CERN

Joint Accelerator Performance Workshop 2022

Slow extraction improvements

Pablo Arrutia

Many thanks to the SPS & PS Operations Teams, all equipment groups, the NA62 experiment and everyone who helped me with this talk:
SY-ABT: M.A. Fraser, F.M. Velotti ,NA62: R. Piandani, J. Engelfried, R. Fiorenza, C. Lazzeroni, M. Piccini, SY-RF: G. Papotti, A. Spierer, SY-BI: E. Calvo, M. Gonzalez Berges, S. Mazzoni, F. Roncarolo, SPS-OP: V. Kain, SY-STI: L. Esposito et al

Intro

Slow extraction improvements and R&D in 2022 aimed at addressing IEF WS 2021 feedback (and more):

- ‘Review **fast spill monitoring** across complex’
- ‘Add planned periods to **work with Experiments** on spill structure in SPS - MDs or commissioning time’
- ‘**Improve spill structure and monitoring in PS and SPS**’: ‘Spill structure (spike, harmonics) and monitoring “flatness of spill and duty cycle as important as intensity”’

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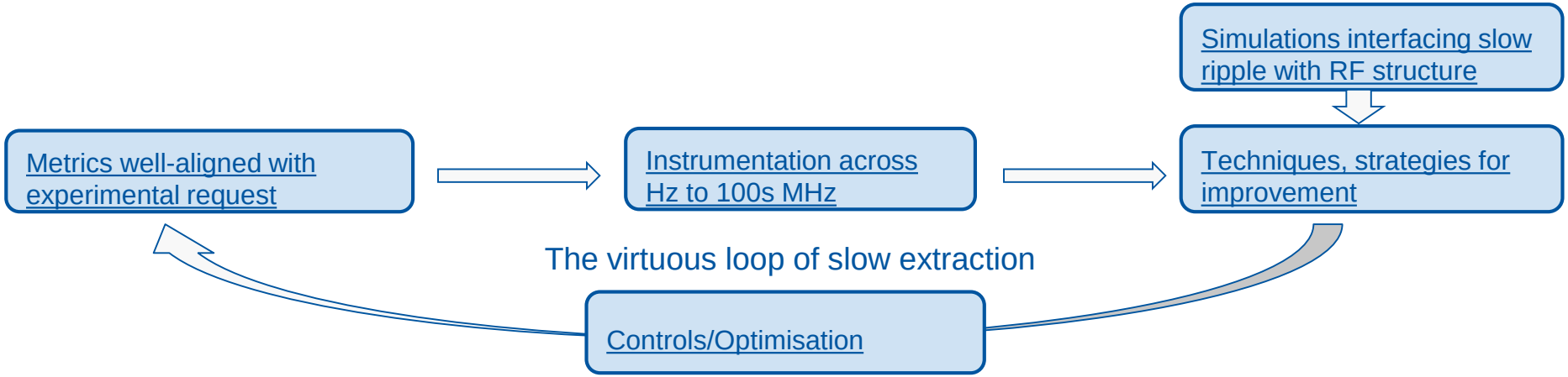
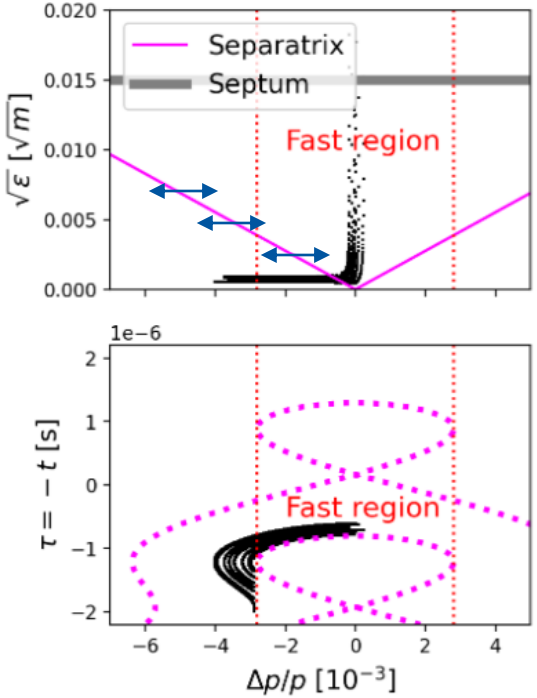


Outline

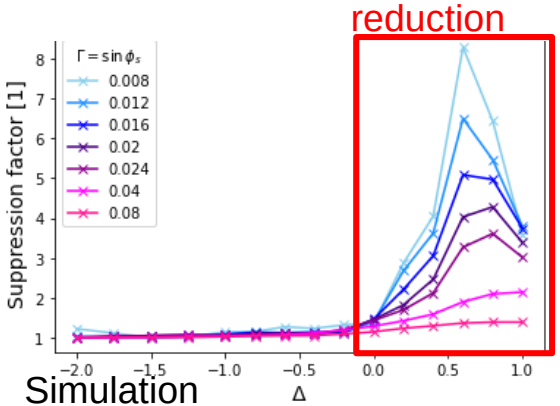
- Empty bucket channelling (EBC)
- Non-local crystal shadowing
- Other topics

Empty Bucket Channelling (EBC)

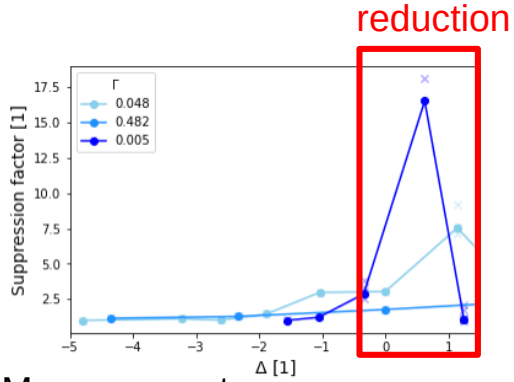
Concept, simulation, MDs



- RF cavities turned on during extraction, with a frequency offset from beam.
- Particles channel between empty buckets -> coherent kicks.
- EBC **improves spill quality across entire low-frequency spectrum.**
- Ripple suppression region identified during July MDs -> Move towards operational tests.



Simulation

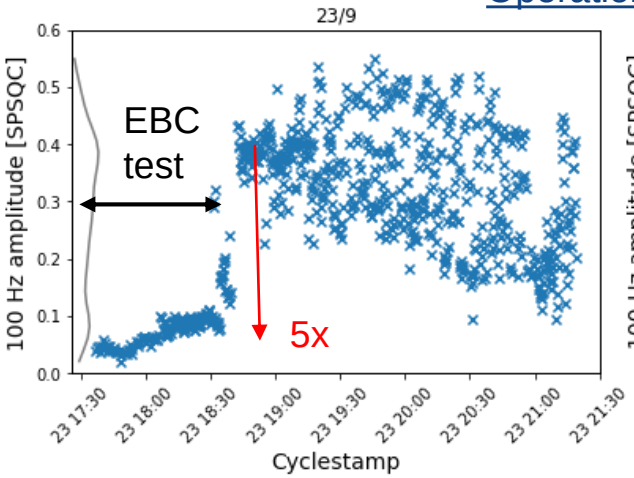


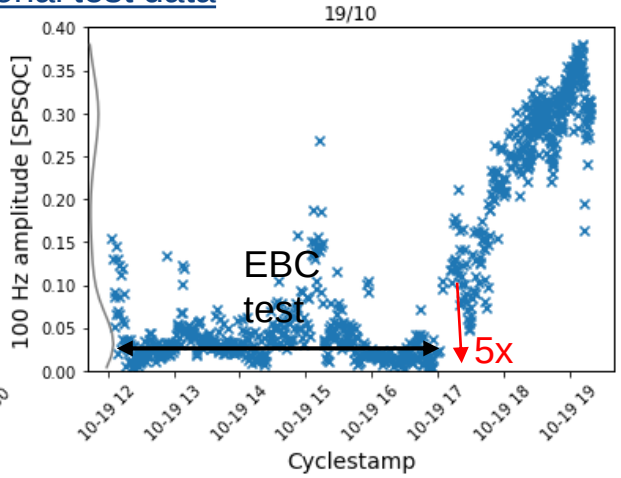
Measurement

Spill quality improvements

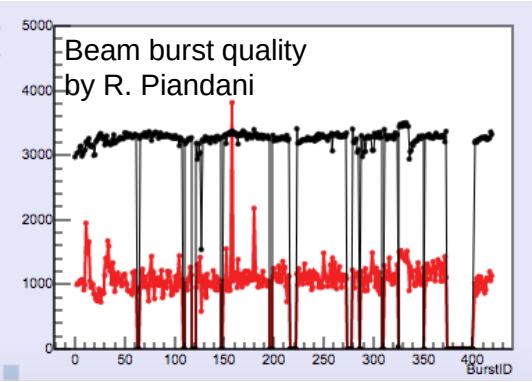
- **Ripple reduction by 5x**, without auto-triggering the feed-forward optimiser. Confirmed by experiments:

Operational test data





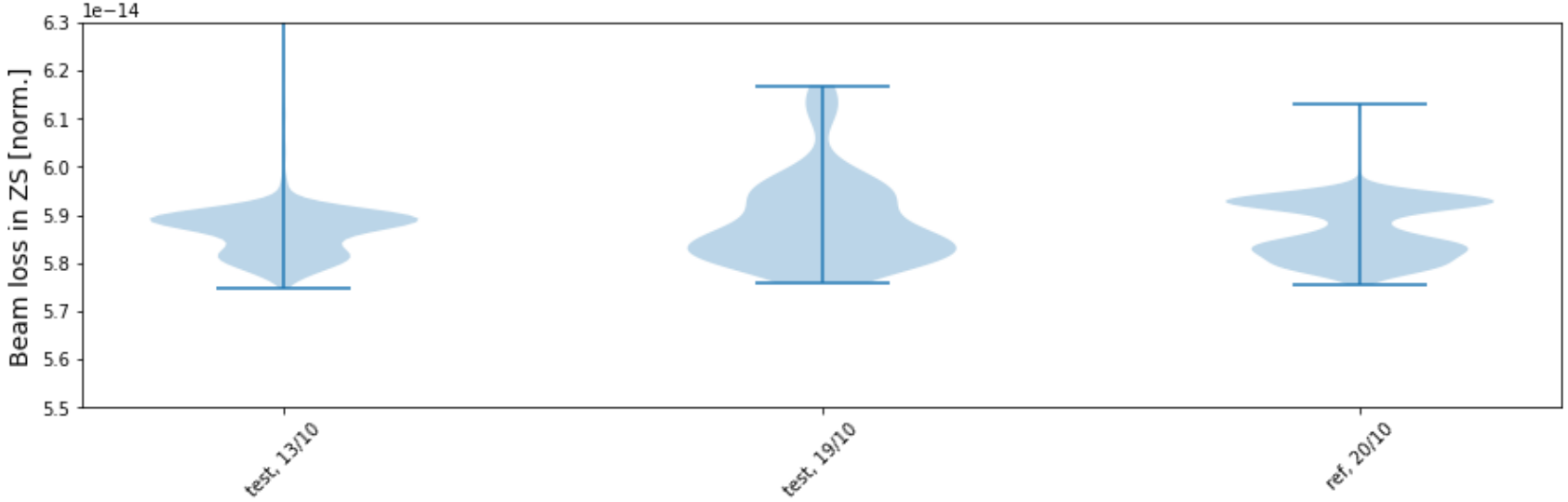
NA62 data



Typically at 1300/1500,
at ~1000 with EBC

Beam loss

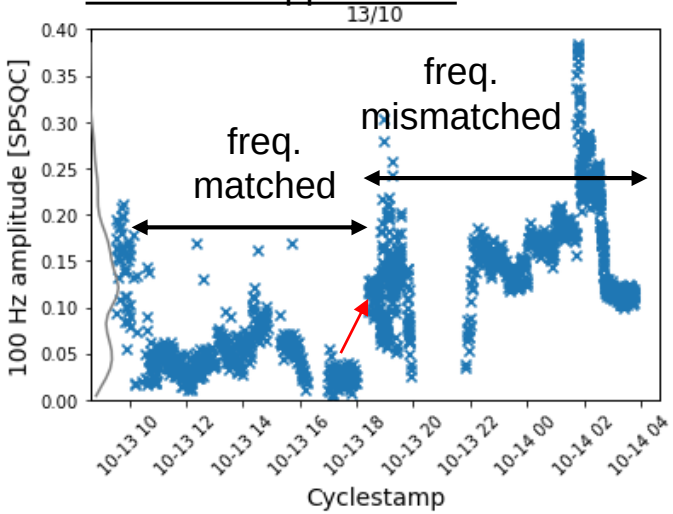
- **Beam losses can be kept under control.**
- **Manipulation is compatible with crystal shadowing** as long as RF voltage kept modest. Otherwise, increase angular spread -> decreased efficiency.



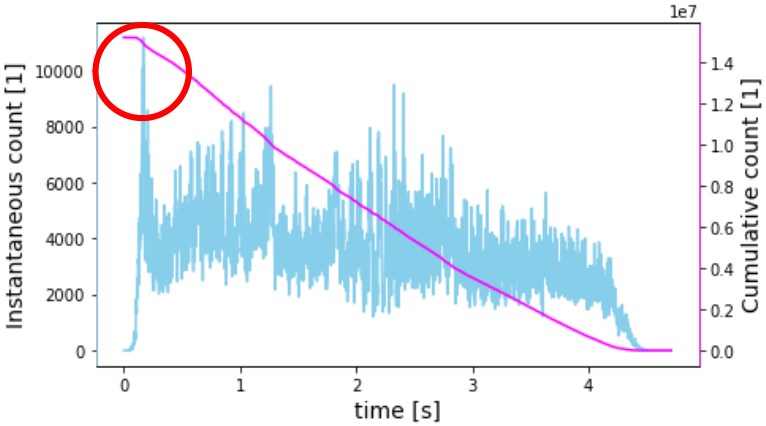
SPS machine stability

- Variations in super-cycle (hysteresis) can mismatch the revolution frequency of the beam with respect to the optimum EBC frequency.
- **Re-alignment strategies being studied**, similar approaches to crystal shadowing.

Reduced suppression:



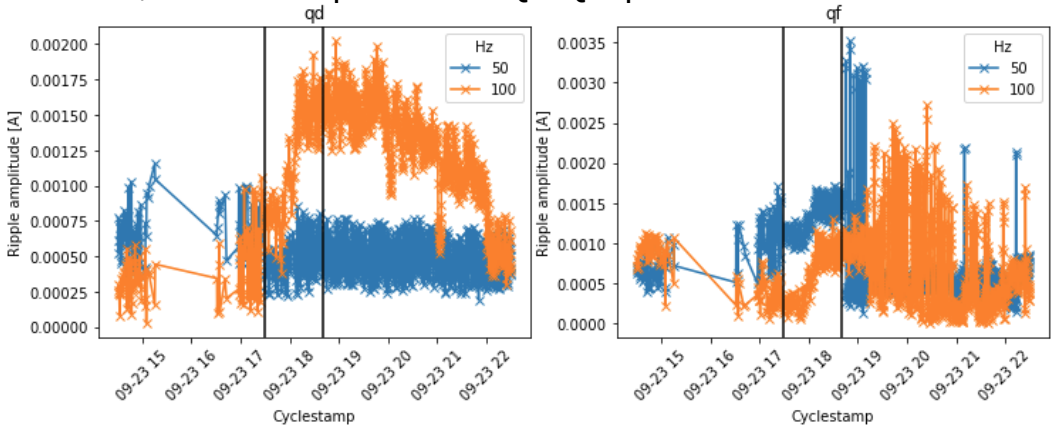
Spike at beginning of burst



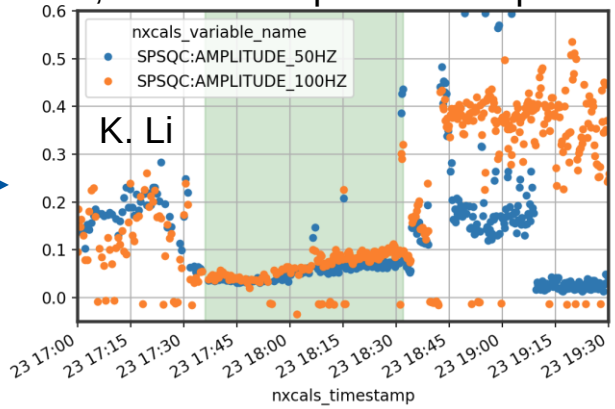
QF/QD ripple drifts

- Power converter **ripple amplitude in QF/QD drift** observed during tests.
- The source of the ripple (100 Hz) needs understanding and attacking, further investigations shown later in this talk.
- EBC suppresses the ripple well but cannot stop the drift.

50, 100Hz components of QF/QD power converters current



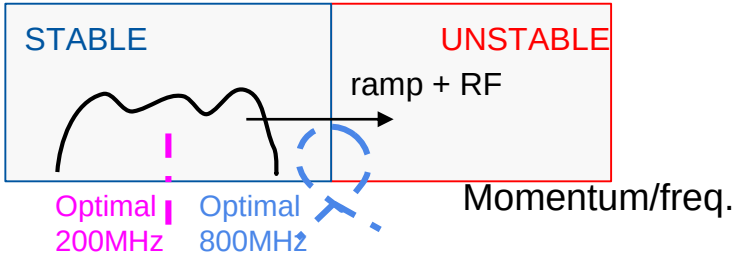
50, 100 Hz components of spill

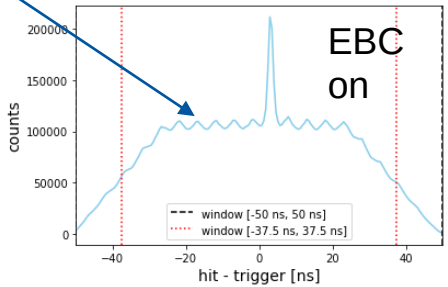


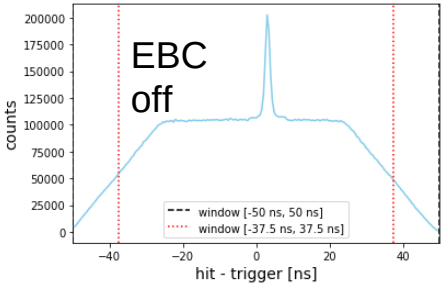
Control of 800 MHz system at FT

The 200 and 800 MHz frequency programs cannot be controlled independently:

- Optimal **settings for 200 MHz debunching compensation and optimal settings for 800 MHz EBC are in conflict**
- Optimising the 800 MHz system for EBC leads to some 200 MHz structure during the debunching
- No 800 MHz structure apparent







Proposal: switch 800 MHz system to independent fixed frequency at SFTPRO FT.

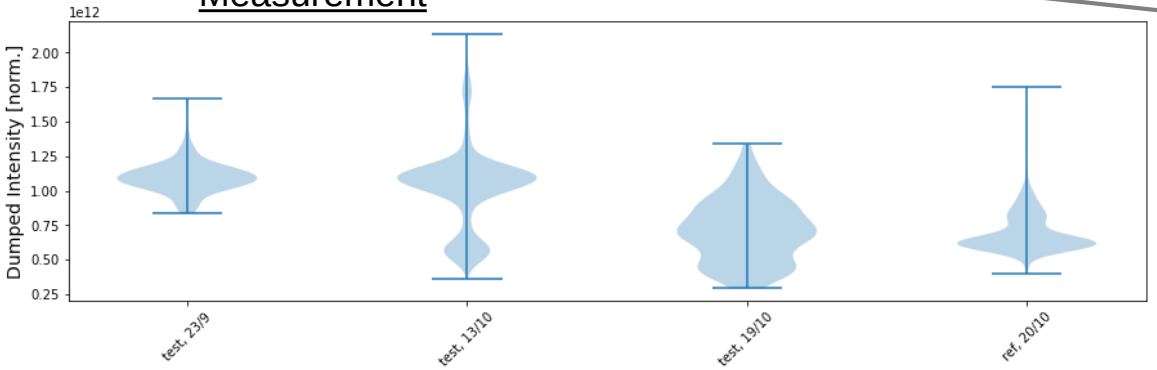
Dumped intensity

Dumped intensity higher than operational for certain scenarios. Possible sources:

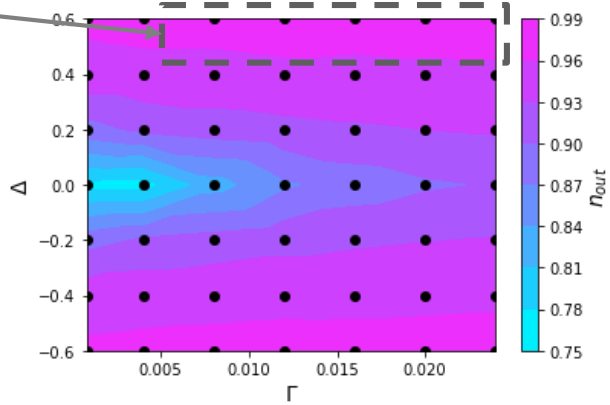
- Some beam is trapped inside bucket (after super-cycle change).
- Some beam crosses resonance too fast to be extracted. Simulations predict < 1% impact from this effect:

Test conditions

Measurement



Pct. beam extracted (simulation)



Open points and follow-up

- Initial iteration with RF suggests **no apparent show-stoppers for the requested 800 MHz feature**, but implementation requires work so priority must be understood.
- **Systematic approach of empty bucket re-alignment must be produced**, either with automated tools or with written procedure. Consists of simple trim offset on frequency. Goes hand-in-hand with machine stability improvements (hysteresis)

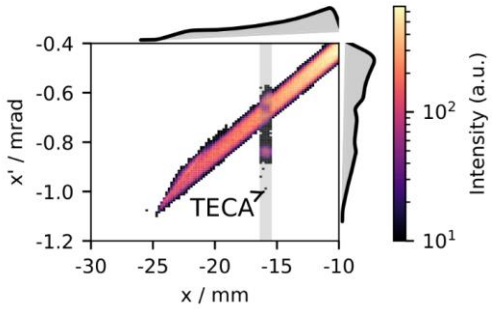
Non-local Crystal Shadowing

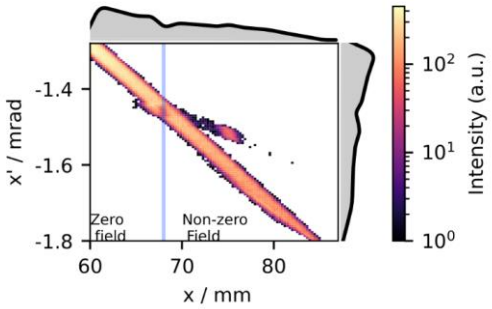
Courtesy of F. Velotti

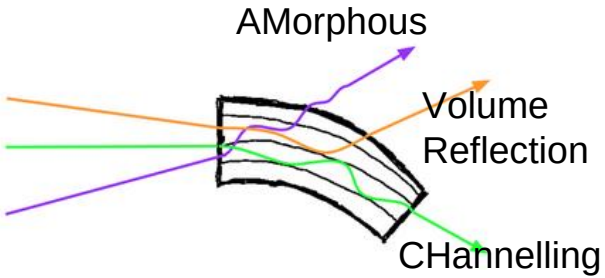
No, not that
kind of crystal...

Concept & Simulations

- Non-local shadowing: **Exploit non-linearities and multi-regime effect to optimise loss reduction** at the ZS via thin crystal.
- To obtain a x4 loss reduction, simulations show that a 1.8 mm thick crystal was needed.
- Only crystal available at the moment was same as in LSS2 (TECS) → 0.8 mm
- Installed in LSS4 on new goniometer during last YETS.

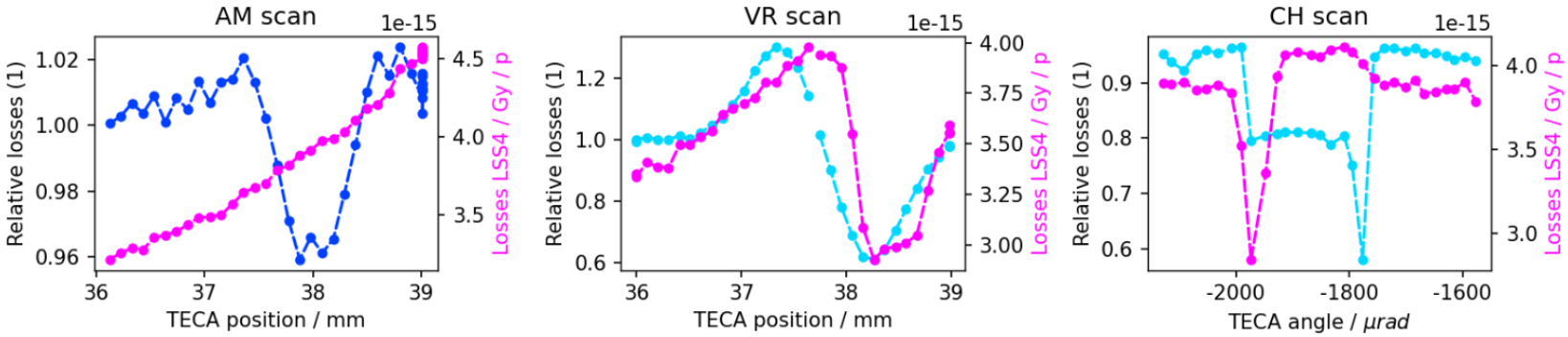






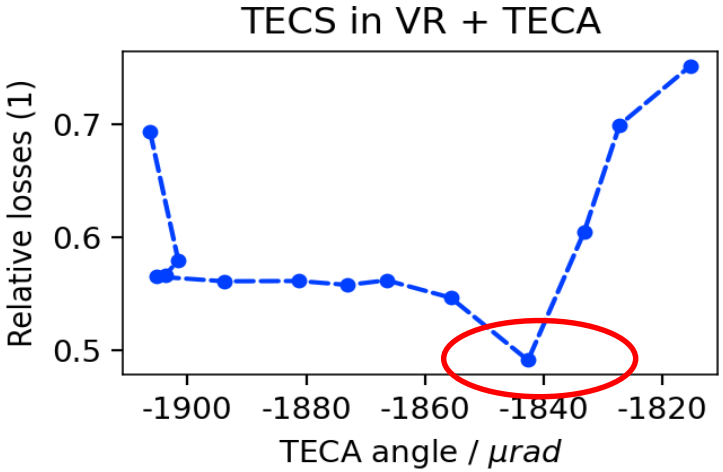
October MD

- Only TECA, non-local shadowing in LSS4.
- Clearly seen that TECA touches more regimes at once (VR, AM, CH) → in case largest part of separatrix is in CH, loss reduction of ~20%
- When optimal sharing between CH+VR+AM → **largest loss reduction ~45%**



November MDs

- Confirmed that mix of regimes minimises losses.
- Hysteresis effects observed between stops.
- Combining both local and non-local systems **brings losses down by 51%** !



Open points and follow-up

- **Large error in crystal movement**
  - Fully dominated the first measurements campaign.
  - Great improvements for the last MD → finally possible to perform scans (e.g. linear).
  - Crystal angular resolution ~10 urad, we need less to accurately probe channelling deep.
- Denser separatrix at TECA location → **high losses in LSS4 as expected**
  - Operational test postponed to next year – need another **discussion with RP**.
  - Probably mask needed → detailed simulations of the expected activation and shielding needed before next year commissioning.
- Propose to do **operational test** (TECA in for about 24h) **on first days of physics.**
- **Awaiting for 1.8 mm crystal to move towards 4x loss reduction.**

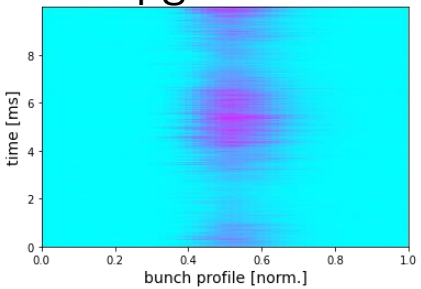
Other topics

PS: a great test bed

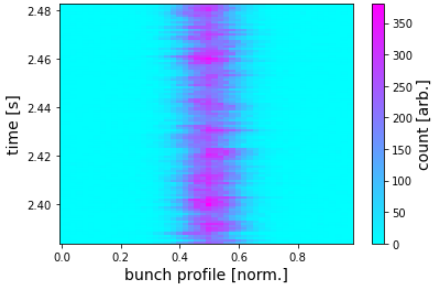
- **PS higher MD availability and lower risk** of equipment damage extremely useful for tests.
- EBC first implemented in PS, **results translated very well to SPS**.
- See M. Delrieux's talk for more examples.
- Crucial addition: dBLM during upcoming YETS (thanks to PBC support).

RF structure

PS

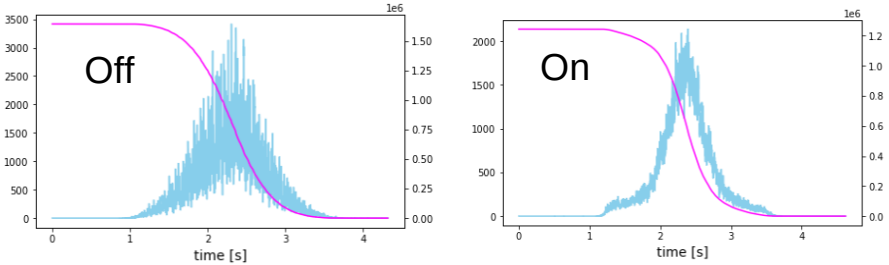


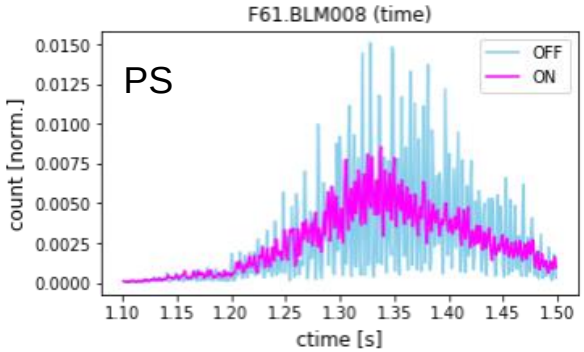
SPS



Spill quality

SPS



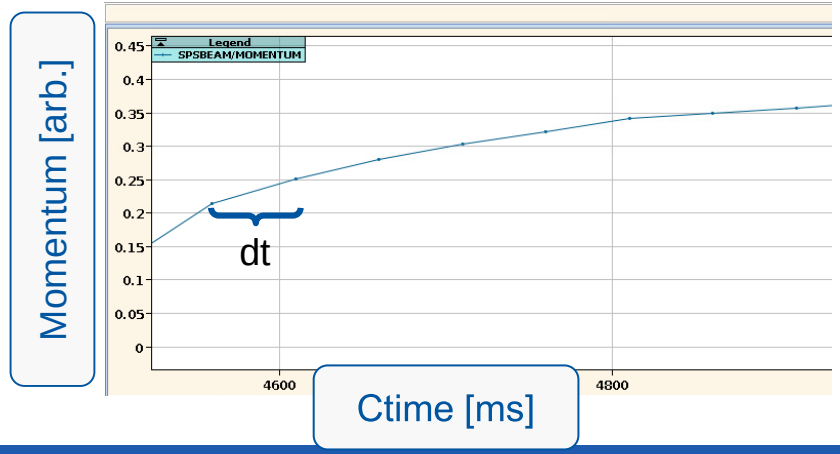


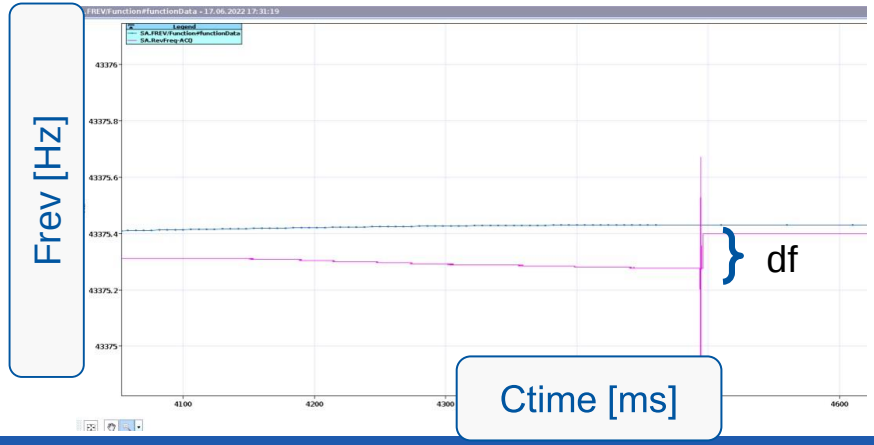
SPS: OP tools, non-OP features

Current auto-spill 50 ms resolution introduces some ripple at 20 Hz, reported by NA62. Suggestions:

- Feature to add low-pass filter to central portion of correction trim.
- Increase resolution (Moves problem to new freq.).

Current frev default behaviour causes freq. jump when loops go off -> not optimal for 200 MHz compensation.

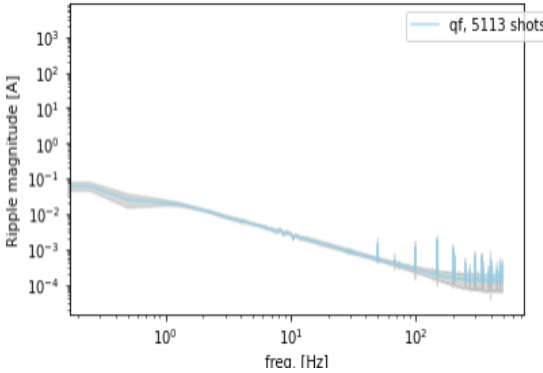


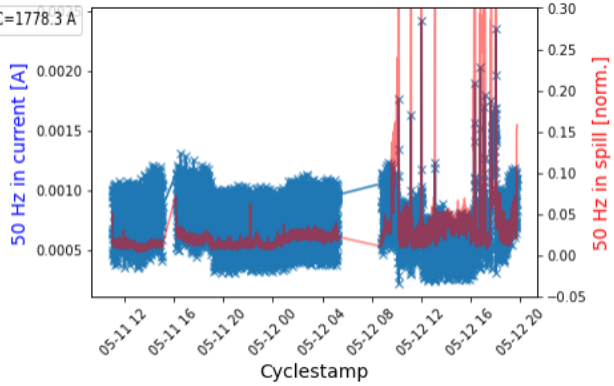


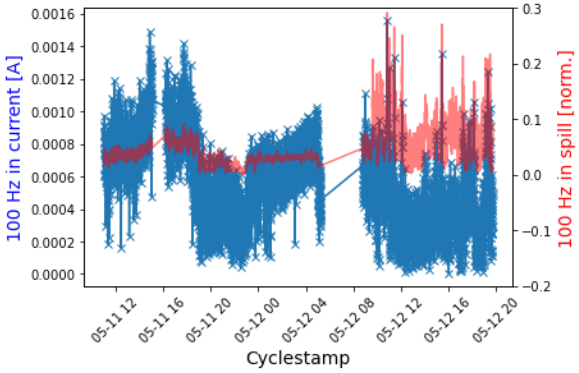
SPS: Power converter analysis

- Power converter stability key component of high-performance slow extraction.
- Investigation of all relevant frequency spectra performed before and after spill deterioration (May 12th 2022).
- **No obvious culprits found** among quads, dipoles and chromatic/harmonic sextupoles.

F-quad analysis



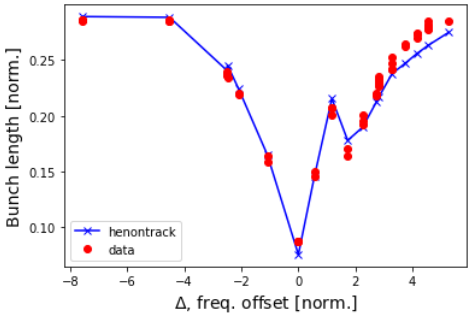


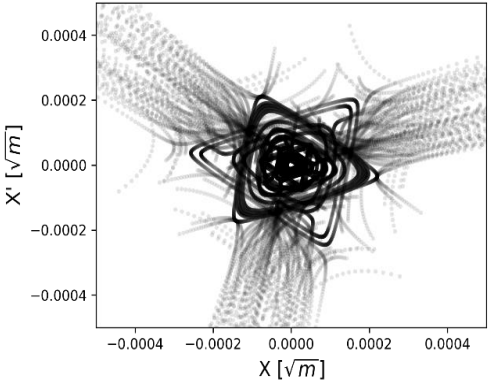


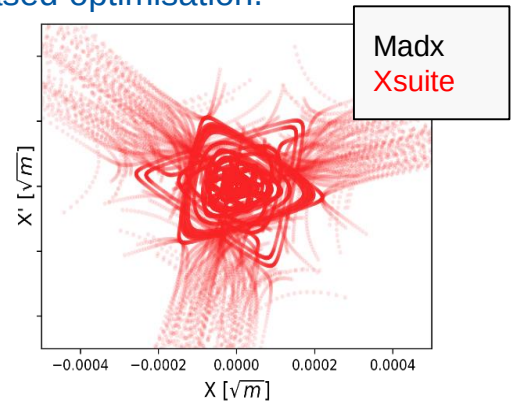
Simulation/tooling

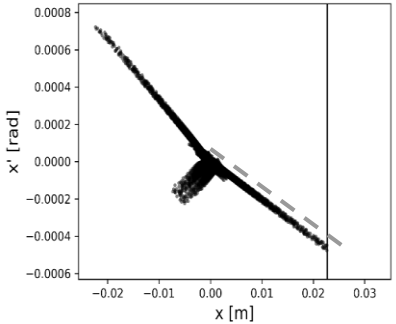
- Computational tools play crucial role for understanding and improving slow extraction performance.
- i-FAST REX WG led by F. Velotti for simulations on slow extraction.
- **Xsuite effort is being supported** and simulations are being benchmarked and ported, exploiting GPU capabilities and python flexibility.
- **EBC tests in SPS in great agreement with simulation** predictions -> potential for model-based optimisation.

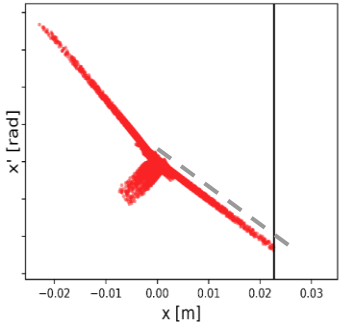
Scan, 200 MHz structure







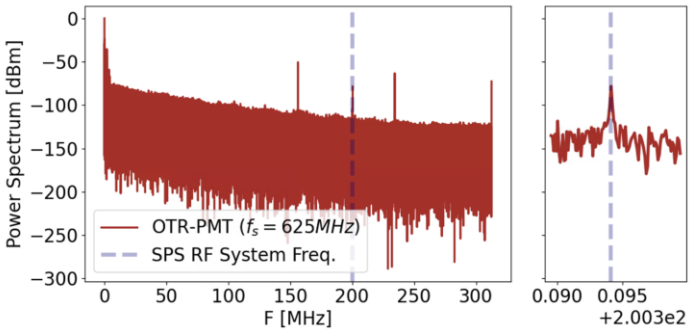




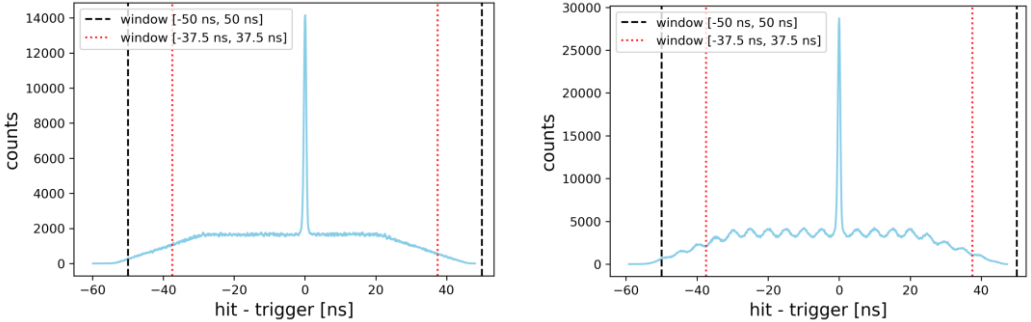
Fast instruments & work with experiments

- Pushing for fast detection devices if experiments need uniformity in the **100s MHz scale -> progress on dBLM and OTR** during EBC MDs.
- **Established workflow with NA62** to exploit their ~70 ps acquisition systems during MDs and tests for EBC.

OTR



NA62 GTK



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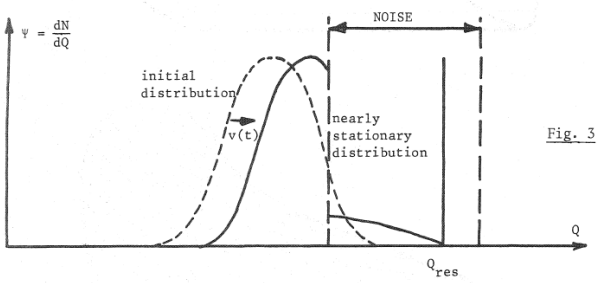
Conclusions & Further Work

- **EBC with 800 MHz system demonstrated 5x ripple improvement,** re-alignment needs addressing, RF frequency offset feature is important.
- **Non-local shadowing combined with local shadowing cut ZS losses in half,** RP considerations for LSS4 on-going, operational test next year.
- RF manipulations to **increase momentum spread** being tested -> faster tune sweep.
- **Noise techniques to be investigated** in PS to extract with fixed magnetic elements (to remove slow drifts) and in SPS to further improve spill quality.
- Will **revisit octupole folding** in SPS in context of ECN3 HI facility to further reduce ZS losses.
- Recommendation: **compile NA & EA spill requirements and limits** in 'common language'.

Noise techniques



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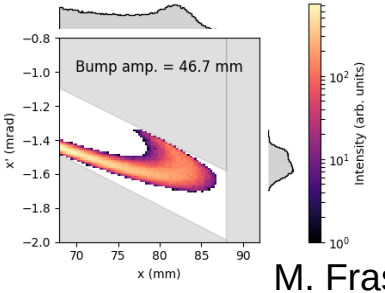
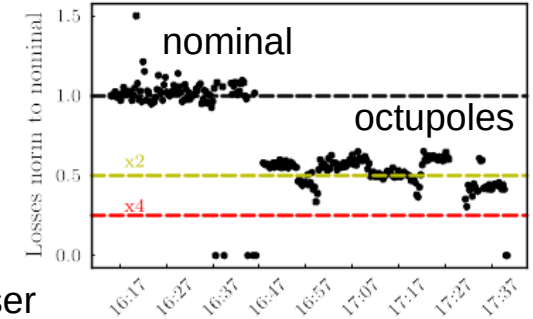
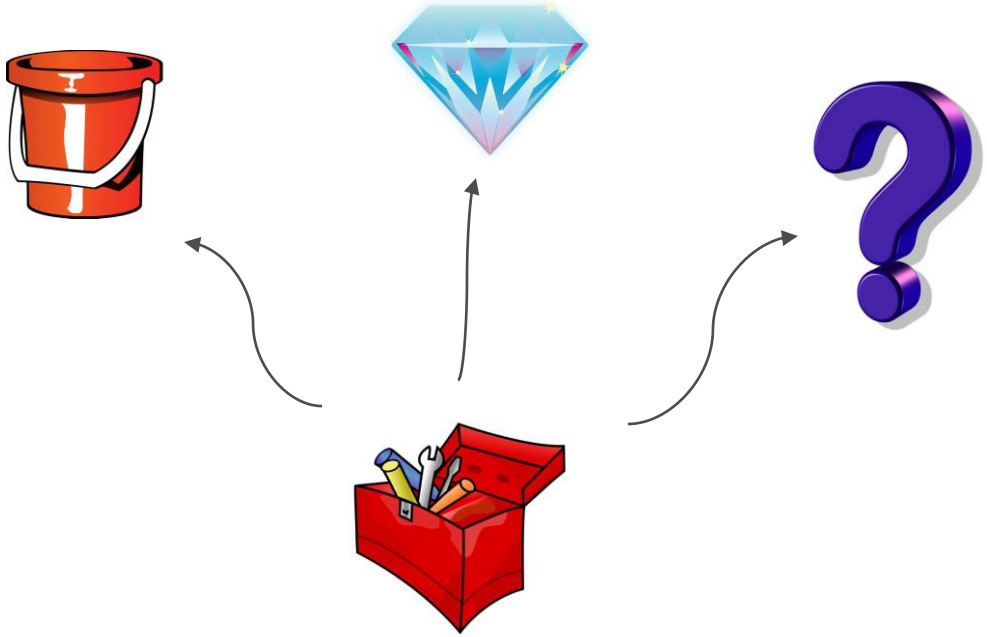
Octupole folding





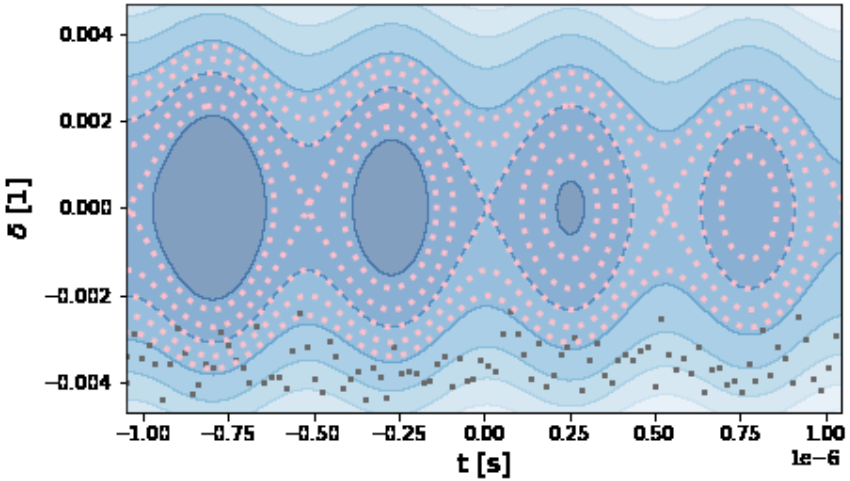
M. Fraser

THANK YOU.



EXTRA SLIDES

EBC


0.004
0.002
0.000
−0.002
−0.004
δ [1]
−1.00
−0.75
−0.50
−0.25
0.00
0.25
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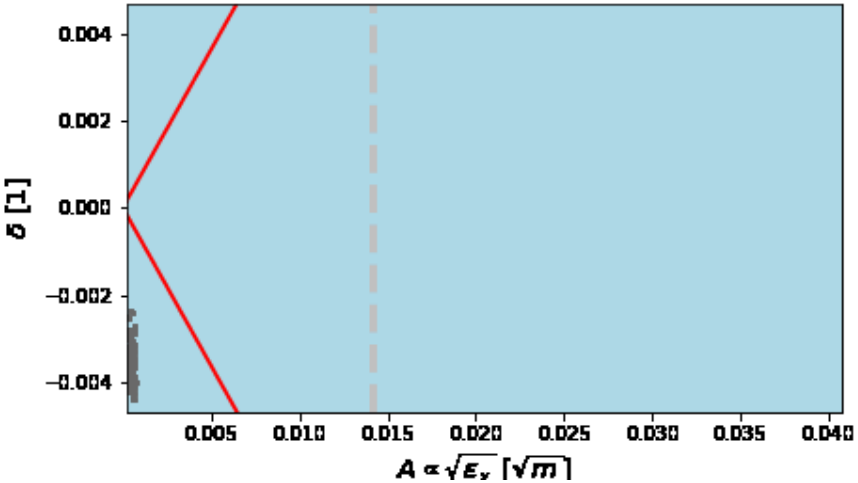
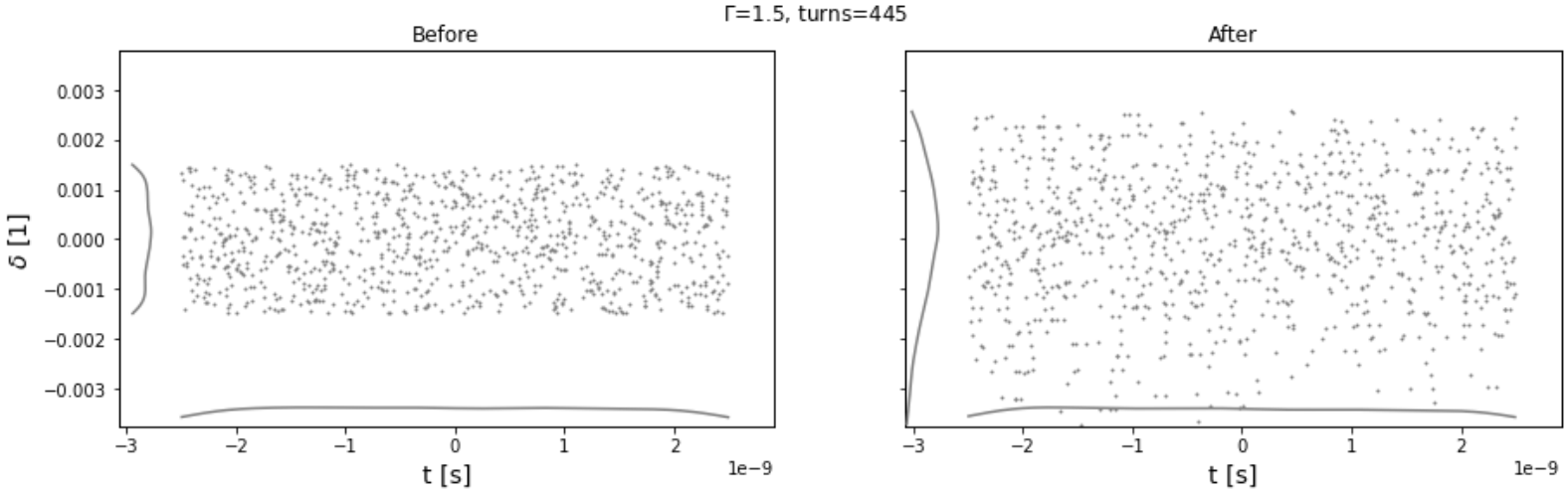

0.004
0.002
0.000
−0.002
−0.004
δ [1]
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
$A \propto \sqrt{\varepsilon_x}$ [$\sqrt{m}$]

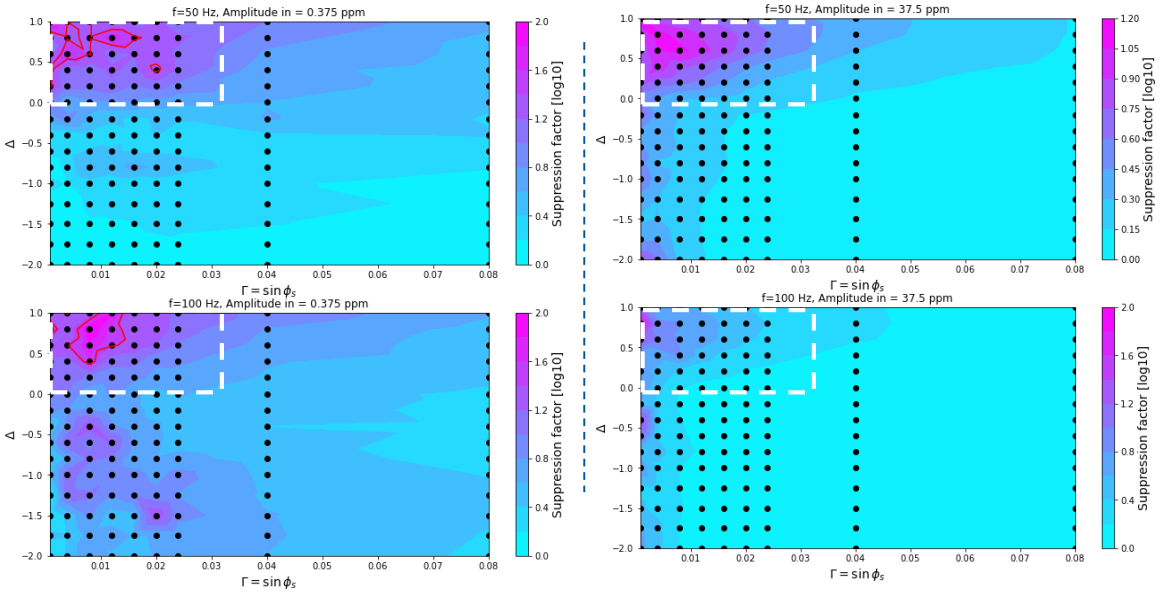
Phase displacement BU



EBC, Simulation: 200 MHz

Ripple suppression

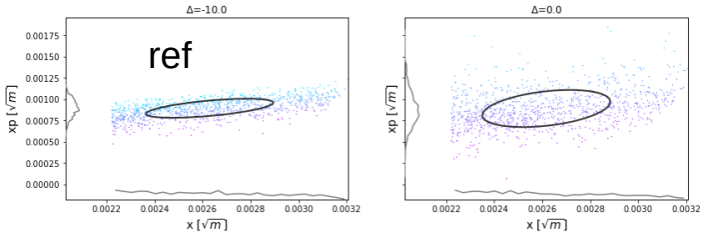
Reductions of up to 2 orders of magnitude predicted by simple simulation model.



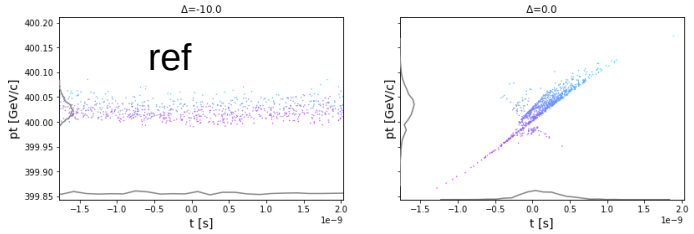
Limitations

High voltages can perturb beam, need to keep it in mind.

Beam size blow-up -> Losses



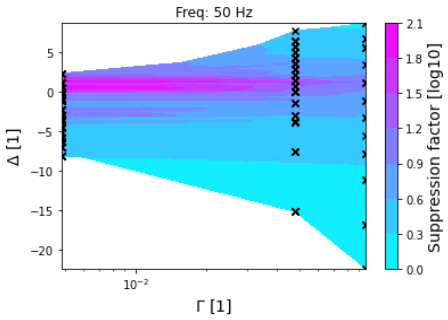
Beam bunching -> event overlap

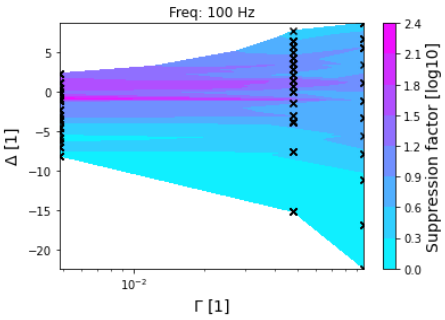


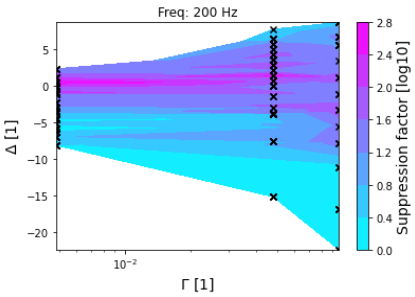
1 period of 200 MHz

EBC, Measurements: Ripple suppression

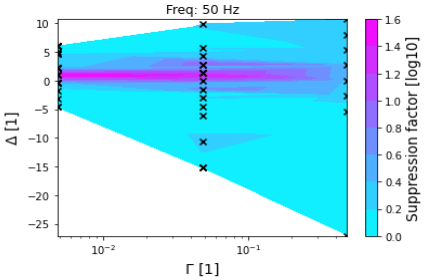
200 MHz

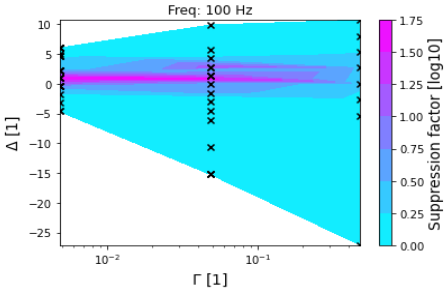


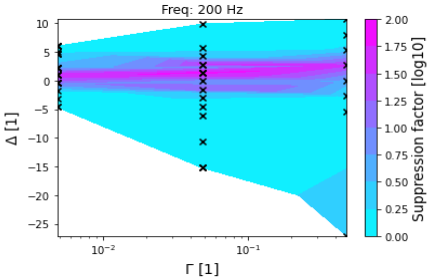


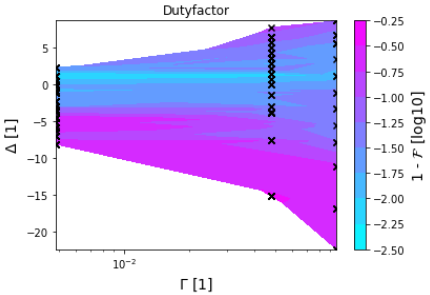


800 MHz

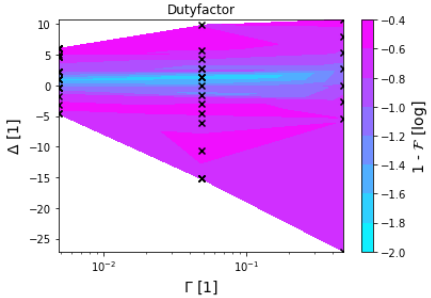




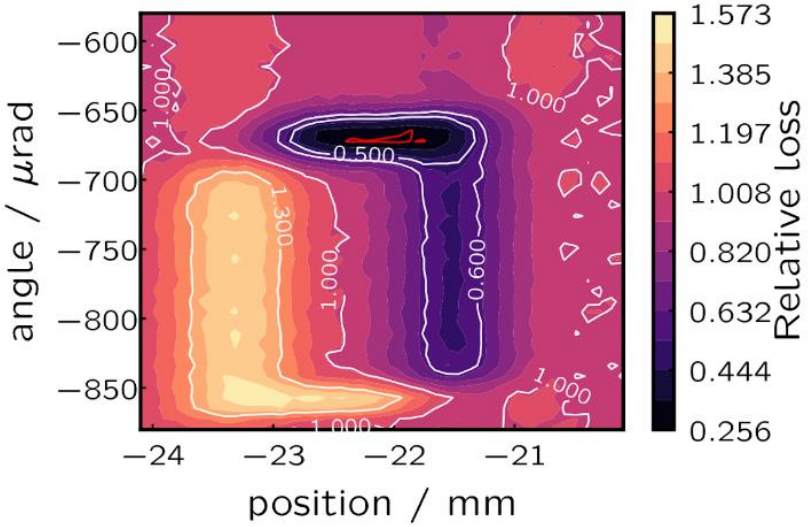


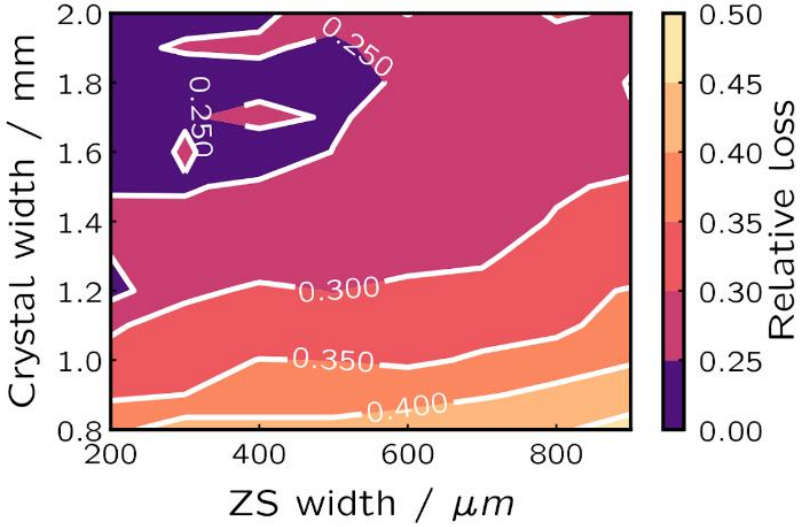


$$\mathcal{F} = \frac{< I(t) >^2}{< I^2(t) >} \leq 1$$ (DC power) : (Total Power)



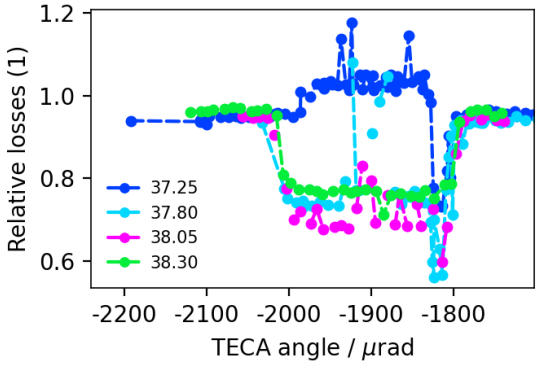
Non-local shadowing – optimisation

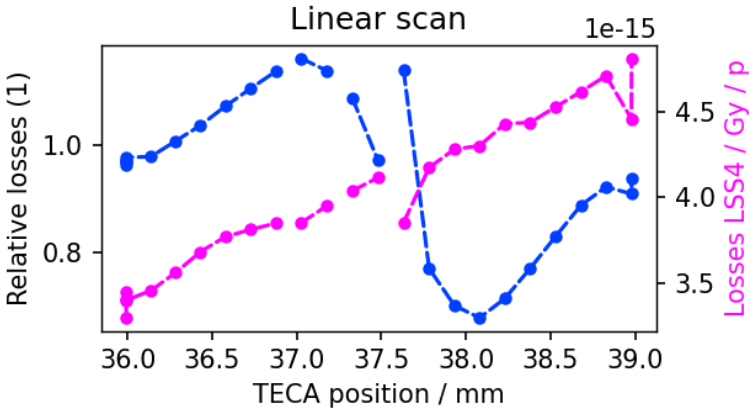


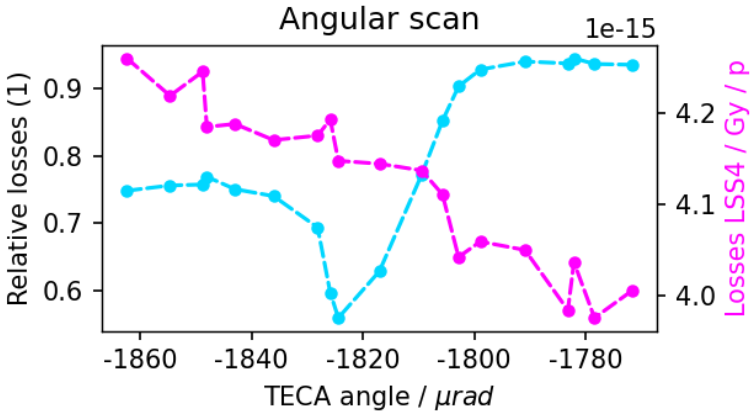


November MD

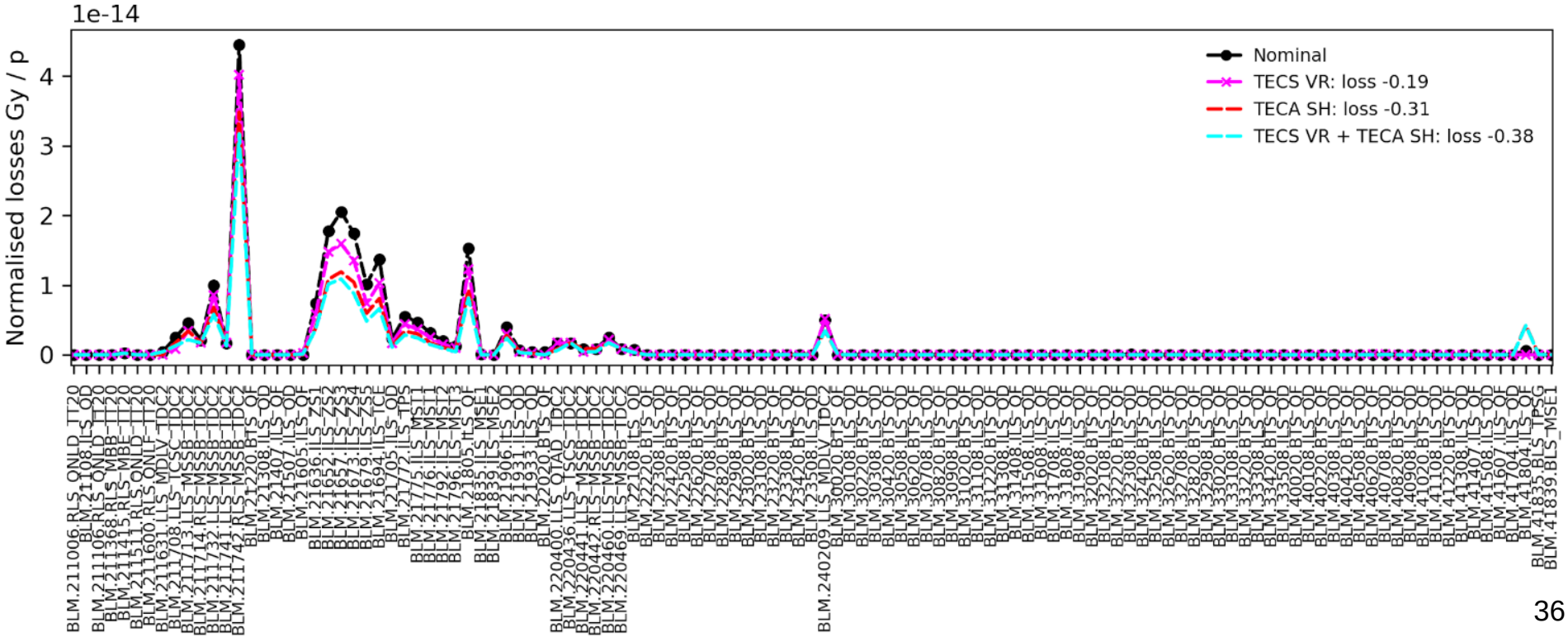
- Complete linear scan and angular scan focusing in shadowing
  - Many angular scan but beam not very stable
  - After AM scan, clear movement of relative alignment of TECA and ZS
  - Loss reduction obtained with TECA only in the same order of previous MD → ~45%



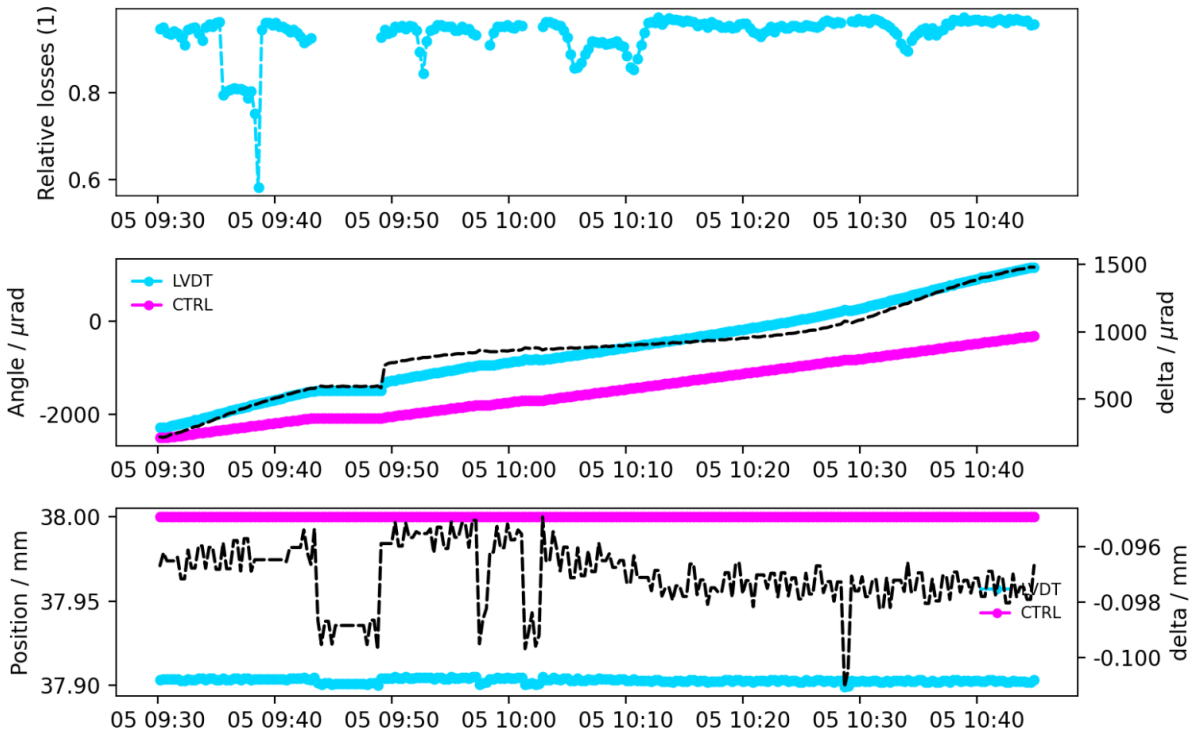




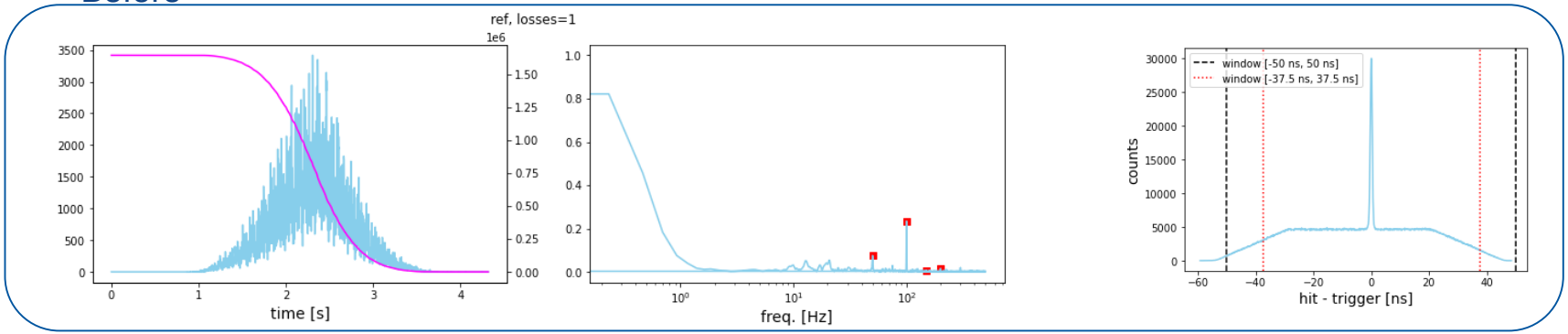
Global loss reduction (unsplit optics in TT20)



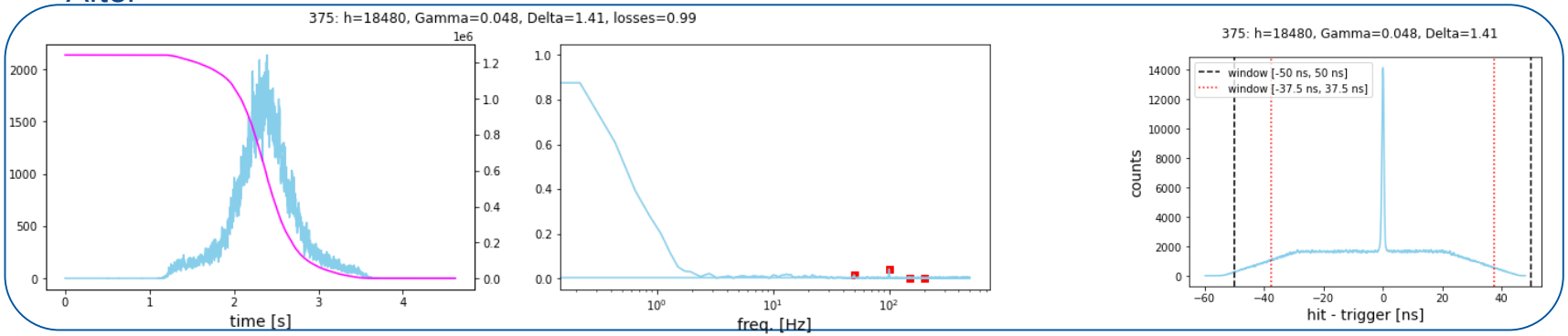
Non-local crystal scans



Before

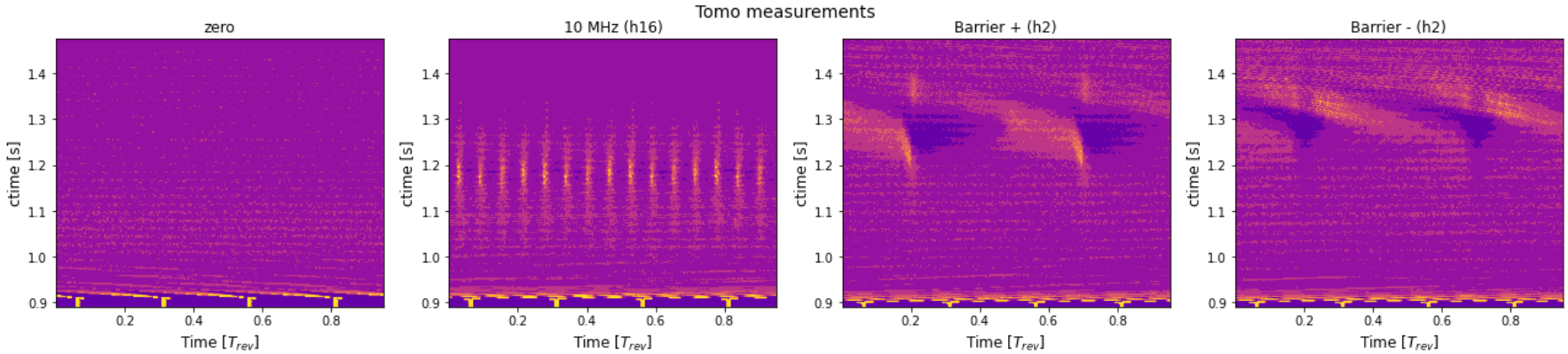


After

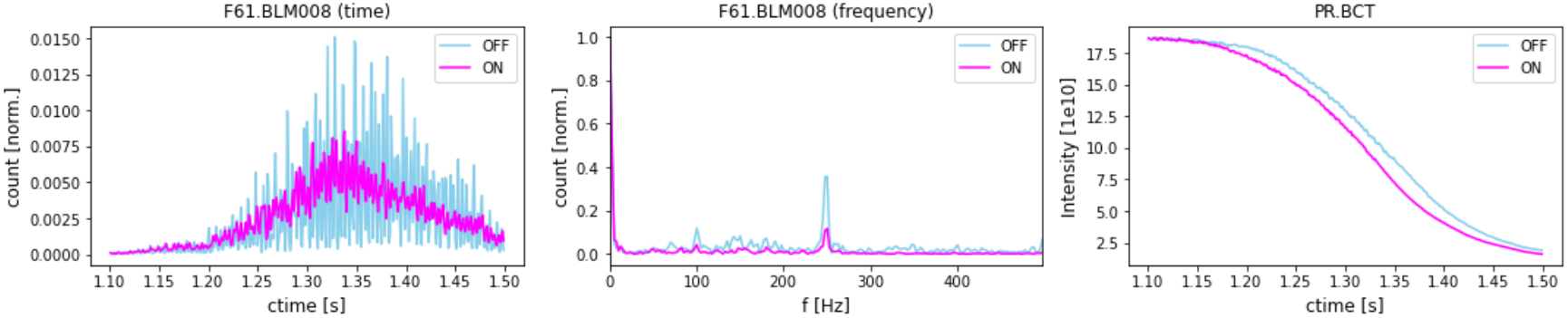


Empty bucket channelling MDs in the PS

- Channelled the beam without extraction both with sinusoidal buckets and barrier buckets:



- Implemented channelling in slow extraction to the EAST area to improve spill quality:



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