COLLECTIVE EFFECTS IN THE EMMA NON-SCALING FFAG

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Abstract

EMMA is an electron accelerator to study beam dynamics in a linear nonscaling FFAG. We wish to verify that the behavior predicted by the theory and simulation is correct. In particular, we will study a novel accelerating mode outside an rf bucket (so-called serpentine acceleration), and the effects of crossing "resonances." In EMMA, some collective effects become a concern even though the beam stays in the ring for only 10 to 20 turns. We report studies of direct space charge, beam loading, and other collective effects with tracking simulations. There is strong possibility of a negative-mass instability for some operation modes.

DIRECT TRANSVERSE SPACE CHARGE

An electron beam from the ALICE (Accelerators and Lasers In Combined Experiments) Energy Recovery Linac Prototype (ERLP) is very bright with small transverse emittance and short longitudinal bunch length. Consequently, the space charge tune shift in the EMMA ring is not negligible. Assuming the following parameters,

Table 1: Beam parameters.

Lorentz factor γ:	20
Number of particles per bunch N:	5 x 10^8 (80pC)
Normalized rms emittance εn,rms:	3 π mm mrad
Rms bunch length σrms:	0.94 mm
Circumference C:	16m

and using the formula for direct space charge, with Gaussian transverse distribution,

$$\Delta Q = -\frac{N r_e}{4\pi\beta\gamma^2\varepsilon_{n,rms}}\frac{C}{\sqrt{2\pi}\sigma_{rms}}$$

The tune shift becomes -0.68, which is a few times more than that of a high intensity proton synchrotron or storage ring. Although a beam stays in EMMA only for 10 to 20 turns, crossing of systematic resonances, especially ones excited by space charge nonlinear force, is a concern.

We use the following simple and non self-consistent model to evaluate space charge effects, and estimate emittance growth, with a multi-particle tracking simulation. We apply a space-charge kick every 10 mm or 0.033 ns. There are 38 kicks in a cell. Charge distribution is assumed as Gaussian throughout acceleration, but the r.m.s. width of the distribution is updated each time step using the coordinates of macro particles. Initially, we assume equal emittance for horizontal and vertical planes, but not afterward. Although the tracking code has longitudinal motions, the space charge force is assumed to be independent of longitudinal position. Namely, all the particles feel the maximum space charge force as if they are always at the bunch centre.

We varied the number of particles in a bunch from 1× 10^7 (1.6 pC) to 1×10^9 (160 pC) and looked at the emittance evolution. Throughout the study, we assumed that the EMMA lattice has no errors. Longitudinal motion, was modelled by constant energy gain, δE, instead of more accurate serpentine acceleration. The energy gain was adjusted so that acceleration is completed in 8 turns; this corresponds, roughly, to an acceleration parameter a=(δE/ΔE)/(ωΔT) of 1/8. A defining property of the EMMA lattice is a 1:1 map between beam energy and cell tune, so the latter is related to turn number. Figure 1 shows emittance evolution as a function of the cell tune when the number of particle is 5×10^8.

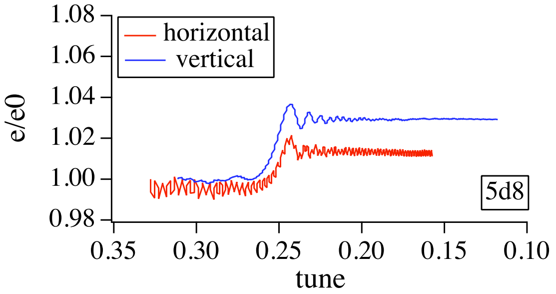

Figure 1: Emittance evolution during acceleration.

It is clear that emittance has a step increase around the cell tune of 0.25 although it appears only when the number of particles is more than 2×10^8. The driving source of the step is the nonlinear force due to space charge [1, 2]. This can be identified in the phase space via four arms extended from the beam's core.

The ratio of the linear and nonlinear components of space charge force can, in principle, be varied through the particle distribution. For example, the nonlinear force becomes zero when the distribution is Kapchinski-Vladimirski (K-V) type. Nevertheless, it is reasonable to assume that the beam from the ERLP has a more or less Gaussian particle distribution and the ratio is similar to what we assumed here. If that is the case, the linear space charge due to 2×10^8 electrons, that is a tune shift of -0.27, gives the threshold for emittance growth due to nonlinear space charge forces.

Another parameter of interested is the acceleration rate. With lower values of parameter a, the number of turns taken to complete acceleration will increase. We have simulated cases with two times and five times slower acceleration. As shown in Figure 2, if the number of particles is less than 1×10^8, then almost no growth occurs even when the acceleration takes 40 turns. There is another concern about space charge effects due to image charge. It is enhanced by the fact that the beam passes through the beam pipe off-centre. This is under study.

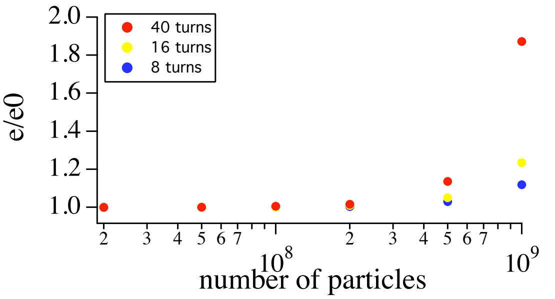

Figure 2: Vertical emittance growth at different acceleration rates.

LONGITUDINAL SPACE CHARGE AND NEGATIVE MASS INSTABILITY [3]

EMMA employs so-called serpentine acceleration as in a muon FFAG [4]. It was realized that parabolic shaped time of flight has transition energy at the centre as shown in Fig. 3. Both above and below transition, space charge collectively acts outwards from the centre of the bunch. However, the response of particles to these forces differs above and below transition. Below transition, there is tendency to debunch which dissipates the space-charge force (positive mass regime). Above transition, the tendency is to rebunch which enhances the space charge force, leading to instability (negative mass regime).

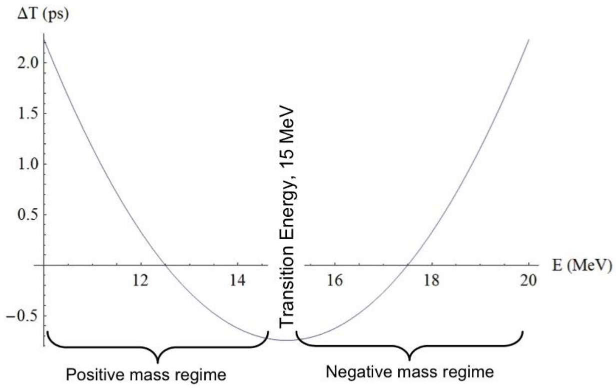

Figure 3: Time of flight between 10 and 20 MeV.

Multi-particle stimulation with the program LONG1D was carried out to look at the effects of longitudinal space charge in the different regimes and with different machine parameters. The rf frequency was chosen so that there are two stable fixed points at (-π/2,12.5) and (π/2,17.5) in units of (radian, MeV) as shown in Figure 4.

Rf acceleration off

First we turned off the rf voltage and observed the evolution of bunch shape at different momentum for the nominal beam current (5×10^8). Below transition energy, space charge promotes faster debunching – via increased energy spread and positive time-dispersion. At (and around) transition energy there appears a microwave-like instability because of the loss of frequency spread. However, it is not a classical microwave instability because the first order time dispersion is zero.

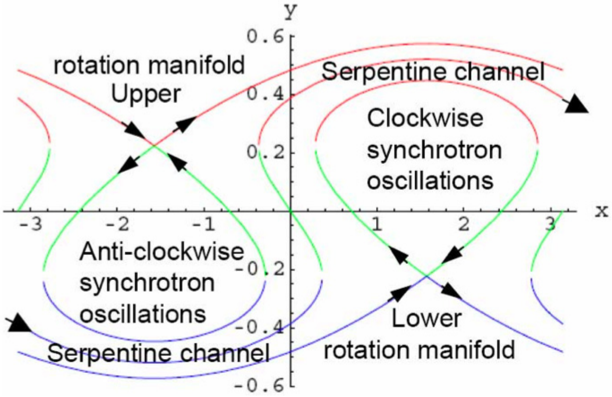

Figure 4: Longitudinal phase space showing serpentine channel. Abscissa is rf phase from –π to +π. x=0 corresponds to the rf crest.

Above transition, space charge promotes rebunching. At around 17.5 MeV, the rebunching and time of flight dispersive tendencies are matched leading to a nearly stable bunch length, but with internal collective motion. At yet higher energy, with a local linear time dispersion, a classical microwave instability develops; see Figure. 5.

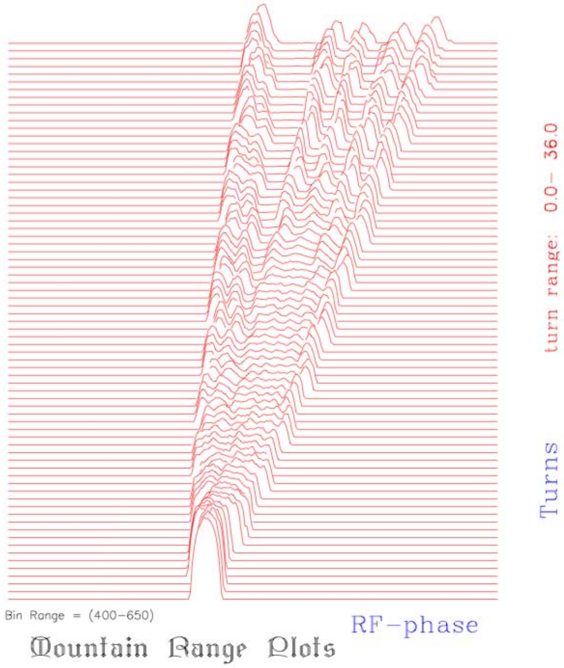

Figure 5: Mountain range plots for a 20 MeV beam. Strong evidence of an instability producing five sub-bunches.

Rf acceleration on

Second, rf voltage is turned on and a beam is injected into the phase space at (-π/2,9.8). There is an average energy again of 0.6 MV/turn. Space charge first promotes debunching and then rebunching as shown in Fig. 6. Although deformation of the bunch internal structure is observed, the motion of the bunch centroid is still dominated by the phase space topology of stable and unstable fixed points which are defined without space charge.

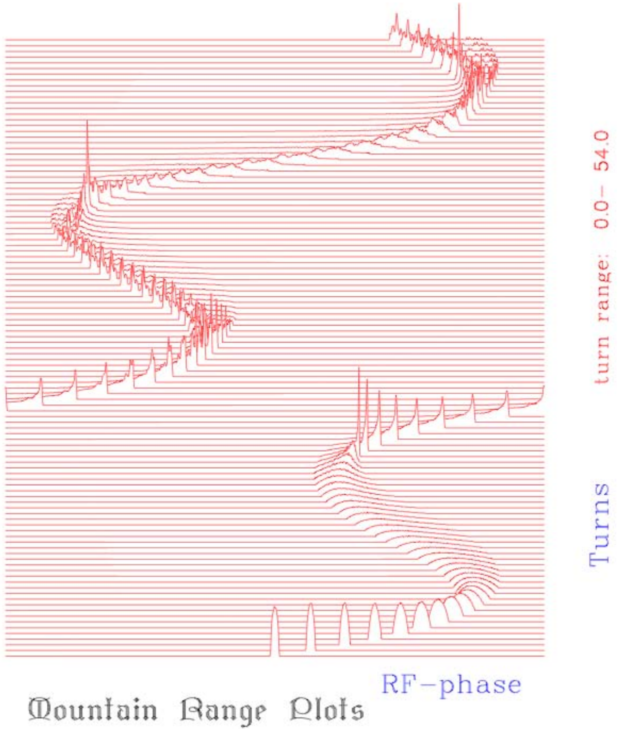

Figure 6: Mountain range plots for a beam accelerated and decelerated with longitudinal space charge.

BEAM LOADING

Rf acceleation on [5]

Beam loading in EMMA was also simulated with LONG1D. The parameters assumed are shown in Table 2.

Table 2: Parameters assumed for the simulation.

Number of cavities:	20
Quality factor:	10,000
Shunt resistance:	2 Mohm
Emittance:	0.375 π eVμs
Energy spread:	0.125 MeV (FW)
Time spread:	12 ps (FW)

We varied applied voltage and beam current to see at what values the deviation of the bunch phase space trajectory from the single-particle motion becomes unacceptable. For example, Figure 7 shows the mountain range plots when the voltage is 0.6 MV/turn and the beam current is 5×10^8. As far as the bunch centroid motion is concerned, deviation is hardly seen with the nominal beam current and even up to 1×10^9 electrons. At 2×10^9 deviation is marked and at 4×10^9, and beyond, the serpentine acceleration is disrupted.

Rf acceleration off

In the early stage of beam commissioning, we may operate EMMA without rf acceleration and measure lattice optics. We studied how the self-induced voltage in rf cavities made momentum oscillations and energy loss as a function of cavity detuning. As shown in Fig. 8, momentum oscillations up to 0.3% are observed with a 1 MHz detuning. The energy loss becomes 1.1% after 1,000 turns, which may deteriorate tune measurement accuracy based on ordinary FFT; but this could be suppressed by larger detuning if the cavity tuning range is enough.

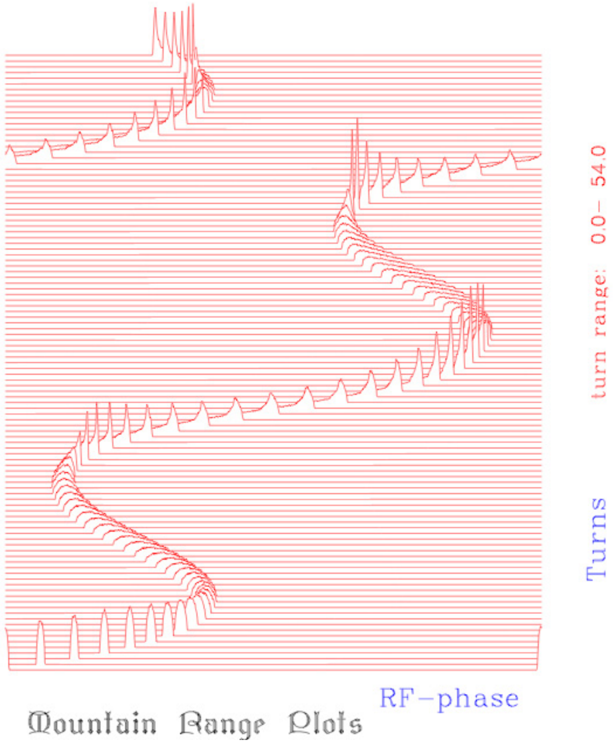

Figure 7: Mountain range plots with beam loading due to the nominal beam current.

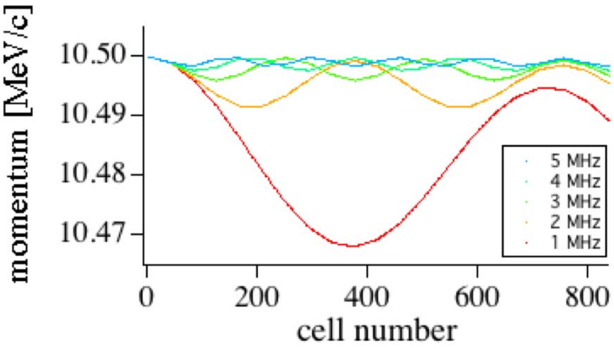

Figure 8: Momentum oscillations due to transient beam induced voltage for the first 20 turns.

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