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A STUDY OF FAILURE MODES IN THE CLIC DECELERATOR*

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Abstract

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Abstract

The CLIC Drive Beam decelerator is responsible for producing the RF power for the main linacs, using Power Extraction and Transfer Structures (PETS). To provide uniform power production, the beam must be transported with very small losses. In this paper failure modes for the operation of the decelerator are investigated, and the impact on beam stability and loss levels is presented. Quadrupole failure, PETS inhibition and PETS RF break down scenarios are being considered.

INTRODUCTION

The CLIC decelerator transports a very high-intensity electron beam where the deceleration induces up to 90% energy spread at the end of the lattice. A tightly focusing FODO lattice ensures transport of particles in the entire energy range and mitigation of the transverse wake fields induced by the PETS. Quadrupole failure leads to blow-up of the beta function as well as effective kicks with respect to a steered trajectory. A mechanism to inhibit the PETS in case of structure break down is planned. The PETS inhibition will change the wake modes, and thus affect the trajectory. In this paper the effect on the beam stability and beam losses for a number of quadrupole/PETS failure and operational scenarios has been quantified by simulation.

METHOD

The input parameters for this study, slightly adapted in order to achieve a maximum energy spread of S=0.90, are based on [1] and [2] and are summarized in Table 1.

There are 24 CLIC decelerator sectors along each linac, differing in length depending on the number of empty PETS slots in the FODO cells, which again depends on the main linac design. For this study a decelerator of 960 m is considered (70% of all possible slots are filled with PETS).

Simulations have been performed using the simulation code PLACET [3]. The PLACET PETS model includes both long and short range wakes. The monopole mode decelerates the beam, and the set of dipole modes kicks the beam transversally. Each mode is defined with amplitude, frequency, damping factor and group velocity, based on field simulations of the PETS [4]. Nominal PETS parameters are used for the simulations. Higher order modes are not taken into account. The beam is modeled as slices in z with varying energy and with second order moments to represent the transverse particle distribution of each slice. Simulating the real pulse length of 240 ns is too CPU intensive. Because of the high Q-factors enough bunches to incorporate most of the wake effect must be simulated (50 used), and to ensure convergence of the single-bunch effects enough slices per bunch must be used (51 used). The real length is mimicked by weighting the last simulated bunch appropriately in the BPMs. For loss studies the beam transverse size was simulated by transversally distributing 11 zero-emittance macro particles for each slice, simulating one dimension with losses taken at $a = a_0/\sqrt{2}$. It was verified that the loss levels were approximately the same for longer simulated beams. The loss levels calculated in this study is our best estimate, but should be taken rather as order of magnitude calculations than precise number.

Table 1: Decelerator lattice and beam parameters.

Parameters	Symbol	Value	Unit
Beam parameters			
Decelerator sector length	L	960	m
Bunch separation	z_{bb}	25	mm
Bunch rms length	σ_z	1.0	mm
Bunches per train	n	2900	-
Initial average current	I_0	94.7	A
Initial energy	E_0	2.35	GeV
Final max. energy spread	S	90.0	-
Initial norm. emit.	$\epsilon_{\mathrm{n\,x,y}}$	150	μm rad
PETS parameters			
Frequency	f_L	12.00	GHz
Impedance [linac conv.]	R'/Q	2.22	kΩ/m
Group velocity	β_g	0.46	-
PETS half-aperture	a_0	11.5	mm
Lattice parameters			
FODO cell length	L_{cell}	2.0	m
FODO phase-advance	μ_{cell}	92	deg
Average beta function	β	1.9	m
Quadrupole misalignment	σ_{quad}	20	μm
BPM misalignment	σ_{BPM}	20	μm
BPM resolution	σ_{res}	2	μm
PETS misalignment	σ_{PETS}	100	μm
Pitch/roll misalignments	$\sigma_{\theta,\phi}$	1	mrad

For some of the studies in this papers losses are calculated, while for others it is of interest to see the relative change of the beam envelope. As standard metric, the 3-σ beam envelope defined as $r = \max \sqrt{(|x_i| + 3\sigma_{x,i})^2 + (|y_i| + 3\sigma_{y,i})^2}$ (maximum along the lattice) is used.

The Drive Beam envelope will increase due to adiabatic undamping as well as dipole kicks due to component misalignment. The need for and use of steering algorithms have been shown in [2], and for the simulations of failure modes we look at results for the cases of uncorrected ma-

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chines (NC), machines corrected using simple 1-to-1 steering (SC) and dispersion-free steered machine (DFS). For each of these steering approaches we average the results over a number of random machines.

LATTICE FOCUSING

The quadrupoles will be scaled such that the lowest energy particles have a constant phase-advance per cell ($\mu_{cell} \approx 90^o$). For a perfect machine, higher energy particles will then be contained in the envelope [5]; the maximum envelope of the lowest energy slice is $(\gamma_i/\gamma_f \varepsilon\hat{\beta})^{1/2} = (10\varepsilon\hat{\beta})^{1/2}$, while for the highest energy it is $(\varepsilon\hat{\beta}_{max})^{1/2} \approx (4.6\varepsilon\hat{\beta})^{1/2}$. We note that as a consequence of the focusing strategy, the FODO stability limit is surpassed at the lattice end if the initial beam energy is too low by a factor $E_{unstable}/E_0 < (1-S)(\frac{\sin(\mu/2)}{\sin(180^0/2)}) + S \approx 0.97$. Because the deceleration scales with current, there is a similar limit for the current: $I_{unstable}/I_0 > \frac{1}{S} - (\frac{1}{S} - 1)\frac{\sin(\phi_0/2)}{\sin(180^0/2)} \approx 1.03$.

Because the quadrupole strength decays linearly along the lattice, a possibility is to put families of quadrupoles in series to limit the number of power supplies. The impact of this will be analyzed below.

QUADRUPOLE FAILURES

We first investigate the effect of random quadrupole failures (failure implies here k=0). Total losses over machines where N random quadrupoles have failed are calculated (averaged over 10 machines) . We note that failure of a quadrupole results in up to 25-fold magnification of the beta function for the lowest energy particles. Figure 1 shows the percentage of the beam lost for 0 to 5 quadrupole faults. For an uncorrected machine, several percent of the beam is lost even with one quadrupole failure, while for a corrected machine one quadrupole failure leads to subpercent loss level. Study of loss maps (not included here) shows that for single quad failure, the average losses take place uniquely at the last part of the machine, as expected by the envelope growth. The effect of failure when F or D quadrupoles fail in pairs is shown in Figure 2. Here even corrected machines suffer from 10% loss levels for a single failure.

QUADRUPOLE POWER RIPPLE

In order to get an estimate of the power supply precision needed, the effect of power ripple is simulated by putting random noise on the quadrupole strength and average over a 100 machines. Figure 3 shows the envelope growth compared to the same machines with no ripple. Ripple up to 10^{-3} is accepted without significant envelope increase . If power supplies are connected in series, the ripple will be correlated. For completeness Figure 4 shows the extreme case where all F's are scaled together and all D's are scaled together. The ripple is now negligible, as expected.

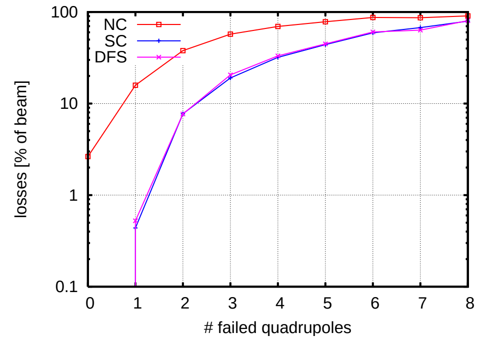

Figure 1: Independent quadrupole failure

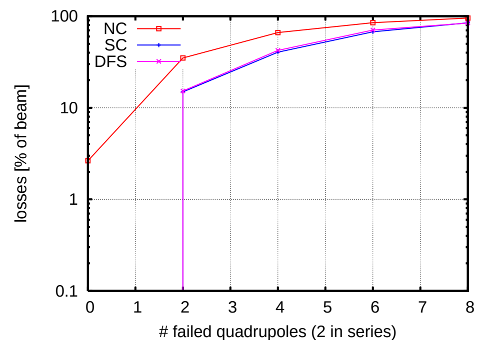

Figure 2: Quadrupole series failure

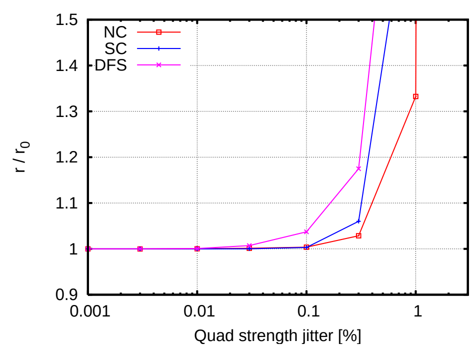

Figure 3: The effect of quadrupole jitter

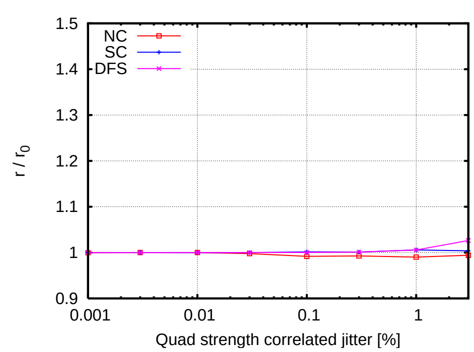

Figure 4: The effect of quadrupole jitter - all quads of one family in series

PETS

The Effect of PETS Inhibition

The lattice contains up to two PETS between each quadrupole, where each PETS extracts $\sim 0.1\%$ of the beam energy. During machine operation it will be necessary to inhibit PETS power production in case of structure breakdown. One mechanism being considered is detuning wedges, described in [4]. The wedges occupy four out of the eight transverse damping slots. A worst-case estimate of how the transverse modes are affected is therefore to double all the transverse Q-factors. In the simulations a PETS is inhibited by setting R'/Q to 0 while doubling Q_T. Inhibiting a PETS affects the beam as follows:

- the lack of deceleration leads to higher minimum beam energy and thus less adiabatic undamping and less energy spread
- dipole wake kicks increase; for a steered trajectory the change of kicks will in addition spoil the steering
- the coherence of the beam energy will increase, and thus also the coherent build up of tranverse wakes

For all the points above we expect the effect to be small for few PETS. However, it is of interest to know how the machine performs with a large number of PETS inhibited. Figure 5 shows the relative change in beam envelope when a number of PETS are inhibited at random positions (averaged over 100 machines). For a dispersions-free steered machine there is indeed a slight decrease of the beam envelope whenever less than 2/3 of the PETS are inhibited. However, for all steering scenarios we observe envelope growth when the major part of the PETS is inhibited.

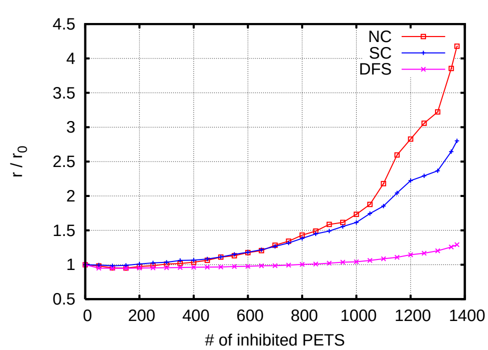

Figure 5: The effect of PETS inhibition

PETS Break Down Voltage

An RF break down will induce transverse voltage in the PETS, with an amplitude depending on many factors, including PETS design. In this section we estimate the maximum acceptable PETS transverse voltage by finding the voltage needed to kick an initial unperturbed beam in a perfect machine so that the maximum centroid envelope along the lattice is 1 mm. An analytical estimate is found as $U = \Delta y' \times E = \frac{r}{A\hat{\beta}} / \sqrt{\frac{E_i}{E_f}} \times E_i = \frac{r}{A\hat{\beta}} \sqrt{E_i E_f}$, where E_i is the energy at the kick location, $\frac{E_i}{E_f}$ the effect of adiabatic undamping, $\hat{\beta}$ the beta function at the kick locations (worst case assumed, $\beta = \hat{\beta}$). A is an estimate for the transverse wake amplification, set to $A = 1.2$ based on previous experience. Figure 6 shows the estimate as well as simulation results (PETS are located at points of varing beta function, and there are varying patterns of empty "slots"). We conclude that, with our criterion of maximum 1 mm centroid motion, there is an acceptance of about 200 kV at the start of the lattice, decreasing towards 50 kV towards the end of the lattice.

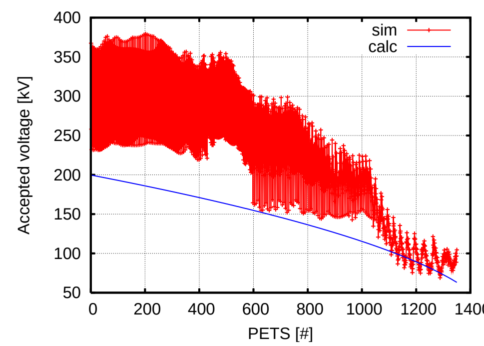

Figure 6: Maximum accepted PETS break down voltage

CONCLUSIONS

A properly steered machine behaves better than an uncorrected one also wrt. failure modes. For a steered machine we conclude: more than two simultaneous quadrupole failures leads to unacceptable loss levels. Quadrupole power supply jitter is acceptable up to 10^{-3}. Inhibiting up to 1/3 of the PETS is not severe for beam stability (up to 2/3 for a dispersion-free steered machine). PETS break down voltage up to 50-200 kV is acceptable for beam stability, depending on PETS position.

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REFERENCES

[1] CLIC parameters 2008, F. Tecker ed., to be issued., *CERN CLIC-Note* (2008)

[2] E. Adli and D. Schulte, Beam-Based Alignment for the CLIC Decelerator, MOPP001, these proc.

[3] D. Schulte et al. *CERN/PS 2001-028* (AE) and *PAC 2001* (2001)

[4] I.Syratchev et al., High RF Power Production for CLIC, *CERN CLIC Note 720* and *PAC 2007* (2007)

[5] The CLIC RF Power Source, H. H. Braun and R. Corsini (eds.), *CERN Yellow Report 99-06* (1999)