Commissioning of ThomX Compton Light Source

Iryna Chaikovska (IJCLab, Paris-Saclay university)
on behalf of the ThomX collaboration

Programme Investissements d'avenir de l'Etat ANR-10-EQPX-51. Financé également par la Région Ile-de-France.
Program « Investing in the future » ANR-10-EQOX-51. Work also supported by grants from Région Ile-de-France.

Outline

- Compton light sources
- ThomX facility: compact Compton light source
- ThomX commissioning status
- Perspectives-Summary

Thom X

Sir Joseph John Thomson

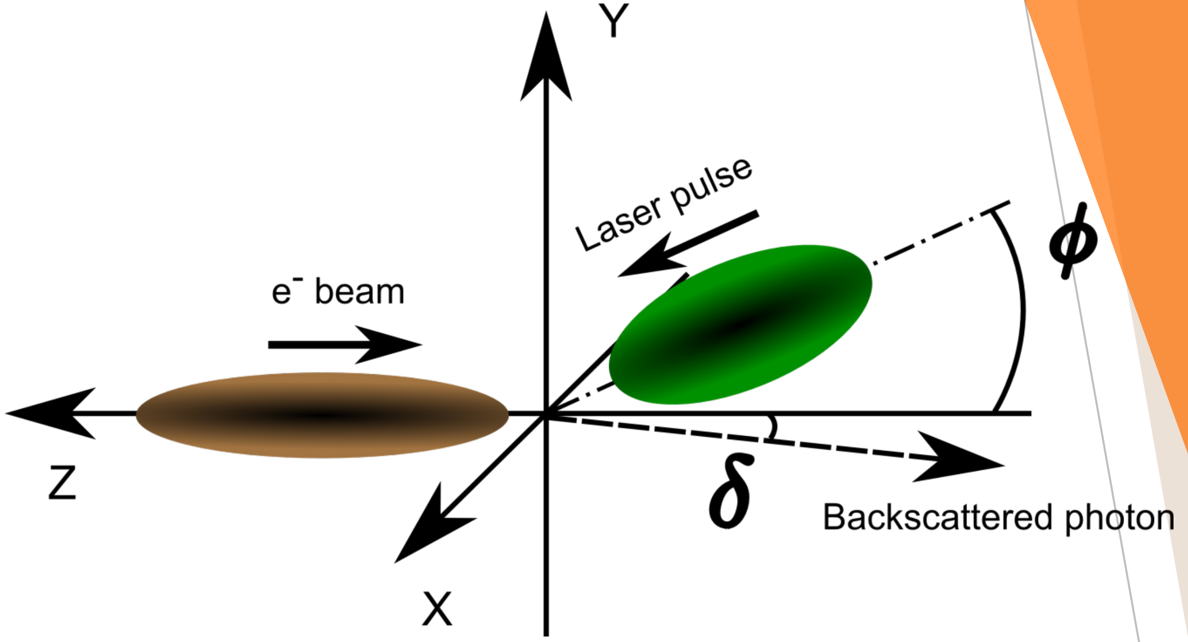
(1856 -1940)

X-rays

Compton light sources

Compton scattering

$$E_\gamma \simeq E_L \frac{4\gamma^2}{1+\gamma^2\delta^2+\frac{\phi^2}{4}}$$



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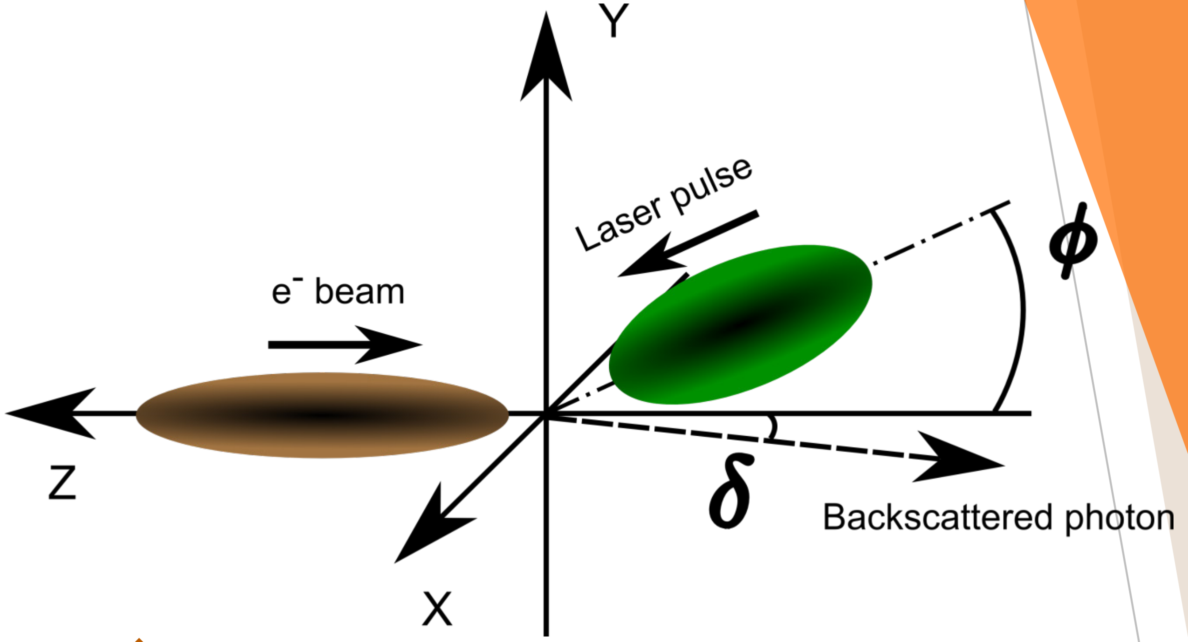

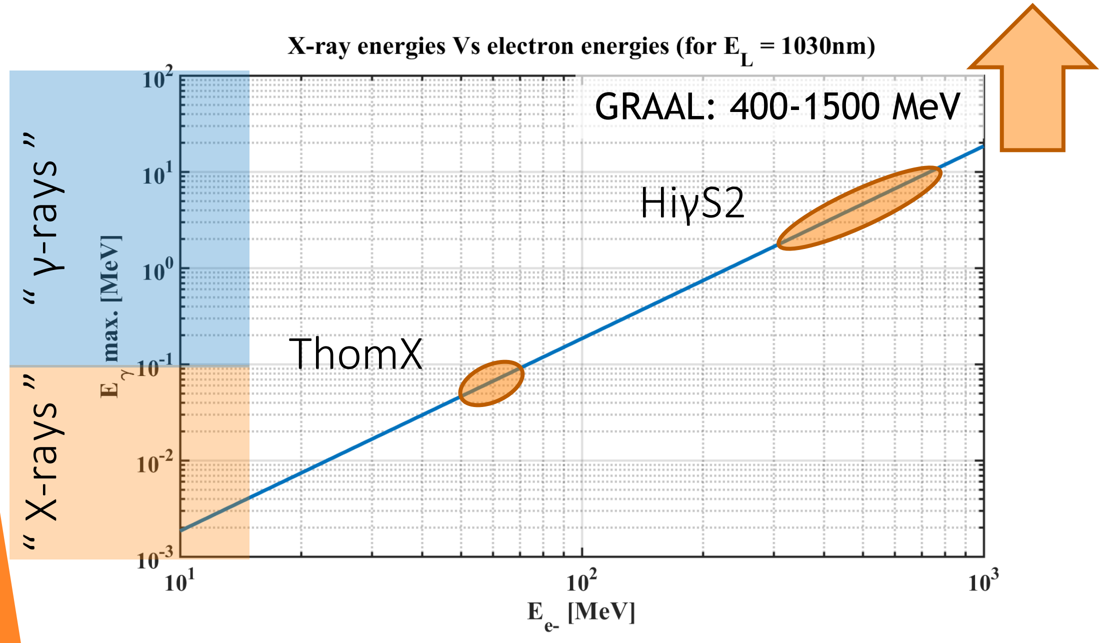

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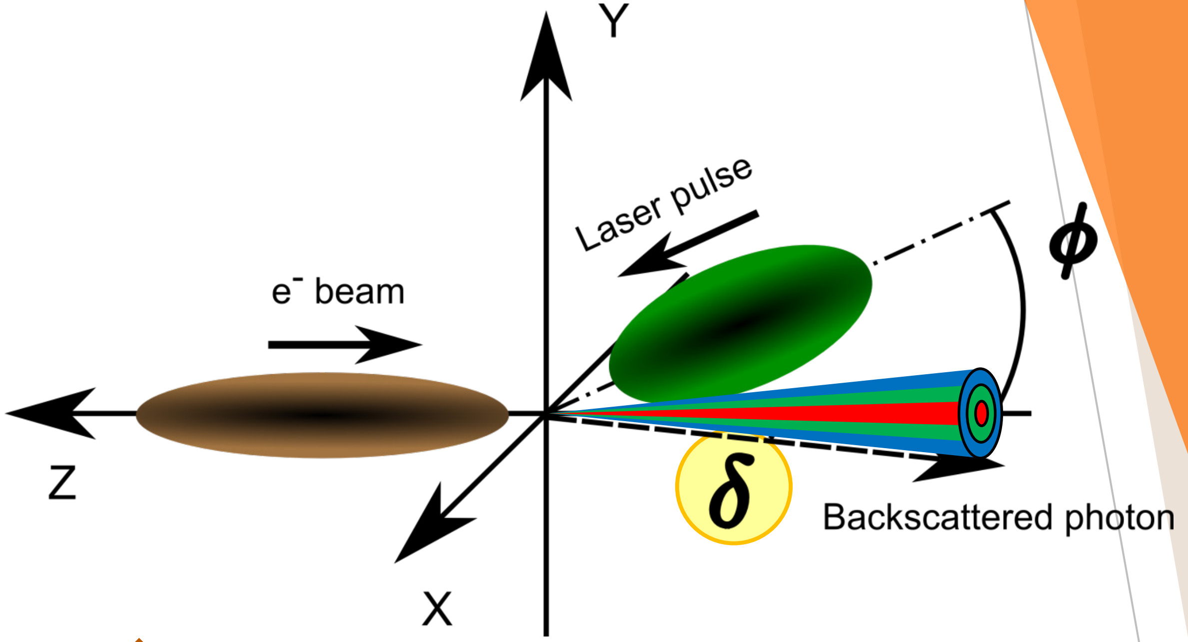

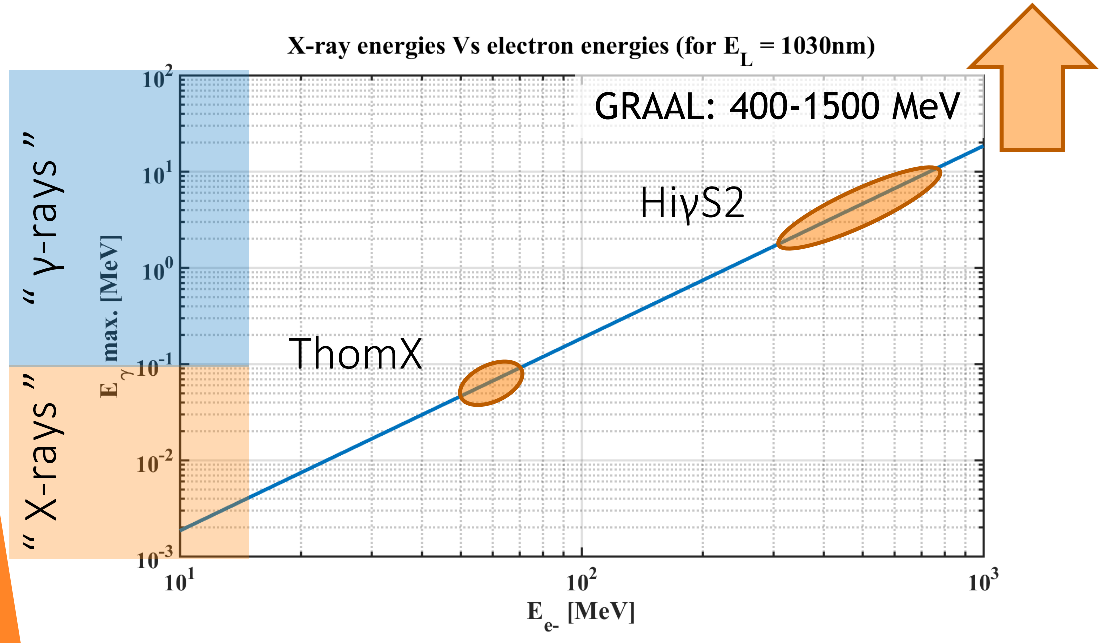

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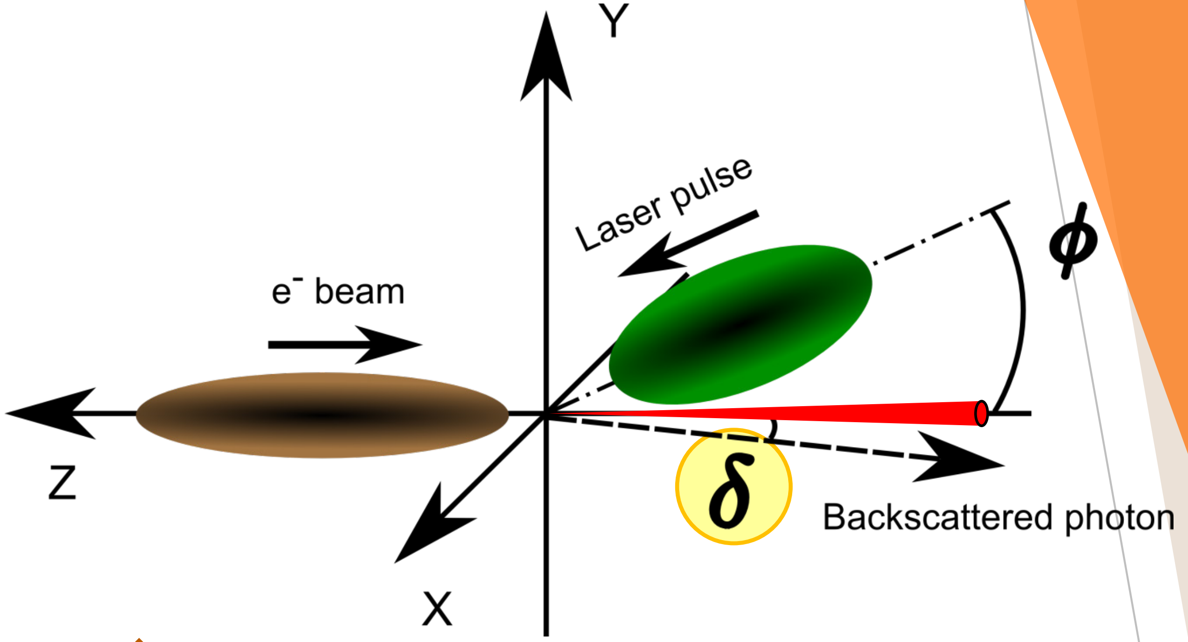

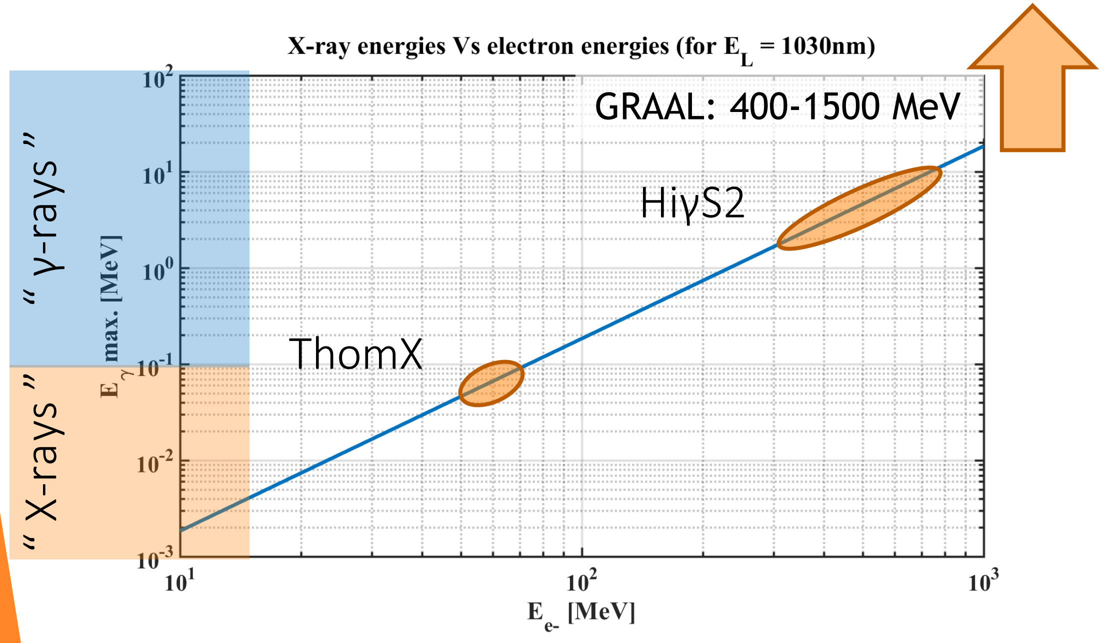

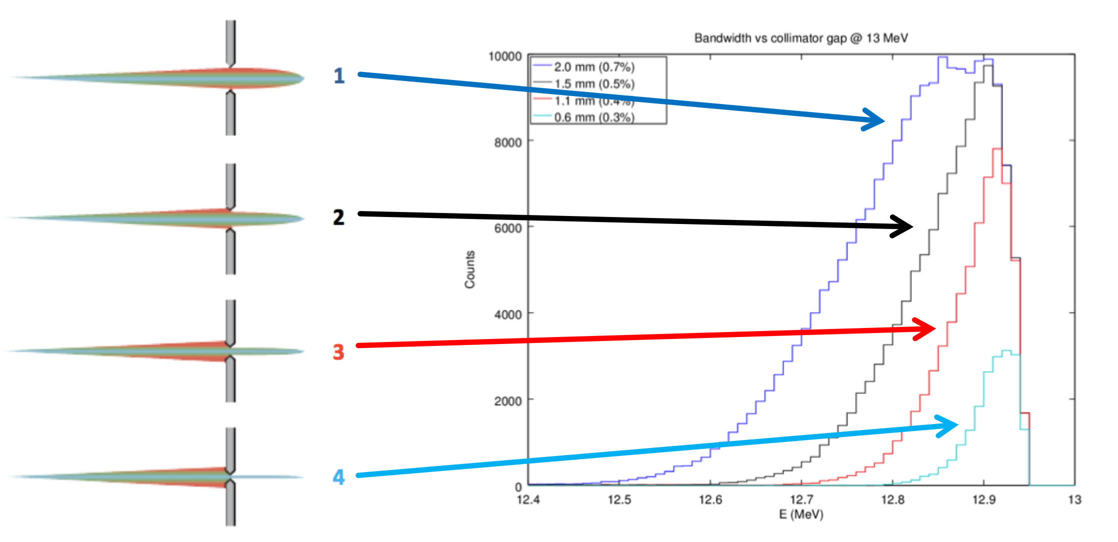

M. Gambiccini, P. Cardarelli et al. technical design meeting collimation and characterisation system review

Compton source: schematic

$$\left\langle \frac{\mathrm{d}N}{\mathrm{d}t} \right\rangle = \sigma_T \mathcal{L}$$

Compton source: schematic

Cross section≈ physics

$$\left\langle \frac{\mathrm{d}N}{\mathrm{d}t} \right\rangle = \sigma_T \mathcal{L}$$

$$\sigma_T \approx 6.6 \times 10^{-25}\ \mathrm{cm}^2$$

➔ Compton/Thomson cross section

Compton source: schematic

Cross section≈ physics

$$\left\langle \frac{\mathrm{d}N}{\mathrm{d}t} \right\rangle = \sigma_T \mathcal{L}$$

Luminosity ≈ geometry

$$\mathcal{L} \approx \frac{f_{rep} N_e N_L}{2\pi\left(\sigma_e^2 + \sigma_L^2\right)}$$

$$\sigma_T \approx 6.6 \times 10^{-25}\ \mathrm{cm}^2$$

➔ Compton/Thomson cross section

Compton source: schematic

Cross section ≈ physics

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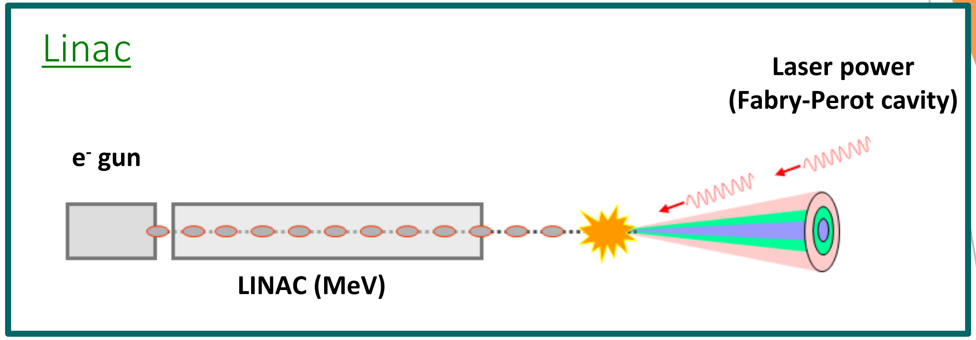
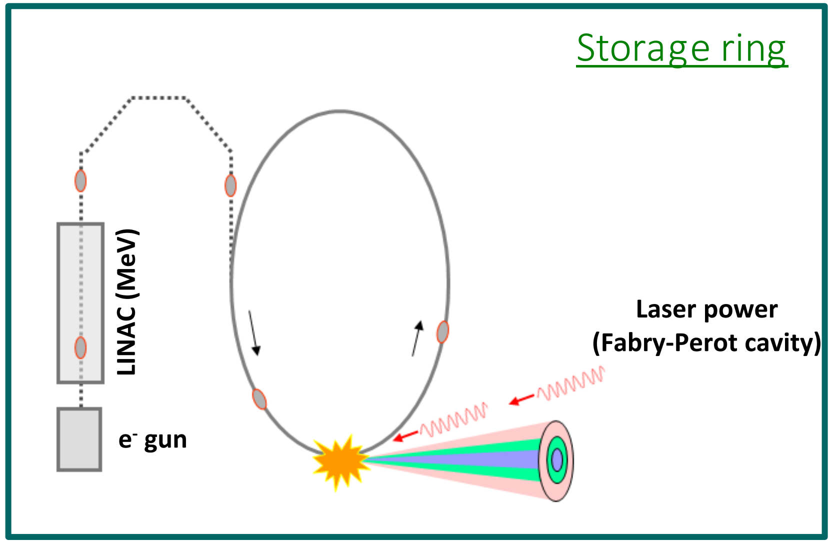
➔ Compton/Thomson cross section

2 main schemes

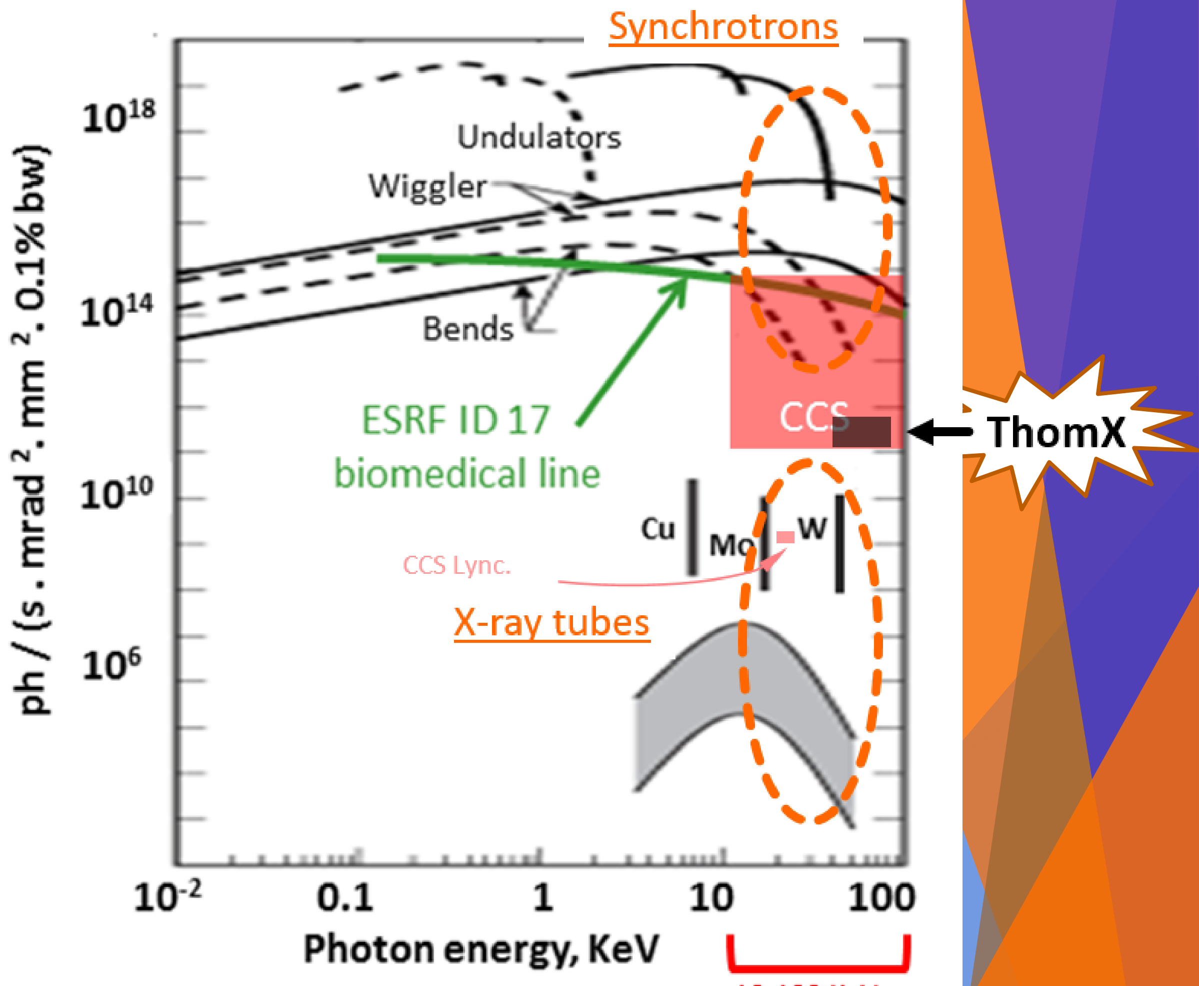




To obtain high flux: ($10^{12} - 10^{13}$ ph/sec)

- f_{rep} (~ 10-100 MHz)
- Laser power= 100kW – 1MW
- e^- charge= ~1 nC/bunch

X-ray sources - Brightness



Physica Medica 32 (2016) 1790–1794

X-ray sources - Brightness

Synchrotrons :

Large-scale facilities, limited access time
High degree of : power, monochromaticity, coherence

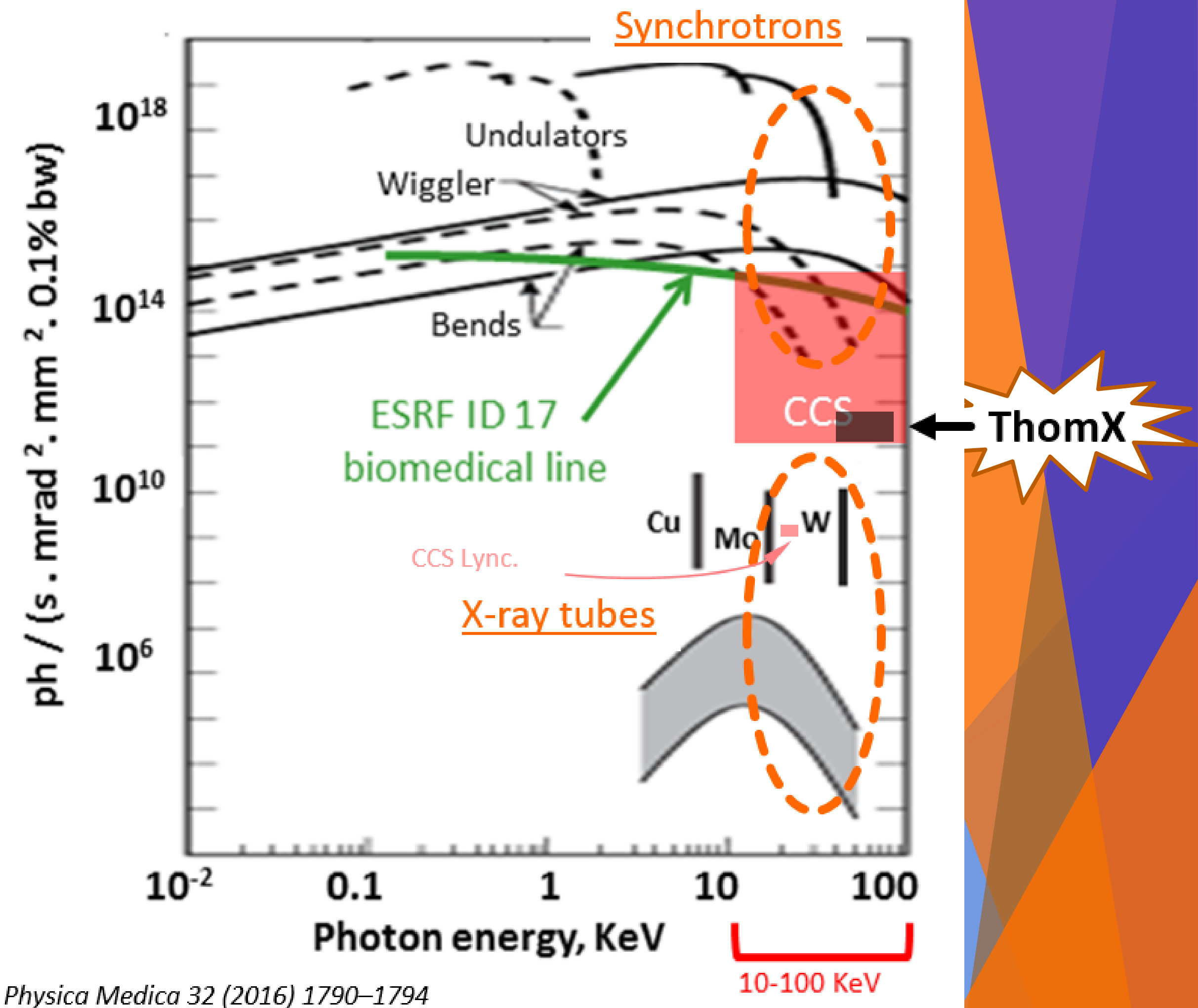
Compact Compton sources :

High brightness beam on **the laboratory-scale facilities** (hospitals, labs, museums…)
Beam is produced in a untypical way

- **Compactness** (footprint ~ 100 m^2)
- **Tunable X-ray beam energy**
- **Large X-ray energy range (keV to MeV)**
- High brightness $10^{11} – 10^{13}$ ph/(s.mm^2.$mrad^2$) in 0.1% BW
- Flux 10^{12} - 10^{13} ph/s

X-ray tubes :

Laboratory-scale sources
Lack of: power, monochromaticity, coherence



Physica Medica 32 (2016) 1790–1794

ThomX facility

Compact Compton light source

ThomX : inside the Orsay campus

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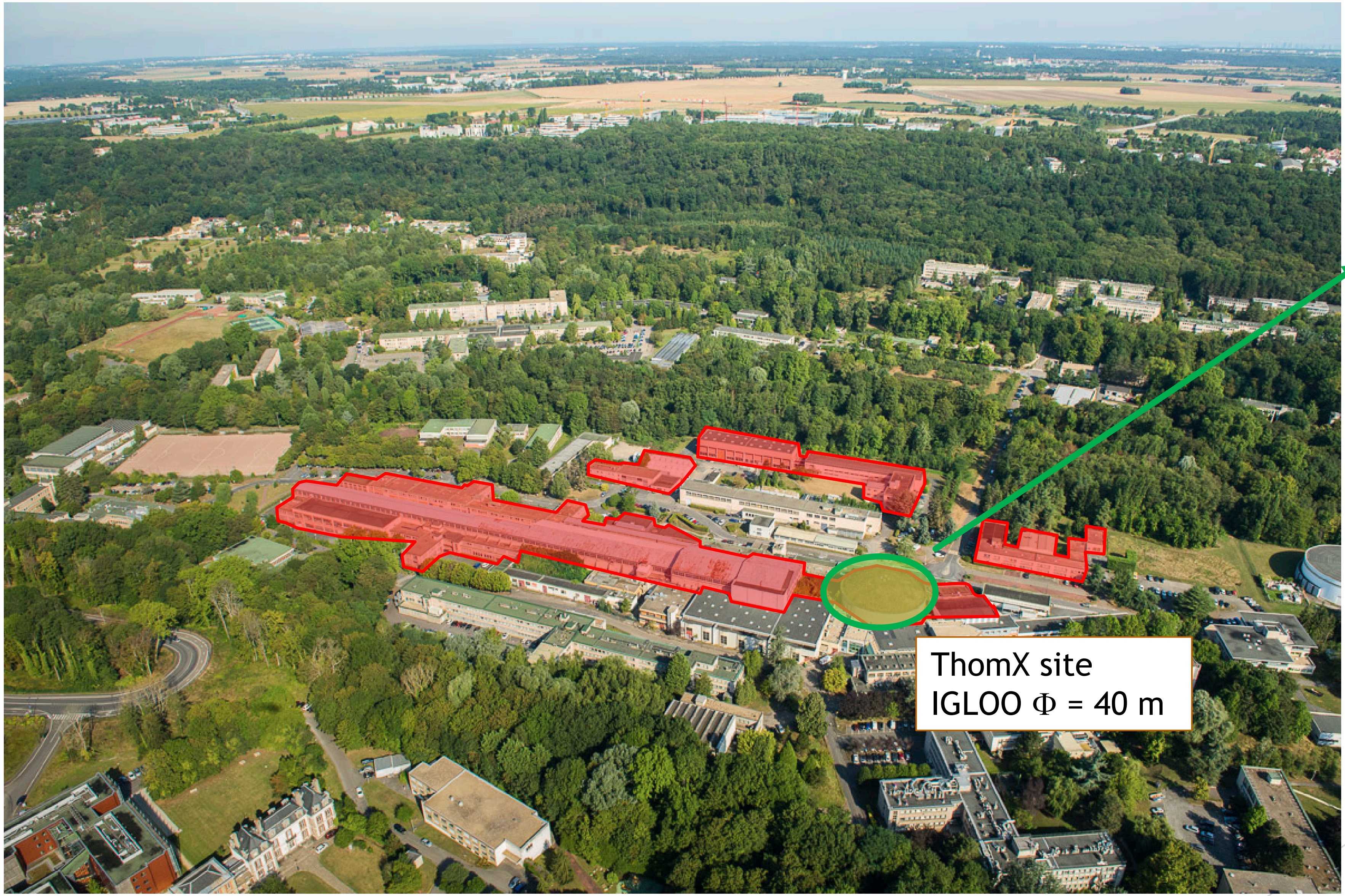


Paris-Saclay

ThomX facility

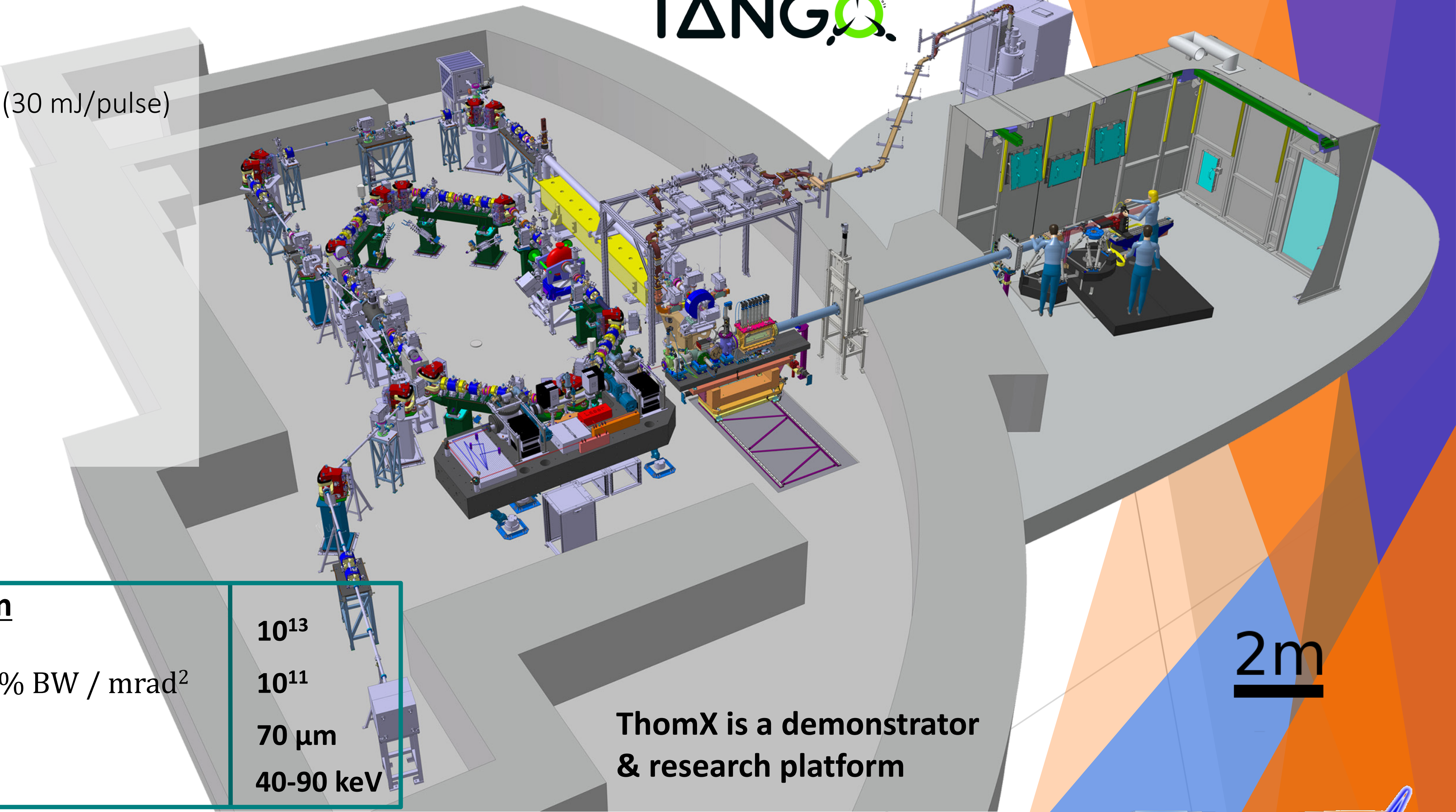
ThomX control system is based on TANGO

ThomX is a demonstrator & research platform

2m

ThomX facility

ThomX control system is based on TANGO



Laser /Cavity system

- average power 100W
- **Stored power up to 1 MW** (30 mJ/pulse)

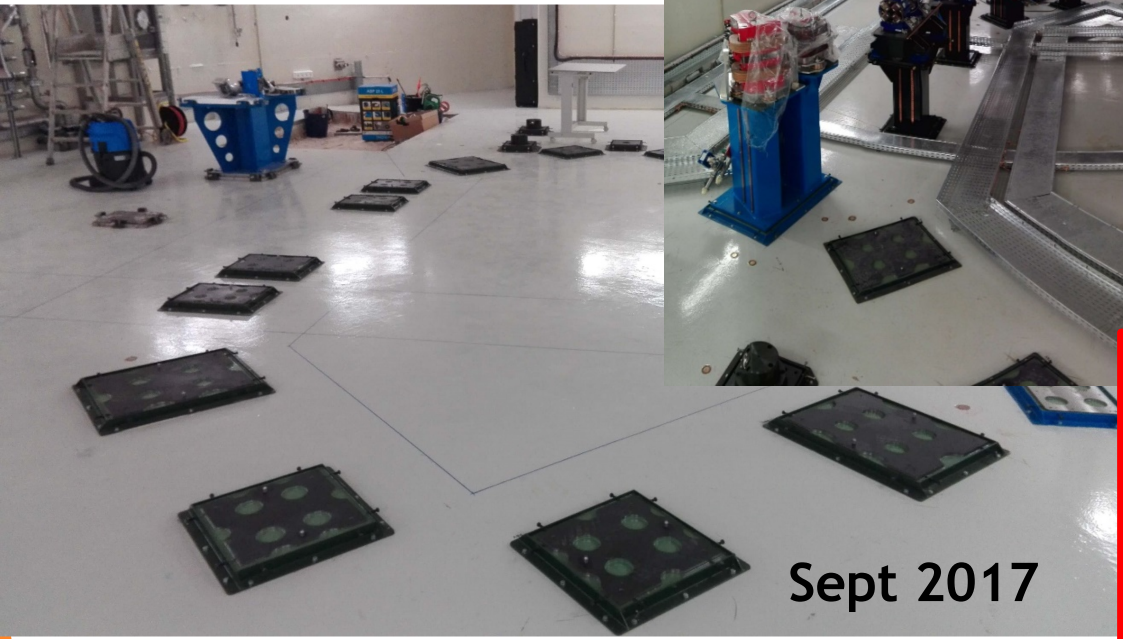
Accelerator

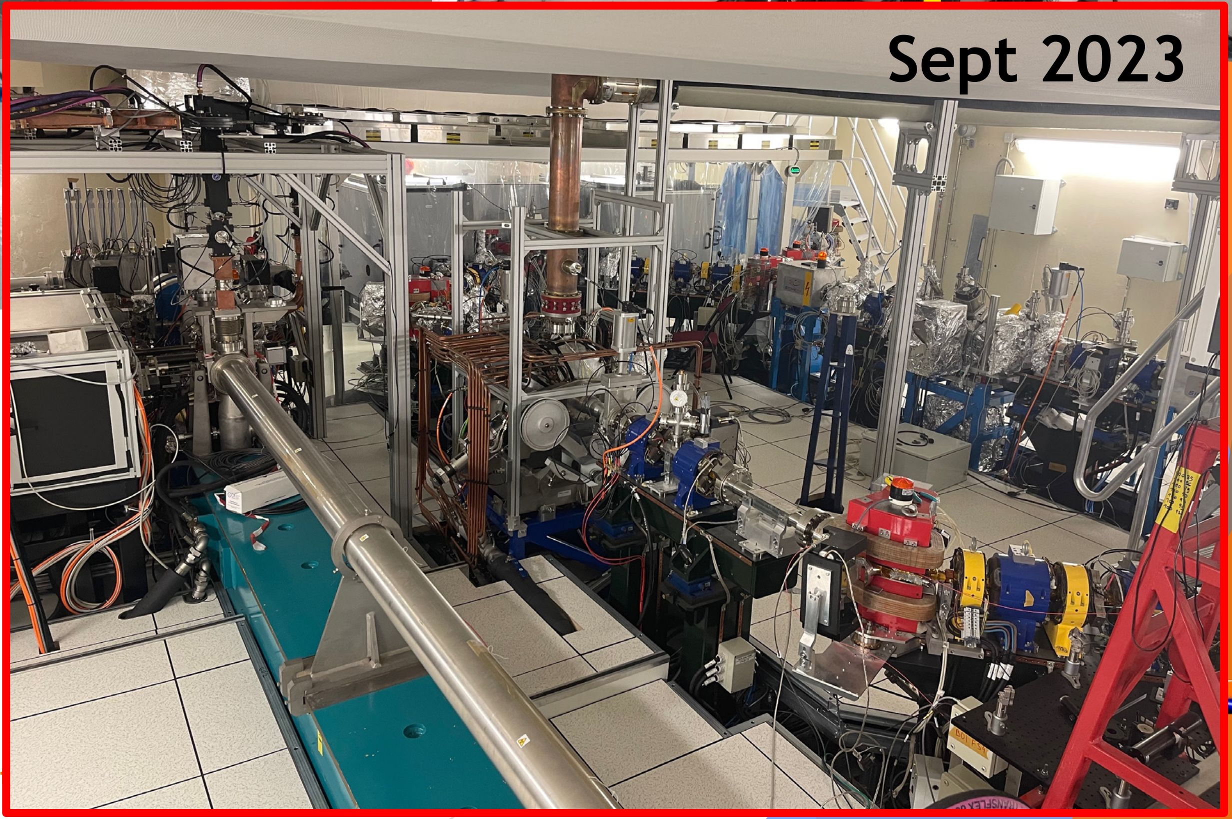
- 1 nc / bunch, f_{rep} 50 Hz
- **50-70 MeV**
- Ring, f_{rep} 16 MHz
- **σ_e ~ 70 µm**
- **ε_N ~ 5-10 mm.mrad**
- τ_e ~ 10-30 ps

X-ray beam	
Flux ph/s	**10^{13}**
Brightness ph/s/ mm^2 / 0.1% BW / mrad^2	**10^{11}**
Transverse size of the source	**70 µm**
E_X on axis	**40-90 keV**

ThomX is a demonstrator & research platform

ThomX integration



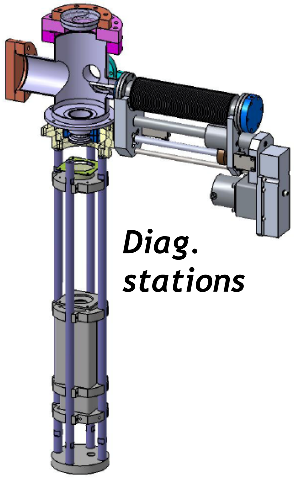


From 2017 to 2023

ThomX beam diagnostics

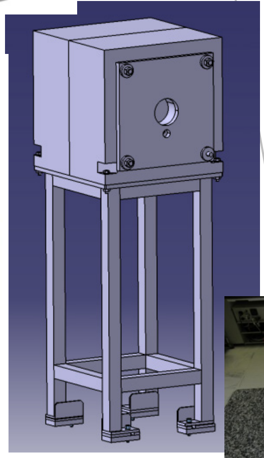
- <u>Charge</u> (3 ICT from Bergoz @ linac entrance, @ linac exit, @ TL + 2 Faraday cups @ beam dumps + 12 BPM in the SR)
- <u>Position</u> (linac/TL: 5 stripline BPM (150 mm), SR: 12 BPM button-type with 4, 6 and 8 electrodes)
- <u>Diagnostics stations</u> (5 stations on linac/TL/EL: calibration plate, YAG/Ce, OTR 100 µm thick screens + Sapphire plate + hole array)
  - transverse profile (imaging system)
  - emittance (quadrupole scan)
  - energy (hor. beam position and size after the dipole)
  - bunch length (Cherenkov radiation + streak camera)
- <u>Bunch transverse profile and bunch length in the SR</u> (Visible Synchrotron Radiation Monitor ➜ synchrotron radiation from a dipole + CCD/streak camera)
- <u>Beam Losses</u> (optical fibers, scintillators).

In-flange ICT & Electronics



Diag. stations

Screen translation stage



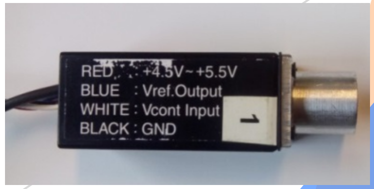
Beam dump

Wavecatcher

Libera Brilliance +

Hammamatsu streak camera

CsI(Tl) + PMT



Fiber beam loss monitor

ThomX facility: milestones

2007 2009 2011 2013 2015 2017 2019 2021 2023 2024

- 2007 : First discussion at LAL (Now IJCLab)
- Jun. 2009 : Conceptual Design Report
- 2012 Funding : French Equipex (ANR-10-EQPX-51)
- 2 Apr. 2014 : Technical Design Report
- 2016 : Building rehabilitation + facility assembly
- 19 May. 2021 : Phase I authorization from French Nuclear Safety Authority
- 29 Jul. 2022 : Phase II authorization from French Nuclear Safety Authority
- 23 Jun. 2023 : First detection of X-rays

AUTORITÉ DE SÛRETÉ NUCLÉAIRE

Phase of operation (ASN)	Max. e- energy (MeV)	Bunch charge (nC)	Repetition frequency (Hz)	Description
I	50	0.1	10	LINAC
II	50	0.1	10	INJECTOR + ring
II(bis)	50	0.1(1)	10 (50)	INJECTOR + ring + X-rays
III	70	1	50	Nominal operation

ThomX commissioning

Linac, Transfer Line and Extraction Line

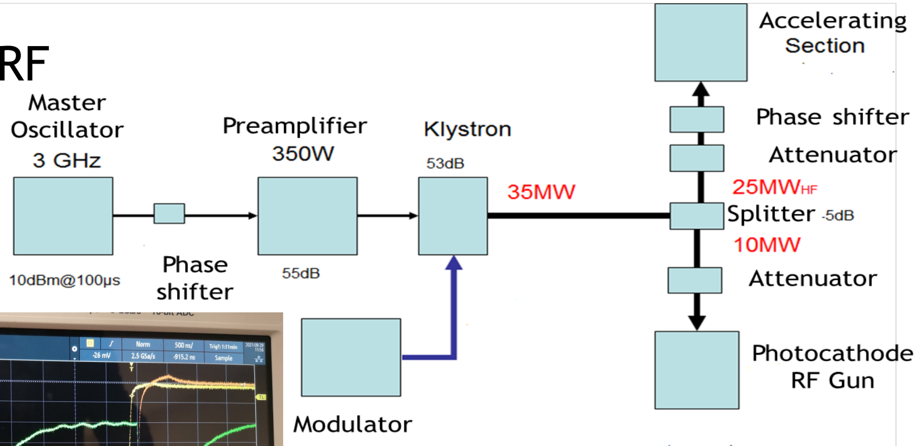
ThomX injector

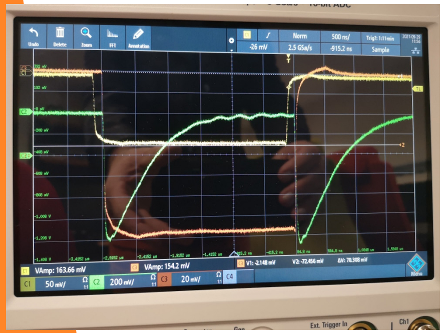
Injector specification

Parameter	Nom. value	Measured	Units
Energy	50/70	50*	MeV
Charge, commissioning/nom.	0.1/1	0.1*	nC
Nb. of bunches per RF pulse	1	1	
Energy spread, rms	<1	0.02	%
Emittance (rms, normalized)	<5	<5	mm·mrad
Bunch length, rms	<5	-	ps
Average current	50	1	nA
Pulse repetition rate	50	10*	Hz

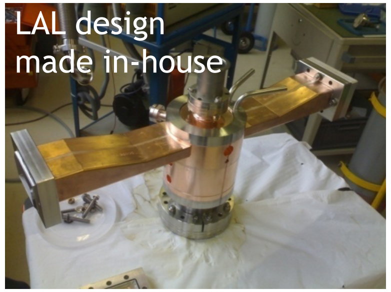
*Limited by the ASN authorization (phase 2bis)

Linac RF





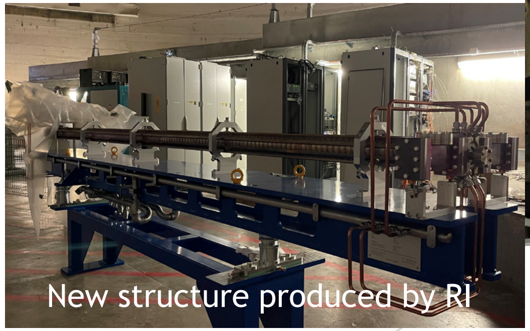
New accelerating structure :
L = 3.2 m, 18.5 MV/m @ 18 MW
For the 70 MeV upgrade



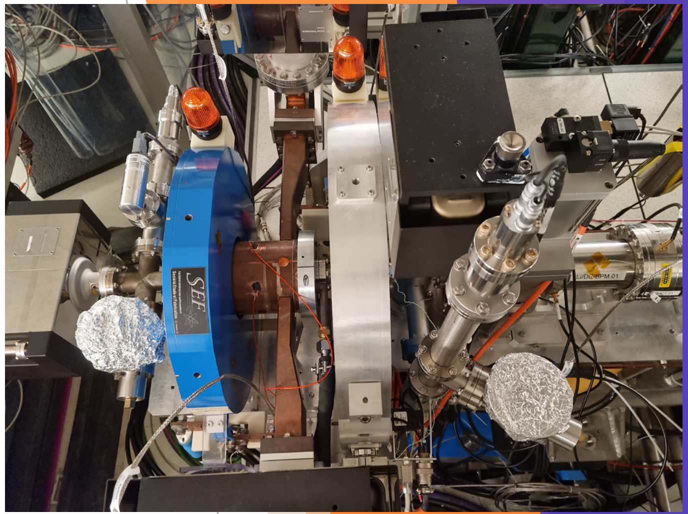
ScandiNova 3 GHz modulator
Toshiba klystron E37310

➜ 2.5-cell RF gun : Ez = 80 MV/m @ 6 MW to reach E = 5 MeV, Charge 0.1/1 nC

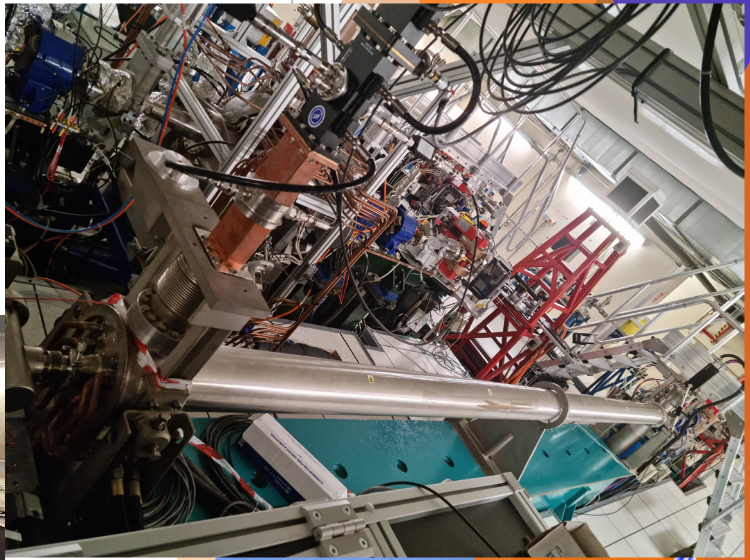
➜ LIL type 4.8-meter long accelerating structure (2998.55 MHz) to reach ~45 MeV @ 9 MW



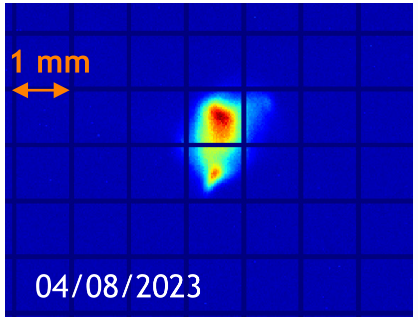
Photocathode RF gun

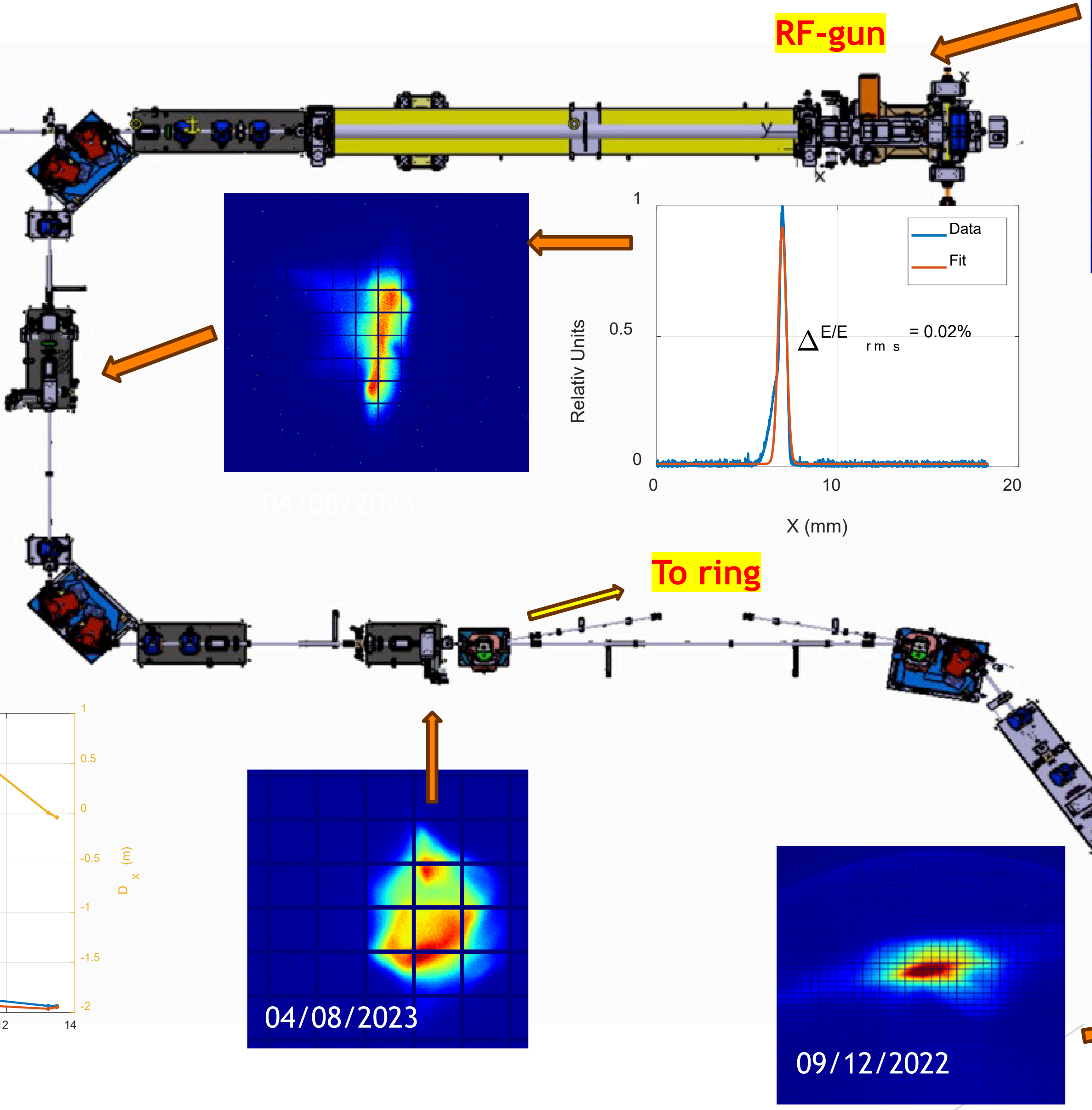


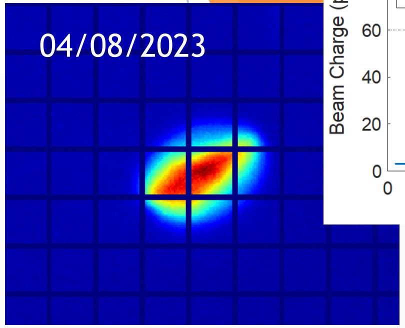
Accelerating structure

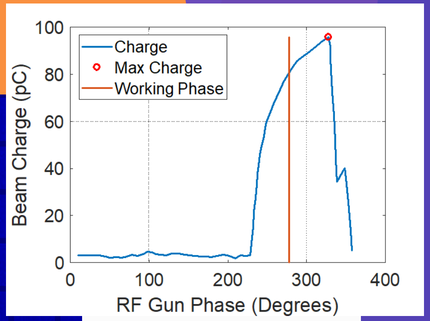


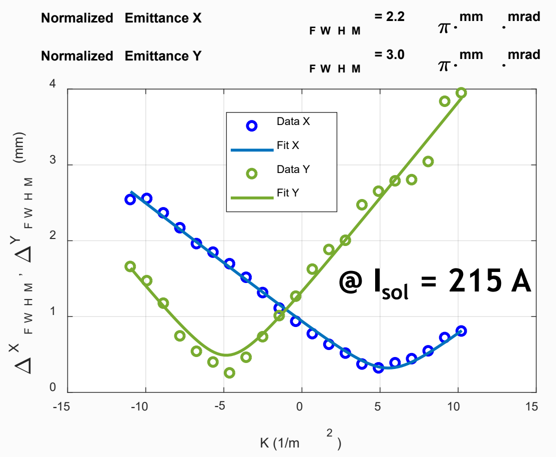
Linac, Transfer Line and Extraction Line



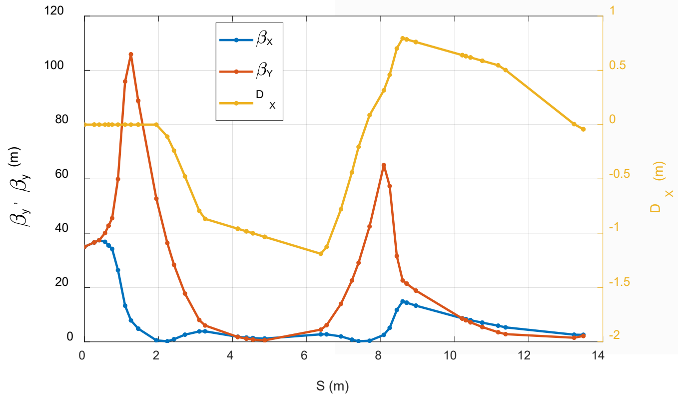




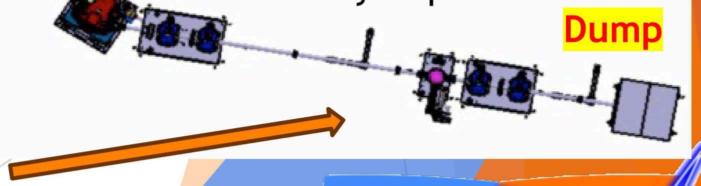




- 6 Dipoles
- 14 Quadrupoles
- 2 Dipoles for inj./extr.
- 8 Correctors



- 7 BPM
- 5 Diagnostic stations
- 3 ICT
- 2 Faraday Cups



System of linear equations for the thick lens approximation is solved c.f. M.C. Ross et al. PAC87

ThomX commissioning

Storage Ring

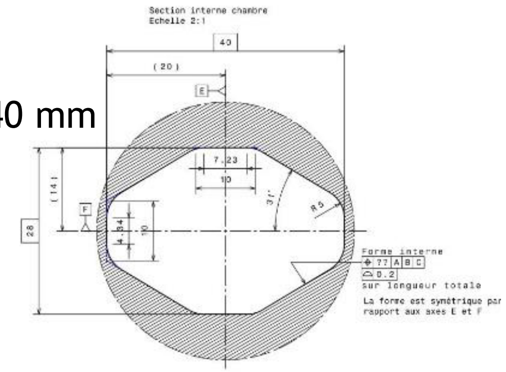
Ring lattice and parameters

- 8 Dipoles
- 24 Quadrupoles
- 12 Sextupoles
- 2 Kickers
- 1 Septum
- 1 RF cavity
- 12 BPM
- 12 Correctors

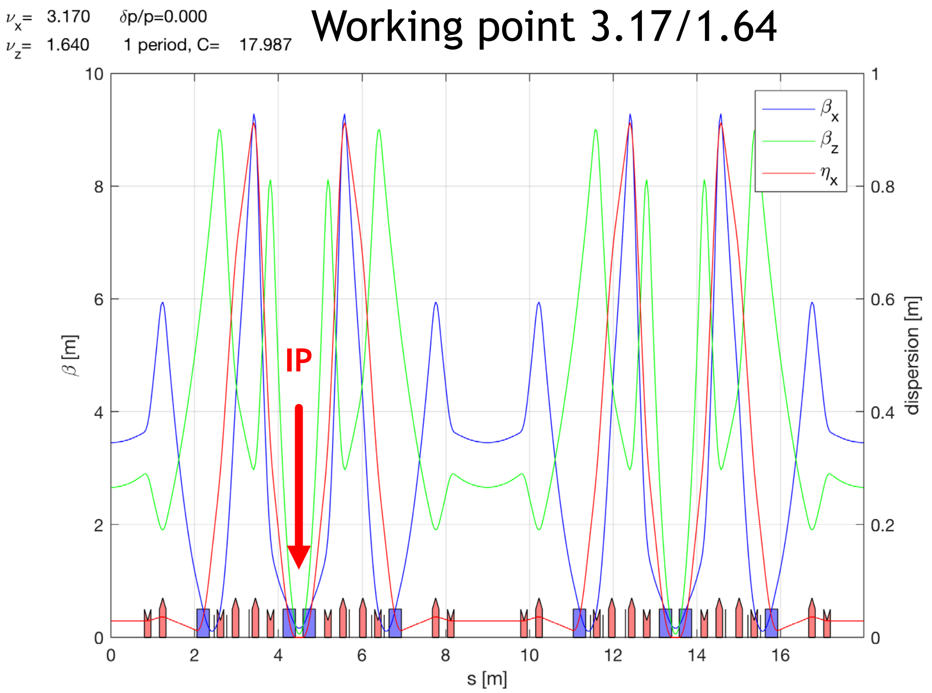
ThomX SR: L = 18 m, T = 60 ns, f_{rep} = 16.7 MHz

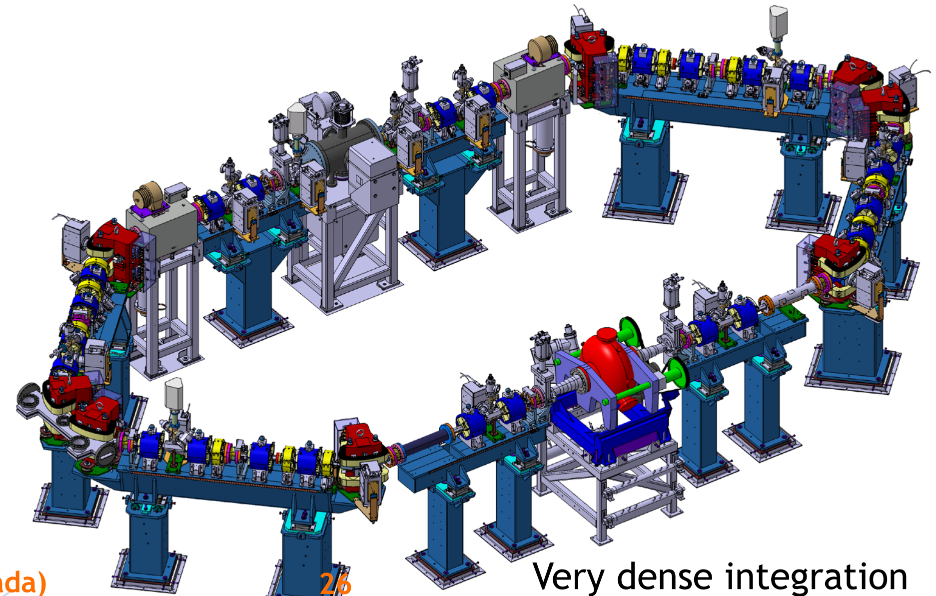
Parameter	Value/Units
Beam energy	50-70 MeV
Bunch Charge	1 nC
Bunch length (rms)	~30 ps
Circumference	18 m
Revolution frequency	16.7 MHz
Current	16.7 mA
RF frequency/Harmonics	500/30 MHz
Momentum compaction	0.0125 - 0.025
Betatron tunes	3.17/1.64
Natural chromaticity	-9/-13
Damping time trans./long.	1.2/0.6 s
Repetition frequency	50 Hz (20 ms)
Beam size at the IP	70 µm
Nominal RF Voltage/cavity	300 kV (500 kV max)
Energy loss per turn	1.57 eV

28x40 mm



Working point 3.17/1.64



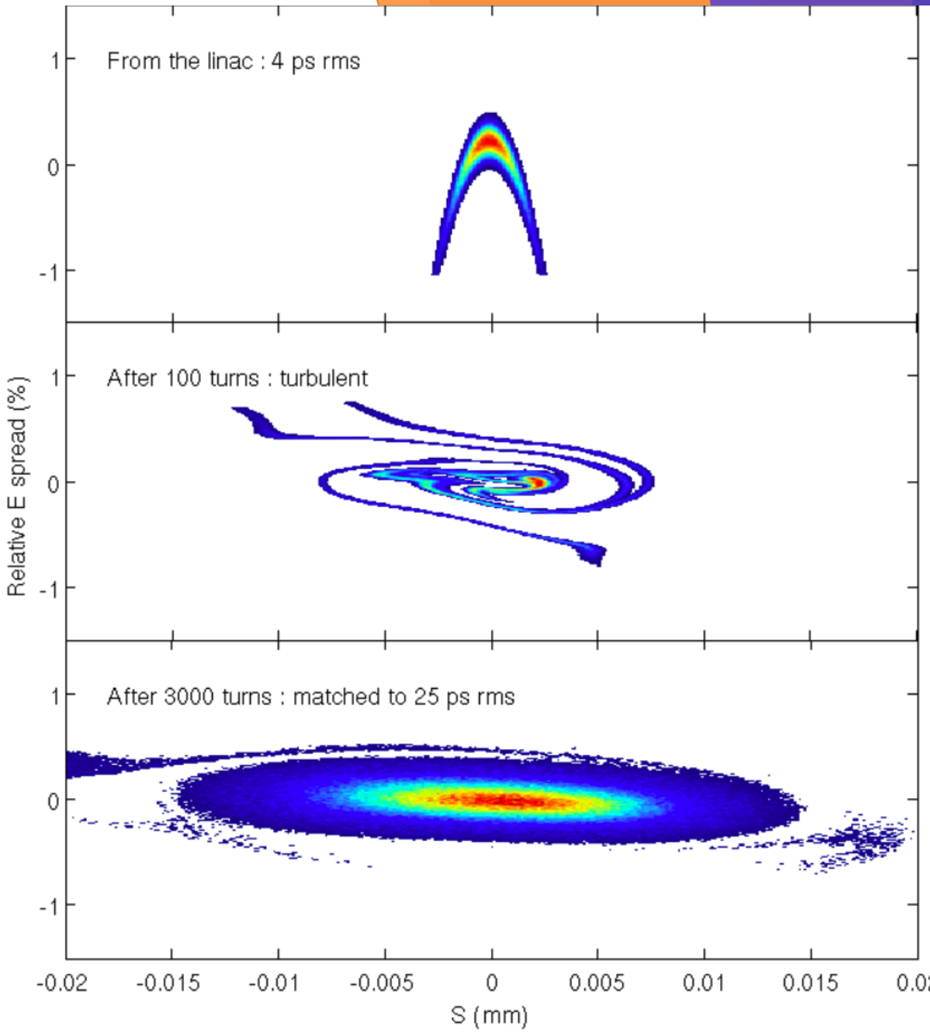


Very dense integration

Ring beam dynamics

The operation and its commissioning is a big challenge due to:

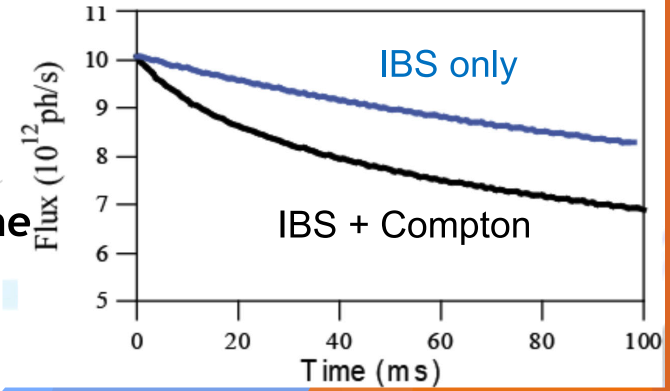
- high particle density (1 nC/bunch) and low energy operation (50-70 MeV)
- mismatched beam injection
- absence of the synchrotron damping (stored time << damping time)
- strong impact of collective effects (intrabeam and Compton scattering, coherent synchrotron radiation, ion instabilities, etc.)



Beam dynamics is very different from usual dynamics in synchrotrons

- longitudinal mismatch of the injected bunch and strong coherent synchrotron radiation => a transient microbunching regime (~ 10 µs). Still controlled at lower charge <100 pC but beam losses and increase in transv. emittance @higher charge (~ 1 nC).
- the intrabeam and Compton scattering, Touschek effect act on the beam dynamics in long term (~ ms) compared to the transient regime => beam losses, increase in transv. emittance and energy spread

Degrade the beam quality and so reduction of the X-ray flux

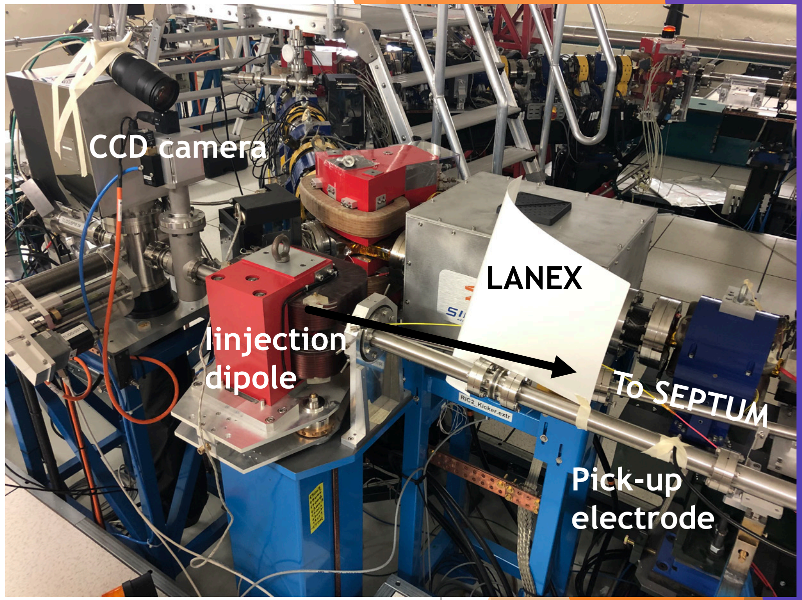


Commissioning steps and results

Injection. BPM single pass and turn-by-turn data, BLM signals.

Phase	Description
B.1	**Injection and first turn :** injection, threading, commissioning beam instrumentation
B.2	**Establish circulating beam:** closed orbit, orbit correction, tunes, chromaticity
B.3	**Stored beam and extraction:** precise measurements, BBA, feedback systems, beam diagnostics (SRM)
B.4	**Machine physics:** LOCO, beta beating, beta function and dispersion, diagnostics, beam dynamics studies

The fast injection and extraction are ensured by a septum and two fast kickers implying single-turn on-axis injection



- Transfer Line : Hor/Vert steerers. Screen and BPM before injection dipole
- Search for proper injection dipole, septum and kicker parameters
- Goal: find signal on the first BPM in the ring + threading
- No signal 😱😩
  - We temporary added custom/simple diagnostics : scintillator, fiber, LANEX screen, pick-up electrode near beampipe to facilitate the first injection
  - Discovered wrong BPM cabling and unplugged BPM

Commissioning steps and results

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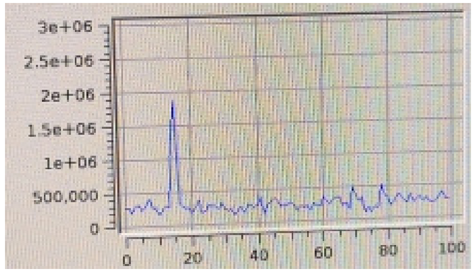
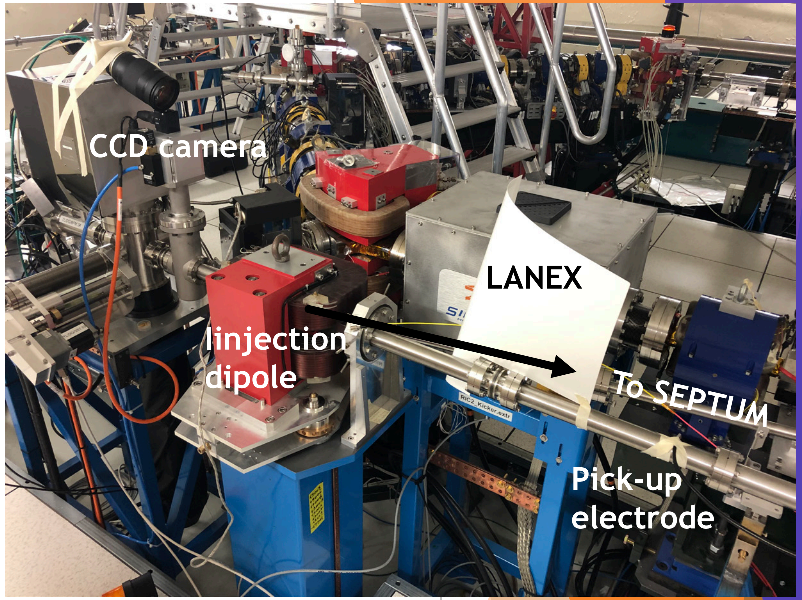
9 Sept 2022 : 1st BPM signal





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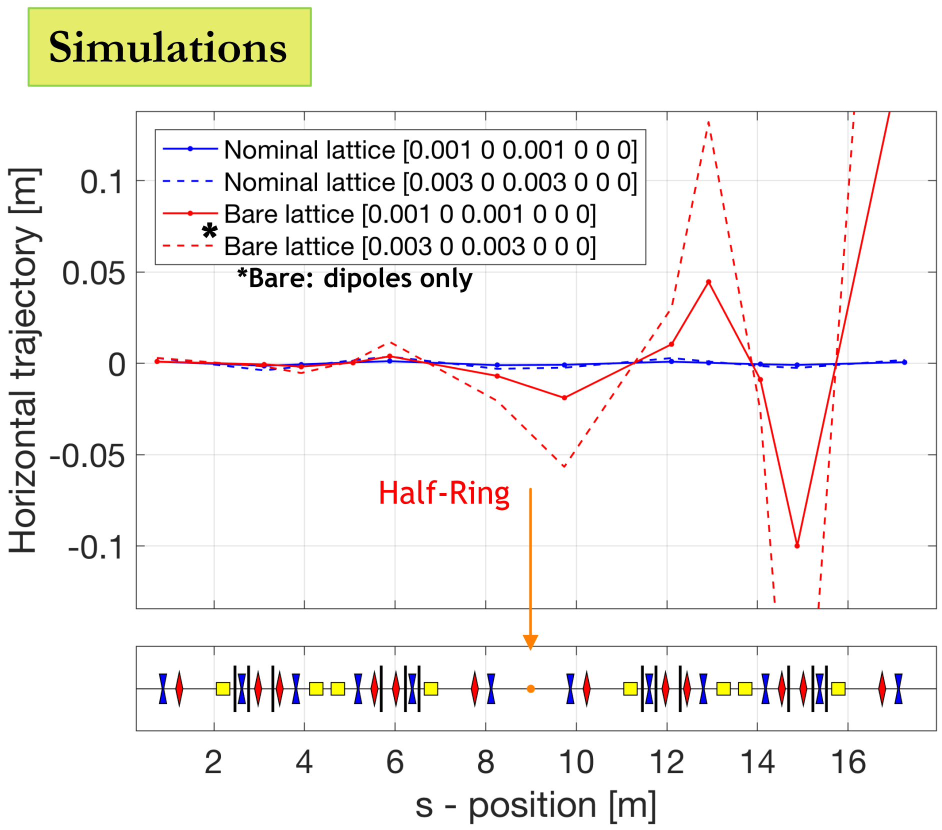
  - Discovered wrong BPM cabling and unplugged BPM
  - BPM signal was detected 👍

Commissioning steps and results

First turn. BPM single pass and turn-by-turn data, BLM signals.



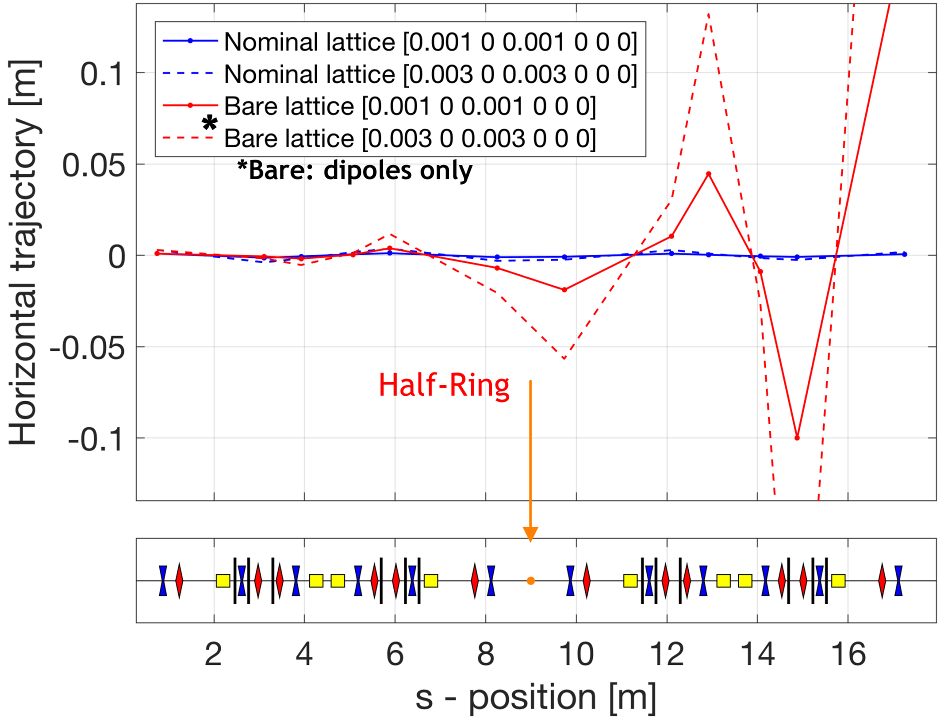
- Signal on the first BPM in the ring : OK
- With only dipoles : beam passes a half-ring (in agreement with simulations)
- Quads switched ON to nominal values : First turn?
- Manual trajectory correction. No closed orbit, ring is "open"

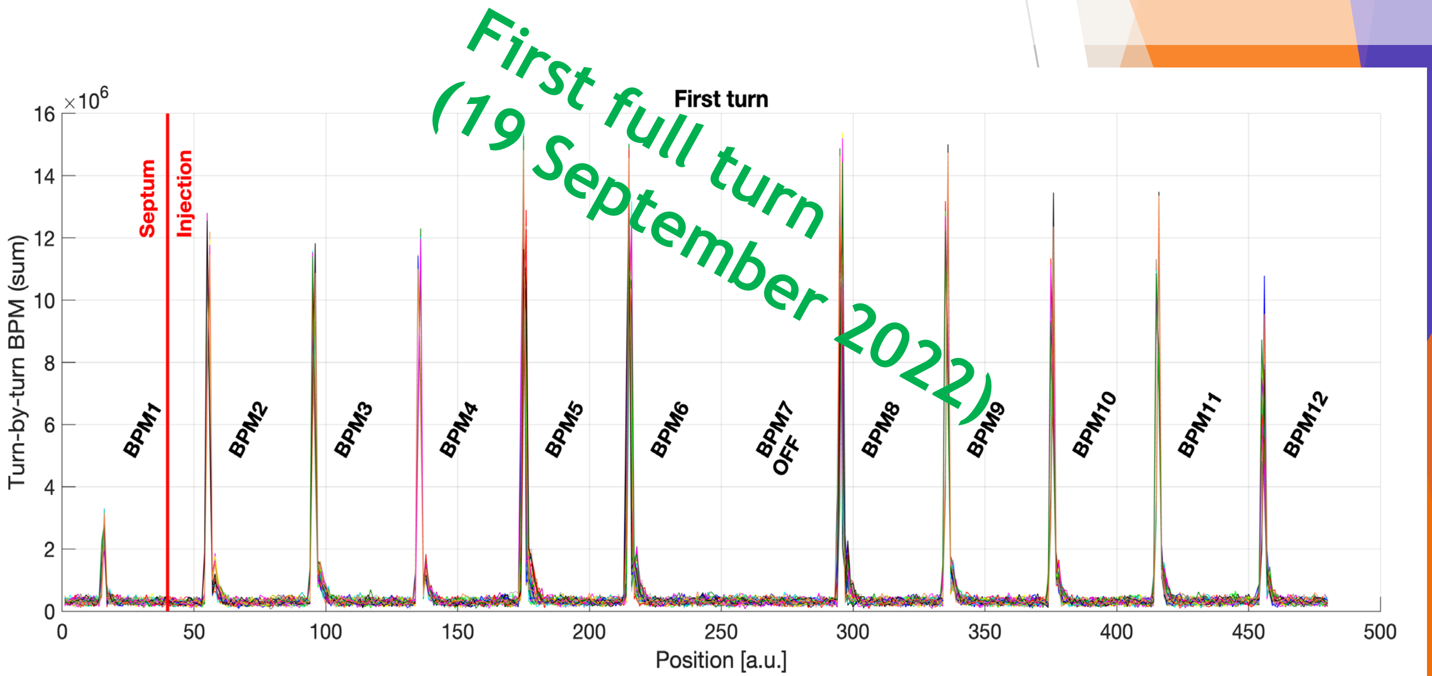
Commissioning steps and results

First turn. BPM single pass and turn-by-turn data, BLM signals.

- Signal on the first BPM in the ring : OK
- With only dipoles : beam passes a half-ring (in agreement with simulations)
- Quads switched ON to nominal values : First turn?
- Manual trajectory correction. No closed orbit, ring is "open"
- Important milestone. First turn!

Simulations





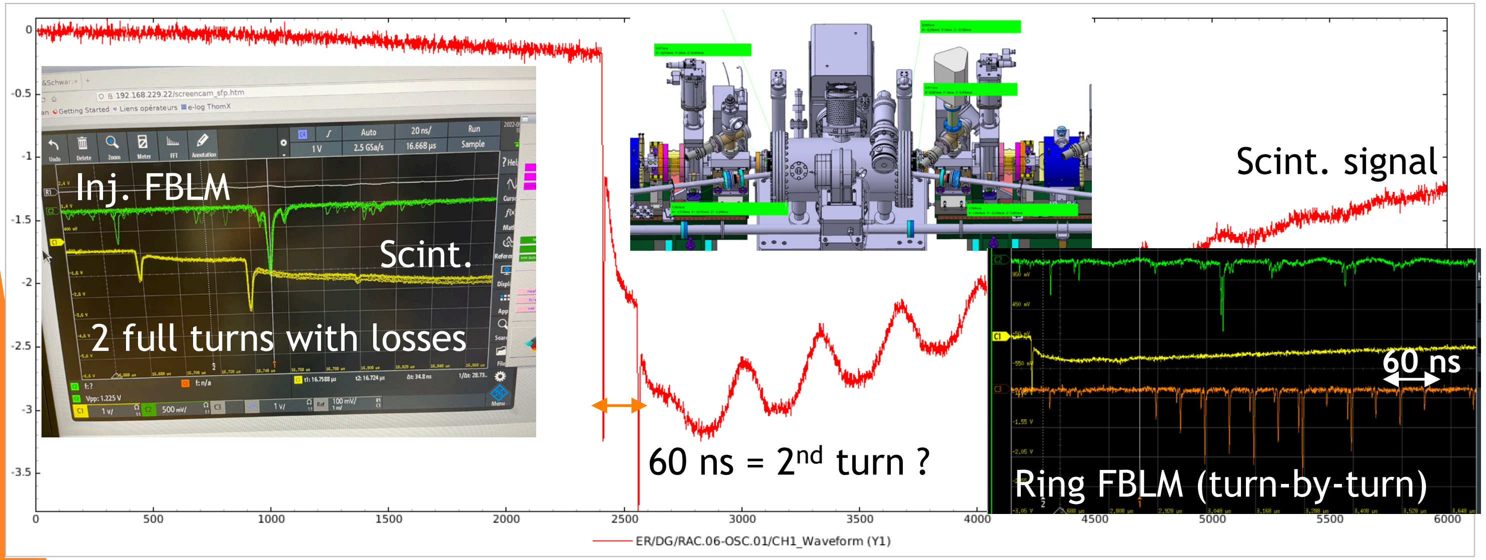
Automatic algorithm RCDS (Robust Conjugate Direction Search) to tune the injection (7 parameters)

Commissioning steps and results

Storage. BPM turn-by-turn data and BLM signals

RF cavity OFF

- Injection optimization and further trajectory correction
- SVD for trajectory correction with response matrix from the open line model
  - Improved, but no more turns. Where is the problem?
  - Obstacle? Quadrupoles?
  - Try to switch OFF the quads on the last ring sector. Sign of the presence of the 2nd and 3rd turns on BLM (scintillator and FBLM) signals
  - Quads polarity check, found one of the opposite polarity



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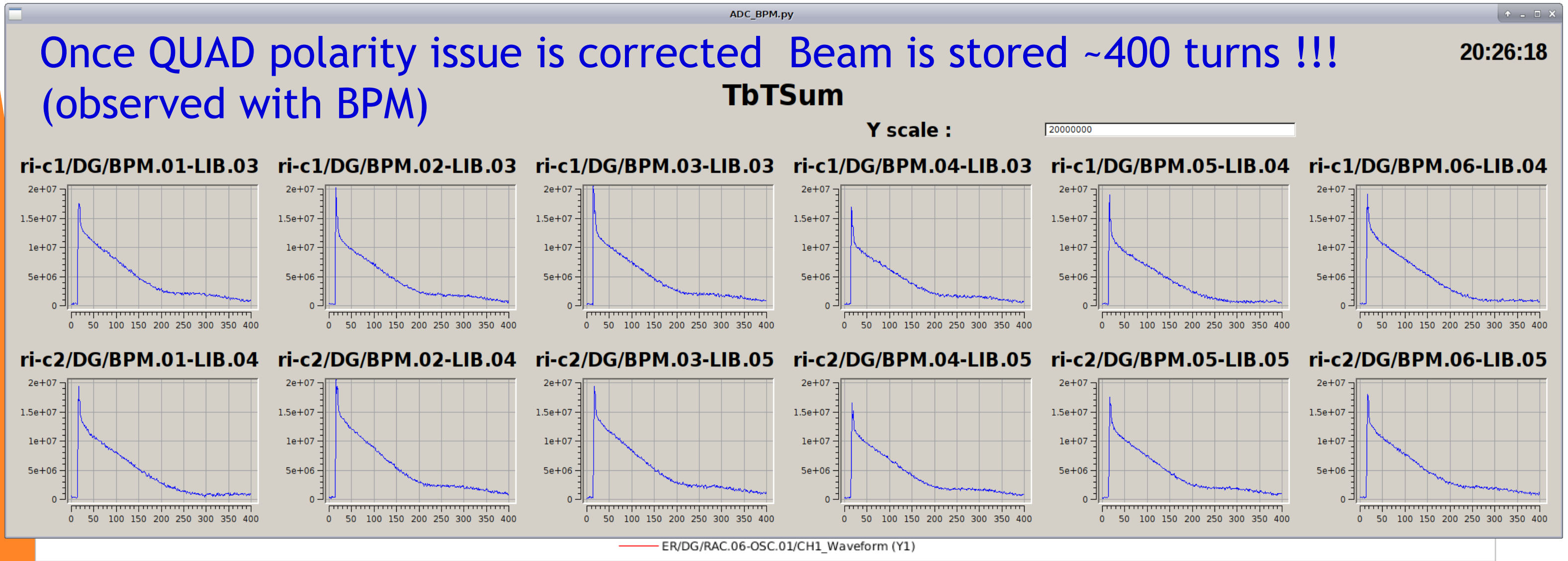
Once QUAD polarity issue is corrected Beam is stored ~400 turns !!! (observed with BPM)



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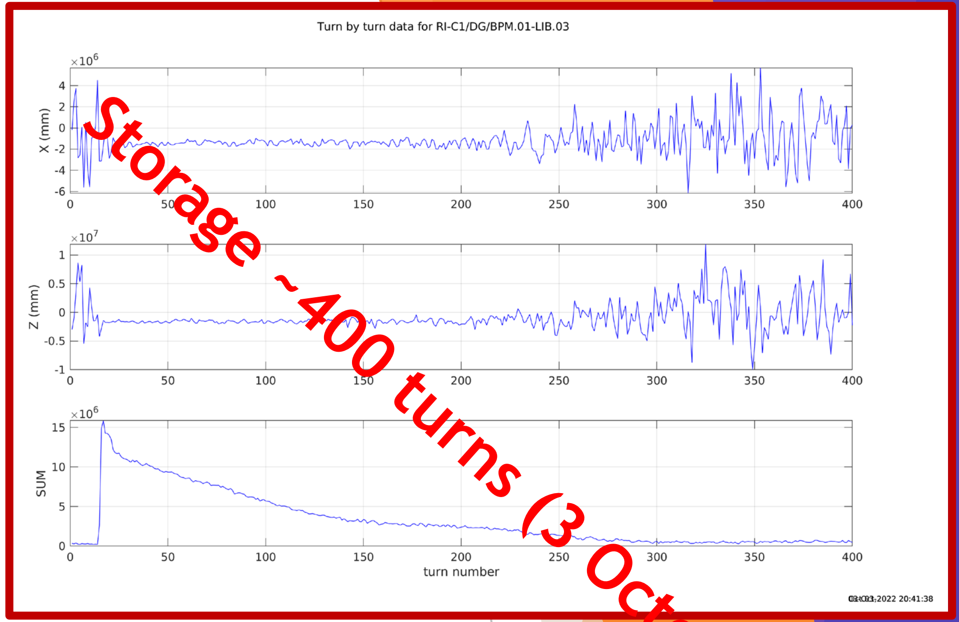
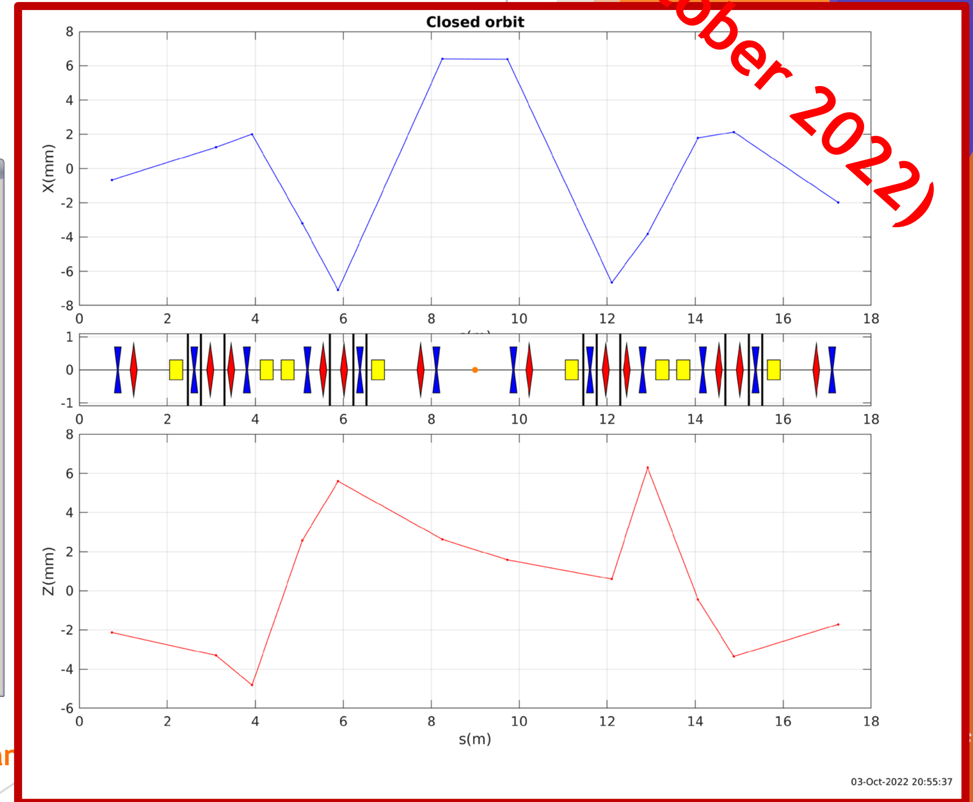
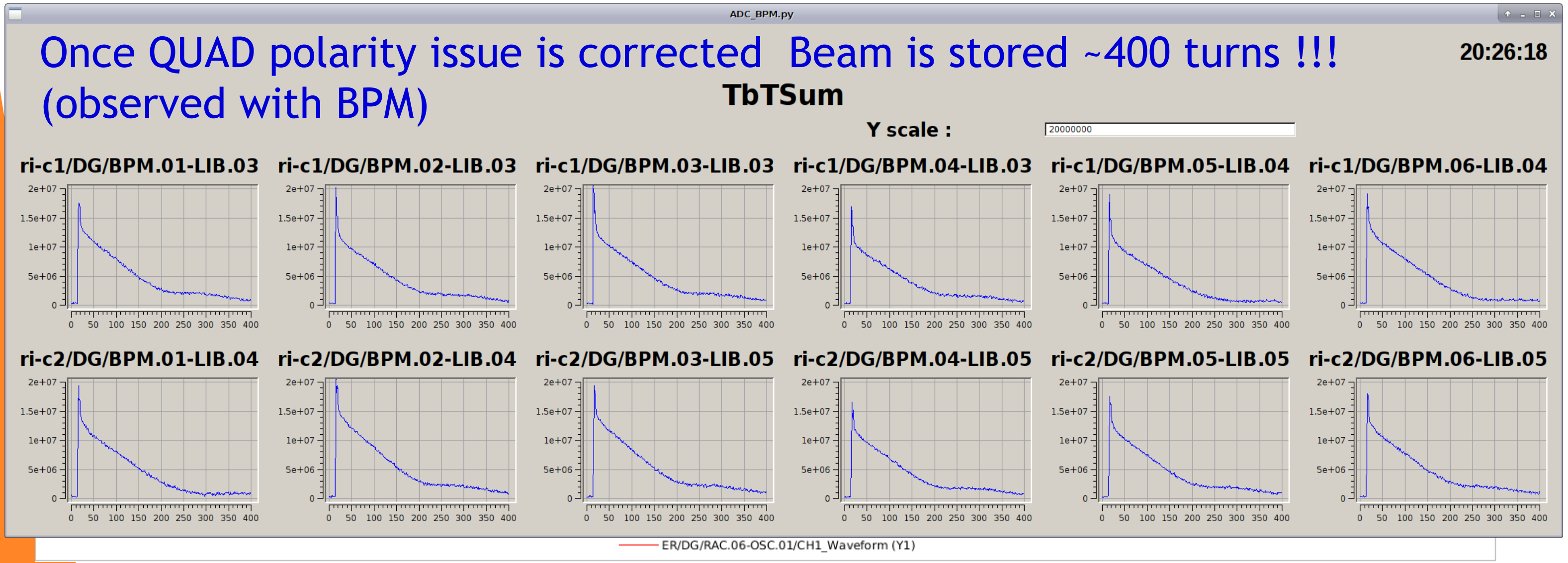
- Stable closed orbit! Important milestone is achieved 👍





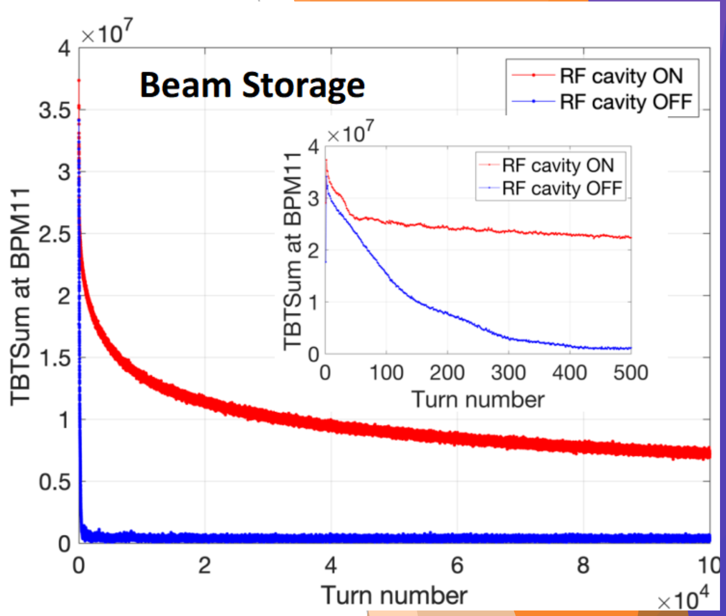


Commissioning steps and results

Storage with RF cavity. BPM and BLM signals. Turn-by-Turn data.

RF Cavity voltage ~30 kV (up to 100 kV)
f_{RF} = 500.41 MHz cf. nominal 500.02 MHz
=> **~14 mm circumference error**

- Switching the RF cavity ON : 500.02 MHz (nominal), up to 50 kV. Goal: beam storage
- No stored beam 😱 😩 Frequency matching ?
- We introduced a new observable: mixed signal from the BPM electrodes and 500 MHz from timing system (ring Low Level RF)
  - Due to this, we could observe with the o-scope when the frequency of the RF cavity matched with the revolution frequency of the e- in the ring
  - After several scans of the RF cavity frequency, we found that the beam can be stored at higher values of the RF frequency only. Why? 🤔



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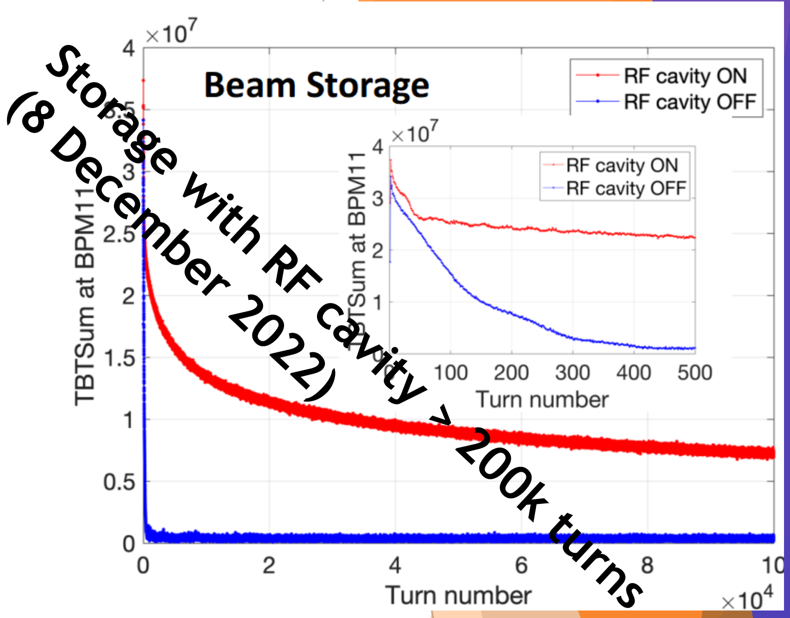
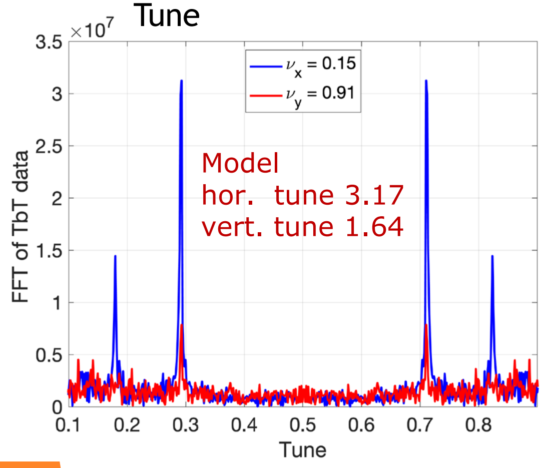
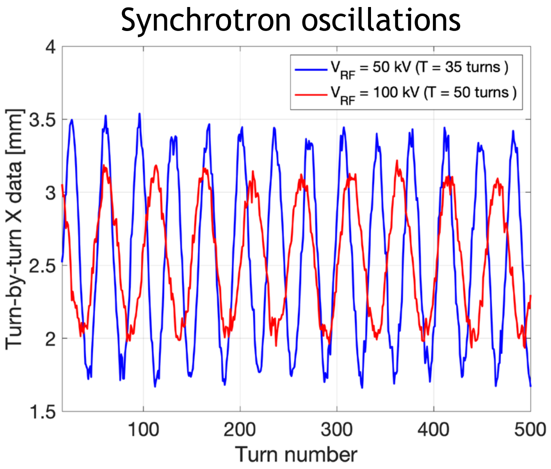
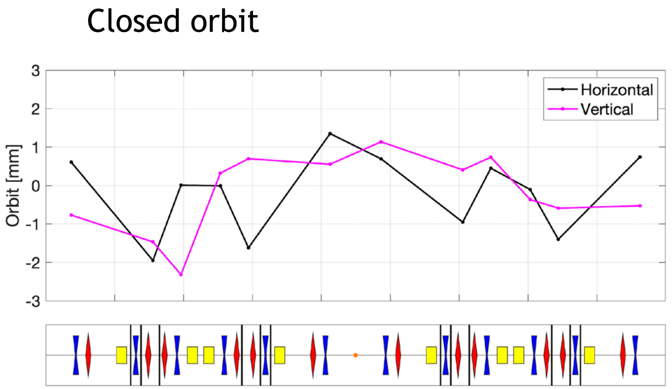
- Stable storage achieved (up to 1 sec, next trigger). Orbit correction, tune measurements, chromaticity tuning. Important milestone is achieved ☺

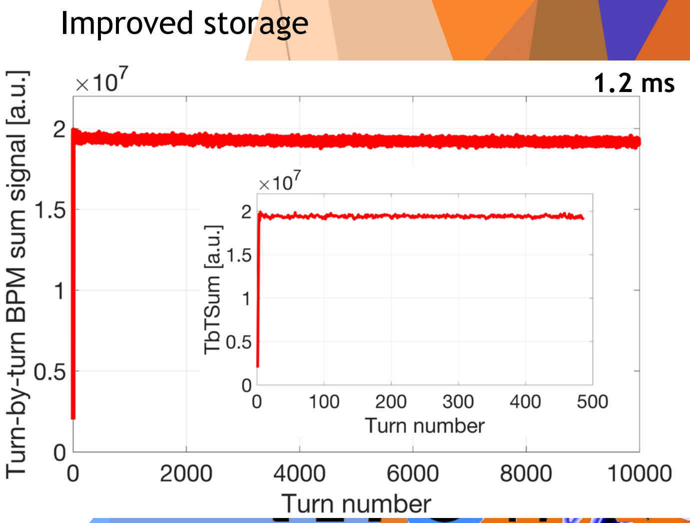








Next: BBA, precise optics studies, LOCO…



An unexpected find: shorter circumference

- The RF frequency is found to be 0.3-0.4 MHz higher. A big difficulty for synchronization with the Fabry-Perot cavity laser (limited BW, ≤ 0.25 MHz)

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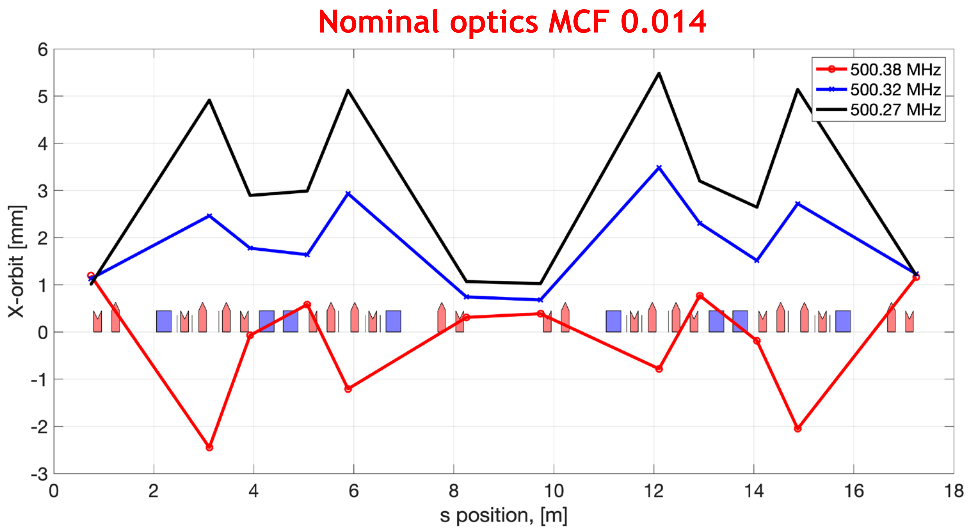

Beam lost < 500.27 MHz

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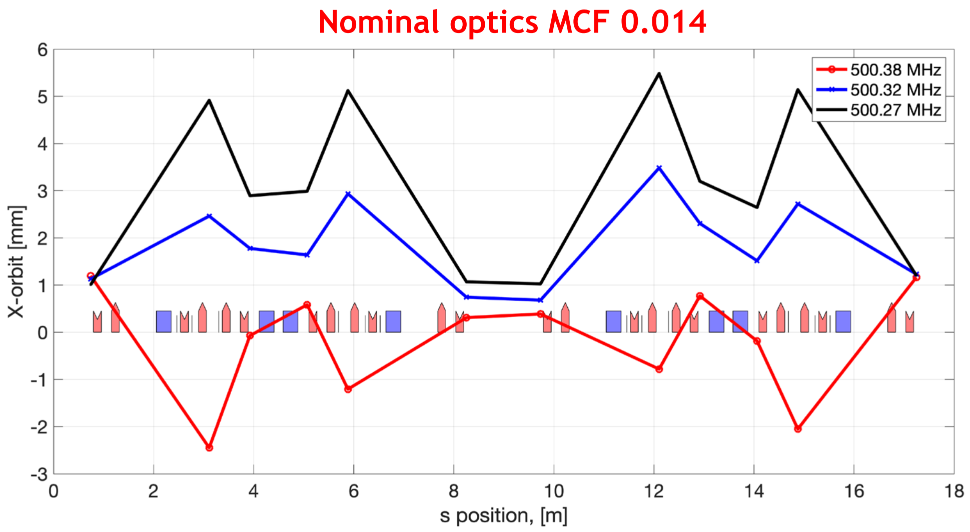

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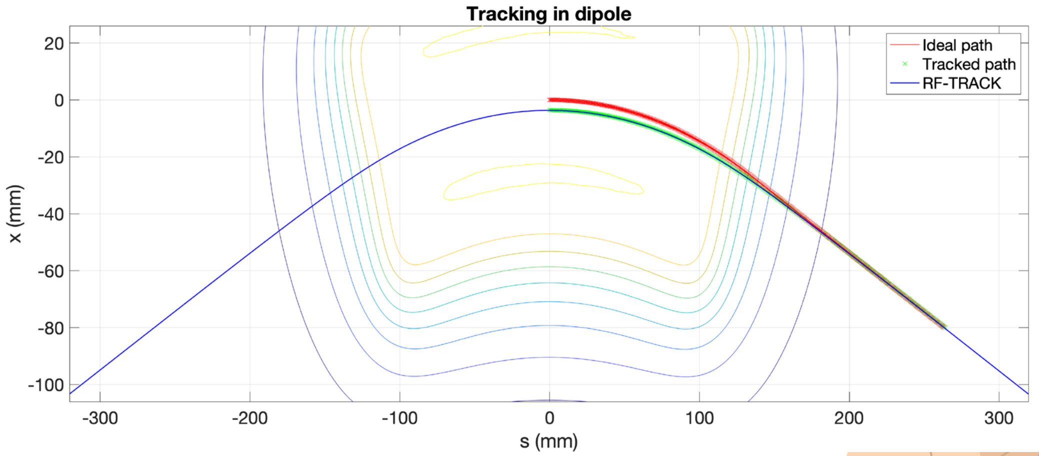
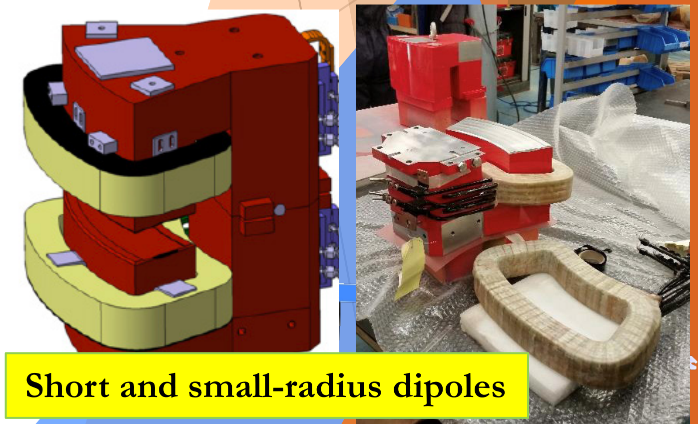
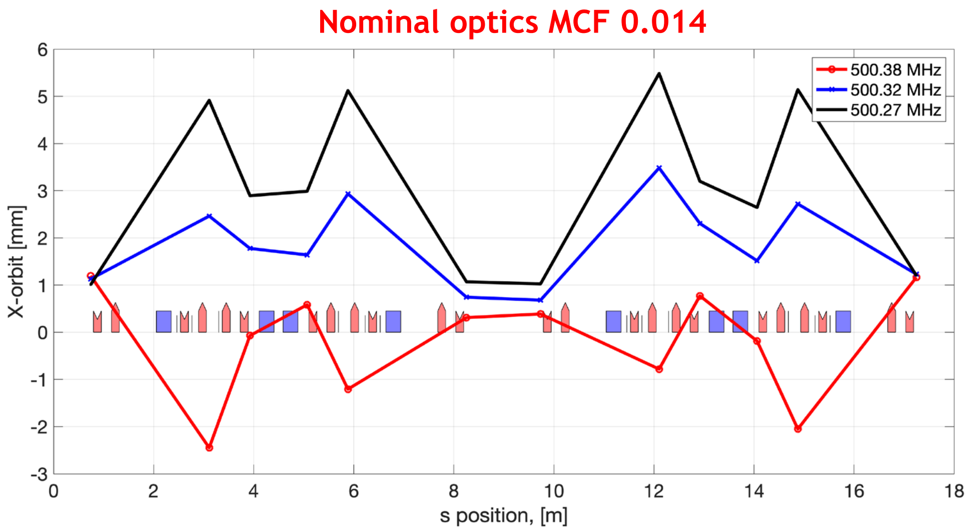


Features of dipoles	
Quantity	14 + 1 (pre-serie)
Radius of curvature	352 mm
Main field B_0	0.7 Tesla
Gap	42 mm
Good field region	+/- 20mm
Integral of field	184.59 mT.m
Current max.	275 Amp
Beam energy	from 50 to 70 MeV



Short and small-radius dipoles

An unexpected find: shorter circumference



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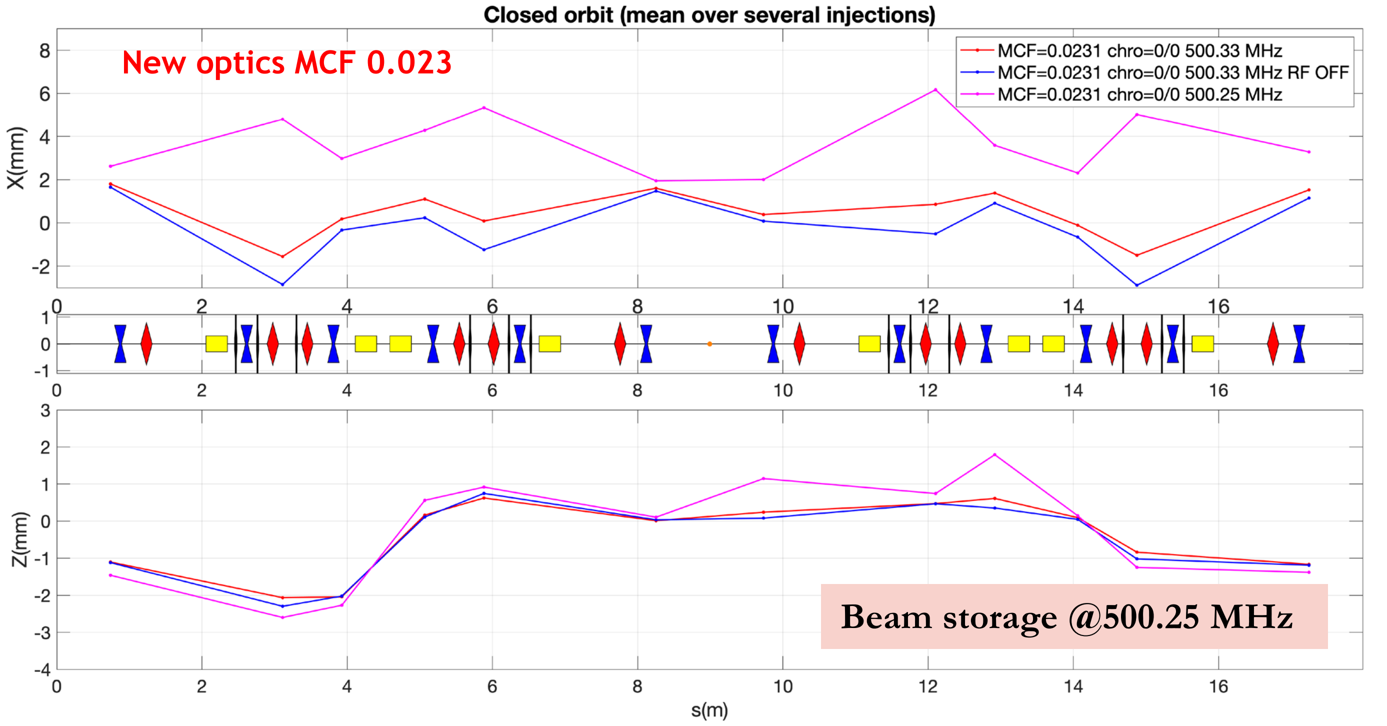


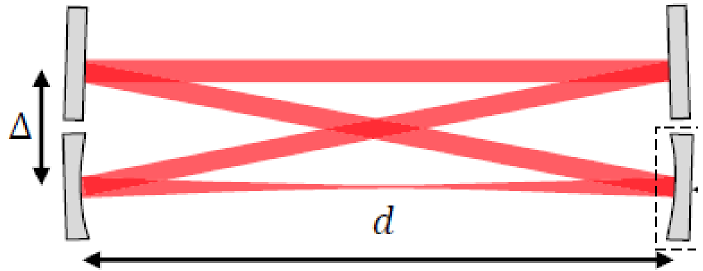
Beam storage @500.25 MHz

- To guarantee the high-intensity X-ray production
  - Temporal solution: new optics with higher value of the MCF (already deployed)
  - Reliable long-term solution: limit the dipole FF with the metallic plates (OPERA simulations ongoing) or mechanically increase the circumference by ~14 mm (studies ongoing, can imply the machine symmetry break up)

ThomX commissioning

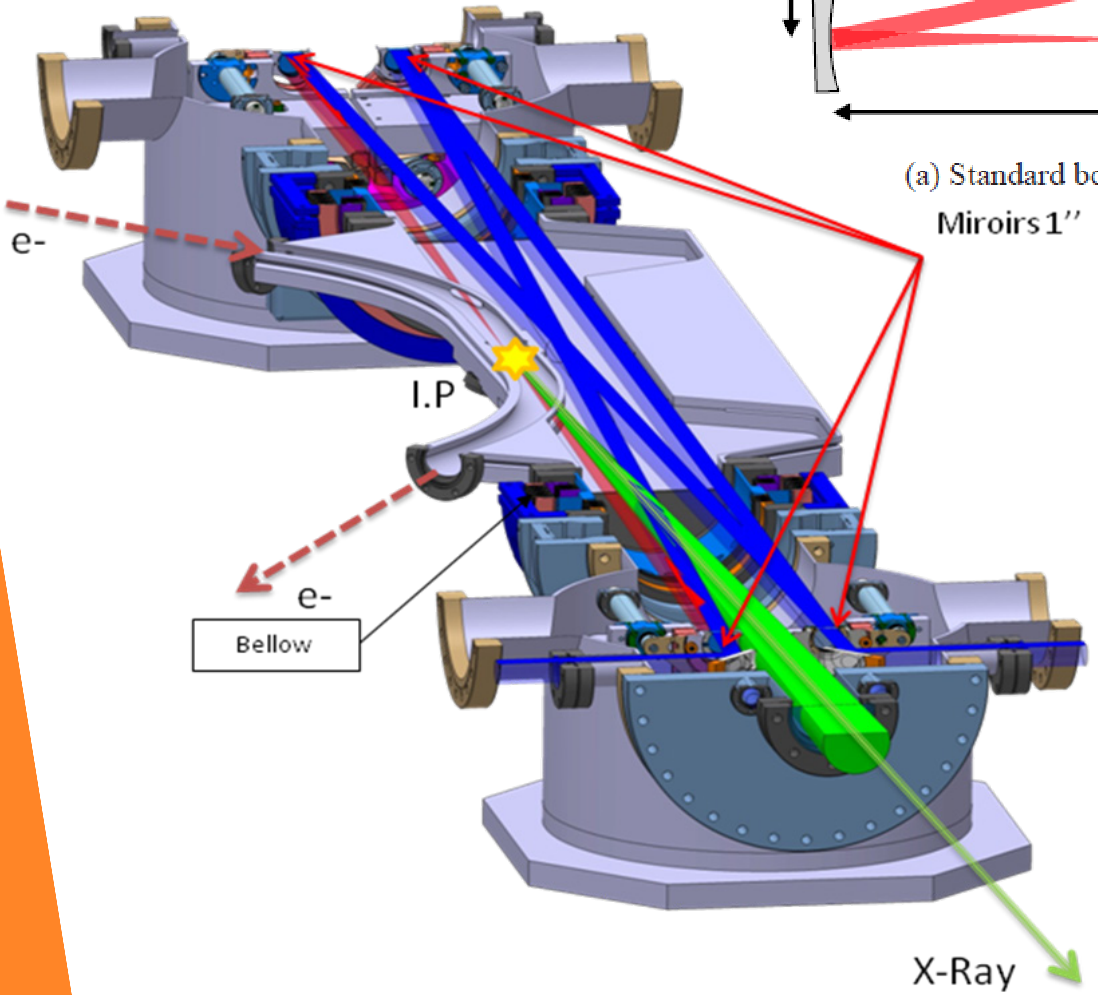
Fabry-Perot cavity and X-line

Fabry-Perot cavity @ThomX

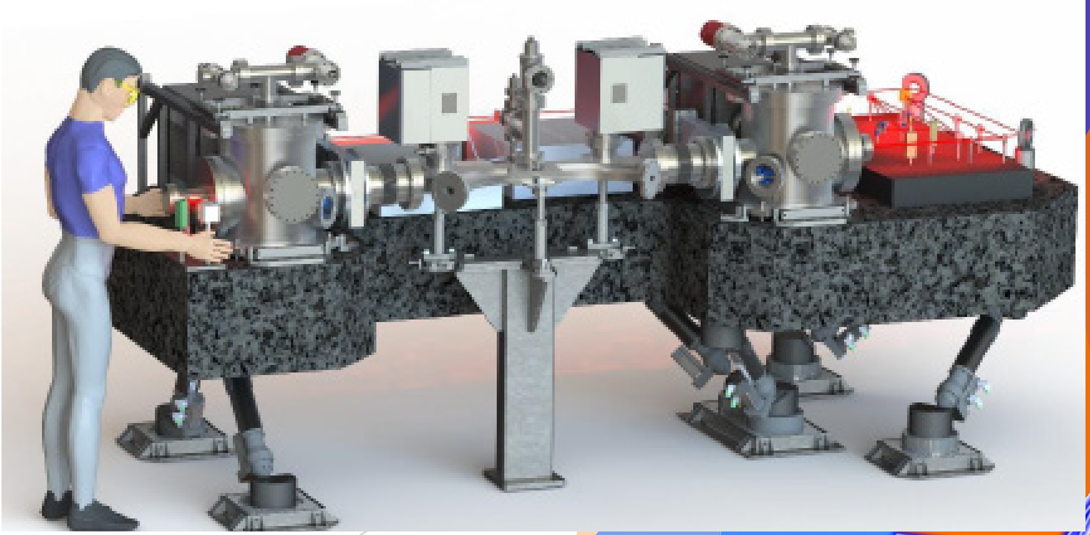


(a) Standard bow-tie (SBT) cavity

Miroirs 1''

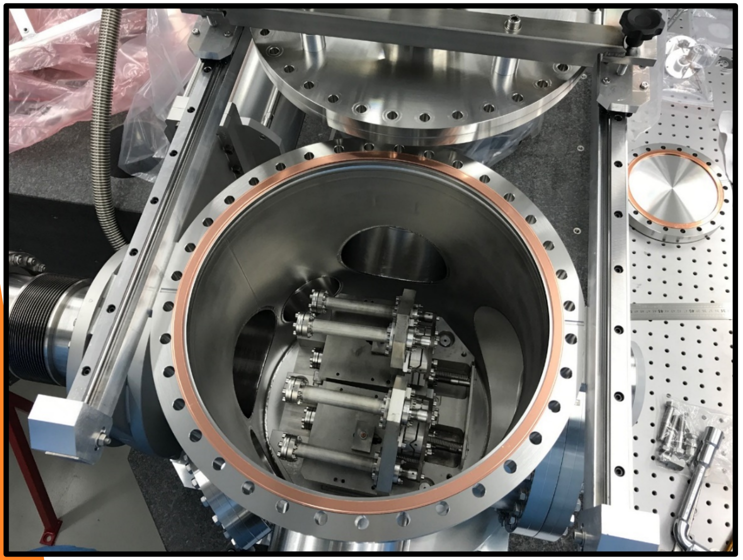


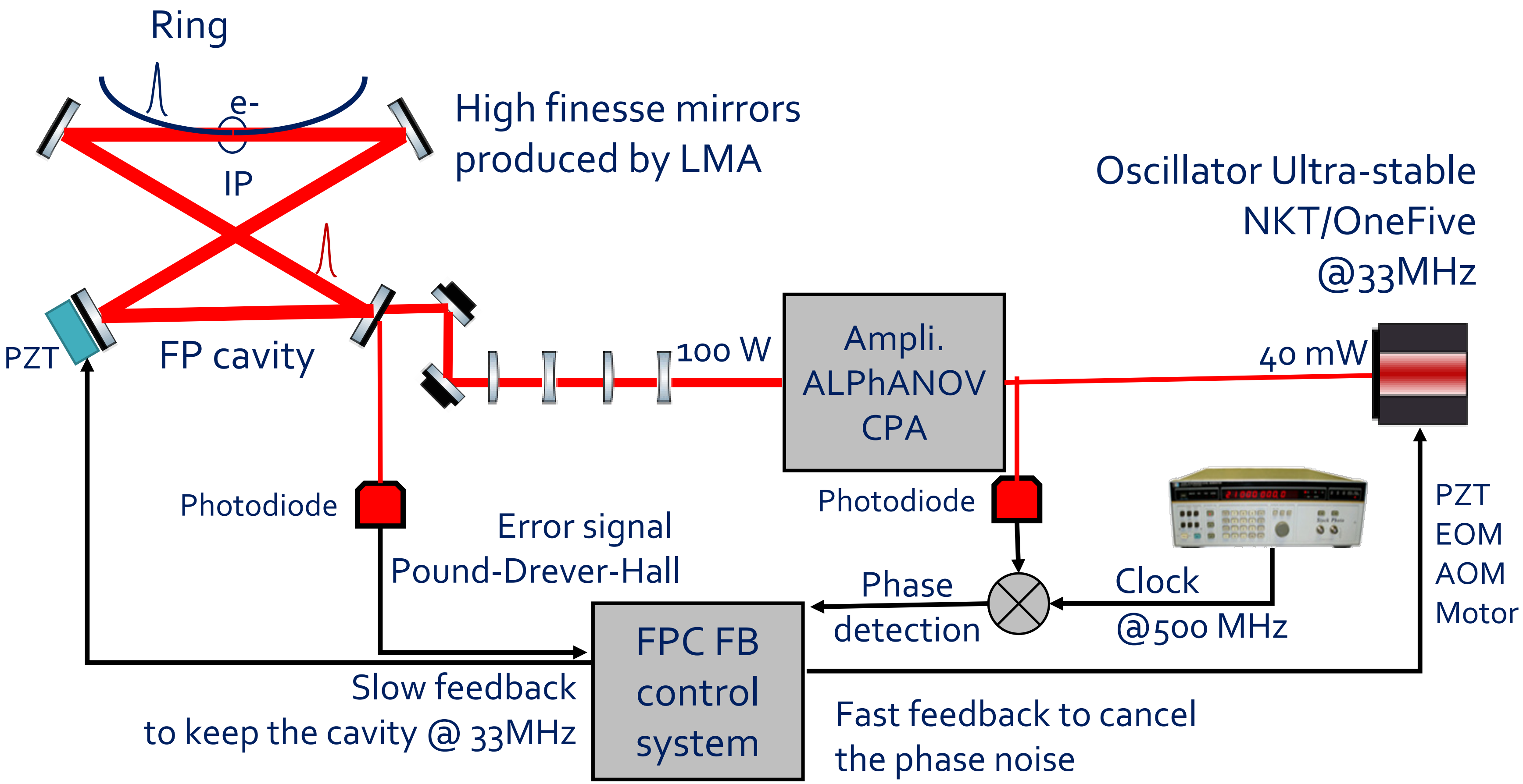
Parameters	Nom. values
Laser repetition frequency	33.3 MHz
Laser wavelength	1031 nm
Optical cavity length	8.994 m
Cavity finesse	40 000
Waist size in the IP	70 µm
Injected power (average)	100 W
Stored power (average)	500 kW (1 MW)



Optical table is installed on the hexapode (µm precision)

Optical system of the Fabry-Perot cavity





vacuum : 10^{-9} mbar

Cleanliness specification : ISO5

Commissioning : Fabry-Perot cavity

Already obtained

- On site: fully assembled. Measured FP-cavity gain : 9500. Stored power : 30 kW
- 80kW measured with ThomX cavity
  - With 133 MHz laser
  - On the test site, not in the accelerator tunnel
- 400kW measured with the ThomX cavity prototype (not stable)
- 200kW measured with the ThomX cavity prototype (long term)

To do

- Mitigation of the high-power issues
  - Huge average power should be stored inside the optical cavity.
  - Mirror thermoelastic deformations (cavity geometry)
- Increase the stored laser power in the cavity ➔ 500 kW
  - 70W (max amp power) x ~70% (max coupling) x 10k (max FP-cavity gain)
- Synchronisation: Fabry-Perot Cavity/Ring with the ~ps jitter
  - A factor of 1000-2000 for the X-ray production

X-line design

X-line design

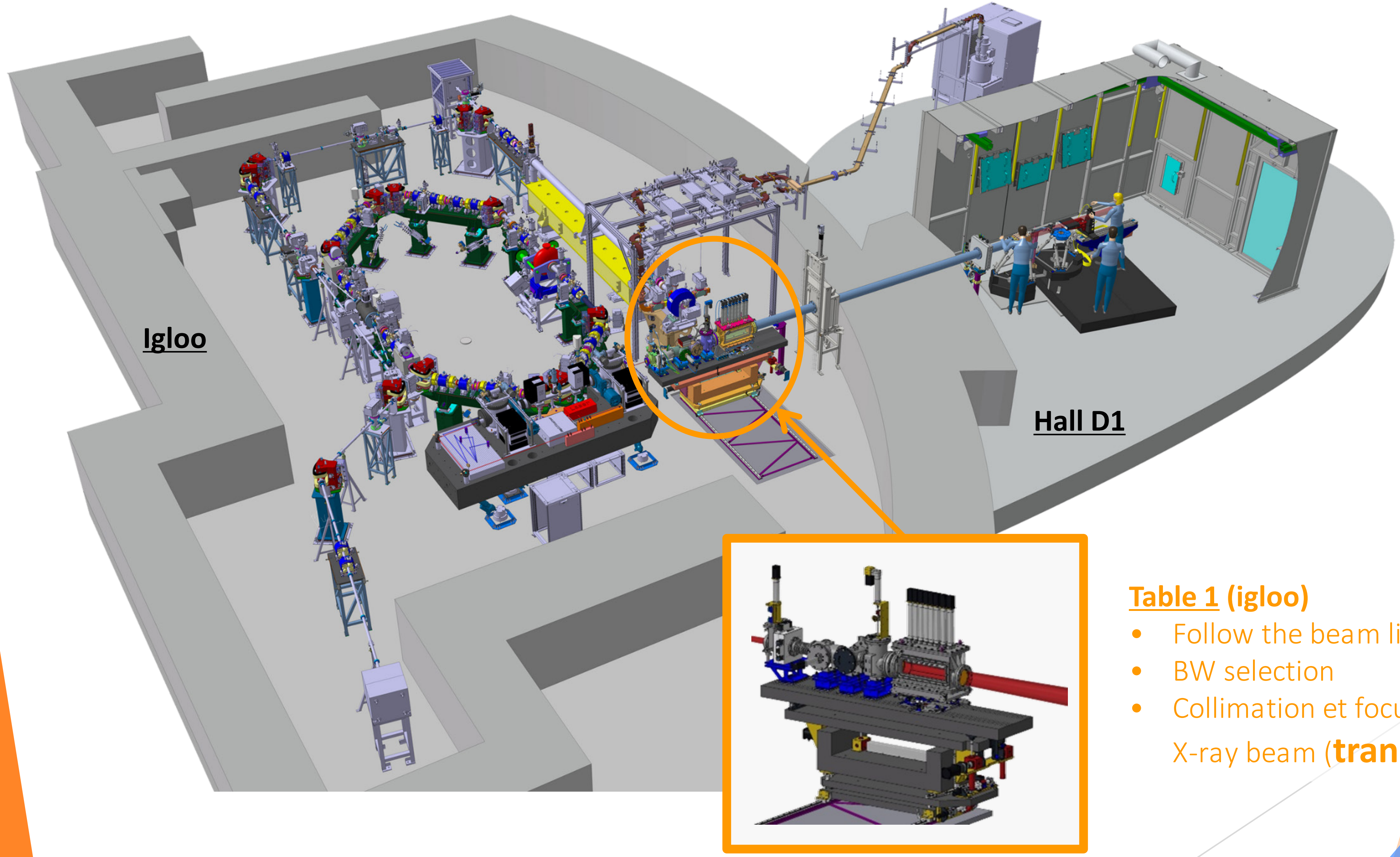
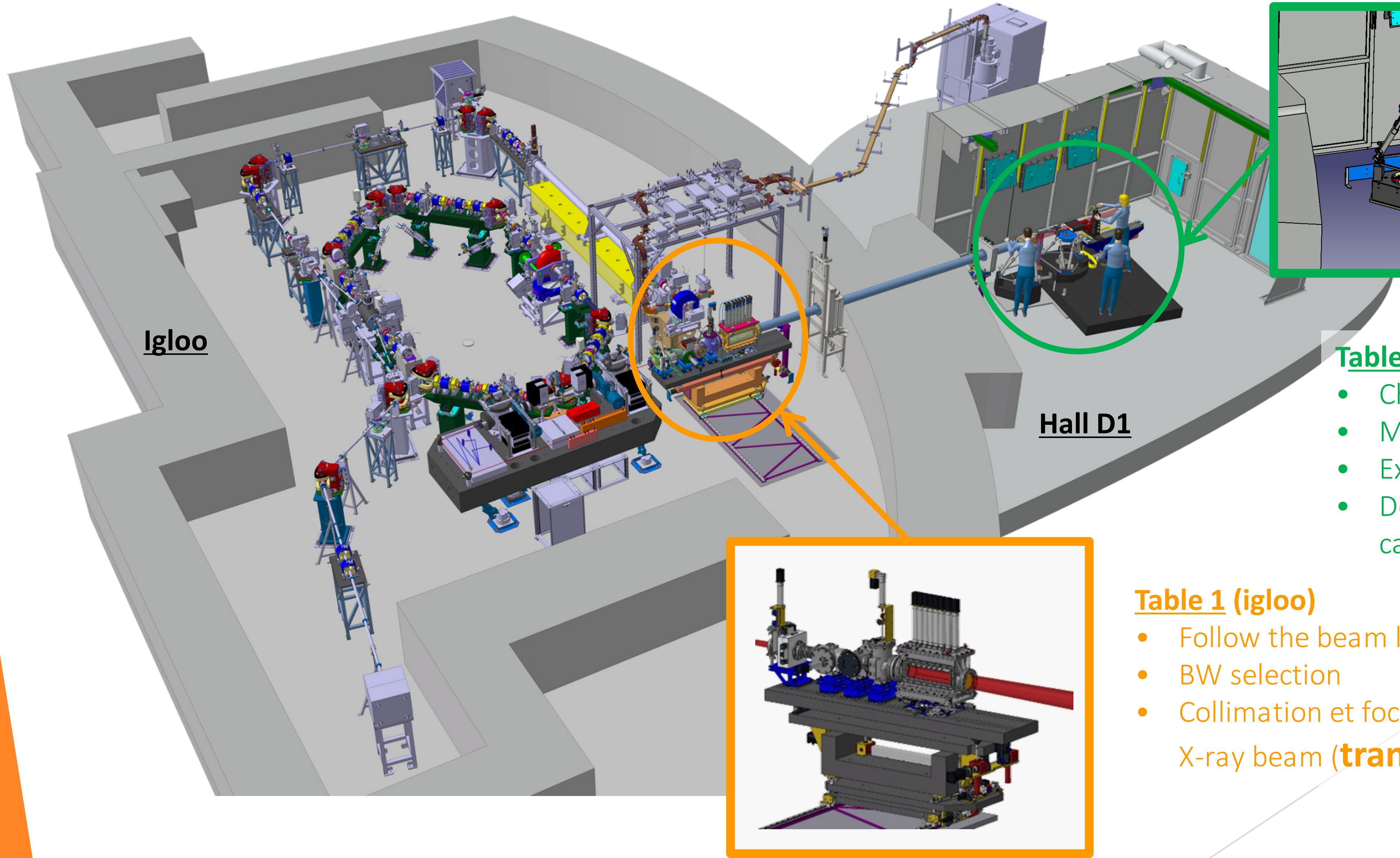


Table 1 (igloo)

- Follow the beam line
- BW selection
- Collimation et focusing of the X-ray beam (**transfocator**)

X-line design



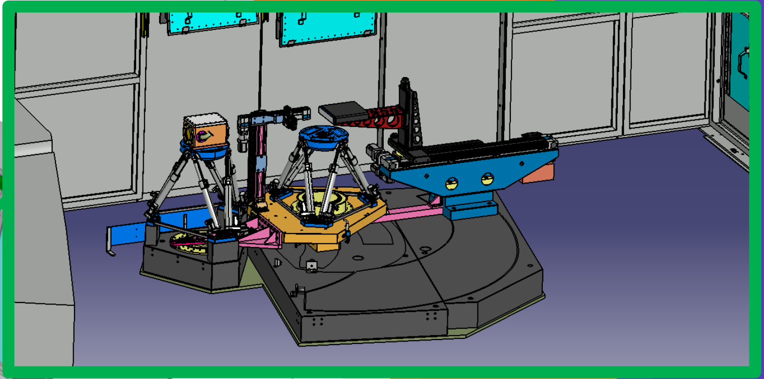


Table 2 (hall D1)

- Characterization of the X-rays
- Monochromator
- Experimental set-ups
- Detectors (spectrometers, X-ray cameras, etc.)

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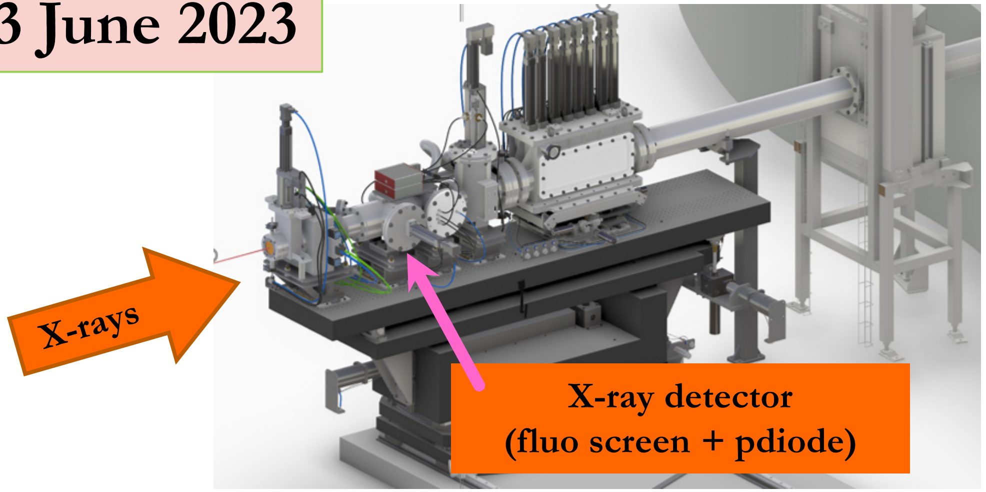
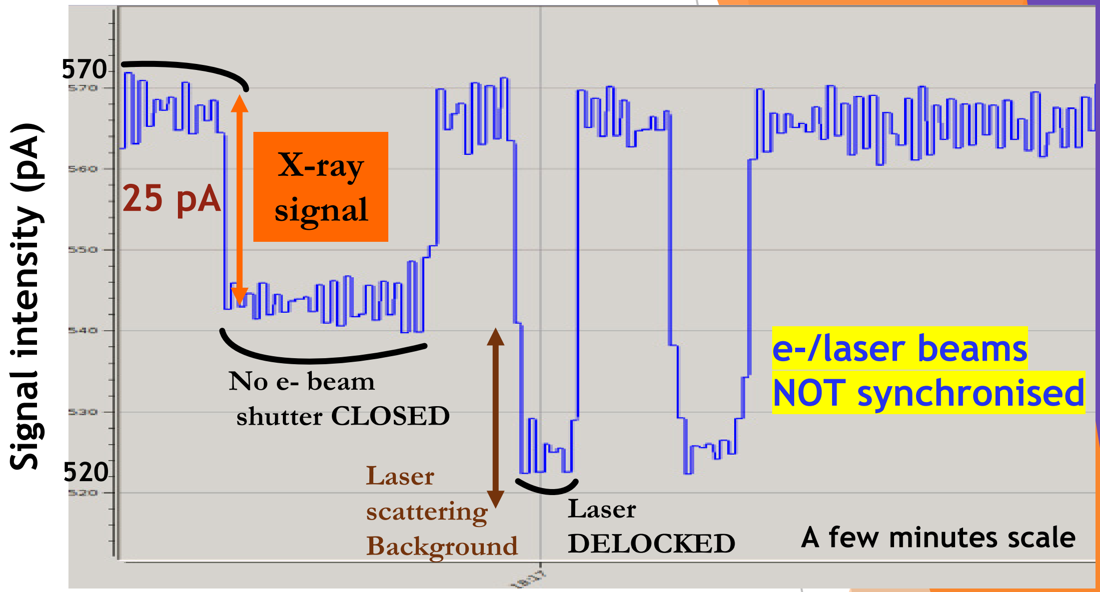
The first X-rays ☺

First X-ray signal

23 June 2023





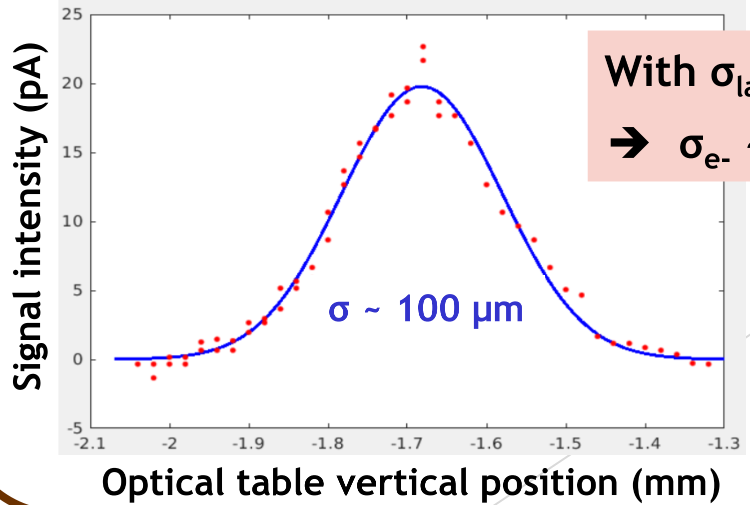
X-ray flux measurement

Measured Flux = ~$6\cdot10^6$ ph/s
Expected ~ $(4-10)\cdot10^6$ ph/s
(uncertainty on stored e^- bunch charge)

Near future: **100 kW** of stored laser power + **synchronisation** of the e^-/laser beams

➔ **Expected Flux ~ 10^{10} - 10^{11} ph/s**

Measurement of e^- beam size σ_{e-} at IP

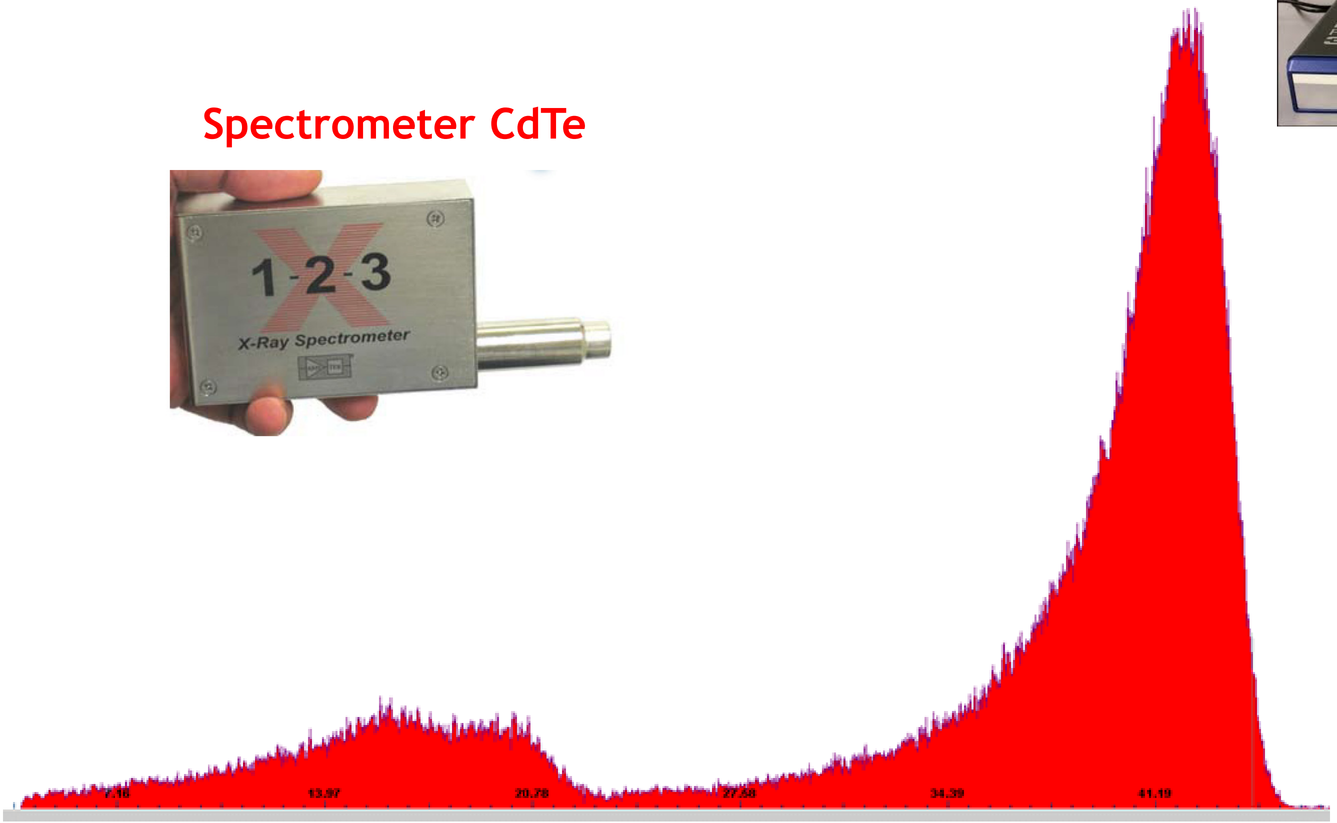


With σ_{laser} = 60 µm
➔ σ_{e-} ~ 80 µm

First spectrum and beam image in X-hutch

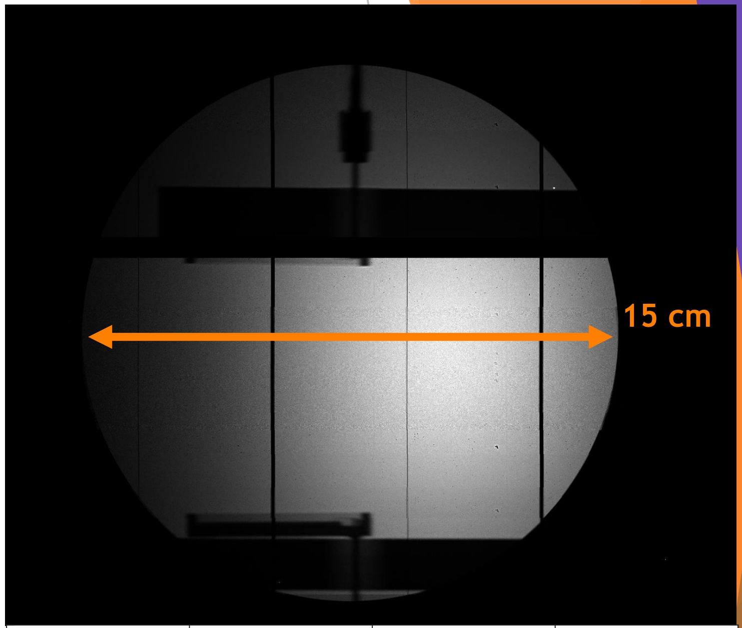
26 July 2023

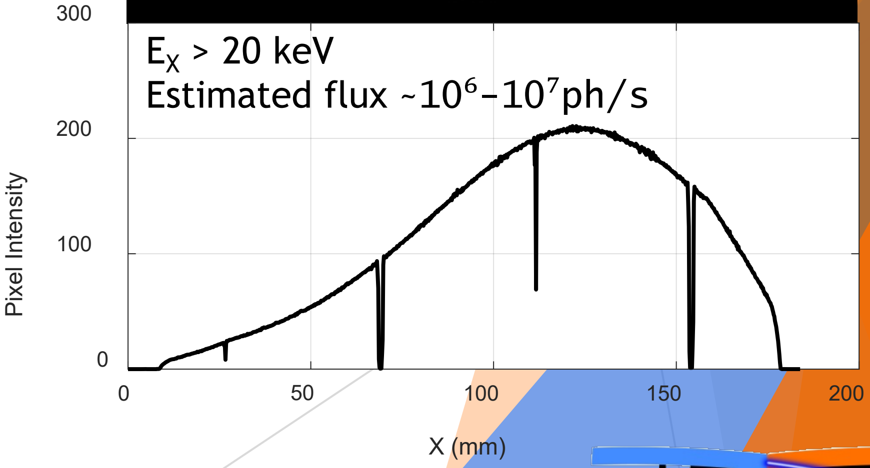
Spectrometer CdTe



Scattering of the X-ray inside the beampipe

Pixel Camera CdTe

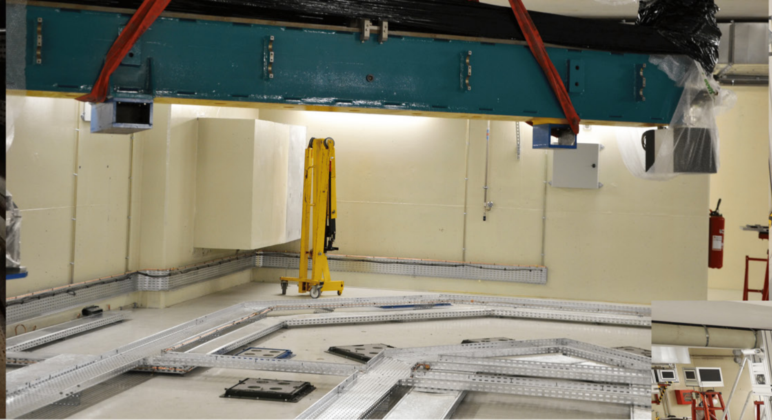
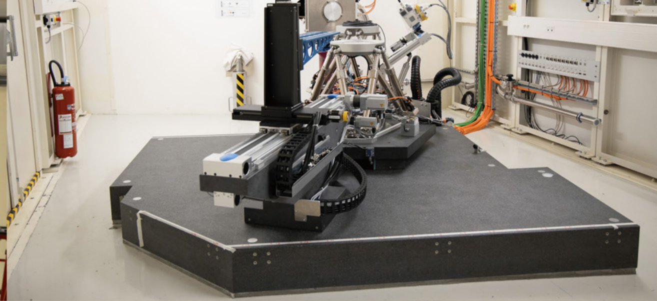
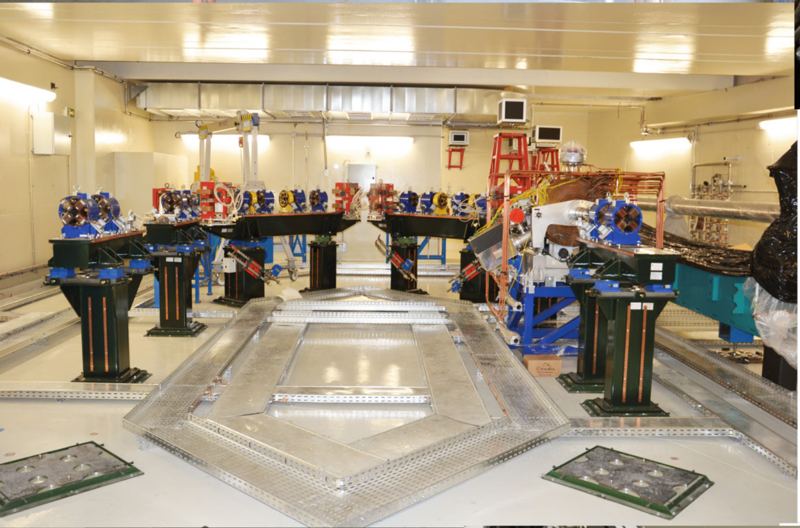




Summary-Perspectives

- **ThomX is a research platform ! Different from commissioning/operation of the user facility.**
- The ThomX commissioning is still ongoing. **Next step : the 1st X-ray experiment** *and e^-/laser synchronization, injector/ring optimization, beam physics, start the ring feedbacks, increase laser power, e^- charge and energy.*
- At this stage, overall accelerator operation is within the TDR expectations ☺
  Great SOLEIL partnership!
- Learned lessons :
  - Thorough subsystem commissioning. Delivered performance of sub-accelerators before starting the next commissioning phase. No rush. Commissioning interleaved with solving the technical issues introduces delays.
  - Available and well-understood/easy to install diagnostics during commissioning.
  - Hardware/control system checks before beam commissioning. Control system and machine status applications ready and tested.
  - Available manpower (technical support + physicists). Expertise doesn't scale with the accelerator size. In-house experience in commissioning.
  - Good and realistic planning is crucial (anticipate potential problems/failures).



Thank you!

ThomX