Booster Transition Crossing

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Fermilab

U.S. DEPARTMENT OF ENERGY

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Outline

- Short resume of previous report
  - Measurement technique
  - Deficiencies of the previous measurements
  - Measurement results
- New measurements
- Preliminary results of simulations of beam acceleration in Booster
- Conclusions

Why good understanding of Transition Crossing is Important?

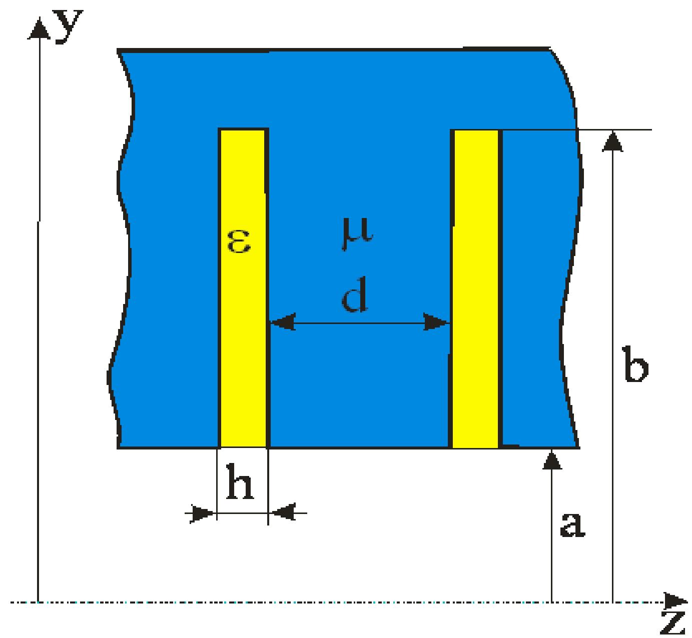
- PIP-II requires 1.5 times increase of beam intensity in Booster within the same longitudinal and transverse emittances
  - Transition crossing represents a problem which has to be resolved before we start digging ground
- A necessity of good understanding was pointed out at
  - DoE CD-0 review (June 2015)
  - XMAC -15 (March 2015)

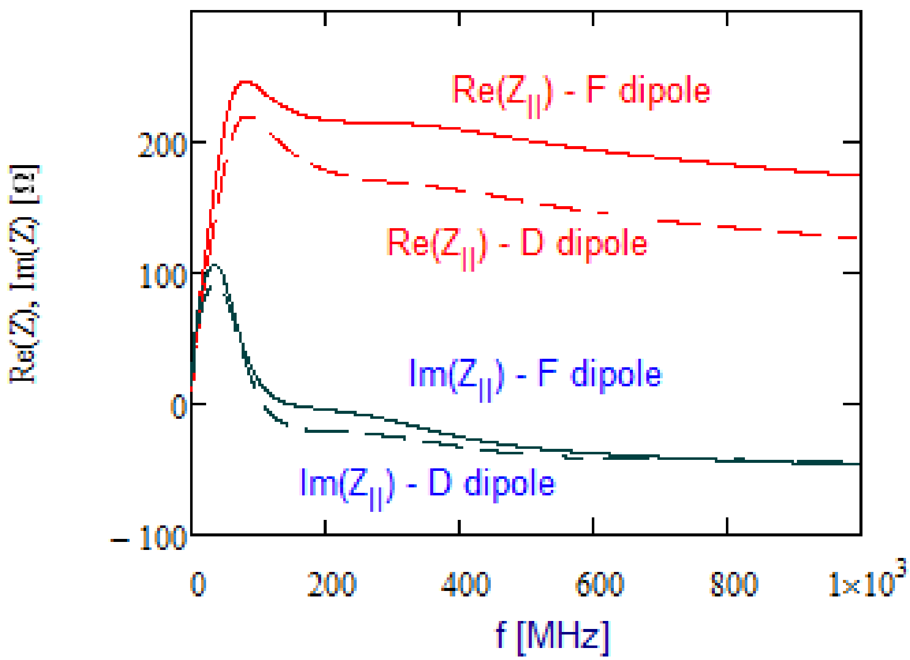
Short Resume of the Previous Report

(presented at Feb. 10, 2015 PIP-II meeting)

Impedance of Booster Laminated Magnets

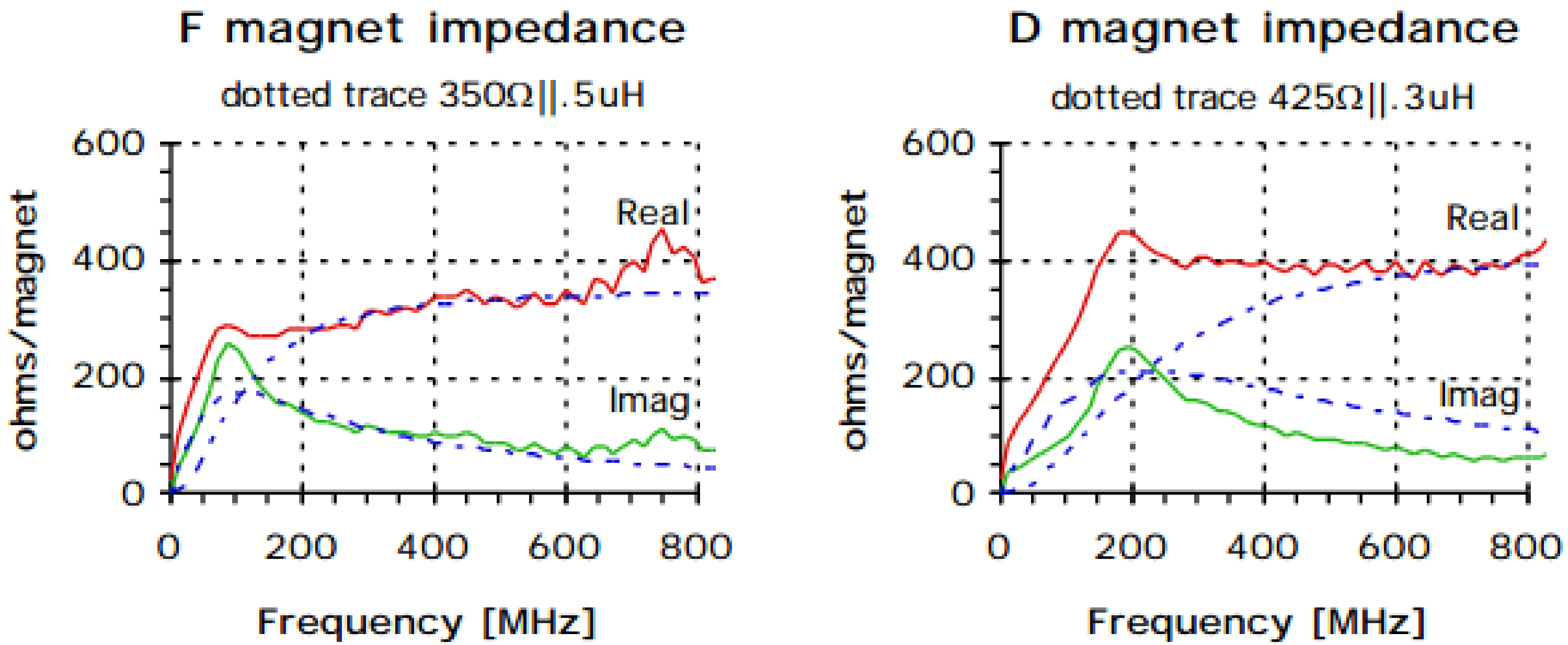
- Laminations greatly amplify impedance
  - (1) $\propto\sqrt{\mu}$, (2) longer current path
- The impedance model is expected work well in a frequency range of 0.1 MHz – 1 GHz.
- It takes into account all important details but actual dipoles do not have well-known parameters: *h*? (Packing factor), ε?, μ?





Dependence of longitudinal impedance of Booster dipole on the frequency computed for F and D dipoles. F dipole has smaller gap and should have larger impedance

Stretched Wire measurements of Longitudinal Impedance of Booster Laminated Dipoles

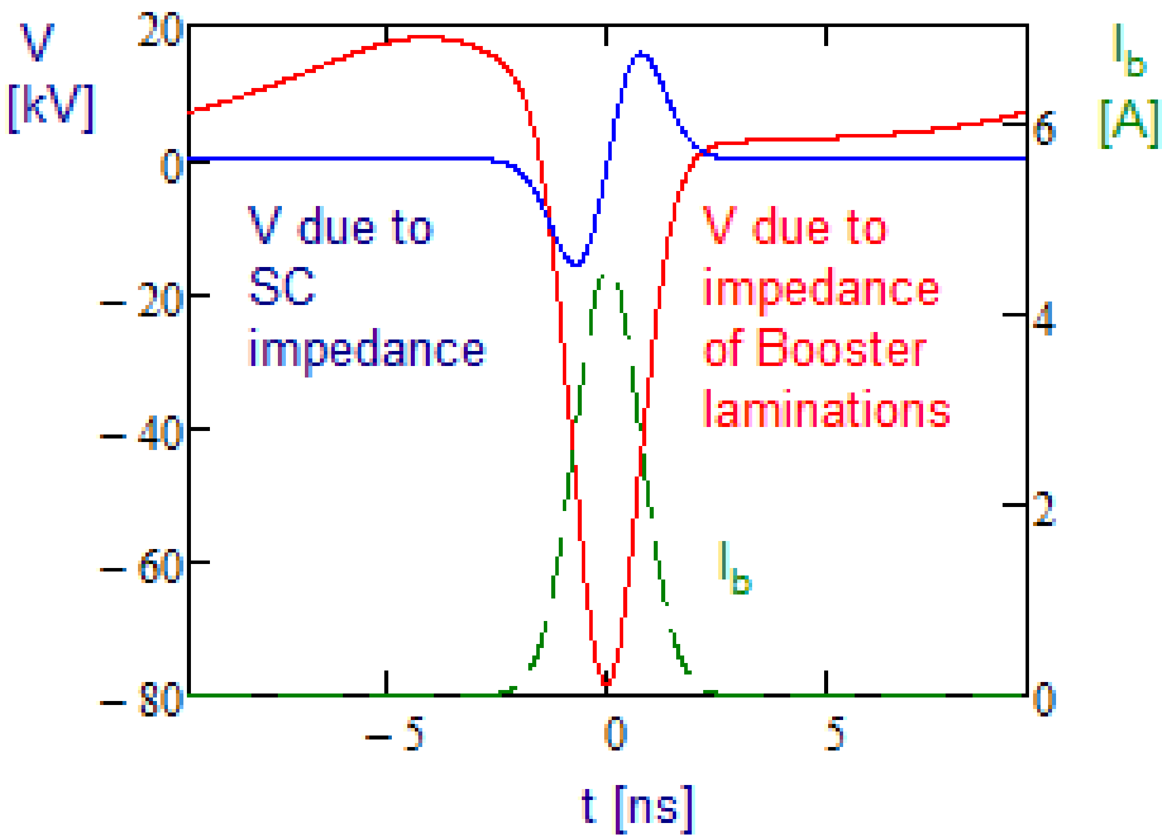


Taken from J. Crisp and B. Fellenz, "Fermilab-TM-2145, March 22, 2001.

- Decent coincidence with the impedance estimate
  - However F magnet impedance ~30% lower than for D-magnet instead of being 10% higher
    - ⇒ We should expect that each dipole has its unique impedance!
    - ⇒ Measurements of total impedance are required

Impedance Induced Voltage Expected from the Model

- Rms bunch length at transition $\sigma_\tau \approx 0.75$ ns
  - Rms width of bunch spectrum $\sigma_f = 1/(2\pi\sigma_\tau) \approx 212$ MHz
    - ⇨ Major contribution to the beam induced voltage comes from the impedance of laminated dipoles



Voltage per turn induced by ring impedances
14 *turn injection,* 82 *bunches,* $4.3 \cdot 10^{12}$ *protons*

Maximum deceleration voltage - 80 kV/turn

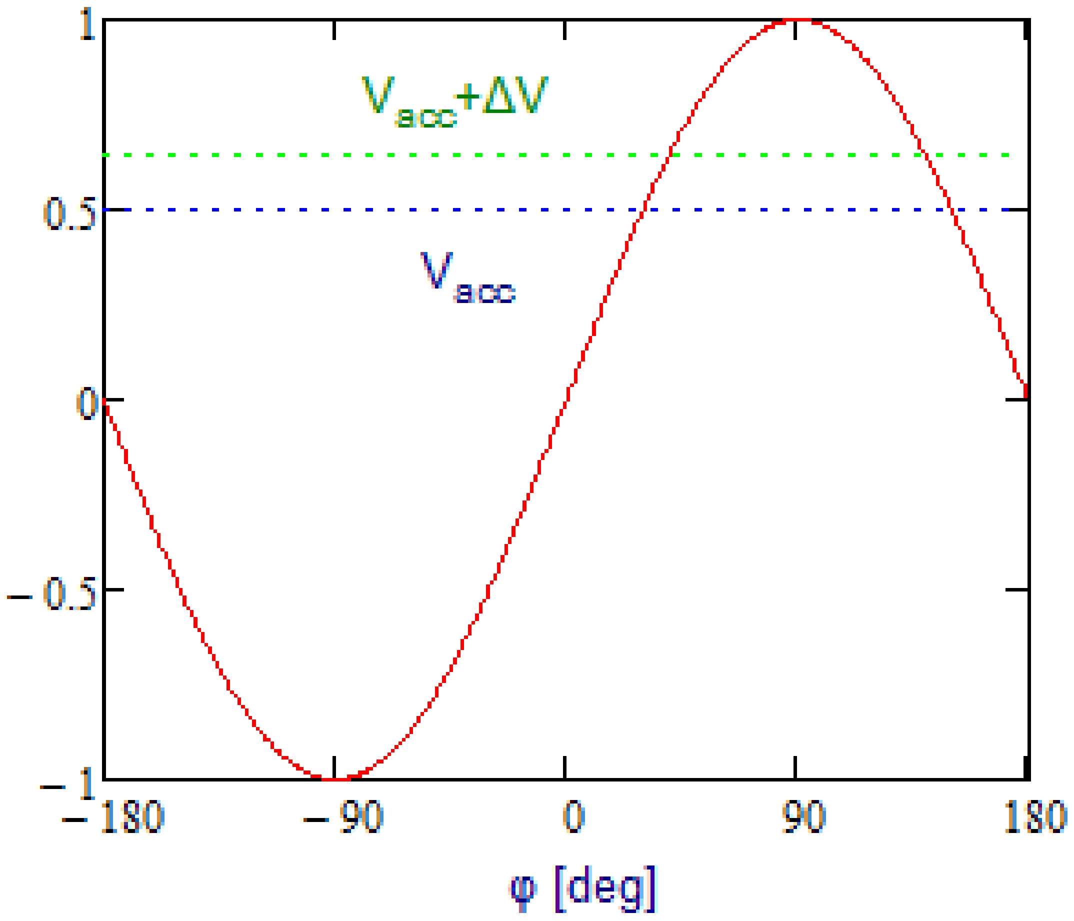
The beam deceleration averaged over bunch:

$$\overline{V} = \int V(s)\rho(s)ds = 54\text{kV/turn}$$

For accelerating voltage of 670 kV (ϕ_{acc}=61°) used in the below measurements it should produce the shift of bunch accelerating phase by **9.9 deg.**

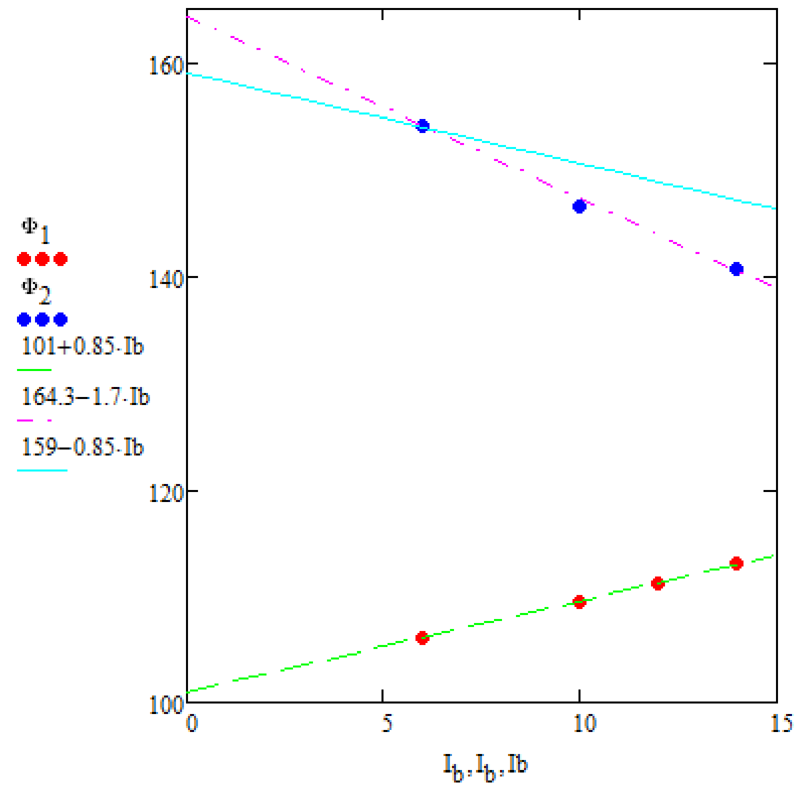
Beam Based Longitudinal Impedance Measurements

- Direct measurements of $Z(\omega)$ requires a continues beam
- Shift of acceleration phase with bunch intensity allows us to check if the considered above model, as well as, measured single dipole impedances are applicable



Measurement Results

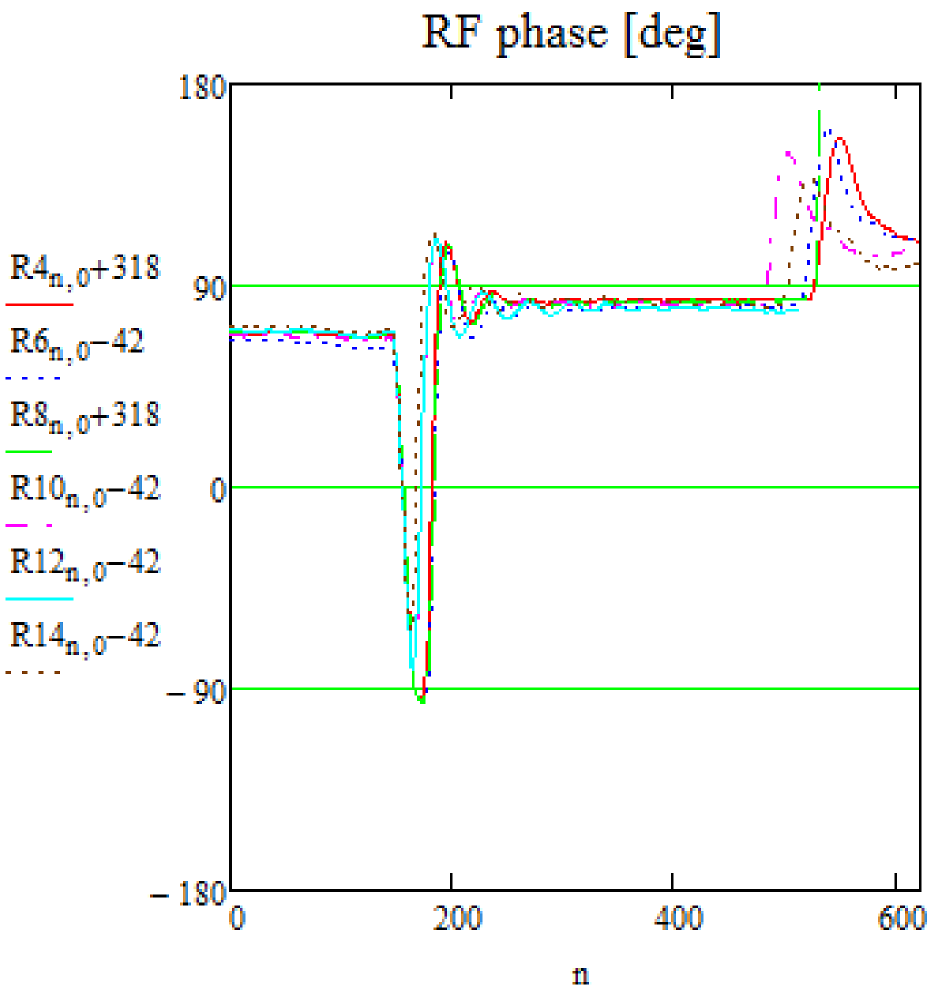
- Based on dependence of accelerating phase on beam intensity
- Phase change at transition yields independent measurement of accelerating voltage (acceleration rate is known to good accuracy)
  => V_0=670 kV, ϕ_{acc}=61->119 deg
  - Accuracy is not great because the slope of the RF phase shift with intensity is twice higher after transition

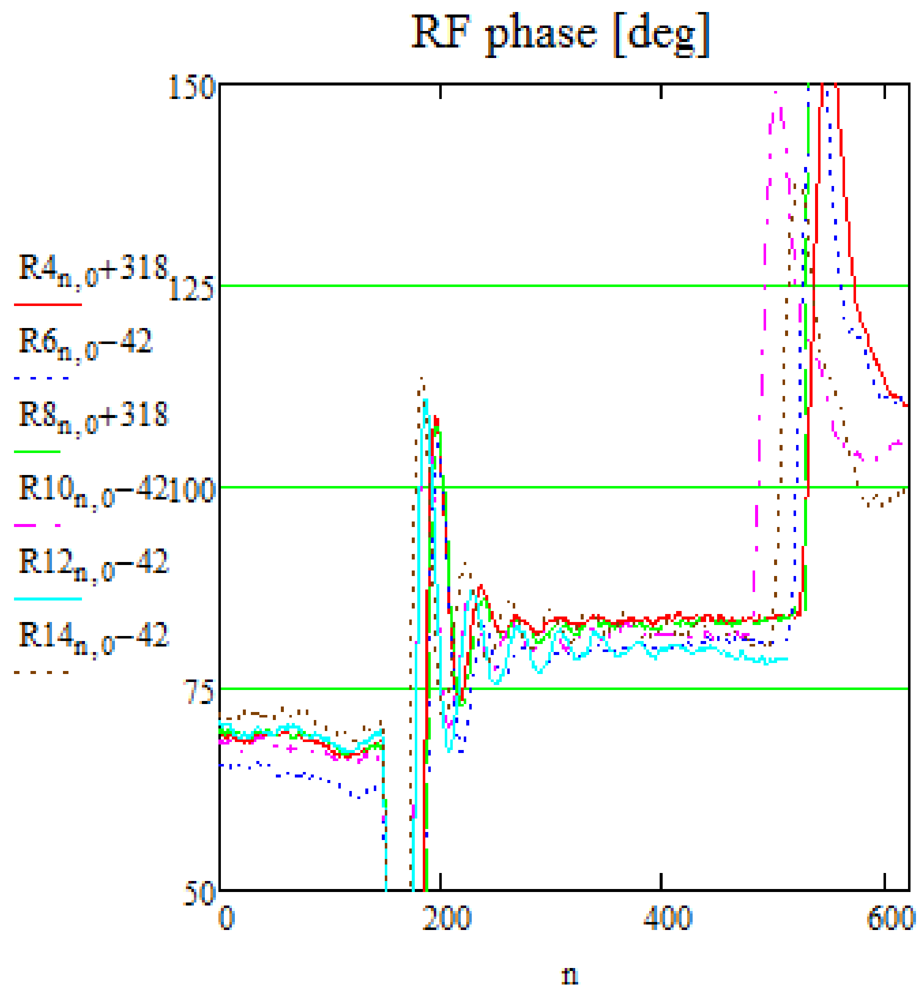


- The value of accelerating phase shift with intensity measured before transition is 11.9 deg. for 14 turn injection ($4.3 \cdot 10^{12}$ p)
- Coincides comparatively well to the expected value of 9.9 deg.
  - Inaccuracy is mainly determined by knowledge of
    - RF voltage and accelerating phase at transition and
    - the bunch length measurement (to be improved by accounting of cable dispersion)
    - Wake changes bunch symmetry (rel. to its center) => changes bunch center
  - Further analysis should improve this results

Unexpected Fact

- Good transition requires wild accelerating phase variations





- Why accelerating phase variation are larger after transition

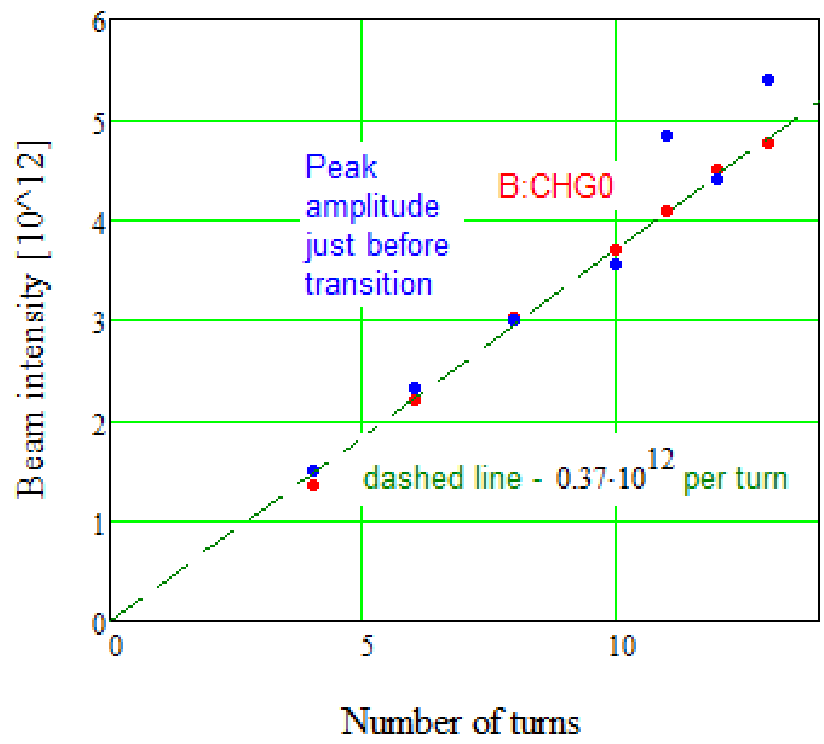
Problems / Unknowns

- We need better knowledge
  - Longitudinal emittance / Longitudinal distribution
  - Absolute calibration of RF voltage
  - Time of actual transition crossing ($\eta = 0$)
- Why the accelerating phase changes with beam intensity are larger after transition?
- Bunch length near transition is affected by frequency resolution of the wall current monitor and the dispersion in the cable
  - The value of this effect has to be well understood
- Experimental measurements have to be appended by simulations which have to verify an accuracy of extracted machine parameters
- Presently the transition crossing is tuned quite well
- Good modeling based on beam measurements is required to make it better and understand implications of 1.5 times larger intensity

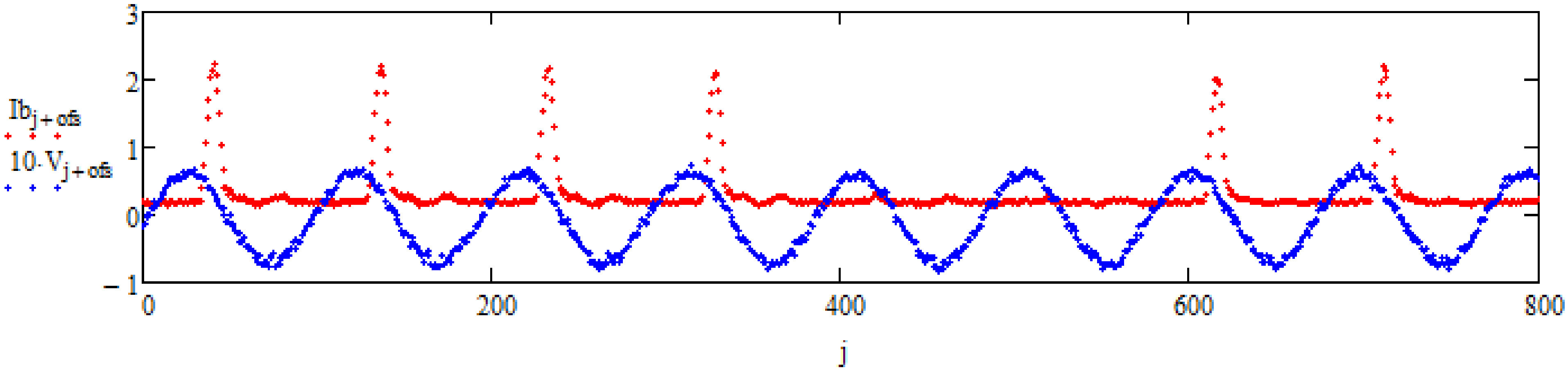
New Measurements and their Results

Data Acquisition and Acquired Data

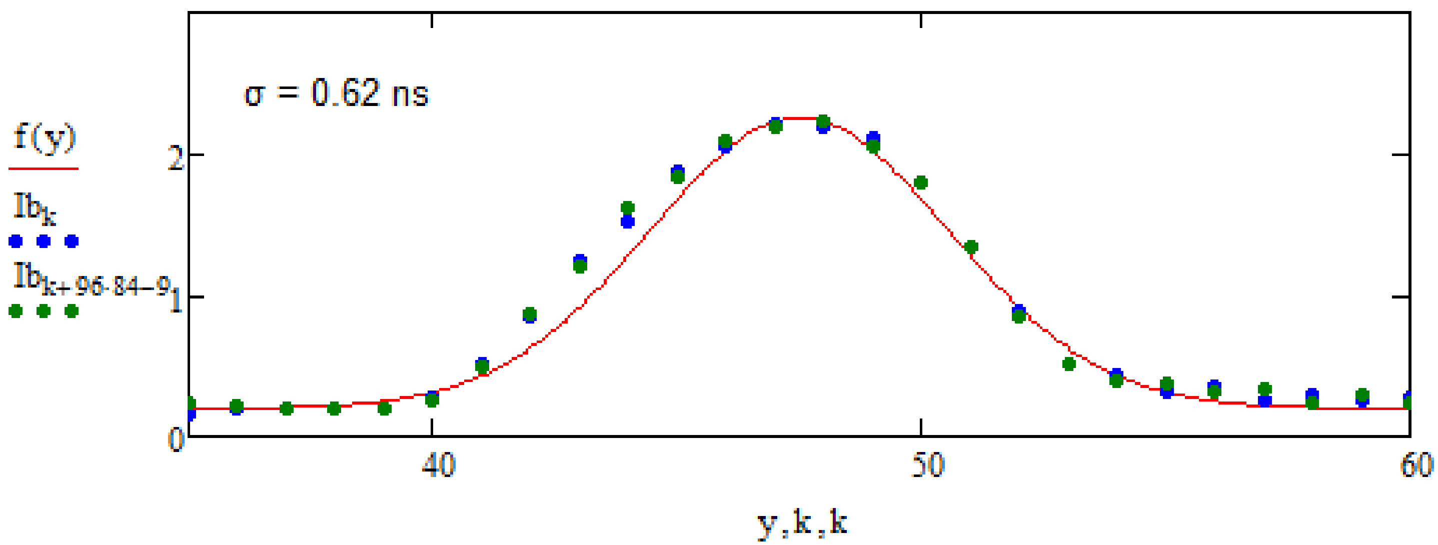
- Fast digital scope (same as before)
  - T=1 ms centered around transition
  - Δt=0.2 ns (instead of 0.533 ns), $5 \cdot 10^6$ points per channel (instead of $1.875 \cdot 10^6$), ~100 points per RF bucket
- Files are long
  - split into two chunks for data analysis
- Signals
  - RF sum
  - Wall current monitor
  - Rpos
- Triggering at the injection or near transition
- Beam parameters
  - Intensity: 4, 6, 8, 10, 11,12 & 13 turn Booster injection
    - 13 turn $=4.81 \cdot 10^{12}$
  - 82 bunches



Typical signals



- Typical rms bunch length
  - 4.5 ns at turn 350 (injection)
  - 0.7 – 0.9 ns at transition

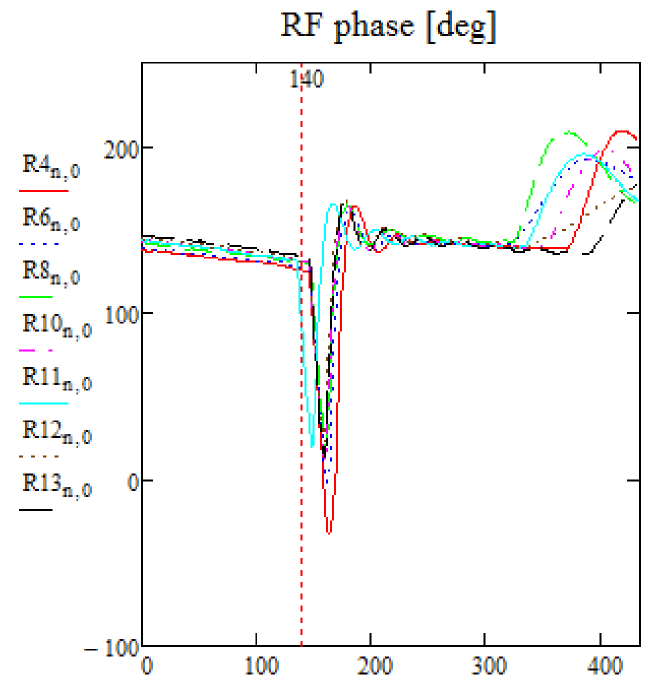


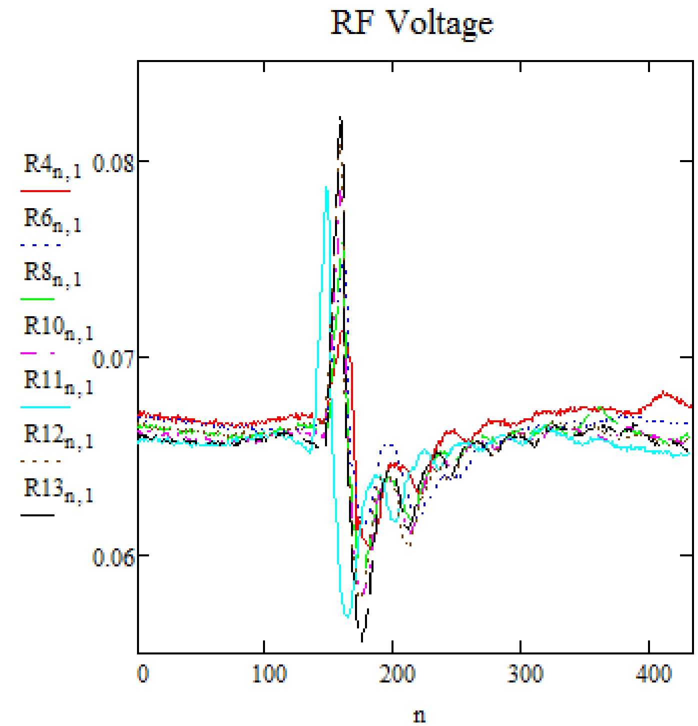
Features of Measured Signals

- There is additional phase difference related to unequal cable lengths. It is driven by rev. frequency change with acceleration:

$$\Delta\phi=2\pi f_{RF}\Delta t$$

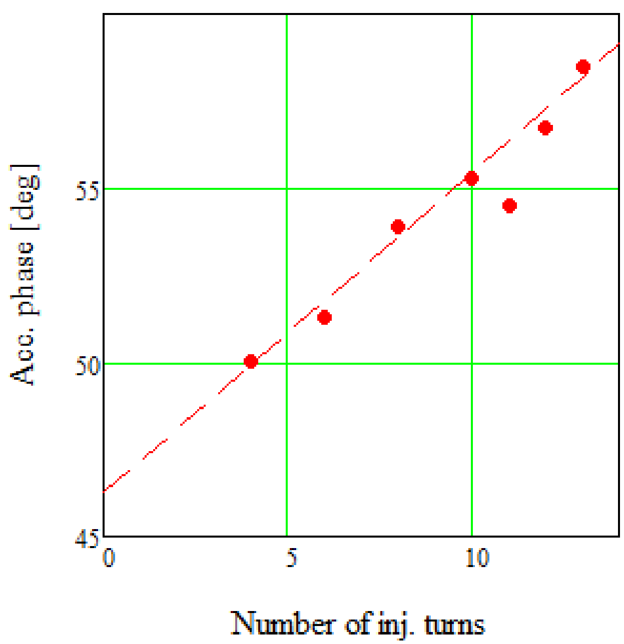
  - It was not observed in the previous measurements
  - The effect is more pronounced in the injection data: $\Delta f/f \approx 7\cdot10^{-3}$ versus $3\cdot10^{-3}$ (1 ms data)
  - The delay is 1.05 μs (315 m for light) for the RF signal relative to the wall current monitor signal
- Beam induces the RF voltage on cavities due to changed RF phase of the beam
  - It yields the total effective impedance of all cavities in the range 240-280 kΩ
  - Shunt impedance: R_{sh}=150 kW/cavity ⇨ feedback suppression ~10 times?

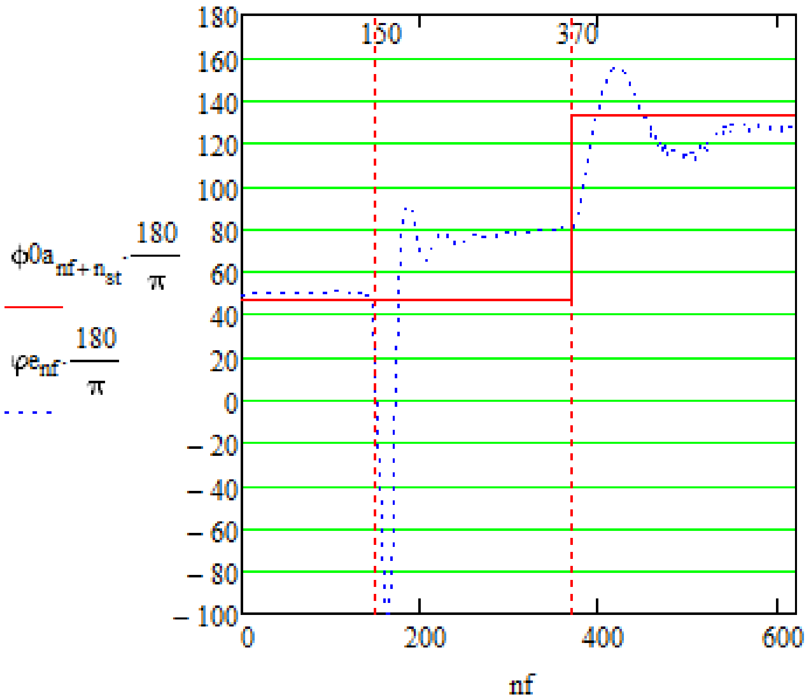




Data Analysis Results

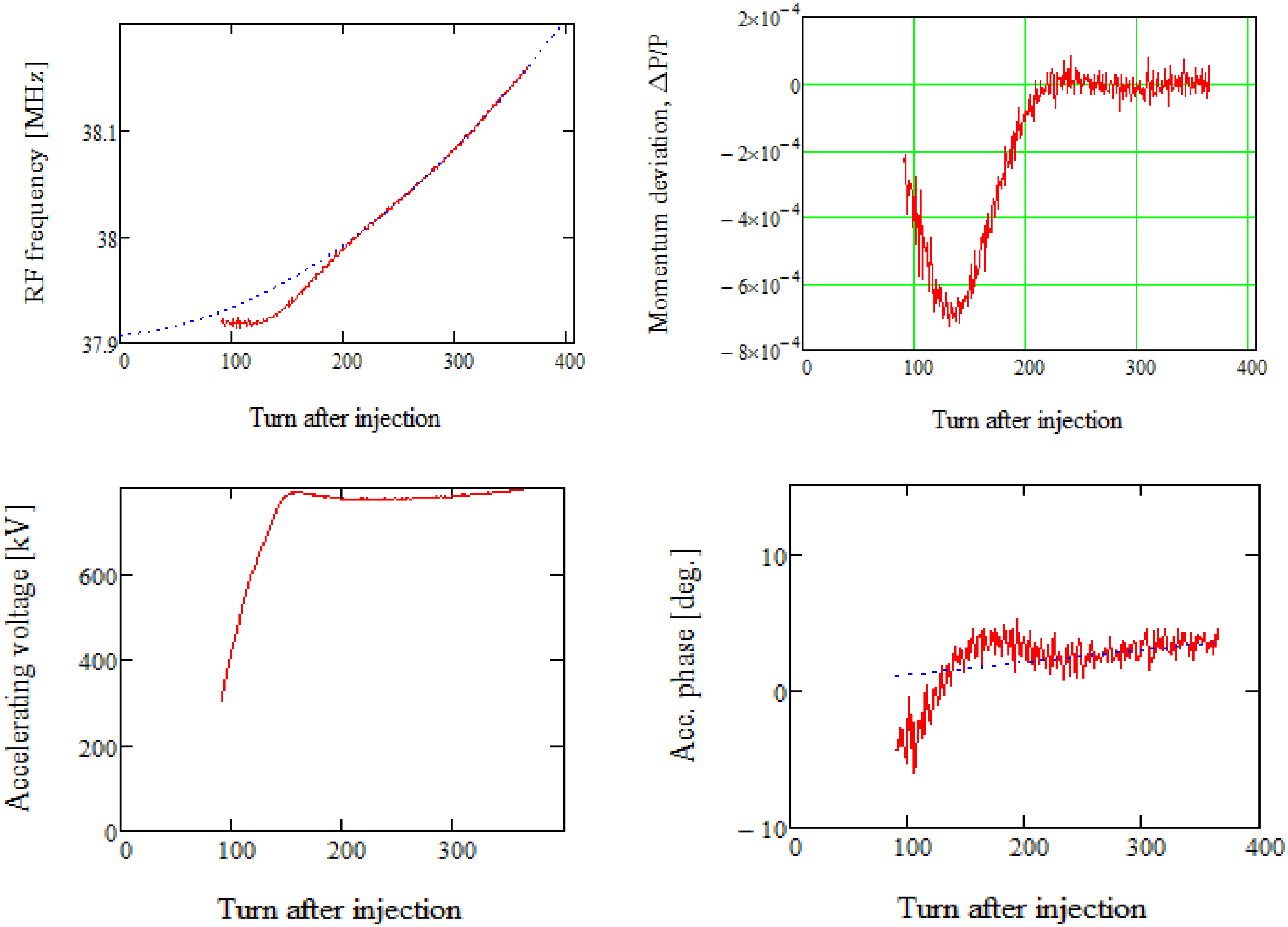
- Rpos measurements are extremely helpful to get calibration for
  - Total RF voltage: $V_{peak}=1.21\cdot10^7\ V_{RFsum}$
  - Average decelerating voltage due to impedance of dipoles: 80 kV/turn for $4.2\cdot10^{12}$
  - Calibration of RPOS for $\Delta p/p$: $\Delta p/p = 0.0694*RPOS_{(V)}$
    - 1.2 times smaller than expected (D=180 cm, dx/dV = 15 cm/V)
  - and Location of transition crossing: RF phase swing starts ~200 turns before transition





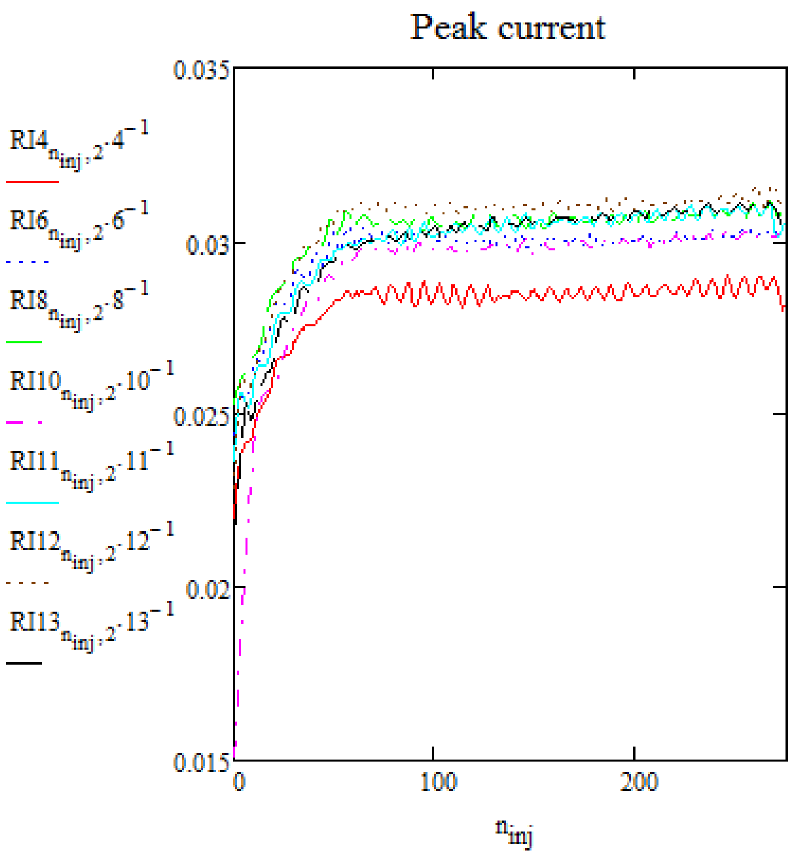
Acc. phase shift on intensity (10.7 deg. for $4.3\cdot10^{12}$ particles)
(11.9 deg. in old measurements with smaller and less accurately measured RF voltage)

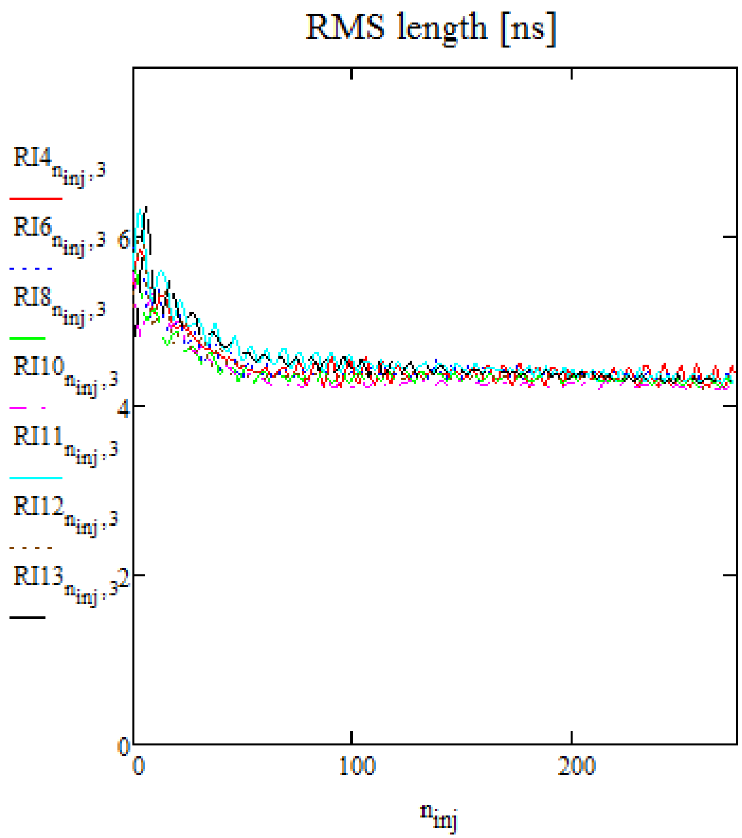
Injection Data



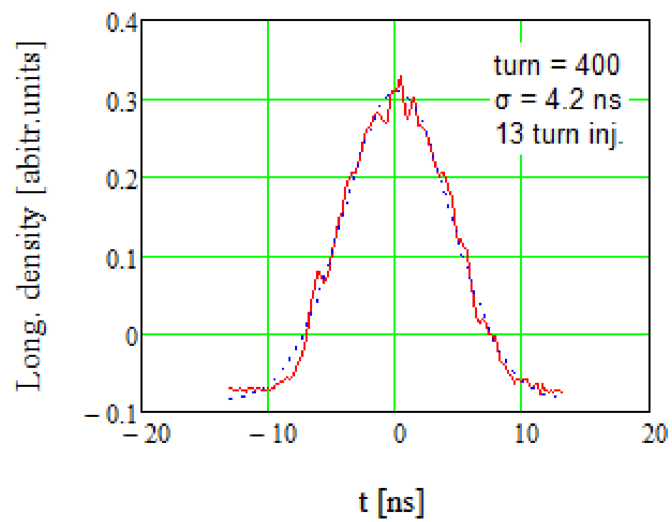
- RPOS feedback puts beam to nominal curve at turn ~220

Injection Data (continue)



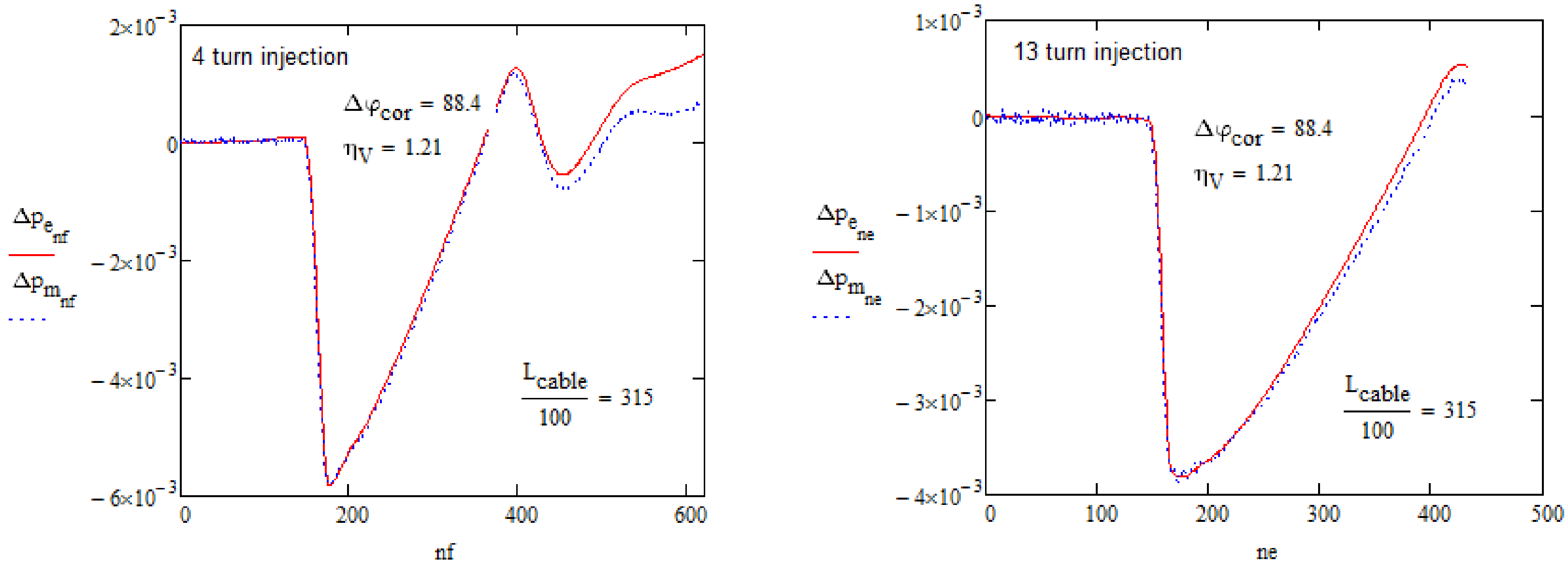


- Knowledge of RF voltage and bunch length yield longitudinal emittance
  - Effect of impedances is automatically accounted in simulations
- Bunch profile is quite close to be Gaussian



RF Phase and Voltage Calibration

- The RF phase swing results in RPOS changes
  - Known: relative phase changes
  - Unknown: phased offset, RF voltage calibration, RPOS sensitivity, deceleration due to impedance

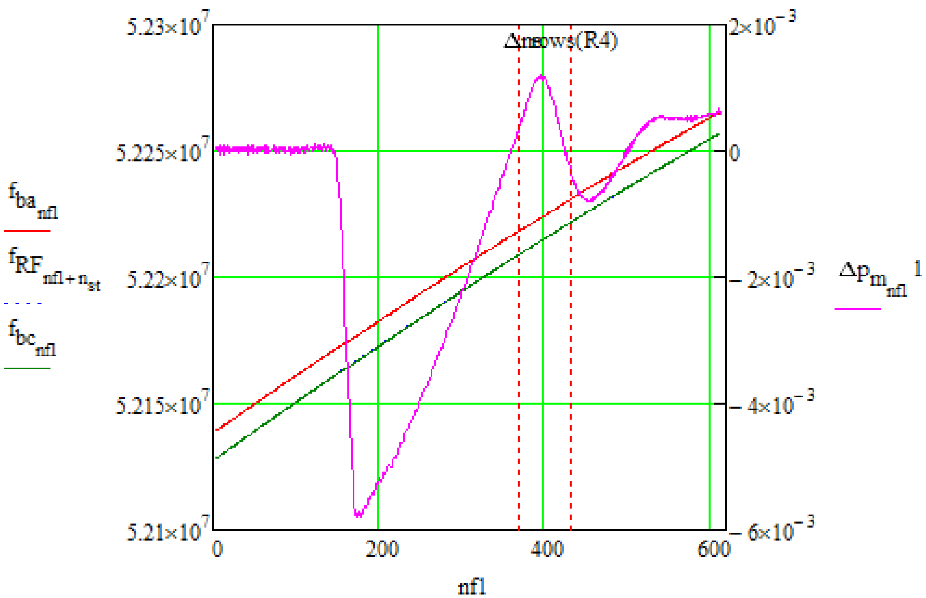


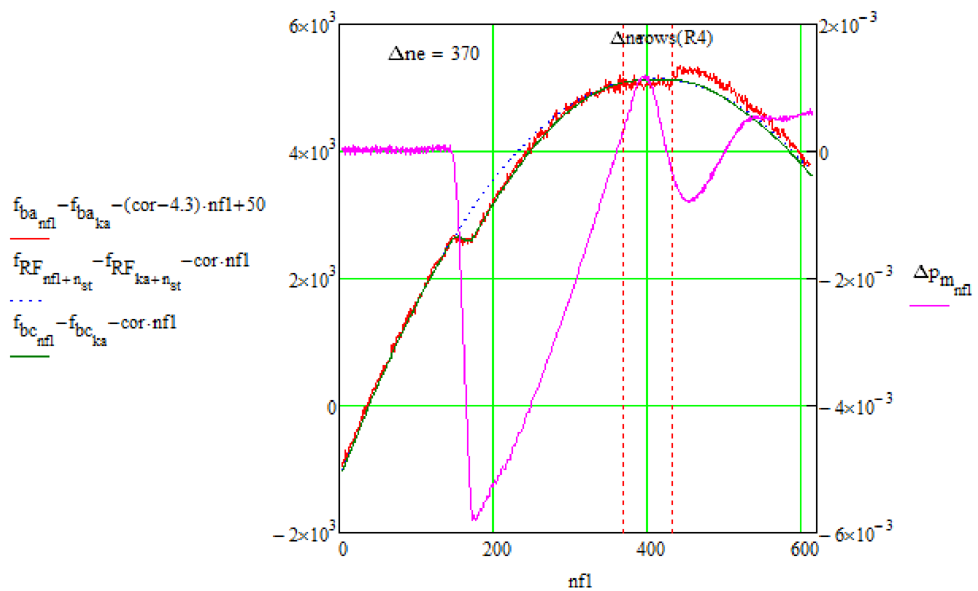
Red - predicted momentum offset, blue – scaled RPOS

- Comparison of predicted and measured momentum offsets for different intensities uniquely yields all unknown parameters
  - Most probably the discrepancy at the end is related to bunch shortening and larger deceleration due to impedance
  - Simulations have to verify it

Transition Crossing Time

- Exact location of transition crossing is required for trustable simulations
- Can be obtained from measured bunch frequency change introduced by the RF phase swing: $\Delta f/f = \eta(n)\Delta p/p$

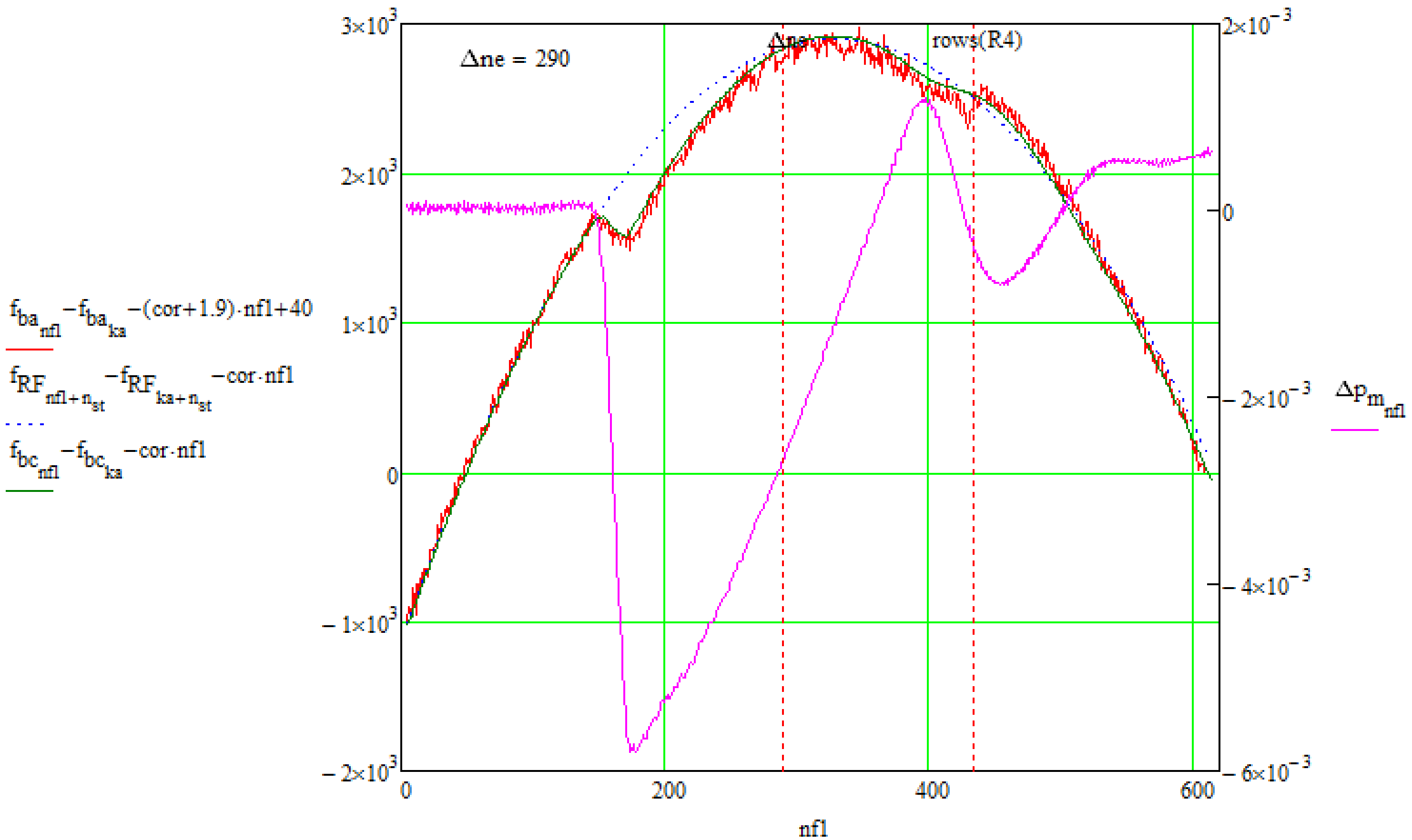




- Removing offset and linear slope makes bunch frequency variation due to Δp/p well visible
- Origin of the second bump ($\Delta f/f \sim 4\cdot10^{-6} \Leftrightarrow \Delta L \sim 2$ mm) is unknown
  - Can be due to minor orbit variation at the transition
  - OR?

Transition Crossing Time (Continue)

- Moving transition crossing by 80 turns earlier allows to make a better fit
  - But requires 1.5 times larger momentum deviation



- Less probable scenario
- Simulations should be helpful to track it down

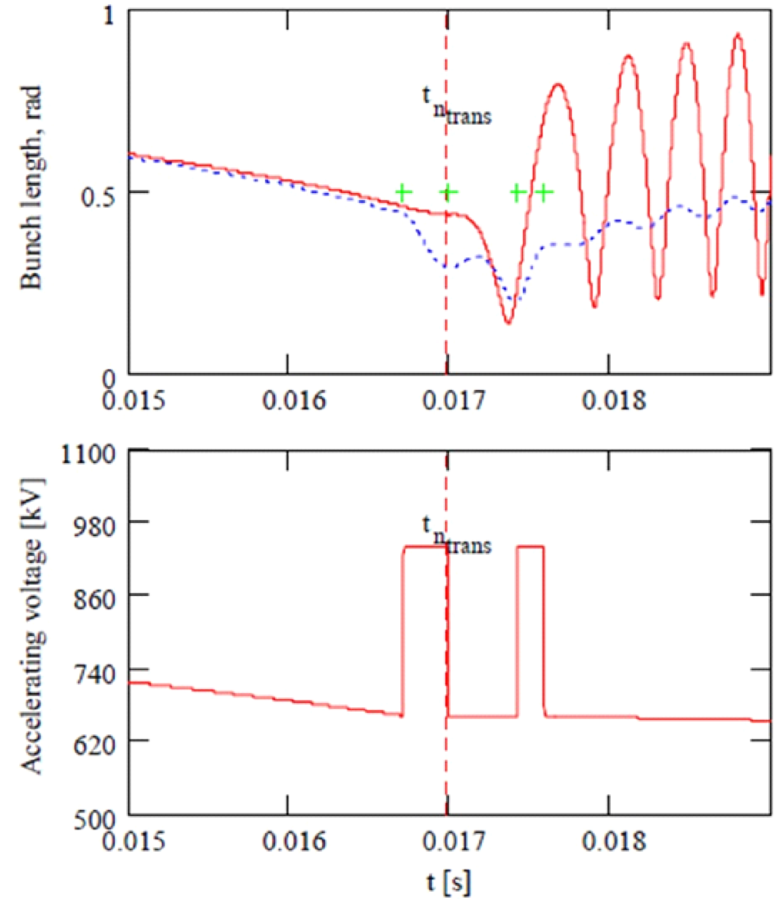
Simulations of the Longitudinal Dynamics and Transition Crossing

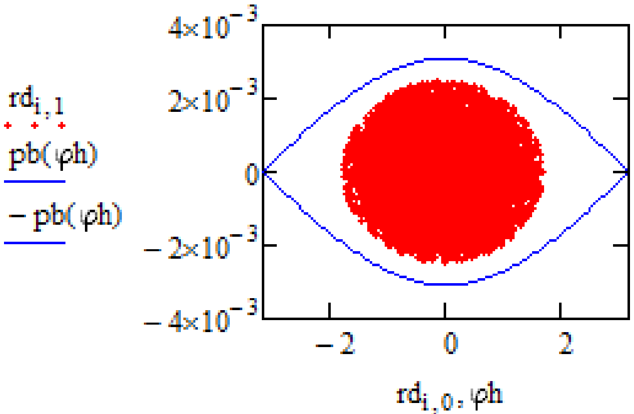
Simulation Program

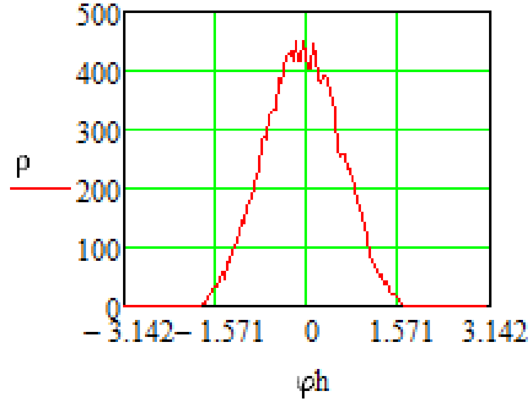
- Combination of C-program (computations) and MATH-CAD (GUI)
- Accounts for impedances of dipoles and space charge
  - Implies 84 equal intensity bunches
  - Impedances of dipoles is calibrated by the measured RF phase with intensity
    - Both impedances are short range
  - Measurements do not exhibit significant difference in behavior for bunches in vicinity of the abort gap
  - Two dampers
    - Dipole – operates similar to RPOS feedback
    - Quadrupole – feedback on oscillations of bunch length
  - Beam is unstable above transition if the dipole damper is not engaged
    - It results large beam loss (>50%)
- New GUI driven software is at the initial stage (F. Ostiguy)
  - Takes into account accumulated experience
- Preliminary results are ready to be shown
  - More work is required to bench mark the simulations

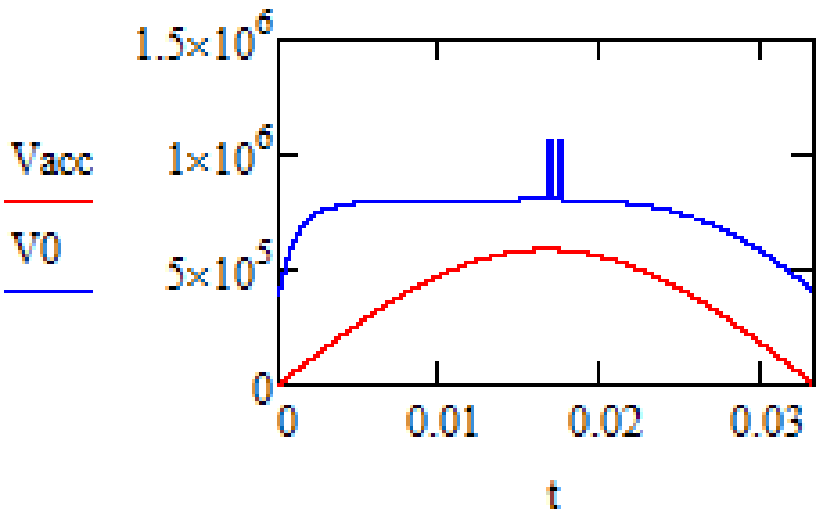
Transition Crossing Simulations with Voltage jumps

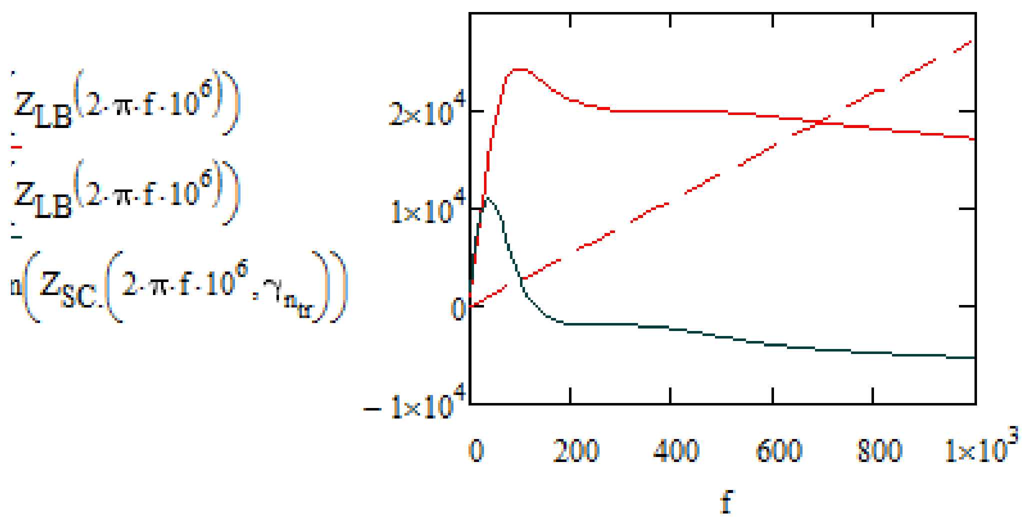
- The method works for nominal Booster intensity.
  - It requires RF voltage close to 1 MV.



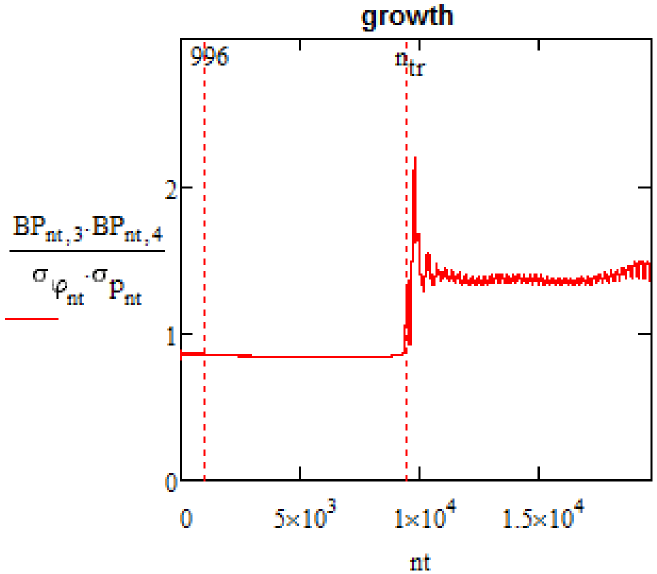


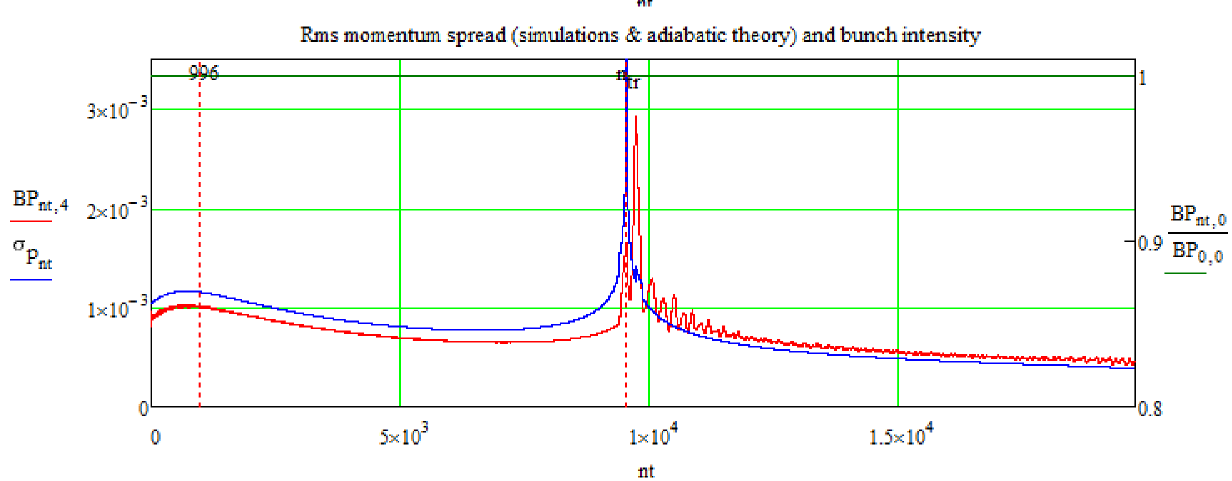


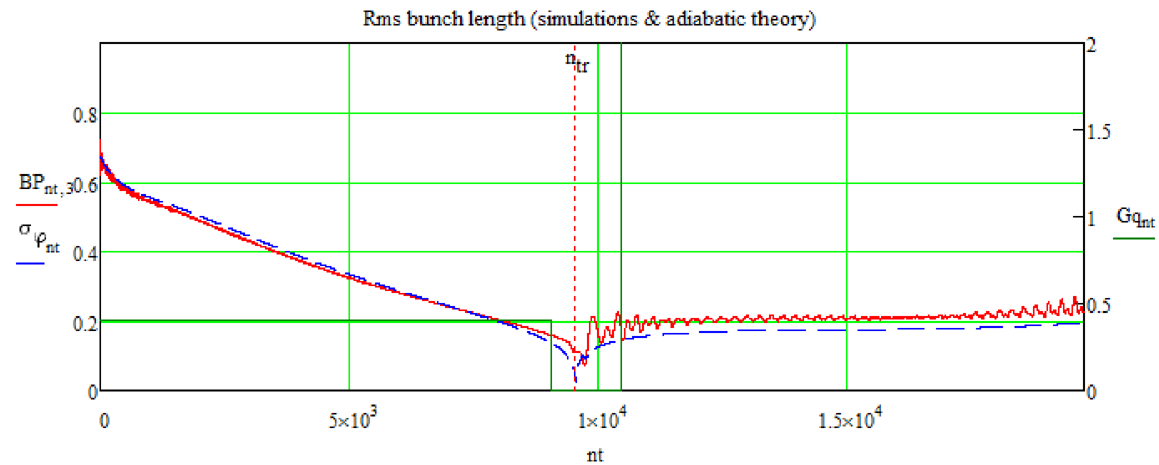




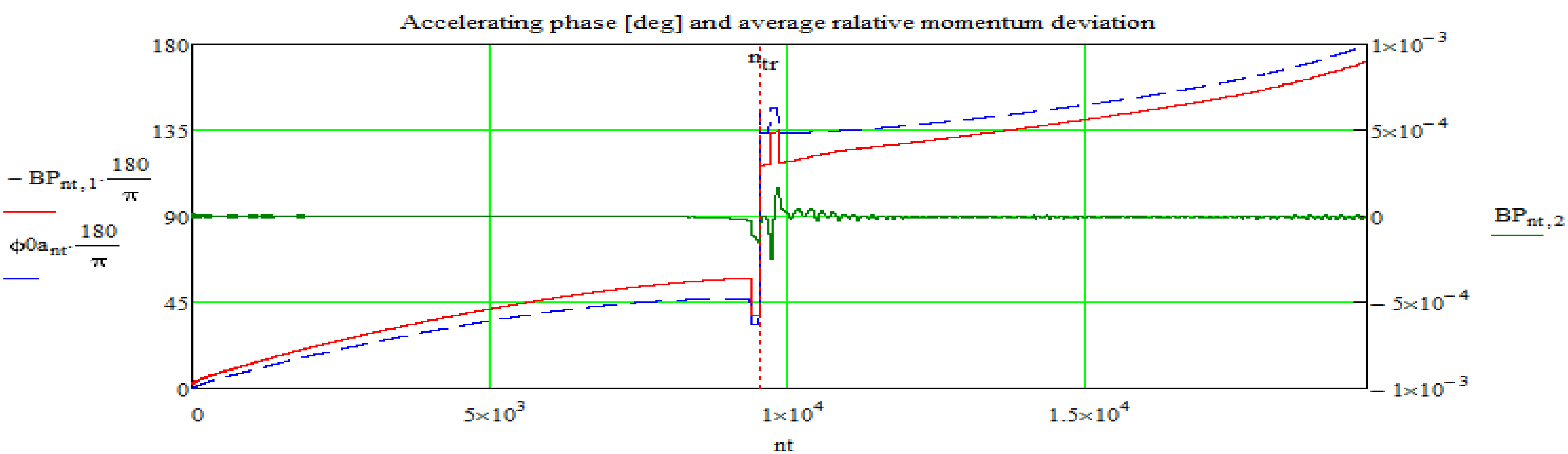
Transition Crossing Simulations with Voltage Jumps (2)



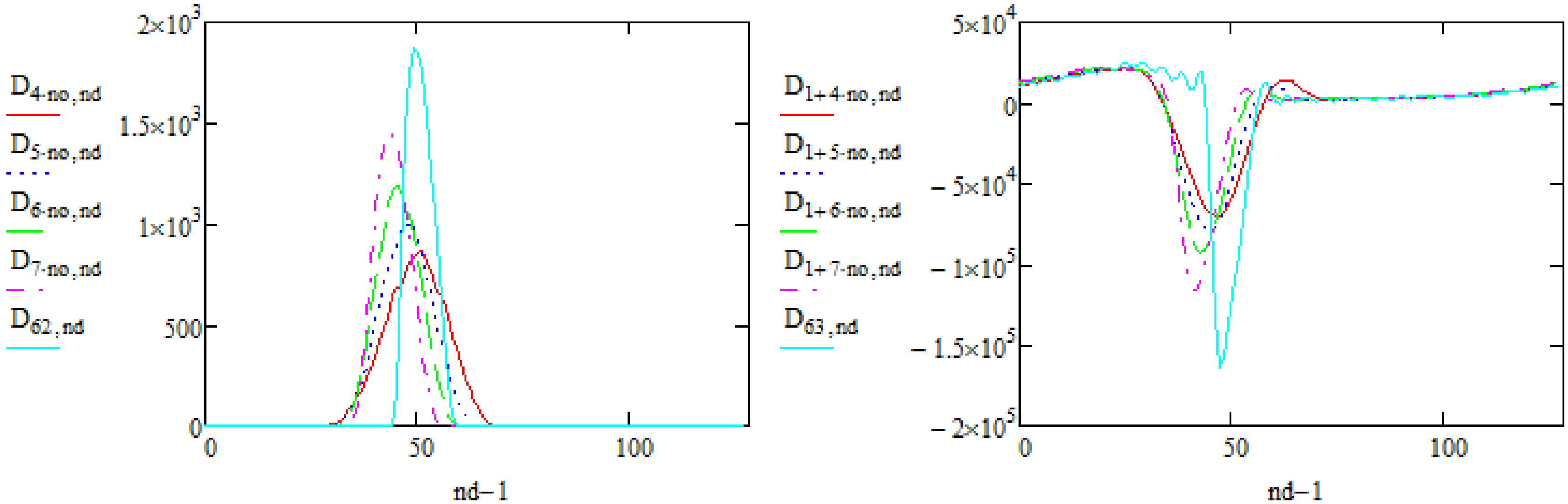




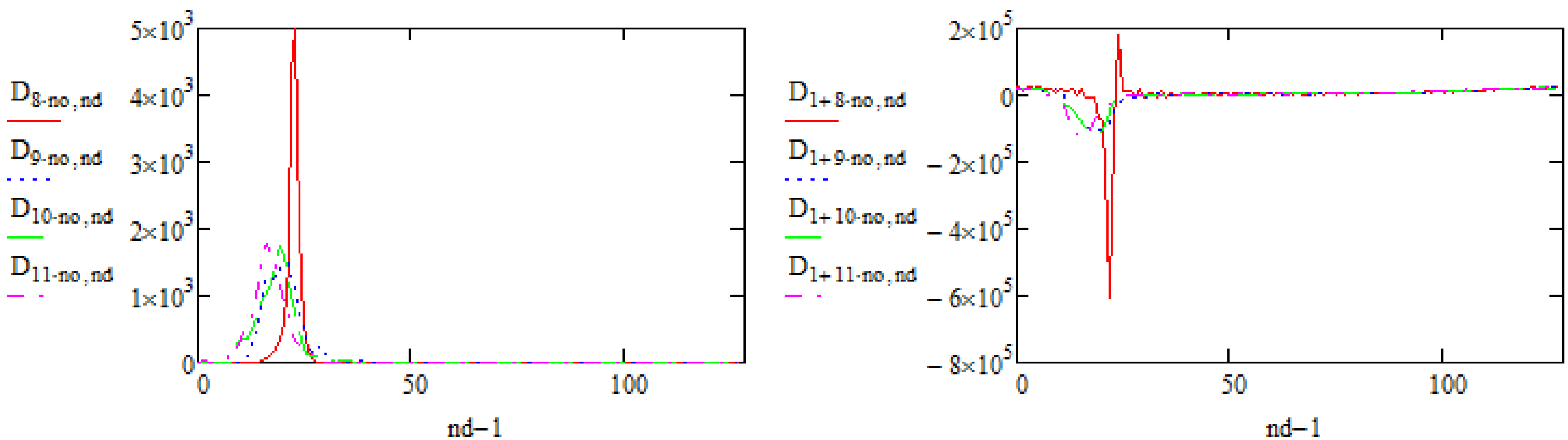
- Moderate ε_L growth



Transition Crossing Simulations with Voltage Jumps (3)



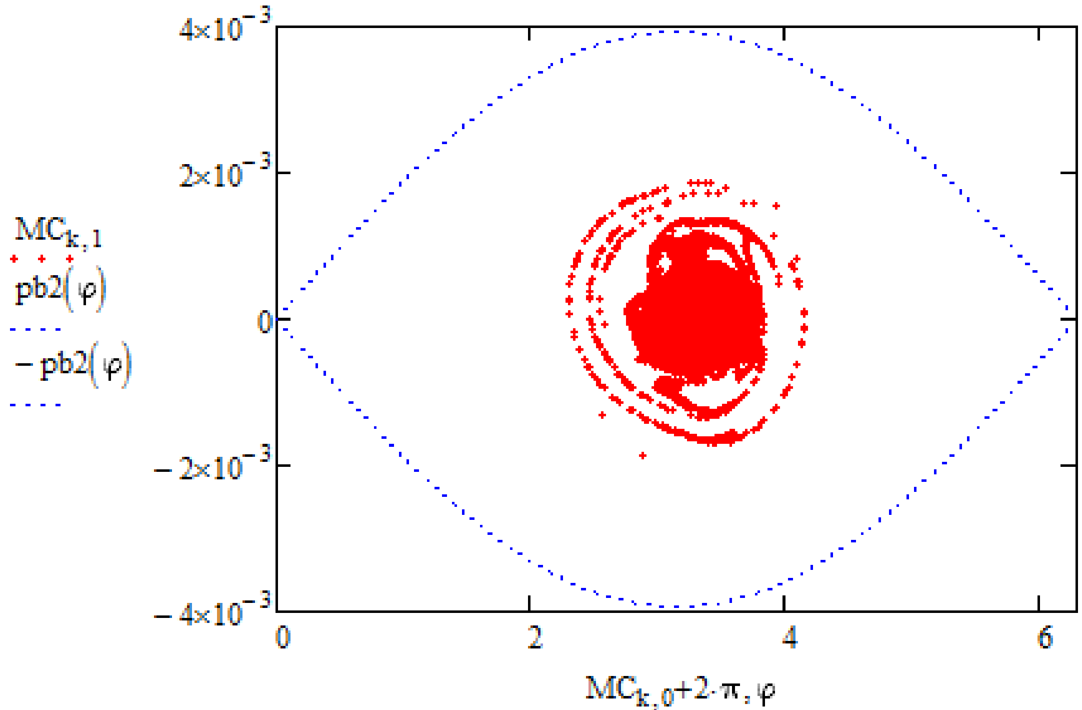
Before transition



After transition

- Bunch gets very short after transition and generates very large decelerating voltage

Transition Crossing Simulations with Voltage Jumps (4)

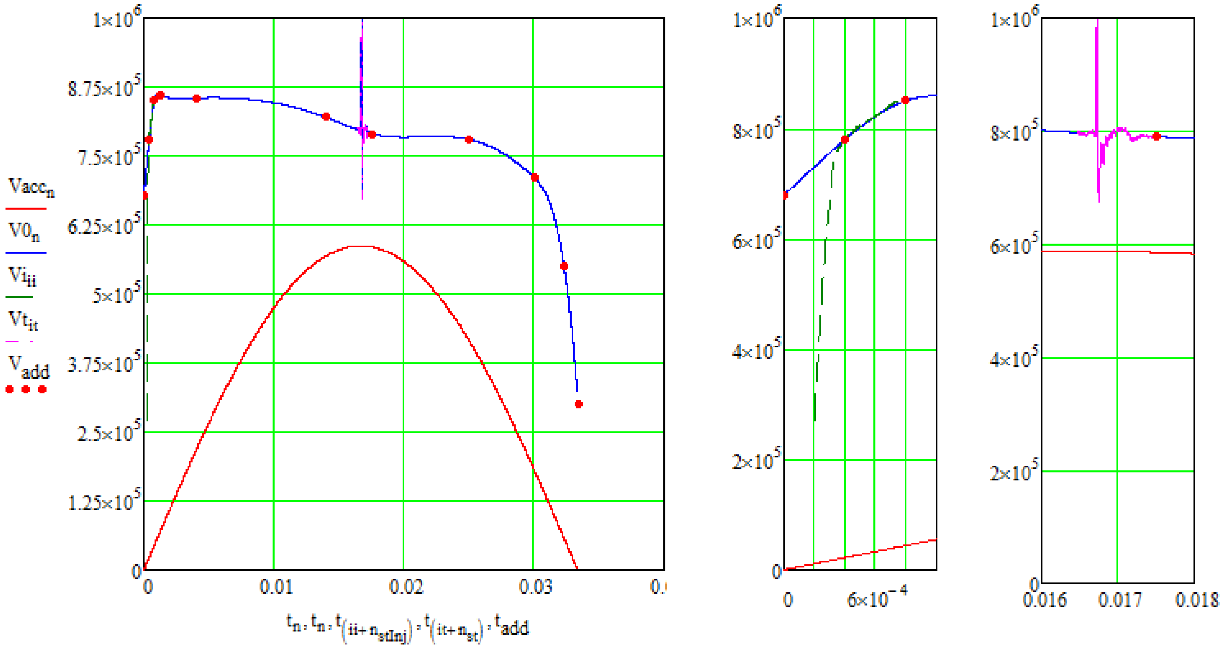


Phase space at the end of accelerating cycle

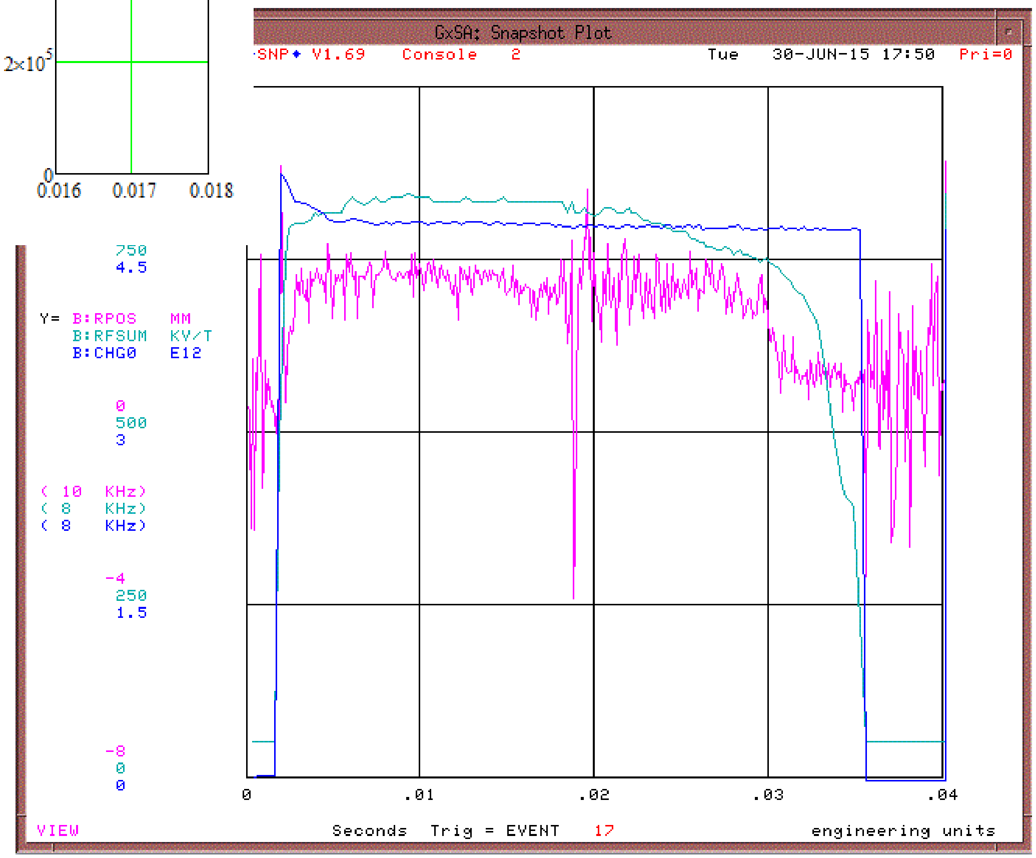
- Large filamentation
  - Need to reduce it if higher is going to be used

Simulations of Present Transition Crossing (13 turn inj.)

- Very preliminary results
- Missing details: Voltage profile

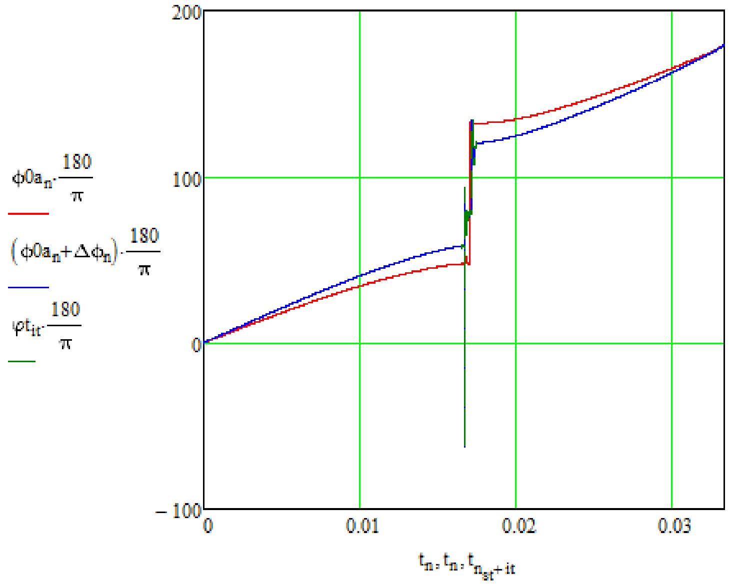


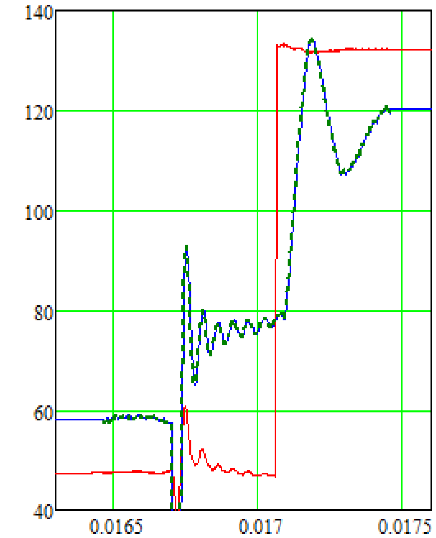
- Voltage profile from B:RFSUM plot is different from measured with scope

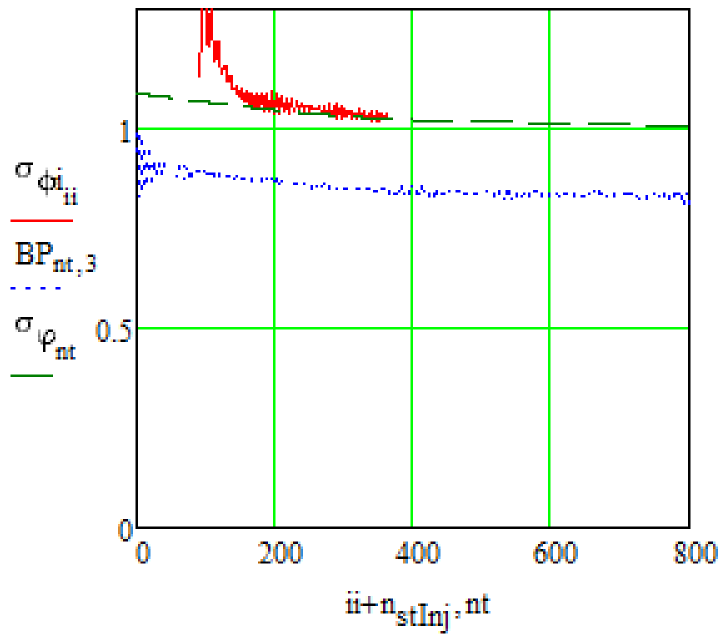


Simulations of Present Transition Crossing (2)

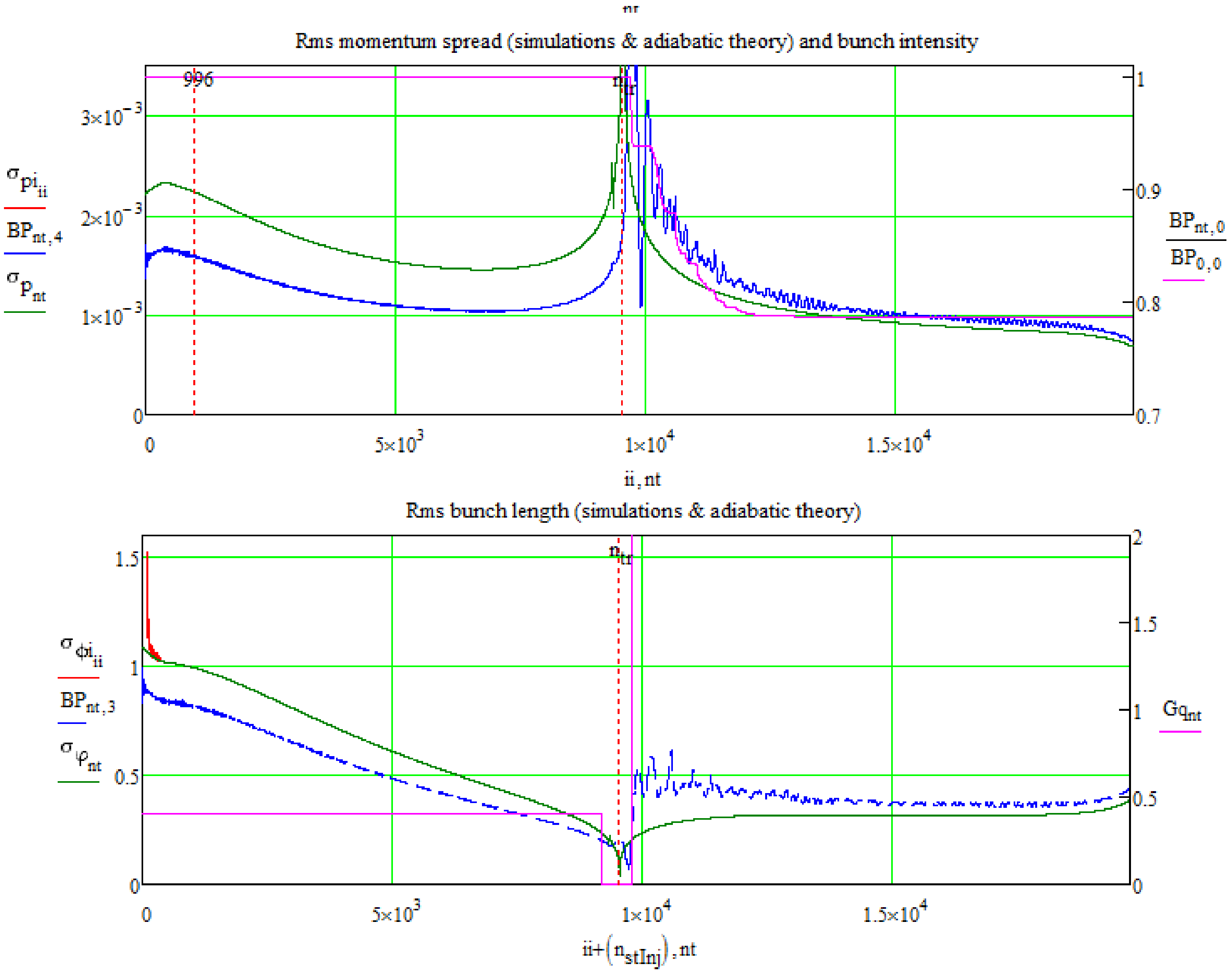
- RF phase dependence is accounted but offsets have to be tuned
  - RPOS will be used for tuning
- Missing details: Adiabatic capture and initial longitudinal distribution
  - Straightforward Gaussin distribution cannot make the rms width the same large as measured
  - Additional data analysys of data taken at injection is required to implement realistic adiabatic capture







Simulations of Present Transition Crossing (2)



- Simulations show too large beam loss
- Details have to be corrected before any conclusions can be drawn

Conclusions

- Measurements showed transition crossing details which were not known before
- It is still work in progress
  - 1-2 months are required to make trustable simulations of the present transition crossing
- Quality of acquired data is good and looks sufficient for bench marking
  - We may need more data in the future
- Analysis of PIP-II transition crossing will follow
  - It will hardly be a straightforward implementation of the voltage jumps technique
    - We also need to find a way how to avoid large energy variations near transition
    - It is already well known that additional RF voltage will be helpful