New Electron Cloud Instability Mechanism and Its Detection and Suppression

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Outline

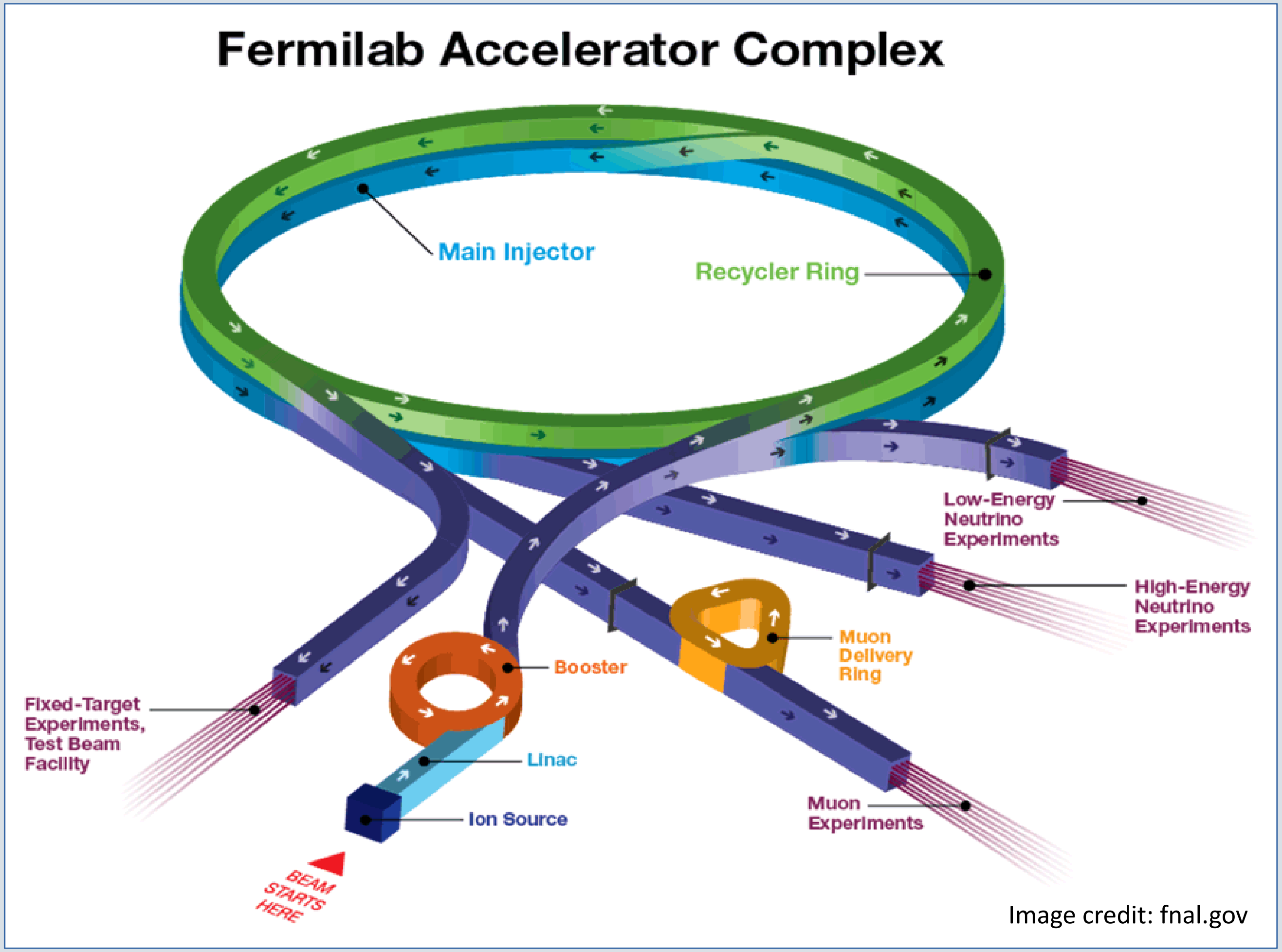
Electron cloud in particle accelerators

Features of the instability in Recycler

Electron cloud trapping in combined function magnets

Stabilization by cleaning bunch

- Different behavior for e-cloud instability in MI & Recycler
- Not a problem in MI, 400 kW obtained
- Significant drawback at the Recycler commissioning
  Took a while to get to the design 700 kW

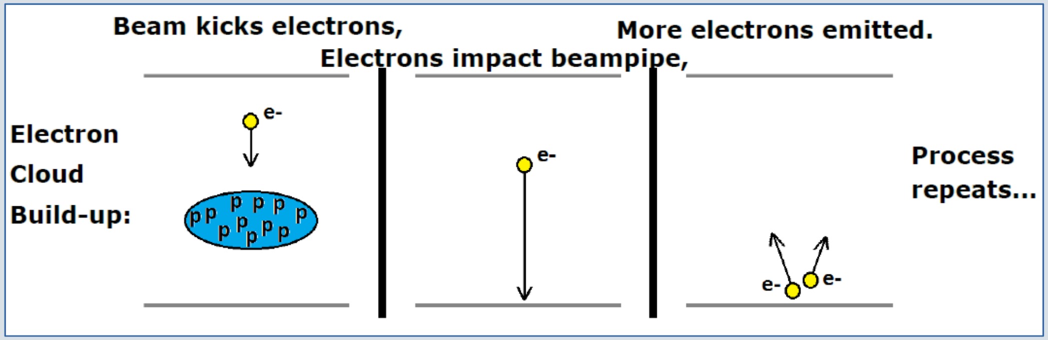


Electron Cloud Build-up

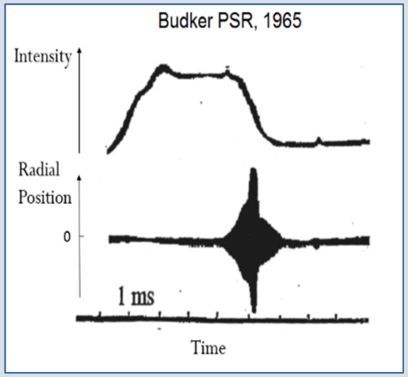
Accumulation of electrons, accompanying the beam starts with
- gas ionization (p) or
- photoemission (e^+)

Beam interaction with the cloud might drive coherent beam instabilities resulting in
- Beam loss, emittance growth
- Observed at ANL, BINP, CERN, LANL, KEK,…

Electron density grows exponentially via secondary emission



Picture by J. Eldred



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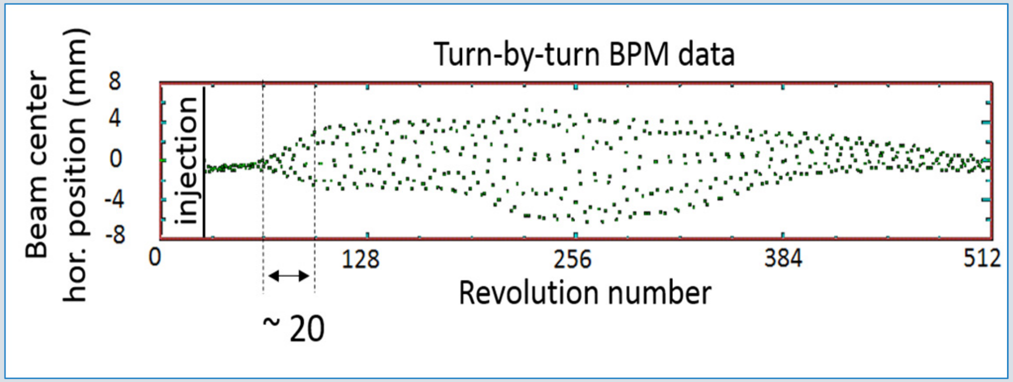
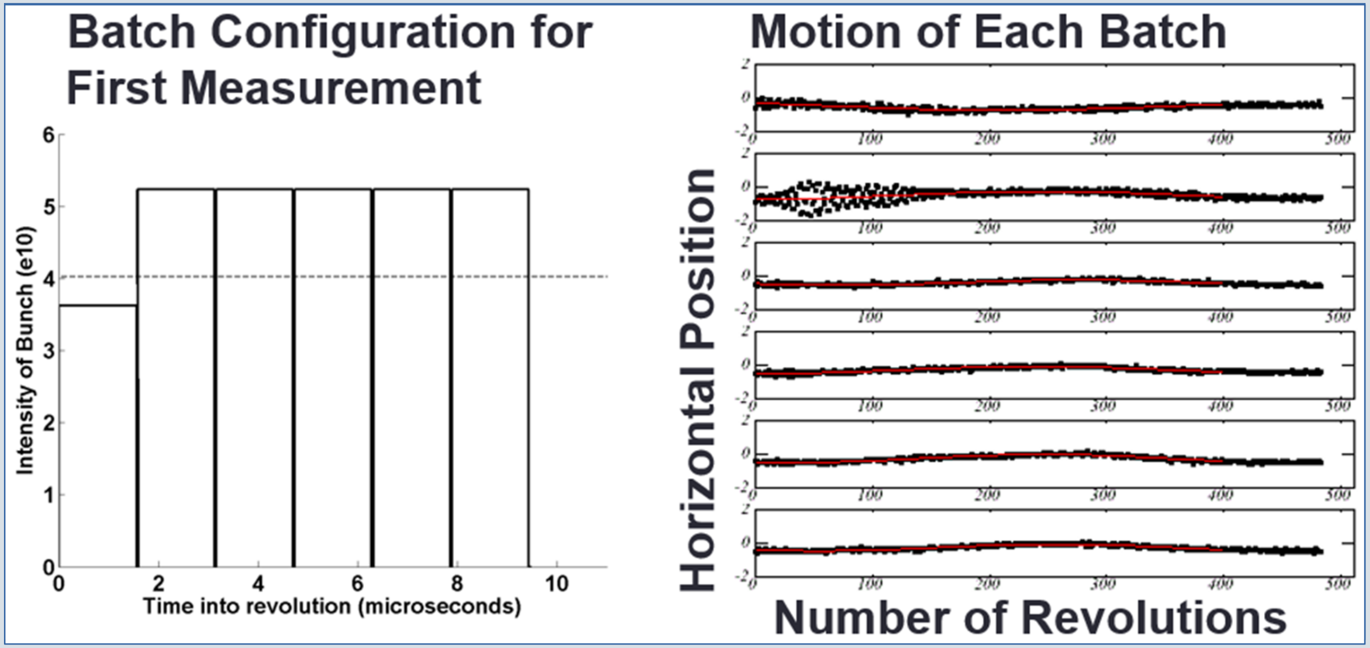
Transverse Beam Instability in Fermilab's Recycler



20-turn growth rate !!!

Proton energy	8 GeV
Circumference	3.3 km
Number of bunches	80 per train
Number of bunch trains	6 (+6)
Bunch intensity	5×10^{10}
Bunch length, rms	~ 2 ns
Bunch spacing	19 ns
Revolution period	11 μs

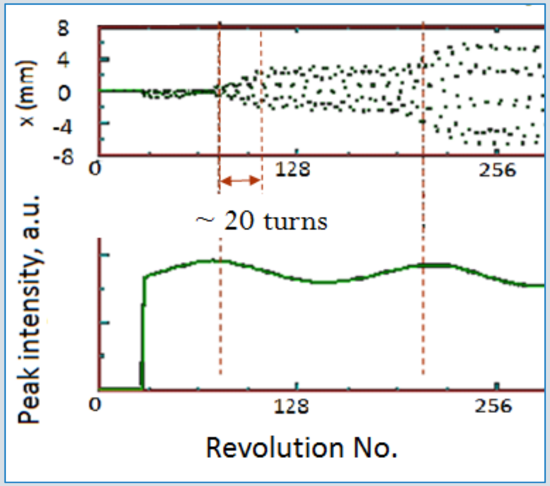
Instability affects only the first batch above the threshold intensity



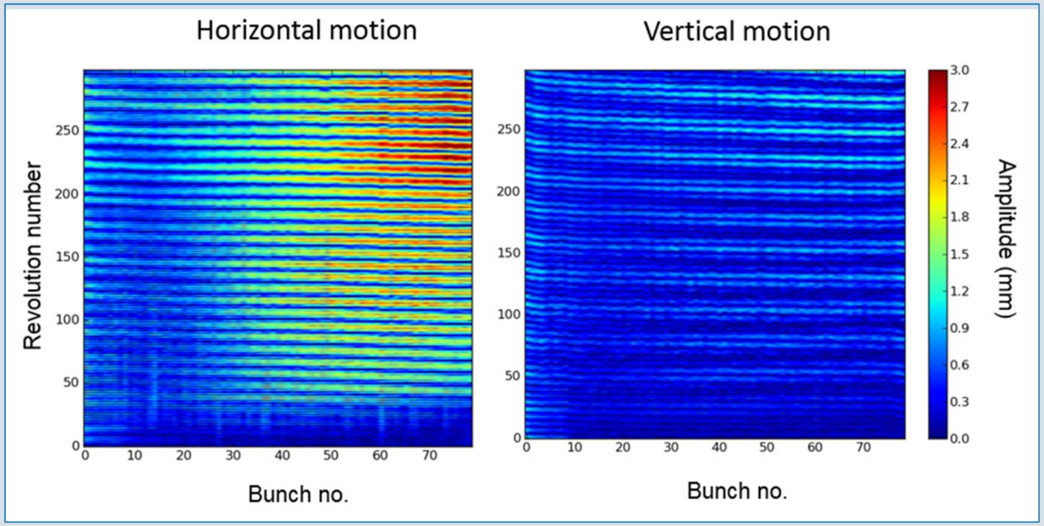
J. Eldred, *HB'14*

Transverse beam instability in Fermilab's Recycler

Triggered by bunch length compression



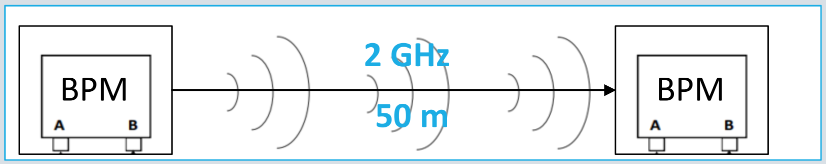
Affects only the horizontal plane



The fast rise time suggests an electron cloud nature of the instability

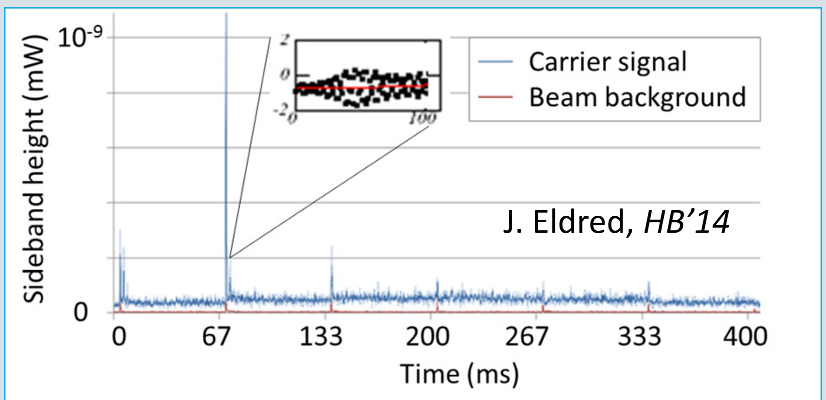
Microwave Measurements Confirm the Presence of Electron Cloud

EC SIGNAL CORRELATED WITH INSTABILITY



$$\varepsilon_{pl} = 1 - \omega_{pl}^2 / \omega_{rf}^2 ,$$
$$\omega_{pl} = 5.64 \times 10^4 \sqrt{n_e}$$

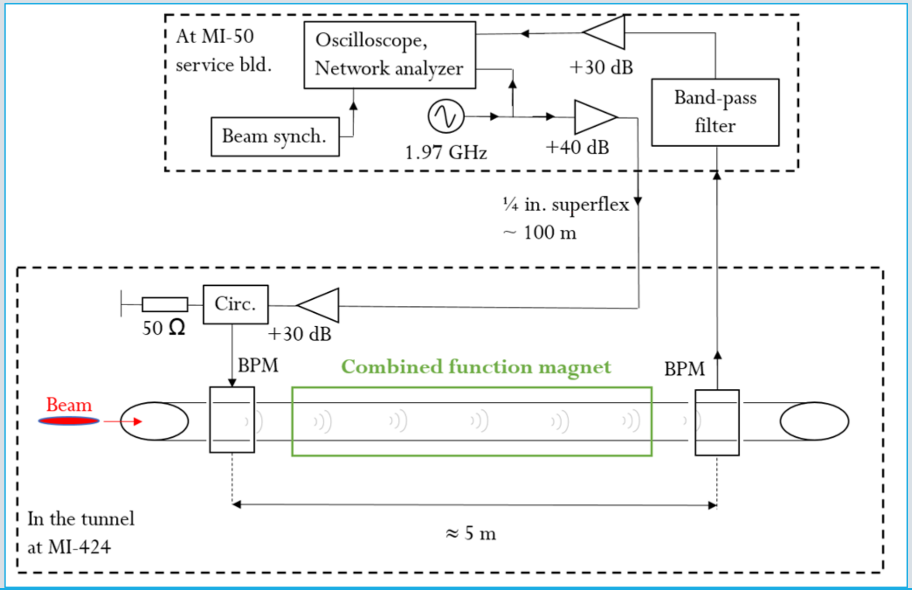
Phase modulation at beam revolution frequency



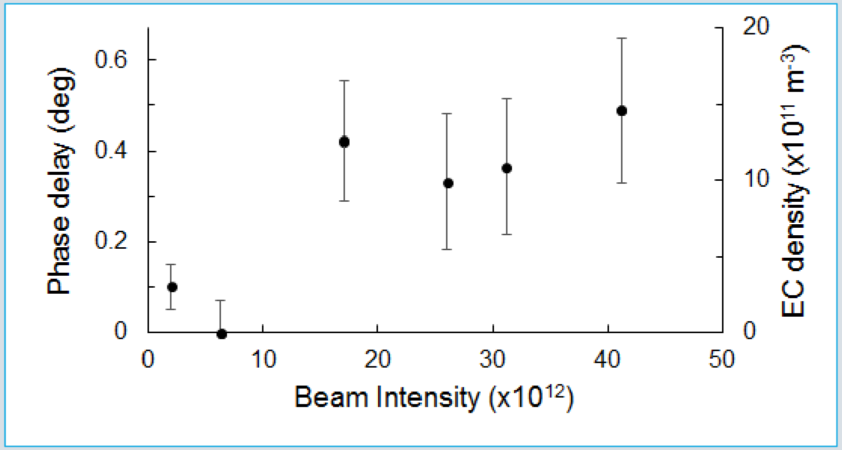
$$\Delta\phi = \frac{\omega_{rf} L_m}{(v_{g,vac} - v_{g,pl})} \propto n_e$$

Microwave observation of electron cloud in a gradient dipole

Using two stripline BPMs installed on both sides of the magnet



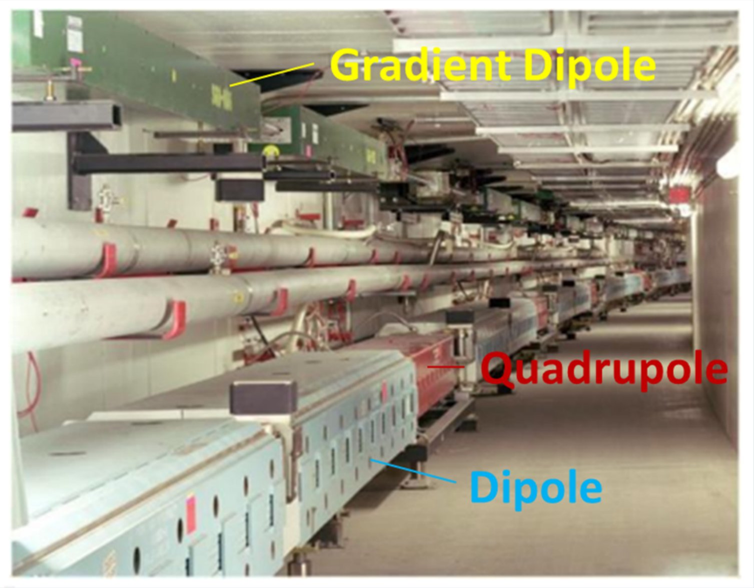
Observing a phase shift above 10^{13} p total beam intensity



S. Antipov's PhD Thesis, 2017

Why the instability has never been observed in Main Injector?

The Recycler (top) and the MI (bottom) rings installed in a common tunnel.



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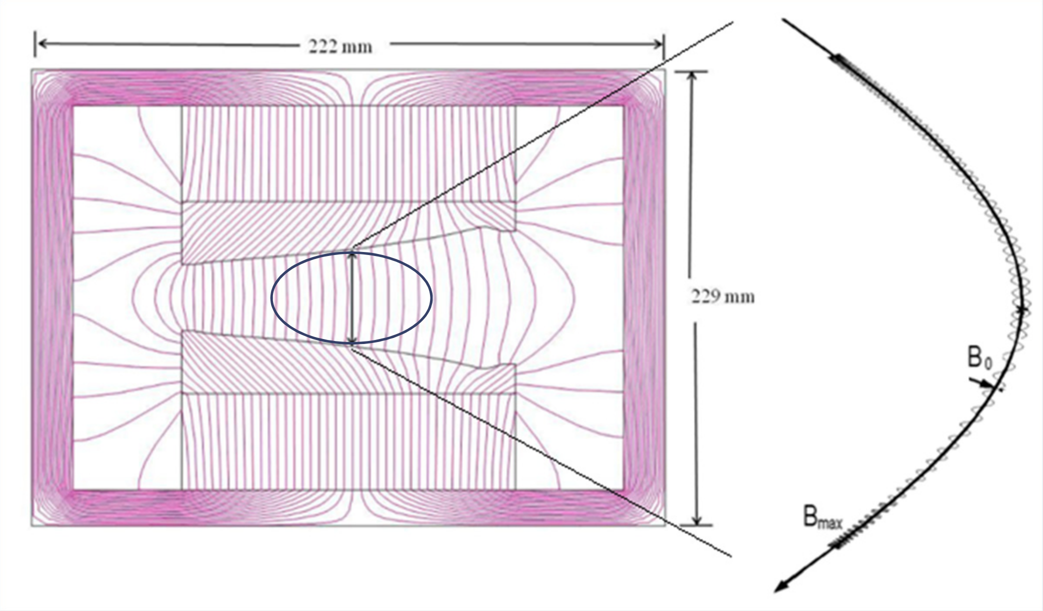
Features of the instability

Electron cloud trapping in combined function magnets

Stabilization by cleaning bunch

Combined function dipole as a “magnetic bottle”

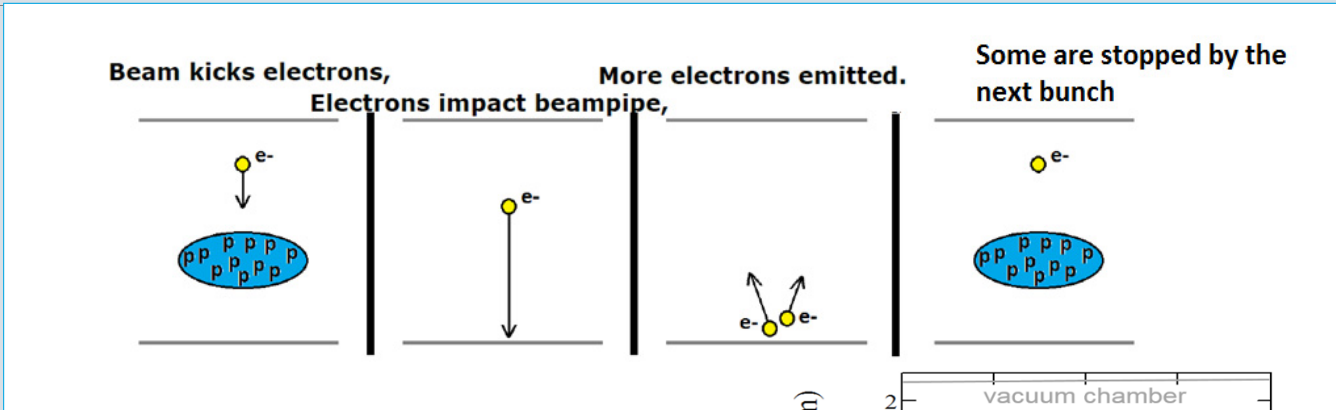
Cross-section of a Recycler permanent combined function dipole



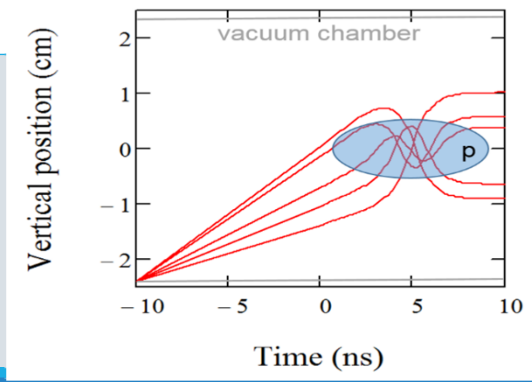
Central field	Gradient
1.38 kG	3.4 kG/m

About 1% of multipacting electrons are trapped by magnetic field

Electrons need to be stopped by the beam in order to be trapped by the magnetic field



Secondary electrons emitted with certain velocities are stopped by the last bunch of the bunch train:



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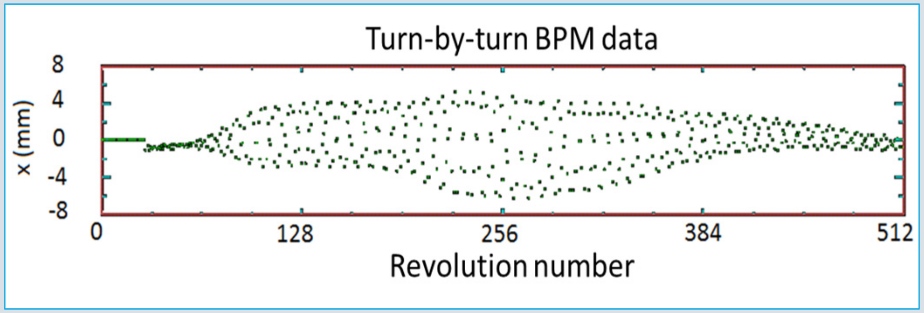
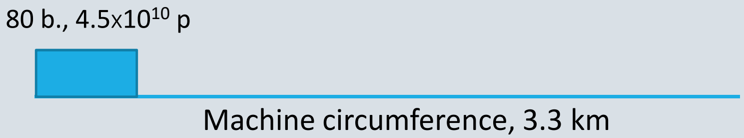
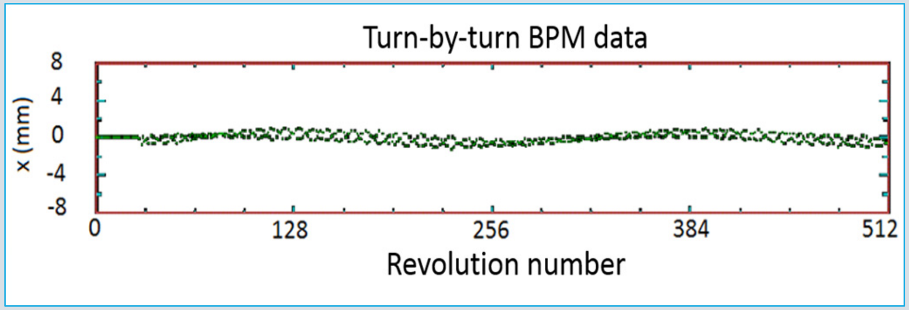
Stabilization by a low-intensity clearing bunch

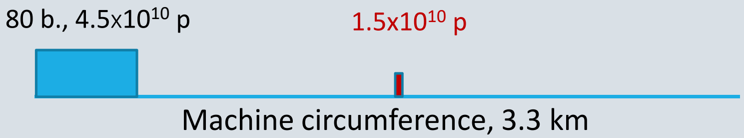
WITHOUT A CLEARING BUNCH





WITH A CLEARING BUNCH





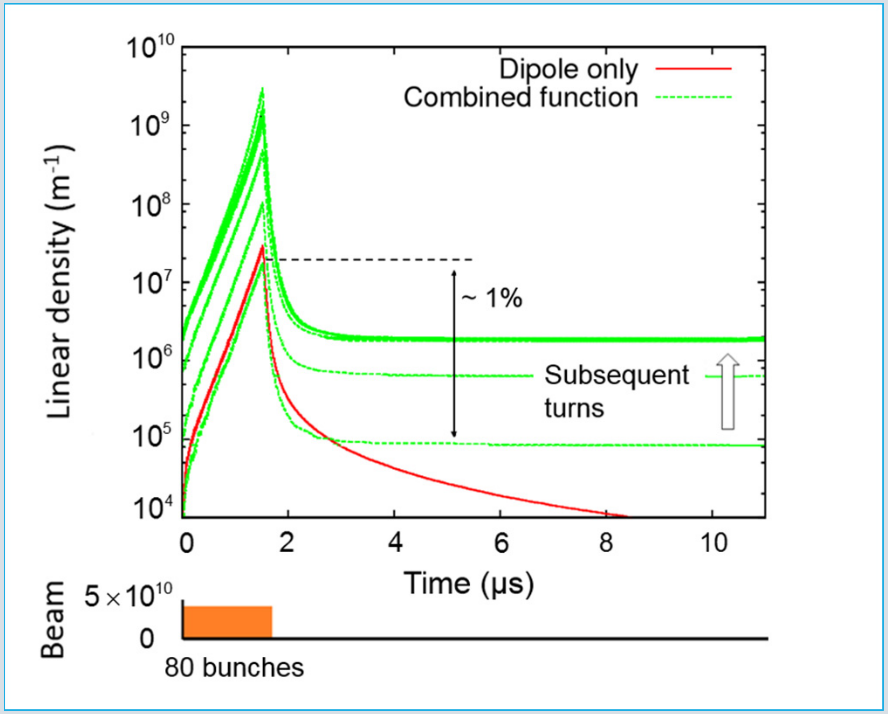
Performed during a special study cycle in Recycler

S. Antipov, *et al., PRAB* **20**, 044401, 2017

Idea inspired by

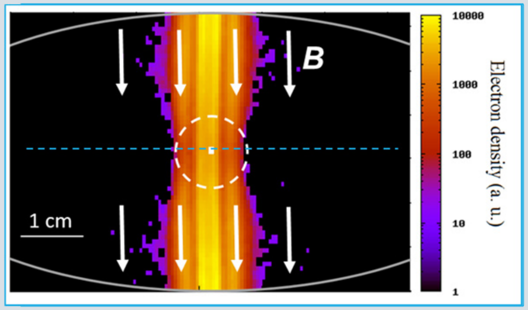
M. Billing *et al.*, *PRST AB* **18**, 041001, 2015

Thanks to trapping, the cloud reaches much higher densities than in a pure dipole



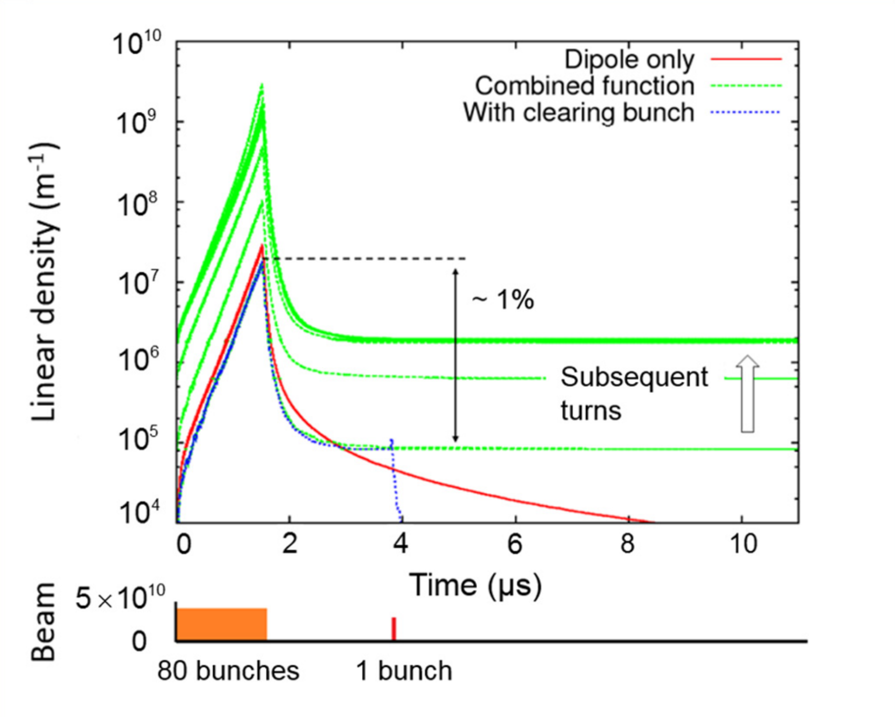
Numerical simulation with PEI code

Electron cloud forms a stripe inside the vacuum chamber



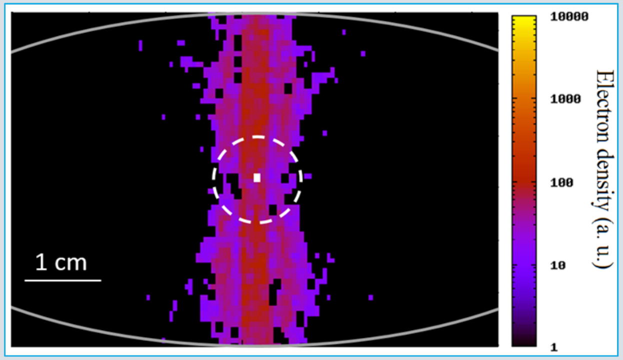
Horizontal coupled-bunch instability with a rise time of 11 turns, mode frequency 0.7 MHz

Clearing prevents the multi-turn the build-up



Numerical simulation with PEI code

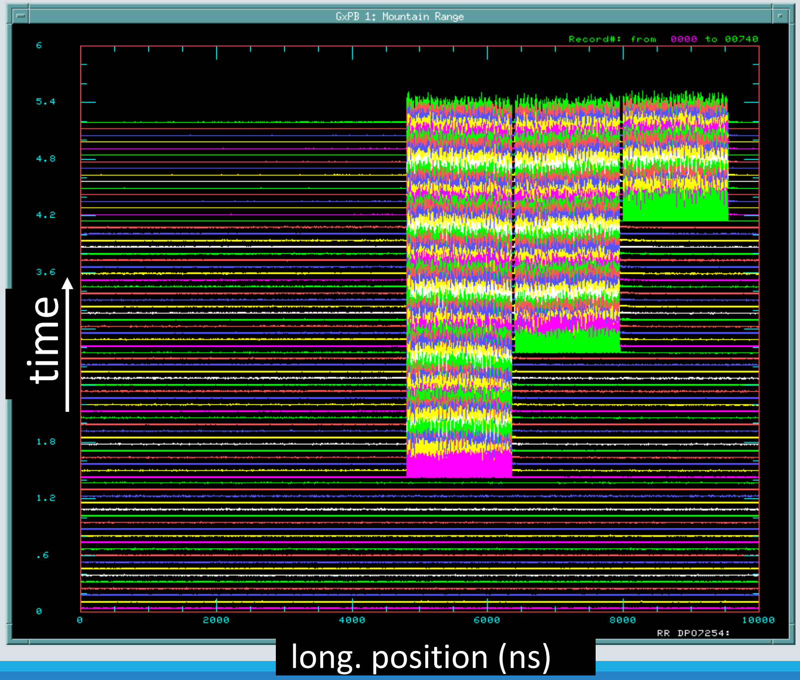
With clearing bunch

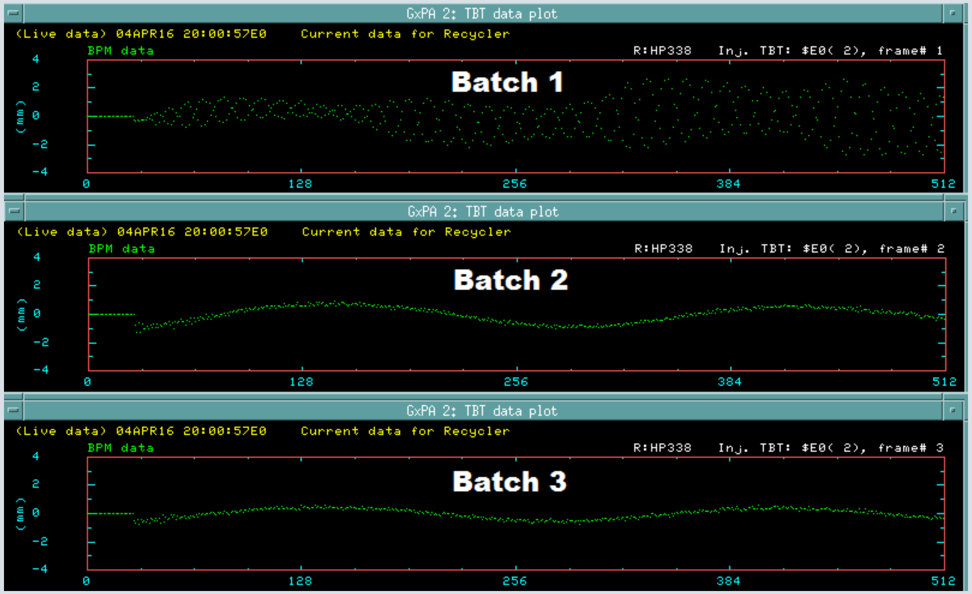


Stable

Stabilization in an operational cycle: No clearing bunch – the first injected batch is unstable

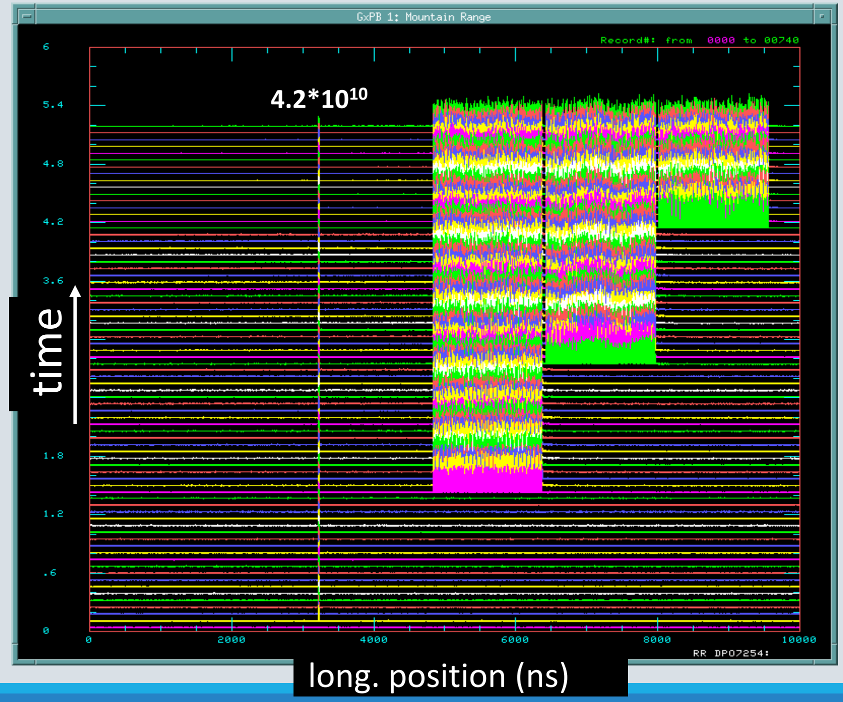
3 Injections: 80 bunches 5.8×10^{10} ppb, 80 bunches



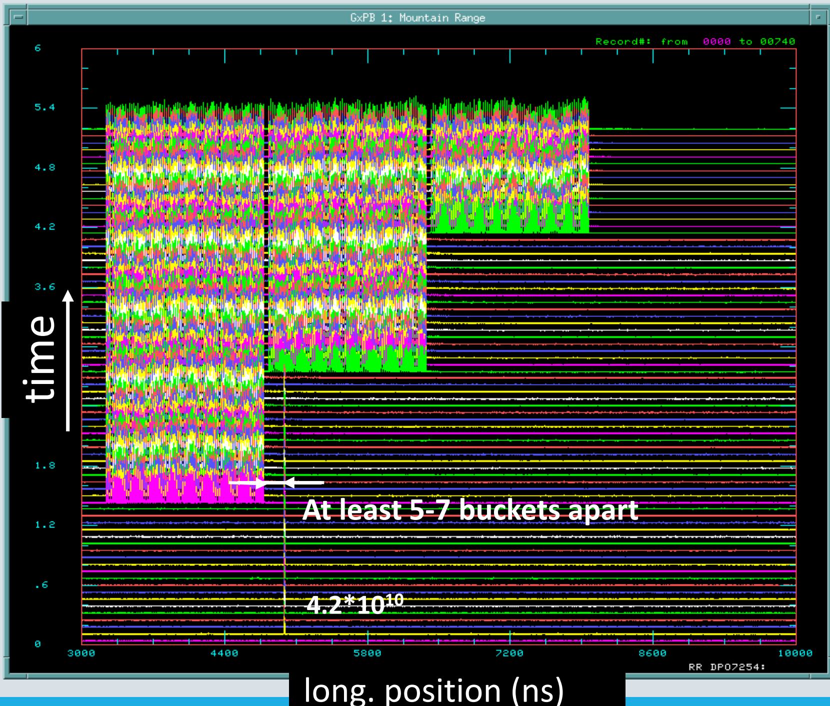


Stabilization in an operational cycle: Adding a clearing bunch – all bathes stable

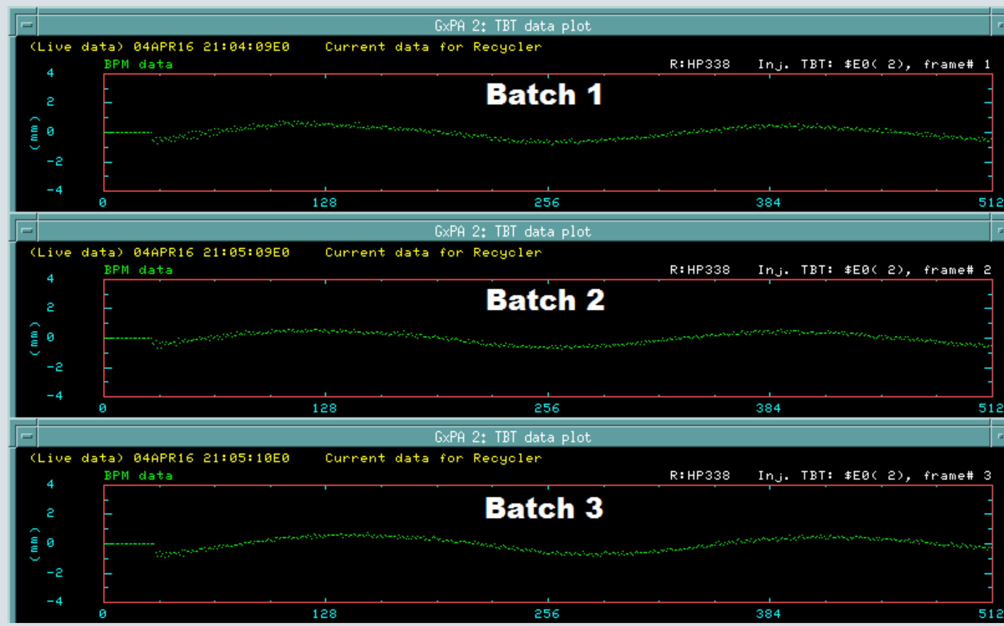
1 bunch + 3 Injections of 5.8×10^{10} ppb, 80 b.



Stabilization in an operational cycle: The bunch can be removed before the second injection



1 bunch + 3 Injections of 5.8x10^{10} ppb, 80 b.



Fast instability was not observed in Recycler during commissioning in 2017

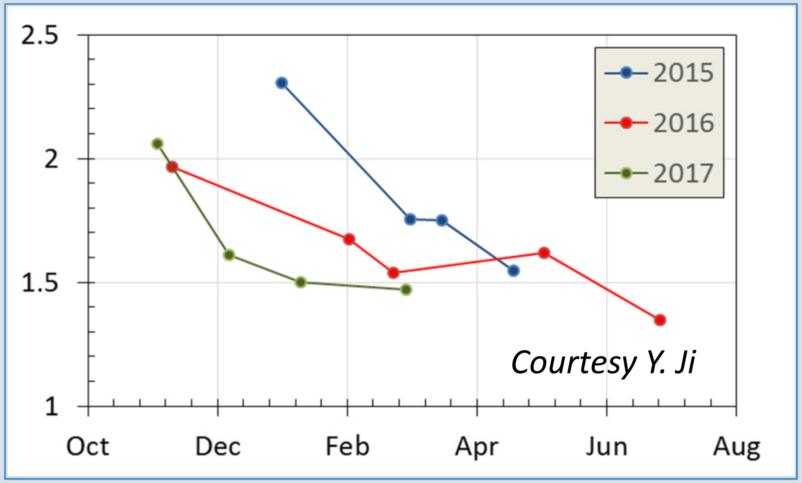
Tried to induce the instability but observed nothing
- High intensity bunches, 6×10^{10} p
- Low chromaticity, -3,-3
- Short bunches

Instability intensity threshold increased during operation already in 2015 & 2016

Possible reasons:
- **Beampipe conditioning**
- **Vacuum changes: Ti Sublimation Pumps → Ion Pumps**

– *R. Ainsworth, FNAL*

SEY of Stainless Steel beampipe measured at the Main Injector test stand



Conclusion

Combined function magnets trap the electron cloud that might drive a transverse instability

- Trapping of the order $10^{-3} – 10^{-2}$ leads to multi-turn accumulation of the cloud
- The cloud reaches the densities orders of magnitude greater than in a pure dipole

The instability affects the first bunch train above the threshold intensity

- Coherent activity in the horizontal plane, leading to a loss of beam intensity

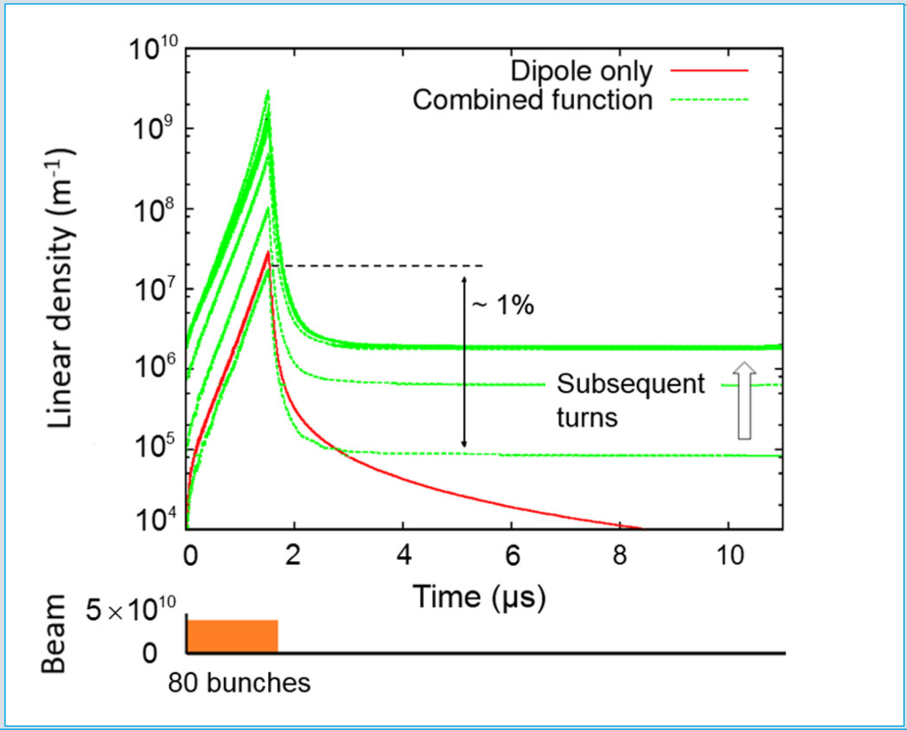
The beam can be stabilized by a cleaning bunch that destroys the trapped cloud

- The cleaning bunch can be removed after stabilizing the first injection; the subsequent injections remain stable

Thank you

QUESTIONS?

Numerical Simulation of Electron Cloud Build-Up

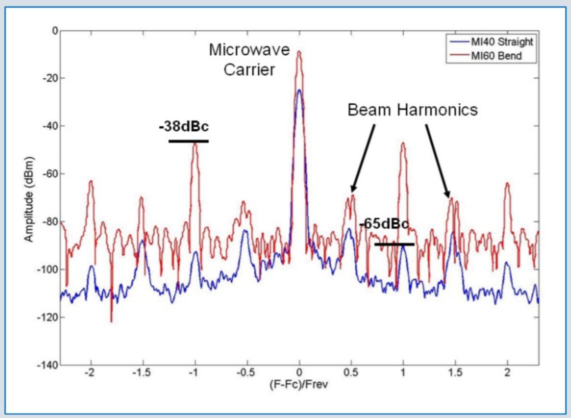


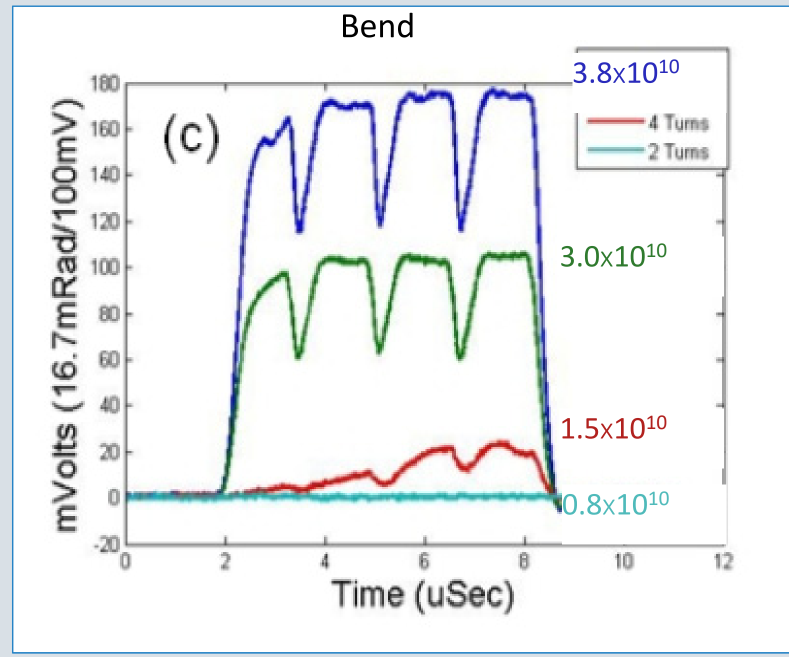
Key parameters used in PEI code

Beam energy	8 GeV
Machine circumference	3.3 km
Batch structure	80 bunches, 5e10 p
Tunes: x, y, s	25.45, 24.40, 0.003
RF harmonic number	588
RMS bunch size: x, y, s	0.3, 0.3, 40 cm
Secondary emission yield	2.1 @ 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

Electron Cloud Observed in Main Injector

Observed in a microwave transmission measurements in bend and straight sections (N. Eddy *et al.*, *PAC'09,* 2009)



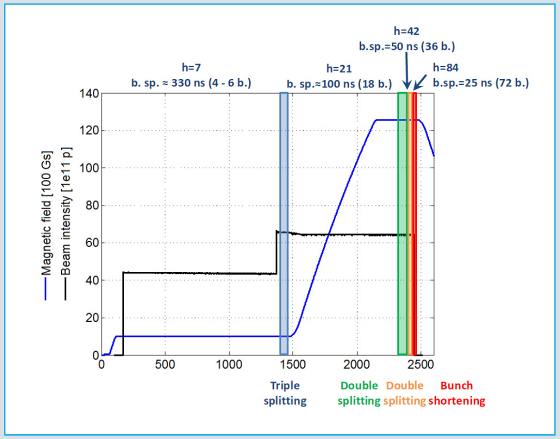


Also seen on RFA (retarded field analyzer) installed in a drift (M. Backfish *et al.*, *IEEE Trans. Nucl. Sci.,* 2016)

No electron cloud driven instabilities were observed in MI

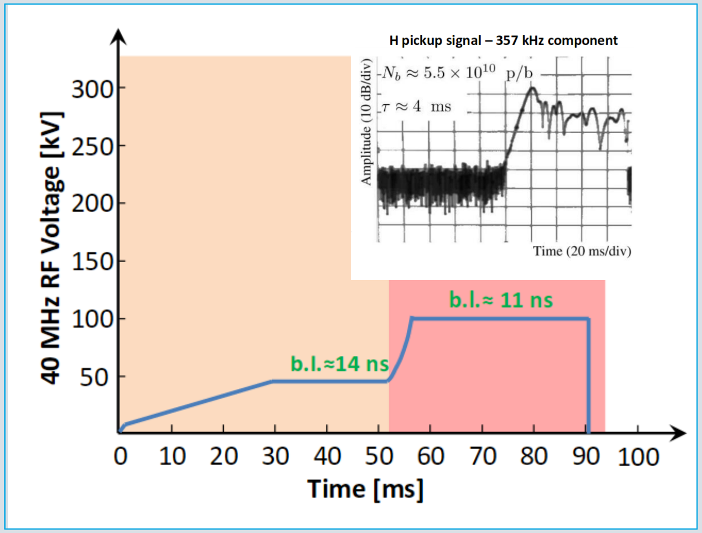
A similar instability in was observed in CERN PS

Electron cloud is observed when bunch length is compressed from 11 to 4 ns



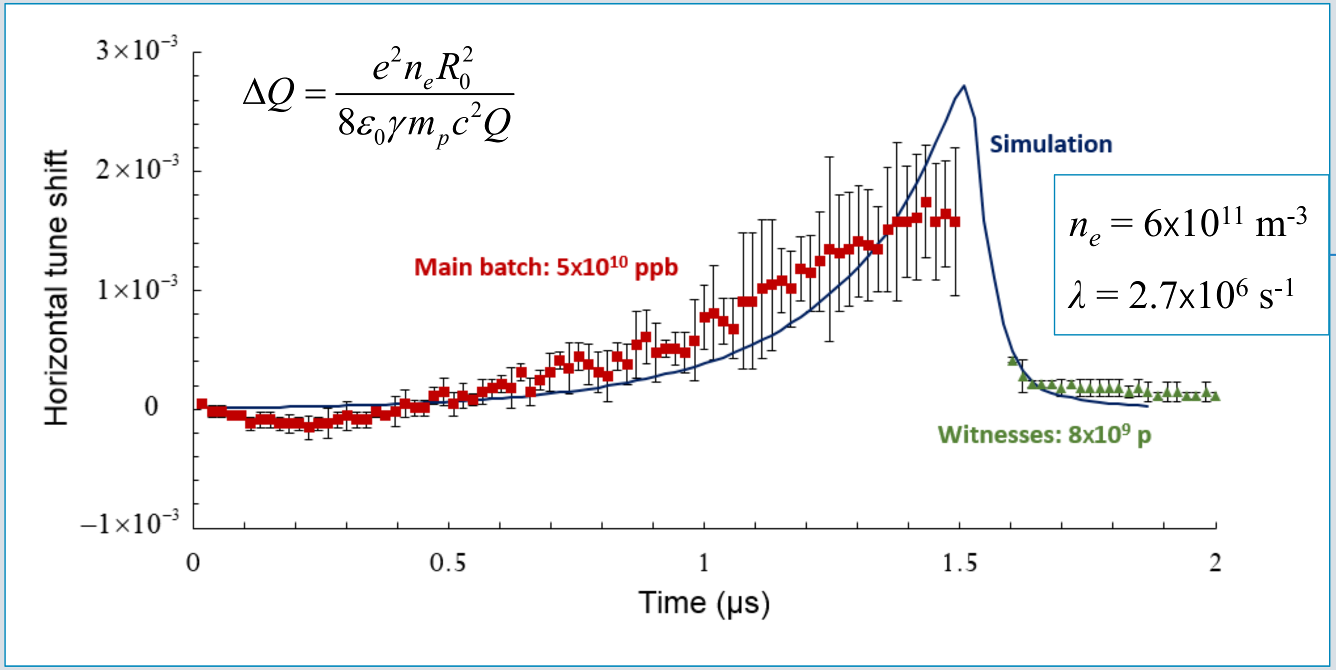
The beam does not interact with the cloud for a sufficiently long time

Instability when the beam is stored for a long time – 100 ms at 11 ns bunch length



R. Cappi *et al.,* PRST AB **5**, 2002; G. Iadarola *et al.*, IPAC'13

Tune measurement agrees with the simulation



$\tau_{\max} \approx 27\text{turns}$

All trapped electrons survive until the next revolution

SCATTERING

Residual gas:

- Pressure $P \sim 10^{-8}$ Torr
- Cross-section $\sigma_C \sim 10^{-15}\,\mathrm{cm}^2$
  - for many gases and $\varepsilon < 10$ eV

Elastic scattering on other electrons:

- Density $n_e < 10^{13}$ m^{-3}
- Cross-section $\sigma_C = 16\pi r_e^2 \left(\frac{m_e c^2}{\varepsilon}\right)^2 \Lambda_C < 10^{-13}\,\mathrm{cm}^2$

Lifetime due to scattering ~ 1 ms

LONGITUDINAL DRIFT

Drift velocity $v_d = \frac{1}{2}\omega_c r_c^2 \frac{dB/dx}{B_0} < 2\times 10^3\,\mathrm{m/s}$

Magnet length 5 m

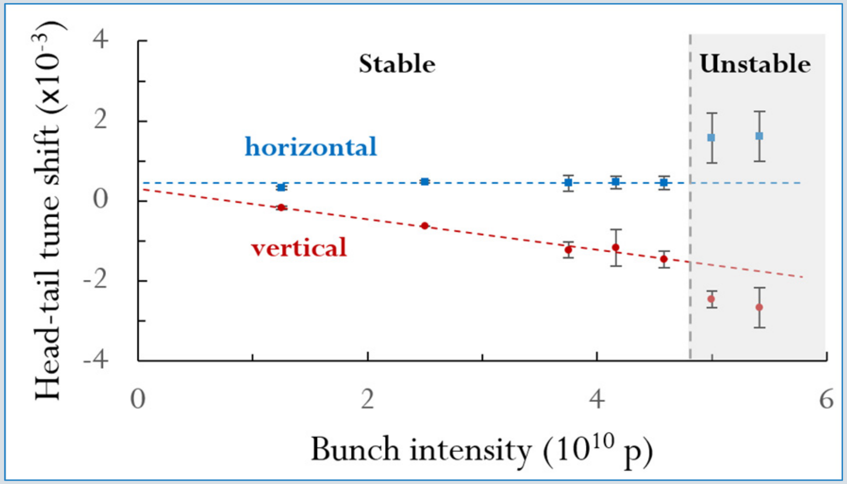
Particles leave the dipole in ~ 1 ms

Cloud lifetime in the absence of beam is significantly larger that the revolution period of 11 μs

Tune shift measurement: Identifying the resistive wall component

Can estimate the RW tune shift measuring at low intensity

- No electron cloud, thanks to its highly nonlinear build-up

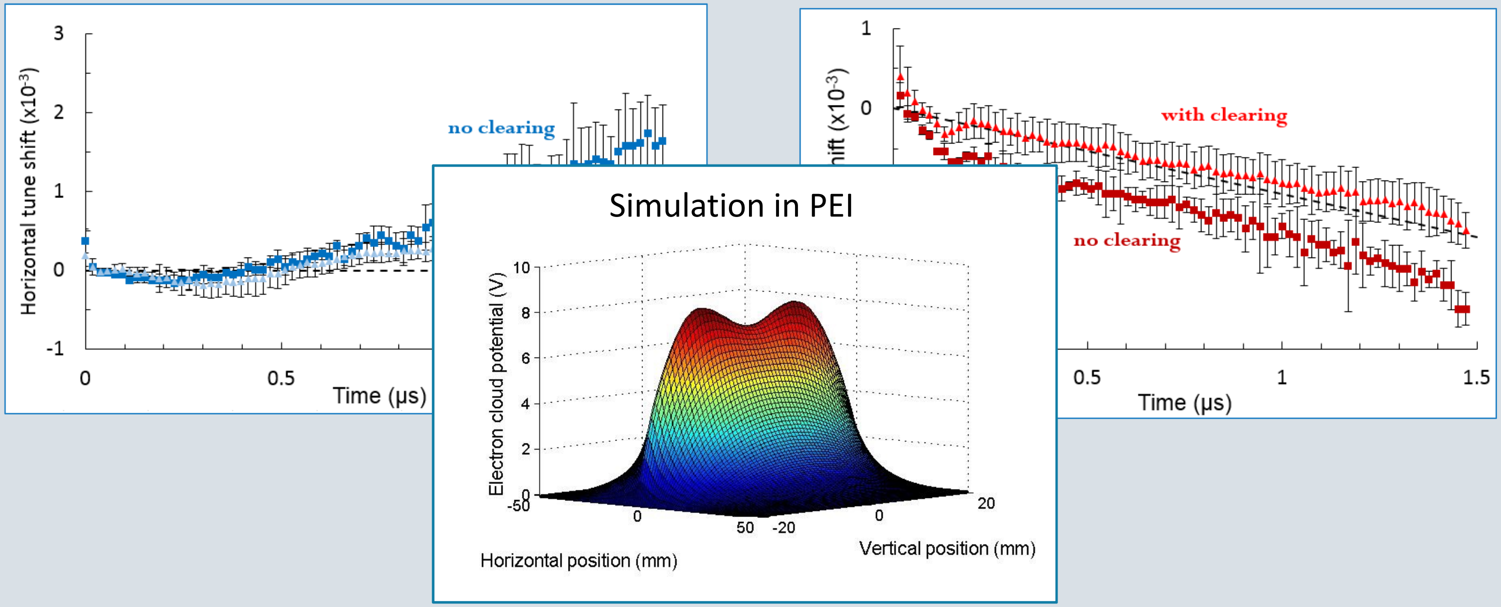


Small offset is caused by the rise time of injection kickers (the head gets a lower kick)

Tune shift measurement:
Agrees with the electron cloud model

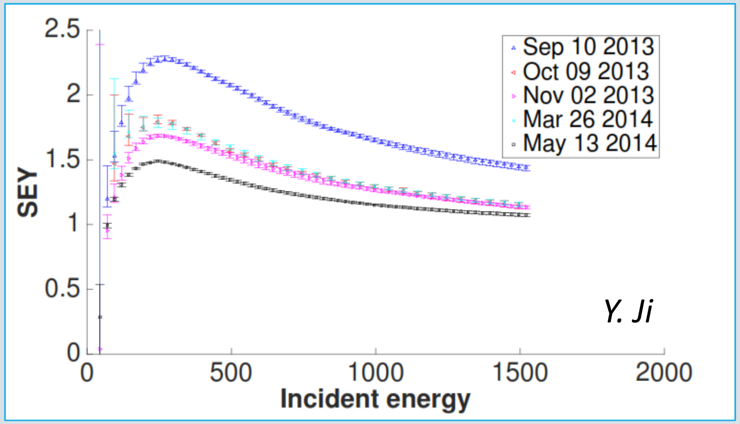
Horizontal focusing

Vertical defocusing



SEY Measurements and Beampipe conditioning

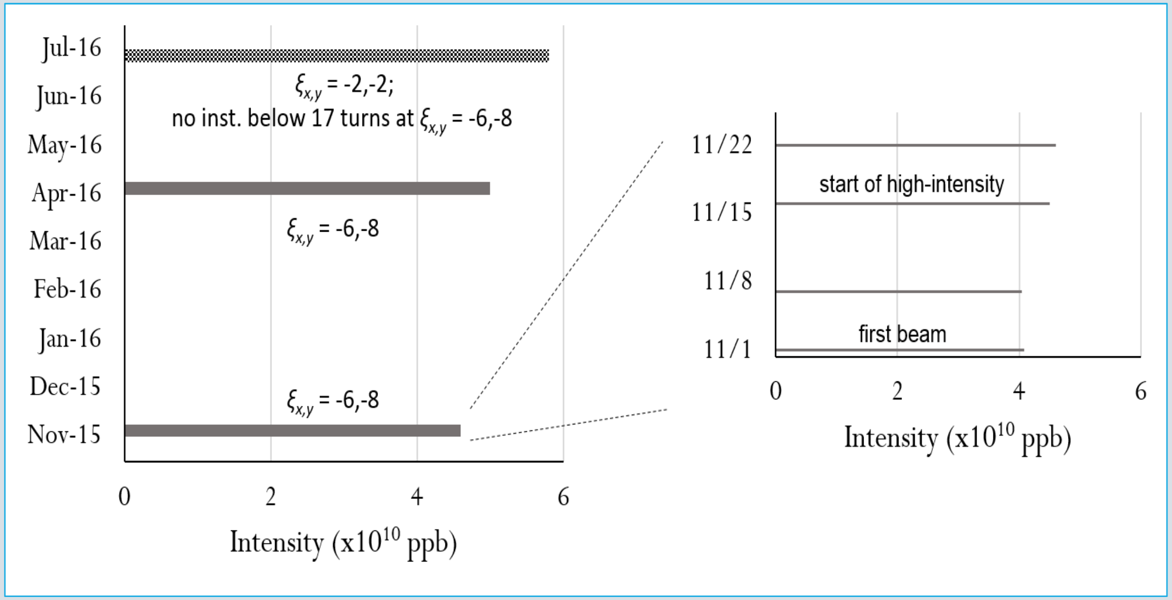
As an accelerator runs high-intensity beam beams the secondary yield of its vacuum chambers decreases



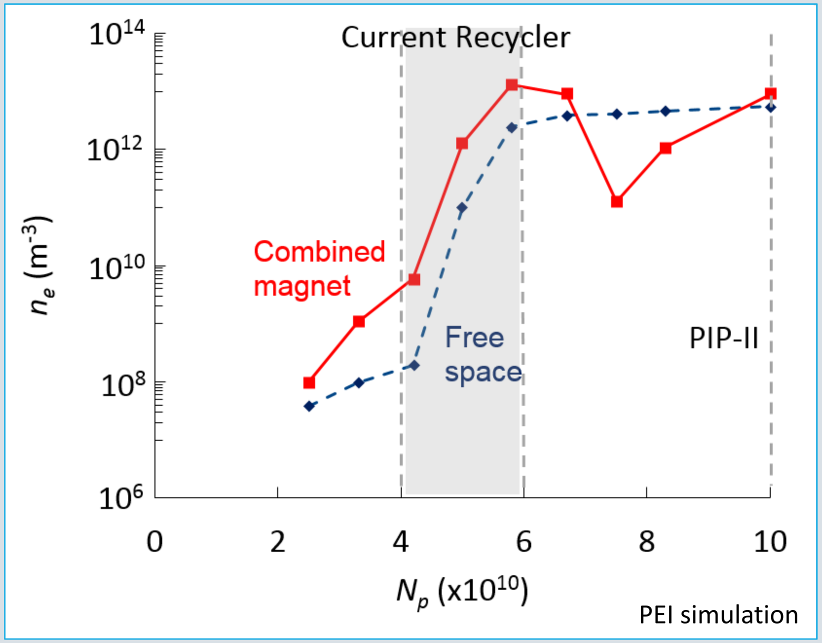
SEY goes up immediately after the beam has been turned off

Fermilab SEY measurement stand at MI

Beampipe conditioning:
Threshold goes up as the machine operates



Cloud density in combined function magnets is expected to decrease at higher intensities



Recycler instability growth rate decreases at higher intensities

7.0×10^{10} ppb