Nonlinear dynamics studies in the Fermilab Tevatron using an AC Dipole

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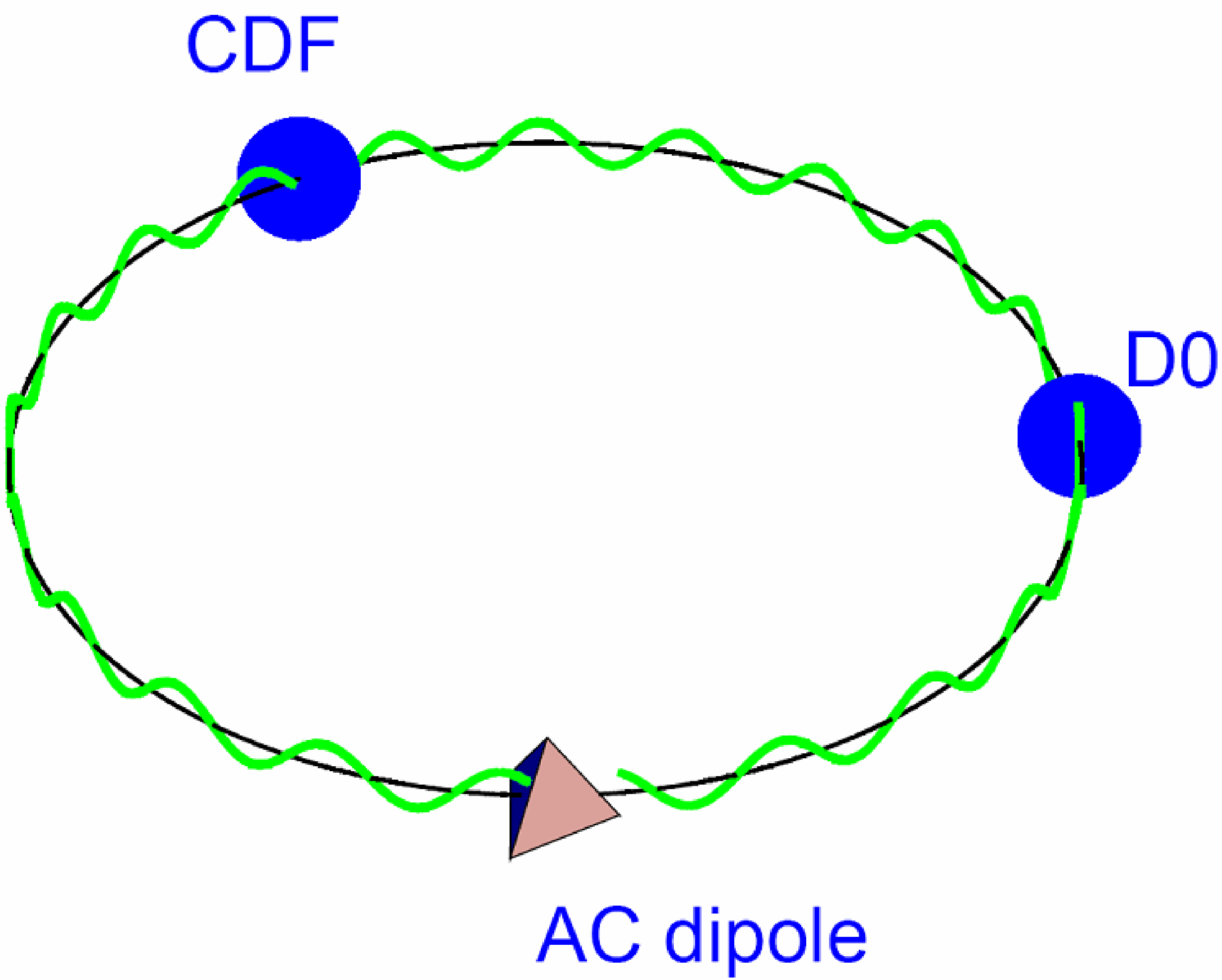
Introduction

- Nonlinear fields in a synchrotron
  - Sextupoles and octupoles to compensate chromaticity and beam instabilities due to high intensity.
  - Magnet imperfections (quadrupole triplets).
- Perturbations to the betatron motion
  - Resonances, amplitude dependent tune (nonlinear detuning effect).
  - May degrade the beam emittance or cause beam losses.
  - Not many prior measurements in the Tevatron.
- A new diagnosis tool: AC dipole
  - Produces clean signals for BPMs to diagnose a synchrotron.
- Studies in the Tevatron
  - Control a sextupole and a group of octupoles (no change in tune)
  - Demonstrate the AC dipole enables to measure the effects caused by these changes.
  - Orbit distortion due to sextupole and detuning due to octupoles.

Why excite the beam?



An AC dipole excites the beam with its sinusoidally oscillating dipole field ($f_{\text{ac dipole}} \sim f_{\text{betatron}}$) .

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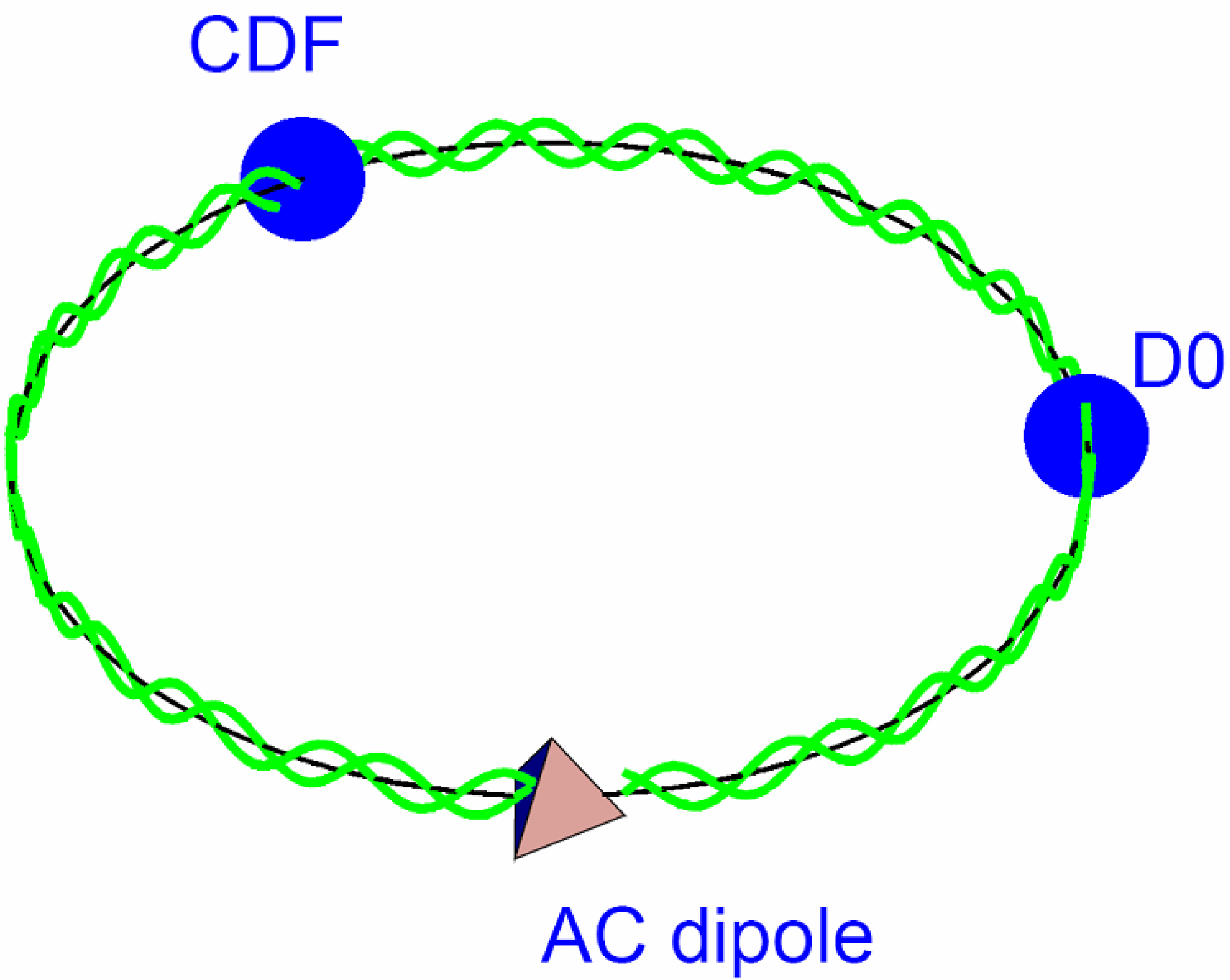

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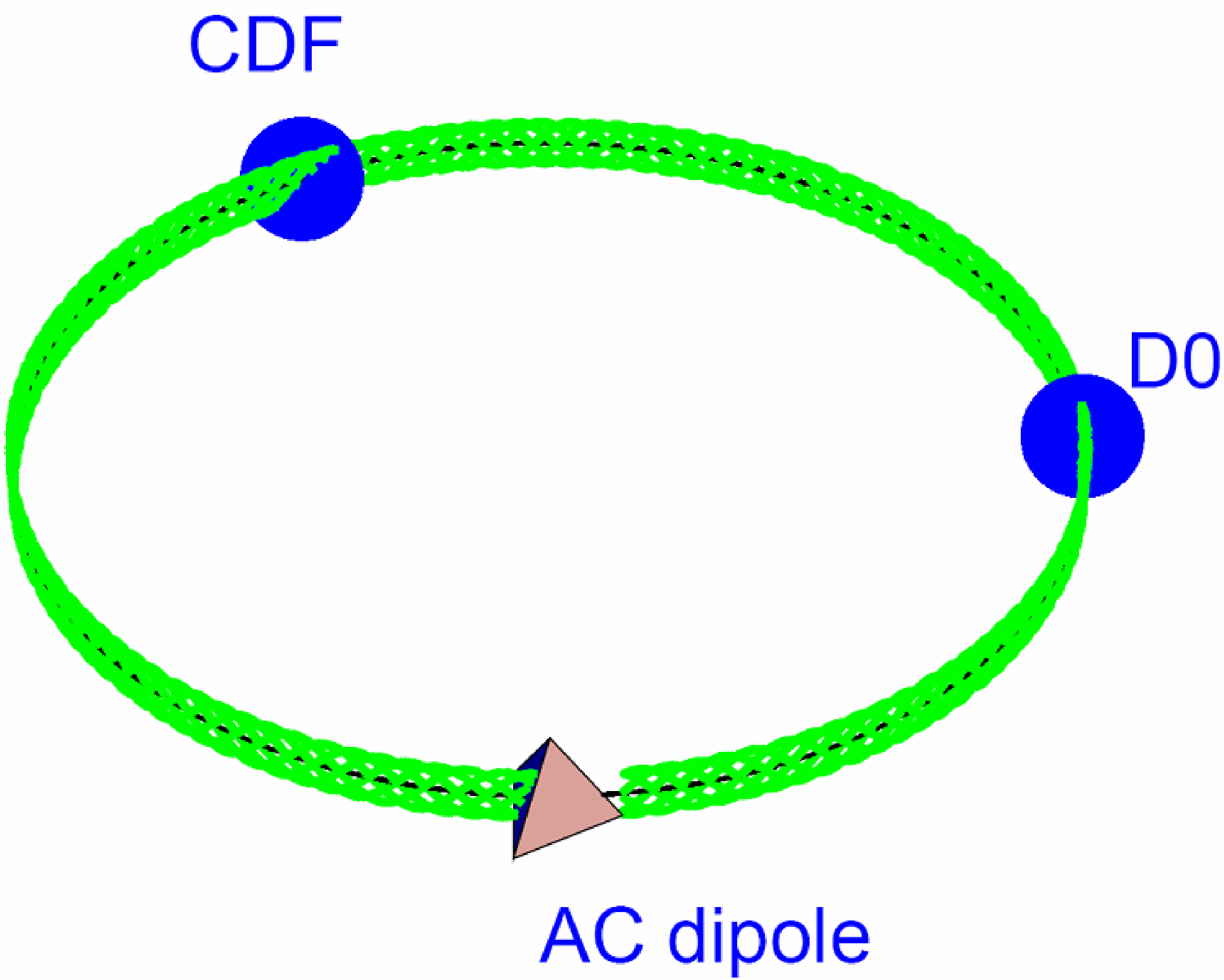

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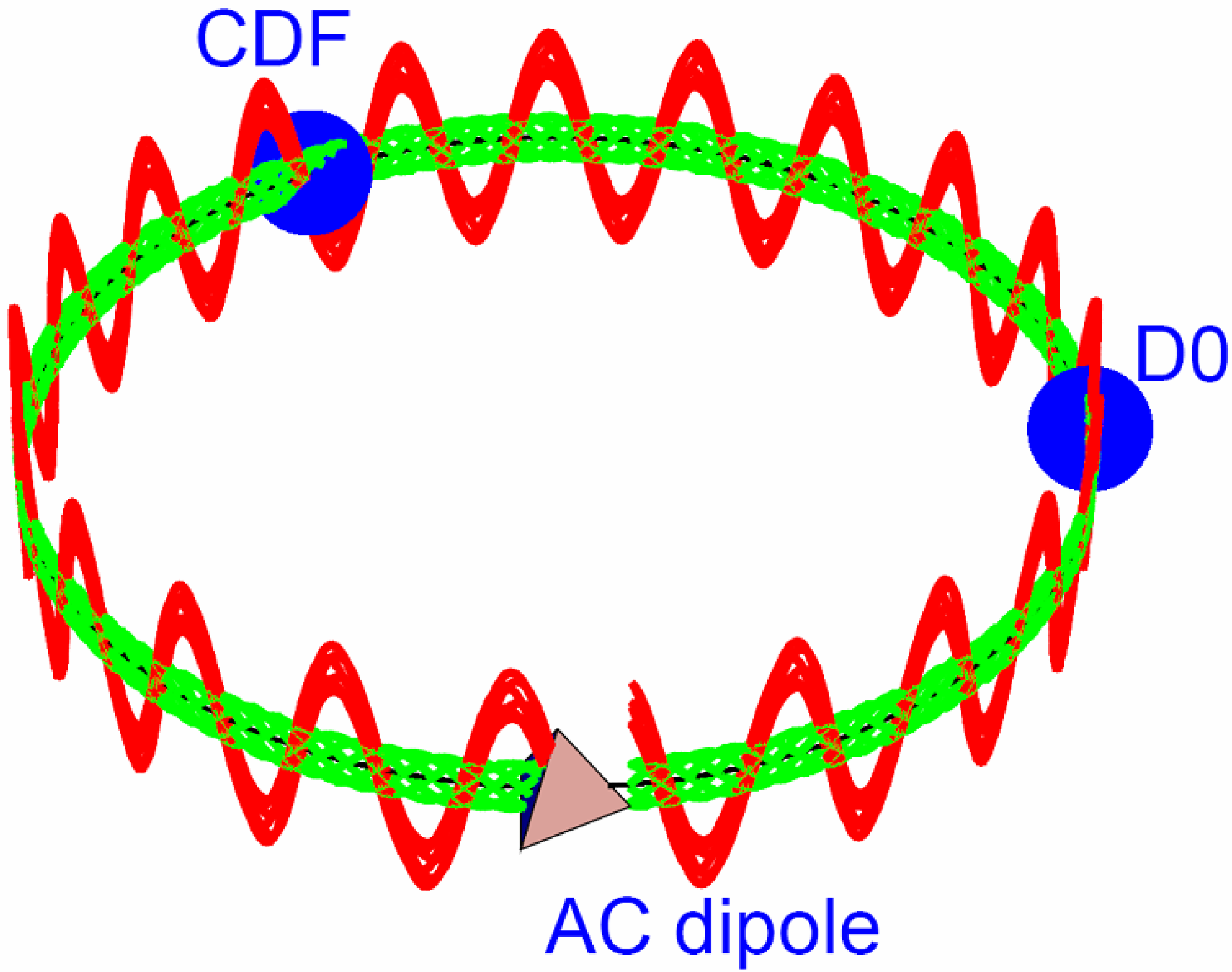


An AC dipole excites the beam with its sinusoidally oscillating dipole field ($f_{\text{ac dipole}} \sim f_{\text{betatron}}$).

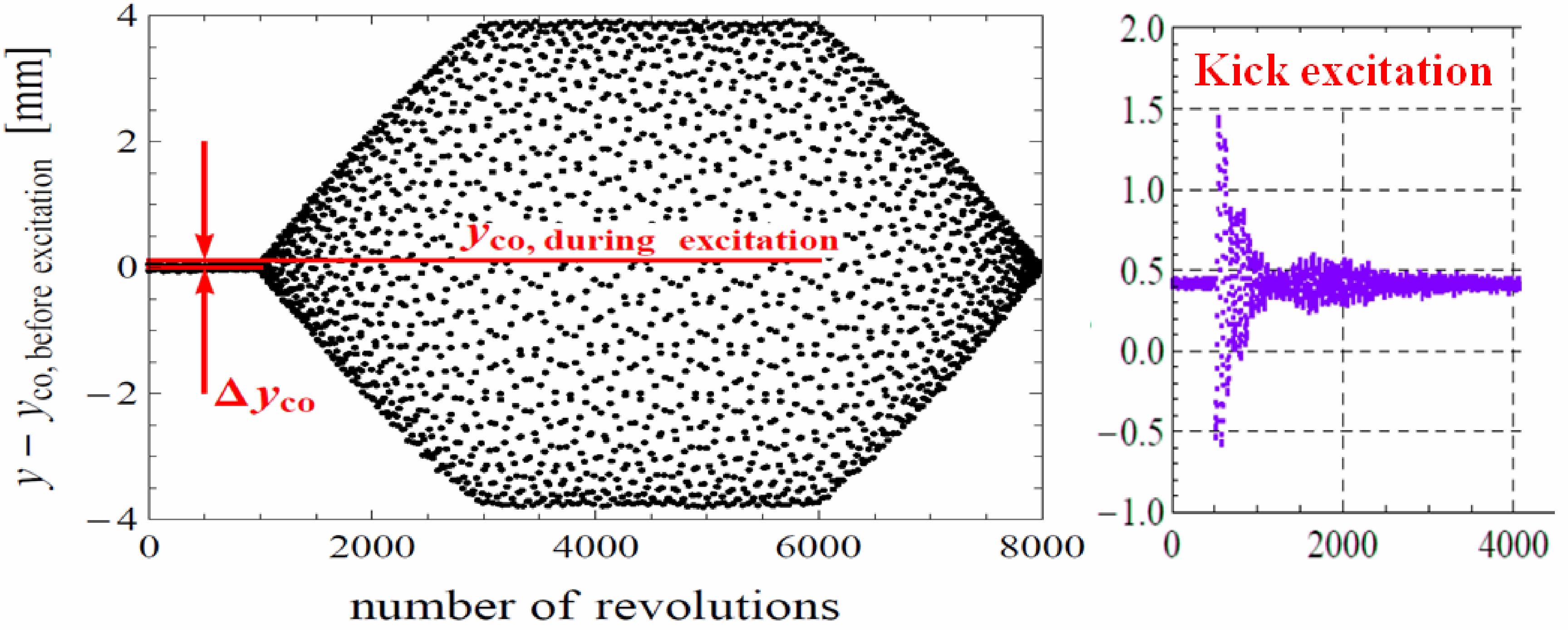
AC dipole

- Produces large sustained beam oscillations with no emittance growth.

$$x_{\mathrm{d}}(n;s) = A_{\mathrm{d}}\sqrt{\beta_{\mathrm{d}}(s)}\cos\left[2\pi\nu_{\mathrm{d}}n + \psi_{\mathrm{d}}(s \mid s_{\mathrm{ac}}) + \chi\right]$$

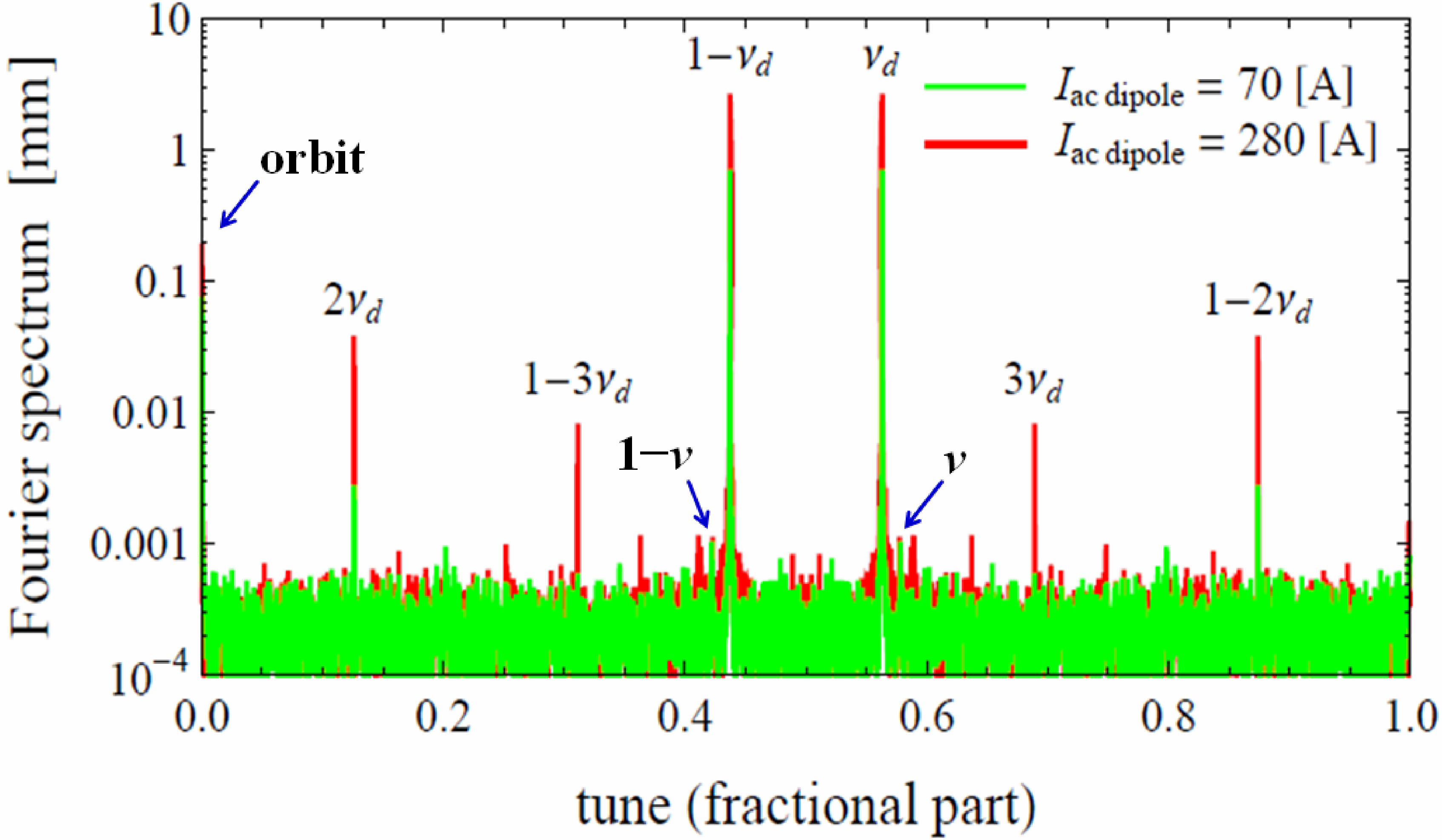
$$A_{\mathrm{d}} \propto I_{\mathrm{ac}} / (\nu_{\mathrm{d}} - \nu)$$

- Direct measurements of linear and nonlinear parameters.
- Originally developed for AGS & RHIC (BNL), tested in SPS (CERN), implemented in Tevatron (FNAL), and will be used in LHC (CERN).

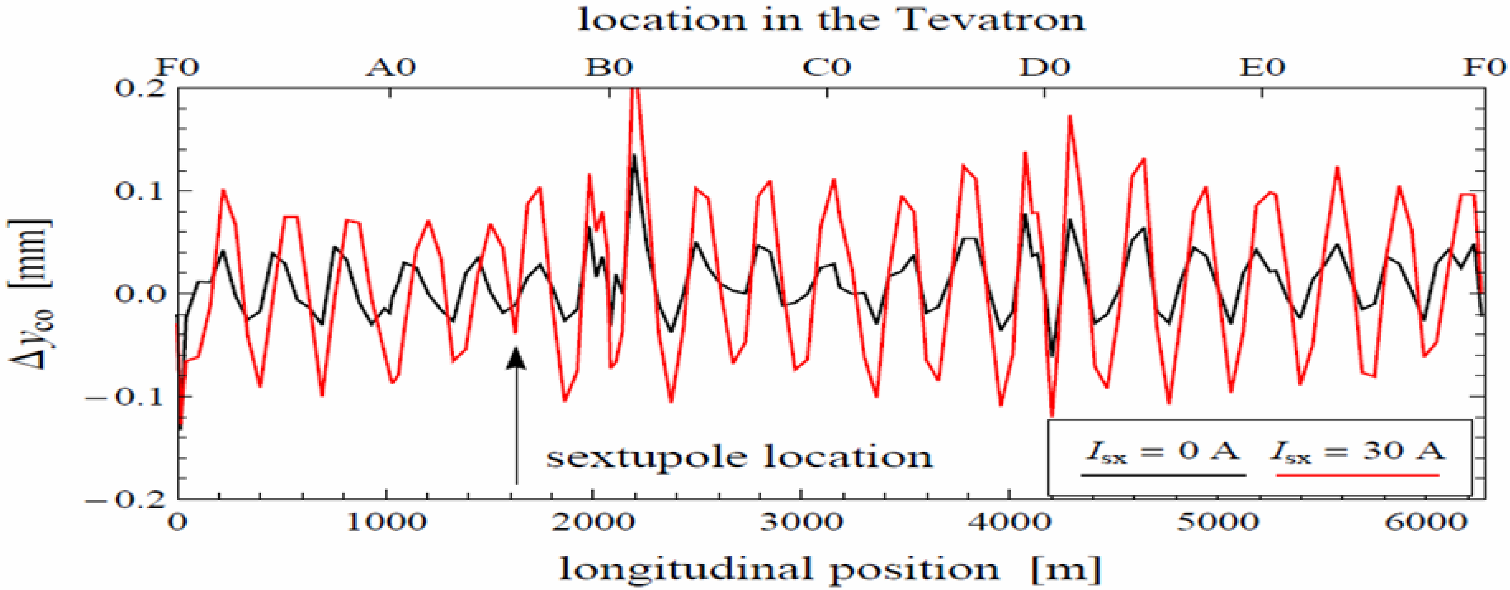


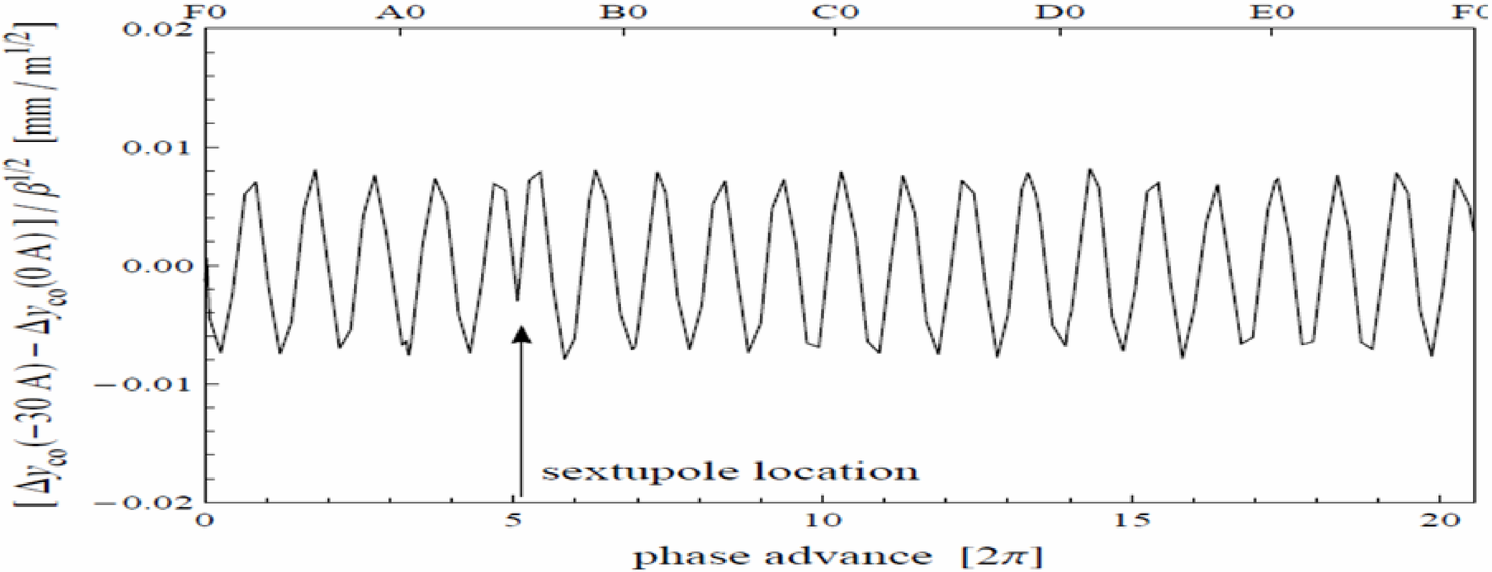
Spectrum of the AC dipole's excitation

- Nonlinear fields → modes with higher tunes.
- Driven oscillations → clean sharp spectrum.



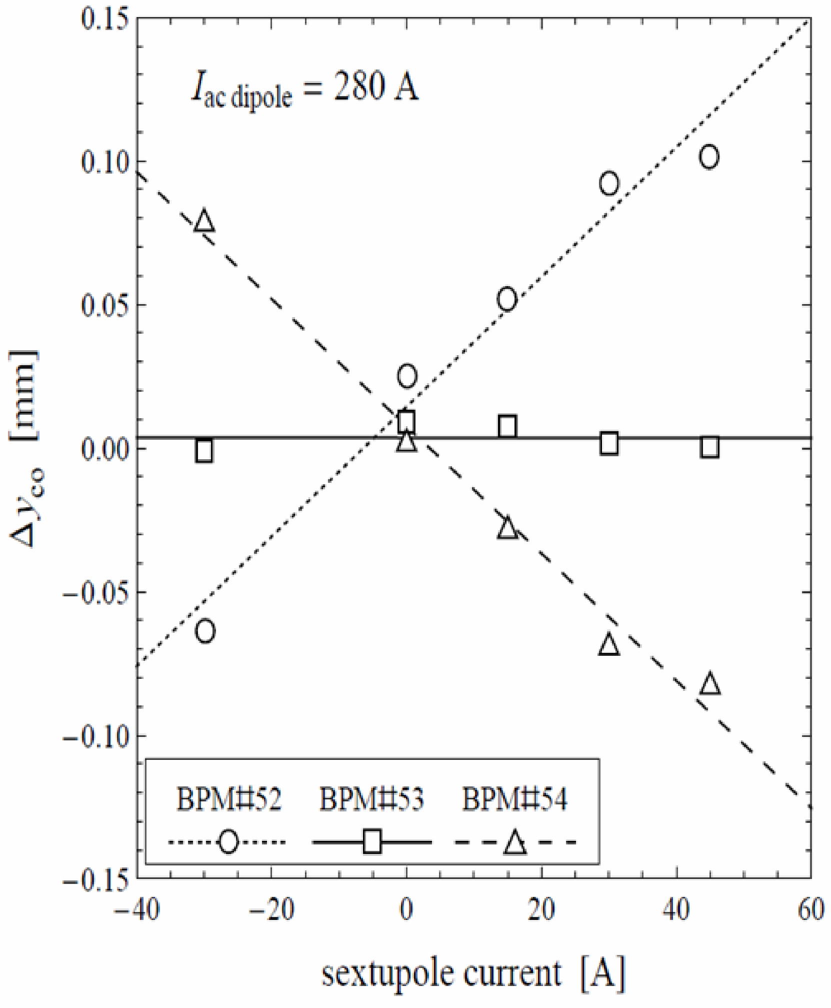
Orbit distortions due to sextuple fields

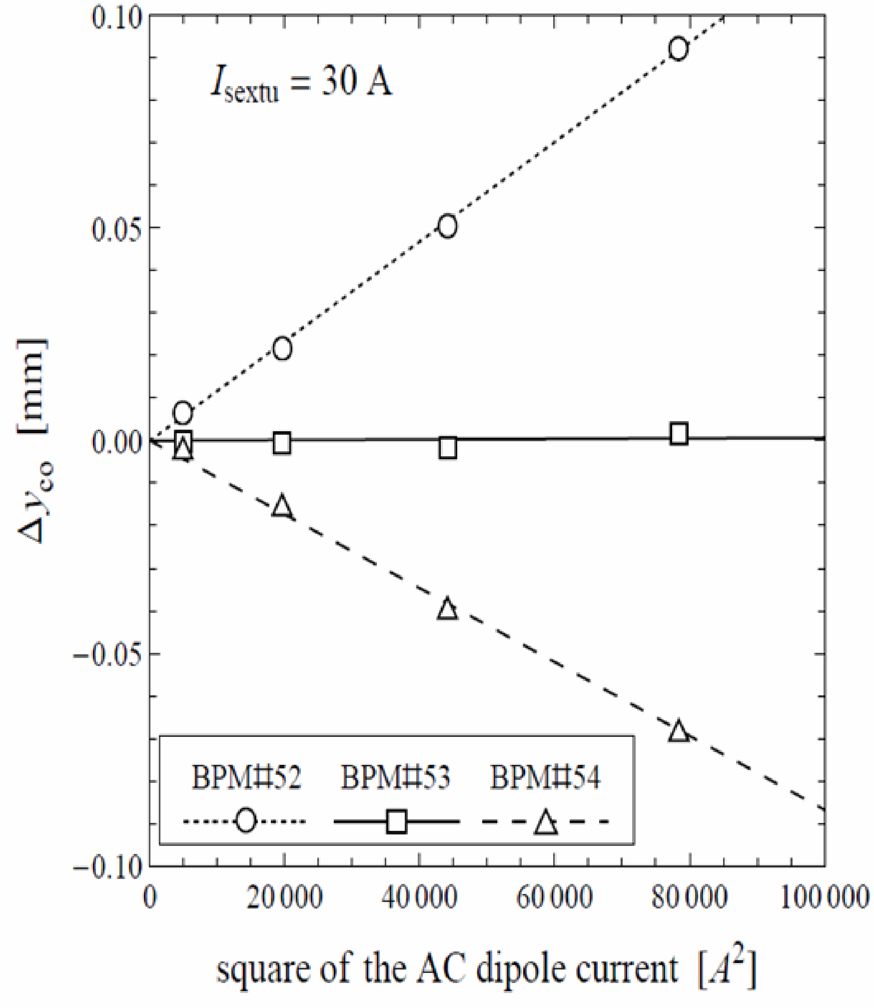




Testing dependences of the orbit distortion

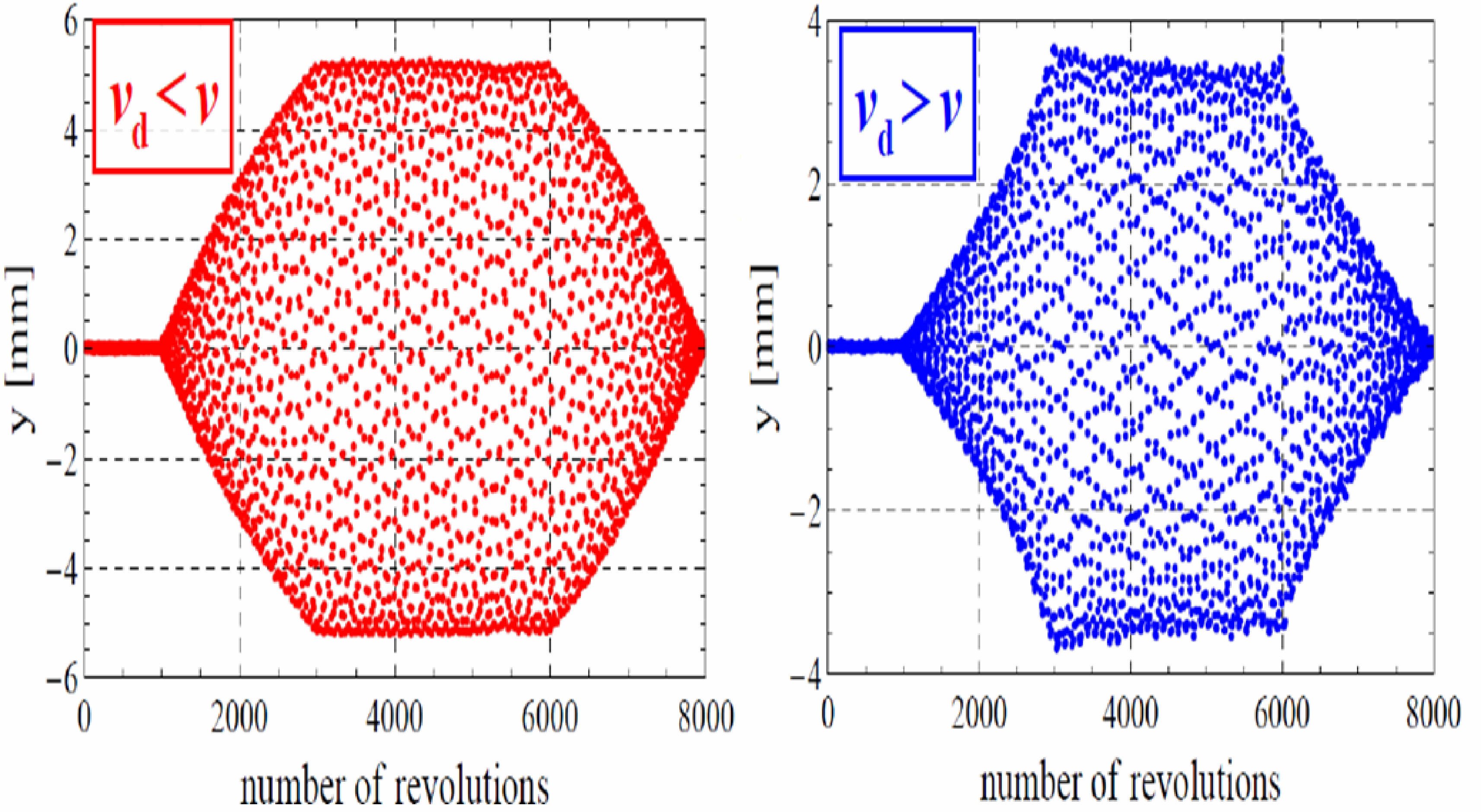
- The orbit distortion is proportional to sextupole fields and A_d^2.





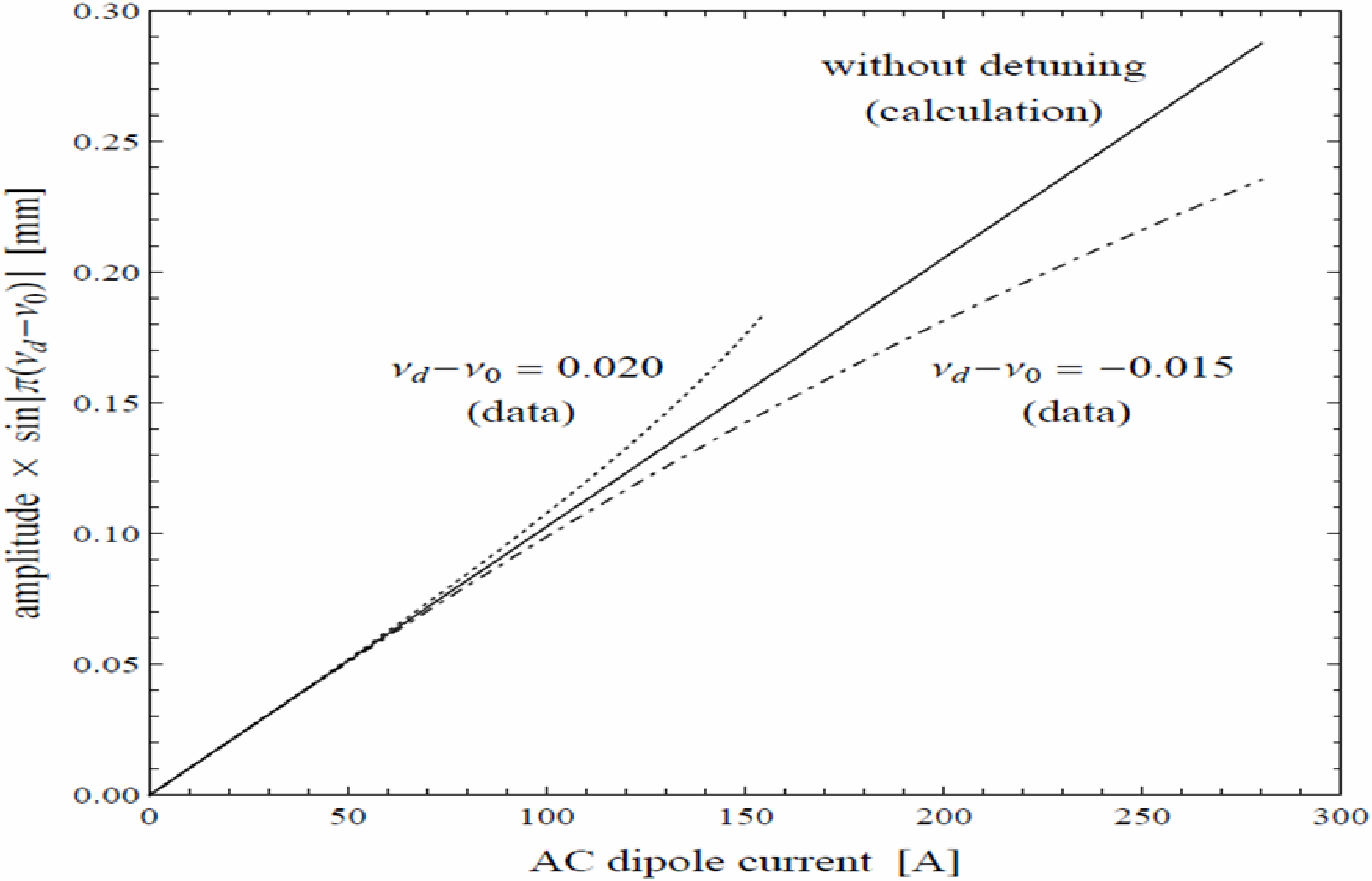
Amplitude modulations due to detuning

- Amplitude is proportional to ~$1/(\nu_d - \nu)$.
- Tune approaches the driving tune along with the amplitude growth.
- Tune moves away from the driving tune along with the amplitude growth.

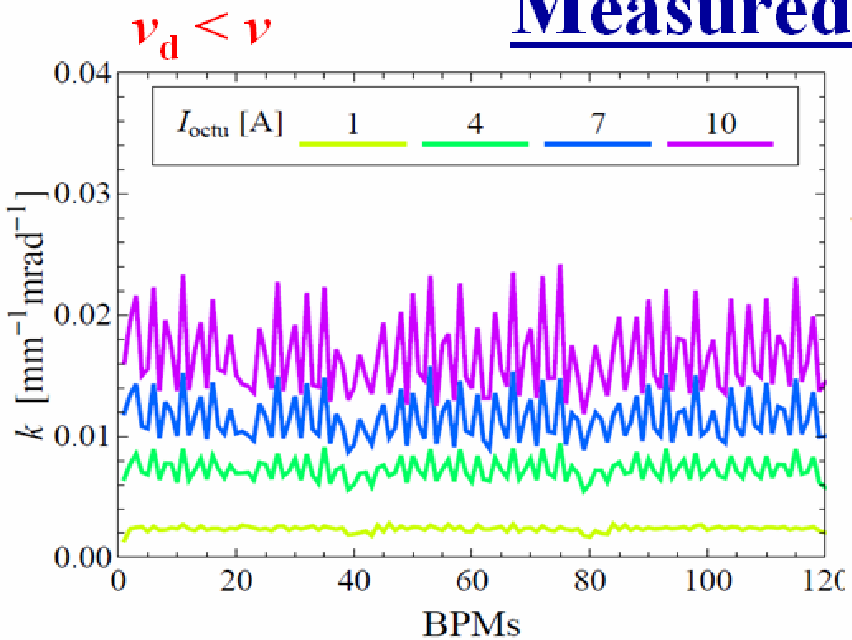


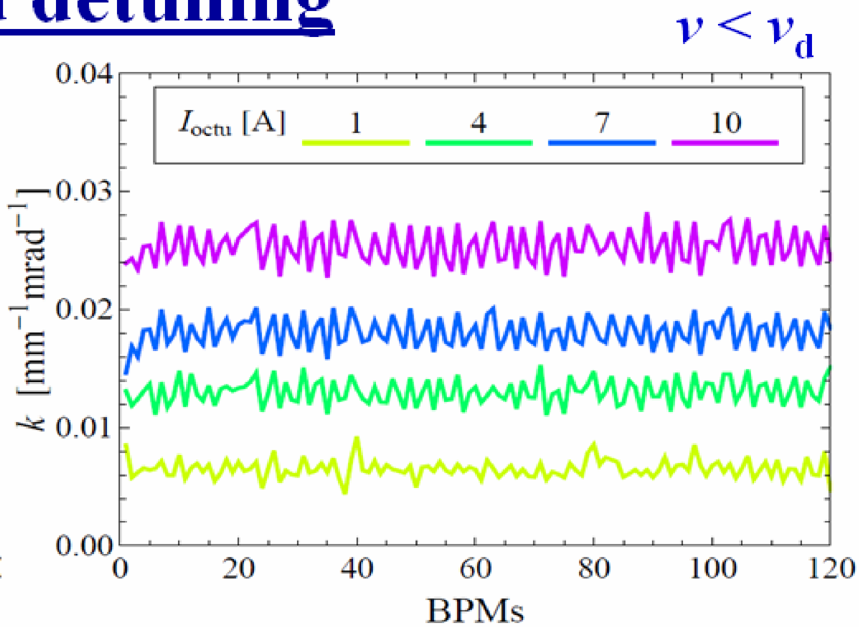
How to determine detuning?

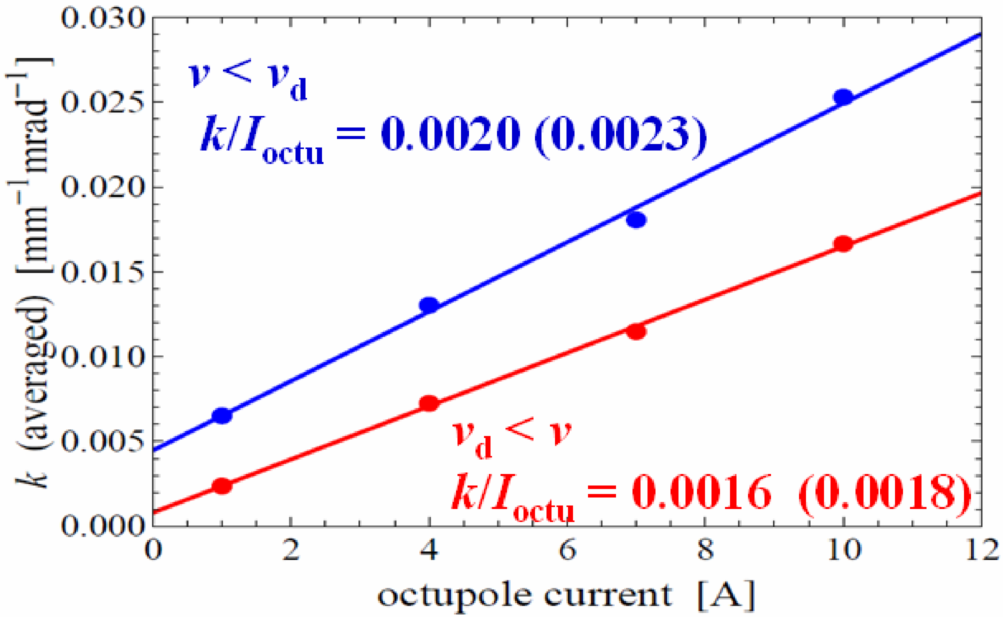
$$a = \frac{cI_{\mathrm{ac}}\sqrt{\beta_{\mathrm{d}}}}{|\nu_{\mathrm{d}} - \nu_0 - \Delta\nu|}, \quad \Delta\nu = \frac{ka^2}{\beta_{\mathrm{d}}} \Rightarrow a\left|\nu_{\mathrm{d}} - \nu_0 - \frac{ka^2}{\beta_{\mathrm{d}}}\right| = cI_{\mathrm{ac}}\sqrt{\beta_{\mathrm{d}}}$$



Measured detuning



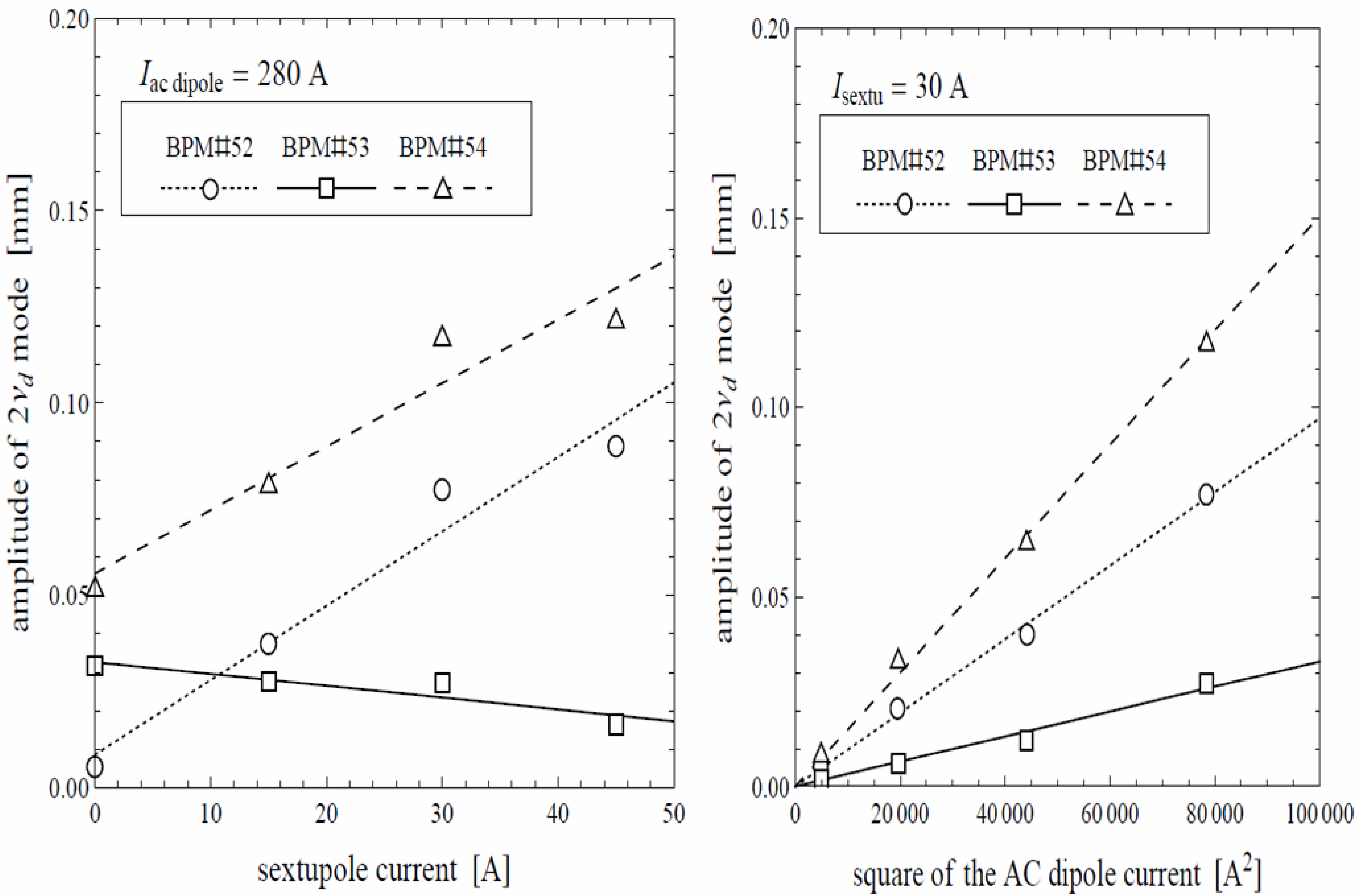




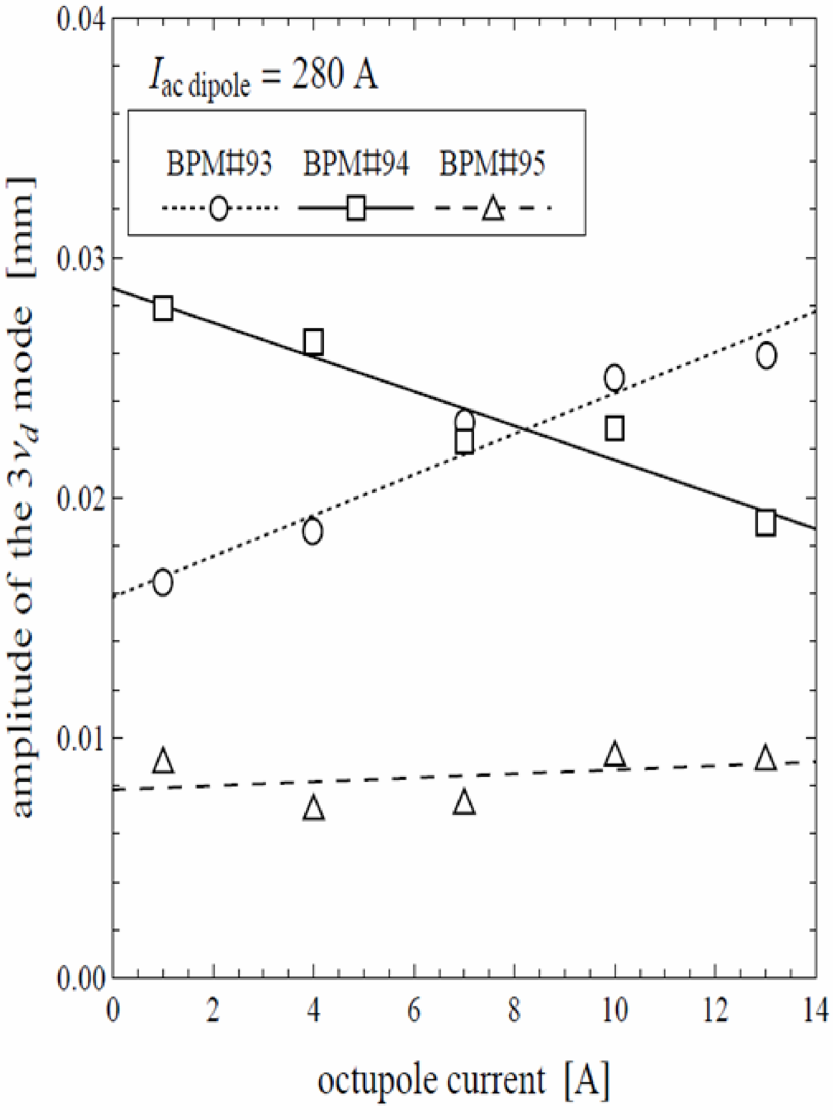
- We measure detuning of the AC dipole excitation.
- Deviation over BPMs is due to modulations of $\beta_d(s)$.

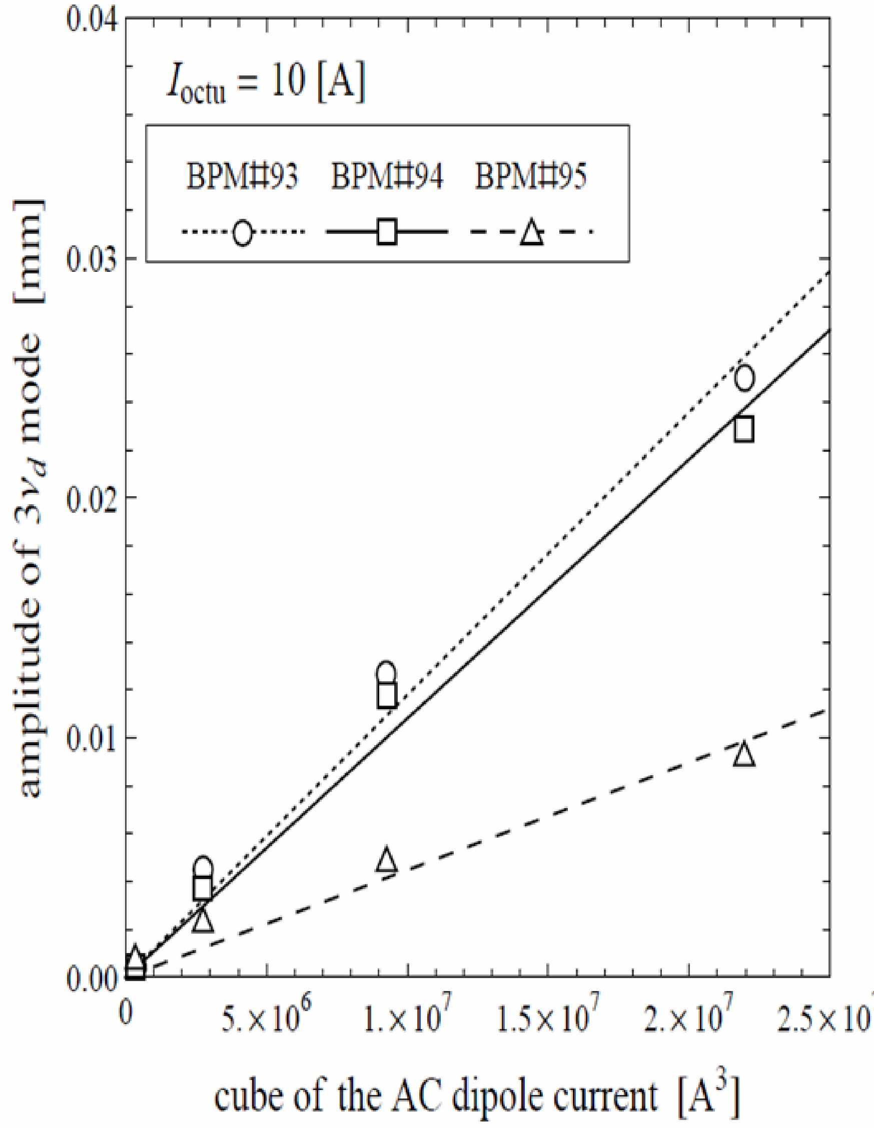
$(k_{free}/I_{octu})_{model} = 0.0019$

Measurements of $2\nu_d$ mode driven by sextupoles



Measurements of $3\nu_d$ mode driven by octupoles





Conclusions

- An AC dipole produces large sustained beam oscillations, enabling non destructive measurements of linear and nonlinear parameters of transverse motions.
- The AC dipole can detect the predicted changes of a sextupole and octupoles in the Tevatron.
- Presented measurement techniques are non destructive and may be useful for a quick diagnostics of nonlinear effects in a synchrotron.
- Future issues:
  - Modulations of the amplitude function and phase advance change resonance driving terms.
  - Coupling

Acknowledgment

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- M. Bai (BNL) and others who originally developed the AC dipole
- US LAPR Collaboration

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Modulation of resonance driving terms

$$S_{\mu}(s)=\int_0^C d\bar{s}\,\frac{B''(\bar{s})\beta(\bar{s})^{3/2}}{16(B\rho)\sin[\pi(\pm2\nu-\nu)]}e^{-i[\pm2\psi(\bar{s})-\psi(\bar{s})]-\pi i(\pm2\nu-\nu)\mathrm{sgn}(s-\bar{s})}$$

$$\Rightarrow S_{\mathrm{d},\mu}(s)=\int_0^C d\bar{s}\,\frac{B''(\bar{s})\beta_{\mathrm{d}}(\bar{s})\beta(\bar{s})^{1/2}}{16(B\rho)\sin[\pi(\pm2\nu_{\mathrm{d}}-\nu)]}e^{-i[\pm2\psi_{\mathrm{d}}(\bar{s})-\psi(\bar{s})]-\pi i(\pm2\nu_{\mathrm{d}}-\nu)\mathrm{sgn}(s-\bar{s})}$$

$$O=\int_0^C d\bar{s}\,\frac{B'''(\bar{s})\beta(\bar{s})^2}{32\pi(B\rho)}$$

$$\Rightarrow O_{\mathrm{d}}(s)=\int_0^C d\bar{s}\,\frac{B'''(\bar{s})\beta_{\mathrm{d}}(\bar{s})^{3/2}\beta(\bar{s})^{1/2}}{32\pi(B\rho)}e^{-i[\pm\psi_{\mathrm{d}}(\bar{s})-\psi(\bar{s})]-\pi i(\pm\nu_{\mathrm{d}}-\nu)\mathrm{sgn}(s-\bar{s})}$$

Analytic expressions of the amplitude modulation

$$\delta_0\equiv\nu_{\mathrm{d}}-\nu_0\,,\quad a_0\equiv\frac{cI_{\mathrm{ac}}}{\delta_0}$$

$$a_{k>0,\,\delta_0<0}=a_0\sqrt{-\frac{\delta_0}{3ka_0^2}}\left[\left(\sqrt{1-\frac{27ka_0^2}{4\delta_0}}+\sqrt{-\frac{27ka_0^2}{4\delta_0}}\right)^{1/3}-\left(\sqrt{1-\frac{27ka_0^2}{4\delta_0}}-\sqrt{-\frac{27ka_0^2}{4\delta_0}}\right)^{1/3}\right]$$

$$a_{k>0,\,\delta_0>0}=a_0\sqrt{\frac{4\delta_0}{3ka_0^2}}\cos\left[\frac{\pi}{3}+\frac{1}{3}\arctan\sqrt{\frac{4\delta_0}{27ka_0^2}-1}\right]$$