PRELIMINARY DESIGN STUDY OF THE NSWC PROTON INDUCTION LINAC+

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Summary

A 5 MeV, 100 A, 3 μsec proton beam is required for the injection into a compact accelerator which uses quadrupole lenses in a betatron-like device at NSWC. As an injector, an induction linac is proposed to utilize technologies developed in magnetic and heavy ion fusion research: A 50 keV, 100 A, 3 μsec proton beam extracted from an ion source used for the PDX-type neutral beam injector, is accelerated by induction modules. The beam size is reduced by solenoidal lenses in three steps as beam energy is increased. The matching section is followed before injection to the quadrupole channel. We present preliminary design details of the proposed intense, long-pulse proton linac.

1. Introduction

It has been well known that the induction linac is very efficient in the acceleration of high current beams [1]. While the induction linac technology is considered to be well established for electron beams [2-5], we have limited experiences on the ion beam acceleration. There are renewed interests in the induction linacs for intense ion beams in connection with heavy ion fusion, neutron production, and other applications. Recently, several groups have reported experimental results of the inductive accelerations of proton beams [6-8]. In these experiments, proton beams up to 1 MeV and 10 kA have been obtained by few induction modules. As we discuss in the later sections, the current at this energy level is well beyond the limiting current for propagation in the drift tubes. Therefore, they have demonstrated beam focusing and transport by space charge neutralization. In addition, they have demonstrated that magnetic insulation of the acceleration gaps prevents electron acceleration. In this early stage of development, however, we strongly believe that many research issues must be resolved for practical intense ion beam accelerators. Some of these issues are the beam quality changes and the multi-stage beam transport for further acceleration.

For the injection of a proton beam to the proposed quadrupole betatron accelerator [9], it requires a high quality, high power beam whose parameters are listed in Table 1. Even though it is, at present, a quite challenging requirement, it could be attainable from the extrapolation of the currently available technologies. In the following sections, we present the details of basic components of the proposed NSWC proton induction linac; i) ion source and preacceleration, ii) induction module, and iii) beam focusing and transport.

Table I. Parameters for NSWC Proton Linac

	SOURCE	PREACCELERATOR	LINAC
ENERGY	50 keV	550 keV	5 MeV
CURRENT	100 A	100 A	100 A
PULSE LENGTH	3 μs	3 μs	3 μs
BEAM RADIUS	15 cm	10 cm	6 cm
NO OF INDUCTION GAPS		1	36
NO OF CORES PER GAP		20	5
TOTAL LENGTH		2 m	18 m

2. Ion Source and Preacceleration

A typical ion source consists of a stable plasma reservoir and an ion extraction system which is essentially an ion diode. The most effective way of ion extraction is the diode operation in the space charge limited regime, following the Child-Langmuir law, which requires sufficient supplies of ions during the extraction period. While the beam quality depends mainly on the electrode shape, the total beam current depends on the cross-sectional area of the extraction grid. For the proton source, the duopigatrons have been widely used in accelerators. In the past decade, however, high quality and high power duopigatron ion sources have been intensively developed for the neutral beam heating of the fusion plasmas. The existing ion sources used in the tokamak heating experiments are listed in Table II.

Table II. Ion Sources for Tokamak Neutral Beam Heating

PDX (Princeton)	50 keV	100 A	30 cm circular
D-III (GA)	80 keV	80 A	10X40 cm rectangular
TFTR (Princeton)	120 keV	60 A	10X40 cm rectangular
JET (Culham)	80 keV	80 A	circular

There are a few thousand apertures on each grid in the extraction system of the duopigatrons. The apertures on the plasma grid are shaped close to the Pierce-geometry for improved beam optics. The physical transparency of the plasma grid is about 35-45%. This type of ion sources has been developed at the Oak Ridge National Laboratory (ORNL) and used for the neutral beam injectors (NBI's) to PLT, PDX tokamks at Princeton, and to ISX at ORNL [10].

The ion beam current extracted from an ion source in the NBI's is usually so large that it is beyond the limiting current for propagation in free space or in the evacuated drift tube. The limiting current in the evacuated drift tube with radius R_c is expressed

$$I_\ell = \frac{I_o\,(\gamma^{2/3} - 1)^{3/2}}{1 + 2\,\ell n\,(R_c/R_b)}\,, \tag{1}$$

where I_o is the Alfven-Lawson limiting current, γ is the relativistic mass ratio and R_b is the beam radius. I_o is 17 kA for electron beams and 31 MA for proton beams. For a proton beam with the beam radius comparable to the tube radius $R_b \simeq R_c$, Eq. (1) is simplified to

$$I_\ell = 3.1 \times 10^7\,(\gamma^{2/3} - 1)^{3/2}, \tag{2}$$

where the limiting current I_ℓ is in ampere unit. As a numerical example, the limiting current of a proton beam is given by I_ℓ = 99 A for 300 keV and I_ℓ = 213 A for 500 keV. One should note that this limiting current does not affect the beam extraction in the NBI since there is a neutral gas cell immediately after the extraction grids. In the neutral gas cell, ions are converted to energetic hydrogen atoms by charge exchange with the residual hydrogen gas. In addition, the remaining charged particles are guided to a beam dump by a bending magnetic field. Therefore, the overall efficiency of the power transported to the target plasma is around 30-40% of the extracted beam power. However, for present purposes, one should avoid this neutralization procedure for further acceleration of beam particles.

One way to overcome this difficulty due to the limiting current is an increase of the particle

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energy immediately after the extraction. In other words, one may consider it as a triode operation; the first two electrodes control the beam current in the space charge limited regime and the last two electrodes increase the beam energy, so that the overall beam perveance is lowered enough to make beam propagation possible in the downstream region. This last stage of acceleration is called a preacceleration. The details of theoretical study on the ion diode and triode operation may be found in reference 11.

Figure 1 is a schematic presentation of an ion source and preaccelerator, or an ion triode. The electrode of the preaccelerator has a large single aperture and it is shaped to improve the entire beam optics. The axial magnetic field is applied to enhance the beam envelope convergence to a further reduced size before injection into the main linac column. In addition to the beam focusing, the magnetic field also provides a magnetic insulation of the preacceleration gap to deflect any electrons backstreaming toward the ion source region. In this gap region, a careful consideration is given in order to minimize electric breakdowns and energy delivered to electrons. The gap voltage is provided by inductively in contrast to the electrostatic voltage applied to the extraction grids.

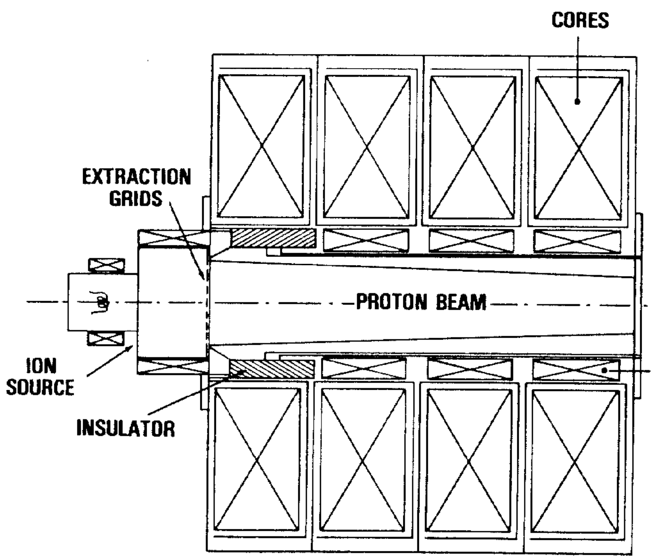

Fig. 1. Schematic of ion source and preaccelerator.

3. Induction Module

The basic physics of the induction cores is the same for both electron and ion accelerators [1]. The well-known core equation in MKS unit is

$$VT = g\ A\ (\Delta B), \tag{3}$$

where V is the gap voltage, T is the pulse length in time, g is a geometric factor less than unity, A is the cross sectional area of the core, and (ΔB) is the magnetic induction swing of core material. The geometric factor g is a function of core dimensions, typically, 0.8-0.9.

The first step in practice of Eq. (3) is a choice of core material. Core materials are commonly divided into two groups depending on the pulse length, either a short pulse or a long pulse. A typical criterion on pulse length is about 1 microsecond. Ferrites are used for short pulses and iron alloys are used for long pulses. Commonly used iron alloys are permalloy, silicon steel, or low-carbon steel. These iron alloys give (ΔB) = 3 T, in comparison to 0.5 T for ferrites. Our choice is silicon steel from a careful comparison between the candidates.

In an induction linac the beam current and the pulse length in time are conserved unless an axial beam bunching is attempted. When the pulse length is fixed at 3 μsec and the final energy at 5 MeV, the total volt-second of the linac cores is 15 V-S. From Eq. (3), the total cross-sectional area of core material is approximately 6.25 m^2 with (ΔB) = 3 T and g = 0.8. The number of gaps is determined by the details of core geometry and other factors. When the number of gaps is taken as 40, each gap voltage is 125 kV and the cross-sectional area per gap becomes 0.156 m^2.

Cores are, in practice, constructed by winding thin foil of magnetic material in order to reduce the eddy current loss. Thin foil of 0.002 inch thick is available commercially for silicon steel. There should be a thin insulation layer between the foil layers, which contributes to the core cross-sectional dimension. The fraction of core material in the cross-sectional area is described in a radial packing factor, ranging from 0.8 to 0.9, depending on the details of the winding method.

The magnitude of the magnetic induction in a toroidal core is inversely proportional to the layer radius. This results in an early saturation of the inner layers than the outer layers, thereby distorting the gap voltage waveform from a flat top distribution. In order to maintain the voltage wave form in a flat top distribution, a radial stacking method has been adopted. In addition, the radial stacking of cores provides a voltage step-up between primary and secondary windings. In this way the high voltage breakdowns in the pulse forming network (PFN) are relieved.

In this core design study, the inner radius of modules is taken as 0.25 m for the transport system of the 100 A proton beam, and the number of radial stacking is 5 cores for effective use of core material. Taking core width as 0.3 m, the outer radius of the module is approximately 0.8 m. When the axial packing factor, the ratio of the core width and the module width, is taken as 0.6, the average accelerating gradient of the linac yields 250 kV/m with 3 μsec pulse length. Finally, the total length of the 5 MeV linac is 20 m long and core material weighs approximately 160 tons.

4. Beam Focusing and Transport

A periodic focusing system is required to transport an intense proton beam through a series of induction gaps. Since the beam is large and circular in this low energy regime, axisymmetric focusing (typically solenoid magnetic field) is more suitable than quadrupole lens focusing. A solenoidal magnetic field is periodically interrupted by the axial space required for induction gaps and for the system access. The subject of how high current is transportable in this kind of long periodic focusing channels, has been investigaged in connection with heavy ion fusion accelerators. In a recent experiment at the University of Maryland, for example, a space charge dominated electron beam has been successfully transported through 40 periods without loss of currents [12].

Let us consider an ideal magnetic distribution shown in Fig. 2. A uniform axial magnetic field B_s occupies an axial length ℓ, followed by free space with an axial length L. The period of the focusing system is $S = \ell + L$. In the transport theory [13], the focusing strength Θ of the solenoidal magnetic channel is expressed as

$$\Theta = \frac{qB_s}{2\gamma m\beta c}\,\ell, \tag{4}$$

where βc is the axial velocity of the ion beam. The periodic channel character is described in terms of a phase advance σ_o of a particle per period in the Larmor frame where σ_o is expressed as

$$\cos \sigma_o = \cos \theta - \frac{1}{2}\frac{L}{\ell}\theta \sin \theta \tag{5}$$

for the limit of zero beam current. In Eqs. (4) and (5), the betatron oscillation is evaluated in a local Larmor frame which is gyrating about the axis with an angular frequency $\omega_L(z) = qB_s/2\gamma m$. When an equilibrium beam envelope changes periodically along the axis at the same period as the focusing system, it is called a matched beam. In this matched beam with non-zero current, the betatron phase advance is shifted to a new value σ, depending on the beam current. In the experiment at the University of Maryland [12], a matched beam has been obtained in the channel strength range of $45^o<\sigma_o<150^o$.

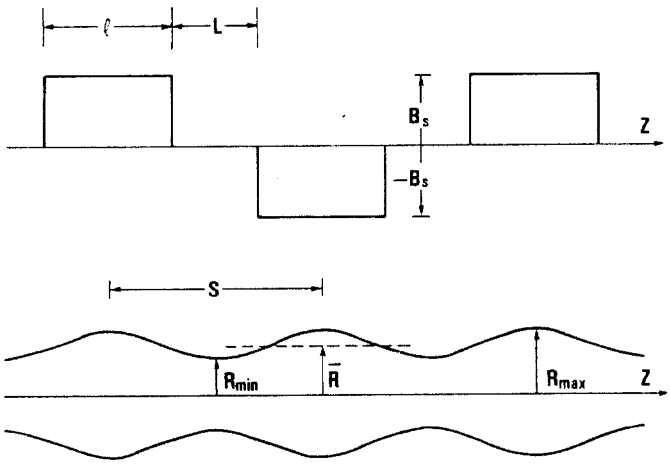

Fig. 2. Schematic of periodic focusing field and matched beam.

The space charge effects from the beam current is conveniently described in terms of the generalized perveance

$$K = \frac{2I}{I_o(\gamma\beta)^3}. \tag{6}$$

Using an ideal particle distribution function, the Kapchinskij-Vladimirskij (KV) distribution, one can find matched beam radii in a periodic channel as

$$\bar{R}_o = \sqrt{\frac{\varepsilon S}{\sigma_o}}, \tag{7}$$

and

$$\bar{R} = \sqrt{\frac{KS}{\sigma_o}}, \tag{8}$$

where $\bar{R}_o$ is the average radius in the zero-current limit, ε is the beam emittance, and $\bar{R}$ is the average radius in the space charge dominated case where the beam emittance is neglected.

For the beam current $I = 100$ A, one can find the physical parameters B_s, $\bar{R}$, ℓ, and L such that the proton beam is well confined inside a long drift tube. In the conceptual design of the transport channel, the following constraints have been taken into account:

(1) $\sigma_o<150^o$, preferably less than 120^o.
(2) $\bar{R} < R_c = 0.2$ m
(3) $\ell = 0.3$ m, $L = 0.2$ m.
(4) $B_s < 2$ Tesla.

For specified periodic length S and beam radius $\bar{R}$, one can easily show from Eqs. (6) and (7) that the beam energy is a function of the phase advance σ_o. Note that a proton beam with its current of 100 A belongs to the space charge dominated case in Eq. (8). Assuming $\bar{R} = 0.1$ m and $S = 0.5$ m, the proper initial beam energy is obtained from a careful consideration of σ_o. One can easily see that 550 keV is most suitable injection energy from Table III. The required magnetic field is then approximately 1.1 T.

Table III. Characteristics of Transport Channel for a Beam of 100 A and Radius of 0.1 m.

	300 keV	425 keV	550 keV
σ_o	180^o	140^o	115^o
K	0.4	0.24	0.16

At the end of the channel the beam energy becomes 5 MeV and the corresponding beam radius $\bar{R}$ is 0.06 m due to the decreased value of K to 0.057. Several beam radii are also listed for higher magnetic field values in Table IV.

Table IV. Matched Beam Radii and Magnetic Field at 5 MeV and 100 A.

$\bar{R}$	0.06 m	0.05 m	0.036 m	0.03 m
B_s	1.1 T	1.2 T	1.8 T	2.2 T

For the injection into the quadrupole betatron accelerator which uses magnetic quadrupole focusing lenses, one needs apparently a reduced beam radius rather than 0.06 m. Therefore, in the middle of the linac channel, one should change the focusing strength from 1.1 T to about 1.8 T. Or, one can compress the beam in the matching section before the injection to the quadrupole lens channel. In either case of the beam compression, a detailed numerical calculation is required for a smooth transition.

Finally, it is worthwhile noting that focusing effects of the interrupted solenoid field are independent of the magnetic field polarity. Thus, the interrupted solenoid field with its alternative polarity is effective not only for the ion focusing but also for creating a cusp magnetic field in the acceleration gap as shown in Fig. 2. This cusp-field is an effective means of the magnetic insulation for electrons in the inductive acceleration gap.

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