CERN'S FIXED TARGET PRIMARY ION PROGRAMME

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MOTIVATION

The renewed availability of heavy ions at CERN for the needs of the LHC programme has triggered interest from the fixed-target community. Specifically since 2006, NA61/SHINE [1] had requested a series of ion species at various momenta, from 10 to 160*A* GeV/*c*. In the absence of a second ion injector, only Pb ions were available during the LHC Pb runs, so that between 2010 and 2013, the SPS first delivered fragmented Be ions from Pb beams [2 - 4]. In the meantime, and in order to satisfy the needs of the experimental collaboration [5], CERN had launched a new project allowing to pursue the experiment with primary ions [6].

The project, which aims at sending several species of primary ions at various energies to the North Area of the Super Proton Synchrotron, has now entered its operational phase.

CERN'S ION ACCELERATOR COMPLEX

CERN's heavy ion production complex was first designed in the 1990s for the needs of the SPS fixed target programme [7, 8], then rejuvenated at the beginning of the XXIst Century [9] in order to cope with the LHC's stringent demands for high brightness ion beams [10]. It currently consists of [11]:

- An Electron Cyclotron Resonance (ECR) ion source, operating in after-glow mode [12]
- A 250 keV/u, 2.66m long Radio Frequency Quadrupole (RFQ) operating at 101.28 MHz
- LINAC3, consisting of three Interdigital H RF cavities, accelerating to 4.2 MeV/u
- LEIR, the Low Energy Ion Ring, a 1.44*Q* GeV/*c* accumulation and cooling storage ring [13]
- The Proton Synchrotron (PS) which accelerates the ions up to 26*Q* GeV/*c* [14]
- The Super Proton Synchrotron (SPS) [15], which can accelerate the fully stripped ions up to 450*Z* GeV/*c*.

During the exploitation period with primary ions, the SPS also accelerates high intensity, high energy proton beams – up to several times 10^{13} protons at 450 GeV/*c* – for other users such as the LHC. Hence, special precautions have to be taken to prevent those beams from being accidentally sent to the North Area, causing a serious accident in the absence of targets during the primary beam runs. A critical part of the project was therefore to design, build and commission a personnel protection system, which inhibits two extraction elements if the beam intensity exceeds a threshold of 2×10^{11} charges [16].

Typical Cycle for Primary Ions

The intensity and emittance requirements for the fixed target beams are less stringent than for the beams destined to be collided in the LHC, and the typical cycle in the injectors is similar to the one used for the LHC "pilot beam". However, in order to be always in the detectable range of the RF loops once debunched and recaptured, the total beam intensity in the SPS has to maintain a minimum value of 2×10^{10} charges throughout the cycle. The debunching phase is essential to deliver a structure-less beam to the experiments.

- Linac3 produces a 200 µs pulse of partially stripped ions at 4.2 MeV/u. Depending on the type of ions, they can be stripped further in the transfer line by a 0.3 µm thick, 75 µg.cm^{-2} carbon foil.
- LEIR takes a single multi-turn injection from Linac3, reduces the transverse emittances and the energy spread by electron cooling, accelerates the ions to 1.44*Q* GeV/*c* on harmonic h=1, and extracts the single bunch towards the PS.
- The PS accelerates the bunch on harmonic h=16, through transition up to 26*Q* GeV/*c*, and rebuckets it into h=169, using an 80 MHz cavity.
- At the exit of the PS, the beam is fully stripped by a 1 mm thick aluminium foil, in the middle of a low-beta insertion designed to minimize transverse emittance blow-up. Since the stripper foil is located in the same transfer line as the high intensity proton beams for other users (AD, nToF, LHC, etc), it needs to move in or out of its position several times per supercycle, according to the particle type.
- The SPS takes 4 injections from the PS, spaced by 2.4 seconds, the common LEIR and PS cycle duration. The four bunches are placed equidistantly in the SPS ring. At the end of the 8.5 s flat bottom, they are accelerated to an intermediate flat top at $\gamma = 11.1$ with a fixed frequency RF system [17].
- The beam is debunched for two seconds, then recaptured by the fixed harmonic RF system and accelerated, to the final extraction momentum, crossing transition if required.
- At top energy, the RF is turned off and the beam debunches naturally, before being slowly extracted on

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a third integer resonance, with a spill duration of about 10 seconds .

The SPS ion beam can be accelerated up to 450*Z* GeV/*c* for fast extraction to the LHC, but for fixed target operations which need a long extraction flat top, the power supplies limit the extraction momentum to 400*Z* GeV/*c*. On the other hand, the stability of magnetic elements in the machine and in the extraction lines imposes a lower limit of the order of 30*Z* GeV/*c* for the magnetic rigidity at extraction. Hence, the initially requested momentum range of 10-160*A* GeV/*c* had to be decreased to 13-150*A* GeV/*c*.

The charge states and typical intensities throughout the complex for the various species are listed in Table 1 below. The parameters for Ar and Pb have been achieved, for Xe they are expected. In order to deliver the requested rate of less than 10^6 ions per 10 second spill, the beam needs to be collimated in the extraction line, and its intensity reduced by more than two orders of magnitude.

Table 1: Charge States and Typical Intensites

Species	**Ar**	**Xe**	**Pb**
Charge state in Linac3	Ar^{11+}	Xe^{20+}	Pb^{29+}
Linac3 beam current after stripping [eμA]	50	27	25
Charge state *Q* in LEIR/PS	Ar^{11+}	Xe^{39+}	Pb^{54+}
Ions/bunch in LEIR	3×10^9	4.3×10^8	2×10^8
Ions/bunch in PS	2×10^9	2.6×10^8	1.2×10^8
Charge state *Z* in SPS	Ar^{18+}	Xe^{54+}	Pb^{82+}
Ions at injection in SPS	7×10^9	8.1×10^8	4×10^8
Ions at extraction in SPS	5×10^9	6×10^8	3×10^8

THE FIRST PHYSICS RUN: ARGON

Preparation in 2013

The ECR source, RFQ and Linac3 were setup and tested during 13 weeks at the beginning of the first long shutdown of the LHC ("LS1"), between February and May 2013 [18]. As argon is gaseous, no additional support gas was needed, and the operation of the source was much simpler than with lead. As an example, the commissioning of the source only took one week, to be compared with four to six weeks in the case of lead. Also the performance after a source stop and restart was much more reproducible.

This first running period, and the maintenance that followed, allowed to identify and mitigate or solve several issues such as the need to modify the access zoning at the end of the linac due to the neutron production of lost argon ions at 4.2 MeV/u, and in the source, the design and wiring of the intermediate electrode, and the procurement of spare plasma chambers to compensate for the higher damage by sputtering during argon operation.

Commissioning in 2014

In addition to the collateral software and hardware changes inherent to a long shutdown, the LEIR machine had to be restarted with argon as a new species after LS1, which took longer than expected.

Conversely, the commissioning of the argon beam in the PS was quite simple: the argon beam rigidity at injection and extraction being identical to those of lead in the PS, the lead magnetic cycle could be reused entirely. Only the frequency programme and the transition crossing time had to be modified.

The SPS was also commissioned with argon in the shadow of the proton physics programme, from October to December, at a rate of two days/weeks, a constraint imposed by the rest of the machine development programme. The first weeks were dedicated to longitudinal adjustments: acceleration on the fixed frequency programme, and debunching efficiency. For each extraction momentum, a different cycle had to be programmed, and each of the 6 SPS operational cycles were prepared before the end of the year.

Physics Run in 2015

The argon run took place right after the yearly technical stop, from February 2015 to April 2015. In the course of eight weeks, the beam was successively delivered to NA61 at 13, 150, 19, 30, 40, and 75*A* GeV/*c* [19]. Due to the presence of LHC cycles in the supercycle, the duty cycle was limited to 20%. In addition to NA61/SHINE, argon beams were also delivered to several other experiments: NA63, Proba-V, CALET, CBM-TOF, UA9, DAMPE and Medipix [20].

TESTS WITH PRIMARY LEAD BEAMS

Future Pb beams have been requested by NA61 for the coming years [21]. In preparation for this, the lead ion beam was sent to NA61/SHINE at 30*A* GeV/*c* for two weeks in November 2015, in the shadow of the LHC's first Pb-Pb run at 5.02 TeV [22]. In addition, the following collaborations were able to take the beam in parallel: HERD (R&D for a detector being proposed for the Chinese Space Station), NUCLEON, RE21, RE29, RE25, SuperTiger (R&D for a balloon born experiment) and HNX (R&D for the Heavy Nuclei eXplorer satellite) [20].

During the next LHC p-Pb run, from November 14th to December 12th, 2016, the Pb beam will be sent to the North Area at three different momenta: 13, 30, and 150*A* GeV/*c*. A subsequent run is planned to take place at 19, 40, and 75*A* GeV/*c*, in November-December 2018, during the last LHC Pb-Pb run before Long Shutdown Two (LS2).

XENON RUN IN 2017

The fixed target xenon run is now planned for the end of 2017. As the LHC is taking lead beams at the end of 2016, there will be no possibility to set up any CERN machine with xenon before 2017. Commissioning the xenon beam in the source, the linac, LEIR, the PS and the SPS, as well as preparing all six new SPS cycles in less than a year will present a new challenge for the accelerator teams. As a consequence, the source and linac will have to start at the end of February, i.e. one month before the end of the extended year end technical stop (EYETS).

In the meantime, the xenon beam has already been prepared in an identical ECR source at iThemba Labs, in South Africa [23]. These machine experiments have allowed to identify several aspects of the future operation. In particular, oxygen will be used as support gas, the source will be used in afterglow mode, and the maximum particle current corresponds to charge states around Xe^{20+}. As the test period was very short, no sputtering damage was observed on the plasma chamber.

The commissioning of the other machines, from the linac to the SPS will benefit from the experience gained with argon in 2014-2015. In particular, for LEIR, the cycle generation software is being reviewed, and as from mid-2016, the machine will be equipped with a new low-level RF system, identical to the one used at the PS Booster [24].

Due to a constraint imposed by the frequency range of their respective RF systems, the PS to SPS handover has to take place at the same frequency as for the Ar^{11+} beam. Xe^{39+}, due to its larger charge-to-mass ratio (0.30 with respect to 0.28 for Ar^{11+}), will have to be extracted from the PS at a momentum lower by 9% than the maximum possible $26Q$ GeV/c. No other issue is expected in the PS, which should commission the xenon beam in two weeks.

Finally, the SPS will use the three summer months to set up the fixed frequency acceleration system, and prepare the six extraction momenta needed by the experiments, in parallel to the proton operations for the LHC, AWAKE, HiRadMat and the North Area, and with a limited number of days per week, taking into account the rest of the machine development programme.

The fixed target xenon run is currently planned to take place during the last eight running weeks of 2017, from October 23rd to December 17th.

CONCLUSION

The fixed target primary ion project has now fully entered its operational phase. Several species of primary ions have already been delivered to the SPS North Area, at momenta ranging from 13 to $150A$ GeV/c.

The continuation of the programme, with the delivery of lead beams in 2016 and 2018, and xenon beams in 2017, in the same momentum range, will allow NA61/SHINE to pursue the quest for the critical point of strongly interacting matter [25]. The large cosmic ray experiments are also expected to benefit from these beams in parallel [20], as the North Area fixed target ion programme is the only place where they can perform the Charge&Energy calibrations.

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