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LHC Injectors Upgrade

LHC Injectors Upgrade Workshop

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Acceleration and longitudinal emittance control in the PSB after LIU

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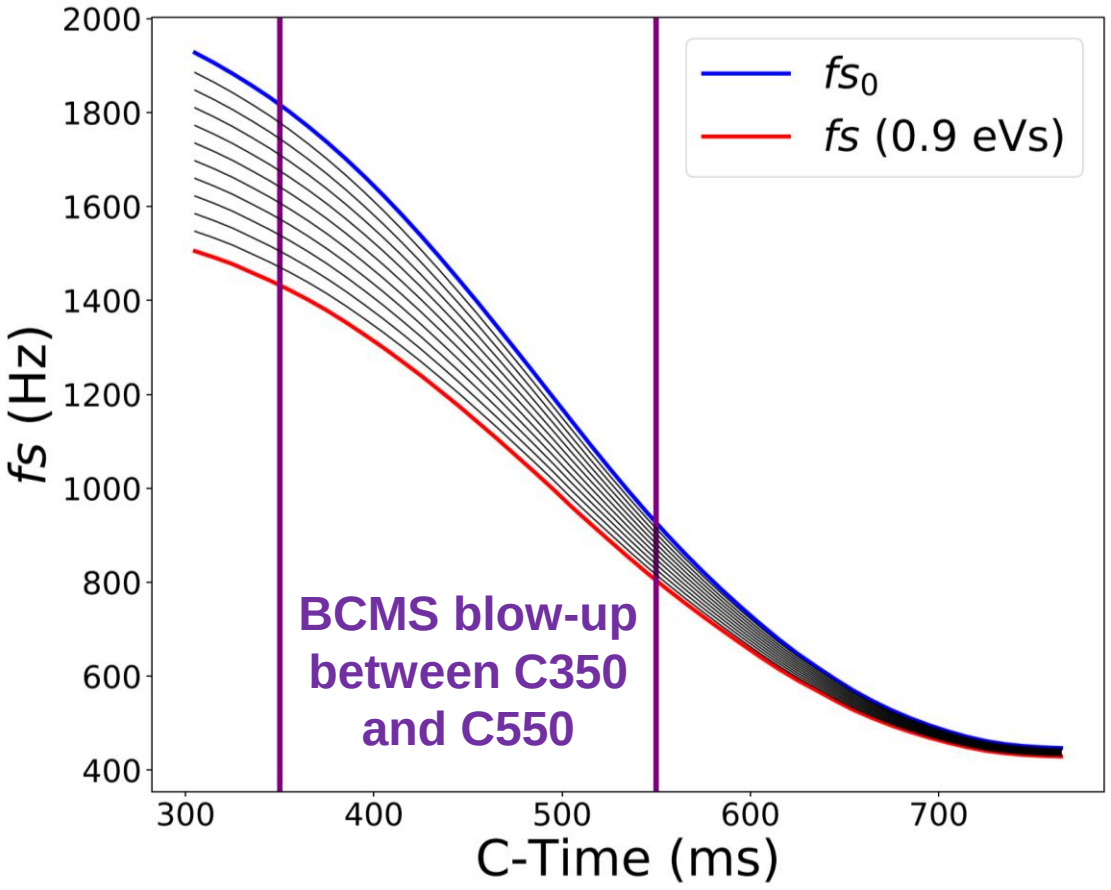
Controlled Longitudinal Emittance Blow-up (1/4)

- **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:**
  - $V_{RF} = V_1 sin(h_1 \omega_{RF} t) + V_2 sin(h_2 \omega_{RF} t + \varphi_2) + V_3 sin(h_3 \omega_{RF} t + \varphi_3 + \varphi_{MOD}(t))$
    - $h_1 = 1,\ h_2 = 2,\ 6 \leq h_3 \leq 20$
    - $\varphi_{mod} = \alpha\, sin(M \omega_{s,0} t + \varphi_0)$
  - Assuming V_1, V_2, φ_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 (ε_l) and noise amplitude (α)

Controlled Longitudinal Emittance Blow-up (2/4)

- **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**



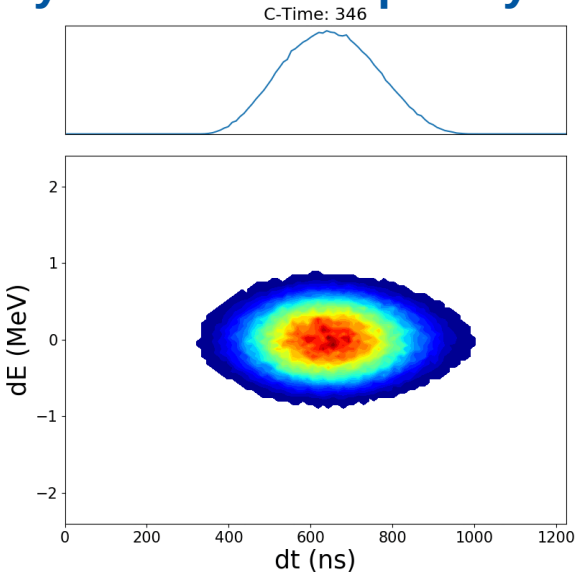
Controlled Longitudinal Emittance Blow-up (3/4)

- **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

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

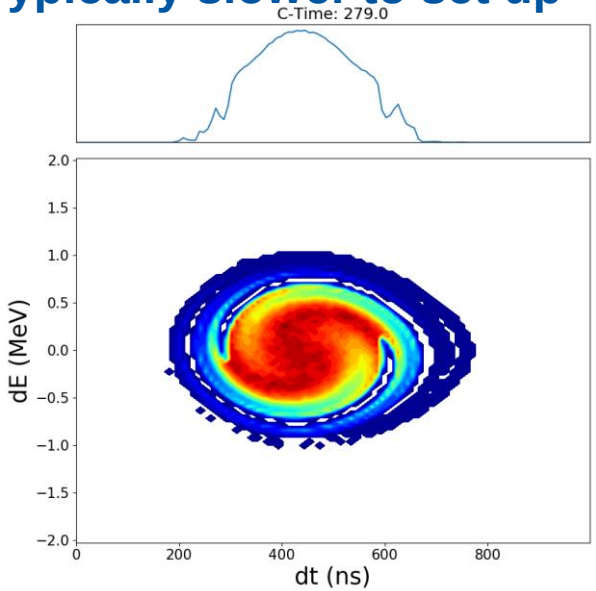


BCMS emittance blow-up (200 ms)

High harmonic (operational):

+ **Fast**
  Easy to follow changing synchrotron frequency

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

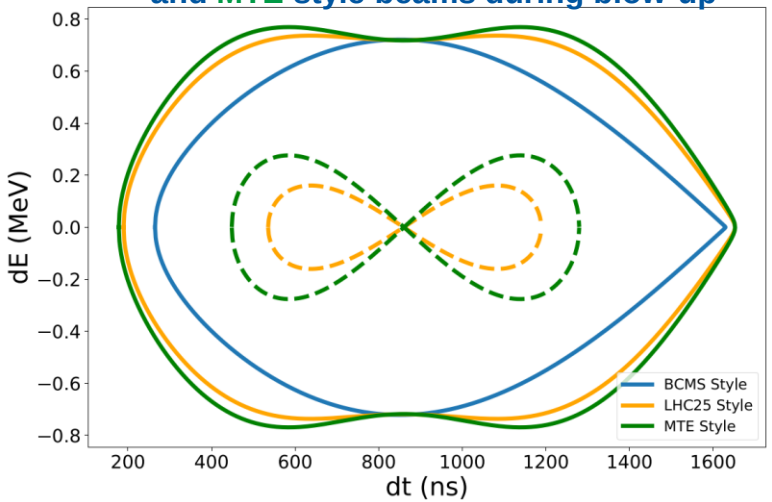


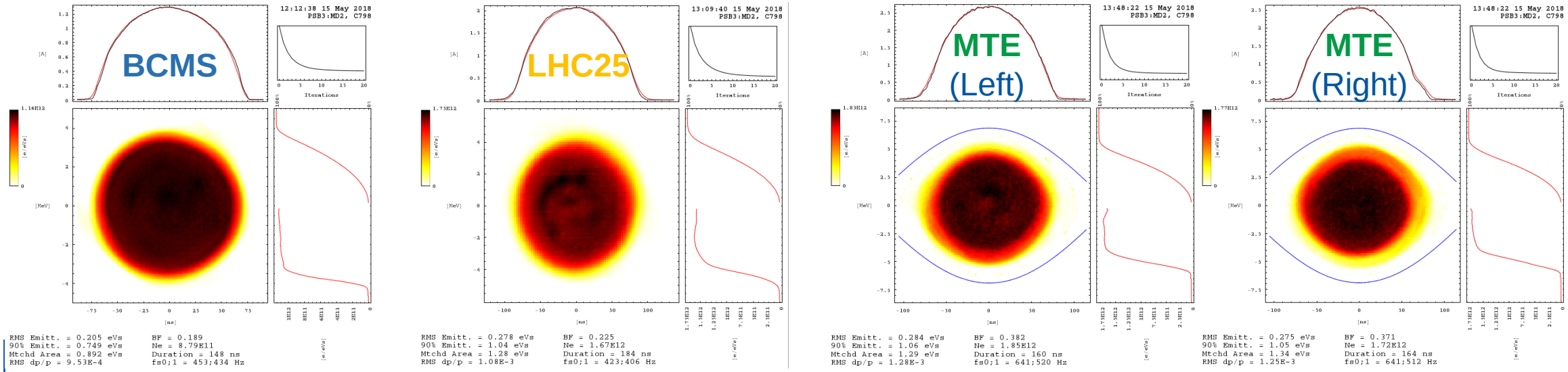
LHCINDIV longitudinal shaving (30 ms)

Controlled Longitudinal Emittance Blow-up (4/4)

- **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) h1 = 8 kV, h2 = 0 kV
  - **LHC25:** Moderate intensity (1.6E12) h1 = 8 kV, h2 = 6 kV, anti-phase
  - **MTE:** High intensity (5.0E12) h1 = h2 = 8 kV, anti-phase (split before extraction)

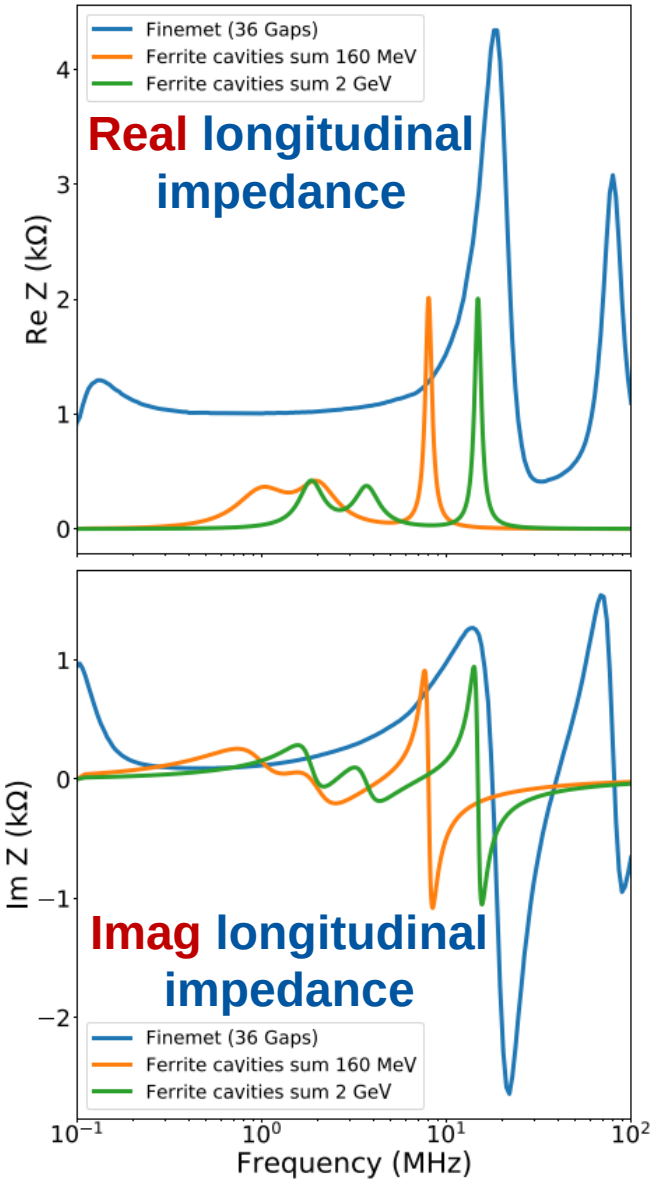
Separatrix variants for BCMS, LHC25, and MTE style beams during blow-up





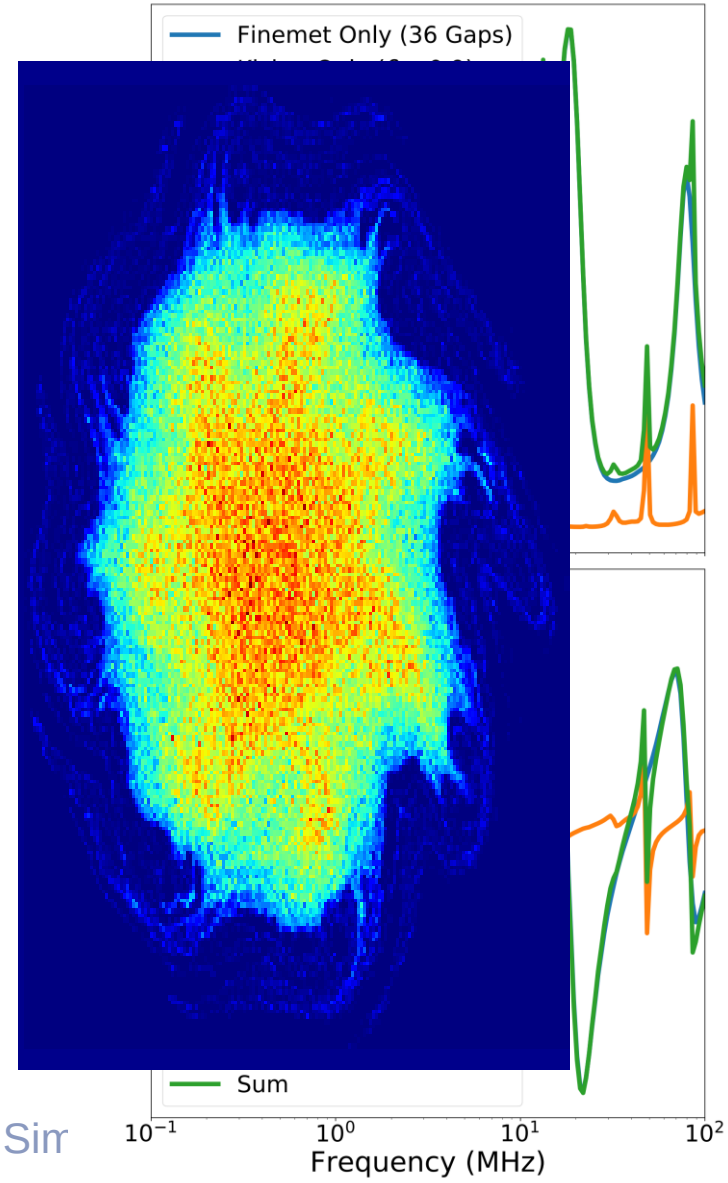
Longitudinal Stability Threshold (1/3)

- **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**



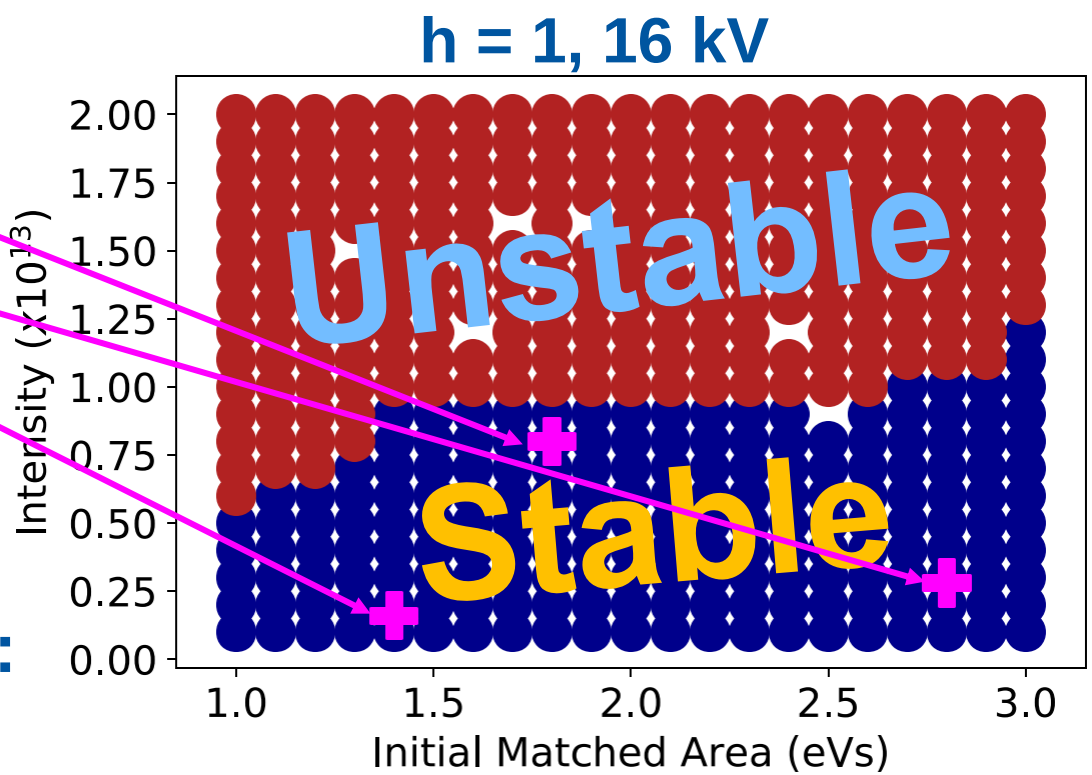
Longitudinal Stability Threshold (2/3)

- **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)



Longitudinal Stability Threshold (3/3)

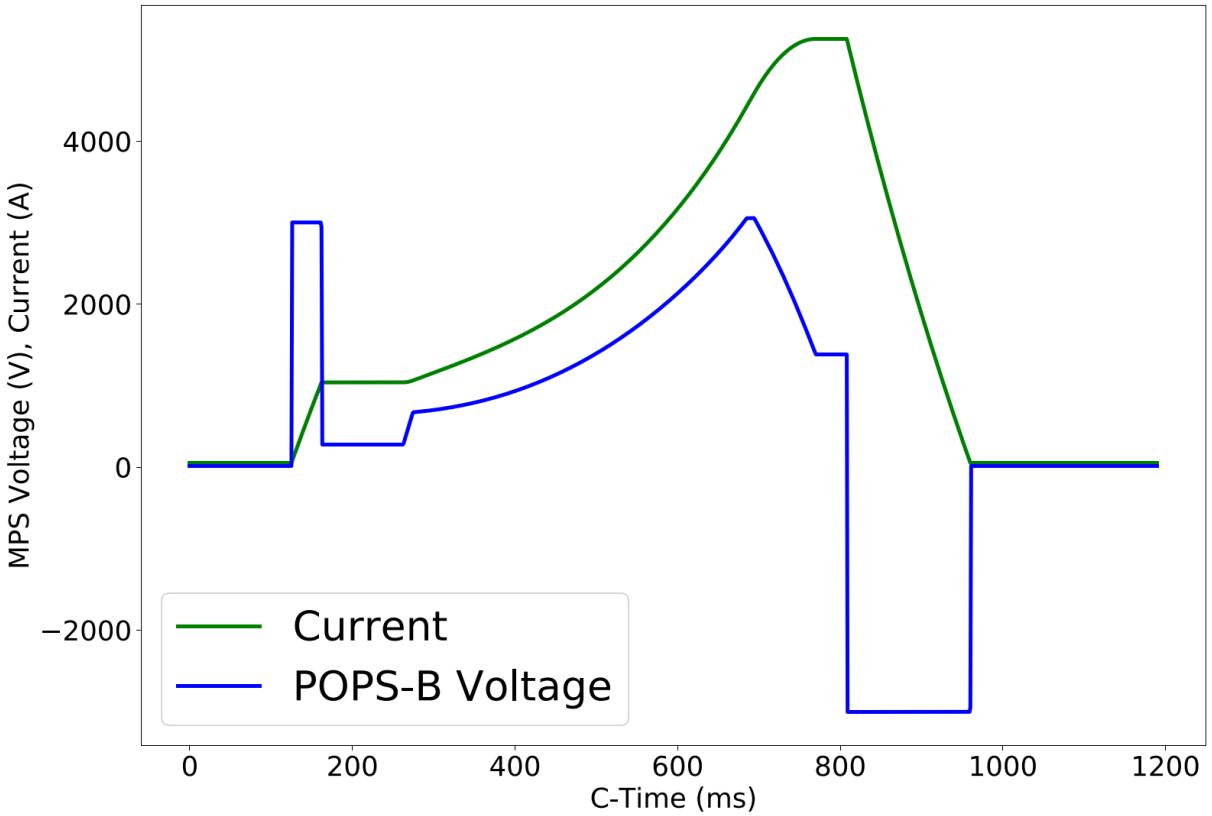
- **All required beams expected to be stable from current simulations, e.g.:**
  - TOF, 1.8eVs, 800x10^{10} PPR
  - LHC25 (post-LS2), 2.8eVs, 280x10^{10} PPR
  - LHC25 (pre-LS2), 1.4eVs, 160x10^{10} PPR



- **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 $\frac{\Delta p}{p}$)

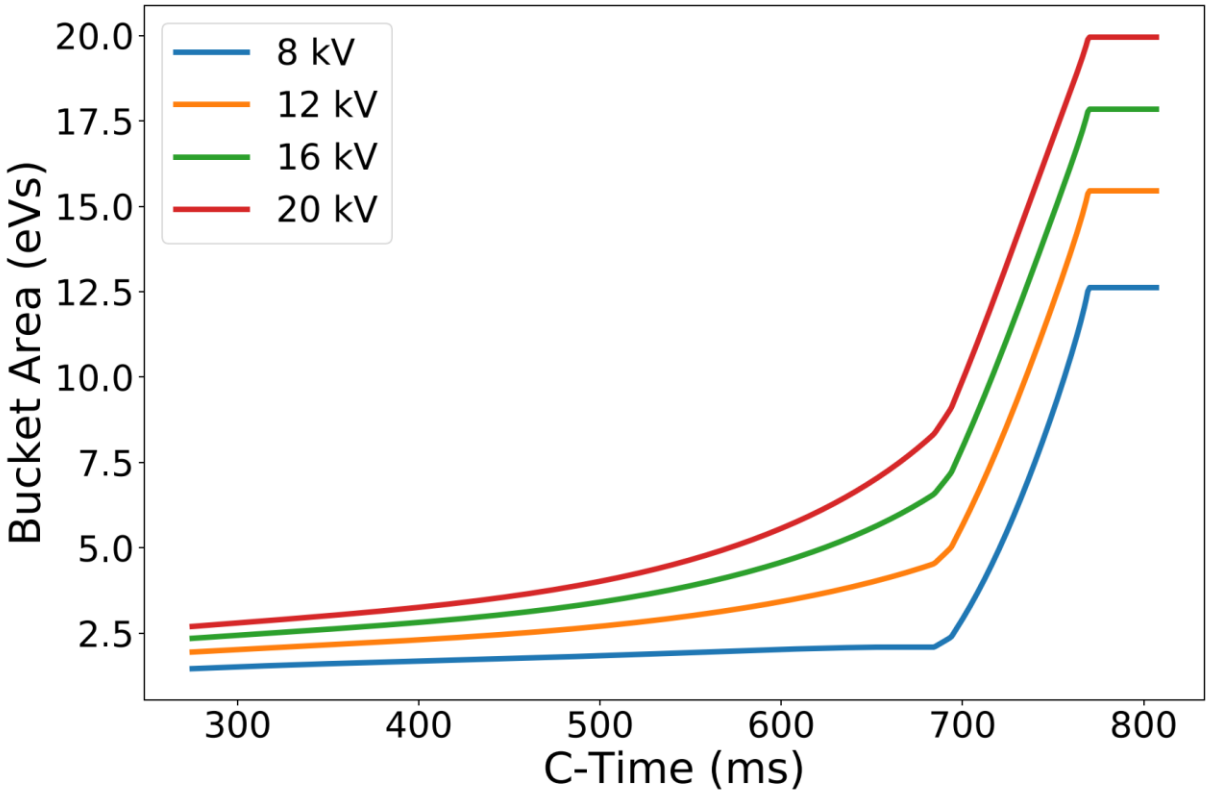
Possibilities for ramp duration reduction (1/3)

- **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**



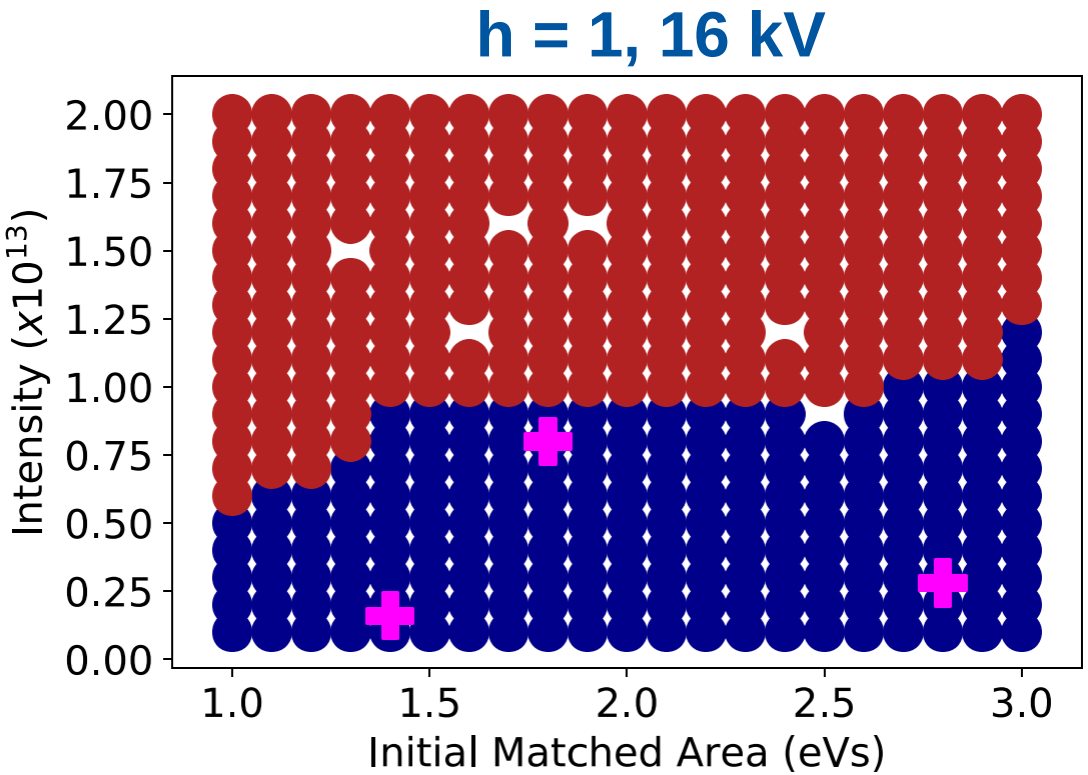
Possibilities for ramp duration reduction (2/3)

- **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**



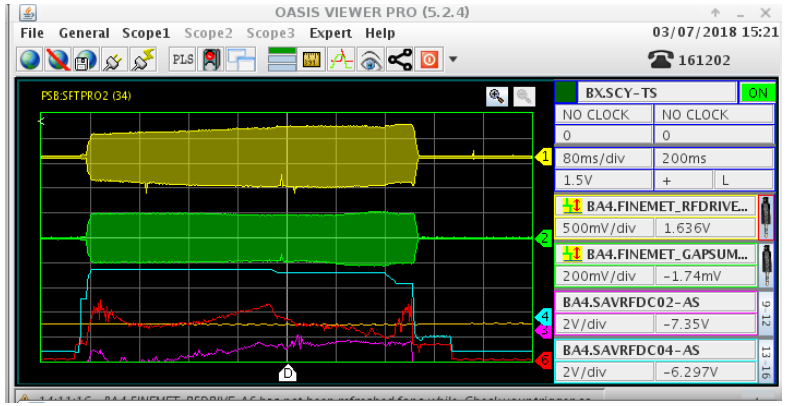
Possibilities for ramp duration reduction (3/3)

- **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**

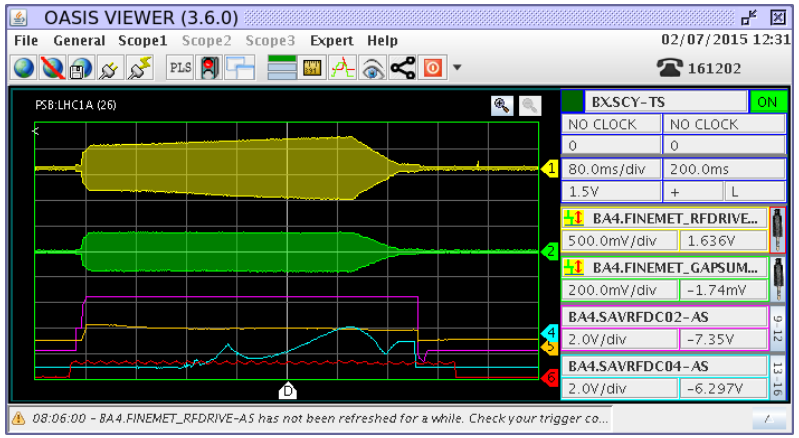


Experience with Finemet® (1/2)

- **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**



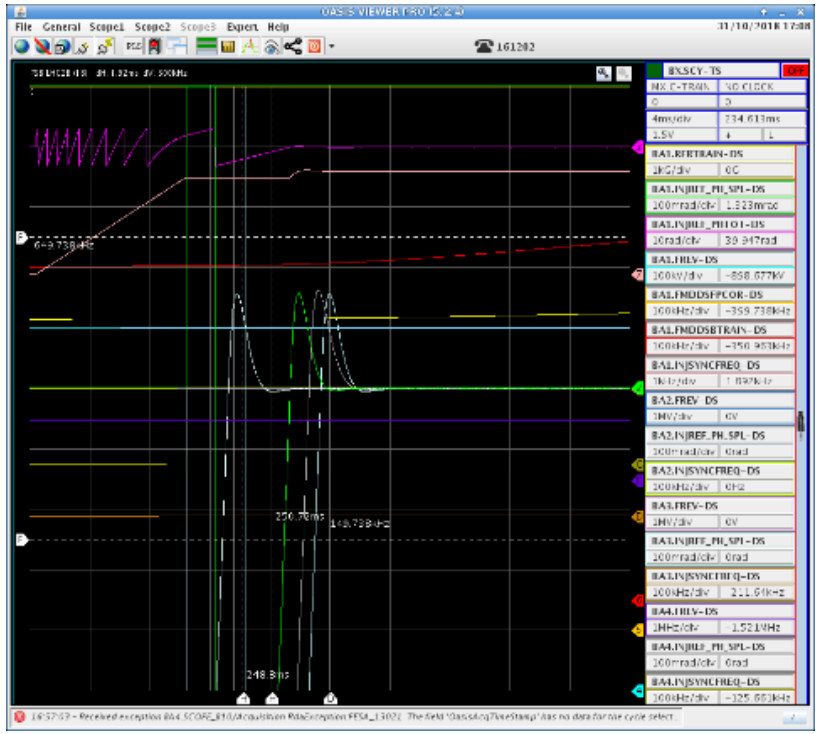
Finemet® system used as 1st harmonic for high intensity ISOLDE type beam



Finemet® system used as 2nd harmonic for LHC25 beam

Experience with Finemet® (2/2)

- **Validated PSB Rings Injection synchronisation**
- **Deployed and validated interface with WR Btrain.**
  - Successful and valuable reliability run from 19th 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 (1.1E13) and splitting (1.05E13)
  - 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 = PPM variable high harmonic)

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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 $\left(\left|\frac{1}{\omega^2}\frac{d\omega}{dt}\right|\right)$ => Synchrotron frequency changes faster requiring faster change of noise band
  - Smaller number of synchrotron periods => Less time available for blow-up