Update on LEIR horizontal instability study

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Acknowledgements: G.Kotzian, T.Levens, E.Métral and the LIU-Ions team

Instabilities observation

- Instabilities occurred before capture with apparently random pattern.
- Harmful during LHC run -> lengthened the ion beam setup time!

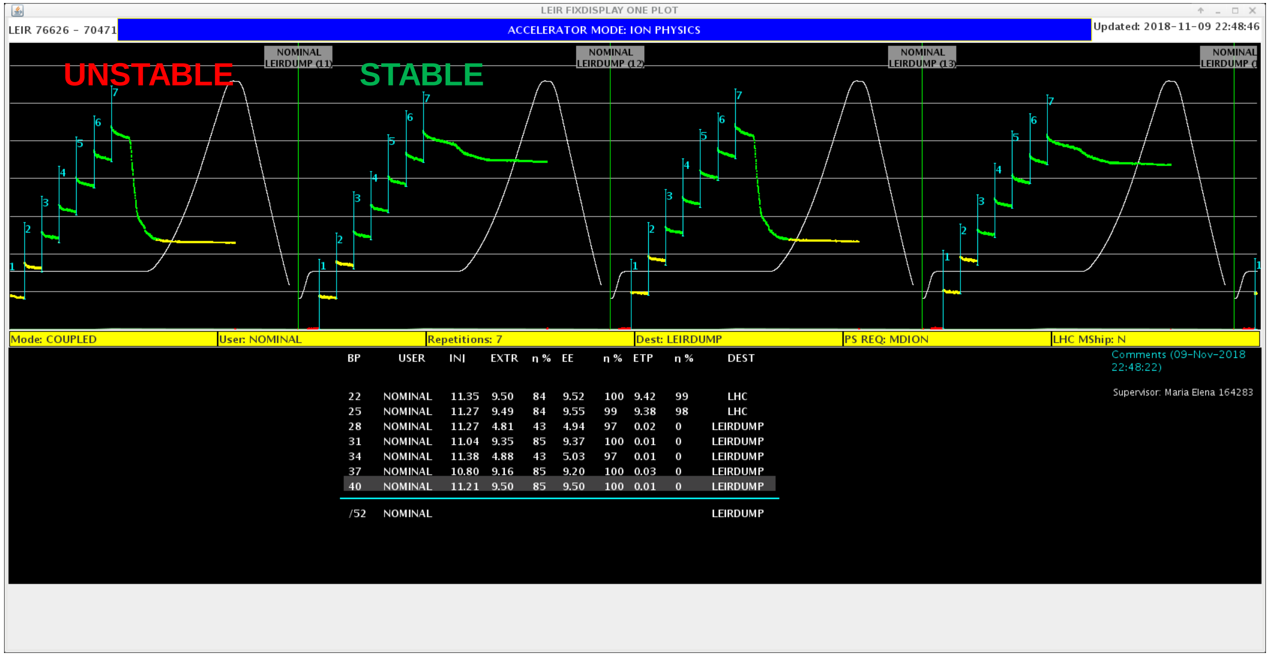
Complete list of known occurrences:

09/11/2018: elogbook link

07/08/2018: elogbook link

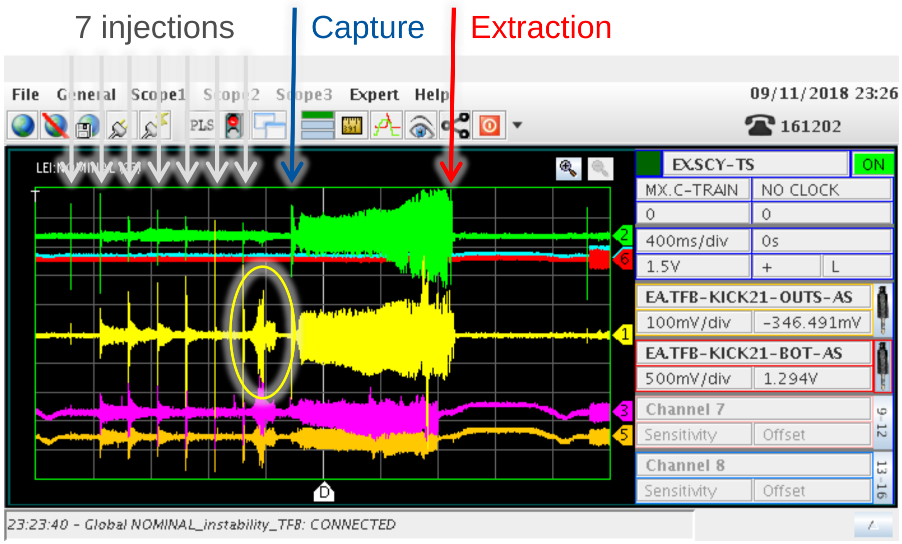
13/11/2018: elogbook link

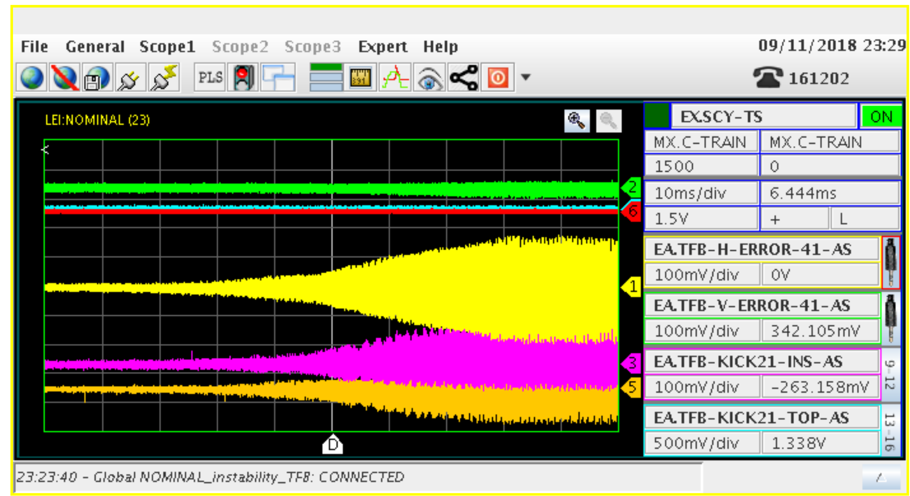
15/11/2018: elogbook link



BP	USER	INJ	EXTR	η %	EE	η %	ETP	η %	DEST
22	NOMINAL	11.35	9.50	84	9.52	100	9.42	99	LHC
25	NOMINAL	11.27	9.49	84	9.55	99	9.38	98	LHC
28	NOMINAL	11.27	4.81	43	4.94	97	0.02	0	LEIRDUMP
31	NOMINAL	11.04	9.35	85	9.37	100	0.01	0	LEIRDUMP
34	NOMINAL	11.38	4.88	43	5.03	97	0.01	0	LEIRDUMP
37	NOMINAL	10.80	9.16	85	9.20	100	0.03	0	LEIRDUMP
40	NOMINAL	11.21	9.50	85	9.50	100	0.01	0	LEIRDUMP
/52	NOMINAL								LEIRDUMP

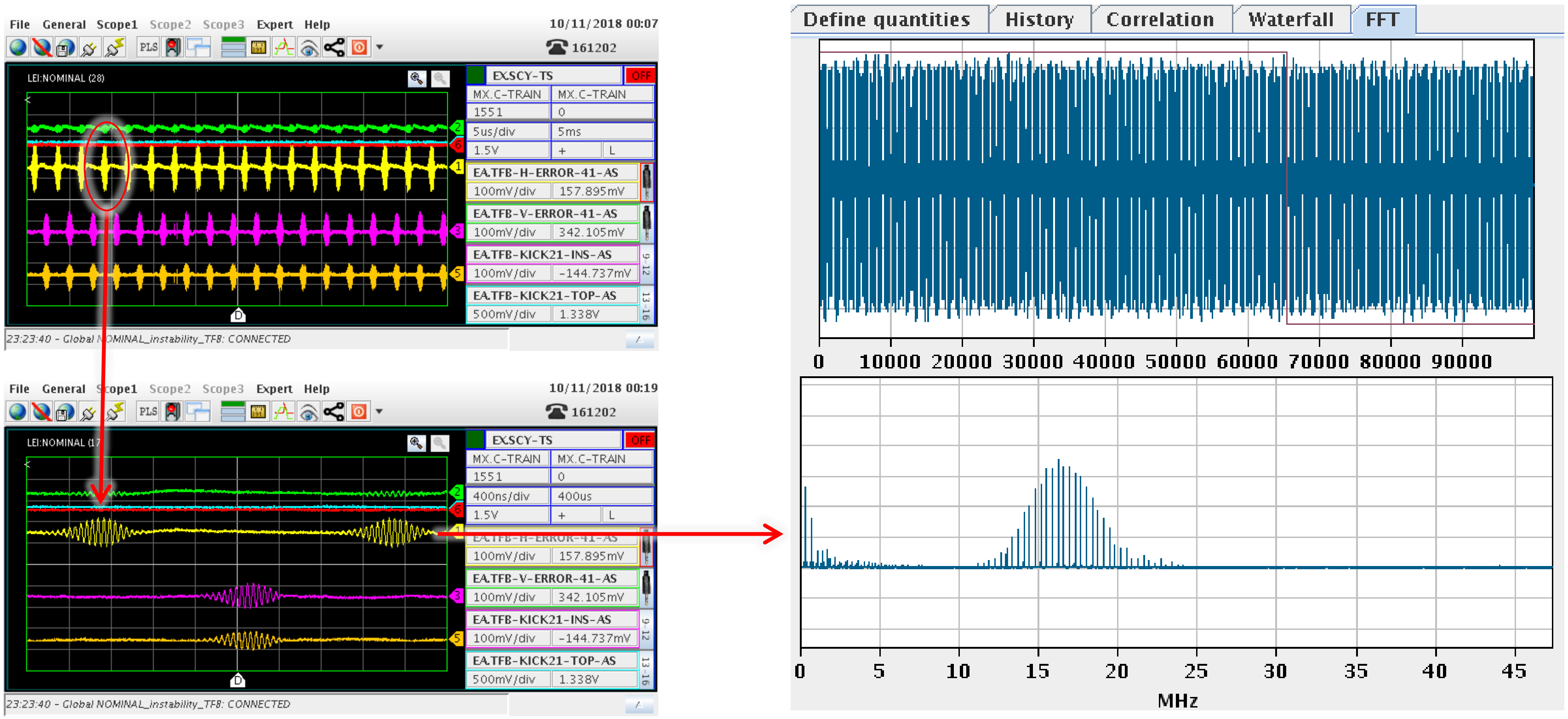
Coherent motion





- Beam looks horizontally unstable.
- Doubles amplitude in $\sim 20\ ms \rightarrow \tau = \frac{20}{\ln 2} \simeq\ 28\ ms$ [~ 10k turns]

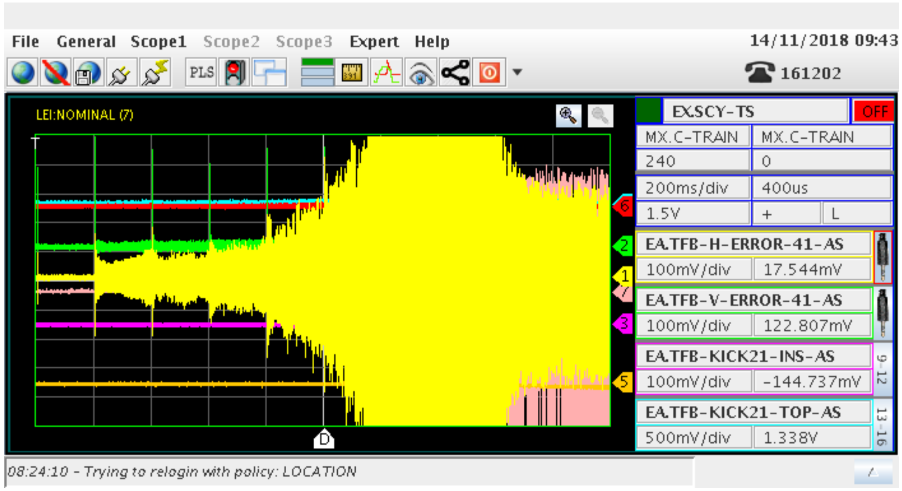
Frequency content

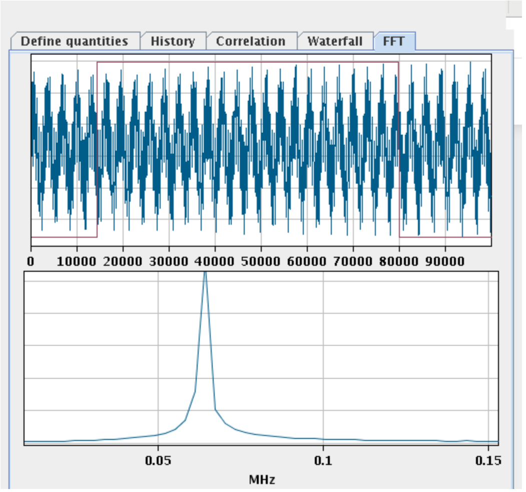


- Broad spectrum between 10 and 20 MHz.
- Can it be an HOM? $f_r \sim 17$ MHz, $Q \sim 3 - 4$

Additional machine observations

- Without damper

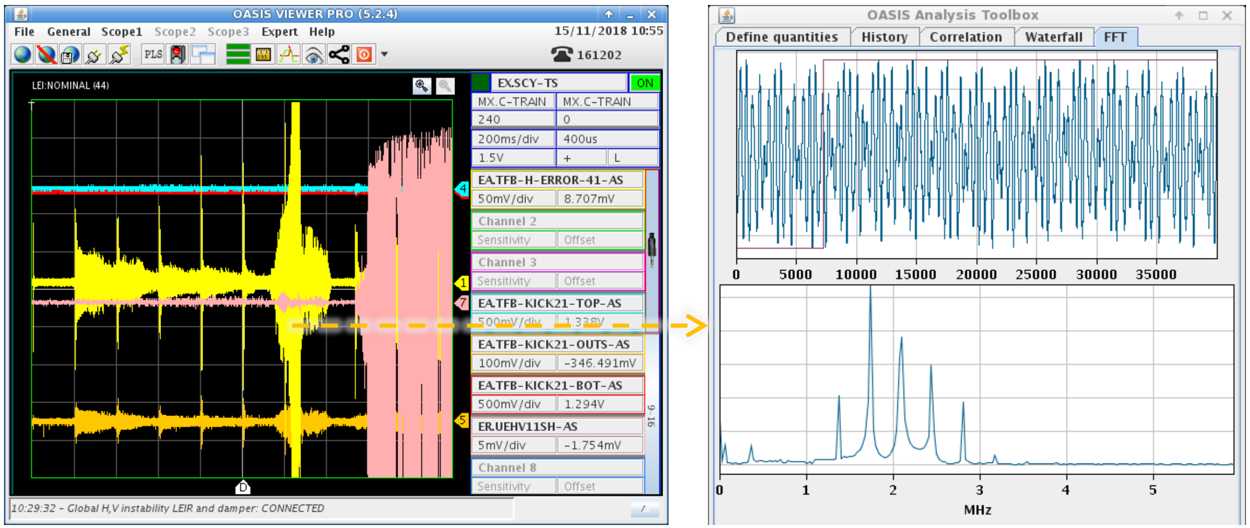




- 1-Qx line unstable (~70 kHz as Qx=1.81 and f0~360kHz).
- Little degradation in performance (small intensity loss).
- Slow growth rate.
- Suspicious activity starting abruptly after the 2nd injection: not yet understood (maybe related to damper pickups sensitivity?).

Additional machine observations

- With damper

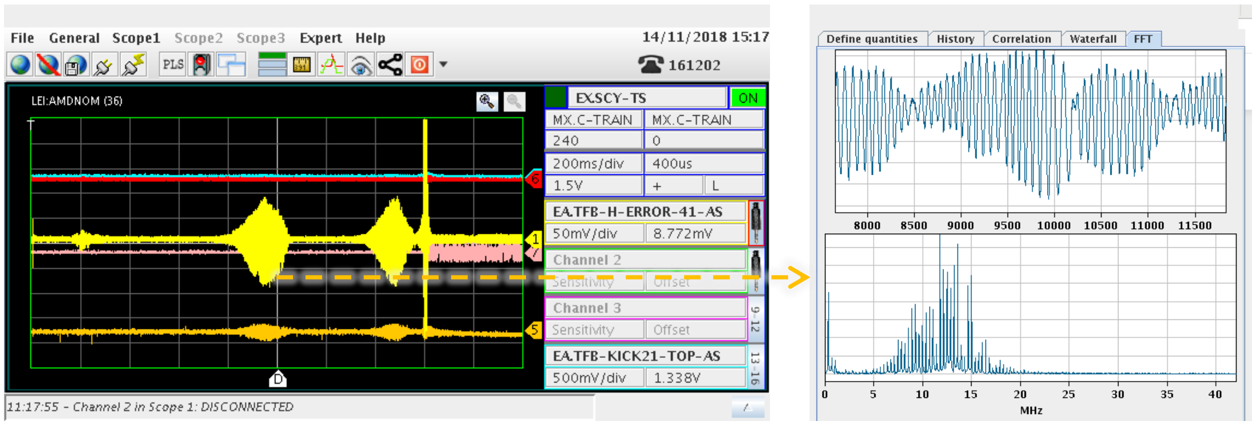


An operational cycle (7 injections, >10e10 c)

- Injection oscillations stay long from 2nd injection onwards.
- Much faster instability observed.

Additional machine observations

- With damper



An MD cycle
(1 injection, ~2e10 c)

- Instability calms and restarts.
- Very “busy” spectrum between 5 and 20 MHz.

→ These observations suggest to investigate more the relation of the damper with this instability (damper settings to be optimized?)

Simulations setup

PyHT has been further adapted to simulate this instability

What we included:

1. Electron cooling: RF-track cooling module, Parkhomchuk formula [1]
2. Longitudinal space charge:
   - Accounts for progressive cooling
   - Implemented as: $\mathrm{W}_{\mathrm{pot,LSC}} = Z_{LSC} * \frac{\partial \rho}{\partial s}$ with $Z_{SC} = -\frac{Z_0 c R}{\gamma^2}\left(\frac{1}{2} + \log\left(\frac{r_p}{r_b}\right)\right)$
3. Transverse space charge (Bassetti-Erskine [2])
4. Damper (impedance-like transfer function)
5. Multiple injections.

What we miss (mainly):

- IBS (M.Zampetakis working on tracking module)

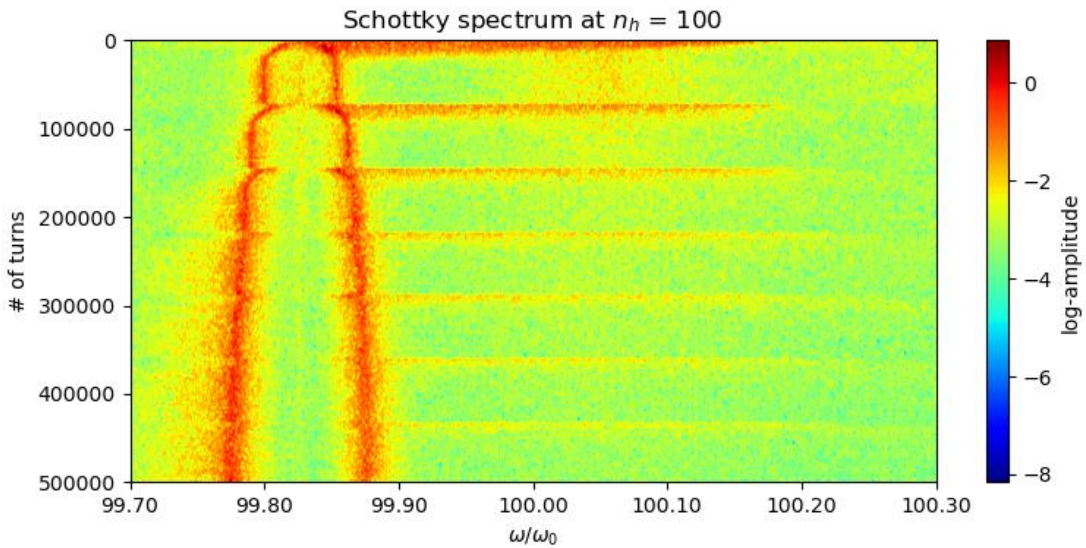
[1] See ABP Injectors WG meeting #11 https://indico.cern.ch/event/952934/
[2] From Adrian Oeftiger-> see main repository https://github.com/PyCOMPLETE/PyHEADTAIL

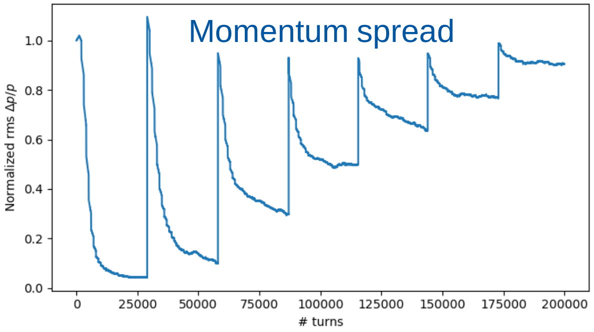
Example: full LEIR accumulation stage

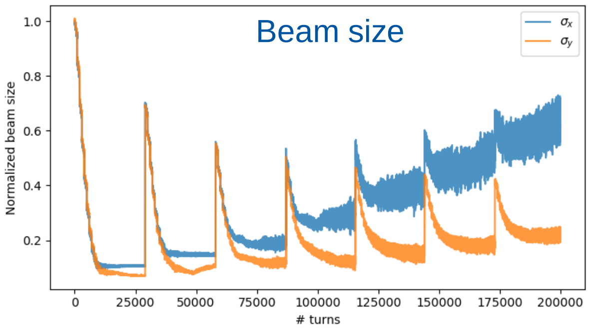
LEIR longitudinal Schottky for multiple injections.

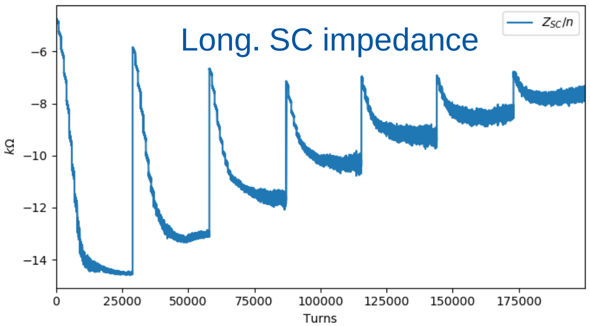
- $2 \cdot 10^{10}$ charges injected at each step every 72000 turns (200 ms).
- Final longitudinal momentum spread an transverse beam size depend on full accumulation stage.
- Here a small resonator present (Rs, Q, f) = ($10^5 \Omega/m$, 50, 15.5 MHz)

NB: 500k turns -> 1w simulation : unfortunately too slow to allow large parameter scan and study the instability mechanism flexibly. Useful for long-term studies (e.g. ML application on Schottky).





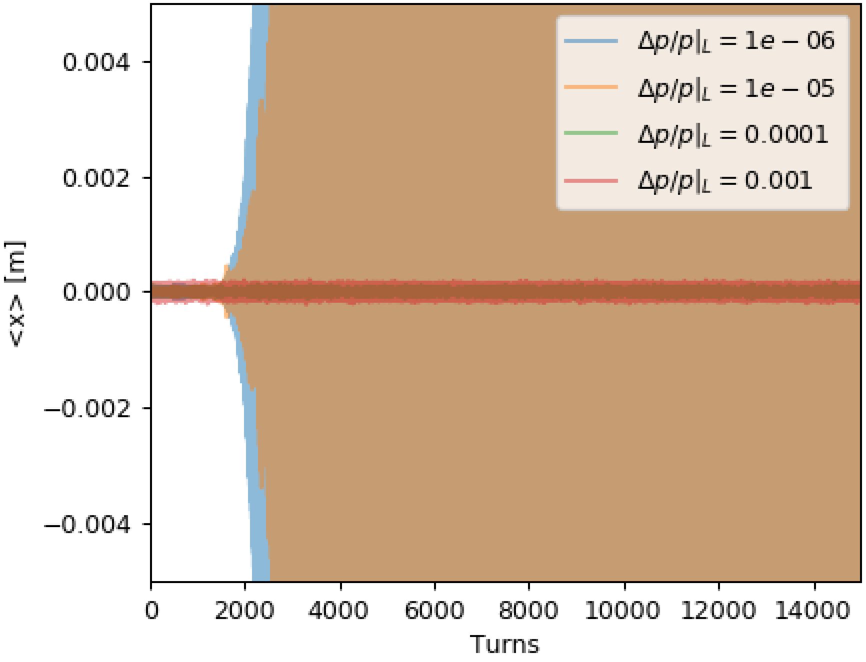


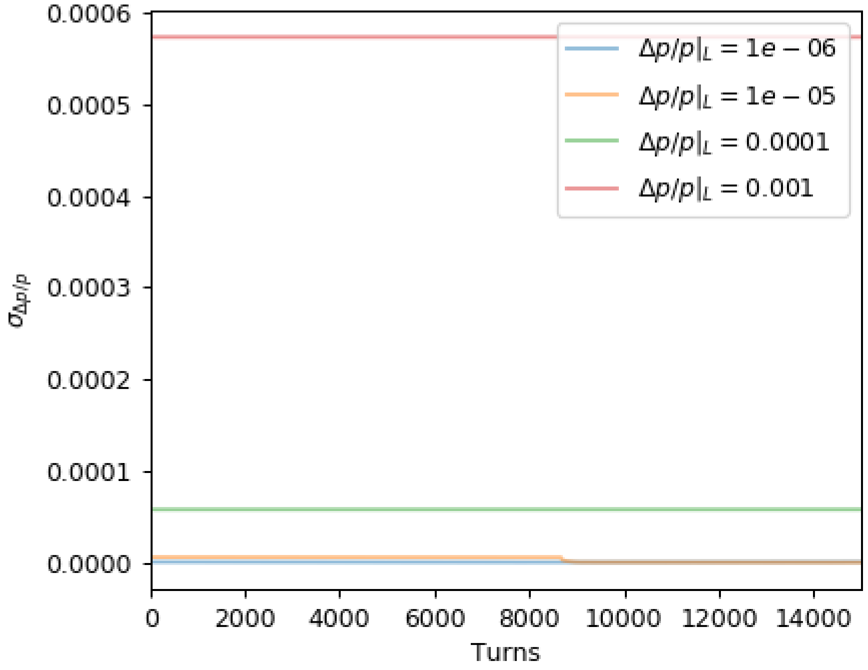


Effect of an horizontal resonator

- HOM: Rs= 10MOhm/m, Q=5, f=17 MHz,
- Uniform distribution in momentum $\frac{\Delta p}{p} \in \left[-\frac{\Delta p}{p}\Big|_L , \frac{\Delta p}{p}\Big|_L \right]$
- No cooling, No space charge

→ Instability threshold at about $\Delta p/p|_L = 10^{-5}$





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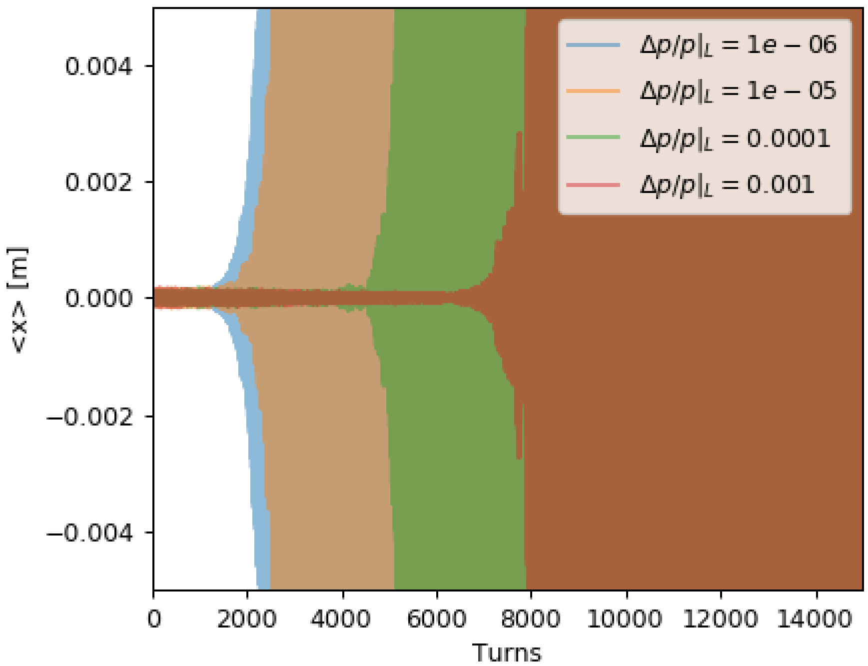
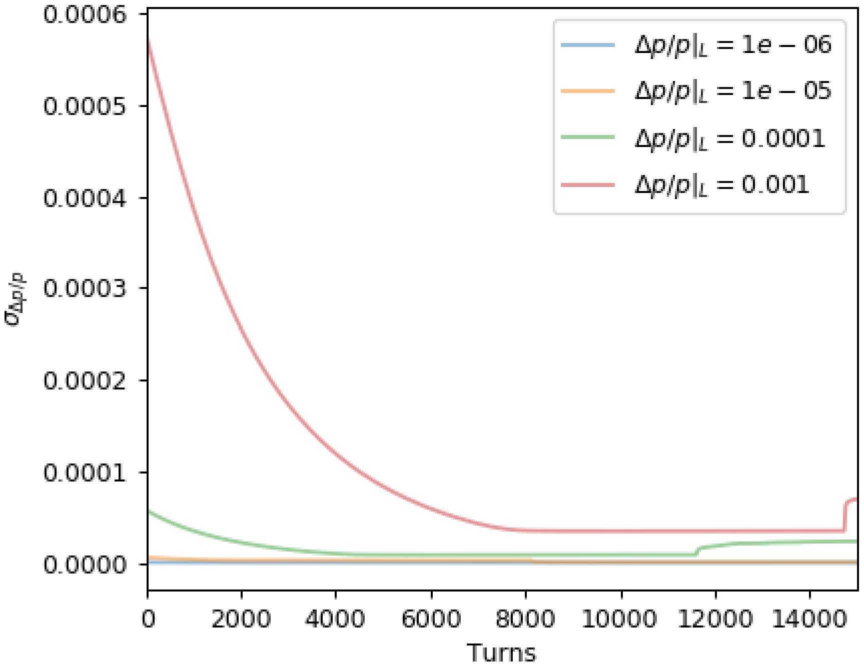
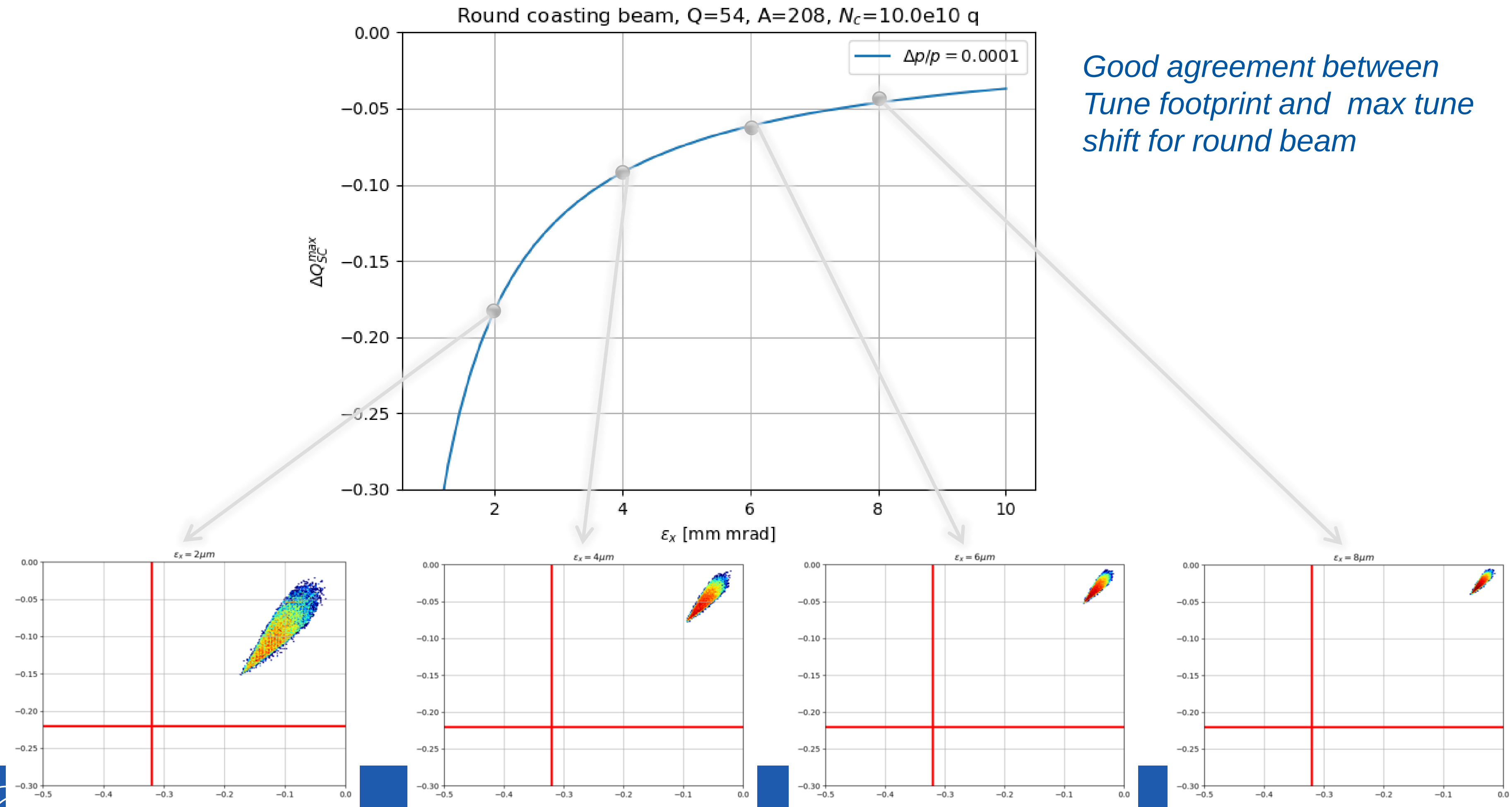
→ Instability threshold reached at few 10^{-5} rms





Space charge benchmark

Let's add space charge (required charge/mass update in [1])



Good agreement between Tune footprint and max tune shift for round beam

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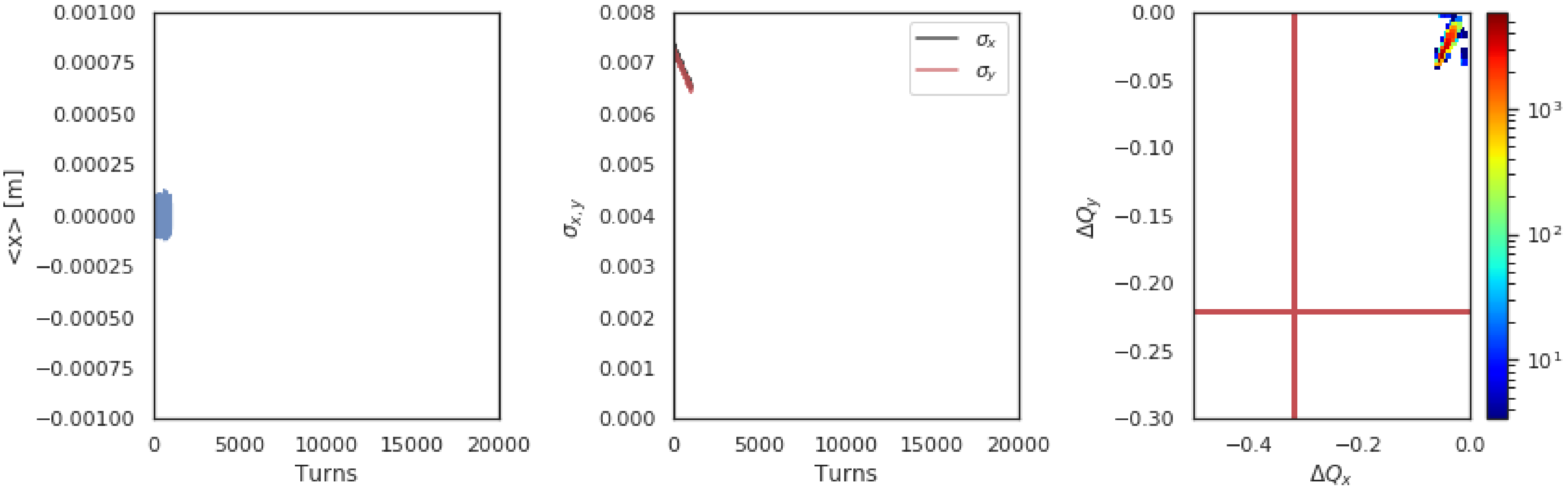

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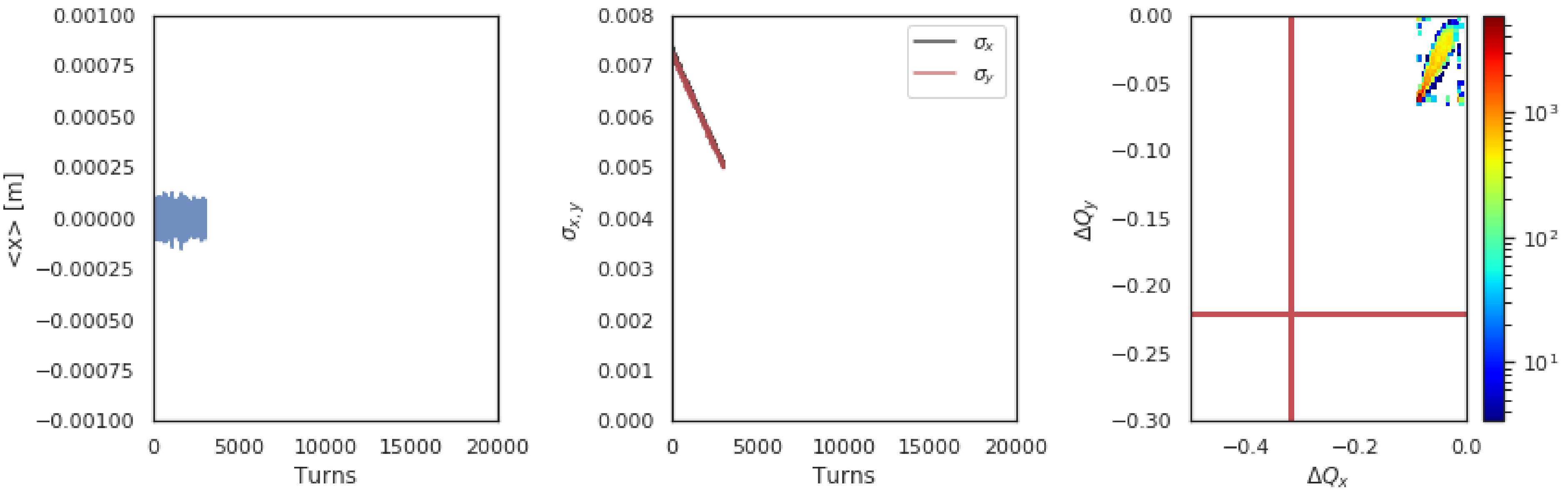

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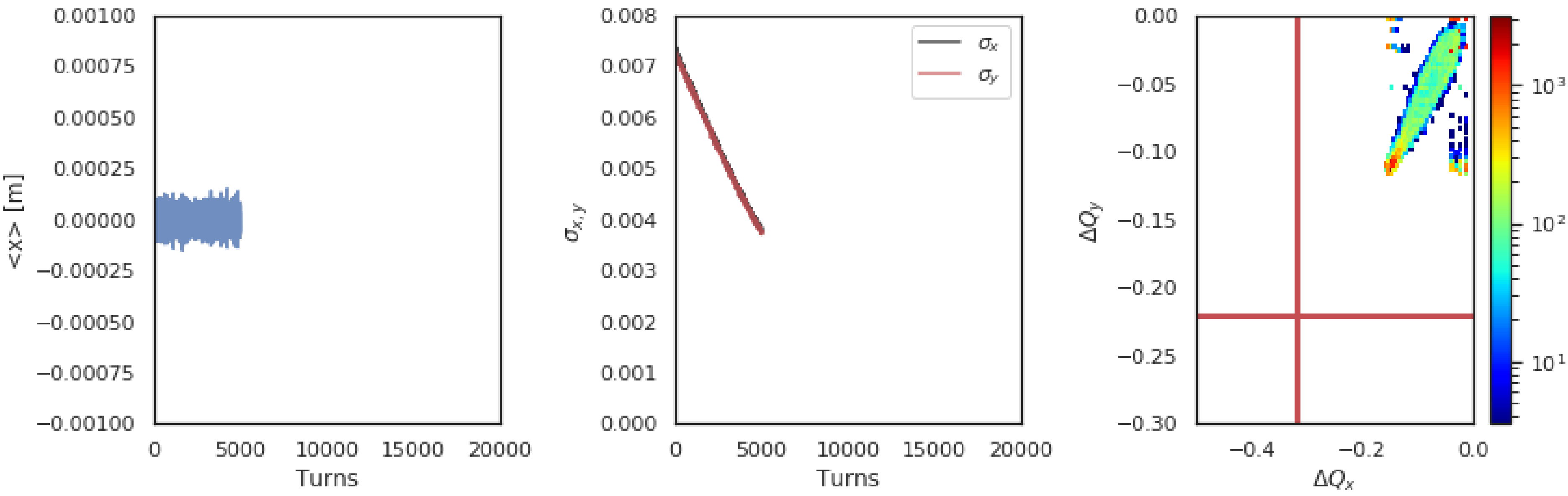

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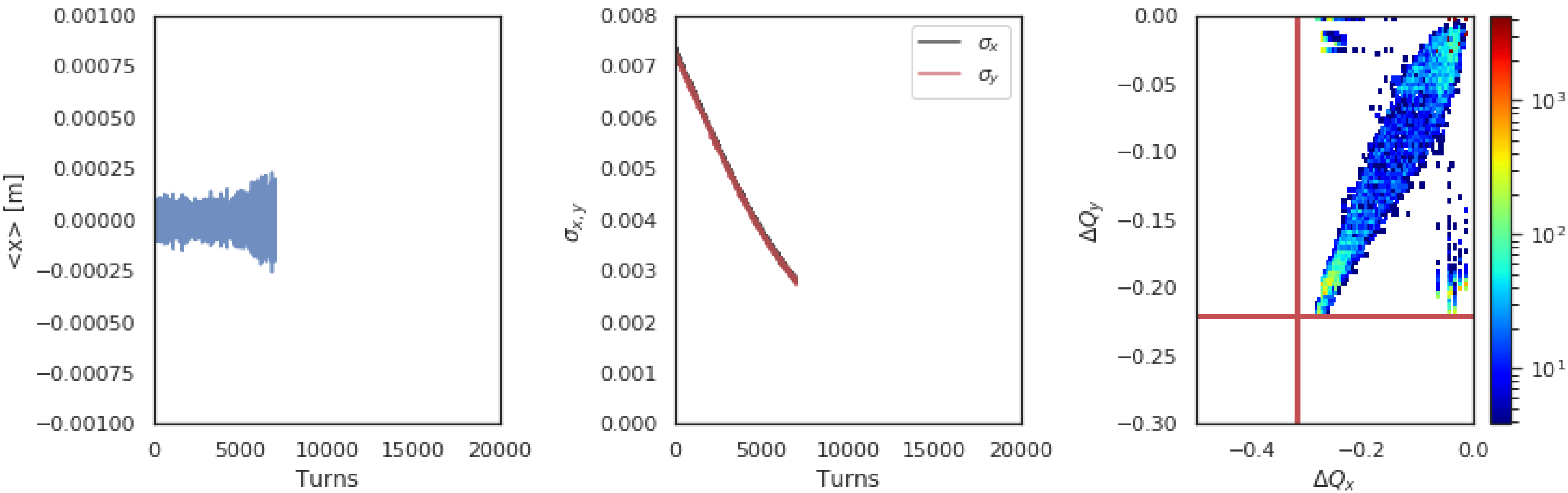

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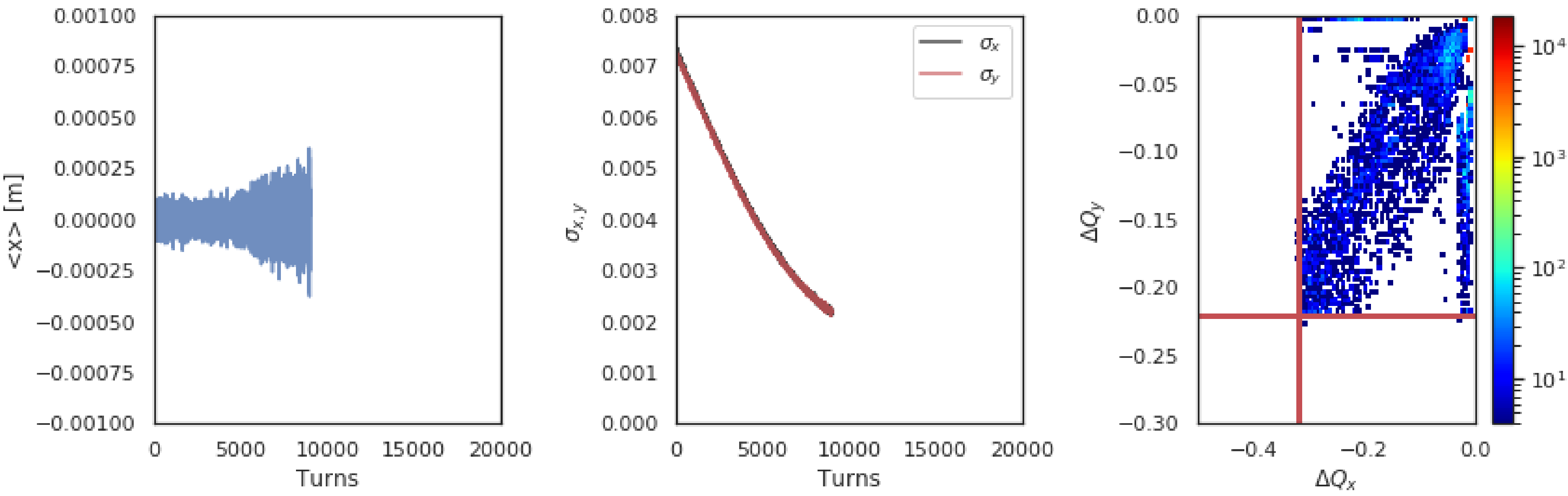

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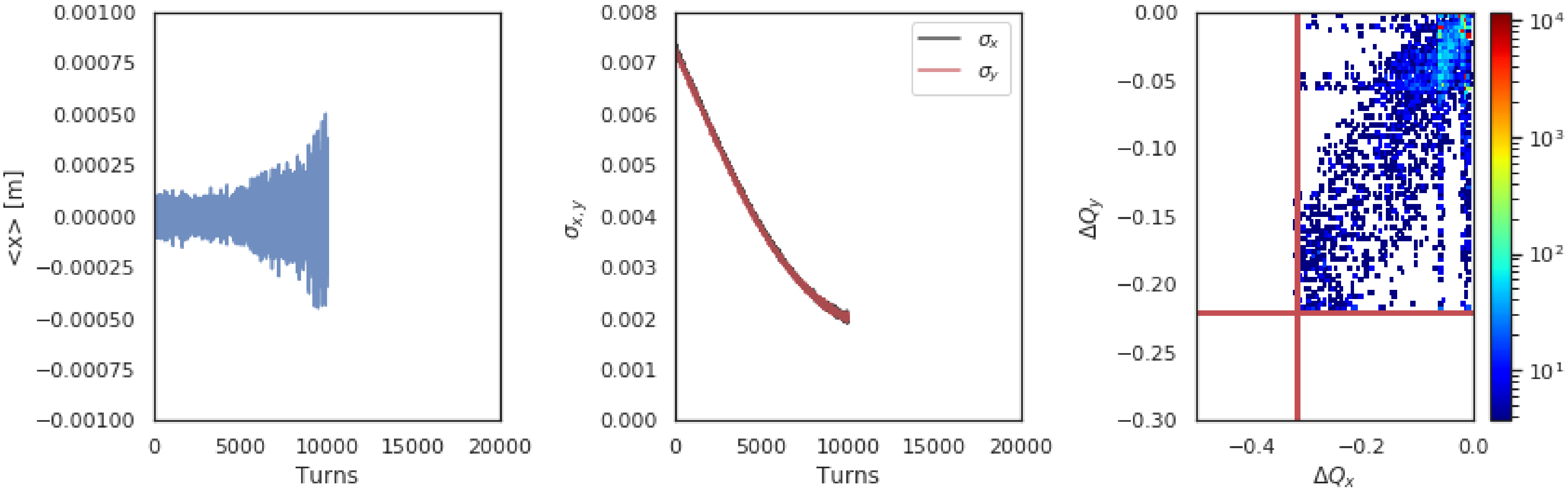

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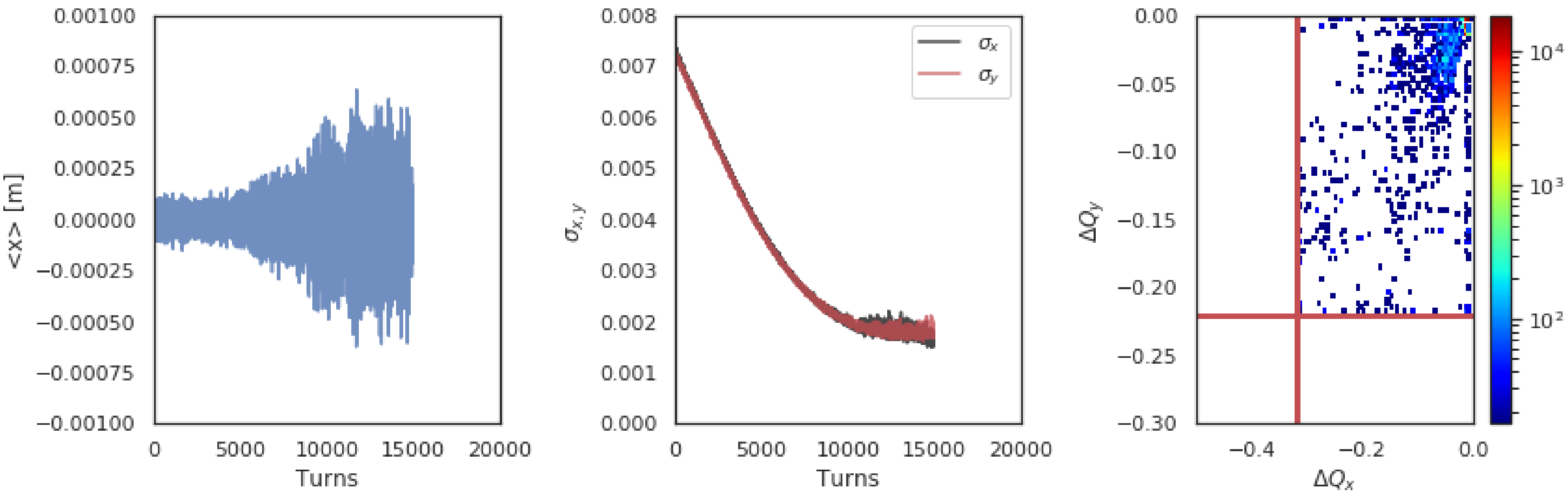

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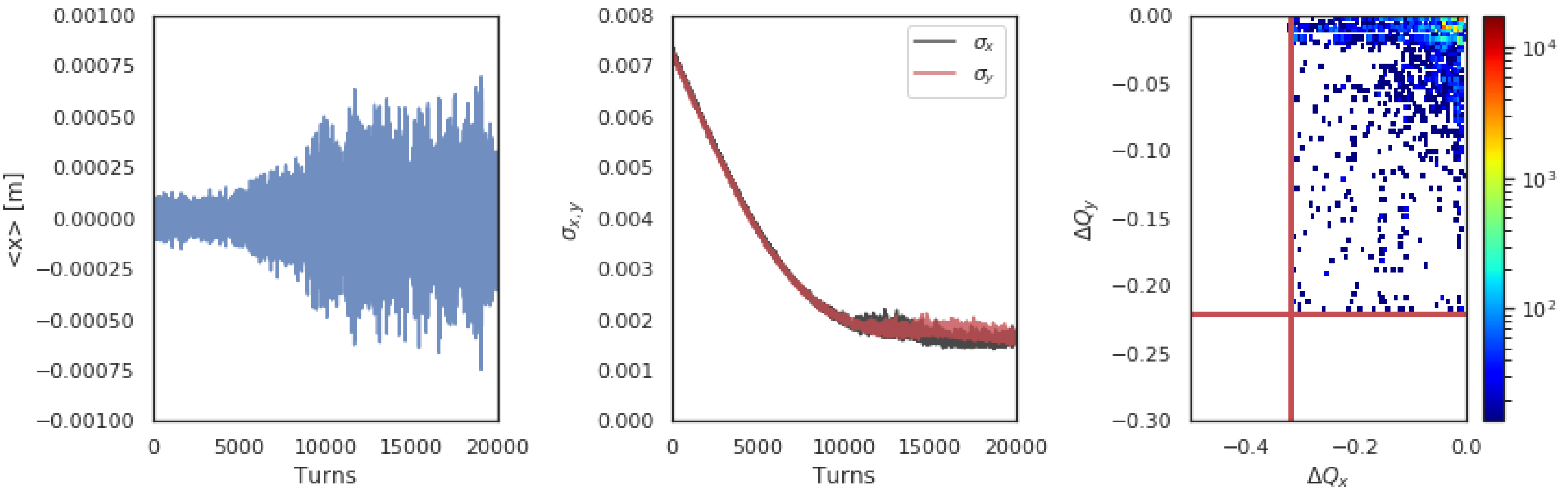
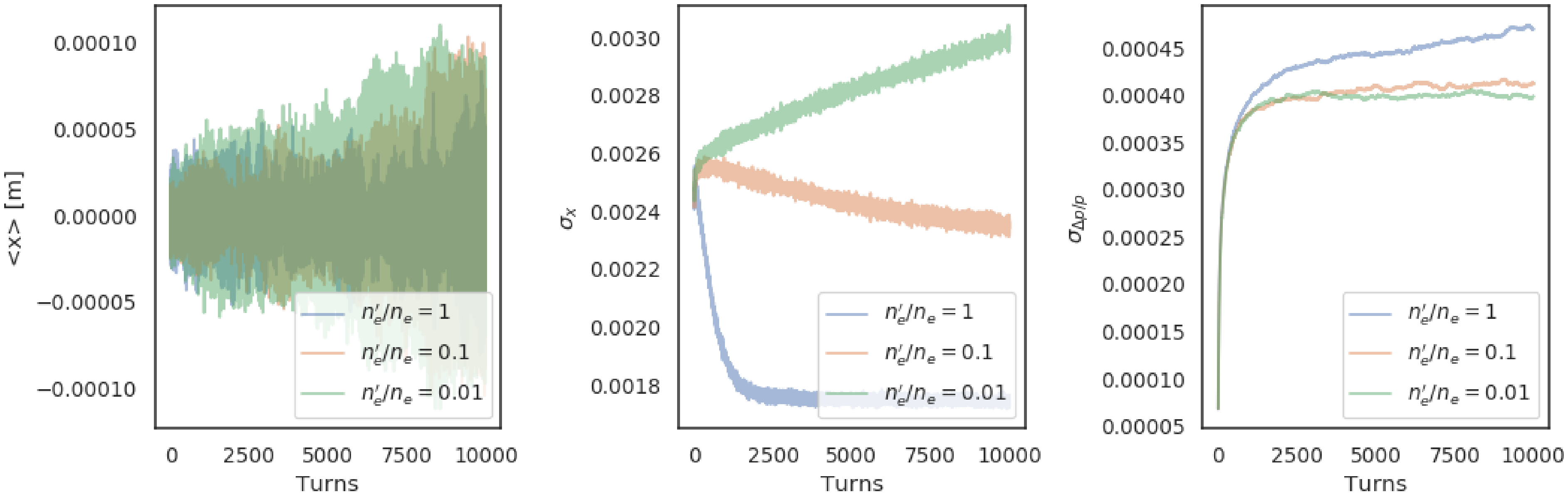


→ The simulation needs to be tuned to the final emittance accounting for the effect of cooling and space charge

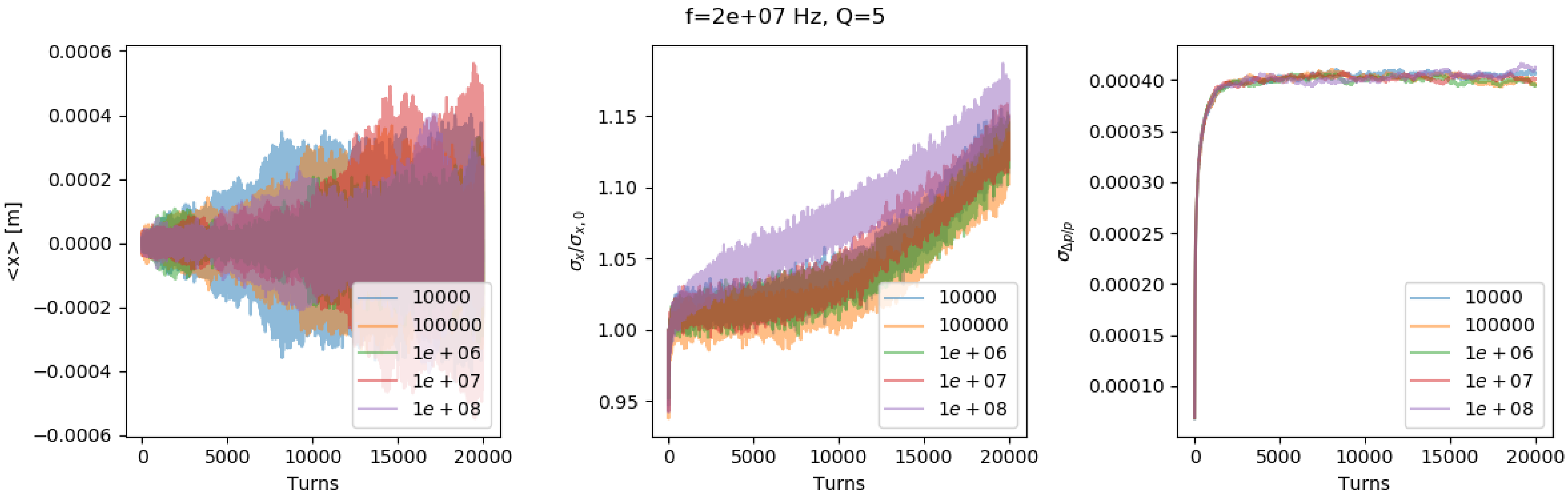
Electron cooling tuning

- Decreasing the transverse cooling force we can get to an equilibrium representative of machine conditions.
- It may represent the effect of angle/offset.



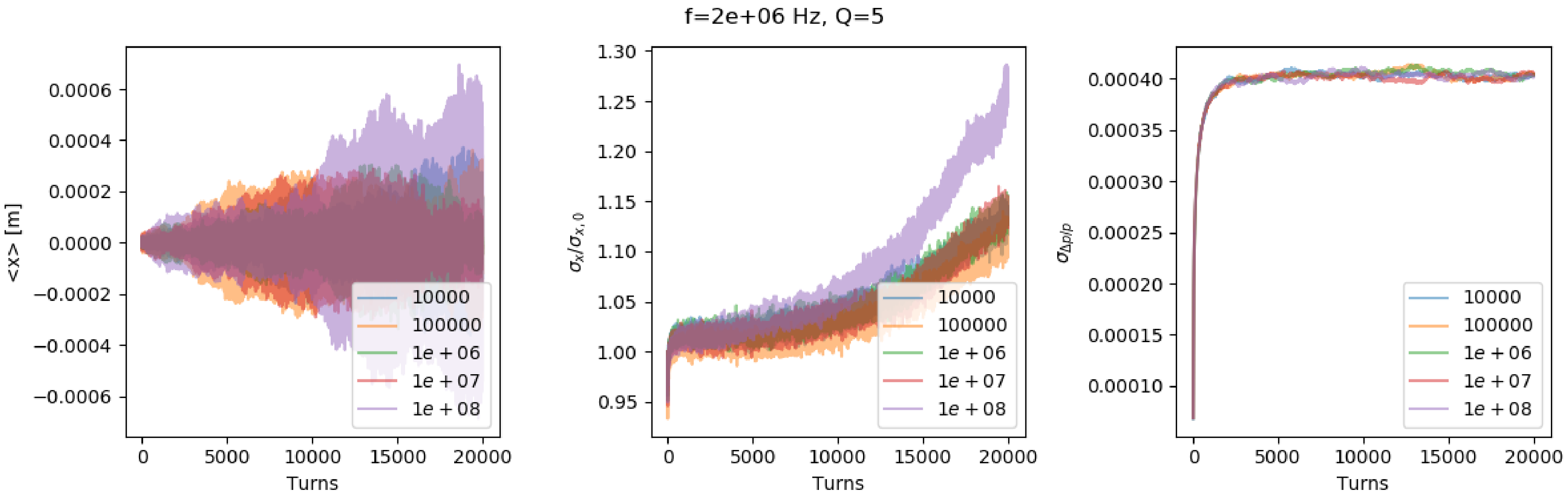
Scan on HOM

- HOM: Rs=variable , Q=5, f=20 MHz
- Uniform distribution in momentum $\frac{\Delta p}{p} \in \left[-\left.\frac{\Delta p}{p}\right|_L , \left.\frac{\Delta p}{p}\right|_L \right]$
- With cooling, with space charge



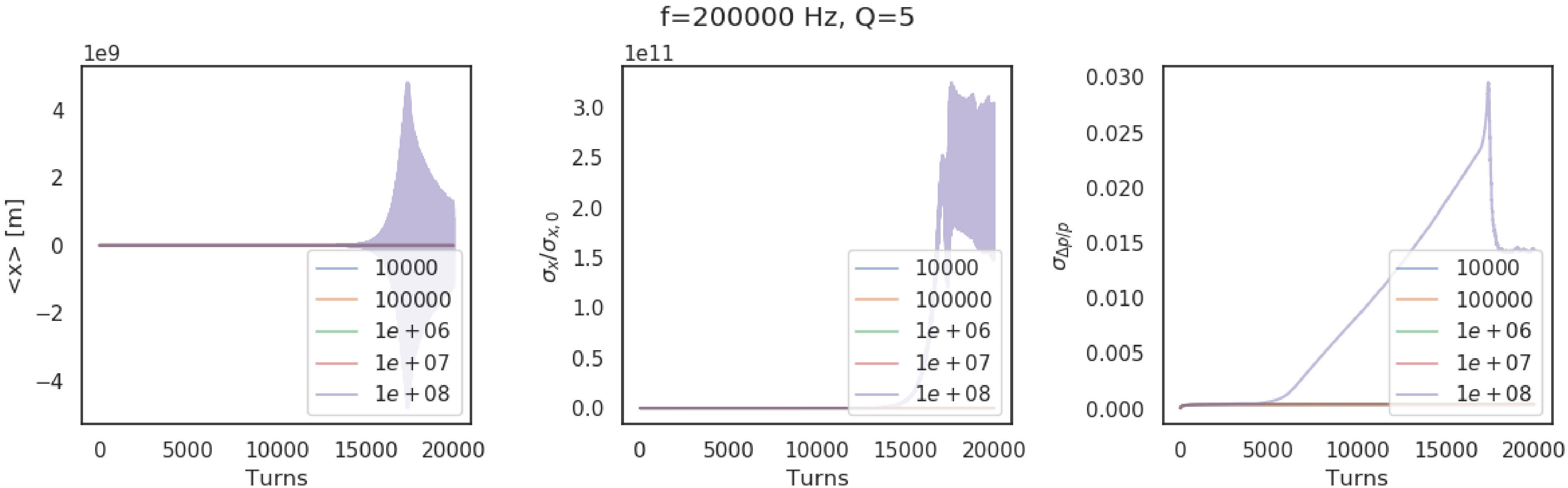
Scan on HOM

- HOM: Rs=variable , Q=5, f=2 MHz
- Uniform distribution in momentum $\frac{\Delta p}{p} \in \left[-\frac{\Delta p}{p}\Big|_L , \frac{\Delta p}{p}\Big|_L \right]$
- With cooling, with space charge



Scan on HOM

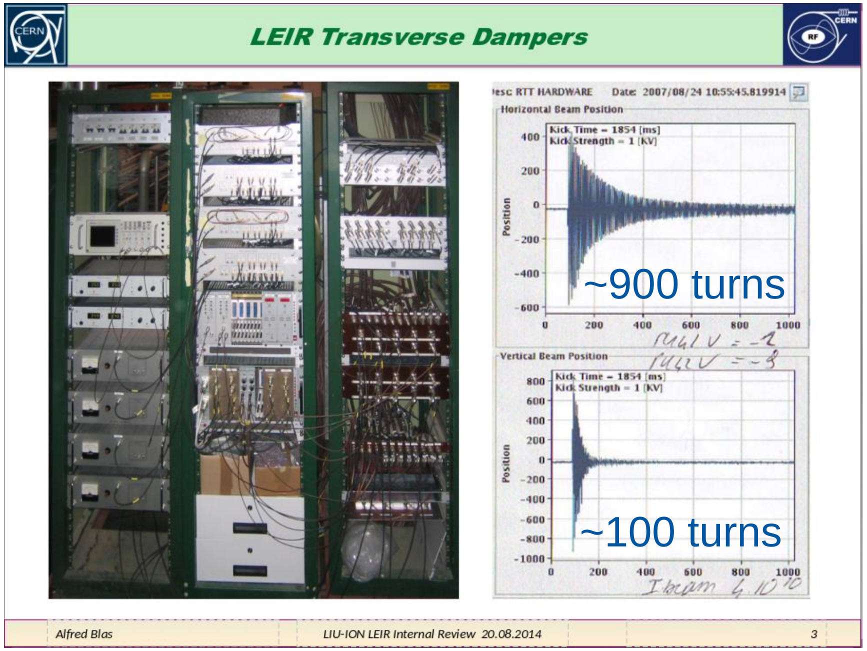
- HOM: Rs=variable , Q=5, f=200 kHz
- Uniform distribution in momentum $\frac{\Delta p}{p} \in \left[-\frac{\Delta p}{p}\Big|_L , \frac{\Delta p}{p}\Big|_L \right]$
- With cooling, with space charge

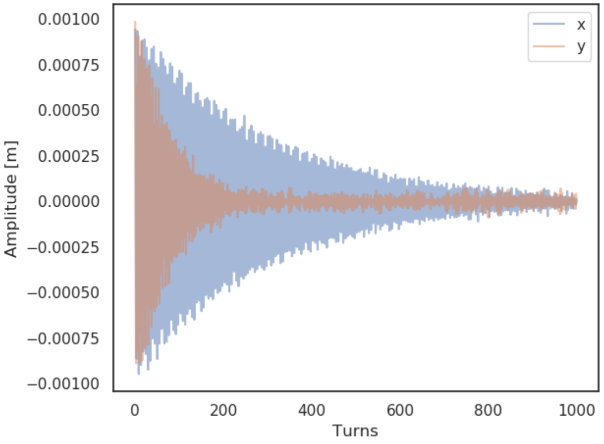


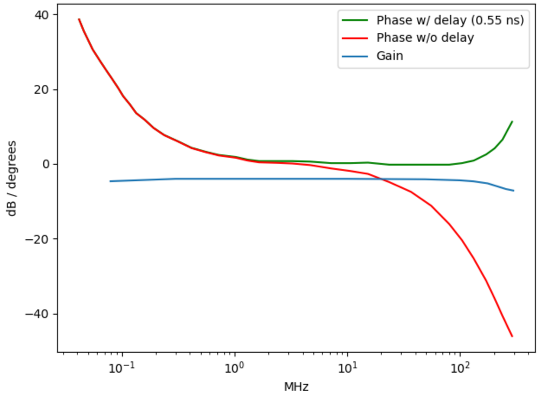
Only low frequency HOMs drive instability in presence of space charge and cooling.

Damper modeling

Old measurements from A.Blas and team in 2014.





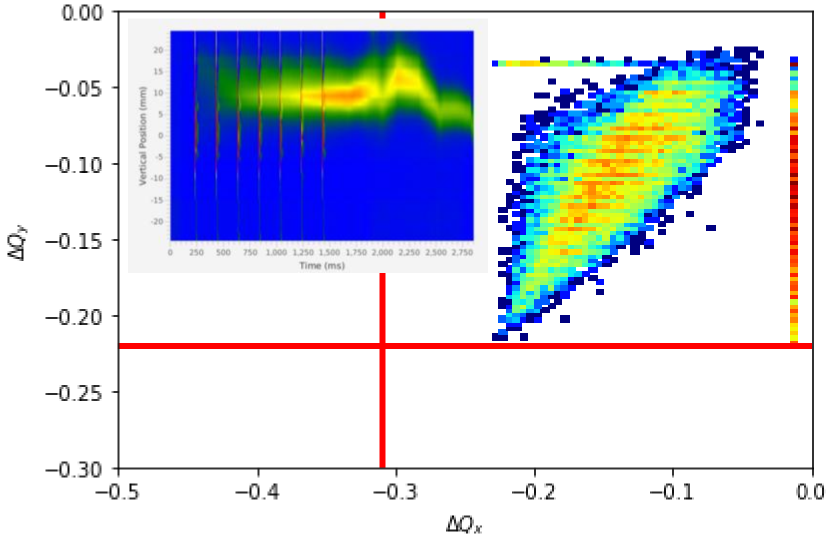


Modeled as an impedance.

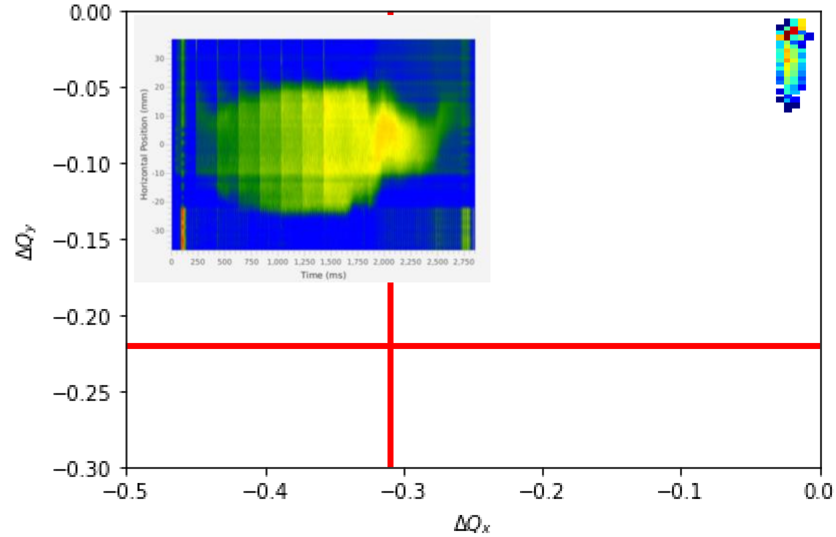
- Gain calibrated to damping time (G_H, G_V)~(1e8, 4e8).
- Phase function as in the measurement

Emittance at high intensity

Due to the horizontal angle in the cooler, the horizontal emittance is ~ 5x the vertical one, i.e. the space charge is largely reduced.



$\sigma_x, \sigma_y = 3mm, 3mm$



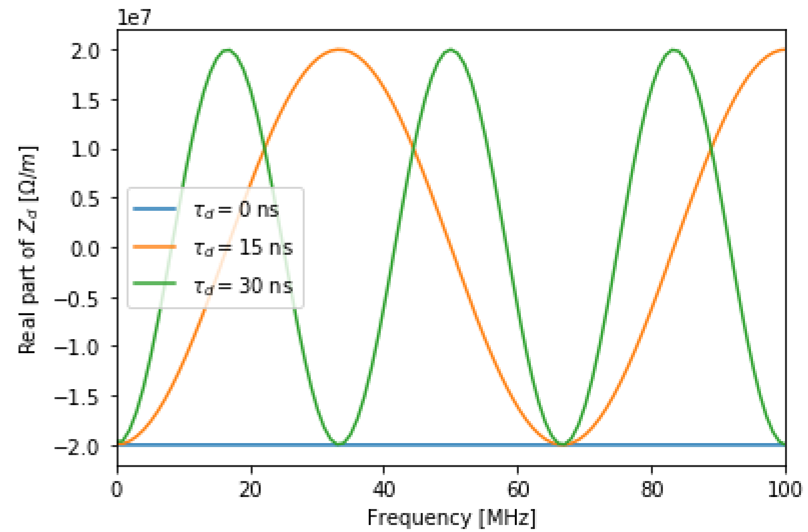
$\sigma_x, \sigma_y = 15mm, 3mm$

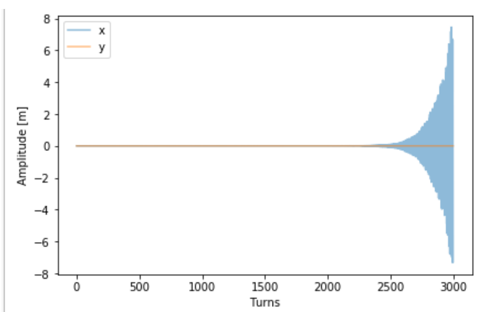
Effect of an electrical delay

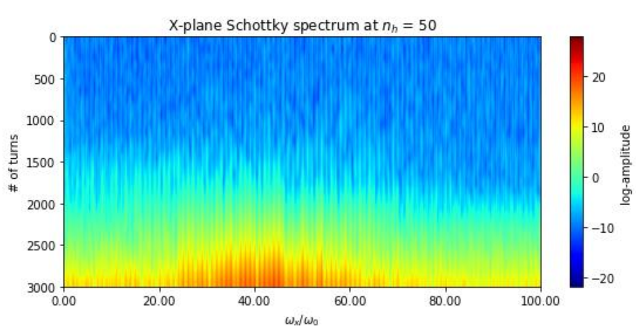
We tried to investigate (preliminarily!) the effect of the electrical delay.

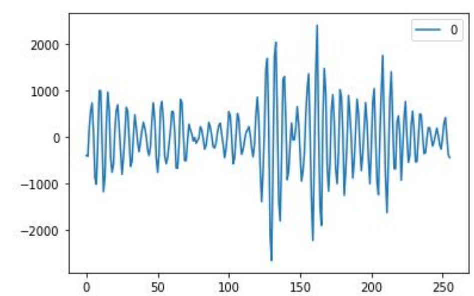
For an electrical delay of 15 ns:

- Similar frequency content and unstable trace but too fast.
- To be continued with damper gain / delay systematic scans.









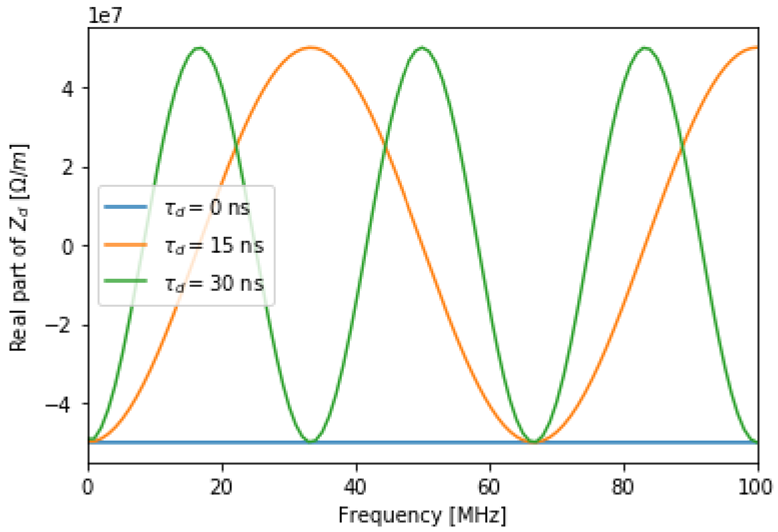
Summary and outlook

- PyHT for coasting beams was further developed to account for space charge (longitudinal and transverse), electron cooling and feedback.
- Full 7-injections simulations are possible even though long to perform.
- Tried to reproduce horizontal instability with HOM source with a single injection at 10e10 c:
  - Instability develops without space charge.
  - With space charge, the transverse cooling needs to be reduced to achieve equilibrium (otherwise hitting half integer resonance).
  - With space charge and cooling, only low frequency (200 kHz range) modes are unstable with large impedance values ($R_s > 10^8\ \Omega/m$)

- Operation with damper is observed to produce worse instabilities than without it: some configuration optimization is needed.
  - Preliminary investigation on the effect of an electrical delay: together with the large feedback gain could lead to instabilities as the observed ones.

Backup

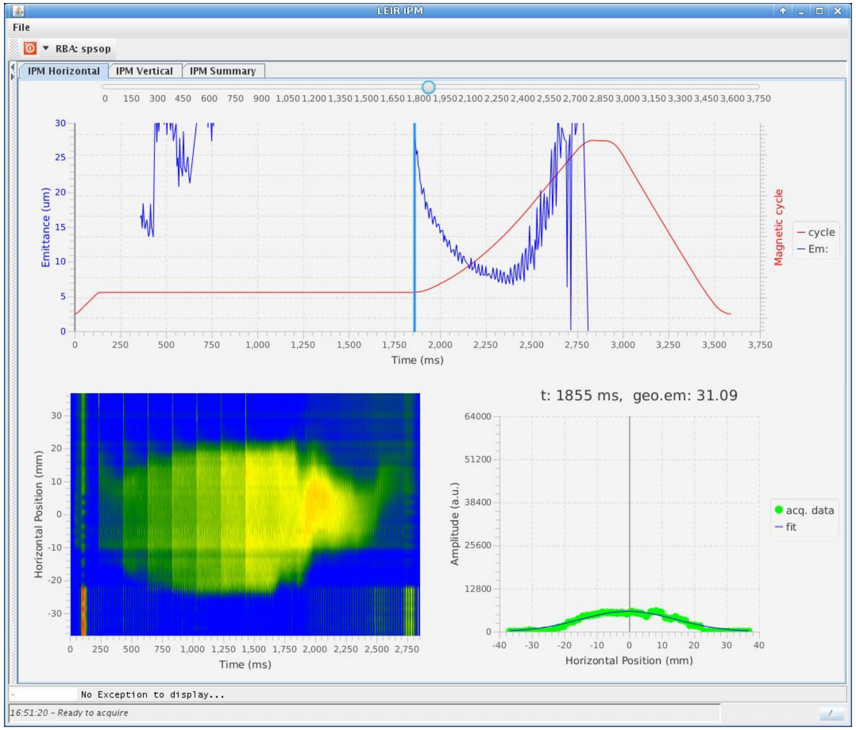
Electrical delay



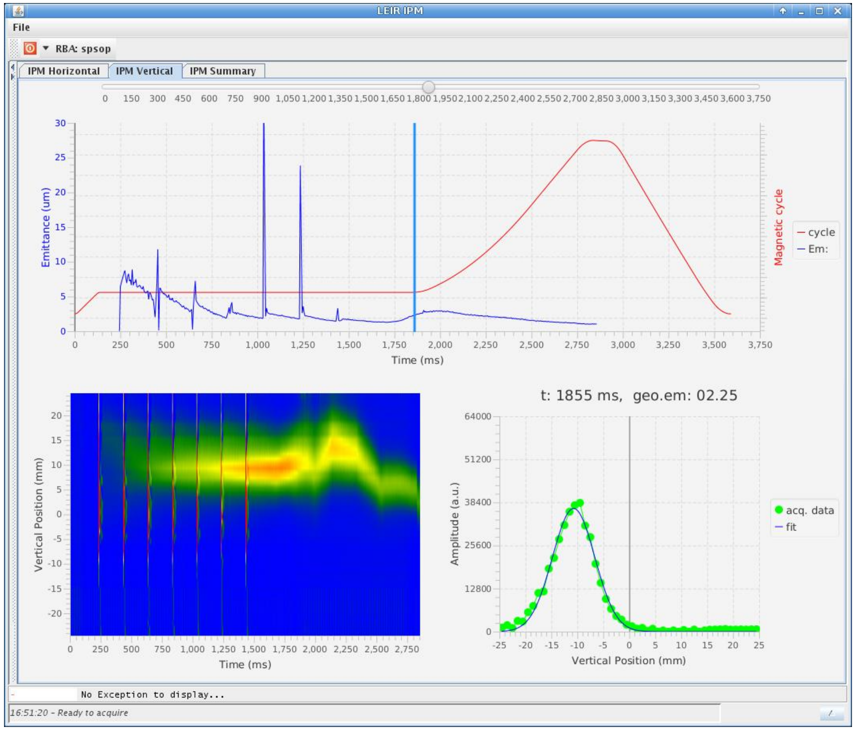
For a gain of $5e7$

IPM for NOMINAL

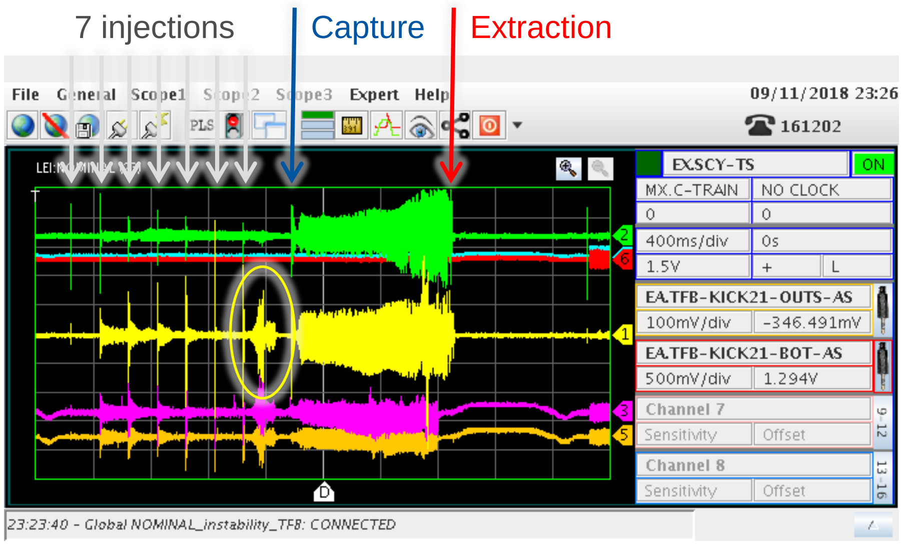
H: 10 mm

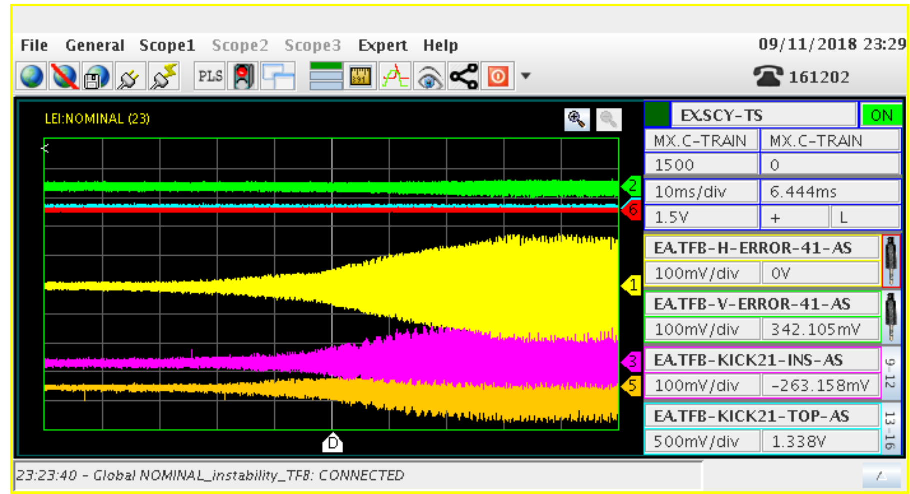


V: 2 mm



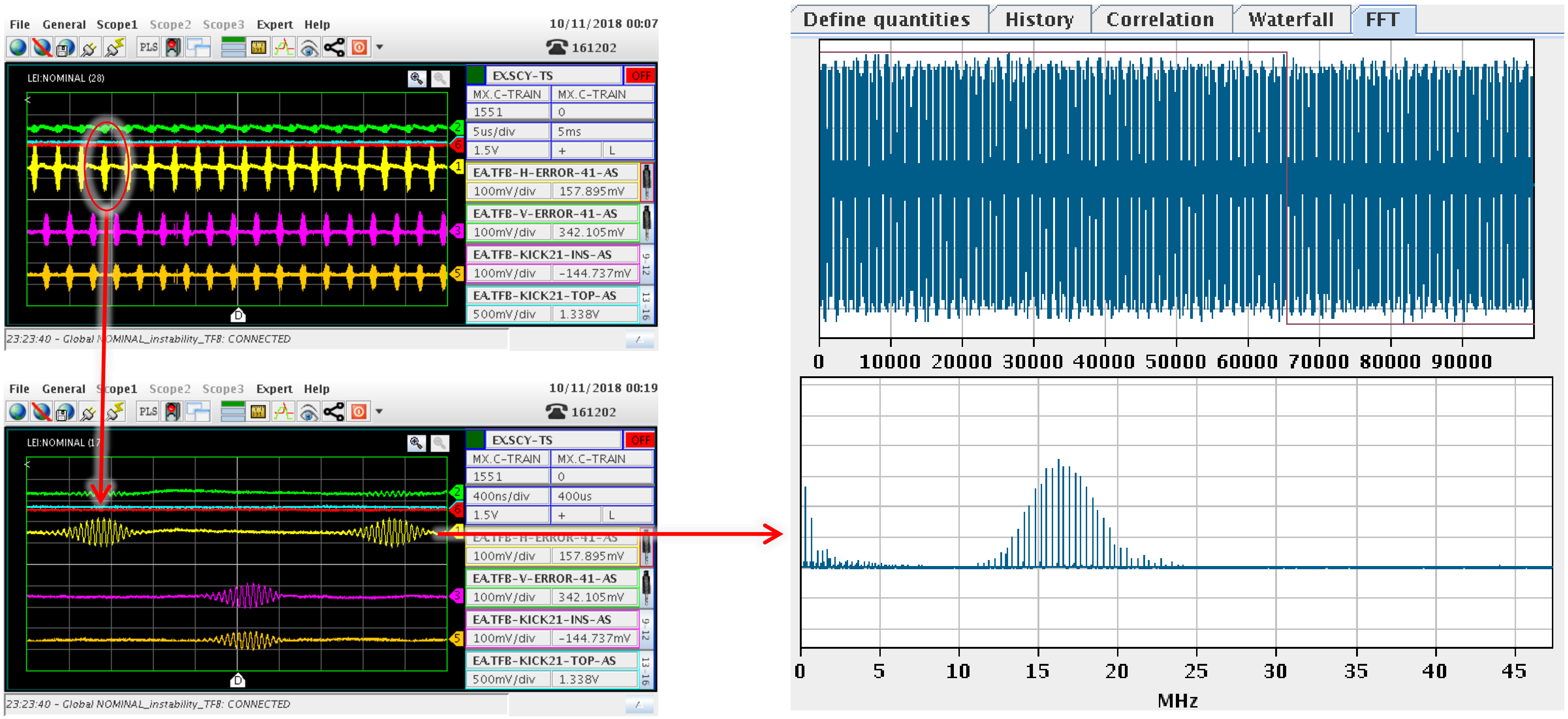
Coherent motion





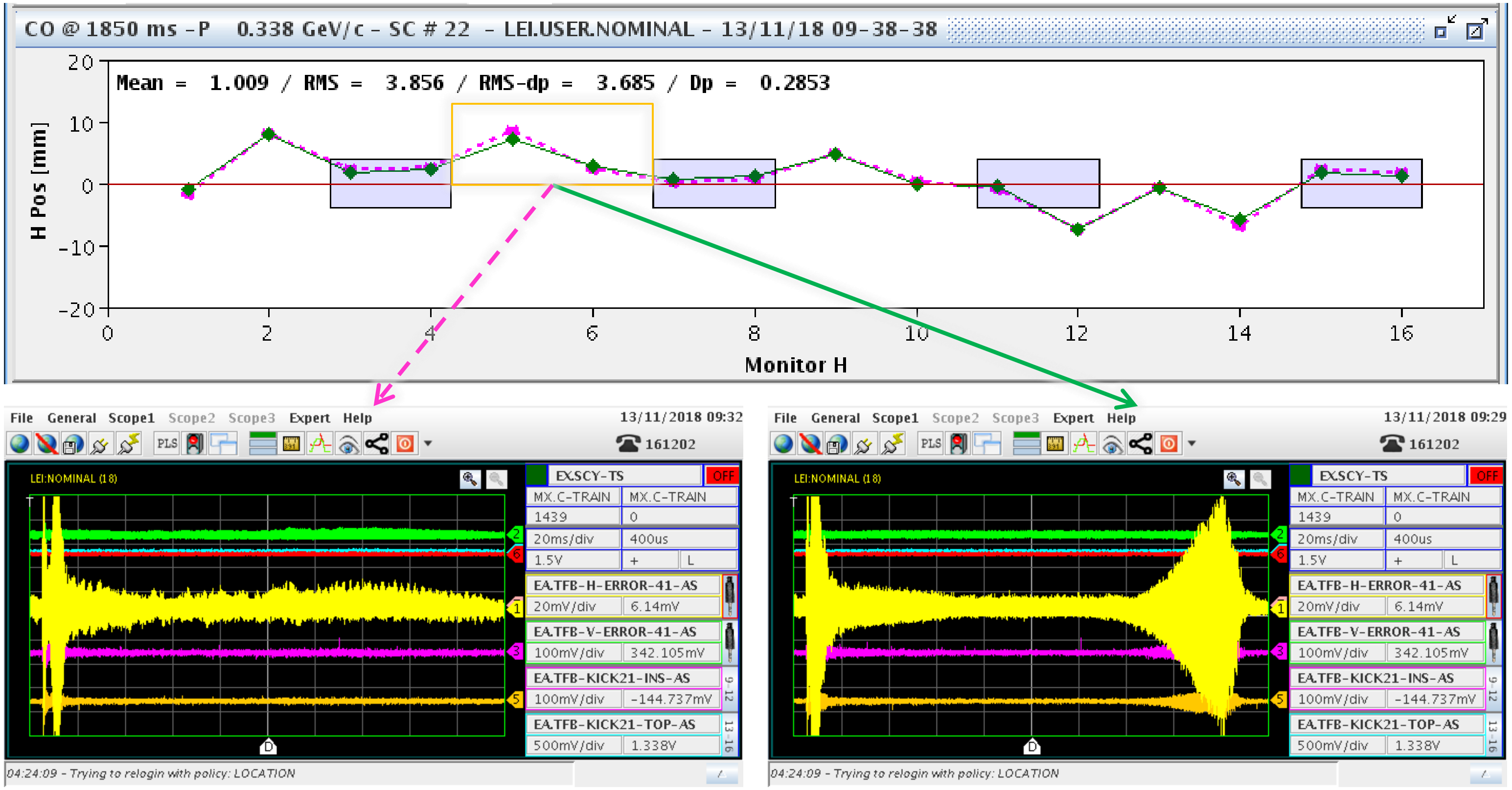
- Beam looks horizontally unstable.
- Doubles amplitude in $\sim 20\ ms \rightarrow \tau = \frac{20}{\ln 2} \simeq\ 28\ ms$ [~ 10k turns]
- Damper was in operation (and properly checked by GerdK)

Frequency content



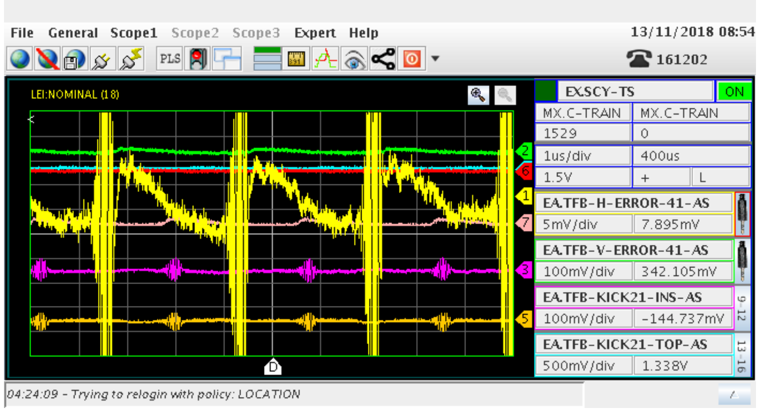
- Large amplitude from 10 to 20 MHz.
- HOM? $f_r \sim 17$ MHz, $Q \sim 3 - 4$

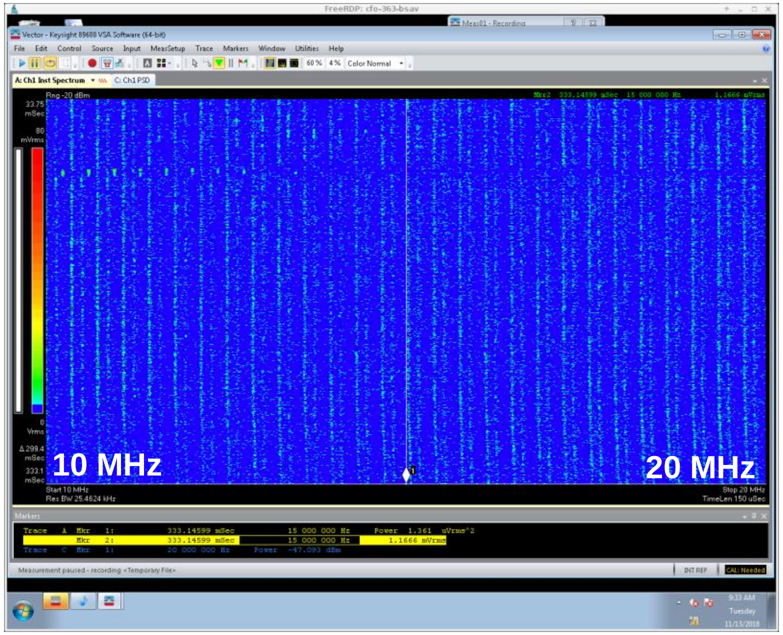
Small angle trim cures the instability

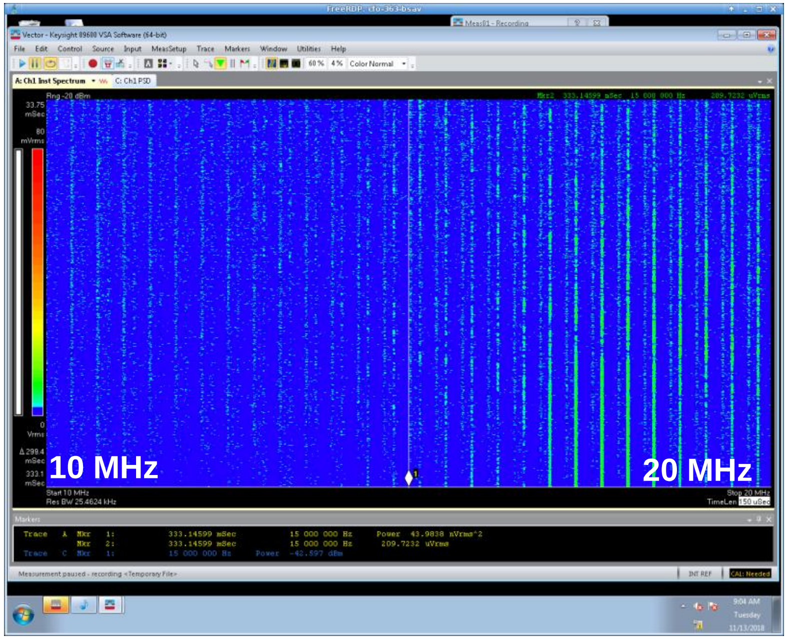


Changing angle (0.5 mrad!) in the cooler directly affects the final H emittance and momentum spread → direct knob on stability diagram!

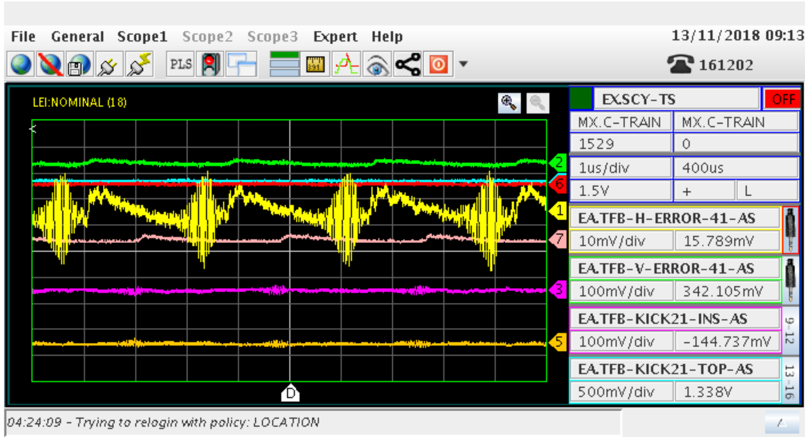
Stable vs Unstable

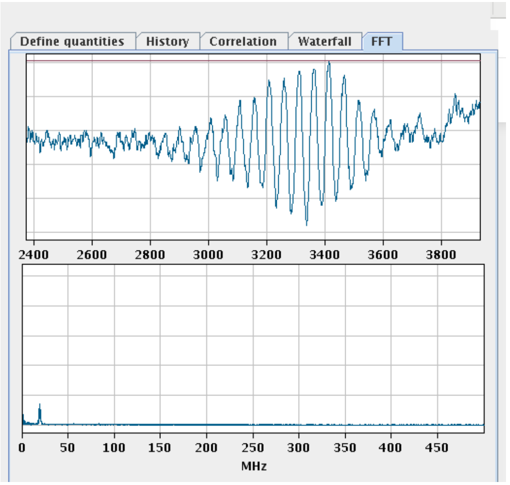


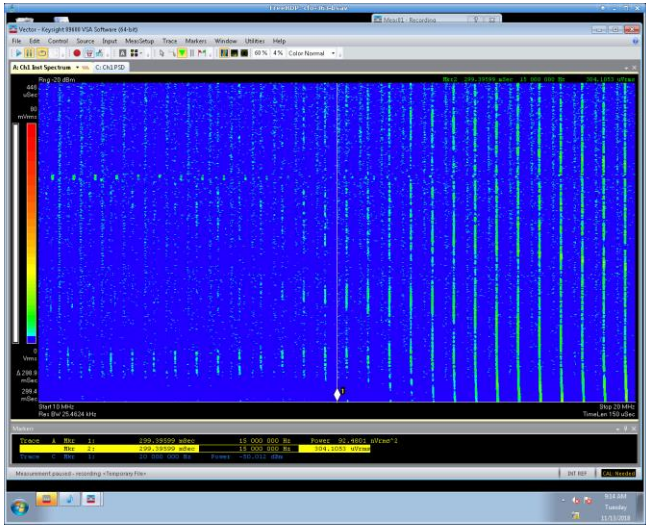


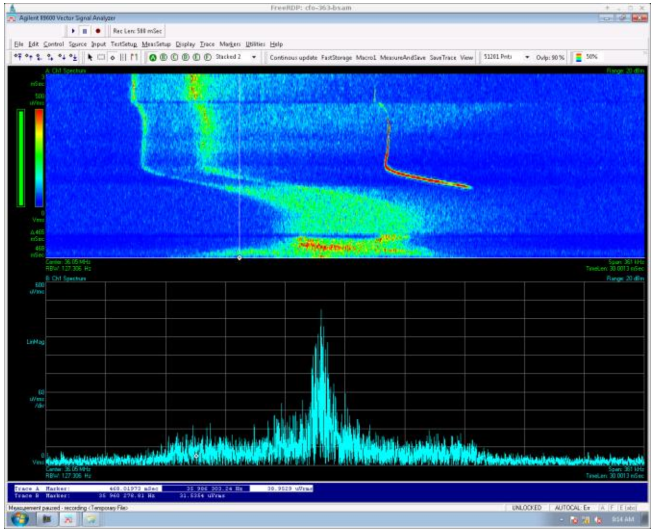


An other shot









Longitudinal SC kick

$$\frac{dZ_{\|}}{dz} = j\frac{Z_0\omega}{2\pi\beta^2\gamma^2 c}\left(\frac{1}{2} + \log\frac{b_e}{r_b}\right).$$

$$W_l(\bar{u}_S, \bar{u}_T, s) = \frac{1}{2\pi}\int_{-\infty}^{\infty} Z_l(\bar{u}_S, \bar{u}_T, \omega) e^{-j\omega s/v}\, \mathrm{d}\omega,$$

recall

$$\delta'(ax) = \pm\frac{1}{a^2}\delta'(x)$$

$$f(t) = \int F(\omega)\, e^{-j\omega t} d\omega \qquad \frac{\partial f(t)}{\partial t} = \int (-j\omega F(\omega)) e^{-j\omega t} d\omega$$

$$Z_l(\omega) = j\frac{Z_0\omega C}{2\pi\beta^2 c\,\gamma^2}\left(\frac{1}{2} + \log\left(\frac{r_p}{r_b}\right)\right) \qquad g = \left(\frac{1}{2} + \log\left(\frac{r_p}{r_b}\right)\right)$$

$$W_l(s) = \frac{1}{2\pi}\int j\omega/\omega_0 \frac{Z_0}{\beta\gamma^2} g e^{-j\omega s/v} d\omega =$$

$$= -\delta'\left(\frac{s}{v}\right)\frac{Z_0}{\beta\gamma^2\omega_0} g = -\delta'(s) v \frac{Z_0 R}{\beta\gamma^2} g$$

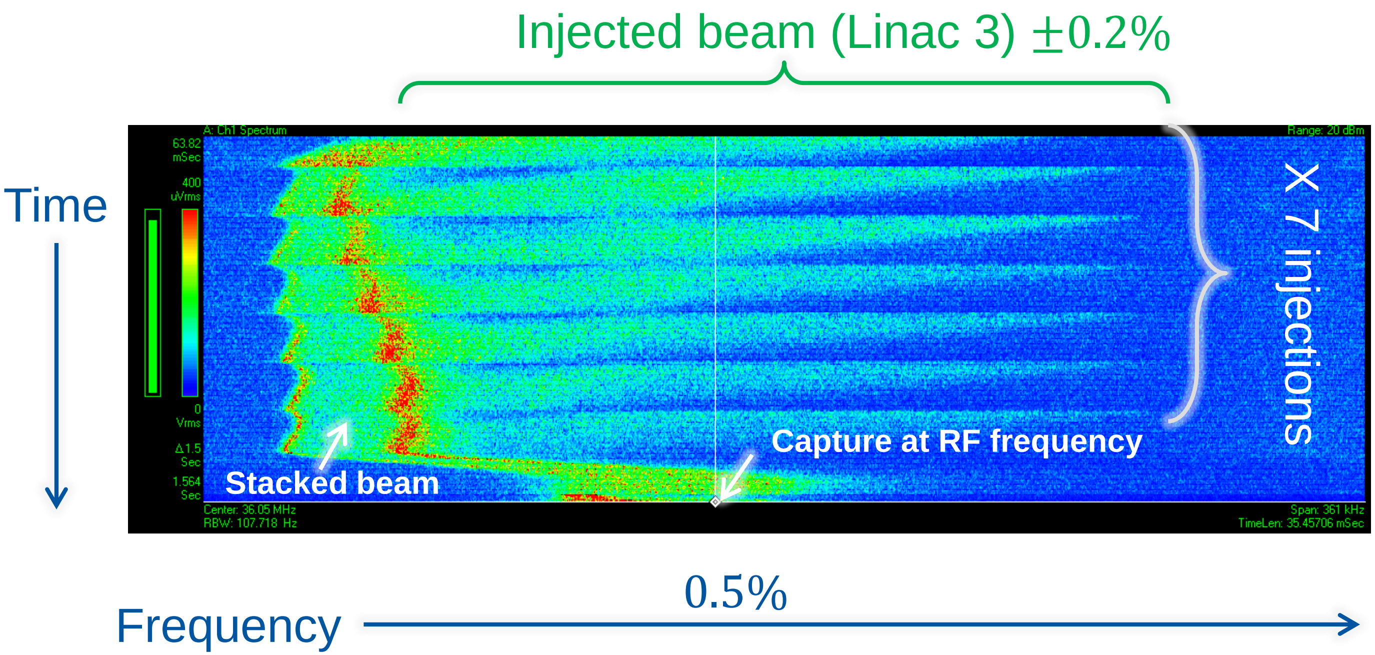
$$= -\delta'(s)\frac{Z_0 cR}{\gamma^2} g$$

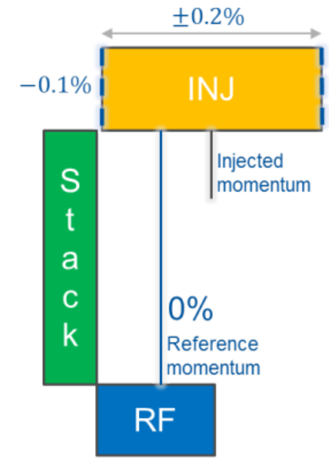
$$W_{pot}(s) = W_l(s) * \rho(s) = \delta'(s) Z_{SC} * \rho(s) = Z_{SC} * \frac{\partial\rho}{\partial s}$$

$$\frac{Z_l(\omega)}{n} = j\frac{Z_0}{\beta\gamma^2} g$$

$$Z_{SC} = -\frac{Z_0 cR}{\gamma^2} g$$

LEIR longitudinal Schottky spectrum





- Complex gymnastics to inject, drag and capture the 7 injections from Linac3