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Beam loss reduction by barrier buckets in the PS

LIU-PS Beam Dynamics Working Group Meeting 34
https://indico.cern.ch/event/842736/

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

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Acknowledgements:

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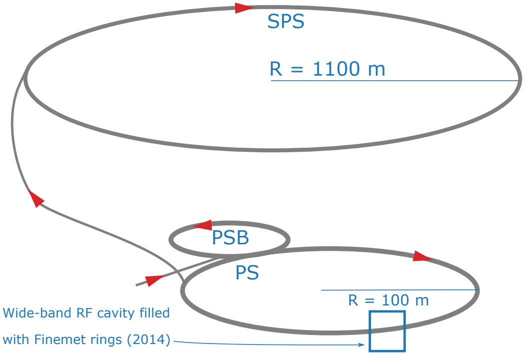
Introduction

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.

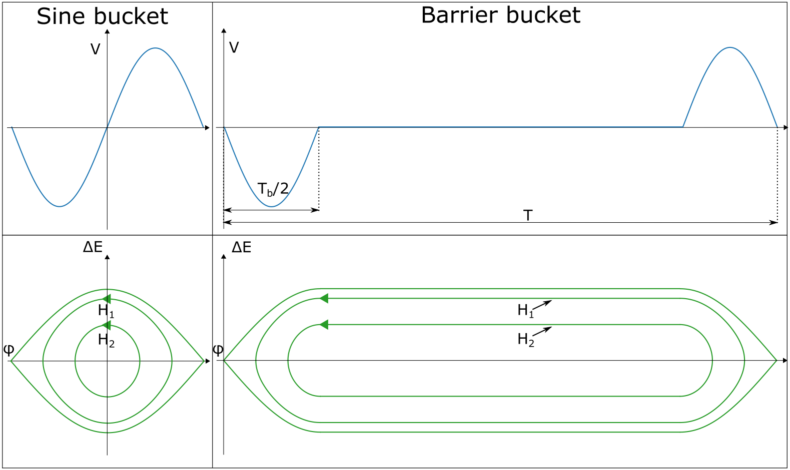
Hamiltonian describing longitudinal particle motion for arbitrary RF

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

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

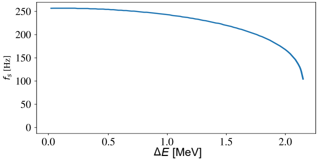
Since T, η, E_0 and β are given: particle dynamics essentially depends only on the integral of the RF voltage. → Indirect shape dependence.

Sine and barrier buckets for injection



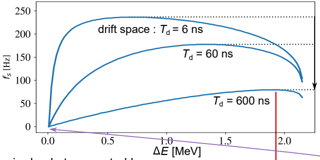
Synchrotron frequency in sine and barrier buckets

Sine bucket, h = 8, 290 ns



E_k = 1.4 GeV
ΔE_{max} = 2.1 MeV
V_{max} = 4 kV

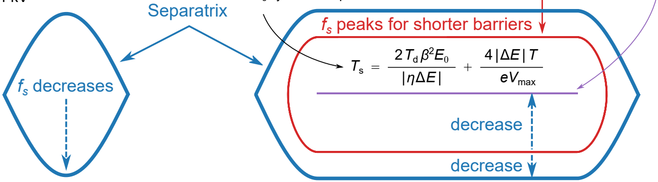
Barrier bucket (sine-like pulse)



Maxima decrease with increasing drift space. f_s turns to monotonic increase with ΔE for long drift spaces.

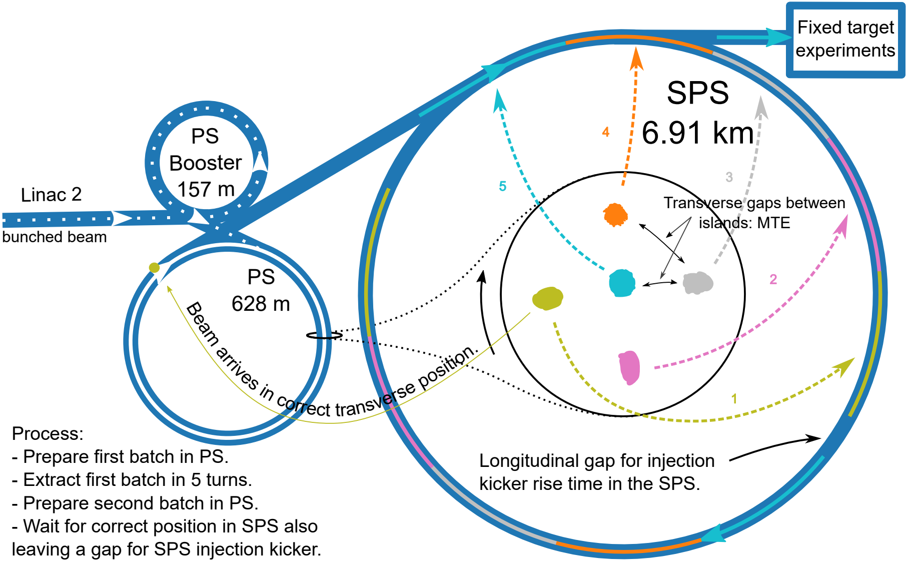
Barrier bucket generated by a square wave described by simple analytic formulae e.g. f_s monotonic: $2T_b < T_d$
T_s synchrotron period.

Corresponds to a line in phase space.



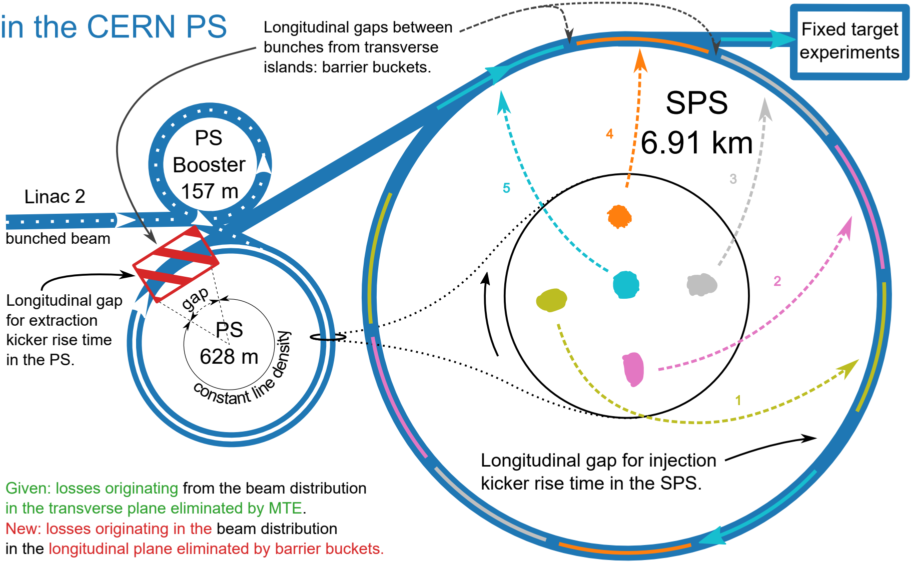
$$T_s = \frac{2T_d\beta^2E_0}{|\eta\Delta E|} + \frac{4|\Delta E|T}{eV_{max}}$$

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.

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

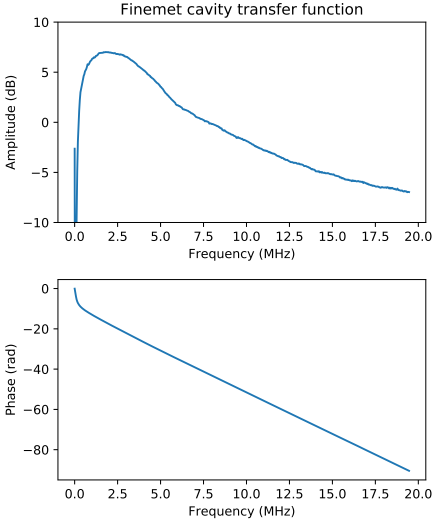
1. Generation of individual RF pulses requires wide-band RF system with sufficient voltage.
2. Pre-distortion of the wide-band pulse.
3. Beam synchronous generation of the barrier pulse.
4. Remote and beam synchronous pulse control (multiple pulses per turn, amplitude and phase).

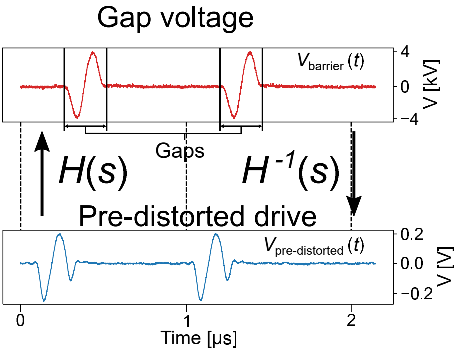
Main challenges 2

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

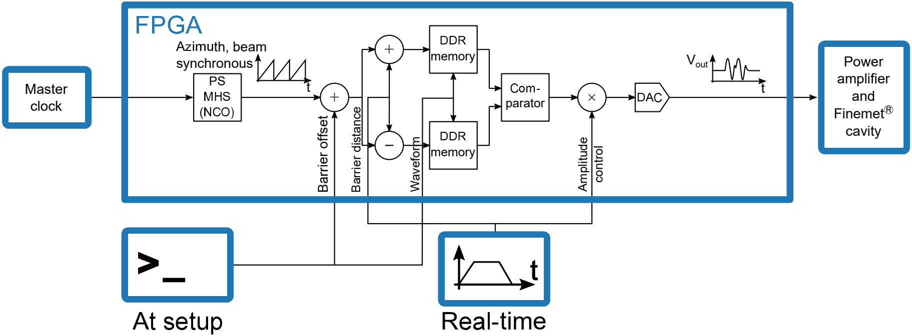




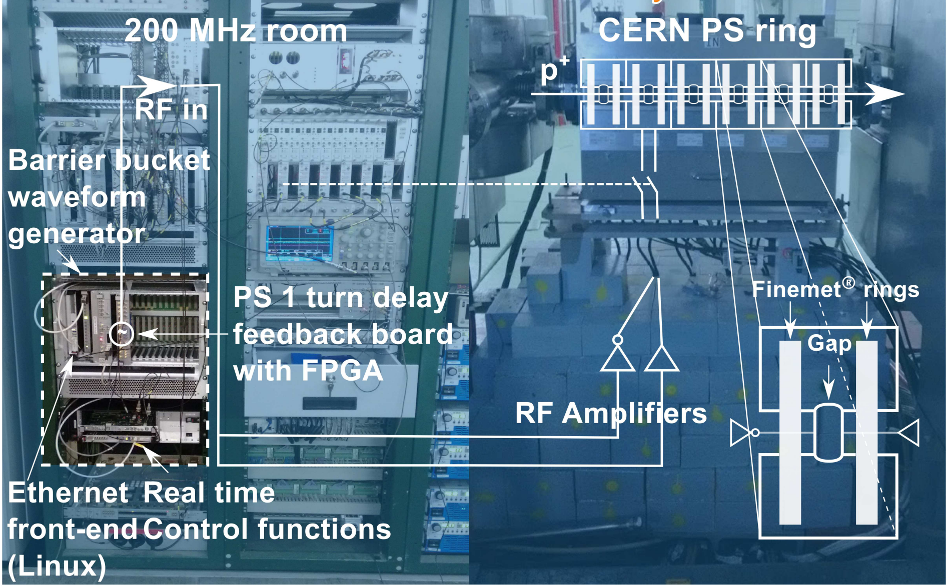
- Usable gap size 150 ns − 300 ns
  frev = 476 kHz (flat-top)

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



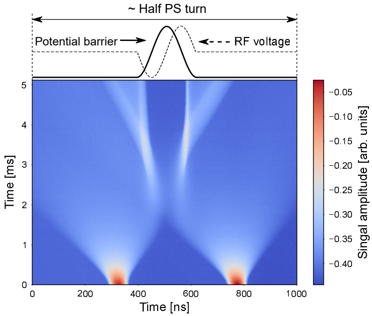
Measurements with beam

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

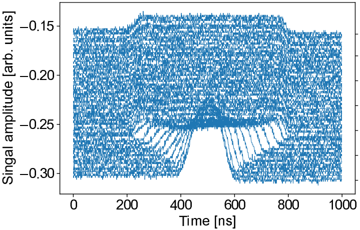
- Low intensity: $N_b = 1{\times}10^{11}$ ppp
- Injection energy: $E_{kin} = 1.4$ GeV
- Negligible beam induced voltage
  - ▷ no compensation necessary
- Phase calibration of the barrier by varying the azimuth of the injected bunch
- One potential barrier per revolution

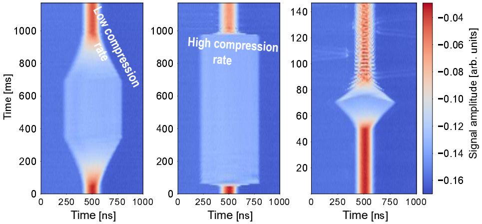


Overlay of two measurements injecting left and right of the barrier

Moving barriers - barrier RF only

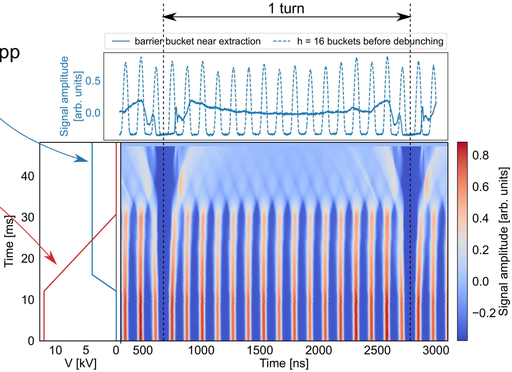
- Low voltage of barrier system, unmatched injection from PSB.
- Matching bunch to low voltage sinusoidal bucket.
- Stretching sinusoidal bucket to a barrier bucket and compression.
- Flat bunch profile needed small corrections of voltage profile (~1%).
- Confirming predicted speed limits for barrier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





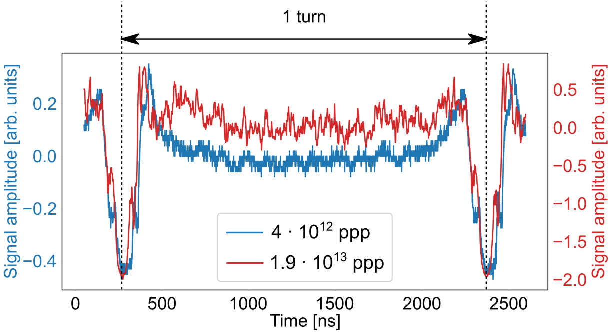
Re-bucketing at flat top - handover from sine to barrier RF

- 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



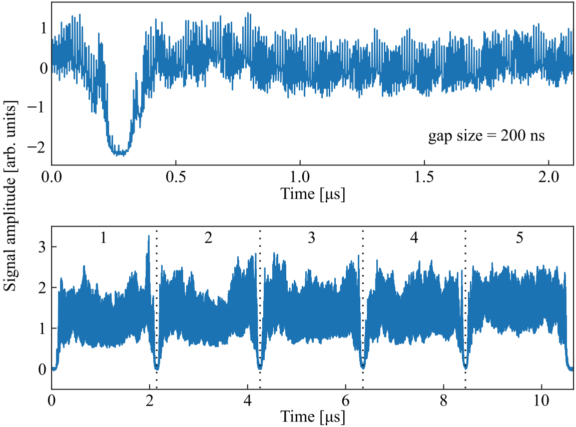
Scaling with intensity

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



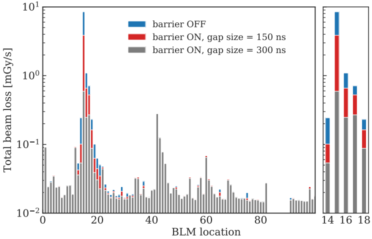
Beam profile at PS-SPS transfer

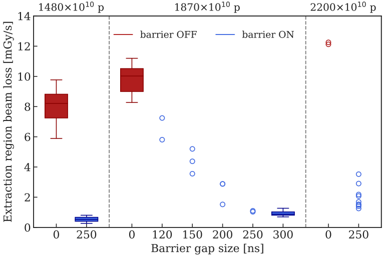
- Longitudinal line density, tomoscope last trace before extraction (top).
- 5 islands with gaps observed in the transfer line between PS and SPS.



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

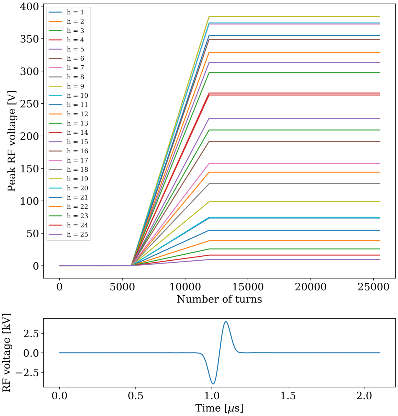
Principle: turn-by-turn tracking of the position of the particles in longitudinal phase space.

- 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:

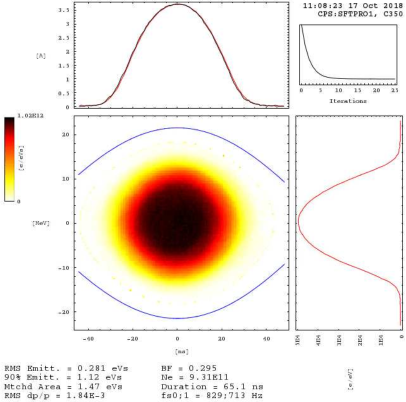
- Barrier RF is not implemented in BLonD.
- Initial conditions: reference only available from earlier in the cycle.

Barrier RF system and voltage program in BLonD

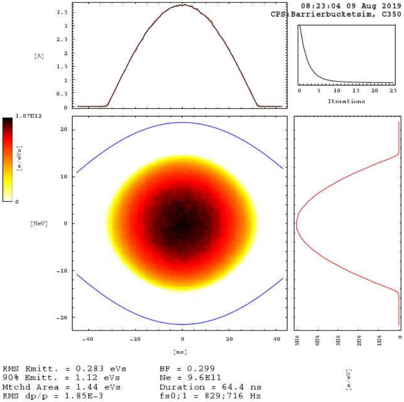


- Uses the existing BLonD RF infrastructure.
- Identical method (same code) as hardware - big time saver.
- Properties: smooth and DC free waveform.
- Programmable parameters: in this example the overall peak amplitude is 4 kV and the gap width corresponds to: $h = 14$, 150 ns at flat top.

Finding a matching standard distribution

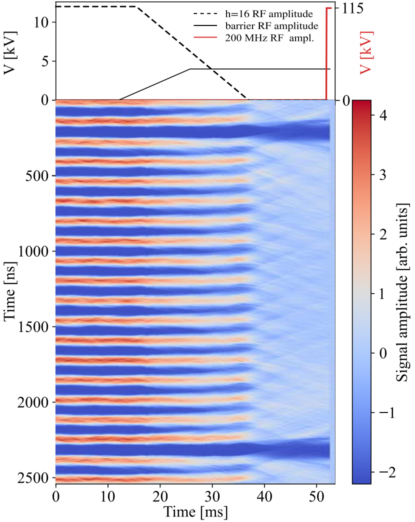


```
11:08:23 17 Oct 2018
CPS:SFTPRO1, C350

RMS Emitt. = 0.281 eVs      BF = 0.295
90% Emitt. = 1.12 eVs       Ne = 9.31E11
Mtchd Area = 1.47 eVs       Duration = 65.1 ns
RMS dp/p = 1.84E-3          fs0;1 = 829;713 Hz
```

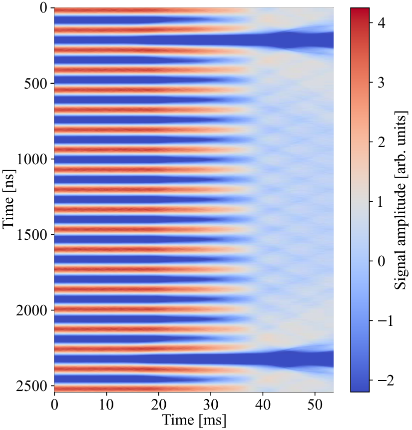


```
08:23:04 09 Aug 2019
CPS:Barrierbucketsim, C350

RMS Emitt. = 0.283 eVs      BF = 0.299
90% Emitt. = 1.12 eVs       Ne = 9.6E11
Mtchd Area = 1.44 eVs       Duration = 64.4 ns
RMS dp/p = 1.85E-3          fs0;1 = 829;716 Hz
```

Longitudinal profile evolution



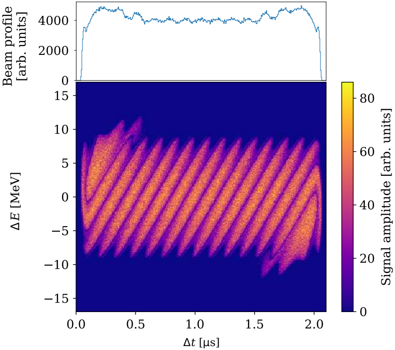
Measured (left) and simulated (right). No intensity effects in simulations.

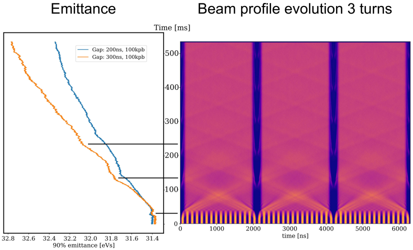


Extraction and longer time scale

- 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 ≈ 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`
  - Model and simulation: `https://gitlab.cern.ch/mivadai/barrierbucket`

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)
- G. Dome: Theory of RF Acceleration and RF Noise, `https://cds.cern.ch/record/863008/files/p215.pdf` (1984)
- S. Y. Lee: Accelerator Physics, 4th Ed. (2019) pp. 317-323.

Our publications related to barrier buckets in the PS:

- Barrier Bucket Studies in the CERN PS, `doi:10.18429/JACoW-IPAC2019-MOPTS106`
- 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`

MTE References

- R. Cappi and M. Giovannozzi: Novel method for multiturn extraction: Trapping charged particles in islands of phase space Phys. Rev. Lett. vol. 88, p. 104 801, 10 Feb. 2002.
- J. Borburgh, S. Damjanovic, S. Gilardoni, M. Giovannozzi, C. Hernalsteens, M. Hourican, A. Huschauer, K. Kahle, G. Le Godec, O. Michels, and G. Sterbini, “First implementation of transversely split proton beams in the CERN Proton Synchrotron for the fixed-target physics programme,” Europhys. Lett., vol. 113, no. 3, 34001. 6 p, 2016.
- S. Abernethy, A. Akroh, H. Bartosik, A. Blas, T. Bohl, S. Cettour-Cave, K. Cornelis, H. Damerau, S. Gilardoni, M. Giovannozzi, C. Hernalsteens, A. Huschauer, V. Kain, D. Manglunki, G. Mtral, B. Mikulec, B. Salvant, J. L. Sanchez Alvarez, R. Steerenberg, G. Sterbini, and Y. Wu, “Operational performance of the CERN injector complex with transversely split beams,” Phys. Rev. Accel. Beams, vol. 20, no. 1, 014001. 21 p, 2017.
- A. Huschauer, A. Blas, J. Borburgh, S. Damjanovic, S. Gilardoni, M. Giovannozzi, M. Hourican, K. Kahle, G. Le Godec, O. Michels, G. Sterbini, and C. Hernalsteens, “Transverse beam splitting made operational: Key features of the multiturn extraction at the CERN Proton Synchrotron,” Phys. Rev. Accel. Beams, vol. 20, no. 6, 061001. 15 p, 2017.
- A. Huschauer, M. Giovannozzi, O. Michels, A. Nicoletti, and G. Sterbini, “Analysis of performance fluctuations for the CERN proton synchrotron multi-turn extraction,” Journal of Physics: Conference Series, vol. 874, p. 012 072, Jul. 2017.
- Summary also highlighting the problem arising from the longitudinal structure at extraction. `https://www.astec.stfc.ac.uk/Pages/Giovannozzi_ral_mte.pdf`

EE and signal processing references

Discrete-time filters, time reversal:

- J. O. Smith III: Introduction to Digital Filters with Audio Applications, (2007) `https://ccrma.stanford.edu/~jos/fp/Forward_Backward_Filtering.html`
- A. V. Oppenheim, R. W. Schaefer, J. R. Buck: Discrete-time signal processing, Prentice Hall (1999) pp. 123-4

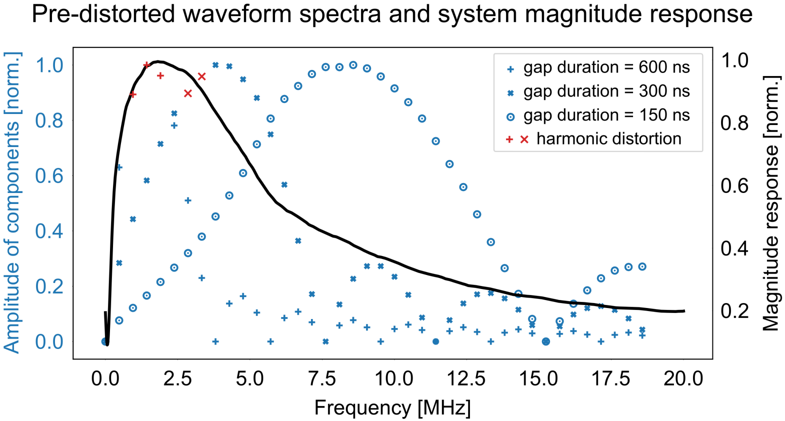
Network theory for RF (S parameters, etc.):

- D. Pozar: Microwave Engineering, Wiley (2012) p. 174-203

Harmonic analysis, symmetries, convergence, properties of sigma:

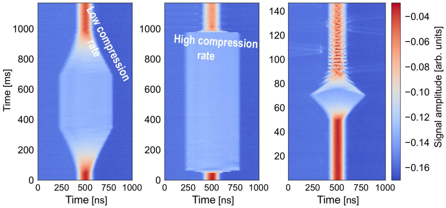
- C. Lanczos: Linear Differential Operators, Martino Publishing (2012) p. 49-52, 74-89

Spare slides


Pre-distorted waveform spectra and system magnitude response
Amplitude of components [norm.]
Magnitude response [norm.]
Frequency [MHz]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
+ gap duration = 600 ns
✖ gap duration = 300 ns
⊙ gap duration = 150 ns
+ × harmonic distortion

Confirming adiabaticity limits using moving barriers

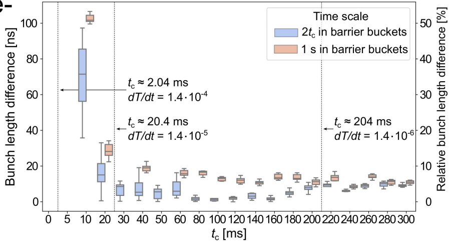
Bunch expansion and compression using moving barriers



- 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.



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:

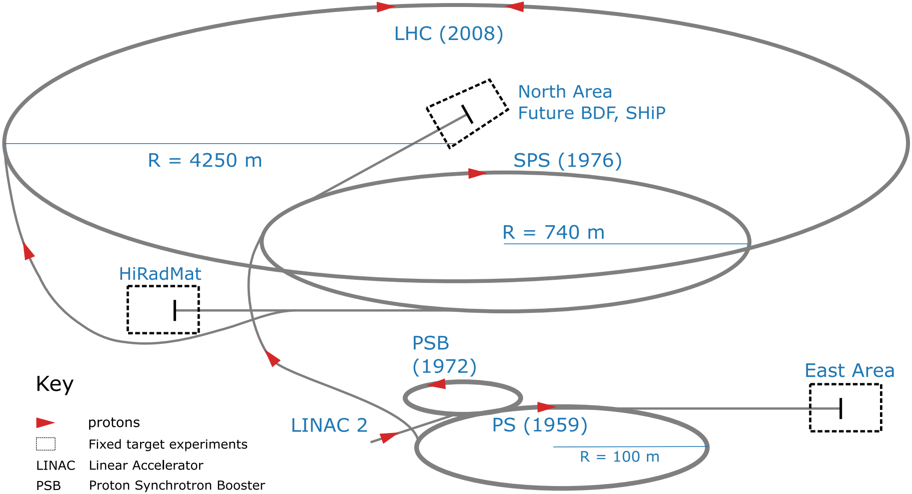
$$V_n(t) = M_n \sin\left(n\omega t + \phi\right) \tag{2}$$

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

$$M_n = \sigma(n) b(n, h) \tag{3}$$

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



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.