Implementing Systems Engineering at the Brazilian Synchrotron: a Workflow for enhanced beamline design

Capella Days 2024

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Summary

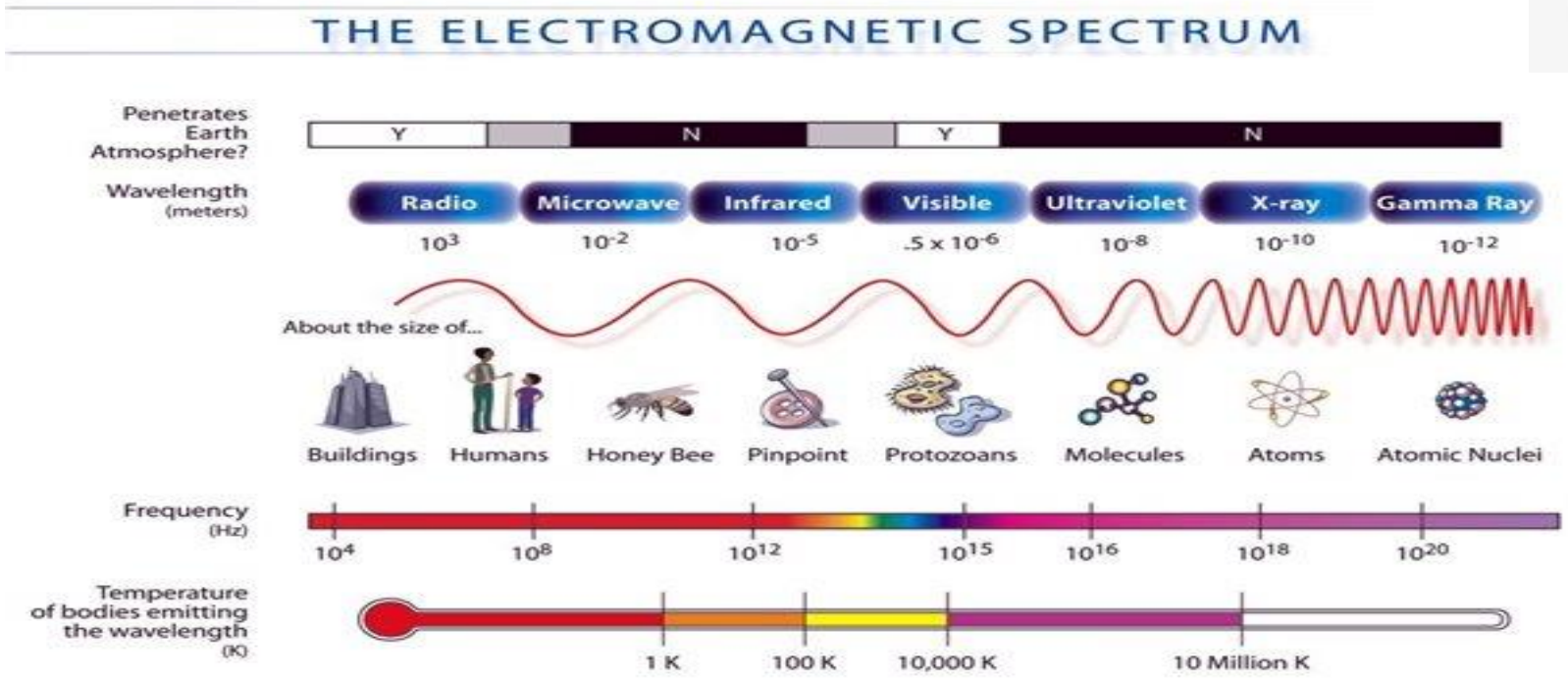
- Who are we? What we do?
- Our Capella-based systems engineering workflow
- Which softwares are we integrating with Capella?

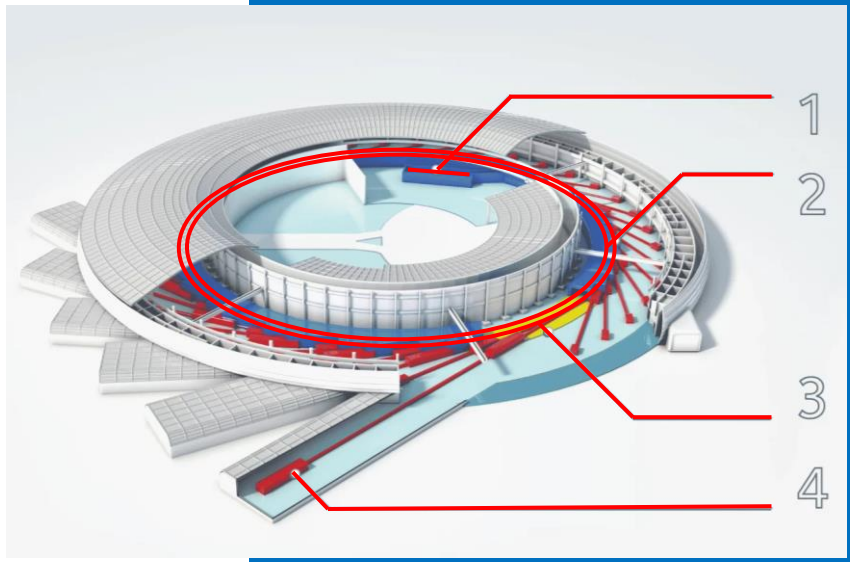
Context

Synchrotron Laboratories

In essence, giant and powerful microscopes!

- Large scientific infrastructure that produces a broad-spectrum light, used to investigate the structure of materials and their interactions in high resolution
- Recently upgraded to 4th generation, granting better imaging capabilities at its beamlines





- 1 – Linear Accelerator (LINAC)
- 2 – Injecting Accelerator (Booster)
- 3 – Main Accelerator (Storage Ring)
- 4 – Experim. Stations (Beamlines)

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4th Generation Synchrotron Labs

Recent greenfield or upgraded facilities

- Upgraded magnet arrangement for granting better light properties through better electron focalization and trajectory stability (~100-1000x gain from previous generations!!)

SIRIUS
Energy 3.0 GeV
Circunference 518 m

Campinas

HEPS (construction)
Energy 6.0 GeV
Circumference 1360 m

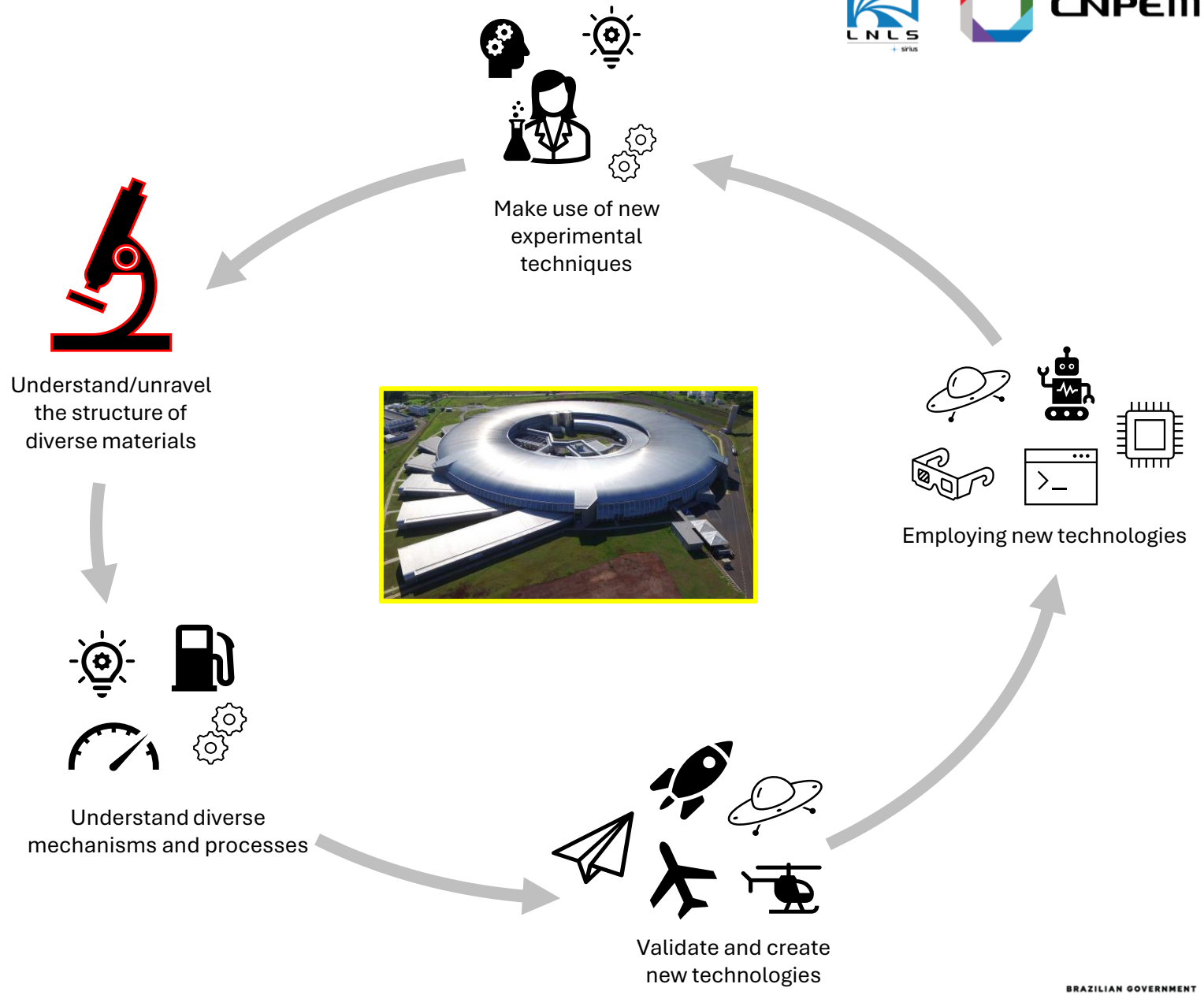
APS-U
Energy 6.0 GeV
Circumference 1103 m

MAX IV
Energy 3.0 GeV
Circumference 528 m

ESRF-EBS
Energy 6.0 GeV
Circumference 844 m

SLS2 (construction)
Energy 2.4 GeV
Circumference 290 m

Sirius/LNLS Mission

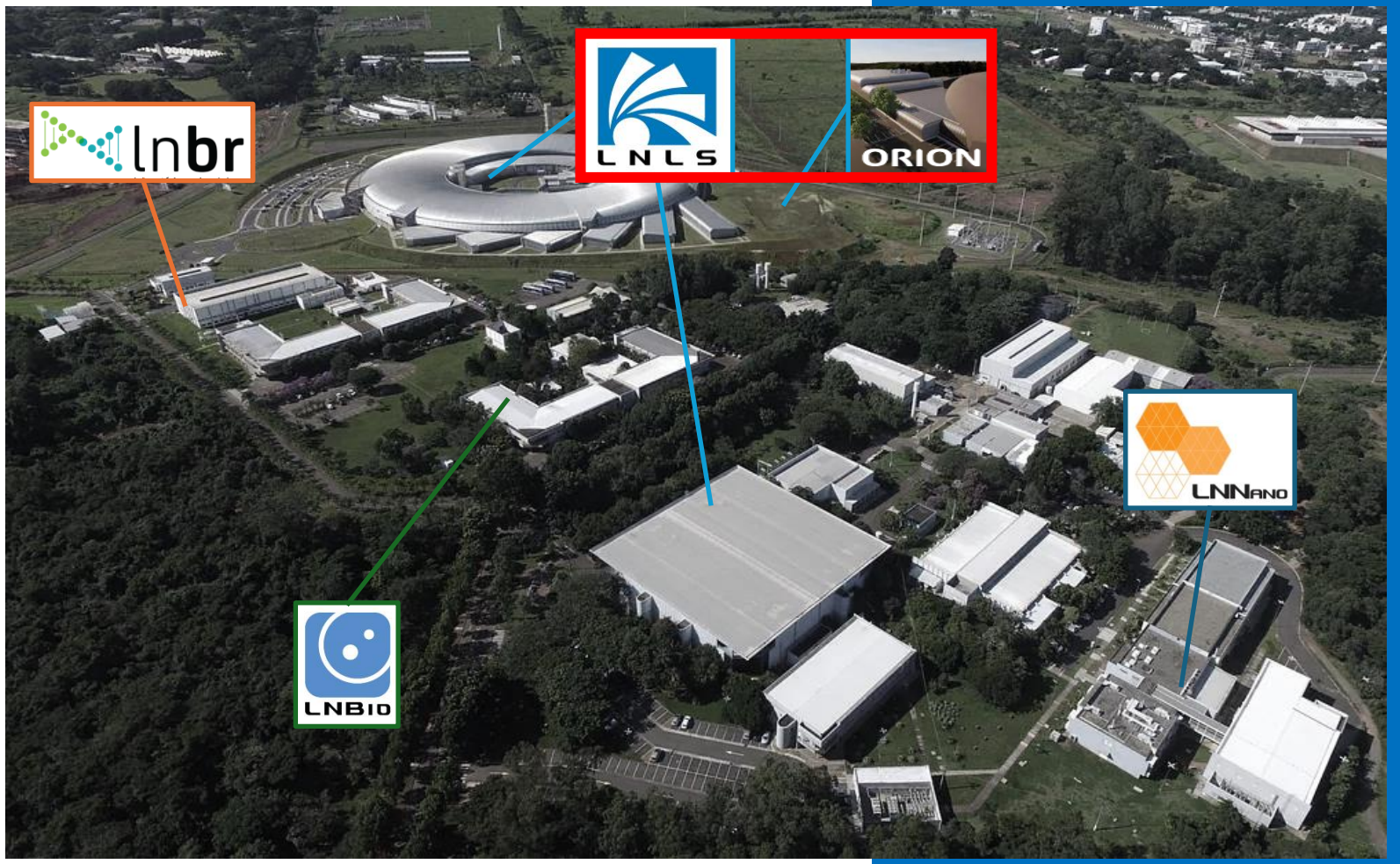


CNPEM/Sirius

- Not the Obeo Eclipse tool, but a particle accelerator instead! ☺
- 2nd Synchrotron Laboratory in Brazil, replacing the 1st one (UVX: 1989-2019)
- One of the brightest lightsources in the world, having only 3 other comparable at the moment (all in Northern Hemisphere)
- Research facility open to users worldwide

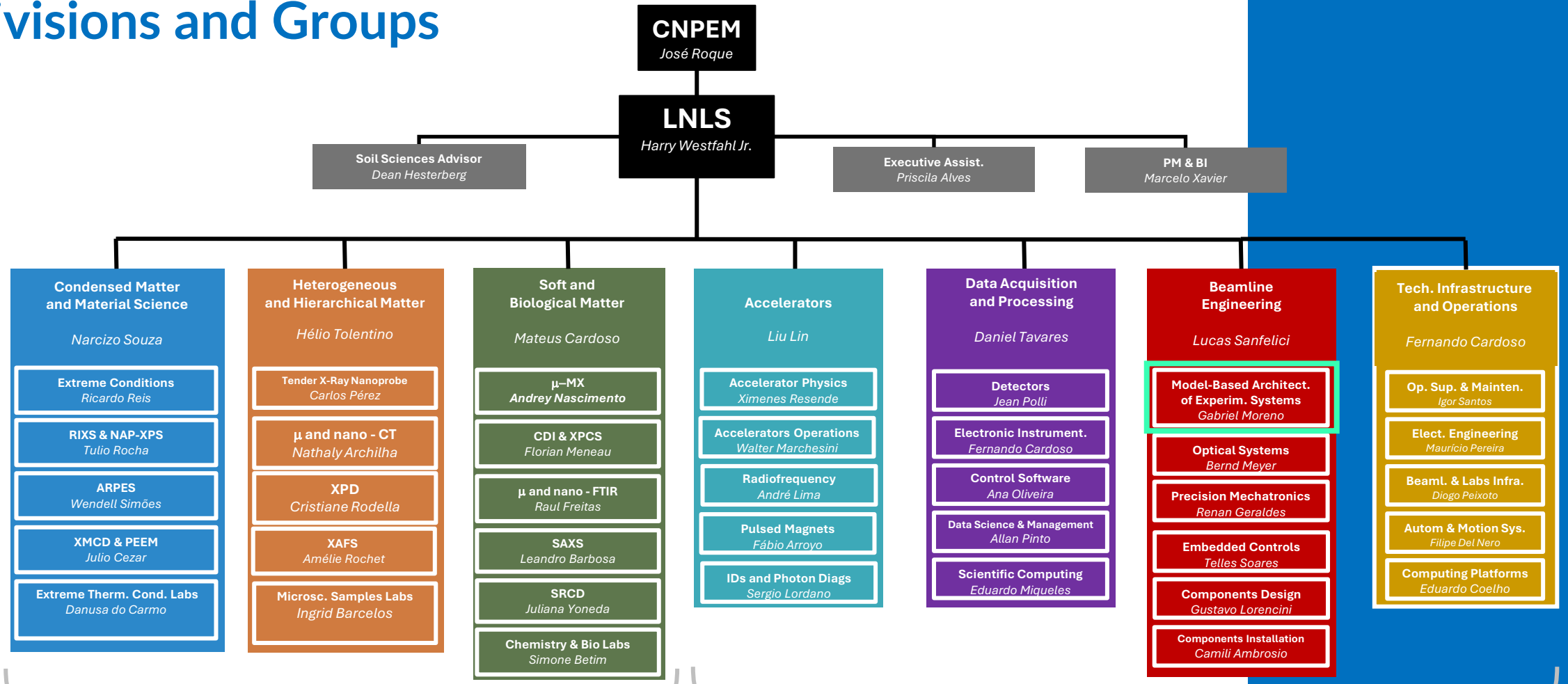
CNPEM

- **CNPEM**
  - Brazil's National Center for Research in Energy and Materials – CNPEM
- **4+1 National Labs**
  - LNLS/Sirius – Synchrotron Lightsource
  - LNBR – Bio-renewables
  - LNBio – Biosciences
  - LNNano – Nanotechnology
  - LNPP/Orion – Max. Biosafety (construction)
- **Beamline Eng. Division (DEL)**
  - MArÉ Group – **M**odeling and **Ar**chitecture of **E**xperimental Systems



Sirius/LNLS People

Divisions and Groups



3 Scientific Divisions
(~150 ppl)

4 Engineering Divisions
(~210 ppl)

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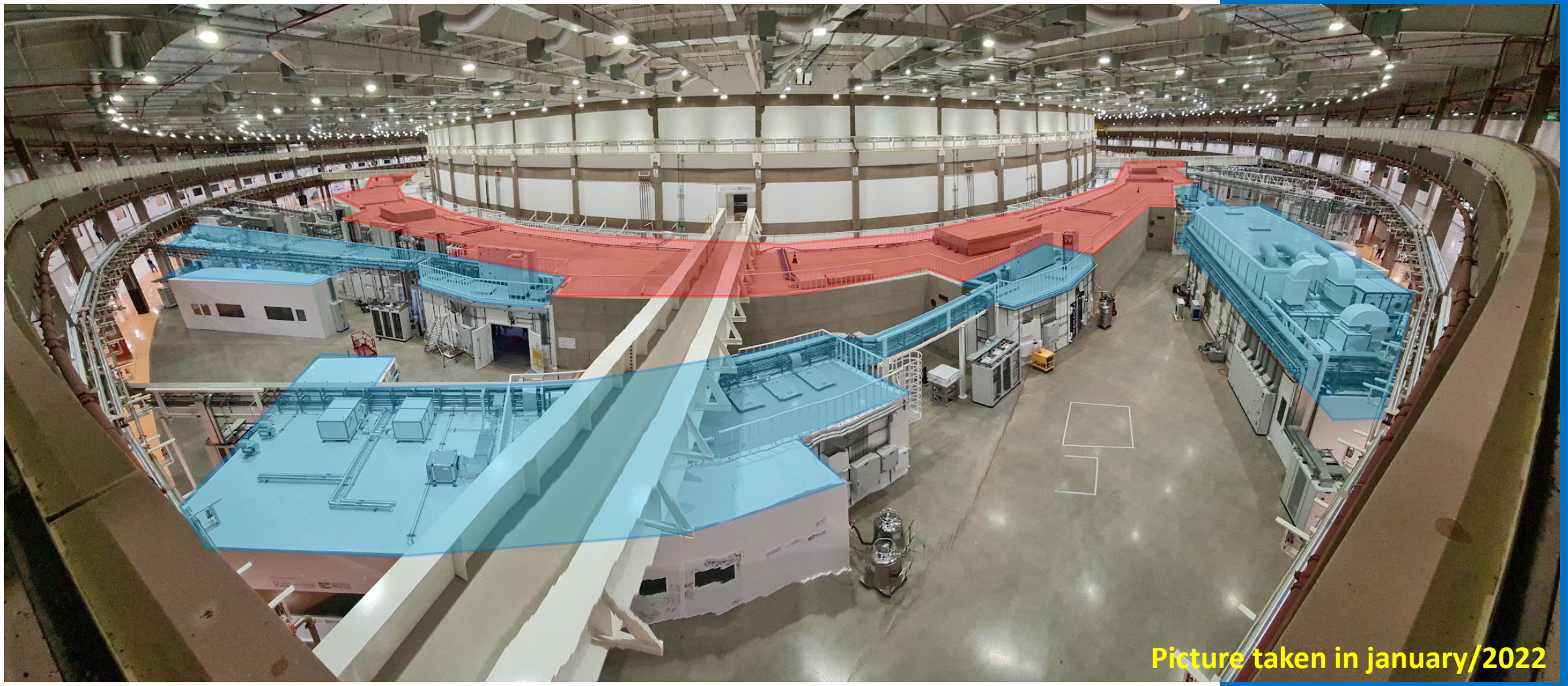
Beamline Design

- Scientific groups work together to create experiments that meet industry and scientific comunity needs
- Engineering groups work together to create instruments that meet scientific/experimental needs
- Synchrotron Beamlines are custom-built to address a specific group of techniques, designed to extract specific information from the analyzed materials
- A synchrotron lab may host dozens of Beamlines, all working simultaneously

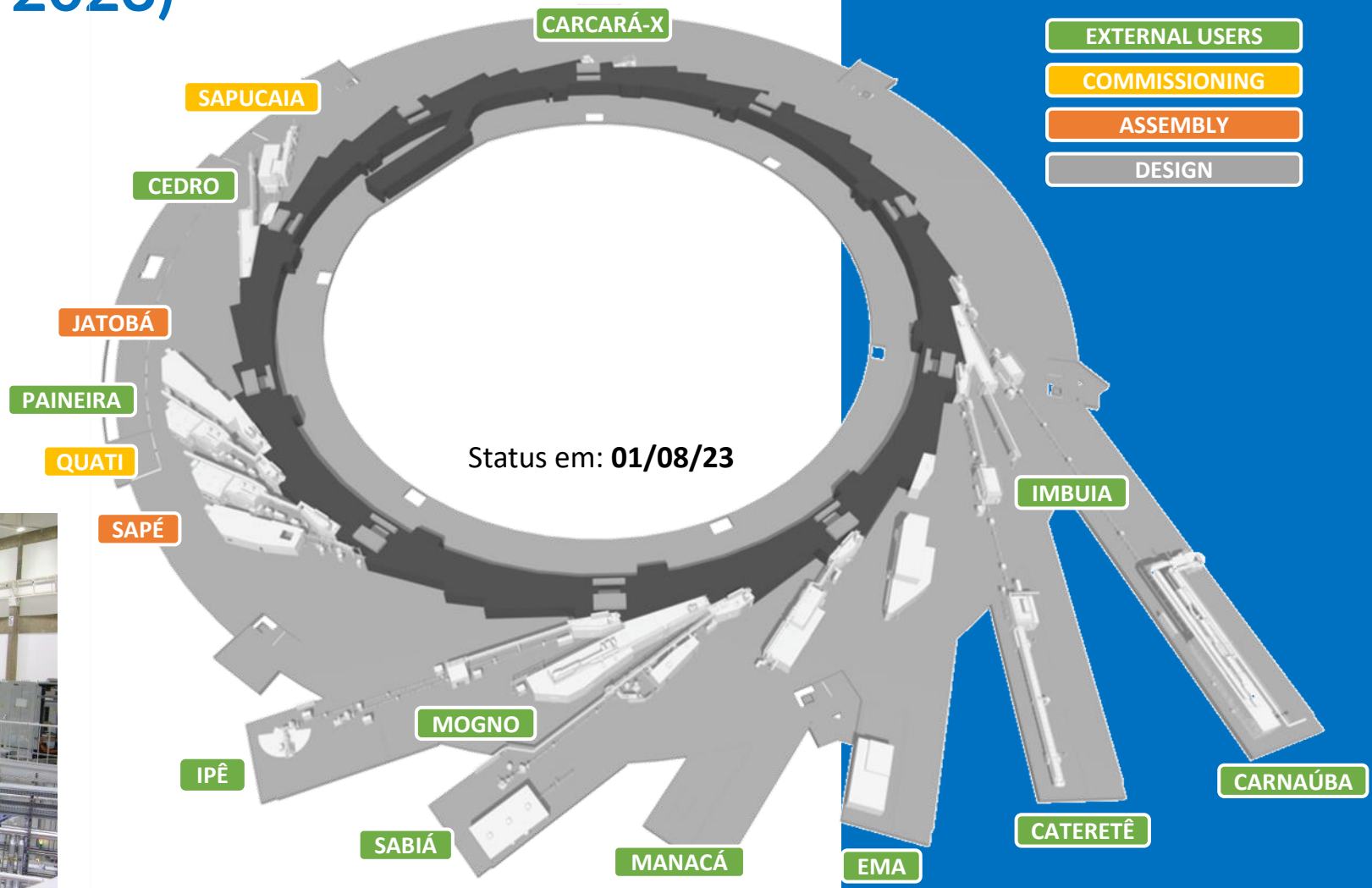
Sirius Beamlines



Sirius Beamlines

Phase I beamlines (2019 – 2023)

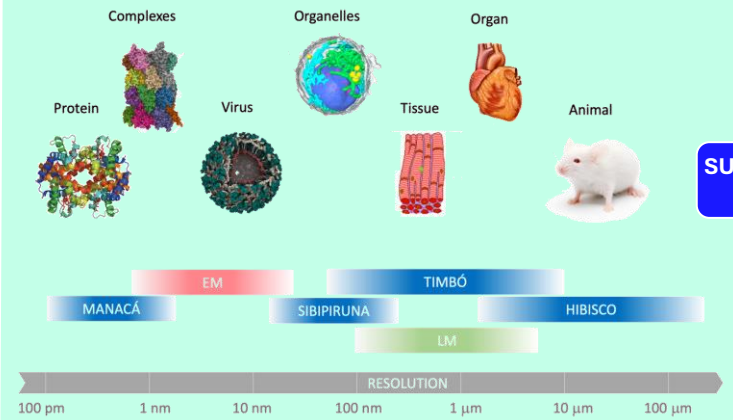
- 15 beamlines built in ~4 years!
  - 11 currently open to users
  - 2 in commissioning phase
  - 2 in assembly and installation phase

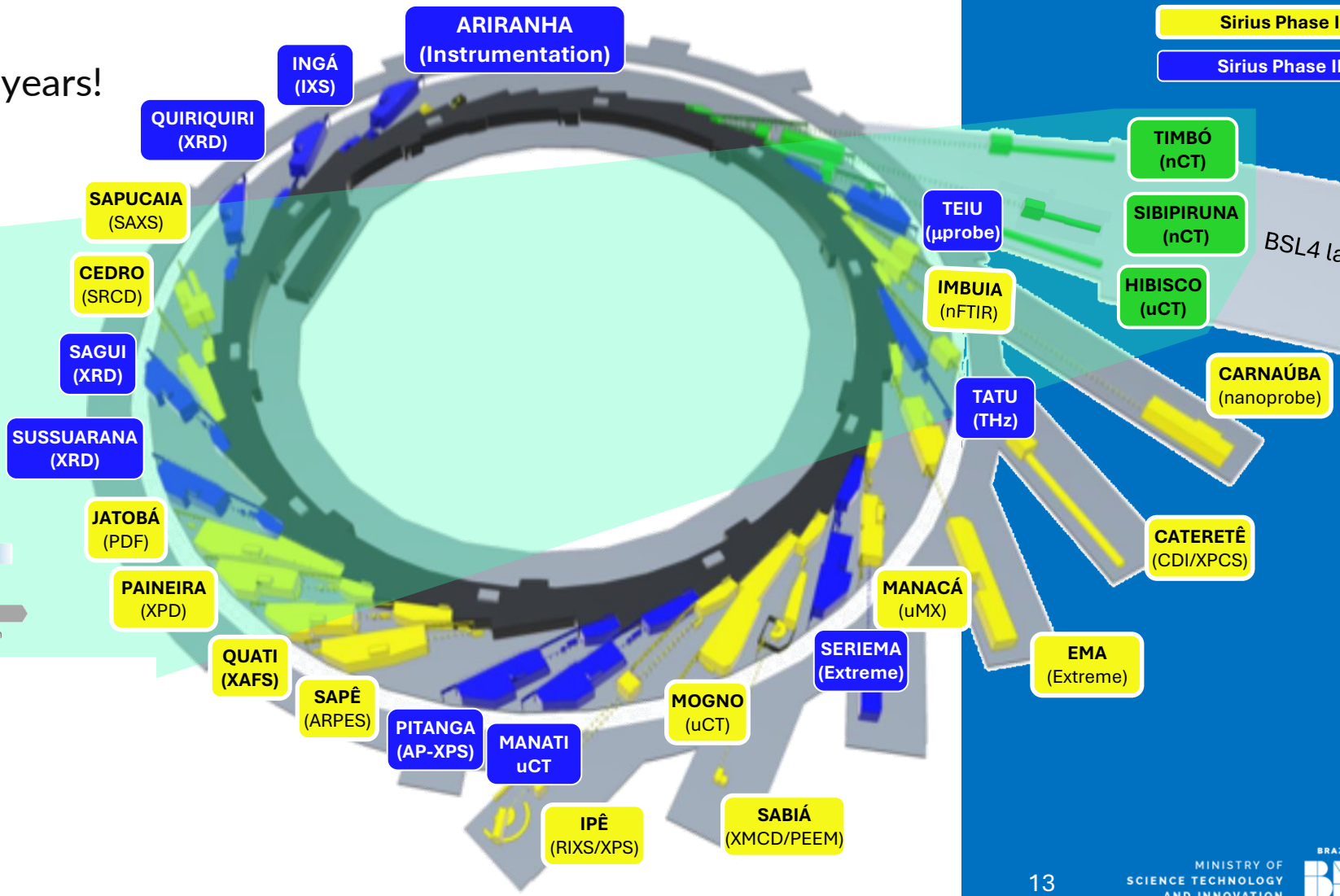


Sirius Beamlines

Phase II beamlines (2024 – 2028)

- 13 new beamlines in next 4 years!
  - 3 deriving to Orion BSL-4 Lab
  - 10 from Sirius





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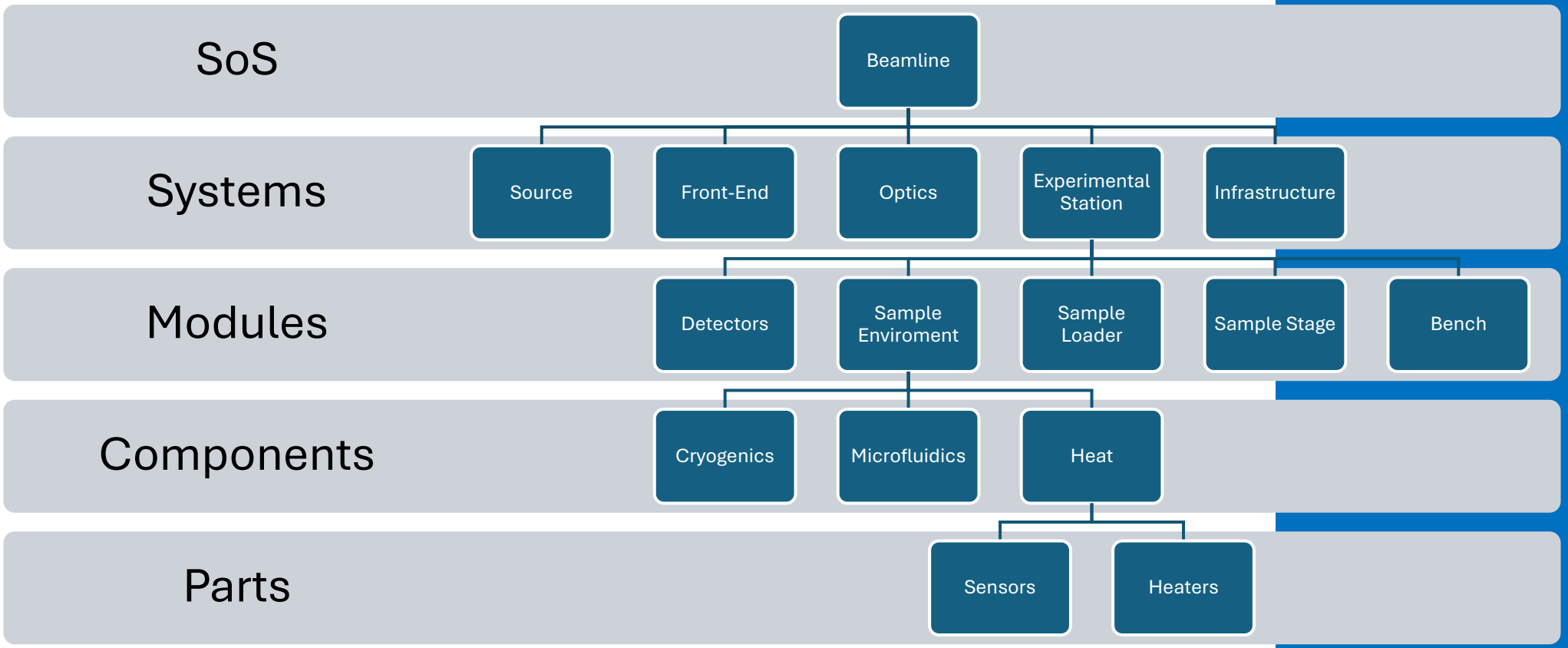
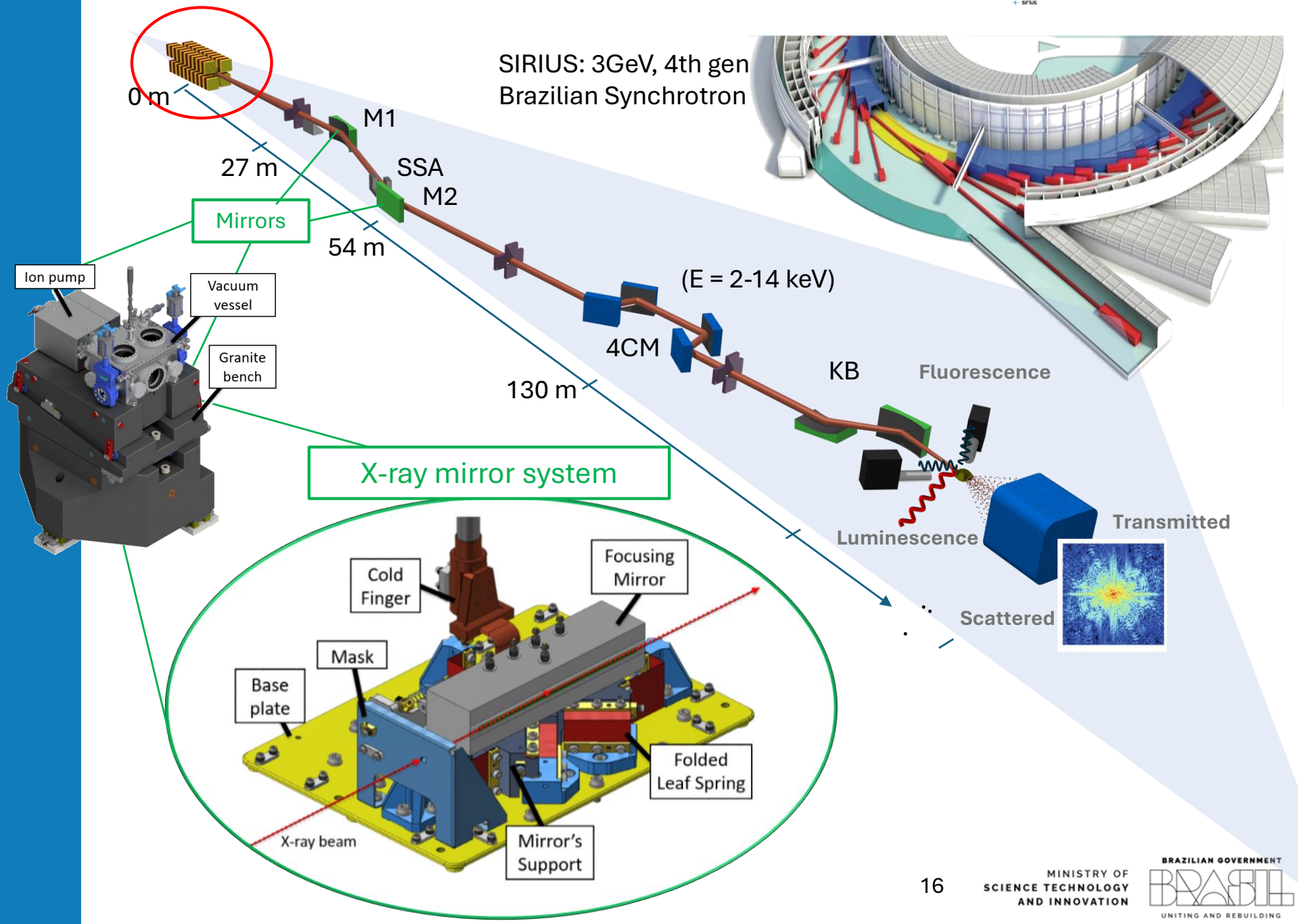
Beamline concept and complexity

What is a beamline?

Common System decomposition



What is a beamline?



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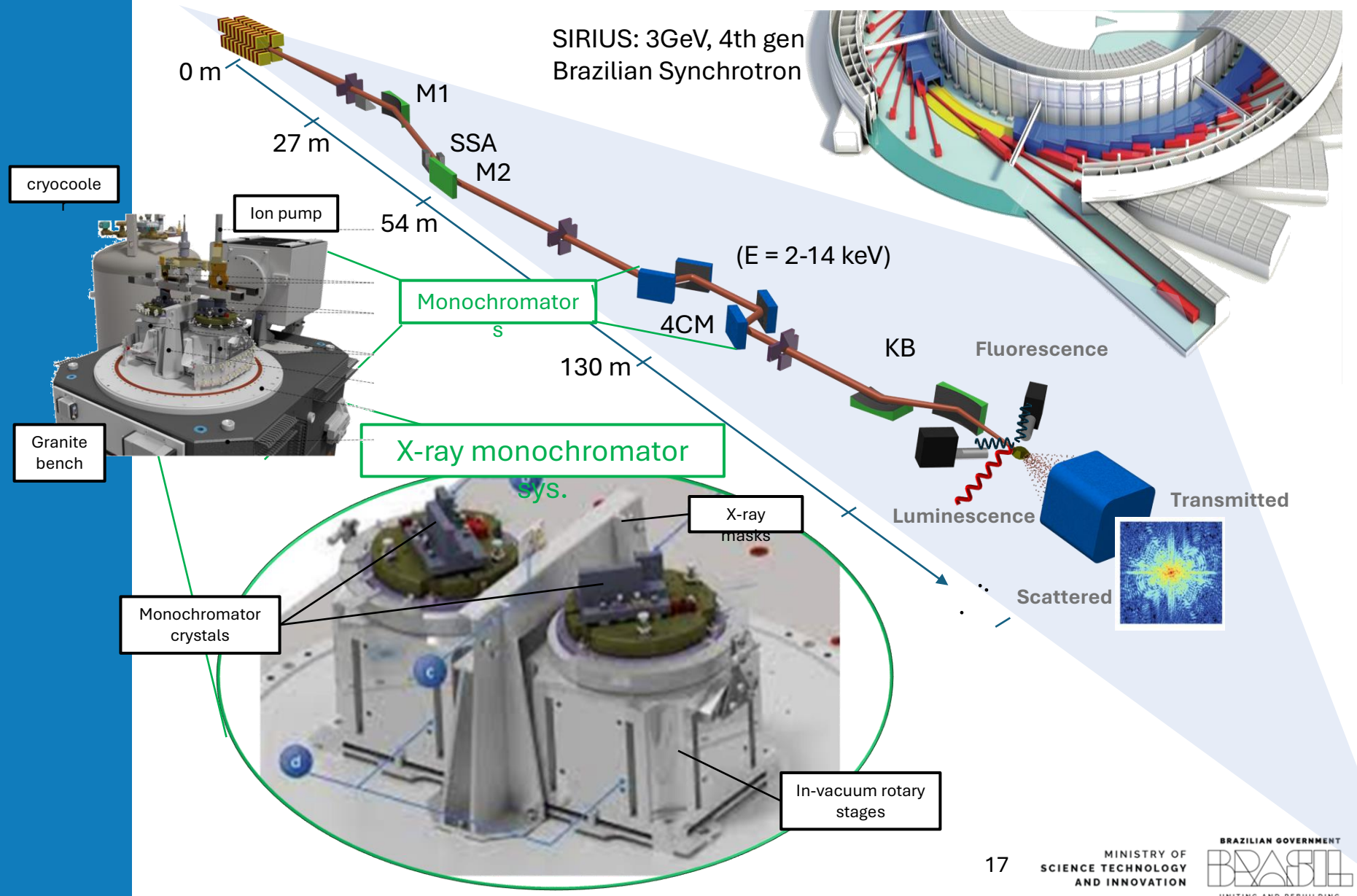

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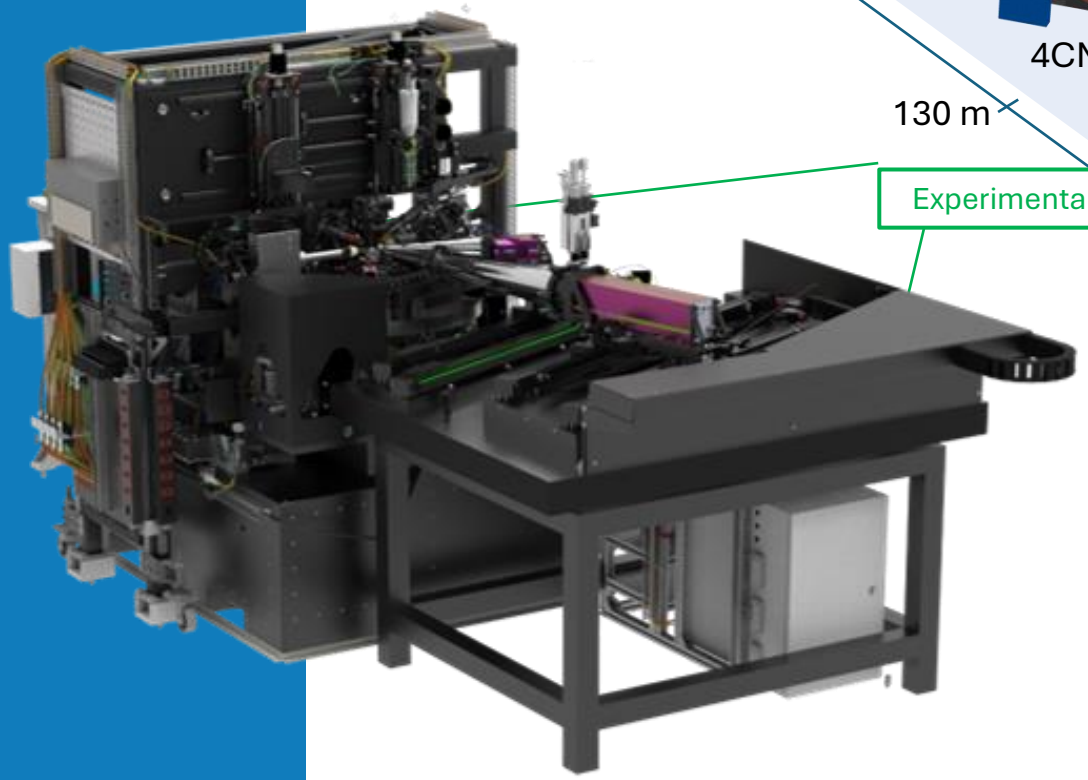

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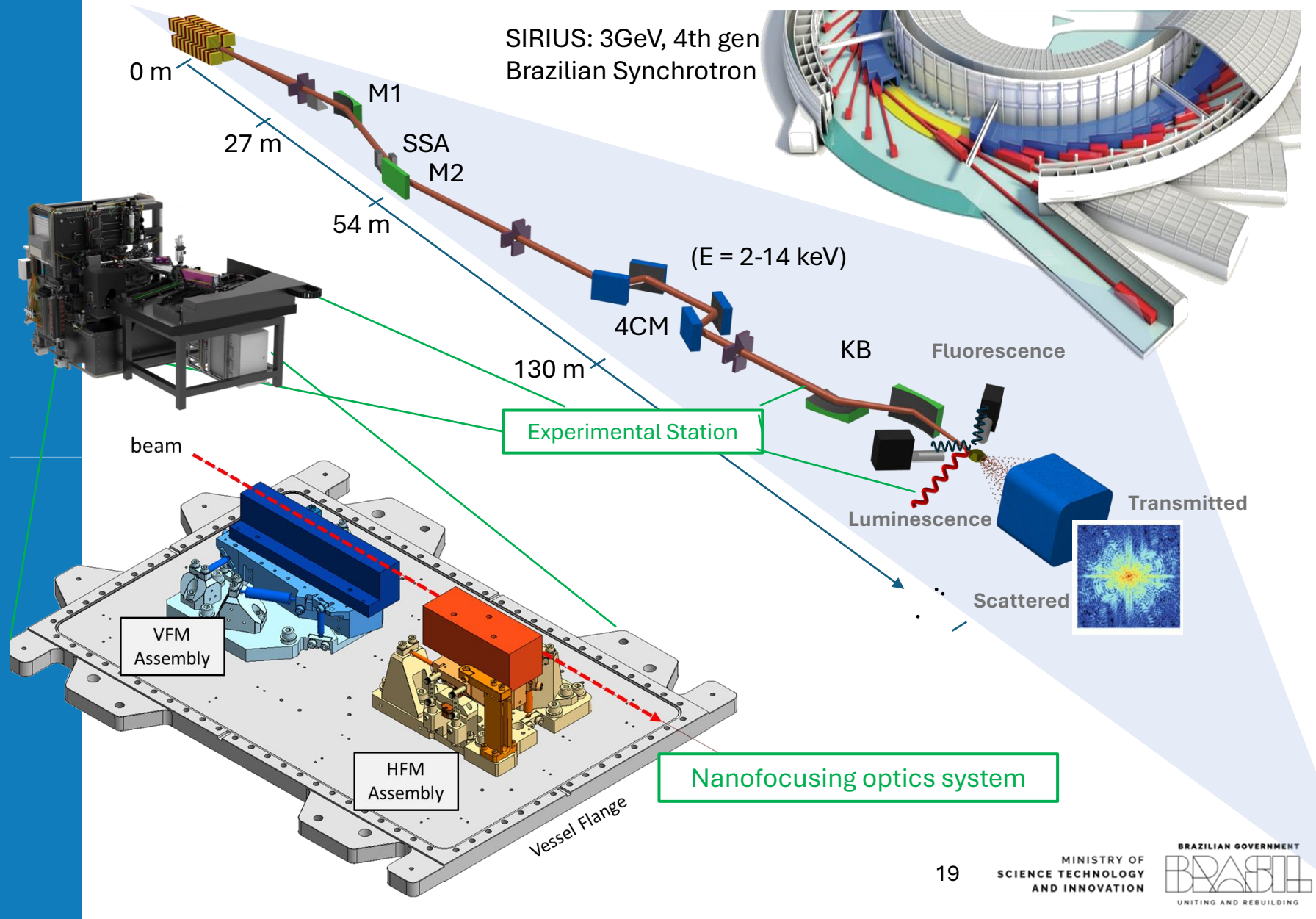

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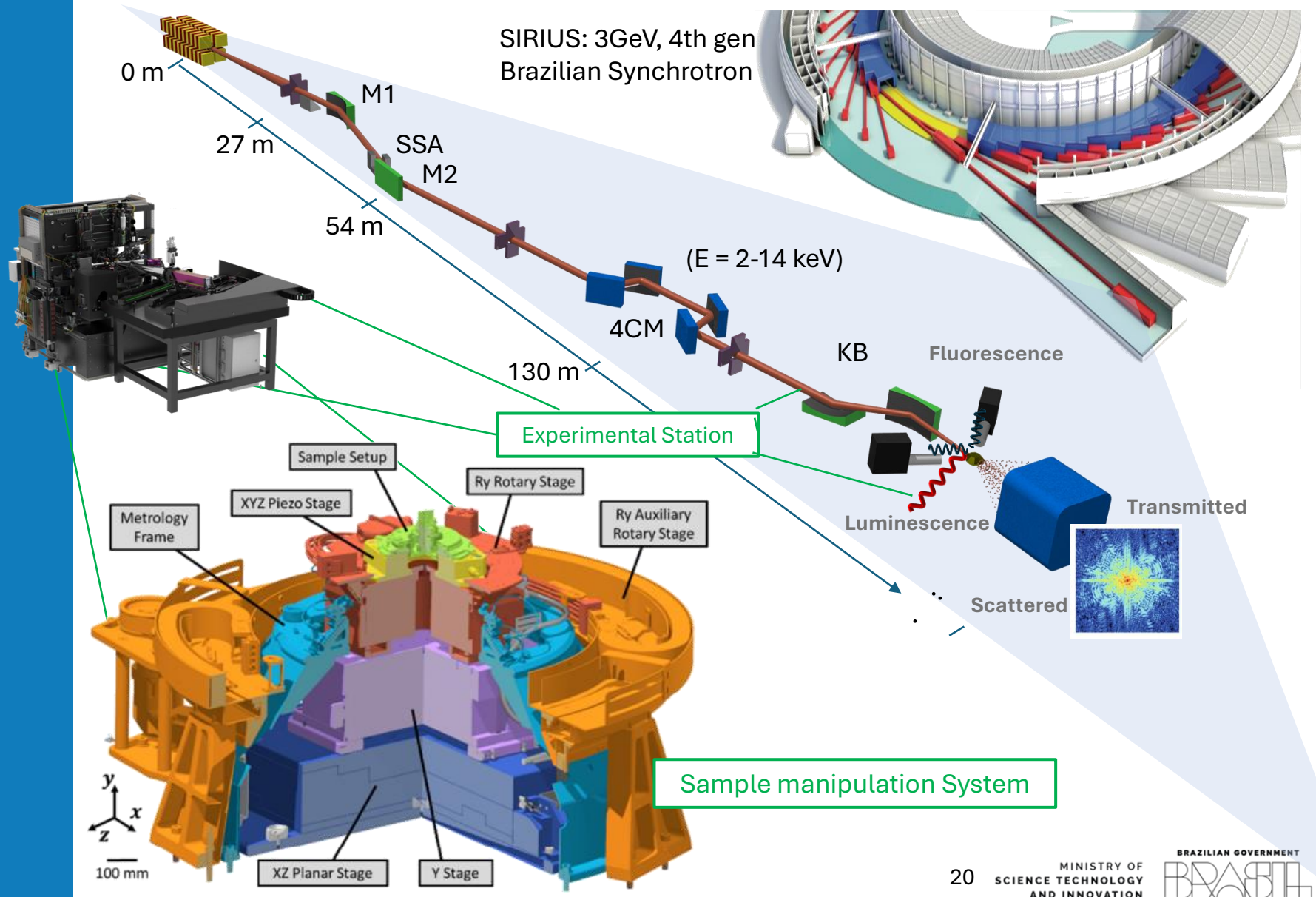

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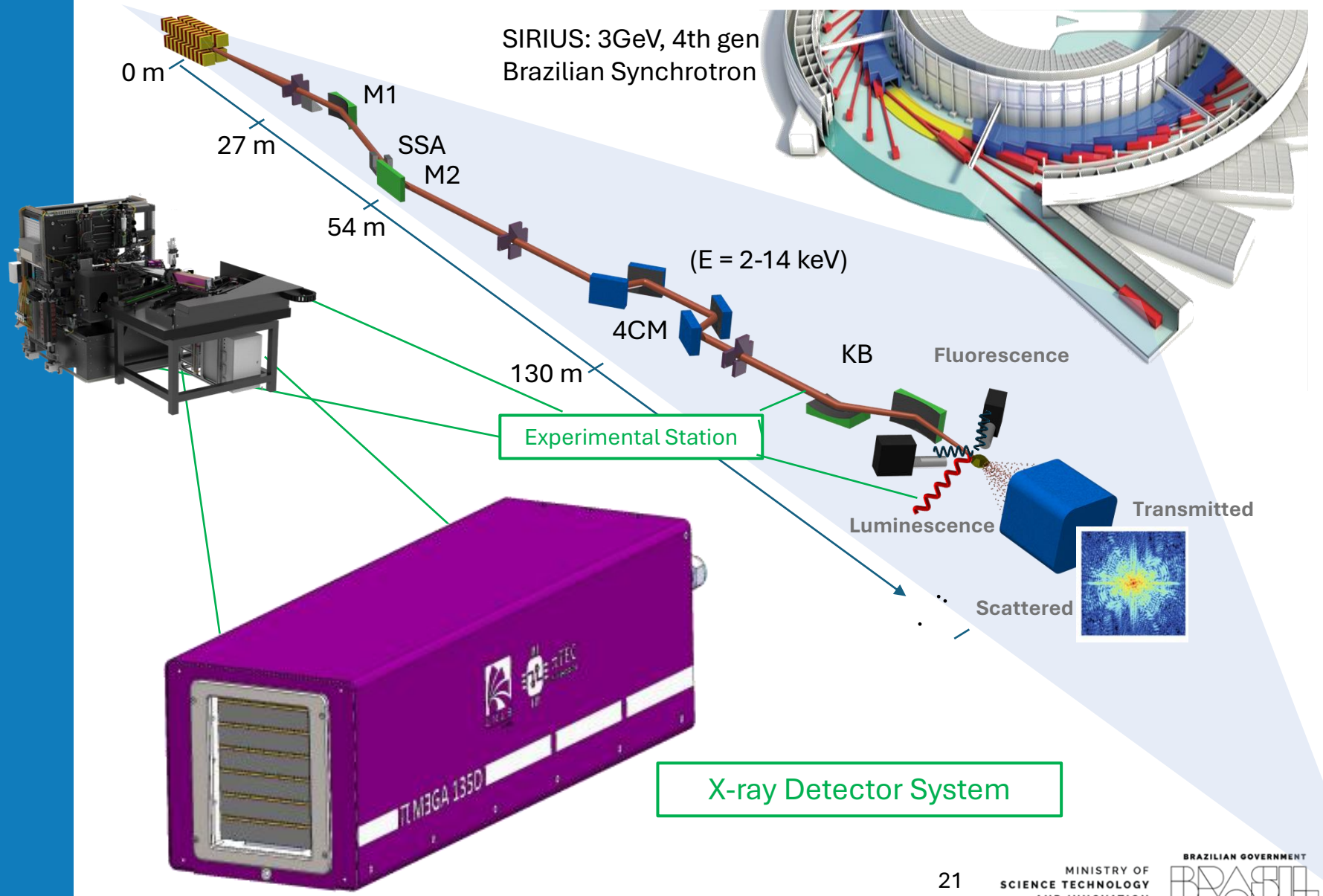
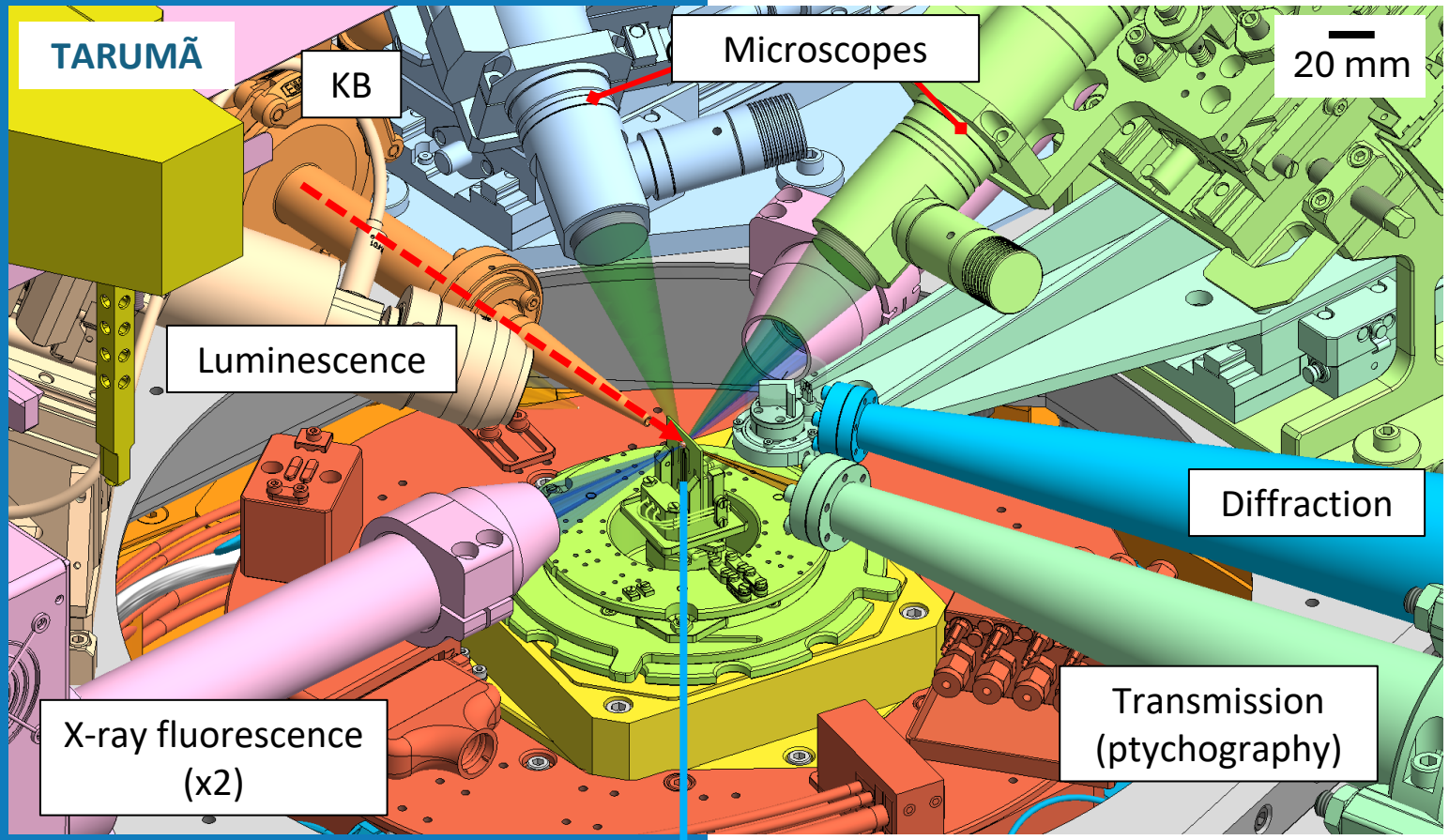


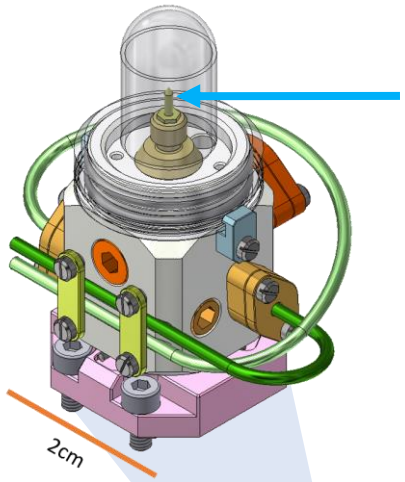
TARUMÃ Station

- **Multi-technique** – experiments *in situ*, *in operando*, *in vivo*

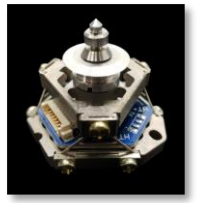


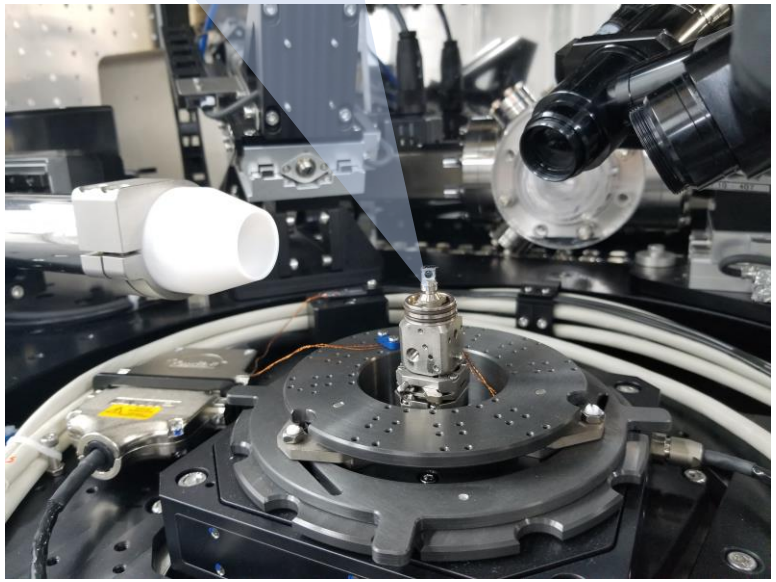
Samples

(Biological, agro, minerals, batteries...)



Various sample holders and environme





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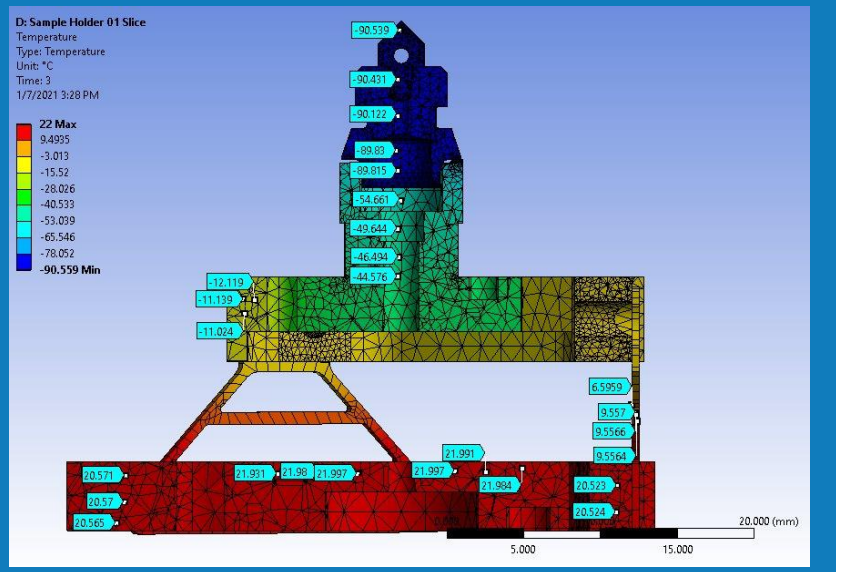
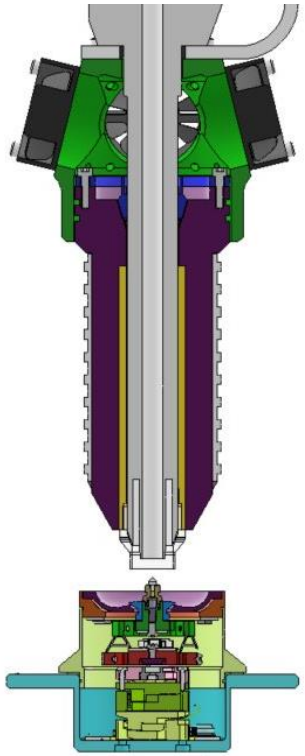
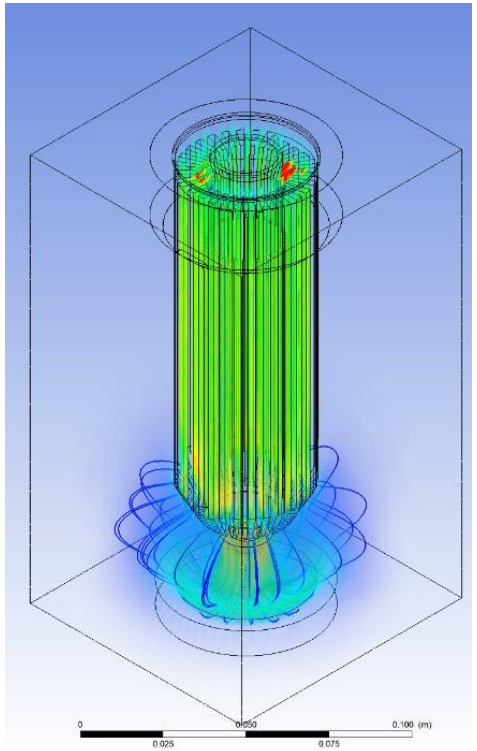
TARUMÃ Station

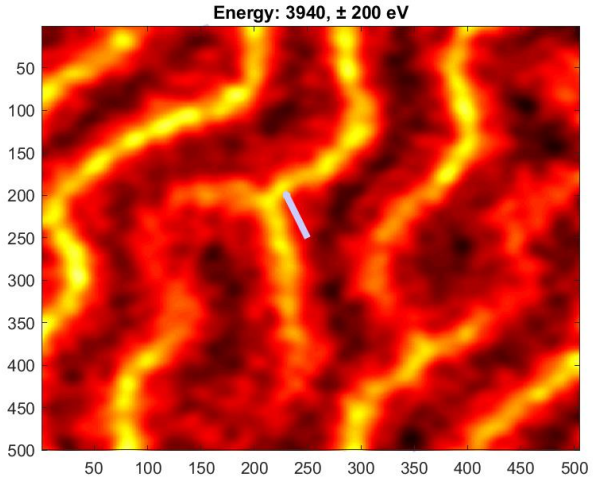
Cryogenic Setup

- Sample temperature target: 122K
- Thermal variations must cause minimal sample displacement (<30nm RMS)
- Must insulate internal dry N2 from atmospheric air
- Must actively avoid water condensation/icing

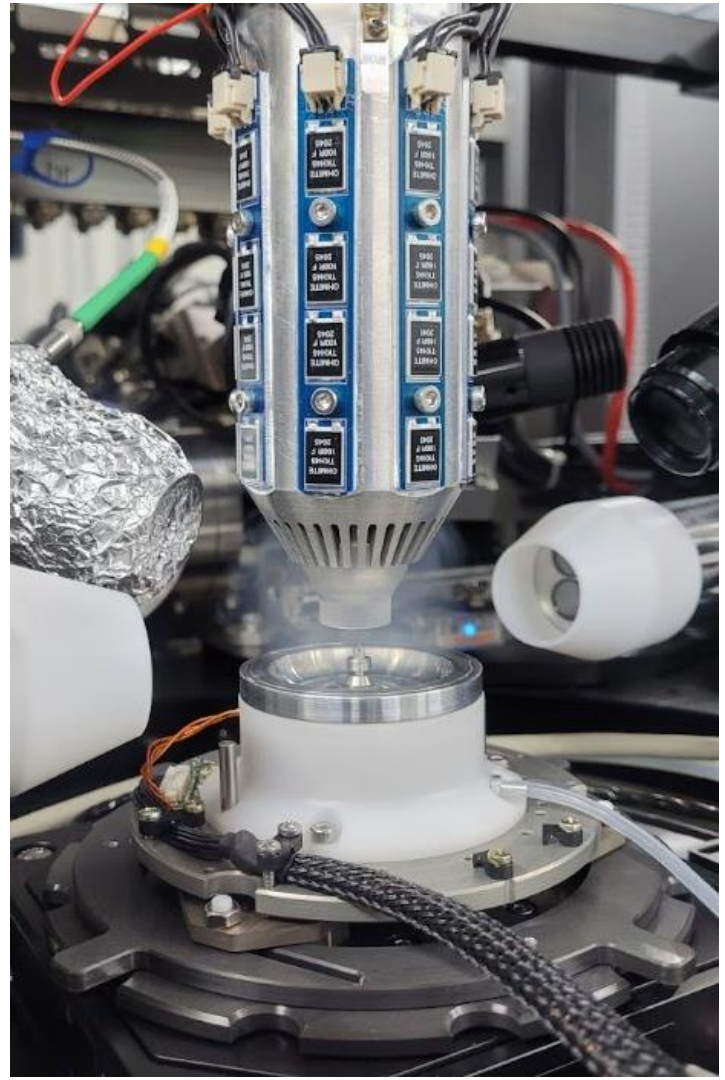








Thermal drift measurement in perovskite sample: 1µm in 7.5h



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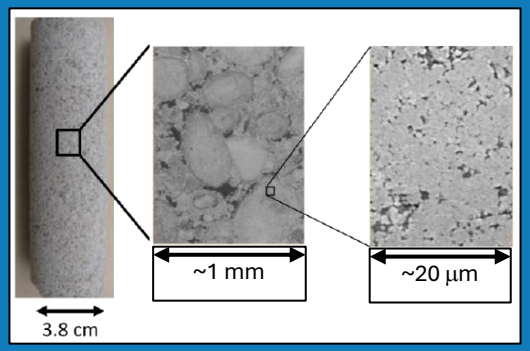
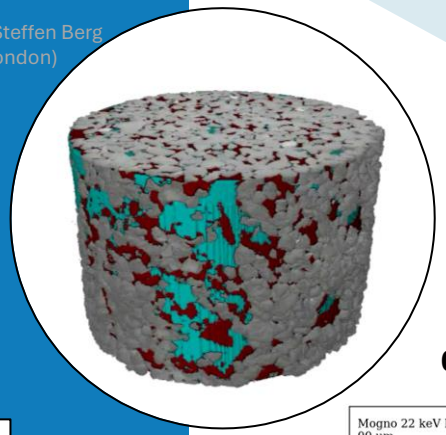
MOGNO beamline

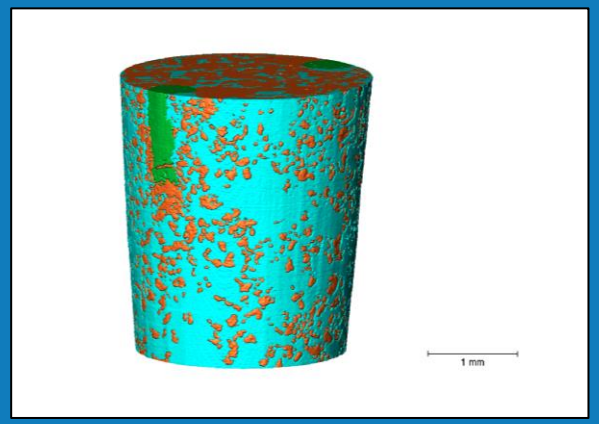
Micro and Nano tomography

- Zoom from 50 to 0.1 µm resolution
- In-situ experiments with rocks in pre-salt reservoir conditions
- Various tomography experiments

Courtesy: Steffen Berg (Shell/IC London)







Courtesy: Talita Ferreira (MOGNO/LNLS)

Secondary Source
0.3 (H) x 800 (V) µm²

Nano-focus
120 (H) x 120 (V) nm²

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Why Systems Engineering for Synchrotrons?

- **Beamlines are Complex Systems:**
  - Highly connected;
  - Performance is highly sensitive to more than one module;
  - Often present competing requirements (i.e. temporal resolution vs. Spatial resolution vs. Environment conditions);
- **Many different stakeholders often involved**
  - Different languages;
  - Different points of view;
  - Different restrictions and needs;
- **Beamline's life-cycle often includes upgrades to keep up with scientific community demands**
- **Many Beamlines are yet to be built (~25)**
  - Reusability opportunities;
  - Technological heritage opportunities;

First steps in SE and MBSE implementation!

- First institutional application of formal SE and MBSE started in 2023
- Better capabilities demands better performance, and pushes for technological advancement
- Many collaborations starting inside and outside Brazil
- Goal: to start showing value in improving future projects with quick-and-easy application of SE and MBSE concepts

Systems engineering workflow for Sirius

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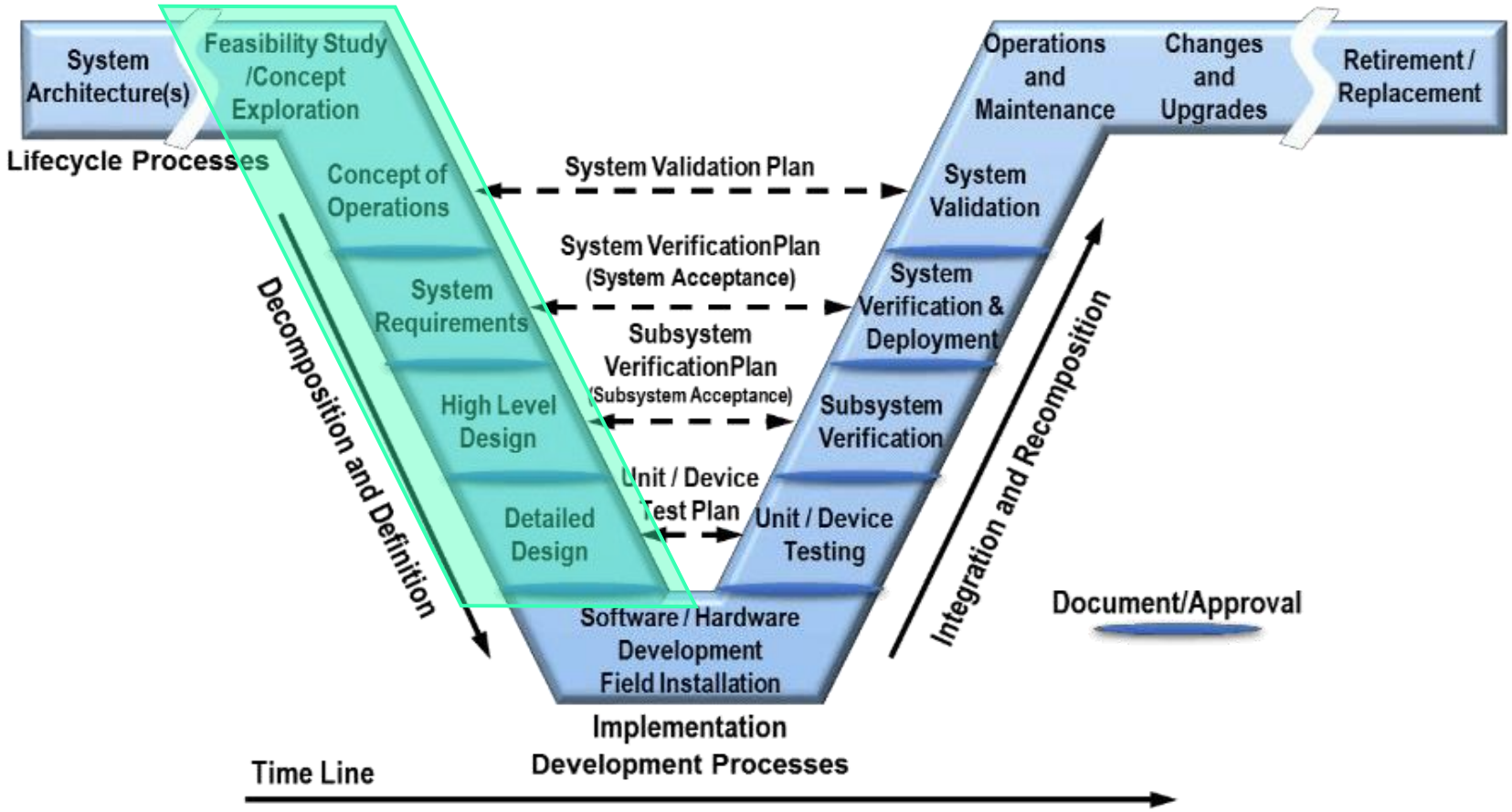
Motivation

According to INCOSE



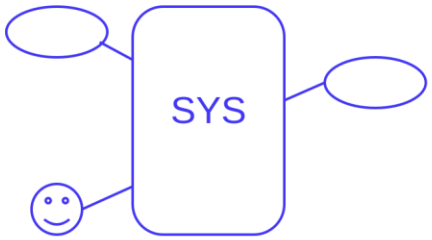
Ref: www.ppi-int.com

Systems engineering promotes structured processes and interdisciplinary collaboration, leading to more efficient project execution and clearer communication across teams.

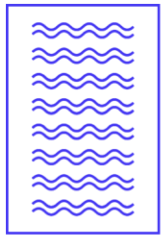
- Fast Growing
- Experience
- Complexity

System Engineering Workflow

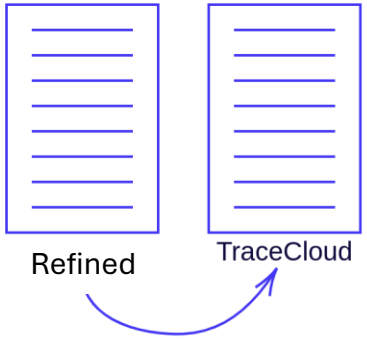
Overview

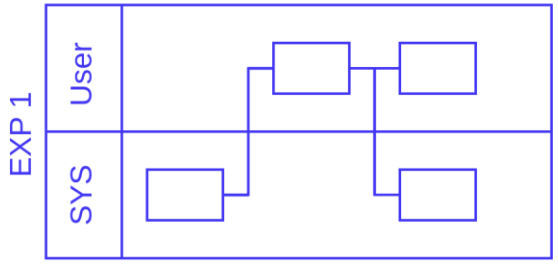


System Interfaces & Capabilities

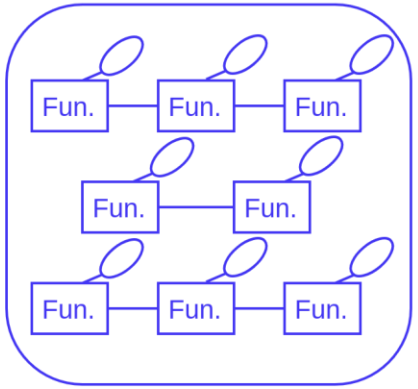


Raw requirements & Stakeholder needs

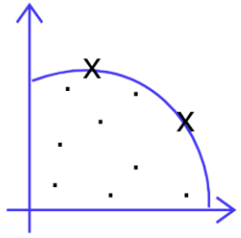




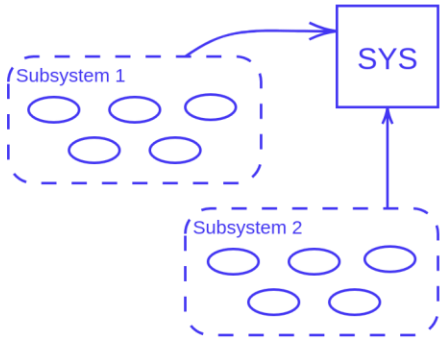
Scenarios diagrams



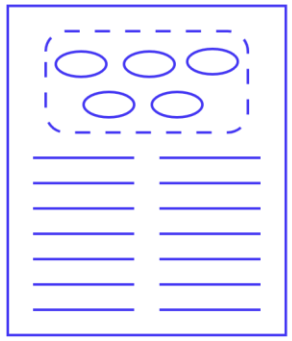
Functional Analysis + Solution Generation



Trade-off analysis



Modularization

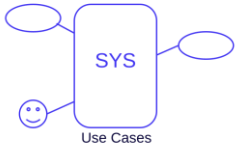


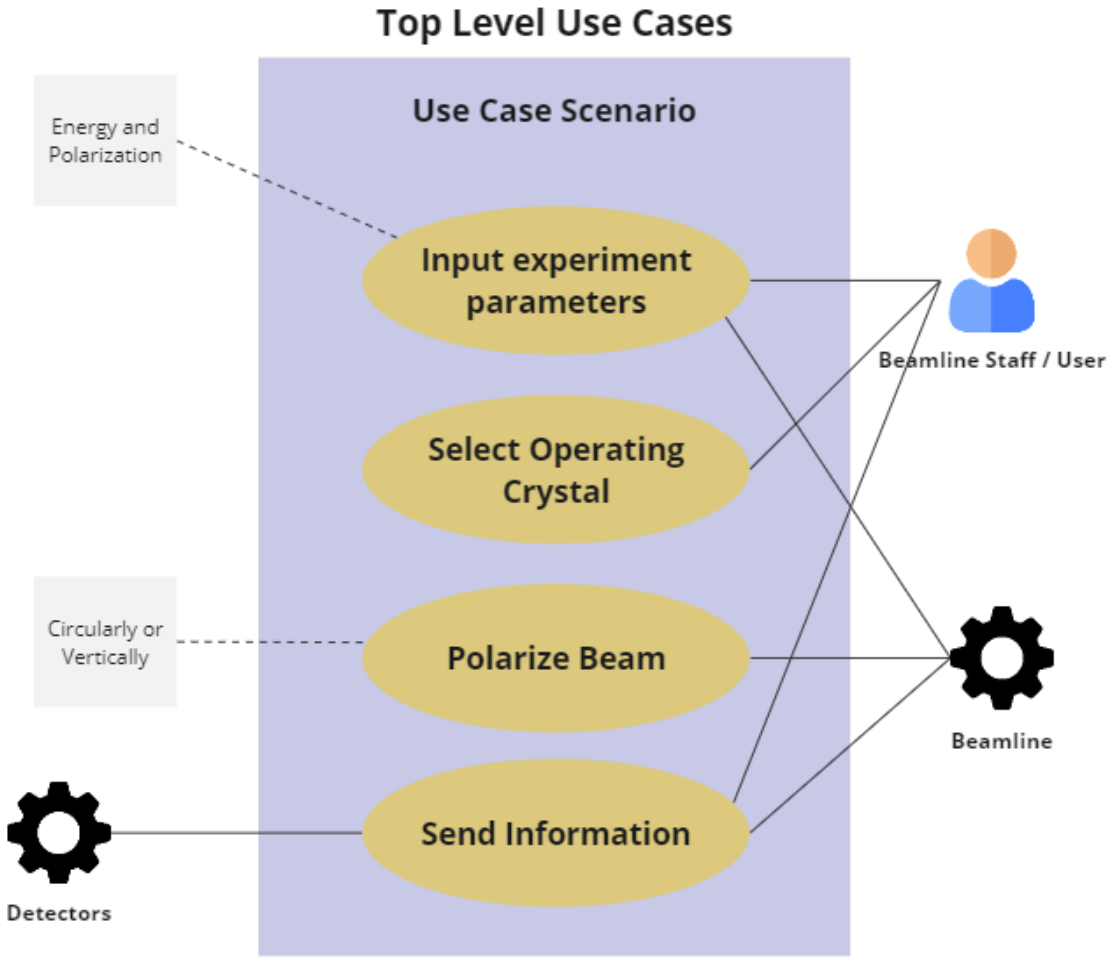
Concept documentation + requirements

We propose an (ideal) Systems Engineering workflow for CNPEM, to gather and manage requirements and architect our systems. The proposal is a fusion of our current design workflow and the traditional one proposed in ES. Each step is described in the following slides.

System Engineering Workflow

Problem Domain – System Interfaces & Capabilities



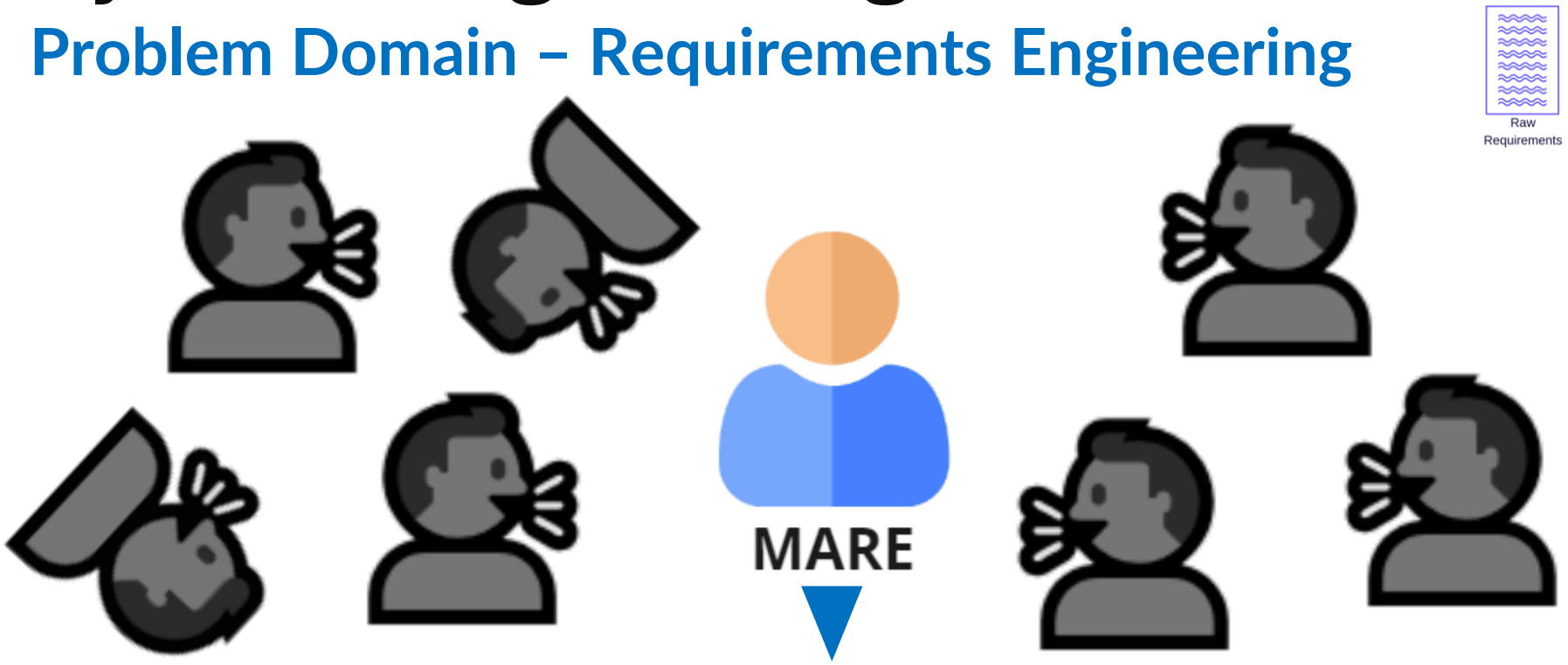


Define Use Case Scenarios (how our system interacts with external actors). The definition of interactions between users and systems could be done here to clarify roles and responsibilities. Identify technology gaps to explore

- Stakeholders
- Interfaces
- Benchmark

System Engineering Workflow

Problem Domain – Requirements Engineering

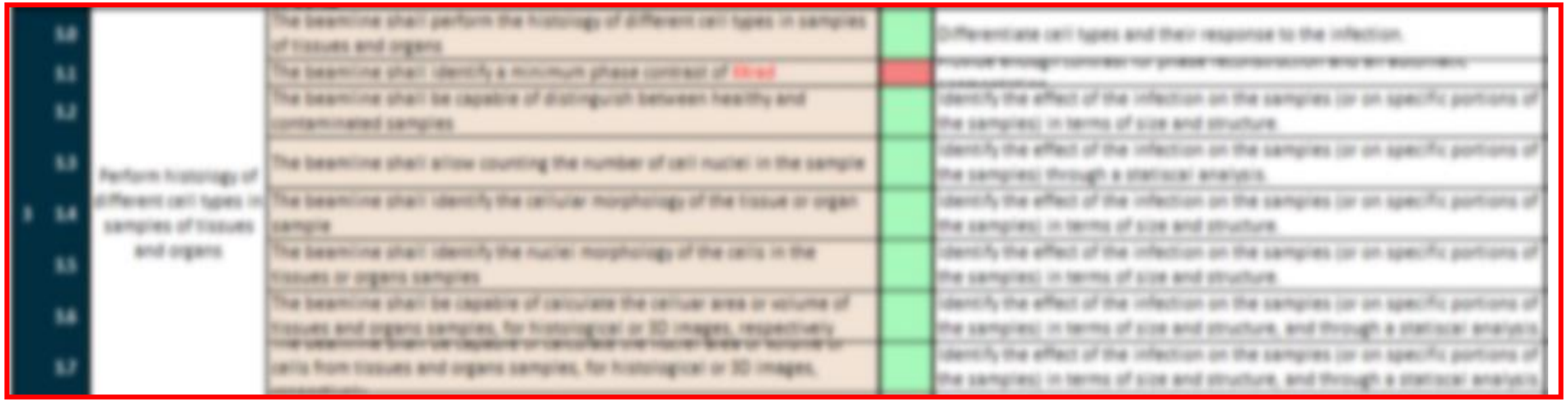


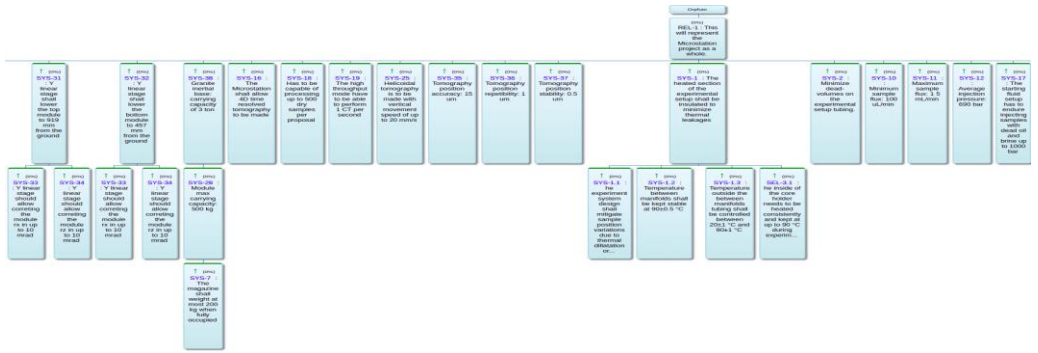
Gather raw requirements from stakeholders and refine them into more descriptive and detailed ones. If needed, break down raw requirements into more than one refined requirement.

- Rewording
- Rationals

System Engineering Workflow

Problem Domain – Requirements Engineering



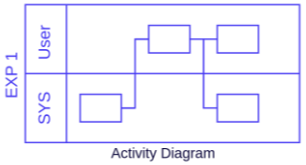


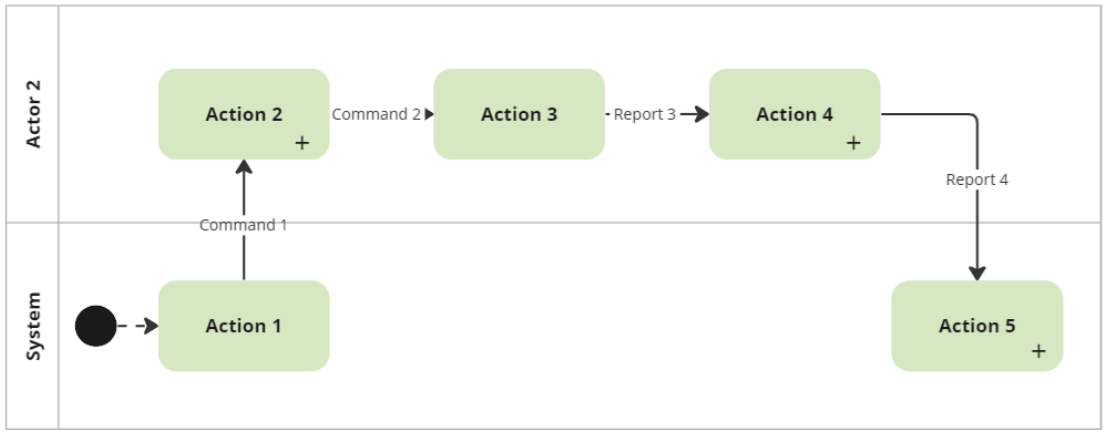
Gather raw requirements from stakeholders and refine them into more descriptive and detailed ones. If needed, break down raw requirements into more than one refined requirement.

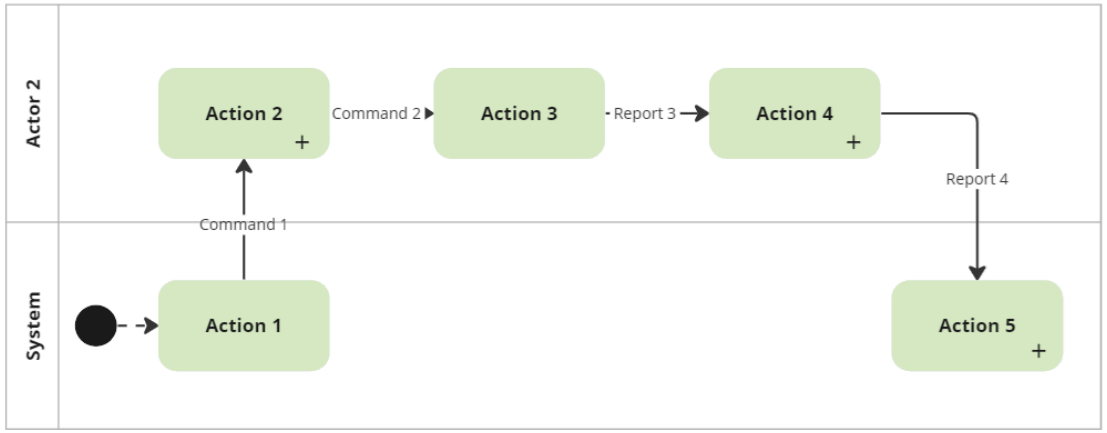
- Functional vs Non-functional
- Traceability
- ReqIF

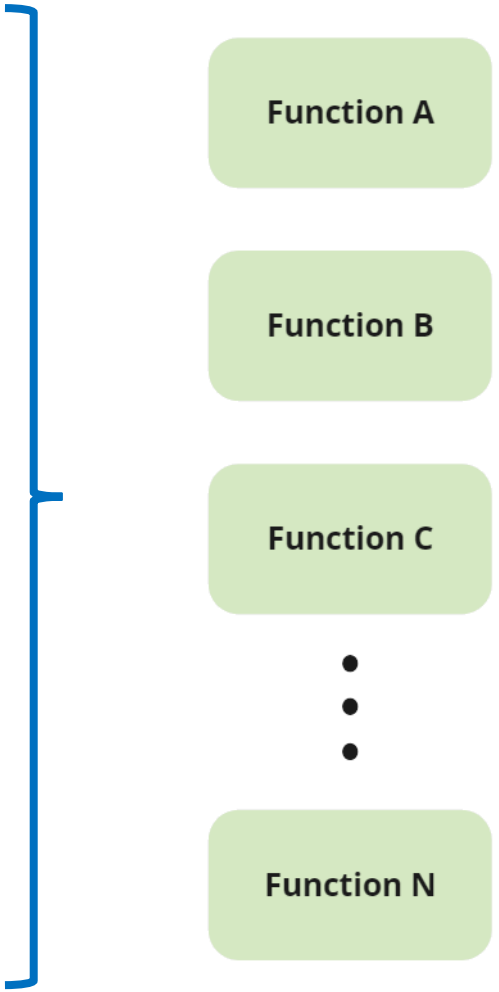
System Engineering Workflow

Problem Domain – Experiment Structure







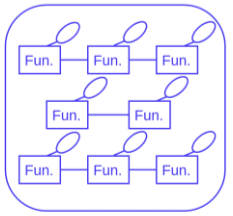


Map the possible uses of the system, experiments, safety procedures, and maintenance. In-depth understanding of what the system should accomplish. Try to keep the problem solution neutral and identify the critical steps and interfaces in the expected workflow.

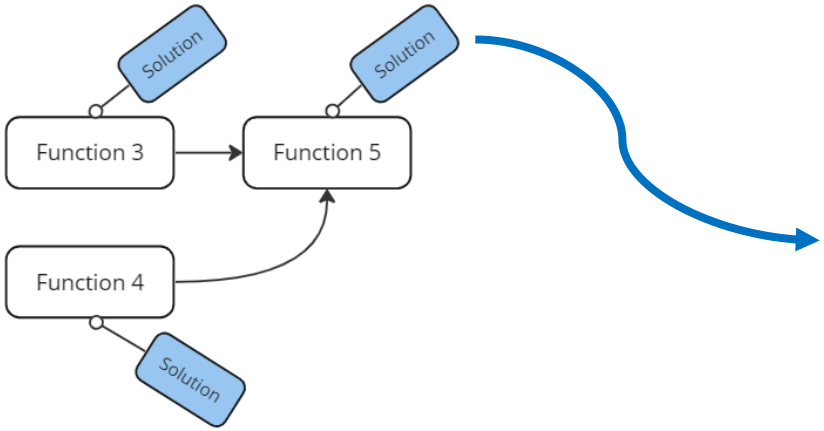
- Mission and capabilities
- Actors and Entities
- Abstractions

System Engineering Workflow

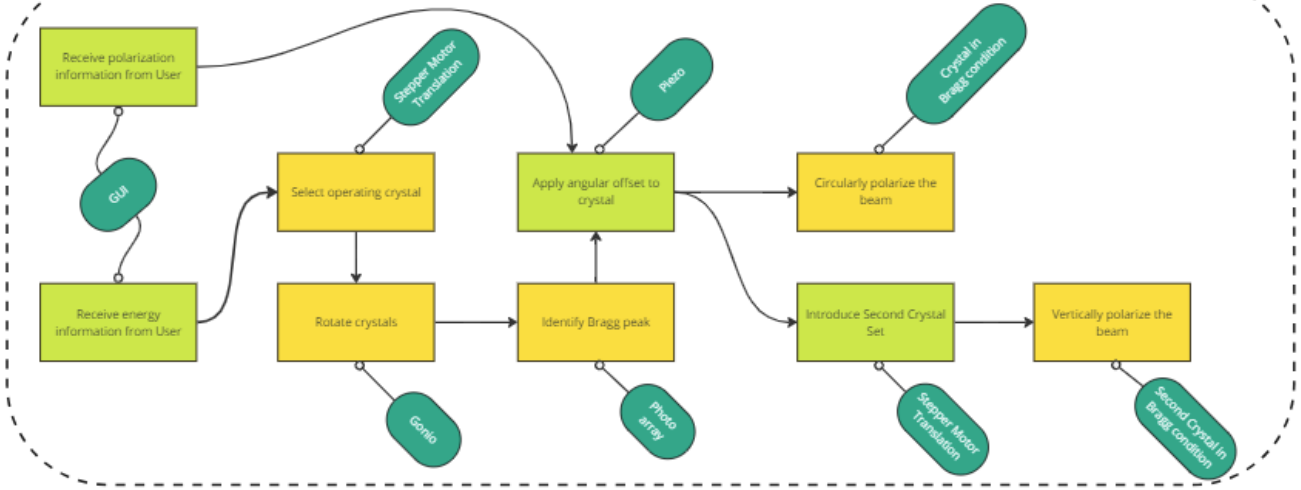
Solution Domain – Solution Proposal



Functional Analysis + Generate Solution



Independent QWP



Identify solutions for system functions. Propose different solutions set to explore interfaces between components. Define possible spin-offs of sub-systems for internal P&D.

- Creativity
- Risk Management
- Experience

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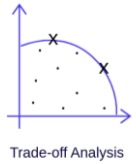
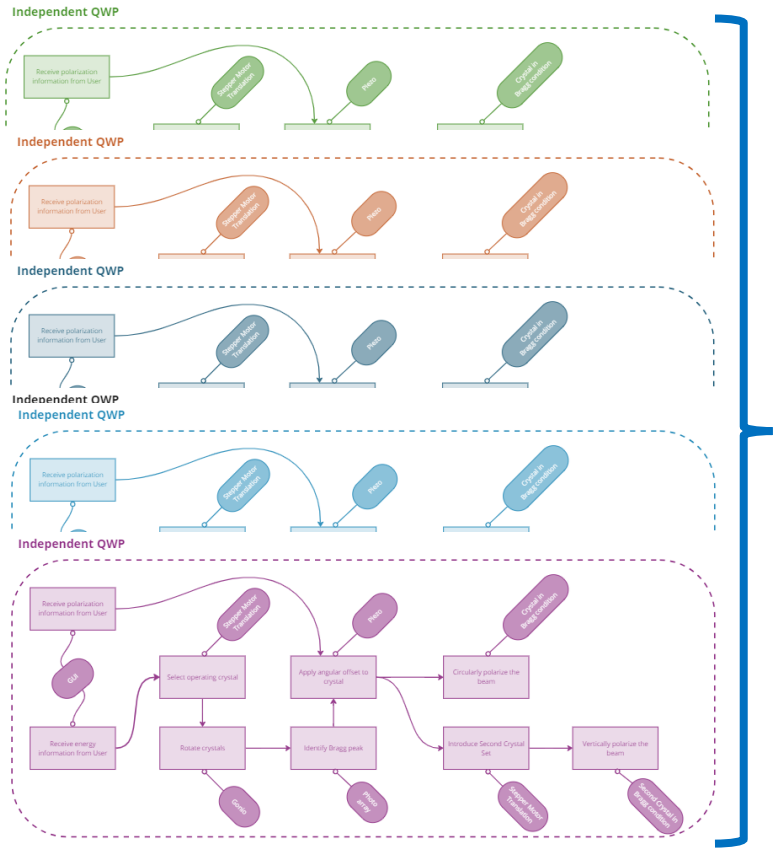
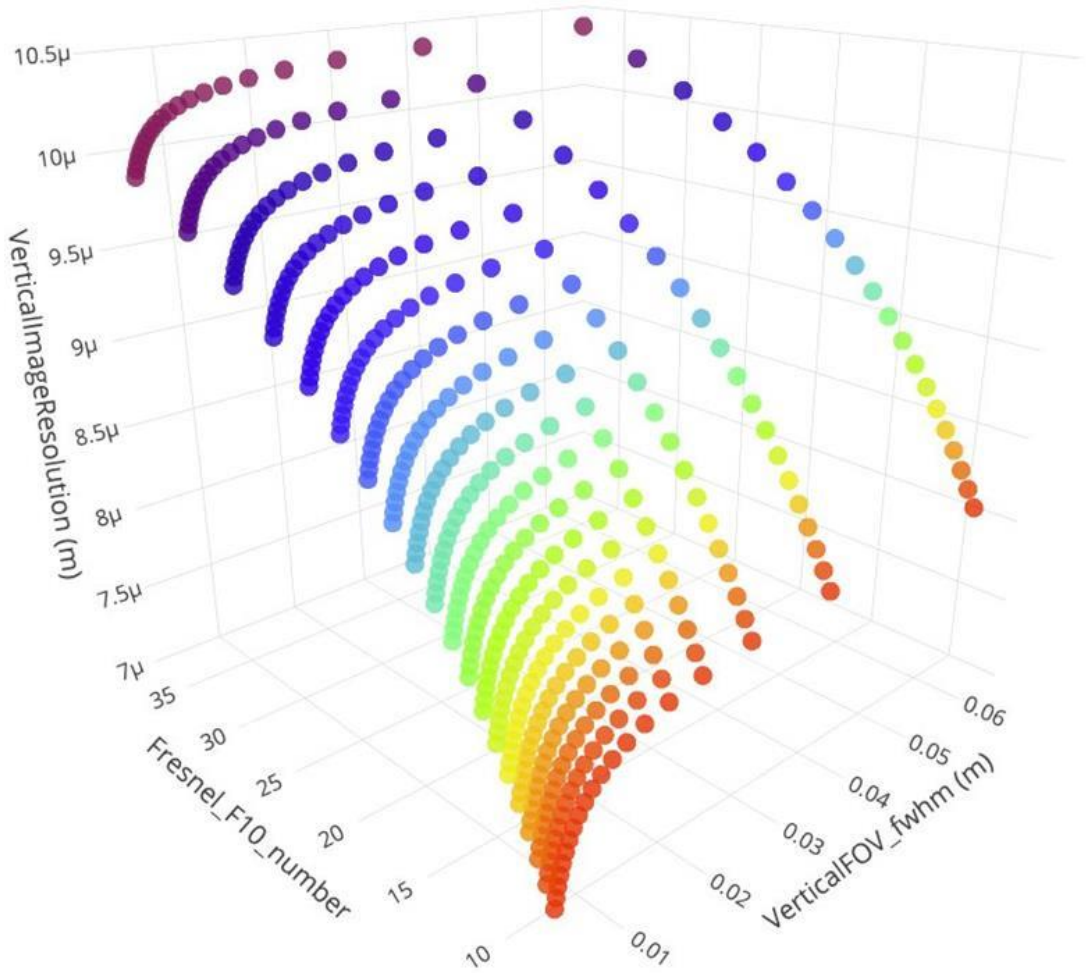
BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

System Engineering Workflow

Solution Domain – Trade-off Analysis







Confront different solutions for the expected functions and different sets of solutions to compose the system. Model the solutions to perform a trade-off analysis.

- Performance
- Cost
- Schedule
- Low-fidelity models

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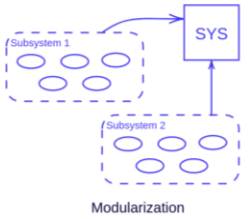
System Engineering Workflow

Solution Domain – Modularization



Mogno Modules DSM

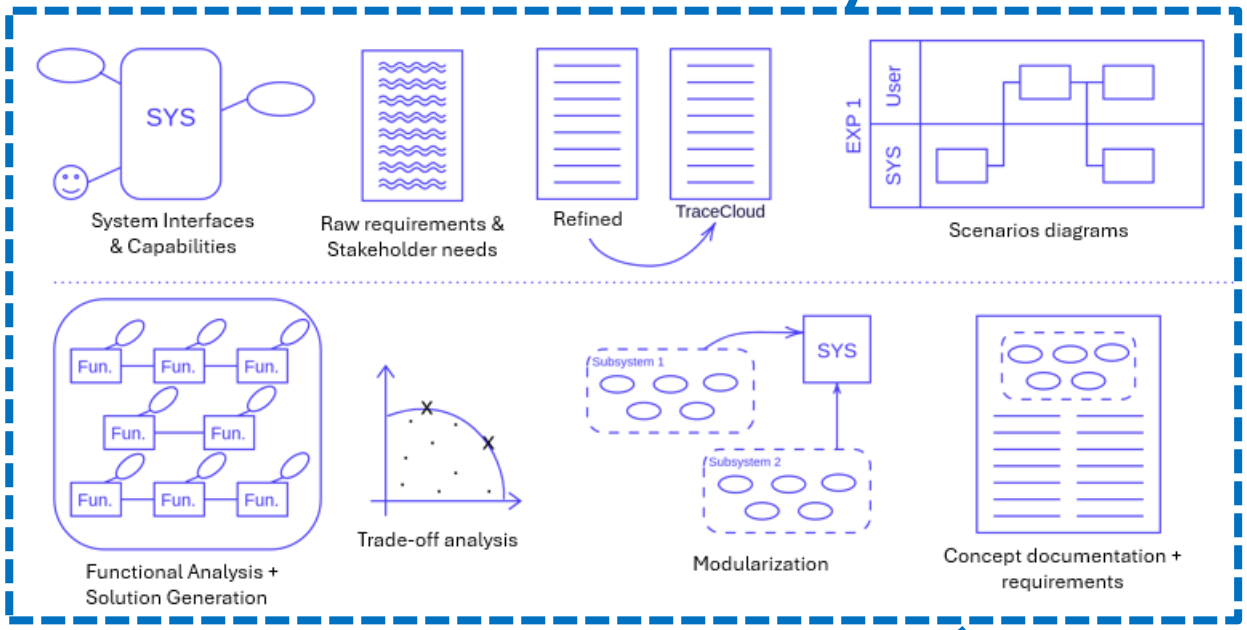
Grouping	Raw Items	Re-Sort Index	Column Items
G16	Forno de Acumuladores	1.0	Forno de Acumuladores
G16	Garrafas de Acumuladores	2.0	Garrafas de Acumuladores
G16	Painel de Valvulas	3.0	Painel de Valvulas
G16	Trocador de Calor	4.0	Trocador de Calor
G17	Auto Balanceador	5.0	Auto Balanceador
G17	Barco (I)	6.0	Barco (I)
G17	Estágio Ry (I)	7.0	Estágio Ry (I)
G17	Estágio XL (I)	8.0	Estágio XL (I)
G17	Estágio XZ (I)	9.0	Estágio XZ (I)
G17	Metrologia	10.0	Metrologia
G17	Núcleo Térmico (I)	11.0	Núcleo Térmico (I)
G17	Slip Ring (I)	12.0	Slip Ring (I)
G17	União Rotativa (I)	13.0	União Rotativa (I)
G20	Barco (S)	14.0	Barco (S)
G20	Estágio Ry (S)	15.0	Estágio Ry (S)
G20	Estágio Ry Auxiliar (S)	16.0	Estágio Ry Auxiliar (S)
G20	Estágio XL (S)	17.0	Estágio XL (S)
G20	Estágio XZ (S)	18.0	Estágio XZ (S)
G20	Estágio ZL (S)	19.0	Estágio ZL (S)
G20	Núcleo Térmico (S)	20.0	Núcleo Térmico (S)
G20	União Rotativa (S)	21.0	União Rotativa (S)
G29	Conjunto de Desacoplamento	22.0	Conjunto de Desacoplamento
G29	Core Holder EndPiece Superior	23.0	Core Holder EndPiece Superior
G29	Forno de pigtails	24.0	Forno de pigtails
G29	Core Holder EndPiece Inferior	25.0	Core Holder EndPiece Inferior
G29	Manifold de Sensores	26.0	Manifold de Sensores
G29	Core Holder	27.0	Core Holder
G32	Conjunto de Transporte do Core Holder	28.0	Conjunto de Transporte do Core Holder
G32	Carro do Core Holder	29.0	Carro do Core Holder
G32	Carro de Bombas	30.0	Carro de Bombas
G32	Carro de Limpeza	31.0	Carro de Limpeza
G32	Bancada de testes de Engenharia	32.0	Bancada de testes de Engenharia
G32	Carro de Acumuladores	33.0	Carro de Acumuladores
G36	Conjunto de troca Inferior	34.0	Conjunto de troca Inferior
G36	Conjunto de troca Superior	35.0	Conjunto de troca Superior
G36	Base de Transferencia	36.0	Base de Transferencia
G36	Plataforma de Transferencia	37.0	Plataforma de Transferencia

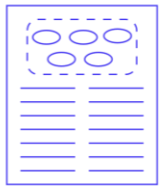
Identify Subsystems and their related requirements and functions. Minimize interfaces between subsystems. Aggregate similar functions and consider LNLS organizational structure and workgroups.

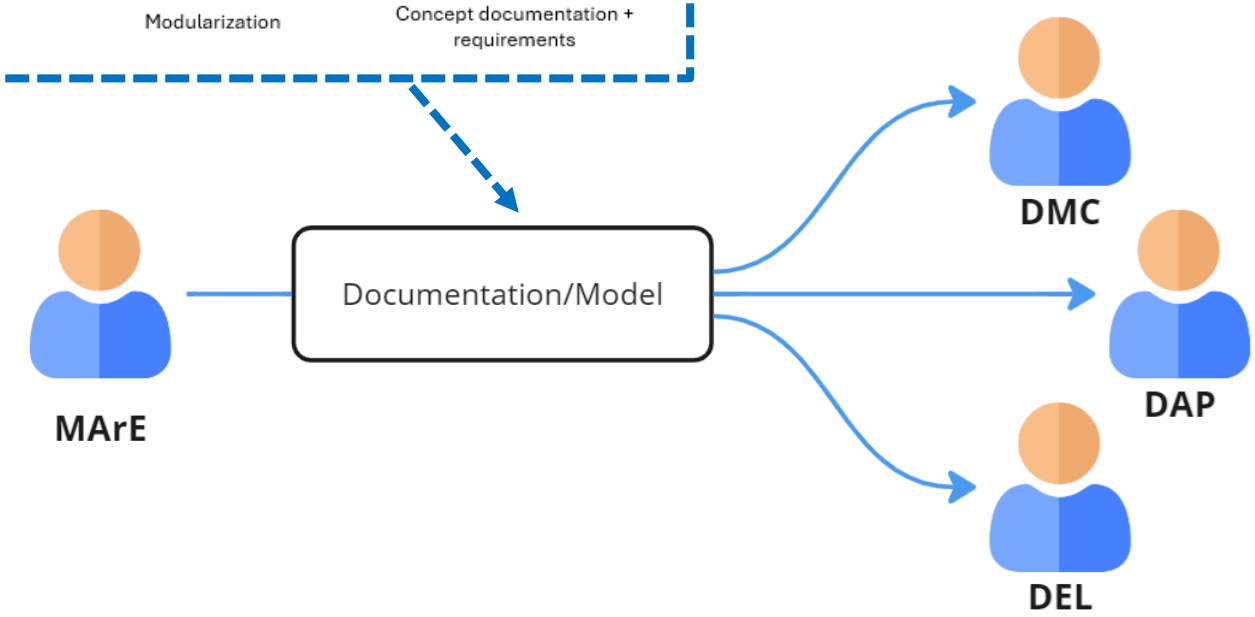
- DSM
- Interfaces
- LNLS teams

System Engineering Workflow

Solution Domain – Sub-system Consolidation







Create documentation and models from requirements, subsystems, and physical modules and share them with other teams (DEL and/or MArE).

- Model x Document
- Interfaces
- Solution Concept

Systems engineering software workflow

System Engineering Workflow

Solution Domain - Model Federation Integration

- Raw requirements compilation
- 1st rewording
- Understanding of rationales

Requirements.xlsx

tracecloud Global

- Requirements rewording and management
- Functional vs non-functional
- Requirement parameters target values

Requirements.csv

- Translation from .csv to .reqif

ReqIF Requirements Interchange Format

Major Requirements.reqif

- Functional analysis, Documentation
- Function and requirement connection
- Solutions alternatives
- Conceptual design

Capella

+

Py4Capella
PVMT
M2Doc
Req. Viewpoint
Ansys MC – Capella Connector

Design

Requirements & Solutions

MC

Info

RE

python

Ansys

MATLAB

- Physical Models connections
- Trade-off, sensitive and robustness
- Solutions results vs requirements

Info/Solutions.m2doc

- Documentation
- Groups interface
- Agreements

Excel

Spec Collection

BEFORE (and currently)

- Brainstorming meetings
- Alignment between different groups
- Cycles of checking and reviewing projects based on predictive modeling

Model to list and manage requirements for the TIMBO beamline, part of the ORION project.

ACRONYMS	
LNLS	Brazilian Synchrotron Light Laboratory
CNPEM	Brazilian Center for Research in Energy and Materials
DMB	Soft and Biological Matter Division
DAT	Deputy Direction of Technology
LNBio	Brazilian Biosciences National Laboratory
MS	Ministry of Health
MCTI	Ministry of Science, Technology and Innovation
TBC	To be confirmed
TBD	To be defined
TBS	To be specified

GLOSSARY
ID
Requiremement
Rationale
Status
Stakeholder
Responsability
Derived from
Type
Stakeholder Need
Stakeholder Constraint
System Reuireement
System Constraint
Verification
Test
Analysis

AFTER (implementation objectives)

- Documentation of Design Rationales (Requirement Tracking)
- Impact analysis for design changes or sub-components
- Repurposing common requirements in similar projects

Class	ID	Requirement	Derived From	Owner	Technical Refining	Rationale	Type	Verification	Neccesary	Appropriate	Unambiguous	Complete	Singular	Feasible	Verifiable	Correct	Conforming
Global	8.6	The sample holders have to be compatible with the setups of other imaging beamlines	8			It is within the LNLS future plans to have unified user access to the infrastructure without beamline restriction. With this, different sizes and shapes of sample holders need to be compatible to more than one experimental station.	SH Constraint		TBC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Global	8.8.1	The Microstation shall be capable to host both in vivo and in vitro tomography	8.8				SH Need		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
LabCon	8.12.1	The inside of the core holder needs to be heated consistently and kept at up to 90 °C during experiments	8.12			Transient temperatures can lead to changes on the rock sample microstructure, inviabilizing zoom and steady state analysis.	Sys Requirement		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
LabCon	8.13	The starting fluid setup has to endure injecting samples with dead oil and brine up to 1000 bar	8			This is the parameters defined together with Petrobras for Semi Reservaroty Condition experiments	Sys Requirement		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dry CT	8.15	Has to be capable of processing up to 500 dry samples per proposal	8				SH Constraint		TBC	TBC	TBC	No	Yes	TBC	Yes	Yes	No
Dry CT	8.16.1	The high throughput mode have to be able to perform 1 CT per second	8.16		If the CT time contains the acceleration and deceleration time, we'll need to increase this time		Sys Requirement		Yes	Yes	Yes	Yes	Yes	TBC	Yes	Yes	No
LabCon	8.18	Accept wet samples with up to 1" diameter inside the appropriate core holder	8			For the space we have available, it was decided to limit the sample size and prioritize the advantages of a	Sys Constraint		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Spreadsheets for requirements and restrictions management (MArE group)

Tracecloud

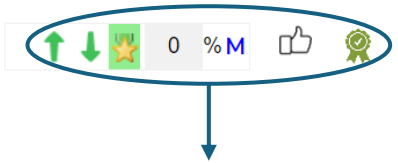
Requirements Management

Organize what we need the system to deliver

.csv

tracecloud Global

- Dependency view
- Reporting
- Version control
- Permissions control



Overall status

Identification and classification

STK-10: The mobile instrumentation cart shall be interchangeable between the experimental systems of support laboratories and beamlines.

To assert the experimental setup can be processed on and off the beamline, without disturbing the sample, so we don't onerate beamtime

debora.jesus@lnls.br

Owner and interested

Examples of the Mogno Microstation project

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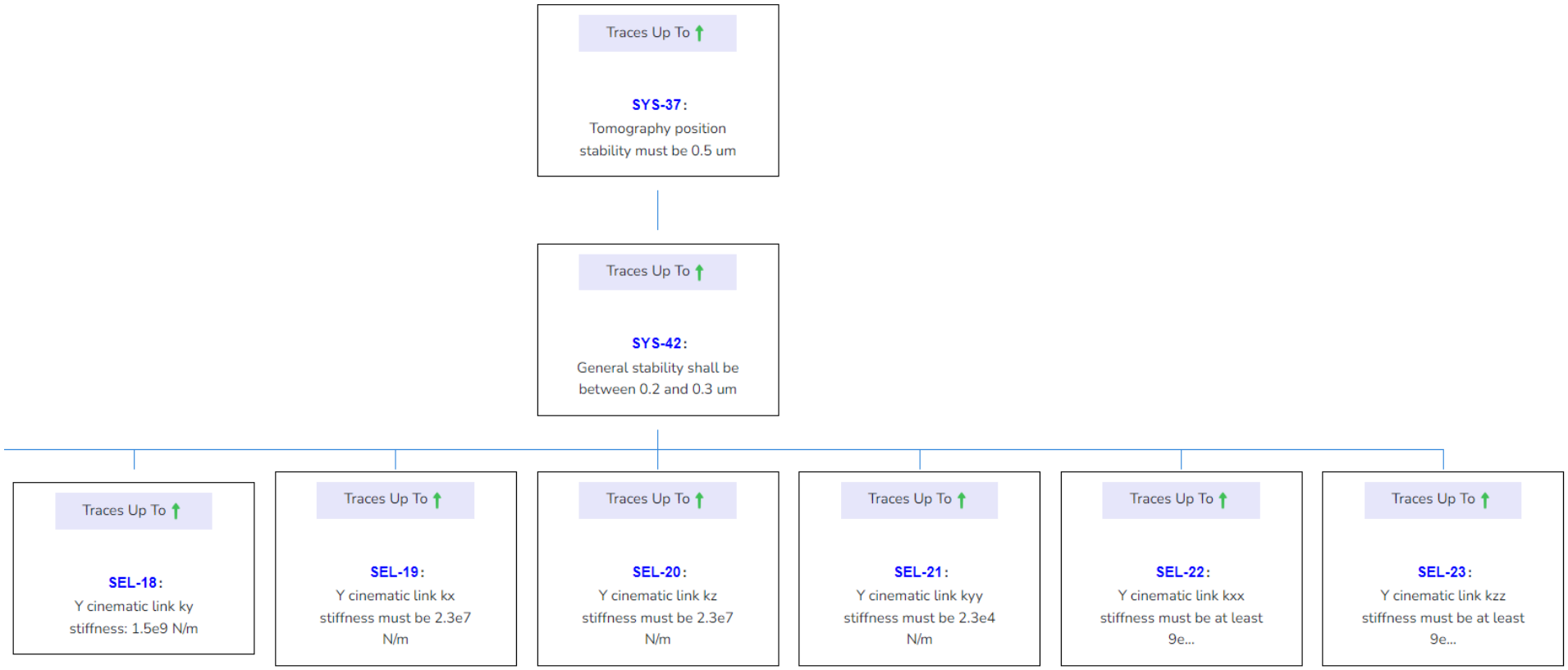
Requirements Management

Organize what we need the system to deliver



tracecloud Global → ReqIF Requirements Interchange Format

Visualization of dependencies between requirements

- Notion of the impacts of changes
- Understanding "bottleneck" parameters

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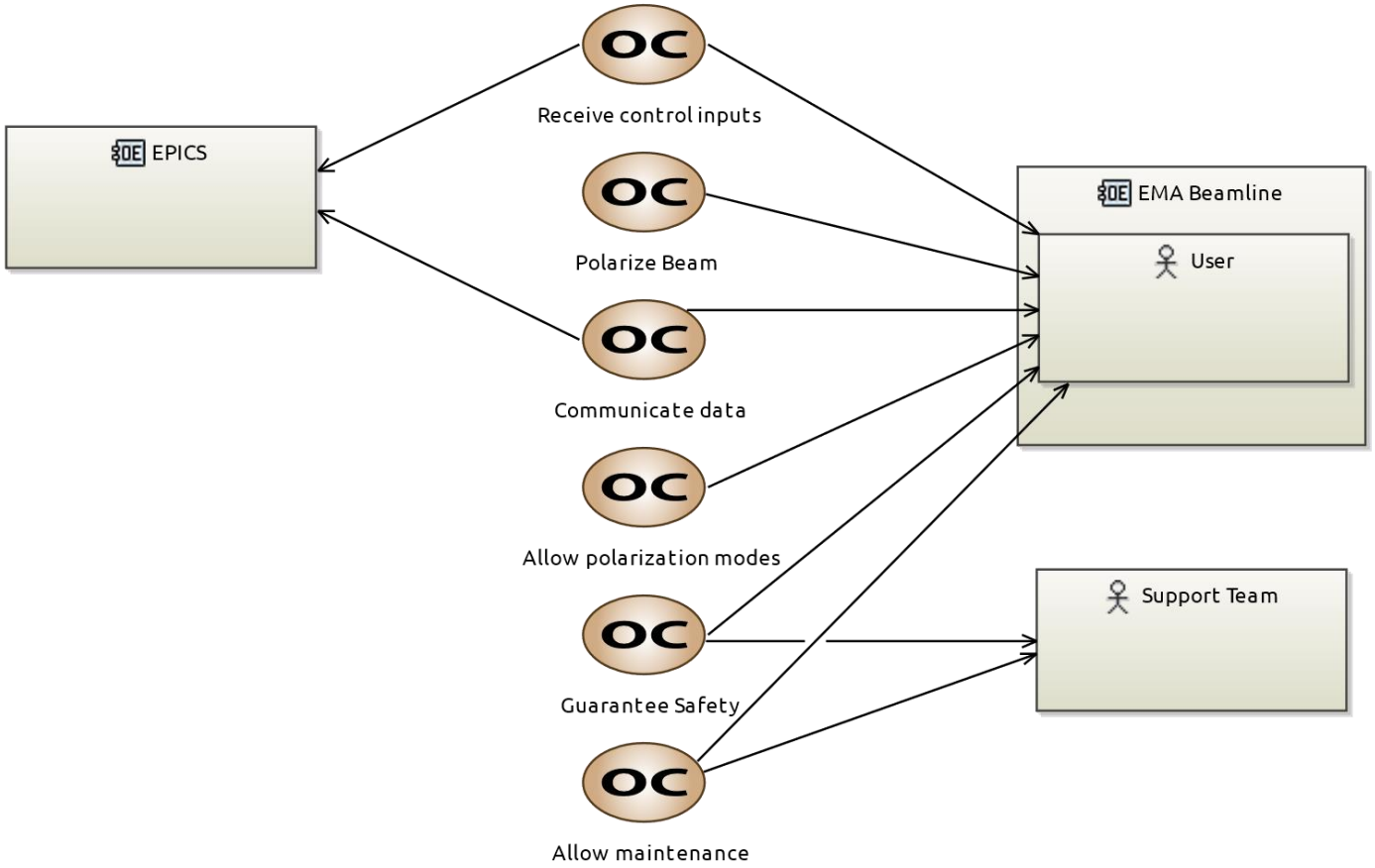
Capella

Capella and Systems Architecture

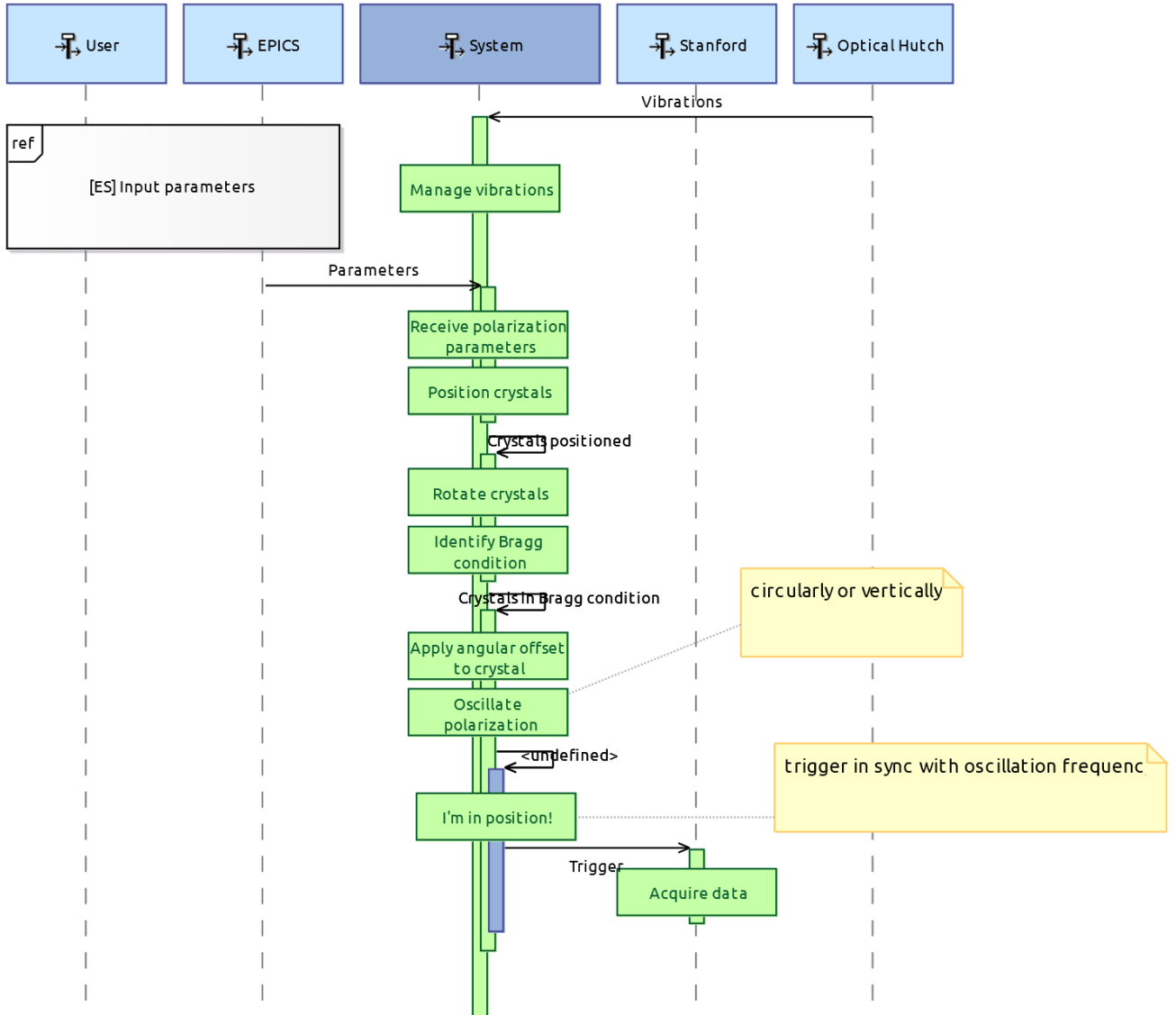
Operational Capabilities



Description of operational capabilities for identifying interfaces between the system's capabilities and the main external agents that will use it.

Capella and Systems Architecture

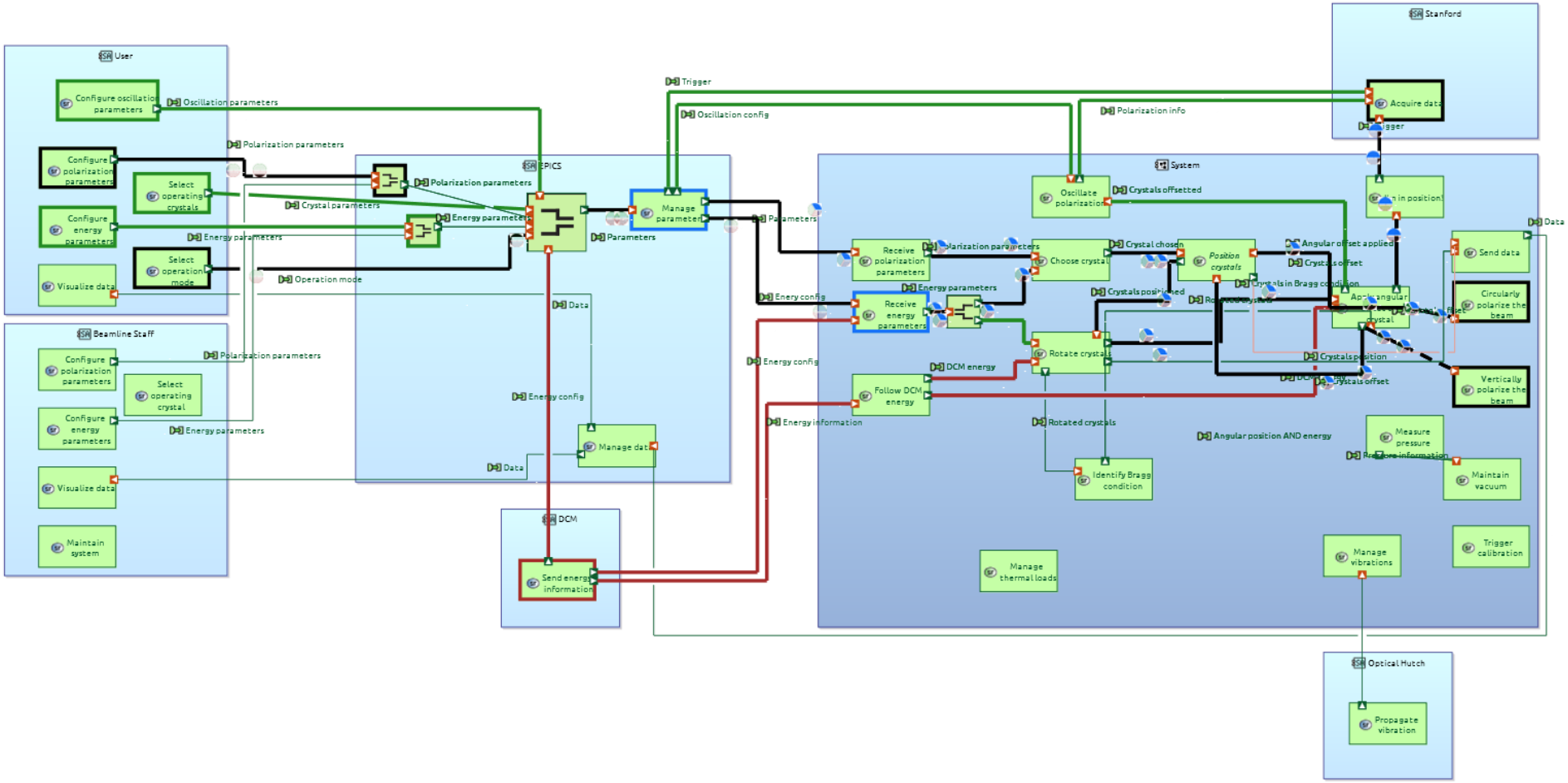
Scenarios



Definition of the timeline for the application of the system's functionalities.

Capella and Systems Architecture

Function Architecture and Functional Chains

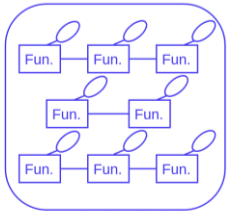


Specification of the functions of the system in question and the external actors with which it interacts. Definition of information exchanges.

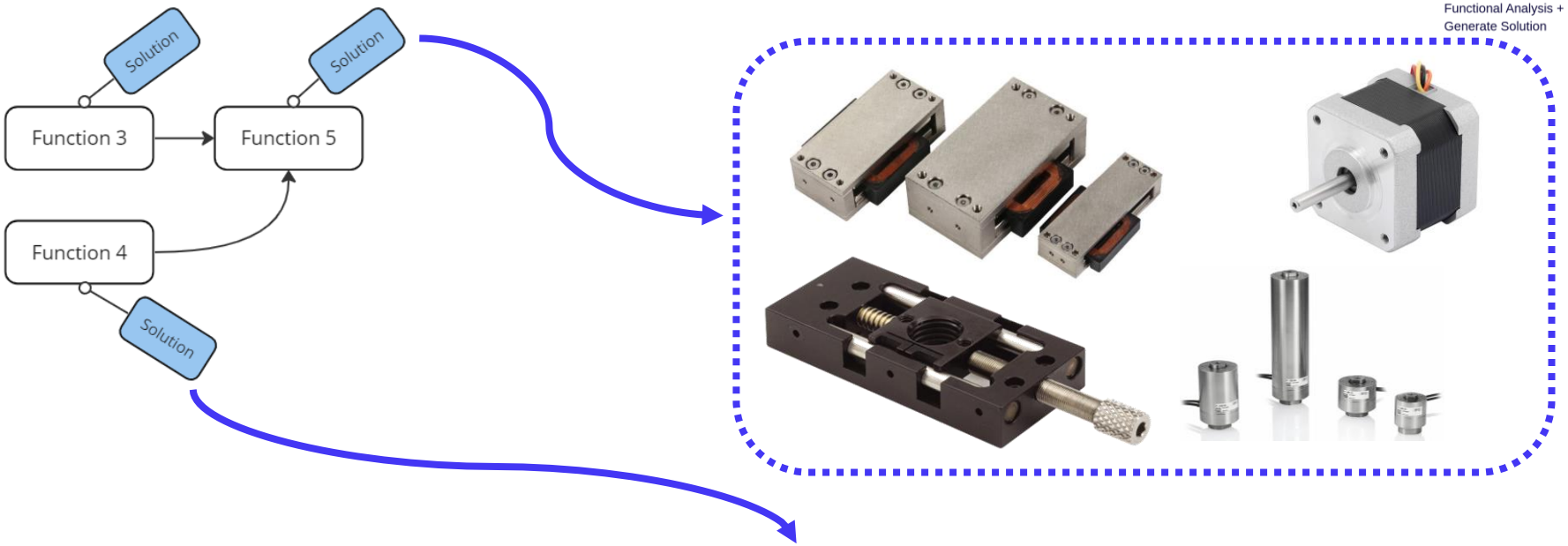
Exchange of information, energy and mass.

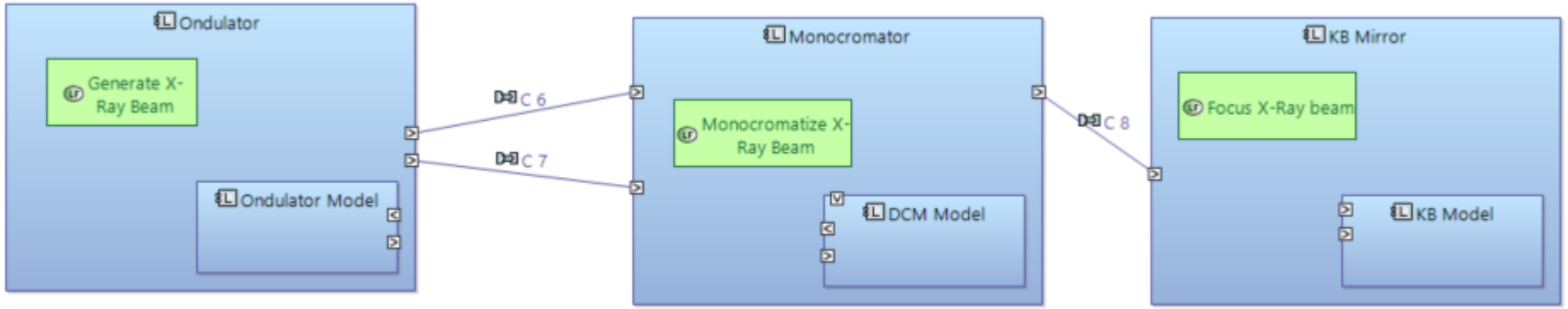
System Engineering Workflow

Solution Domain – Solution Proposal



Functional Analysis + Generate Solution



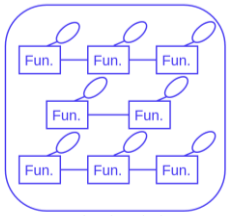


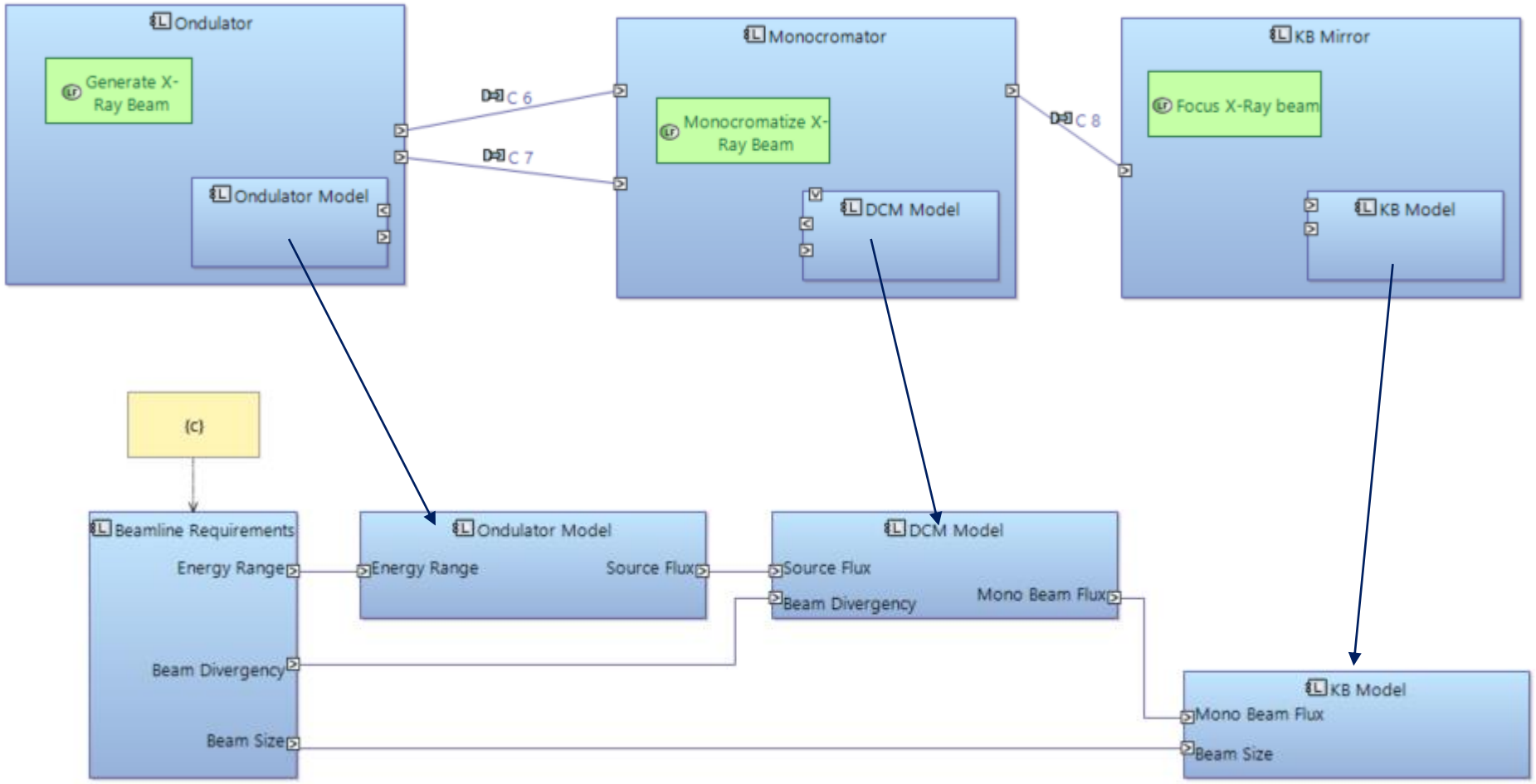
Identify solutions for system functions. Propose different solutions to explore interfaces between components. Define possible spin-offs of subsystems for internal R&D. Model integrated solutions.

- Creativity
- Risk Management
- Experience

System Engineering Workflow

Solution Domain – Solution Modeling

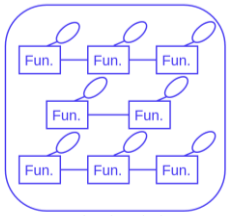


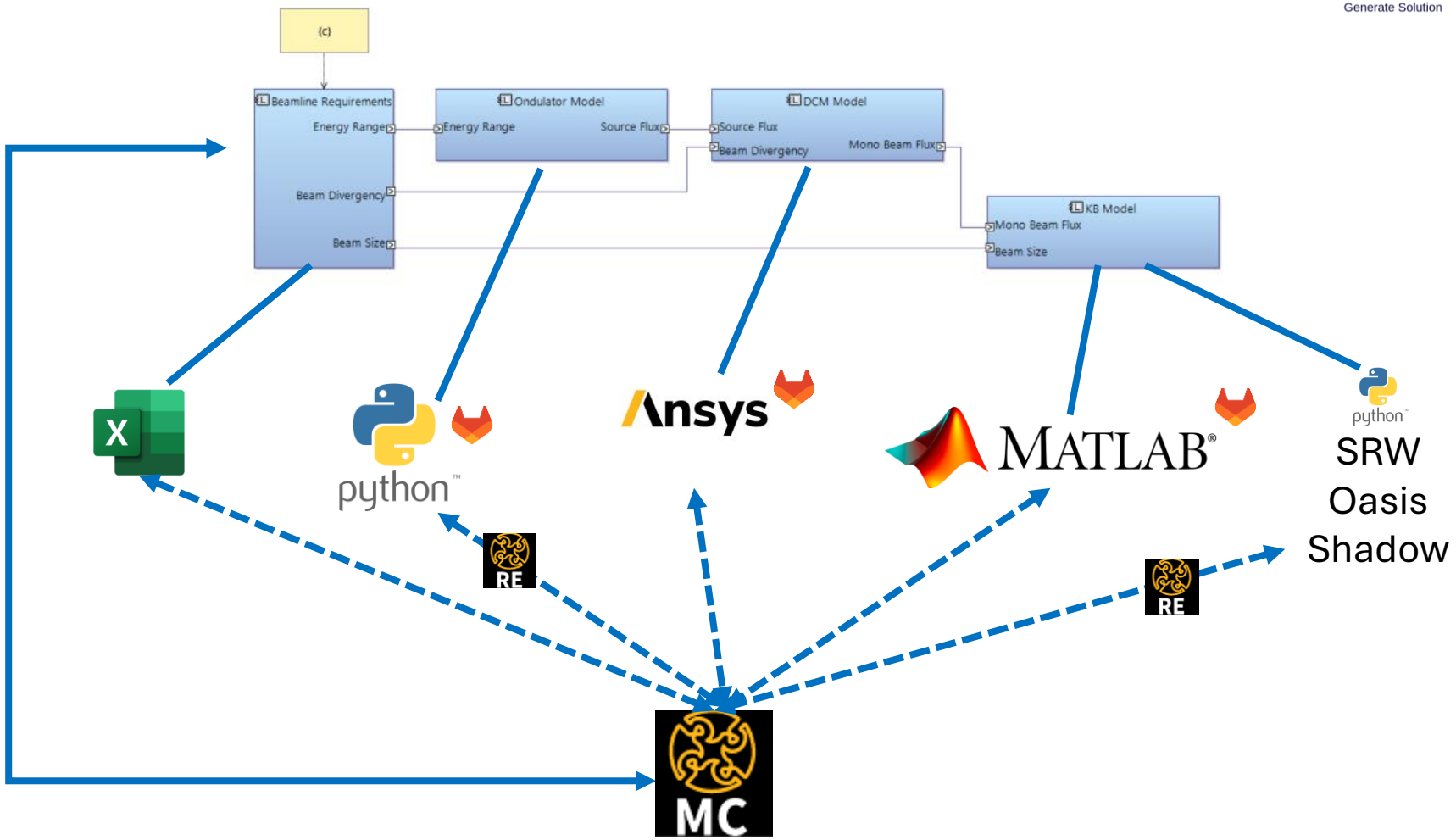


Identify solutions for system functions. Propose different solutions to explore interfaces between components. Define possible spin-offs of subsystems for internal R&D. Model integrated solutions.

System Engineering Workflow

Solution Domain - Model Federation Scheme

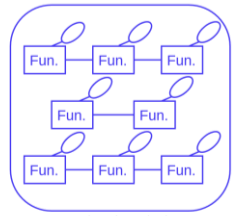




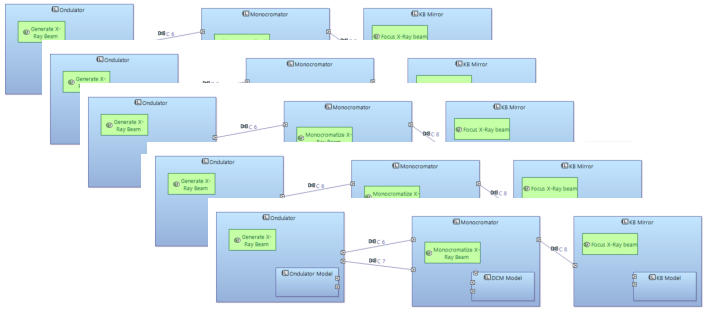
Trigger code by Capella and save the results to a common file (.yaml). Capella can access this file using python4Capella and allocate parameter in the model (good for automatic reporting). In addition, Capella can trigger optimizations in model federation through ModelCenter

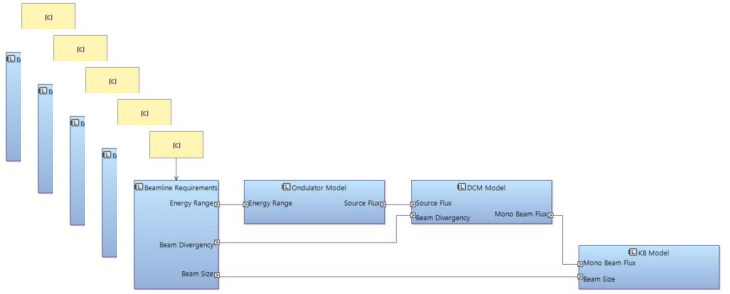
System Engineering Workflow

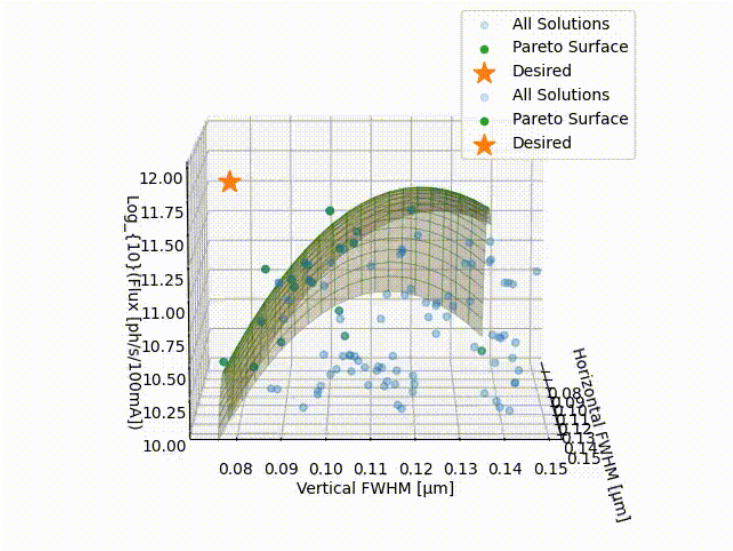
Solution Domain – Solution Trade-off



Functional Analysis + Generate Solution







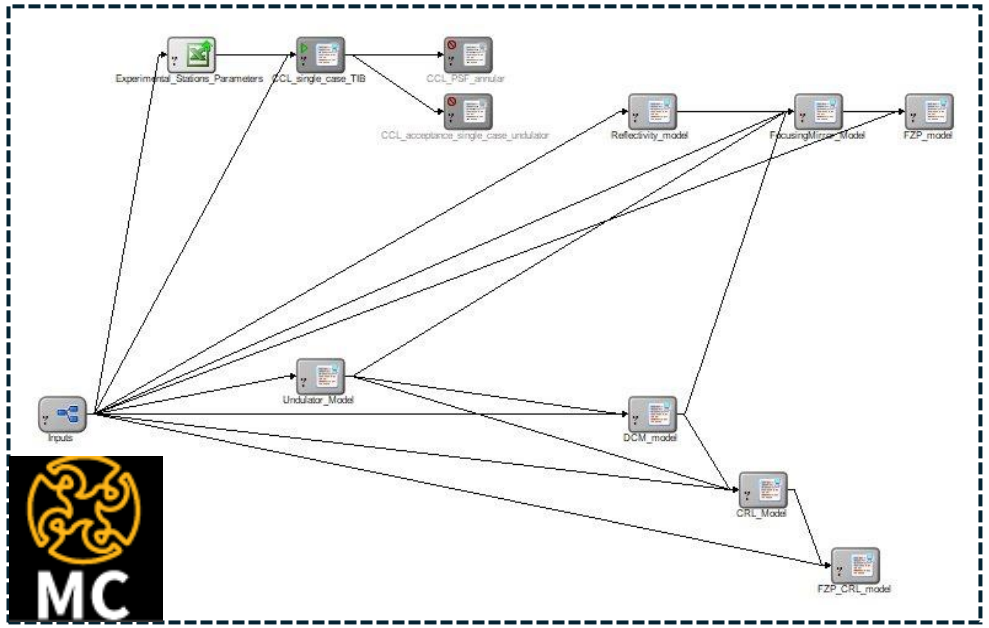
Identify solutions for system functions. Propose different solutions to explore interfaces between components. Define possible spin-offs of subsystems for internal R&D. Model integrated solutions.

ANSYS Model Center

ANSYS Model Center

ORION Models and Capella integration

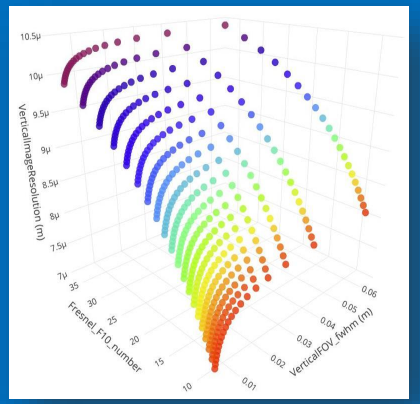
Capella



Capella

- Creativity outputs
- Comparative study of models
- Trade offs
- Optimizations
- Optimal design
- Definitive project parameters

How to select the best arrangement to satisfy the requirements of the beamline experiment?
With Model Center, it is possible to simulate, based on the same input parameters, different models and/or scenarios and study their respective outputs.



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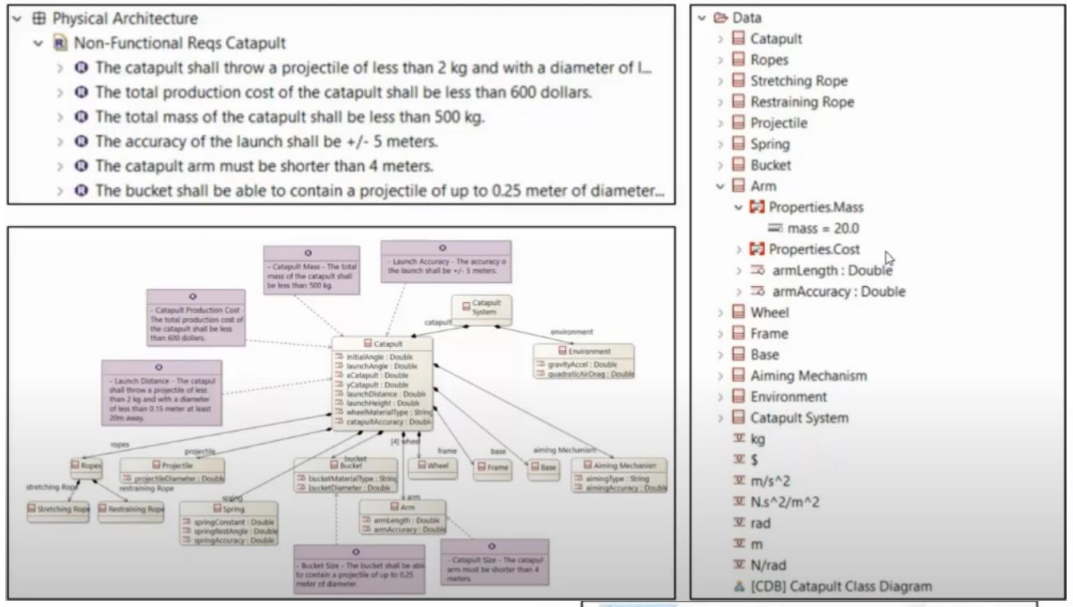
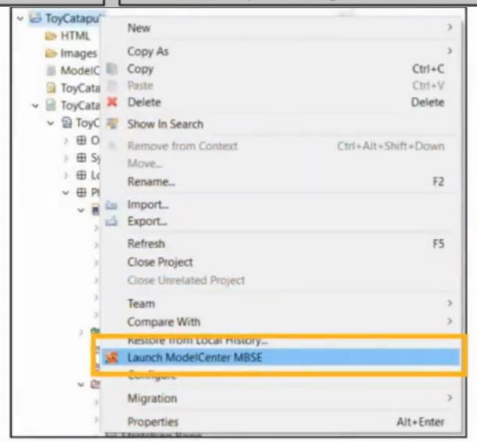
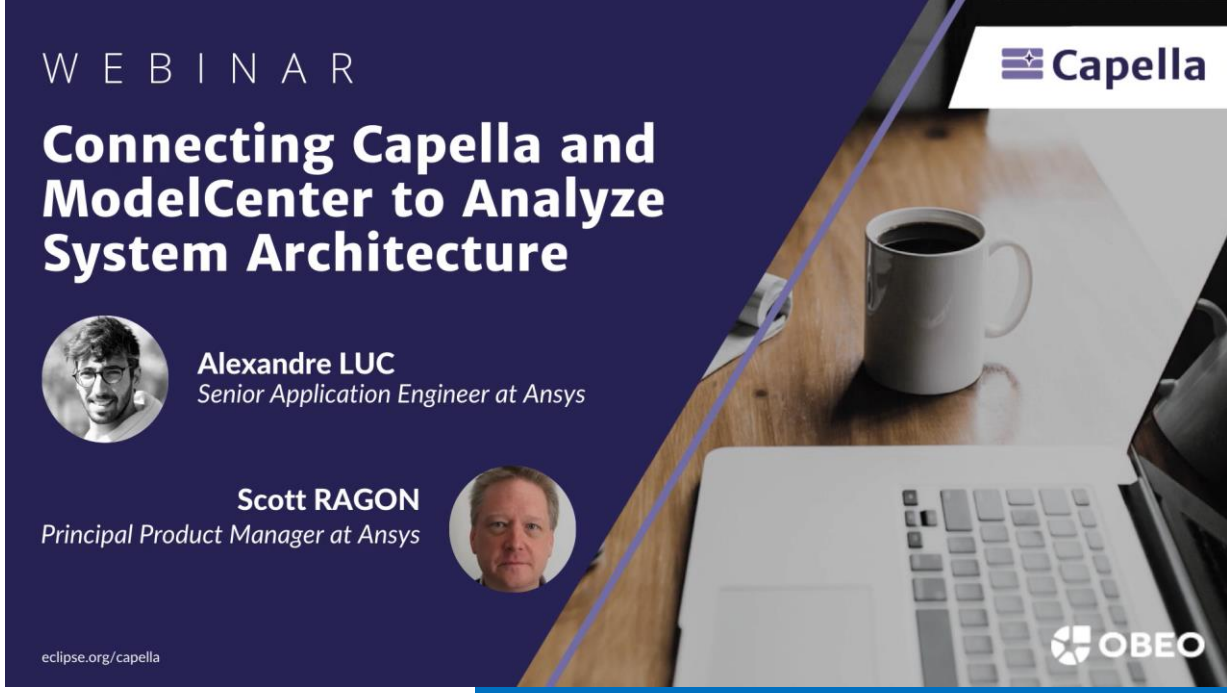
Ansys Model Center

Capella integration





Launch ModelCenter MBSE



Our application is based on the “Connecting Capella and ModelCenter To analyse System Architecture” Capella Webinar, available on Obeo’s website and on Youtube at the Eclipse Capella channel.

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BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

Last, but not least...

Conclusions

- While trying to develop a tailored system engineering application, we value most finding the right tool for each job than developing a tool for each job.
- Capella's wide range of third part integration has been crucial to developing an as seamless as possible multi-software flow.

Thank you!

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...any questions?

LNLS Laboratório Nacional de Luz Síncrotron

CNPEM Centro Nacional de Pesquisa em Energia e Materiais

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