Acceleration and Transition Crossing in Booster

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Accelerator Physics and Technology Seminar

April 26, 2016

Fermilab

U.S. DEPARTMENT OF ENERGY

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Outline

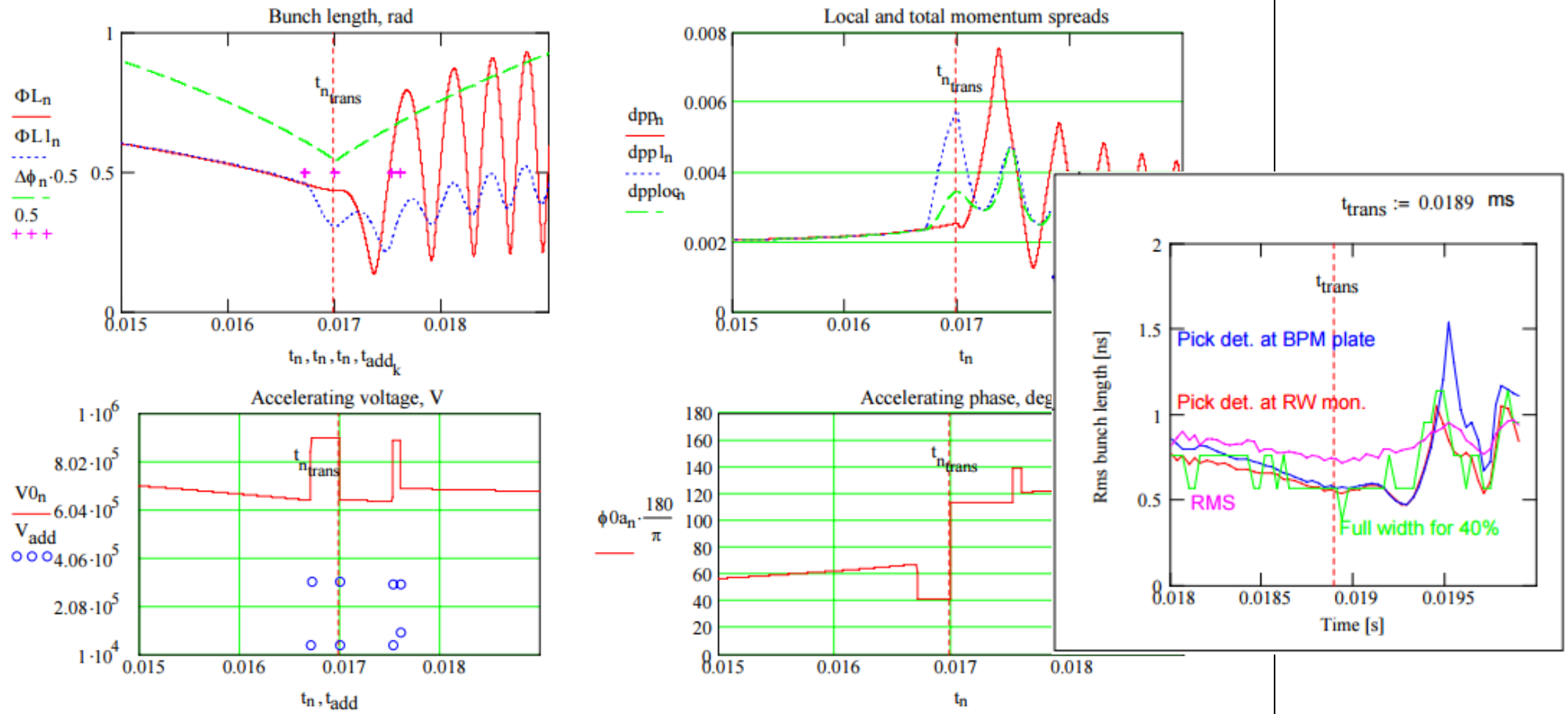
- Introduction
- Booster Longitudinal impedance
- Beam based measurements
- Preliminary simulation results
- Conclusions

Recent History

- Transition crossing has been one of the major bottlenecks limiting Booster intensity
- My involvement to this problem started ~2005 (reported at HB-2006)
  - Change of beam space charge force from repulsion to attraction at transition results in longitudinal quadrupole oscillations ⇒Loss
  - RF voltage jump technique was proposed to suppress it
    - Linear model, V. Lebedev, 2005
    - Simulations, Xi Yang, 2007
  - Empirical tuning of the transition crossing, B. Pellico
    - Formally looks different – in essence it is quite close to the voltage jump technique
    - Has been greatly improved in recent years
  - Both theory and experiment were quite shallow compared to the recent developments considered to be essential for to PIP-II
- PIP-II requires 1.5 times larger intensity within the same emittances
  - Persistent efforts to understand present transition crossing
    - Great improvements both in experiment and simulations

Recent History (1)

Suppression of the bunch self-focusing (actually overfocusing)



Two pulses. Length and time of the second pulse depends on intensity; for 5e12

- First pulse - duration of ~300 μs just before transition
- Second pulse – duration of ~80 μs, 530 μs after transition

Slide from "Coherent Instabilities in Fermilab Booster" presented at FNAL seminar, June 2006

- Impedance of Booster laminated magnets was completely missed in early considerations – Now we see its significance to the problem.

Acceleration of Low Intensity Beam

- At low intensity
  - Linearized motion equations can be integrated
    ("Acc. Physics" by S. Y. Lee)

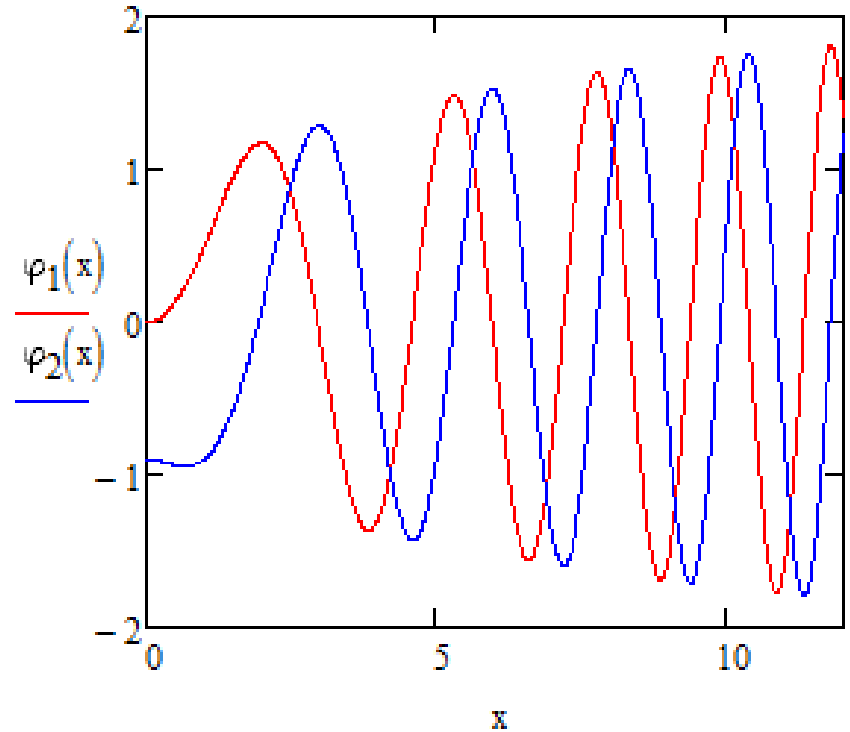
$$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\Delta p}{p}\right) = \dfrac{\omega_0 e V_0 \cos(\varphi_{acc})}{2\pi\beta^2\gamma m c^2}\phi, \\ \dfrac{d\phi}{dt} = q\omega_0\eta(t)\dfrac{\Delta p}{p}, \quad \eta(t) = \alpha - \dfrac{1}{\gamma^2} = \dfrac{2t}{\gamma_t^3}\left(\dfrac{d\gamma}{dt}\right) \end{cases}$$

  - No beam loss and emittance growth at transition
  - For FNAL Booster $\tau_{ad} \approx 200\ \mu s$

$$\tau_{ad} = \left[\frac{\pi\cdot\beta^2\cdot m\cdot c^2\cdot\gamma_t^4}{\omega_0^2\cdot q\cdot e\cdot V_0\cdot\left|\cos(\varphi_{acc})\right|}\cdot\left(\frac{d\gamma}{dt}\right)^{-1}\right]^{\frac{1}{3}}$$

$$\frac{d}{dx}\left[\frac{1}{x}\cdot\left(\frac{d}{dx}\varphi(x)\right)\right] + \varphi(x) = 0 \qquad \text{where: } x = \frac{t}{\tau_{ad}}$$

$$\varphi_1(x) := x\cdot Jn\left(\frac{2}{3}, \frac{2}{3}\cdot x^{\frac{3}{2}}\right) \qquad \varphi_2(x) := x\cdot Yn\left(\frac{2}{3}, \frac{2}{3}\cdot x^{\frac{3}{2}}\right)$$



Acceleration of Low Intensity Beam (2)

At small intensity

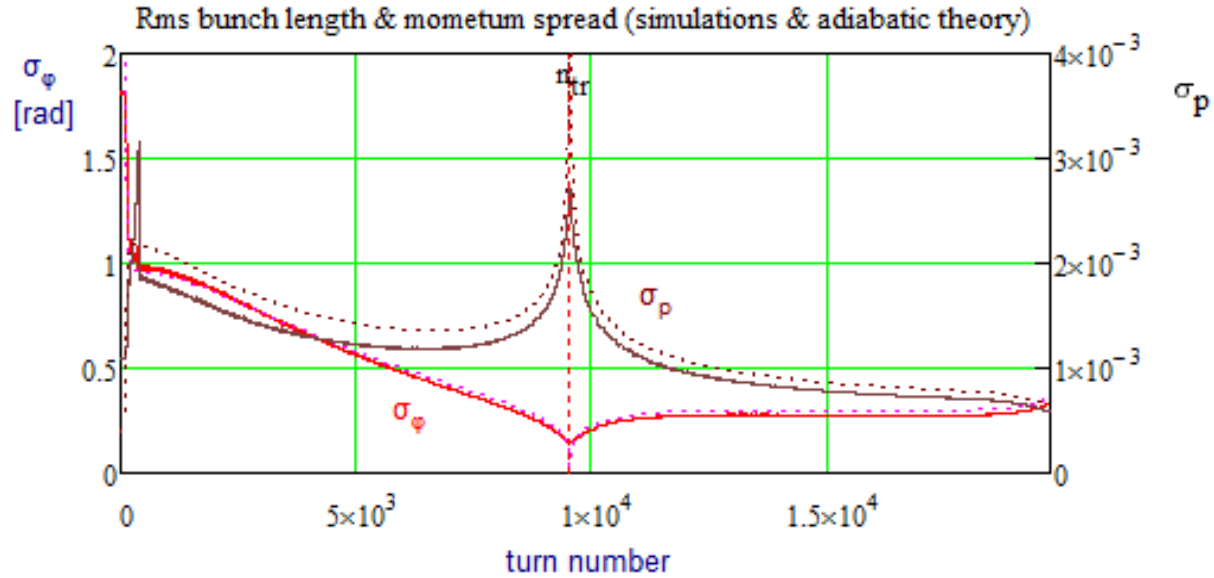
- Operation at 20 Hz with 800 MeV (PIP-II) does not require additional RF voltage for the same RF bucket size

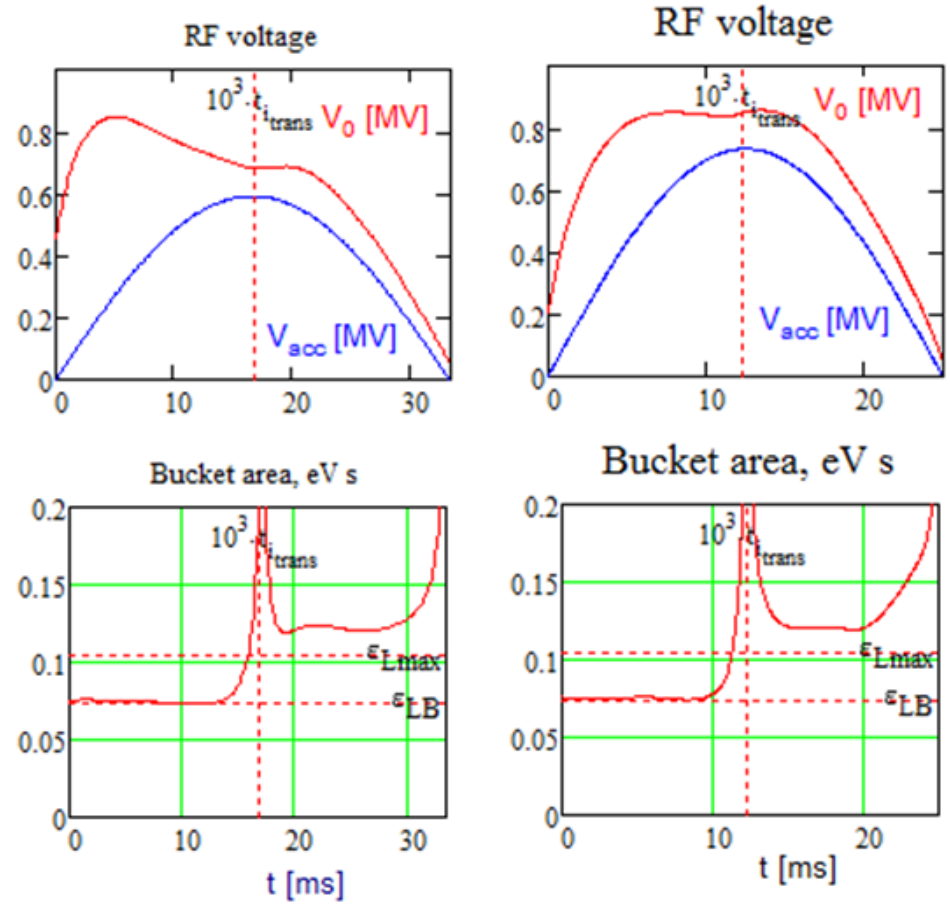
- Bunch length is getting quite short and weakly depends on machine parameters

$$\sigma_\varphi = \frac{\sqrt[6]{6}\,\Gamma(2/3)}{\pi}\,\frac{q^{2/3}\omega_0^{2/3}\sqrt[3]{\tan(\varphi_{acc})}}{(d\gamma/dt)^{1/6}\,\beta_t^{1/3}\gamma_t^{2/3}}\sqrt{\frac{\varepsilon_L}{mc^2}}$$

$$\frac{\sqrt[6]{6}\,\Gamma(2/3)}{\pi} \approx 0.581$$

where $\varepsilon_L = \pi\sigma_p\sigma_s$ is the total aria in the longitudinal phase space (L. emit. expressed in eV s)





15 Hz 20 Hz

Longitudinal Impedance of the Booster

- Two major contributors to the Booster longitudinal impedance
  - Space charge

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

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

    - Decreases fast with beam energy but is still important near transition due to very small bunch length
    - Grows linearly with frequency

      Repulsion below transition

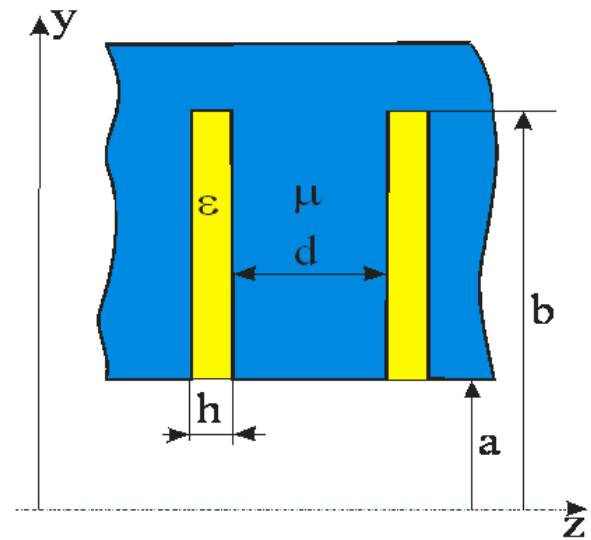
      Attraction above transition

      $\Rightarrow$ Quadrupole oscillations
    - $r_{chamber}/\sigma_\perp = 4$ is used in the simulations
  - Wall resistivity
    - Strong beam deceleration at transition where the bunch has the shortest length ($\sigma_t \sim 0.5$ ns, $I_{peak} \sim 7$ A)

Impedance of Booster Laminated Magnets

- Longitudinal impedance of round pipe per unit length

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



- 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

Permeability of Soft Steel

- At high frequencies the skin depth is smaller or comparable to the magnetic domain size
- Measurements @FNAL in summer of 2011

Proceedings of IPAC2012, New Orleans, Louisiana, USA WEPPD079

MEASUREMENTS OF MAGNETIC PERMEABILITY OF SOFT STEEL AT HIGH FREQUENCIES *

Yu. Tokpanov#, V. Lebedev, W. Pellico, Fermilab, Batavia, IL 60510, USA

- Wave propagation in transmission line made from soft steel and located in external magnetic field

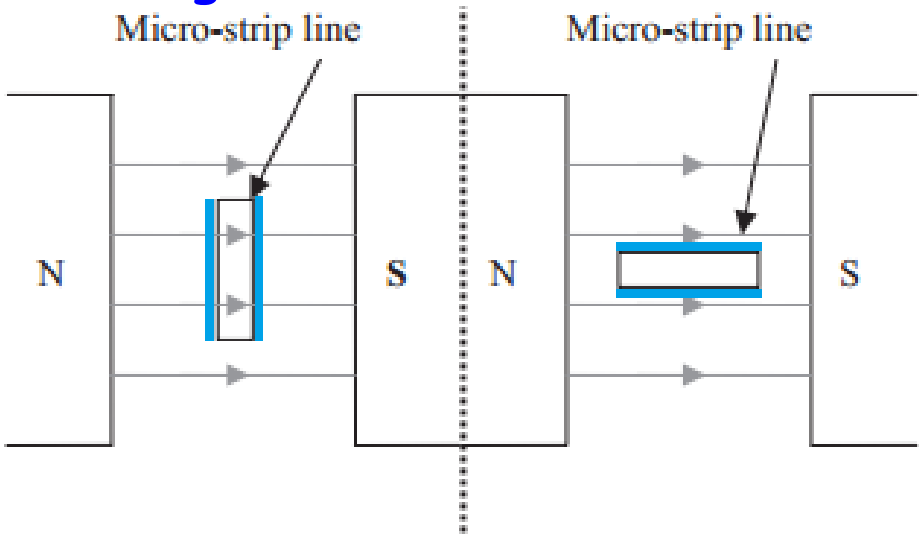
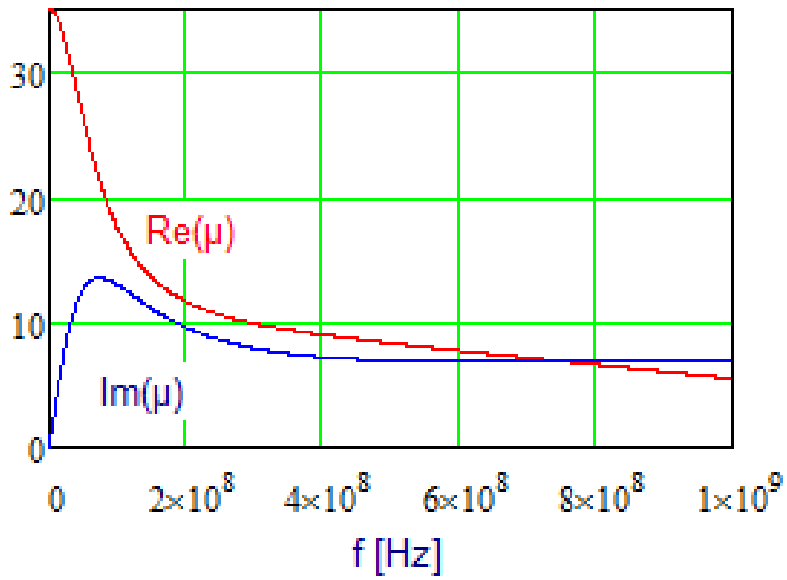


Figure 1: Schematics of the experiment with steel in DC magnet. The normal orientation is represented on the left, and the parallel one on the right.

Permeability of Soft Steel: Results [Tokpanov, IPAC2012]

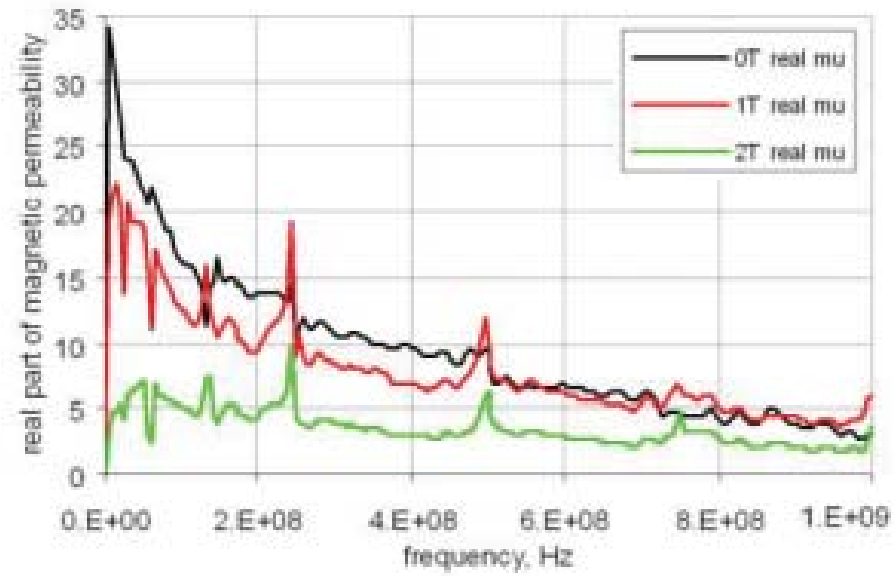
- μ used in the simulations



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

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

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



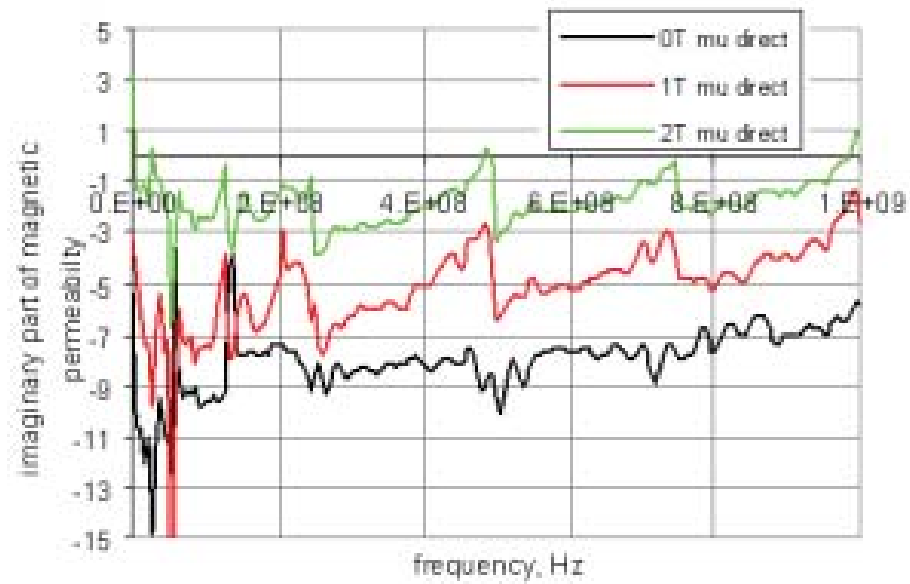
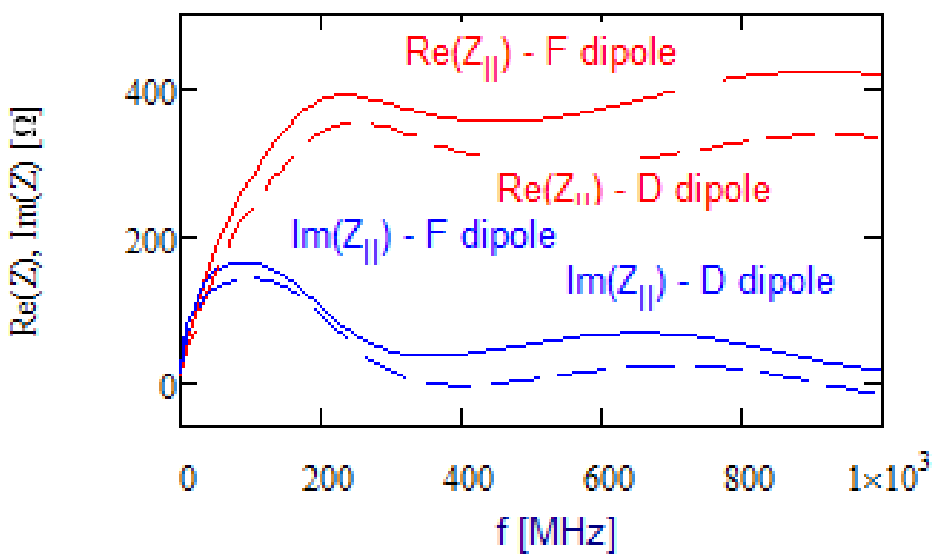


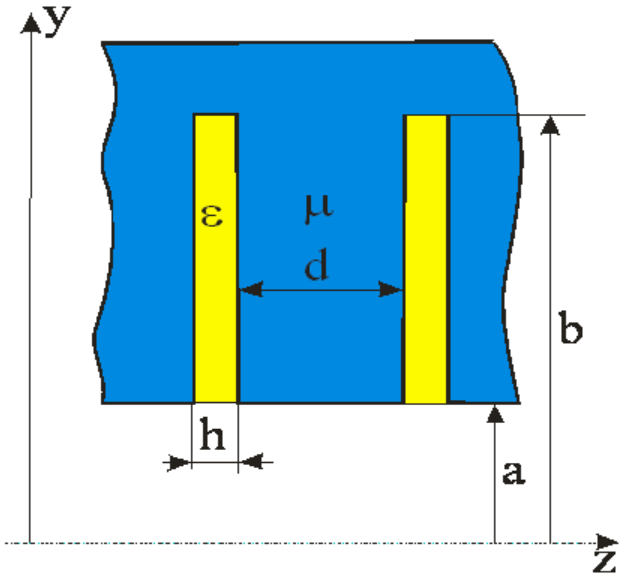
Figure 3: Dependence of magnetic permeability of steel on frequency for different magnetic fields for the case of magnetic field normal to the strip plane.

Parameters for the Impedance Calculation

- Initially *h* was taken from the packing factor 98.5% (Booster design report) and insulating layer thickness: *h*=10+2*10 μm
- ε: epoxy & insulating oxide layer on steel (ε~2 - 3)
- h and ε are updated based on beam measurements
- F dipole has smaller gap and larger impedance

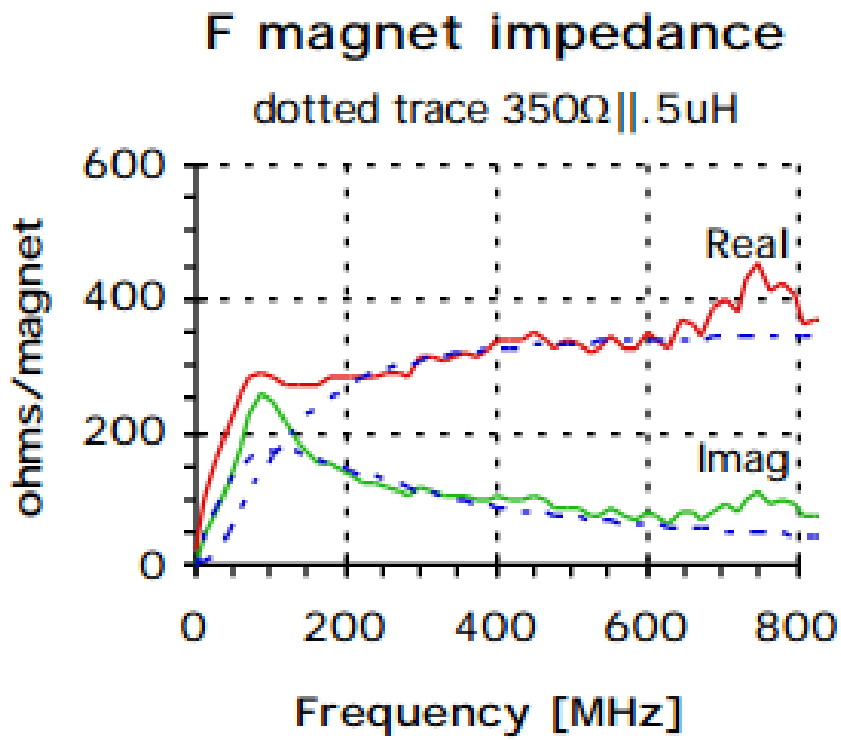
Dipole type	F	D	
Dipole length	2.89		m
Number of dipoles	48	48	cm
Half-gap, *a*	2.1	2.9	cm
Lamina half-height, *b*	15.2		cm
Lamina thickness, *d*	0.64		mm
Dielectric crack width, *h*	45		μm
Conductivity, σ	$2.07\cdot10^{16}$ ($2.3\cdot10^{6}$ Ω^{-1} m^{-1})		s^{-1}
Dielectric permittivity, ε	2.5		

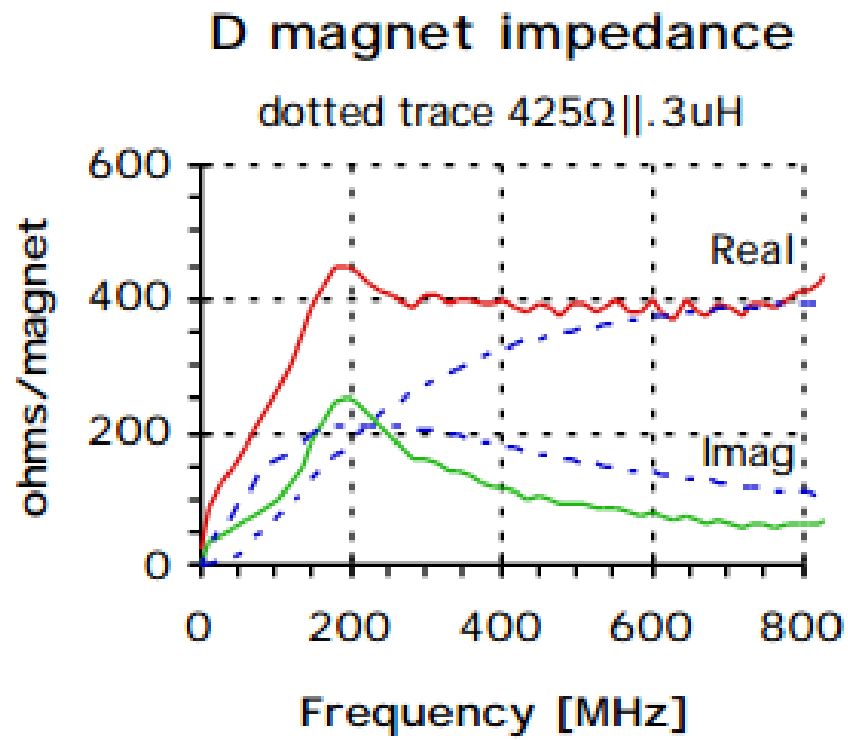




Dependence of longitudinal impedance of Booster dipole on the frequency computed for F and D dipoles.

Stretched Wire Measurements of Longitudinal Impedance of Booster Laminated Dipoles

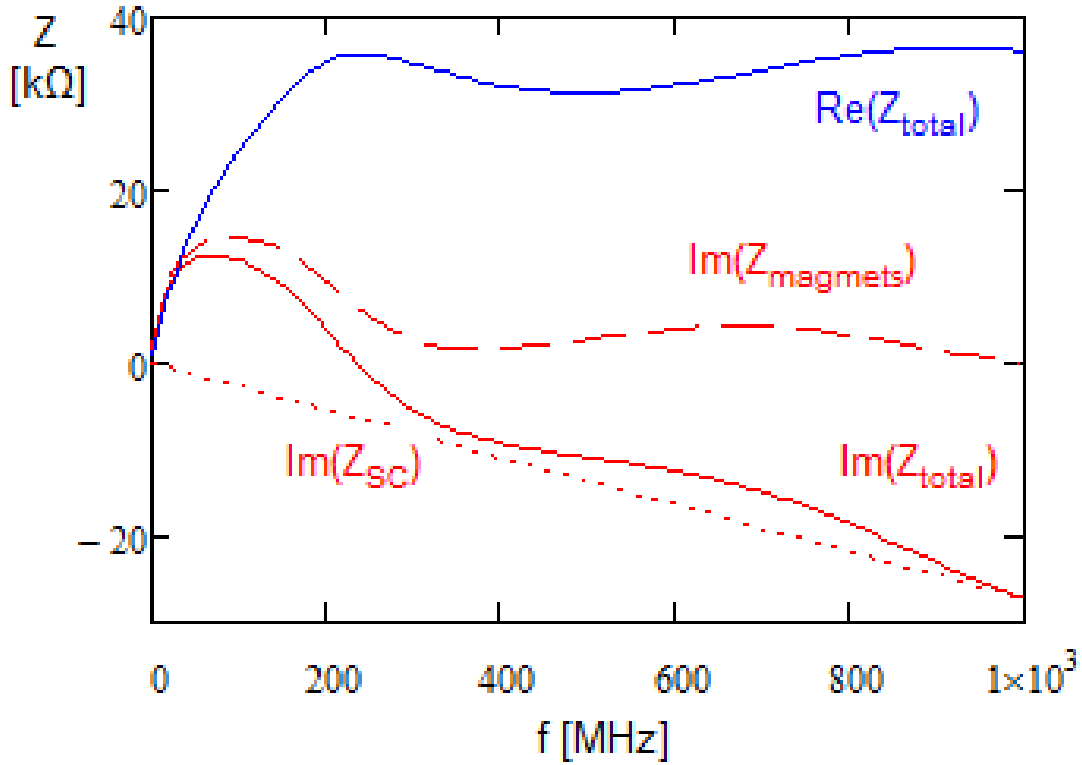




Taken from J. Crisp and B. Fellenz, "Fermilab-TM-2145, March 22, 2001.

- 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**

Total Longitudinal Impedance of the Booster

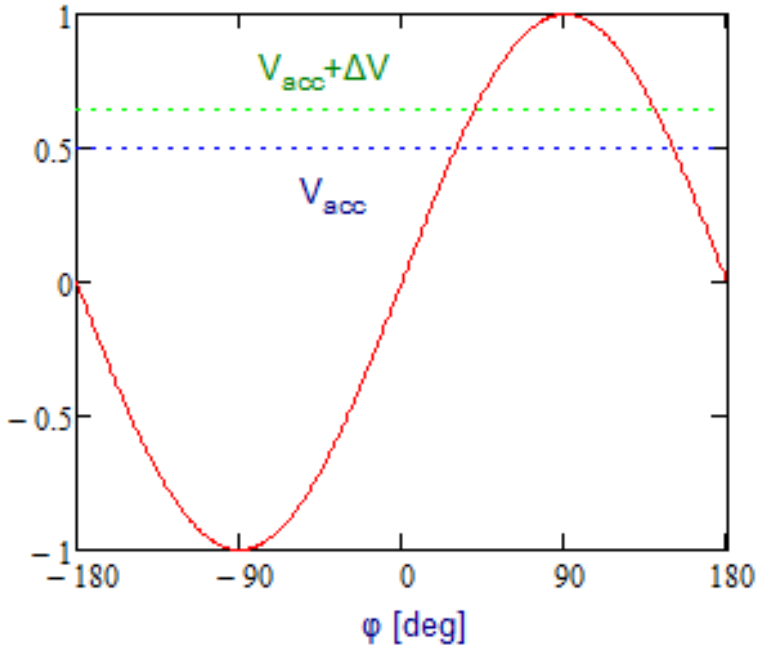


Total longitudinal impedance of the Booster at transition. The impedance value was tuned to the beam-based measurements

- Imaginary part of the space charge impedance is partially compensated by the resistive wall impedance of dipoles
  - At transition the bunch spectrum is extended to 300 – 500 MHz
- Note that wire measurements have noticeably larger imaginary part of the impedance
  - It is not accounted in the below simulations

Beam Based Measurements of the Long. Impedance

- Direct measurements of $Z(\omega)$ requires a continues beam
  - Continues beam does not look readily available even at injection energy
  - It is impossible near or at transition
    - $\mu(B)$ can make significant correction
- Shift of acceleration phase with bunch intensity allows us to check if the considered above model and wire measurements are applicable
  - Minor adjustments are used for the final tune of the impedance model
    - They do not change significantly the shape of the impedance curve
- ϕ_{accel} is obtained from comparison of
  - RF phase (coming from RFSUM) &
  - Bunch arrival time (coming from RW monitor)

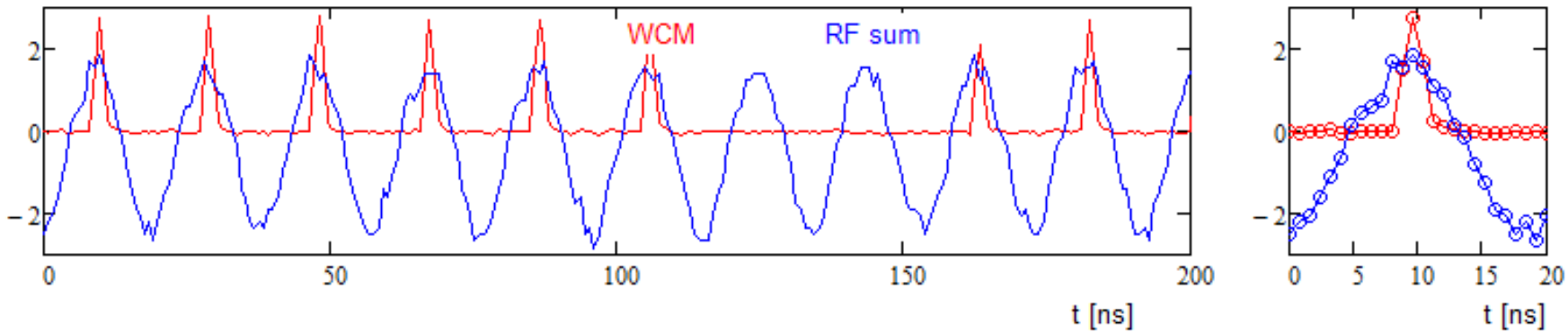


Booster Transition Crossing Studies

- Present transition-X is quiet sophisticated and well-tuned. It effectively suppresses quad-oscillations introduced by the crossing.
- Optimization of transition-X at PIP-II intensity requires good modeling of Booster acceleration and its long. impedance
- 4 sets of measurements
  - Jan, July & Nov /2015
  - Jan/2016)
- Usefulness of data was improved with time
- The last set of measurement is mostly useful and it will be only discussed
  - Data analysis of July'15 data are in PIP-II.doc.db
  - Out of 2 Booster RW monitors the RW monitor with better time resolution was used
- Data are taken at injection and transition
  - Bunch intensities: 4, 8, 12 & 15 turns (2 data sets @ each measurement)
  - 4.8 ms are acquired for each data set
  - Only first 3.6 ms out of 4.8 were used in the analysis due to limitation of data analysis software

Data Acquisition and Preliminary Data Analysis

- RF sum + RWM + Rpos (0.8 ns sampling time, $4.5 \cdot 10^6$points)



- Needed to have sufficiently long measurements (>3.5 ms) => only few points on bunch length for transition-crossing data
- Data analysis
  - Fitting RF signal for each period of sinusoid yields
    - ⇒ (1) RF voltage & (2) zero crossing time
      - o RF frequency is computed from zero crossing time
  - Fitting WCM signal to a Gaussian pulses yields for each period
    - ⇒ (1) Bunch arrival time, (2) Peak height & (3) Peak width
      - o DC offset is not used
      - o Bunch frequency can be computed from Bunch arrival time
  - Time difference between RF zero crossing and corresponding bunch arrival time yields the relative accelerating phase
    - correction for cable length difference has to be additionally accounted

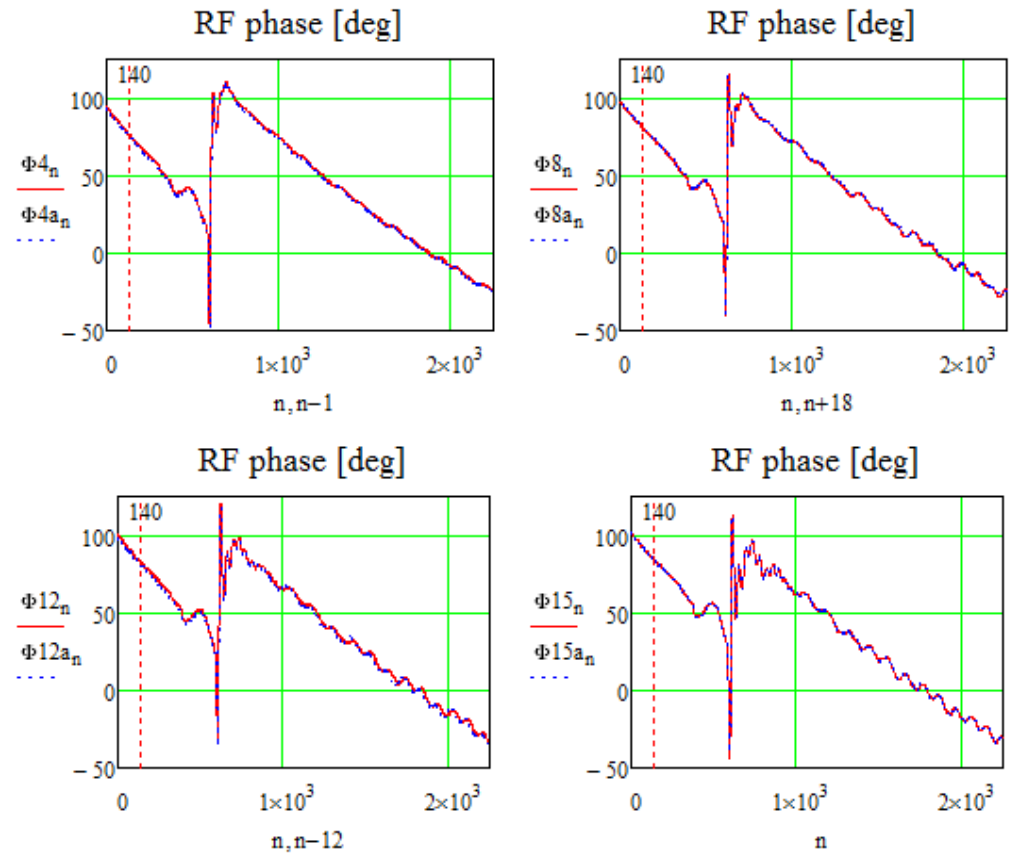
Measurements and Corrections for φ_{acc}

- Good reproducibility for 2 sets at each intensity
  - "Transition RF swing" shifts up to 18 turns
  - Both voltage and phase reproduce well
- There is large phase shifts with energy due to difference in cable lengths

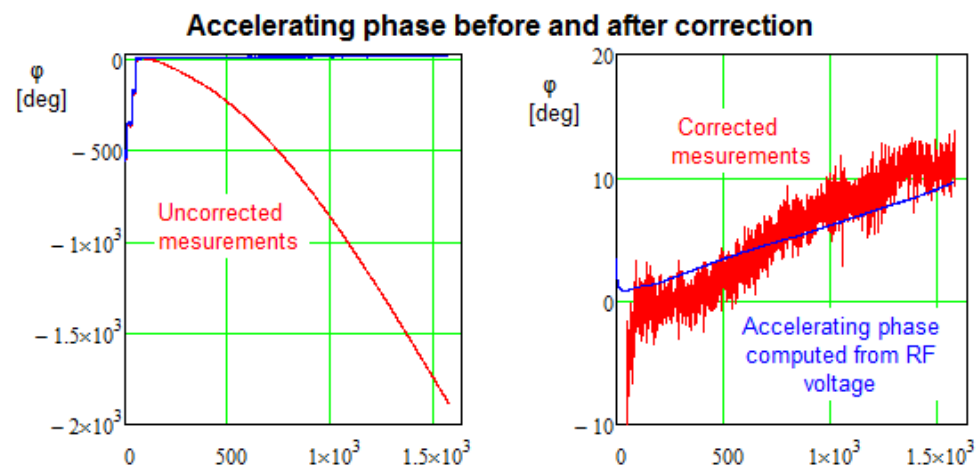
$$\delta\varphi = \left(\omega(t) - \omega(t_0)\right)\Delta T$$

  - Injection data more sensitive to this effect due to larger chance in RF frequency,

    Δt=1.549 μs



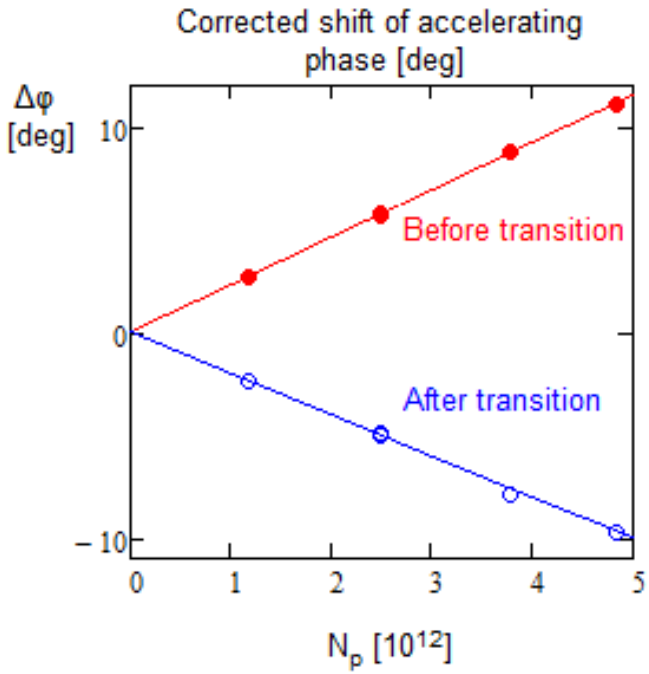
Accelerating phase at transition

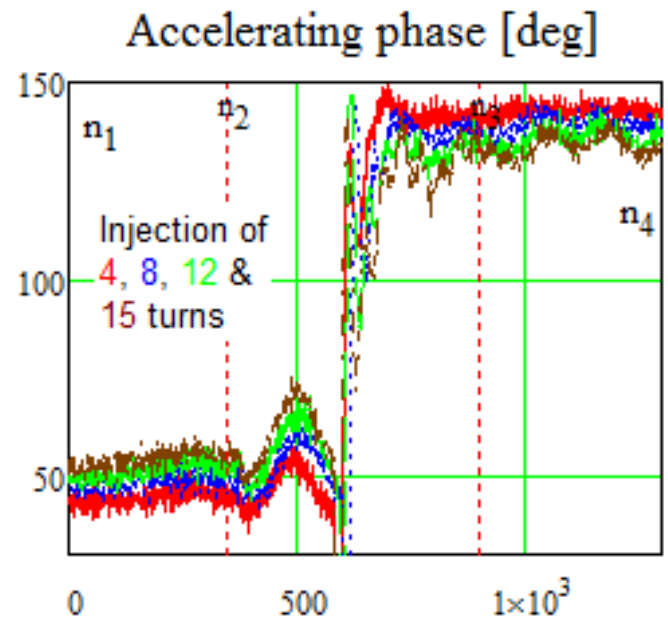


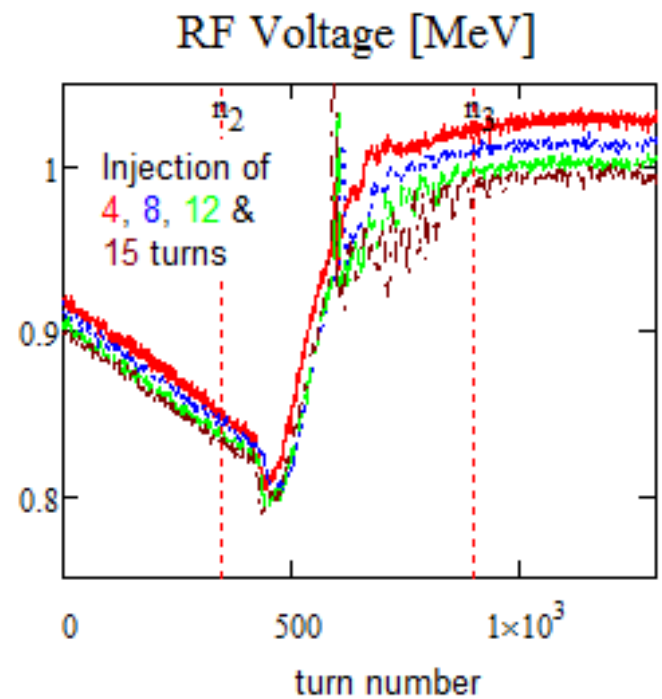
Accelerating phase at injection

Accelerating Phase Shift with Beam Intensity

- The accelerating phase is shifted with intensity close to expectations
- A decrease of RF voltage with intensity increases the resulting shift by ~25%
- Smaller shift after transition is related to larger value of RF voltage after transition



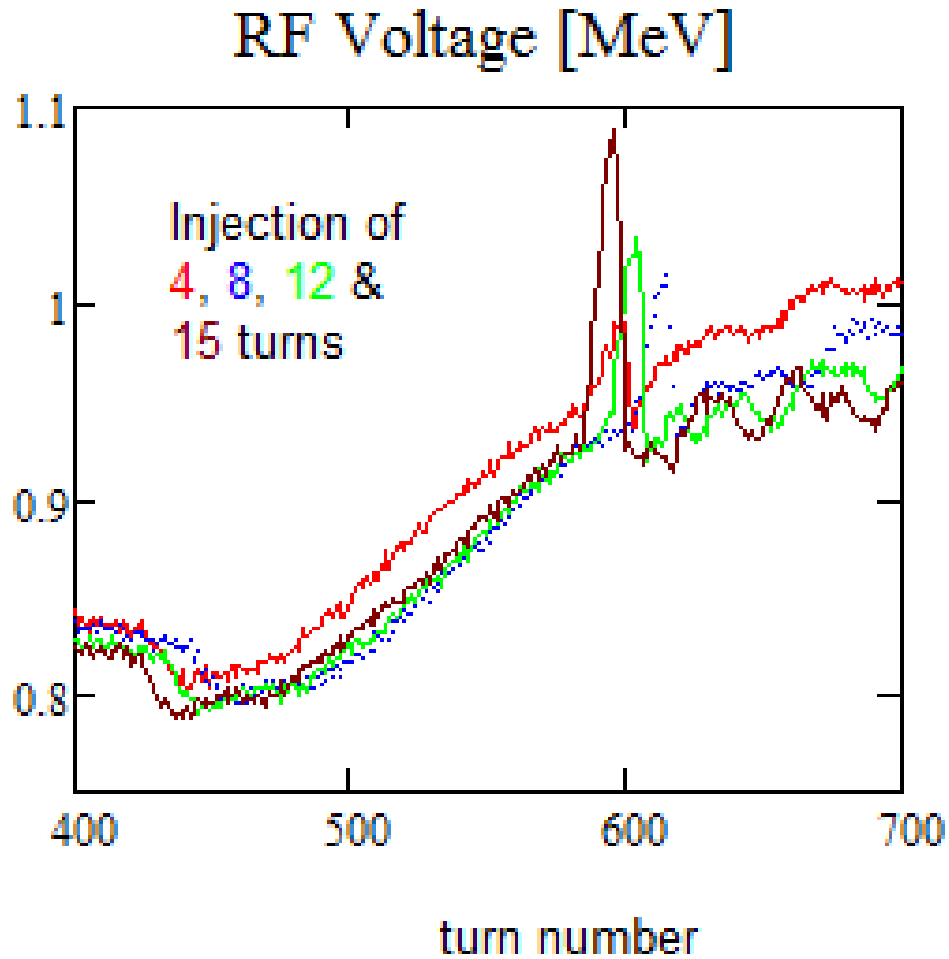




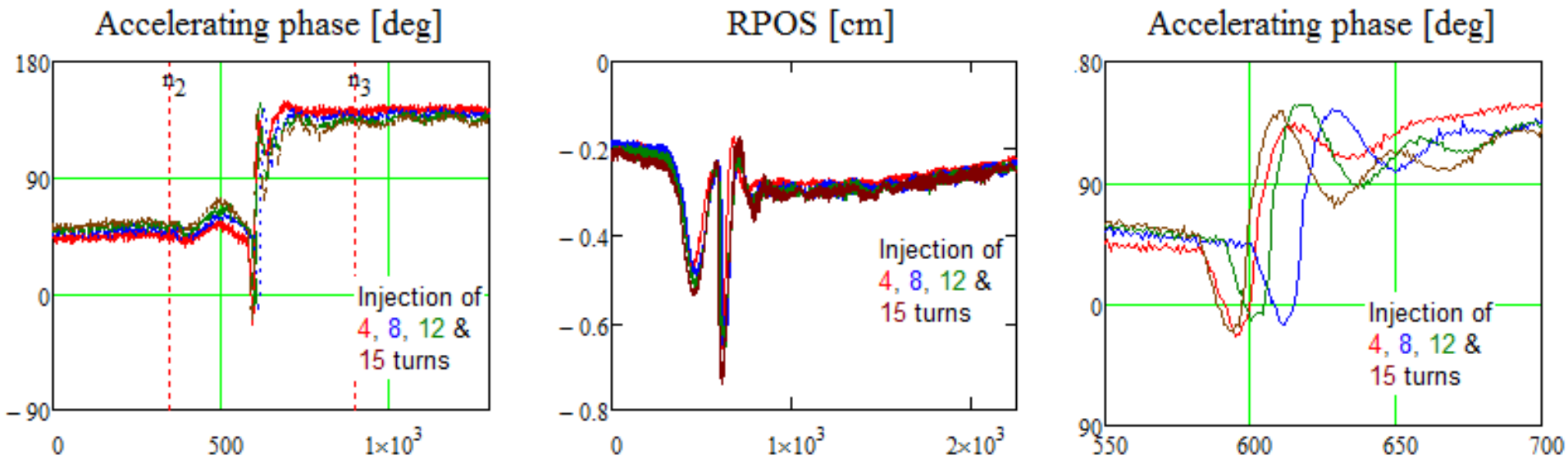
Points presented on the plot are computed by averaging between n_1 and n_2 for data before transition and n_3 and n_4 after transition. An addition due to voltage drop with intensity is subtracted.

Beam Loading

- Accelerating phase shift required by transition crossing changes the beam loading phase and results in a spike in the RF voltage
- Cavity feedbacks mostly suppress the beam induced voltage
  - However short spike of ~150 kV is generated near transition
    - Total shunt impedance of all cavities at transition: R_{sh}=20*145 kΩ
    - Corresponding beam induced voltage (0.5 A) * R_{sh} = 1.5 MV
      ⇒ Suppression is about 10 times

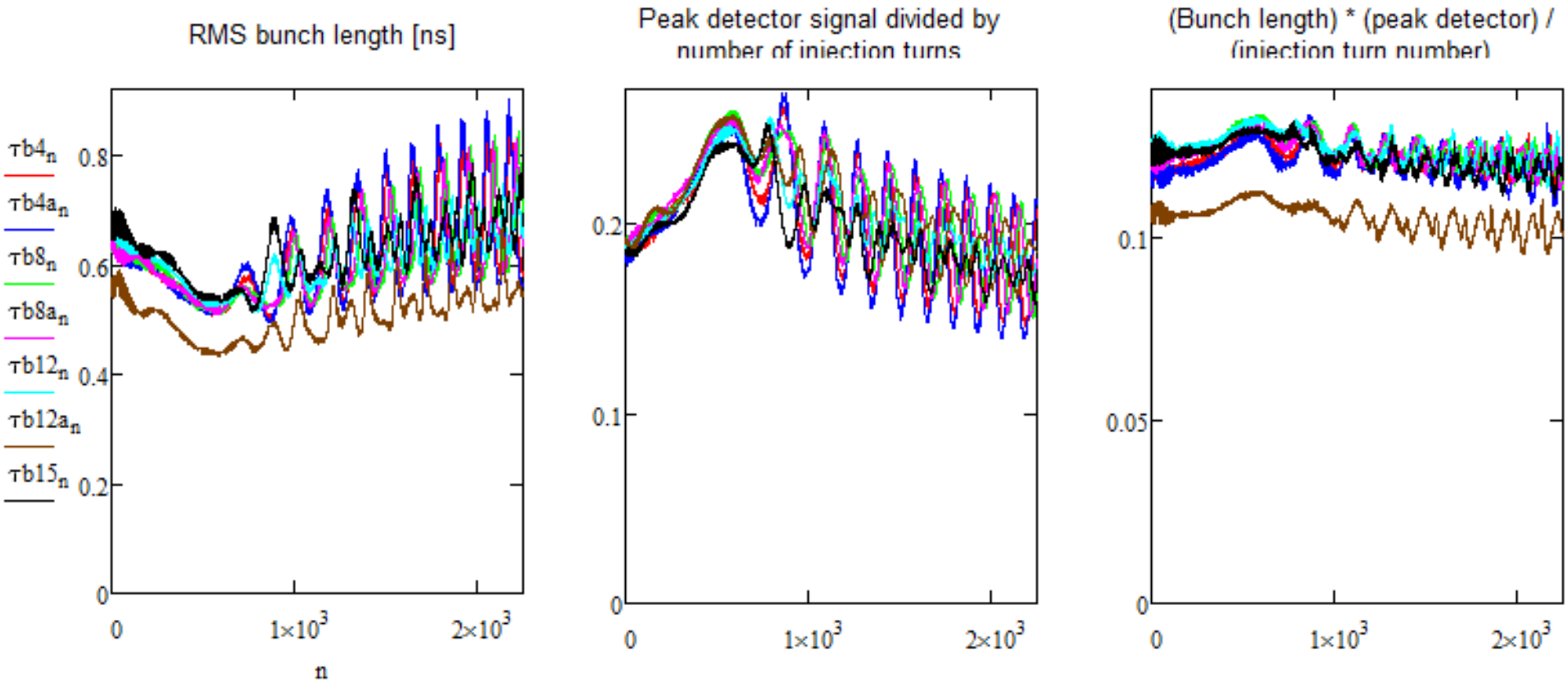


Accelerating Phase Swing Near Transition



- Accelerating phase experiences very large variations near transition (phase swing)
- For about 10 turns the phase is turned to deceleration
- This phase swings results in considerable droop in beam energy clearly see at RPOS

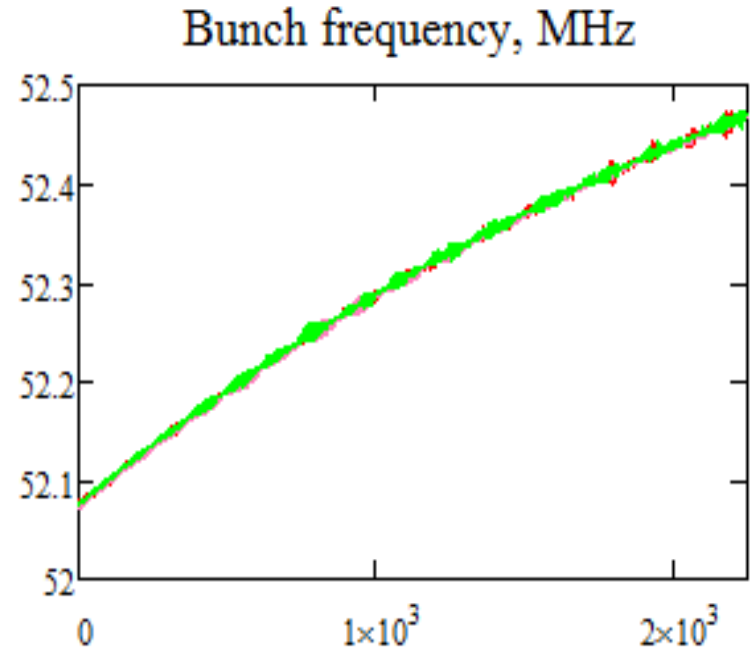
Bunch Length and Peak Detector



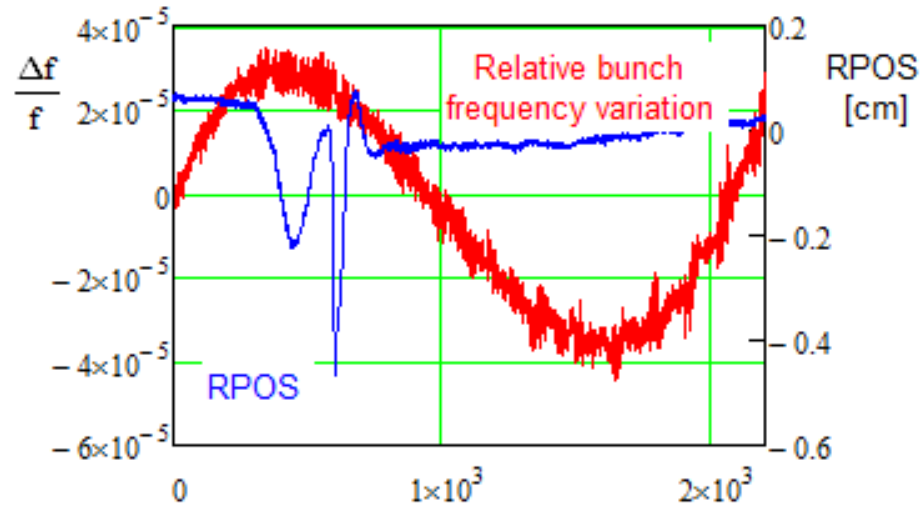
- Bunch length and peak detector are uncorrelated
  - Phase and amplitude of the bunch length oscillations are used to tune simulations to measurements
- Variations of their product are ~5 times smaller but not constant
  - Possible sources are the dispersion in cable and finite time resolution of Resistive Wall Monitor

Bunch and RF Frequencies

- Dependencies of bunch and RF frequencies on time verify timing of the transition crossing measurements
- Variations of RPOS do not produce detectable changes in bunch frequency
- It yields limitations on the slip factor value ($\eta<2\cdot10^{-3}$) and distance from the transition ($\Delta n<250$)
  - Here we use: $\Delta f/f=5\cdot10^{-6}$, $\Delta p/p=2.5\cdot10^{-3}$
- Transition crossing simulations are sensitive to transition crossing location of ~10 turns



$$\left(\frac{\Delta f}{f}\right)_n = \frac{f_n - \left(f_0 + f_p \cdot n + f_{pp} \cdot n^2\right)}{f_n}$$

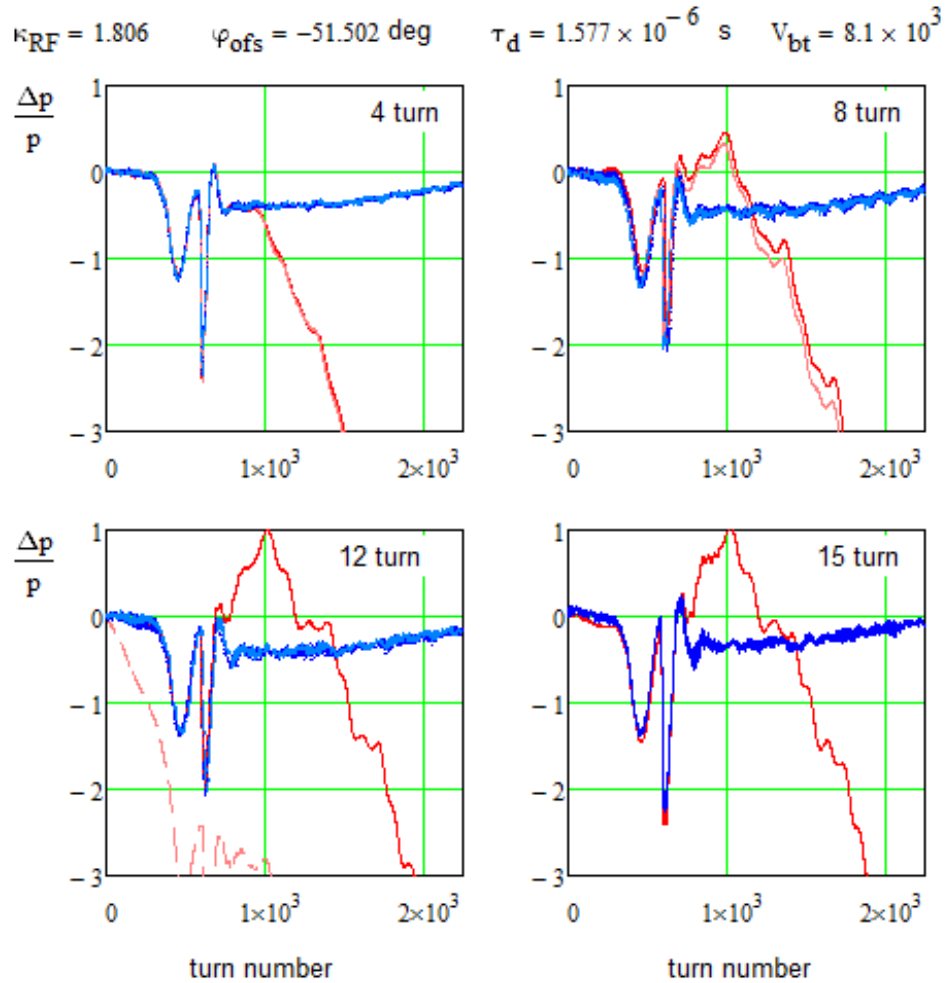


Phenomenological Model

- Reference beam energy at each turn is determined by magnetic field in dipoles: $B(t) = \frac{B_{\max} + B_{\min}}{2} + \frac{B_{\max} - B_{\min}}{2}\cos(\omega_{ramp} t)$
- Beam energy growth is driven by

$$E_{n+1} = E_n + e\left(V_0 \sin\left(\varphi_{acc_n}\right) - V_{beam_n}\right), \quad V_{beam_n} = \frac{A_V N_p}{\tau_{b_n}}$$

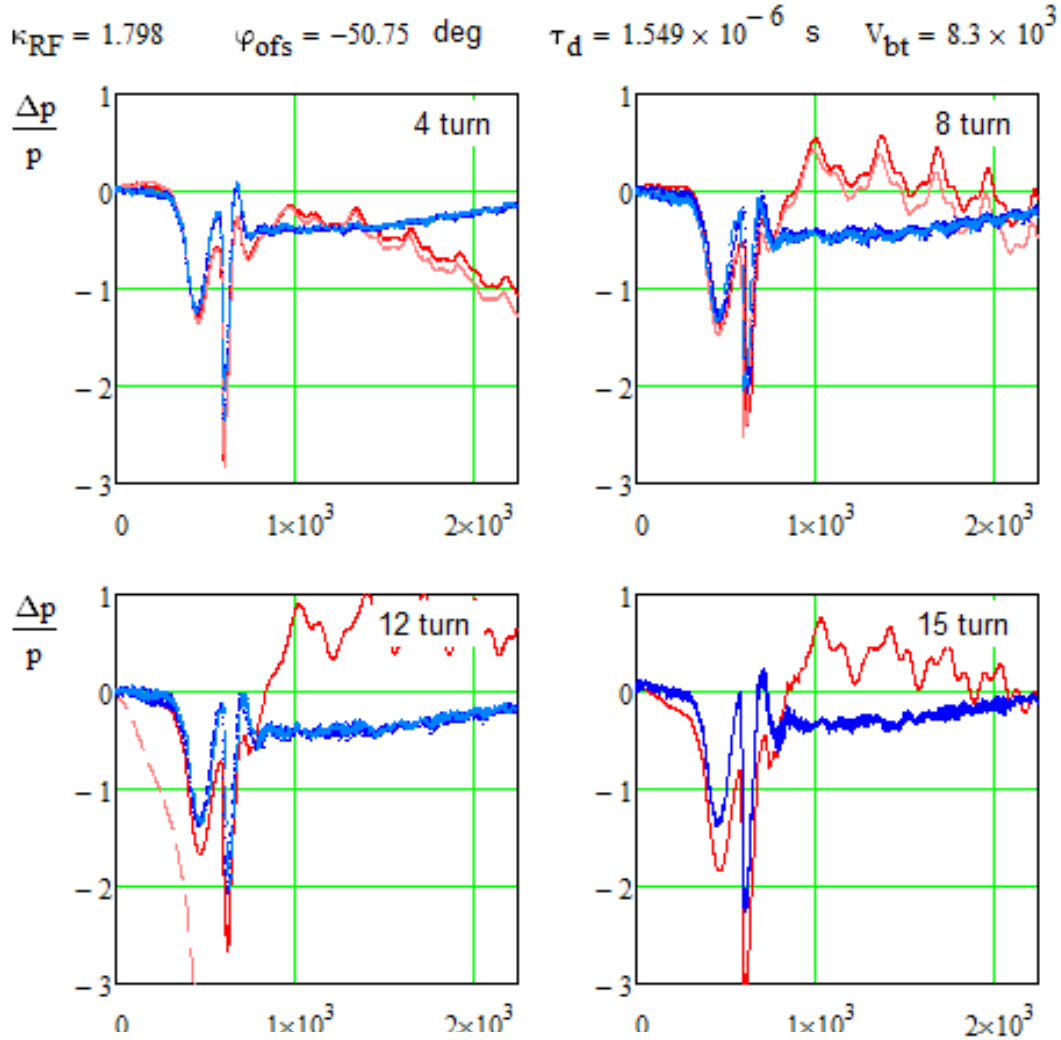
- The difference yields the momentum deviation which is independently measured by RPOS
- A presence of fast RF phase swings near transition greatly helps us to calibrate (1) RF voltage sum, (2) offset of accelerating phase, (3) RPOS and (4) find average beam deceleration due to impedance
  - Differnce is extremly sensitive to minor change in parameter values



Parameters are fitted for the first 900 turns of 4 turn data

Phenomenological Model (2)

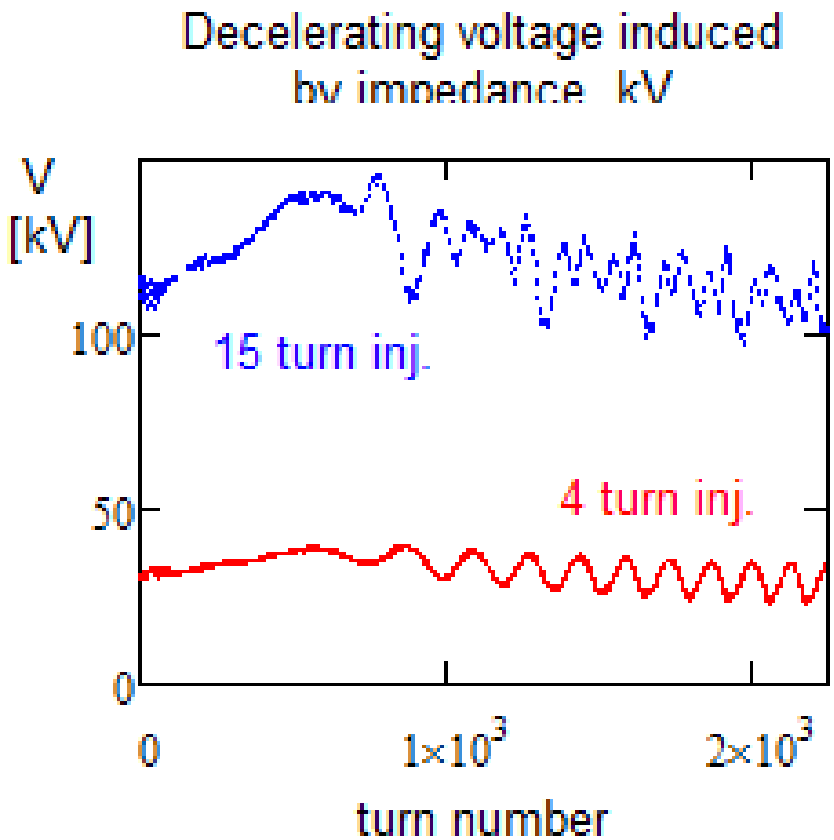
- Fitting the entire set of data does not make significant changes for calibration of RF voltage and phase
  - RF voltage calibration states well within 1% and RF phase within 1 deg.
- It is sufficient for transition crossing simulations
- The reason for discrepancy is unknown: asymmetry of potential well, dispersion in cable can make minor changes in accelerating phase correlated with bunch length, …



Parameters are fitted for the entire sets of 4 and 15 turn data

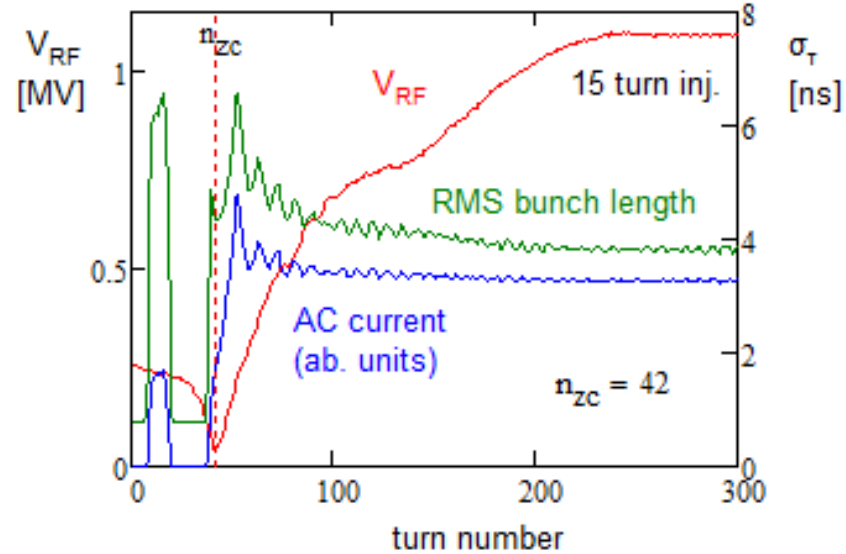
Signal Calibrations Resulting from Data Analysis

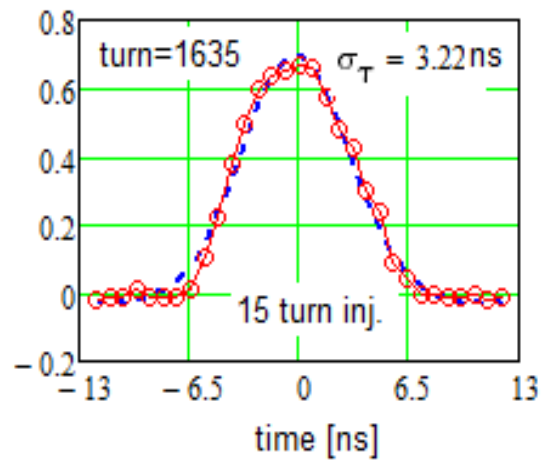
- Data analysis yields:
  - Total RF voltage: $V_{peak}=(1.8\pm0.01)\cdot10^7\ V_{RFsum}$
  - Calibration of RPOS for $\Delta p/p$ @ transition: $\Delta p/p = 0.067*RPOS_{(V)}$
    - ~1.25 times smaller than expected (D=180 cm, dx/dV = 15 cm/V) corresponding to D_{eff}=225 cm
  - Peak decelerating voltage average over the beam distribution is ~140 kV for 15 turn injection
- Voltage calibration at injection cannot be accurately derived from the data
  - It is determined by quality of RF sum circuit and is unknown
  - The same voltage calibration as at transition is assumed
- RPOS calibration at injection is different due to optics changes but it is insignificant for numerical simulations

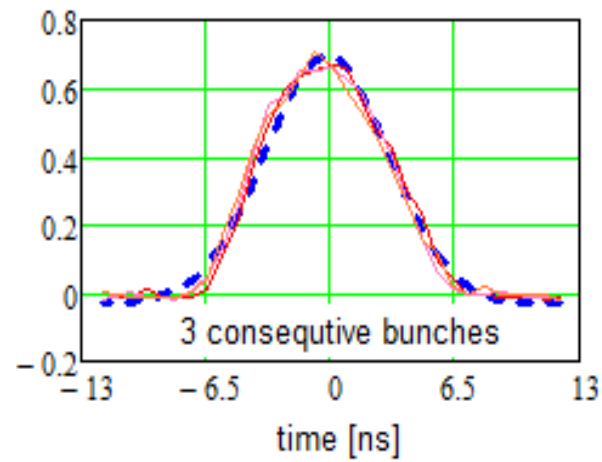


Measurements of Adiabatic Bunching

- Bunching takes about 50 turns yields the longitudinal emittance
- Dependence of bunch frequency on time yields time of magnetic field minimum and injection energy for the reference particle (as well as the energy of injected beam)
  - Typically Bmin is achieved at turn ~40
- After bunching the bunch profile is close to a Gaussian with slightly truncated tails
  - Fall time is increased due to dispersion in the cable and finite resolution time for RWM, and asymmetry of RF bucket due to acceleration (opposite effect after X)
  - Lumpiness resulting from injection are well observed to about turn 600

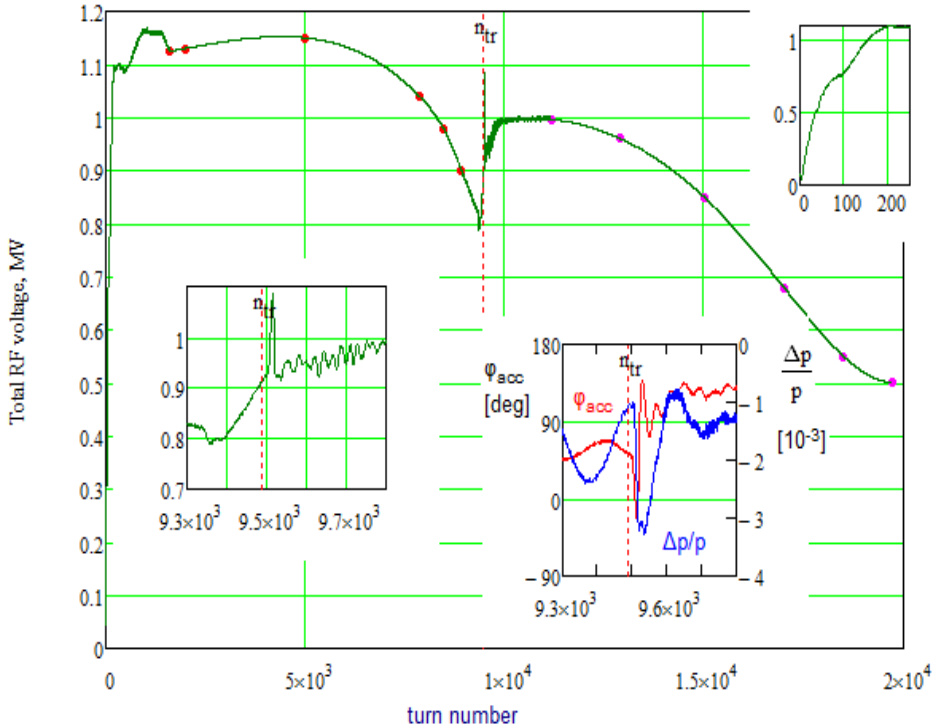


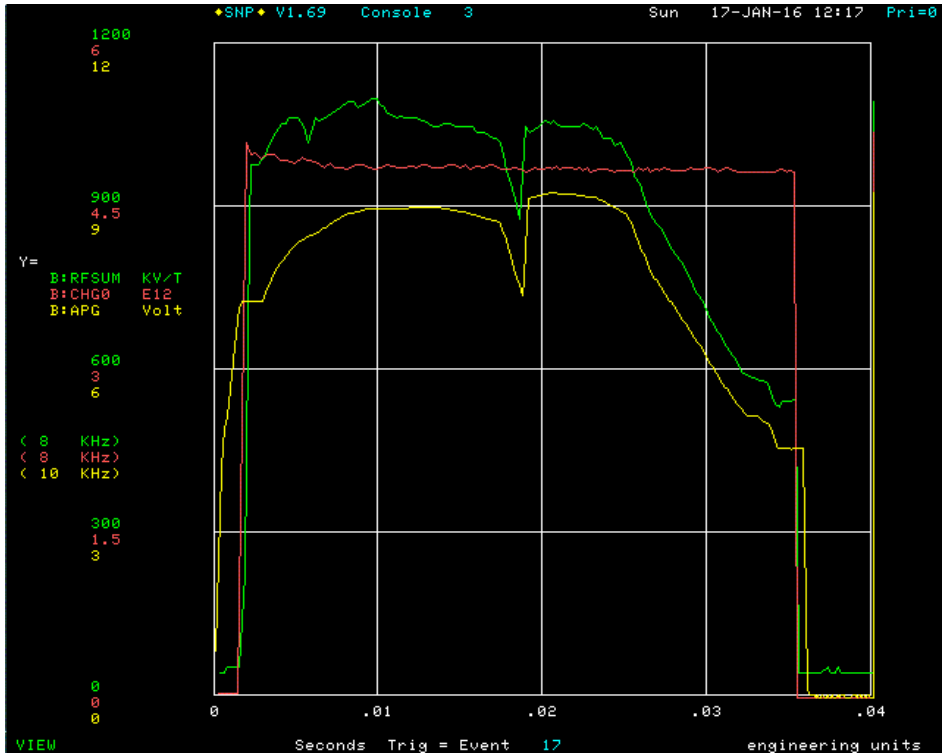




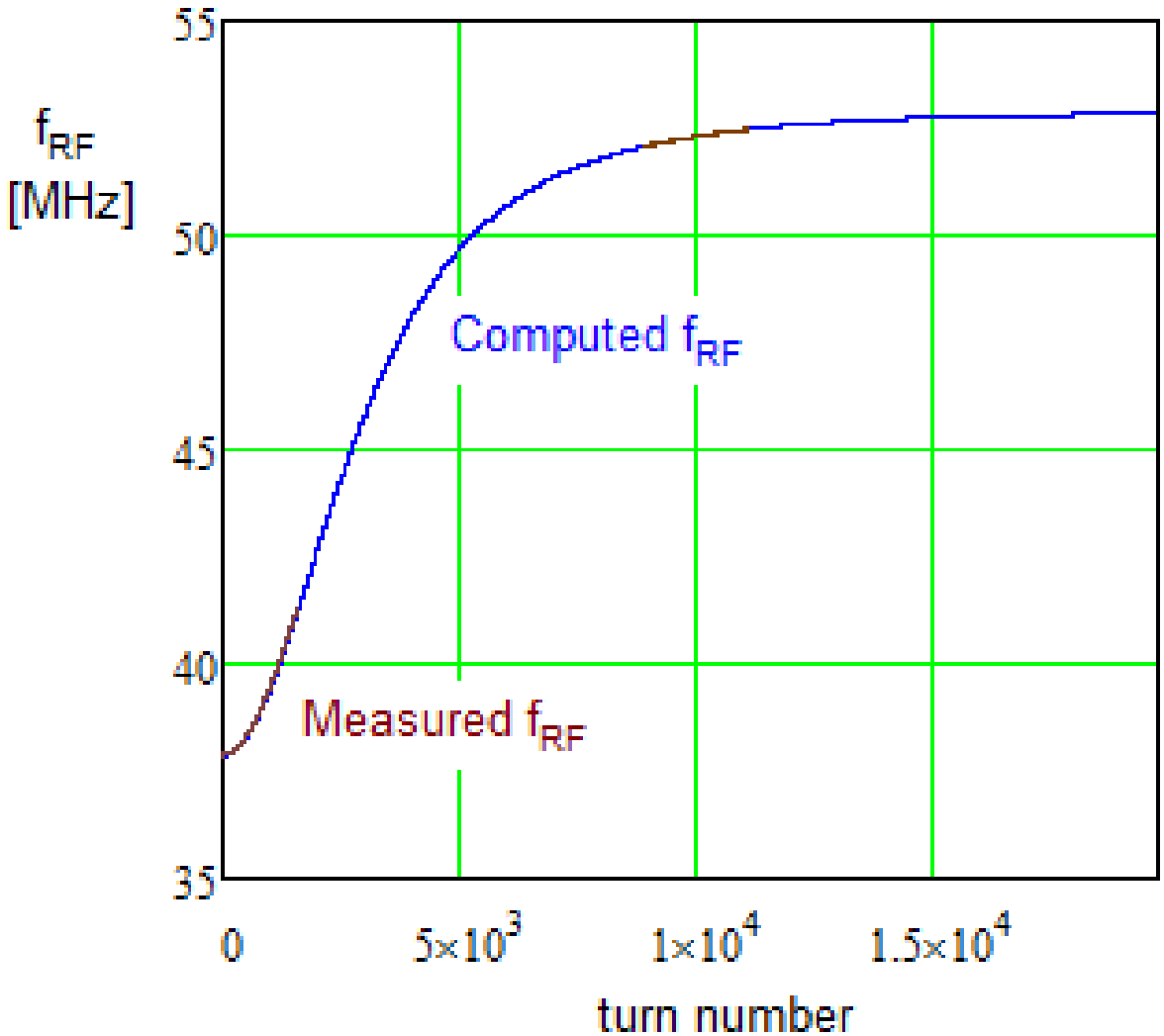
RF Voltage for Numerical Simulations

- RF wave form is built from measured RF voltage at inj. & around X
- RF wave form was interpolated for the rest of the cycle
  - Minor inaccuracies of interpolation are irrelevant to simulations
  - There is about 10% discrepancy between RF sum measured directly with scope and delivered by Control system
    - Origin has to be traced down
- Time of transition wave form was adjusted relative the transition crossing time based on simulation results





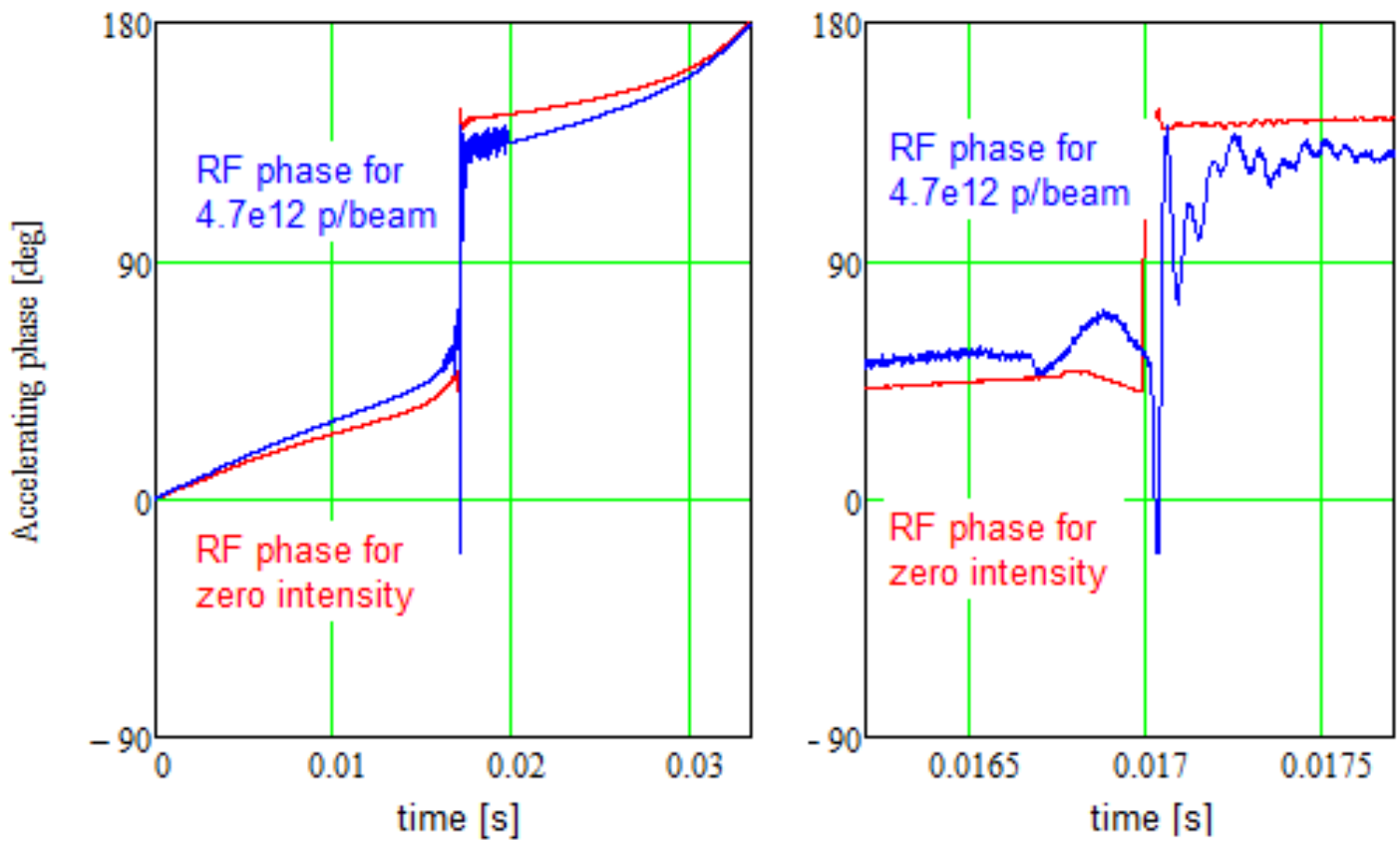
RF Frequency in Numerical Simulations



- Measured RF frequency well coincides with the model for injection and extraction energies of 0.400 and 8 GeV

Accelerating Phase in Numerical Simulations

- Beam automatically adjusts correct accelerating phase due to motion adiabaticity
- However it does not work near transition
  - Measured RF phase was used
    - Additionally a numerical dipole feedback kept the beam momentum offset at the measured values (RPOS)



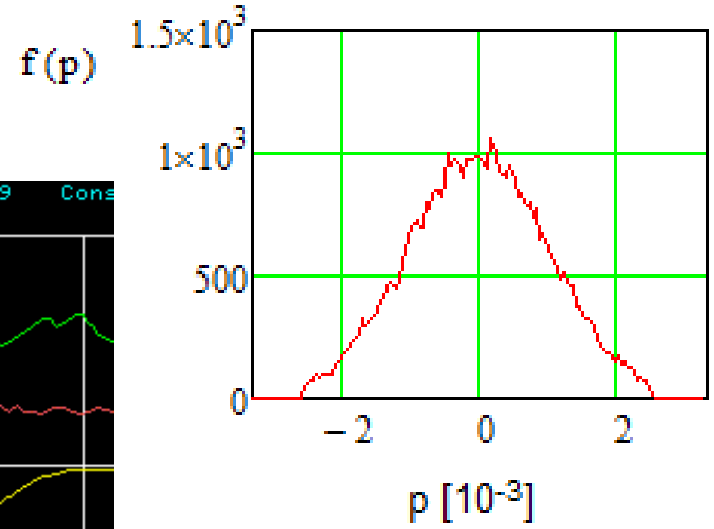
Simulation Program

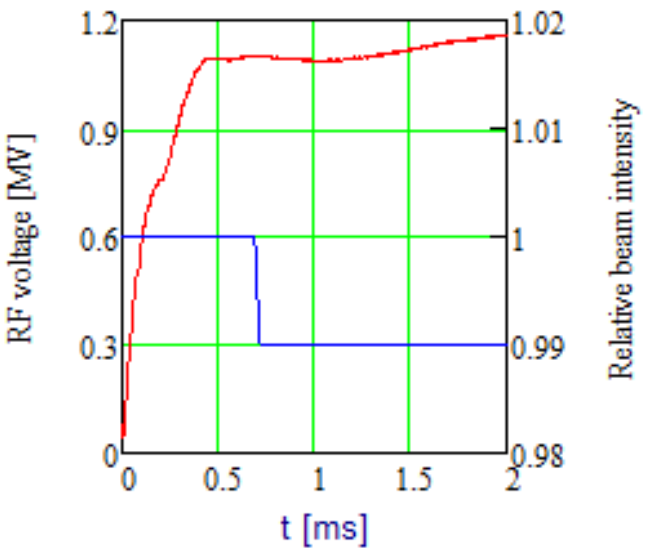
- Combination of C-program (computations) and MathCad (GUI)
- Accounts for impedances of dipoles and space charge
  - Implies 84 equal intensity bunches
  - Impedances of dipoles is calibrated by the measured RF phase with intensity
  - Measurements do not exhibit significant difference in behavior for bunches in vicinity of the abort gap
    - Both impedances (space charge & Res. Wall) are short range
  - Two dampers
    - Dipole – operates similar to RPOS feedback
    - Quadrupole – feedback on oscillations of bunch length
  - Beam can be unstable above transition if dampers are not engaged
    - At large intensity can result in large beam loss (>50%)
- New GUI driven software is at the initial stage (F. Ostiguy)
  - Takes into account accumulated experience
- Simulations for the largest measured intensity (15 turn) are only presented below

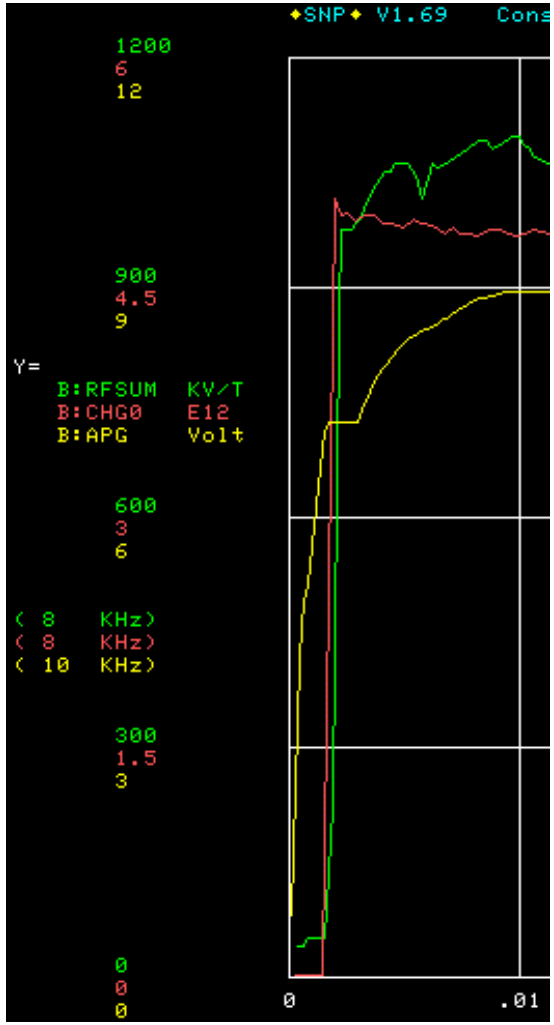
Adiabatic Bunching and Initial Longitudinal Emittance

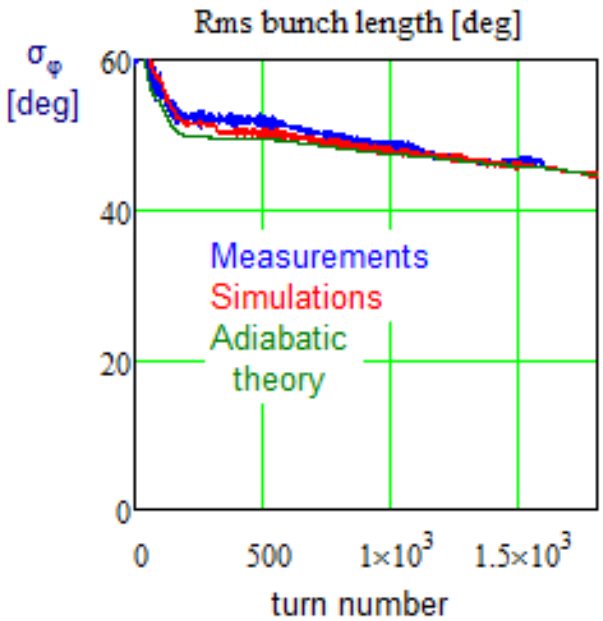
- Longitudinal distribution is Gaussian in momentum with tails truncated at 2.4σ
  - Its width was adjusted to match bunch length measured at injection
  - Beam loss in simulations of 1% is also comparable to what has to be expected from measurements

Initial momentum distribution used in simulations

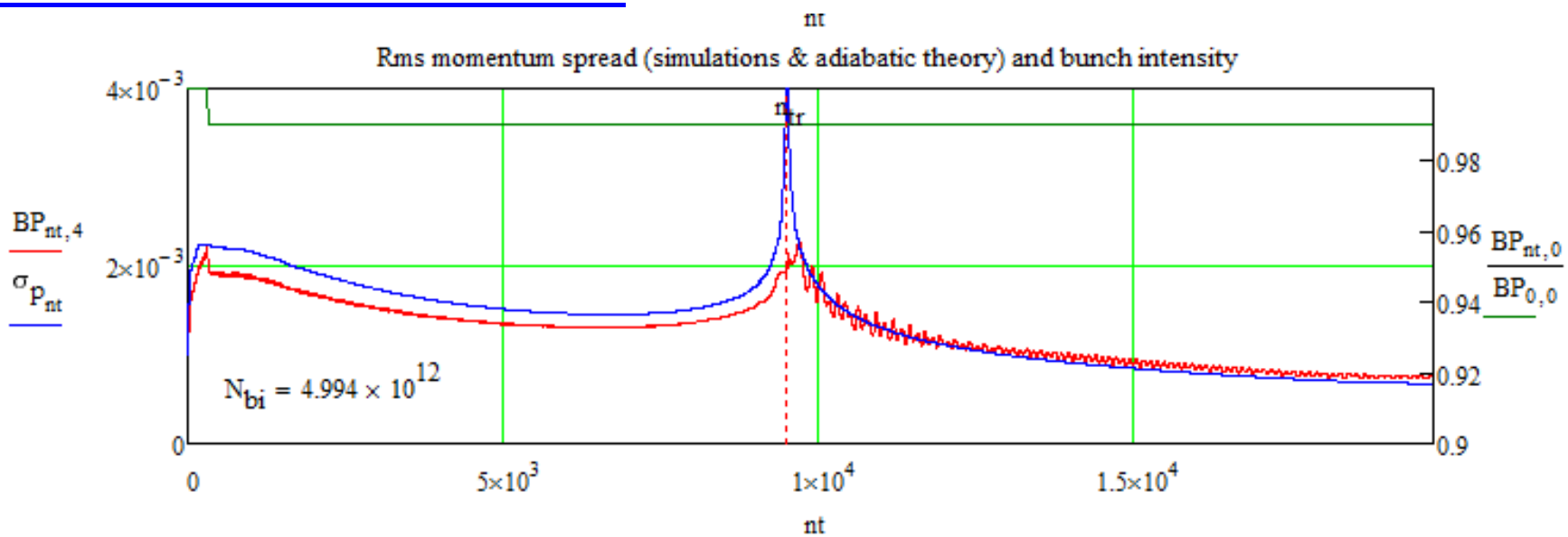




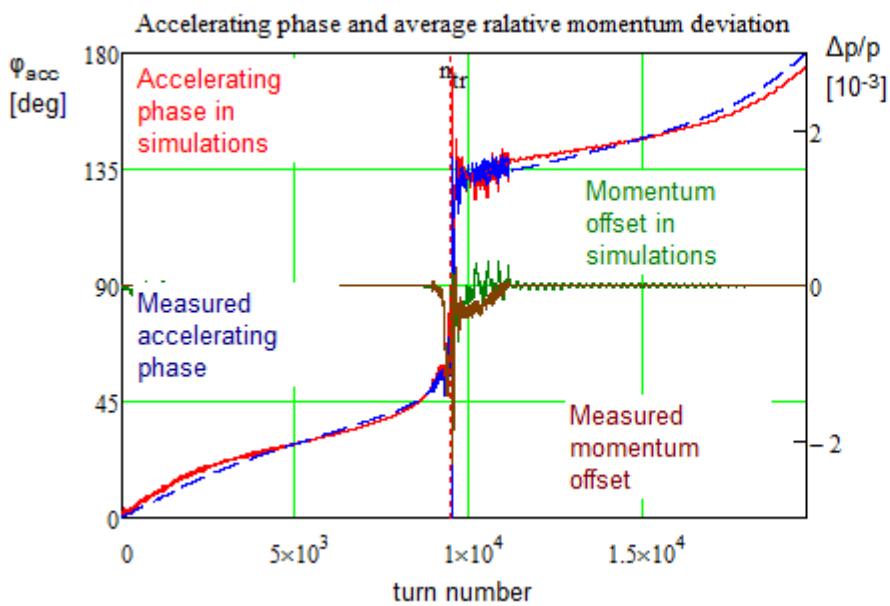


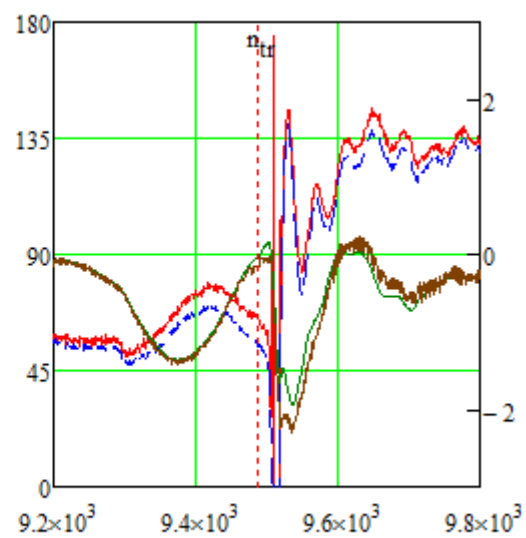


Simulation Results



- Same is in the measurements there is no beam loss due to transition

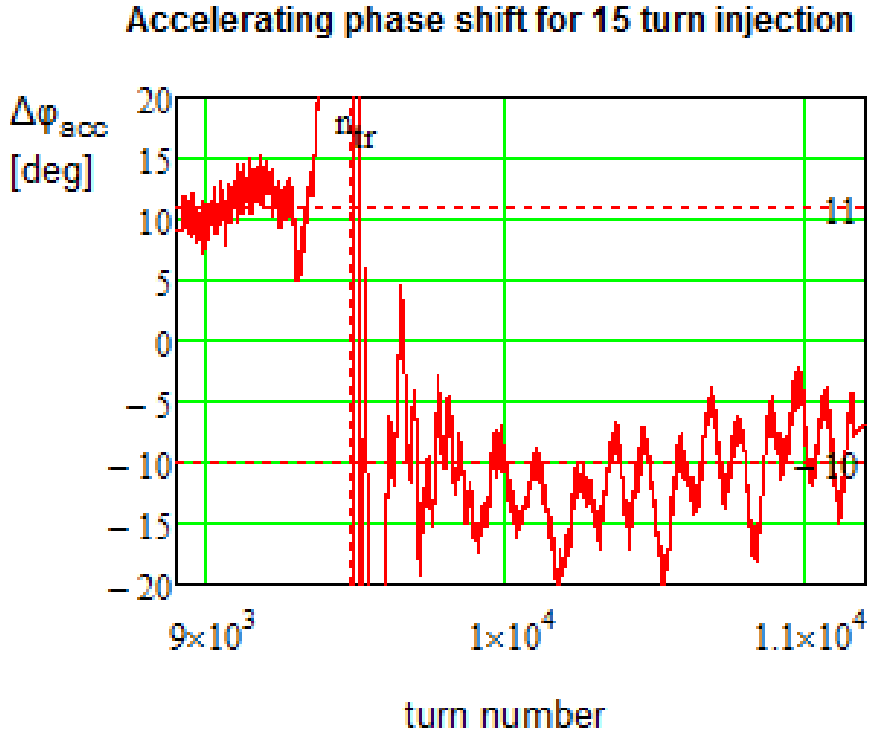


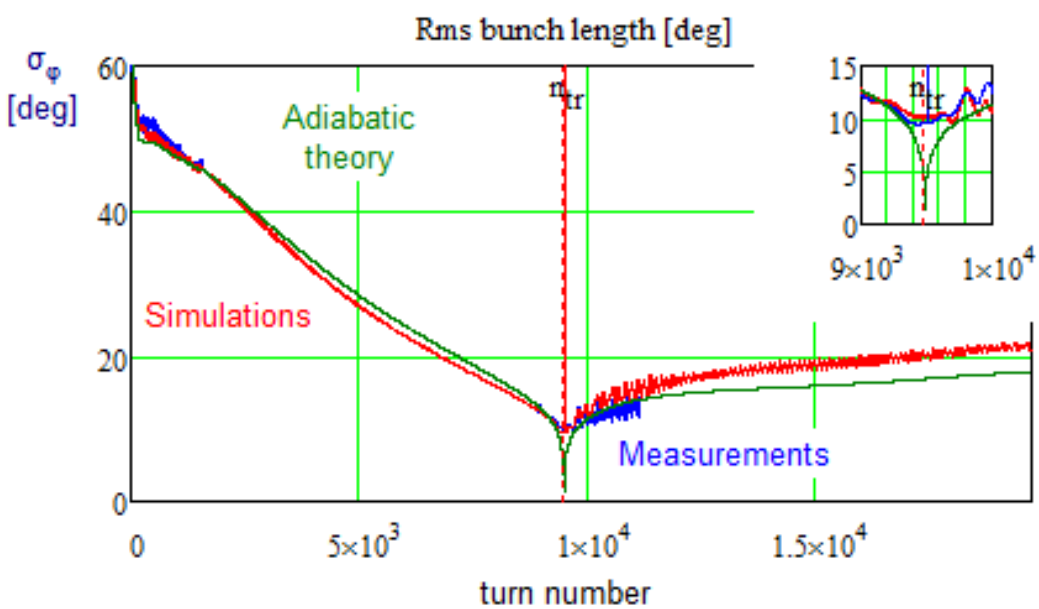


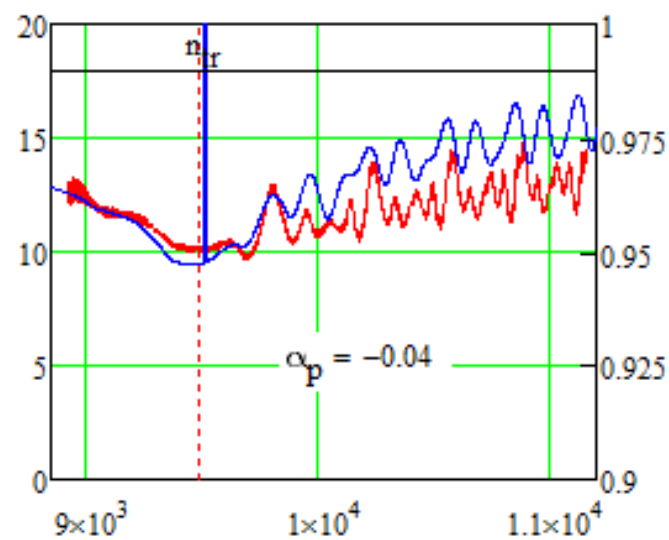
- Momentum offset & φ_{acc} are close in measurements and simulations

Simulation Results (2)

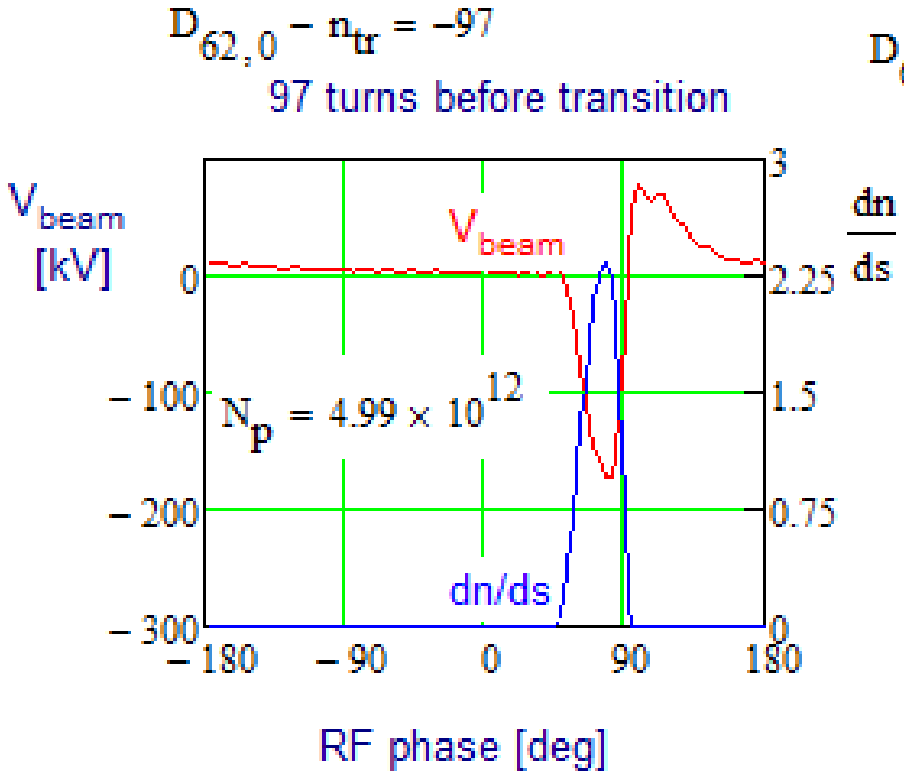
- The accelerating phase shift due to impedance is the same as measured
- The same as in measurements strong suppression of quadrupole oscillations is observed
  - Some discrepancies are still there
  - Non-zero second order slip factor is required to match phase of oscil.

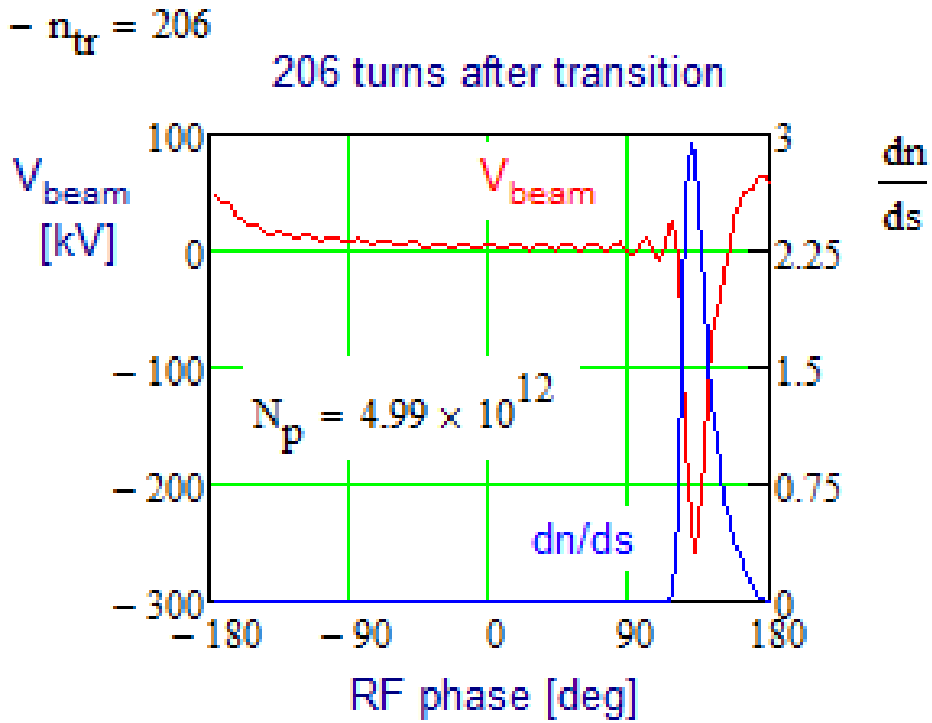




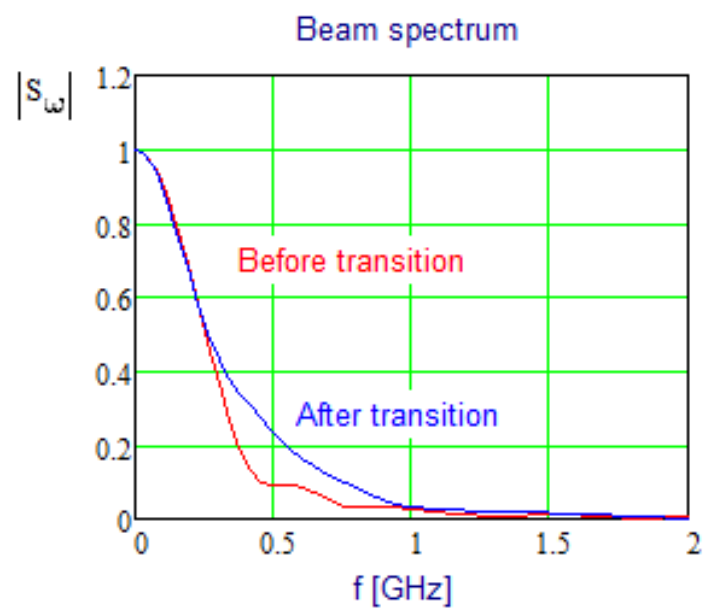


Simulation Results (3)

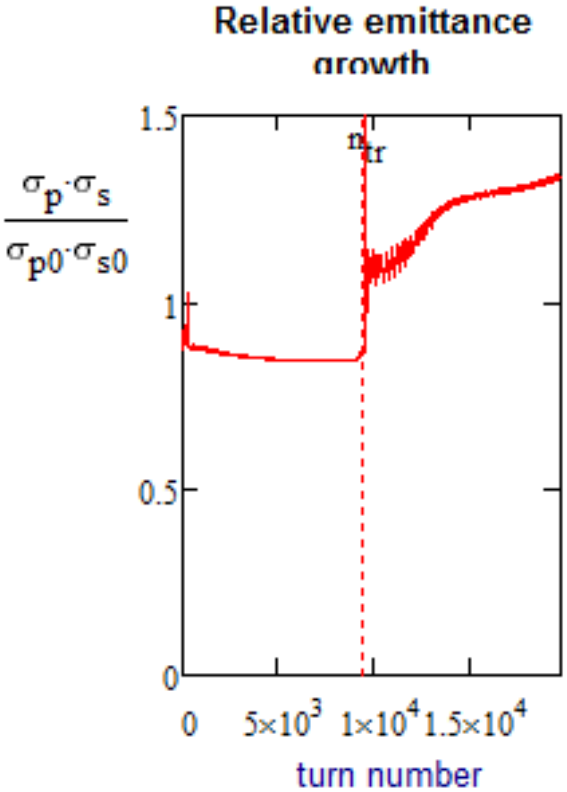


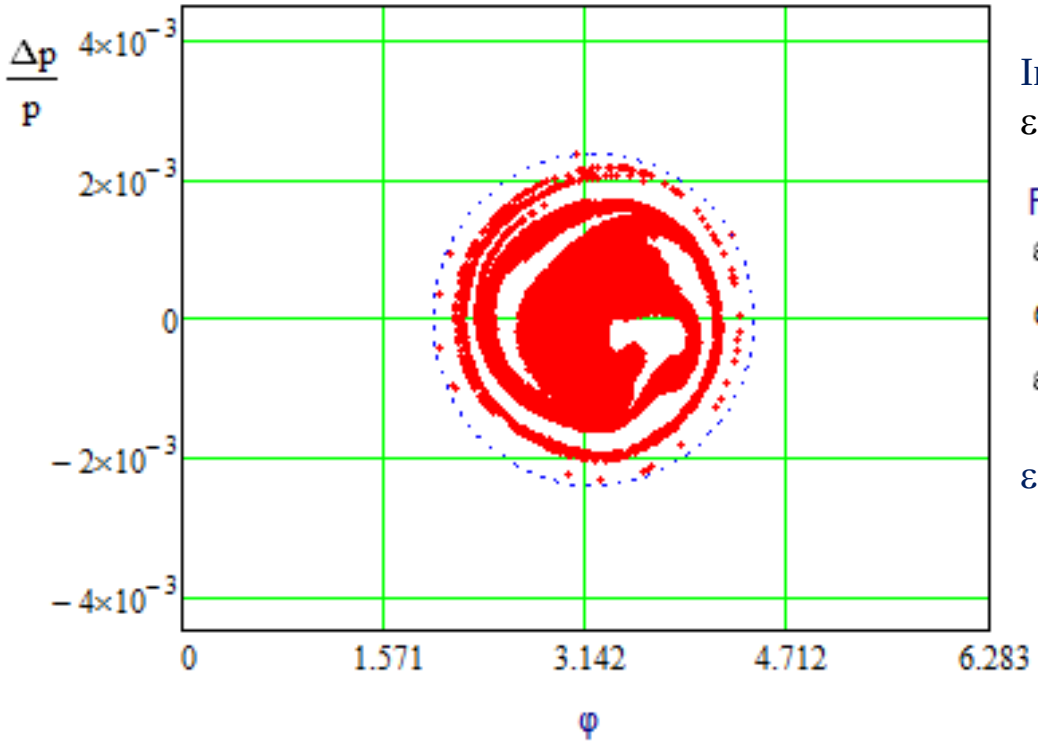


- Shortly after transition
  - Peak decelerating voltage achieves 250 kV/turn
  - Bunch spectrum extends to ~1 GHz



Simulation Results (4)





Initial

ε_{100Inj}=0.091 eV s

Final

ε_{rms} = 0.024 eV s

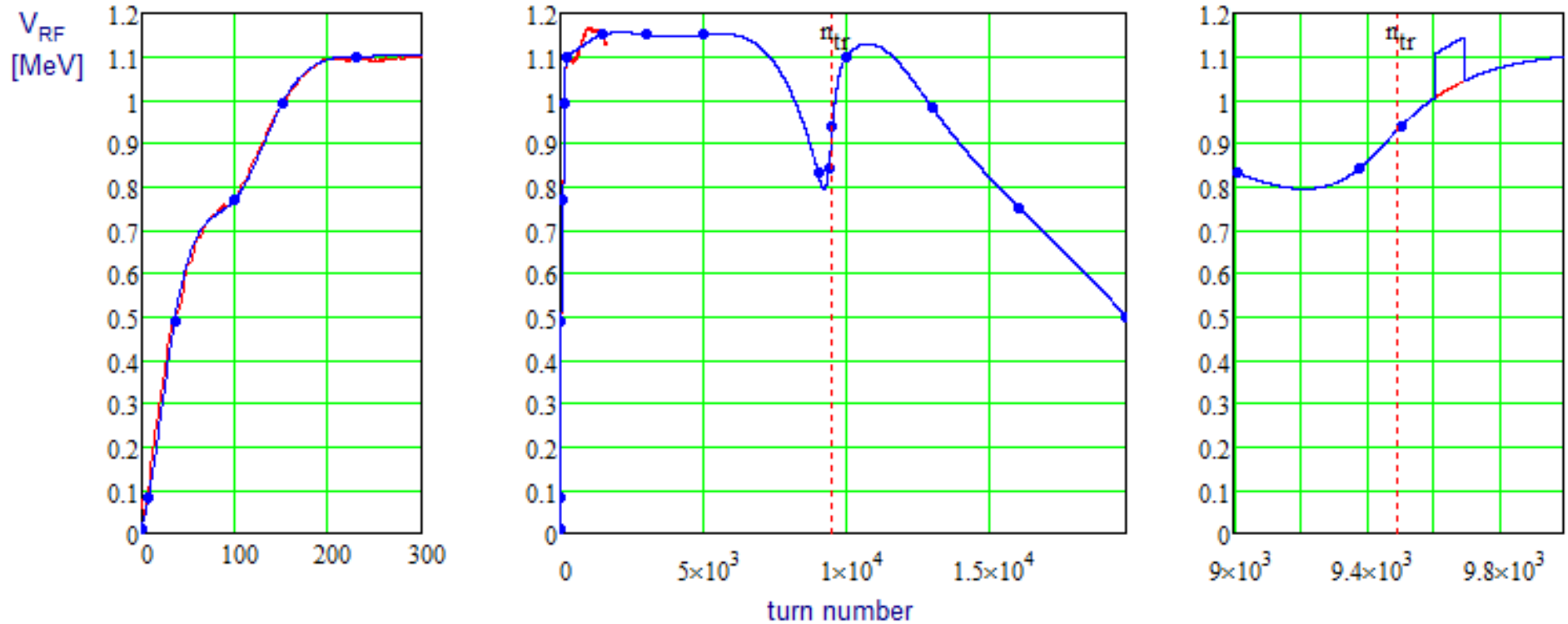
$6\cdot\varepsilon_{rms}$ = 0.141 eV s

ε_{100} = 0.251 eV s

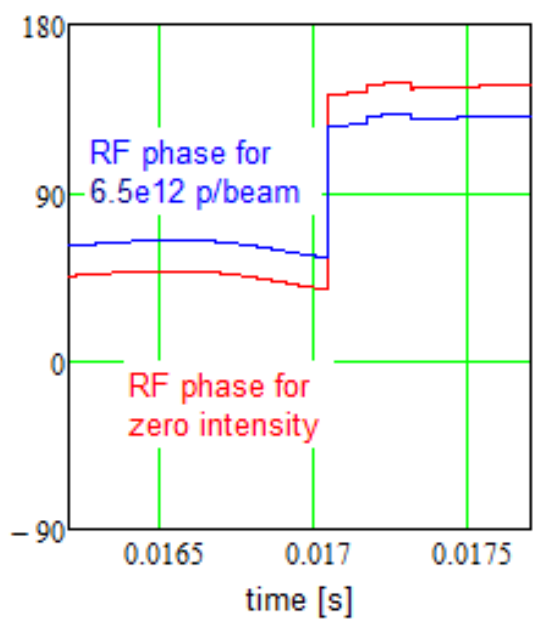
$\varepsilon_{100}/\varepsilon_{100inj}$=2.76

- Simulations exhibited moderate emittance growth similar to what we observe in the measurements

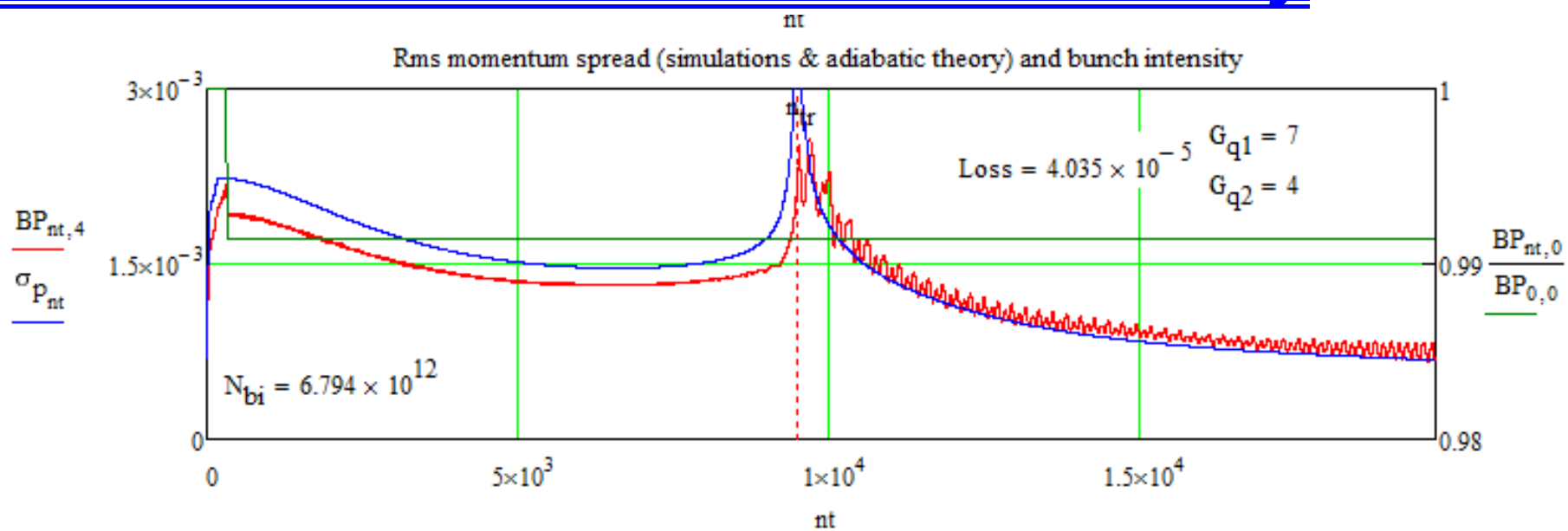
Simulations for PIP-II Intensity: RF Waveform

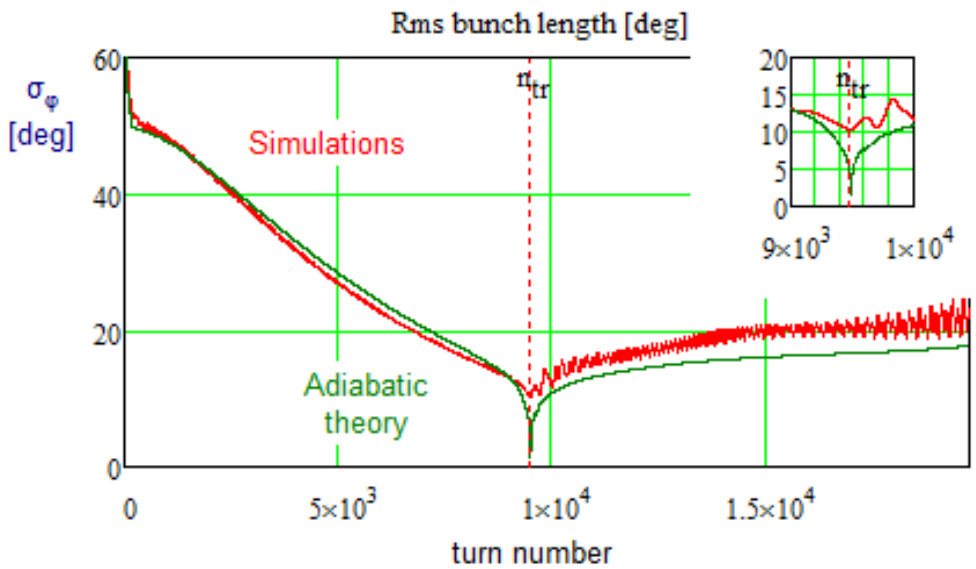


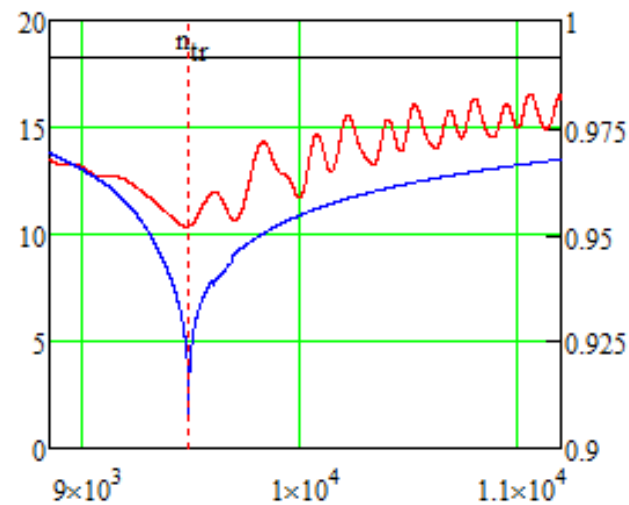
- RF curve is similar to what we have for present Booster
  - Still 15 Hz ramp rate, 1.15 MV maximum
  - Transition phase jump is delayed by 30 turns
  - No RPOS manipulations, single voltage jump shortly after tr. X



Results of Simulations for PIP-II Intensity

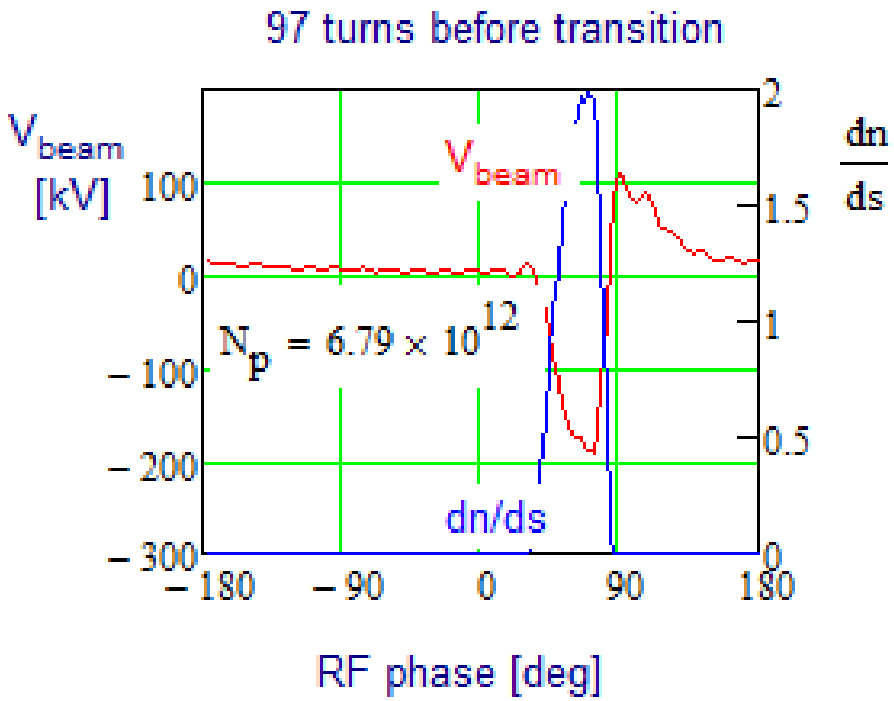


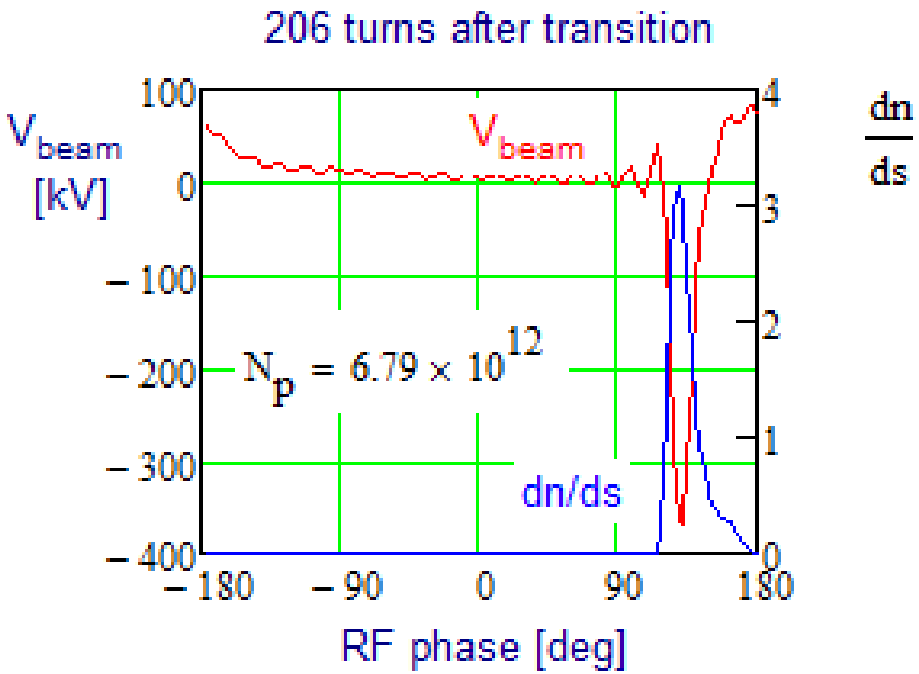




- No beam loss at transition and moderate quadrupole oscillations

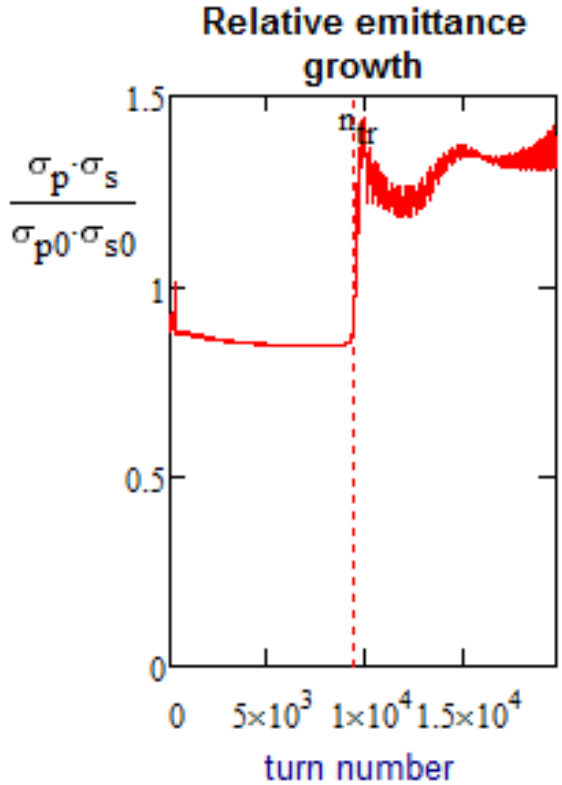
Results of Simulations for PIP-II Intensity (2)

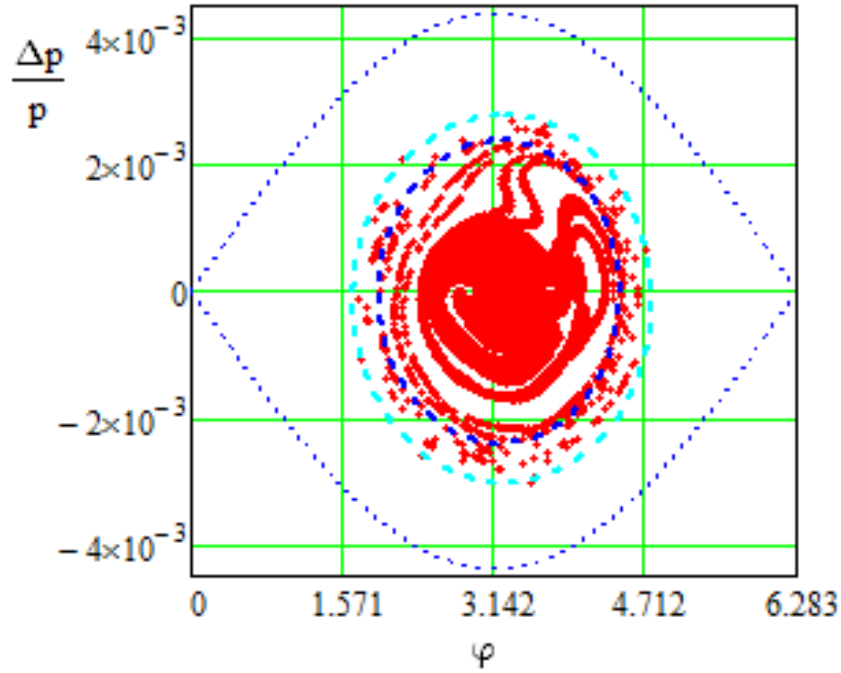




- Peak deceleration voltage grew from 250 to 350 kV

Results of Simulations for PIP-II Intensity (3)





Initial

$\varepsilon_{100Inj} = 0.091$ eV s

Final

$\varepsilon_{100} = 0.378$ eV s

$\varepsilon_{rms} = 0.023$ eV s

$6 \cdot \varepsilon_{rms} = 0.138$ eV s

$\frac{\varepsilon_{100}}{\varepsilon_{100Inj}} = 4.154$

- Rms emittance growth is only about 2% larger than the present 15 turn intensity
  - However 100% emittance growth is 1.5 times larger

Conclusions

- Measurements showed transition crossing details which were not known before
- It is still work in progress
  - More work for transition crossing studies are required
    - Optimization
    - 20 Hz ramp rate
      - Expected to be better due to longer bunch length at transition