The ThomX Compton Source

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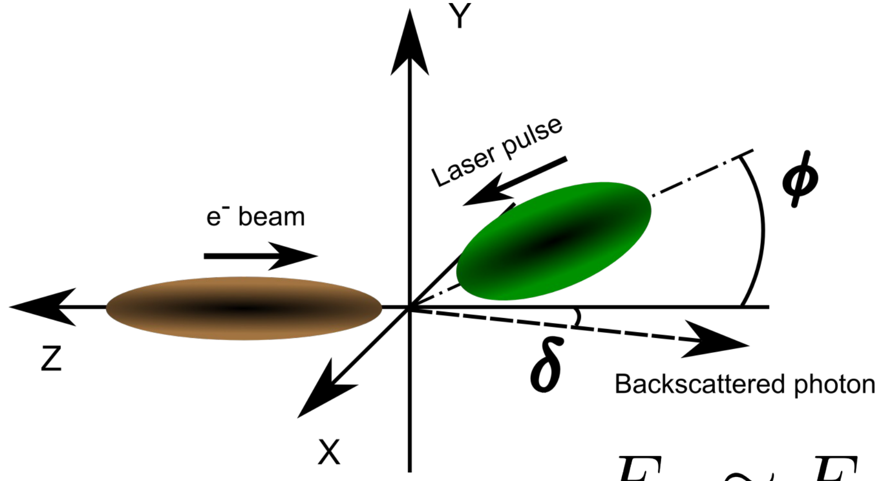
on behalf of the ThomX collaboration

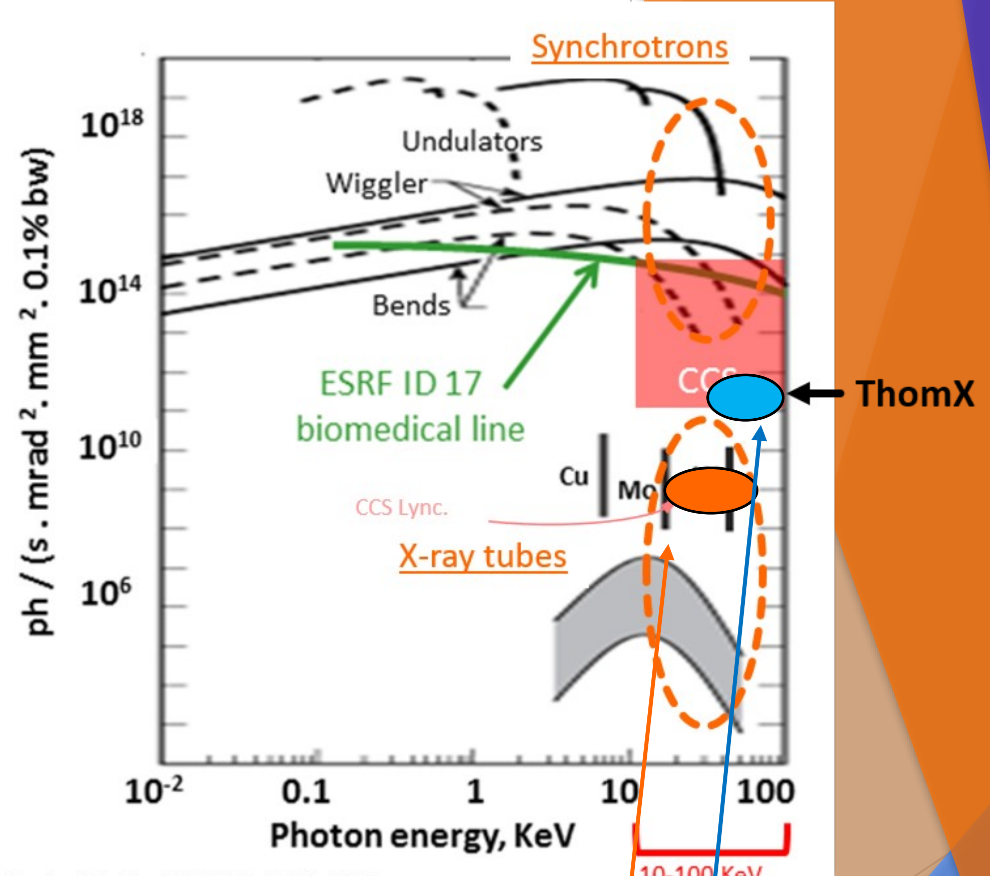
Programme Investissements d'avenir de l'Etat ANR-10-EQPX-51. Financé également par la Région Ile-de-France.
Program « Investing in the future » ANR-10-EQOX-51. Work also supported by grants from Région Ile-de-France.

Compact Compton Sources

X-rays produced by Compton interaction



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



Physica Medica 32 (2016) 1790–1794

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

nominal	energy	flux	brightness
ThomX (Orsay, FR)	45-90 keV	10^{13} ph/s	~ 10^{11}
MuCLS Lync. Tech (Munich, DE)	15-35 keV	10^{10} - 10^{11} ph/s	10^{8} - 10^{9}

***Only 2 "high-flux" Compton sources currently in the world**

ThomX

Sir Joseph John Thomson
(1856 –1940)

X-rays

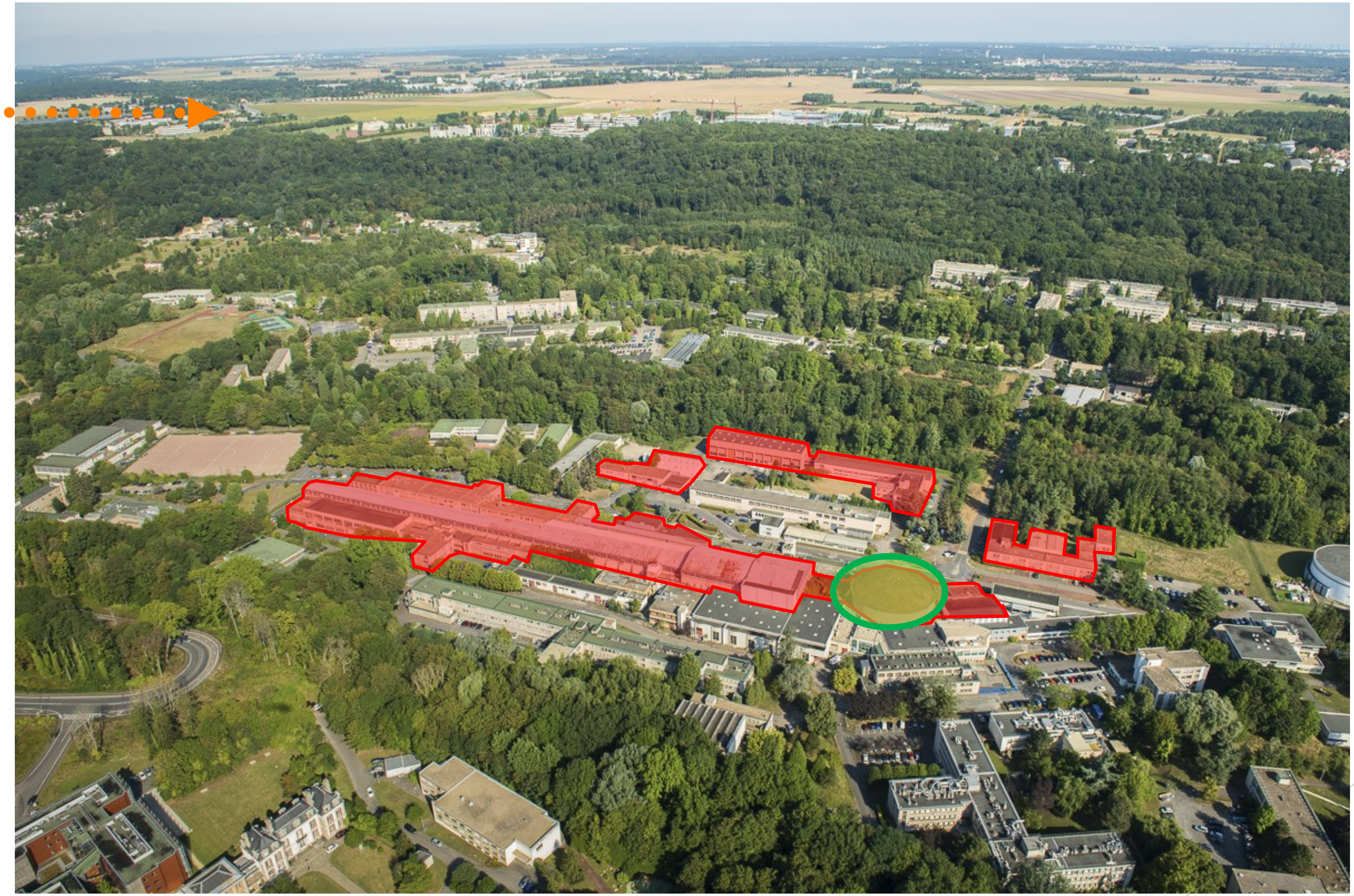
ThomX facility

Compact Compton light source

ThomX : on the Orsay campus

SOLEIL
~2km

Using the former LURE DCI building



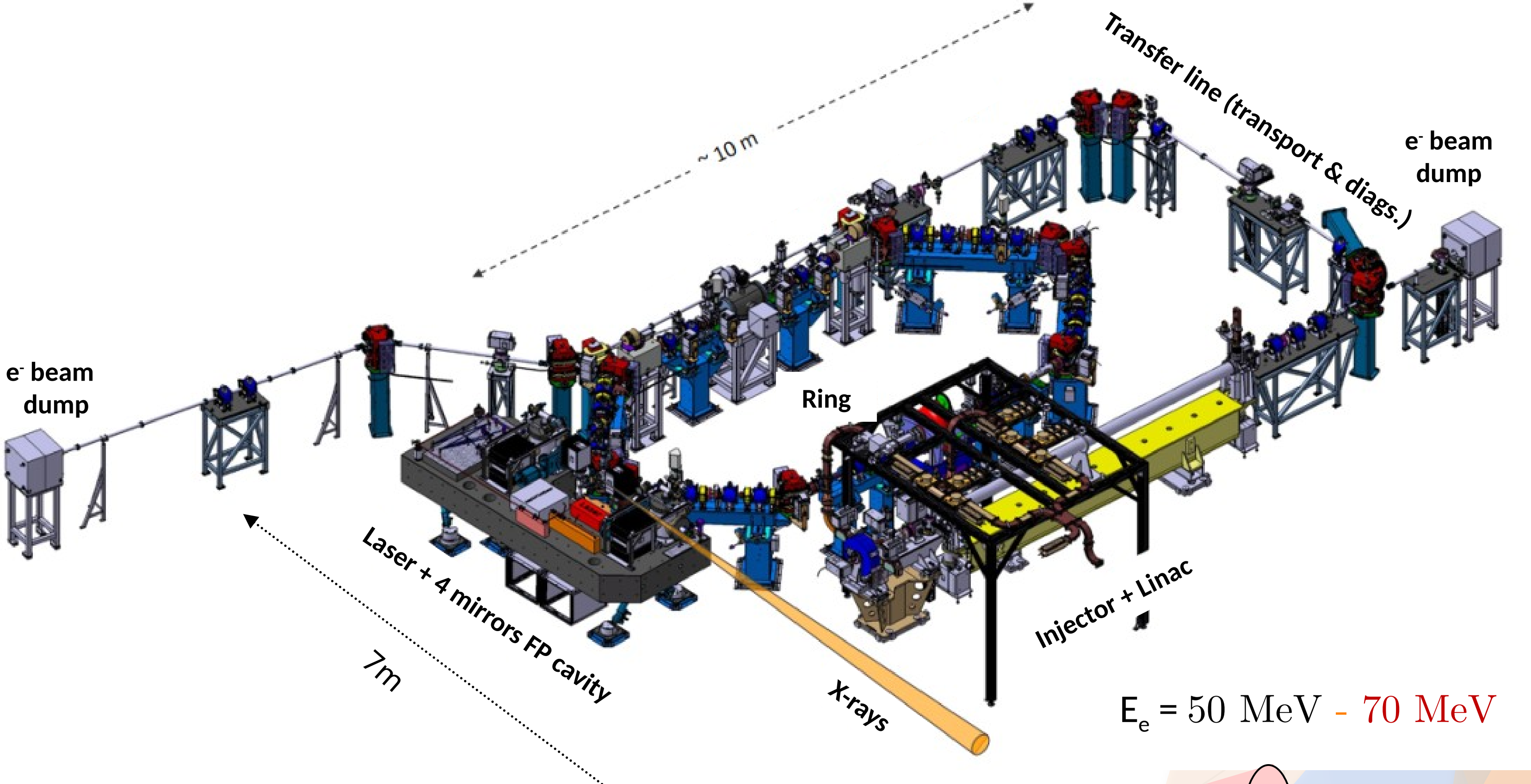
Orsay Campus with Saclay in the back

ThomX facility

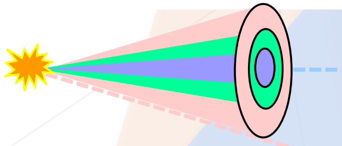
ThomX target is a high AVERAGE FLUX ➔ many electrons and laser photons colliding in a small volume at high frequency !

$$F \approx f_{coll} \frac{N_{ph} N_e}{4\pi\sigma_r^2}$$

aximize collision frequency
aximize electron bunch char
aximize laser pulse power
nimize source size



E_e = 50 MeV - 70 MeV



X-rays energy scales with γ^4

Users: cultural heritage, bio-medical and therapy applications, crystallography, X-ray imaging…

ThomX is a demonstrator & research platform

Compact X-ray source, affordable for museums, hospit

ThomX facility: milestones

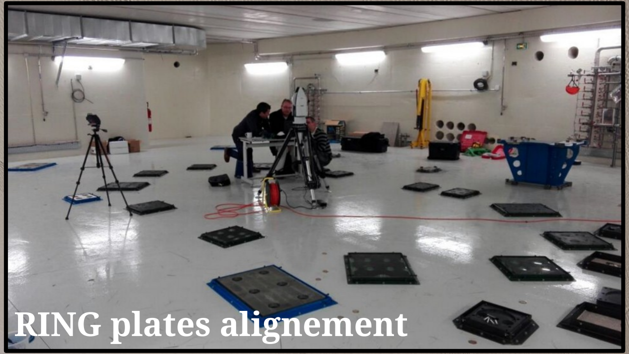
Budget : National Research Agency (ANR) /Equipex 12 M€
Installation and operation (2012-2023)

Civil engineering: 2,2 M€ (local Essonne funding)

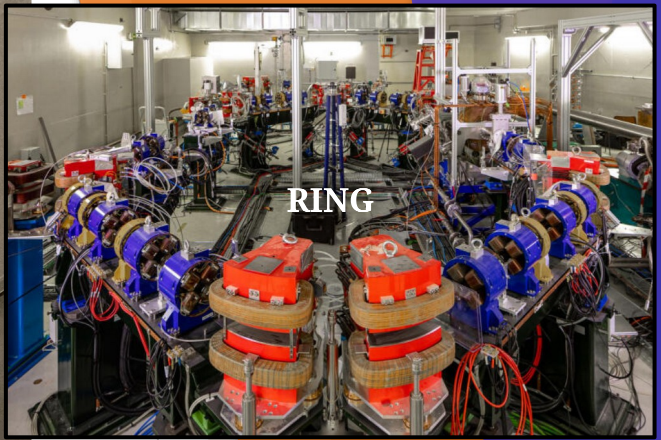
University Paris-Sud, CNRS/IN2P3, SESAME, IJCLab : ~ 1 M€

8 French partners :
LAL/IJCLab, SOLEIL, CELIA, LAMS, ESRF, NEEL, INSERM,Thalès

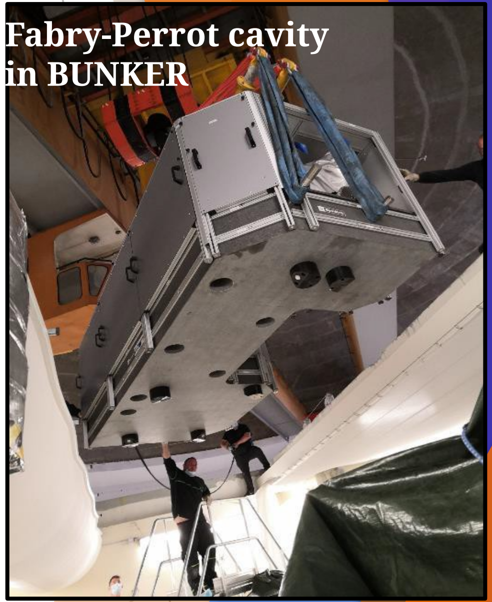

Civil engineering

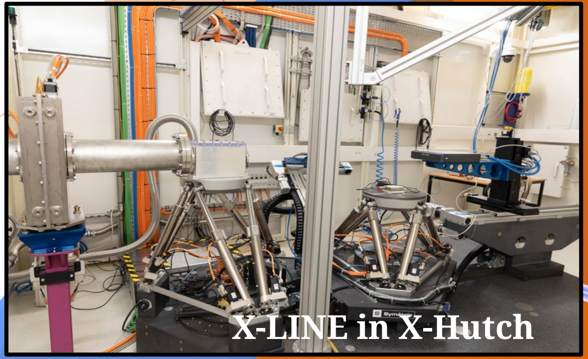

RING plates alignement


X-LINE
table

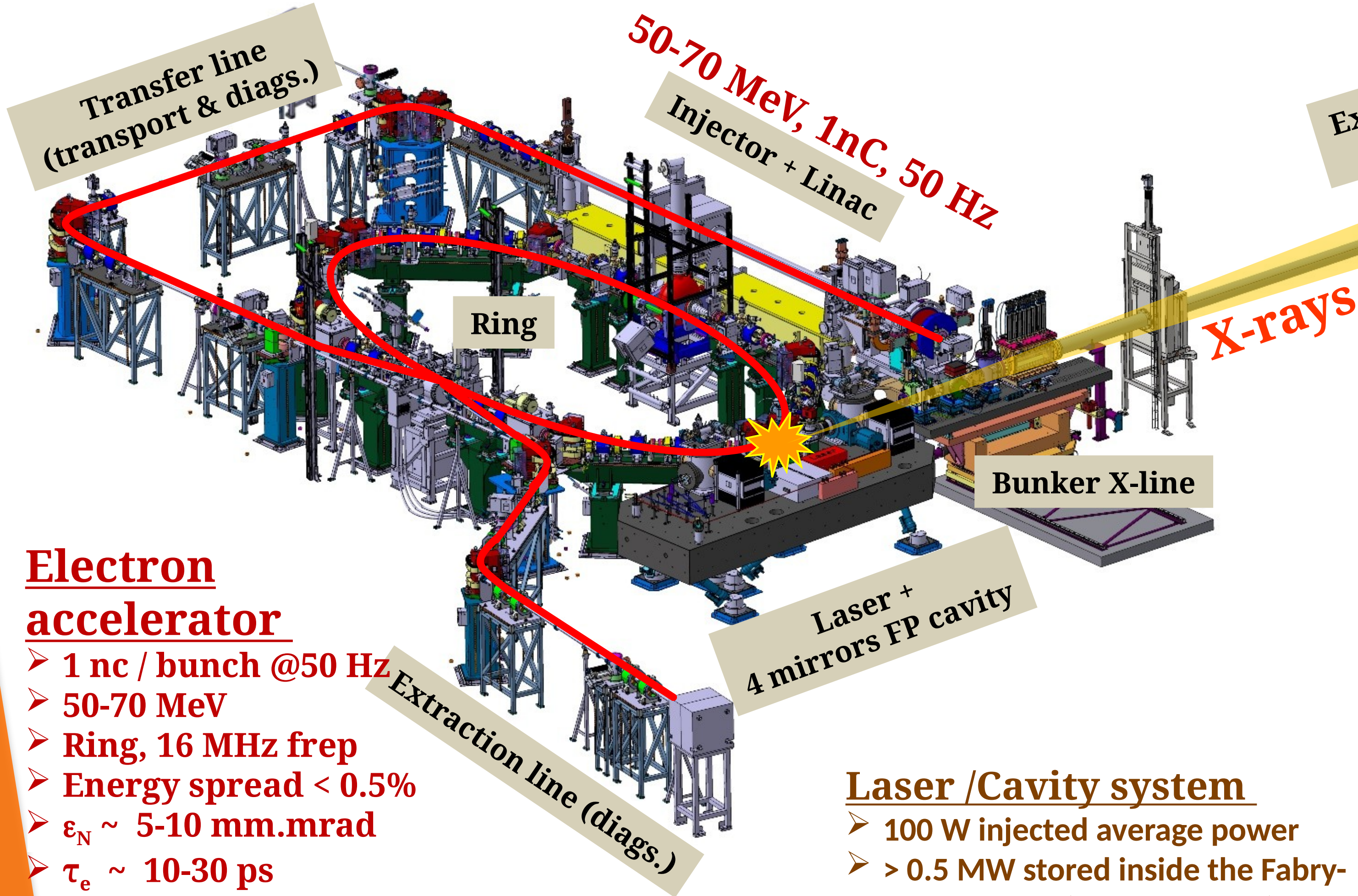

RING


ThomX facility
April 2025


Fabry-Perrot cavity
in BUNKER

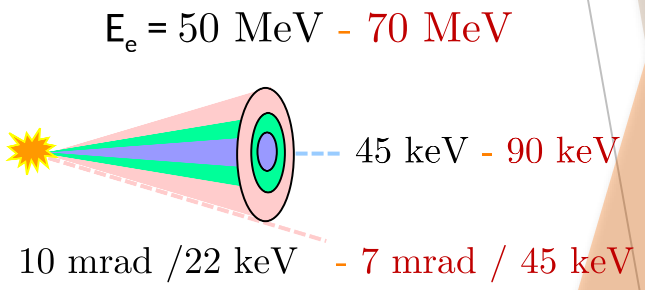

X-LINE in X-Hutch

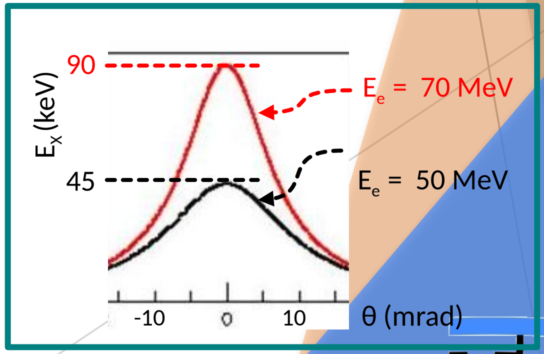
ThomX facility: nominal parameters



X-ray beam

- Flux ~ 10^{13} ph/s
- Brightness ~10^{11} ph/(s.mm^2.mrad^2) in 0.1% BW
- σ_x ~ 70 µm
- On-axis Energy ~ 45 – 90 keV





Electron accelerator

- 1 nc / bunch @50 Hz
- 50-70 MeV
- Ring, 16 MHz frep
- Energy spread < 0.5%
- ε_N ~ 5-10 mm.mrad
- τ_e ~ 10-30 ps
- $\sigma_e \gtrsim$ 70 µm

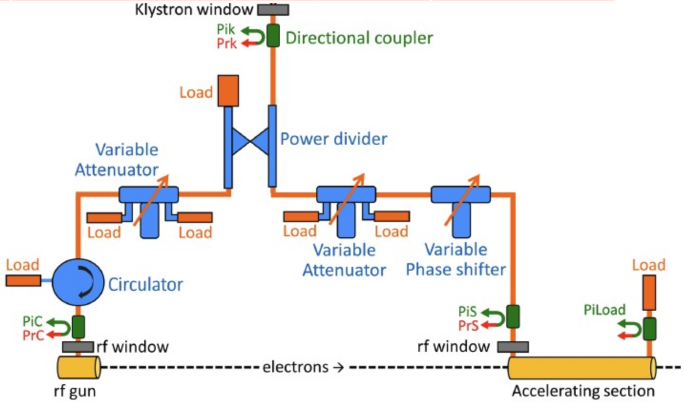
Laser /Cavity system

- 100 W injected average power
- > 0.5 MW stored inside the Fabry-Perrot cavity (~ 15 mJ/pulse)

ThomX injector

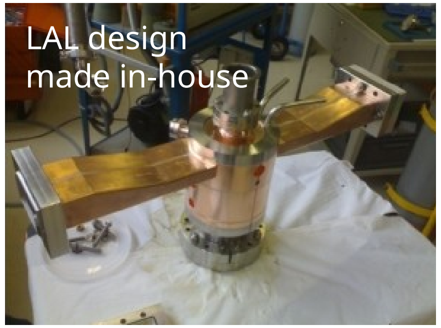
Standard design of photoinjector + S-band RF structure + Transfer/Extraction Line

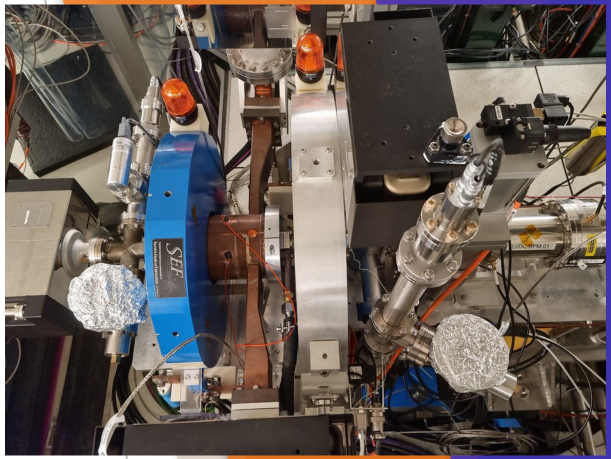
Injector specification			
Parameter	**Nom. value**	**Measured**	**Units**
Energy	50/70	40, 50, 61.5, 70	MeV
Charge, commissioning/nom.	0.1/1	>0.2	nC
Nb. of bunches per RF pulse	1	1	
Energy spread, rms	<1	0.08	%
Emittance (rms, normalized)	<5	<5	mm·mrad
Bunch length, rms	<5	3.9	ps
Average current	50	1	nA
Pulse repetition rate	50	10	Hz



ScandiNova modulator, 3 GHz Toshiba klystron E37310

Photocathode RF gun

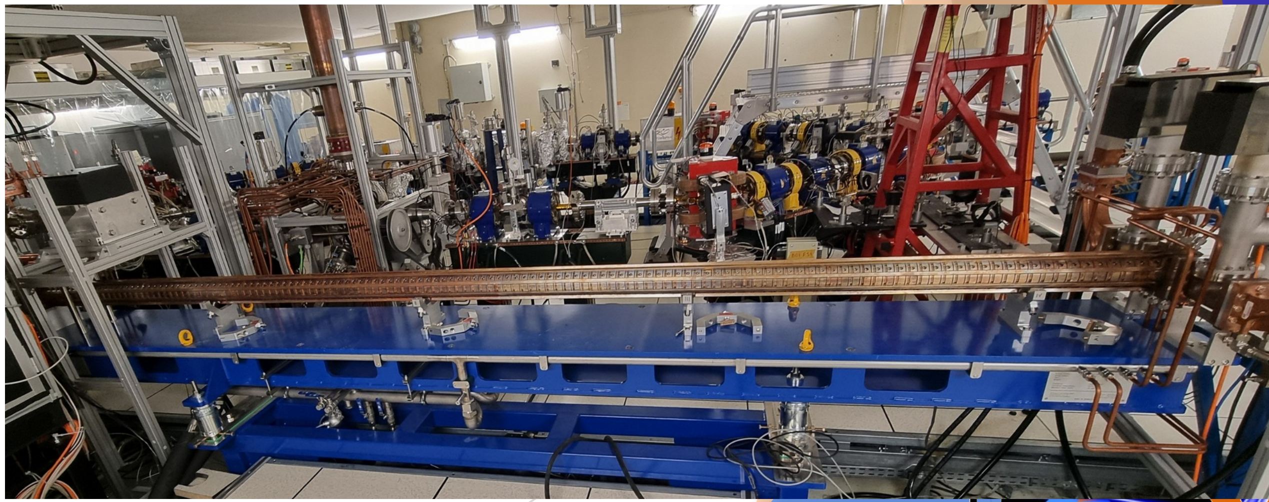




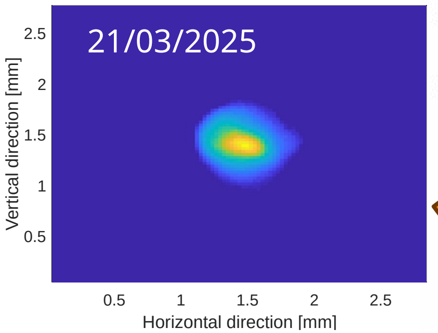
➜ 2.5-cell photocathode RF gun : Ez = 80 MV/m @ 6 MW to reach E = 5 MeV, Charge 0.1/1 nC

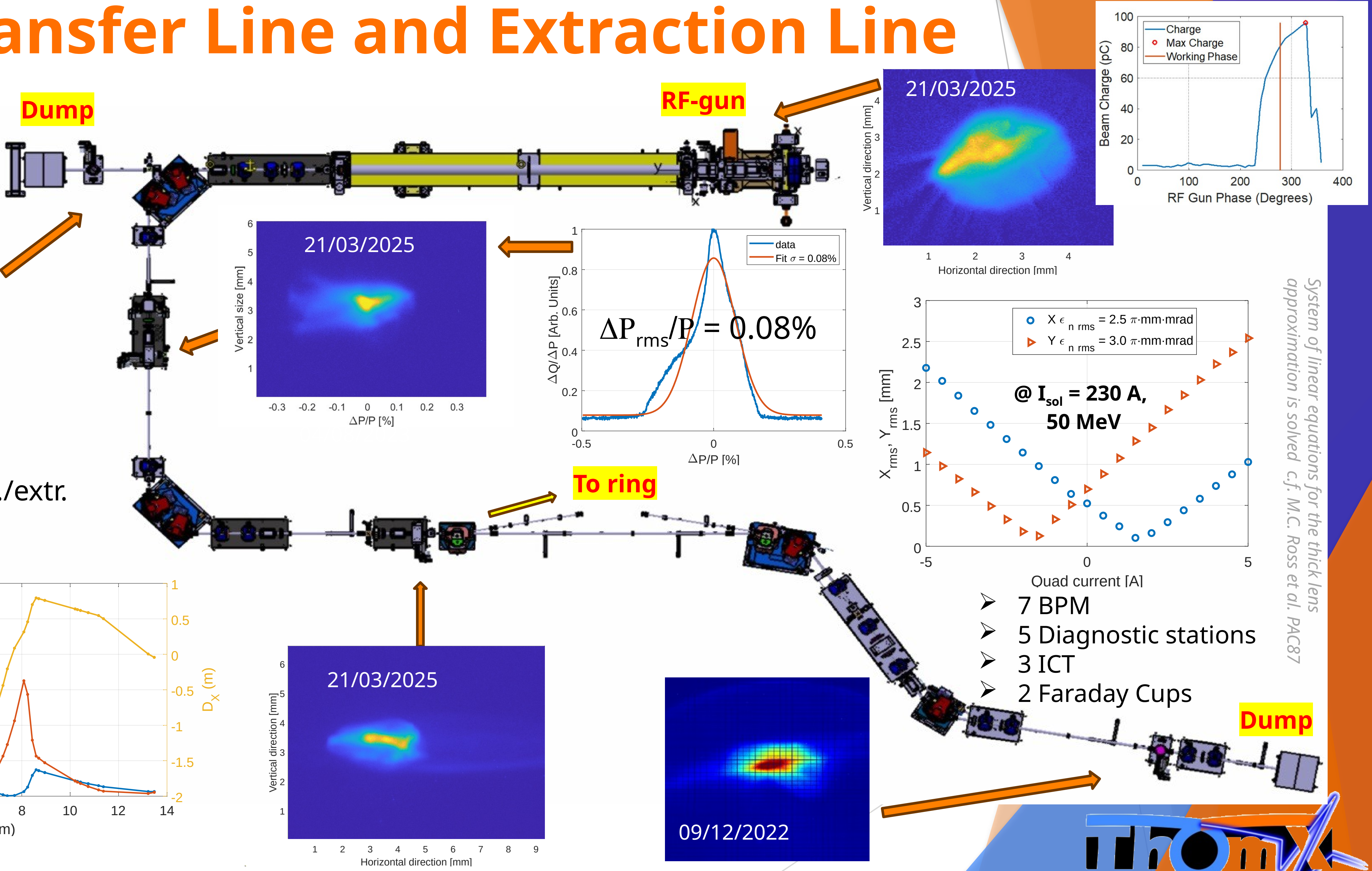
Accelerating structure

➜ S-band :4.8-meter long accelerating structure (2998.55 MHz) to reach ~45 MeV @ 11 MW

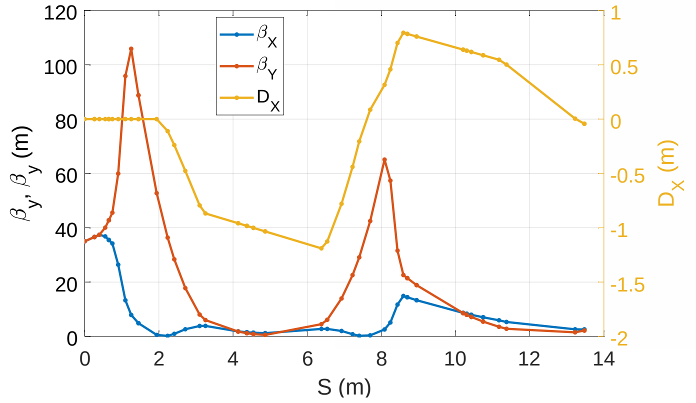


Linac, Transfer Line and Extraction Line





- 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

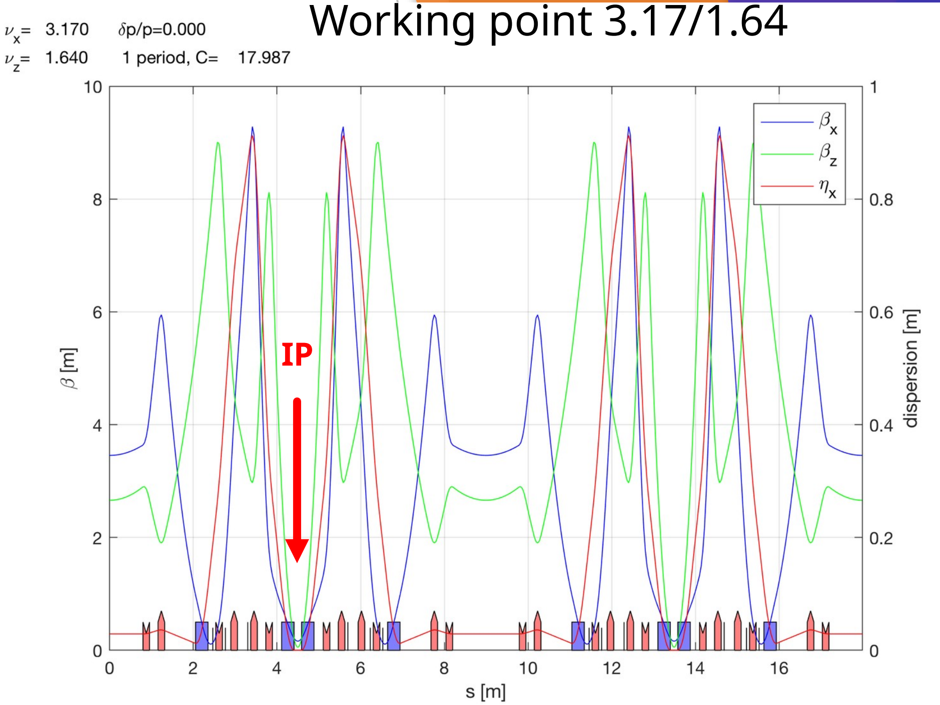
Ring lattice and nominal parameters

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

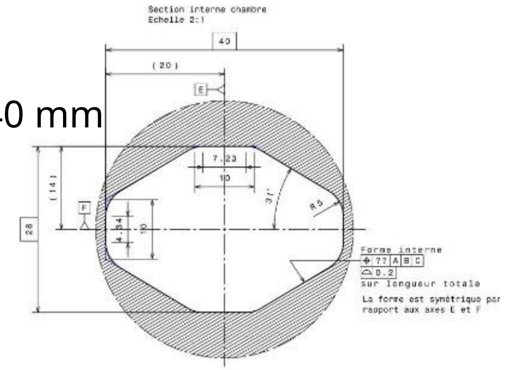
ThomX SR: L = 18 m, T = 60 ns, f_{rep} = 16.7 MHz

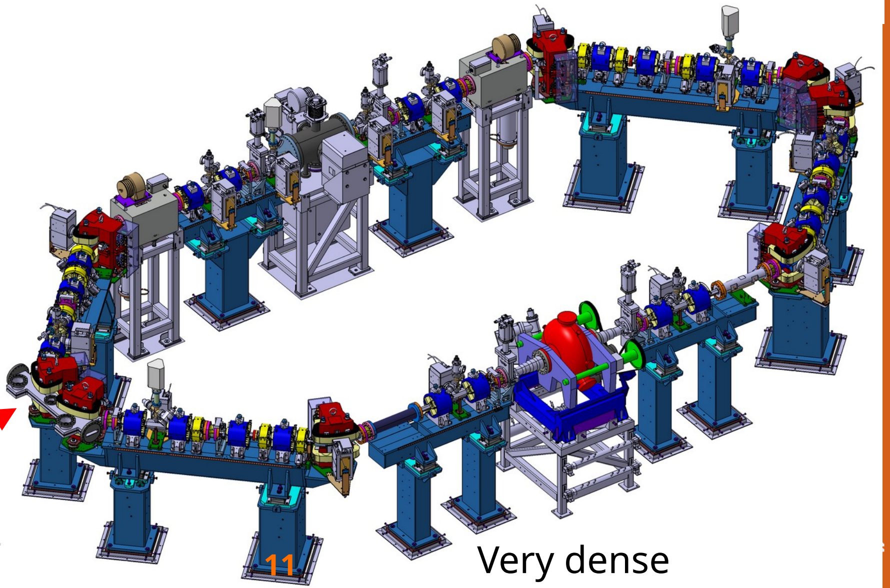
Parameter	Value/Units
Beam energy	50-70 MeV
Bunch Charge	1 nC
Bunch length (rms)	~30 ps
Circumference	18 m
Revolution frequency	16.7 MHz
Current	16.7 mA
RF frequency/Harmonics	500/30 MHz
Momentum compaction	0.0125 - 0.025
Betatron tunes	3.17/1.64
Natural chromaticity	-9/-13
Damping time trans./long.	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

Working point 3.17/1.64



28x40 mm





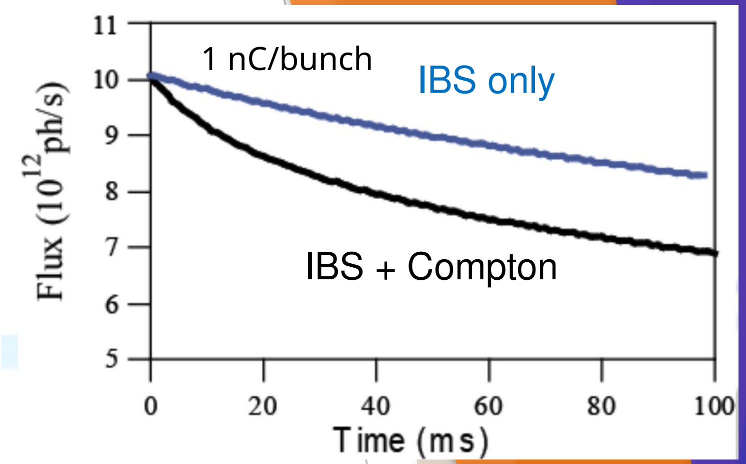
IP

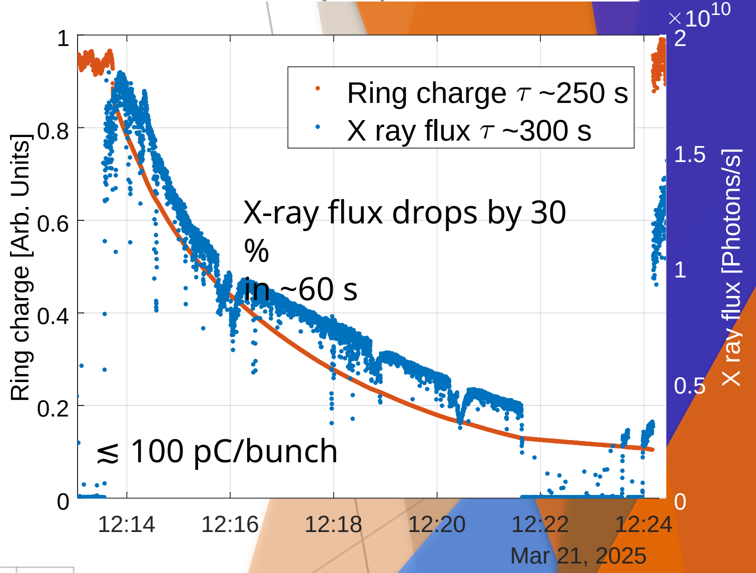
Very dense integration

Ring commissioning highlights

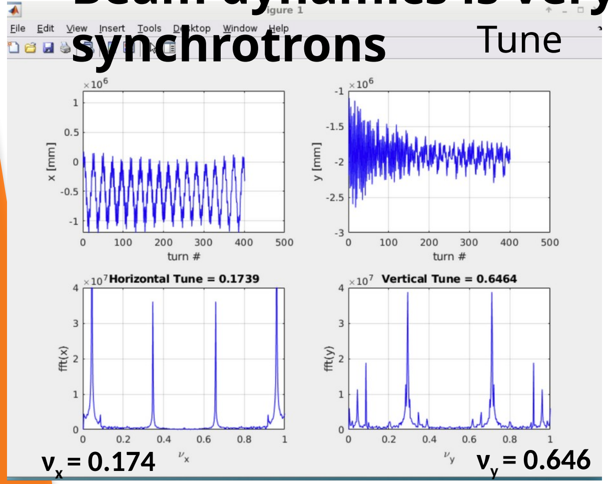
The Ring operation and its commissioning is a big challenge due to :

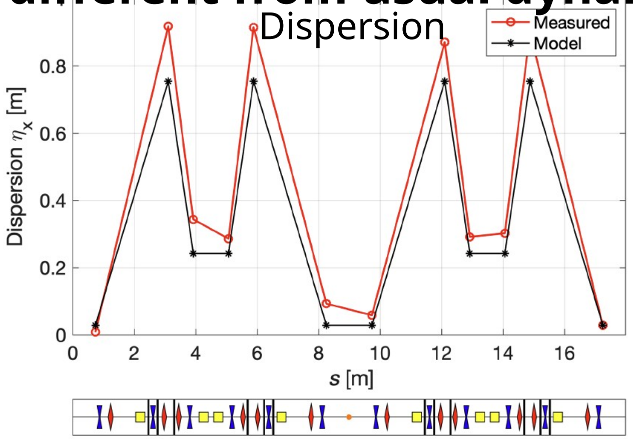
- high particle density (1 nC/bunch) and low energy operation (50-70 MeV)
- mismatched beam injection
- absence of the synchrotron damping (stored time << damping time)
- strong impact of collective effects (intrabeam and Compton scattering, coherent synchrotron radiation, ion instabilities, etc.)

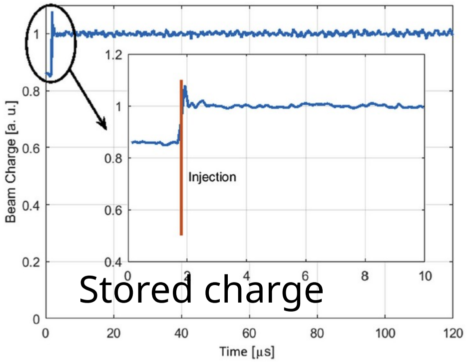


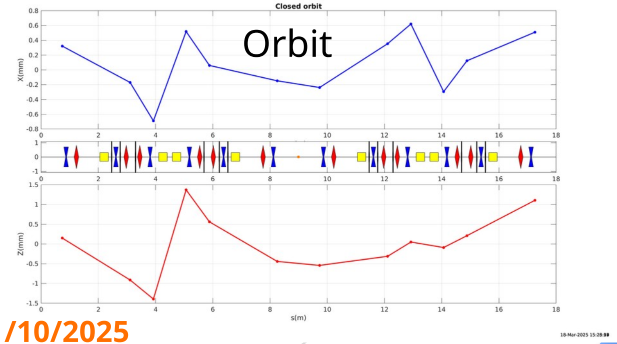


Beam dynamics is very different from usual dynan synchrotrons









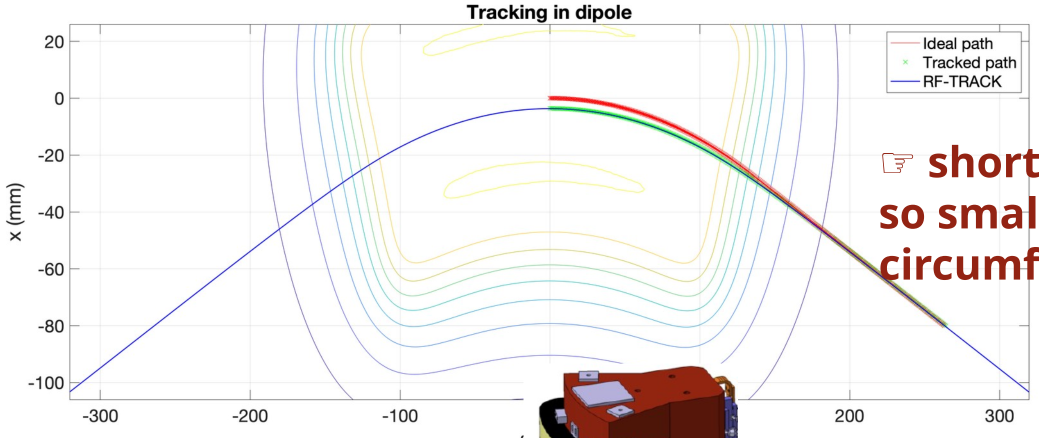
Model hor./vert. tune
3.17/1.64

Improvement in beam storage: @10 Hz ~95 %
Physics model vs. real machine: good.
Work in progress!

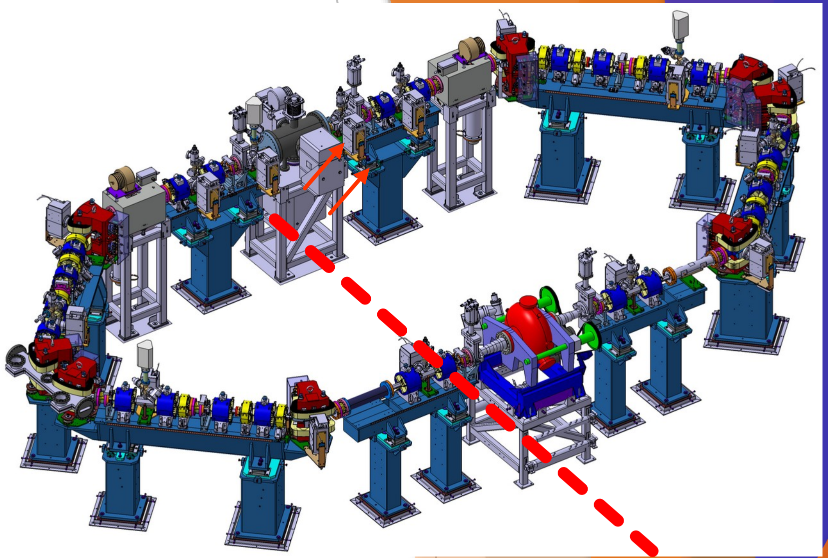
An unexpected find: shorter circumference

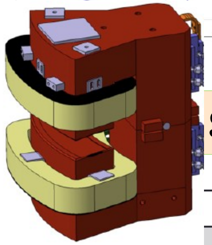
EXAMPLE

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



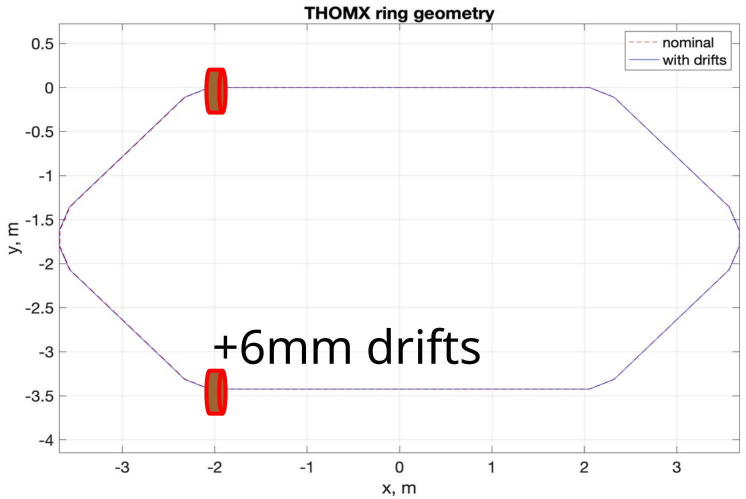
☞ **shorter pathlength and so smaller total circumference**





Short and small-radius dipoles

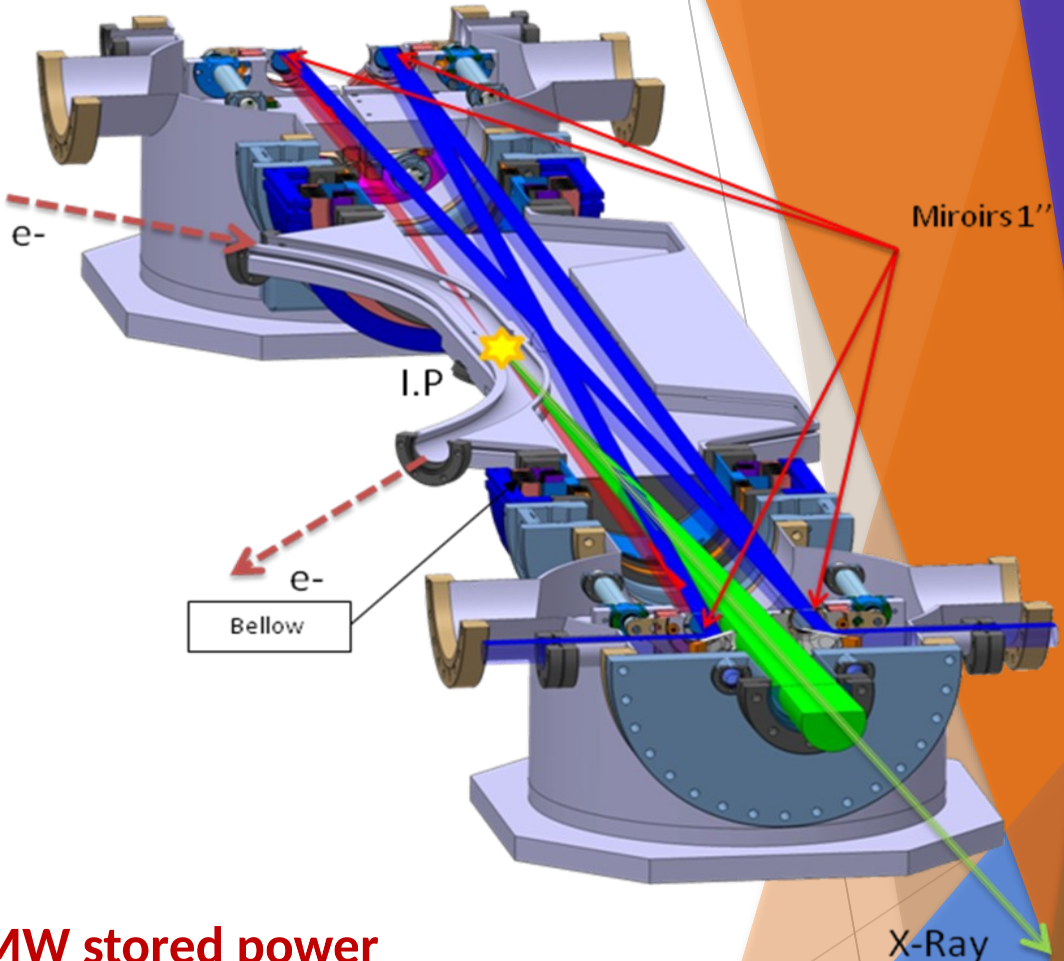
Features of dipoles	
Quantity	14 + 1 (pre-serie)
Radius of curvature	352 mm
Main field B_0	0.7 Tesla
Gap	42 mm
Good field region	+/- 20mm
Integral of field	184.59 mT.m
Current max.	275 Amp
Beam energy	from 50 to 70 MeV

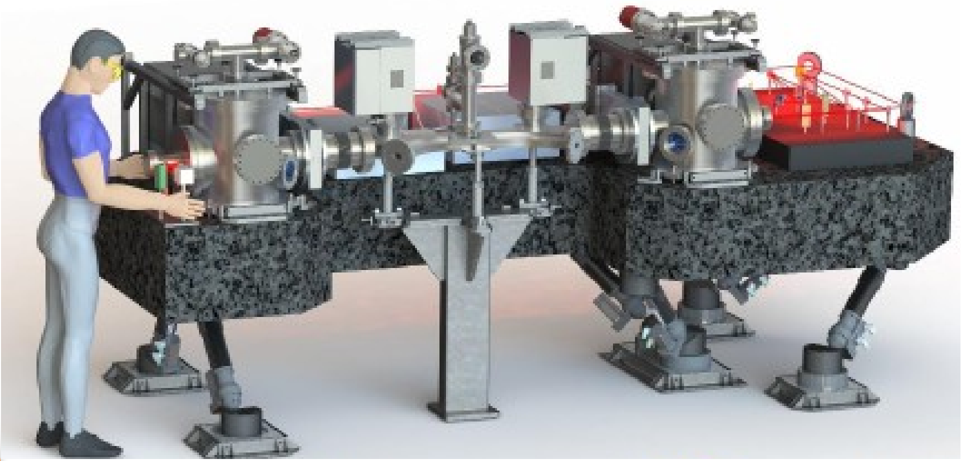


➔ **To guarantee the high-intensity X-ray production: mechanical extension of the ring by ~12 mm**

Fabry-Perot cavity @ThomX

- Oscil. LASER 40 mW, 33.3 MHz, 10-15 ps, 1031 nm
- Optical FIBER AMPLIFICATION
  (fibers doped with Ytterbium)
  → 50 - 100 W (1 - 2 µJ/pulse)
- Optical CAVITY AMPLIFICATION
  4 mirrors planar cavity
  2 plan & 2 spherical
  Optical path ~ 9 m
  Gain 10000

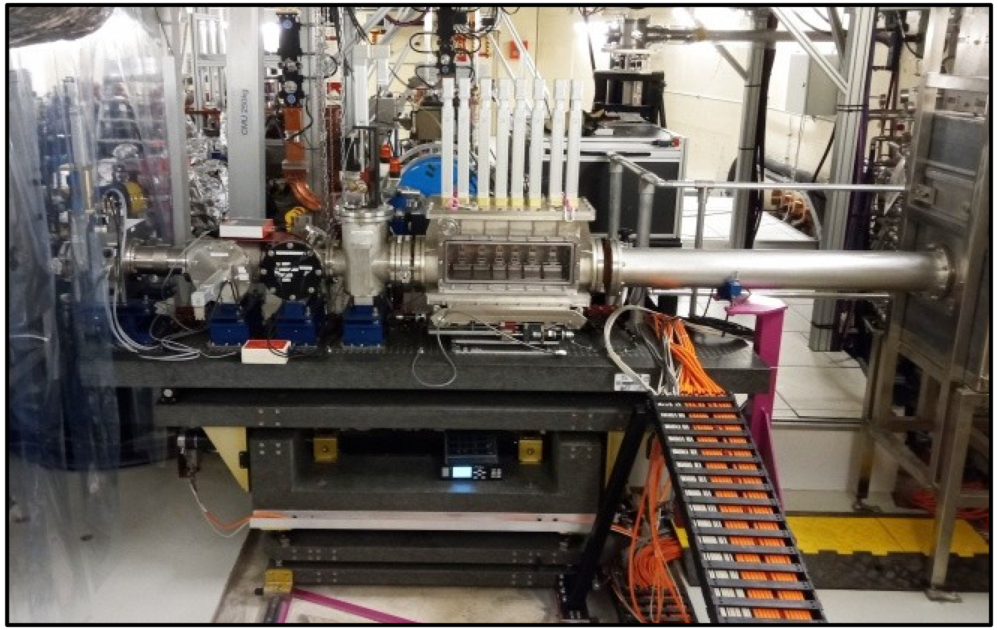




Optical table is installed on the hexapode (µm precision)

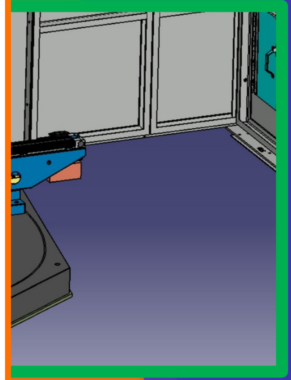
- 0.5 - 1 MW stored power
- Length ~ 10 ps (rms)
- Spot size ~ 70 µm (rms)

X-line design



X-LINE elements inside bunker

X-LINE in X-Hutch



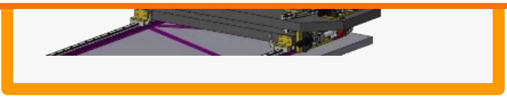
the X-rays

ps

meters, X-ray

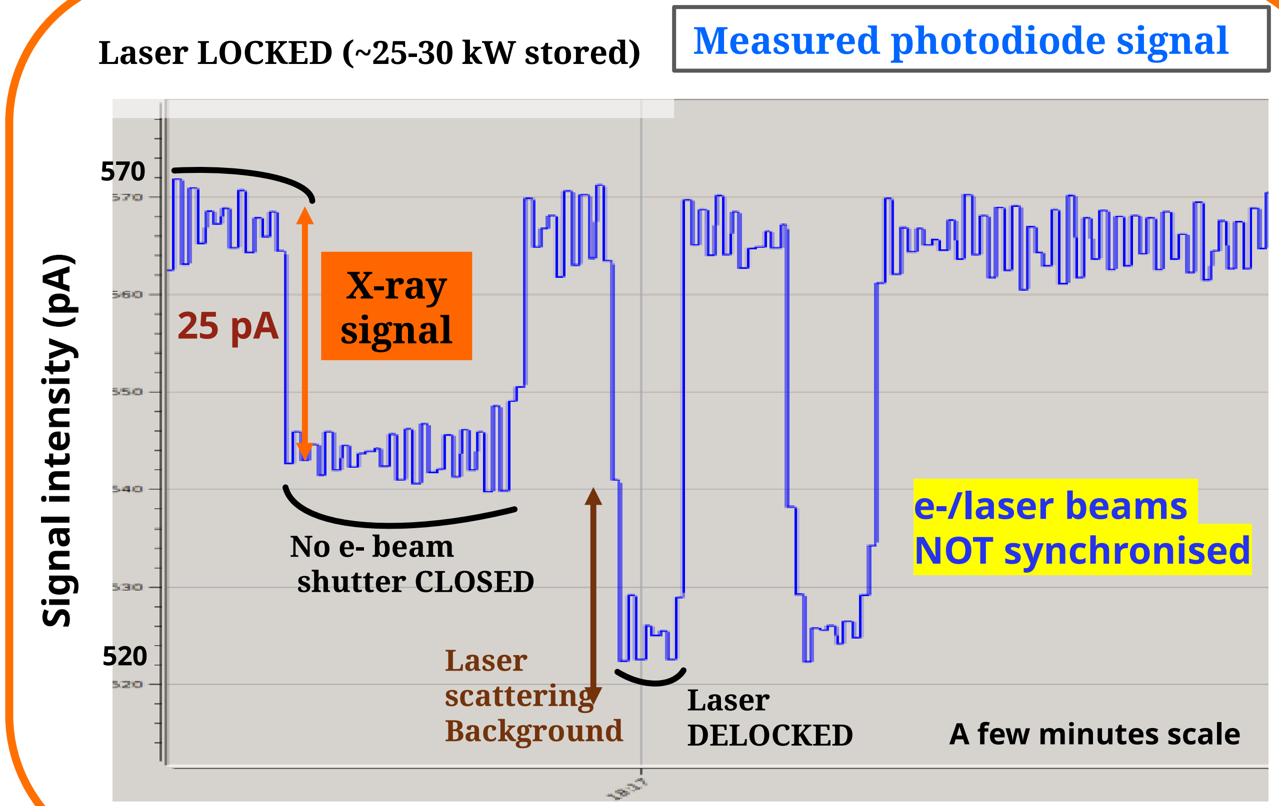
m

beam (translocator)



The first X-rays ☺

23 June 2023



X-ray flux measurement

Expected Flux ~ $(0.5 - 2) \cdot 10^7$ ph/s

(uncertainty on stored e⁻ bunch charge and bunch length)

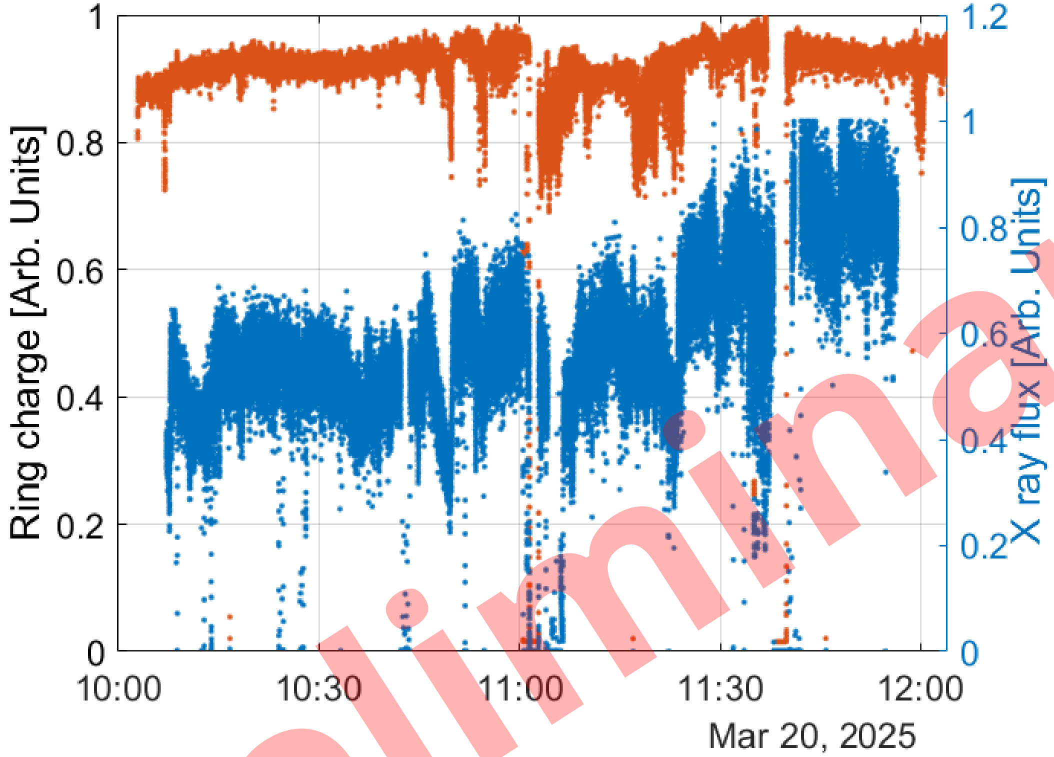
Measured Flux ~10^7 ph/s

M. Jacquet et al. "First production of X-rays at the ThomX high-intensity Compton source."
Eur. Phys. J. Plus 139, 459 (2024)

Current X-ray operational performance

Spectrometer CdTe

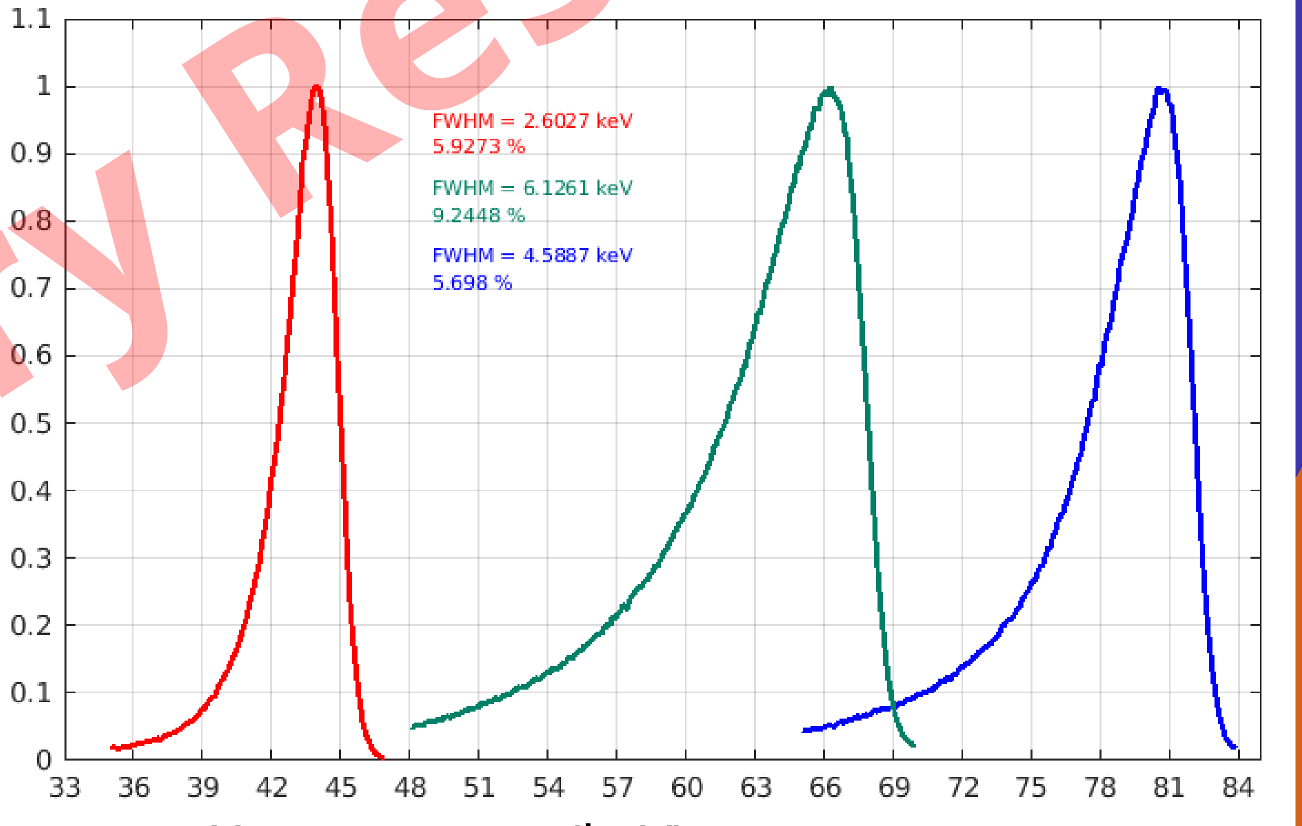
ABSOLUTE FLUX measurement in X-Hutch with a calibrated diode



Calibrated Si diode (Canberra)

Total FLUX ~ 3 × 10¹⁰ ph/s

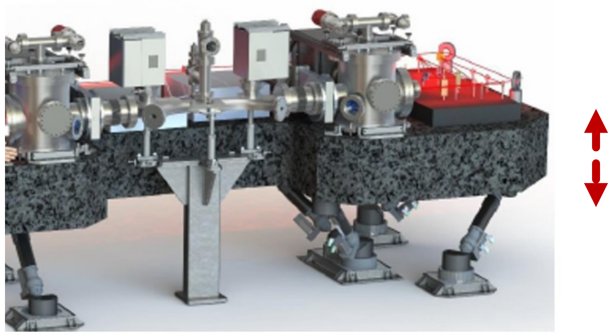
Spectrum

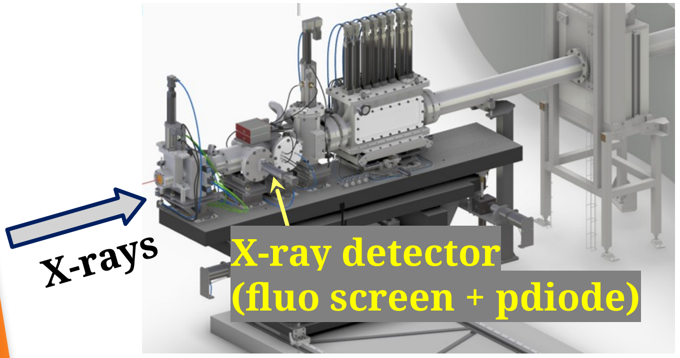


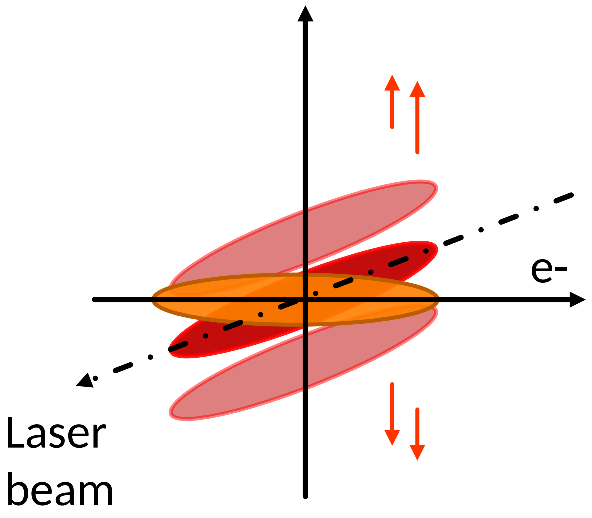
X-rays energy (keV)
for electrons at 50 MeV, 61 MeV and 70 MeV

Ring operation highlights

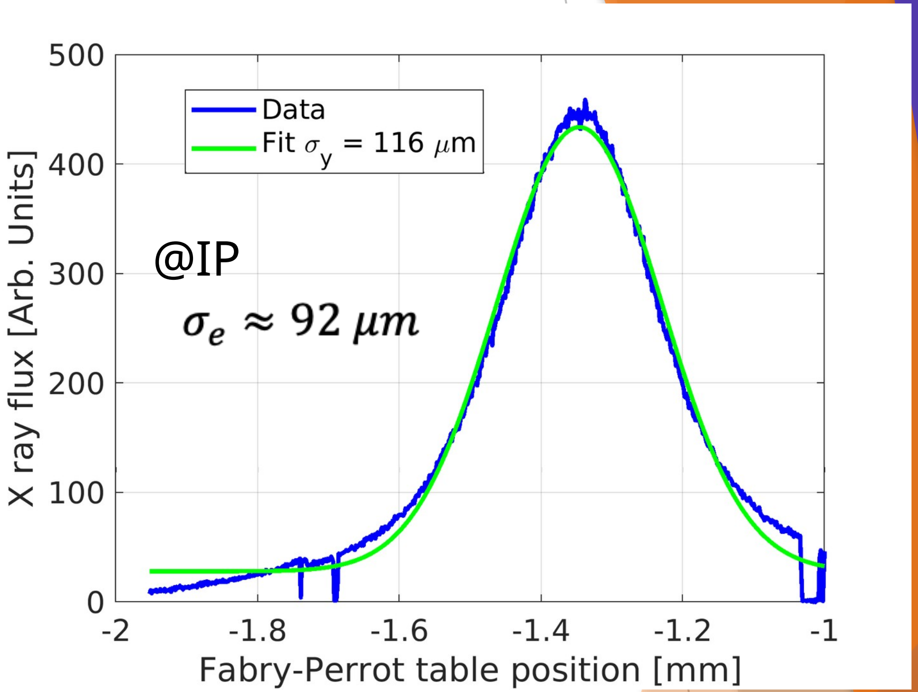
Measurement of the vertical e- beam size @IP







$$\sigma_{scan} = \sqrt{(\sigma_e^2 + \sigma_L^2)}$$



Using/Assumed $\sigma_L \approx 70\mu m$
Typical operational values for e- beam @IP
➔$\sigma_e \approx 90 - 150\ \mu m$

From the model and using injector measured emittances

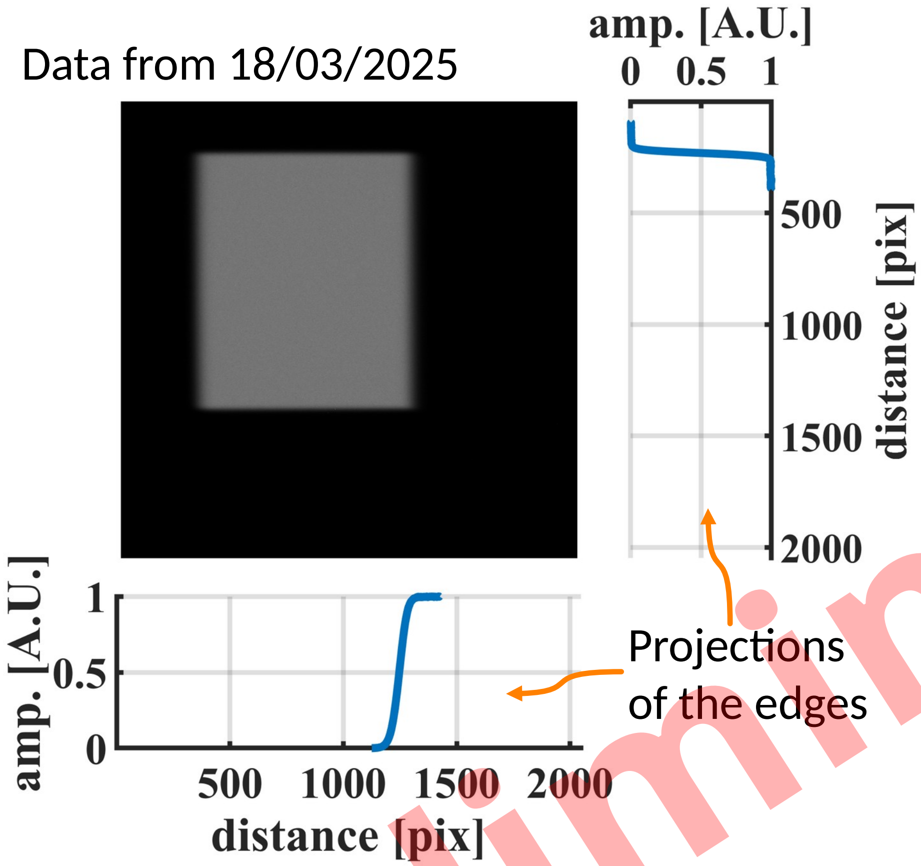
Minimum $\sigma_e^{VERT} \approx 60 - 120\ \mu m$ **(expected)**

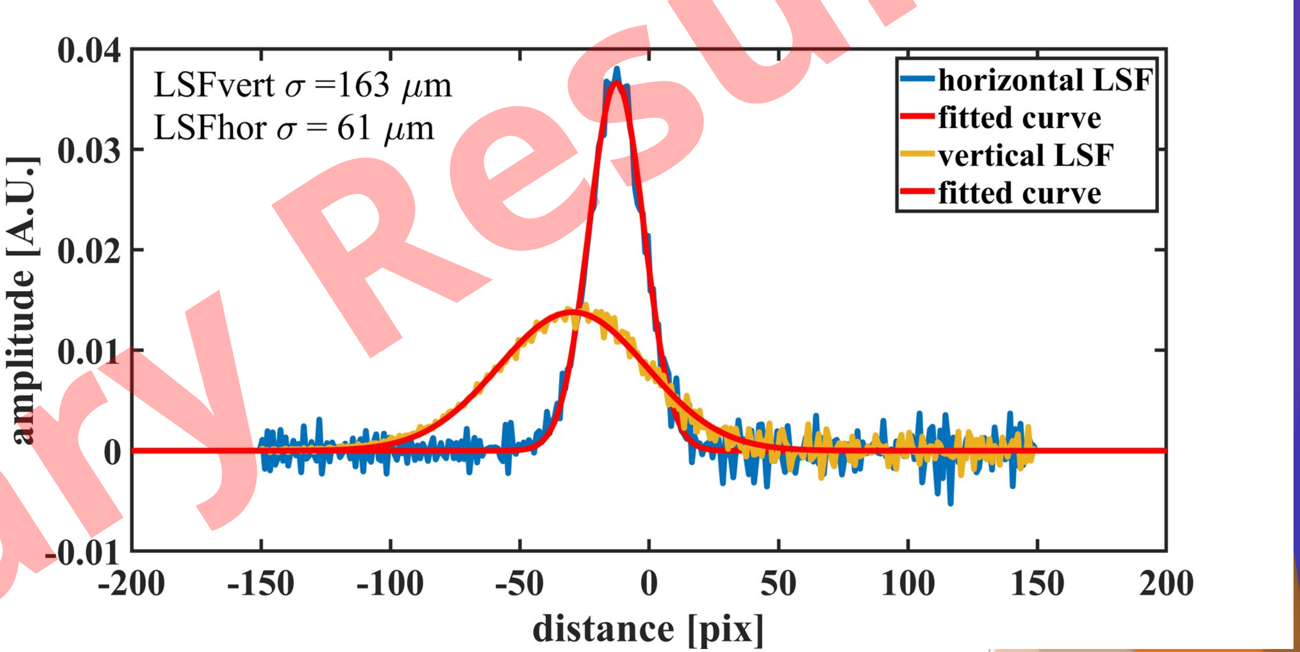
➔long scan duration (many minutes)

☞ good extraction of electron beam size @IP

Source size measurement

Data from 18/03/2025

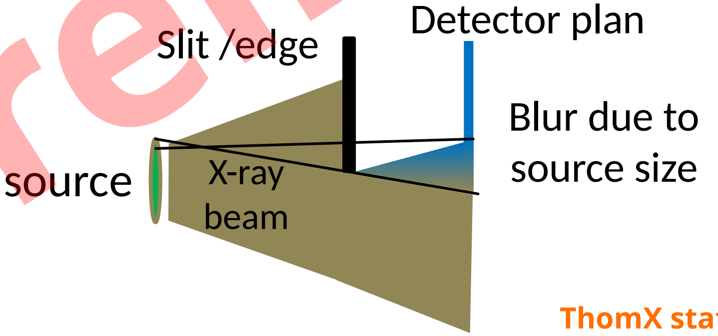




$$\sigma_{source} = \frac{\sigma_e \sigma_L}{\sqrt{\sigma_e^2 + \sigma_L^2}}$$

Using/Assumed $\sigma_L \approx 70\mu m$

➔ $\sigma_e \approx 124\ \mu m$ (vert.)



« single shot » online source size measurement:

☞ **Electron beam size extraction @IP**

☞ **X-ray source position estimation**

e- vert. beam size is in good agreement with other measurements and model

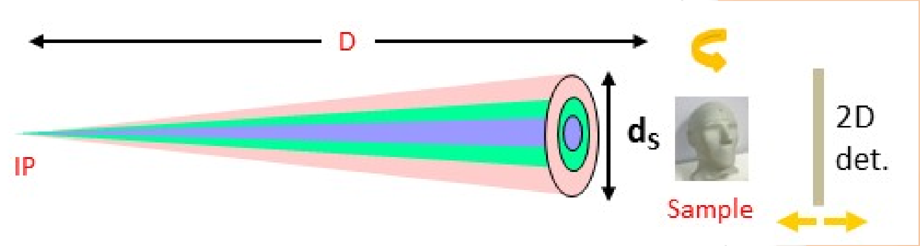
Two ways to use the Compton beam

1. Divergent beam in 2D

Biomedical/cultural heritage applications

- Conventional Radiography
- K-edge subtraction
- Phase contrast imaging
- RADIOTHERAPY

IMAGING



- Several cm diameter
- Pink beam (few % - 30%)
- Flux ~ 10^{11} - 10^{13} ph/s
- 40 - 90 keV

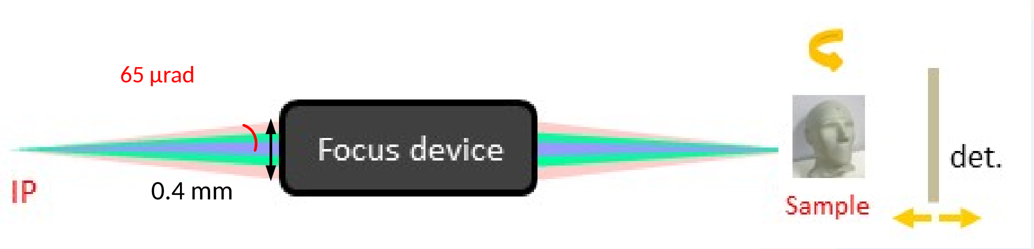
→ Measure large samples in a single exposure (patient, materials …)

2. Beam core

(Cultural heritage, material science, biomedical)

- Fluorescence spectroscopy
  →Chemical composition
- Diffraction
  → Structural analysis

Focalisation = refractive lenses = Transfocator



- beam: mm down to less than 150 µm
- few % to 0.01 % spectral width with mono.)
- Flux ~ 10^{8} - 10^{10} ph/s
- energy 40 - 90 keV

Preliminary analysis: characterization of the X-ray ThomX setup

A. Bravin[1], P. Coan[2], L. Franzoni[1], F. Merighi[1] and ThomX collaboration

[1]University Milano Bicocca (Milan, Italy)
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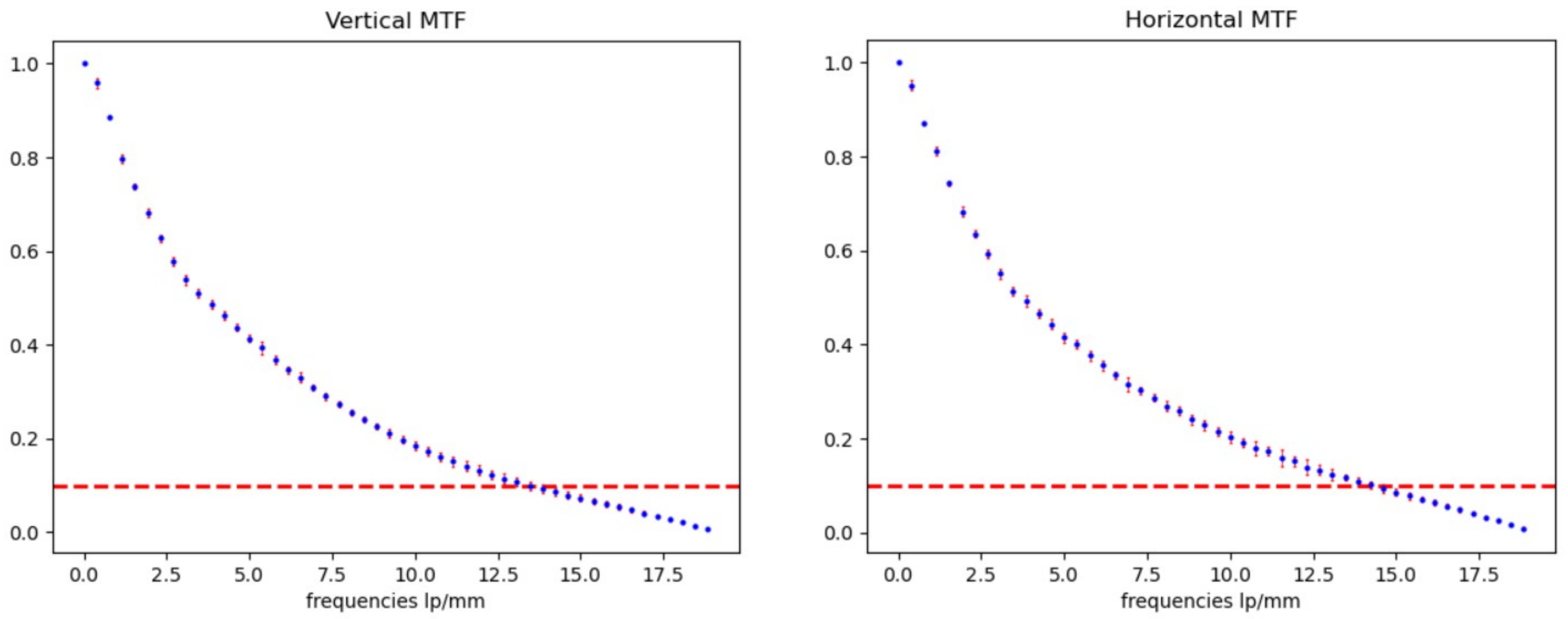
Assessment of the spatial resolution

First step: resolution of the taper optics Photonic Science detector

MTF (modulation transfer function) describes the system response to different spatial frequencies/various sizes

- **MTF value of 1** at low spatial frequencies ➔ **low-frequency (large-scale) details are transferred with full contrast**
- **Smaller MTF** (as the spatial frequency increases) ➔ **the system is less effective at reproducing finer details**

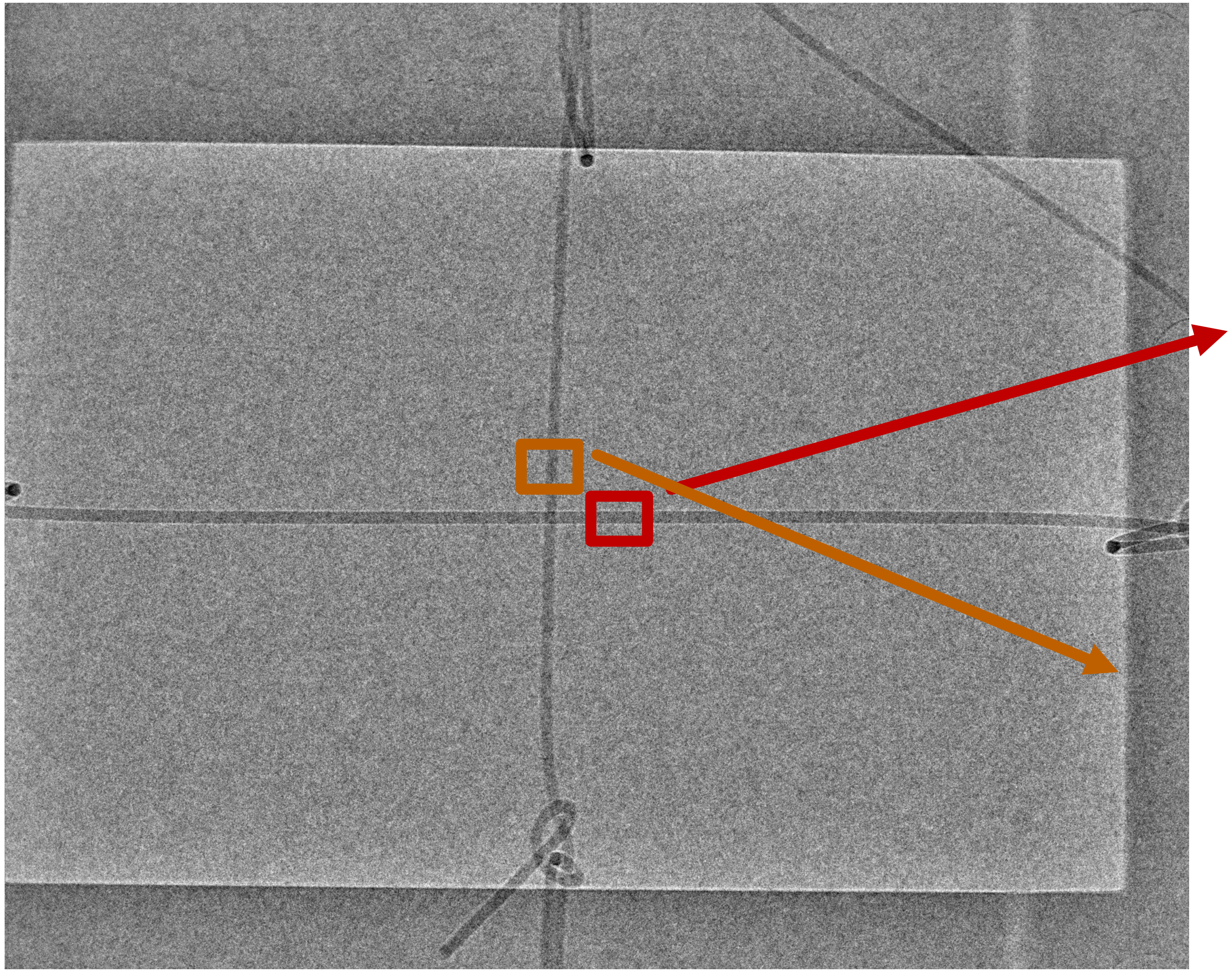


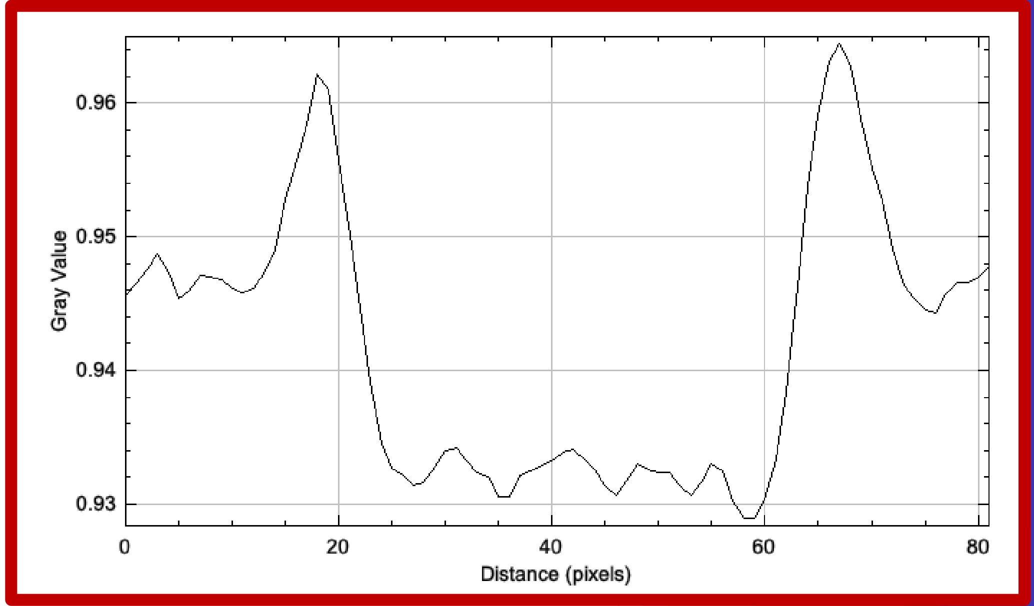
Assessing the 10% MTF value is common method to evaluate the effective spatial resolution of an imaging system

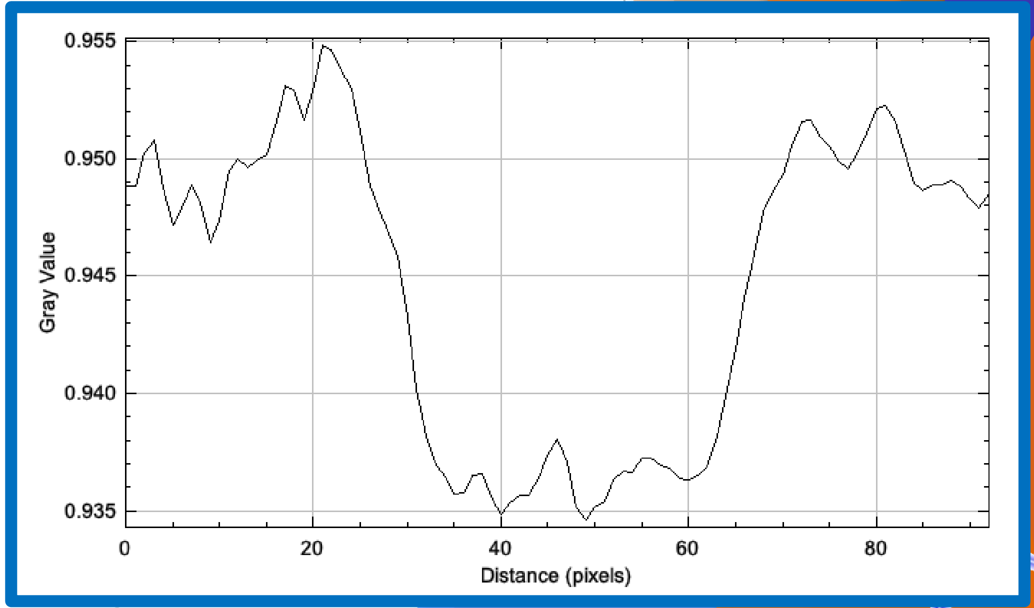
Detector @ThomX: 13–14 line pairs per millimetre (lp/mm)
Should fulfil the requirement of resolving the blur generated @X-ray ThomX setup

Radiography: phase contrast imaging assessment

Wire/fishing line (propagation based) ~ 4,5m



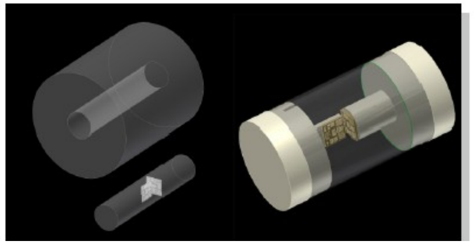




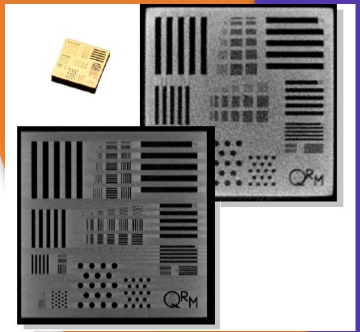
Fishing line has only 1-2% absorption

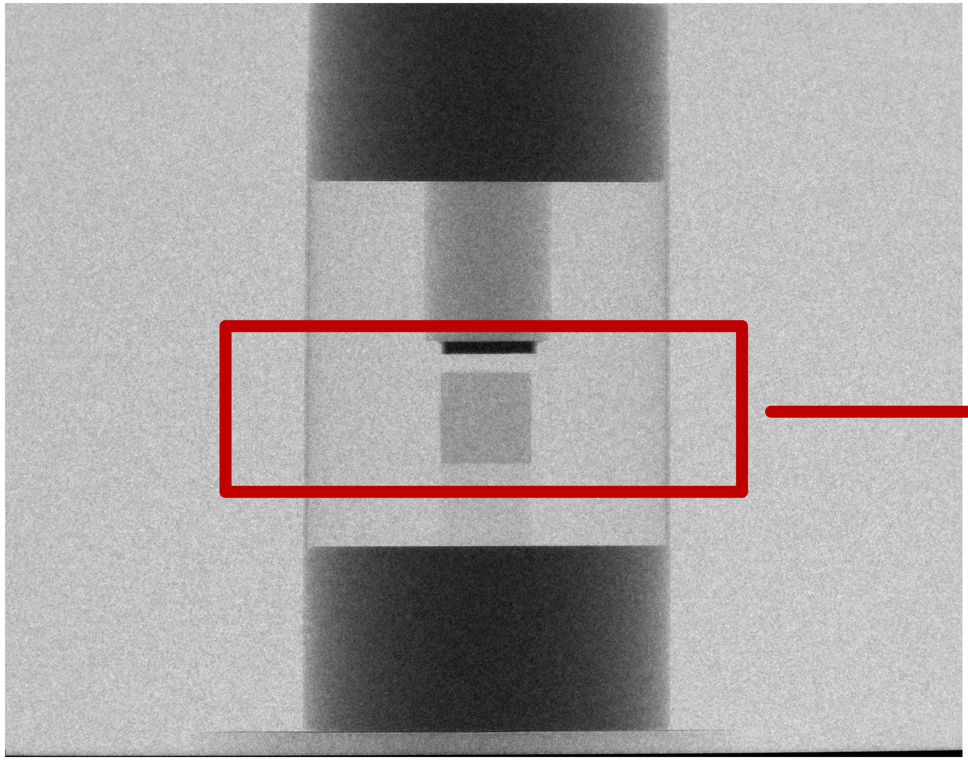
First Computed Tomography (CT)

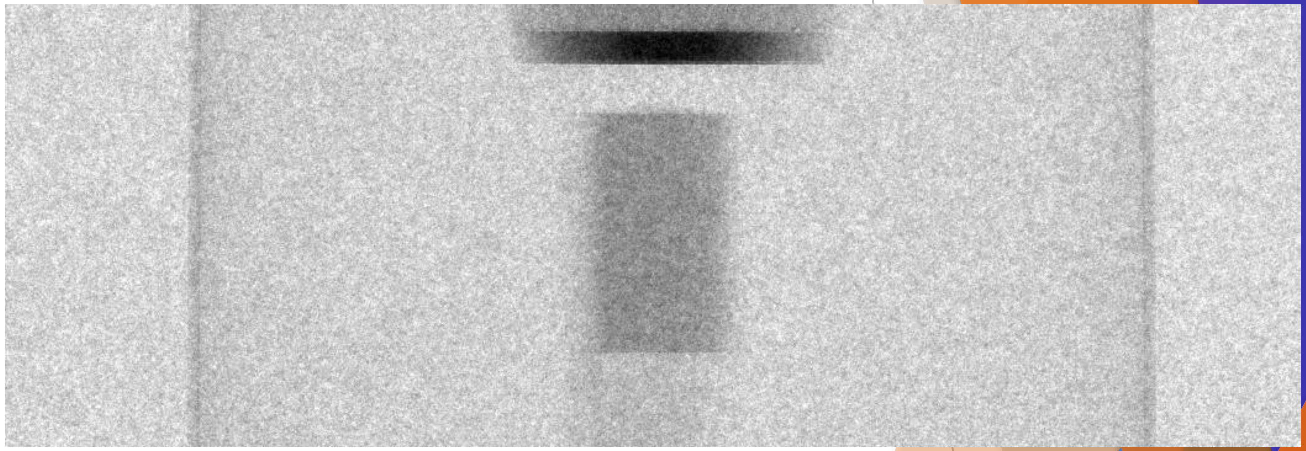
Technique for 3D Imaging



Phantom



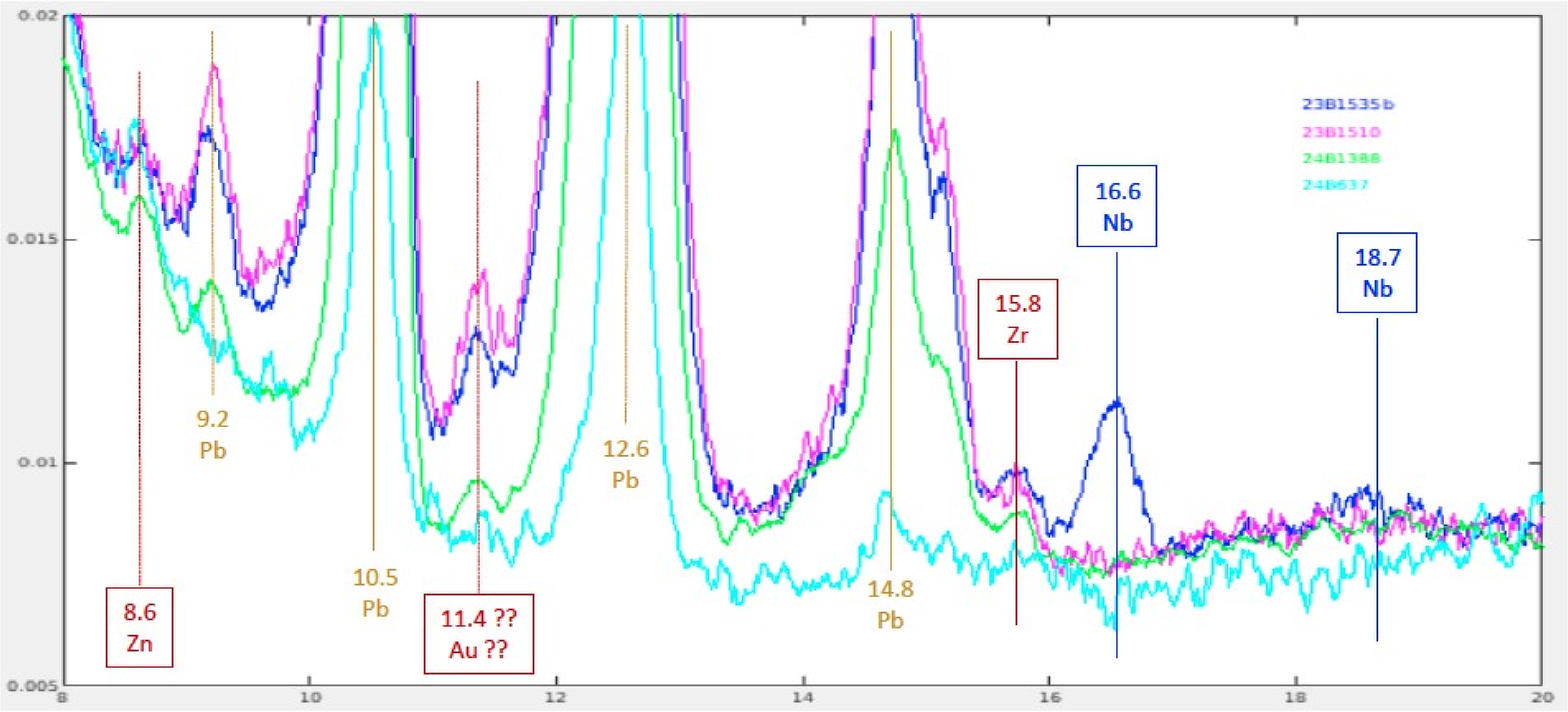




Sample: Bar Pattern
1000 projections from 0°to 180°

Next Steps:
Volume reconstruction and post-processing

Recent measurements: Prostate biopsy

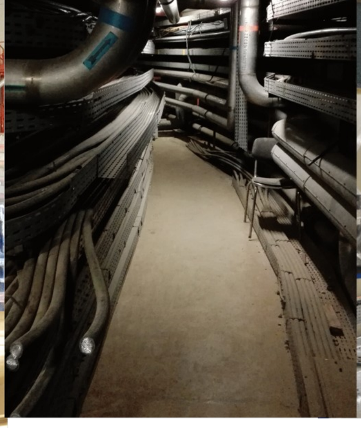
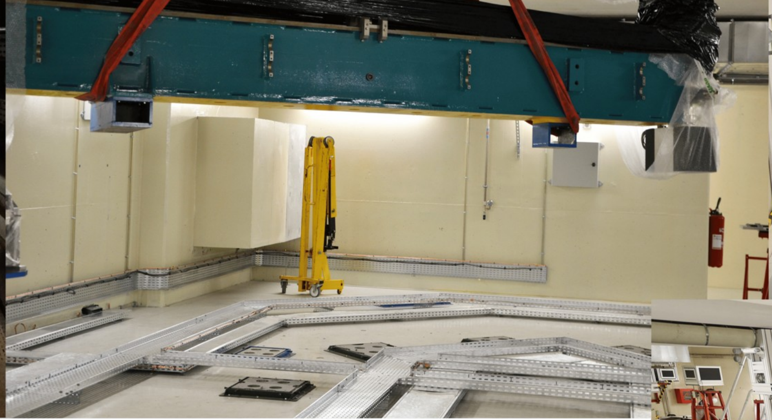
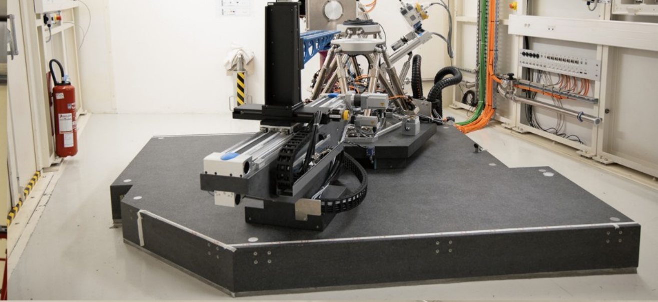
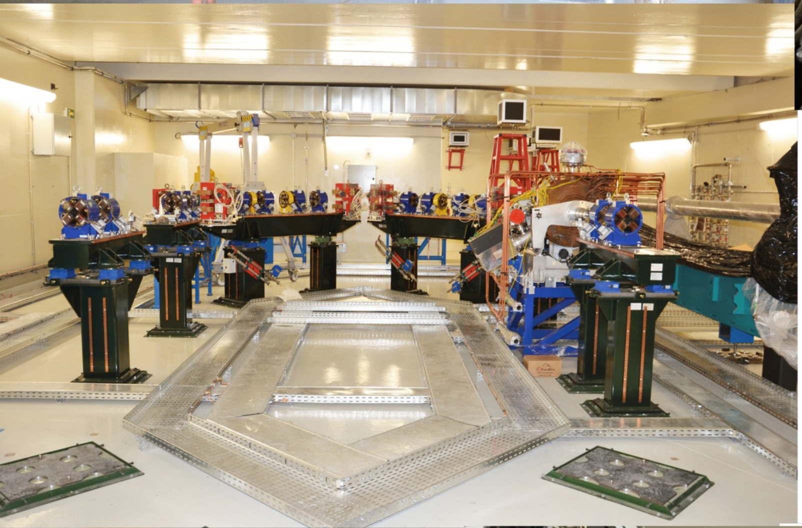


Prostate biopsy taken from patient exposed to metals

Summary

- **ThomX is a research platform and demonstrator !**
  Different from commissioning/operation of a user facility.
- X-ray flux of **~3 $\times$ 10^{10} ph/s** is already **demonstrated**. Several working points available at 40 MeV, 50 MeV, 61.5 MeV and 70 MeV. **Characterization of X-rays is in progress.**
- **Currently one of the most advanced Compton source in operation: 10^{11} – 10^{12} ph/s expected in near future !**
- Recent cathode change (Mg): increase of the e- charge aiming for 1 nC (Mg photocathode) and operation at 50 Hz.
- Fabry-Perrot cavity stored power gradually will be increased up to 500 kW. **Goal: ~10^{12} ph/s**
- **successful first X-ray experiments /commissioning :** standard/phase contrast imaging, tomography, fluorescent spectroscopy … to be continued.
- **The help from SOLEIL's team has been invaluable to us.**

M. Alkadi, et al. "Commissioning of ThomX Compton source subsystems and demonstration of 10^{10} x-rays/s."
Phys. Rev. Accel. Beams 28 (2025): 023401

Thank you!

ThomX