BEAM LOSS STUDIES FOR HIGH POWER PROTON DRIVERS

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Abstract

Proton drivers with 5 MW average beam power are needed for short pulse spallation neutron sources as well as for neutrino factories. The main design goal is to avoid activation at the linac end and to guarantee loss free ring injection afterwards. Particle loss is caused by the development of a halo around the dense beam core. Only particles with large amplitudes in real space can cause activation. Loss free ring injection however requires at the linac end very limited energy and phase fluctuation of the bunch center and an unfilamented 6d phase space distribution.

Numerical results are presented for noticeable mismatch later on caused by correlated field errors for bunched beams in periodic focusing channels. Monte Carlo simulations are shown for the 214 mA ESS linac by assuming a matched input distribution, but $\pm 1\%$ correlated field errors at 70 MeV for a limited number of periods. Clearly visible is then at the 1334 GeV final energy more than 10% mismatch of all 3 beam radii, modest halo formation and quite large shift in energy and phase of the bunch center.

For a space charge effected, but not dominated linac design, the single particle amplitude is limited to twice the initial mismatched core size. But in phase space single particles can have values above $40 * \epsilon_{rms}$ for 30% mismatch of an unfilamented beam at the entrance of the high energy linac section. This case represents halo formation caused by current fluctuations and accumulated field errors.

1 BEAM LOSS BY EXCITING A 90^O RESONANCE DUE TO CORRELATED FIELD ERRORS

Particle loss is caused by the development of a halo around the dense beam core, driven by mismatch, high space charge and temperature anisotropy. For realistic particle distributions with nonlinear space charge forces, particles inside the beam core can have different tunes. Parametric particle-envelope resonances can occur between the single particle tune and the frequency of the mismatched oscillating beam core [1].

In a periodic focusing channel additional resonances and instabilities, which don‘t exist in an uniform channel, can influence the single particle motion. The envelope-lattice instability effects the whole bunch, whereas especially the 90^o particle-lattice resonance drives single particles either to large radial or axial amplitudes . A parametric particle -lattice resonance can be excited either by temperature exchange or by mismatch [2].

For a space charge effected, but not dominated linac design with moderate temperature anisotropy, visible halo formation requires about 30% mismatch of the 3 beam radii if the envelope-lattice instability and either radial or axial 90^o particle-lattice resonances are avoided . As field errors are typically at the % level, it is generally believed that field errors cannot be lead to 30% mismatch of the beam radii. The argument is correct for uncorrelated field errors in an uniform focusing channel. But it is not necessarily valid for correlated field errors in a periodic focusing channel.

In Fig. 1 the oscillations of the rms phase width are shown for matched zero current beam in a periodic transport channel with 90.3^o longitudinal zero current tune. For the first 40 focusing periods, correlated RF errors of +1% resp. -1% from period to period are assumed. After 20 ”superperiods”, no error distribution is applied. Clearly visible are amplitude modulated phase oscillations with 180^o/period in the error free transport channel above period number 40. The phase width differs by more than 10% from its matched input value, compared to about 0.25% as expected from an uniform focusing channel with 1% field error. The reason is the enforced superperiod with its about 180^o longitudinal zero current tune. Having +1% resp. -1% field error from period to period in an uniform focusing channel, these superperiod channel is unstable for an error free longitudinal zero current of $90^o \pm 0.3^o$.

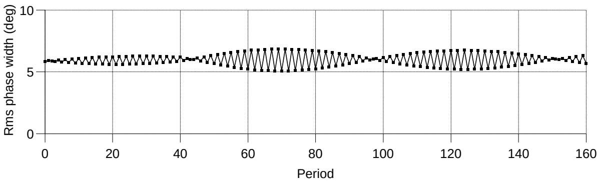

Figure 1: Phase oscillation for a matched zero current beam with (+1%,-1%) correlated RF-errors over 40 periods

In Fig. 2, 2d projections of a matched 214 mA bunched beam are shown after 160 focusing periods again by assuming correlated RF errors of +1% resp. -1% from period to period for the first 20 superperiods. The transverse zero current tune is 92^o. The resulting maximal transverse beam radii are greater than 3 times the initial ones, whereas the maximum phase width is only 1.5 times the initial one. Both transverse phase planes show a small beam core surrounded by many halo particles. In the longitudinal phase plane however the initial bunch core is still existing, but few single particles have an energy spread twice as large than the maximum initial one. The not shown error free, but by 30% initial mismatched case leeds to very similar particle distributions after 160 periods [2].

For a high power linac layout the radial and axial zero current tunes should be below 90^o which can result in low-

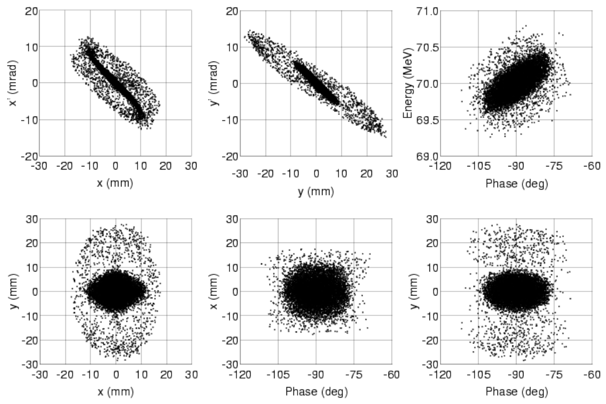

Figure 2: Particle projections after 160 periods for a matched 214 mA beam with (+1%,-1%) RF - errors

ering the accelerating gradients. In addition there can be an envelope-lattice instability if the mode frequency of the in phase radial-axial high mode is nearby 180^o. As a rule of thumb, also the envelope-lattice instability is avoided by choosing the radial and axial zero current tunes below 90^o each.

2 HALO FORMATION BY EXCITING A 60^O RESONANCE DUE TO CORRELATED FIELD ERRORS

In most high intensity linac layouts crossing either the 60^o transverse or longitudinal zero current tune value cannot be avoided. By assuming a correlated field error sequence of (+1%, 0%, -1%) resp. from period to period, such a superperiod will lead to halo formation, but the maximal single particle amplitudes are limited here.

In Fig. 3 the rms radius in y-direction and the phase width are shown for a matched zero current beam in a periodic focusing channel by assuming (+ 10%, 0%, - 10%) RF field errors for 10 superperiods. The transverse resp. longitudinal zero current tunes are 60.4^o resp. 59.96^O. After 30 periods both shown radii oscillate with 120^O /period. The radial oscillations are caused by the radial defocusing part of the RF field. Both beam radii are increased by about 50% in the 10 superperiods.

In Fig. 4 y-rms radii oscillations are shown for beams by assuming (+1%, 0%, -1%) quadrupole field errors for 10 superperiods either for a matched zero current or a full current beam. The zero current beam is the same as of Fig 3. The transverse focusing period consists of a long RF section, followed by a short doublet connected to one power supply. For the zero current beam, the by (+1%, 0%, -1%) doublet errors caused radial oscillations looks very much the same as the in Fig. 3 shown oscillations caused by (+10%, 0%, -10%) RF field errors .

The full current beam has equal transverse and longitudinal temperatures and very moderate tune depressions. The in phase high mode frequency is 116^O for the error free case. The by (+1%, 0%, -1%) quadrupole field errors caused radial oscillations, again with about 120^O/period, looks very much the same as the for the zero current beam case. For a zero current beam, quadrupole field errors cannot cause any kind of longitudinal phase oscillations. For a full current bunch however, there exists a pure transverse quadrupolar eigenmode [3], but its required equal amplitude and out of phase oscillation cannot be fulfilled by a doublet connected to one power supply only. After about 60 focusing periods all 3 rms radii are oscillating in phase with about 20% amplitude and 120^O/period, as expected for the in phase radial-axial high mode, see Fig. 4 and Fig. 5. Due to the modest tune depressions of only 0.86, no halo formation is caused by these 20% beam radii oscillation .

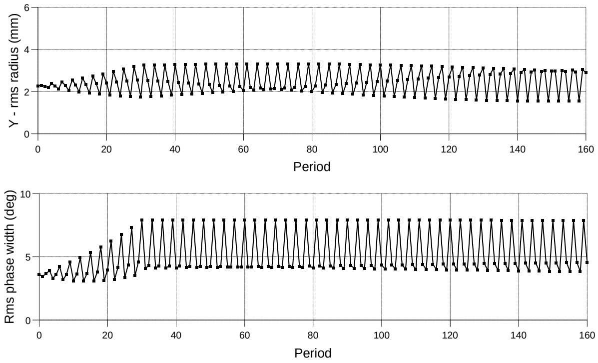

Figure 3: Beam radii oscillation for a matched zero current beam with (+10%, 0%, -10%) RF - errors

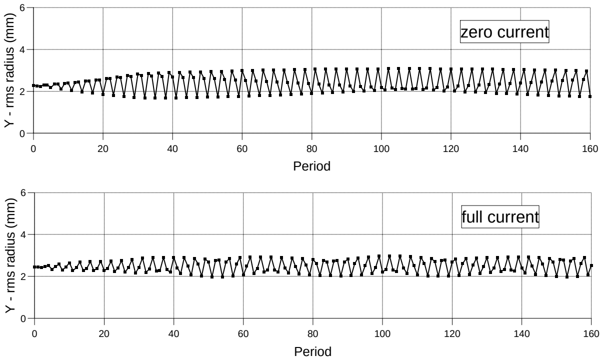

Figure 4: Transverse oscillations for a matched zero and full current beam with (+1%, 0%, -1%) doublet - errors

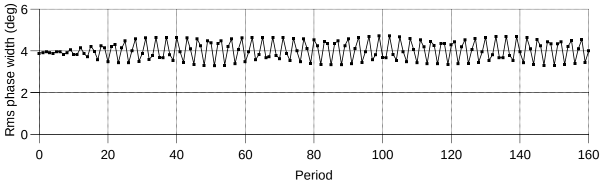

Figure 5: Resulting phase oscillations for the same full current beam as before

3 MONTE CARLO SIMULATIONS OF THE ESS LINAC

All the results above are for a bunched beam transfer line without acceleration. The conclusions are also valid for the design of a high current linac. The difference is the crossing of dangerous particle-lattice resonances, but with tune depressions as small as 0.7.

As an example 10000 particle Monte Carlo simulations results are shown for the 214 mA ESS 700 MHz coupled cavity linac which accelerates the beam from 70 MeV up to 1334 GeV [4]. The ratio between full and zero current tunes is greater than 0.7 both transversely and longitudinally. The ESS linac consists out of 132 focusing periods where a long RF section is followed by a short doublet connected to one power supply. The transverse zero current tune is 92^o at injection and decreases below 60^o above 230 MeV. For the error free matched case there are no particles outside $15 * \epsilon_{rms}$ at the linac end [2]. The maximum single particle amplitude is limited to 2 times the initial mismatched core size even for 30% mismatch at 70 MeV [5].

In Fig. 6 the y-rms radii along the ESS linac are shown for the error free case and by assuming (+1%, 0%, -1%) quadrupole field errors for the first 10 superperiods from 70 MeV to 322 MeV on. At the ESS linac end about 10% radii oscillations are excited compared to the error free case. Modest halo formation is the consequence : there are about 10^{-3} particles outside $15 * \epsilon_{rms}$ at the linac end.

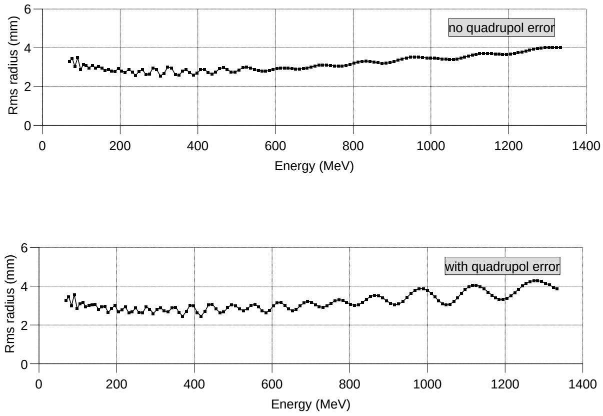

Figure 6: Rms beam radius along the ESS linac for the matched case (upper graph) and by assuming (+1%, 0%, -1%) doublet - errors (lower graph)

In Fig. 7 the energy and phase oscillation of the bunch center are shown by assuming (+1%, 0%, -1%) RF field errors for the first 10 superperiods from 70 MeV to 322 MeV on. The by 10 superperiods caused energy and phase shift at the linac end is about the same as the rms values of distributions obtained by doing many calculations with $\pm 1\%$ and $\pm 1^o$ uncorrelated RF errors.

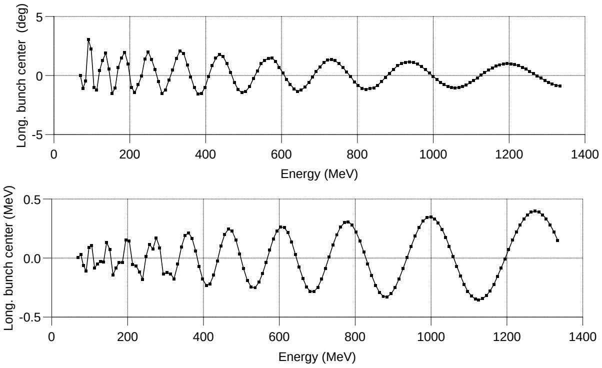

Figure 7: Energy and phase oscillation of the bunch center caused by (+1%, 0%, -1%) RF - field errors

For a space charge effected, but not dominated linac design with moderate temperature anisotropy and by avoiding lattice resonances and instabilities, the single particle amplitude is limited to twice the initial core size for up to 30% mismatch of an unfilamented beam. Similar results are obtained by particle - core simulations of dc beams in a periodic quadrupole focusing channel [6]. But in phase space more than 10^{-3} particles can be outside $20 * \epsilon_{rms}$ going up in phase space above $40 * \epsilon_{rms}$ [2]. These halo formation especially in the longitudinal plane can cause activation of following compressor rings.

The halo formation caused by current fluctuation, filamented RFQ output distribution and accumulated field errors can be represented by 30% mismatch of an unfilamented beam at the entrance of the error free high energy linac section. By exciting separately all 3 bunched beam eigenmodes with its different amplitude ratios, the maximum halo formation is similar to one obtained from many different runs with errors. But the bunch center is shifted in energy and phase due to RF field errors, which has to be considered by reducing the energy spread before ring injection. For the layout of the ESS linac to ring transfer line, there are less than 10^{-4} particles outside ± 2 MeV after bunch rotation, including halo formation caused by 30% mismatched at 70 MeV and ± 4 MeV resp. $\pm 6^o$ final shift of the bunch center [5].

4 REFERENCES

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