H^- injector for ADRIA

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Abstract

The synchrotron of the ADRIA project, proposed for the upgrading of LNL accelerator complex, have the capability to accelerate protons with an injection energy of 210 MeV, repetition rate of 50 Hz and an average current of about 32 μA. In this paper we shall spell out a new proposal for the H^- injector in this mode of operation.

The main components of the linac are a double frequency (32.5 MHz, 65 MHz), an RFQ and DTL cavities (425 MHz). The buncher gives to the bunch sequences the time structure corresponding to the Synchrotron RF frequency at injection. The shunt impedance in DTL cavities (equipped with rare earth quadrupoles) remains sufficiently high up to the synchrotron injection energy.

1 INTRODUCTION

A new project, called ADRIA [1], has been proposed for the upgrading of the Laboratori Nazionali di Legnaro; its main constituent is synchrotron able to accelerate both heavy ions and protons a magnetic rigidity of about 22 T-m (6 GeV for protons). Moreover for protons high average current mode (50 Hz repetition rate) is foreseen, a maximum energy of 1.2 GeV. In this paper we will spell out proposal for the linac to be used as a H^- injector in the proton mode.

At the injection into the ADRIA Booster the beam energy is 210 MeV, which corresponds to a revolution frequency of 0.65 MHz and, limiting the Laslett tune shift to less than 0.2, the maximum number of protons that can be injected within a normalized transverse emittance of 25 mm-mrad is about 50×10^{11}. The injection scheme foresees 120 injection turns and that requires an H^- beam pulse 185 μs long with an average current of 4.3 mA. The injection will be performed with the charge exchange methode, "from bunch to bucket", being the RF stationary buckets formed from the first turn of injection.

The frequency of the bunch sequences for one synchrotron separatrix must be equal to the initial synchrotron radio frequency, which is 32.5 MHz since the Booster harmonic number is 50; moreover the phase dimension of each bunch sequence must be small enough to be captured in one separatrix. One of the possible means to fulfill this condition is to choose a linac rf frequency equal to the initial synchrotron frequency. Of course there is no need to keep the same frequency along the whole linac. It is possible to increase the linac rf frequency while the particle energy grows. One can construct a linac with several multiple frequencies in subsequent cavities to reduce the rf power dissipation and the total linac length. Such scheme is one of the most direct ways to achieve high capture of the beam into the synchrotron buckets.

A linac with multiple frequencies was proposed as an injector of the EHF project [2]. A similar scheme with four multiple frequencies proposed also for ADRIA [1]. This linac, successfully combining the RFQ sections with DTL and side coupled cavities, allows to fulfill all requirement mentioned above.

We give below an alternative linac injector scheme to satisfy the same requirements, which contains some different features that are worth to be discussed. To achieve the proper time structure the linac is preceded by a low-frequency input buncher, operating at 32.5 MHz, and the following linac does not need multiple frequencies. That leads to some advantages: the whole accelerator can be operated at the same frequency and consequently the power supply system will be simpler; the rf frequency can be chosen sufficiently high; the problems concerning the longitudinal matching associated to the frequency jumps between sections are avoided.

In the proposed scheme the DTL focusing system, as in some modern accelerators, consists of rare earth quadrupoles that need no power supply. Due to the use of those quadrupoles the drift tubes dimensions are very small and the RF power losses in the cavities at high frequency are comparatively low. The shunt impedance in DTL cavities (equipped with rare earth quadrupoles) at frequencies of 400-450 MHz remains sufficiently high up to proton energies of 200-250 MeV. The value of shunt impedance reaches the same level as at the frequency of 150 MHz (in DTL with electromagnetic lenses) for the proton energy of 100 MeV. Rare earth lenses made of magnetic rods assembled inside drift tubes were developed at ITEP [3].

2 DESCRIPTION OF THE INJECTOR

Fig. 1 gives a block diagram of the proposed linac. It consists of several subsequent parts: the electrostatic preinjector, the low frequency buncher, one RFQ section and seven drift tube cavities. Buncher is operated at the initial frequency of the synchrotron 32.5 MHz (the second harmonic can be added). Linac rf frequency may also be not an exact multiple of this value. To be able to have a resonable accelerating field in RFQ and DTL parts the frequency of about 425 MHz was chosen. The buncher voltage must be properly phased with linac electric field to avoid intensity instability in the ring chamber. The schemes to provide this with good accuracy are well known. Each synchrotron separatrix will be filled with three injector bunches.

As evaluations show the input bunching of the beam will be 75% with one frequency buncher and 85% if the second harmonic in the buncher is added.

For current limit calculations it was assumed: the normalized beam emittance in the RFQ 1 mm-mrad, in the DTL 1.5 mm-mrad. The real emittance of the beam will be much smaller than it is assumed here. We will have some reserve for a case of mismatch of the beam.

Main parameters of the linac in all its sections are given in tables 1-6. Basic parameters are taken from ref. [1].

Table 1: Linac specifications

Kind of particles		H^-
Output energy	MeV	211.
Average output current	mA	4.3
Initial radio frequency in PS	MHz	32.5
Beam pulse duration	μs	185
Repetition rate	Hz	50

Table 2: Transmissions

Low frequency bunching in 90^0	85%
RFQ capture efficiency	90%

The low-frequency buncher, compressing the beam in 90^0 at 32.5 MHz, fills up 3 buckets of the RFQ. The RFQ capture efficiency is roughly equal to the transmission of the linac; the bunching efficiency in 90^0 gives the pecentage of the transmitted particles compressed in 3 DTL periods of the 13 contained in a booster rf period. We will refer to this scheme as to the 3/13.

The overall efficiency of the linac, considering 85% bunching efficiency, 90% RFQ and DTL transmission efficiency and 95% capture efficiency into the synchrotron, is of the order of 73%. Consequently in order to have 4.3 mA average current delivered to the Booster the dc current from the preinjector has to be 5.9 mA. The peak current at the input of the RFQ is of 22 mA.

Table 3: Main Parameters of the Linac

		RFQ	DTL
Input Energy	keV	40	2500.
Output Energy	MeV	2.5	211.
RF frequency	MHz	425.	425.
Total length	m	1.7	93.
Normalized acceptance	mm.mrad	1.8	3.0
Current Limit	mA	75	175
RF power dissipation	MW	0.2	12.
RF power for acceleration	MW	0.05	4.2
RF duty cycle		1.75%	1.75%

The effective gap voltage in the two-frequency buncher is about 3.1 kV at the frequency of 32.5 MHz and about 1.55 kV at the frequency of 65 MHz. The power dissipation in the buncher is negligibly small compared to linac cavities. The drift distance needed to have the proper bunching is about 75 cm.

Table 4: RFQ Linac

Diameter of the cavity	D	160	mm
Average radius	R_0	3.1	mm
Minimum aperture	a	2.07	mm
Equilibrium Phase	$\lvert\phi_s\rvert$	$90^0 - 30^0$	
Modulation coefficient	m	1.1-2.0	
Adjacent vanes voltage	U_L	84	kV
Maximum surface field	E_s	$40(2^*E_{KP})$	MV/m
Transverse phase advance	μ	0.373-0.454	rad
Minimum transverse phase shift rate per period	ν_f	0.294-0.364	rad
Output bunch width	$\Delta\phi$	59^0	
Output momentum spread	$\Delta p/p$	± 1.1%	
Output separatrix momentum spread	g	± 2.15%	
Current limit	I_{max}	75	mA

Table 5: DTL Linac

Average electric field	E	3	MV/m
Equilibrium Phase	ϕ_s	-25^0	
Diameter of the Drift tubes	d	70-62	mm
Outer radius of Drift tubes curvature		20	mm
Inner radius of Drift tubes curvature		7	mm
Aperture Diameter		6.4	mm
Maximum surface field	E_s	24	MV/m
Input separatrix momentum spread	g	± 2.22%	

As mentioned above in the DTL structure the transverse focusing will be made using the quadrupole lenses made of rare earth compounds as SmCo or NdFeB. This will lead to very small lenses and drift tubes. The major result of this choice is that the shunt impedance, defined as :

$$Z = \frac{E_0^2}{2dP/dz},$$

is kept at resonable values for all the DTL cavities (table 6).

The figures in the tables present preliminary results of analytical calculations, but they serve only as a direct evidence of feasibility and rationality to make such a linac. They reflect the real situation good enough.

As one can see, there is no reason to construct a superconducting linac. The electric energy stored in each cavity is about 10-15 J. It is much lower than the energy deposit needed for acceleration. We may add during the beam pulse about 0.7 MW for acceleration in each cavity and therefore there is no reason to use low power RF generators for cavity excitation. In addition, any instability of compensation system will lead to quenching.

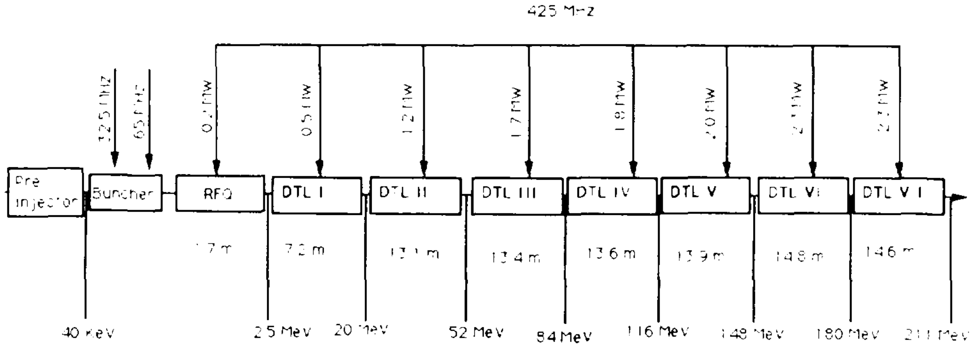

Figure 1: Block diagram of the Linac

Table 6: DTL Linac Cavities

Parameters	cavities:	I	II	III	IV	V	VI	VII
Output energy	MeV	20	52	84	116	148	180	211
Cavity diameter	cm	48	42	37	36	35	33	33
Length	m	7.2	13.1	13.4	13.6	13.9	14.8	14.6
Gap coefficient		.18-.34	.20-.30	.22-.30	.25-.33	.29-.35	.33-.36	.34-.39
Drift tubes diam.	cm	7.0	7.0	7.0	6.2	6.2	6.2	6.2
Quad Gradient	KG/cm	15	5.34	3.2	3.26	3.33	3.38	3.50
Quad length	cm	2.5	7.5	15.	17.5	20	20	20
μ		.586	0.691	0.764	0.885	1.061	1.086	1.120
ν_f		0.413	0.481	0.520	0.564	0.609	0.611	0.615
Normalized acceptance	mm-mrad	3.0	3.5	3.8	4.1	4.4	4.4	4.4
Output g	%	1.26	1.05	0.96	0.90	0.86	0.83	0.80
Shunt Impedance	M Ω/m	67	50	36	34	32	29	29
RF Power								
-dissipation	MW	0.5	1.2	1.7	1.8	2.0	2.3	2.3
-for acceleration	MW	0.35	0.64	0.64	0.64	0.64	0.64	0.62
Energy deposit								
for beam pulse	J	65	118	118	118	118	118	115

Finally some words have to be spent about injection requirements into the booster. The injection is delicate since it is desirable to generate in the six dimensional phase space a stationary distribution that transversally occupies homogeneously the available emittance and longitudinally have the highest possible bunching factor, defined as the ratio between average and peak current circulating in the ring. In this way it is maximized the charge that can be accumulated for a given Lasslett tune shift.

The procedure to generate such a distribution (called sometimes "painting" ref [2] pag. 199) has been studied for 2/24 time structure (EHF) and 1/40 (ADRIA, injection 211 MeV). Our scheme 3/13 has still to be studied, but according to experience gained, 3 bunches should give better results for the filling of the longitudinal phase plane. On the other hand the losses among the 15% of particles contained in the 10 "empty" buckets have to be investigated. If they are not tolerable some improvements are still possible in the injector, as for example the substitution of the double-drift buncher by an RFQ working at 32.5 MHz. In this way is still kept main part of the advantages of this injector design. Moreover we mention that the linac works well below its current limit, so that the choice between 80, 100 or 120 turns injection can be done according to convenience of the injection process.

Between the RFQ and the DTL a chopper could be placed to create an empty gap of about 150 ns needed for the booster extraction kicker.

Taking into account the revolution period in the booster synchrotron 1.54 μs, about hundred injection turns and the repetition rate 50 Hz, the total number of accelerated particles per second will be $2 \cdot 10^{14} p/s$, equal to 32μA.

The losses at injection in Booster are of the same order or less than in the well known projects of similar synchrotrons. (KEK, number of accelerated particles per second N=$6 \cdot 10^{13} p/s$ [4], ZGS, N=$3 \cdot 10^{13} p/s$ [5], AGS, N=$5 \cdot 10^{13} p/s$ [6]).

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