Review of Beam Dynamics and Space Charge Resonances in High Intensity Linacs

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Much progress in design studies for MW p-linac projects in last view years (SNS, KEK-Jaeri, ESS, CERN-SPL, ...) - *not reviewed here*

This paper discusses:

Recent progress in narrowing the gap between **theory models and realistic MW-linac design**

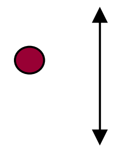
- Non-equipartitioned design
- Free energy conversion of mismatch
- Halo size
- Random errors

Acknowledgments:
SNS Project Office, ORNL/BNL
NERSC Computer Center, LBL

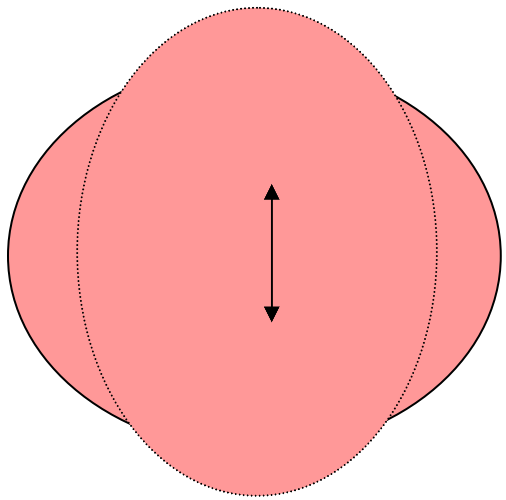
Concept: „Linac beams are governed by resonances“

not only circular accelerators!

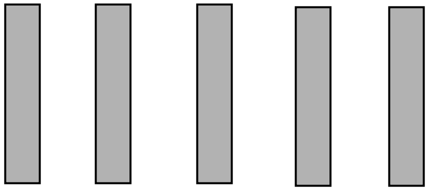
3 types:



core - single particle
-> halo



core - core
-> equipartition



core - periodic focusing structure

avoided by $\sigma_0 < 90^0$

Tools

- No experiments yet *)
- Analytical Theory
- Simulation Comparison
  - IMPACT 3D
    (Qiang/Ryne), highest performance
    10^6 particles –PIC code
    used for „ideal test channel“
  - CERN-SPL with IMPACT 3D 10^6 particles
  - ESS with PARTRAN + PICNIC 3D *(Pichoff et al.)* $10^4 \ldots 10^5$ particles
  - SNS *with* PARMILA 10^5 particles

*) ***free energy concept** tested in LEDA at LANL (2002)*

Non-equipartitioned design

Jameson, Hofmann et al., ... (1981, 1998, 2001)

- „Equipartitioning“ (longitudinal - transverse energy exchange):

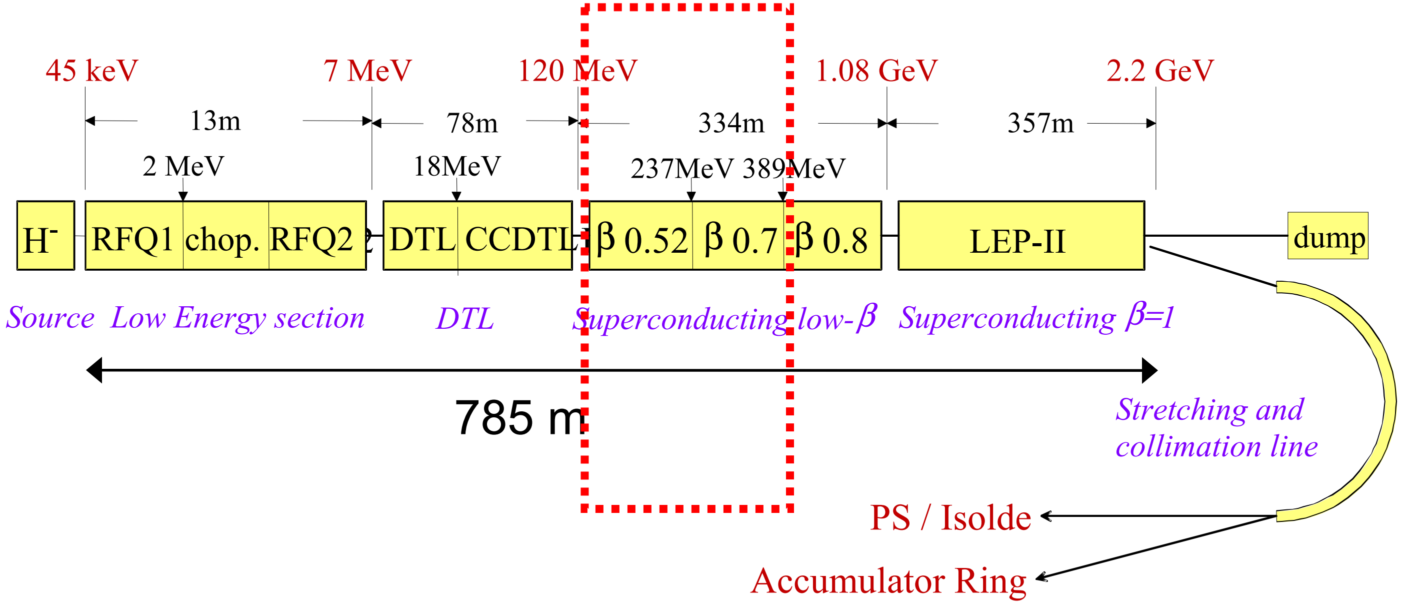
  only by difference resonances driven by space charge

  - not subject to „thermodynamics“
  - analytic theory & 3D simulation tests*: Phys.Rev.E 1998, PRL 2001, PAC01*
- Relax stringent condition of equal energies !

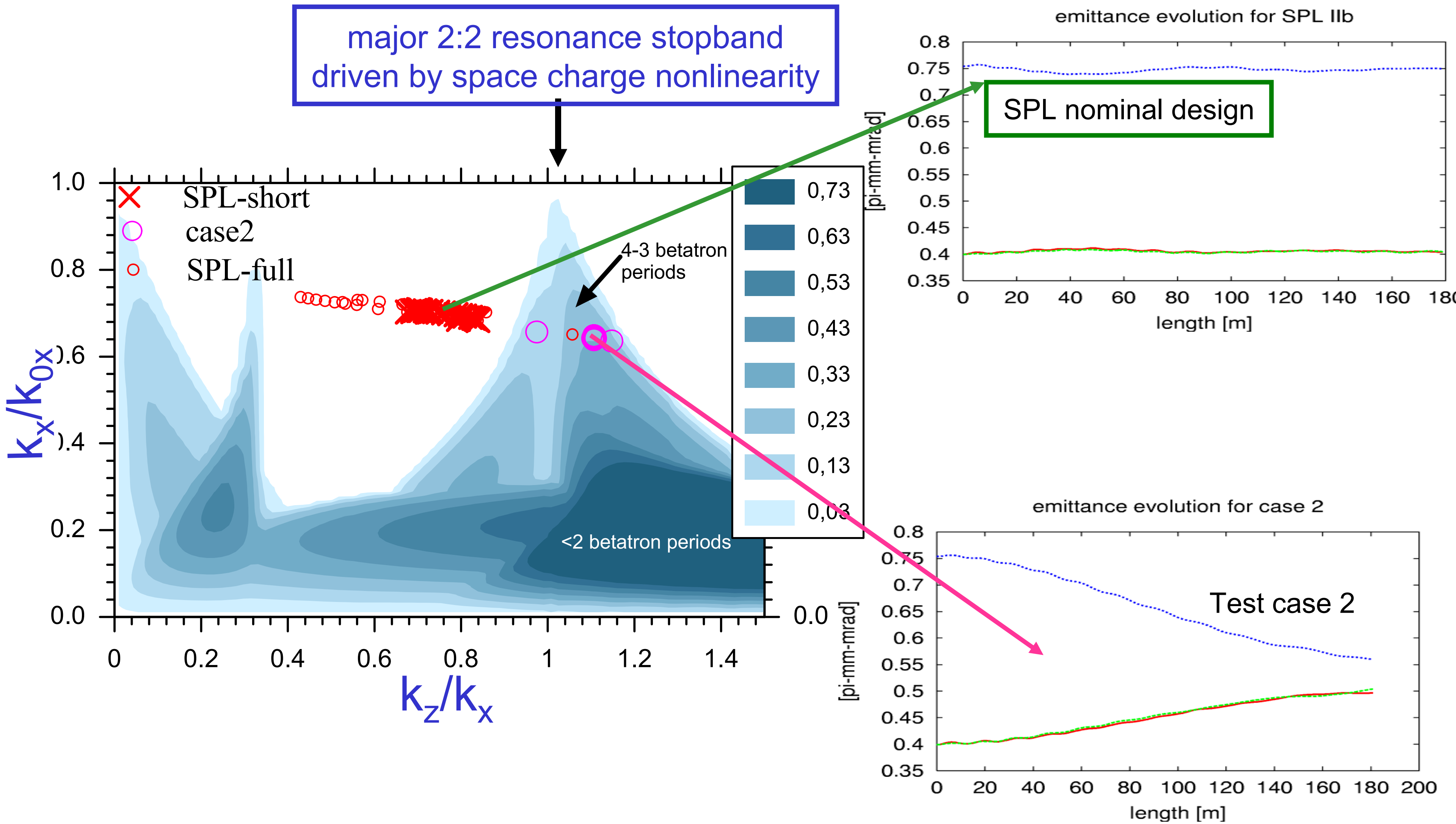
  (still enforced for KEK-JAERI project)

Theory tested for CERN Superconducting Proton Linac Study

- demonstrated even on first two sections of sc linac!



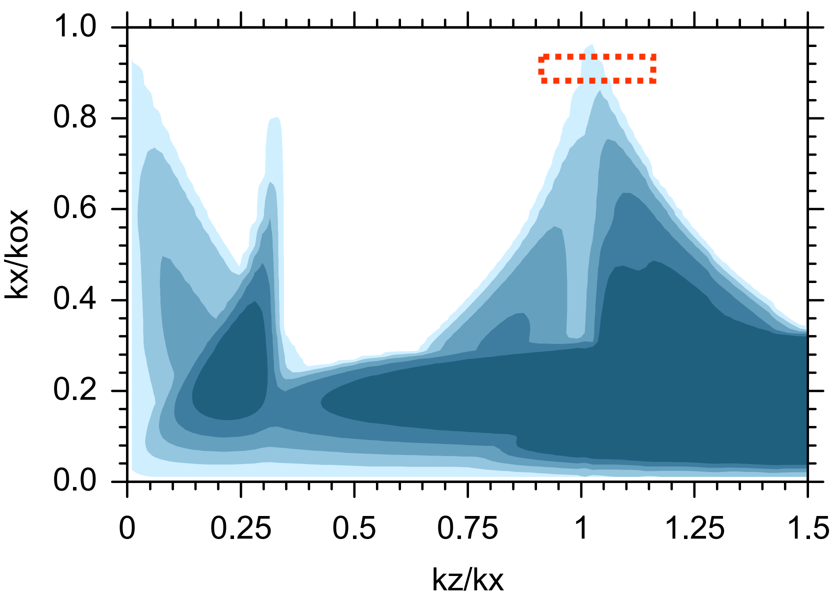
"Stability Charts" for $\varepsilon_z/\varepsilon_{x,y}=2$: CERN SPL study



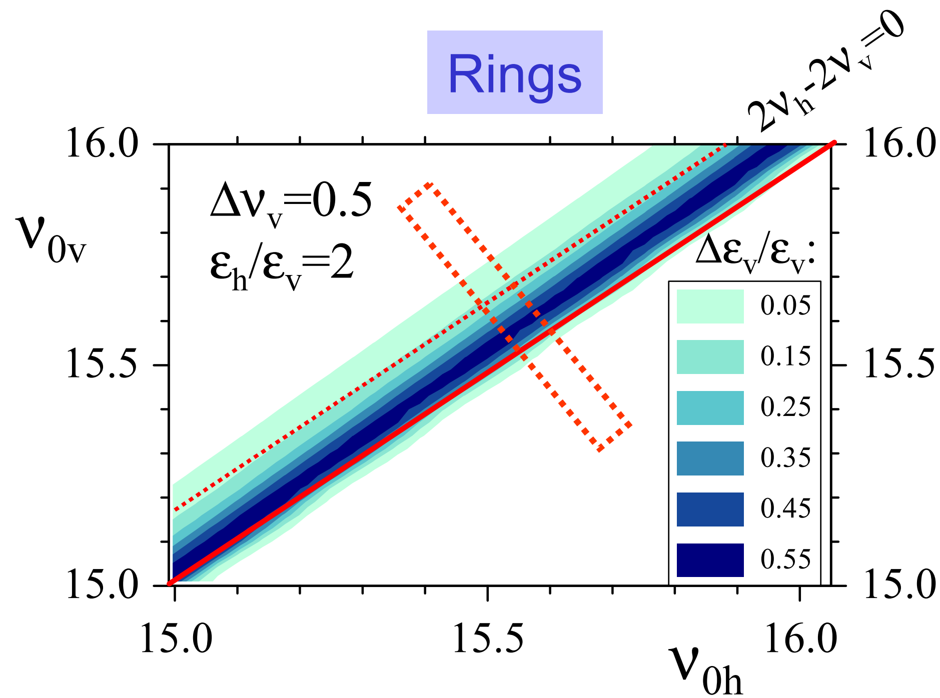
Linac 2:2 resonance – Ring „Montague –resonance“

Montague:
4-th order: $2\nu_x - 2\nu_y \sim 0$

Linac



Rings



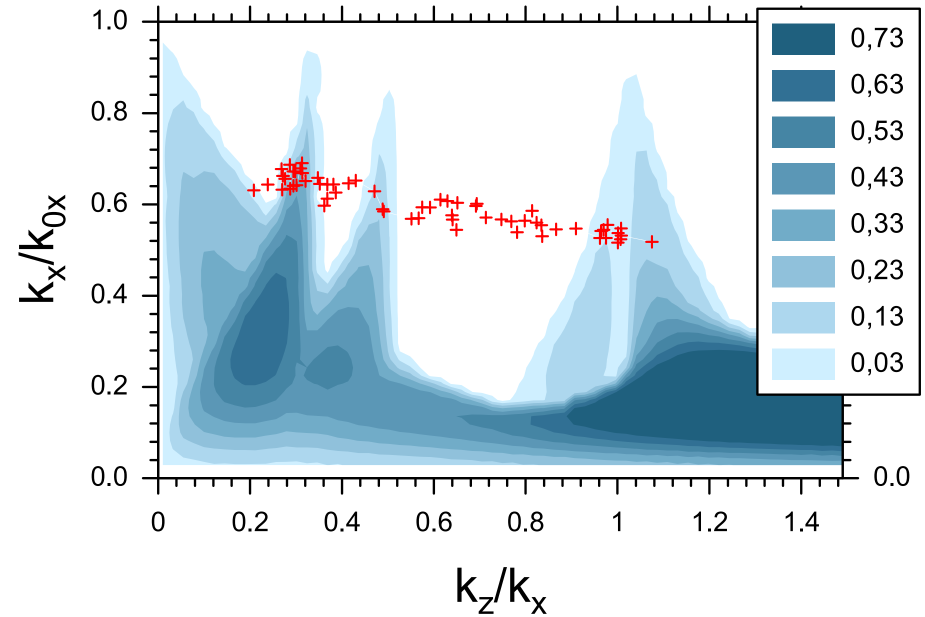
detailed measurement: *Sakai et al. PAC01*

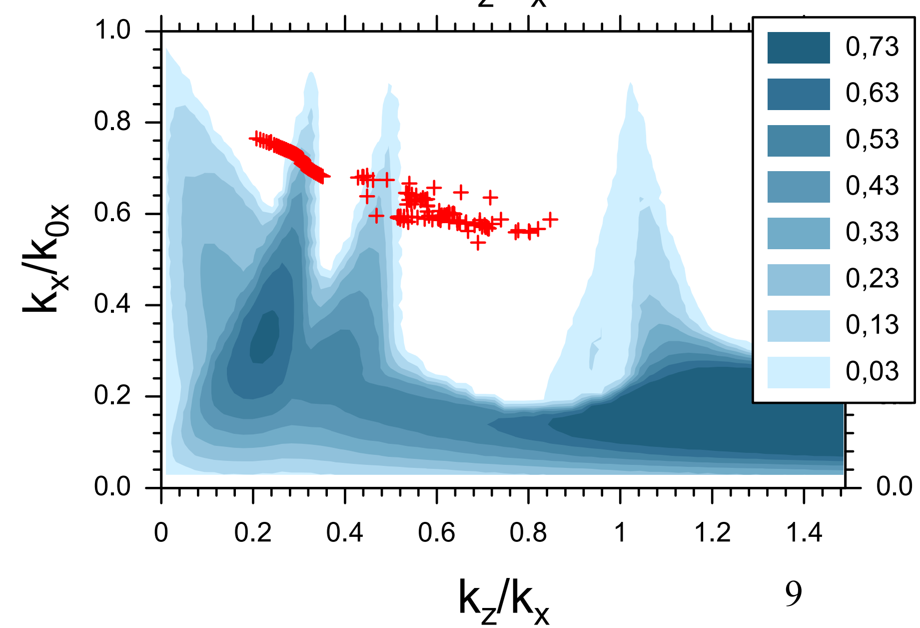
SNS ($\varepsilon_z/\varepsilon_{x,y}$=1.4) and ESS ($\varepsilon_z/\varepsilon_{x,y}$=1.3)

Transverse r.m.s emittance growth:

	for $\varepsilon_z/\varepsilon_{x,y}$
SNS	
~ 17%	1.0
~ 27%	1.4
~ 40%	2.0
ESS	
~ 10%	1.3

- Enough design flexibility with sufficiently broad k_z/k_x-footprint
- need to make sure that $\varepsilon_z/\varepsilon_{x,y}$ stays within design limits!





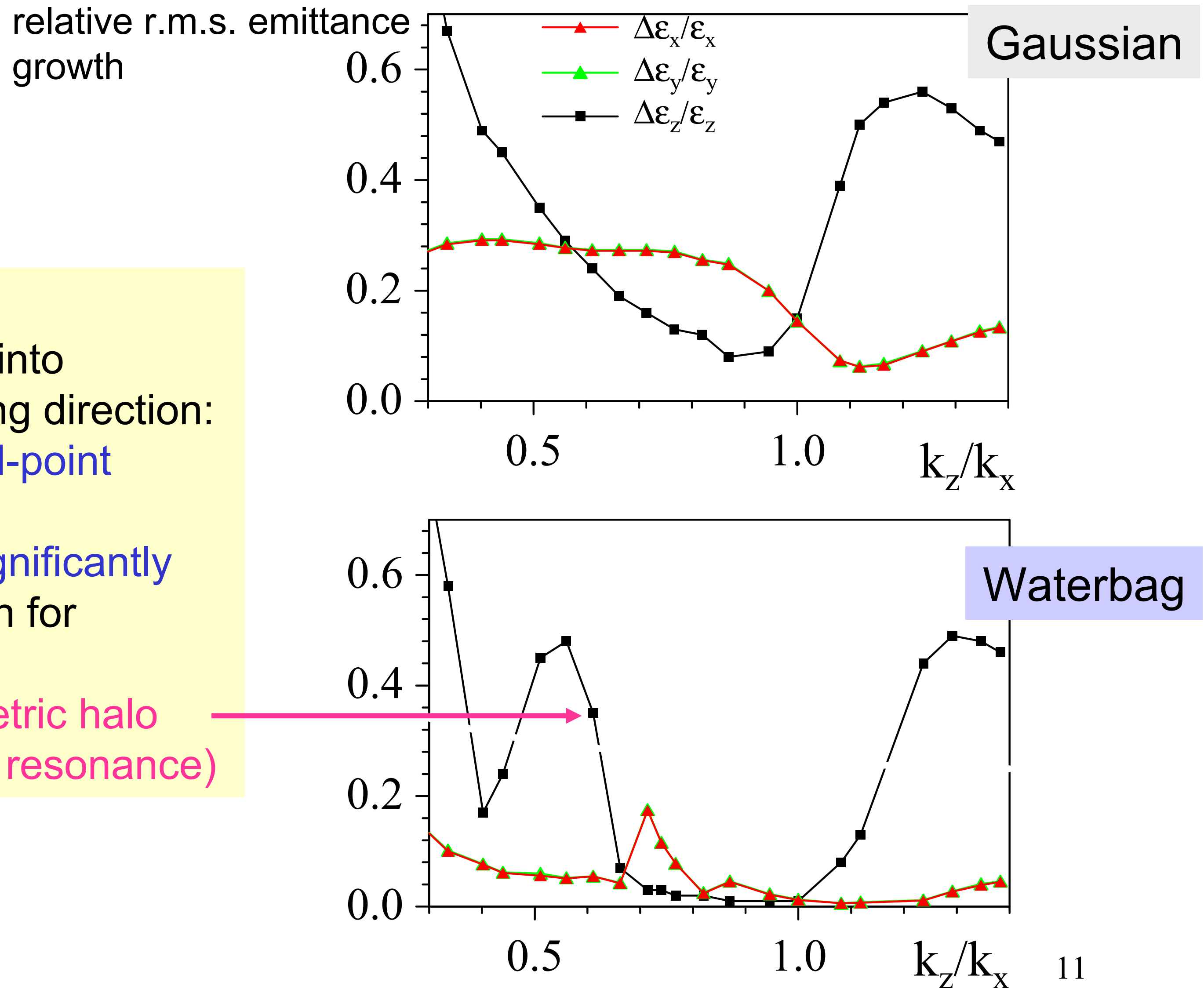
Mismatch induced halo

- 2:1 parametric halo (idealized)
  Gluckstern, Wangler, ...
  we extend it to anisotropy in ellipsoidal bunches with k_z different from k_x
  -> multi-dimensional parameter space!
- increased complexity can be reduced by „free energy equivalence"
  in 1D: *Reiser, Cucchetti, …(1991)*
  revisited here and generalized to a key concept in 3D
  -> 1 parameter = r.m.s mismatch

Main tool: IMPACT 3D simulation to scan over k_z/k_x -space

for „constant focusing channel“

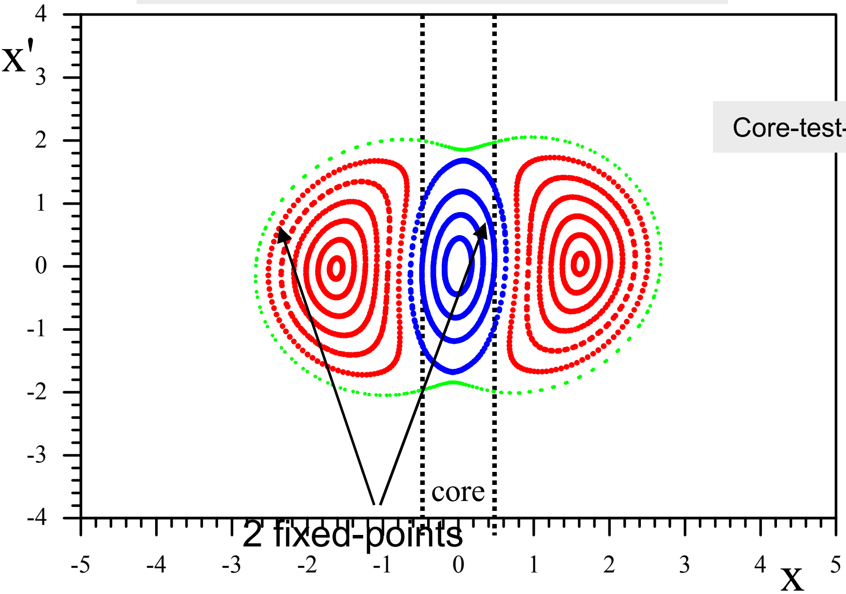
10^6 particles / linear rf force/ 30% mismatch in x,y,z



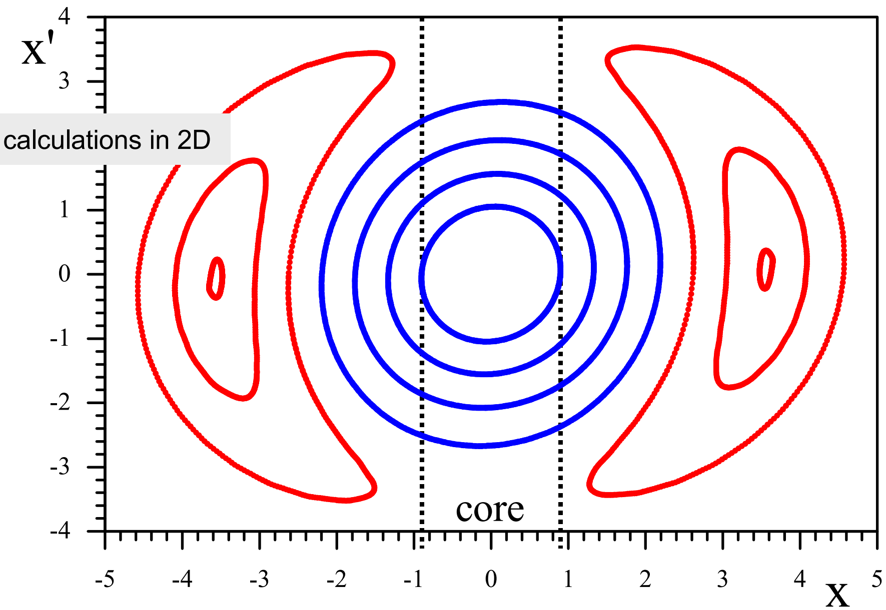
- most of growth into stronger focusing direction: resonance fixed-point „attracted“
- for waterbag significantly less growth than for Gaussian
- not only parametric halo (also 4-th order resonance)

Key is attraction of fixed-points by stronger focusing

Round beam breathing mode



Core-test-particle calculations in 2D



Weaker focusing in x ($k_x<k_z$):
halo amplitude in principle
arbitrarily large,
but won't be populated populated!

but: attracted for $k_z>k_x$

New concept:

Free energy equivalence of r.m.s. mismatch

Equivalence of

average emittance growth – free energy

$(\Delta\varepsilon_x/\varepsilon_x + \Delta\varepsilon_y/\varepsilon_y + \Delta\varepsilon_z/\varepsilon_z)/3 \sim \alpha\,(M_{rms}-1)^2$

- ~ independent of k_z/k_x for Gaussian (initial tails needed!)
- ~ independent of mismatch vector M_x, M_y, M_z – rms mismatch enough !

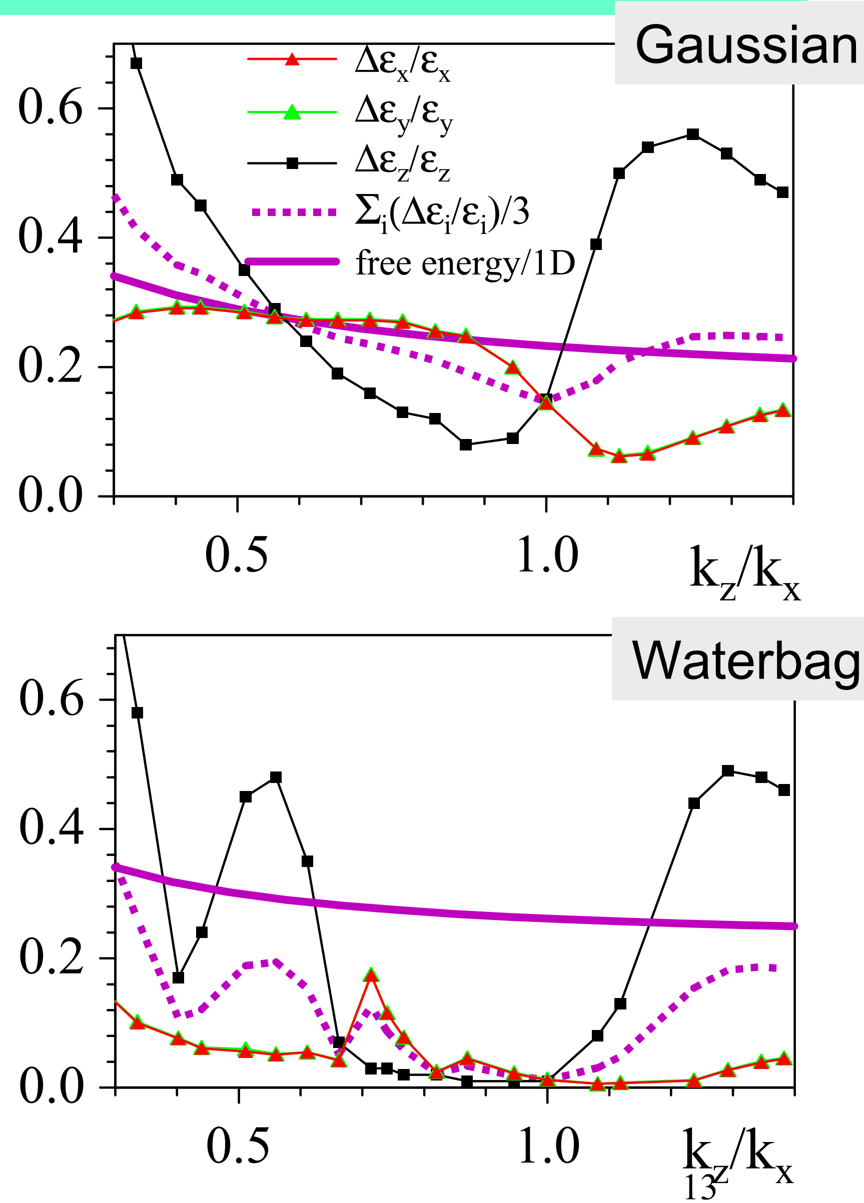
$(M_{rms}-1)^2 = [(M_x-1)^2 + (M_y-1)^2 + (M_z-1)^2] / 3$

- value given to good accuracy by 1D analytical equivalence:

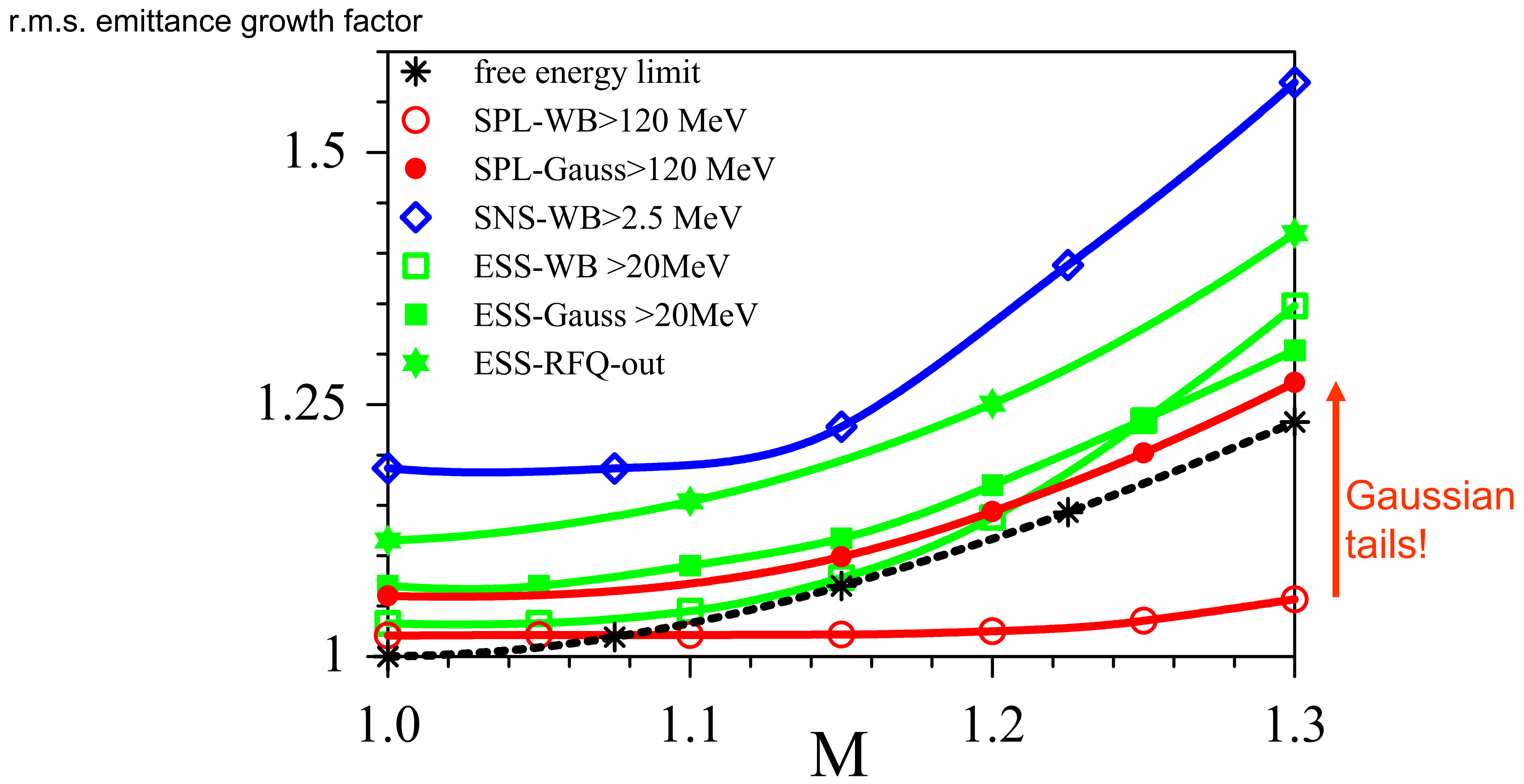
$\Delta\varepsilon/\varepsilon \sim \alpha\,(M-1)^2 \sim E_{mismatched} - E_{matched}$

„free energy", *Reiser, 1991*

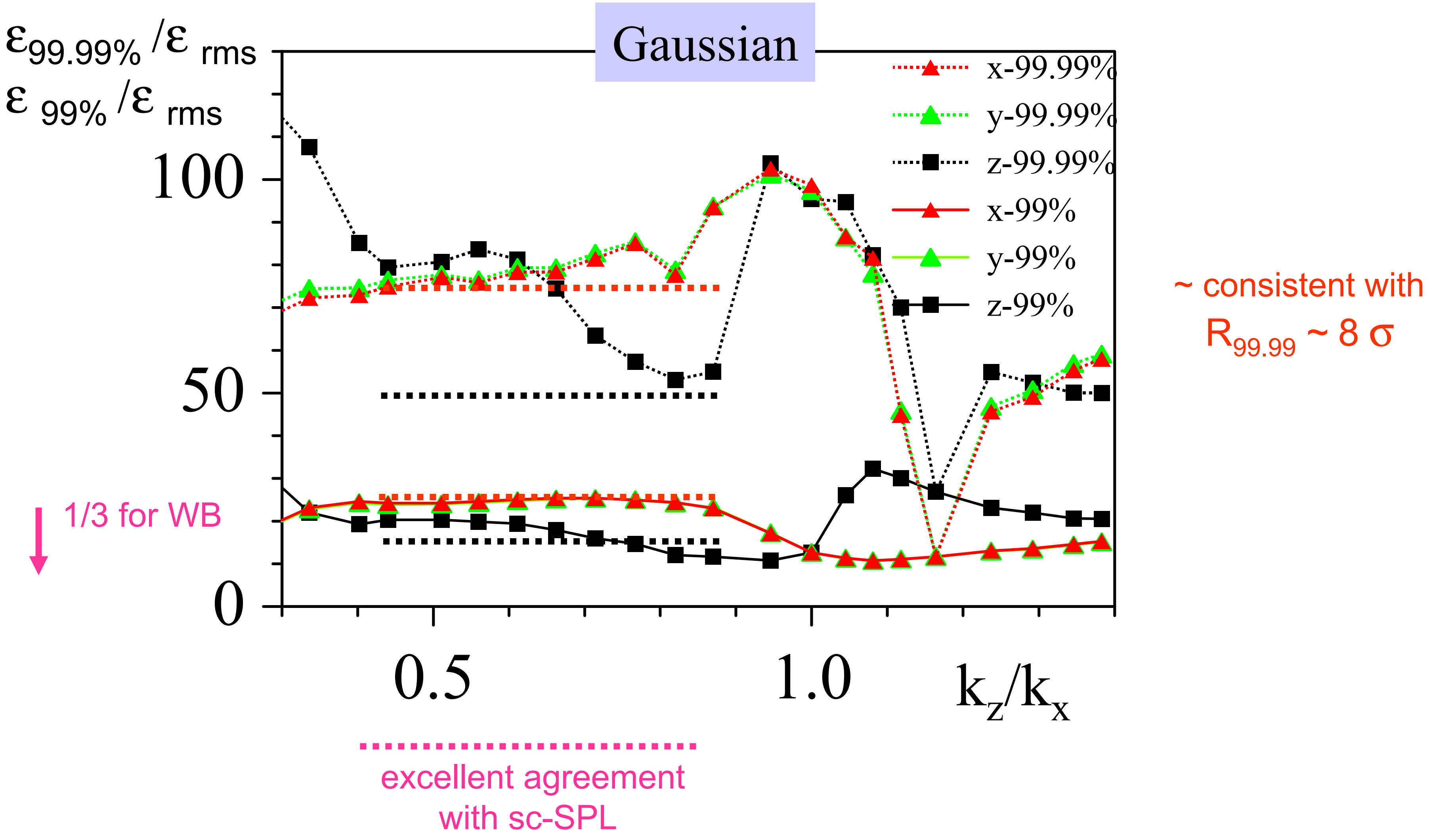
α only weakly inreasing with space charge



Comparison: designs - free energy



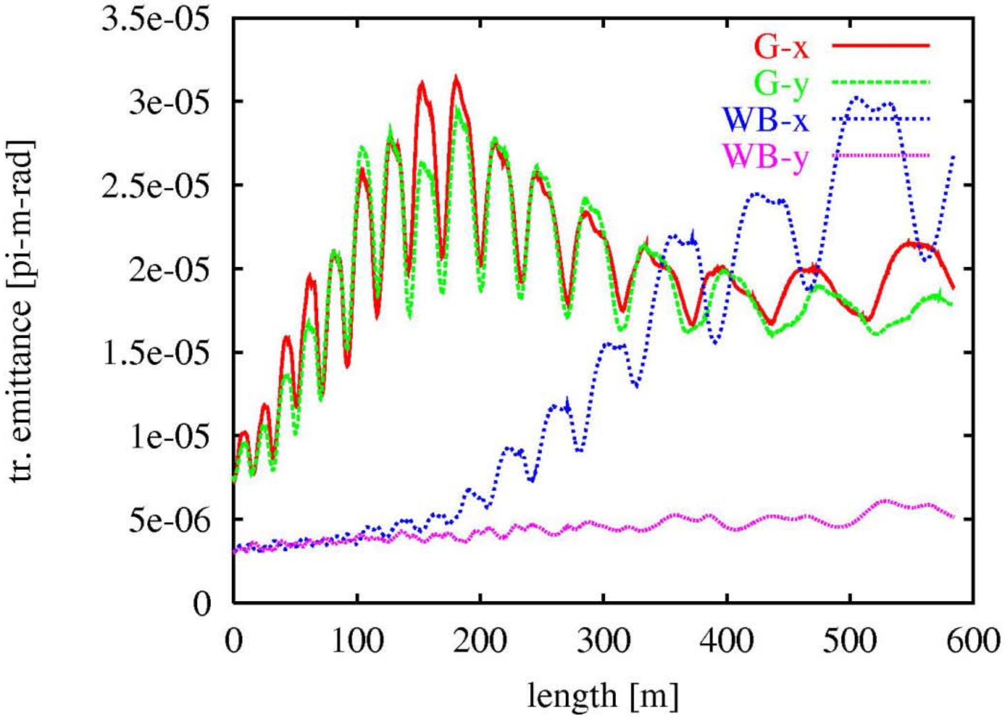
outer halo: $\varepsilon_{99\%}/\varepsilon_{rms}$ and $\varepsilon_{99.99\%}/\varepsilon_{rms}$ excellent agreement with sc CERN-SPL



Initial tails induce fast enough halo formation

even for relatively short linacs

growth rate ~ current



Mismatch & Entropy

Total entropy flow

(Lawson, Lapostolle, Gluckstern,1973)

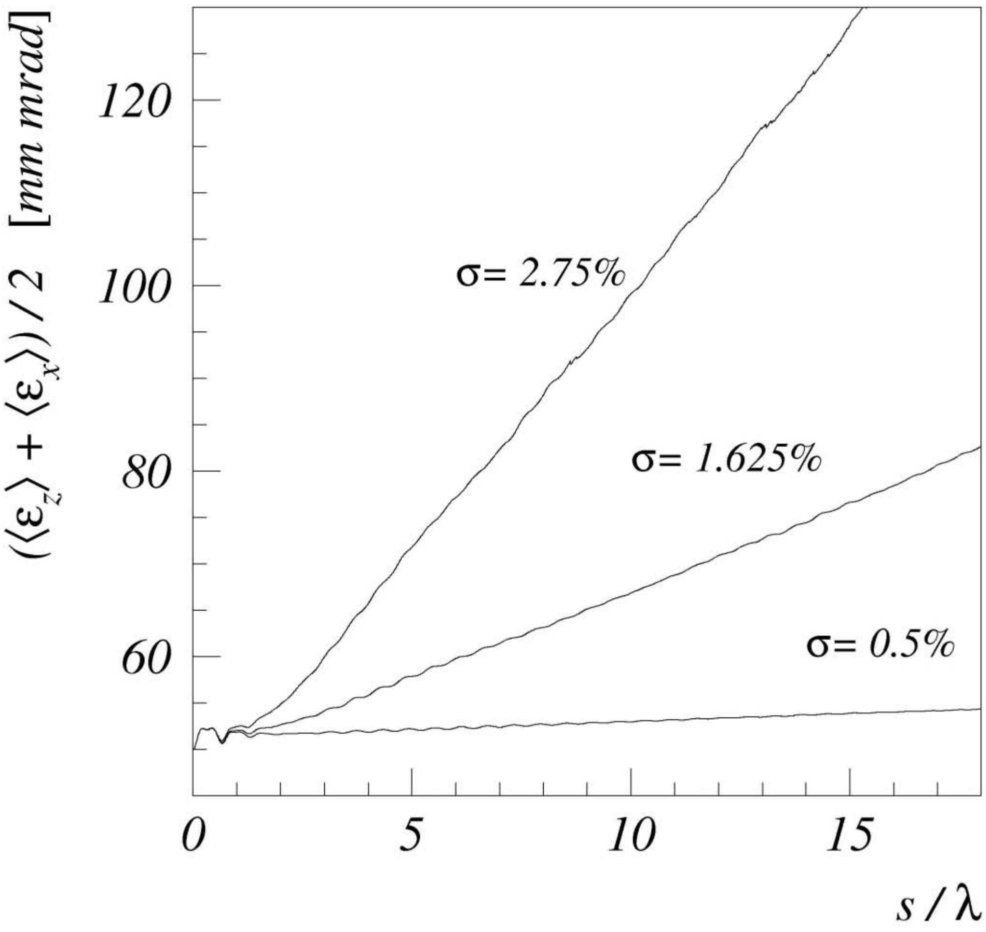
$\Delta S = (\Delta\varepsilon_x/\varepsilon_x + \Delta\varepsilon_y/\varepsilon_y + \Delta\varepsilon_z/\varepsilon_z)/k_B$ ~ rms mismatch

flow into transverse and longitudinal may be against „thermodynamics“ („hotter“ gets still „hotter“)

Random error in a quad channel

with σ= r.m.s error strength

continuous transformation of „mismatch free energy“ into linearly growing rms emittance



Poster G. Franchetti WEPLE117

Conclusion

- Idealized theory models successfully „tracked“ in complex linacs
- Parametric (2:1) resonance halo dominates picture
- initial tails fully convert mismatch to free energy limit
  - scraping tails reduces rms and 99% halo
  - 99.99% bounded below ~ 8 σ
- Significant reduction of parameter complexity by equivalence
  Free energy equivalence using rms mismatch strength
- More work on random error sources needed!