CONCEPTUAL INJECTOR DESIGN FOR AN ELECTRON-ION-COLLIDER FRONT-END

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Abstract

The 2015 Long Range Plan for Nuclear Science recommended a high-energy high-luminosity polarized Electron Ion Collider (EIC) as the highest priority for new facility construction [1]. A hadron linac with a final energy of 40 MeV/u for heavy ions and up to 130 MeV for protons with an upgrade path to higher energies is required as the first step of the hadron accelerator chain [2]. For energies above ~5 MeV/u, a linac utilizing superconducting cavities likely has a lower cost than that provided by room temperature (rt) structures whereas rt structures are preferred for energies below ~5 MeV/u The front-end consists of two separate injectors based on efficient H-mode cavities, one optimized for heavy ions (Pb^{30+}) and the other optimized for protons and deuterons.

INTRODUCTION

The driver linac for a future electron-ion collider must accelerate all ion species to a final energy of at least 130 MeV for p and to 40 MeV/u for heavy ions e.g., Pb. The linac above 5 MeV/u could consist of superconducting quarter- and half-wave resonators similar to those of the FRIB [3] project. The A/q values vary between 1 (p) and 7 (Pb^{30+}). The highest beam current is expected for light ions (up to 10 mA) and the lowest for heavy ions (<1 mA).

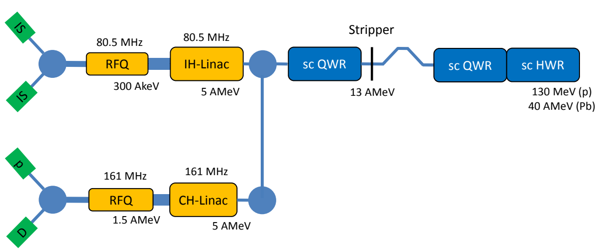

Figure 1: Conceptual layout of the hadron driver linac with two front-ends.

Preliminary investigations have shown that it is advantageous to use two separate front-ends for light and heavy ions. Though it is possible by adjusting the voltage levels to accelerate all species with one front-end, the focusing especially in the RFQ is very weak for protons because the focusing power is proportional to the electrode voltage. Additionally the beam current and corresponding space charge effects for light ions will be significantly higher compared to that of heavy ions. Therefore two dedicated front-ends each with a final energy of 5 MeV/u are proposed. The so-called New Four-Section Procedure (NFSP) [4] enables the efficient design of the two RFQs. The heavy ion front-end is based on IH-cavities at 80.5 MHz whereas, the light ion front-end will use CH-cavities at 161 MHz. At 5 MeV/u either beam will be injected into the superconducting main linac. Figure 1 shows the conceptual layout of the driver linac.

HEAVY ION FRONT END

The frequency for heavy ions with A/q=7 should be around 100 MHz. For this conceptual study, 80.5 MHz has been chosen to take advantage of existing FRIB accelerating structures above 5 MeV/u. As is most common for heavy ion injectors, a 4-Rod RFQ is proposed. Preliminary beam dynamics simulations show a transmission greater than 90%. The required RF power is less than 100 kW with an assumed shunt impedance of 180 kΩm and an electrode voltage of 65 kV. The RFQ accelerates from 10 keV/u to 300 keV/u. Table 1 summarizes the RFQ main parameters.

Table 1: Parameters Heavy Ion RFQ

RF structure		4-Rod RFQ
A/q		7
f	MHz	80.5
E_{in}	keV/u	10
E_{out}	keV/u	300
U	kV	65
R_p	kΩm	180
L	m	<4
P_c	kW	<100
I	mA	1
$\epsilon_{in, rms, norm}$	π mm mrad	0.2
T	%	>90

The heavy ion beam is then injected into the drift tube linac (DTL) that consists of four IH-cavities operated at 80.5 MHz. These cavities have a high shunt impedance and can be operated at high gradients especially at low duty factors. The IH-DTL concept is similar to the 2 AMeV EBIS-injector at BNL [5] and the 3.5 MeV/u NICA-injector in Dubna [6]. The IH-cavities provide a total effective voltage of 33 MV. The first cavity houses an internal quadrupole triplet lens. After the first cavity transverse focusing is provided by inter-tank lenses. Each cavity generates voltages between 7 and 10 MV with lengths of between 2.2 and 2.5 m resulting in gradients of about 4 MV/m. The RF power

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varies between 120 and 160 kW resulting in an amplifier power of up to 250 kW allowing for additional power to accommodate beam loading and low-level control. At this power level and pulsed operation solid state amplifiers are appropriate [6]. Table 2 summarizes the main parameters of the heavy ion IH-DTL. Figure 2 shows the conceptual layout and Fig. 3 shows the IH-cavity for the BNL EBIS Linac which is very similar to the first cavity of the heavy ion front-end.

Figure 2: Conceptual layout of the heavy ions front-end (without source and LEBT).

Figure 3: IH-cavity of the BNL EBIS Linac is very similar to the first IH-cavity of the heavy ion front-end [4].

LIGHT ION FRONT END

The light ion front-end can accelerate ions up to A/q=2, i.e. primarily, protons and deuterons. The linac provides 10 MV of voltage. Beam currents of 10 mA for protons and 5 mA for deuterons have been considered. The 161 MHz frequency is twice as high as for the heavy ion front end so as to provide more efficient acceleration.

Table 2: Parameters IH-DTL

Parameter	Unit	IH1	IH2	IH3	IH4
f	MHz	80.5	80.5	80.5	80.5
E_{in}	MeV/u	0.3	1.7	3.0	4.0
E_{out}	MeV/u	1.7	3.0	4.0	5.0
U_{eff}	MV	10	9	7	7
Gaps		27	19	15	14
Z_{eff}	MΩ/m	280	255	200	160
$Z_{eff} \cdot \cos^2 \varphi$	MΩ/m	252	230	180	145
L	m	2.5	2.2	2.4	2.4
Aperture Ø	mm	20	20	20	20
P_c	kW	160	160	120	140
Amplifier	kW	250	250	250	250
Tripletts		1	0	0	0

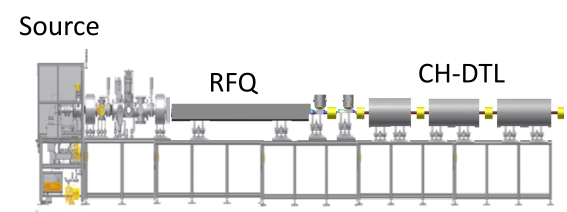

Figure 4: Conceptual layout of the light ion front-end.

The input energy into the RFQ is 30 keV/u which is high enough for the low energy beam transport at the beam current of 10 mA. The RFQ output energy is 1.3 MeV/u which is high enough for efficient acceleration in the following 161 MHz drift tube structures. The proposed RFQ structure is a 4-Rod RFQ that will be similar to the MYRRHA-RFQ [7] and to the FRANZ-RFQ [8]. Table 3 summarizes the light ion RFQ main parameters.

Table 3: Parameters Light Ion RFQ

RF structure		4-Rod RFQ
A/Q		2
f	MHz	161
E_{in}	keV/u	30
E_{out}	MeV/u	1.3
U	kV	65
R_p	kΩm	83
L	m	≈4
P_c	kW	≈220
I (p/D)	mA	10/5
$\epsilon_{in, rms, norm}$	π mm mrad	0.2
T	%	≈100

The drift tube linac (DTL) of the light ion front-end provides acceleration from 1.3 MeV/u to 5 MeV/u. For the frequency of 161 MHz IH or CH-cavities are suitable candidates. For this conceptual study, CH cavities have been

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investigated. Three short cavities are required to provide 7.4 MV using conventional beam dynamics with constant negative synchronous phase. Each cavity provides between 2 and 2.8 MV.

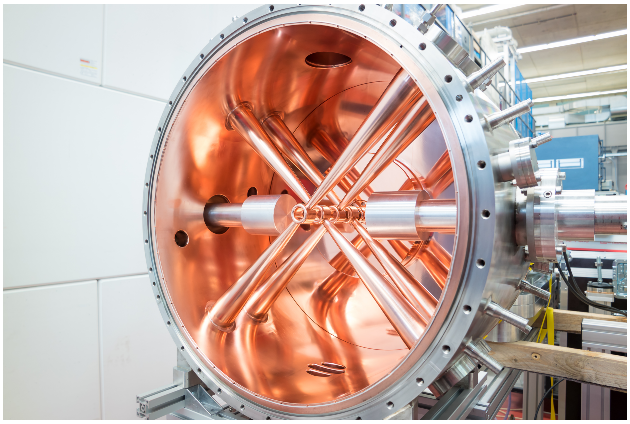

Figure 5: CH-cavity for the FRANZ Linac that is similar to the first CH-cavity of the light ion front end.

The estimated shunt impedance is between 75 MΩ/m for the first cavity and 55 MΩ/m for the last cavity. The necessary RF power is about 100 kW for RF losses and up to 125 kW with beam. The appropriate amplifier size is around 150 kW for which solid state amplifiers are suitable. The transverse focusing is provided by inter-tank triplets. Table 4 summarizes the main parameters of the light ion CH-DTL. Figure 4 shows the conceptual layout and Fig. 5 shows the CH-cavity for the FRANZ linac that is similar to the first cavity of the light ion front-end.

Table 4: Parameters CH-DTL

Parameter	**Unit**	**CH1**	**CH2**	**CH3**
f	MHz	161	161	161
E_{in}	MeV/u	1.3	2.3	3.6
E_{out}	MeV/u	2.3	3.6	5.0
U_{eff}	MV	2.0	2.6	2.8
Z_{eff}	MΩ/m	75	65	55
$Z_{eff} \cdot \cos^2 \varphi$	MΩ/m	69	60	50
L	m	0.6	1.0	1.4
Aperture Ø	mm	20	20	20
P_c	kW	100	110	112
L	m	0.6	1.0	1.4

SUMMARY

A future electron-ion collider requires an ion linac that can accelerate a wide range of ion species from protons to heavy ions (Pb). In this conceptual study two separated room temperature front ends for light and heavy ions are proposed. Both are based on efficient H-mode cavities. The two frond-end solution can provide the best performance for the wide range of A/q and beam currents. Further investigations including detailed beam dynamics and RF simulations are necessary to optimize the design with respect to RF frequency, transition energies, power requirements and cavity design.

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