Resistive-Wall Instability Observed at Fermilab Recycler Ring

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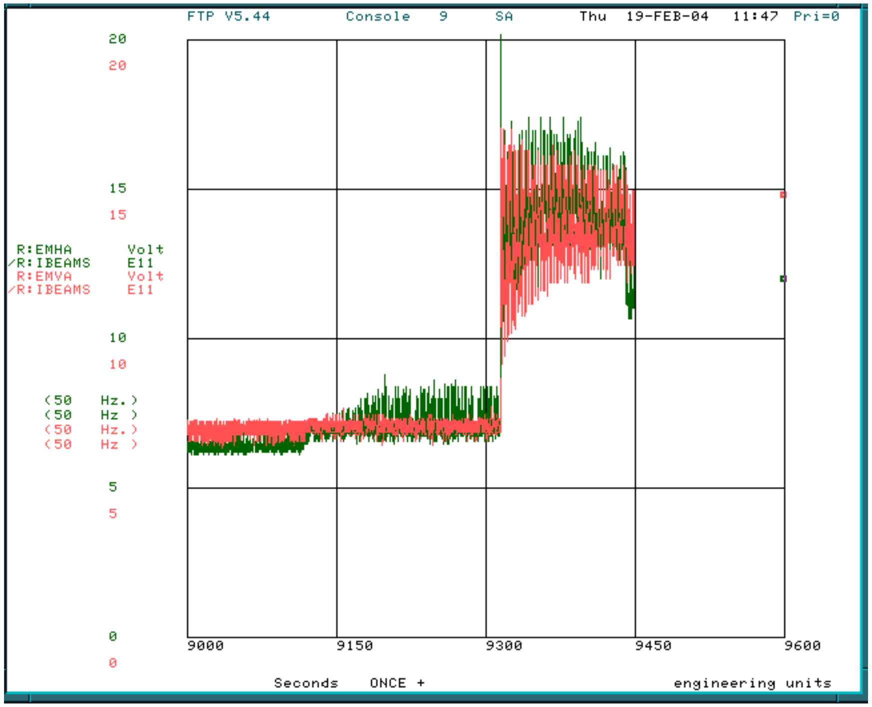
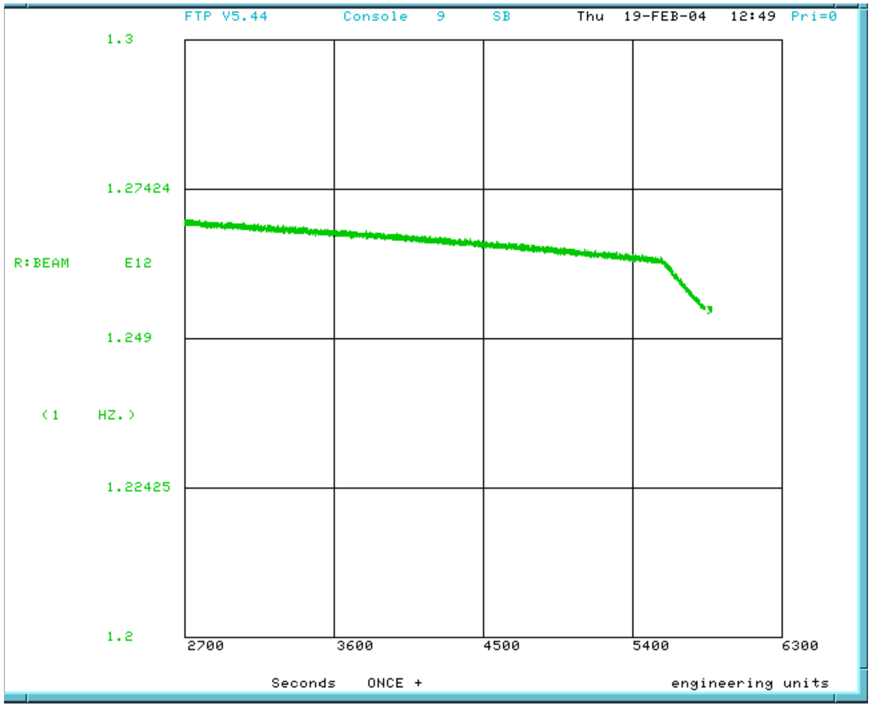
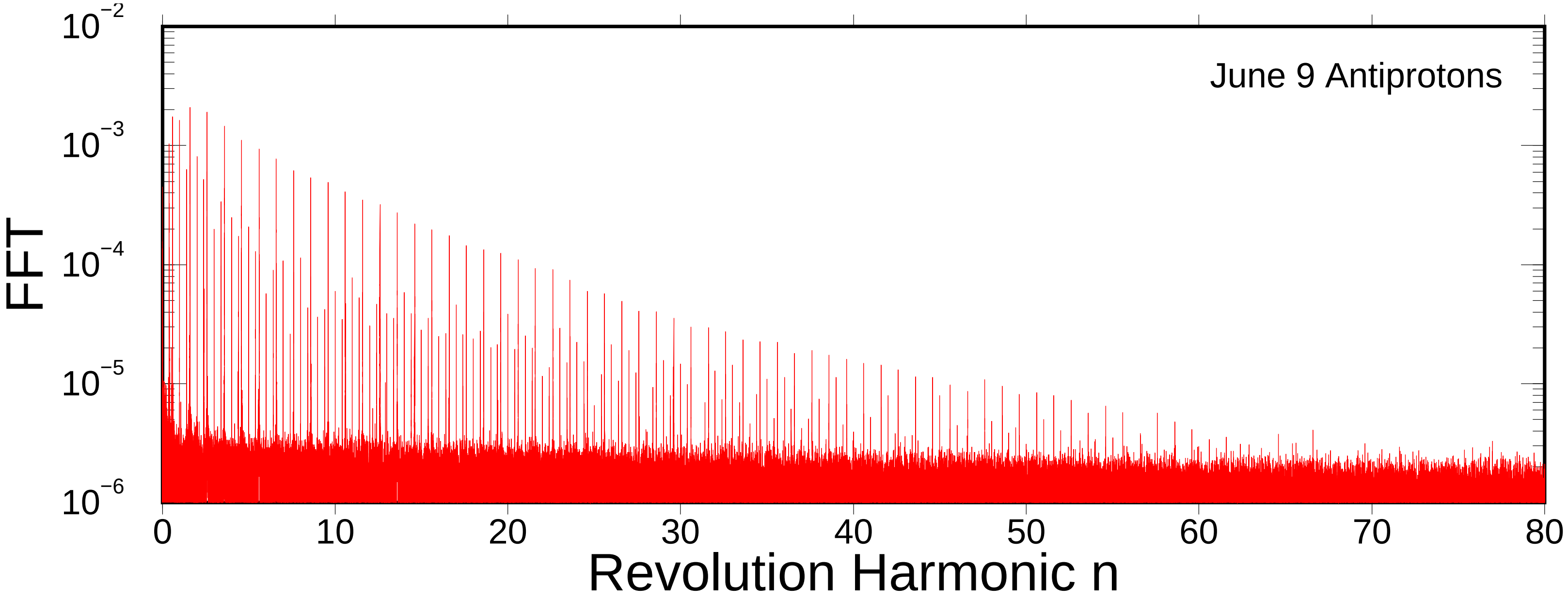
Transverse Instabilities





- First documented on Feb. 19, 2004.
- $\bar{p}$ with $N_b = 28 \times 10^{10}$ stored at 8.938 GeV, length $t_b = 3.5\ \mu$s
- Rms energy spread 3 MeV, ϵ_{N95} increases from 6 to 13π mm-mr.

- First to blame was trapped ion.
- Spectrum measurement indicates resistive-wall driven.



- This belief was fortified by inducing similar instabilities on a proton beam that cannot trap ions.
- Want to compute growth rates and compare with observations.

Dispersion Relation

- $\bar{p}$ beam is between two barriers.

  At 3 MeV offset, syn period $T_{\rm syn} \gtrsim \dfrac{2T_b}{|\eta|\delta} = 2.4$ s ,

  $T_b = 3.5\ \mu$s, $\eta = -0.008812$.

- Growth time ~ 20 ms $\Longrightarrow$ safe to treat beam as coasting.

- Disp. relation for bi-Gaussian distribution: $U + iV = \dfrac{1}{w(z_1)}$

  where $U + iV = -\dfrac{i\pi\Delta\omega_y}{\sqrt{2\pi}\sigma_\delta|S_y|\omega_0} = -\dfrac{eI_0\beta^2 cZ_1^\perp}{4\sqrt{2\pi}\nu_y\omega_0\sigma_E|S_y|}$.

  effective chromaticity $S_y = \xi_y - \eta(n + \nu_y)$.

- Growth rate is $\dfrac{1}{\tau} = \mathcal{I}m\,\Omega = \sqrt{2}\sigma_\delta|S_y|\omega_0\,\mathcal{I}m\,z_1$.

Transverse Impedance in Fermilab Recycler

- Elliptical beam pipe: $Z_1^V=(1-i)\dfrac{21.9}{\sqrt{n-[\nu_y]}}$ MΩ/m for $n=1,\ 2,\ 3,\cdots$.

- Space-charge: Uniform distribution for scraped p beam,

  $$Z_1^V\Big|_{\text{spch}}=i\frac{Z_0R}{\gamma^2\beta^2a^2}=i\frac{Z_0\nu_y}{\gamma\beta\epsilon_{N95}}\qquad\qquad(a=\text{ beam radius})$$

  Stochastically cooled $\bar{p}$ beam has bi-Gaussian distribution:

  $$a=\sqrt{2}\sigma_y\qquad\longrightarrow Z_1^V\Big|_{\text{spch}}=i\frac{3Z_0\nu_y}{\gamma\beta\epsilon_{N95}}\ .$$

- p has $\epsilon_{N95}=6\pi$ mm-mr $\longrightarrow Z_1^V\Big|_{\text{spch}}=i162$ MΩ/m

  $\bar{p}$ has $\epsilon_{N95}=3\pi$ mm-mr $\longrightarrow Z_1^V\Big|_{\text{spch}}=i971$ MΩ/m.

  will be reduced by $-i28.6$ MΩ/m from wall-resistivity for $n=1$

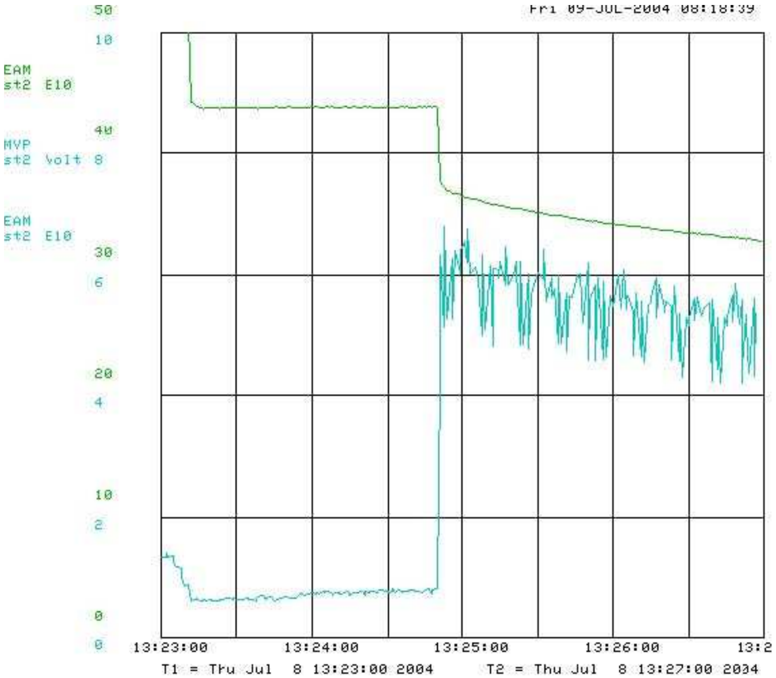
  and $\sim -i30$ MΩ/m from other discontinuities.

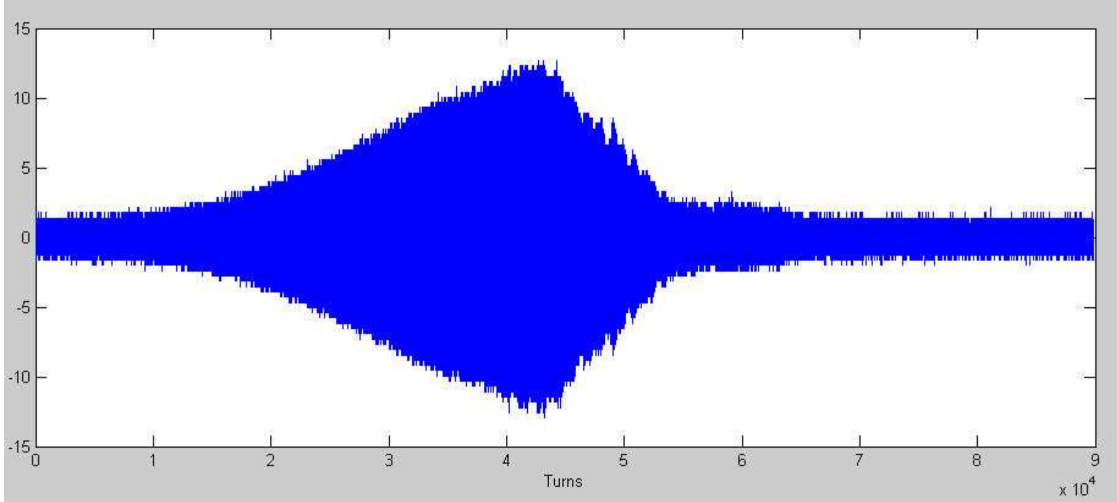
- Contributions from other discontinuities are small below ~ 20 MHz or $n = 220$ rev. harmonics.

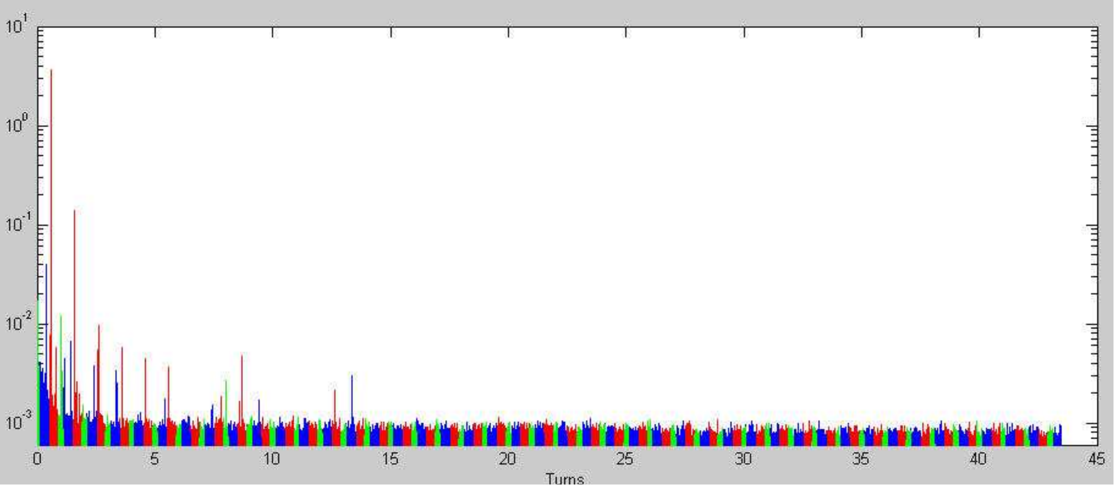
- Strong space charge will suppress Landau damping.

Induced p Instabilities

(J. Crisp and M. Hu)



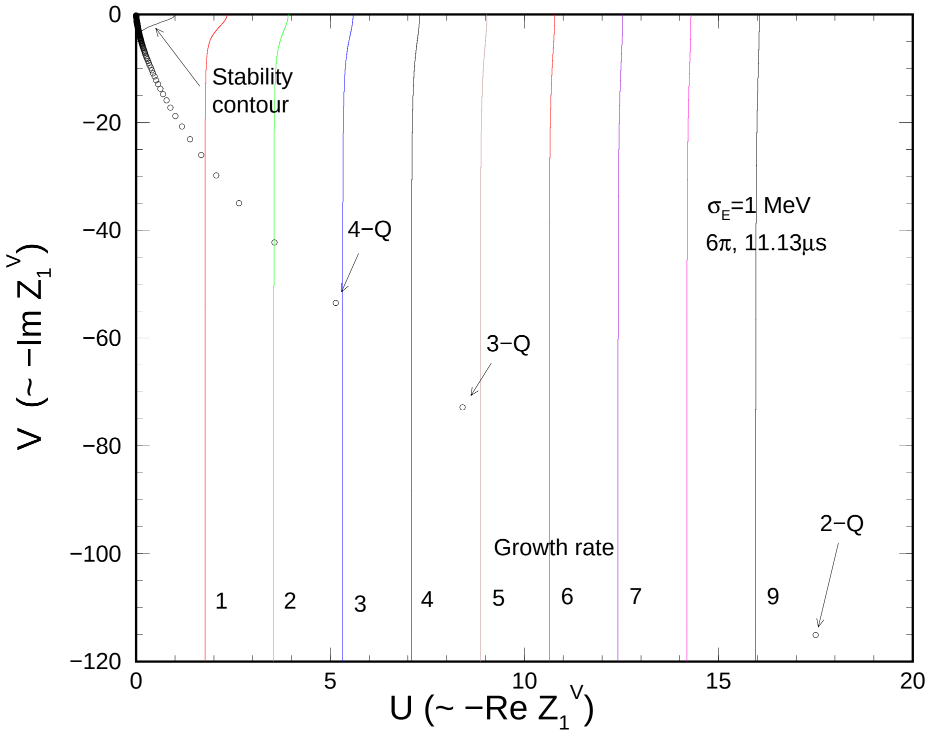


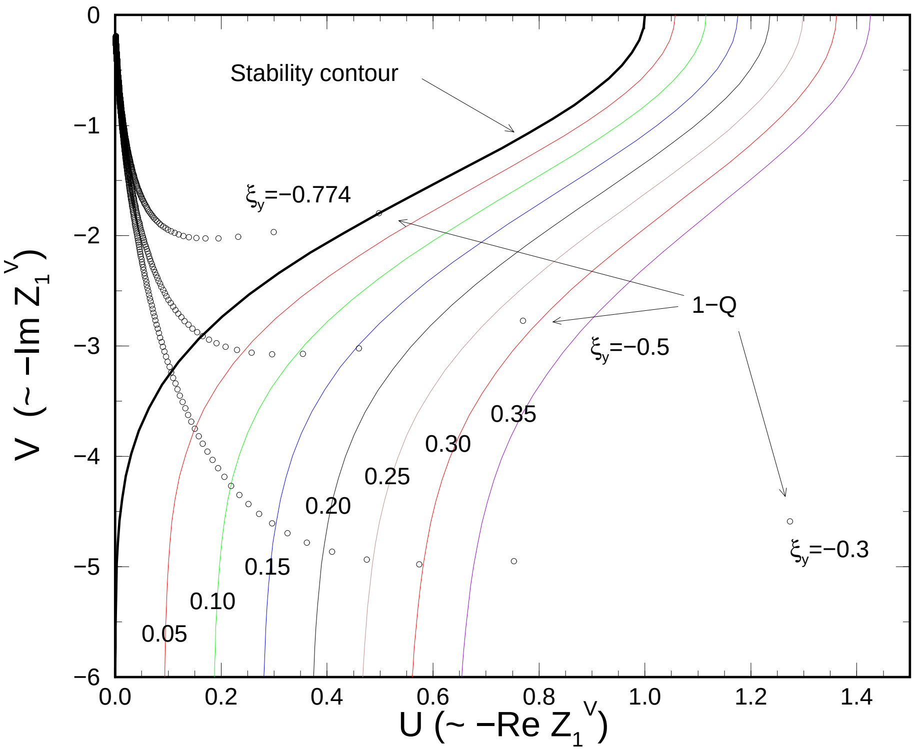


Diff. signals sampled at 8 MHz.

Growth subsided after ~ 40000 turns (445 ms).

Lower sidebands (red) much stronger than lower (blue) and harmonics (green).



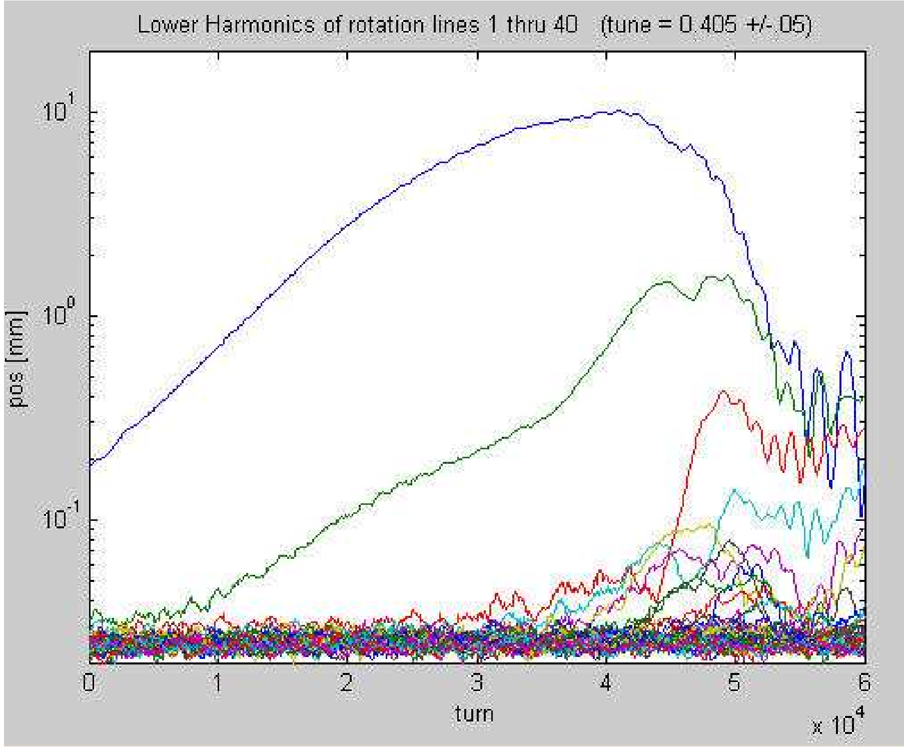


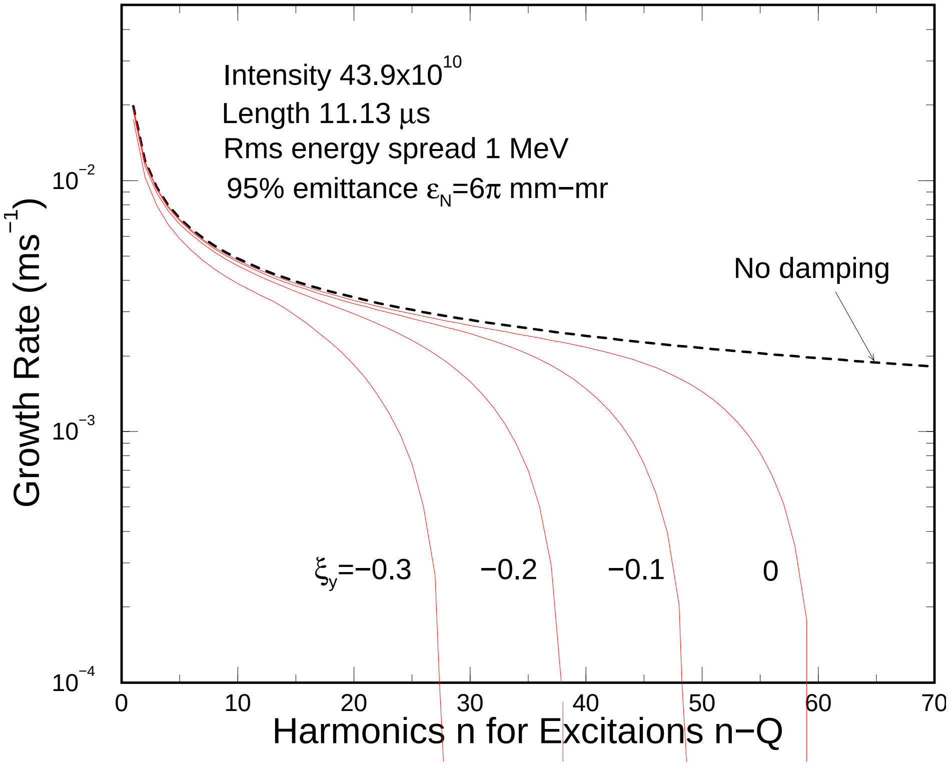
Left: $\xi_y = 0$, $(1 - Q)$ off-scale at $(U, V) = (78, -281)$

Landau damping is significant only in the curved part of contours.

At straight part of contours, no damping

Growth rate without damping: $\dfrac{1}{\tau} = -\dfrac{eI_0 c\,\mathcal{R}e\, Z_1^V}{4\pi\nu_y E}$.





Left: Amplitudes of first 40 lower betatron sidebands.

	Observed	Theory
$(1-Q)$	75 ms	51 ms
$(2-Q)$	105 ms	84 ms

Problems:

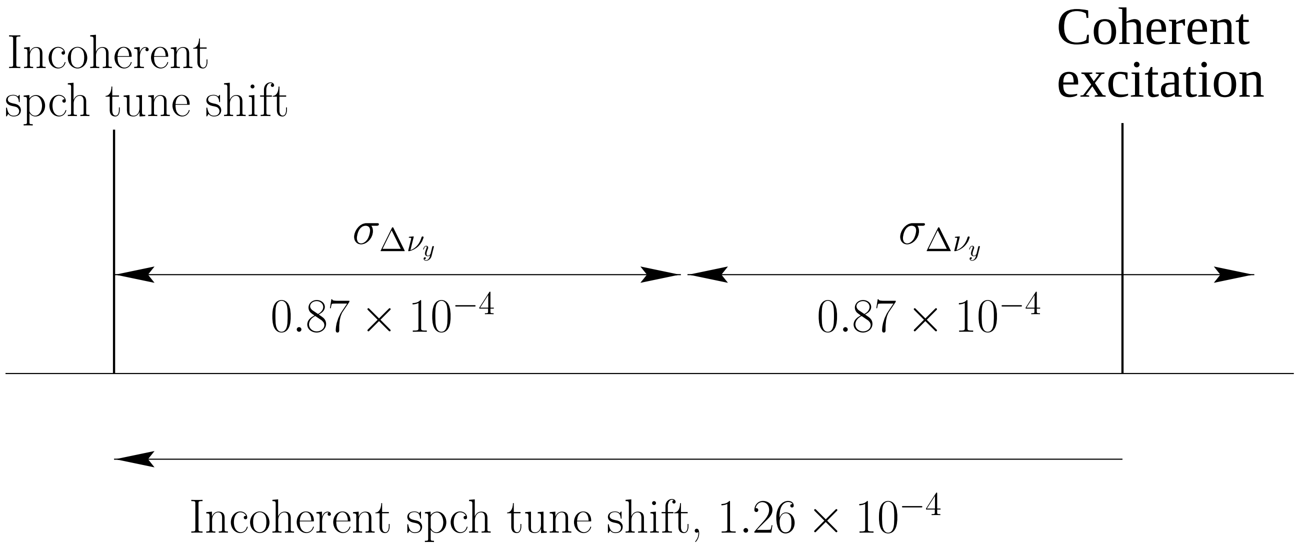
1. At $\xi_y = 0$, up to 60 sidebands are unstable, but see up to $\sim$ 20 only.

2. Also need to turn off skew quad at SQ408 to induce instabilities.

- $\mathcal{R}e\, Z_1^V$ is responsible for the growth,

  but space charge shifts tune spread away from coherent excitation.

- Incoherent tune shift: $\Delta\nu_y\Big|_{\text{incoh}} = i\dfrac{eI_0R}{4\pi\beta E\nu_y}Z_1^V$.



Incoherent
spch tune shift

Coherent
excitation

$\sigma_{\Delta\nu_y}$ $\sigma_{\Delta\nu_y}$

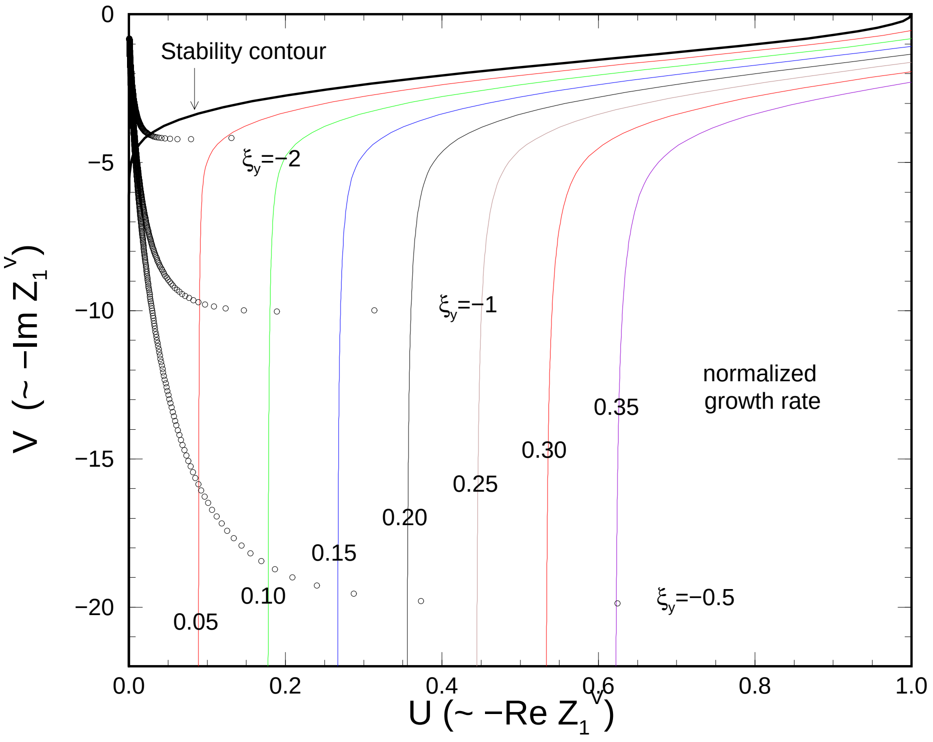
0.87×10^{-4} 0.87×10^{-4}

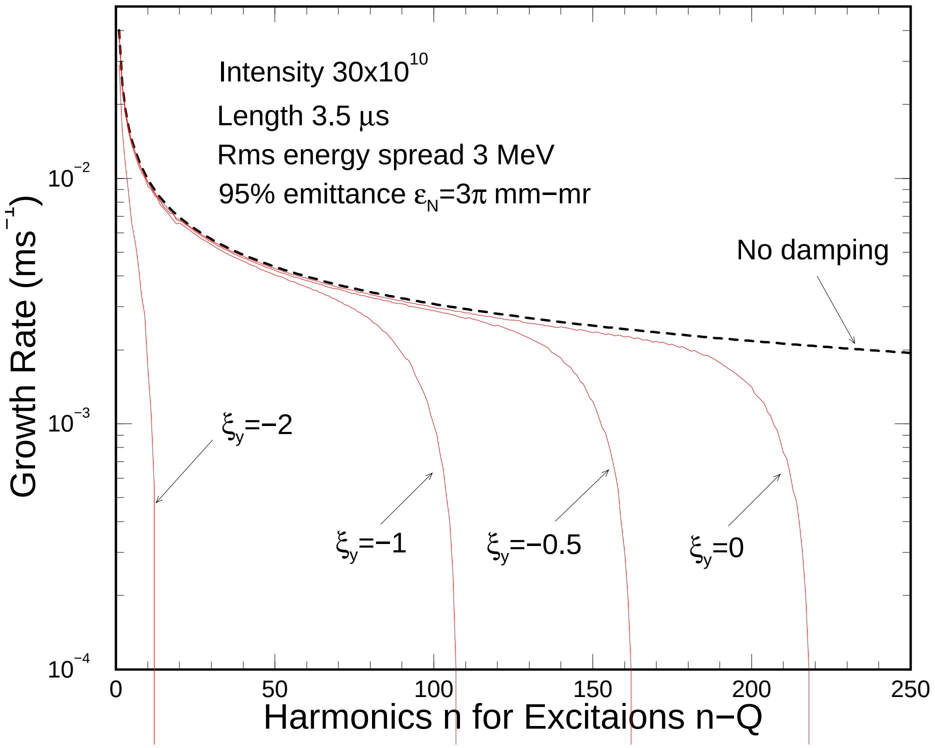
Incoherent spch tune shift, 1.26×10^{-4}

- Instabilities could not be induced without scraping p beam heavily.

  This verifies that space charge plays an important role here.

Induced $\bar{p}$ Instability on June 9 (J. Crisp and M. Hu)





$\sigma_E = 3$ MeV, $\epsilon_{N95} = 3\pi$ mm-mr.

Problems:

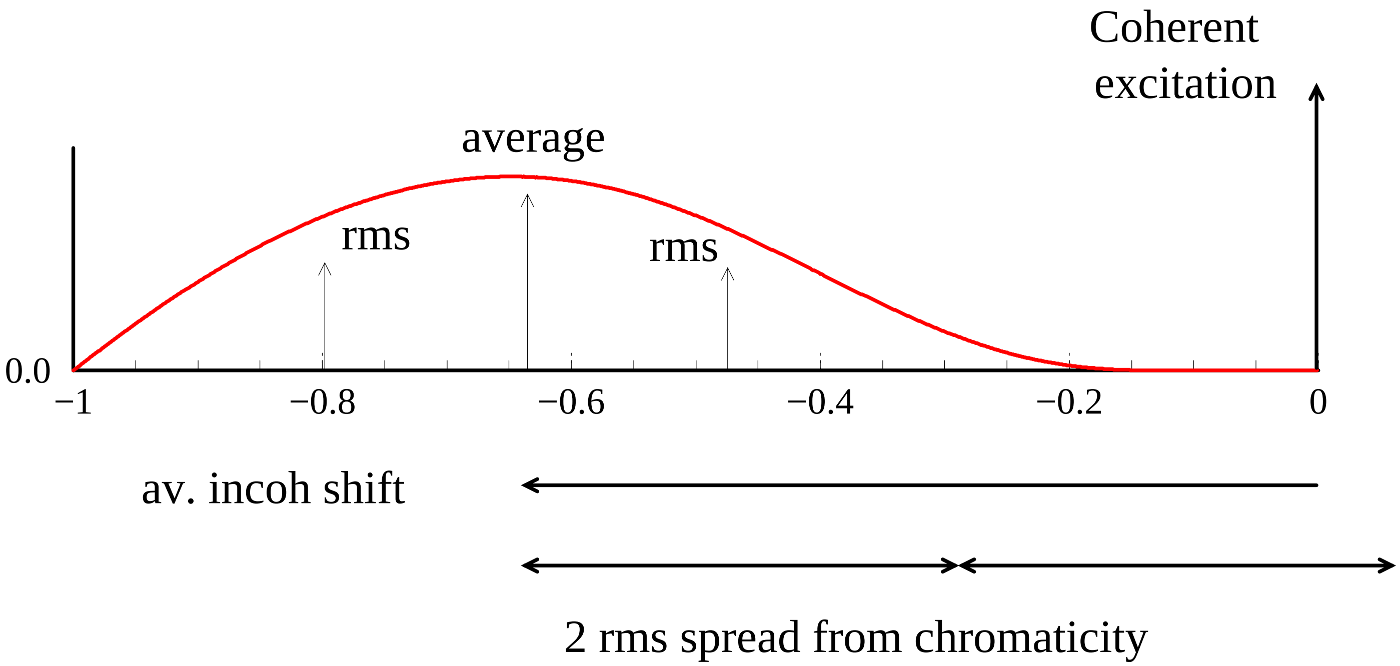
1. At $\xi_y = -2$, no instability is observed,

   but theory predicts the first 12 sidebands are unstable.

2. At $\xi_y = 0$, observed instabilities are up to ~ 70 sidebands only,

   but theory predicts first 250 sidebands unstable.

Space-Charge Effect and Landau Damping



Conclusions

- Measured sideband spectrum points to instabilities driven by resistive wall.
- Computed growth rates appear larger than observed.
- Not so many sidebands are unstable in observation.
- Space charge impedance estimation may be too large.

  But overestimation is unlikely:
  - In p, we assume uniform distribution which gives the smallest space charge imp.
  - In $\bar{p}$, stochastic cooling makes the distribution very bi-Gaussian, and has been verified by measurement using scrapers.

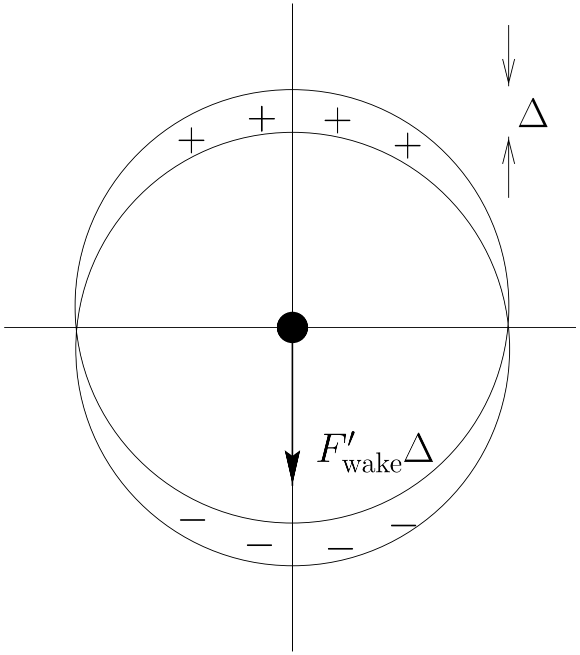
- Some argue that $Z_1^V\Big|_{\text{spch}} = i\dfrac{Z_0 R}{\gamma^2\beta^2 a^2}$

  should not be there.

- They argue that when

  oscillation amp $>$ beam radius,

  displaced charges will not be seen.



Beam shifted upward by Δ

- I think the argument is incorrect.

- Observed p beam instabilities do depend on heavy scraping.

  and $\bar{p}$ instability required rather cooled beam.

- Note that $Z_1^{\perp}\Big|_{\text{spch}} \propto \rho\Big|_{r=0}$, center of beam, and corresponds to the largest incoherent spch tune shift.

- Maybe one should use something that is averaged over the beam.

- Problems with skew quad SQ408:
  - No more natural trans. instabilities recorded after SQ408 was repaired.
  - Do not understand why we need to turn off SQ408 to induce instabilities.
  - Maybe the beam gets jittered horizontally and needs coupling to the vertical to start instability.
  - Maybe the strong horizontal-vertical coupling moves tune footprint to cover parametric resonances.