LHC Injectors Upgrade
SPS: impedance model and instability in the transverse plane

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SPS transverse impedance model

Elements included in the database:

- Wall impedance that takes into account the different SPS vacuum chambers (analytical calculations)
- Kickers (CST 3D simulations)
- RF cavities (200 MHZ and 800 MHz) without couplers (CST 3D simulations)
- Broadband impedance of step transitions (CST 3D simulations)
- Horizontal (BPH) and vertical (BPV) beam position monitors (CST 3D simulations)
SPS kicker impedance model

Tsutsui model

Vertical

Horizontal

CST Particle Studio is found to be a reliable tool to simulate the impedance of ferrite loaded components
SPS kicker impedance model

SPS kicker magnet

Tsutsui model

C-magnet model

Realistic models: longitudinal cell segmentation and serigraphy
SPS kicker impedance model: experimental benchmark

→ Beam induced heating measurements
  - The impedance model of the SPS extraction kicker with and without serigraphy can explain the beam induced heating observed in the SPS machine


→ Bench impedance measurements (stretched wire method)
SPS kicker impedance model: comparison with bench measurements for the MKP11955 module

Longitudinal Impedance

Confimation of the 3D simulation model
SPS kicker impedance model: comparison with bench measurements for the MKP11955 module

Confirmation of the 3D simulation model
SPS transverse impedance model

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\[ Z_{\perp}^{SPS}(f) = \sum_{i=1}^{N} \frac{\beta_{\perp}^{i}}{\langle \beta_{\perp} \rangle} Z_{\perp}^{i}(f) \]
SPS transverse impedance model

Peaks due to the serigraphy of the extraction kickers
SPS transverse impedance model

Broadband impedance mainly from kickers, step transitions and wall
SPS transverse impedance model

Peaks due to the RF system and BPMs
SPS transverse impedance model

Benchmark with beam measurements

- Coherent tune shift
- Instability behavior
SPS transverse impedance model

Benchmark with beam measurements

- Coherent tune shift
- Instability behavior

A. W. Chao, Physics of collective beam instabilities in high energy accelerators
Benchmark of the SPS transverse impedance model: tune shift measurements

Vertical coherent tune shift: Measurements performed in September 2012

Fractional part of the vertical tune

Bunch Intensity

SPS vertical tune shift measurements
Benchmark of the SPS transverse impedance model: tune shift measurements

Vertical coherent tune shift: Measurements performed in September 2012

Fractional part of the vertical tune vs. Bunch Intensity

- SPS vertical tune shift measurements
- Impedance model (only kickers)
Benchmark of the SPS transverse impedance model: tune shift measurements

Vertical coherent tune shift: Measurements performed in September 2012

- SPS vertical tune shift measurements
- Impedance model (only kickers)
- Impedance model (kickers and wall)
Benchmark of the SPS transverse impedance model: tune shift measurements

Vertical coherent tune shift: Measurements performed in September 2012
Benchmark of the SPS transverse impedance model: tune shift measurements

The SPS impedance model explains more than 90% of the measured vertical coherent tune shift
Benchmark of the SPS transverse impedance model: tune shift measurements

Horizontal coherent tune shift: Measurements performed in February 2013

The SPS impedance model predicts a very small horizontal tune shift (almost flat) in agreement with the measurements.
SPS transverse impedance model

Benchmark with beam measurements
- Coherent tune shift
- Instability behavior
Benchmark of the SPS transverse impedance model: instability behavior

Two regimes of instability in measurements

- **Fast instability** threshold with linear dependence on $\varepsilon_l$
- **Slow instability** for intermediate intensity and low $\varepsilon_l$

Very well reproduced with HEADTAIL simulations

- SPS impedance model includes kickers, wall, BPMs and RF cavities
- Direct space charge not included

![Graph showing measurements and HEADTAIL simulations](image)

**Island of slow instability**

4.5x10^{11} p/b @ 0.35 eVs
Benchmark of the SPS transverse impedance model: instability behavior

**Measurements**

- $\varepsilon_i = 0.27$ eVs
- $N = 2.2 \times 10^{11}$ p/b

**HEADTAIL simulations**

- $\varepsilon_i = 0.30$ eVs
- $N = 2.2 \times 10^{11}$ p/b

**Island of slow instability**

- $4.5 \times 10^{11}$ p/b @ 0.35 eVs
Benchmark of the SPS transverse impedance model: instability behavior

Measurements versus simulations. The figure shows the comparison between measurements and HEADTAIL simulations for Q20. The diagrams illustrate the behavior at a nominal energy of 0.35 eVs, with a beam intensity of $4.5 \times 10^{11}$ p/b. The Island of Slow Instability is highlighted in the simulation data, indicating a region of slow growth rate.
New elements to be added in the model

Simulations are ongoing or must be finalized

- Septa
- Wire scanner
- Non standard elements (special transitions, valves)

Update due to future installations and modifications

- New wire scanner
- New kicker for high bandwidth feedback system
- New MSI-V septum
- Serigraphy of the last MKE (7/8 were already serigraphed in the 2012)
Summary

The present SPS transverse impedance model includes kickers, wall, cavities, BPMs and step transitions

- The kickers are the main contributors to the SPS broadband impedance (about 40% of the measured coherent tune shift)

- The present SPS impedance model explains more than 90% of the measured coherent tune shift

- HEADTAIL simulations based on the SPS impedance model reproduce very well the instability behavior
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Thank you for your attention
Stability diagram: Q26

- Measured onset of instability linear in $\varepsilon_l$
  - As expected, slower losses (lower growth rate) slightly above threshold

- Linear dependence and instability thresholds reproduced in HEADTAIL
  - SPS impedance model includes kickers, wall, BPMs and RF cavities

![Image of stability diagram with measurements and simulations](image-url)
SPS kicker impedance model: comparison with beam induced heating observation (MKEs)

\[ \Delta W = (f_0 e N_{beam})^2 \sum_{p=-\infty}^{p=\infty} \left| \tilde{A}(p\omega_0) \right|^2 \text{Re} \left[ Z_{||}(p\omega_0) \right] \]

Beam induced heating: measurements (25/04/2012)

\[ \frac{\Delta T_{MKE}}{\Delta T_{MKE_{ser}}} = 4 \]

\[ \Delta T_{MKE_{ser}} = 5 \text{ [K]} \]

Power loss from the impedance model

\[ \frac{\Delta W_{MKE}}{\Delta W_{MKE_{ser}}} \]

Bunch length during the experiment
F. Caspers, T. Kroyer, M. Barnes, E. Gaxiola et al.

Realistic models: SPS extraction kicker (MKE-L)

Seven out of eight SPS extraction kickers have been serigraphed

Serigraphy
Evolution of the extraction kickers in the SPS

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Realistic models: MKE kicker with serigraphy
Comparing MKE with and without serigraphy

\[ f = 44 \text{ MHz} \]

\[ \lambda = \frac{c}{f \sqrt{\varepsilon_{\text{eff}} \mu_{\text{eff}}}} \approx 0.78 \text{ m} \approx 4L_{\text{finger}} \]
The peak observed in the MKE with serigraphy is a quarter-wavelength resonance on the finger length.
Kickers play a major role in the SPS total impedance.

The trend of the transverse effective impedance along the last 10 years is in good agreement with the expected changing of the kicker impedance model.

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Pumping ports

2000 → Impedance reduction campaign: shielding of the pumping ports, lepton cavities etc.)

\[ \Delta = Z_{2000}^{y_{\text{eff}}} - Z_{2001}^{y_{\text{eff}}} = 13.1 \, M\Omega / m \]

The broadband impedance due to step transitions can give significant contribution to the coherent tune shift.