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DESIGNS OF HIGH-INTENSITY PROTON LINACS WITH NON-EQUIPARTITIONING*

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Abstract

Superconducting RF technology is playing a more and more important roles in high-power proton linacs. Zero-current periodic phase advance less than 90 degrees and equipartitioning design are considered very important principles in the linac design. Due to the very high construction and operation costs, it is very important to optimize the design to lower the costs. With the technical advancement, higher accelerating field can be obtained. In order to take this advantage, it is of much interest in increasing the longitudinal phase advance to shorten the linac or reduce the cost. In this paper, we present the design method that keeping the longitudinal phase advance as large as possible but smaller than 90 degrees to maximize the use of the available accelerating gradient. Even though this method does not observe the equipartitioning condition, we can also obtain very good beam dynamics results by placing the tunes in resonant-free regions. The design and simulation results by applying this method to the SPL and China-ADS linac will be presented.

INTRUDUCTION

Beam instability can lead to emittance growth, and can affect both stationary and non-stationary initial distribution. Stability problem was first examined in 1970 in continuous focusing channel by Gluckstern [1], who analysed the K-V distribution. Collective instabilities caused by space-charge forces can cause emittance growth if the bunches in an RF linac have different longitudinal and transverse temperatures. This effect was first demonstrated in theoretical study by Jameson [2]. Hofmann et al. extended Gluckstern's stability analysis of the K-V distribution to periodic solenoid and quadrupole channels [3][4]. He found that unstable collective modes occur if the tune depressions in both directions fall below a threshold curve and depends on the ratio of oscillation frequencies, which can be shown in Hofmann chart. The most destructive modes are those of the quadrupole type, which are identical to the envelope instabilities studied by Struckmeier and Reiser [5]. To avoid these quadrupole type instabilities, the zero-current periodic phase advance should be smaller than 90 degrees.

By now the Hofmann chart is a very important tool in linac design, and equipartitioning lattices are adopted by most designs, for example at SNS [6], and in the UNILAC at GSI [7], which showed the first experimental evidence of space charge driven emittance coupling in high intensity linear accelerators. Emittance coupling in the intense beam can be summarized as [8]:

- Equipartitioning beam is not necessary to avoid emittance exchanged, and it would be sufficient if one avoids resonance region in the Hofmann chart;
- Emittance exchanged depends on the crossing speed (inversely proportional) of resonance stop bands;
- On equipartitioning, even main resonance will disappear but splitting of emittances and consistent emittance growth may happen.

With the success of SNS, the superconducting linac is considered as the best choice design for high-power proton linacs, such as Project-X, IFMIF, SPL, C-ADS accelerator and ESS, which have changed technology roadmap. Due to the very high construction and operation costs of superconducting linac, it is very important to optimize the design to lower the costs. Usually, the longitudinal emittance is larger than the transverse ones from the front-end, thus a design based on equipartitioning design will have the transverse phase advances per period larger than the longitudinal ones. However, with the technical advancement, higher accelerating field can be obtained. In order to take this advantage, it is of much interest in increasing the longitudinal phase advance to shorten the linac or reduce the cost.

In this paper, we present the design method that keeping the zero-current longitudinal phase advance as large as possible but smaller than 90 degrees to maximize the use of the available accelerating gradient, meanwhile the transverse phase advances are determined by placing the tunes in resonant-free regions. Another advantage is that there is smaller magnetic striping loss for H^- linac. However, this method will have a lower tune depression in the transverse direction, which should be considered carefully. We have applied the method to the SPL and China-ADS linac.

SPL DESIGN OPTIMIZATION

The SPL [9] is a superconducting linac under study at CERN, designed to providing a 5 GeV/4 MW H^- beam suitable for neutrino facilities and potentially also for other users. Fixed target experiments are foreseen at lower energies, like ISOLDE at about 1.4 GeV or EURISOL at 2.5 GeV. The SPL accelerates H^- from 160 MeV to 5 GeV by 5-cell elliptical cavities (704.4 MHz) whose geometric β are 0.65 in the low energy part and 1.0 in the high energy part, as shown in Fig.1.

To reduce the length of SPL, we explored the possibility of maximizing the use of the available accelerating gradient, which also means a higher longitudinal phase advance. The new designs have a higher phase advance in

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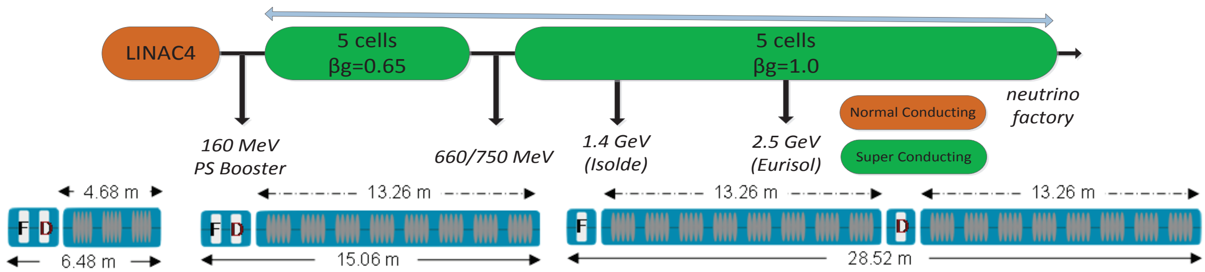

Figure 1: SPL conceptual layout.

Table 1: Comparison of Simulation Results of Different Designs

	Baseline design	Optimized-design-I	Optimized-design-II
Max. E_{acc} of Low-β cavity (MV)	20.4	20.4	19
Max. E_{acc} of high-β cavity (MV)	26.5	26.5	25
Max. Cavity power @ 40 mA (kW)	1000	1000	1000
Cavity number	244	237	248
Magnet number	80	70	68
Total length (m)	505	487.6	503.7
SC length (m)	398.58	388.44	406.38
Horizontal rms emittance growth (%)	5.1	6.9	8.8
Vertical rms emittance growth (%)	7.1	5.3	8.0
Longitudinal rms emittance growth (%)	5.2	0.3	-1.8
Horizontal 99% emittance growth (%)	9.9	15.0	29.3
Vertical 99% emittance growth (%)	13.2	15.7	17.3
Longitudinal 99% emittance growth (%)	59.4	15.5	2.1

the longitudinal plane even though the longitudinal emittance is larger. To avoid emittance exchange, we keep the ratio between the zero-current longitudinal and transverse phase advance around k_z/k_x=1.25 which is in a resonance-free region, as shown in the corresponding Hofmann chart in Fig.2.

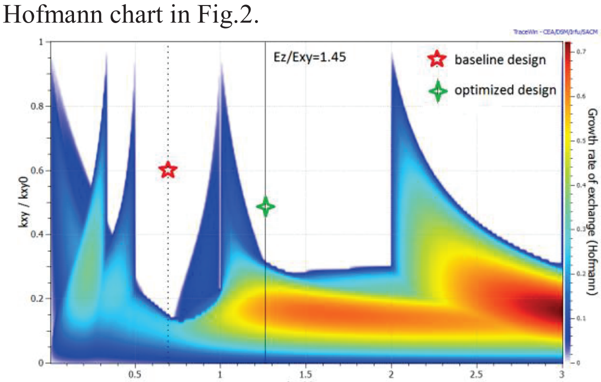

Figure 2: Working point of different design in Hofmann Chart.

From the comparison shown in Fig. 3, we can see that we only obtain benefit in the low energy section with the new design, and this can be explained that the accelerating gradient and the phase advance already reach the limit in the high energy section in the baseline design. Because of the long separations between the sections for extracting beams of different energies, it is very difficult to match between different sections. We designed two optimized lattices with different E_{acc} limits and the simulation results are shown in Table 1. From the comparison we can see that the optimized designs have fewer cavities and magnets, meanwhile the needed magnetic gradients are lower which helps with reducing the losses caused by magnetic stripping.

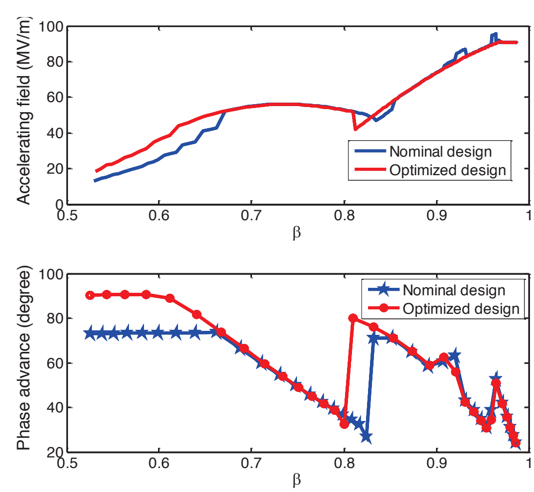

Figure 3: Comparison between baseline design and optimized design.

C-ADS MAIN LINAC DESIGN

The C-ADS (or China-ADS) project is a strategic plan to solve the nuclear waste problem and the resource problem for nuclear power plants in China, which has important implications for China's energy development. The C-ADS

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accelerator is a CW (Continuous-Wave) proton linac [10], which includes two major sections: the injector section and the main linac section. The injectors accelerate the proton up to 10 MeV and the main linac boosts the energy from 10 MeV up to 1.5 GeV. The general layout of the linac is shown in Fig. 4. Two identical injectors will be operated in the mode of one as the hot-spare of the other. However, two different injector schemes are shown in Fig.1, and this means that in the early developing phase two different approaches of injector will be developed in parallel by two teams.

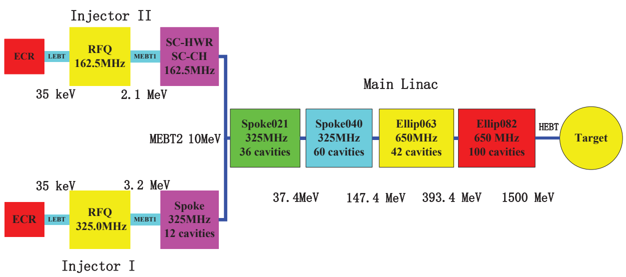

Figure 4: Layout of the C-ADS driver accelerator.

Because of different technology roadmap of two different Injectors we can obtain different emittances at the exit of MEBT2, which are shown in Table 2. Earlier, we designed two main linac lattices for the two injectors following equipartitioning rule. Because the longitudinal emittance is larger in the case of the injector scheme II, the longitudinal phase advances are smaller, which means low accelerating efficiency and also need an additional HWR superconducting cavity section [11]. Here we use the non-equipartitioning method to design the main linac using the same accelerating structure for the injector scheme II,

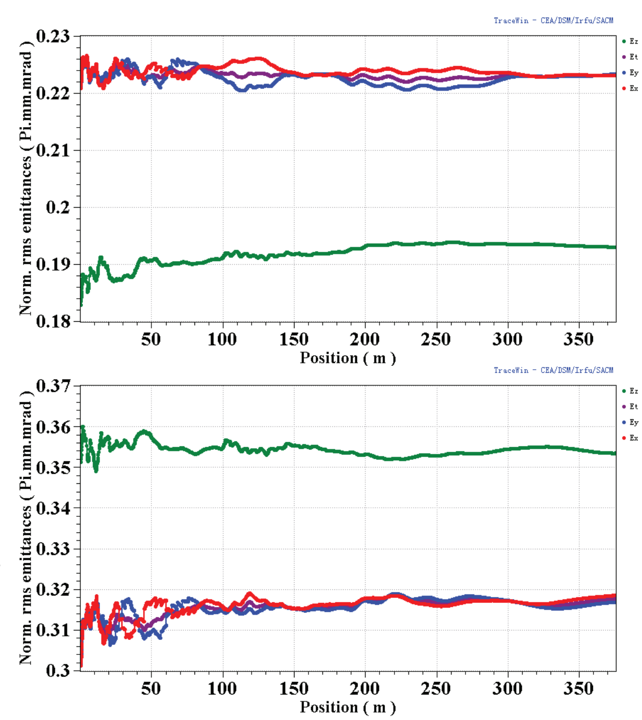

Figure 5: Emittance growth for injector scheme I (top) and injector scheme II (down).

meanwhile the linac almost follow the equipartitioning rule for the injector scheme I.

Table 2: Beam Parameters at Entrance of Main Linac

Parameters	Unit	Injector scheme I	Injector scheme II
Frequency	MHz	325.0	162.5
$\varepsilon_{n,rms,t}$	π mm-mrad	0.22	0.3
$\varepsilon_{n,rms,l}$		0.182	0.35

Compared to the former design, the new design can shorten the linac length by about 50 m and have fewer 28 cavities fewer for the injector scheme II. The simulation results are shown in Fig. 5, and we can see that emittance growth is smaller than 6% for the two injectors. Because the frequency of the injector scheme II is half of injector scheme I, the longitudinal acceptance of the main linac for the injector scheme II is smaller but acceptable.

CONCLUSION

In this paper, we present the non-equipartitioning design method to maximize the use of the available accelerating gradient to shorten the linac or reduce the linac cost, which will become realistic with the development of superconducting technology in the future. We applied the method to make optimized designs to the SPL and C-ADS main linac. The beam dynamic performance are found reasonably good.

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