BEAM DYNAMICS SIMULATIONS OF SARAF ACCELERATOR INCLUDING ERROR PROPAGATION AND IMPLICATIONS FOR THE EURISOL DRIVER

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Abstract

Beam dynamics simulations of SARAF (Soreq Applied Research Accelerator Facility) superconducting RF linear accelerator have been performed in order to establish the accelerator design. The multi-particle simulation includes 3D realistic electromagnetic field distributions, space charge forces and fabrication, misalignment and operation errors. A 4 mA proton or deuteron beam is accelerated up to 40 MeV with a moderated rms emittance growth and a high real-estate gradient of 2 MeV/m. An envelope of 40,000 macro-particles is kept under a radius of 1.1 cm, well below the beam pipe bore radius. The accelerator design of SARAF is proposed as an injector for the EURISOL driver accelerator. The Accel 176 MHZ β_0=0.09 and β_0=0.15 HWR lattice was extended to 90 MeV based on the LNL 352 MHZ β_0=0.31 HWR. The matching between both lattices ensures smooth transition and the possibility to extend the accelerator to the required EURISOL ion energy.

INTRODUCTION

The simulation in this work for a proton or a deuteron beam starts downstream a 4 m long, 1.5 MeV/u 176 MHz RFQ. The SARAF lattice consists of three quadrupoles at the 0.65 m MEBT, two low energy cryostats, each containing six HWRs of β_0=0.09 [1] and four medium energy cryostats with eight HWRs of β_0=0.15 at 176 MHz [2]. This lattice [3] is a modification of the previous SARAF linac lattice presented in [4,5]. Each period in the cryostat consists of a solenoid followed by two HWRs, as described in Fig. 1. The tune is based on the TRACK-35 code [6] and is benchmarked with the GPT code [7,4].

BEAM DYNAMICS

Deuterons Tune

The initial distribution at the MEBT entrance is the output distribution of the 5 mA RFQ deuteron beam dynamics simulated using PARMTEQ [8], scaled to 4 mA. The MEBT quadrupoles field was adjusted using TRACE3D to enable smooth entrance to the first cryostat with a beam transverse rms size (x,y) of 2 mm, the typical transverse size along the linac, to eliminate mismatch ratio fluctuations instabilities [9,10]. The first HWR is used as a buncher with low amplitude and a synchronous phase of -90 degrees. There is a drift space in place of the second HWR to enlarge the bunching distance. This tune enables convergence conditions at the third and the fourth cavities which are tuned to near zero synchronous phase.

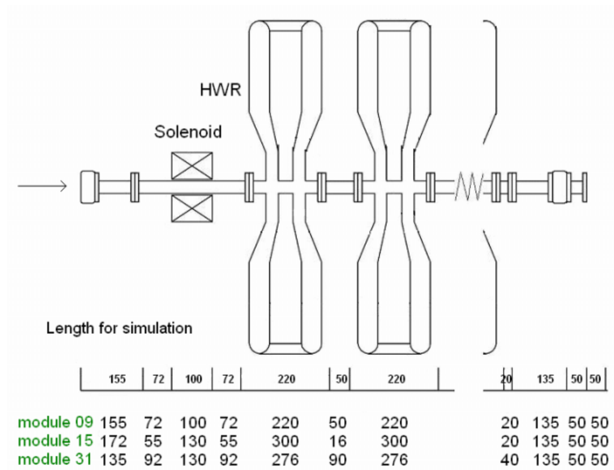

Figure 1: The period of one solenoid followed by two HWRs in the first cryostat and a table of the longitudinal dimensions in all three cryostat types.

The β mismatch conditions at the third cavity (β=0.056) shifts this zero phase to an effective acceleration phase of -52 degrees at the first gap and +52 degrees at the second gap. This shift moves the acceleration field at each gap to the linear acceleration region for all the bunch particles. At the first cryostat exit, the last two cavities amplitude is decreased to 0.6 of the nominal value and their phases are -50º and -20º, respectively. At the second cryostat entrance the first cavity phase is -60º and the next one is 0º. From this point on the synchrounous phase varies around -20º, excluding the entrance and exit cryostat cavities. In those cavities the negative phase was enlarged to stabilize the particles transfer between cryostats.

The solenoid fields were adjusted according to a recommendation made by Ostroumov *et al.* [11]: use the minimum amplitude that is required to control the 'last particle' at the bunch. The transverse period was taken as the distance between consecutive solenoids according to the recommendation to keep the geometric period as small as possible [12]. These recommendations contribute to a reduction in the phase advance in each beam period which enhances beam stabilization. The beam transverse envelope size for 40 k macro particles simulation is kept under 0.9 cm (machine errors are NOT included). An additional significant reduction in the envelope radius might increase the phase advance per period along the linac and contribute to halo formation.

For the suggested EURISOL driver, the SARAF lattice was extended by one more medium energy cryostat and four high energy cryostats with eight HWRs of β_0=0.31 at

352 MHz [13]. The deuteron energy at the linac exit, 42 m downstream the 3 MeV RFQ exit, is 89.4 MeV. This energy gain is achieved with 1% increase in the rms longitudinal emittance (Fig. 2a) and 31% increase in the normalized rms transversal emittance (Fig. 2b). Each phase advance period consists of a solenoid followed by two HWRs. Between the first and the fifth period the periodic transversal phase advance is below the longitudinal one due to initial beam matching conditions at low β (Fig. 2c). We used for the extended lattice an available β_0=0.31cavity design including its 3D fields. However the smooth transition between the medium and high energy cryostats shows that β_0=0.31 is not far from the optimal synchronous β for the high energy cavities. Such a design reduces the number of cavities types and the linac cost.

Error analysis

In order to study the effect of random errors along the linac, 100 simulations were performed, each with a different realization of the random errors. The errors distributions are given in Table 1. Misalignment, rotation errors and static amplitude and phase errors are uniformly distributed in the given ranges whereas the dynamic phase and amplitude errors are described by a Gaussian distribution with the given rms values, truncated at three standard deviations [6]. Similar distributions are given by Accel for SARAF linac [14].

The longitudinal phase focusing was increased to enlarge the longitudinal acceptance and as a consequence minimize beam loss due to the introduction of random errors. The maximum longitudinal phase width (the deviation of the external macro particle at the bunch from the synchronous phase) is 40° while the local synchronous phase is -20° (Fig. 2d). The maximum envelope transversal size for the errors simulation is 1.1 cm, while the cavity bore radius is 1.5 cm (Fig. 2e).

Table 1: Error Distributions

	Error Type	Error range
quad	Misalignments [x,y,z] (mm)	[±0.1, ±0.1, ±0.1]
	Z rotation (mrad)	±1.5
	Amplitude [static, rms dynamic] (%)	[±1, 0.25]
sol	Misalignments [x,y,z] (mm)	[±0.1, ±0.1, ±0.1]
	Amplitude [static, rms dynamic] (%)	[±1, 0.25]
HWR	Misalignments [x,y,z] (mm)	[±0.2, ±0.2, ±0.2]
	Z rotation (mrad)	±3*
	Amplitude [static, rms dynamic] (%)	[±1, 0.25]*
	Phase [static, rms dynamic] (deg)	[±0.5, 0.125]*

***** A half range of these values were used at the 1st HWR

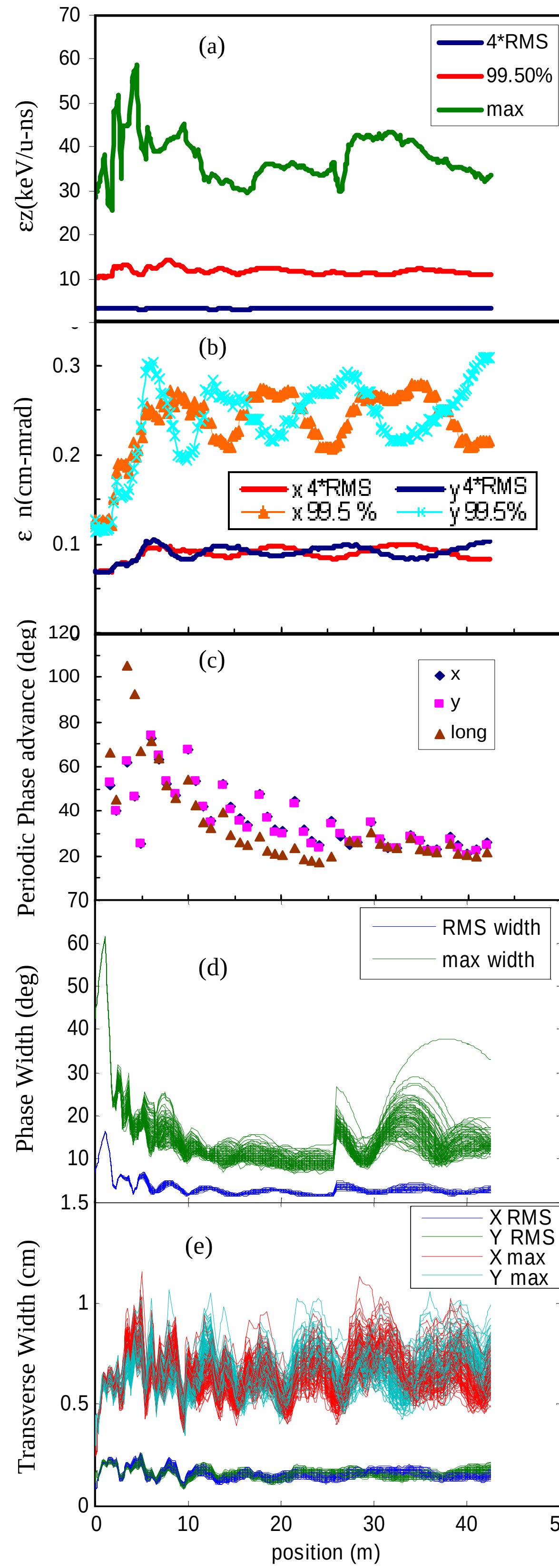

Figure 2: Beam dynamics simulation results described in the text as function of position along the linac starting at the RFQ exit.

Benchmark Simulation

The GPT benchmark for a deuteron beam is presented in Fig. 3. One can see that the benchmark approves the beam dynamics evaluation with TRACK. The longitudinal rms emittance growth at the end of the seventh module is 1-2% in both codes for a deuteron beam. The normalized rms transversal emittance growth is 22% in TRACK and 23% in GPT (Fig. 3). There are minor differences between GPT and TRACK. The beam bunch energy deviation between the codes along the linac up to 52 MeV at 25 m from the RFQ exit is lower than 0.2%.

Proton Simulation

A beam dynamics simulation for a proton beam along the SARAF linac up to 40 MeV was studied. The envelope radius for error simulation with 40k macro particles is below 0.7 cm except in the first solenoid of the second cryostat where the envelope radius reaches 0.9 cm. The phase width after the buncher is below 35º at the entrance to the second cryostat and below 20º from this point on. The GPT benchmark for a proton beam gives generally similar results to the deuteron beam dynamics benchmark. The solenoid and acceleration fields which were optimized for 4 mA current are accepted for zero current too. This feature is important for a real time linac tune which starts at a low current.

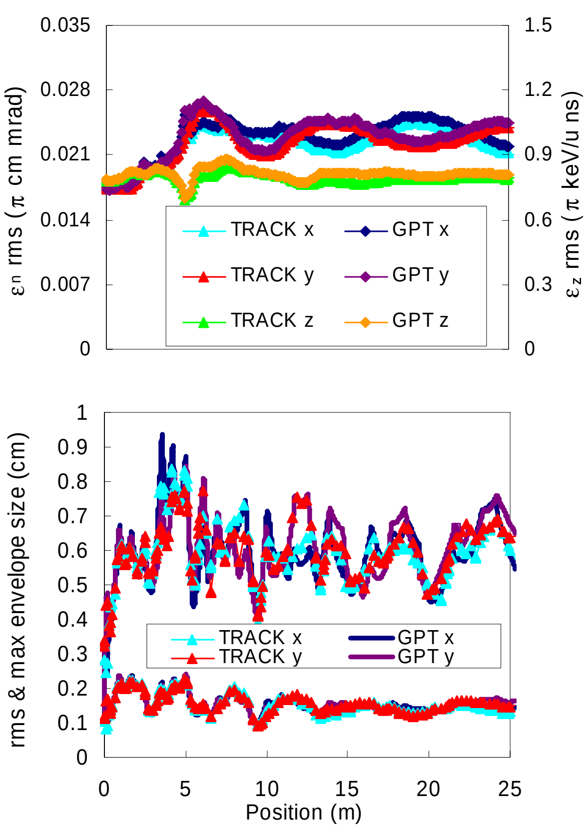

Figure 3: Beam dynamics simulation benchmark for a deuteron beam TRACK vs. GPT.

SUMMARY

- The SARAF linac beam dynamics evaluation predicts an efficient acceleration of both proton and deuteron beams up to 40 MeV.
- A TRACK vs. GPT benchmark show good agreement between the codes for both proton and deuteron beam dynamics simulations.
- The extended SARAF SC linac is a good candidate for an injector to the EURISOL driver with an average energy gradient of 2.0 MeV/m.

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