The C70 ARRONAX Hands-on phase and operation

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

Operation and Maintenance team:
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C.Huet, L.Lamouric, E.Mace,
F.Poirier

IPAC 2011: “C70 and beamlines status”, WEPS69
IPAC 2012: “C70 Hands-on phase”, MOPPD024

Cyclotron ARRONAX
Historical Background

- October 2008: Inauguration
- March 2010: Low intensity Irradiation
- October 2010: 24h at 750 pμA on beam dumps
- Dec. 2010: Final machine reception
- 2011-12: Hands-on phase with an extended program on tuning and exploration of beam parameters for users.
ARRONAX goal

- A tool to produce radionuclides for research in nuclear medicine
  - Imaging: $\beta^+$ radioelements for PET (ex: $^{82}\text{Sr}/^{82}\text{Rb}, ^{44m/44}\text{Sc}, ^{52}\text{Fe}, ^{64}\text{Cu}$ ...)
  - Therapy: $\alpha$ immunotherapy ($^{211}\text{At}$), $\beta$ radioelements: $^{67}\text{Cu}, ^{47}\text{Sc}$

Radioelement for therapy

- Acceleration
- Particles Beam
- Target irradiation
- Production of radioelements in the target by transmutation
- Chemical extraction
- Separation
- Purification
- Marking

Tomographic imaging of the heart

- Cyclotron ARRONAX
- Radioactive medical element (experimental)
- $^{99}\text{Tc}$-MIBI SPECT
- $^{82}\text{Rb}$-PET
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- A tool for radiochemistry/radiobiology research
  - notably alpha radiolyse of water (eg nuclear waste storage)
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  - notably alpha radiolysis of water (eg nuclear waste storage)

- A tool for physics research
  - Particularly studies of material under irradiation
  - Development of detection system
  - Measurements of nuclear data

Experience « Stacked Foils »
Cross section measurements:
exemple from 17 to 69 MeV- (100 nA)

PIXE - Particle Induced X-ray Emission
- Non destructive Characterisation Method of multielements material, quantitative
- Dvt of measuring bench
- (~nA)
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- A tool for training and education
  - University of Nantes
  - École des mines of Nantes
  - CHU (academic hospital) of Nantes
  - Permanent and dedicated trainings

- An industrial production site for medical needs
Characteristics

- **C70 Cyclotron build by IBA:**
  - Isochron cyclotron with 4 sectors
    - RF: 30.45 MHz
    - Acceleration Voltage: 65 kV
    - Max magn. field: 1.6T
  - ~4m of diameter
  - Max kinetic energy/n: 30-70 MeV
  - Normalised emittance before extraction: $\gamma e_x = \sim 4\pi$ 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 to adapt the beam to the entrance of the cyclotron, and finally the spiral inflector
  - Extraction: stripper (-) or electrostatic deflector (+)

<table>
<thead>
<tr>
<th>Extracted Particles</th>
<th>Energy range (MeV)</th>
<th>Highest possible current (µAe)</th>
<th>most common current range (µAe)</th>
<th>Nb of particles / bunch at 1 µAe</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+</td>
<td>30 - 70</td>
<td>375 x 2</td>
<td>0.05 – 80 x 2</td>
<td>205 $10^3$</td>
</tr>
<tr>
<td>He2+</td>
<td>70</td>
<td>70</td>
<td>0.07 – 0.1</td>
<td>102 $10^3$</td>
</tr>
<tr>
<td>HH+</td>
<td>35</td>
<td>50</td>
<td>0.1 – 1</td>
<td>410 $10^3$</td>
</tr>
<tr>
<td>D+</td>
<td>15 - 35</td>
<td>50</td>
<td>0.05 – 1.2</td>
<td>205 $10^3$</td>
</tr>
</tbody>
</table>

- **2 strippers:** carbon based foils, eff=\sim 95%
- **1 deflector:** 66kV, eff<<90%
Beamlines Today

6 vaults, around the cyclotron, accommodate the beamlines

Beamline with irradiation station accommodating rabbits with samples

Beamline for neutronic activator

3 beamlines are dedicated to low current (<1.2 μA) in the same vault
1 of these is a top-bottom line with a vertical dipole

Beamlines:
- 8 in total
  - 5 dedicated to average and high current
  - 3 dedicated to low (or very low) current

Cyclotron ARRONAX
Operators deal with basically every aspects of the accelerator: Operation, maintenance, users, developments (beamline, diagnostics), computers, mechanics, beam dynamics.

To comply with french law on industrial accelerators (yes this cyclotron falls into this class by its use), they have to pass a national certificate: camari

Each operator is 3 times a week in charge of the operation with/without a senior (that is when every one is on site) for none “heavy weeks”.

GMO: 6 persons
3 have more than 3 years of experience and are “senior operators”
Operations

Very diverse weeks in terms of beam parameters and beamlines: particles types, energies, beam size, inter-bunch time,...

“None-heavy” operational weeks:

<table>
<thead>
<tr>
<th>Maintenance</th>
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<tbody>
<tr>
<td>D+</td>
</tr>
<tr>
<td>He2+</td>
</tr>
<tr>
<td>H+</td>
</tr>
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</table>

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<tbody>
<tr>
<td>CC</td>
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<tr>
<td>P1</td>
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<td>P2</td>
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<td>P3</td>
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<td>A1</td>
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<td>A2</td>
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<tr>
<td>AX3</td>
<td></td>
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<td></td>
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<tr>
<td>AX4</td>
<td></td>
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<td></td>
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<tr>
<td>AX5</td>
<td></td>
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</tbody>
</table>

Tuning of the machine and beamline is performed before sending the beam to the users and can take up to a few hours

+ heavy weeks: so called production week: Approximately, once a month over a week the group is on 24h operation with 38.5 hours/week/ope

Require a minimum of 4 persons for this

Agenda of a scheduled week not a cyclotron/beamline use
For these production weeks: e.g. 24 hours/days over 5 days

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<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mornings</td>
<td>6h30 → 14h12</td>
<td>x5/week</td>
<td>op1</td>
</tr>
<tr>
<td>Evenings</td>
<td>14h00 → 21h42</td>
<td>x5/week</td>
<td>op2</td>
</tr>
<tr>
<td>Nights*</td>
<td>21h15 → 6h45</td>
<td>x4/week</td>
<td>op3</td>
</tr>
<tr>
<td>Days</td>
<td>9h00 → 17h42</td>
<td>x5/week</td>
<td>op4 (5-6)</td>
</tr>
</tbody>
</table>

With this scheme (tested 3 times so far) each operator keeps the same time slot: 
Results:
- Worked well but
- Tiredness
- Operation Information is being lost (to some degree), counterbalanced by the use of elog

15 to 30 min of overlay between shifts
+ op during days to help deal with operation + maintenance
*Backed up by the presence of a lab personnel

Cyclotron ARRONAX
Single 80 µA runs on target at irradiation station

- 80.23 µA, $\sigma_{\langle i \rangle} = 1.35$ µA
- 1.6% intensity losses (of overall time)

Dual run:
- $\sigma_{\langle i \rangle} = 2.2$ µA (average over both beams)

Stability studies: in view of safety of machine, beamlines, and targets before intensity ramp-ups

Operators are constantly tuning the machine even on steady runs

On neutronic activator 300 µA

Test of strategy for current ramp-ups up to 200 µA and to 300 µA (Constrains from the user are in addition)
Beam Transport and lines

~10-15 m

Switching magnets
- Steerers
- Quadrupoles 10T/m max
- Wobbler
- Faraday cups
- Collimators
- Diagnostics

Need for Beam Transport Strategy

- It is primarily dependent on what is behind the collimators i.e. if the experimental target is far downstream and which intensity is used.
1) Current optimisation, using inserted Faraday cups, and/or beam dumps at end of line if there is one
2) Beam transverse size optimisation
   - At high current and on an irradiation station with a rabbit, the beam is centred on the collimators upstream the station. The electrical deposit is the measurements
   - At low current, and for specific needs, optimisation is slightly more complex and relies on dipoles and quadrupoles modifications to get the right beam.

→ diagnostics

Cyclotron ARRONAX
The main diagnostics are:

- **Current measurements (I_{mean}):**
  - 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
Diagnostics II

Profiler NEC 80 (83):
- 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

Alumina foil (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.

On-line analysis of beam x-y density

Cyclotron ARRONAX
Maintenance

• The maintenance knowledge is mainly based on existing Cyclotron at lower energies (30 MeV) for Preventive
• Curative: The strategy used here is get-to-know the machine
  – 4 weeks/year: Main maintenance (done with GMO/IBA)
  – Weekly (Mondays) beamline-cyclotron round watch:
    • List of check-ups done by ARRONAX maintenance group.
  – Building up a “memory” of the machine problems via an electronic logbook (see later)
  – Keeping the information flow between cyclotron designer and ARRONAX (both ways):
    • Tasks/Information exchange charts in use at each IBA/Arronax technical meeting since beg. 2011. (very helpful to recall problems and keep tracks, and make sure there is a resolution in view)
  – Training of the GMO team with radio protection group
**Electronic log book (elog)**

- Multi-parameters table filled in by the GMO (Operation & Maintenance Group) → from PSI

<table>
<thead>
<tr>
<th>ID</th>
<th>Date d'intervention</th>
<th>Motif intervention</th>
<th>Interventionant</th>
<th>Structure</th>
<th>Localisation</th>
<th>Equipement</th>
<th>Statut Cycle</th>
<th>Etat après intervention</th>
<th>Action</th>
<th>Texte</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>vendredi, 01 avril 2011 - 17:03</td>
<td>Surveillance</td>
<td>PORIER P.</td>
<td>Cyclo</td>
<td>Ax3</td>
<td>Circuits de refroidissement</td>
<td>Intervention sans conséquence</td>
<td>OK</td>
<td>Déclaration/Diagnostique</td>
<td></td>
</tr>
<tr>
<td>68</td>
<td>mardi, 16 août 2011 - 16:28</td>
<td>Panne</td>
<td>MACE E.</td>
<td>Cyclo</td>
<td>salle alimentation</td>
<td>Magnétome</td>
<td>Intervention sans conséquence</td>
<td>OK</td>
<td>Termine</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>vendredi, 08 juillet 2011 - 13:56</td>
<td>Preventif</td>
<td>GIRAILT S.</td>
<td>Cyclo</td>
<td>Ax4</td>
<td>Lignes transport eau radioactive</td>
<td>Intervention sans conséquence</td>
<td>OK</td>
<td>Déclaration/Diagnostique</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>mercredi, 16 mars 2011 - 16:37</td>
<td>Panne</td>
<td>MACE E.</td>
<td>Cyclo</td>
<td>salle alimentation</td>
<td>RF (amplis; Dose; Accord Gene)</td>
<td>à arrêter</td>
<td>OK</td>
<td>Termine</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>vendredi, 22 juillet 2011 - 13:53</td>
<td>Panne</td>
<td>HUET C.</td>
<td>Cyclo</td>
<td>salle alimentation</td>
<td>Stations d'irradiation</td>
<td>possible</td>
<td>OK</td>
<td>Termine</td>
<td></td>
</tr>
</tbody>
</table>

**Maintenance (12 global parameters):**
- ID number
- Message Date
- Intervention date
- Intervention reason (failure, surveillance, preparation)
- Person in charge
- Structure (cyclo, environment)
- Location (beamlines, cyclo, technical rooms,...)
- Equipment (beam dump, irradiation stations, strippers, sources, water cooling, cryo pump,...)
- Status of the cyclotron
- Action (finished, ongoing,...)
- Comments + attached files

**Beam on (25 parameters):**
- Pilots, particles, beamlines, targets, energy, current, comments, attached files,...

This is not a tracking tool but it will help to define later the data base required
Present and Future

• The C70 ARRONAX cyclotron prototype is in the hands-on phase:
  – Operations et Maintenances have lead to a high beam uptime (>85%)
    • Injection solenoid has been changed
  – The maintenance and operation group in charge of the cyclotron and its beamlines are gathering the know-how, important for the future of the machine:
    • Time constrain from future users will tighten
    • Towards 3x8 hours and more “industrial standards”

• For the long term use:
  – Some key points to consolidate:
    • Beam strategy optimisation and tuning
    • Studies on beam repeatability
    • Beam characterisation: off-line & on-line codes to check beams
  – Some necessary work: Extension of diagnostics
    • Energy measurements after degradation
    • Studies for Beam Loss monitor, Beam position monitor, ....
    • Development of Data acquisition system for beamlines, cyclotron
  – Continuous development of lines and cyclotron:
    • Installation of energy degrader
    • Neutronic activator (several beam tests done → ok)
    • Increase of current sent to the sample carriers (rabbits).
Further

• The group will grow up in numbers
  – Plan is mostly to keep them with operation/maintenance tasks + a specialisation
  – Still relying a lot on flexibility of the operators as we are far from smooth operation
  – Nearly no automation in beam tuning:
    • New possible scheme is being studied based on new diagnostics to be put in: with a Parallel machine/human interface (manpower...gasp!) connected to existing PLC
  – Operators agenda will probably change in view of the latest runs
  – One of the hot topics that we can foresee is communication and tracking information:
    • We’ll look at tools (software) that offer this possibilities: CMMS + APS?
Thank you!
Cyclotron Adaptations

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

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.
- GMO + J.L Delvaux (IBA)

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

More work on transverse optimisation has to be done.

To get towards more user friendly setup.
Beamline Adaptations

- Energy degrader for proton and alpha (Subatech/ARRONAX)
  - In order to get a larger range of available energies (10 to 30 MeV)
    - Protons: Aluminium window of diameter= 10 mm, water thickness = 0.7 mm
    - Alpha: Rotating wheel with 20 aluminium plates (1.25 mm thick)
  - Degrader Installation has been done and the water cooling system has been tested
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?

An exemple with G4beamline:

G4beamline beamline layout

Particles losses along the beamline

Beam transverse size along the line

Preliminary work from <2 student, W.Tan - EMN