New Longitudinal Beam Production Methods in the CERN Proton Synchrotron Booster

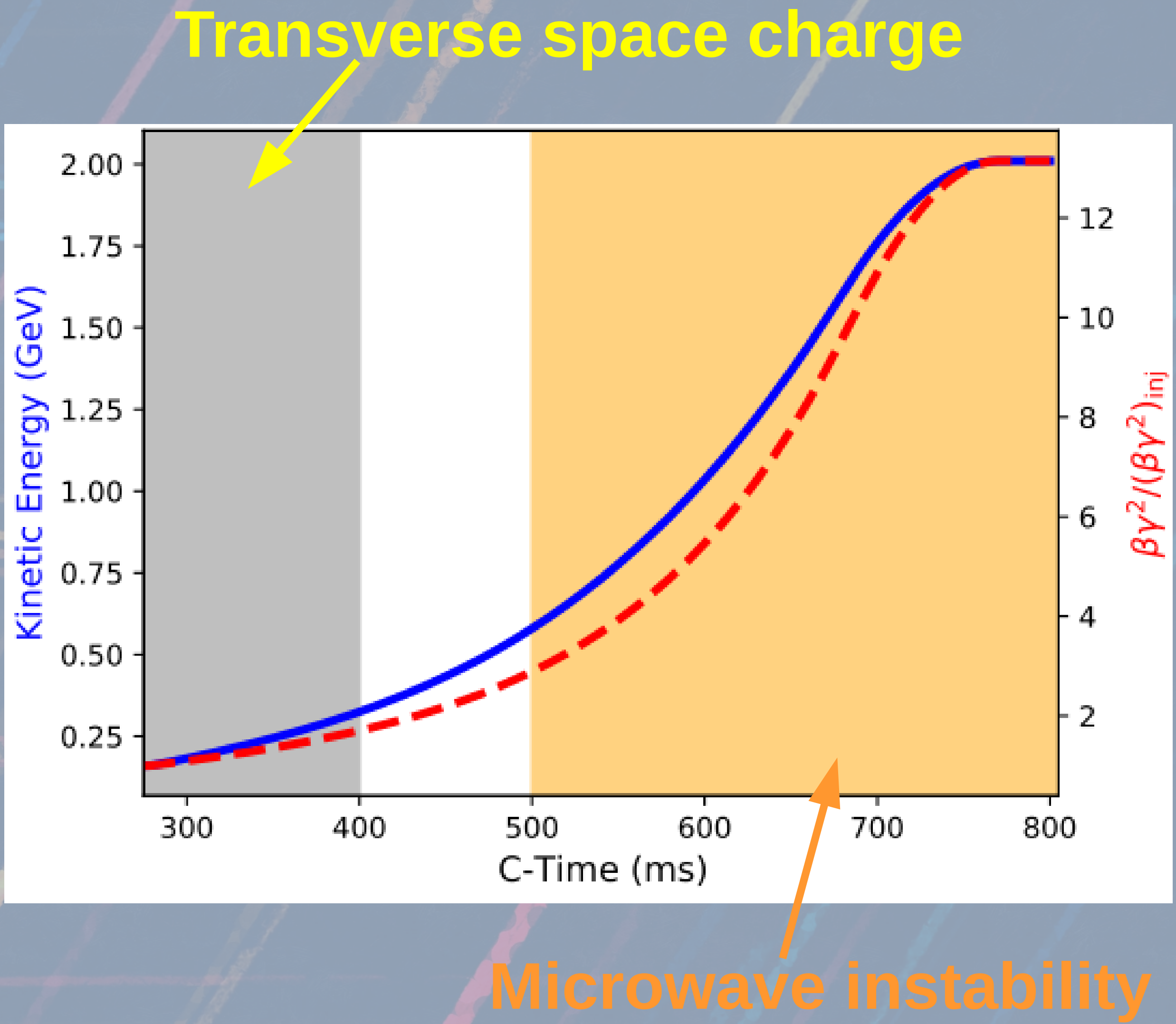
S. Albright, F. Antoniou, F. Asvesta, H. Bartosik, C. Bracco, E. Renner

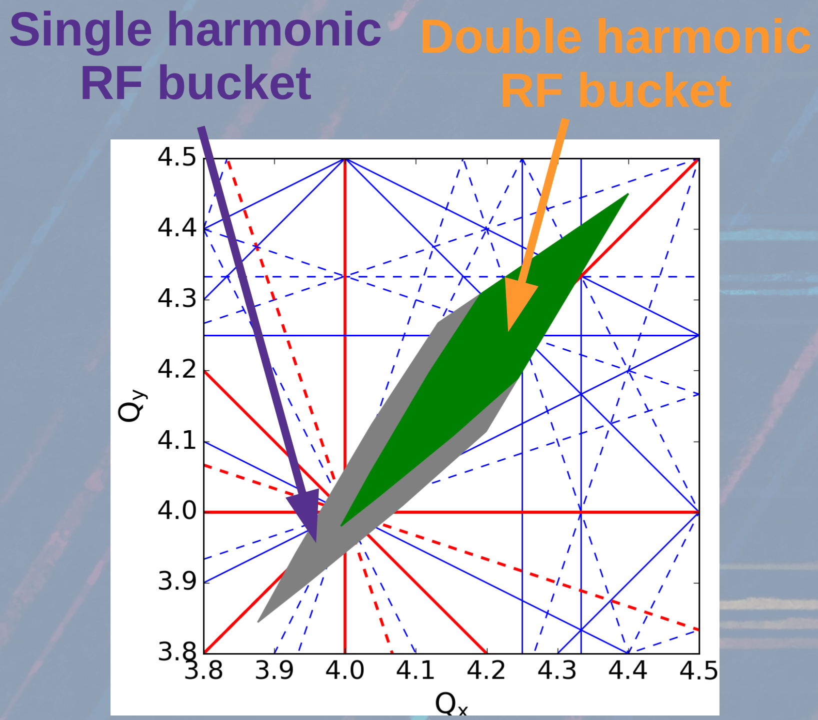
Abstract:

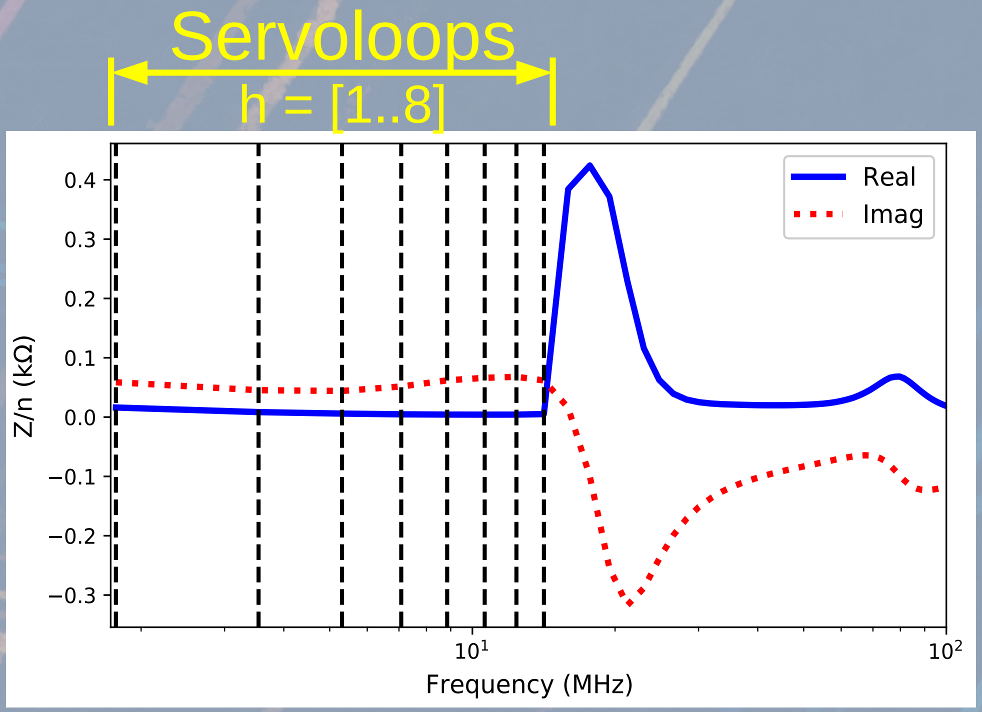
As part of the LHC Injectors Upgrade (LIU) project, significant improvements were made to the CERN Proton Synchrotron Booster (PSB) during the 2019/2020 long shutdown, including a new Finemet-based wideband RF system, renovated longitudinal beam control, and a new magnetic cycle. To meet the requirements of the diverse experimental programme, the PSB provides beams with intensities spanning three orders of magnitude and a large range of longitudinal emittances. To maximise the brightness, in particular for the LHC beams, the voltages at low energy are designed to reduce the impact of transverse space charge using a second RF harmonic in bunch lengthening mode. At high energies, the risk of longitudinal microwave instability is avoided by optimising the longitudinal distribution to raise the instability threshold. RF phase noise is applied to provide controlled longitudinal emittance blow-up and to shape the longitudinal distribution. This paper discusses the design of the RF functions used to meet the beam specifications, whilst ensuring longitudinal stability.

The LHC Injectors Upgrade project requires the brightness of LHC filling cycles from the Proton Synchrotron Booster (PSB) to be increased by a factor 2. The PSB upgrades include increased injection energy from 50 MeV to 160 MeV, increased extraction energy from 1.4 GeV to 2 GeV, and new broadband Finemet RF cavities.

To design the longitudinal beam production scheme, there are two main considerations. At the start of the cycle, transverse space charge must be minimized to avoid beam degradation. At the end of the cycle, the impedance of the Finemet cavity can provoke microwave instability, which must be avoided.







A double harmonic RF bucket with the higher harmonic in anti-phase gives bunch lengthening. Longer bunches have a lower line density, which leads to reduced tune spread. The smaller tune footprint allows some resonance lines to be avoided, reducing the risk of losses and/or emittance growth.

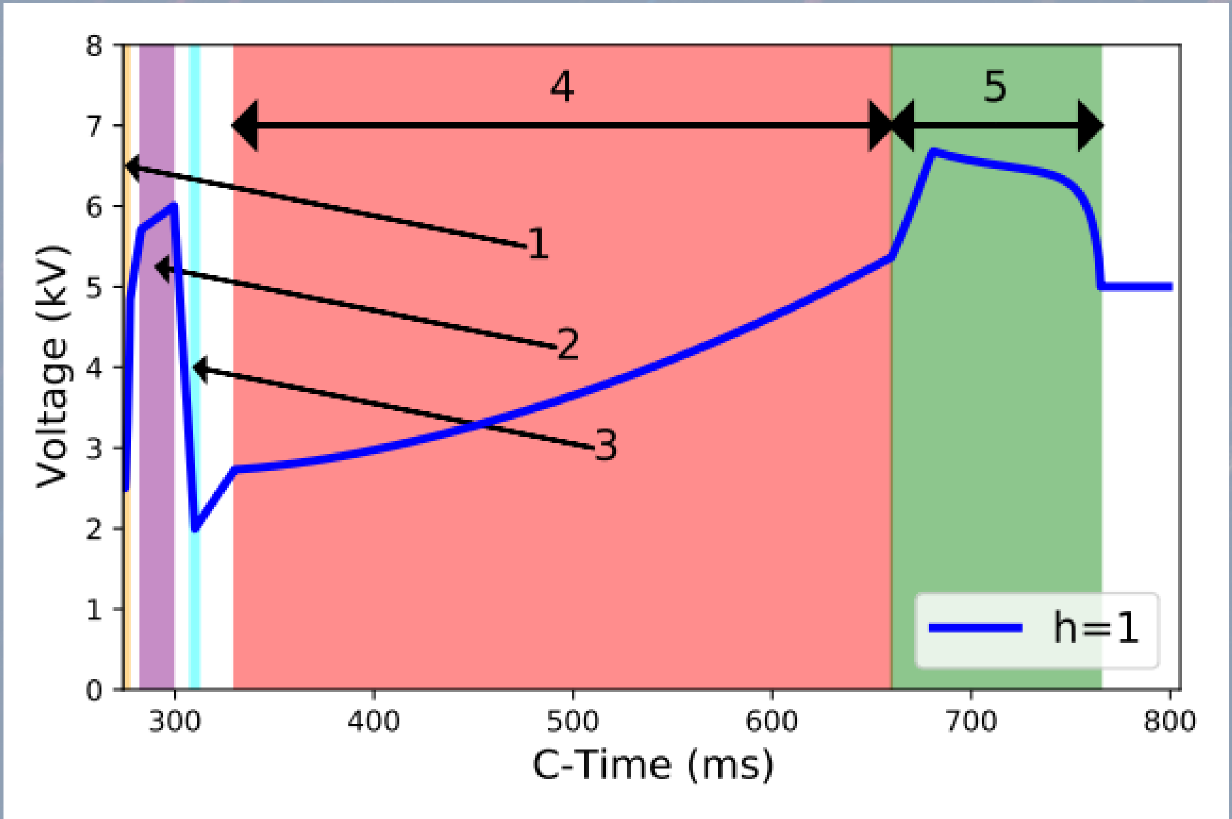
The broadband Finemet cavities very flexible operation, but also introduce a strong impedance. Servoloops operating at h=[1..8] will counteract the induced voltage, reducing the impedance seen by the beam. The 18 MHz peak can provoke microwave instability, which is best avoided by maximising the energy spread.

	LHC Single-Bunch	LHC Multi-Bunch	nTOF	SFTPRO
Bunches per ring	1	1	1	2
Protons per bunch	$5x10^{9} – 1.2x10^{11}$	$3.5x10^{12}$	$8.5x10^{12}$	$2.5x10^{12}$
Longitudinal emittance (eVs)	0.2 – 0.3	3	1.7	1.3
Longitudinal Manipulations				
Low Energy	Intensity and emittance control	Space charge reduction		
Intermediate Energy	-	Controlled longitudinal emittance blow-up		
High Energy	-	-	Bunch shortening	Longitudinal splitting

Across operational beams and those for machine studies, there is an almost limitless range of longitudinal beam parameters that can be produced. The beam types discussed here cover the main parameter space for beams to experimental facilities, and can be adapted to suit other requirements.

LHC Single-Bunch

Bunches per ring	Intensity per bunch	Longitudinal emittance
1	$5x10^{9} – 1.2x10^{11}$	0.2 – 0.3

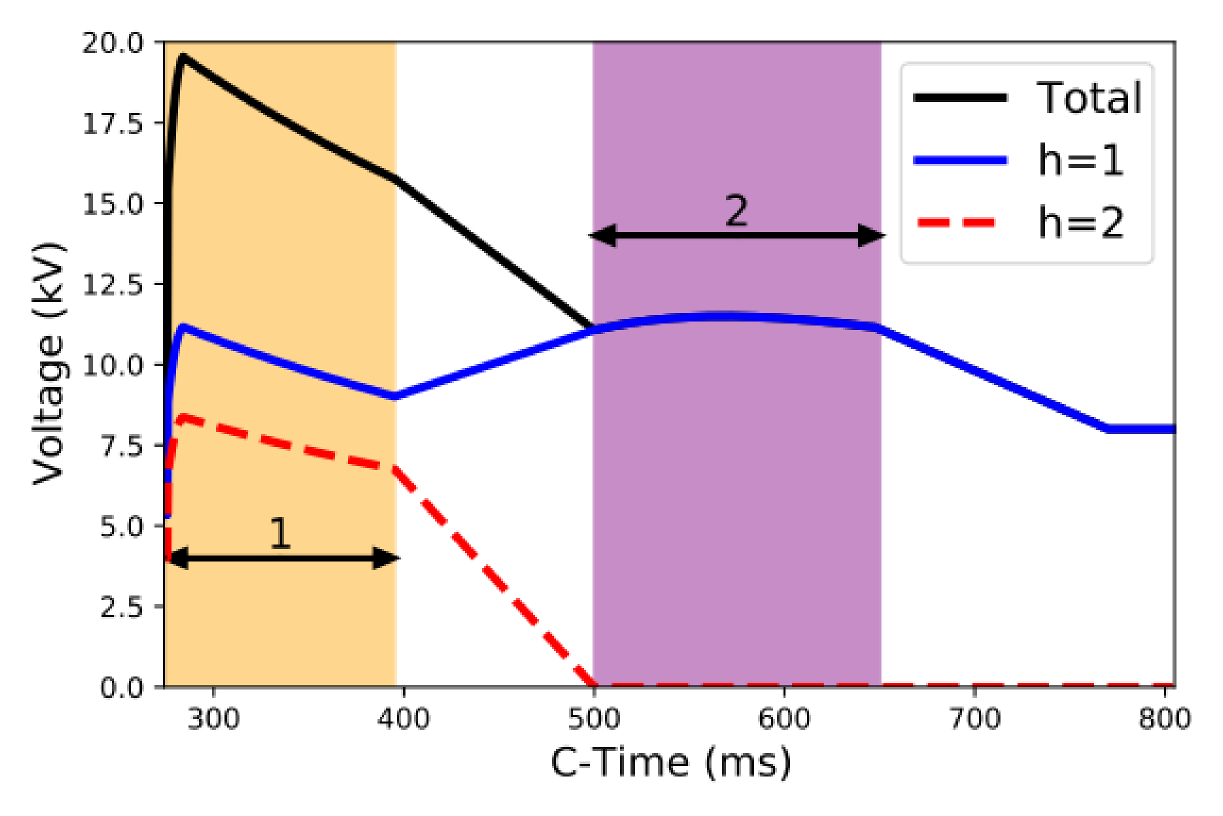


The challenge of this beam is to produce the very low intensity and longitudinal emittance in a reproducible and controlled way.

1) 2.5 kV at injection for small injected emittance, then adiabatic ramp to 5 kV for acceleration
2) Constant synchrotron frequency with longitudinal shaving for intensity control
3) Acceptance bottleneck to remove large amplitude particles and set longitudinal emitance
4) Constant acceptance to maintain Landau damping
5) Linear change in synchronous phase to prevent a dipole kick while reducing dB/dt

LHC Multi-Bunch

Bunches per ring	Intensity per bunch	Longitudinal emittance
1	$3.5x10^{12}$	3

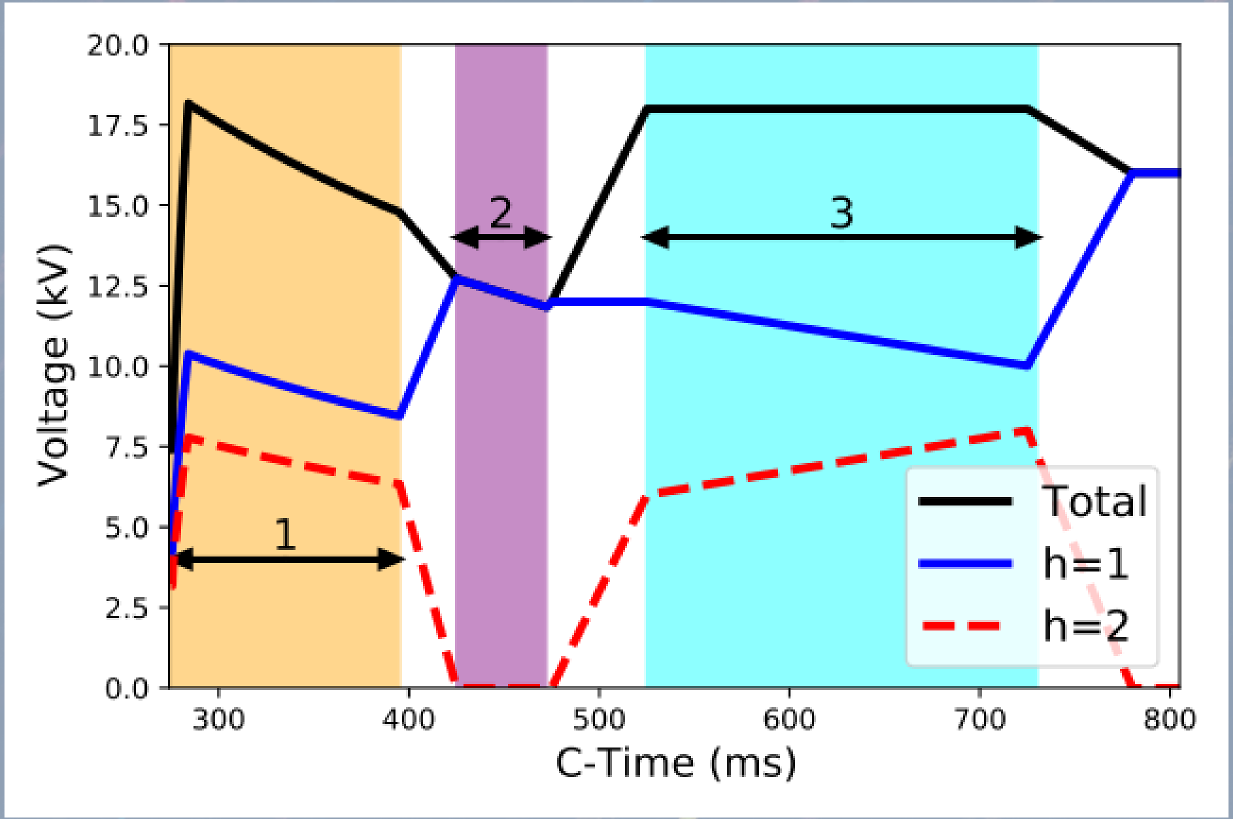


This beam requires high brightness and a large longitudinal emittance. Bunch lengthening at the start will reduce the impact of space charge, then phase noise will be applied for controlled longitudinal emittance blow-up.

1) Fixed acceptance with bunch lengthening (second harmonic in anti-phase)
2) Controlled longitudinal emittance blow-up using band limited RF phase noise

nTOF

Bunches per ring	Intensity per bunch	Longitudinal emittance
1	8.5×10^{12}	1.7

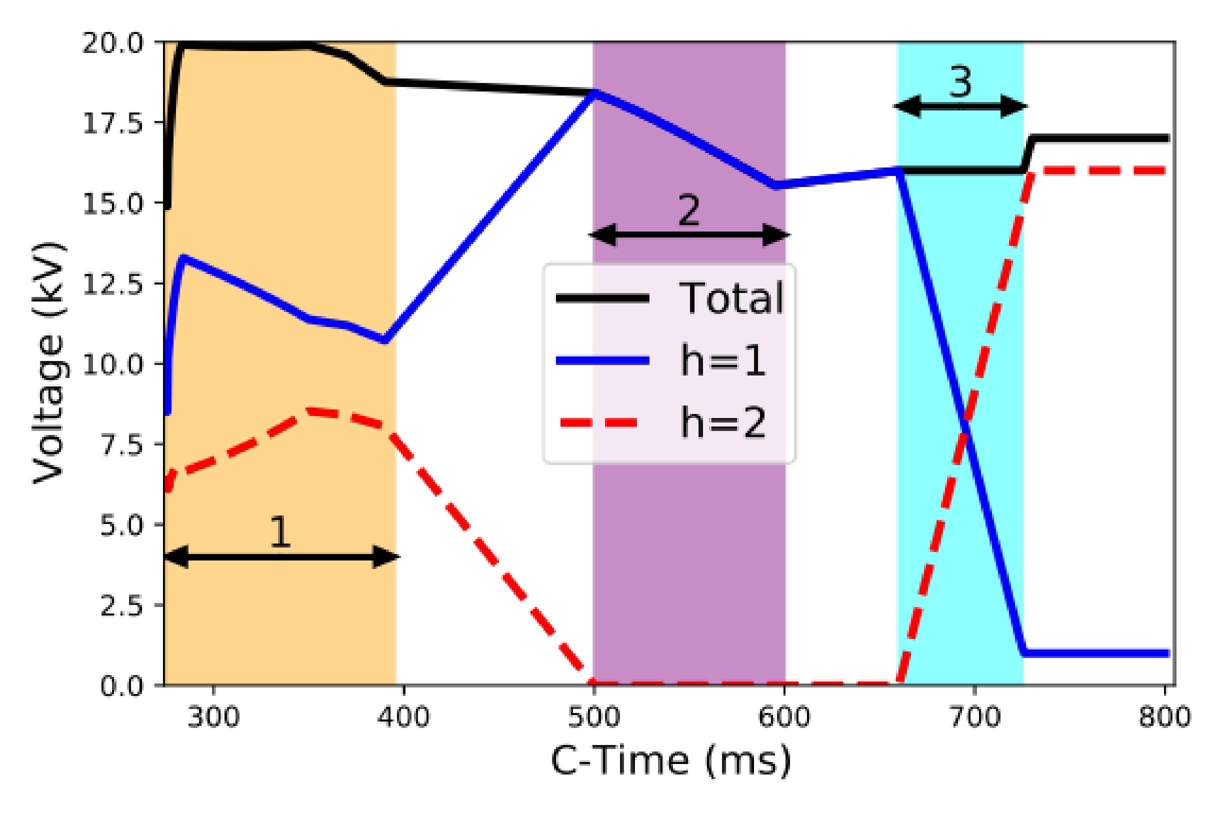


The beam for the neutron Time-Of-Flight facility (nTOF) is the highest intensity beam and the most susceptible to longitudinal instability.

1) Fixed acceptance with bunch lengthening (second harmonic in anti-phase)
2) Controlled longitudinal emittance blow-up using band limited RF phase noise
3) Bunch shortening (second harmonic in phase) to increase the energy spread and raise the microwave instability threshold

SFTPRO

Bunches per ring	Intensity per bunch	Longitudinal emittance
2	$2.5x10^{12}$	1.3



This the only cycle where two bunches are extracted. Longitudinal splitting is done as late in the cycle as possible as accelerating in h=1 is easier, but must not be too late or there may be a microwave instability.

1) Fixed acceptance with bunch lengthening (second harmonic in anti-phase), a non-constant h2:h1 ratio allows larger acceptance but increases space charge effects
2) Controlled longitudinal emittance blow-up using band limited RF phase noise
3) Longitudinal splitting

Conclusion:

After the upgrades during Long Shutdown 2, the operational capabilities and flexibility of the CERN PS Booster have been significantly increased, in part due to the new Finemet based RF systems. This paper explored the method used to design voltage functions for the main beam types required for operational users. This required considering space charge mitigation, controlled longitudinal emittance blow-up and longitudinal microwave instability. The PSB is in the process of being commissioned and the proposed functions are being tested with beam and optimised.