Evolution of the Inverse Compton Scattering X-ray Source of the ELSA Accelerator (CEA DAM, France)

Working group : Compact Light Sources

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Verkehrshaus Luzern

université PARIS-SACLAY

LABORATOIRE MATIERE EN CONDITIONS EXTREMES

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

cnrs

Summary

1. Introduction

Inverse Compton X-ray Source

- **Monochromatic and directional radiation sources with high temporal resolution**

- **Compact sources for imaging or diagnostic characterization**

  eg., ELSA (versatile : pulsed single shot - recurrent)

  ➢ 532 nm laser ($E_p = 2{,}3\ eV$) + relativistic electrons ($E_e = 18\ MeV$)

  → X-ray photons $E_X = 12\ keV$

  eg., THOMX (recurrent)

  ➢ 1030 nm laser ($E_p = 1\ eV$) + relativistic electrons ($E_e = 50\ MeV$)

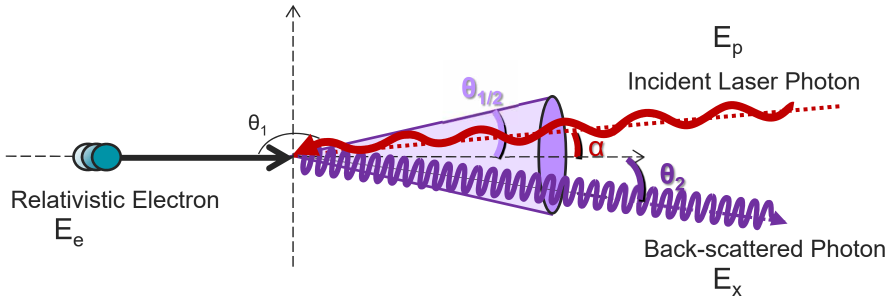
  → X-ray photons $E_X = 45\ keV$

- **Very high-energy X-ray sources for high-energy physics**

  eg., Laser Electron Photon beamline at SPring-8 (LEPS)

  ➢ 351 nm laser ($E_p = 3{,}5\ eV$) + relativistic electrons ($E_e = 8\ \mathrm{GeV}$)

  → X-ray photons $E_X = 2{,}9\ \mathrm{GeV}$



$$\mathrm{E}_X = \frac{4\gamma^2 E_p}{1 + \gamma^2\theta_2^2 + \frac{\alpha^2}{4}}$$

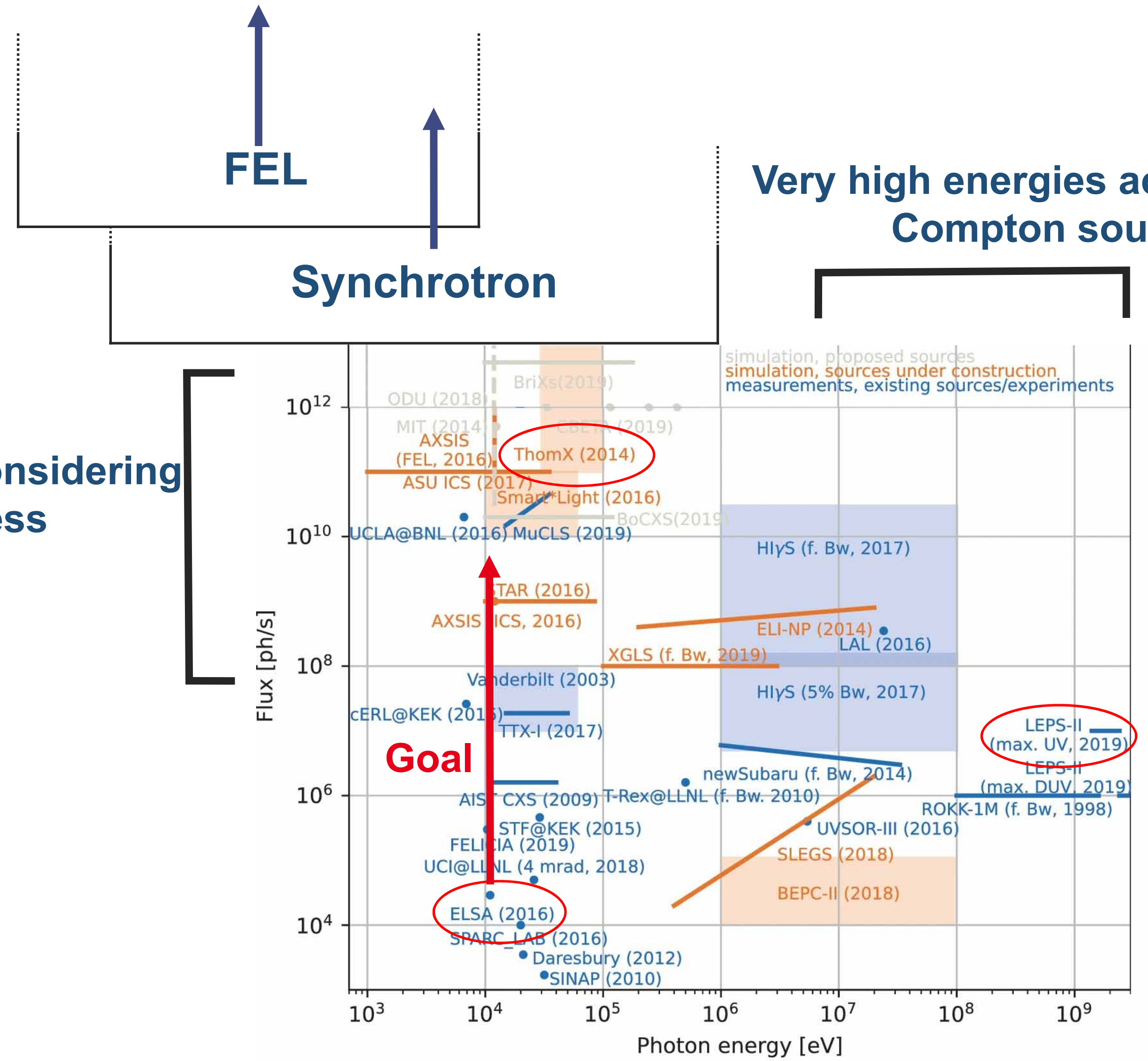
$$\mathrm{E}_X(\theta_2 = 0) = 4\gamma^2 E_p$$

$$\theta_{1/2} = \frac{1}{\gamma}$$

Comparisons of different sources

Very high energies accessible to Compton sources

Significant flux considering compactness



Storage Ring-Based Inverse Compton X-ray Sources
Cavity Design, Beamline Development and X-ray Applications
Author: Benedikt Sebastian Günther

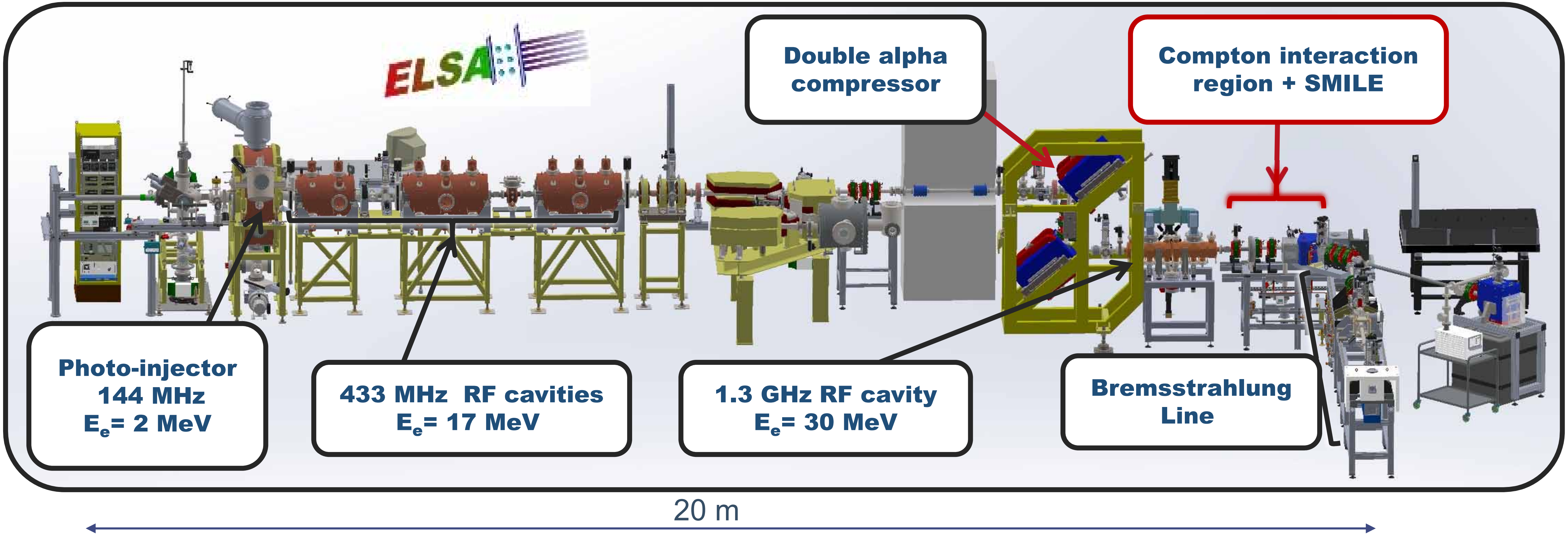
https://doi.org/10.1007/978-3-031-17742-2

2. ELSA Accelerator

(CEA DAM, France)

ELSA Accelerator (CEA DAM, France)

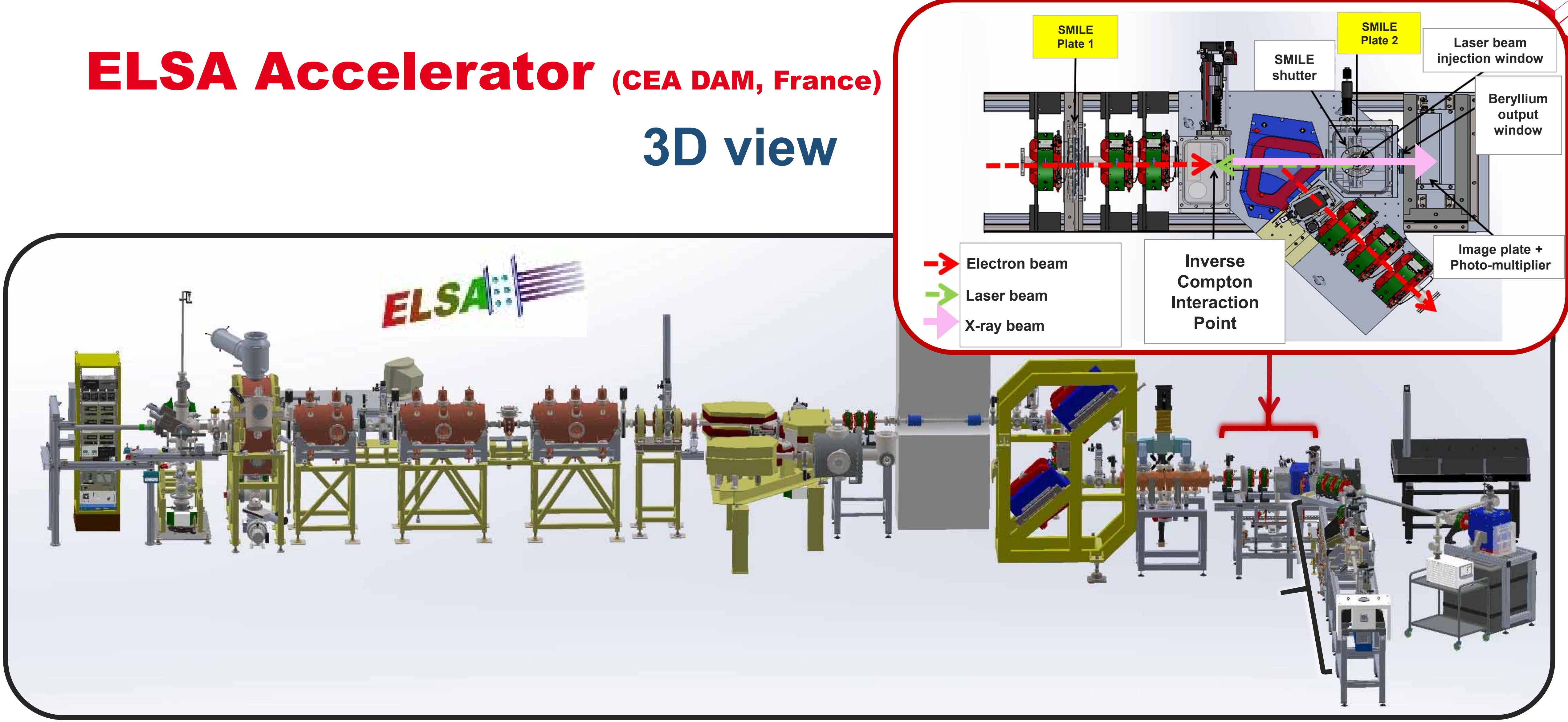
3D view



Typical bunch charge : 0.1 – 3 nC
Bunch duration : 15 – 100 ps
1 – 10000 bunches per train (1 – 5 Hz)
Emittance : 2 – 30 µm

ELSA Accelerator (CEA DAM, France)

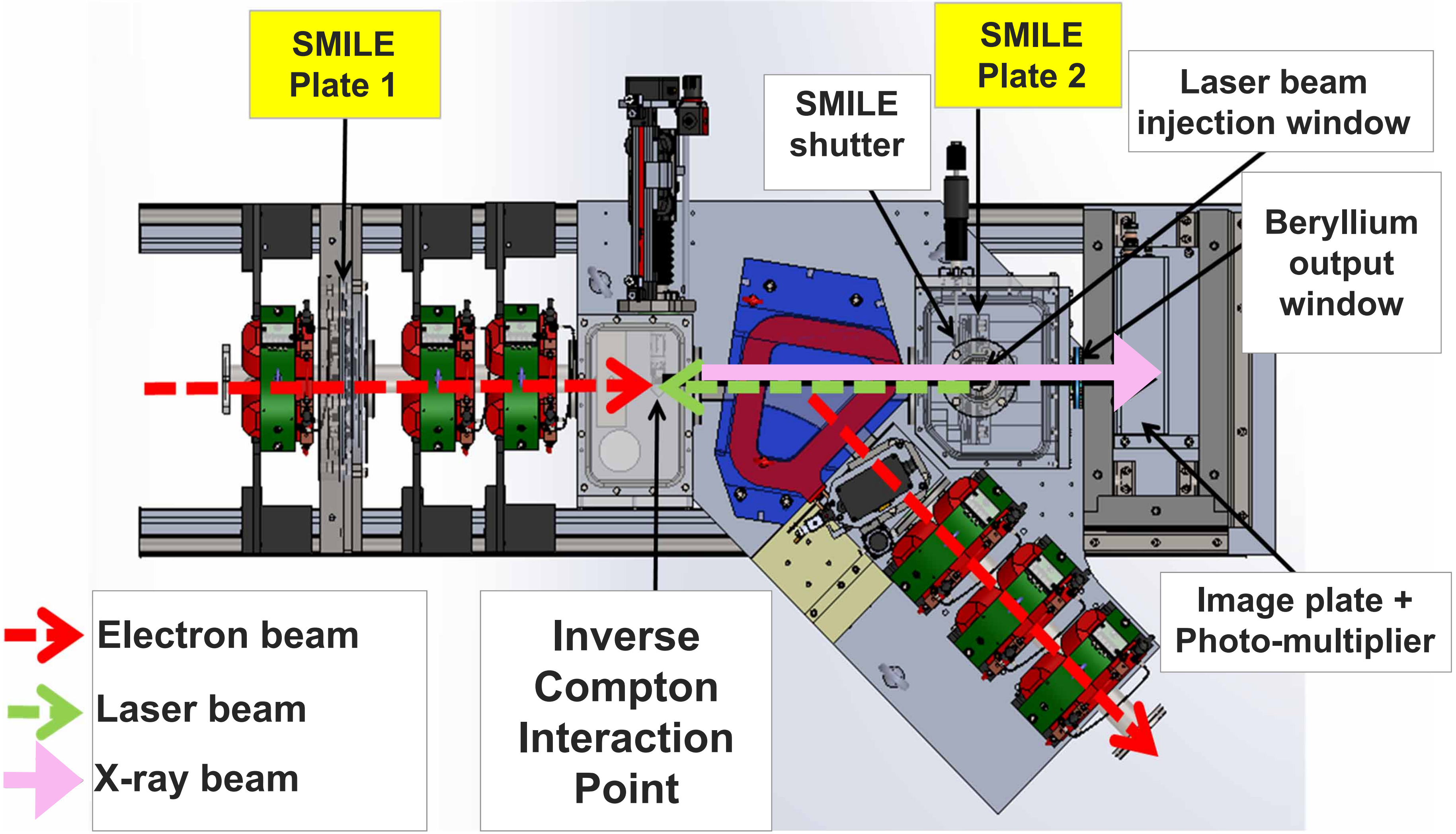
3D view



3. The Inverse Compton X-ray Source at ELSA

The Inverse Compton X-ray Source at ELSA

Top view of the interaction point

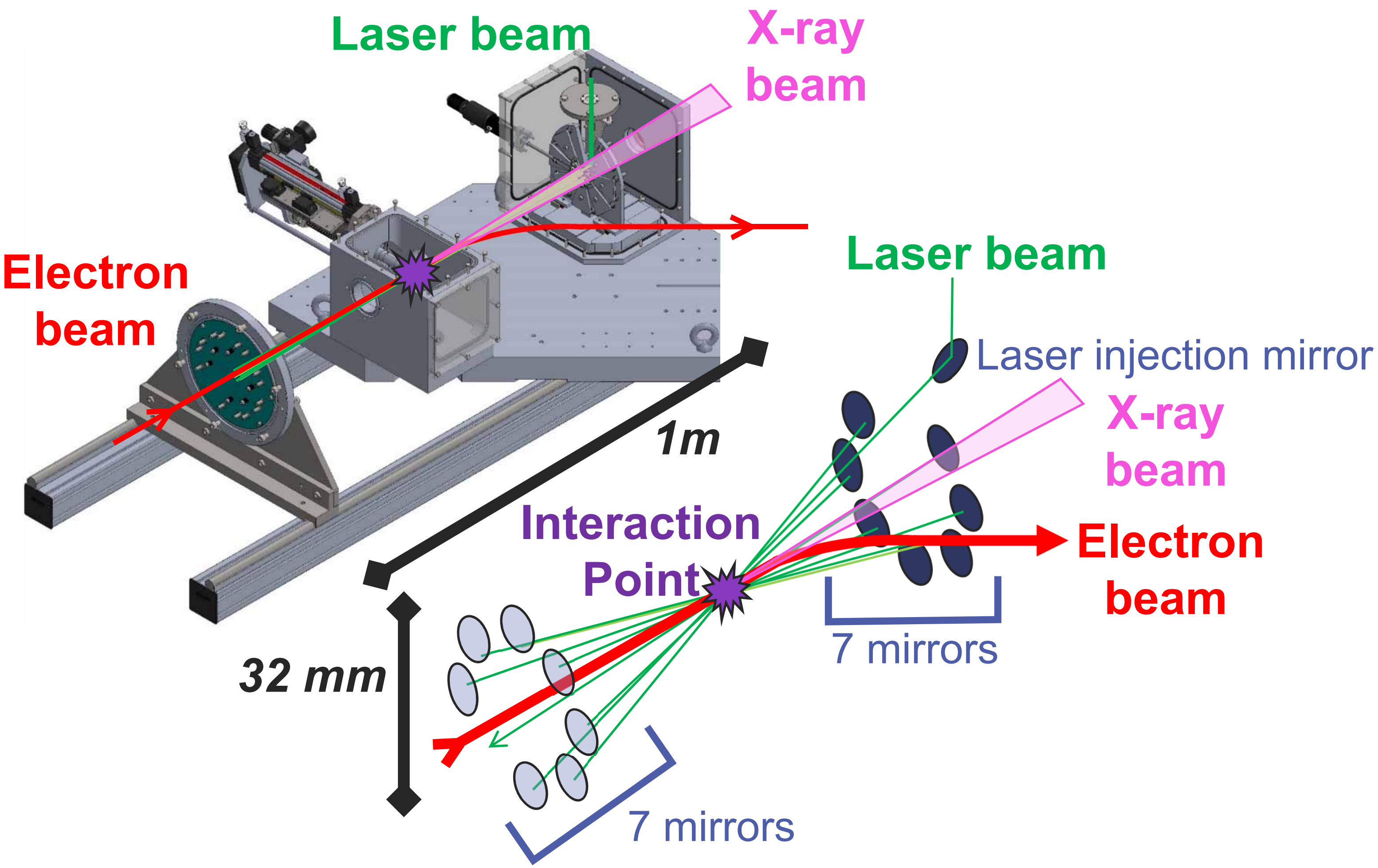


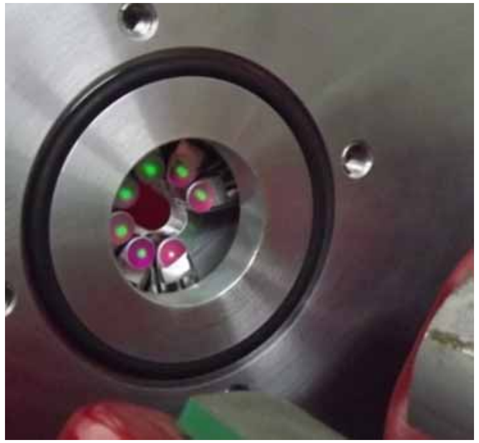
The Inverse Compton X-ray Source at ELSA

3D view of the interaction point and SMILE device

SMILE :

Système
Multi-passage
Interaction
Laser
Electron

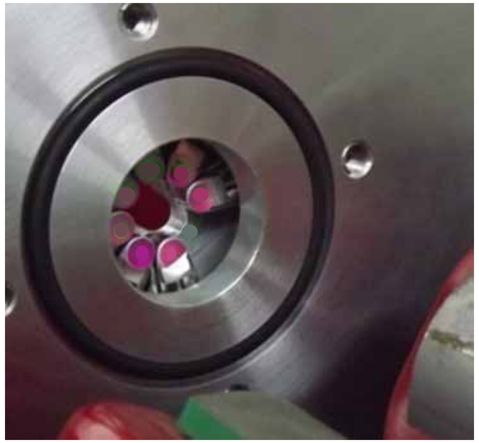




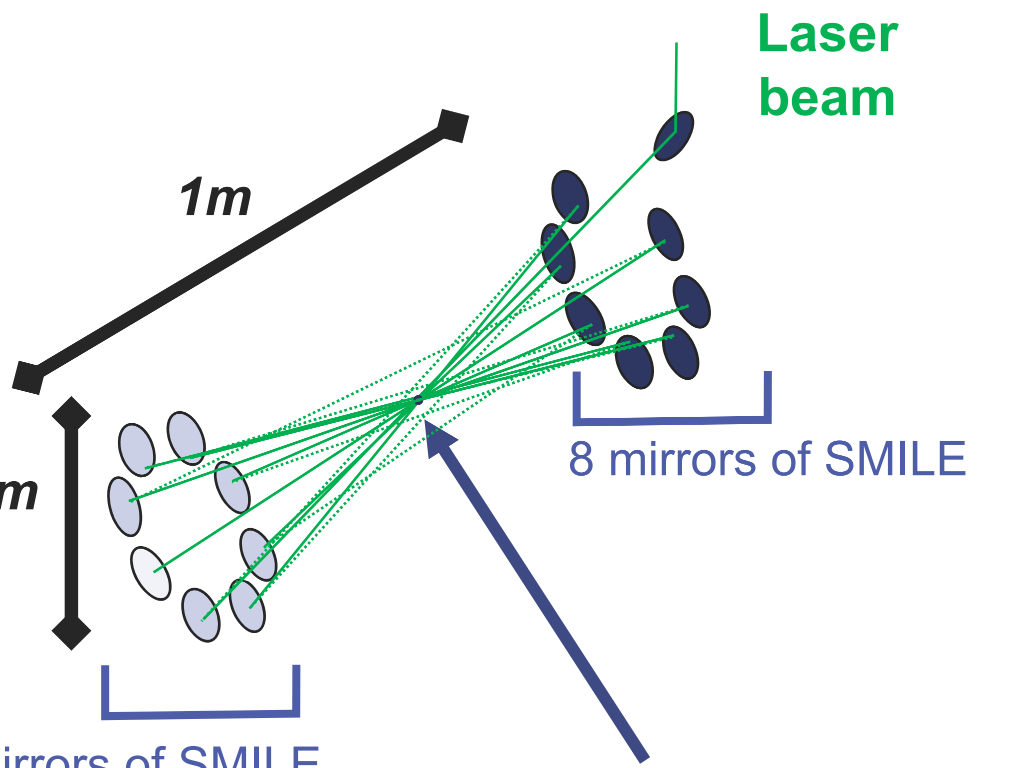
View of the laser impacting the mirrors surfaces

The Inverse Compton X-ray Source at ELSA

Schematic of SMILE



View of the laser impacting the mirrors surfaces

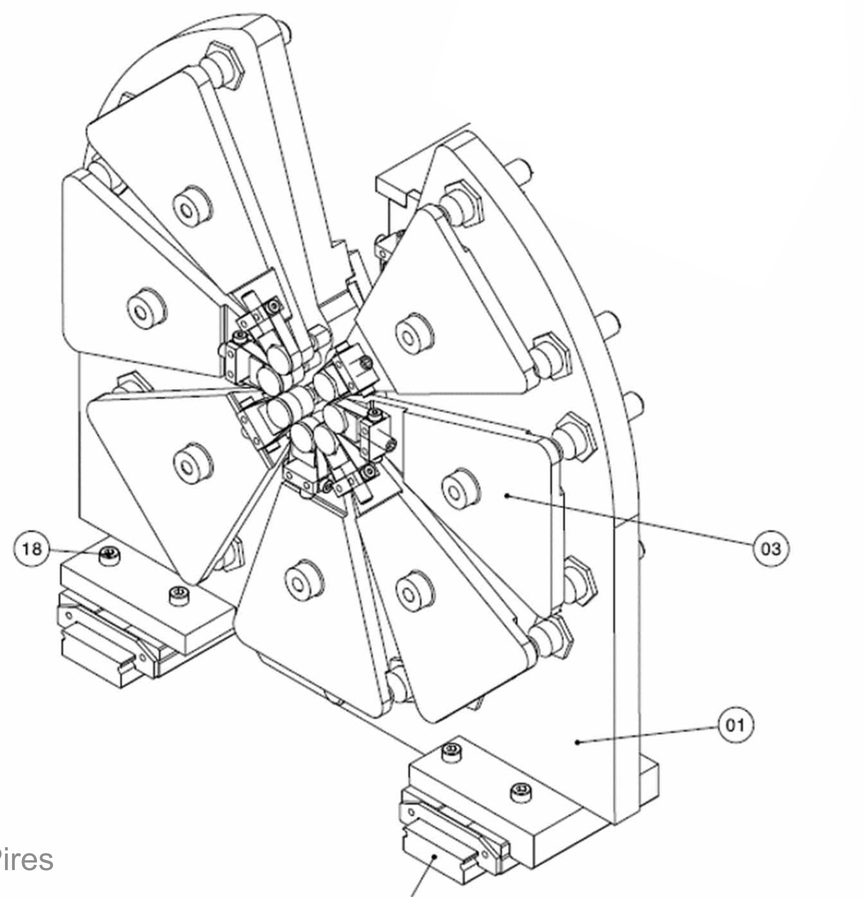


<u>Counterintuitive</u> to use a multipass system for a single shot interaction (Primary use of ELSA Compton source)

The Inverse Compton X-ray Source at ELSA

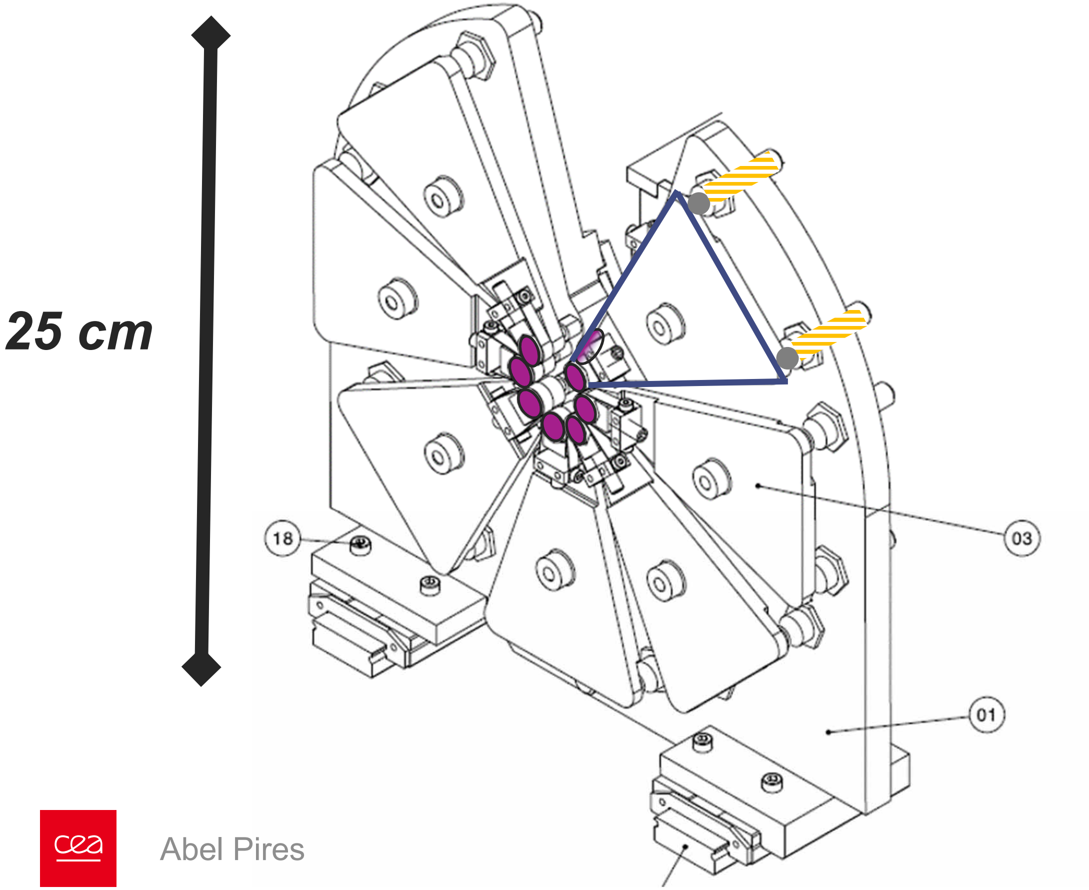
Optomechanical design for high angular precision

25 cm

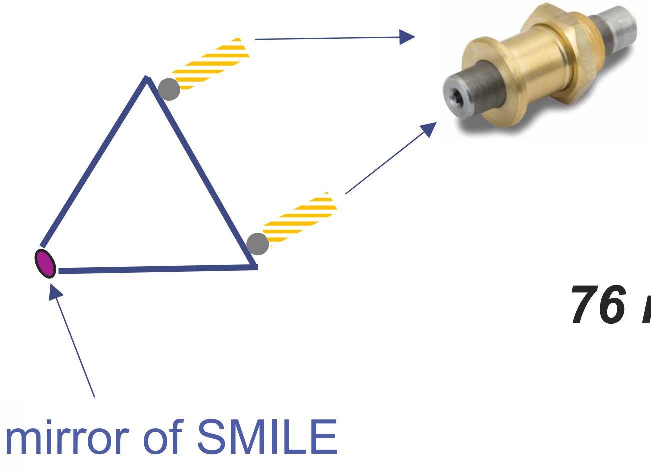


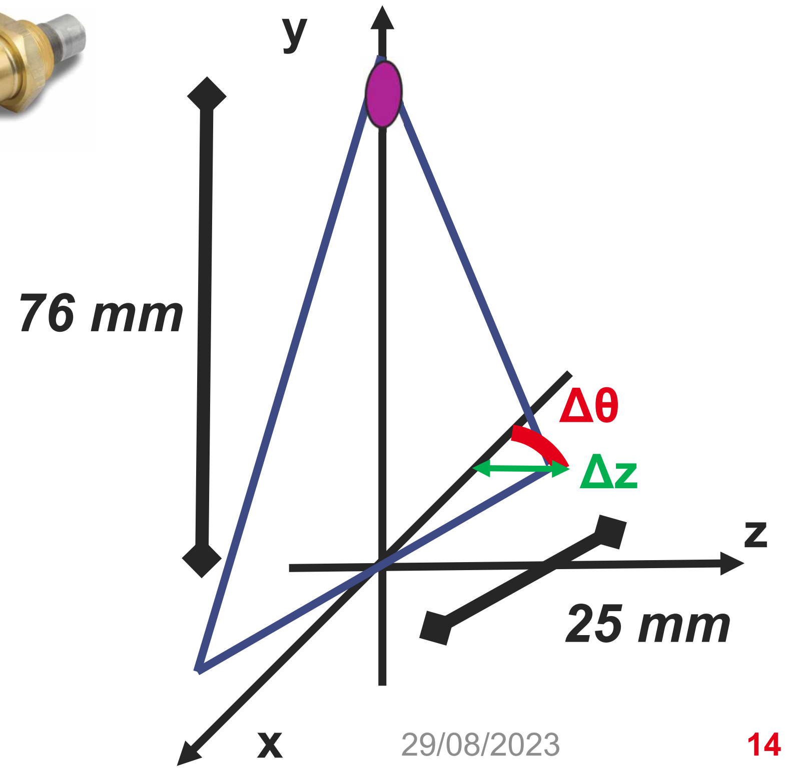
The Inverse Compton X-ray Source at ELSA

Optomechanical design for high angular precision



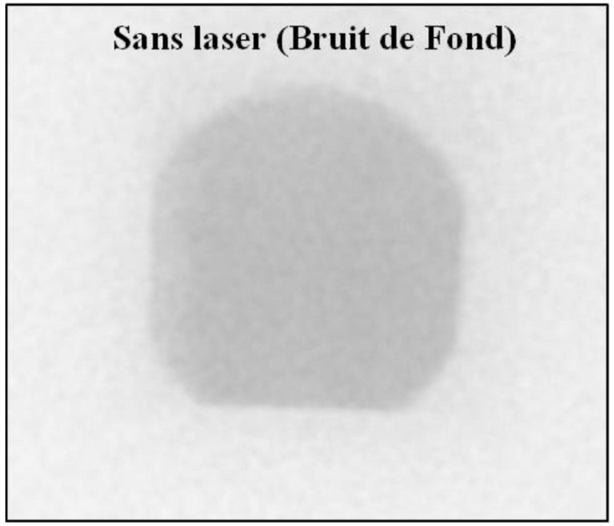
Fine threaded screw
100µm thread
1° of rotation leads to **Δz = 277nm** and **Δθ ≈ 11 µrad**

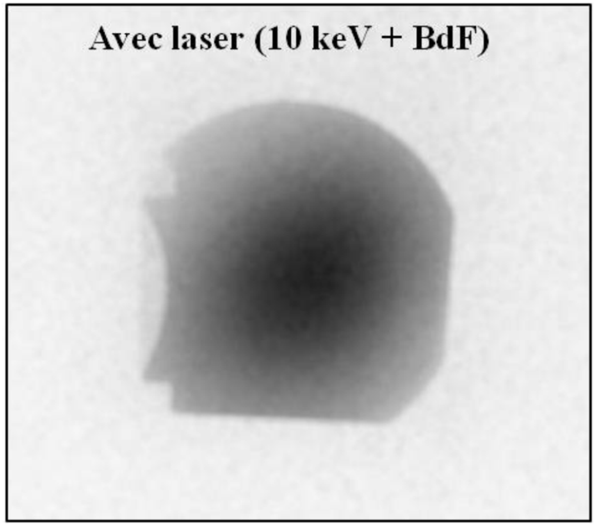




The Inverse Compton X-ray Source at ELSA

First Experimental results in 2010 (without SMILE)

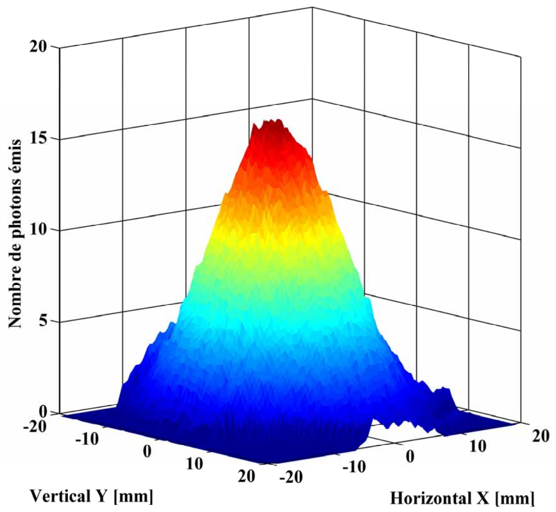




2011 experiments	17 MeV
Electron beam	
Kinetic Energy (MeV)	17
Bunch Charge (pC)	200
Emittance (µm H-V)	
rms spot size (µm H-V)	100 - 80
Bunch duration (ps)	30
Laser beam	
Wavelength (nm)	532
Pulse energy (mJ)	0,2
rms spot size (µm H-V)	40 - 65
Pulse duration (ps)	30
X-rays	
Energy (keV)	11
Half angle of radiation (mrad)	10 (30)
Nb of photons per bunch	2,3 (3,7)
Peak photon flux (ph/s)	7,6 10^{10} (1,2 10^{11})
Average flux (ph/s)	3,4 10^{3} (5,4 10^{3})

"Instrumentation developments for production and characterisation of Inverse Compton Scattering X-rays and first results with a 17 MeV electron beam, "
Nucl. Instrum. Meth. A, vol. 622, pp. 129-135, 2010,
Author : Anne-Sophie Chauchat
https://doi.org/10.1016/j.nima.2010.07.034

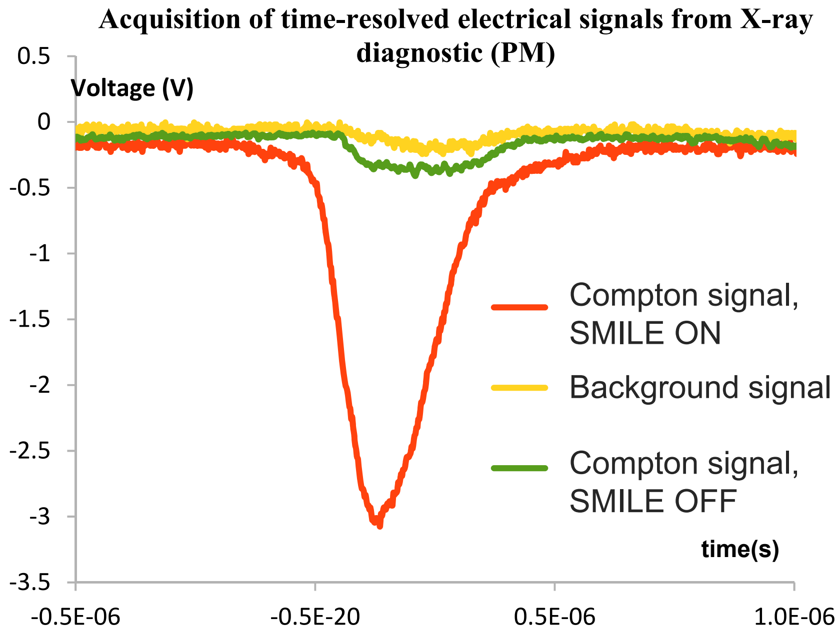
Étude de la production de ayonnement X par diffusion Compton sur l'installation ELSA
Author : Anne-Sophie Chauchat
https://theses.hal.science/tel-00652588



The Inverse Compton X-ray Source at ELSA

Experimental results in 2016

- With 17,7 MeV and 30 MeV electrons



2016 experiments	17.7 MeV		30 MeV	
Electron beam				
Kinetic Energy (MeV)	17.7		30	
Bunch Charge (pC)	400		400	
Emittance (µm H-V)	7.8 - 18.9		21 - 45	
rms spot size (µm H-V)	105 - 73		125 - 180	
Bunch duration FWHM (ps)	34		25	
Laser beam				
Wavelength (nm)	532		532	
Pulse energy (mJ)	2 (0,25 without SMILE)		2 (0,25 without SMILE)	
rms spot size (µm H-V)	84 - 64		79-101	
Pulse duration FWHM (ps)	34		25	
X-rays				
Energy (keV)	12		33	
Half angle of radiation (mrad)	10	(24)	10	(13)
Nb of photons per bunch	110	(340)	293	(908)
Peak photon flux (ph/s)	$3,2\ 10^{12}$	$(1\ 10^{13})$	$1,2\ 10^{13}$	$(3,6\ 10^{13})$
Average flux (ph/s)	$2,9\ 10^{4}$	$(8,8\ 10^{4})$	$2,0\ 10^{4}$	$(6,2\ 10^{4})$

"Inverse Compton scattering X-ray source yield optimization with a laser path folding system inserted in a pre-existent RF linac,"
Nucl. Instrum. Meth. A, vol. 840, pp. 113-120, 2016,
Author : Annaïg Chaleil
https://doi.org/10.1016/j.nima.2016.10.008

Développement d'une source de rayonnement X par diffusion Compton inverse sur l'accélérateur ELSA et optimisation à l'aide d'un système d'empilement de Photons
Author : Annaïg Chaleil
https://hal.science/tel-01435076/

4. Strategy for Source Optimization

Strategy for Source Optimization

Summary

	Pitfalls :	Solutions :
Interaction area	- Beams alignment - Mechanical stability	Re-design the interaction area (SMILE 2)
Laser	- Efficiency of frequency doubling	Using the laser at 1064nm instead of 532nm with a remote alignment method
Laser	- Laser Induced Damage Threshold (LIDT) - Non-linear effects	Temporal stretching by CPA (Chirped Pulse Amplification)
Electrons	- Space charge effects	Twiss parameters and charge that maximize X-ray yield
Electrons	- Bunch duration	Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression
Electrons (+)	- Bunch energy - Train duration	Upgrading the 1.3 GHz cavity and Klystron system

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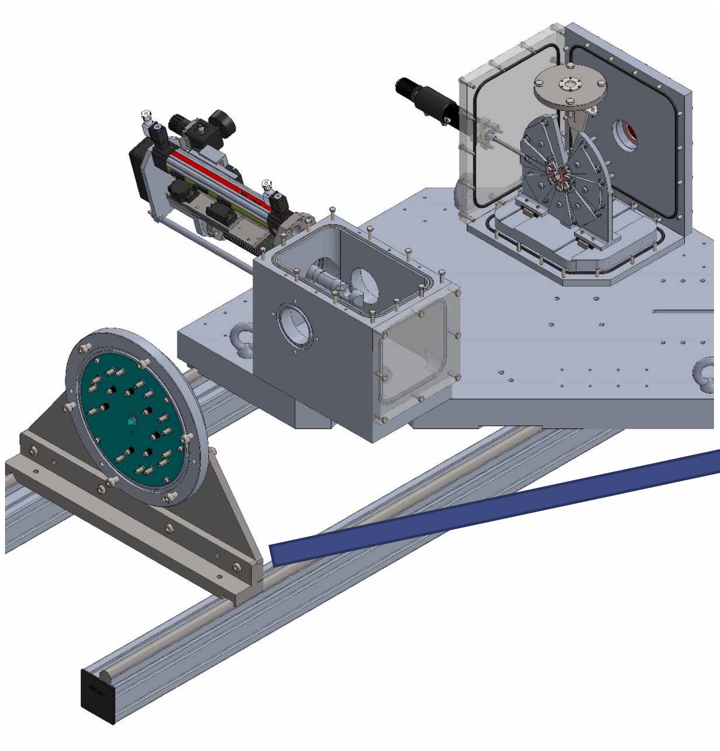
Strategy for Source Optimization

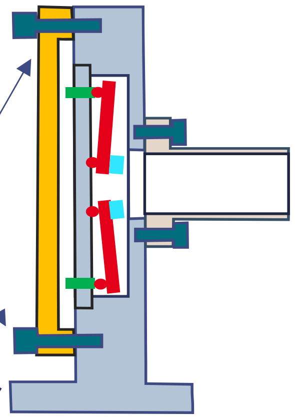
Re-design of the interaction area (SMILE 2)



Old Design :

Mechanical constraints

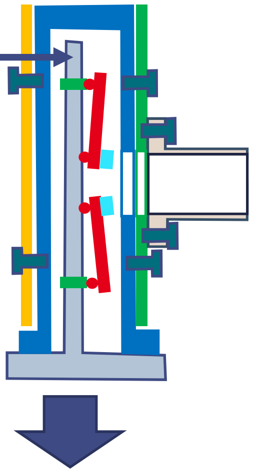
➔ Deformation

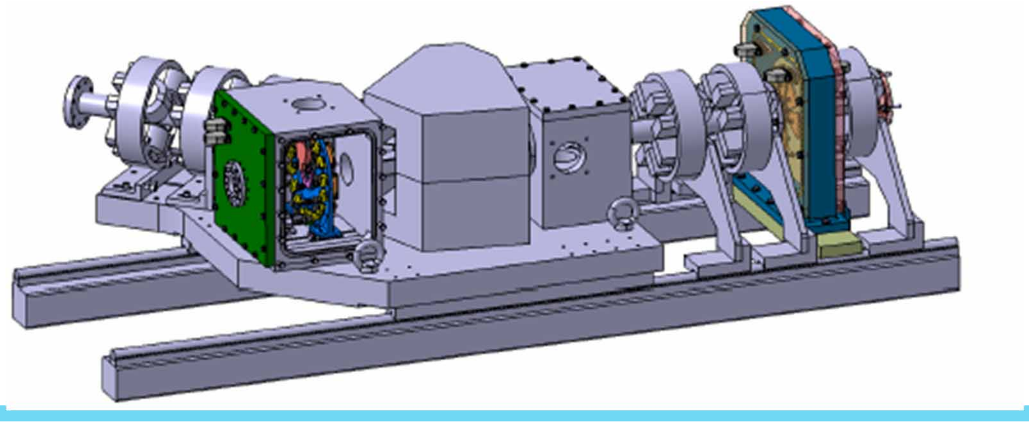


New Design idea :

No constraint on the plate even when pumping or screw tightening

➔ No Deformation when pumping and closing the SMILE



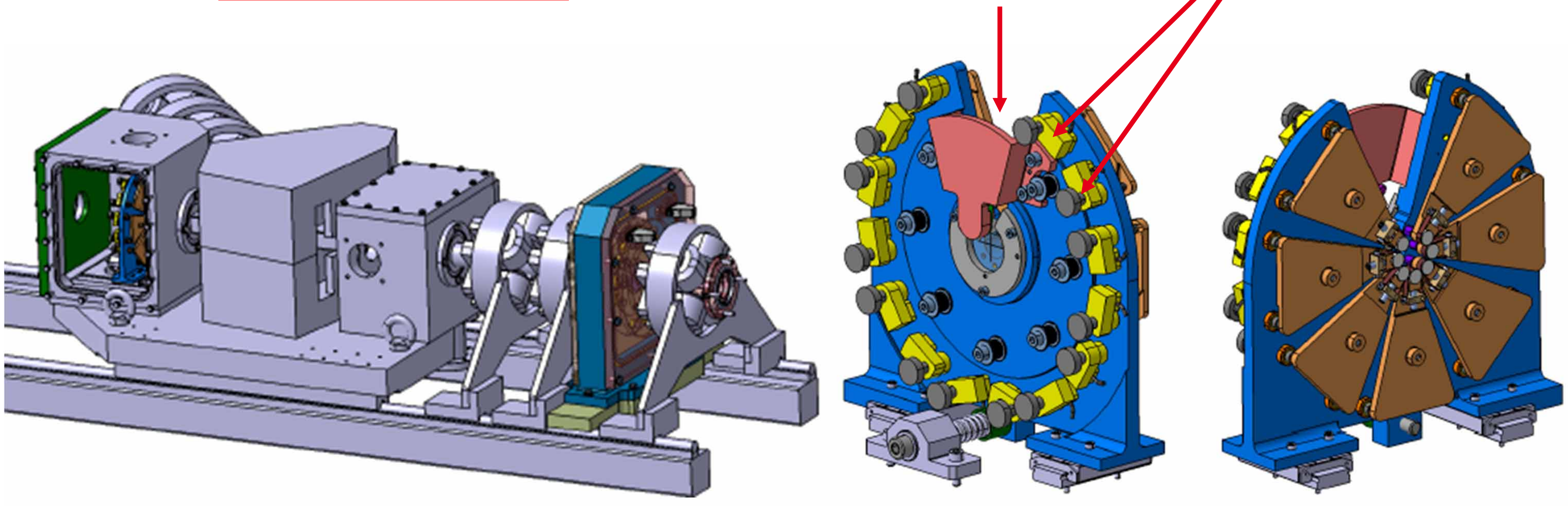


Strategy for Source Optimization

Re-design of the interaction area (SMILE 2)

SMILE 2 :
- **motorization with piezo actuator = fine thread screw driven by a piezo or manually**
- **new design of the laser entrance mirror system :**

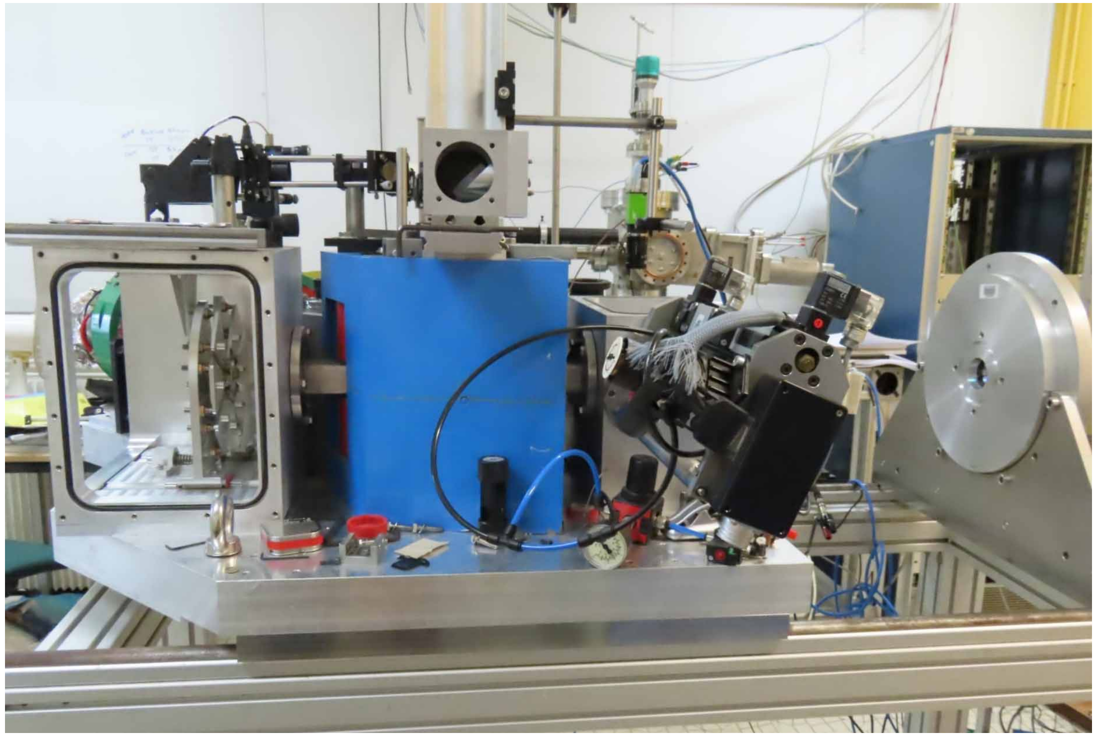
  ➔ **No mechanical link with the external structure**



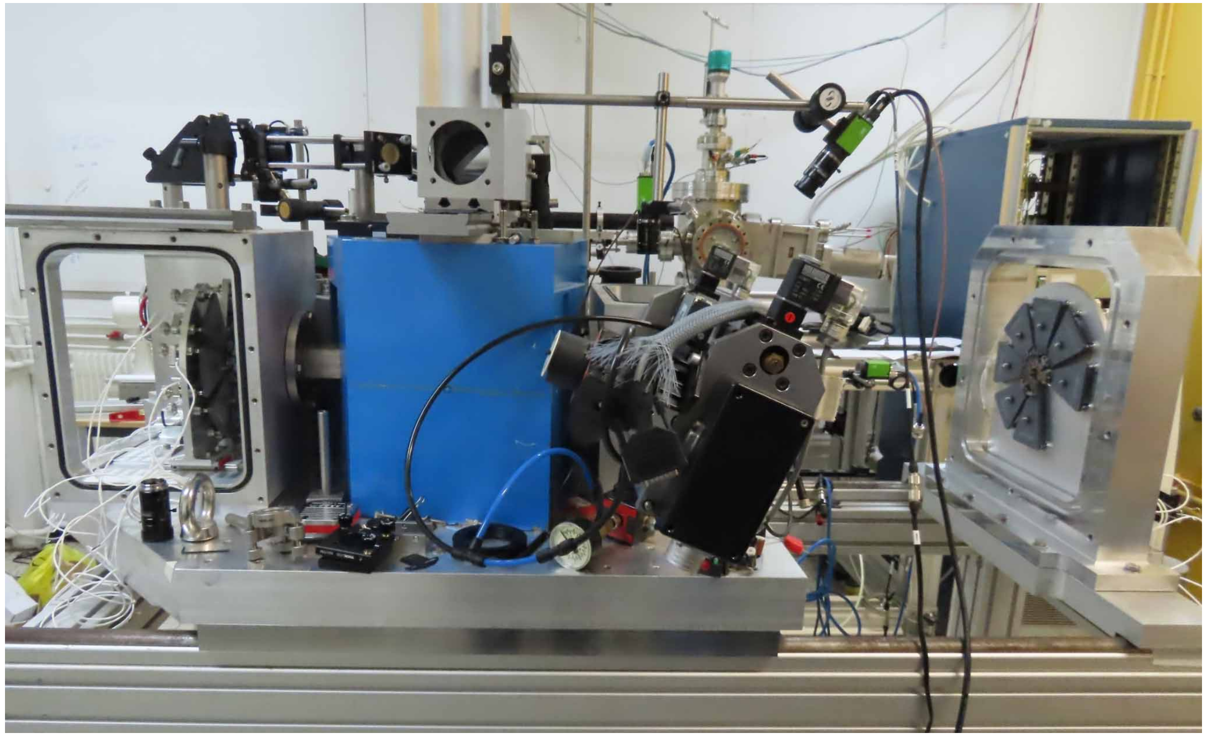
Strategy for Source Optimization

Re-design the interaction area (SMILE 2)

SMILE



SMILE 2 : operational



Strategy for Source Optimization

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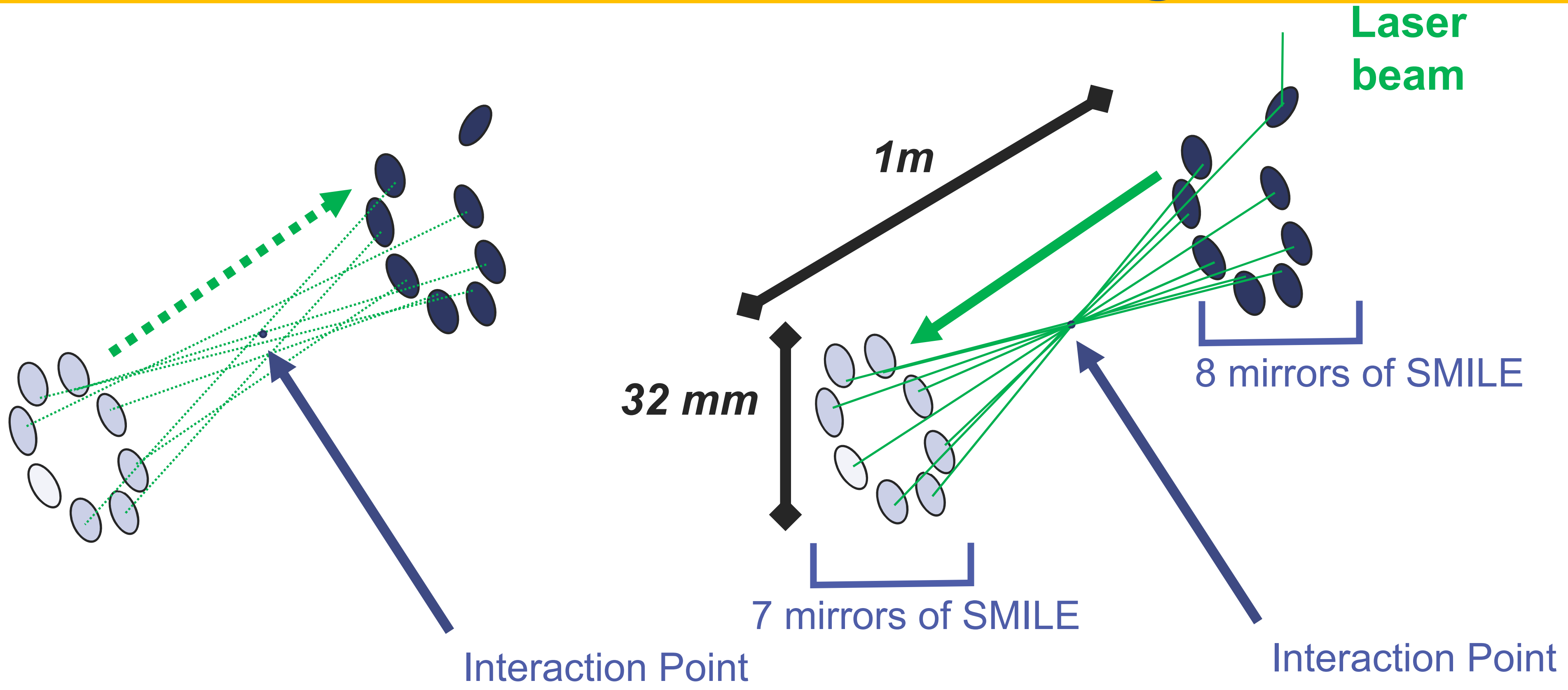
Strategy for Source Optimization

Using the laser at 1064nm with a remote alignment method

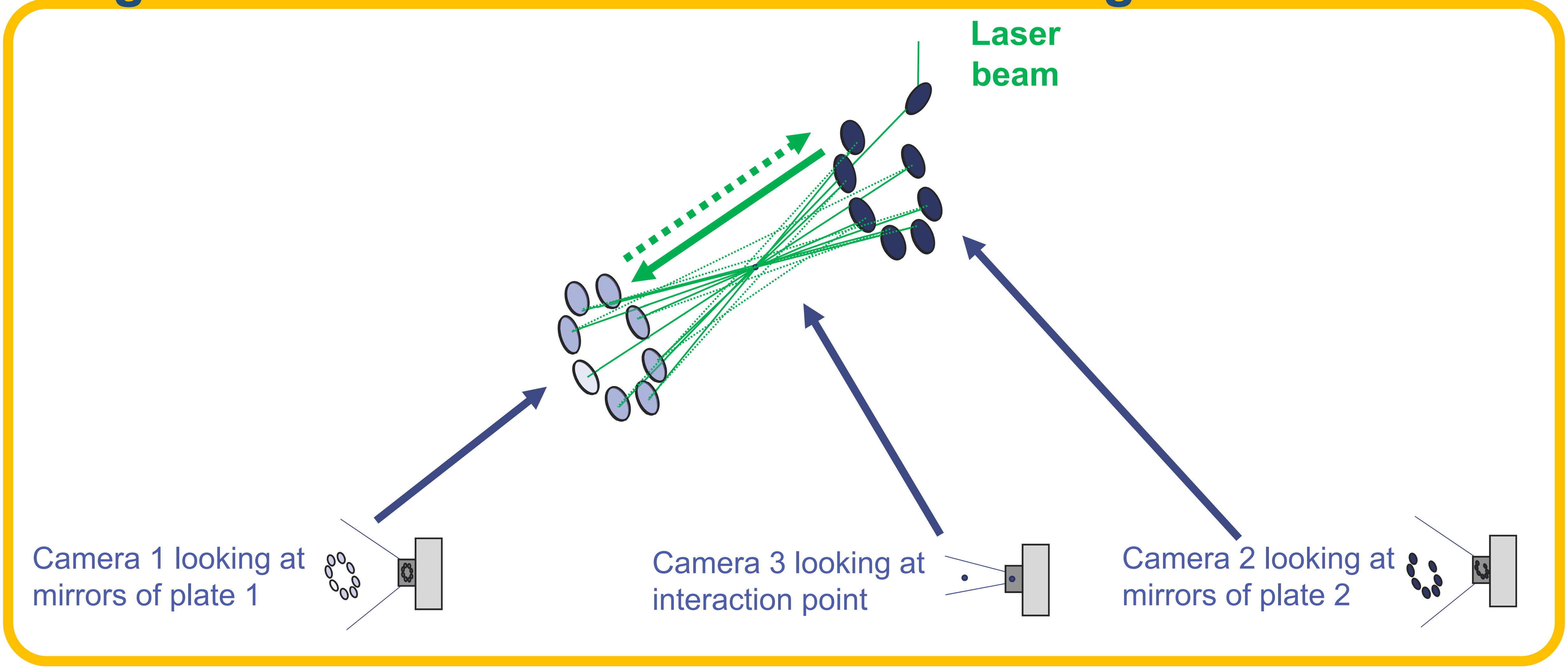


Backward path go ***around*** the interaction point

Forward path go _through_ the interaction point

Strategy for Source Optimization

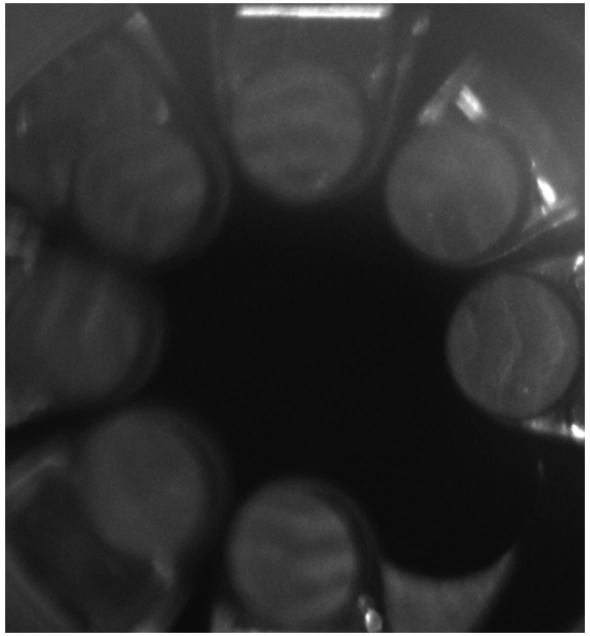
Using the laser at 1064nm with a remote alignment method

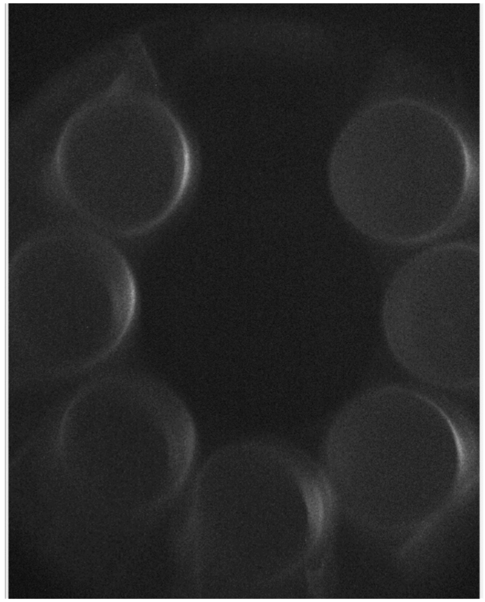


Strategy for Source Optimization

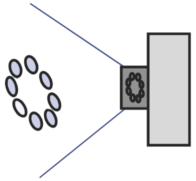
Using the laser at 1064nm with a remote alignment method

Without laser beam

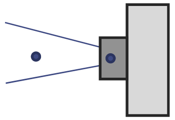




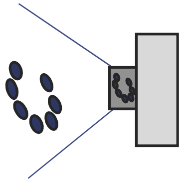
Camera 1 looking at mirrors of plate 1



Camera 3 looking at interaction point



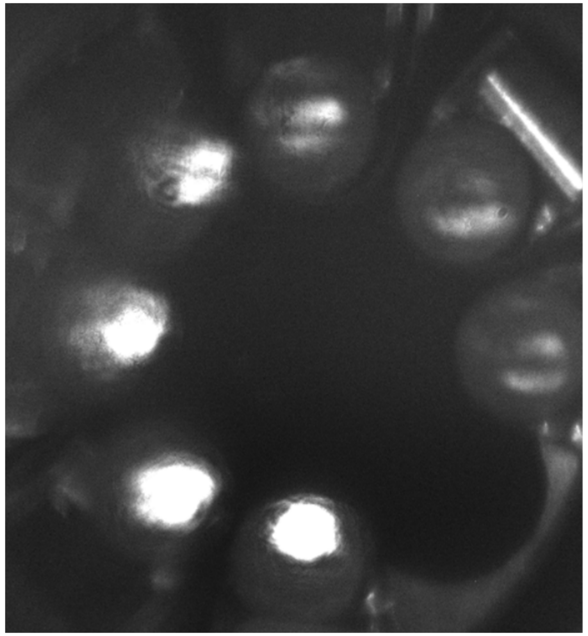
Camera 2 looking at mirrors of plate 2

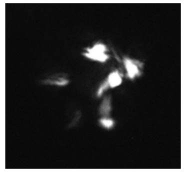


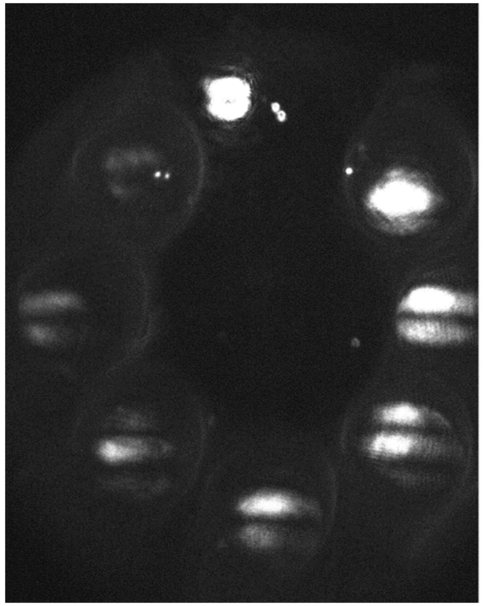
Strategy for Source Optimization

Using the laser at 1064nm with a remote alignment method

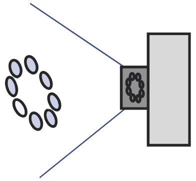
With laser beam



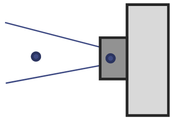




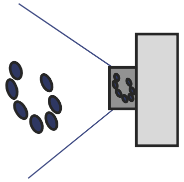
Camera 1 looking at mirrors of plate 1



Camera 3 looking at interaction point



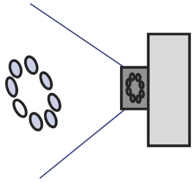
Camera 2 looking at mirrors of plate 2



Strategy for Source Optimization

Using the laser at 1064nm with a remote alignment method

Camera 1 looking at mirrors of plate 1



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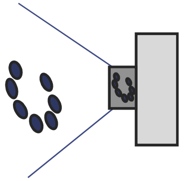
Camera 2 looking at mirrors of plate 2



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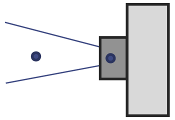
Camera 3 looking at interaction point



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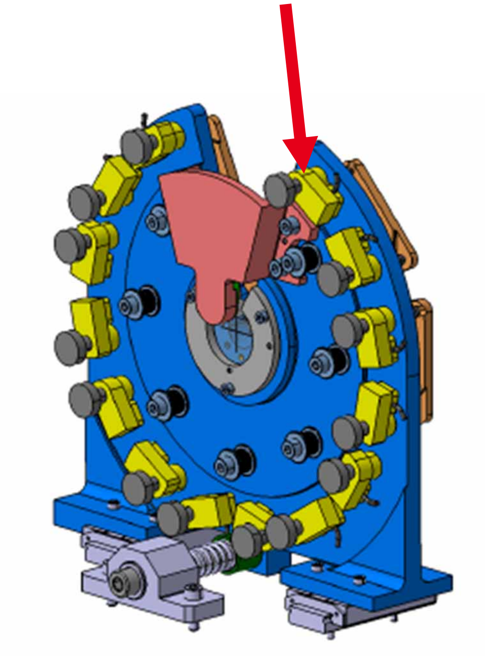
Piezo actuators



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remote alignment method for 532nm and 1064nm

+

Possibility to automatize

Strategy for Source Optimization

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Electrons	- Space charge effects	Twiss parameters and charge that maximize X-ray yield
Electrons	- Bunch duration	Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression
Electrons +	- Bunch energy - Train duration	Upgrading the 1.3 GHz cavity and Klystron system

Strategy for Source Optimization

Temporal stretching by CPA (Chirped Pulse Amplification)

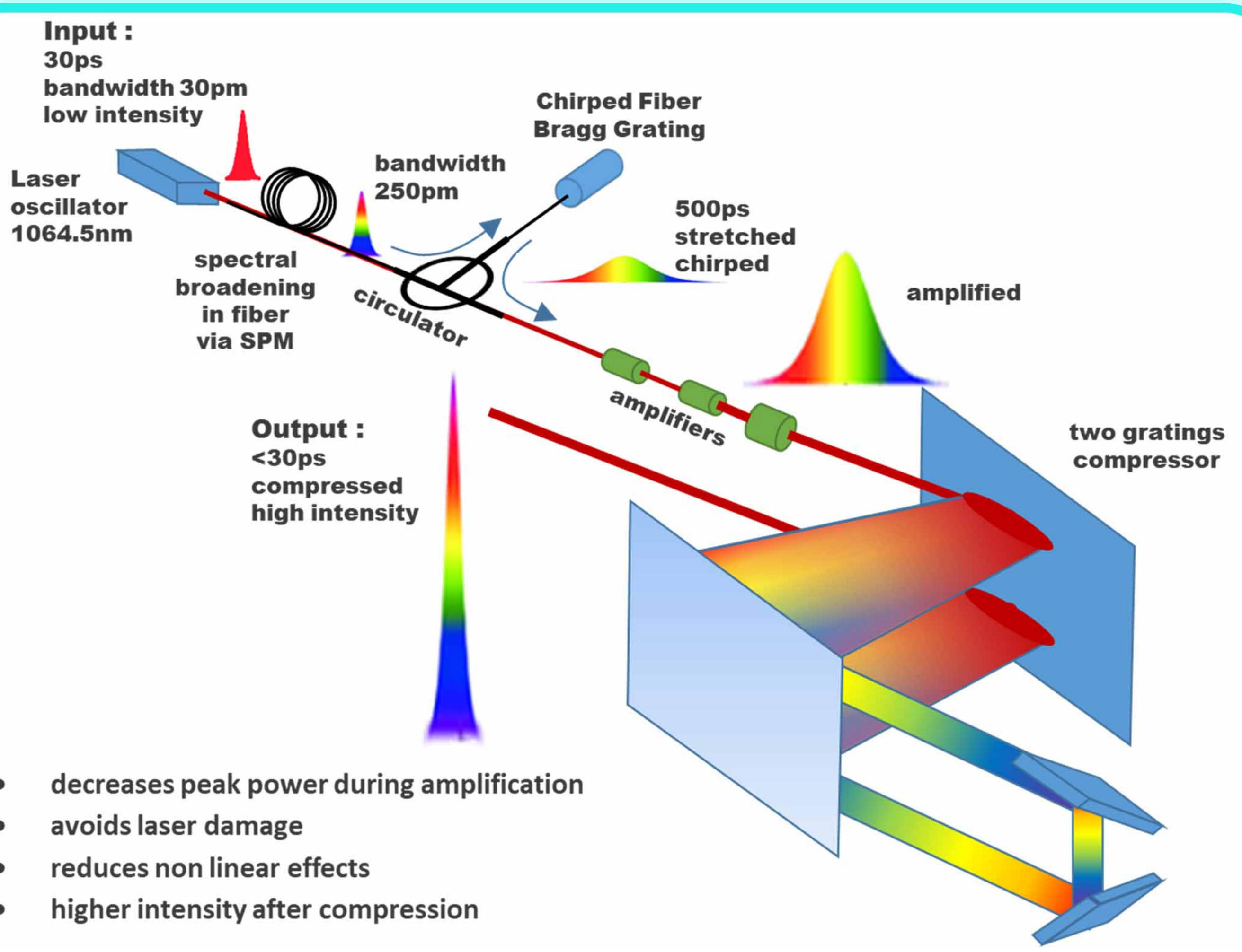
Pitfalls :
- Laser Induced Damage Threshold (LIDT)
- Non-linear effects

Specificity :

- **Nd:YAG at 1.064 µm, bandwidth: 250 pm**
- **(very narrow bandwidth for CPA)**
- high line density (1850 l/mm),
- high laser resistance
- high efficiency (> 96%)
- angle of incidence = 78°
  2° apart from the Littrow angle to enhance dispersion
- distance between gratings = 1.7 m

Status :

System designed and delivered properly, started alignement in August

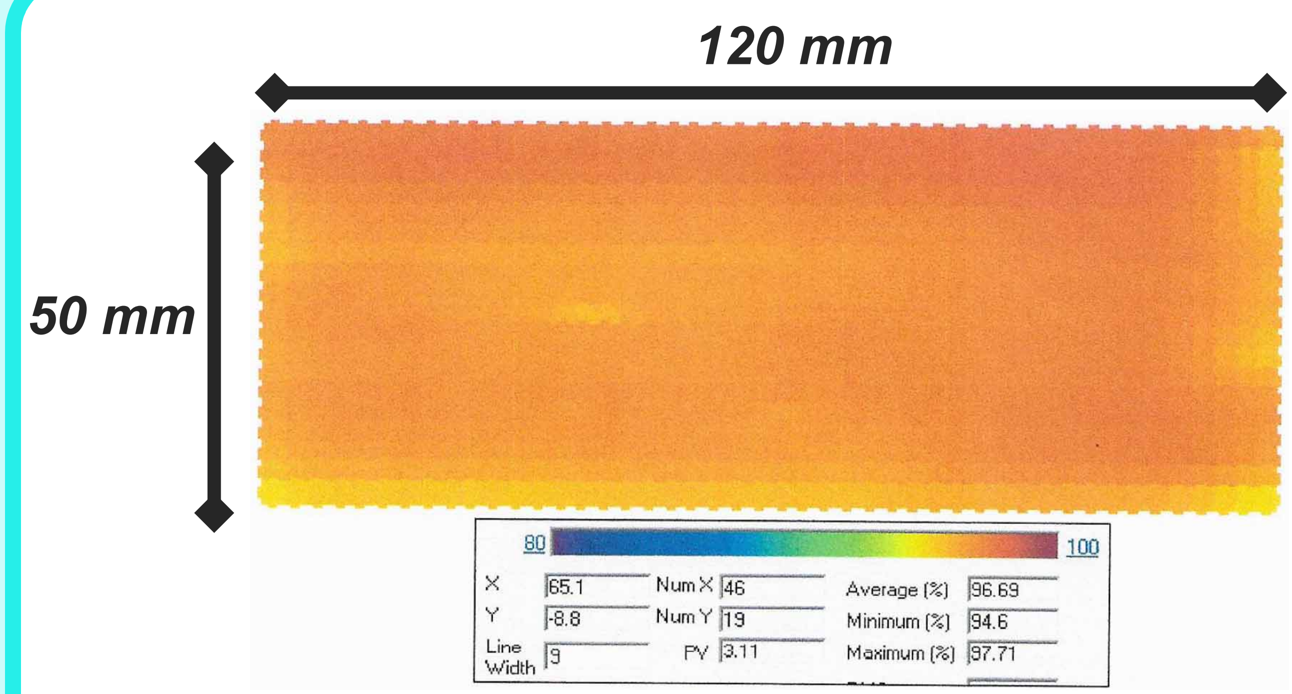


- decreases peak power during amplification
- avoids laser damage
- reduces non linear effects
- higher intensity after compression

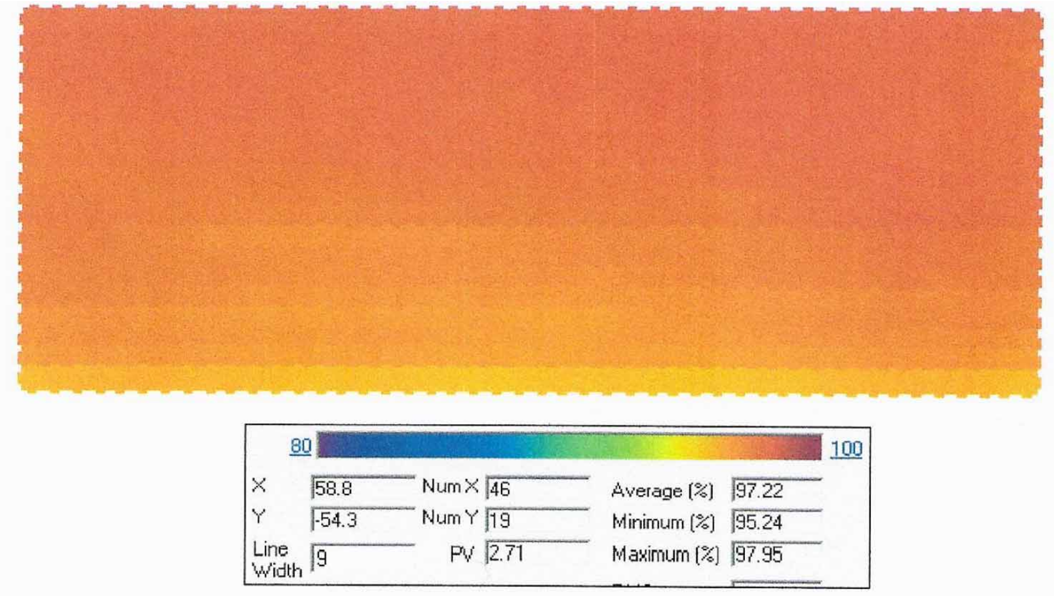
Strategy for Source Optimization

Temporal stretching by CPA (Chirped Pulse Amplification)

(credit : Plymouth Grating Laboratory)



Grating 1
Average efficiency :
96,69%

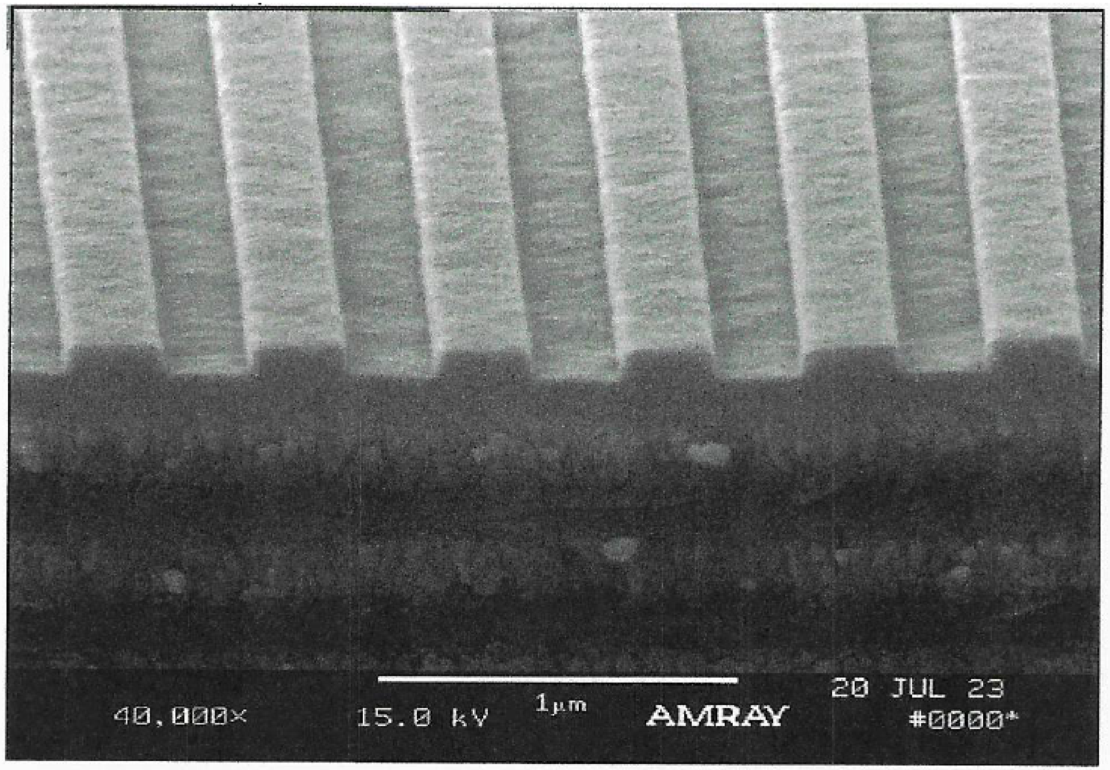


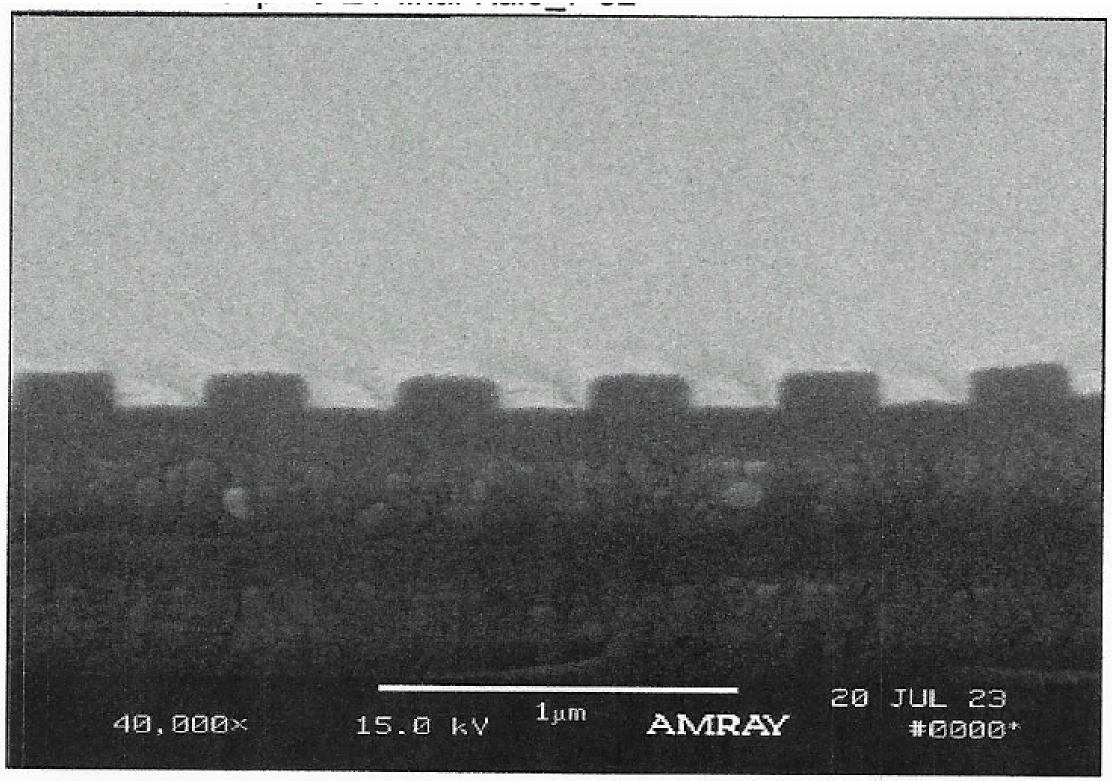
Grating 2
Average efficiency :
97,22%

Strategy for Source Optimization

Temporal stretching by CPA (Chirped Pulse Amplification)

SEM imaging *(credit : Plymouth Grating Laboratory)*





Strategy for Source Optimization

Optimization for single shot and recurrent mode

	2016	Upgrade	
Electron beam			
Kinetic Energy (MeV)	30	↗	
Bunch Charge (pC)	400	↗	
Emittance (µm H-V)	21 - 45	↘	
rms spot size (µm H-V)	125 - 180	↘	
Bunch duration FWHM (ps)	25	↘	
Laser beam			
Wavelength (nm)	532	532 or 1064	
Pulse energy (mJ)	2 (0.25 without SMILE)	↗↗↗	
rms spot size (µm H-V)	79-101	↘	
Pulse duration FWHM (ps)	25	↘	
X-rays			
Energy (keV)	33	larger range	
Half angle of radiation (mrad)	10 (13)	↘	
Nb of photons per bunch	293 (908)	↗↗↗↗	
Peak photon flux (ph/s)	$2.3\ 10^{13}$ $(7.1\ 10^{13})$	↗↗↗↗↗↗	
Peak surface photon flux (ph/s/cm²) (detector located at 800mm)			
Average flux (ph/s)	$2.0\ 10^{4}$ $(6.2\ 10^{4})$	↗↗↗↗	

- Re-design the interaction area (SMILE 2)
- Using the laser at 1064nm instead of 532nm with a remote alignment method
- Temporal stretching by CPA (Chirped Pulse Amplification)
- Twiss parameters and charge that maximize X-ray yield
- Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression
- Upgrading the 1.3 GHz cavity and Klystron system

Expectations :

- Very high yield increase for single shot mode
- High yield increase recurrent mode

5. Conclusion

Conclusion - Prospect

Work under progress (related to this presentation) :

- CPA System parts received - alignment in progress right now.
  Tests scheduled sept-oct 2023 (lab)
- Finalization of the alignment system before : nov 2023 (lab).
- Relocation of the whole system on ELSA : nov 2023.

  - **Compton source experiments on ELSA : dec 2023 – Feb 2024**

Other works in progress :

- Simulation, Twiss paramater optimization (see IPAC23 Proceedings https://doi.org/10.18429/JACoW-IPAC2023-TUPL172)
- Field linearizer for bunch compression improvement : new cavity installed 07/23. Still in test.

Long term prospect :

- Automatization of SMILE alignment
- Studies under way for an upgrade, including new 1.3 GHz cavity/klystron/modulator.

THANK YOU

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