1 GeV PROTON LINEAR ACCELERATOR OF THE LARGE HADRON FACILITY

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Abstract

A 1 GeV proton linear accelerator is designed as an injector of rings. It supplies H^- ions for not only nuclear physics but also materials science in Japanese Hadron Facility.

Introduction

Japanese Large Hadron Facility is being planned to be built adjacent to the 12 GeV proton synchrotron and TRISTAN at KEK. It will cover following four arenas; Kaons, Neutrons, Mesons and Exotic nuclei. It includes both proton and heavy-ion accelerators. High intensity proton beams are used not only for nuclear physics but also for materials science. For the latter, a pulsed neutron- and meson- facility had been proposed as GEMINI, a 800 MeV synchrotron with a 100 MeV linac, intensity goal of which was 500 μA, about two times of ISIS. Obviously, however, a pulse-compresser ring with a full energy linac is favorable as an accelerator complex because of its lower beam losses. A high energy injector linac will improve beam intensity and quality of the 12 GeV proton synchrotron. Thus, a 1 GeV proton linac is conceptually designed reminding that this injector linac must accelerate much more beams compared with injectors of conventional high energy synchrotrons.

Beam Requirements

The proposed accelerator complex consists of a 1 GeV proton linac, a 50 Hz rapid cycling synchrotron, a slow cycling synchrotron or stretcher, a sophisticated linac for various heavy ions up to uranium and the upgraded 12 GeV proton synchrotron. The rapid cycling synchrotron accelerates 1 GeV protons to 2 GeV. Its harmonic number is two. One of two bunches is supplied to a neutron production target and the other to a meson target or the stretcher ring. Each beam current required is more than 100 μA. To reduce beam losses at injection into the synchrotron, the injected beam should not be continuous but bunched to match with the rf buckets of the synchrotron, so that the linac intensity is 20 mA average over a macro-pulse and about 50 mA instantaneously. Beam pulse duration is 200 μs to achieve the intensity mentioned above or 2.5×10^{13} ppp. Other demandants of the 1 GeV protons are the 12 GeV synchrotron and an ISOL. Protons required by these two groups are much less than that for production of the pulsed neutrons and mesons. If the 1 GeV protons are used to yield same amount of neutrons, their current must be doubled. Further, more protons might be required by the arenas or by other new users, thus the design goal is set to be 20 mA with a pulse width 400 μs. The repetition rate is 50 Hz at the beginning, but may be increased up to 100 Hz in the future. Beam parameters are summarized in Table 1.

Table 1 Beam parameters for linac design

Particle	H^-
Energy	1 GeV
Beam intensity	
instantaneous	∿ 50 mA
macro-pulse	20 mA
time average	400 (800) μA
Pulse duration	400 μs
Repetition rate	50 (100) Hz
Beam emittance (90 % normalized)	5 πmm·mrad

Low-β Section

Ion source

The charge-exchange injection system is now the standard scheme of high-intensity proton synchrotrons. So, H^- ions are generated and accelerated in the injector. A multicusp H^- ion source with a cesiated molybdenum converter is supplying typically stable 20 mA beams of 3 πmm-mrad normalized to the linac of the 12 GeV synchrotron at KEK. Consumption of cesium is greatly reduced by the lanthanum-hexaboride cathodes which operate at much lower temperature of 1400-1500°C than that of tungsten cathodes. Arcing occurs every two hours or so in the accelerating column, but it is not serious as only several beam pulses miss in 20 Hz operation. The source is mounted directly in the high gradient column for the duoplasmatron and no special precaution is made to prevent leakage of cesium to the accelerating gap. This means that it might be possible to reduce arcing further, but still a source without cesium is preferable. A volume production H^- source is being developed.

Alvarez linac

The 200 MHz, 20 MeV injector linac was completed in 1974 and upgraded to 40 MeV in 1985 at KEK. Its effective shunt impedance reaches to the maximum around 10 MeV, and decreases gradually with the energy. As the shunt impedance is proportional to a square root of the resonant frequency of the linac, the Alvarez linac accelerates protons to 100 MeV and then transfers them to a high-β linac, the frequency of which is chosen to be about three times of the Alvarez linac. The presently operating rf system consists of a synthesizer, a solid-state amplifier, two RCA-7651 tetrodes, an RCA-4616 tetrode and Thomson TH-516 triode. As several times ten kilo-watts solid-state amplifiers are already commercially available, a TH-516 or its equivalent power tube can be driven by a solid-state amplifiers. Although most of the operating Alvarez linacs have 200 MHz systems, a 400 MHz one is technically feasible with advantages of higher shunt impedance and high gain rf sources of klystrons. Selection of the system mostly depends on a high-β linac which accelerates protons from 100 MeV to 1 GeV. In this design, a straightfoward extention of the presently operating system is primarily assumed. A 100 MHz RFQ linac will inject 2 MeV beams into the 200 MHz Alvarez section. Parameters are listed in Table 2.

High-β Section

Single-cell cavity

The basic idea of coupling cavities was established about 20 years ago. The side-coupled cavities (SCC), which achieve both high shunt impedance and enough coupling, have worked for 15 years at LAMPF. A disk-and-washer cavity (DAW) is accelerating electrons in the accumulator ring of TRISTAN and many on-axis-coupling alternating-periodic-structure (APS) cavities have become operational in its main ring since last November. They are axially symmetric and have no coupling irises, so that their configurations are reliably calculated by SUPERFISH and make fabrication easy. As they work in cw mode, frequency tuners at every accelerating cell compensate detuning due to wall loss,

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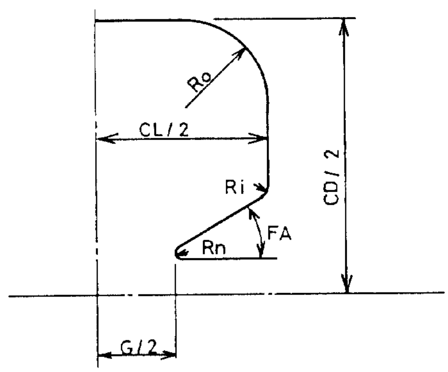
which is usually not serious in injector linacs of high energy synchrotrons. A L-band SCC seems adequate for relatively light duty machines. It is complemented by a 400 MHz Alvarez linac in low-β region.

The rf single cavities have been widely used for particle acceleration. A series of these cavities was proposed as single-cell structure in SNQ[1]. When these cavities are excited by individual amplifiers, which are connected to each cavity, this structure has some flexibility of operation as already pointed out. Even if the rf power is divided and fed to each cavity, some merits of the system still remain. When the proton energy increases from 100 MeV to 1 GeV, its β changes from 0.43 to 0.88, so that unit cell lengths of a conventional linac must change proportionally to β. On the other hand, the single-cell structure linac has a series of identical cavities. This is extremely suitable for large-scale production. Each cavity has a tuner with a feedback loop, and it can tolerate large wall loss inevitably due to high-duty and/or high-field operation. It is also the strongest structure against beam loading. Each cavity needs its own coupler, rf window and circulator if necessary. Even their number is great, rf powers handled by them are low enough to ensure their dependable operation. To reduce beam loss in high β region, for example 1 % or less, the beam hole is decided to be 5 cm in diameter. For higher frequencies, more cavities with their accessories are needed. For lower frequencies, shunt impedances deteriorate. As enough experiences on 500 MHz-band high-power rf system are accumulated at KEK, the high-β section is designed in this frequency band. Figure 1 shows a quadrant of a model of the unit cell with its dimensions and their contributions to the resonant frequency.



Frequency	f	507 MHz	
Cell length	CL	240.0 mm	$\Delta f/\Delta CL$ = - 1.0 kHz/μm
Cell diameter	CD	382.2 mm	$\Delta f/\Delta CD$ = - 1.0 kHz/μm
Gap length	G	110.0 mm	$\Delta f/\Delta G$ = 1.4 kHz/μm

R_i = 10 mm, R_o = 60 mm, R_n = 5 mm, FA = 30°

Fig. 1 A quadrant of a unit cell with its dimensions and their contributions to the resonance.

Figure 2 shows the effective shunt impedance of the single-cell linac as a function of β. A module of the single-cell structure contains eight unit cells as shown in Fig. 3. The main parameters of the linac are shown in Table 2.

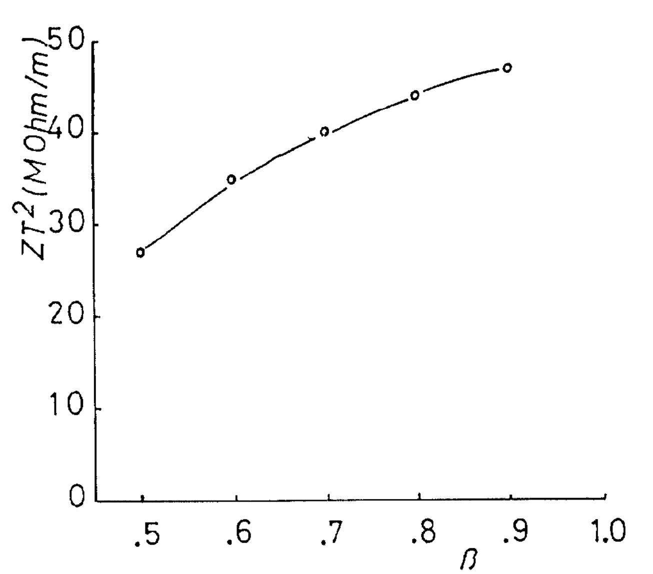


Fig. 2 Effective shunt impedance of single-cell linac.

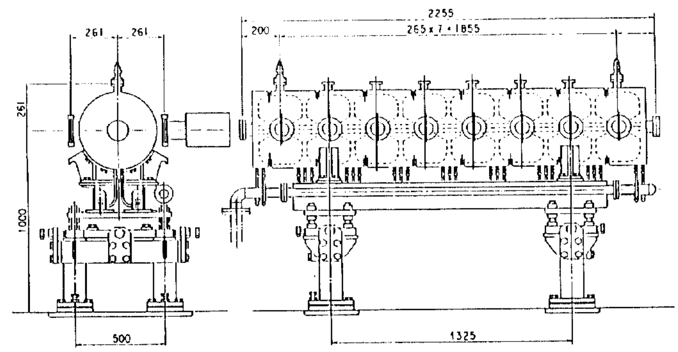


Fig. 3 A module of single-cell structure.

Table 2 Main parameters of 1 GeV linac

Ion Source	Volume production
RFQ	
frequency	100 MHz
energy	2 MeV
Alvarez linac	
frequency	200 MHz
energy	100 MeV
No. of tanks	5
length	70 m
average field	2.5 MV/m
structure power	6 MW
beam power	2 MW
High-β linac	
frequency	500 MHz
energy	1000 MeV
No. of modules	208
length	520 m
average field	3.2 MV/m
structure power	72 MW
beam power	18 MW

Beam dynamics

As the cavities are not coupled each other, it is possible to upgrade the energy by adding rf power later. This causes in practice, however in some extent, random deviation of the phase from the design value in each cavity. Effects of the phase error and the accelerating field error are estimated. The focusing parameters are determined so that β function of the synchronous particle is the upper of Fig. 4, where the synchronous phase ϕ_s is -26°. As the rf defocusing force obviously depends on the phase, a β function of a particle which starts at -46° is the lower of Fig. 4. When a Gaussian error of σ = 5° is added to the phases of the cavities, these two β functions change to that shown in Fig. 5. Comparing these figures, the phase oscillation accompanied by rf defocusing is predominant over the random phase error of this size.

According to multi-particle tracking, random error of the phase affects little the transverse acceptance, where the input particles distribute in ± 0.5 MeV and ± 25°. The longitudinal acceptance decreases by 10 % due

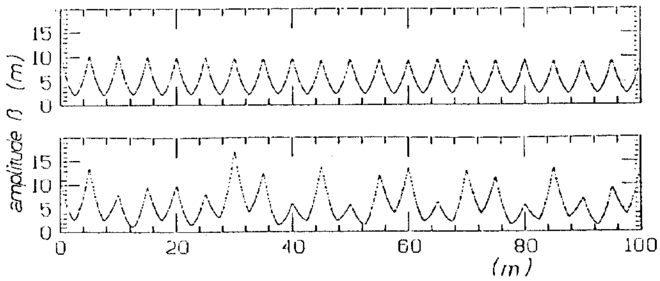


Fig. 4 β functions of the single-cell linac.
upper: for synchrnous particle, ϕ_s = - 26°.
lower: for phase-oscillating particles, ϕ = - 46°.

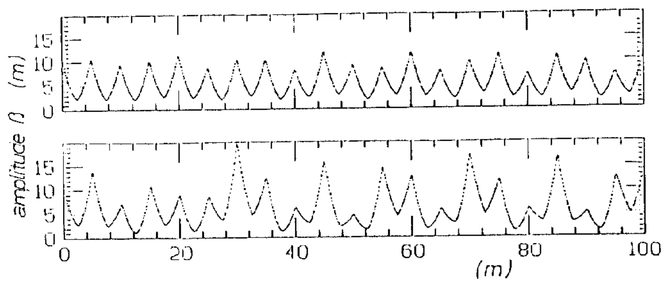


Fig. 5 Gaussian phase error σ = 5° is introduced to each cavity, "upper" and "lower" correspond to those of Fig. 4.

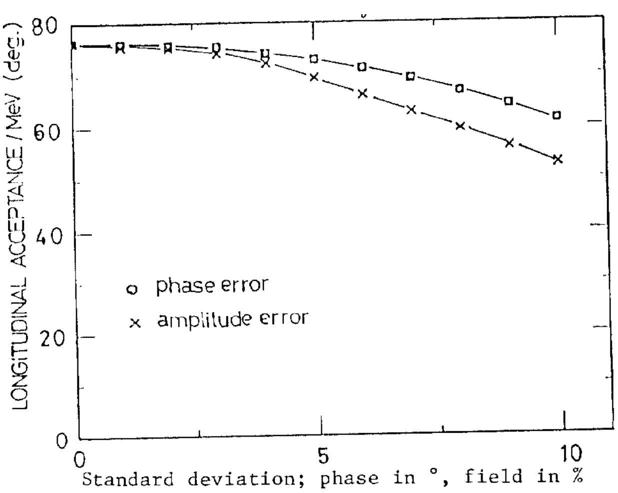


Fig. 6 Phase or field error vs. longitudinal acceptance.

to the random errors of the phase (σ = 7°) or of the field (σ = 5 %) as shown in Fig. 6.

Emittances of the output beam are calculated by PARMILA with an assumption of input particles of ± 25°, ± 0.5 MeV and 7 πmm·mrad normalized. The transverse emittance is scarecely affected and longitudinal one is more sensitive to the errors. The energy of the output beam shifts by 0.1 % for the phase error of σ = 7° or for the field error of σ = 5 %. The energy spreads are ± 0.35 - 0.40 % for both errors.

RF system

Solid-state amplifiers are quickly developing in VHF and UHF bands as TV transmitters. They will remove difficulties associated with lives of electron tubes. Although their size and cost are not yet suitable for linacs today, they are hoped to be acceptable in the future. Figure 10 shows a design of the rf system for a single-cell linac, where it is no more necessary to

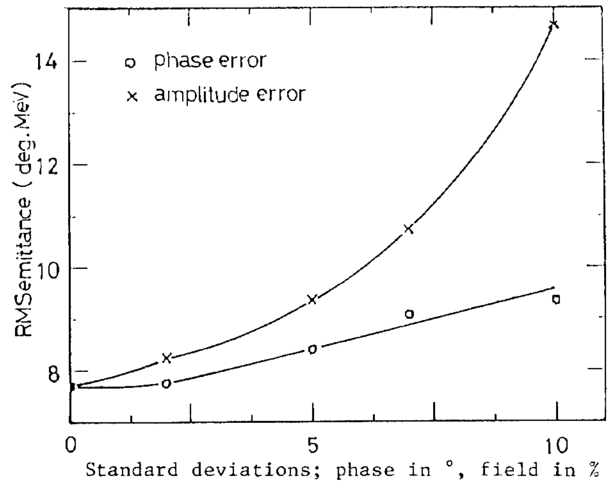


Fig. 7 Phase or field error vs. RMS longitudinal emittance.

conbine extremely high rf powers. The output power of a klystron can be divided and fed to each cavity. After the phase of each cavity is fixed, the single-cell linac will be operated as a conventional linac.

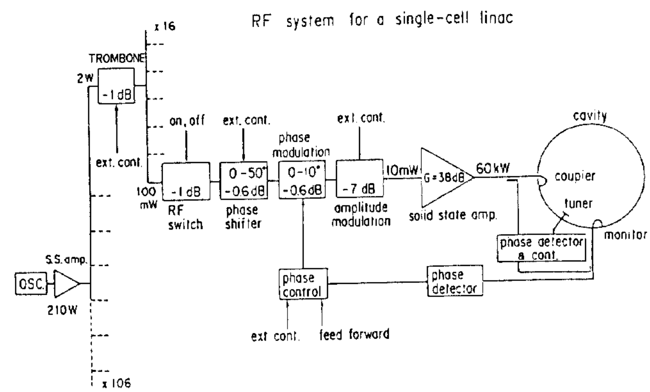


Fig. 8 An rf system based on a high power solid-state amplifier.

Conclusions

A 1 GeV proton linac is designed for Japanese Large Hadron Facility which includes arenas of not only nuclear physics but also materials science. Its average beam current and duty factor are much more than those of injectors for high energy synchrotrons. As the phase and the field of each cavity distribute randomly around the design values in a single-cell linac, their effects on beams are estimated. Other systems are also being studied.

Acknowledgements

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Reference

1) SNQ Project Proposal, KFA Jülich, December 1984.