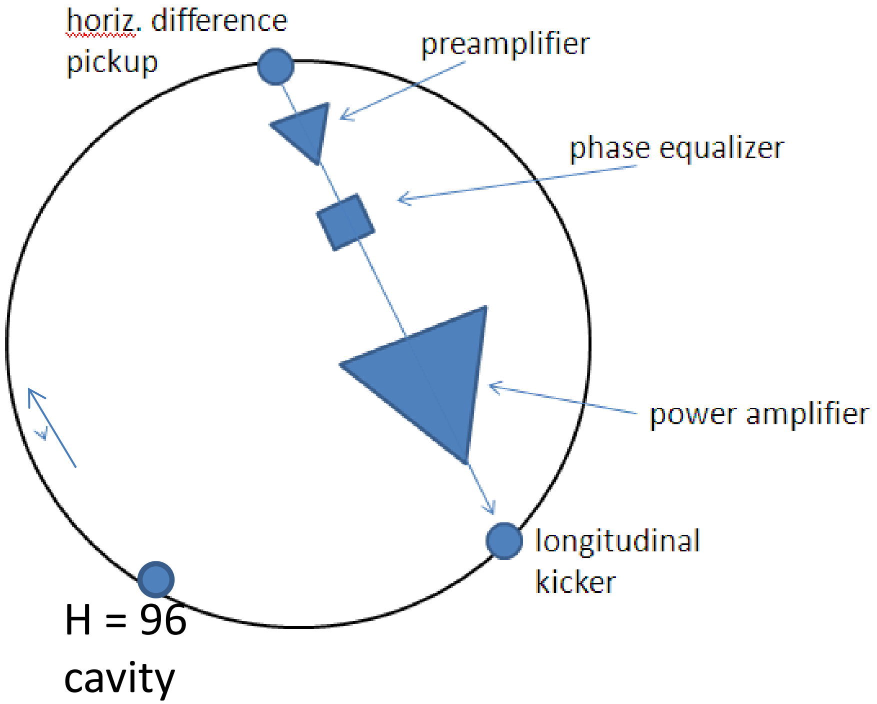
Time-domain bunched beam stochastic cooling in NICA with Palmer radial pickup method.

Lars Thorndahl, Cern

Approach: follow 1e4 particles during 1.200 turns as a simulation for 1e9 ions in NICA during 120e6 turns (~ 200 s) [1] (typical Nica example).

For each ion on each turn at the kicker, kicks caused by signals from all ions are applied (and also the kick from the H = 96 bunching cavity).

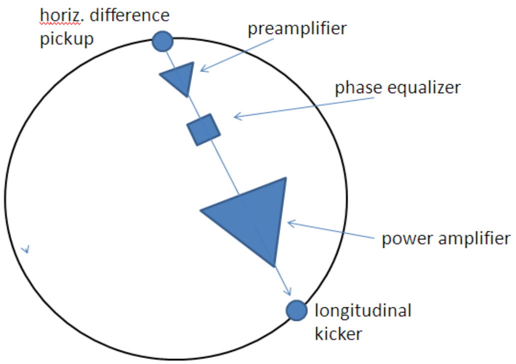
Advantages: 1) Effects of synchrotron oscillations are included automatically.
2) The beam feedback effect: change of Schottky signals when the feedback loop is closed (check on instabilities)



Six system elements are given in the freq. domain:

1) Single bunch dirac pulse
2) Loop pickup, horiz. difference
3) Preamplifier 3-6 GHz
4) Phase equalizer
5) Power amplifier 3-6 GHz
6) Longitudinal loop kicker

All elements are cascaded (by multiplication) in the freq. domain.
An inverse Laplace transformation yields the time-pulse at the kicker:



assume single ion in the bunch

freq. domain:

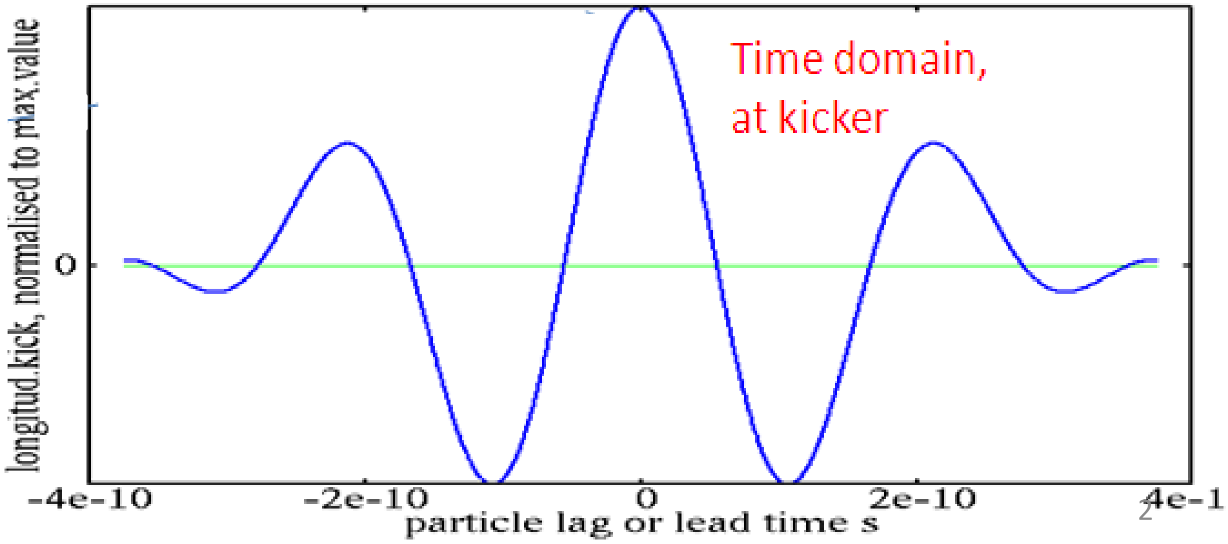
Single-ion Dirac function:

Integral of $2q$ df over the working band real! q: charge/ion

pickup & kicker: sin ($\pi f/9$ GHz) real!

preamplifier x phase equaliser x power amplifier: real constant value!

After LAPLACE transformation:



Time domain, at kicker

Coherent cooling effect & unwanted mixing

Unwanted mixing between pickup and kicker: (for + - 3sigma kin. energy offsets).

The feedback electric length is adjusted for the nom. particle energy.

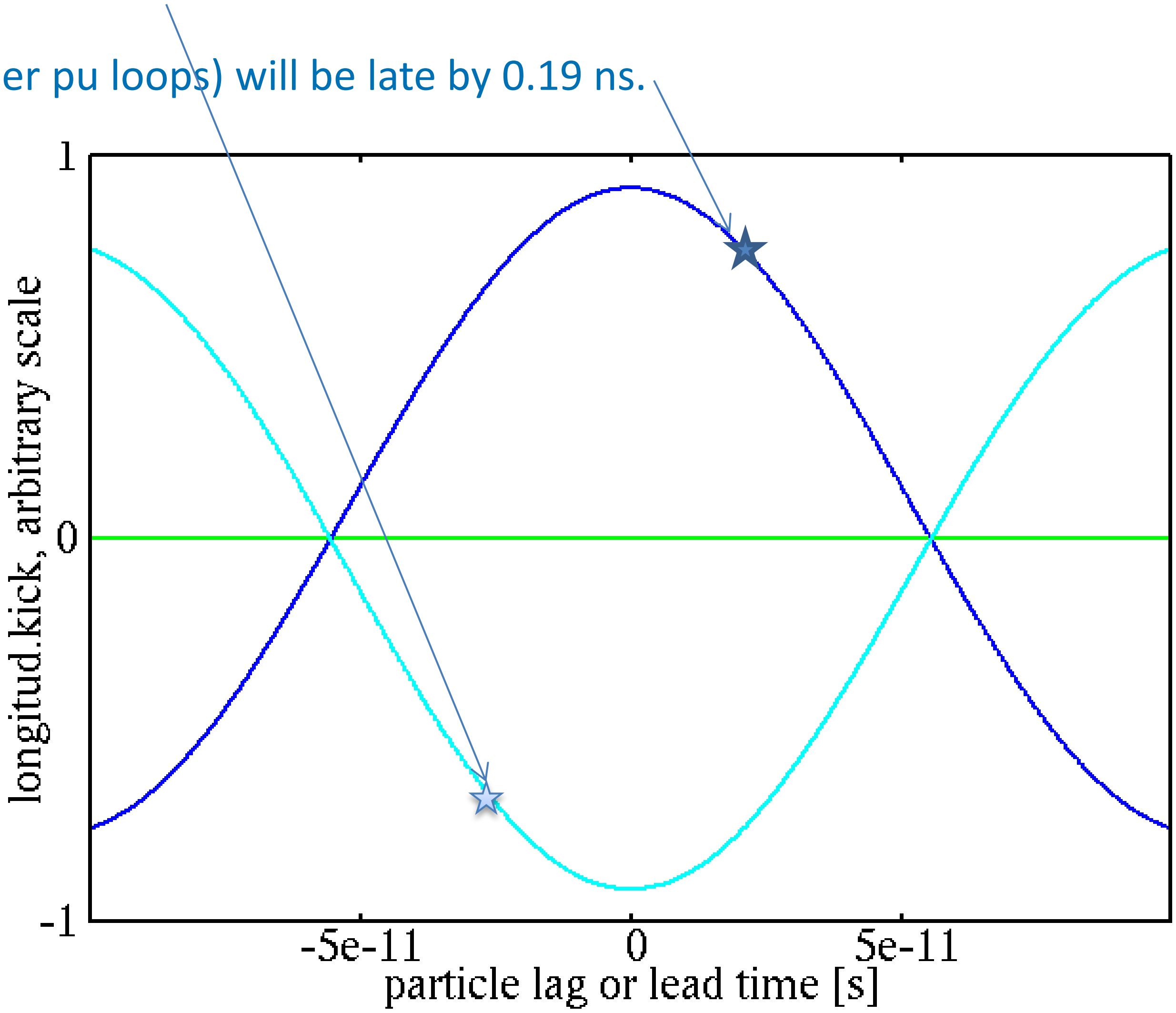
High energy particle (grazing outer pu loops) will arrive too early by 0.19 ns with respect to its pulse peak.

Low-energy particle (grazing inner pu loops) will be late by 0.19 ns.

At Kicker

System gain g:

fraction of ion energy error removed per turn (coherent effect)



Expanded time scale !

NICA RING, COOLING Phase 2, Takeshi Katayama

Initial gaussian distribution in longitud. phase plane

Circumference: 503.04 m

Gamma=4.76, particles: 1e9 ions, 197Au97

Initial rms dp/p = 0.00069 , eta = 0.02423

Initial rms length = 1.11e-9 s

cavity voltage: 500 V peak, H = 96

Time of flight pickup to kicker =0.58e-6 s

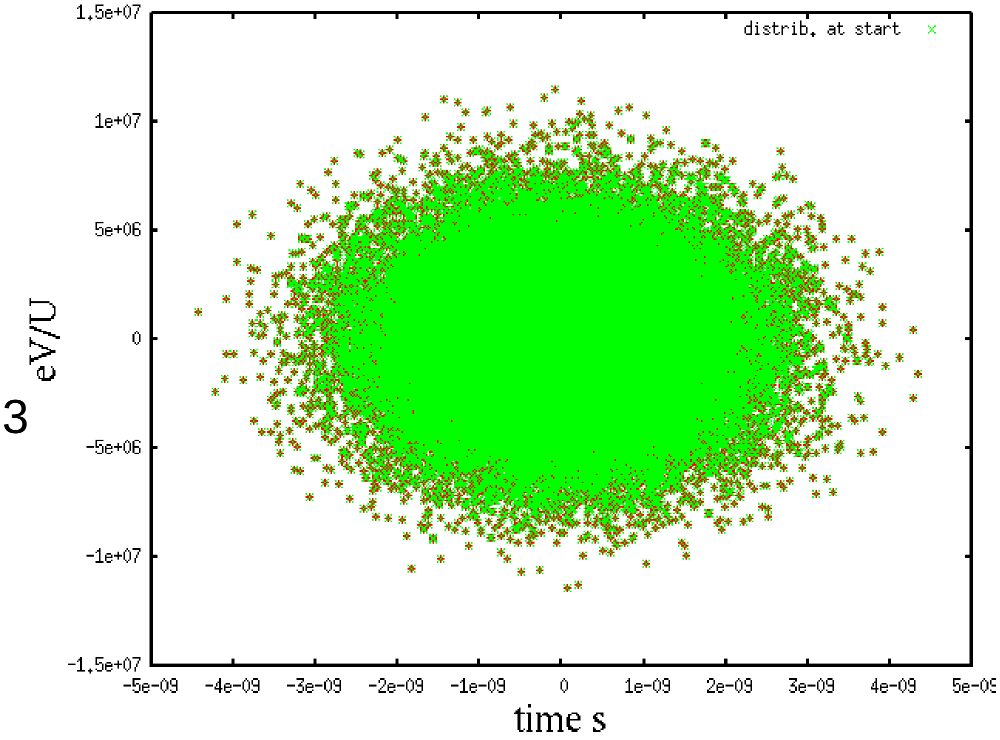
Local eta pickup to kicker = 0.014

Dispersion at pickup = 3 m

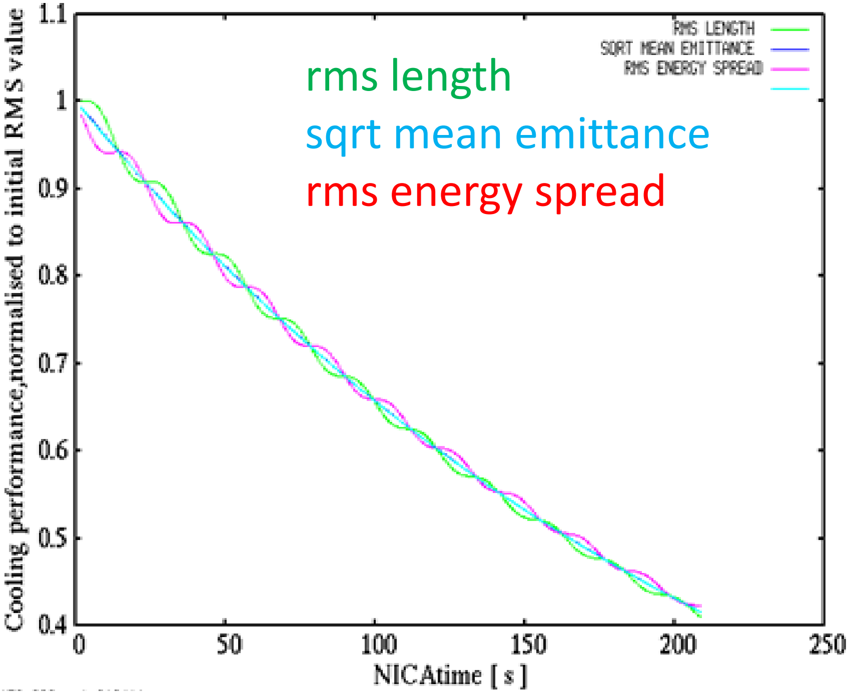
Band = 3 – 6 GHz

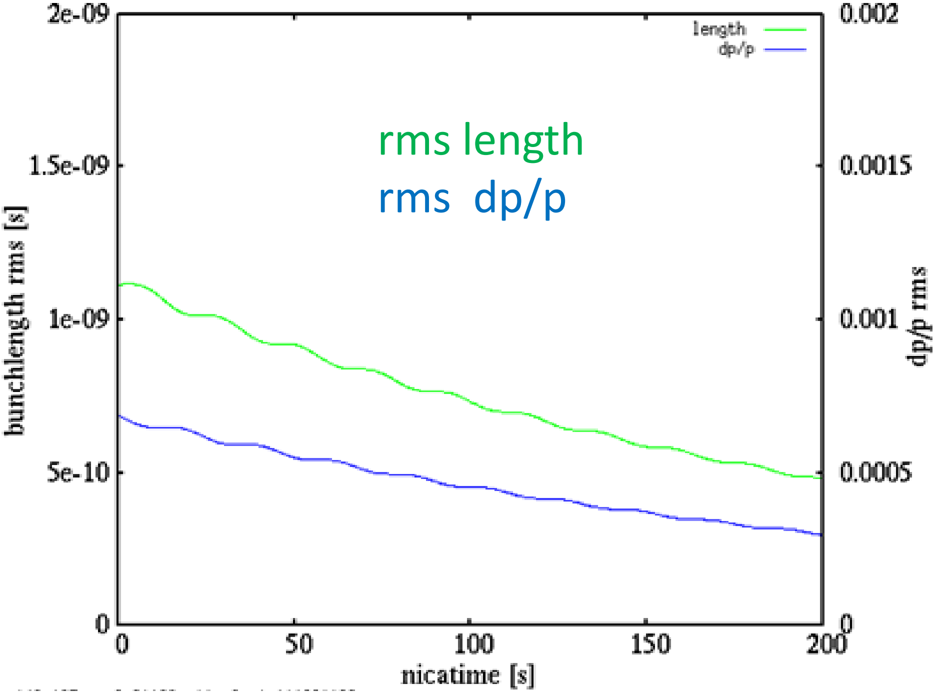
loop pick up and kicker

longitudinal phase plane



Only coherent cooling effects are accounted for:



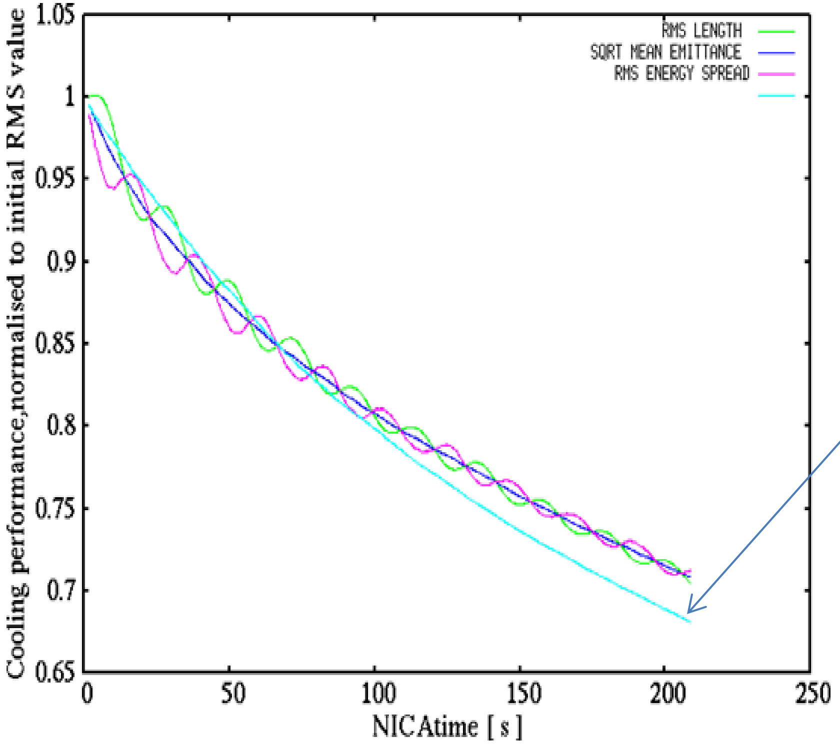


normalized with respect to initial,
60% reduction

10 000 sim. ions
gain -0.0016/turn
1200 simulation turns

Small oscillations are due to synchrotron motion!

Both coherent cooling and incoherent heating kicks are accounted for:



betatron rms amplitude

Only 30% reduction instead of 60% !

About 4 hours on HP 7900 pc !

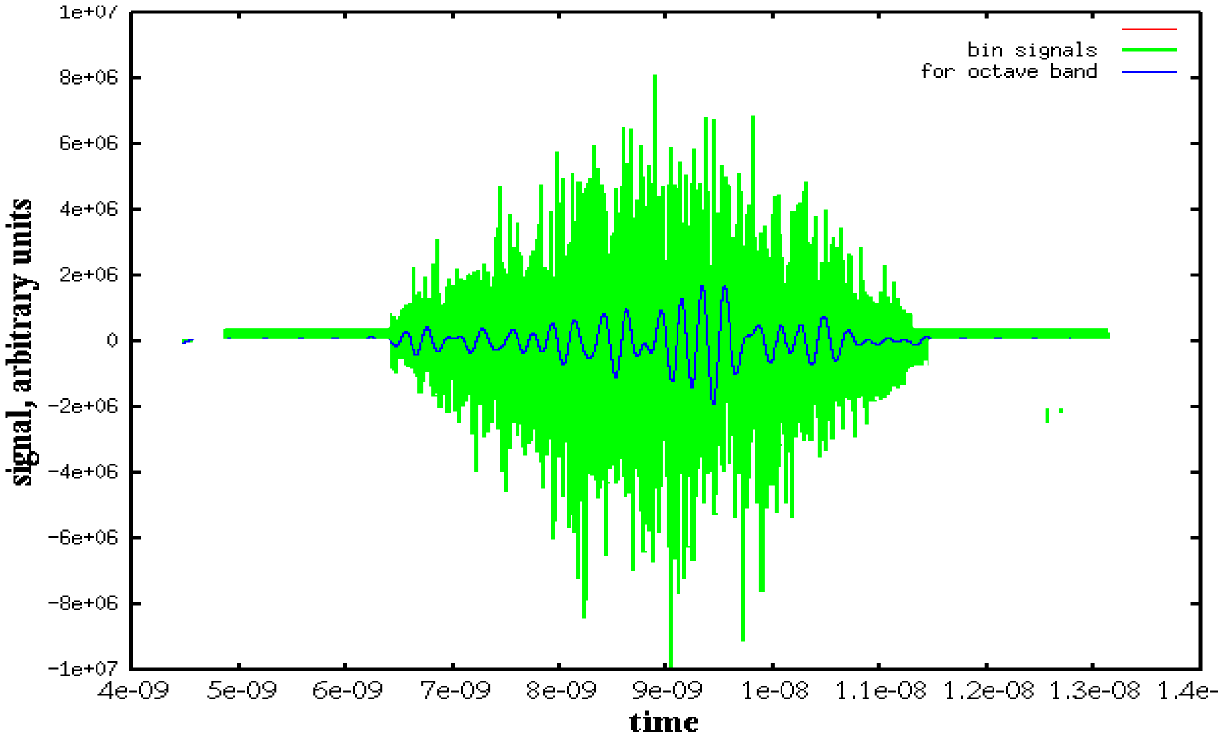
Computation time proportional to N++3

Binning of pickup time signal to reduce the computation time

Daniel Schulte

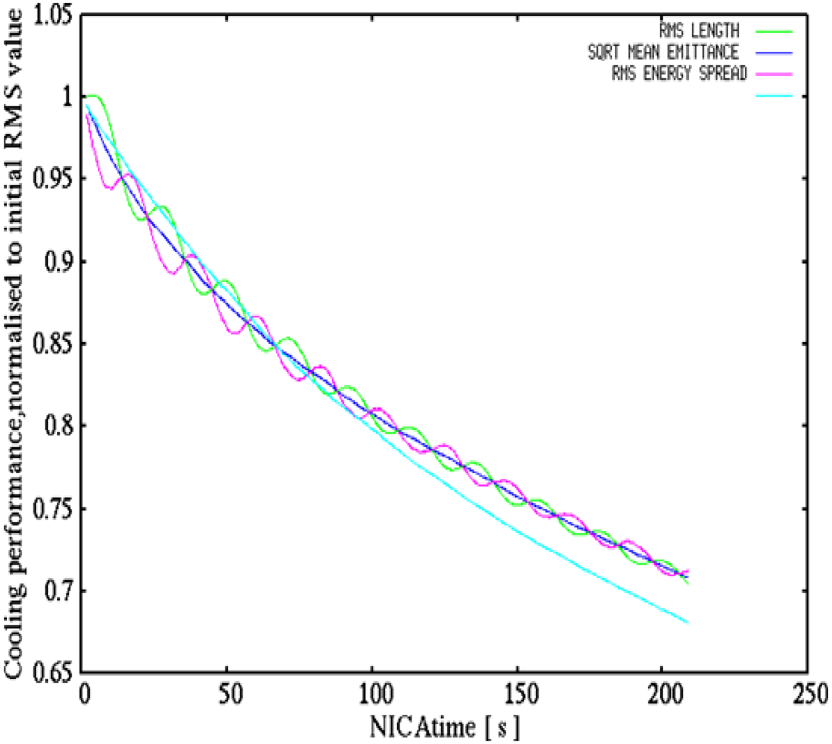
- At each turn, after the pickup, a sorting procedure places in chronological order the N ions in M bins with weights proportional to their energy deviation from the nom. energy. There are typically M = 2**14 bins in the bunching cavity period (~ 15 ns). See green background.
- An FFT computes M/2 complex harmonics of the global bunch signal.
- The 6 system characteristics (pu, preamplifier, phase equaliser, power amplifier and kicker) are introduced by multiplication, all in complex notation, with the complex harmonics. An inverse FFT delivers the 3-6 GHz correction signal at the kicker.

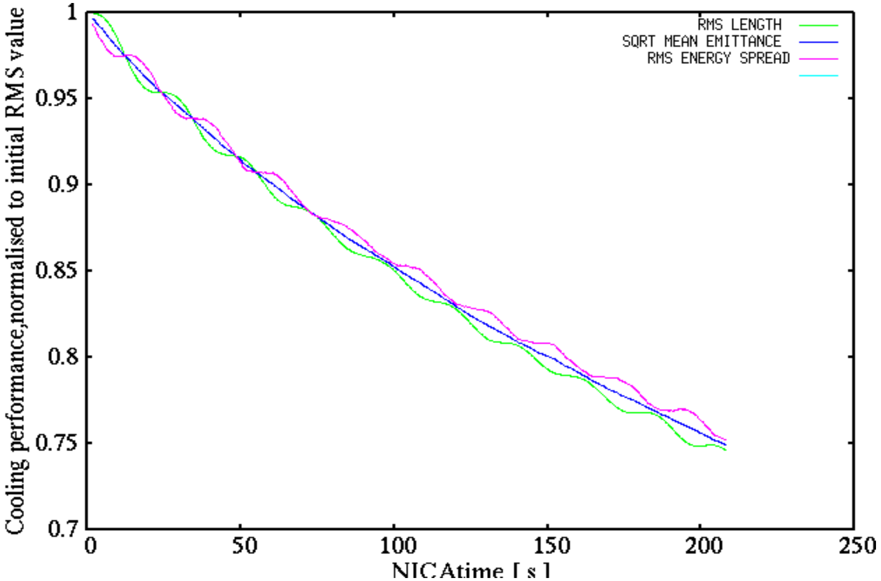
See blue curve



All frequencies outside the 3-6 GHz band are automatically eliminated !

The binning method gains by having computation times proportional to M for the sorting and FFT procedures, times M for the number of simulation turns in the ring, resulting in computation times proportional to M**2 only.



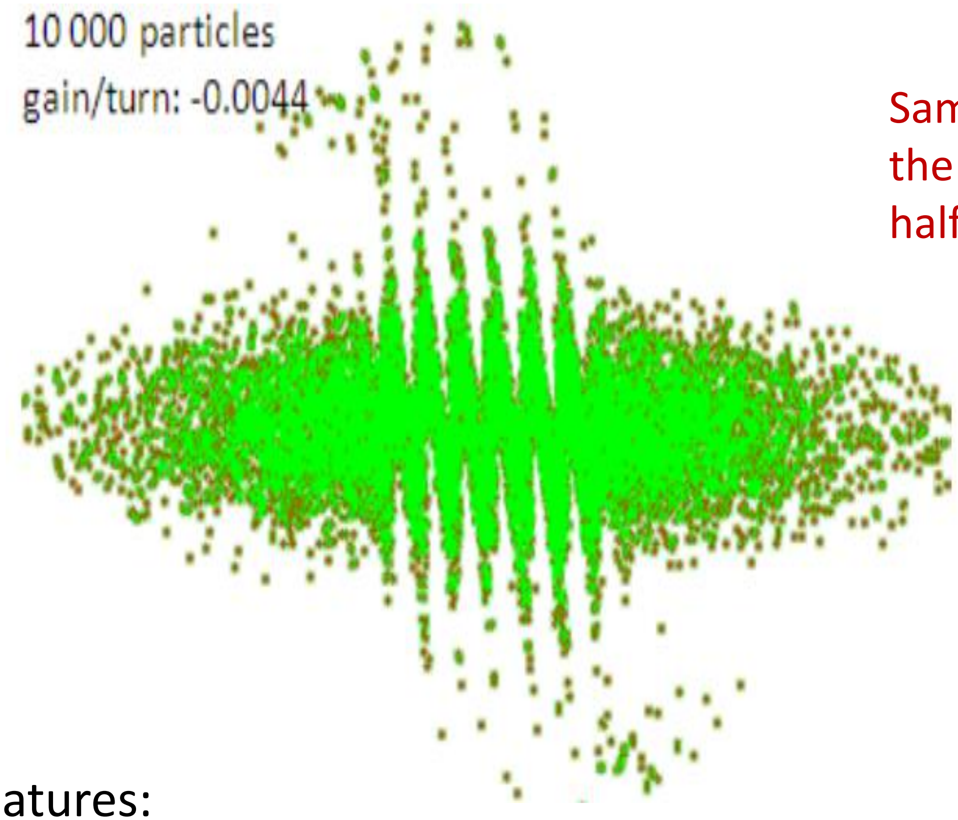


Particle by particle turn by turn method
4 hour computation time, HP 2900 pc

Binning method
10 min. computation time

Caution: the 2 results differ slightly, the reason is not understood !

Instability for high gains: (seen in the longitudinal phase plane)



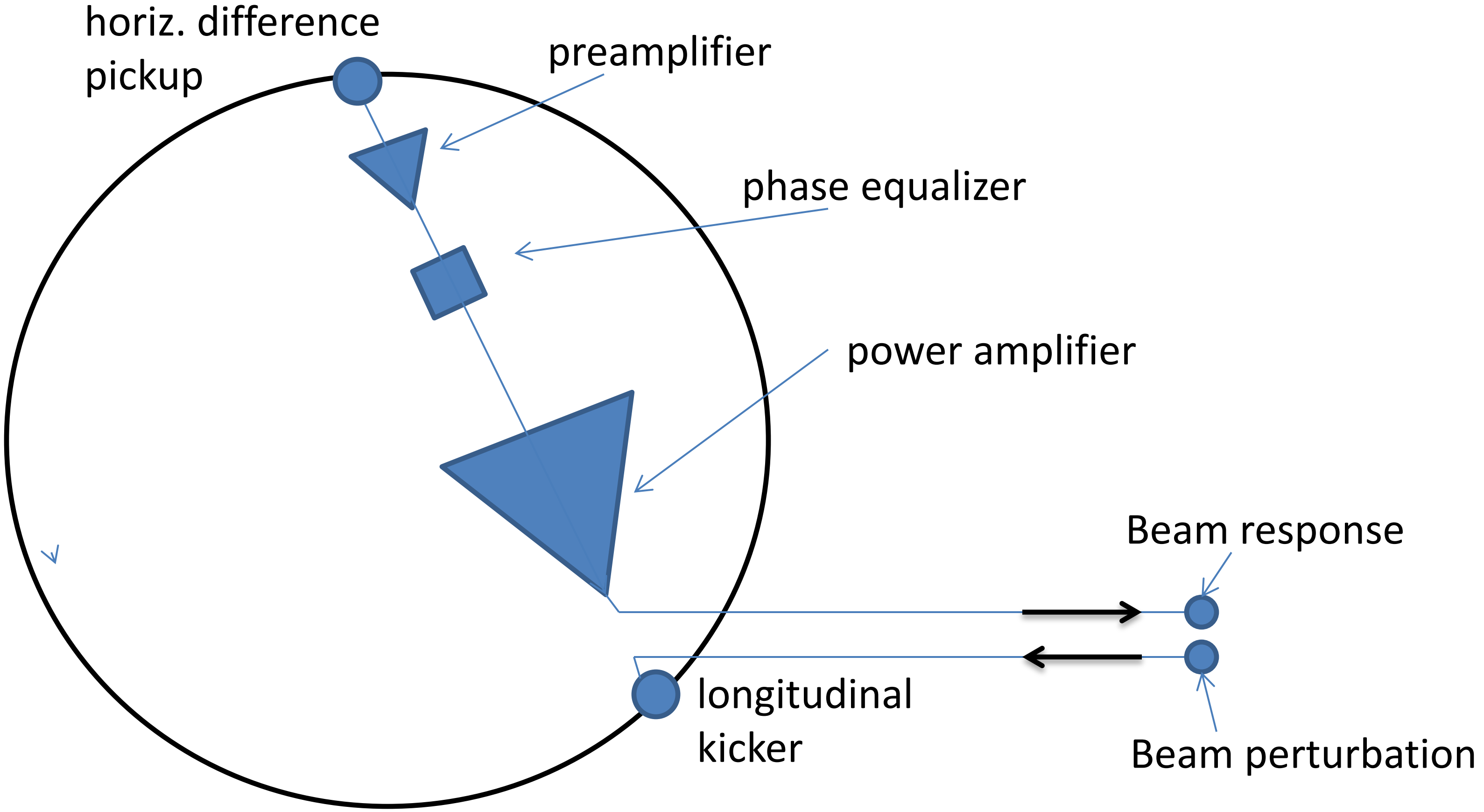
Same instability also for twice the amount of particles and half the gain!

Instability also seen with the binning method

Instability features:

a) midband (4.5 GHz) where the gain is highest.
b) drift in opposite directions for upper and lower energy ions.
c) upper and lower energy ions are in antiphase causing big pu signals.
d) upper and lower energy ions move towards buckets in antiphase.

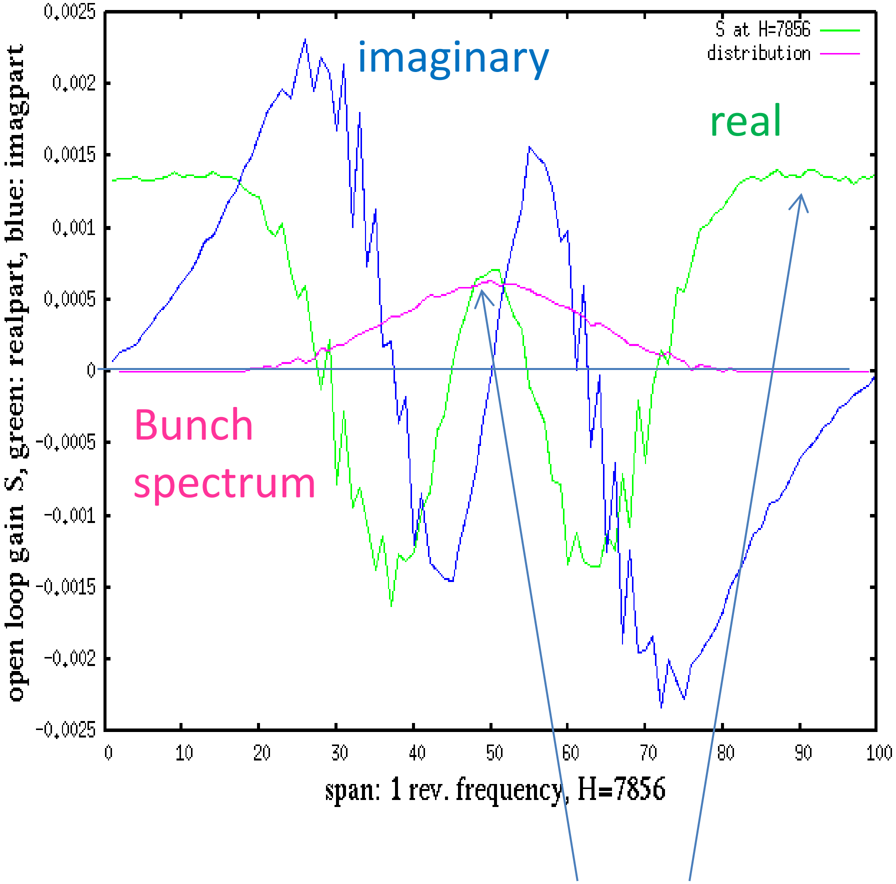
Attempt to explain instability with BTF and Nyquist diagrams



Perturbation over typically 1000 turns (0.01 sigmaE/turn), phasorial averaging of response to eliminate Schottky signals.

Perturbation around H = 7856,

Beam transfer function

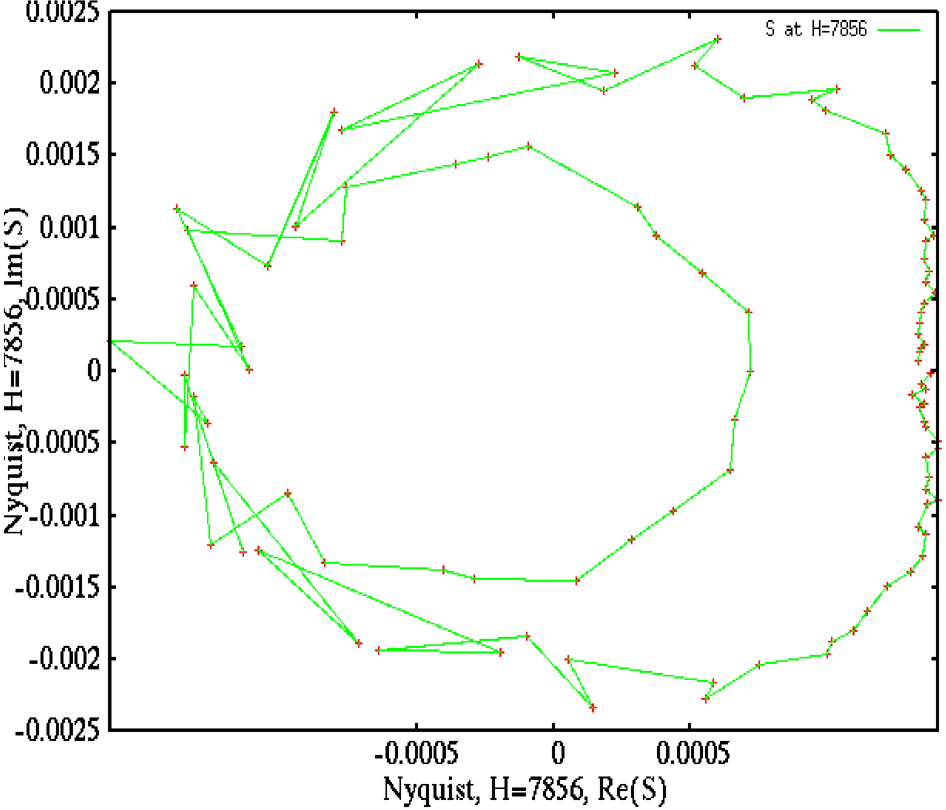


Realpart not zero at centre nor at halfway between centres.

Due to bunching ?

Response around H = 7856

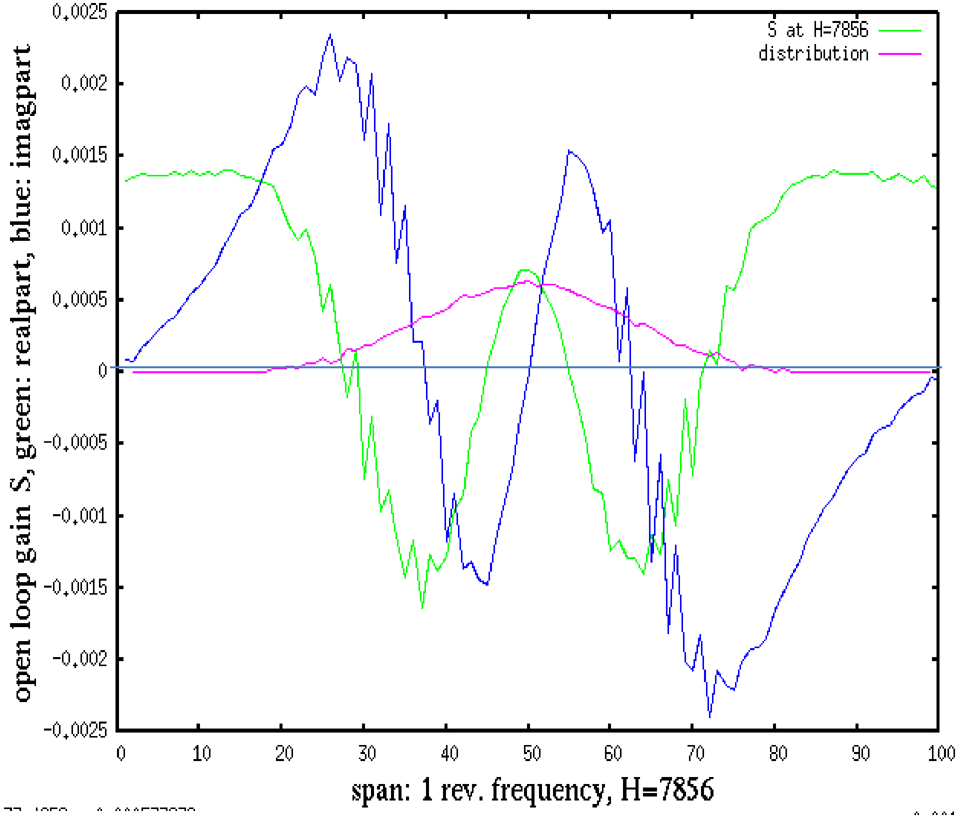
Nyquist diagram



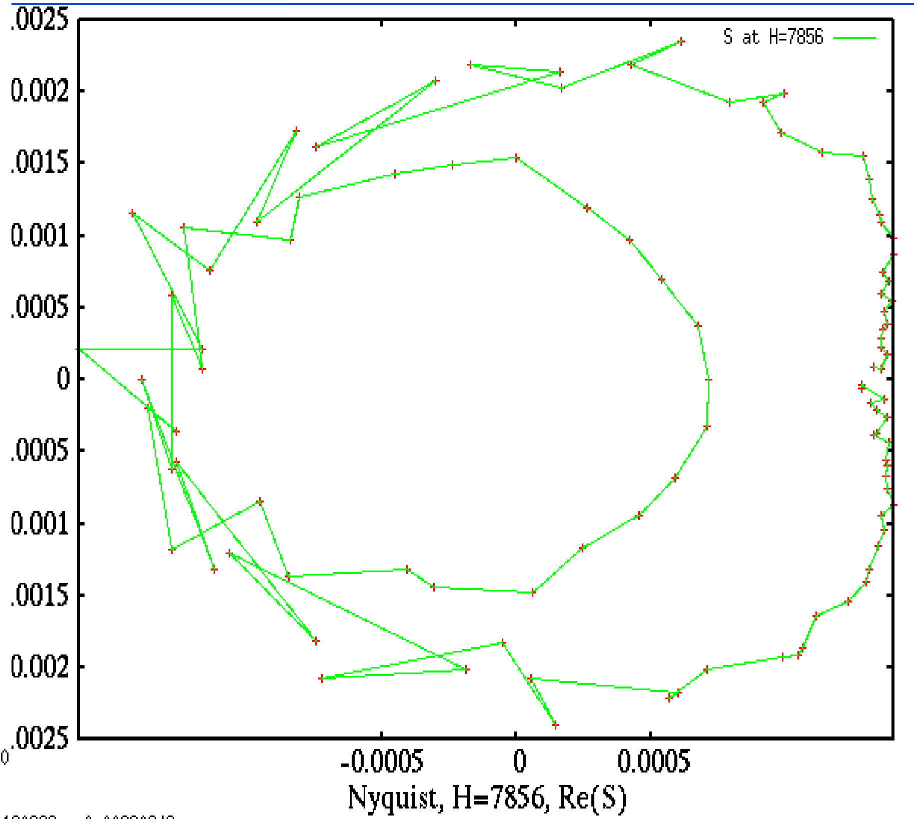
max. value of realpart = 0.0014, far too small to explain the instability !

Perturbation around H = 7856, Response around H = 7857

Beam transfer function



Nyquist diagram

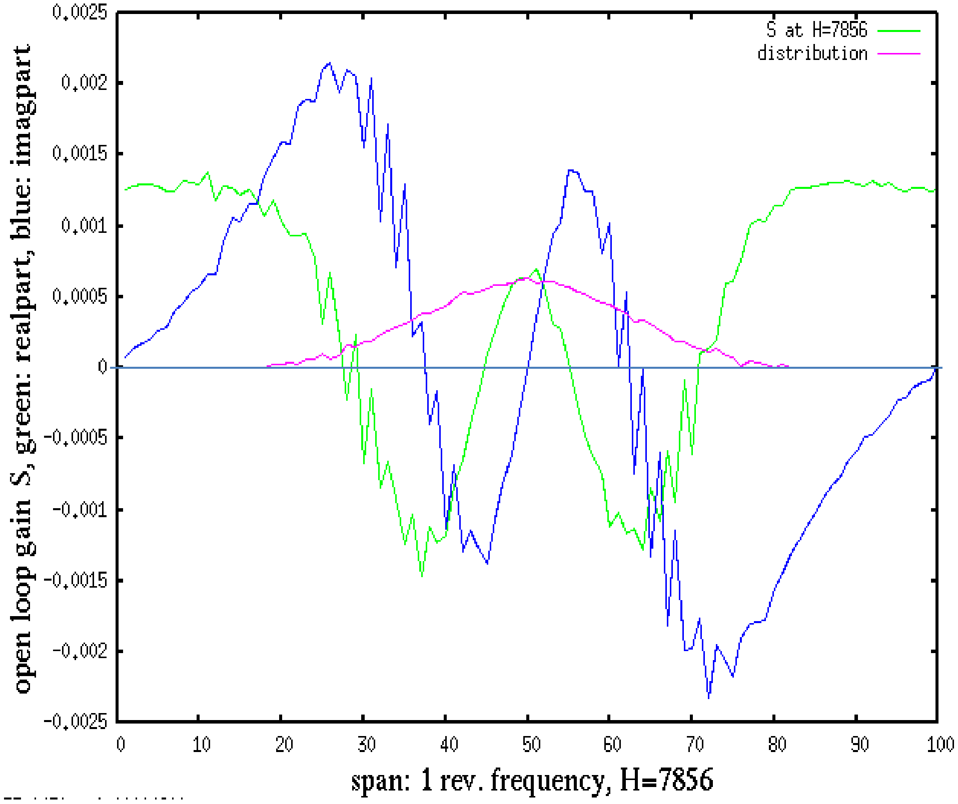


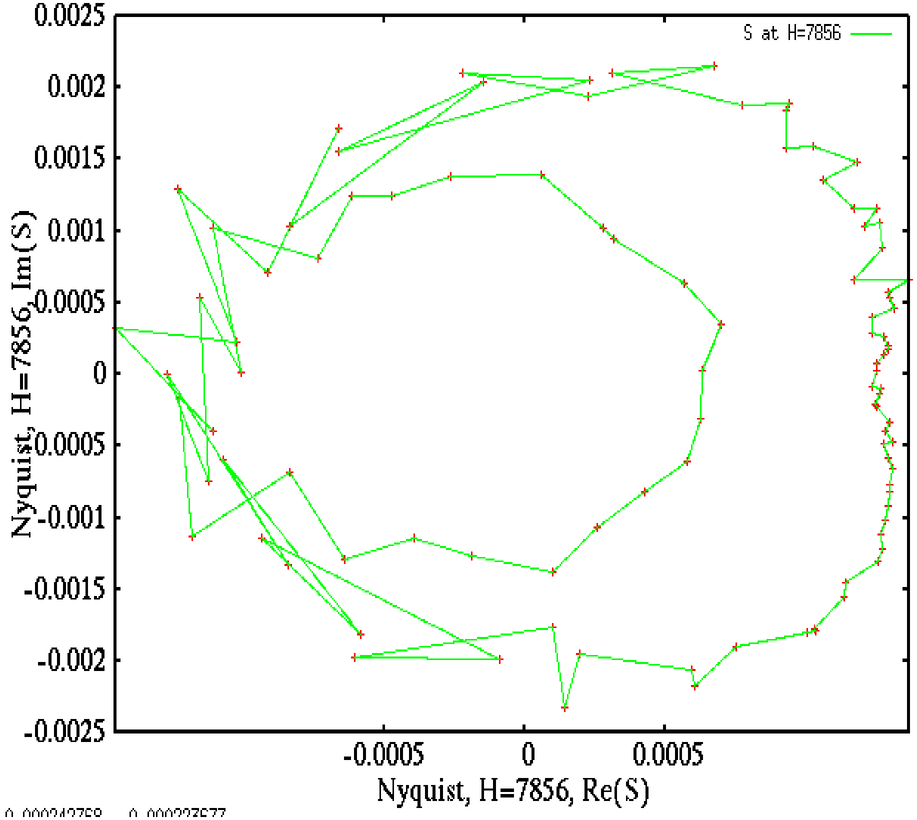
Realpart not zero at centre nor at halfway between centres.

phase reference:
time of passage of bunch centre

Perturbation around H = 7856, Response around H = 7956

Response 100 harmonics higher

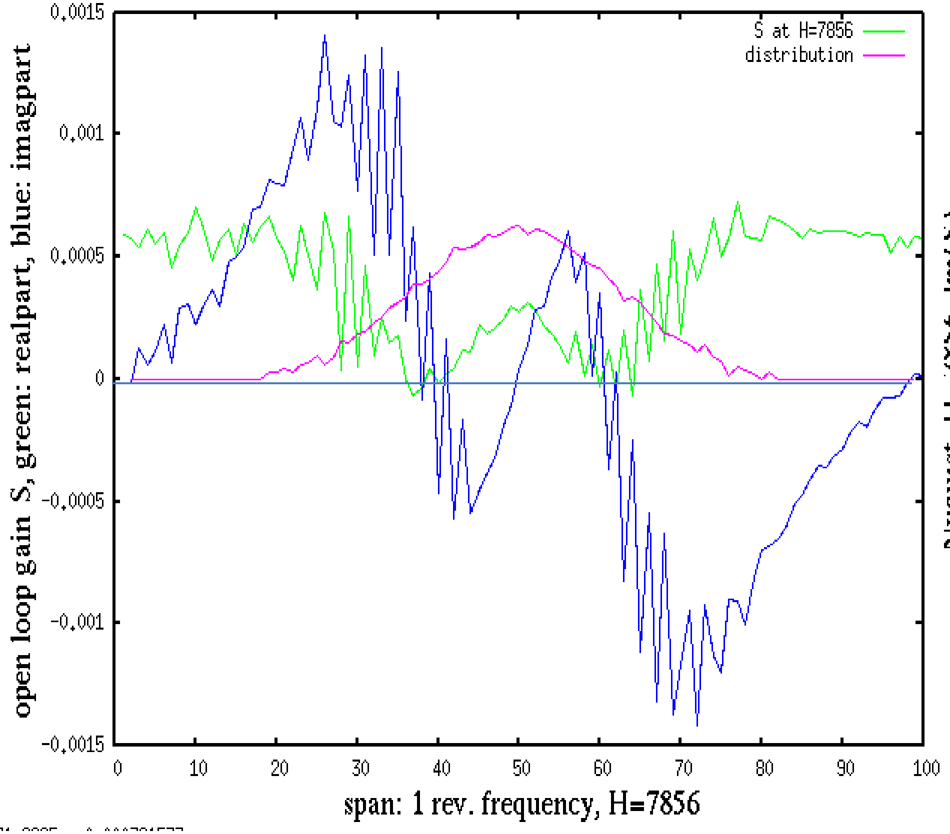


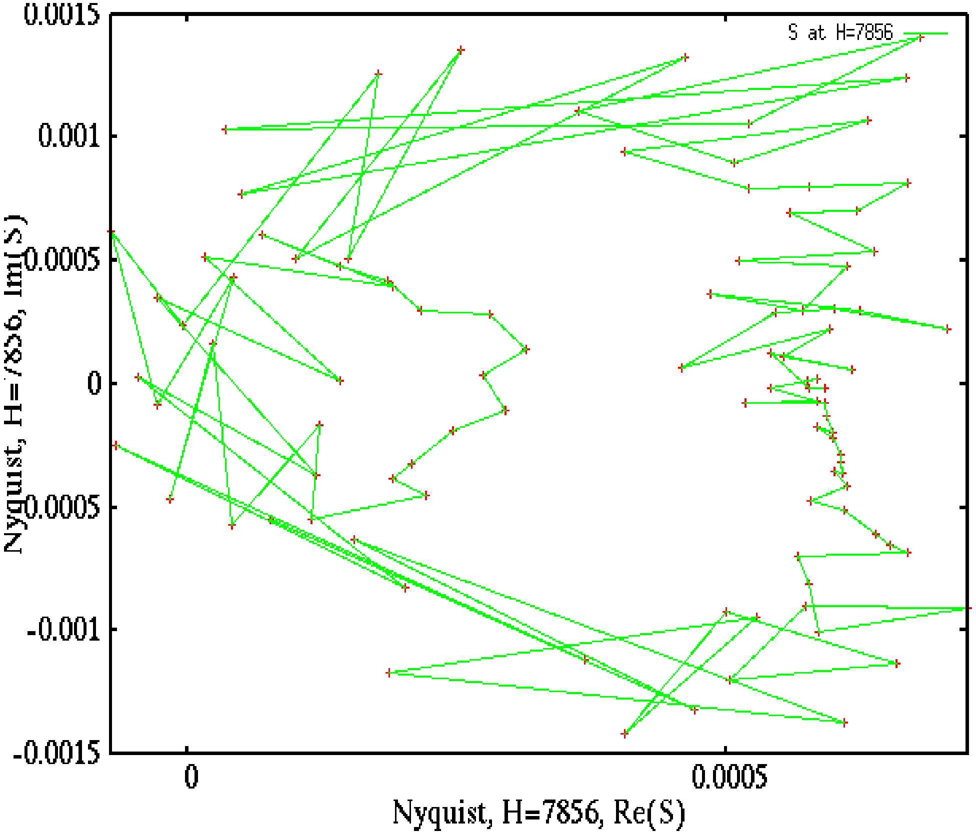


phase reference:
time of passage of bunch centre

Perturbation around H = 7856, Response around H = 8256

Response 400 harmonics higher





phase reference:
time of passage of bunch centre

Conclusions

a) Momentum cooling simulations of bunches including the synchrotron motion is feasible over a few thousand turns, evaluating for each ion, at each turn, the effects of all ions via the feedback system.

b) Cooling of betatron oscillations, taking into account the shrinking longitudinal emittance, can conveniently be part of the simulation.

c) Binning of the pickup signals could permit the use of one order of magnitude more sim. ions and sim. turns.

d) Further work remains to understand the longitud. instability at midband. Possibly this instability is not real?

Acknowledgements

-Thanks to Takeshi Katayama for the Nica cooling case [3] used for testing of the method and for his extensive advice and explanations during the numerical experimentations.

-Daniel Schultes binning proposal [2], making simulations over more than 10 000 turns feasible, could be particularly useful for future investigations.

-Dieter Moehl helped with the understanding of the bucket dynamics during stoch. cooling.

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References

[1] M. Blaskiewicz and J. M. Brennan, "Bunched beam stochastic cooling in a collider", Physical Review special topics-Accelerators and beams 10, 061001 (2007)

[2] Daniel Schulte, private communication, March 2013.

[3] Takeshi Katayama, private communication, April 2011