RF pinger commissioning and beam dynamics studies at NSLS-II

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- Description of NSLS-II RF system
- Model of longitudinal beam dynamics with RF pinger
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- RF pinger studies at NSLS II
  - Momentum aperture measurement
    - single RF cavity with and without damping wigglers
    - two RF cavities
  - Experiment on crossing half integer resonance
- Summary

Introduction

- **RF pinger** = Sudden change of RF cavity phase or voltage, which will induce longitudinal beam oscillations

- It is known and has been used in accelerators for various applications
  - γ_T-crossing in hadron machines
  - dispersion measurements at ATF
  - Pulse length manipulation with RF phase jump

- **RF jump or RF pinger** presents a powerful tool for investigation of beam dynamics

J. E. Griffin, FERMILAB-TM-1784.
K. Kubo, ATF Internal Report ATF-97-19 (1997).

Introduction

Motivation

- NSLS-II storage ring RF system has digital ramp control function, which enables rapid change of the cavity $\varphi(t)$ and $A(t)$

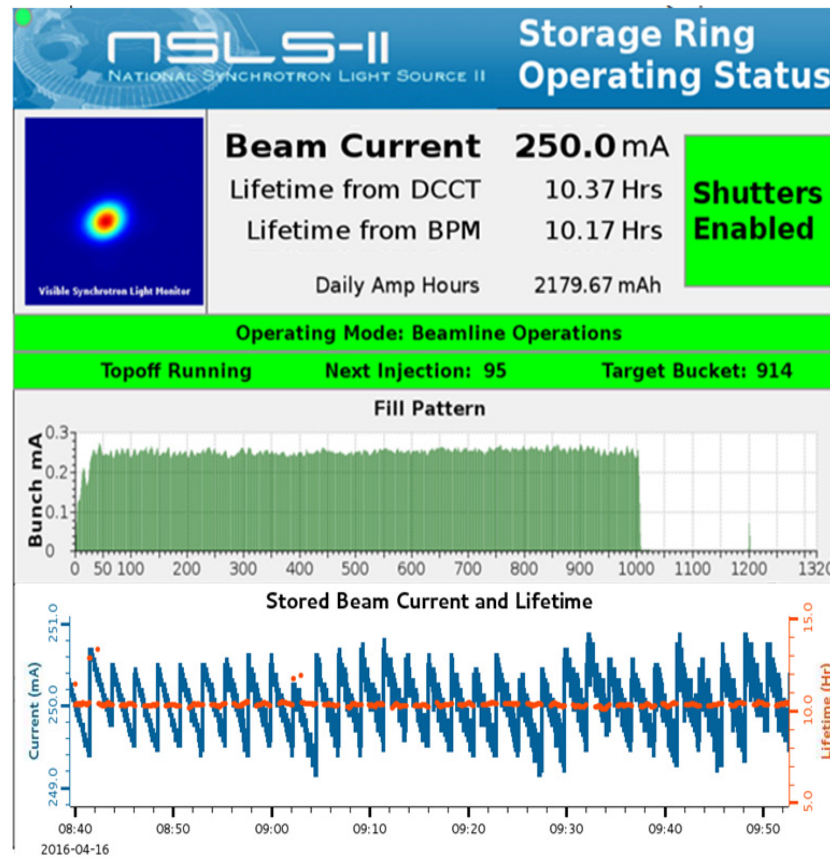
- NSLS-II RF system and SR BPM system are synchronized with precise timing control and data acquisition at high rate

- Using RF phase jump, we measured machine momentum aperture
  - RF momentum aperture with and without damping wigglers (DWs)
  - Assessed momentum aperture limits along the ring

- Studied dynamics of the beam crossing ½ resonance with stopband width control

NSLS II overview

- National Synchrotron Light Source (NSLS-II) is a new 3 GeV, 500 mA, high-brightness synchrotron light source facility at the Brookhaven National Laboratory, funded U.S. Department of Energy (DOE).
- SR circumference is 792 m with 1 nm-rad horizontal and 8 pm-rad vertical emittance.
- SR commissioning started in later March 2014
- Six project beam lines operated in Dec. 2014
- Top off routine operation started in October 2015
- 11 beamlines in top off operation at 250 mA
- Stored beam current up to 400 mA

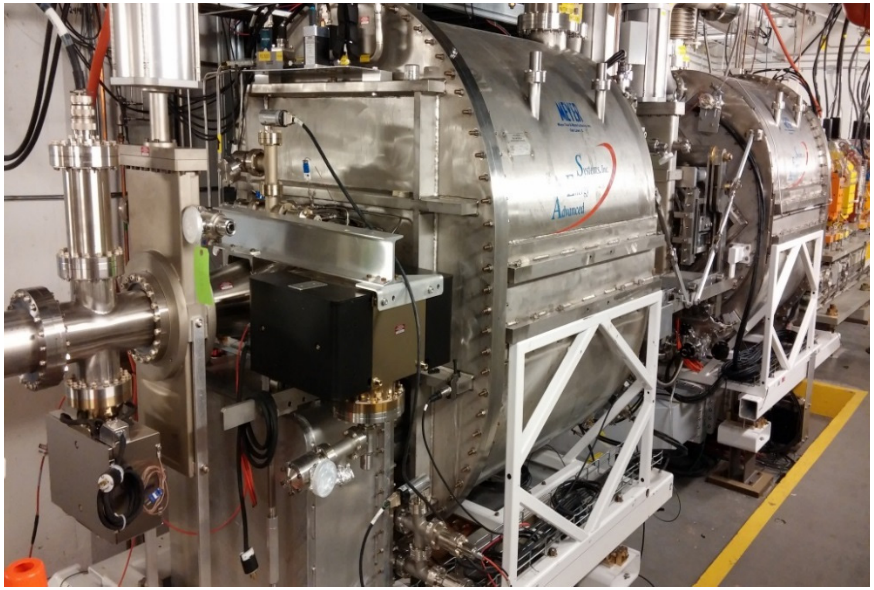


G-M Wang, et.al, Rev. Sci. Instrum. 87, 033301 (2016)
WEPOY05, WEPWO0[58-60]

Storage Ring RF system

- Two SC 500MHz RF cavities with 300 kW transmitters commissioned and operated up to 1.8 MV
- Cavities are over-coupled at low beam current $P_{forward} \approx P_{reflected}$
- LLRF controller (developed at NSLS-II) is capable of generating flexible set-point tables and finely control parameters of RF feedback
- With flexible and fast digital LLRF controller we can manipulate with $\varphi(t)$ and $A(t)$ of cavity field within short timescale (1/4 of T_s)
- It also enables ramp down function for Equipment Protection System purposes (RF voltage comes down in ~1ms)

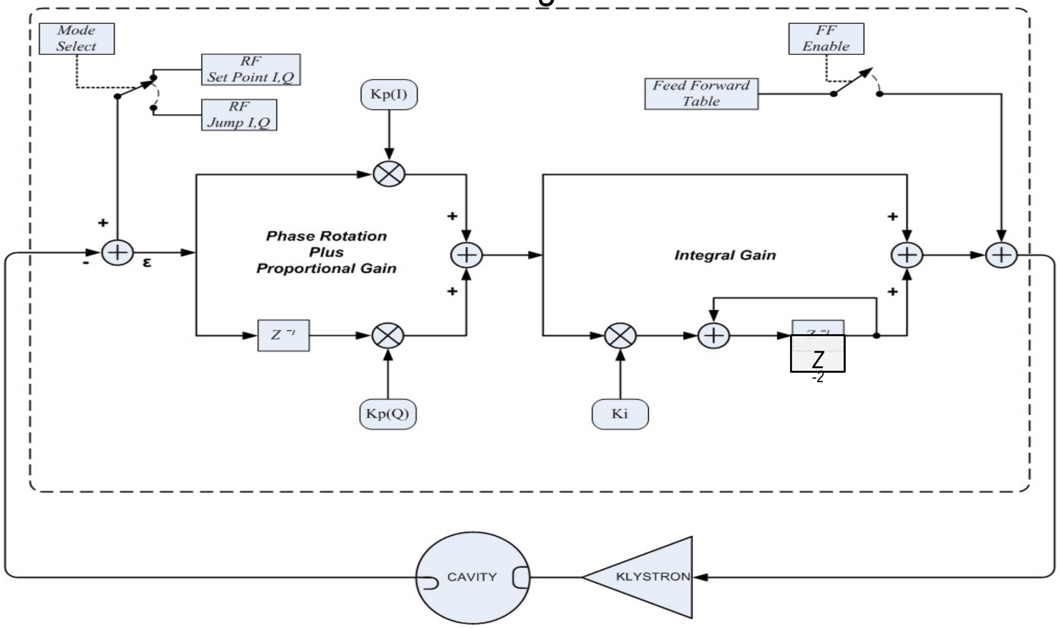
RF cavities in NSLS-II tunnel



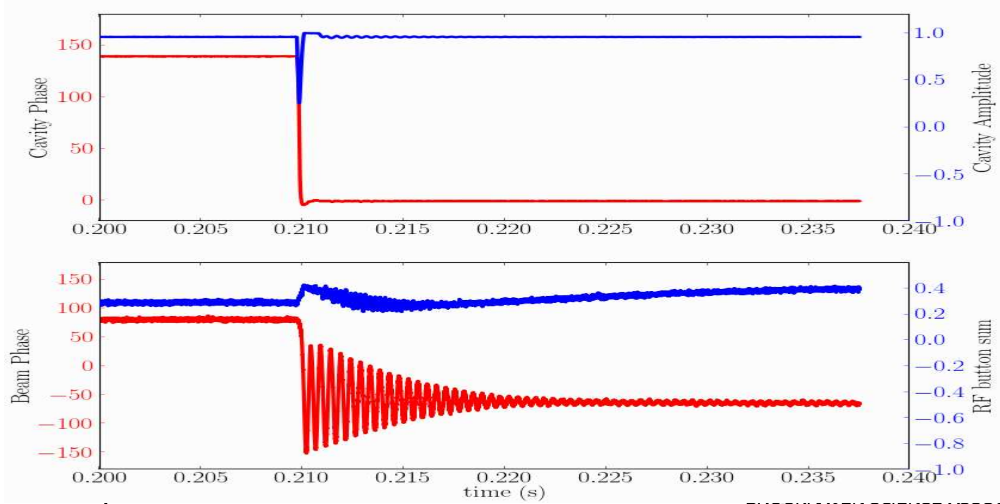
SR RF system: LLRF

- RF setpoint consists of field φ(t) and A(t).
- RF cavity loop can operate in either feedforward or feedback mode
- Feedforward mode: supply ramp table (Δφ(t), ΔA(t))
- Feedback mode: supply (Δφ, ΔA) based on K_p (proportional gain), K_i (integral gain)
- RF jump: alternate cavity amplitude and phase setpoint

LLRF block diagram



RF Circular buffer data

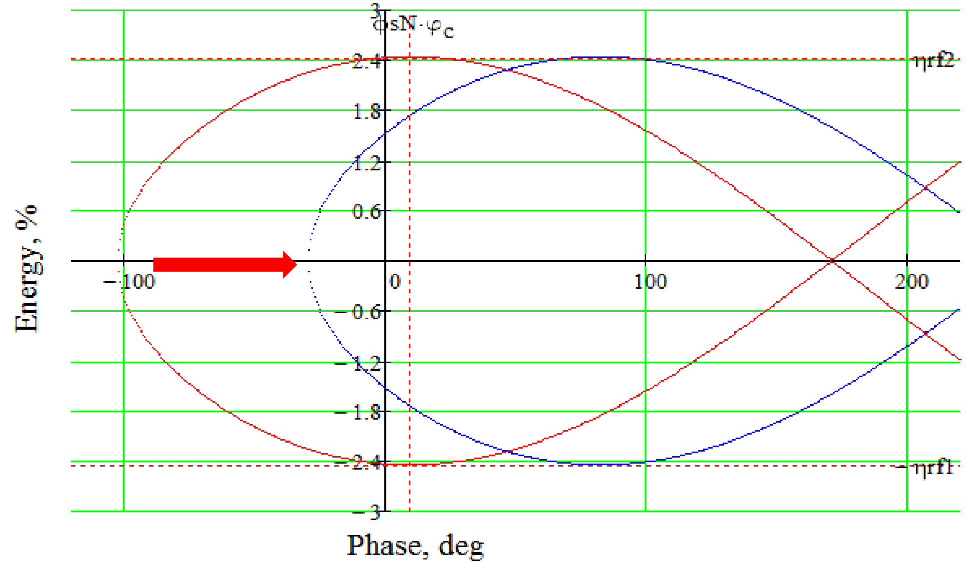


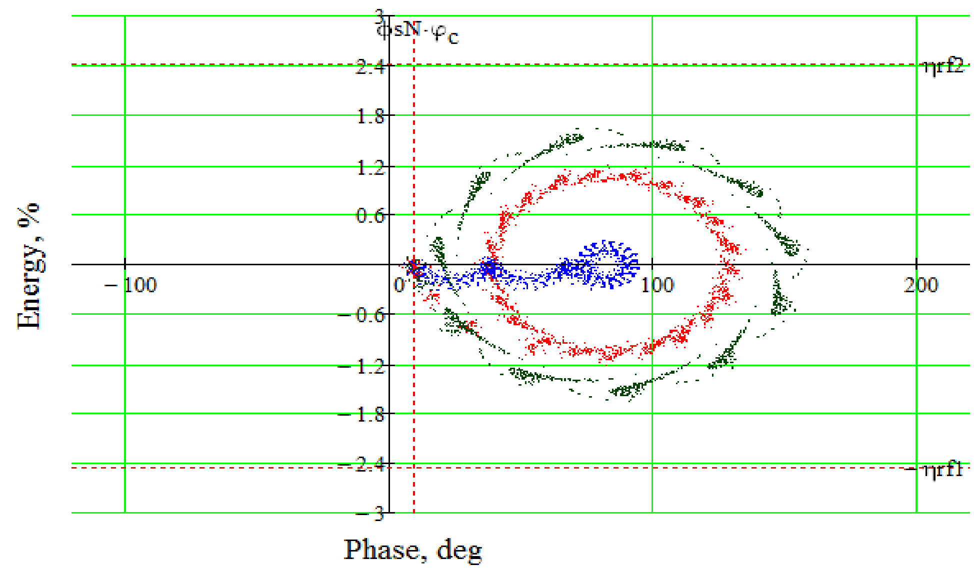
Model of longitudinal beam dynamics

- Speed of RF jump (dφ/dt) is limited by transmitter trip due to high $P_{reflect}$ or waveguide arc

- Developed a simple 1D model with various ramp shapes → Model study RF phase jump with predefined curve (linear, exponential or measurement curve) with short, medium or long transition period

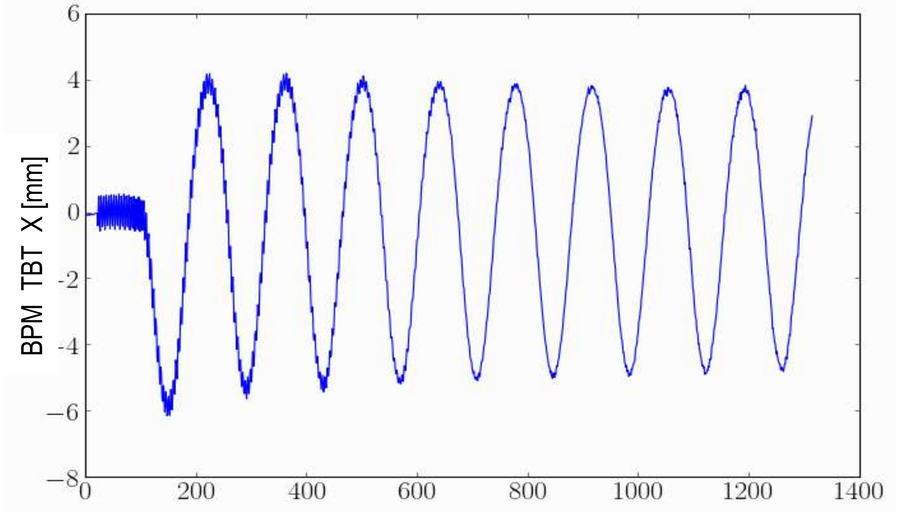
- RF gain K_p, K_i was optimized to control RF phase jump period within ¼ of synchrotron period without RF system trip

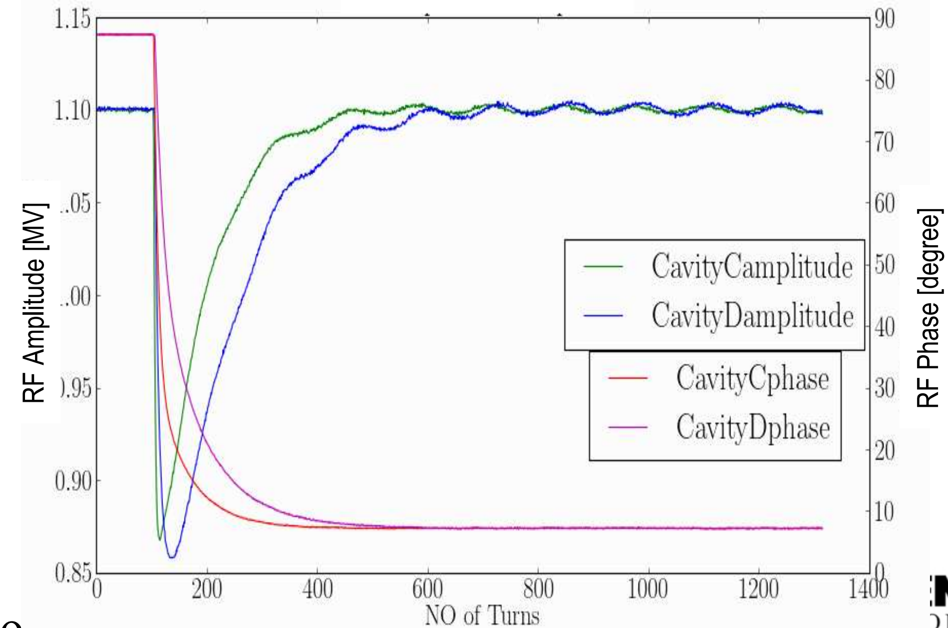




RF phase jump implementation

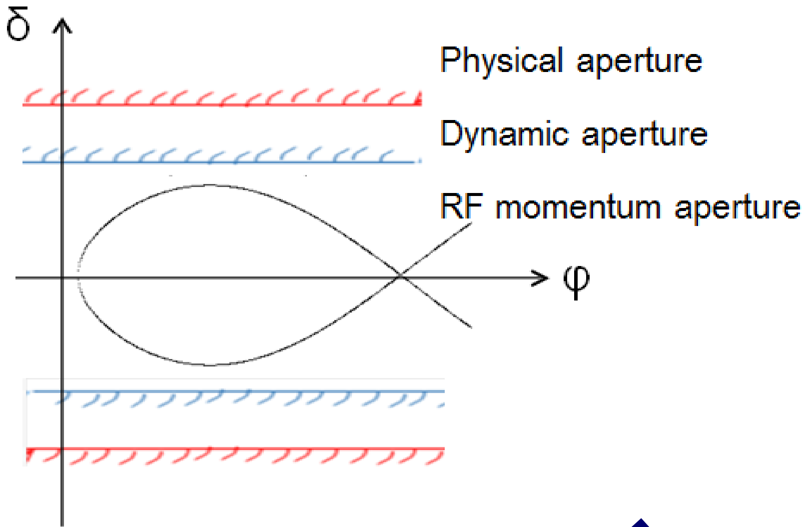
- RF phase jump: the following signals are synchronized and triggered together
  - SR BPMs TBT position & sum signals
  - X/Y Pingers
  - Other beam diagnostics
- LLRF system: record data in 5 channels (4 MHz sampling rate) for diagnostic and monitor purpose
  - cavity field and phase
  - beam phase and intensity signal
- RF phase jump is implemented on feedback mode and dφ/dt is controlled by gain (K_p, K_i)



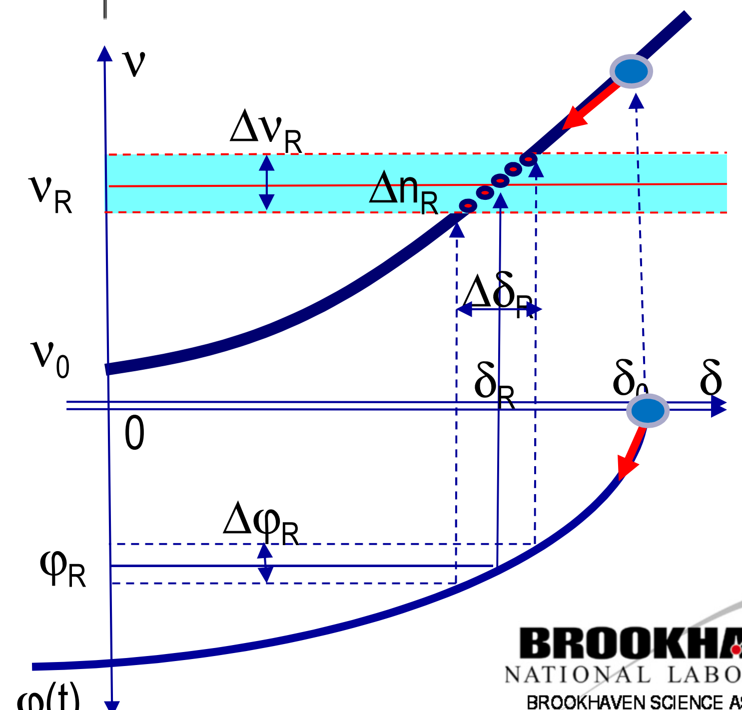


RF pinger studies at NSLS II

- Momentum aperture studies
  - with and without DWs
  - Loss locations corresponding to momentum aperture limit



- Crossing ½ resonance stopband
  - Chromatic tune footprint crosses major resonance (multi bend achromat lattice)
  - Studied case of beam dynamics while crossing ½ resonance via energy modulation by RF pinger

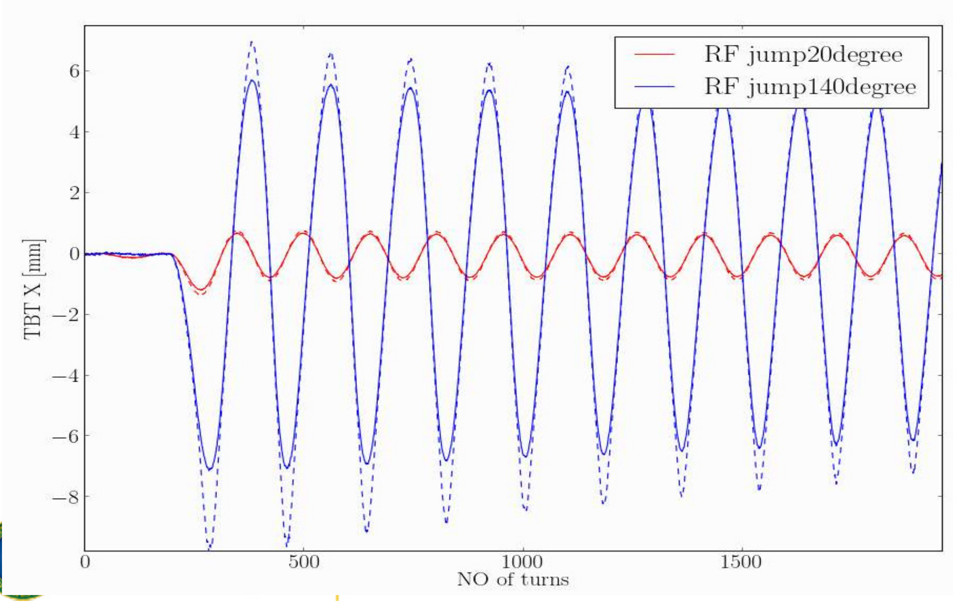


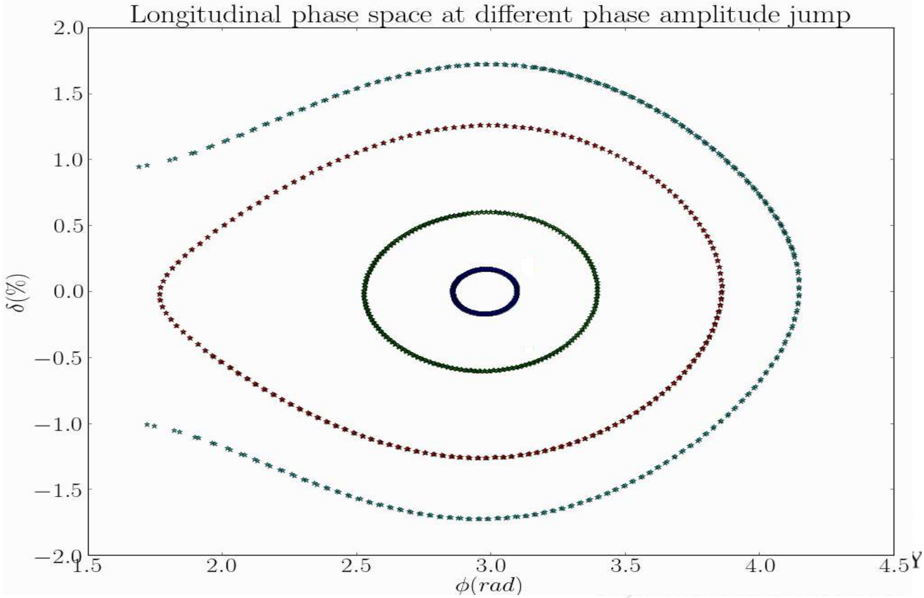
Data processing

- Beam energy oscillation δ from RF phase jump is measured with dispersion region BPMs TBT X, or δ_{max} 2% corresponding to X_{max} 10 mm: $x = \eta_1 * \delta + \eta_2 * \delta^2$
- BPM nonlinearity with large beam offset: 5th order correction

$$x_{mea} = p_{10}\left(\frac{\Delta}{\Sigma}\right)_x + p_{30}\left(\frac{\Delta}{\Sigma}\right)_x^3 + p_{50}\left(\frac{\Delta}{\Sigma}\right)_x^5$$

- Transformation from x→ δ (applied for 1st and 2nd order dispersion): $\delta = \frac{2x}{\left(\eta_1 + \sqrt{\eta_1^2 + 4\eta_2 x}\right)}$
- Retrieval of longitudinal phase space motion during RF jump
  - TBT X→ δ
  - RF button signal→ ϕ

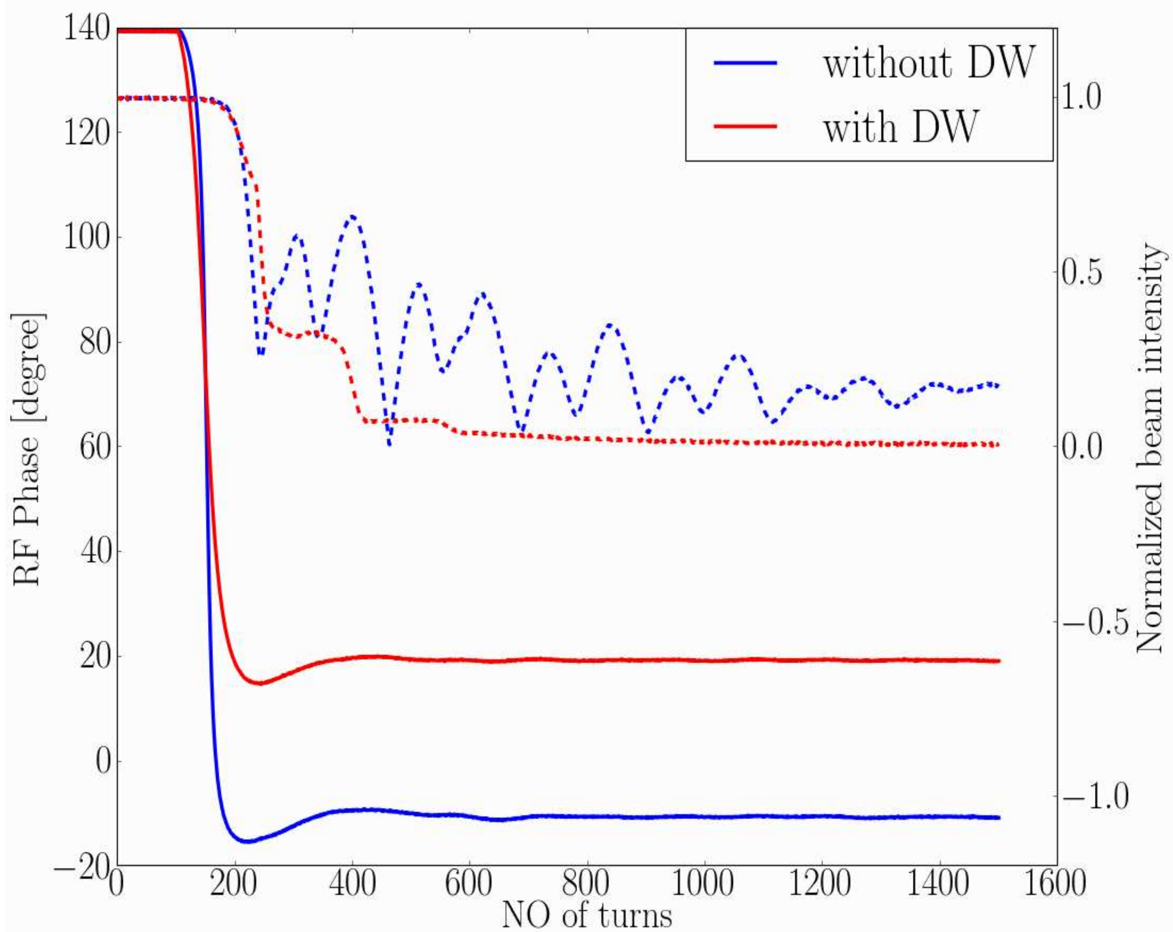




Momentum aperture: RF acceptance

- SR momentum aperture at full RF voltage by design, δ ~2.6%
- One cavity: voltage 1.77 MV, $d\varphi>160^o$ (RF bucket height δ, 2.4% w/o DWs, 1.8% with DWs)
- Beam: a few mA in 40 buckets

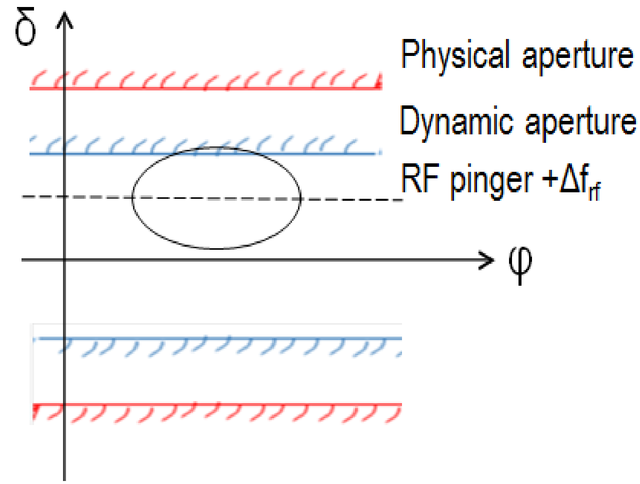
- Case 1: without DWs, beam lost with $d\varphi$ at 150^o, measured δ_{max}, 2.4%
- Case 2: with DWs, beam lost with $d\varphi$ at 120^o, measured δ_{max}, 1.8%
- Conclusion: **measured momentum aperture is limited by RF bucket height** as predicted



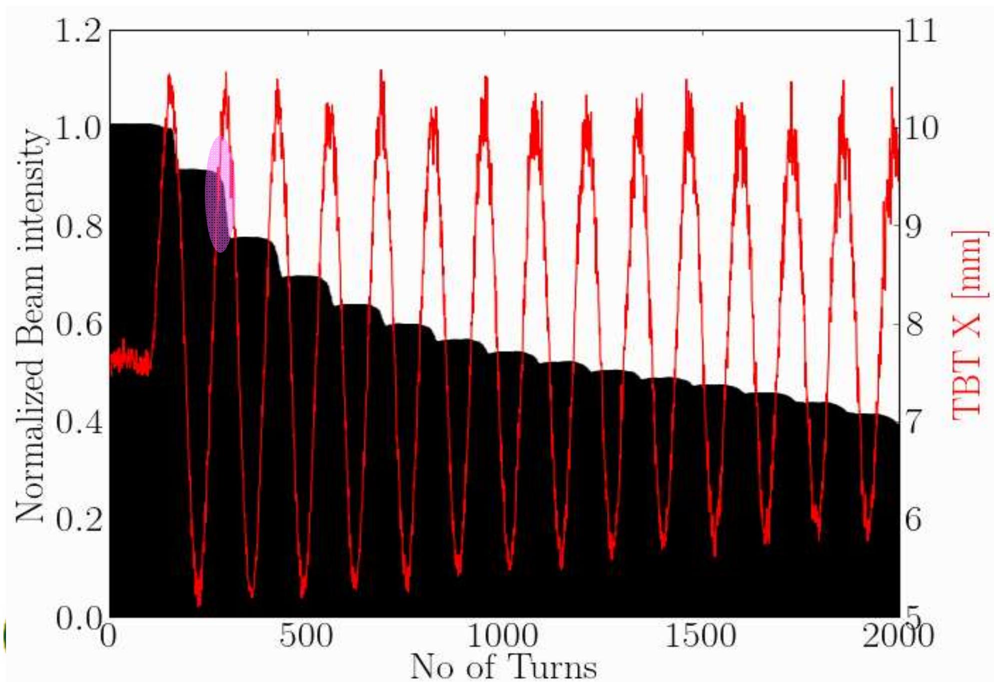
C. Steier, et.al, Phys. Rev. E 65, 056506

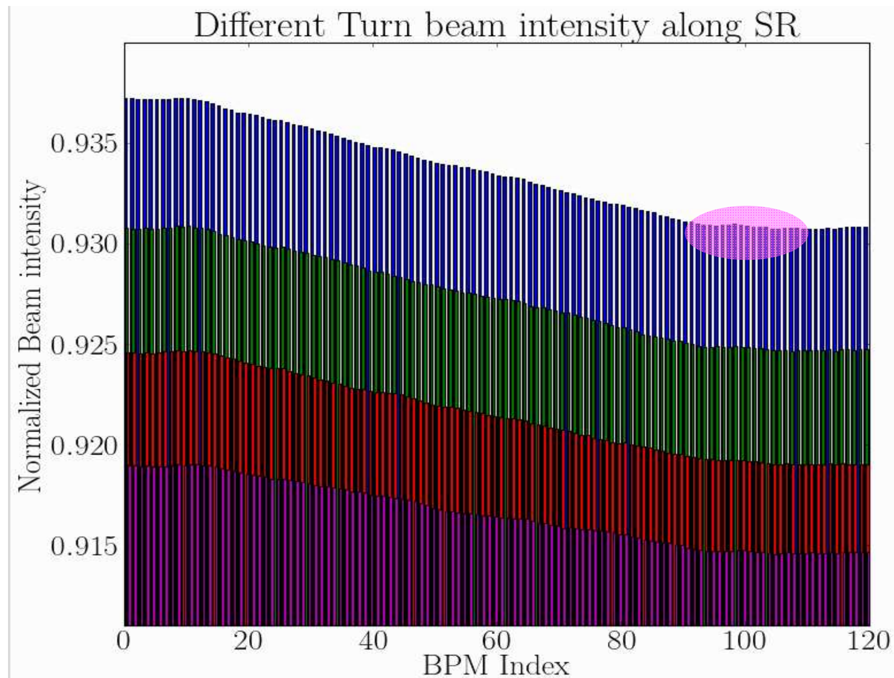
Momentum aperture: search for loss locations

- Two cavities with total voltage 2.2 MV, phase jump upto 80 degree→ δ_{max} 1.2%
- Shift beam off momentum
- Via RF phase jump we measured and located SR momentum aperture limit
- $I_{raw} = [I_i^{p1}, \ldots, I_i^{pn}, I_{i+1}^{p1} \ldots] \rightarrow \overline{I_i^{pj}} =< I_i^{pj}, \ldots, I_i^{pj+k} >$



- **Localize dynamic aperture limit** with BPM sum signal



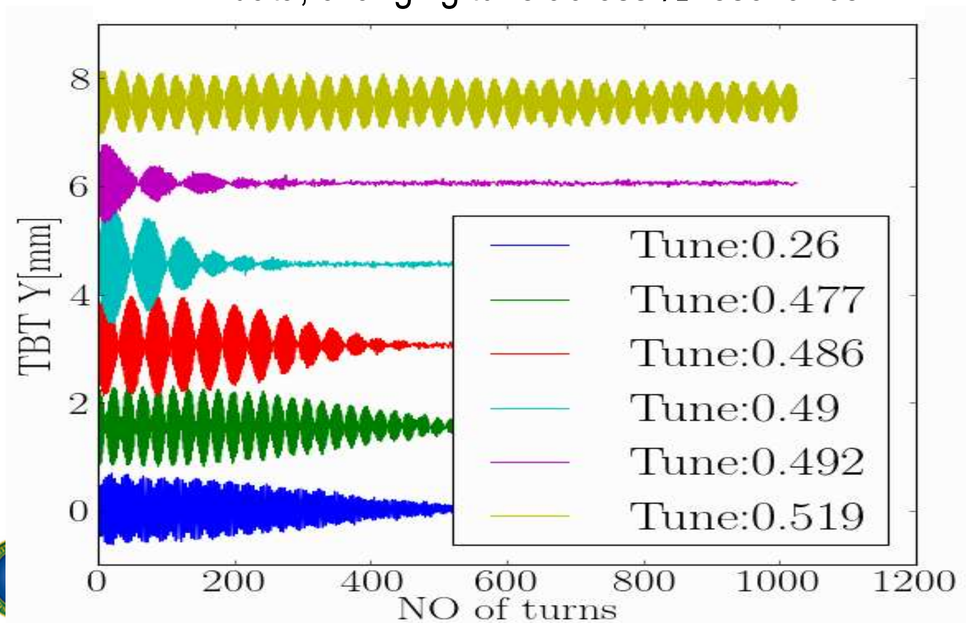


Crossing stopband of a major resonance

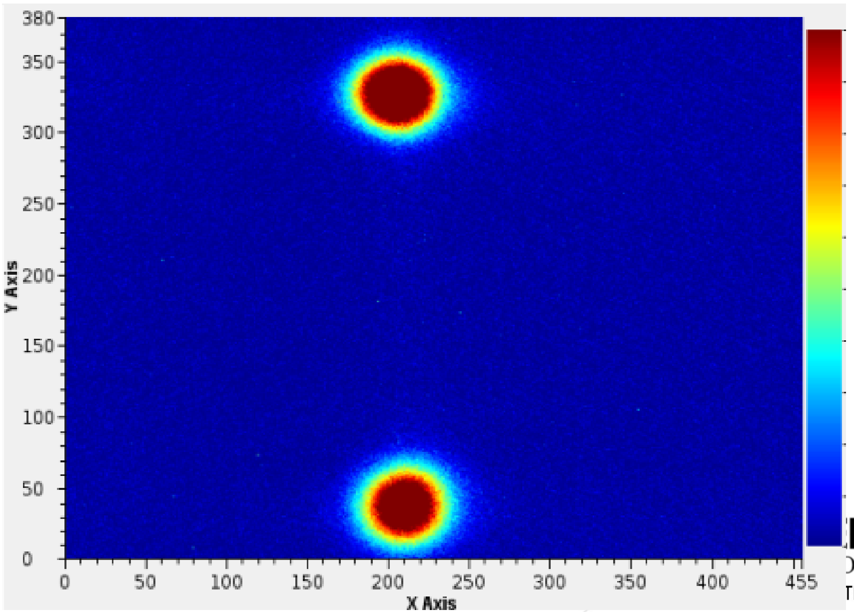
- High performance synchrotron light sources require large momentum aperture
- Strong sextupoles result in large tune swing potentially crossing major resonances
- If off-energy tune footprint crosses a major resonance → particle loss → short lifetime
- We studied **crossing ½ resonance** via RF jump in details
  - Create lattice with high 2nd order chromaticity ξ_{y1}~1, ξ_{y2}~300
  - Control stopband width
  - Excite beam energy oscillation by RF pinger

$$\nu_y = \nu_{y0} + \xi_{y1} * \delta + \xi_{y2} * \delta^2$$

TBT data, changing tune across ½ resonance

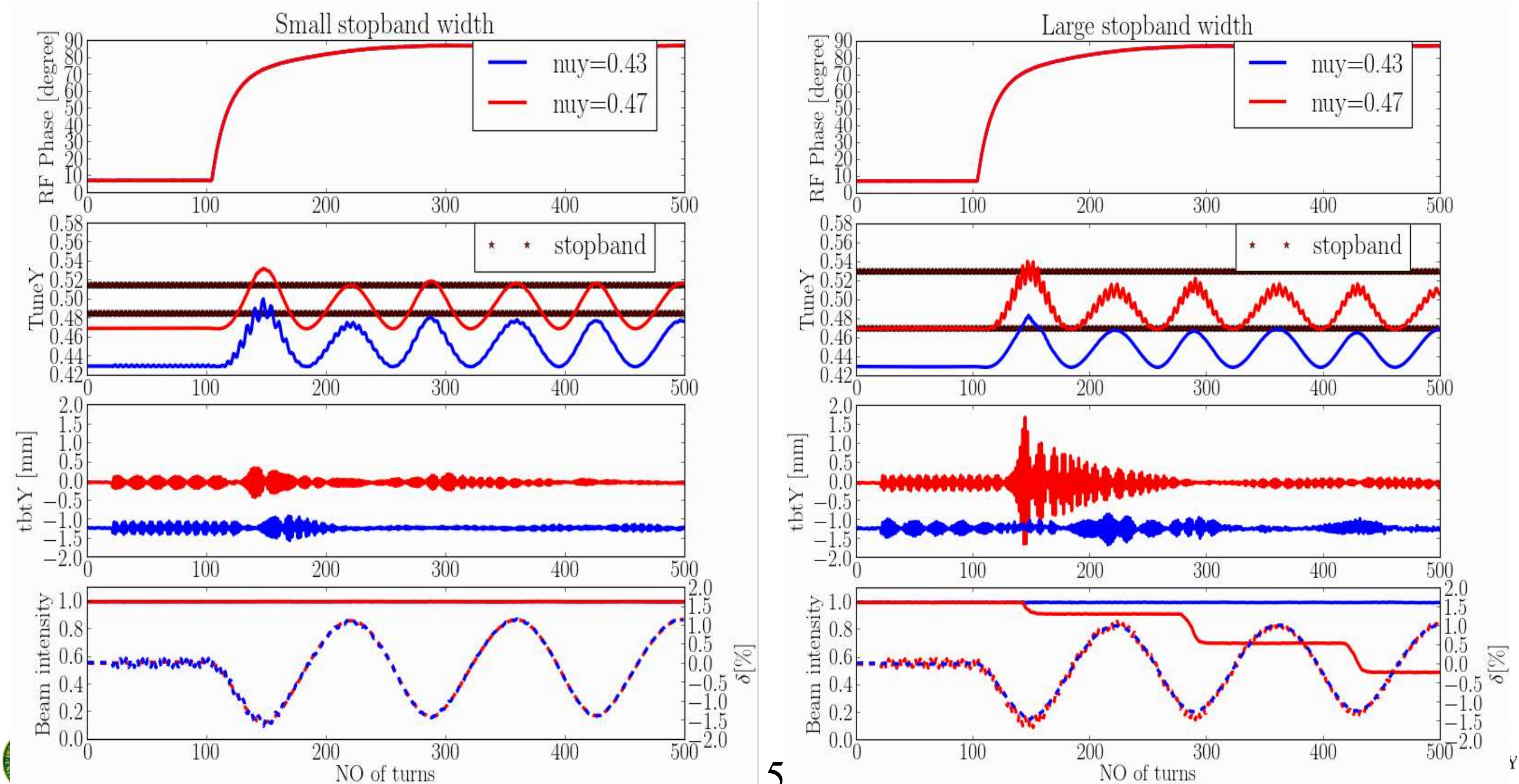


SLM image



Crossing ½ resonance: vary stopband width

- The resonance stopband width can be adjusted by controlling harmonic quads strength
- With small stopband width, beam can cross ½ without loss
- With large stopband width, beam will lose while crossing ½ resonance



Summary and outlook

- High precision RF pinger system was commissioned and used in experiments at NSLS II
- Following beam dynamics were studied with RF pinger
  - **Momentum aperture is limited by RF acceptance** at low RF voltage as measured without and with DW. It agrees with prediction that momentum aperture is limited by RF bucket height
  - Processing beam intensity from BPMs TBT sum signal as a function of machine azimuth we **localized beam losses due to momentum aperture limit**
  - We demonstrated that **beam can cross ½ resonance without loss** by controlling resonance stopband width
- Plan more beam dynamics study with RF pinger, including harmonic excitation of coherent beam motion or synchrotron tune shift with beam current

Acknowledgement

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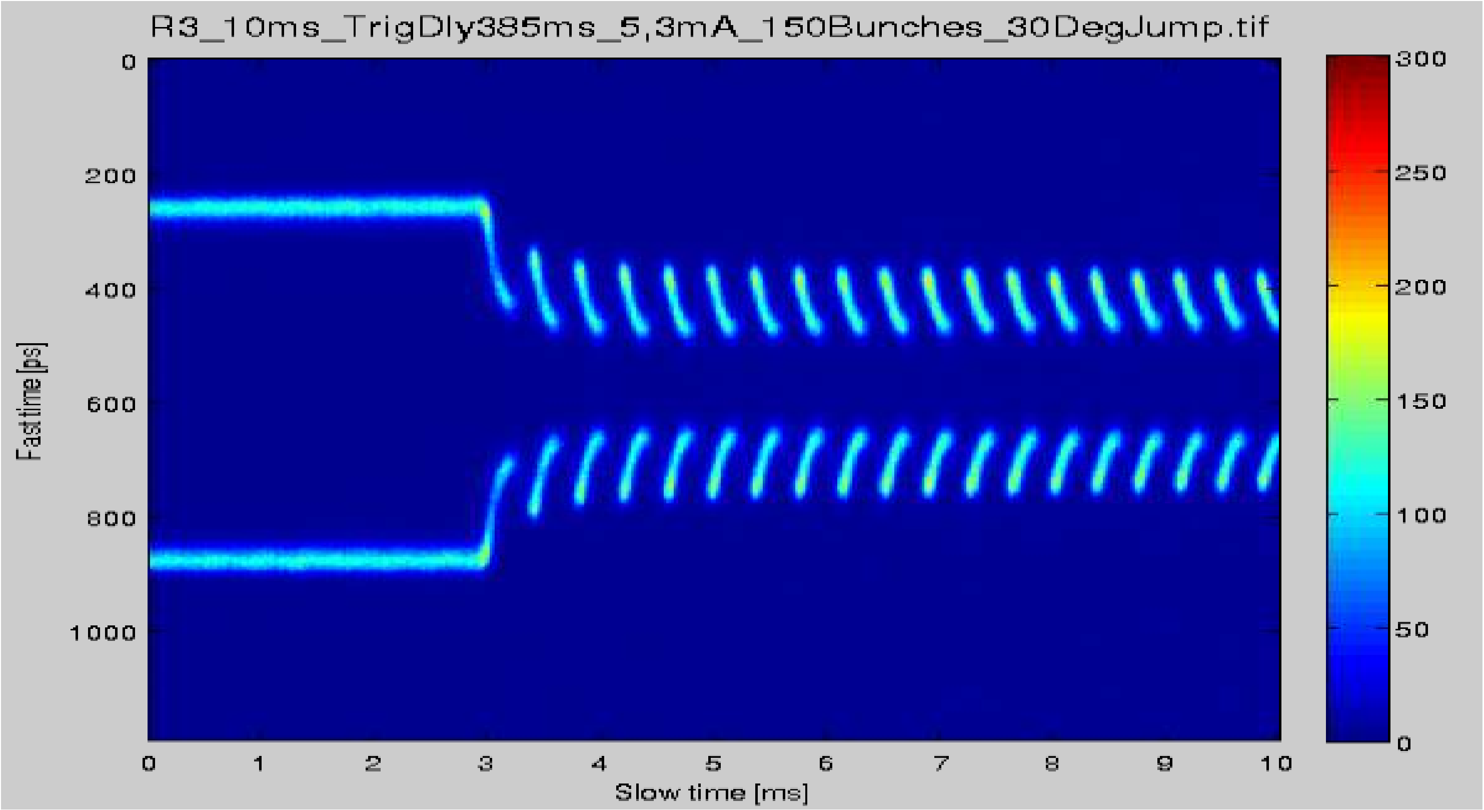

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