Challenges in Beam Intercepting Devices and Targetry technology for CERN’s accelerator complex

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Disclaimer & acknowledgments

- Only a subset of the different palette of activities will be discussed, focusing on specific challenges and examples on how these are been tackled.

Beam Intercepting Devices

Safety function
- Beam stoppers
- Beam dumps

Beam cleaning & control
- Collimators
- Scrapers
- Strippers
- Slits

Physics
- Particle producing targets
~250 devices scattered from the Linac chopper dump (3 MeV) to the LHC main dump (7 TeV)
What type of challenges do we have?

- Devices must be able to withstand operation and accident scenarios, plus protect delicate equipment
  1. **UHV** requirements ($10^{-10}$ mbar) also in movable parts
  2. **High energy densities** (~kJ/cm$^3$/pulse) as well as **power densities** (several MW/cm$^3$)
  3. **High beam intensity/energy** (~500 MJ for LHC dump)
  4. **High average deposited power** (~250 kW for LIU SPS beam dump or ~350 kW for Beam Dump Facility)
  5. **Physics requirements**, often implying the use of non-structural materials (Pb or Ir)
  6. **Impedance**, especially for colliders
  7. **Radiation damage** on absorbing materials
What we are doing for LS2

LIU (incl. L4 connection)

Consolidation

LHC experiments upgrade

SPS Access

SPS Fire Safety

AWAKE

HL-LHC

Dismac

ElenA

East Area consolidation

26 September 2019

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What we are doing for LS2

Will be renovating roughly ~70 beam intercepting devices and 2 target areas, amongst the most challenging of the accelerator complex.
LHC collimators
- Complex movable devices in UHV, roughly 100 devices
- Water cooled brazed Glidcop jaws with CfC, MoGR and Inermet
High energy density

LHC beam dump (2x)
- 300 MJ of dissipated energy
- 500 MJ >2021, 720 MJ from 2026
High beam energy

LHC injection dump (2x)
- 5 m long device, moving in UHV with 10 μm precision
- Sandwich of graphite, Cu, TZM backstiffener
High energy density

SPS internal beam dump
- 26-450 GeV/c
- Water cooled – graphite absorber in CuCrZr mass
- 70 kW → 250 kW from 2021
High average deposited power

PS Internal beam dump
- 1.4-26 GeV/c
- ~100 kJ circulating energy
- Movable dump in UHV
- Graphite with HIP CuCrZr
UHV and movable devices

Some examples
Challenge: UHV and movable parts
PS Internal Dump

- Main dump(s) of the CERN’s Proton Synchrotron
- Beam up to 200 kJ, could have to cope with 80 kW
- Due to PS configuration, the dump are movable devices in UHV
- Cycle time ~300 ms
- Revolution time of PS 2.1 μs
- Dump is shaving/scraping the beam over the cycle time, ~150k revolutions
- Dump mass ~10 kg
- Cycle time ~300 ms
- Revolution time of PS 2.1 μs
- Dump is shaving/scraping the beam over the cycle time, ~150k revolutions
- Dump mass ~10 kg
Design of the dump assembly

Vacuum chamber

Actuation mechanism

Pumping port

Dumping core (inside)

1050 mm

650 mm

1185 mm

175 kg
Design of the dump assembly

Pumping port

Vacuum chamber

Dumping core (inside)

Actuation mechanism

650 mm

175 kg
But how is the core built?

- Old generation was based on a water cooled Cu-OFE block
- Graphite (SGL7550) is required now to cope with higher beam intensities (and higher power) as well as CuCrZr owing to higher strength
- Only solution to remove the heat was based on diffusion bonding by hot-isostatic pressing (HIP) between CuCrZr and 316L tubes
But how is the core built?

- Old generation was based on a water-cooled Cu-OFE block.
- Graphite (SGL7550) is required now to cope with higher beam intensities (and higher power) as well as CuCrZr owing to higher strength.
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Intermezzo: diffusion bonding by HIP

- Hot Isostatic Pressing (HIP)
  - **Maximum thermal efficiency** (diffusion bonding all around the tube – perfect TCC)
  - Compatible with UHV
  - Versatile – different geometries possible
  - Reproducible
  - Sensitivity to tolerances but manageable *once known*

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Targetry and beam intercepting devices activities at CERN

2.5 h

950 C, 100 MPa
Challenges & status

- Prototype dump successfully run for 1.5 M cycles
  - ~10 years operation
- Final dump being assembled, together with the final HIP runs for the different cores (3x)
- Attention to material compatibility with UHV is critical
- All on track for installation in the PS in April 2020
Challenge: High energy density
Roles of the collimation system

- Halo cleaning vs. quench limits (SC machines)
- Passive machine protection
- Concentration of losses/activation in controlled areas
- Reduction total dose on accelerator equipment
- Cleaning physics debris (for colliders)
- Optimise background in the experiments
- Beam tail/halo scraping, halo diagnostics

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- 375 MJ/beam <2019
- 520 MJ/beam (2021-2024)
- 720 MJ/beam >2026
Collimation HL-LHC upgrade baseline

Completely new layouts
Novel robust material: CuCD
IR1+IR5, per beam:
4 tertiary collimators (TCTs)
3 physics debris collimators
3 fixed masks

Cleaning: DS coll. + 11T dipoles, 1 unit per beam

Ion physics: dispersion suppressor (DS) collimation

~20 new collimators being built for CERN LS2 (2019-2020)
... while ~40 foreseen for LS3

9 low-impedance, high robustness secondary collimators: coated MoGr
Each collimator jaw designed (and tested!) to cope with:
- 10 kW steady losses of 1 hour
- Direct beam impact at injection and during asynchronous beam dumps at 7 TeV
Beam test of coating on collimators jaws

- HiRadMat test of Cu and Mo coated graphite jaws to understand coating adherence under beam impact scenarios
  - Same energy density as for a potential similar impact in the LHC
  - Extensive campaign of simulations vs. experimental results
Surface damage detail in Cu coating: grazing impact

- Microscopic analysis confirms Cu coating **melting as predicted by simulations**
- Mo coating **not melting**, as predicted, but appearing to have spallation damage
LHC Injection Beam Dump, currently being constructed

- Injected beam
- Low Z jaws (2 blocks of graphite per jaw)
- 0.9 m Titanium
- 0.7 m Copper

Ion pump

LHC Injection Beam Dump, currently being constructed on 26 September 2019

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~200 μm flatness of absorbing blocks over the entire length
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- TZM backstiffener
- CuCrZr absorber
- TiGr5 clamps
- Graphite SGL7550

8 mm @ injection
~100 mm @ physics

Gap
Validation of jaw resistance at HiRadMat

Dose rate ~500 μSv/h at contact

Flatness = 0.188 mm (Pre-beam) EDMS 1897213

Flatness = 0.192 mm (After-beam) EDMS 2080201
**Challenge**: High average deposited power
SPS internal beam dump

- Due to the specific design of the SPS, the dump is internal in UHV.
- Heavily used in the machine, to allow flexibility and setting up beams – should not be a showstopper for operation and has to be reliable for all beams scenarios.

- Up to 2018 at its 4th generation (TIDVG4):
  - 70 kW (max) dissipated power
  - 4.2 MJ beam energy
- For LHC Injector Upgrade (LIU) Project → 5th generation is being built:
  - 250 kW dissipated power
  - 5.3 MJ beam energy
SPS internal beam dump

- Due to the specific design of the SPS, the dump is **internal** in UHV
- Heavily used in the machine, to allow flexibility and setting up beams – should **not** be a showstopper for operation and has to be reliable for all beams scenarios

**Challenges:**
- Materials with high robustness against beam impact
- UHV compatibility
- Good cooling power and thermal contact with absorbing materials
- Limited space longitudinally
- High residual dose rate
- Reliability on the long-term

- **250 kW** dissipated power
- **5.3 MJ** beam energy
What could happen with insufficient cooling?

Endoscopy results from a previous generation internal dump, which operated until 2012

→ Complete removal of Al and focus on thermal contact with Cu sink
Window: 163.4 x 47 mm
The copper rests in the stainless tube.
Position and orientation is guaranteed by the keys.
The top gap is 4mm.

Injected beam
Circulating beam
Dumped beam (painted)
Graphite inside the CuCrZr core

Medium/high-Z absorber

TIDVG₄ core fully assembled and ready for insertion in the vacuum tube

TIDVG₄ core being pulled into the vacuum chamber

TIDVG₄ core fully inserted (upstream)

Final leak detection (upstream w/ water manifolds)
But with the LHC Injector Upgrade Project...

...the current dump will not be sufficient:

1. Need to cope with **higher beam power** (and deposited)
2. Need to comply with **strict radiation protection** rules

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Table 3: HL-LHC beam load parameters for internal dump

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>HL-LHC Standard</th>
<th>LIU-8C</th>
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<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Energy</td>
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<td>Brightness</td>
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<td>Stored energy</td>
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<tr>
<td>Pulse period</td>
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<td>Max. dumps / l</td>
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<tr>
<td>Average power</td>
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<tr>
<td>Consecutive d&lt;sub&gt;4&lt;/sub&gt;</td>
<td></td>
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</tr>
</tbody>
</table>

~520 t cast iron
90 t concrete
50 t marble

6 meters
11 meters
Graphite SGL7550

CuCrZr jacket, HIPed to 316L tubes (water cooling)

Circulating beam

Dumped beam (painted)
... to reality!
... to reality!
... to reality!
Core being design with HIP technology

All items on track for production and installation of the new dump in SPS during summer 2020

Good bonding and absence of cracks at the 316L surface
**Challenge**: High beam energy

*Low density core*
LHC external beam dump

- Circulating beams in the LHC have a kinetic energy of around $300 \text{ MJ/beam}$ (until 2018) → the LBDS is taking care of its extraction from the ring
- **Beam diluted** over the extraction time of $84 \, \mu s$

[Diagram of beam dump system]

- External dump (TDE)
- Dilution kickers (MKBH/V)
- Quadrupole protection collimator (TCDQ)
- Septa collimator (TCDS)
- Extraction septa (MSD)
- Extraction kickers (MKD)
LHC external beam dump

High and low-density segments:

Low-density flexible Graphite sheets:

Currently:
- **240 MJ** deposited in graphite
- **20 MJ** in the 318L shell
LHC external beam dump

High and low-density segments:

- 240 MJ deposited in graphite
- 20 MJ deposited in the 318L shell

Currently:

- Temperature [deg C]
- Depth [cm]

Can be used from -250°C up to approx. 3000°C (in protective gas)

Sublimation temperature °C > 3000
Titanium (G2) - Maximum Stress - HLLHC25ns - 6V2H
Recent information and future plans

- Over the course of the last 2 years, several N2 leaks occurred in the nitrogen line close to the dump → dump was then instrumented.
Future plans on LHC beam dump

- Several upgrade plans are foreseen during LS2, to reduce dose to personnel during interventions to fix the leaks
  - Including upgrade of the downstream dump window (TiGr2 to TiGr5) and improved instrumentation

1. **Optimize the graphite core configuration** for HL-LHC, since temperature up to 2000 °C for regular operation might not be acceptable for the core (*cyanide formation, sublimation, etc.*)

2. **Sudden thermal expansion** of the 318L (*60 °C in 84 µs*, due to 20 MJ, 80 MJ/m³) might be responsible for the **significant vibrations** and **permanent displacement** of the dump
Conclusions

- **Beam intercepting devices** and **Targetry technologies** at CERN are being upgraded due to LIU and HL-LHC Project requirements.

- Several other topics **not discussed**, including pbar target, neutron targets, ISOLDE as well as future project such as Beam Dump Facility & FCC.

- All activities are requiring **significant technological development** and **material R&D**.

- Collaboration such as RaDIATE on radiation damage (including J-PARC!) providing an excellent platform for developments.
Thanks!