Life-cycle and operability of Particle Accelerators - Part 2/2

JUAS 2025

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Why is difficult to have steady operations on particle accelerators ?

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- Power- Energy & Motion

  Electricity, cooling, regular motion systems

-Critical and/or sensitive Technologies

  Radio-Frequency, vacuum, electronics, cryogenics, software, …

- Risks

  radiation-protection, …, costs, …

-Complexity

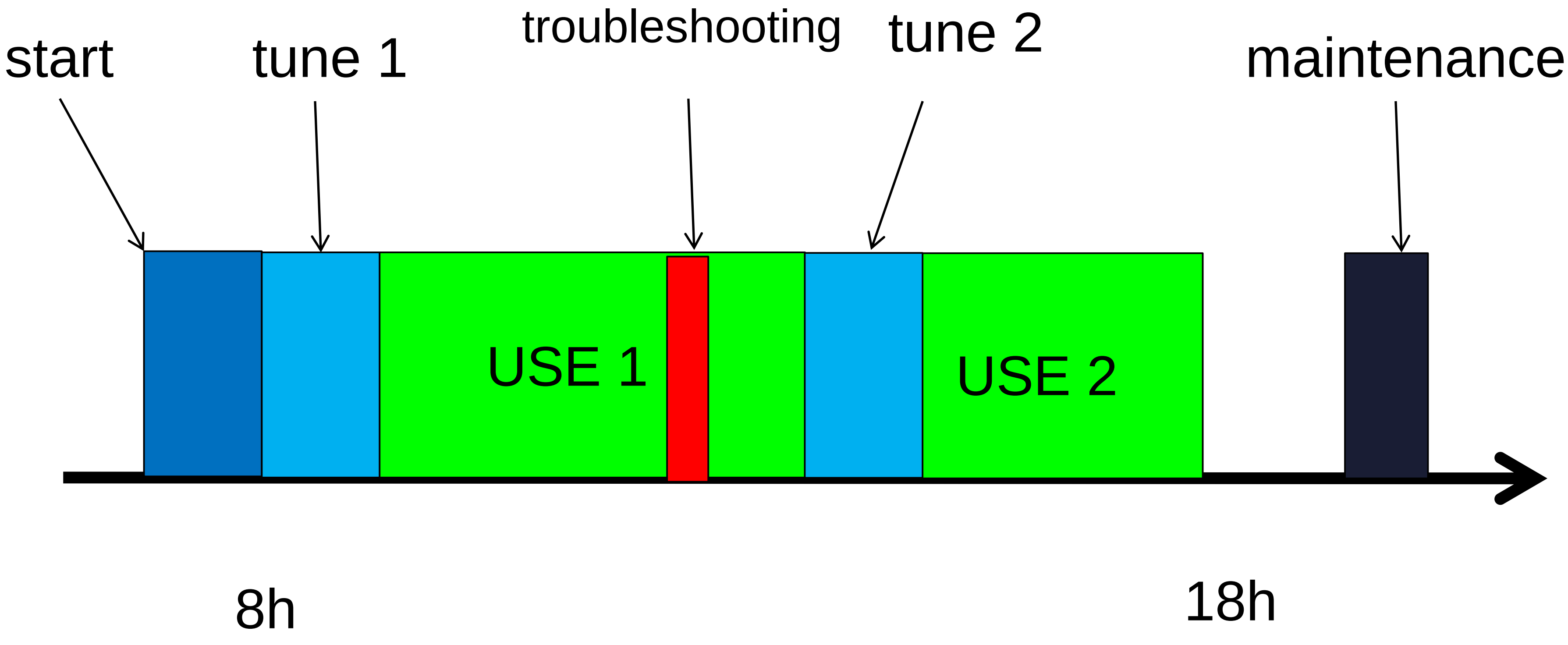
  mix of technologies, %research%production, regulations

- Using &Users (Customers / Providers)

  beams: current, energies, duration, …

It’s a challenge to have smooth operations

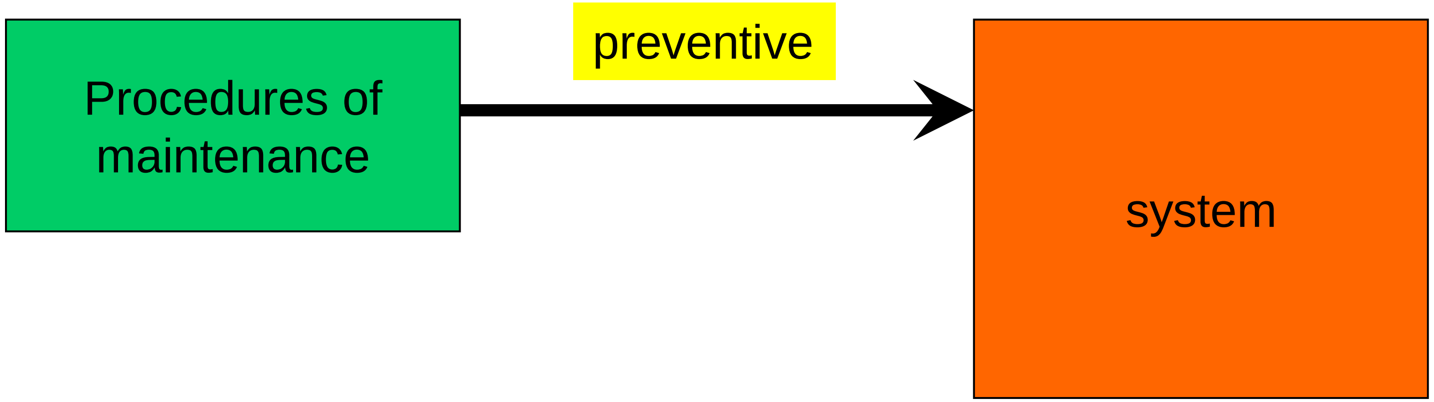
for (large) Particle Accelerators !



start
tune 1
troubleshooting
tune 2
maintenance
USE 1
USE 2
8h
18h

Maintenances

Modelisation, experience



Inspect, clean, check, lubrify, calibrate, read, replace, test ,…

Example of preventive maintenance procedures (cyclotron C230-IBA)

ACC8650589	Checking the C230s RF Parameters
ACC9413705	Servicing the RF Coupler
ACC4313750	Check the calibration and service the yoke temperature Probe
CC11713905	Lubricating the radial probe
CC12252964	Inspecting the external cooling piping and connections
ACC8713698	Servicing the Central Region
ACC9113696	Checking the tightness of the cyclotron screws
ACC9249418	Check the MC blocks clamp and pancake tightening
ACC9349415	Servicing the harmonic Coils
ACC9552399	Service the cavity tuning motor - coupling check
ACC9613704	Adjusting the fine tuning capacitor
ACC9713735	Inspecting the cyclotron piping
ACC9813703	Serviving the radial proble vacuum seals RF gaskets and contract brackets
CC10013751	Servcing the Yoke Temperature Probe
CC10352391	Check the deflector movement position
CC10452394	Check the deflector enterance and exit gaps
CC10550251	check the gradient corrector gaps
CC10952766	Vacuum clean the cyclo
CC11350587	Using Aluminum foil make sure all contacts are touching
CC11652779	Checking/Replacing the mobile and fixed capacitors
CC12152966	Inspecting RF Contacts
CC10752390	When the HV cable is shorted on the PS side check if the resistance between HV electrode and septum is 200k?±10%.
CC10652388	Visualy inspect the HV cable on both sides
CC11113697	Replacing the Cyclotron Median Plane RF gasket
ACC1201745	Yoke Lifting UT
CC12551979	Measuring the Upper Main Coil Clamps' Deflection
ACC1950581	Check MC Interlocks
ACC2049425	Check the deflector interlocks
_4330JF6S7	RF / startup
ACC7342125	PBS Test after BPS Intervention

Maintenances

Modelisation, experience

Procedures of maintenance

preventive

corrective

system

- Awareness of problem(s)
- Diagnosis
- Fix-replace
- test

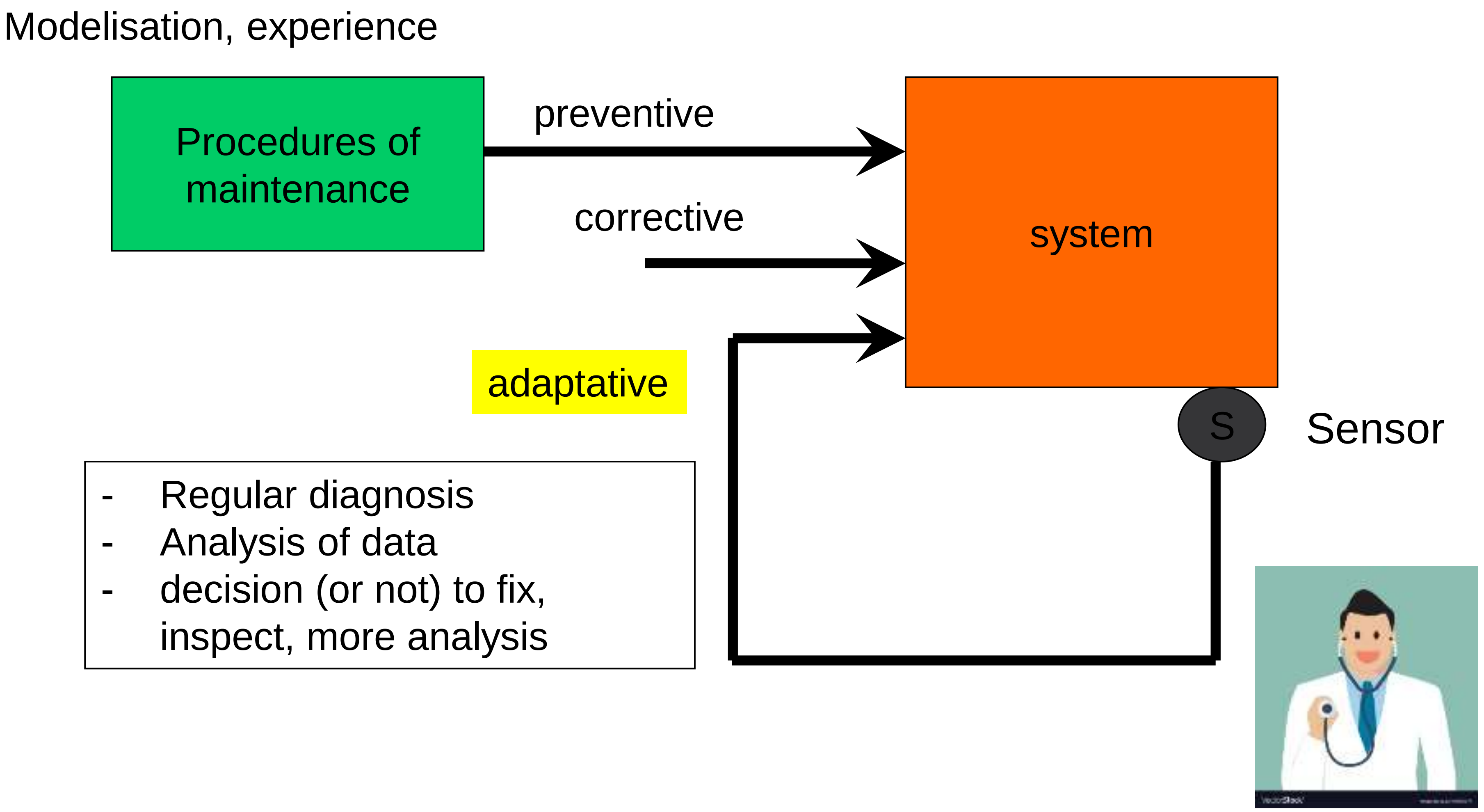
Event @CPO - Cyclotron C230

Ion Source pollution
+ RF event
+ deflector pollution
+ RF tube + PS RF …

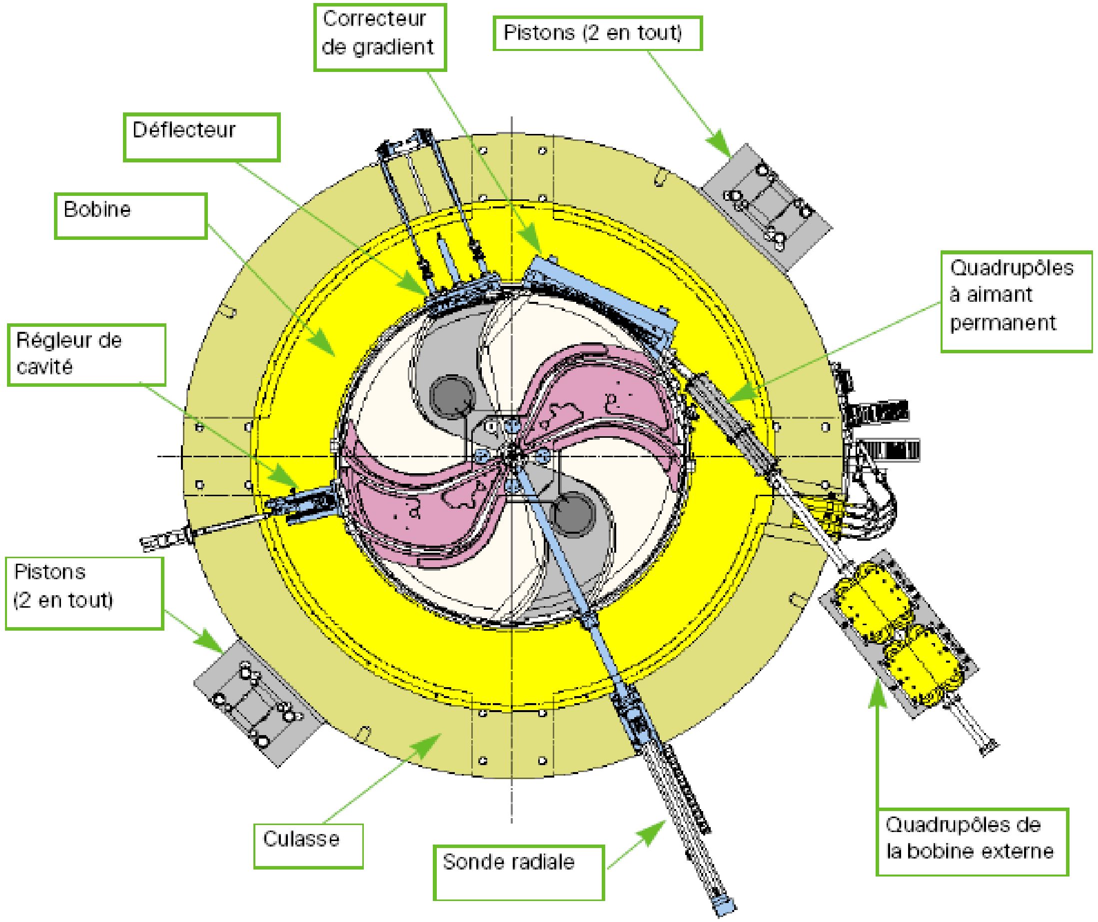
5 days OFF

→ **small RF event**
+ mix of <u>simultaneous</u>
inappropriated conditioning
(Ion Source ,RF, Deflector)

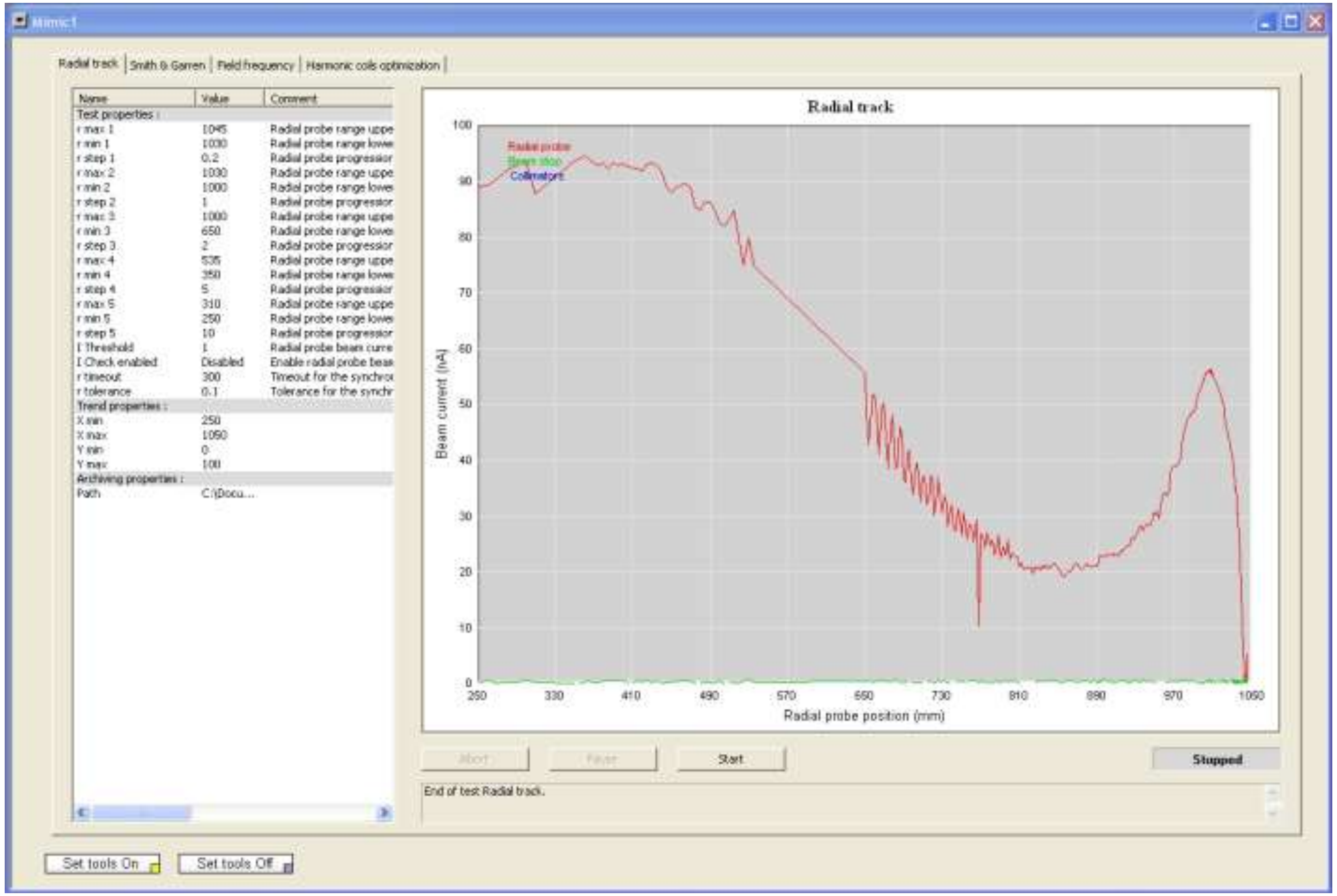
Maintenances



Diagnostic of beam inside cyclotron: the radial probe

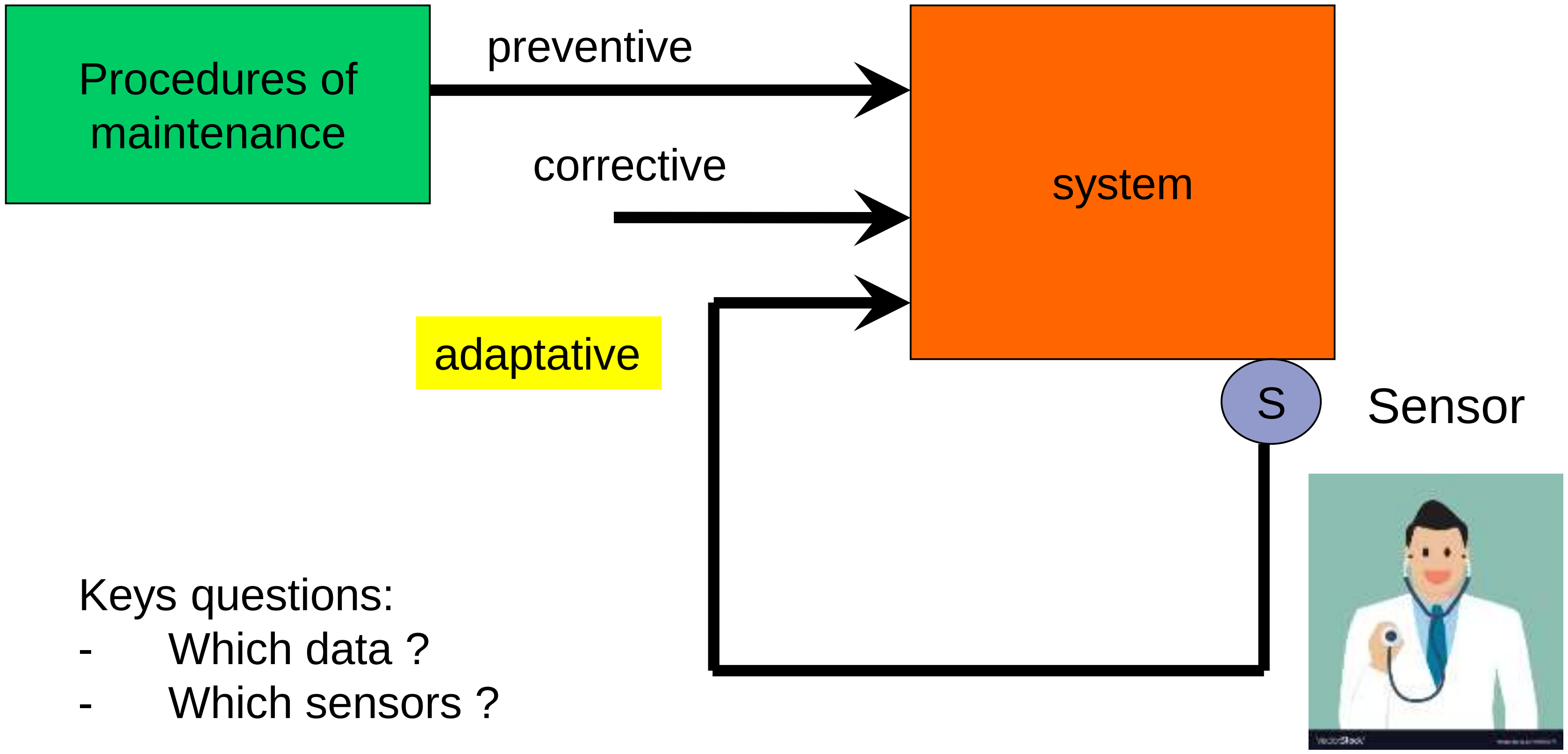


Example of result of radial track (C230IBA@CPO)



Maintenances

Modelisation, experience



Keys questions:
- Which data ?
- Which sensors ?

Thermography inspection C230 @ CPO

Cyclotron thermographie du 13 octobre 2011

Mesures	°C
Sp1	70°C

Paramètres

Emissivité	0.95
Temp. réfl.	20 °C

connexions inter bobines 3 et 4 bobines inferieures. Point chaud max 70°C en sp1 A surveiller

13/10/2011 06:32:34

IR_0069.jpg

13/10/2011 06:32:34

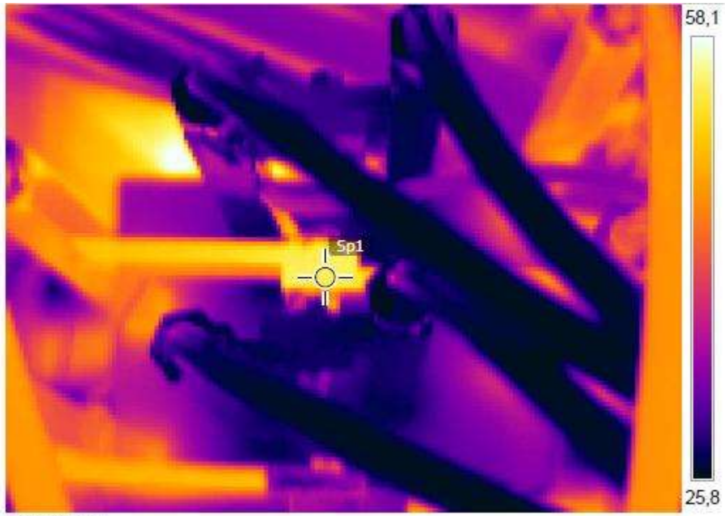
DC_0070.jpg

Sp1	54°C

Paramètres

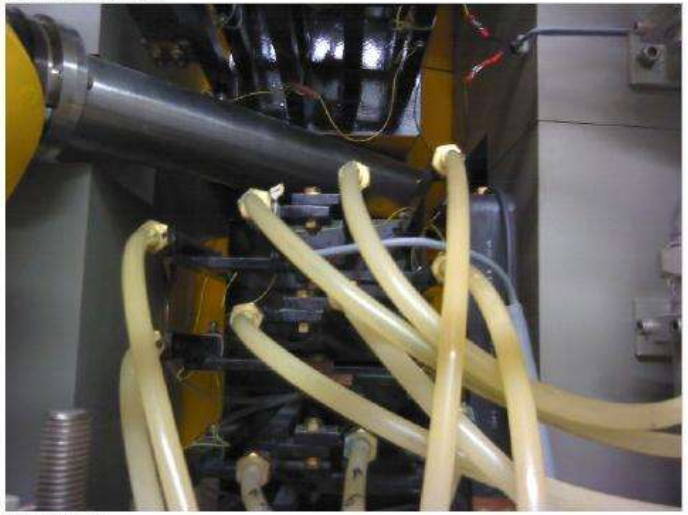
Emissivité	0.95
Temp. réfl.	20 °C

Bobines inferieurs 3 et 4



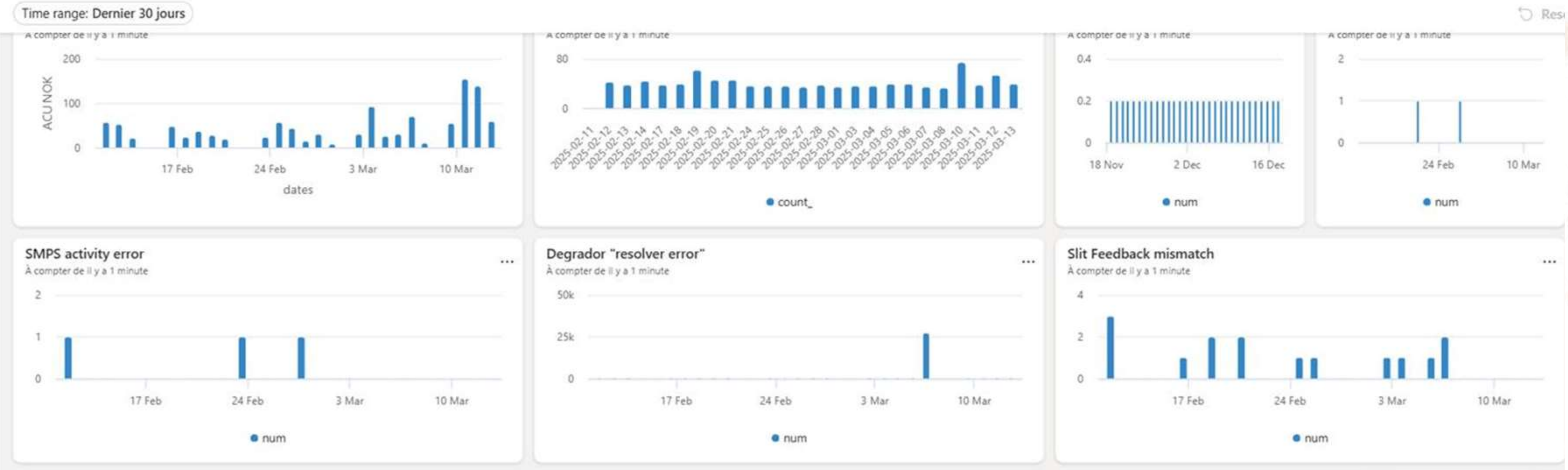
IR_0219.jpg

08/11/2011 07:15:17

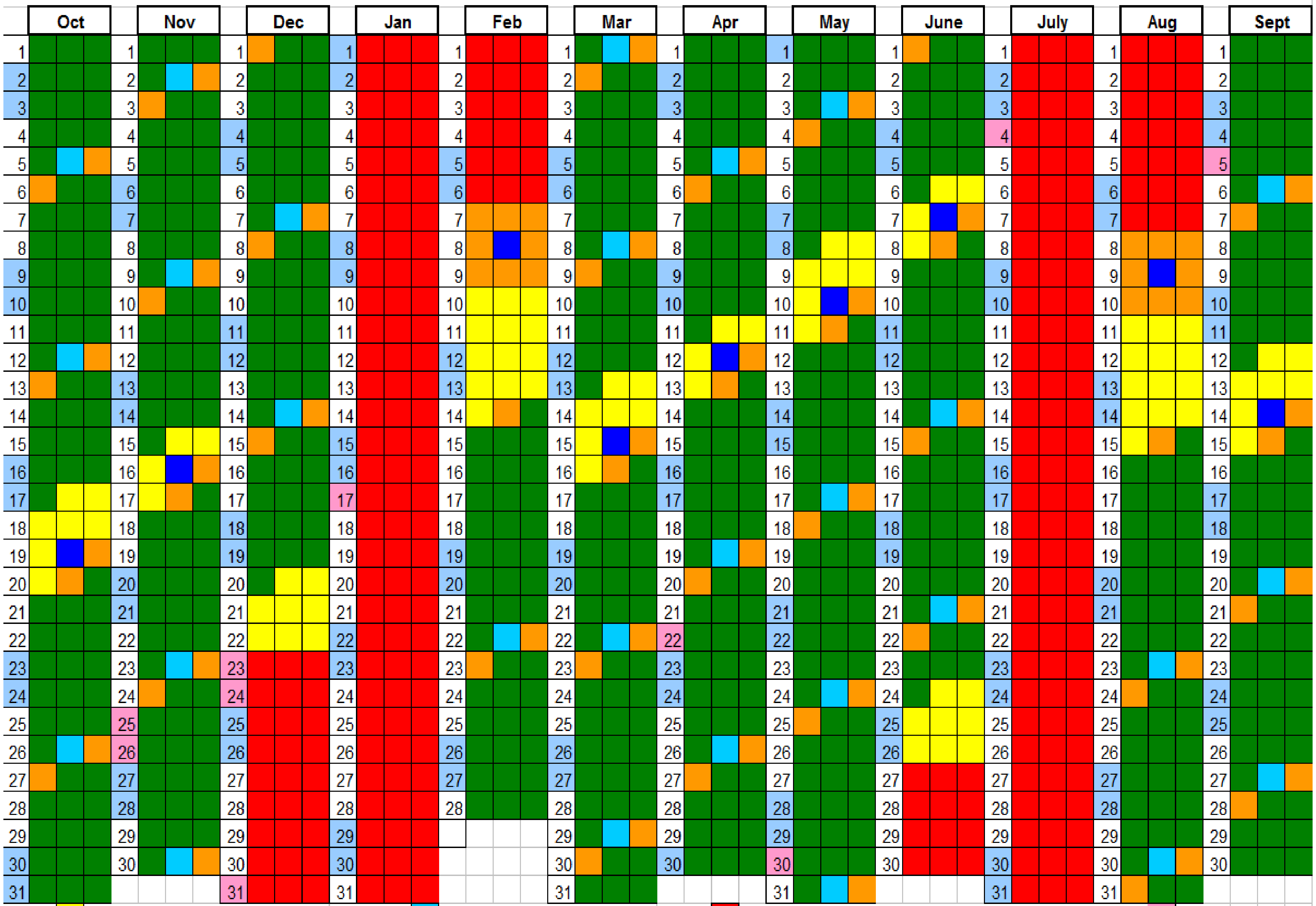


DC_0220.jpg

Example of weekly indicators followed-up



Run Schedule for FY 2011



Accelerator Physics
Accelerator Startup/Restore
Optional Maintenance Periods
Neutron Production
Machine Downtime Major Periods(Maintenance/Upgrades)
Scheduled Maintenance
Holiday

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The « operations » for an accelerator

-All the process to be managed in order to deliver the required beam (and associated services) during the planned period

This includes:

- Startup of the system, Tuning of the beam
- check of the normal behaviour of the systems during the use
- monitor and record parameters (automatic or manual, log-books, …)
- fix any unplanned event (troubleshooting, corrective actions level 1,2,…)

- planning of the activities (discussion with users): day, month, year
- managing the documentation (procedures, drawings, …)
- training of operators level 1, 2, …

- in direct relation with maintenance and project issues

POLL # 2

Reliability

Definition of reliability

1st basic approach

$$\text{Reliability} = \frac{\text{Time the systems works} - \text{Time of breakdowns}}{\text{Time the system works}}$$

Definitions of reliability

The reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time

The reliability (R(t)) is the probability to have no failure at the time t.

MTBF: Mean Time Between Failures

MTTR: Mean Time To Repair

The availibility of the system is the ratio of the time when the system is operational by the time it was supposed to be operational

Availibility* = MTBF / (MTBF+ MTTR)

* (definition of this lecture)

exercise

An accelerator is used from 10:00 to 20:00

During this period, there were:

- **8 small failures of ion sources lasting 5 min for each**
- **2 times (15h and 19h) a failure of a magnet power supply, requiring 30 min to retune the beam**

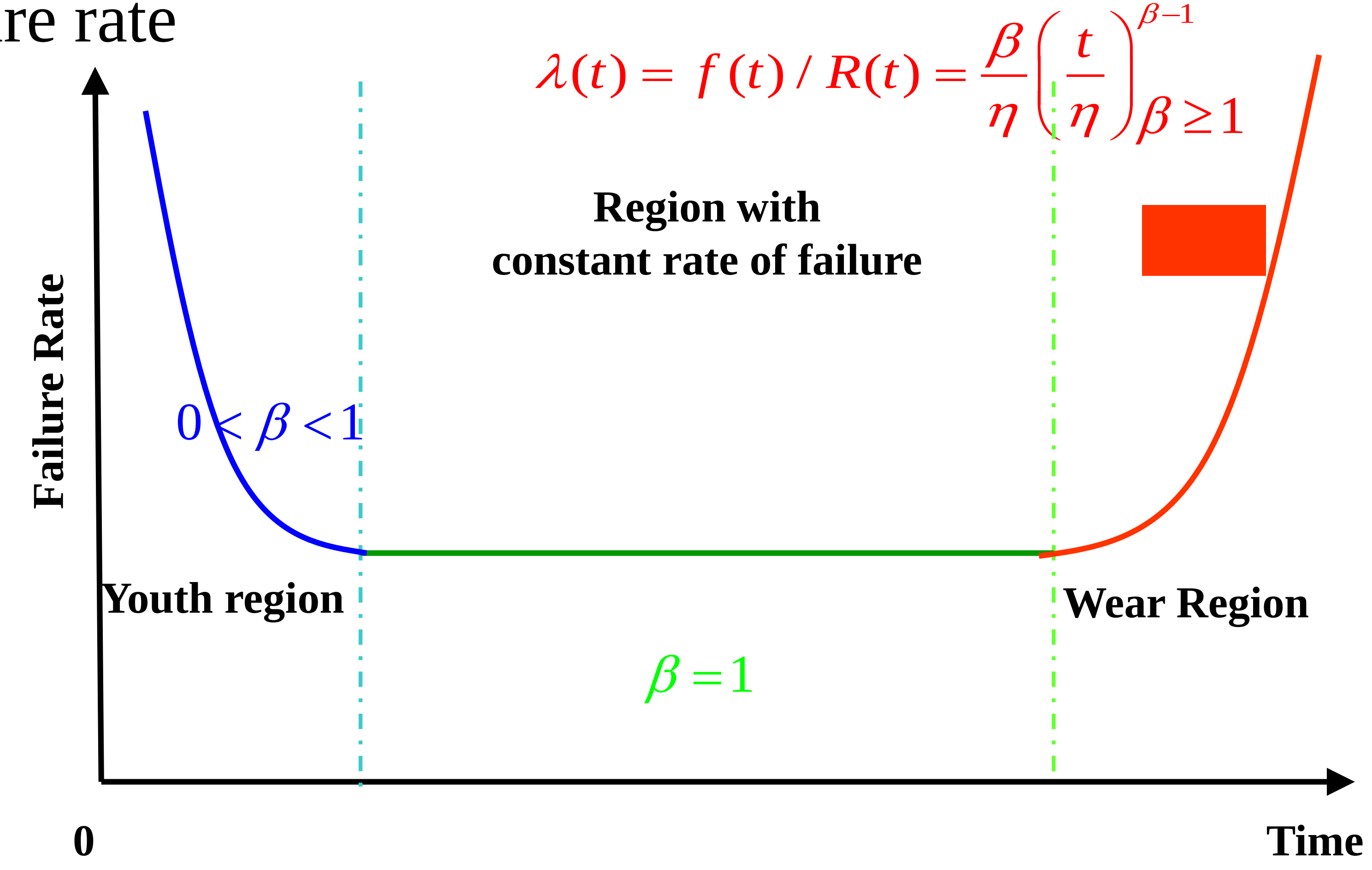
1. What is the global MTBF ?

2. What is the global MTTR ?

3. What is the problem to solve first to do the best « physics » ?

The reliability Weibull Model (bath curve)

Failure rate



Series Components – Part Count

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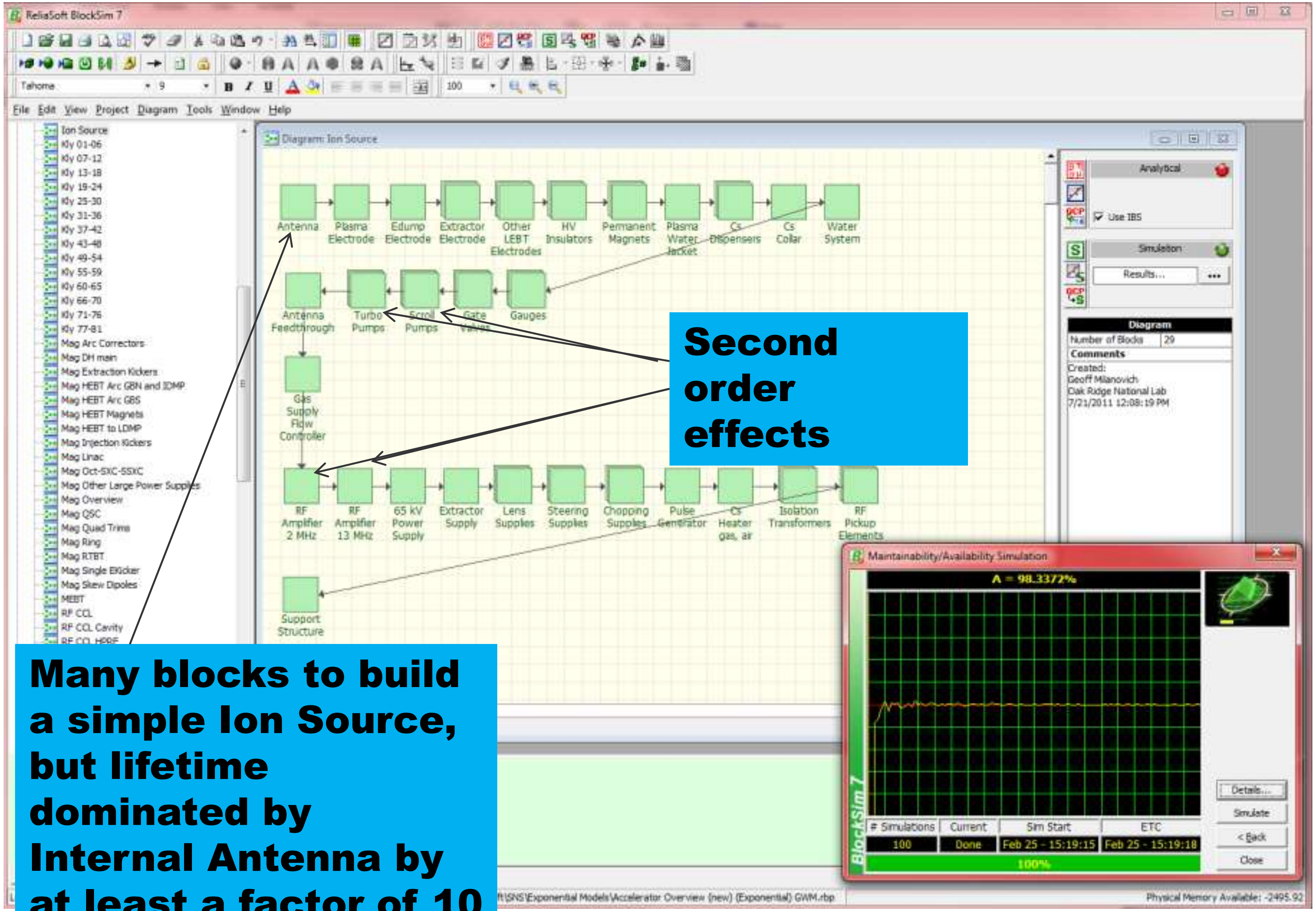
An integrated circuit board consists of the following components each having a CFR.

Component	a-Failure Rate(10^{-5})	b- Quantity	(a) x (b)
Diodes, silicon	.00041	10	.0041
Resistors	.014	25	.3500
Capacitors	.0015	12	.0180
Transformer	.0020	2	.0040
Relays	.0065	6	.0390
Inductive devices	.0004	12	.0048
		total	.4199 x 10^{-5}

$$R_{system}(t) = e^{-\sum_{i=1}^{n} \lambda_i t} = e^{-0.000004199t}$$

$$MTTF_{system} = 1/\lambda_{system} = 1/(0.4199 \times 10^{-5}) = 238152$$

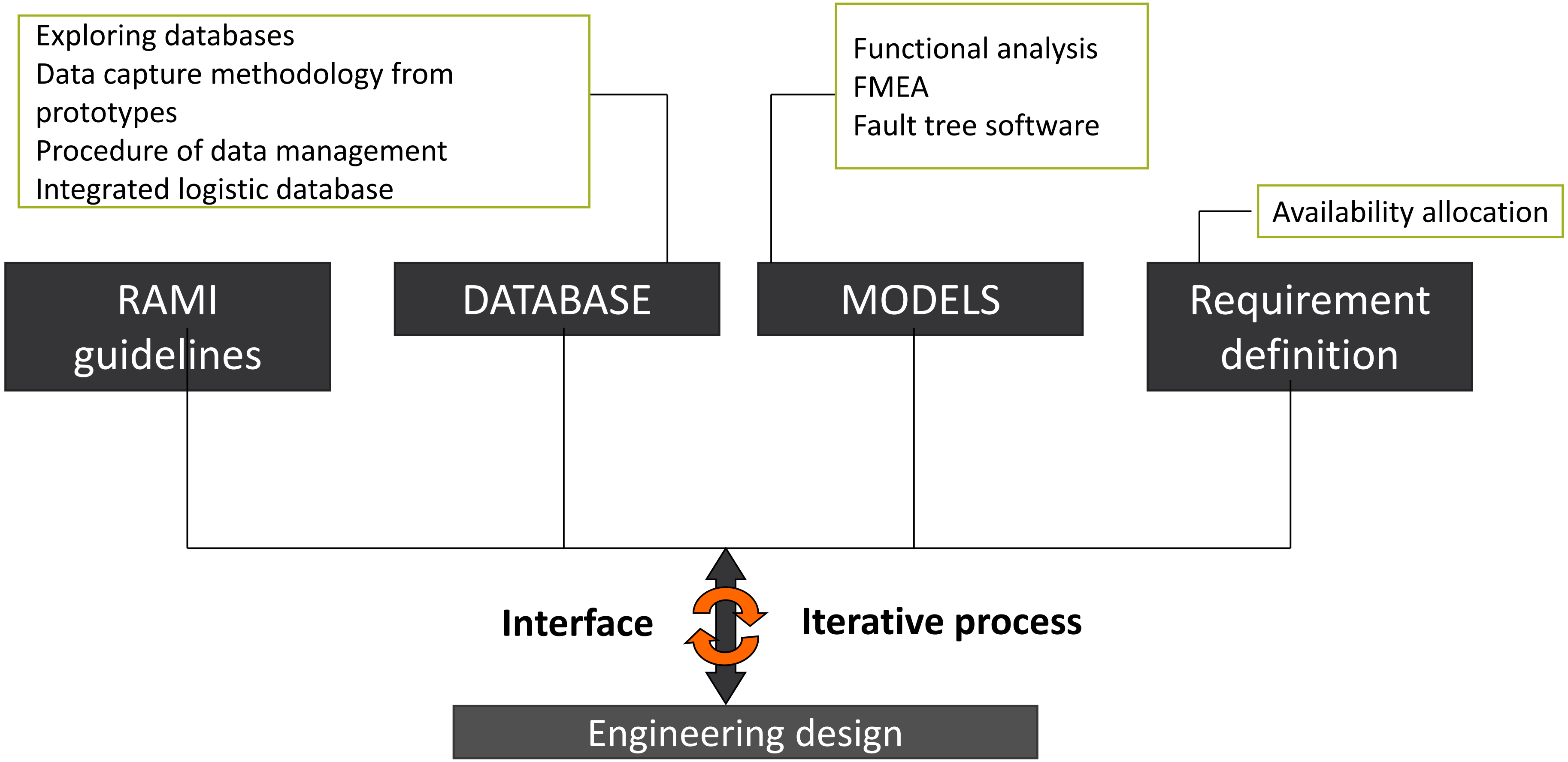
Software to modelize to reliability by design



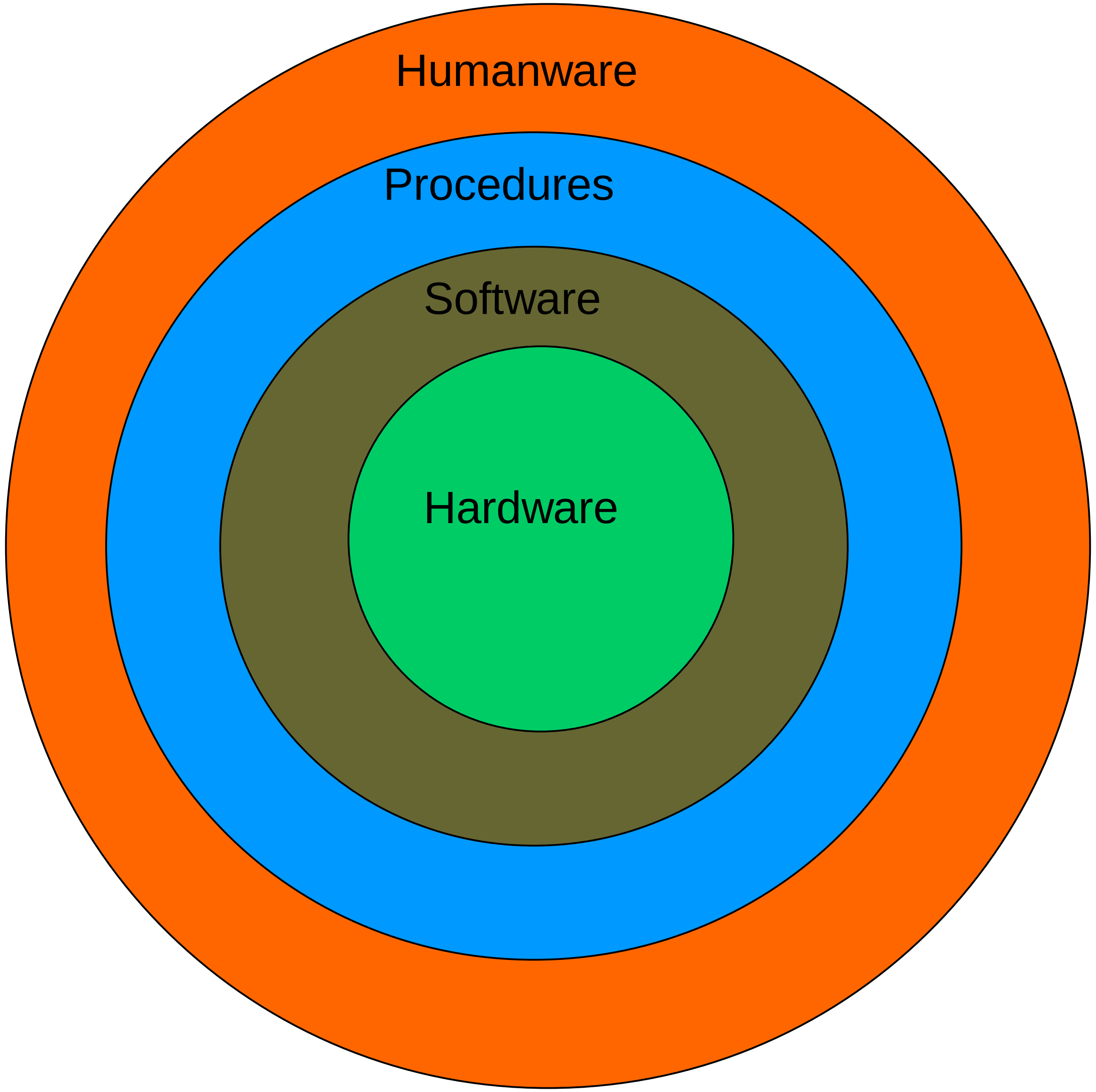
Second order effects

Many blocks to build a simple Ion Source, but lifetime dominated by Internal Antenna by at least a factor of 10

RAMI approach (Reliability, Availability, Maintainability, Inspectability)



the 4 layers of reliability



Concepts and reliability

Principles to **increase** the reliability:

During design:

- Redundancy
- Over-engineering
- maintainability- accessibility

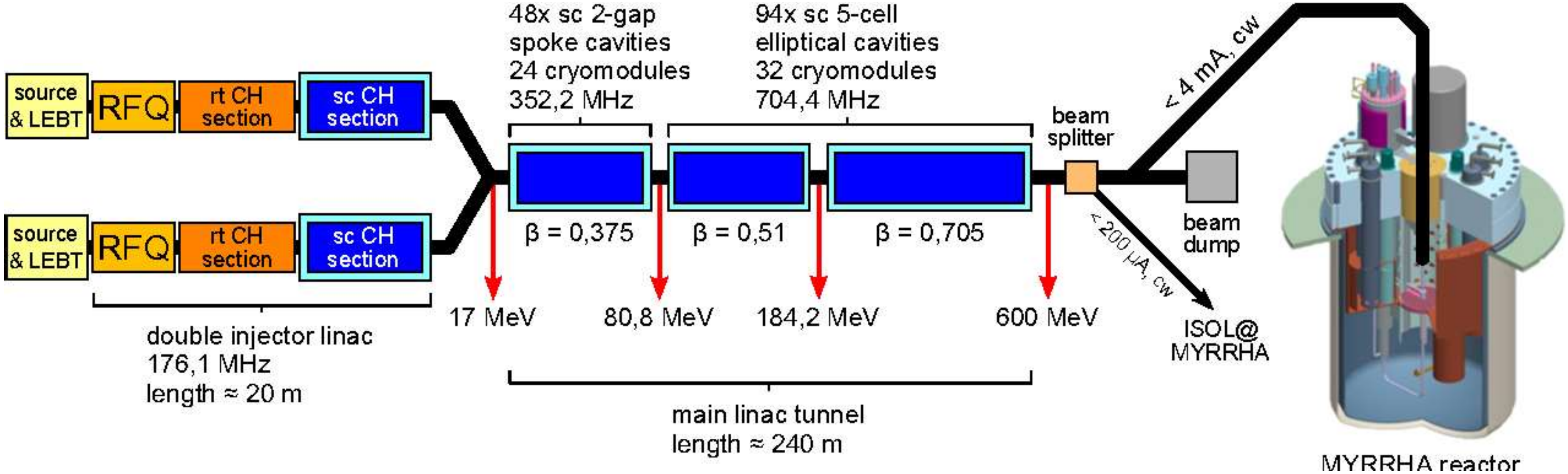
For operations:

- good and well-trained staff
- appropriated program and slots of maintenances (preventive, adaptative)
-Large storage of spare parts
- …

Parameters of a project than can **decrease** the reliability:

- Lonely experience
- Many technological innovations
- Number of specific interfaces
- Pressure on quality, budget, delay
- Low number and low quality of tests
- …

The MYRRHA Project
« Accelerator Driven System - ADS »



Reliability for particle accelerators

Synchrotron light-source:
first real intense approach for reliability

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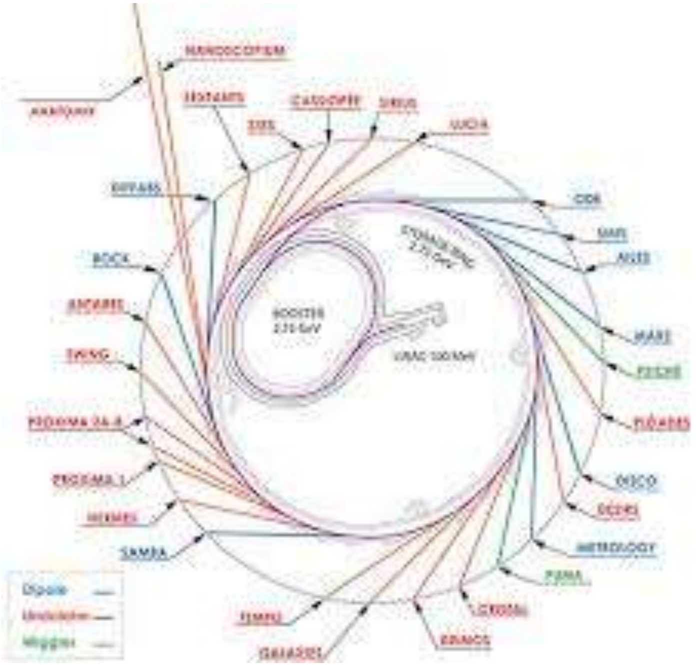
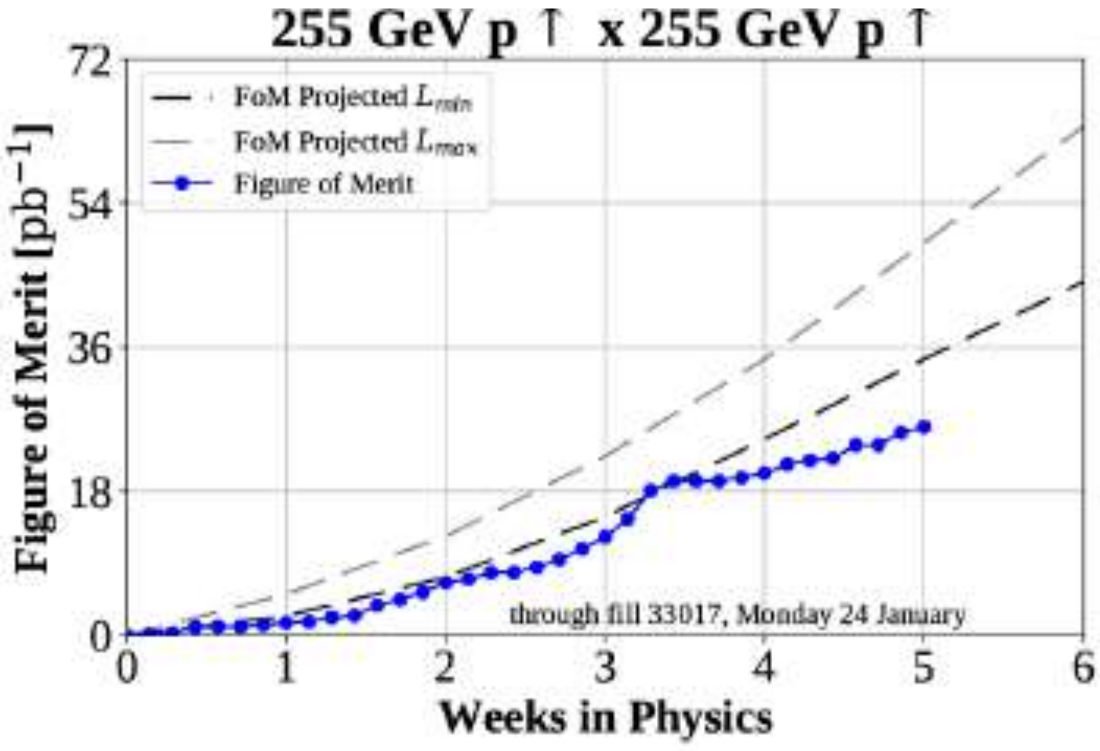
synchrotron Soleil



Reliability for synchrotron

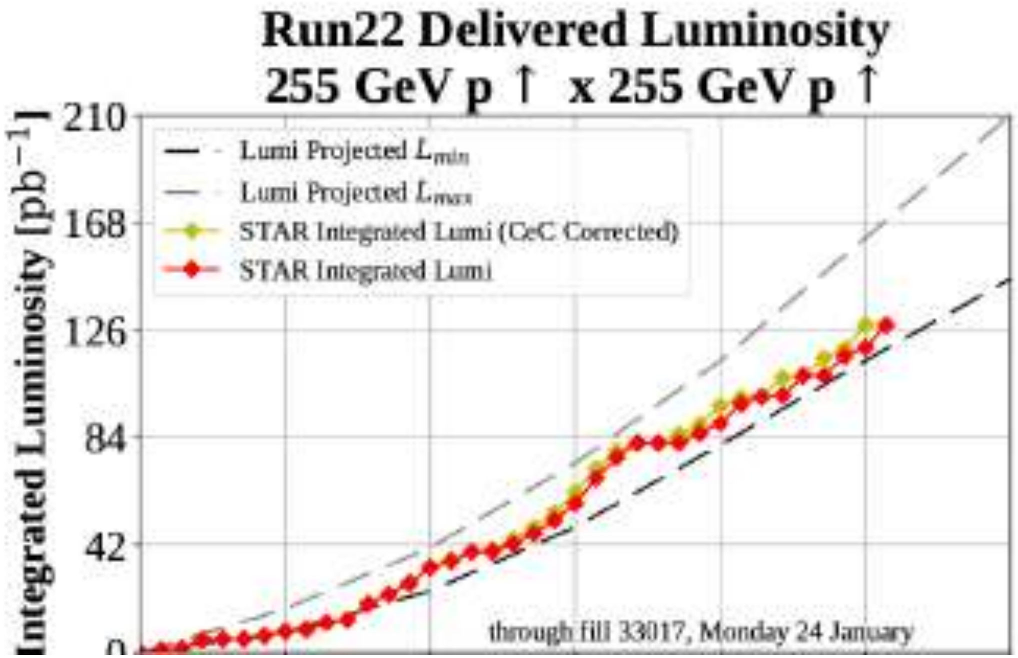
Annex 2
Metrics for synchrotron-sources of light

Example from RHIC – expectations from DOE on luminosity



Courtesy K. Hock/R. Terheide

Preliminary Luminosity, Figure of Merit (LP²) data for RHIC



POLL # 3

Safeties

2 kinds of safety considerations in an accelerator facility

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O to protect Humans (personal, patients, public, sub-contractors, …)

Radiations, fire, electricity, chemical products, …, sotware virus , ….

- **to protect Systems**

  Mechanical or electrical breaks, quenches, contaminations, …

…

Safety & Avaibility

Safety vs Avaibility

« the» CERN event (september 2008)

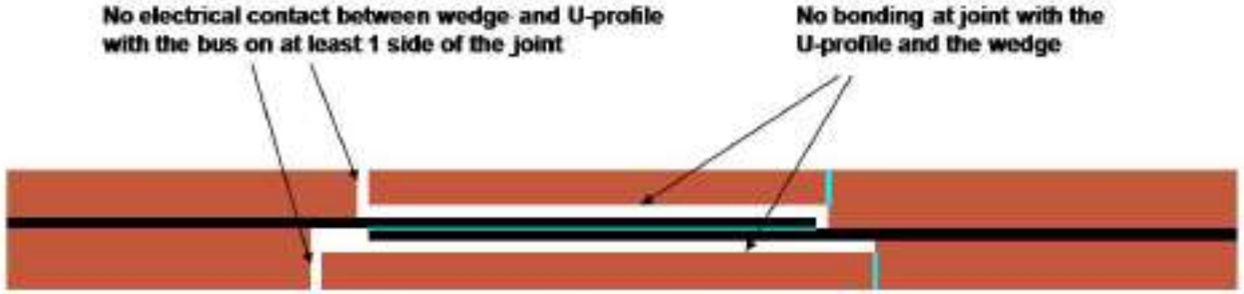


Figure 7: Model of resistive joint in bus bar
with bad electrical and thermal contact with the stabilizer

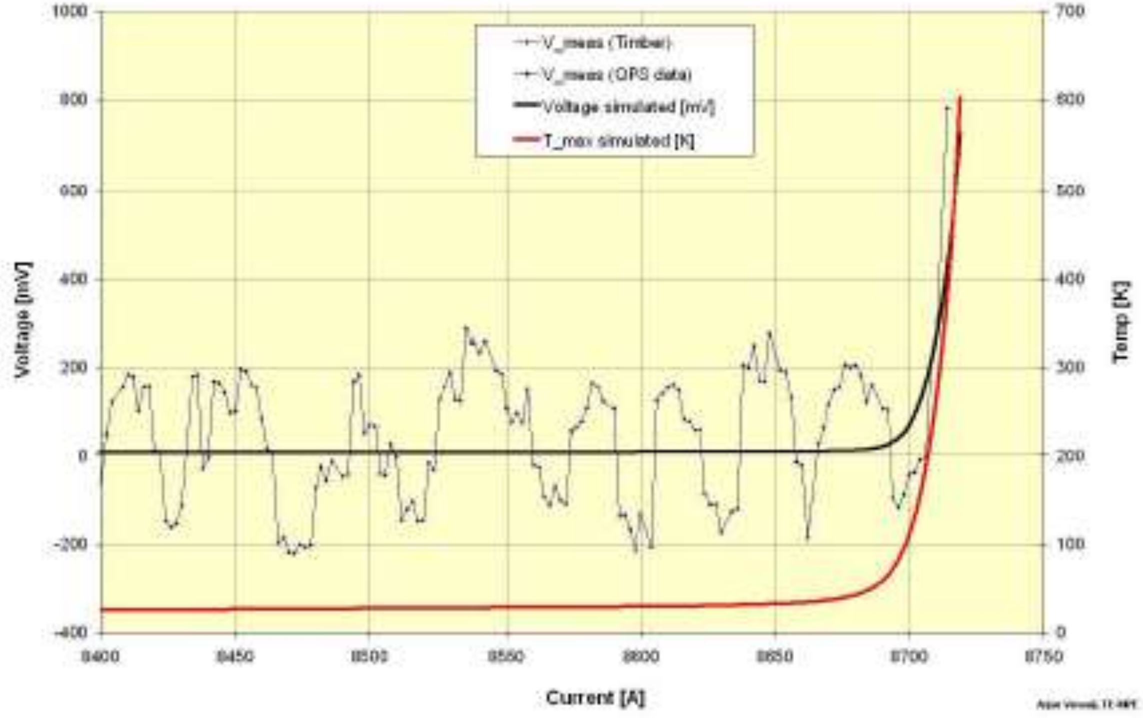
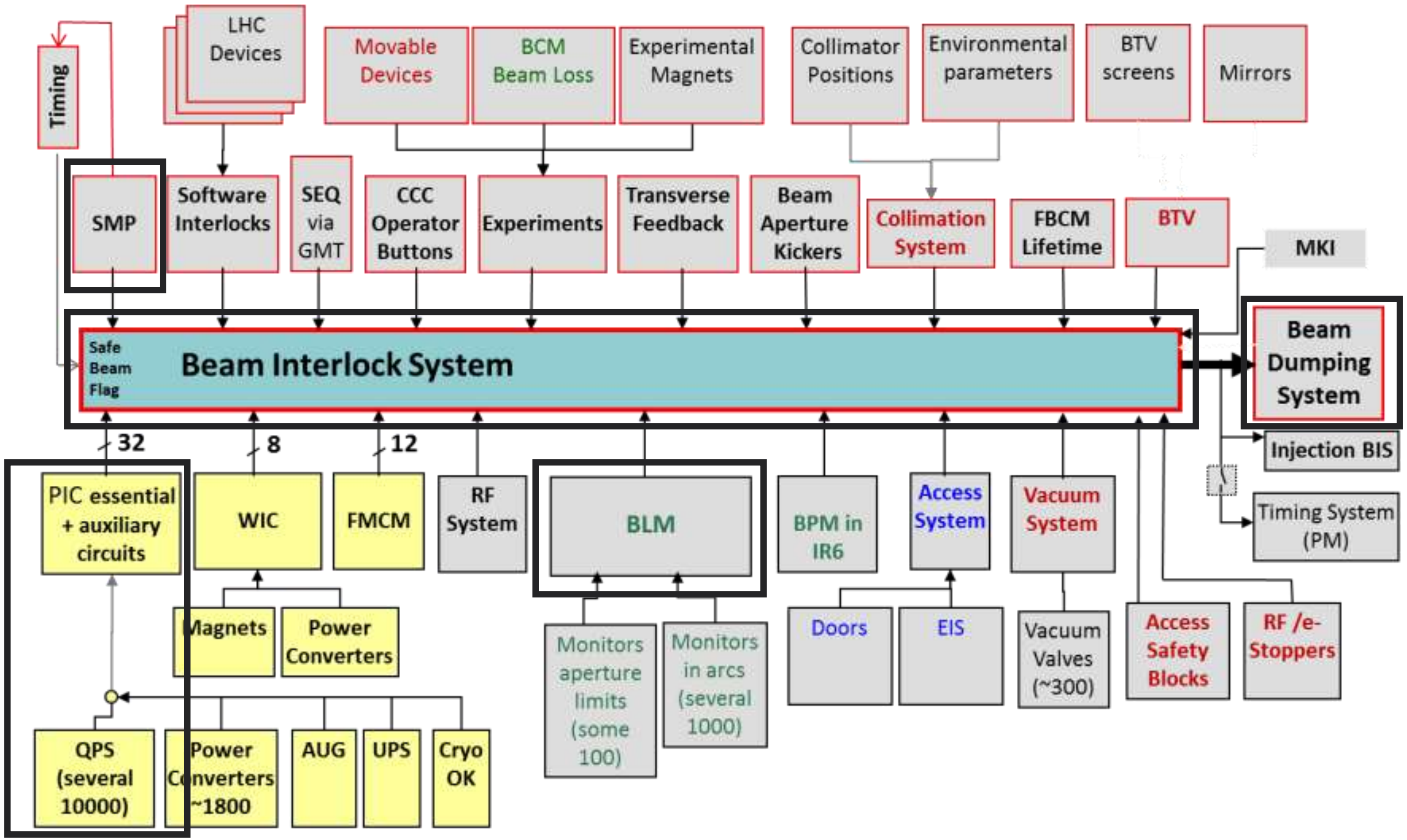


Figure 8: Measured and simulated parameters of the incident

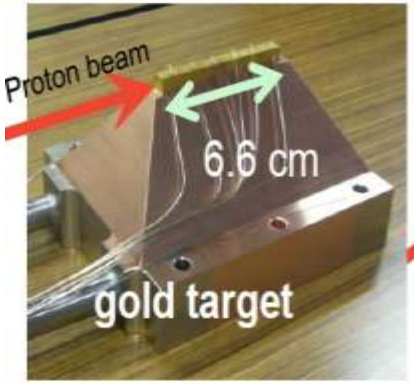
LHC Machine Protection Layout

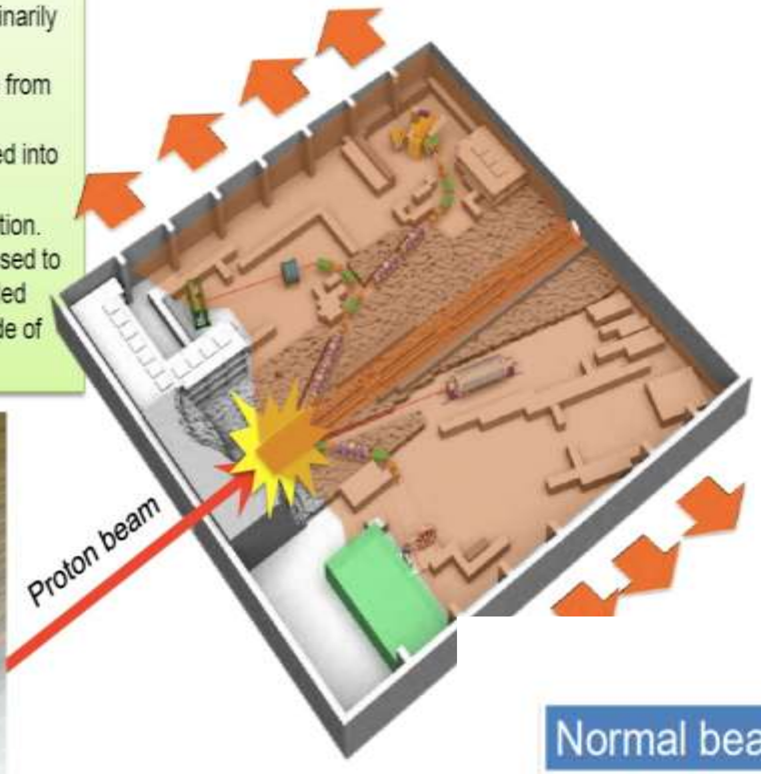


Radioactive Material Leak Accident at the Hadron Experimental Facility (JAPAN)

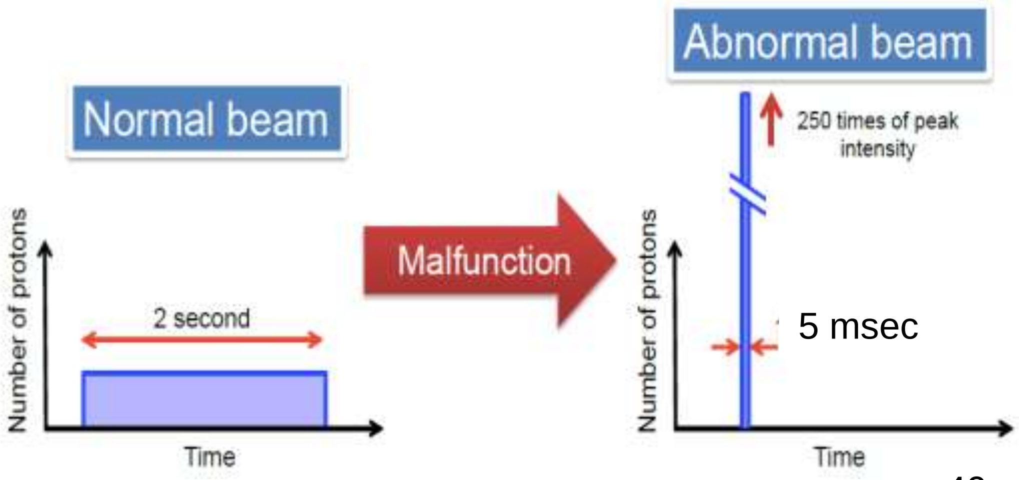
11:55 on May 23 2013

- An abnormal proton beam was injected to the gold target.
- The target heated up to a extraordinarily high temperature.
- Radioactive material was released from the target.
- The radioactive material was leaked into the HD hall.
  → Workers were exposed to radiation.
- The radioactive material was released to the outside of the radiation controlled area and to the environment outside of the HD hall.





In this accident, the proton beam was extracted at a much shorter time than in normal operation. This was due to the malfunction of the beam extraction system of the MR, which resulted in the gold target being bombarded with a very short pulsed beam.



Reliability and life-cycle

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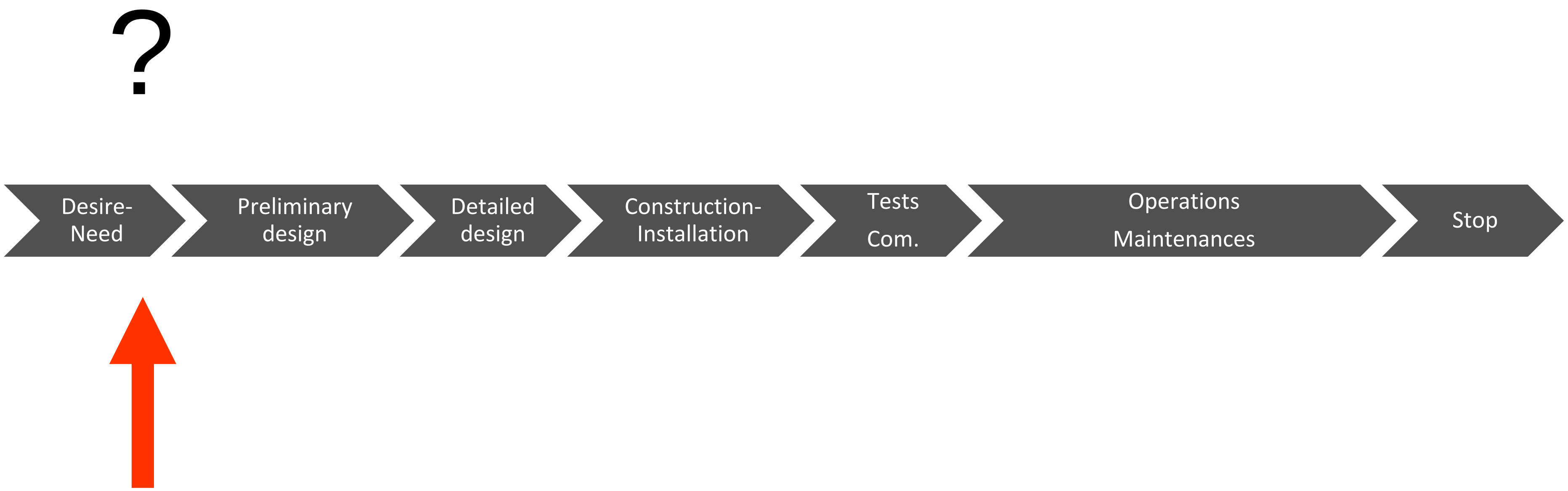
Life-cycle of accelerators



The (wellknown) recipes for a good reliability

A system (hardware & software) well designed
- specifications, model of developpement, tests
- principles of reliability, a lot of diagnosis

A well-maintained system
- Preventive, real, adaptative, reactivity for corrective
- Spare parts (a lot, ready for use)
- time dedicated for operations and also for maintenances

Human resources and good organization
- people trained, skilled, enough, here when required
- efficient and clean organization, data-base, Knowledge Management

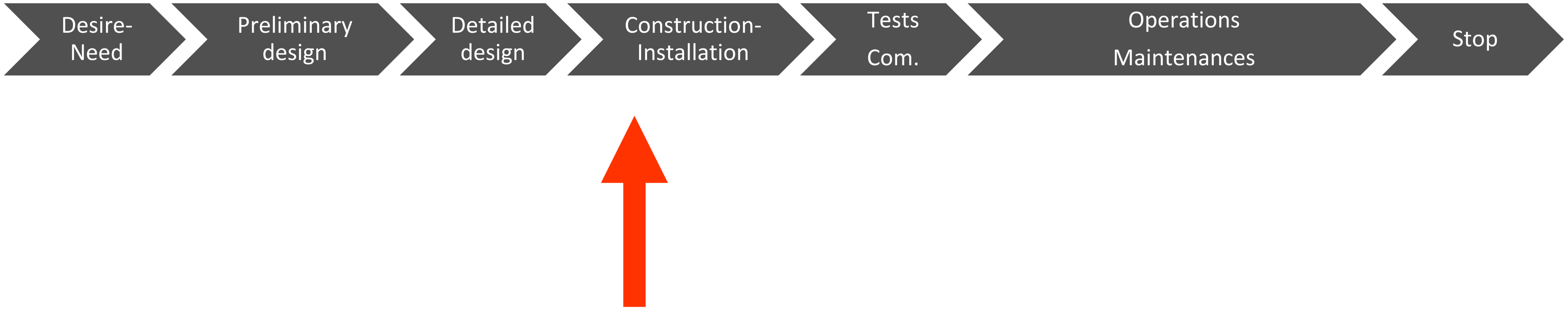
Briefly: resources (men.hours, budget), consistency, willingness…

SSC: The Super Superconducting Collider

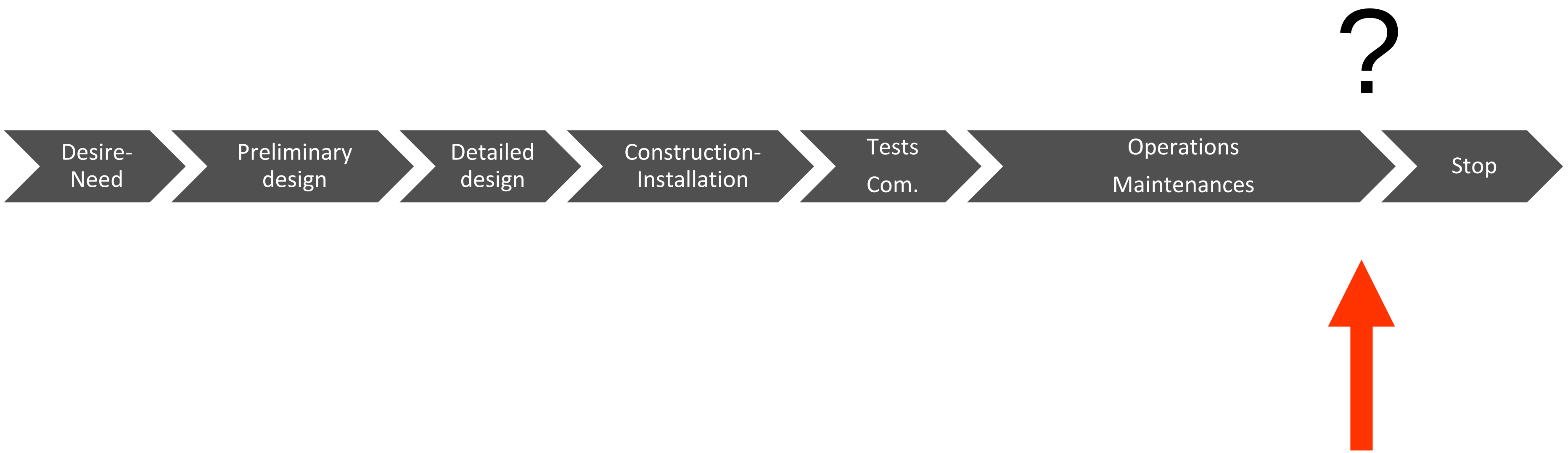
South of Dallas - 89 km – 80 TeV protons

Starts 1991-1993
Then cancelled

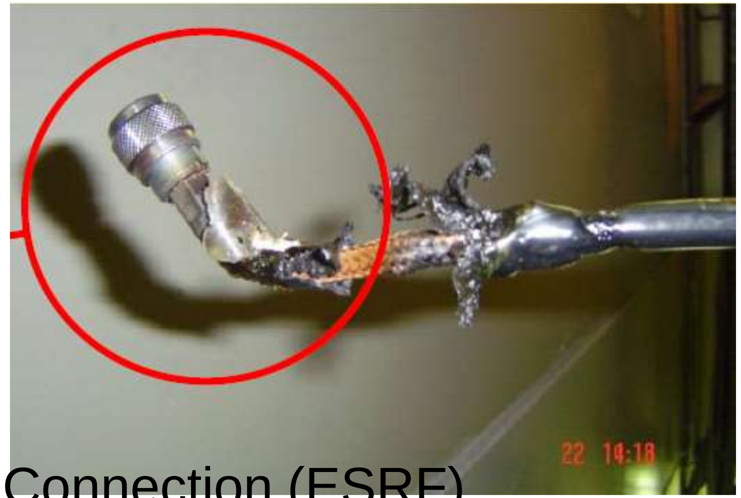
Life-cycle of accelerators



Life-cycle of accelerators



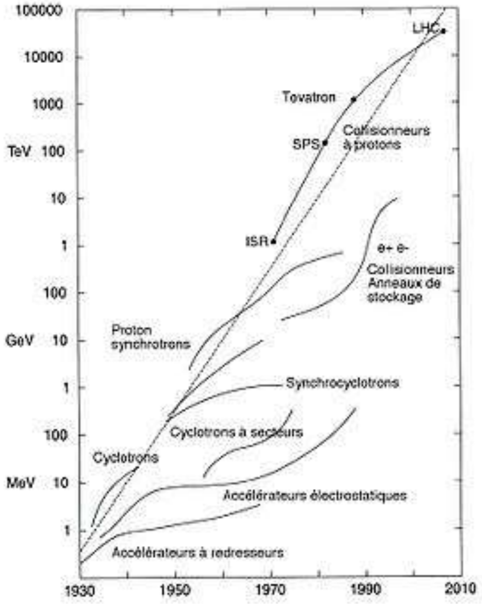
A failure – a small (or big) death



Connection (ESRF)

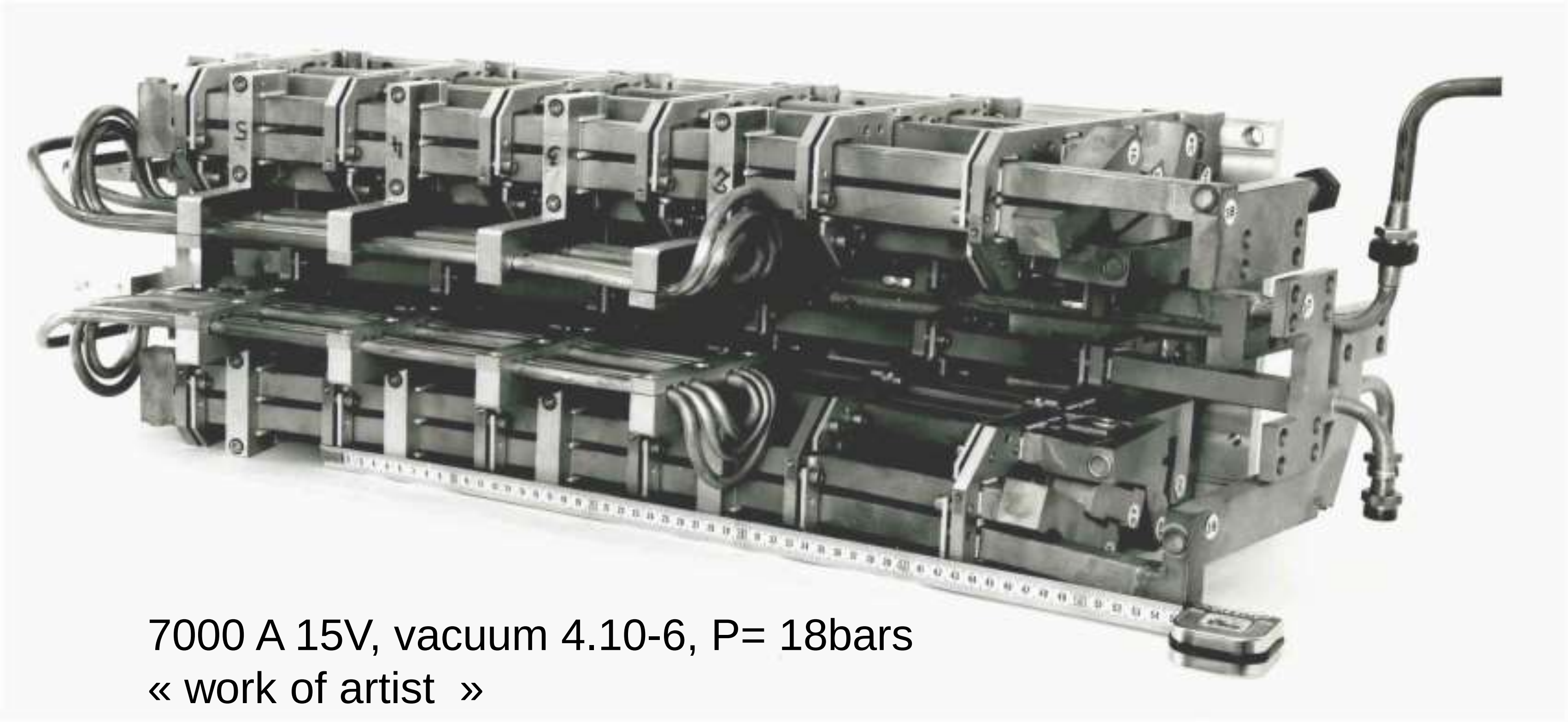
Main coil (SC200-Orsay)

Obsolescence



Orphan system

Electromagnetic channel (with septum) of synchro-cyclotron of Orsay



7000 A 15V, vacuum 4.10-6, P= 18bars
« work of artist »

Example of document IUCF
annex 3

first page

last page « Is the capability … »

Reliability and accelerators

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- **Concepts: principles to increase reliability, risks to consider**

- **Definition : Importance to agree on (what, how, mode, constraints/freedoms, …)**

- **Maintenance: % determinist (mechanical, cooling, …) % based on monitoring (systems + organisations)**

- **Responsabilities: to etablish and clarifiy (systems, organization, Quality assurance, test, …)**

- **Information: how to get as soon as possible (other experiences, test, …), how to keep during the life of accelerator.**

Last trends:

- Sustainability and Energy savings
- Artificial Intelligence

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Sustainability → Minimize the impact on the environment

Minimize the pollutions and emissions

Minimize the consumption of energy, water, …

Minimize the waste - maximize the recycling

Minimize the risks (not only radiation, ….)

Maximize the life-time

……

For **direct** and **indirect** considerations.

Ex: process fo building, travel for meetings, …

Case of Particle Accelerators – many issues with impact

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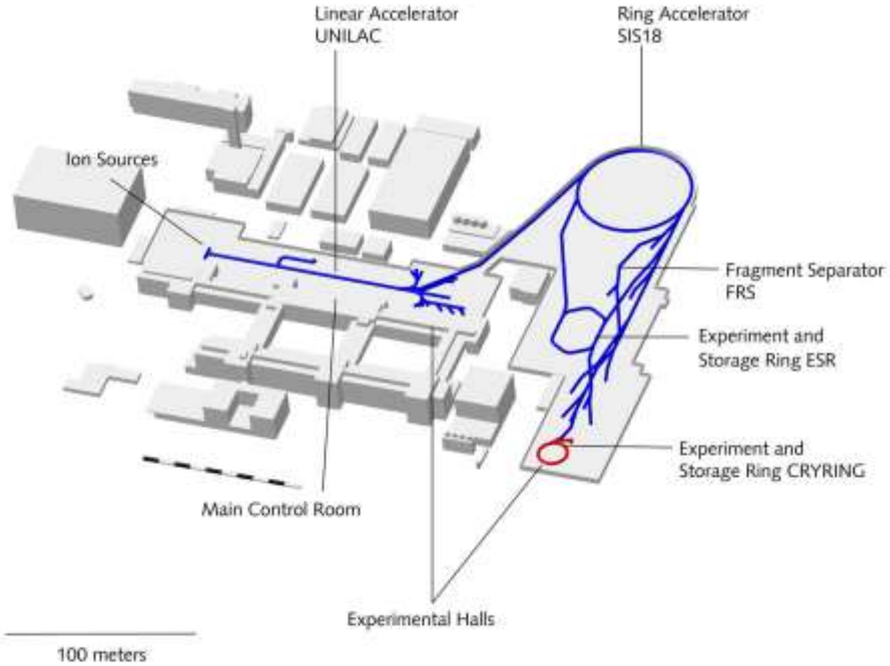
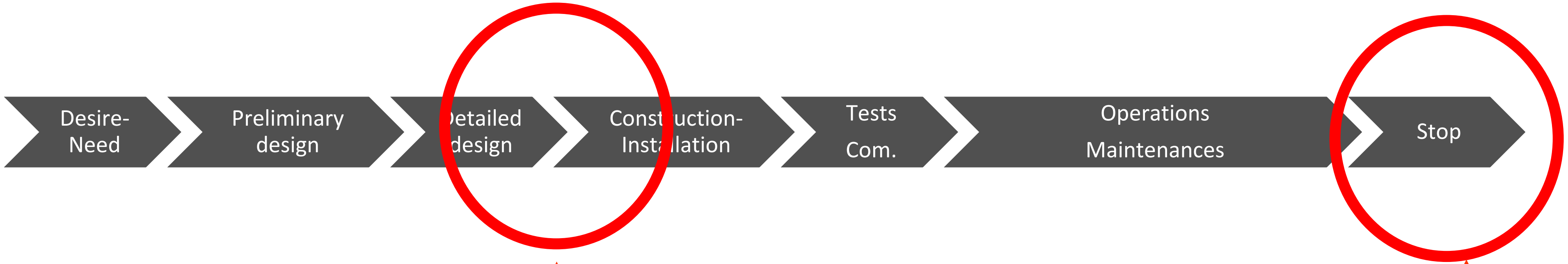


- Large system and facility
- Many components
- High consumptions of energy (1st : Electricity)
- Many dangers (radiation, electricity, gaz, …)
- An high demand in digital ressources
- …

Sustainability to consider during all the life-cycle

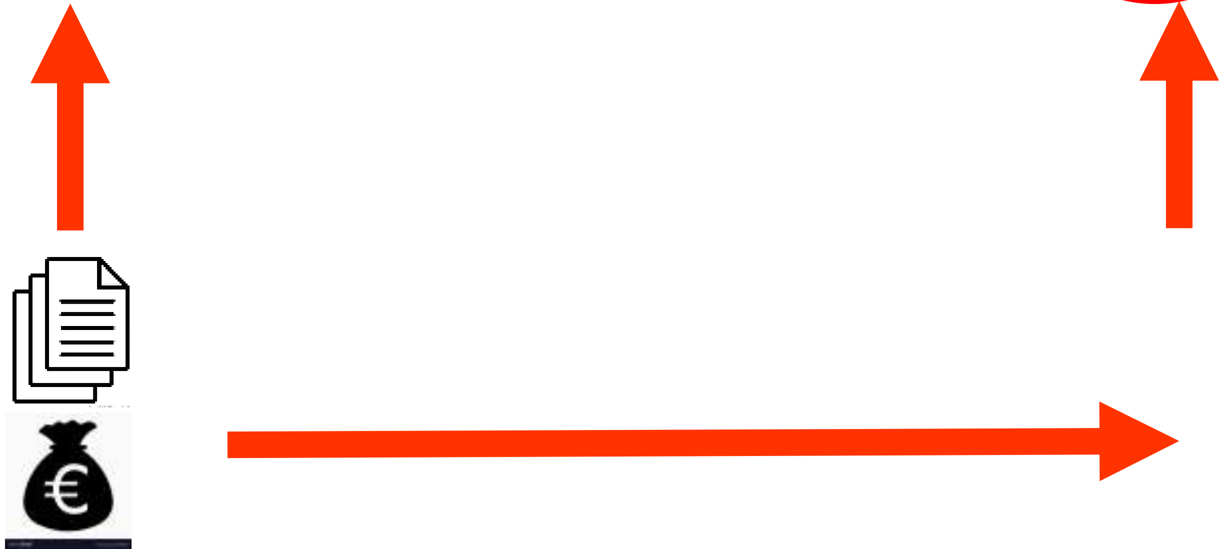
Willingness + Regulations



Example for the dismantling :

before starting to build or to buy
a new accelerator

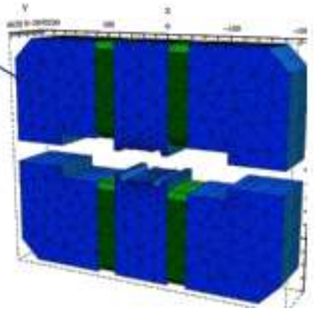
You must give the procedure +
book the funding



Example of solutions

Permanent magnets @ ESRF

ESRF canting magnet (dipole field)



Less electricity
Less cooling
Less wires and tubes

But some rare earth …

RF Cavities @ SFTC -UK

Slide: Andrew Vic

Thin Film Superconducting RF

- **Bulk niobium cavities** have been the choice for SRF for the last 50 years
- Use a considerable amount of natural material
- Performance limit of niobium has been reached
- Costly to produce
- Run at a temperature of 2 K
  - A considerable cryogenic demand and energy load

Benefits of thin films

- Use a copper supporting cavity
  - Better thermal properties, cheaper material and production
- Use different superconducting materials (e.g. Nb_3Sn, NbN and MgB_2)
  - Better performing materials than Nb that can't be formed into solid cavities
- Higher operation temperature of new alloys
- Reach higher accelerating gradients

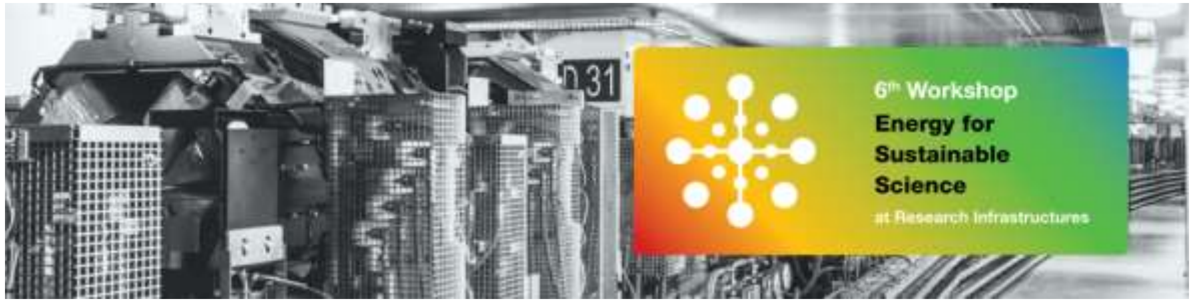
Ben Shepherd • Sustainable Accelerators • ESSRI Workshop 2022

Standards

ISO 50001 Energy management systems - Requirements with guidance for use, is an international standard created by the International Organization for Standardization (ISO).

ISO 20121 - Event sustainability management systems — Requirements with guidance for use

Workshops



Permanent behaviour

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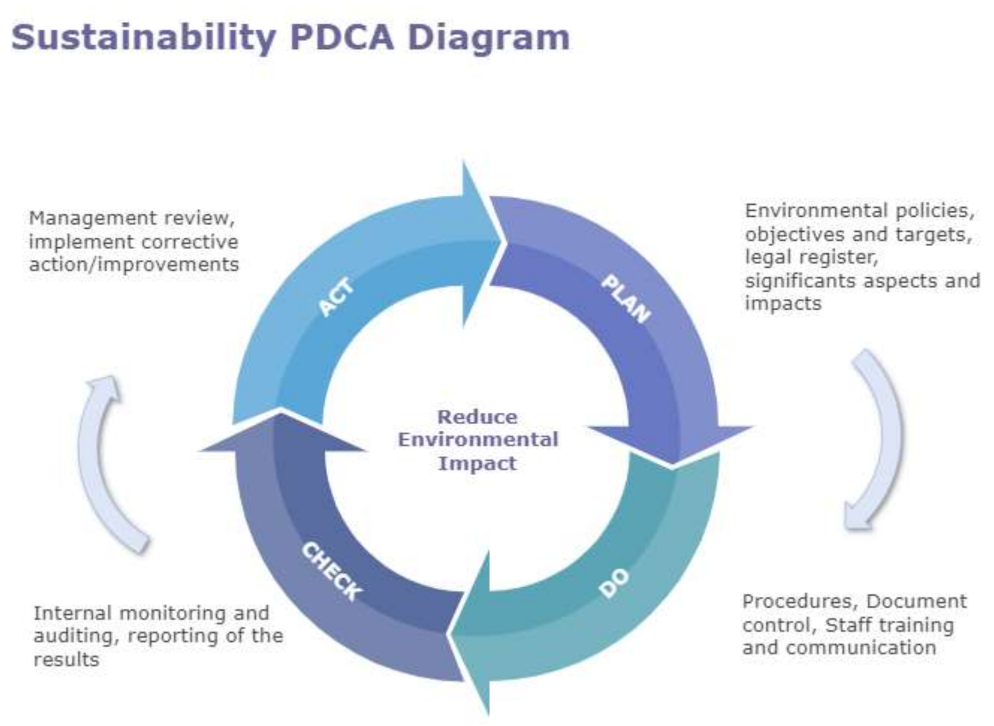

The energy crisis impact with a major increase of the cost of Energy

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Impact

- The budget of electricy cost explodes (In Europe: **+ 150 - 300 %)**

- This obliged to reconsider drastically the **experimental program** and the capacities of the facilty

Possibles actions

Short term

- increase the energy budget and decrease others
- Optimize the use – track the wastes
- Decrease the time of use

Middle term

- Change the process (ex: transition to supra)
- Optimize with the electricity grids and capacities
- Recyle the heat produced
- …

Long-term

- new data to consider business plan for further facilites
- choose sciences with reasonable energy ?

Last trends:

- Artificial Intelligence

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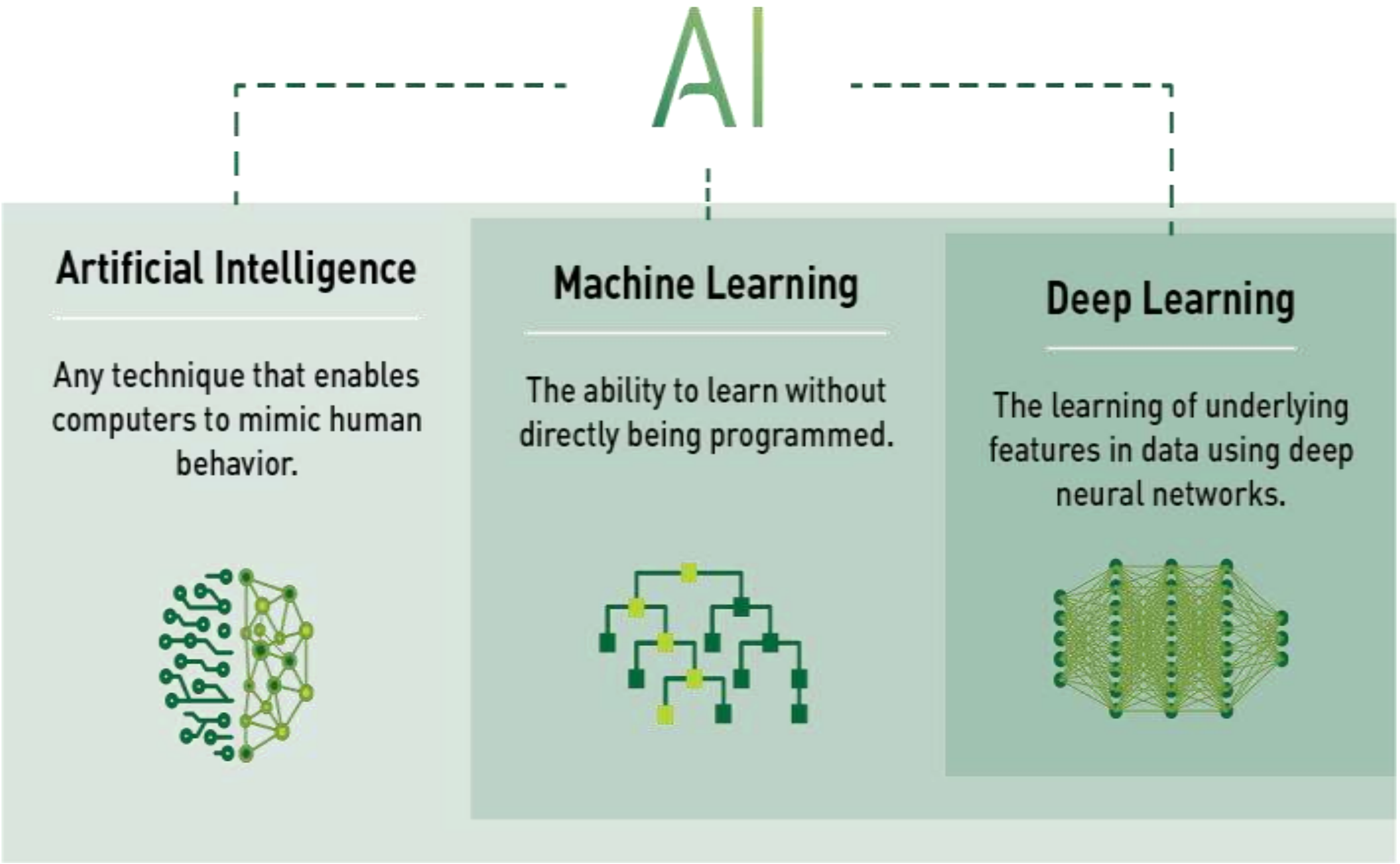
AI vs Machine Learning vs Deep Learning



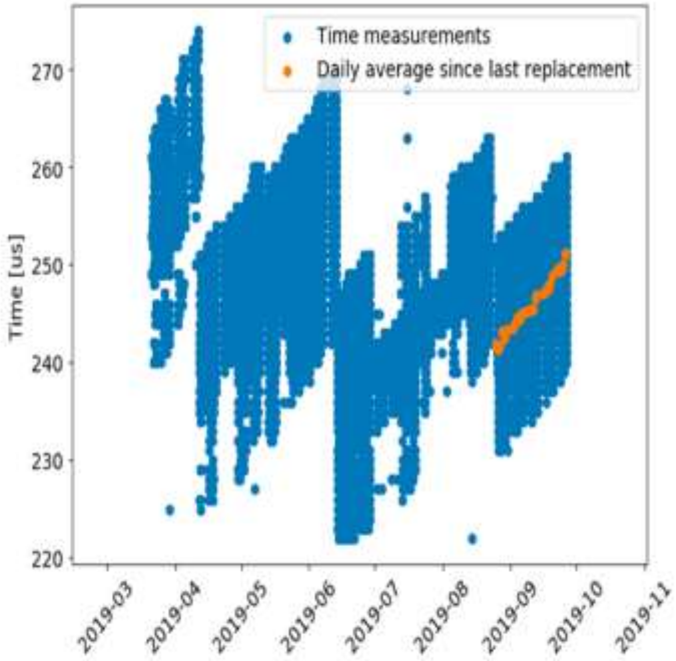
Dr Ing Gianluca Valentino

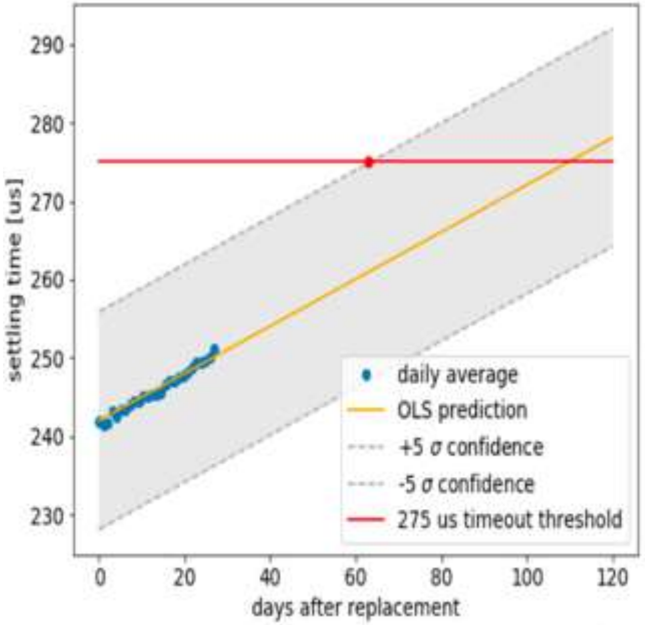
Department of Communications and Computer Engineering
University of Malta

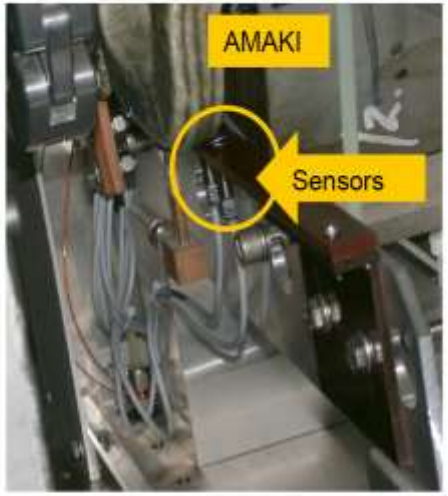
Possible applications for reliability in accelerators

Prediction of Remaining Useful Lifetime (RUL)

Example: AMAKI deflecting magnet at PSI COMET cyclotron







- More complex systems may require multi-variate analysis which cannot be visualized..
- ML needed to understand which features (inputs) are reducing RUL and to predict it from data

P. Fernandez Carmona et al (PSI), “Introducing Big Data Analysis in a Proton Therapy Facility to Reduce Technical Downtime”, ICALEPCS’19

Conclusion

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14h15

Lifecycle

Operations

In the perfect world

History

Preparation by groups

Team works

15h15

Break

Your Presentations

Business

Reliability

In the real world

Last trends

16h15

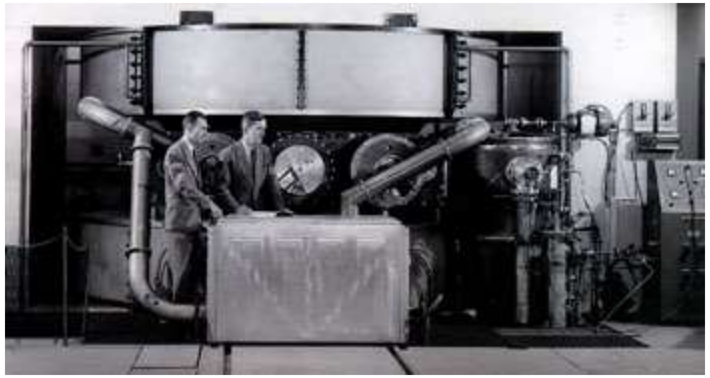
Sustainability

Thank you for your attention

bonus

Synchro-cyclotron - HCL

Harvard (1949-2003)



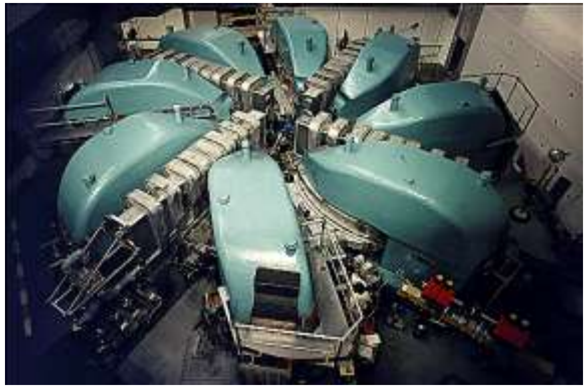
Cyclotron 88 inch - LBL

Berkeley (1961 - …)

Cyclotron PSI (590 MeV)- CH

designed for 100 µA (1974)

an now at 2,2 mA (2012)



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