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DEVELOPMENT AND BENCHMARKING OF THE IMPACT-T CODE

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Abstract

The multi-particle tracking code IMPACT-T is widely used to calculate the particle motion in high intensity linacs. The code is a self-consistent three-dimensional beam dynamics simulation toolbox that utilizes the particle-in-cell method in the time domain. In collaboration between PKU and LBNL, an RFQ module was implemented to the IMPACT-T code, which enables simulations of the accelerator front-end. In order to benchmark the newly developed module in the IMPACT-T code, we have simulated the beam transport in Beijing Isotope Separation On-Line (BISOL) high intensity deuteron driver linac. It consists of a 3 MeV RFQ and 40 MeV superconducting rf linac with four cryomodules. After comparing the simulation results with Parmteqm and TraceWin, we obtained a very good agreement, which represents the validation of the RFQ module in IMPACT-T.

INTRODUCTION

The IMPACT-T code suite is a time-based parallel tracking program for charged particles in accelerator. It includes three-dimensional space-charge solver based on particle-in-cell (PIC) method to efficiently and accurately treat space charge dominated beams [1]. From the simulation point of view, the basic equation we have to solve is shown as Eq. (1).

$$F = qe(E + v \times B) \tag{1}$$

The electric and magnetic field strength are a combination of external fields (E_{ext}, B_{ext}) and space charge fields of beam (E_{sc}, B_{sc}), as shown in the Eq. (2).

$$\begin{aligned} E &= E_{ext} + E_{sc} \\ B &= B_{ext} + B_{ext} \end{aligned} \tag{2}$$

For the different modules in the IMPACT-T code, the external fields can be described either with analytic formula or with static or RF electromagnetic field maps. The critical and time-consuming part is the space charge effect. In the IMPACT-T, the 3-D Poisson equation is solved by PIC method and Green function. At last, the leap-frog method is used to integrate Eq. (1) to push the particles to get coordinates and velocities at the next time loop, which makes the whole process self-consistent.

In collaboration between LBL and PKU, a RFQ module and SRF module have been integrated to the IMPACT-T code. After updating, IMPACT-T is able to do simulation about RFQ and superconducting linac. In order to benchmark the newly developed module in the IMPACT-T code, we have simulated the beam transport in Beijing Isotope Separation On-Line (BISOL) high intensity deuteron driver linac. It consists of a 3 MeV RFQ and 40 MeV superconducting rf linac (SRF linac) with four cryomodules, as shown in Fig. 1.

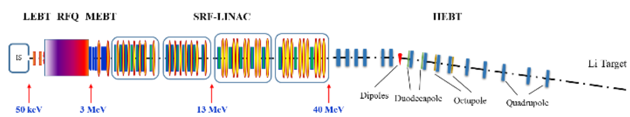

Figure 1: Schematic layout of BISOL deuteron driver linac.

RFQ MODULE

The popular RFQ design code Parmteqm uses position as an independent variable and has a two-dimensional space charge solver [2]. These approximations might introduce significant errors at lower energy for high intensity proton/ion beams [3]. Consequently, an RFQ module was implemented to the IMPACT-T code. In the RFQ module, the external field E_{ext} can be rebuilt by the corresponding 8-term potential function as shown in Eq. (3). All coefficients can be obtained from the Parmteqm output file PARIOUT.TXT.

$$\begin{aligned} U(r,\theta,z) = \frac{V}{2}\{&A_{01}(\frac{r}{r_0})^2 cos2\theta + A_{03}(\frac{r}{r_0})^6 cos6\theta \\ &+[A_{10}I_0(kr) + A_{12}I_4(kr)cos4\theta]\cos(\mathrm{kz}) \\ &+[A_{21}I_2(2kr)cos2\theta + A_{23}I_6(2kr)cos6\theta]\cos(2\mathrm{kz}) \\ &+[A_{30}I_0(3kr) + A_{32}I_4(3kr)cos4\theta]\cos(3\mathrm{kz})\} \end{aligned} \tag{3}$$

where, $k=\pi/L$, L is the length of transition cell. The $A_{01}\ldots A_{32}$ coefficients values can be calculated by linear interpolation at each z. However, the potential has corresponding modification in Radial Matching Section (RMS) cell and transition cell (including m=1 cell and fringe cell) in order to accurately describe electric field. For the space charge, both effects of interior of the beam and the adjacent bunches are included.

Table 1: General Parameters of BISOL RFQ

Parameter	Value	unit
Particle	D	
Frequency	162.5	MHz
Input energy	50	keV
Output energy	3	MeV
Vane length	5.03	m
Beam current	20	mA
Inter-vane voltage	60~75	kV
Max peak surface electric field	19.87	MV/m
Kilpatrick coefficient	1.46	
Min/max average aperture	3.94/5.09	mm
Max. modulation factor	1.90	

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In order to benchmark the RFQ model, we simulated a charged deuteron beam transporting through a RFQ of BISOL deuteron driver linac based on IMPACT-T and Parmteqm code. The basic RFQ design specifications are listed in Table 1. The 20 mA deuteron beam is accelerated from 50 keV to 3.0 MeV with the length of 5.05 m.

The 10^5 macro-particles are tracked along the BISOL RFQ with same 4D water-bag distribution type. In order to exclude the influences of space charge effect, the simulation results at zero current are carefully compared firstly, including RFQ out beam Twiss parameters, transmission efficiency and beam distribution. The final output beam phase space distribution is shown in Fig. 2 (up). It shows that the IMPACT-T results agree with Parmteqm results quite well. After that, the simulation results at 20 mA are compared in detail. The final beam phase space distribution is shown in Fig. 2 (down). Output beam Twiss parameters and normalized rms emittance are listed in Table 2. It is seen that the Twiss parameters of two codes are very close. However, it seems that the beam border in the transverse plane of IMPACT-T is a little larger than Parmteqm and the normalized emittance of IMPACT-T is bigger than Parmteqm almost 8%. This might be due to the approximation of the space charge force calculation in the Parmteqm code as mentioned above.

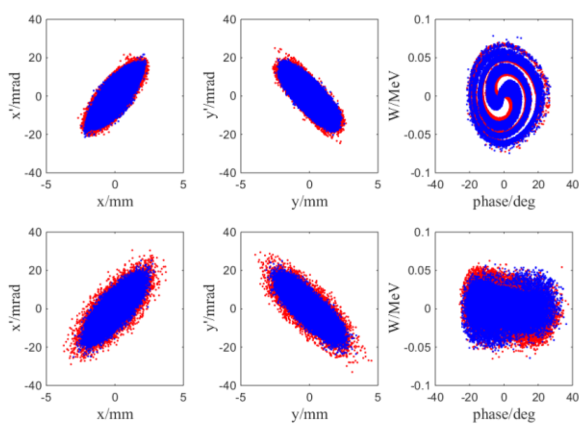

Figure 2: Particle beam phase space distribution at the exit of RFQ from Parmteqm (blue) and IMPACT-T (red) (up: 0 mA, bottom: 20 mA).

Table 2: Comparison of Detailed Simulation Results

Code		Parmteqm	IMPACT-T	Unit
Current		20		mA
Input $\varepsilon_{n,rms}$		0.20		mm·mrad
Exit energy		3.03	3.04	MeV
Exit $\varepsilon_{x,n,rms}$		0.205	0.218	mm·mrad
Exit $\varepsilon_{y,n,rms}$		0.201	0.215	mm·mrad
Exit $\varepsilon_{z,n,rms}$		0.245	0.268	mm·mrad
x	α	1.45	1.36	
	β	0.24	0.25	mm/mrad
y	α	-1.40	-1.17	
	β	0.21	0.21	mm/mrad
z	α	-0.16	-0.23	
	β	1.75	1.52	mm/mrad
Transmission		99.4	99.3	%

In addition, we also study the effects of beam current on transmission efficiency according to two codes. The results are shown in Fig. 3. With the beam current increases, the transmission efficiency from IMPACT-T is lower compared with Parmteqm. It indicates the space charge force calculated by IMPACT-T is larger than that of Parmteqm, especially for the high beam current.

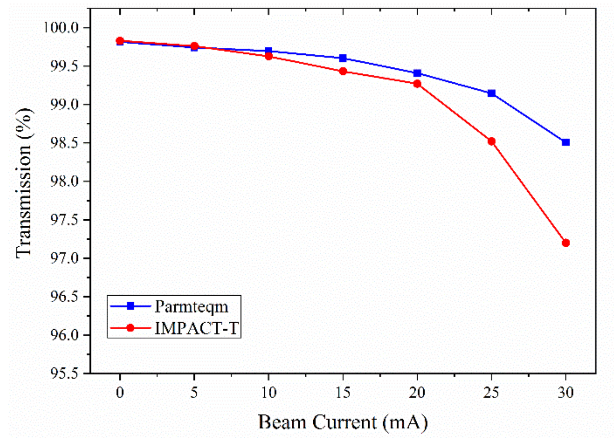

Figure 3: RFQ transmission with different beam current.

SRF MODULE

The SRF linac of BISOL is composed of superconducting half wave resonator (HWR) cavities and solenoids. For HWR cavities, the 3D discrete field maps obtained by CST are used to calculate the field at the particle position. For solenoids, the magnetic field is influenced by the edge effect [4], as shown in Eq. (4).

$$\begin{aligned} B_z &= B_z - \frac{r^2}{4}\frac{d^2B(z)}{dz^2} \\ B_r &= -\frac{r}{2}\left(\frac{dB(z)}{dz} - \frac{r^2}{8}\frac{d^3B(z)}{dz^3}\right) \end{aligned} \tag{4}$$

Where *B(z)* is the magnetic field along the beam axis. In addition, the 3D discrete magnetic field also can be used in the code. In order to benchmark the SRF model, we simulated a charged deuteron beam transporting through a BISOL SRF linac. Its basic design specifications are listed in Table 3. The 10 mA deuteron beam is accelerated from 3 MeV to 40 MeV with two types of HWR cavities (0.09 and 0.16) with approximately 22.5 m long.

Table 3: General Parameters of BISOL SRF Linac

Parameter	Value	unit
Particle	D	
Frequency	162.5	MHz
Input energy	3	MeV
Output energy	40	MeV
Total length	22.5	m
Beam current	10	mA
Cryomodule number	4	
HWR Beta	0.09 & 0.16	
HWR cavities No.	32	
Solenoids No.	22	

We perform the simulations using two independent codes: IMPACT-T and TraceWin (10^5 macro-particles

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with same distribution) [5]. The synchronous phase of HWR cavities is set to be same for both two codes. As before, the beam transmissions at zero current and full current were simulated, respectively. The simulation results at 10 mA are presented in this paper. Figures 4 and 5 show the beam energy growth along the SRF linac and the final beam phase space distribution, respectively. The deviations of emittance are 2 % and 5 % in the transverse and longitudinal plane, which illustrates the good similarity between two codes. The detailed beam parameters are summarized in Table 4.

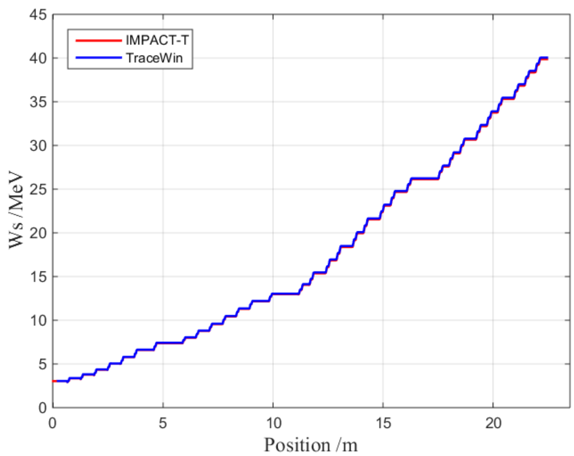

Figure 4: Energy increments along the SRF linac.

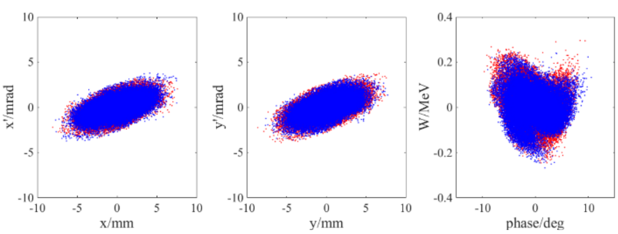

Figure 5: Particle beam phase space distribution at the exit of SRF linac. (Blue: TraceWin, red: IMPACT-T).

Table 4: Comparison of the Ellipse Parameters

Code		TraceWin	IMPACT-T	Unit
Beam Current		10		mA
Exit energy		40.0	39.9	MeV
Exit $\varepsilon_{x,n,rms}$		0.232	0.229	mm·mrad
Exit $\varepsilon_{y,n,rms}$		0.231	0.237	mm·mrad
Exit $\varepsilon_{z,n,rms}$		0.267	0.253	mm·mrad
x	α	-0.73	-0.74	
	β	2.95	3.17	mm/mrad
y	α	-0.75	-0.80	
	β	3.21	3.48	mm/mrad
z	α	-0.19	-0.31	
	β	4.00	3.64	mm/mrad

Figure 6 shows the beam rms envelope and normalized rms emittance along the SRF linac. It is seen that the longitudinal deviation is larger than transverse, especially in the back part. This might because of the different definition method of HWR phase for two codes. Other possible reasons will be fully investigated in future work.

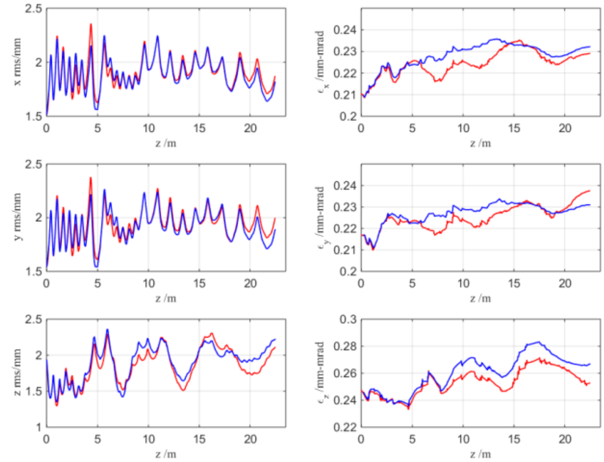

Figure 6: Beam rms envelope and normalized rms emittance along the SRF linac. (Blue: TraceWin, red: IMPACT-T).

CONCLUSION

The benchmark simulation results for the BISOL driver linac show a good agreement between the codes IMPACT-T and TraceWin. More studies on the beam halo formation, design reliabilities and beam stabilities are planned for the coming future.

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