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HEAVY ION PHYSICS

Design, Modeling and Simulations in the RACE Project: Preliminar study for the development of a transport line.

C. O. Maidana[1], A. W. Hunt[1] , D. Beller[2] and K. Folkman[2]

[1] Idaho Accelerator Center & Idaho State University, Department of Physics, PO Box 8106, Pocatello, ID 83209 - USA

[2] Idaho Accelerator Center, Idaho State University, 1500 Alvin Ricken Drive, Pocatello, ID 83201 - USA

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Abstract. As part of the Reactor Accelerator Coupling Experiment (RACE) a set of preliminary studies were conducted to design a transport beam line that could bring a 25 MeV electron beam from a Linear Accelerator to a neutron-producing target inside a subcritical system. Because of the relatively low energy beam, the beam size and a relatively long beam line (implicating a possible divergence problem) different parameters and models were studied before a final design could be submitted for assembly. This report shows the first results obtained from different simulations of the transport line optics and dynamics.

Keywords: Reactor Accelerator Coupling ; RACE Project ; U.S. Advanced Fuel Cycle Initiative ; Computational Beam Physics
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1. Introduction

The RACE Project, which is being conducted within the U.S. Department of Energy's Advanced Fuel Cycle Initiative (AFCI), is a series of accelerator-driven subcritical systems (ADSS) experiments. These ADSS experiments will be conducted with a compact, subcritical assembly at Idaho State University's Idaho Accelerator Center (ISU-IAC), and with TRIGA reactors at the University of Texas at Austin and at the Texas A&M University. In these experiments, source neutrons will be generated by using electron accelerators to induce photonuclear reactions in heavy-metal targets. These accelerator/target systems produce a source of 10^{12} n/s, which will then initiate fission reactions in the subcritical systems [1].

The RACE Project can be divided into the linear accelerator and reactor systems.

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The linear accelerator that will be utilized, generates an electron beam of $25MeV$, with an average beam diameter of $2.5mm$ and unmeasured initial divergence. This beam must be transported over a distance of nearly $10m$ to the reactor's core, where the distance of the last drift could be as long as $4m$. As a consequence, different configurations of the electron optics and the beam dynamics associated to such designs must be studied.
To accomplish our objectives, we start our studies making use of the code COSY INFINITY [2], its differential algebra PDE solver and tracking tools. Here we emphasis in the fact that tracking is a precise tool to determine the particle trajectory (treating weak and strong non-linearities regime by equal). And even though, one can be tempted to use a perturbative approach, this gives a worse approximation of motion and fails when non-linearities become too strong.

2. General Considerations

Since the final accelator that will be utilized is unknown, we desire a beam transport system that is insensitive to the emittance of the electron beam. Hence, the first general problem to solve was to show that the transportation of the beam can be done even in the case of very large divergence, larger than $0.2rads$ in each phase space for the particles in the central trajectory. These divergences are much larger than would be encountered from an electron LINAC and demonstrate the insensitivity of the transport system on the emittance.
In electron accelerators the main source of non-linearities are the sextupoles used for chromatic corrections. Because of this, and because a small beam size incident on the target should be avoid, due to heat transfer concerns, a point to parallel system would be a better option than a point-to-point system. Also there is no need for a highly parallel beam, so, a single quadrupole doublet can be used.
This beam is injected to the beam line for its transportation to the subcritical systems. Since the beam travels over a long distance, its final size is governed by the angular divergence of the beam, so it is necessary to make this angular divergence in the beam line as small as possible.

3. General Problem: Point to parallel system

Because we want to work with different types of LINAC's, the relatively small magnetic quadrupoles and to avoid undesirable effects, we should inject the electron beam into the quadrupoles magnetic field with small or no drifts to generate a point to parallel system. Using COSY INFINITY [2], we simulated the behavior of the different elements, setting up a system of two magnetic quadrupoles with opposite sign of the magnetic field, drifts with lengths to be determine and adding constraints such as 4 m long final drift.
Because we are not focusing the beam, chromaticities and nonlinearities appear to

have a negligible effect. The fringe fields however do affect some of the off energy electrons adding some non-linearities that require further analysis. The tracking of particles launched with different initial coordinates and angles seems to be stable in both planes of the phase space. The Quadrupoles have a length of 13.4cm and aperture of 10cm, where the aperture is defined as the distance between the pole tip and the central trajectory. The results could be appreciated in Table 1, where we can see the magnetic field strengths for both quads. We also can notice that separation between quadrupoles should be minimum (drift of 0.022m) and the distance between the last quad and the final 4m beam line is 0.174m, leading to a final drift of 4.174m between the last optical element and the target. The beam half width is expressed using the root mean square definition, where 39% of the particles are contained in the matched ellipse.

Table 1. Numerical Values for a point-to-parallel system for the transport of the e beam with the minimum requirements accomplished.

Quadrupoles	**Total Length Quads plus drifts**
+0.0875 T −0.0925 T	4.4m

Beam half width rms	cm
(x, y)	$(1.195, 4.720)$

4. Particular Case: Varian Linac

After the general results obtained in the system explained above simulations for the transport line from a Varian Linac with an electron source of the Pierce type [3] was studied. The study was made with magnetic quadrupoles with a length of 13.4 cm and 2.6cm half aperture (d). Linear and non-linear studies up to third order with full fringe field computation were made. The worst case divergence for the beam at the entrance of the transport line was calculated to be 5$mrad$.
The divergence in both planes could be controlled well for the purpose. An increase in the nonlinearities and chromatic effects are expected when the fringe fields are included but such effects were not seen for this simple configuration. The fringe field falloff is based on the description of the s-dependence of multipole strengths by a six parameter Enge Function (Fig. 1). Using COSY's Differential Algebra based numerical integrator (Eight order Runge Kutta with automatic step size control); the resulting map including fringe field effects is computed using a default set of Enge coefficients [4].

Studying the trace of the transfer map (Table 2) and the tracking picture of the particles (Fig. 2 where the dynamical aperture is defined as the region of transition, in phase space, between apparently stable and unstable parts), we can see the system is stable in the range of injection with the exception of a few off energy electrons, but more detailed study is required about the vacuum system, concentration and

Table 2. Linear Transfer Map with Fringe Fields. System Stable. Explanation of the notation can be found in [2], where $a = p_x/p_0$, $b = p_y/p_0$.

(x,...)	(a,...)	(y,...)	(b,...)
-0.0583	-0.0941	0.0000	0.0000
11.3577	1.1757	0.0000	0.0000
0.0000	0.0000	0.0956	-0.1152
0.0000	0.0000	8.0056	0.8171
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

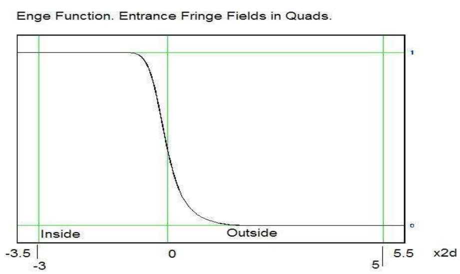

Fig. 1. Enge Function representing the Fringe Field falloff at the entrance of the Quadrupoles in units of full aperture ($D = 2d$).

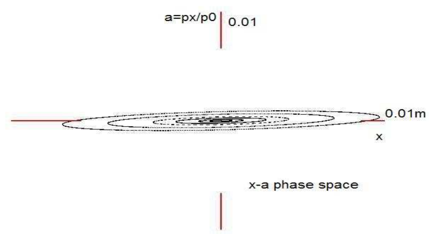

Fig. 2. Tracking Picture: x-a plane. One thousand particles tracked. Third order nonlinearities. Dynamic aperture: 12 mm.

identity of the particles remaining in the beam line and space charge effects after certain time of operation must be done. We should highlight that in the non-linear case, the question of stability is very difficult to answer due to the often non-existance of invariants. The numeric values obtained for the lattice are shown in Table 3.
The beam twiss parameters characterize the phase space ellipse where the particles are contained, satisfying:

$$\gamma x^2 + 2\alpha x a + \beta a^2 = \epsilon_x \tag{1}$$

$$\gamma y^2 + 2\alpha y b + \beta b^2 = \epsilon_y \tag{2}$$

These parameters should not be confused with the accelerator/cell parameters $(\alpha_i, \beta_i, \gamma_i)$ that characterize the invariant ellipse. The three quantities α, β, γ are useful to describe characteristics of the beam such as its width and stability.//

Table 3. (a) Parameters (SI Units). (b) The half aperture computed for the Quads is 2.6cm with a length of 13.4cm. (c) Dimensions of the beam at the end of the beam line for non-linear simulations (third order), and fringe field computation.

	Beam Twiss and Accelerator Parameters	Drift	Length (m)
Alpha	0.0026; 0.743	1	0.1024
Beta	0.0003; -13.69	2	0.3451
Gamma	0.0253; -0.11	3	9.0000
	$\alpha_i\beta_i - \gamma_i^2 = 1$	Total	9.7155

(a)

Quads	Strength (T)
1	-0.0123
2	+0.0125

(b)

Beam width 95% -x	0.081cm
Beam width 95% -y	0.230cm

(c)

5. Conclusions

Different configurations have been studied for the transportation of the electron beam from the Linac to the Reactor. Here we have shown one of such configurations, where the transport could be done even for a relatively large and unknown divergence with little knowledge of the injector linac. The results of the general simulations were applied for the design of the transport line using values of a commercially available LINAC.

The system contains just a quadrupole doublet and allows the transportation of the electron beam for a total distance of 9.71m respecting the constraint of 9.3m for the final beam line. The beam size is small enough to not interfere with the reactor elements and the design is simple and not difficult to implement. Non-linearities don't seem to have any important effect and fringe fields seems to behave well. A general diagram of the system is shown in Fig. 3.

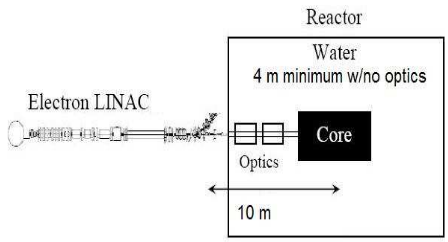

Fig. 3. Diagram of the system.

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Notes

E-mail: maidana@physics.isu.edu, huntalan@physics.isu.edu

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