

STUDY OF FAST INSTABILITY IN FERMILAB RECYCLER

S. A. Antipov, The University of Chicago, Chicago, IL 60637, USA
P. Adamson, S. Nagaitsev, M.-J. Yang, Fermilab, Batavia, IL 60510, USA

Abstract

One of the factors which may limit the intensity in the Fermilab Recycler is a fast transverse instability. It develops within a hundred turns and, in certain conditions, may lead to a beam loss. Various peculiar features of the instability: its occurrence only above a certain intensity threshold, and only in horizontal plane, as well as the rate of the instability, suggest that its cause is electron cloud. We studied the phenomena by observing the dynamics of stable and unstable beam. We found that beam motion can be stabilized by a clearing bunch, which confirms the electron cloud nature of the instability. The findings suggest electron cloud trapping in Recycler combined function magnets. Bunch-by-bunch measurements of betatron tune show a tune shift towards the end of the bunch train and allow the estimation of the density of electron cloud and the rate of its build-up. The experimental results are in agreement with numerical simulations of electron cloud build-up and its interaction with the beam.

FAST INSTABILITY

In 2014 a fast transverse instability was observed in the proton beam of the Fermilab Recycler. The instability acts only in the horizontal plane and typically develops in about 20 revolutions. The instability also has the unusual feature of selectively impacting the first batch above the threshold intensity of $\sim 4 \cdot 10^{10}$ protons per bunch (Fig. 1). These peculiar features suggest that a possible cause of the instability is electron cloud. Earlier studies by Eldred et. al. [1] indicated the presence of electron cloud in the Recycler and suggested the possibility of its trapping in Recycler beam optics magnets.

The fast instability seems to be severe only during the start-up phase after a shutdown, with significant reduction being observed after beam pipe conditioning during beam scrubbing runs [2]. It does not limit the current operation with slip-stacking up 700 kW of beam power, but may pose a challenge for a future PIP-II intensity upgrade.

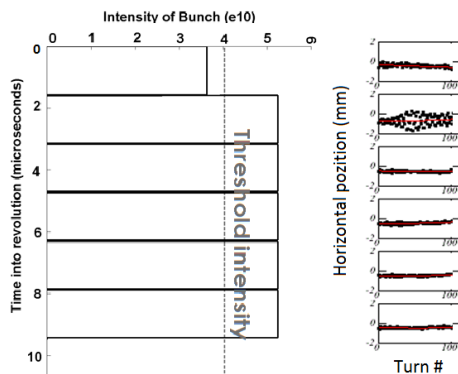


Figure 1: The first batch above the threshold intensity suffers the blow-up after injection into the ring [2].

ELECTRON CLOUD TRAPPING

The most likely candidates for the source of electron cloud in Recycler are its combined function magnets. They occupy about 50% of the ring's circumference. In a combined function dipole the electrons of the cloud move along the vertical field lines, but the gradient of the field creates a condition for 'magnetic mirror' (Fig. 2) – an electron will reflect back at the point of maximum magnetic field if the angle between electron's velocity and the field lines is greater than:

$$\theta > \theta_{\max} = \cos^{-1}(\sqrt{B_0 / B_{\max}}). \quad (1)$$

The particles with angles $\theta_{\max} < \theta \leq \pi/2$ are trapped by magnetic field. For Recycler magnets (Table 1), Eq. (1) gives a capture of $\sim 10^{-2}$ particles of electron cloud, assuming uniform distribution.

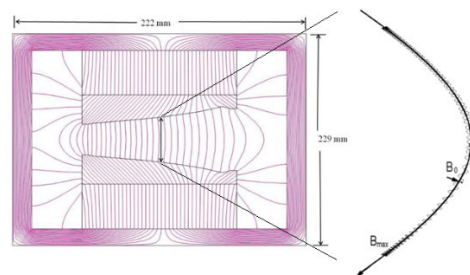


Figure 2: Electron cloud can get trapped by magnetic field of a combined function magnet.

We simulated electron cloud build-up over multiple revolutions in a Recycler dipole using the PEI code [3]. The input parameters of the simulation are summarized in Table 1. For a pure dipole field, the cloud rapidly builds up during the passage of the bunch train and then decays back to the initial ionization electron density in about 300 RF buckets, or $\sim 6 \mu\text{s}$ (Fig. 3). When the field gradient is added, up to 1% of the electron cloud stays trapped, increasing the initial density on the next revolution. The final density, which the cloud reaches after ~ 10 revolutions, is two orders of magnitude greater than in the pure dipole case (Fig. 3). The resulting cloud distribution is a stripe along the magnetic field lines, with higher particle density being closer to the walls of the vacuum chamber (Fig. 4).

At lower densities $\sim 10^{-2}$ of particles are trapped, which agrees with an estimate from Eq. (1); as the density of electron cloud increases the trapping ratio goes down to $\sim 10^{-3}$, probably due to the space charge of electron cloud. A bunch of $5 \cdot 10^{10}$ protons, added 120 RF buckets after the main batch, destroys the trapped cloud, preventing the multi-turn build-up (Fig. 3).

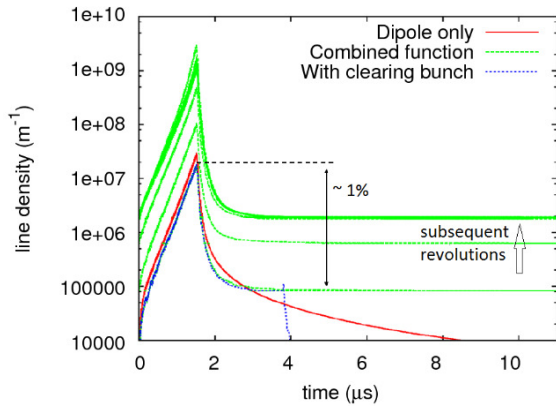


Figure 3: In a combined function magnet the electron cloud accumulates over many revolutions, reaching much higher line density, than in a dipole. A clearing bunch destroys the trapped cloud, preventing the accumulation.

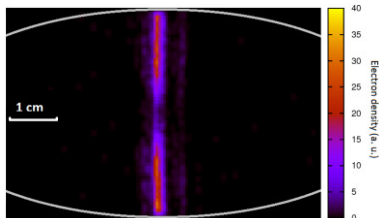


Figure 4: Electron cloud forms a stripe inside the vacuum chamber; its horizontal position - beam center

WITNESS BUNCH TEST

We used a clearing bunch technique, similar to that used at Cornell [4] to check whether the instability is caused by trapped electron cloud. If a trapped electron cloud is present in the machine, a single bunch of high enough charge following the main batch, will kick it and clear the aperture. This clearing of electron cloud then can be noted by observing a change in beam dynamics.

Figure 5 (top) shows the increase beam center oscillations, measured by BPMs, of an unstable batch of $3.6 \cdot 10^{12}$ p. The horizontal oscillations rapidly grow, leading to beam dilution and a loss of a fraction of intensity, then the beam is stabilized by the dampers. When a single clearing bunch of $\geq 1 \cdot 10^{10}$ p is injected in the machine before the high-intensity batch, the later remains stable (Fig. 5, bottom). The position of the clearing bunch does not change the picture – it can be as far as half of the ring (or $\sim 5 \mu\text{s}$) apart from the batch, suggesting that there is a portion of the electron cloud that survives over one revolution, and it can be removed with a clearing bunch. This agrees qualitatively with the simulation of electron cloud build-up and trapping in Recycler dipoles (Fig. 3).

Figure 6 depicts the betatron tune shift within the 80-bunch train with respect to the first bunch, measured over 600 revolutions with a stripline detector, with the dampers off during the measurement. Since the space charge does not change the coherent tune and the resistive wall creates a negative tune shift, the positive horizontal tune shift is a clear signature of the presence of a negative charge at the beam center. The vertical tune shift is negative, indicating

that the maximum density of the cloud is outside the beam, which agrees qualitatively with the simulated distribution (Fig. 4). When a clearing bunch is added, the tune shifts decrease, indicating a reduction of electron cloud density, which agrees with the simulation (Fig. 3). The remaining linear slope in the vertical tune shift is likely to be due to the resistive wall impedance. According to the recent measurements, in Recycler the vertical impedance is about five times larger than the horizontal [5].

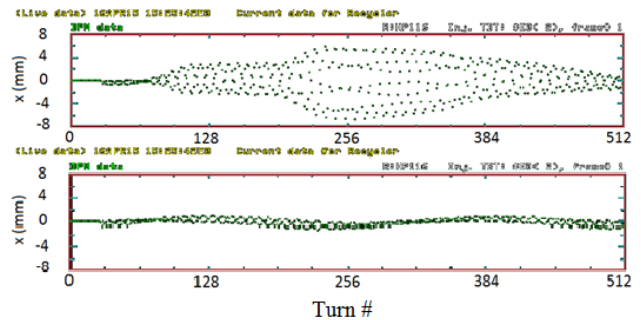


Figure 5: Without the clearing bunch the beam of $3.6 \cdot 10^{12}$ p blows up in about 20 turns (top); with the clearing bunch of $1 \cdot 10^{10}$ p it remains stable (bottom).

In the final test we put a witness bunch of low intensity – $8 \cdot 10^9$ p, insufficient to clear the electron cloud, at different positions behind the high-intensity batch and measured the shift of its betatron tune. We then compared the tune shifts within the batch and after its passage with an estimated tune shift from the electron cloud:

$$\Delta Q = \frac{e^2 n_e R_0^2}{4 \epsilon_0 \gamma m_p c^2 Q}, \quad (2)$$

where n_e is the cloud density at the beam center, obtained from the simulation. The experimental results are in good agreement with the simulation (Fig. 7) and the small discrepancies may come from the multiple assumptions used in Eq. (2): smooth focusing optics, uniform distribution of electron cloud in the ring and throughout the cross-section of the beam pipe.

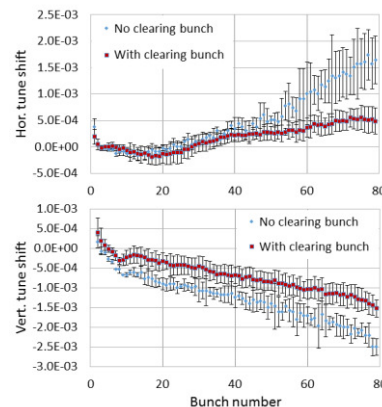


Figure 6: Presence of the clearing bunch reduces the tune shift between the head and the tail of the high-intensity bunch train: $5 \cdot 10^{10}$ ppb, 80 bunches. The error bars represent the spread between different measurements.

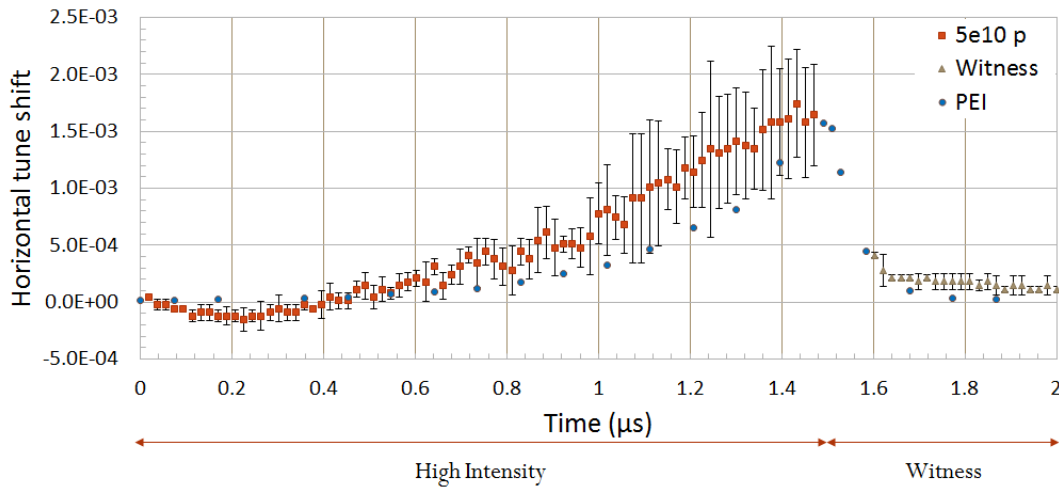


Figure 7: Results of the electron cloud simulation agree with the measured horizontal tune shift. Beam: $5 \cdot 10^{10}$ ppb, 80 bunches, followed by one witness bunch of $0.8 \cdot 10^{10}$ at various positions. The gap between the high-intensity batch and the witness is due to the rise-time of the injection kickers.

The resulting dependence allows to the estimation of the maximum density of electron cloud at the beam center – $n_e \sim 1 \cdot 10^{12} \text{ m}^{-3}$. It grows by an order of magnitude in 40 bunches (800 ns) and falls after the beam has passed in 10 bunches (200 ns). These estimates are necessary for constructing a mathematical model of the instability, which is currently under development at Fermilab.

Table 1: Recycler Parameters for Simulation in PEI

Beam energy	8 GeV
Machine circumference	3.3 km
Batch structure	80 bunches, $5e10$ p
Tunes: x, y, z	25.45, 24.40, 0.003
RF harmonic number	588
RMS bunch size: x, y, z	0.3, 0.3, 60 cm
Secondary emission yield	2.5 @ 250 eV
Density of ionization e^-	10^4 m^{-1} (at 10^{-8} Torr)
B-field and its gradient	1.38 kG, 3.4 kG/m
Beampipe	Elliptical, 100 x 44 mm

CONCLUSION

A fast transverse instability in the Fermilab Recycler might create a challenge for PIP-II intensities. Understanding its nature is important for making predictions about the machine performance at higher intensities.

We have observed that the fast instability can be mitigated by injection of a single low intensity clearing bunch. This finding suggests that the instability is caused by electron cloud and the cloud is trapped in Recycler magnets. Bunch-by-bunch measurements of betatron tune have shown a tune shift towards the end of the bunch train. The

tune shift decreases after the addition of the clearing bunch, which is also consistent with the electron cloud picture.

The most probable source of trapping is the combined function magnets, occupying around 50% of Recycler circumference. According to numerical simulations in PEI, $\sim 10^{-2} - 10^{-3}$ of particles are trapped by magnetic field of those magnets. That allows the electron cloud to gradually build up over multiple turns, reaching final intensities orders of magnitude greater than in a pure dipole.

The results of electron cloud build-up simulation in Recycler combined function dipoles agree qualitatively with the observed stabilization of the beam by a clearing bunch and quantitatively with the measurements of betatron tune shift. According to the simulations, the estimated cloud density is $\sim 10^{12} \text{ m}^{-3}$ and the characteristic times of its build-up and decay are 40 and 10 RF periods respectively.

A more detailed study of electron cloud trapping in combined function magnets and its effect on beam stability is currently under way.

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