# SYSTEM DESIGN OF A SUPERCONDUCTING LINAC FOR THE HIGH-INTENSITY PROTON ACCELERATOR PROJECT (KEK/JAERI JOINT PROJECT)

Kazuo Hasegawa* and Nobuo Ouchi, JAERI, Tokai-mura, Ibaraki-ken,319-1195, Japan
Ken Mukugi, Mitsubishi Electric Co., Kobe-shi, Hyogo-ken, 652-8555, Japan

*Abstract*

System design of a superconducting (SC) linac has been carried out for the KEK/JAERI joint project for high-intensity proton accelerator. The energy range of the SC linac is 400 to 600 MeV. The cavity frequency is 972 MHz. The geometrical beta of the cavity is synchronized with the proton velocity to minimize a phase slip in the cavity. The peak surface field of the cavity is up to 30 MV/m. Two cavities are laid in a doublet focusing lattice. The number of module is 11 and the length of the SC linac section is 58 m. The present SC linac design and the beam simulation results are presented.

## 1 INTRODUCTION

The Japan Atomic Energy Research Institute (JAERI) and the High Energy Accelerator Research Organization (KEK) are proposing "the Joint Project for high-intensity proton accelerator facility"[1] by merging their original Neutron Science Project (NSP)[2] and the Japan Hadron Facility Project[3,4]. The facility will be constructed at the JAERI-Tokai site in Ibaraki-ken. The accelerator complex consists of 600 MeV linac, 3 GeV rapid cycling synchrotron (RCS) and 50 GeV synchrotron. The linac plays two roles; one is to inject the beam to the RCS, and the other is to provide the beam to the ADS. The high energy part of the 600 MeV linac uses superconducting (SC) cavities, which can be a prototype of the future CW accelerator for the ADS applications.

## 2 SC LINAC DESIGN

Since the 50 GeV synchrotron requires several-GeV injection beams, the accelerator scheme is based on the RCS injection in contrast to the scheme of a full-energy linac and a storage ring option as the SNS or the ESS project. The $H^-$ beam from the linac is injected to the RCS during 0.5 msec, which is limited by the flat bottom of the sinusoidally varying magnetic filed of the 25 Hz RCS.

Figure 1 shows the block diagram of the linac[5]. A peak current of 50 mA for $H^-$ ion beam of 0.5 msec pulse duration is accelerated at a repetition rate of 50 Hz. The linac uses normal conducting cavities up to 400 MeV. By using an ac switching magnet at 400 MeV, the half (25Hz) of the beam from the linac is injected to the RCS, while the other half is further accelerated up to 600 MeV by the SC linac simultaneously. An rf frequency of 324 MHz has been chosen for low-energy structures and 972 MHz for high-energy structures.

Figure 2 shows a schematic view of the lattice structure and Table 1 summarizes the parameters of the SC linac. The SC linac consists of cryomodules containing two 9-cell 972 MHz niobium accelerating cavities. Quadrupole magnets provide focusing with a doublet lattice located in a room temperature region between cryomodules; these regions also contain beam diagnostics and vacuum systems.

According to the cavity developing group, changing the cavity shape would not increase the construction cost very much. Therefore, to minimize a phase slip, we have taken

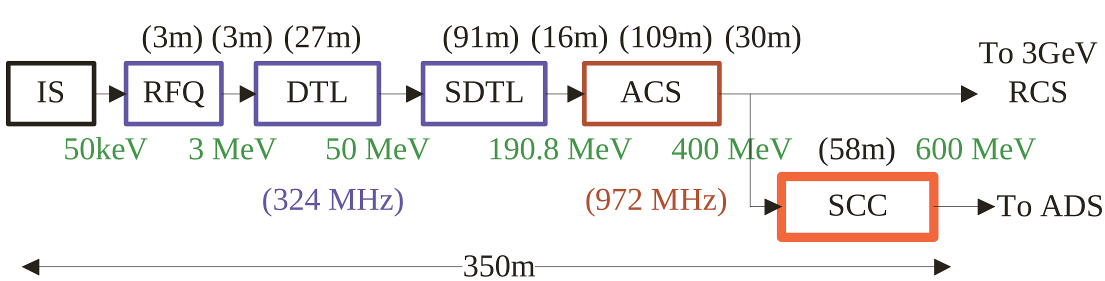


Fig.1 Block diagram of the linac

IS: Ion Source, RFQ: Radio Frequency Quadrupole linac, DTL: Drift Tube Linac, SDTL: Separated-type Drift Tube Linac, ACS: Annular Coupled Structure linac, SCC: Supercnducting Cavity linac

*hasegawa@linac.tokai.jaeri.go.jp

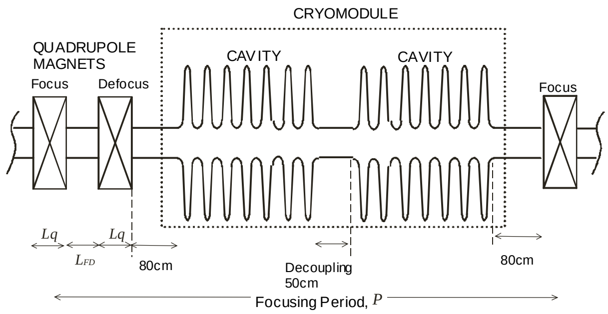


Fig.2 Lattice structure of the SC linac

Table 1 SC linac parameters

| | | |
|---|---|---|
| Energy | 400-600 | MeV |
| Frequency | 972 | MHz |
| Cavity beta | 0.717-0.789 | |
| Section Length | 57.7 | m |
| E0 | 12.5-14.3 | MV/m |
| Eacc | 9.7-11.1 | MV/m |
| Number of Cavities | 22 | |
| Sync. Phase | -30 | deg |
| Total RF power @50mA | 10 | MW |
| Number of Klystrons | 11 | |
| Aperture Radius | 45@cavity 30@Q | mm |
| Number of cells | 198 | |

proton velocity synchronous cavities as a reference design. The cavities in one cryomodule consist of identical cells.

Based on the quench condition experiments for the high-field SC cavities, the maximum accelerating field is determined by a multipacting referred to the maximum magnetic field. In the present design, maximum magnetic field is set to be 525(Oe), which corresponds to the peak electric field of 30 MV/m for about $\beta$=0.7 cavities. Average synchronous phase is –30 deg.

When we accelerate negative hydrogen beams, we have to consider the Lorentz stripping: an electron of $H^-$ is detached in the magnetic field. There is a sharp rise of the loss rate as the magnetic field increases. The curve in Fig. 3 is the field limit at the beam duct radius of 3 cm and the loss rate of $10^{-8}$(/m). The Q-magnet length and the drift length have been designed within the field limit. Figure 4 shows the zero-current transverse and longitudinal phase advance. In this design, transverse phase advance at zero current is set to be 85 deg.

Total length and the number of the cyromodules are 58 and 11, respectively. We have used 11 groups of cavity types, and two groups of cryomodule in length for the spare modules or replacement convenience. If we use one-beta cavity concept during the SC linac, the number of module is 12 and a little more emittance growth is observed than that of the synchronous cavity concept under the mismatch input condition.

Two cavities in the cryomodule are controlled by one rf system. The vector sum control technique of two cavities has been applied in the rf control simulation study[6]. The cavity field stabilization is performed by the feed back control. The feed forward control provides the waveform and the beam loading compensation.

## 3 BEAM SIMULATION RESULTS

The beam simulations are carried out with the PARMILA code, which is modified for the superconducting linac design. The simulation starts with 10000 macroparticles in a six-dimensional water bag distribution. The 90 % emittances and RMS beam sizes along the SC linac are shown in Fig. 5. Emittance growth rates in the transverse and the longitudinal directions are 1.8 % and –0.5 %, respectively. The beam sizes are nearly constant, because the energy range is not so wide in this SC linac. Ripples of the transverse sizes are due to the modulation of the doublet focusing system. The RMS beam size in the transverse direction is 0.2 cm at the highest. The bore radius is 3 cm at the quadrupole magnets and 4.5 cm at the cavities. The ratio of bore radius to RMS beam size is greater than 15, which would

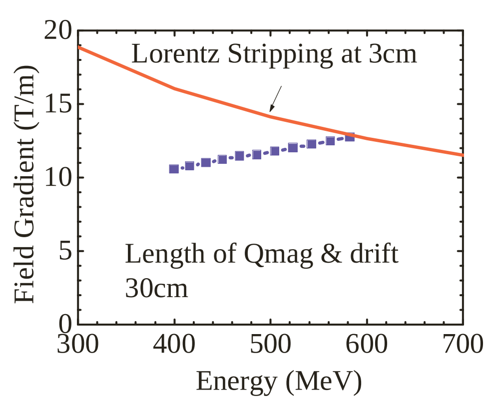


Fig.3 Field gradient of the Q magnet and the Lorentz stripping limit

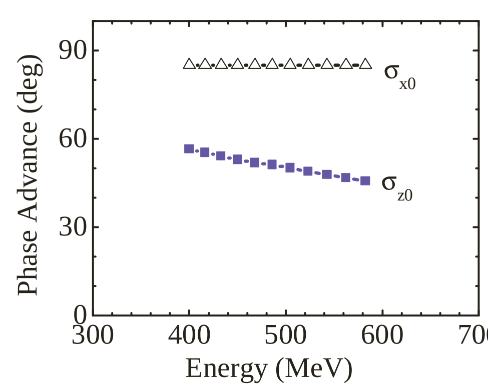


Fig.4 Zero current phase advance
$\sigma_{x0}$:transverse, $\sigma_{z0}$:longitudinal

be enough for the beam loss considerations in the linac.

Figure 6 shows the phase space x-x', y-y' and W-phi projections, and the spatial x-y projection at the exit of the linac. These calculations show that the beam is well behaved and the energy spread is about ±1 MeV.

One of the upgrade paths to increase the beam power is to use the SC linac as an injector of the RCS or storage ring. The RCS or storage ring requires an injection beam quality with a momentum spread at the order of ±0.1 %, which refers to the energy spread less than about ±1 MeV. The energy spread shown in Fig. 6 can be reduced by a debuncher cavity. The centroid energy jitter due to the rf phase and amplitude control error brings an uncontrollable energy spread. Therefore, these effects have been evaluated in the beam simulations. Phase and amplitude errors of the cavity field have been introduced independently. The 100 cases of the calculations have been carried out and average output energies are evaluated statistically. The energy jitter is obtained using the standard deviations of the histogram. The values of standard deviations at ±1 deg. phase error and ±1 % amplitude error are ±0.26 MeV and ±0.24 MeV, respectively. The total energy spread is estimated to be ±0.41 MeV, which corresponds to be the standard deviation of $\Delta p/p=\pm 0.03$ % including the ±0.2 MeV energy spread from the injector part. After the confirmation of the beam quality as well as the pulse mode operation control technique, the SC linac will be an injector to upgrade the beam power in the future plans of the project.

## 4 MATCHING SECTION

A matching section between the previous ACS linac and the SC linac is studied with the TRACE-3D code. Since the ACS and the SC linacs have the similar doublet focusing lattice, the matching section uses also the doublet scheme. To adjust the beam line length to the parallel beam line to the RCS injection line, the matching section has 7 doublet lattices. To obtain the longitudinal matching, a buncher cavity with a gap voltage ($E_0TL$) of 6.4 MV is used in the 4-th doublet lattice.

The phase space plots and the beam envelopes are shown in Fig. 8. The beam envelops from the last ACS section to the whole SC linac are shown in Fig. 9. A slight mismatch is observed in the longitudinal envelope and further matching study will be carried out.

## 5 SUMMARY

System design of the SC proton linac has been carried out for the KEK/JAERI joint project. For the reference design, we have chosen the synchronous beta cavity concept. Further optimisation work will be studied to make a good deal with the construction cost and the beam quality. Detailed building design work up to 450 MeV part has almost completed as the first phase of the construction. The construction of the building will be started from the next Japanese Fiscal year.

## 6 REFERENCES


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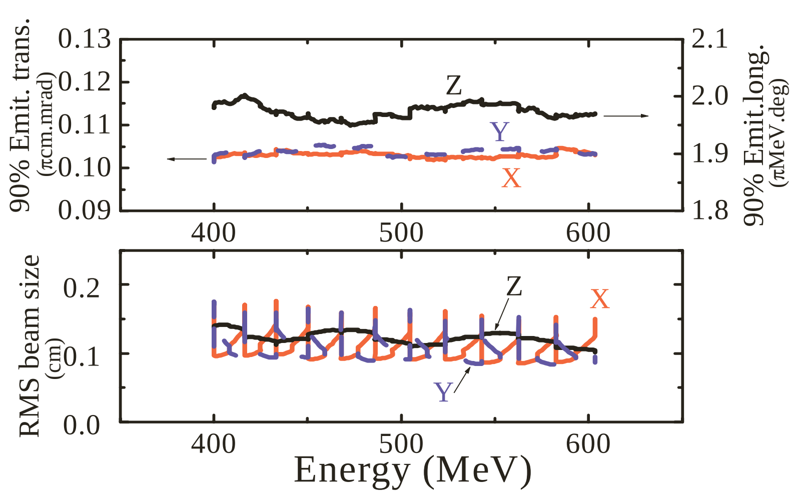


Fig.5 90% emittances and RMS beam sizes.

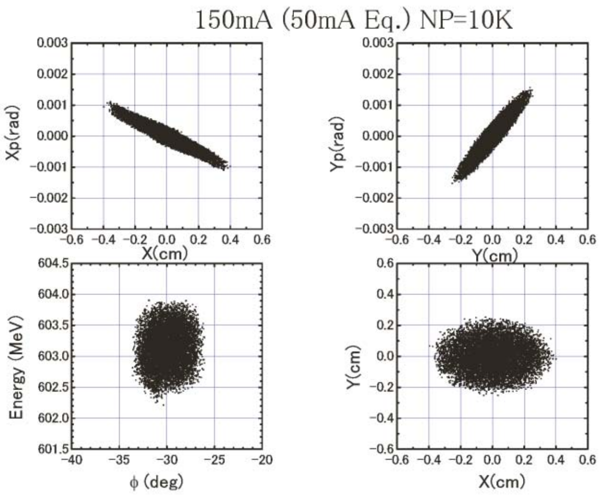


Fig.6 x-x', y-y', W-phi phase space plots and x-y spatial plots at the exit of the SC linac

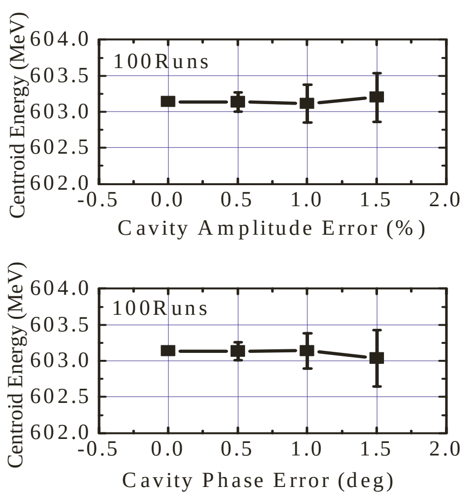


Fig.7 Energy jitter of the beams obtained from the rf control error analysis

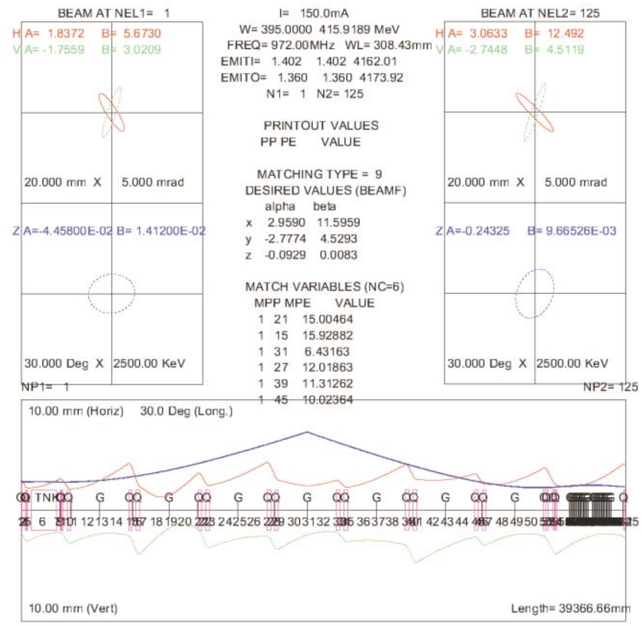


Fig. 8 Results of the MEBT study with TRACE-3D. Phase space plots and beam envelopes from the last ACS section (left) to the 1-st SC section (right).

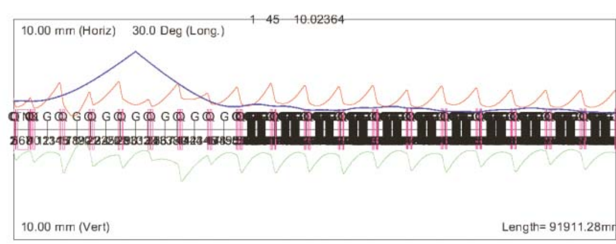


Fig. 9 Results of the MEBT study. Beam envelopes from the last ACS section to the whole SC linac.