LIMIT CYCLE INSTABILITY OF PROTON BEAMS GENERATED BY NONLINEAR ELECTRON-COOLING FORCE

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The electron-cooling drag force is provided by a scattering process between protons and cooling electrons, which have a relatively small velocity spread. When the velocity of a proton is larger (smaller) than that of cooling electrons, the energy exchanged resulting from Coulomb scattering give rise to a reduction (boost) in the longitudinal velocity of the proton. Thus, all protons will damp to the velocity of the cooling electrons. The energy gain/loss per revolution for the proton is called the drag force, usually measured in eV/turn/Amp or keV/s/Amp and normalized to an electron beam current of 1 A. For a small velocity deviation between the proton and cooling electrons, the drag force is linearly proportional to the velocity deviation, and is maximum when the velocity deviation is equal to the velocity spread of the cooling electrons. At a large velocity deviation between the proton and cooling electrons, the drag force decreases with the inverse square of the velocity deviation.[1]

The drag force is nonlinear when the velocity deviation is near the velocity spread of the cooling electrons. In the IUCF Cooler nonlinear beam-dynamics experiments, we have found that when the velocity deviation between the proton and electrons is larger than the velocity spread of cooling electrons, the proton will damp to a limit cycle where the threshold of the limit cycle instability is related to the electron temperature and the amplitude of the limit cycle instability can be used to identify the cooling force.[2] We found that the Hopf bifurcation was asymmetric with respect to the relative velocity deviation. This means that protons see a different velocity spread of the cooling electrons at a positive or negative velocity deviation.

In these experiments, we measured the amplitude of the limit cycle as a function of the RF frequency shift, which is equivalent to a change in the proton closed orbit. Thus, if the dispersion functions at the cooling region are not zero, the effective temperature seen by protons may be different due to the space-charge depression of the cooling electrons. This effect can be checked by a proper alignment of the proton beam with respect to the

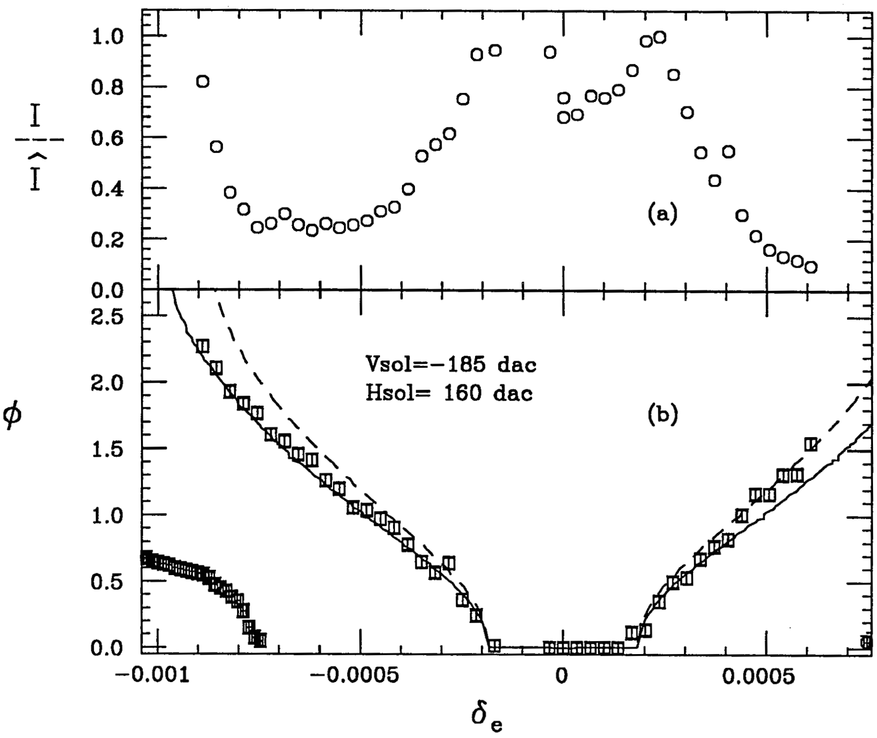

Figure 1. The upper plot shows the beam current vs. $\delta_e = (f - f_0)/\eta f_0$. The lower plot shows the beam response (peak phase and momentum amplitude) in degrees.

cooling electrons. Since cooling electrons are guided by the main solenoid at the point where proton and electron beams merge into each other, the alignment of electrons and protons can be achieved by adjusting the direction of the solenoidal field. For a properly aligned electron beam, the proton closed orbit will be symmetric with respect to the RF frequency shift even in the presence of a possible nonzero dispersion function.

We thus performed experiments with careful beam alignment between the protons and electrons. The lower plot of Fig. 1 shows the measured amplitudes of the limit cycle as a function of the relative momentum deviation $\delta_e = (f - f_0)/\eta f_0$, where f is the RF frequency of the proton beam, f_0 is the reference RF frequency, and η is the phase-slip factor. The upper plot of Fig. 1 shows the corresponding beam current in the Cooler. We note that the Hopf bifurcation is symmetric with respect to δ_e for the aligned proton and electron beams. Furthermore, the beam current correlates very well with the threshold of Hopf bifurcation.

A particularly notable feature in Fig. 1 is the increase in beam current at a somewhat large velocity deviation. This may indicate that the synchrotron bucket can accumulate beam particles with this velocity deviation. In a model calculation, this may provide evidence for a binary collision model of electron cooling.

1. H. Poth, Phys. Rep. **196**, 135 (1990).
2. D.D. Caussyn, *et al.*, Phys. Rev. Lett. **73**, 2696 (1994); Phys. Rev. E **51**, 4947 (1995).