Tune shifts in the Recycler

Recycler department meeting

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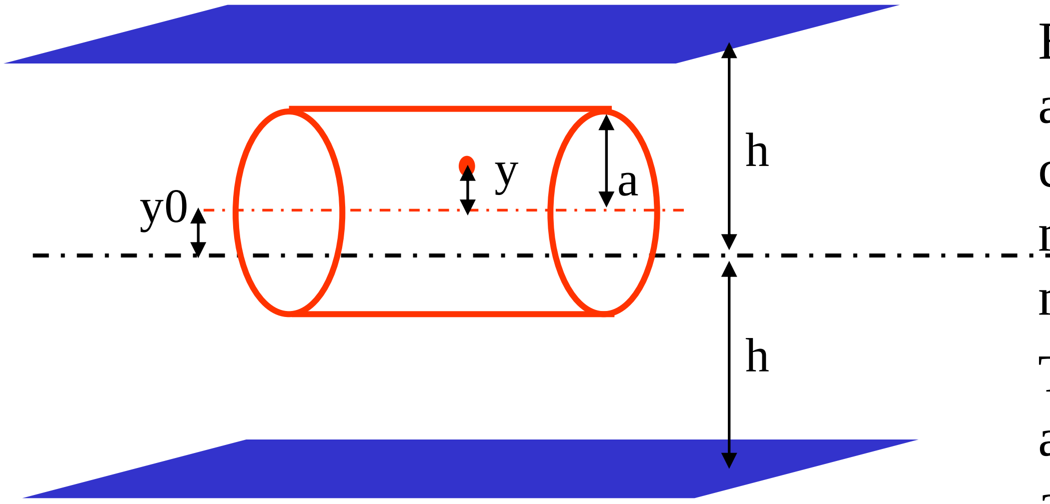
Thanks to Martin Hu for setting up the measurement and to Alexey Burov, Valery Lebedev, Sergei Nagaitsev, Lionel Prost, and Stan Pruss for discussions

Introduction

- The initial goal was to estimate the density of secondary electrons in the cooling section by the pbar tune shift
- Martin Hu set up the measurement; the effect was found to be small
- In addition, I made simple estimations related to RR tune shifts
- Two parts:
  - RR tune shift due to pbar space charge
  - Estimation for the secondary electron density

Tune shift estimation



Effect of the image charges and currents in the vacuum chamber, magnets, and magnetic shielding is modeled by two plates.

The current density is assumed to be constant across the beam.

For estimations, h = 20 mm
(RR vacuum chamber is 100 X 48 mm)

- Two effects
  - The beam interacts with image charges and currents (coherent tune shift)
  - Motion of an individual particle is affected by the beam's space charge and image charges and currents (incoherent tune shift)

Tune shift estimation

- Space charge tune shift (round beam, in center)

$$\Delta\nu_{sc}(0) = -\frac{r_p P_{RR} N_p}{2\cdot(2\pi)^2 \nu \beta^2 \gamma^3 a^2 BF} \approx -0.008\frac{N_p[10^{12}]}{\varepsilon_{n95}[\pi\cdot mm\cdot mrad]BF}$$

- Incoherent tune shift

$$\Delta\nu_{inc\frac{y}{x}} = \Delta\nu_{sc} + \Delta\nu_{Laslett} \approx \Delta\nu_{sc}\left[1 \pm \frac{\pi^2}{8}\left(\frac{a}{h}\right)^2 \left(\beta\cdot BF\cdot\gamma^2 + 1\right)\right] \approx$$

$$\approx \Delta\nu_{sc}\left(1 \pm 0.15\cdot BF\cdot\varepsilon_{n95}\right)$$

- Coherent tune shift

$$\Delta\nu_{coh\frac{y}{x}} \approx \pm\Delta\nu_{sc}\cdot 0.15\cdot BF\cdot\varepsilon_{n95} \approx \mp 0.0012\cdot N_p\left[10^{12}\right]$$

Formulas are from

Handbook of Accelerator Physics and Engineering, by A.Chao and M.Tigner

Symbols:

r_p – classical proton radius

N_p – number of pbars

P_{RR}- RR perimeter

ν - RR tune (25)

β,γ - relativistic factors

a- rms beam radius

BF- bunching factor, j_{av}/j_{max}

ε_{n95}- transverse normalized 95% emittance

Numbers

Estimation for $Np = 200$, $BF \sim 0.5$, $\varepsilon_{n95} \sim 2$:

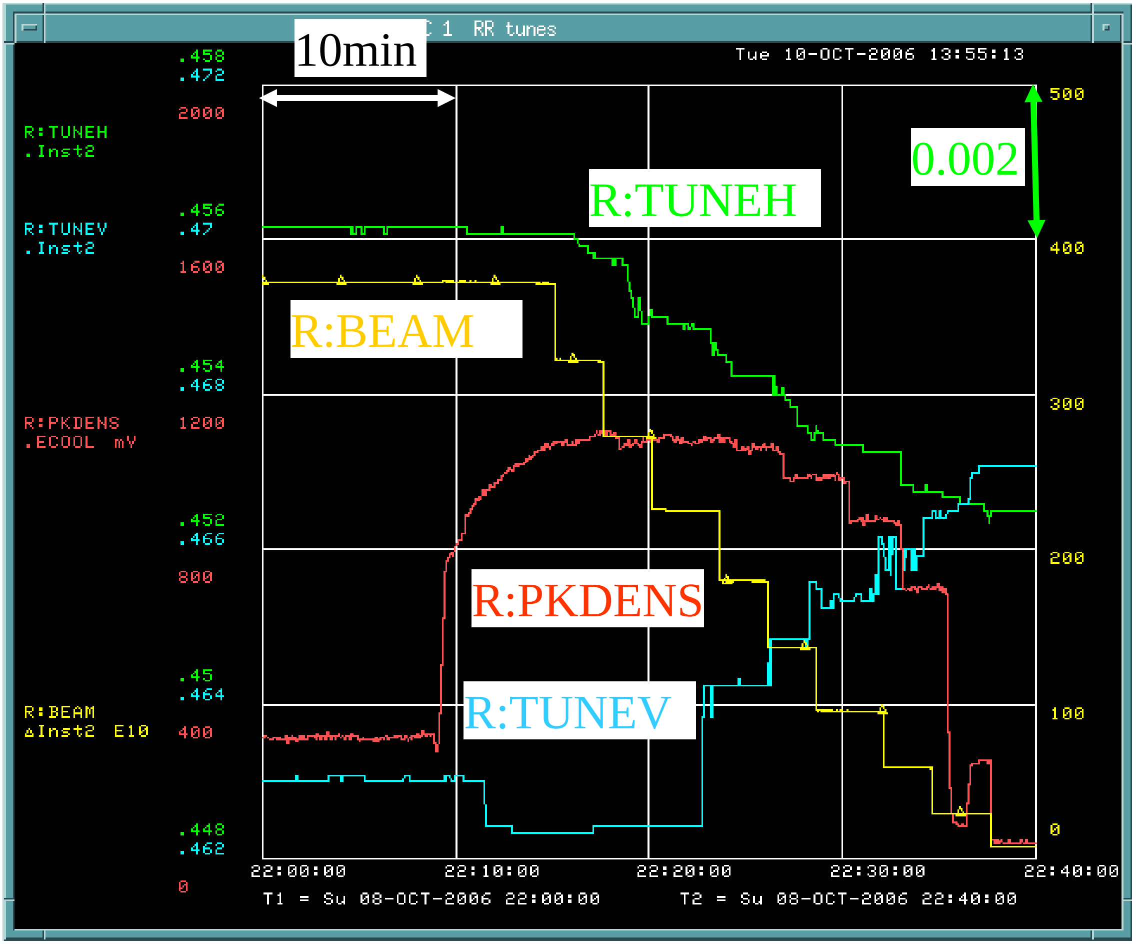
$$\Delta\nu_{inc\frac{y}{x}} \approx -0.016 \cdot (1 \pm 0.15)$$

$$\Delta\nu_{coh\frac{y}{x}} \approx \mp 0.0024$$

In this case, the main factor that determines crossing resonances by individual particles is the direct space-charge field.

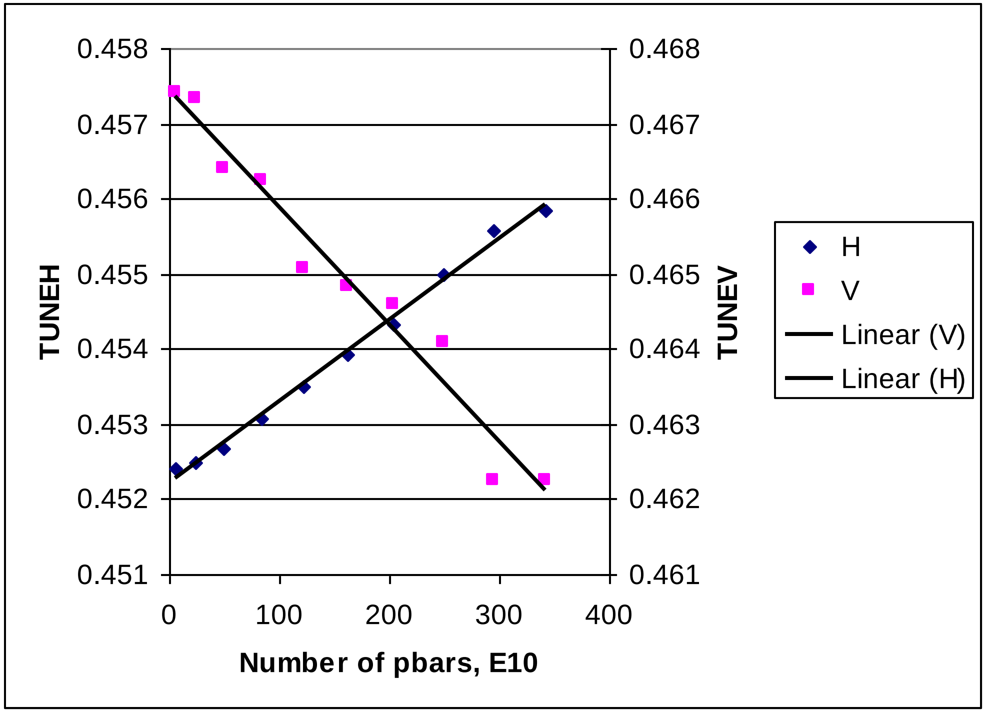
However, in tune measurements we see only the coherent tune shift.

Tunes in the time of a shot to Tevatron on Oct 7, 2006



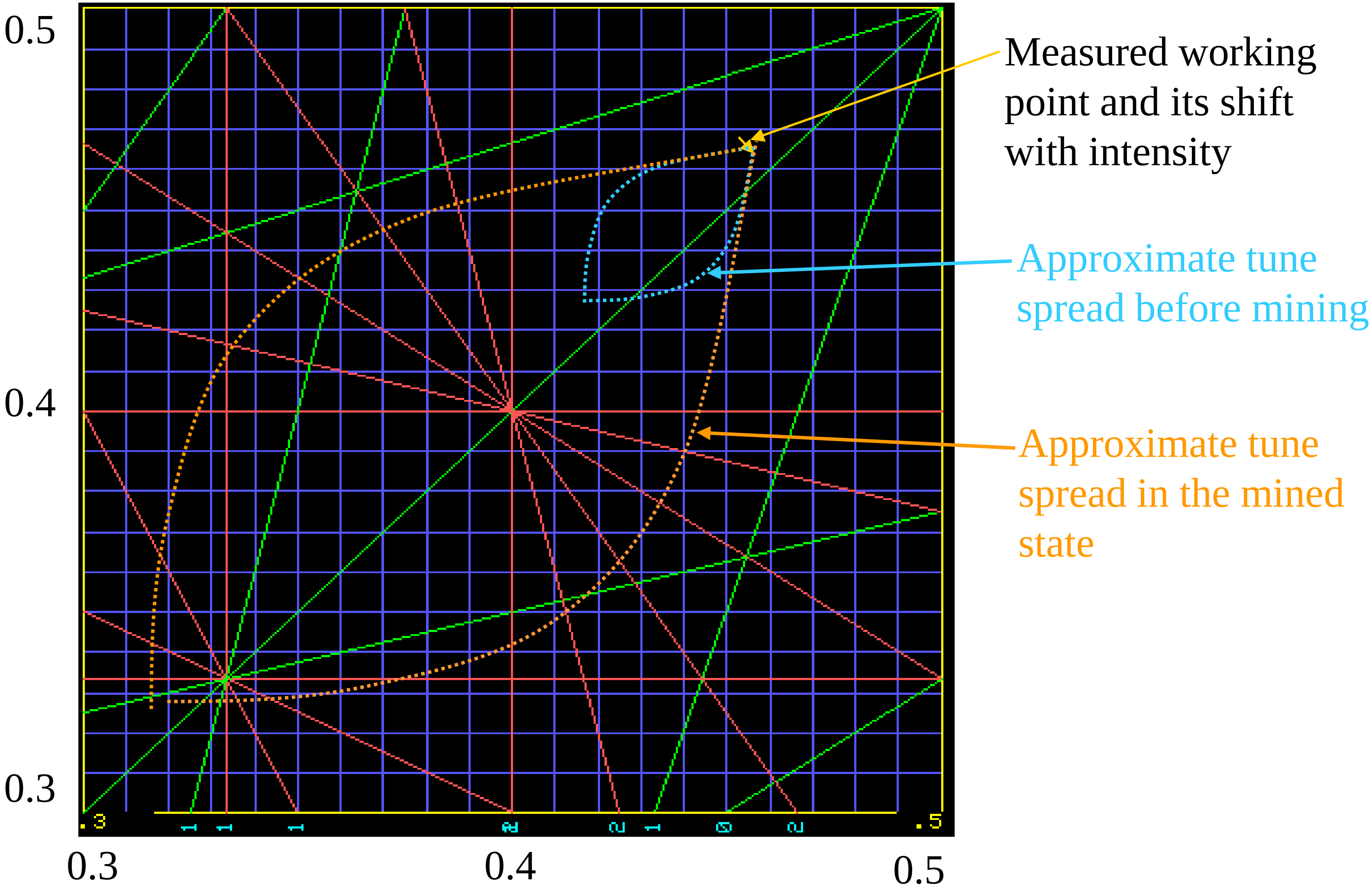
Measured tune shifts are linear with the average current and do not change with the peak current.

Tunes in the time of a shot to Tevatron on Oct 7, 2006 (cont.)



- Tunes changed by +0.0011 (H) and -0.0016 (V) per 100E10.
- That simple estimation gives 0.0012 (h = 20 mm)

Tune diagram



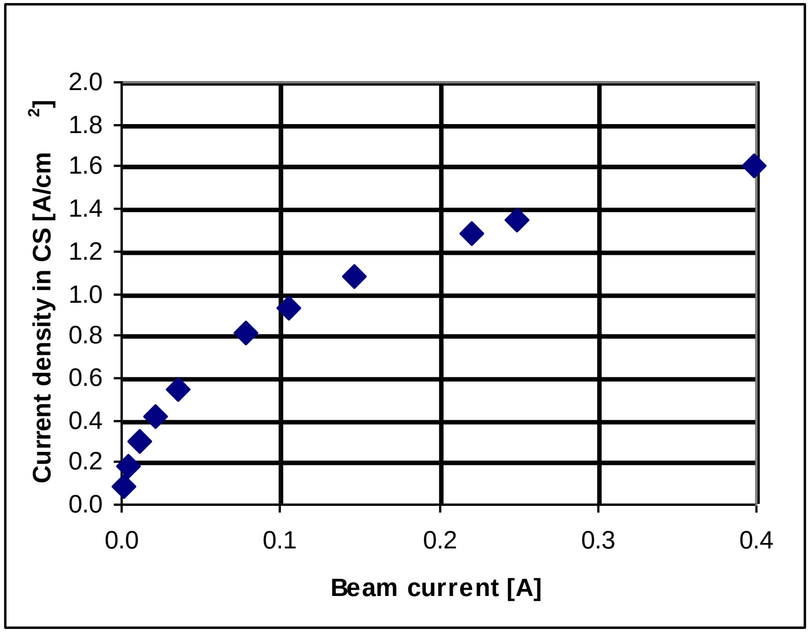
Tune diagram with resonance lines up to 5th order.

At mining, axial particles may reach 3rd resonance lines.

Tune shift due to the electron beam

- Only direct space charge effect (round vacuum chamber, the electron beam is centered)

$$\Delta\nu_{pe} = -\frac{r_p \cdot P_{RR} \cdot L_{cs}}{(2\pi)^2 \nu\beta^3\gamma^3 a_e^{\ 2}} \frac{I_e}{e \cdot c} \approx -0.98 \cdot 10^{-4} \cdot J_e \left[\frac{A}{cm^2}\right]$$



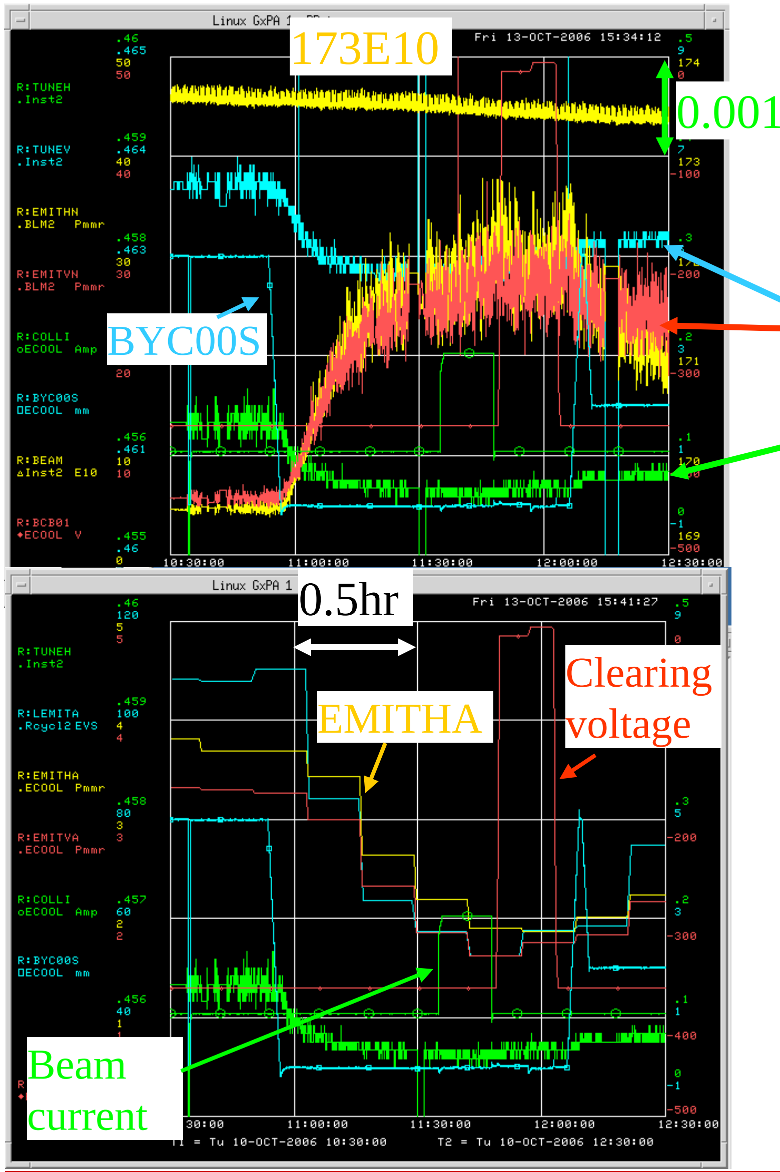
Calculated electron current density on the axis of the cooling section as a function of the beam current.

Increase of the electron beam current from 0 to 0.1 to 0.2 A should shift both tunes by $-9\cdot10^{-5}$ and by additional $-3\cdot10^{-5}$.

Measurement on October 10, 2006

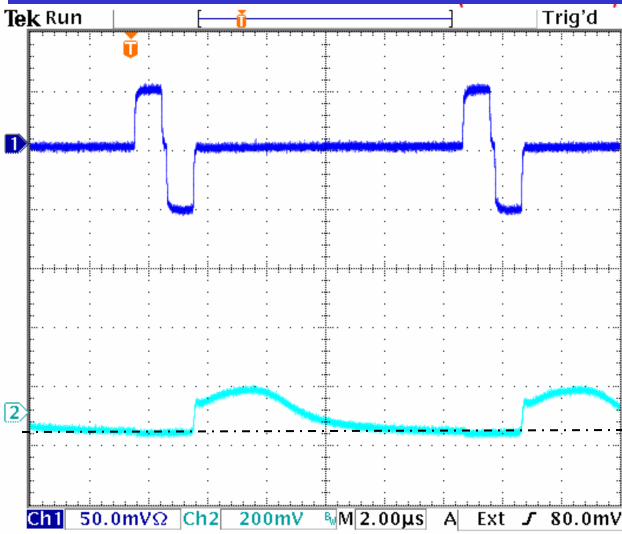
- The goal was to record effects of the electron beam on tunes, hoping to put a limit on the density of secondary electrons
- MI was ramping 3 times per min that made the tune signal much cleaner than usually
- Martin set up SA so that the tune averaging time was 20 sec instead of standard 800.

Measurement on Oct 10, 2006 (cont.)

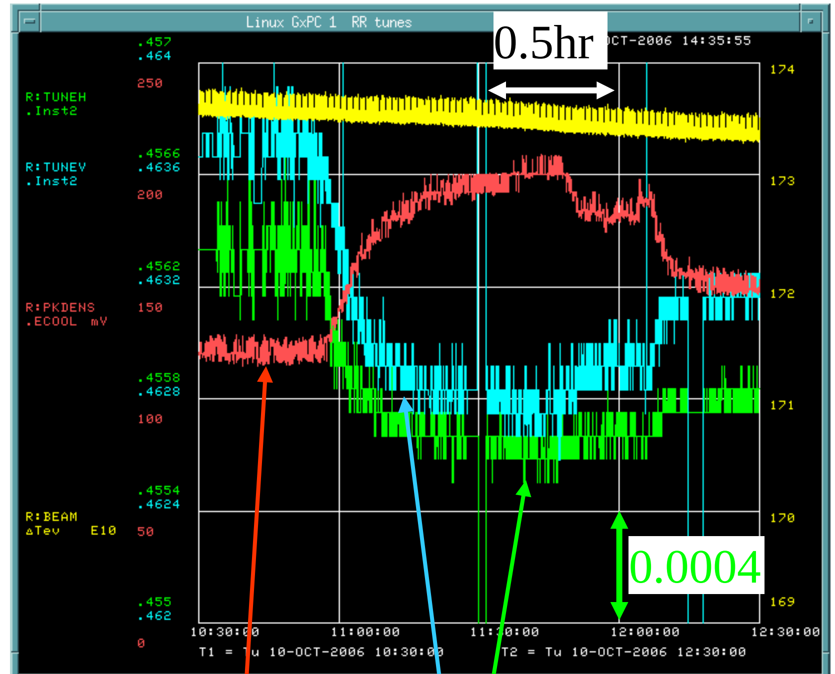


- The 0.1 A electron beam was moved from 5 mm offset to the axis.
  - Immediately, the power in 21 MHz started to grow and the tunes went down
  - Tunes stabilized in ~10 min, while emittances were still being cooled down
- The e-beam current was increased to 0.2 A and then decreased back to 0.1A
  - Very small changes
- Clearing voltage in CS was turned off
  - Very small changes

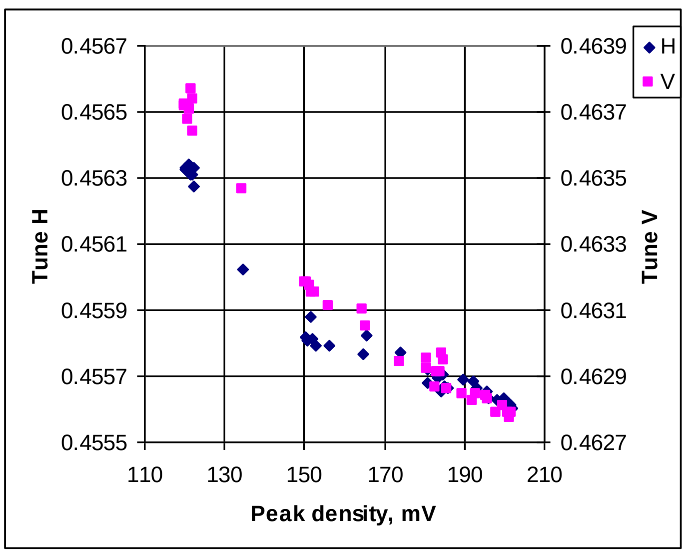
Correlation with the peak current



RWM after ~15 min of e-cooling

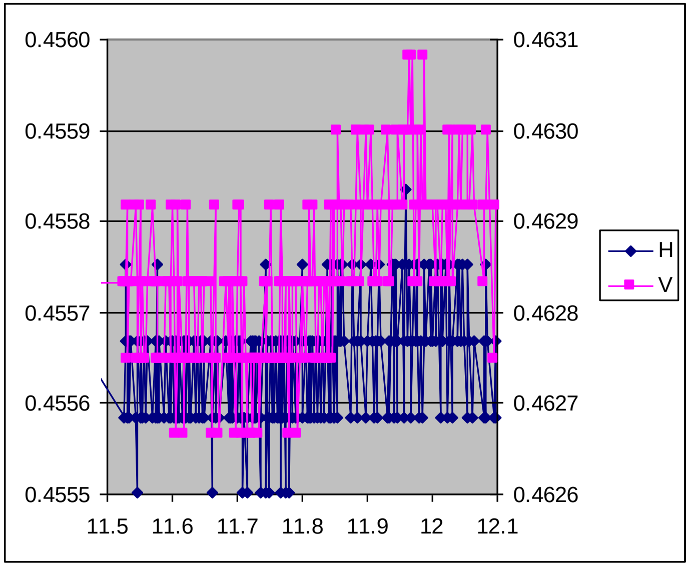


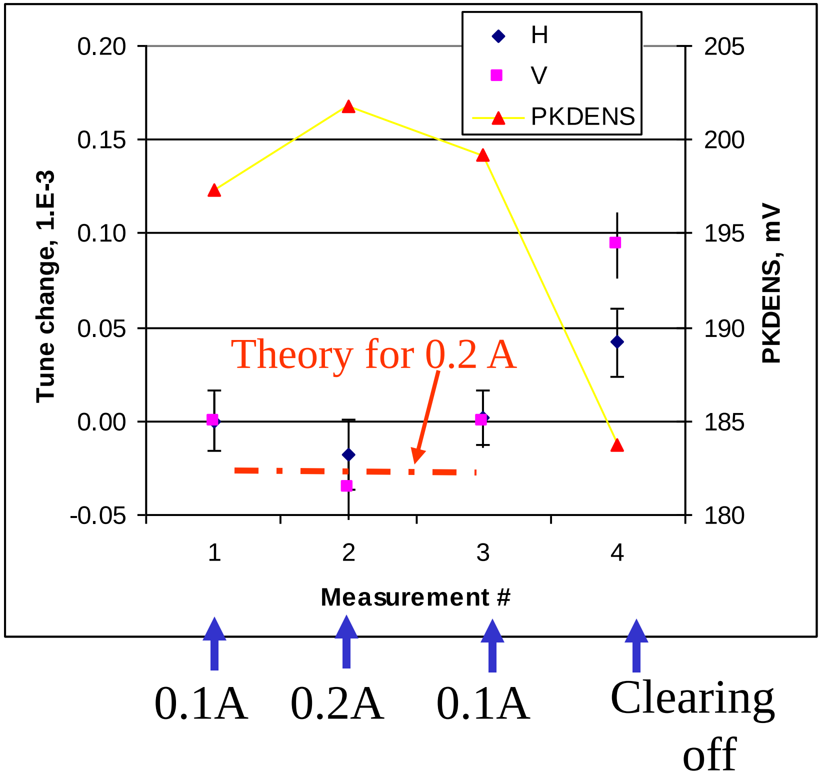
There is a correlation between the peak density and tunes



Tunes vs the peak density (3 min averages).
The tunes changes as $-8.6 \cdot 10^{-6}$ /mV.

Shifts due to electrons





There are small changes in tunes with an increase of the electron beam current and with removing clearing voltage that are in line with expectations, but at the same time the peak current was changing as well due to changed cooling conditions.

Changes with respect to the initial tunes ("0.1A") after increasing the beam current to 0.2 A and after turning clearing off in units of 10^{-3}.

Summary

- Measured tune shift due to pbar space charge is in agreement with a simple estimation.
- The estimated incoherent tune shift is significantly larger and goes as high as 0.1 in the time of mining.

- The tunes change ~ 0.001 after turning on electron cooling. The change takes ~0.5 hr, correlates with changes in the peak pbar density, and has no explanation.
- The power in 21 MHz signal correlates rather with coldness of pbars then with the presence of the electron beam.
- A response to the increase of the e-beam current from 0.1 to 0.2 A is ~ $-3 \cdot 10^{-5}$ and doesn't contradict to an estimation.
- Response to turning off the clearing voltage in the cooling section is small and corresponds to $\gamma^2 n_{e\_sec}/n_e \sim 1$, i.e. ~ 1% relative density of secondary electrons. The 10% density required to explain the radial dependence of the drag force and the discrepancy of the electron beam size measurement does contradict to the measurement.