The Inverse Compton Scattering X-ray source of the ELSA accelerator at CEA-DAM

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Summary

1. Introduction

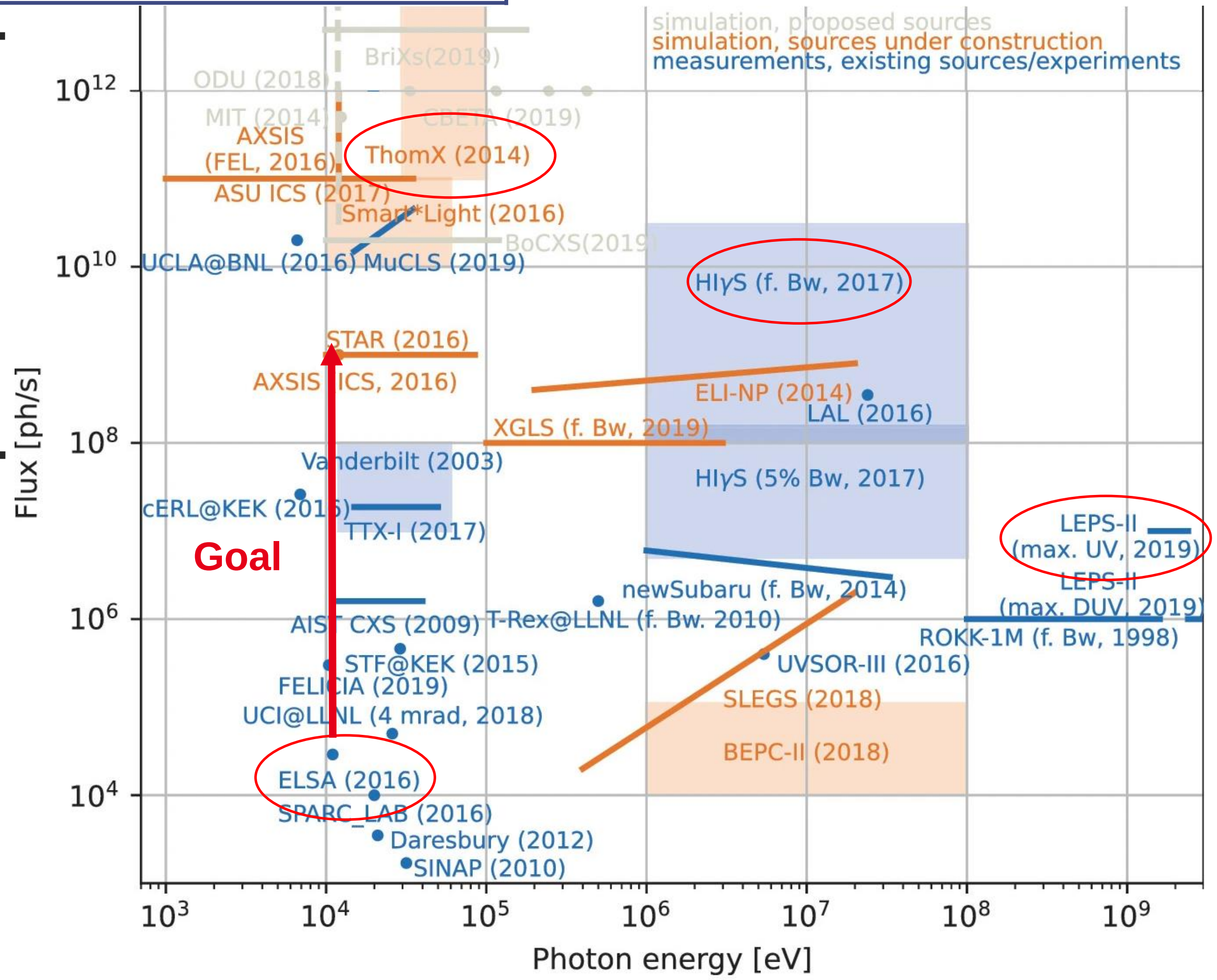
Introduction

FEL

Synchrotron

Very high energies accessible to Compton sources

Significant flux considering compactness



Around ~50 ICS design in the world,
Few operational setup,
Few currently in comissioning

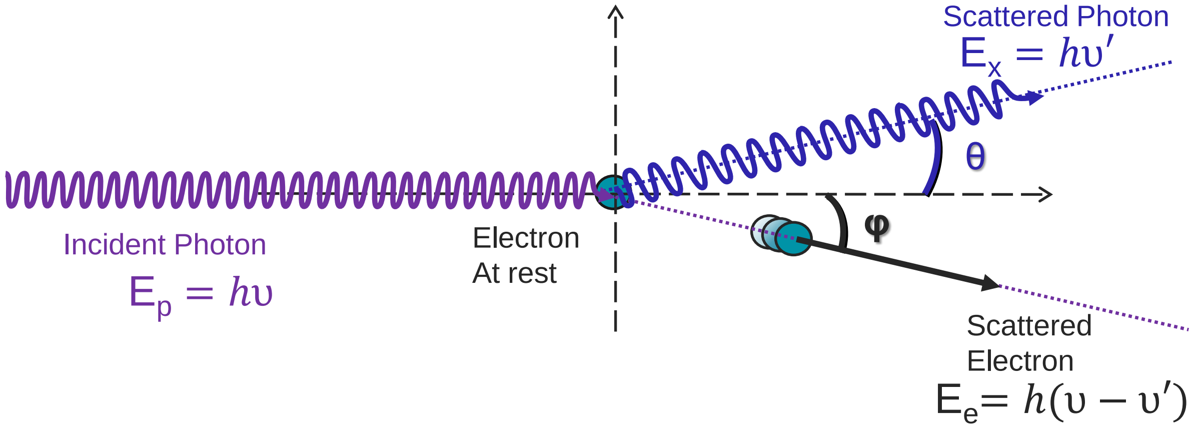
Storage Ring-Based Inverse Compton X-ray Sources
Cavity Design, Beamline Development and X-ray Applications
Author: Benedikt Sebastian Günther

Introduction

Compton Scattering and Inverse Compton Scattering

Compton Scattering

- **Transfer of energy from the photon to the electron**

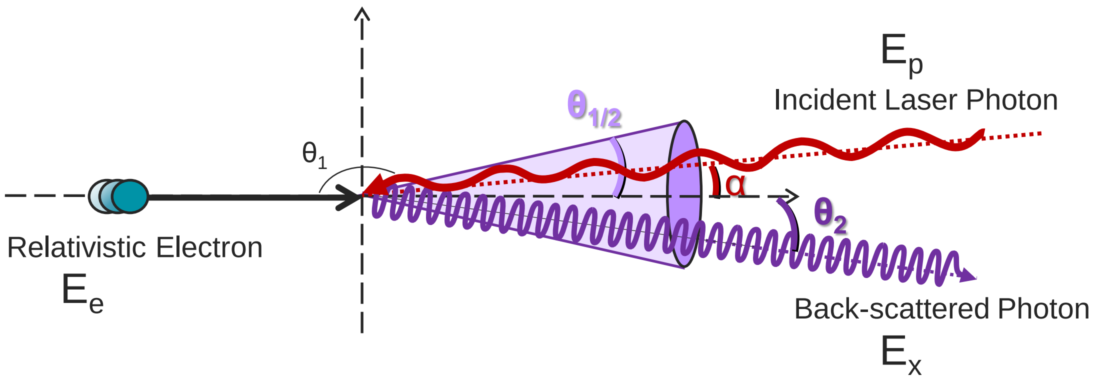


$$E_X = \frac{E_p}{1 + \frac{E_p}{m_e c^2}(1 - \cos\theta)}$$

Inverse Compton Scattering

- **Transfer of energy from the electron to the photon**

$$E_p \ll \gamma m_e c^2$$



$$E_X = \frac{2\gamma^2(1+\cos\alpha)}{1+\gamma^2\theta_2^2}$$

$$\alpha \ll 1: \quad E_X = \frac{4\gamma^2 E_p}{1+\gamma^2\theta_2^2+\frac{\alpha^2}{4}}$$

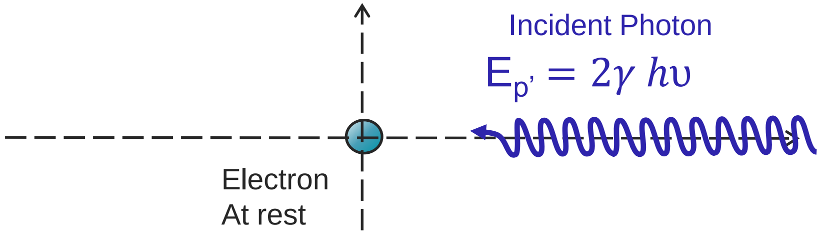
$$E_X(\theta_2 = 0) = 4\gamma^2 E_p$$

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

Introduction

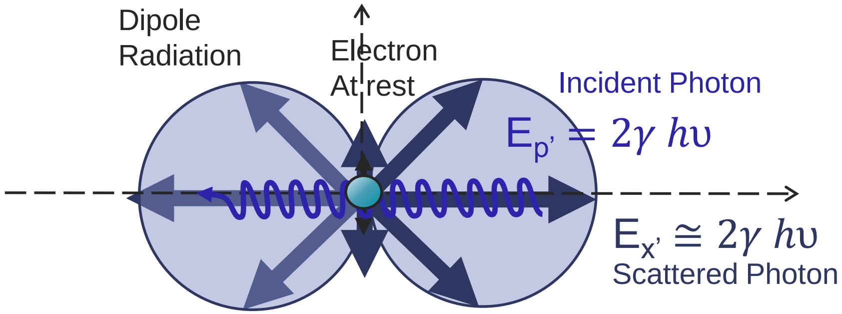
Inverse Compton Scattering

IN THE REFERENCE FRAME OF THE ELECTRON | **IN THE LABORATORY REFERENCE FRAME**



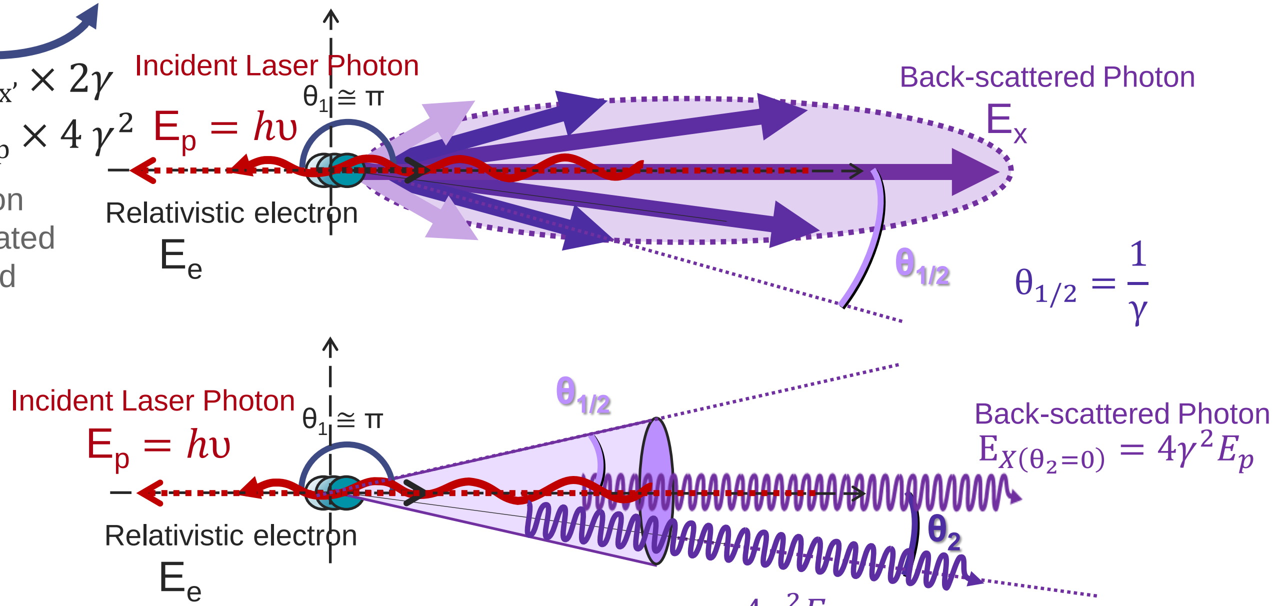
$E_{p'} = E_p \times 2\gamma$

IN THE REFERENCE FRAME OF THE ELECTRON | **IN THE LABORATORY REFERENCE FRAME**



$$E_{X(\theta_2=0)} = E_{x'} \times 2\gamma = E_p \times 4\,\gamma^2$$

+ Emission concentrated forward



$$E_{X(\theta_2\neq0)} = \frac{4\gamma^2 E_p}{1+\gamma^2\theta_2^2}$$

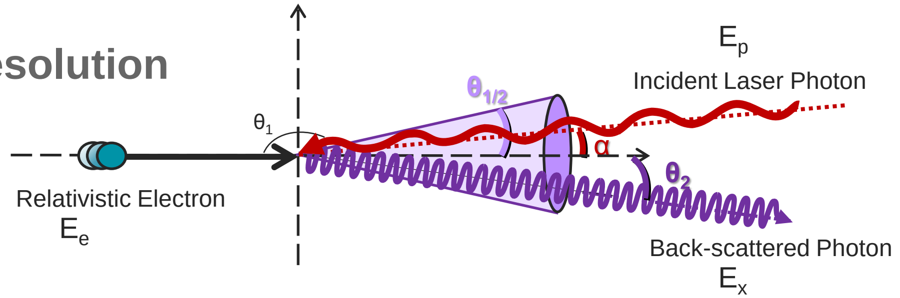
The change of reference frame induces a relativistic Doppler effect that depends on the angle.
The radiation is concentrated in a cone emitted forward in the laboratory reference frame.

Introduction

Inverse Compton X-ray Source

Inverse Compton X-ray Source : (laser + electron bunch → X-ray)

- **Monochromatic and directional radiation sources with high temporal resolution**
- **Compton scattering cross section is very small**
  → need lot of efforts to increase yield



ELSA ICS source :

- **Compact X-ray source for diagnostic characterization (for Laser Mega Joule)**
- **versatile : single shot (primary use) – recurrent**
  - 532 or 1064 nm laser ($E_p = 2{,}3$ or $1{,}1\ eV$) + relativistic electrons ($E_e = 17 - 30\ MeV$)

→ X-ray photons $E_X = 5 - 33\ keV$

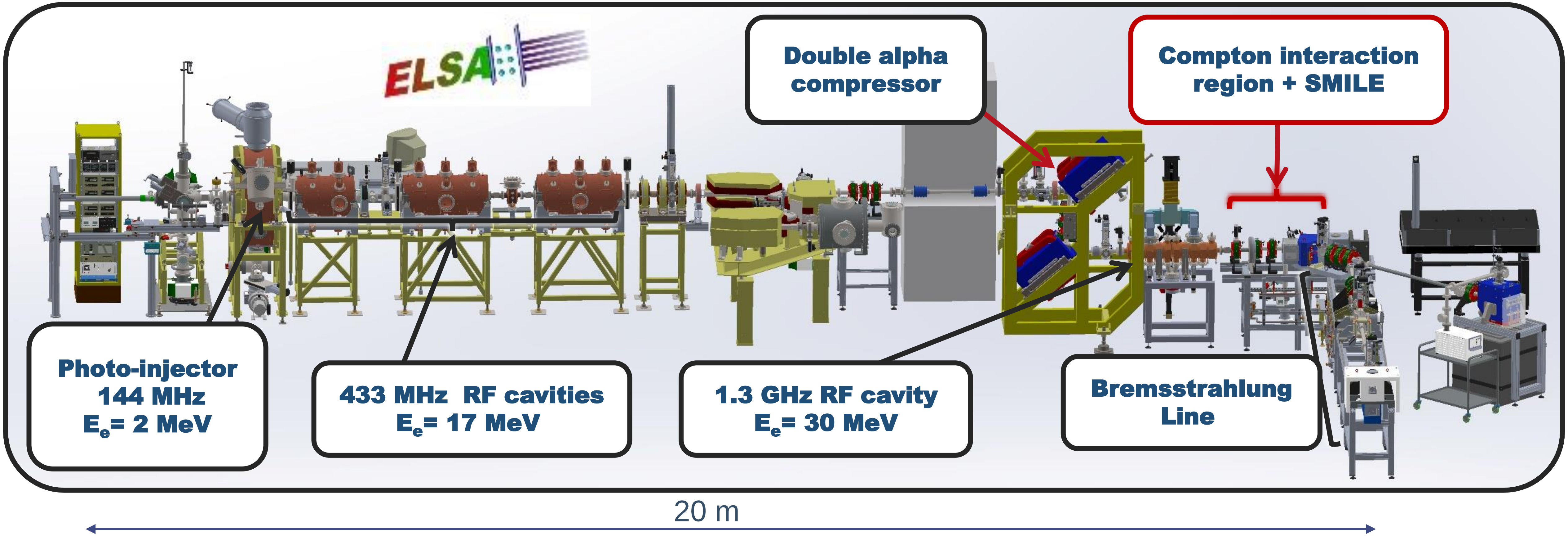
$$E_X = \frac{4\gamma^2 E_p}{1 + \gamma^2\theta_2^2 + \frac{\alpha^2}{4}}$$

$$E_X(\theta_2 = 0) = 4\gamma^2 E_p$$

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

Introduction

ELSA Accelerator (CEA DAM, France)



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

Introduction

Important parameters

For the electron beam, need at the same time :

- High bunch charge (0,1-2 nC)
- Short bunch (0,1-30 ps)
- Good emittance (0,1 – 5 µm.rad)
- High energy (> 10s MeV - GeV)

+ Small energy dispersion, Compactness, High repetition rate, Versatility (energy range, rep. rate..)…

Hard to optimize all of this on an existing machine
More room for optimization on new design (compact storage ring, ERL, X-band linac..,)

Introduction

Comparisons of different kind of ICS sources

- **Compact sources for imaging or diagnostic characterization (~keV X-rays)**

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

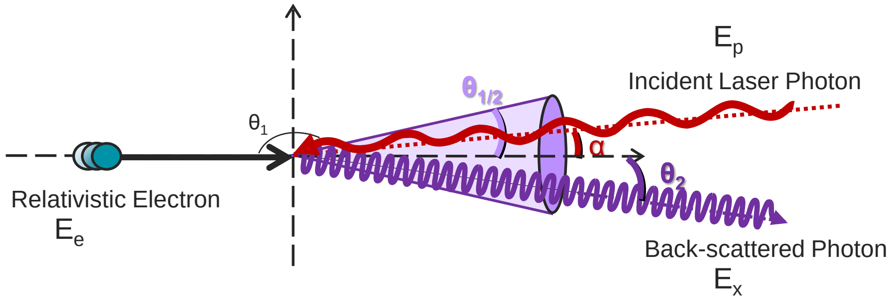
  ➢ 532 or 1064 nm laser ($E_p = 2{,}3$ or $1{,}1\ eV$) + relativistic electrons ($E_e = 17 - 30\ MeV$)

  → X-ray photons $E_X = 5 - 33\ keV$

  eg., THOMX (compact storage ring : recurrent)

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

  → X-ray photons $E_X = 45\ keV$



- **Higher energy X-ray for nuclear physics (~MeV X-rays/γ)**

  eg., HIγS (FEL storage ring)

  ➢ 175 nm FEL ($E_p = 7{,}1\ eV$) + relativistic electrons ($E_e = 1{,}11\ \mathrm{GeV}$)

  → X-ray photons $E_X = 130\ \mathrm{MeV}$

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

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

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

- **Very high-energy X-ray sources for high-energy physics (~GeV X-rays/γ)**

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

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

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

⚠ For high energy electrons, $\mathrm{E}_X < \frac{4\gamma^2 E_p}{1+\gamma^2\theta_2^2+\frac{\alpha^2}{4}}$ due to recoil

Introduction

Comparisons of different kind of ICS sources

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

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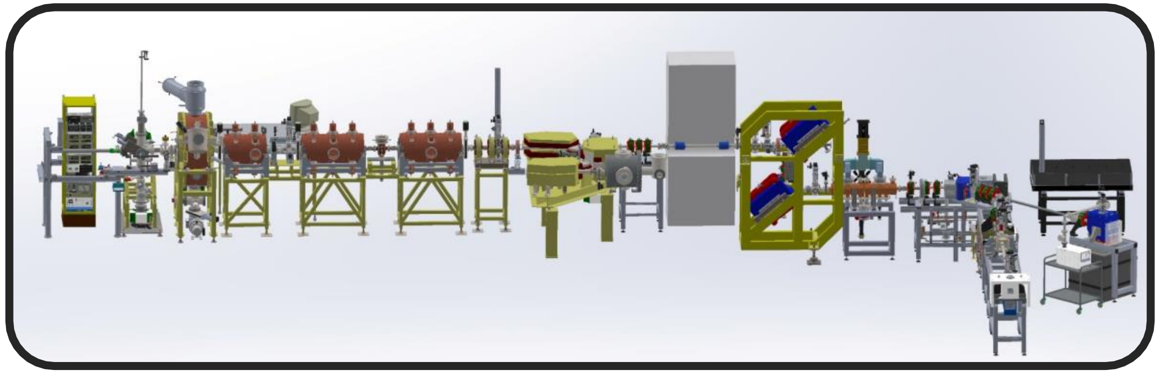

eg., THOMX (compact storage ring : recurrent)

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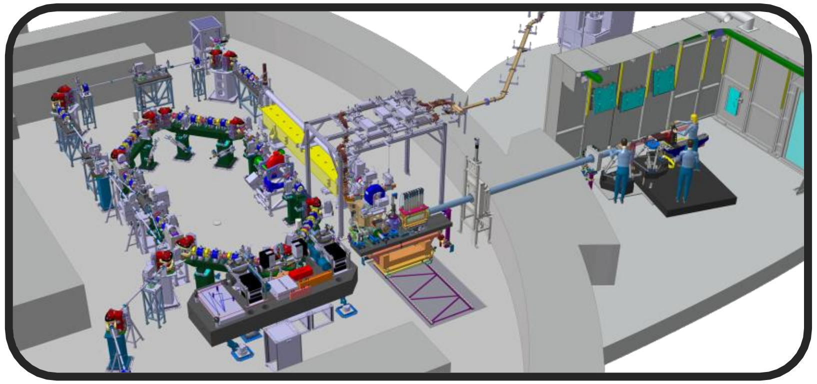

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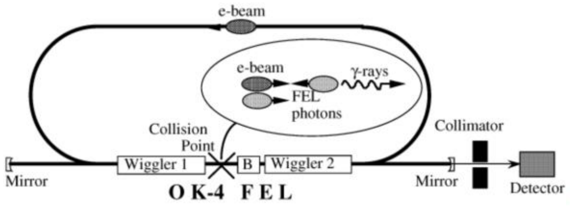
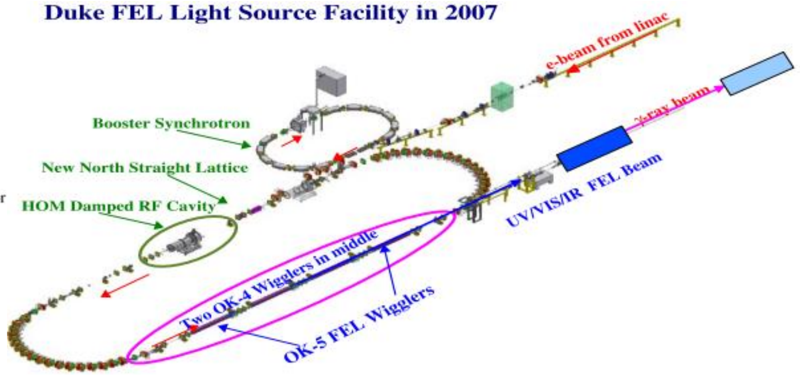
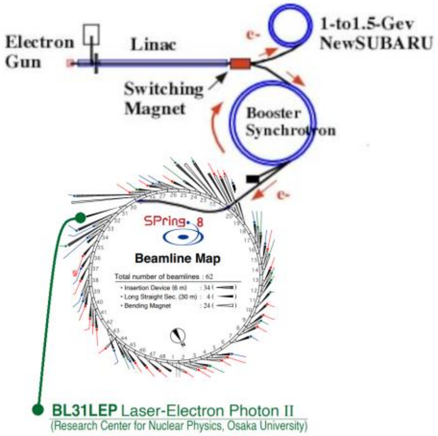
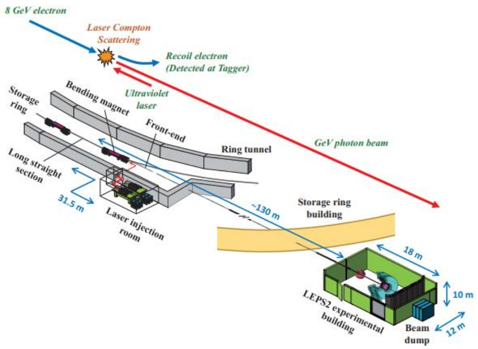




eg., Laser Electron Photon beamline at SPring-8 (LEPS, synchrotron)

- 351 nm laser ($E_n = 3{,}5\ eV$) + relativistic electrons ($E_e = 8\ GeV$)
  → X-ray photons $E_X = 2{,}9\ GeV$



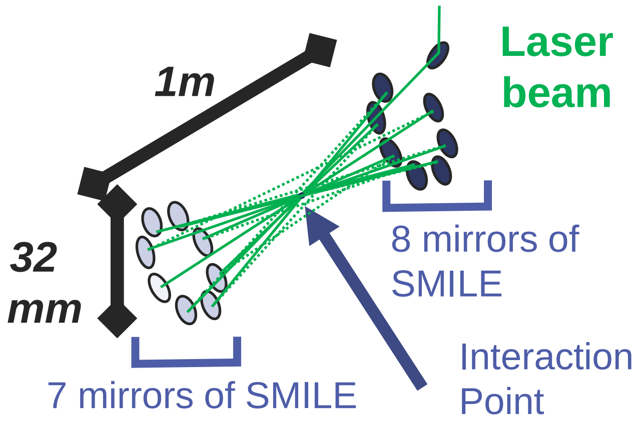


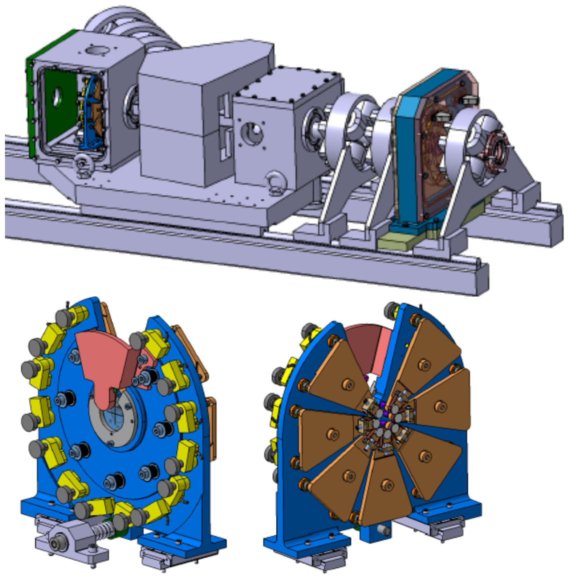
Introduction

Comparisons of different laser interaction system

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

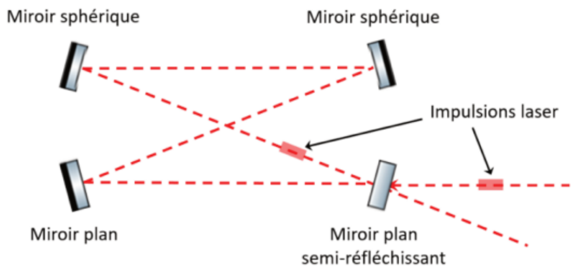
- SMILE recirculator

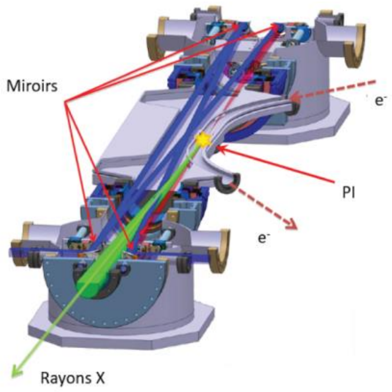




eg., THOMX (compact storage ring : recurrent)

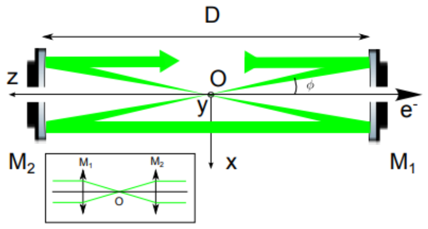
- Fabry-Perot Cavity

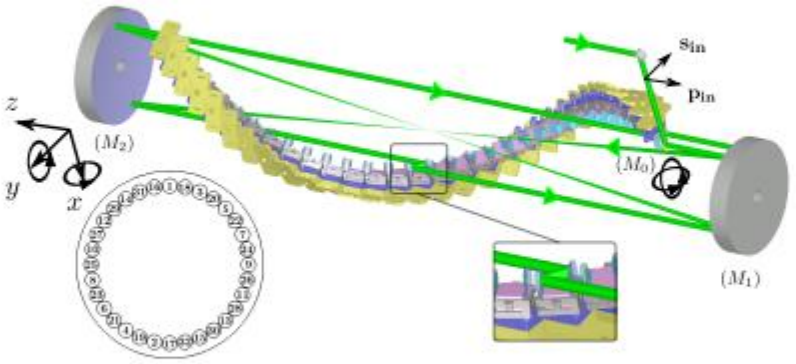




eg., ELI-NP

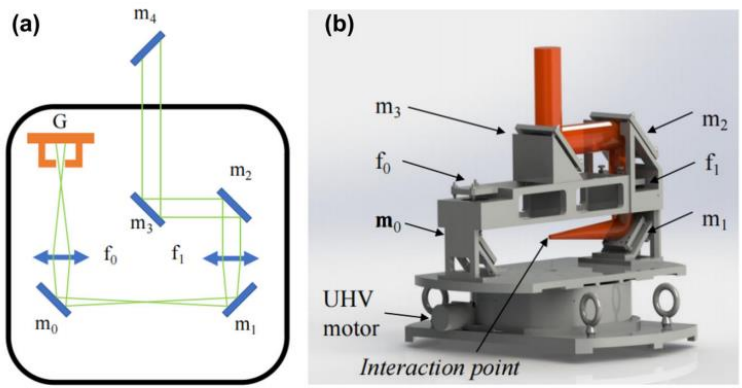
- Dragon-Shape recirculator





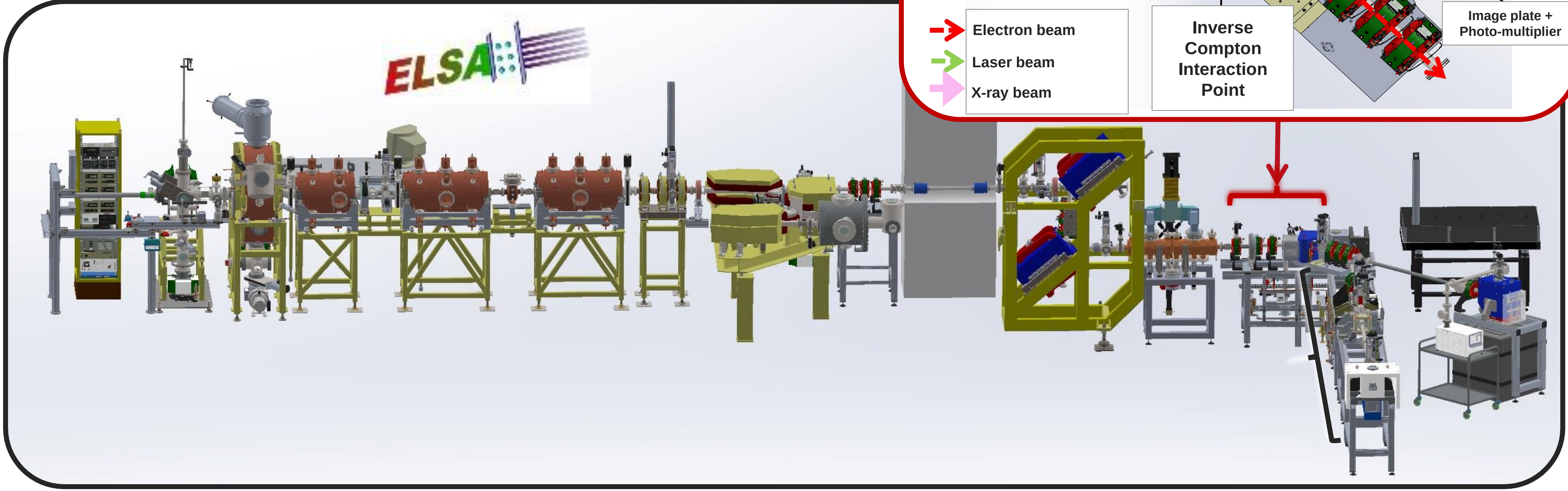
eg., SLEGS

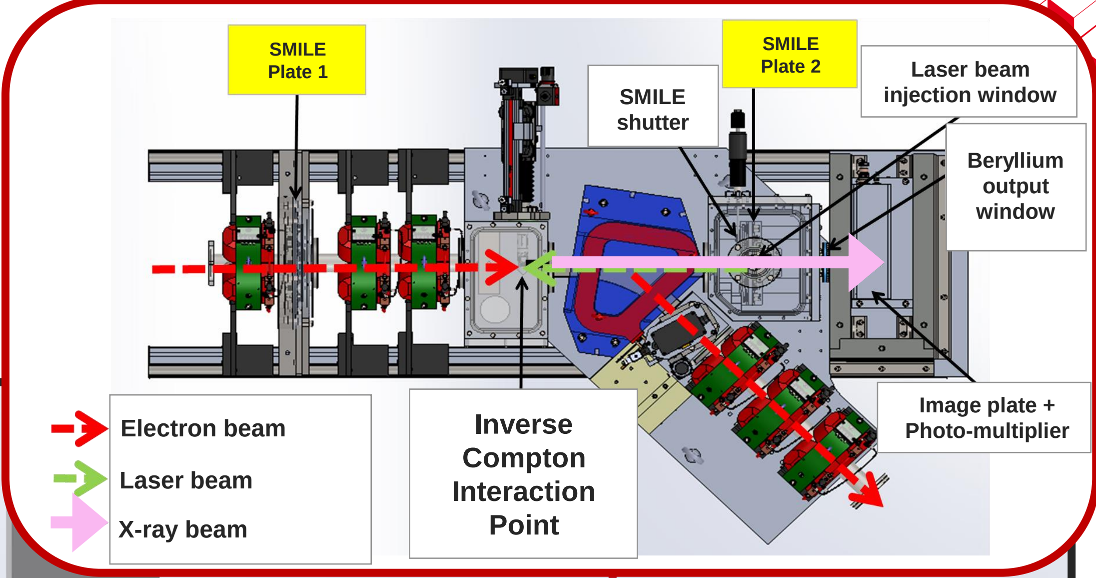
- Rotating laser optical system



2. The Inverse Compton X-ray Source at ELSA

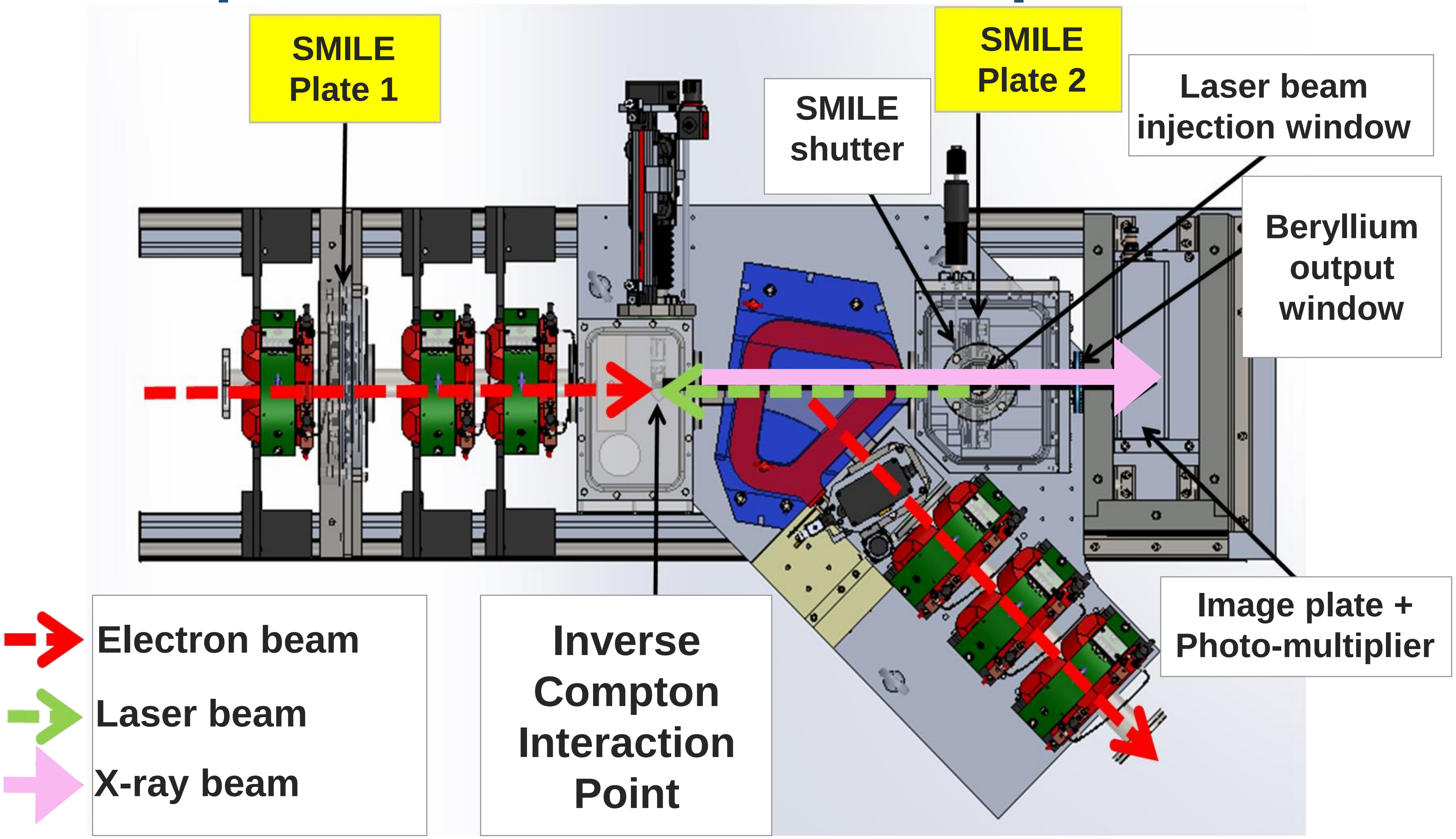
Compton interaction area





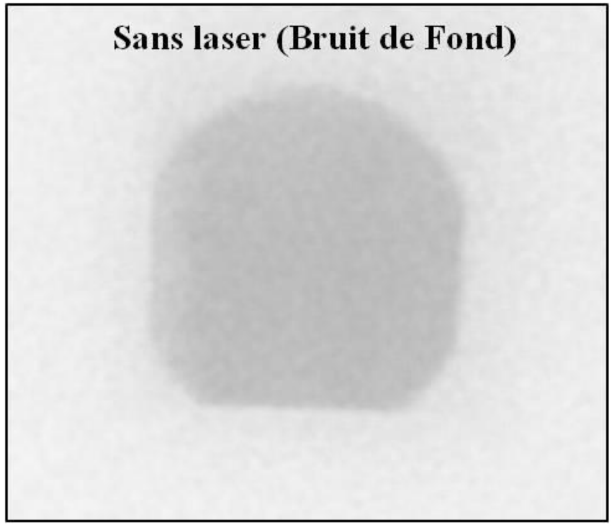
The Inverse Compton X-ray Source at ELSA

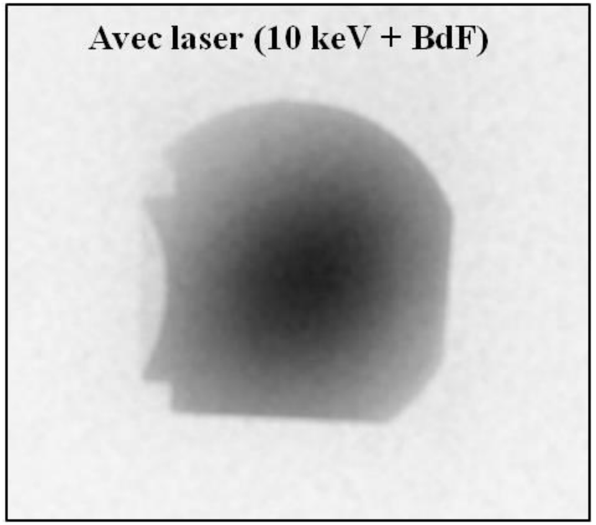
Top view of the interaction point



The Inverse Compton X-ray Source at ELSA

First Experimental results in 2010 (without SMILE)

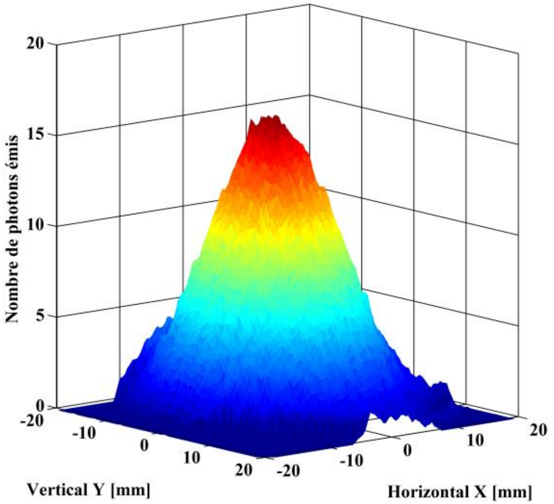




2011 experiments	17 MeV
Electron beam	
Kinetic Energy (MeV)	17
Bunch Charge (pC)	200
Emittance (µm H-V)	
rms spot size (µm H-V)	100 - 80
Bunch duration (ps)	30
Laser beam	
Wavelength (nm)	532
Pulse energy (mJ)	0,2
rms spot size (µm H-V)	40 - 65
Pulse duration (ps)	30
X-rays	
Energy (keV)	11
Half angle 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

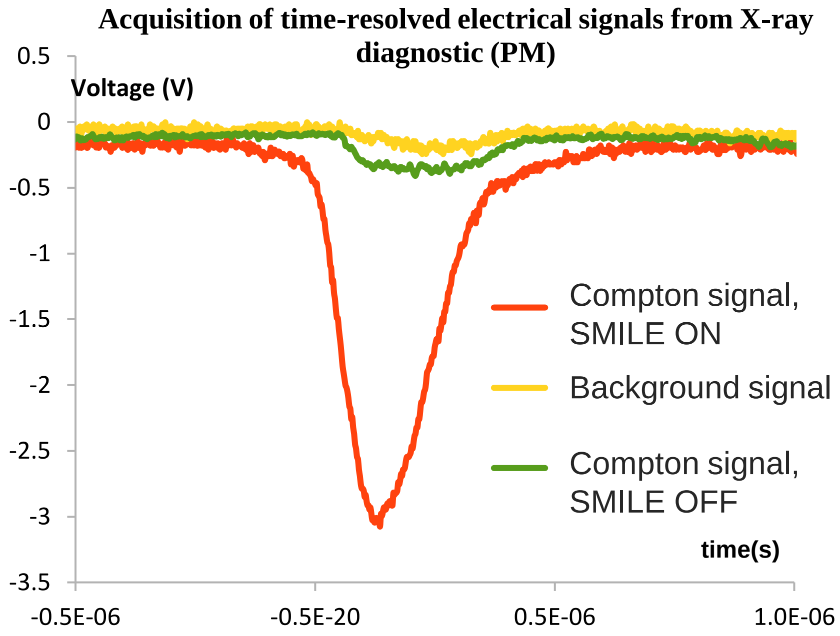
Étude de la production de ayonnement X par diffusion Compton sur l'installation ELSA
Author : Anne-Sophie Chauchat
https://theses.hal.science/tel-00652588



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/

The Inverse Compton X-ray Source at ELSA

Strategy for Source Optimization

	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

3. Re-design the interaction area (SMILE 2)

Strategy for Source Optimization

Summary

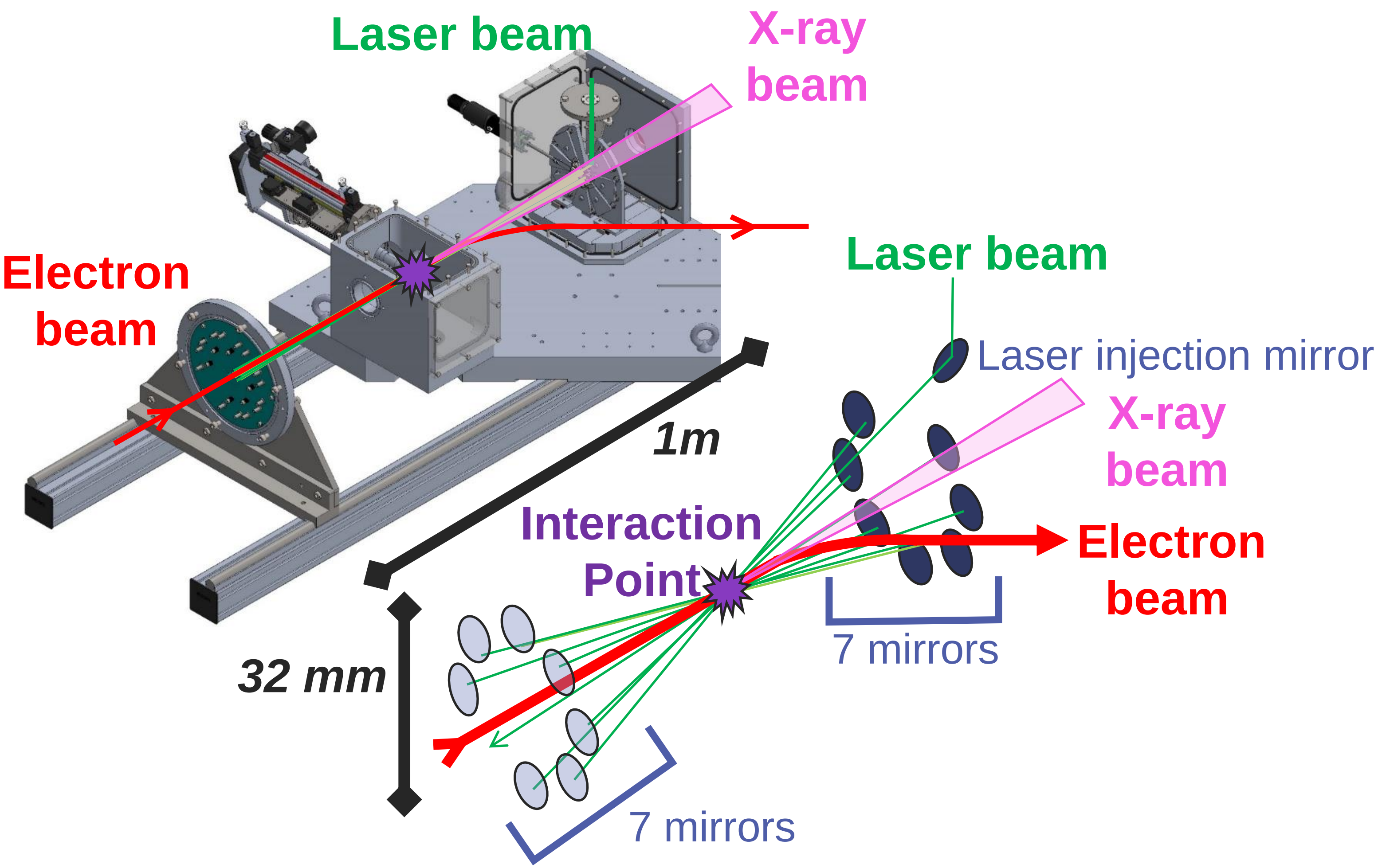
	Pitfalls :	Solutions :
Interaction area	- Beams alignment - Mechanical stability	Re-design the interaction area (SMILE 2)
Laser	- Efficiency of frequency doubling	Using the laser at 1064nm instead of 532nm with a remote alignment method
	- Laser Induced Damage Threshold (LIDT) - Non-linear effects	Temporal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

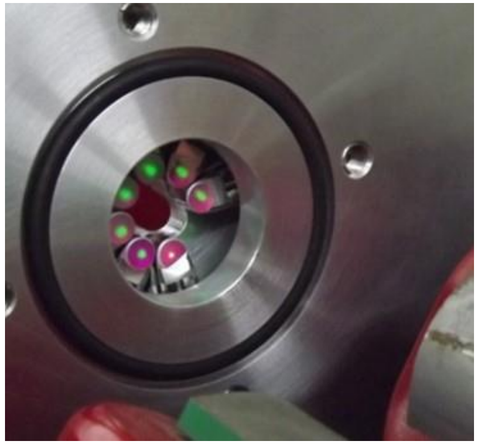
Re-design the interaction area (SMILE 2)

3D view of the interaction point and SMILE device

SMILE :

Système
Multi-passage
Interaction
Laser
Electron

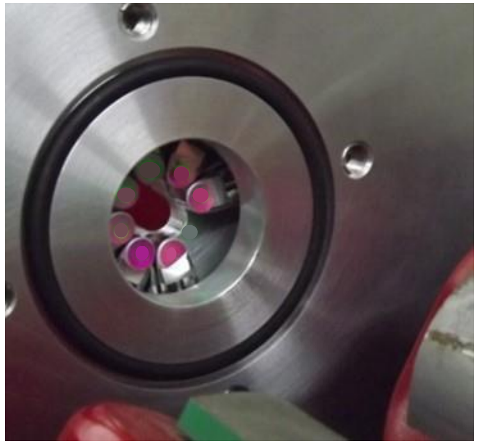




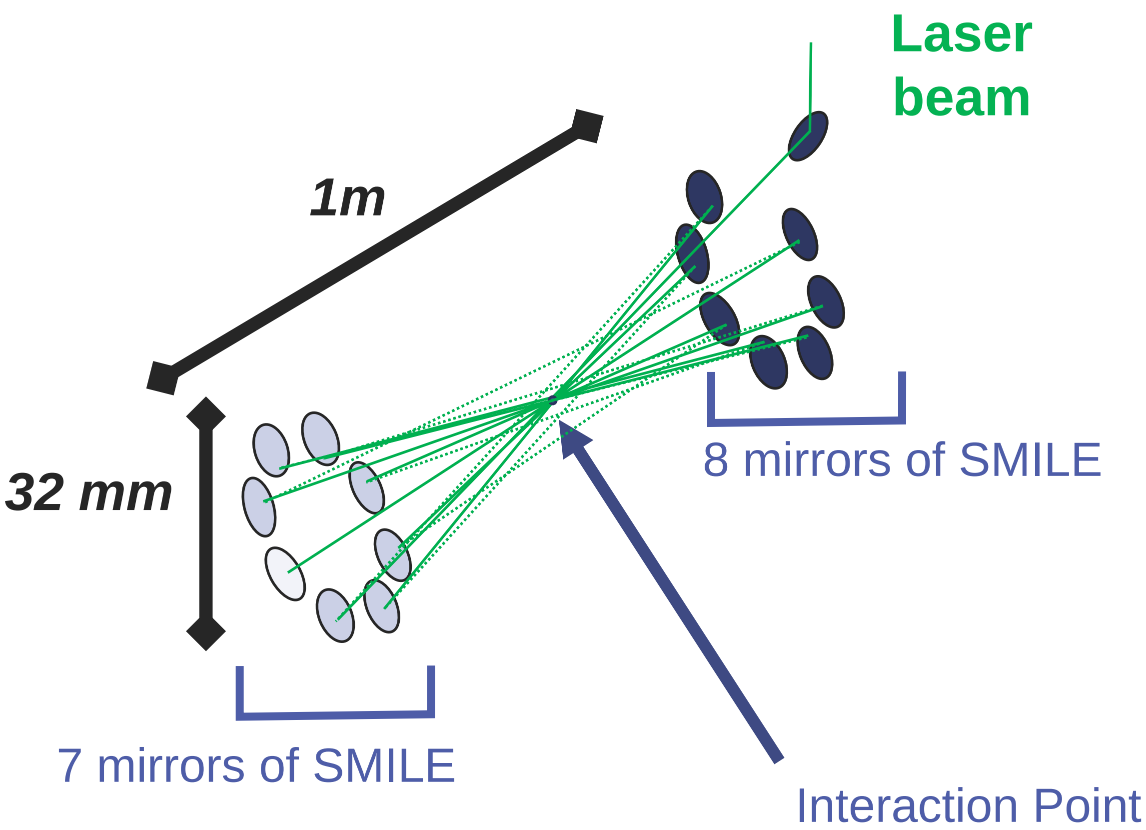
View of the laser impacting the mirrors surfaces

Re-design the interaction area (SMILE 2)

Schematic of SMILE



View of the laser impacting the mirrors surfaces

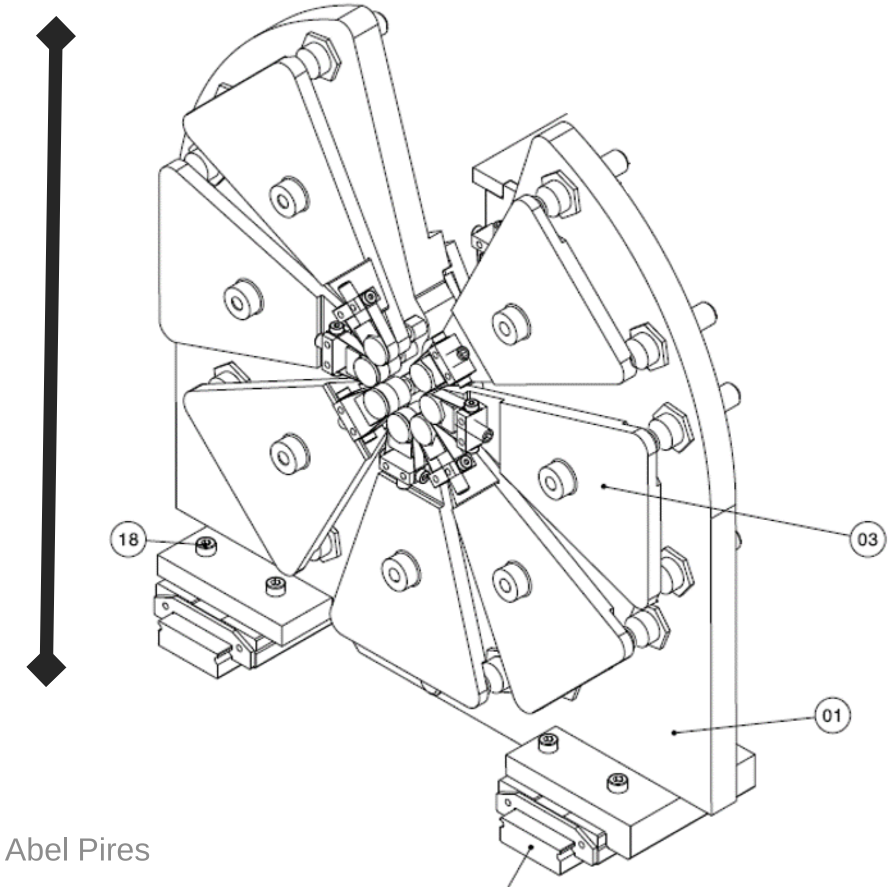


<u>Counterintuitive</u> to use a multipass system for a single shot interaction, but efficient (primary use of ELSA Compton source)

Re-design the interaction area (SMILE 2)

Optomechanical design for high angular precision

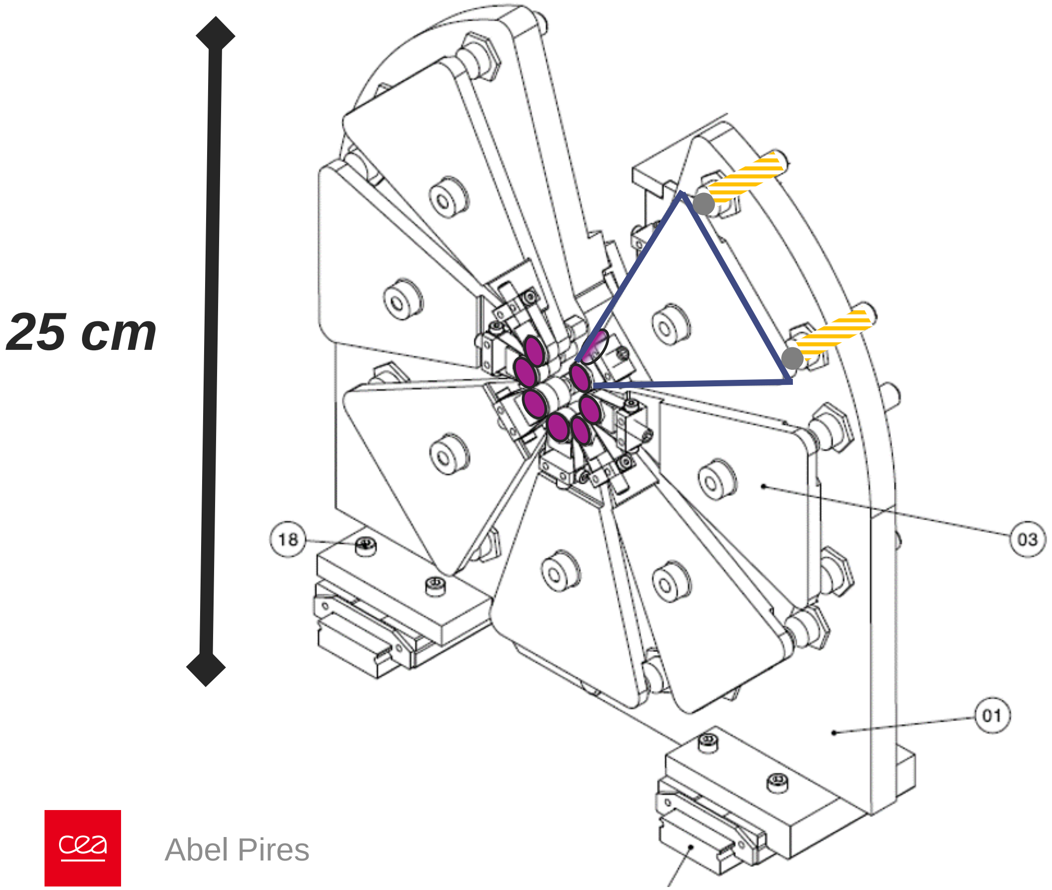
25 cm

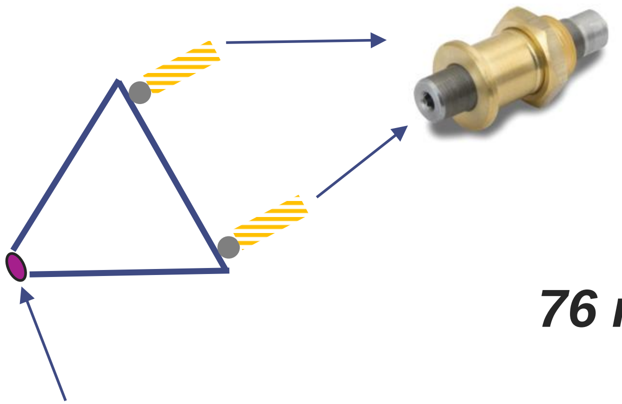


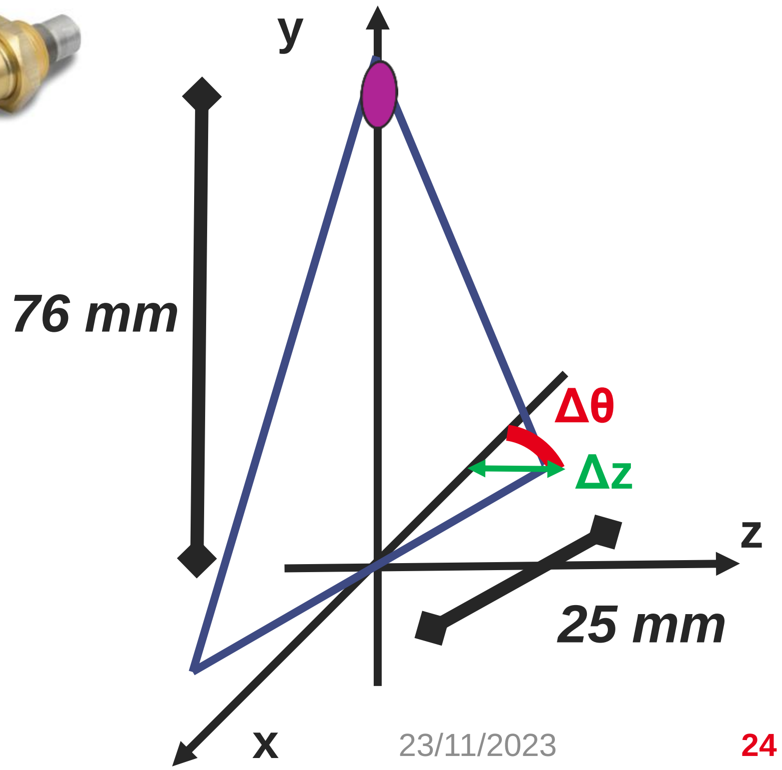
Re-design the interaction area (SMILE 2)

Optomechanical design for high angular precision

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

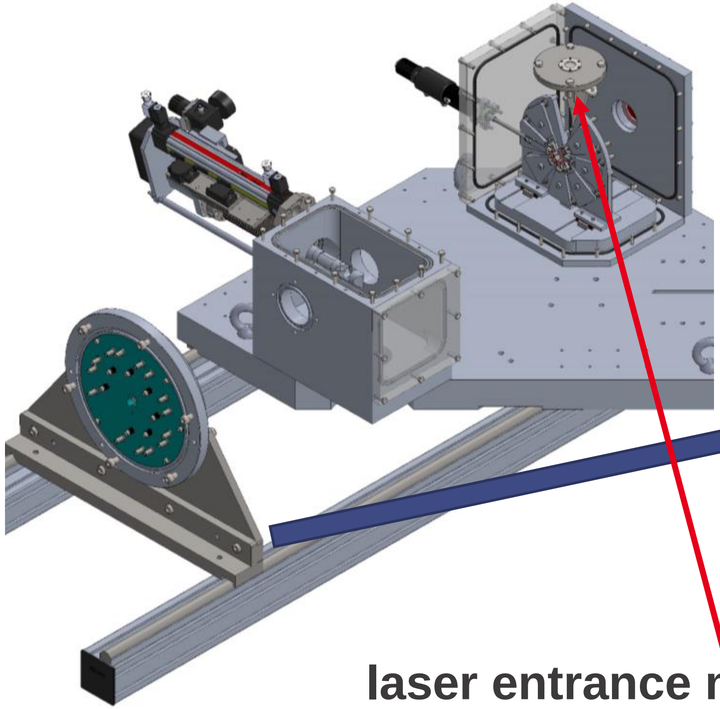






Re-design of the interaction area (SMILE 2)

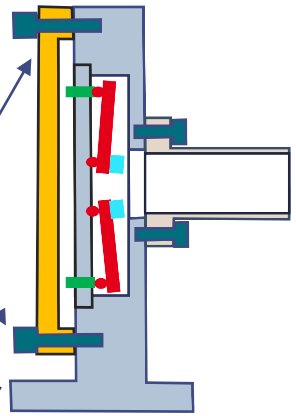
Release constraints due to tightening and pumping



Old Design :

Mechanical constraints

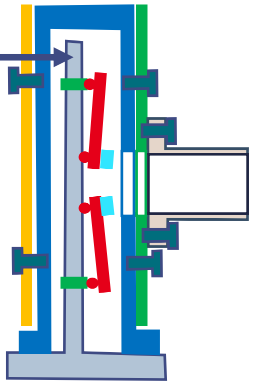
➔ Deformation

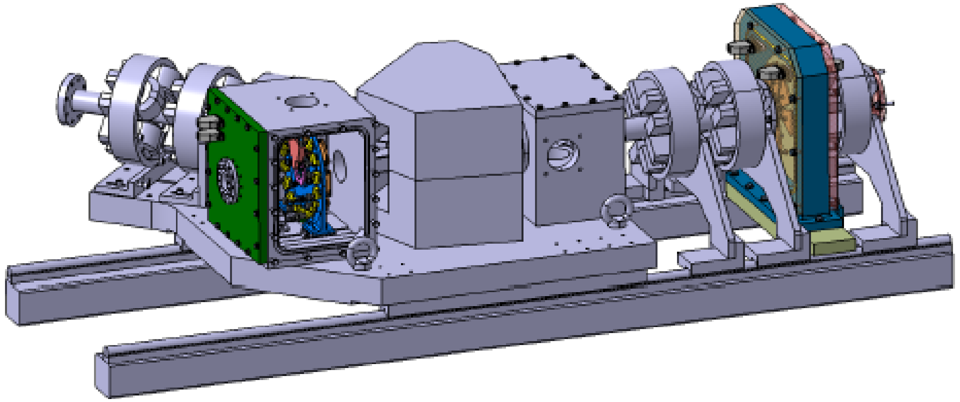


New Design idea :

No constraint on the plate even when pumping or screw tightening

➔ No Deformation when pumping and closing the SMILE





laser entrance mirror system
➔ mechanical link with the external structure

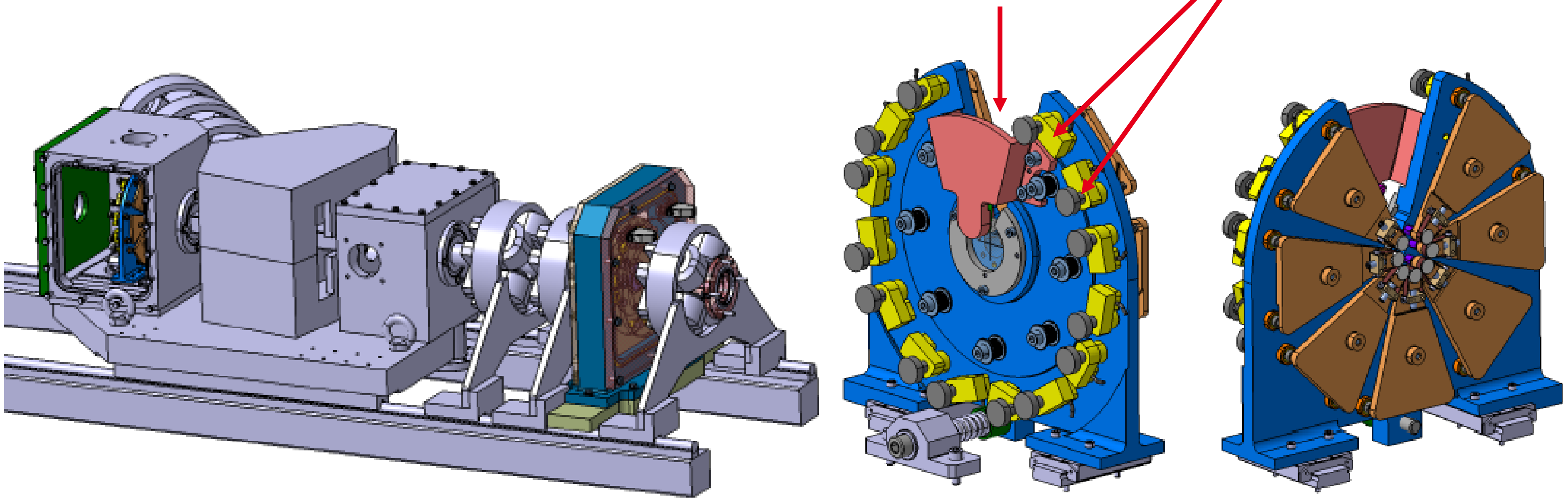
Re-design of the interaction area (SMILE 2)

Motorization and new laser entrance

SMILE 2 :

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

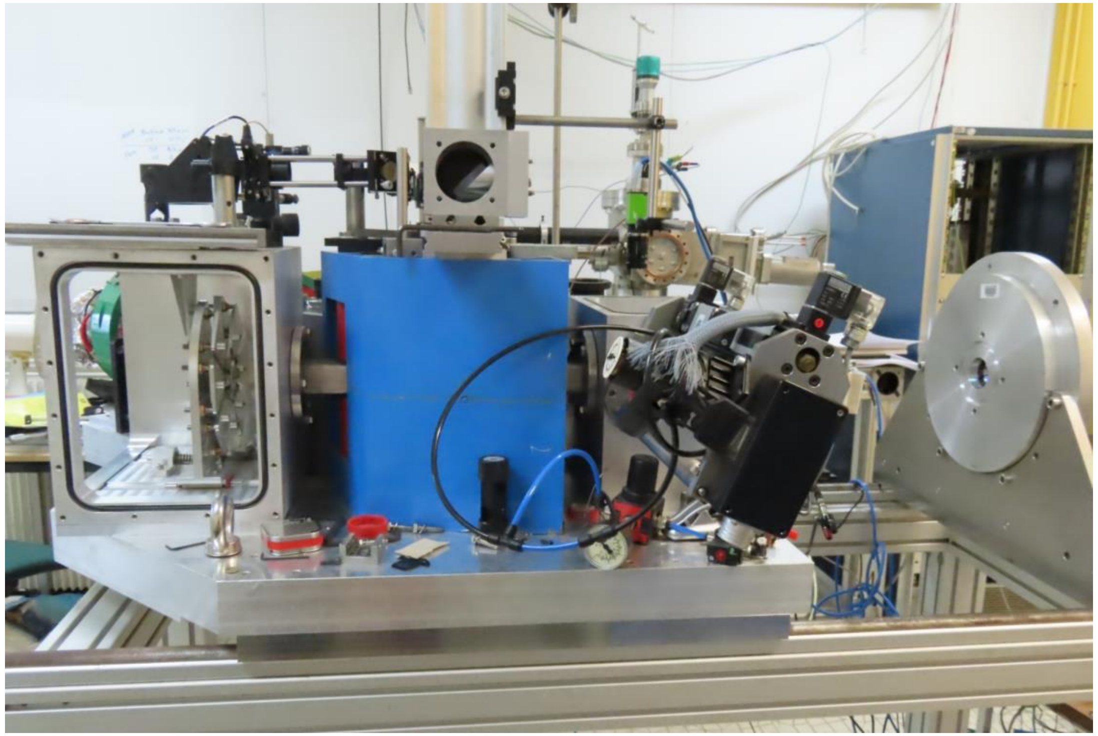
  ➔ No mechanical link with the external structure



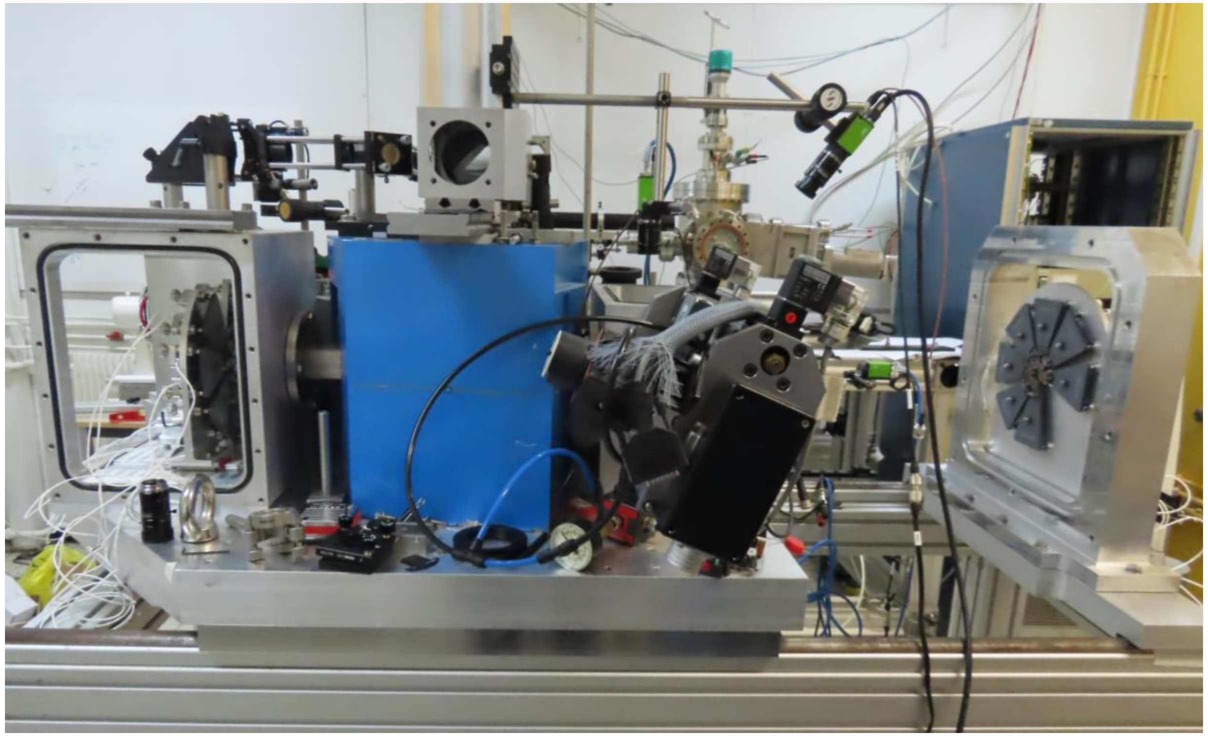
Re-design of the interaction area (SMILE 2)

Photos of the system evolution

SMILE



SMILE 2 : operational



Strategy for Source Optimization

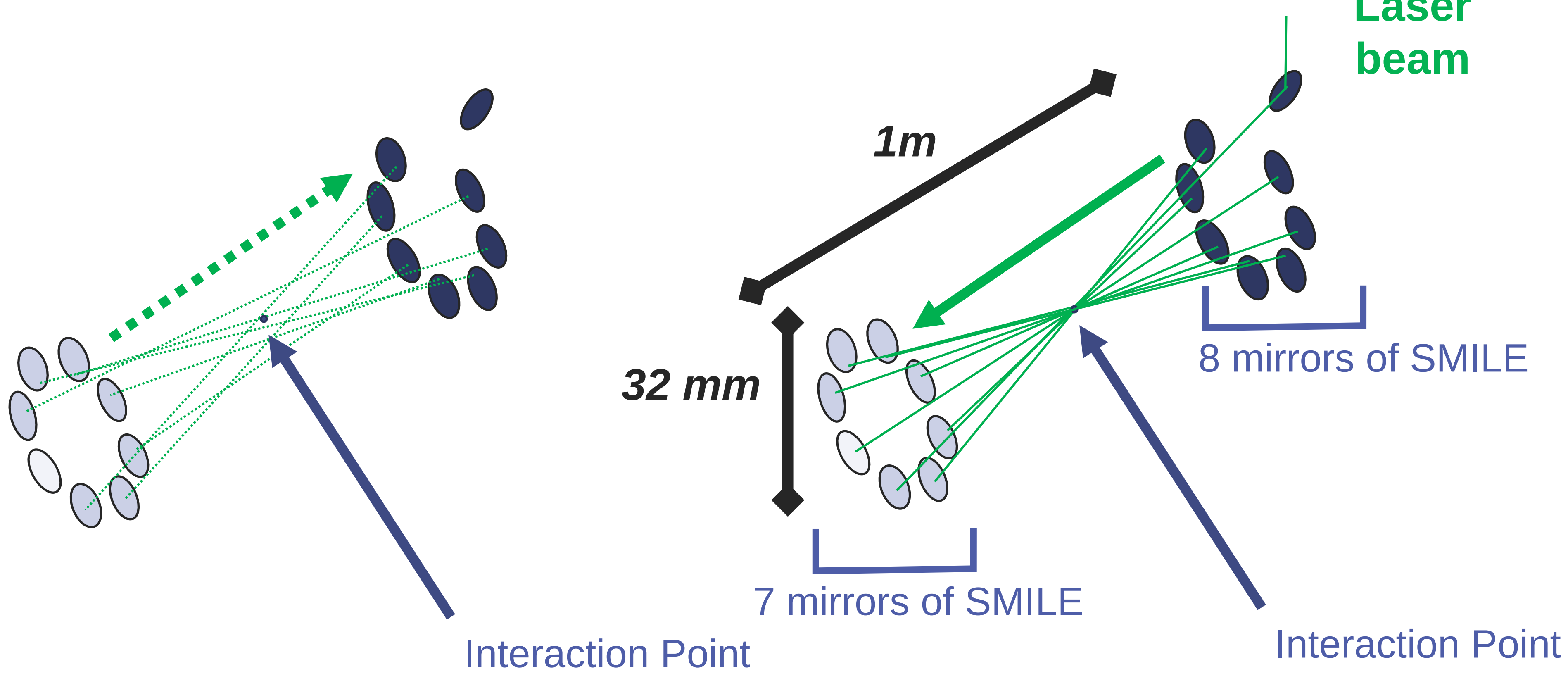
Summary

	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 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
	- Bunch duration	Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression
+	- Bunch energy - Train duration	Upgrading the 1.3 GHz cavity and Klystron system

4. Using the laser at 1064nm with a remote alignment method

Using the laser at 1064nm with a remote alignment method

Schematic of SMILE



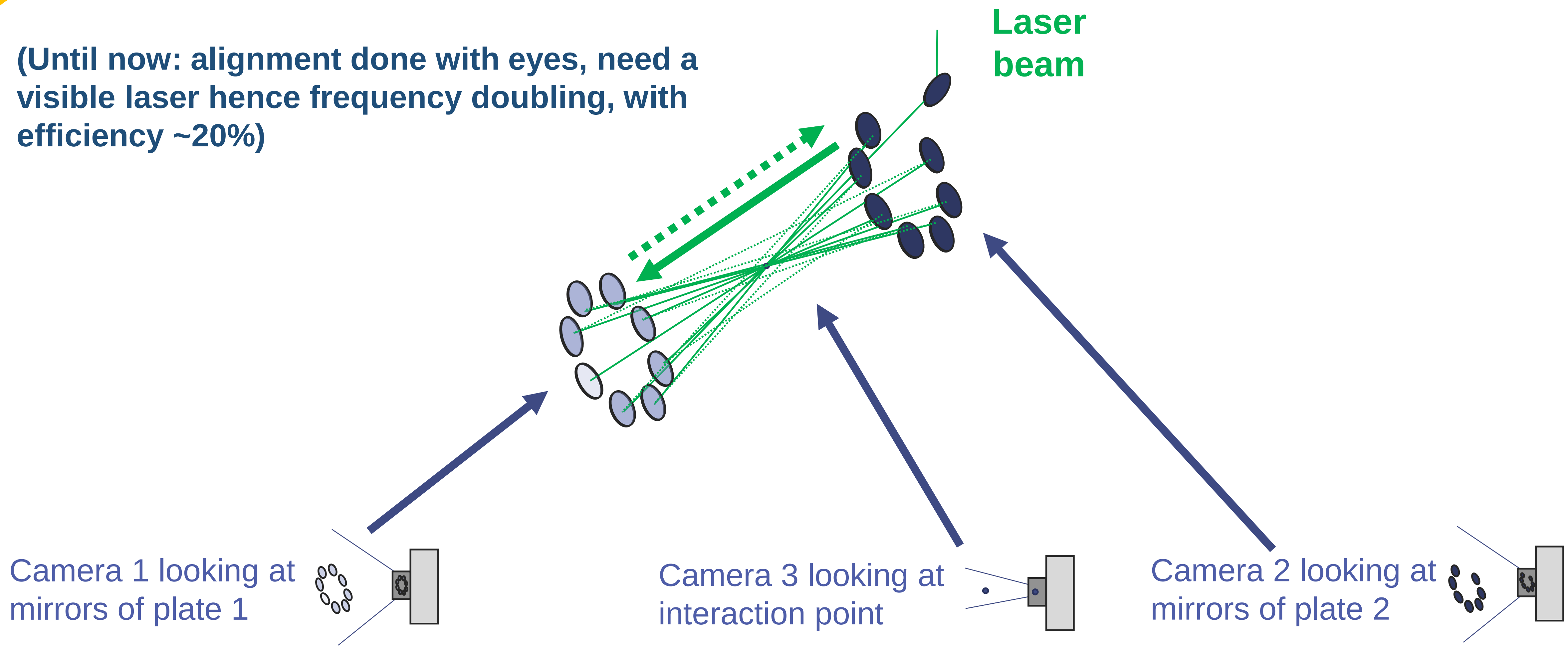
Backward path go ***around*** the interaction point

***Forward* path go *through* the interaction point**

Using the laser at 1064nm with a remote alignment method

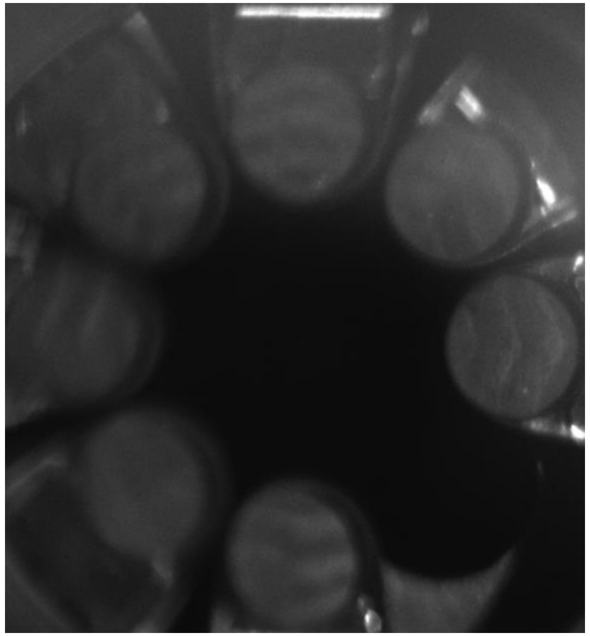
Imaging beam alignment with cameras

(Until now: alignment done with eyes, need a visible laser hence frequency doubling, with efficiency ~20%)

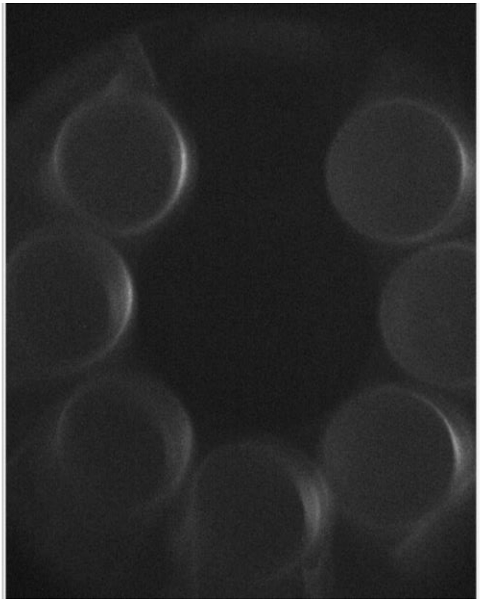


Using the laser at 1064nm with a remote alignment method

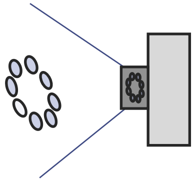
Image of the SMILE mirors



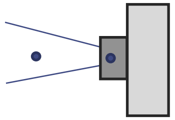
Without laser beam



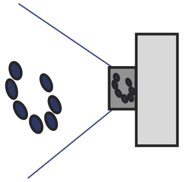
Camera 1 looking at mirrors of plate 1



Camera 3 looking at interaction point



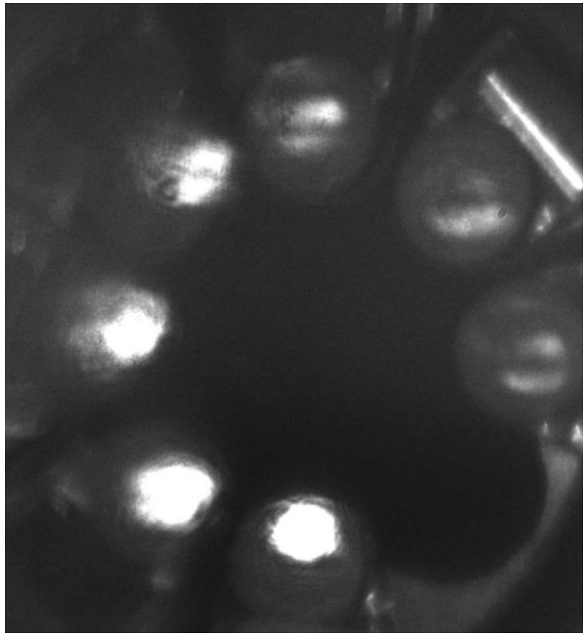
Camera 2 looking at mirrors of plate 2

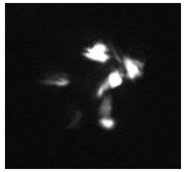


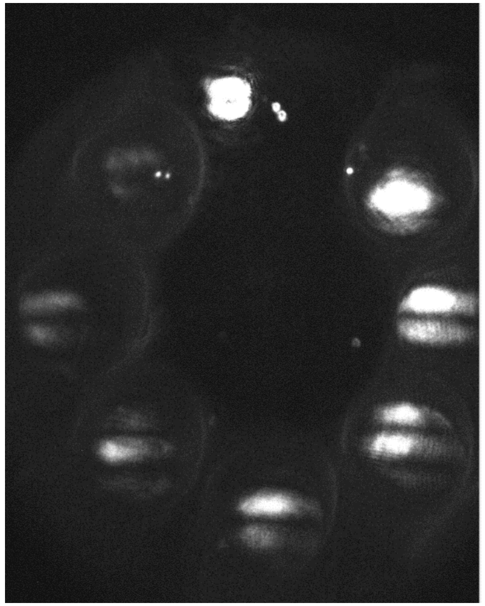
Using the laser at 1064nm with a remote alignment method

Laser positions on the mirors

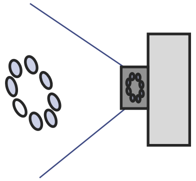
With laser beam



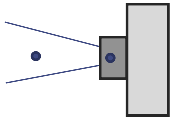




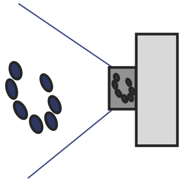
Camera 1 looking at mirrors of plate 1



Camera 3 looking at interaction point



Camera 2 looking at mirrors of plate 2



Using the laser at 1064nm with a remote alignment method

Remote method, possibility to automatize

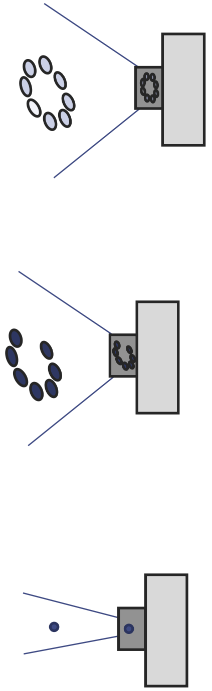
Camera 1 looking at mirrors of plate 1

+

Camera 2 looking at mirrors of plate 2

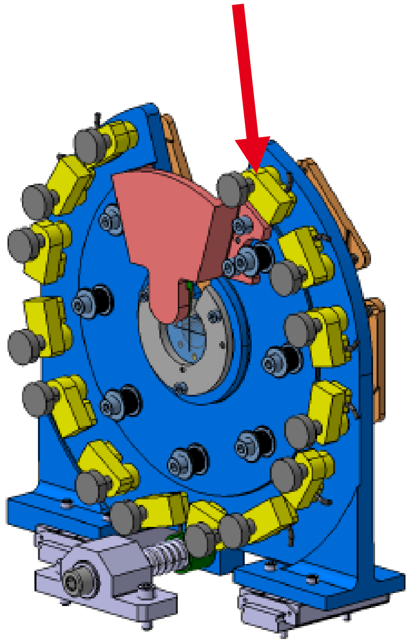
+

Camera 3 looking at interaction point



+

Piezo actuators



=

remote alignment method for 532nm and 1064nm

+

Possibility to automatize

Strategy for Source Optimization

Summary

Pitfalls : | Solutions :

	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 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
	- Bunch duration	Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression
	+ - Bunch energy - Train duration	Upgrading the 1.3 GHz cavity and Klystron system

5. Temporal stretching by CPA (Chirped Pulse Amplification)

Temporal stretching by CPA (Chirped Pulse Amplification)

CPA system overview

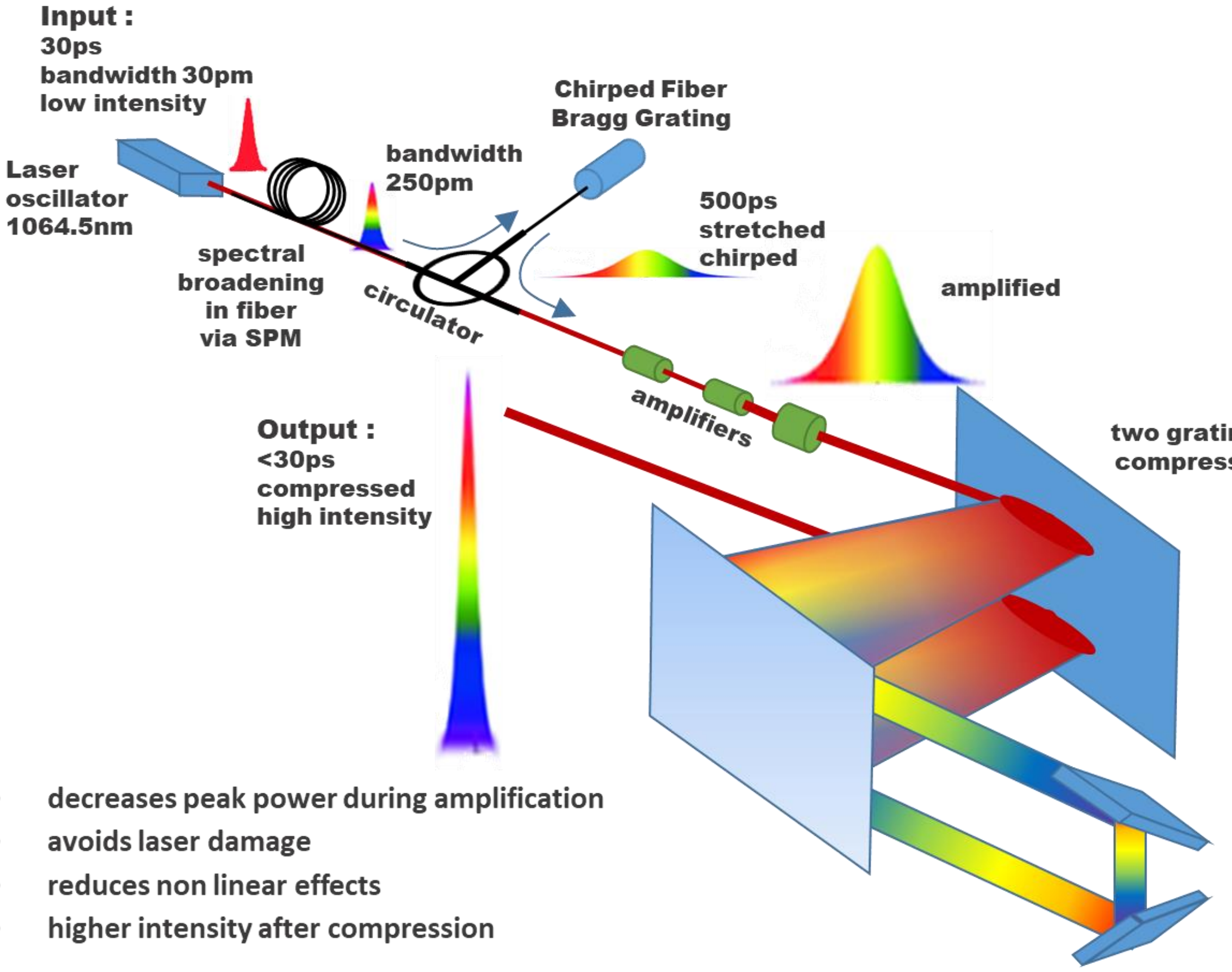
Solution for :
- Laser Induced Damage Threshold (LIDT)
- Non-linear effects

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



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

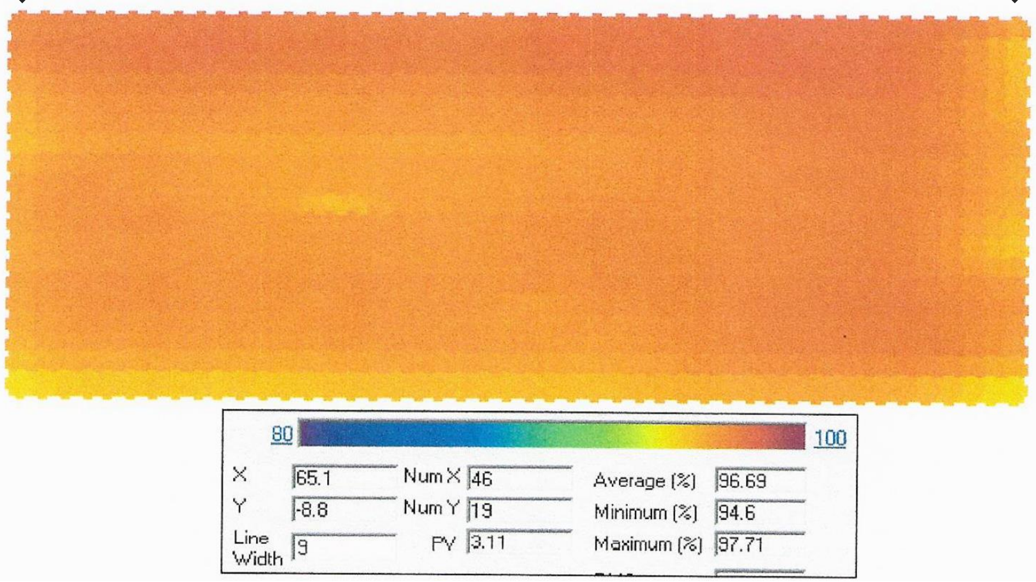
Temporal stretching by CPA (Chirped Pulse Amplification)

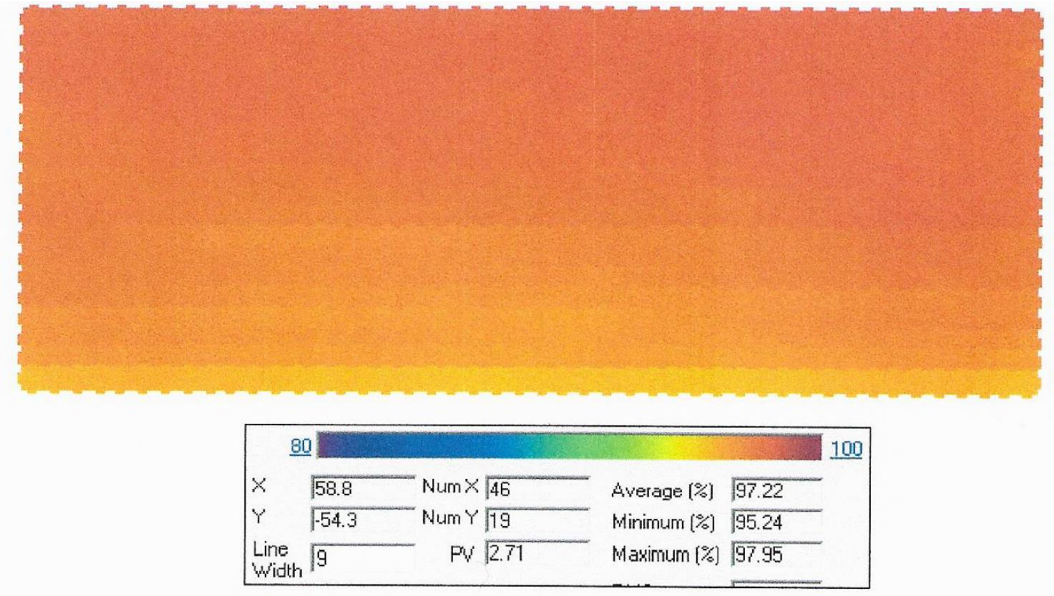
Gratings efficiency map

(credit : Plymouth Grating Laboratory)

120 mm

50 mm





Grating 1
Average efficiency :96,69%
$(0,9669)^4 = 0,874$

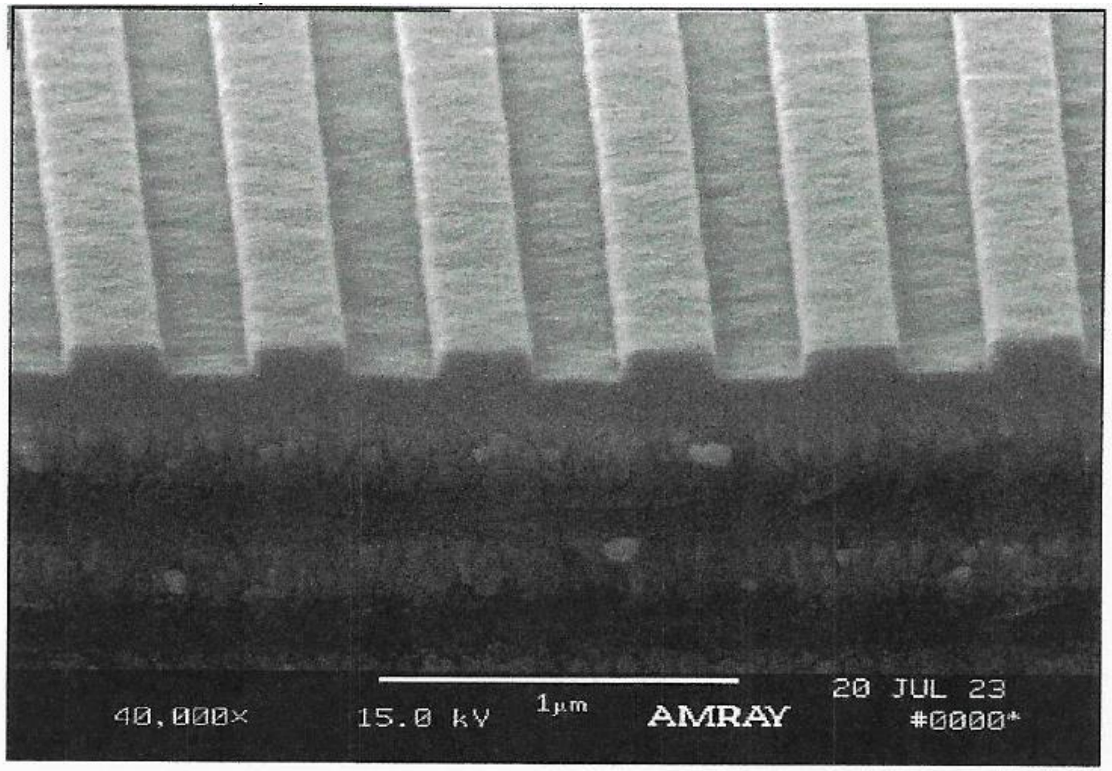
$(0,9)^4 = 0,656$

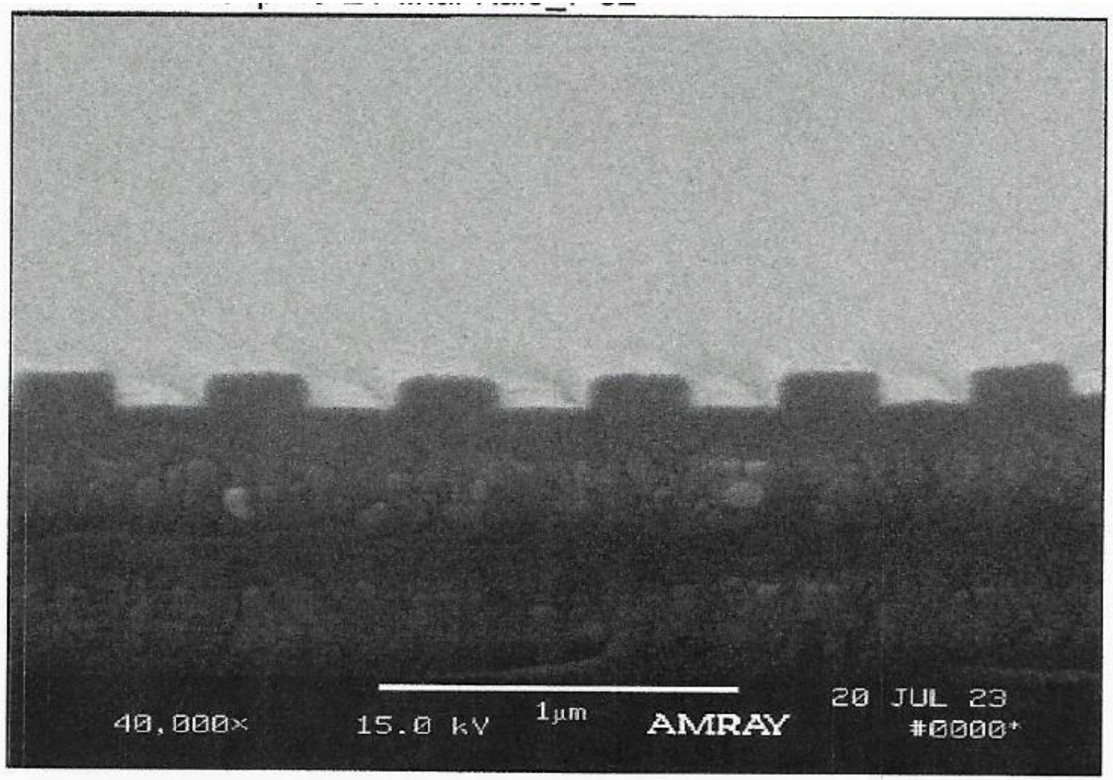
Grating 2
Average efficiency : 97,22%
$(0,9722)^4 = 0,893$

Temporal stretching by CPA (Chirped Pulse Amplification)

SEM imaging of the gratings

(credit : Plymouth Grating Laboratory)





Strategy for Source Optimization

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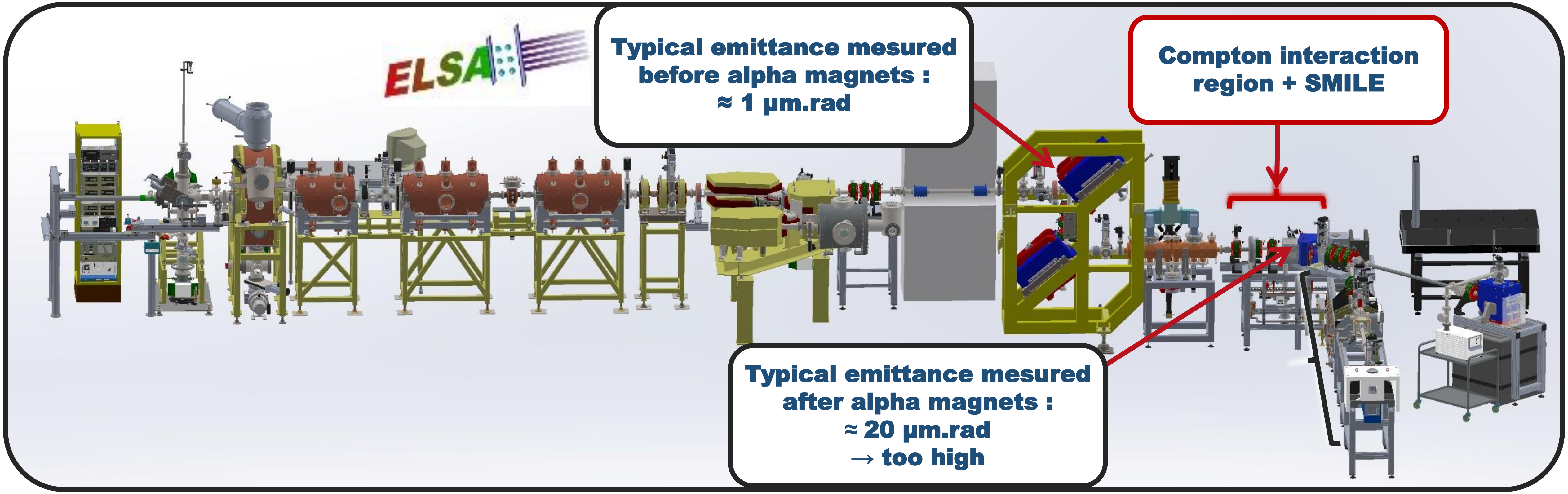
Electrons	- Bunch duration	Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression
Electrons (+)	- Bunch energy - Train duration	Upgrading the 1.3 GHz cavity and Klystron system

6. Twiss parameters and charge that maximize X-ray yield

Twiss parameters and charge that maximize X-ray yield

Mesured emittances

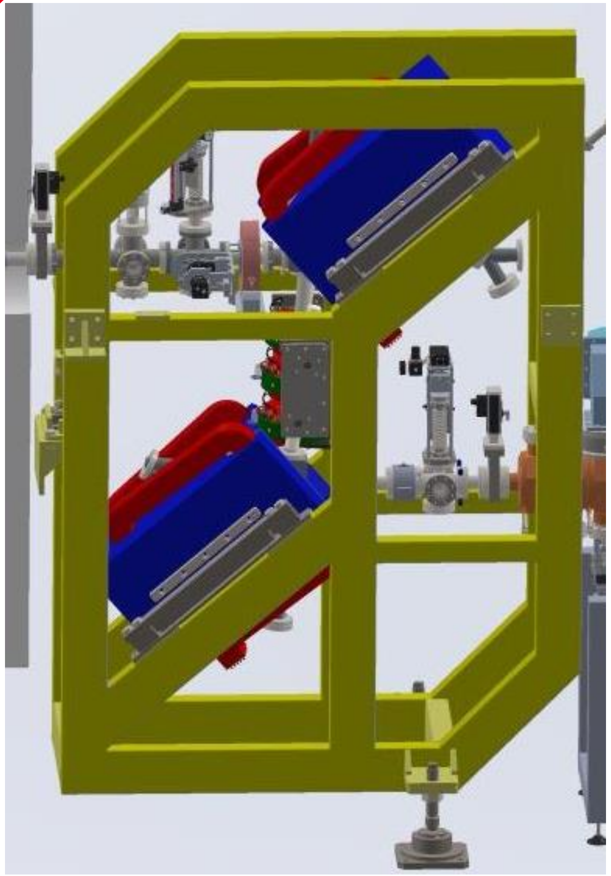


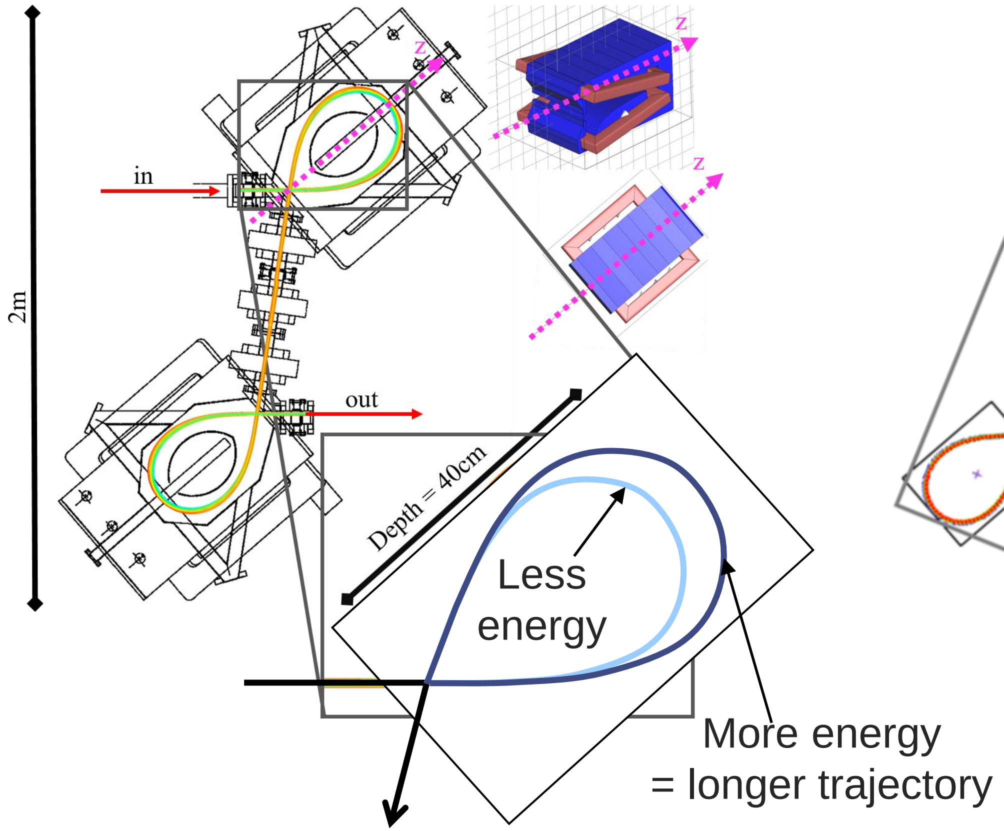
- Is it possible to reach desired flux with a double alpha magnets compressor ?

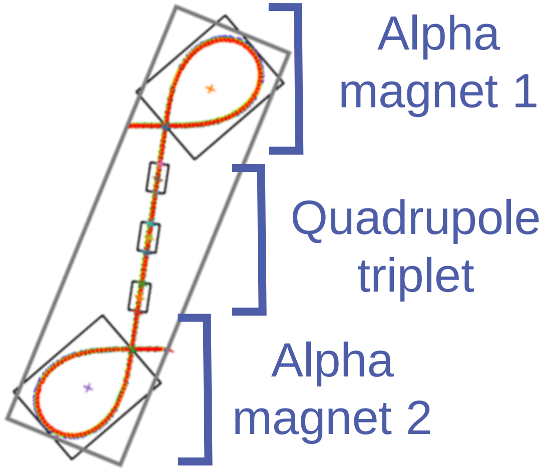
→ Simulation using different codes
⚠ Space charge

Twiss parameters and charge that maximize X-ray yield

Double alpha magnet compressor







→ all particles at c = take more time

Twiss parameters and charge that maximize X-ray yield

Simulations codes

Some simulation codes that consider space charge

CST PS (Dassault System)

+ **Electrodynamic**
+ Field maps

- In the **laboratory frame**

- Slow
- **Static mesh**, need a lot of meshcells
- Not specific to accelerator physic
- Can't perform optimization task easily
- Can't simulate Compton interaction

→ Already in use in the lab for RF simulation

TraceWin (CEA Saclay)

+ **Transfer Matrix** or field maps
+ Specific to accelerator physic
+ Fast
+ Can perform optimization task easily
+ **Adapt mesh** at each time step

• In the **reference particle frame**

- **Electrostatic**
- Can't simulate Compton interaction

→ Already in use in the lab

RF-Track (CERN)

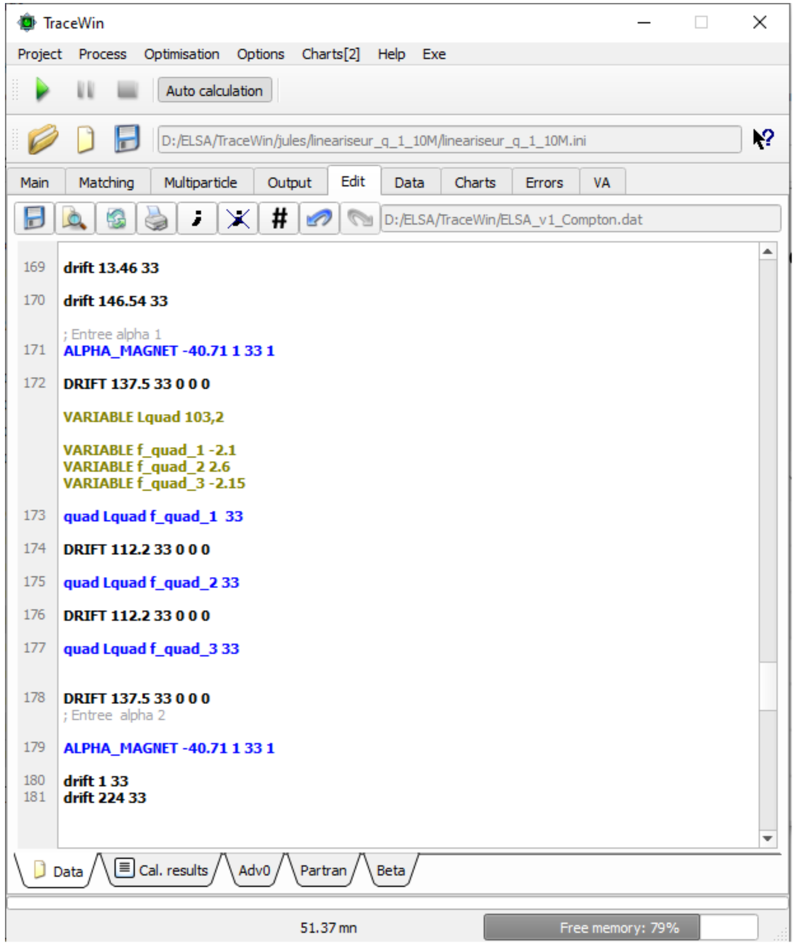
+ Field maps
+ **Electrodynamic**
+ Specific to accelerator physic
+ Fast
+ Can perform optimization task easily
+ Can simulate Compton interaction
+ **Adapt mesh** at each time step

- In the **laboratory frame**

→ Starting to use it now, thanks Andrea Latina !

Twiss parameters and charge that maximize X-ray yield

Using transfer matrix in TraceWin



The final matrix of a fraction of a alpha magnet (on which, X_s and θ_s are kept almost constant) :

$$\begin{pmatrix} \cos\theta_0 + (1-\cos\theta_0)\cdot\frac{\rho_0\cdot\sin\theta_s}{X_s} & \rho_0\cdot\sin\theta_s & 0 & 0 & 0 & \rho_0\cdot(1-\cos\theta_0) \\ -\frac{\sin\theta_0}{\rho_0}\cdot\left(1-\frac{\rho_0\cdot\sin\theta_s}{X_s}\right) & \cos\theta_0 & 0 & 0 & 0 & \sin\theta_0 \\ 0 & 0 & \cos\left(\sqrt{K}\rho_0\theta_0\right) & \frac{\sin\left(\sqrt{K}\rho_0\theta_0\right)}{\sqrt{K}} & 0 & 0 \\ 0 & 0 & -\sqrt{K}\cdot\sin\left(\sqrt{K}\rho_0\theta_0\right) & \cos\left(\sqrt{K}\rho_0\theta_0\right) & 0 & 0 \\ K_\varphi\cdot\left(\sin\theta_0 + (\theta_0-\sin\theta_0)\cdot\frac{\rho_0\sin\theta_s}{X_s}\right) & K_\varphi\cdot\rho_0\cdot(1-\cos\theta_0) & 0 & 0 & 1 & K_\varphi\cdot\rho_0\cdot(\theta_0-\sin\theta_0) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

With: $K = \frac{k\cdot\sin\theta_s}{X_s}$,

And: $K_\varphi = \frac{2\pi\cdot f_{RF}}{\beta_0 c}$.

The matrix of the full element is a product of all matrixes for varying X_s and θ_s.

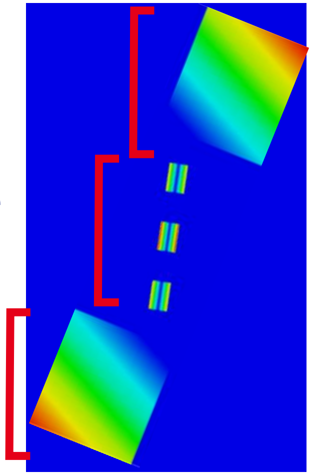
Twiss parameters and charge that maximize X-ray yield

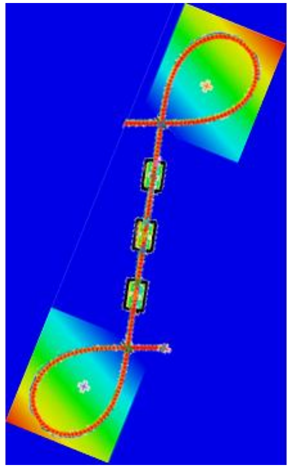
Using fields maps in CST

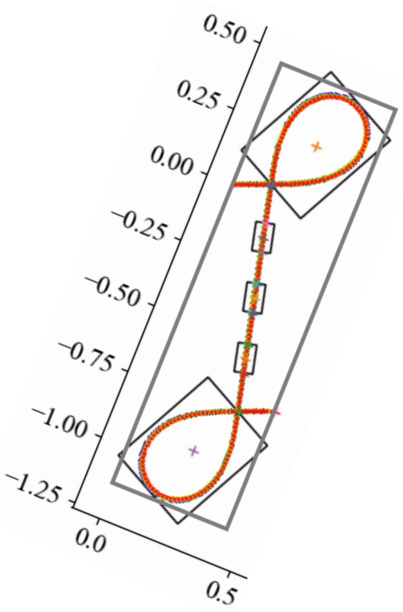
Alpha magnet 1

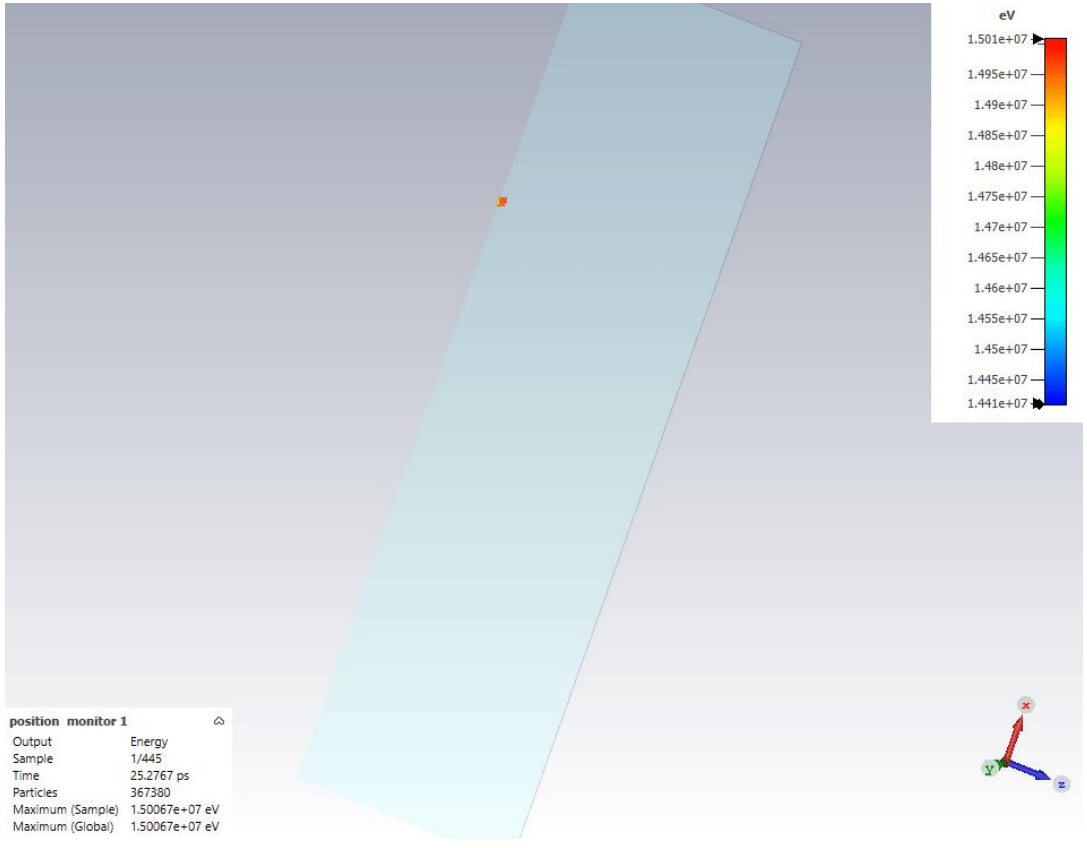
Quadrupole triplet

Alpha magnet 2





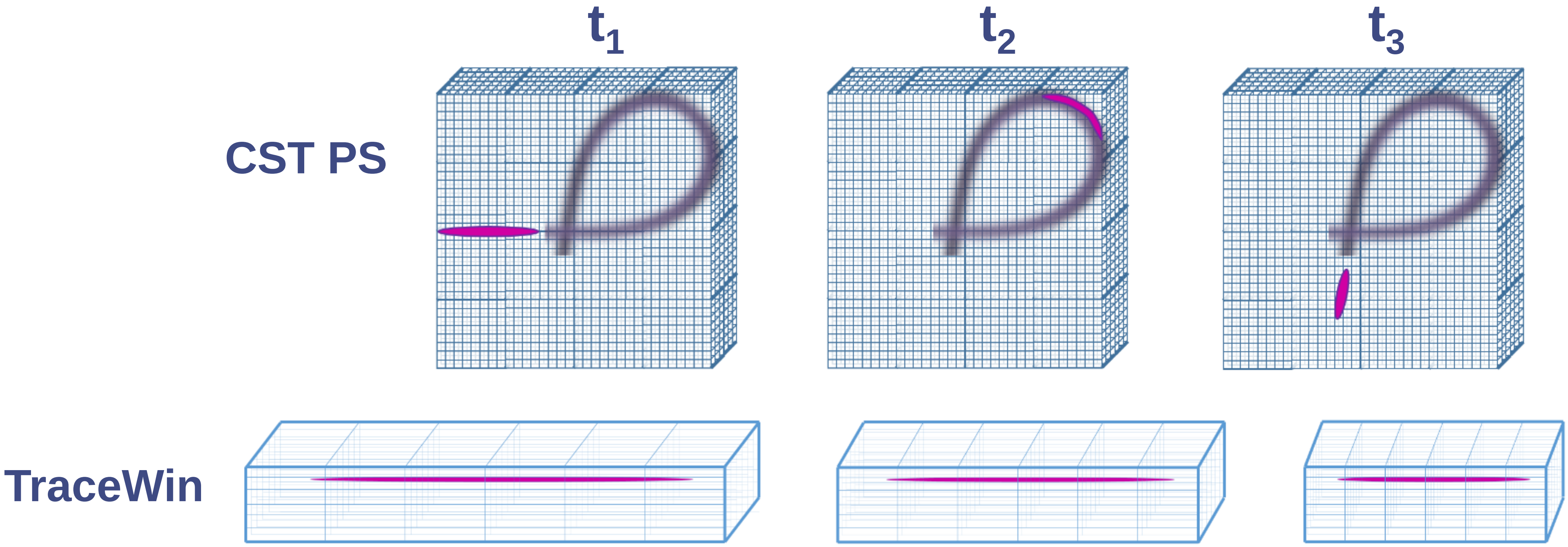




Twiss parameters and charge that maximize X-ray yield

Mesh in CST vs TraceWin

3D mesh cells for PIC algorithm and space charge computation



Twiss parameters and charge that maximize X-ray yield

PIC in CST vs TraceWin

Calcul PIC électrostatique

Bunch frame:

$v << c \Rightarrow \vec{j}$ negligible $\Rightarrow$ ***electrostatic assumption***

- charge density ρ projected on meshgrid
- V(ρ) scalar potential (Poisson's equation)
- E(V) electric field
- Lorentz boost (change of frame)★
- F=q(E + V^B) Lorentz force, update velocities
- update positions

TraceWin

CST PS

Calcul PIC électrodynamique

Lab. Frame or important transverse velocities :

v ~~<<~~ $c \Rightarrow$ ~~$\vec{j}$ negligible~~ $\Rightarrow$ ***~~electrostatic assumption~~***

- Charge density ρ and current density $\vec{J}$ projected on meshgrid
- V(ρ) scalar potential (Poisson's equation) and $\vec{A}$ vectoril potential (Ampere's equation)
- E(V) electric field and $\vec{B}(A)$ magnetic field
- Lorentz boost (change of frame) ★
- F=q(E + V^B) Lorentz force, update velocities
- update positions

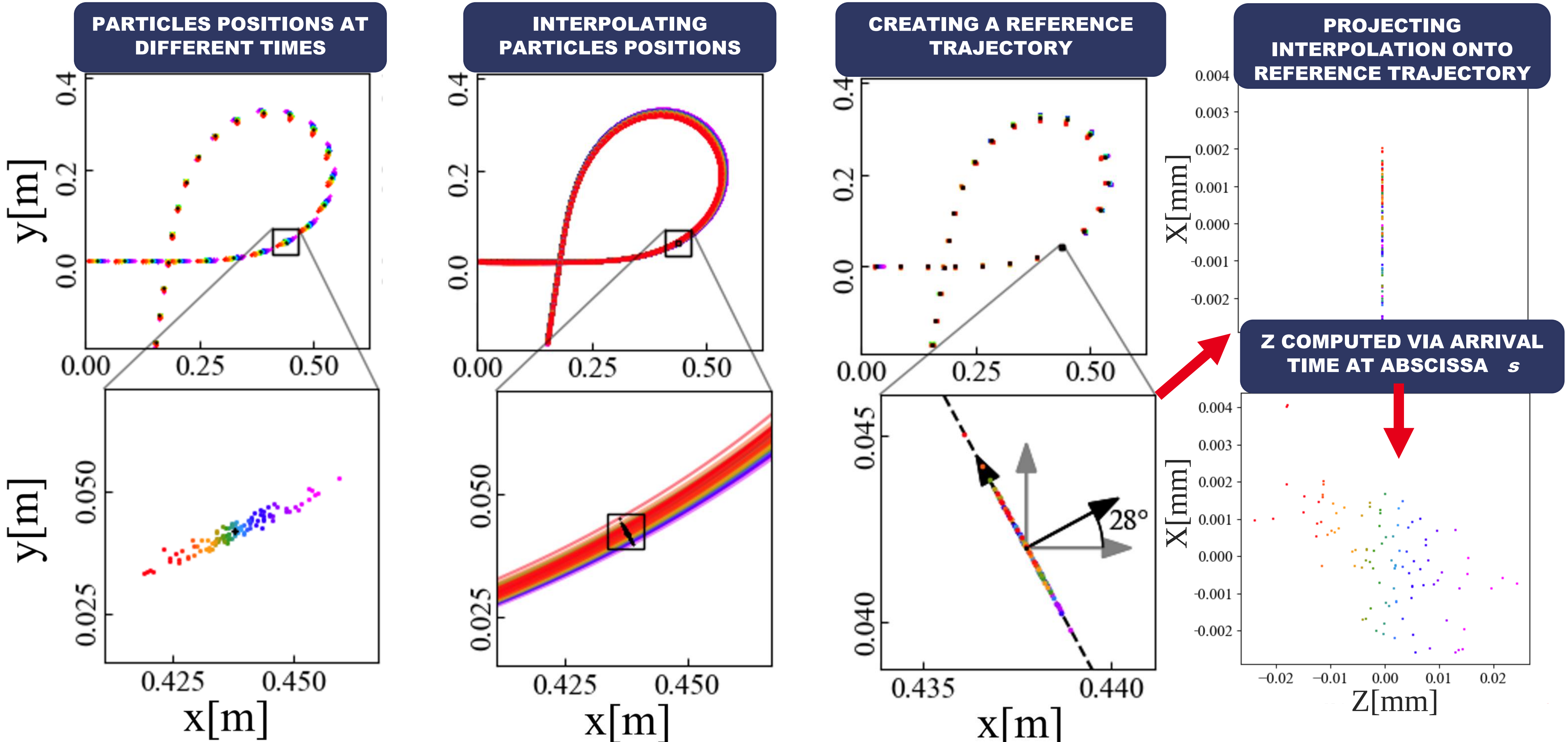
★

$$\begin{cases} E'_x = E_x \cdot \\ E'_y = \gamma(E_y - \beta c B_z) \cdot \\ E'_z = \gamma(E_z + \beta c B_y) \cdot \\ B'_x = B_x \\ B'_y = \gamma(B_y + \frac{\beta}{c} E_z) \\ B'_z = \gamma(B_z - \frac{\beta}{c} E_y) \end{cases}$$

E_{lab} and B_{labo} from E_{bunch} and B_{bunch}

Twiss parameters and charge that maximize X-ray yield

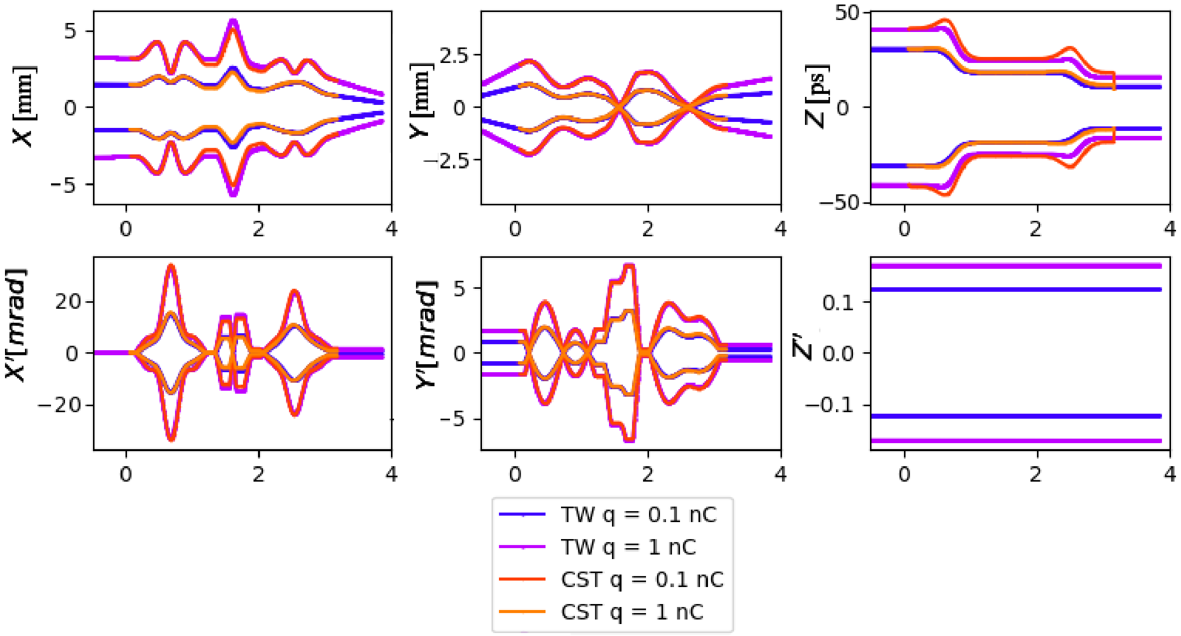
Key steps from laboratory frame to reference frame

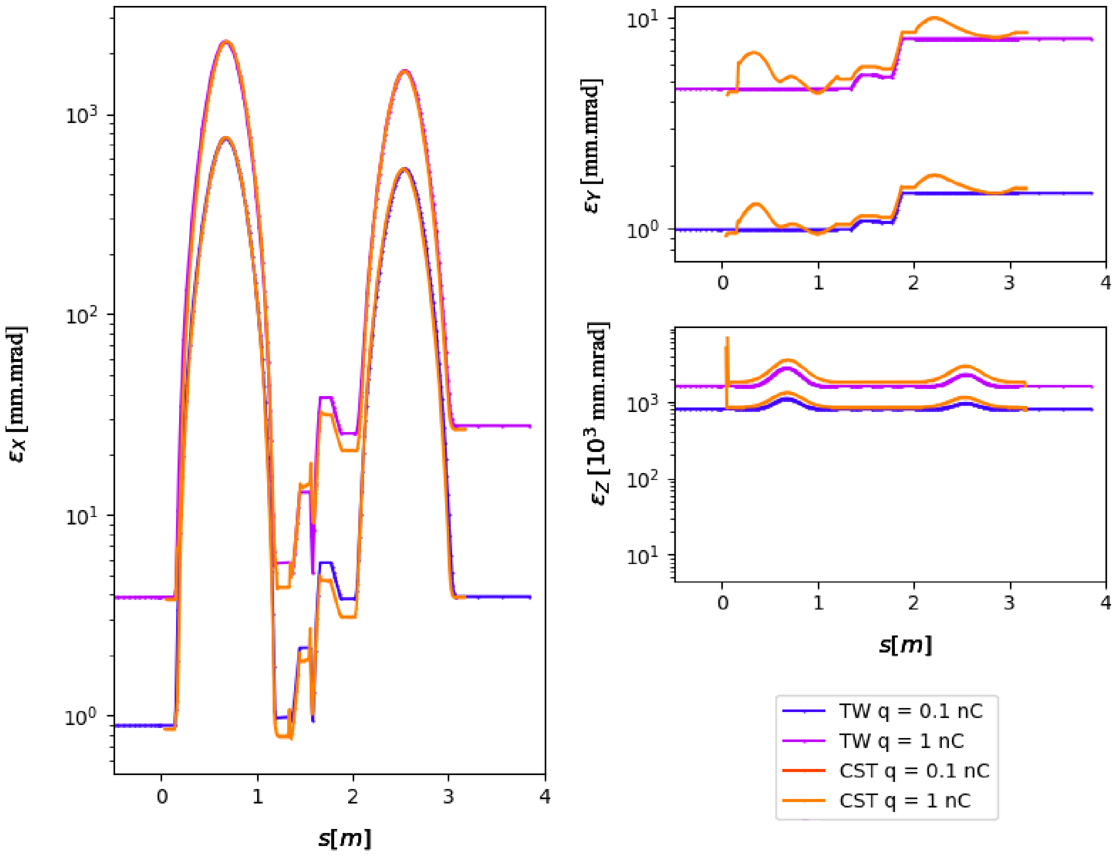


Twiss parameters and charge that maximize X-ray yield

Finally, good agreement between CST and TraceWin

Envelop RMS

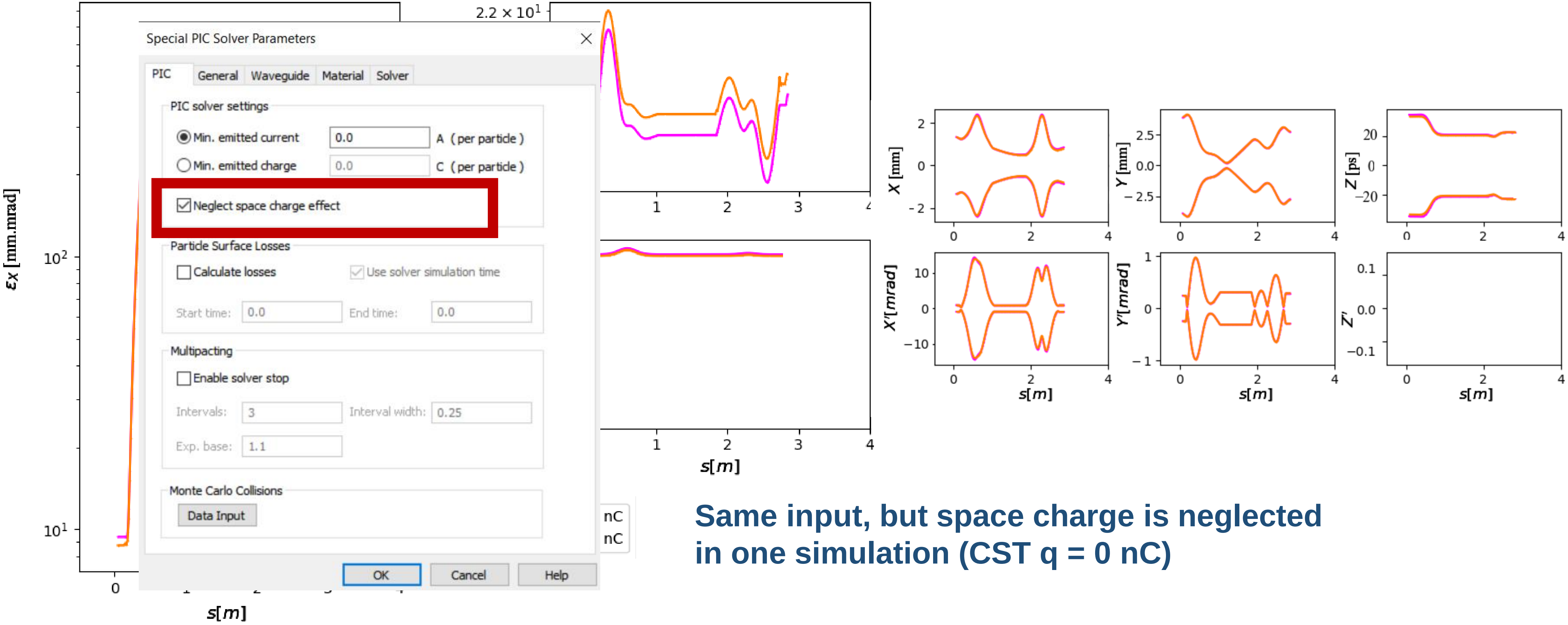




Good agreement between CST and TraceWin even for higher charges

Twiss parameters and charge that maximize X-ray yield

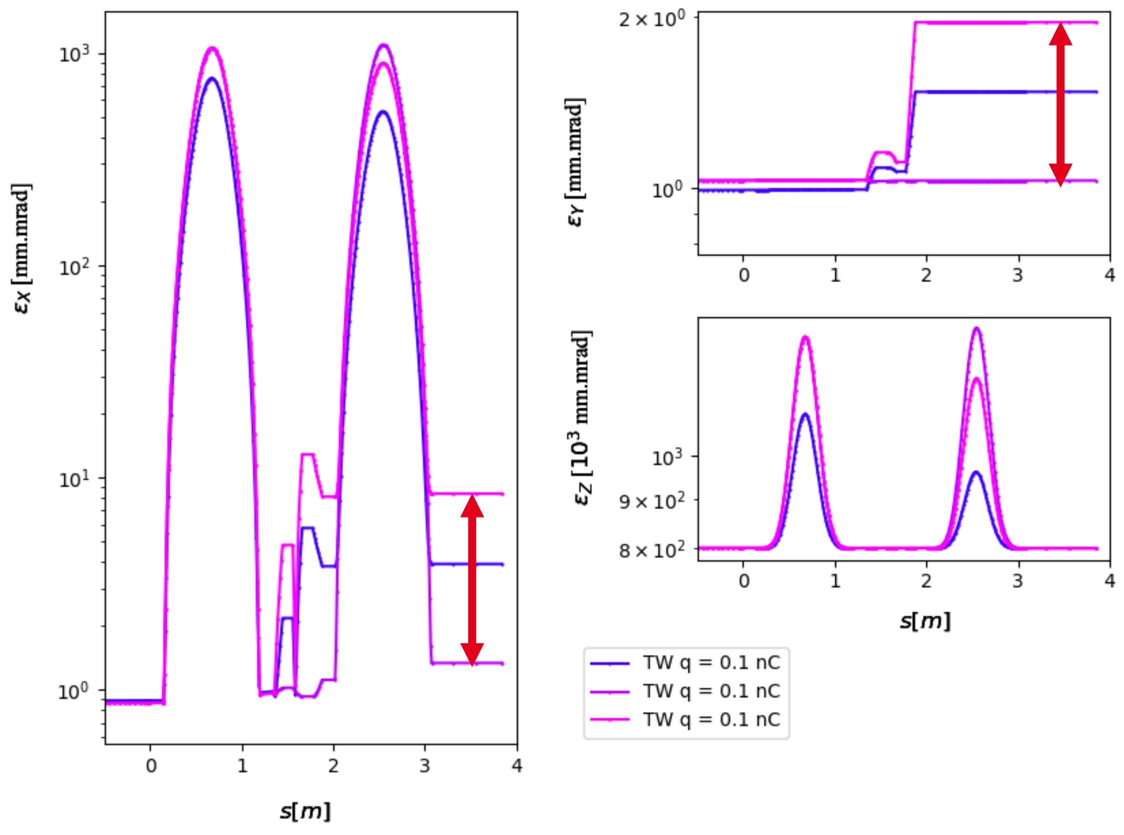
Space charge effects maybe not as important as expected

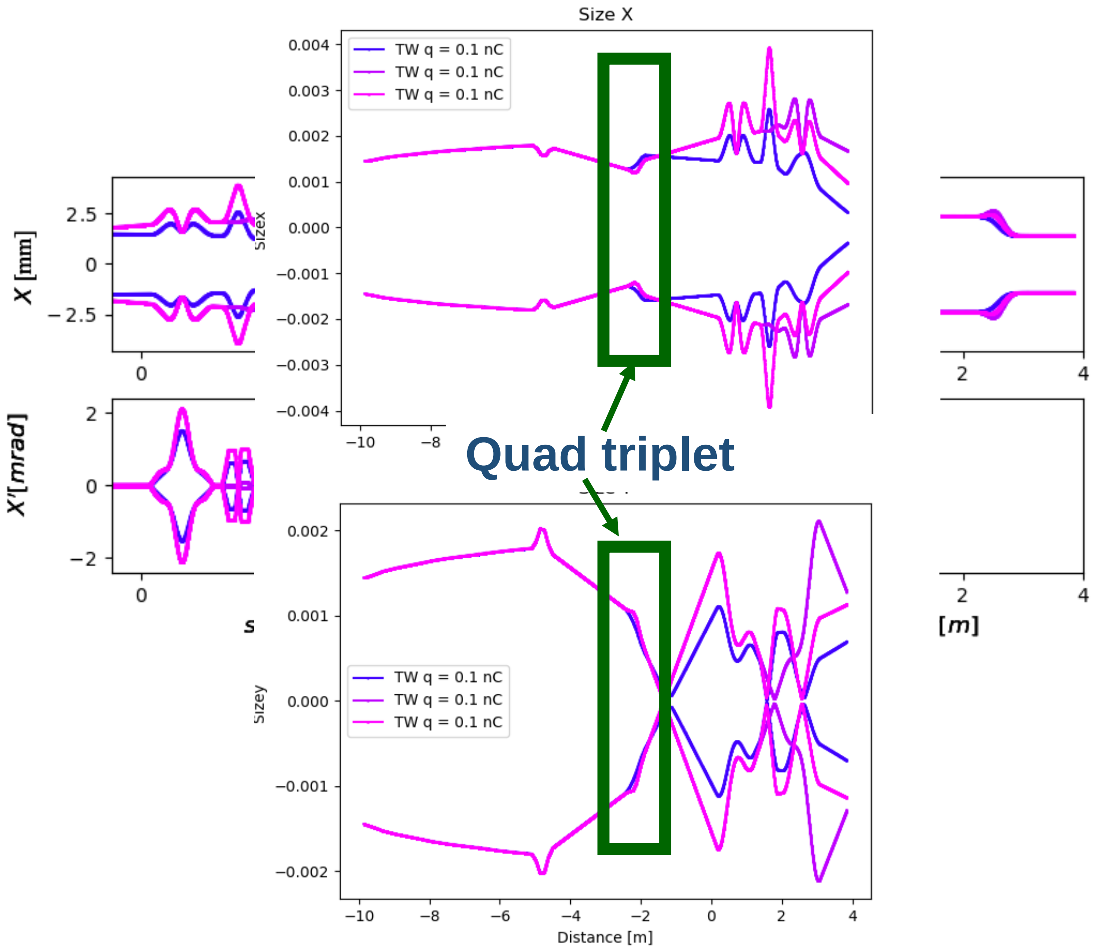


Same input, but space charge is neglected in one simulation (CST q = 0 nC)

Twiss parameters and charge that maximize X-ray yield

Most important : good matching at the entrance





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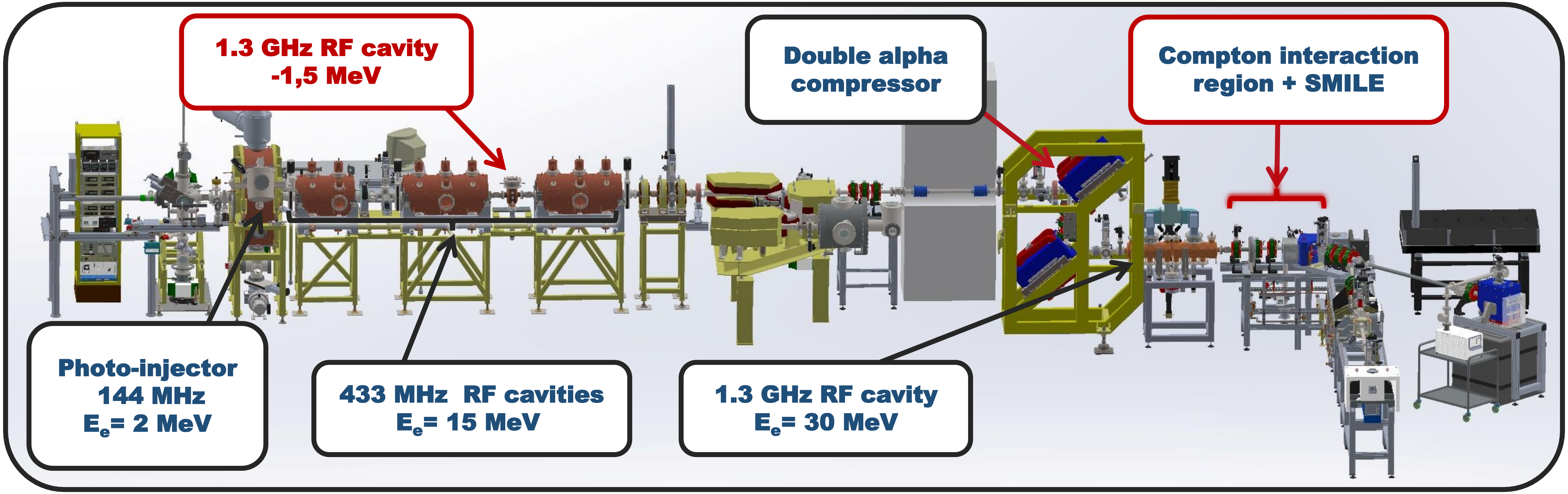
Electrons	- **Bunch duration**	**Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression**
Electrons (+)	- Bunch energy - Train duration	Upgrading the 1.3 GHz cavity and Klystron system

7. Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression

Decelerating 1.3 GHz cavity to linearize chirp

ELSA Accelerator (CEA DAM, France)

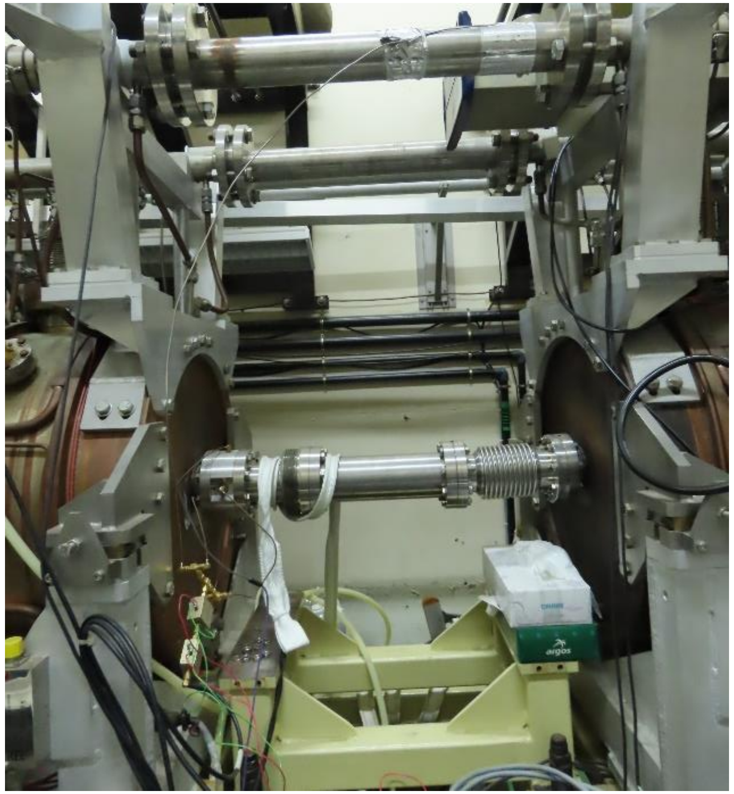


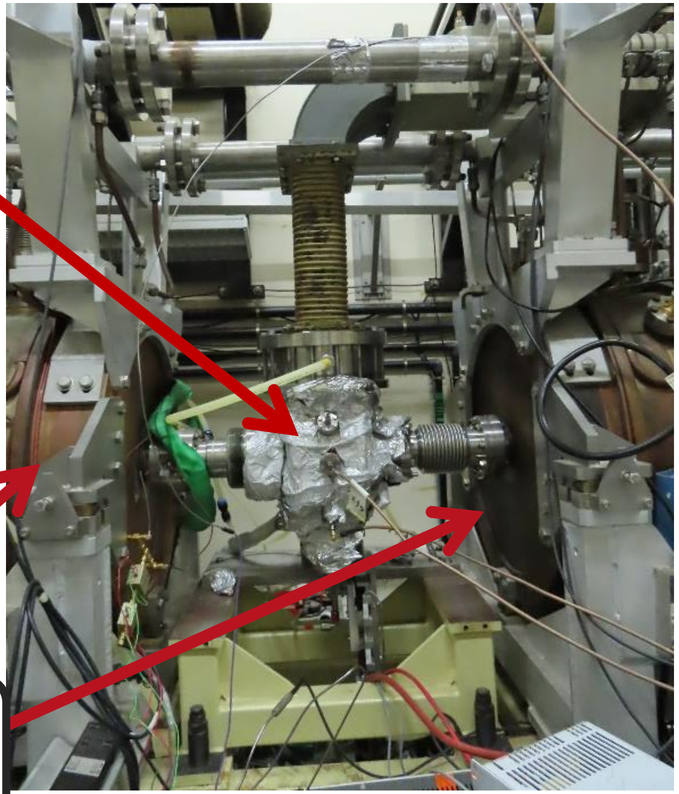
- We aim for shorter bunch duration, this contributes to optimize the flux. A way to obtain shorter bunch is to linearize the chirp before magnetic compression
- An alpha magnet induces a linear magnetic compression - similar to a chicane – which means that a linearly chirped bunch will be correctly compressed (better than a quadratically chirped bunch as we had until then)

Decelerating 1.3 GHz cavity to linearize chirp

Installation of the 1.3 GHz cavity between two 433 MHz cavities

- Before and after installation of the 1.3 Ghz cavity (Martin COLLET and Vincent JACOB)

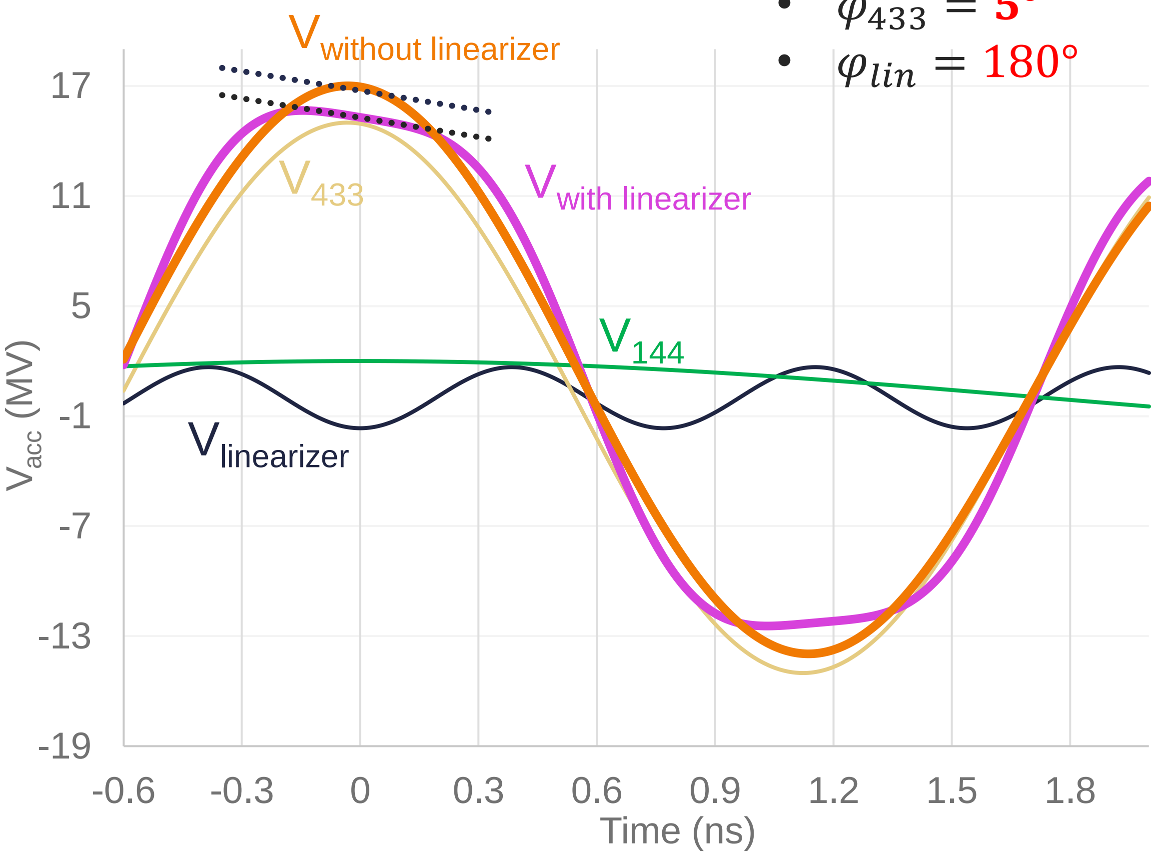


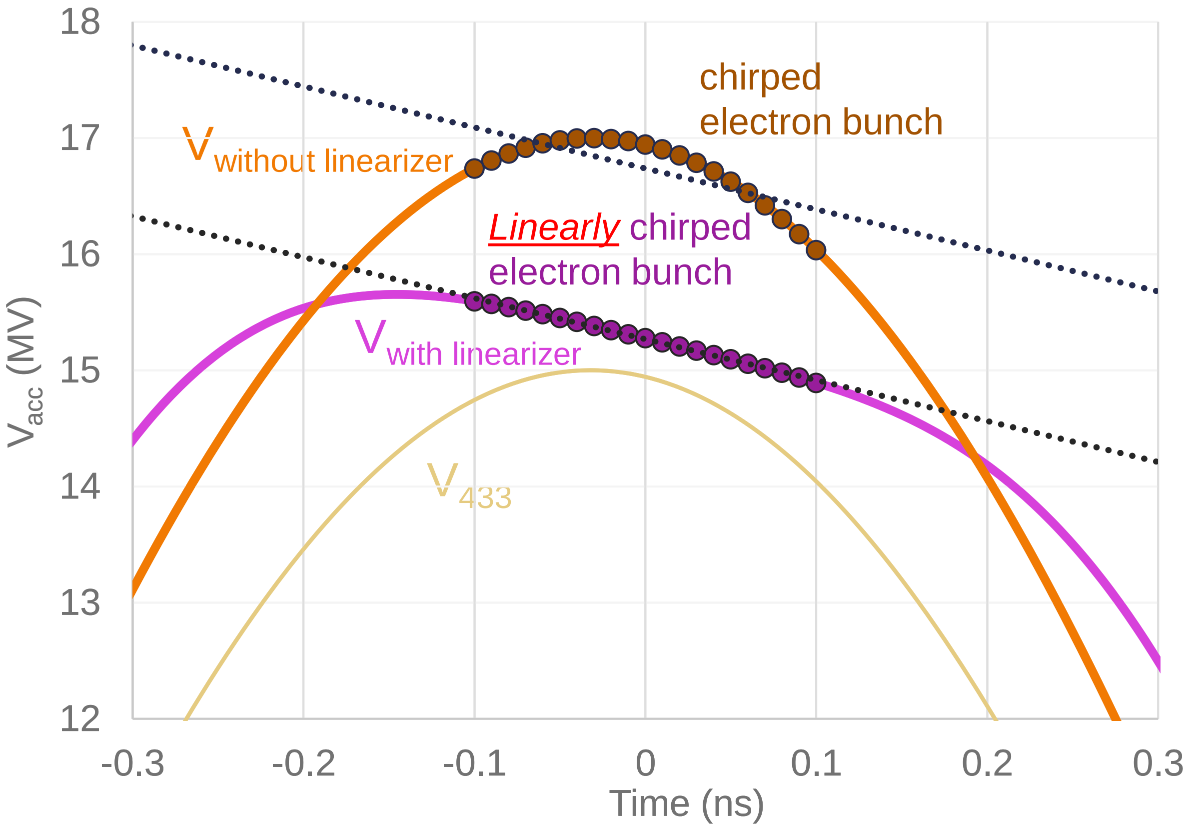


Decelerating 1.3 GHz cavity to linearize chirp

Linearize chirp with appropriate phases

- $\varphi_{144} = 0°$
- $\varphi_{433} = 5°$
- $\varphi_{lin} = 180°$



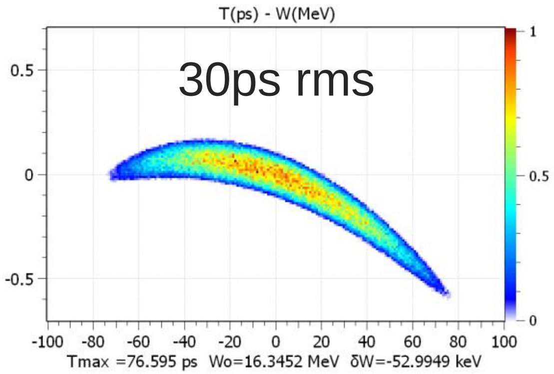


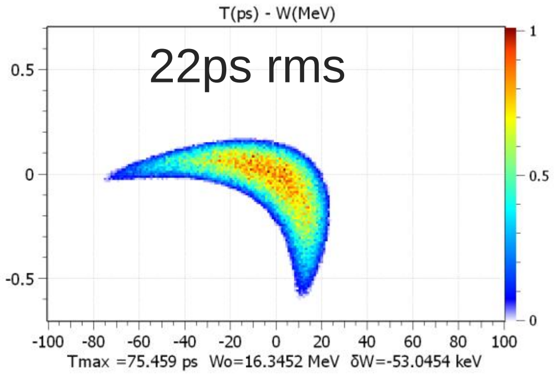
Decelerating 1.3 GHz cavity to linearize chirp

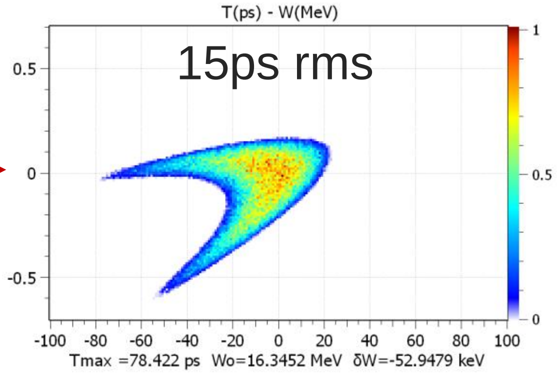
Compression with and without linearizer

Before compressor | **After one alpha magnet** | **After two alpha magnets**

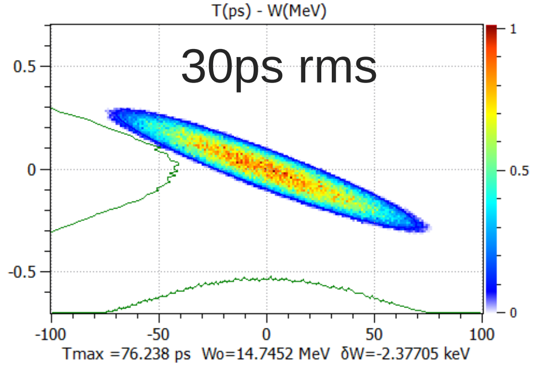
Without linearizer

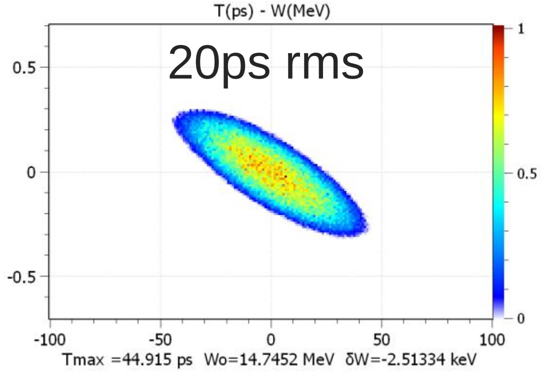


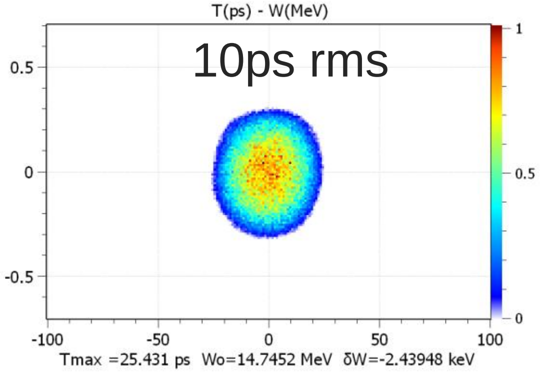




With linearizer







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 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

- Bunch duration

Using a decelerating 1.3 GHz cavity to achieve linear chirp before compression

\+
- **Bunch energy**
- **Train duration**

Upgrading the 1.3 GHz cavity and Klystron system

8. Upgrading the 1.3 GHz cavity and Klystron system

Upgrading the 1.3 GHz cavity and Klystron system

Third phase of renewal (144 MHz and 433 MHz already done)

➢ Current 1.3 GHz system

- We can do :
  - 30 MeV, **10 µs**

  (~1400 bunches per train at 144 MHz)

- Klystron THALES TV2022
  - Pulse duration 10 µs
  - Power 20 MW
  - Constraints : pulse duration and power

- Cavities
  - Standard copper structure (elliptical cells)
  - 2 times 5 cells, coupled
  - Constraints : 13 MV/m maximum accelerating gradient, only 10 cells

➢ Future 1.3 GHz system

- Need :
  - 40 MeV, **100-200 µs,** 10 Hz

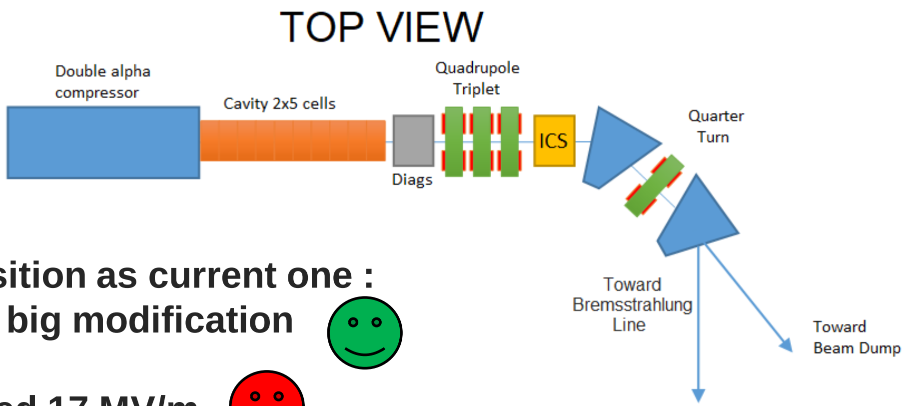
  (~28500 bunches per train at 144 MHz)

- Klystron :
  - (Two ?) Klystron(s) with longer pulse duration and high power

- Cavities
  - New cavities, to achieve higher number of cells
    - eg. twice 2 times 5 cells = 20 cells
    - or 4 times 3 cells = 12 cells
  - Or higher gradients in the cells (17 MV/m)

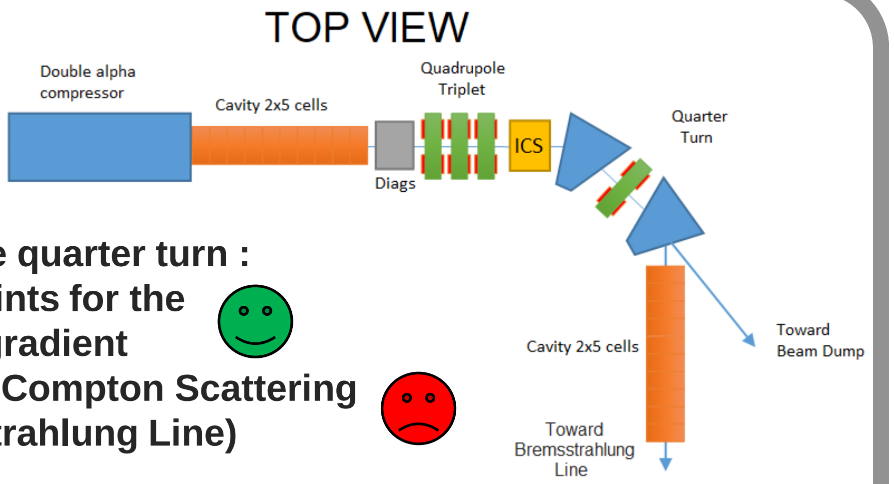
Upgrading the 1.3 GHz cavity and Klystron system

Possible positions for new cavities



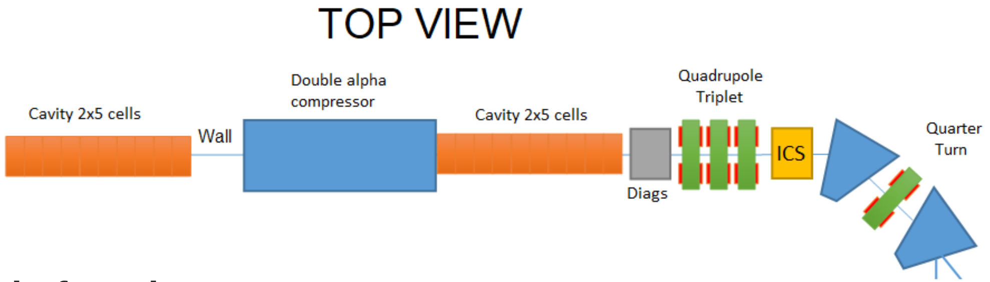
Same position as current one :

- **no big modification**
- **need 17 MV/m**



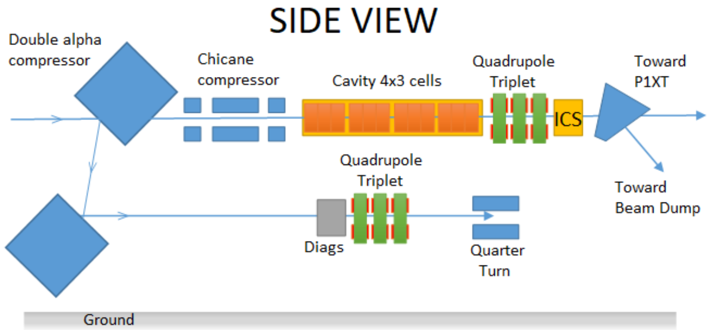
New cavity after the quarter turn :

- **less constraints for the accelerating gradient**
- **not used for Compton Scattering (only Bremsstrahlung Line)**



New cavity before the compressor :

- **less constraints for the accelerating gradient**
- **need to remove an existing (but not useful) half-turn before the compressor → huge effort**



Different cavity (4x3 cells) above the actual line

- **no alpha compressor, but chicane (better for emmitance)**
- **line is 3 meters above the ground**

9. Conclusion

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

Conclusion - Prospect

Work under progress (related to this presentation) :

- CPA System parts received - alignment in progress right now.
- Finalization of the installation of SMILE 2
- Relocation of the whole system on ELSA
- **Finalization of simulations**
  - **→ benchmark TraceWin, CST and RF-Track, compare with experiments**
  - **→ optimize transport with realitistic parameters to maximize ICS X-ray flux**

- **Compton source experiments on ELSA : dec 2023 – Feb 2024**
  - **→ Achieve flux as high as possible**
  - **→ Characterize the source parameters with appropriate diagnostics**

Long term prospect :

- Automatization of SMILE alignment

- Studies under way for the upgrade of the new 1.3 GHz cavity/klystron/modulator system.

THANK YOU

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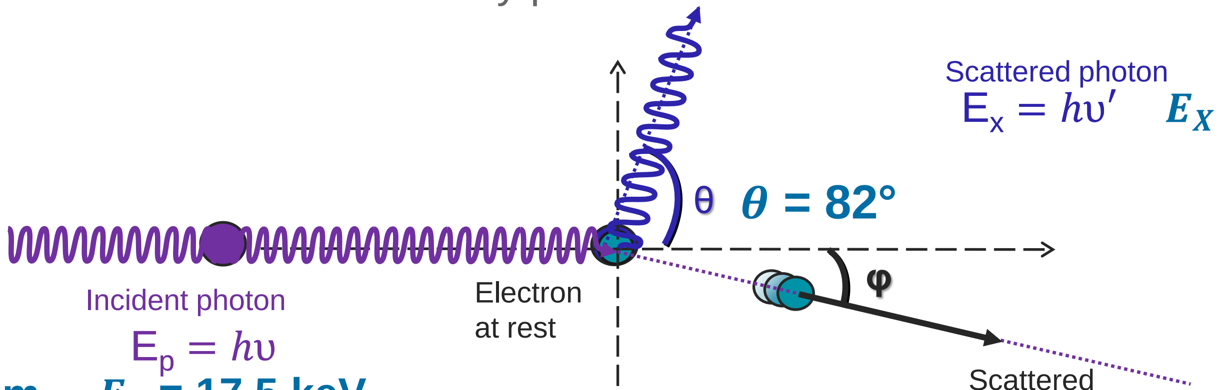
History

- ❖ **1922: Arthur Holly Compton conducts an experiment demonstrating that electrons and photons are particles.**

  - ➢ Study of the collision between X-ray photons and electrons at rest



Scattered photon

$E_x = h\upsilon'$ $\boldsymbol{E_X}$ **= 17 keV**

$\boldsymbol{\theta}$ **= 82°**

Incident photon

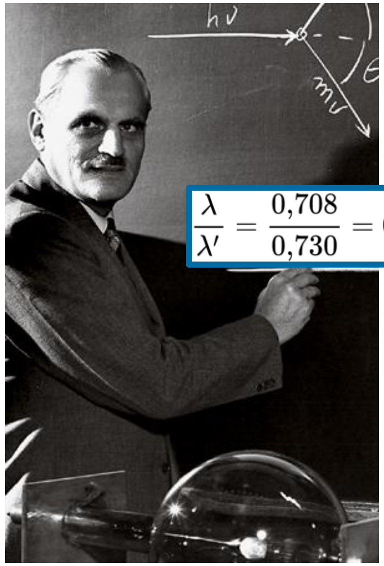
$E_p = h\upsilon$

Electron at rest

K-line of molybdenum $\boldsymbol{E_p}$ **= 17,5 keV**

Scattered Electron

$E_e = h(\upsilon - \upsilon')$ $\boldsymbol{E_e}$ **= 0,5 keV**



$$\frac{\lambda}{\lambda'} = \frac{0{,}708}{0{,}730} = 0{,}969$$

  - ➢ Observation: decrease in photon energy after the collision (increase in wavelength)

  - ➢ Note : elastic scattering, kinetic energy is conserved

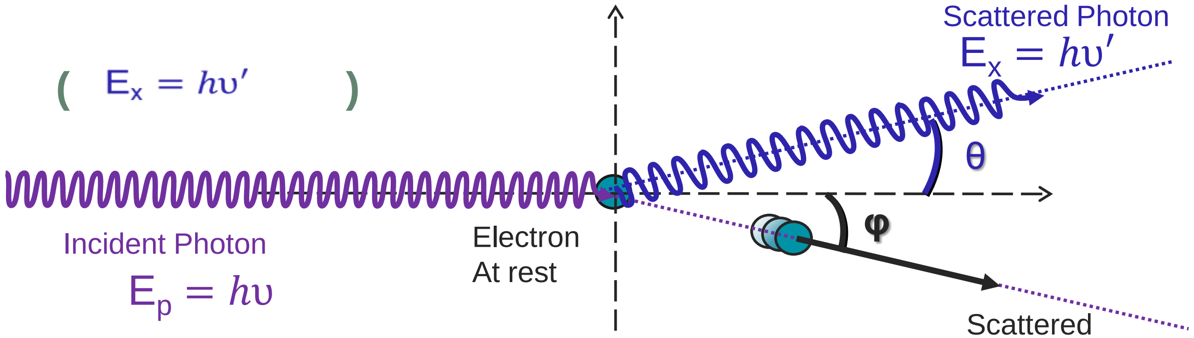
BACK-UP SLIDES

Compton Scattering and Inverse Compton Scattering

Compton Scattering

- Transfer of energy from the photon to the electron

E_X = 17 keV



$E_p = h\upsilon$

E_p = 17,5 keV

$E_e = h(\upsilon - \upsilon')$

E_e = 0,5 keV

Ex: K-line of molybdenum: scattering angle θ = 82°

$$E_X = \frac{E_p}{1 + \frac{E_p}{m_e c^2}(1 - \cos\theta)}$$

Inverse Compton Scattering

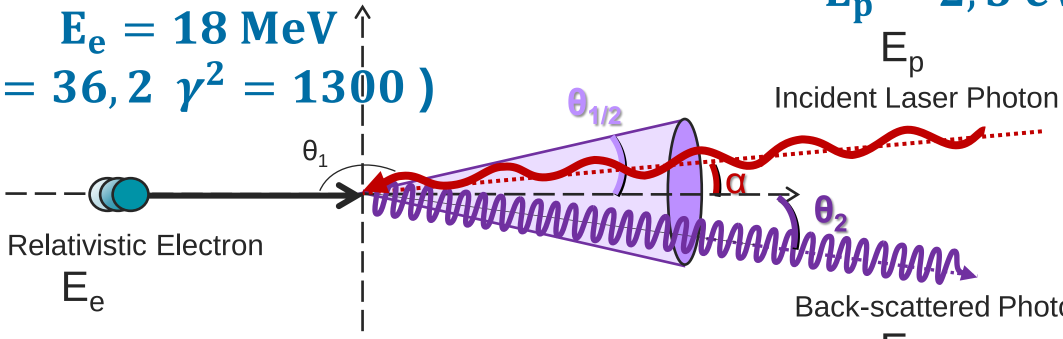
- Transfer of energy from the electron to the photon

$$E_p \ll \gamma m_e c^2$$

$E_p = 2,3$ eV

$E_e = 18$ MeV

$(\gamma = 36,2 \;\; \gamma^2 = 1300\,)$



E_x

Ex: laser 532 nm + relativistic electron → X−ray photon

$$E_X = \frac{4\gamma^2 E_p}{1 + \gamma^2\theta_2^2 + \frac{\alpha^2}{4}}$$

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

$\theta_{1/2}$ = 27,6 mrad

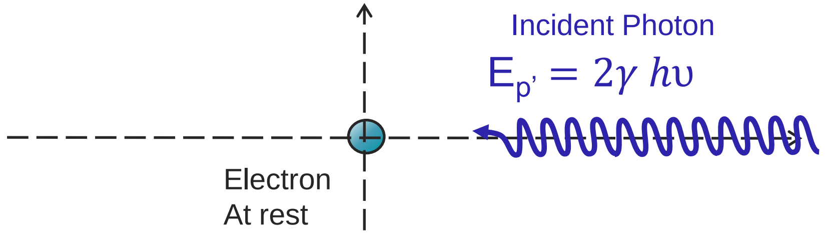
$$E_X(\theta_2 = 0) = 4\gamma^2 E_p$$

E_X = 12 keV

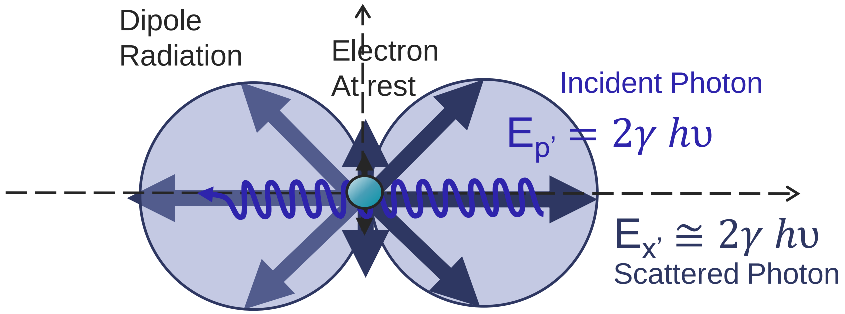
BACK UP SLIDES

Thomson Scattering

IN THE REFERENCE FRAME OF THE ELECTRON



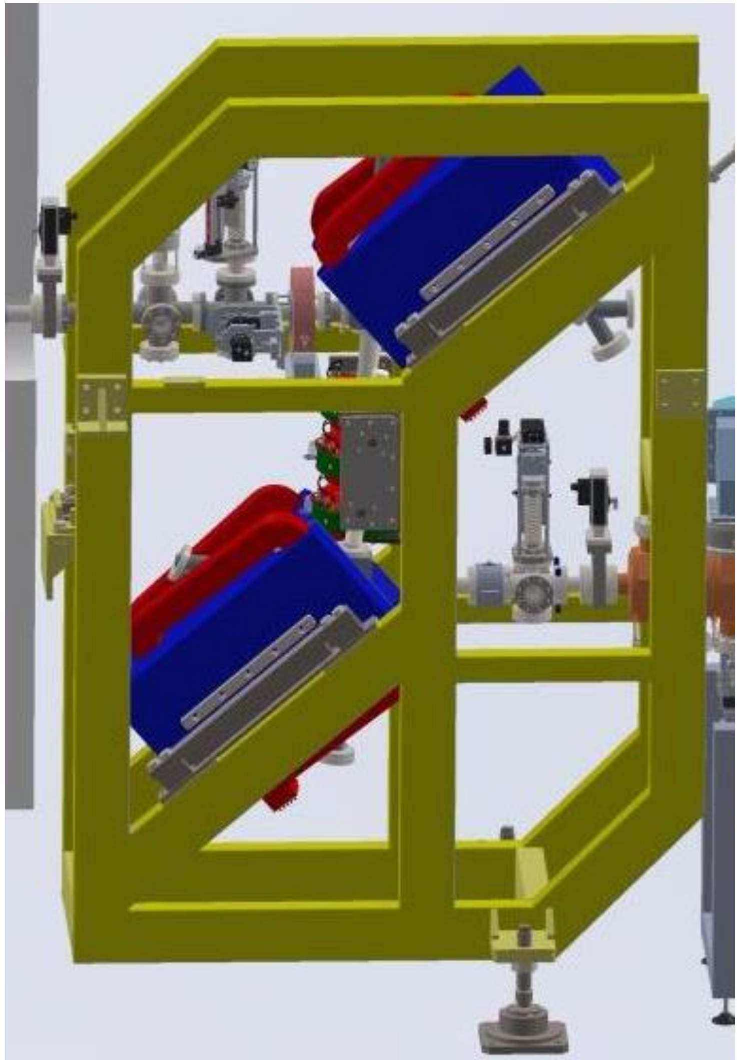
IN THE REFERENCE FRAME OF THE ELECTRON

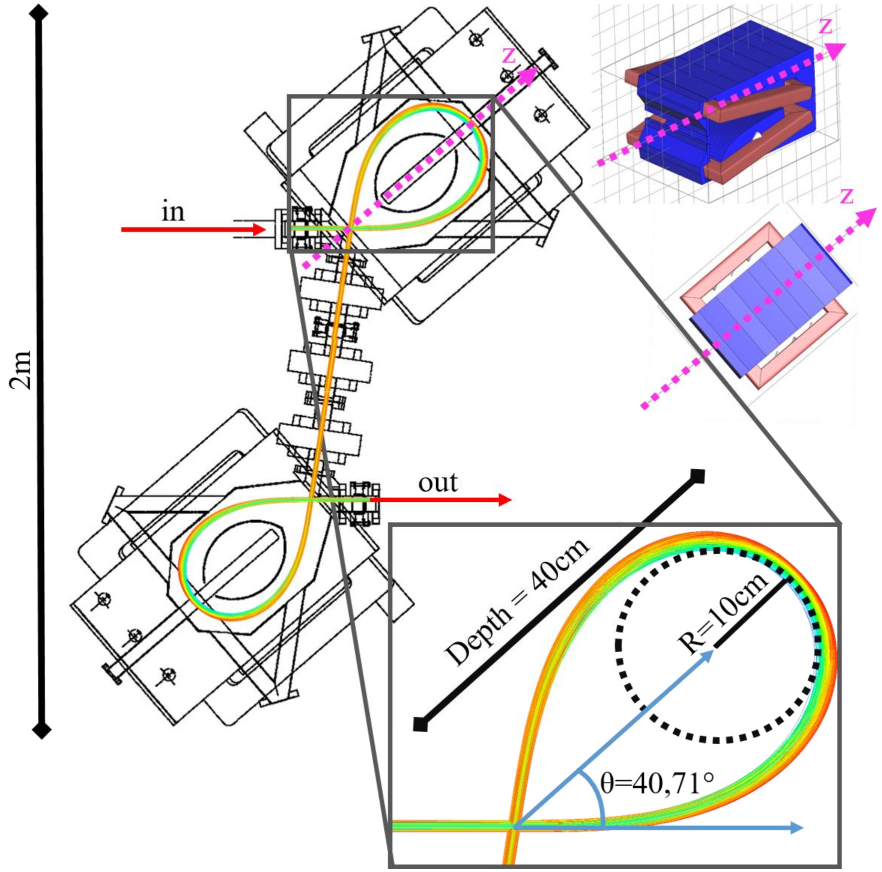


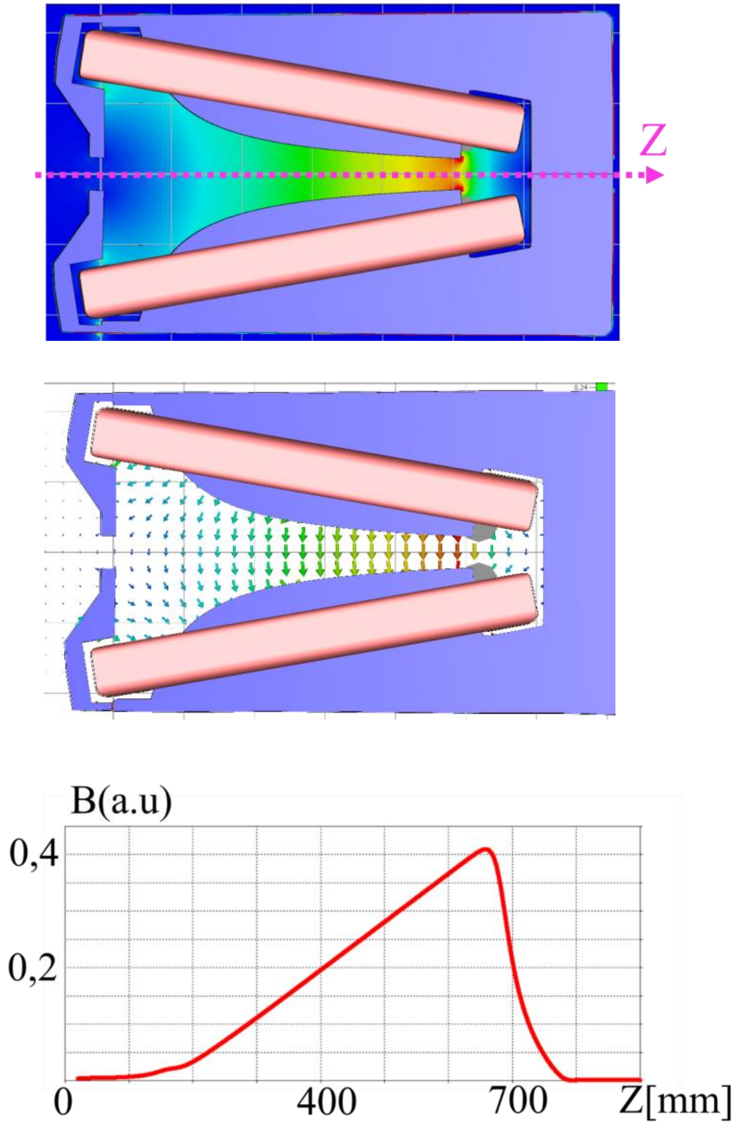
- Incident photon energy small compared to electron rest mass Ep << $m_e c^2$
- Negligible transfer of energy from the photon to the electron, but photon scattered with an angle
- Thomson Scattering in the reference frame of the electron ≅ Inverse Compton Scattering in the lab frame

BACK UP SLIDES

Alpha magnets field



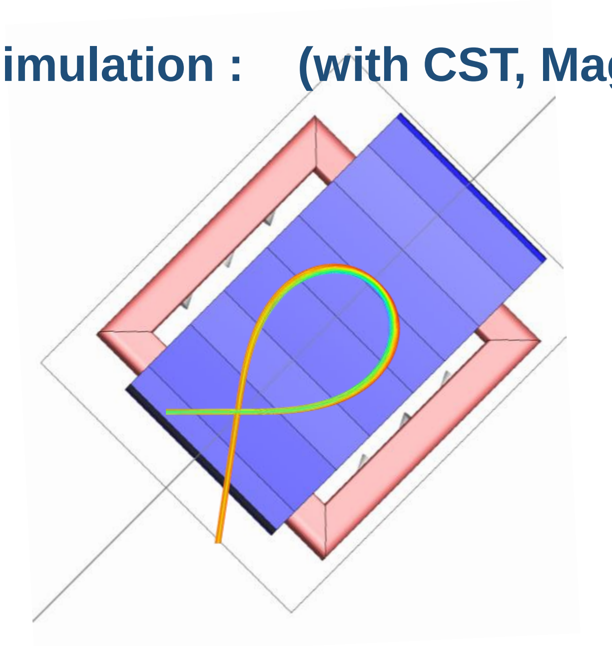


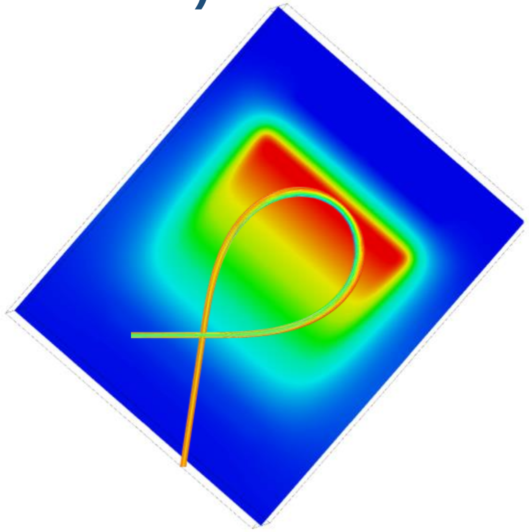


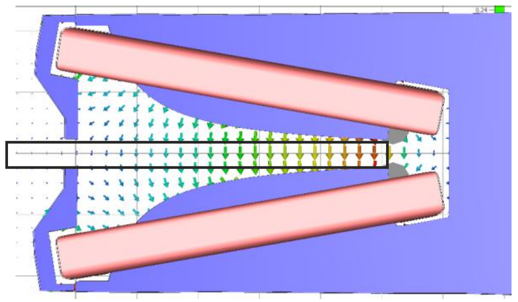
BACK UP SLIDES

Simulation of alpha magnet vs analytical model

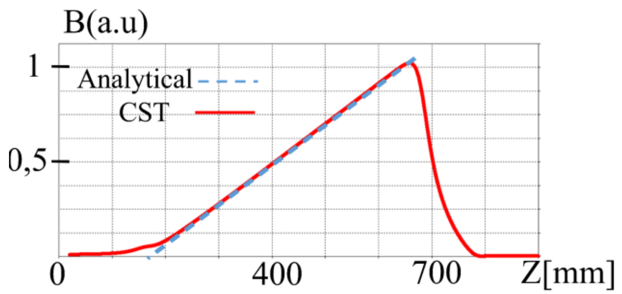
Simulation : (with CST, Magnetostatic module)

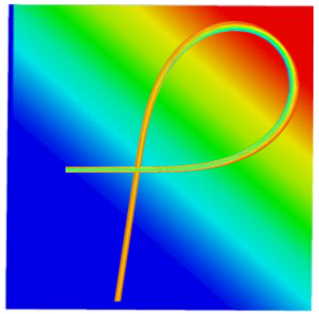






Analytical field :





- We used only the analytical field