TU3PBI02

Linac Code Benchmarking with High-Intensity Experiments at the UNILAC

L. Groening, W. Barth, W. Bayer, G. Clemente, L. Dahl, P. Forck, P. Gerhard, I. Hofmann, M.S. Kaiser, M. Maier, S. Mickat, T. Milosic, G. Riehl, H. Vormann, S. Yaramyshev, *GSI, Germany*

D. Jeon, *ORNL, U.S.A.*

D. Uriot, *CEA/Saclay, France*

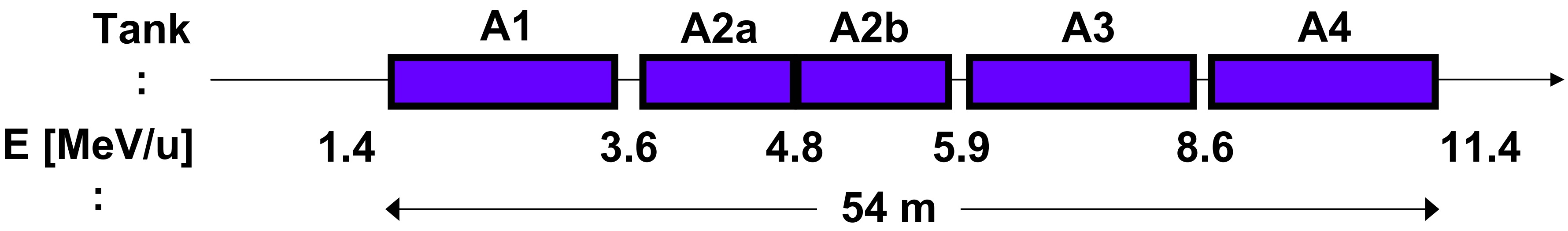
R. Tiede*, Goethe University of Frankfurt a.M., Germany*

- Introduction and set-up
- Reconstruction of initial distribution
- Comparison of measurements and simulations
  - moderate mismatch
  - small mismatch
- 4^{th}-order space charge driven resonance
- Summary

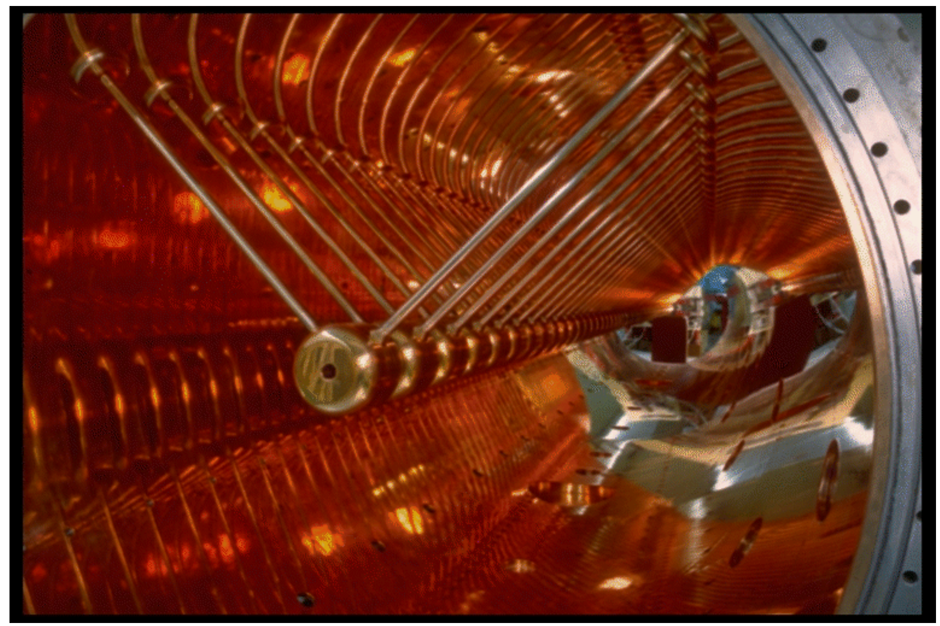
Phys. Rev. ST Accel. Beams **11** 094201 (2008)

accepted by Phys. Rev. Lett.

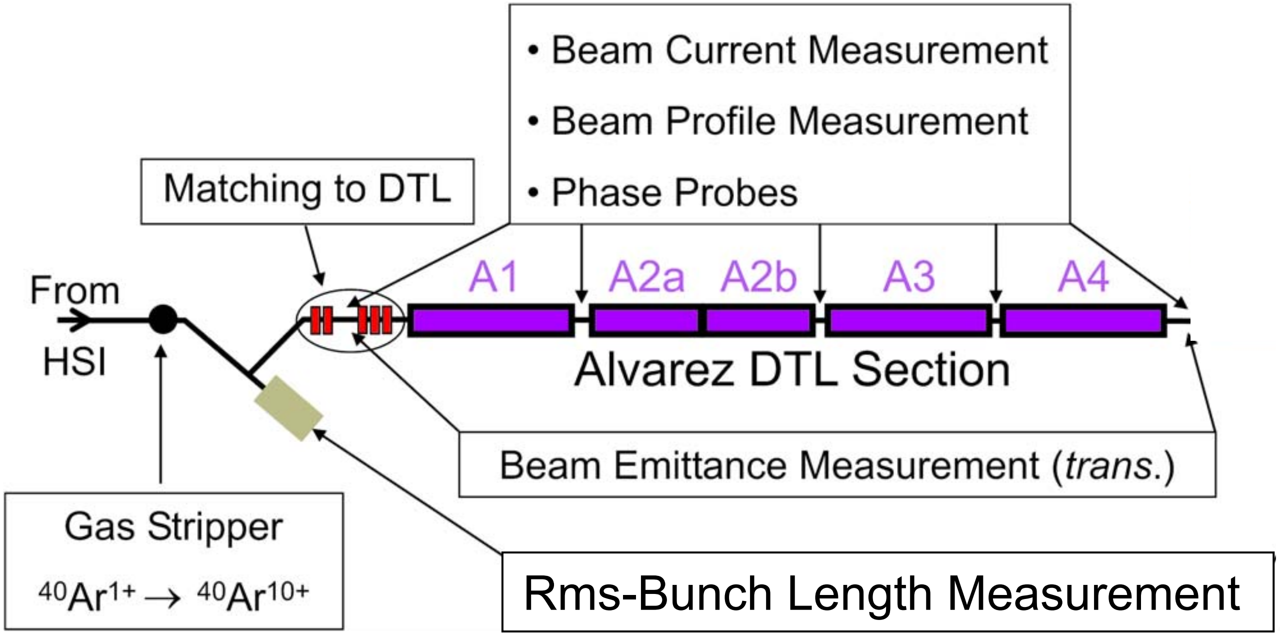
Case to Benchmark: Emittance Growth along UNILAC Alvarez DTL at GSI



- 5 independent rf-tanks
- 108 MHz
- 192 rf-cells
- F-D-D-F focusing
- Inter-tank focusing : F-D-F
- Synchr. rf-phases -(30°,30°,30°,25°,25°)

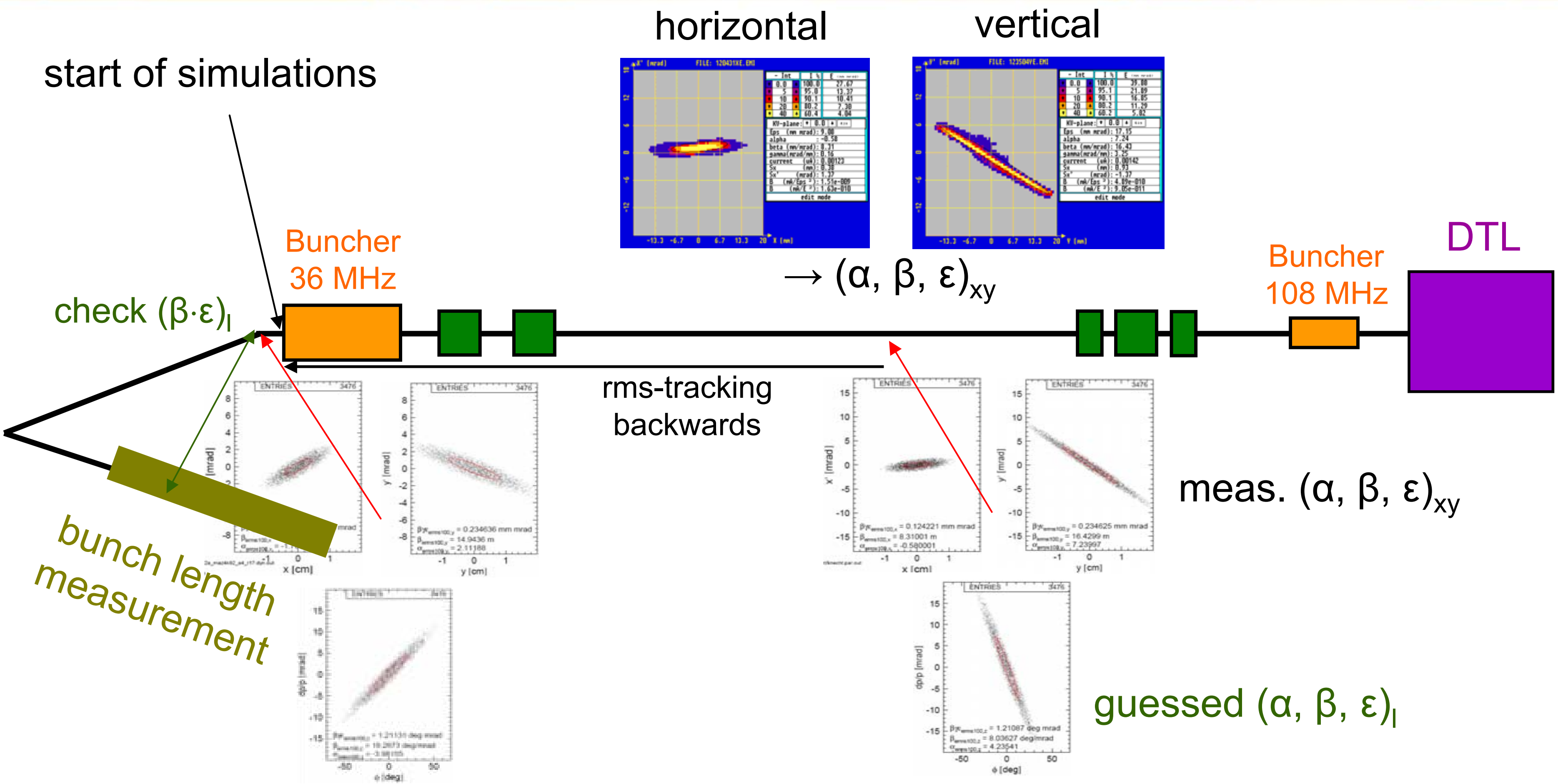


Experimental Set-up & Procedure



- set beam current to 7.1 mA of $^{40}Ar^{10+}$
- measure hor., ver. emittance, and long. rms-bunch length at DTL entrance
- set DTL transverse phase advance to values from 35° to 130° (undepressed)
  - tune depression varied from 14% (130°) to 43% (35°)
- measure transmission, hor., and ver. rms-emittance at DTL exit

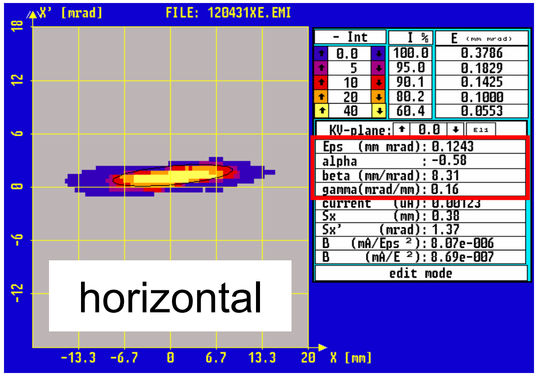
Reconstruction of Initial rms-Parameters



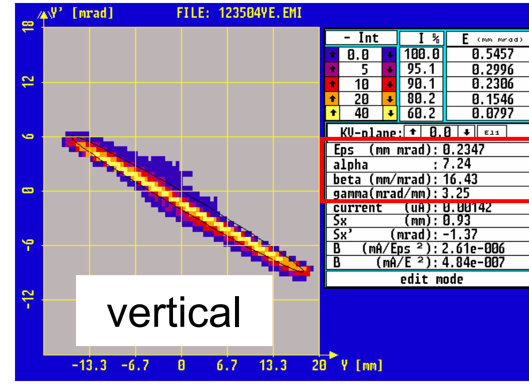
1. selfconsistent KV-backtracking, i.e. finding $(\alpha,\beta,\varepsilon)_l$ that fit to measured bunch length
2. verification whether applied machine settings give full transmission w/o tails

TU3PBI02

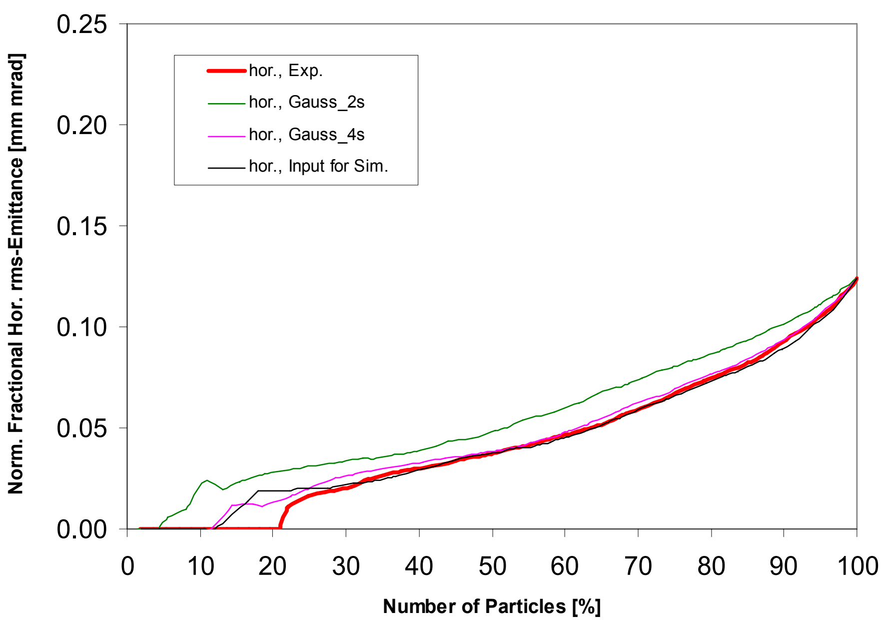
Reconstruction of Initial Type of Distribution

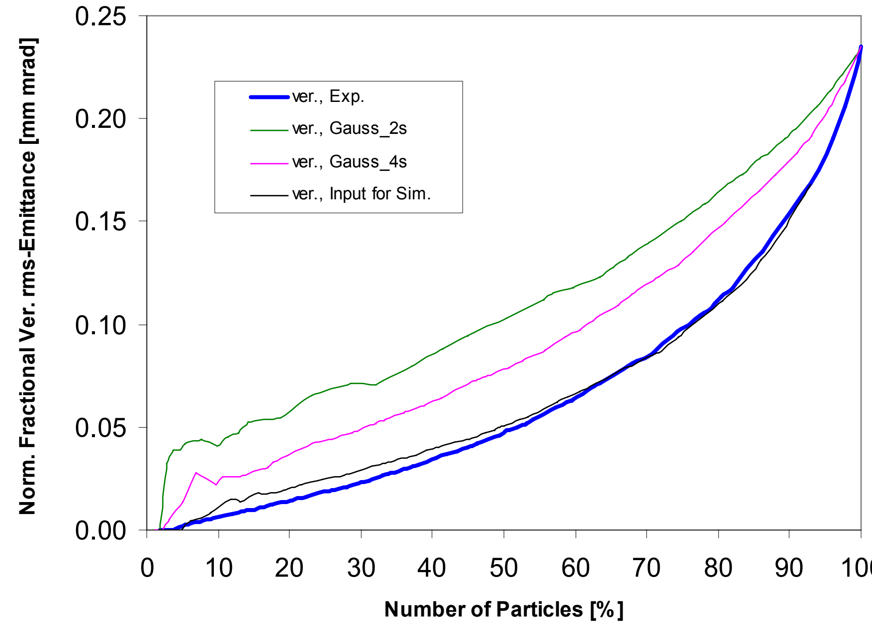


measured in front of DTL



measured initial distribution inhabits different amount of halo horizontally and vertically





Reconstruction of Initial Type of Distribution

- Gauss, Lorentz, Waterbag, KV distributions do not fit the measured amount of halo
- Several functions tried in order to fit halo in both planes
- Function found as:

$$\frac{dN}{dV} = f\,(X, X', Y, Y', \Phi, \delta P/P)$$

$$\tilde{R}^2 = X^2 + X'^2 + Y^{1.2} + Y'^{1.2} + \Phi^2 + (\delta P/P)^2$$

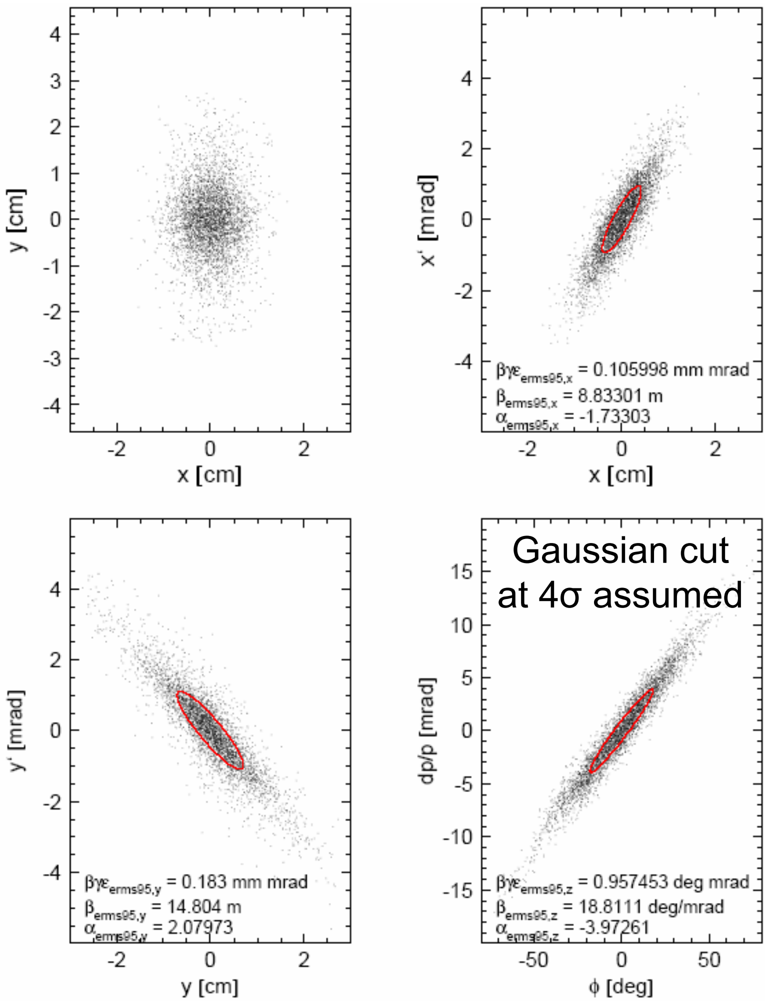
$$f(\tilde{R}) = \frac{a}{2.5 \cdot 10^{-4} + \tilde{R}^{10}}, \quad \tilde{R} \leq 1$$

$$f(\tilde{R}) = 0, \qquad \tilde{R} > 1,$$

applying different powers for different planes, the amount of halo can be reproduced in each plane separately

Initial Distribution and Codes

initial distribution



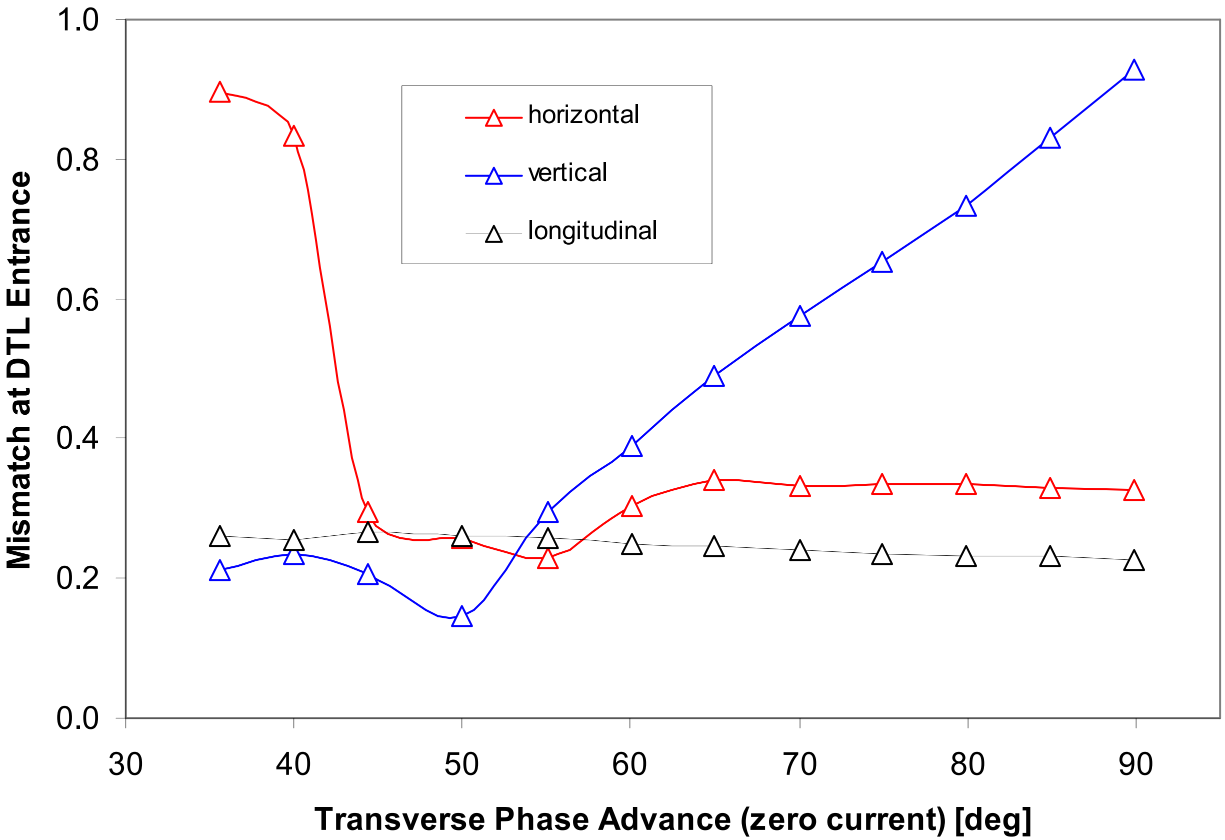
Simulations with four different codes as used by the participating labs:

DYNAMION (GSI)
PARMILA (SNS)
TraceWin (CEA/Saclay)
LORASR (Univ. of Frankfurt)

	Solver	Boundaries	No. of Part.	CPU Time	Rf-Gap
DYNAMION	3D-part.-part.	open	$4.3 \cdot 10^3$	20 h	tracking
PARMILA	PICNIC-3D	open	$2 \cdot 10^5$	30 min.	non-linear kicks
TraceWin	PICNIC-3D	open	$2 \cdot 10^5$	30 min.	non-linear kicks
LORASR	PICNIC-3D	open	$2 \cdot 10^5$	1 h	tracking

Mismatch to Periodic DTL → Moderate Mismatch Case

rms-tracking algorithm for reconstruction of initial distribution was used to estimate mismatch to DTL

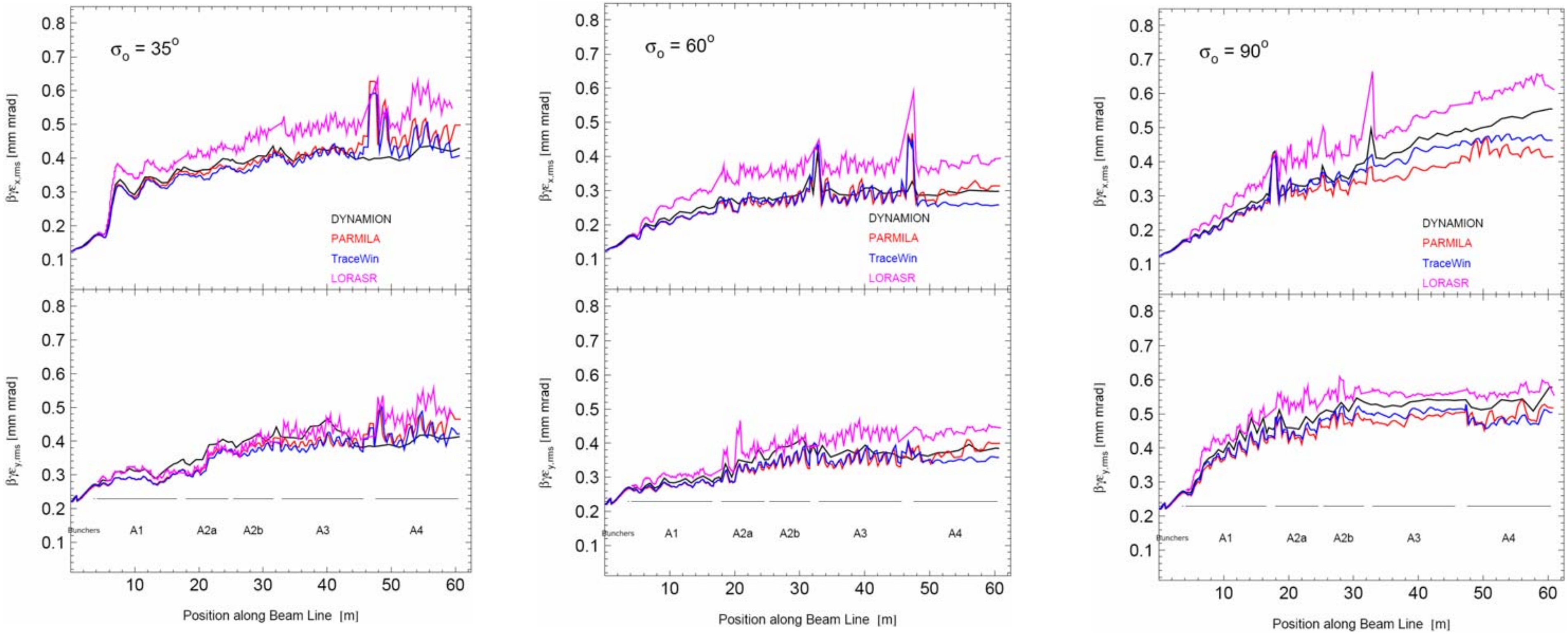


$$M = \left[1 + \frac{\Delta + \sqrt{\Delta(\Delta+4)}}{2}\right]^{1/2} - 1$$

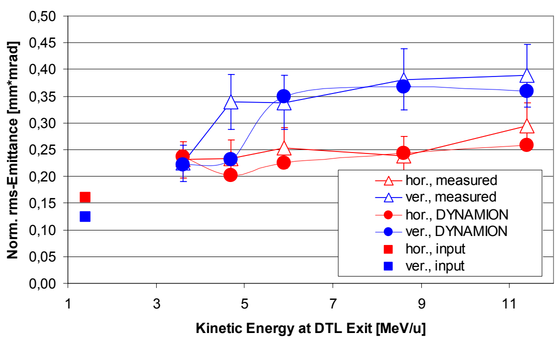
$$\Delta = (\Delta\alpha)^2 - \Delta\beta\Delta\gamma \,,$$

T.P. Wangler, *Rf Linear Accelerators*, p. 217

Evolution of Simulated rms-Emittances

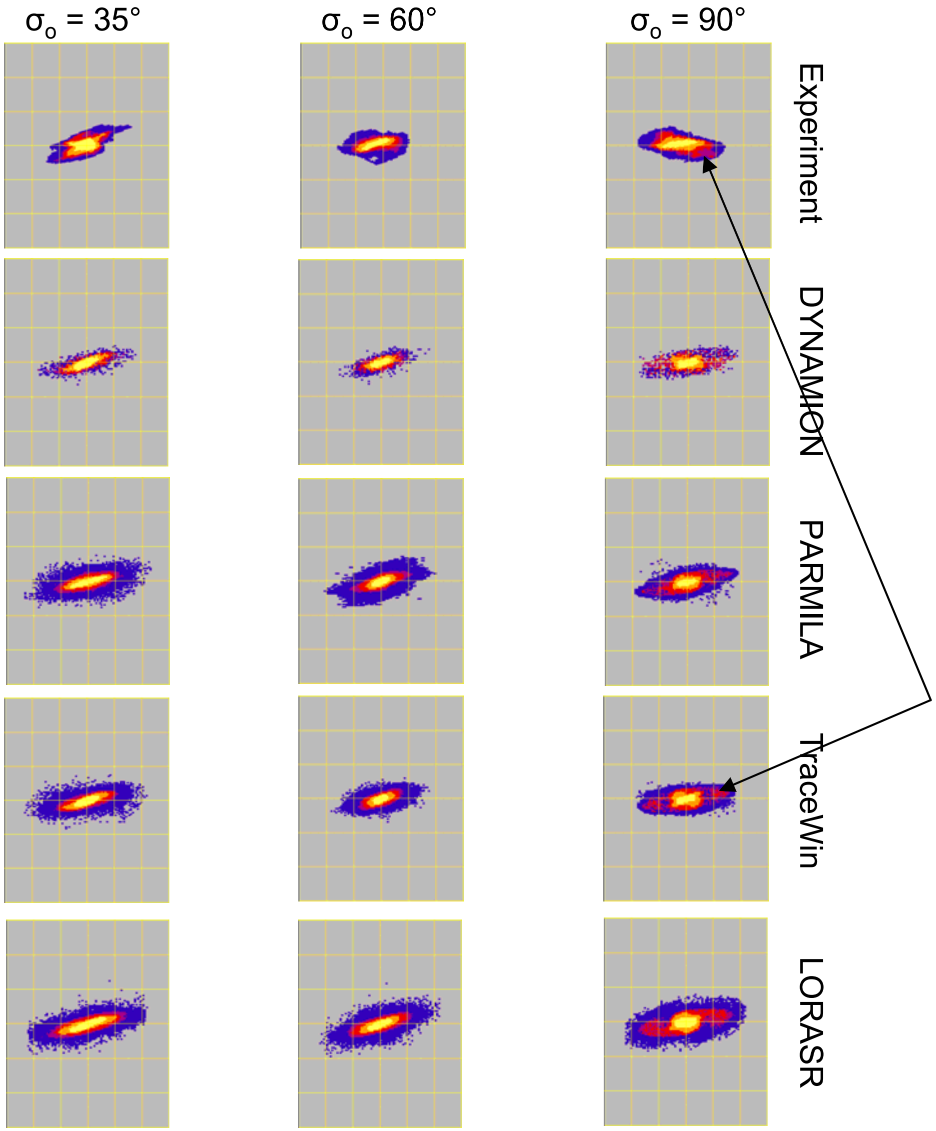


- Growth occurs mainly along first two tanks
  - (agrees to previous UNILAC experiments) ⟶



- Lowest growth at intermediate phase advances

Shapes of Final Distributions (Horizontal)

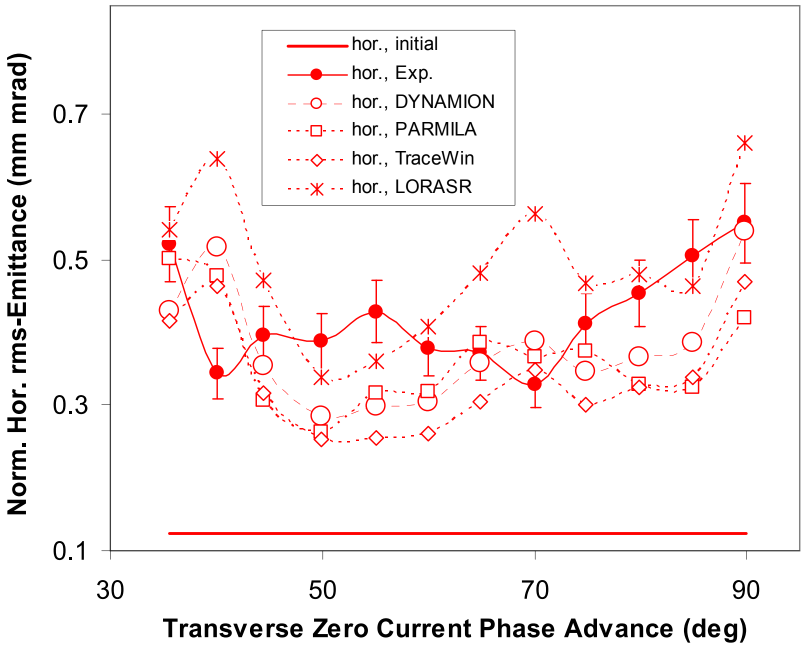


	Int / Int_max [%]
blue	0 – 5
purple	5 – 10
red	10 – 20
orange	20 – 40
yellow	40 -100

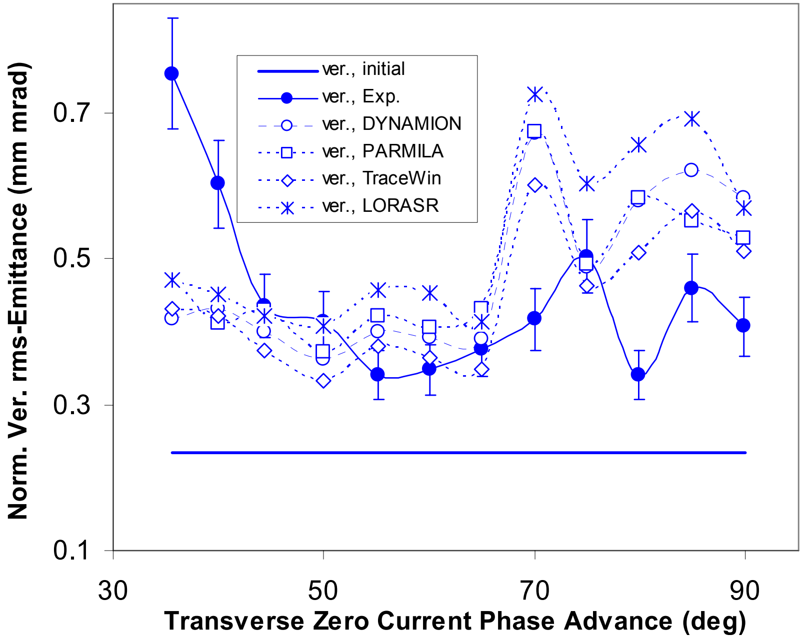
- Core: good agreement (ex. 35°)
- 90°: "wings" seen in exp. & sims
- Deviations at lowest densities

Emittances as Function of Phase Advance

horizontal



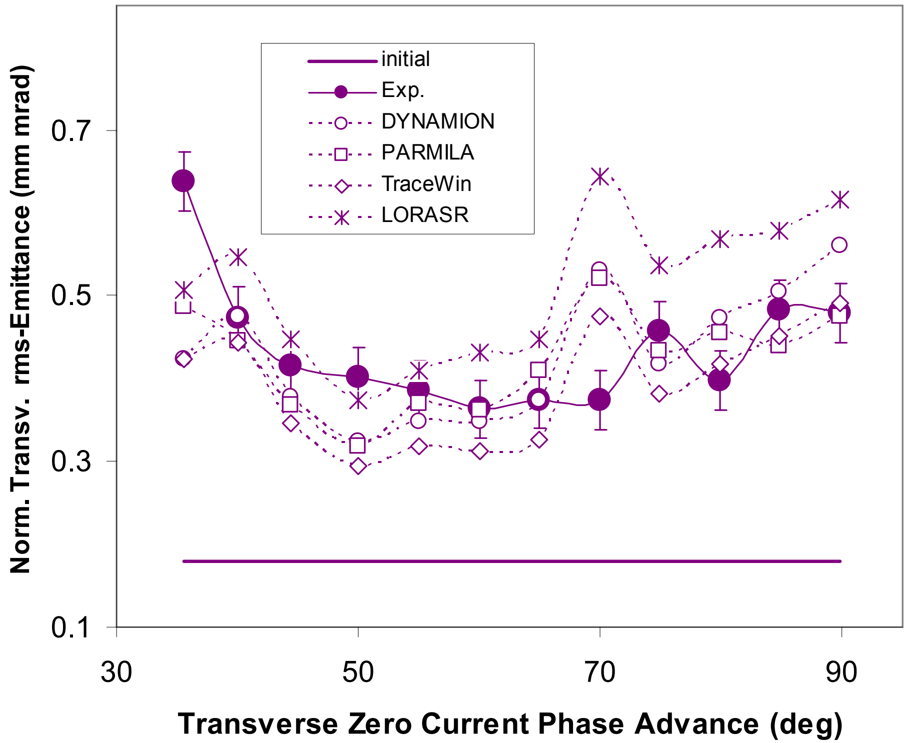
vertical



- Codes reproduce the dependence on phase advance qualitatively
- Differences w.r.t. to absolute final emittance values

Emittances as Function of Phase Advance

(horizontal + vertical) / 2



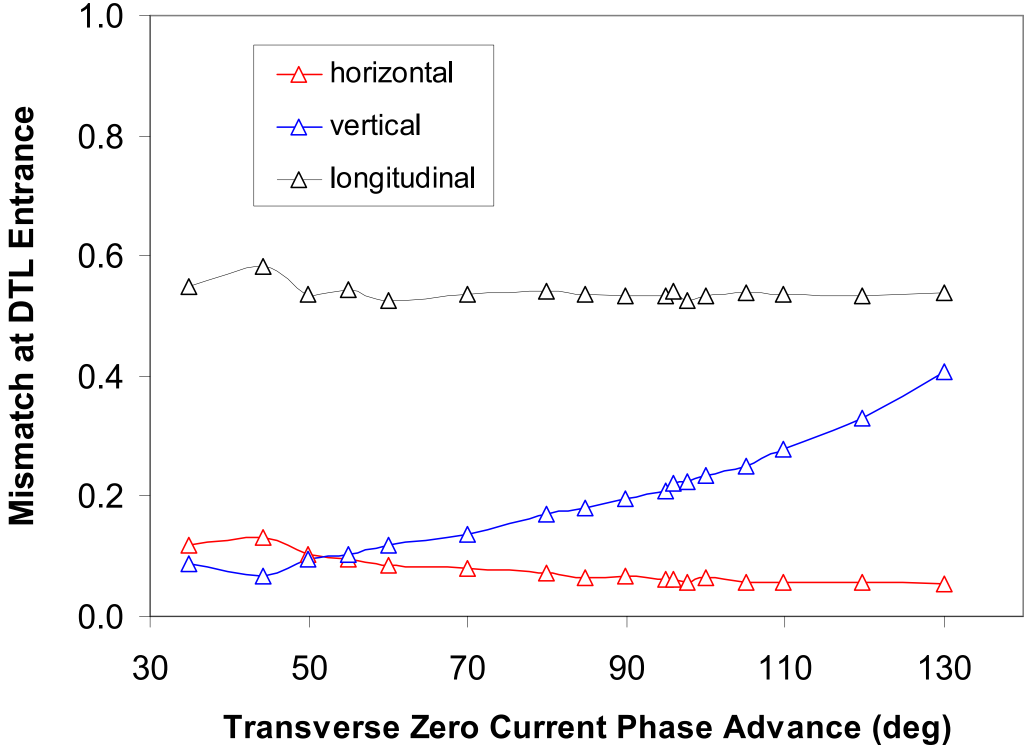
- Quantitative agreement among codes better for the sum of transverse emittances
- Reduced fluctuation of data points w.r.t. average behavior
- Experimental data within bandwidth of codes

Mismatch to Periodic DTL → Small Mismatch Case

- D. Jeon found that UNILAC DTL might allow to measure 4th-order space charge resonance

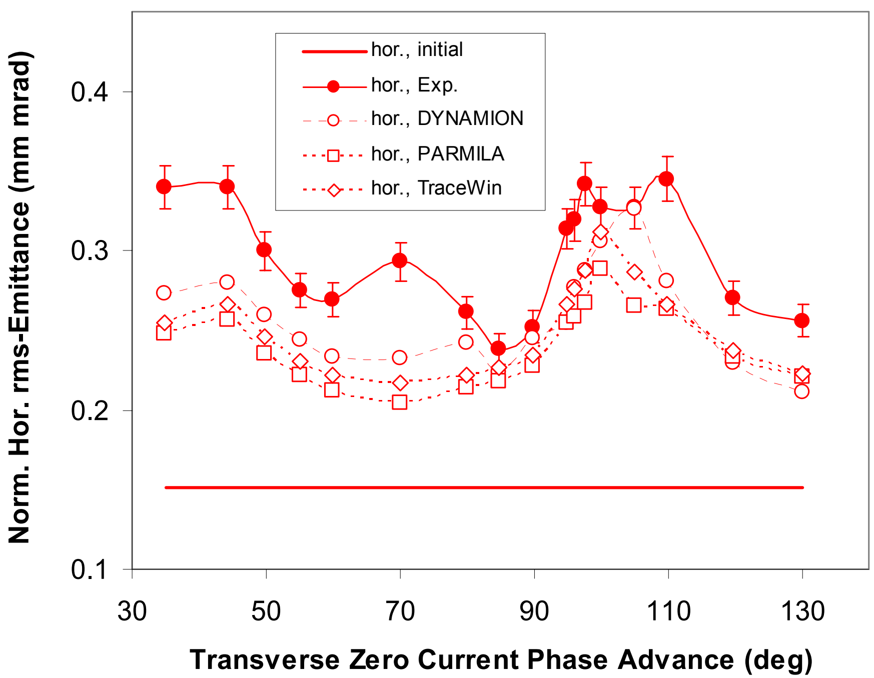
  -> Poster FR5REP078 & LINAC2008

- second campaign used just 1st DTL tank to avoid inter-tank mismatch
- algorithm for reconstruction of initial distribution used to minimize mismatch to DTL

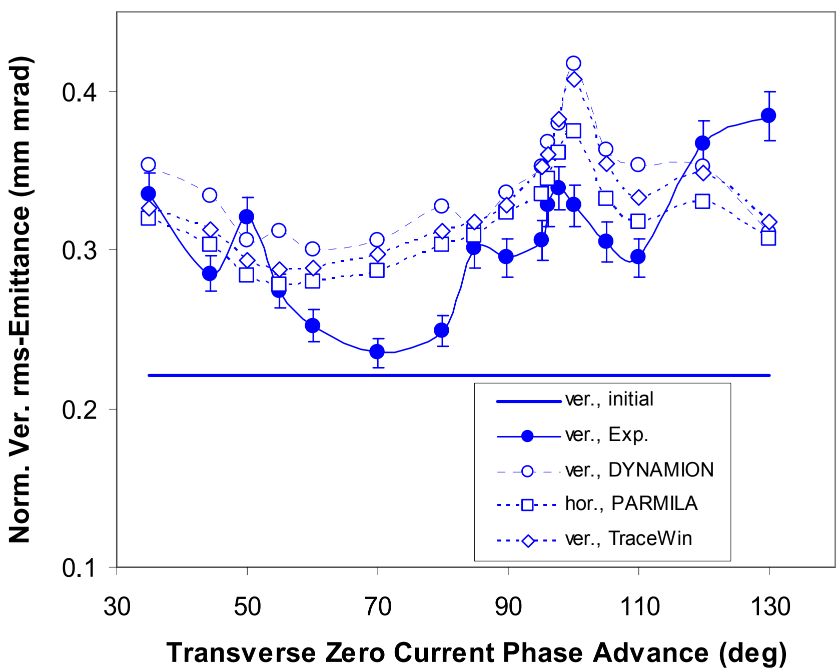


Emittances as Function of Phase Advance

horizontal



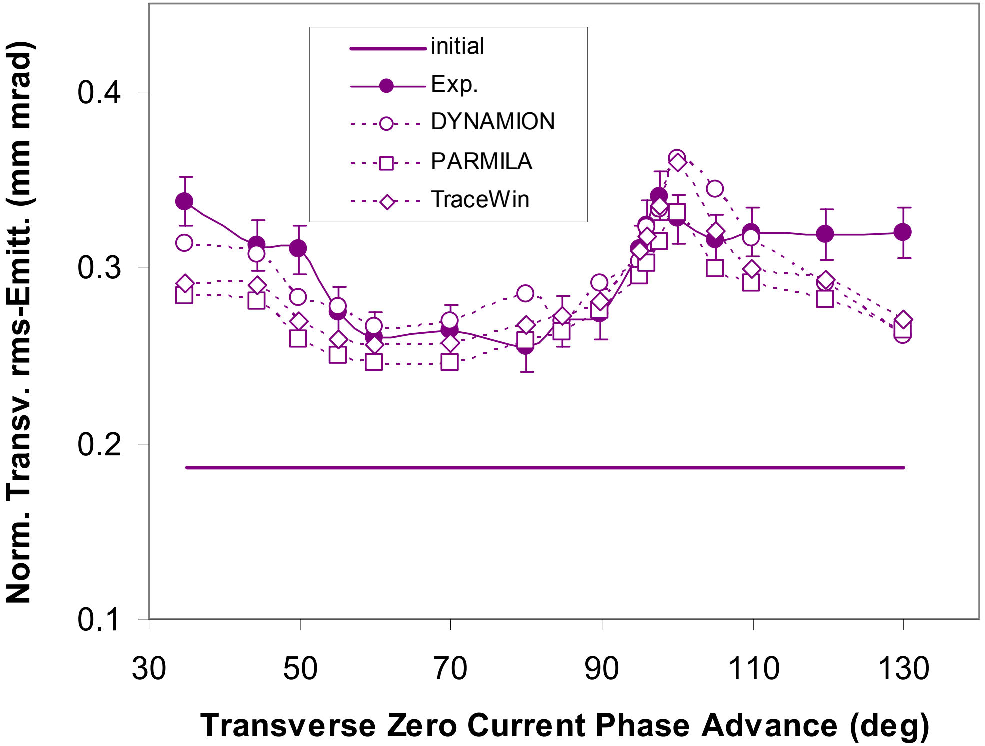
vertical



- Codes generally underestimate horizontal emittance
- Codes generally overestimate vertical emittance
- Codes reproduce peak at about 100°

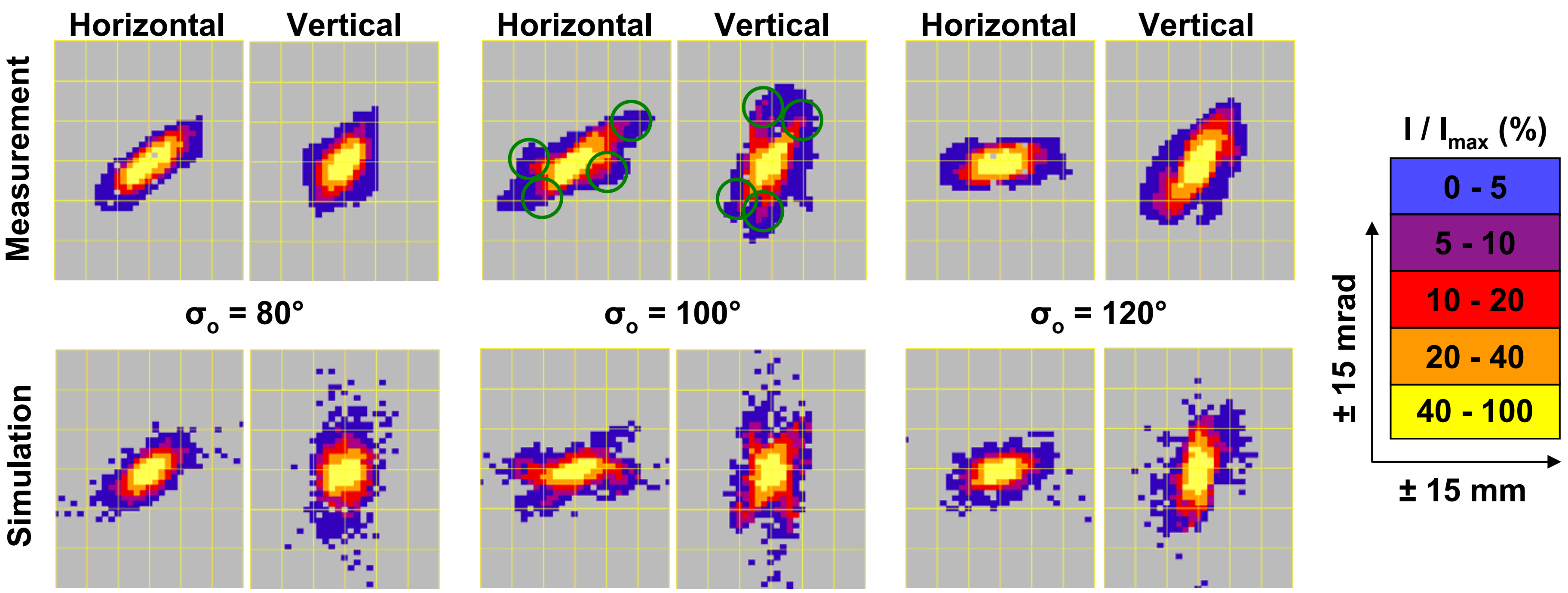
Emittances as Function of Phase Advance

(horizontal + vertical) / 2



- Very good agreement with codes below 100°
- Codes reproduce beginning of stop-band at 90°
- Beyond 100°: codes predict decreasing emittances

Phase Space Distributions after 1st DTL Tank



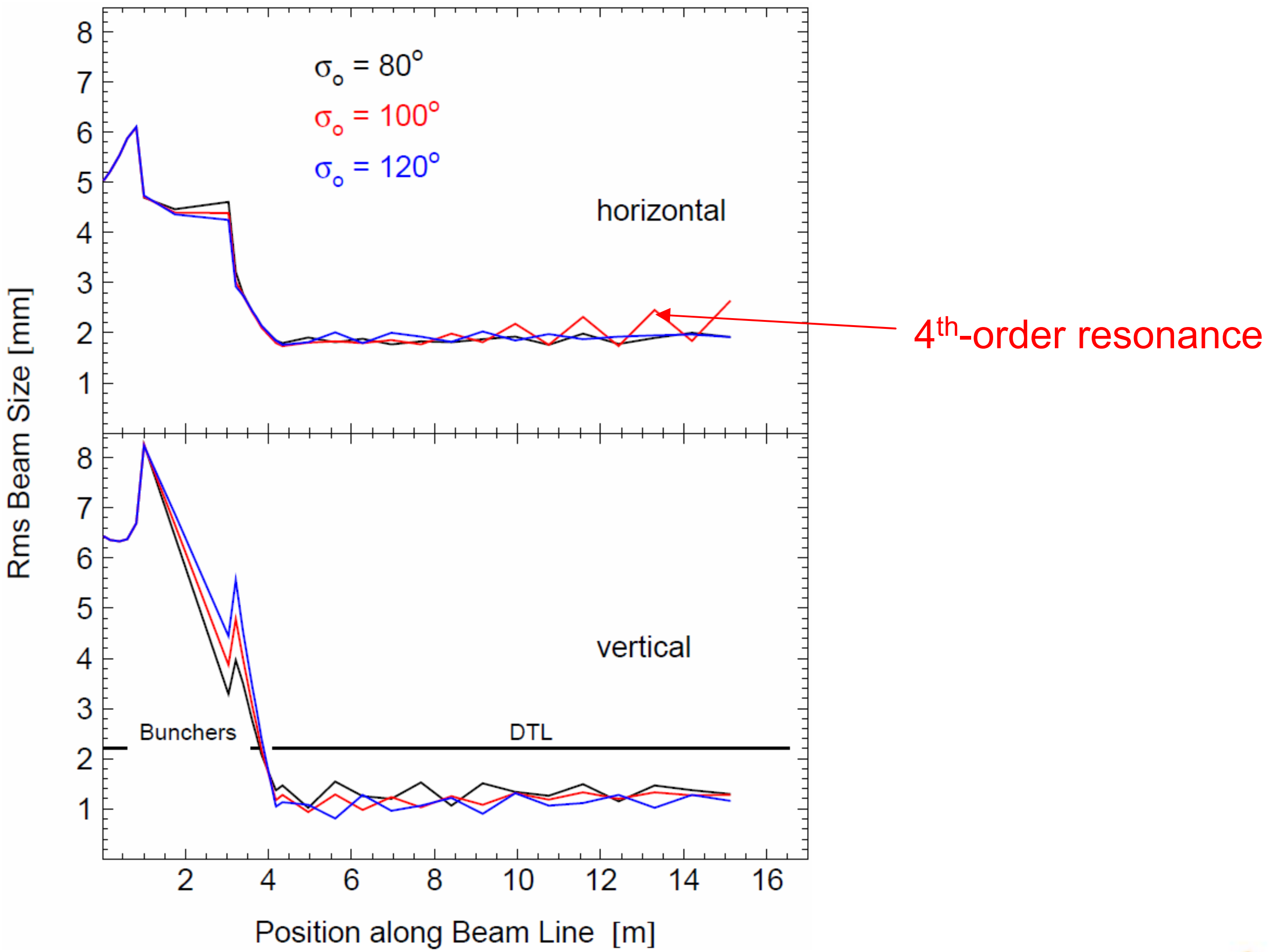
Evidence for 4th-order resonance

- driving force is beam space charge
- resonance dominates over envelope instability

→ as predicted by D. Jeon, Poster FR5REP078 & LINAC2008

Impact of Envelope Instability I

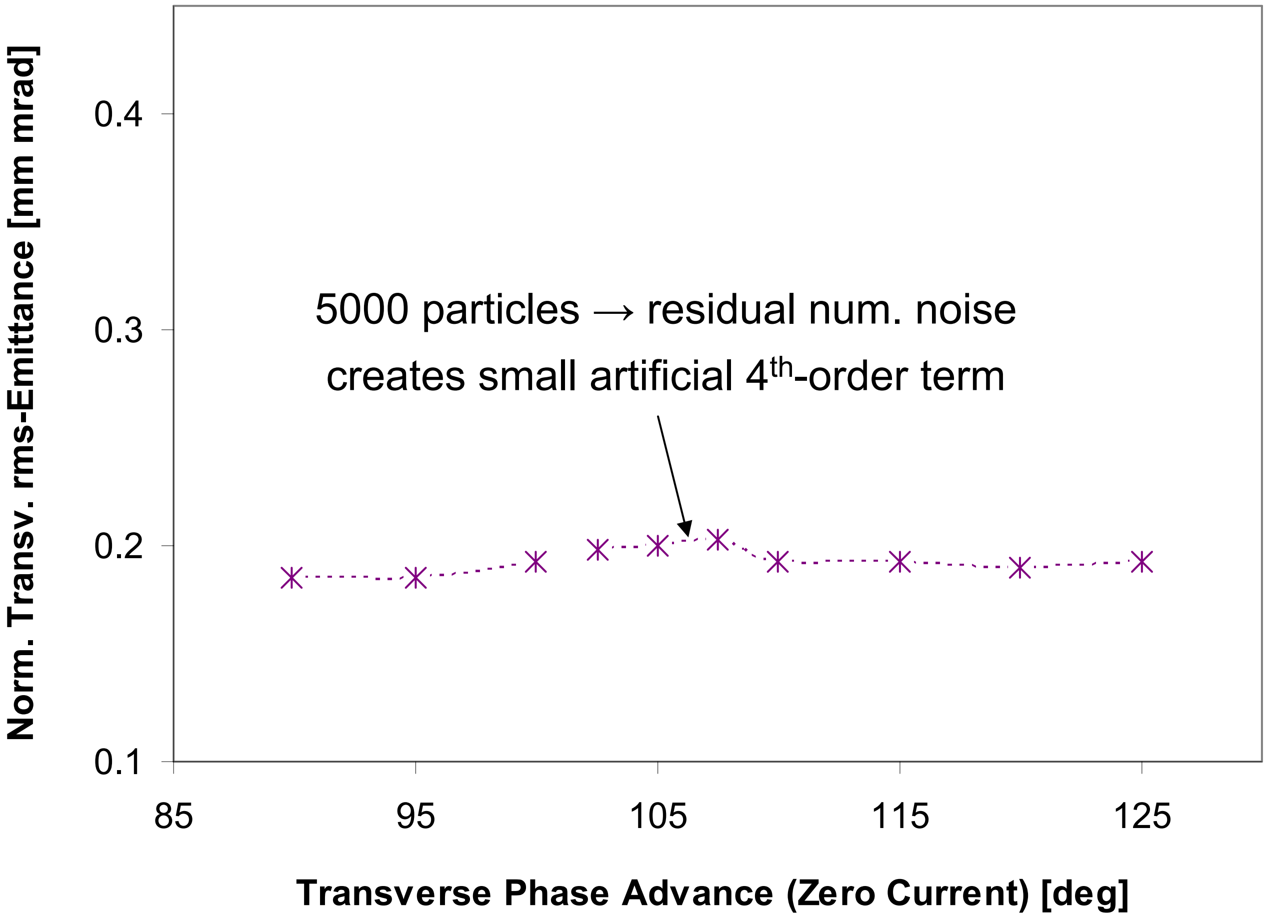
Simulated envelopes → no instability at $\sigma_o > 90°$



Impact of Envelope Instability II

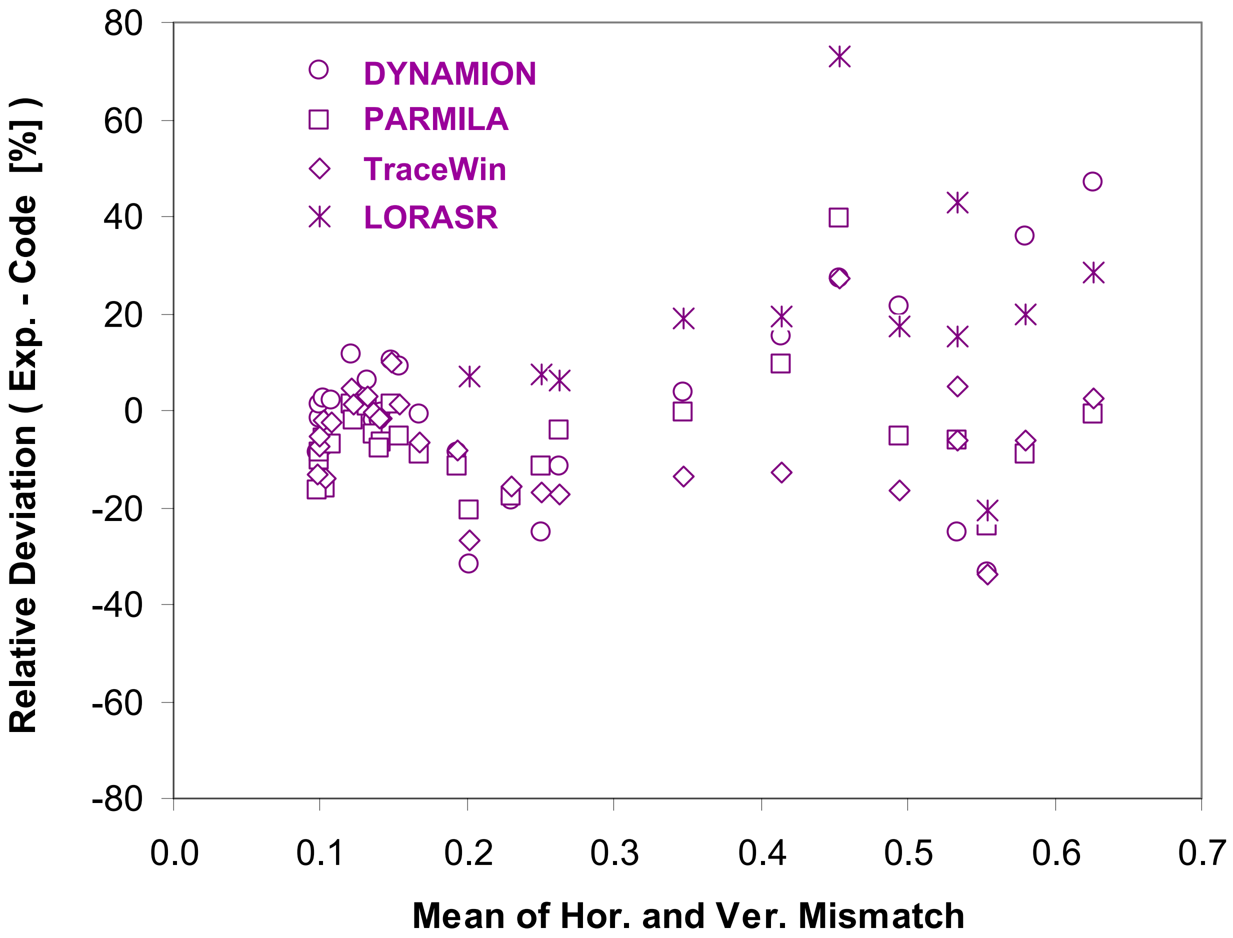
Simulation with KV distribution → no significant growth

(KV has no 4th-order potential term)



Reliability of Codes: Impact of Mismatch

Relative Difference of measured and simulated mean transverse rms-emittances



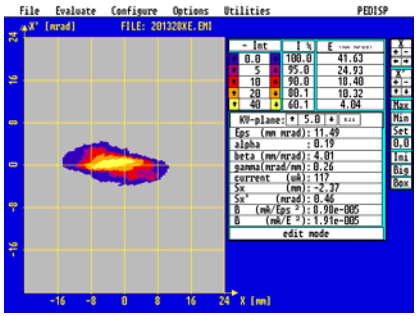
Summary

- Codes describe well the behavior of sum of hor. and ver. emittances
- Within single planes agreement between measurments and codes is fair
  → Might be due to missing knowledge on initial inter-plane correlations
- Reliability of codes decreases with mismatch
- Differences among codes increase with mismatch
- Experimental evidence for 4th-order space charge resonance in linear accelerator
- Resonance dominates over the envelope instability

We acknowledge the support of the European Community – Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395)

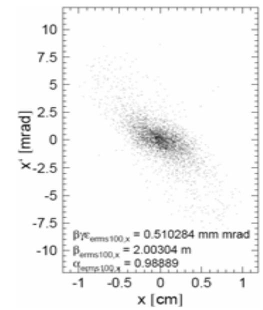
Data Reduction

Measurement



- projection of 6-dim to 2-dim plane
- matrix of pixels
- pixel size 0.8 mm / 0.5 mrad
- evaluation based on pixel contents

Simulations

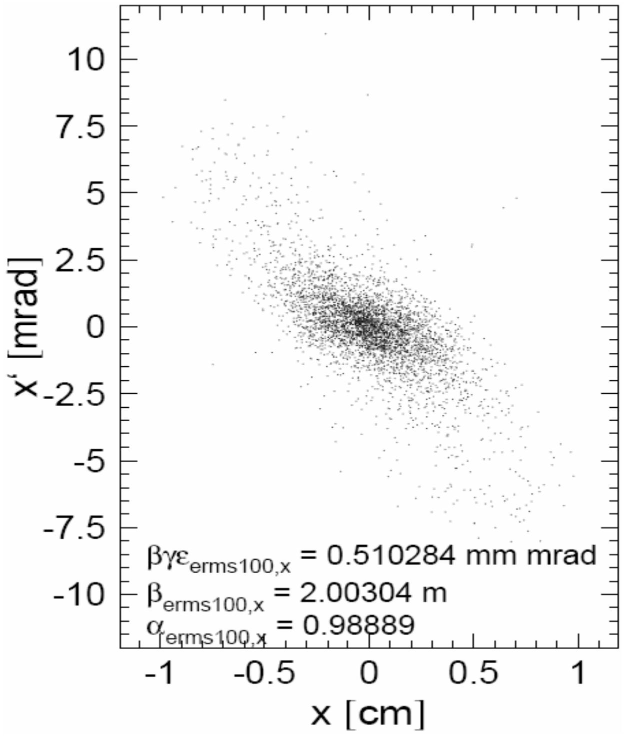


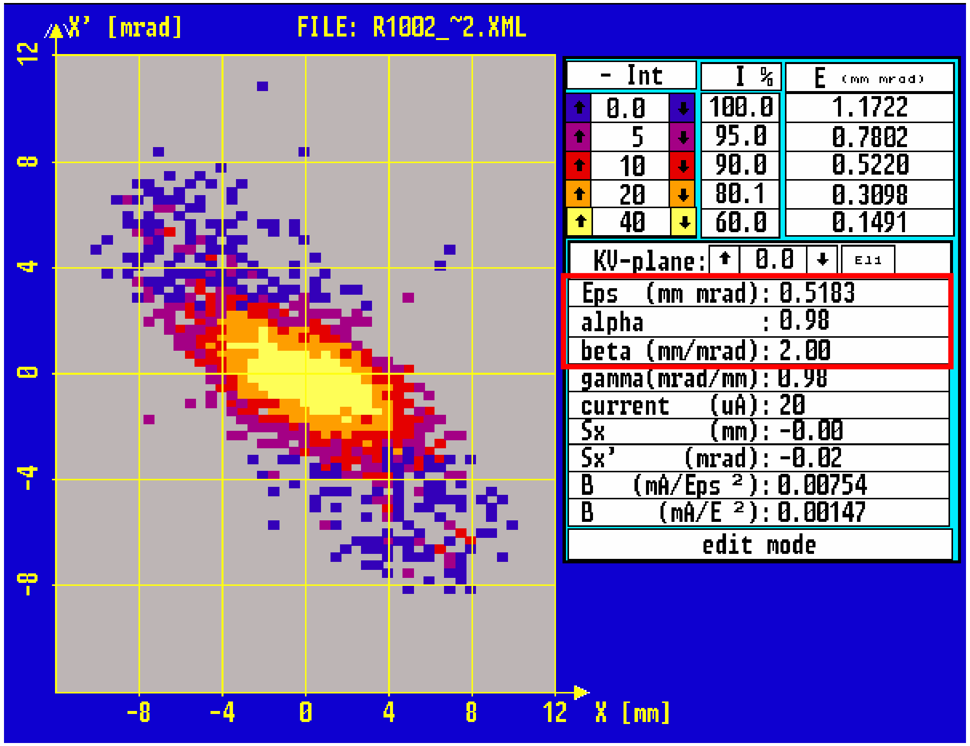
- full 6-dim information available

to compare measurement and simulation adequately, the evaluation procedures must be identical

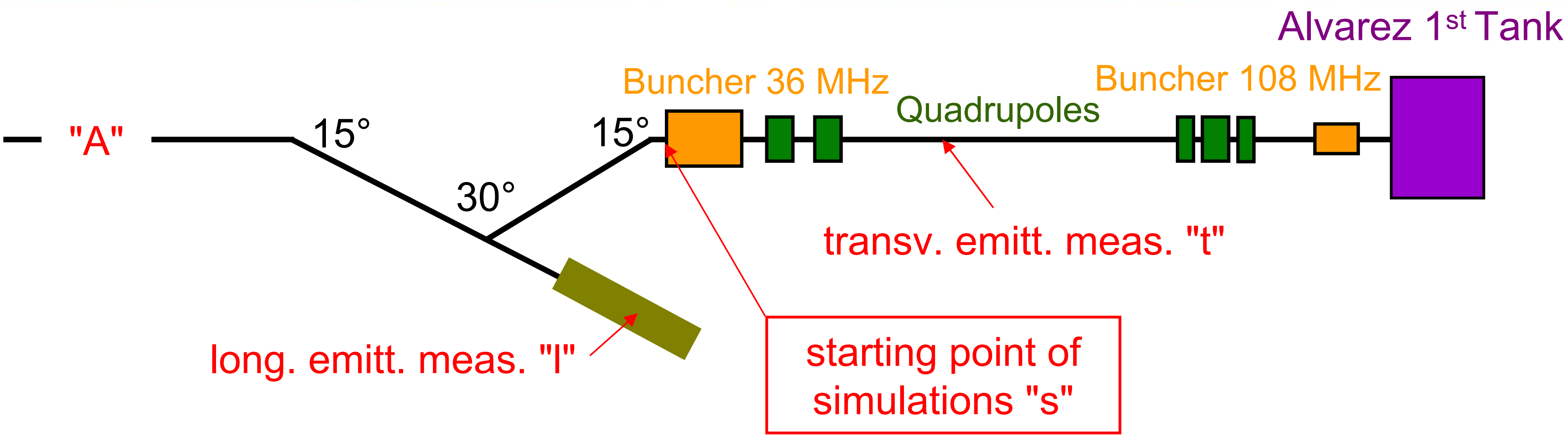
Data Reduction

- particle coordinates from simulations are projected onto virtual meas. device
- projection is evaluated as a measurement





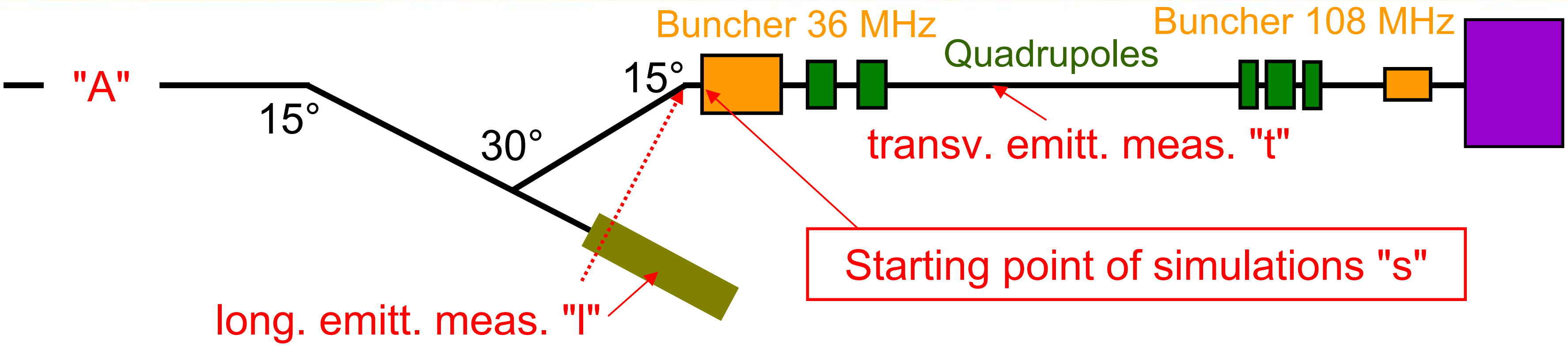
Construction of initial Distribution for Simulations



- measured long. rms-Twiss parameters seemed not realistic, just bunch length ok
- DTL transmission is very sensitive to 36 MHz buncher setting, i.e. long. mismatch
- applied buncher settings resulted in full DTL transmission and minimized low energy tails

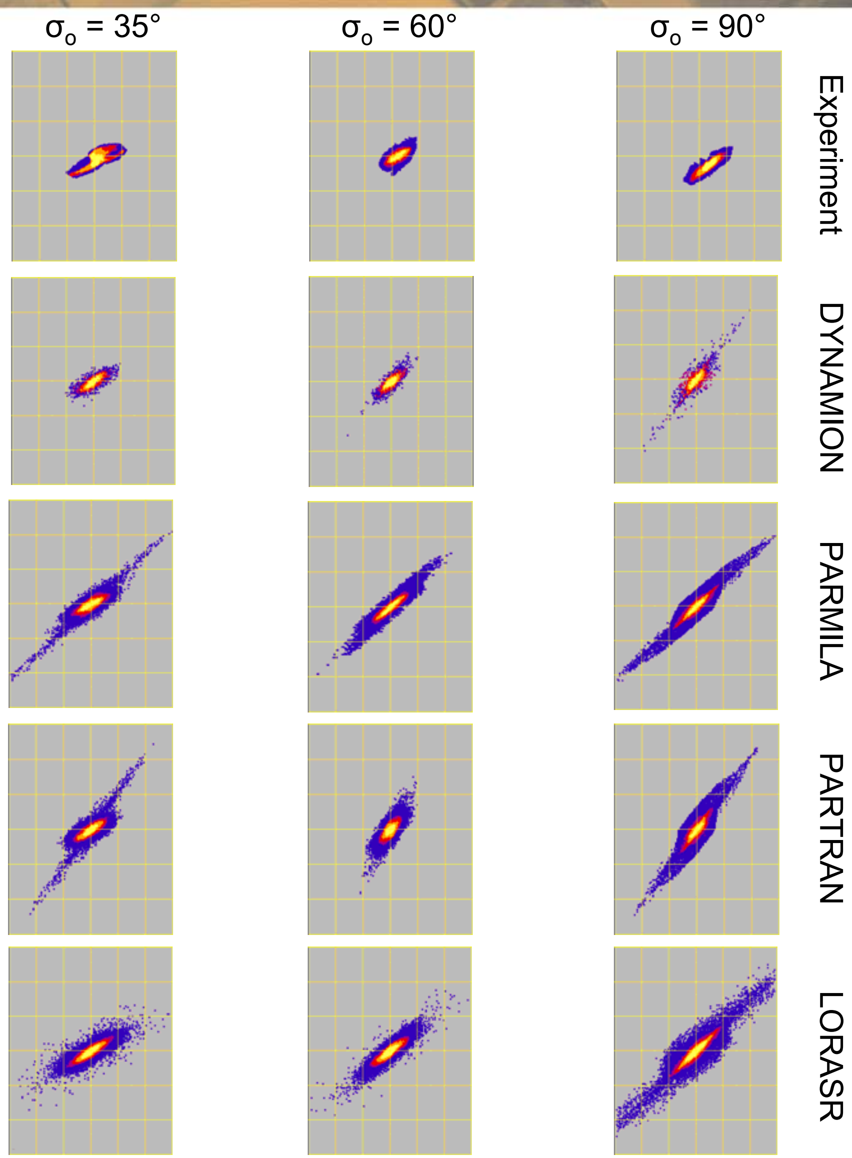
  -> useful in re-constructing the long. input distribution by simulations
- transv. and long. emittance were measured at different locations, i.e. at "t" & "l"
- distances from "l" and "s" to point "A" differ by 0.4 m
- to merge transv. & long. measurements together some approximations (tricks) were used

Construction of initial Distribution for Simulations



- to merge measurements together some approximations (tricks) were used :
  - "transport" from "l" to "s" approximated by drift of 0.4 m (with space charge)
  - at "t": combine measured x&y-rms-Twiss parameters with guessed long. rms-Twiss parameters
  - rms-tracking with space charge from "t" to "s-0.4m", using applied machine settings
    - if bunch length at "s-0.4m" agrees reasonably with measured one at "l": -> ok
    - if not: -> do different guess on long. Twiss parameters at "t"
  - put "s"-rms-Twiss parameters (x,y,l) into matching routine
  - compare suggested 36 MHz-buncher settings with those used during experiment
    - agreement: -> ok, distribution reconstructed
    - no agreement: -> do different guess on long. Twiss parameters at "t"

Shapes of Final Vertical Distributions



	Int / Int_max [%]
	0 – 5
	5 – 10
	10 – 20
	20 – 40
	40 -100

- core: good agreement
- deviations at lowest densities

Space Charge Driven Resonance of 4th-order

density of beam core with octupolar component:

$$\rho(r) = \rho_o(s) \cdot \left[1 - \frac{r^2}{R(s)^2}\right], \quad r \leq R(s)$$

the field caused by the core:

inside core:

$$E_r = \frac{18 \cdot I}{\pi \epsilon_o \cdot R(s)^2 \beta c} \left[r - \frac{r^3}{2R(s)^2}\right], \quad r \leq R(s)$$

octupolar field component ~r^3

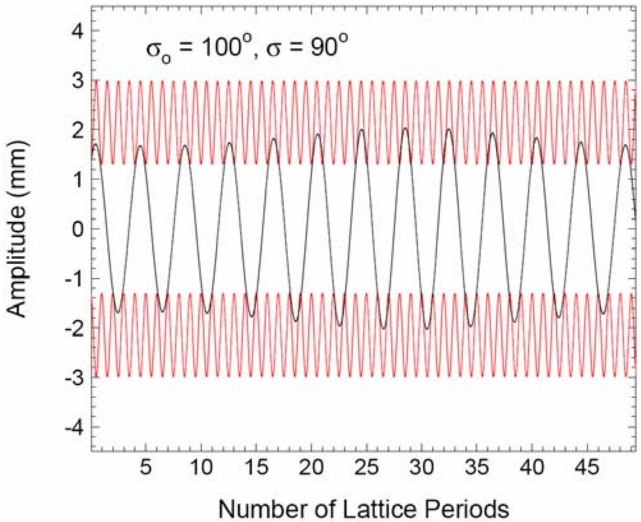
outside core:

$$E_r = \frac{9 \cdot I}{\pi \epsilon_o \cdot \beta c \cdot r}, \quad r \geq R(s)$$

force on single particle:

$$r_p'' = -\sigma_o^2 \, r_p + \frac{e \cdot q}{A \cdot m_u} \cdot E_r$$

external quad focusing — core



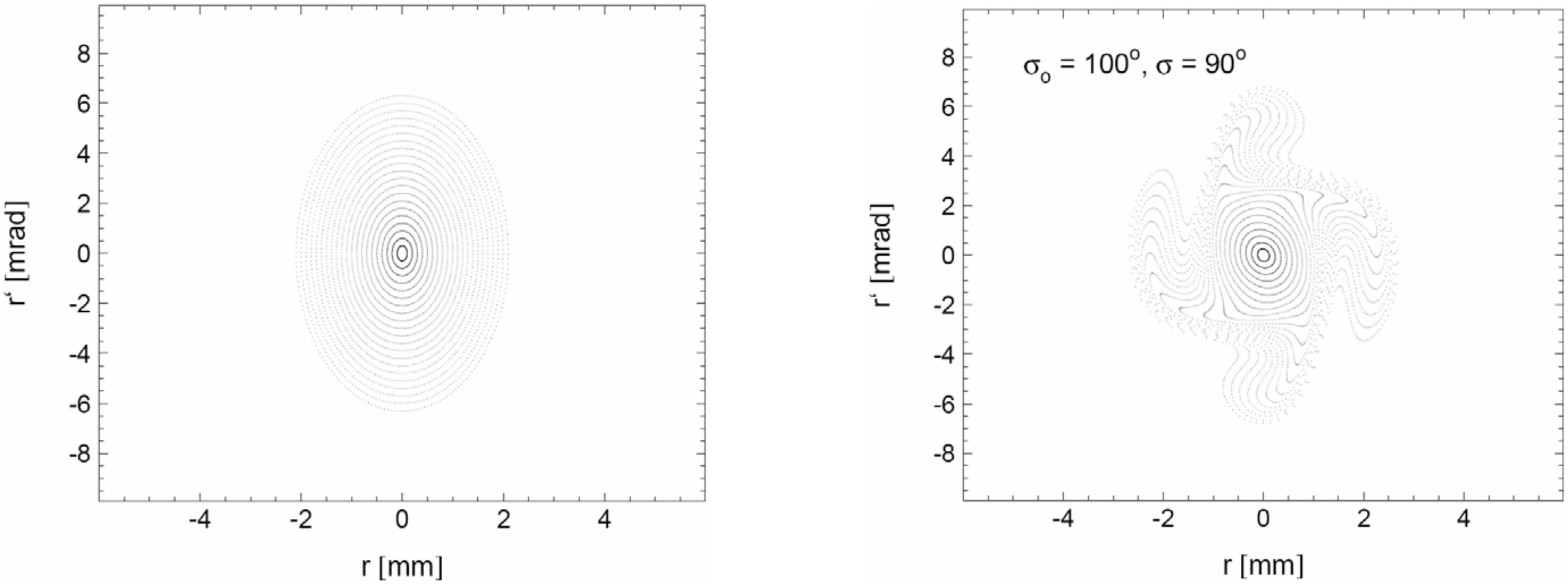
Resonance condition: depressed particle tune <u>σ = 360°/4</u> < σ_o

Space Driven Resonance of 4th-order

<u>tracking many particles using particle-core model</u>

initial phase space

final phase space



Four wings are the characteristic feature of a 4th-order resonance