Halo Coupling & Cleaning due to Space Charge Resonance in High Intensity Beams

CERN-SC2013

CERN, April 16-19, 2013

Ingo Hofmann

GSI Darmstadt / Helmholtz-Institut Jena

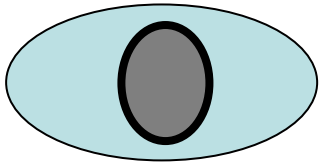
Overview

- Introduction
- Coupling of core emittances at "main resonance" $2k_z$-$2k_x$=0 (in rings "Montague resonance" $2Q_x$-2Qy=0)
- Coupling of halo emittances
- Apply to cleaning of halo
- Analytical estimates – extended charts
- Conclusion

Halo – sources & symmetry

Some linacs & rings – some only rings

- What is a halo?
  - accurate definition doesn't matter (Halo'03, Montauk)
  - density typically below 1% level & "far from core" - beyond 3...4σ
  - halo emittances can have **different ellipticity** (asymmetry) than core



- Gas scattering, Intrabeam scattering (IBS) – **symmetric halo**
- Mismatch – halo might be **asymmetric** between planes
- Nonlinear machine resonances: driving terms **asymmetric** in x and y
- Space charge driven resonances – **asymmetric**
- Collective effects, E-cloud effects, Beam beam effects, ...

We don't worry about the origin of halo!

- focus is on **coupling & cleaning**
- employ intrinsic space charge resonance – **no external "device"**
- suggest application to **linacs** – maybe to rings

Some background to coupling & halo:

Linacs:

Limited longitudinal acceptance

- source of loss out of RF bucket - transverse acceptance often big enough
- emittance transfer strategy was suggested *)
  - ✓ from longitudinal to transverse → scraped at controlled position (before high energy part)
  - ✓ extra hardware (dipoles, quads, RF)
  - ✓ not attempted for high current beams

*) *pointed out to me by A. Chao*

Present work stimulated by **C-ADS discussion following HB2012** in Beijing

- Injector II: 10→ 20 mA and $\varepsilon_z/\varepsilon_x$ 0.85→1.3
- need larger synchronous phase (S. Fu et al, Proc HB2012)

Rings:

A. Chao, M. Month, NIM 1976, *Dynamic beam halo cleaning by a **nonlinear resonance***

- suggest tune modulation → islands move and carry particles from core into tail
- probably never realized – risky due to **external source of resonance**?

E. Metral, 1998, head-tail damping in PS

- damping by tail in one plane **transferred to other plane** by **linear coupling resonance Q_h-Q_v=n**

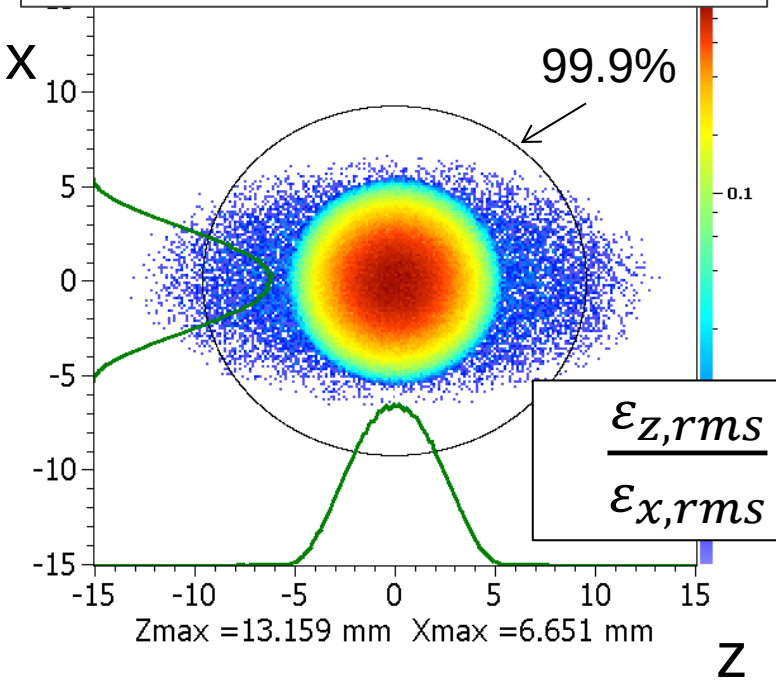
Montague resonance benchmarking at PS 2003 (CERN & GSI)

- space charge induced **$2Q_h$-$2Q_v$=0**

Core – halo emittances

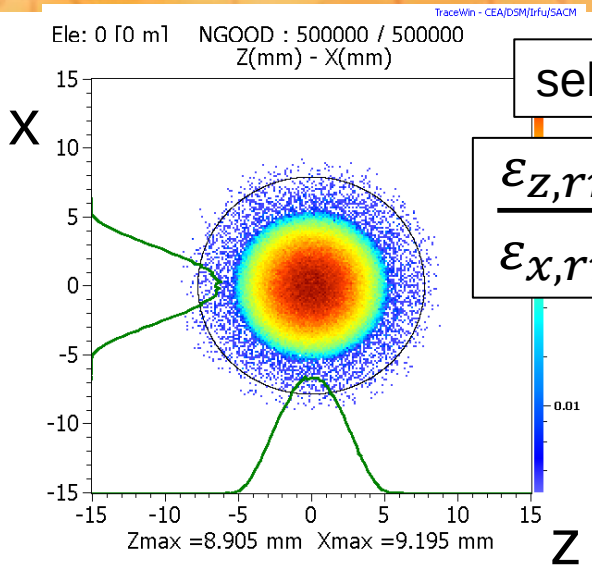
treated here as independent quantities

in general expected to be non-self-similar (resonances, mismatch etc.)



$$\frac{\varepsilon_{z,rms}}{\varepsilon_{x,rms}} \neq \frac{\varepsilon_{z,halo}}{\varepsilon_{z,halo}}$$

self-similar (IBS etc):

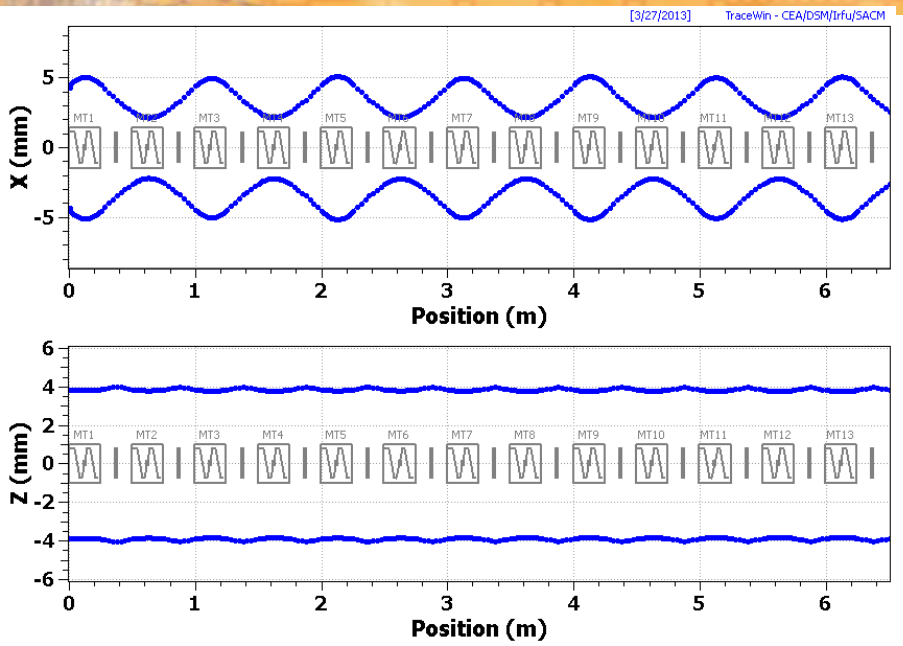


$$\frac{\varepsilon_{z,rms}}{\varepsilon_{x,rms}} = \frac{\varepsilon_{z,halo}}{\varepsilon_{z,halo}}$$

Can we "trade" halo emittances independently? Gain an additional free knob?

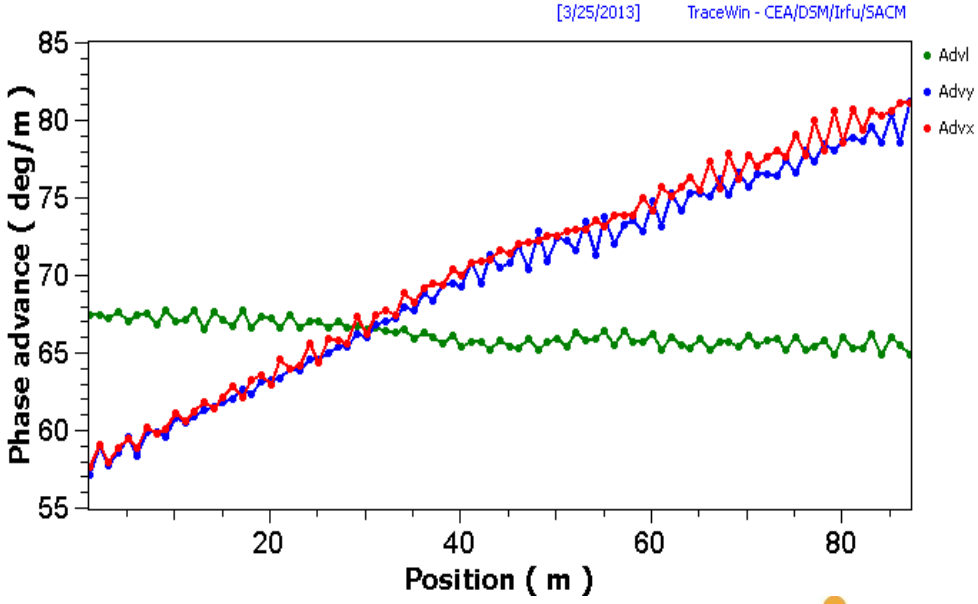
in rings: x-z → x–y analogy

Our model:
"Idealized" simulations in periodic lattice + RF



TRACEWIN:

- ❑ idealized lattice
- ❑ crossing of tunes ($k_{0,z}$ fixed)
- ❑ use Gaussian cores
- ❑ + extra-Gaussian halos (n times)

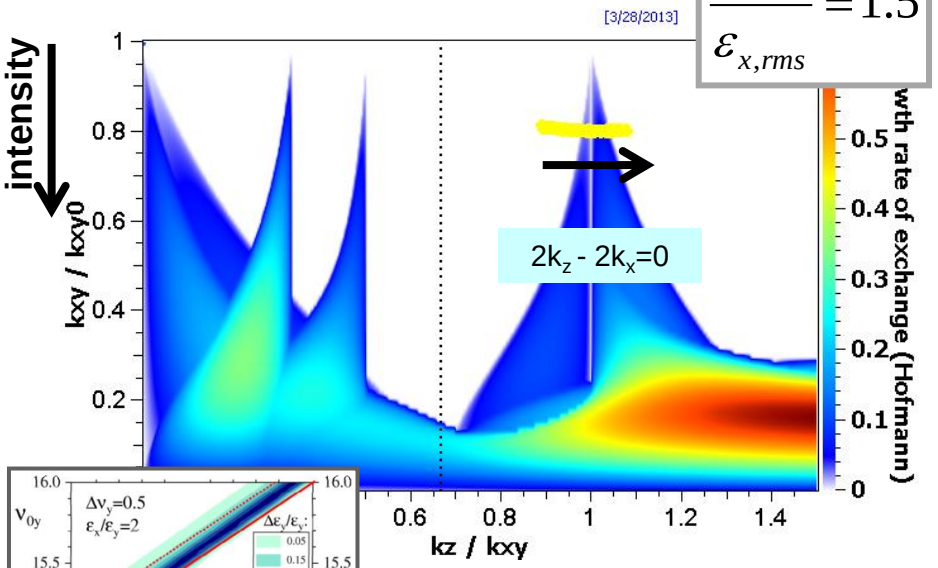


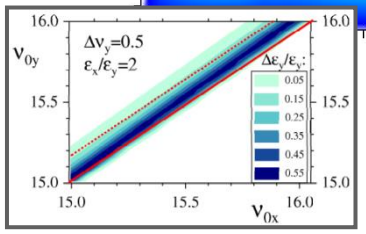
Crossing of main resonance

k_{0x} =85°→70° k_{oz}=74°

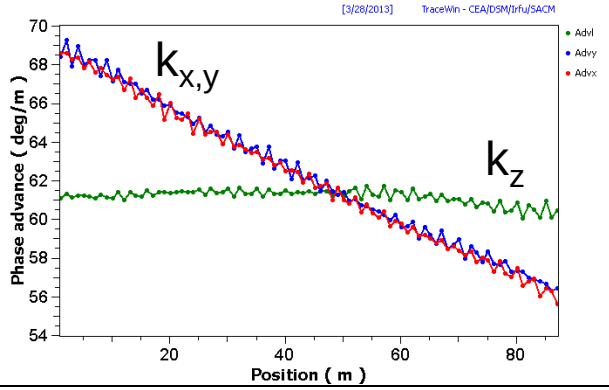
Chart indicates (colored) regions, where space charge coupling (by low order space charge modes) may occur

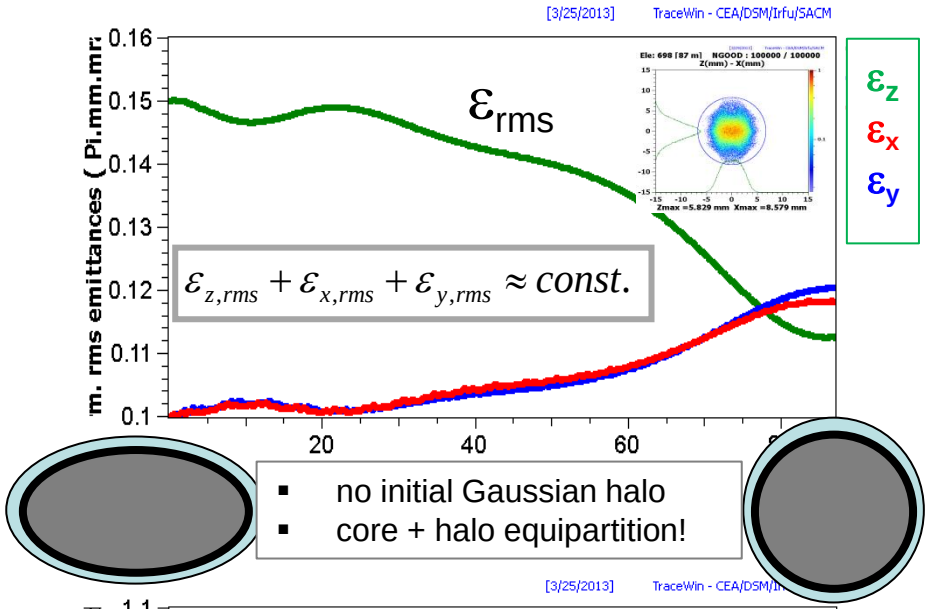
$$\frac{\varepsilon_{z,rms}}{\varepsilon_{x,rms}} = 1.5$$



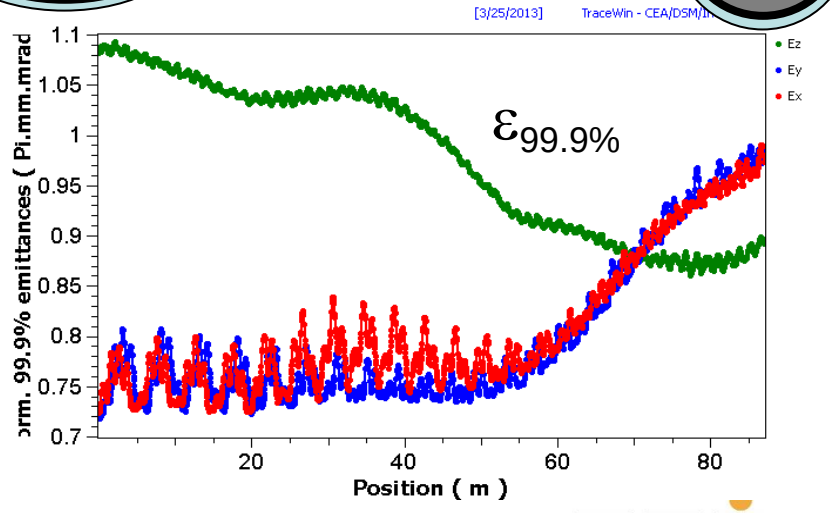


Ring-Montague



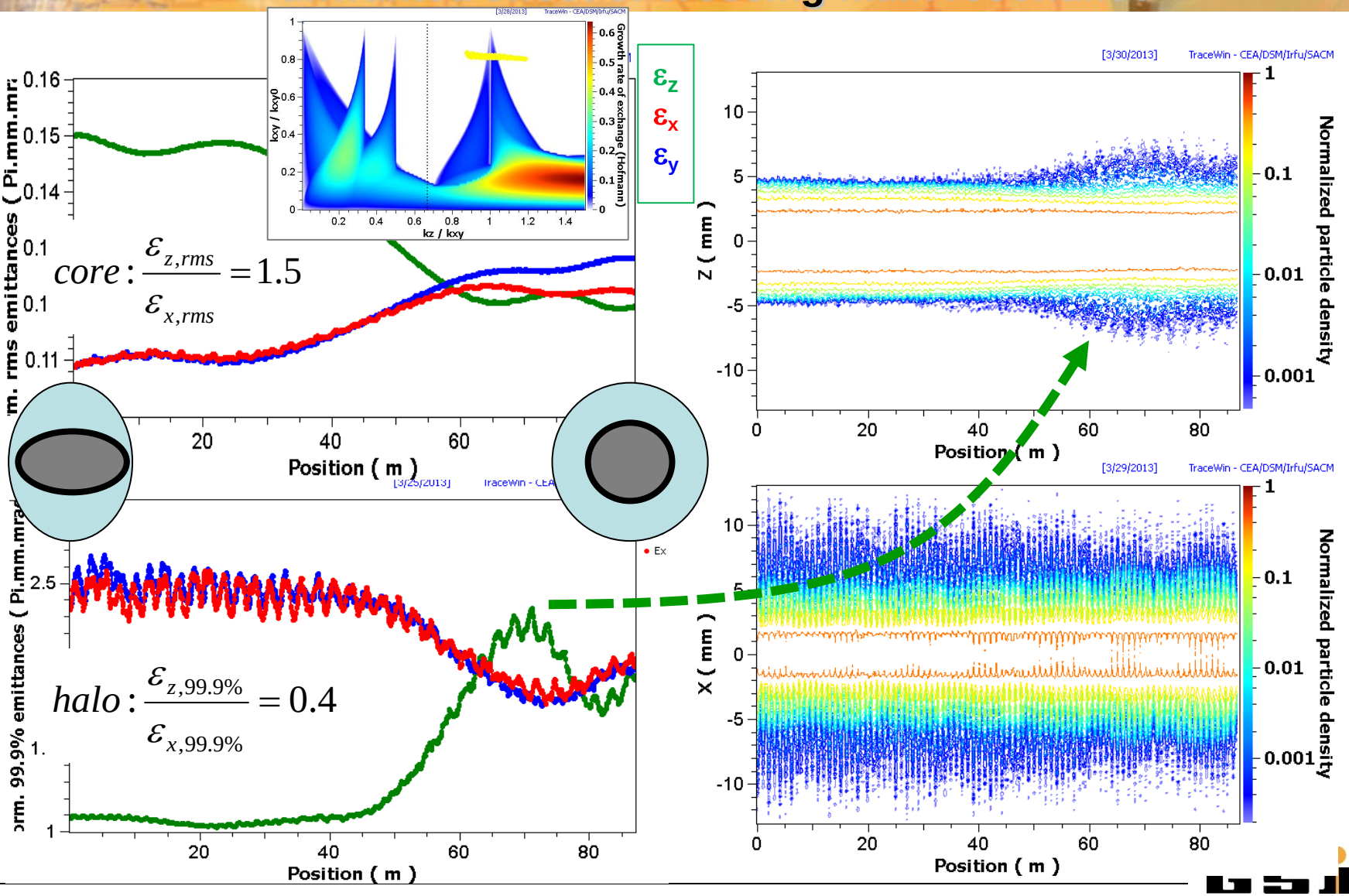


- no initial Gaussian halo
- core + halo equipartition!



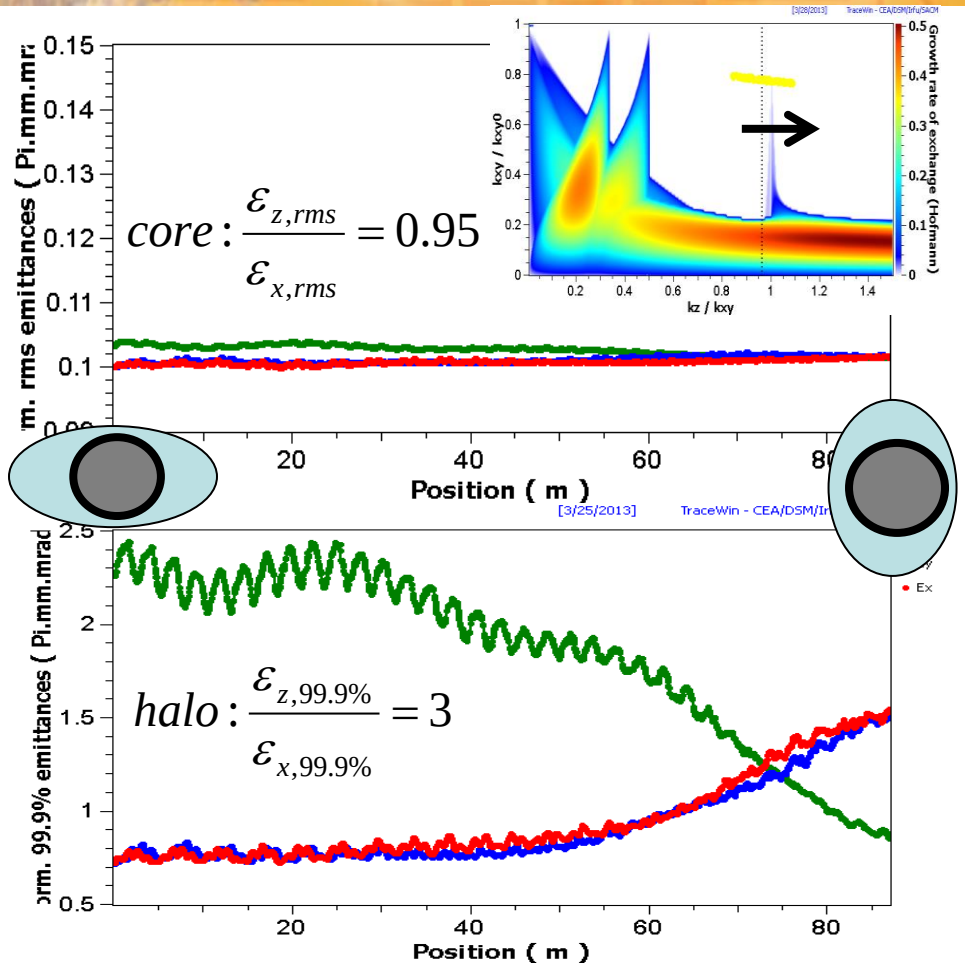
Initial halo ratio inverted

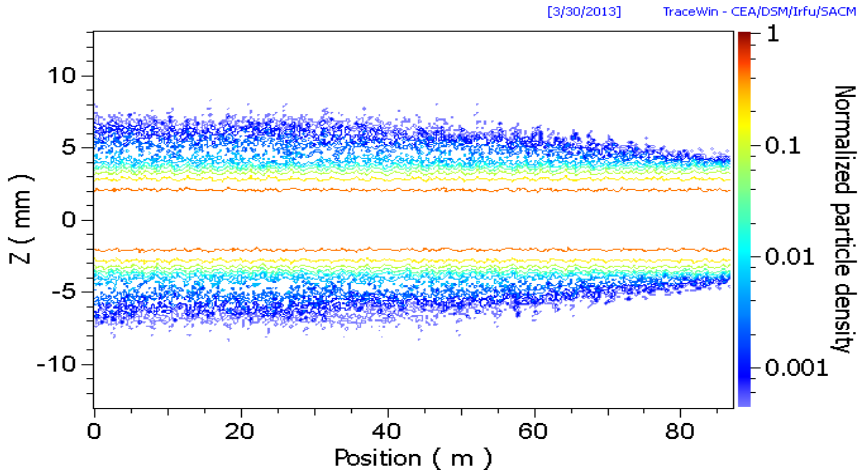
→ transverse halo pumps longitudinal - halo equipartitions unwanted effect of crossing main resonance

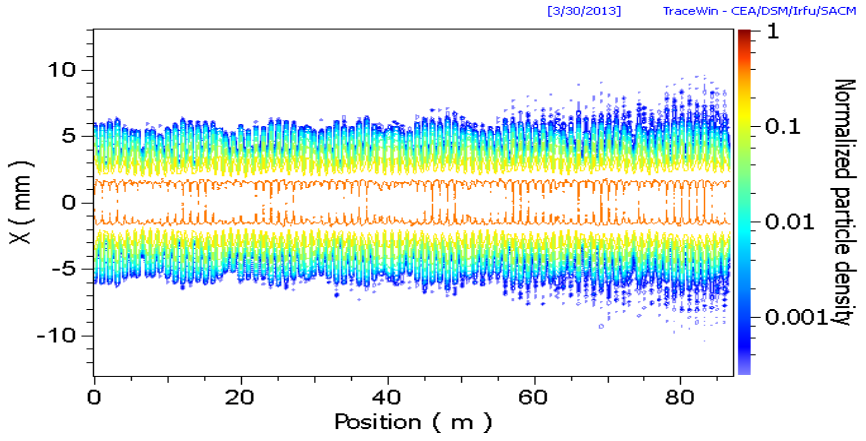


Initially only longitudinal halo + core EP'ed

→ turns into purely transverse halo



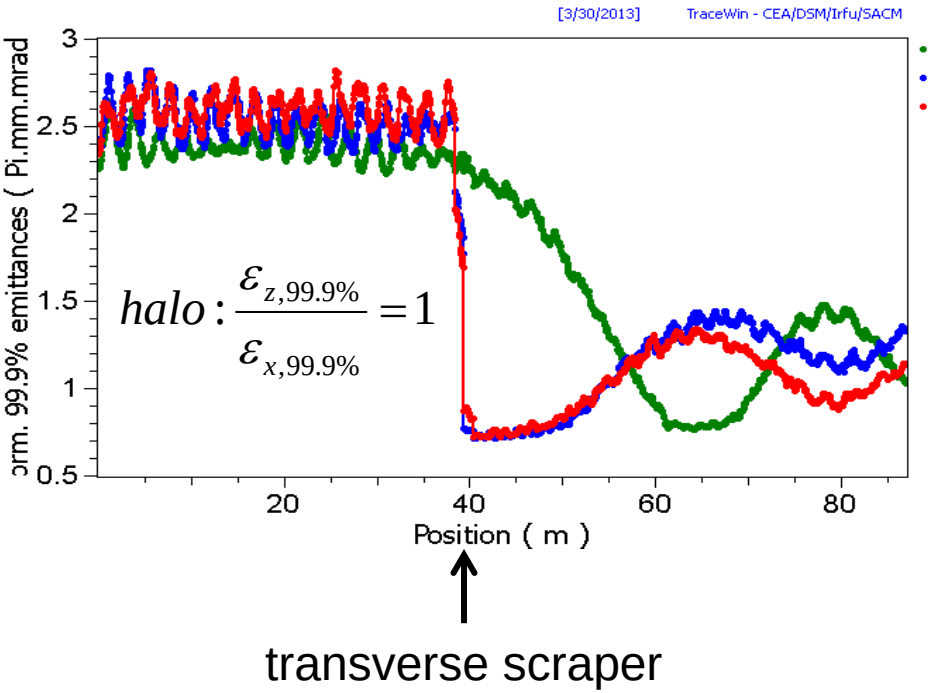




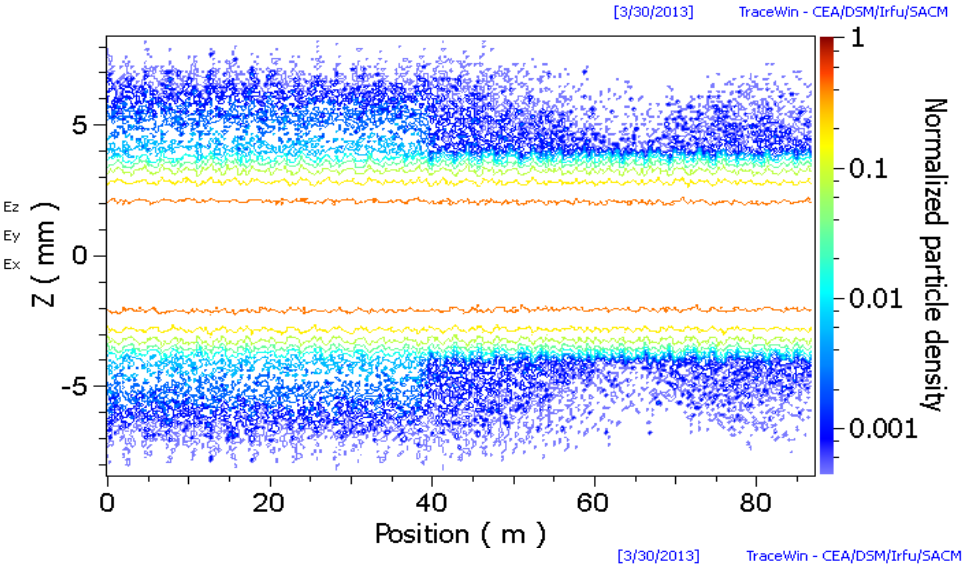
Initially both halos

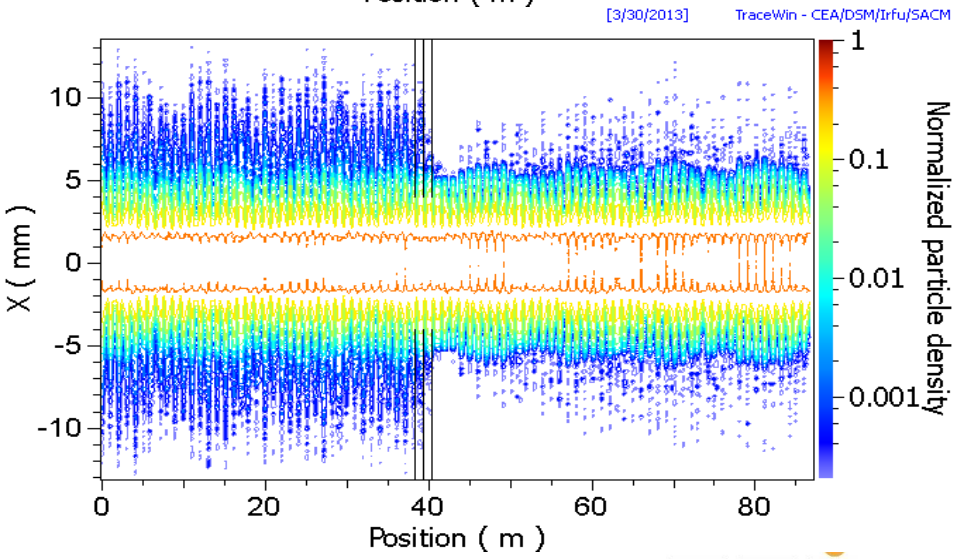
→ need active transverse scraping first

longitudinal halo shrinks & partially exchanges with transverse



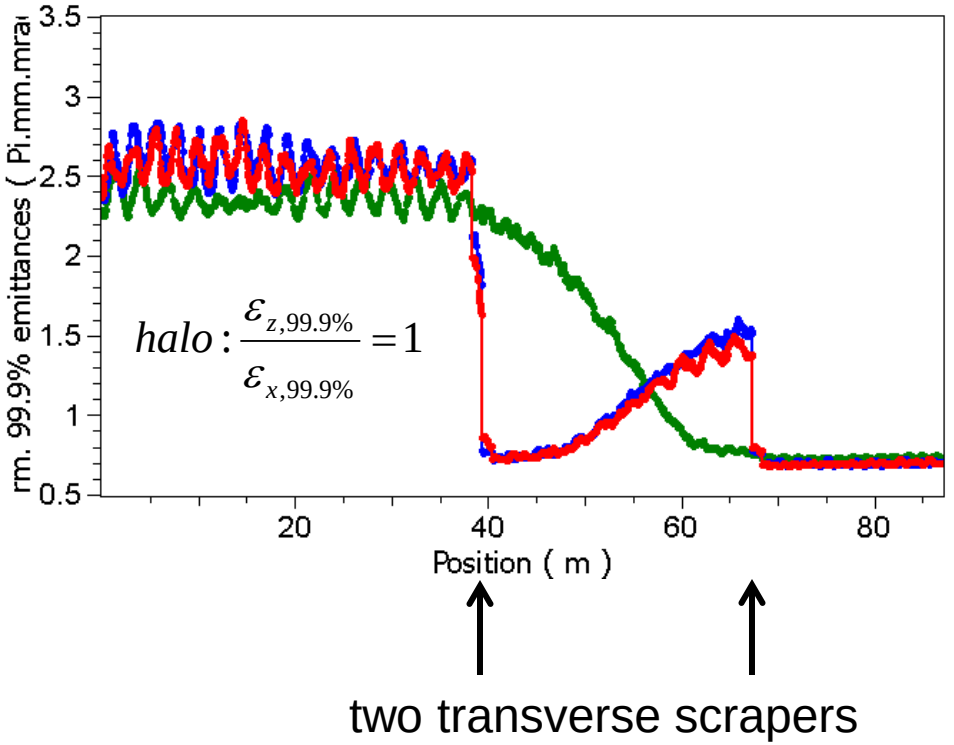
transverse scraper

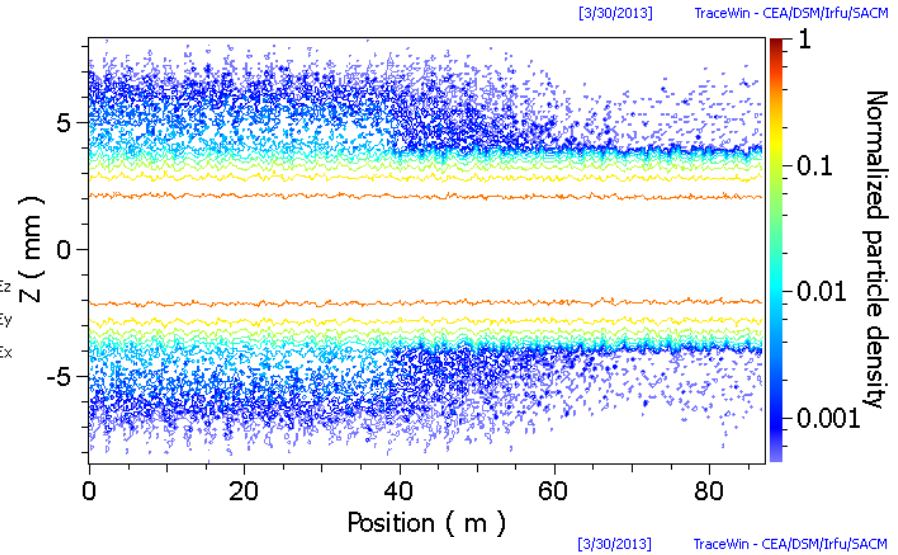


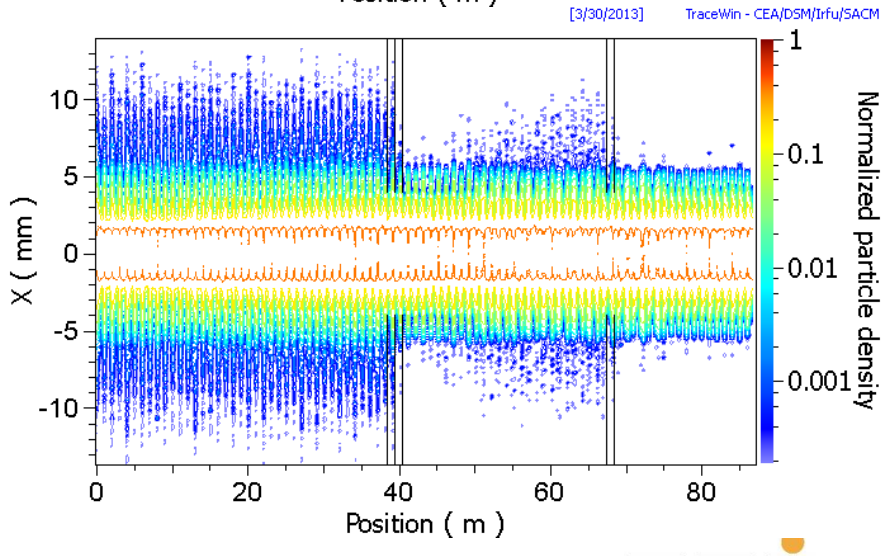


Repeated transverse scraping

is most effective and cleans all planes

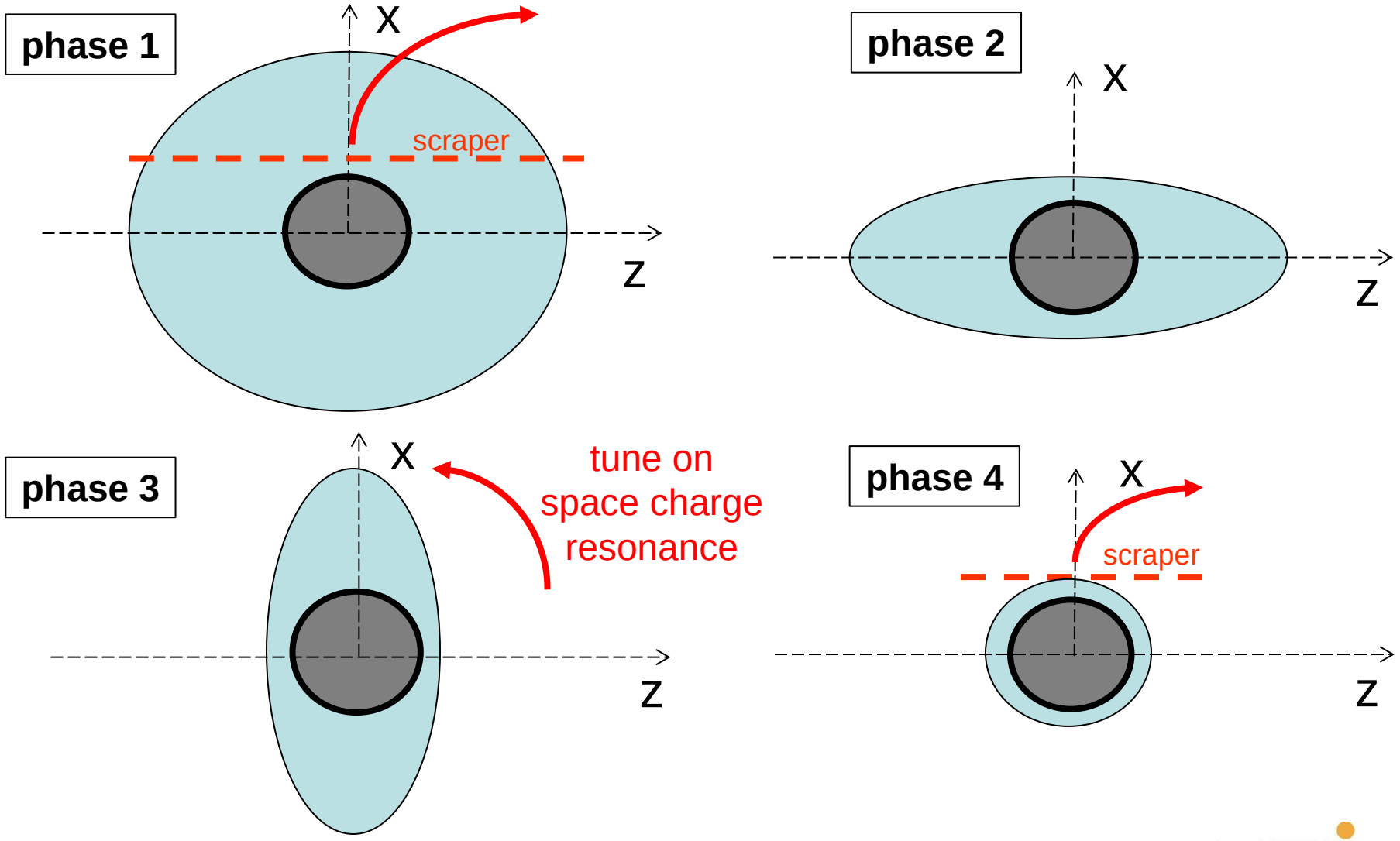






Schematics of controlled halo cleaning

by transverse scraper + "main resonance"



Semi-analytical scaling laws

- describing core & halo stop-bands separately -

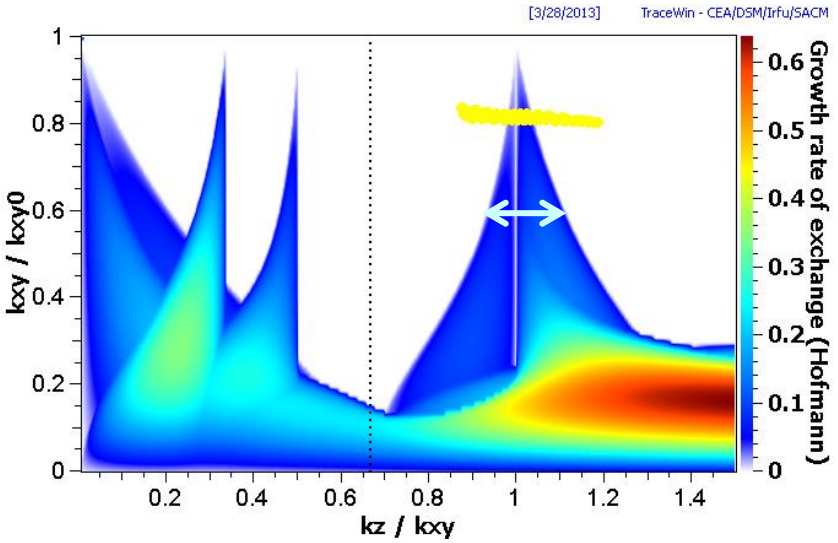
see I.H. and G. Franchetti, PRSTAB 9 (2006)

scaling of stop-band width:

geometrical term *differs for core & halo* **x** **space charge term** *acts on both*

$$\delta\left(\frac{k_z}{k_x}\right) \approx \frac{3}{2}\left(\sqrt{\frac{\varepsilon_z}{\varepsilon_x}} - 1\right) \times \frac{\Delta k_z}{k_{z0}} \Big/ \frac{k_x}{k_{x0}}$$

$$\frac{\Delta k_z}{k_{z0}} = \frac{1}{\sqrt{\varepsilon_z / \varepsilon_x}} \frac{\Delta k_x}{k_{x0}}$$

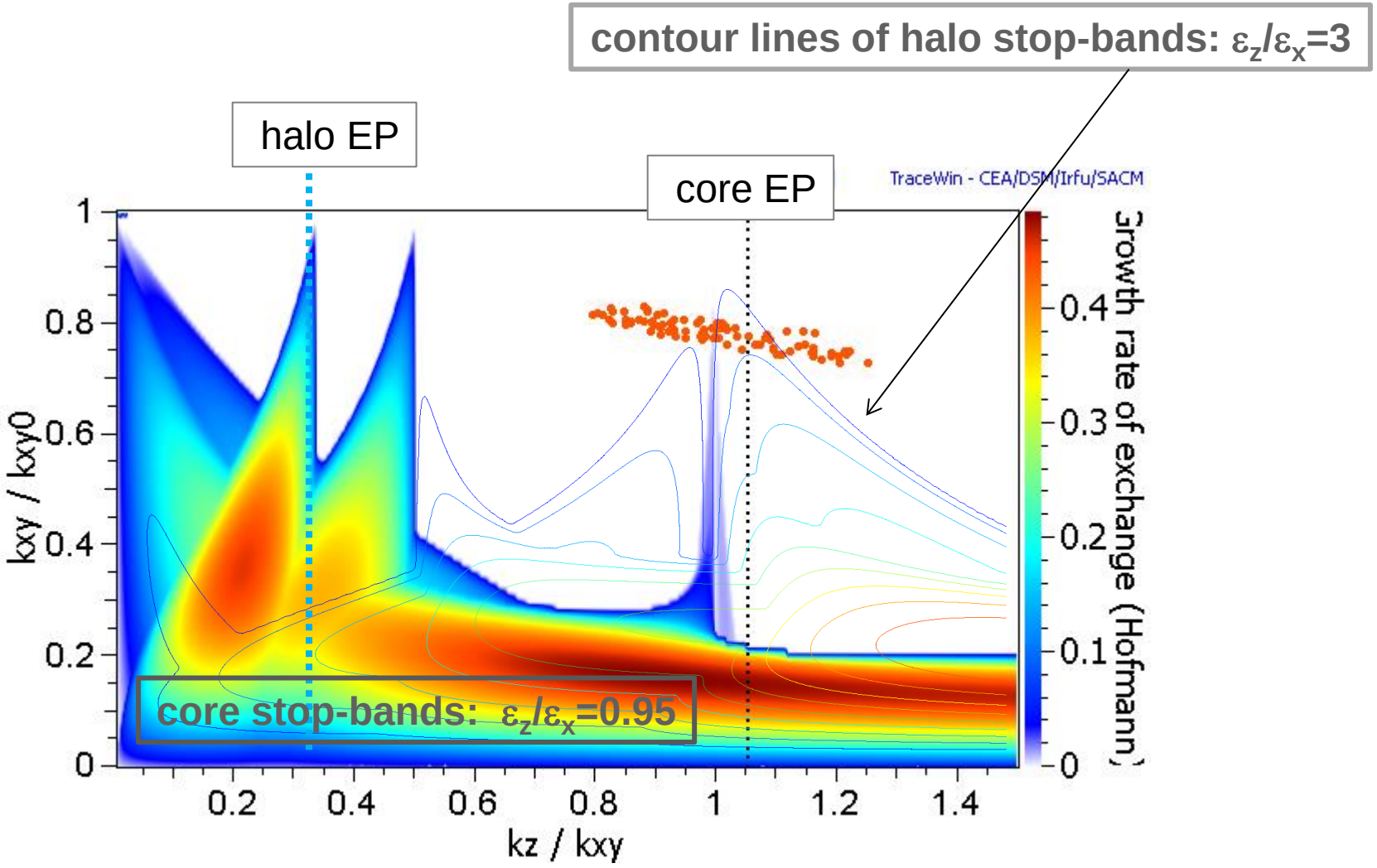


Example: $k_x/k_{x0} \sim 0.6$; $\varepsilon_z/\varepsilon_x = 1.5$
→ $\delta \sim 0.18$
in good agreement with charts

Can be used to establish

"Extended stability chart" for core + halo

different emittance ratios – same space charge driving



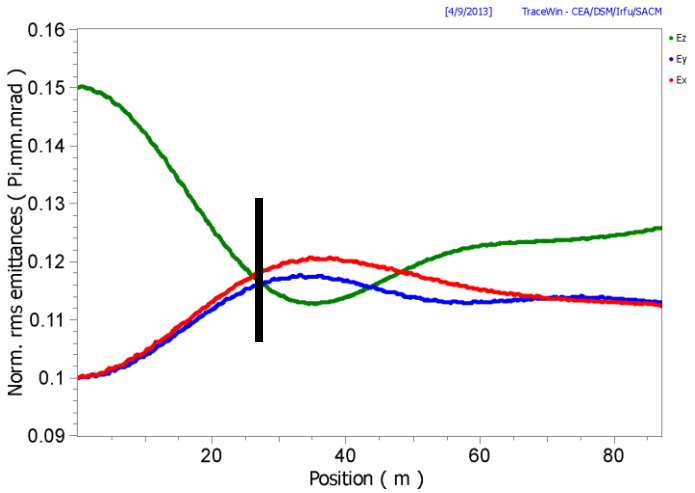
Scaling for "exchange time"

how many cells needed for space charge "main resonance"?

core & halo ~ on same time scales

Scaling for emittance exchange (on stop-band):
number of cells to reach exchange:

$$N_{cells} \approx \ldots \frac{360}{k_{ox}} \left(\frac{\Delta k_z}{k_{oz}} \right)^{-1}$$



TRACEWIN emittance exchange

- ✓ shows good confirmation of the scaling within $\varepsilon_z / \varepsilon_x = 1 \ldots 2$
- ✓ typically only 10...20 cells in high current linac

Conclusions

- **Asymmetry of halo** (with respect to core) should be considered
  - in halo population **and** in halo cleaning procedures
  - space charge coupling may act **different on core and halo emittances**
- Pumping of halo from **one plane into another** by space charge "main resonance" (or any other)
  - may be undesirable (easily overlooked?)
  - might be a useful strategy to enhance Landau damping
- Main application: pumping of halo into preferred plane for **scraping**
  - controlled by **"extended stability chart"** for core + halo
  - **no external nonlinearity needed –** only space charge nonlinearity – **low risk!**
- An option to **reduce loss** in a high current machine
  - in linacs (**longitudinal acceptance loss!) – in rings?** (Montague resonance)
  - should work in principle **– practical demonstration?**