A CONCEPTUAL DESIGN STUDY OF SUPERCONDUCTING PROTON LINEAR ACCELERATOR FOR NEUTRON SCIENCE PROJECT

Y. Honda[+], K. Hasegawa, N. Ouchi, J. Kusano, and M. Mizumoto
JAERI Proton Accelerator Laboratory, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan

Abstract

The Neutron Science Project (NSP) at Japan Atomic Energy Research Institute (JAERI) calls for an 8MW cw and pulsed proton linac. The current JAERI design proposes a superconducting proton linac for the energy range from 100MeV to 1.5GeV. Here, the present linac structure and the beam simulation are described.

1. INTRODUCTION

The NSP at JAERI has been proposed for the research of nuclear transmutation technology and basic science with a spallation neutron source [1]. The project calls for an 8 MW proton linac which accelerates 5.3mA average-current cw and pulsed beams up to 1.5GeV.

The superconducting (SC) rf-cavity structure is the main option for the energy part from 100MeV to 1.5GeV because by using the SC structure, less power is consumed in cw operation than by using a normal conducting (NC) structure. The less risk of beam loss for the larger bore size of the SC structure is also expected.

At present, the SC linac is composed of 8 β sections. Each section has identical 5-cell cavities optimized for a geometrical velocity β_g described in Figure 1 with surface peak field (Epeak) of 16MV/m. The total number of cavities is 284, and the length of the SC linac is 690m. The lattice type is the doublet (FDO) focusing with 2 cavities per lattice. The quadrupole magnet gradients are determined with the equipartitioned condition and the matched envelope equations for minimum emittance growth [2]. The transverse and longitudinal emittance growth in the simulation without any errors are both 1% as described Table 1. The performance of the SC linac with the RF amplitude and phase variations and the quadrupole magnet misalignment was also studied in this proceeding.

2. DESIGN FRAMEWORK

2.1 *β sections and β_g of cavities*

The procedure for the determining β sections and the β_g of cavities is derived in the view of the bunch phase slip with respect to the RF phase in the cavity. Because one type of cavity is used in a β section for some economical reasons, the velocity of bunch is not always synchronous to the RF in the cavity and the phase slips occur. If the electrical field on axis in a cavity is described as a sine or cosine curve, to find the minimum phase slip is to find the β sections which have the same maximum phase slip derived from the equations (1), and the β_cs of each section which has the least maximum phase slip.

$$\beta_1=(\beta_0^{\,n-1}\,\beta_n)^{1/n},\qquad \beta_k=\beta_1\,(\beta_1/\beta_0)^{k-1}\ (k=2,\dots,n-1)$$
$$\beta_{gk}=\beta_{g1}\,(\beta_1/\beta_0)^{k-1}\quad (k=2,\dots,n)\qquad (1)$$

where

n:No. of sections , $\beta_0,..,\beta_n$:boundaries of β sections,
$\beta_{g1},..,\beta_{gn}$:geometrical velocity of the cavity in the sections.

In real design, some adjustments of β sections and β_g are needed because the electrical field on axis in the end cell is very different from a sine or cosine curve for the leakage electrical field from the cavity to the beam pipe.

2.2 *Beam Dynamics Parameters*

For the design of the linac structure, the beam dynamics parameters of the cavity have to be prepared. Cavities of several β_g with 5 cells are designed using the electro-

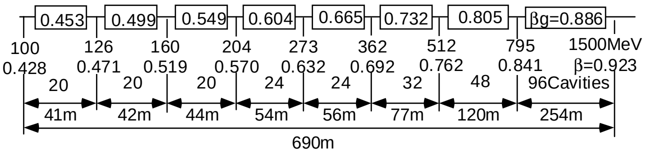

Figure 1. Linac structure

Table 1. Basic SC linac parameters

Ion	H^-, H^+
Frequency	600 MHz
Energy	100 to 1,500 MeV
Final Beam power	8 MW
Pulsed peak beam current	30 mA
CW beam current	5.3 mA
Cells per cavity	5
Cavities per lattice	2
Quadrupole lattice type	Doublet (FDO) focusing
Synchronous phase	−30 degrees
Surface peak field (Epeak)	16 MV/m
Eacc	2.4 to 8.0 MV/m
Number of β sections	8
Number of cavities	284
Length	690 m
Trans. phase adv. per period [degree]	64 to 16(zero current: σ_{to}) 39 to 9 (space charge: σ_t)
Long. phase adv. per period [degree]	48 to 11(zero current: σ_{lo}) 27 to 6 (space charge: σ_l)
σ_t/σ_{to}, σ_l/σ_{lo}	0.6, 0.6
Trans. rms Emit.(no error)	0.0400 to 0.0404 π cm-mrad
Long. rms Emit. (no error)	0.421 to 0.425 π MeV-deg

[+] Mitsubishi Heavy Industries Ltd., 10 Oe-cho, Minato-ku, Nagoya-shi, Aichi-ken, 455-8515, JAPAN magnetic field-solver codes SUPERFISH and MAFIA to obtain fitting functions for the beam dynamics parameters which depend on β_g from 0.428 to 0.923. The derived fitting functions are the electrical field on axis, the surface Epeak/average field (E_0), the cell length, and the R/Q of the cavity. The transit time factors of cavity and cell are derived from the fitting function for the electrical field.

The comparatively larger bore of the cavity results in a leakage electrical field to the beam pipe and the leakage field may influence to the longitudinal beam dynamics. Here, some part of the beam pipe is treated as a virtual cell.

2.3 The lattice

The present lattice type is the doublet (FDO) focusing with 2 cavities per lattice as described in Figure 2. Because the output beam from this linac is injected into the storage ring, the longitudinal emittance growth is strictly restricted. The quadrupole magnet gradients of this linac are determined with the equipartitioned condition and the matched envelope equations for minimum transverse and longitudinal emittance growth [2]. The transverse wave numbers under the equipartitioned condition, which give the quadrupole magnet gradients, are derived from the matched envelope equations with the transverse and longitudinal emittances, the beam current, and the longitudinal wave number [3].

The quadrupole magnet gradients are restricted by the neutralization of H^- beams by magnetic stripping [4]. For example, the magnet strength of 4.2T gives the H^- loss rate of 10^{-8}/m at 1.5GeV. The length of the magnet is determined from the restriction.

2.4 The linac structure design

To obtain the linac structure design, the reference of linac structure is prepared. The reference has each 5-cell cavity synchronous to the velocity of input bunch with the surface Epeak of 16MV/m. The synchronous phase of the reference linac is set to –30 degrees. The number of cavities becomes 281 so that the reference has 281 β sections. The length of the reference becomes 680m.

The number of β sections is determined to make the rms emittance and the length of the linac almost the same as those of the reference. Linacs with 5 to 9 β sections are studied under the following conditions.

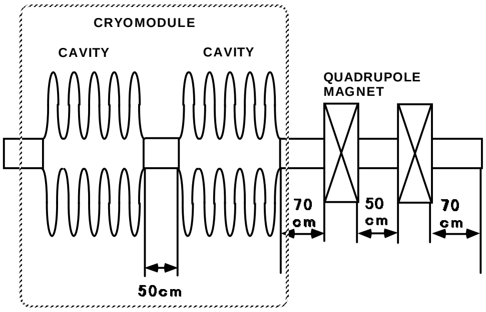

Figure 2. The lattice structure

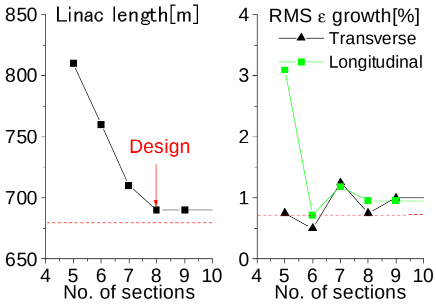

Figure 3. The study of β sections

(1) β sections, beam dynamics parameters and lattice are determined with the procedure written in the previous subsection.

(2) The number of cavities per klystron is set to 4. One of 4 cavities under a klystron has the surface Epeak 16MV/m and the 4 cavities are fed with the same RF power.

(3) The phase slips make the phase condition worse in the end cell and the virtual cell. The synchronous phases are determined to make the longitudinal rms emittance almost the same as that of the reference.

(4) The length of the quadrupole magnets in the last β section is set to 35cm and that of other sections is set to 30cm for an H^- loss rate under 10^{-8}/m at 5cm from the beam axis.

The result of the study described in Figure 3 shows that the length and emittance of the linacs with over 8 β sections are almost the same as those of the reference. At present, the linac with 8 β sections described in Table 2 is selected as the main option. The linac with 8 β sections has 284 cavities and the length of 690m. The magnet gradients are 3.6 to 5.5 T/m low enough for the given H^- loss rate. The wave numbers transit smoothly at the edge of the section as described in [3].

3. BEAM SIMULATION

The simulation result using the modified PARMILA code without any errors is shown in Figure 4. The beam current is set to 90mA(=30mA×3) because there is 3 times frequency jump between the DTL and the SC linac. The transverse rms beamsizes are 1.6 to 3.1mm. They decrease first and then increase a little with periodical oscillation and betatron oscillation for some mismatches. The longitudinal rms beam size decreases from 3.1 to 1.1mm with oscillation in the first part because of some mismatches. The transverse and longitudinal rms emittances at the input to the SC linac (100MeV) were set to 0.0400 π cm-mrad and 0.421 π MeV-deg, respectively. The corresponding rms transverse and longitudinal emittances at 1.5 GeV were 0.0404 π cm-mrad and 0.425 π MeV-deg, respectively. The 1% growth of the rms emittance is as a result of the equipartitioned condition.

The performance of the linac with the RF variations

Table 2. Results with RF amplitude and phase errors

Amplitude/phase errors	Long. rms ε growth		Bunch center output energy spread(1σ)
	Ave.	Max.	
±1.0%/±1.0deg.	1%	2%	0.8MeV
±2.0%/±2.0deg.	2%	9%	1.9MeV
±3.0%/±3.0deg.	12%	35%	3.3MeV

Table 3. Results of 20 simulations with a set of errors

Trans. rms ε growth	Ave. 4%, Max. 8%
Long. rms ε growth	Ave. 2%, Max. 5%
Bunch center displacement from axis	Ave. 5.21mm, Max 8.39mm
Bunch center output energy spread	0.8MeV(1σ)

and quadrupole magnet displacement was studied. The errors were taken from a uniform distribution within the specified limits. Twenty simulation runs were done in each case. From Table 2, the amplitude and the phase errors must be within ±1.0% and ±1.0degree, respectively for the $\Delta E/E$ at output within ±0.2%. For ±0.10, ±0.20, and ±0.30mm quadrupole displacement, the bunch shifts were 5.08, 8.37, and 13.77mm in average and 6.59, 12.13, and 26.57mm in maximum, respectively. For ±0.10, ±0.15, and ±0.25degrees quadrupole magnet roll errors, the transverse emittance growth were 2, 4, and 8% in average, and 4, 6, and 15% in maximum, respectively. From these results, the following set of error tolerances that include RF amplitude and phase variations, and magnet misalignment in displacement, tilt and roll was chosen.

- RF amplitude/phase errors, ±1.0%/±1.0deg.
- Quadrupole magnet displacement error, ±0.10mm
- Quadrupole magnet tilt/roll errors, ±0.25deg./±0.15deg.

The results described in Table 3 do not show any significant effect to the linac and the storage ring. The typical output phase-space distributions with and without errors are shown in Figure 5. The distribution has a little more particles on the edge and the centroid of the beam-bunch is slightly shifted compared with the error-free case.

4. CONCLUSION

The present SC linac with 8 β sections is designed in the view of the bunch phase slip with respect to the RF phase in the cavity and the lattice under the equipartitioned condition. This linac is an effective option for its shorter length and lower emittance growth.

5. REFERENCES

[1] M. Mizumoto, et al., ‘A PROTON ACCELERATOR FOR THE NEUTRON SCENCE PROJECT AT JAERI’, in these proceedings.

[2] R. A. Jameson, AIP Conference Proceedings 279, 969, 1993, ed. J. S. Wurtele.

[3] K. Hasegawa, et al., ‘BEAM DYNAMICS STUDY OF HIGH INTENSITY LINAC FOR THE NEUTRON PROJECT AT JAERI’, in these proceedings.

[4] Jason J.A, et al., ‘NEUTRALIZATION OF H^- BEAMS BY MAGNETIC STRIPPING’, IEEE TRANS. ON Nucl. Sci, NS-28, 2704, 1981.

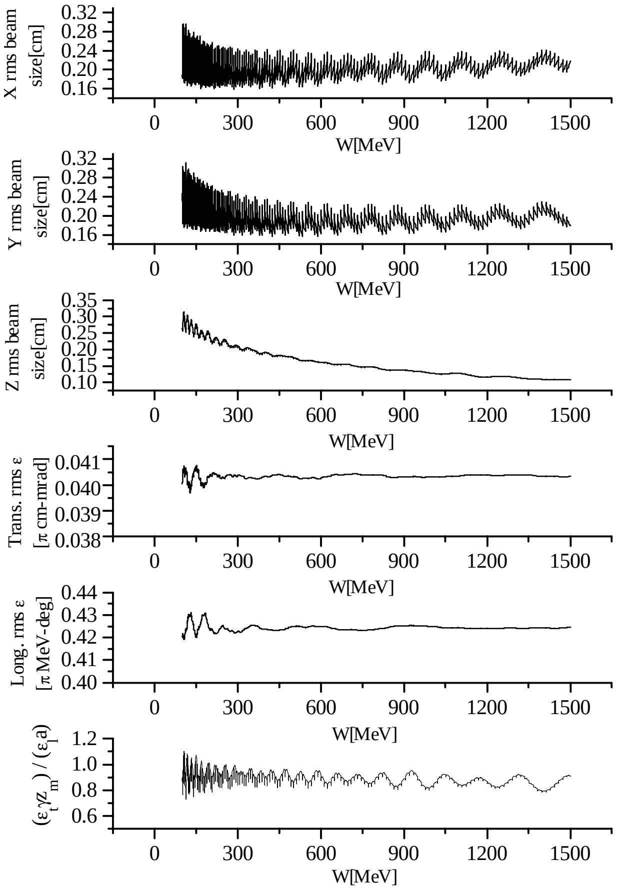

Figure 4. Rms beam sizes, emittances, and the relation between them for 90mA current without any errors

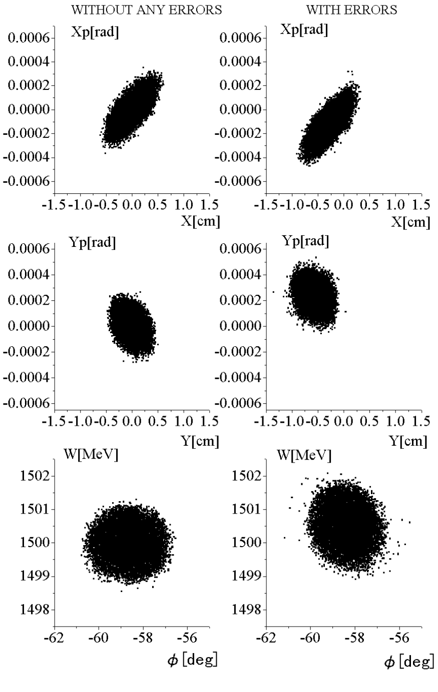

Figure 5. Output phase space distributions at 1.5GeV without any errors and with a set of errors.