BEAM ACCELERATION AND TRANSITION CROSSING IN THE FERMILAB BOOSTER

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Abstract

To suppress eddy currents, the Fermilab Booster has no beam pipe; rather, its combined function dipoles are evacuated, exposing the beam directly to the magnet laminations. This greatly increases the ring resistive wall impedance which, in combination with the space charge impedance, substantially complicates longitudinal dynamics at transition. The results of experimental studies of beam acceleration near transition are presented here. Comparisons of observed beam parameters and simulations yields calibrations for the rf program and quantitative information on the model of Booster longitudinal impedance. The results are used to analyze transition crossing in the context of 1.5 times intensity increase for PIP-II – a future upgrade of the Fermilab accelerating complex.

Longitudinal Impedance of the Booster

- Two major contributors
- Space charge

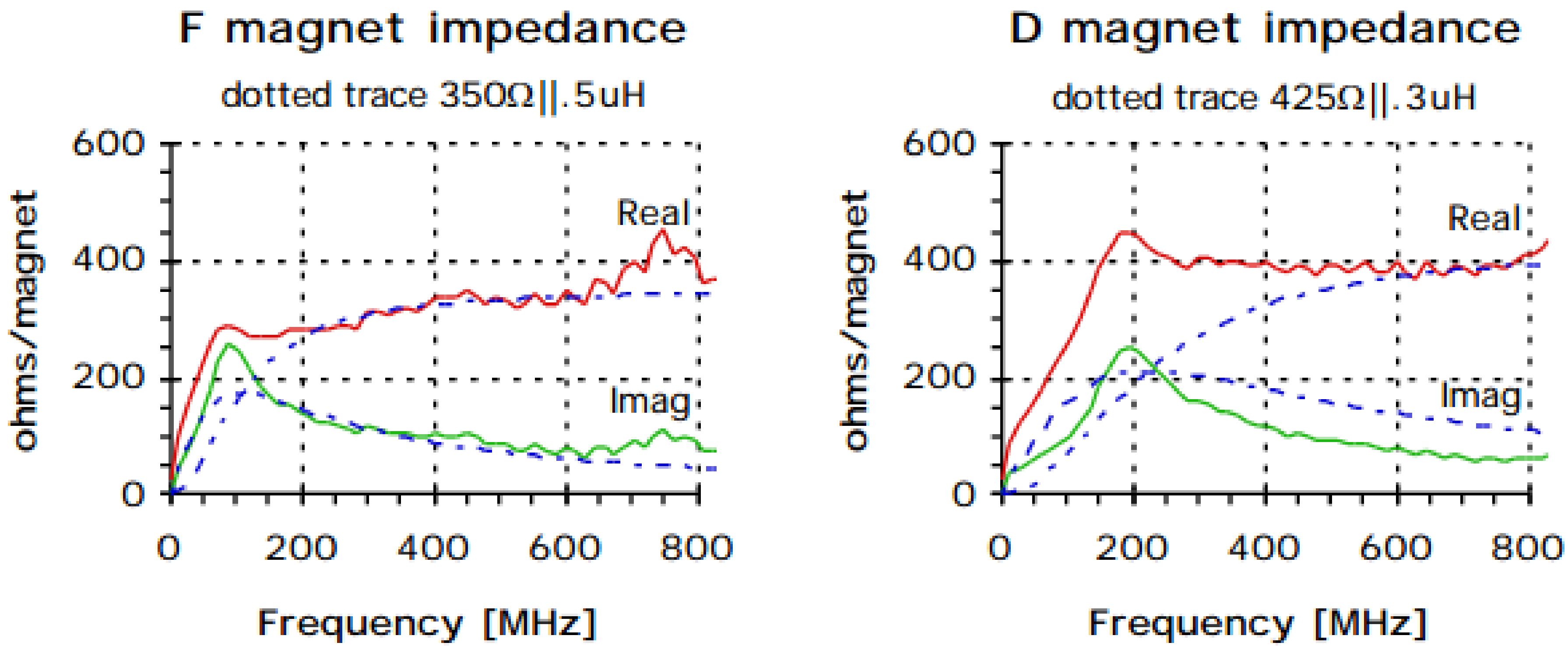
$$Z_{\|_{SC}}(\omega) \approx -iZ_0 \frac{\omega}{\beta\gamma^2\omega_0} \ln\left(\frac{r_{chamber}}{1.06\,\sigma_\perp}\right), \qquad \frac{r_{chamber}}{\sigma_\perp} \geq 2\,, \quad Z_0 \approx 377\,\Omega\,.$$

  - 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
  - Excites quadrupole oscillations
- 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)
    - To decent accuracy deceleration $\propto I_{beam}(t)$

Stretched Wire Measurements of Longitudinal Impedance of Booster Laminated Dipoles



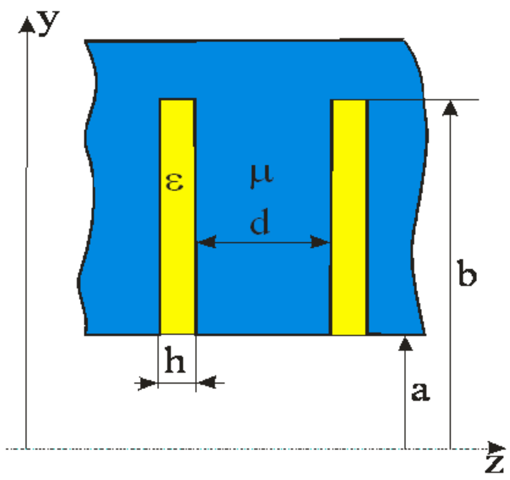
Taken from J. Crisp and B. Fellenz, "Fermilab-TM-2145, March 22, 2001.

- 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!

Impedance of Booster Laminated Magnets

- $Z_{||}$ for 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
- $Z_{||}$ for flat laminated chamber/unit length

[*"Acc. Physics at the Tevatron Collider", editors V. Lebedev and V. Shiltsev*]

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

where:

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

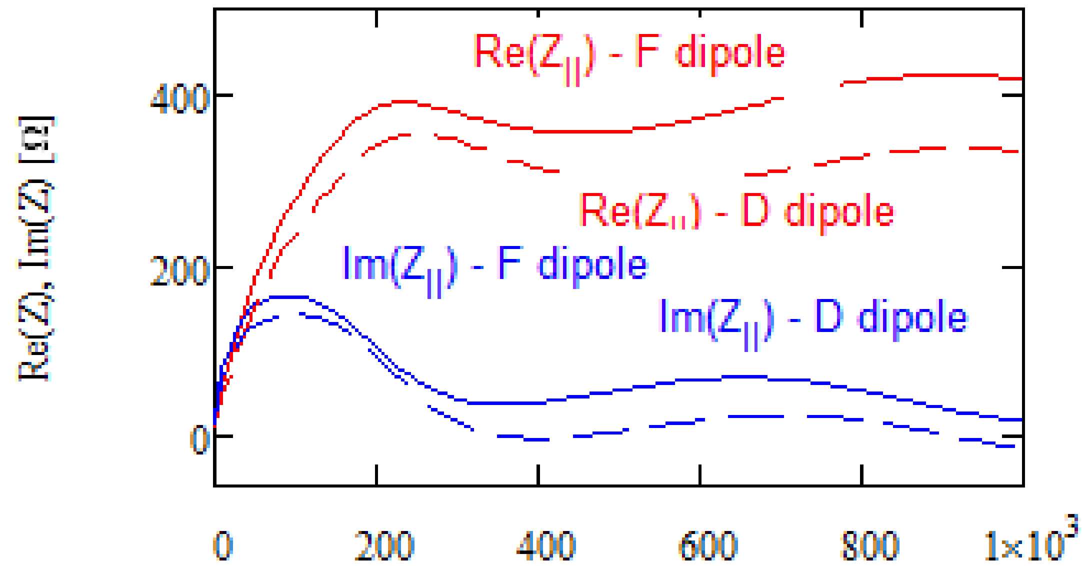
$$k_y(\xi)=\sqrt{\frac{\varepsilon\omega^2a^2}{c^2}\left(1+(1-i)\frac{\mu\delta_S}{h}\right)-\xi^2}\,,$$

- Impedance model works well in a range [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?

Parameters for the Impedance Calculation

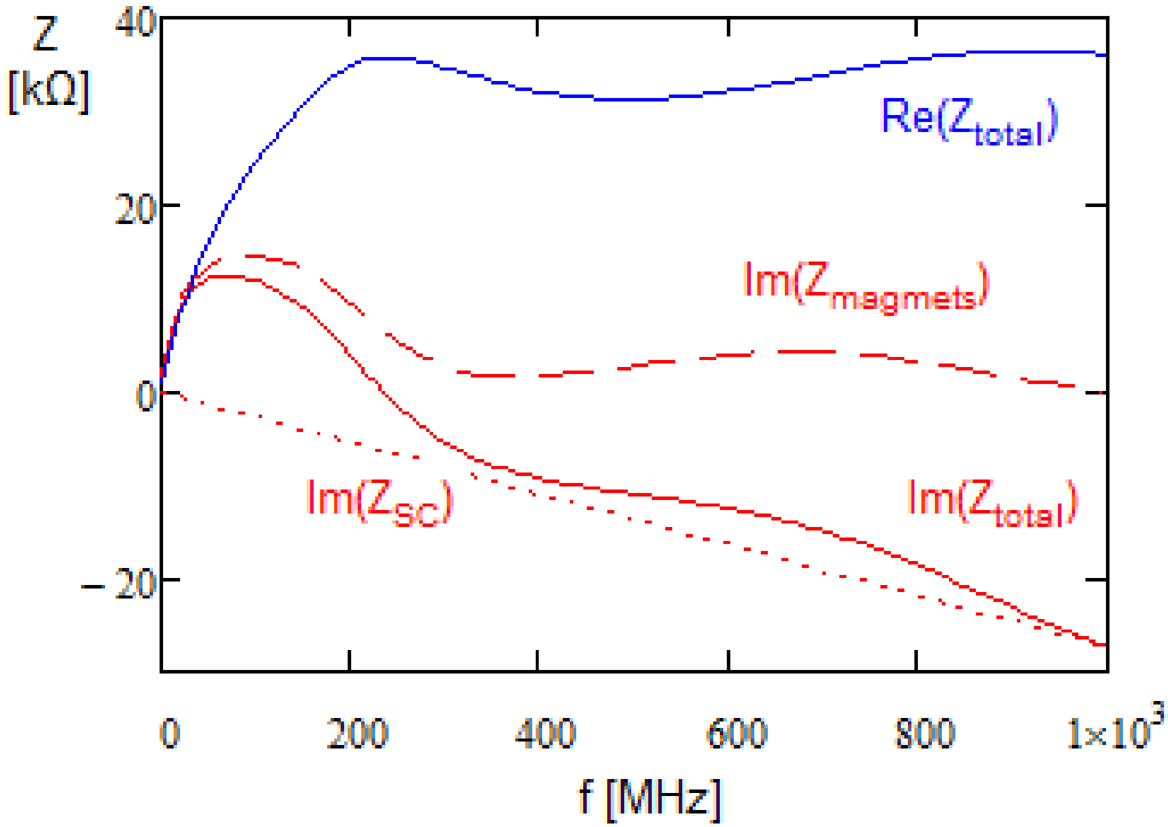
- $\mu=\mu'+i\mu''\in[30\rightarrow7]$measured up to 1 GHs (IPAC'2012)
- Initially *h* was taken from the packing factor 98.5% (Booster design report) and insulating layer thickness: *h* =10+2*10 μm
- ε: epoxy & insulating oxide layer on steel (ε~2 - 3)
- h and ε are updated based on the beam measurements
- 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	$2.3\cdot10^{6}\ \Omega^{-1}\ m^{-1}$		s^{-1}
Dielectric permittivity, ε	2.5		



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

Total Longitudinal Impedance of the Booster

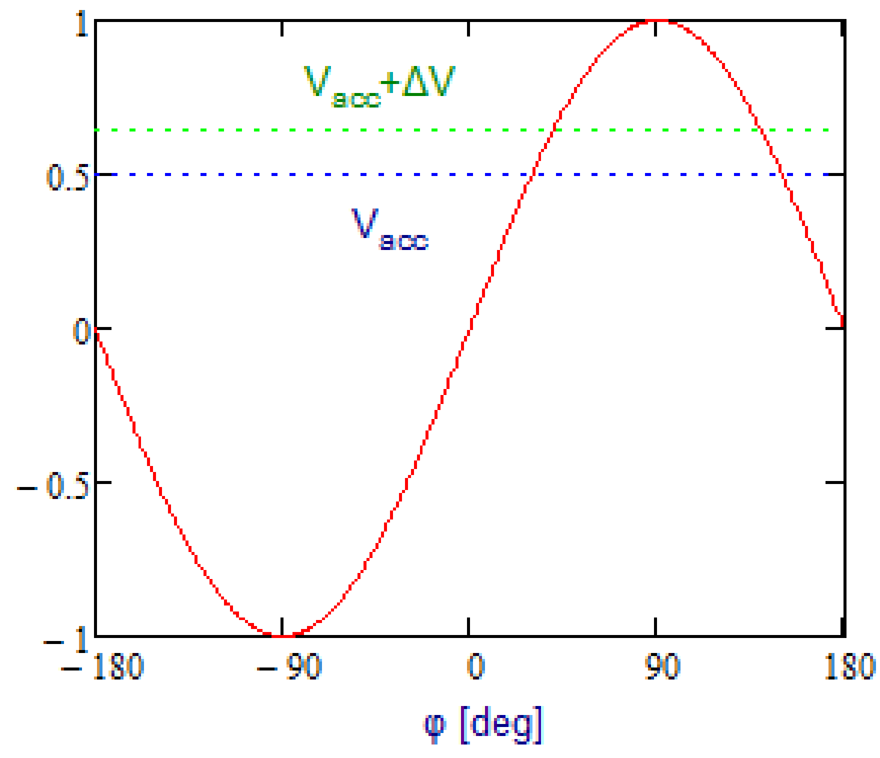


Total $Z_{||}$ for Booster at transition. The value is tuned to the beam-based measurements

- Imaginary part of the space charge impedance is partially compensated by resistive
  wall impedance of dipoles
- At transition, bunch spectrum extends to 300 - 500 MHz

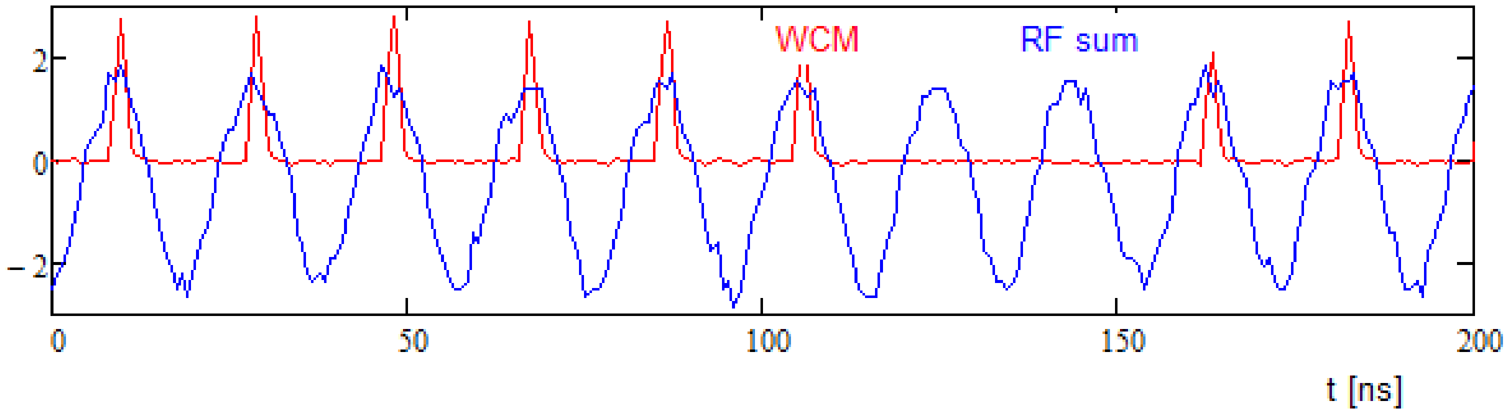
Beam Based Measurements of the Long. Impedance

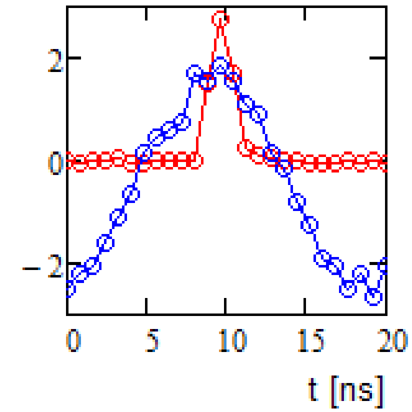
- Direct measurement of $Z_{||}(\omega)$ requires a continues beam
  - Continues beam does not look readily available even at injection energy
  - It is impossible near or at transition
  - $\mu(B)$ can make significant correction
- Shift of acceleration phase with bunch intensity allows us to check 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



Data Acquisition

- Data are taken at injection and transition
- Out of 33 ms Booster acceleration time 3.6 ms are acquired for each data set
- Bunch intensity: 4, 8, 12 & 15 turns($4.8 \cdot 10^{12}$ in 82 bunches)
  - 2 data sets @ each measurement
- RF sum + RWM + Rpos
  - 0.8 ns sampling time, $4.5 \cdot 10^{6}$samples

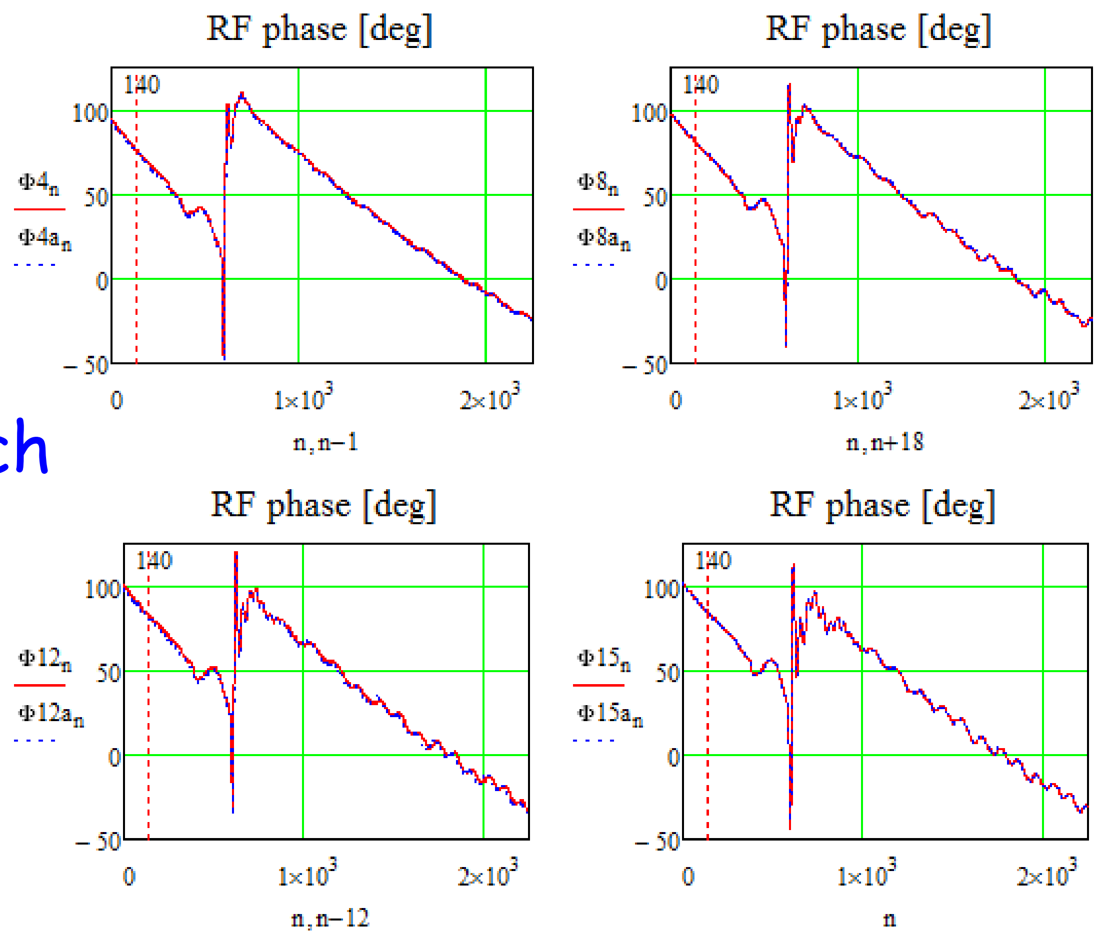




- Needed to have sufficiently long measurements (>3.5 ms) => only few points on bunch length for transition-crossing data

Preliminary Data Analysis

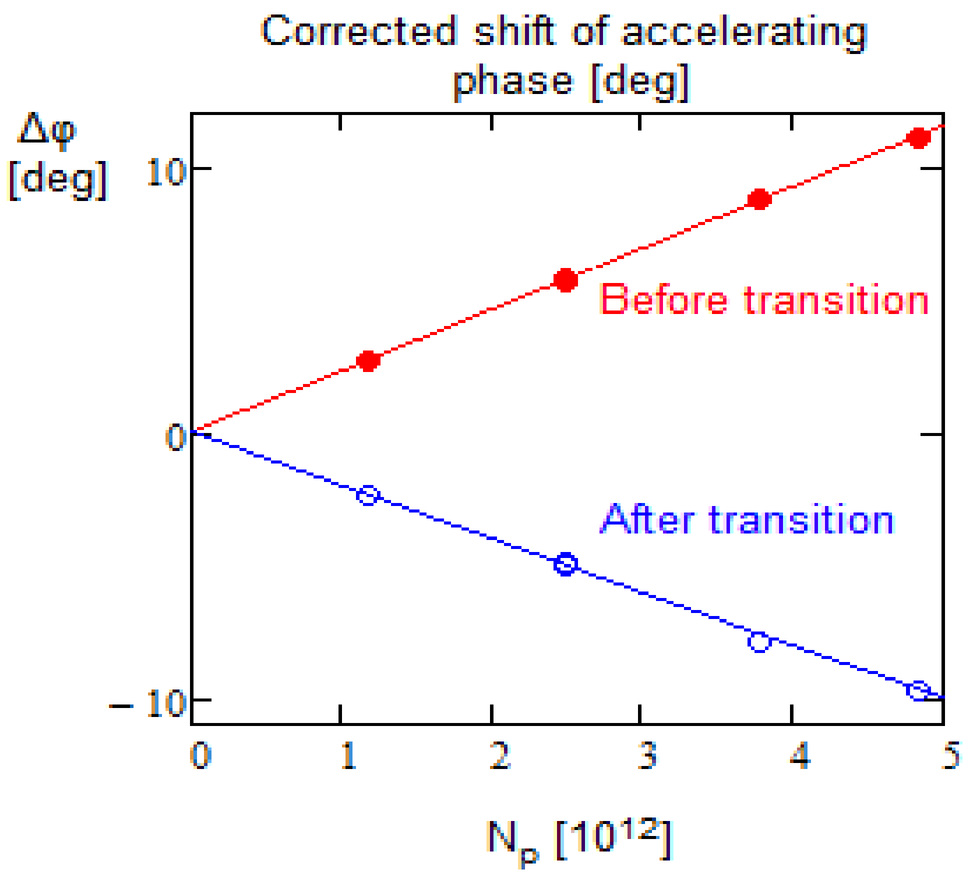
- Fitting RF signal for each period of sinusoid yields
  - (1) RF voltage & (2) zero crossing time
- Fitting WCM signal to Gaussian pulses yields for each period
  - (1) Bunch arrival time,
  - (2) Peak height &
  - (3) Peak width
- Time difference between RF zero crossing and bunch arrival time yields accelerating phase
  - correction for cable length difference has to be additionally accounted

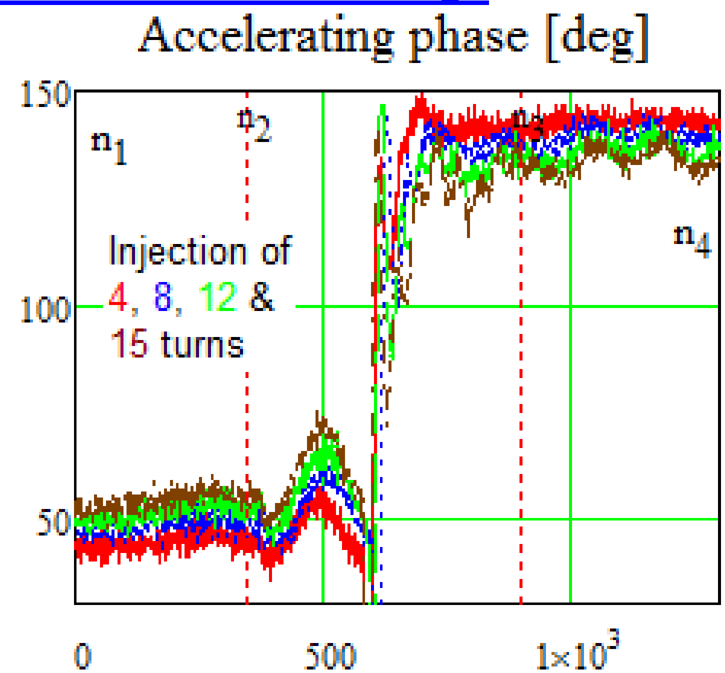


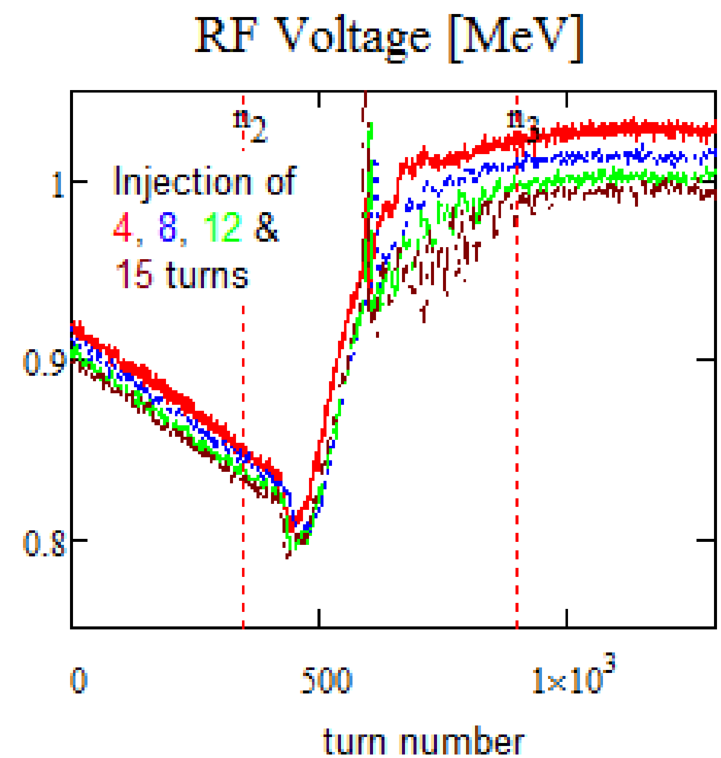
Accelerating phase near transition

Accelerating Phase Shift with Beam Intensity

- Accelerating phase is shifted with intensity close to expectations
- Decrease of RF voltage with intensity increases $\Delta\phi$ by ~25%
- Smaller $\Delta\phi$ after transition is related to larger RF voltage after transition





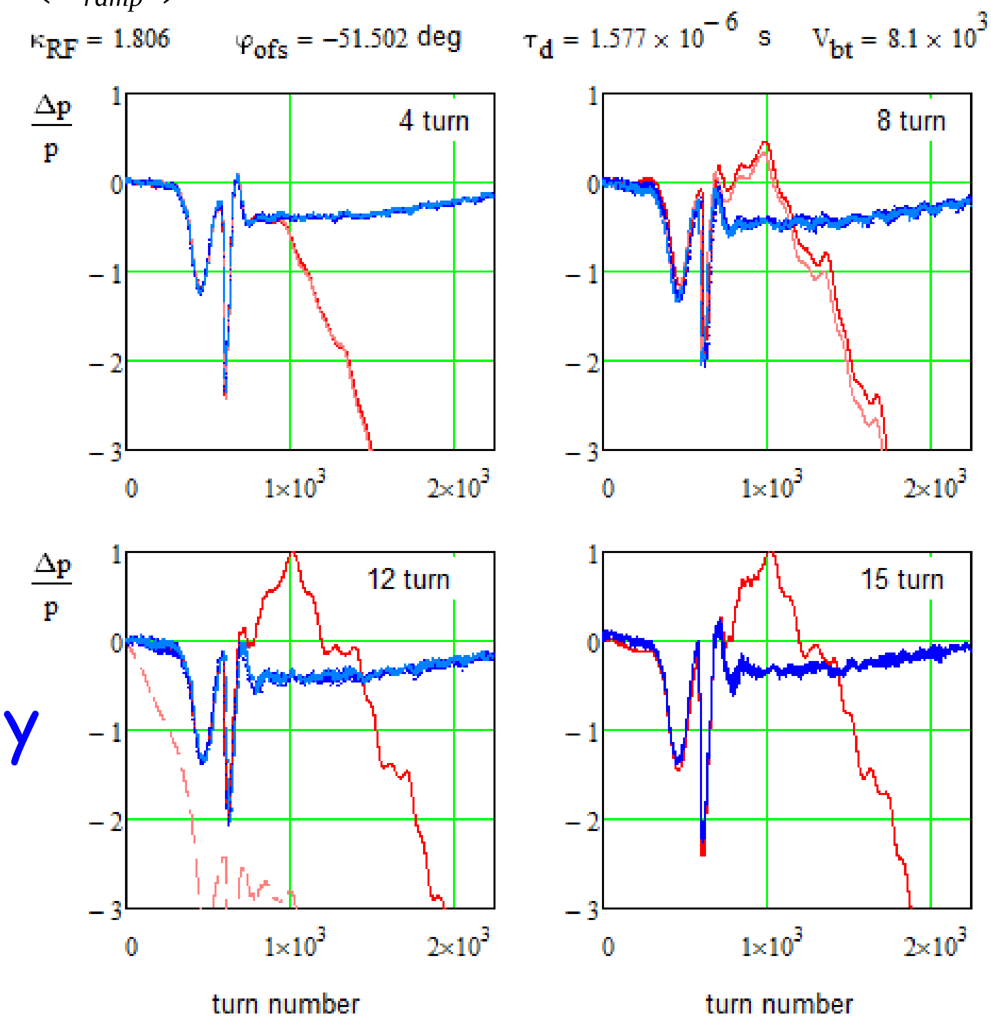


Phenomenological Model for Data Analysis

- Reference beam energy 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 is driven by

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

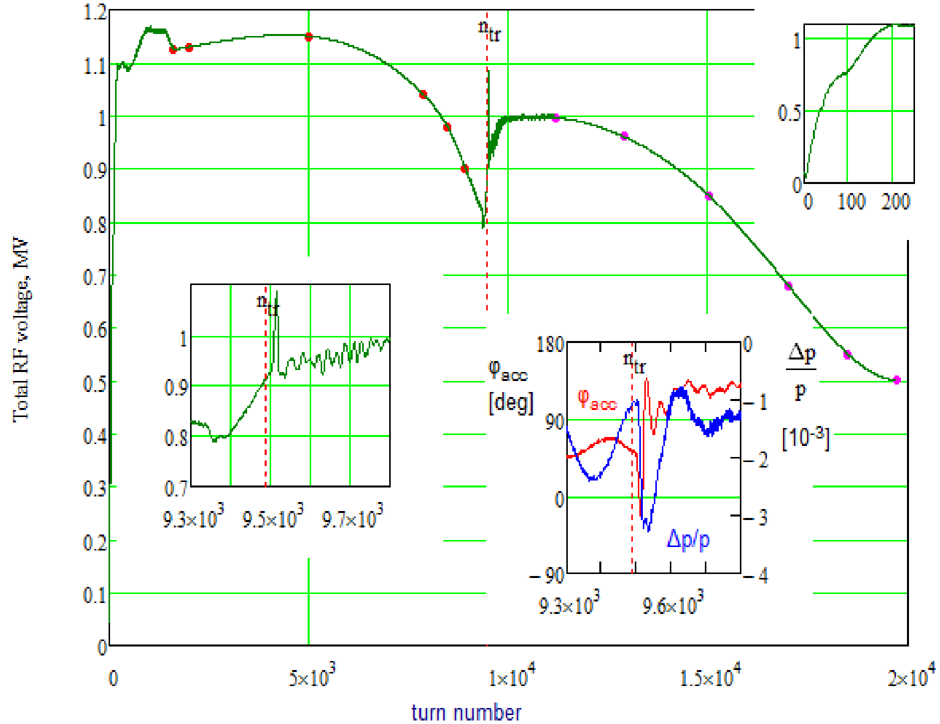
- The difference drives $\Delta p/p$ which is independently measured by RPOS
- Presence of fast RF phase swings near transition greatly helps us to calibrate
  - RFSUM (RF voltage sum)
  - Offset and slope for ϕ_{acc}
  - RPOS ($\Delta p/p$)
  - Average deceleration due to $Z_{||}$

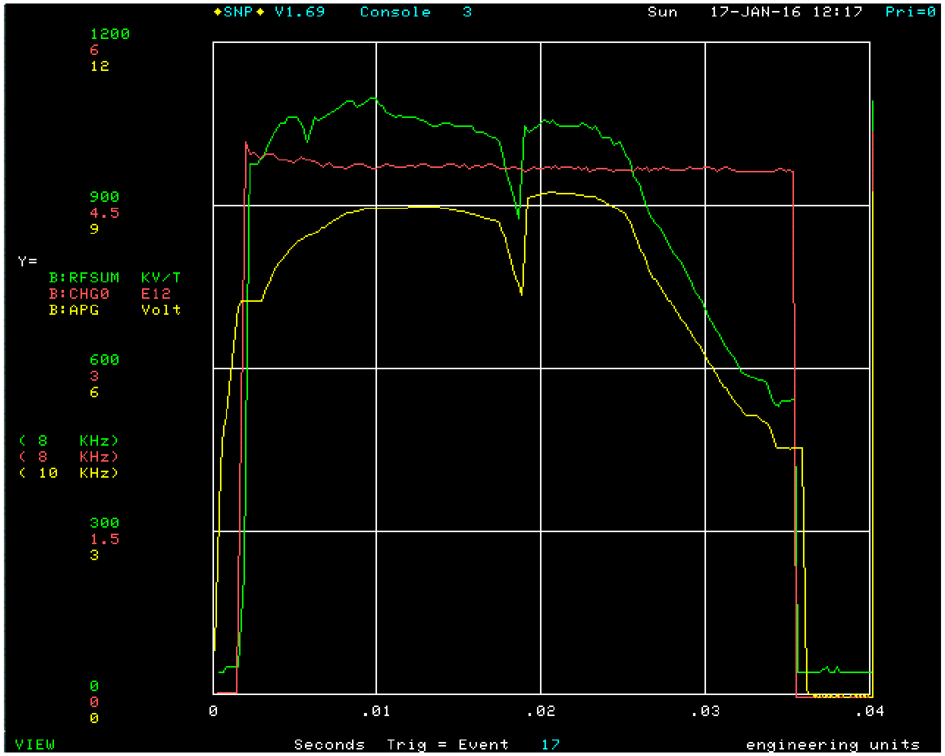


Parameters are fitted for the first 900 turns

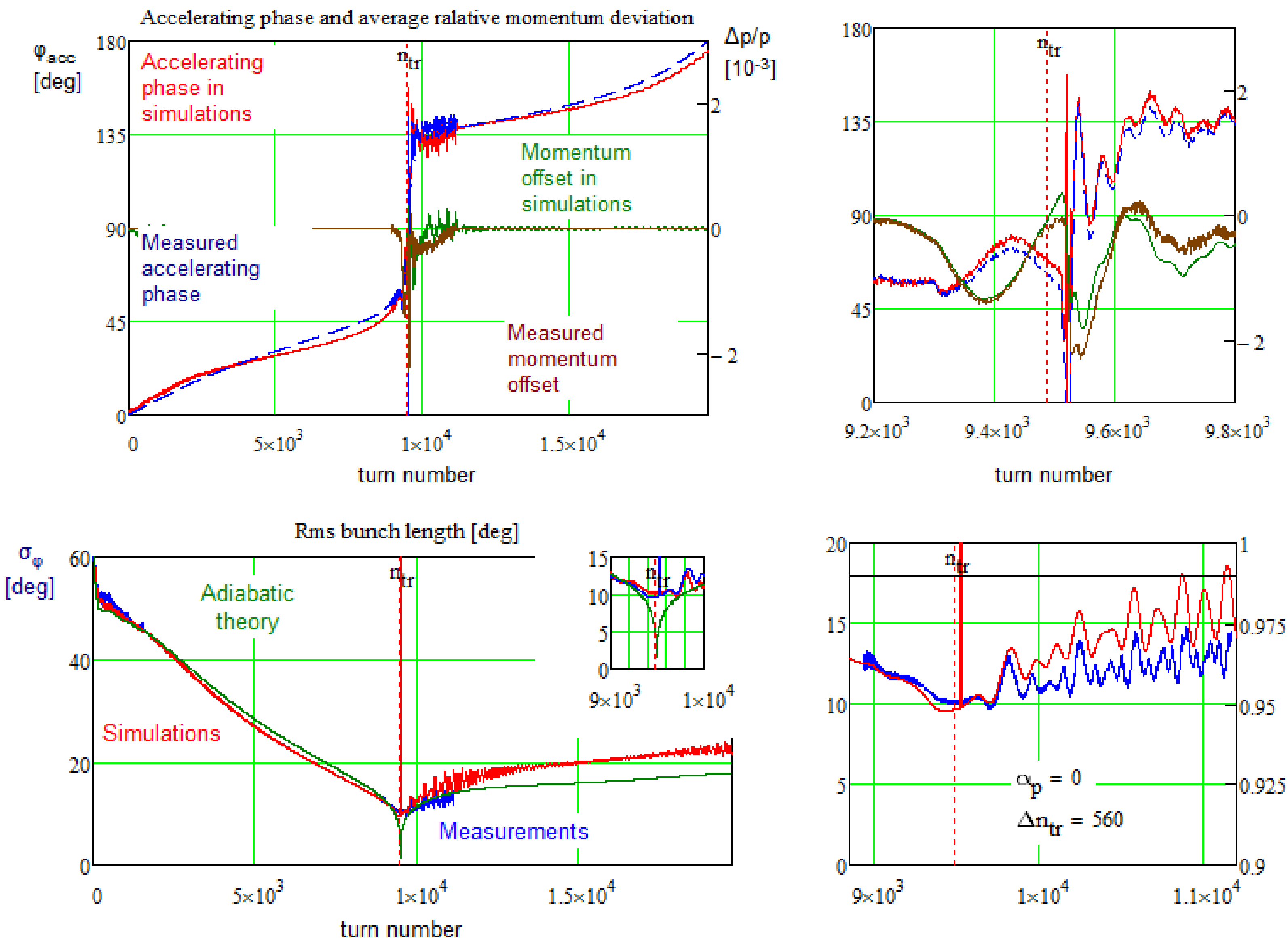
RF Voltage for Numerical Simulations

- RF wave form is built from measured RF voltage at inj. & around transition
- RF wave form was interpolated for the rest of the cycle
- Minor inaccuracies of interpolation are irrelevant to simulations
- Time of transition wave form was adjusted relative the transition crossing time based on simulation results

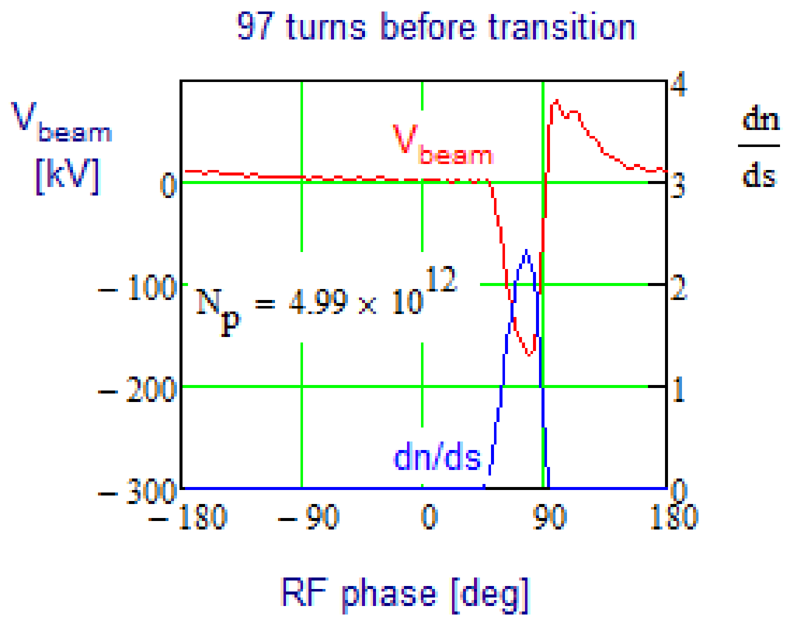


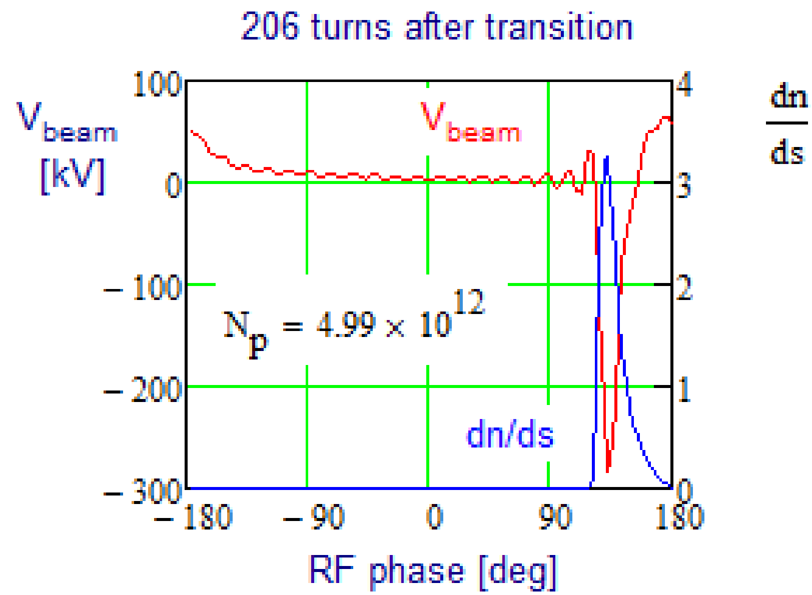


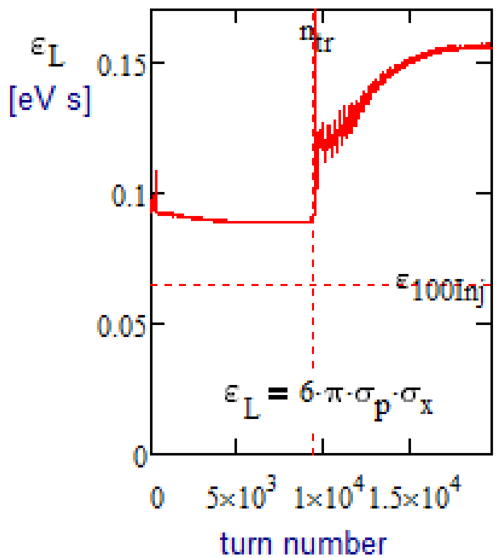
Simulation Results

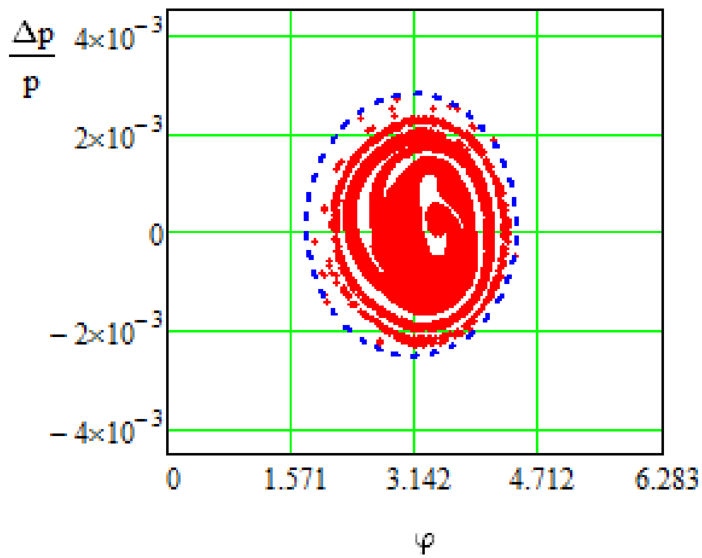


- Same is in measurements no beam loss due to transition
- $\Delta p/p$ & φ_{acc} are close in measurements and simulations









Initial

$\varepsilon_{100Inj} = 0.065$ eV s

Final

$\varepsilon_{100} = 0.295$ eV s

$\varepsilon_{rms} = 0.026$ eV s

$6 \cdot \varepsilon_{rms} = 0.157$ eV s

$\dfrac{\varepsilon_{100}}{\varepsilon_{100Inj}} = 4.542$

- After transition the peak decelerating voltage ~ 250 kV
- Simulations exhibited moderate emittance growth similar to what we observe in the measurements