Beam loss reduction by barrier buckets in the PS

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Part of the PhD project: Beam loss reduction by barrier buckets in the CERN Accelerator Complex

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Introduction
New use of the PS Finemet® cavity

- A wide-band (400 kHz - ∼ 10 MHz) Finemet cavity installed in the PS in 2014.
- Allows wide-band RF manipulations: non-sinusoidal RF is possible.
- Original purpose: kicker for the coupled-bunch feedback.
- New use case: beam loss reduction for fixed target beam at extraction.
Hamiltonian describing longitudinal particle motion for arbitrary RF

Particle motion in a barrier bucket generated by a $V_0(t)$ voltage pulse can be described by:

$$H(\Delta E, \Delta t) = \frac{\eta}{2\beta^2 E_0} (\Delta E)^2 - \frac{\int_0^{\Delta t} eV_0(\tau)d\tau}{T}$$ (1)

Since $T$, $\eta$, $E_0$ and $\beta$ are given: particle dynamics essentially depends only on the integral of the RF voltage. $\rightarrow$ Indirect shape dependence.
Sine and barrier buckets for injection

![Diagram of Sine and Barrier Buckets](image)

- Sine bucket
- Barrier bucket

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Synchrotron frequency in sine and barrier buckets

Sine bucket, $h = 8$, 290 ns

Barrier bucket (sine-like pulse)

Maxima decrease with increasing drift space. $f_s$ turns to monotonic increase with $\Delta E$ for long drift spaces.

Corresponds to a line in phase space.

$E_k = 1.4$ GeV
$\Delta E_{\text{max}} = 2.1$ MeV
$V_{\text{max}} = 4$ kV

Barrier bucket generated by a square wave described by simple analytic formulae e.g. $f_s$ monotonic: $2T_b < T_d$
$T_s$ synchrotron period.

$f_s$ decreases for shorter barriers

Separatrix

$T_s = \frac{2T_d\beta^2E_0}{|\eta\Delta E|} + \frac{4|\Delta E|T}{eV_{\text{max}}}$

decrease

decrease

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Conventional multi-turn extraction in the CERN PS

Process:
- Prepare first batch in PS.
- Extract first batch in 5 turns.
- Prepare second batch in PS.
- Wait for correct position in SPS also leaving a gap for SPS injection kicker.
- Extract second batch in 5 turns.

Bunches in CERN PS:
- Linac 2
- Booster 157 m
- PS 628 m
- SPS 6.91 km

Fixed target experiments

Transverse gaps between islands: MTE

Longitudinal gap for injection kicker rise time in the SPS.

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Beam loss reduction by barrier buckets in the PS
Barrier buckets combined with the multi-turn extraction in the CERN PS

Given: losses originating from the beam distribution in the transverse plane eliminated by MTE.
New: losses originating in the beam distribution in the longitudinal plane eliminated by barrier buckets.
Motivation and challenges
Motivation

1. Intensity increase of fixed target beams from the SPS.
2. Bottleneck: losses at extraction from the PS to the SPS (in the longitudinal structure of the beam).
3. Aim: reducing losses via a special RF manipulation.
   3.1 Introduce a gap to avoid losses at extraction.
   3.2 Existing wide-band cavity with power amplifier capable of achieving this goal is already given.
Main challenges 1

1. Generation of individual RF pulses requires wide-band RF system with sufficient voltage.
2. Pre-distortion of the wide-band pulse.
4. Remote and beam synchronous pulse control (multiple pulses per turn, amplitude and phase).
Main challenges 2

1. Combination of two highly complex beam manipulations:
   - barrier bucket;
   - transverse splitting and 5-turn extraction;
   - longitudinal and transverse beam dynamics usually well decoupled, but not independent for this process.

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

**Finemet cavity transfer function**

- **Amplitude (dB)** vs. **Frequency (MHz)**
- **Phase (rad)** vs. **Frequency (MHz)**

- **Gap voltage**
  - **$H(s)$**
  - **$H^{-1}(s)$**
  - **$V_{\text{barrier}}(t)$**
  - **$V_{\text{pre-distorted}}(t)$**

- **Usable gap size** 150 ns – 300 ns
- **$f_{\text{rev}} = 476$ kHz (flat-top)**

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Beam synchronous arbitrary waveform generator

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

200 MHz room

RF in

Barrier bucket waveform generator

PS 1 turn delay feedback board with FPGA

Ethernet Real time front-end Control functions (Linux)

CERN PS ring

\( p^+ \)

RF Amplifiers

Finemet® rings

Gap

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Beam loss reduction by barrier buckets in the PS
Measurements with beam
Measurement campaign

1. Low intensity and injection energy tests - system validation.
2. Moving barrier tests: scanning for barrier speed to confirm predicted limits.
3. Moving to high energy: new cycle, getting closer to foreseen operational conditions.
4. Scanning intensity: higher intensity, flatter profile observed.
5. Loss reduction is proven. Combination of the two beam manipulations performed for the first time.
Measurements at injection energy

- Low intensity: $N_b = 1\times10^{11}$ ppp
- Injection energy: $E_{\text{kin}} = 1.4$ GeV
- Negligible beam induced voltage
  - no compensation necessary
- Phase calibration of the barrier by varying the azimuth of the injected bunch
- One potential barrier per revolution
Moving barriers - barrier RF only

- Low voltage of barrier system, unmatched injection from PSB.
- Matching bunch to low voltage sinusoidal bucket.
- Stretching sinusoidal bucket to a barrier bucket and compression.
- Flat bunch profile needed small corrections of voltage profile (~1%).
- Confirming predicted speed limits for barrier compression rate.

\[\text{Signal amplitude [arb. units]}\]

![Signal amplitude graph](image_url)

\[\text{Time [ns]}\]

![Time graph](image_url)

\[\text{Low compression rate}\]

![Low compression rate graph](image_url)

\[\text{High compression rate}\]

![High compression rate graph](image_url)
Re-bucketing at flat top - handover from sine to barrier RF

- One potential barrier per turn; intensity: $3 \cdot 10^{12}$ ppp
- Wide-band, barrier bucket RF amplitude (blue) increased
- Main, $h = 16$ RF amplitude lowered (red)
- Synchrotron frequency low, short time scale
  - remnants of initial conditions visible
- Potential barrier must be placed between $h = 16$ buckets to preserve quality
Scaling with intensity

- No cancellation of beam induced voltage, only RF system open loop transfer function compensation
- Higher intensity $\Rightarrow$ flatter profile observed

![Graph showing signal amplitude over time with two curves for different intensities.]

- Blue line: $4 \cdot 10^{12}$ ppp
- Red line: $1.9 \cdot 10^{13}$ ppp

1 turn
Beam profile at PS-SPS transfer

- Longitudinal line density, tomoscope last trace before extraction (top).
- 5 islands with gaps observed in the transfer line between PS and SPS.

![Graph showing beam profile and signal amplitude over time](image-url)

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Significant loss reduction at extraction

- Data from beam-loss monitors.
- Extraction region is straight sections 14 to 18.
- Combined beam loss for the extraction region significantly reduced.
- Consistent in the probed intensity range.

Plots: A. Huschauer
Particle tracking simulations
Particle tracking

Principle: turn-by-turn tracking of the position of the particles in longitudinal phase space.

- Difficult to measure distribution in the longitudinal phase space → delivering observables from the simulated phase space and comparing it with the measurements.
- No beam induced voltage and no intensity effects in the first simulations.

Challenges:

- Barrier RF is not implemented in BLoND.
- Initial conditions: reference only available from earlier in the cycle.
Barrier RF system and voltage program in BLonD

- Uses the existing BLonD RF infrastructure.
- Identical method (same code) as hardware - big time saver.
- Properties: smooth and DC free waveform.
- Programmable parameters: in this example the overall peak amplitude is 4 kV and the gap width corresponds to: $h = 14$, 150 ns at flat top.
Finding a matching standard distribution

Beam loss reduction by barrier buckets in the PS
Longitudinal profile evolution

Measured (left) and simulated (right). No intensity effects in simulations.
Extraction and longer time scale

- Slow synchrotron motion.
- Shoulders and spikes, two bunches reflecting.
- No time for full filamentation.

Calculated (analytical) maximum synchrotron frequency for a similar bucket generated by a square wave $\approx 7$ Hz.
Conclusions and next steps
Conclusions

- LLRF system developed for the Finemet® RF system to generate barrier buckets in the PS. Validation with beam.
- Beam losses originating in the longitudinal structure of the beam at extraction reduced virtually to zero in the PS.
- Barrier bucket RF for the BLonD simulator developed.
- Particle tracking simulations show that the barriers affect the beam near the gap only.
- VHDL and Python code developed with git version control. Test benches in the case of VHDL and unit tests in the case of Python were also developed.
  * Hardware: https://gitlab.cern.ch/BE-RF-PLDesign/PS/EDA-02175-V2-BarrierBuckets
  * Simulation: https://gitlab.cern.ch/mivadai/BLonD/tree/bbEPL
Next steps

1. Complete analysis of beam measurements and compare with tracking simulations including intensity effects.
   - Study coupling of longitudinal and transverse beam dynamics.
   - Beam dynamics simulations in the SPS.
2. Study possible options for synchronization
3. With beam after LS2 (beyond the PhD):
   - tests related to intensity effects;
   - confirm low synchrotron periods at extraction.
Barrier bucket and longitudinal BD references

Arbitrary RF and barrier bucket (sine and square)

- J. E. Griffin et. al: Isolated Bucket RF Systems in the Fermilab Antiproton Facility PAC’83 (1983)

Our publications related to barrier buckets in the PS:

- Beam Manipulations with Barrier Buckets in the CERN PS, doi:10.18429/JACoW-IPAC2019-MOPTS107

CERN Meetings related to the beam tests with barrier buckets:

- RF PS developments and 2018 run: https://indico.cern.ch/event/763456/
- Machine Studies Working Group: https://indico.cern.ch/event/767405/
- LIU-SPS Beam Dynamics Working Group: https://indico.cern.ch/event/799195/
- LIU-PS Beam Dynamics Working Group: https://indico.cern.ch/event/842736/

CERN Beam Longitudinal Dynamics code BLonD, http://blond.web.cern.ch

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MTE References


- Summary also highlighting the problem arising from the longitudinal structure at extraction. https://www.astec.stfc.ac.uk/Pages/GiovannozziRal_mte.pdf
EE and signal processing references

Discrete-time filters, time reversal:

Network theory for RF (S parameters, etc.):

Harmonic analysis, symmetries, convergence, properties of sigma:
Spare slides
Pre-distorted waveform spectra and system magnitude response

- Gap duration = 600 ns
- Gap duration = 300 ns
- Gap duration = 150 ns
- Harmonic distortion

Amplitude of components [norm.]

Frequency [MHz]

Magnitude response [norm.]
Confirming adiabaticity limits using moving barriers

**Bunch expansion and compression using moving barriers**

- Beam tests using two, azimuthally moving barriers
- Expansion and compression time $t_c$ varied
- Two time scales used.

**Bunch length difference measurement results**

- Adiabaticity limits: low synchrotron frequencies 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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Further differences of the simulations w.r.t. the beam tests

1. The peak RF voltage is not exactly the same for all gap widths, especially for very wide or very narrow gaps, because of the transfer function ($S_{21}$) of the cavity and amplifier.

2. No moving barrier feature in the simulation.

3. No induced voltage in simulation.

4. No intensity effects in simulation.

5. No transverse structure assumed, but transverse-longitudinal coupling seemed to be small with the Multi-Turn Extraction (MTE).
Wide-band RF in BLonD for barrier buckets - multiple RF systems

The output of a single BLonD RF system is:

\[ V_n(t) = M_n \sin(n\omega t + \phi) \]  \hspace{1cm} (2)

The magnitude of one barrier harmonic for a given \( h \) is:

\[ M_n = \sigma(n) b(n, h) \]  \hspace{1cm} (3)

Where the effect of \( \sigma(n) \) is equivalent to the effect of a zero phase response low-pass filter and \( b(n, h) \) is a Fourier coefficient.

Barrier waveform criteria still apply. Preserving the azimuthal position of the barrier independently of the gap width and smoothing parameters is desirable.
CERN's main accelerators and fixed target experiments

LHC (2008)  
North Area  
Future BDF, SHiP

R = 4250 m  
SPS (1976)

R = 740 m  
PSB (1972)

HiRadMat

LINAC 2  
PS (1959)

R = 100 m  
East Area

Key

- protons
- Fixed target experiments
- LINAC  Linear Accelerator
- PSB  Proton Synchrotron Booster
- PS  Proton Synchrotron
- SPS  Super Proton Synchrotron
- LHC  Large Hadron Collider

HiRadMat  High Radiation to Materials
SHiP  Search for Hidden Particles
BDF  Beam Dump Facility

Original by Forthommel CC-BY-SA 3.0 Accessed 13/08/2018, Changes: adapted to the PhD project.
Single particle dynamics

Single particles orbiting: mean energy and period. Energy, time and phase deviations are shown, too.