Highlights and New Challenges for WP14

C. Bracco on behalf of WP14

Outlines

- **Highlights:**
  - Injection system
    - MKI
      - Run I-II history
      - Operational performance with first prototype
      - MKI-Cool
    - TDI
      - Run I-II history
      - New design
      - Status

- **New Challenges:**
  - Beam dump
The LHC Injection System

Injected beam

Lambertson septum (H-kick)

Kicker magnet (V-kick)

F-quad
The LHC Injection System

- **Injected beam**
- **Circulating beam**
- **F-quad**
- **D-quad**
- **Kicker magnet (V-kick)**
- **Lambertson septum (H-kick)**

**MSI:** injection septa

**MKI:** injection kickers

**Vertical plane**
The LHC Injection System

Injected beam

Circulating beam

Injected beam

Kicker magnets (4 in the LHC)

TDI absorber jaws

Front view

Nominal Kick
The LHC Injection System

MSI: injection septa
MKI: injection kickers
TDI: injection dump

Injected beam
Circulating beam
Injected beam
Kicker magnets (4 in the LHC)

TDI absorber jaws
Front view
No Kick (injected)
Erratic kick (circulating)
The LHC Injection System

Injected beam

MSI: injection septa

MKI: injection kickers

TDI: injection dump

Circulating beam

Kicker magnets (4 in the LHC)

Front view
The LHC Injection System

- MSI: injection septa
- MKI: injection kickers
- TDI: injection dump
- TCDD: injection dump mask

Injected beam

Circulating beam

Injected beam

Kicker magnets (4 in the LHC)

Front view
The LHC Injection System

Injected beam

MSI: injection septa
MKI: injection kickers
TDI: injection dump

TCLIA: auxiliary protection collimator
TCLIB: auxiliary protection collimator
TCDD: injection dump mask

Circulating LHC beam

Injected batch

Miss-kicked injected beam
Kicked Circ. beam
Over-kicked inj. beam

$\Delta \mu_y = 90^\circ$
$\Delta \mu_y = 180^\circ + 20^\circ$
$\Delta \mu_y = 360^\circ - 20^\circ$
The LHC Injection System

- MSI: injection septa
- MKI: injection kickers
- TDI: injection dump
- TCDD: injection dump mask
- TCLIA: auxiliary protection collimator
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Injected beam

Circulating LHC beam

Injected batch

Δμy = 90°

Δμy = 180° + 20°

Δμy = 360° - 20°
Four kickers pulsed at 25 kV, ~ 5 kA Magnet operated at $\sim 10^{-11}$ mbar to limit risk of flashover

33 cells each consisting of U-core ferrite yoke between two high voltage plates and two ceramic capacitors between a HV and a grounded plate.

A 3 m long alumina tube with screen conductors is placed within the aperture of the magnet:

- Allow a fast magnetic field rise-time (low eddy currents)
- Limit longitudinal beam coupling impedance (limit beam induced heating $\rightarrow$ ferrite permeability reduction)

The screen conductors are directly connected to the beam pipe at the downstream end whilst the upstream end is capacitively coupled.

At both ends 9 ferrite rings are installed to damp low-frequency resonances.
Run I:

- Long conditioning time to reach target normalised pressure \(<E-23\) mbar/p (~280 hours with 50 ns beam for magnet replaced during TS in 2012)

- Beam induced heating physics fills ➔ In a few occasion > 1 hour waiting time before next fill to allow for kicker cooling down.
Run I:

- Long conditioning time to reach target normalised pressure $< E^{-23}$ mbar/p (~280 hours with 50 ns beam for magnet replaced during TS in 2012)
- Beam induced heating physics fills $\Rightarrow$ In a few occasion > 1 hour waiting time before next fill to allow for kicker cooling down.

LS1 actions:
- NEG coating and NEG cartridges at interconnects
- New chambers 15 $\Rightarrow$ 24 screen conductors, ion bombardment of vacuum tank (not very effective)
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Run II:
- Long conditioning time for new alumina chambers (~400 hours with 25 ns beam).
- MKI8D normalized pressure systematically higher than MKI2D
- Factor 3 reduction in beam induced heating \( \implies \) no more stops in Run II
- Further improvement needed for operations with HL-LHC beams
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**Prediction for Run 2 (2748 bunches of ~1.2e11 ppb) and HL-LHC**

![Graph showing power deposition and Curie temperature predictions for Run 2 and HL-LHC.](image)

**Max. Power deposition for Run 2 (W/m) vs. Max. Power deposition for HL-LHC (W/m)**

**Max. ferrite temperature predicted for Run 2 vs. Max. ferrite temperature predicted for HL-LHC**

**Courtesy of L. Vega**

**Curie Temperature**

**Ferrite rings**
- Cell#1
- Cell#2
- Cell#3
- Cell#4
- Cell#5
- Cell#6
- Cell#7

**Temperature (°C)**
- 40
- 90
- 140
- 190
- 240
- 290
- 340

**Power deposition (W/m)**
- 0
- 200
- 400
- 600
- 800
- 1200
- 1400

**Courtesy of M. Barnes**
Upgraded MKI Operational Performance

- MKI8D prototype with Cr2O3 coated alumina tube installed in YETS 2017-2018
- MKI2D exchanged in EYETS 2016-2017 conditioned in >40°C to a factor 3 better than MKI8D

Courtesy of M. Barnes

MKI2: Start time = 2017-04-29 00:00:00, End time = 2017-10-01 00:00:00, Start/End beam1 elapsed time = 0.0/1533.3hrs (131.3C), since 2017-04-29 00:00:00
MKI8: Start time = 2017-04-29 00:00:00, End time = 2017-10-01 00:00:00, Start/End beam2 elapsed time = 0.0/1518.4hrs (134.3C), since 2017-04-29 00:00:00

8b4e beam operation

Normalized pressure (mbar/p)

Beam Integral (C)
Upgraded MKI Operational Performance

- MKI8D prototype with Cr2O3 coated alumina tube installed in YETS 2017-2018
- MKI2D exchanged in EYETS 2016-2017 conditioned in >40 C to a factor 3 better than MKI8D
- Faster initial beam conditioning of Q5-MKI8D in 2018 (~20 C) than Q5-MKI2D in 2017 (uncoated tubes);
- In addition, with 25ns beam: “historical” higher normalized pressure at Q5-MKI8D than at Q5-MKI2D has “disappeared”

Courtesy of M. Barnes
Upgraded MKI Operational Performance

Upgraded MKI beam screen magnet shows a significantly lower temperature than those of the Post-LS1 MKIs.

Still not enough for operation with HL-LHC beams.

*Note: PT100 offset, at ambient temperature, corrected.
Upgraded MKI Operational Performance

Upgraded MKI beam screen design (only MKI8D)

Still not enough for operation with HL-LHC beams.

Courtesy of M. Barnes

Upgraded MKI8D beam screen magnet shows a significantly lower temperature than those of the Post-LS1 MKIs.

4B3 ferrite rings only

Removed part of cylinder

Post-LS1 design

Temperature [°C]

Date

17/04/2018
27/04/2018
07/05/2018
17/05/2018
27/05/2018

Upgraded design

No cooling

Courtesy of L. Vega

593.7

190.0
Upgraded MKI Operational Performance

Upgraded MKI beam screen design (only MKI8D)

Post-LS1 design

Upgraded MKI8D beam screen magnet shows a significantly lower temperature than those of the Post-LS1 MKIs. Still not enough for operation with HL-LHC beams.

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MKI-Cool Prototype

Ferrite-Cu vacuum brazing

Some issues during brazing tests:
- 1st assembly – significant voids in brazing;
- 2nd assembly – good brazing, but longitudinal cracks in ferrite.
- Final assembly showed good brazing and no cracks

Heating/cooling rate <760°C
max. 50°C/h
Brazing temperature: 790°C

Observations:
Brazed area >90%. Some local reflections, but in general homogenous.

Thermal measurements to assess Thermal Conductance between ferrite and cooling pipes

Courtesy of M. Terrek Moester

Courtesy of F. Motschmann

Courtesy of L.O. Bjorkqvist
MKI-Cool Prototype

Optimised design of capacitively coupled end of beam screen:

- Length of ferrite cylinder: 60 mm, trade-off between total power reduction and mechanical properties
- Inner radius 38 mm and 10 mm thickness for uniform heat distribution and efficient heat extraction through cooling system
- Extended double cavity to smooth out the longitudinal heat distribution ➔ lowest temperature despite higher power
- Length and disposal of screen conductors (with constraints imposed by HV behavior)

<table>
<thead>
<tr>
<th></th>
<th>Single cavity</th>
<th>Double cavity</th>
<th>Extended double cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total power</td>
<td>348 W</td>
<td>366 W</td>
<td>364 W</td>
</tr>
<tr>
<td>Max. temperature</td>
<td>106°C</td>
<td>88.4°C</td>
<td>80.6°C</td>
</tr>
</tbody>
</table>

Prototype ready for vacuum and HV conditioning and installation in IR2 in March 2020

Courtesy of L. Vega and V. Vlachodimitropoulos
The TDI History

1. Cu beam screens deformed and sliding contacts blocked (TDI.4L2 and TDI.4R8)

2. Increased outgassing during fills (mainly at TDI.4L2 ➔ background in ALICE)

3. Thermal drift of jaw positions measure by LVDTs (TDI.4L2 and TDI.4R8), no straightforward correlation LVDT <-> actual jaw deformation. Interlock limits adjusted several times.
The TDI History

- Original design (Run I)

LS1:
- Reinforced beam screen made of stainless steel and improved sliding contacts (ceramic spheres)
- Ti coating on Al blocks to reduce SEY
- NEG cartridges installation
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Run II – 2015:
- Quality issues with hBN blocks after treatment in vacuum at high temperature → replaced with graphite with Cu coating in YETS
- Vacuum spikes at TDI.4R8 during injections (build up pressure) and spurious spikes during physics → limit on maximum number of injected bunches (96 BCMS).
- Ti coating found degraded over large surface areas and blisters found on Cu coating of Al frame.
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Run II – 2015:
- Strong pressure increase at TDI.4R8 while moving the jaws to parking, the problem was solved by retracting the jaws to 40 mm instead of 55 mm (e-cloud as possible explanation)
- No more intensity limitations during Run II

Run II – 2016 \(\Rightarrow\) 2018:
- No more intensity limitations during Run II

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Graphite R7550

Beam2 intensity
New Design TDI ➔ TDIS

- Three independent shorter modules (1.6 m each) ➔ improve alignment accuracy and reduce beam induced deformation.
- The modules are installed on a common girder, aligned on surface and transported as a single device in the tunnel (spares under vacuum and ready for installation with reduced bake out in the tunnel).
- Minimise impedance (beam induced heating): materials, coating, longitudinal and lateral RF fingers, tapering, tank and transition geometry, cooling, etc.
- Improve vacuum performance: materials, coating, operational gaps.
- Improve mechanics and diagnostics
- Improve spare policy: full assembly vacuum conditioned (additional sector valves) for installation in tunnel without bake-out

Courtesy of L. Gentini
HiRadMat Tests

- HRMT-28 (June 2017): graphite and 3D CC ➔ both survived and flatness within specs (<100 μm) ➔ R7550 graphite chosen as low Z absorber material

<table>
<thead>
<tr>
<th>Jaw flatness</th>
<th>Graphite Sigrafine® R7550 (SGL)</th>
<th>Graphite 2123 PT (Mersen)</th>
<th>3D C/C A412 (Mersen)</th>
<th>Sepcarb® 3D C/C (Airbus Safran Launchers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Impacts</td>
<td>80 μm</td>
<td>56 μm</td>
<td>128 μm*</td>
<td>44 μm</td>
</tr>
<tr>
<td>After Impacts</td>
<td>96 μm</td>
<td>58 μm</td>
<td>82 μm</td>
<td>44 μm</td>
</tr>
</tbody>
</table>

- HRMT-35 (August 2017): visible traces on Cu coating but no apparent surface rupture ➔ baseline: not to apply any Cu coating since cooling capacity enough against resistive wall beam induced heating

- HRMT-45 (August 2018): validation of new jaw design and back-stiffener material (Molybdenum Zirconium TZM) in case of deep beam impact

* Possible block movement during handling
One TDIS module at:

First TDIS being assembled, it will be completed by end October 2019 ➔ ready for installation in IR2 in Q2 2020

Next steps:
- Cabling, impedance measurements and vacuum tests
- 2nd TDIS ready by end of March 2020 ➔ installation in IR8 in Q3 2020
- 3rd and 4th TDIS (spares) ready by July 2020

Courtesy of M. Calviani and D. Carbajo Perez
The LHC Beam Extraction and Dump System
The LHC Beam Extraction and Dump System

MSD: extraction septa

MKD: extraction kickers

TDE

Q5L

MKD

Q4L

MKB

TCDQ

MSD
(3x5)

MKB
(4H – 6V)

TCDS

MKD
(15)

Q4R

Q5R

Beam 1

Beam 2
The LHC Beam Extraction and Dump System

TCDQ: Q4 protection

MSD: extraction septa

TCDS: septa protection

MKD: extraction kickers

TCDQ (15)

MKD (4H – 6V)

MSD (3x5)

TCDS

Q5L

Q4L

Q5R

Q4R

Beam 1

Beam 2
The LHC Beam Extraction and Dump System

- **MKD**: extraction kickers
- **TCDS**: septa protection
- **MSD**: extraction septa
- **TCDQ**: Q4 protection
- **TDE**: Beam dump
- **MKB**: dilution kickers

The LHC Beam Extraction and Dump System

**Beam 1**
- Q5L
- Q4L
- TCDQ
- MKD
- MKB
- MSD (3x5)
- TCDS

**Beam 2**
- Q4R
- Q5R
- MKD (15)
- TCDS

**MKB**: dilution kickers

**TDE**: Beam dump
The LHC Beam Extraction and Dump System

- **TCDQ: Q4 protection**
- **MSD: extraction septa**
- **TCDS: septa protection**
- **MKD: extraction kickers**
- **MKB: dilution kickers**
- **TDE: Beam dump**

**Beam 1**
- Q5L
- Q4L
- MKD
- MKB (3x5)
- TCDQ
- MSD (4H – 6V)
- TCDS
- Q4R
- Q5R

**Beam 2**
Beam Dump TDE: Known Issues

- Robustness of upstream and downstream windows in case of dilution failure

**Upstream Window**

- SS316LN
- SAFETY FACTOR AGAINST YIELDING
- Necessary Margin: Underneath, safe operation is not guaranteed

**Downstream Window**

- Titanium (commercially pure)
- SAFETY FACTOR AGAINST YIELDING

\[ S_y = \frac{R_y}{\sigma_{eq}} \]

- Lower limit: Underneath, the material deforms permanently

Courtesy of T. Polzin
Beam Dump TDE: Known Issues

- Robustness of upstream and downstream windows in case of dilution failure
- New downstream window (pure Ti $\rightarrow$ Ti-Gr5) will be replaced in LS2, design compatible with HL-LHC operation and MKB erratic failures over all range of delays (new MKB retriggering system)

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Upstream Window
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- Uncertainty on core behavior (>1800° C during nominal dumps, up to ≥ 3000 ° C in case of dilution failures)

<table>
<thead>
<tr>
<th>Number of active MK8V</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
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<tbody>
<tr>
<td>4</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
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<tr>
<td>0</td>
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<td><img src="image34.png" alt="Image" /></td>
<td><img src="image35.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Courtesy of C. Wiesner and M.I. Frankl
Beam Dump TDE: Known Issues

- Robustness of upstream and downstream windows in case of dilution failure
- New downstream window (pure Ti $\rightarrow$ Ti-Gr5) will be replaced in LS2, design compatible with HL-LHC operation and MKB erratic failures over all range of delays (new MKB retriggering system)
- Ongoing studies for upstream window (replacing SS with Ti-Gr5, removing CFC disk?)
- Uncertainty on core behavior (>1800° C during nominal dumps, up to $\geq$ 3000 ° C in case of dilution failures)
- Started collaboration with NTNU/SINTEF (Norway) institute for SIGRAFLEX characterization and possible new materials for core
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- Started collaboration with NTNU/SINTEF (Norway) institute for SIGRAFLEX characterization and possible new materials for core
- Proposed to install two additional horizontal MKBs (more sensitive in H plane since only 4 magnets operated at with higher voltage) to sensibly reduce the risk and the sensitivity to any possible failure (erratic and flashover)
New Challenges: TDE vibrations

- **High intensity dumps** (16L2 issue) leading to major nitrogen leaks at UD62 (Beam 2) dump (>>10 mbar*l/s). A small leak appeared also at UD68. Main mitigations:
  - Flanges periodically tightened plus replacement of gaskets
  - Nitrogen line and surface supply (YETS 2017/2018)
  - Installation of interferometer to measure dump movements
- Measured **vibrations** during high intensity normal dumps and a permanent displacement towards the downstream shielding wall ➔ suspected cause of leak. Larger vibrations and displacements when moving to higher intensities.

Investigating a new design which addresses all known issues (robustness, vibration and drifts) to insure no impact on HL-LHC availability and minimize interventions to reduce radiation exposure to personnel.

<table>
<thead>
<tr>
<th>Vibration Data of Two Dumps in UD62 - 14.07.18 with a Loss of Three Vertical Kickers</th>
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</thead>
<tbody>
<tr>
<td><strong>Displacement in mm</strong></td>
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<td>Time after Impact in s</td>
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<td></td>
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<tr>
<td>Horizontal displacement in front of the dump</td>
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<tr>
<td>Aligned displacement</td>
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<tr>
<td>Vertical displacement</td>
</tr>
</tbody>
</table>

**Courtesy of T. Polzin**
Conclusions

- Operational experience during first LHC run allowed to identify the weak points of the injection and the extraction systems

- Some mitigations were put in place during LS and YETS for TDI and MKI but not good enough for operation with HL-LHC beams ➔ upgraded designs proposed
  - MKI-cool prototype almost ready for installation in IR2 in Q1 2020 to be tested with beam in Run III ➔ series production
  - First TDIS being assembled and ready for installation in Q2 2020, second one will be installed in Q3 2020 and two spares will be also ready in 2020

- Main new challenge: design of a beam dump addressing all known issues (robustness, vibrations and displacements) and allowing a safe operation both in nominal conditions and in case of dilution failures (proposal to add 2 MKBH to reduce risk and sensitivity to failures)
Thank you for your attention!
Beam Induced Heating

If the temperature goes above the Curie temperature and the permeability decreases, magnet inductance is reduced, leading to reduced rise-time and magnet strength.

Above the Curie Temperature the ferrite temporarily loses its permeability.
MKI8D Removed from LHC during TS3, 2012

Capacitively coupled end of beam screen (and outline of U-ferrite)

Directly connected end of beam screen (and outline of U-ferrite).
Highest heating at downstream end, where LHS ferrite leg is unshielded from circulating beam.