Booster Longitudinal Impedance

Valeri Lebedev and Chandra Bhat

PIP-II weekly meeting
February 10, 2015
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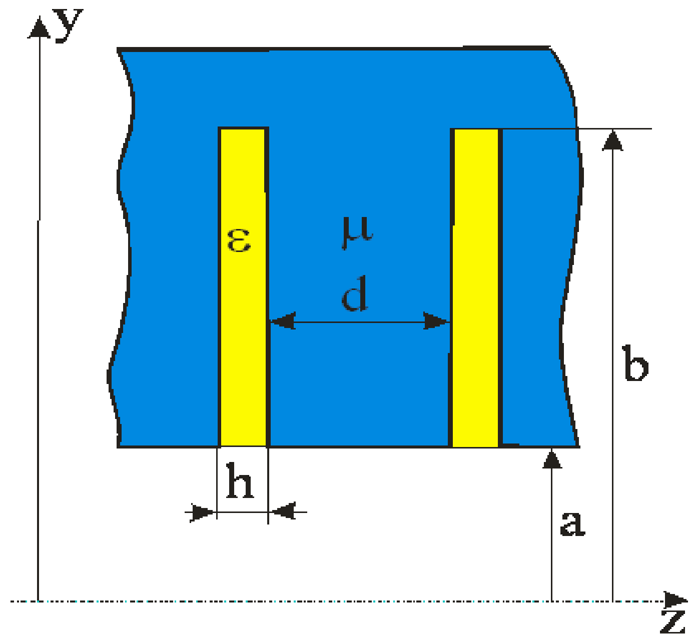
Why Knowledge of Longitudinal Impedance is Important?

- 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

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

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

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

where:

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

- Accuracy: the model is good in the required frequency range (0.1 MHz – 1 GHz)
  but: *h*? (Packing factor), ε?, μ?

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

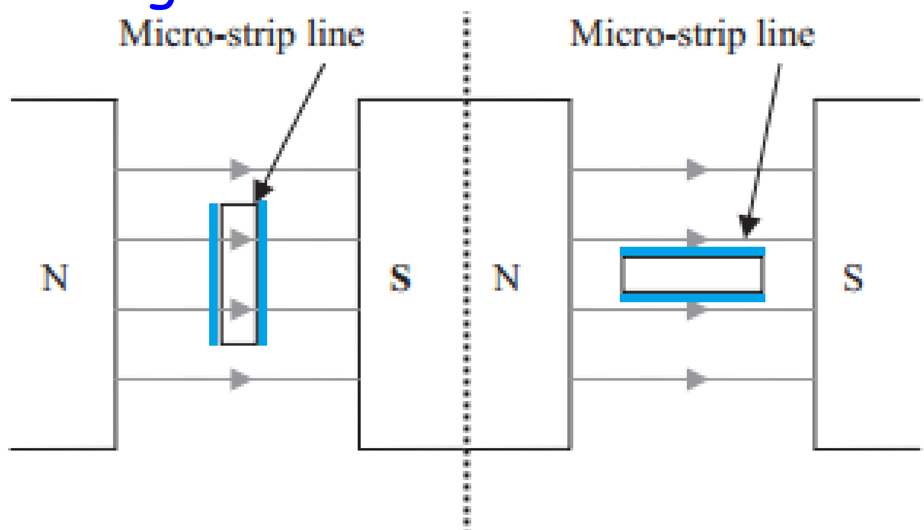
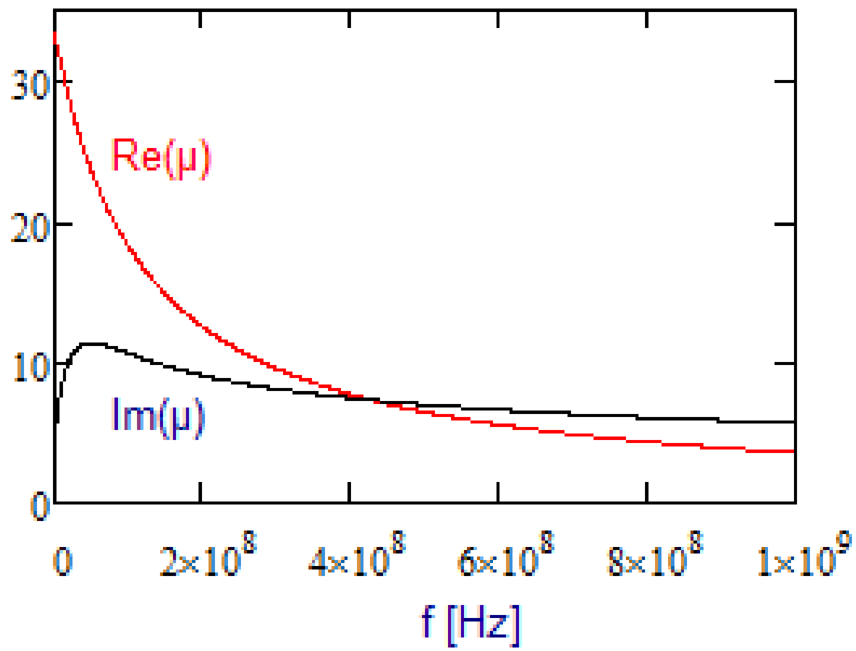


Figure 1: Schematics of the experiment with steel in DC magnet. The normal orientation is represented on the left, and the parallel one on the right.

Permeability of Soft Steel: Results

- Magnetic permeability used in the estimates



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

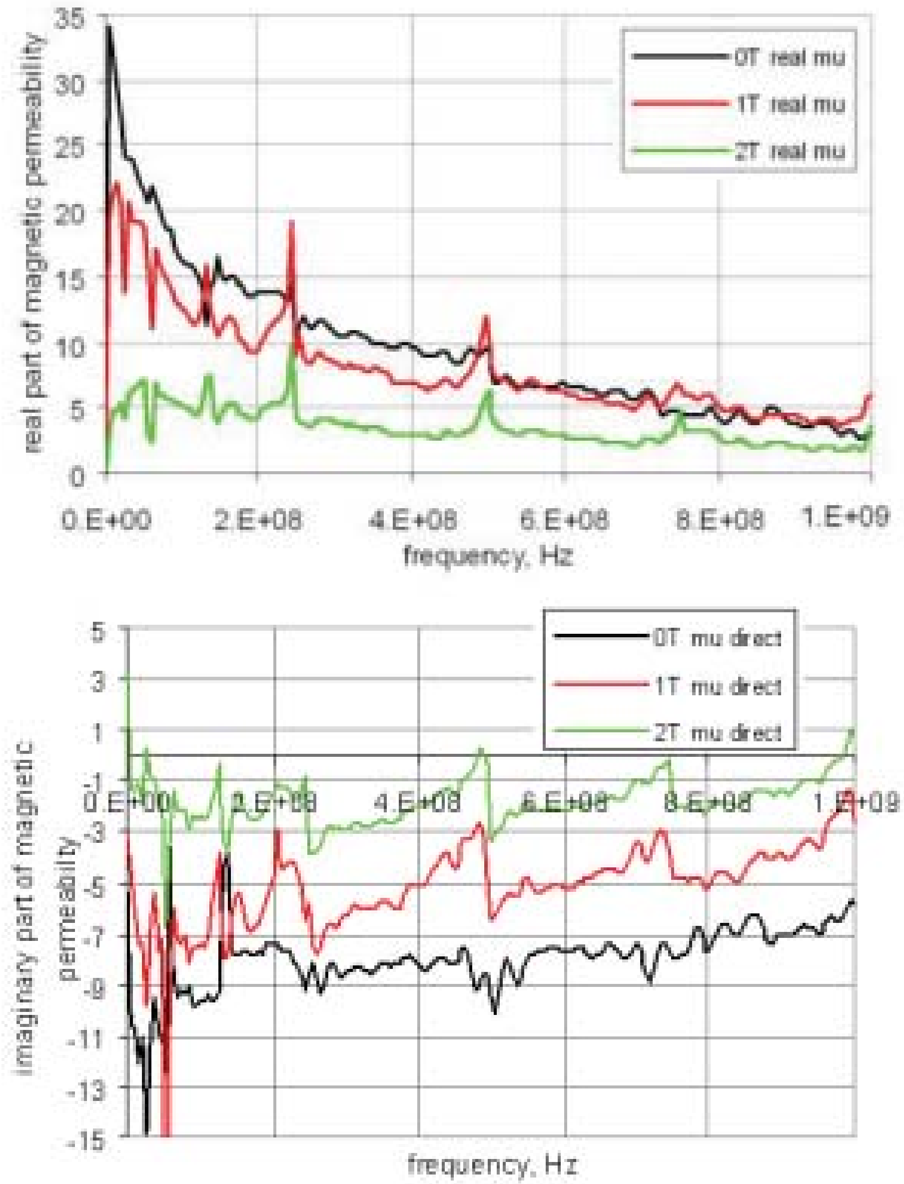
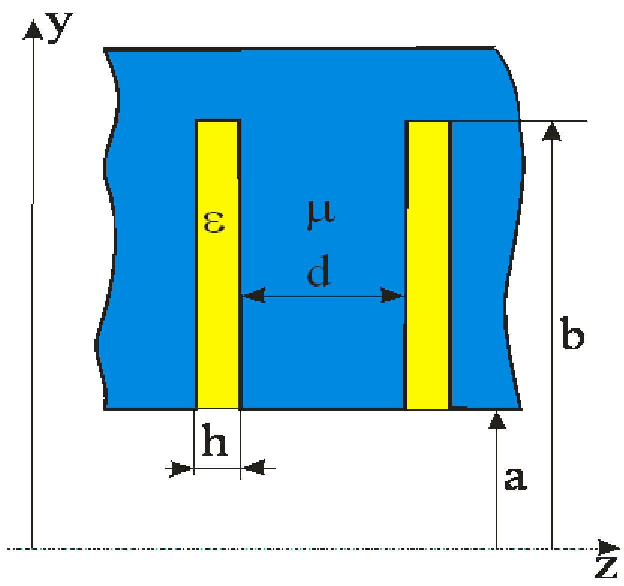


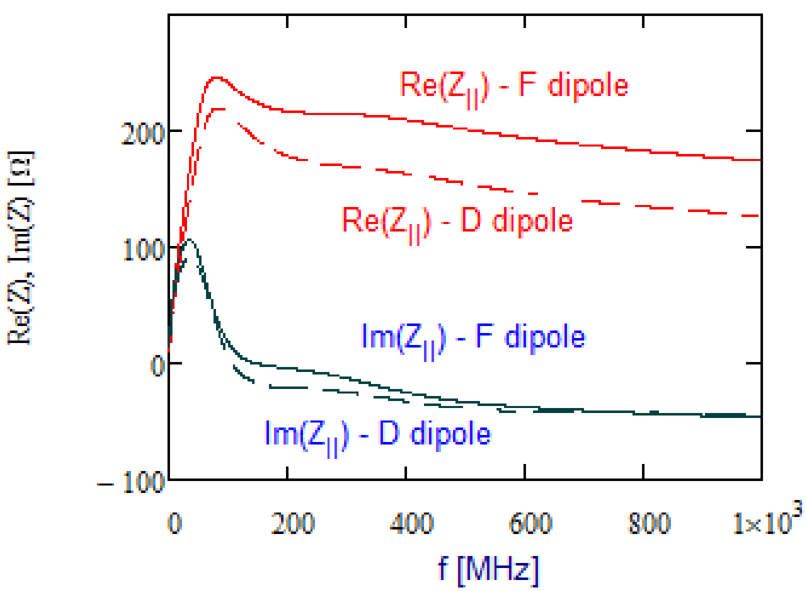
Figure 3: Dependence of magnetic permeability of steel on frequency for different magnetic fields for the case of magnetic field normal to the strip plane.

Parameters for the impedance estimates

- Gap between plates is taken from known packing factor (Booster design report)
- Dielectric gap: epoxy + insulating oxide layer on steel
- F dipole has smaller gap and larger impedance

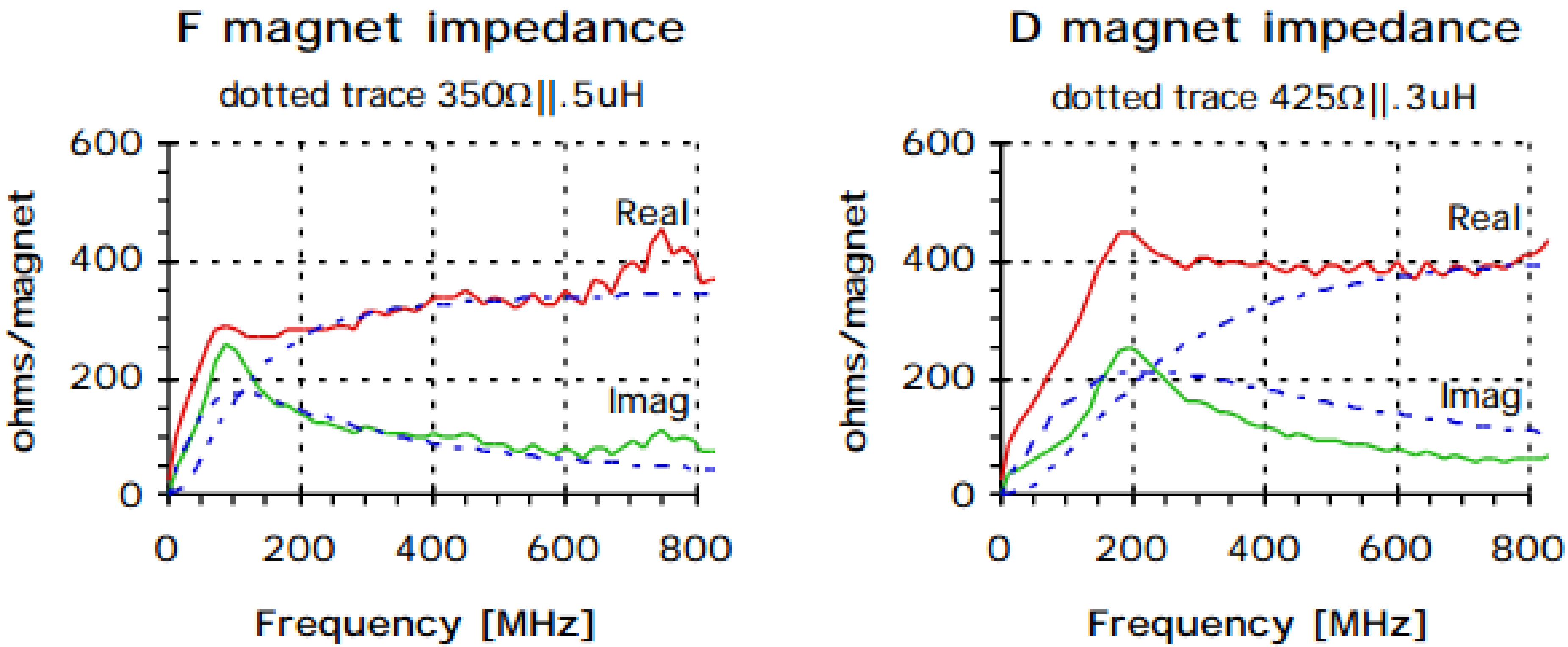
Dipole type	F	D	
Dipole length	2.89		m
Number of dipoles	48	48	cm
Half-gap, a	2.1	2.9	cm
Lamina half-height, b	15.2		cm
Lamina thickness, d	0.64		mm
Dielectric crack width, h	20		μm
Conductivity, σ	$2.07\cdot10^{16}$ ($2.3\cdot10^{6}\ \Omega^{-1}\ m^{-1}$)		s^{-1}
Dielectric permittivity, ε	4.75		





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

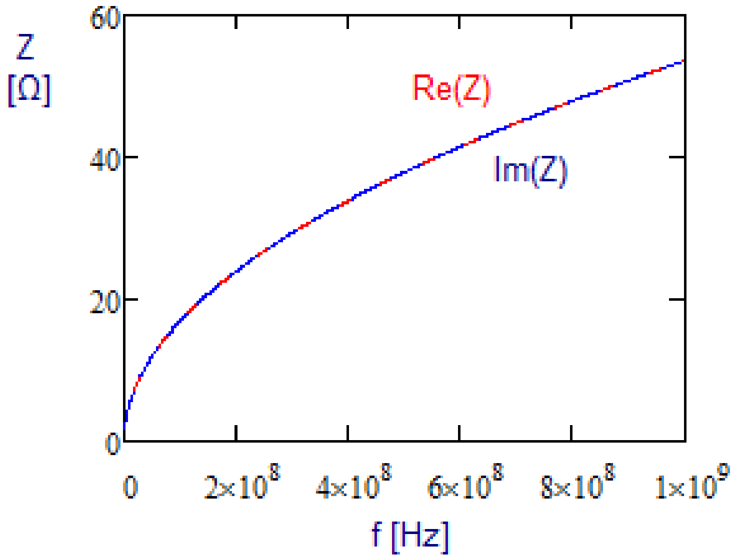
Wire Measurements of Dipole Impedance



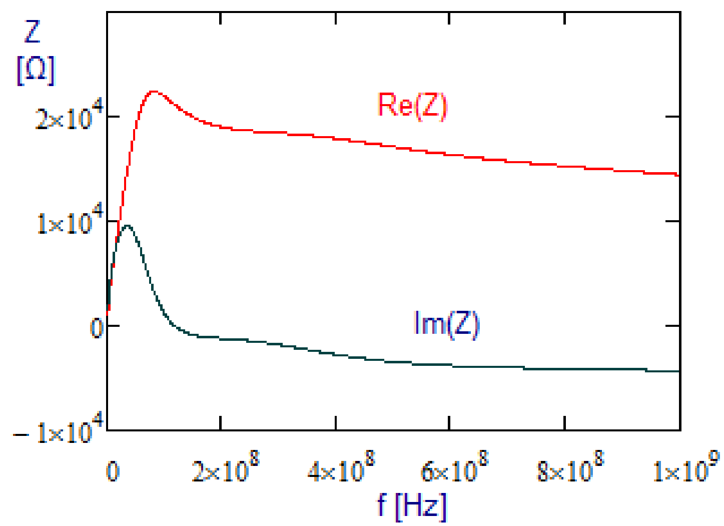
Taken from: James L. Crisp and Brian J. Fellenz, "Measured Longitudinal Beam Impedance of Booster Gradient Magnets", Fermilab-TM-2145, March 22, 2001.

- 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

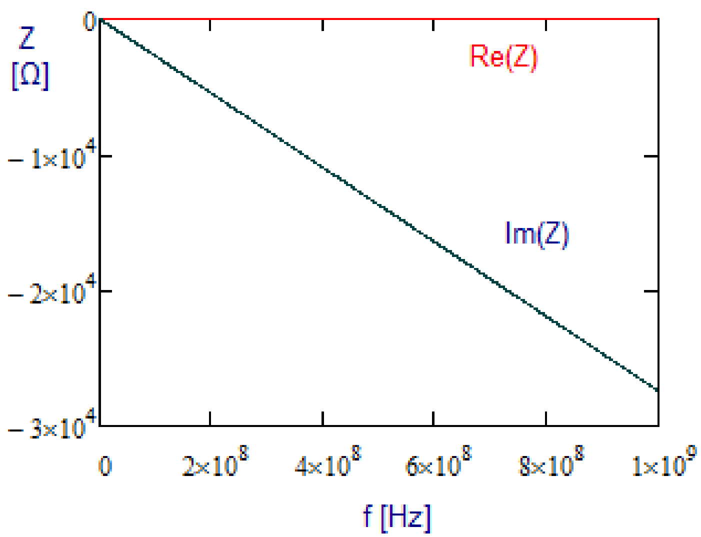
Contributions to the Total Booster Impedance



Resistive impedance of stainless steel vacuum chamber: L=197 m, ρ=74·10^{-6} Ω/cm, a=4.13 cm



Total resistive impedance of Booster laminated magnets: 48 F dipoles +48 D dipoles



Space charge longitudinal impedance at transition: L=474.2 m, $a/\sigma_\perp$=4

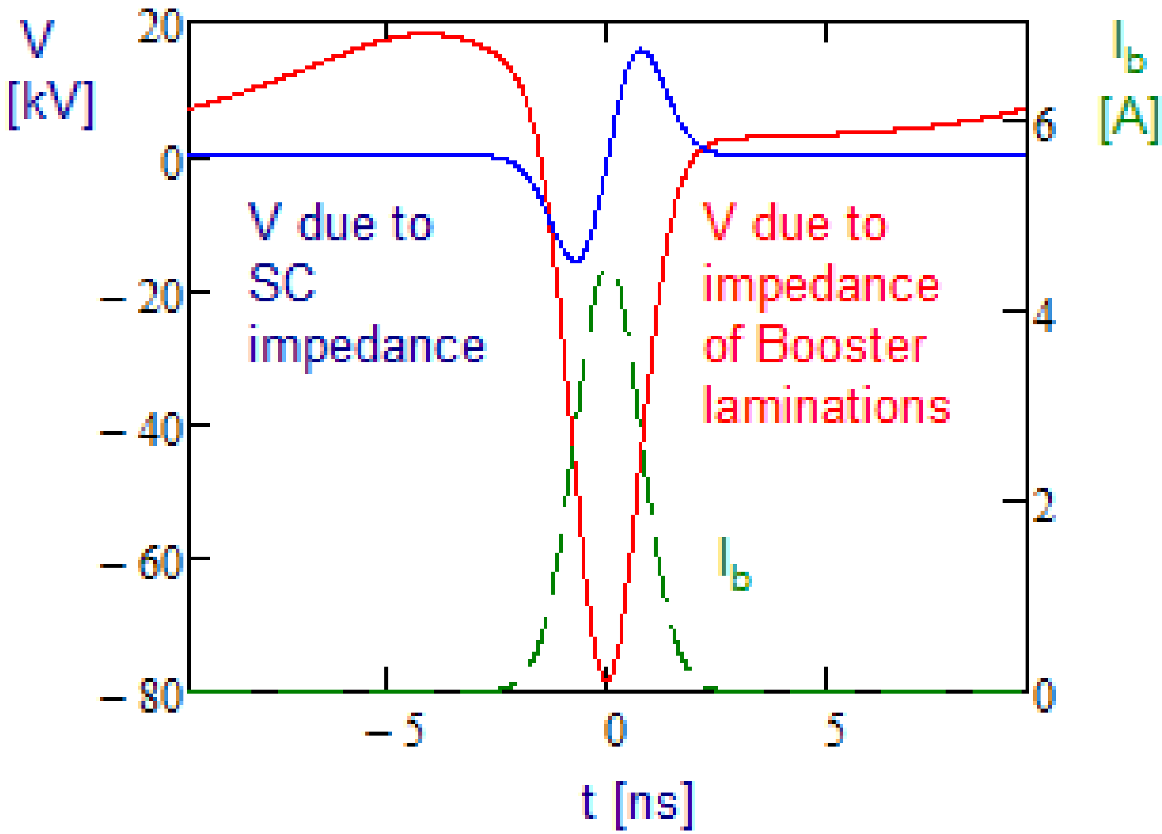
- Space charge Longitudinal impedance (per unit length)

$$Z(\omega) \approx -i\frac{Z_0 c}{4\pi}\frac{2\omega}{\beta^2\gamma^2c^2}\ln\left(\frac{a}{1.06\,\sigma_\perp}\right)$$

- Stainless steel chamber contribution is negligible
- Impedance of laminations dominate the total impedance

Impedance Induced Voltage

- 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

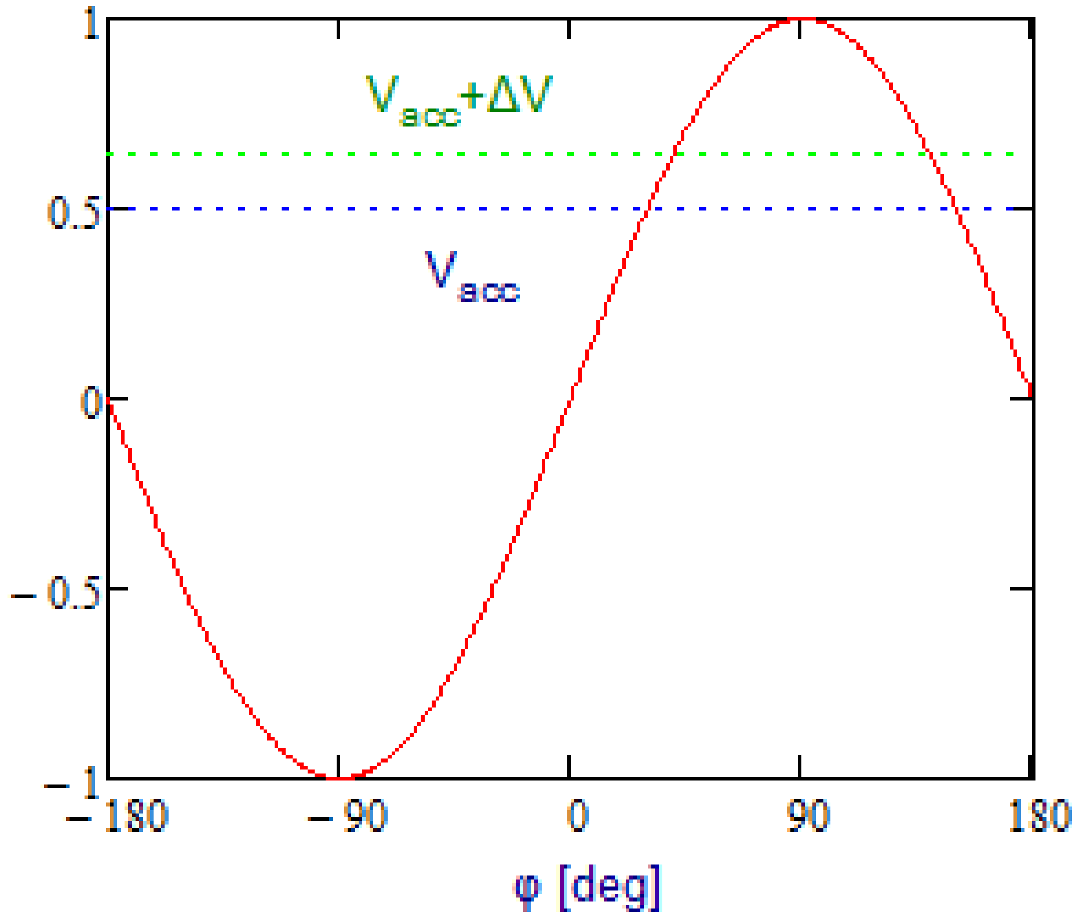
The beam deceleration averaged over bunch:

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

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.**

Longitudinal Impedance Measurements

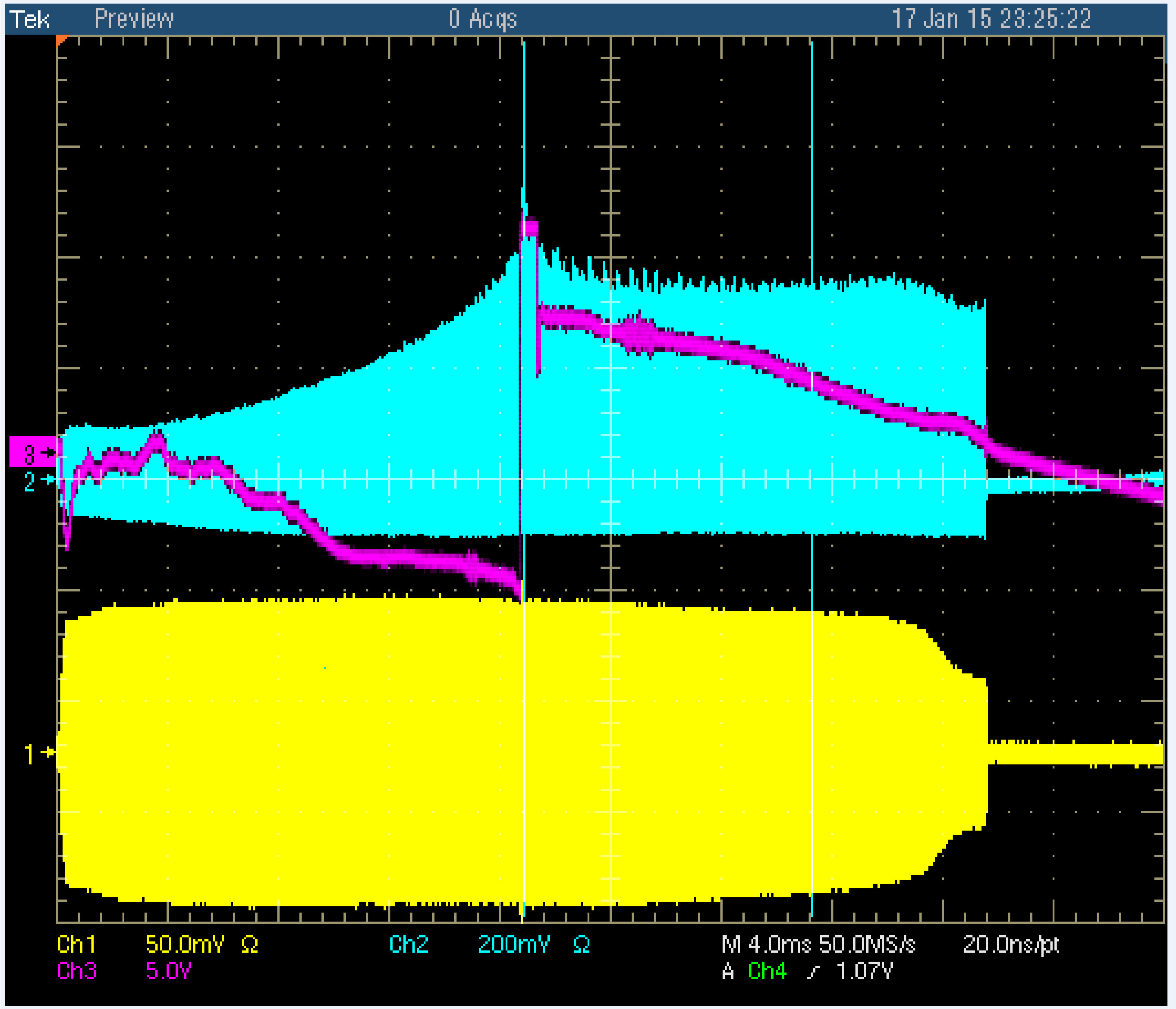
- Direct measurements of $Z(\omega)$ requires a continues beam
- Shift of acceleration phase with bunch intensity allows us to check if the considered above model, as well as single dipole measurements, are applicable



Data Acquisition and Acquired Data

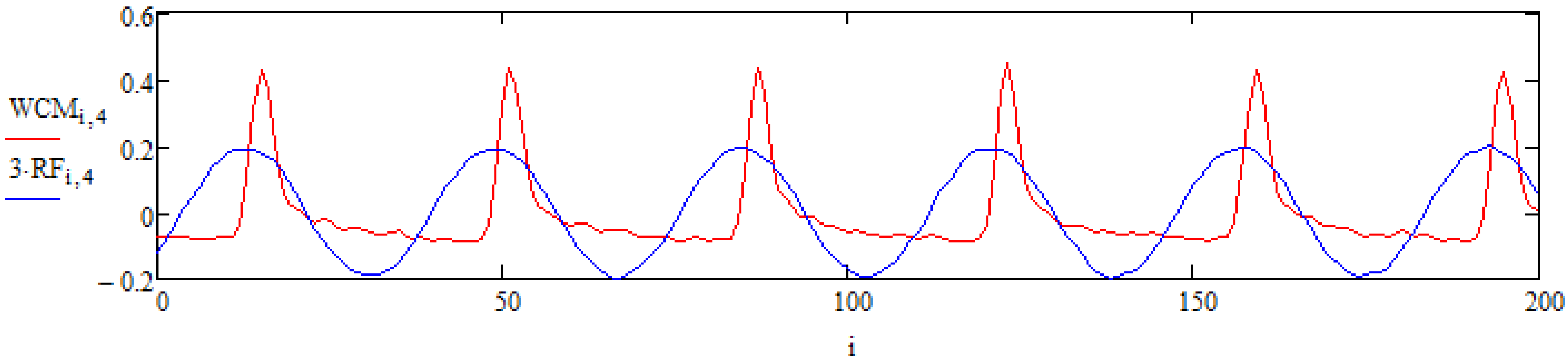
- Fast digital scope
  - T=1 ms centered around transition
  - Δt=0.533 ns, $1.875 \cdot 10^6$ points per channel, 36 points per RF bucket
- Signals
  - RF sum
  - Wall current monitor
- Beam parameters
  - Intensity: 4, 6, 8, 10, 12 & 14 turn Booster injection
    - 14 turn =$4.3 \cdot 10^{12}$
  - 82 bunches,)

Supplemental measurements



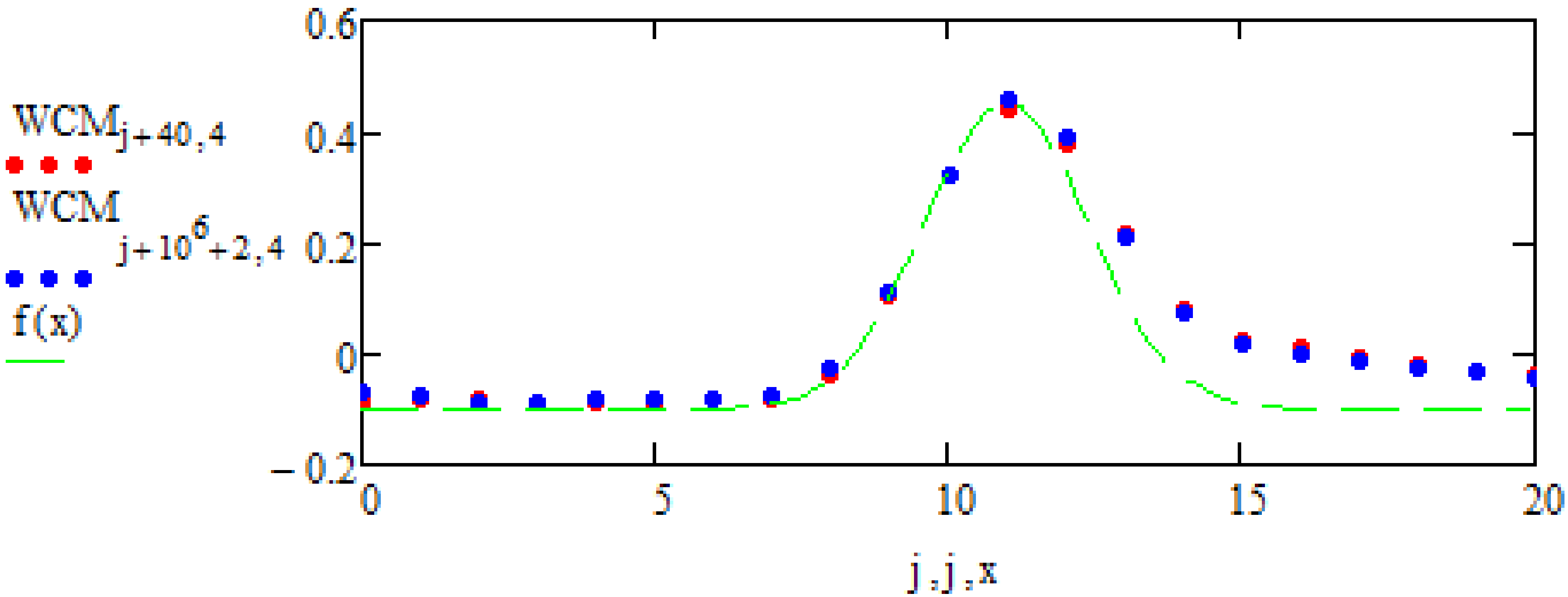
- Signals coming from low level RF were also aquired but their analysis was not carried out yet

Measured Signals and Data Analysis



- An algorithm computes
  - RF signal
    - Zero crossing time for each period
    - RF voltage for each period (relative units)
  - WCM signal
    - Fitting by parabola in vicinity of each peak (each bunch at each turn)
      - ⇒ Bunch arrival time
      - ⇒ Peak height
      - ⇒ Peak width
  - Time difference between RF zero crossing and bunch arrival time yields the relative accelerating phase

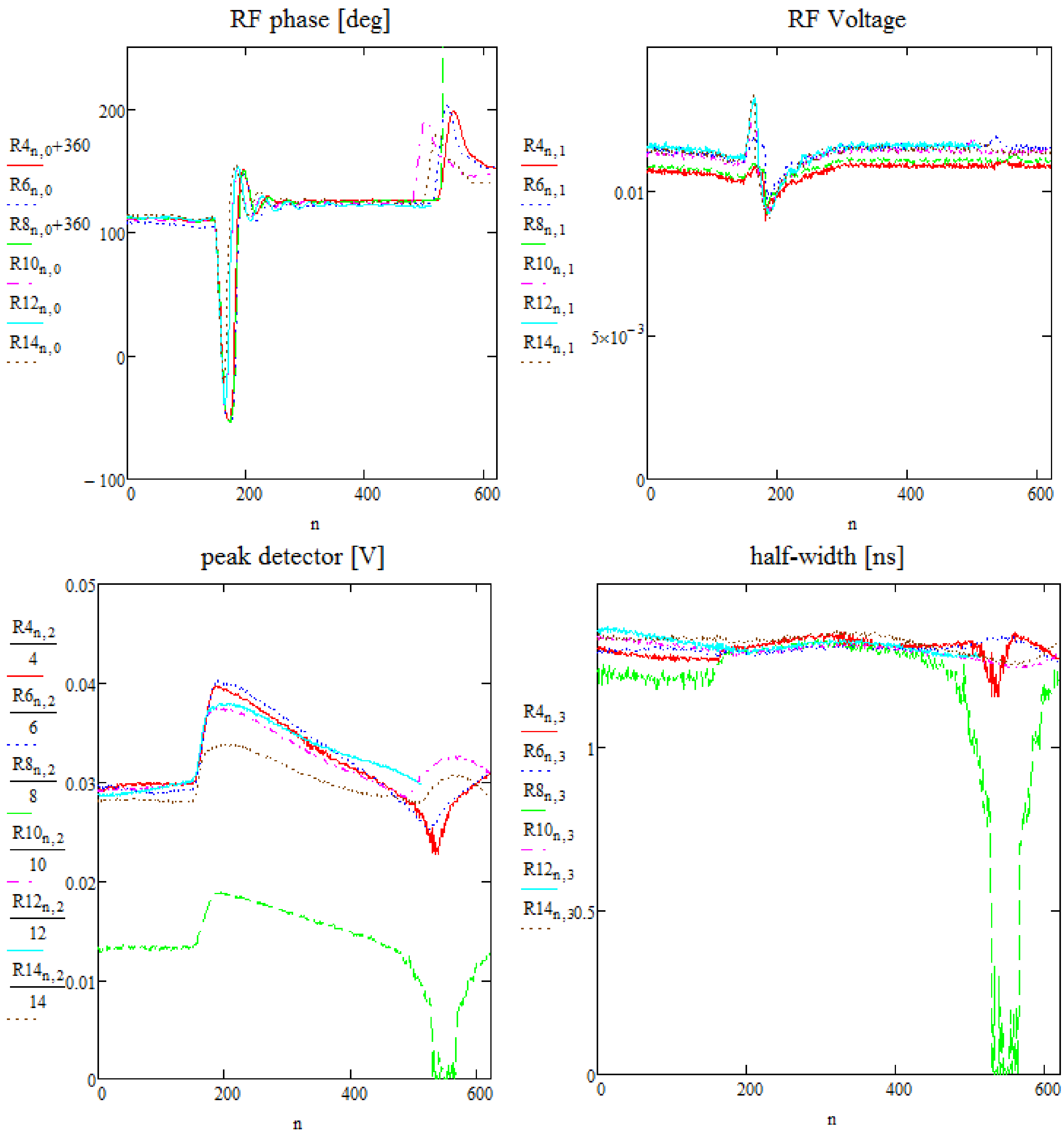
RMS bunch length



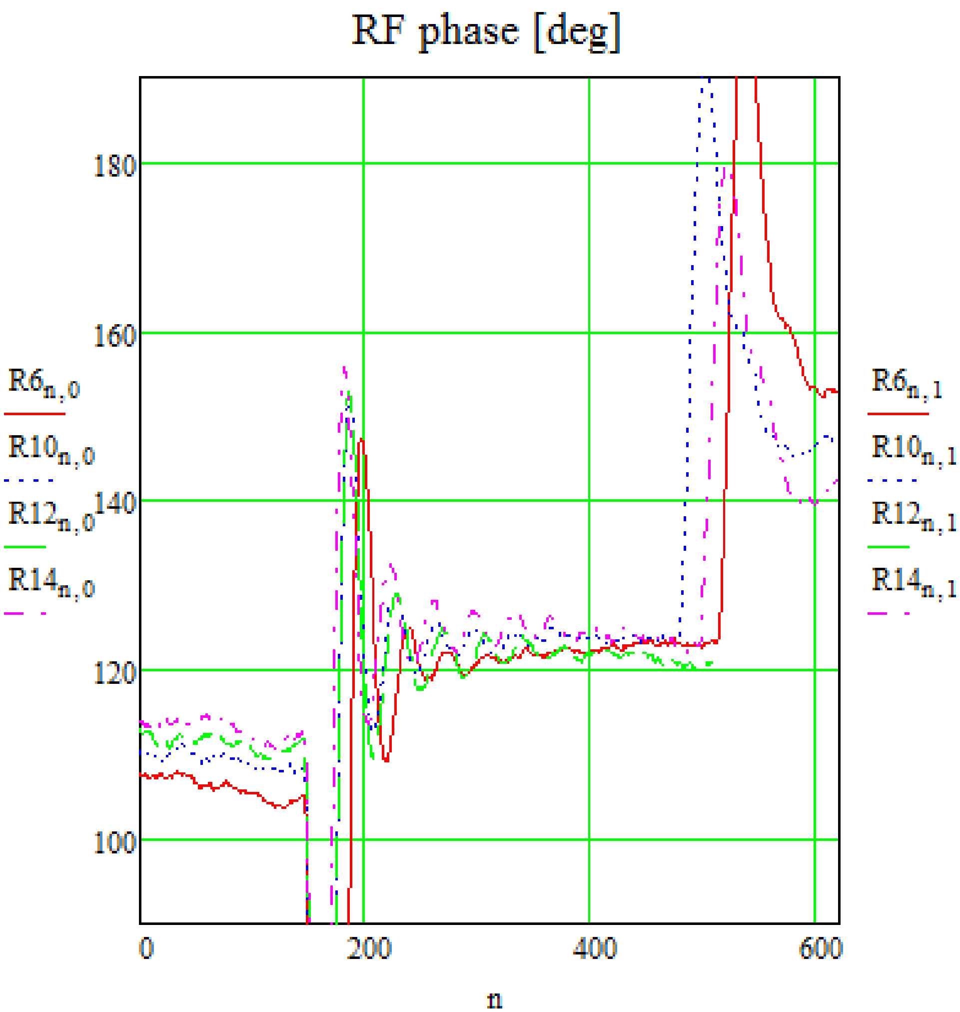
- Small variations in presented data (1 ms near transition)
  - Rms bunch length is ~0.75 ns
- Dispersion in the cable widens the bunch signal
  - Rms bunch length (time) is estimated from the emittance
    - Coincides with the experience obtained from other similar measurements
  - Better accounting for cable dispersion is required

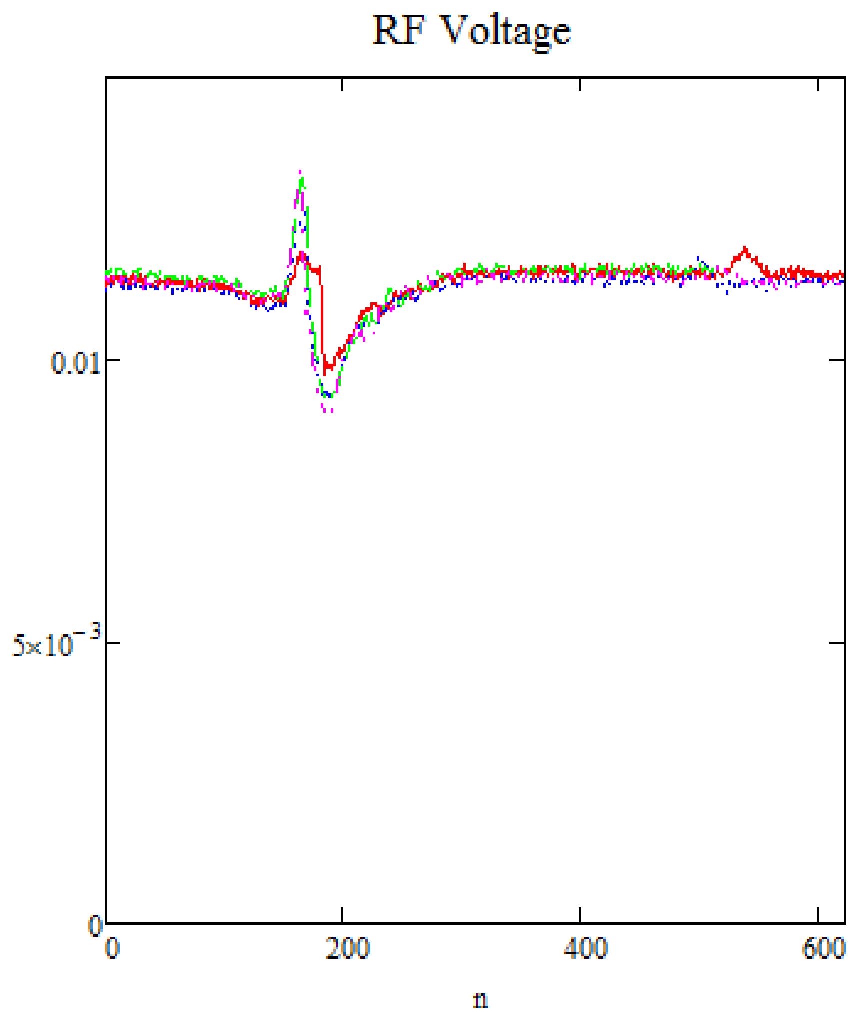
Results

- Only data which are consistent were left for further analysis
  - 6, 10, 12 & 14 turns
  - 4 & 8 turns (red and green) are excluded



Results (2)

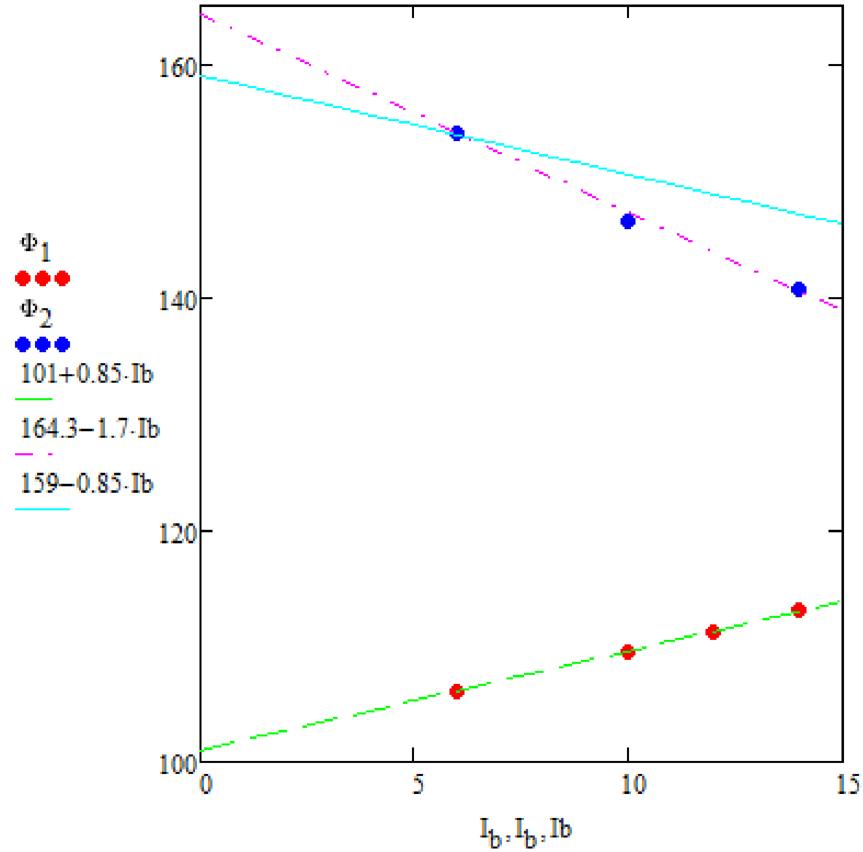




- Expected dependence of phase shift on intensity
- The transition results in additional energy loss and therefore the phase shifts after transition can be screwed up

Results (3)

- 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 ($4.3\cdot10^{12}$ 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

Conclusions

- Experimental measurements of effective longitudinal impedance verified that the model of laminated dipole impedance describes the observations comparatively well
  - Additional analysis is required to improve an accuracy of the measurements
- At transition, when the bunch is short, the peak of beam deceleration due to Booster longitudinal impedance will be in the range 130-150 kV/turn for PIP-II parameters