EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Installation and commissioning of the ISRS Ion Test-bench and Multi-Harmonic Buncher at HIE-ISOLDE

9 January 2025

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Abstract

Along the last years the Isolde Superconducting Recoil Separator (ISRS) collaboration has developed a R&D program to assess the feasibility of building a compact spectrometer for HIE-ISOLDE as described in the LOI-I-228(2021). Hereby we present a follow-up LOI to continue the R&D activity by the installation and test at ISOLDE of two prototypes, the Ion Test Bench (IONTB) and the Multi Harmonic Buncher (MHB), during the LS3 period 2026-2028. The collaboration is requesting the ISOLDE and Neutron Time-of- Flight Committee (INTC) the required approval and space allocation for the proposed activity, as well as the endorsement to find additional funds and resources from national and EU programs.

Requested shifts: No shifts are requested at present.

1. INTRODUCTION

The HIE-ISOLDE facility accelerates a unique worldwide variety of radioactive ions up to collision energies close to 10 MeV/A. The physics program covers a broad range of nuclear structure studies, from shell-evolution to nuclear astrophysics. To fully profit from the new facility our collaboration has proposed the construction of the "Superconducting Recoil Separator" ISRS (LoI-INTC-I-228) [1]. ISRS [2] will extend the HIE-ISOLDE physics program by in-beam and focal-plane particle-gamma correlation studies.

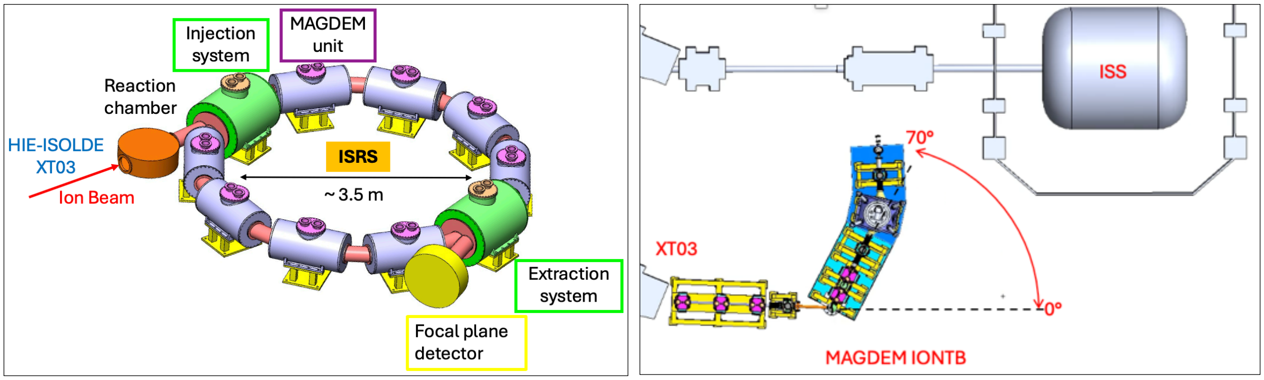


Figure 1. Left: Present layout of ISRS at XT03. **Right:** IONB at XT03 showing rotation around reaction chamber.

The design of ISRS is based on an array of superconducting multifunction magnets (Canted Cosine Theta, CCT), integrated into a compact FFAG particle storage ring. A/Q analysis of reaction fragments is achieved by combining cyclotron frequency and RF extraction with ToF and PID at the focal plane [3]. The ISRS collaboration has recently launched an R&D program during the period 2023-2026 funded by Spanish grant [4], which covers most activities described in the Letter of Intent-I-228 (2021) [1]. A summary of the project status and results can be found at the ISRS project web site [5] and publications [2] [3] [6] [7] [8] [9]. The present ISRS layout is shown in Figure 1 (Left).

The objective of this LOI is to continue the R&D program during LS3 2026-2028 with the installation and test at ISOLDE of two prototypes, the Ion Test Bench (IOB) and the Multi-Harmonic Buncher (MHB), which are developed to prove the performance of ISRS. These prototypes can also be used after LS3 for physics experiments. The collaboration is thus requesting the INTC the required approval and space allocation in the experimental hall. As the present R&D grant ends by 2026, we also request the endorsement to participate in national and EU programs to provide the funds needed to develop this activity.

2. THE ION TEST BENCH

One of the key elements of the ISRS spectrometer is the prototype of magnet "MAGDEM" (MAGnet DEMonstrator), the basic building block of the ISRS particle storage ring. MAGDEM is an extremely compact, helium-free Nb-Ti CCT superconducting magnet cooled by a single GM cryocooler that incorporates the nested quadrupole and dipole functions. The cryostat features a 200 mm clear aperture for the circulation of the heavy ion fragments, and it is only ~750 mm long. The innovative design incorporates a dipole coil (2.3 T) inside a quadrupole coil (10 T/m), providing the 36-degree bend needed for ion analysis/storage in the ISRS ring.

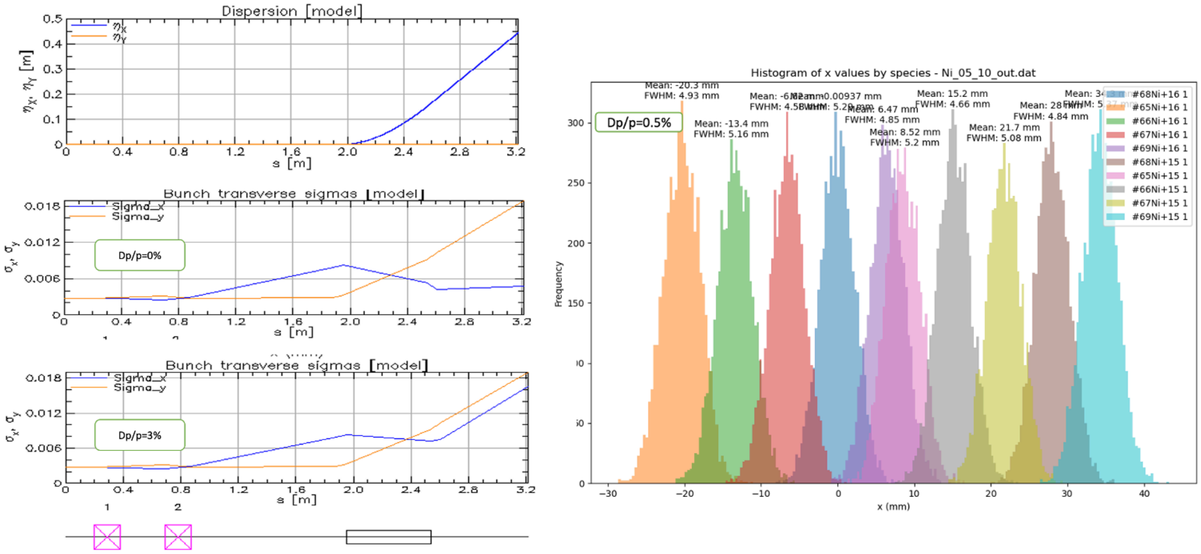


Figure 2. Left: IONTB Beam optics (MADX). **Right:** Mass spectrum of Ni isotopes.

The Ion Test-Bench (IONTB) is a magnetic system that integrates MAGDEM into an optical system to perform nuclear reactions to prove its performance and test beam dynamics simulations. The system also incorporates the reaction chamber, focussing systems, and focal plane detectors, delivered by the present R&D project. Thus, IONTB can use MAGDEM dipole function to work as a linear spectrometer and carry out experiments at HIE-ISOLDE with a limited mass resolution up to A~60. The completion and installation of IONTB at XT03 during LS3 requires additional funding. The IONTB design is very compact, see Figure 1 (Right) and Figure 3, to minimise interaction with other experiments (ISS). Further details are given below.

Beam transport and mechanical integration

The beam transport has been optimised for 5-10 MeV/u beams of ^{9}Li and ^{68}Ni, with a momentum dispersion of 3-10% and neighbouring charge states. A transport calculation at

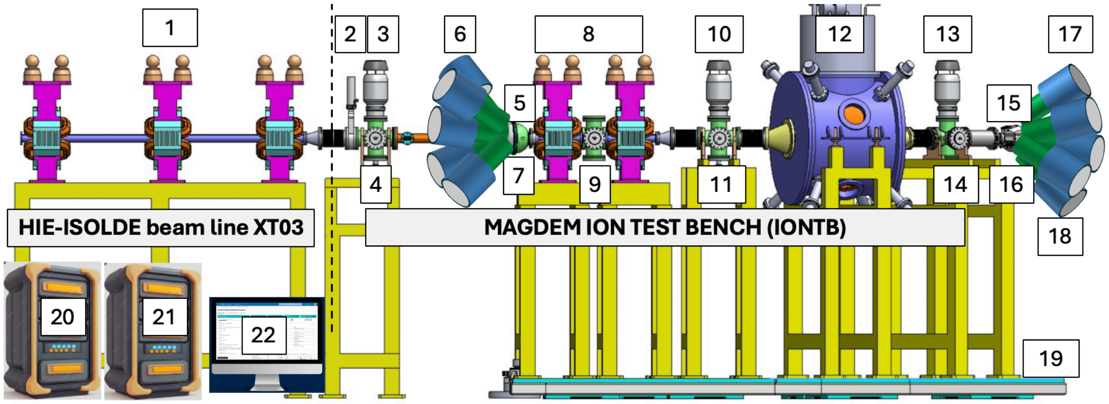


Figure 3. Mechanical integration of IONTB showing relevant subsystems: 1.HIE-ISOLDE triplet/XT03, 2.Beam valve, 3.Diff. pumping, 4.Beam diagnostics, 5.Reaction chamber (RC), 6.RC-Gamma array, 7.RC-Particle detector array, 8.Quadrupole doublet, 9.Beam diagnostics, 10.Vacuum system, 11.Beam diagnostics, 12.MAGDEM, 13.Vacuum system, 14.Beam diagnostics, 15.Focal plane chamber(FP), 16.FP-Particle detector array, 17.FP-Gamma array, 18.Beam dump, 19.Rotary platform, 20.Data acquisition and control (DAC) hardware, 21.Machine & personal protection system (MPS & PPS) hardware, 22.DAC-Software.

E=10 MeV/u is shown in Figure 2 (left), with a resolving power of 0.466. An example of mass spectra for Ni isotopes at different charge states is shown in Figure 2 (right).

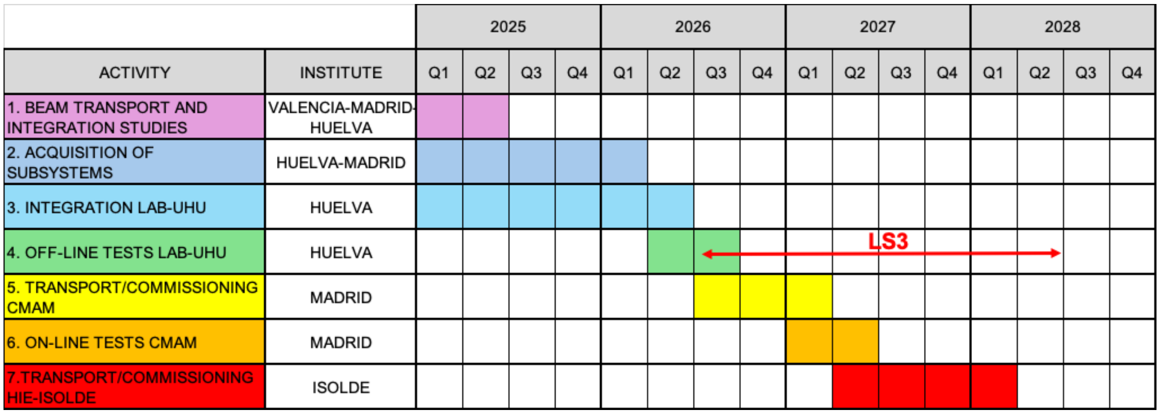
The mechanical integration is shown in Figure 3 with the relevant subsystems. The design allows accommodation of gamma and neutron detector arrays at the reaction chamber and/or focal plane, and the structure can rotate up to 70° around the reaction target. The total length of IONTB is ~3.5 m and fits at the XT03 beamline ensuring minimum interaction with neighbouring experiments at XT02 (ISS). Discussions on structural and safety following CERN regulations are underway. An upgrade presently under study can get up to 3 cm/% mass dispersion keeping the same footprint.

The provision of subsystems and ancillary systems is advancing according to project schedule. The superconducting magnet MAGDEM, has been designed and ordered, delivery is expected by the end of 2025. For the focusing quadrupoles the collaboration is recycling existing CERN units, for which power supplies are also available in the collaboration. A tailor-made focussing quadrupole is also under design for the higher resolution option.

Developments of SiC detectors for focal plane and beam diagnostics are also well advanced and prototypes have already been tested in CMAM-Madrid. The complete data acquisition was purchased and is already in operation for experiments. The reaction chamber and rotary platform and supporting structures are designed and ready to be purchased. The provision of ancillary systems such as vacuum (pipes, pumps), beam diagnostics, control systems, is under evaluation; delivery of all subsystems are expected before the end of June 2026. Several results have been published; a summary can be found at the ISRS web [5].

Ion Beam Tests and Nuclear Physics program

Tests with stable and radioactive beams are foreseen after LS3 to prove the performance of the magnet against the beam dynamics of ISRS for a range of isotopes and energies. Beams of ^{9}Li, ^{68}Ni, ^{132}Sn, ^{185}Hg, ^{224}Ra are currently produced at HIE-ISOLDE with intensities > 10^4 pps on target. Beam transport simulations will be tested by measuring beam parameters and fragment distributions using the quadrupole doublets, beam diagnostics, and beam emittance meters. IONTB can also be used for gamma-particle experiments involving single- and multi-nucleon transfer reactions, inelastic, and fusion-evaporation reactions, among others. The nuclear physics program will require gamma and neutron detector arrays to be placed at the reaction chamber and/or focal plane detector. The collaboration is presently



		2025				2026				2027				2028			
ACTIVITY	INSTITUTE	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. BEAM TRANSPORT AND INTEGRATION STUDIES	VALENCIA-MADRID-HUELVA	🟪	🟪														
2. ACQUISITION OF SUBSYSTEMS	HUELVA-MADRID	🟦	🟦	🟦	🟦	🟦											
3. INTEGRATION LAB-UHU	HUELVA	🟦	🟦	🟦	🟦	🟦	🟦										
4. OFF-LINE TESTS LAB-UHU	HUELVA						🟩	🟩 ←			LS3				→		
5. TRANSPORT/COMMISSIONING CMAM	MADRID							🟨	🟨	🟨							
6. ON-LINE TESTS CMAM	MADRID									🟧	🟧						
7.TRANSPORT/COMMISSIONING HIE-ISOLDE	ISOLDE										🟥	🟥	🟥	🟥			

Figure 4. Proposed planning for IONTB. The LS3 period is shown with the red line.

working on a selection of physics cases with beams from ^{9}Li to ^{68}Ni for cases not easily doable and complementary to ISS and MINIBALL. Nonetheless, the use of IONTB for nuclear physics experiments will require the approval of the INTC.

Planning

The planning for IONTB installation at XT03 is summarised in Figure 4. Beam transport and integration studies will finish by Q2 2025, and the acquisition of components by Q1 2026. The system will be integrated at Huelva University and the off-line test will be performed by Q2-Q3, 2026. During Q3 2026 the system will be transported to “Centro de Análisis de Materiales (CMAM)” in Madrid to be tested and commissioned using the 5 MV Tandetron facility in Q1-Q2 2027. Transport and installation at HIE-ISOLDE is foreseen for Q1 2028.

3. THE MULTIHARMONIC BUNCHER

For optimal operation of ISRS, the present HIE-ISOLDE LINAC frequency of 101.28 MHz must be scaled down to 1/10 of the frequency. To achieve this goal, a multi-harmonic buncher (MHB) must be placed at the medium energy beam line (MEB), prior injection into the accelerator. The new buncher design must overcome the technical challenges imposed using radioactive beams: low energy dispersion (< 1%), high transmission (> 95%) and reduced space for bunch formation (< 5 m).

The conceptual design of the MHB has finalised and has been presented in different conferences (see [8] [9]). Due to the intended final location of the MHB in the ISOLDE linac, before the REX RFQ, a standard 4-way CF63 vessel has been chosen. One of the critical elements is the required feedthrough for the electrodes. We have chosen a tailor made double CF63 HN connector based on the VACOM W-HN50-GS-SE-CE-NI model. This model can work up to 7 GHz and up to 7kV DC voltage. Visual inspection, vacuum, metrology and RF characterization measurements have been performed. In particular, the MHB RF response has been measured by applying an RF signal through the coaxial feedthrough’s ports. The S11dB and S21dB response signals have been measured for frequencies in the working range. The results compared very well to those obtained with FEM simulation.

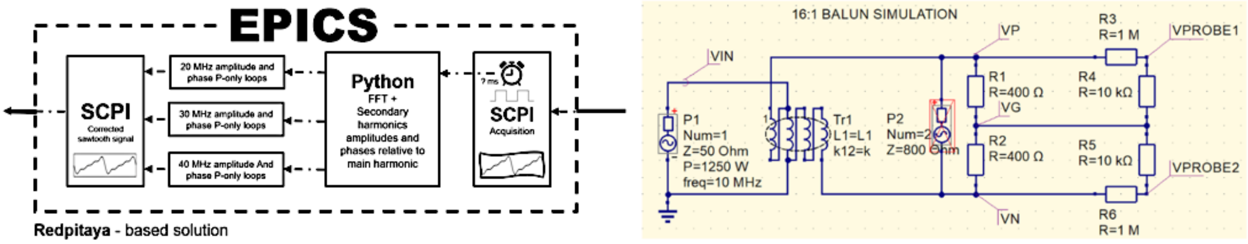


Figure 5. Left: RF distribution system control system schematic. Right: Balun coupling scheme.

RF distribution System Control System

The control system proposed is based on the PyDev EPICS module and developed entirely in EPICS as a high-level RF control system. The digitized sawtooth signal is sent as an input to a python function executed as part of the processing of an EPICS PV. This function outputs the amplitude and phase of the secondary harmonics (20 MHz, 30 MHz and 40 MHz) with respect to the main harmonic signal (10 MHz). These values are treated as actual errors in amplitude and phase in dedicated P-only control loops for each harmonic in amplitude and phase (a total of 6 loops). Each control loop outputs the corrected amplitude and phase of the secondary harmonics to adapt to the main frequency amplitude and phase. The whole system is synchronized by the digitized sawtooth signal PV SCAN field, which behaves as the control system main clock.

In the new configuration the EPICS based control system proved to acquire and correct the amplitude and phase deviations within a 20 µs of control loop periods. The SignalLab250-12 redpitaya running a Linux armv7l operating system with a 5.15.0-xilinx board improves the control system execution time as well as its size and cost. Figure 5 (Left) shows the current control system logic. The system has been tested together with the LZY-22+ RF driver, and it is able to correct the perturbations on the amplified signal. LZY-22+ is a ruggedized High Power Amplifier can deliver 30W output signals across its entire operating bandwidth, from 0.1-200 MHz. The integration of the RFE-24M30M1K7X+ amplifier is on-going.

Once the signal is amplified, it must be conditioned to feed the cavity electrodes and to monitor it. For that, we have designed a coupling scheme based on a *balun* ("balanced to unbalanced"), see Figure 5 (Right), to convert signals between balanced and unbalanced forms. Baluns are commonly employed in RF applications to interface balanced components, where conductors carry equal and opposite signals without involving ground in signal transmission, with unbalanced components, such as coaxial cables, where a single conductor carries the signal, and ground serves as the return path. In our application, the balun interfaces the ISOLDE ISRS Multi Harmonic Buncher (MHB) with the RF amplifier coax cable (unbalanced component).

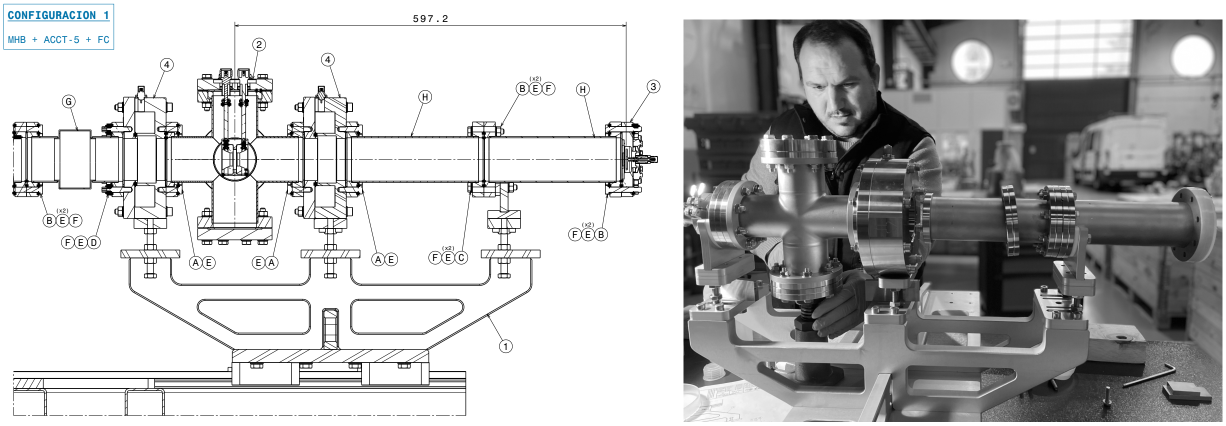


Figure 6. MHB Configuration 1 installed in the Bilbao injector in December 2024.

<u>Ion Test Bench Diagnostics</u>

In order to be able to test in Bilbao the same cavity that we aim to use in ISOLDE, we need to match the same β that we will encounter at CERN facility. For that, three different cases have been studied (H^+, H_2^+, N^+), and we finally decided to use H^+/H_2^+ as the reference beam. The tests will be done with H_2^+ ~10 keV beam to produce up to 0.5 mA beam current.

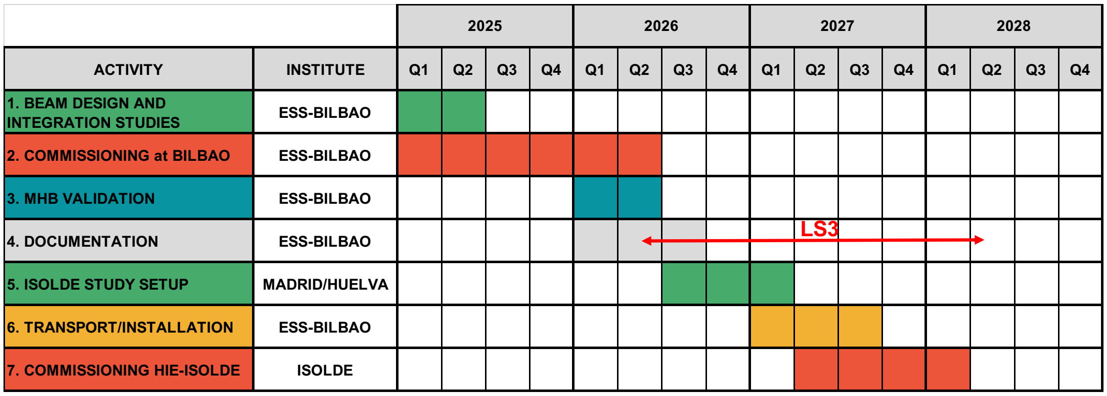
Figure 6 shows the configuration 1 already installed inline. From left to right, we are using: ACCT4, MHB, ACCT5 and Faraday Cup (FC). The main purpose of this configuration is to adjust the most suitable LEBT solenoid configuration that enhances the transmission of H_2^+. The configuration of the ion source will be monitored. It must be highlighted that 10 keV extraction mode is far from the design 45 keV mode and it needs to be fine-tuned. The location of the FC was chosen to be as close as possible to the Fast Faraday Cup (FFC) that will be used in upcoming configurations.

MHB test program

The objective of the test program is to prove the performance of the MHB using the similar injection energy per nucleon as for the REX-ISOLDE RFQ, e.g. E= 5 keV/u, $^{22}Na^{5+}$ from few femto-amps to pico-amps. This is orders of magnitude below the current employed in the injector at ESS-Bilbao. Once the nominal beam parameters are characterised, we could measure the acceptance of the cavity in terms of range of isotopes and energies. This activity will be carried out when ion beams are available at ISOLDE.

Planning

The final goal is to install the MHB in the low energy area of ISOLDE to test the operation and performance in real working conditions. The exact place for the setup must be decided. A summary of the planning is given in Figure 7. Once the cavity has been tested in Bilbao during 2025 with the same $\beta = 0.00328$, the MHB will be validated during 2026 and documented. Once validated, we will study the beam characteristics from the ISOLDE low energy experimental line. Some adjustments might be required such as supporting structures, focusing systems and adjustment of the required diagnostics. Then, some months will be required to install, cold commission and finally tests with beam by stable and/or radioactive beams by the end of LS3.



		2025				2026				2027				2028			
ACTIVITY	INSTITUTE	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. BEAM DESIGN AND INTEGRATION STUDIES	ESS-BILBAO	🟩	🟩														
2. COMMISSIONING at BILBAO	ESS-BILBAO	🟥	🟥	🟥	🟥	🟥	🟥										
3. MHB VALIDATION	ESS-BILBAO					🟦	🟦										
4. DOCUMENTATION	ESS-BILBAO					▨	▨	▨			LS3						
5. ISOLDE STUDY SETUP	MADRID/HUELVA							🟩	🟩	🟩							
6. TRANSPORT/INSTALLATION	ESS-BILBAO									🟨	🟨	🟨					
7. COMMISSIONING HIE-ISOLDE	ISOLDE										🟥	🟥	🟥	🟥			

Figure 7. Planning for the installation and test of MHB at ISOLDE.

4. COLLABORATION REQUEST

The objective of the LOI is completing the production of IONTB and MHB, and the installation and cold commissioning at ISOLDE during LS3 2026-2028. For this activity additional funding is required as the present Spanish grant ends by June 2026. Therefore, the collaboration is requesting the ISOLDE and Neutron Time-of- Flight Committee (INTC) the required approval and space allocation for the activity, as well as the endorsement to find additional funds and resources from national and EU programs.

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