CHAPTER IV

THE PROTON DRIVER

4.1 Introduction

The production of neutron rich exotic beams at the SPES project is related to the direct reaction of a proton beam on an UCx target. The exotic species, produced by Uranium fission, will be extracted from inside the target by ISOL technique.

To be competitive in the international scenario of the research with exotic beams, a fission rate of $10^{13}$ fission/s is recommended.

The proton beam necessary to reach this fission rate using the direct target technique described in the next chapter has to have the following characteristics:

- Energy of the order of 40-50 MeV
- Minimum current 200 µA (~ $1.2\times10^{15}$ p/s)
- Beam spot size on the target Φ 40 mm (circle area 1260 mm²)
- Primary proton flux ~ $1\times10^{12}$ p/(mm²*s)
- Beam uniformity on the target ± 1%
- Beam time structure CW to minimise the target thermal stress and fatigue
- Beam intensity stability on target
  - Fast (time scale µs) ± 10%
  - Medium (time scale s) ± 1%
  - Slow (time scale min) ± 1%
- Machine reliability 90% of the scheduled working time
- Machine availability ≥ 5000 h/Y

On top of the previous specification, as open options for future upgrades, it is required to the primary accelerator system (from now on defined as Driver): to be able to serve contemporary users (two or more); to be able to deliver in excess of 1.5 mA of proton beam current; to be able to deliver deuteron and α beams.

The Driver needed for the SPES complex consists in:

- The source(s) (proton/d/ α)
- The accelerator
- The transfer line
- The field level control system (operation, status, safety, security, logging)

The ancillaries (cooling system, electrical power distribution, dry nitrogen distribution system, high pressure air distribution system) are not, strictly speaking, included in the Driver but at the end of the present chapter we will define some guidelines to be passed to the building and the services designers.

The accelerator, for this energies and intensities, can be either a LINAC or a Cyclotron. In the last years the linac options has been studied in details and successfully prototyped for various aspects; the linac chosen in INFN-LNL 220 report was composed by the source TRIPS, developed by LNS, the TRASCO RFQ and a normal conducting DTL, for which a prototype is now being built with common CERN and INFN effort.
On the other hand the beam performances necessary for SPES can also be reached by a commercial cyclotron of new generation. Advantages and disadvantages of the LINAC and cyclotron have been accurately evaluated by the design group and by the SPES steering committee. The conclusion of this analysis was that, even if both solutions are able to guarantee the required performances for RIB production, and the possibility of feeding a second user beam line, nevertheless the cyclotron solution has the advantage to be completely independent, leaving the possibility of full time use of the high intensity RFQ beam for medical and interdisciplinary applications. The choice of a commercial solution is also dictated by practical reasons, mainly lack in human resources for the design phase and shortage in time.

The cyclotron technology is mature and the market has already “off the shelf” integrated solution for the medical isotope production with the beam energy and beam intensity figure very close to the SPES requirements (e.g. \( \approx 1 \text{ mA}, \approx 30 \text{ MeV} \) protons). The possible Construction Companies propose turn key systems, established, tested, reliable, available and mature.

In addition for medical application one new product is coming to operation. This new Cyclotron, built by an European company for a French Research Institute, is well suited for the SPES requirements (chapter IV addendum).

In the present chapter the major technical specifications, requirements and constraints are described in order to be able to prepare the technical description necessary for the acquisition bid of a “turn key” system.

4.2 The source(s)

Here we focus on the proton beam generation, leaving the requests for light particle (Deuterons and \( \alpha \)) for the possible upgrade of the RIB complex.

The high level specs of the proton source are:

1. External source.
2. Beam intensity sufficient to guarantee the required beam on target (order of magnitude tens of mA either negative or positive depending on the extraction system).
3. High beam quality in terms of:
   - Beam stability \( \pm 1\% \)
   - Transverse beam emittance (both planes) \( \leq 1 \pi \text{ mm mrad} \) (1 \( \sigma \), norm)
   - Availability \( 6000 \text{ h/Y} \)
   - Reliability \( \geq 95\% \) of the scheduled time.
4. Easy to maintain.
5. CW operation.
6. Spare part availability for at least 15 years following the acceptance.

The source must be part of an integrated system.

The operation must be as easy as reasonably achievable in terms of: start up time (from source off and from stand by status if any), shut down, beam change (applicable after the upgrading) etc.

The source as a whole, including the operation system and the integration in the control system of the accelerator that serves, is a part commercially available; no major R&D must be performed.

4.3 The accelerator

As mentioned above in order to acquire the accelerator on the commercial market we require a Cyclotron able of delivering proton beams with the characteristics described above in terms of beam quality, intensity and stability.

The main general characteristics of the accelerator are:
1. Vertical injection with high efficiency electrostatic deflector.
2. Multiple contemporary extraction line (at least two with different energy capability).
3. High orbit separation at extraction energies (as reasonably achievable).
4. Easy operation.
5. Easy maintenance.
6. Beam extraction efficiency
7. Low extraction transverse emittance (both planes) ≤ 4 π mm mrad (1 σ, norm)
8. Availability ≥ 6000 h/Y
9. Reliability ≥ 95% of the scheduled time.
10. CW operation.
11. Spare part availability for at least 15 years following the acceptance.

The design of the Cyclotron must be proved to be robust, efficient and reliable in terms of:

- Beam dynamics (injection, beam losses few %, instability control, tune space working area, extraction, orbit separation at the extraction, energy dependence of the transverse emittances)
- Injection system (transfer line(s) from the source(s), inflector)
- Central Region (break down consideration, capability of p, d and α beams, high efficient capture)
- Magnetic Field distribution (main field hill-valley distribution, correction coils, extraction channels)
- RF system (robust, easy to maintain, external)
- Vacuum system (oil free, 10⁻⁶ mbar or better)
- Start up from machine off and from machine stand by;
- Beam tuning (internal beam diagnostics, extraction energy, extraction channel, eventually particle species);
- Maintenance (regular, extraordinary, emergency);
- Safety: the system has to follow the ALARA (As Low As Reasonably Achievable) principle for any possible hazard connected to the operation and to the maintenance. Possibly the accelerator has to be CE marked as components and as whole systems.

The accelerator will deliver beam for the target production of the RIB facility and, eventually, for different users located in adjacent experimental areas.

Consequently we require to have two extraction channels 180° apart with different extraction energy (from 35 to 70 MeV protons) and variable intensity splitting capabilities (from 50-50 to 90-10)

### 4.4 The transfer line

The layout of the beam line transfer for the cyclotron is shown in figure 4.1. At the exits of the Cyclotron, 180° apart, there are two distribution magnets with three channels each in order to deliver the beam(s) to:

- The two RIB production target (one from day one and the other in the foreseen upgrade of the facility).
- The new experimental area.

The RIB production targets are installed inside a shielding concrete bunker, because of the neutrons, and the transfer line must cross the shielding using holes that avoid neutron leaks towards the Cyclotron vault.

The Cyclotron is oriented, in the present layout, with the two extraction channels placed on the north-south direction. The two RIB production bunkers are southbound and the experimental area is northbound.
The topology of the building is such that minimize the length of the transfer lines and that permits the contemporary operation of both the RIB target.

The distribution magnets have three exit each, in the present layout, $0^\circ$, $45^\circ$ and $-45^\circ$ (negative angles in the counter clockwise direction).

The transfer lines must preserve the transverse emittances, and contain: dipoles ($45^\circ$ and $90^\circ$ bending combined function) quadrupole lens for the transverse focussing and beam diagnostics. The line(s) that serves the experimental area will be studied when the final users will specify the required beam characteristics from now on we will focus on the RIB production related ones.

The RIB target productions need a CW beam well distributed over a circle of 40 mm diameter with a uniformity of $\pm$ 1% in intensity and a flux of $10^{11}$ p/(mm$^2$*s). Consequently there is no need of RF bunching system in the transfer lines and the optic has to end with a beam as parallel as possible. At present we do not foresee any rastering or wobbling system for the beam spreading on target.

These transfer lines are at the same level, ground floor, and included in the same vault that houses the Cyclotron.

4.5 The control system

The Driver is not an isolated accelerator but is the starting point of a RIB facility and as such it must be considered as far as the control system is concerned. The operation, the security and the safety of the Driver are parts of the similar functionality of the other parts of the complex, sources, transfer lines and secondary beam accelerators.

The field level of the control system (beam instrumentation, local PLC controller, data transmitter, power supply controller, failures indicators, interlocks etc.) can be optimized in order to reach the required performances (first but not only the reliability and the safety) and it has to be connected/connectable with the RIB complex supervising system described afterward (chapter IX).

Fig. 4.1: Schematics of the Cyclotron with the transfer lines to the RIB production target stations.
In order to have the reasonable confidence of a lifetime of the Driver control system of no less than 20 years all the components of the control system will be commercial standard easy to find and well supported by the production companies (e.g. Siemens S7 PLC).

The control system/data handling architecture is based on field instrumentation with ADC units, VME crates, Ethernet links and switching boards (100 MB/s) connected to the high level/human interface control system via optic fibres (1 GB/s) (see 9.1.1).

### 4.6 The ancillaries

As mentioned above the ancillaries and the technical infrastructure are described elsewhere (chapter XIII) but it is worth to summarize some essential needs for the Driver.

#### 4.6.1 The electrical power system

The Driver vault and the connected service environments have to be served by a complete electrical distribution net on industrial standards including: 400 V 3 phases (bars system), 220 V single phase, diesel generator backed up 220 V single phase, UPS backed up emergency 220 V single phase, breakers and general switches.

The single phase distribution net has to be noise free.

The power network has to be located in independent and isolated channels, different from the signal cables channels.

The electrical power consumption, all included form the source(s) to the production target, must be minimized and in no case has to overcome 1 MVA.

#### 4.6.2 The water cooling

The water cooling system has to provide temperature controlled water flow to cool all the Driver parts that needed it: the magnet, the power supply and the RF system.

The system is a closed circuit system that utilises treated water to avoid cavitations and biological pollution.

#### 4.6.3 Alignments

The alignment of the Cyclotron and of all the transfer lines is foreseen to be with a c construction of an optical reference line off axis with precision monuments for the first alignment and for the following survey.

Every single piece will have reference markers, positioned, aligned and checked off line and they will be placed on independent moving system ether on girders or on single supports in order to properly align them along the optical reference.

In special positions there will also be placed stable columns for the optical devices (levels, telescope etc.) possibly equipped on Taylor-Hobson spheres as reference position.

Every couple of years a survey campaign if strongly recommended.

#### 4.6.4 Power supply and RF system gallery

The power supply and the RF system will be housed close by the equipment that they have to serve. This “gallery”, needed for the shielding of the electronics, has to be accessible all time, even during the machine operation, for maintenance and survey.

#### 4.6.5 The driver control system room

The operator interface control room will be integrated in the complex control room and is described elsewhere.
It is foreseen to have a room close by the Cyclotron Vault and accessible at any time, even during the machine operation, properly radiation shielded containing all the electronic rack, the field control PLC’s, the Ethernet switchboards etc. needed for the operation, the status logging, the faults control. This includes local control keyboards and monitors.

The hierarchy of the control architecture that avoids interrupt conflicts and safety/security problems will be described elsewhere.

4.6.6 Heavy load handing systems

In the Cyclotron vault there will be need to move heavy components (e.g. magnets) mainly during the Driver assembly. Afterwards the handling of heavy load is limited. Consequently there are two options: to install a crane, to use mobile lifting equipments for the installation and for the extraordinary maintenances. The final choice will be made in the building design specification.

The most heavy component of the Driver is the Cyclotron. Usually the commercial Cyclotrons of this size have imbedded the machine itself.

4.6.7 Hazardous material handling

We will follow the standard procedure for the hand on maintenance accelerator related component.

The sensitive parts of the Cyclotron, mainly the extraction channel components and the stripers in case of stripping extraction, will be check by the Radioprotection dept. before any hands on operation.

No special equipment for hazardous material handling is foreseen for the Driver.

4.7 Conclusions

A proton driver based on a cyclotron with energy 40-50 MeV and current 0.2 mA fulfils the requirements for the SPES project as the direct target is actually designed for 8kW power. A driver with a capability of 50KW (70 MeV, 0.75 mA) with the possibility of a current upgrade reaching 1.5mA and a beam power of 100kW is indeed very interesting for the development of the SPES project, as further developments of SPES will be in the direction to increase the maximum sustained power in the target, with the aim to increase the RIB intensity and to follow the EURISOL trend for a 100kW direct target.

4.8 Chapter IV addendum: technical specifications of a Commercial Cyclotron suitable as Driver for the SPES project.

A commercial cyclotron, with characteristics which fulfil the needs for the SPES project, was recently developed by IBA: the Cyclone® 70 (C70). In the following the description of this machine is reported following the IBA paper at the last Cyclotrons conference held in October 2007. Since the end of 2005, IBA has been working on the development of the 70MeV Cyclone, the ARRONAX Cyclotron for the Region des Pays de la Loire in Nantes, France. The cyclotron can deliver protons, deuterons and alphas, it is actually under installation and the first beam is expected this year.

The cyclotron, equipped with a multicusp external ion source, produces high intensity, variable energy H⁺ (30-70MeV, 750µA) on two exit ports. The unique magnet structure is composed of three layers: sector, pole and pole cover. Furthermore, compensation coils are wound around each of the poles in order to obtain the different isochronous fields. The RF system at about 30.4MHz consists of a 200 kW RF amplifier coupled to a home-made cavity. Extraction is then obtained by stripping. The overview of the development of the cyclotron subsystems will be reported.
4.8.1 **Scope**

The Cyclone® 70 is an ambitious project that occupies a major role in the R&D activities of IBA’s Technology Group business unit. This unique cyclotron is a powerful and flexible tool that is the answer to the radiochemistry and oncology needs related to the ARRONAX (Accélérateur Recherche Radiochimie Oncologie Nantes) project. For the development of this prototype, IBA has concentrated its twenty plus years of expertise in cyclotron technology. Indeed, the Cyclone® 70 is a mixture of proven techniques commonly used in models like the Cyclone® 30 and the Cyclone® 230 to which newly developed technology related to the particular specifications of the accelerator, namely the combination of alphas and protons, is added. IBA can accept the challenge of delivering a pure proton cyclotron in an extremely tight schedule of 24 months also for SPES project.

The deliverables of the Cyclone® 70 project for SPES are the following:

i) Accelerating beam H-

ii) Extracted beams H+

iii) Extracted energy continuously variable between 30 and 70 MeV

iv) Beam Intensity 750 eµA (possible upgrading up to 1500 eµA. IBA availability but cost and terms to be defined).

The cyclotron is equipped with two exit ports allowing for dual beam extraction for protons. On the technical side, the magnetic calculations were the first major challenge. At this stage the choice of using correction coils to profile the alpha magnetic field was a turning point for the development of the machine. This choice steered the magnetic design to a unique inner iron configuration composed of three specific layers: a sector, a pole and a cover. The correction coils are wound around the pole. The mechanical design presented a delicate problem concerning the iron pileup so that the magnetic gap could be precisely guaranteed. The retained solution was the use of carefully machined spacers between each part that ensure the final gap. The machining phase was a major challenge for both IBA and the sub-contractor. To ensure the quality of the results, the collaboration between the two was very intense. During the last two months of the machining, identified as the critical period during which the parts were reaching their final dimensions, a day to day follow-up ensured an almost perfect result. To map the cyclotron, a new measuring system was developed with the constraint of being able to move in a particularly narrow magnetic gap (30mm).

The inflector as well as the use of an electrostatic deflector for beam centring, will be realized having as main goal the optimization of the proton acceleration even in the perspective of future possible current improvement up to 1500 eµA. Before shipping the cyclotron, the goal is to perform as many unit and integration tests as possible to reduce the risk of having to deal with major problems during the 8 months of installation and testing on site.

4.8.2 **General description**

The Cyclone® 70 is an isochronous, fixed magnetic field and RF frequency, cyclotron with a diameter of just under 4m weighing over 120T. Its main sub-systems are here briefly outlined.

**Magnet structure:** the cyclotron is based on the deep valleys concept, used on the other IBA models but distinguishes itself by its particular magnet structure composed of three layers and specific magnetic extraction channels.

**Sources:** A well specialized high intensity multi-cusp source will delivered high current proton beams.

**Injection and central region:** The injection line and the central region have been designed from the constraint of accelerating only high intensity protons (1500 eµA). The configuration of the injection line and central region will also play an important role in achieving the 750µA extracted proton beam as expected for the acceptance test.

**RF:** The RF system is composed of a 200 kW amplifier and a 7 kW pre-driver, controlled by an IBA low level controller. The working frequency is around 30.4MHz. The RF cavity is a home made design based on a CST model. It is composed of two dees and four accelerating gaps. The accelerating voltage is 65kV and around 20kW of power is needed to sustain it. Particles with a q/m = 1 are accelerated in harmonic mode 2.
Vacuum: The vacuum system is composed of four cryogenic pumps of 5800l/s. The main chamber is split in the median plane and two extraction chambers ensure the connection to the two switching magnets.

Extraction systems: The proton beams are extracted by strippers. As for the stripping mechanism, modifications to the Cyclone® 30’s model were done for cooling reasons. The cyclotron is equipped with two stripping mechanism installed on each beam port. This allows for dual beam operation with the corresponding particles. At its highest capacity, the cyclotron will accelerate up to 100 kW of proton beam in dual beam mode.

Control system and user interface: The control system is based on a Siemens S7 PLC. The user interface is based on the existing Cyclone® 30 interface developed with InTouch. The cyclotron control system will be integrated inside the general control of SPES discussed in Chapter 9.

4.8.3 Central region design

The approach used designing the central region can be divided in the following steps:

i) Construct an OPERA3D model of the cyclotron magnet and use it to create isochronous field maps for the protons and a detailed 3D field map in and around the inflector volume.

ii) Design the Dee and dummy Dee geometry by using the maximum available azimuthal space in between the two pole covers. The accelerating gap was chosen not smaller than 5 mm in order to avoid voltage breakdown. Solve the geometry with OPERA3D and obtain a 3D potential map around the median plane as needed by the tracking code.

iii) Determine the accelerated equilibrium orbit (AEO) for protons, by backtracking from high energy towards the center in the isochronous magnetic field and realistic dee-structure. The particles are started on a static equilibrium orbit (SEO) and have an RF phase that gives maximum energy gain. The energy of the SEO is optimized such that the final energy of the backtracked particle is exactly equal to the injection energy.

iv) Determine the crossing point of the backtracked AEO’s at injection just before entrance into the first accelerating gap. This is the point where the electrostatic deflector must be placed.

v) If necessary modify the geometry of the tee-tip in the center in such way to get that reasonable deflector voltages will do the job.

vi) Obtain an initial estimate of the inflector central design orbit. For this purpose a special mode of the tracking code is used in which the inflector is simulated by an electric field that is always perpendicular to the orbit. Within this mode the inflector is specified by its electric bend radius \( A \), its tilt parameter \( k' \), its length \( L \) (measured along the orbit), entrance height above the median plane \( z_0 \), rotation angle \( \alpha \) around the z-axis, and fringe field parameters.

The code allows to automatically optimizing the parameters \( L \) and \( z_0 \), so that the particle is injected exactly onto the median plane. The code also allows to automatically optimizing the angle \( \alpha \) so that the injected orbit passes through the crossing point. Optimization of the injected orbit angle at the crossing point is done by changing the tilt parameter \( k' \) in order to get the better transmission.

vii) Construct the real 3D inflector electrodes around the estimated reference orbit using OPERA3D.

viii) Verify the design by orbit tracking in the real 3D electric and magnetic fields and make small modifications to the inflector if needed.

4.8.4 Injection line design

For optical design of the injection line, a good estimate was needed of both transverse phase space ellipses that would provide the best match to the cyclotron. Therefore a very large 4D transverse phase space containing 300000 particles was tracked through the cyclotron axial bore, the inflector and central region and the first 50 turns into the cyclotron (for \( H \) up to 7.5 MeV). The particle was considered as accepted if it is within the horizontal and vertical eigenellipses of the cyclotron. The eigen-ellipses corresponding with a half beam size of 4 mm was used. For \( H \)- this corresponds with horizontal and vertical emittances of 43\( \pi \) mm-mrad and 23 \( \pi \) mm-mrad respectively. These the values calculated for the multi-particle version. Better value
will be obtained in case of C70 for SPES due to the optimization that will be done for the proton only machine.

Particles that were not in those eigen-ellipses were removed from the initial injected beam and then the remaining injected phase space was analyzed. Since this is a full 4D phase space, it contains correlations between both transverse directions that cannot be realized in practice. For that reason a subset of the full 4D phase space was extracted which would correspond to a beam without such correlations. It was found that this subset corresponded very well to a round beam. From this it was concluded that the best match to the cyclotron corresponds with a round beam at the cyclotron bore entrance. These conditions were used in TRANSPORT for fitting purposes. Comparing the emittances at injection and after 50 turns, we can estimate the emittance growth factors. These are 2.7 horizontally and 1.4 vertically for the $H$- beam. Two turbo pumps are installed directly behind the cusp source; one of them is installed in the vertical beam-line, just above the cyclotron. The horizontal line contains a solenoid for focusing and a small correction dipole for steering in both planes. A quadrupole triplet is used to restore rotational symmetry of the beam (round beam) which was lost due to the asymmetric optics of the bend magnet. Further downstream are two solenoids that are used to match the beam to the cyclotron optics. The second solenoid is inserted in the cyclotron upper yoke.

Within the third solenoid the envelopes attain a maximum value and are then strongly focused to a size of a few millimetres corresponding with the calculated matching condition.

4.8.5 Extraction by stripping

The H- isochronous field map was obtained from a 3D magneto static model calculation by TOSCA. Single particle tracking studies have been used for determining the adequate stripper positions as a function energy, in the range 35–70 MeV, in such a way that all paths cross in the centre of the switching magnet. The extraction process by stripping redefines the horizontal phase space parameters, whereas the vertical phase space is considered to be unchanged. These redefinitions have been obtained by multi-particle tracking studies for the energies 70 MeV, 60 MeV and 35 MeV. The initial Twiss parameters were obtained from the $MAD$ analysis of a suitable closed orbit. The normalized emittance of the circulating beam is taken as $\varepsilon^N_{\text{H}} = 6 \, \pi \, \text{mm mrad}$.

<table>
<thead>
<tr>
<th>$T$ [MeV]</th>
<th>70</th>
<th>60</th>
<th>35</th>
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<tbody>
<tr>
<td>$\varepsilon_{\text{H}}$ [(\pi) mm mrad]</td>
<td>3.0</td>
<td>3.3</td>
<td>6.0</td>
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A correction of the optics on the path to the switching magnet is obviously not possible in this case. Even so, the envelope function $\beta_s$ stays well below 20 m at the centre of the switching. Figure 4.2 shows a tracking simulation of the 70 MeV proton beam from the stripper to the switching magnet.
Fig. 4.2: Tracking simulation in the TOSCA field for the 70 MeV extraction, stripper to switching.