Reduction of extraction losses with barrier buckets in the PS

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Reduction of extraction losses with barrier buckets in the PS

**Motivation**
- RF and beam interaction
- Extraction of fixed target beams

**Implementation:**
- Wide-band waveform generation
- FPGA Firmware
- Installation

**Measurements with beam:**
- Validation
- MTE + barrier buckets
- Loss reduction

**Particle tracking simulations:**
- Wide-band RF in BLonD
- Longitudinal profile evolution

**Conclusions and next steps**
Motivation and introduction
Motivation

- Intensity increase of fixed target beams from the SPS.
- **Bottleneck: losses at extraction** from the PS to the SPS during the rise time of the kicker magnet.
  - Due to beam without RF structure.
- **Aim**: reducing losses via a special RF manipulation.
  - Introduce a longitudinal gap to avoid losses at extraction.
  - Try to use existing equipment to make a suitable gap.
Multi-Turn Extraction (MTE) of fixed target beams in the PS

- Reducing losses by transversely separating the beam that is extracted from the rest that is circulating.
Multi-Turn Extraction (MTE) without gaps

Process:
- Prepare first batch in PS.
- Extract first batch in 5 turns.
- Prepare second batch in PS.
- SPS triggers extraction of second batch in 5 turns.
New: mitigation of residual losses from longitudinal structure

Longitudinal gaps combined with the Multi-Turn Extraction in the PS

Idea: longitudinal gap in the beam for the rise-time of the kicker magnet.

Method: creating a so-called RF barrier bucket synchronised in PS with (1) the extraction kickers and (2) with the already circulating beam in the SPS.
RF interacting with particles

- Energy kick to particles at each turn at a cavity.
- Changes the next arrival time and energy.
- $E_0$, $T$ are constant for the same bending field.
- Results in periodic oscillations similar to those of a pendulum $\rightarrow$ RF buckets.

$E_0, T \xhookrightarrow{\Delta E_1, \Delta t_1} \Delta E_2, \Delta t_2$

Beam loss reduction with barrier buckets - M. Vadai (QMUL, CERN)
Mechanical analogy: pendulum for bucket with sinusoidal RF voltage

- Pendulum in a gravitational field.
- Periodic motion: restoring force $\sim \sin \phi$.
  Linear only for small angles $\sin \phi \approx \phi$. 

Beam loss reduction with barrier buckets - M. Vadai (QMUL, CERN)
Pendulum in a gravitational field.
Periodic motion: restoring force $\sim \sin \varphi$.
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Momentum ($p$) plotted for every angle ($\varphi$) for a motion with a given maximum potential energy (height).
Closed trajectories up to the separatrix.
$p - \varphi$ phase plane plot also called phase space.
Mechanical analogy: extended pendulum for barrier buckets

- Bobs on a rigid rod.
- Friction-less track.

\[ \phi \]

\[ p \]

\[ \mu = 0 \]
\[ m_{rod} = 0 \]

\[ v_b = \text{const.} \]
\[ v_o = \text{const.} \]

\[ v_b > v_o \]
Mechanical analogy: extended pendulum for barrier buckets

- Bobs on a rigid rod.
- Friction-less track.
- Reflection is the same as a normal pendulum.
- Drift region or drift space introduced ▷ period made much longer.

▷ Going to a synchrotron:
  ▷ Typical RF voltage \( \sim \sin \phi \)
  Same non-linear effect on a charged particle as on a bob.

\[ \frac{d(\Delta p)}{d\phi} = 0 \]
Conventional buckets and barrier buckets made by RF voltage

- Single harmonic, narrow band waveform: good for acceleration
- Multi harmonic, wide-band waveform

Drift region:
- $\Delta E = 0$
- $\frac{d(\Delta E)}{dt} = 0$

1 turn

Barrier RF buckets

Reflection region:
- $\frac{d(\Delta E)}{dt} \approx eV(\Delta t) / T$
- $\frac{d(\Delta E)}{dt} \sim V(\Delta t)$
- Indirect dependence on $V$ shape.

Beam loss reduction with barrier buckets - M. Vadai (QMUL, CERN)
A wide-band (400 kHz $\sim 10$ MHz) cavity already installed in the PS (SS02) in 2014.

Original purpose: kicker for the coupled-bunch feedback.

Allows to generate signals with large bandwidth at cavity gap: non-sinusoidal RF is possible.

Great, but a few ingredients still missing...
Main challenges 1: LLRF drive needed

- Generating the wide-band, isolated pulse at the cavity gap.
  (1) Making the gap (reflection region) - **sine-like part**.
  (2) Making the drift space - **zero part** > tails are not allowed.

- The wide-band system distorts a pulse applied at the input: **pre-distortion** scheme needed.

- **Beam synchronous** generation of the barrier pulse. Correct frequency and phase.

- Control: remote and beam synchronous pulse control (multiple pulses per turn, amplitude and phase).
Main challenges 2: beam test plan

- Full validation of the PS barrier bucket system alone with beam at different energies and intensities below and above transition.

- Test handover options from conventional RF to barrier RF with beam.

- Combination of two complex beam manipulations:
  - barrier bucket;
  - transverse splitting and 5-turn extraction.

- Priorities driven by the accelerator schedule.
  - Fast hardware implementation needed.
  - All measurements with beam had to be obtained before the beginning of LS2, end of 2018.
Hardware implementation
Generation of single, sinusoidal pulses at the cavity gap.

- Compensation is needed for the system frequency response.
- Achievable gap size is limited by the system bandwidth.
- Usable gap size: 150 ns – 300 ns
  \[ f_{\text{rev}} = 476 \text{ kHz} \] (flat-top)

Beam loss reduction with barrier buckets - M. Vadai (QMUL, CERN)
Beam synchronous arbitrary waveform generator

- Programmable azimuth with respect to circulating beam.
- Two pre-distorted pulses per turn with real time azimuth control.
- Amplitude modulation.
Barrier bucket LLRF and cavity installation

- 200 MHz room
- CERN PS ring
- Barrier bucket waveform generator
- RF in
- PS 1 turn delay feedback board with FPGA
- Ethernet Real time front-end Control functions (Linux)
- RF Amplifiers
- Finemet® rings
- Gap
- Beam loss reduction with barrier buckets - M. Vadai (QMUL, CERN)
Measurements with beam
Proof-of-principle measurements at injection into the PS

- One potential barrier per revolution.
- Injection energy: $E_{\text{kin}} = 1.4$ GeV.
- Low intensity: $N_b = 1 \times 10^{11}$ ppp
  - Negligible beam induced voltage
    - No compensation necessary.
- Finding the phase of the new system.
Proof-of-principle measurements at injection int the PS

Overlay of two measurements:

- Injecting to the left and to the right hand side of the barrier.
- Particles reflecting off the barrier.

Potential barrier RF voltage ~ Half PS turn

Singal amplitude [arb. units]
Controlling bunch length with moving barriers

- Unmatched injection from PSB.
- Controlled longitudinal blow up and clean kick to match with sine bucket.
- Stretching sinusoidal bucket to a barrier bucket.
- Flat bunch profile needed small corrections of voltage profile (~1%).
Adiabaticity of bunch length manipulation

**Beam in sine bucket to barrier bucket by stretching and compression.**
*Testing speed limits.*

<table>
<thead>
<tr>
<th>Expansion and compression time varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two time scales used</td>
</tr>
<tr>
<td>time scale 1</td>
</tr>
<tr>
<td>time scale 2</td>
</tr>
</tbody>
</table>

Results

- Adiabaticity limits: slow synchrotron motion in barrier buckets
- Increase of absolute bunch length difference w.r.t. original bunch length when moving barriers too fast
- Measurements agree with analytical estimations and beam tests in the AGS.

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Beam loss reduction with barrier buckets - M. Vadai (QMUL, CERN)
Conventional buckets to barrier bucket at flat-top

- 14 GeV/c momentum, nominal MTE without splitting. Getting closer to foreseen operational conditions.

- Wide-band, barrier bucket RF amplitude (blue) increased
- Main, $h = 16$ RF amplitude lowered (red)

- Short time scale, synchrotron motion slow.

- Potential barrier must be placed between $h = 16$ buckets to preserve quality
What happens at high intensity?

- No cancellation of beam induced voltage, only RF system open loop transfer function compensation
- Higher intensity $\Rightarrow$ flatter profile observed
- Unexpected observation to be explained by simulations.
Combination with MTE

- Longitudinal profile just before the 5-turn extraction.

- 5 islands with gaps observed in the transfer line between the PS and SPS.
Loss reduction at PS extraction

- Beam-loss monitors along the ring
- Beam-loss in the extraction region.

Combined beam-loss in the extraction region significantly reduced
- Consistent in the probed intensity range.
- Basically loss-free Multi-Turn Extraction.

Plots: A. Huschauer
Particle tracking simulations
Longitudinal tracking of particles

- Principle: turn-by-turn tracking of the position of the particles in longitudinal phase space.
  - Difficult to measure distribution in the longitudinal phase space
    - compare simulated line density with the measurements.
  - No intensity effects yet in the first simulations.

- Challenges:
  - Barrier RF not implemented in the simulation tool BLonD.
  - Initial conditions cross-checked with measurements earlier in the cycle.
F-domain – sum of 25 harmonics with $\sigma$-modulation:

★ easy to implement bandwidth limits;
★ compatible with BLonD;
★ less harmonics needed – lower bandwidth requirement;
★ equivalent to zero phase low-pass filtering;
★ important for correct azimuthal gap position.

Example voltage program:
$h = 16\,\text{RF} \triangleright \text{barrier RF handover: measured and simulated}$

Measured profiles at extraction with at high intensity: $1.9 \times 10^{13}$ ppp

BLonD simulated profile evolution for the same RF voltage program without intensity effects.
Simulated phase space at extraction

- No time for full filamentation due to slow synchrotron motion.
- Shoulder and spike formation at extraction.
- Investigate potential effects of particles with higher energy offsets on the SPS.
Conclusions and next steps
Conclusions

- LLRF system developed for the Finemet® RF system to generate barrier buckets in the PS. Fully validated with beam.

- Beam losses originating in the longitudinal structure of the beam at extraction reduced virtually to zero in the PS.

- Barrier bucket RF implemented in BLoND.

- Particle tracking simulations confirm that a few particles are reflected at the barriers. Time is too short.
Next steps

- Complete analysis of beam measurements and compare with tracking simulations including intensity effects:
  - beam dynamics simulations in the SPS;
  - study coupling of longitudinal and transverse beam dynamics.

- Study possible options for synchronisation:
  - synchronise the barrier buckets in the PS with the circulating beam in the SPS.

- With beam after LS2 (beyond the scope of the PhD):
  - beam tests related to intensity effects;
  - benchmark simulations for longer debunching time.
Thank you for your attention.