TH303

Experimental Observation of Space Charge Driven Resonances in a Linac

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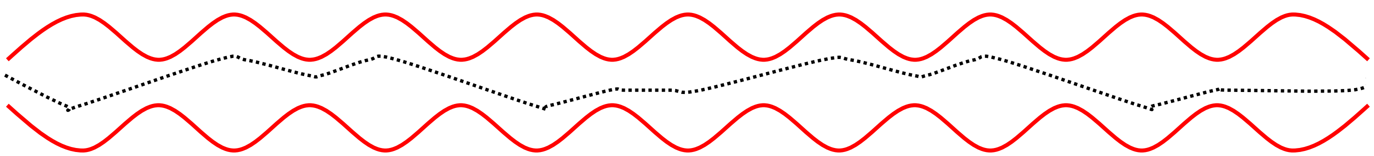
- Transverse Resonance in a Linac
- Experiment: Set-up & Results
- Parametric Resonance (inter-plane coupling long. ↔ transv.)
- Experimental Results

campaign embedded into HIPPI: High Intensity Pulsed Proton Injectors

HIPPI was part of the EU-supported CARE activity

Transverse Resonance in a Linac

- perturbing device (magnet, cavity, ...) acts on particle just once
- single devices cannot cause resonant perturbation
- high beam current :
  - space charge (sc) acts on particle
  - sc force acts permanently
  - sc force varies with envelope size
  - periodic change of envelope → periodic sc force on particle



$\sigma_{part} < \sigma_{env} = 360°$

Model for Resonance

- matched envelope
- envelope has radial symmetry
- periodically breathing envelope, phase advance σ_{env}
- particle experiences :
  - constant external focusing σ_o
  - electric field of breathing envelope with radius R(s)

envelope charge density depends on radius r :

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

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

breathing with σ_{env}

creating a field :

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

octupolar field component (r^3)

Single Particle Motion

single particle equation (lattice + sc) :

$$r'' + \left[\sigma_o^2 - \Delta\sigma^2\right] r = a \cdot r^3 \cdot e^{i\sigma_{env} s}$$

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

depressed phase advance

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

envelope oscillates 4 times faster than single particle

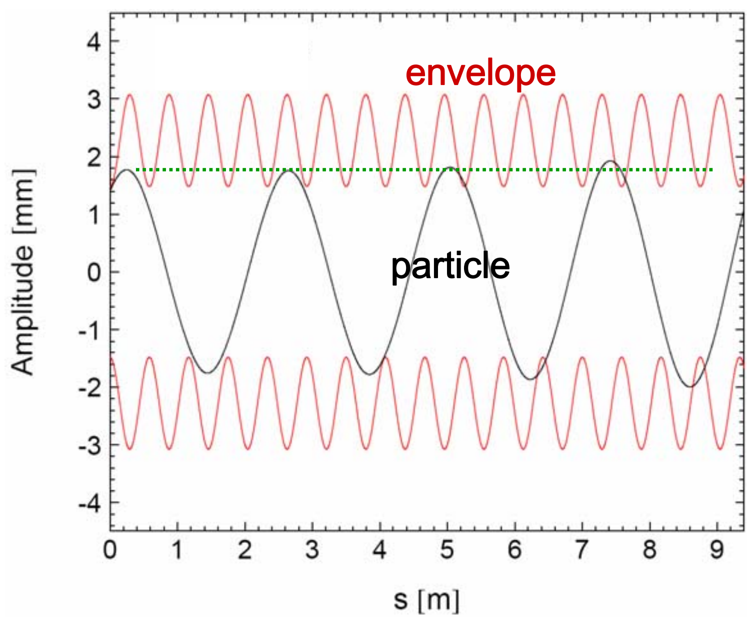
$\sigma_{env} = 360° \rightarrow \sigma = 90°$

4th order resonance occurs at $\sigma = 90°$, i.e. $\sigma_o \geq 90°$

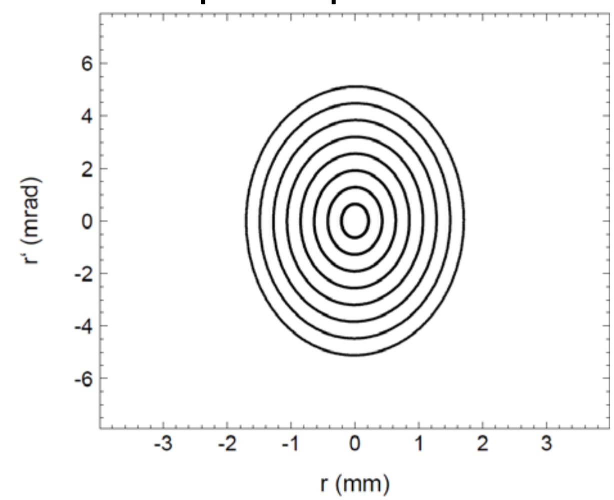
Numerical Integration of Diff. Equation

f_oscillation (envelope) = 4 * f_oscillation (particle)

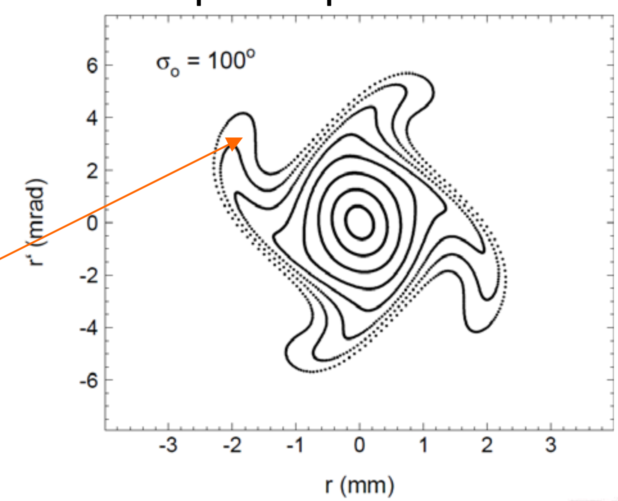
→ resonant excitation of single particles



initial phase space distribution



final phase space distribution



4 wings: characteristic feature of 4^{th} order resonance

Measuring the 4th Order Resonance

Direct measurement requires :

- measurement of the phase space distribution (no quad scan)
- 100% beam transmission (resonant "wing" particles lost first)
- matched beam envelope :
  - periodic perturbation by space charge
  - mitigate mismatch emittance growth

DTL matching with space charge is most difficult part of experiment

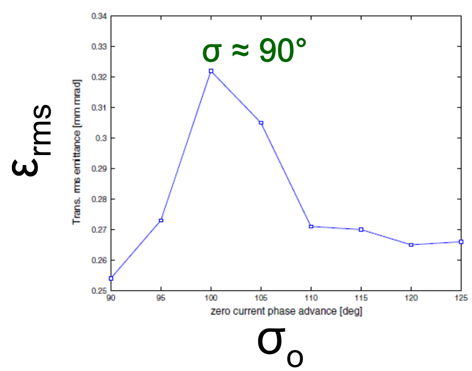
4th Order Resonance in a Linear Accelerator

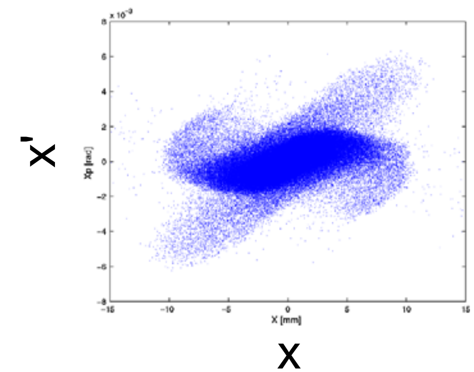
• never observed directly

• simulations by D. Jeon (SNS/ORNL) suggested measuring resonance at GSI UNILAC

• simulations predicted dominance over envelope instability

→ PRST-AB **12**, 054204 (2009)





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

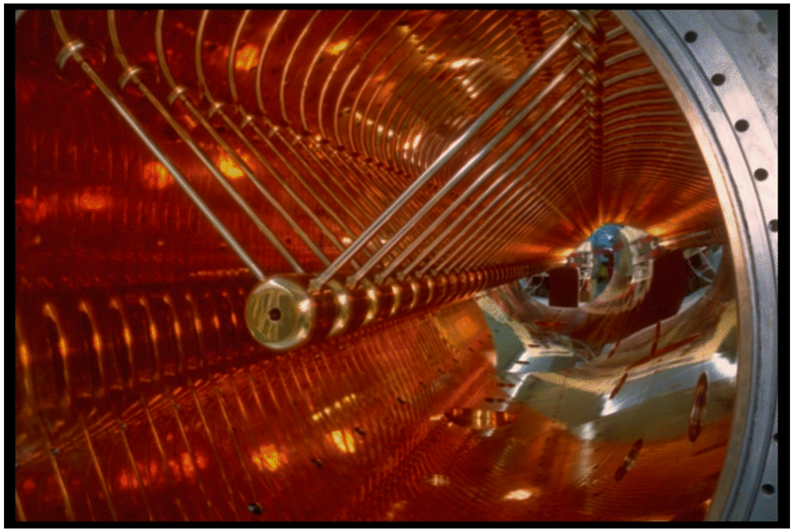
• install beam emittance measurement unit behind first DTL tank

• exploit experience from previous experiments to optimize UNILAC settings (matching !)

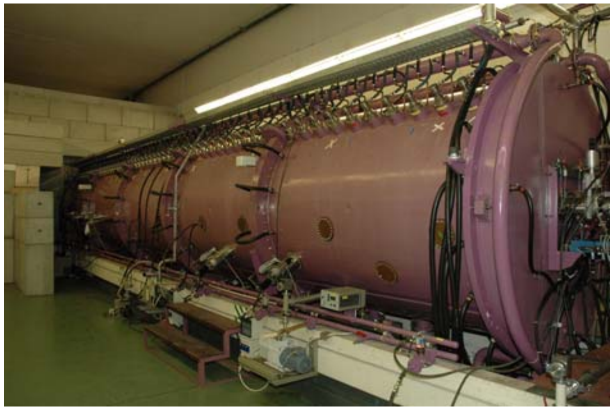
• measure phase space distributions and extract rms emittances

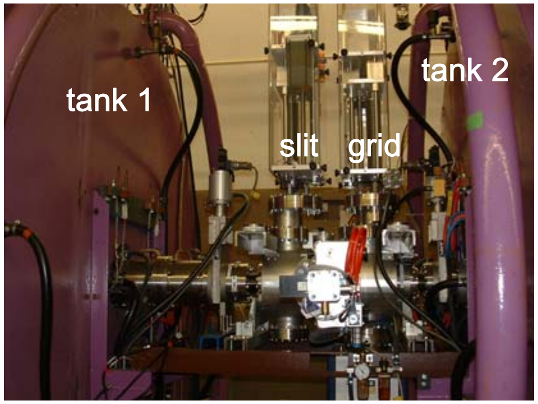
UNILAC Alvarez DTL : 1st tank

- ions: protons to uranium
- acceleration: 1.4 – 3.6 MeV/u
- 108 MHz
- synchr. rf-phase -30° → $\sigma_{l,o}$ = 43°
- F-D-D-F focusing
- 15 full lattice periods
- length ≈ 12 m
- max. transv. phase advance σ_o :
  - protons : 180°
  - $^{40}Ar^{10+}$: 180°
  - $^{238}U^{27+}$: 62°

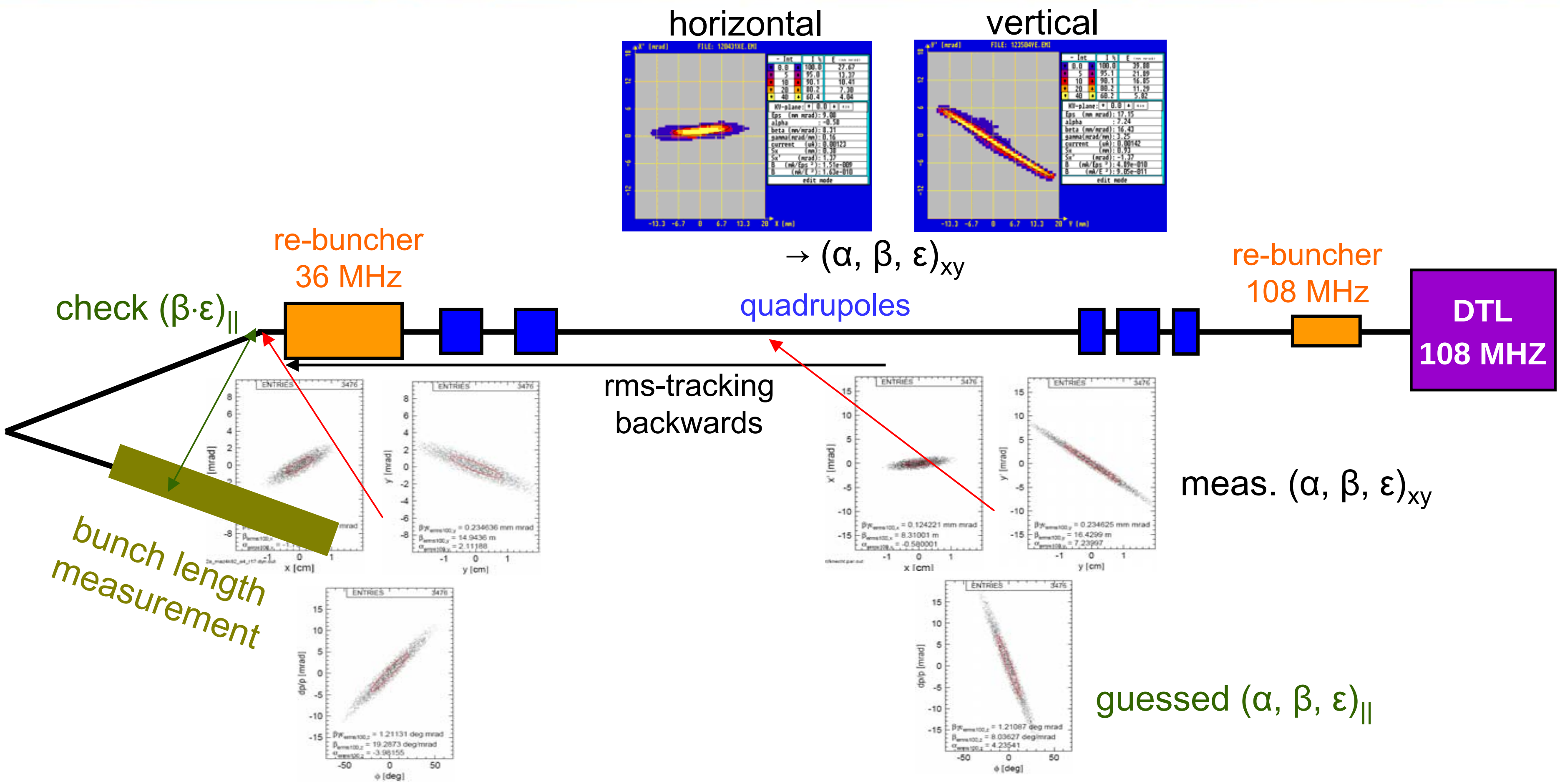


$^{40}Ar^{10+}$, 7.1 mA →





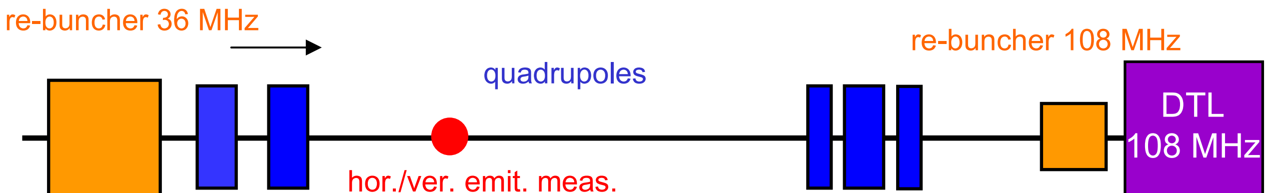
Matching: Reconstruction of Beam rms Parameters at DTL Entrance

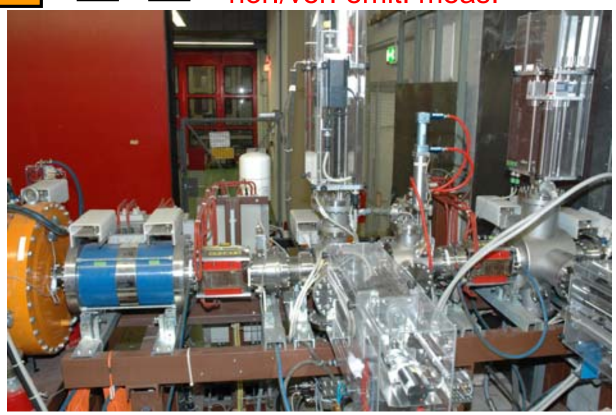


1. selfconsistent backtracking finding $(\alpha,\beta,\varepsilon)_{||}$ that fit to measured bunch length
2. verification: settings reproduce 100% transmission, no low-energy tails

Matching to Periodic Solution with Space Charge

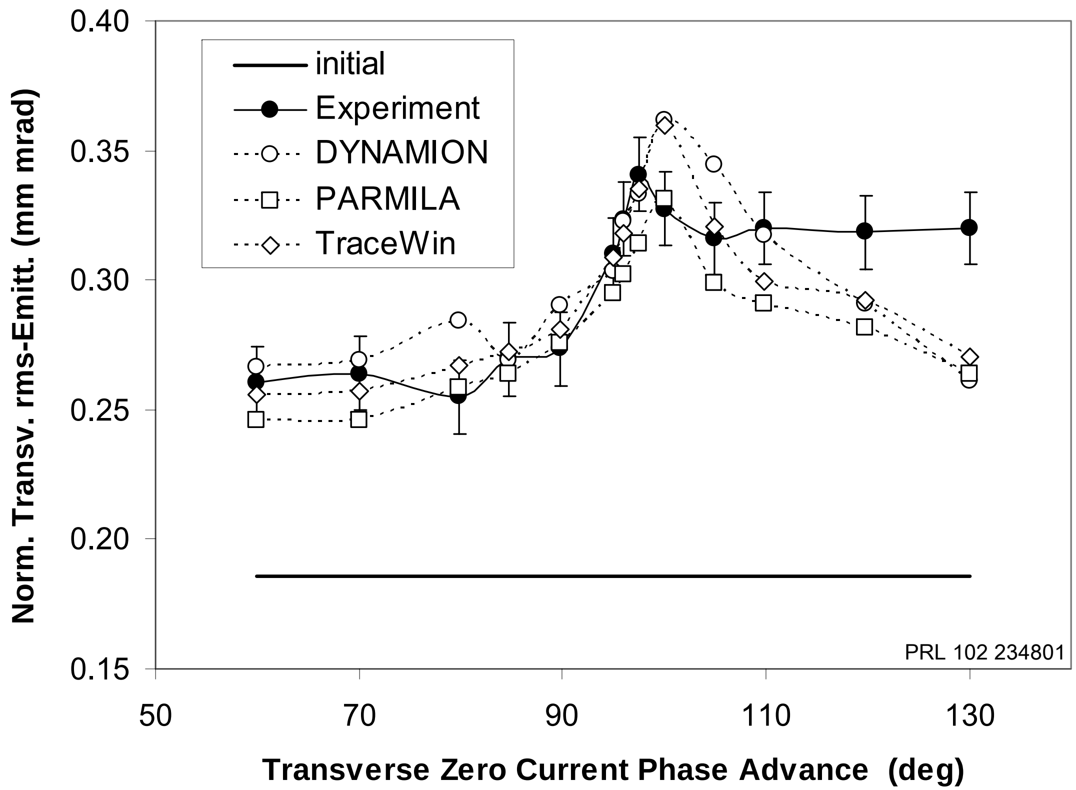
- beam parameters at beginning of matching section from emittance measurement
- periodic solution at DTL entrance calculated numerically
- section to be set to match this solution
- 7 knobs : 5 quadrupoles + 2 re-bunchers





- rms envelope equations to obtain beam Twiss params. at DTL entrance
- seven variables to minimize one value, i.e. the sum of mismatches hor., ver., and long.
- solved numerically

Measurements: DTL Exit rms Emittance vs. σ_o

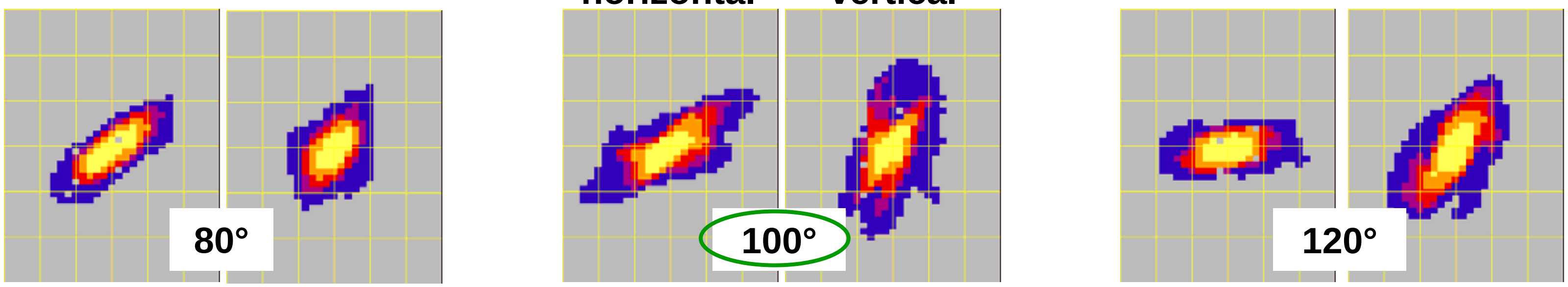


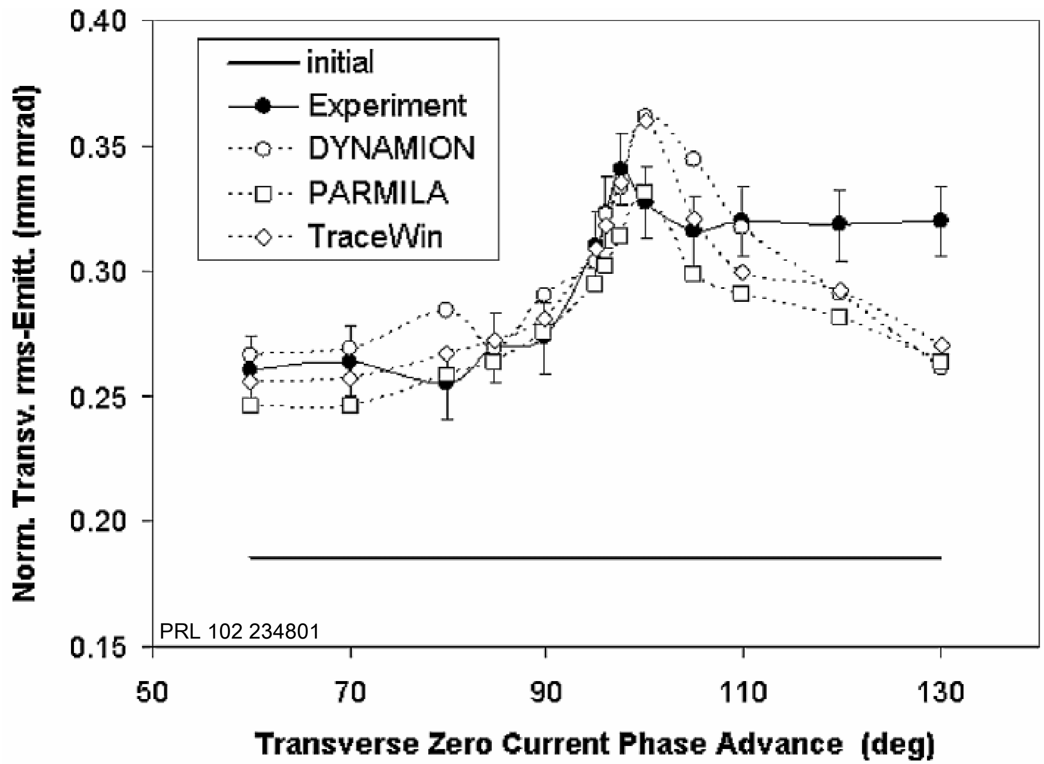
- strong growth approaching $\sigma_o \approx 100°$
- tune depression: $\sigma_o \approx 100° \rightarrow \sigma \approx 90° = 360° / 4$
- good agreement with three simulation codes
- strong hint for space charge driven 4^{th} order resonance

Proof for 4th Order Resonance in the UNILAC

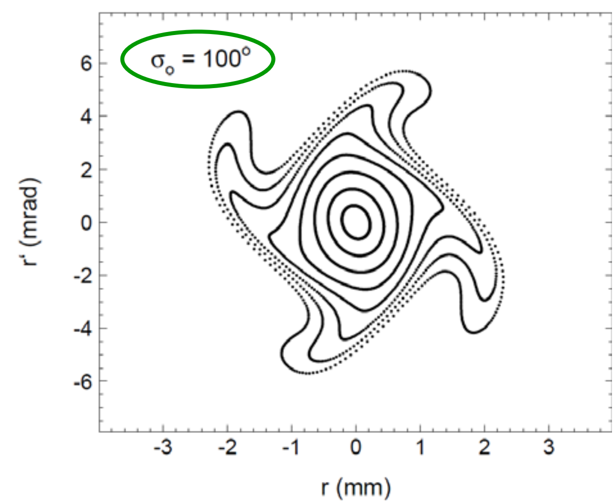
measurements

horizontal vertical



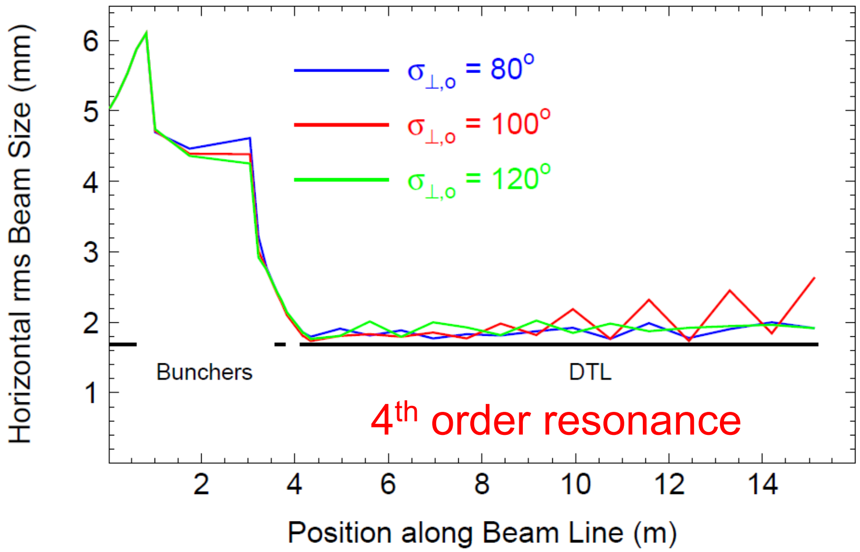


4 wings were observed

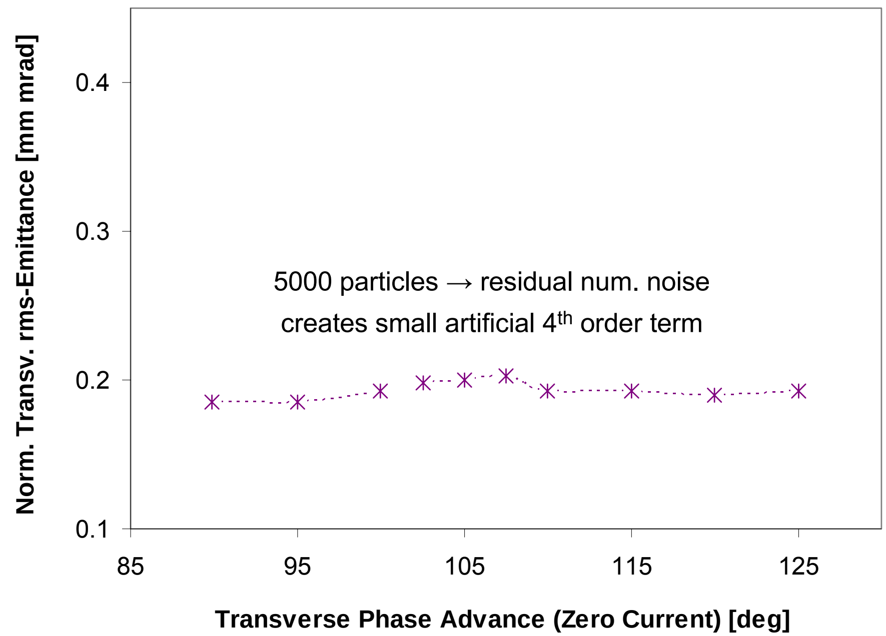


Envelope Instability ?

simulated envelopes
→ no instability at σ > 90°



simulated rms emit. growth
KV beam, no 4th order term → no growth

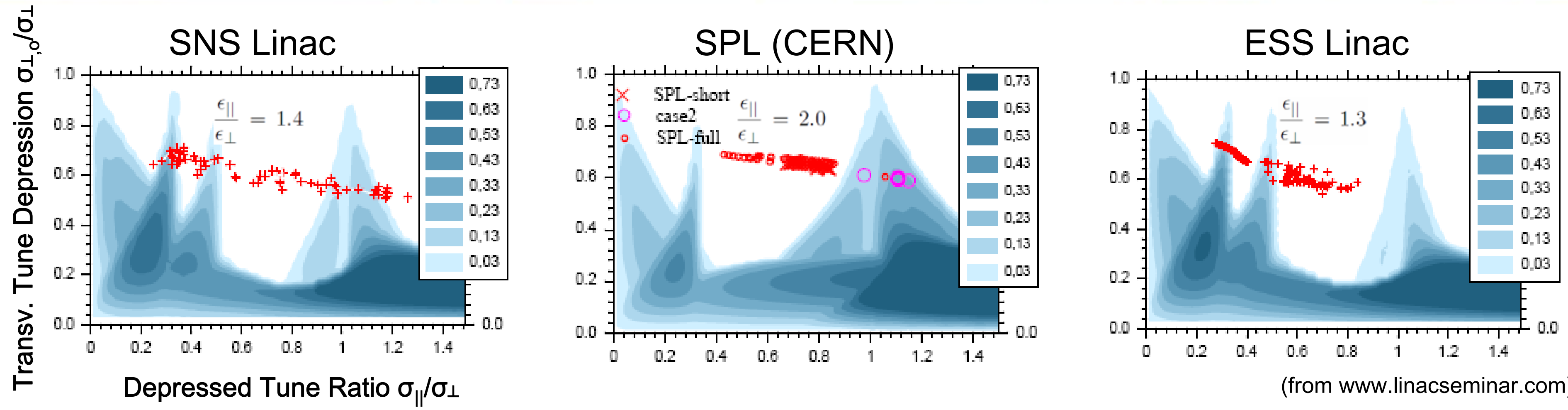


DTL too short and/or mismatch too small
for envelope instability growth

Proof for 4th Order Resonance in the UNILAC

- first direct measurement of space charge driven resonance
- resonance dominates envelope instability as predicted by D. Jeon in PRST-AB **12**, 054204 (2009)
- evidence for enveloped-matched operation of the UNILAC DTL
- details in PRL **102**, 234801 (2009)

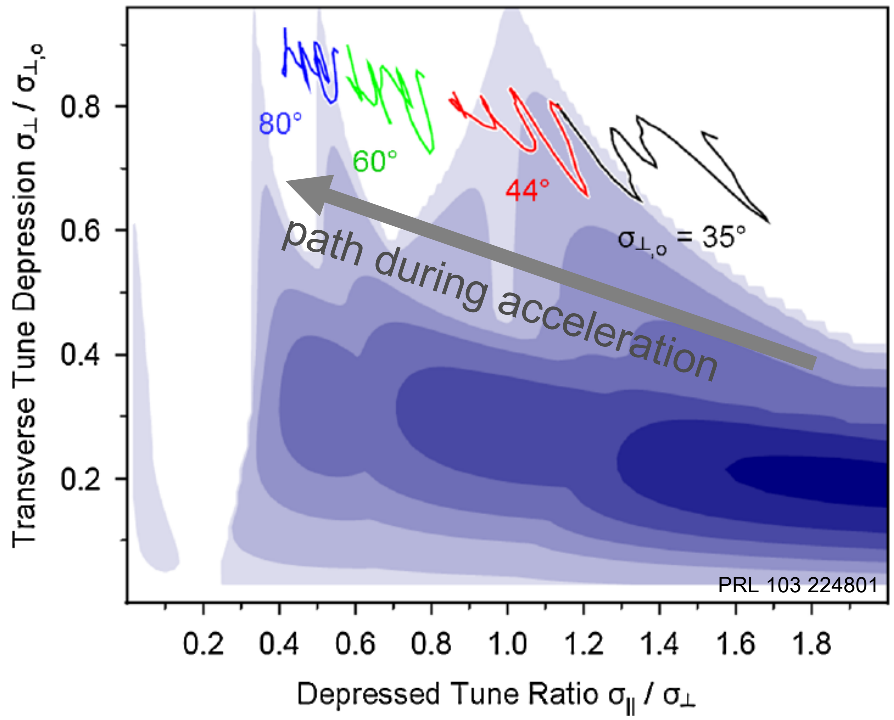
Parametric Resonances from Inter-Plane Coupling

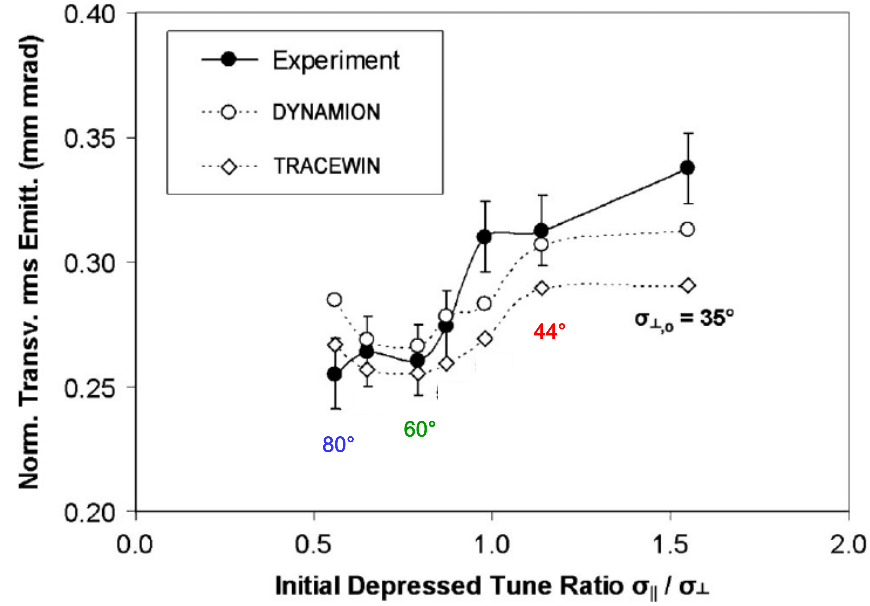


(from www.linacseminar.com)

- Hofmann charts: well excepted linac design tool
- simulations: just $\sigma_{||} \approx \sigma_{\perp}$ harmful to machine performance
- no experimental verification
- experiment done at GSI UNILAC, first DTL tank

Evidence for Parametric Resonance at the UNILAC





- tune ratio approaches 1.0 → increased transv. growth measured
- result in good agreement with simulations

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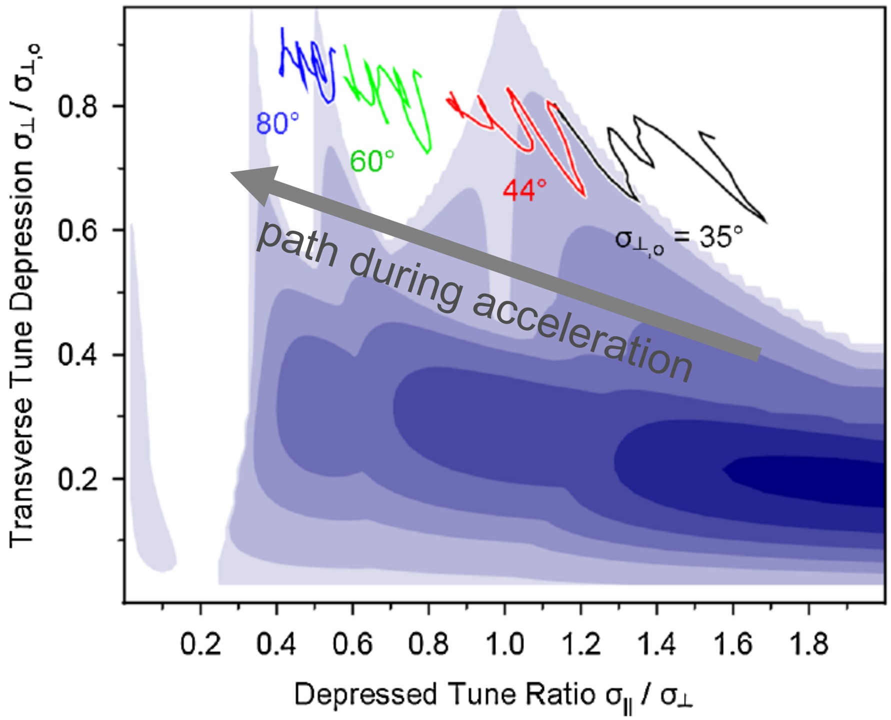
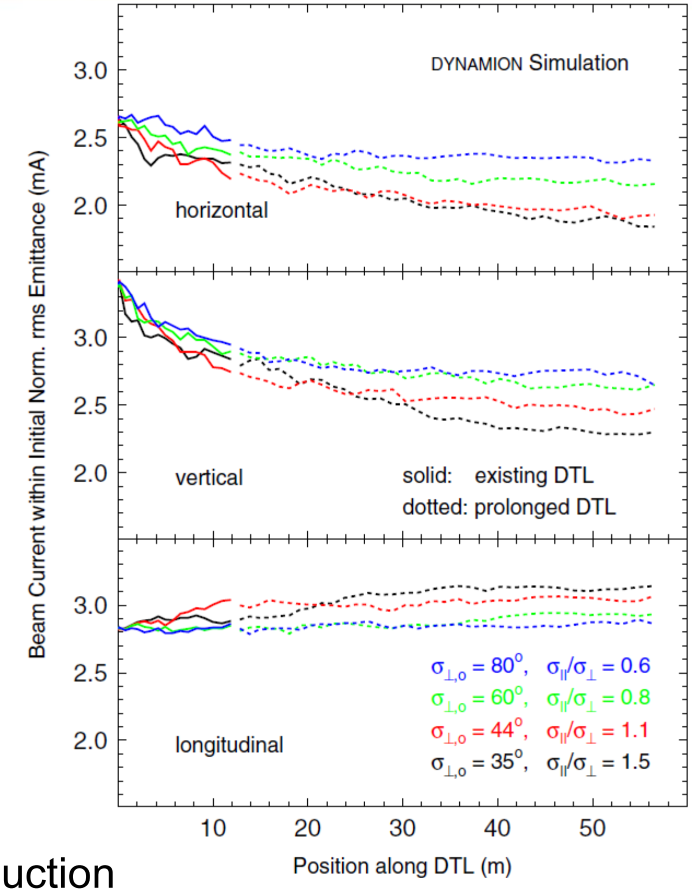
Evidence for Parametric Resonance at the UNILAC





- transv. growth comes along with longitudinal emittance reduction
- strong evidence for long.→ transv. emittance transfer

Hofmann's Charts confirmed, details in PRL **103**, 224801 (2009)

Summary

- first direct measurement of 4th order space charge driven resonance

- UNILAC DTL: 4th order resonance dominates envelope instability (exp. confirmation)

- first experimental confirmation of Parametric Resonance (Hofmann Charts)