BEAM DYNAMICS OF A HIGH CURRENT IH-DTL STRUCTURE FOR THE ITEP-TWAC INJECTOR

S. Minaev, T. Kulevoy B. Sharkov (ITEP, Moscow)
U. Ratzinger, R. Tiede (IAP, University Frankfurt / Main)

Abstract

A powerful ion injector based on the laser source is needed for an efficient operation of the Tera Watt Accumulator (TWAC) accelerator complex including a heavy ion synchrotron and a storage ring, which is under progress now at ITEP, Moscow. The Inter-digital H-type drift tube linac (IH DTL) structure operating at 162 MHz is proposed for the second stage of the injector linac behind of an 81 MHz RFQ. Consisting of independently driven sections with inter-tank quadrupole triplet focusing, this structure will accelerate highly stripped ions with charge-to-mass ratio above 1/3 in the energy range from 1.57 AMeV at the RFQ exit to 7 AMeV needed for injection to the synchrotron. A maximum beam current up to 100 mA is expected for medium ions like Carbon. Since the operating RF frequency is duplicated at the entrance to the IH-DTL in order to reduce the size and power consumption of the structure, space charge effects become strong. Beam dynamics and structure parameters are discussed in details.

INTRODUCTION

A Tera Watt Accumulator (TWAC) complex [1] is in progress at ITEP now. Aiming on the accumulation and compression of high energy heavy ion beams for dense plasma generation, this complex includes the heavy ion synchrotron and a storage ring. So long an injector of highly stripped ions is not powerful enough for efficient TWAC operation. A new laser source will deliver the ions with charge-to-mass ratio above 1/3. Maximum beam current up to 100 mA for C^{4+} ions is expected, being considerably complemented by other charge states. Since the enlarged emittance and considerable energy spread are typical for a laser source, direct injection into the RFQ accelerating structure without charge state separation has been decided. In order to accelerate such a beam, a 6 m long high acceptance RFQ section operating at the relatively low frequency of 81 MHz with the output energy of 1.57 AMeV has been designed and is presently under construction now [2]. The energy of 7 AMeV must be gained within 7 m behind of the RFQ. Relatively high energy gain per length unit was the main reason why the Inter-digital H-type drift tube linac (IH-DTL) has been chosen for the final stage of the injector. Other advantages of the IH structure such as efficiency, reliability and compactness have also been taken into account.

The duplicated frequency of 162 MHz is chosen for the IH structure in order to reduce the transverse size and RF power consumption. But the influence of space charge is duplicated in this case too because only every second bucket is filled by particles. Additionally, the apertures of the double-frequency structure are getting smaller. As a result, beam current of 100 mA becomes equivalent to 200 mA from the viewpoint of focusing ability. Space charge dominated beam dynamics is discussed below as well as the general layout and structure parameters.

BEAM DYNAMICS AND STRUCTURE LAYOUT

Beam dynamics studies were performed by using the LORASR code which was developed and suited for IH structures [3] with a KONUS drift tube array [4]. Transverse beam focusing in IH structure is based on a powerful quadrupole triplet channel with low-capacitive π-mode drift tube accelerating sections between neighbored triplets; the larger the number of accelerating gaps in one section, the higher can be the structure efficiency. Being much larger in all sizes than the drift tubes, triplet lenses can be installed either inside of the RF tank (in vacuum) or between separated tanks (on air). In order to simplify tank and lens design, on-air inter-tank triplets have been chosen for the TWAC injector. Fig.1 sows the calculated layout of the structure including three IH tanks, two external rebunchers, diagnostic box, four quadrupole triplet lenses and one small single quadrupole lens directly at the RFQ exit, which provides the space for rebuncher and diagnostic box. The same figure shows the 98% beam envelopes in both transverse directions at full current of 100 mA. The values of magnetic field gradient are calculated to be constant for all lenses as well as the aperture radii, namely, 48 T/m and 20 mm, respectively. At the same time, the tank aperture is growing with the beam energy as Fig.1 shows.

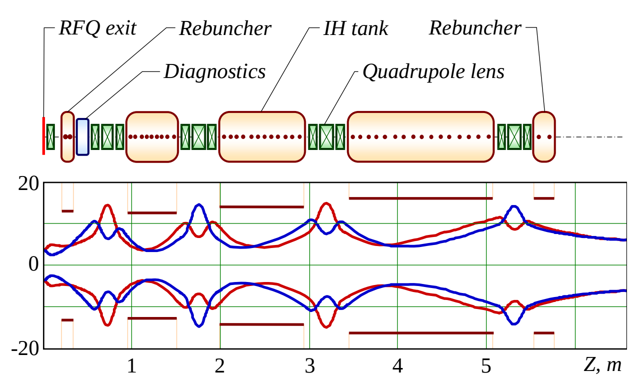

Figure 1. Accelerating structure layout and transverse beam envelopes at full current

Fig. 2 compares the transverse *x*- and *y*- envelopes calculated for a maximum current of 100 mA and for zero current. Since the structure has been originally optimized for 100 mA, a special focusing profile with reduced magnetic gradients has been found for zero current beam operation in order to avoid envelope oscillations. One can see that the transverse size of full current beam is enlarged by less than 50% due to space charge.

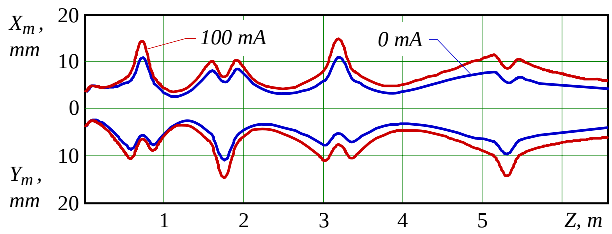

Figure 2. Transverse envelopes for 98% of particles at full current and at zero current

Fig. 3 shows the phase of RF field (in cosine account) seen by the center of the bunch when crossing the gap middle plane.

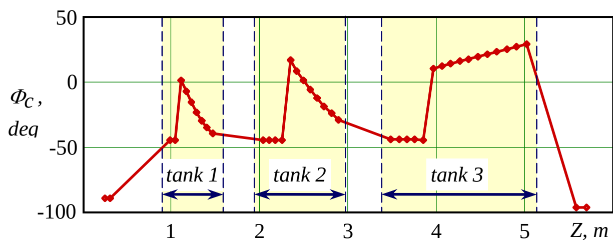

Figure 3. Phase pattern of the bunch center along the IH structure

One can see that the phase in the first two-gap external rebuncher is naturally chosen as -90°. Phase patterns in the first and second tanks are typical for IH-DTL: short internal rebuncher (in our case at -45°) is followed by so-called "zero degree" section, calculated for some virtual reference particle, crossing the gap centers at maximum field. In practice, the energy of this reference particle is chosen lower than the energy of the real bunch, so that the phase of bunch center is sliding from the slightly positive value to the negative "bunching" phase range. Such a phase profile allows a maximum number of accelerating gaps between focusing lenses, keeping bunch stability and acceptable emittance growth.

The energy spread at the injector output should not exceed ± 0.5 %. This requirement can be satisfied only by a considerable artificial increase in bunch length keeping the longitudinal emittance. Therefore, some additional debunching energy spread has to be given and then after drift space it must be compensated by a final buncher. Aiming to reduce the needed drift space, the third accelerating IH tank is used as a debuncher too; that is why tank 3 has been calculated not as a typical unit. After a conventional internal rebuncher, the phase of the bunch center in tank 3 is specified as uniformly increasing from 10° to 30°, moving to "debunching" direction as Fig. 3 shows. A final two-gap external rebuncher uses the phase value of -95° in order to compensate small non-linear effects appearing after tank 3.

Fig. 4 and Fig. 5 show the 98% longitudinal envelopes of accelerated bunch and the energy spread along IH structure, respectively. These values are traditionally measured in IH structure with respect to the virtual synchronous particle position, which is higher in energy than the real bunch center in zero degree sections. For this reason, both phase envelopes and particle energy are shown asymmetrically at the tanks 1 and 2, moving down in zero degree sections. At the same time, tank 3 has no zero degree section because the phases of the bunch center in the accelerating gaps are introduced there directly. That is why the phase and the energy are measured from the bunch center, resulting in nearly symmetric envelopes.

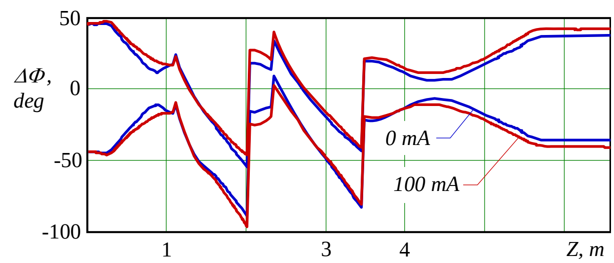

Figure 4. Phase envelopes for 98% of particles along IH structure

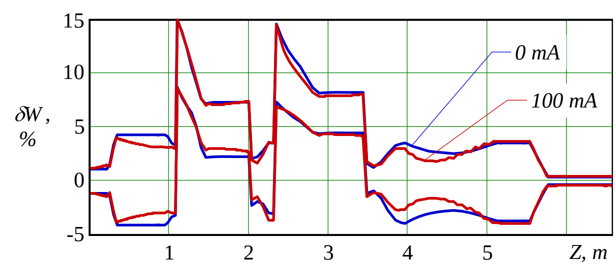

Figure 5. Energy spread for 98 % of particle along IH structure

As Fig. 4 shows, the phase spread of the input bunch is rather large - around 90° due to the duplicated frequency of the IH structure. It means that the buncher is needed at a short distance behind of the RFQ; otherwise the bunch will become too long, leading to non-linear distortions. On the other hand, the buncher can not be installed directly at the RFQ exit because the large transverse angular spread would result in unacceptable transverse beam size. As a compromise, a low-aperture short single quadrupole lens is installed at the distance of 3.5 behind of the edge of RFQ electrodes. Reducing the critical angular spread in *x*- direction, this small lens provides enough space both for the buncher and for a diagnostic box. Afterwards the quadrupole channel with FDF0DFD lattice begins.

Fig. 6 illustrates the evolution of the longitudinal emittance at the phase-energy plane. An ideal elliptic configuration of the bunch injected to IH structure becomes divergent, getting high energy spread in tank 3.

Then this spread is minimized by the last external buncher. Finally, it does not exceed the value of ± 35 AkeV, satisfying requirements for synchrotron injection.

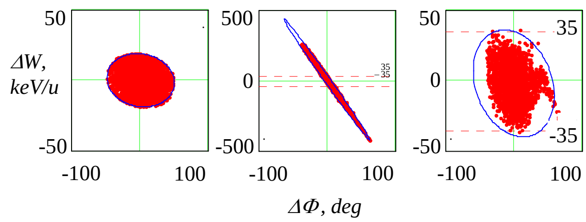

Figure 6. Longitudinal emittance at the RFQ exit, at the exit of tank 3 and behind of the final external buncher

Structure parameters have been calculated and optimized for a maximum beam current of 100 mA. But if zero current is injected to the same structure, some mismatching occurs in both transverse and longitudinal directions, although 100% transmission is kept. For this reason, a modified profile of magnetic field gradients has been found especially for zero current. Gradients are reduced by around 4% in average, but not identically for all lenses. The effective gap voltage of the first external buncher is reduced from 160 kV to 145 kV for zero current.

CALCULATED PARAMETERS OF IH-DTL STRUCTURE

The calculated parameters of the IH structure are given at Table 1. A high current ion beam with A/q=3 gains an effective voltage of 16.4 MV within the length of 5.75 m including two rebunchers and diagnostics. Although the transverse emittance is increased by 40% due to non-linear space charge action, it fits to synchrotron acceptance as well as the energy spread.

Table 1: General parameters of IH-DTL

Operating frequency	*MHz*	162.72
Charge-to mass ratio		1/3
Beam current	*mA*	100
Input energy	*AMeV*	1.57
Output energy	*AMeV*	7.04
Final energy spread	*%*	± 0.5
Transv. emittance (norm)	*mm*mrad*	3*π
Long. emittance (norm)	*AkeV*ns*	16.2
Transv. rms emit. growth	*%*	40
Long. rms emit. growth	*%*	22
Total length	*m*	5.75
Number of RF tanks		3
Number of RF bunchers		2
Total gap number		41
Tank aperture diameter	*mm*	25 - 38
Gap / period ratio		0.48 – 0.4
Effective gap voltages	*kV*	370 - 700
Maximum on-axis field	*MV/m*	14
Lens aperture diameter	*mm*	40
Magnetic field gradient	*T/m*	48

A distribution of gap length along the whole structure is shown at Fig. 7, while the effective gap voltages are presented by Fig. 8.

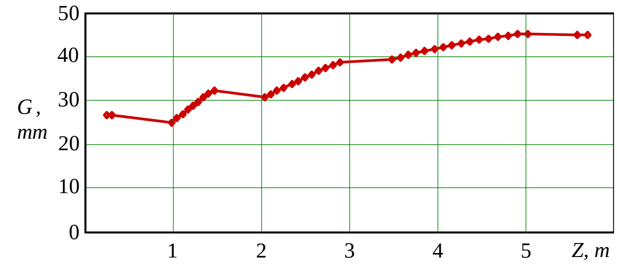

Figure 7. Gap lengths along IH structure

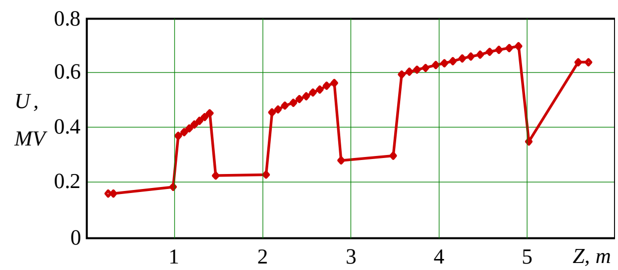

Figure 8. Effective gap voltages along IH structure

One can see that the RF voltages applied to the gaps are growing proportionally to the gap length, keeping the on-axis electric field close to the value of 14 MV/m. At the same time, linear distribution of the RF voltage can be easily realized in the short IH tank.

CONCLUSIONS

The calculated IH-DTL accelerating structure will deliver the high current heavy ion beam with parameters required for synchrotron injection including small energy spread ± 0.5%. If necessary, this value may be reduced even more with enlarged drift space and with 81 a MHz final buncher. Although a system of separated tanks complicates the RF powering, the mechanical design of the tanks and lenses might become simpler and cheaper.

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