Self-consistency in nonlinear resonances with space charge

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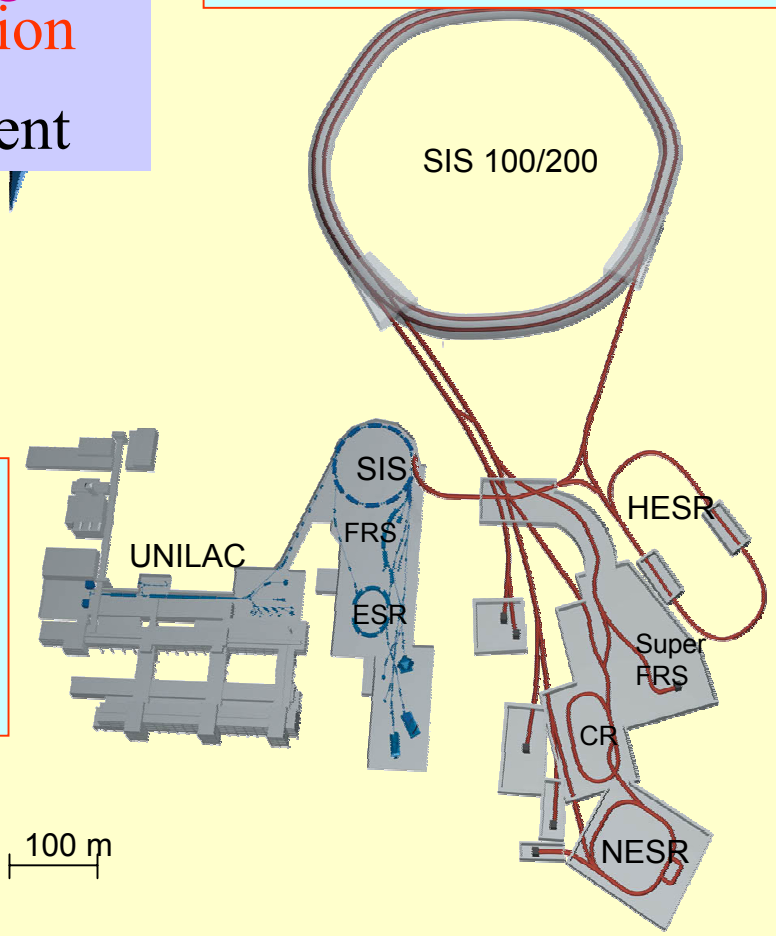
- Benchmarking project – 2D aspects
  "3D" see Talk by G. Franchetti et al.
- Coherent resonance effects
- Code comparison
- Long-term effects

Scope

- understand interplay of space charge & nonlinear resonance + halo formation
- benchmark simulation by experiment

between injection pulses:
~ 10^6 turns at $\Delta Q \sim 0.15$
predict blow-up & loss (<1%)

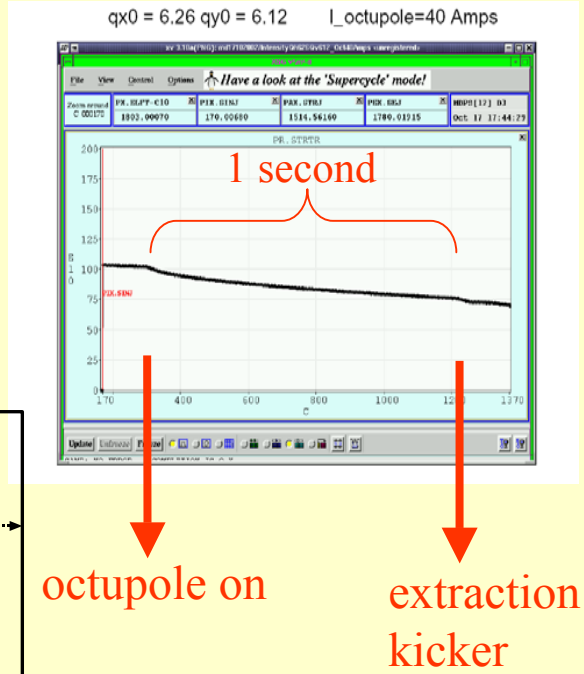


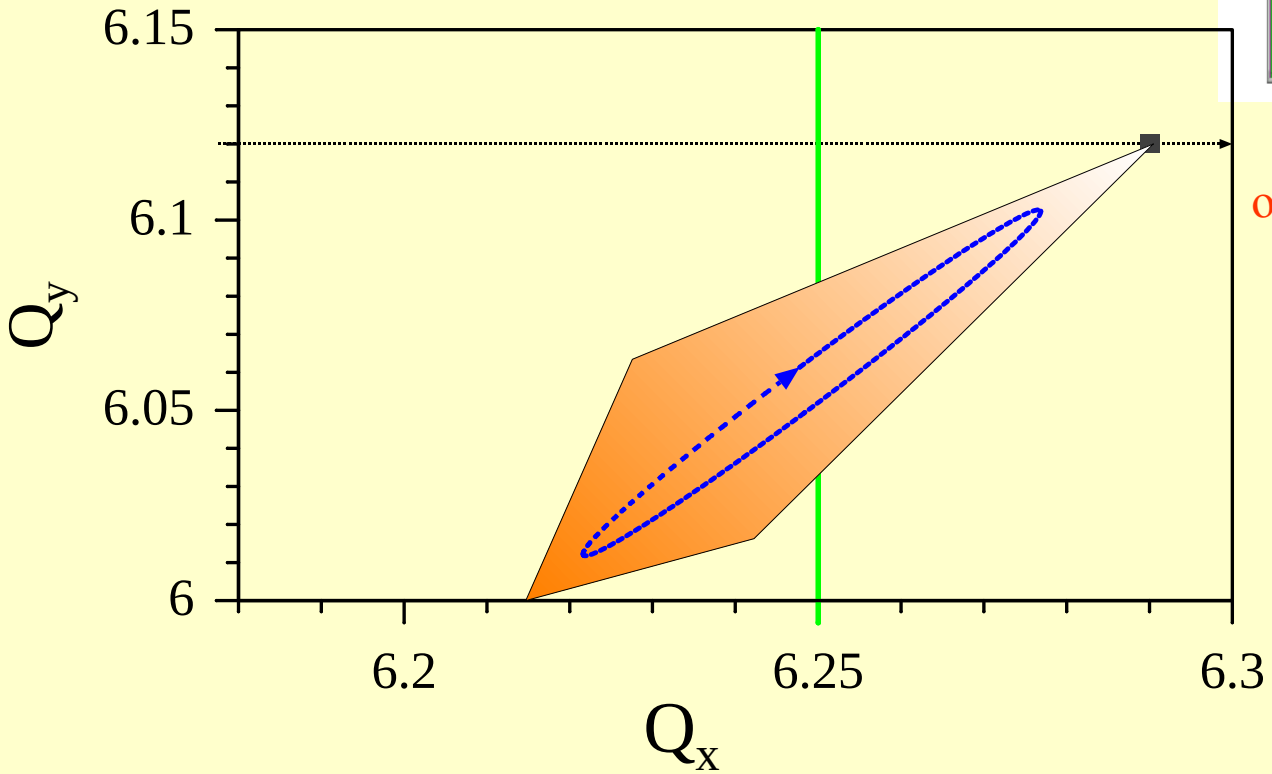
Application to:
International Facility for Ions and Antiprotons at GSI

We proposed experiment to CERN-PS group

to test our theoretical concept presented at 2002 ICFA-beam dynamics workshop (Fermilab)

- **October 2002**:
- 1 s long flat-bottom 1.4 GeV
- 200 ns long single bunch 10^{12} p
- single octupole (k_3=50 m^{-3}): $4Q_x$=25
- ΔQ_x = - 0.075 (maximum)
- various (fixed) horizontal working points





Systematic study of mechanisms

- First step: 2D PIC-simulation
- Using MICROMAP code & IMPACT
- 10^5 & 10^6 particles on 64x64 grid for ~ 10^3 turns
- Constant focusing and **stationary conditions** *
- Compared with analytical 2D space charge model

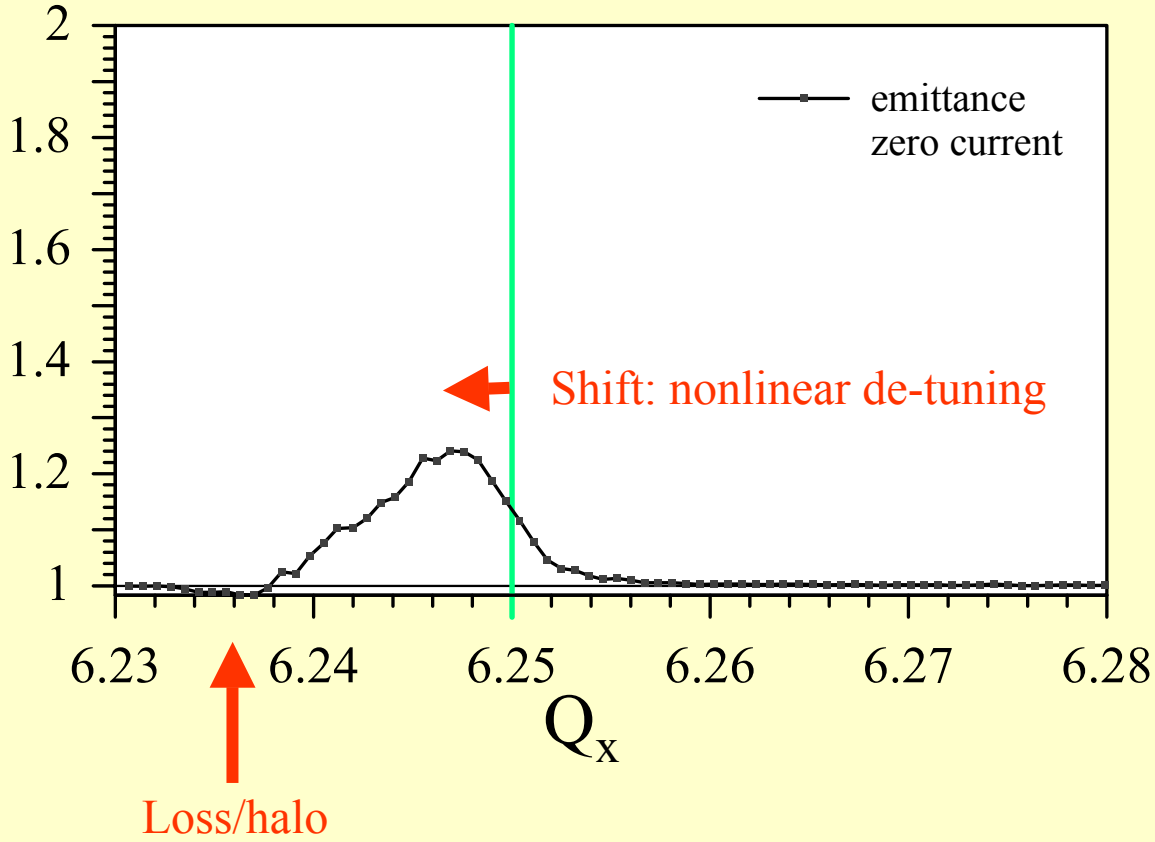
* no acceleration, rf bunching, cooling …

Resonance driving and de-tuning

For zero space charge:

- maximum rms emittance growth ~ 23% - no crossing / beam accumulation
- only weakly dependent on k_3 and distribution function

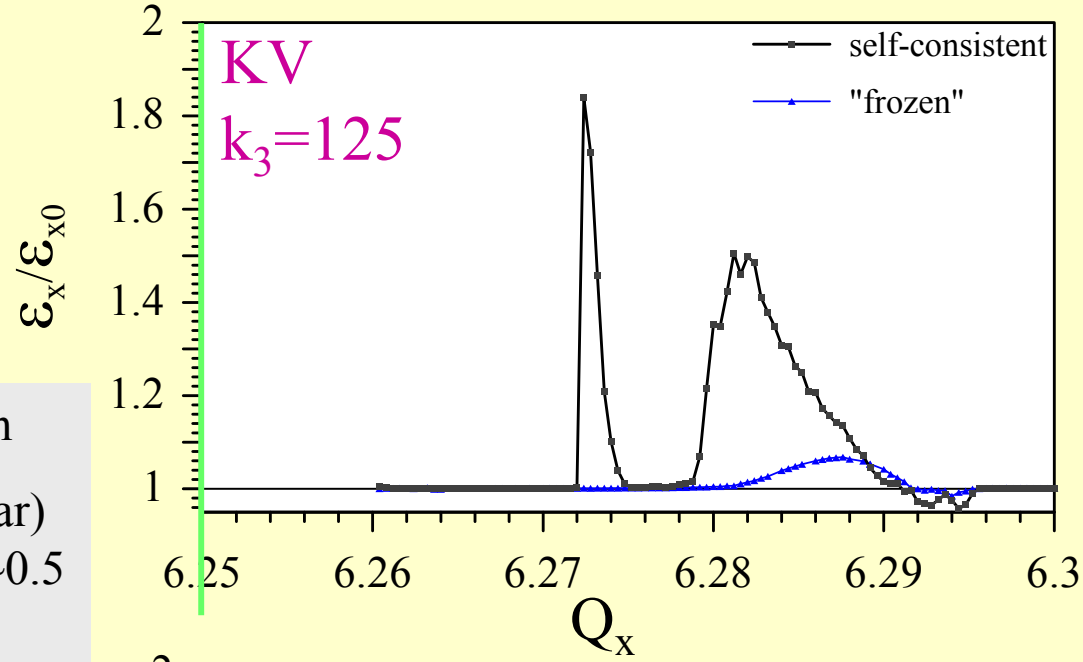
Gaussian
k_3=125

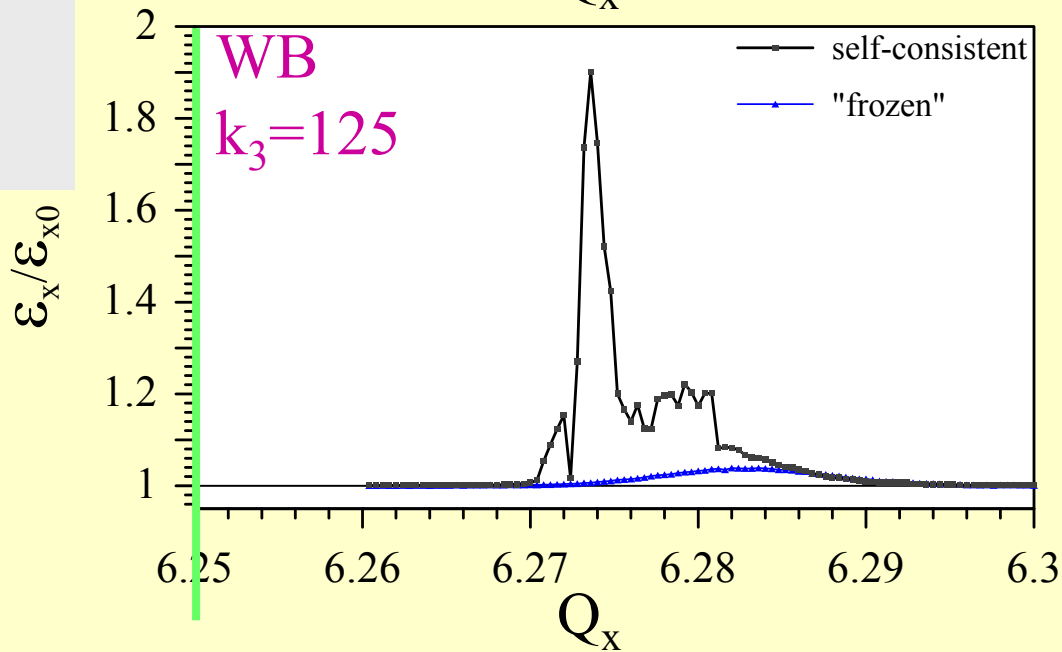


Coherent Effects for KV and WB: 80% peak

- Large coherent effect for both
- Peaks: second order (nonlinear) envelope instability with $C_2 \sim 0.5$

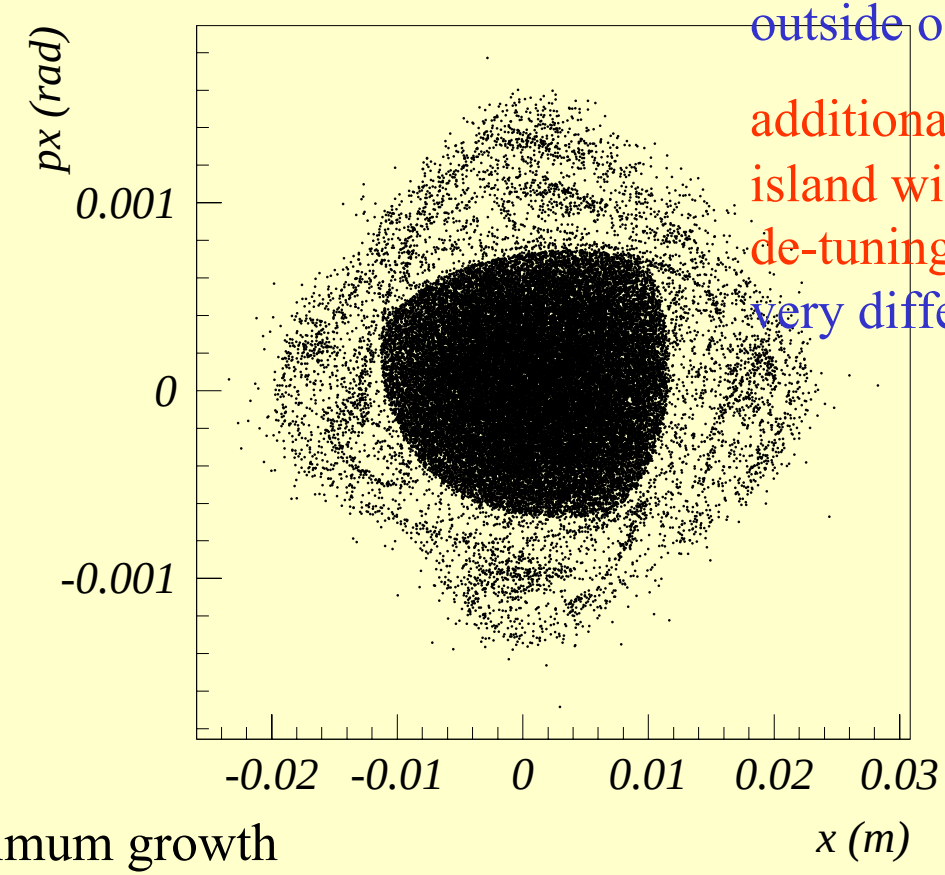
  i.e. 2x „coherent advantage“
- Incoherent („frozen“) effects negligible





Horizontal phase space

$q_{x0} = 6.2687$

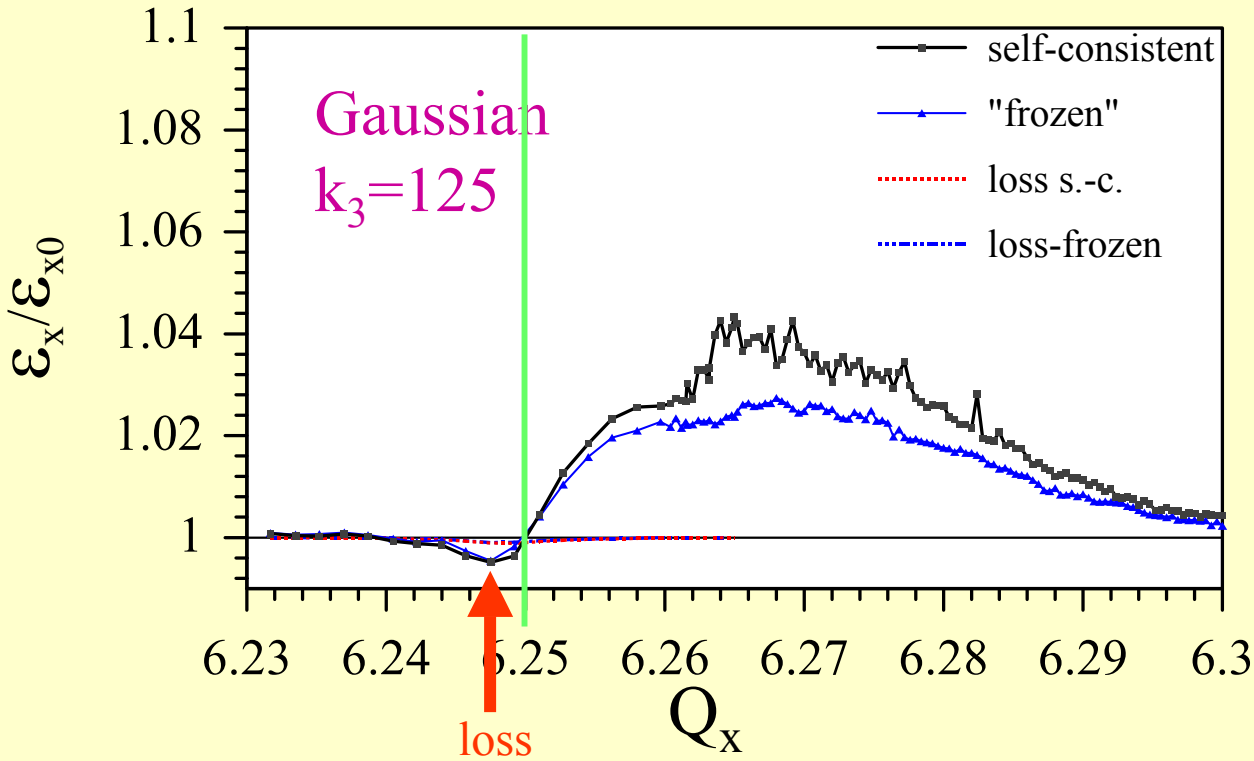


halo: islands of resonant motion outside of core

additional halo size given by island width ~ below 4σ due to de-tuning by space charge – very different in 3D!

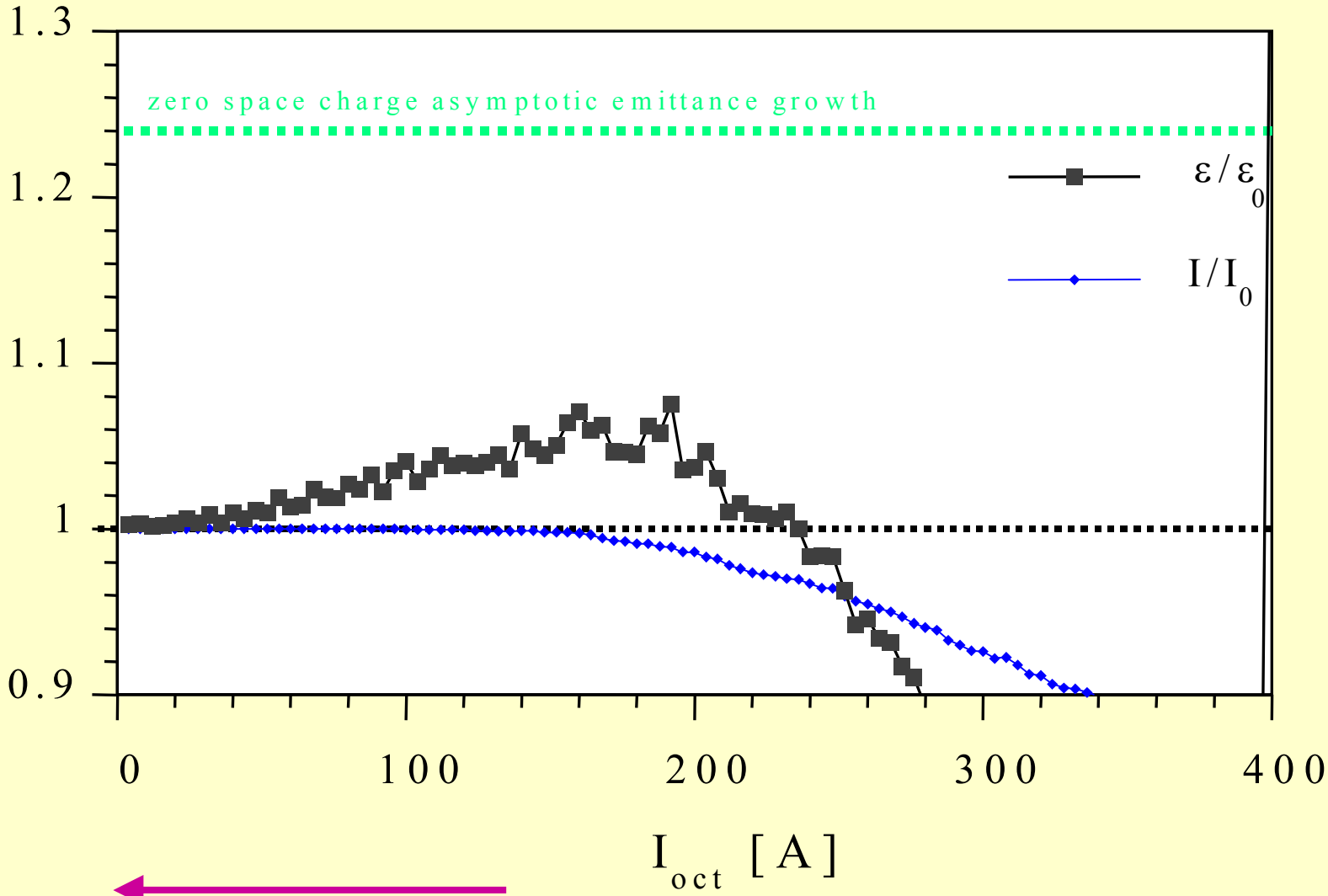
WB at maximum growth

Gaussian ~ *only incoherent* response < 4%



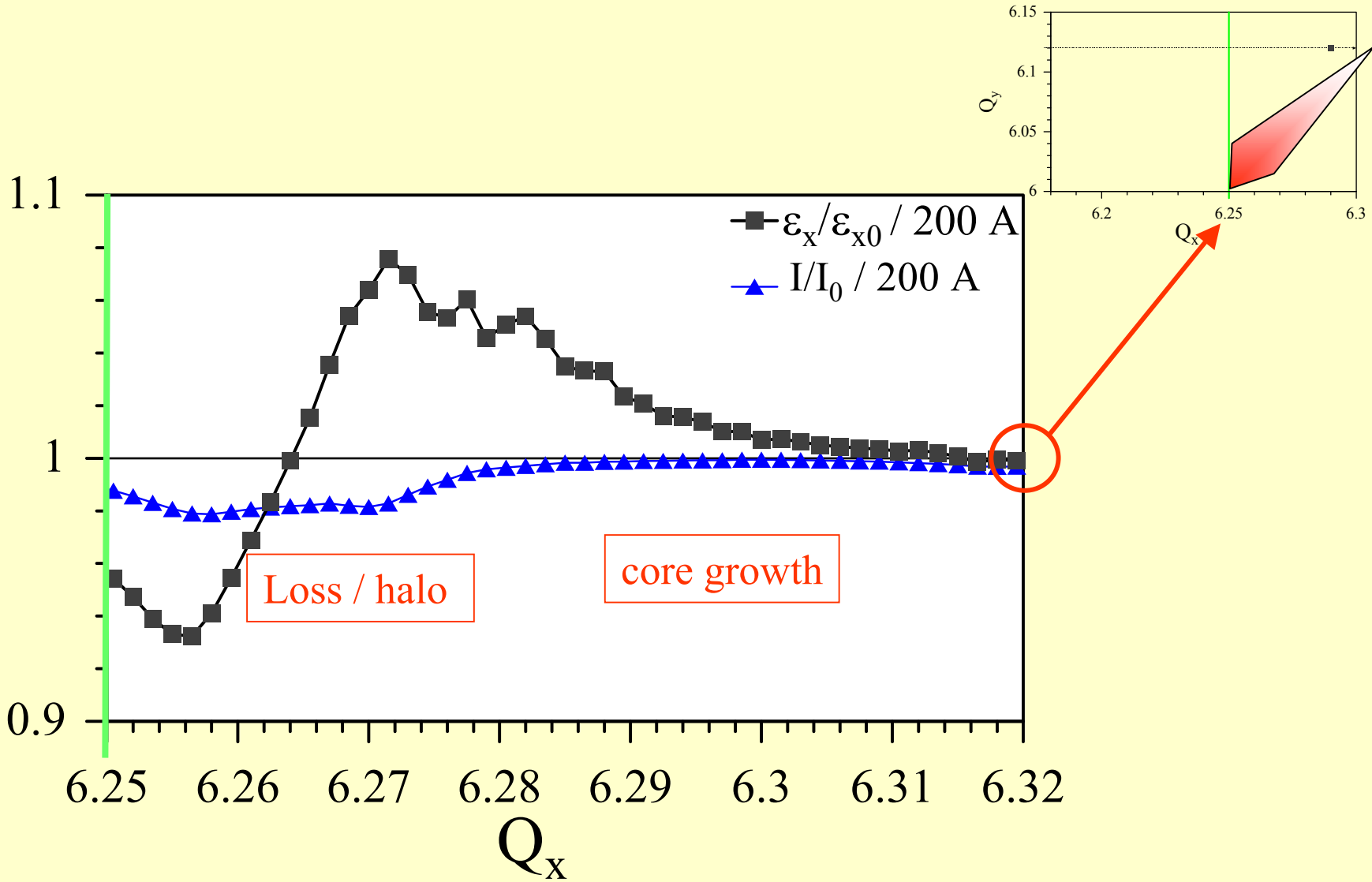
- Coherent effect ~ suppressed → little emittance growth
- but: would be different if tune crossing through resonance!
- Incoherent („frozen“) effects ~ sufficient representation

Strongly suppressed rms growth due to space charge de-tuning



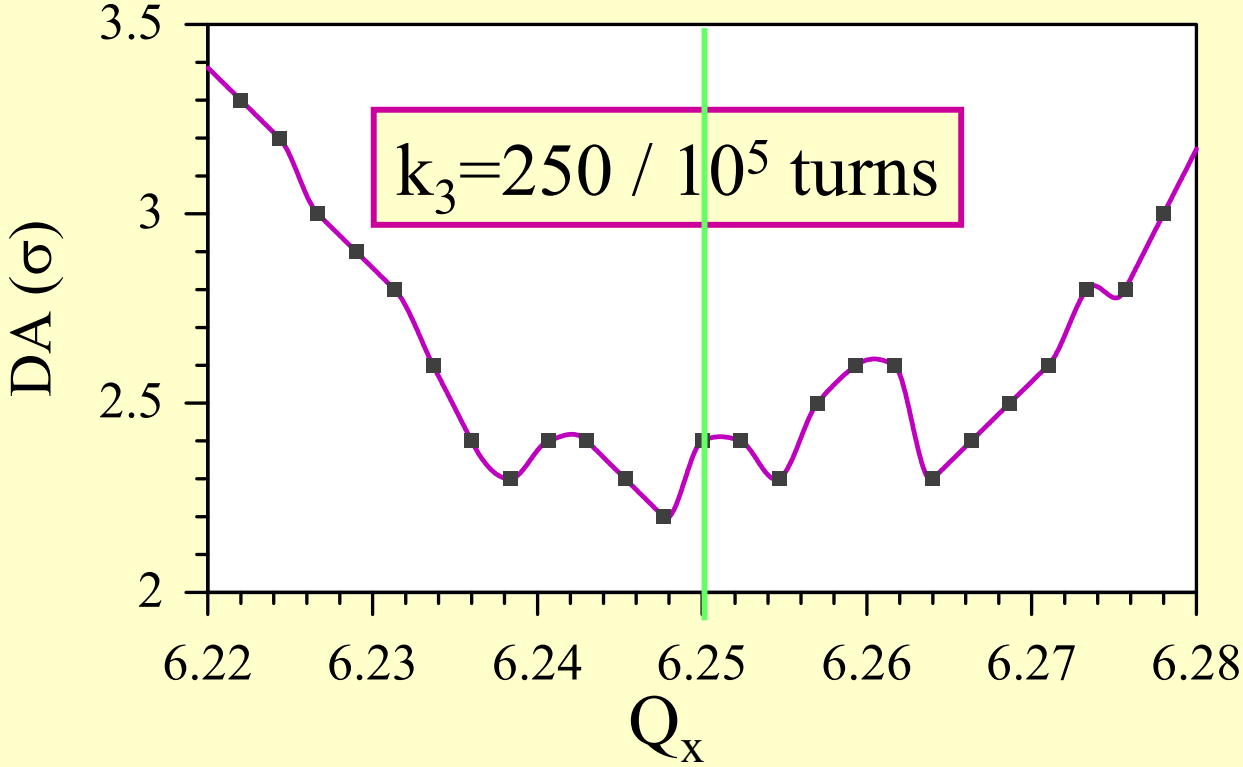
Resonance driving << space charge de-tuning

Significant loss appears for k_3=250 (200 A): two regimes: **core growth & loss/halo**



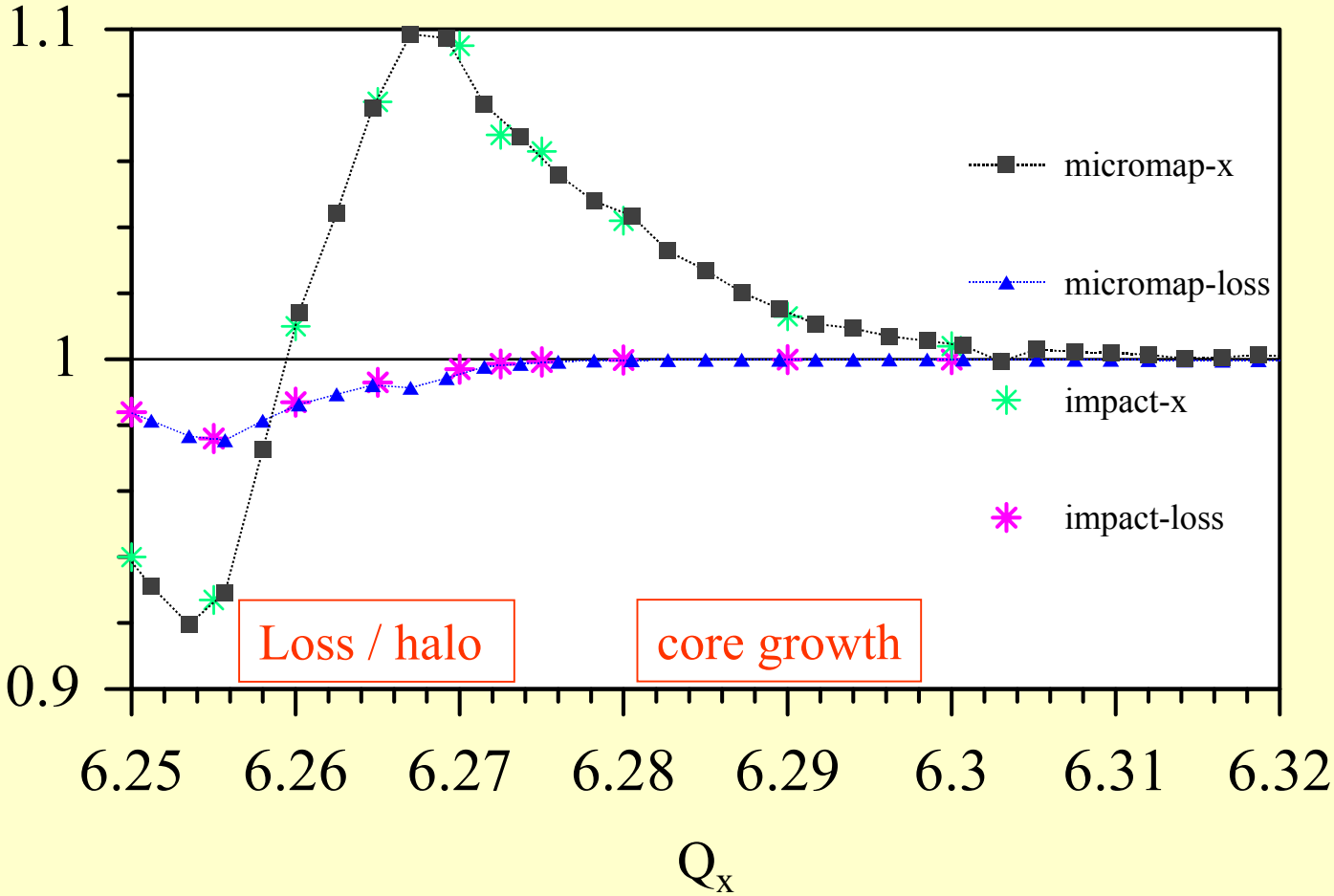
Confirmed by dynamic aperture calculation:

is found to shrink into beam - eliminating first halo, then core



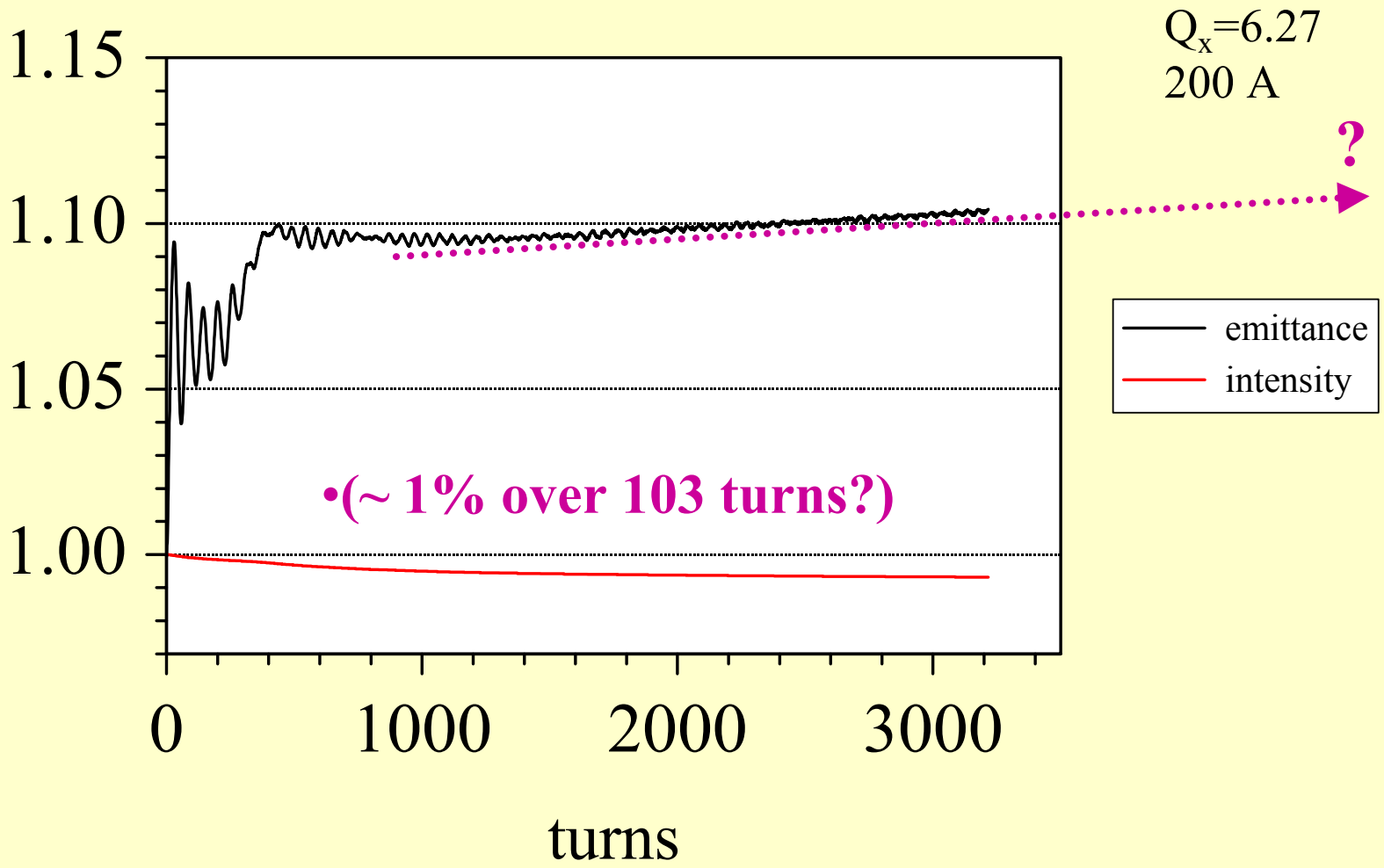
- DA ~ $1/k_3^{1/2}$
- ~ 5 σ for k_3=50

Code comparison: with IMPACT 3D/coasting beam



- Identical boundaries – Gaussian – k_3=250
- 1 M particles in IMPACT vs. 100 K in MICROMAP
- 1000 turns
- **Excellent agreement**

Longer run from IMPACT /10^6 particles:

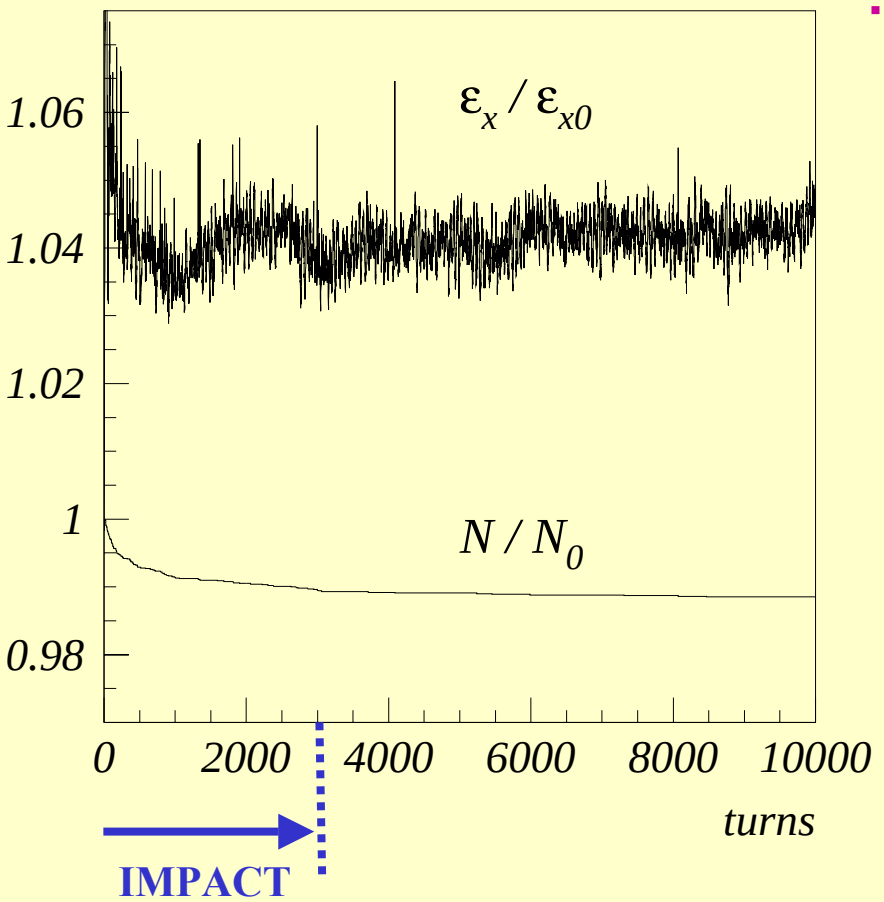


- Origin of slowly rising rms emittance not clear
- Continuing slight loss
- Resonance diffusion or PIC-noise?

Clarify slow growth: compared with analytical space charge

Gauss' law on round beam – noise-free

$q_{x0} = 6.2737$



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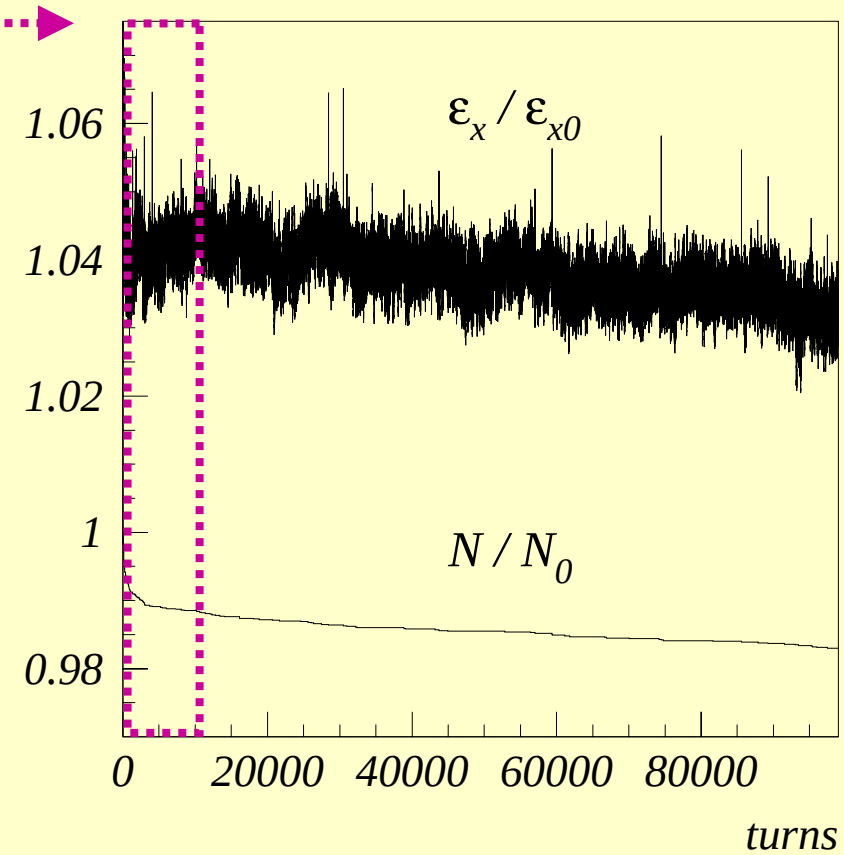

- Resonance diffusion could be origin
- No continuing growth in 2D

Conclusion

- Gaussian ~ no coherent resonance effect
- little difference between self-consistent and „frozen-in“ space charge (stationary beam)
- Discovered „halo“ and „core emittance growth“ regimes (large k_3!)
- Self-limiting due to space charge de-tuning
- Suggests advantage of square „barrier“ buckets
- Basis for benchmarking 2D->3D invite you to join this effort – see our webpage (coming soon)