Non-Destructive Beam Measurements

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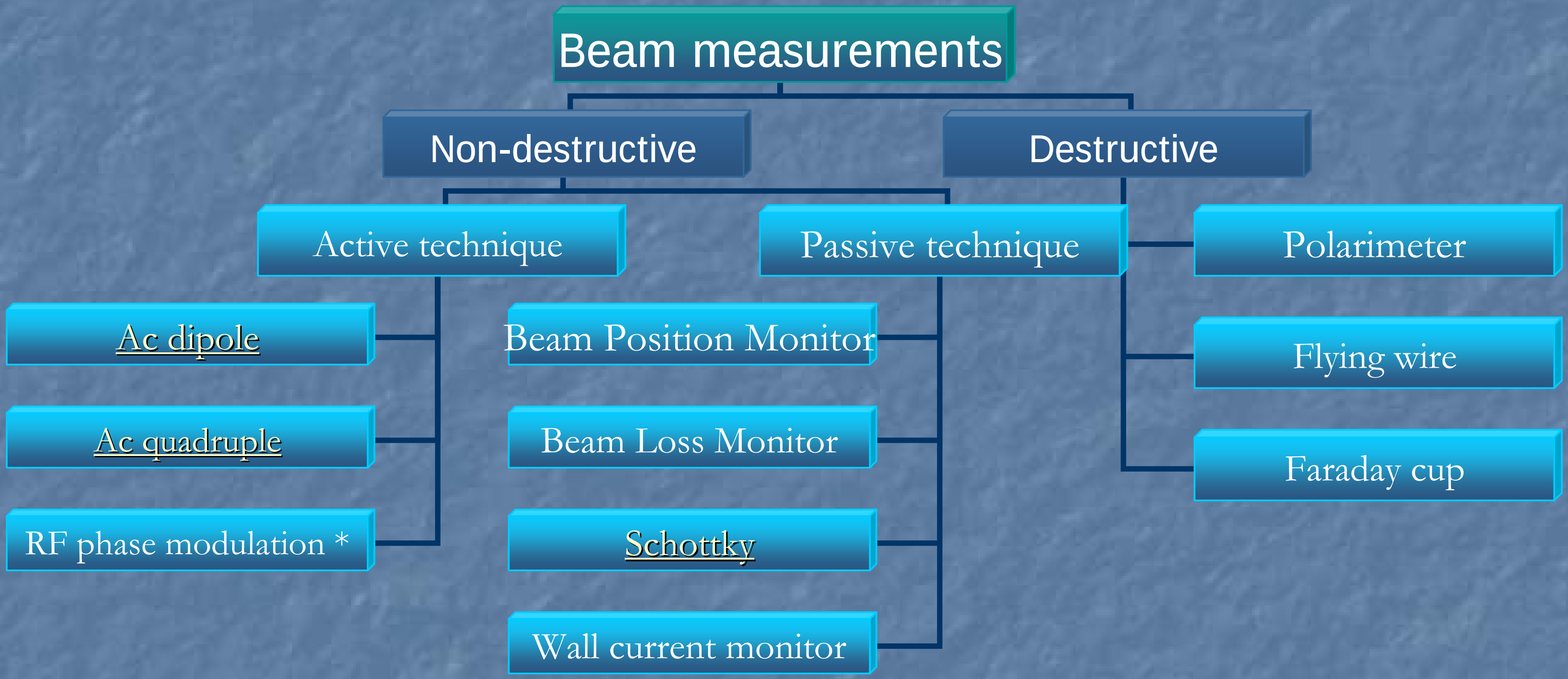
Beam Measurements



- O. S. Bruning, W. Hofle, R. Jones, T. Linnecar, H. Schmickler, *Chromaticity Measurements via RF Phase Modulation and Continuous Tracking*, Proceedings of PAC2003

Active non-destructive technique: AC dipole

- AC dipole: a dipole magnet with oscillating field.
- AC dipole is known as shakers in the electron machines to excite coherent oscillation by driving beam at its betatron frequency
- The technique of using an ac dipole to achieve a long lasting coherent oscillation in the hardon machine was first developed in the Brookhaven AGS. The experiment was later on repeated in the CERN SPS
- The Brookhaven AGS beam experiment also demonstrated the beam emittance can be restored if the excitation of ac dipole gets ramped up/down adiabatically.

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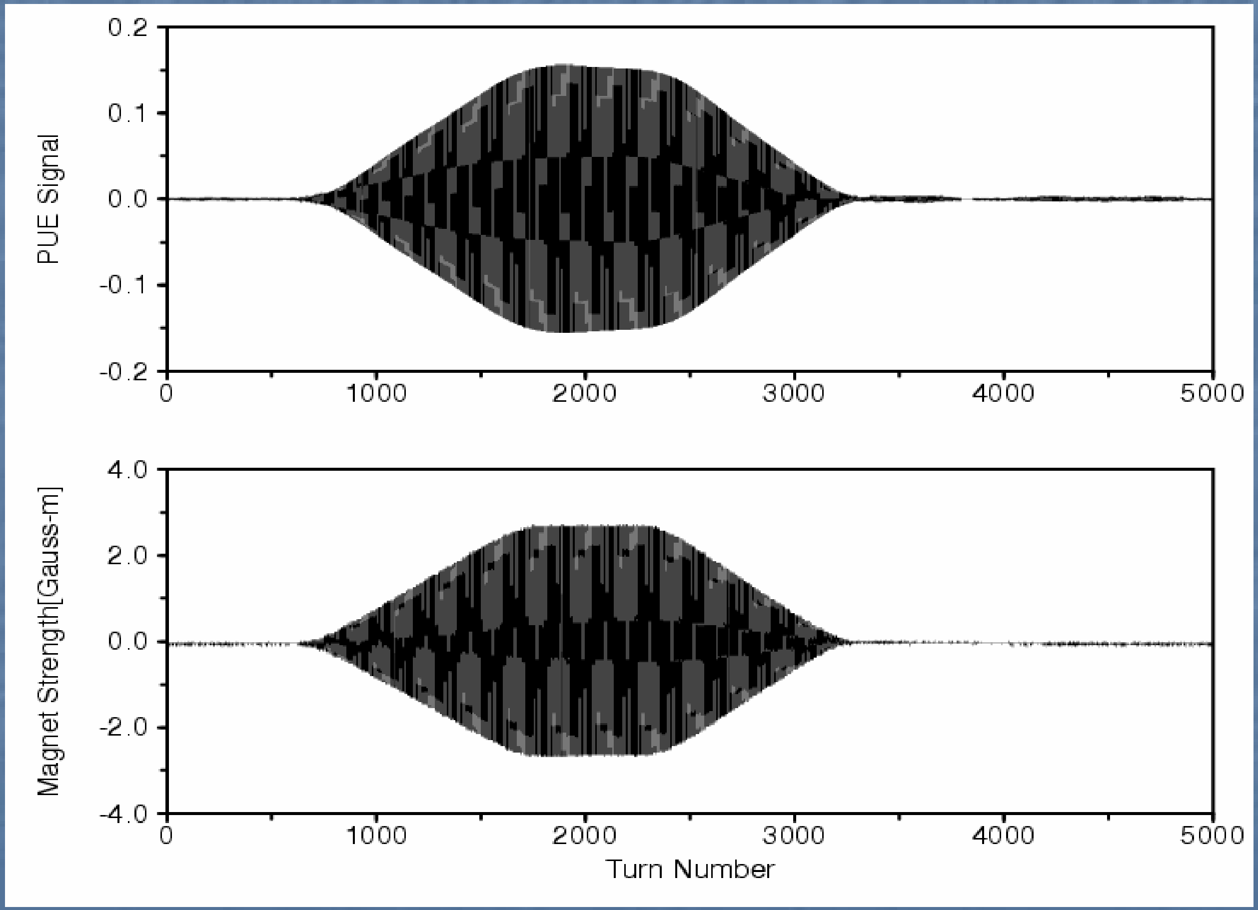
Active non-destructive technique: AC dipole

- Ac dipole driven coherent oscillation in the Brookhaven AGS



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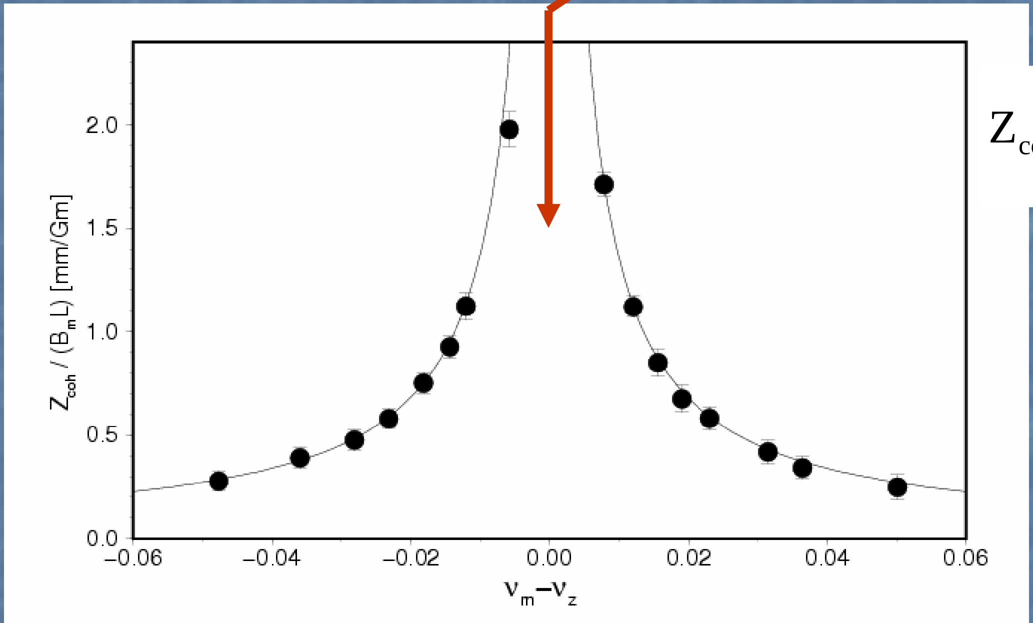
Active non-destructive technique: AC dipole

- Amplitude of driven coherent oscillation in a linear machine

Beam becomes unstable if $\nu_m = \nu_z$

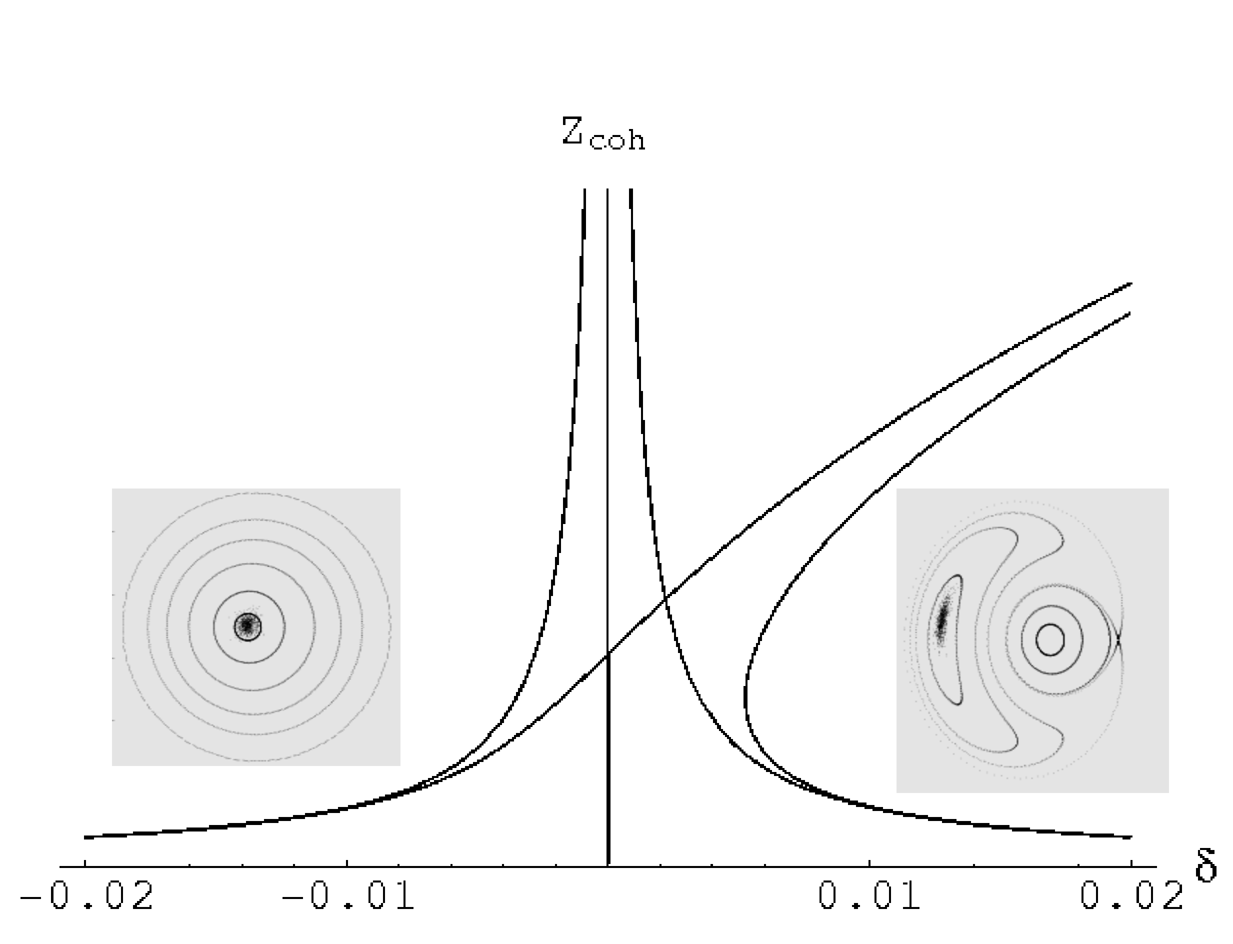


$$Z_{coh}(s) = \frac{\Delta B_m L}{4\pi B\rho |\nu_m - \nu_z|} \sqrt{\beta(s)\beta_m}$$

- O. Berrig, W. Hoflem, R. Jones, J. Koopman, J-P. Koutchouk, F. Schmidt, SL-Note-00-062 MD, Nov. 2003
- M. Bai et al., Physical Review E. Vol 5, (1997)

Active non-destructive technique: AC dipole

- Driven coherent oscillation with non-linear detuning



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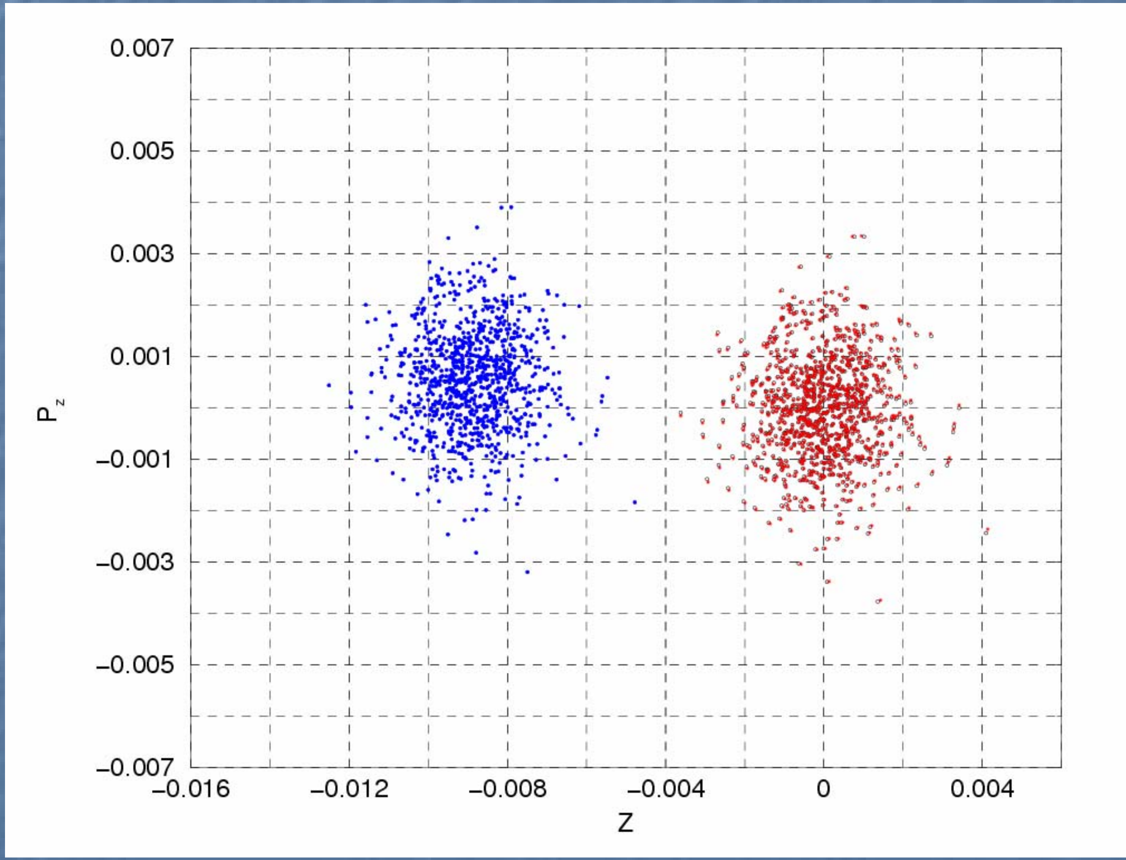
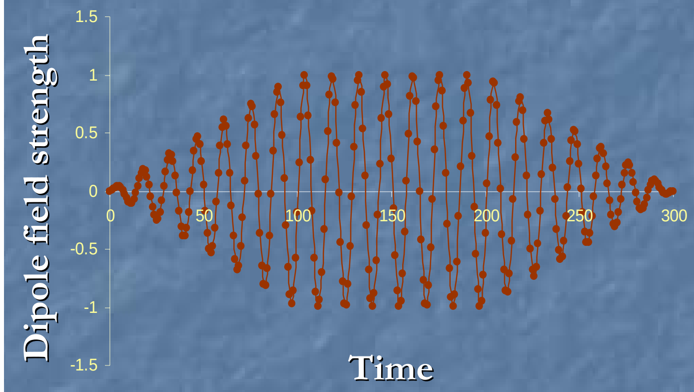
Active non-destructive techniques: AC dipole

- Adiabatic excitation allows the particles in the beam to follow the external driving force so that the beam distribution gets restored after the excitation.





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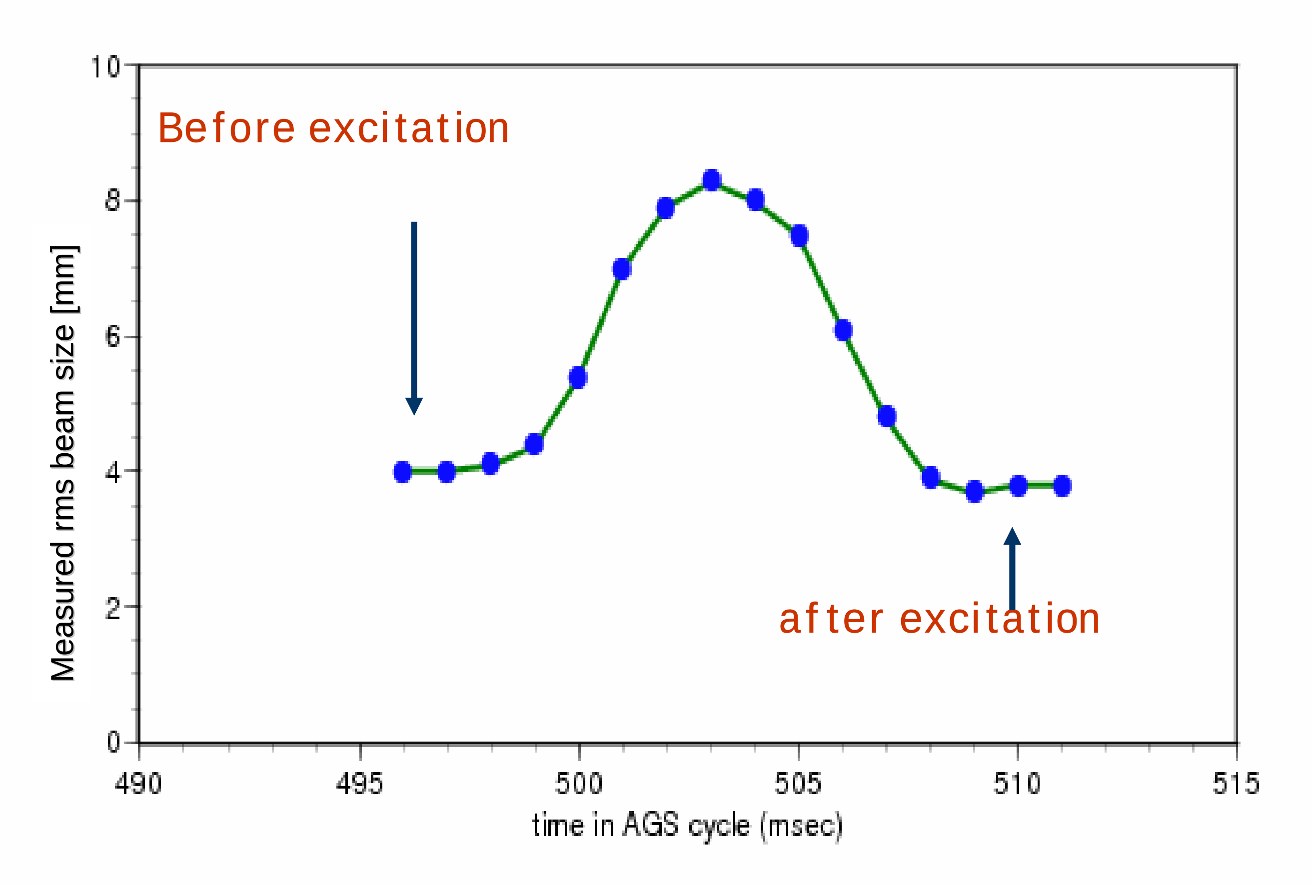
Active non-destructive techniques: AC dipole

- Beam size measurement results of the beam experiment with ac dipole in the Brookhaven AGS



Experimental results in the Brookhaven AGS

AC dipole applications: Linear Optics measurement

- Use the coherent oscillation driven by an ac dipole to measure the betatron functions and phase advances between bpms

$$\beta_1 \frac{m_{11}^{1,2}}{m_{12}^{1,2}} - \cot\varphi_{12} = \beta_1 \frac{m_{11}^{1,3}}{m_{12}^{1,3}} - \cot\varphi_{13}$$

$$\beta_1 = \beta_1^m \sqrt{\frac{\beta_2/\beta_1}{\beta_2^m/\beta_1^m}} \frac{\sin\varphi_{12}^m}{\sin\varphi_{12}}$$

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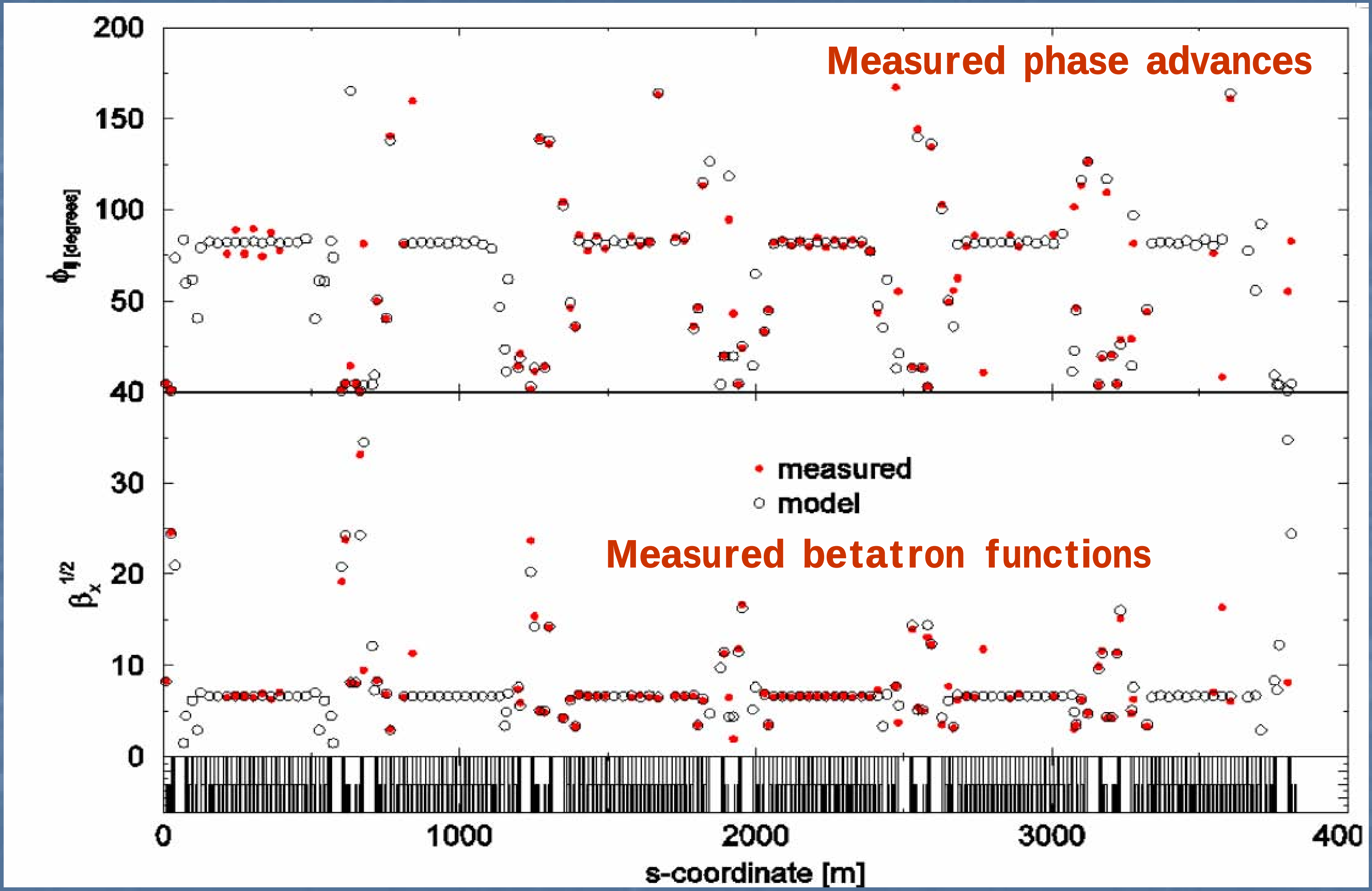
AC dipole applications: Linear Optics measurement

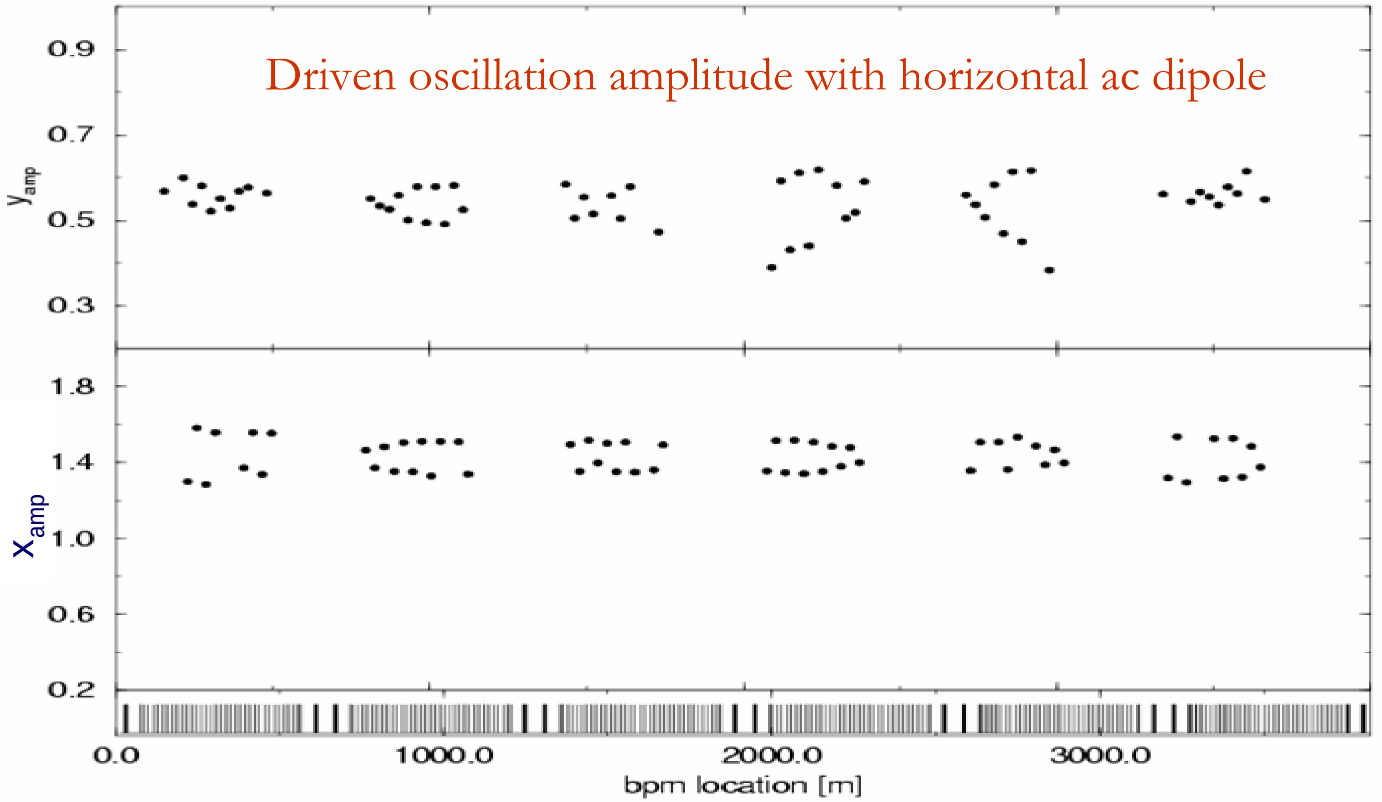


AC dipole applications: Linear coupling measurement

- Driven coherent oscillation with non-zero coupling

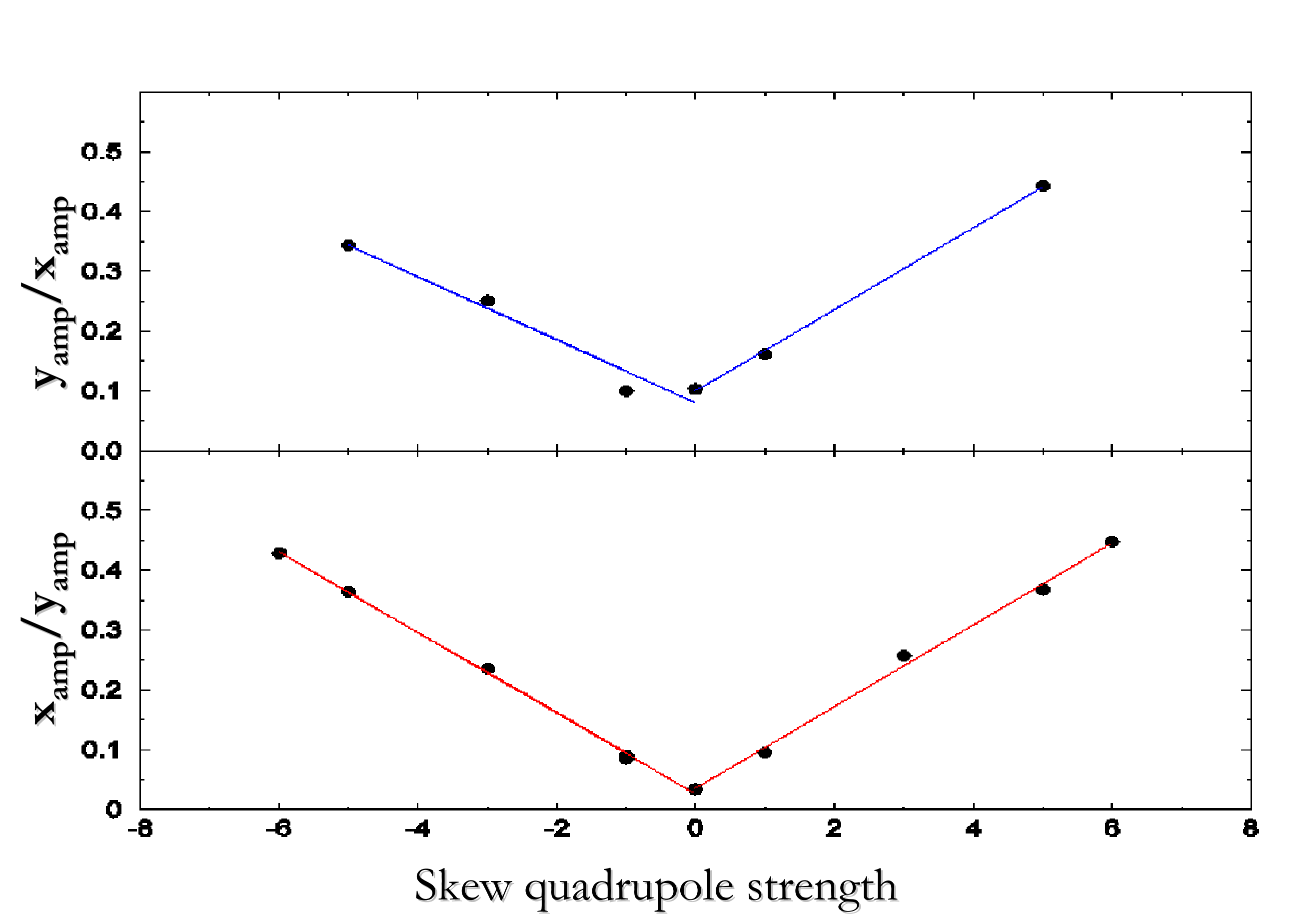
$$x = \gamma \frac{\sqrt{\beta_x}}{4\pi B\rho\delta_x}(\gamma\delta x')\cos(Q_m\theta + \chi)$$

$$y = \frac{\sqrt{\beta_y}}{4\pi B\rho\delta_x}(\gamma\delta x')[\bar{c}_{22}\cos(Q_m\theta + \chi) + \bar{c}_{12}\sin(Q_m\theta + \chi)]$$



AC dipole applications: Linear coupling measurement

- The measured ratio of amplitudes for horizontal (top) and vertical (bottom) AC dipole excitation with different skew quadrupole settings.



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AC dipole applications: Non-linear resonance measurement

- Non-linear resonance driving term
  - Normal form with free oscillation

R. Bartolini and F. Schmidt, LHC Project Note 132, 1998

$$x(n) - ip_x(n) = \sqrt{2J_x}\, e^{i(2\pi\nu_x n + \chi_x)} - 2i\sum j f_{jklm} (2J_x)^{\frac{j+k-1}{2}} (2J_y)^{\frac{l+m}{2}} \times e^{i[(1-j+k)(2\pi\nu_x n+\chi_x)+(m-l)(2\pi\nu_y n+\chi_y)]}$$

Non-linear resonance driving term

Spectral line @ (1-j+k, m-l) ~ resonance @ (j-k, l-m)

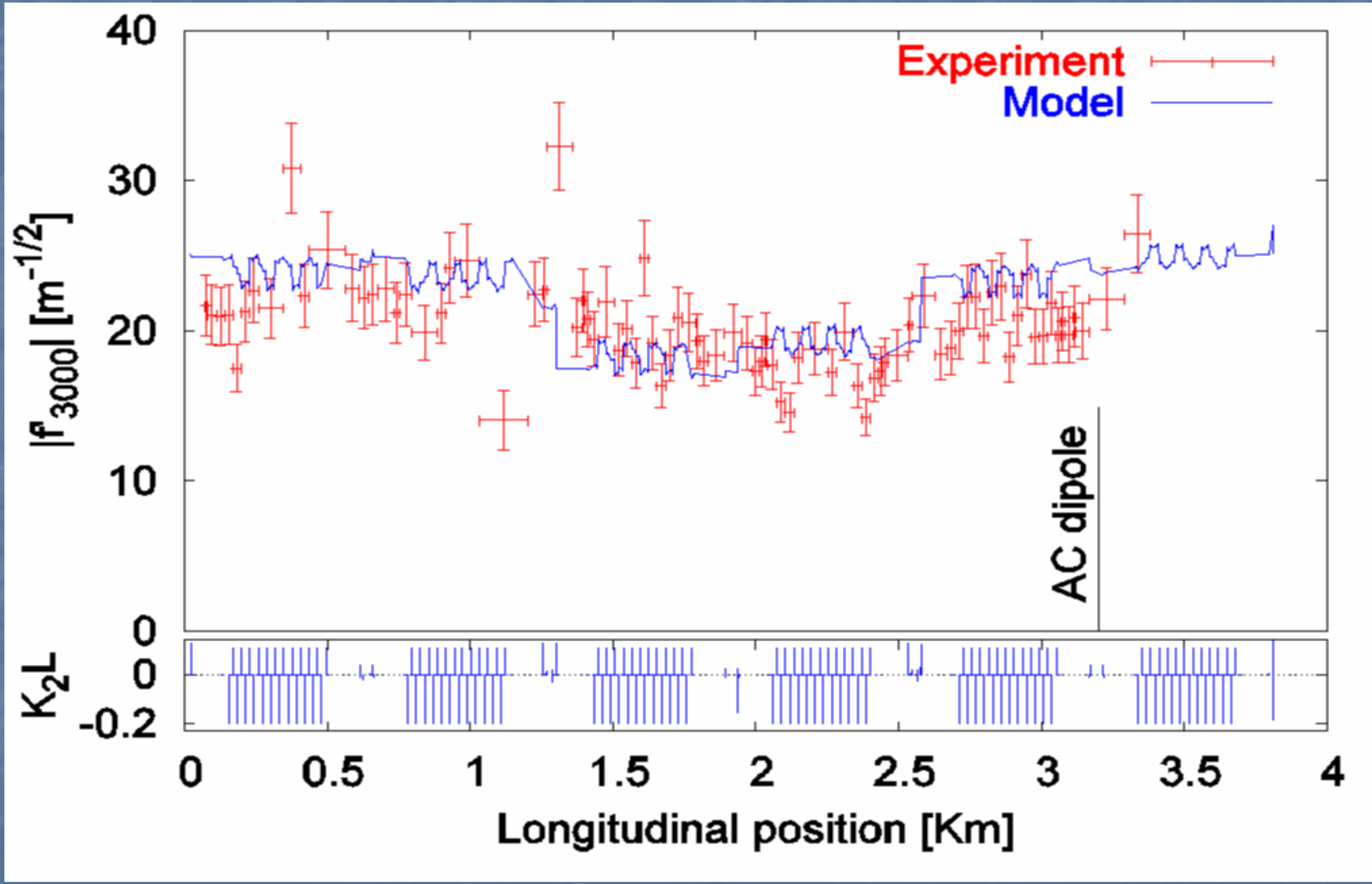
  - Normal form with driven coherent oscillation

$$x(n) - ip_x(n) = 2i\sum j f'_{jk00} (2J_x)^{\frac{j+k-1}{2}} \times e^{i[(1-j+k)(2\pi\nu_{mx} n+\chi_x)]}$$

Normal form of particle motion under the influence of an ac dipole,
R. Tomas, Phys. Review ST-AB, Vol. 5, 054001

AC dipole applications: Non-linear resonance measurement

First 3rd order resonance driving term measurement in RHIC with ac dipole



Courtesy of R. Tomas

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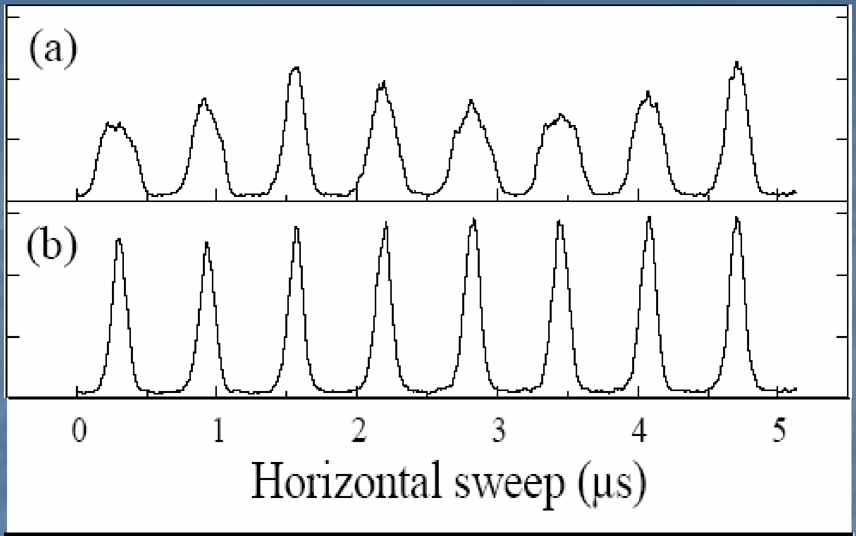
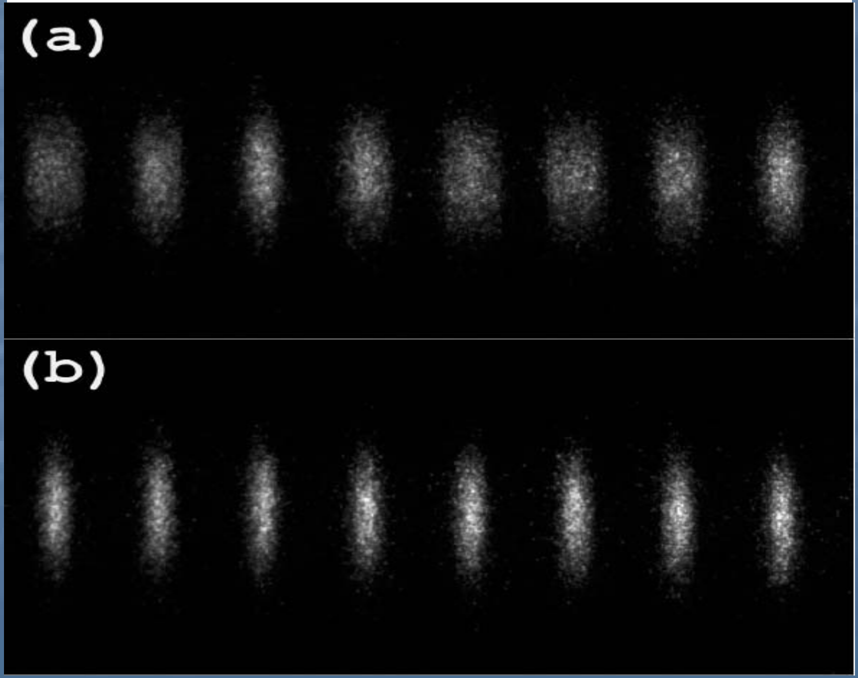
Active non-destructive techniques: AC quadrupole

- AC quadrupole: oscillating quadrupole field
- Coherent quadrupole oscillation can be obtained by driving the beam with an ac quadrupole at twice of the betatron frequency (KEK)
- A stable coherent quadrupole mode oscillation can also be induced by driving the beam nearby the twice of the betatron frequency

Quadrupole-mode transfer function and the nonlinear Mathieu instability
Weiming Guo and S. Y. Lee, Physical Review E, Vol. 65, 066505

Active non-destructive technique: AC quadrupole





- AC quadrupole driven quadrupole mode oscillation observed in the KEK photon factory.
- Case (a): measured beam size with an ac quadrupole excitation
- Case(b): no ac quadrupole oscillation

S. Sakanaka, etc, Excitation of a transverse quadrupole-mode oscillation of the electron bunch using a high frequency quadrupole magnet, Proceedings of 2001 Particle Accelerator Conference, Chicago, P. 393.

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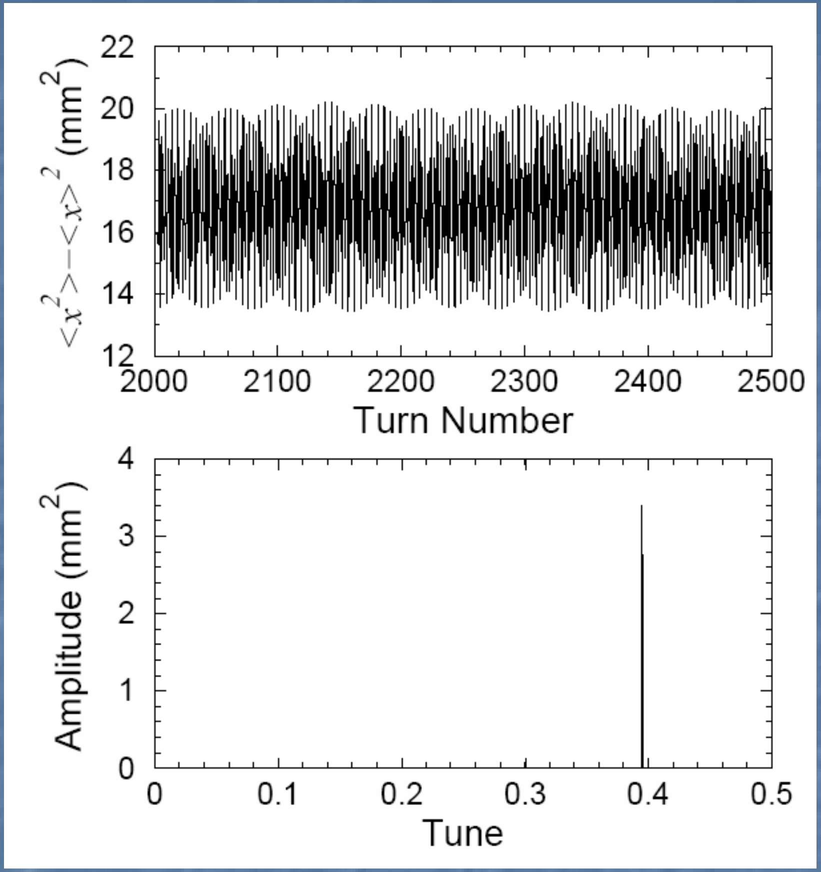

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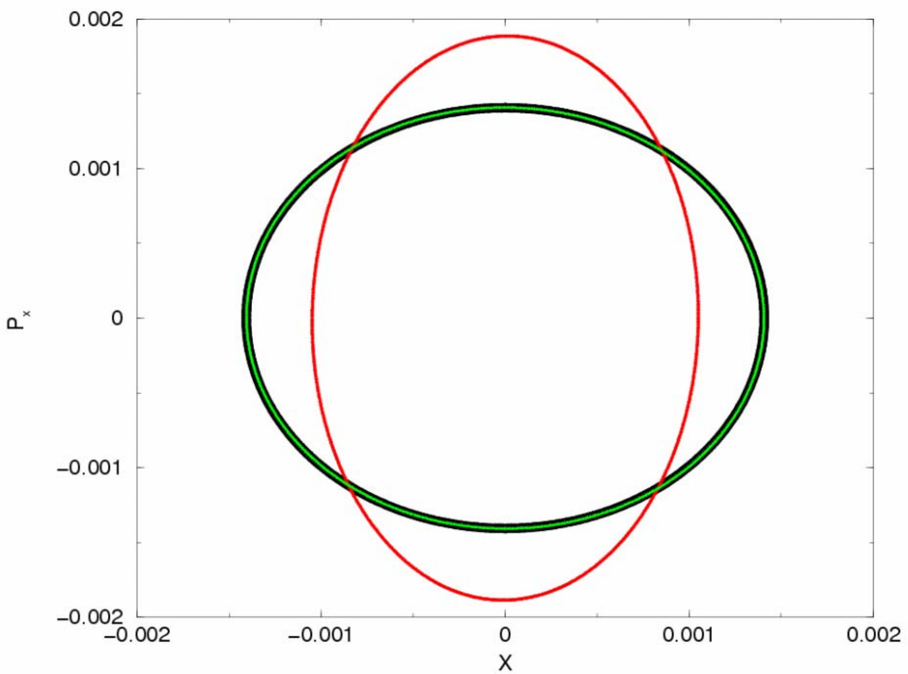
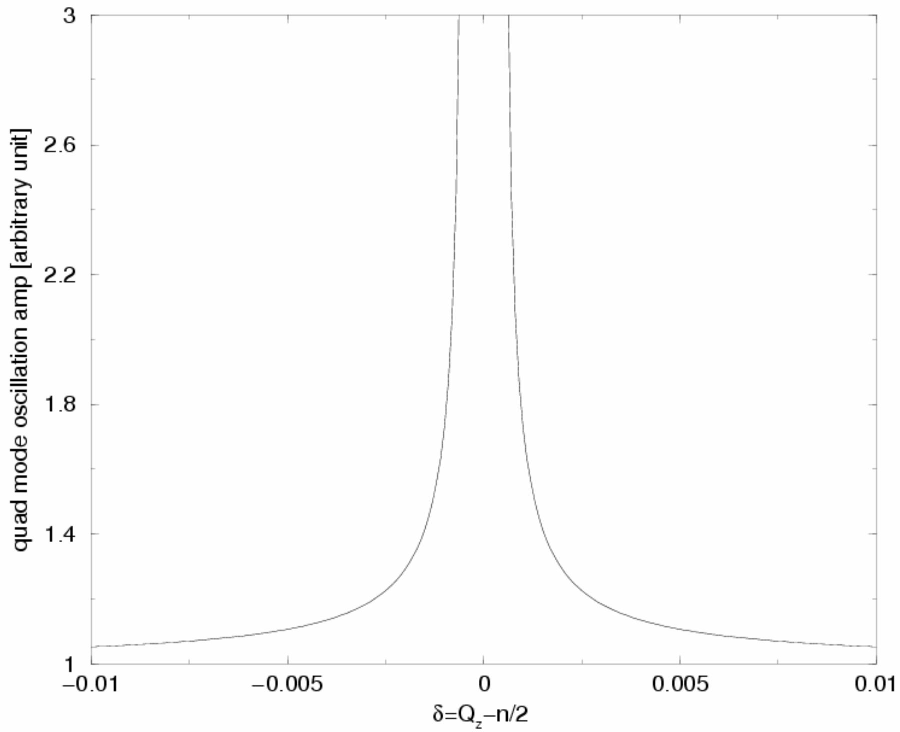




Red: ac quadrupole at a fixed excitation amplitude after and it gets slowly ramped up/down

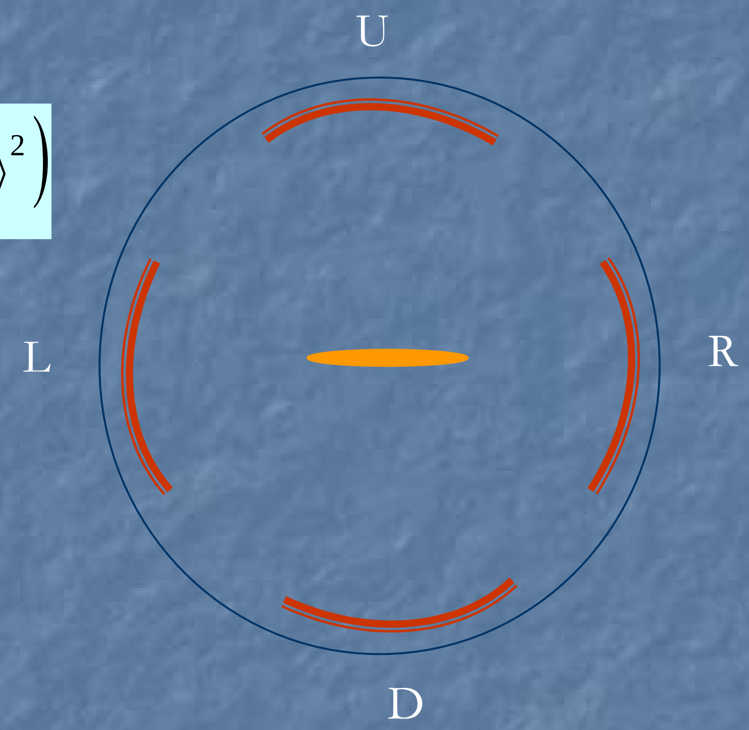
Black&green: before and after the ac quadrupole excitation

Active non-destructive techniques: AC quadrupole application

- Measure beam emittance

$$Q = \frac{(R+L)-(U+D)}{L+R+U+D} \propto \sigma_x^2 - \sigma_y^2 + \left(\langle x\rangle^2 - \langle y\rangle^2\right)$$

$$Q(n) \propto Q_0 + \left(\sigma_x^2 + \sigma_{p_x}^2\right)\sin(2\pi\nu_m n)$$



- Other applications
  - Mismatch compensation
  - Overcome intrinsic spin resonance

Quadrupole-mode transfer function and the nonlinear Mathieu instability

Weiming Guo and S. Y. Lee, Physical Review E, Vol. 65, 066505

Passive technique: Schottky spectrum

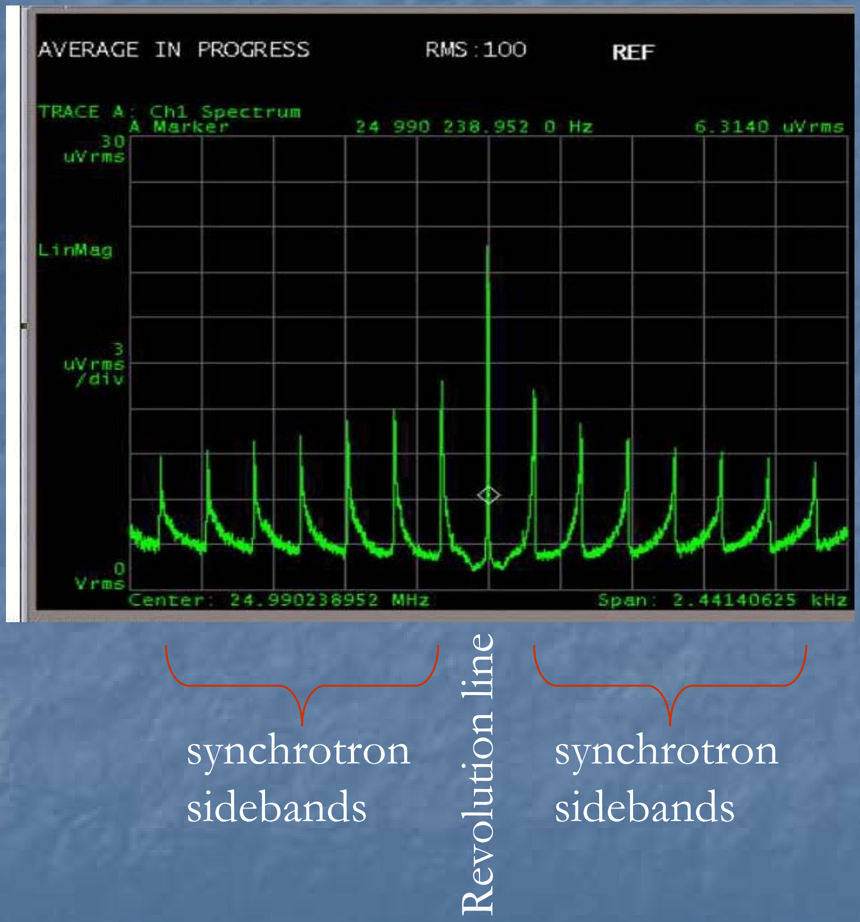
- Longitudinal spectrum of a bunched beam

$$I_{i,n} = 2ef_0\,\mathrm{Re}\left[\sum_{k=-\infty}^{k=\infty} J_p\left(n\omega_0\hat{\tau}_i\right)e^{j\left(n\omega_0 t+k\omega_{syn}t+k\psi_i\right)}\right]$$

- Synchrotron tune:
  - Distance between each band
- Momentum spread
  - The spread of each band

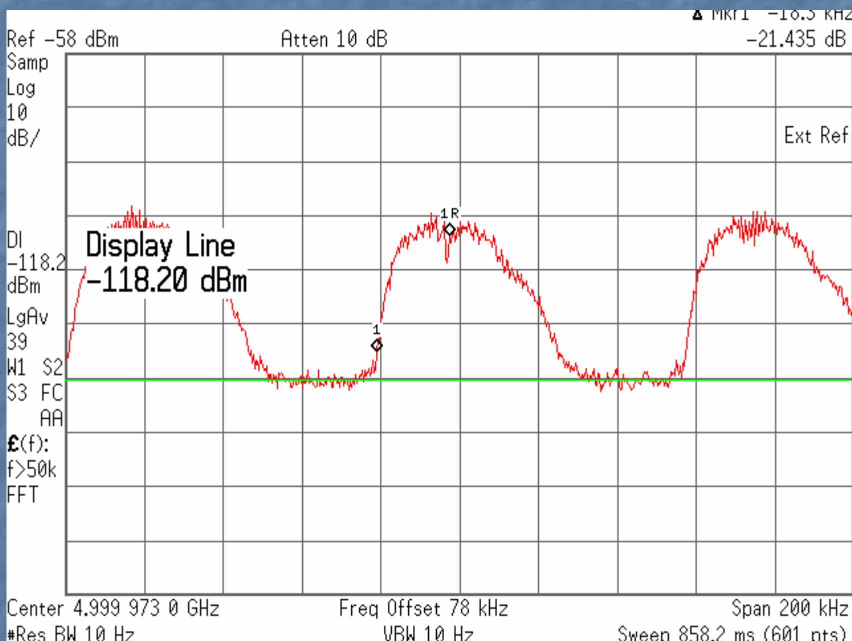
Longitudinal Schottky spectrum in RHIC

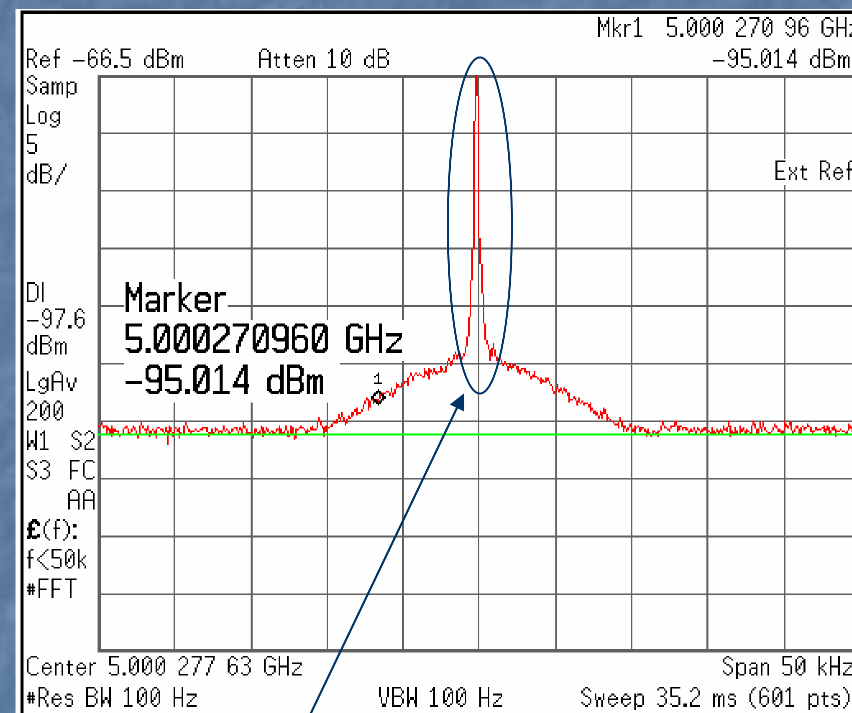
Courtesy of J. Brennan



Passive techniques: Schottky

- Longitudinal Schottky Spectrum

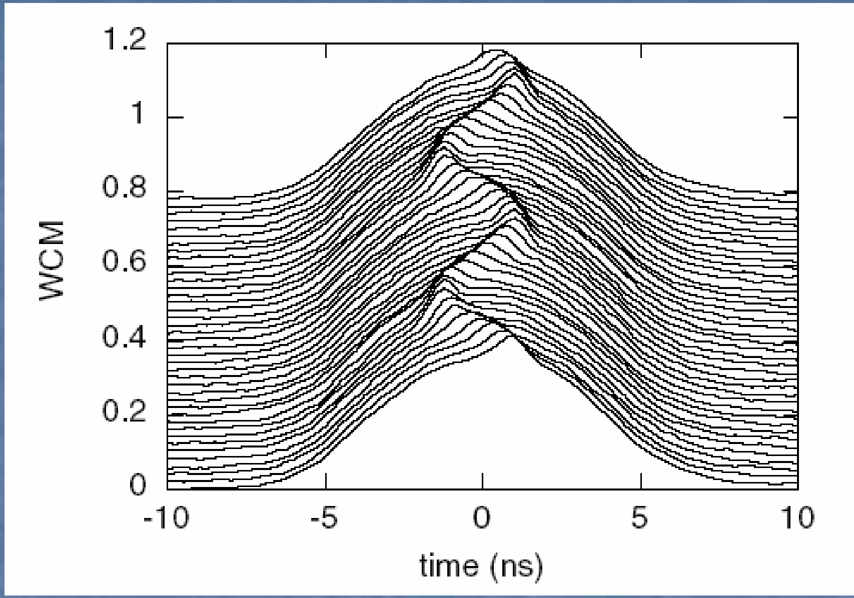


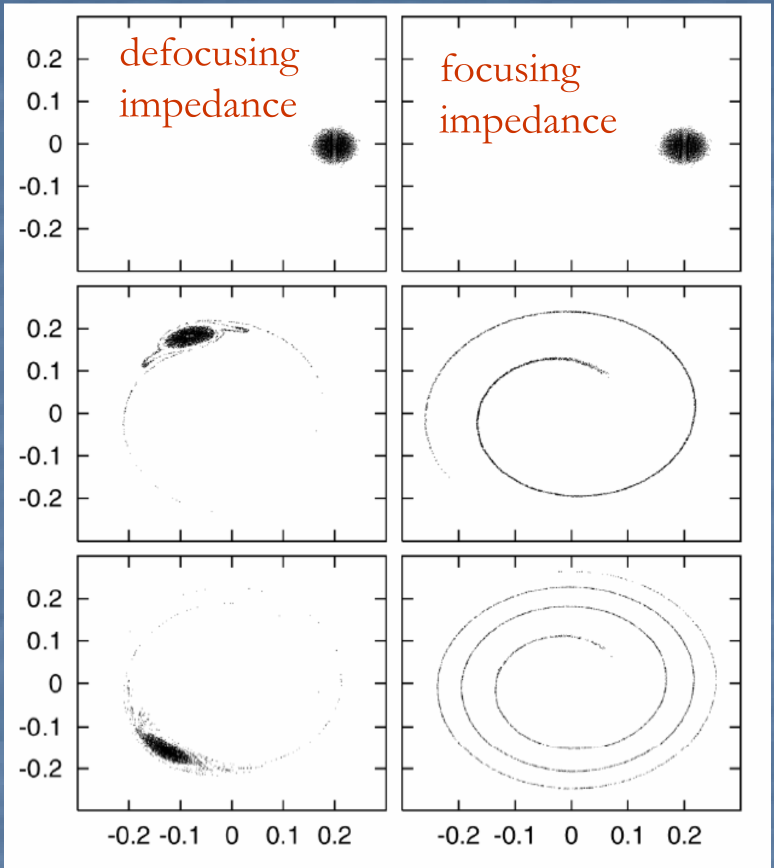


No persistant coherent spike on the Au Schottky spectrum: IBS

Persisted coherence in the proton spectrum

Solitons in proton beam observed in RHIC





Longitudinal Solitons in RHIC

M. Blaskiewicz, J. M. Brennan, P. Cameron, W. Fischer, J. Wei, Proceedings of the 2003 PAC

Longitudinal Solitons Bunched Beam

M. Blaskiewicz, J. Wei, A. Luque, H. Schamel, Physical ReView Special Topics-AB, Vol 7, 044402 (2004)

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Passive techniques: Schottky spectrum

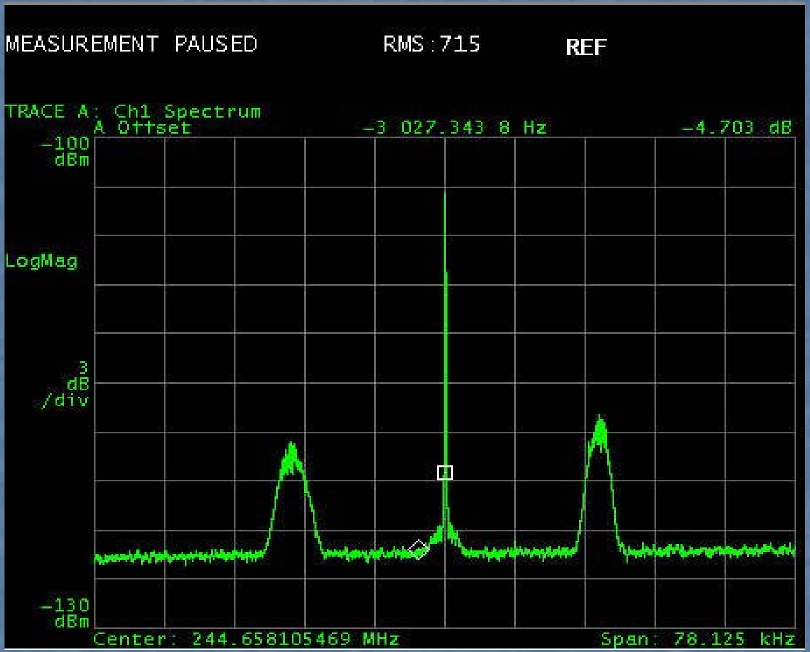
- transverse spectrum of a bunched beam

$$x_{i,n} = 2ef_0 A_i \,\mathrm{Re}\left[\sum_{k=-\infty}^{k=\infty} J_p\big((n\pm q)\omega_0\hat{\tau}_i\big)e^{j\left(\left((n\pm q)\omega_0 t + k\omega_{syn}\right)t + k\psi_i + \varphi_i\right)}\right]$$

- Betatron tune
  - Distance between the betatron side band and the revolution line
- Chromaticity
  - Difference of the width of the betatron sidebands on either side of the revolution line
- Emittance
  - Power of each betatron band

Transverse Schottky spectrum in RHIC

Courtesy of K. Vetter



betatron sideband

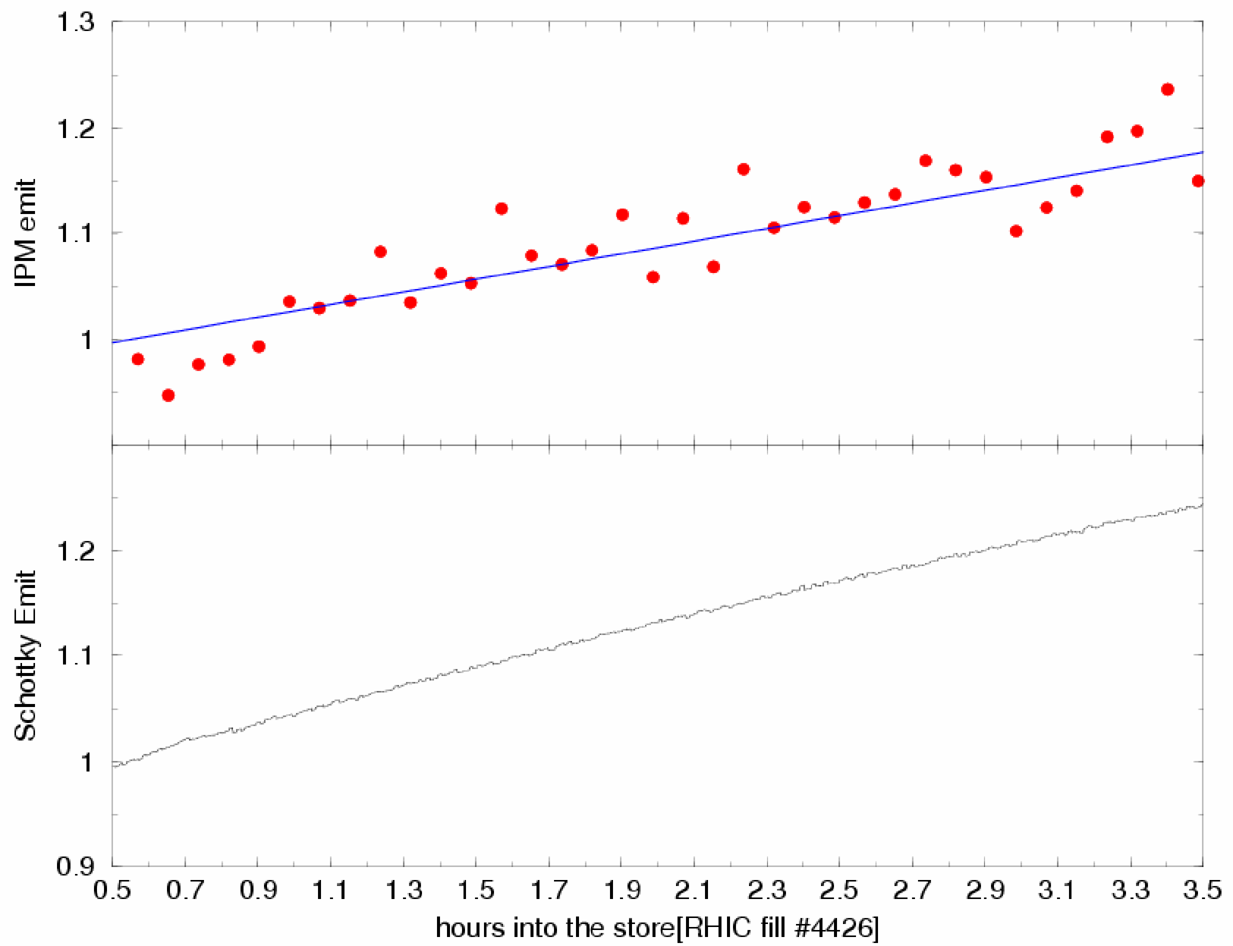
Revolution line

betatron sideband

Passive technique: Schottky

- Schottky emittance measurement

emittance growth during the store



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Summery

- AC dipole has demonstrated to be a powerful tool to induce long lasting coherent oscillation which is necessary for measuring the machine optics parameters as well as studying the non-linear behavior of the beam. It has been routinely applied in the Brookhaven RHIC to measure the phase advances as well as betatron functions.
- The quadrupole-mode oscillation induced by an AC quadrupole can have great potential in non-destructive beam measurements as beam manipulations
- Ever since its use in the CERN ISR, the Schottky detectors have been widely employed in high energy hadron accelerators. In addition to the tune information, Schottky spectrum also provides a lot of information on the transverse tune spread as well as the beam emittance.

Acknowledgement

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