Losses at Flat Bottom: TWC 200 MHz, Beam Loading and More

2016-11-03

Contents

Travelling Wave Structure

Travelling wave structure for SPS

- W. Schnell, 1965, and G. Dôme, 1977

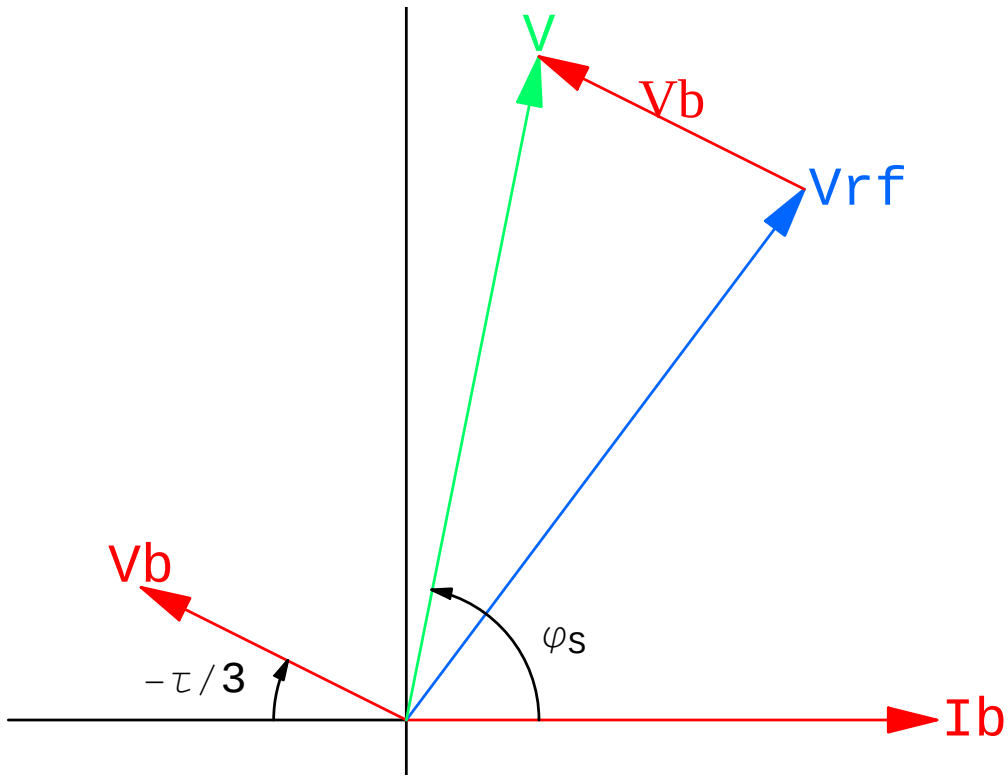
Effective voltage seen by the beam upon one traversal

$$V = Z_1 I_{\mathrm{g}} + Z_2 I_{\mathrm{b}}$$

- $Z_1 = \sqrt{\frac{R_2 Z_0}{2}} \frac{\sin \tau/2}{\tau/2} l$
- $Z_2 = -\frac{R_2}{8} \left[\left(\frac{\sin \tau/2}{\tau/2} \right)^2 - j2 \frac{\tau - \sin \tau}{\tau^2} \right] l^2$
- $\tau = \frac{l}{v_{\mathrm{g}}} (\omega - \omega_0)$
- R_2: TWC series impedance
- v_{g}: TWC group velocity
- Z_0: line impedance
- linearised $\omega - k$ diagram

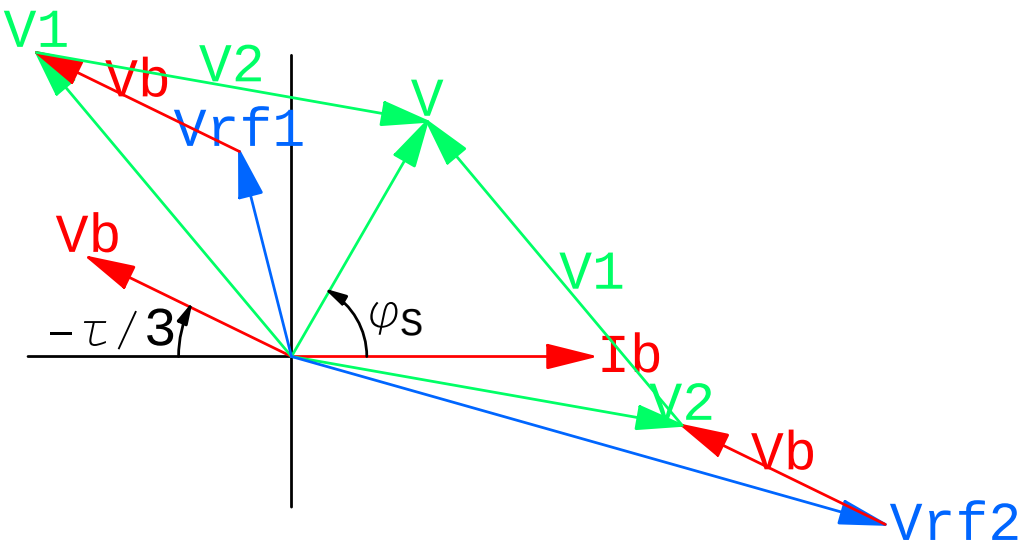
Travelling Wave Structure

Vector Diagram



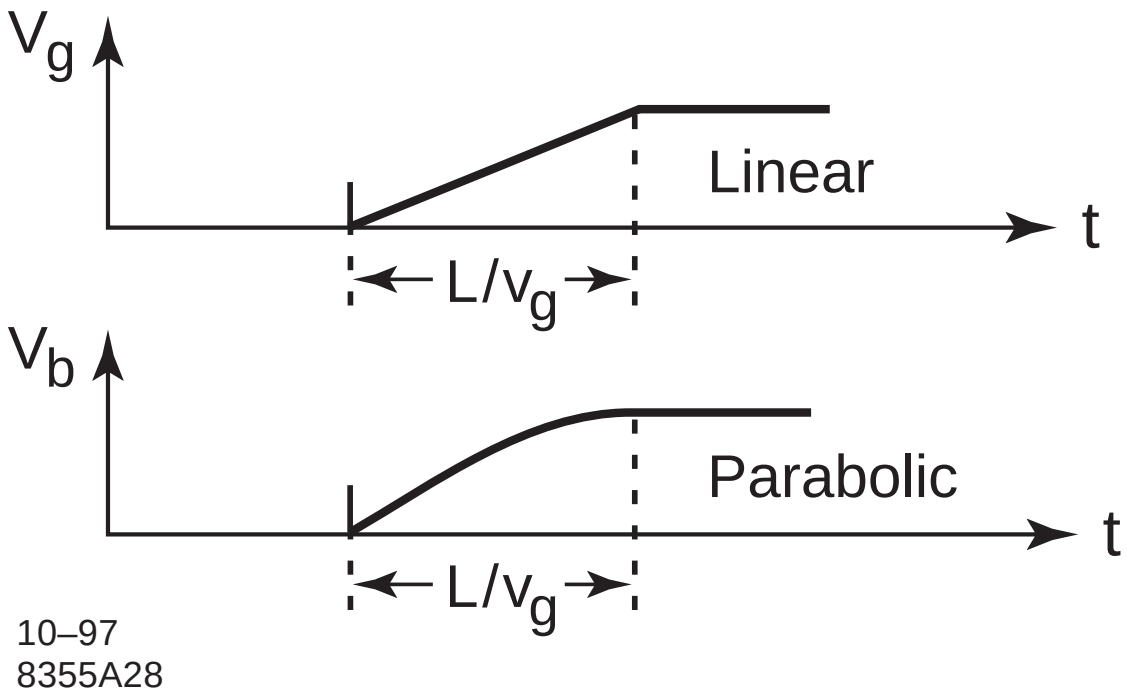
Travelling Wave Structure

Counterphasing of Equal Length Structures



Travelling Wave Structure

Step Response



Travelling Wave Structure

With

- $\vec{V} = \vec{V}_{\mathrm{RF}} + \vec{V}_{\mathrm{b}}$
- $\rho = \left(\frac{\sin \tau/2}{\tau/2}\right)^2 - j2\frac{\tau - \sin\tau}{\tau^2}$
- $\alpha = \arg \rho$

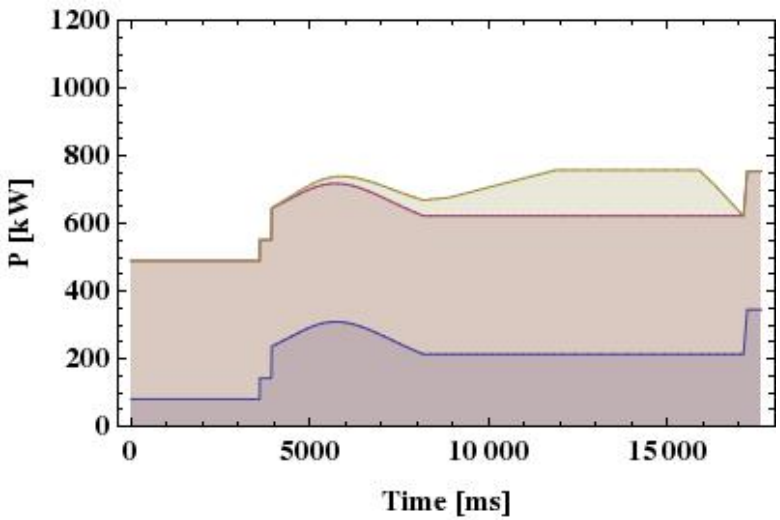
$$P = \left(\frac{\tau/2}{\sin \tau/2}\right)^2 \left\{ \frac{1}{R_2 I^2} V^2 + \frac{R_2 I^2}{64} I_{\mathrm{b}}^2 + \frac{1}{4} V I_{\mathrm{b}} \rho \cos(\alpha - \varphi_{\mathrm{s}}) \right\}.$$

Travelling Wave Structure

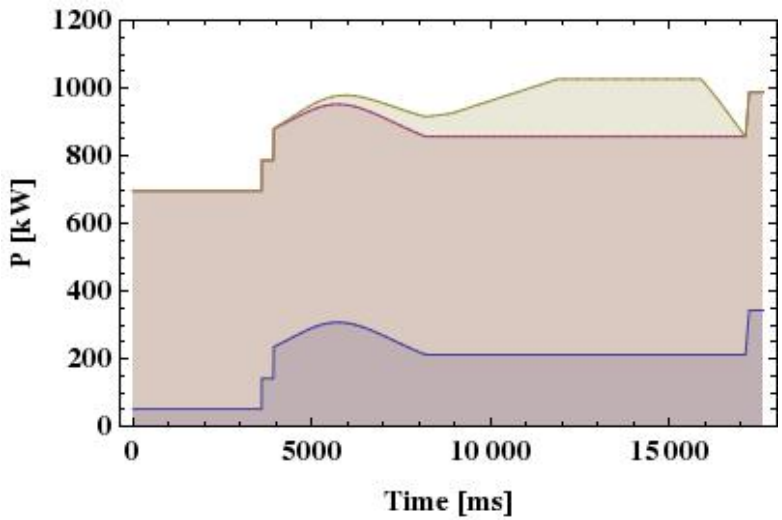
Example

- 72 bunches, 25 ns bunch spacing,
- MD_SCRUB_26_L26400_Q20
- $N_{\mathrm{Q}} = 1.7 \times 10^{11}$, $I_{\mathrm{pk}} = 2.1$ A
- cosine-squared bunches of 1.5 ns ($f_{\mathrm{shape}} = 0.92$), $I_{\mathrm{b}} = 1.9$ A

4 Sections



5 Sections



Travelling Wave Structure

Simplified Power Requirements
With $\tau = 0$

$$P = \frac{1}{R_2 l^2} V^2 + \frac{R_2 l^2}{64} I_\mathrm{b}^2 + \frac{1}{4} V I_\mathrm{b} \cos(\varphi_\mathrm{s}),$$

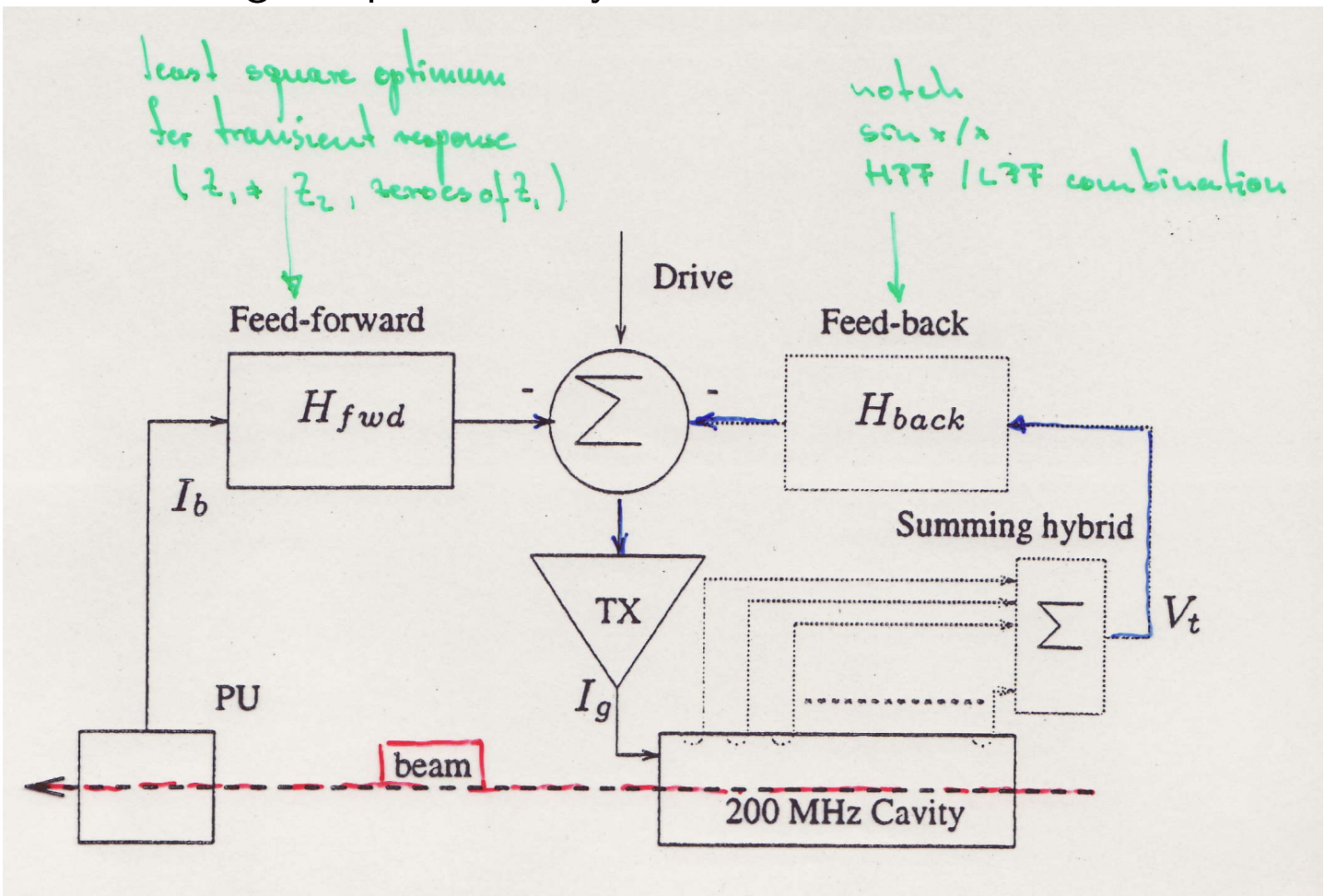
and

$$I_\mathrm{opt} = \sqrt{\frac{8V}{R_2 l_\mathrm{b}}}.$$

- no transient beam loading
- uniform azimuthal beam distribution
- no beam loading angle variation
- no counterphasing

Feedback/Feed-forward

Beam loading compensation by feed-forward and feedback



Feedback/Feed-forward

Feedback at injection

Figure 11: Compensation of the beam loading at injection with the feed-back. I/Q components of V_t (AC coupled) showing the progressive compensation turn after turn, $20\mu s$ per div., $T_{rev} = 23\mu s$. (One batch of 48 bunches, 0.83×10^{11} protons per bunch, four sections cavity, MD session 30^{th} Aug. 2000).

P. Baudrenghien et al, 2001

- Q26, Q20

Feedback/Feed-forward

Feed-forward at injection

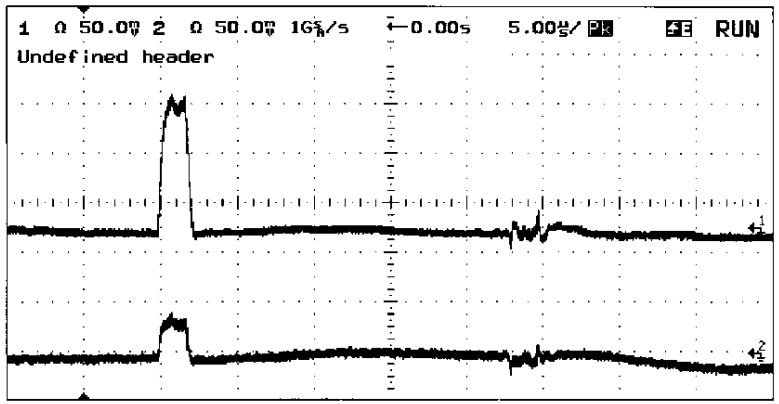


Figure 5: Compensation of the beam loading at injection with the feed-forward. I/Q components of V_t (AC coupled): The time window ($5\mu s$ per div.) shows the first turn where no compensation can be applied, and the second turn (after one revolution period $T_{rev} = 23\mu s$) with the full correction from the feed-forward. (One batch of 72 bunches, 0.7×10^{11} protons per bunch, four sections cavity, MD session 2^{nd} Nov. 2000).

P. Baudrenghien et al, 2001

At 1 ms after injection

feedback

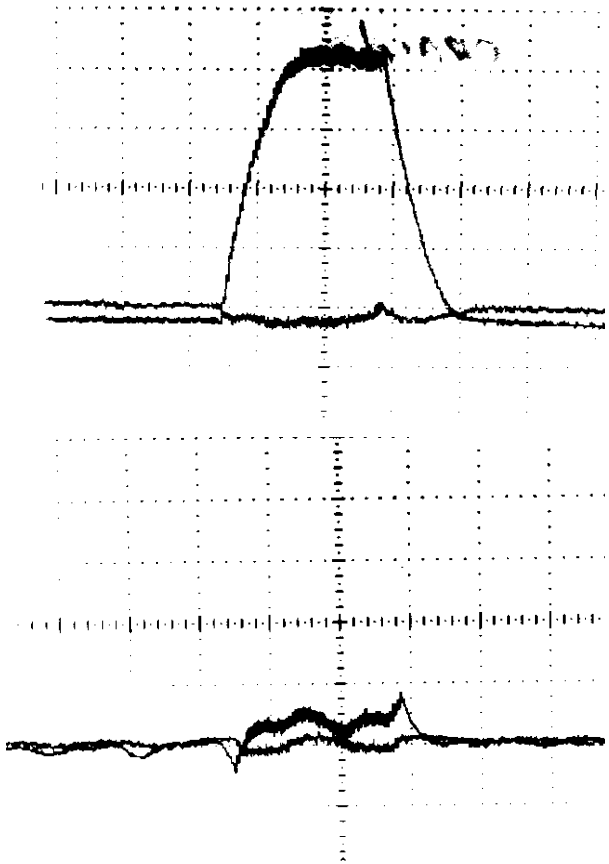


Figure 12: I/Q components of V_t (AC coupled) injection (500 ns per div.). Top: no compensation feed-back on. Beam conditions as in Figure 11.

feed-forward and feedback

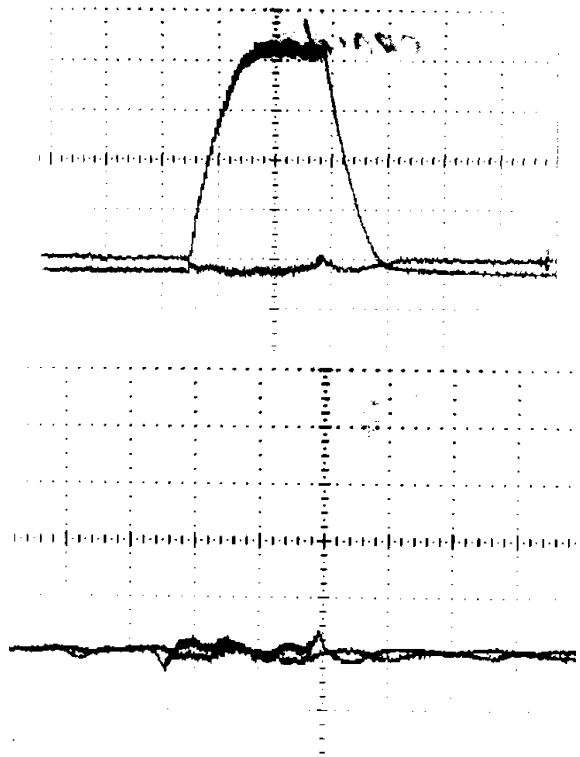


Figure 16: I/Q components of V_t (AC coupled) 1 ms after injection (500 ns per div.). Top: no compensation. Bottom: feed-forward and feed-back pair on. Beam conditions as in Figure 11.

P. Baudrenghien et al, 2001

Feedback/Feed-forward

Limitations

- $Z_1 \neq Z_2$
- f_0, dispersion
- cavity voltage measurement
- feedback and f_s (Q26/Q20)
- noise
- bandwidth of amplifiers

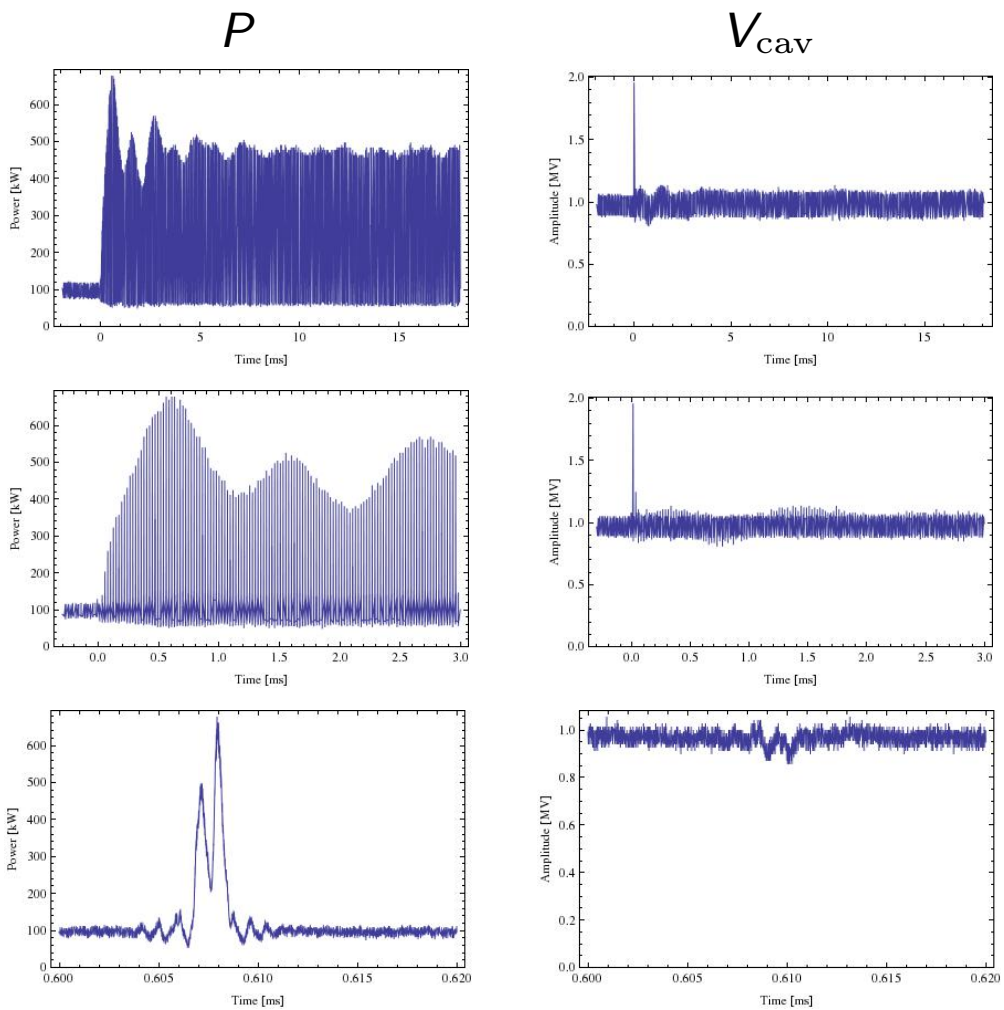
Limits of Beam Loading Compensation

- beam loss at flat bottom
- injection
- examples of P, V_{cav} for TWC200-4 (5 sections)
- voltage partition: not discussed
- counter-phasing: not discussed
- V_{min}: not discussed

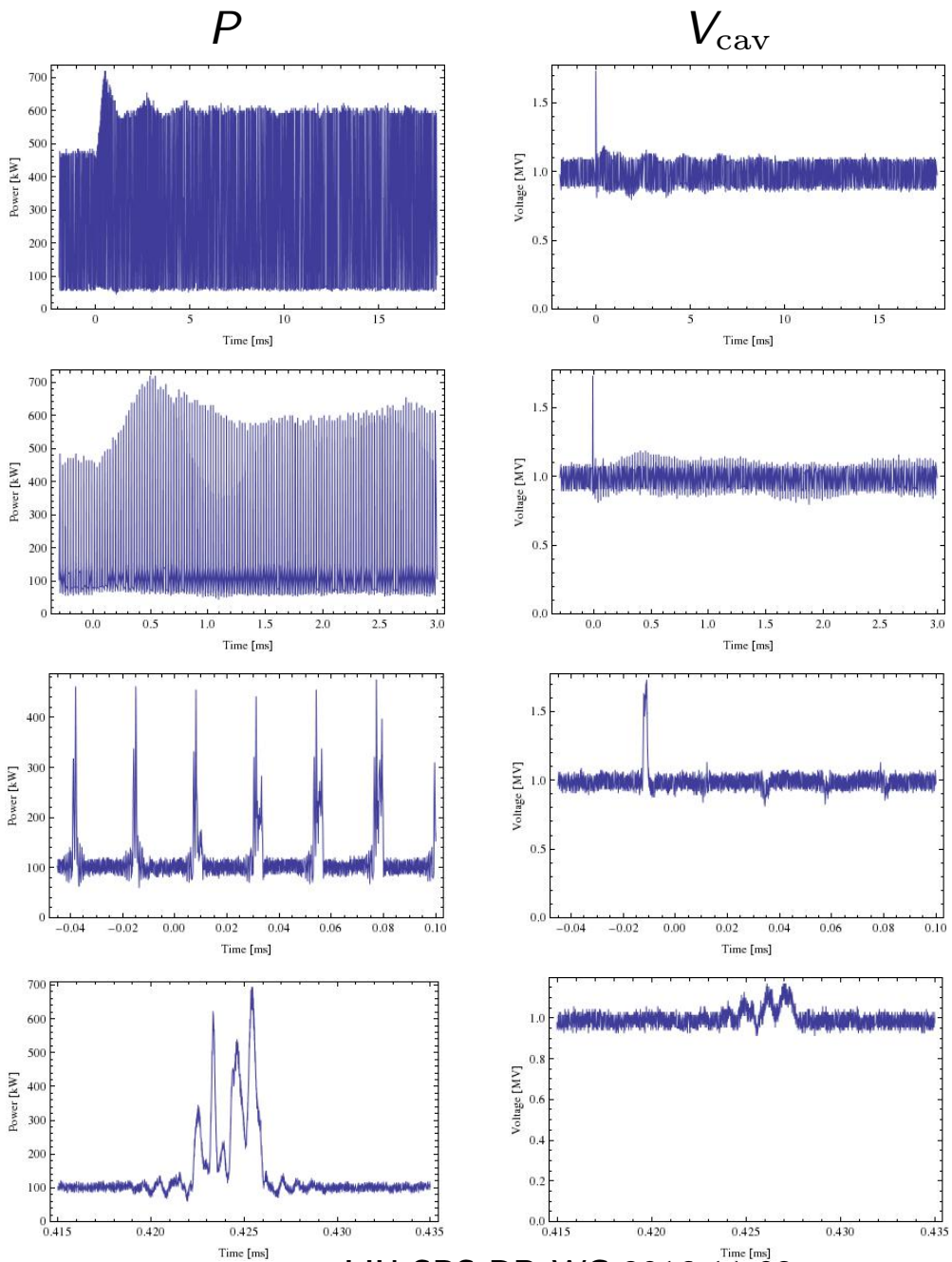
Limits of Beam Loading Compensation

- MD_SCRUB_26_L26400_Q20, 2014-11-05
- 72 bunches with 25 ns bunch spacing, 3 batches
- $N_{\mathrm{Q}} = 1.25 \times 10^{11}$

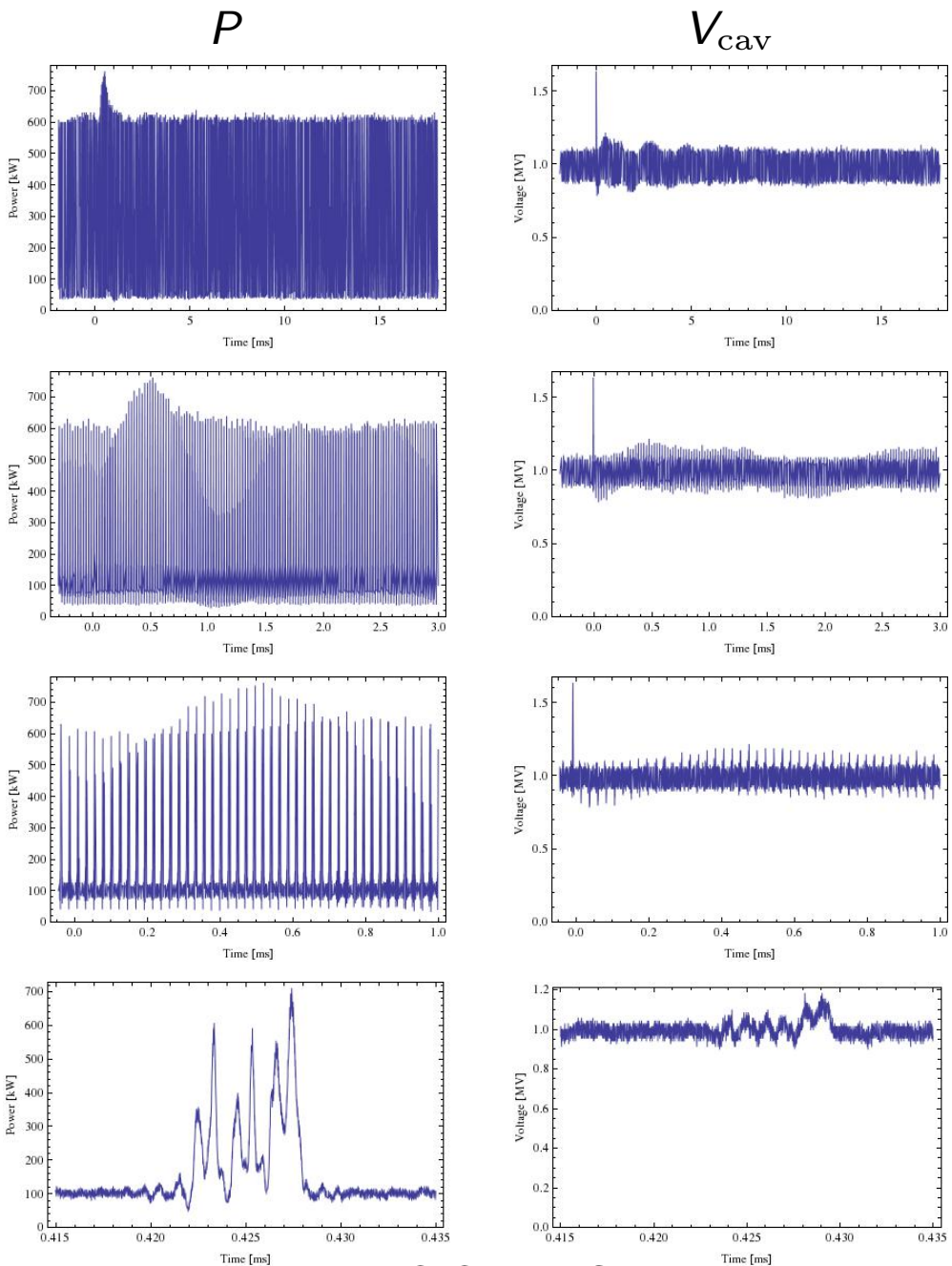
Injection 1



Injection 2



Injection 3

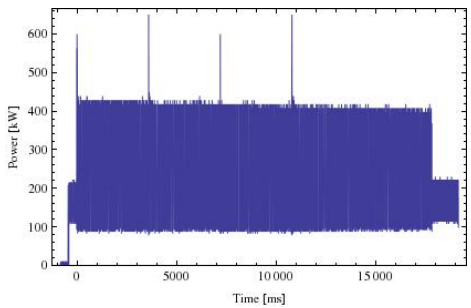


Limits of Beam Loading Compensation

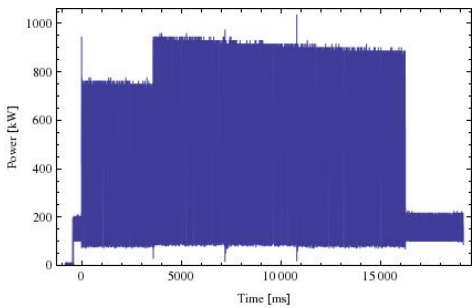
- MD_SCRUB_26_L26400_Q20, 2015-04-13
- 72 bunches with 25 ns bunch spacing, 4 batches
- $N_{\mathrm{Q}} = 1.5 \times 10^{11}$

Flat Bottom

$P(\mathrm{TWC200-1})$



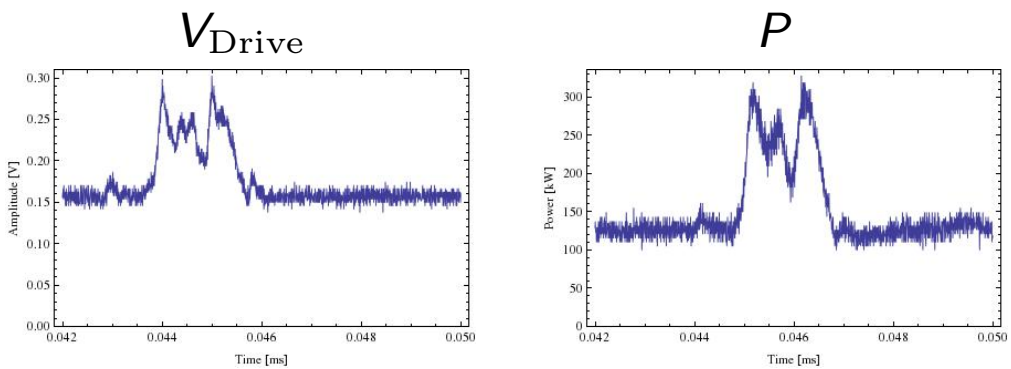
$P(\mathrm{TWC200-4})$



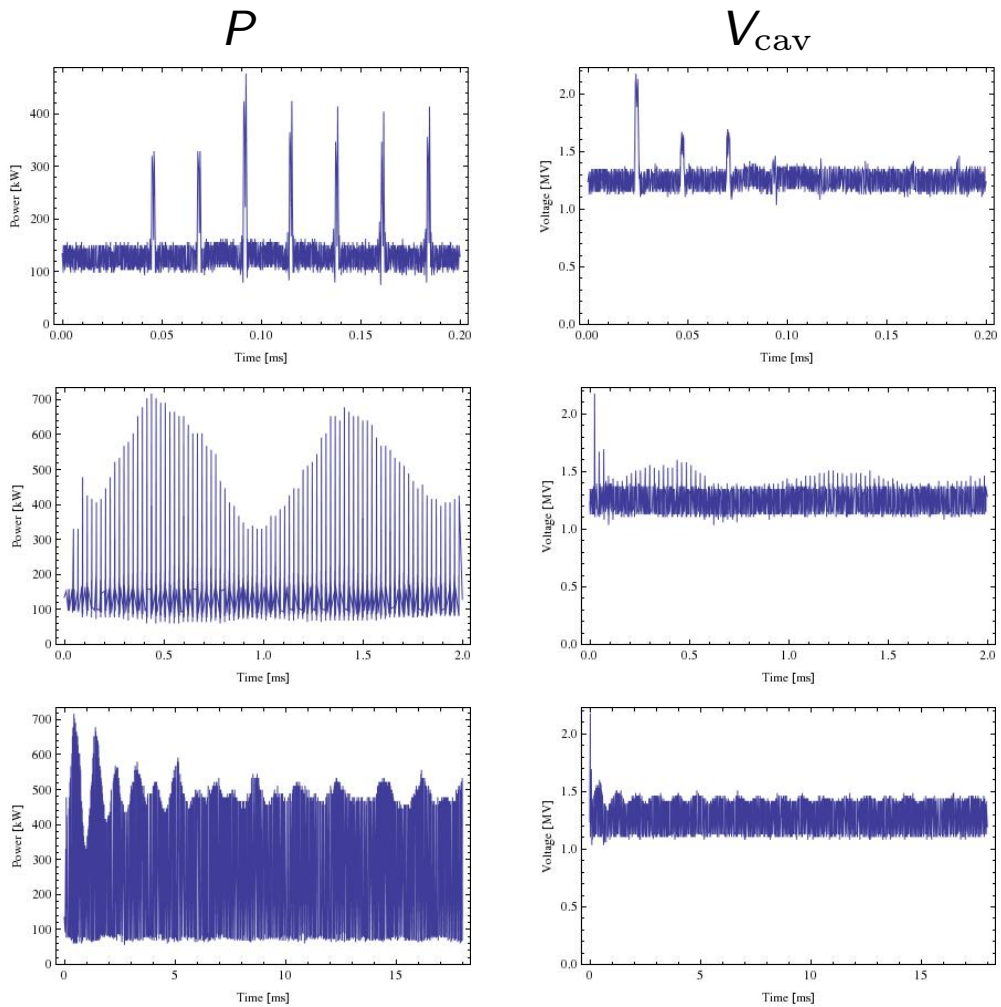
Limits of Beam Loading Compensation

- MD_SCRUB_26_L26400_Q20, 2014-12-10
- 72 bunches with 25 ns bunch spacing, 1 batch
- $N_{\mathrm{Q}} = 1.7 \times 10^{11}$

Injection

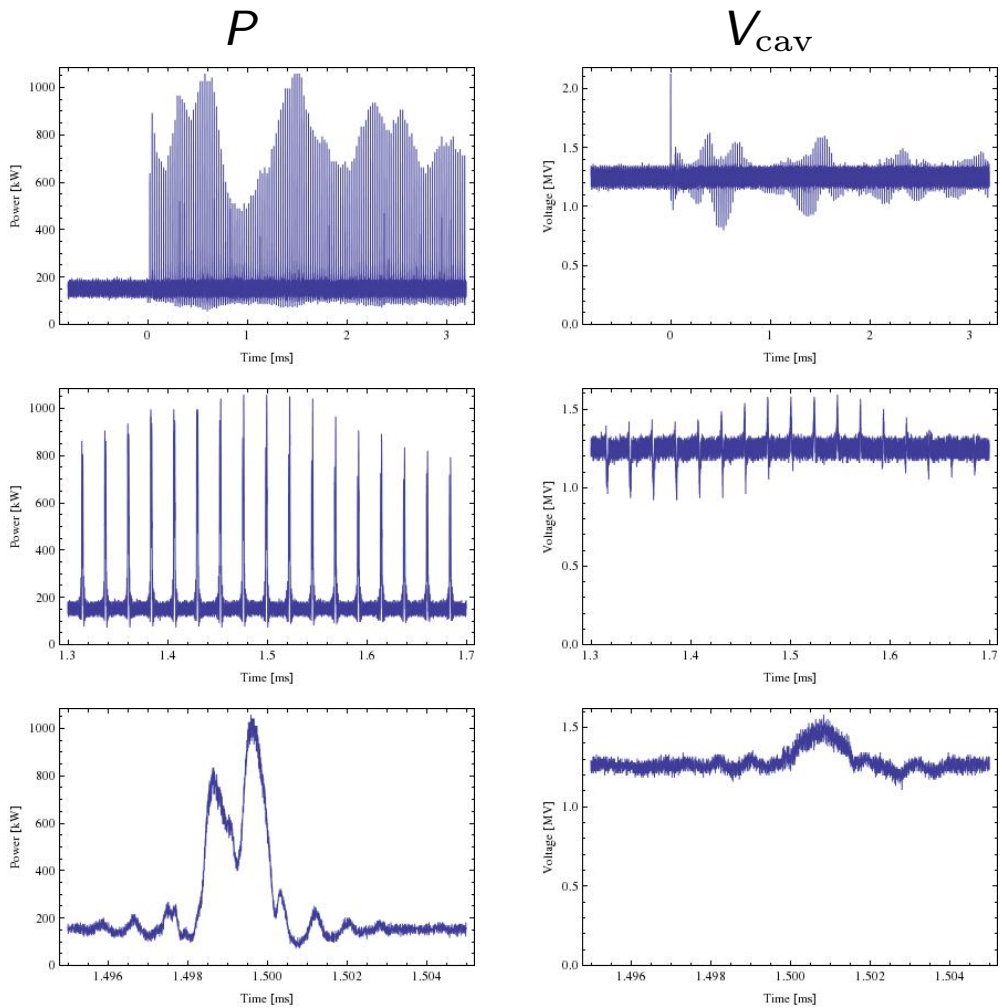


Injection



Limits of Beam Loading Compensation

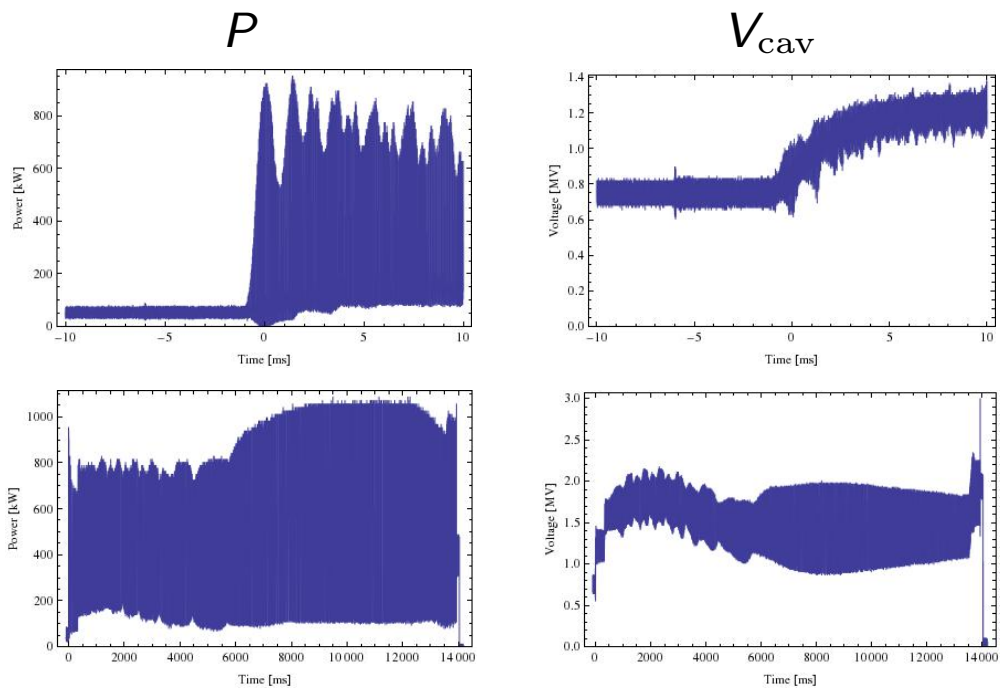
- MD_SCRUB_26_L26400_Q20, 2015-06-01
- 72 bunches with 25 ns bunch spacing, 1 batch
- $N_{\mathrm{Q}} = 1.9 \times 10^{11}$



Limits of Beam Loading Compensation

- MD_SCRUB_26_L26400_Q20, 2015-05-08
- 72 bunches with 25 ns bunch spacing, doublet, 1 batch
- $N_{\mathrm{Q}} = 1.7 \times 10^{11}$ at injection

Injection and whole cycle



Losses at Flat Bottom

- S shape phase space distribution (bunch rotation in CPS)
- feedback/feed-forward
  - injection oscillations
  - peak power limit
  - 1st/2nd batch power increase
  - f_s, Q26/Q20
  - h/w limitations
- longitudinal dampers
  - Q26/Q20
- TWC 800 MHz