12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB038

SIMULATION OF THE FILLING PATTERN DEPENDENT REGENERATIVE BEAM BREAKUP INSTABILITIES IN ENERGY RECOVERY LINACS

S. Setiniyaz* [1], R. Apsimon [1], Engineering Department, Lancaster University, Lancaster, UK
P. H. Williams, Cockcroft Institute, Daresbury Laboratory, Warrington, UK
[1] also at Cockcroft Institute, Daresbury Laboratory, Warrington, UK

Abstract

The interaction of a transversely displaced beam with the higher modes (HOM) of the accelerating cavities causes building up HOM voltages in the cavity, which in turn kicks the beam and increases the offset further. This is known as regenerative beam breakup (BBU) instability and it sets the beam threshold current for the stable beam operation. A study by Setiniyaz *et al.* [1] showed the filling pattern and recombination schemes of multi-turn energy recovery linacs (ERLs) can create many different beam loading transients, which can have a big impact on the cavity fundamental mode voltage and RF stabilizes. In this work, we extend the study of the filling pattern and recombination schemes to the BBU instabilities and threshold current. In the ERLs, the accelerated and decelerated bunches can be ordered differently while they pass through the cavity and form different filling patterns. Each pattern has a unique bunch energy sequence and bunch arrival times and hence interacts with cavity uniquely and thus drives BBU differently. In this paper, we introduce a simulation tool to investigate the filling pattern dependence of the ERL BBU instability.

INTRODUCTION

There is growing interest in recirculating Energy Recovery Linac (ERL) technology as it combines the high brightness of conventional electron linacs with the high average powers of the storage rings. This is achieved by recovering the kinetic energy (KE) of the used bunches by decelerating them in accelerator cavities [2]. Potential applications for ERLs include free-electron laser (FEL) drivers for industrial and academic uses [3,4]; high luminosity colliders for high energy and nuclear physics [5,6]; and laser inverse Compton scattering γ ray sources [7,8].

Bunches passing through the cavity will excite transverse higher modes (HOM) voltage proportional to their transverse offsets. In turn, the HOM voltage will deflect the subsequent bunches and increase their offsets, consequently forming a positive feedback loop between HOM voltage and bunch offset. There exist a certain threshold current I_{th}, which below/above it the HOM voltage and bunch offsets will decay/grow. The growth of the HOM voltage and bunch offsets will cause beam loss, and thus I_{th} is the highest stable current in the accelerator. This phenomenon is known as the regenerative beam breakup (BBU) instability [9,10] and sets the limitation on beam current.

While studies have been undertaken to investigate BBU instabilities for ERLs [11–17], there hasn't been one extensively focused on the impact of the filling patterns on the ERL BBU instabilities. Filling patterns and bunch recombination schemes can generate many different beam loading transients that each can interact with RF cavity and HOM uniquely. Consequently, some filling patterns will outperform others in terms of BBU instability and would allow higher threshold currents.

FILLING PATTERN

The filling pattern describes the order in which bunches are injected into the ERL ring over subsequent turns and which has already been shown by Setiniyaz [1] to have a major impact on the stability of the RF system. Note that the bunches should not be all injected at one turn in multi-turn ERLs as it will create a huge drop/increase in the cavity voltage, but instead they should be injected one bunch per turn per packet. Sudden drop/increase in the cavity voltage should be avoided for the sake of the beam and RF stability. Here "packet" refers to a pack of bunches that pass through the cavity together as shown in Fig. 1. Multiple same packets fill up the ERL ring. Generally, not all the RF cycles are filled with a bunch, but rather some RF cycles are empty. Therefore, the RF cycles can be divided into blocks where 1 bunch occupies multiples of RF cycles called intra packet blocks.

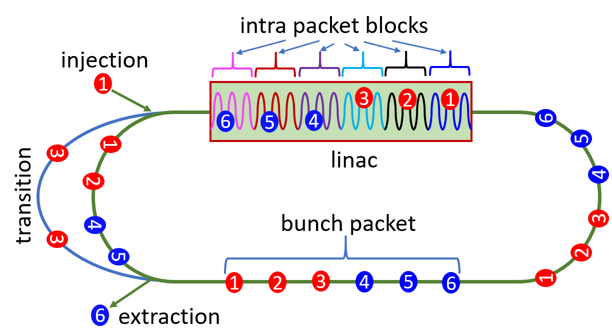


Figure 1: Bunch packets in the ERL. The RF cycles The red/blue bunches at the peak/trough are being accelerated/decelerated. Different intra packet blocks are colored differently. Bunches at the third turn go through a transition arc where there is at least an extra half RF cycle delay.

The filling pattern in Fig. 1 is {1 2 3 4 5 6}, where the 1st bunch goes to the 1st block, the 2nd bunch goes to the

* s.saitiniyazi@lancaster.ac.uk

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB038

2nd block, and so on so forth. Similarly, a filling pattern {1 3 2 4 5 6} would describe the 1st bunch goes to the 1st block and 2nd bunch goes to the 3rd block and so on so forth. Filling patterns can be of two types: FIFO (First In First Out) and SP (Sequence Preserving) [1]. In FIFO, the bunches remain in the same block but their turn number changes, and consequently packets passing through the RF cavity change turn by turn as well. In the SP case, the bunches can jump between blocks to keep the turn numbers in the packet the same. In this work, we will only simulate the SP scheme.

SIMULATION CODE

Code Algorithm

The code adopted the ERLBBU algorithm [16–18] and a new module is added to the code to include the effect of filling patterns where bunches' energies and arrival times. The code can estimate the threshold current for the given pattern. The code starts with the existing HOM voltage. A bunch injected to the accelerating cavities will excite HOM voltage $\delta V_{H,\,R}$ proportional to their offset described by

$$\delta V_{H,\,R} = \frac{\omega_H^2}{2c} q_b \left(\frac{R}{Q}\right)_H x, \tag{1}$$

where $\omega_H = 2\pi f_H$ with f_H being the HOM frequency, q_b is the bunch charge, $\left(\frac{R}{Q}\right)_H$ is geometric shunt impedance of the HOM, and x is the bunch offset. Simultaneously, the bunch will receive a kick $\Delta x'$ from the HOM given as

$$\Delta x' = \frac{V_{H,\,I}}{V_{beam}}, \tag{2}$$

where $V_{H,\,I}$ is the imaginary part of the HOM voltage as the kick is from the magnetic field and V_{beam} is the beam voltage, pc/e. The newly exited voltage $\delta V_{H,\,R}$ is added to the real part of the HOM voltage as the beam couples electrically

$$V_{H,\,R,\,new} = V_{H,\,R,\,old} + \delta V_{H,\,R}, \tag{3}$$

where $V_{H,\,R,\,new}/V_{H,\,R,\,old}$ is the real part of the new/old HOM voltage. The HOM voltage V_H can be given as

$$V_H = V_{H,\,R} + V_{H,\,I}. \tag{4}$$

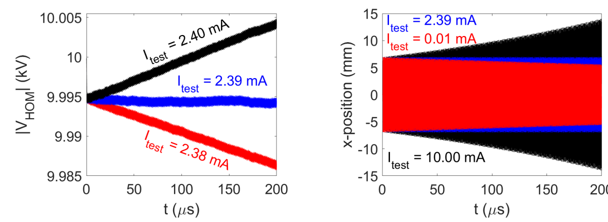
The next bunch will arrive dt later and voltage change during this time are given as

$$V_H(dt) = V_H e^{-\frac{\omega_H dt}{2Q_L}} e^{i\omega_H dt}, \tag{5}$$

where Q_L is loaded HOM Q-factor. A simple one-turn map is used to map the bunch's x and x' from one to the next.

Benchmarking

Benchmarking against the experimental results presented in Table 5.1 of Ref. [17] provided consistent results. Our code predicted $I_{th} = 2.39$ mA, which is slightly closer to the experimental results than other simulation codes and analytical models. The code starts with a test current and an initial HOM voltage of 10 kV. Bunches are injected with small Gaussian transverse offset jitters. The code estimates if the cavity voltage increases or decreases over time under the test current, as shown in Fig. 2(a), and generates a new test current accordingly. New test currents are generated repeatedly until the I_{th} is determined within a user-defined tolerance range. As can be seen in Fig. 2(a), at the threshold current of 2.39 mA the cavity HOM voltage becomes stable. The assumed parameters are given in Table 1. The magnitude of the transverse offset of the bunches also increases or decreases in a similar fashion to the HOM voltage as shown in Fig. 2(b).



(a) (b)

Figure 2: HOM voltage (a) and particle x-position in the cavity (b) when test current I_{test} is above (black), below (red), and at (blue) the threshold current.

Simulation Results

The threshold currents are estimated for a frequency range 1.2 MHz as the threshold currents are quasi-periodic as shown in Fig. 3. We observe the threshold current changes slightly from one period to the next. The simulation results showed the threshold current is pattern dependent as shown in Fig. 4 and the close patterns have similar threshold currents. The average threshold current over the 1.2 MHz period is shown in Fig. 5 for 120 patterns. The average threshold current seems to be random. This could be due to the fact changing filling pattern changes bunch energies and arrival times in the packet and they interact in a complicated way. When phase advance is integer times of the π, the threshold current is much higher. We see the filling pattern playing a huge effect on the threshold current that one can increase the threshold current by a factor of 5 by selecting the best pattern.

CONCLUSION

We have developed a simulation tool to investigate the impact of filling pattern choice in a multi-pass ERL on regenerative BBU instability. With simulation, we demonstrated the filling pattern dependence of the regenerative BBU instability threshold current. We observed a factor of 6 difference in the threshold current between worst and best patterns. The filling pattern changes bunch energies and arrival times in the packet at the same time and the interaction of these two factors causes the threshold current to appear to be random over 120 patterns of the 6-turn ERL. Nevertheless, our simulation tool is effective to find the highest threshold current

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB038

Table 1: 6-Turn ERL BBU Simulation Parameters

Parameter	Unit	Value
fundamental mode frequency f	MHz	1497.0
HOM frequency f_{HOM}	MHz	2105.4–2106.6
HOM loaded Q-factor $Q_{L,HOM}$		6.11×10^6
HOM geometric shunt impedance $\left(\frac{R}{Q}\right)_{HOM}$	Ω	29.9
revolution period for non-transitioning bunch T_{rev}	ns	801.67
revolution period for transitioning bunch $T_{rev,t}$	ns	802.01
bunch energies at turn 1–6	MeV	7.3, 46.3, 85.3, 124.3, 85.3, 46.3
bunch spacing	T_{RF}	10
injected beam RMS offset $\sigma_{x,offset}/\sigma_{y,offset}$	μm	10/1

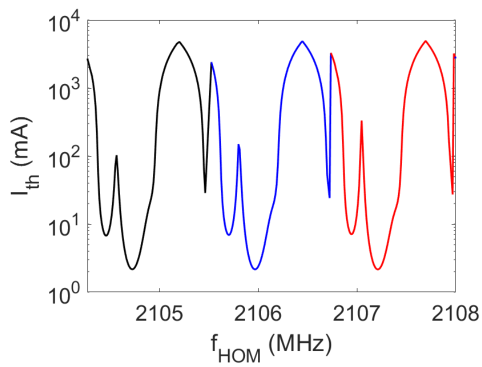


Figure 3: Quasi-periodicity of I_{th}.

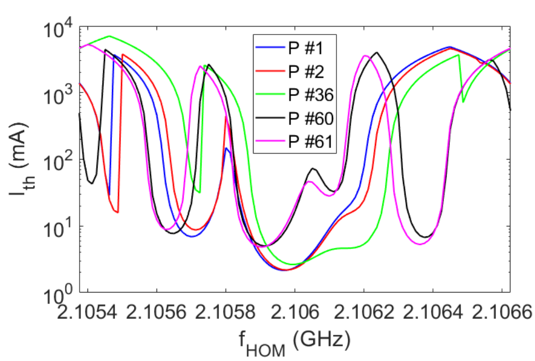


Figure 4: Threshold current vs HOM frequency of pattern number 1, 2, 36, 60, and 61. Phase advance $\mu = 1.5\pi$.

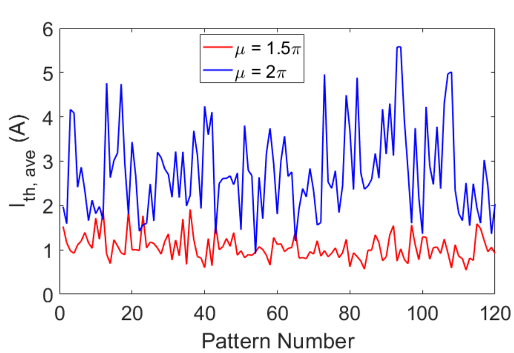


Figure 5: Average threshold current vs patterns.

and best filling pattern and will assist in the design of future ERL projects.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Graeme Burt for his useful suggestions and insights. The studies presented have been funded by STFC Grants No. ST/P002056/1 under the Cockcroft Institute Core Grant.

REFERENCES

[1] S. Setiniyaz, R. Apsimon, and P. H. Williams, "Implications of beam filling patterns on the design of recirculating energy recovery linacs", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 23, no. 7, p. 072002, Jul. 2020. doi:10.1103/PhysRevAccelBeams.23.072002

[2] L. Merminga, "Energy Recovery Linacs", in *Synchrotron Light Sources and Free-Electron Lasers*, E. Jaeschke, S. Khan, J. Schneider, J. Hastings, Ed. Switzerland: Springer, Cham, 2016, pp. 419–457.

[3] Y. Socol, "High-power free-electron lasers–technology and future applications", *Optics & Laser Technology*, vol. 46, pp. 111–126, Mar. 2013. doi:10.1016/j.optlastec.2012.06.040

[4] Y. Socol, G. N. Kulipanov, A. N. Matveenko, O. A. Shevchenko, and N. A. Vinokurov, "Compact 13.5-nm free-electron laser for extreme ultraviolet lithography", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 14, p. 040702, Apr. 2011. doi:10.1103/PhysRevSTAB.14.040702

[5] J. L. Abelleira Fernandez *et al.*, "A Large Hadron Electron Collider at CERN Report on the Physics and Design Concepts for Machine and Detector", *J. Phys. G: Nucl. Part. Phys.*, vol. 39, p. 075001, 2012. doi:10.1088/0954-3899/39/7/075001

[6] A. Accardiet *et al.*, "Electron-Ion Collider: The next QCD frontier", *Eur. Phys. J. A*, vol. 52, p. 268, 2016. doi:10.1140/epja/i2016-16268-9

[7] M. Shimada and R. Hajima, "Inverse Compton scattering of coherent synchrotron radiation in an energy recovery linac", *Phys. Rev. ST Accel. Beams*, vol. 13, p. 100701, Oct. 2010. doi:10.1103/PhysRevSTAB.13.100701

[8] T. Hayakawa *et al.*, "Nondestructive assay of plutonium and minor actinide in spent fuel using nuclear resonance fluorescence with laser Compton scattering γ-rays", *Nuclear*

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB038

Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 621, pp. 695-700, Sep. 2010. doi:10.1016/j.nima.2010.06.096

[9] O. H. Altenmueller *et al.*, "Beam Break-Up Experiments at SLAC", in *Proc. 1966 Linear Accelerator Conf. (LINAC'66)*, Los Alamos, NM, USA, Oct. 1966, paper VI-02, pp. 267-280.

[10] V. K. Neil and R. K. Cooper, "Coherent Instabilities In High Current Linear Induction accelerators", *Part. Accel.*, vol. 1, pp. 111-120, 1970.

[11] G. H. Hoffstaetter and I. V. Bazarov, "Beam-breakup instability theory for energy recovery linacs", *Phys. Rev. ST Accel. Beams*, vol. 7, p. 054401, 2004. doi:10.1103/PhysRevSTAB.7.054401

[12] W. Lou and G. H. Hoffstaetter, "Beam breakup current limit in multiturn energy recovery linear accelerators", *Phys. Rev. Accel. Beams*, vol. 22, p. 112801, 2019. doi:10.1103/PhysRevAccelBeams.22.112801

[13] V. Volkov and V. M. Petrov, "Beam Break Up Instability Analysis for Cavities, Linacs and Energy Recovery Linacs", in *Proc. 29th Linear Accelerator Conf. (LINAC'18)*, Beijing, China, Sep. 2018, pp. 537-539. doi:10.18429/JACoW-LINAC2018-TUPO091

[14] C. D. Tennant *et al.*, "First observations and suppression of multipass, multibunch beam breakup in the Jefferson Laboratory free electron laser upgrade", *Phys. Rev. ST Accel. Beams*, vol. 8, p. 074403, 2005. doi:10.1103/PhysRevSTAB.8.074403

[15] L. Merminga, "RF stability in energy recovering free electron lasers: theory and experiment", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 483, pp. 107-112, 2002. doi:10.1016/S0168-9002(02)00293-0

[16] E. Pozdeyev, C. Tennant, J. J. Bisognano, M. Sawamura, R. Hajima, and T. I. Smith, "Multipass beam breakup in energy recovery linacs", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 557, pp. 176-188, 2006. doi:10.1016/j.nima.2005.10.066

[17] C. D. Tennant, "Studies of energy recovery linacs at Jefferson laboratory: 1 GeV demonstration of energy recovery at CEBAF and studies of the multibunch, multipass beam breakup instability in the 10 kW FEL upgrade driver", Ph.D. dissertation, College of William & Mary - Arts & Sciences, Williamsburg, USA, 2006.

[18] E. Pozdeyev, "Regenerative multipass beam breakup in two dimensions", *Phys. Rev. ST Accel. Beams*, vol. 8, p. 054401, 2005. doi:10.1103/PhysRevSTAB.8.054401