SPS TWC 200 field regulation during ramp
Simulations with HL-LHC beam using rigid-bunch model

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Parameters (1/3)

- **Beam**
  - 2.3 $10^{11}$ ppb
  - bunching factor = 0.93
  - 72 bunches, 25 ns spacing
  - 4 batches

- **Cavities [1]**
  - Caution: The group velocity must be taken positive while the particle velocity must be taken negative for a backward wave structure [1]

$$\tau = \frac{NI}{v_g} \left(1 - \frac{v_g}{v}\right)$$
Parameters (2/3)

- **TX**
  - Butterworth model
  - -3 dB single-sided bandwidth of 1.5 MHz (Philips and Siemens)
  - -15 dB at 4 MHz (Philips) and 2.5 MHz (Siemens)
  - According to measurements done in 2003 [2]
  - No measurement on new solid-state TX yet (4sec cavity)

- **LLRF**
  - OTFB ON
  - Feedforward ON. See design/details in [3]
  - Clamping of drive at TX input at 1 MW (3 sections) and 1.6 MW (4 sections)
Parameters (3/3)

- Longitudinal dynamics
  - Consider steady state only (no oscillation). OK for ramping and at extraction. Not OK for capture transients.
  - Each bunch stays at $\phi_s$ with respect to total voltage in corresponding bucket
Extraction with 10 MV
• Phase deviation (at 200 MHz) of bunch phase with respect to the RF wavelength
• The beam fluctuation is from 1.54 to 1.75 degrees rms and from 10.2 to 11.2 degrees peak-to-peak for the four filters used
• The improvement from more aggressive filters is marginal
Results: Uncompensated beam loading |V-Vset|

- The total beam induced voltage is around **11 MV without compensation**
- With the regulation it is reduced to **900 kV (8%)** for first and last bunches and around **100 kV (0.9%)** in middle of batch
- Regulation BW has little effect
4 batches of 72b with 8 empty bunches in between: Phase deviation

• Phase deviation (at 200 MHz) of bunch phase with respect to the RF wavelength

• OTFB with most aggressive filter (Passband 0.5 $F_{zero}$)

• The rms phase deviation is 2.0 degrees. The peak-to-peak is 15.6 degrees

• This is a bit worse than single batch (1.75 deg rms, 10.2 deg pk-pk)

• The bunches right after the short gaps are the worst (about -9 deg phase deviation).
• Peak power is **885 kW for 3-section** and **1387 kW for 4-section**, a few tens kW worse than 72b

• Margins are now 13% and 15.4% respectively (w.r.t. 1 MW and 1.6 MW)

• Comparing these peaks to the calculated 665 kW/1123 kW, we conclude that the regulation requires 33% (3 sec) and 23% (4 sec) power overshoot.
Ramping
• We use the **same momentum ramp and voltage program as in 2018**, that is only 7 MV at extraction. **So ignore the results at extraction.** Refer to slides 5-8 for 10 MV at extraction.

• The simulation gives voltages different for the various bunches, and different from program due to the uncompensated beam loading.
Power required

- The *Steady State* is calculated assuming perfect beam loading compensation and NO overshoot due to LLRF regulation.

- The *Peak* is measured (simulation) with the LLRF regulation. It reaches (about) **960 kW for 3-section** and **1480 kW for 4-section**, to be compared to **885 kW and 1387 kW** respectively at extraction with 10 MV (slide 8).

- The required regulation margin is also max towards the end of the ramp.

![Diagram showing power over time](image)

- **Steady state power max at end of ramp**
- **Peak power reached at end of ramp**
Phase spread along batches

- The Peak-to-peak phase variation is **24 degrees** in the ramp, to be compared to the **15.6 deg** at extraction with 10 MV (slide 7)
- It is maximum during filling. Reaches **44 degrees peak-peak**. Caution: we have used $f_b=0.93$ thru the simulation.
Can we be more inventive?
Alternative algorithm?

- The pre-LS2 and post-LS2 OTFB impose constant RF voltage amplitude and phase during the turn -> huge power transient at head of batch.

- The LHC Full-Detuning algorithm accepts variation of the RF voltage phase along the batch -> large reduction in required power. That is not readily applicable to the SPS because:
  - Significant stable phase during ramp
  - Capture losses in LHC if bunches are not equispaced

- But...there is no need to regulate the RF voltage outside beam segments.

- Idea: New algorithm:
  - Keep RF voltage amplitude and phase constant during beam segment
  - Optimize RF voltage outside beam segment to minimize peak requested power

- No time to develop that in 2021...but the new uTCA platform is flexible enough to implement a new regulation later.
Conclusions

- We have simulated the Feedforward, OTFB, TX including BW limitation, Cavity and have clamped the drive (LLRF output) at 1 MW/1.6 MW equivalent TX output power.
- The beam is modelled as an RF current with one vector (amplitude/phase) for each bunch (25 ns spacing).
- The bunch/bucket voltage remains at $\phi_s$ at all time. OK for stable conditions (extraction). Not OK in presence of injection transients.
- As anticipated, the peak power requirements are not reached at extraction with 10 MV, but at the end of the accelerating ramp.
- There we reach 960 kW for 3-section and 1480 kW for 4-section, using the 2018 voltage program during ramp.
- That is still below the 1000 kW and 1600 kW but ... not much.
- The peak-to-peak phase variation along the 4x72 b reaches 24 RF degrees during the acceleration ramp.

Thank you for your attention.

Questions? Comments?
References


Back-up slides
• Cavities (cont’d)

- In TWCs, the beam can induce voltage at frequencies where the TX drive cannot induce voltage. That is unlike SWCs. In addition cavity $Q$ very low (100/140), TX BW comparable to cavity BW, **all not favorable for transient beam loading compensation.**

• TX

  - Butterworth model
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• LLRF

  - Feedforward ON. See design/details in [3]
  - Clamping of drive at TX **input** at 1 MW (3 sections) and 1.6 MW (4 sections)
• LLRF (cont’d)
  ▪ OTFB ON: The regulation aggressiveness was changed by using filters with increasing Passband (0.2 – 0.5 fraction of first cavity zero). Gain 40 (linear) on the $F_{rev}$ lines ($a = 63/64$).
• Uncompensated beam induced voltage for 3-sections (left) and 4-sections cavity
• For the 4-sections cavity the degradation on first bunch of batches 2,3,4 is almost a factor two (400 kV compared to 220 kV)
• Large drive demanded by feedforward there and...clamped by the power limitation -> degraded compensation
Feedforward [3], 4-sections cavity

- Top: Response of the cavity to a step beam current (orange) and compensation voltage from feedforward (blue). 25 ns between samples. The fit is very good!

- Bottom: TX power (arbitrary units)
  - We observe a reasonable spike when the beam enters the cavity, and a very large spike after the cavity filling time
  - This second spike corresponds to about 4 times the steady-state power -> 4.5 MW!
  - This is clamped at 1.6 MW -> poor compensation at the head of the batch