BEAM DYNAMICS STUDY OF THE HIGH-POWER ELECTRON BEAM IRRADIATOR USING SUPERCONDUCTING CAVITY

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Abstract

At KEK, a compact 10 MeV, 50 mA accelerator design was proposed for irradiation purposes. The current design includes a 100 kV DC thermionic electron gun with an RF grid, a 1-cell normal-conducting buncher cavity, and a Nb3Sn superconducting cavity that accelerates the beam to final energies of 10 MeV. The goal of this beam dynamics study is to suppress the beam loss (to the ppm level) in order to reduce the thermal load due to the beam hitting the cavity. Especially, the initial electron energy (100 keV) is low and the space charge effect is large. The main challenges are to optimize the beam shape without beam losses and to simultaneously control and transport multiple parameters of the accelerator components. Here, we present a method for optimizing beam transport and report the results of optimizing beam transport using this accelerator design.

INTRODUCTION

At the Compact Energy Recovery Linac (cERL) at KEK [1], an irradiation beam line was constructed and successfully commissioned [2]. Following the recent trend in accelerator science to design a compact high-current irradiation-type accelerators [3], [4] and based on the results of irradiation experiments at the cERL [5], we aim to develop a 50 mA electron beam irradiation facility working at the total beam energy of 10 MeV.

High-current beam acceleration can be achieved by using a superconducting cavities (SCs). In recent years, niobium tin (Nb_3Sn) accelerating cavities have attracted attention as next-generation accelerating cavities to replace Nb accelerating cavities. A higher transition temperature (18.3 K) of Nb_3Sn makes it possible to operate the beam using only a simple small refrigerator instead of the conventional large He refrigerator. That allows to design a compact facility. The conceptual design of the proposed machine with special emphasize on the Nb_3Sn SCs implementation is given in [6].

The overall design of the machine assumes the electron beam to be of 10 MeV and 50 mA. Figure 1 shows a schematic of the entire system. It includes: an injector part with an electron gun of specific design, superconducting cryomodule, and an irradiation part, so that the machine can irradiate a large current beam. In order to evaluate the acceleration acceptance of an electron beam irradiation facility, we performed a three-dimensional particle tracking including the space-charge effect with the acceleration cavity system consisted of a buncher, two 1-cell SCs, and five 2-cell SCs. We found solutions to mitigate the beam loss applying a multi objective optimization. In the present study the beam dynamics issues associated with the irradiator design are discussed in details.

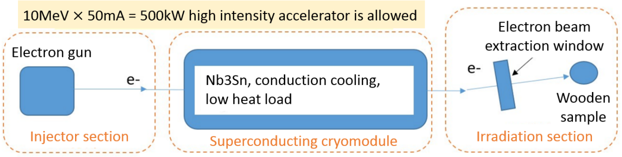

Figure 1: Conceptual design of 10 MeV, 50 mA accelerator using Nb_3Sn superconducting cavity.

SYSTEM OVERVIEW

The electron gun is a 100 kV thermionic DC gun with an RF grid [7] that produces a repetitive longitudinally packed pulsed electron beam at 650 MHz. After that, we assumed to compress the pulsed beam in the beam direction in a 1-cell normal-conducting buncher cavity, and then accelerate it to 10 MeV using two 1-cell SCs ($\beta = 0.8$)[1] [8] and five 2-cell SCs. The RF frequency of all SCs is 1.3 GHz. The buncher cavity operates at 650 MHz. Two solenoids were installed before and after the buncher to provide transverse focusing. In the irradiation section there are two quadrupoles placed 1 m downstream the cryomodule to adjust the beam size. Then the beam is bent downward by the dipole and reaches the extraction window (See Fig. 2).

Originally we used a 1.3 GHz buncher cavity identical to those at cERL. The beam velocity-modulated in the buncher cavity compresses the bunch length to about 30 ps at the first SC position (Z 2.4 m). This corresponds to a phase width of about ±14 degrees for an acceleration frequency of 1.3 GHz. Bunch compression is seen at 1.3 GHz with RF phase nonlinear components and can also be a source of loss. It is possible to reduce these losses with a collimator, but it is difficult to compress the 100 ps bunch length with 1.3 GHz cERL buncher. Therefore, we redesign and apply the buncher cavity based on 650 MHz to increase the RF phase range and effectively perform bunch compression.

The beam energy is accelerated up to 10 MeV by approximately 2 MV per cavity with five 2-cell cavities, which is feasible with Nb_3Sn. When accelerating in the 2-cell SC cavity after passing through the buncher, the acceleration does not occur immediately. This is because the energy of the beam (100 keV) is in the non-relativistic region, and the speed of the beam is not close to the speed of light. The 2-cell cavity does not accelerate properly due to the mismatch of the cavity cells, resulting in loss of energy. In

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[1] Low-β resonators are just cavities that accelerate efficiently particles with velocity $\beta < 1$.

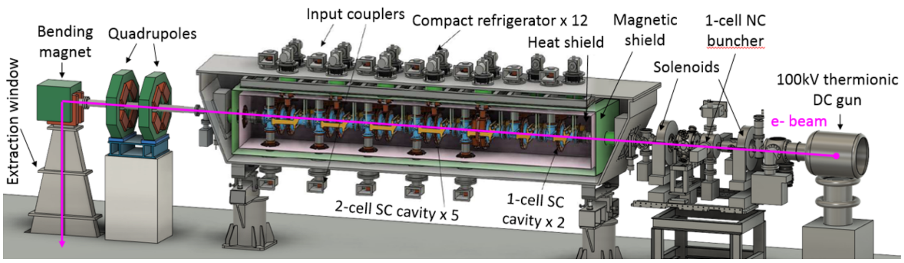

Figure 2: Layout of accelerator components.

order to eliminate cavity mismatch, each cell of the 2-cell cavities is made independent and the beam is slightly pre-accelerated by two 1-cell ($\beta = 0.8$) cavities. As the graphs of the minimum speed of transportation (see Fig. 3) read, if the minimum velocity is less than zero, the beam will run in the opposite direction, and it will be impossible to use it as an accelerator. If the amplitude of the cavity is increased too much, it will enter a region where the beam cannot be accelerated properly. The region that satisfies the condition that the energy finally rises without reverse run is wider for the $\beta = 0.8$ cavity.

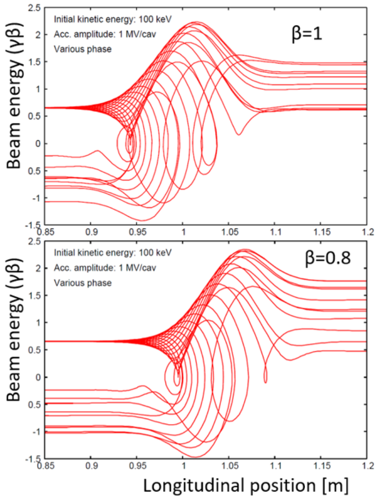

Figure 3: Minimum speed of transportation for $\beta = 1$ 1-cell cavity (top) and $\beta = 0.8$ 1-cell cavity (bottom).

BEAM DYNAMICS

Simulation Setup

To study the beam dynamics in the compact Nb_3Sn accelerator, the injector part and the superconducting cryomodule were introduced into simulation. The electron gun distribution was included in this calculation, and the beam transport calculation was performed with the layout shown in Fig. 4. We started the calculation by giving the particle distribution of the 100 keV beam at the cathode of the electron source. For the electron gun, solenoids, buncher and 2-cell cavities simulation the 1D field distributions of those from cERL were used. For the 1-cell cavity, the gap length of the TESLA cavity was reduced $\beta = 0.8$, and the 1D field distribution was used. General Particle Tracer [9] was used for the calculation. For the initial beam parameters please refer to Table 1.

Table 1: Initial Parameters of Electron Beam

Parameter	**Value**
Bunch charge	77 pC (50 mA at 650 MHz)
Number of particles	10^6 in tracking, 2000 in optimization
Electron gun energy	100 keV
Cathode size	5.73 mm (uniform)
Initial bunch length	100 ps (Gaussian $\pm 4\sigma$)

The motivation of the simulation study was the following. Assuming an initial beam, optimization was performed by a simulation including the space charge effect of a multi-particle beam, so that the beam parameters at the exit of the accelerator were confirmed.

The electron emission surface of the hot cathode is approximately 10 mm, and the mean transverse energy (MTE) is 0.5 eV is used to generate a beam. The beam diameter at the electron gun exit is approximately 8 mm at its maximum. To control the space charge effect solenoid focusing is introduces into the design. Thus, the first solenoid focuses the beam, so that the beam diameter becomes 10 mm or less at the collimator position. Then the beam expanding on passing through the buncher cavity is focused again by the second solenoid. The beam size reaches the maximum diameter of 28 mm at the second solenoid, which is smaller than the beam pipe diameter of 60 mm. Therefore, it can be inferred that the beam loss at this location can be sufficiently suppressed. Another point is that the essential beam size relaxation at the second solenoid location allows in the following effectively shrink the transverse beam size in the cryomodule.

Optimization Strategy

The optimization strategy was: for given layout of the accelerator, it was necessary to adjust the amplitudes and phases of cavities, and strengths of the solenoids to find the optimum conditions. Namely, to reach the target energy (10 MeV), the energy width of the emitted beam was required to be narrow, so that there was no loss during transportation. For low velocity beams the parameters are intricately corre-

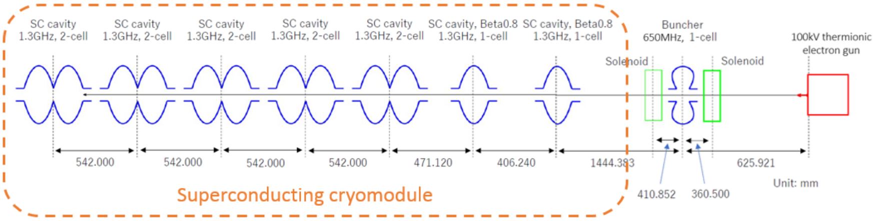

Figure 4: Layout of the injector and the superconducting cryomodule.

lated. In addition, the influence of the space charge effect is also large. For this reason, simultaneous optimization of multiple parameters was necessary.

Optimization targets were the following: (1) to minimize final bunch length; (2) to minimize maximum beam size during transportation; (3) minimize final energy spread; (4) minimize maximum amplitudes of the cavities; (5) final energy should be reached. Then the distribution of 1,000,000 particles was set up, and the magnetic field of the solenoids on the transport of the beam, the acceleration voltages and the phases of the buncher and SCs were set as free parameters. The beam energy is accelerated up to 10 MeV by approximately 2 MV per cavity with five 2-cell cavities. The acceleration gradient is below 10 MV/m. Bayesian optimization toolbox [10] and solver based on multidimensional Newton-Raphson algorithm [11] were used independently for the optimization to reach a reliable model of the accelerator. Their results converged. Then the acceleration voltages and phases of the buncher and SCs were confirmed. Together with it, the solenoids suppressed beam divergence due to the large initial space charge effect. As the final result of the optimizations, it was possible to transport the beam without hitting the 70 mm beam pipe.

Results and Discussion

The final results of the optimization procedure are summarized in Table 2. The evolution of the beam parameters is shown in Fig. 5.

Table 2: Optimized Parameters

Cavity name	**Amplitude MV/cav.**	**Crest ϕ deg.**	**ϕ off. deg.**
Buncher	0.0024	-58.8	-90.0
INJ1 (1-cell)	0.36	-62.8	1.0
INJ2 (1-cell)	0.35	-127.9	0.0
INJ3 (2-cell)	1.19	145.4	-85.9
INJ3 (2-cell)	1.88	-42.2	4.2
INJ3 (2-cell)	1.89	-174.5	0.0
INJ3 (2-cell)	1.90	56.4	0.0
INJ3 (2-cell)	1.91	133.6	0.0
Solenoid name	**Current (A)**		
SL1	2.75		
SL2	1.24		

Let's discuss the major knobs that could be used to control and to tune the beam. To control the bunch length effectively a combination of the buncher phase and the first 2-cell cavity phase offset is used in the model. Buncher cavity involves so-called "zero-cross bunching" to compress the bunch and to leave its phase space linear. Then the bunching process launched at the buncher is stopped using a velocity bunching technique in the first 2-cell cavity (phase offset added to the crest phase). The bunch length behaviour is given in Fig.5 on top. Target compression achieved (see Table 3).

A key knob to control the transverse beam size (Fig.5 in the middle) is solenoid focusing. As it was mentioned above, the relaxation of the beam size at the location of the second solenoid (after the buncher cavity) is crucial for the minimization of the beam size in the presence of the strong space charge force. The cavity focusing effect turned to make a small impact into overall beam size minimization. Nevertheless, the beam size at the exit of the cryomodule is good (5.41 mm). Additional tuning available through 2 quadruples at the irradiation section.

Since the main acceleration occurs in five 2-cell cavities, energy tuning knobs are naturally amplitudes of those cavities. One should keep in mind, that the first 2-cell cavity is responsible for the velocity bunching. Therefore the fine energy tuning should be done via rest four 2-cell cavities. Let us remind that 1-cell cavities are indispensable for the slight acceleration of the 100 keV beam coming from the electron source. This stage is of a great importance to reach the final energy of 10 MeV with a cryomodule. Another point is on the energy spread behaviour. It increases after accelerating in two 1-cell cavities since those oppose a considerable fringe field effect on the beam as reads the energy graph in Fig.5 in the bottom.

SUMMARY

Assuming an initial beam distribution, we performed three-dimensional beam tracking including the space charge effect. As a result of optimization by two independent methods mentioned above, the result of transportation with no loss was obtained. Based on the above calculation results and on the design of the injection section, Nb_3Sn cryomodule, and irradiation section [6], we designed the entire irradiator. By using the Nb_3Sn cavities, it is possible to accelerate 10 MeV and 50 mA without loss, and a very compact irradiation accelerator can be achieved.

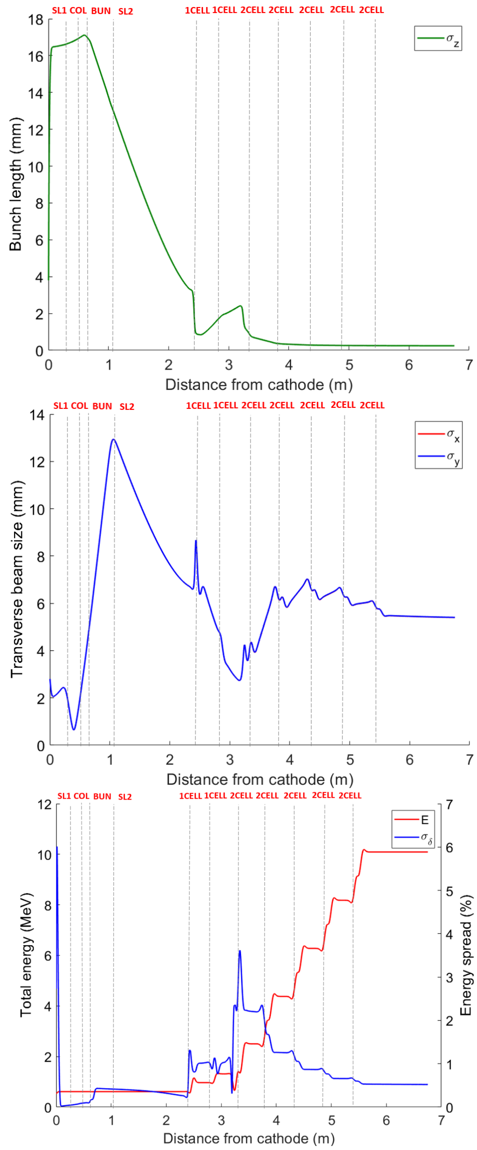

Figure 5: Time evolution of the beam parameters through the transportation line: rms bunch length (top); rms transverse beam size (middle); energy and energy spread bottom).

Table 3: Beam Parameters at the Exit of the Cryomodule

Parameter	Value
Total energy	10.09 MeV
Rms bunch length	0.29 mm / 0.86 ps
Rms transverse beam size	5.41 mm
Energy spread	0.52%

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