STATUS OF THE BEAM DYNAMICS CODE DYNAC*

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Abstract

The efficacy of using the beam dynamics code DYNAC [1] as an online beam simulation tool for the Facility for Rare Isotope Beams (FRIB) [2] and its concomitant Reaccelerator (ReA) is discussed. DYNAC was originally developed at CERN, where a set of accurate quasi-Liouvillian beam dynamics equations was introduced for accelerating elements, applicable to protons, heavy ions and non-relativistic electrons.

A numerical method has been added, capable of simulating a multi-charge state ion beam in accelerating elements (i.e. cavities). Beam line devices such as sextupoles, quadrupole-sextupoles as well as electrostatic devices are now also included. Capability of second order calculations for a multi-charge state beam has been implemented. A Radio Frequency Quadrupole (RFQ) model has been added and a preliminary comparison of beam simulation results with beam measurements on the ReA RFQ is reported. Benchmarking of the code for a multi-charge state beam is discussed. The three space charge routines contained in DYNAC, including a 3D version [3], have remained unchanged.

MAGNETIC DIPOLE WITH GRADIENT

The capability of simulating a multi-charge state beam in a magnetic dipole has been added to DYNAC using a computationally efficient matrix formalism. The FRIB Front End (FE) contains two Electron Cyclotron Resonance (ECR) sources, followed by a source and charge state selection line using magnetic dipoles (see Fig. 1).

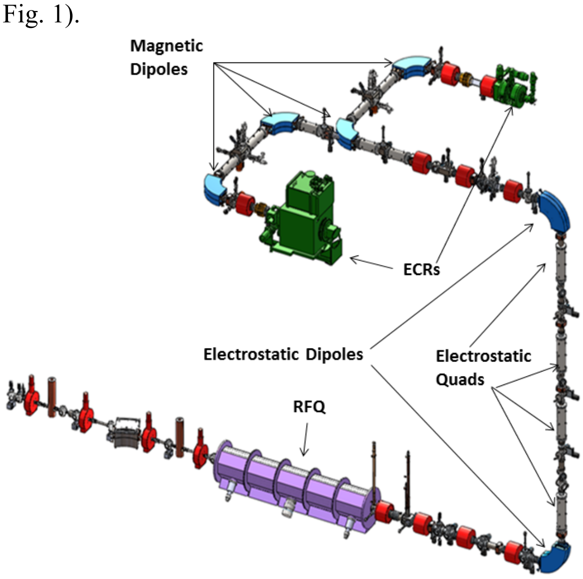

Figure 1: FRIB FE layout.

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The DYNAC hard edge model for this dipole, which has an effective field length of 1 m, has been benchmarked against TRACK [4], which used a 3-D representation of the 1.7 m long field. This dipole has a field gradient of about 0.93. The output distributions are shown in Fig. 2 for a 12 keV/u uranium beam with charge states 33+ and 34+. Table 1 shows numerical results based on 4k macro-particles. The differences in the vertical phase plane are smaller than in the horizontal one.

Table 1: DYNAC and TRACK Horizontal Emittance Data for a Multi-Charge State Beam Tracked Through a FE Dipole

Parameter	U^{33+}	U^{34+}
α_x,DYNAC	0.431	0.360
α_x,TRACK	0.465	0.440
β_x,DYNAC	2.586	2.695
β_x,TRACK	2.605	2.551
ε_x,DYNAC	54.03	53.72
ε_x,TRACK	54.28	53.94

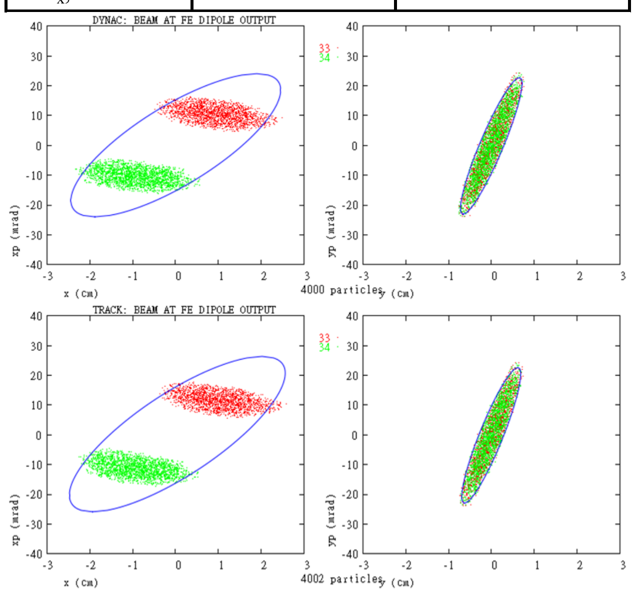

Figure 2: Horizontal emittances (left) and vertical (right) for DYNAC (top) and TRACK (bottom) for a multi-charge state beam tracked through the FE charge selection dipole.

ELECTROSTATIC QUADRUPOLES

To benchmark the electrostatic quadrupole model, a two charge state output beam from the FE charge selection dipole was simulated in a lattice containing six electrostatic quadrupoles. In DYNAC a 20 cm effective length hard edge model was used, whereas TRACK used a 3-D representation of a 30 cm long field. Again, there is good agreement between the two codes (see Table 2).

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Table 2: DYNAC and TRACK Horizontal Emittance Data for the Electrostatic Quadrupole Benchmark

Parameter	U^{33+}	U^{34+}
α_x,DYNAC	1.762	1.724
α_x,TRACK	1.759	1.679
β_x,DYNAC	5.638	5.500
β_x,TRACK	5.676	5.494
ε_x,DYNAC	54.27	53.96
ε_x,TRACK	54.50	54.12

ACCELERATING CAVITIES

The analytical method in DYNAC for simulating accelerating elements cannot be used for multi-charge state beams. A numerical method has been added to DYNAC, capable of simulating a multi-charge state ion beam in accelerating elements (i.e. cavities). This routine has been benchmarked against the simulation code IMPACT [5]. For this comparison, the case of a uranium beam with charge states 33+ and 34+ passing through the 100 accelerating cavities of the FRIB Linac Segment 1 (LS1) was taken. The FRIB superconducting (SC) driver linac is of a compact design (see Figure 3). The FE delivers a 500 keV/u beam to LS1, which consists of 3 cryomodules with 4 SC β=0.041 cavities each followed by 11 cryomodules with 8 SC β=0.085 cavities each, taking the beam to 16.6 MeV/u. Transverse focusing is achieved with SC solenoids, which are mounted inside the cryomodules.

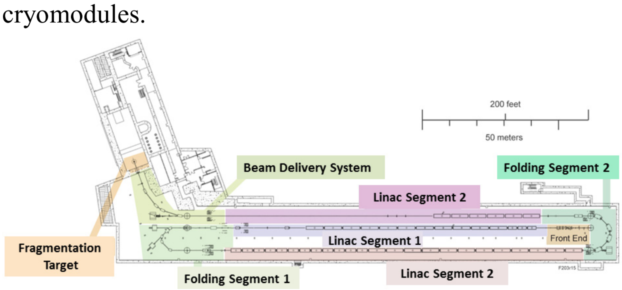

Figure 3: FRIB driver linac layout.

For the DYNAC/IMPACT comparison, the macro-particles were tracked from the FE output through LS1 to the charge stripper in the following Folding Segment 1 (FS1) including a chicane consisting of 4 dipoles with a 5° bend each and 2 matching cryomodules.

Table 3: Emittance Data at the FRIB Charge Stripper Input

	U^{33+}			U^{34+}		
	H	V	L	H	V	L
α_{DYNAC}	0.016	-0.029	0.844	-0.379	-0.095	0.056
α_{IMPACT}	-0.008	0.051	0.813	-0.277	0.012	0.082
β_{DYNAC}	0.396	0.378	1.6E-4	0.248	0.243	2.5E-4
β_{IMPACT}	0.429	0.422	1.6E-4	0.261	0.279	2.6E-4
ε_{DYNAC}	2.284	2.279	2181.1	2.333	2.360	2944.7
ε_{IMPACT}	2.287	2.283	1965.8	2.316	2.348	2580.1

Table 3 shows emittance data for the transverse (H, V) planes (units are mm/mrad (Twiss β) and mm.mrad (ε)) and longitudinal plane (units are deg/keV (Twiss β) and keV.deg (ε)) for each of the two charge states based on simulations with about 20k macro-particles.

Good agreement between the two codes was obtained, except for the longitudinal emittance, which is about 10 to 12 % smaller with IMPACT than with DYNAC for 33+ and 34+ respectively. The corresponding phase space plots are shown in Figure 4. Changing the number of steps (i.e. step size along the z-axis) in either the DYNAC or IMPACT numerical routine can decrease these differences, though they are within the accuracy of longitudinal emittance measurements.

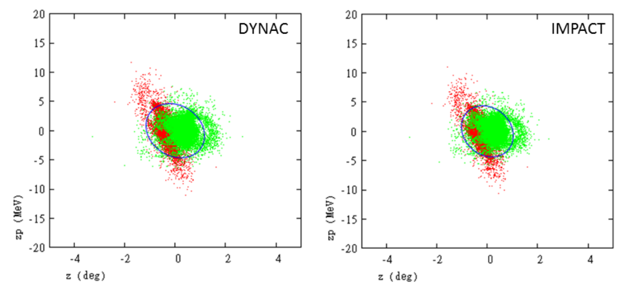

Figure 4: Longitudinal phase space plots for DYNAC (left) and IMPACT (right) at the charge stripper input for U33+ (red) and U34+ (green).

Table 4 shows the output energy for each of the two charge states. The difference on the energy gain through LS1 is less than 0.02%.

Table 4: Beam Energy at the FRIB Charge Stripper Input

	U^{33+}	U^{34+}	Unit
DYNAC	16.7187	16.7197	MeV/u
IMPACT	16.7216	16.7234	MeV/u

QUADRUPOLE-SEXTUPOLE MAGNET

For the purpose of benchmarking combined function quadrupole-sextupole magnets, the transport of a 5 charge state uranium beam from the charge stripper in FS1 to the Linac Segment 2 input (see Figure 3) was taken as this section contains four quadrupole-sextupole magnets. This section also contains two matching cryomodules and another chicane consisting of four dipoles with a 5° bend each as well as a bending section made up of four 45° dipoles. In this second order simulation, DYNAC results for about 20k macro-particles were compared to those obtained with IMPACT (see Table 5). Again, good agreement between the two can be observed.

RFQ

An RFQ model has been added to DYNAC, using as input the relevant parameters from the RFQ cell by cell data listed in a PARMTEQ output file. The case of a uranium beam with charge states 33+ and 34+ passing through an RFQ with an output energy of 500 keV/u was studied and compared with data obtained from RIAPMTQ [6]. The longitudinal emittances are within 12% and the transverse within less than 4%. The difference in output energy is about 0.4%. These differences are in part due to the lack of precision in the table of available external

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Table 5: Emittance Data at the FRIB LS2 Input. The Units are as for Table 3

	U^{76+}			U^{77+}			U^{78+}			U^{79+}			U^{80+}		
	H	V	L	H	V	L	H	V	L	H	V	L	H	V	L
α_{DYNAC}	0.303	-0.132	-0.707	0.290	-0.108	-0.392	-0.009	-0.128	-0.136	-0.276	0.015	0.112	-0.211	0.361	0.330
α_{IMPACT}	0.207	-0.135	-0.694	0.218	-0.122	-0.386	-0.022	-0.137	-0.131	-0.242	0.015	0.121	-0.203	0.366	0.347
β_{DYNAC}	2.848	3.512	8.1E-5	2.253	2.556	6.5E-5	1.826	2.354	5.9E-5	2.249	2.239	5.9E-5	3.161	1.842	6.6E-5
β_{IMPACT}	2.568	3.453	7.9E-5	2.121	2.548	6.5E-5	1.826	2.377	5.9E-5	2.174	2.266	5.9E-5	2.980	1.857	6.6E-5
ε_{DYNAC}	2.379	2.501	17.32	2.476	2.418	16.84	2.514	2.457	16.60	2.522	2.439	16.81	2.548	2.473	16.52
ε_{IMPACT}	2.399	2.501	17.29	2.485	2.415	16.82	2.510	2.454	16.57	2.502	2.438	16.78	2.515	2.473	16.50

parameters used as input by DYNAC for this particular RFQ.

DYNAC beam simulations for the ReA RFQ have been made for a single charge state beam, accelerated from 12 to 600 keV/u. Preliminary results of transverse emittance measurements at the RFQ output are shown in Figure 5, as well as DYNAC beam simulation results for the nominal RFQ settings.

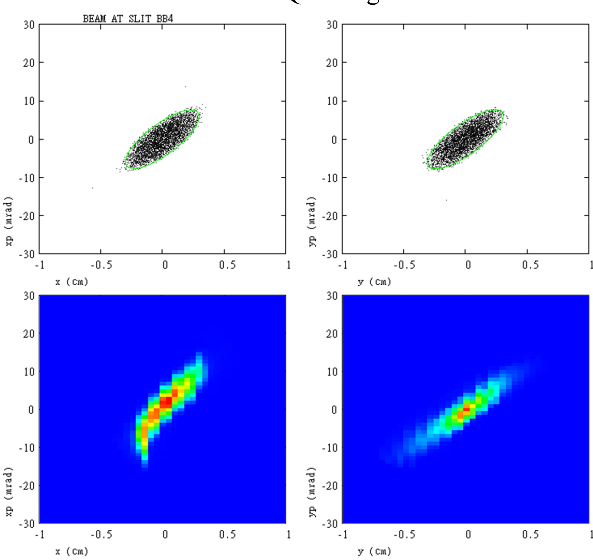

Figure 5: Preliminary results for the horizontal (left) and vertical (right) phase planes at the output of the ReA RFQ for DYNAC (top) and measurement (below).

About up to 10% emittance fluctuation has been observed in results from these measurements. Investigation in possible causes of the differences visible in Figure 5 is under way.

ONLINE MODEL

Online models are necessary for both commissioning and operations. Envelop (matrix) tracking, though computationally efficient, has limitations for treating multi-charge state, heavy ion beam dynamics. DYNAC does not have these limitations and is computationally efficient: simulating a 20k macro-particle two charge state beam through the 100 cavities in LS1 takes about 64 sec on a 2.93 GHz CPU with a 4 GB 1067 MHz RAM. Reducing to 1k macro-particles (see Figure 6) yields an execution time of about 3 sec, which is sufficiently low for online modelling. For a single charge state beam, the analytical model takes about 10.7 seconds for 20k macro-particles and about 0.7 seconds for 1k macro-particles.

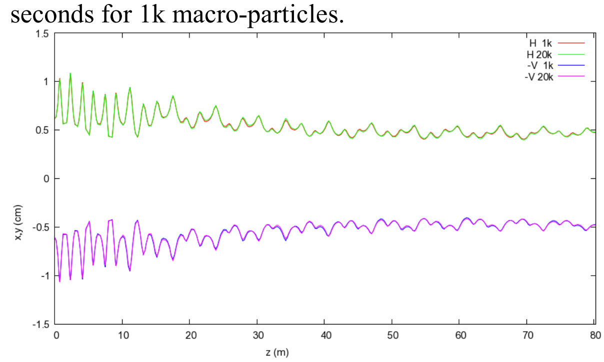

Figure 6: LS1 transverse beam envelopes for 1k and 20k macro-particles.

STATUS AND PLANS

It has been demonstrated that DYNAC is a good candidate for online modelling. Multi-charge state functionality has been added and benchmarked for the various new beam line elements. At ReA the code is used in commissioning. The charge stripper model is being refined, the analytical model for accelerating elements is under further development and a model for electrostatic dipoles is planned.

DYNAC and its graphics post-processor will work on Linux, MAC and MS Windows. The source code is available at http://dynac.web.cern.ch/dynac/dynac.html

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