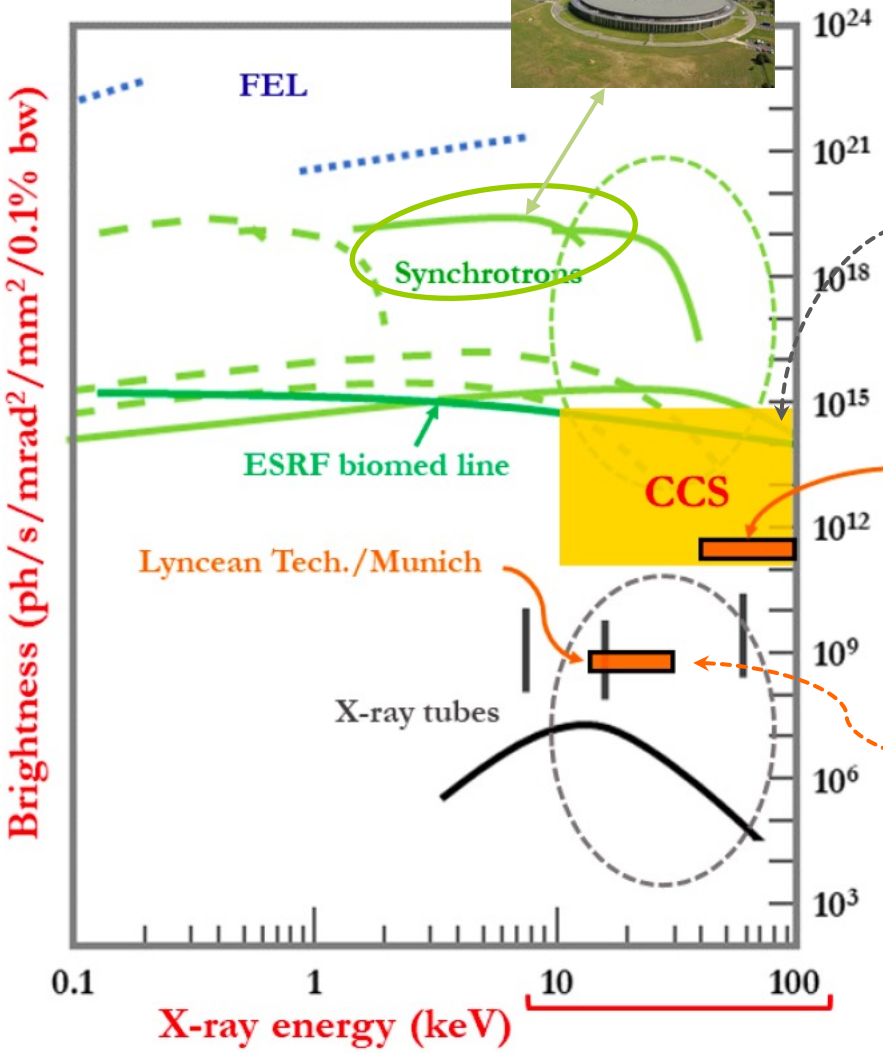
ThomX status and plans

Iryna Chaikovska (IJCLab)
on behalf of the ThomX collaboration

Thanks to ThomX colleagues, especially to H. Monard and A. Moutardier for providing the materials for these slides

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.*

ThomX: Compton back-scattering-based X-ray source



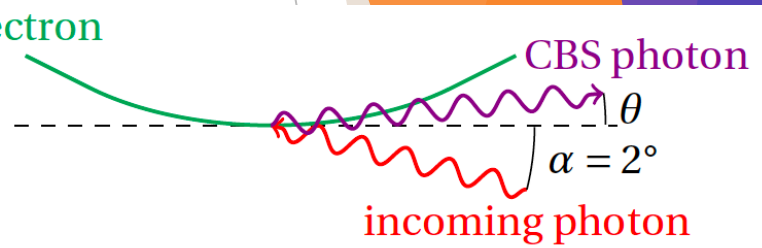
Next future Compact Compton Sources (CCS)

Superconducting electron guns

Not yet mature technology

The only high flux CCS machine in operation
Flux ~ 10^{10} - 10^{11} ph/s
(Munich/Lync. Tech.)

ThomX : 45-90 keV
Flux ~ 10^{12} - 10^{13} ph/s
Brill ~ 10^{10} – 10^{11} unit



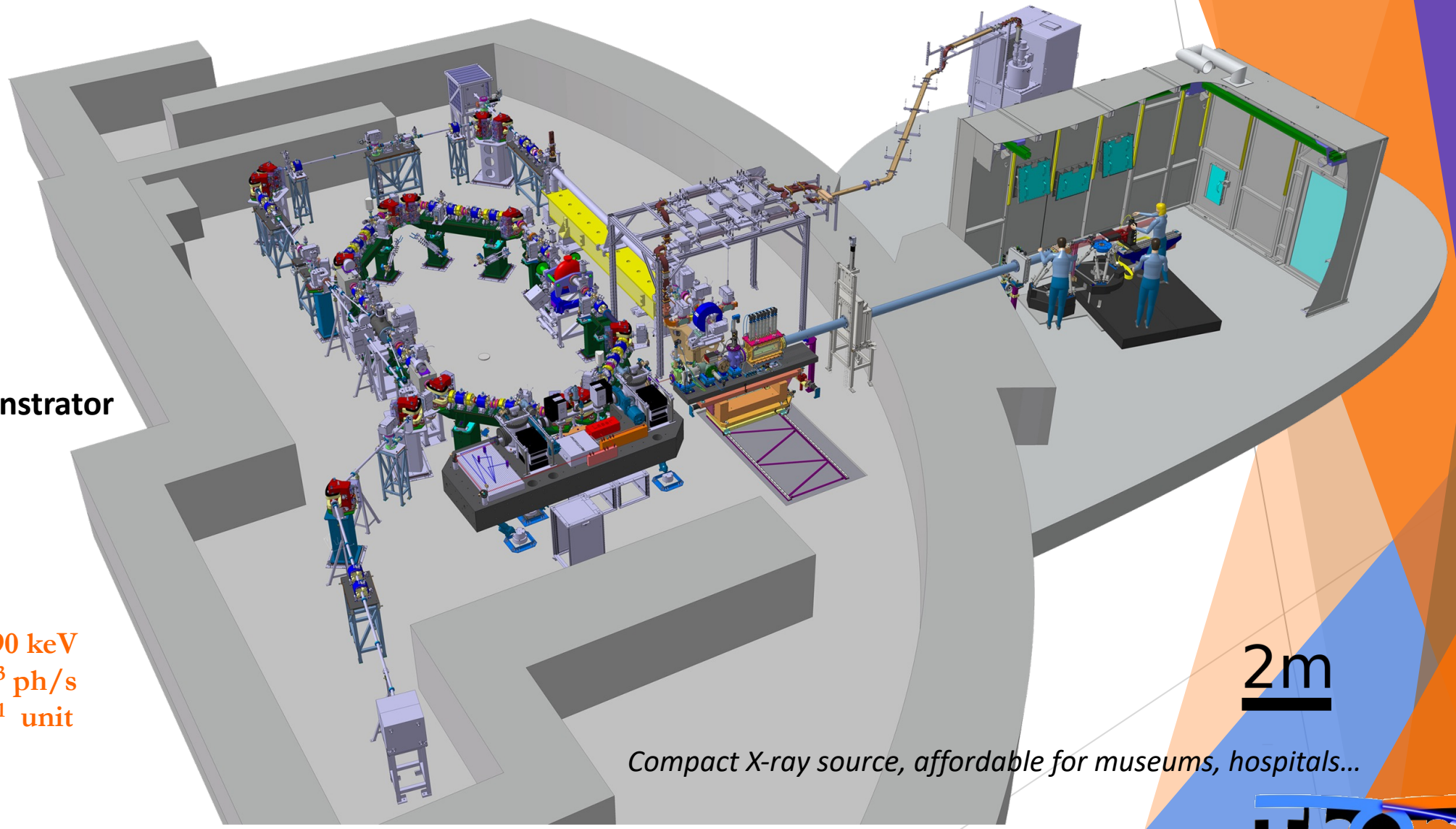
- CBS : momentum transfer from e^- to γ
- Maximal energy gain ($\theta = 0°$):

$$E_{CBS,max} = 4\left(\frac{E_e}{m_e c^2}\right)^2 \times E_\gamma = 4\gamma^2 \times E_\gamma = 45\,\text{keV}$$

with : $\gamma \approx 100$ the Lorentz factor

ThomX facility

ThomX target is a high AVERAGE flux => many electrons and photons colliding in a small volume at high frequency



ThomX is a demonstrator

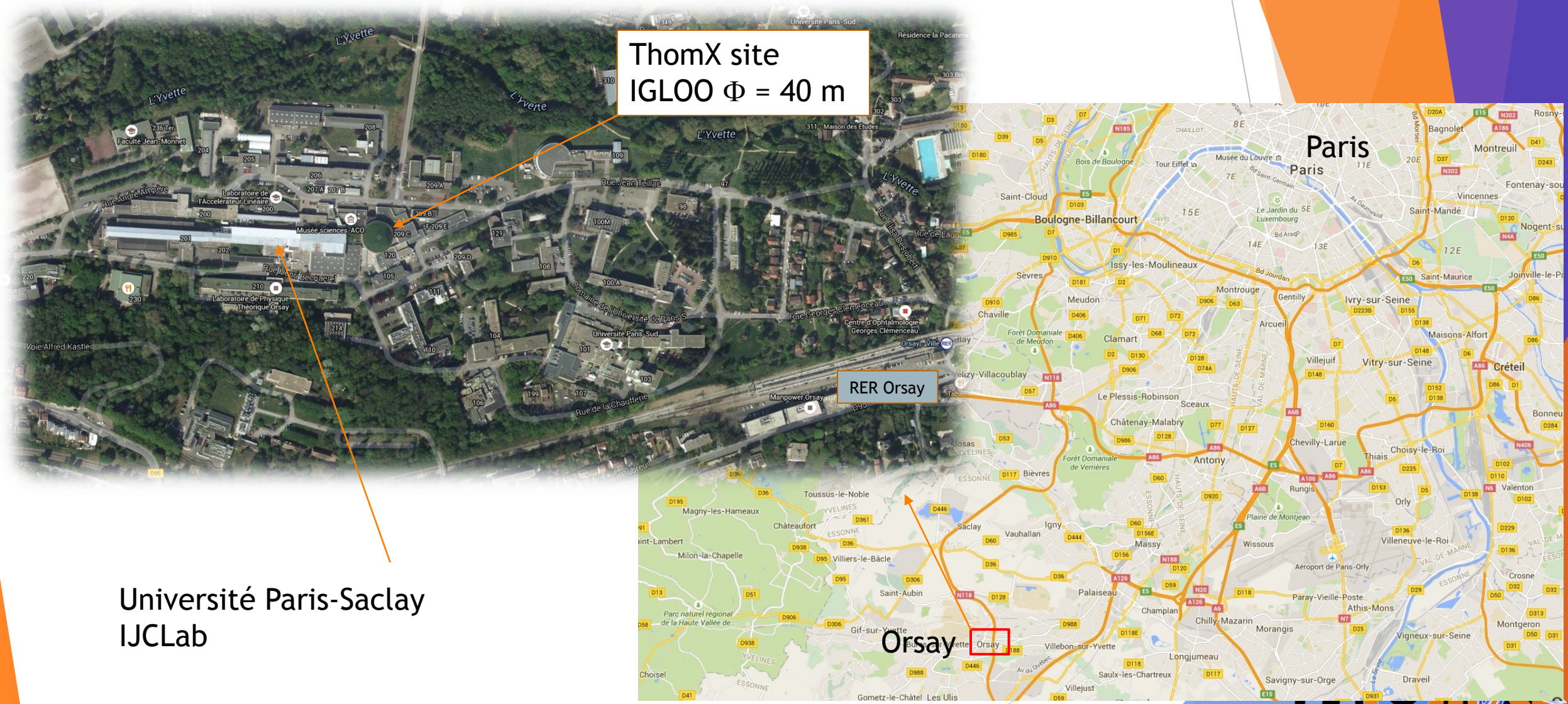
ThomX : 45-90 keV
Flux ~ 10^{12} - 10^{13} ph/s
Brill ~ 10^{10} – 10^{11} unit

2m

Compact X-ray source, affordable for museums, hospitals…

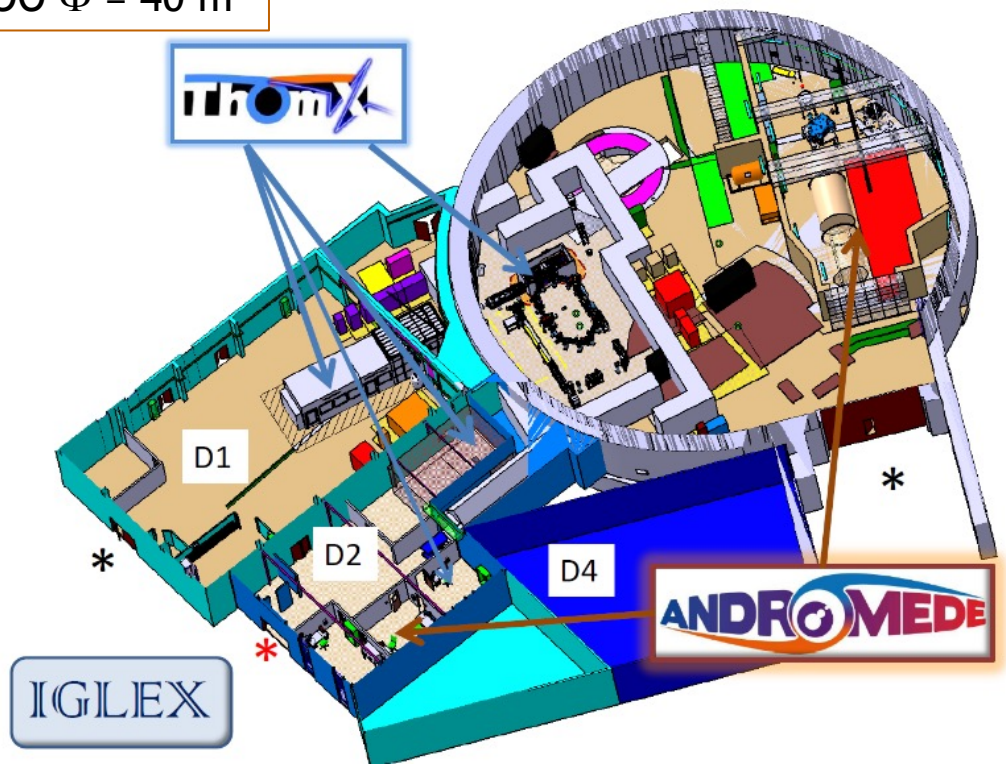
Users: cultural heritage, bio-medical and therapy applications, crystallography, X-ray imaging…

ThomX facility location



ThomX budget and manpower

ThomX site
IGLOO Φ = 40 m



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

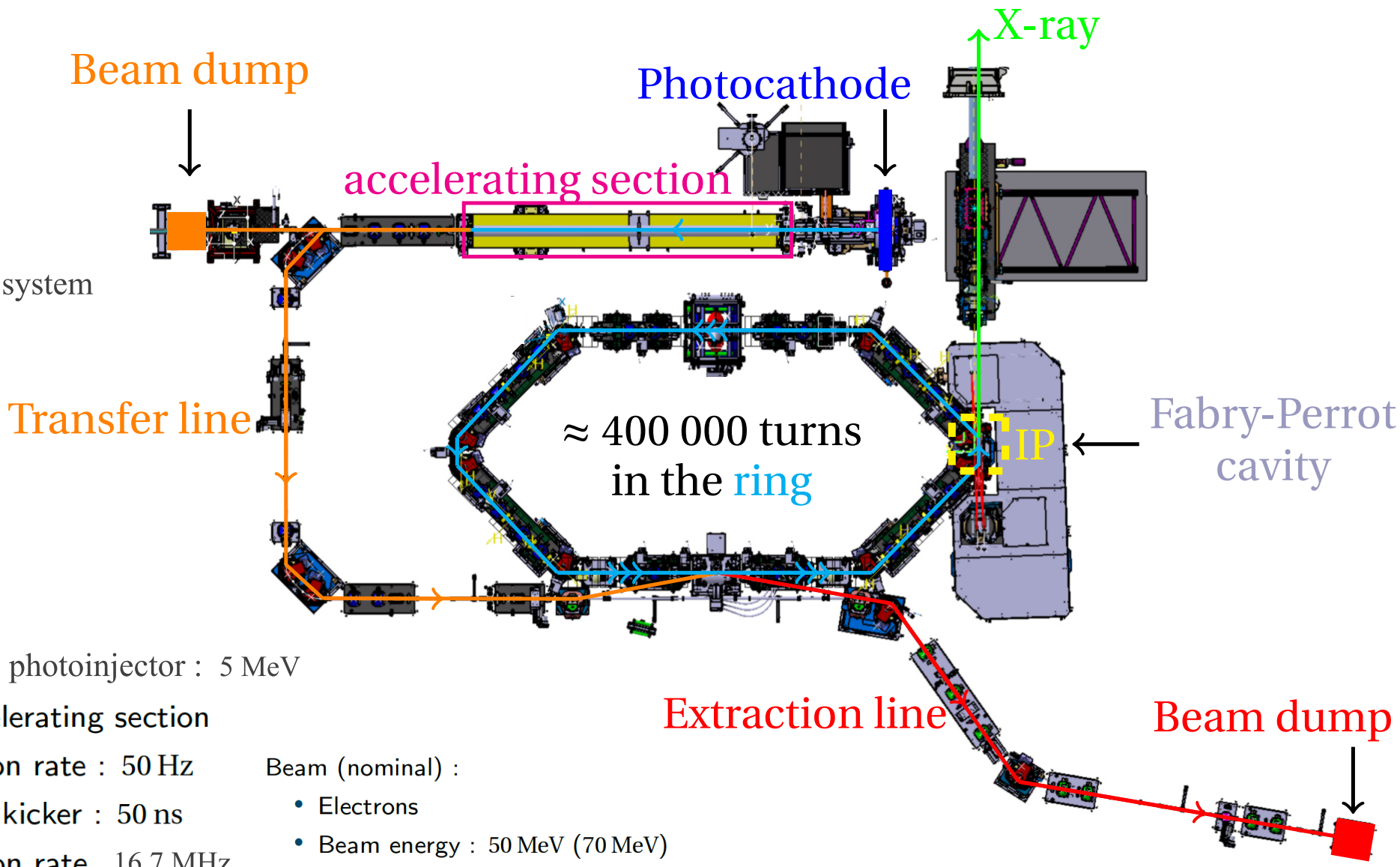
Civil engineering: 2,2 M€
(local Essonne funding)

8 french partners :
LAL/IJCLab, Soleil, CELIA, LAMS, ESRF, NEEL, INSERM,Thalès

New research platform IGLEX (old IGLOO building in the Orsay Campus)

ThomX accelerator

The ThomX control system is based on Tango.



Accelerator :

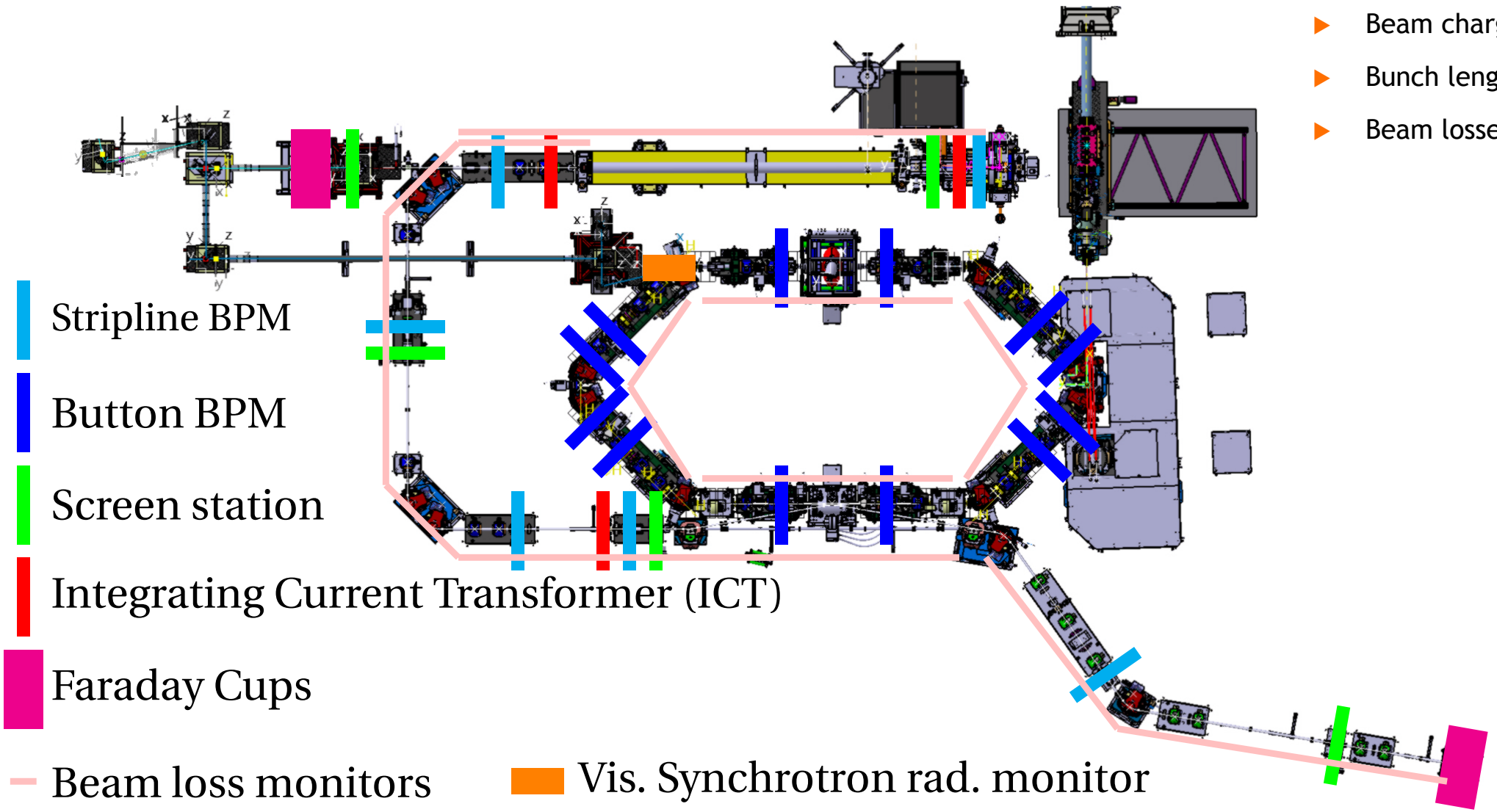
- Made in-house photoinjector : 5 MeV
- 4.5m LIL accelerating section
- Linac repetition rate : 50 Hz
- Fast injection kicker : 50 ns
- X-ray repetition rate 16.7 MHz
- Surface : 70 m^2

Beam (nominal) :

- Electrons
- Beam energy : 50 MeV (70 MeV)
- Beam charge : 1 nC
- Transverse emittance : 5 πmmmrad

ThomX beam diagnostics

- Beam position (BPM)
- Transverse profile (Diagnostic stations, VSRM)
- Beam charge (ICT, FC)
- Bunch length (Streak camera)
- Beam losses (FBLM, Scintillators)



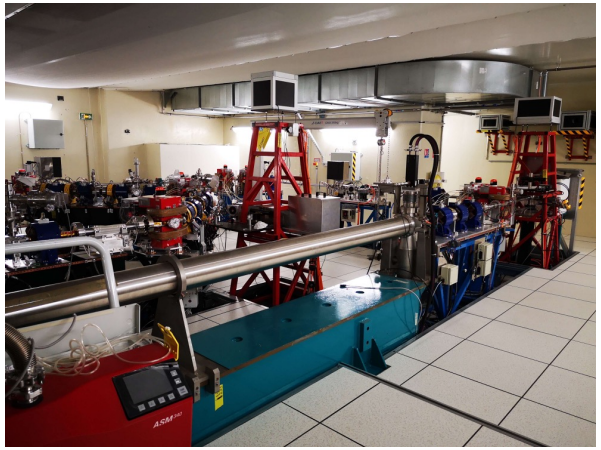
ThomX commissioning stages

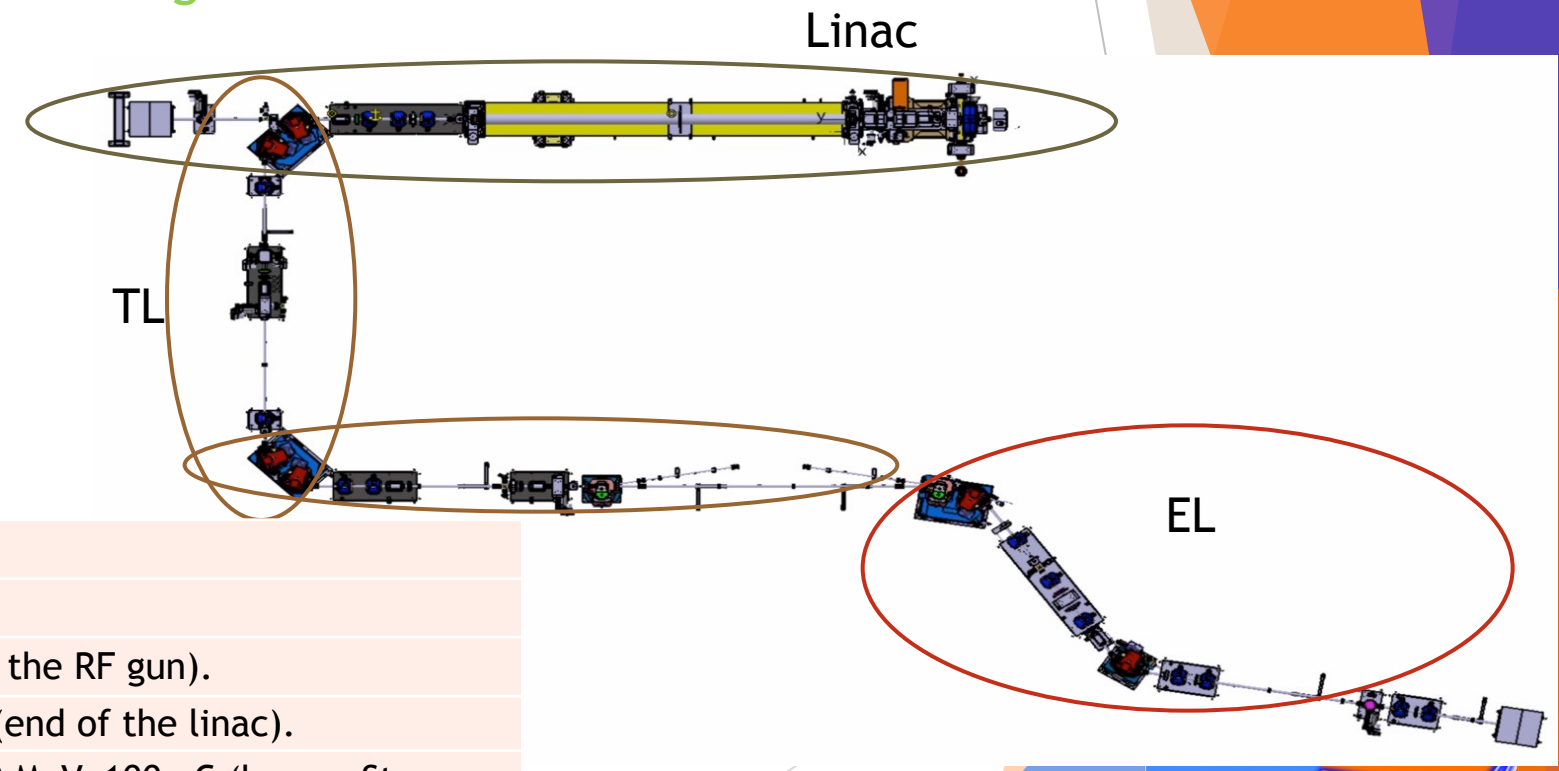
Stage	Objective	Beam Energy	Charge	Frep	Bunch Length	Energy Spread	Emittance	X-ray Energy	X-ray Flux
HC	**Hardware commissioning**								
TC	**Technical commissioning**								
	Beam commissioning (BC)								
A	**Injector commissioning**								
	RF gun + Linac	50 MeV	10→100 pC	0→10Hz	2-8 ps	0.2-0.4 %	~2 μm rad		
	RF gun + Linac + TL + EL	50 MeV	10→100 pC	0→10Hz	2-8 ps	0.2-0.4 %	~5 μm rad		
B	**Ring commissioning**								
	First turns + stored beam	50 MeV	100 pC	0→10Hz	2-8 ps (inj)	0.2-0.4 % (inj)	~5 μm rad (inj)		
C	**FPC commissioning + first X-rays**								
	Optimization of the IP	50 MeV	100 pC	0→10Hz	2-8 ps (inj)	0.2-0.4 % (inj)	~5 μm rad (inj)	45 keV max	10^{9}-10^{10} ph/s (@100kW)
D	**Commissioning at nominal charge** RF gun + Linac + TL + EL + SR	50 MeV	1 nC	0→50Hz	2-8 ps (inj		LI: 5 μm rad RI: 7-8 μm rad	45 keV max	10^{11}-10^{13} ph/s (@500kW)
E	**X-ray production towards nominal operation**								
	Increasing X-ray flux to nominal	50 MeV	1 nC	50Hz	2-8 ps (inj		7-8 μm rad	45 keV max	~10^{13} ph/s (@500kW)
F	**Commissioning and operation at 70 MeV**	70 MeV	1 nC	0→50Hz	2-8 ps (inj			90 keV max	~10^{13} ph/s (@500kW)

Commissioning Linac+TL+EL (ongoing)

- RF conditioning of the acc. structures (RF gun + LIL section)
- Test and validation of the equipment (technical commissioning with beam)
- Beam commissioning. Final goal : Get the beam 50 MeV, 100 pC

at 10 Hz, optimized for the injection in the ring

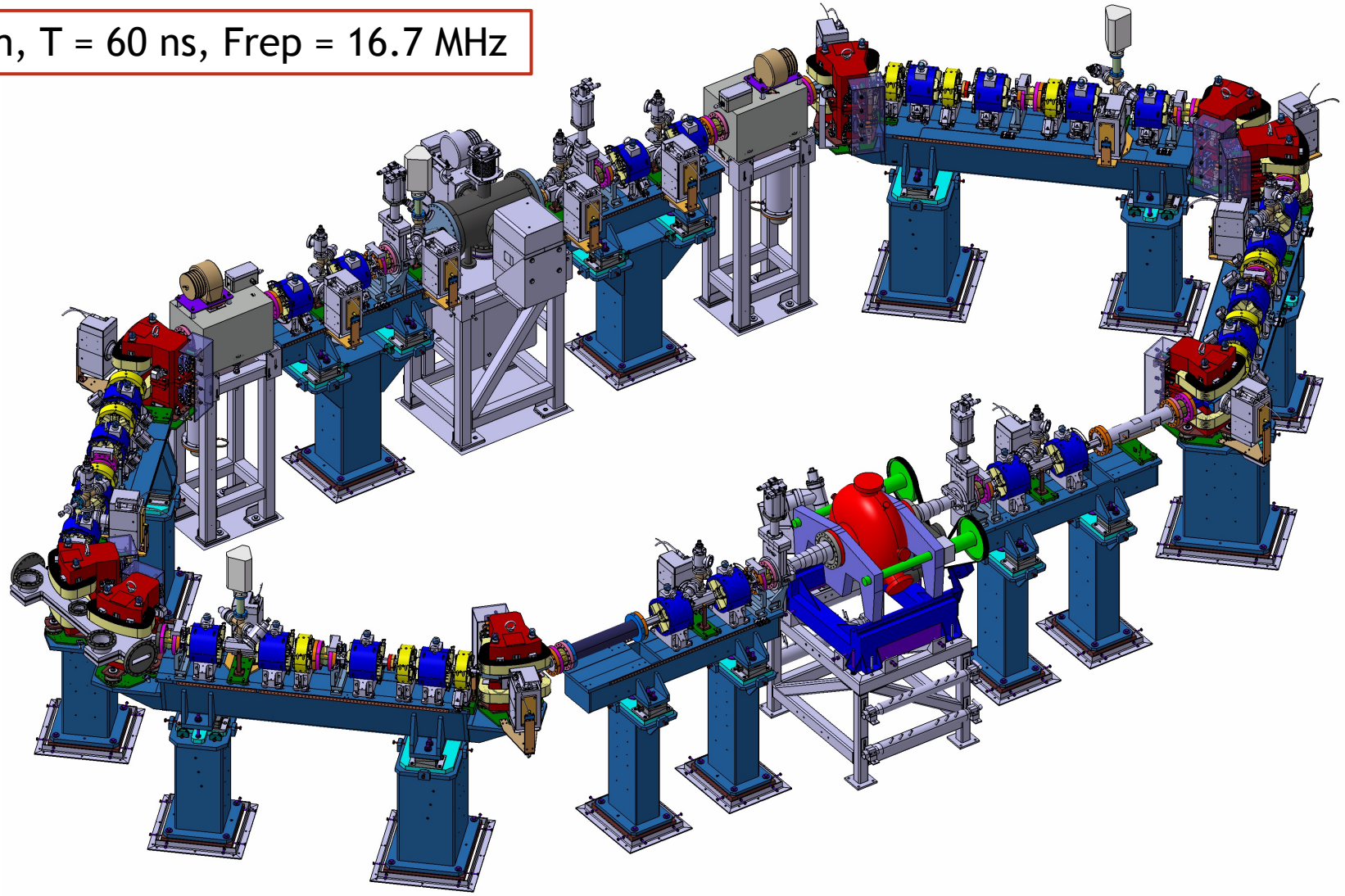




Phase	Description
A.1	RF conditioning: RF gun and LIL section.
A.2	First electron beam ~5 MeV, 100 pC (exit of the RF gun).
A.3	First electron beam 50 MeV, 100 pC, 10 Hz (end of the linac).
A.4	Bending to the TL and then EL: transport 50 MeV, 100 pC (bypass Storage Ring).
A.5	Injection in the Storage Ring.

ThomX Storage Ring

ThomX SR: L = 18 m, T = 60 ns, Frep = 16.7 MHz

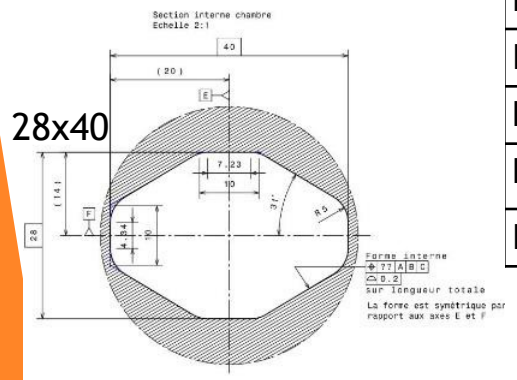


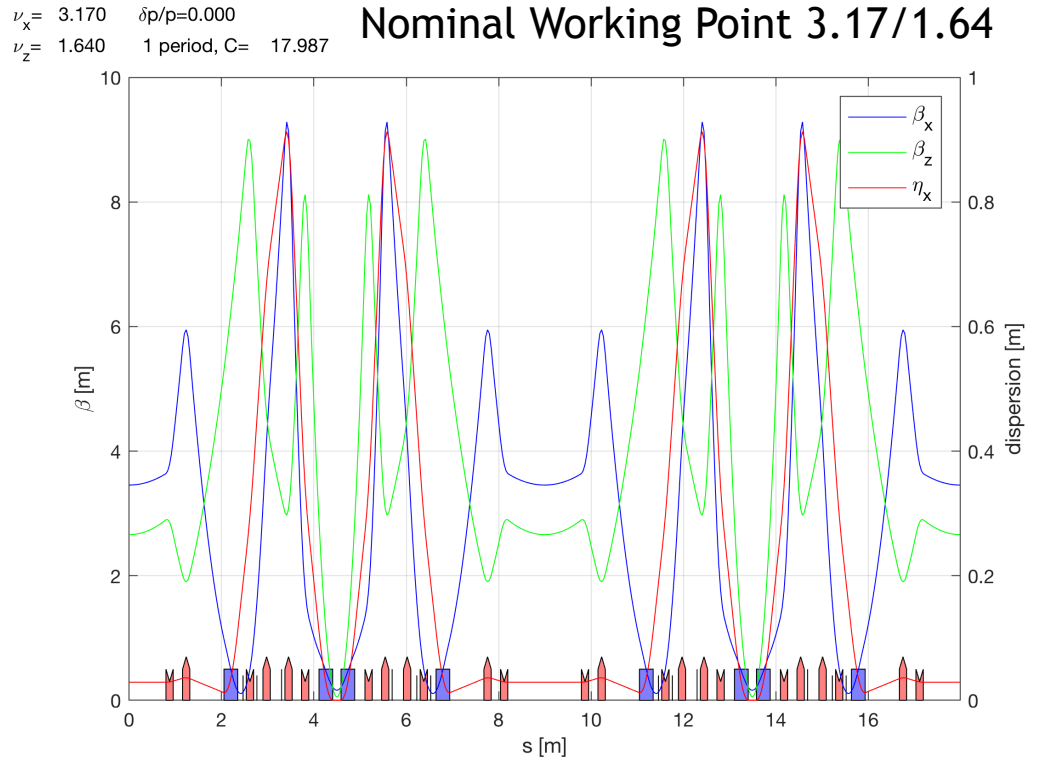
Ring lattice and parameters

ThomX SR: L = 18 m, T = 60 ns, Frep = 16.7 MHz

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

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
Beam size at the IP	70 µm
Nominal RF Voltage/cavity	300 kV (500 kV max)
Energy loss per turn	1.57 eV





ThomX Lattices Day 1

AT lattices:

ThomX_017_064_r56_02_chro00
ThomX_017_064_r56_03_chro00
ThomX_017_064_r56_04_chro00
ThomX_017_064_r56_02_chro11
ThomX_017_064_r56_03_chro11
ThomX_017_064_r56_04_chro11

Ring commissioning with beam (phases)

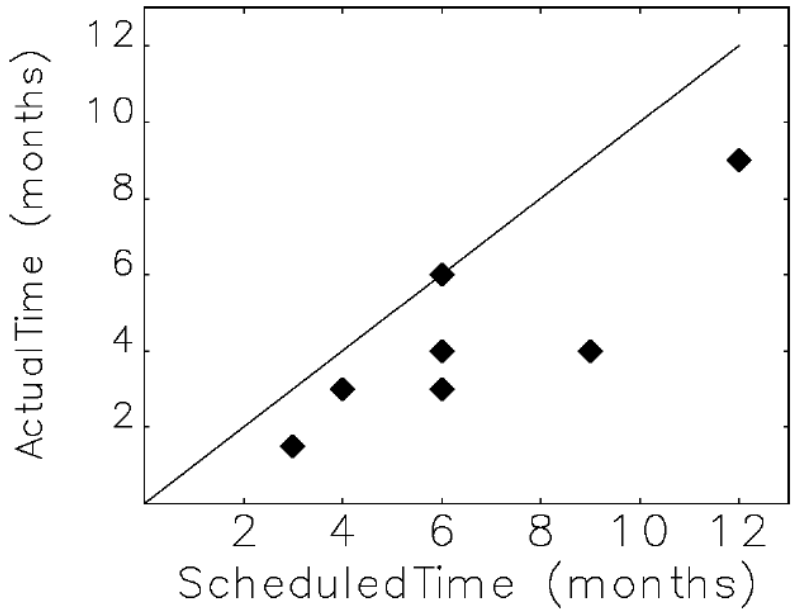
Phase	Description
B.1	**Injection and first turn: injection commissioning, threading, commissioning beam instrumentation**
B.2	**Establish circulating beam: closed orbit, orbit correction, tunes, chromaticity**
B.3	**Stored beam and extraction: precise measurements, BBA, feedback systems, beam diagnostics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

Phase	Description
C	Operation with FPC and IP optimization: position and phase scan
D	Ring commissioning at nominal charge: injection tuning and feedback test at the nominal charge, higher α_p optics
F	Ring commissioning at 70 MeV: repeat the necessary commissioning steps (phase B)

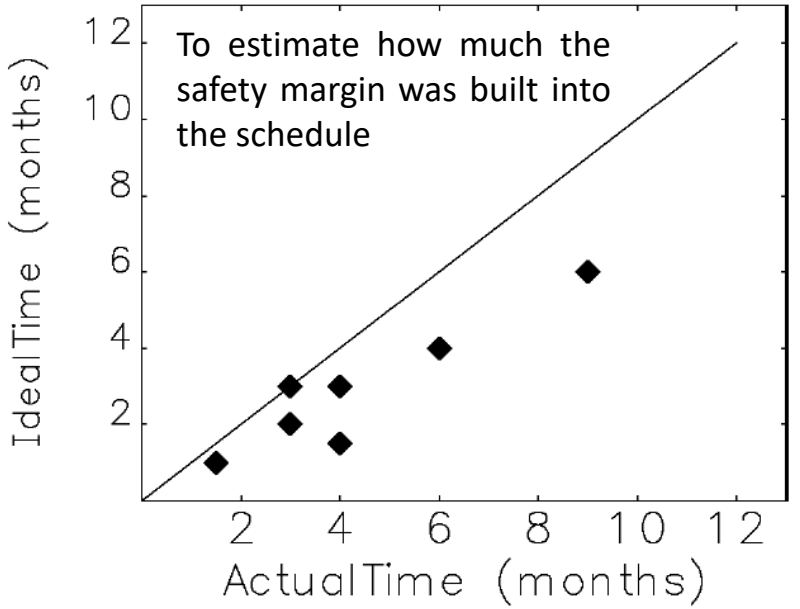
Duration of the ring commissioning

<u>According to the survey</u>
<u>(ALBA, BESSY-II, DLS, PLS-II, SOLEIL, SSRF, SPEAR3)</u>

M. Borland et al., Survey of Commissioning of Recent Storage Ring Light Sources, IPAC15



- Scheduled duration ranged between 3 and 12 months (commissioning typically took much less time than scheduled)
- Five of seven responding facilities stated that commissioning could be done in **<u>3 months</u>** or less (if nothing had gone wrong).
- Mostly 24/7, but with interruptions for repairs/installation in some cases



Duration of the ring commissioning =>ThomX

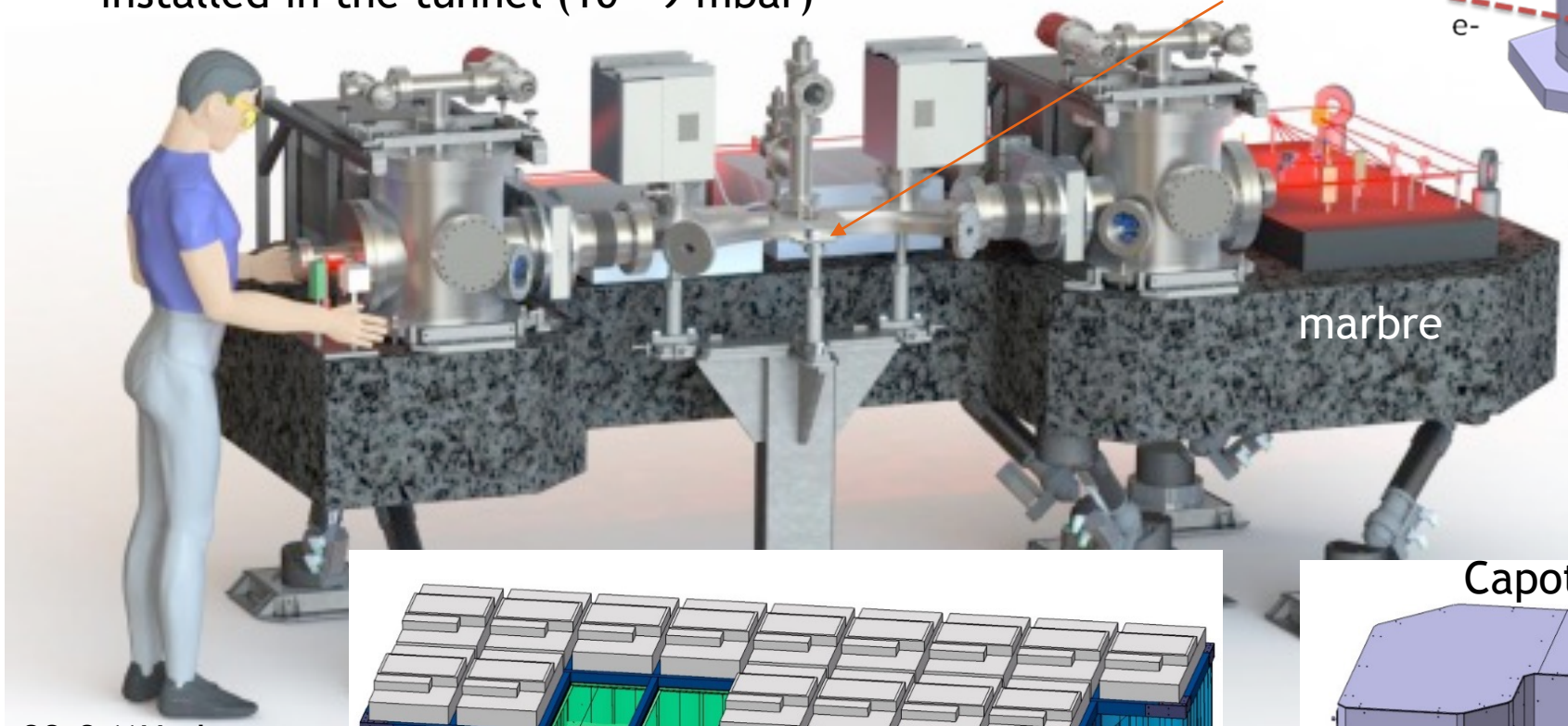
- Difficult to scale:
  - Operation from 8h45 to 17h45 (IJCLab opening hours) 4 days a week.
  - Operation will be carried out by blocks of 3 weeks followed by 1 week of scheduled maintenance.
  - *Reduced manpower compared to other facilities.*
- **ThomX SR commissioning duration => 60 weeks**

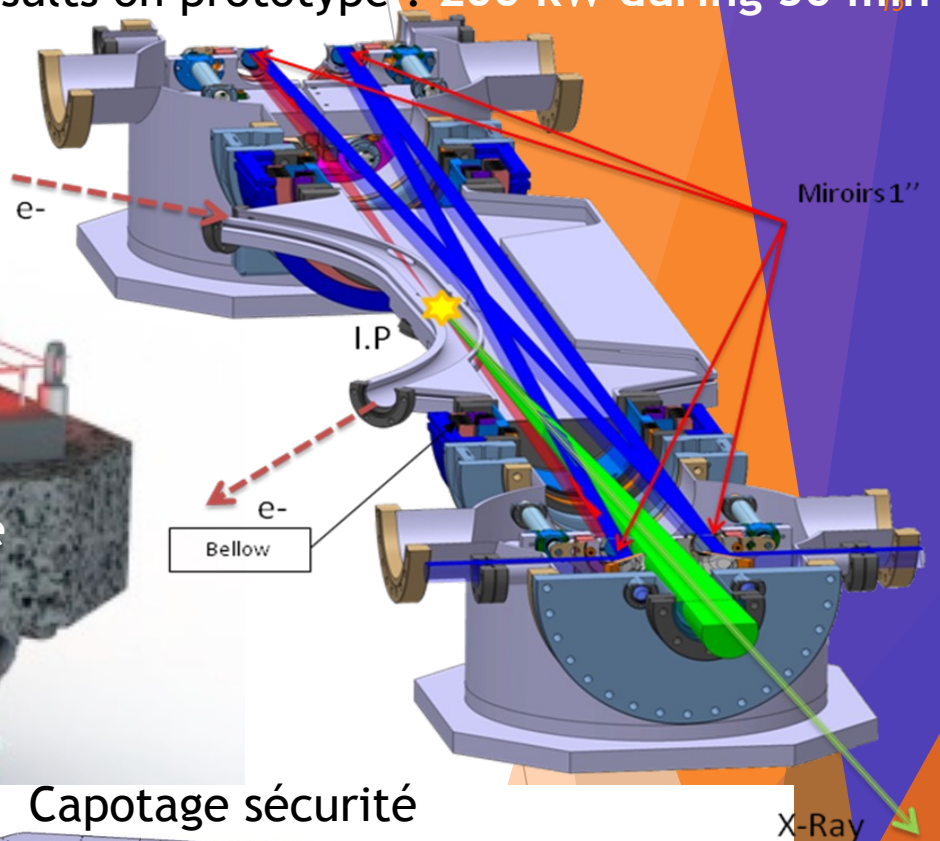
How many personnel were involved in commissioning (according to the survey)?
Between 6 and 18 physicists were involved, with a **median of 7**. Between 5 and 7 operators were involved, with a **median of 5**. **In total, between 15 and 50 personnel were involved, with a median of 30.**

Fabry-Perot Cavity (FPC)

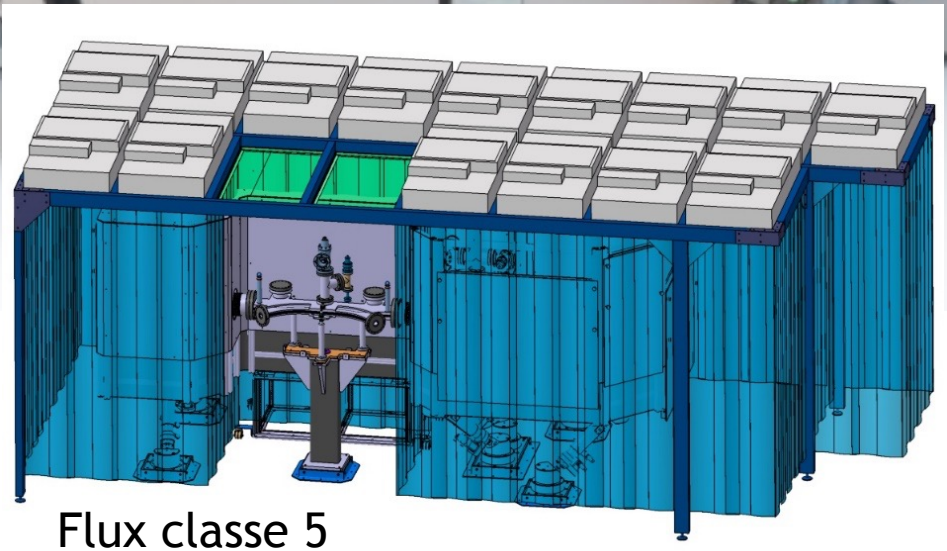
Results on prototype : **200 kW during 30 min**

Final version of FPC (+ laser+ amplification) is installed in the tunnel (10^-9 mbar)



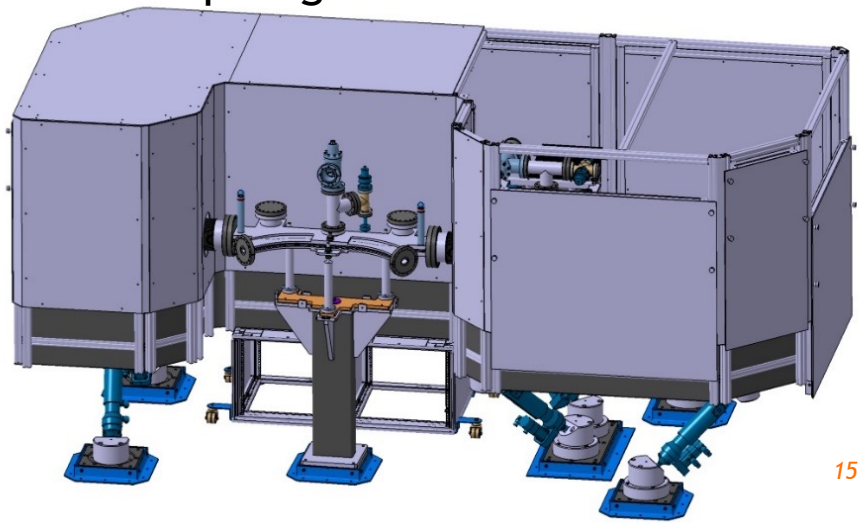


33.3 MHz laser
P = ~40-100 W
λ = 1030 nm
FPC Finesse/Gain
F=17k => G=4k
G = 13k (nom.)
Waist = ~100 µm

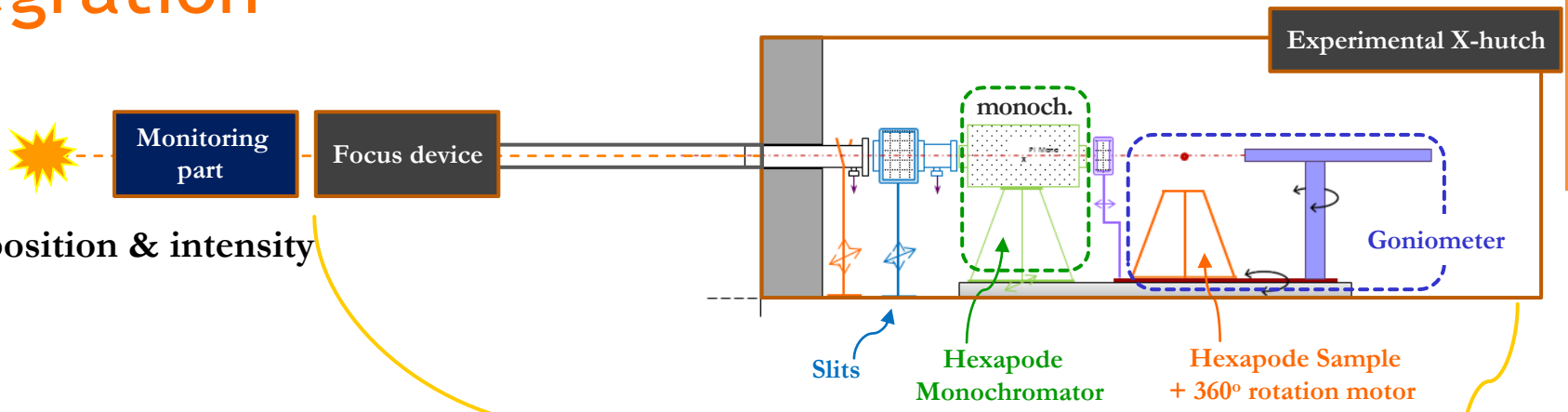


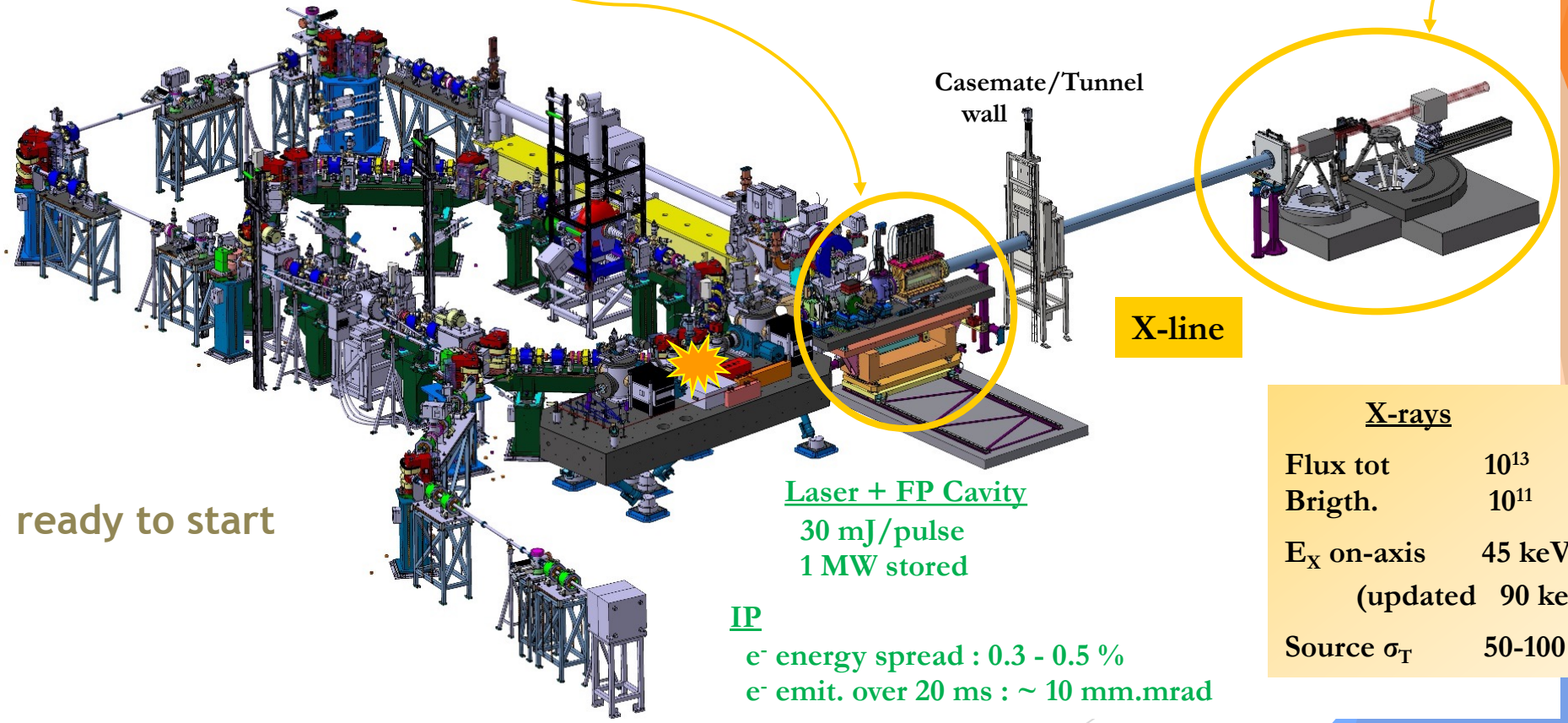
Flux classe 5

Capotage sécurité



X-line integration





X-line : ready to start

Laser + FP Cavity
30 mJ/pulse
1 MW stored

IP
e⁻ energy spread : 0.3 - 0.5 %
e⁻ emit. over 20 ms : ~ 10 mm.mrad

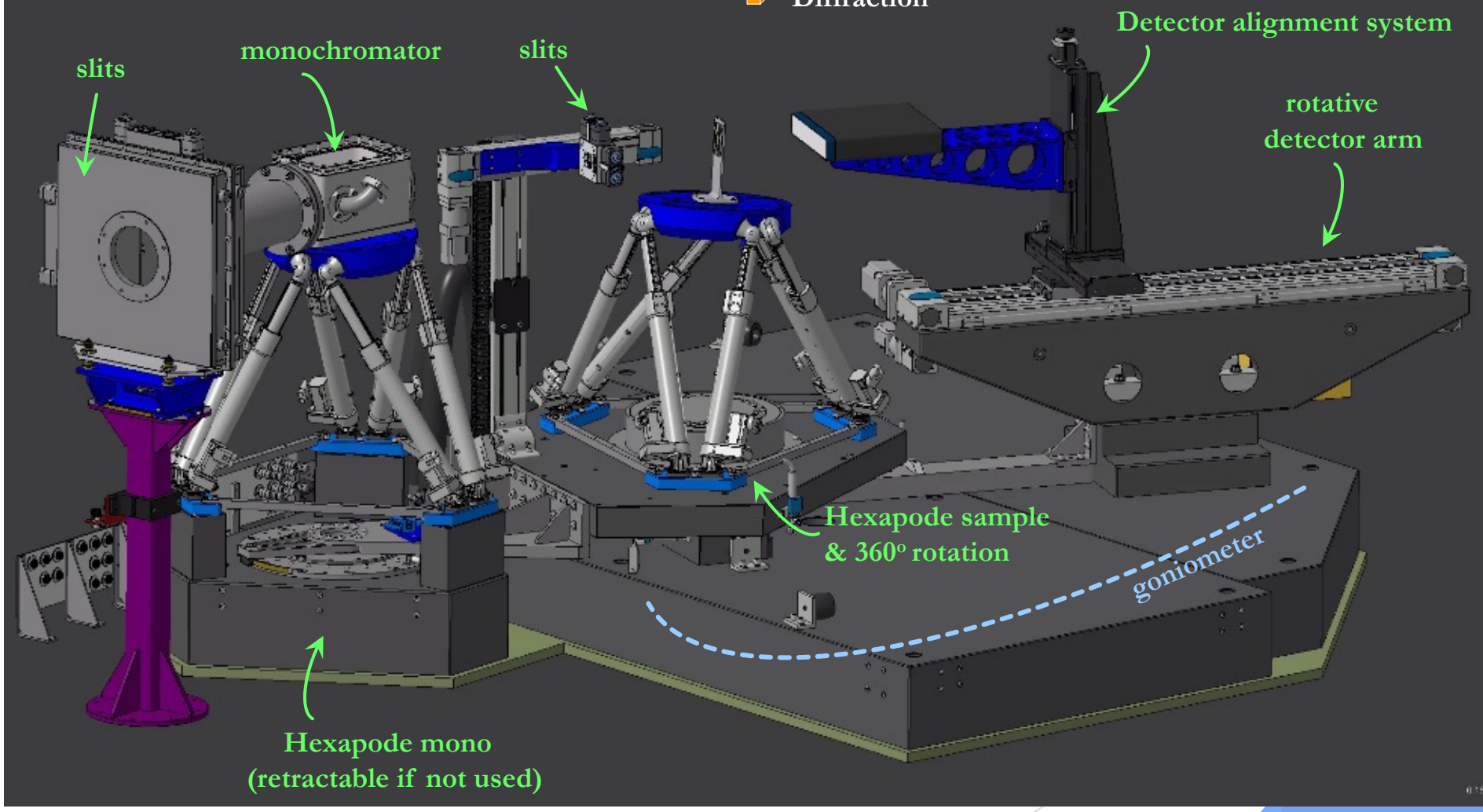
X-rays

Flux tot	10^{13}
Brigth.	10^{11}
E_X on-axis	45 keV
(updated	90 keV)
Source σ_T	50-100 µm

X-ray experimental hutch integration

→ Design a modulable equipment in order to be able to explore the main analysis techniques

- Standard imaging
- Phase contrast imaging
- Tomography
- Fluorescence spectroscopy
- Diffraction



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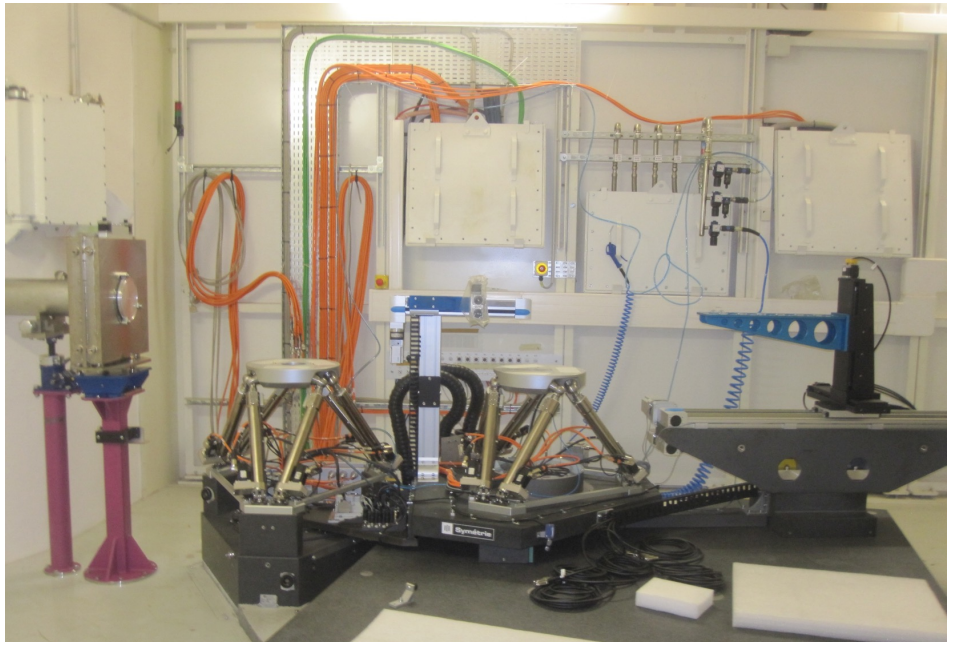
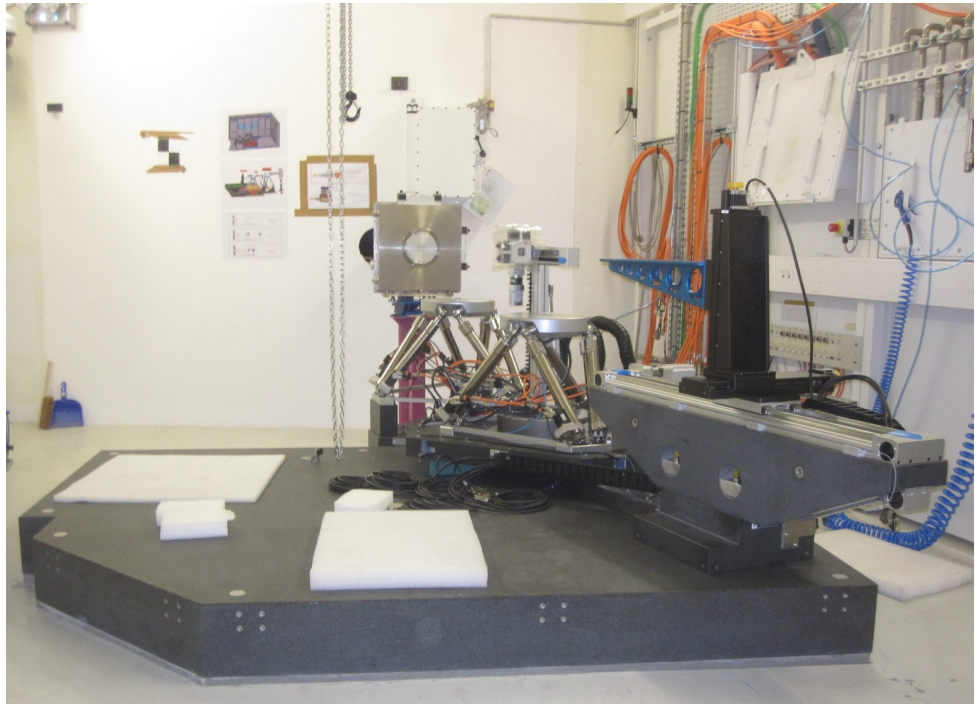
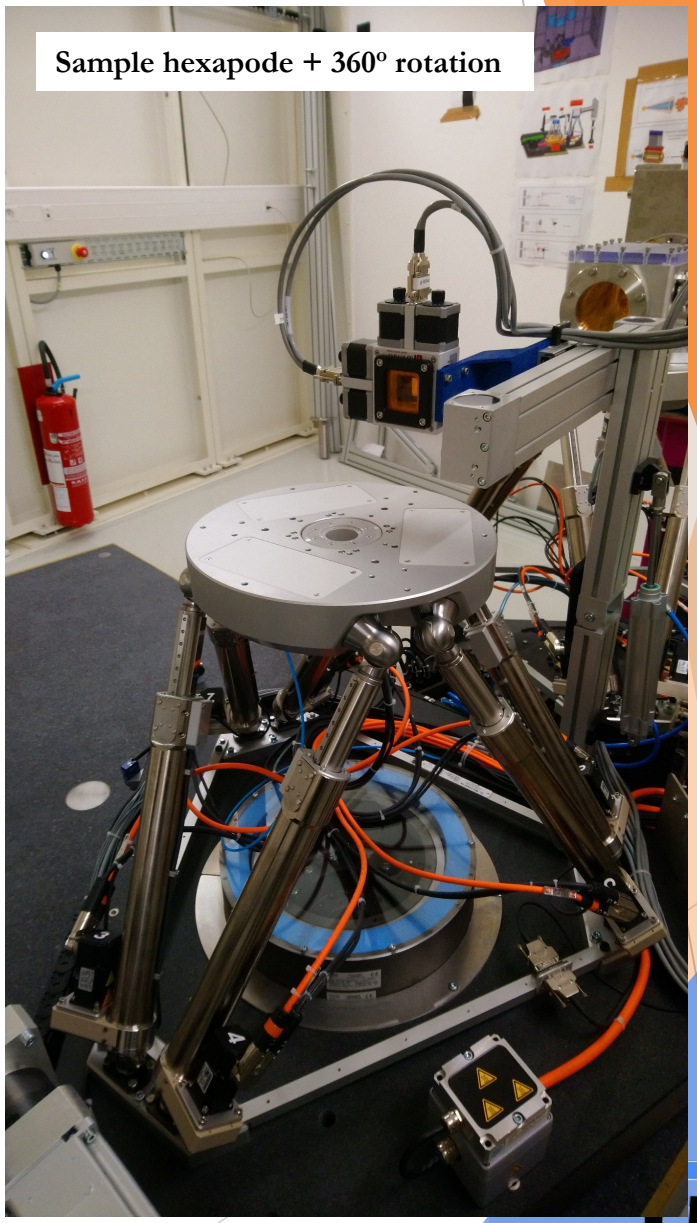






Commissioning of the FPC and X- line (phases)

Phase	Description
C.1	Installation and alignment of the Fabry-Perot cavity and the laser.
C.2	Increasing the laser power up to 100 W. Measurements of the stored laser power. Checking the modes and stability.
C.3	Alignment and synchronization of the laser and electron beam. Test of the first X-ray production.
C.4	First measurements of the X-rays: angular spectrum, flux, spatial profile.
C.5	Characterization of the X-rays for the experiments.

Start X-ray production and first experiments as soon as possible

Commissioning of the FPC and X- line will be performed at the same time.

To optimize the planning, alternation of the machine physics studies and X-ray production

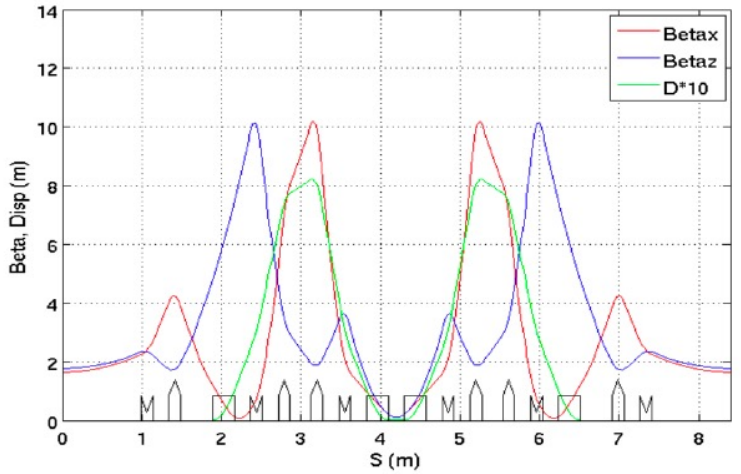
ThomX: from the beginning up to now

ThomX main dates

2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

- 2007 : First discussion at LAL (Now IJCLab)
  - Jun. 2009 : Conceptual Design Report

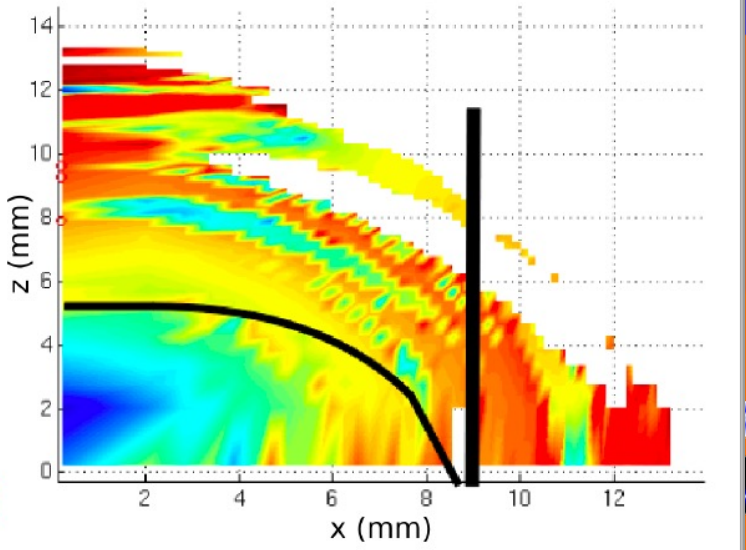
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE ⇒ IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis



← Half ring lattice :
- Interaction point : $\sigma = 70\,\mu m$

→ Ring acceptance study :
- Blue : particles stored
- Red : particles not captured
- Black ellipse : beam pipe

- https://accelconf.web.cern.ch/IPAC10/papers/thpe060.pdf



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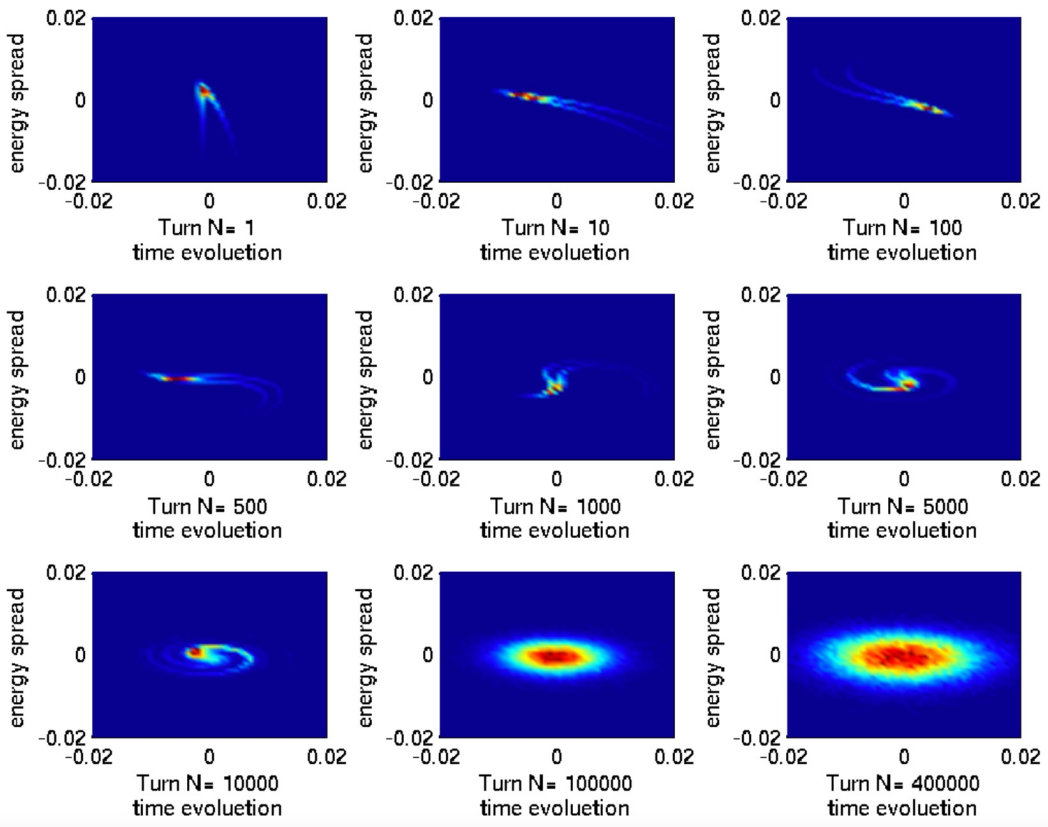

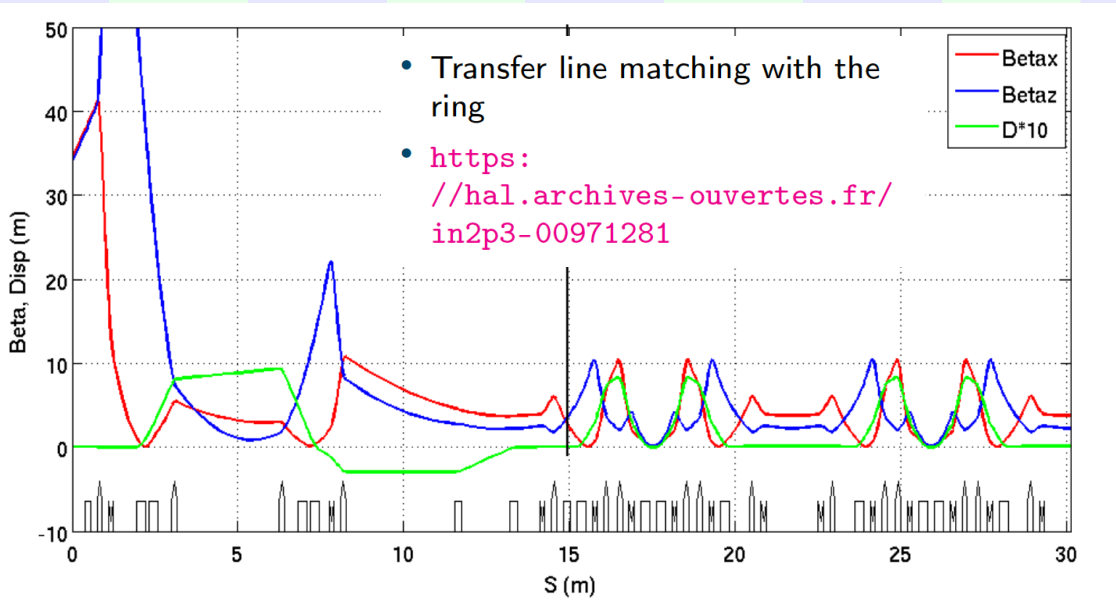

Iryna C

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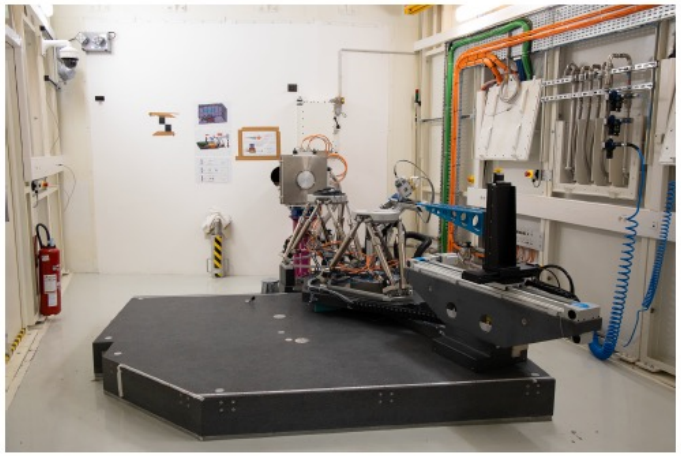
- 2 Apr. 2014 : Technical Design Report
- Building rehabilitation + facility assembly

ThomX site
IGLOO Φ = 40 m

April 2016

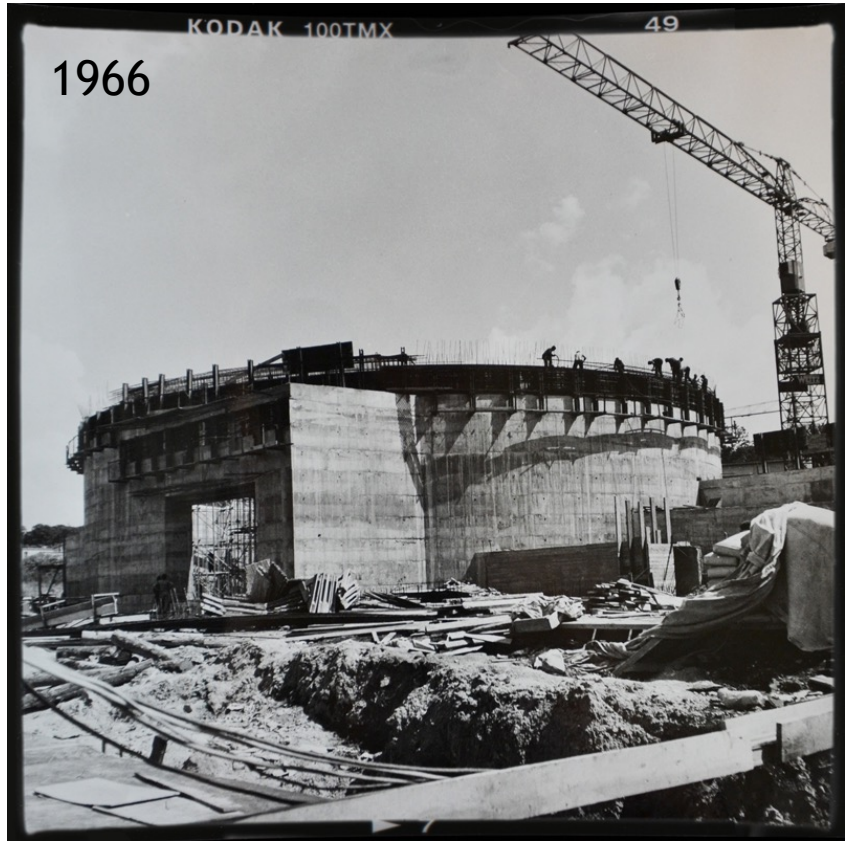
May 2016

May 2018



January 2021

Historical view : IGLOO building



Déclassement INB
Dec 2015

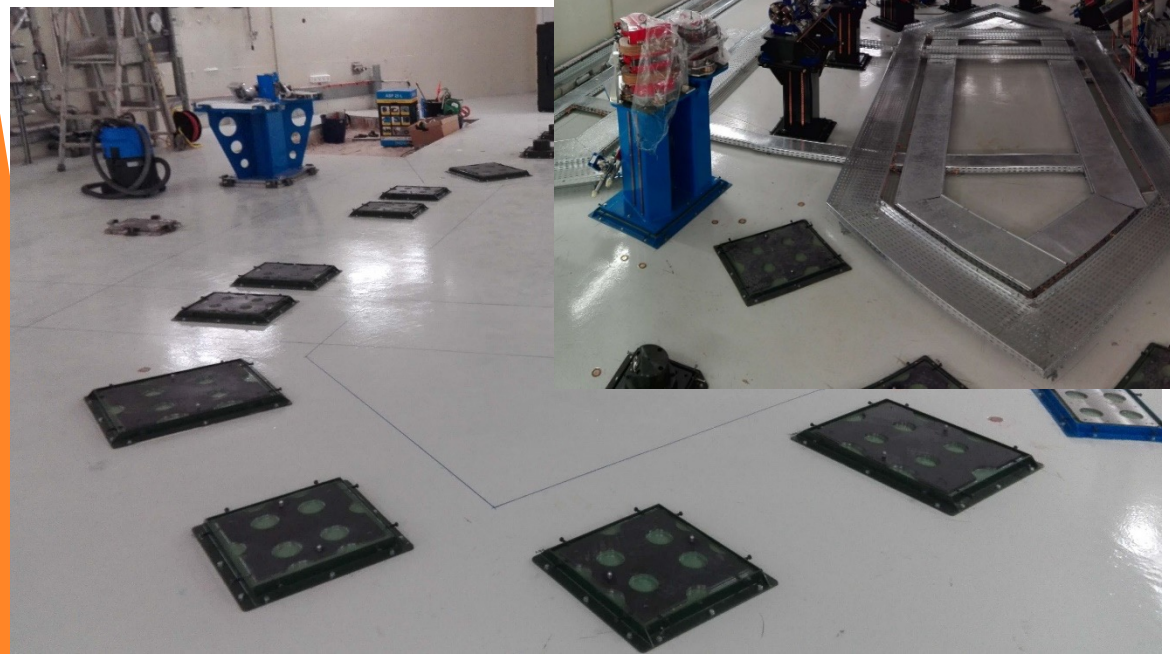
Building
Duation ~1 year
delay ~ 2 month

Future : igloo ext, D3, D4

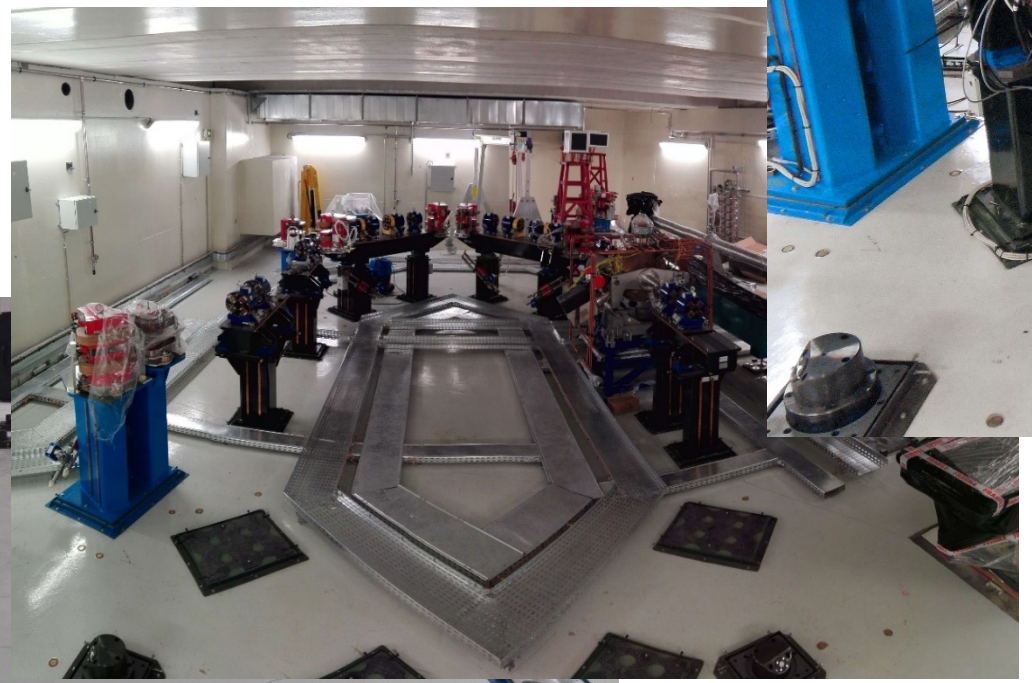
Ring integration

Casemate/tunnel

Autumn 2017



Spring 2018



Winter 2019

Magnets : SigmaPhi + ALBA

LAL + SOLEIL (alignement)

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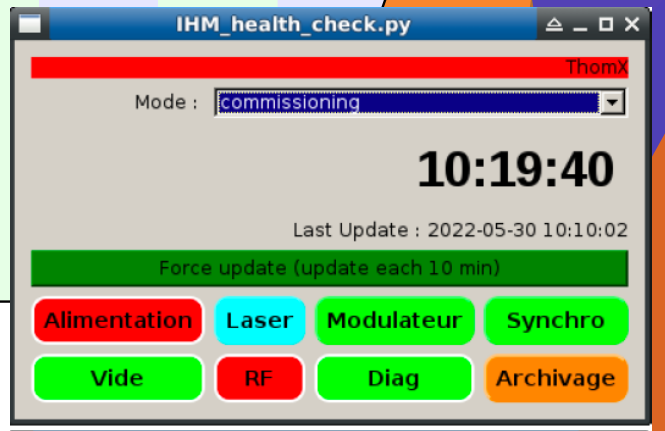
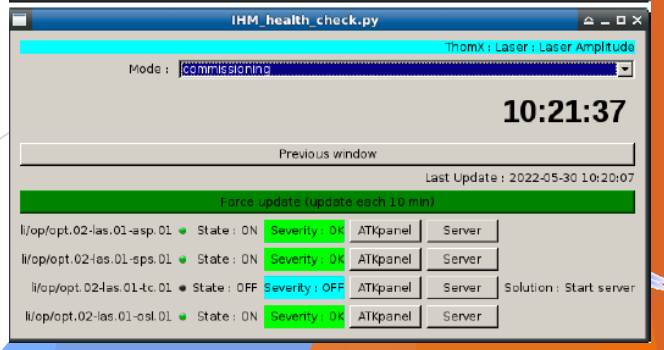
- 2 Apr. 2014 : Technical Design Report
- 2016 : Building rehabilitation + facility assembly
- 2019 : Dry run without RF power

- Dry run without RF
- First dry run : 1 day
- Second dry run : 1/2 day
- Some issue have been pointing out
  - Lots of Device Server to manage
  - ⇒ GUI developed : Health check
- moutardier@ijclab.in2p3.fr





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- 2016 : Building rehabilitation + facility assembly
- 2019 : Dry run without RF power
- 19 May. 2021 : Phase I authorization from French Nuclear Safety Authority

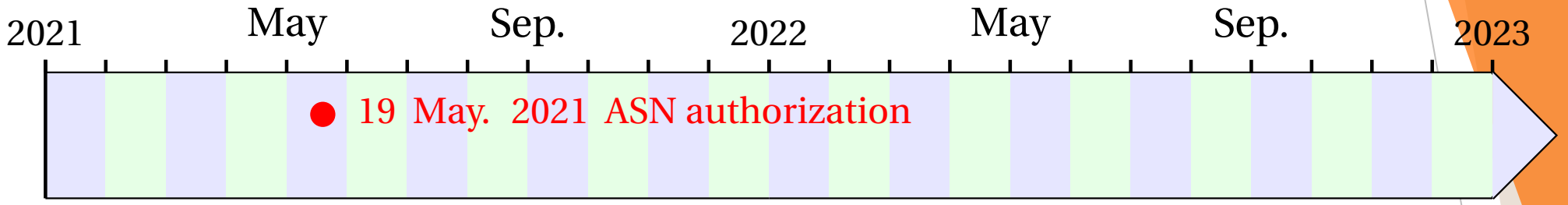
AUTORITÉ DE SÛRETÉ NUCLÉAIRE

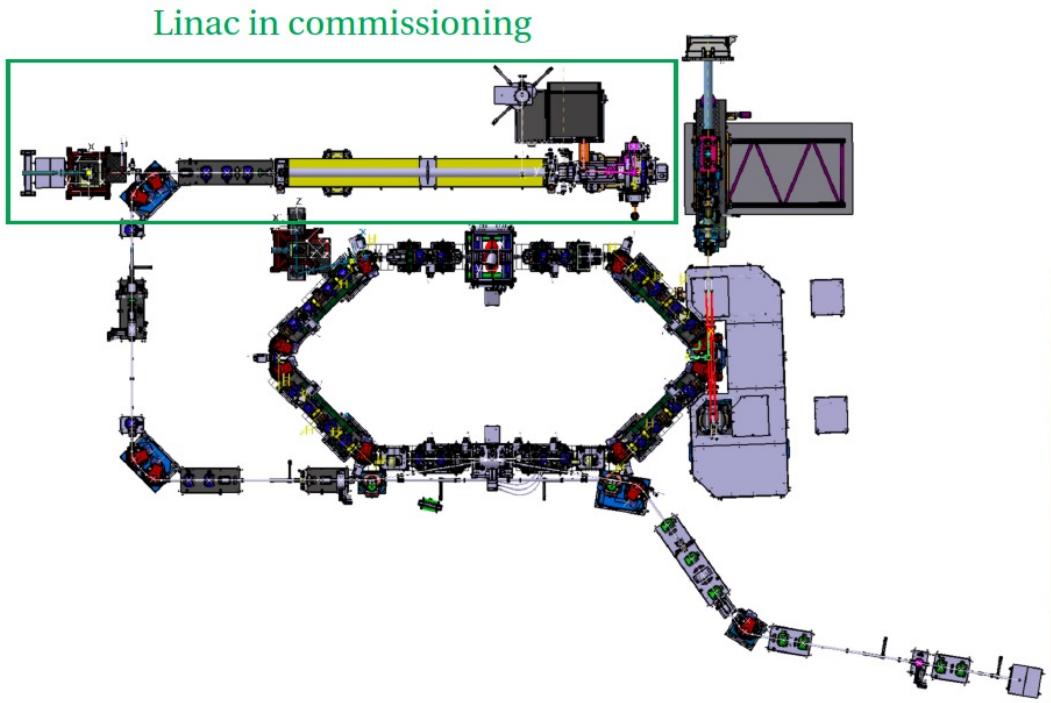
✓ Linac commissioning authorization

- https://fr.wikipedia.org/wiki/Fichier:Logo_ASN.svg

Phase d'exploitation	Energie max. des électrons (MeV)	Charge par paquet (nC)	Fréquence de tirs (Hz)	Descriptif
1	50	0,1	10	LINAC
2	50	0,1	10	LINAC+anneau
2bis	50	1	50	LINAC+anneau
3	70	1	50	Fonctionnement nominal

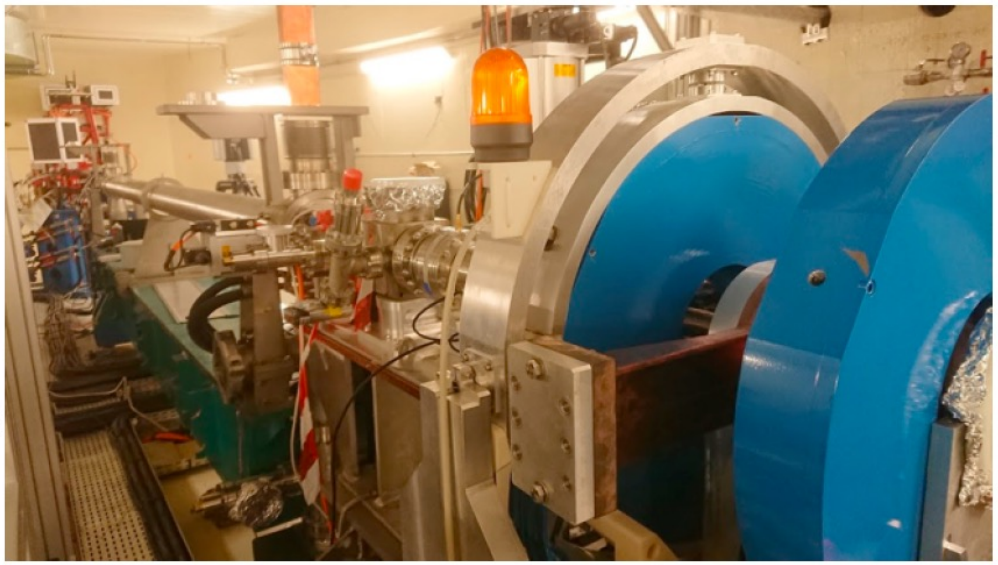
ThomX: ASN authorization phase I



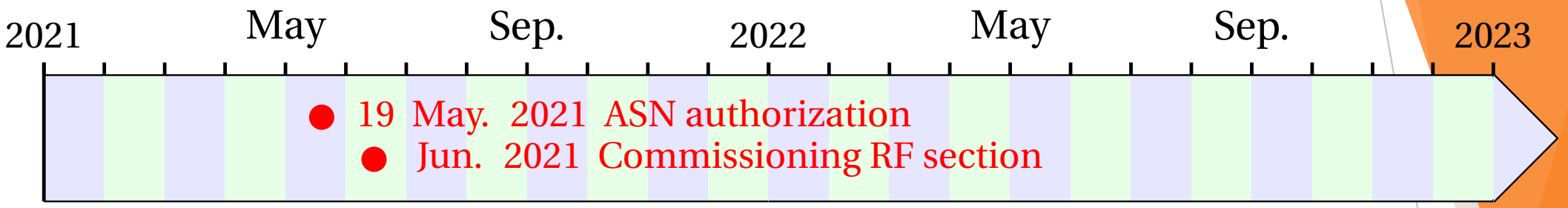


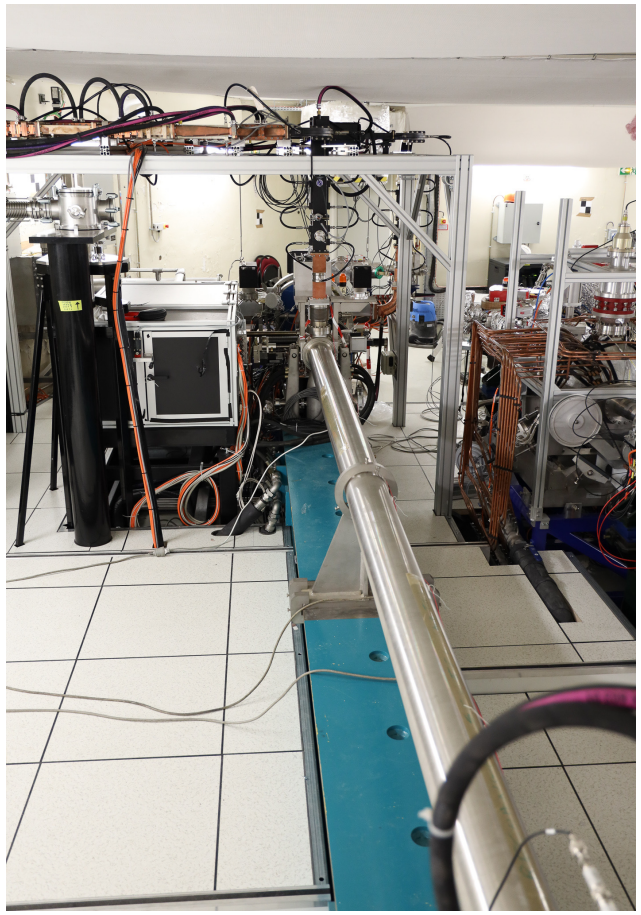
Nominal parameters of phase I :

- Repetition rate : 10 Hz
- Beam energy : 50 MeV
- Beam charge : 100 pC
- Transverse emittance : 2πmmmrad



ThomX: commissioning main dates





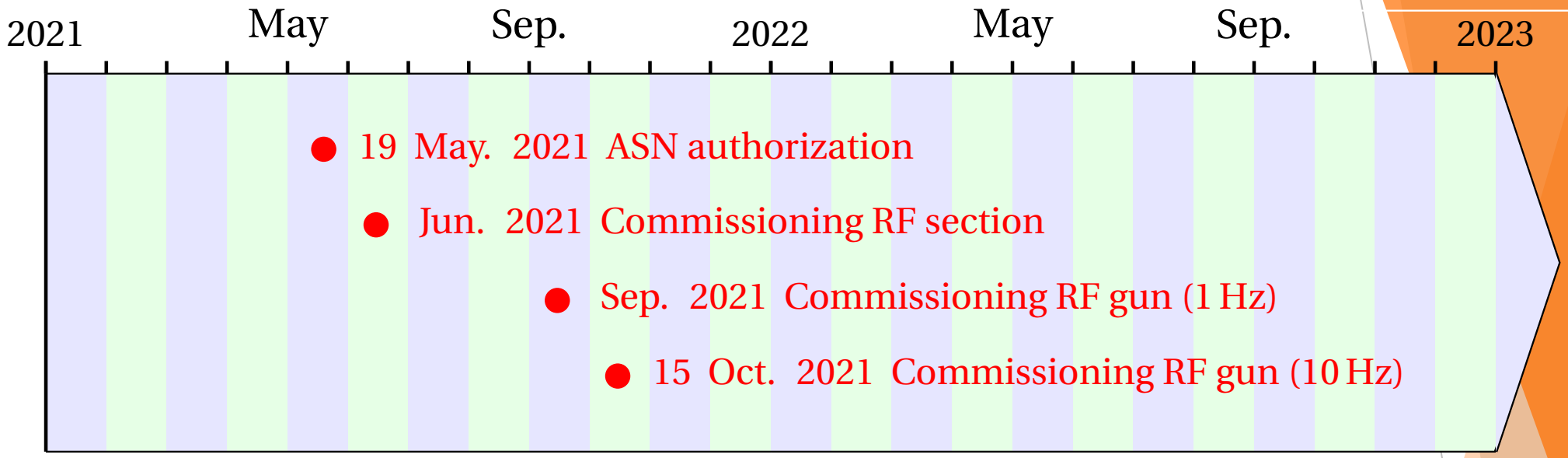
3 GHz source: done by ScandiNova (klystron Toshiba E37310)

← Accelerating section (upstream)

- Lep Injector Linac lend by SOLEIL
- 10 Hz
- 9 MW
- 1 day for RF test, 1 day for section commissioning

LIL section conditionning (10 MV/m, 10 Hz, 3 µs)

ThomX: commissioning main dates



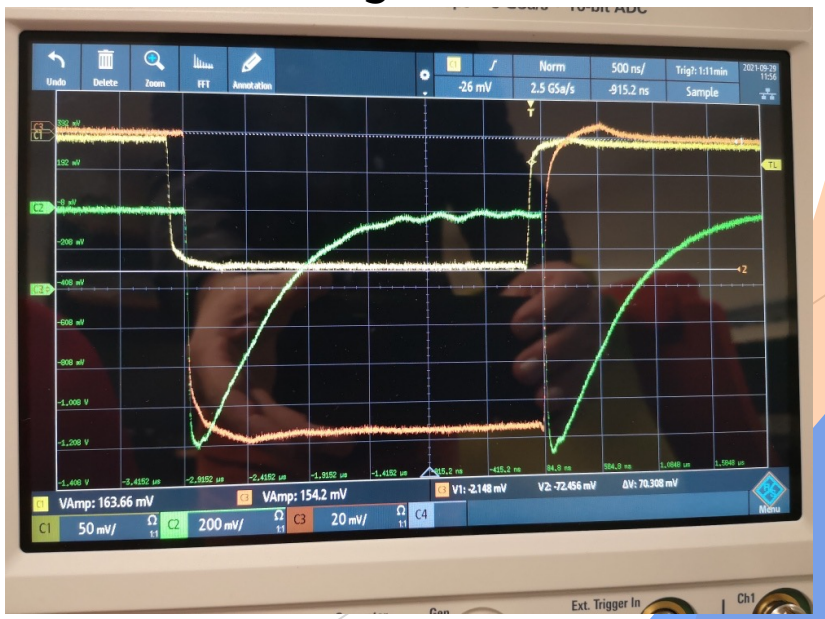
Made in-house RF gun 2.5 cell

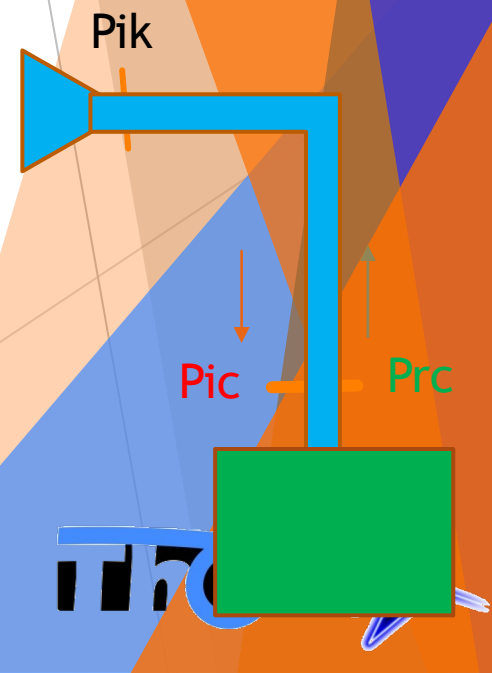
6 MW – 3,0 μs – 1-10 Hz

E_Z = 80 MV/m

3 weeks + 1 week

RF signals

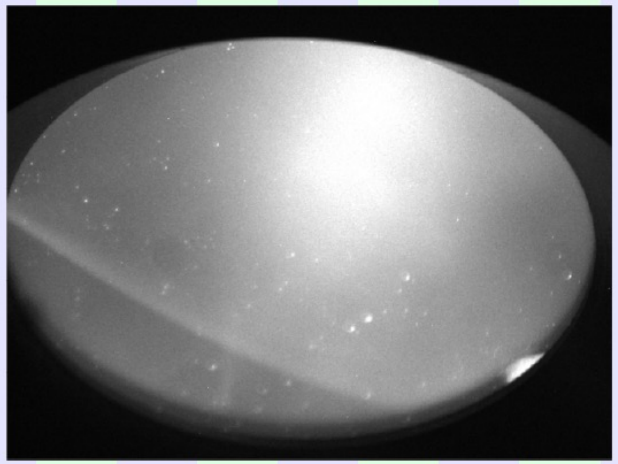




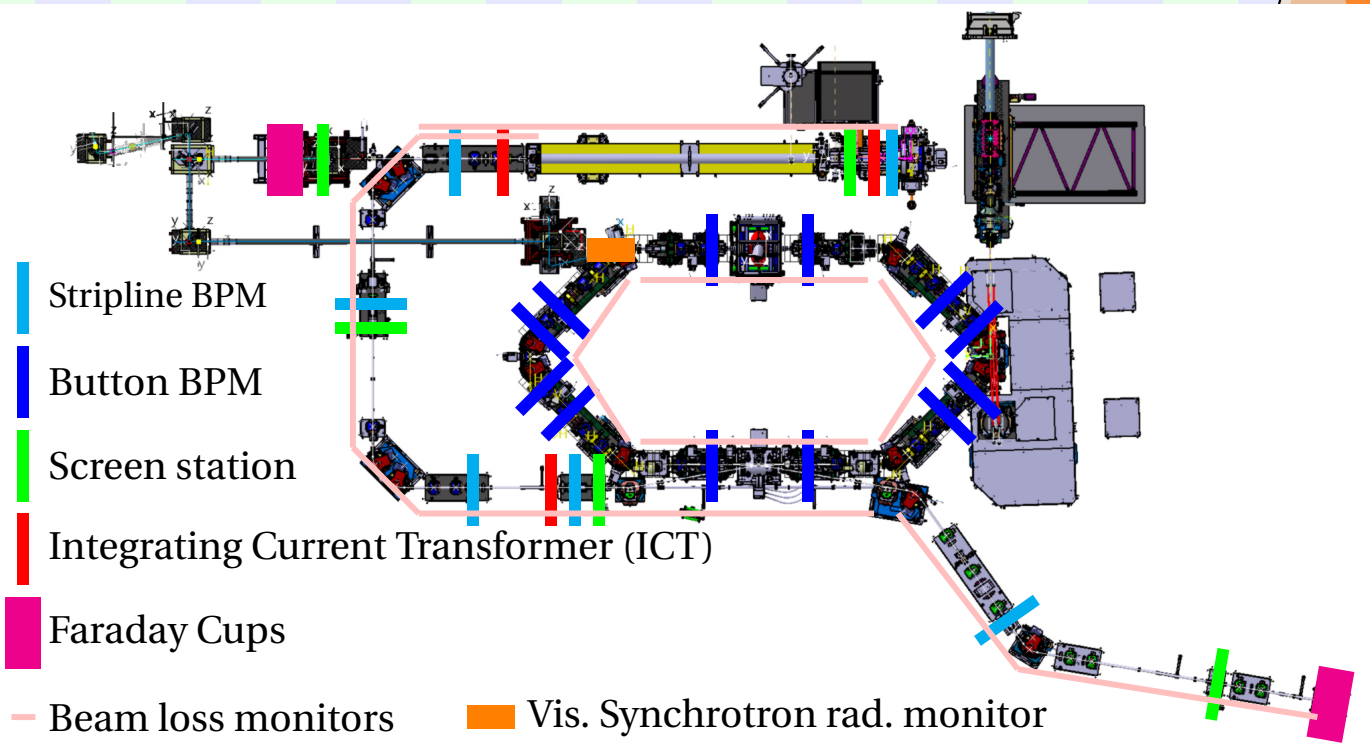
ThomX: commissioning main dates

2021 May Sep. 2022 May Sep. 2023

- 19 May. 2021 ASN authorization
- Jun. 2021 Commissioning RF section
- Sep. 2021 Commissioning RF gun (1 Hz)
- 30 Sep. 2021 First dark current



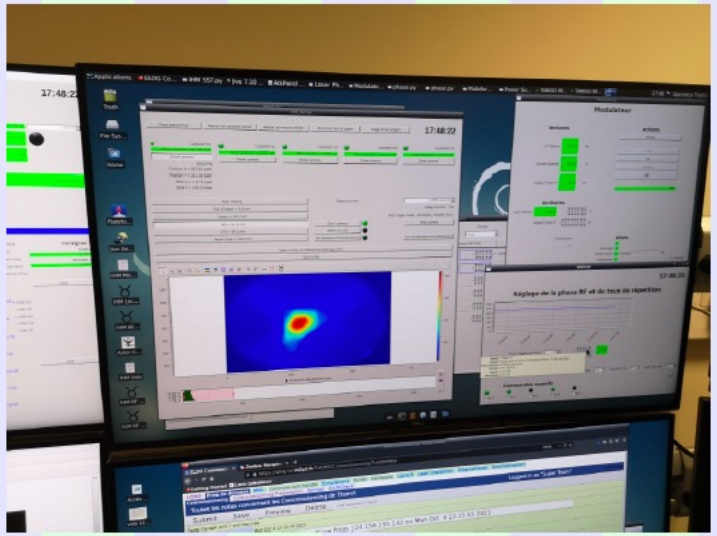
- Dark current
- YAG:Ce screen
- After the gun



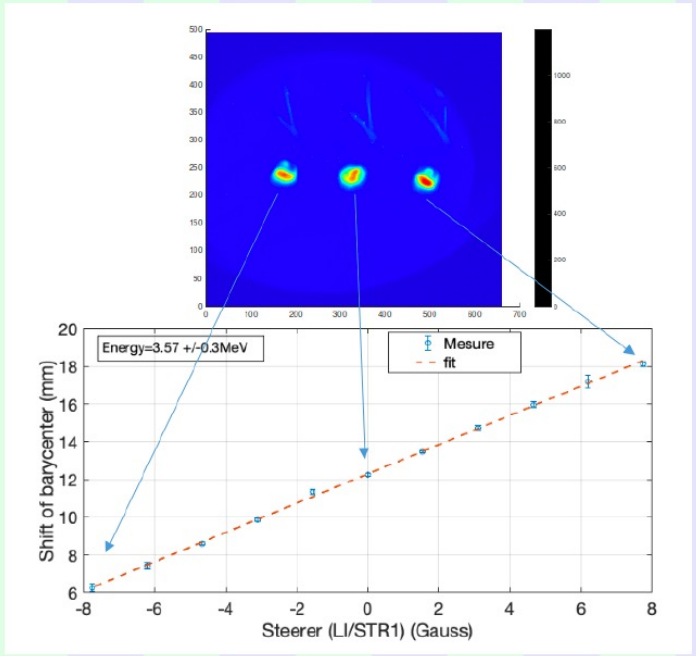
ThomX: commissioning main dates

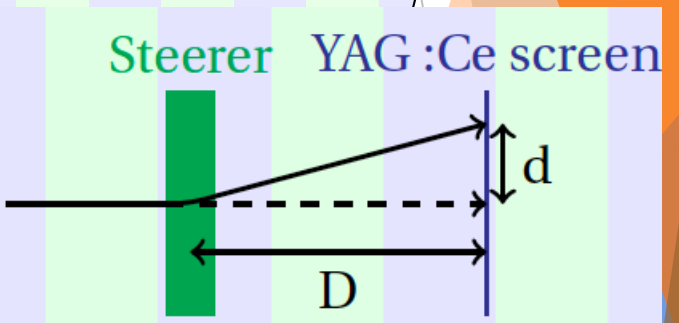
2021 — May — Sep. — 2022 — May — Sep. — 2023

- 19 May. 2021 ASN authorization
- Jun. 2021 Commissioning RF section
- Sep. 2021 Commissioning RF gun (1 Hz)
- 30 Sep. 2021 First dark current
- 4 Oct. 2021 First e^- beam after the gun (4 MeV)



- Photo-emitted electrons
- YAG:Ce screen
- After the gun





$$E = L_{mag} \times D \times \frac{\Delta B}{\Delta d}$$

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- Sep. 2021 Commissioning RF gun (1 Hz)
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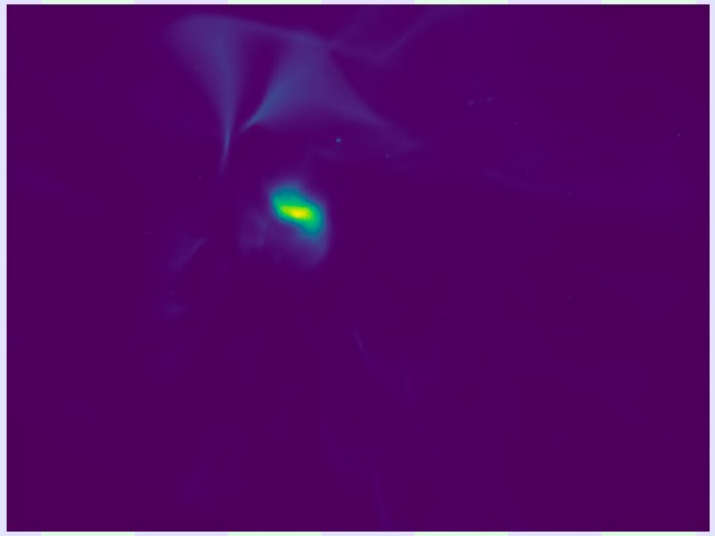
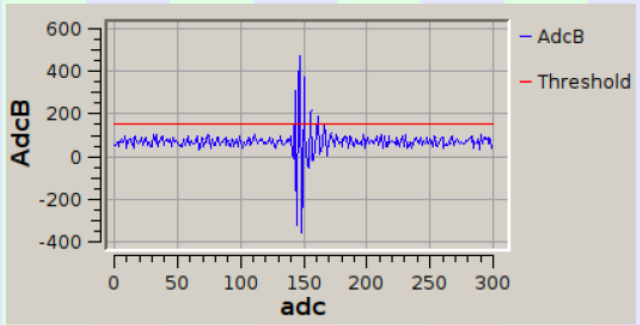
- 4 Oct. 2021 First e^- beam after the gun (4 MeV)
- 6 Oct. 2021 First e^- beam after the section (37 MeV)





- Photo-emitted electrons
- YAG:Ce screen
- After the section

- Blue : Beam Position Monitor signal on top electrode
- Red : triggering threshold
- Electronics : Libera brilliance +

ThomX: commissioning main dates

2021 — May — Sep. — 2022 — May — Sep. — 2023

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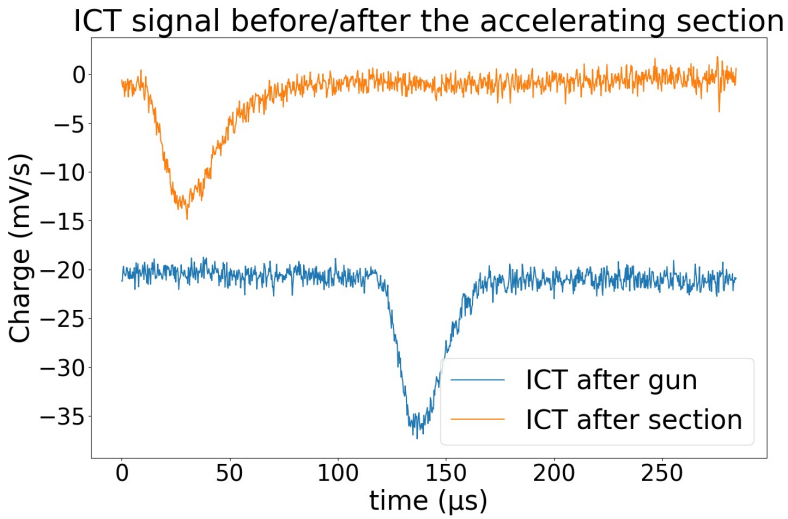
- Sep. 2021 Commissioning RF gun (1 Hz)
- 30 Sep. 2021 First dark current
- 4 Oct. 2021 First e^- beam after the gun (4 MeV)
- 6 Oct. 2021 First e^- beam after the section (37 MeV)
- 7 Oct. 2021 Max allowed charge transmitted (100 pC)
- 15 Oct. 2021 Commissioning RF gun (10 Hz)



- Integrating Current Transformer (ICT) signal :
  - Blue : after the gun
  - Orange : after the section

ThomX: commissioning main dates

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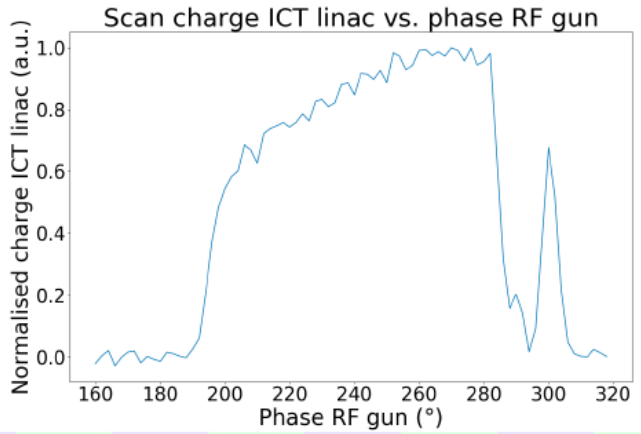
- 6 Oct. 2021 First e^- beam after the section (37 MeV)
- 7 Oct. 2021 Max allowed charge transmitted (100 pC)
- 15 Oct. 2021 Commissioning RF gun (10 Hz)
- 20 Oct. 2021 First e^- beam at 10 Hz



Beam charge after the gun vs. gun phase

- 10 Hz ⇒ faster measurement

ThomX: commissioning main dates

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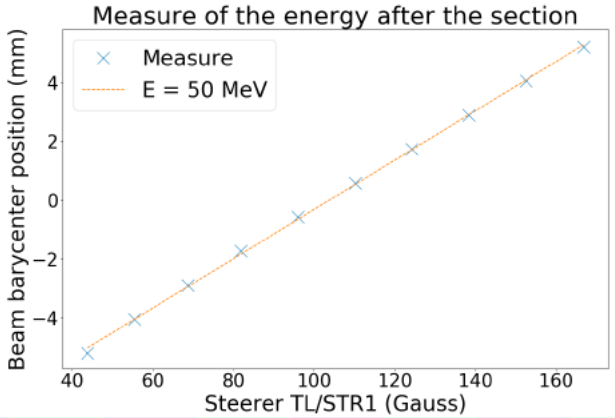
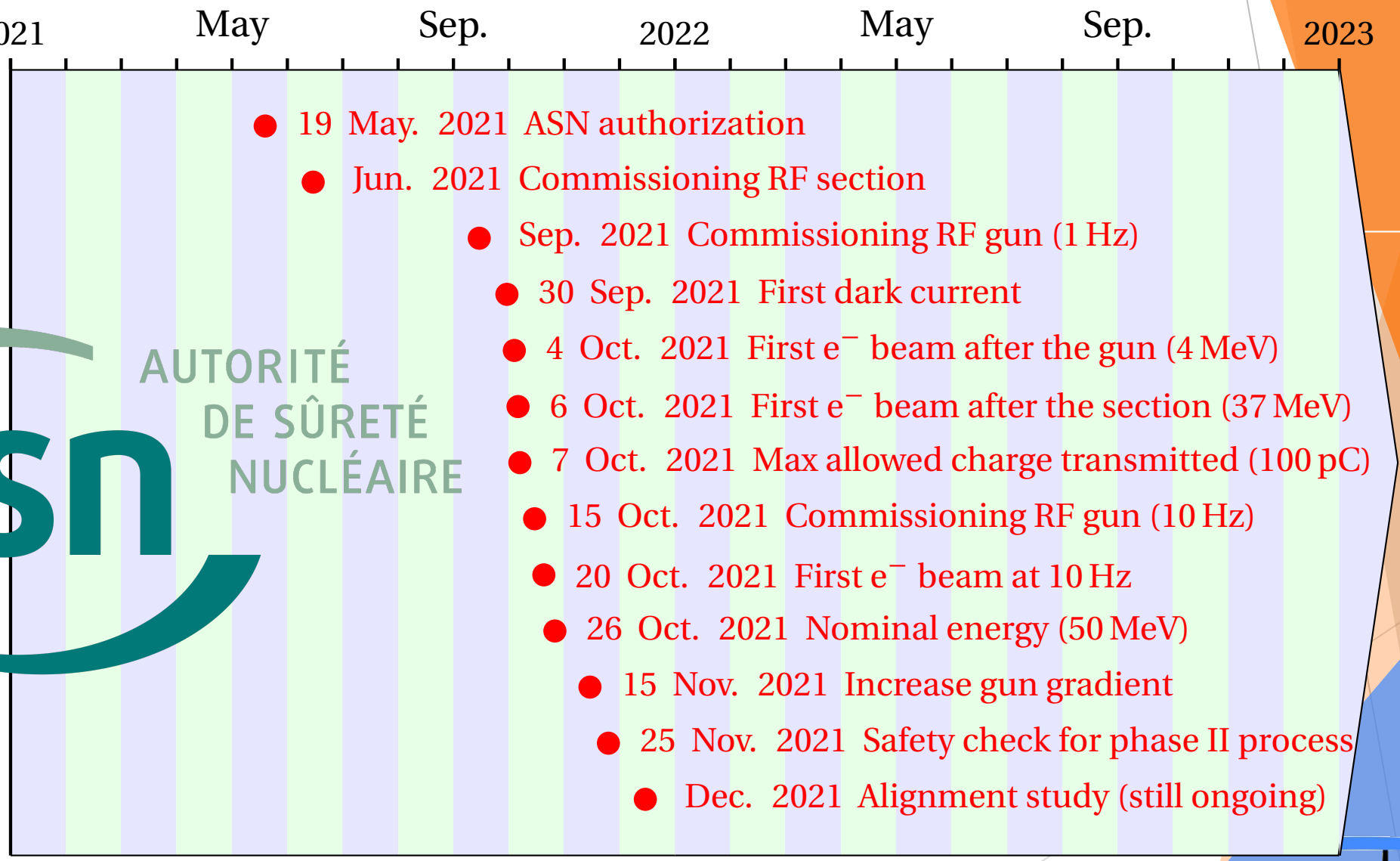
- 6 Oct. 2021 First e^- beam after the section (37 MeV)
- 7 Oct. 2021 Max allowed charge transmitted (100 pC)
- 15 Oct. 2021 Commissioning RF gun (10 Hz)
- 20 Oct. 2021 First e^- beam at 10 Hz
- 26 Oct. 2021 Nominal energy (50 MeV)



- Steerer after the section
- Screen before the dump

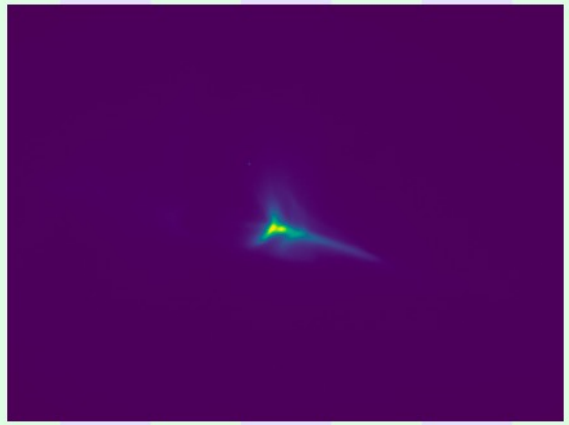
ThomX: commissioning main dates



AUTORITÉ DE SÛRETÉ NUCLÉAIRE

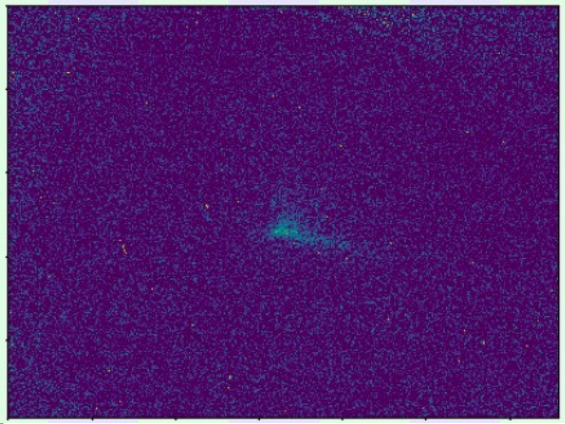
ThomX: commissioning main dates

2021 — May — Sep. — 2022 — May — Sep. — 2023



↑ YAG screen (one exposure)

↓ OTR screen (100 exposure)



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- 6 Oct. 2021 First e^- beam after the section (37 MeV)
- 7 Oct. 2021 Max allowed charge transmitted (100 pC)
- 15 Oct. 2021 Commissioning RF gun (10 Hz)
- 20 Oct. 2021 First e^- beam at 10 Hz
- 26 Oct. 2021 Nominal energy (50 MeV)
- 15 Nov. 2021 Increase gun gradient
- 25 Nov. 2021 Safety check for phase II process
- Dec. 2021 Alignment study (still ongoing)
- 14 Jan. 2022 First OTR light

See : A. Moutardier et al., “Characterization of the Electron Beam Visualization Stations of the ThomX Accelerator”, presented at the IPAC’22, Bangkok, Thailand, Jun. 2022

ThomX: commissioning main dates

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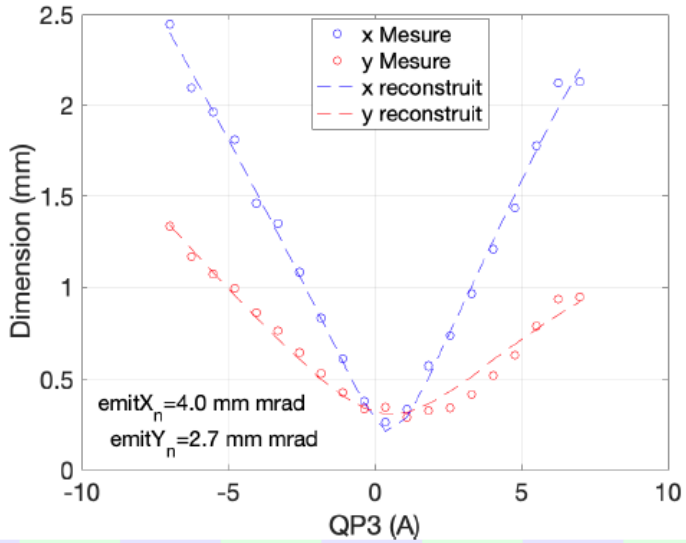
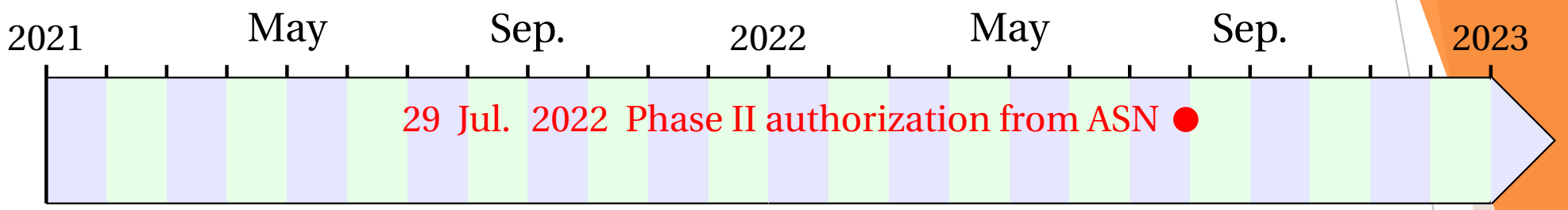
- 20 Oct. 2021 First e^- beam at 10 Hz
- 26 Oct. 2021 Nominal energy (50 MeV)
- 15 Nov. 2021 Increase gun gradient
- 25 Nov. 2021 Safety check for phase II process
- Dec. 2021 Alignment study (still ongoing)
- 14 Jan. 2022 First OTR light
- 15 Apr. 2022 Emittance measurement

Quad-scan after the section



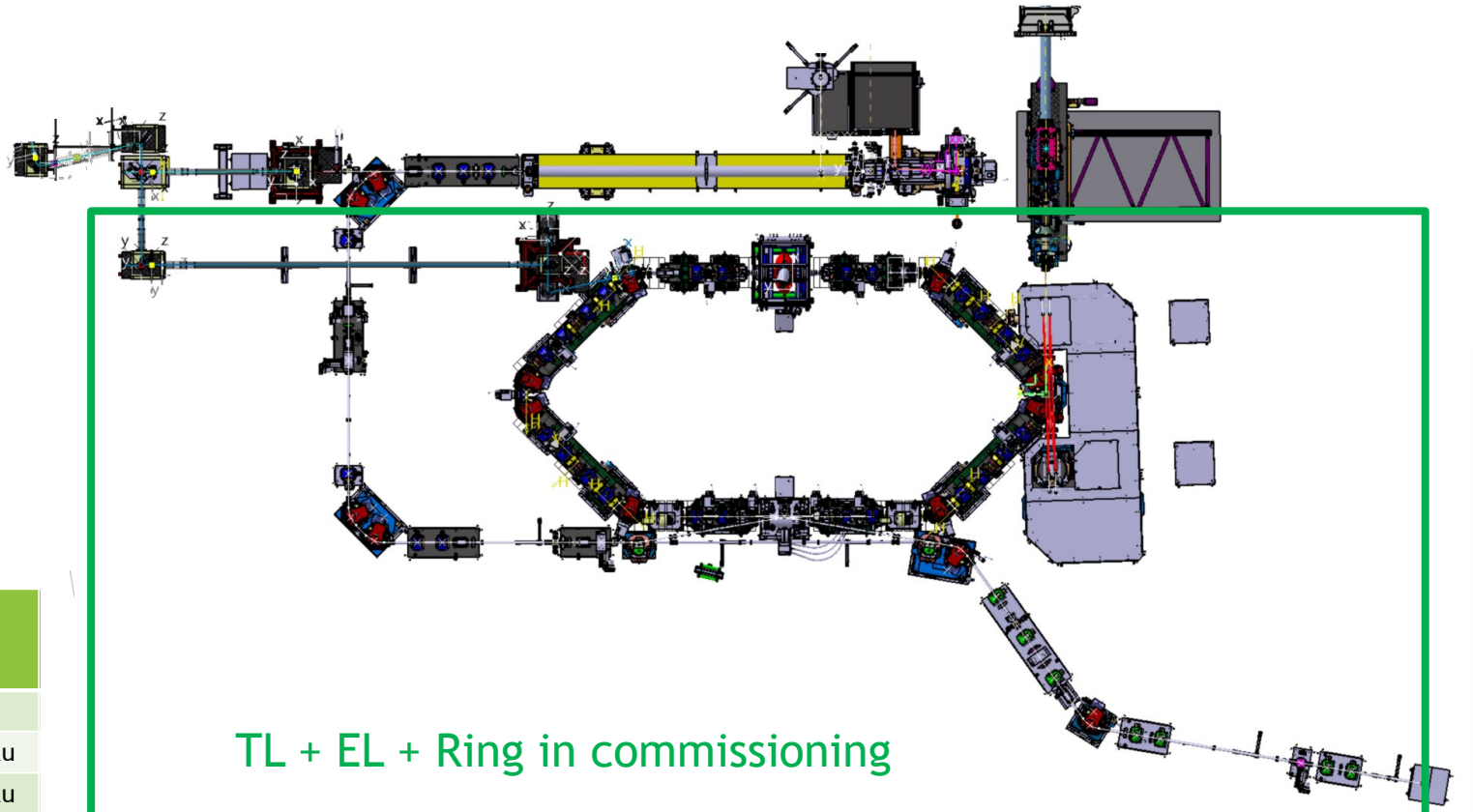
- $\epsilon_x \approx 40\,\mathrm{nm\,rad}$
- $\epsilon_y \approx 30\,\mathrm{nm\,rad}$
- $\epsilon_{xn} \approx 4\pi\,\mathrm{mm\,mrad}$
- $\epsilon_{yn} \approx 3\pi\,\mathrm{mm\,mrad}$

ThomX: ASN authorization phase II



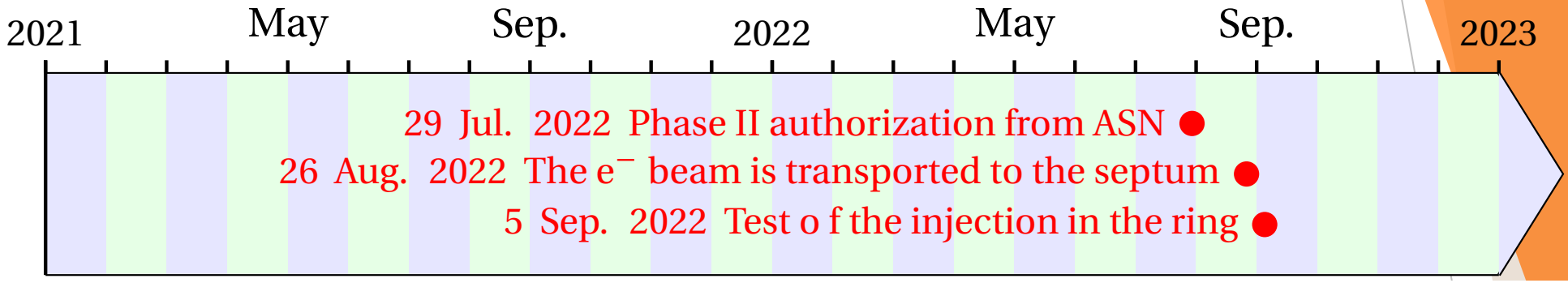
AUTORITÉ DE SÛRETÉ NUCLÉAIRE

Phase d'exploitation	Energie max. des électrons (MeV)	Charge par paquet (nC)	Fréquence de tirs (Hz)	Descriptif
1	50	0,1	10	LINAC
2	50	0,1	10	LINAC+anneau
2bis	50	1	50	LINAC+anneau
3	70	1	50	Fonctionnement nominal

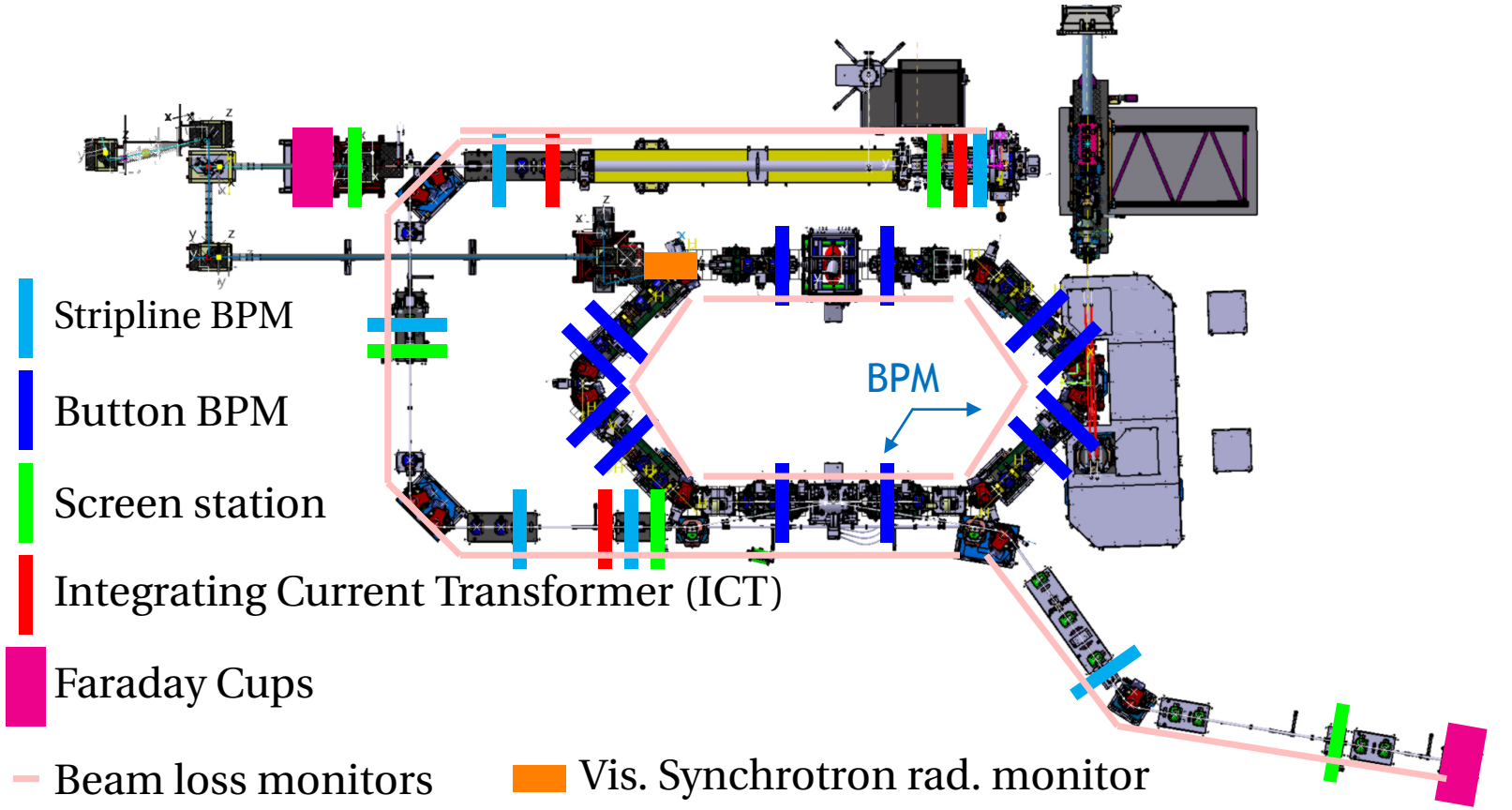


TL + EL + Ring in commissioning

ThomX: ASN authorization phase II



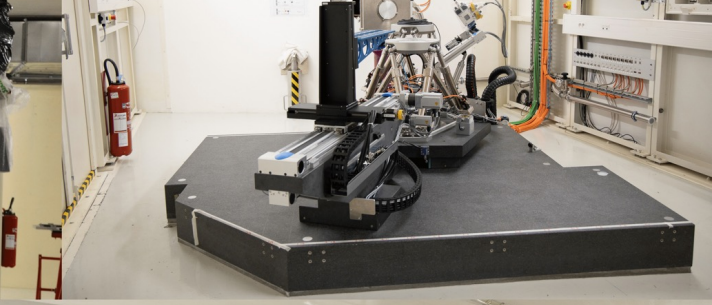
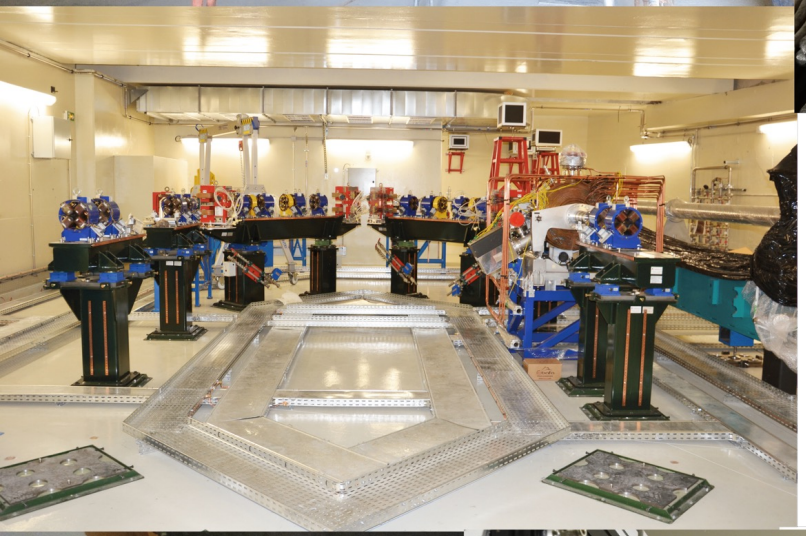
- e- beam is @ last screen station before the injection area
- Start-up of the septum and kickers
- First injection in the ring is planned for this week
- Goal: signals at first BPMs and close the 1st turn.



Summary-Perspectives

- The ThomX commissioning is ongoing. For the Linac:
  - Repetition rate : 10 Hz
  - Beam energy : 50 MeV
  - Beam charge : 100 pC
  - Transverse emittance : optimization under progress (laser optimization, alignment studies)
    - Theory : 2π mm mrad
    - Measured ≈ 4π mm mrad
- Fabry-Perrot cavity optimization under progress. X-line is ready for the commissioning.
- Next steps (ongoing) :
  - TL+EL commissioning (energy spread optimization, matching, orbit correction, characterization and optimization for ring injection ...)
  - Start of the ring commissioning. First X-rays are expected during 2023.
- **The commissioning and operational experience is of great importance for the future Compton sources.**



Tnank you!