Some Comments About June 9 Induced Instability at the Recycler Ring

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Coasting Beam Consideration

- $\bar{p}$ beam: Intensity $N_b = 28 \times 10^{10}$, length $t_b = 3.5\ \mu$s

  $\longrightarrow I_{\text{local}} = eN_b/t_b = 12.8$ mA.

- Treating as coasting beam, vertical microwave stability limit:

$$|Z_1^V| \lesssim \frac{4\sqrt{2\pi}\nu_V \sigma_E}{eI_{\text{local}}\beta R} \left| \underbrace{\xi_V + \eta\Big(|n| - [\nu_V]\Big)}_{S_V,\ \text{effective chromaticity}} \right| .$$

  With $\nu_V = 24.415$, $\sigma_E = 3$ MeV, $|Z_1^V| \lesssim 109\, S_V$ MΩ/m .

  At $\xi_V = 0$, the stability limits are $|Z_1^V| \lesssim \begin{cases} 0.54\ \text{M}\Omega/\text{m} & \text{for } (1{-}Q) \\ 1.47\ \text{M}\Omega/\text{m} & \text{for } (2{-}Q) \end{cases}$

- Growth rate without Landau damping:

$$\frac{1}{\tau} = \frac{ecI_{\text{local}}\,\mathcal{R}e\,Z_1^V}{4\pi\nu_V E} = 1.40\,\mathcal{R}e\,Z_1^V\ \text{M}\Omega/\text{m} \quad \Big[\mathcal{R}e\,Z_1^V \text{ in M}\Omega/\text{m}\Big] .$$

Resistive Wall Impedances

Assuming elliptical SS beam pipe $2a = 3.75''$ by $2b = 1.75''$,

$$Z_0^{\|} = (1+j)11.68\, n^{1/2}\ \Omega\ ,$$

$$Z_1^H = (1+j)11.79 \left| n - [\nu_H] \right|^{-1/2}\ \text{M}\Omega/\text{m}\ ,$$

$$Z_1^V = (1+j)21.92 \left| n - [\nu_V] \right|^{-1/2}\ \text{M}\Omega/\text{m}\ ,$$

	Stability limit (MΩ/m)	$\mathcal{R}e\, Z_1^V$ (MΩ/m)	Growth time (ms)
$1-Q$	0.54	28.66	24.9
$2-Q$	1.47	17.41	41.0
$3-Q$	2.40	13.62	52.3
$4-Q$	3.33	11.55	61.6
$5-Q$	4.26	10.24	69.7
$6-Q$	5.18	9.28	76.9
$7-Q$	6.11	8.54	83.6
$8-Q$	7.04	7.96	89.7
$9-Q$	7.97	7.48	95.4

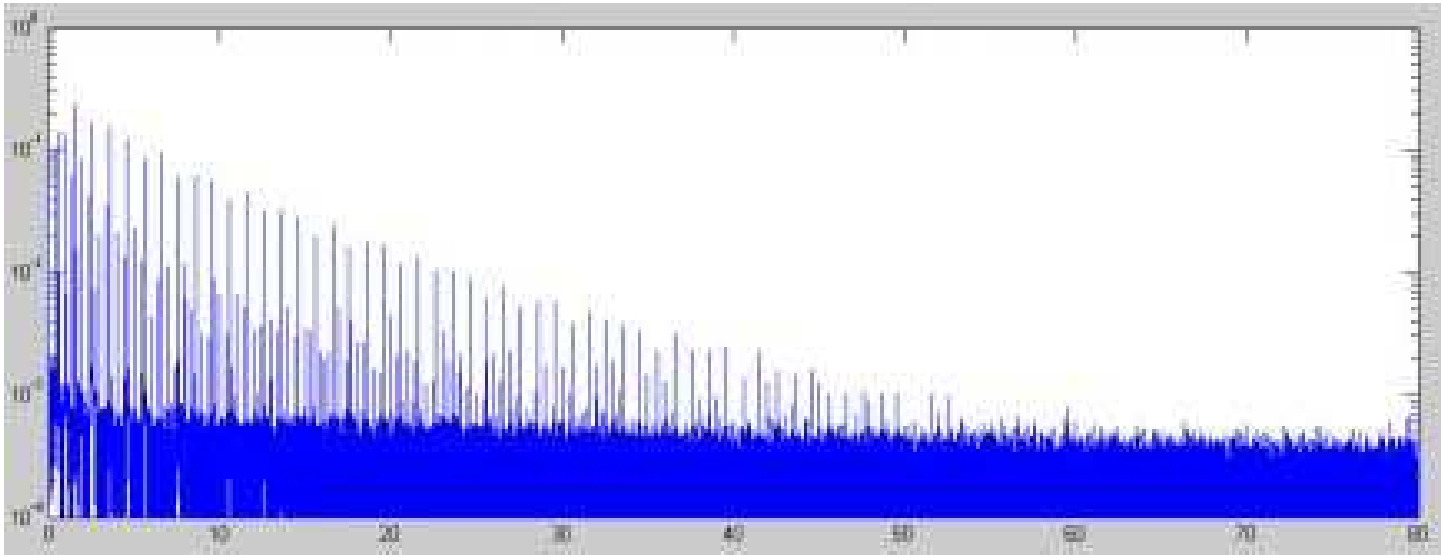
Finite Beam Length

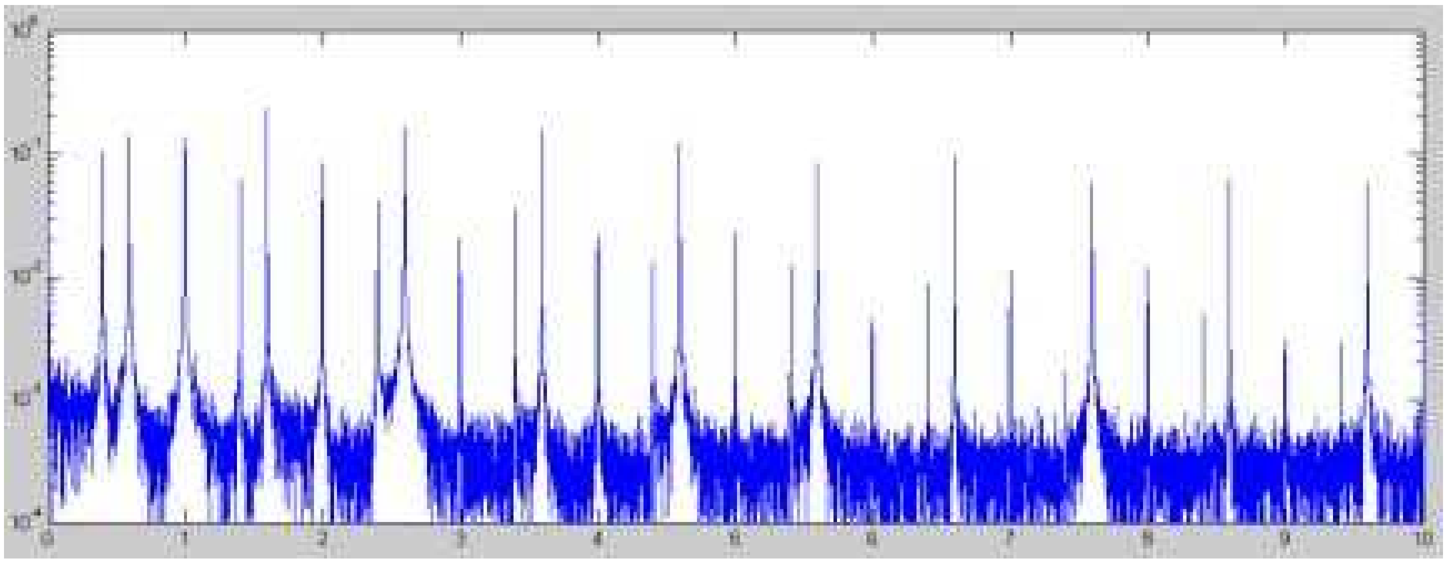
- Since beam has finite length $t_b = 3.5\ \mu$s, wave excited has $\lambda < 2t_b$, or $f > 1/(2t_b) = 143$ kHz.

- $(1 - Q) \longleftrightarrow 52.5$ kHz

  $(2 - Q) \longleftrightarrow 142$ kHz

  Therefore $(1 - Q)$ not well excited and $(2 - Q)$ excited most.





Note that pre-amp on VP522 has flat response from 10 kHz to 10 MHz.

Equal growth rate $\longrightarrow$ logarithmic behavior.

Lower freq. sidebands grow faster $\longrightarrow$ curves more than logarithmic.

Bunch Consideration

- Rms mom. spread is $\sigma_p = 3$ MeV/c. Particles drift per turn

$$\Delta t = |\eta| T_0 \frac{\sigma_p}{p_0} = 3.20 \times 10^{-5}\ \mu\text{s}\ ,$$

they take $2t_b/\Delta t = 219000$ turns to drift in both directions.

they take $2 \times 6000/2 = 6000$ turns to move inside the 2 barriers.

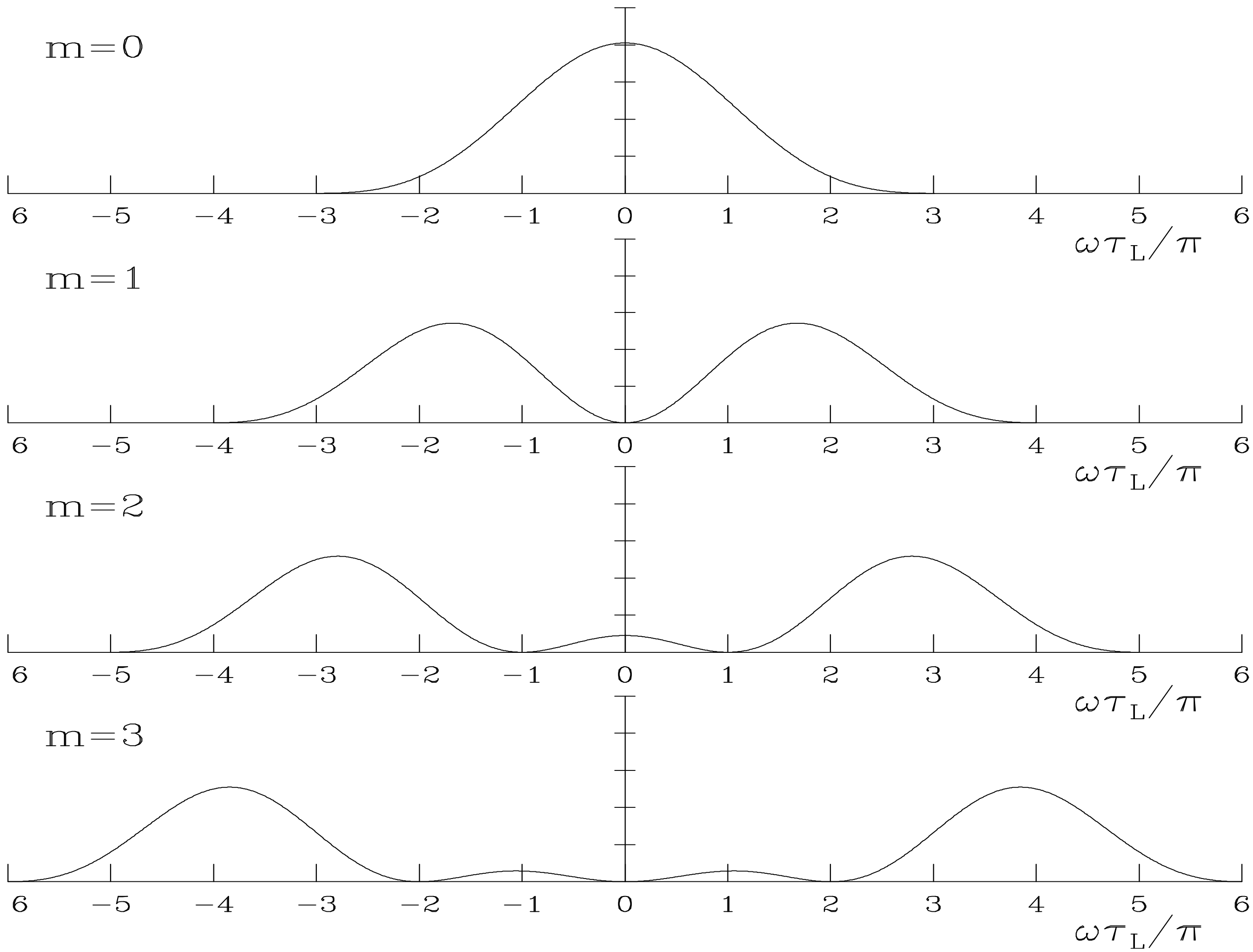
Synchrotron period is $223000 \times 11.13 \times 10^{-6} = 2.5$ s.

- Thus for $t \gtrsim 1.25$ s, the head and tail exchange position.

  Then the beam can no longer be treated as a coasting beam.

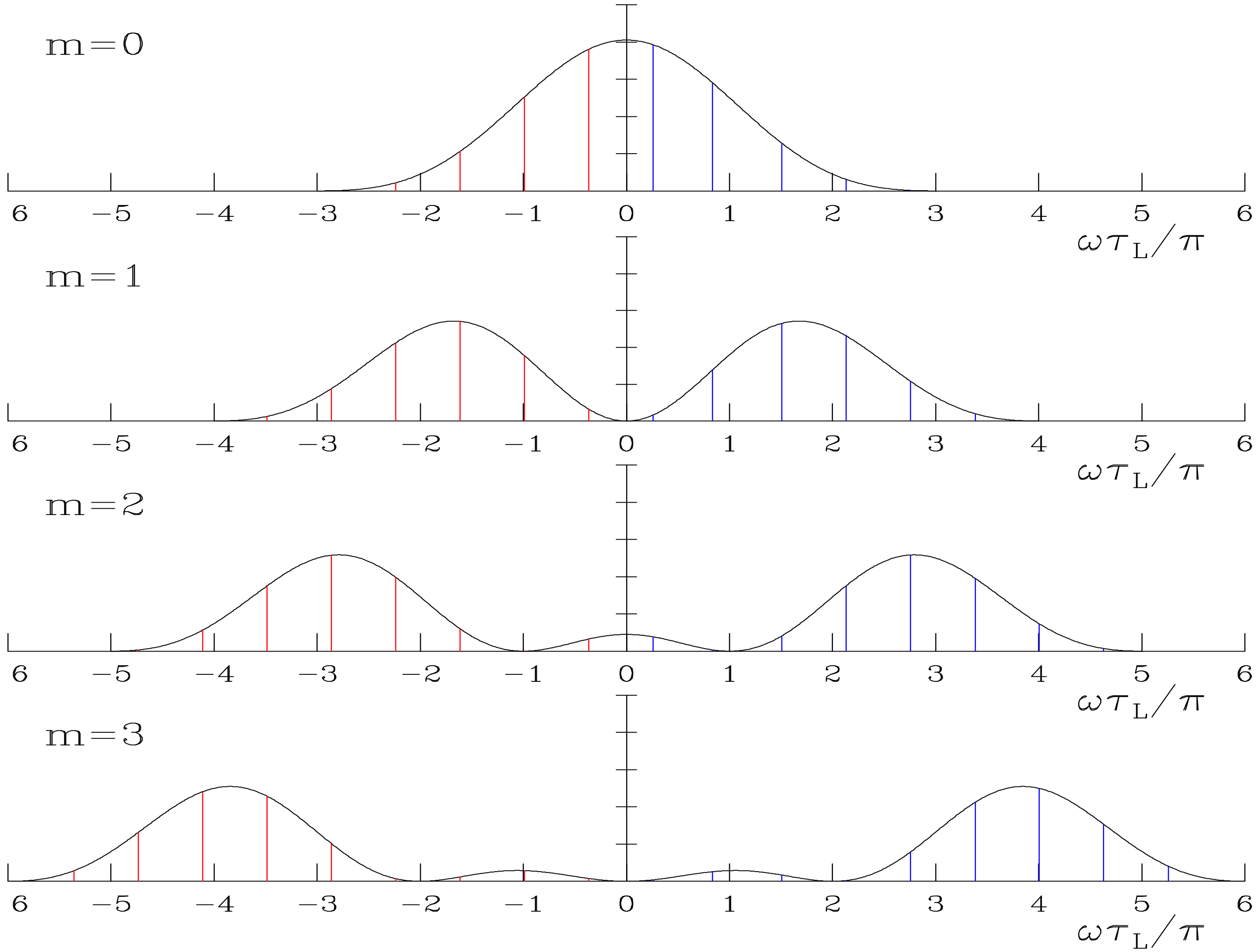
• Individual rev. harmonics are no longer independent eigenstates.

Eigenmodes are bunch modes which contain many harmonics.



• For the $\tau_L = 3.5$ μs beam,

one unit in above $\longrightarrow$ 143 kHz near $(2-Q)$ sideband.



- If $\xi_V = 0$, $m = 0$ mode is stable

  since $(0 + Q)$ dominates over $(1 - Q)$.

- This is Robinson-type stability problem.

  Higher order modes if unstable, should have small growth rates.

Mechanism of Instability

1. Sudden pulsing of QCL moves the beam sideway horizontally, initiating horizontal betatron oscillations.

2. Vertical and horizontal coupling induces vertical betatron oscillations.

3. Because head of beam is not affected by tail, beam is considered coasting. Lower sidebands of all harmonics are excited as eigenmodes except $(1-Q)$ which has wavelength too long.

4. After roughly 1/2 rms syn. period, tail particles reach the head position. Several harmonics interfere with each other.
   E.g., damping power of $(n+Q)$ upper sidebands start to cancel the growth of $(n-Q)$ lower sidebands.

5. Beam has reach steady state of a bunch:

   $m = 0$ mode stable, $m \geq 1$ modes, which can be slightly unstable, will be damped by tune spread and/or stochastic cooling.

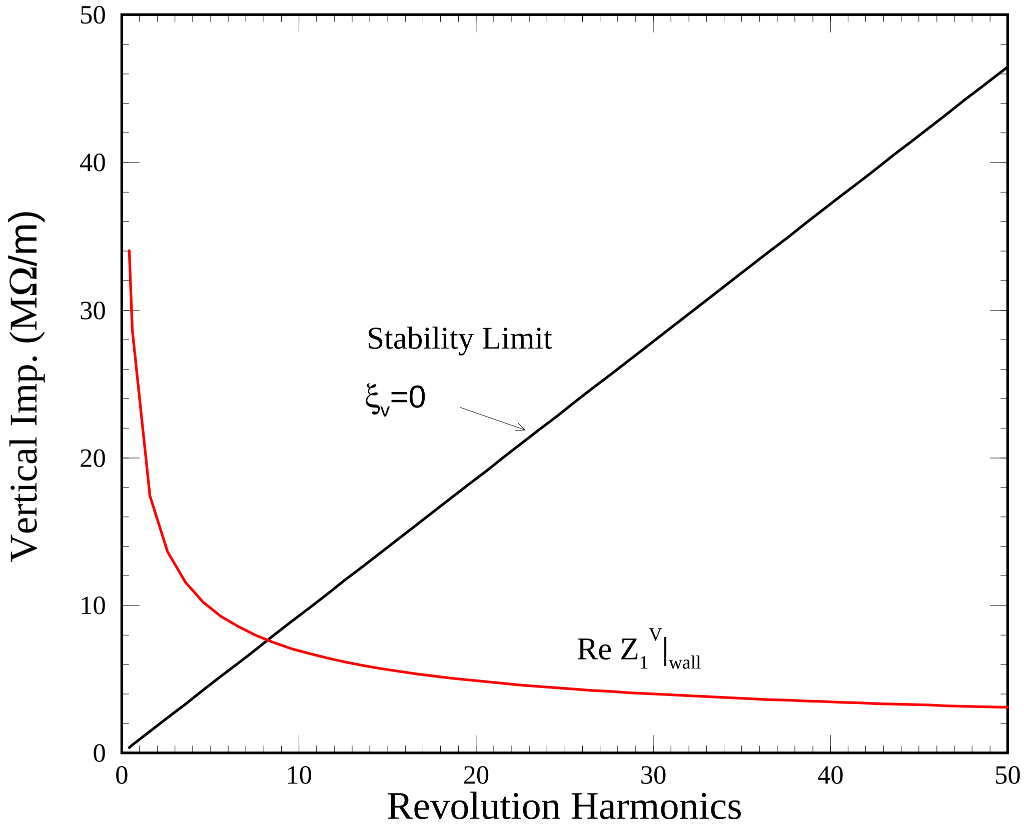
6. The instability can persist only for about a syn. period.

New experiment on June 21 has confirmed this.

Remaining Problems

- Experiment shows excitation of sidebands up to at least $(55-Q)$, but with only resistive wall impedance, sidebands starting at $(9-Q)$ or 0.77 MHz are stable.

  We cannot imagine appreciable amount of $\mathcal{R}e\, Z_1^V$ at such low freq.

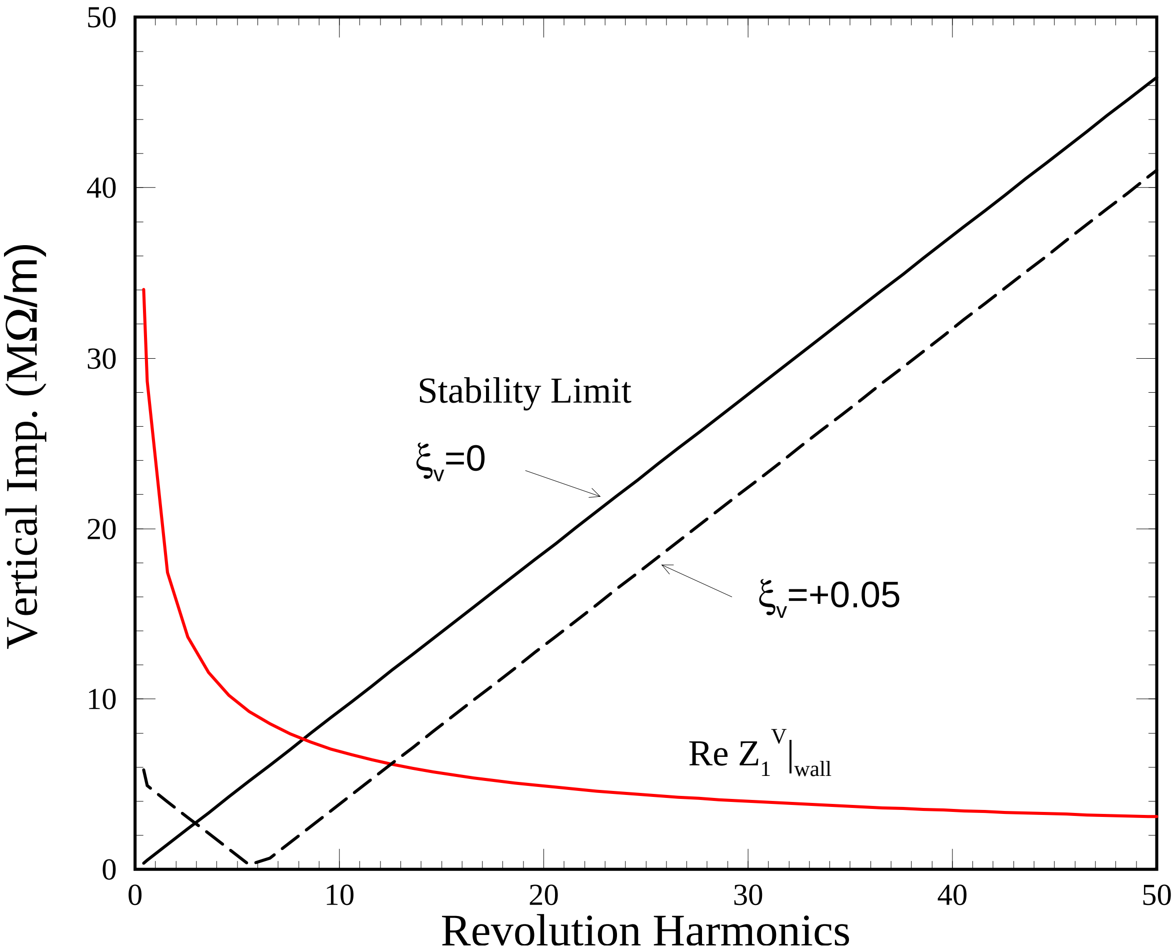


Stability limit: $$|Z_1^V| \lesssim \frac{4\sqrt{2\pi}\nu_V\sigma_E}{eI_{\rm local}\beta R}\left|\xi_V + \eta\Big(|n| - [\nu_V]\Big)\right| \, .$$

↑

-0.049 for $(6-Q)$

Small ξ_V helps but not much.



- **Chromaticity:**

  1. Chromaticity shifts spectrum to the right by

     $f_\xi = \dfrac{\xi_V f_0}{\eta} = -117.5\xi_V f_0,$ with $\eta = -0.008511$

  2. One unit of ξ_V shifts spectrum by -117.5 rev. harmonics.

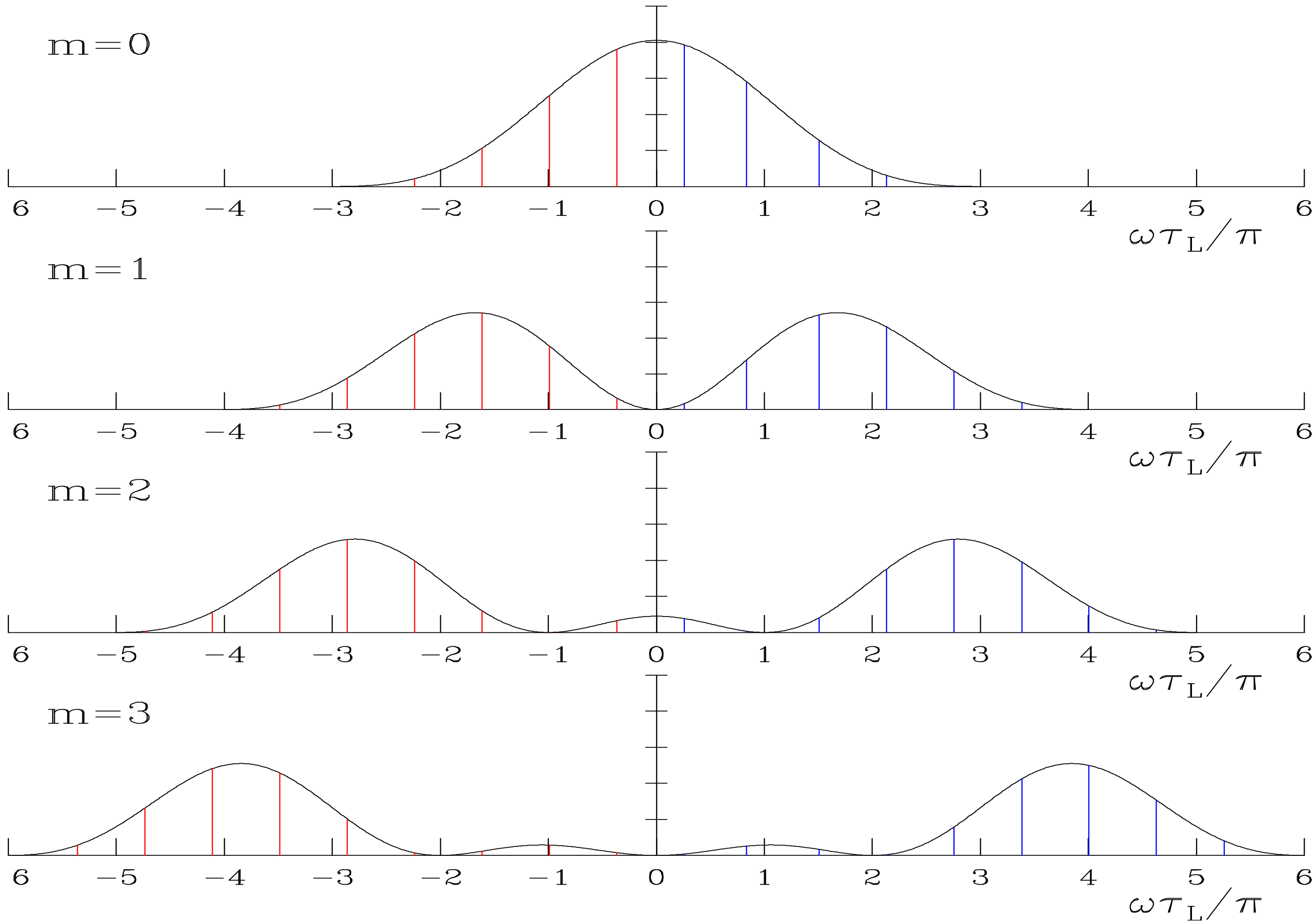
     Even $\xi_V = -0.01$ shifts spectrum by 1.17 rev. harmonics.

     This is not a problem because the shift is more at Tevatron where $\eta = 0.0028$.

  3. What bothers us here is the long bunch length.

     We care about betatron phase shift across the bunch.

	τ_L	η	ω_ξ/ω_0	$\frac{\omega_\xi \tau_L}{\pi}$
Tevatron	4 ns	0.0028	-118	0.135
Recycler	3 μs	-0.008511	357	-73.9



4. Thus we are not so sure where the bunch spectrum is with respect to the rev. harmonics.

5. But these bunched-beam head-tail instabilities should be very slow.

- **Is the beam stable?**

  1. Even without pulsation of QCL, the beam appears to be metastable, because a small trans. disp. can start sideband excitation.

  2. Maybe small trans. disp. are damped by stochastic cooling, thus preventing evolution into instability.

     Only large trans. disp. that cannnot be damped fast enough will lead to instability.

  3. If this is true, long proton beam should be very unstable, because of absence of stochastic cooling.

4. Remember that the stability limit and growth rate do not depend on transverse emittance at all.

   So stability does not depend on transverse density.

   Proton beam with larger local current should be more unstable.

5. Should try to do experiment with

   intense and long p beams

   and $\bar{p}$ beams of different transverse emittances.

Comments from the Floor

1. Space-charge contribution to the Recycler impedance is large and should be included in the consideration of stability limit.

2. Since synchrotron period is more than one order of magnitude larger than the instability growth time in the coasting-beam approximation, bunch-beam consideration should be irrelevant to the instability.

3. The pulsing of the QCL takes a long duration (of the order of a second). The effect to the beam transverse offset is adiabatic and no instability should be induced.