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Emittance coupling driven by space charge in the CSNS linac

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Abstract In the conventional design of RF linacs, the bunched beams are not in thermal equilibrium. The space charge forces couple the particle motions between the transverse and the longitudinal directions. Furthermore it will cause the equipartitioning process which leads to emittance growth and halo formation. In the design of the China Spallation Neutron Source (CSNS) linac, three cases are investigated using the Hofmann stability charts. In this paper, we present the equipartitioning beam study of the CSNS Alvarez DTL linac.

Key words high current linac, space-charge coupling, beam instability

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1 Introduction

In the high current linac as well as in the high power synchrotron, the space charge effects play a dominant role in the beam physics. These effects can induce the emittance coupling when the resonance is fulfilled in some cases. The space charge driven coupling reveals the collective and nonlinear behavior which causes the emittance growth and the formation of halo[1]. There, the emittance exchange can happen between the longitudinal and transverse degrees of freedom known as "equipartitioning". Furthermore the halo formation[2—4] and the associated beam loss due to this equipartitioning process may cause excessive radioactivity especially for high power accelerators.

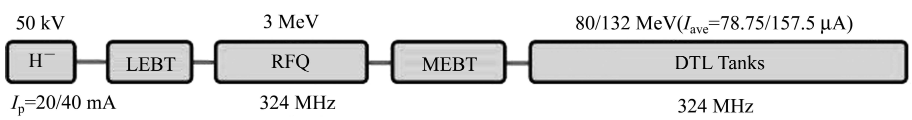

Fig. 1. Layout of the CSNS linac.

The China Spallation Neutron Source mainly consists of a high intensity linac and a rapid cycling synchrotron of 1.6 GeV. As shown in Fig. 1, the main parts of the CSNS linac are a 3.0 MeV RFQ accelerator and a conventional Alvarez DTL structure which accelerates the H^- ion from 3.0 MeV to 132 MeV. The operating RF frequency is 324 MHz and the duty factor of 1.05% has been chosen for all of the RF structures. Table 1 shows the main reference design parameters of the CSNS linac[5].

The emittance exchange in unstable areas of the instability charts developed by Hofmann has already been demonstrated for idealized cases[6]. The goal of this study is to optimize the layout using this valid chart for the CSNS linac.

Table 1. DTL linac design parameters.

	phase I	phase II
length/m	34.46	61.566
beam energy/MeV	80	132
Max. repetition rate/Hz	25	25
peak current/mA	15	30
chopper beam-on factor(%)	50	
average pulse current/mA	7.5	15
average current/μA	78.75	157.5
Max. beam pulse length/ms	0.42	0.42
Max. beam duty cycle(%)	1.05	

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2 Equipartitioning & stability charts

Space charge can lead to emittance exchange known as "equipartitioning" in linacs, or space charge coupling in high current synchrotrons. For a bunched beam, there exists a beam coupling between the transverse and longitudinal directions through the space charge force. The coupled fourth order envelope equation for a short bunch, where the image effects are negligible, can be expressed as[1]

$$k_{x0}^2 a - \frac{3}{2}\frac{Nr_{\mathrm{c}}}{\beta_0^2\gamma_0^3}\frac{1}{az_m}\left(1-\frac{1}{3}\frac{a}{\gamma_0 z_m}\right) - \frac{\varepsilon_{nx}^2}{\beta_0^2\gamma_0^2 a^3} = 0\,, \quad (1)$$

$$k_{z0}^2 z_m - \frac{3}{2}\frac{Nr_{\mathrm{c}}}{\beta_0^2\gamma_0^4}\frac{1}{az_m} - \frac{\varepsilon_{nz}^2}{\beta_0^2\gamma_0^6 z_m^3} = 0\,. \quad (2)$$

The applied transverse and longitudinal focusing forces acting on the particles are presented respectively by the wave numbers[7]

$$k_{x0} = \frac{\sigma_{x0}}{n\beta_0\lambda}\,, \quad (3)$$

$$k_{z0} = \left(-\frac{2\pi q E_m \sin\varphi_0}{\lambda m c^2 \beta_0^3\gamma_0^3}\right)^{1/2}. \quad (4)$$

The wave numbers k_x and k_z that include the space-charge defocusing effect are

$$k_x^2 = k_{x0}^2 - \frac{3}{2}\frac{Nr_{\mathrm{c}}}{\beta_0^2\gamma_0^3}\frac{1}{a^2 z_m}\left(1-\frac{1}{3}\frac{a}{\gamma_0 z_m}\right), \quad (5)$$

$$k_z^2 = k_{z0}^2 - \frac{3}{2}\frac{Nr_{\mathrm{c}}}{\beta_0^2\gamma_0^4}\frac{g}{az_m^2}\,. \quad (6)$$

The ratio of the longitudinal temperatures ($T_{//}$) and transverse temperature ($T_\perp$) has the relation

$$\frac{T_{//}}{T_\perp} = \frac{k_z\varepsilon_z}{k_x\varepsilon_x}\,, \quad (7)$$

where ε_z, ε_x are the normalized emittances. Then the equipartitioning condition ($T_\perp = T_{//}$) can be expressed in the form

$$\frac{k_z\varepsilon_{nz}}{k_x\varepsilon_{nx}} = 1\,. \quad (8)$$

A self-consistent description of collectively driven resonance has first been proposed adopting the Vlasov perturbation approach to the 2D K-V distribution in Ref. [2]:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \dot{x}\frac{\partial f}{\partial x} + \dot{z}\frac{\partial f}{\partial z} + \dot{p}_x\frac{\partial f}{\partial p_x} + \dot{p}_z\frac{\partial f}{\partial p_z} = 0\,. \quad (9)$$

The distribution function $f(x,\ z,\ p_x,\ p_z)$ can be expressed in terms of the transverse and longitudinal Hamiltonians and temperature in the laboratory frame[8]

$$f(x,z,p_x,p_z) = \frac{NTv_x/v_z}{2\pi^2 m\gamma a^2}\delta\left(H_{0z} + TH_{0x} - m\gamma v_z^2\frac{a^2}{2}\right), \quad (10)$$

where the energy anisotropy T is the ratio of oscillation energies in x and z and it can be written for harmonic oscillation[9]

$$T = \frac{\varepsilon_z k_z}{\varepsilon_x k_x}\,. \quad (11)$$

The two temperature ($T_\perp$, $T_{//}$) distributions do not satisfy the stationary Vlasov equation. The transverse-longitudinal coupling through the space charge forces may lead to relatively rapid change of the distribution towards thermal equilibrium ($T_\perp = T_{//}$). This equipartitioning process is particularly strong in the high current RF linac.

The solution of the linearized Vlasov equation results in the dispersion relation for eigenmodes with space charge potential expanded in polynomials in x and z. The order of the polynomial describes the perturbed space-charge potential, and exponential instability is found in certain regions of the parameter space. Emittance exchange requires resonant coupling, which can take place only if an intrinsic resonance condition is satisfied.

Details of the above approach can be found in Refs. [2, 10—12], where it is shown that eigenmodes with nonlinear space charge coupling forces may grow exponentially in the vicinity of certain internal resonance conditions.

3 Simulation

In the following we carry out the actual linac tune values of various designs and plot the tune footprint on the Hofmann charts for the nominal emittance ratio $\varepsilon_z/\varepsilon_{x,y} = 2$[8]. The characteristic regions (in grey) of the chart indicate where the third and fourth order modes of collective space charge density oscillations can expect to cause emittance transfer.

The simulations use the layout of the DTL linac sections of the CSNS (3.0—132 MeV, 30 mA current) and start with an initial K-V distribution. Our simulations have been carried out with PARMILA using the space charge routine SCHEFF.

The stability chart and the tune footprint relating to the CSNS DTL linac design are shown in Fig. 2. The quadrupole gradients are modified so that we can obtain three different lattices that fall into various areas of the stability chart in Fig. 2. The tune ratio k_z/k_x for three cases varies over a large scale (0.122—1.23).

Figure 2 indicates that "Case 1" and the first four periods of Case 2 are located in an unstable area, while the remaining periods of "Case 2" and "Case 3" lattice should both be stable. In the designs of Case 1 and Case 2, the emittance coupling must occur because the pronounced 2:2 resonance center at the tune ratio $k_z/k_x = 1$ is not avoided. Furthermore the design of Case 1 with increased tune ratio shows overlap with the resonance band unfortunately at $k_z/k_x = 1.1$, where an e-folding distance of only 3—4 betatron periods is predicted. The design of Case 2 has a similar effect at its beginning section. For Case 3, it locates at the "safe" region and the coupling does not occur. The corresponding rms emittance evolution result is plotted in Fig. 3.

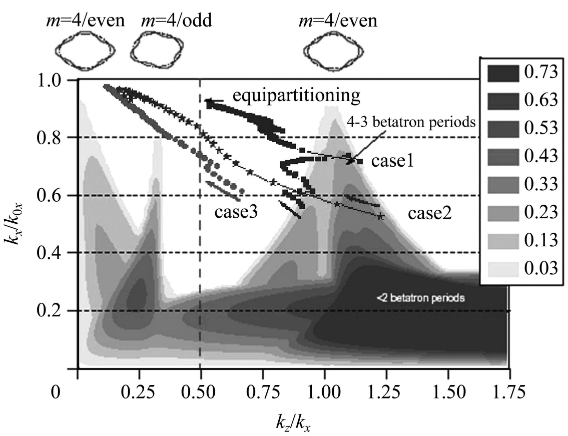

Fig. 2. Stability chart for the CSNS DTL linac nominal emittance ratio $\varepsilon_z/\varepsilon_{x,y} = 2$ with setups for various simulations.

The evolutions of rms emittances simulated by PARMILA for three cases are shown in Fig. 3.

Clearly, in Case 1 and the beginning section of Case 2 there is a visible emittance coupling between the longitudinal and the transverse planes, which agrees with the prediction of the Hofmann chart. For Case 3, in agreement with the chart, we cannot observe any emittance transfer in the longitudinal and transverse planes. We note that in Case 1 the change of the longitudinal emittance is more pronounced than the changes of the transverse one, since there is one "hot" plane, the longitudinal one, which is feeding the two "cold" transverse planes. In other words, the "energy" associated with the longitudinal plane is shared by both transverse degrees of freedom. For this reason the rms emittance evolution in the longitudinal plane has more intensive oscillation than that of the transverse. This explanation can also be used in Case 2. The final transverse (longitudinal) rms emittances change by +5% (−1.25%) for Case 1, compared with +13.3% (−0.75%) for Case 2, and 2% (+3.75%) for Case 3.

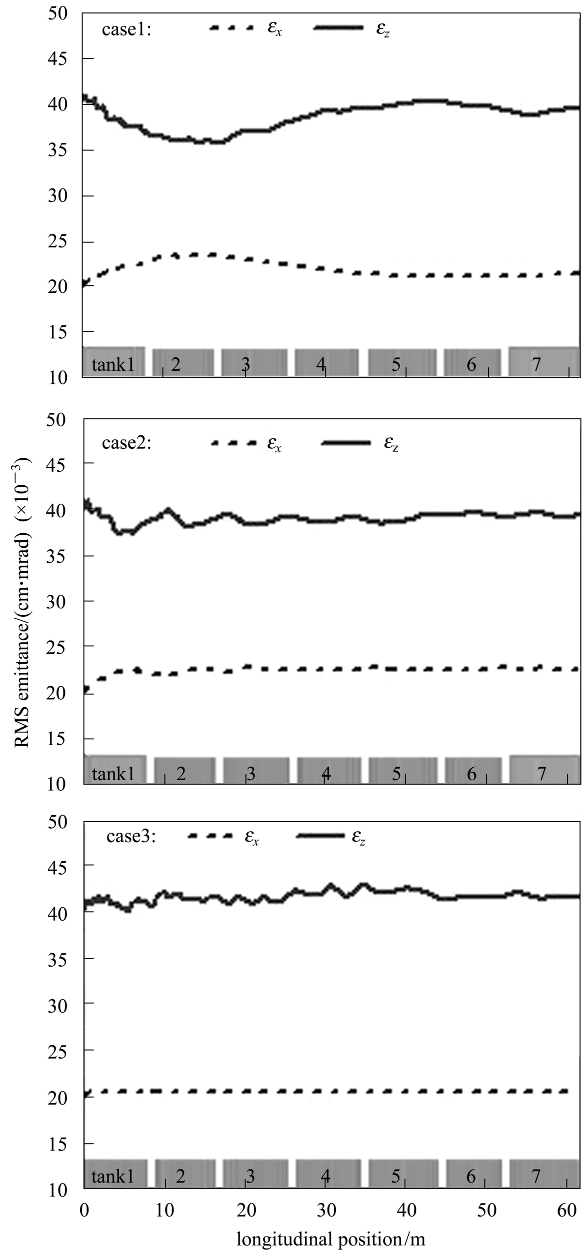

Fig. 3. RMS emittance evolutions for three designs.

4 Conclusion

Hofmann's stability charts have been successfully applied in various high intensity linac projects such as CERN-SPL, the SNS and the ESS superconducting linac[13—15] and should be regarded as a new tool in the design of linac lattices. As the Hofmann chart predicted, the rms emittance conservation of matched beams can be considered to be "safe" as long as the major fourth order 2:2 resonance is avoided. These studies to analyze the emittance growth as well as the halo formation using the Hofmann stability charts for the CSNS linac should be further investigated in the near future.

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References

1 Reiser M, Brown N. Phys. Rev. Lett., 1995, **74**: 1111—1114
2 Hofmann I. Phys. Rev. E, 1998, **57**: 4713—4724
3 Gluckstern R L. Phys. Rev. Lett., 1994, **73**: 1247—1250
4 Gluckstern R L et al. Phys. Rev. E., 1998, **58**: 4977—4990
5 FU Shi-Nian, FANG Shou-Xian, WEI Jie. Proceedings of LINAC 2006. Knoxville, Tennessee, USA
6 Hofmann I, Boine-Frankenheim O. Phys. Rev. Lett., 2001, **87**: 034802
7 Reiser M. Theory and Design of Charged Particle Beams. New York: John Wiley & Sons, 1994
8 Hofmann I, Franchetti G, Boine-Frankenheim O et al. Phys. Rev. ST Accel. Beams, 2003, **6**: 02402
9 QIANG J, Ryne R D, Hofmann I. Phys. Rev. Lett., 2004, **92**: 174801
10 Hofmann I, QIANG J, Ryne R D. Phys. Rev. Lett., 2001, **86**: 2313
11 Hofmann I, QIANG J, Ryne R D. Proceedings PAC99, New York, USA, 1999
12 Hofmann I, Boine-Frankenheim O. Phys. Rev. Lett., 2001, **87**: 034802
13 Hofmann I, Franchetti G, QIANG J et al. Proceedings of EPAC2002. Paris, France
14 Hofmann I, Franchetti G, Boine-Frankenheim O et al. Proceedings PAC01. Chicago, USA, 2001
15 Gerigk F, Vretenar M, Ryne R D. Proceedings PAC01. Chicago, USA, 2001