EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Design study of a Superconducting Recoil Separator for HIE-ISOLDE

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Abstract

The HIE-ISOLDE facility at CERN delivers presently the largest range of low-energy radioactive beam available worldwide. The relevant features of the atomic nucleus are investigated by Coulomb excitation, transfer, deep inelastic and fusion-evaporation reactions. These studies can benefit from the use of a high-resolution spectrometer which selects and quantifies the beam-like reaction fragments from the intense primary beam. The collaboration has carried out preliminary design studies to assess the feasibility of developing a compact superconducting recoil separator. In this LoI the collaboration is requesting the endorsement of the INTC to commit resources to continue with a proof-of-concept project and participate in national and EU funding programs.

Requested shifts: No shifts are requested at present. **Beamline:** not applicable.

1 INTRODUCTION

Nowadays a major part of the nuclear physics activity is developed at international radioactive beam facilities, which have led the way in the unprecedented expansion of the capabilities for investigating the structure of the atomic nucleus and the nuclear interaction. The new achievements and discoveries in nuclear science have been possible by continuous introduction of cutting-edge technologies in both detector systems and particle accelerators where CERN has played a leading role.

The radioactive beam facility *"Isotope mass Separator On-Line facility"* (ISOLDE) at CERN started operation 50 years ago [1], and since then several transformations and upgrades have resulted in a world leading facility, most remarkably the recent commissioning of the *"High Intensity and Energy – ISOLDE"* (HIE-ISOLDE) linac accelerator [2], able to drive the radioactive species produced at ISOLDE from 0.5 up to about 10 MeV/A.

Most spectrometers are based on the concept originally developed at Daresbury [3], and presently ray-tracing spectrometers are the most efficient way to achieve large angular and momentum acceptance and resolution. Examples of such spectrometers are PRISMA [4], VAMOS [5] and MAGNEX [6]. The performance of these devices using HIE-ISOLDE beams was already studied in the past [7]. A Letter-of-Intent concerning the installation of a recoil separator was submitted in 2010 to the *ISOLDE and Neutron Time- of -Flight Experiments Committee* [8].

A recent innovative development is the spectrometer ISLA [9] designed for the future ReA12 accelerator at NSCL/FRIB, where the use of an isochronous design and RF systems allows to achieve a much superior performance to previous spectrometers. More recently, our collaboration carried out the study of a very compact recoil separator for radioisotopes, *the Isolde Superconducting Recoil Separator (ISRS),* that can meet the demanding requirements imposed by reaction studies with radioactive beams at HIE-ISOLDE using a different approach. The proposed spectrometer is based on a superconducting (SC) Fixed-Field Alternating-gradient (FFA) mini-ring [10]. This machine will be able to store a wide range of masses and momentum spread and separate them from the main beam using radiofrequency devices, reducing the size with respect to standard non-SC recoil separator configurations.

As discussed in [9], with present technologies ToF resolutions around ~ 1 ns can be achieved, and for a flight time of about 1 μs the m/q resolution can reach values close to 1/2000. The ring design concept used for ISRS can provide large storage times and therefore a much larger ToF capable of reaching unprecedented mass resolution and primary-beam rejection. By the use of CCT multifunction magnets and FFAG very large solid angles > 100 msr and momentum acceptances $\Delta p/p > 20\%$ could be achieved with a very compact configuration.

The purpose of this proof-of-concept study is to explore the limits of this conceptual design for mass spectrometry/recoil separation and the feasibility of building a future machine. The innovative design takes advantages of the latest developments in compact superconducting magnet systems [11] and FFAG particle dynamics [12], increasing significantly the physics capabilities of the HIE-ISOLDE facility and ensuring that CERN expertise will continue playing a leading role in nuclear physics and related fields. The ISRS project was recently endorsed by the Isolde Collaboration Committee in 2019 [13]. In this LoI, the collaboration is asking the INTC to endorse the R&D phase of this project, which will be focussed on a detailed proof-of-concept study of 5 years duration.

2 PHYSICS OPPORTUNITIES

The technological progress on radioactive beam accelerators and the parallel advances in efficient particle detection systems, has opened up the possibility to observe the changes in the nuclear properties when moving from the "normal" stable nuclei to the most exotic systems near the neutron or proton drip lines. A compact mass separator will significantly increase the number of accessible exotic nuclei for critical studies with sufficient precision using the beam intensities and energies available at the HIE-ISOLDE.

The wide production of isotopes at HIE-ISOLDE makes it possible to test theories by selecting specific combinations of (N, Z) maximising the effect to be probed. Regions dominated by nuclear haloes, skins, molecular clusters, pear shapes, islands of inversion, shape coexistence, nuclear pairing or isospin mixing, are now fully accessible to the experimentalists (Figure 2). The synthesis of the known chemical elements occurs in stellar scenarios following very specific nuclear-reaction paths, frequently involving beta-unstable nuclei. Their exotic structure and reaction dynamics has been proved to be critical in the understanding of astrophysical observations and the development of detailed nucleosynthesis models.

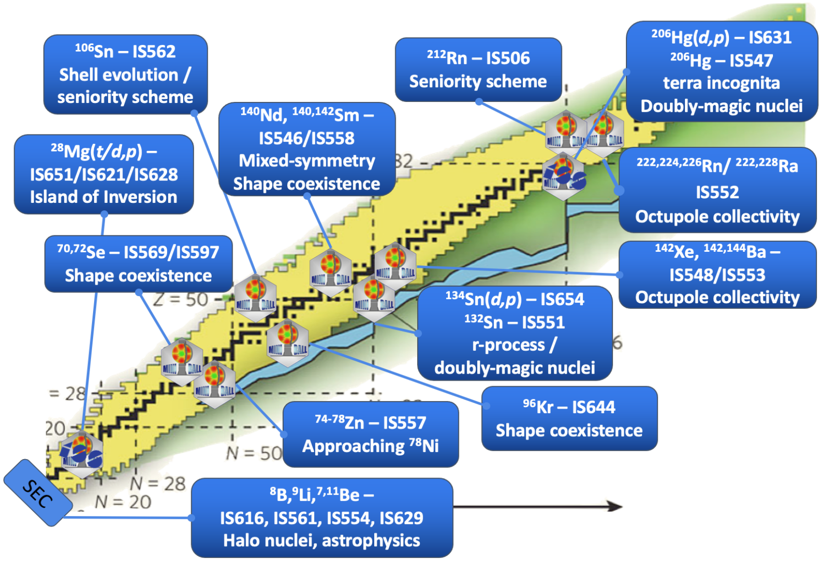

Figure 2. Recent physics cases investigated at HIE-ISOLDE (Courtesy of L. Gaffney, ISOLDE EPICS Workshop 2019).

The physics program will entail the detection at ISRS of various recoils in coincidence with complementary detector arrays, taking advantage of the existing detector setups like the gamma-particle array Miniball [14] and T-REX [15], the particle array GLORIA [16], the neutron array SAND, the multi-purpose reaction chamber SEC [17] and the spectrometer ISS [18]. The plans for a future extension of the experimental hall [19] and the installation of a Storage Ring [20] constitutes an opportunity for the realisation of experiments with stored secondary beams, which combined with the high resolving power of ISRS spectrometer will make a unique facility world-wide. The new spectrometer will allow an application of several reaction mechanisms described below to produce exotic nuclei in the energy levels of interest, decays of which can be observed by detecting particles or photons with the existing and planned detection systems mentioned above.

The potential of *Coulomb dissociation* at a few MeV/u has rarely been used despite having much high cross sections, due to the relatively complex reaction dynamics. Core fragments associated with Coulomb dissociation should be detected in the spectrometer in a narrow cone up to ~15° around the beam axis in coincidence with the neutrons, particles and gammas ejected in the breakup.

Direct transfer reactions in inverse kinematics [22, 23] where the light outgoing particle is a neutron, a spectrometer is the best way to select the reaction channel. The outgoing reaction cone is rather narrow and symmetrical around the beam axis for transfer reactions in inverse kinematics. Typically the cone ranges from ±15° for lighter projectiles to about ±1° for heavier beams. Nuclear structure studies around $N \approx 82$ and $N \approx 126$ and reactions relevant for the s, p and rp process nucleosynthesis around $Z \approx 50$ and $Z \approx 82$ can include reactions of this type.

A large number of nuclei [24, 25, 26] can be produced in *multinucleon transfer reactions*, via *deep inelastic, quasi-elastic and quasi-fission reactions,* where the spectrometer should analyse individual exit channels. This mechanism can populate states in heavy nuclei so far unobserved, decaying by gammas and neutrons. With the choice of suitable reactions a number isotopes including the drip line ^{78}Ni or r-nuclei around N=126 [27] can be produced. In particular multi-nucleon transfer reactions allow for producing neutron-rich nuclei in the Terra Incognita. The$^{137\text{-}144}$Xe+^{208}Pb can populate the closed-shell region N=126, which is crucial for both studying shell-quenching and the r-process, being its last "waiting-point" before the production of trans-bismuth elements and the fission cycling. Depending on the physics case, direct or inverse kinematics with light or heavy targets will be used, and the spectrometer should be able to rotate to cover the grazing angle (~ 50 - 70 degrees).

Fusion evaporation reactions in inverse kinematics. The recent intensity upgrade of HIE-ISOLDE has made possible the use of fusion-evaporation reactions for nuclear spectroscopy. Selection of fusion evaporation residues using magnetic devices has been done in many experiments with stable beams in the past [28]. Consequently, a versatile device may be used also in such a program with radioactive beams. One example here is the opening up of a variety of possibilities for lifetime measurements, e.g. using standard and triple foil plungers [29].

Low energy transfer, breakup and fusion reactions. The studies of exotic nuclei are mainly based on reactions induced by radioactive beams at different energies [30]. High energies ~ 100 MeV/A are more suitable to probe single particle aspects, whereas low energies ~5 MeV/A will emphasize collective behaviour associated with nucleon correlations. Beam-like fragments are emitted at very small angles close to the beam axis whereas neutrons and gammas must be recorded in coincidence to tackle the dynamics of the reaction process.

3 PHYSICS REQUIREMENTS

The low intensity of the radioactive beams demands large momentum and solid angle acceptance, while the physics program requires excellent mass, charge, energy, time and good angular resolution at the focal plane for Doppler corrections and kinematical reconstruction of the reaction. A preliminary list of minimum physics requirements obtained from existing proposals is summarized in Table 1. As discussed in Section 1, the expected performance of the ISRS spectrometer should be superior. Thus a review of the physics requirements is foreseen during the first stage of the project, while a detailed Whitebook including physics program and technical design will be developed along the 5 years project duration.

For standard spectrometers, good angular resolution is obtained with a small acceptance, or by the use of large focal planes with an efficient trajectory reconstruction system. Additionally, the size of the present HIE-ISOLDE experimental hall constrains the footprint of the spectrometer to an area of ~5 x 5 m^2, including the detector setup. The plans for future extension of the hall should relax this prerequisite, but the present design project aims for maximum compactness by means of state-of-the-art accelerator technologies.

Momentum acceptance	± 10%	Solid angle	100 msr
Resolving power p/Δp	2000	Charge resolution ΔQ/Q	1/70 (FWHM)
Angular acceptance	+/- 10°	Mass resolution ΔM/M	1/250 (FWHM)
Angular resolution	0.1°	Rotation	0 - 70°

Table 1. Minimum spectrometer requirements

4 PRELIMINARY DESIGN STUDIES

A preliminary design-study of ISRS was already carried out based on a SC mini-ring concept of only 3.5 m lenght and a FFAG lattice of ten SC combined-function nested magnets [10]. The compact magnet design (20 cm length) was inspired in a previous SC medical gantry study [31]. The beam optics study was carried out with the codes BMAD [32], G4beamline [33], covering a range of isotopes from ^{11}Li up to ^{234}Ra with (d,p) reactions. With a beampipe radius of 10 cm, the momentum and angular acceptances were $\Delta p/p \sim \pm 10\%$ and $\delta\theta \sim$ +/-100 mrad, respectively. Tuning the optics to the isochronous mode for a given A/Q (reference Bρ) the revolution frequency depends only on A/Q, and the ToF between neighbouring masses can be modified by a suitable RF system synchronized to the duty cycle. For the particular case of ^{233,234}Ra at 10 MeV/u, a ToF separation of about 10 ns could be achieved for storage times of ~ 2 μs.

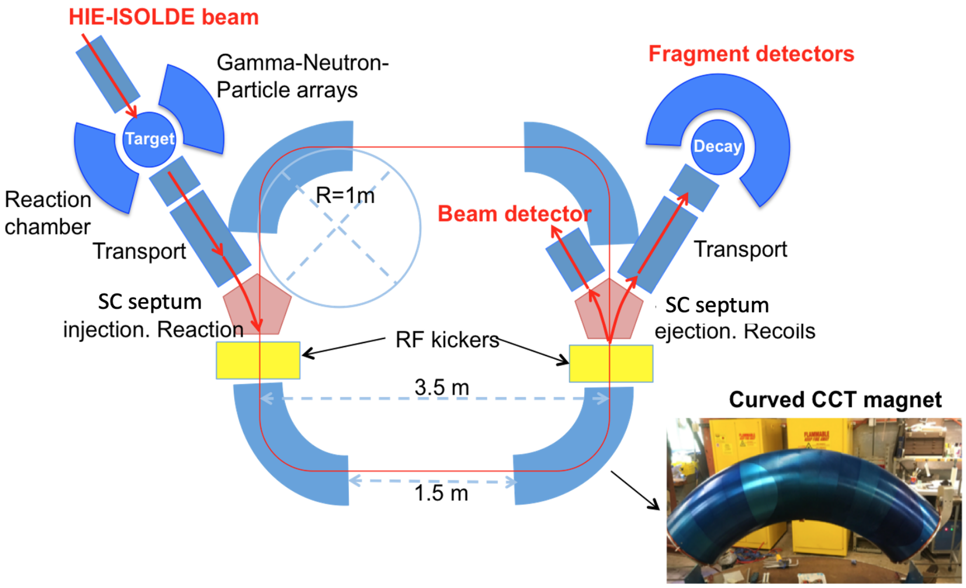

Figure 2. Updated version of the conceptual layout of ISRS. The ring consists of curved CCT magnets and straight sections to include the injection/extraction systems and beam diagnostics. A prototype of an assembled curved CCT magnet is shown on the bottom right (courtesy of Lucas Brouwer from LBNL).

This model has evolved to a new concept based on the innovative Canted-Cosine-Theta (CCT) magnets [34] and four straight additional sections to allocate injection/extraction systems and beam diagnostics. The design of the injection and extraction system is technically very challenging and will constitute an important task. Figure 2 shows a simplified sketch of this new tentative layout, with a total flight path of 12.28 m. It consists of 4 curved CCT magnets of 1.6 m length, 200 mm bore diameter, 1 m bending radius and 90 degree bending angle. For a maximum magnetic rigidity of 2.2 T m, the dipole must sustain a maximum field of 2.2 T. The coil configuration could be similar to Ref. [36] each one hosting two alternating-gradient (FDFDF) quadrupole layers nested inside two outer dipole layers. The field of these SC magnets will remain constant and the ISRS will operate as an isochronous non-scaling FFAG system.

The choice of CCT magnets on its ability to produce combined function fields with large apertures and large momentum acceptance. The magnet-system design and optimisation have strong synergies with medical beam therapy systems and CERN accelerator beam manipulation. The use of curved CCT magnets have been considered for the new generation of medical gantries [35], with a first prototype already built at the Lawrence Berkeley National Laboratory [36]. We have selected a magnet technology that has significant advantages in terms of design flexibility, magnetic field quality (very low errors) and importantly fast development time with relatively low expected costs compared to the classical magnet structures.

The CCT coil design was first published in the 1960's but it is only now becoming popular thanks to recent manufacture technology breakthroughs with the first series of 3 Tesla 2.2 m long 100 mm aperture set of magnets that will be part of the CERN LHC-High Luminosity upgrade [37, 38], along with several other magnets for the FCC project. The CERN LHC Hi-lumi magnets are fully developed and are being produced in industry. The design of the nested dipole and quadrupole baseline for the ISRS project follows already developed technology and it can add novelty, high-performance and compactness with the transformation to a curved magnet design. In a simpler configuration, the quadrupole layers could be designed with just three alternating-gradient components (FDF). If necessary, in order to simplify magnet manufacture, the curved CCT magnet might be split into smaller pieces or be replaced by three smaller straight CCT magnets in series, with a bending angle of 30 degree each. In this case, the ISRS could be characterised as a Johnstone's isochronous non-scaling FFAG ring [39]. According to preliminary studies, to guarantee transverse orbit stability, the quadrupole gradients can reach up to 40 T/m. Straight and bent CCT options will be considered in the proof-of-concept study planned by the collaboration.

The operation of ISRS is determined by the beam time structure of HIE-ISOLDE [40, 41] and bunch separation should be of the order of 100 ns. This can be achieved by using a multi-harmonic buncher (MHB) to be developed in this project [42], which could also extend the gap ~ 200 ns, thus improving the ToF capabilities. The operation of the MHB coupled to the EBIS [41] shall be studied to optimise the operation modes of the ISRS.

The injection and extraction systems are key parts of the ISRS. As a first step, the possible operation modes (DC with continuous input, or pulsed mode with an injection-storage-extraction cycle) will be studied. In the pulsed mode the beam capturing efficiency depends on the ratio of revolution time and storage time, which in turn will limit the achievable signal-to-noise ratio. If a pulsed mode (offering longer storage times) is affordable, in the straightforward concept, a combination of a septum magnet and an RF kicker could be inserted in two opposite straight sections for injection and extraction, as shown in Fig. 2. A potential solution based on a Superconducting Shield (SuShi) septum [43] or an opposite-field septum [44], and a RF helical stripline chopper [45] is now being investigated. The proposed septum concepts promise a magnetic field difference of 3 or 1.4 T with a wall thickness of around 20 or 4 mm, respectively. Given the very tight space available for these systems in the present conceptual design of Figure 2, the feasibility of this concept - especially for the kicker - is very challenging. If this option turns out not to be possible, the present ring concept will be modified and/or injection/extraction systems to achieve a satisfactory solution. The study of the technical details and specifications of the injection/extraction system will thus constitute one of the main tasks of the R&D project.

The proposed cryostat prototype for Curved CCT nested coils, will use a classical LHe cooling method well adapted to be installed in a laboratory infrastructure (CERN), allowing faster cooling speed and in principle suitable for global prototype tests, precise measurements and eventual modification and optimization of coils installation and associated instrumentation. This type of coil requires, in principle, a simple and thin yoke (playing the role of magnetic shielding), but the more critical design aspect could be the number of current leads. In order to power the nested coils (see table of Appendix 1), 4 power supplies will be needed (1 for dipole coils and 3 for quadrupole coils), leading to 8 current leads (2 for dipole and 6 for quadrupoles). The current leads using Hi-Tc materials will be installed to supply the coils, the currents in these coils range from 2300 to 2700 A.

The development of compact gantries using superconducting coils confirms the interest for analysing different cooling methods. For example, the cooling by conduction methods, using cryocoolers, can provide the required cooling at temperatures close to 4K. The first problem is the cool down time of the cold mass by conduction from room temperature to 4K. A special attention must be focused on the use of the cooling power available on the two stages (40K, 4K) of the cryocoolers in order to reduce the coils cooling time as much as possible. The second critical aspect is the available cryogenic power at nominal temperature, and the technical feasibility of equipment to allow the cooling and the operation of the magnet at its operating temperature. The main interest of this approach is to eliminate the need for liquid helium and all the associated safety and maintenance constraints when installed on rotating gantry. Another cooling possibility is to use liquid helium as cooling fluid and use cryocoolers to produce the required cryogenic power.

A test bench suitable for characterising magnet prototypes with sufficient accuracy and precision to verify its performance should be designed and constructed. It may be necessary to use integral (stretched wire/rotating coil) techniques as well as point-by-point (Hall probe) techniques. The test bench will comprise the cryostat; a motion system; a Hall probe or set of probes; (optionally) a measurement coil; and a data acquisition system.

5 COLLABORATION REQUEST AND TIME SCHEDULE

In this LoI the collaboration is requesting the endorsement of the ISOLDE and Neutron Time-of-Flight Committee to commit the resources needed to proceed with a Proof-of-Concept study and participate in national and EU funding programs. The R&D activity will be focussed on beam dynamics, buncher, magnet and cryogenics design, injection/extraction system, test bench, physics detectors and prototyping. A review of the physics requirements is foreseen during the first stage of the project, while the Whitebook will be developed along the 5 years project duration. A summary of the relevant tasks and time schedule is given in the Appendix 2.

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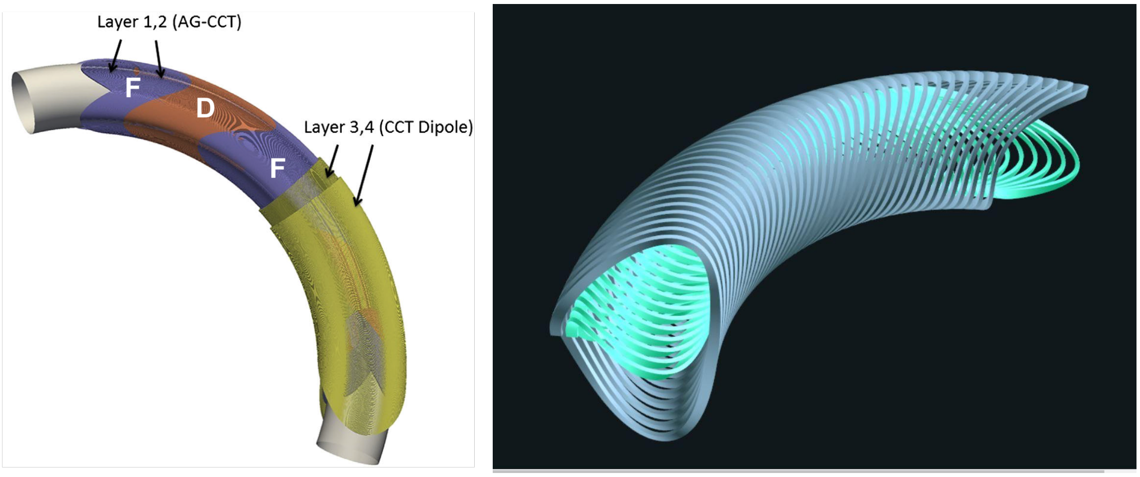
APENDIX 1. CCT magnet parameters.

CCT magnet parameters	Model straight magnet			Curved prototype magnet		
	Dipole	**Common Values**	**Quadrupole**	**Dipole**	**Common Values**	**Quadrupole**
Clear Central Aperter (mm)		200 mm			200 mm (may reduce after optimizasion)	
Magnet length		1.6 m			1.6 m	
Magnet form		Straight			Curved 1 m radius	
Magnet Mass		~1500 kg no Iron			~5000 kg no Iron	
Magnetic Field	2.6 T		40 T/m	3 T		40 T/m
Field intergral	1.96 T.m					
Operation current [Amps]	2700		2300	2700		2300
Inductance [mH]		282.33			~ 280	
Stored energy [MJ]		1.53			1.53	
Operating temperature [K]		4.5			4.5	
Conductor Margin [% short sample]	~ 60%		~ 60%	~ 60%		~ 60%
Quench Protection		Quench protection CLIQ or quench heaters			Quench protection CLIQ or quench heaters	
Quench hot spots		< 200 K			< 200 K	
Quench voltages		< 1 kV			< 1 kV	
Circuits / power supplies	1		3	1		3
Current leads warm to cold	2		6	2		6



Left: Coil layers of a curved 90 degree CCT magnet. The outer layers correspond to the dipole, and the inner layers correspond to a FDFDF alternating quadrupole configuration [11]. Right: Example of a curved CCT dipole with twisting quadruple produced by the Rat software.

APENDIX 2. Time schedule.

	1st y			2nd y			3rd y			4th y			5th y		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1. Physics program															
1.1 Requirements review	■	■	■												
1.2 Whitebook	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
2. Beam dynamics															
2.1 Design specifications	■	■	■												
2.2 Selection of machine layouts and lattices	■	■	■	■											
2.3 Ring simulations refinement				■	■	■									
2.4 Injection/extraction simulations refinement				■	■	■									
2.5 Error calculations and tolerances							■	■	■	■					
3. CCT magnets and cryostats															
3.1 Straight nested magnet prototype															
3.1.1 Modelling and detail drawings	■	■	■												
3.1.2 Components and construction			■	■											
3.1.3 Cold Test					■										
3.2 Curved nested magnet prototype															
3.1.1 Modelling and detail drawings	▒	▒	▒	▒											
3.1.2 Components and construction				▒	▒	▒	▒	▒							
3.1.3 Cold Test									▒						
3.3 Curved cryostat															
3.1.1 Modelling and detail drawings			▒	▒											
3.1.2 Components and construction				▒	▒	▒	▒	▒							
3.1.3 Cold Test									▒	▒					
3.4 Mounting magnets in curved cryostat and test															
3.4.1 Cryostating											▒	▒	▒		
3.4.2 Test of magnets in cryostats											▒	▒	▒	▒	
4. Injection/extraction															
4.1.1 Septum magnet concept				▒	▒	▒	▒	▒							
4.1.2 Septum magnet prototype									▒	▒	▒	▒	▒		
4.2.1 Fast Kicker design concept				▒	▒	▒	▒	▒							
4.2.2 Fast Kicker prototype									▒	▒	▒	▒	▒		
6. Magnet test bench															
6.1 Test bench specifications	▒	▒													
6.2 Design of test bench hardware		▒	▒												
6.3 Test bench software			▒												
6.4 Procurement and commissioning				▒											
6.5 Magnet testing				▒	▒	▒	▒	▒	▒	▒					
7. Buncher															
7.1 Multiharmonic buncher															
7.1.1 MHB EM and beam dynamics design	▒	▒	▒	▒											
7.1.2 MHB engineering design				▒	▒	▒	▒	▒	▒						
7.1.3 MHB prototyping									▒	▒	▒	▒			

7.1.4 MHB testing													▨	▨	▨
7.2 Solid State Power Amplifier (SSPA)			▨	▨	▨										
7.2.1 SSPA design						▨	▨	▨	▨						
7.2.2 SSPA prototyping									▨	▨	▨	▨			
7.2.3 SSPA testing												▨	▨	▨	▨
8. Detector systems															
8.1 Beam detectors															
8.1.1 Design study	■	■	■	■	■	■	■								
8.1.2 Prototyping				■	■	■	■	■	■	■	■				
8.1.3 Test										■	■	■	■	■	
8.2 Focal plane detectors															
8.2.1 Design study	■	■	■	■	■	■	■								
8.2.2 Prototyping				■	■	■	■	■	■	■	■				
8.2.3 Test										■	■	■	■	■	