LHC Injectors Upgrade Workshop

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Acceleration and longitudinal emittance control in the PSB after LIU

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Controlled Longitudinal Emittance Blow-up (1/4)

- **Longitudinal emittance blow-up in PSB required for:**
  - Longitudinal stability in the PSB
  - Space charge reduction in the PS

- **Previously blow-up has been provided by single-tone modulation of a high harmonic:**
  - \[ V_{RF} = V_1 \sin(h_1 \omega_{RF} t) + V_2 \sin(h_2 \omega_{RF} t + \varphi_2) + V_3 \sin(h_3 \omega_{RF} t + \varphi_3 + \varphi_{MOD}(t)) \]
    - \( h_1 = 1, \ h_2 = 2, \ 6 \leq h_3 \leq 20 \)
    - \( \varphi_{mod} = \alpha \sin(M \omega_s t + \varphi_0) \)
  - Assuming \( V_1, V_2, \varphi_2 \) “fixed” leaves a minimum 5-dimensional parameter space \( (V_3, h_3, \varphi_3, \alpha, M) \)

- **Band limited phase noise reduces the size of parameter space and therefore complexity:**
  - \[ V_{RF} = V_1 \sin(h_1 \omega_{RF} t + \varphi_N(t)) + V_2 \sin(h_2 \omega_{RF} t + \varphi_2 + 2\varphi_N(t)) \]
  - \( h_1 = 1, \ h_2 = 2 \)
    - \( \varphi_N = f(\omega_s, \varepsilon_l, \alpha) \)
  - The only “free” parameters are target longitudinal emittance \( (\varepsilon_l) \) and noise amplitude \( (\alpha) \)
• Band limited phase noise can be used to excite particles within a well defined synchrotron frequency band

• During acceleration the synchrotron frequency reduces and the target band gets narrower

• The noise program must follow the band between small amplitude frequency and frequency at target longitudinal emittance
Controlled Longitudinal Emittance Blow-up (3/4)

- Two available methods have different advantages and disadvantages, both are expected to be used after LS2:

**Phase noise (new to PSB):**
- Directly target required emittance
- Typically faster to set up

**High harmonic (operational):**
- Fast
- Easy to follow changing synchrotron frequency

**Slow**
- Difficult to follow changing synchrotron frequency

**Requires additional harmonic**
- Typically slower to set up

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**BCMS emittance blow-up (200 ms)**

**LHCINDIV longitudinal shaving (30 ms)**
• Initial phase-noise demonstration in 2017 for thesis of D. Quartullo
  ▪ Demonstrated in MD and predicted to be effective via simulations for after LS2

• Successful reliability run in 2018 in main beam parameter spaces:
  ▪ **BCMS:** Low intensity (0.85E12) $h_1 = 8$ kV, $h_2 = 0$ kV
  ▪ **LHC25:** Moderate intensity (1.6E12) $h_1 = 8$ kV, $h_2 = 6$ kV, anti-phase
  ▪ **MTE:** High intensity (5.0E12) $h_1 = h_2 = 8$ kV, anti-phase (split before extraction)
Longitudinal Stability Threshold (1/3)

- Major changes that could impact beam stability:
  1. New injection and extraction energy (160 MeV and 2 GeV)
  2. Replacement of ferrite cavities (C02, C04, C16) with Finemet® cavities

- Comparison of cavity impedance before and after LS2 (C16 at h=8)
  - Moved from tuned resonant cavities (ferrite) to un-tuned broadband cavities (Finemet®)
  - Finemet® impedance reduced at specified harmonics by servo loops counteracting induced voltage

- Finemet® cavities will allow much greater flexibility, increase in the total voltage (20 kV total instead of 8 kV at h = 1 and 8 kV at h = 2), and have the benefit of being modular
**Longitudinal Stability Threshold (2/3)**

- **Longitudinal impedance sources after LS2:**
  - Finemet® (broad band, maximum 4.4 kΩ), independent of β
  - Extraction kicker (narrow band, maximum 2 kΩ at f < 100 MHz), varies with β
  - Space charge (Z/n = 603 Ω at 160 MeV), varies with β
  - Other impedances |Z| < 100 Ω in frequency range of interest, most independent β

- **Finemet® LLRF servo loops control beam loading – effective impedance reduction**
  - Simulations to date used servo loops on h=1..8, target is h=1..16 (to be validated)
  - Frequency domain model of servo loops used in simulation
  - with servo loops at h=1..8 the stability threshold is determined by the 18 MHz peak (microwave instability)
• All required beams expected to be stable from current simulations, e.g.:
  ▪ TOF, 1.8eVs, 800x10^{10} PPR
  ▪ LHC25 (post-LS2), 2.8eVs, 280x10^{10} PPR
  ▪ LHC25 (pre-LS2), 1.4eVs, 160x10^{10} PPR

• Additional stability margin is expected:
  1. Servo loops on more Finemet® harmonics
  2. Careful design of RF program (e.g. h = 2 in bunch shortening to increase $\frac{\Delta p}{p}$)
Possibilities for ramp duration reduction (1/3)

- Baseline ramp duration is 530 ms with extraction at C805, earlier extraction of interest for the PS with LHC type beams

- Requirements and limitations:
  EDMS PSB-OP-ES-0001

- Comfortably within POPS-B limits for:
  - $V$ – Max allowed = 3 kV
    - Reached briefly at max $dB/dt$
  - $dV/dt$ – Max allowed = 1 kV/ms
    - Max during ramp: ~0.13 kV/ms
  - $dI/dt$ – Max allowed = 28 A/ms
    - Max during ramp 18 A/ms

- No problems for magnets and POPS-B to increase ramp rate
Possibilities for ramp duration reduction (2/3)

- Available current and voltage from Finemet® amplifiers (includes programmed voltage and beam loading compensation):
  - Numerical calculation of small high intensity beam (1 eVs, 800x10^{10}) and 12 kV at h = 1 the maximum amplifier current is \(~28\) A (max allowed = 30A)
  - Longitudinal acceptance at 12 kV increasing through ramp
- For low intensity beams (LHC25, BCMS) the RF systems are expected to be able to accommodate a faster ramp
Possibilities for ramp duration reduction (3/3)

- Low intensity beams (LHC25, BCMS) comfortably below simulated instability threshold

- Maximum acceptable ramp rate not currently known, requirements:
  - Maintain longitudinal stability – shorter bunches will sample higher frequencies more strongly
  - Maintain adiabaticity – $\frac{d^2B}{dt^2}$ may start to matter
  - Enough time for controlled emittance blow-up

- Possible subject of studies during LS2
Experience with Finemet® (1/2)

- Working with present prototype system since 2015 with reliability runs and extensive MD program each year
- Nominal LHC beams, and high intensity beams for other users produced with Finemet® system replacing:
  - $h = 1$ (600 kHz - 1.75 MHz)
  - $h = 2$ (1.2 - 3.5 MHz)
  - high harmonic longitudinal blow-up cavity (6 - 16 MHz)
- The Finemet® system also used as multiple harmonic system providing 3.5 kV on $h = 1$ and $h = 2$ simultaneously
- Finemet® used for record accelerated intensity (1.1E13) and record split intensity (1.05E13)
- For the 2017 & 2018 reliability runs, there were no issues to report, with ~99% availability of the system
- Nominal beam parameters were achieved when using the Finemet® system for operational beams
Experience with Finemet® (2/2)

- Validated PSB Rings Injection synchronisation
- Deployed and validated interface with WR Btrain.
  - Successful and valuable reliability run from 19\textsuperscript{th} April 2018 for validation and debugging
- LLRF Ring 0 upgraded (Sept 2018) and operated with post-LS2 h/w configuration (5 boards)
- Deployed (2018) in LLRF lab a test system that implements servo loops at 16 harmonics
- First half 2019: Validate closure of servo loops on 16 harmonics for voltage/phase control or beam loading compensation
  - Required input for beam dynamics simulations to investigate increase of instability threshold
- Operational harmonics controlled: h = 1, 2, 3, x (x = high h for blow-up)
- Longitudinal emittance blow-up: same methods as before LS2 (high harmonic, phase noise)
Conclusion and outlook:

- **Controlled longitudinal emittance blow-up with two methods**
  - Two methods available, single tone modulation of high harmonic and band limited phase noise
    - High harmonic: Acts quickly – will be used for longitudinal shaving
    - Phase noise: Easier to control – will be used for longitudinal emittance blow-up

- **Simulations of longitudinal stability after LS2 included servo loops on Finemet® h=1..8**
  - All required beams within stable region
  - Final stability margin expected to be higher than current prediction
    - Final number of servo loops to be confirmed in lab tests this year, further studies will take place over LS2
    - Microwave instability threshold can be raised by more careful design of RF program e.g. to increase $\frac{\Delta p}{p}$

- **Faster ramp to allow shorter PS flat bottom appears possible**
  - Margin exists for all hardware with low intensity (LHC25, BCMS, …) beams
  - Minimum duration not yet known, possible area of study over LS2

- **Experience with the Finemet® test cavity has been very positive**
  - Intensity records for acceleration ($1.1\times 10^{13}$) and splitting ($1.05\times 10^{13}$)
  - Demonstrated as $h = 1$, $h = 2$, $h = 1 + 2$, and high harmonic for longitudinal blow-up and shaving
  - LLRF will allow voltage and phase control at $h = 1$, $2$, $3$, $x$ ($x = \text{PPM variable high harmonic}$)
Questions to be answered:

1. How does the experience with the longitudinal emittance blow up by phase noise compare to particle tracking? What are the limitations of this blow-up technique? Can we completely retire the blow-up using modulated higher-harmonic RF?

2. Limitations and margins with new 2 GeV cycle (duration from injection to extraction)?

3. What are the expected longitudinal stability limitations due to the new Finemet® RF system with LLRF feedback?

4. How far are we with commissioning of Finemet® RF system and relative LLRF (with specs for future operation – which harmonics, what functions for blow up)?
Questions answered:

- How does the experience with the longitudinal emittance blow up by phase noise compare to particle tracking?
  - Both simulations and MDs during run 2 showed good results with phase noise in the PSB

- What are the limitations of this blow-up technique?
  - Primary limitations are speed and difficulty of following synchrotron frequency, neither is a showstopper but may have implications for a faster ramp

- Can we completely retire the blow-up using modulated higher-harmonic RF?
  - No, required for longitudinal shaving (LHCINDIV) and beneficial if fast blow-up is required

- Limitations and margins with new 2 GeV cycle (duration from injection to extraction)?
  - No hard limits at the moment, significant work will be required to find fastest acceptable ramp for LHC type beams

- What are the expected longitudinal stability limitations due to the new Finemet® RF system with LLRF feedback?
  - Impedance peak at 18 MHz will limit stability if fewer servo loops than expected can be operated. If all $h = 1..16$ servo loops are available the limitation is not yet known

- How far are we with commissioning of Finemet® RF system and relative LLRF (with specs for future operation – which harmonics, what functions for blow up)?
  - HLRF progressing on schedule, LLRF and beam experience during run 2 puts us in a good position for putting the new systems into operation, $h = 1, 2, 3, X$ will be available for control in voltage and phase with blow-up via phase noise or high harmonic
Controlled Longitudinal Emittance Blow-up (2/4)

- Synchrotron frequency and spread change relatively quickly in the PSB and the ramp is short
- Due to the short, fast ramp there was some skepticism about applicability of phase noise in the PSB
- Comparison of PSB with LHC ramp:
  - Adiabaticity \( \left[ \frac{1}{\omega^2} \frac{d\omega}{dt} \right] \) => Synchrotron frequency changes faster requiring faster change of noise band
  - Smaller number of synchrotron periods => Less time available for blow-up