Transition Crossing

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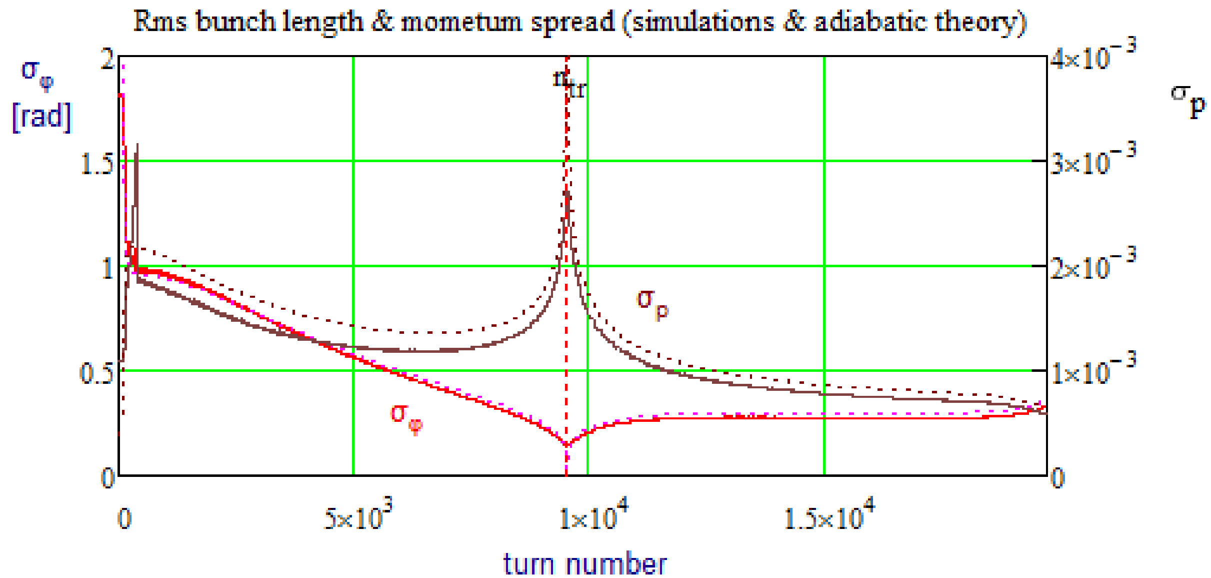
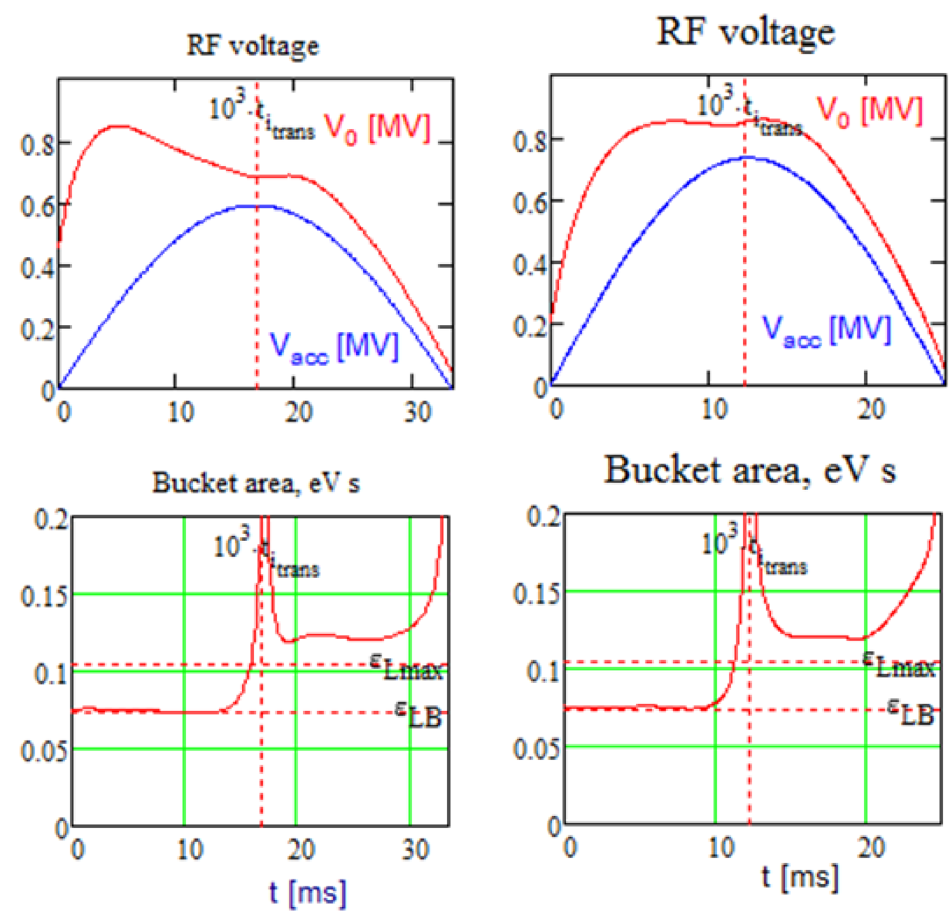
Outline

- Introduction
- Booster Longitudinal impedance
- Beam based measurements
- Preliminary simulation results
- Conclusions

Acceleration of Low Intensity Beam

- No beam loss at transition
  - For present parameters of linac beam
    - ~3% loss at adiabatic bunching
    - Acceptable maximum momentum spread ($\sigma_{p|transition}$ =2.75·10^{-3})
    - Minimum bunch length ($\sigma_{t|transition}$ =0.42 ns)
- No emittance growth at transition
- Operation at 20 Hz with 800 MeV (PIP-II) does not require additional RF voltage for the same RF bucket size





15 Hz

20 Hz

Longitudinal Impedance of the Booster

- Why Knowledge of Longitudinal Impedance is Important?
  - PIP-II requires 1.5 times increase of beam intensity in Booster within the same longitudinal and transverse emittances
  - Transition crossing can be a problem
  - Discussion will be concentrated at the beam energy range near transition crossing
- Major contributors to the Booster longitudinal impedance
  - Space charge
    - Decreases fast with beam energy but is still important near transition due to very small bunch length
    - Grows linearly with frequency

      Repulsion below transition

      Attraction above transition

      $\Rightarrow$ Quadrupole oscillations

$$Z_{\|_{SC}}(\omega) \approx -iZ_0 \frac{\omega}{\beta\gamma^2\omega_0} \ln\left(\frac{r_{chamber}}{1.06\,\sigma_\perp}\right),$$

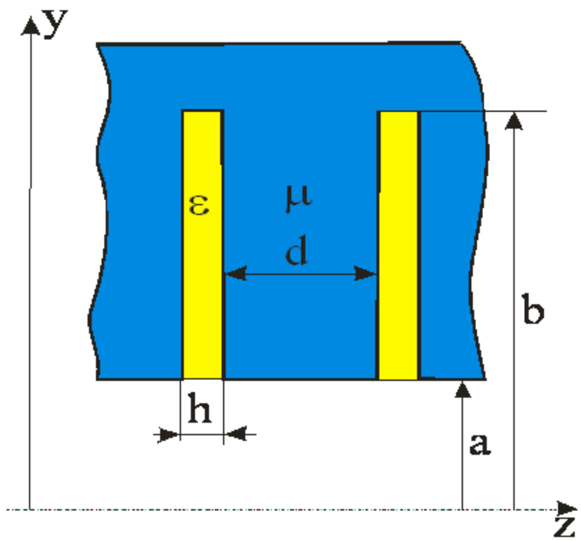
$$\frac{r_{chamber}}{\sigma_\perp} \geq 2\,, \quad Z_0 \approx 377\,\Omega\,.$$

  - Wall resistivity
    - Strong beam deceleration at transition where the bunch has the shortest length (σ_t~ 0.5 ns, I_{peak}~ 7.5 A)

Impedance of Booster Laminated Magnets

- Longitudinal impedance of round pipe per unit length

$$Z(\omega)=\frac{Z_0 c}{4\pi}\frac{1+i}{2\pi a\delta_S\sigma}=\frac{Z_0 c}{4\pi}\frac{1+i}{ac}\sqrt{\frac{\mu\omega}{2\pi\sigma}}\,,\qquad \delta_S=\frac{c}{\sqrt{2\pi\sigma\omega\mu}}$$



- Laminations greatly amplify impedance
  - (1) $\propto\sqrt{\mu}$, (2) longer current path
  - Impedance of flat chamber per unit length [1]

$$Z_{\|_{LM}}(\omega)=iZ_0\frac{\omega}{2\pi c}\int_0^\infty\frac{F_L(\xi)}{1+F_L(\xi)\tanh\xi}\frac{d\xi}{\xi\cosh^2\xi}$$

where:

$$F_L(\xi)=\frac{h}{d+h}\frac{\xi}{k_y(\xi)}\left(1+(1-i)\frac{\mu\delta_S}{h}\right)\tan\left(k_y(\xi)\left(\frac{b}{a}-1\right)\right),$$

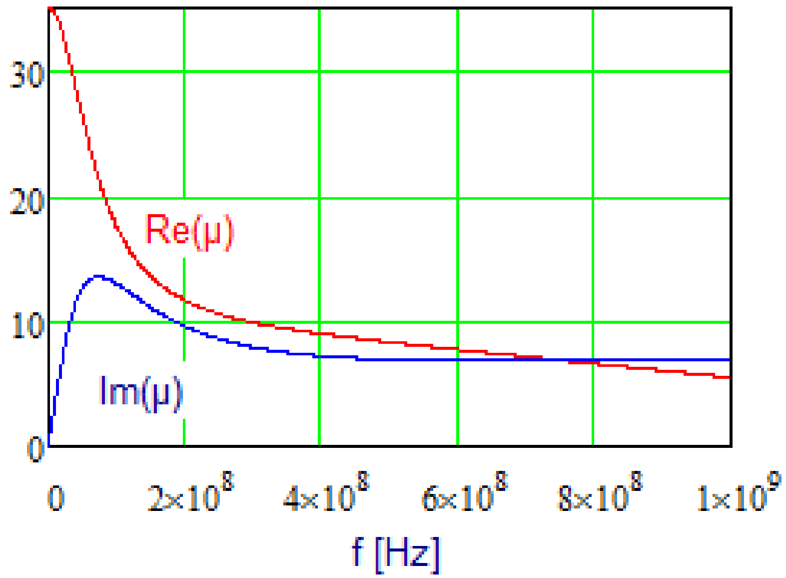
$$k_y(\xi)=\sqrt{\frac{\varepsilon\omega^2a^2}{c^2}\left(1+(1-i)\frac{\mu\delta_S}{h}\right)-\xi^2}\,,$$

- 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?

[1] “Accelerator Physics at the Tevatron Collider”, editors V. Lebedev and V. Shiltsev

Measured Permeability of Soft Steel [Tokpanov, IPAC2012]

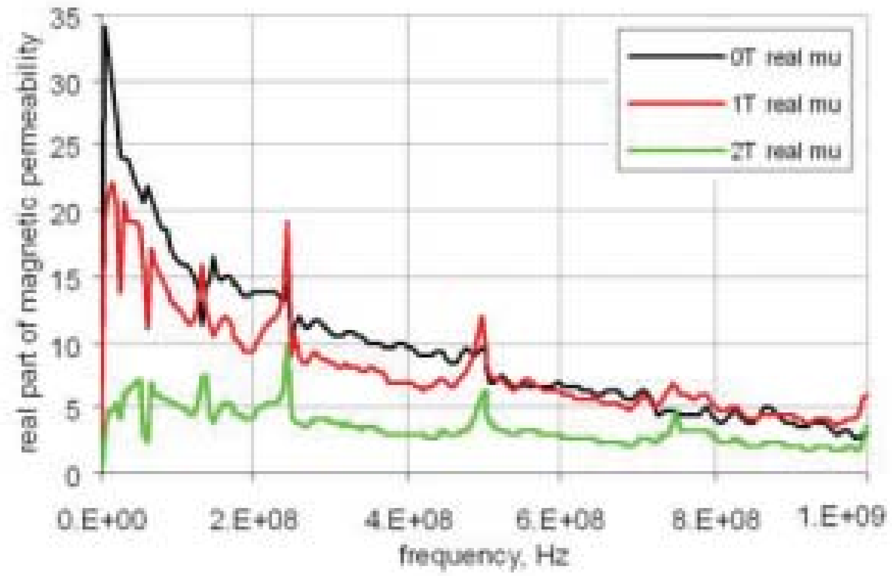
- μ used in the simulations



$$\mu(\omega) = \frac{26}{1+i\omega/\omega_1} + \frac{9}{(1+i\omega/\omega_2)(1+i\omega/\omega_3)},$$

$$\omega_1/2\pi = 70\ \text{MHz},\ \omega_2/2\pi = 1.5\ \text{GHz},\ \omega_3/2\pi = 6\ \text{GHz},$$

- Both real and imaginary parts are taken into account
  - ♦ Steel conductivity at high frequencies is assumed to be the same as for DC



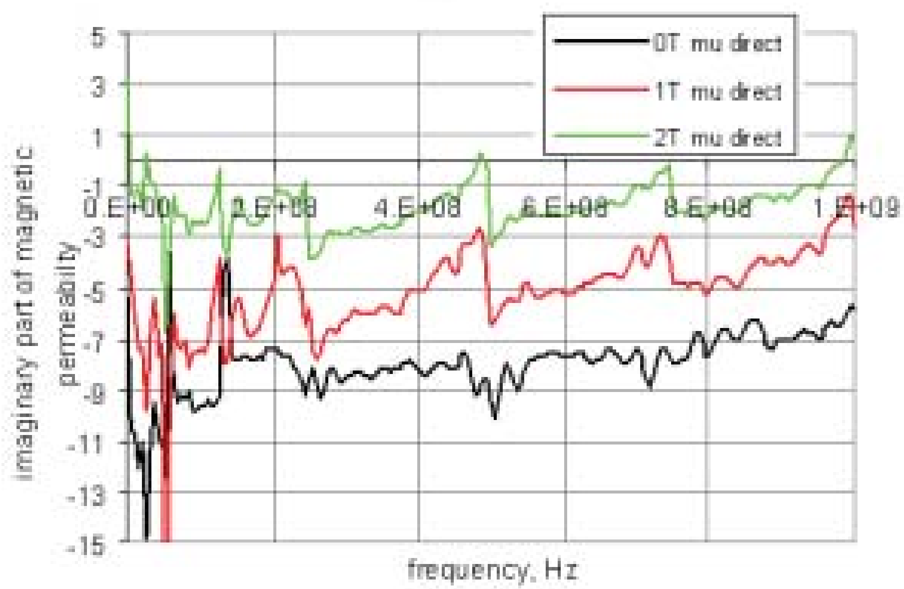


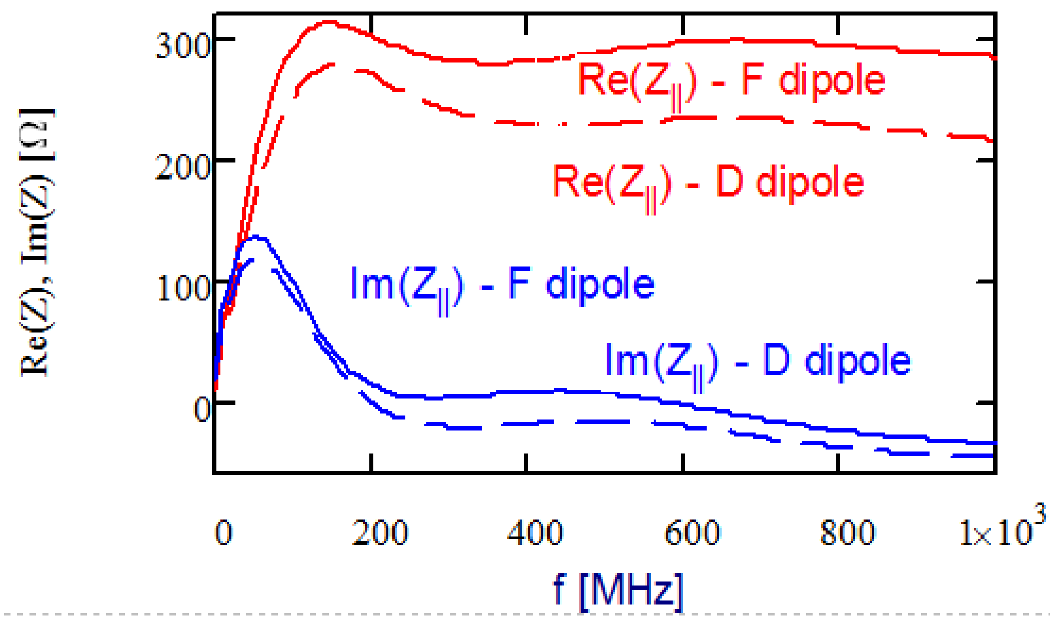
Figure 3: Dependence of magnetic permeability of steel on frequency for different magnetic fields for the case of magnetic field normal to the strip plane.

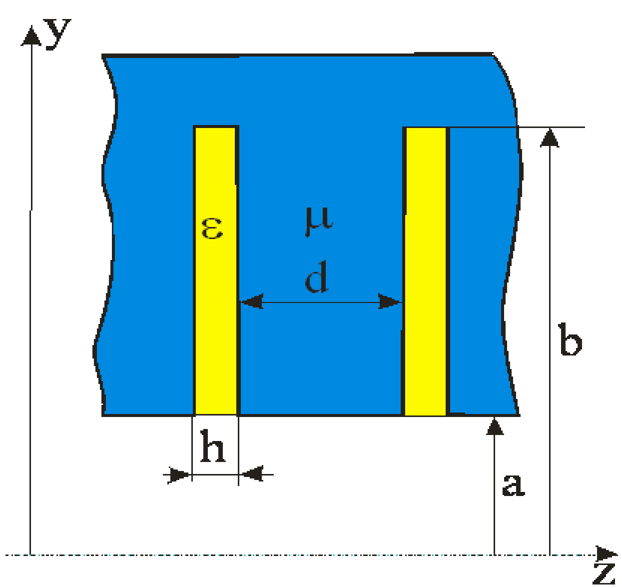
Parameters for the Impedance Calculation

- Gap between plates is taken from known packing factor (Booster design report)
- Dielectric gap: epoxy + insulating oxide layer on steel
  - The value is updated based on beam measurements

Dipole type	F	D	
Dipole length	2.89		m
Number of dipoles	48	48	cm
Half-gap, *a*	2.1	2.9	cm
Lamina half-height, *b*	15.2		cm
Lamina thickness, *d*	0.64		mm
Dielectric crack width, *h*	25		μm
Conductivity, σ	$2.07 \cdot 10^{16}$ ($2.3 \cdot 10^{6}\ \Omega^{-1}\ \mathrm{m}^{-1}$)		s^{-1}
Dielectric permittivity, ε	2.5		

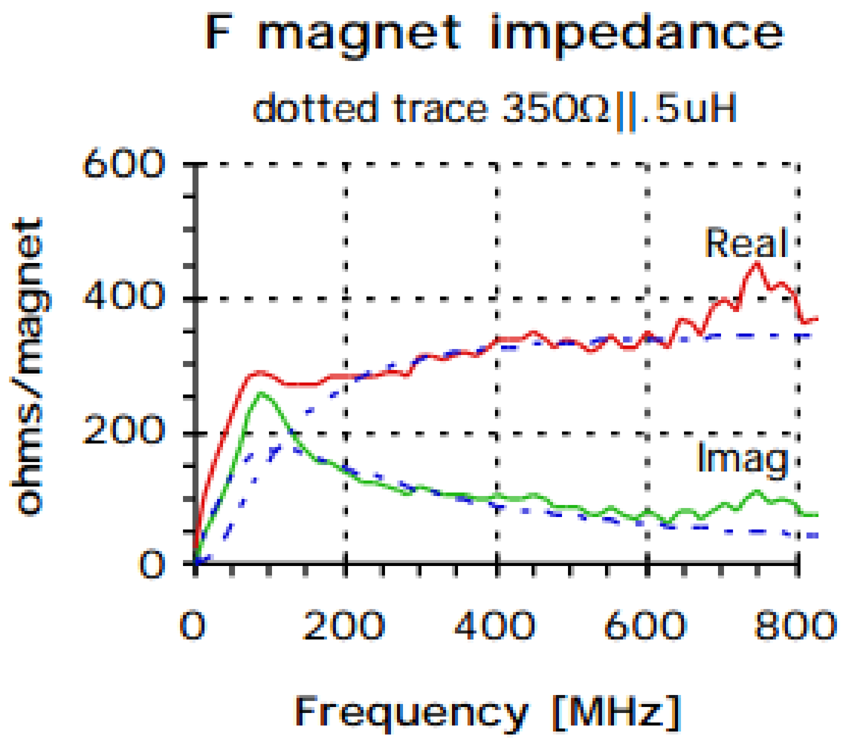
- F dipole has smaller gap and larger impedance

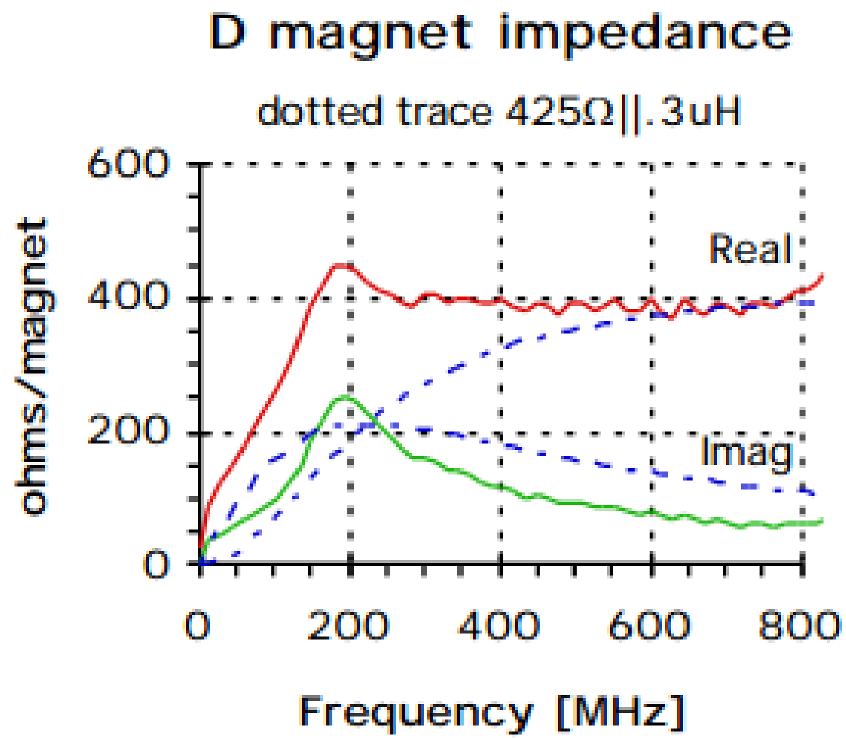




Dependence of longitudinal impedance of Booster dipole on the frequency computed for F and D dipoles.

Stretched Wire Measurements of Longitudinal Impedance of Booster Laminated Dipoles





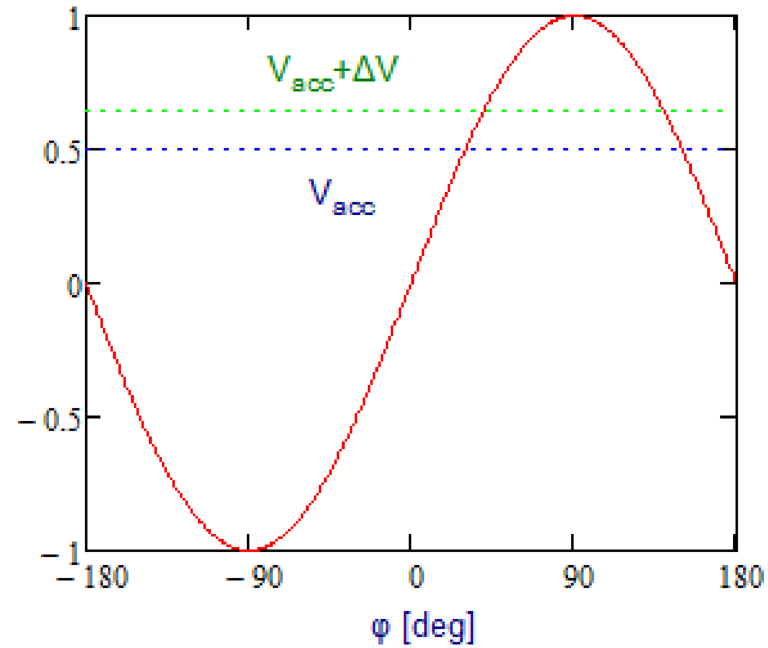
Taken from J. Crisp and B. Fellenz, "Fermilab-TM-2145, March 22, 2001.

- 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
- Expected decelerating voltage = (7.5 A)*(300 Ω)*(48 dipoles)≈**100 kV**

Beam Based Measurements and their Results

Beam Based Measurements of the Long. Impedance

- 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 is applicable
  - Minor adjustments are used for the final tune of the model
    - They do not change the shape of the impedance curve
- ϕ_{accel} is obtained from comparison of
  - RF phase: RFSUM &
  - Bunch timing: RW monitor
- Two sets of measurements

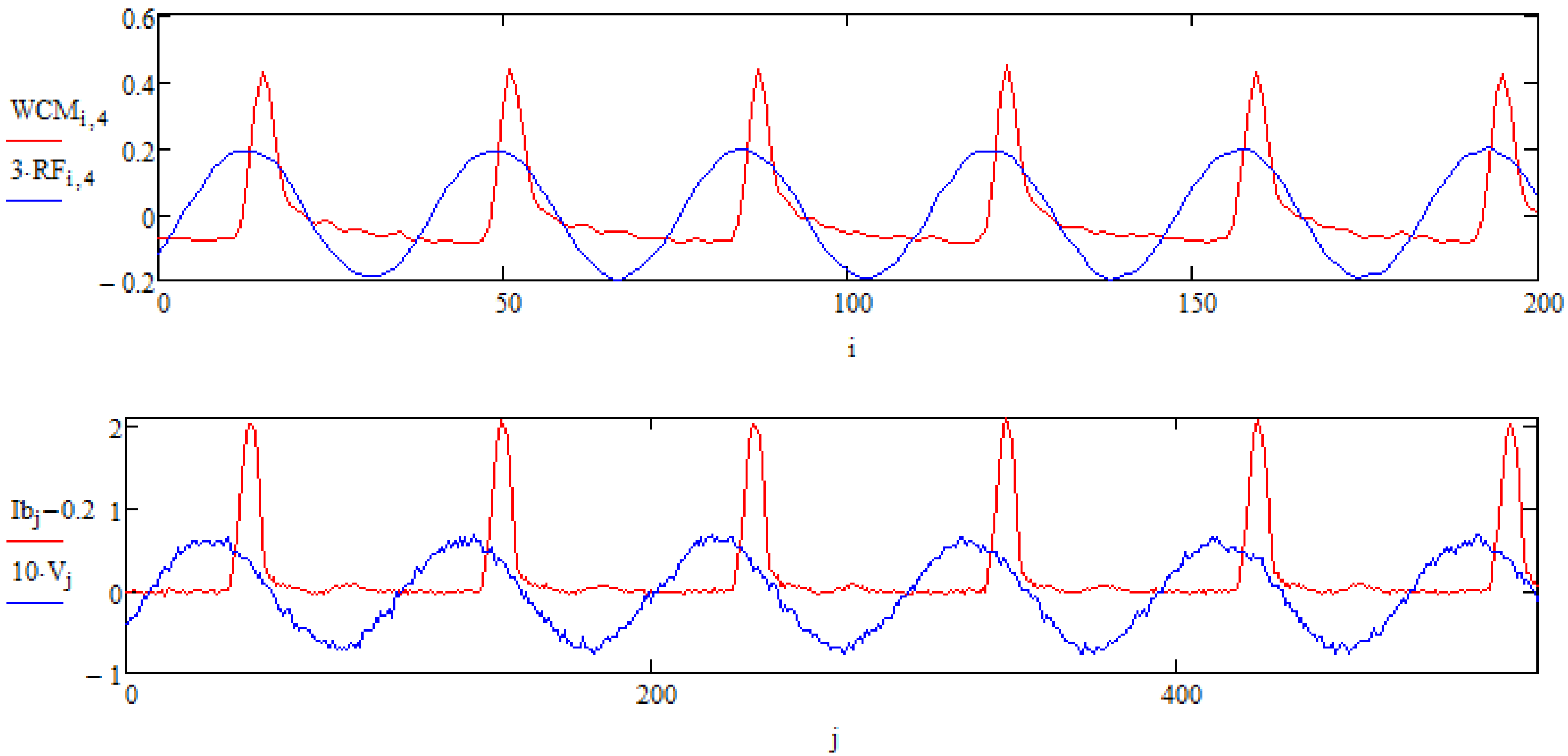


1. January 17/2015
   - 1 ms around transition
     - bad time resolution of RW monitor
2. July 6/2015
   - 1 ms around transition + 1 ms around transition
     - improved time resolution of RW monitor
   - Additional measurement of RPOS (Radial position) signal

Data Acquisition and Acquired Data

- Fast digital scope
  - T=1 ms centered around transition
    - 1st set: Δt=0.533 ns, $1.875 \cdot 10^6$ points per ch., 36 points per RF bucket @ TC
    - 2nd set: Δt=0.2 ns, $5 \cdot 10^6$ points per channel, 96 points per RF bucket @TC
- Signals
  - RF sum
  - Wall current monitor
  - RPOS for the second set of measurements
- 1st set measurements Beam parameters:
  - Intensity: 4, 6, 8, 10, 12 & 14 turn Booster injection
    - 14 turn $=4.3 \cdot 10^{12}$ in 82 bunches
- Similar for the 2nd set

Measured Signals and Data Analysis

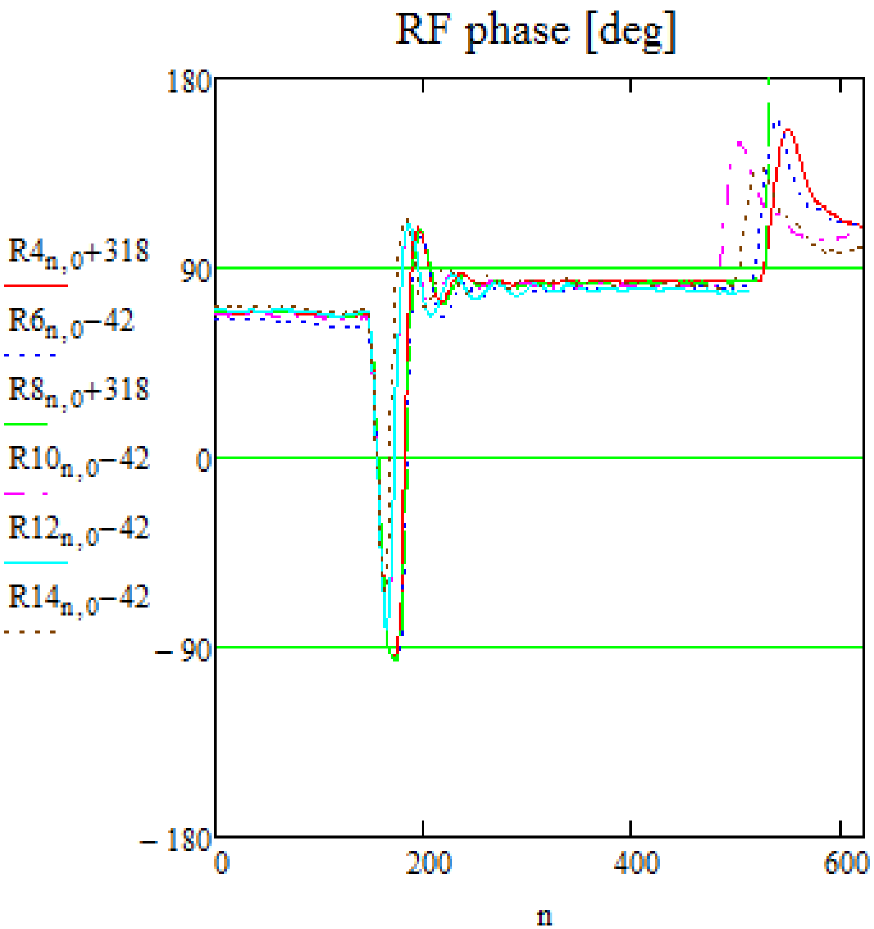


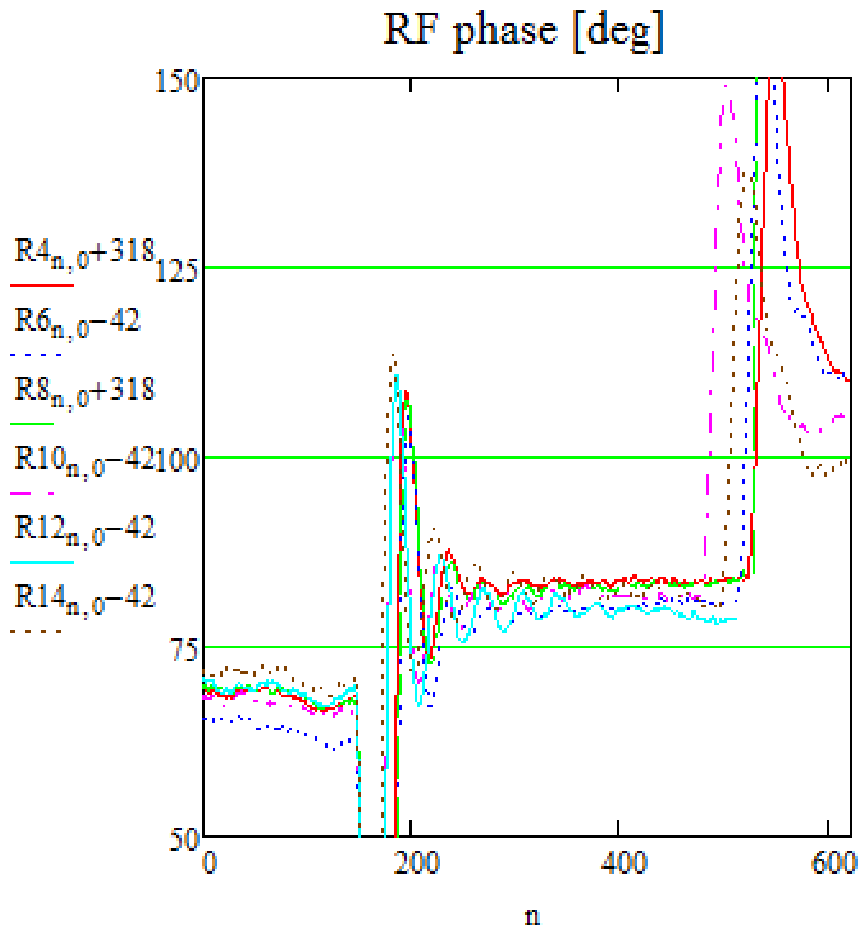
The second set of measurements has better time resolution (another WCM + better cable) but more noise in WCM signal

- An algorithm computes
  - Fitting RF signal for one period of sinusoid yields for each period
    - (1) zero crossing time & (2) RF voltage
  - Fitting WCM signal to a Gaussian pulses yields for each period
    - (1) Bunch time, (2) Peak height (3) Peak width & (4) DC offset
  - Time difference between RF zero crossing and bunch arrival time yields the relative accelerating phase – correction for cable length difference is accounted

RF Phase for Present Transition Crossing

- Good transition requires an RF phase being at maximum deceleration for a short time
- An increase of accel. phase with intensity is close to expectations
- Larger variations in accelerating phase after transition point out to a stronger deceleration after transition => shorter bunch

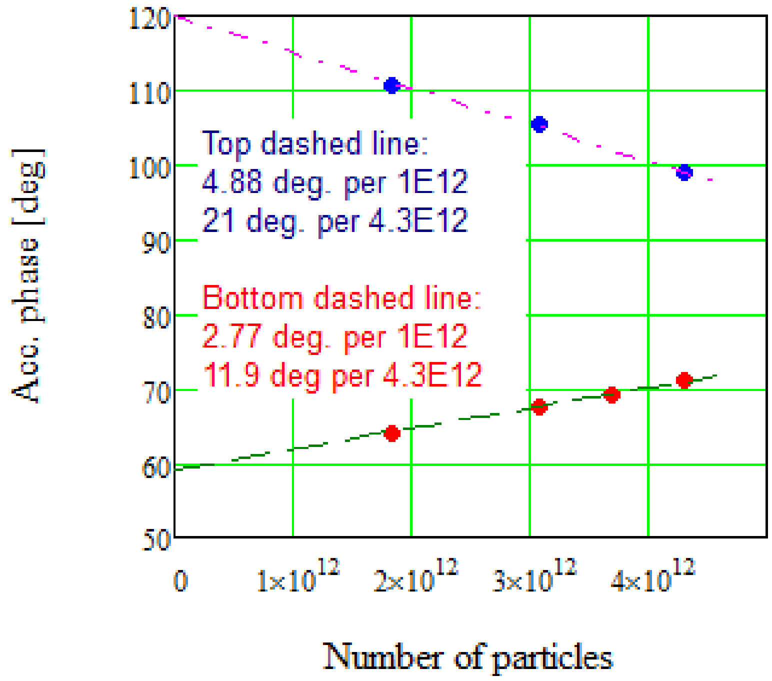




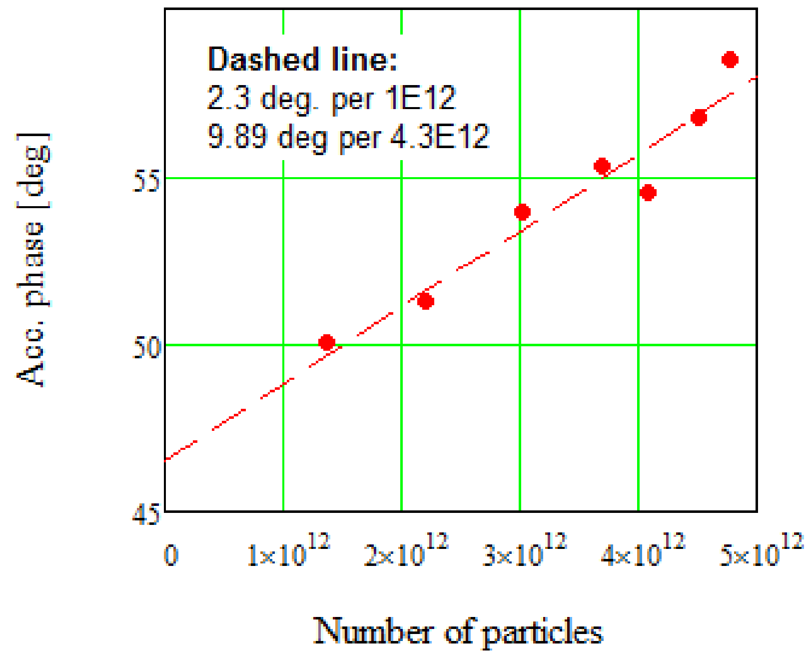
Measurement Results

- The second set of measurements yields a weaker dependence of accelerating phase on the beam intensity due to higher accelerating voltage
- Both sets verify that the deceleration voltage is ~100 kV at nominal intensity
- RPOS data acquired for the second set and the measurements at the injection energy allowed calibration of all relevant parameters
  - That allows detailed comparison between simulations and measurements

Results of the 1st set of measurements



Results of the 2nd set of measurements

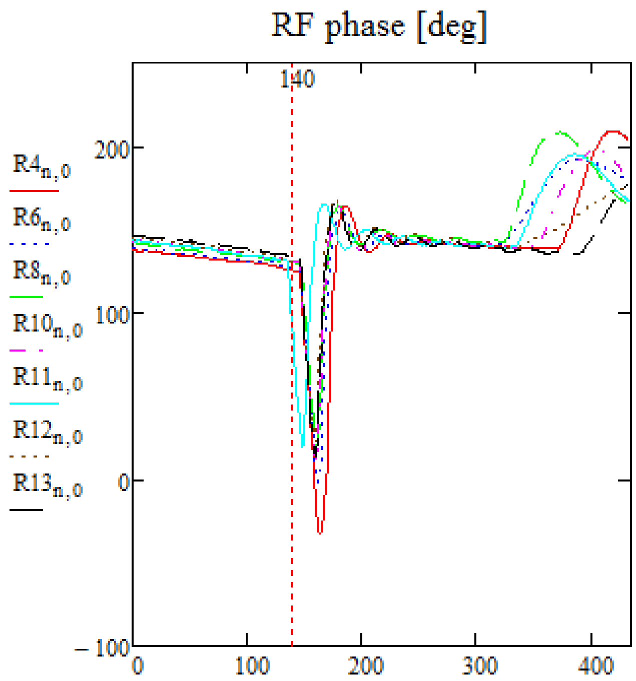


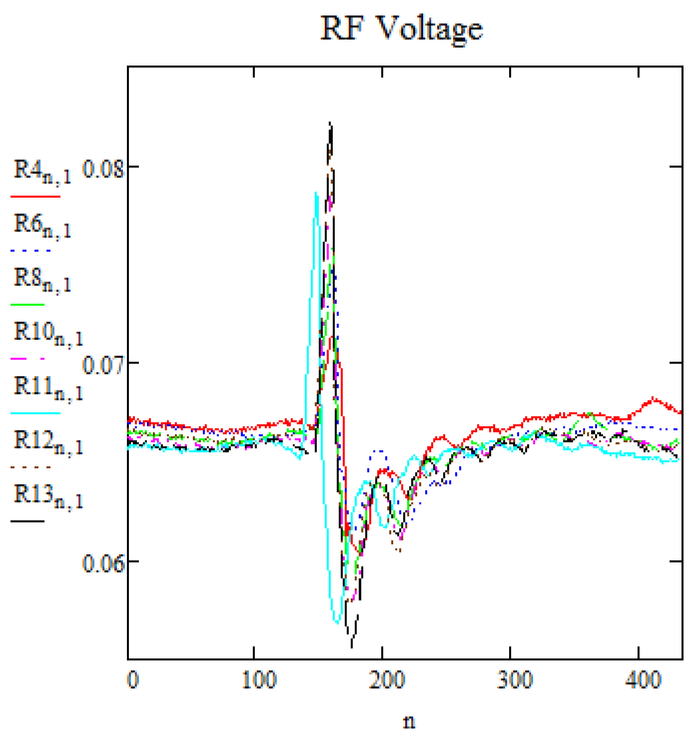
Features of Measured Signals

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

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

  - Not observed in the 1st set of measurements
  - The effect is more pronounced in the injection data: $\Delta f/f \approx 7\cdot 10^{-3}$ versus $3\cdot 10^{-3}$
  - 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?



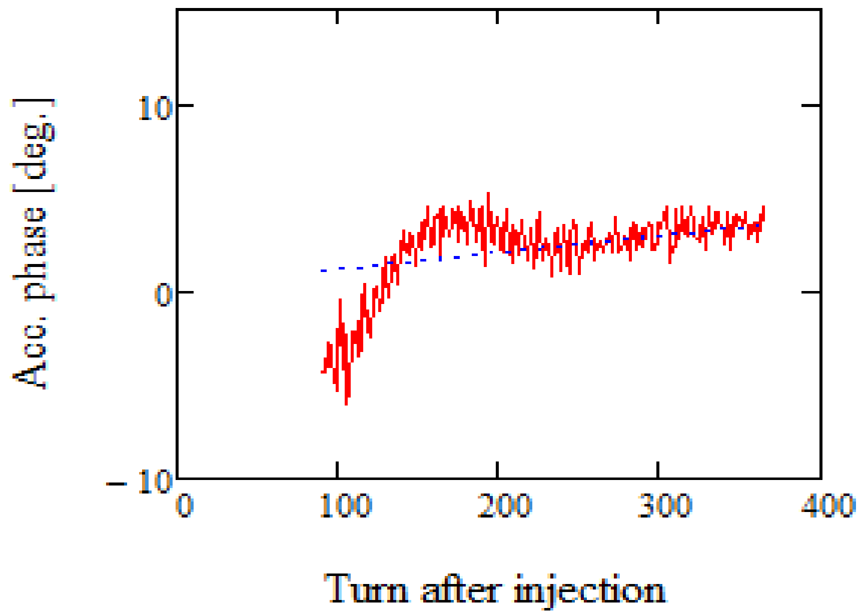


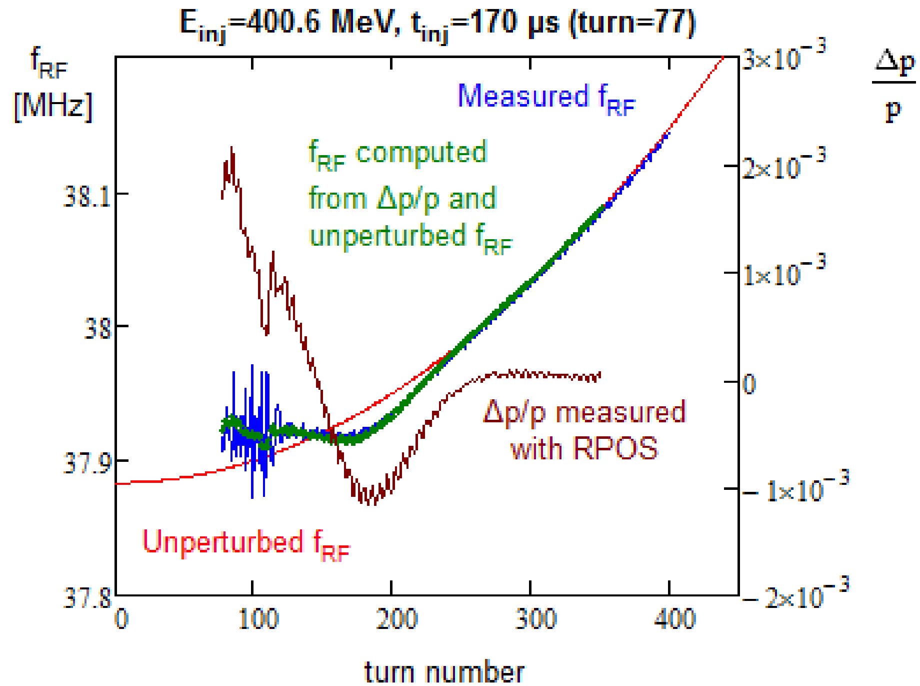
Signal Calibration Resulting from Data Analysis

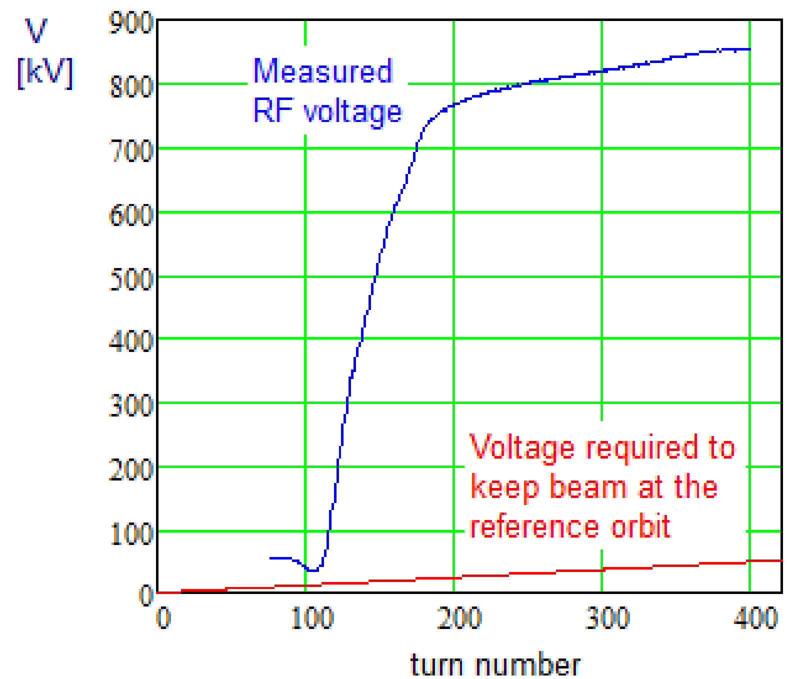
- Addition of Rpos measurements and injection data were allowed to obtain accurate calibrations for the following signals:
  - Total RF voltage: $V_{peak}=1.21\cdot 10^{7}\ V_{RFsum}$
  - An estimate of average decelerating voltage due to resistive wall impedance: 80 kV/turn for $4.2\cdot 10^{12}$
  - Calibration of RPOS for $\Delta p/p$ @ transition: $\Delta p/p = 0.0694 * RPOS_{(V)}$
    - 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

Injection Data (2^{nd} data set, 13-turn injection)

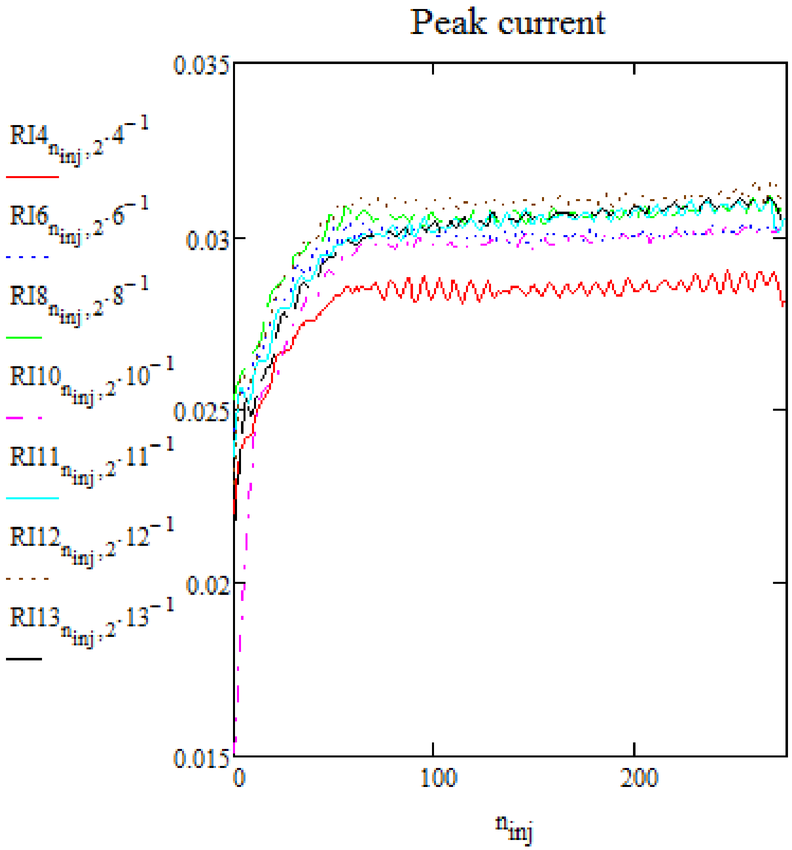
- Beam injection is 170 μs (77 turns) after magnetic field reaches its minimum
- RPOS feedback puts beam to nominal orbit at turn ~220

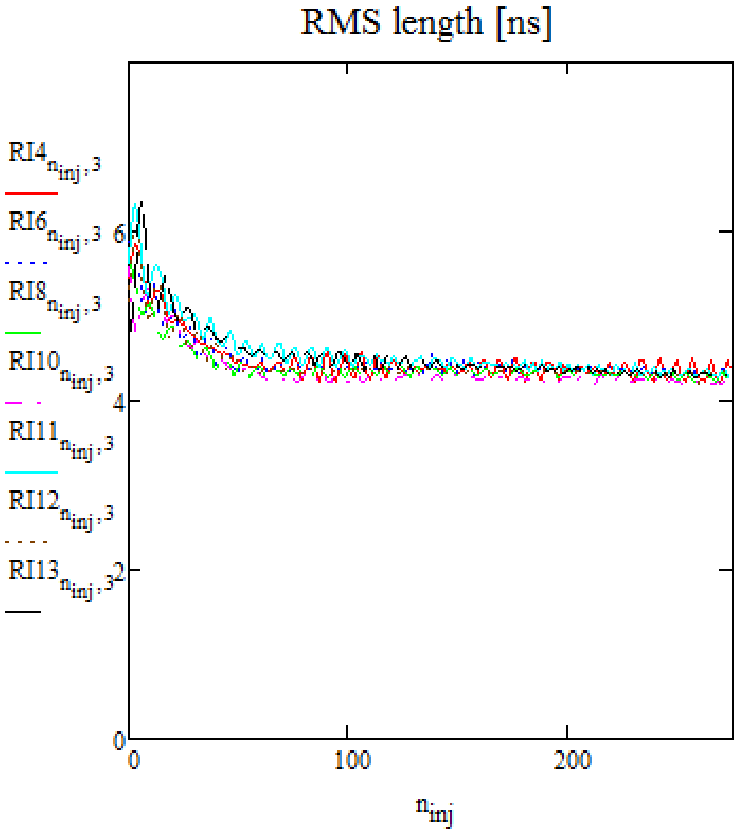




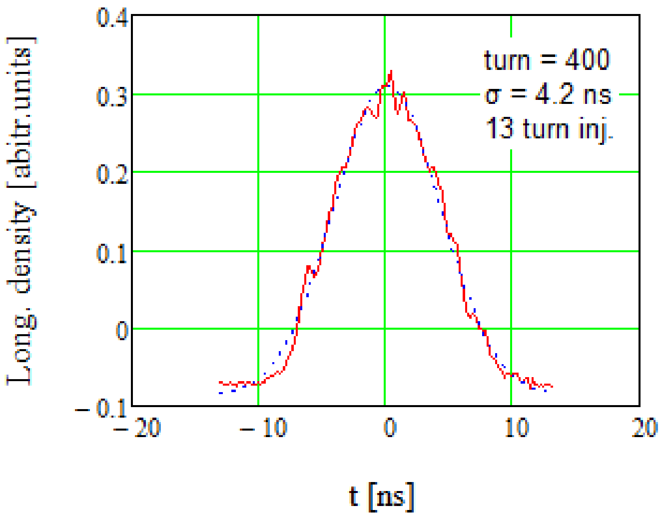


Injection Data (continue)



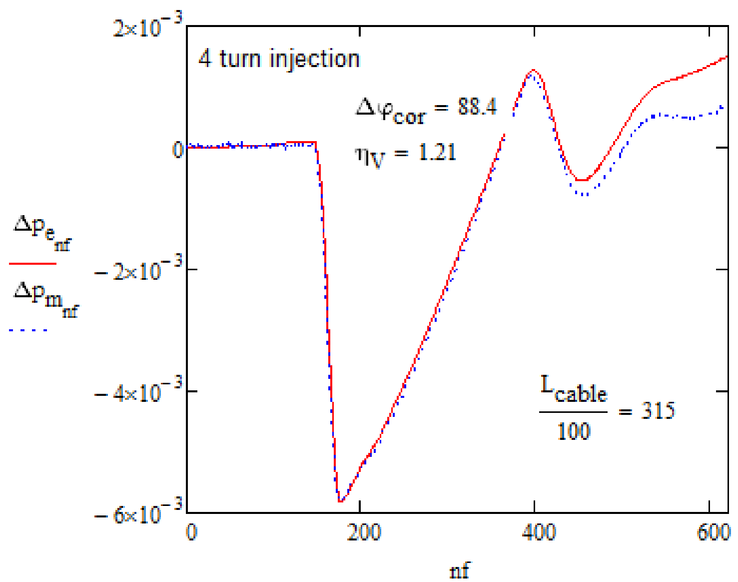


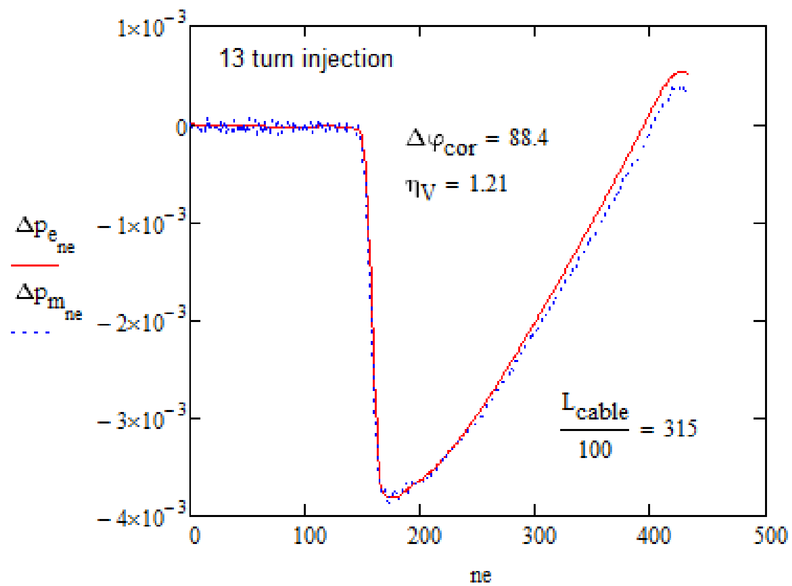
- Knowledge of RF voltage and bunch length yields the longitudinal emittance
  - Effect of impedances is automatically accounted in simulations
- Bunch profile is close to a slightly truncated Gaussian



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

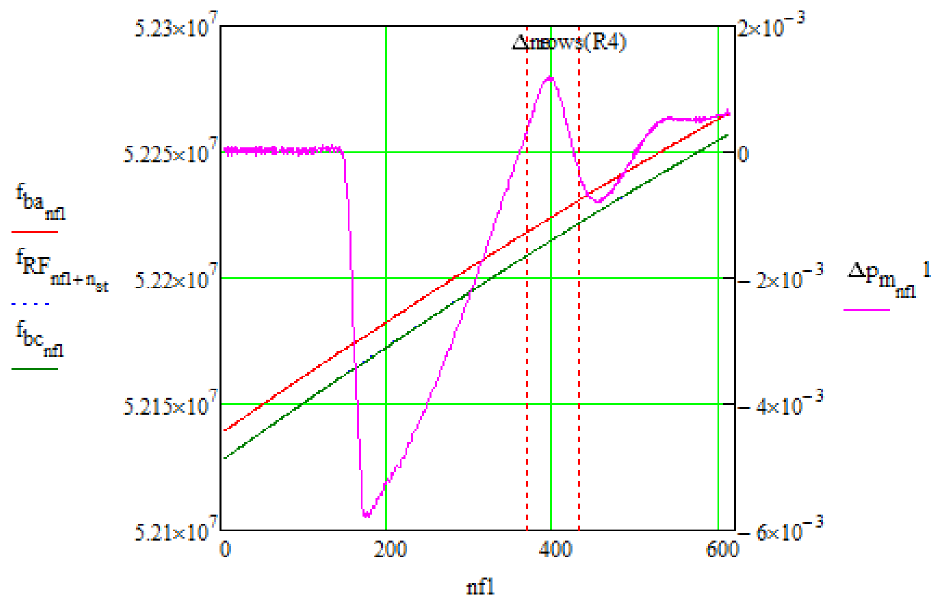
- Comparison of predicted and measured momentum offsets for different intensities uniquely yields all unknown parameters
  - Most probably the discrepancy at the end is related to bunch shortening and larger deceleration due to impedance
  - Simulations have to verify it

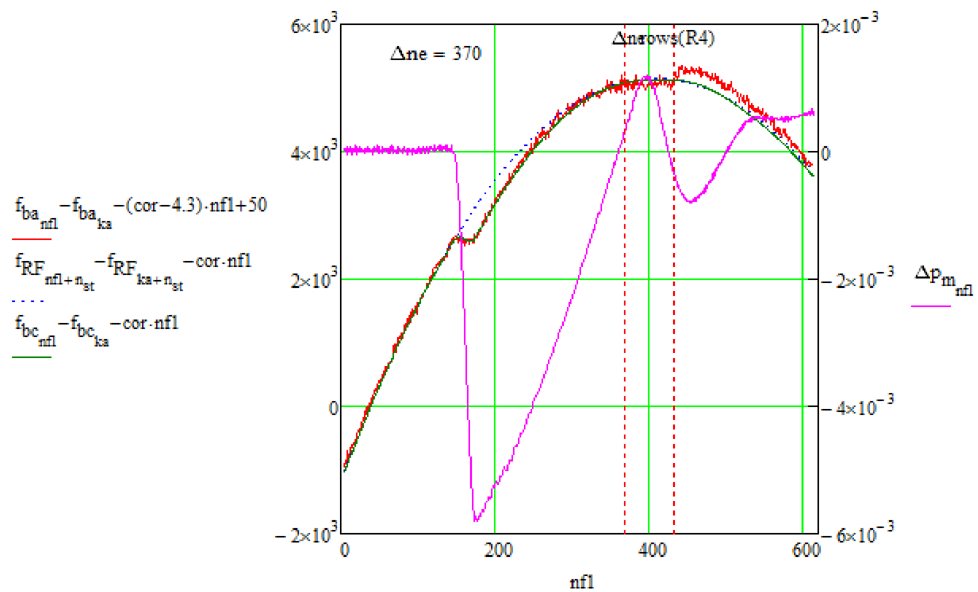
Transition Crossing Time

- Exact location of transition crossing is needed 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 $\Delta p/p$ swing well visible
- Origin of the second bump is unknown
  - Can be due to minor orbit variation at the transition ($\Delta f/f \sim 4\cdot10^{-6} \Leftrightarrow \Delta L \sim 2$ mm)
    - A proof should follow





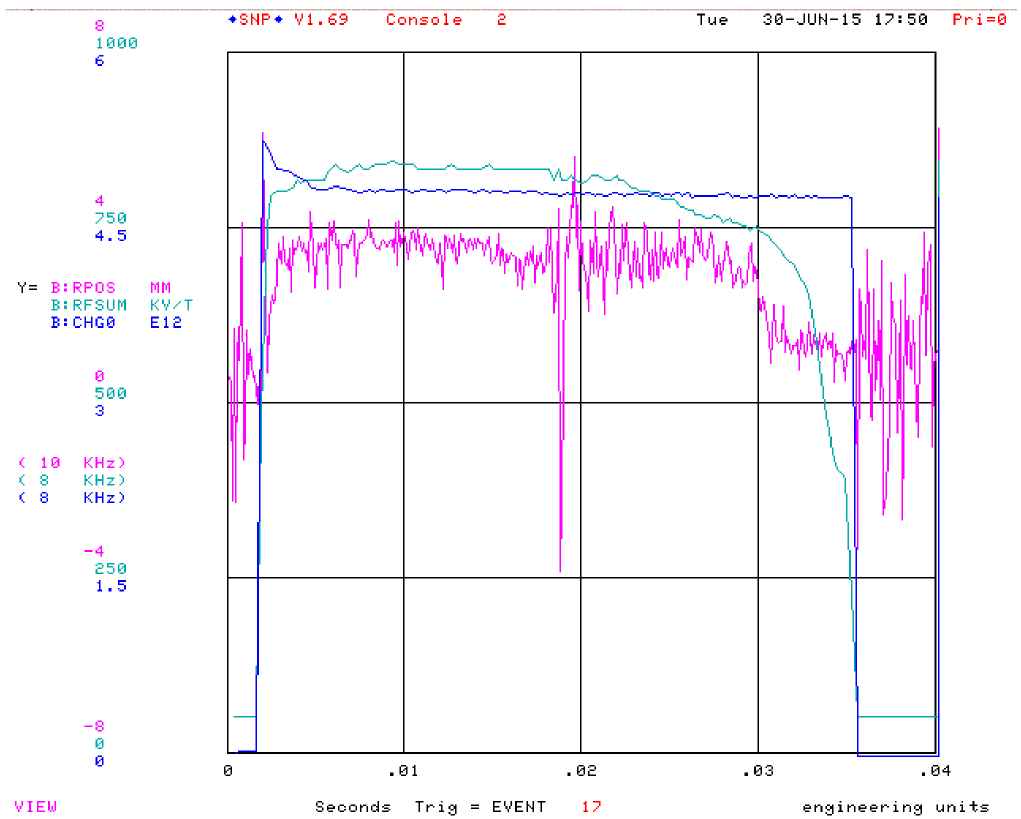
Simulations versus Measurements

Simulation Program

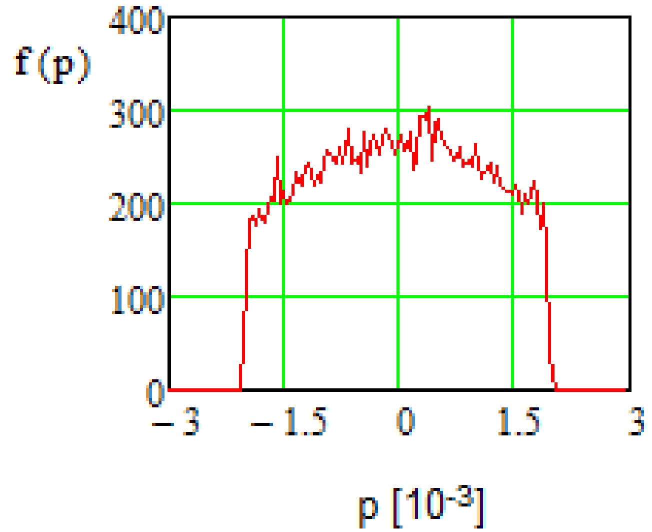
- Combination of C-program (computations) and MathCad (GUI)
- Accounts for impedances of dipoles and space charge
  - Implies 84 equal intensity bunches
  - Impedances of dipoles is calibrated by the measured RF phase with intensity
  - Measurements do not exhibit significant difference in behavior for bunches in vicinity of the abort gap
    - Both impedances are short range
  - 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

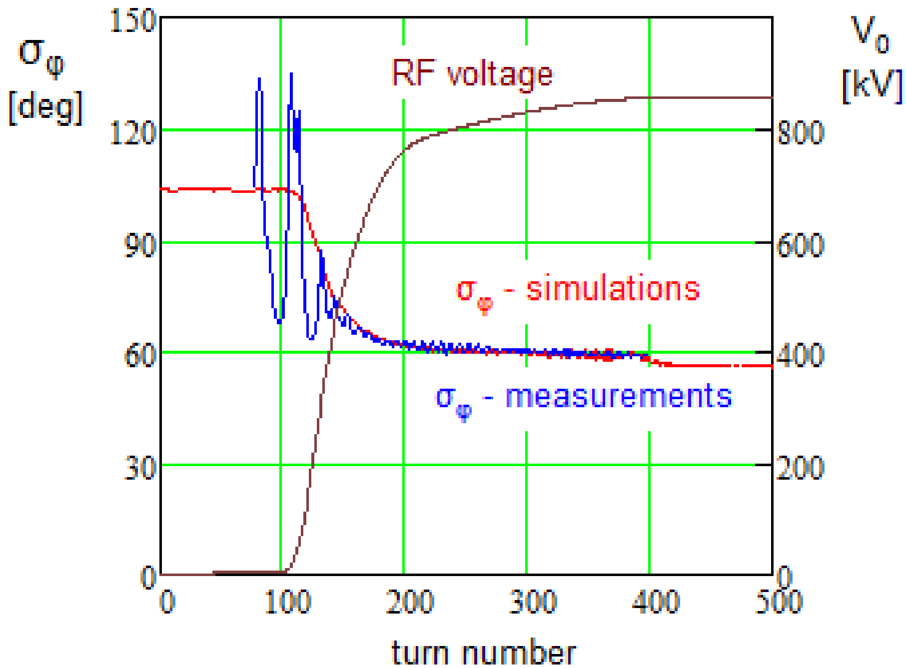
Adiabatic Bunching and Initial Longitudinal Emittance

- Measured bunch length is quite large
  - It requires almost rectangular momentum distribution if injected beam (before adiabatic bunching)
  - Simulations –
    4% loss @ turn 400 (0.88 ms)
  - Measurements -
    5% loss @ ~0.7 ms



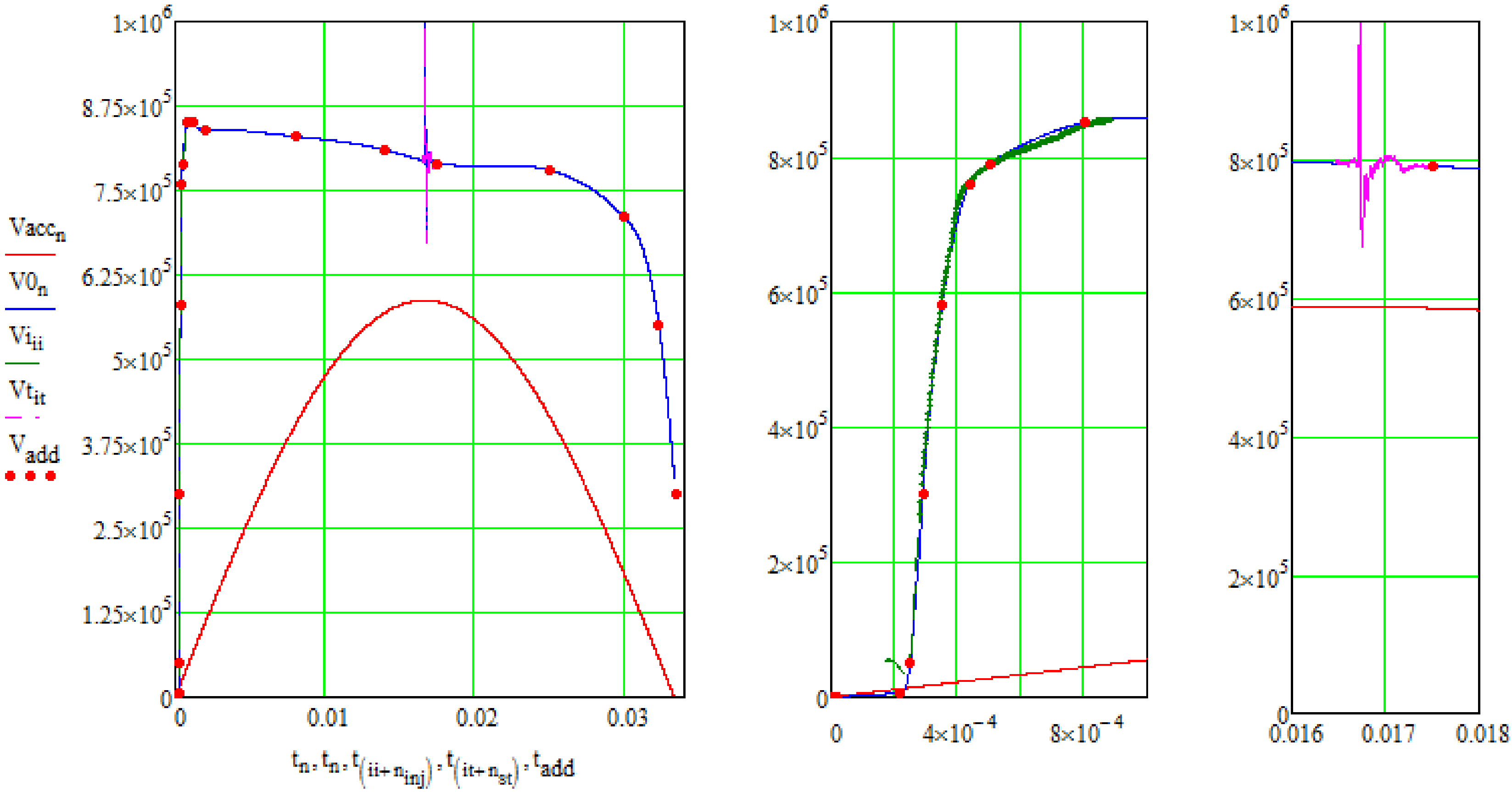
Initial momentum distribution used in simulations





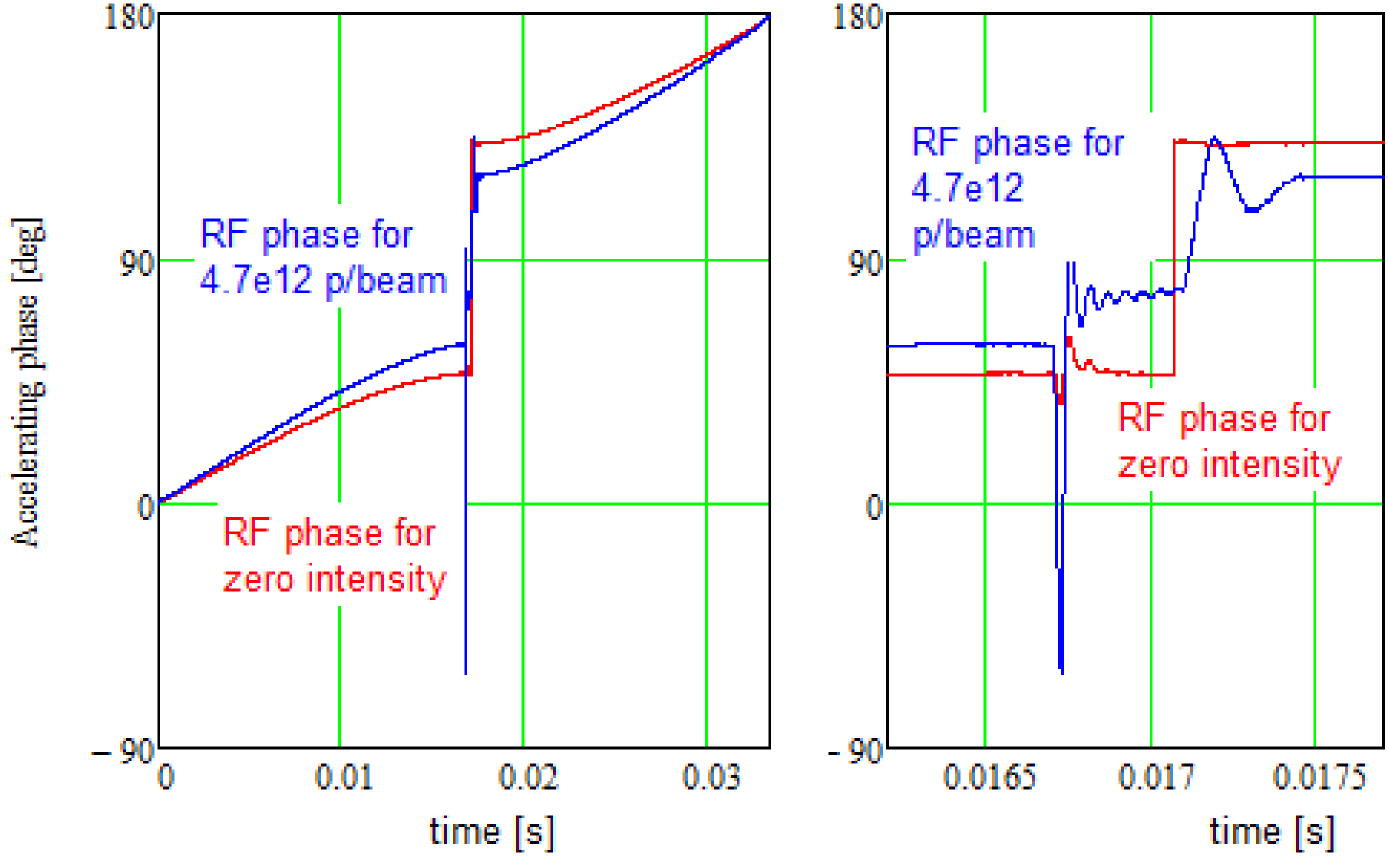
Input to Simulations – RF Voltage

- RF voltage was calibrated at transition
  - The same calibration is used at injection
  - There is discrepancy between RFSUM from control system (B:CHG0) and RFSUM measured by the scope
- RF voltage for the rest of the cycle was set to be similar to the B:CHG0 data



Input to Simulations – RF Phase

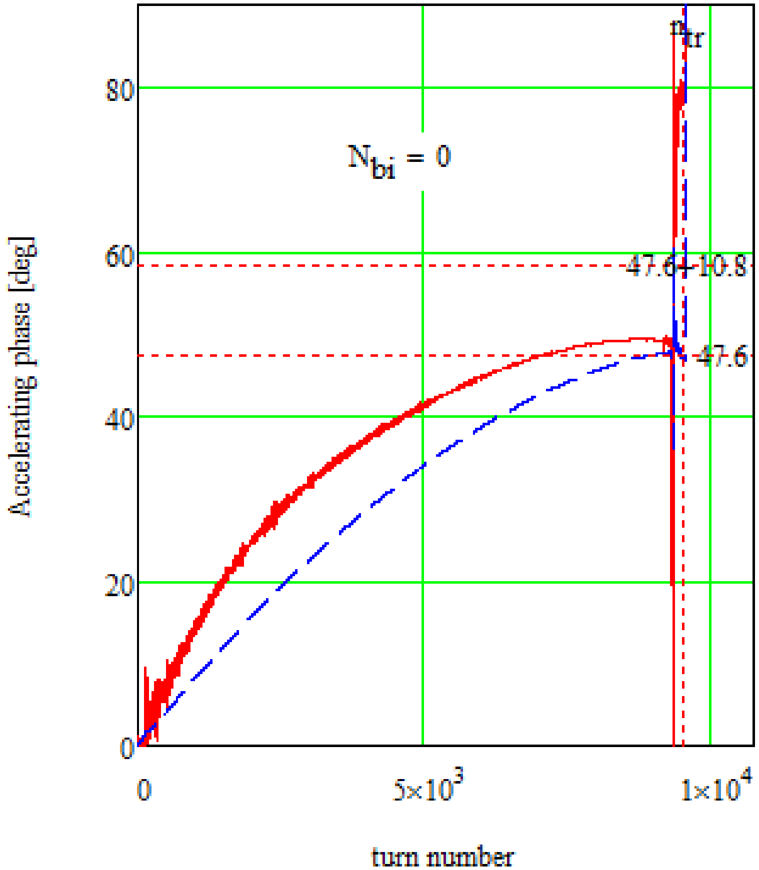
- RF phase was set so that to keep the beam at the reference orbit everywhere except 1 ms near transition
- Phase offset was introduced into the phase profile to adjust for a reduced value of the phase jump at transition

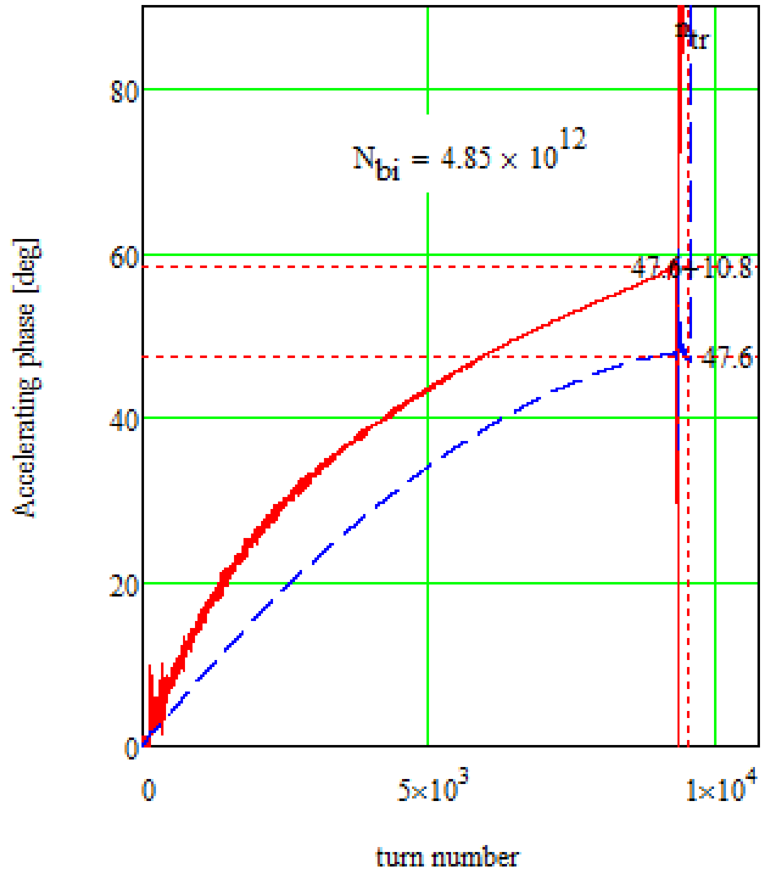


- Both feedbacks were off near transition to avoid feedback effect on the RF phase

Input to Simulations – Longitudinal Impedance

- Parameters of laminated magnets were adjusted to obtain correct shift of accelerating phase with intensity

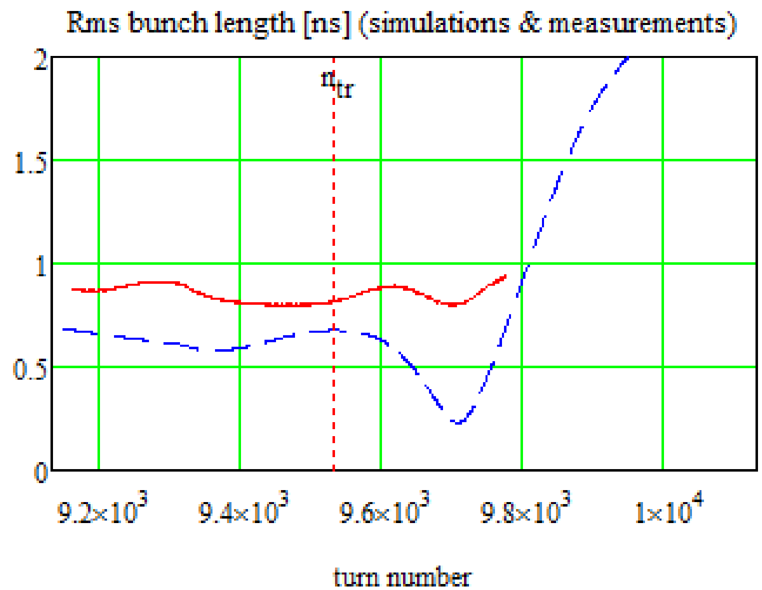




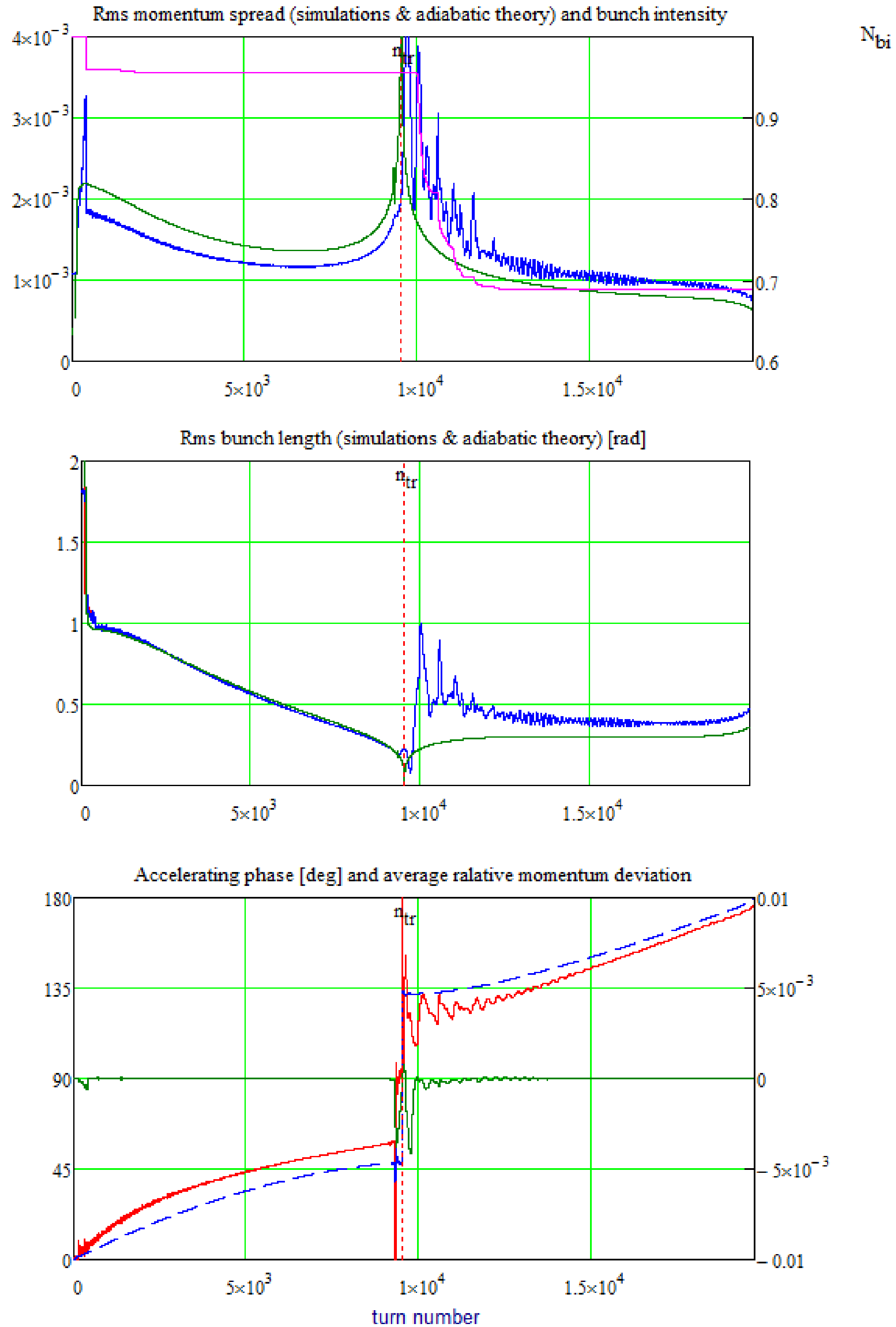
- Asymmetry of the RF bucket separates the center of the bucket and the beam center of the gravity

Preliminary Simulation Results for 13 turn injection

- Beam loss in simulations (of ~30%) greatly exceeds observations (close to zero)
- Simulated beam size near transition is below measured

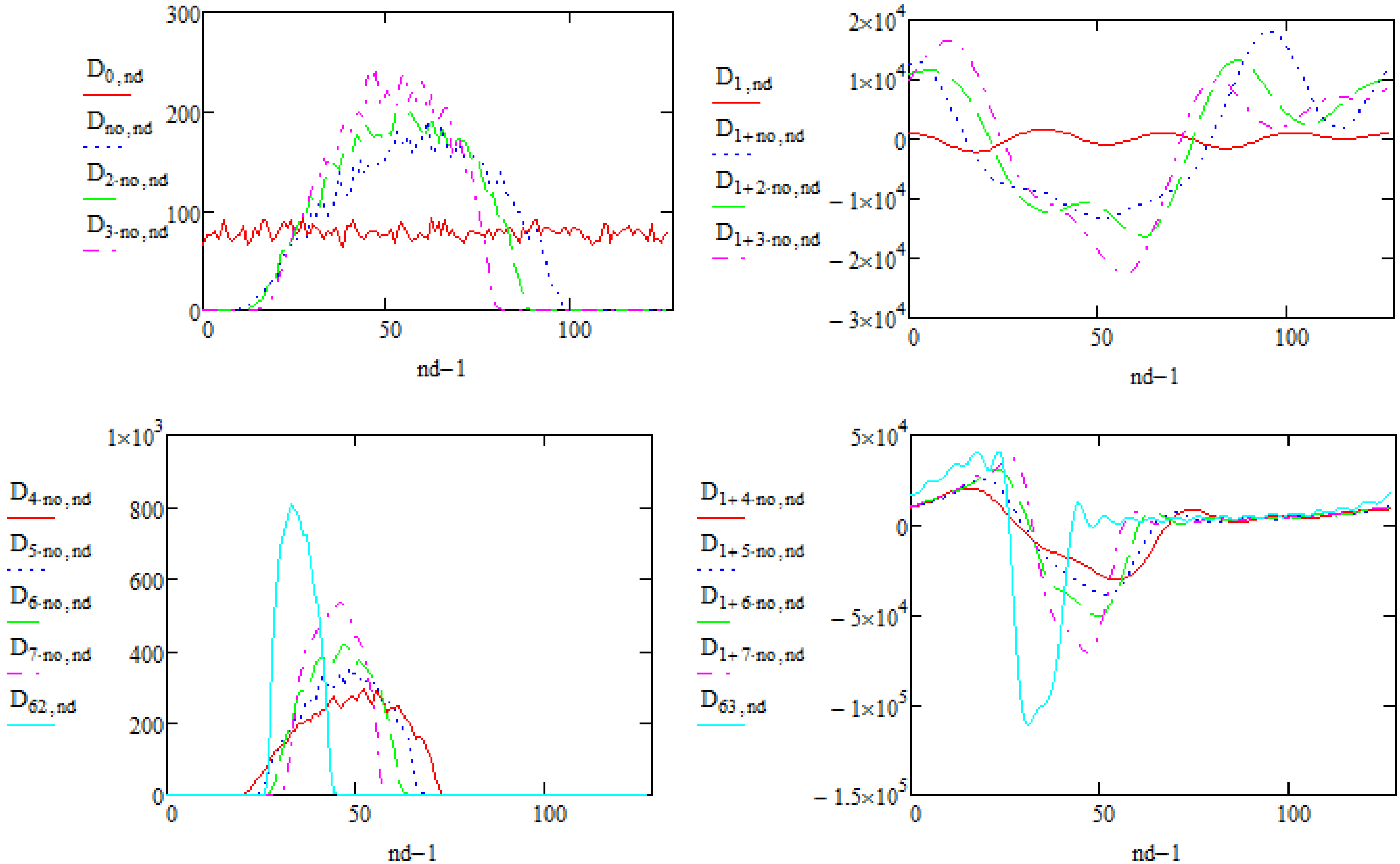


- A longer measurement would help to resolve the problem



Preliminary Simulation Results for 13 Turn Injection (2)

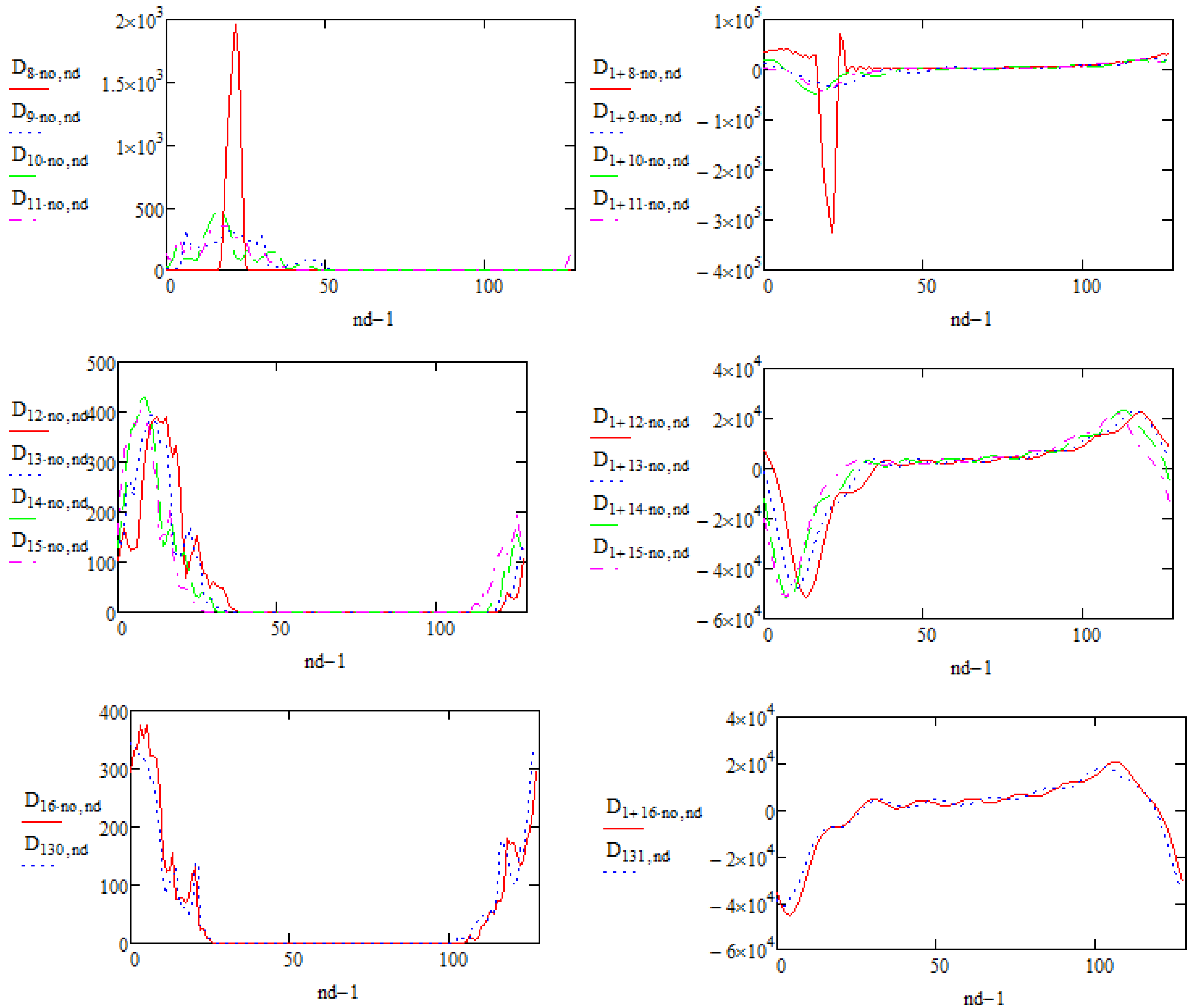
Bunch distributions and voltages before transition



Preliminary Simulation Results for 13 Turn Injection (2)

Bunch distributions and voltages after transition

After transition



Conclusions

- Measurements showed transition crossing details which were not known before
- It is still work in progress
  - 1-2 months are required to match ends for the present transition crossing
  - We need more data
    - Longer times (1 ms -> 2 ms)
- 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 required at PIP-II intensity