Studies and Upgrades on the cyclotron C70 ARRONAX

Freddy Poirier (Arronax/CNRS)

On behalf of the accelerator group

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

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

ARRONAX

Tuesday, the 12th of September 2016
Proton cyclotrons and linacs for radio-isotopes
(tentative map)

Arronax is positioned among the high power cyclotrons

Several new proton machines are being commissioned/built at 70 MeV (IBA/Best)
Characteristics

- C70 Cyclotron 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: $\gamma\varepsilon_x = 4\pi \text{ mm mrad} \ (\text{simulation})$

- 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 (+)

![Diagram of cyclotron components]

- 2 strippers: carbon based foils, eff=95%
- 1 deflector: 66kV, eff<<90%
- Running
- Testing/modification

Vault for the neutronic activator

New Neut. Activator

Water cooling

Alpha pulsing

Simplified carbon α Energy Degraders

Proton degrader

Irradiation station

Irradiation station

Irradiation station

Irradiation station for rabbits at end of line

Cyclotron (30.45 MHz, 65 kV) in the central vault

3 beamlines in 6th vault with a top-bottom capability, used mostly for low current experiments e.g. PIXE, stacked foils, radiolysis, physics, radiobiology. Beam exit from a kapton foil
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
Operations

• RF use:
  – 2015: 4400 hours
  – 2016 (projected): similar

Dual mode operation with protons:
✓ Here stable run over 98 hours
✓ $\langle I \rangle = 101.5 \, \text{e}\mu\text{A}$, $\sigma_{\langle I \rangle} = 5.4 \, \text{e}\mu\text{A}$
✓ Breakdowns $= 1.8\%$ of the overall time
✓ Vacuum in the center of the machine $= 4 \times 10^7 \, \text{mbar}$
✓ Neutral current $(H^0) = 9 \, \text{e}\mu\text{A}$ in 2014 (18µA in 2012)

Now running at 150µA on target
Machine studies

• Twofolds, mostly driven by users needs
  – Users wants high current,
    • Mitigate potential target damages (beamline also)
  – 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 (towards emittance measurements)
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)
Studies at high intensity (>10uA)

Are the settings in the machine adequate?

- 3 Compensation coils in addition to the main coil
- 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

Magnetic field in the machine

Additional compensation coils

Cyclo magnet mapping

Stable area

Intensity [uA] on faraday cups at extraction
Studies at high intensity (>10uA)

- Are the settings in the beamlines adequate?
  - Quad-scan to check the beam dimension and setting of the quads and losses along the beamlines
  - Can the beam characteristics be tackled? Emittance?

Using a simulation model, and a technique close to single wire but with collimators, first measurements of the emittance were performed at Arronax:
- Indicated us that we can approach the emittance measurements without new tools:
  - It takes time though and needs dedicated scans
On-going Developments

- New upgrade on the control server → done
- Collaboration with IBA for new collimators
- Beam loss monitors (BLM)
  - 1 running prototype
    - EPICS updated system thanks to Master students and iThemba
- Alpha pulsing: on-going work (next slide)
- Parallel data acquisition system for cyclotron → done
- For the future:
  - extension for several BLM
  - Beamline modification
  - Extension of our EPICS network to support beam and technical diagnostics
Pulsation

- **Goal:** modify the inter-bunch space from 32.8 ns to a few millisec
- **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
  - Adapted for all particles

New electronics and EPICS control system

A.Leateron, E. Mace + previous M2 students

Proof of principle = ok
Control system adequate for trains

Users also want to have trains with only 32.8 ns inter-bunch time →
Need to change the power system of the chopper: Solid-state?
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 and techniques for maintenance have to be developed
  – Operation:
    • Implementation of a foundation to support EPICS software based tools
  – Beam diagnostics are highly needed
    • Looking for specialist and collaborations
  – Thorough simulations of accelerator/beamlines are also needed:
    • Help to grasp the impact of the parameters
    • Help to refine the technics (emittance measurements, ballistic beam-based alignment?)
• Thank you!

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ARRONAX Activities

- 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 ($^{211}\text{At} \rightarrow$ preclinic phase), $\beta$-radioelements: $^{64}\text{Cu}$ (preclinic phase), $^{47}\text{Sc}$

![Diagram of radioelement production and imaging](image-url)
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- A tool for radiochemistry & radiobiology research
  - Specifically alpha radiolysis of water (eg nuclear waste storage).
  - Radiobiology with characterisation of dosimetry tools and living cells (with GANIL,ICO,INFN)

- An outil for the research in Physics
  - Notably study of materials under radiation
  - Development of detection systems
  - Measurements of nuclear data

- An outil for training
  - Université de Nantes
  - Ecole des mines de Nantes
  - CHU de Nantes
  - Continuing education

- A site of industrial production for medical needs

- OH production at 62 MeV
  - M. Fattahi et al. (Subatech)

- Alpha 13MeV/u
  - C. Koumeir, et al.

- Radiograpf-chromatic characterisation after irradiation
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PIXE/PIGE - Particle Induced X-ray Emission
- Non destructive Characterisation Method of multielements material, quantitative
- Dvt of measuring benches
- (~nA)

Experiment « Stacked Foils » - Sc44
Cross section measurements:
example from 9 to 35 MeV- (100 nA)

C.Duchemin
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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
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

Particles losses along the beamline

Beam transverse size along the line

Details close to beamline end

Works from students, W. Tan, D. Guiraud, S. Picot
Cyclotron initial alpha pulsing

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

Chopper:
- 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

Inter-bunch time from 330 ns to ~5 s

![Graph showing inter-bunch time](image-url)

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

GA + J.L Delvaux (IBA)
Diagnostics I

The main diagnostics are:
- **Current measurements** ($I_{\text{mean}}$):
  - 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)
- **Profiler**: measures the beam density
- **Alumina foils**: or thin film foils for location and size measurements at end of line
Diagnostics II (low intensity)

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