ICAP 09

Comparison of Different Simulation Codes with UNILAC Measurements for High Beam Currents

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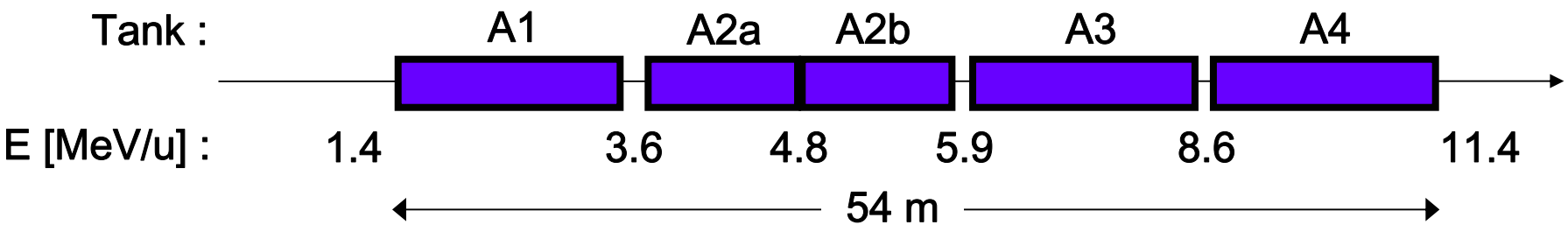
- Introduction and set-up
- Reconstruction of initial distribution
- Comparison of measurements and simulations
- Beam matching with space charge
- Octupolar space charge driven resonance
- Summary

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

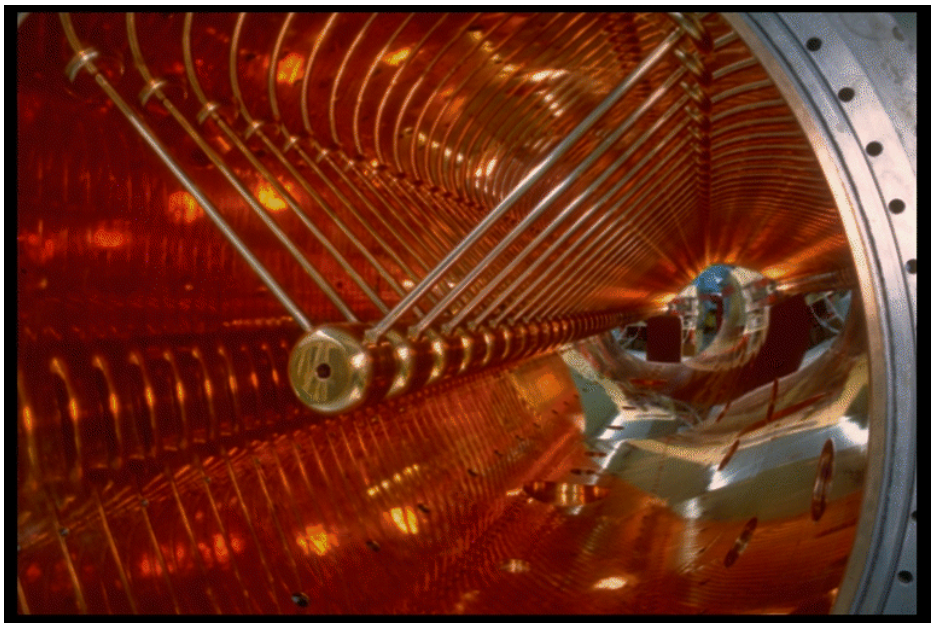
Phys. Rev. ST Accel. Beams **12**, 054204 (2009)

Phys. Rev. Lett. **102**, 234801 (2009)

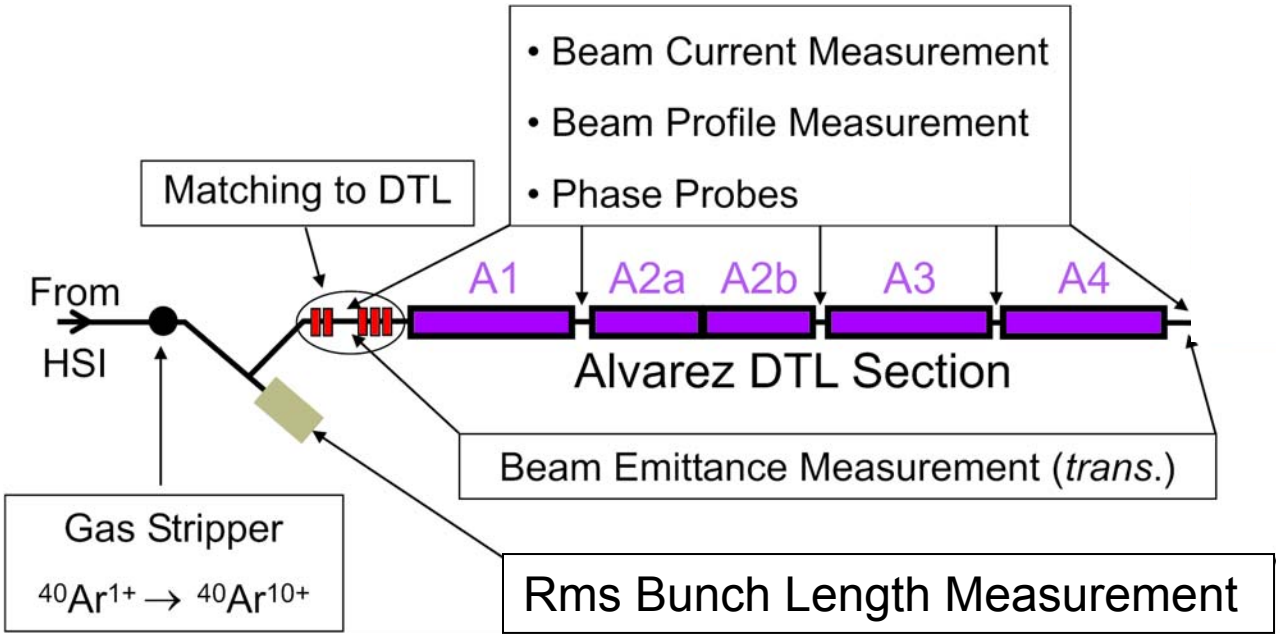
Case to Benchmark: Emittance Growth along UNILAC Alvarez DTL at GSI



- 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°)

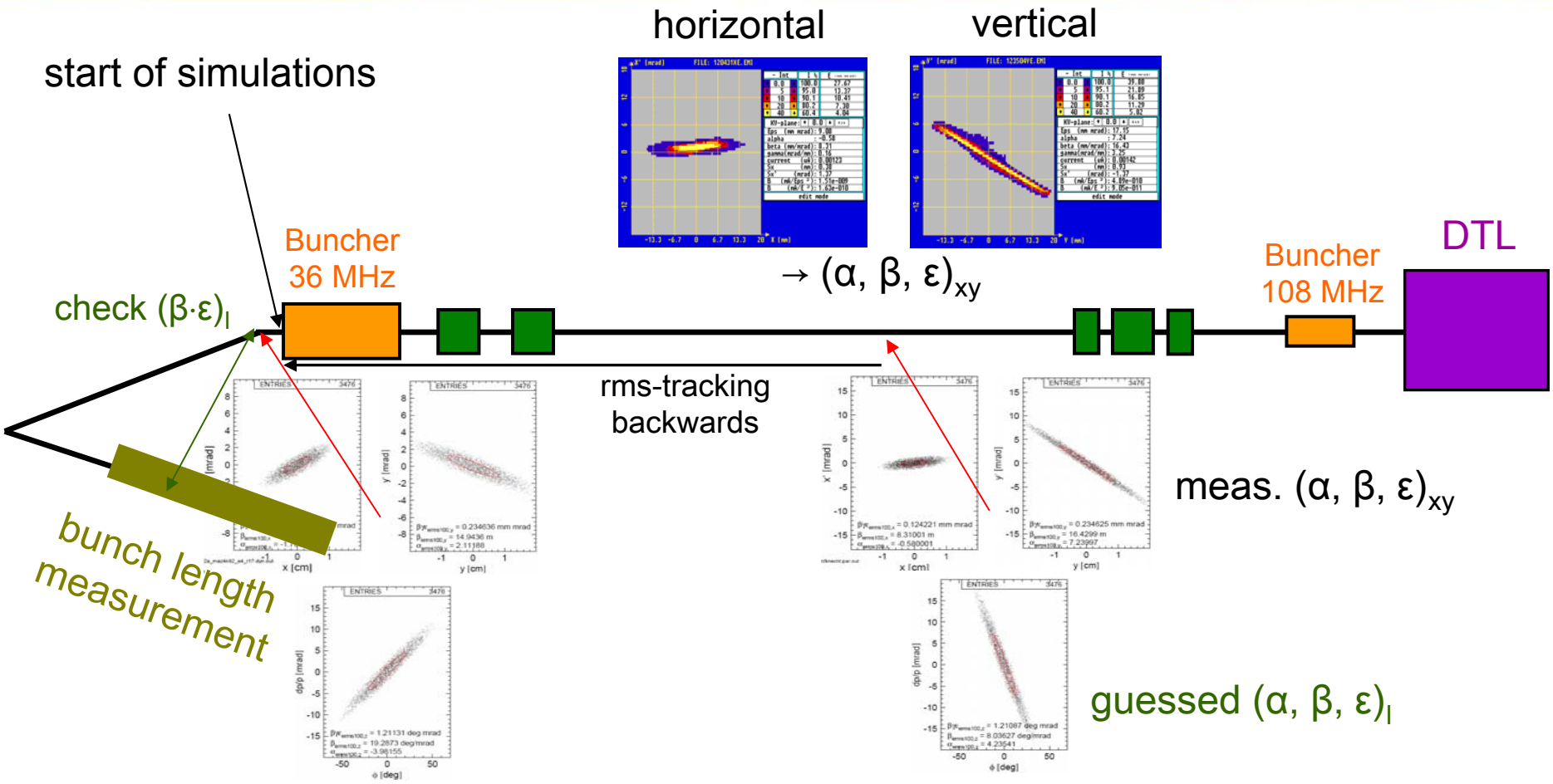


Experimental Set-up & Procedure



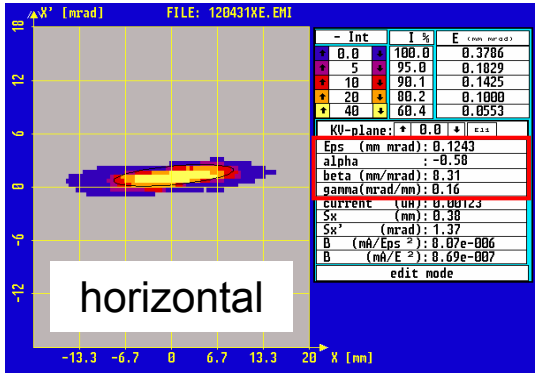
- set beam current to 7.1 mA of $^{40}Ar^{10+}$
- measure hor., ver. emittance, and long. rms-bunch length at DTL entrance
- set DTL transverse phase advance to values from 35° to 130° (undepressed)
  - tune depression varied from 14% (130°) to 43% (35°)
- measure transmission, hor., and ver. rms-emittance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

Reconstruction of Initial rms-Parameters

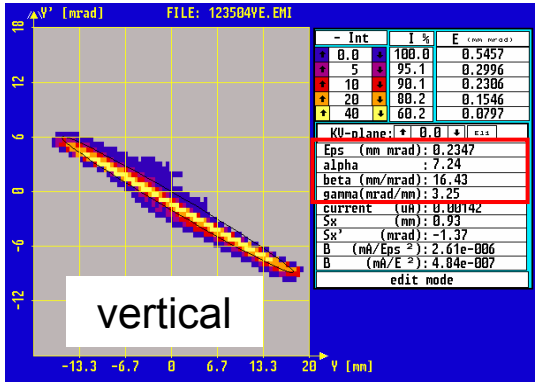


1. selfconsistent KV backtracking, i.e. finding $(\alpha,\beta,\varepsilon)_l$ that fit to measured bunch length
2. verification by sims whether applied machine settings give full transmission w/o tails

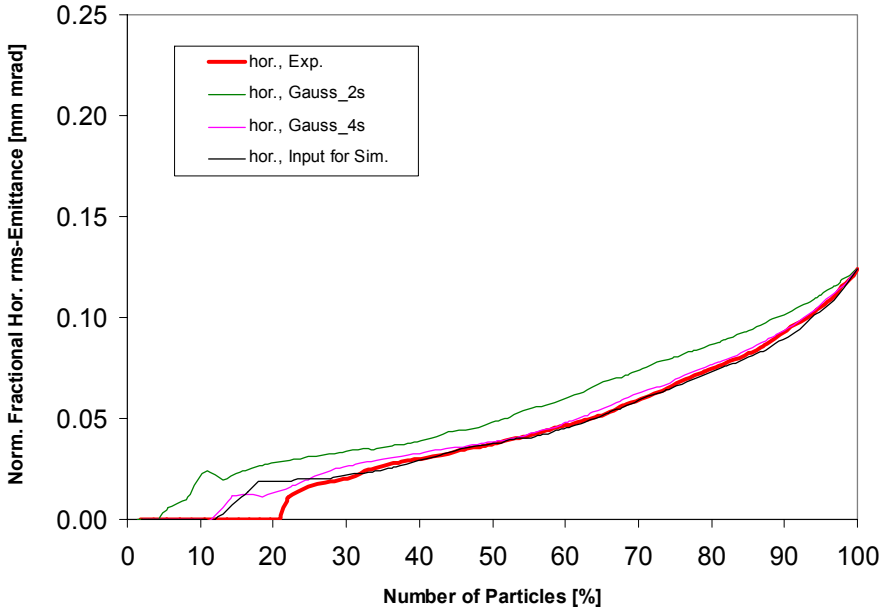
Reconstruction of Initial Type of Distribution

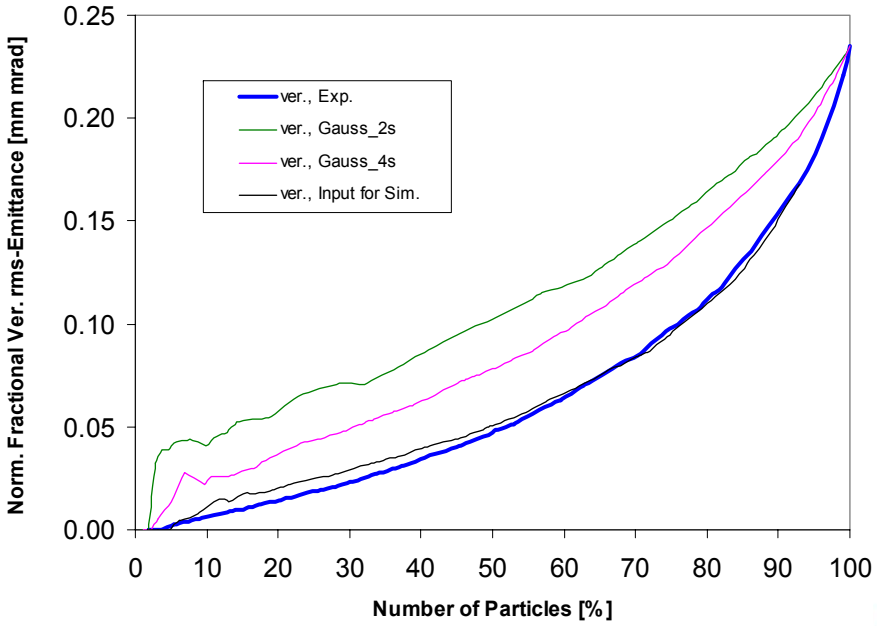


measured in front of DTL



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:

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

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

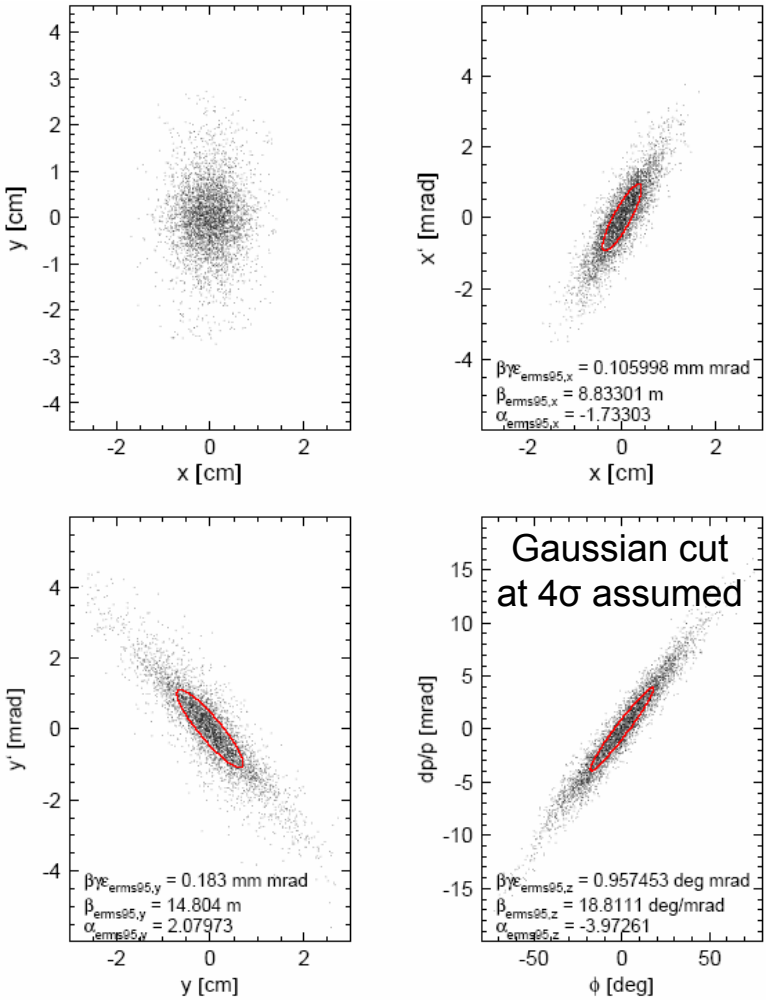
$$f(\tilde{R}) = \frac{a}{2.5 \cdot 10^{-4} + \tilde{R}^{10}}, \quad \tilde{R} \leq 1$$

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

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

Initial Distribution and Codes

initial distribution

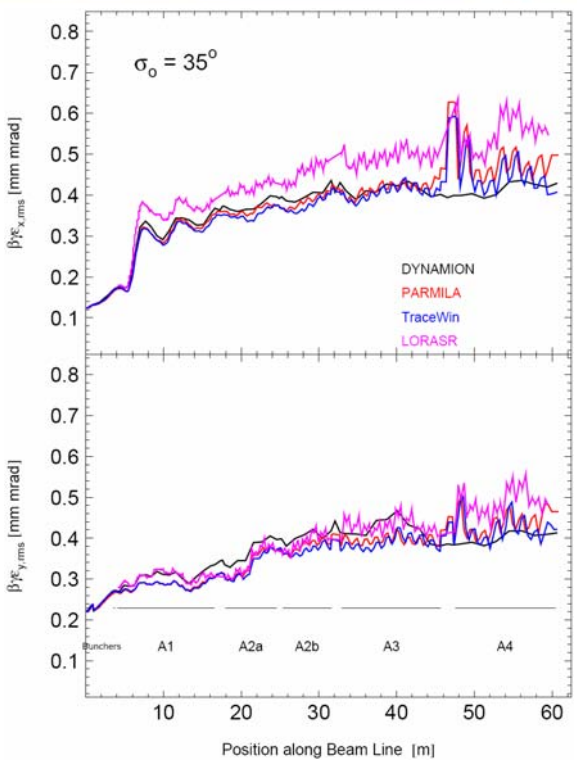


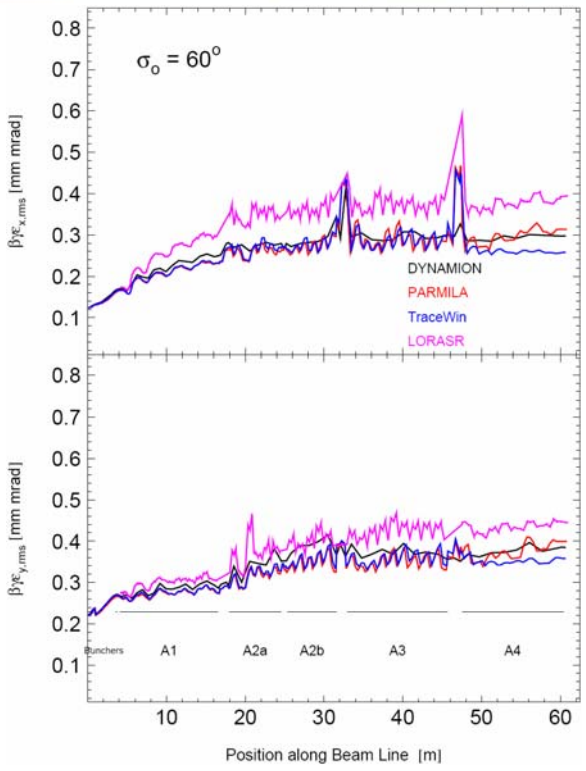
simulations with four different codes as used by the participating labs:

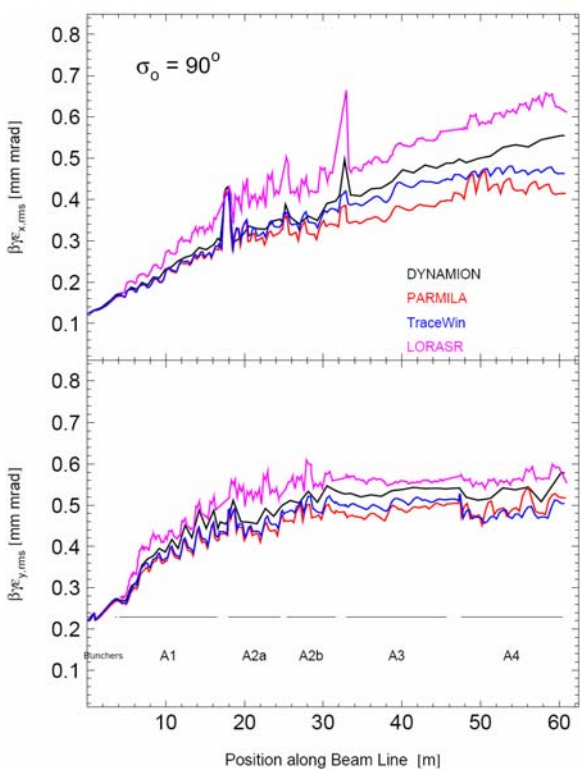
DYNAMION (GSI)
PARMILA (SNS)
TraceWin (CEA/Saclay)
LORASR (Univ. of Frankfurt)

	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

Evolution of Simulated rms Emittances

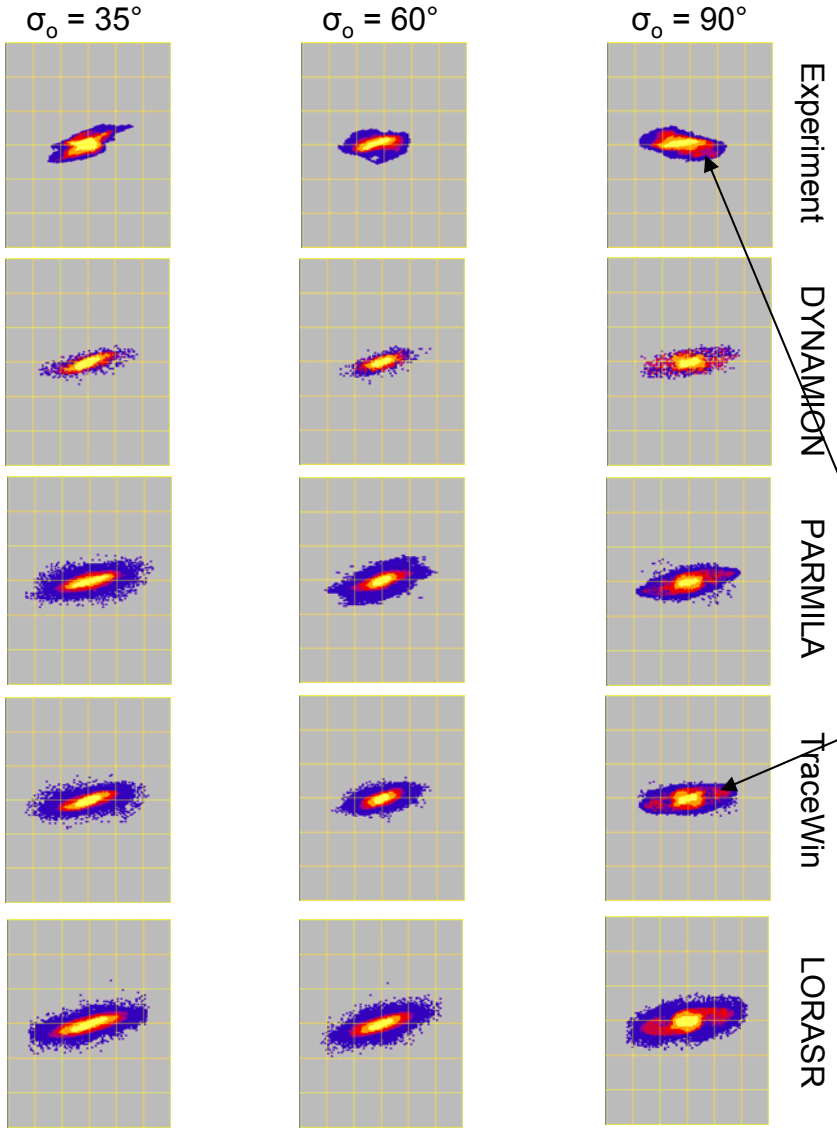






- growth occurs mainly along first two tanks
- lowest growth at intermediate phase advances

Shapes of Final Distributions (Horizontal)

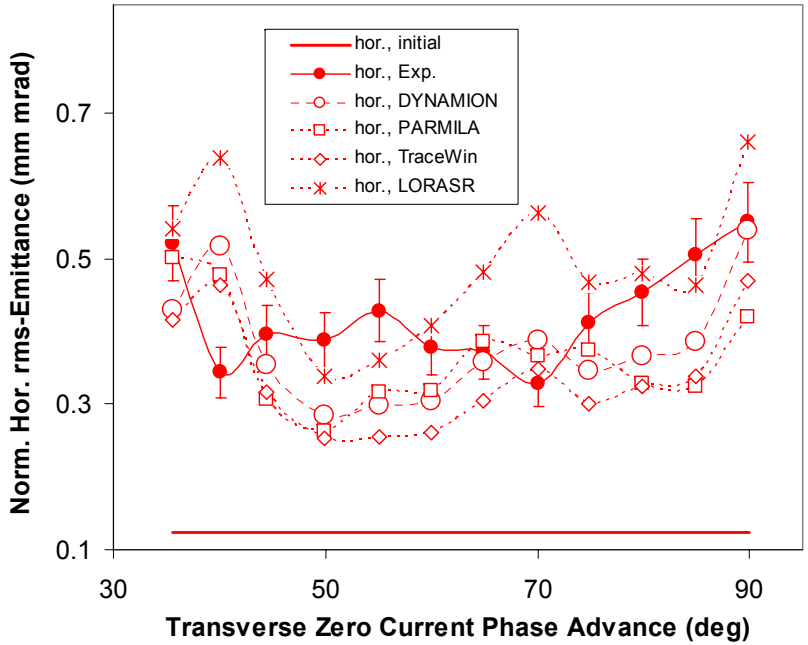


	Int / Int_max [%]
	0 – 5
	5 – 10
	10 – 20
	20 – 40
	40 -100

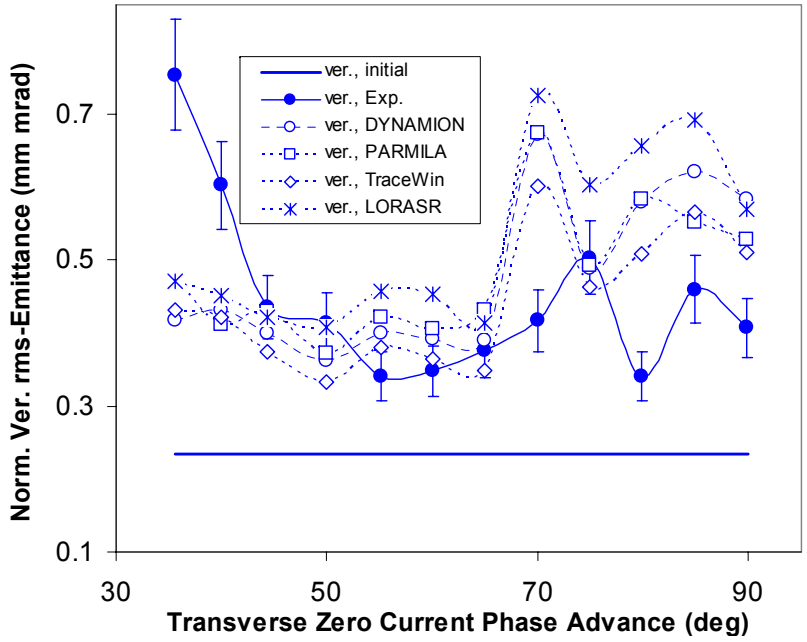
- core: good agreement (ex. 35°)
- 90°: "wings" seen in exp. & sims
- deviations at lowest densities (halo)

Emittances as Function of Phase Advance

horizontal



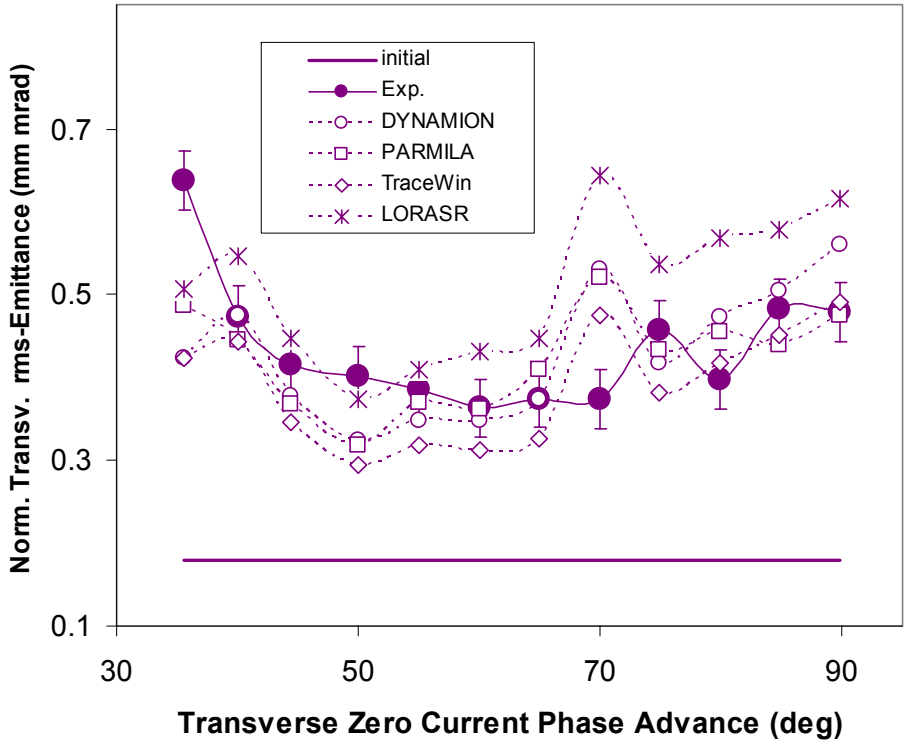
vertical



- 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

Matching to Periodic DTL with Space Charge

matching including space charge is based on rms envelope tracking following a system of coupled diff. eqs*

horizontal

$$a_x'' + \kappa_x(s)a_x - \frac{\varepsilon_{r,x}^2}{a_x^3} - \frac{3K_3(1-f)}{(a_x+a_y)a_z} = 0$$

vertical

$$a_y'' + \kappa_y(s)a_y - \frac{\varepsilon_{r,y}^2}{a_y^3} - \frac{3K_3(1-f)}{(a_x+a_y)a_z} = 0$$

rms beam sizes — beam emittance

ext. foc. strengths — beam current

and

longitudinal

$$a_z'' + \kappa_z(s)a_z - \frac{\varepsilon_{r,x}^2}{a_z^3} - \frac{3K_3 f}{a_x a_y} = 0$$

We have defined a three-dimensional space-charge parameter

$$K_3 = \frac{qI\lambda}{20\sqrt{5}\pi\varepsilon_0 mc^3\gamma^3\beta^2} \quad [\mathrm{m}],$$

*Th. Wrangler: "RF Linear Accelerators", Wiley Intersience, p. 278, (1998)

Periodic Solution with Space Charge

at entrance to first DTL cell (rms):

- ε_x , ε_y , ε_z given by initial distribution
- $\beta_{x,i}$, $\beta_{y,i}$, $\beta_{z,i}$ guessed at first iteration
- $\beta_{x,i}$, $\beta_{y,i}$, $\beta_{z,i}$
- $\alpha_{x,i} = \alpha_{y,i} = \alpha_{z,i} = 0$!!!

↓

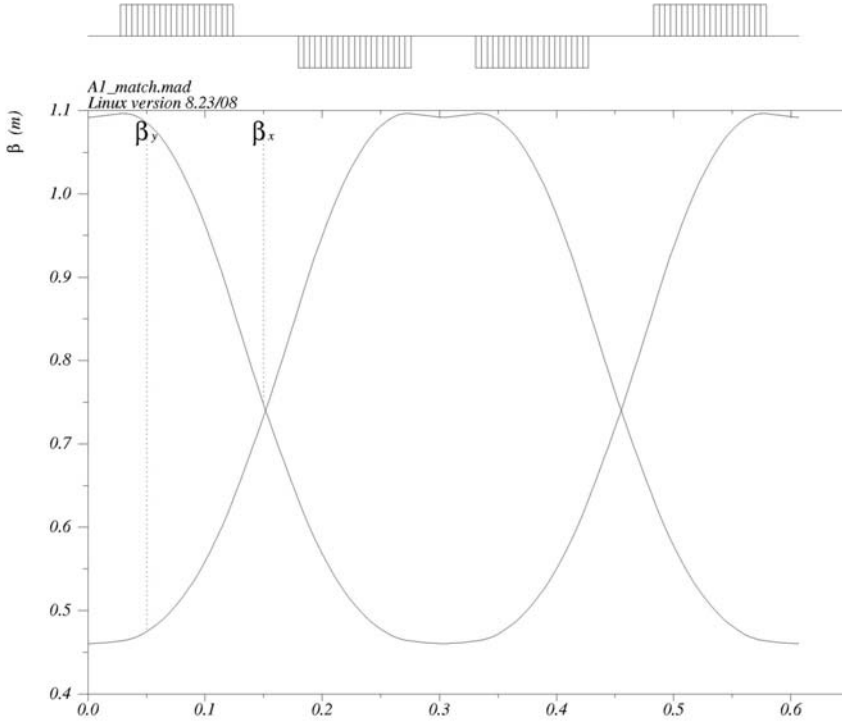
rms tracking through complete F-D-D-F DTL cell including 4 rf-kicks

↓

obtain $\beta_{x,f}$, $\beta_{y,f}$, $\beta_{z,f}$ at cell exit

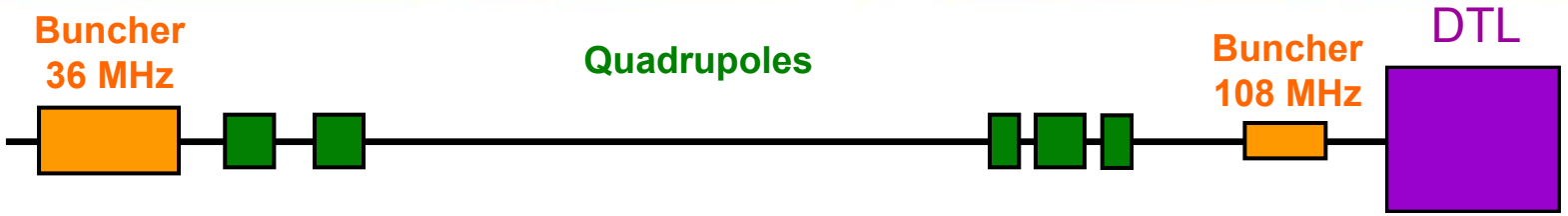
↓

new iteration: $\beta_{x,i} = (\beta_{x,i} + \beta_{x,f}) / 2$, ...



convergence after ≈ 25 iterations, i.e. < 1 sec CPU time

Matching to Periodic DTL with Space Charge



- Twiss parameters at entrance to matching section are known (α_i, β_i)
- Twiss parameters at exit of section (α_f, β_f) depend on seven variables ($f_1 \ldots f_7$)
- mismatch at DTL entrance from T. Wanglers definition; $\Delta\alpha = \alpha_f - \alpha_{per}$

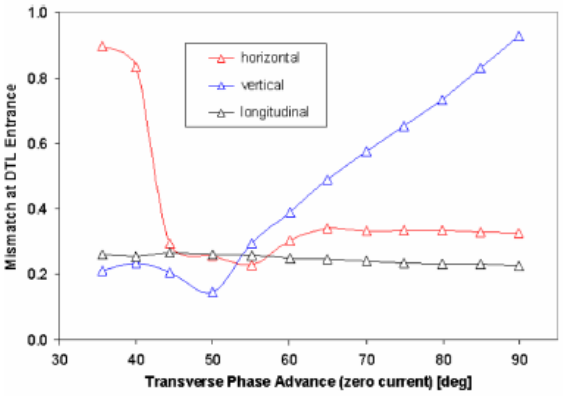
$$M = \left[1 + \frac{\Delta + \sqrt{\Delta(\Delta+4)}}{2}\right]^{1/2} - 1$$

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

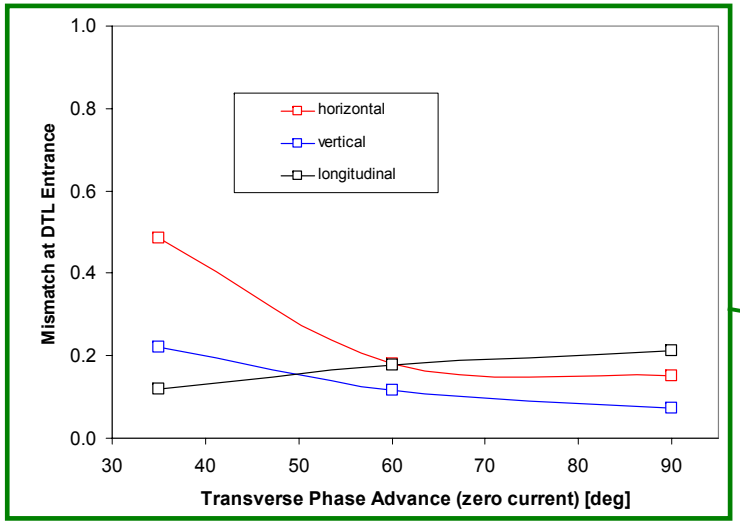
- define function F ($f_1 \ldots f_7$) := $M_x^3(\ldots) + M_y^3(\ldots) + M_z^3(\ldots)$
- find ($f_1 \ldots f_7$) that minimize F using *powell* routine from "Num. Recipies in C"

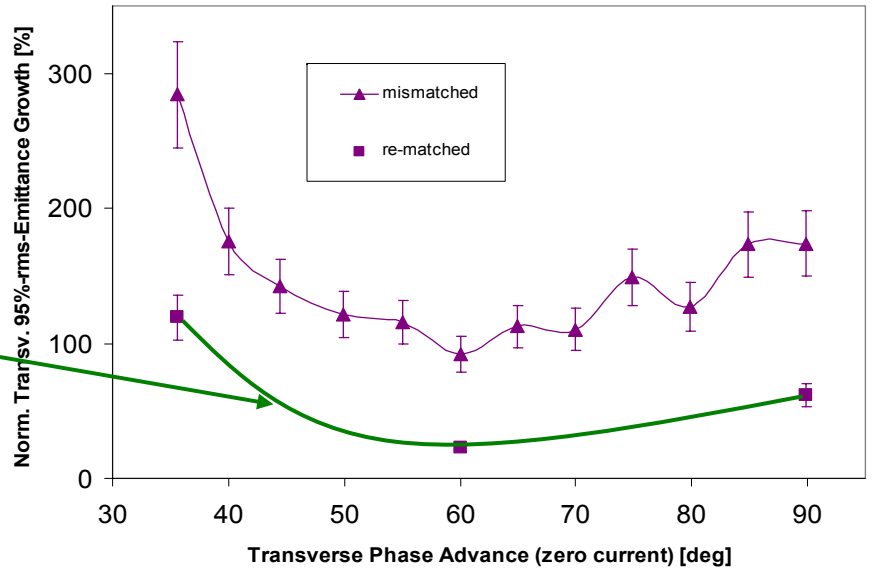
Experimental Investigation of Matching

evaluation of mismatch of last measurement :



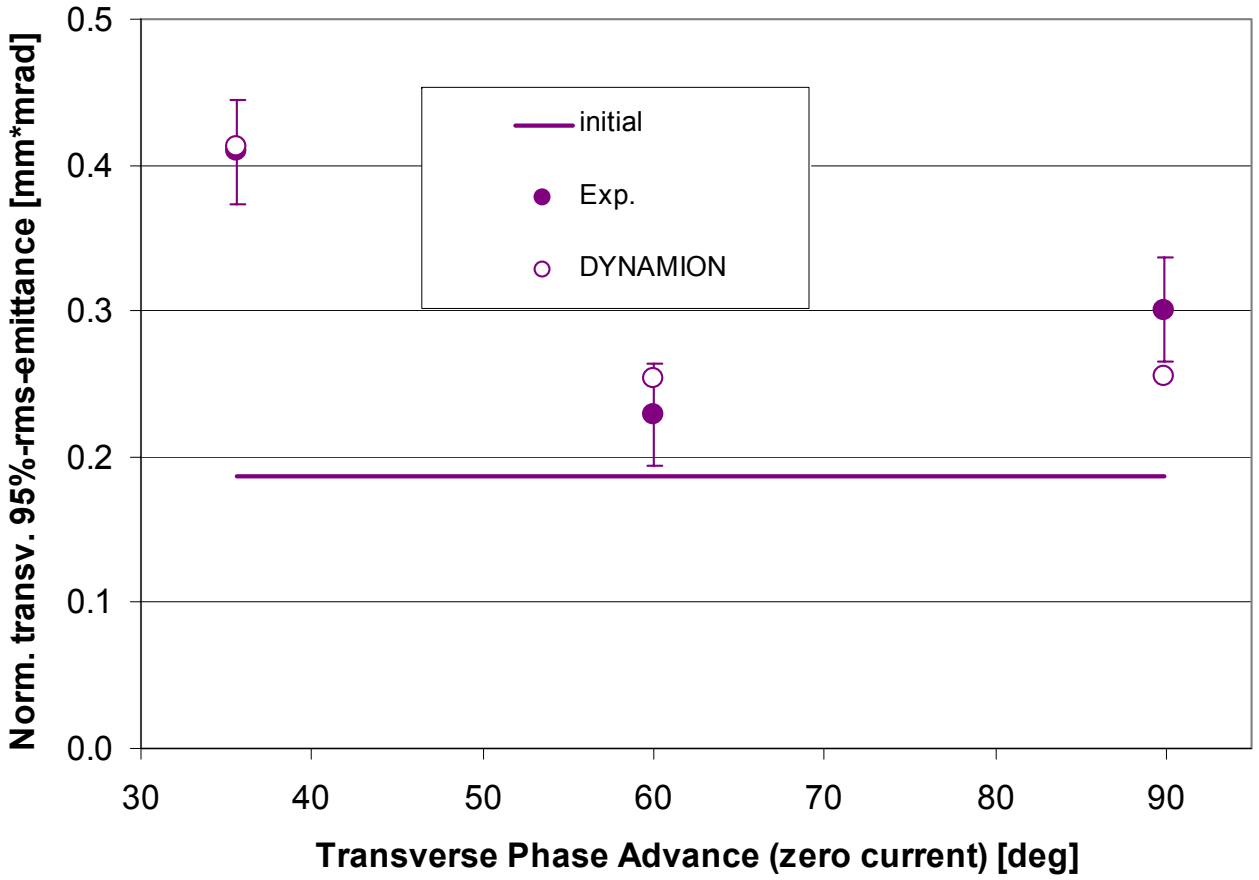
applying matching routine



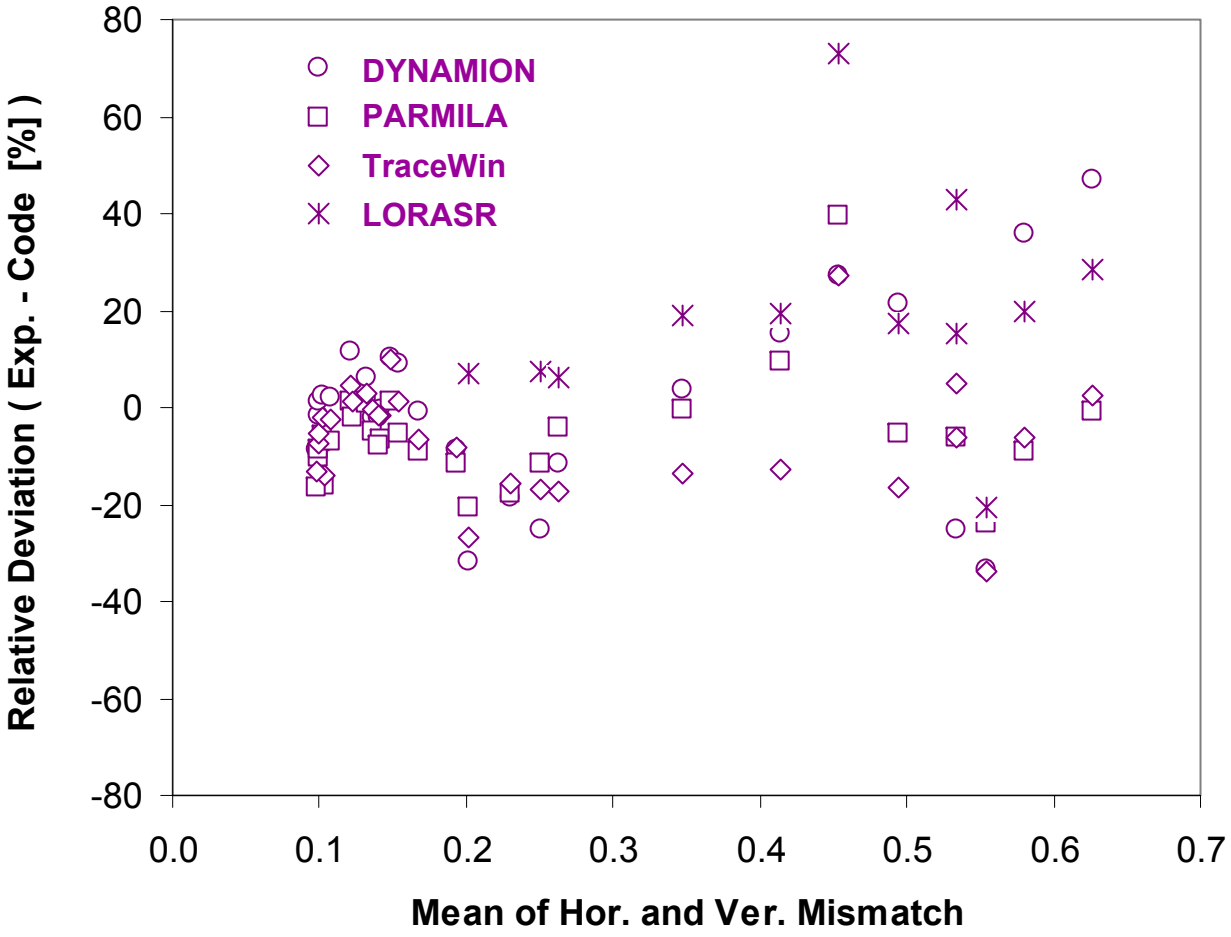


Matching & Simulation-Experiment Agreement

reduced mismatch :



Reliability of Codes: Impact of Mismatch



Space Charge Driven Resonance in a Linac

- assumption of a periodically breathing beam envelope with phase advance σ_{env}
- envelope has radial symmetry
- single particle experiences:
  - constant external focusing with σ_o
  - electric field of breathing envelope

envelope charge density depends on radius r :

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

density component (r^2), $r^{\geq 4}$ neglected

creating a field :

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

octupolar field component (r^3)

Single Particle Motion

single particle motion driven by two components :

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

external quad focusing

field from envelope (perturbation)

perturbed oscillator equation :

$$r'' + \sigma_o^2 r = a \cdot r^3 \cdot e^{i\sigma_{env} s}$$

frequency of external perturbation from envelope breathing

solution by ansatz :

$$r(s) \sim e^{-i\sigma_o s}$$

Plugging into oscillator equation :

$$r'' + \sigma_o^2 r \sim a \cdot e^{i(\sigma_{env} - 3\sigma_o)s}$$

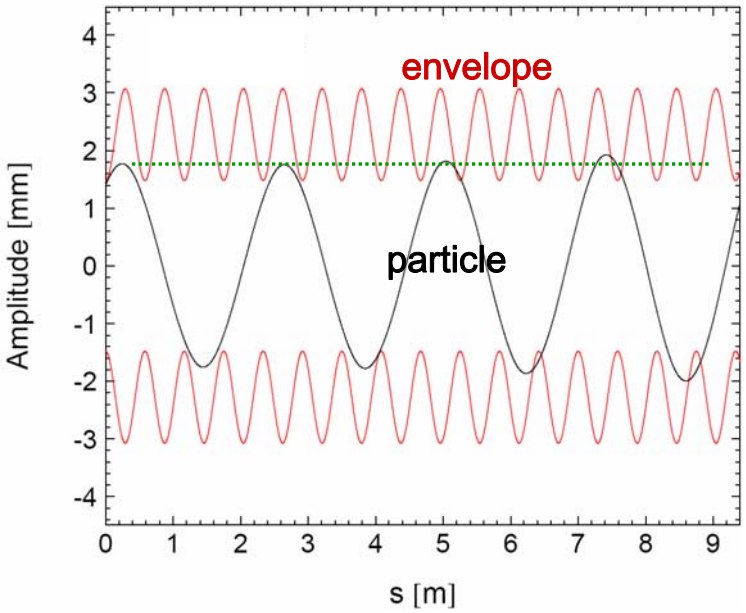
resonance condition : $\sigma_{env} = 4\sigma_o$

→ envelope oscillates 4 times faster than single particle

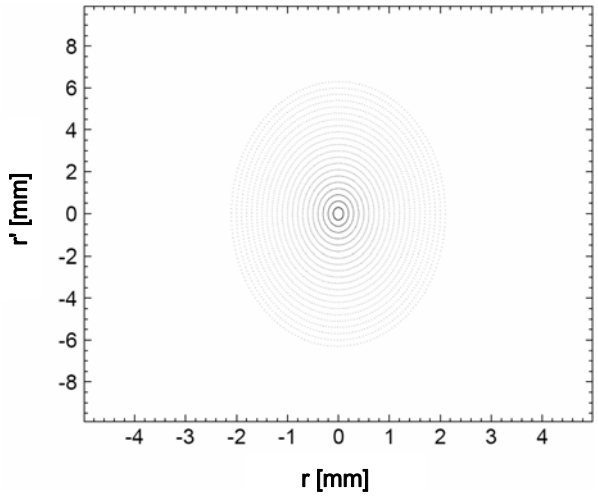
Model for Resonance

f_oscillation (envelope) = 4 * f_oscillation (particle)

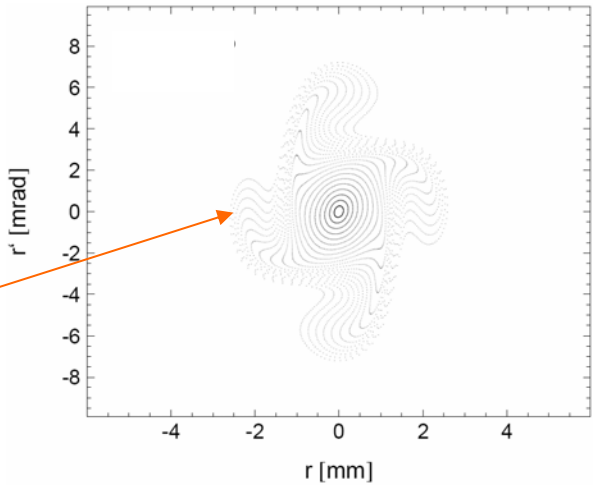
→ resonant excitation of single particle



initial phase space distribution



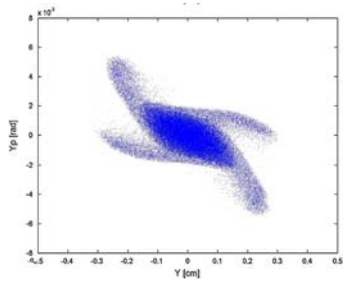
final phase space distribution



4 arms: characteristic feature of octupolar resonance

Octupolar Resonance in a Linear Accelerator

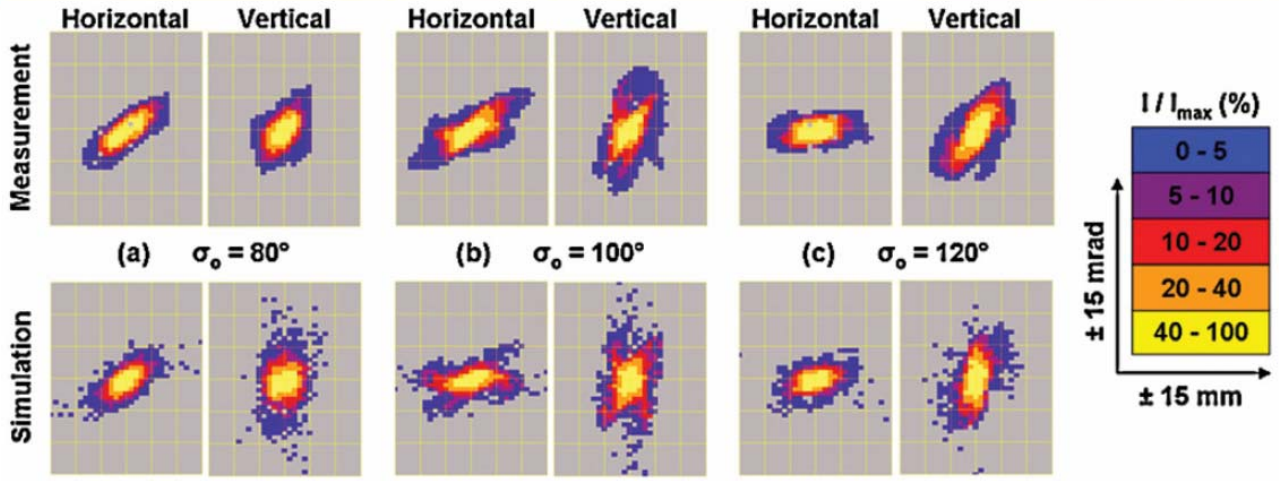
- never observed directly worldwide (linac nor ring) due to insufficient machine/beam control
- requires very small mismatch to assure envelope periodicity
- cannot be seen behind multi-tank DTL due to inter-tank mismatch
- simulations by D. Jeon (SNS) suggested to measure this resonance at GSI UNILAC

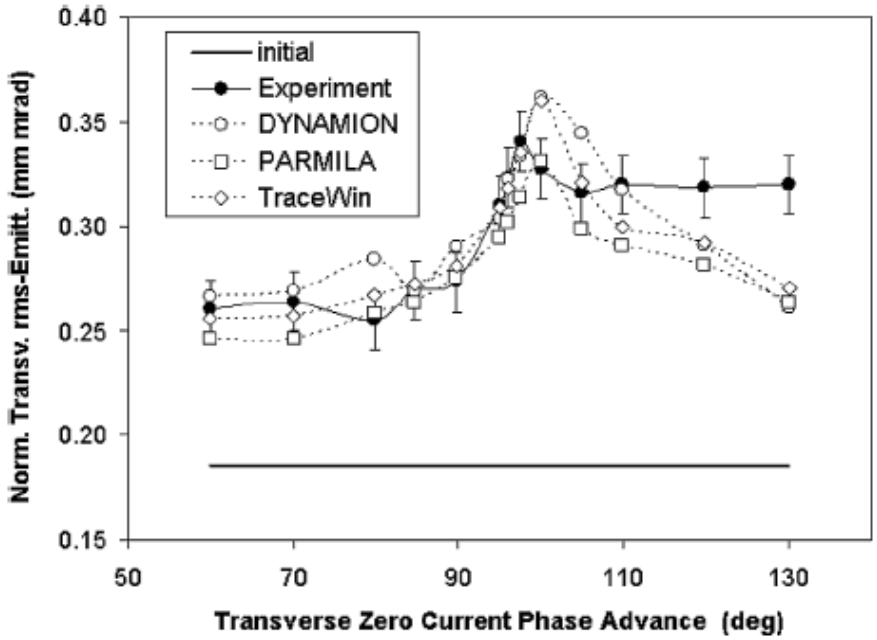


<u>Experiment at GSI UNILAC :</u>

- install beam emittance measurement unit after first DTL tank
- measure phase space distributions and rms emittances

Evidence of Octupolar Resonance in the UNILAC





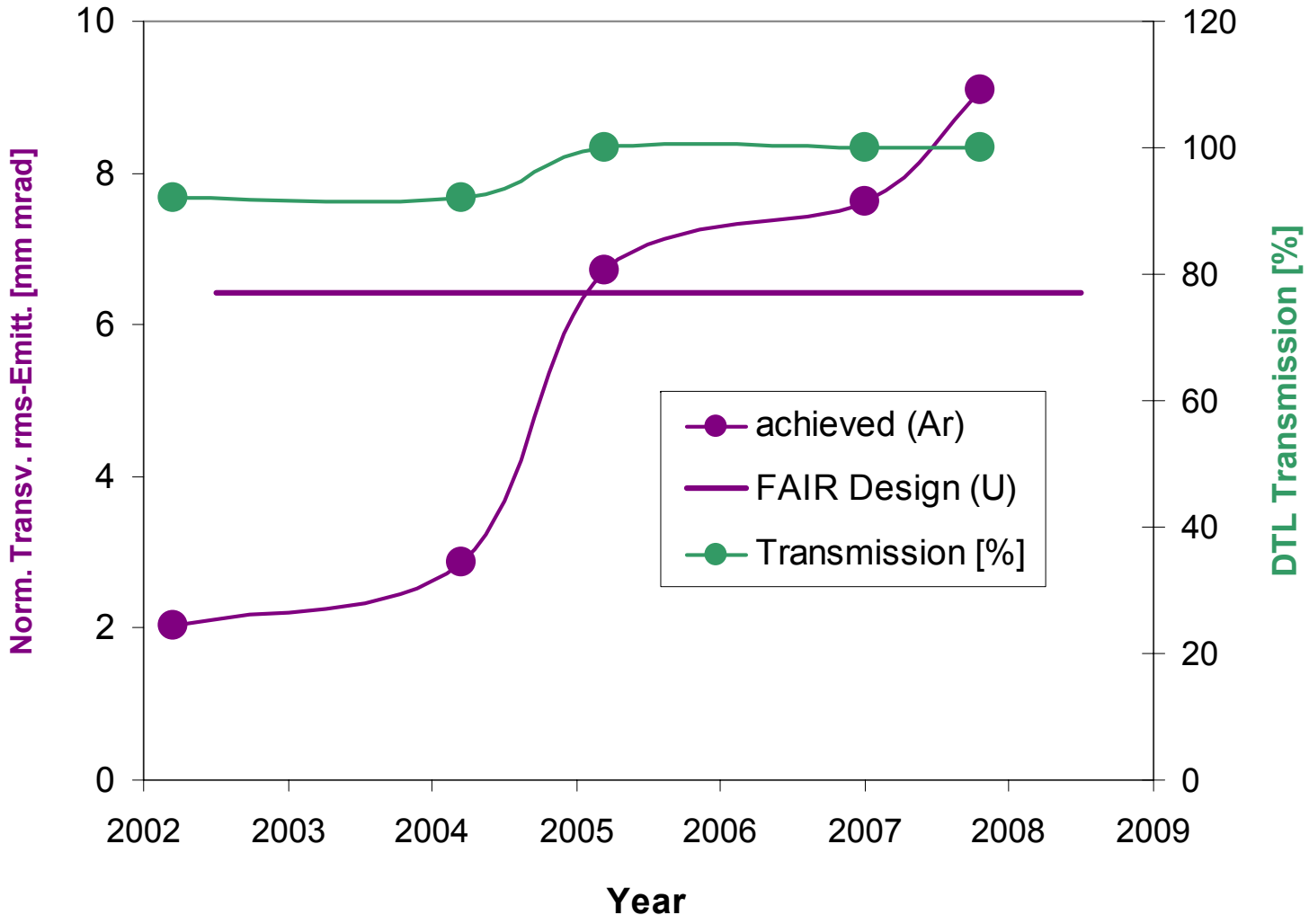
- 4 arms were observed
- strong emittance growth was observed

Summary

- **Codes describe well the behavior of sum of hor. and ver. emittances**
- **Within single planes:**
  - considerable differences among codes

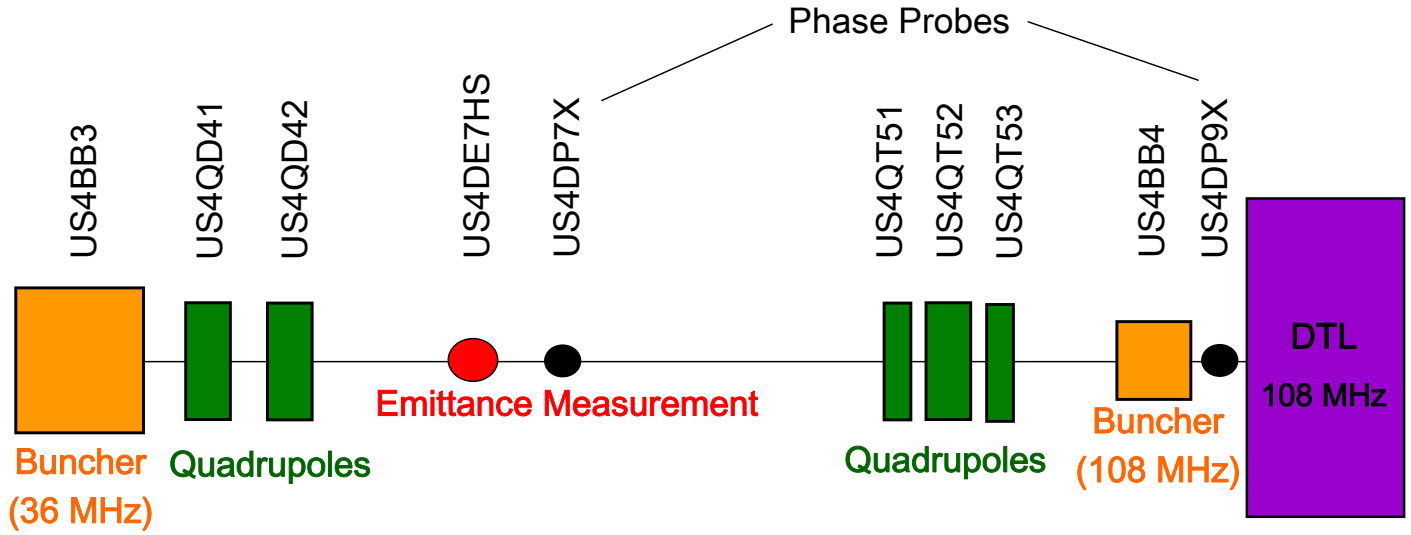
  → agreement between measurements and codes is just fair
- **Reliability of codes increases with quality of matching**
- **Differences among codes decrease with quality of matching**
- **Agreement with measurements does not depend on number of particles**
- **Experimental evidence for octupolar space charge resonance in linear accelerator**

Development of UNILAC Beam Brilliance



Matching to Periodic Solution with Space Charge

- after periodic solution assumed to be known
- section prior to DTL needs to be set to exactly match this solution
- seven available knobs: five quadrupoles, 2 bunchers



- seven variables to minimize one value → sum of mismatches in hor., ver. and long.
- envelope equations + numerical recipies (Powell routine) can do the job (theoretically)

Routine to For Matched Injection into DTL

Input

I_mean [emA]:	9.5
q:	10.0
A:	40.00
beta_rel:	0.054638
rf-freq [MHz]:	108.408
unnorm. hor. rms-emit. [mm mrad]:	3.0
meas. hor. beta-func. [m]:	5.33
meas. hor. alpha:	2.09
unnorm. ver. rms-emit. [mm mrad]:	2.25
meas. ver. beta-func. [m]:	11.49
meas. ver. alpha:	4.94
unnorm. long. rms-emit. [deg mrad]:	50.0
meas. long. beta-func. [deg/mrad]:	22.175
meas. long. alpha:	3.379
MAZ of first A1 cell:	4.5
During US4-emitt. measurement:	
Strength of US4QD41 [1/m]:	2.139
Strength of US4QD42 [1/m]:	-2.090
Strength of US4QT51 [1/m]:	0.905
Strength of US4QT52 [1/m]:	-2.839
Strength of US4QT53 [1/m]:	2.911
Slider of US4BB3 [V]:	4.0
Slider of US4BB4 [V]:	0.0

Output

Best fitting settings are:

q_US4QD41 = 1.982 1/m
q_US4QD42 = -1.852 1/m
q_US4QT51 = 0.833 1/m
q_US4QT52 = -3.254 1/m
q_US4QT53 = 2.659 1/m
sl_BB3 = 4.278 V
sl_BB4 = 0.881 V

Best fitting Twiss parameters are:

beta_x = 1.847 m
alpha_x = 0.104
beta_y = 0.887 m
alpha_y = 0.050
beta_l = 3.073 deg/mrad
alpha_l = -0.458

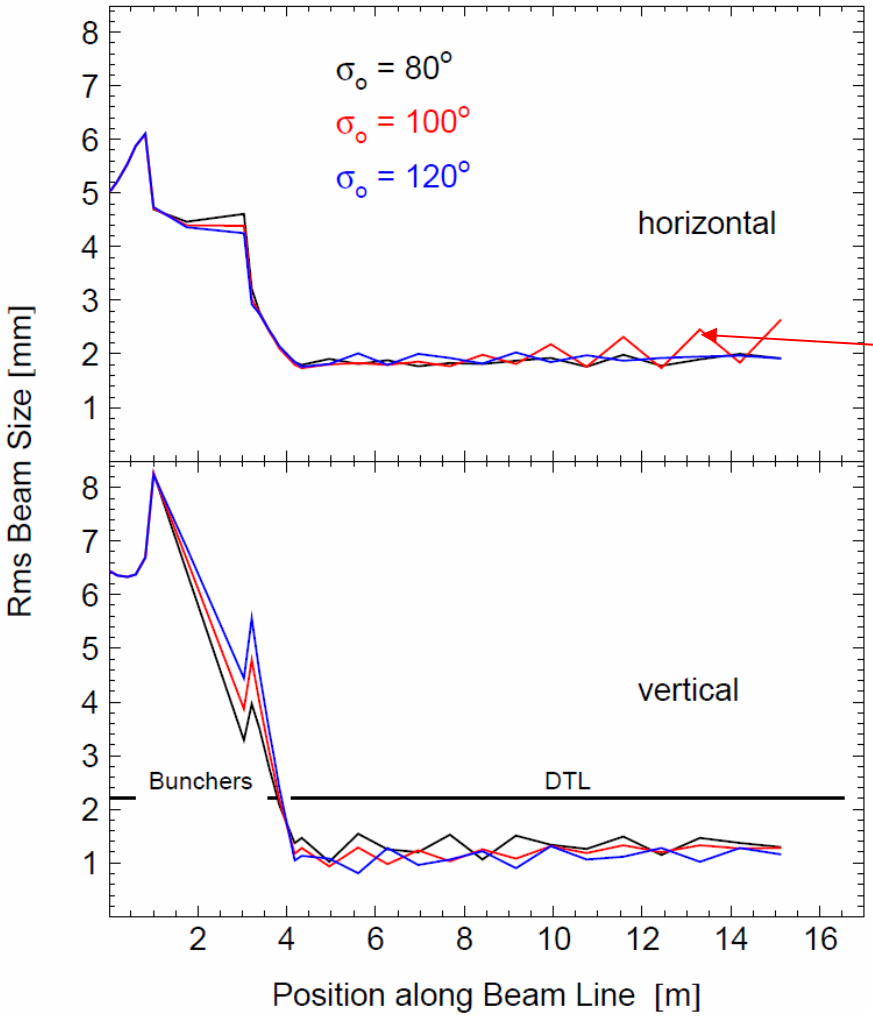
remaining mismatch: 0.02

Periodic solution before 1st gap of Alvarez Tank I:

beta_x = 1.85 m, alpha_x = 0.10, DPhi_x = 29.7°
beta_y = 0.89 m, alpha_y = 0.05, DPhi_y = 26.6°
beta_l = 2.40 °/mrad, alpha_l = -0.11, DPhi_l = 34.7°

Impact of Envelope Instability I

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

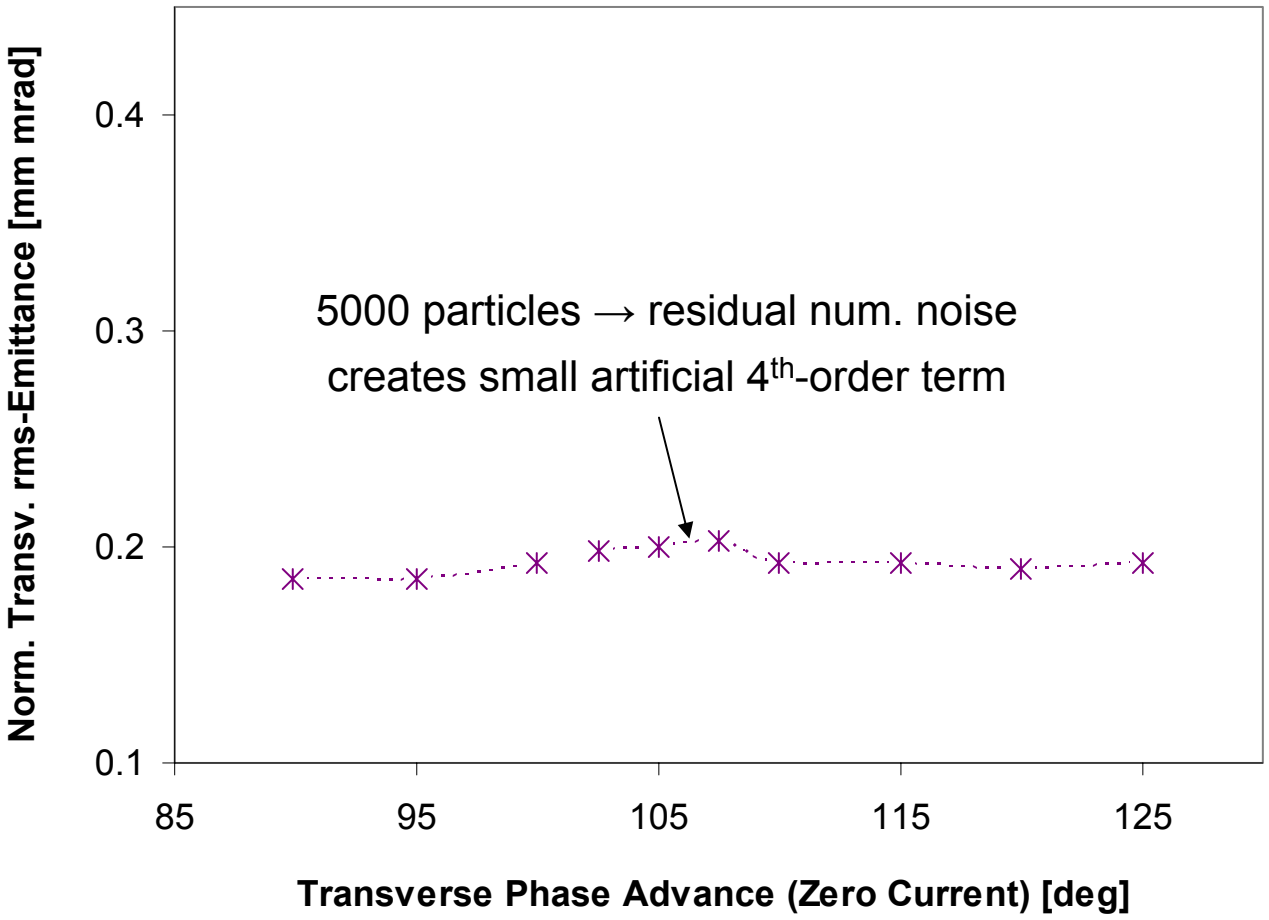


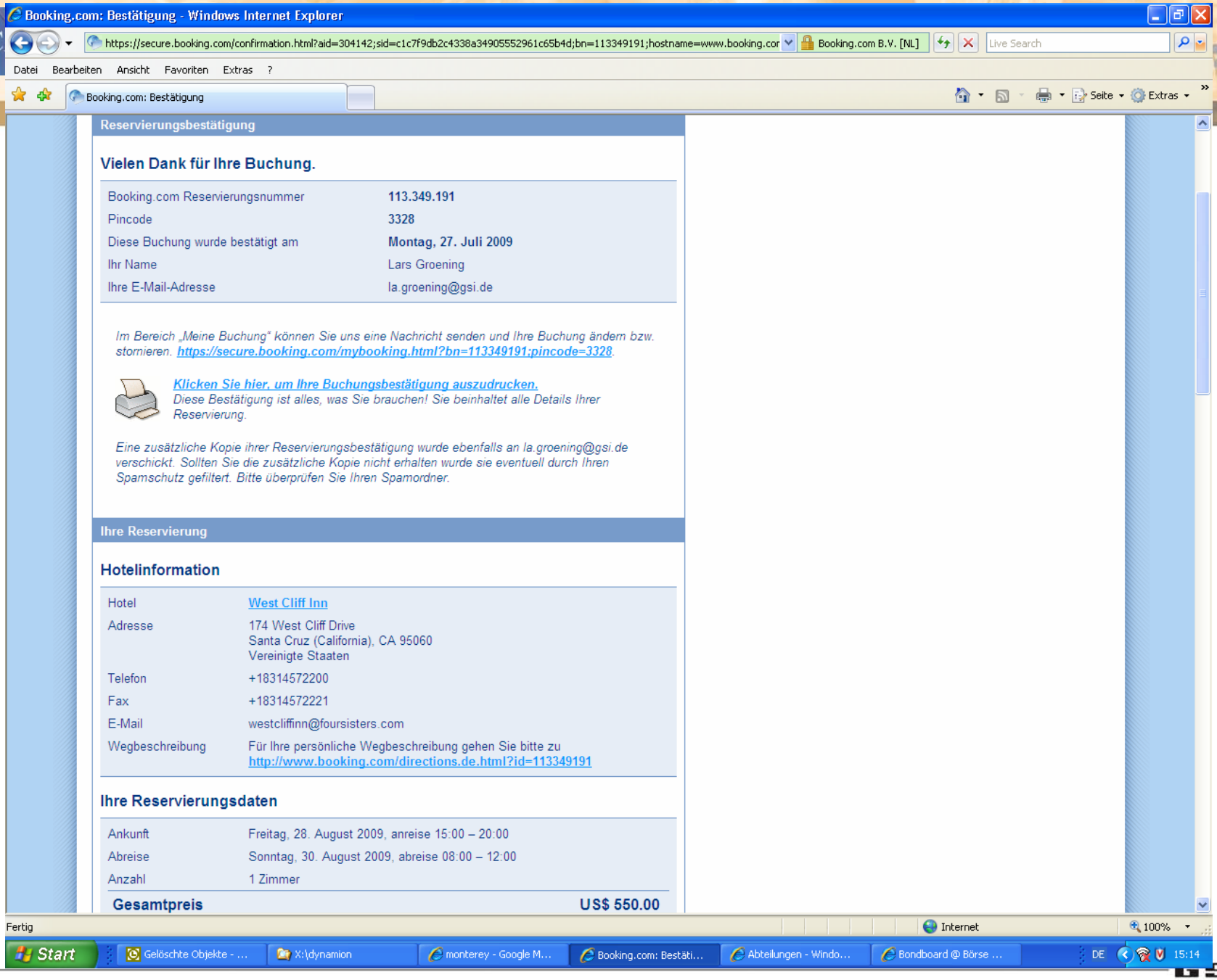
4th-order resonance

Impact of Envelope Instability II

Simulation with KV distribution → no significant growth

(KV has no 4th-order potential term)




Booking.com: Bestätigung - Windows Internet Explorer
https://secure.booking.com/confirmation.html?aid=304142;sid=c1c7f9db2c4338a34905552961c65b4d;bn=113349191;hostname=www.booking.com
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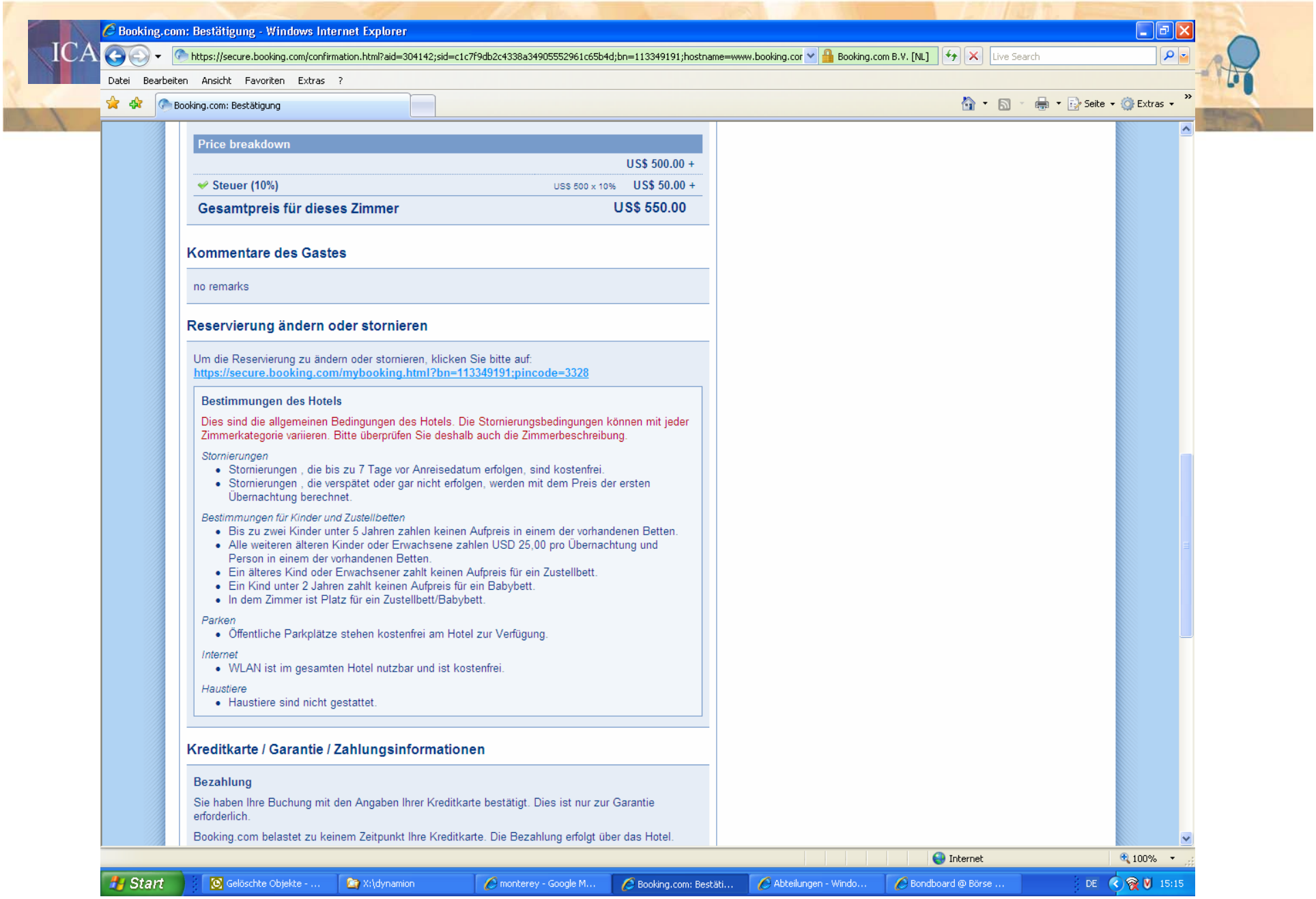
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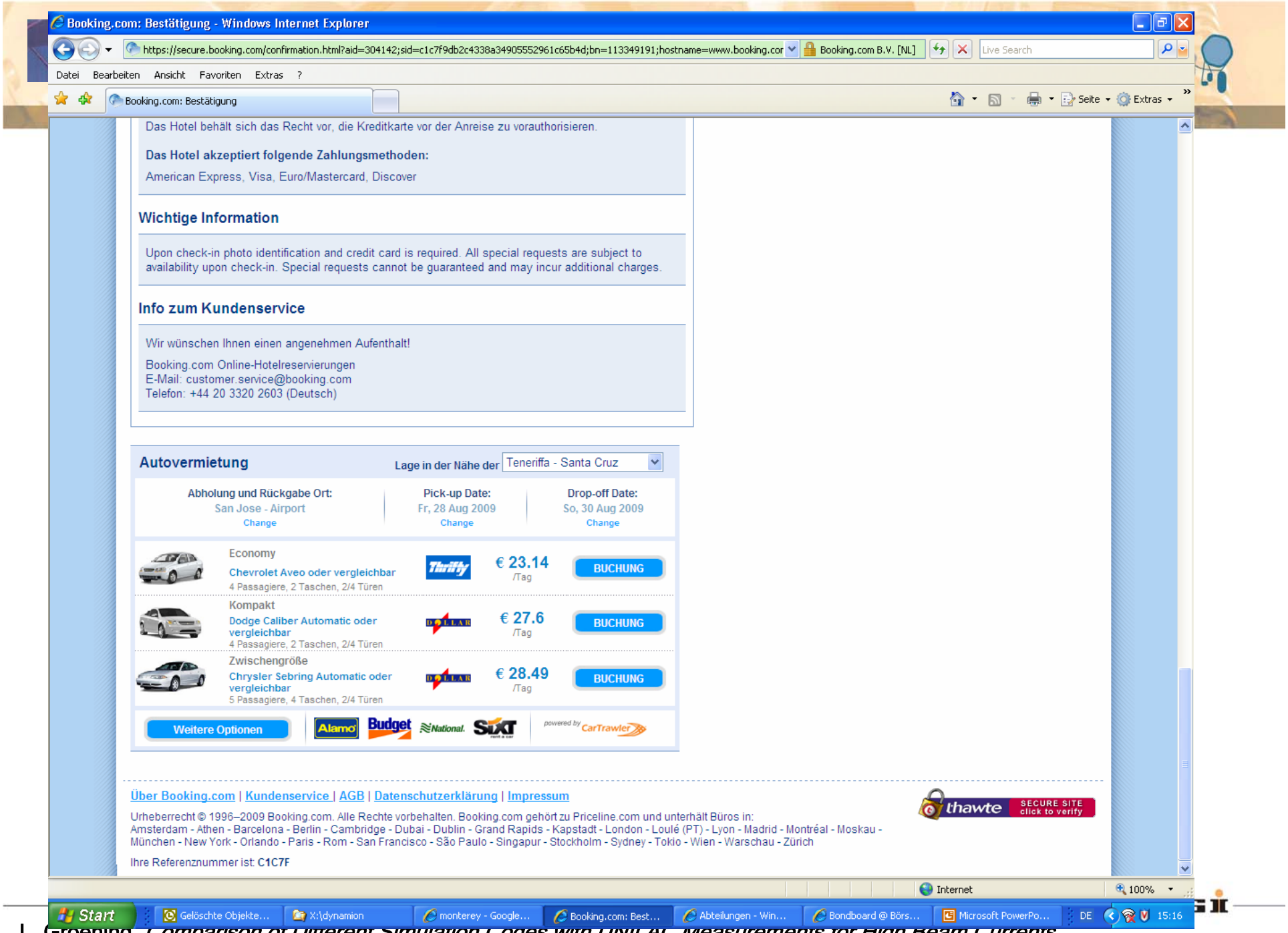
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