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 Alveraz 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]

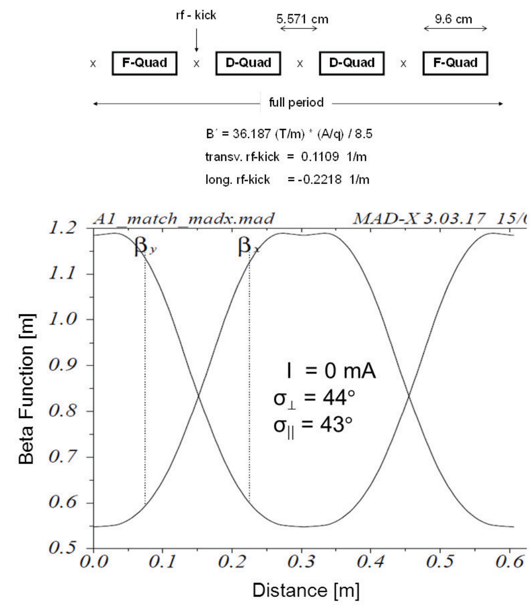

Figure 1: First period of the first DTL of the UNILAC together with an example for transverse periodic solutions.

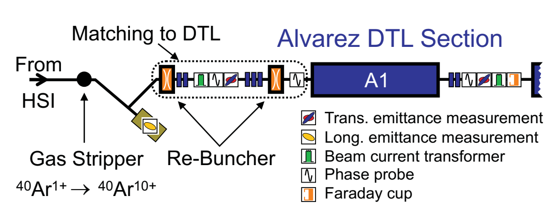

Figure 2: Schematic setup of the experiments (not to scale) [3].

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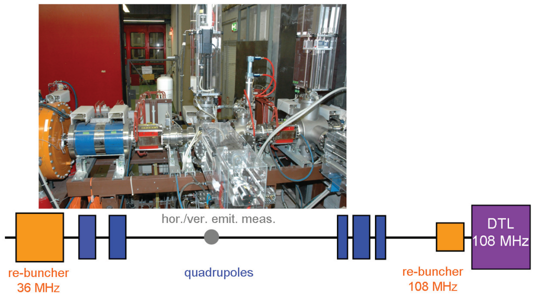

Figure 3: Photograph of the matching section preceding the DTL.

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

$$F(f_1...f_7) = M_x^3(...) + M_y^3(...) + M_z^3(...) \quad (1)$$

as a function of the seven focusing strengths in the matching section, the matching is optimized for the setting $f_1 \ldots f_7$ that minimizes F. Minimization of F is done numerically. The residual mismatches achieved in experiments are $0.6/ \leq 0.4/0.1$ in the long./ver./hor. plane. Longituidinally 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 $^{40}Ar^{10+}$ 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.

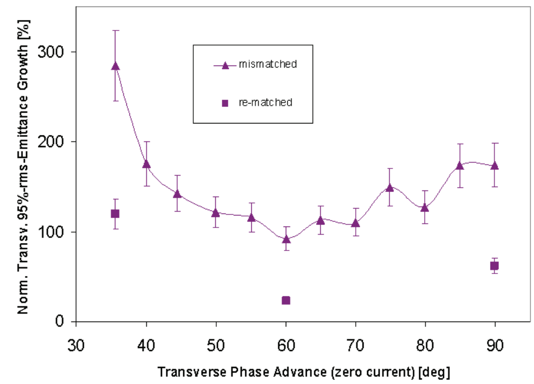

Figure 4: Growth of the mean value of horizontal and vertical 95% rms emittance as a function of the transverse zero current phase advance for a mismatched and for a matched injection into the DTL [6].

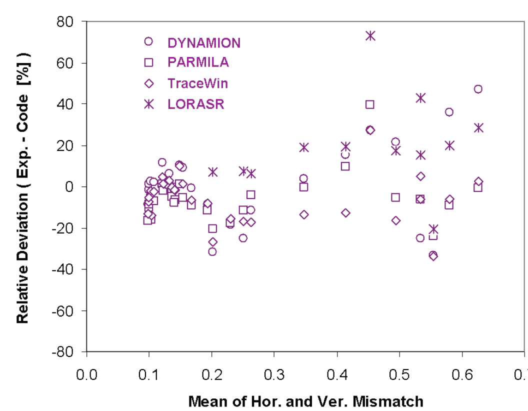

Figure 5: Relative deviation between final transverse rms emittances as measured and as predicted by simulation codes versus the mean of horizontal and vertical mismatch to the DTL. The longituidanal mismatch was constant at 0.6.

FOURTH ORDER AND PARAMETRIC RESONANCES

The transverse envelope instability together with mismatch [8] was considered the cause of emittance growth at 90° 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 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° of

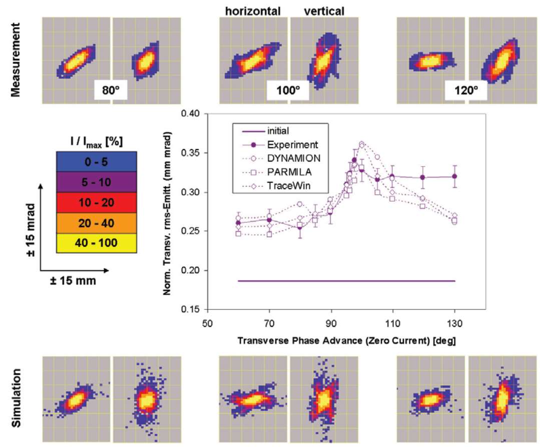

Figure 6: Upper and lower [3]: phase space distributions at the exit of the first DTL tank as obtained from measurements and from the DYNAMION code for phase advances $\sigma_{\perp,o}$ of 80°, 100°, and 120°. Left (right) side distributions refer the horizontal (vertical) plane. The scale is ±15 mm and ±15 mrad. Fractional intensities refer to the phase space element including the highest intensity. Center: Mean of horizontal and vertical normalized rms emittance behind the first DTL tank as a function of $\sigma_{\perp,o}$.

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 rises for even ratios of longitudinal to transverse tunes [10] and beams with different emittances in the longituidinal 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 reveiling 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 instable 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.

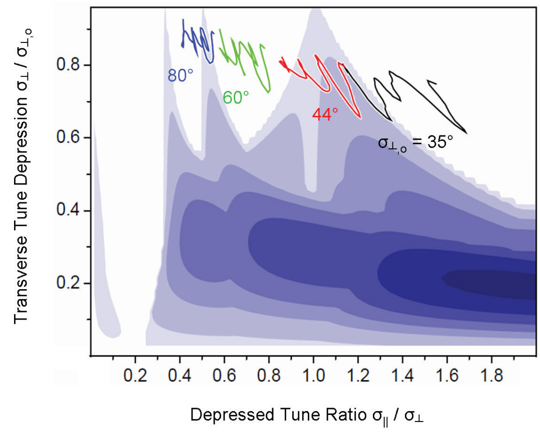

Figure 7: Hofmann stability chart and beam paths during the experiments for transverse to horizontal rms emittance ratio of 10 and simulated paths of the depressed tunes for transverse zero current phase advances as indicated [11].

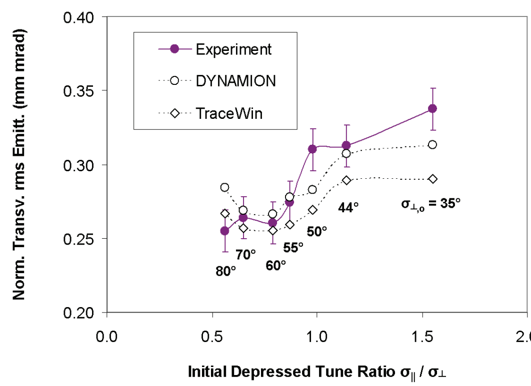

Figure 8: Mean of horizontal and vertical rms emittance at the DTL exit as a function of the initial ratio of depressed longitudinal and transverse tune $\eta = \sigma_{\|}/\sigma_{\perp}$ [11].

REFERENCES

[1] W. Barth et al., Proc. of XXII Linac Conf., (2004).

[2] P. Forck et al., Proc. of the XX Linac Conf., Monterey, U.S.A., (2000).

[3] L. Groening et al., Phys. Rev. Lett. **102**, 234801 (2009).

[4] L. Groening et al., Phys. Rev. ST Accel. Beams **11**, 094201 (2008).

[5] T.P. Wangler, Rf Linear Accelerators, (2nd Ed. Wiley-VCH, Weinheim, 2008), p. 299.

[6] L. Groening et al., Proc. of ICAP2009, San Francisco, U.S.A. (2009).

[7] see Ref. [5], p. 319.

[8] M. Reiser, Theory and Design of Charged Particle Beams, (John Wiley & Sons Inc., New York, 1994), p. 240.

[9] D. Jeon et al., Phys. Rev. ST Accel. Beams **12**, 054204 (2009).

[10] I. Hofmann et al., Phys. Rev. Lett. **87**, 034802 (2001).

[11] L. Groening et al., Phys. Rev. Lett. **103**, 224801 (2009).

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