The MYRRHA LEBT
Commissioning & Space Charge Compensation Experiments

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The MYRRHA project

MYRRHA
Multi-purpose hYbrid Research Reactor for High-tech Applications
At Mol (Belgium)

Demonstrate the physics and technology of an Accelerator Driven System (ADS) for transmuting long-lived radioactive waste

High power proton beam (up to 2.4 MW)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tr>
<td>Proton energy</td>
<td>600 MeV</td>
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<tr>
<td>Peak beam current</td>
<td>0.1 to 4.0 mA</td>
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<td>Repetition rate</td>
<td>1 to 250 Hz</td>
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<td>Beam duty cycle</td>
<td>$10^4$ to 1</td>
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<td>Beam power stability</td>
<td>$\pm 2%$ on a time scale of 100ms</td>
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<td>Beam footprint on reactor window</td>
<td>Circular $\varnothing 85$ mm</td>
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<td>Beam footprint stability</td>
<td>$\pm 10%$ on a time scale of 1s</td>
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<tr>
<td># of allowed beam trips on reactor longer than 3 sec</td>
<td>10 maximum per 3-month operation period</td>
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<td># of allowed beam trips on reactor longer than 0.1 sec</td>
<td>100 maximum per day</td>
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<tr>
<td># of allowed beam trips on reactor shorter than 0.1 sec</td>
<td>unlimited</td>
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Extreme reliability

- to minimise thermal stress and fatigue on target, reactor core,...
- to ensure 80% availability (reactor re-start procedures: ~20 h).
Reliability guidelines for an ADS accelerator design:

- **Robust design** i.e. robust optics, simplicity, low thermal stress, operation margins...
- **Redundancy** (serial where possible, or parallel) to be able to tolerate/mitigate failures
- **Repairability** (on-line where possible) and efficient maintenance schemes

Layout of the MYRRHA linac: **Double injector + Superconducting linac**

![Diagram of MYRRHA Linac Design]( Courtesy of J.-L. Biarrotte)
### Accelerator Background & Project Support

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<td><strong>End 90’s : 1st accelerator projects for ADS (APT/AAA, TRASCO, …)</strong></td>
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<td><strong>2002-2005 : MYRRHA as one of the 3 reactor designs within the PDS-XADS FP5 project</strong></td>
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**Eurotrans (FP6)**
MYRRHA : XT-ADS demo.
Linac 600 Mev – R&D on reliability-
GUINEVERE & GENEPI-3C

**MAX (FP7)**
- Start-to-end reference design w. error study
- Prototyping : elliptical and spoke cavity, RF ampli., RFQ mock-up, CH-DTL cavities
- Reliability model
- Design Review

**CDT (FP7) – HEBT design**

**MARISA (FP7)**
LEBT construction – 176 MHz RF amplifier–

**MYRTE (H2020)**
- Injector construction & commissioning
- Beam Characterisation & Control
- SRF cavities (spoke Cryomodule – CH )
- Reliability & specific R&D

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**MYRRHA PHASE 1 (100 MeV)**
Construction & Commissioning of the first Accelerator section -> 100 MeV
**MYRRHA Linac injector**

![Diagram of MYRRHA Linac injector with energy levels and components](image)

Source & LEBT

176.1 MHz 4-Rod RFQ

CH-cavities

30 keV

1.5 MeV

5.9 MeV

17 MeV

32 m

**TUPVA062**: Construction of the MYRRHA Injector, D. Mäder et al.

**TUPVA068**: The New Injector Design for MYRRHA, K. Kümpel et al.

**TUPVA069**: Test of a High Power Room Temperature CH DTL Cavity, N. F. Petry et al.

**TUPVA070**: Dipole Compensation of the 176 MHz MYRRHA RFQ, K. Kümpel et al.

**TUPVA071**: The MYRRHA RFQ: Status and First Measurements, H. Podlech et al.

**THPVA006**: Space-Charge Compensation in the Transition Area Between LEBT and RFQ, P. Schneider et al.
LEBT Functions

• The Low Energy Beam Transfer line (LEBT) is the first 3 meters of the MYRRHA accelerator

• Ensure the ‘safe’ beam transport from the source to the RFQ:
  ➢ Minimise the beam losses → Increased Reliability

• Condition the beam for the RFQ
  ➢ Required parameters at the RFQ entrance:
    \[ \varepsilon_{\text{RMS,norm.proton}} \leq 0.2 \pi \text{ mm.mrad} \]
    \[ \beta = 0.04 \text{ mm}/\pi \text{ mrad} \]
    \[ \alpha = 0.88 \]

• ‘Clean’ the proton beam from other species \((H_2^+, H_3^+)\)
  ➢ The ion source produces protons but also \(H_2^+, H_3^+\) (ionisation of \(H_2\) gas)

• Give/Create the temporal beam time structure (‘holes’ / pseudo-pulsed beam / power mitigation)

\emph{Proposed MYRRHA beam time structure for operation:}

- long blue pulses are sent to the reactor (mean power is adjusting with pulse length)
- short red ones are sent to ISOL experiment
MYRRHA LEBT Design and Construction

- Design, Construction & Commissioning funded by EU projects (MAX, MARISA, MYRTE) and SCK-CEN

- Collaboration:
  - **LPSC (CNRS)**: solenoid design, collimation, vacuum chamber, experimental area, part of the control system, ...
  - **SCK-CEN**: Chopper + collimation cone, ...
  - **Cosylab (+ADEX)**: Specific control system developments

- **Compact design**: ~ 3 meters long with two solenoids
  - A minimum of elements/magnet to tune (Reliability)
  - Simple design (Reliability)
  - Minimise the number of electrostatic elements (Reliability)
  - Shorter Space Charge Compensation transients than in a longer version
  - No ‘clean’ ions separation to ensure a direct proton current monitoring

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TUPAB092: MYRRHA Control System Development, R. Modic et al.
Beam dynamics : Space Charge & Compensation

- **Defocusing effect**: Coulomb repulsion of charged particles inside the beam

- **2 contributions (Lorentz)**:
  - Electrostatic: repelling Force
  - Magnetic: attractive Force (charged particles in movement)

  Radial force seen by one particle of a continuous (DC) cylindrical and homogenous beam

  \[
  F_r = \frac{(1 - \beta_L^2)}{\beta_L} \frac{q I}{2\pi \varepsilon_0 c} \frac{r}{R^2} \quad (r < R)
  \]

  \(\beta_L\) : reduced speed

  \(\varepsilon_0\) : vacuum permittivity

  \(q\) : charge

  \(I\) : beam current

- **Complex phenomena, difficult to model, depends on many parameters**: influence of the vacuum chamber walls, beam transverse and longitudinal distribution, different species/ions, residual gas interaction, etc.

- **A solution to compensate the beam diverging effect in the LEBT**:

  → Use the ionisation of the residual gas in the vacuum chamber.
The LEBT installed at LPSC Grenoble

- ECR ion source
- Solenoid 1 + Steerers
- Faraday Cup
- Collimation system
- Collimation cone + ACCT
- Allison Scanners
- Solenoid 2 + Steerers
- Chopper
- Faraday Cup
LEBT tuning

- **Goal**: tune the solenoids & steerers settings to optimise the transmission through the LEBT and to match the beam into the RFQ

- **Solenoid scan on the beam transmission**
  - $I_{\text{source}}$ set at 9 mA, hard to regulate below this value (dropout in another plasma mode)
  - Beam current & Twiss parameters measured 26.2 cm after the hole of the collimation cone (FC + Allison scanner)

- Estimation of the beam parameters to be expected at the Emittance-meter location with TraceWin (SCC comp. : ~ 85%, $\varepsilon_{RMS,\text{norm.proton}} = 0.1 \text{ mm.mrad}$)

- **Requirement at RFQ input**
  - $\beta = 0.04 \text{ mm/mrad}$ & $\alpha = 0.88$

- **Estimation**: 262.5 mm after the RFQ injection hole
  - $\beta \sim 2.9 \text{ mm/mrad}$ & $\alpha \sim -12.5$
Transmission map : Tuned LEBT

- $I_{\text{source}} = 9 \text{ mA}$
- $P = 7 \times 10^{-6} \text{ mbar}$
- Collimator aperture : 48 mm
- Steerers settings inside solenoid 2 :
  - $I_{\text{steererH}} = -0.5 \text{ A}$
  - $I_{\text{steererV}} = 2 \text{ A}$

a) No collimation
b) With collimation
Transmission map: Tuned LEBT + Kr injection

- $I_{\text{source}} = 9 \text{ mA}$
- $P = 2.4 \times 10^{-5} \text{ mbar (Kr injection)}$
- Collimator aperture: 48 mm
- Steerers settings inside solenoid 2:
  - $I_{\text{steererH}} = -0.5 \text{ A}$
  - $I_{\text{steererV}} = 2 \text{ A}$

- Gas injection (pressure, type) has an effect on the transmission in steady state and therefore on the space charge neutralisation
- Already observed on several experiments:
  - R. Ferdinand et al., "Space-charge neutralization measurement of a 75 keV, 130 mA hydrogen-ion beam”, Proceedings of PAC’97, Vancouver, B.C., Canada,1997
Evolution of the Emittance in the middle of the LEBT as function of the gas pressure

- the focussing strength of the solenoid is kept constant ($I_{\text{sol}}=69A$)
- Argon or Krypton gas injected
- The beam current is kept constant at the emittance measurement location: $I_{\text{proton}} \approx 8.5$ mA

In steady state we observed that the emittance decreases while residual gas pressure is increased.

~1.5 m from the source extraction hole
Space charge compensation

- For a given focussing strength of the solenoid:
  → the beam divergence is changing with the gas pressure

![Graph](image1)

- P = 9.2 $10^{-6}$ mbar

- P = 5.4 $10^{-5}$ mbar
**Space charge compensation degree**

- Measurement of the space charge neutralisation degree with **Kr injection**: \( \eta = 1 - \frac{\Phi_c}{\Phi_0} \)

- Careful – several assumptions:
  - 4-grid analyser (low and noisy signal)
  - Beam distribution assumed Gaussian

\[
\phi(0) = \frac{l}{4\pi\varepsilon_0 \beta c (1 - e^{-r_b^2/2\sigma_b^2})} \left[ -\frac{\ln(2. \sigma_b^2)}{2} - \frac{1}{2} \ln \left( \frac{\sigma_b^2}{2. \sigma_b^2} \right) + \frac{1}{2} \sum_{k=1}^{\infty} \frac{(-1)^{k+1}}{k} \frac{(-r_b^2/2. \sigma_b^2)}{k!} + \left(1 - e^{-r_b^2/2\sigma_b^2}\right) \ln \left( \frac{r_{\text{vac.chamb}}}{x_b} \right) + \ln(x_b) \right]
\]

- Beam radius calculated from emittance measurements
- Space charge compensation time measured as function of the pressure (Kr injection)
  - Beam current measured with the ACCT in the final collimation cone
  - $\tau_{95\%}$ : time to reach 95% of the maximum value
  - Chopper rise time : $\sim 400$ ns

![](chart.png)

- 500 $\mu$s macro-pulse
LEBT final tuning

- $I_{\text{source}} = 9 \text{ mA}$
- $P = 2.4 \times 10^{-5} \text{ mbar (Kr injection)}$
- **Collimator aperture : 37 mm**
  - $I_{\text{out}} = 4.5 \text{ mA}$
  - Steerers settings inside solenoid 2 :
    - $I_{\text{steererH}} = -0.5 \text{ A}$
    - $I_{\text{steererV}} = 2 \text{ A}$

- $\varepsilon_{YY}^{\text{rms, norm.proton}} = 0.08 \pi \text{ mm.mrad}$
- $\beta_{yy}$ vs $\alpha_{yy}$ vs $I_{\text{solenoid1}} = 71 \text{ A}$
- $\beta_{yy}$ vs $I_{\text{solenoid2}}$ vs $\alpha_{yy}$
CONCLUSIONS & Future work

- The MYRRHA LEBT is fully commissioned
  - Effect of gas on Space charge compensation experimentally measured
  - Tuned to provide the right beam parameters (Twiss, emittance) at RFQ input

- Analysis of experimental data for SCC studies in progress
  - Model development With WARP for a better understanding of the Physical process of SCC in the LEBT
    - As studied for example on LINAC4 C. A. Valerio-Lizarraga et al., Phy.Rev. ST Accelerator & beams, 2015
    - Assess the effect of Emittance-meter on measurement accuracy
    - Phd thesis of Frédéric Gérardin at CEA Saclay
  - To anticipate on the future re-tuning & operation

- Next step : LEBT will be moved to Louvain-la-Neuve for RFQ and injector commissioning (2018)
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