Characterization of Transverse Beam Motion in Booster

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Measurement Procedure

- Signals of from damper pickups are digitized with 0.4 ns sampling time for about 1/3 of Booster cycle (6236 turns out of ~20,000) in the middle of accelerating cycle (covers transition crossing)
  - ♦ Hybrid is used to generate sum and difference signals
    - • Effective pickup radius (half aperture) – a=32 mm
- Data for vertical and horizontal motions were acquired at different cycles
- Data processing
  - ♦ Boundaries for each RF bucket are found
 - ♦ Beam positions for each bunch are computed

  $$x_n = A_n\, a \quad \text{where } A_n \text{ is computed using RMS fitting} \quad \vec{\mathbf{D}}_n = A_n \vec{\mathbf{\Sigma}}_n + C_n$$

- Presentation of data
  - ♦ Bunch positions turn-by-turn for each bunch
  - ♦ Bunch positions averaged over one turn
  - ♦ Spectra of bunch motion
 - ♦ Dependences of longitudinal modes of bunch motion on time

Horizontal Bunch Motion Averaged over One Turn

■ Positions of all bunches at a given turn are averaged (except the gap)

Beam position averaged over one turn [mm]
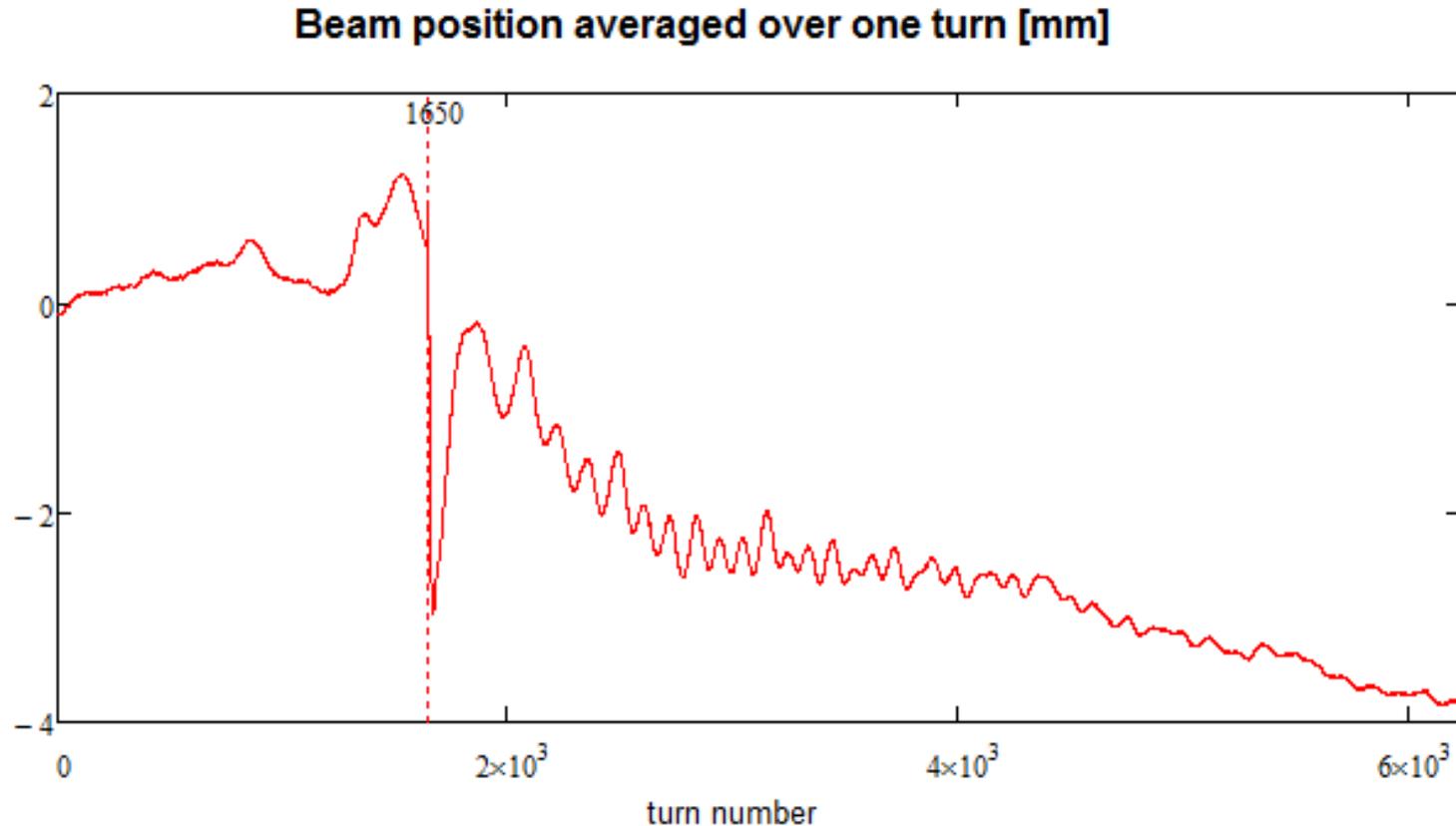


■ Transition crossing is clearly seen at turn number of ~1650 (counted from the beginning of data acquisition
■ Excellent accuracy of the beam position measurement: RMS deviation due to noise is about 3 μm
   ♦ Digitization noise is the main source of errors (8 bit scope)

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Spectrum of Horizontal Beam Motion of All Bunches

Beam position averaged over one turn [mm]
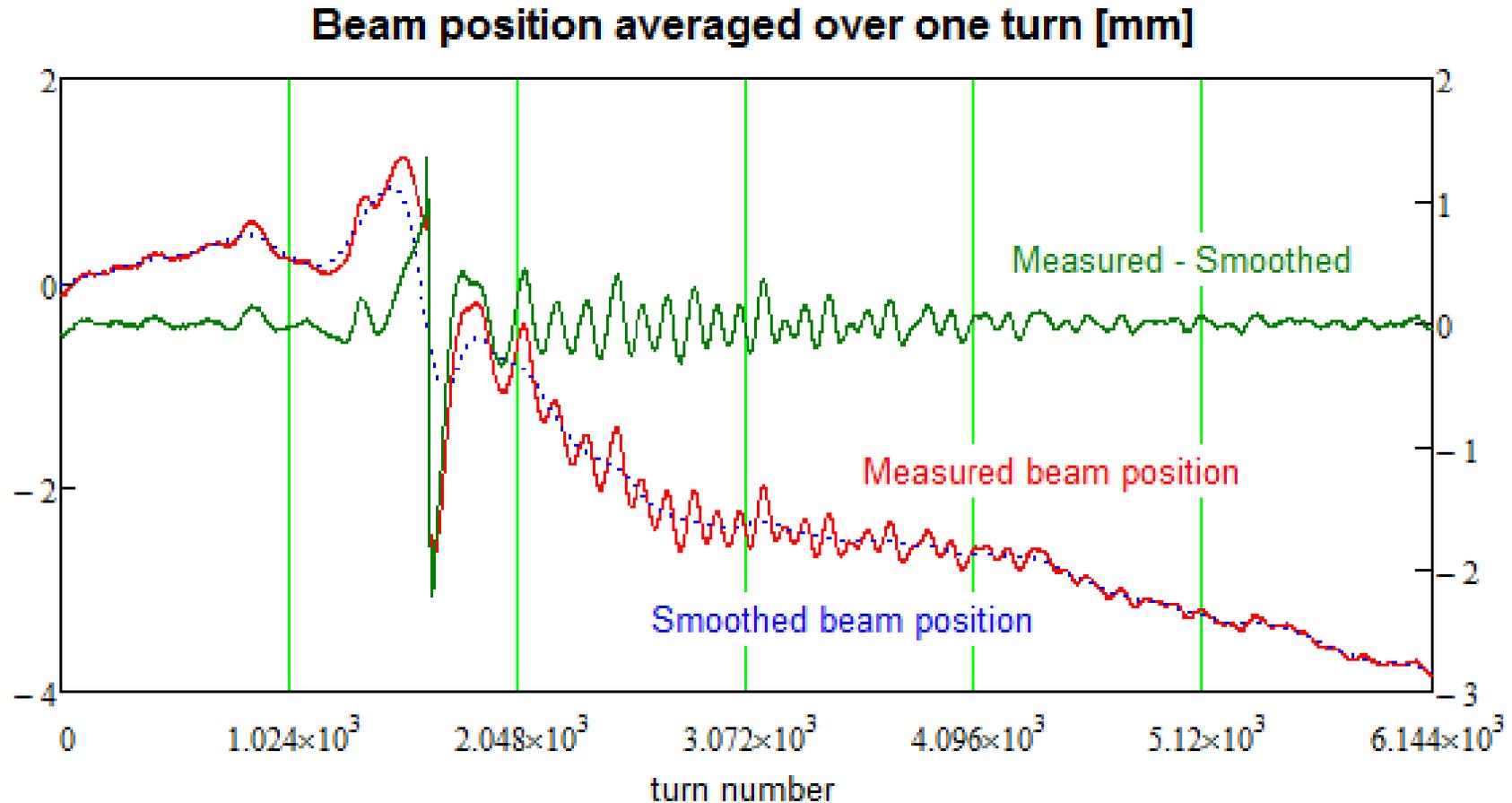
- Two remove low frequency noise the smoothed beam motion was subtracted from its measured value
- All data were split in 6 regions
- FFT was done for each of 6 regions
  numbered 0 to 5; 1024 turns (points) per region

# Spectrum of Horizontal Beam Motion of All Bunches (2)
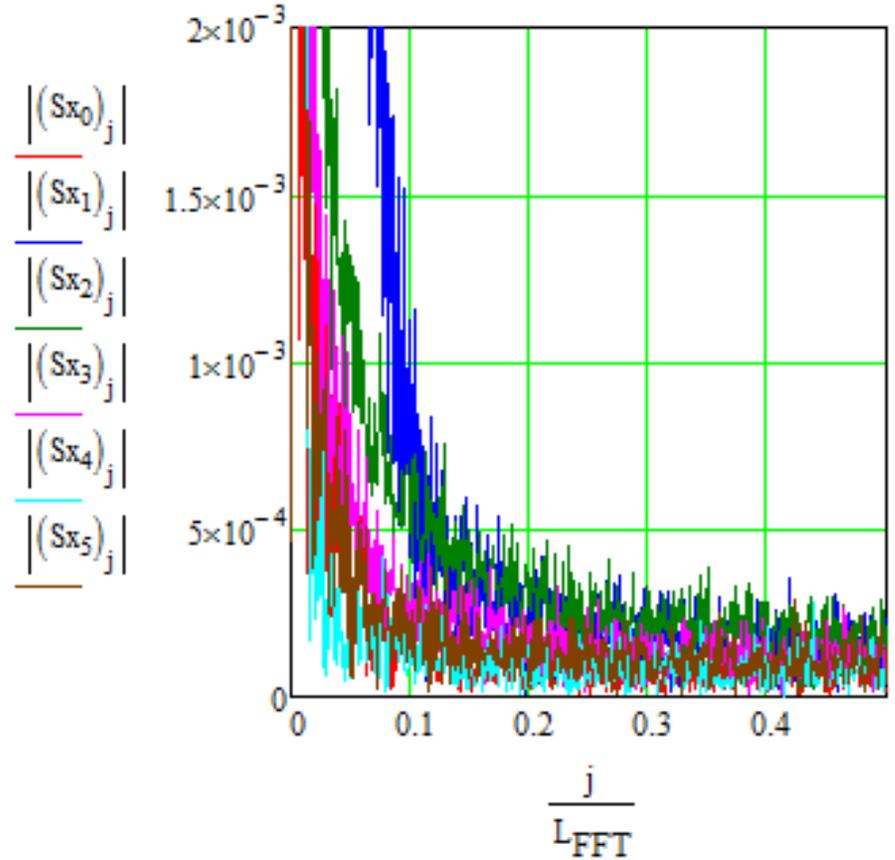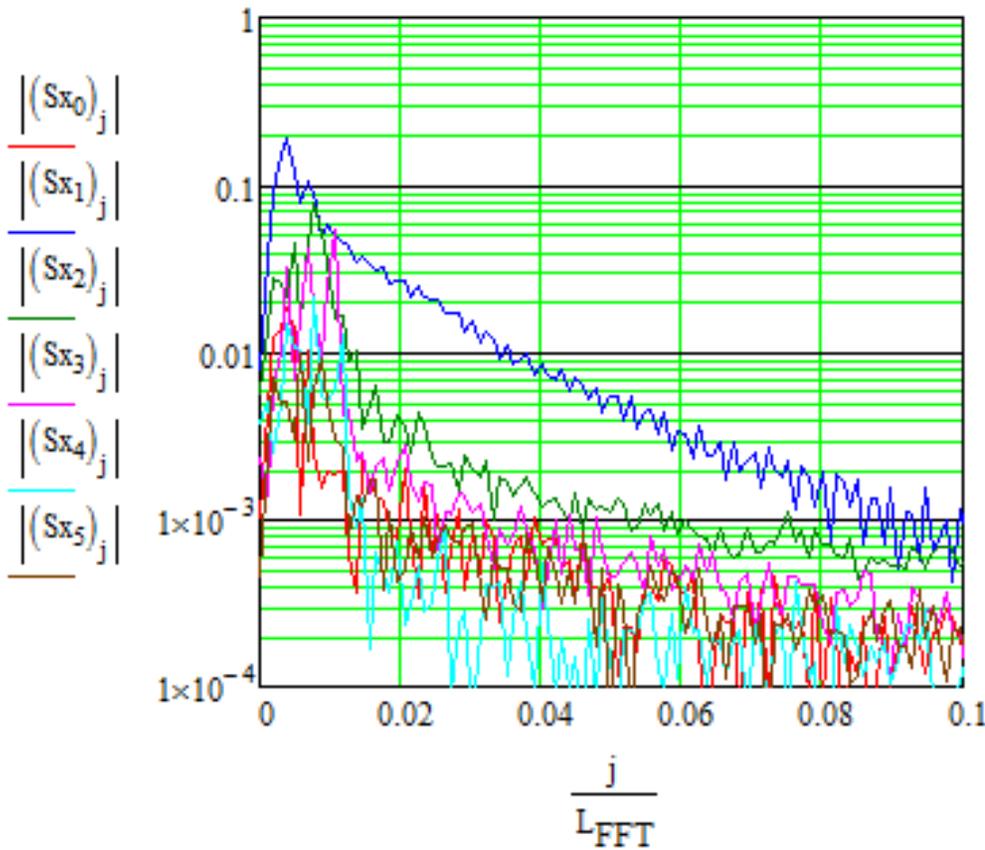
- Region 1 where transition crossing happens has significantly larger spectrum
- There is no measurable motion at the betatron frequencies. Low frequency motion Q<0.015 (f<10 kHz) is present with the rms values <50 μm

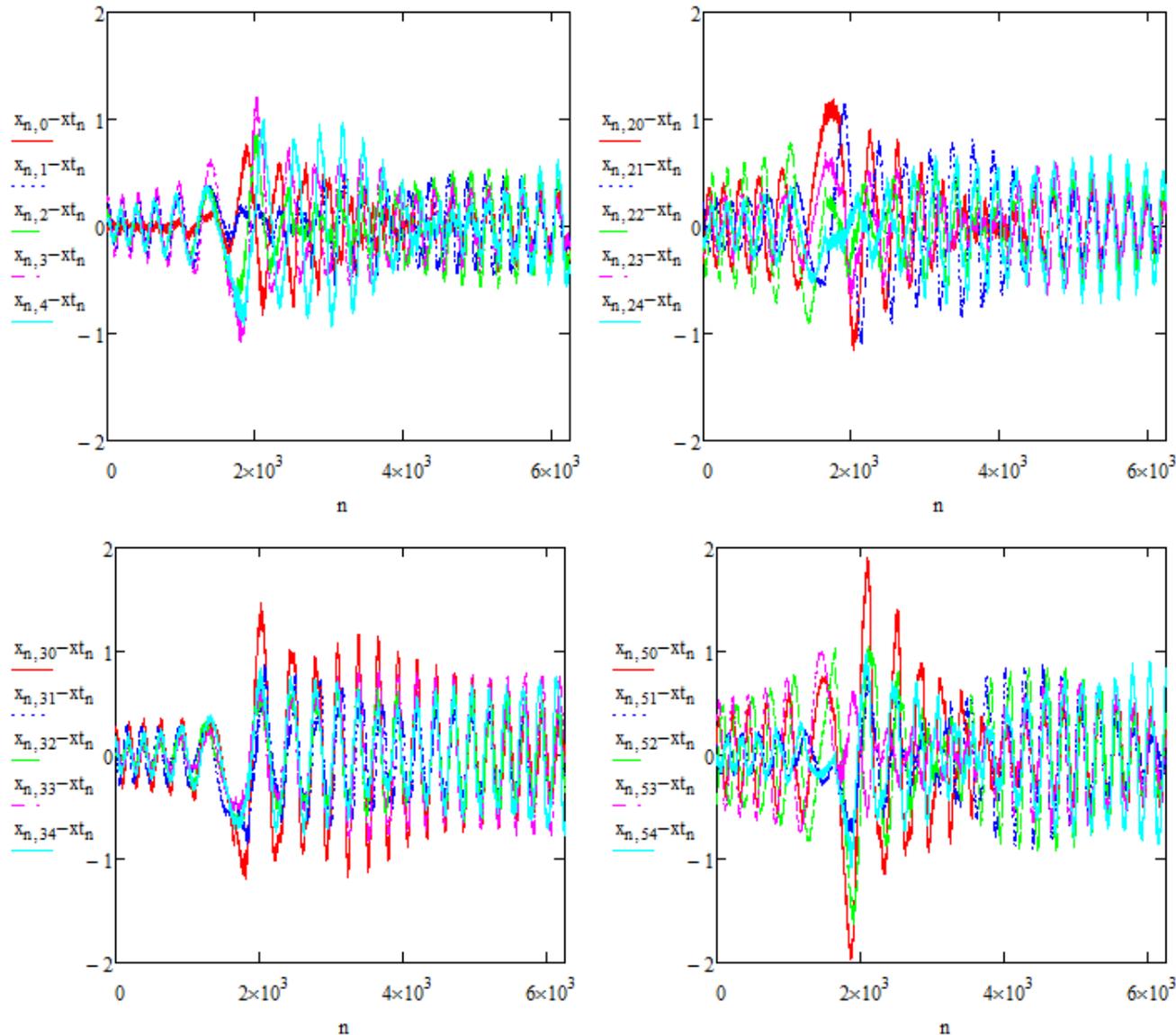"Characterization of Transverse Beam Motion in Booster", V. Lebedev, Fermilab, August 13, 2019
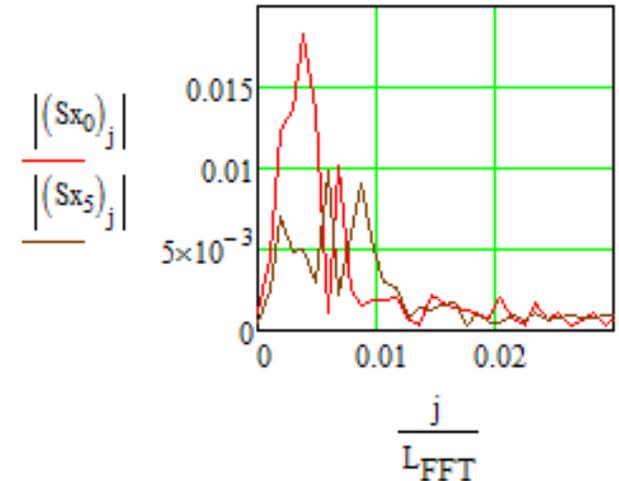
Horizontal Motion of Separate Bunches

- There is considerable bunch displacements relative to the average beam position, about ±0.5 mm
- Positions at nearby turns are close but changes significantly with time
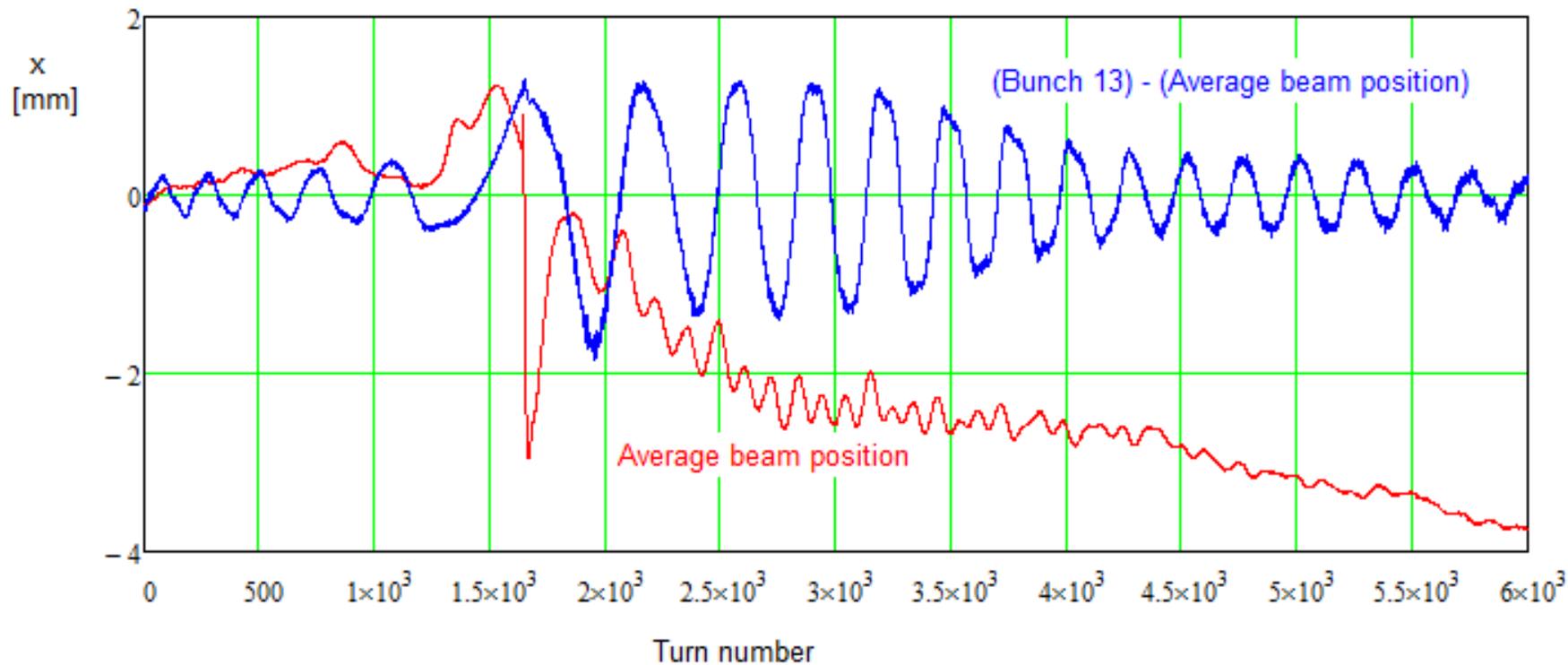- Many harmonics of bunch positions are present
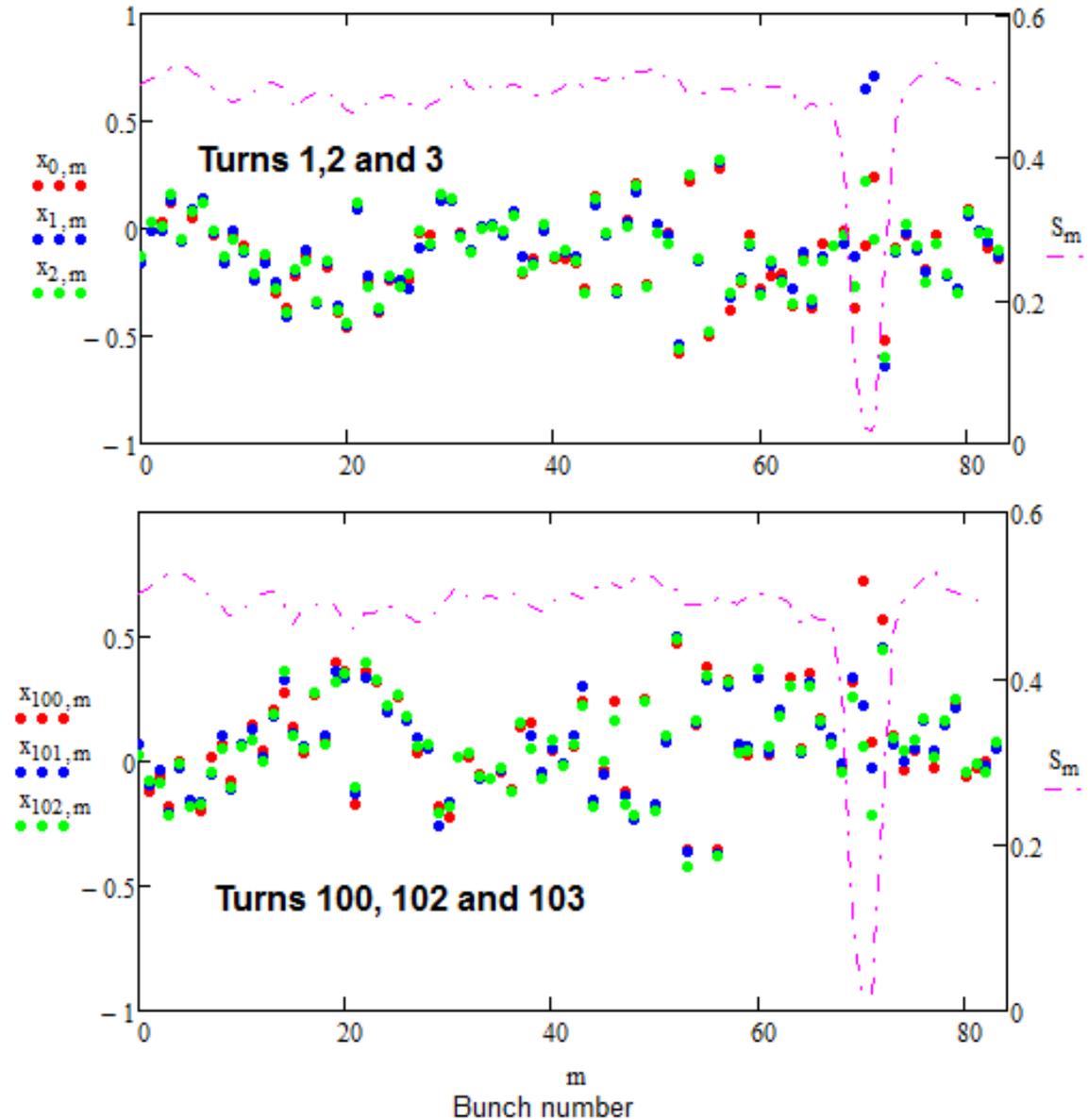
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Horizontal Motion of Separate Bunches (2)

Bunch positions on the turn number relative to the average beam position for bunches 0-4, 20-24, 30-34, 50-54

■ Positions of bunches are oscillating at synchrotron frequency

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# Horizontal Motion of Separate Bunches (3)

- **Bunches are moving at the synchrotron frequency relative to the average beam position**
- **The transition crossing excites motion of the average beam position**
  - ◆ The motion is damped (LLRF helps but how much?)
  - ◆ It happens at frequency of longitudinal quadrupole motion
    - • Approximately double synchrotron frequency
    - • Frequency is shifted up by particle interaction (impedance)
    - • Bunch length changes -> changes in bunch deceleration -> energy change

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Modes of Relative Horizontal Bunch Motion
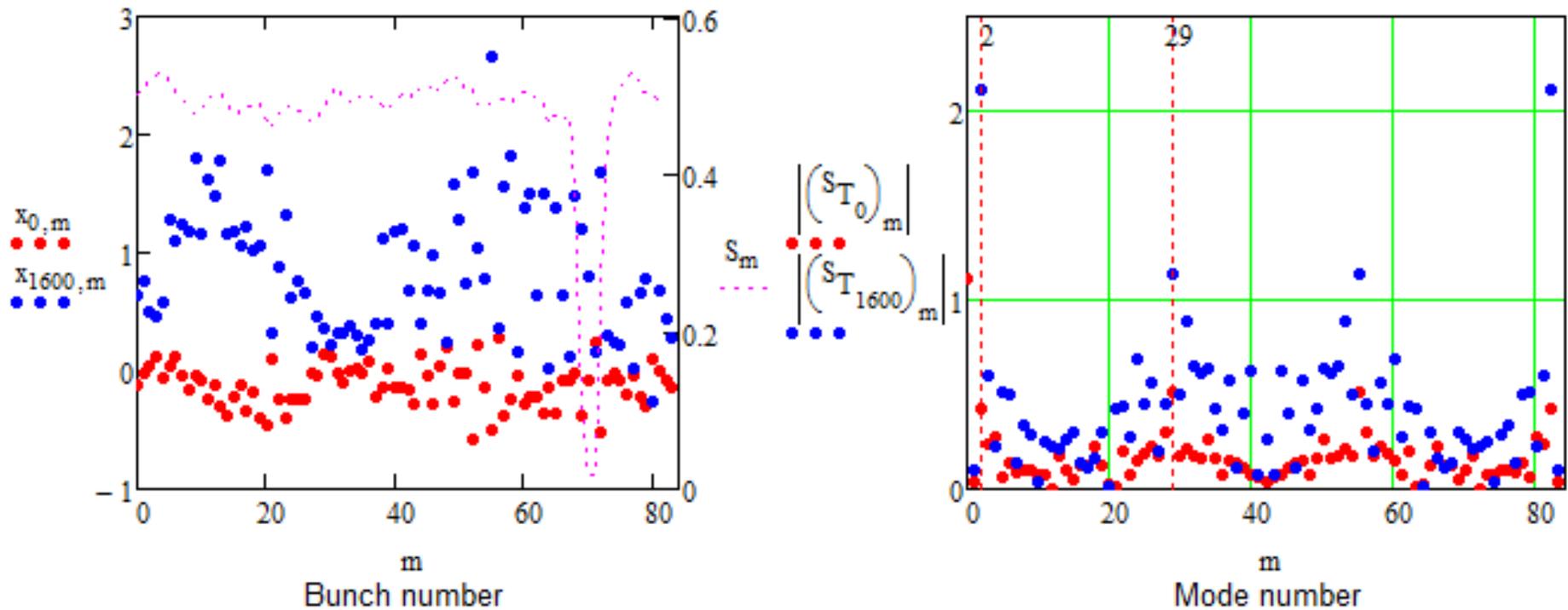
- Synchrotron motion results in energy variations which we observe as bunch position variations
- There many harmonics in relative bunch motion
  - Modes 2 and 29 (or 80 and 55) dominate at both the turns 0 and 1600

Modes of Relative Horizontal Bunch Motion (2)
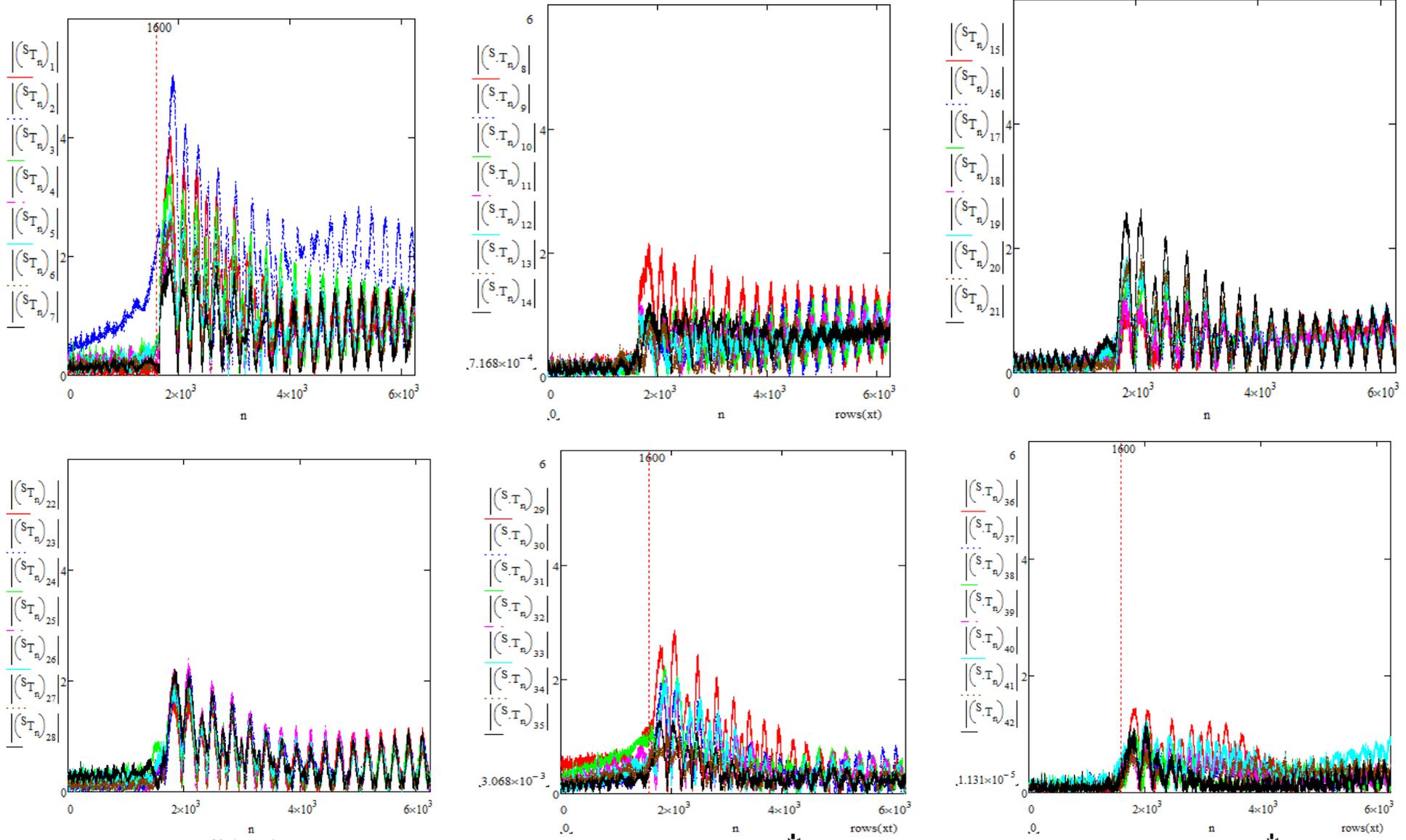
- Modes 2 and 29 are most unstable before transition
- Mode 2 looks as a real problem and needs to be damped.

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Vertical Bunch Motion Averaged over One Turn

- Positions of all bunches at a given turn are averaged (except the gap)

Beam position averaged over one turn [mm]
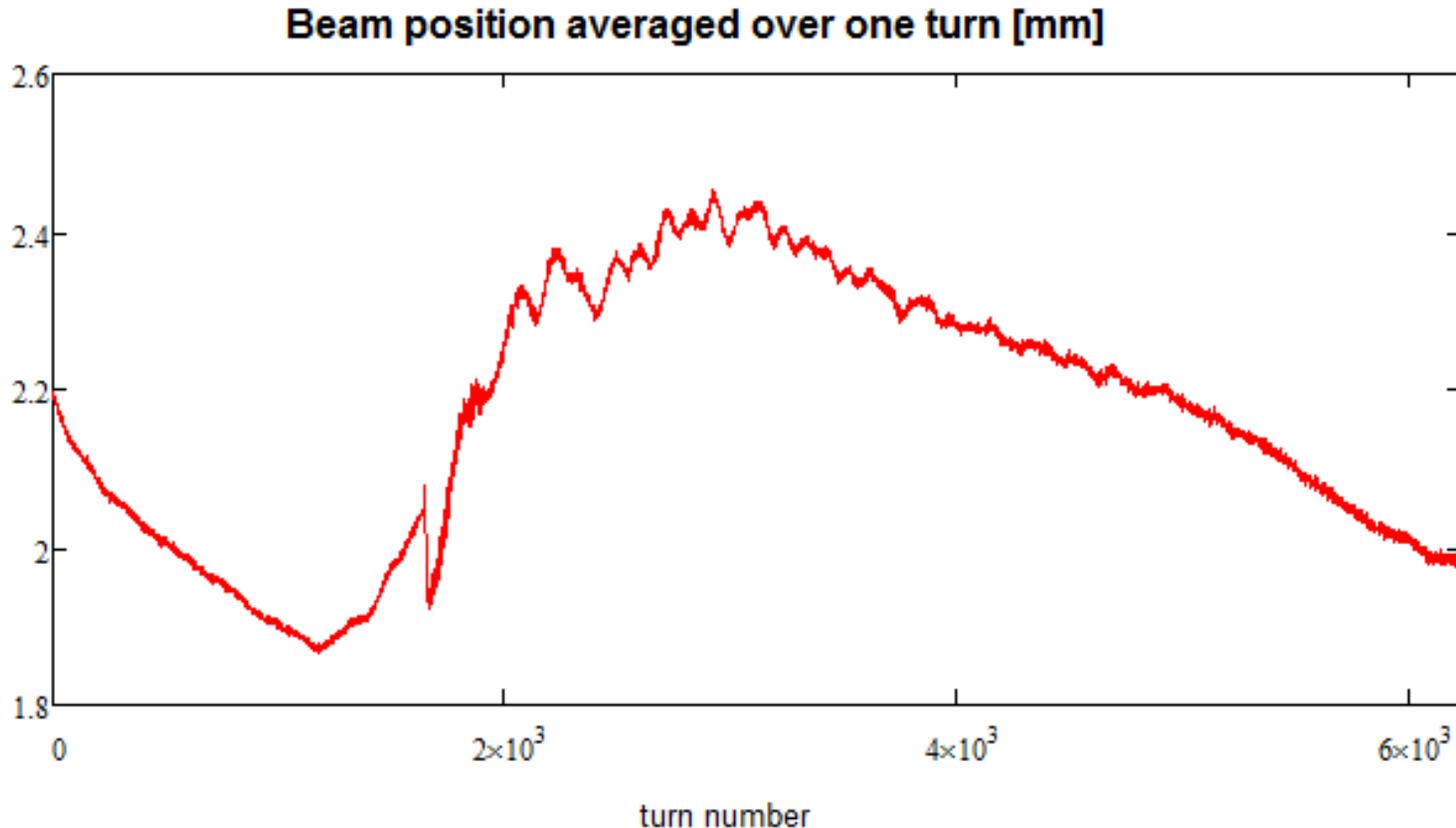
- Transition crossing is also clearly seen at turn number of ~1650 (counted from the beginning of data acquisition
- Excellent accuracy of the beam position measurement:
  RMS deviation due to noise is about 3 µm
 - Digitization noise is the main source of errors (8 bit scope)

Spectrum of Vertical Beam Motion of All Bunches
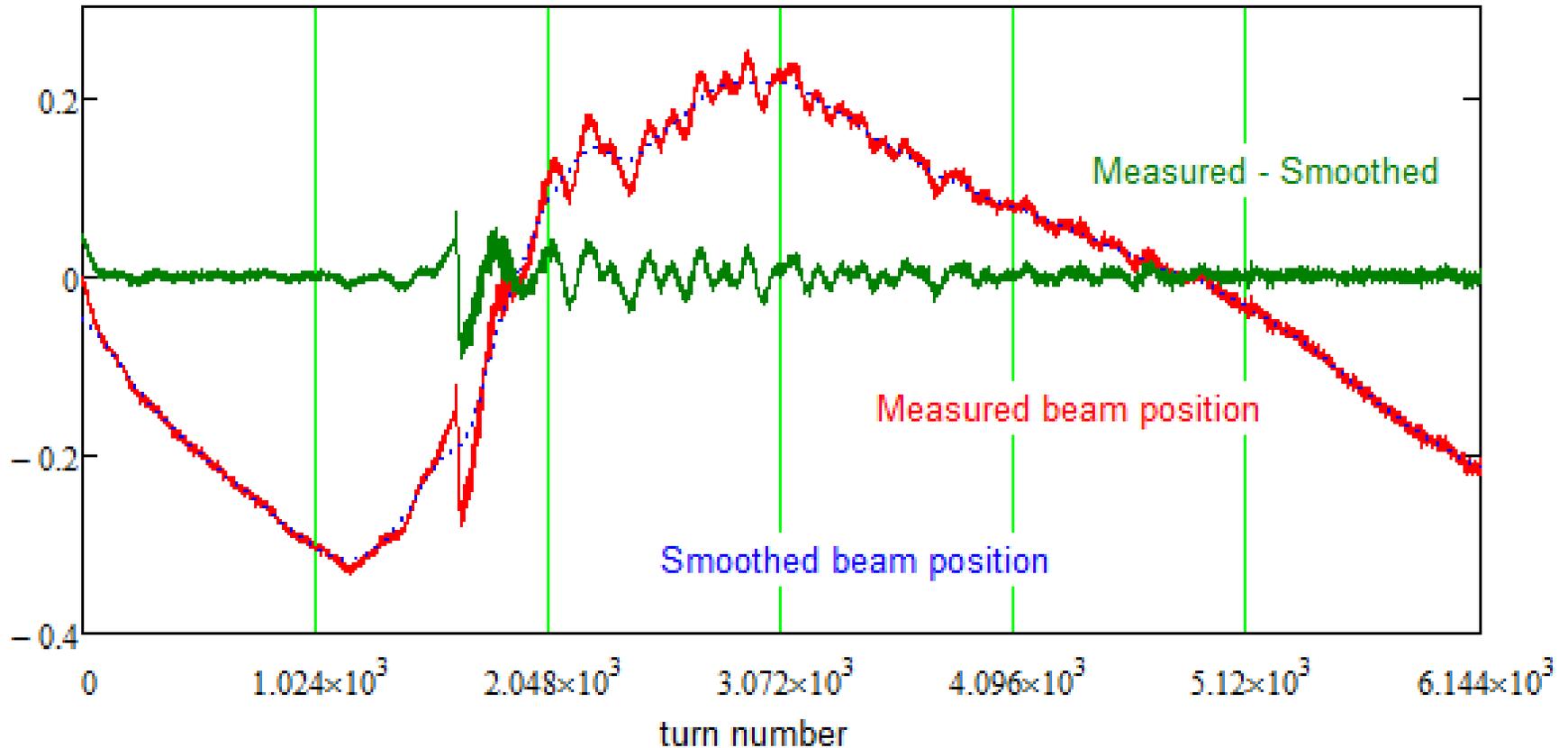
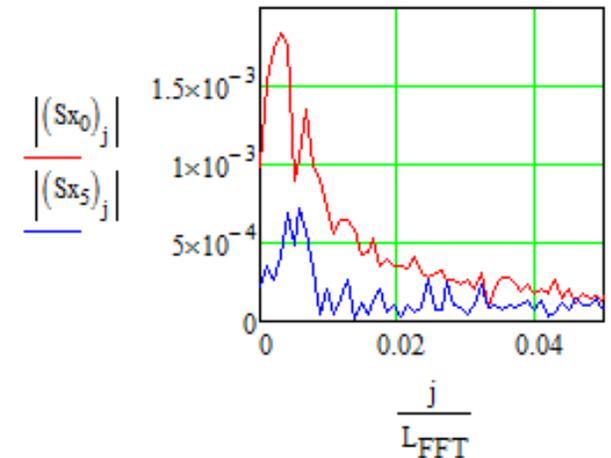**Beam position averaged over one turn [mm]**

- Two remove low frequency noise the smoothed beam motion was subtracted from its measured value
- All data were split in 6 regions
- FFT was done for each of 6 regions numbered 0 to 5; 1024 turns (points) per region

Spectrum of Vertical Beam Motion of All Bunches (2)
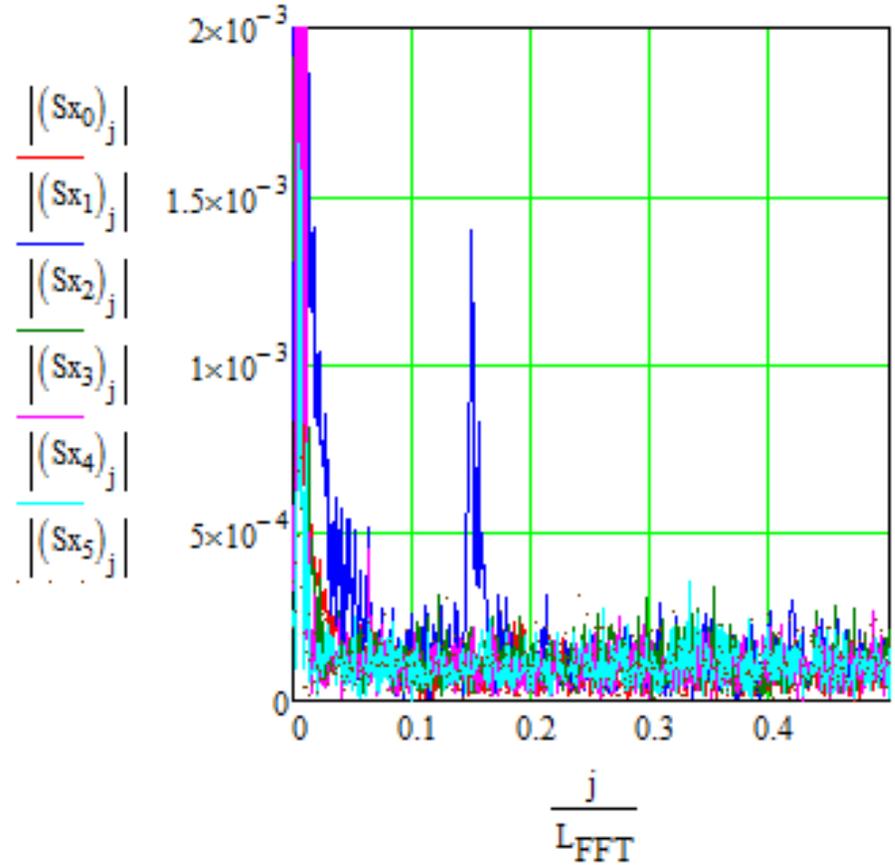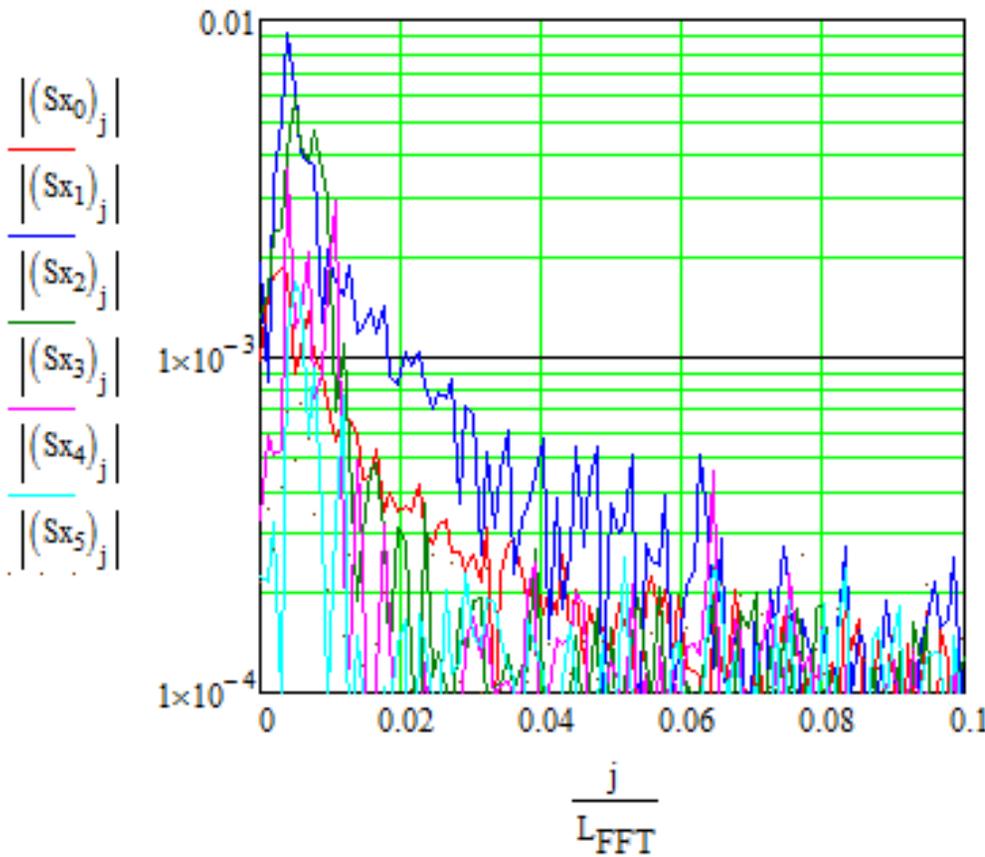
- Region 1 where transition crossing happens has significantly larger spectrum
- Transition excites the betatron motion; the betatron frequency ~0.85
- Low frequency motion Q<0.015 (f<10 kHz) is present with the rms values <10 μm

"Characterization of Transverse Beam Motion in Booster", V. Lebedev, Fermilab, August 13, 2019
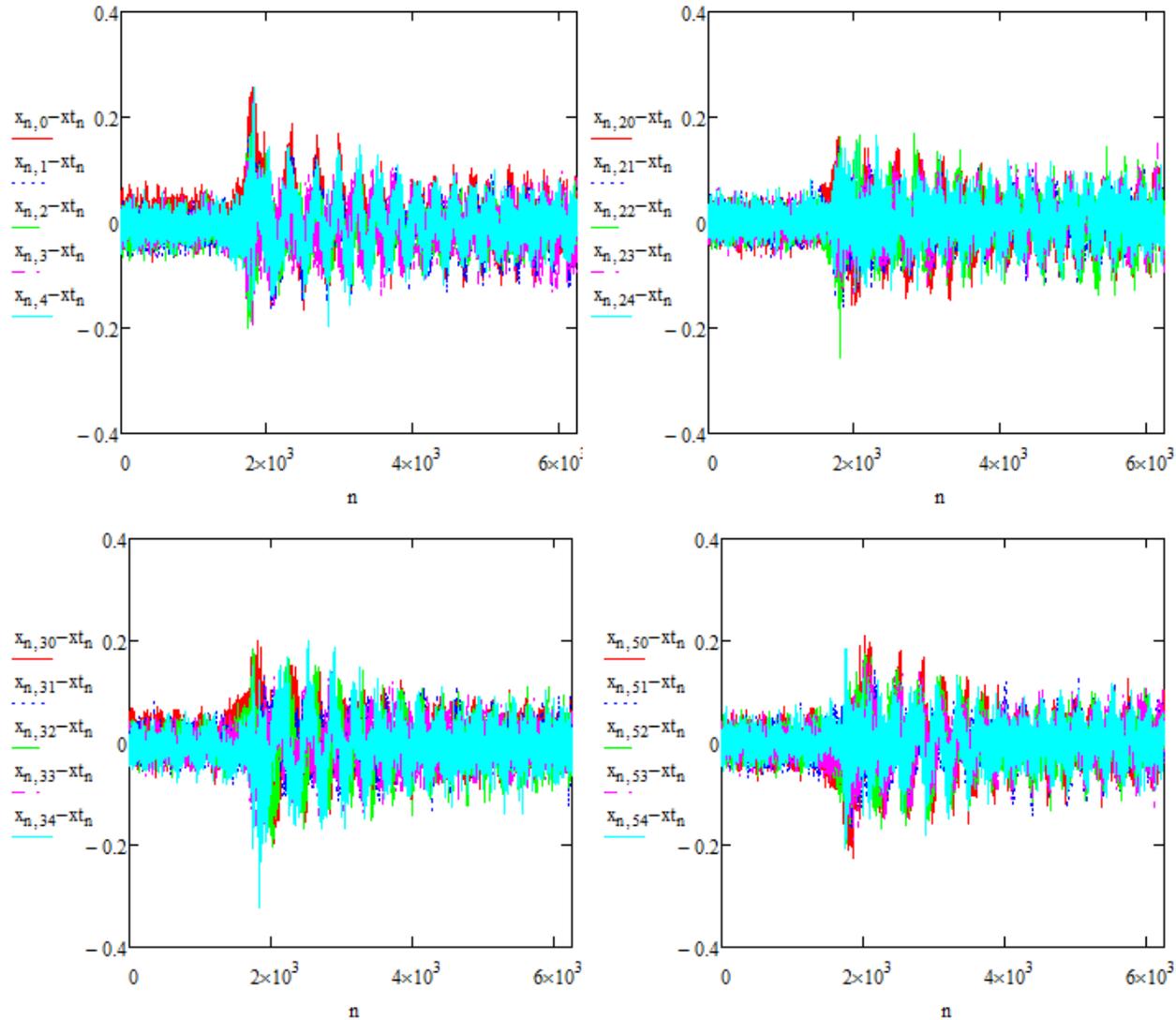
Vertical Motion of Separate Bunches

- In difference to the horizontal plane there is now observable motion of bunches relative to the average position before transition
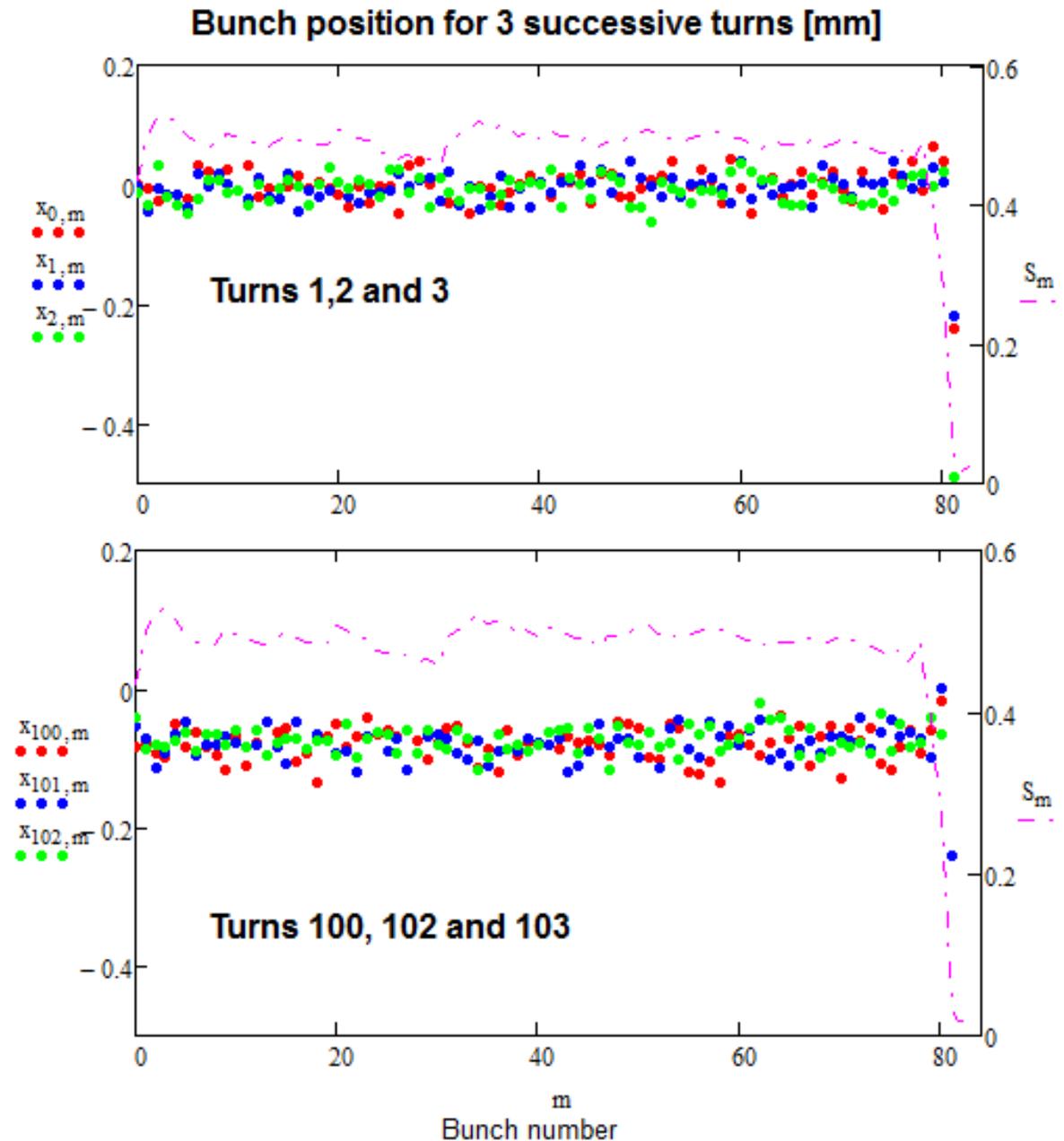
Bunch position for 3 successive turns [mm]

Turns 1,2 and 3

Turns 100, 102 and 103

m
Bunch number

Vertical Motion of Separate Bunches (2)

Bunch positions on the turn number relative to the average beam position for bunches 0-4, 20-24, 30-34, 50-54

- Transition excites oscillations at the synchrotron frequency with about 5 times smaller amplitude