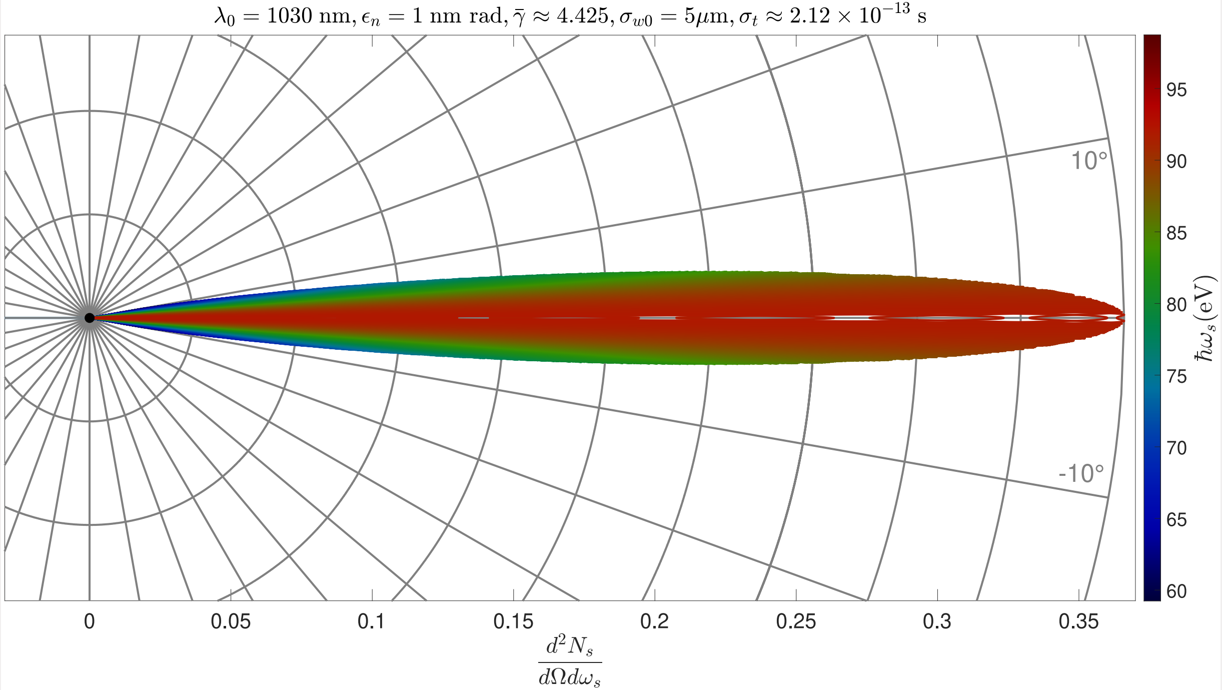


Inverse Compton Scattering (ICS) soft X-ray source

EUV wavelength

$$\lambda_X = \lambda_0 \frac{1-\beta\cos\theta_X}{1+\beta\cos\theta_0}$$

$$\left.\begin{array}{l}\lambda_0 = 1030\ \mathrm{nm} \\ U = 1.75\ \mathrm{MeV}\end{array}\right\} \Rightarrow \lambda_X = 13.5\ \mathrm{nm}$$



Inverse Compton Scattering (ICS) soft X-ray source

- narrowband, easily tunable wavelength
- clean, highly directional

Inverse Compton Scattering (ICS) soft X-ray source

- narrowband, easily tunable wavelength

- clean, highly directional

BUT:

- limited ***photon yield*** due to small Thomson cross section

- limited ***spatial coherence*** due to emittance electron beam

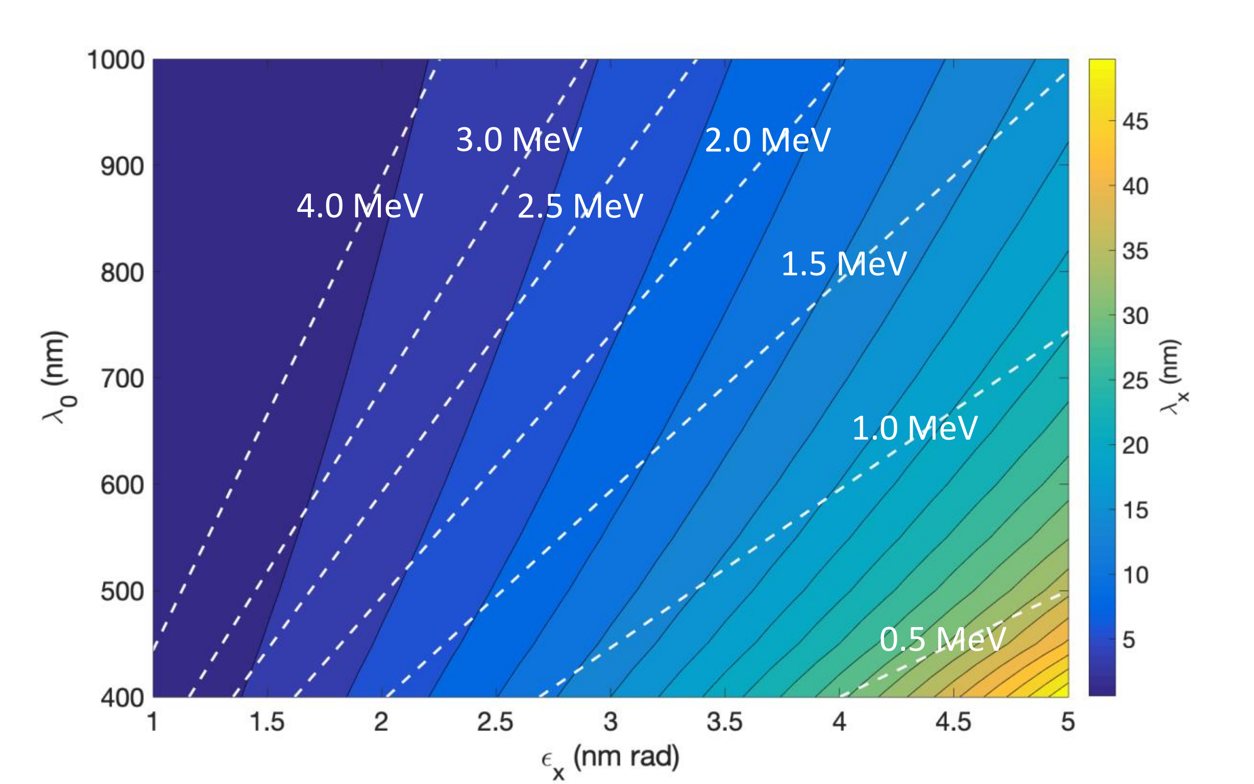
Spatial coherence: diffraction limited ICS

emittance condition

$$\varepsilon_n = \gamma\beta \frac{\lambda_X}{4\pi} \Rightarrow \lambda_X = 4\pi \frac{\varepsilon_n}{\gamma\beta}$$

Inverse Compton Scattering

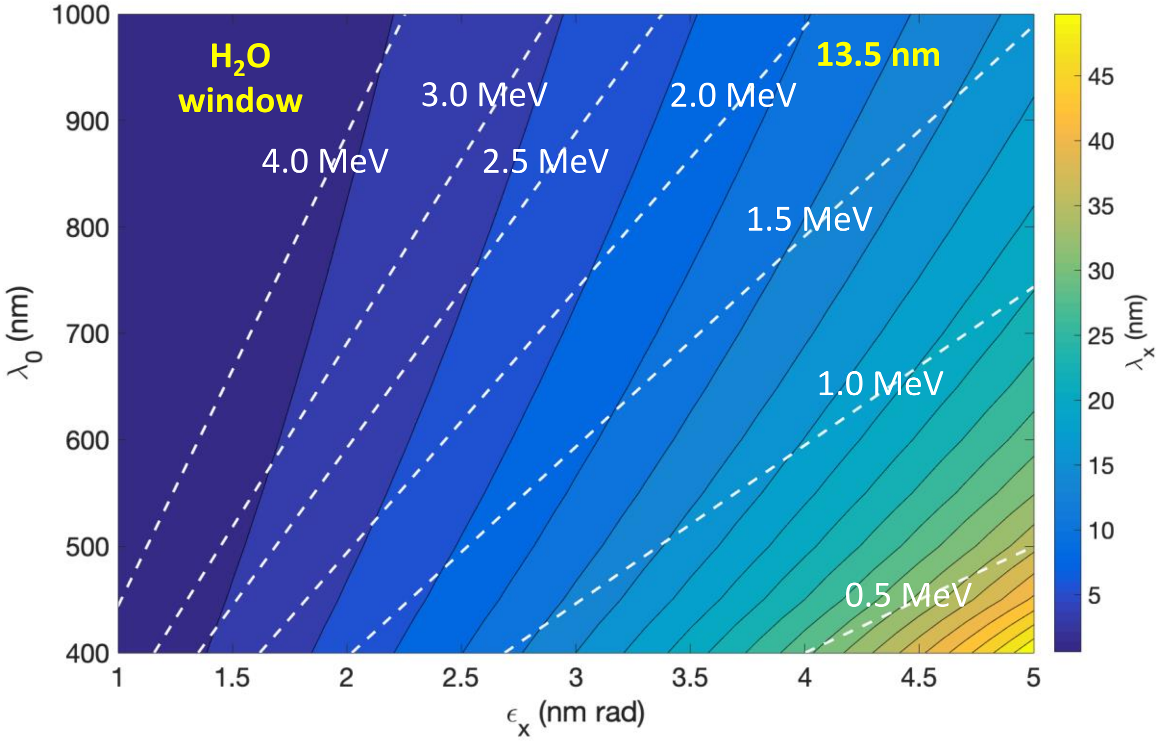
$$\lambda_X = \lambda_0 \frac{1-\beta}{1+\beta}$$



TU/e

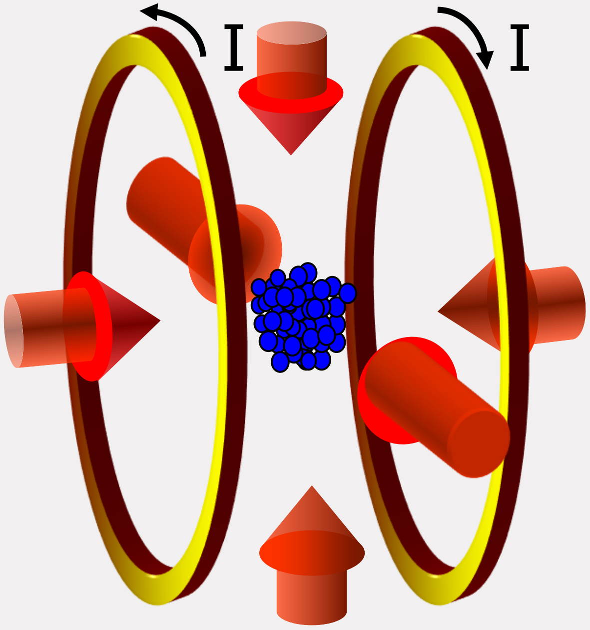
Spatial coherence: diffraction limited ICS

Ultracold electron source allows generation of **diffraction limited EUV beams** by Inverse Compton Scattering



TU/e

Ultracold atoms



Magneto-Optical Trap (MOT)

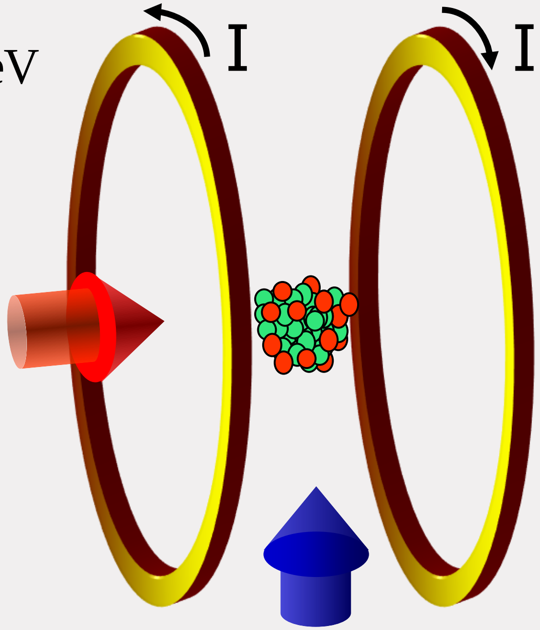
$N \leq 10^{10}$ Rb atoms

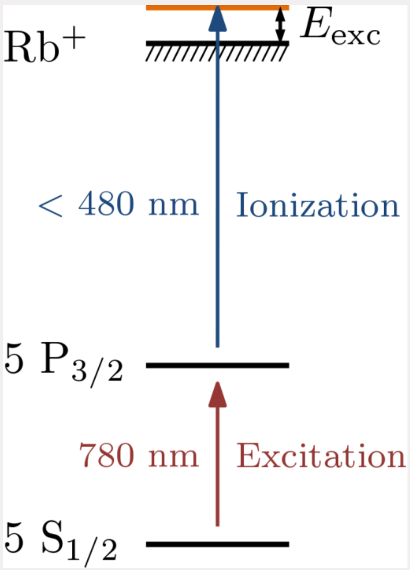
$R = 1$ mm, $n \leq 10^{18}$ m^{-3}

$T \approx 100$ μK

Ultracold plasma

T_e » 10 K, kT_e » 1 meV

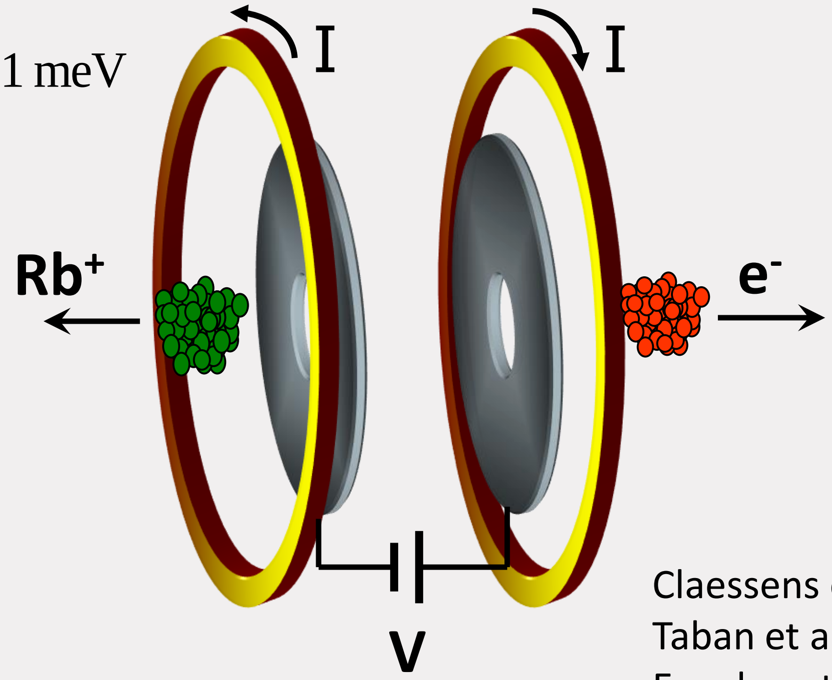




Killian et al., PRL **83**, 4776 (1999)

Ultracold charged particle beams

T_e » 10 K, kT_e » 1 meV



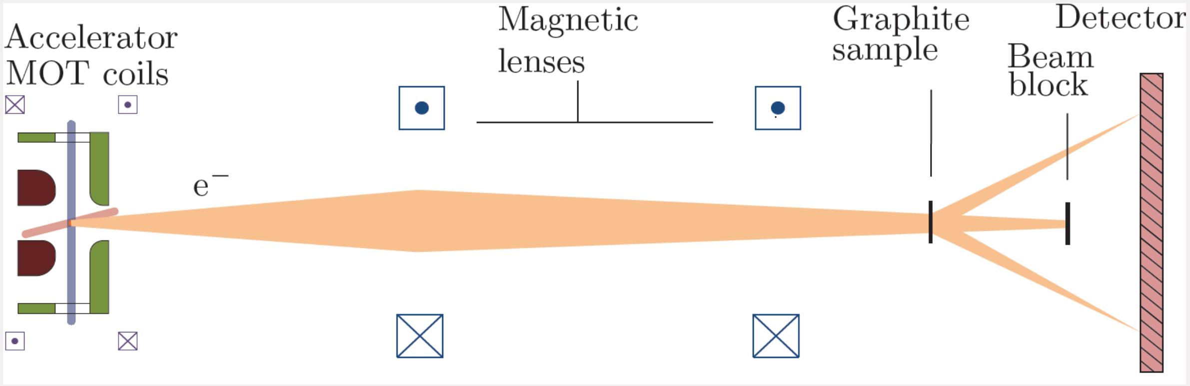
normalized emittance
(focusability)

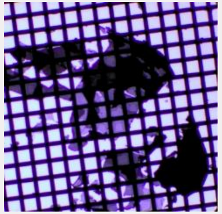
$$e_n = s_x \sqrt{\frac{kT_e}{mc^2}}$$

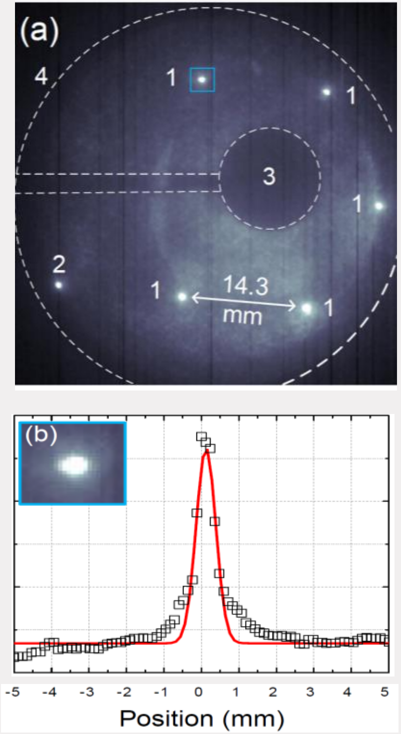
e_n » 1 nm rad

Claessens et al., PRL **95**, 164801 (2005)
Taban et al., EPL **91**, 46004 (2010)
Engelen et al., Nature Comm. **4**, 1693 (2013)

Electron temperature



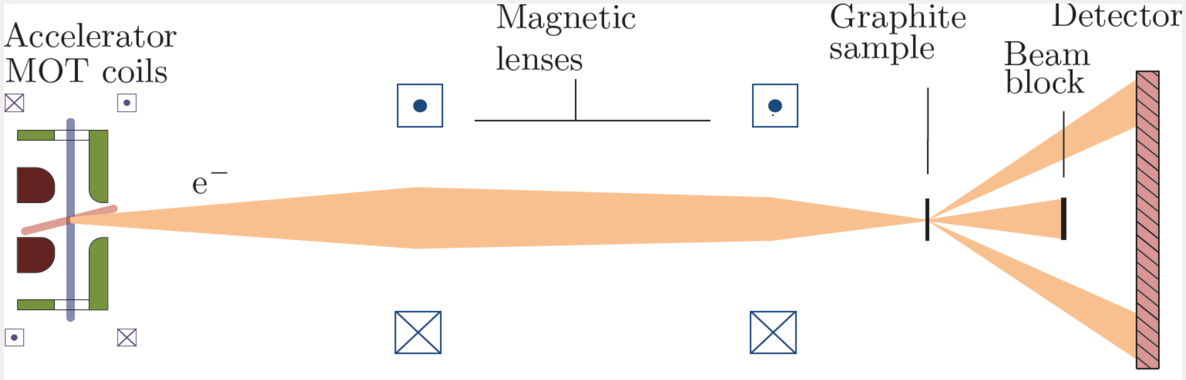


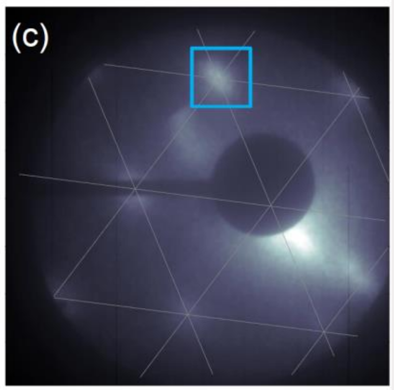


Electron energy: 13.2 keV

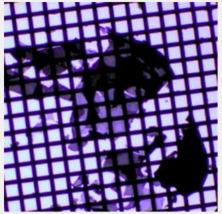
Van Mourik et al., Struct. Dyn. **1**, 034302 (2014)
Physics Today, July 2014

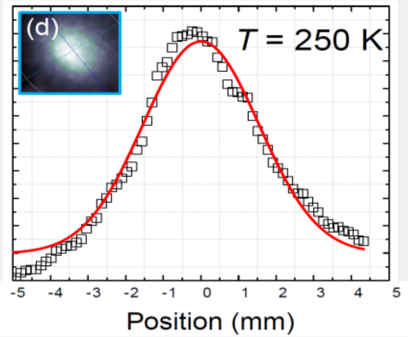
Electron temperature





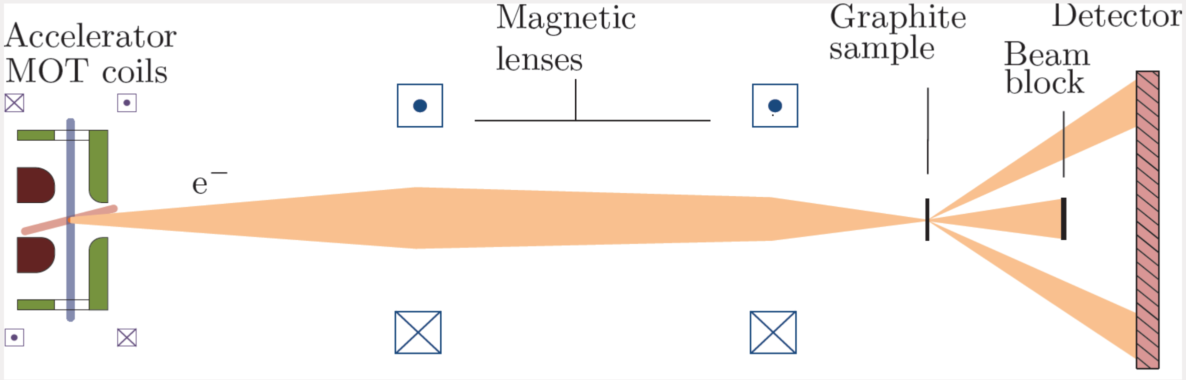
Electron energy: 10.8 keV

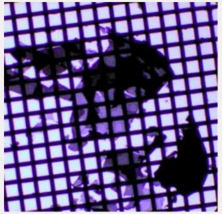


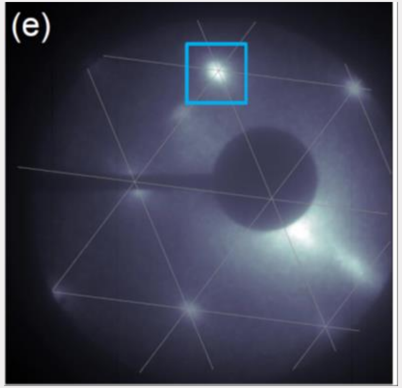


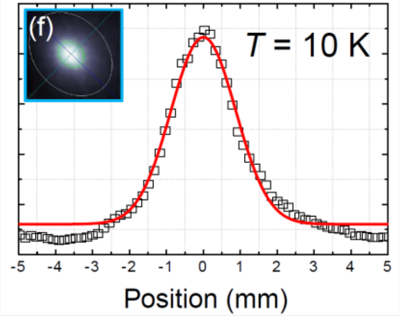
Van Mourik et al., Struct. Dyn. **1**, 034302 (2014)
Physics Today, July 2014

Electron temperature





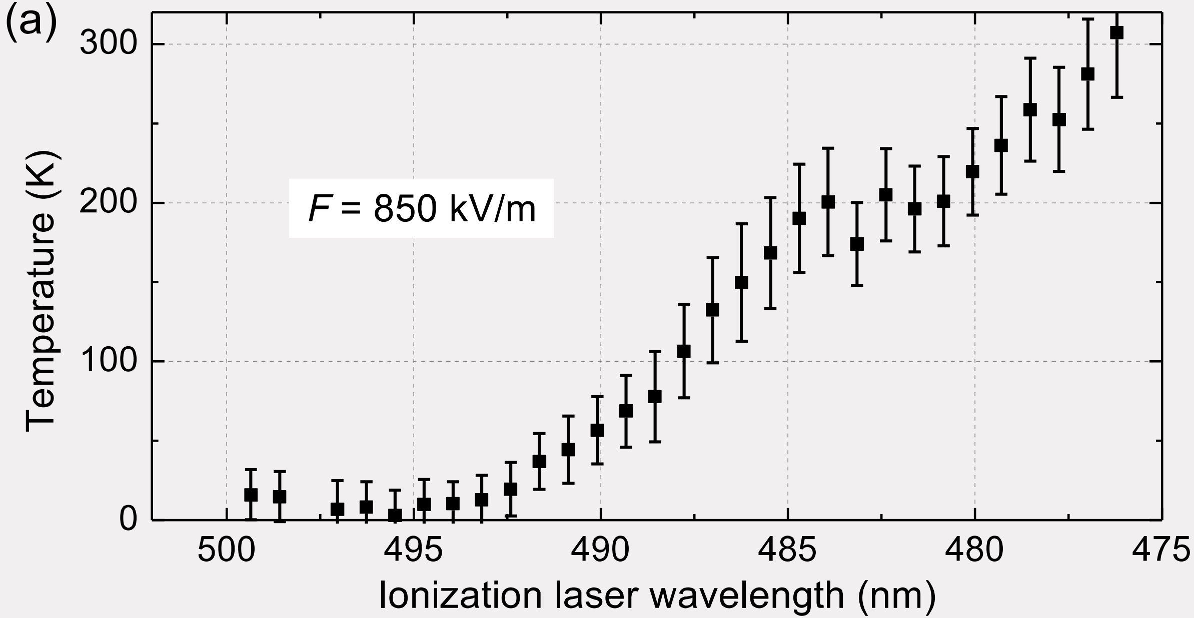


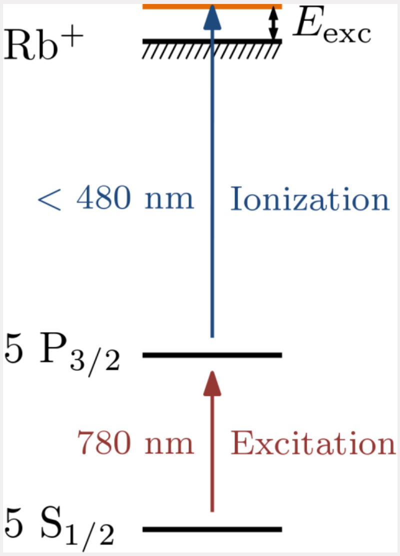


Electron energy: 10.8 keV

Van Mourik et al., Struct. Dyn. **1**, 034302 (2014)
Physics Today, July 2014

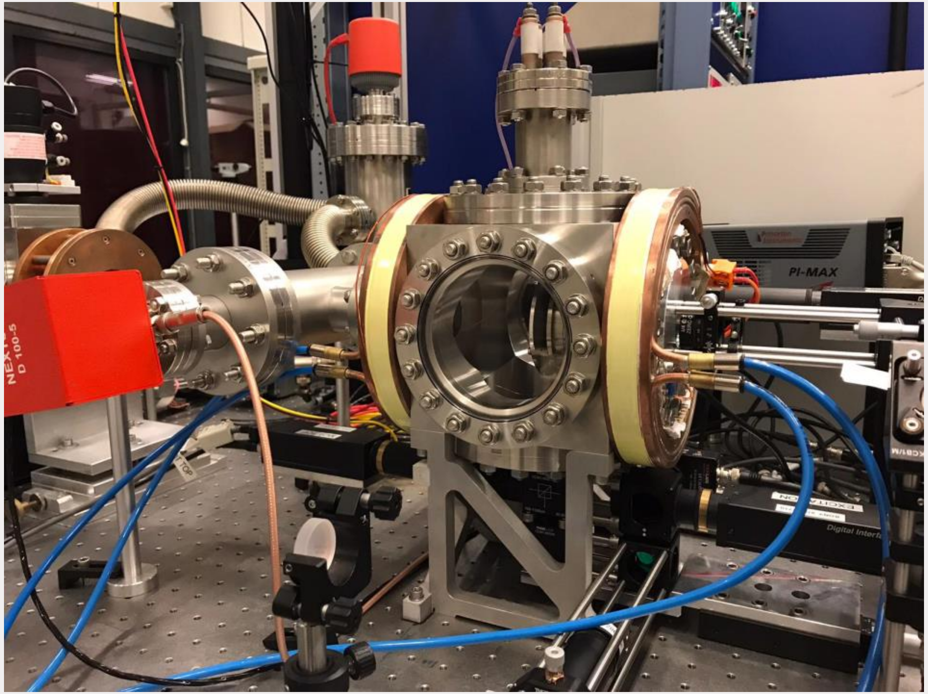
Electron temperature

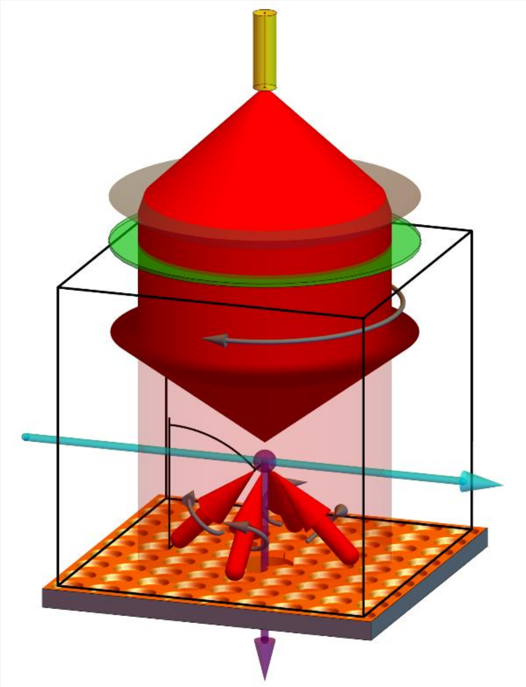




Van Mourik et al., Struct. Dyn. **1**, 034302 (2014)
Physics Today, July 2014

New: compact ultracold & ultrafast electron source



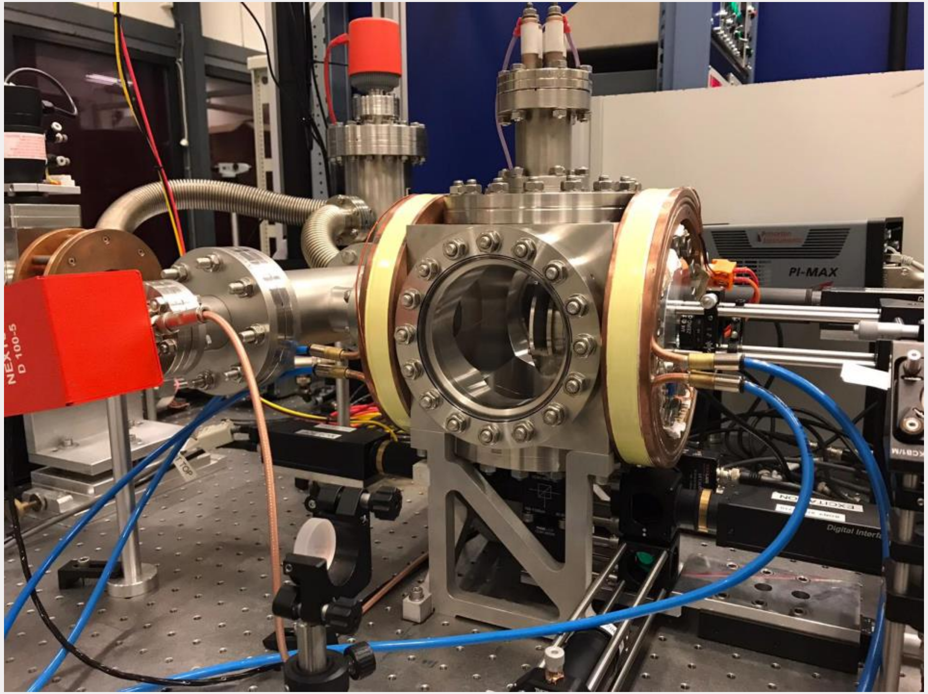


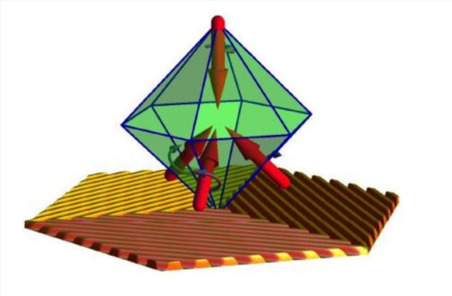
University of Strathclyde Glasgow

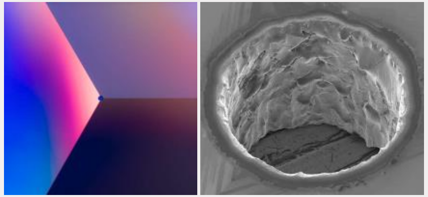
Franssen et al., PR-AB **22**, 023401 (2019), *editors' suggestion*

TU/e

New: compact ultracold & ultrafast electron source



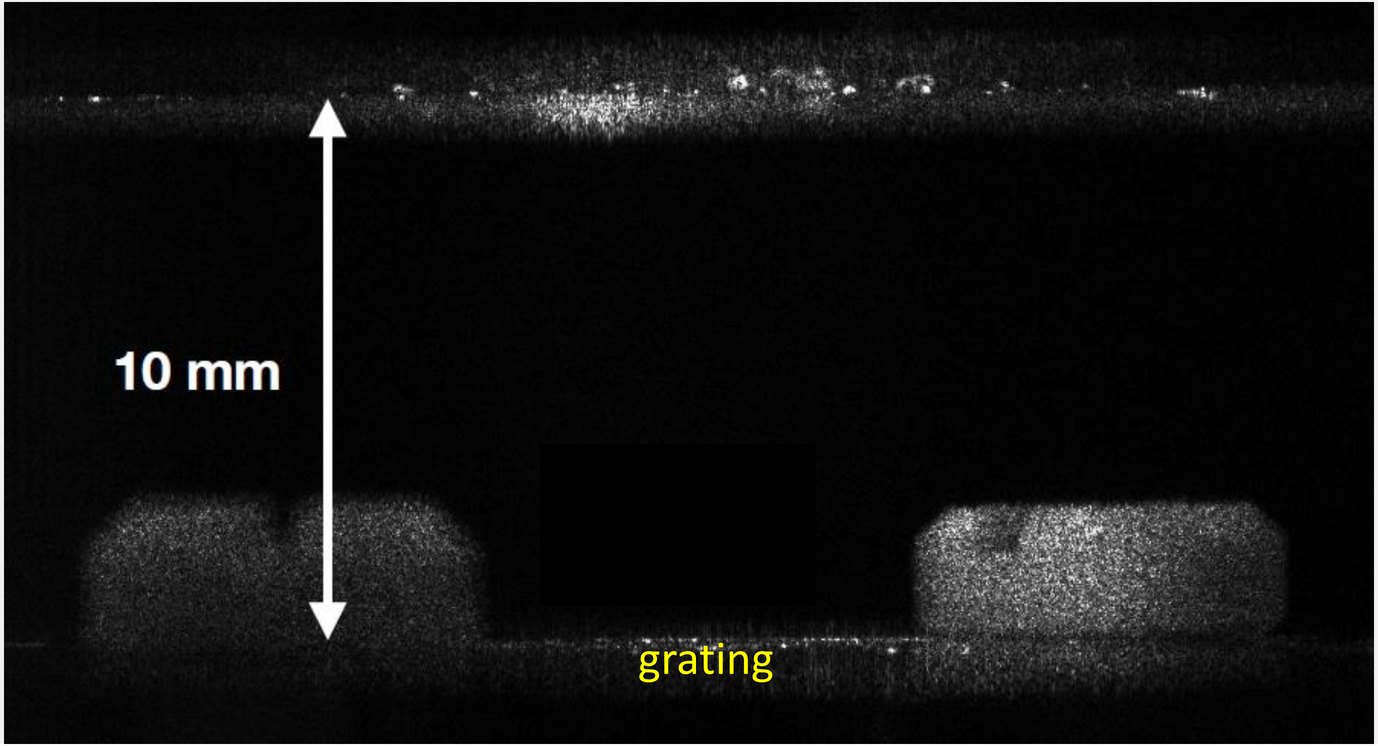




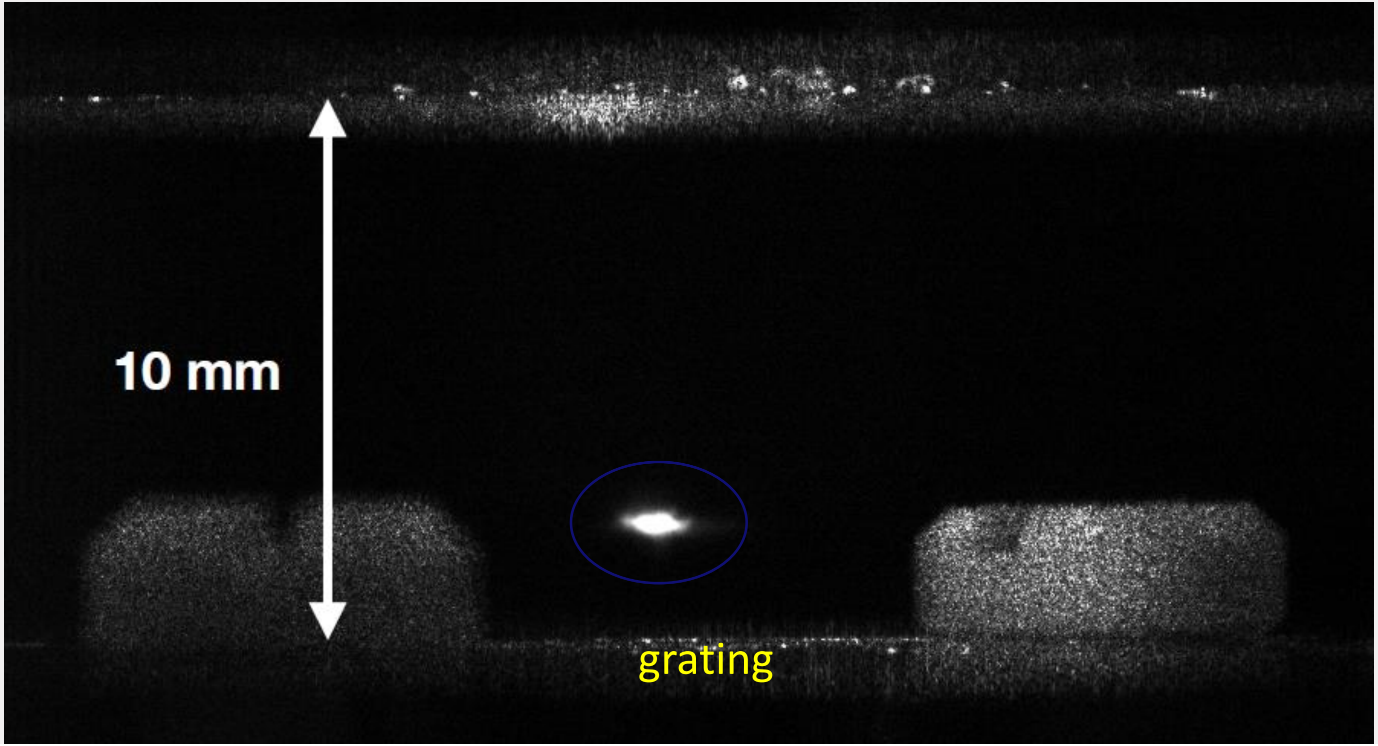
- grating MOT based
- diode laser, fiber optics based
- compact, turn-key operation

Franssen et al., PR-AB **22**, 023401 (2019), *editors' suggestion*

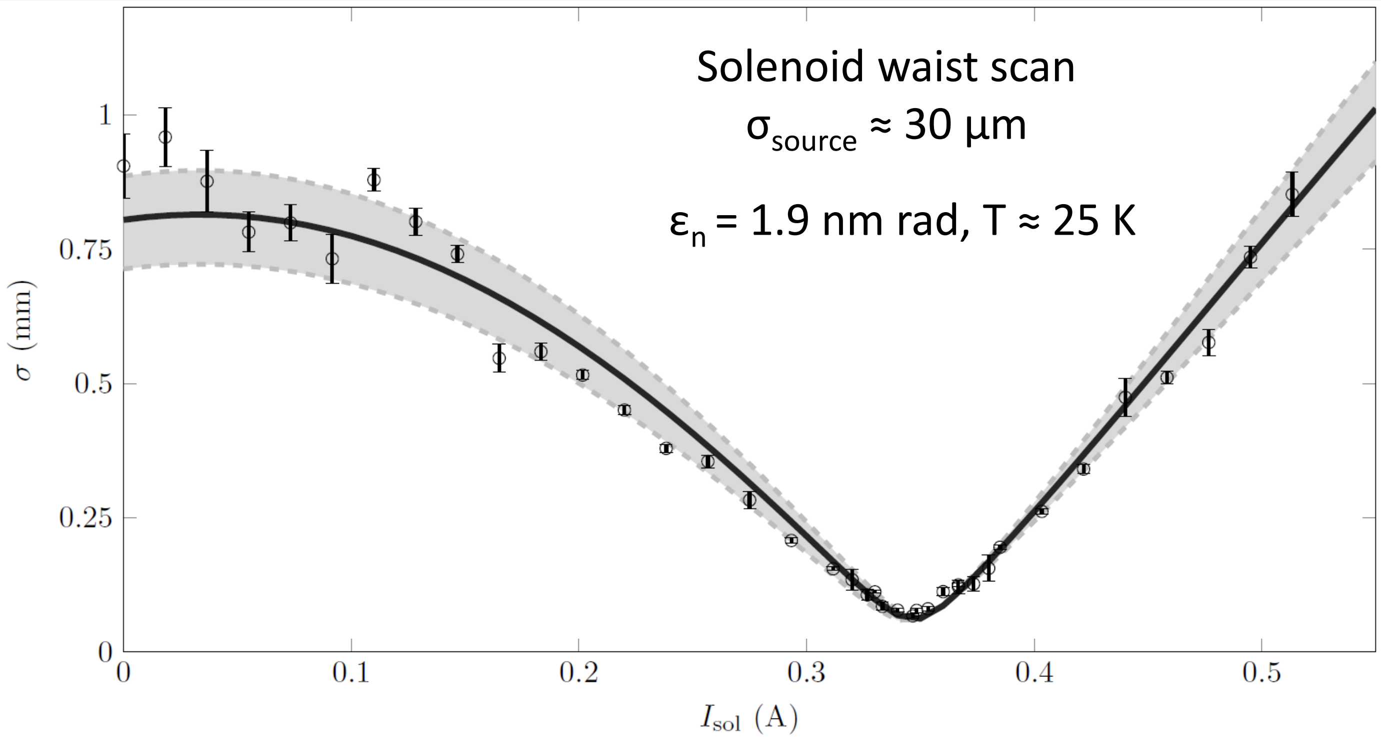
Laser cooling & magneto-optical trapping of atoms



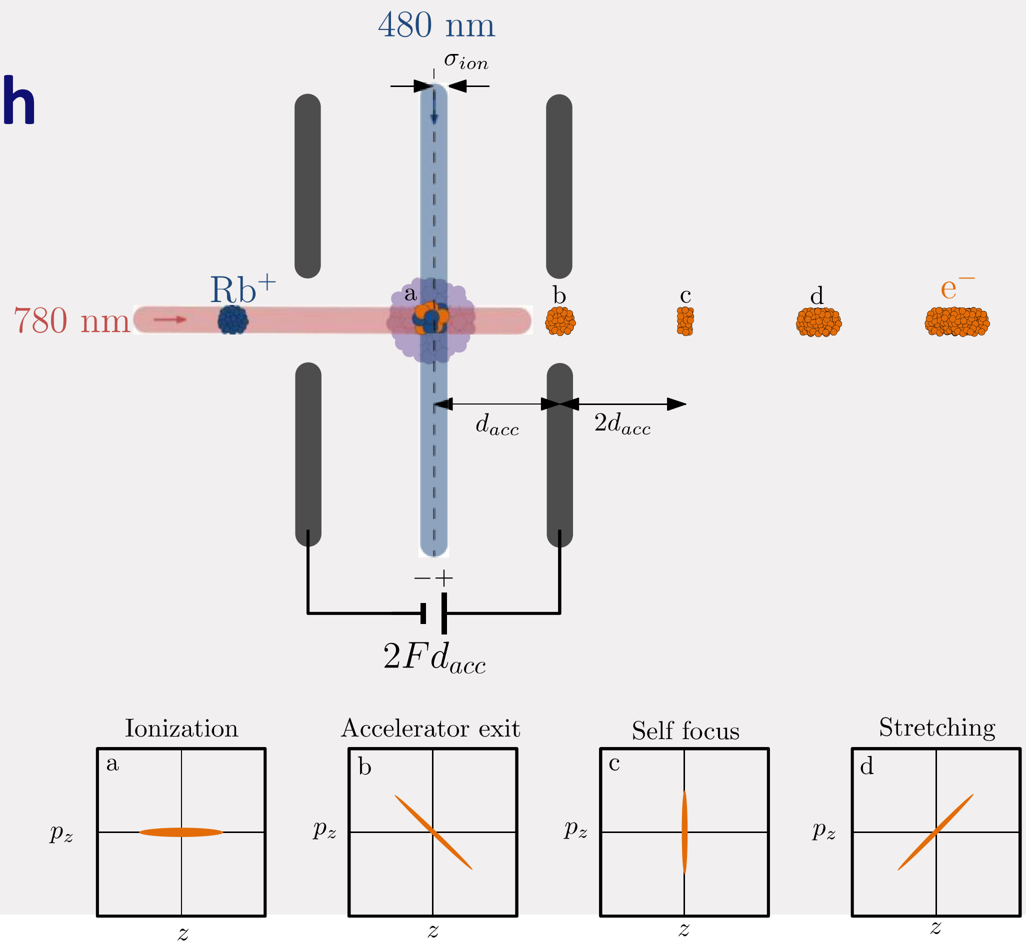
Laser cooling & magneto-optical trapping of atoms



Normalized emittance & source temperature

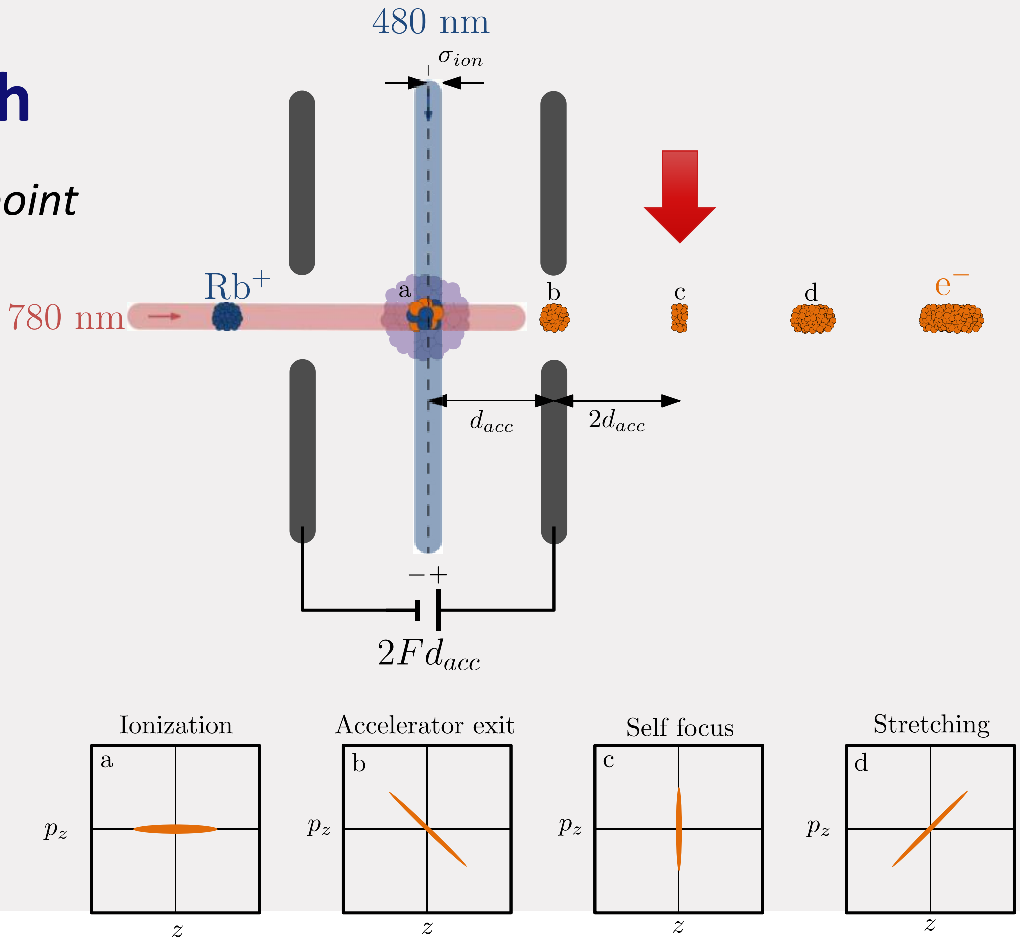


Bunch length



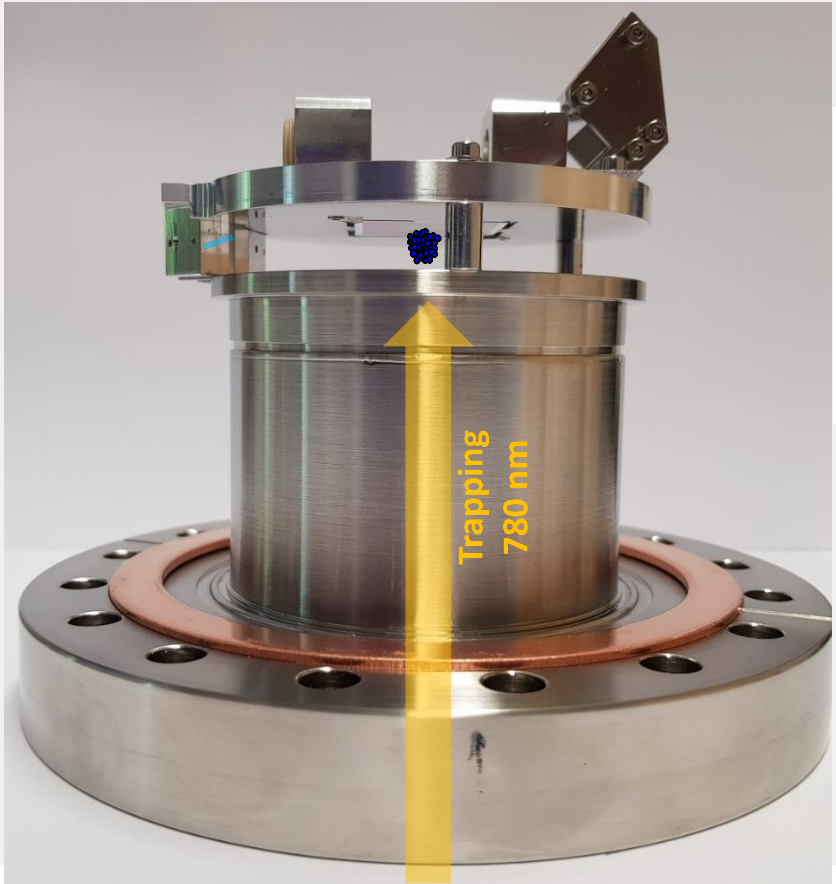
Bunch length

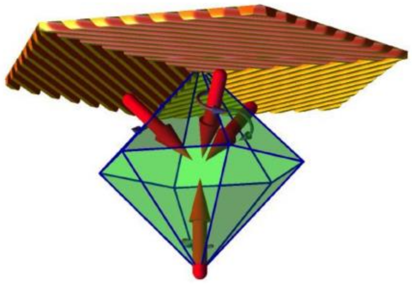
in self-compression point



Bunch length

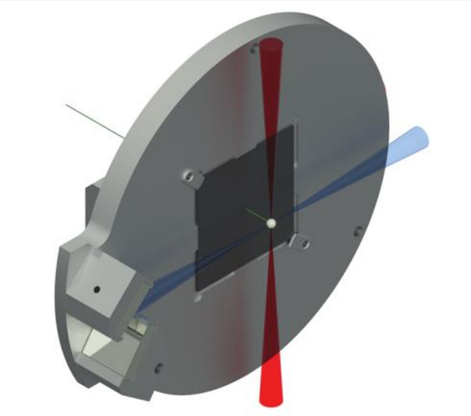
in self-compression point

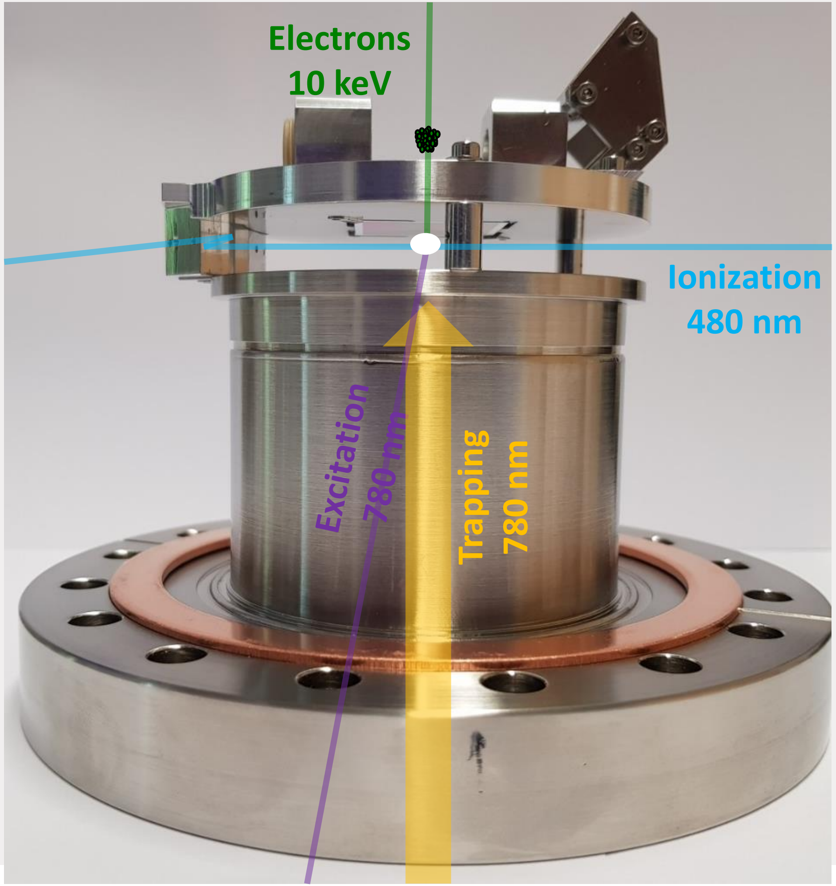




Bunch length

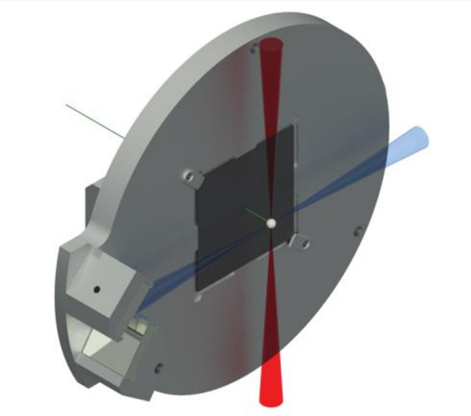
in self-compression point

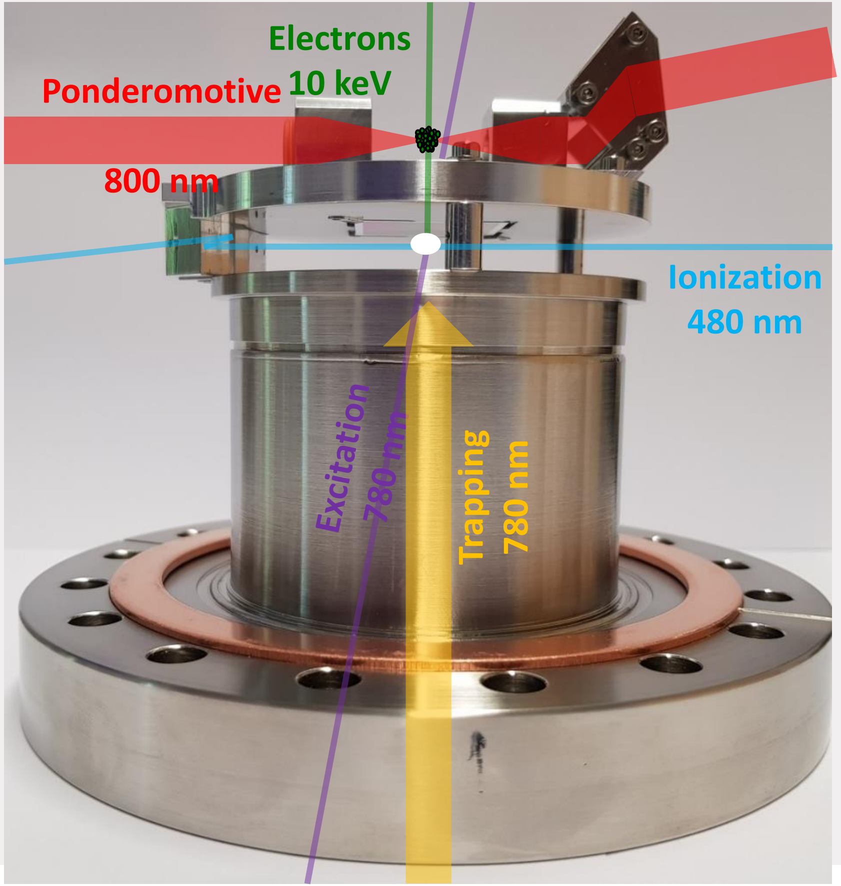


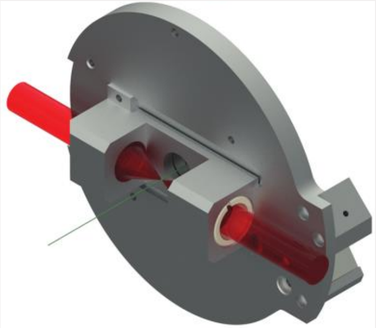


Bunch length

in self-compression point



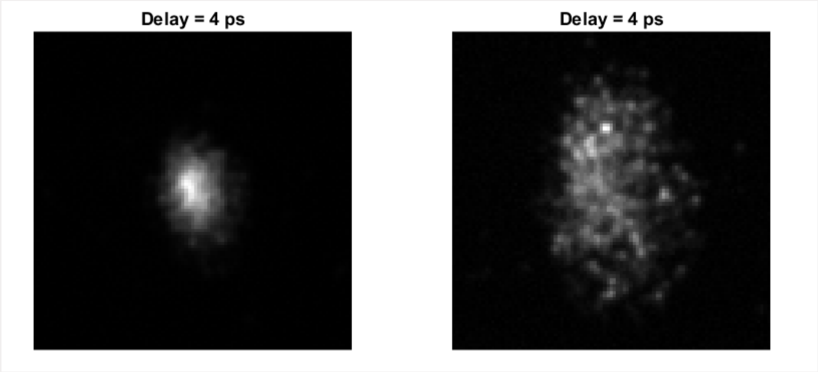




Bunch length

in self-compression point

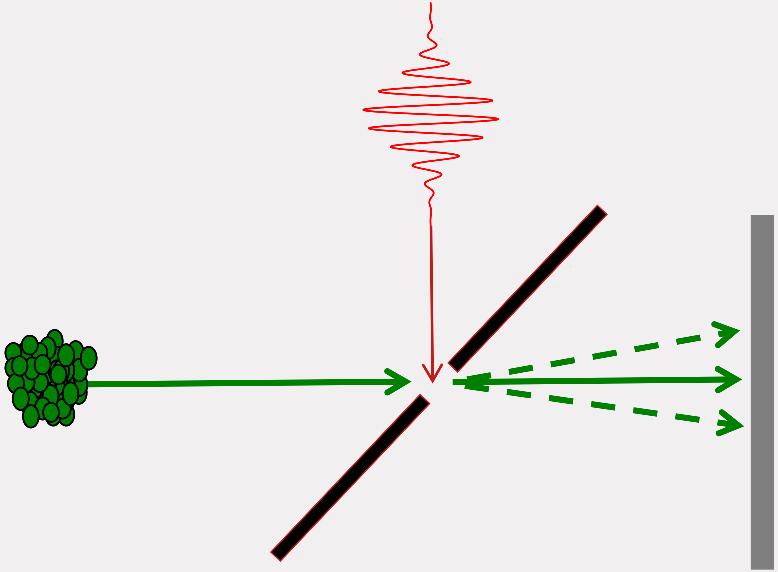
electron beam on detector



laser off

laser on

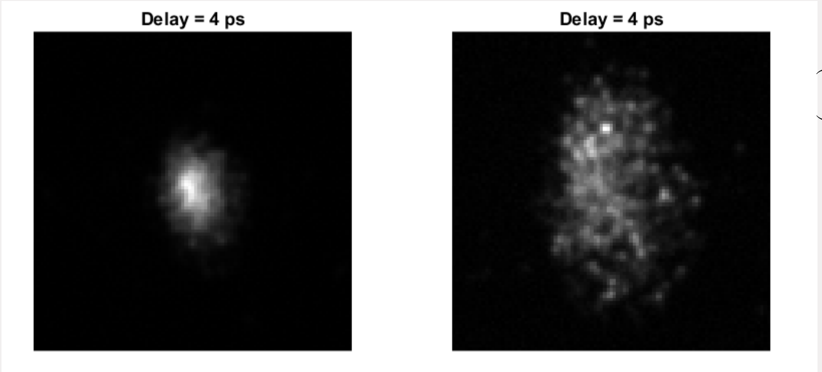
t = 0 pinhole ‘plasma’ measurement



Bunch length

in self-compression point

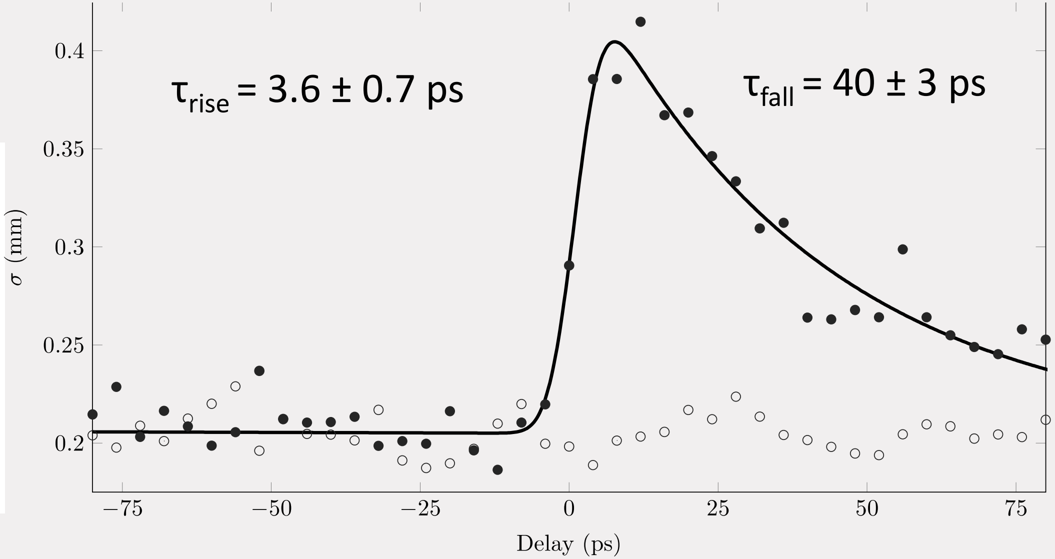
electron beam on detector



laser off

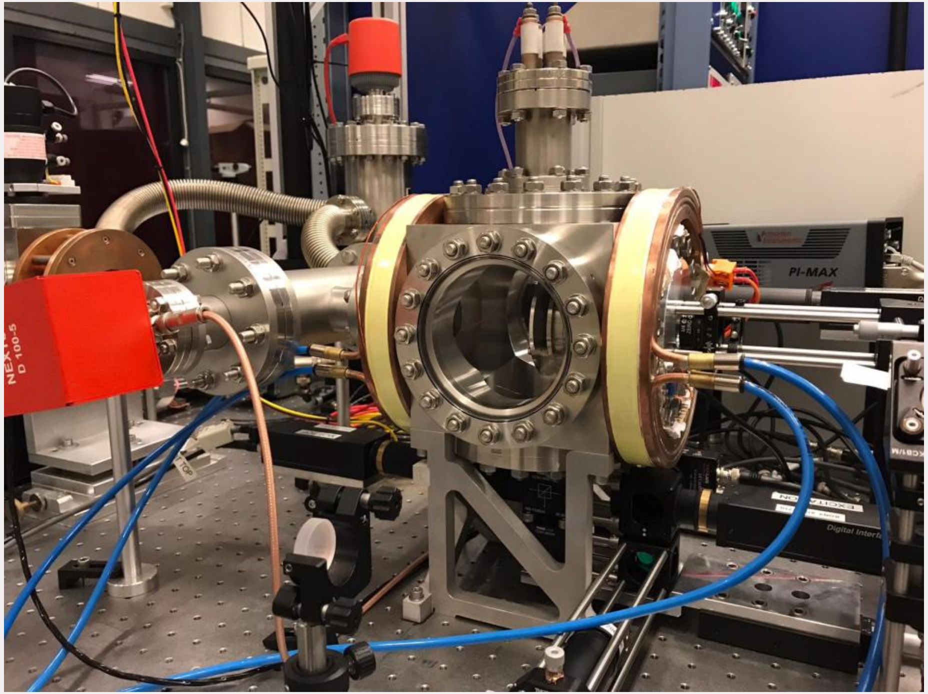
laser on

t = 0 pinhole ‘plasma’ measurement



pulse length < 4 ps

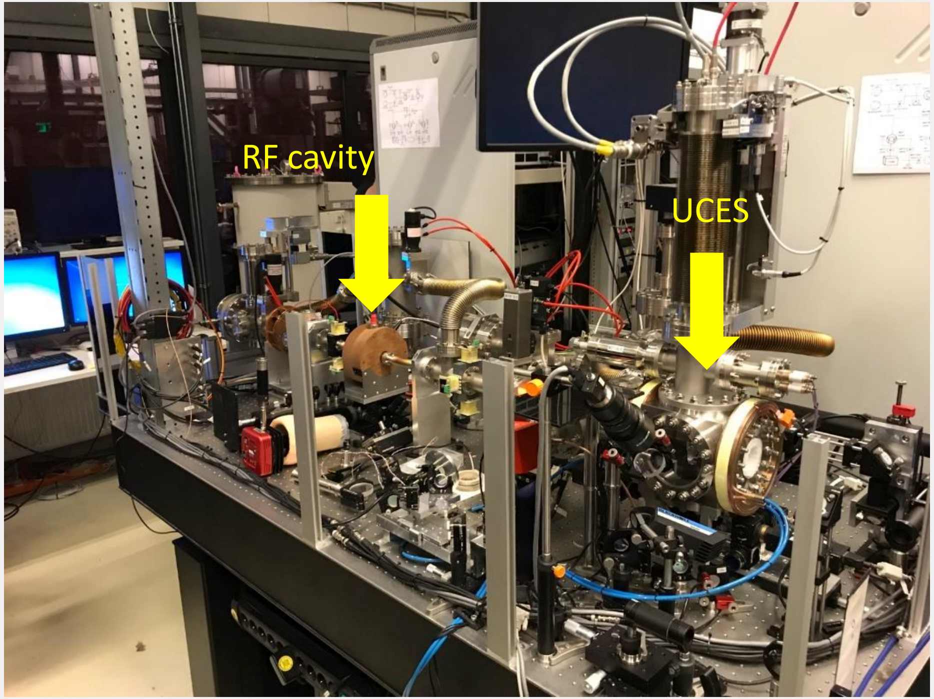
New: compact ultracold & ultrafast electron source



- $T_e \approx 10$ K, $\varepsilon_n \approx 1$ nm rad, 10 keV
- ~10^3 electrons/bunch @ 1 kHz
- < 4 ps bunch length
- grating MOT based
- diode laser, fiber optics based
- compact, turn-key operation

Franssen et al., PR-AB **22**, 023401 (2019), *editors' suggestion*

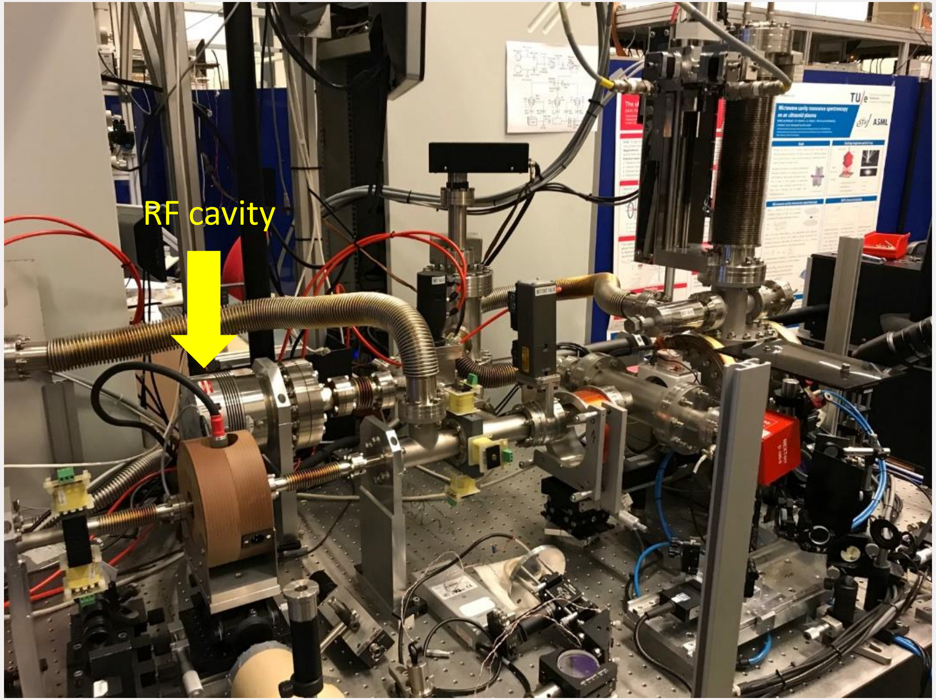
New: compact ultracold & ultrafast electron source



- $T_e \approx 10$ K, $\varepsilon_n \approx 1$ nm rad, 10 keV
- ~10^3 electrons/bunch @ 1 kHz
- < 4 ps bunch length
- *Soon*: RF acceleration to ≥ 55 keV
- More charge

Franssen et al., PR-AB **22**, 023401 (2019), *editors' suggestion*

New: compact ultracold & ultrafast electron source

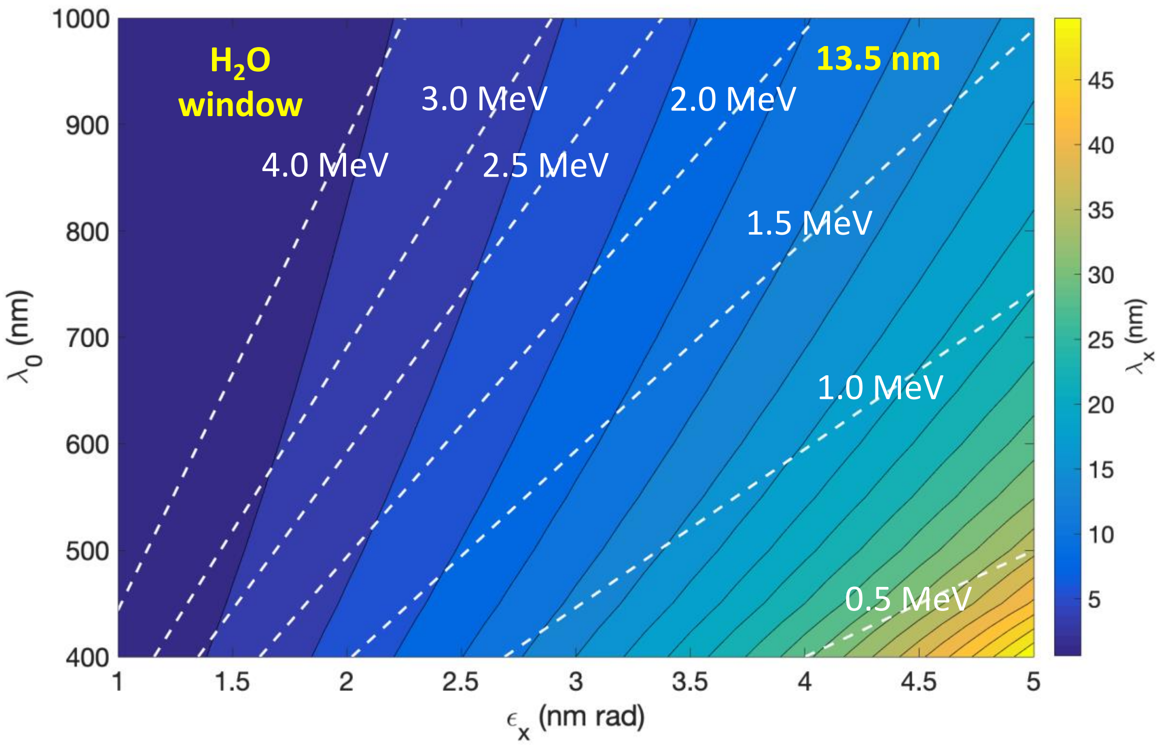


- T_e≈10 K, ε_n≈1 nm rad, 10 keV
- ~10^3 electrons/bunch @ 1 kHz
- < 4 ps bunch length
- *Soon*: RF acceleration to ≥ 55 keV
- More charge

Franssen et al., PR-AB **22**, 023401 (2019), *editors' suggestion*

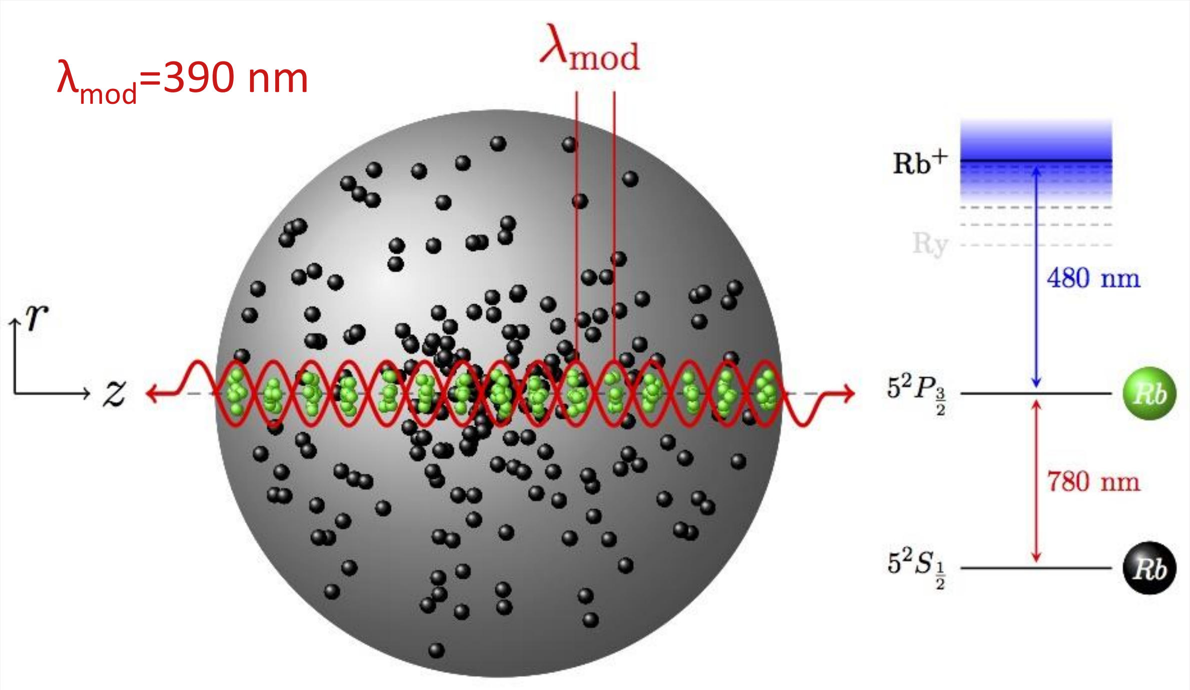
Spatial coherence: diffraction limited ICS

Ultracold electron source allows generation of **diffraction limited EUV beams** by Inverse Compton Scattering

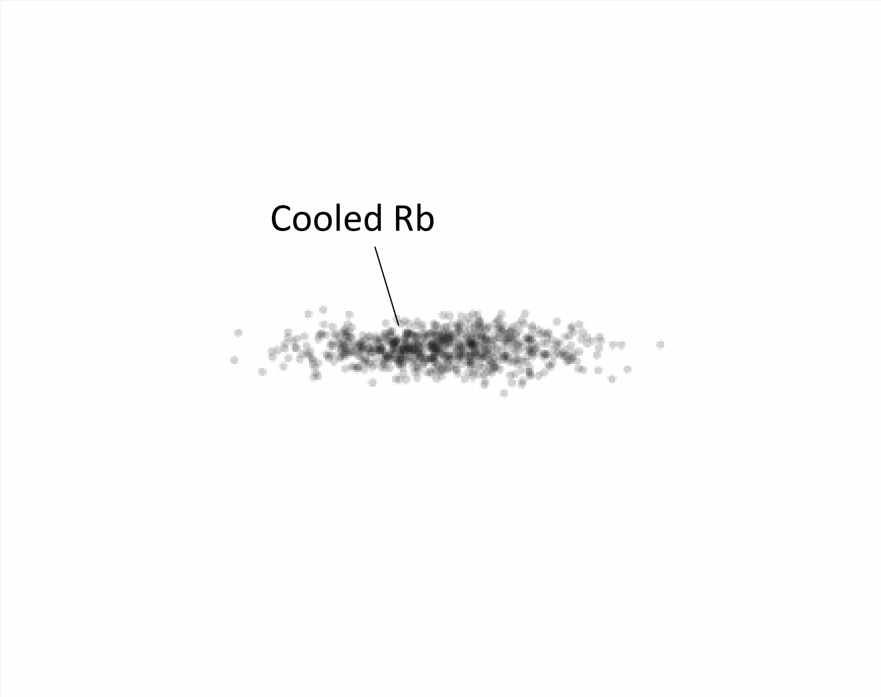


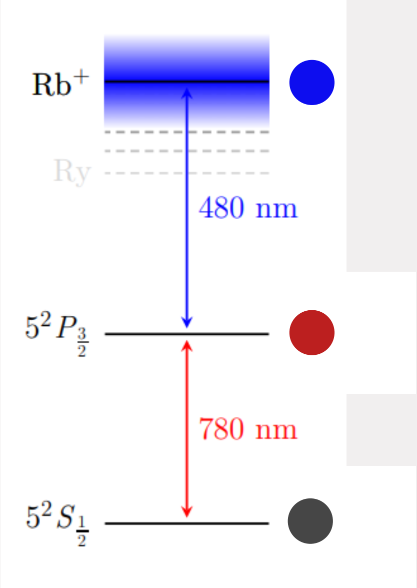
TU/e

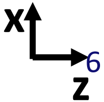
Temporal coherence: micro-bunching



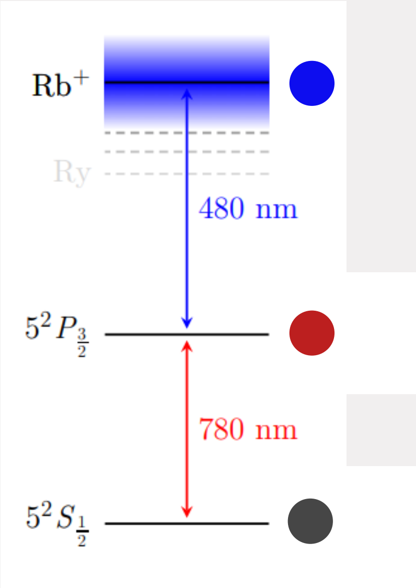
Micro-bunched electron beam: excitation





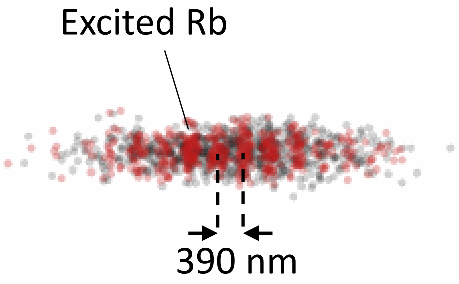


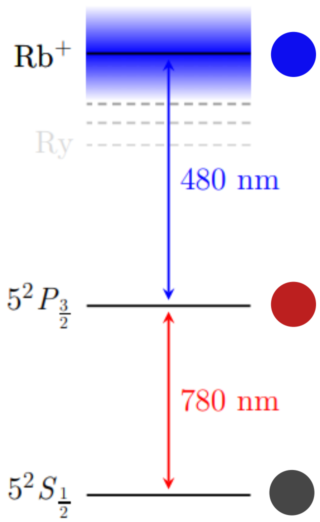
Micro-bunched electron beam: excitation

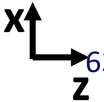


x
z

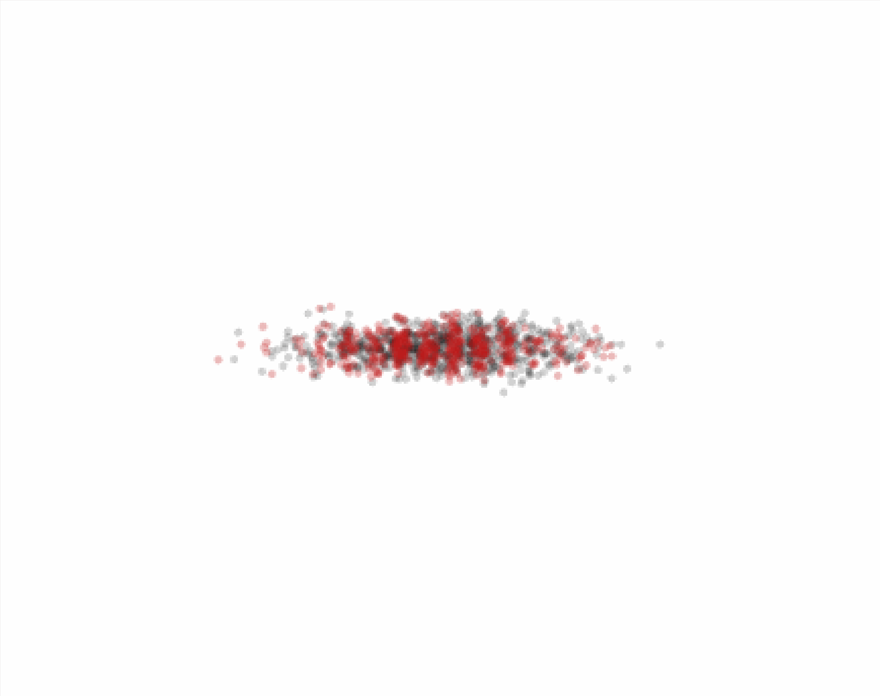
Micro-bunched electron beam: excitation

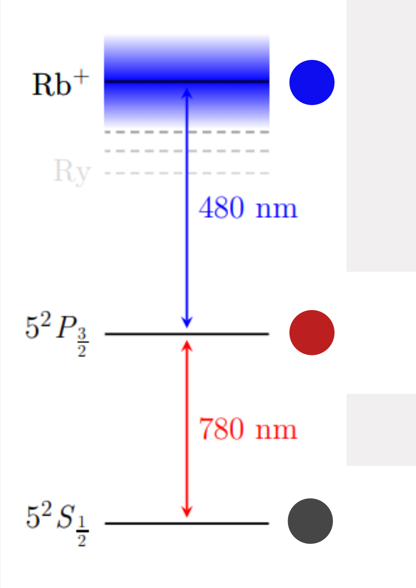




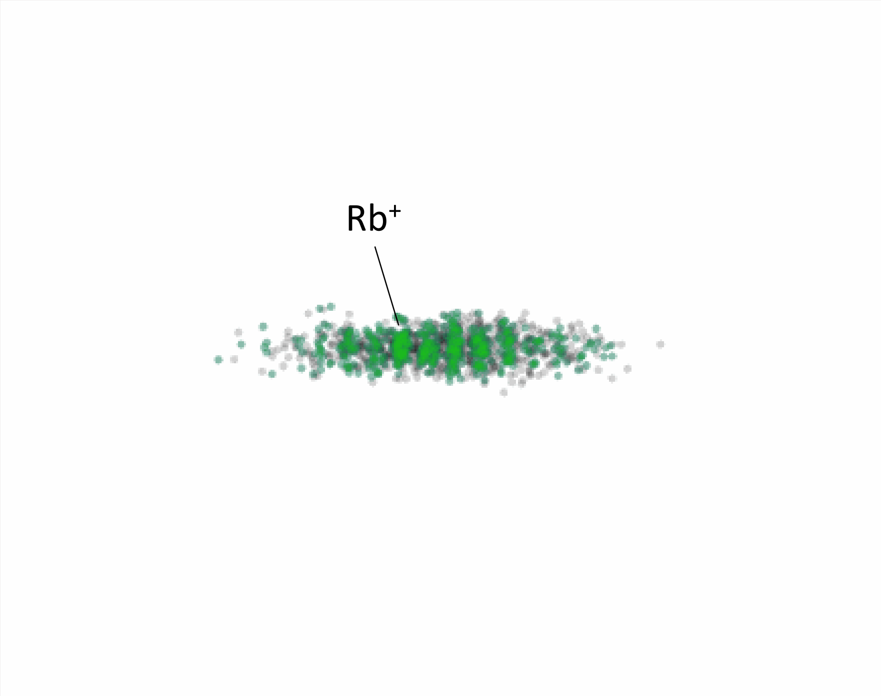


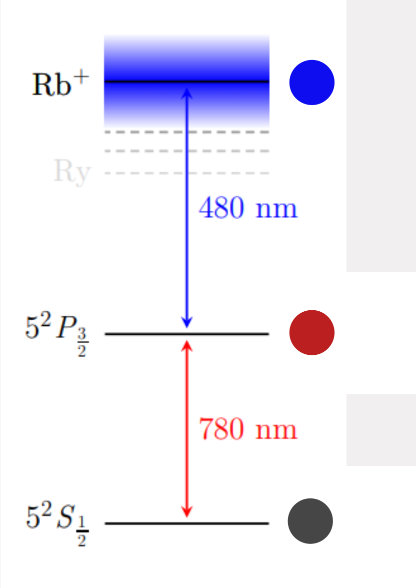
Micro-bunched electron beam: ionization



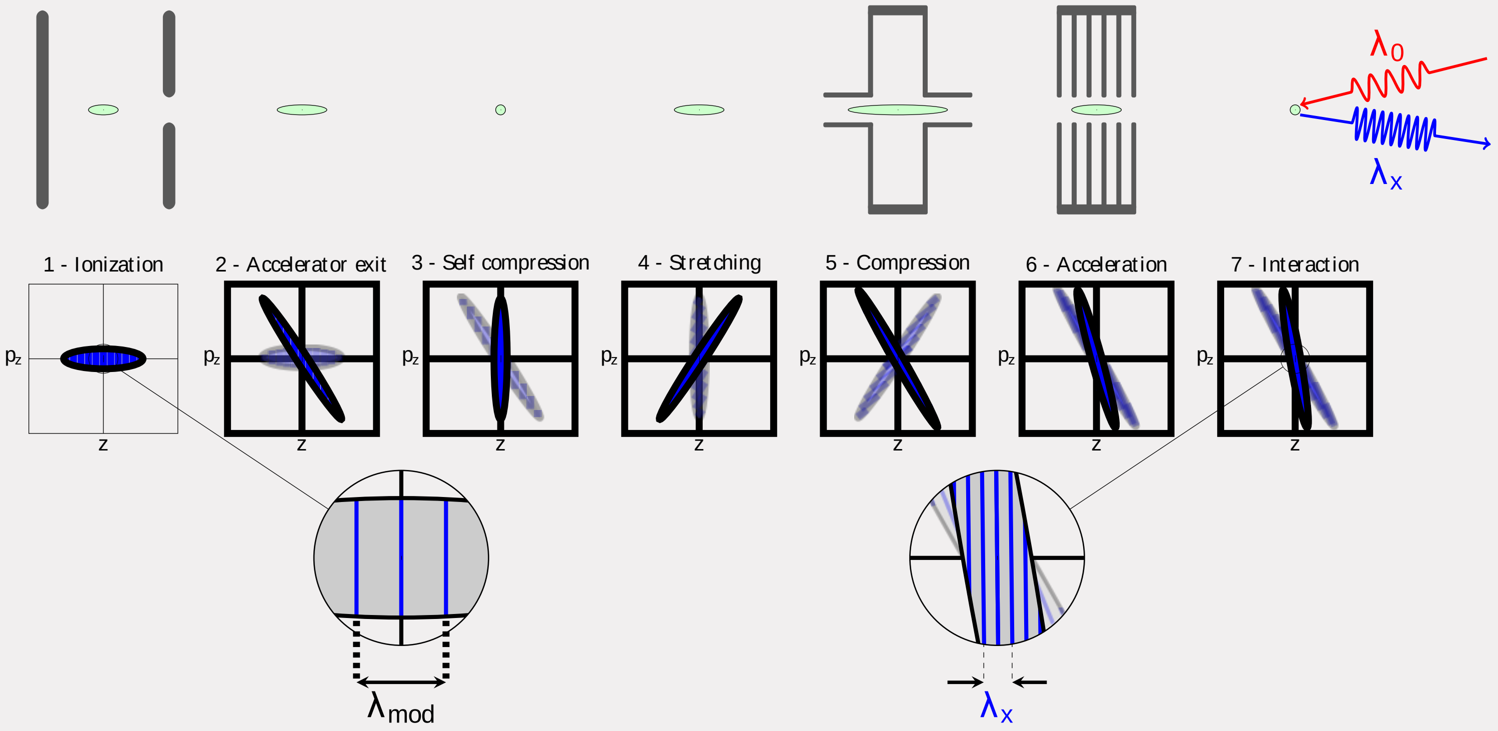


Micro-bunched electron beam: acceleration



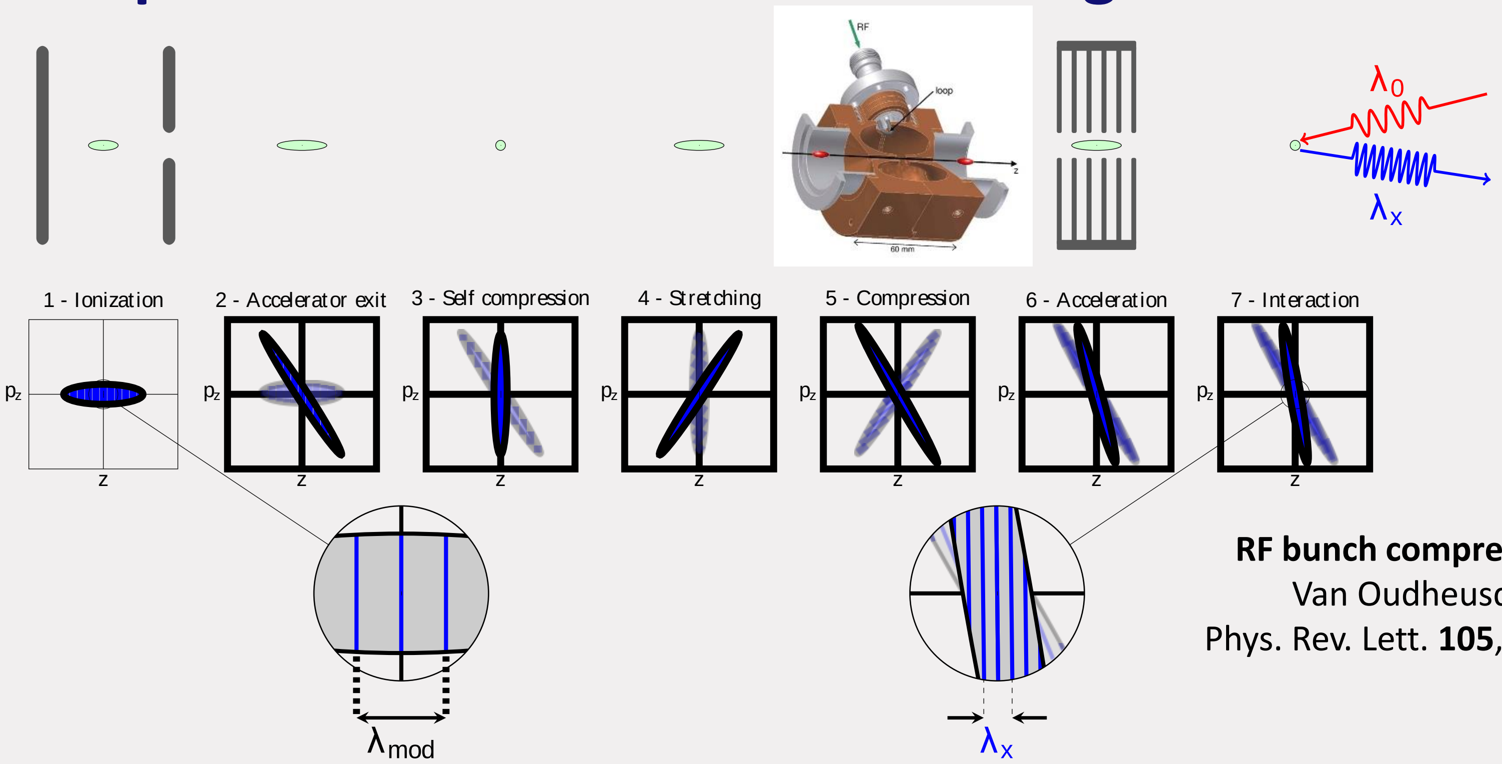


Temporal coherence: micro-bunching



TU/e

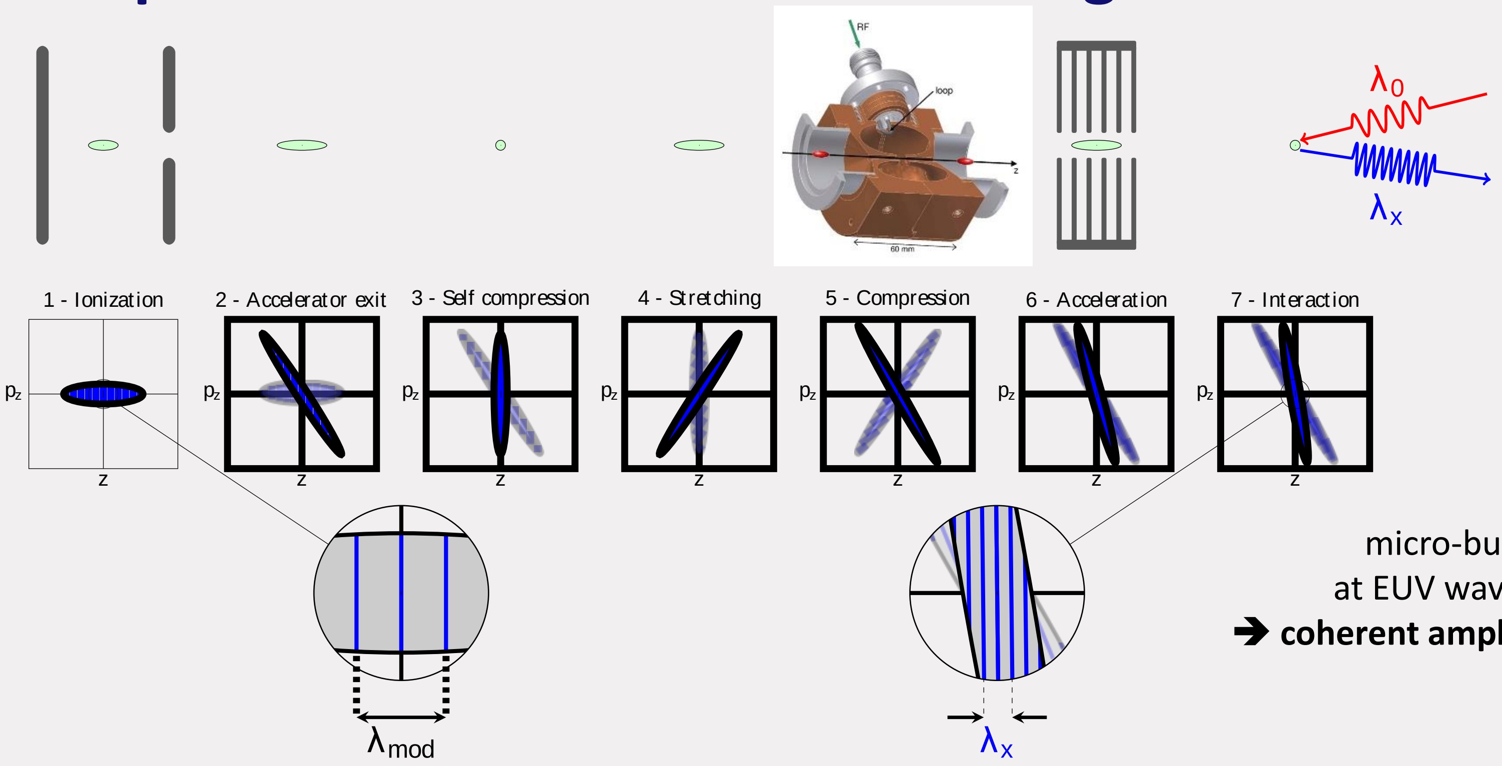
Temporal coherence: micro-bunching



RF bunch compression > 100×
Van Oudheusden et al.,
Phys. Rev. Lett. **105**, 264801 (2010)

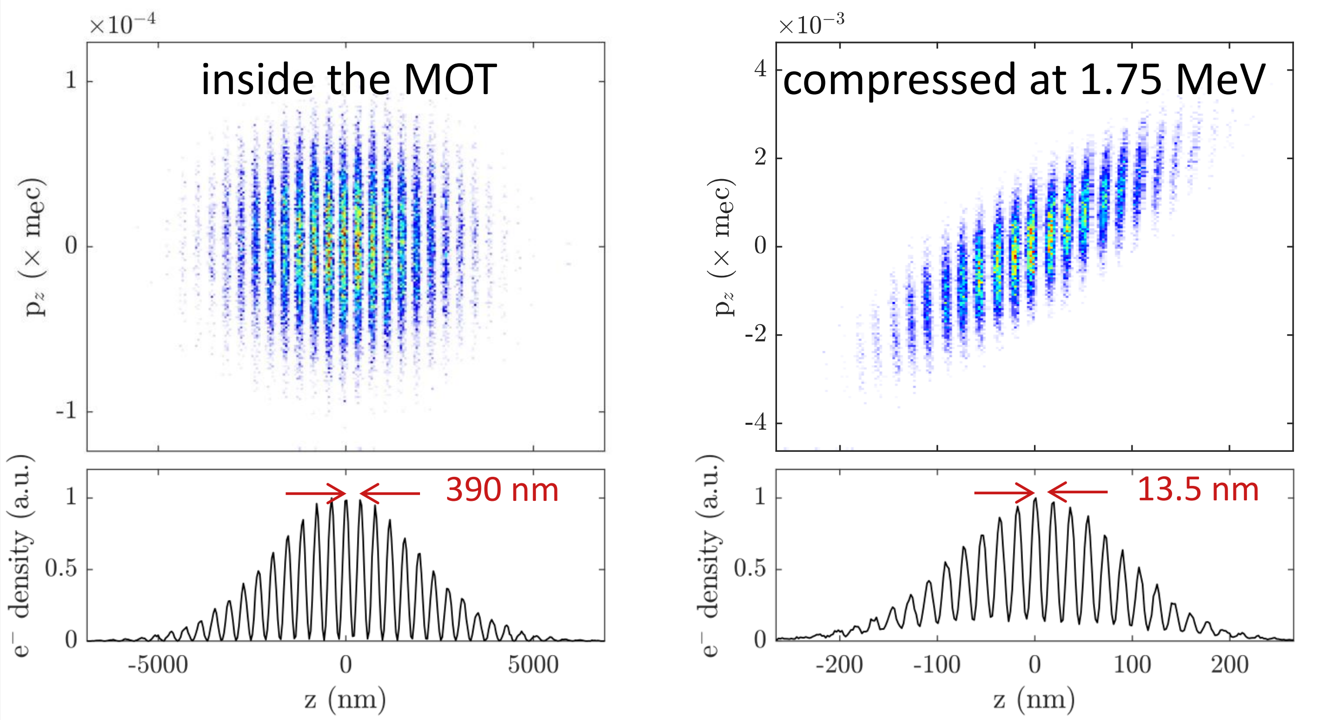
TU/e

Temporal coherence: micro-bunching



micro-bunching
at EUV wavelengths
➔ **coherent amplification of ICS**

Temporal coherence: micro-bunching



preliminary
GPT simulations

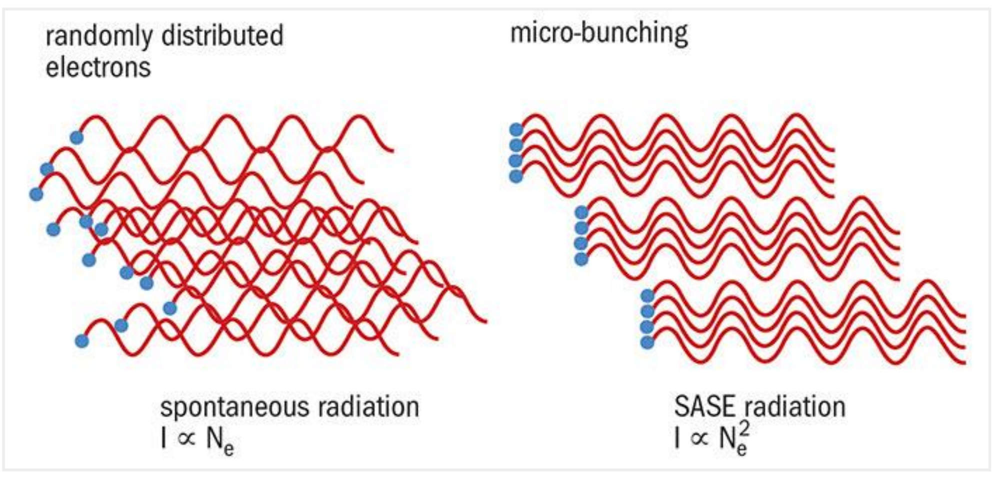
- realistic fields
- T_e = 10 K
- small bunch
- no space charge

micro-bunching
at EUV wavelengths
➔ **coherent amplification of ICS**

Temporal coherence: micro-bunching

micro bunching
at EUV wavelengths
➔ **coherent amplification of ICS**

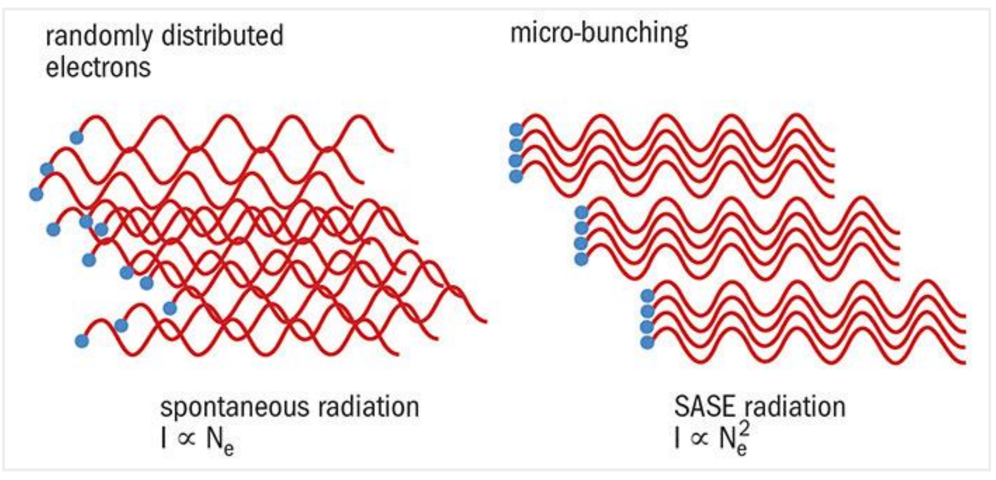
$$\Phi_X = f(1+N_e)N_e N_0 \frac{\sigma_T}{2\pi w_0^2}$$



Temporal coherence: micro-bunching

micro bunching
at EUV wavelengths
➔ **coherent amplification of ICS**

$$\Phi_X \propto N_e^2$$



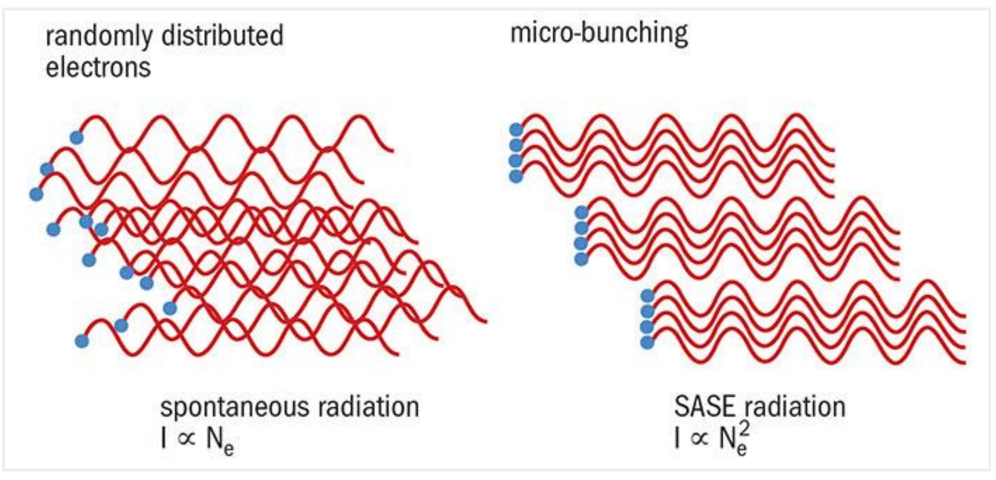
$$\left.\begin{aligned} f &= 1\ \text{kHz}, \\ E_p &= 200\ \text{mJ} \\ \lambda_0 &= 1030\ \text{nm} \\ w_0 &= 10\ \mu\text{m} \\ Q &= 0.1\ \text{pC} \end{aligned}\right\} \Rightarrow \Phi_X = 4\times 10^{13}\ \text{photons/s}$$

E_x = 0.6 μJ/pulse

P = 0.6 mW

Temporal coherence: micro-bunching

micro bunching
at EUV wavelengths
➔ **coherent amplification of ICS**



$$F_X \propto N_e^2$$

$$\left.\begin{array}{l} f = 1\text{ kHz}, \\ E_p = 200\text{ mJ} \\ \lambda_0 = 1030\text{ nm} \\ w_0 = 10\ \mu\text{m} \\ Q = 0.1\text{ pC} \end{array}\right\} \Rightarrow F_X = 4\times 10^{13}\text{ photons/s}$$

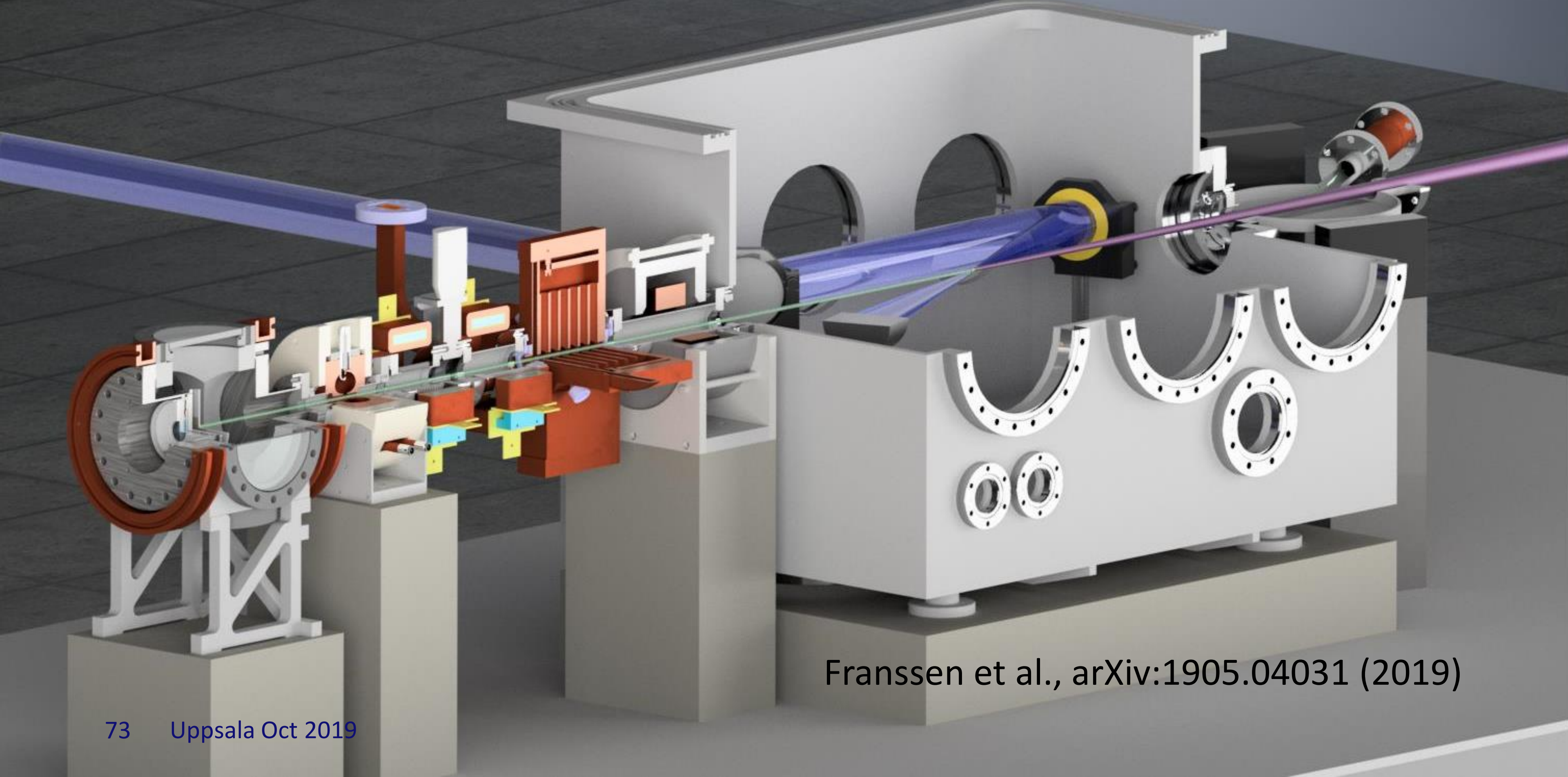
E_x = 0.6 μJ/pulse★

P = 0.6 mW★

★ ***too good to be true***

TU/e

ColdLight: from laser-cooled atoms to coherent soft X-rays

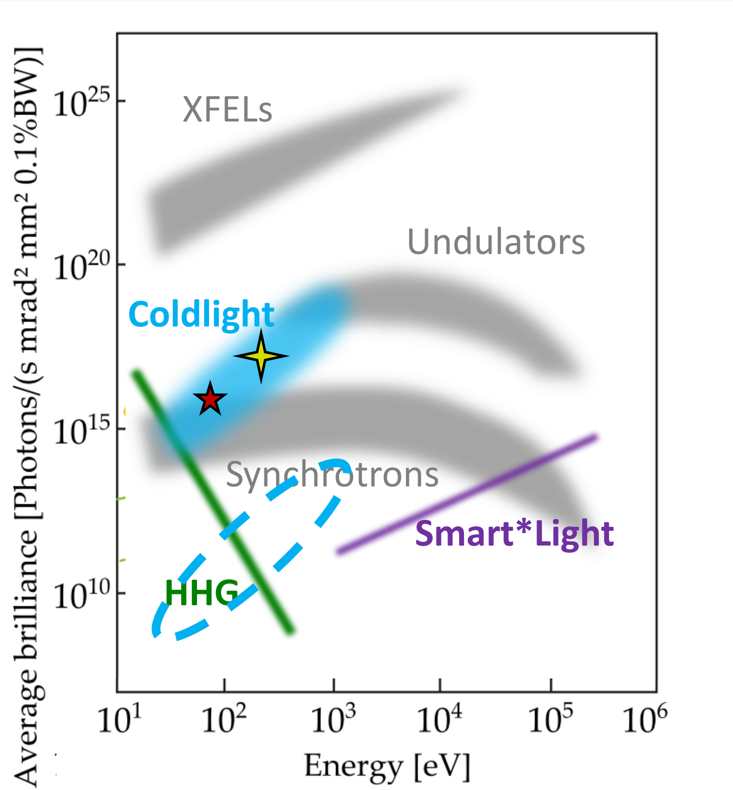


Franssen et al., arXiv:1905.04031 (2019)

ColdLight summary

- ColdLight: **Laser-cooled electron source for ICS soft X-ray** generation
- 10 K (1 meV) electron source temperature; < 4 ps pulse length
- RF acceleration & bunch compression & higher bunch charge soon
- **Full spatial and temporal soft X-ray coherence**; coherent amplification...?

High-brilliance X-ray sources



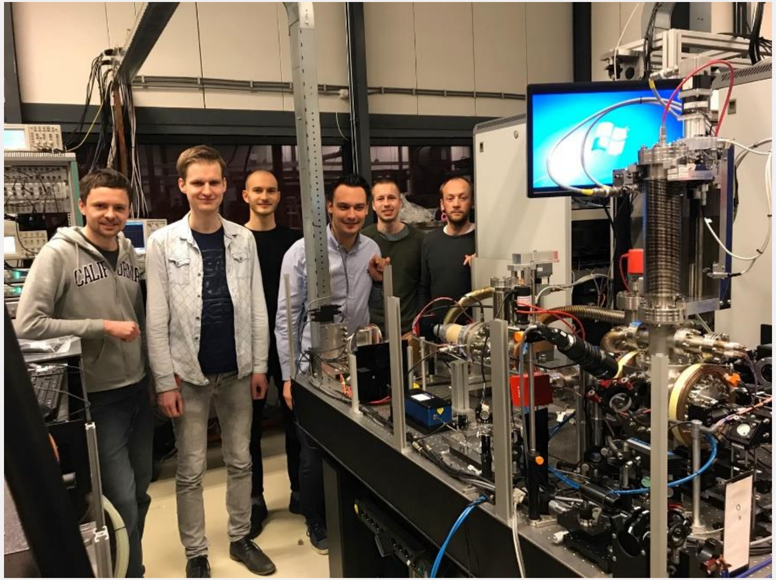
Large scale facility

13.5 nm

Water window

Acknowledgments

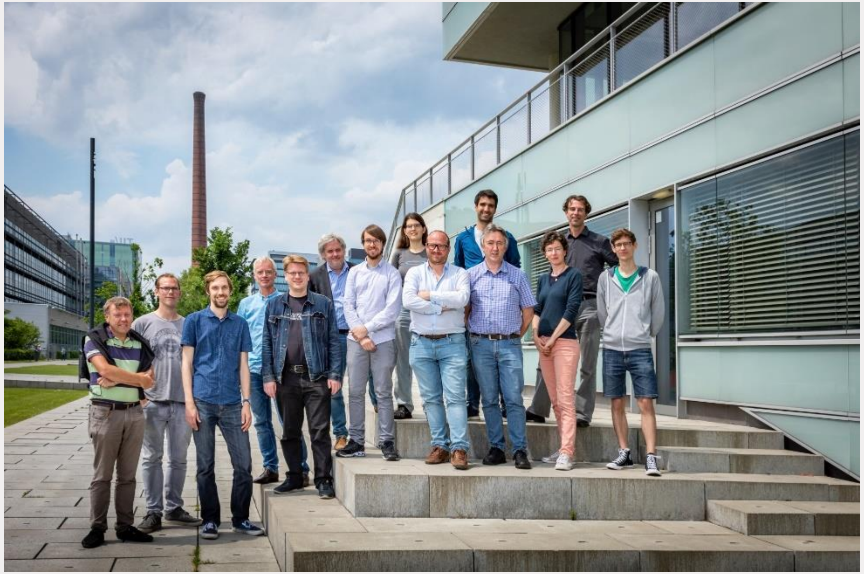
ColdLight team



Eddy

Harry

Smart*Light team



NWO

AccTec BV

ASML

Interreg
EUROPESE UNIE
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

TU Delft

TU/e