A DEDICATED 70 MEV PROTON LINAC FOR THE ANTIPROTON PHYSICS PROGRAM OF THE FUTURE FACILITY FOR ANTIPROTON AND ION RESEARCH (FAIR) AT DARMSTADT

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Abstract

The antiproton physics program of the proposed International Accelerator Facility at Darmstadt is based on a rate of $7\cdot10^{10}$ cooled antiprotons per hour. To provide the primary proton intensities a proton linac is planned, which will be operated independently from the existing UNILAC for heavy ions. The proposed linac comprises a proton source, a RFQ, and a DTL. Its operation frequency of 352 MHz allows for an efficient acceleration to up to 70 MeV using normal conducting Crossed-bar H-cavities. These CH-cavities show high shunt impedances as known from IH-structures, but allow for much higher relative particle velocities of up to 50 %. The beam pulses with a length of at least 25 µs, a current of 70 mA, and total normalized transverse emittances of 2.8 µm will allow to fill the existing synchrotron SIS within one multi-turn-injection up to its space charge limit of $7\cdot10^{12}$ protons. The maximum SIS ramping rate limits the applied proton linac repetition rate to 4 Hz. This paper gives an overview of the proposed proton linac. The status of the design including beam dynamic studies will be reported. We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).

INTRODUCTION

A new international Facility for Antiproton and Ion Research (FAIR) is projected at GSI in Darmstadt [1], for which the existing UNILAC and the synchrotron will serve as injectors. Beside radioactive ion research a major part of the experimental program is dedicated to pbar physics (Fig. 1). The need at FAIR sums up to $7\cdot10^{10}$ cooled pbar/h. Taking into account the pbar production and cooling rate this is equivalent to $2\cdot10^{16}$ primary protons/h to be provided by a chain of accelerators comprising an injector linac and two synchrotrons. The achievable primary proton rate is limited by the repetition rate and by the space charge limit (SCL) of the first synchrotron SIS12 (4 Hz). The scaling of its SCL with $\beta^2\gamma^3$ in connection with the cycle times of the two synchrotrons requires an injector providing protons of at least 18 MeV. The SIS12 is filled during one injection pulse by horizontal multi-turn injection (MTI). To reach the SCL, the beam brilliance B_n provided by the injector linac must be above a minimum value, which depends on the specific parameters of the MTI [2]:

$$B_n \equiv \frac{I}{\beta\gamma\varepsilon_x} \geq 63.6\frac{\text{mA}}{\mu\text{m}}\cdot\frac{(\beta\gamma)^2}{\eta_{MTI}} \equiv B_{n,\min}\ , \qquad (1)$$

where I is the proton beam current, ε_x is the total horizontal emittance, and η_{MTI} is the efficiency of the

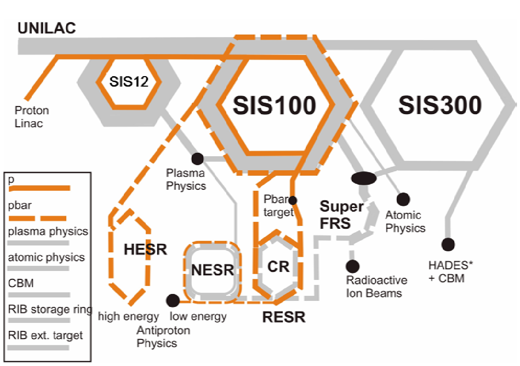

Figure 1: Schematic overview of the accelerator chain to provide cooled antiprotons at FAIR.

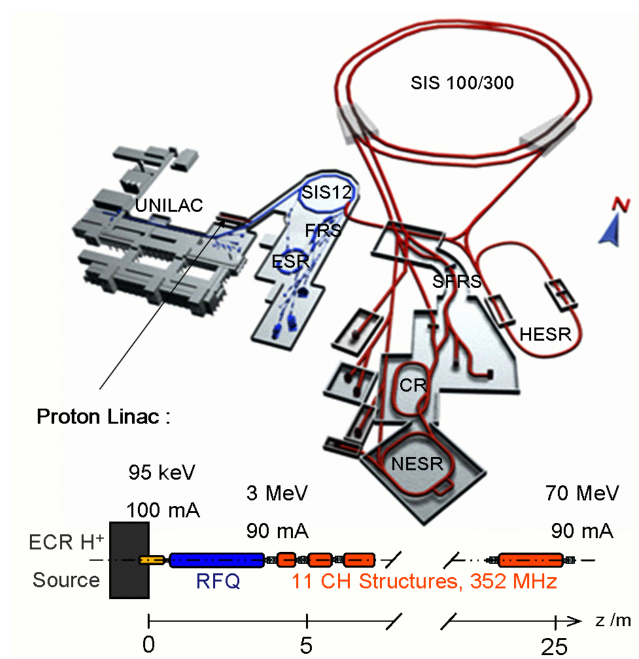

Figure 2: Schematic overview of the new proton injector linac and its implementation into FAIR. The quoted proton currents include safety margins.

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MTI. Although the existing UNILAC [3] provides ions from protons to uranium, its design is optimized for heavy ion operation. It could provide a proton beam of 18 MeV with currents of 0.25 mA and a normalized emittance of 1 µm. However, the resulting brilliance is at least one order of magnitude below $B_{n,\min}$, which even increases with higher energies (Eq. 1). Accordingly, a dedicated proton injector linac (Fig. 2) is projected within FAIR which will be operated independently from the existing UNILAC. Table 1 summarizes its design parameters.

The required primary proton rate can be achieved using an injector of 18 MeV. In this case the pbar cooling time is equal to the cycle time for primary proton delivery and the accelerator chain would be fully stretched with pbar production. Higher injection energies increase the SCL of SIS12 hence reducing the number of required SIS12 cycles. Accordingly, the primary proton cycle is shortened thus disengaging capacity for cycles providing other ion species. For a multi-ion facility like FAIR the choice of the proton injector energy is a trade-off between efficient use of cycle times and linac economics.

The injection energy of 70 MeV was considered as an adequate compromise. It results in a pbar duty cycle of 40 % and still allows for linac operation at one single rf-frequency. The output current was set to 70 mA, which imposes challenging but attainable currents on the front-end system. The total normalized transverse design emittances were set to 2.8 µm. Assuming a multi-turn efficiency η_{MTI} of 60 %, the corresponding brilliance B_n amounts to 25 mA/µm leaving a comfortable margin with respect to the required value of $B_{n,\min}$ = 16 mA/µm.

Table 1: Parameters of the FAIR proton linac design.

Source	H+, ECR, 95 keV, 110 mA
LEBT (2-solenoid foc.)	95 keV, 100 mA, 0.3 µm*
RFQ (4-rod / 4-windows)	3 MeV, 90 mA, 0.4 µm* *(norm., rms)
DTL (352 MHz, rt) current emittance rel. momentum spread rf pulse max. beam pulse max. repetition rate	11 CH-structures, 70 MeV 90 mA (design) 70 mA (operation) 2.8 µm** $\pm 5\cdot10^{-4}$ 250 µs 25 - 100 µs 5 Hz **(norm., tot)
Overall linac length	≈ 30 m

FRONT-END SYSTEM

An ECR type proton source seems the best choice with respect to long-time reliability and the required time for source maintenance. The ECR design proton current was set to 110 mA to be delivered at pulses of 1 ms length at 5 Hz. The LEBT design is based on 2-solenoid focusing to provide at least 100 mA of protons for the injection into the subsequent RFQ. This focusing scheme will also assure the separation of protons from H_2^+ and H_3^+ ions. At CEA/Saclay the SILHI source & LEBT set-up [4] is under operation which fits well to our requirements with respect to the design beam parameters.

Accordingly, the input beam parameters of the RFQ are chosen in agreement with the output parameters at the LEBT demonstrated experimentally at SILHI. Joint measurements on various beam parameters are planned at CEA/Saclay for the beginning of 2005 in order to optimize the matching into the RFQ. Based on former measurements performed at cw-operation of SILHI, the design input current and transverse emittances for the RFQ are chosen as 100 mA and 0.3 µm (norm., rms), respectively. These parameters allow for at least 90 mA and less than 0.4 µm at the RFQ output. Conceptual RFQ designs are currently under development for two different RFQ types simultaneously (Fig. 3): at the University of Frankfurt a RFQ of 4-rod type is proposed [5] while at ITEP/Moscow the layout of a 4-windows RFQ is under investigation.

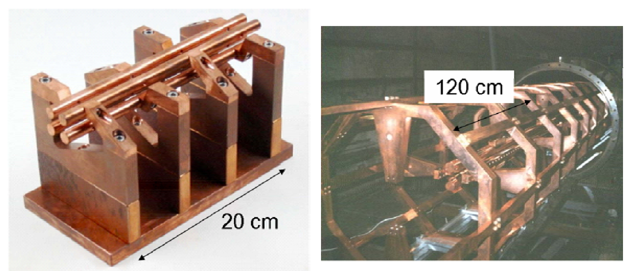

Figure 3: Part of a model for a 4-rod RFQ at 352 MHz (left) [5] and a prototype of a 4-windows RFQ at 27 MHz [6] (right).

The 4-rod type is successfully in use at several proton linacs and the University of Frankfurt acquired a huge experience in 4-rod RFQ design and construction, which is less arduous with respect to 4-vane types and its costs are significantly lower. However, 4-rod RFQs inhabit an intrinsic magnetic dipole field component due to the asymmetric installation of their stems, which can be compensated partially. We foresee the construction of a cold model to optimize the rf-field quality.

4-vane RFQs in turn offer higher field quality and an increased mechanical stability. This type is commonly in use at recent high intensity proton linacs operating at frequencies higher then 300 MHz. However, these features come along with a more complicated implementation of cooling and with increased overall costs with respect to a 4-rod RFQ. The 4-windows type RFQs developed at ITEP/Moscow [6] promise to merge the advantages of the 4-rod and of the 4-vane types, i.e. high field quality at moderate costs. A 4-windows RFQ is foreseen to be used within the RIA project [7] and is also an interesting option for the FAIR proton linac. On the other hand both types considered (4-rod & 4-windows) had not been built at a frequency of 352 MHz yet. Design studies are done for both types and the decision on the final design of the FAIR proton linac RFQ is scheduled for spring of 2005.

MAIN LINAC

In order to reduce the overall linac costs, the main objective of the linac design is to maximize the acceleration efficiency. At heavy ion linacs very high effective shunt impedances were achieved using Interdigital H-mode (IH) structures in combination with the KONUS beam dynamics [8]. There is a high interest to extend the successfully demonstrated features of IH-structures to light ion linacs, i.e. to higher particle velocities of up to β=0.5. Accordingly, Crossed-bar H-mode (CH) structures (Fig. 4) are presently under development at the University of Frankfurt [9]. They are operated in the H_{210}-mode and the installation of the stems result in an even higher mechanical stability with respect to IH-structures.

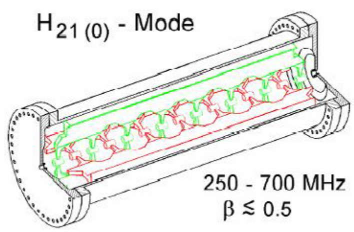

Figure 4: Sketch of a Crossed-bar H-structure (CH) presently under development at the University of Frankfurt [8].

The FAIR proton linac output energy of 70 MeV can be reached with 11 independent CH-tanks operated at one single rf frequency of 352 MHz, which developed to a common operating frequency of the low energy part of projected high current proton linacs in Europe. With the CH-structures velocity dependent effective shunt impedances ranging from 45 MΩ/m to 100 MΩ/m seem attainable corresponding to a total rf power of up to 1.3 MW per cavity including beam loading of up to 0.5 MW at 70 mA. The rf pulse length will be 250 µs at 5 Hz resulting in a rf duty cycle being very close to the present layout of Linac4 at CERN [10]. Since both linacs will operate at 352 MHz, a joint CERN/GSI development and commissioning program on pulsed klystron power supplies at 352 MHz was initiated. It implies systematic testing of the CH-structures at GSI in 2006. A study on mechanical structure design including investigations on tolerable deformations is under progress as well.

Multi-particle simulations on the CH-DTL KONUS beam dynamics were done [11] for different layouts of the beam optics at the DTL entrance. Figure 5 shows the beam envelopes along the section. The RFQ-DTL matching section can be designed very compact if the matching quadrupoles will be integrated into the first cavity. Alternatively, a dedicated matching section before the DTL offers increased flexibility for the operation of the linac and will simplify the design of the first cavity. Both options are presently under investigation and show full transmission of a 70 mA input beam with an emittance of 0.3 µm from the RFQ. The emittance growth

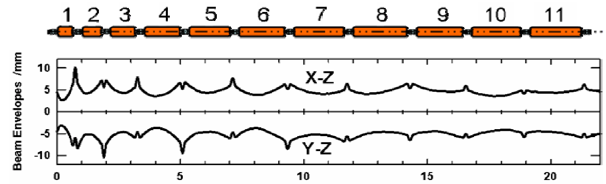

Figure 5: Transverse beam envelopes along the CH-DTL according to multi-particle simulations [11].

is sufficiently small in order to attain the design emittances at the injection into the SIS12. However, it is foreseen to achieve a design which also copes with a DTL input current of 90 mA.

SUMMARY

The requirements of the FAIR project on primary proton intensities can be met with a new dedicated injector linac providing 70 mA of protons at 70 MeV. The use of CH-structures allows for high effective shunt impedances and thus for a compact 352 MHz linac. The design of the RFQ and of the DTL section is in progress. Recent simulations on beam dynamics show that all requirements on beam quality can be fulfilled. The design of the front-end including the RFQ is planned to be completed in 2005 and CH-structure testing will start in 2006. A TDR is scheduled for 2007 followed by the beginning of civil construction.

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