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FAST BEAM-ION INSTABILITY IN CTF3

An estimation of vacuum requirements for CTF3

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Abstract

This note investigates the fast beam-ion instability for CTF3 with the purpose to estimate the vacuum requirements for CTF3. Theoretical formulas from an unpublished CLIC Note by T.O. Raubenheimer and D. Schulte were used to determine the instability thresholds.

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Abstract
This note investigates the fast beam-ion instability for CTF3 with the purpose to estimate the vacuum requirements for CTF3. Theoretical formulas from an unpublished CLIC-Note by T.O. Raubenheimer and D. Schulte [1] were used to determine the instability thresholds.

Fast Beam-Ion Instability

The fast beam-ion instability is caused by the interaction of the charged electron beam and the rest gas molecules in the beam pipe. The molecules get ionized by a passing electron bunch and can rest 'trapped' in the center of the beam pipe leading to deflections within following bunches. This single pass effect can lead to emittance growth along the bunch train, especially at the end of the bunch train. The fast beam ion instability was observed in the Advanced Light Source [2].

The trapping condition is fulfilled if the transverse velocity of the ions is so small that they stay within the bunch size before the next bunch arrives which pulls them back in. This condition is expressed in a transverse frequency *fi* which has to be smaller than the bunch repetition frequency.

$$4f_i \le \frac{c}{L_{sep}}$$

The bunch repetition frequency is expressed as the ratio of the speed of light c and the bunch distance L_{sep}. The transverse ion frequency can be calculated using the following formula, where Q_i is the ion charge in units of the elementary charge, N is the number of electrons per bunch, r_e is the classical electron radius, m the electron mass, M the ion mass and σ the beam size. This formula assumes a round beam.

$$f_i = \frac{c}{\pi\sigma}\sqrt{\frac{Q_i N r_e \frac{m}{M}}{6L_{sep}}}$$

Ones this trapping condition is fulfilled the instability can be described with a characteristic rise time τ_e. The rise time below is again a simplified expression for round beams taking into account the variation of the ion frequency due to the changing lattice parameters. According to the reference mentioned there is some experimental uncertainty concerning this rise time but for the estimations of this note it should be good enough.

$$\frac{1}{\tau_e} = \frac{P\sigma_{ion}}{kT}\frac{N n_B r_e c}{\sqrt{72}\varepsilon a}\frac{1}{\sqrt{Q_i}}$$

Here P is the partial gas pressure of the relevant ion species, σ_{ion} is the ionization cross section, n_B the number of bunches in the train, ε the beam emittance and kT the Boltzmann factor. The parameter a is used to consider the lattice and can be estimated to about 0.1 for a FODO lattice.
The emittance will start to grow if the beam stays longer in the machine than this characteristic rise time. The instability can't grow if the condition $t / \tau_e \sim 1$ is met.

CTF3 beam parameters

L_{sep}:	10/20 cm	3/1.5 GHz bunch repetition rate
N:	$1.4/2.0\ 10^{10}$	Nominal/PETS mode
n_B:	2100	
ε:	100 μm	
σ:	10-100 μm	
t:	330/500/1650 ns	Linac/+Delay Loop/+Combiner Ring

Instability conditions in CTF3

In a baked vacuum system the rest gas is dominated by Hydrogen and CO as a typical heavy molecule. A not baked system would be largely dominated by water vapor. It can be seen in the formulas that the heavy molecules are more relevant. The following calculations assume CO^+ molecules. The ionization cross section for CO and tens of MeV electrons is about $2*10^{-22}$ m^2 [1].
The transverse frequency for CO in CTF3 amounts to 28 MHz taking the worst case in all parameters. Consequently the rest gas ion can be trapped in CTF3. In the case of a smaller beam (10 μm), Hydrogen Atoms and 20 cm bunch spacing, the transverse frequency goes up to 1.5 GHz and the trapping condition would be not fulfilled anymore.
However for the following it is assumed that the rest gas ion can be trapped in CTF3.
Using the parameters mentioned above the rise time of the fast beam ion instability accounts to $1/\tau_e = 2*10^{10}*P$ [1/s Pa].
The required rest gas pressures to avoid emittance growth due to fast beam ion instability can be estimated for the different parts of the machine as follows:

Linac:	$< 1.5 *10^{-4}$ Pa	$1.5 *10^{-6}$ mbar
Delay Loop:	$< 1.0 *10^{-4}$ Pa	$1.0 *10^{-6}$ mbar
Combiner Ring:	$< 3.0 *10^{-5}$ Pa	$3.0 *10^{-7}$ mbar

The partial pressure of the most critical heavier ion species like CO are contributing probably only partly to the overall rest gas pressure. However these estimates should be considered as rough and therefore an additional margin of a factor of 10 should be applied.

Conclusion

A rest gas pressure in the low 10^{-8} mbar range should be sufficient to avoid emittance growth from fast beam ion stability in CTF3. The Combiner Ring vacuum is the most sensitive part of the machine due to the multiple passes.

References

[1] T. O. Raubenheimer und D. Schulte, „Fast Beam-Ion Instability in CLIC“, unpublished und unfinished CLIC-Note, private communication with D. Schulte
[2] F. Zimmermann et al. “Experiments on the Fast Beam-Ion Instability at the ALS”, SLAC-PUB-7617, 1997