Benchmarking of rms-Emittance Growth Simulations with UNILAC Experiments

L. Groening, W. Barth, W. Bayer, G. Clemente, L. Dahl, P. Forck,
P. Gerhard, I. Hofmann, G. Riehl, S. Yaramyshev, *GSI, Germany*

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

D. Uriot, *CEA/Saclay, France*

R. Tiede*, University of Frankfurt, Germany*

- Introduction and set-up
- Data reduction
- Reconstruction of initial distribution
- Results of experiment and simulations
- Emittance growth reduction by rms-matching
- Summary

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

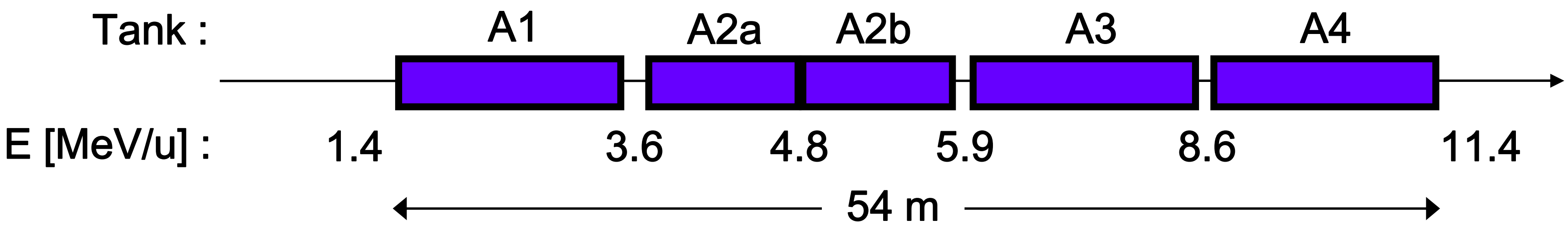
Situation 2003

- Design of future high-intensity machines relies on prediction of codes (Linac-4, SPL, FAIR p-linac, GSI UNILAC & RAL upgrade
- Many codes exist that simulate beam dynamics in a DTL
- Some codes have been benchmarked against each other (Nath, Ryne, Stovall, SNS; Ostroumov, ANL; Franchi, GSI; ...)
- Code-code benchmarking assumed: periodic lattices, matched beams, design emittances, initial distributions from text book

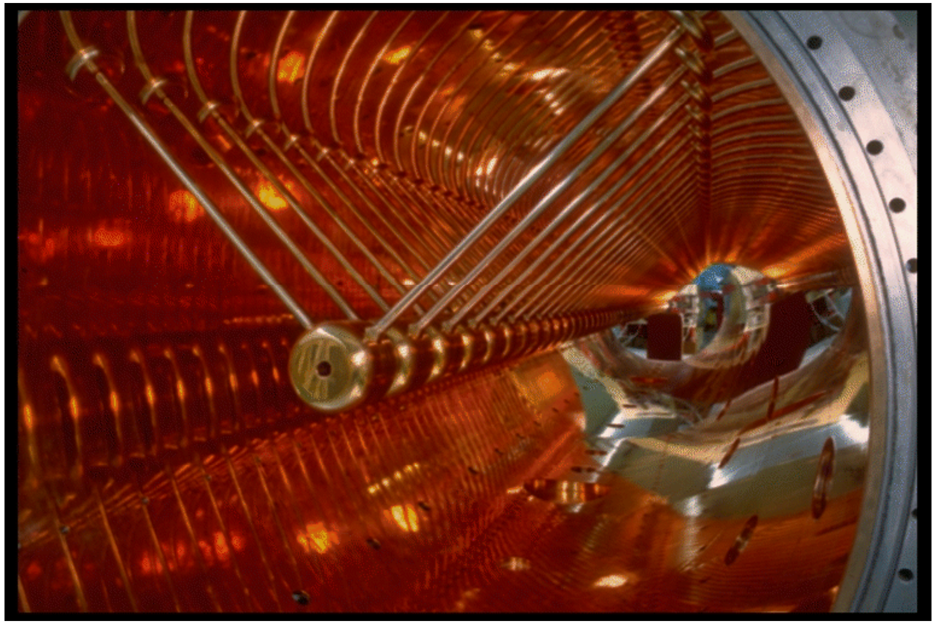
- Within CARE a benchmarking of codes with beam experiments was conducted, i.e:
  - real machine lattice with intersections that interrupt periodicity
  - non-perfect matching
  - emittances larger than design values
  - limited knowledge of initial conditions (no 6d-diagnostics available)
  - initial distributions different from text book distributions

- Objective: to what extend we can rely on the predictions of codes ?

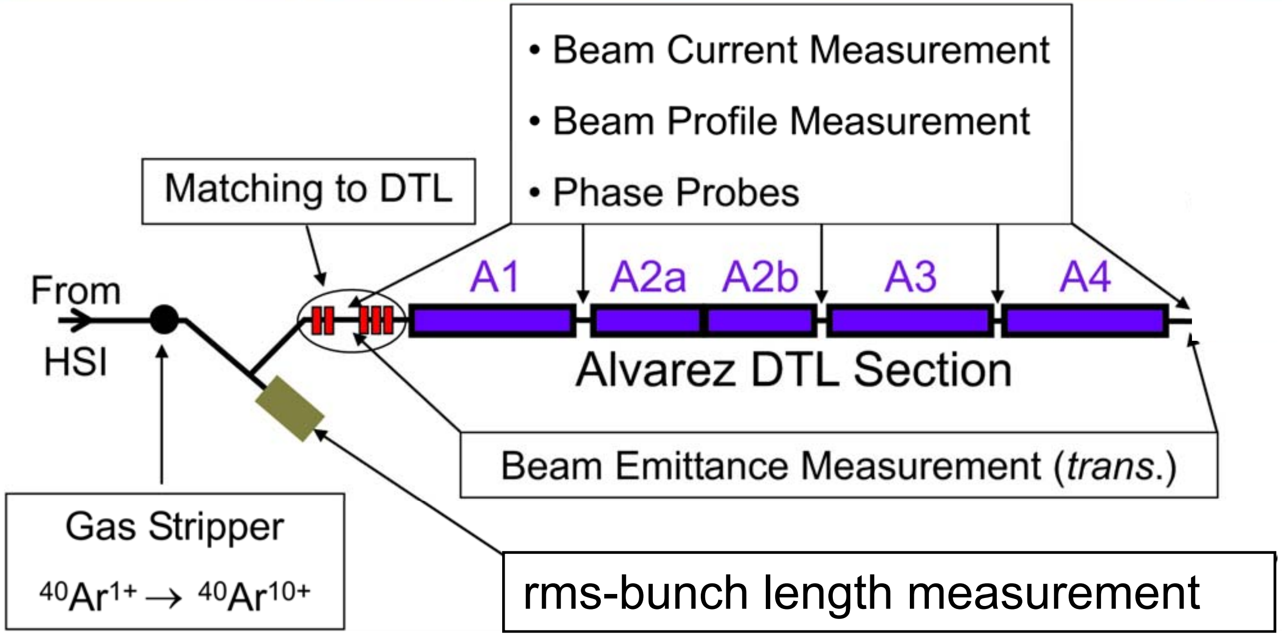
Case to Benchmark: Emittance Growth along GSI UNILAC Alvarez DTL



- 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°)



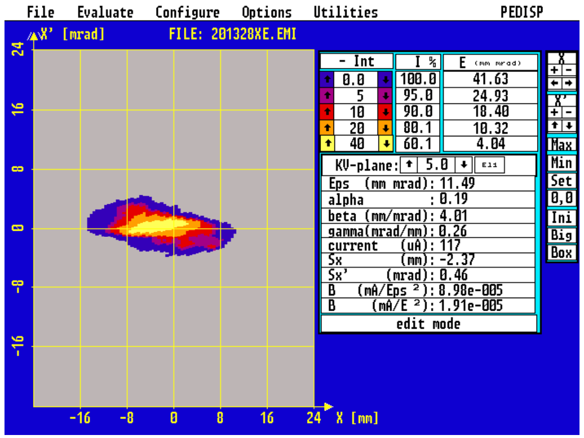
Experimental Set-up & Procedure



- 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 90°
    - tune depression varied from 21% (90°) to 43% (35°)
- measure transmission, hor., and ver. rms-emittance at DTL exit

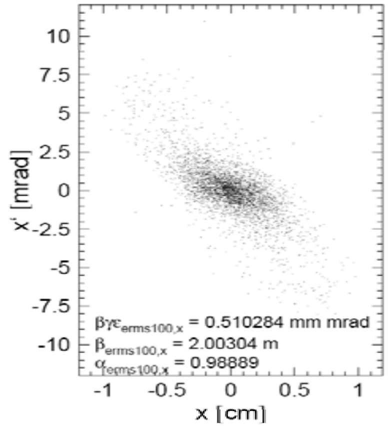
Data Reduction

Measurement



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

Simulations

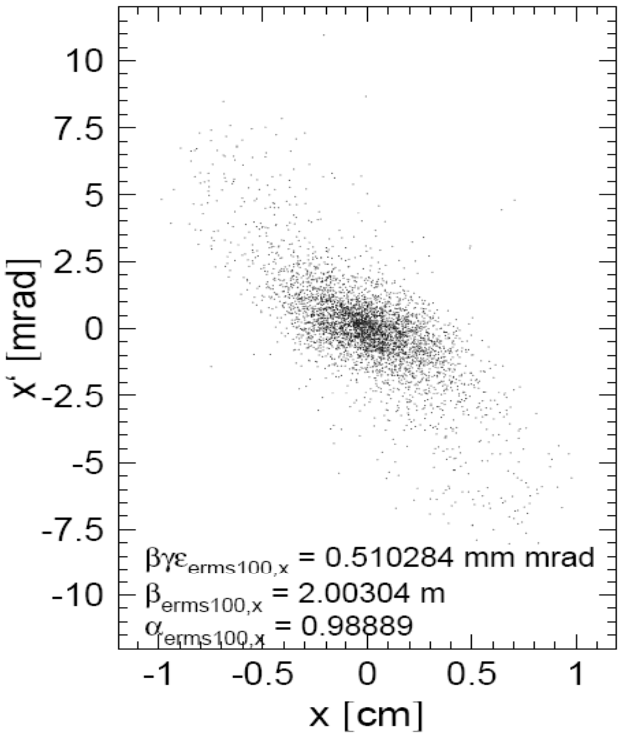


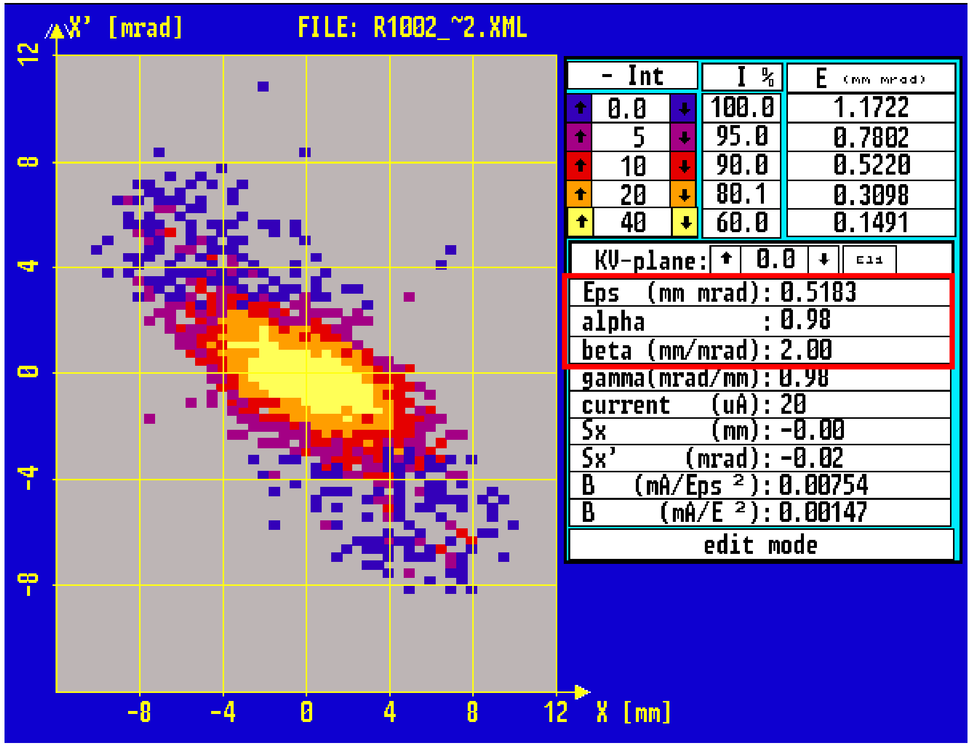
- full 6-dim information available

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

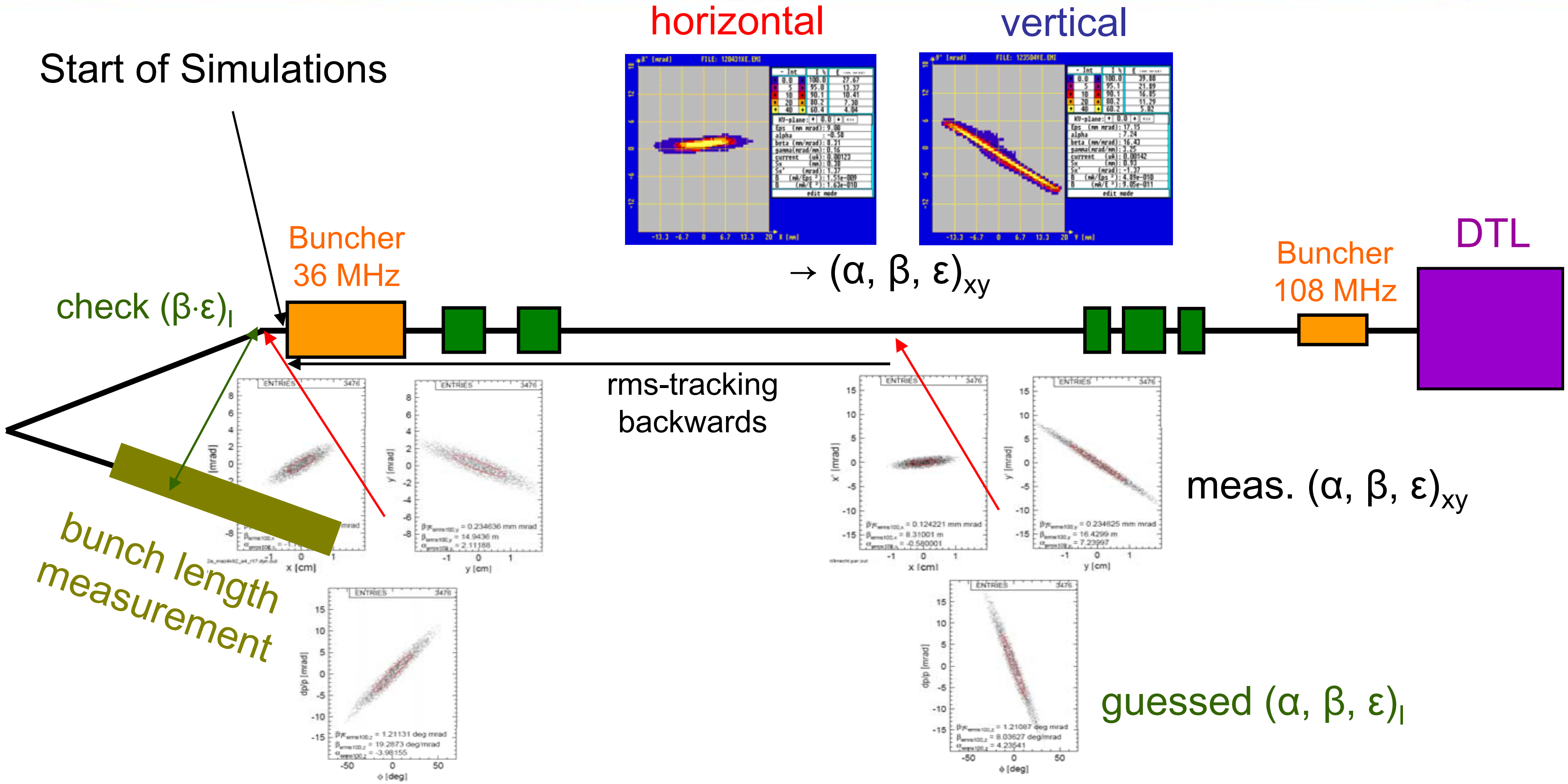
• particle coordinates from simulations are projected onto virtual meas. device

• projection is evaluated in the same way as a measurement



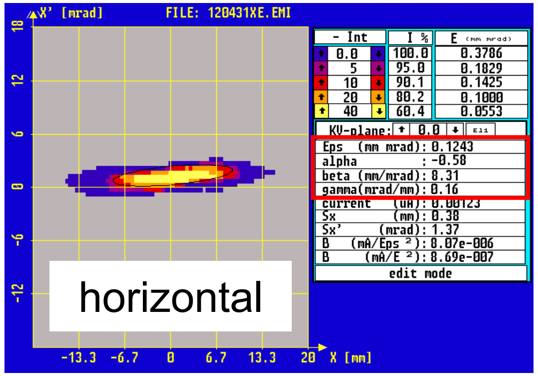


Reconstruction of Initial rms-Parameters

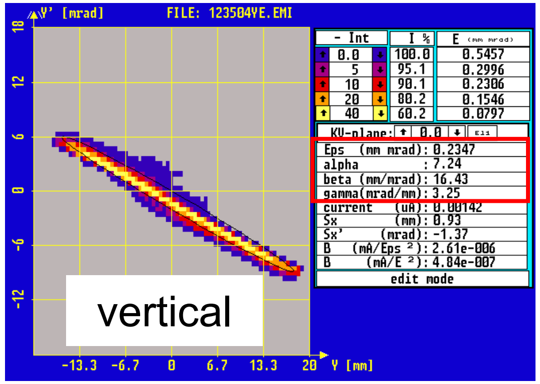


1. Selfconsistent backtracking finding $(\alpha,\beta,\varepsilon)_l$ that fit to measured bunch length
2. Varification wether applied machine settings give full transmission w/o tails

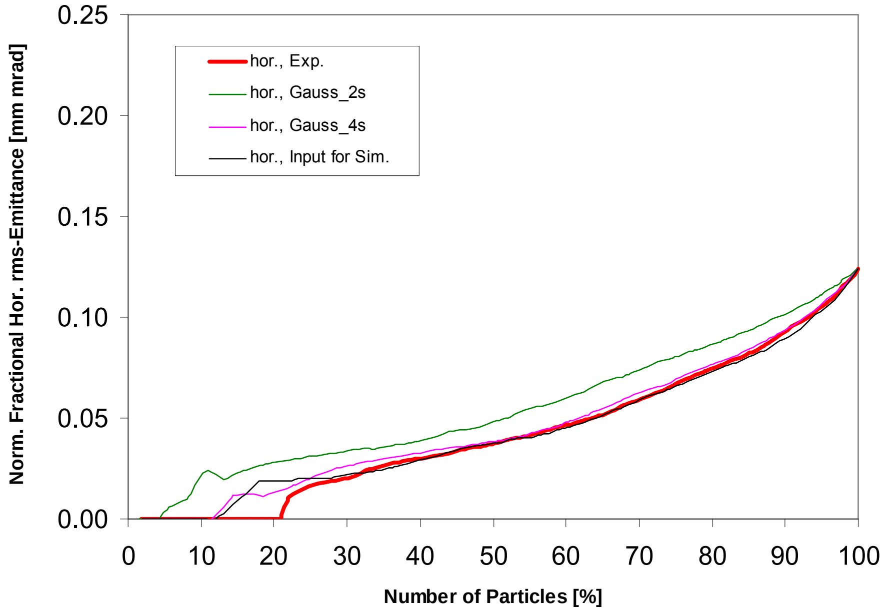
Reconstruction of Initial Type of Distribution

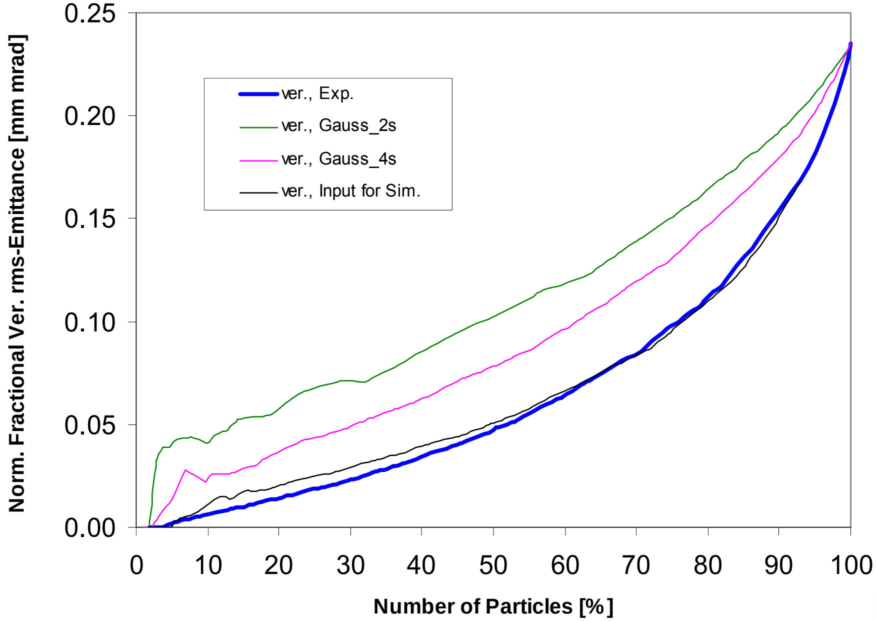


measured in front of DTL



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:

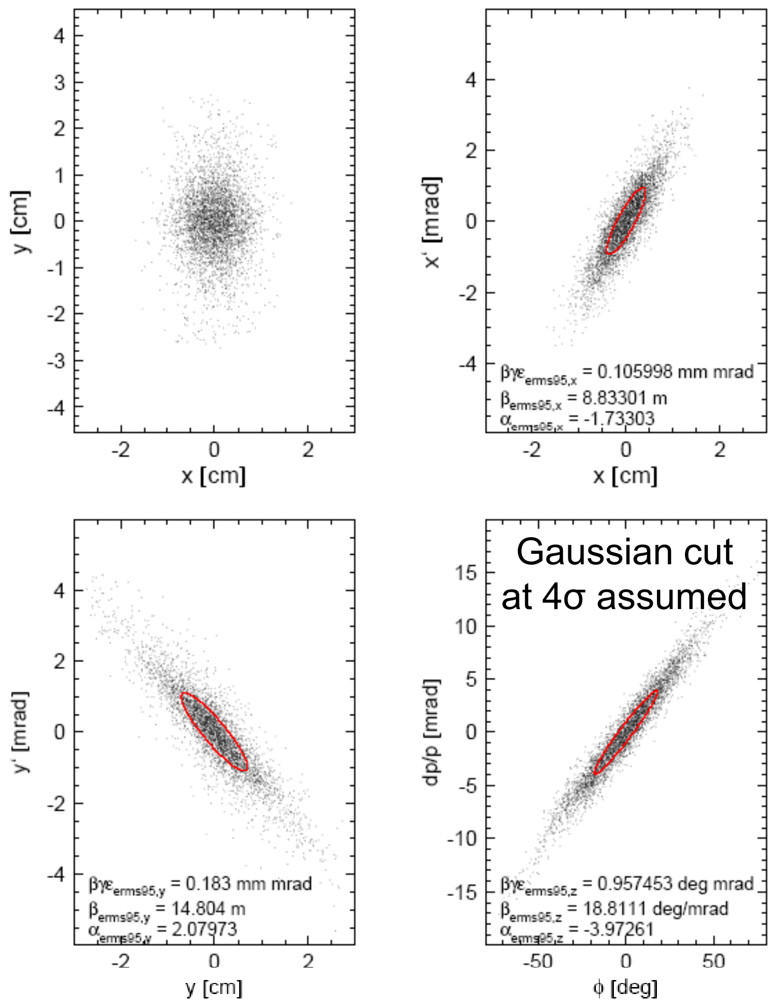
$$\frac{dN}{dV} = f\left(X, X', Y, Y', \Phi, \delta P/P\right)$$

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

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

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

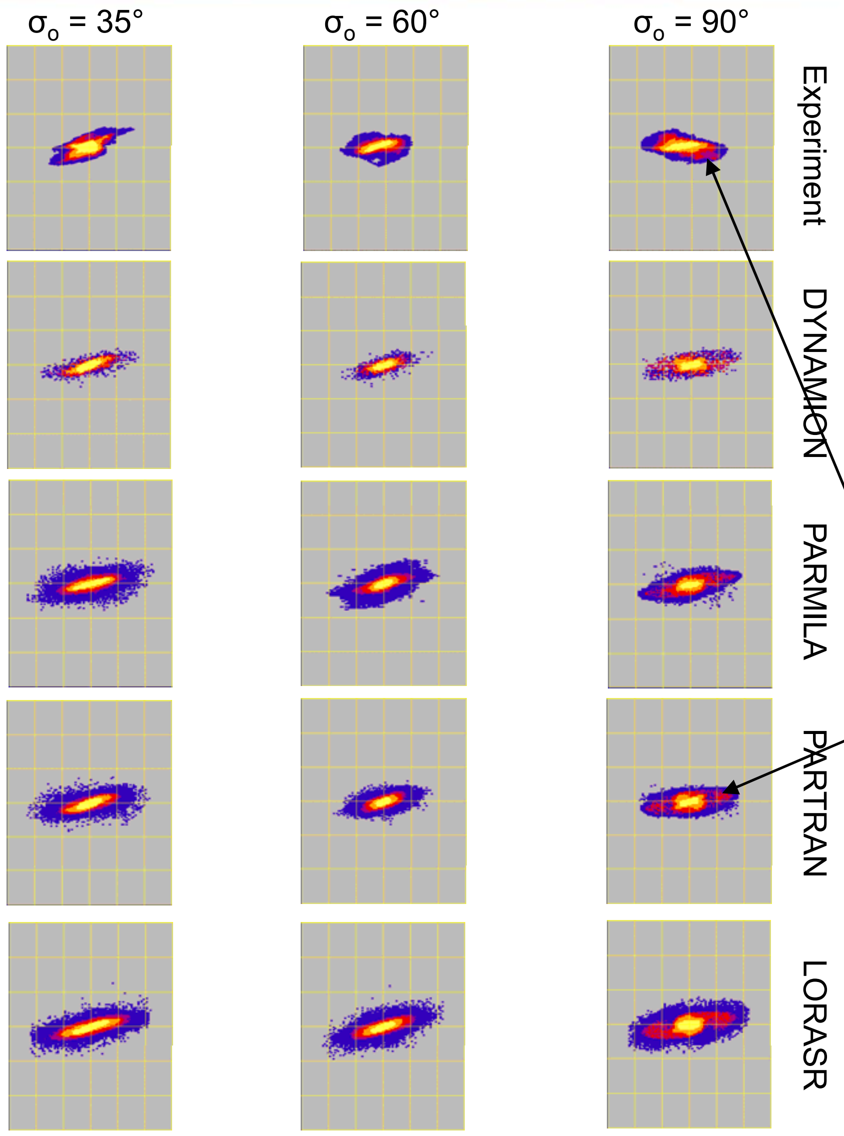
applying different powers for different planes, the amount of halo can be reproduced in each plane separately initial distribution



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

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

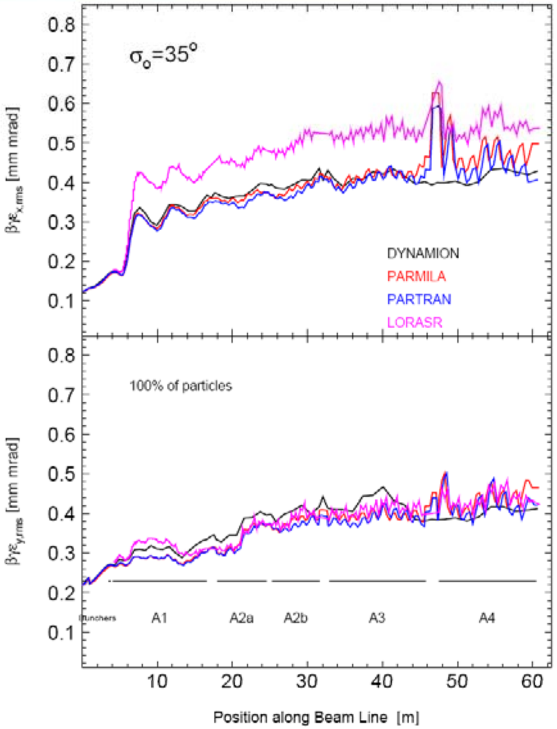
	Solver	Boundaries	No. of Part.	CPU Time	Rf-Gap
DYNAMION	3D-part.-part.	open	$4.3 \cdot 10^3$	20 h	tracking
PARMILA	PICNIC-3D	open	$2 \cdot 10^5$	30 min.	non-linear kicks
PARTRAN	PICNIC-3D	open	$2 \cdot 10^5$	30 min.	non-linear kicks
LORASR	PICNIC-3D	open	$2 \cdot 10^5$	1 h	tracking

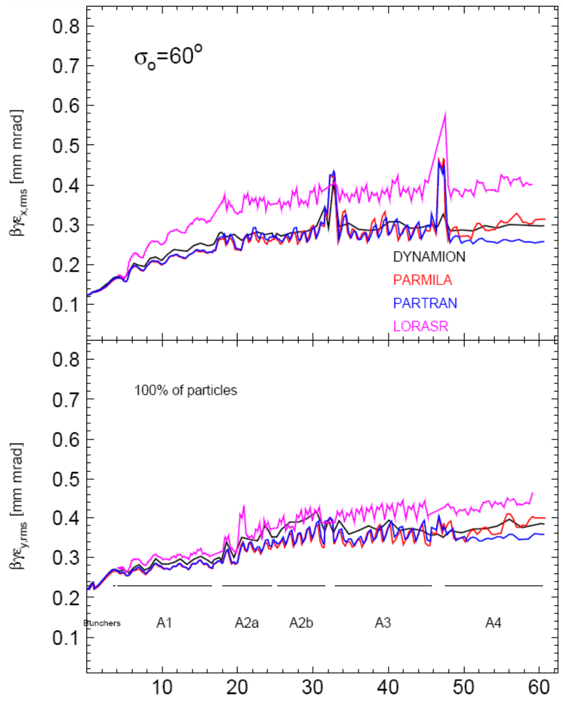


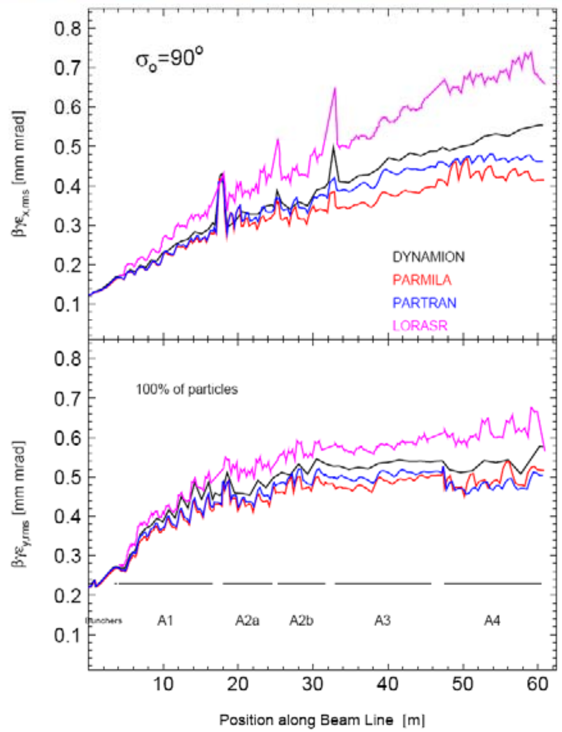
	Int / Int_max [%]
(blue)	0 – 5
(purple)	5 – 10
(red)	10 – 20
(orange)	20 – 40
(yellow)	40 -100

- core: good agreement (ex. 35°)
- 90°: "islands" seen in exp. & sims
- deviations at lowest densities

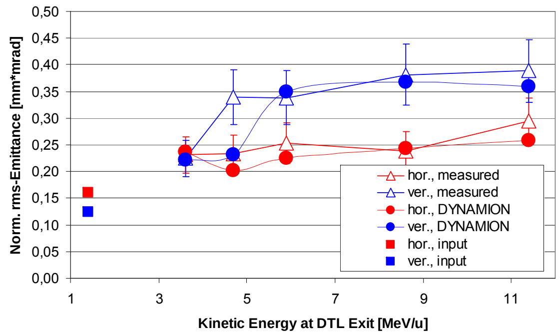
Evolution of Simulated rms-Emittances





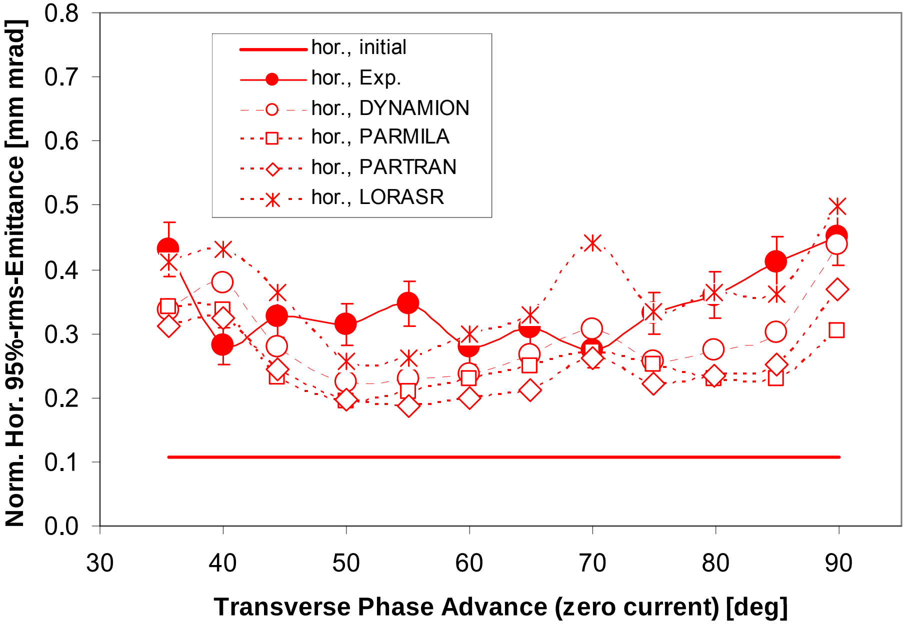


- growth occurs mainly along first two tanks
  - (agrees to previous UNILAC experiments) →
- lowest growth at intermediate phase advances

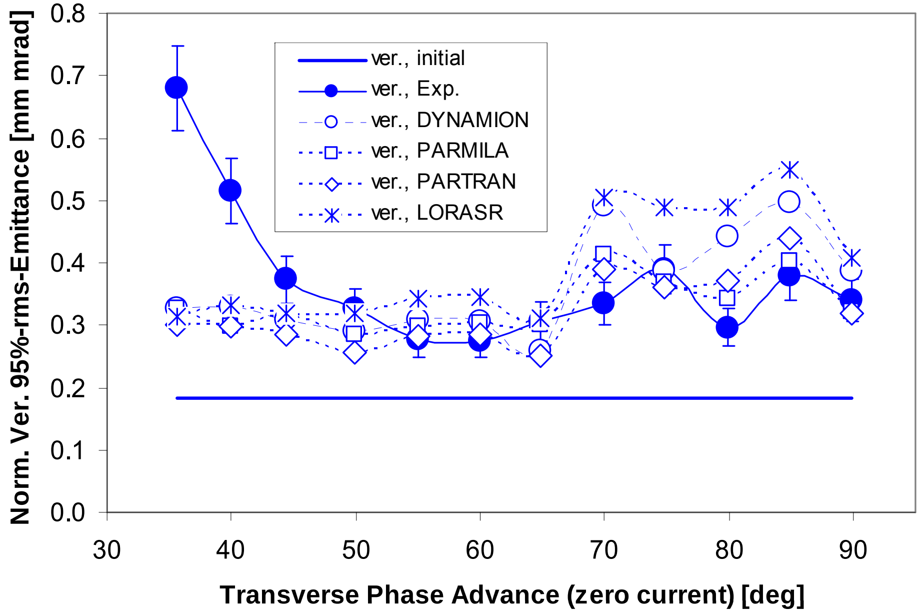


Final 95%-rms Emittances as Function of Phase Advance

horizontal



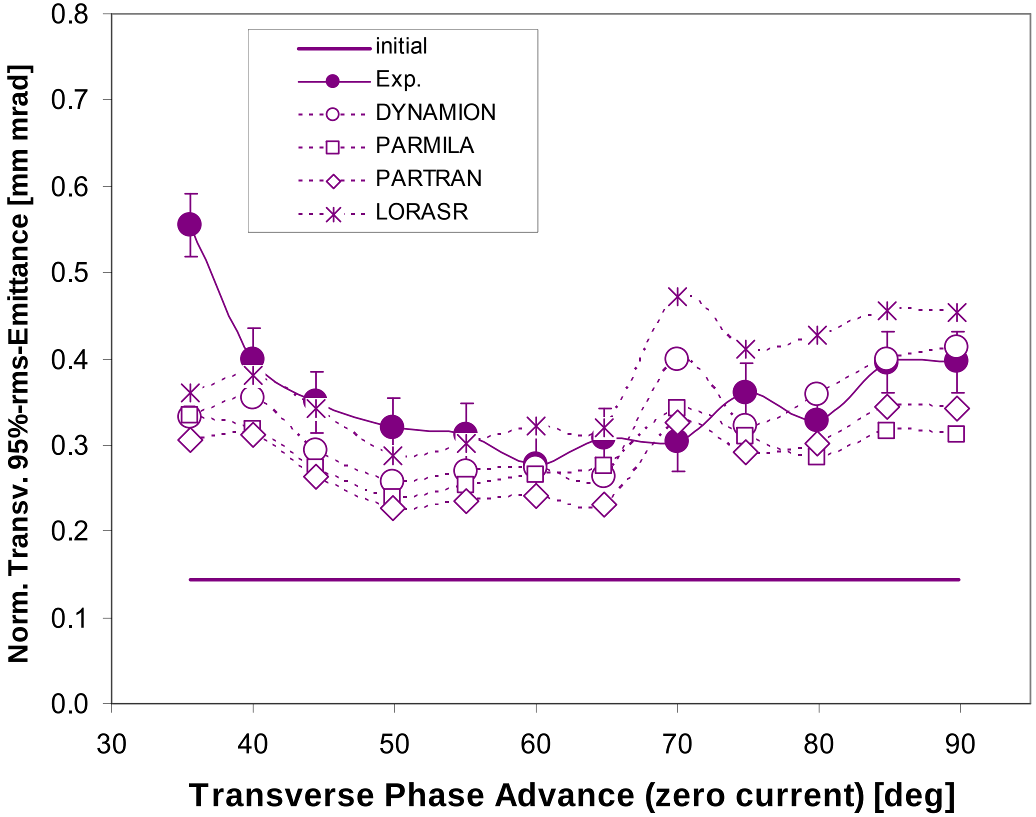
vertical



- codes reproduce the dependency on phase advance qualitatively
- differences w.r.t. to aboslute final emittance values

Final 95%-rms Emittances as Function of Phase Advance

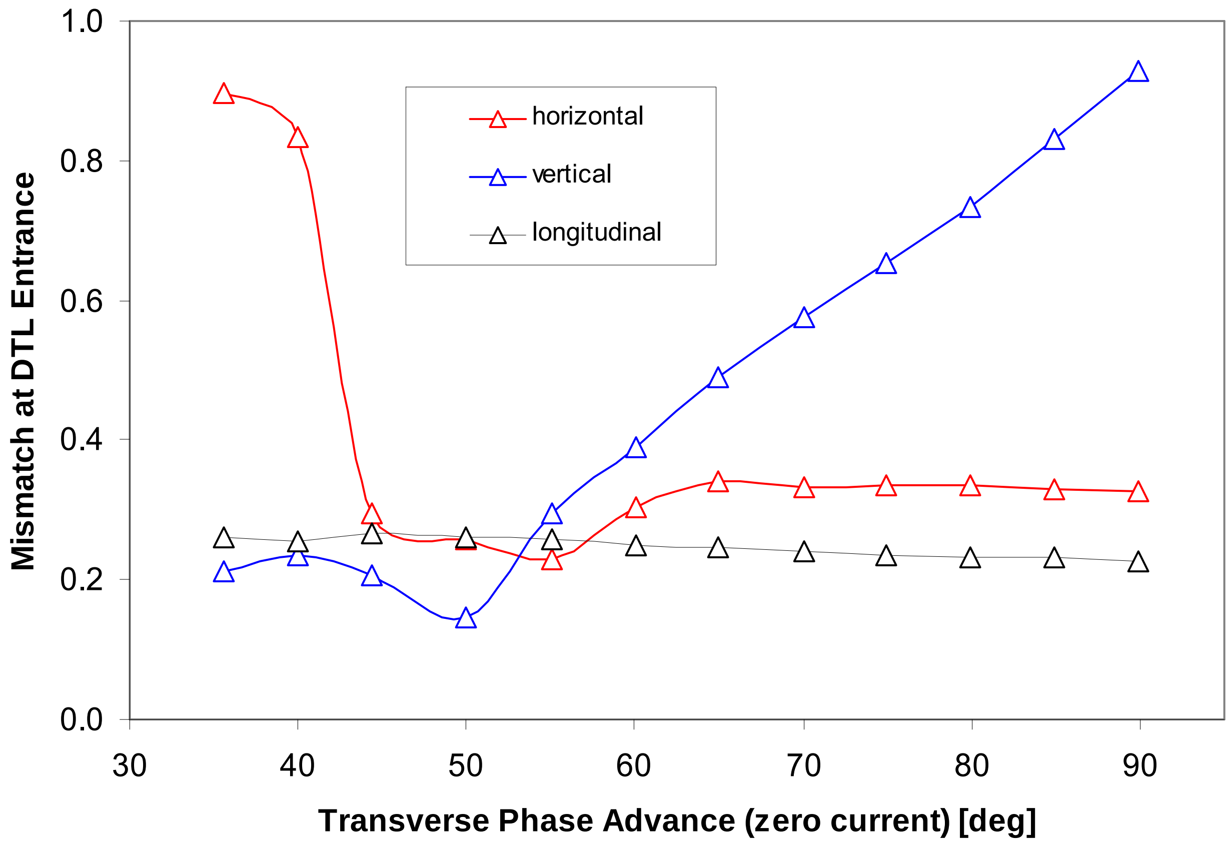
(horizontal + vertical) / 2



- quantitative agreement among codes higher for the sum of transverse emittances
- reduced fluctuation of data points w.r.t. average behavior

Mismatch to Periodic DTL Solution

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



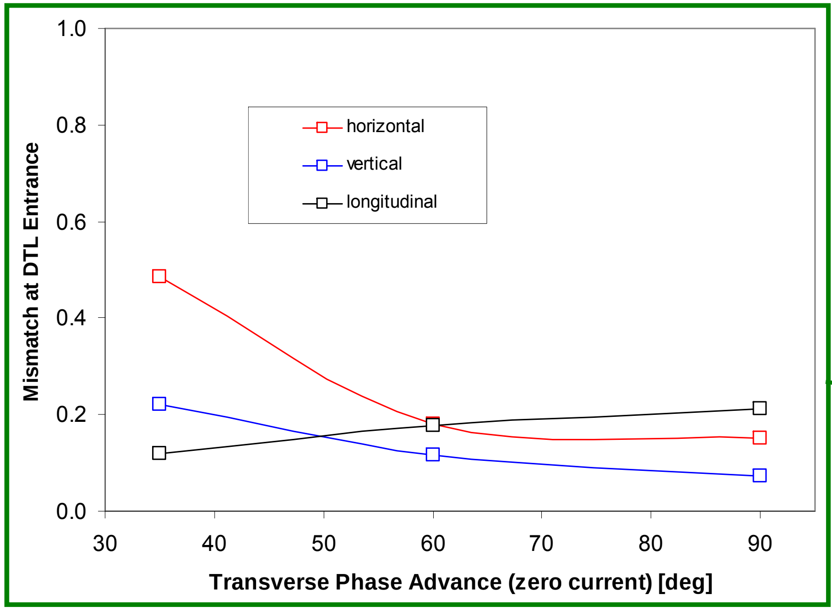
$$M = \left[1 + \frac{\Delta + \sqrt{\Delta(\Delta + 4)}}{2}\right]^{1/2} - 1$$

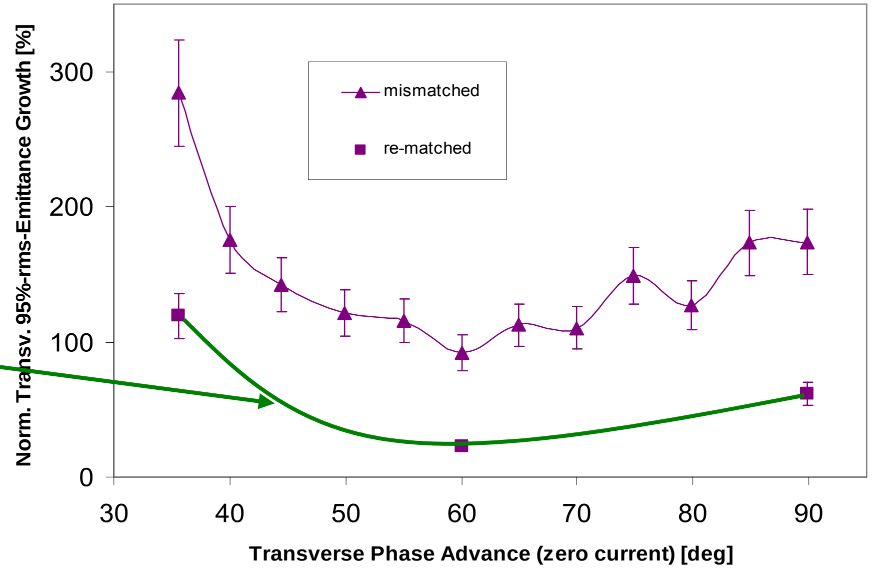
$$\Delta = (\Delta\alpha)^2 - \Delta\beta\Delta\gamma \,,$$

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

Reduction of Mismatch

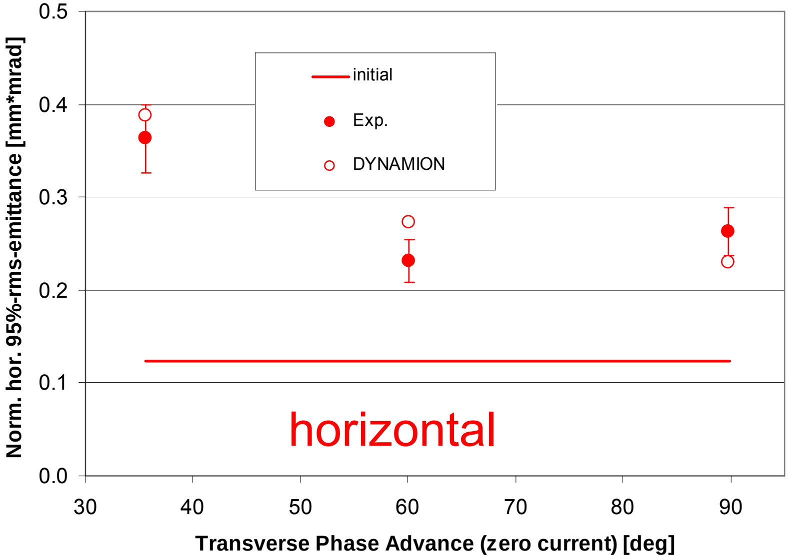
- algorithm used to rms-match (incl. space charge) the initial distribution to periodic DTL
- test of matching by re-measuring emittance growth (one year later)

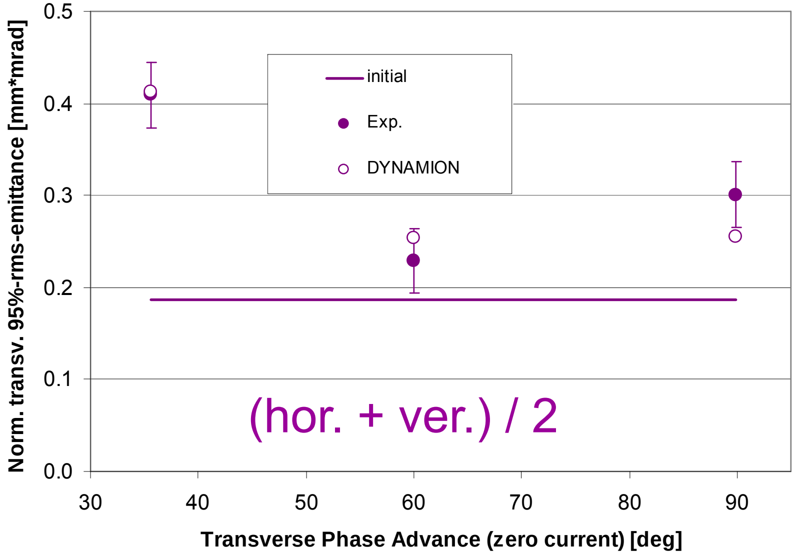


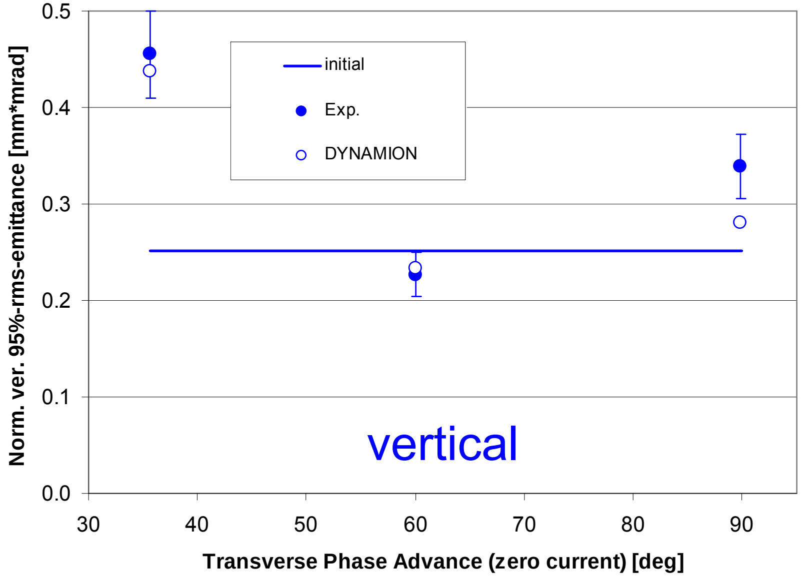


- significant reduction of emittance growth by rms-matching including space charge
- reduction demonstrates that algorithm to reconstruct initial rms-values is valid

Reduction of Mismatch (Benchmarking with DYNAMION)







for matched beams codes seem to describe well the experiments even in each plane separately

Summary

• rms-emittance growth along a 5-tank DTL measured for 12 phase advances from 35° to 90°

• Measurements simulated using four codes (DYNAMION, PARMILA, PARTRAN, LORASR)

• Special emphasis put on reconstruction of amount of halo of initial distribution

• Codes describe well the behavior of measured sum of hor. and ver. emittances

• Systematic reduction of rms-mismatch to DTL under space charge conditions

• Predictions of codes agree to measurements for well-matched beams

• rms-mismatch reduction resulted in considerable emittance growth reduction

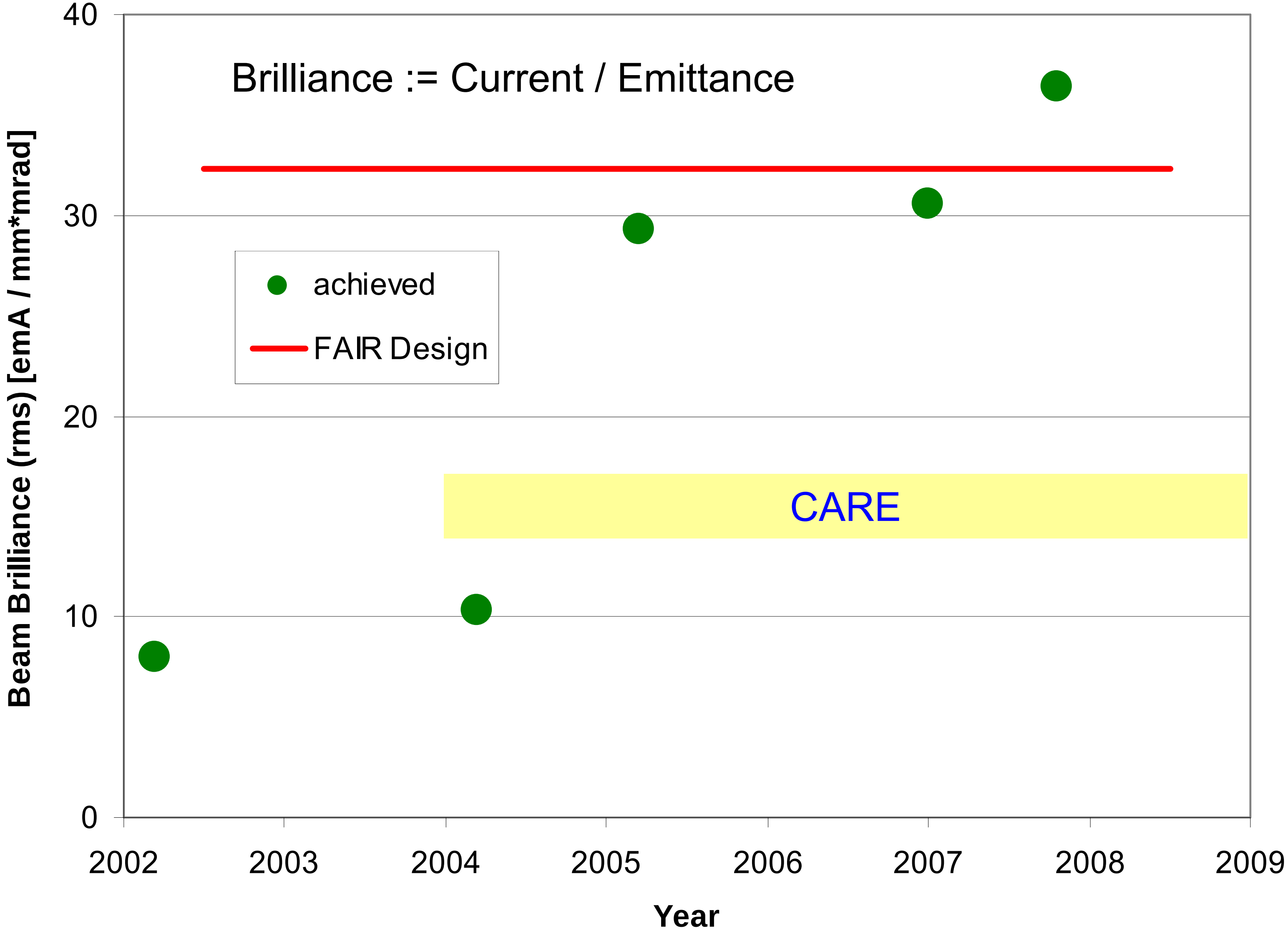
• Codes can predict qualitative dependency of emittance growth

• Absolute values depend from the code

• Predictions are more accurate for matched beams

• Accurate predictions on halo characteristics seem still very hard to be achieved

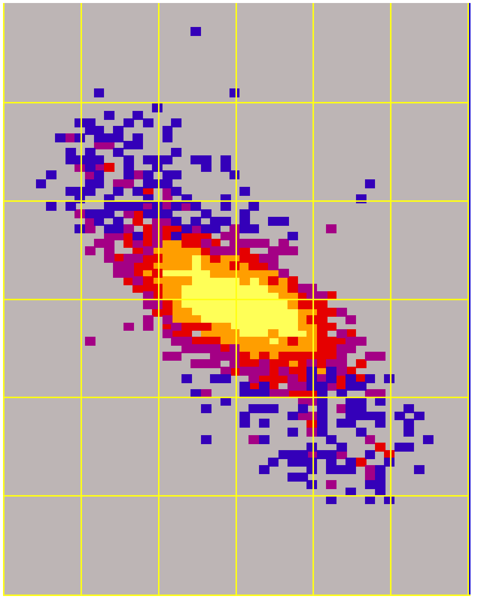
Development of UNILAC Beam rms-Brilliance during CARE



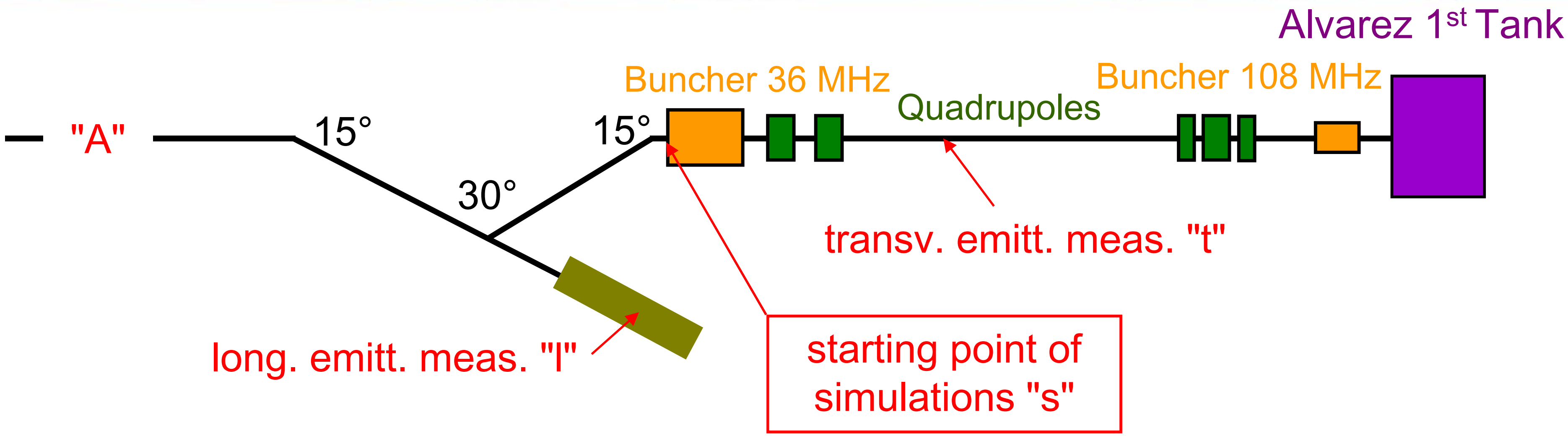
Definition of fractional rms-Emittance

<u>rms-emittance from a fraction of p% of the total intensity</u>

- calculate sum $\sum_{100}$ of all pixel contents
- sort pixels from top by their contents
- sum them up until the fraction p from $\sum_{100}$ is reached
- use the pixels included in this sum for rms-emittance evaluation

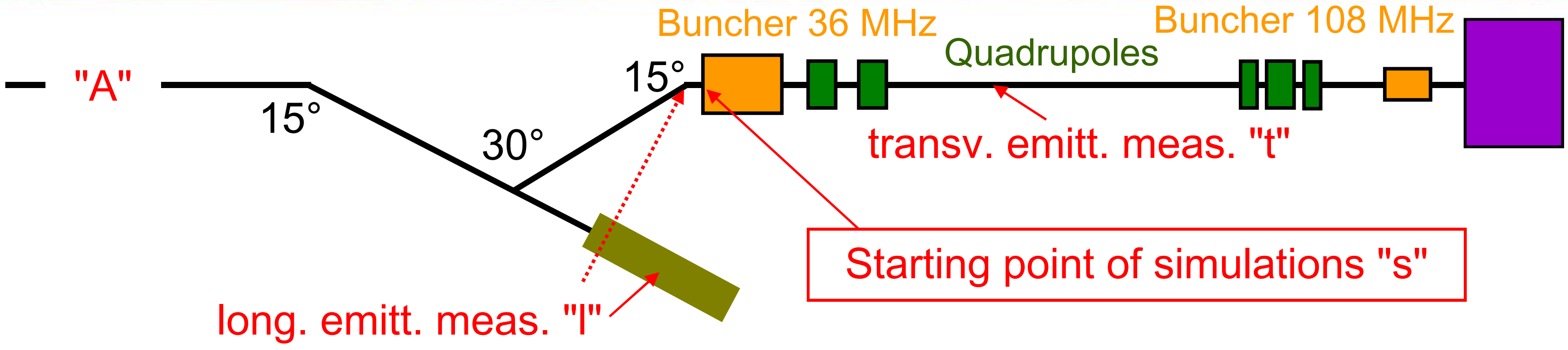


Construction of initial Distribution for Simulations



- 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"