Upgrades of the Nuclotron Injector for Acceleration of Ions with Z/A = 0.28

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1. Abstract

An upgrade for the front section of the Nuclotron Injector is presented. The aim of this upgrade is to decrease the minimal charge-to-mass ratio of ions accelerated from 0.33 to 0.28. It consists of a transverse wall placed 1.1 m from the front flange of the linac, separating the 14.4 meter tank into two distinct RF cavities, and replacement of the 11 drift tubes in the first cavity, extending the transverse acceptance of the linac. This upgrade makes possible the acceleration of iron, cobalt, copper and krypton ions in the Nuclotron. Upgrades to both Laser and EBIS sources are also planned, to increase the linac output current and the atomic number of accelerated ions.

2. Introduction

The mass limit for the LU-20 Nuclotron Injector is currently set by the requirement that ion charge-to-mass ratio

Fig. 1

Z/A must be equal to or greater than 1/3.An upgrade of the linac front section has been proposed, and has now in fact been carried out, allowing for acceleratio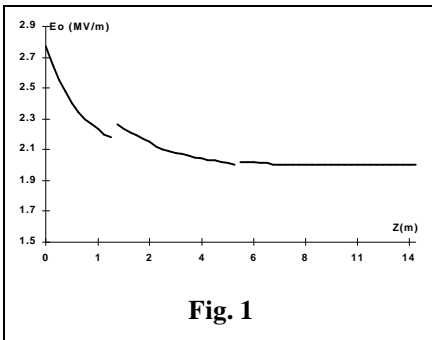n of ions with $Z/A=0.28$. This paper describes the upgrade; commissioning experiences are detailed in a follow-on paper.

The LU-20 linac was originally constructed as a proton injector. For ion acceleration, operating in the second harmonic mode is necessary, leading to unfavorable transit-time factors for the original drift-tube geometries. Electric fields needed for efficient acceleration are shown in **Fig. 1**, requiring either a very large tank tilt, or a general increase of field levels.

As producing the required field distribution is not possible with the present RF system, operation in the $2\beta\lambda$ mode to date has been achieved by increasing the overall strength of the accelerating field to a level where capture of particles can take place. This choice is not optimum: in addition to not being able to reach the most desirable gradients for the front end of the tank, the extra RF power is wasted on the largest part of the linac tank. Moreover, the existing quadrupole lenses in the front end of the linac are unable to supply the gradients required to effectively focus ions with $Z/A<0.5$, leading to further beam losses throughout the linac. By placing a diaphragm at the location of the 11th drift tube, the tank is divided into two separate resonators that can be excited to different levels. By replacing the first 11 drift tubes, as well, and improving the quadrupole magnets in them, better accelerating and focusing efficiency can be achieved. Note, no changes are required to the remainder of the linac.

3. The accelerating-focusing system of the first compartment

3.1. *Accelerating structure.*

To provide the greatest energy gain of a particle, the gap factor $\alpha = g/L$ (**g** is the gap between drift-tube faces and **L** is the length of the accelerating cell) should be as small as possible and constant. The tuning of each accelerating cell to the resonant frequency is realized by selecting the drift tube diameter.
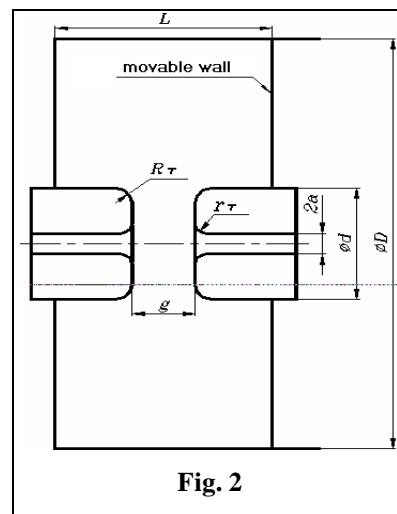

Fig. 2

Operational experience for linacs in our frequency range (145 Mhz) indicates that stable operation is possible if electric field gradients do not exceed 11MV/m on the axis of the accelerating gaps (E_g) and 25MV/m on the surfaces of the drift tubes (E_s) [1]. From these considerations, we have selected a gap factor α of 0.2 and have set the rounding radii of the drift tubes at R_t=12mm and r_t=8mm (see **Fig. 2**). To characterize the accelerating structure, it is necessary to know the dependence of the transit-time factor **T** (at the harmonic number **k**) on the velocity of an accelerating particle. As a first approach, for the simplified model of the accelerating period (R_t=0 and r_t=0) the dependence of the diameters of the drift tube on particle velocity was determined by the method of partial areas [2]. Then using the results of these calculations and the chosen geometric parameters **2a**, R_t, r_t and α, a full-scale model of an accelerating period was made (see **Fig. 2**). It has a movable

bottom and changeable drift semitubes, and so can be configured to make measurements for any of the relevant accelerating periods

The calculation of the accelerating structure was carried out by the method of sequential approaches using experimental dependencesof T(β), d(β) [3]:

$$\int_{b_0}^{b_n} \frac{db}{(1-b^2)^{3/2} T(b)} = n\frac{z}{A}\frac{keE_0 l \cos j_s}{m_0 c^2}$$

The new drift tubes differ in construction from the old ones by the omission of tuning disks. The new drift tubes are also not vacuum-tight. The drift tubes are fastened using two rods; the principal one is used to feed and cool the quadrupole lenses, the second one located under 90° prevents mechanical vibration of the drift tubes. The ends of the rods are fixed in special adjusting devicesfor precise alignment

A special tuning unit (cylindrical piston) is installed at the input wall of the first tank section to provide exact tuning to the resonant frequency of the main compartment. The frequency range allowed by this tuner is 100 kHz, two times wider than expected detuning.

3.2. Focusing system

A FODO focusing periodicity was selected for the new drift tubes, to match that in the main tank.
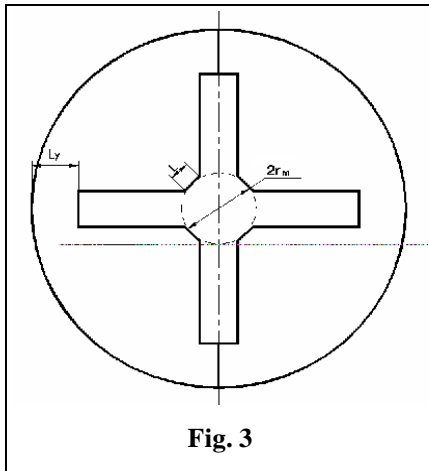
Fig. 3

To obtain acceptable values of the gradients in the quadrupole lenses and not to decrease significantly the throughput of the linac, a compromise value of **cosμ** equal to 0.6 was taken, where μ is the average phase advance. For ions with Z/A=0.3, the maximum gradients reach values up to 100 T/m. Fortunately, because of the very low duty factor required for the LU-20, these magnets can be run in a pulsed mode. A Brookhaven concept [4] with a trapezoidal pole configuration has been adopted for the magnet design, based on simplicity of manufacturing and assembly, and on a pole profile which provides good field gradient with acceptable nonlinearities. A schematic of this design is shown in **Fig. 3**. The full aperture of the quadrupole lens is set at $2r_m=2.2$ cm, the size of the flat pole is chosen according to the recommendations of Plotnikov [5], to suppress the sextupole component of the magnetic field. The magnet cores are assembled from sheet electrotechnical steel, and consist of two halves joined by a metal ring.
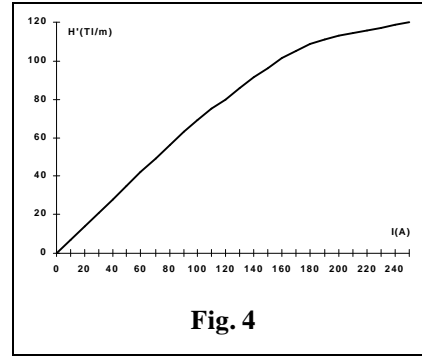
Fig. 4

This construction allows a greater number of turns in the winding and hence greater field gradient, and also simplifies assembly of the quadrupole magnets.

Each quadrupole magnet is an integral part of its drift tube, so the magnetic axis of the lens is rigidly connected to the aperture of the drift tube. The misalignment of the linac geometric axis to the lens magnet axis does not exceed 0.05mm. The lens median planes are adjusted using a special fixture to an accuracy of ±30′. After assembly, the magn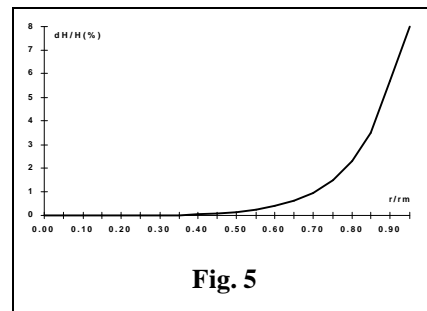etic characteristics of the new drift tubes were measured on a test stand. The dependence of the gradient on the exciting current in lens number 3 is shown in **Fig. 4**. The dependence of the magnet field nonlinearity on radius at the working current in the exciting winding is shown in**Fig. 5**.

Fig. 5

Table 1

Injection energy (ions)	W_0	150 keV/nucleon
Output energy (ions)	W_k	496 keV/nucleon
Minimum ratio Z/A		0.3
Working frequency	f	145MHz
Resonator length	L	1.15m
Number of drift tubes	N	10+2 semitubes
Resonator quality	Q	10000
Avr. amplitude of field on axis	E_0	2.2MV/m
Synchronous phase	φ_s	-29°
Aperture	2a	20mm
Structure of focusing period		FODO
Characteristic parameter	cosμ	0.6
Gradients of quadrupole lenses	H′	100...40 T/m
Acceptance	A	220π·mm·mrad

The main parameters of the accelerating-focusing structure of the new first tank are shown in **Table 1**.

4. RF-power system

A block-diagram of the RF-power system is shown in **Fig. 6**.This system provides maximum excitation in the linac tanks. The main resonator tank is powered by two "Rodonit" autogenerators, each with an output power of
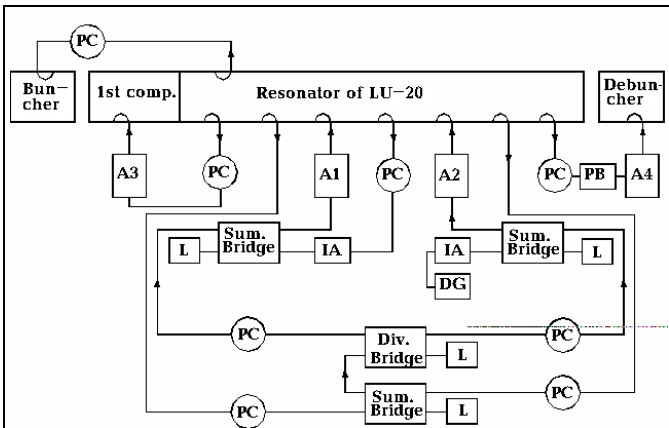
Fig. 6

PC are Phase Changers, A1, A2 are amplifiers (1st and 2nd channels of "Rodonit", IA are intermediate amplifiers, L are 75 Ohm loads, PB is a phase bridge, A3 is the generator of the 1st tank, A4 is the debuncher generator, DG is the reference source.

3MW. Both generators have a positive feedback loop through the tank. To excite the main mode TM_{010} the highest modes TM_{011} and TM_{012} are suppressed

Table 2
The main parameters of the RF-amplifier

Number of cascades	3
RF-power in pulse	0.5MW
RF-pulse duration	500μs
Minimum pulse to pulse duration	2000
Working frequency	145.0±0.5MHz

To feed the first tank a standalone generator (A3, **Fig. 6**) was built. This generator is excited from the main resonator via a connecting loop. The anode circuits of the generators are fed by a modulator consisting of a double pulse-forming pulse-line. The main parameters of the RF-amplifier are shown in **Table 2**.

Automatic control systems provide the required amplitude and phase stability. This system should provide adequate compensation for phase perturbations arising in the resonators and RF-amplifier cascades. As there are two standalone objects, each requiring phase perturbation compensation, two automatic control systems are needed. One of them is an automatic phase tuning system (APT), the second system is an automatic frequency tuning system (AFT).

5. Ion sources.

Completion of the Nuclotron Injector Upgrade project will require, in addition to the linac modifications, improvements to the ion sources to provide higher ion intensities and better charge-state distributions. These improvements have been studied and designed, but have not been implemented in the present phase of the upgrade project.

5.1. *Laser ion source*

An upgrade of the laser ion source, currently used for beams up to Mg, has been planned as a part of this Upgrade project [6]. A new CO_2 laser will be able to operate at a frequency up to 5 Hz at an output pulse peak power up to 25 MW and a beam divergence of less than $5 \cdot 10^{-4}$ rad. The planned laser beam focusing system with a parabolic mirror will provide a flux density up to $3 \cdot 10^{11}$ W/cm^2 on the target. The up-dated laser ion source is expected to produce Fe^{16+} ion beams at an intensity of more than 10^{10} ion/pulse.

5.2. *Electron beam ion source (EBIS)*

The "Krion-2" EBIS source [7] will also be upgraded. A new electron optics system will provide an 8 keV, 2.5 A electron beam with about 200 A/cm^2 beam density. To reach these electron beam parameters with a magnetically immersed Pierce type gun, a 5 T superconducting solenoid will be manufactured using a high precision winding technology. Design of the electron collector and the ion beam optics, based on IGUN [8] simulations, has been performed. The electron collector design provides satisfactory formation of about 1 mA of ion beam with 1.5 keV electron beam energy on the collector surface. The upgraded "Krion-2" EBIS will provide a variety of ion species with high and moderate charge states. For example, iron ion beams of Fe^{16+} and Fe^{24+} will have intensities of $3 \cdot 10^9$ ion/pulse and $1 \cdot 10^9$ ion/pulse respectively. Note, to inject solid materials into the EBIS trap, an external MEVVA-type ion source will be used [9].

6. References

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