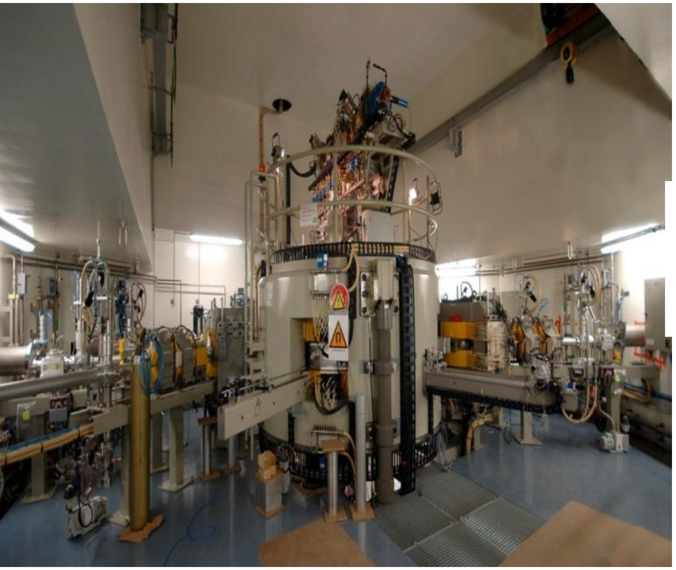
Experience with a High Energy and High Intensity Cyclotron

Freddy Poirier (Arronax/CNRS)
On behalf of the accelerator group

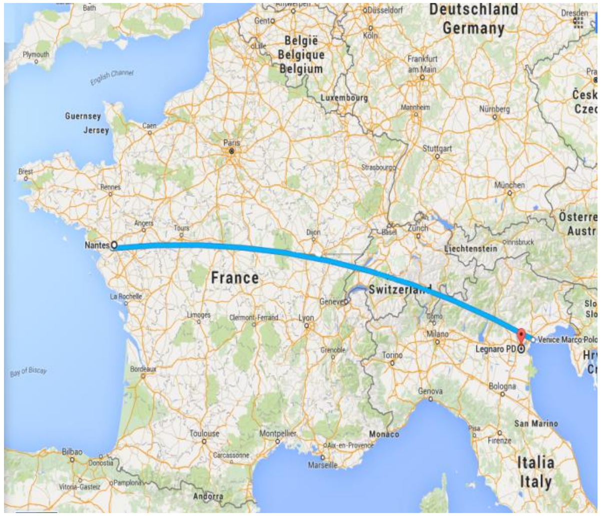
CYCL13: “On-Going operations with the cyclotron C70”, MOPPT010



ARRONAX

ARRONAX: Accelerator for Research in Radiochemistry and Oncology at Nantes Atlantique.

IPAB march 2016

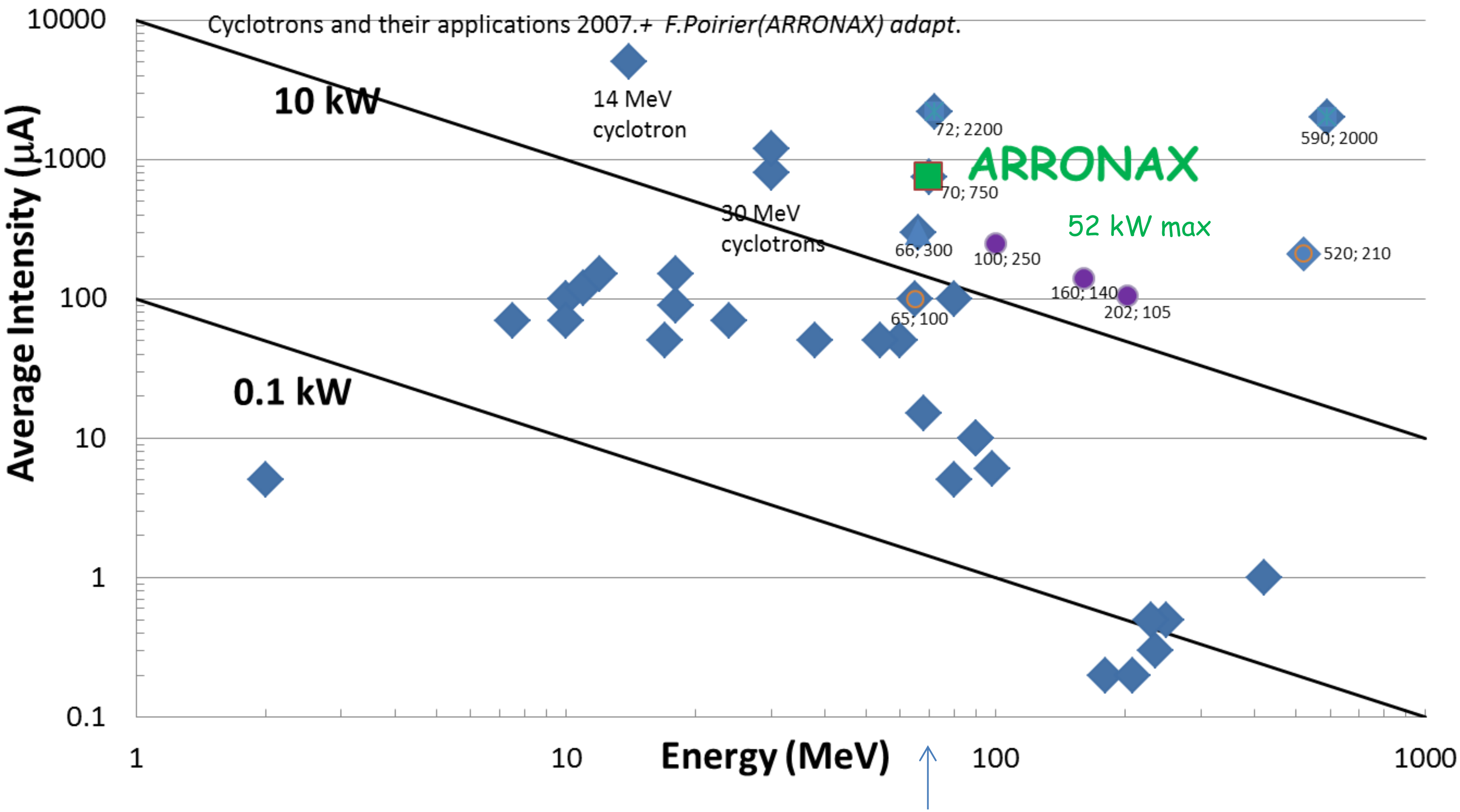


ARRONAX

High Energy and High Intensity (HEHI)?

- My students asked for comparison between accelerators.
  - And here is a tentative map that I show
    - similar to the HEP european strategy map of 2013 for accelerators
    - Rather incomplete

Proton Cyclotrons and Linacs for Radio-isotopes



Arronax is positionned among the high power cyclotrons

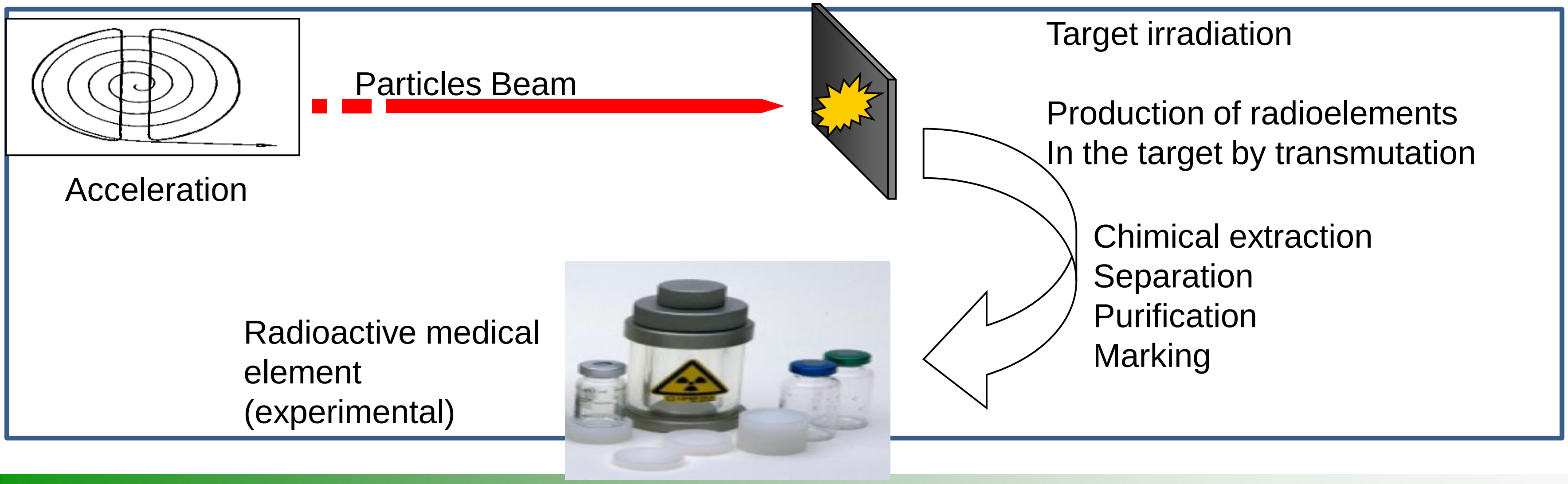
Several new proton machines are being built at 70 MeV (see next talk)

ARRONAX

- Public Interest Group (GIP):
  - Public research institute, private accounting
  - Research through collaboration
  - Provide also beam time for research
- Small team: 34 full time equivalent
  - 11 in the accelerator group (not every one full time)
- Activities:
  - Produce radionuclides for research in nuclear medecine
  - Radiochimistry/radiobiology research
  - Physics research (staked foils, pixe/pige)
  - Training and education
  - Also an industrial production site for medical needs

ARRONAX

- Public Interest Group (GIP):
  - Public research institute, private accounting
  - Research through collaboration
  - Provide also beam time for research
- Small team: 34 full time equivalent
  - 11 in the accelerator group (not every one full time)
- Activities:
  - Produce radionuclides for research in nuclear medecine



Motivations for radionuclides

There is a demand for **radionuclides:**

- with various **Half-lives:** to match with vector distribution time in targeted therapy
- with various **decay radiations**:

  imaging / therapy

  short range High LET vs long range Low LET (Linear Transfert energy)
- with various **Chemical properties**
- produced via **generator** (ease the availability)
- To be used for the **<u>Theranostics</u>** approach

Theranostics: treatment strategy that combines **thera**peutics with diag**nostics**
Selection of radionuclides that can be used for:

- radiations for both imaging and therapy (^{117m}Sn)
- same element (^{64}Cu/^{67}Cu, ^{124}I/^{131}I, …)
- comparable properties (^{99m}Tc / ^{188}Re)

Radionuclides production : our priority list

- **Radionuclide targeted therapy**:
  - ^{211}**At** (α emitter)
  - ^{67}Cu, ^{47}Sc (β^- emitters)
- **Dosimetry prior therapy** :
  - Radionulide pairs β^+/β^- : **$^{64/67}$Cu, $^{44/47}$Sc**
- **Imaging** :
  - Cardiology: **^{82}Sr/^{82}Rb**
  - Oncology: **^{68}Ge/^{68}Ga**
  - Hypoxia : **^{64}Cu + ATSM**
  - Immuno–PET (**^{64}Cu, ^{44}Sc**, …)
- **Neutron production for particle activation: ^{166}Ho**

ARRONAX

afaq ISO 9001 Qualité AFNOR CERTIFICATION

Radionuclides production : our priority list

– **Radionuclide targeted therapy**:

^{211}**At** (α emitter)

^{67}Cu, ^{47}Sc (β^- emitters)

– **Dosimetry prior therapy** :

Radionulide pairs β^+/β^- : **$^{64/67}$Cu, $^{44/47}$Sc**

- **Imaging** :

Cardiology: **^{82}Sr/^{82}Rb**

Oncology: **^{68}Ge/^{68}Ga**

Hypoxia : **^{64}Cu + ATSM**

Immuno–PET (**^{64}Cu, ^{44}Sc**, …)

-Neutron production for particle activation: ^{166}Ho

Projectile

Alpha

Proton

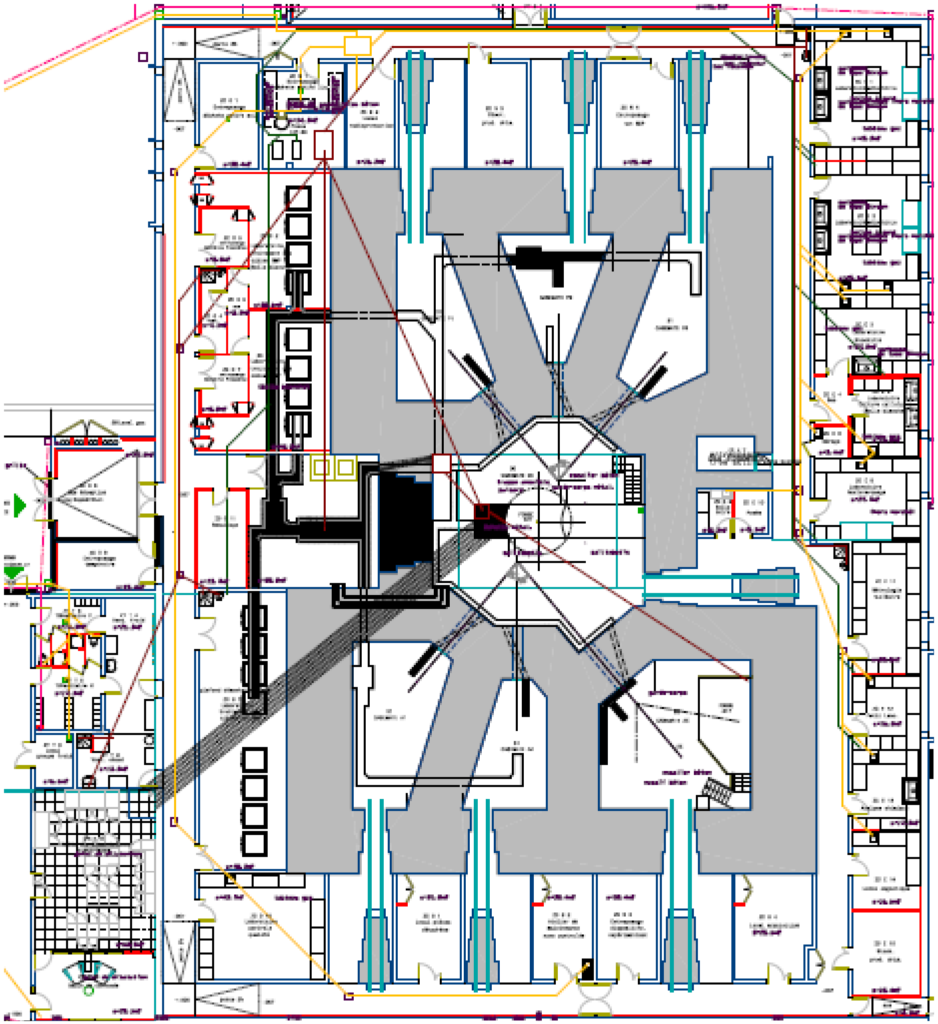
Deuteron/ proton

Proton

Deuteron

proton

The existing facility



6 experimental vaults

4 vaults connected through a **pneumatic system** to hot-cells

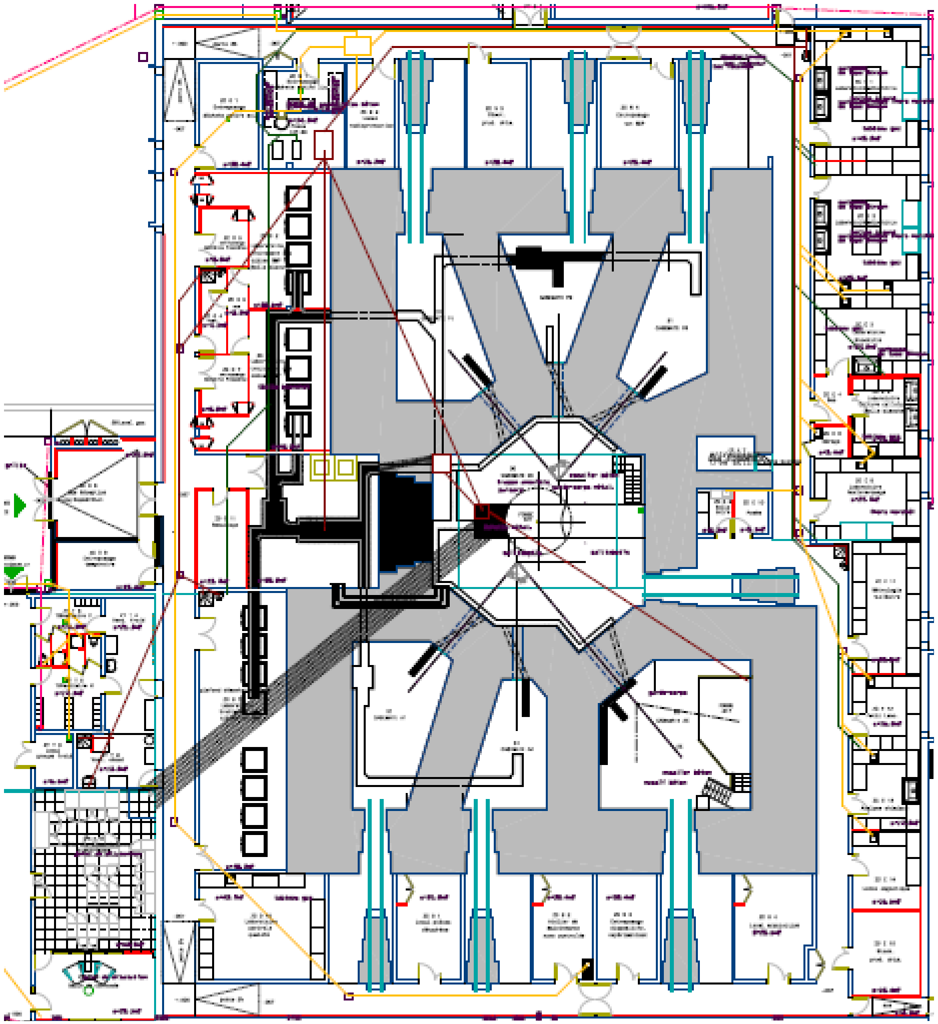
5 dedicated lines of hot cells for chemical treatments

2 lines in a sterile environment

ARRONAX

afaq ISO 9001 Qualité AFNOR CERTIFICATION

The existing facility



6 experimental vaults

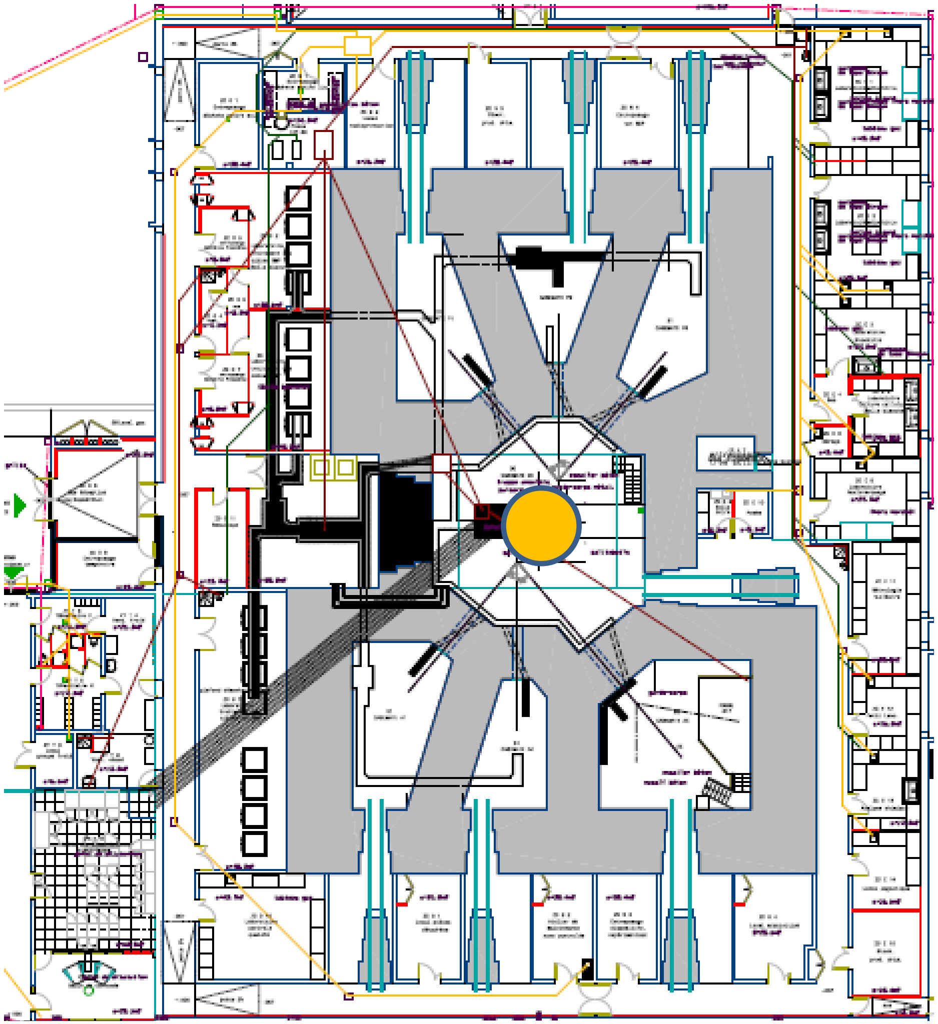
4 vaults connected through a **pneumatic system** to hot-cells

5 dedicated lines of hot cells for chemical treatments

2 lines in a sterile environment

Laboratories available for research: Quality control, metrology, Radiochemistry, biology; radiolabeling,…

The existing facility



And the accelerator itself

6 experimental vaults

4 vaults connected through a **pneumatic system** to hot-cells

5 dedicated lines of hot cells for chemical treatments

2 lines in a sterile environment

Laboratories available for research: Quality control, metrology, Radiochemistry, biology; radiolabeling,…

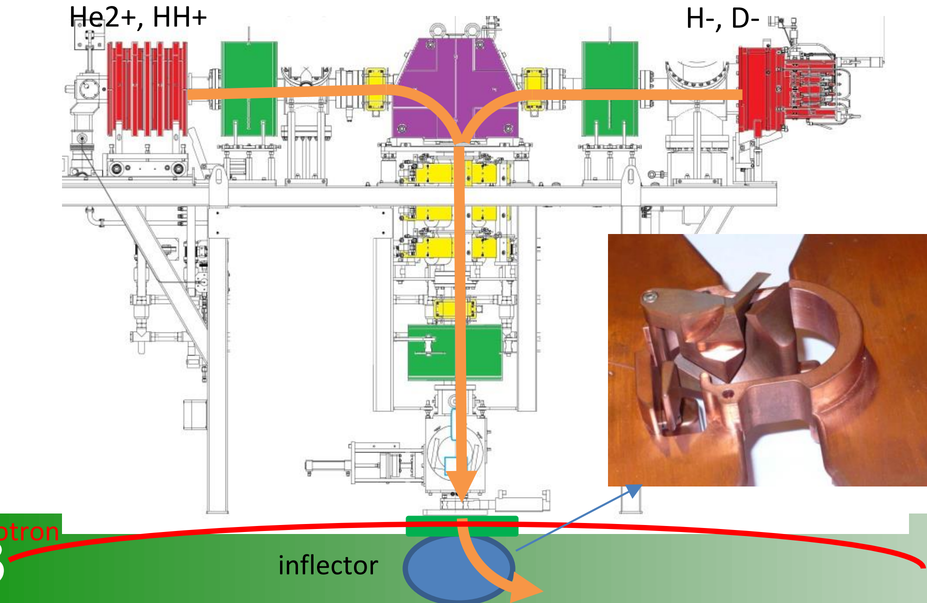
Some important beam characteristics for radioisotopes production

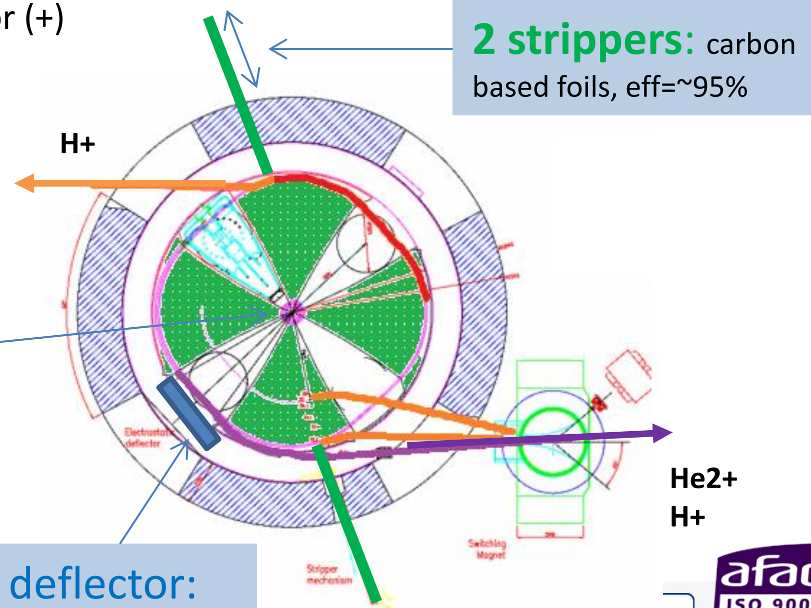
- For us, end-of-line users want a beam with:
  - Good Stability with a high mean intensity
    - High integrated intensity is required in the end
    - Possibly over long hours
  - Smoothness for the beam:
    - In **time**: less possible peaks and breakdowns eg thermal stress minimised
  - Precision (to a certain level) at the target location
    - In **position** (w/wo wobbling)
    - In **size**
    - In **energy** to be at the right cross-section for production
- For research users, it's tighter usually

- In accelerator terms, the 7 basic beam characteristics are an important knowledge, also with our industrial machine and even more if you are at the limits on the target:
  - $\langle x\rangle, \langle x'\rangle, \langle y\rangle, \langle y'\rangle$
  - $\langle E\rangle$
  - Δt
  - $\langle I\rangle$

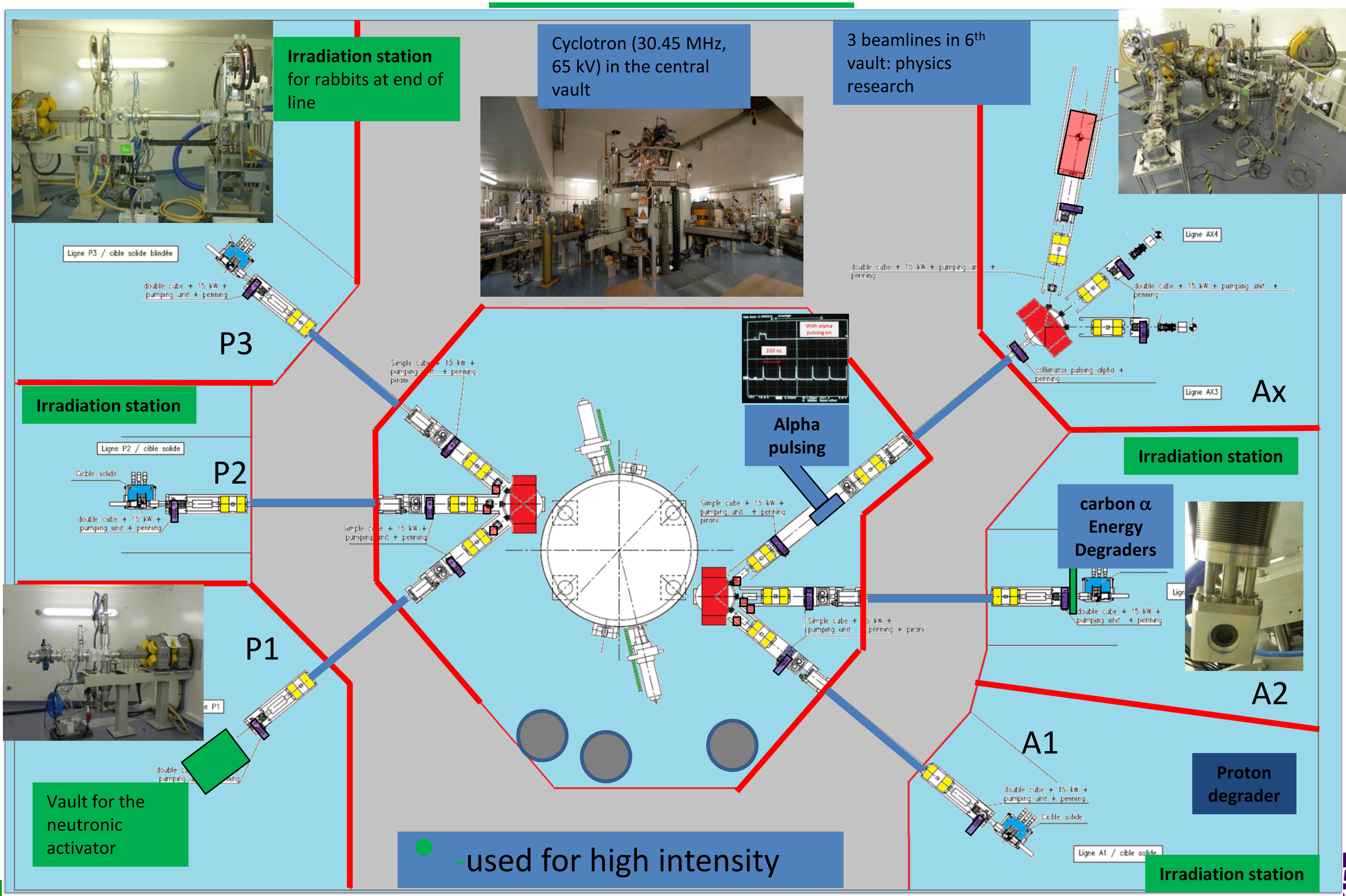
Cyclotron Characteristics

- C70 Cyclotron prototype build by IBA:
  - Isochron cyclotron with 4 sectors
    - RF: 30.45 MHz
    - Acceleration Voltage: 65 kV
    - Max magn. field : 1.6T
  - Max kinetic energy/n: 30-70 MeV
  - Normalised emittance before extraction: $\gamma\varepsilon_x$=~4π mm mrad (simulation)
- Main additional elements:
  - 2 Multiparticle sources.
    - Multicusp (H-,D-) with multiple magnets, 5mA max.
    - Supernanogan ECR ion source (He2+,HH+)
  - Injection: Series of magnetic elements (glaser, steerer, quad.) on the top of the cyclotron and finally the spiral inflector
  - Extraction: stripper (-) or electrostatic deflector (+)





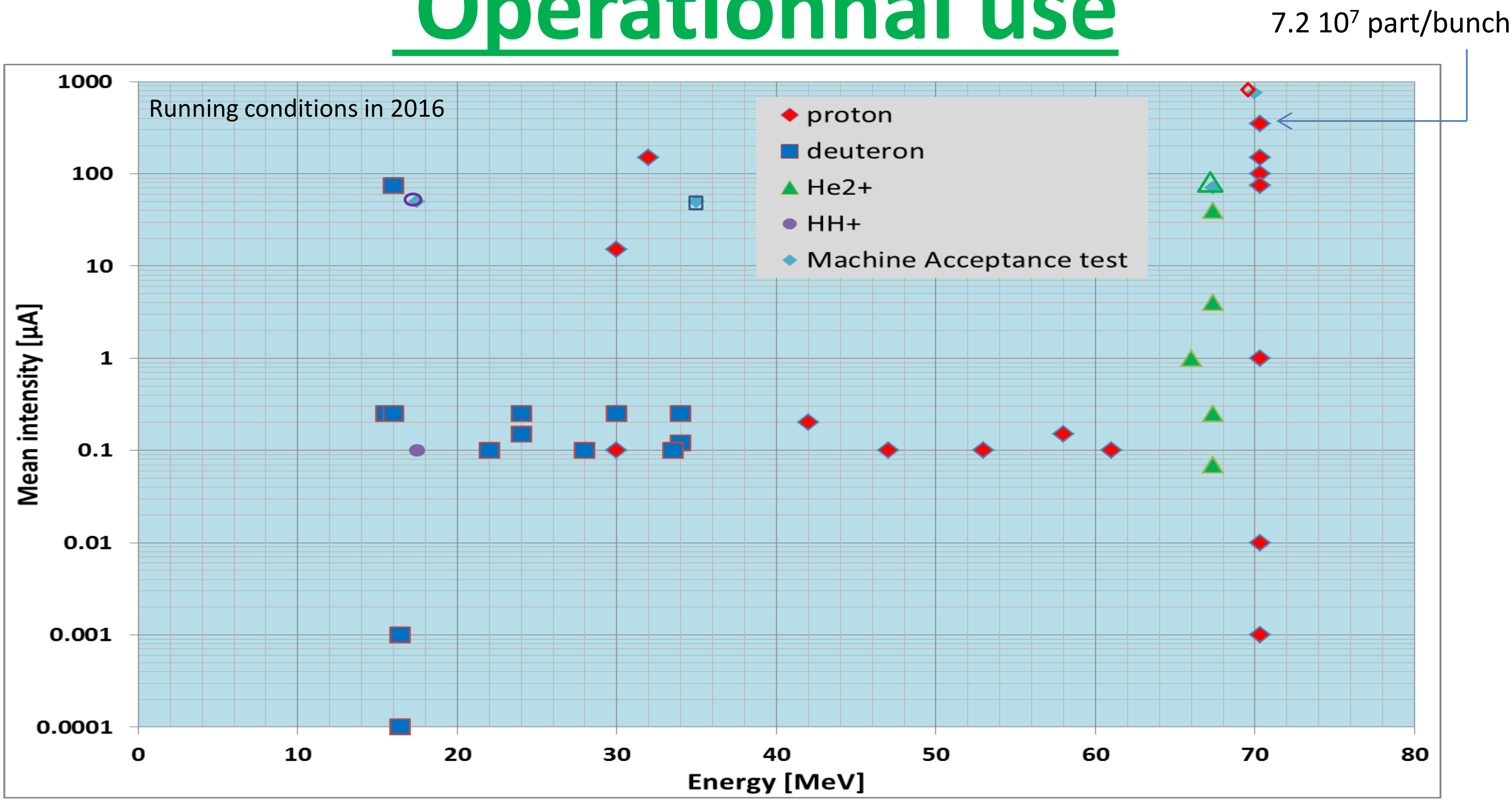
Beamlines



Irradiation station for rabbits at end of line
Cyclotron (30.45 MHz, 65 kV) in the central vault
3 beamlines in 6th vault: physics research
Ligne P3 / cible solide blindée
double cube + 15 kW + pumping unit + penning
P3
Irradiation station
Ligne P2 / cible solide
P2
P1
Alpha pulsing
Ligne AX4
Ligne AX3
Ax
Irradiation station
carbon α Energy Degraders
A2
A1
Proton degrader
Vault for the neutronic activator
used for high intensity
Ligne A1 / cible solide
Irradiation station

ARRONAX

Operationnal use

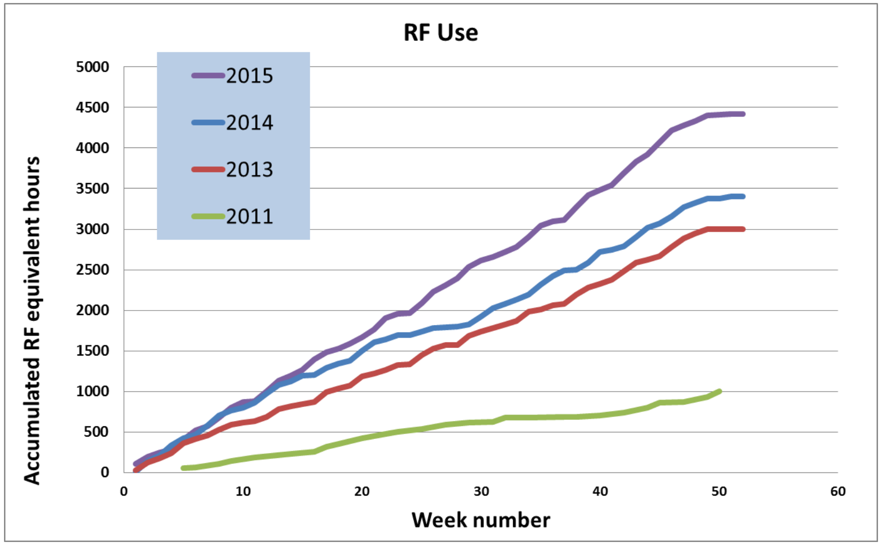


- **Large range of intensity and energy:**
  - 7 orders of magnitude of intensity
    - Runs for Radio-isotopes at high intensity and high integrated intensity
    - R&D runs → Precisions in operation
  - Several beamlines in use and bunches frequencies variation not included here

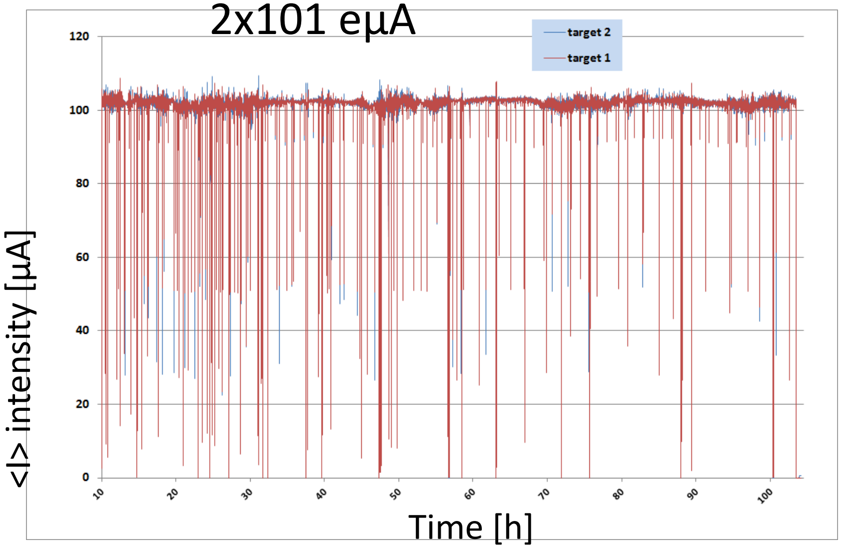
ARRONAX

afaq ISO 9001 Qualité AFNOR CERTIFICATION

Operations



A typical run for radio-isotope (beg. 2015)



- RF use:
  - 5 years of run
  - With increasing RF time usage:
    - 2014: 3400 h
    - 2015: 4400 h
    - 2016 (projected): similar
  - Including:
    - Runs at 350µA on target (neutronics)→>3500µAh
    - Couple of weeks at twice 100µA → 42000µAh

Dual mode operation:

✓ Here stable run over 98 hours

✓ <I>=101.5 eµA, $\sigma_{<i>}$=5.4 eµA

✓ Breakdowns = 1.8% of the overall time

✓ Vacuum in the center of the machine =4x10^7 mbar

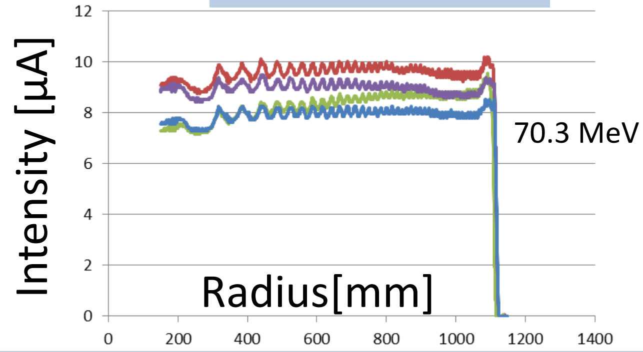
✓ Neutral current (H^0) = 9eµA in 2014 (18µA in 2012)

- Overall Machine operation can change over time
  - Global Instabilities on the beam characteristics
  - Settings
  - Elements (magnets,…)
  - Cooling
- Also Careful checks have to be performed as:
  - Beam at high intensity can lead to
    - Activation of beamlines component
    - Damages of beamlines component
    - Damages inside the machine
  - Beam Impacts the radio-isotopes target
    - Damages to the target

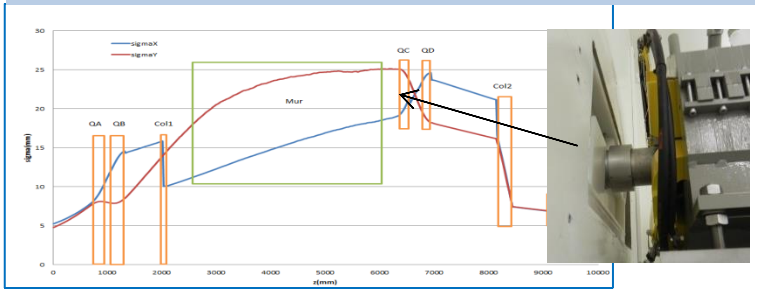
Some exemples

- Energy precision:
  - strippers at extraction indicated discrepancies
    - Checks with machine radial scan and users
      - Solution: recalibration & continuous checks
- Damages:
  - Lossed particles in the beamlines:
    - At location of maximum beamsize: gasket dammaged
      - Solution: protection & measurements (BLM)
  - Target destruction:
    - Peak in intensity due to miss-tuning
      - Solution: procedure and MPS limits
    - Note: This can have a major impact on the cooling facility

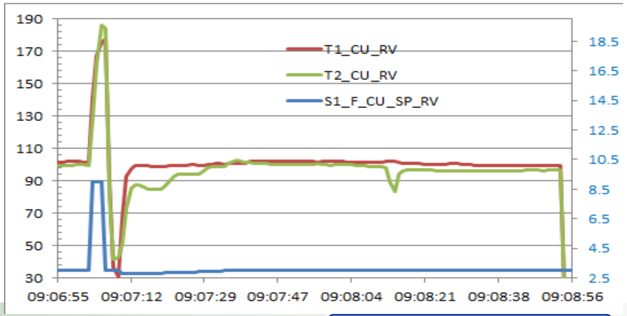
Radial scan



Beam transverse size along the line



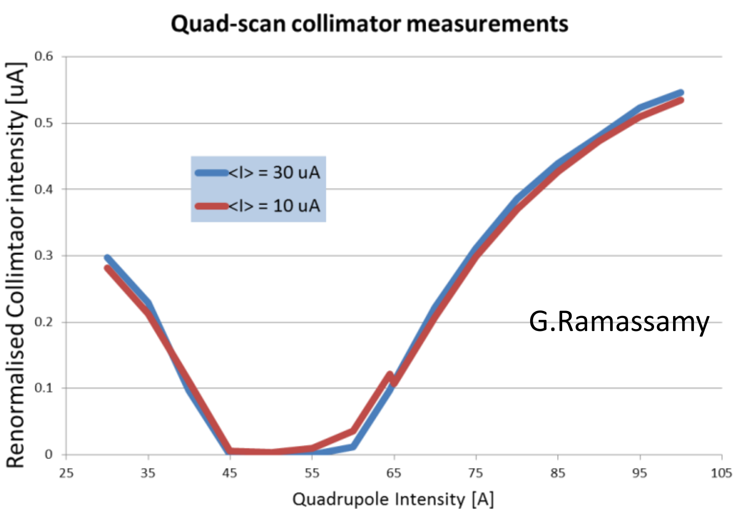
Peak intensity



Studies at intensity (>10uA)

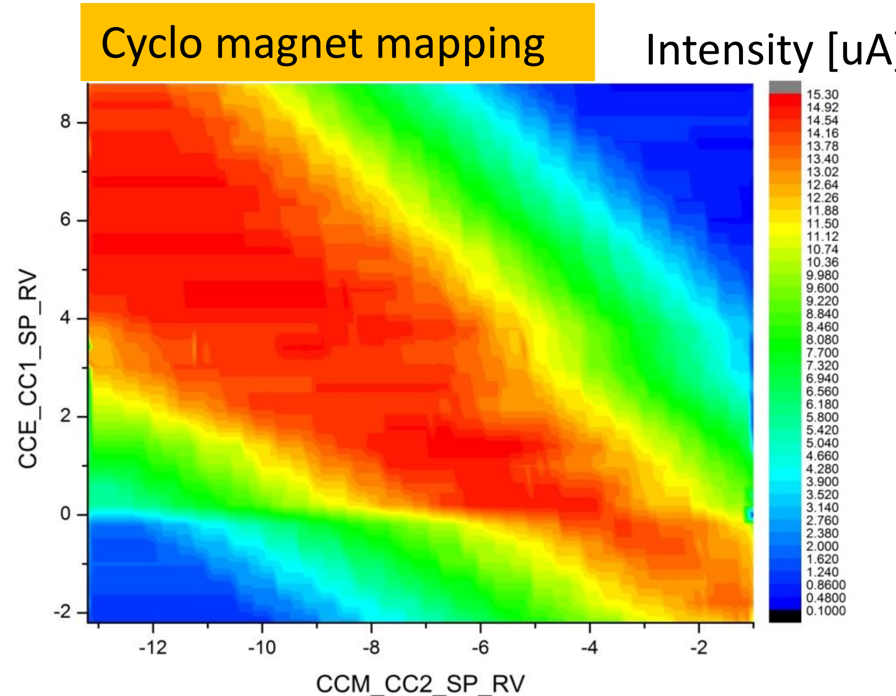
Are the settings in the machine and beamlines adequate?

- Mapping of the extracted intensity from the machine has shown several region to use/avoid, for the accelerator magnets setting:
  - Included check of isochronicity
  - On-going work for all magnets, history and pilots technics
  - On operation, setting modification accordingly
- Quad-scan to check the beam dimension and setting of the quads and losses along the beamlines



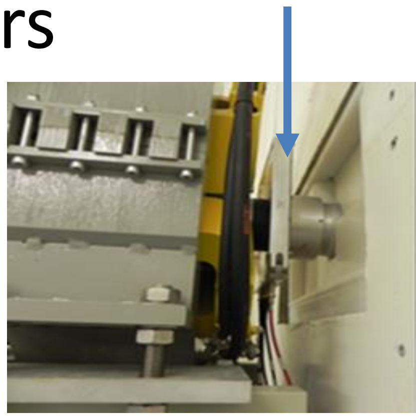
Quad-scan results

Cyclo magnet mapping



On-going Developments

- New upgrade on the control server → done
- Collaboration with IBA for new collimators
- Beam loss monitors (BLM)
  - 1 running prototype
  - On-going extension for several BLM



- Alpha pulsing: on-going work
- For the future:
  - Parallel data acquisition system for cyclotron and several diagnostics follow-up
  - Beamline modification

Conclusion

- Arronax C70 is up and running:
  - ~5 years of experience
  - Machine is used for very various and wide range of runs/parameters
  - Success in responding to the users needs (happy?)
- Maintenance and interventions are high:
  - New CMMS (maint. Management software) used → better tracking
  - 150 interventions/year
  - Specific applied maintenance technics due to activation in place
- Several developments are necessary and being done:
  - Tools for maintenance have to be developed
  - Beam diagnostics are highly needed
    - Looking for specialist and collaboration
- Beam dynamics studies and needs are slowly being addressed
  - First for operational requirements → the road is long

Thank you!

The ARRONAX project is supported by:

the **Regional Council of Pays de la Loire**

the **Université de Nantes**

the **French government** (CNRS, INSERM)

the **European Union**.

Several of these projects are supported in part by the “Agence National de la Recherche”, called “Investissements d’Avenir”, Equipex ArronaxPlus n°ANR-11-EQPX-0004

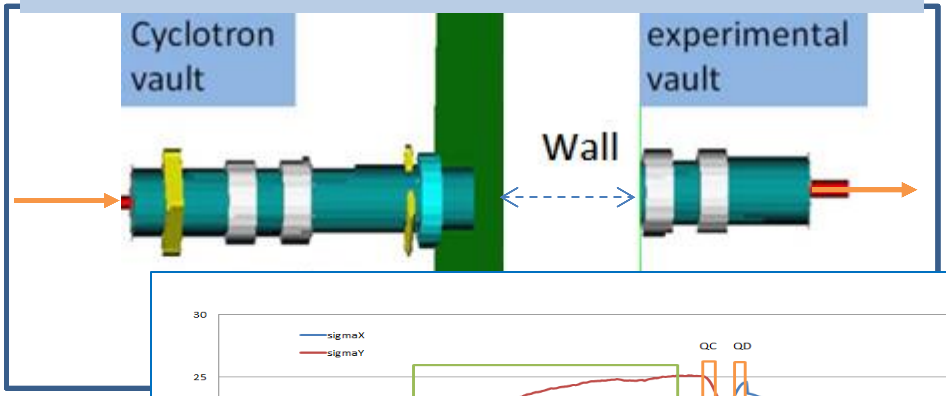
Arronax Plus

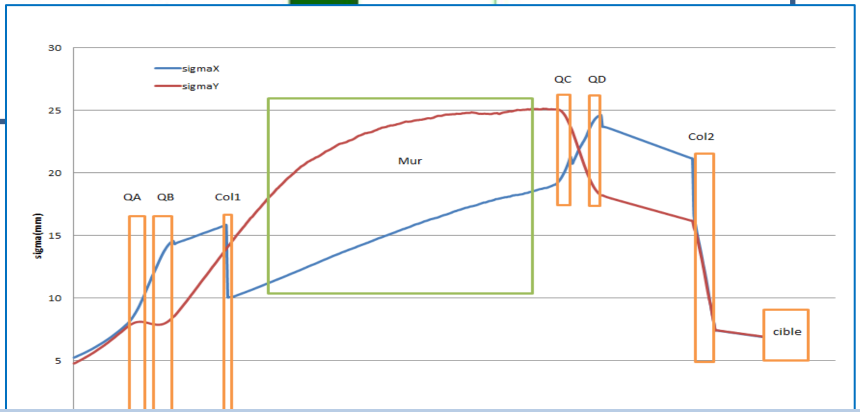
Simulation

- Development of simulation with G4beamline, Astra &Transport:
  - General simulation studies
  - Support and confirm Beam transport strategies
  - Benchmark/Confirmation of beam characteristics (beam size, particles losses, emittance,…) + users are in demand of this
  - Extrapolation to high current technique?

Exemples with G4beamline:

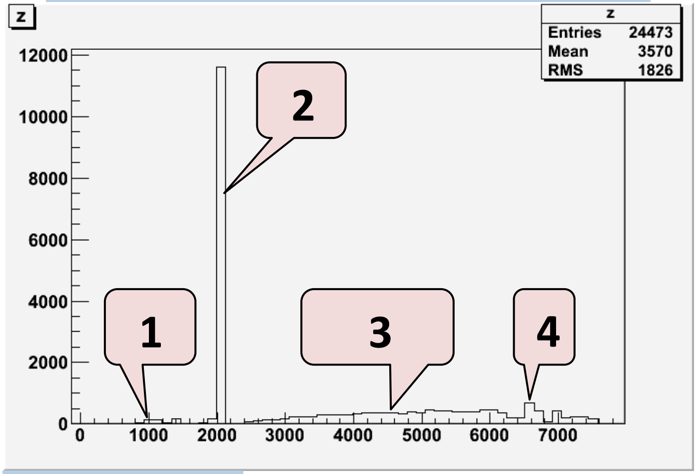
G4beamline beamline layout



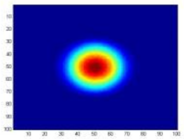


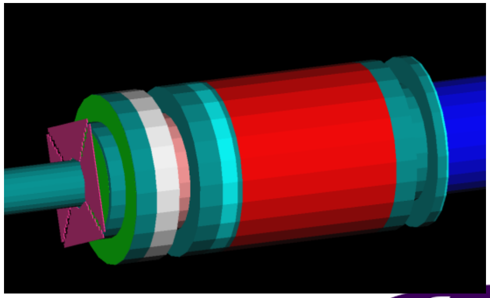
Beam transverse size along the line

particles losses along the beamline



Details close to beamline end

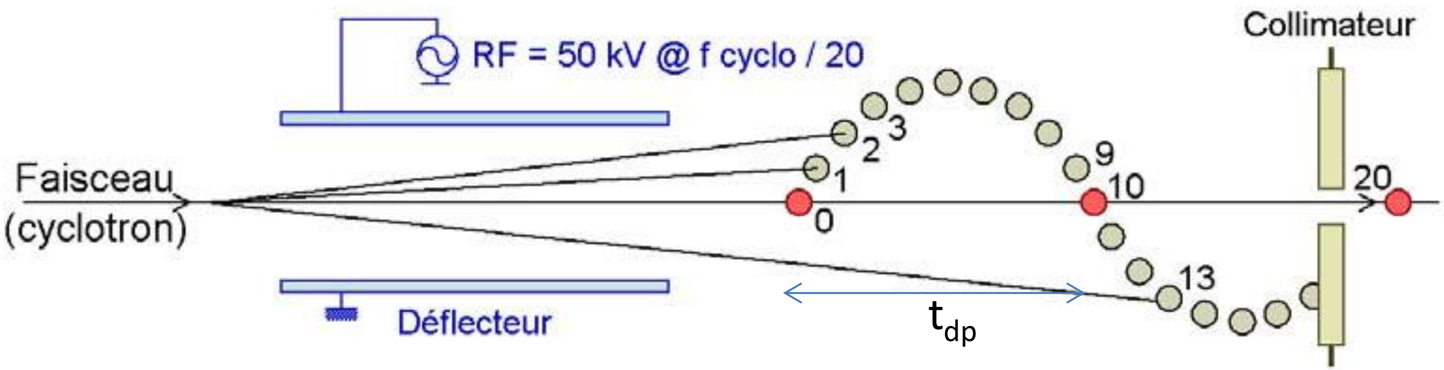




Works from students , W.Tan, D.Guiraud, S.Picot

Cyclotron Adaptations

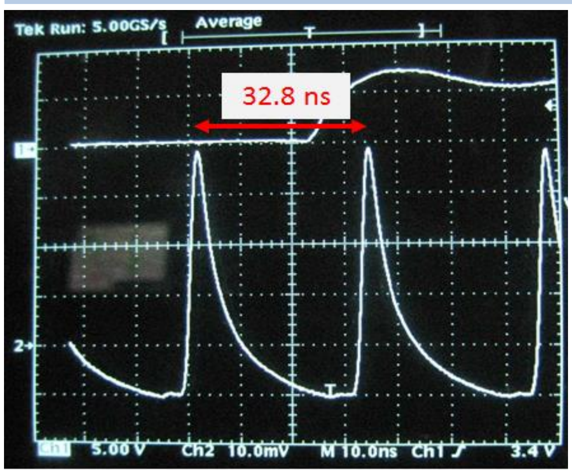
- Alpha pulsing: Deflectors for inter-bunch time modification (He2+/2011-12):
  - Periodic Deflector on the beamline 50 kV @ $f_{cyclo}/20$
  - Aperiodic Deflector in the injection timed to the period. def.



+

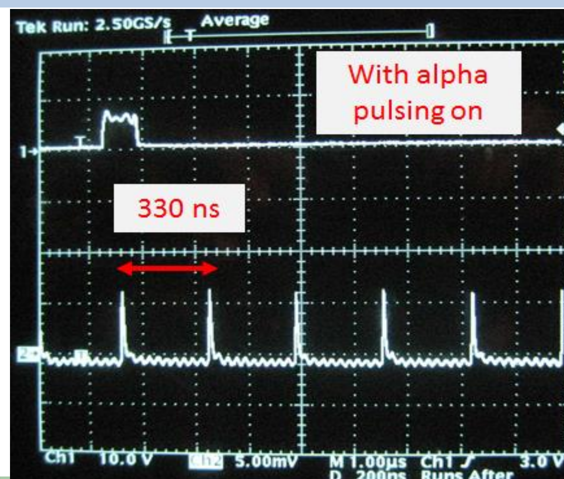
Aperiod. Def.: increases the inter-bunch time by n x t_{dp}.

Inter-bunch time from 330 ns to ~5 s



Combination of an aperiodic deflector in injection and a RF 50 kV, 1.5MHz deflector on the beamline.

GA + J.L Delvaux (IBA)

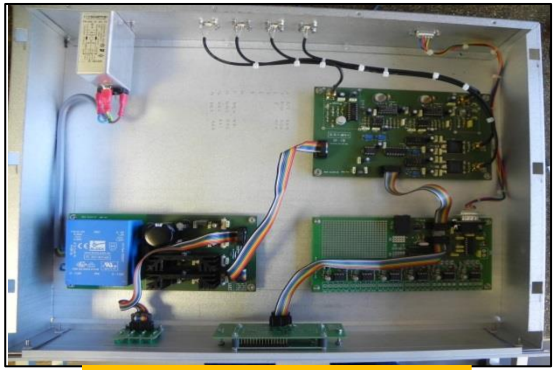


More work on transverse optimisation has to be done

To get towards more user friendly setup

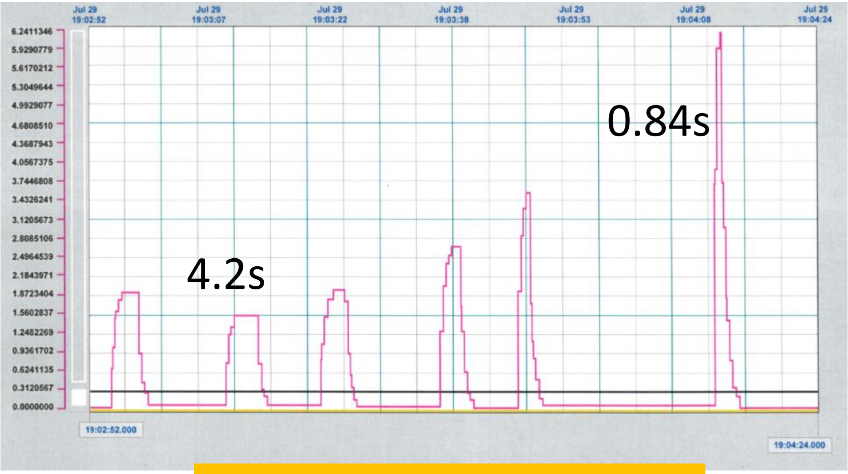
Alpha pulsing

- Goal: modify the inter-bunch space from 32.8 ns to ~5sec
- Initial system built by IBA.
  - Based on a 3kV chopper in the injection and a 50kV deflector in one beamline
- System adapted to new users specification: → bunch train
  - Drive the chopper to allow start/stop modes
  - Modify the electronics/software



New electronics

E. Mace



Proof of principle= ok

Diagnostics I

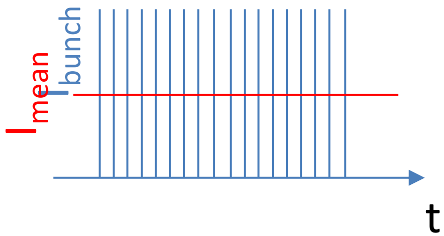
The main diagnostics are:

- **Current measurements (Imean):**
  - On the 4 individual fingers of the collimators → aperture from 10 to 30 mm limiting the transverse size right at exit of collimators,
  - Faraday cups:
    Water cooled layers of titanium /aluminium
    15kW max (i.e ~210µA at 70MeV)
  - Beam dumps combined or not with a current integrator (at very low current)

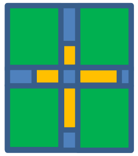
- **Profilers:** measures the beam density

- **Alumina foils:** or thin film foils for location and size measurements at end of line

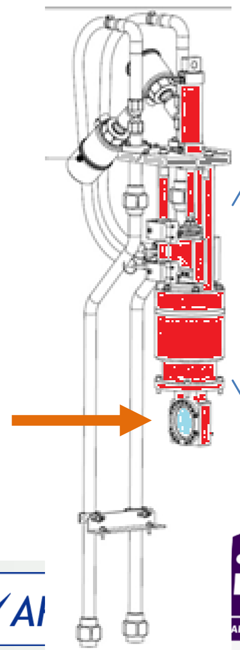
Mean current



Collimator readings

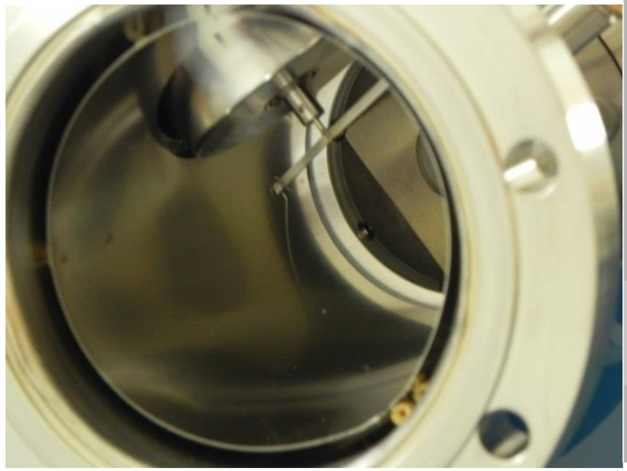


Faraday cup

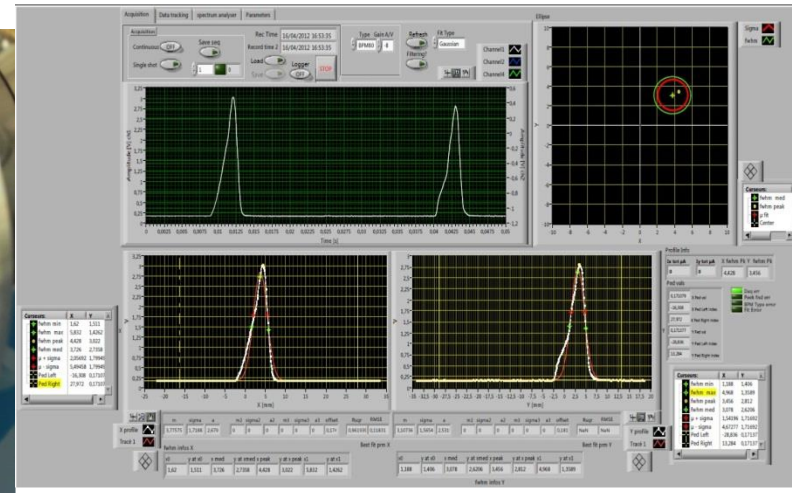


Diagnostics II

<u>Profiler NEC 80 (83)</u>:
- Installed downstream a collimator
- A single wire, frequency 18 Hz (19Hz)
- Helicoidal Radius = 2.7 cm (5.31)
- Limit (theo.)=150 µA for a 10 mm beam

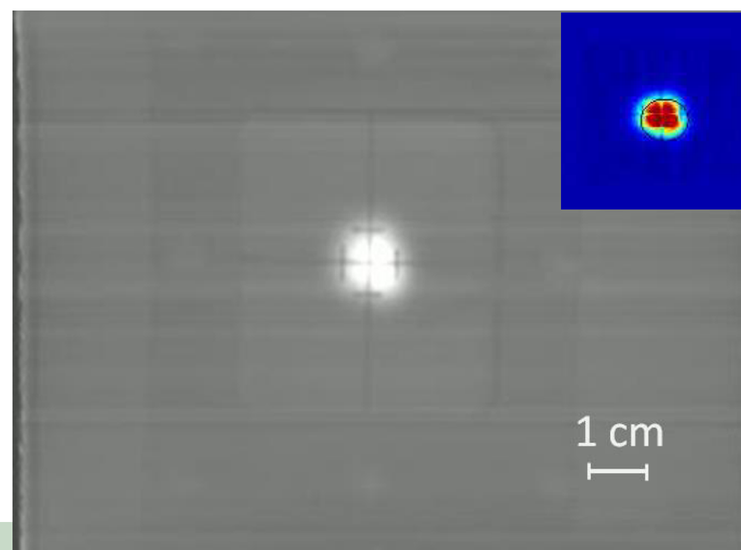


On-line analysis of beam *x-y* density



<u>Alumina foil</u> (AlO3) - thickness 1 mm:
- Installed outside the line, downstream the exit thin kapton (75 µm) window
- Check of the center and beam size
- ~1nA <I_{moy}<~150 nA for protons and alpha
- Vidikon Camera (radiation hard)

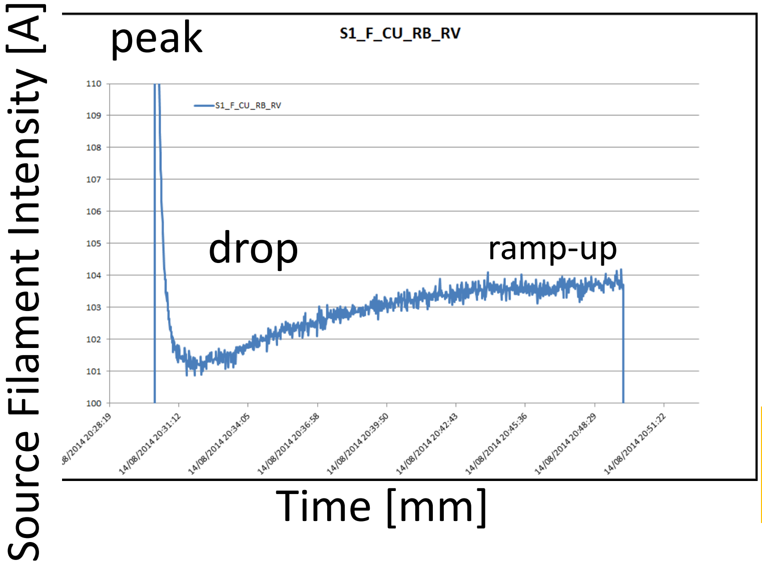
- → Off-line analysis code is developed in GMO, based a Matlab tool from LAL.



Machine studies

- Mostly driven by users needs:
  - Beginning of 2015 at high current,
    - started to have major beamline gaskets and target dammages
    - Exact reasons unknown (→ beam dynamics related studies – see later slide)
  - Users wants to have lower intensity/more precise beam in a short time
- The studies spans over:
  - Source studies
  - End-of-line beam characteristics
  - Mapping of the magnets
  - Beamlines beam dynamics studies including quad-scan

Studies at low intensity (<1uA)



Intensity from the source follows a specific pattern (peak, drop and ramp-up) before stabilisation which occurs after several tens of minutes:

- Impact on how early we can do a stable beam
- Impact on how soon we can perform maintenance (exponential decrease kicks-in)

→Adaptation of source filament use
(confirmed also with end-of-line users measurements)

Beam stability at low current 20 pA
(Dosion – LPC Caen/Arronax team):

Intensity
Geometry

→ 40 µm beam geometric instability: recipe in use validated for this specific use (with strategy of beam blow-up in injection)