METHOD AND RESULTS OF SYSTEMATIC BEAM MATCHING TO A PERIODIC DTL

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Abstract

Systematic investigations on high current 3d-beam matching to a periodic Alvarez-type DTL are reported. Twiss parameters at the entrance of a matching section to the periodic structure were concluded from transverse and longitudinal measurements. Periodic solutions in 3d were calculated including space charge using the measured rms emittances. The matching was performed by rms beam size tracking and employing a numerical routine to set the matching section, which comprises five quadrupoles and two re-bunchers. Matching allowed for significant emittance growth reduction and for verification of non-linear beam dynamics effects along the DTL.

INTRODUCTION

For beams with non-negligible space charge forces mismatch is the main source for emittance growth. A matched beam means that the beam’s second moments are equal to the periodic solutions of the effective focusing lattice. The latter is the sum of external focusing devices and internal space charge forces. In case of mismatch the beam is not in thermal equilibrium with its environment (the effective lattice) and the corresponding free energy is transferred into emittance. Systematic matching in all three dimensions is therefore indispensable for emittance growth mitigation being a fundamental figure of merit for any DTL. Growth from mismatch delutes growth from higher order effects as resonances due to beam self forces. Thus, experimental observation of resonances is a strong evidence for good matching and high quality beam diagnostic. This proceeding describes the method and results of beam matching at the DTL of the Universal Linear Accelerator (UNILAC) at GSI [1]. The periodic UNILAC DTL comprises five Alvarez type rf-tanks operated at 108 MHz. Its injection energy is 1.4 MeV/u and the first tank (to which the beam needs to be matched) comprises 63 rf-gaps at synchronous phase of -30° providing acceleration to 3.6 MeV/u. Adjacent rf-gaps are separated by a drift tube housing a single quadrupole. The focusing lattice as shown in Fig. 1 is of the transverse F-D-D-F type.

MATCHING PROCEDURE

Beam diagnostics [2] required for matching is performed along the matching section (Figs. (2,3)). This section comprises a longitudinal and two transverse emittance measurement units, a beam current monitor, and phase probes. To match the beam in all three dimensions two re-bunchers and five quadrupoles are used. The matching procedure starts with the three emittance measurements. From the location of transverse emittance measurements the beam is rms tracked backwards to the entrance of the first re-buncher [4]. With respect to rms beam properties that position is almost equivalent to the position of the longitudinal emittance measurement unit. The rms tracking [5]
is based on measured transverse rms properties and on assumptions on the longitudinal rms properties of the beam. After the backward tracking the longitudinal properties are compared to the measured ones. The initial assumption for this backward tracking are re-iterated until agreement is reached, i.e. the initial distribution is considered as being reconstructed from measurements. Using the rms parameters of the reconstructed distribution at the entrance to the first re-buncher as initial condition for the tracking equations towards the DTL, the final rms parameters at the DTL entrance depend on the focusing strengths $f_j$ of the two re-bunchers and the five quadrupoles of the section. The final rms parameters together with the periodic solution define the mismatch $M_i$ in each plane [7]. Matched injection is achieved if $M_i$ is zero in each of the three planes. Defining

$$F(f_1...f_7) = M_x^3(...)+M_y^3(...)+M_z^3(...)$$

as a function of the seven focusing strengths in the matching section, the mismatch is optimized for the setting $f_1...f_7$ that minimizes $F$. Minimization of $F$ is done numerically. The residual mismatches achieved in experiments are $0.6/\leq0.4/0.1$ in the long./ver./hor. plane. Longitudinally the matching quality was limited by the bunch lengths at the entrance to the first re-buncher together with rf-curvature. The experiments referred to in the following were performed with $^{40}\text{Ar}^{10+}$ ions with an effective pulse current of 21.3 emA at 108 MHz. The transverse tune depressions reached from 14% to 40%.

**EMITTANCE GROWTH REDUCTION AND SIMULATION CODE RELIABILITY**

The main benefit of matching is illustrated in Fig. 4, i.e. significant reduction of emittance growth by a factor of about five. The upper curve was obtained prior to systematic matching investigations and the mismatch values in all three planes were estimated to about 1.2, respectively. Matching allows for high current operation without losses of the full UNILAC Alvarez DTL at transverse tune depression of up to 40%. Additionally, systematic mismatch control revealed that mismatch reduction significantly increases the reliability of beam dynamics simulation codes [6]. Figure 5 shows the relative difference between measured and simulated emittances behind the DTL for different initial transverse mismatches. As matching improves, the codes work better in reproducing experimental observations. Additionally, the differences among the codes decrease with the beam matching quality.

**FOURTH ORDER AND PARAMETRIC RESONANCES**

The transverse envelope instability together with mismatch [8] was considered the cause of emittance growth at $90^\circ$ of effective transverse phase advance. The underlying theory assumes a KV-distribution. Real distributions are better described through Gaussians and parabolic profiles. These feature higher order terms of the charge density as a function of the off-axis distance. As pointed out in [9] it is a resonance driven by the fourth order space charge potential term which increases transverse emittances at $90^\circ$ of...
transverse phase advance. It does so much faster wrt the envelope instability. Figure 6 shows the measured distortion of the transverse phase space distribution due to the fourth order resonance. Thanks to matching the resonance could be confirmed directly in an experiment [3]. The observed distortions were reproduced very well by several simulation codes. The instability is driven by mismatch whereas the resonance is mitigated by mismatch. Accordingly, for a matched beam the stop band must be avoided for the resonance and not for the instability. The second resonance driving relevant emittance growth is the parametric resonance. It arises for even ratios of longitudinal to transverse tunes [10] and beams with different emittances in the longitudinal and transverse plane. Although the resonance, also referred to as equipartitioning, has been known and respected as a DTL design criterion since long, its experimental observation was not achieved prior to sufficient mismatch control. The experimental campaign revealing the transverse fourth order resonance gave also evidence of the parametric resonance [11]. Figure 7 displays the paths of beam tunes along Hofmann’s stability chart for different transverse focusing settings along the first DTL tank of the GSI UNILAC. The corresponding initial tune ratios and the emittances measured behind the DTL are shown in Fig. 8. The latter shows a stepwise increase of transverse emittance if the stop band of equal tunes is crossed. It could be confirmed that crossing the unstable regions of Hofmann’s chart leads to measurable increase of transverse emittances. The simultaneous decrease of longitudinal emittance was not measured since no device for that was available. However, the decrease was observed in simulations.

REFERENCES