Machine Element Contributions to the PS Longitudinal Impedance Model

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Overview

- PS Impedance Model
- Specific Examples:
  - Resonant Impedance Source: Internal Dump
  - Broadband Impedance Source: Kicker KFA45
  - Beam Induced Heating: LHCb VELO SMOG2
- Thoughts on Machine Element Impedance Analysis
- Conclusion
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Motivation for the Impedance Model

- Necessary to continue to build & maintain a longitudinal impedance model of the PS machine
- Build CST models for Wakefield & Eigenmode simulations
  - From CATIA files (when available), otherwise 2D drawings
- Confirm Wakefield & Eigenmode simulations with measurement (when possible and required)
  - RF measurements
  - Machine Development (MD’s)
- Provide confirmed results for BLonD code
- Identify objects whose impedance can be reduced
- The impedance model is kept updated on: [https://gitlab.cern.ch/longitudinal-impedance/PS/](https://gitlab.cern.ch/longitudinal-impedance/PS/)
Machine Elements of the PS Impedance Model

- Cavities
- Kicker Magnets
- Beam Instrumentation Equipment
- Vacuum Elements

Beam Instrumentation: Vertical BGI

Transverse Feedback Kicker

Kickers: BFA09

Vacuum Valves

*From A. Lasheen

![Graph showing impedance over frequency](chart.png)
Large impedances at low frequencies

Coupled Bunch Instabilities

Large impedances at high frequencies

Microwave Instabilities

Microwave instability at transition crossing

Measured profiles with Tomoscope at transition with different BUP settings

- Microwave instability right after transition is responsible of uncontrolled emittance blow-up and generation of tails ≈ more intensity in satellite bunches
- Occurs with the higher bunch intensity with the 3 bunches beam (same total intensity as the 4 bunches beam), cured with controlled emittance blow-up (BUP) (also measured with Xenon
  https://indico.cern.ch/event/710567/)
- Same observations in the KEK-PS end 90’s [1]
- Study useful for impedance source identification and general benchmark of transition crossing simulations (also beneficial for p+ beams)

https://indico.cern.ch/event/792563/

https://indico.cern.ch/event/865045/contributions/3644833/
Narrowband Impedance Source
Example: Internal Dump

- Typically Simpler Geometry
  - No ferrites
- Probe measurements
- Eigenmode solver
  - Wakefield solver*

*Long run times

Source of:
- Coupled Bunch Instabilities
  - (low frequency)
- Microwave Instability
  - (high frequency)

Broadband Impedance Source
Example: Kicker Magnet KFA45_17

- Typically Complex Geometries
  - Ferrites present
- Wire measurements
  - Post process for Long Imped.
- Wakefield solver
  - Simulated wire meas.

Source of:
- Loss of Landau Damping
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Overview of PS Internal Dump

- Fast Internal Dump
- Replacement for installed PS Dumps
  - Straight sections 47 & 48
  - Installed vacuum vessels are rectangular

Original Proposed Design

- Cylindrical Vessel
- Actuator
- Dump Pad
- PS Beam Pipe
- To Ion Pump

First Impedance Reduction Step:
minimize tank size

- Actuator
- Dump Pad
- PS Beam Pipe
- To Ion Pump
3 Additional Potential Impedance Mitigations

⇒ Due to complexity only beam pipe tapers used
⇒ Reduces shunt impedances

1. Beam pipe tapers
2. Coating of Dump Arm
3. Loops

Presented: https://indico.cern.ch/event/718539/contributions/2952914/
Initial Simulations of Circular Tapers: Comparing Eigenmode to Wakefield

Taper to Circle

Confirms Eigenmode results corresponds to Wakefield
=> Use Eigenmode for design studies

PS Dump Circular Taper: Wakefield & Eigenmode Simulation Results

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Final CST Model & Pictures* of the Dump

*Thanks EN-STI!
Probe Measurement Results*

Low measured Q-factors attributed to difficulties with material definition of dump pad

[Graph showing measurement and EM-simulation Q-factor results]

*Thanks to Dhiren Jhugroo

https://indico.cern.ch/event/887960/contributions/3744241

https://indico.cern.ch/event/887960/contributions/3744241

103 MHz Mode

Clean Peak

Weak Coupling (<100 mdB)
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Kicker Magnet: KFA45 Overview

- New KFA45 magnet (KFA45_17)*
  - Provides fast beam deflection for injection into PS
  - New magnet updated for 2.0 GeV beams (1.4 GeV for old magnet)
- Overall very similar to old KFA45
  - Larger Ferrites
  - Slight Changes in Module Frame Geometry
- EM Single Wire Measurements
  - Magnet with & without System
- Compare to Simulation Results
  - Frequency Domain Solver
    - (S-Parameters)
    - Wakefield

* ECR: 1969894
3D CST Model of the KFA45_17
Wire Measurements

- Measure broadband impedance using a single wire
  - Over couples to highly resonant structure (Can’t Measure Q-Values)
- Measurements done using a Vector Network Analyzer (VNA)
- Requires a matching network
  - VNA is 50 ohms and device under test (DUT) must be matched to it
- Post-process the Insertion Loss ($S_{21}$) to determine the longitudinal impedance
  - Python Script
  - See ref [1]
Initial Simulation vs Single Wire Measurement

Measured Modes (6 MHz & 16.5 MHz)

Simulated mode at 73 MHz appears in both Wakefield and S-Parameter Wire Simulations

HV cables are all shorted (Short-Short)
Simulated Mode at 73.5 MHz

Simulated mode at 73 MHz appears in both Wakefield and S-Parameter Wire Simulations but **not in measurements**
Approach to Inconsistencies between Simulation and Measurements

1. Confirming the Ferrite Definition (Interpolation Issues?)
   • Wanted to confirm CST is correctly handling imported permeability values (CMD5005)
   • → Same permeability curve generated

2. Checking the CST Solver Methods
   • Discrete vs Frequency Reduced Order Model
   • → No difference between solvers

3. Wire possibly over coupling to 73 MHz mode?
   • Try Probe Measurements
   • → No measurements possible below 200 MHz (noise floor)

4. Geometric Element missing???

* https://indico.cern.ch/event/719807/contributions/2958886
Missing Element: Transition Pieces

- Connecting all the grounding rails from one module to the next (4 modules) to the tank body on either side
  - Impedance Reduction

Ground plates

Grounding Rails for Ground Plates

Transition Piece*
Schematic-based Wire Simulations

- Using SNP files (touchstone) of 3D simulations of HV Boxes and KFA45 wire measurement setup
- Cables and terminations included in the schematic
  - ‘ideal’ cable
- Simulate various measurement cases

Cables
Connections
from KFA45 HV Box Connections

CST Schematic

KFA45 Module

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Single Wire Impedance Measurements & Simulations

Wire Measurement of KFA45 System

- Ion Pumps (2x)
- HV Boxes (4x)
- Port 1

CST Model of KFA45 Module

- Short To HV box

CST Schematic

- Open cables is configuration for circulating beam

HV Box

- CAD
- CST
1. See effect of ferrites damping resonances at lower frequencies (<50 MHz)
2. Resonances are reproduced in simulation (CST Schematic)
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LHCb VERTex LOcator (VELO) Overview

- Current VELO Situation
  - No heating or impedance issues

- New VELO Design for LS2
  - Closer to beam during operation
  - Twice the bunch intensity

- Need to analyze the longitudinal impedance
  - Also potential heating of SMOG2 Cell

- Various simulation and challenges...

CAD Model

CST Model
VELO Challenges

- Large, Complex Structure
  - VELO consists of rows of corrugations
  - Wakefield Suppressors shape is ill defined
  - Long run time in Wakefield simulation
    - Large mesh size
    - Resonating structure
  - Typically measure object to benchmark simulation model

- Actual LHCb VELO not available
  - Mockup of VELO provided by NIKHEF
    - Includes Wakefield suppressors
    - Smaller mockup tank
  - Wire measurements of VELO mock up
    - Benchmark model
    - Determine impedance of VELO itself

CST Model of Complete VELO with SMOG2

CST Model of Mockup

CST Model of Wakefield Suppressor

CST Model of VELO Mockup in Closed Position

Mockup

CAD Model
VELO Mockup: Wire Measurement Setup & S-Parameters

Adding foam to damp tank modes → only see impedance from VELO structure

Post-processing of measured S-Parameters in Python to determine the longitudinal impedance (See ref [1] and extra slides)

[Graph showing measured S21 values with and without foam, indicating changes across frequency]
VELO Mockup **Closed**: Compare CST Simulations & Measurement of Foam/No Foam Case

Adding foam to damp tank modes:
→ Only see impedance from VELO structure
→ Disentangle tank modes & possible VELO modes
→ Shows that the VELO itself is a broadband impedance source
Complete VELO model with SMOG2 (Open Position)
Simulations of Complete VELO Model with SMOG2 in Open & Closed Position

- In the closed position, the gap is small thus little coupling to outer tank (few resonance modes)
  - Impedance is broadband

➢ Simulate heating of the VELO in the Open Position

**Impedance of Open Position**

<table>
<thead>
<tr>
<th>CST SIM Long. Imped of Complete VELO SMOG2 Wire Meas. (Match Res 225 ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>[Graph showing impedance vs frequency]</td>
</tr>
</tbody>
</table>

**Impedance of Closed Position**

<table>
<thead>
<tr>
<th>CST SIM Long. Imped of Complete VELO SMOG2 Wire Meas. (Match Res 225 ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>[Graph showing impedance vs frequency]</td>
</tr>
</tbody>
</table>
Beam Spectrum with Single Mode Shifts

HL LHC Beam: 2748 Bunches, 1.2 ns Bunch Length, 2.3E11 ppb

Original Impedance Values
Worst Case with Possible Shift of +/- 20.0 MHz

Eigenmode Simulations - VELO SMOG Open
~200 Modes

Thanks to colleagues in BE-RF-BR for the beam spectrum code
Total Losses

- Sum of all mode losses
  - Uniform Freq. Shift (1 KHz steps)
- Single mode losses
  - Shift to nearest beam spectrum line

With no freq. offset (directly from Eigenmode results) → Negligible Heating (13.73 W Total)
Aluminum SMOG2 CELL

Mode at 326 MHz, Shifting 6.12 MHz $\rightarrow \sim 14$ Watts

Mode at 365 MHz, Shifting 4.44 MHz $\rightarrow \sim 10$ Watts
VELO Summary

- Wire measurements of VELO mockup confirmed the CST simulation model
  - Impedance of the VELO itself is broadband
  - Coupling from the VELO to the vacuum tank depending on position (open vs closed)
- Calculated power deposited into the modes via two methods
  1. Power into single modes, each shifted to a beam spectrum line
  2. Total power into all modes, with uniform frequency shifts of 1 KHz steps
- Results show that comparing the two heating methods that the heating is typically dominated by a single problem mode
  - 326 MHz mode shifted by 6.12 MHz → 14 W on SMOG cell
  - 365 MHz mode shifted by 4.44 MHz → 10 W on SMOG cell
- Note these results presented are for a single beam
  - Two beams would result in worst case scenario heating of x 4
  - Maximum heating on the SMOG cell is 48 W
  - 326 MHz mode shifted by 6.12 MHz to strike a beam spectrum line
General Takeaways Regarding Analysis of Machine Element’s Impedance

- Different simulation and measurement tools depending on the element’s general behavior (broadband vs resonant)
  - Eigenmode vs Frequency Solver vs Wakefield
  - Probe measurements vs. Single wire measurements
  - Model simplifications are not trivial
- Material definitions are vital
- For certain elements beam based heating should be performed
Conclusion

- A multitude of machine elements have been simulated and measured
  - Kickers, vacuum elements, beam instrumentation devices, etc.
  - A few cases shown have been presented here
- Machine Elements have been incorporated into the impedance model for the beam dynamics experts
- Python scripts developed for postprocessing (Toolbox)
  - Beam heating, single wire impedance measurements, VNA data handling, Q-value calculations, etc.
Acknowledgements

- **Impedance Measurement Team**
  - Christine Vollinger, Patrick Kramer, Aaron Farricker, Dhiren Jhugroo, Lukas Matter

- **PS Longitudinal Impedance Model**
  - Alex Lasheen

- **PS Dump**
  - Lorenzo Teofili, Martin Gillet, Kristian Anderson & EN-STI

- **KFA45 Measurements**
  - Alvaro Colomo, Nuria Cintas & TE-ABT-PPE

- **VELO Studies**
  - Benoit Salvant, Carlo Zannini, SMOG2 Team, NIKHEF & BE-RF-BR: Beam Dynamics Team
Thanks for Everything BR Team!
References

Past PS Longitudinal Impedance Model Presentations

- PS Impedance Model Update: KFA28 & BFA09 IWG #37
  - https://indico.cern.ch/event/879306/contributions/3725675/
- PS-BD-WG #27
  - https://indico.cern.ch/event/801198/contributions/3329723/
- Long. Limit. With LIU-PS RF Upgrades and Mitigation Strategy
  - https://indico.cern.ch/event/750790/contributions/3108016/
- SPS Injection Losses Review
  - https://indico.cern.ch/event/672967/contributions/2753563/
- PS-BD-WG #6
  - https://indico.cern.ch/event/678530/contributions/2779037/
- PS-BD-WG #1
  - https://indico.cern.ch/event/662292/contributions/2704441/
Past PS Internal Dump Presentations

- Preliminary PS Dump Measurement Outcome
  - IWG#38
  - https://indico.cern.ch/event/887960/contributions/3744241
- Recommendation from the IWG on PS Dump
  - IWG#20
  - https://indico.cern.ch/event/733072/contributions/3023362/
- Update on the longitudinal impedance of the internal beam dump (with couplers)
  - PS-BD-WG#14
  - https://indico.cern.ch/event/718539/contributions/2952914/
- Update on the longitudinal impedance of the beam dump
  - PS-BD-WG#12
  - https://indico.cern.ch/event/710562/contributions/2918960/
- Update of the impedance calculations for the new PS dump
  - IWG#18
  - https://indico.cern.ch/event/707776/contributions/2931874/
- PS Dump Impedance Preliminary Study
  - IWG#14
  - https://indico.cern.ch/event/671318/contributions/2746286/
Past KFA45 Presentations

- KFA45, Completed measurements and simulations with cables included
  - IWG#35
  - https://indico.cern.ch/event/844161/contributions/3565650/
- Measurements of the kicker KFA45 outcome
  - IWG#33
  - https://indico.cern.ch/event/830722/contributions/3479602/
- PS kicker PI.KFA45 (ECR 1969894) kickers with larger size ferrites
  - IWG#22
  - https://indico.cern.ch/event/764129/contributions/3171804/
- Update on the longitudinal impedance mode
  - PS-BD-WG #1
  - https://indico.cern.ch/event/662292/contributions/2704441/
Past VELO Presentations

- Impedance and Heating Analysis of SMOG2/ LHCb VELO
  - TREX#24 Presentation
    - https://indico.cern.ch/event/814592/contributions/3399712/
- Wire Measurements of VELO Mockup
  - Benchmarking of VELO Simulation Model with the Mockup Measurements
    - Wire Measurements and Simulations Presented
    - https://indico.cern.ch/event/698038/contributions/3124154/
- Simulations and Measurements of VELO Mockup
  - Wire Measurements and Simulations Presented
  - Complete VELO Simulation results
    - https://indico.cern.ch/event/764129/contributions/3171803/
- VELO/SMOG2 Simulations
  - Simulations of the Complete VELO with SMOG 2 Device
    - Wire, Eigenmode and Wake Simulations
    - https://indico.cern.ch/event/765714/contributions/3178576/
- Preliminary Work on VELO Heating Simulations
  - Method and Early Simulation Results
    - https://indico.cern.ch/event/797962/contributions/3316163/
- Impedance Effects on SMOG2
  - Presentation to PBC-FT (Gas Targets)
    - https://indico.cern.ch/event/797685/contributions/3314381/
- VELO SMOG2 Heat Load Localization Analysis
  - Two different analysis methods of heating presented
    - https://indico.cern.ch/event/802620/contributions/3337181/
    - https://indico.cern.ch/event/808587/contributions/3368997/
Object with Just Tapers

- Cooling Loops not an impedance issue
- Heating could be a potential issue
  - *Currently being investigated by EN-STI*
HOM Couplers

- Limited geometric free design parameters => HOM Coupler
- Placed in bottom of vacuum vessel
- Stripline HOM was explored
  - Parallel to dump arm
  - Increase in vessel size to accommodate
    - Increase of 385 & 540 MHz mode R-shunt
    - Unsatisfactory performance
- Two shorted loops
  - Couple to Modes at 385 & 540 MHz
    - H-Field
With HOM Coupler Field Patterns

Mode at 352 MHz

Mode at 543 MHz

E-Field

H-Field

Mode at 352 MHz

Mode at 543 MHz

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Coupling Loops Geometry

Beam View

Side View

Bottom View

Beam View

Beam
VELO Heating Simulations Overview

- CST Eigenmode simulations of the VELO with the SMOG2 in the open position
  - ~200 Modes
  - Manually doing convergences
- HL-LHC Beam Spectrum
- Use the total power deposited number and eigenmode simulation results to determine the power deposited on the specific elements of the VELO with SMOG2
  - Heavy python-based post processing
  - Calculating the total power deposited into each mode from HL-LHC Beam
  - **Allow for worst case scenario** frequency shift between +/- 20 MHz
- Two different analysis methods for heating of components
  1. Individual mode power of individually frequency shifted modes
     - Each mode is snapped to the closest bunch spacing harmonic
  2. Total power of uniformly frequency shifted modes
     - Run using 1 KHz frequency shift steps
Longitudinal Impedance Calculations[1]

• Log Formula:
  - \( Z = -Z_L \ln S_{21} \)
  - \( S_{21} = \frac{S_{21, VELO}}{S_{21, REF}} \)
  - \( S_{21, REF} \) is ideal reference line (match resistors & elect. length)

• Series resistor matching (\( R_s \))
  - \( R_s = Z_L - Z_0 \)
  - \( Z_0 \) is the 50 ohm of VNA
  - \( Z_L \) is the impedance of the Device Under Test (DUT)
    - From Measurement, Simulation or Hand Calculations