STABILITY CHARTS FOR THE IFMIF SRF-LINAC

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Abstract

Among the most recent projects, the IFMIF-EVEDA accelerators aim for the highest intensity, leading to a multi-MW beam power at relatively low energy [1]. The concern for such accelerated beams is the predominance of the self-field energy upon the beam energy. In these conditions, the space charge effect is at its maximum, which triggers different nonlinear mechanisms implying emittance growth, halo formation and finally, particle lost. In this proceeding we show the stability charts constructed for the IFMIF SRF-Linac, with which are identified the collective space charge resonances responsible for transverse-longitudinal emittance exchange and emittance growth.

INTRODUCTION

The IFMIF project (International Fusion Materials Irradiation Facility), aims at studying materials which must resist to very intense neutron radiations in future fusion reactors. The objective is to construct the world most intense neutron source capable of producing 10^{17} *neutrons/s* at 14 *MeV*. A major system of this project is its two accelerators producing each of them 125 *mA*. Deuteron particles up to 40 *MeV* interact with Lithium target. In a first phase called EVEDA (Engineering Validation and Engineering Design Activity), a full scale prototype accelerating particles up to 9 *MeV* is being studied and constructed in Europe, to be installed in Japan [2].

In each of the two IFMIF accelerators, D^+ particles are first accelerated by the source extraction system, then by the long Radio-Frequency Quadrupole (RFQ) and finally the Superconducting Radio-Frequency Linac (SRF-Linac) composed of four cryomodules. The first cryomodule contains 8 periods of 1 solenoid and 1 resonator ($\beta = 0.094$). The second cryomodule contains 5 periods of 1 solenoid and 2 resonators ($\beta = 0.094$). The last two cryomodules contain 4 periods of 1 solenoid and 3 resonators ($\beta = 0.166$). The total length of four cryomodules is about 22.5 *m*. At low energy, the synchronous phase starts at $-50°$ and then grows linearly with beam energy up to $-30°$. Given the beam intensity of 125 *mA*, the maximum RF power per cavity is 75 *kW* for the low-β resonators and 150 *kW* for the high-β resonators. A gradient of 4.5 *MV/m* and apertures in the $40-50$ *mm* range were chosen for the superconducting resonators. Two Half-Wave-Resonator families, with different geometric β- values, are enough to cover the acceleration from the RFQ exit (5 *MeV*) to the final energy (40 *MeV*). The axial field of the superconducting solenoid is kept around 6 *T* in order to use the classical NbTi technology for the coils [2].

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In the space charge dominated regime , the space charge effects result in emittance growth and halo formation, which contribute to beam losses. The nonlinear space-charge forces coupling the longitudinal and transverse directions may cause emittance exchange among different degrees of freedom if some internal resonance conditions are satisfied [3]. The main resonance band in this context is the fourth order difference resonance, which occurs in the vicinity of equal longitudinal and transverse focusing strengths. Recently, it was reported [4] the first experimental evidence of this phenomenon in a high intensity linear accelerator, the UNILAC at GSI. The emittance exchange in unstable areas of the stability charts [3] has already been demonstrated for idealized long bunches. Hofmann's stability charts have been successfully applied in some high intensity linac projects [4] and should be regarded as a new tool in the design of linac lattices. The goal of this proceeding is to see in which extent those stability charts can be applied to a short periodic focusing structure and 3D bunched beams like the IFMIF SRF-Linac.

STABILITY CHARTS FOR THE IFMIF SRF-LINAC

A self-consistent description of collectively driven resonance has first been proposed adopting the Vlasov perturbation approach to the 2D K-V distribution. 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. Details of the above approach can be found in Ref. [3], where it is shown that eigenmodes with nonlinear space charge coupling forces may grow exponentially in the vicinity of certain internal resonance conditions.

To explore the sensitivity of the IFMIF SRF-Linac design to space charge resonances, numerical simulations have been performed with TraceWin [5]. The beam distribution taken as input is the output beam from the Medium Energy Beam Transport (MEBT) , composed of more than 10^6 macroparticles. See Fig. 1.

In Fig. 2 we plot the tune footprint on the Hofmann charts for the nominal emittance ratio $\epsilon_z/\epsilon_x = 1.5$. The characteristic regions of the chart indicate where the collective space charge density oscillations are expected to cause emittance transfer and growth. It is noteworthy that the unstable regions of these modes merge into the single-particle resonance conditions of difference resonances: $\nu_z - 2\nu_x \approx 0$ and $2\nu_z - \nu_x \approx 0$ for the third order even and odd modes; and $2\nu_z - 2\nu_x \approx 0$ and $\nu_z - 3\nu_x \approx 0$, as well

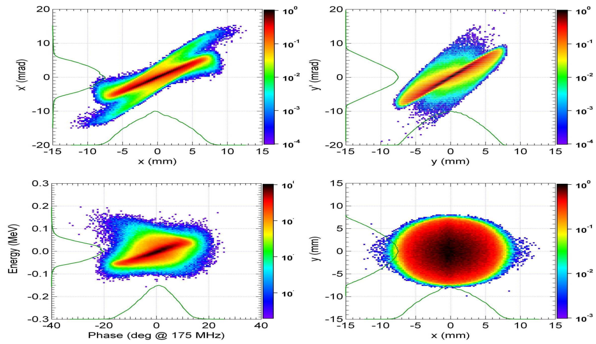

Figure 1: Beam density distribution at the IFMIF SRF-Linac entrance.

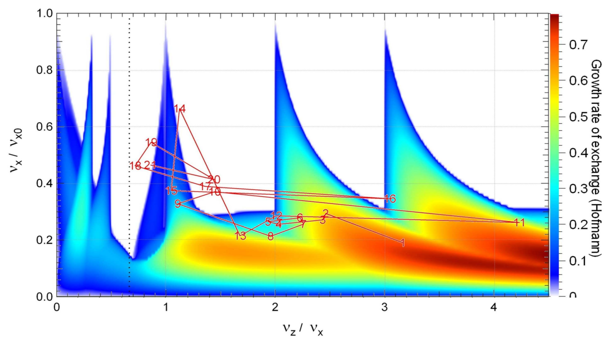

Figure 2: Stability chart for the IFMIF SRF-Linac nominal emittance ratio $\epsilon_z/\epsilon_x = 1.5$. Dashed line indicate equipartition tune ratio.

as $3\nu_z - \nu_x \approx 0$, for the fourth order even and odd modes. Note that a important peak is associated with the *4th*-order coupling resonance $2\nu_z - 2\nu_x \approx 0$. Two peaks at $\nu_z - 3\nu_x \approx 0$ and $\nu_z - 2\nu_x \approx 0$ have an addition direct effect on emittance transfer and growth. It should be noted that much stronger transverse tune depression (below 0.3) removes the isolated stop bands, and emittance coupling results for all tune ratios, with the exception of very small tune depression $(0.2, ..., 0.1)$, where the beam becomes increasingly equipartitioned anyway [3]. Note that the tune footprint of IFMIF SRF-Linac reference design (red line) varies over a large interval: it intercepts the resonances $2\nu_z - 2\nu_x \approx 0$, $\nu_z - 2\nu_x \approx 0$ and $\nu_z - 3\nu_x \approx 0$. Also note that a part of tune footprint overlaps with the region (tune depression below 0.3) where resonances form a continuum, which Ingo Hofmann called the "sea of instability " [3].

The normalized emittance variation is shown in Fig. 3. The graph shows the emittance coupling between the longitudinal and the transverse planes. We note that the change of the longitudinal emittance is more pronounced than the changes of the transverse ones, since there is one "hot"plane, the longitudinal one, which is fed by 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 larger oscillations than those of the transverse planes. This energy exchange involves variation of emittance ratio and therefore a changing

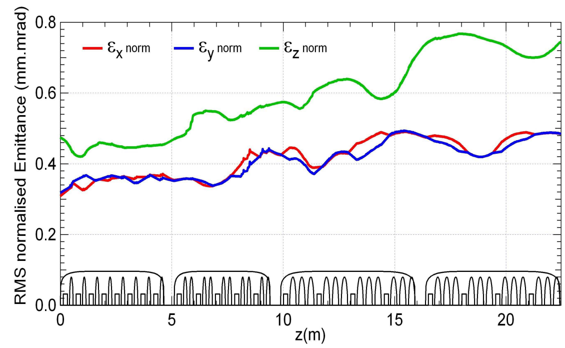

Figure 3: Normalised emittance along the IFMIF SRF-Linac.

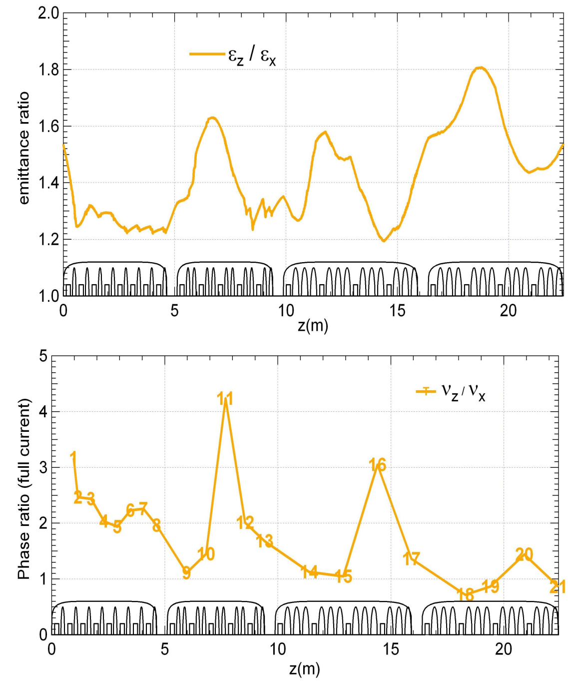

Figure 4: Variation of emittance ratio and tune ratio along the IFMIF SRF-Linac.

chart topology, resulting in a variation of the unstable area. Due to the changing r.m.s. emittances the beam becomes mismatched. The growth of the rms emittance can be very sensitive to ν_z/ν_x, see Fig. 4, due to the motion of stable fixed points for the parametric resonance and due to the appearance of space charge driven resonances. It has been shown by Franchetti et al. [3] that with stronger focusing in a given plane, the fixed point in that plane for the typical $2:1$ parametric resonance moves closer to the core. This results in more particles being involved in the parametric resonance in that plane and emittance growth.

Figure 4 shows that whenever the z and x tune numbers are close to each other, there is emittance exchange caused by the fourth order resonance stopband near tune ratio 1. In the IFMIF SRF-Linac, this effect takes place in about 1-2 betatron periods without space charge.

Now we modified the IFMIF SRF-Linac design to avoid the *4th*-order coupling resonance $2\nu_z - 2\nu_x \approx 0$ centered

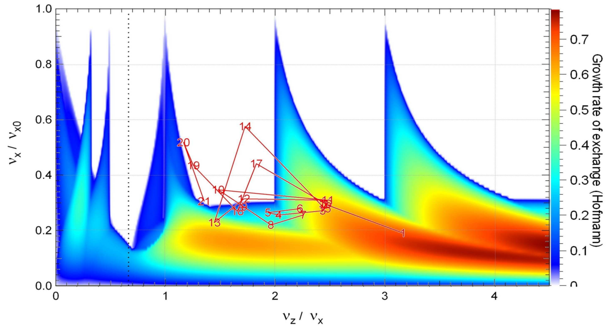

Figure 5: Stability chart for $\epsilon_z/\epsilon_x = 1.5$. IFMIF SRF-Linac design modified. Dashed line indicate equipartition tune ratio.

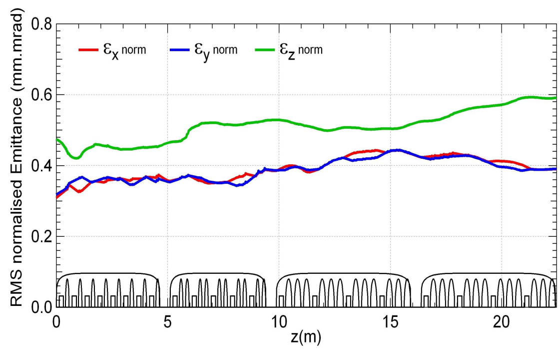

Figure 6: Normalised emittance along the IFMIF SRF-Linac design modified.

at the tune ratio $\nu_z/\nu_x = 1$. The strength of solenoid magnetic field and the strength of cavity electric field are modified. In Fig. 6 we plot the new tune footprint on the Hofmann charts for the emittance ratio $\epsilon_z/\epsilon_x = 1.5$. Note that the tune footprint of IFMIF SRF-Linac design modified avoids the resonance $2\nu_z - 2\nu_x \approx 0$. It intercepts the resonance $\nu_z - 2\nu_x \approx 0$. Yet note that a part of tune footprint overlaps with the “sea of instability ”.

The normalized emittance variation for the IFMIF SRF-Linac design modified is shown in Fig. 7. There are still emittance coupling between the longitudinal and the transverse planes and emittance growth - both weaker than the IFMIF SRF-Linac reference design. Now these effects are caused by the ressonance $\nu_z - 2\nu_x \approx 0$ and the “sea of instability ”.

Figure 7 shows that whenever the tune ratio is near 2 there is emittance exchange caused by the third order resonance stopband ($\nu_z - 2\nu_x \approx 0$).

CONCLUSIONS

We have identified the modes of collective space charge density oscillations that are responsible for the transfer and growth of the emittance in the IFMIF SRF-Linac. Unstable areas should be avoided in the design of high intensity linacs because of the development of beam halo during energy exchange. In this proceeding, resonance conditions was improved by moving the tune ratios from the fourth

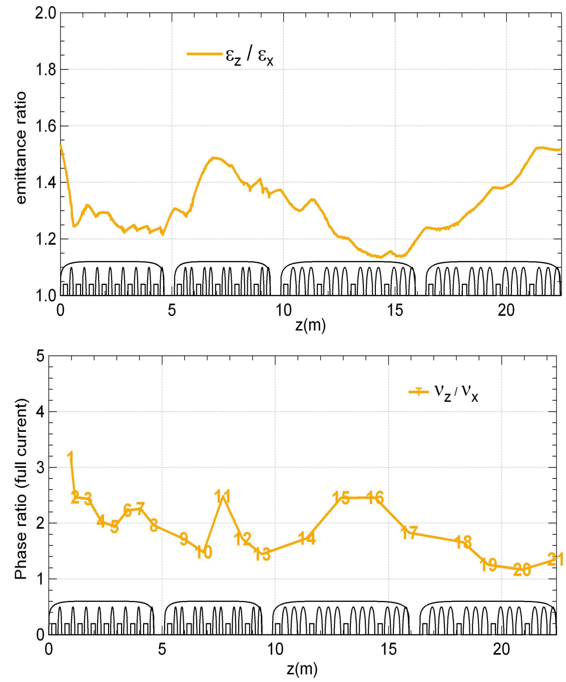

Figure 7: Variation of emittance ratio and tune ratio along the IFMIF SRF-Linac design modified.

order resonance. We are analysing two other IFMIF SRF-Linac modified designs. In the first case the tune footprint on the stability charts is near the equipartition line while, in the second case it is in the white region between the resonances $2\nu_z - 2\nu_x \approx 0$ and $\nu_z - 2\nu_x \approx 0$ [6].

ACKNOWLEDGMENTS

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