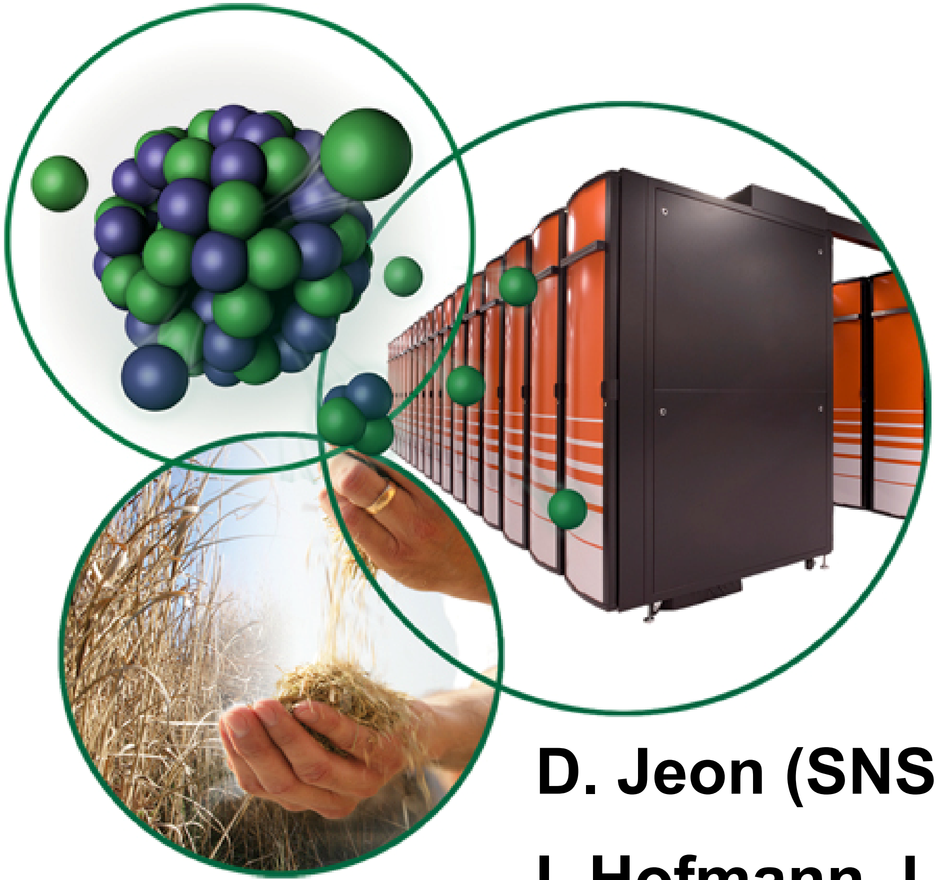
The 4ν=1 resonance of a high intensity linac



D. Jeon (SNS)

I. Hofmann, L. Groening, G. Franchetti (GSI)

HB 2008 August 25-29, 2008

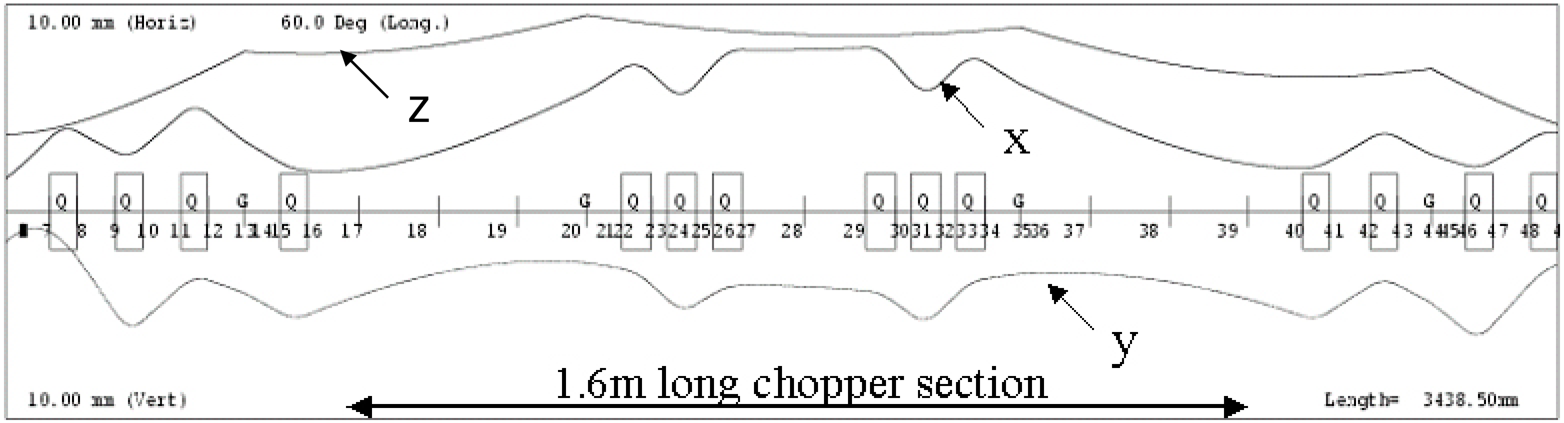
OAK RIDGE National Laboratory

- **This work is the result of the collaboration between GSI and SNS.**
- **Thanks to J. Galambos, S. Henderson for the support.**

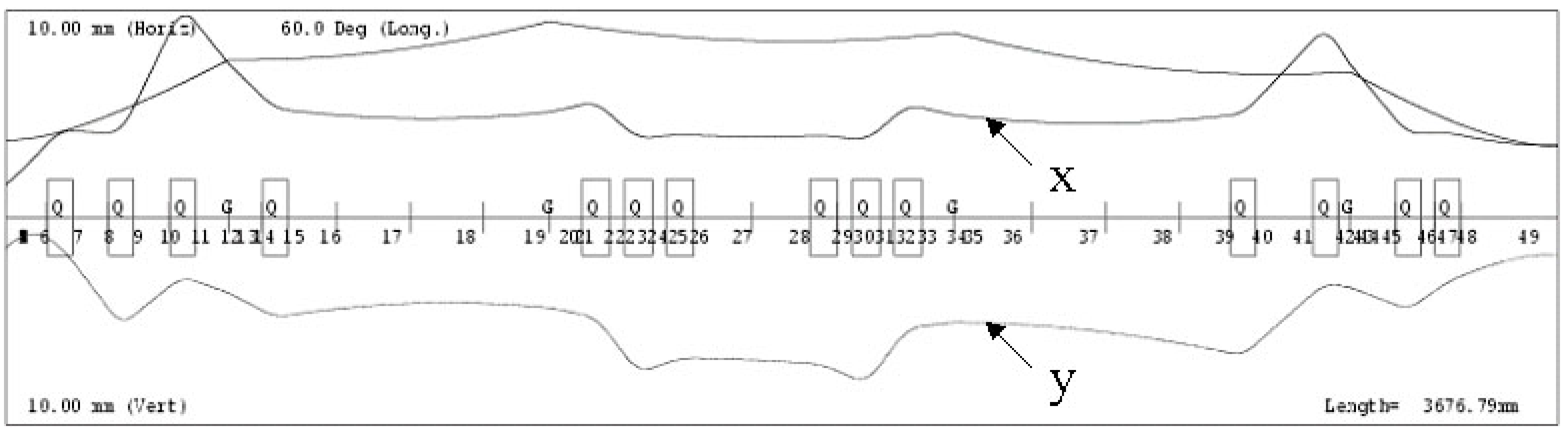
History of halo formation mechanisms

- **Until 1998, mismatch was the only known mechanism of halo formation.**
- **Late 1998, halo formation by the $2\nu_x - 2\nu_y = 0$ resonance in the ring was discovered by D. Jeon (presented by J. Holmes at PAC99) → leading to other resonance induced halo studies in the ring.**
- **Since then coupling resonance in the linac has been studied extensively by many.**
- **Other halo formation mechanisms have been discovered such as non-round beam (D. Jeon, APAC07), rf cavity (M. Eshraqi) etc.**
- **Widely believed that there is no other resonance in the linac…**

Review
Non-Round Beam induced Halo Formation
Optics modification improves beam quality

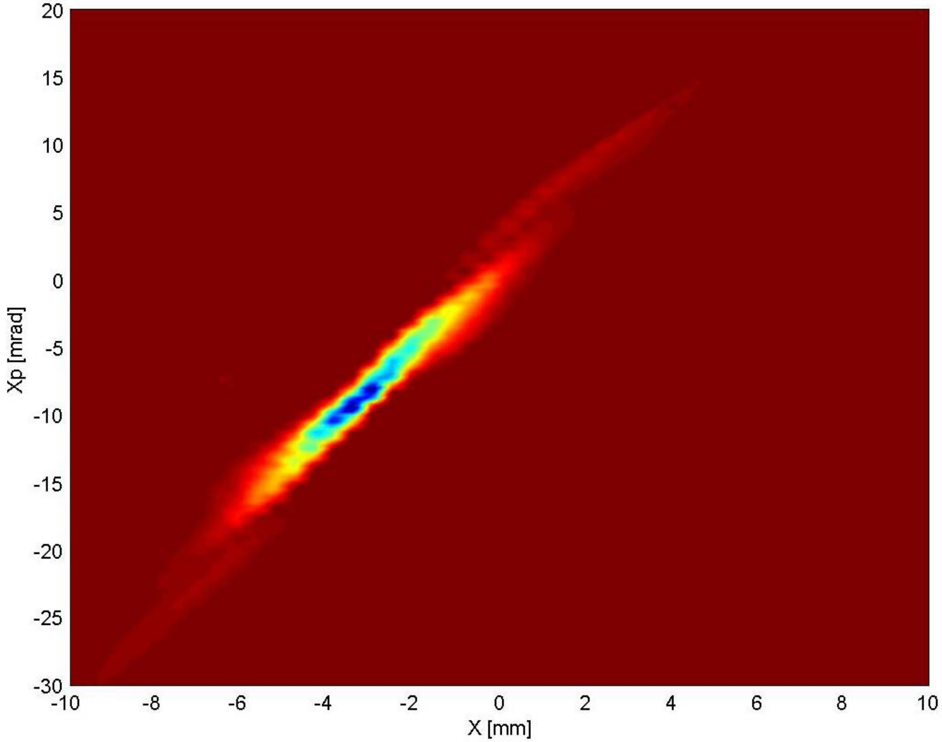


Nominal SNS MEBT Optics



Round Beam MEBT Optics

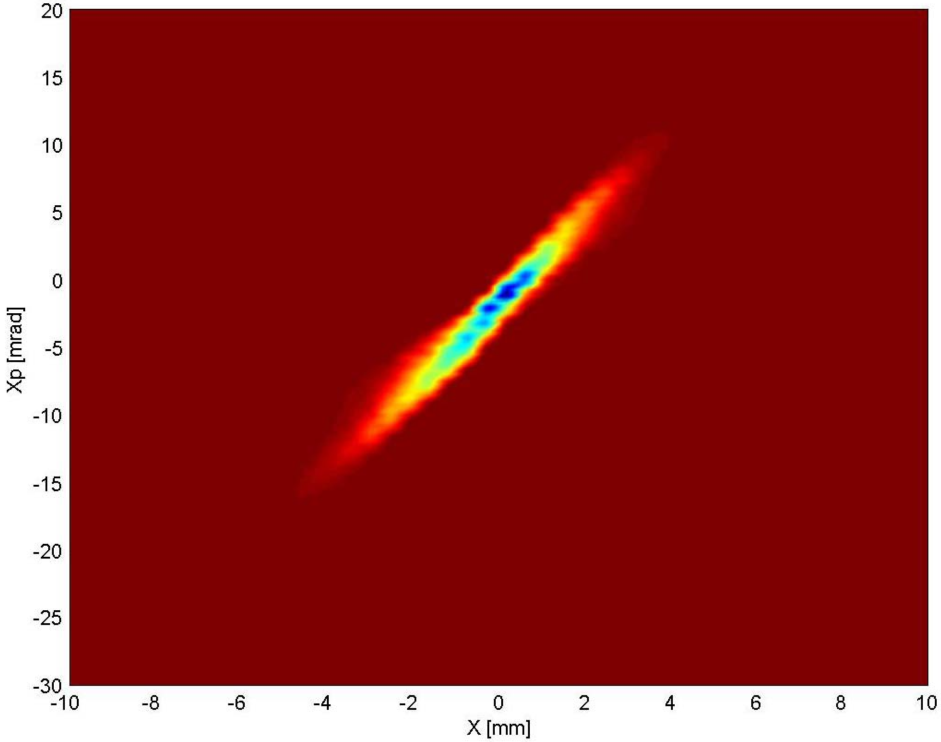
Round Beam Optics improves X beam quality (Emittance Measurement)



Nominal Optics

ε_X= 0.349 mm-mrad (1% threshold)

0.454 mm-mrad (0% threshold)



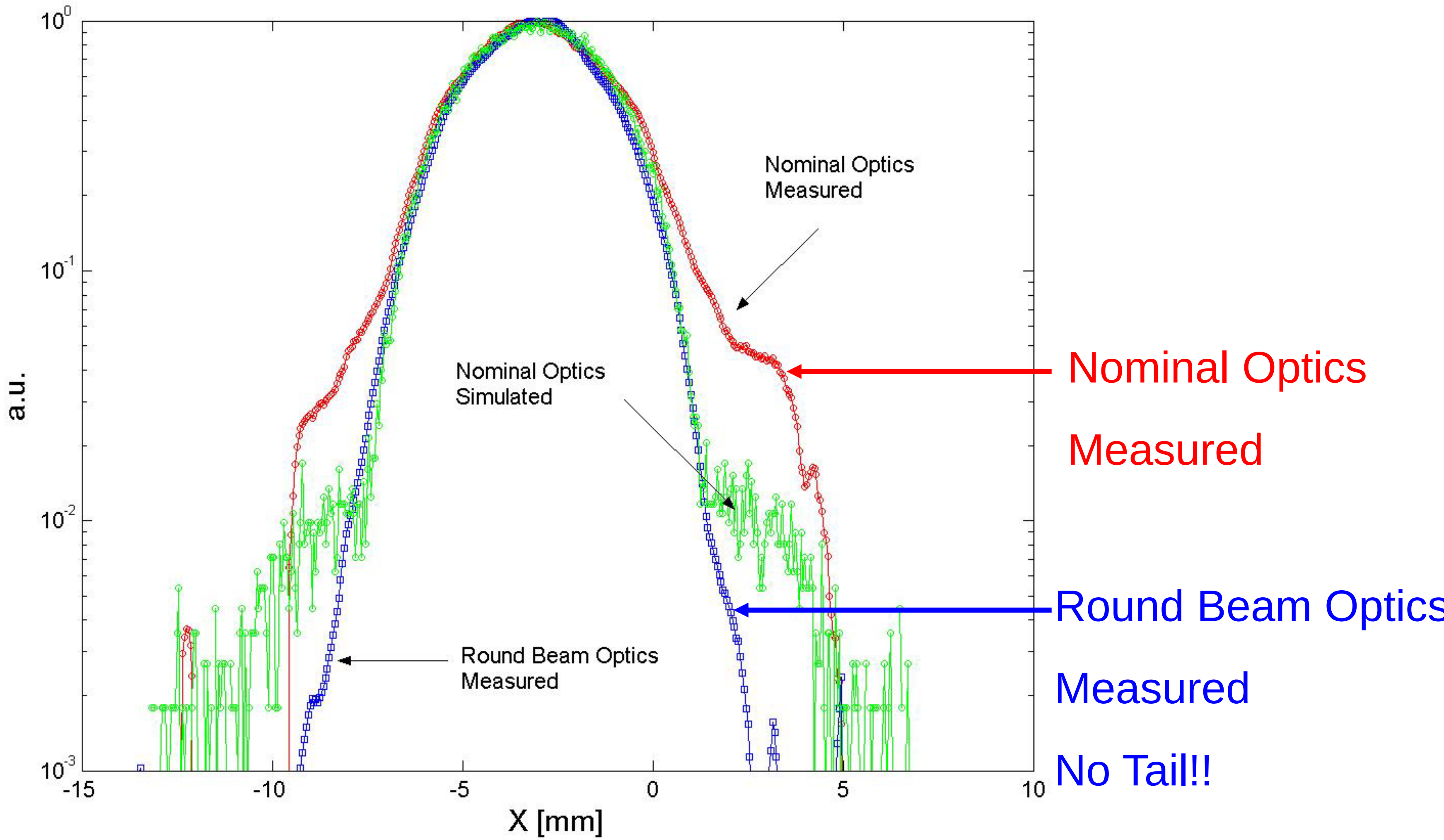
Round Beam Optics

ε_X= 0.231 mm-mrad (1% threshold)

0.289 mm-mrad (0% threshold)

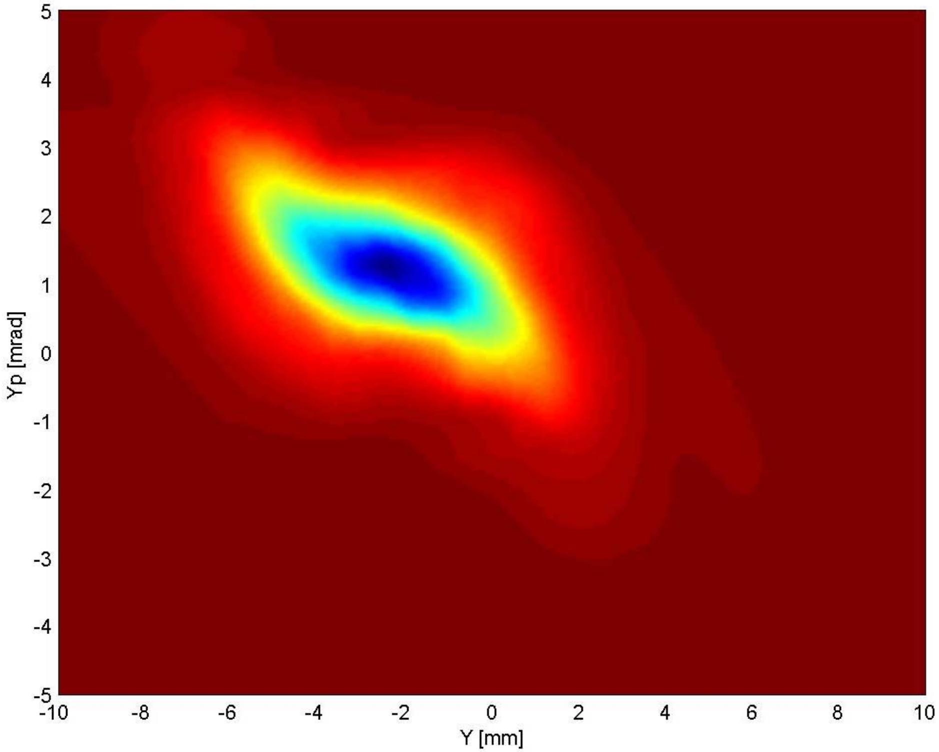
- **Round Beam Optics reduces halo and rms emittance in X significantly**

Tail is significantly reduced for Round Beam Optics



- **Round Beam Optics reduces beam tail visibly**
- **This tail is the source of beam loss in downstream linac**

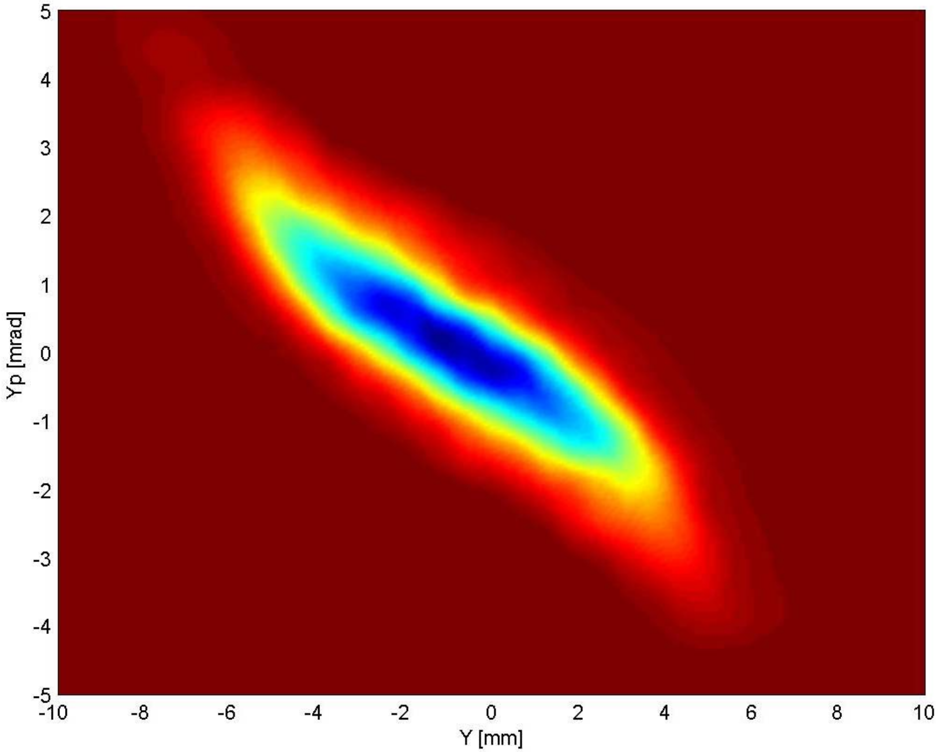
Round Beam Optics improves Y beam quality (Emittance Measurement)



Nominal Optics

ε_Y= 0.353 mm-mrad (1% threshold)

0.472 mm-mrad (0% threshold)



Round Beam Optics

ε_Y= 0.264 mm-mrad (1% threshold)

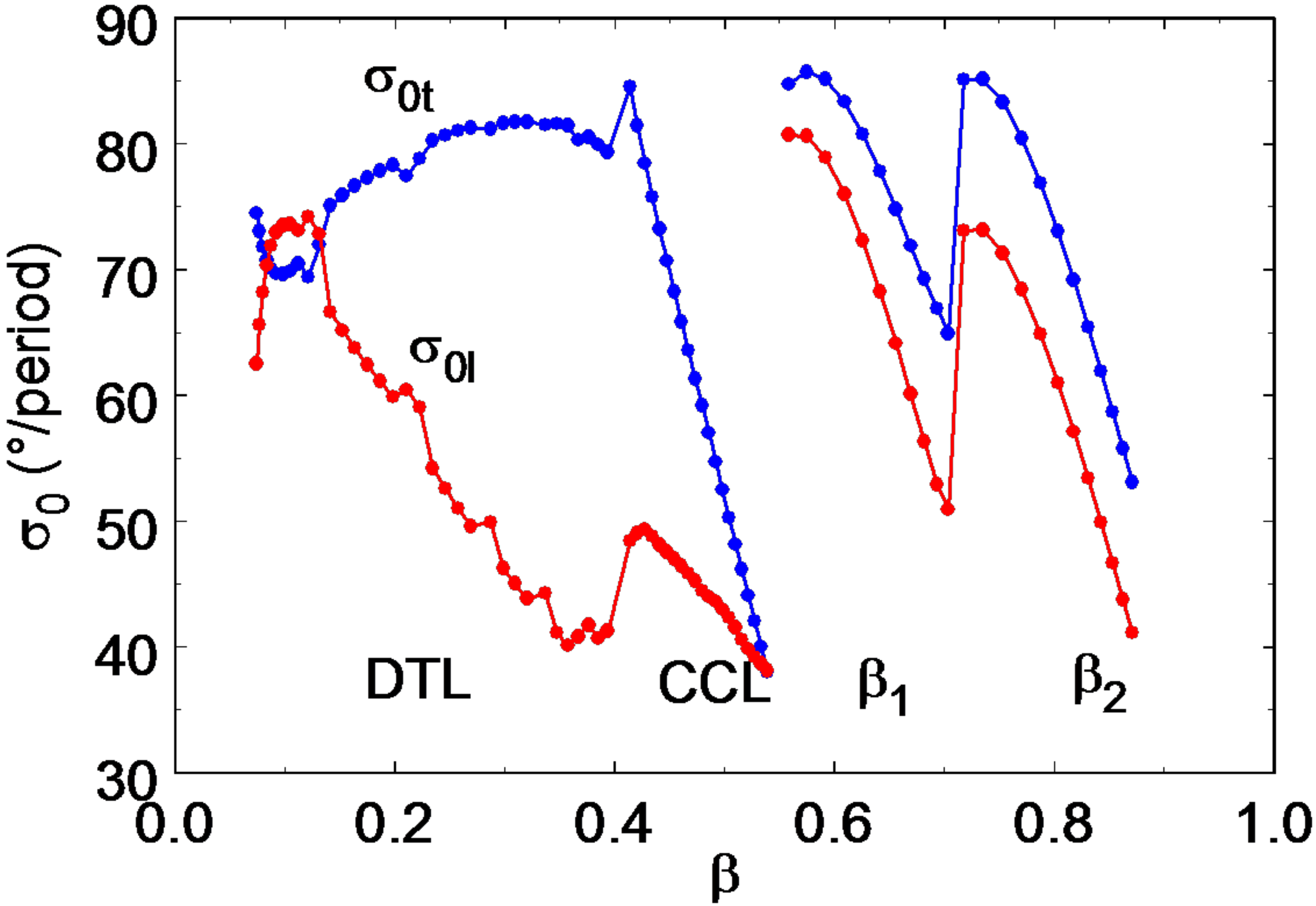
0.306 mm-mrad (0% threshold)

- **Round Beam Optics reduces halo and rms emittance in Y significantly**

Envelope instability

- **Envelope equation predicts envelope instability at 90° phase advance.**
- **Linac design including the SNS linac has avoided the 90° phase advance because of the envelope instability!**
- **GSI UNILAC has the capability to scan well beyond 90° phase advance + emittance scanner.**
- **D. Jeon made a proposal to GSI to do an experiment to measure the stop-band of the envelope instability.**

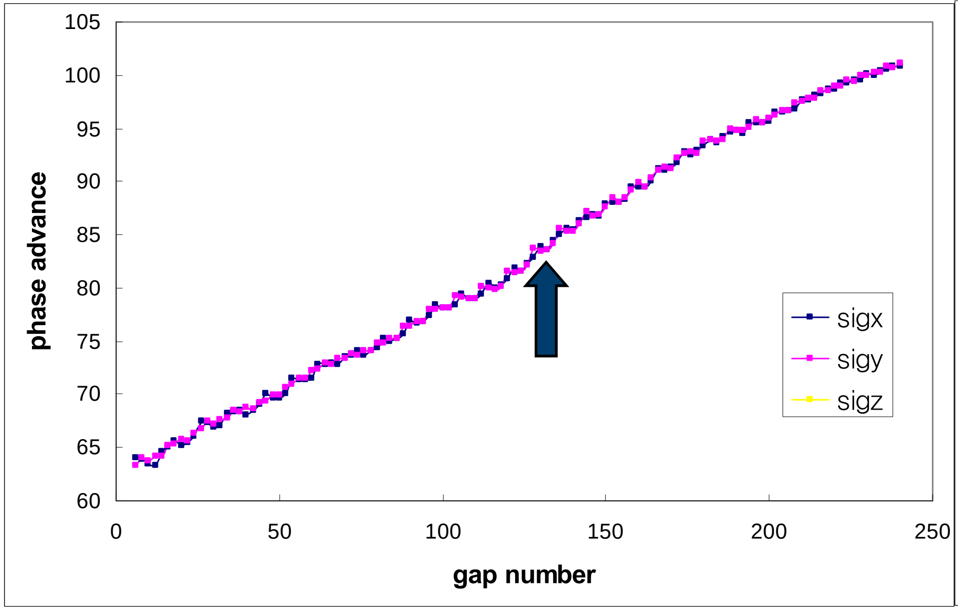
SNS Linac design
Phase & Quad Laws Avoid the Envelope Instability and the Coupling Resonance

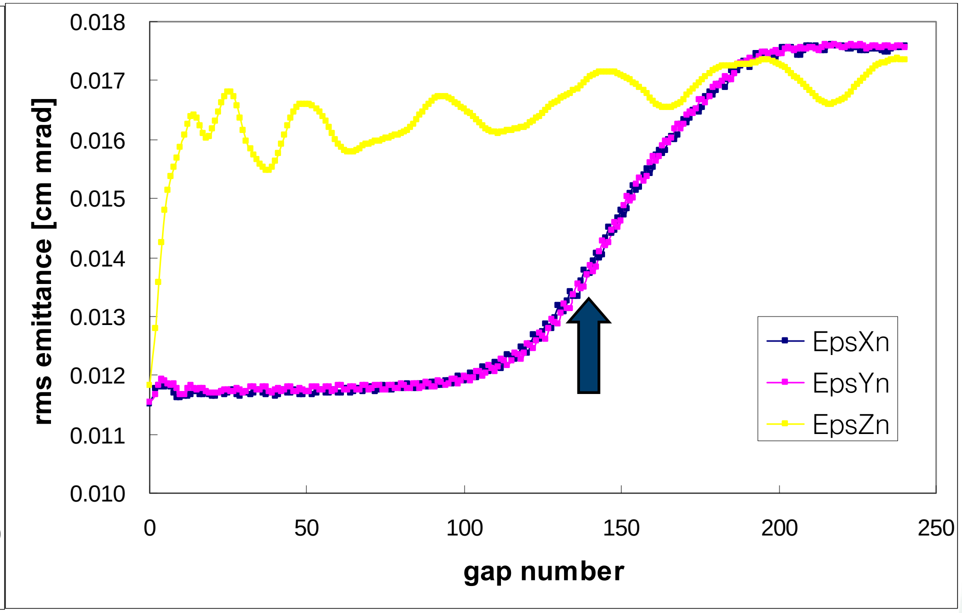


Discovery of the $4\nu=1$ resonance of a linac driven by space charge

- **Linac simulation study finds the $4\nu=1$ resonance when the depressed phase advance is about 90°, rather than the envelope instability.**
- **This $4\nu=1$ resonance is dominating over the better known envelope instability and practically replacing it.**
- **It should be stated that linac design should avoid 90° phase advance because of the $4\nu=1$ resonance rather than the envelope instability!!**

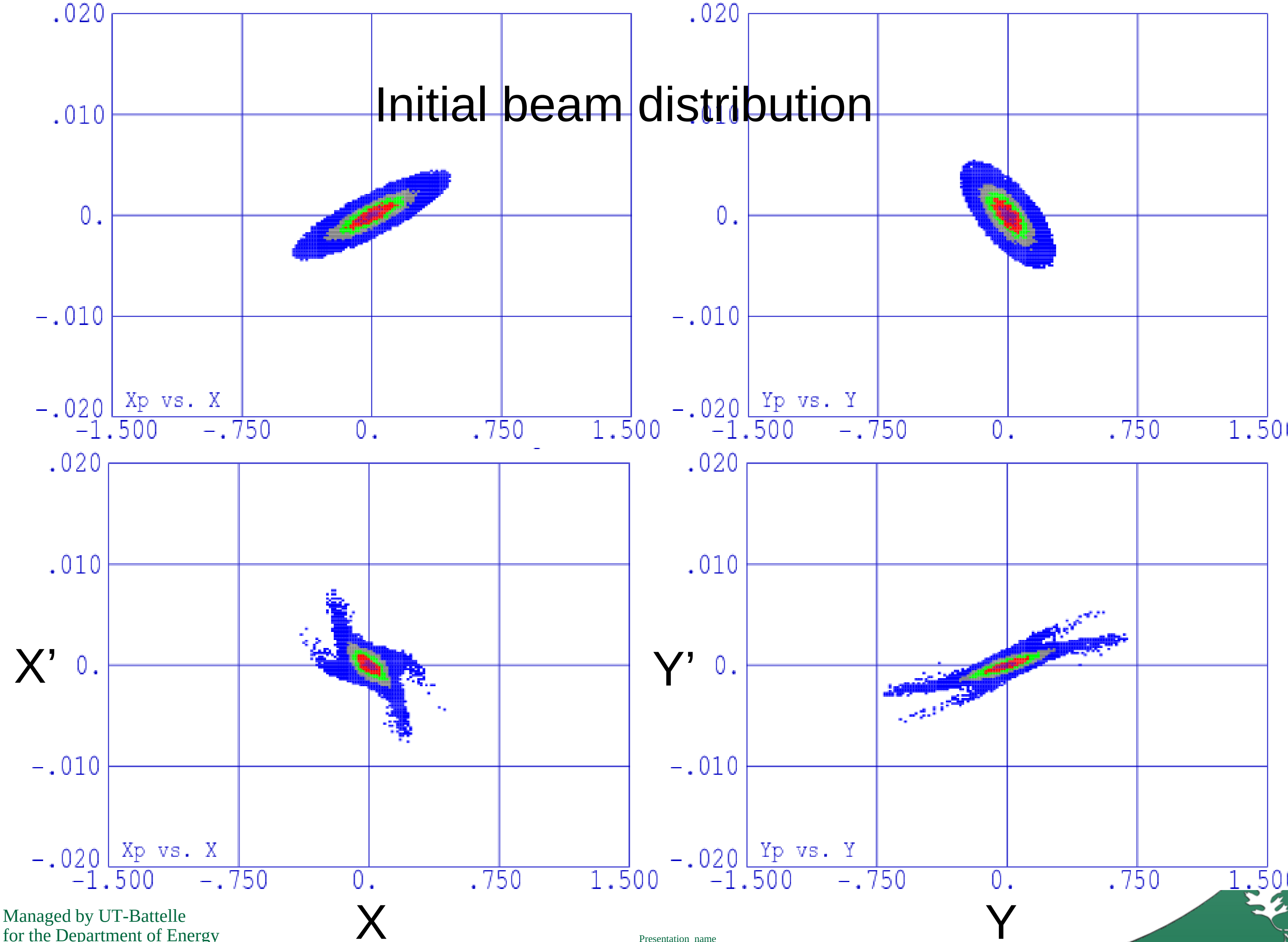
4ν=1 resonance crossing from below



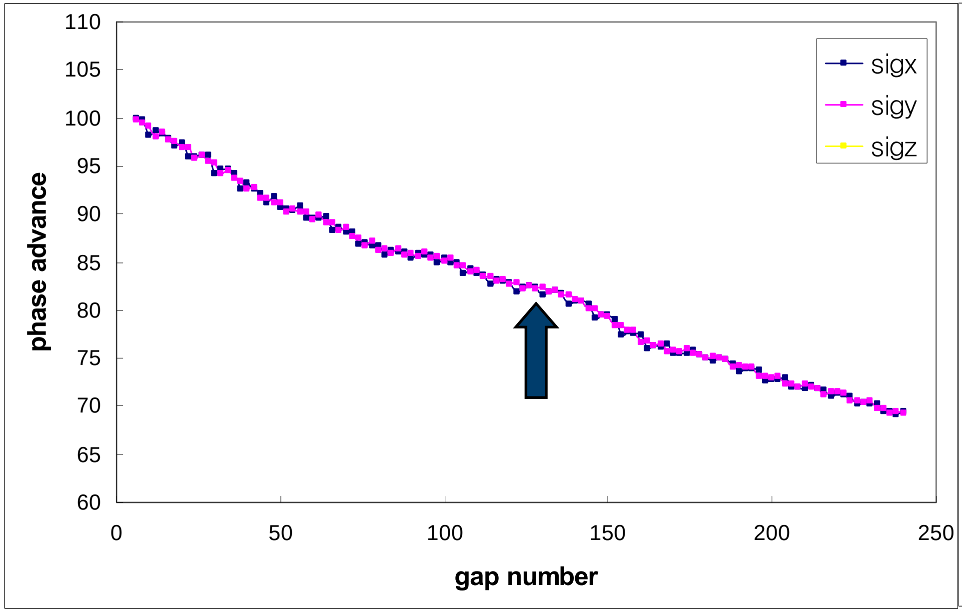


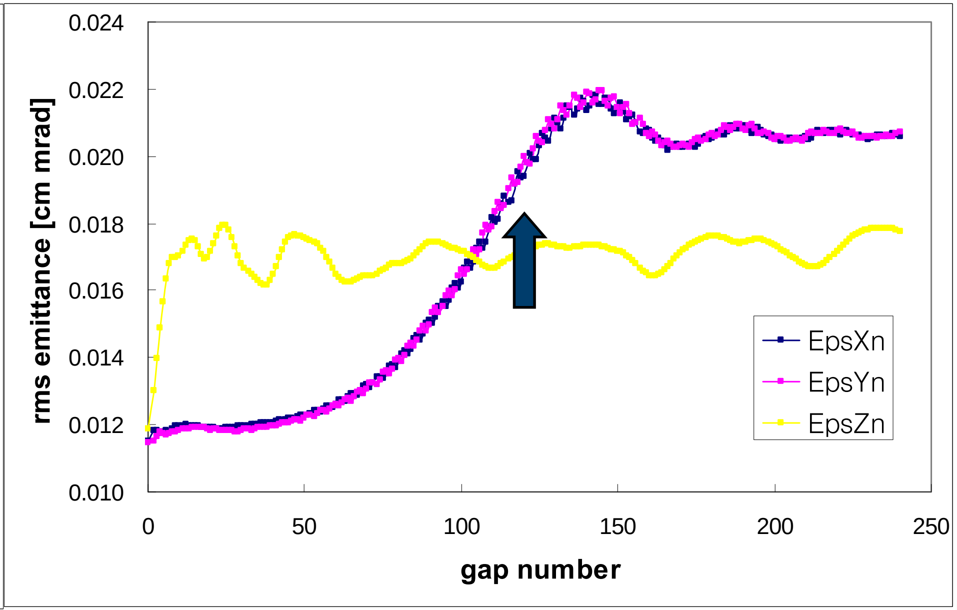
- **phase advance**
- **rms emittance**

Beam distribution when crossing the 4ν=1 resonance from below



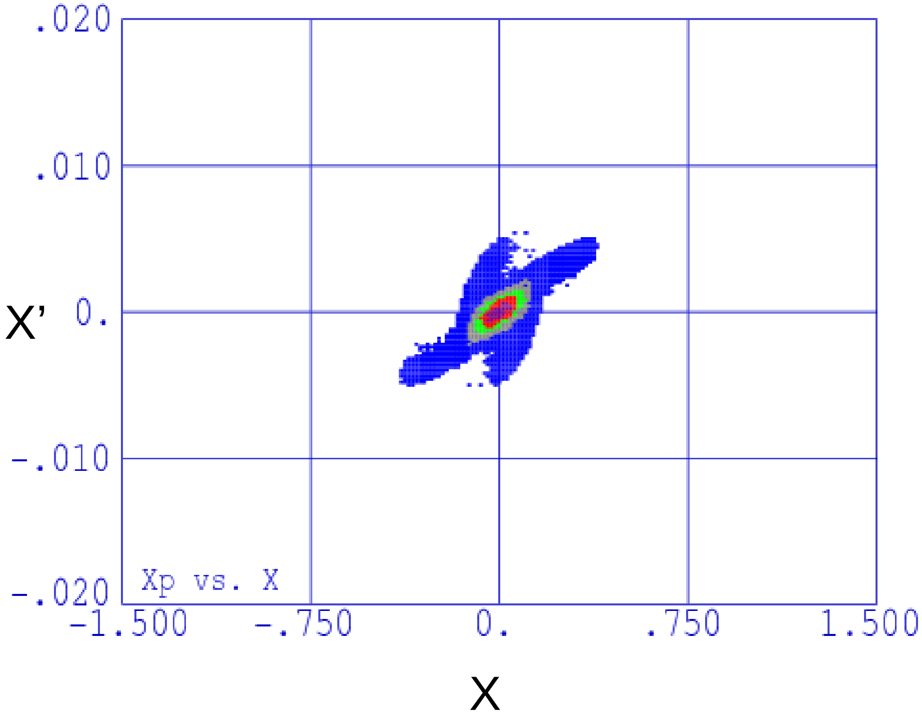
4ν=1 resonance crossing from above

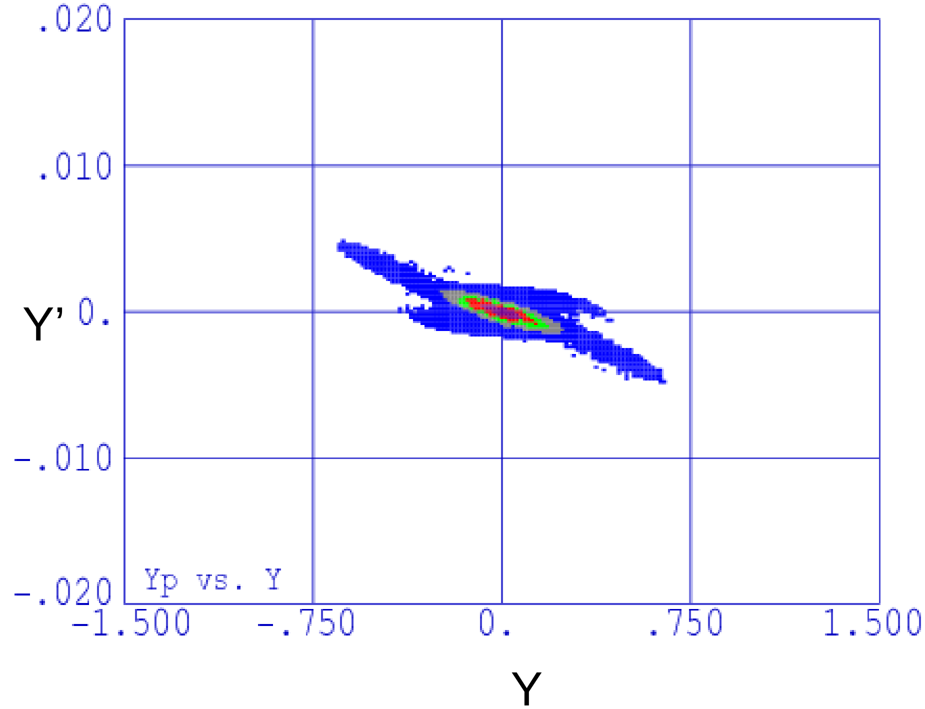




- **phase advance**
- **rms emittance**

Beam distribution when crossing the $4\nu=1$ resonance from above

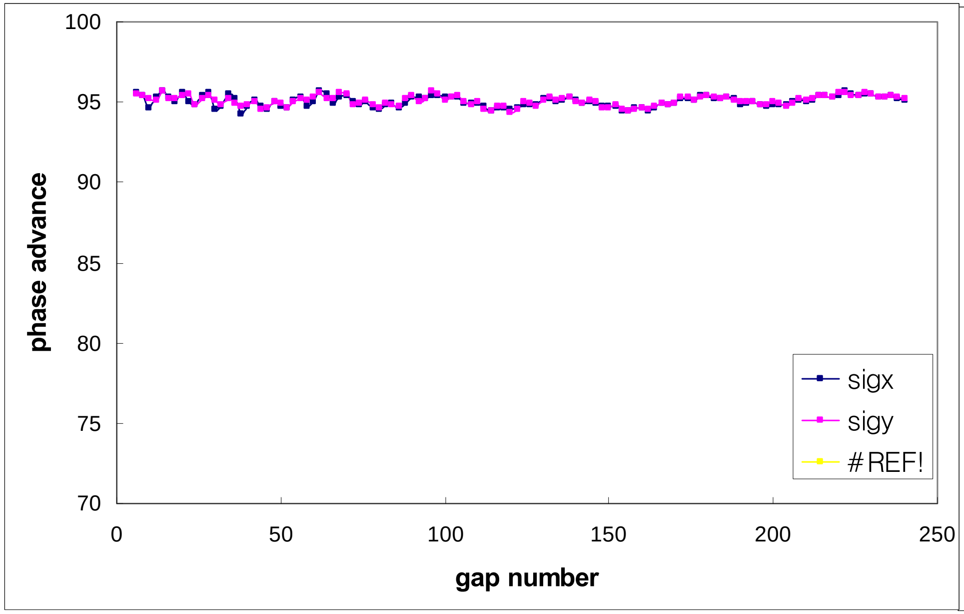


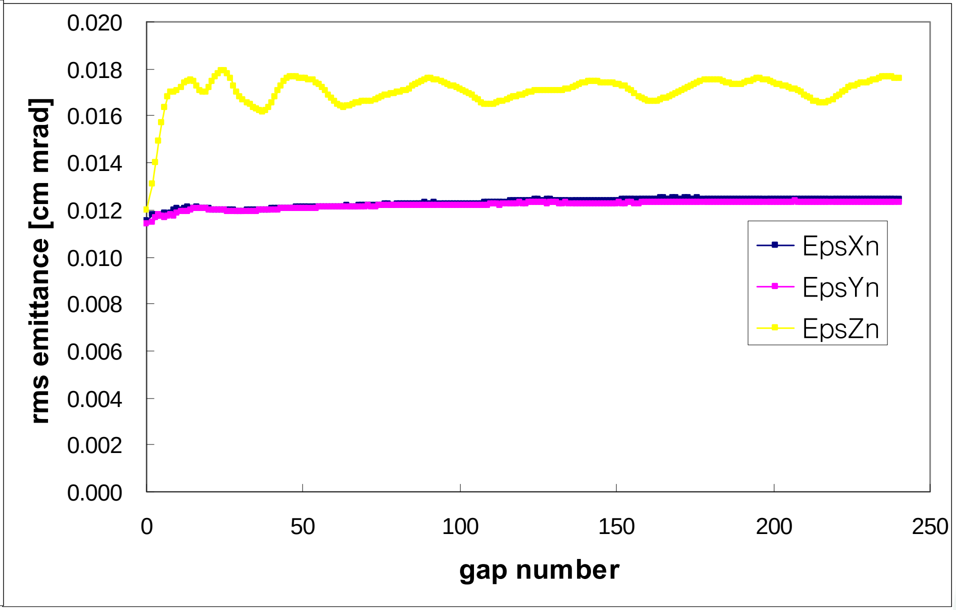


- **Stable fixed points move from the origin afar.**
- **This traps beam particles.**

No resonance effect $\sigma > 90°$

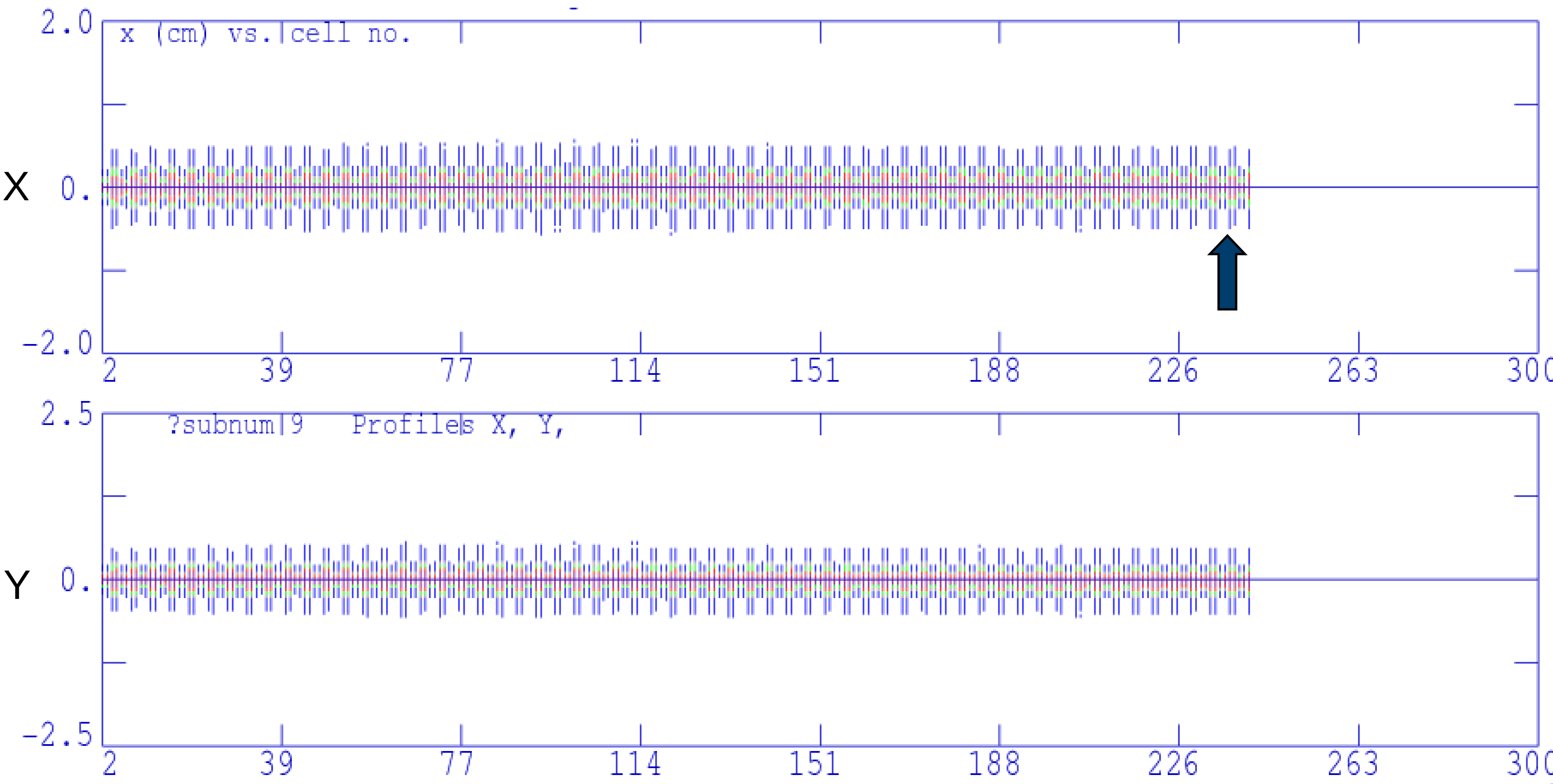
When $\sigma \sim 95°$



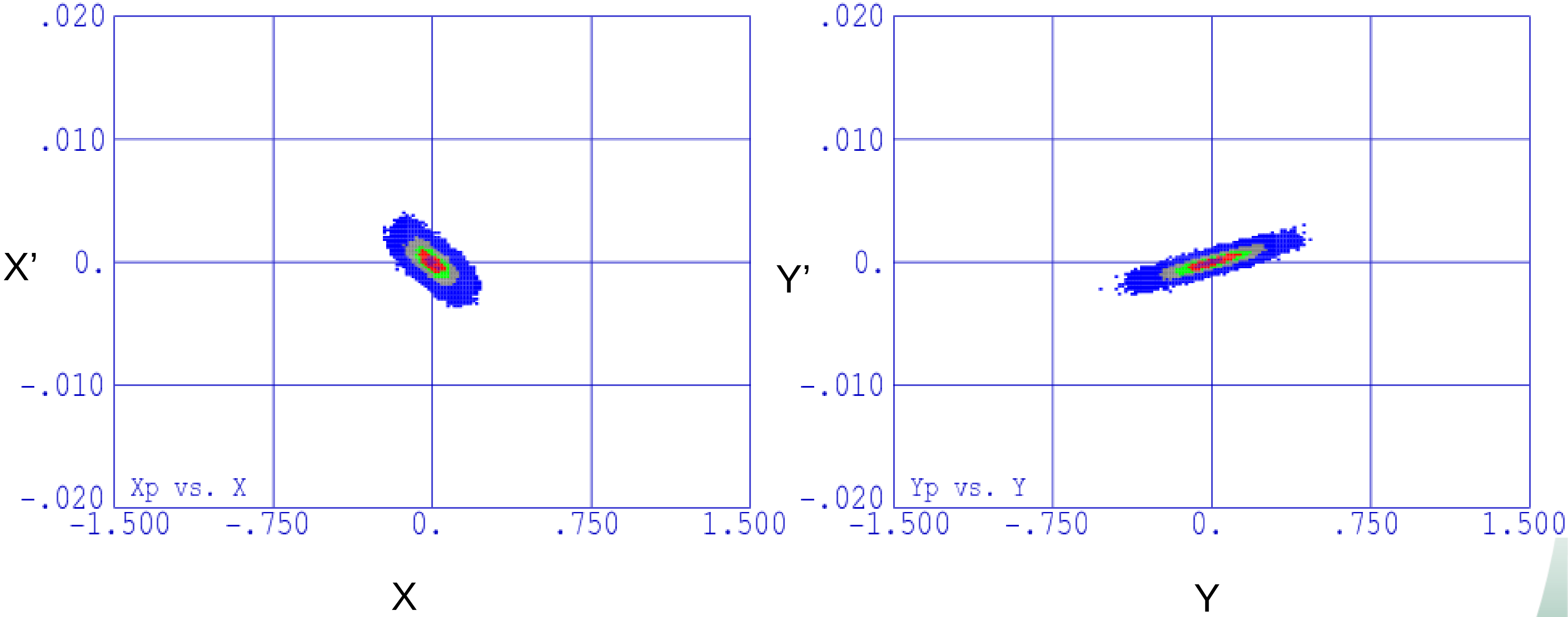


- **phase advance**
- **rms emittance**

It seems that no resonance effect σ > 90º When σ ~ 95°



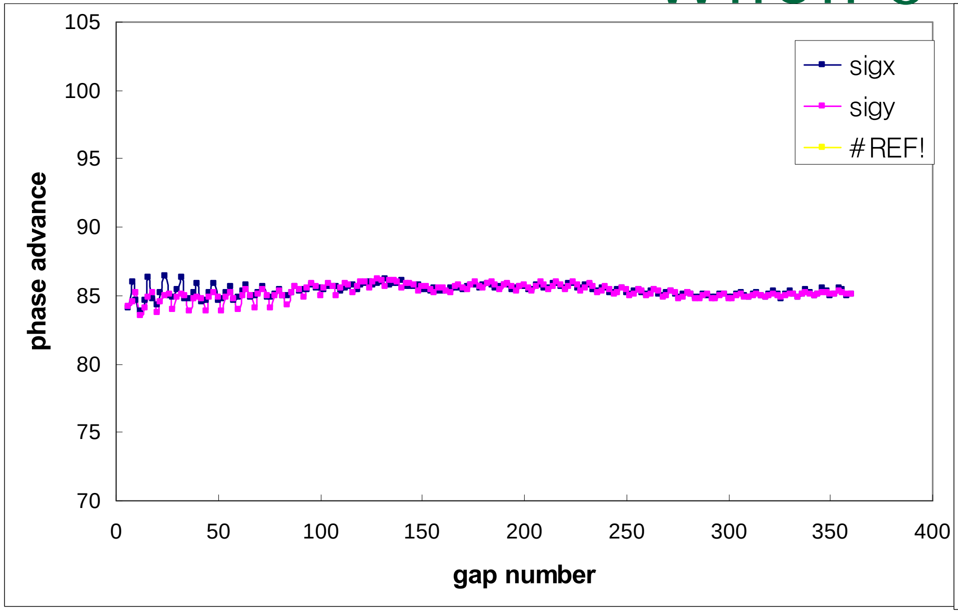
It seems that no resonance effect $\sigma > 90^{o}$
When $\sigma \sim 95^{\circ}$

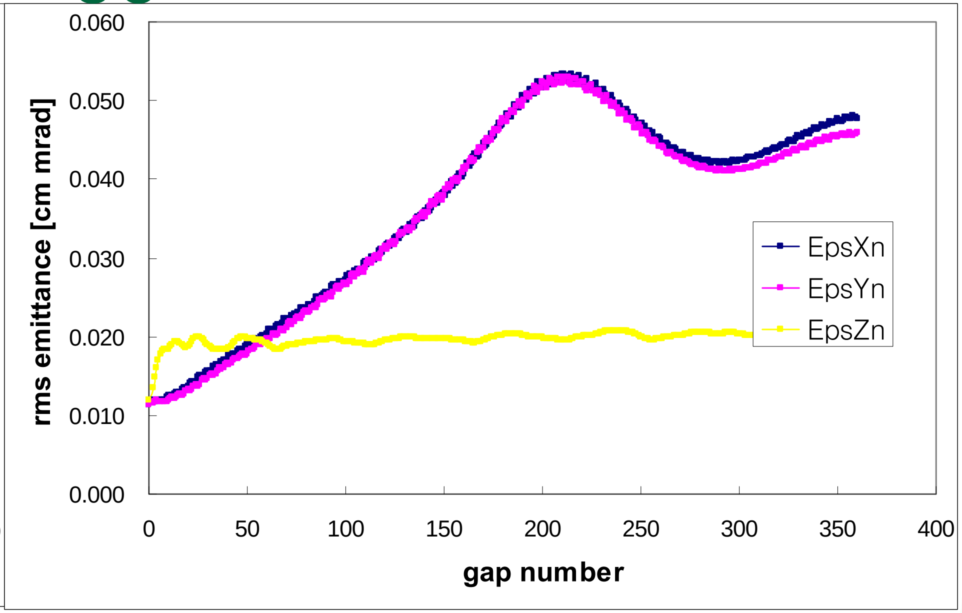


There is no sign of resonance effect on the beam distribution

Resonance takes effect for σ <= 90º

When σ ~ 85°

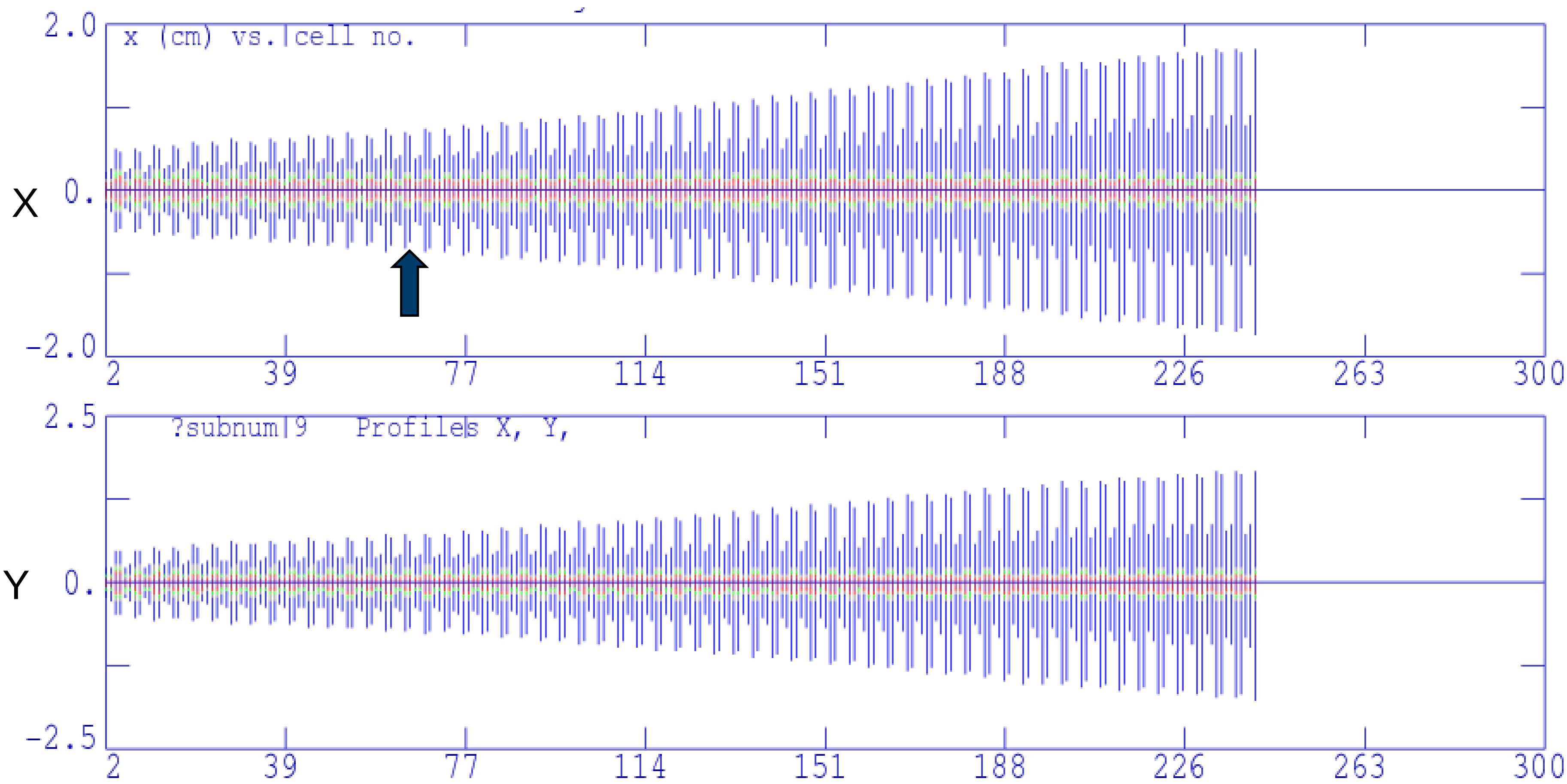




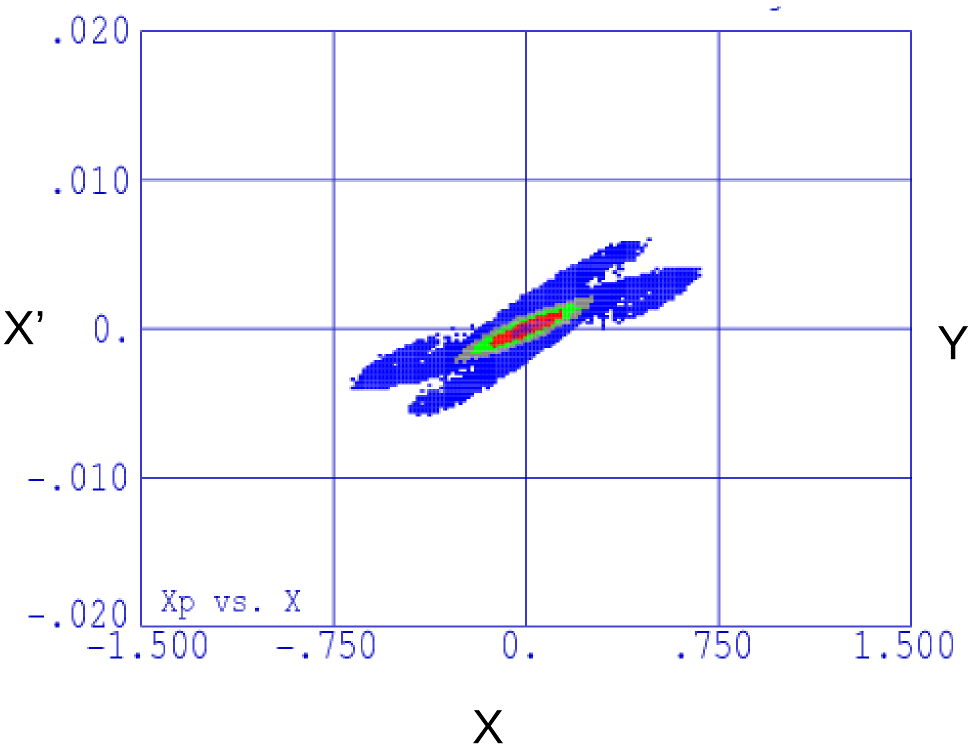
- **phase advance**
- **rms emittance**

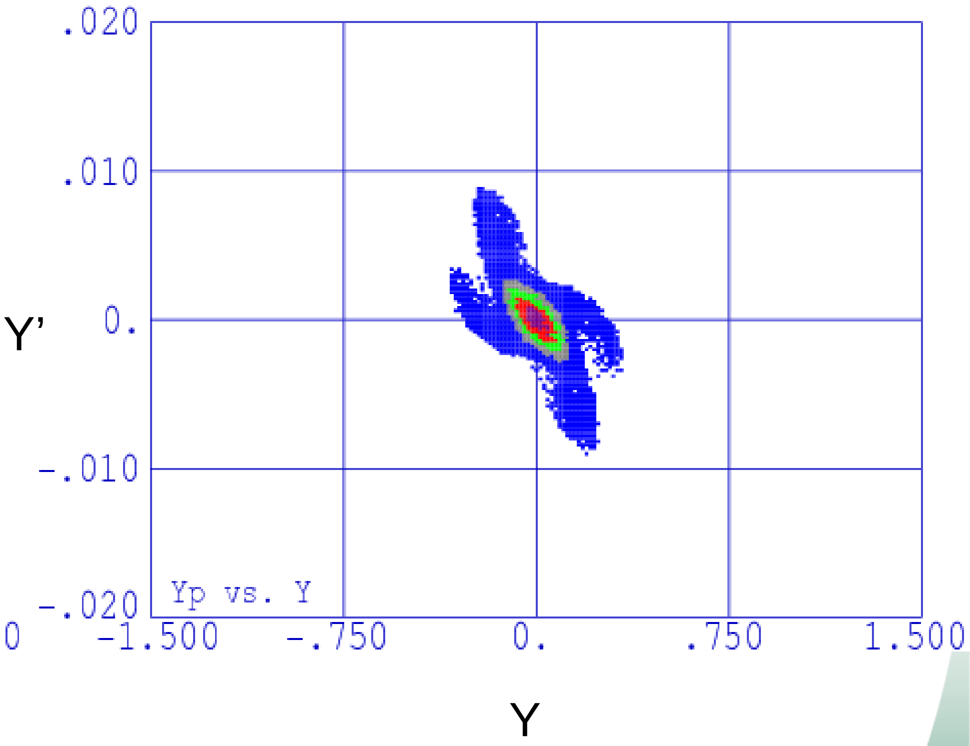
- **Emittance growth when σ <= 90°**

resonance effect σ <= 90º
When σ ~ 85°

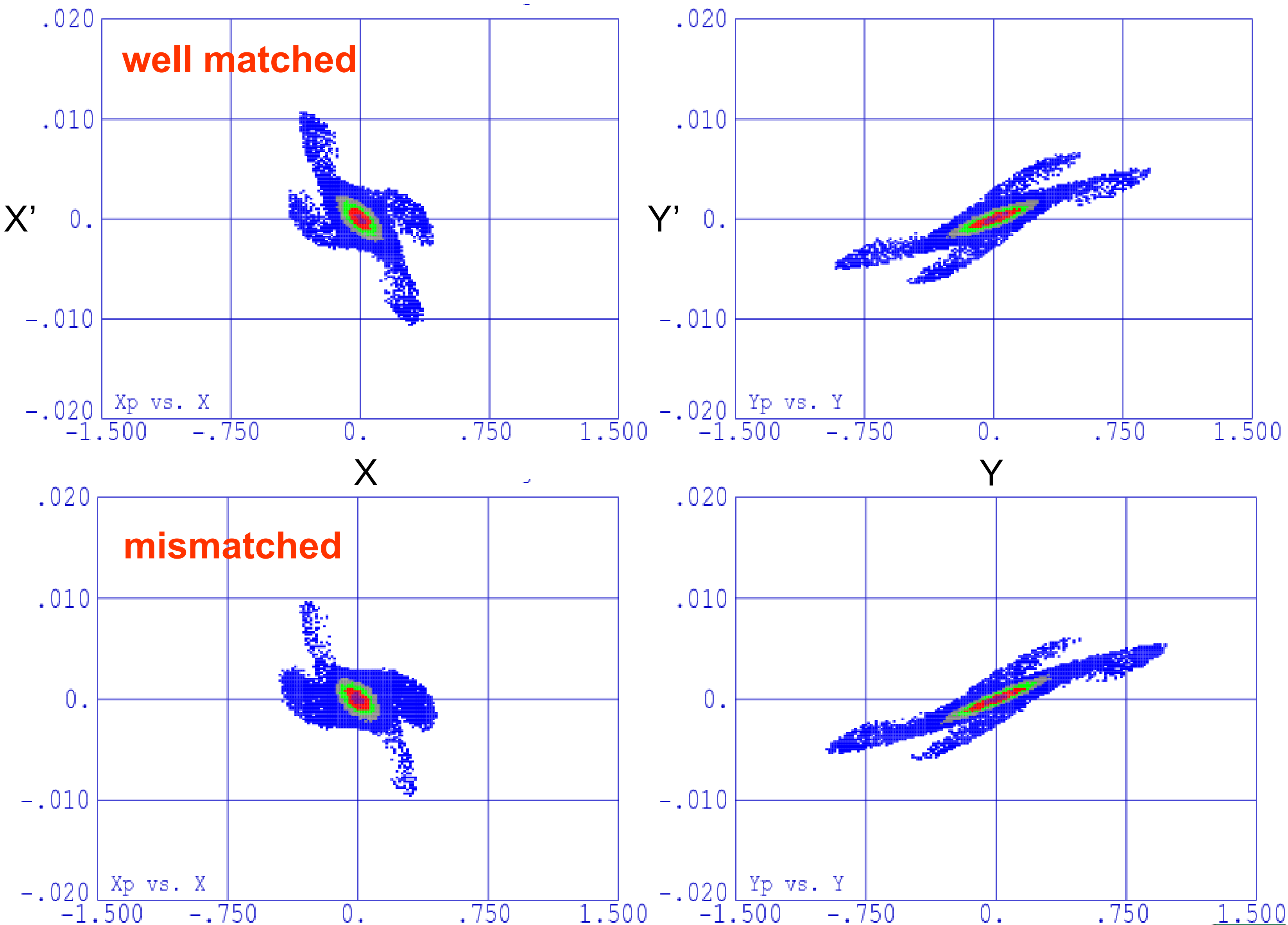


resonance effect σ <= 90º
When σ ~ 85°





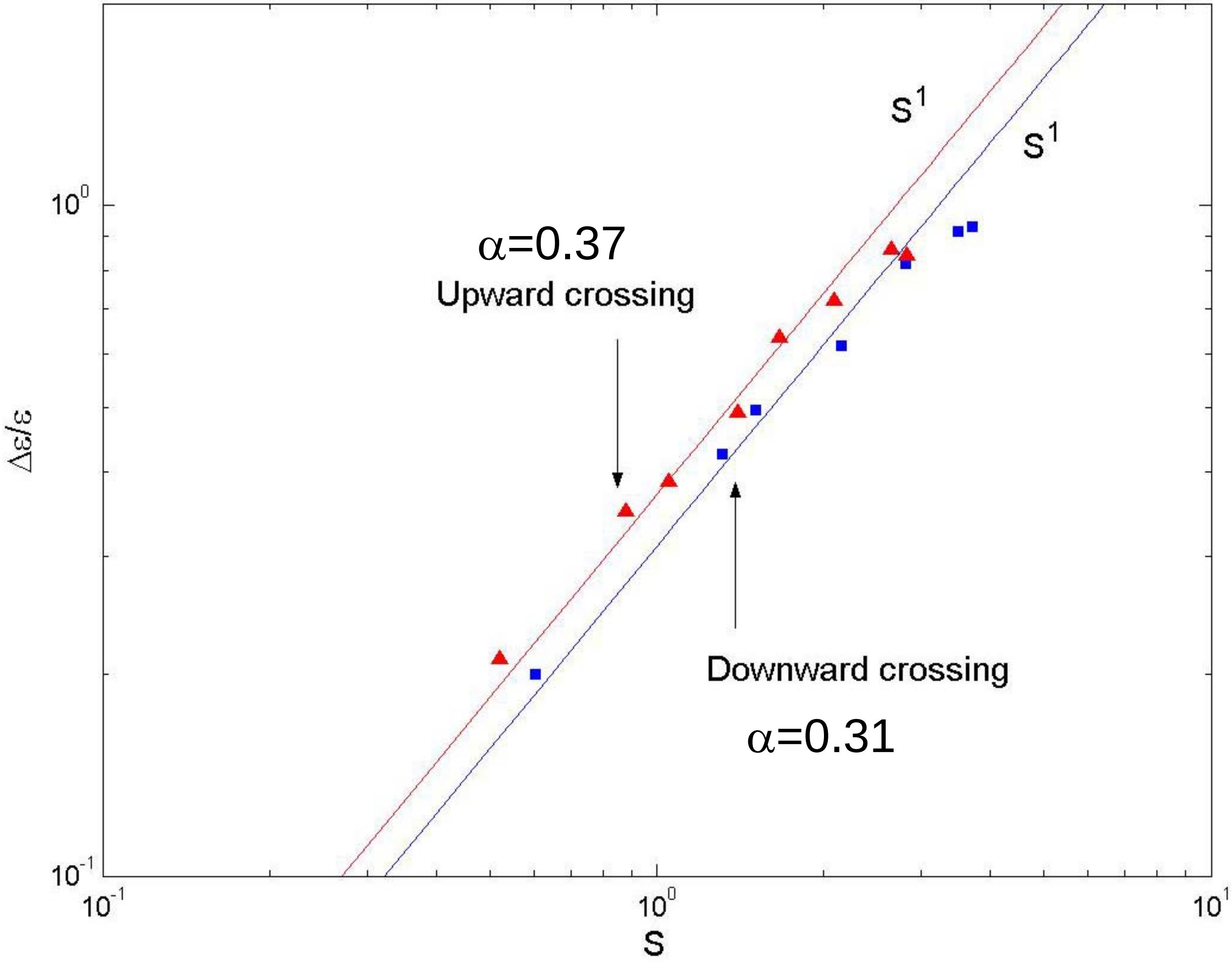
Effects of input beam mismatch
effects of resonance and mismatch manifest



Scaling law when crossing the 4ν=1 resonance

- **Emittance growth is a function of S≡ $\Delta\nu\Delta n = (\Delta\nu)^2/(d\nu/dn)$. (I. Hofmann et al)**
- $\varepsilon \approx (1 + \alpha\Delta\nu\Delta n)\, \varepsilon_o$
- $\Delta\varepsilon/\varepsilon_o \approx \alpha\Delta\nu\Delta n$
- **For the linac 4ν=1 resonance, the emittance growth is a linear function of $\Delta\nu\Delta n$.**

Scaling law when crossing the resonance



$$S \equiv \frac{(\Delta\nu)^2}{\dot{\nu}}$$

- $\Delta\varepsilon/\varepsilon_o \approx \alpha\Delta\nu\Delta n = \alpha S$.
- **For downward 4ν=1 resonance crossing, $\alpha \approx 0.31$**
- **For upward 4ν=1 resonance crossing, $\alpha \approx 0.37$**

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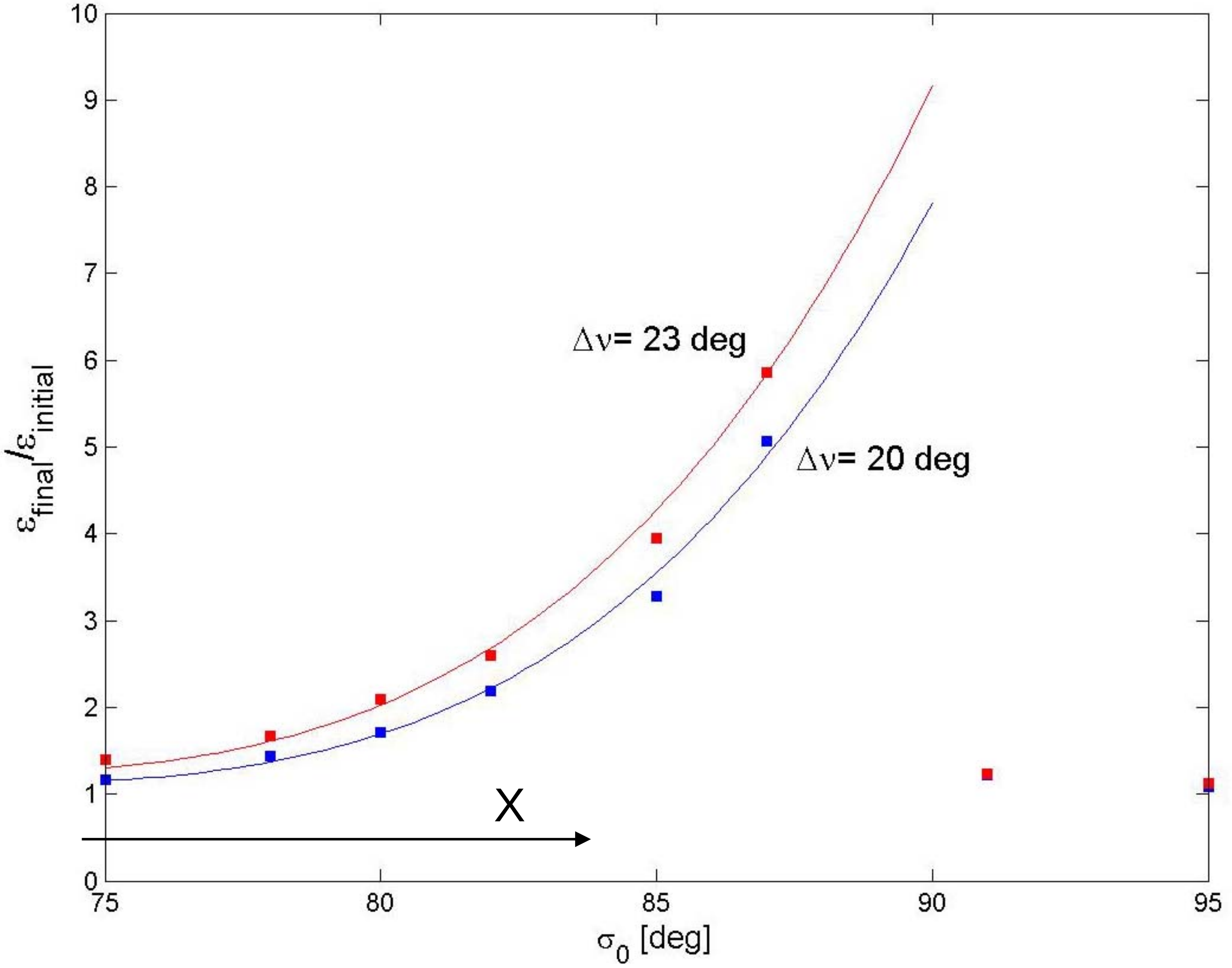
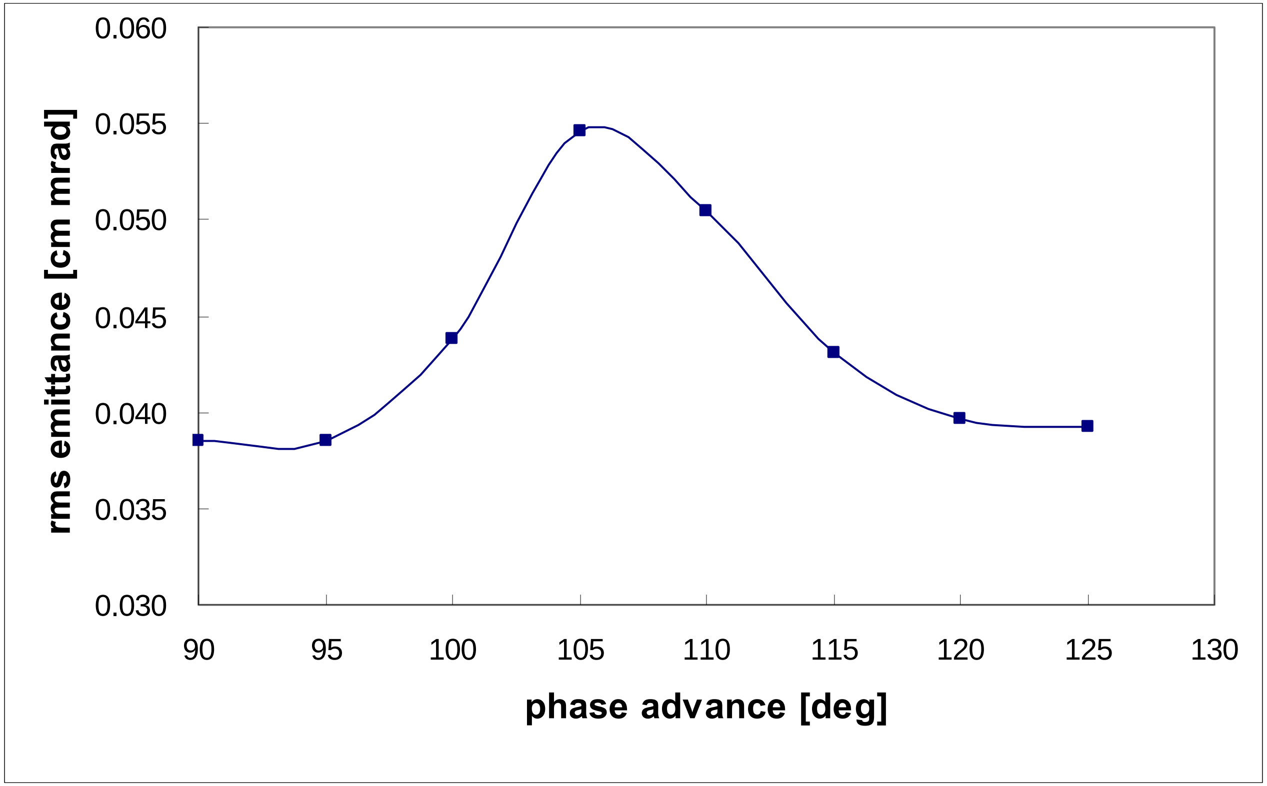
Emittance growth for fixed phase advance



- **roughly proportional to $X^{3.5}$**

Efforts to measure the 4ν=1 resonance stop-band using the GSI UNILAC



- **Simulated ε_{rms} vs σ_0 at the end of Tank A1 of UNILAC.**
- **About 45% of rms emittance increase is anticipated.**
- **New emittance scanner to be installed between Tank A1 and A2.**

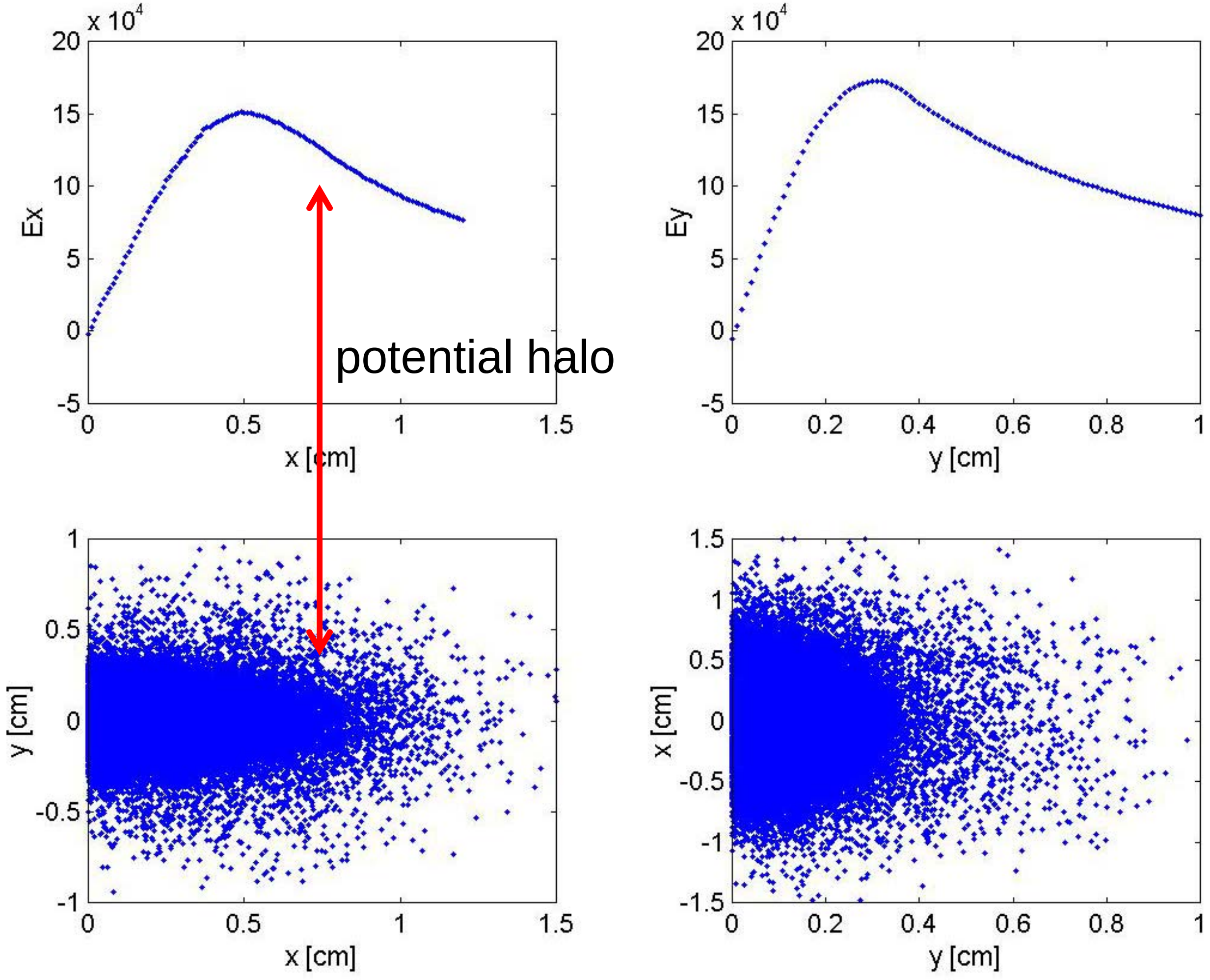
Summary

- **Discovery of a new halo formation mechanism, $4\nu=1$ resonance for a linac was made.**
- **This is one step forward to Grand Unification of Linac and Ring beam dynamics.**
- **Linac design should avoid 90° phase advance because of the $4\nu=1$ resonance rather than the better known envelope instability!!**
- **Efforts are undertaken to measure the $4\nu=1$ resonance stop-band at GSI, Germany.**
- **Is envelope instability a theoretical artifact??**

- **Thanks for the attention.**

Fraction of core in x plane sees nonlinear space charge force, resulting in halo formation in x plane

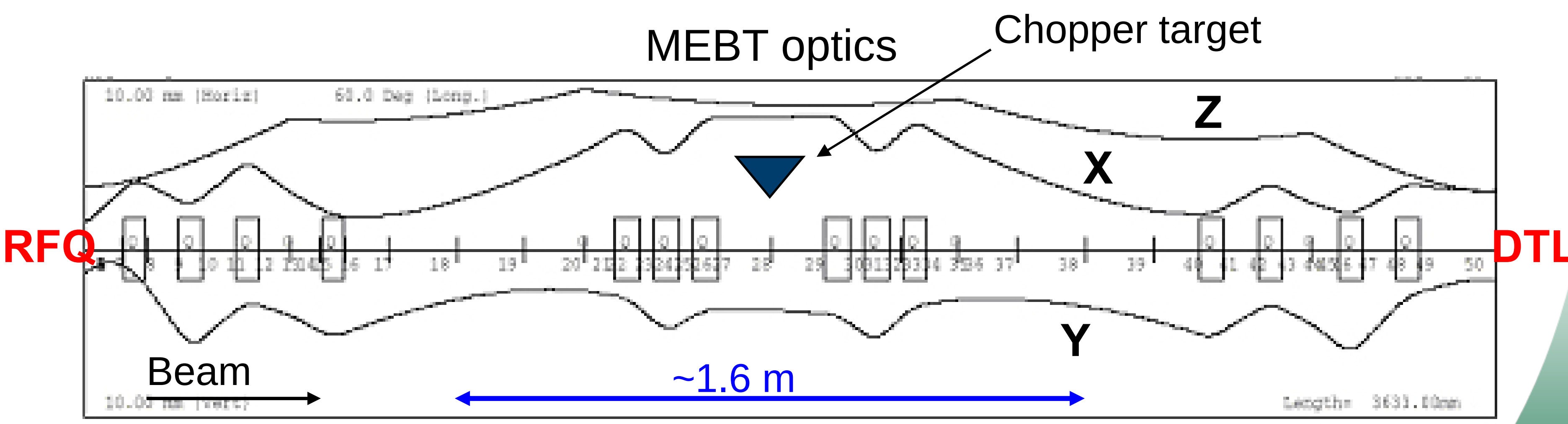
Beam at the chopper target



Space charge force and real space distributions

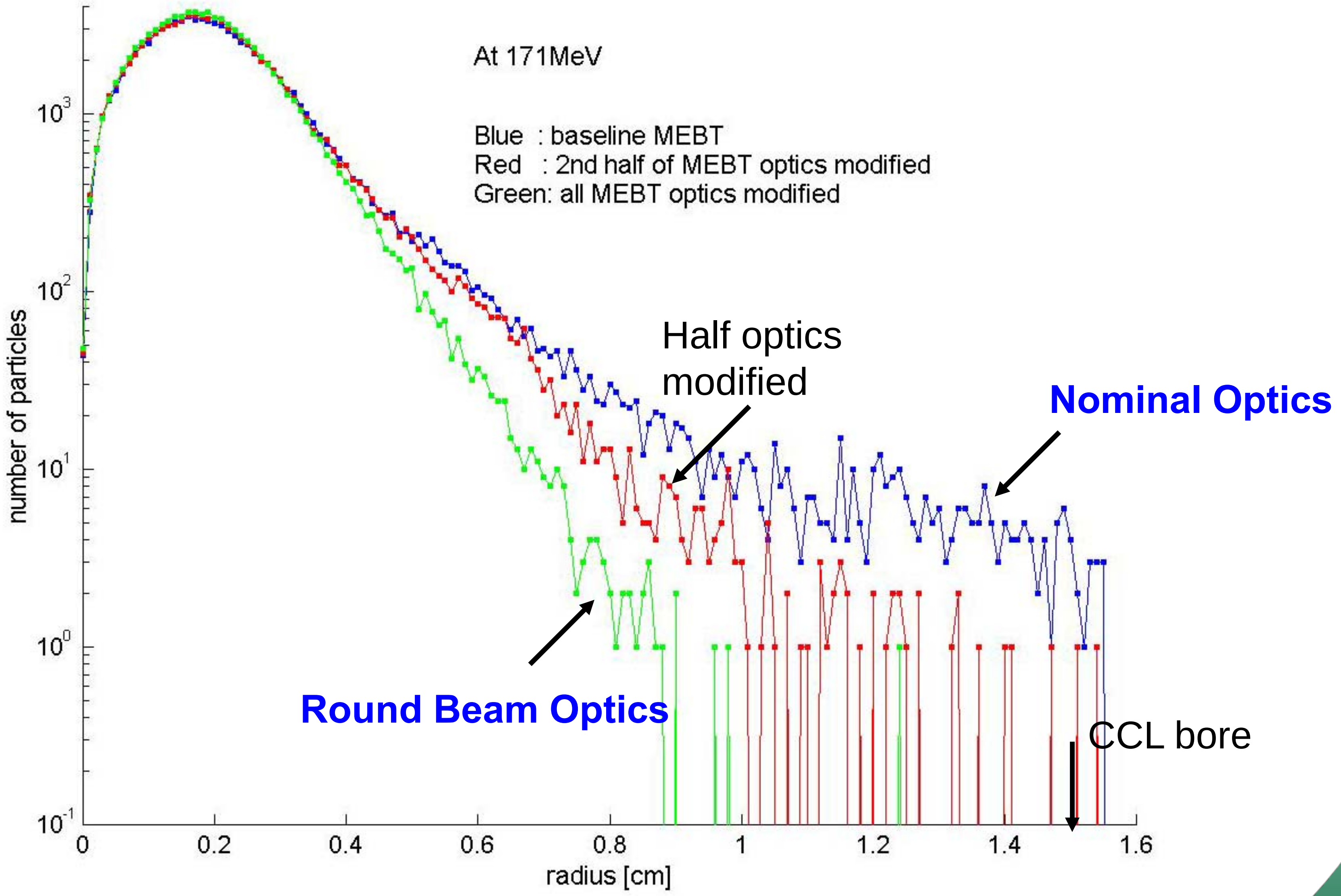
Sources of Front End halo generation

- MEBT is the largest contributor to FE halo generation
- Nonlinear space charge force stemming from a large transverse beam eccentricity generates halo in MEBT
  (D. Jeon *et al*, PRST-AB **5**, 094201 (2002))
- As minor contributors, several FE components and physical effects may contribute to the generation of beam halo

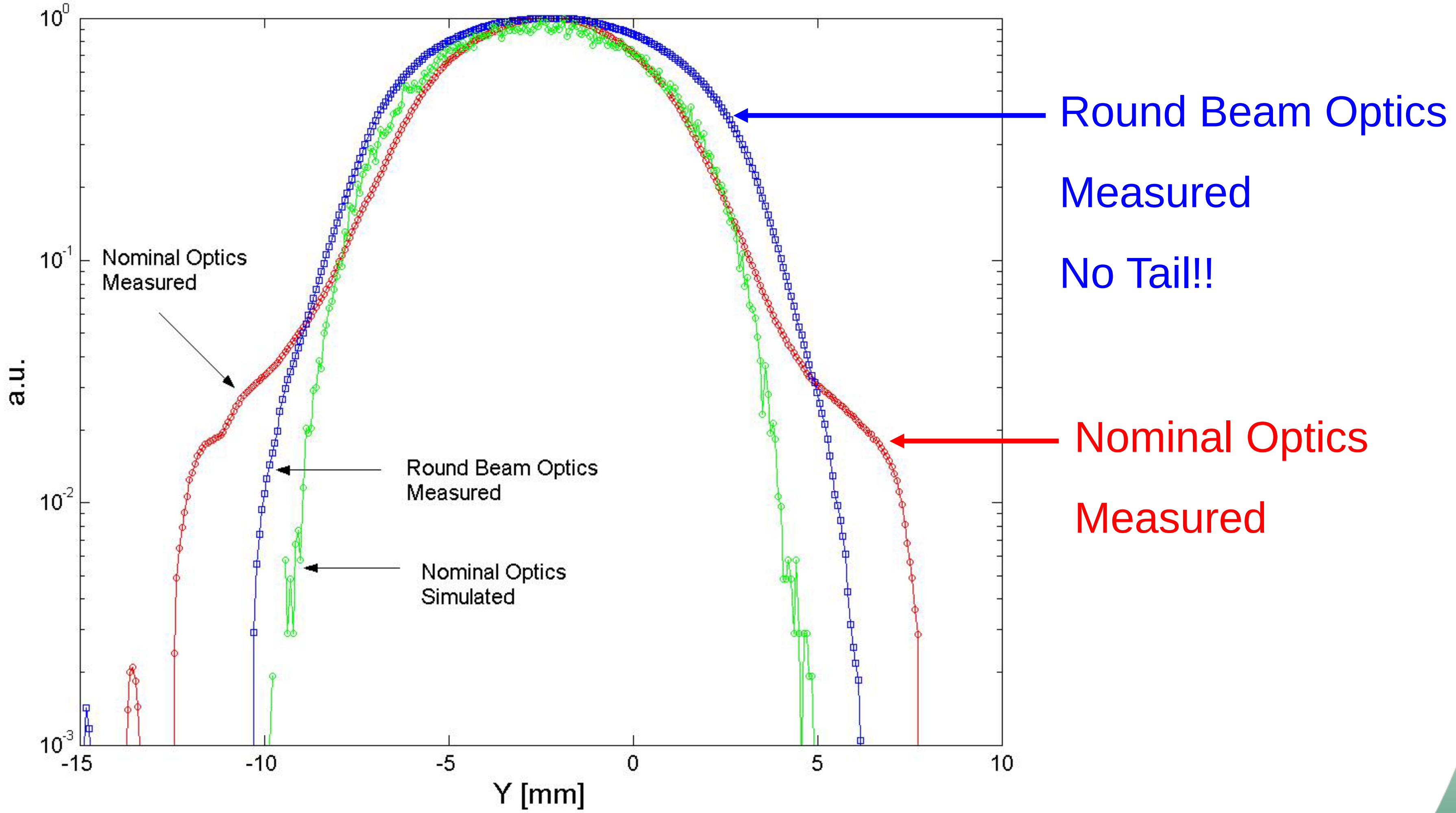


Region with a large transverse beam eccentricity ~2:1

Optics modification alone reduces halo significantly in simulations (Simulation)

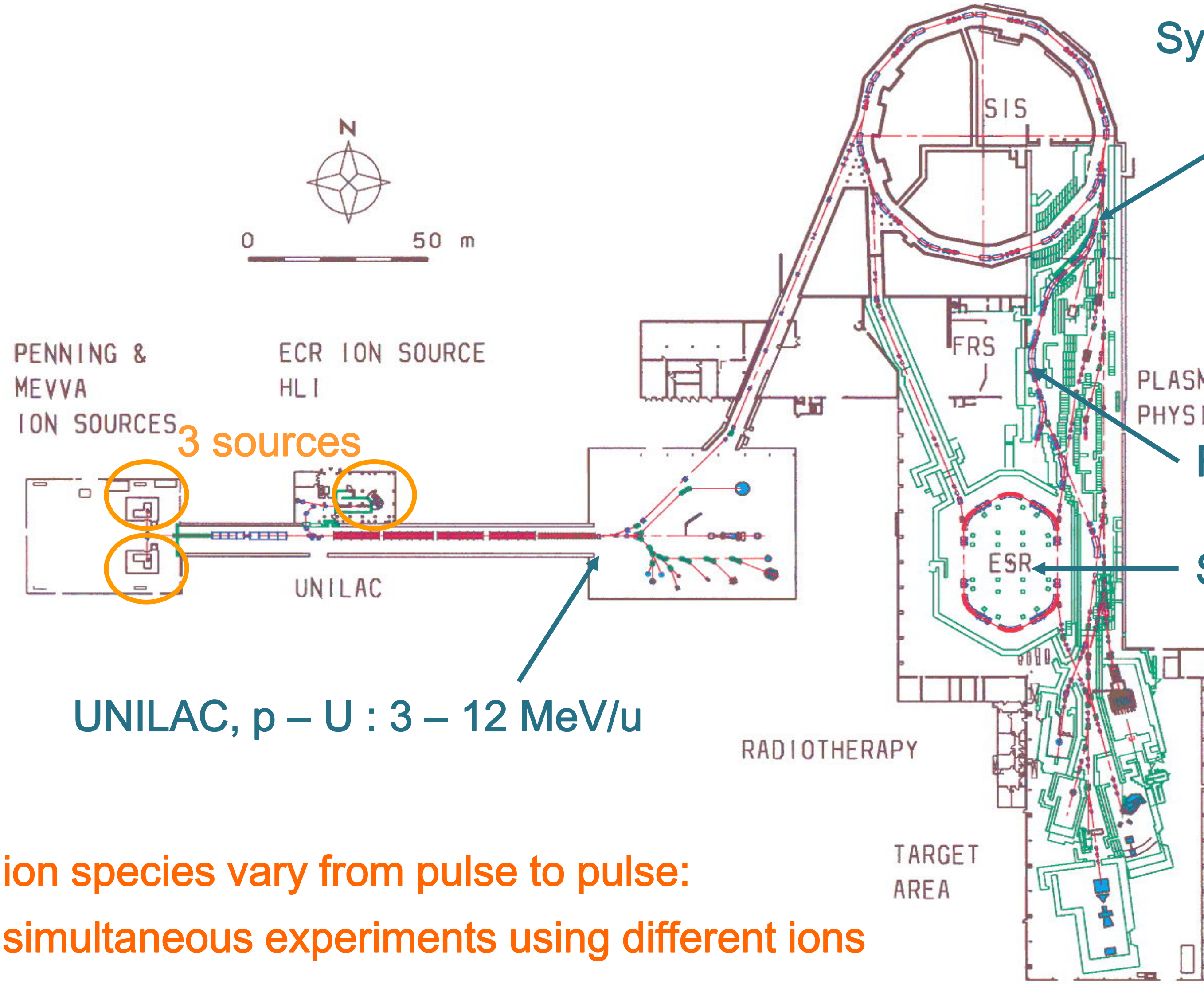


Tail is significantly reduced for Round Beam Optics



- **Round Beam Optics reduces beam tail visibly**
- **This tail is the source of beam loss in downstream linac**

Gesellschaft für Schwerlonenforschung GSI



Synchrotron, Bρ = 18 Tm

p: 4 GeV

Ne: 2 GeV

U: 1 GeV

3 sources

Fragment Separator

Stor. Ring, Bρ = 10 Tm

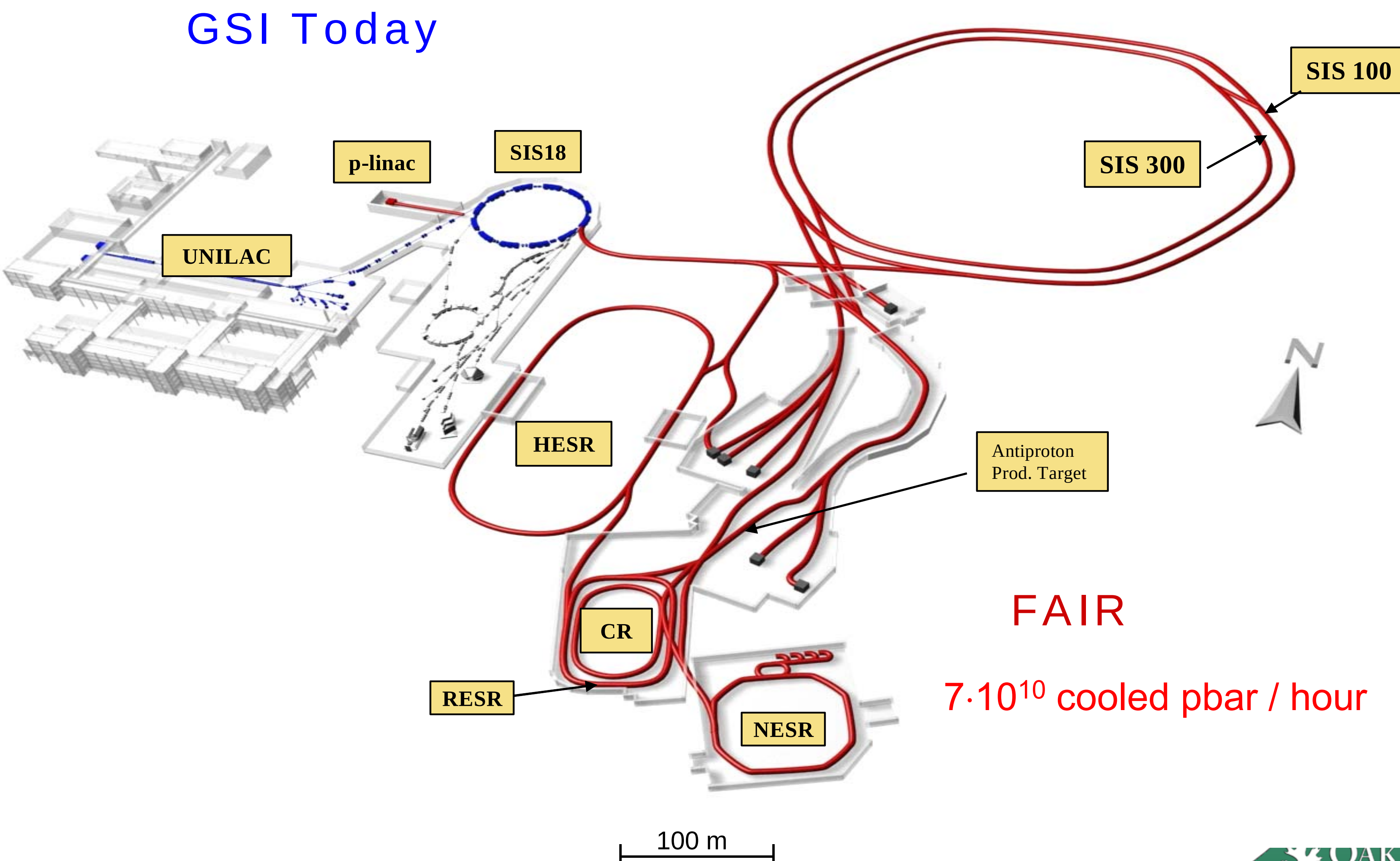
UNILAC, p – U : 3 – 12 MeV/u

High Energy Physics

ion species vary from pulse to pulse:

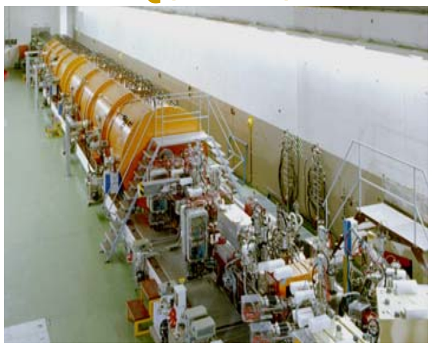
simultaneous experiments using different ions

FAIR: Facility for Antiproton and Ion Research



UNILAC at GSI: Overview

RFQ, IH1, IH2



Alvarez DTL

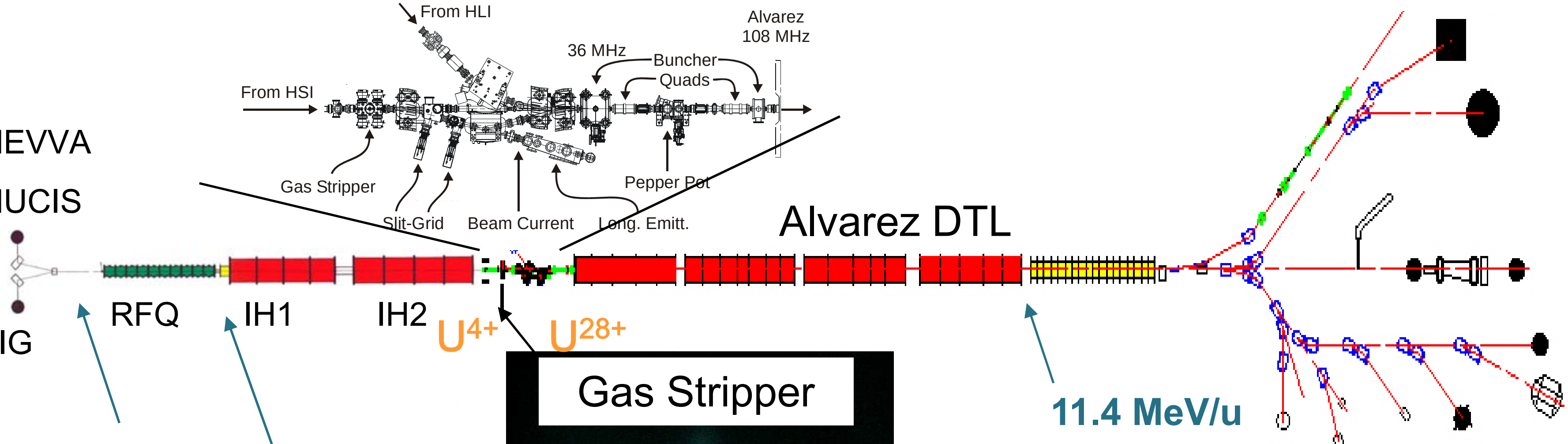
Single Gap Resonators

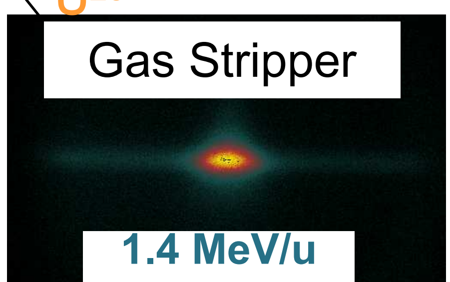
Transfer to Synchrotron

MEVVA

MUCIS

PIG





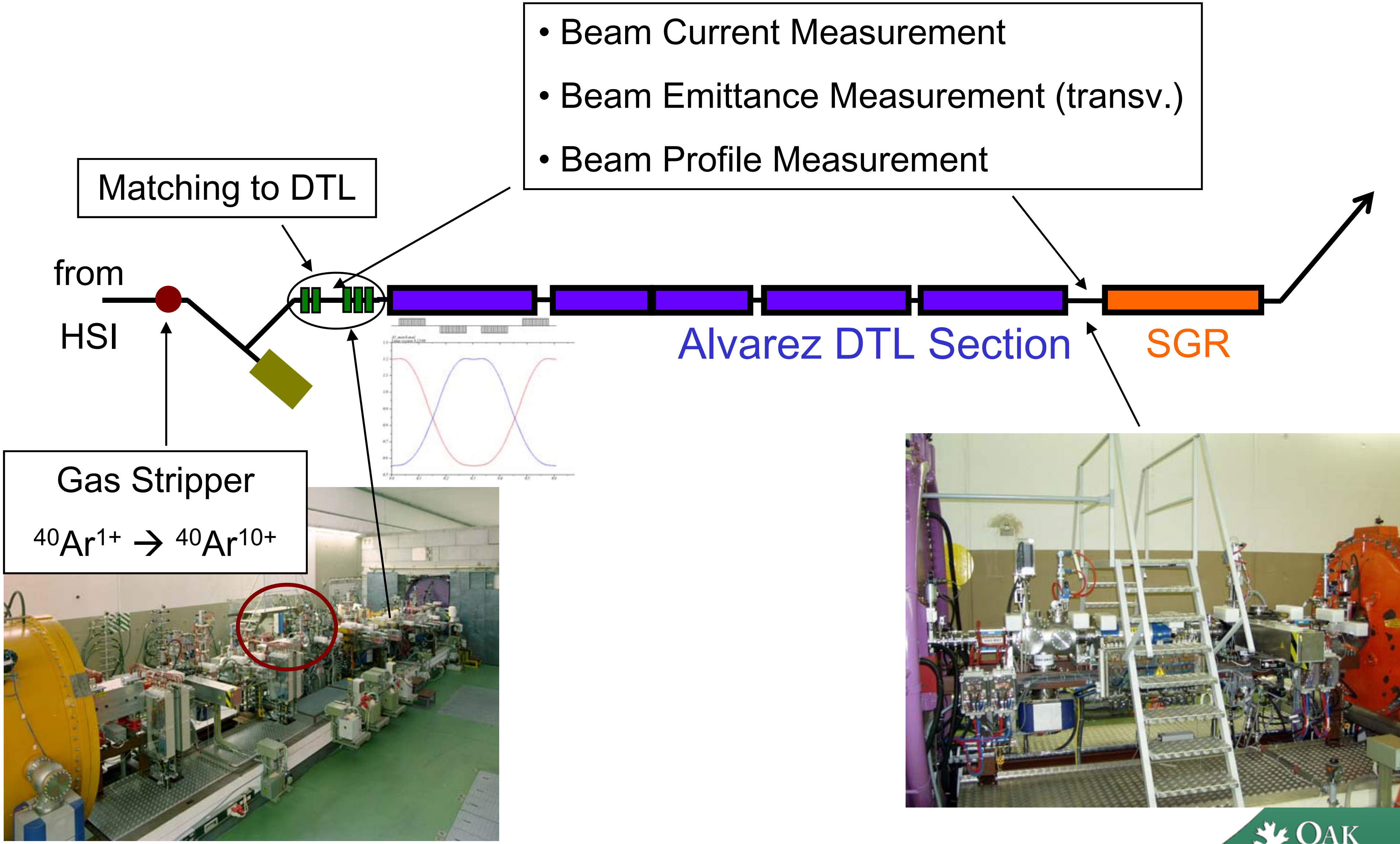
2.2 keV/u
β = 0.0022

120 keV/u
β = 0.016

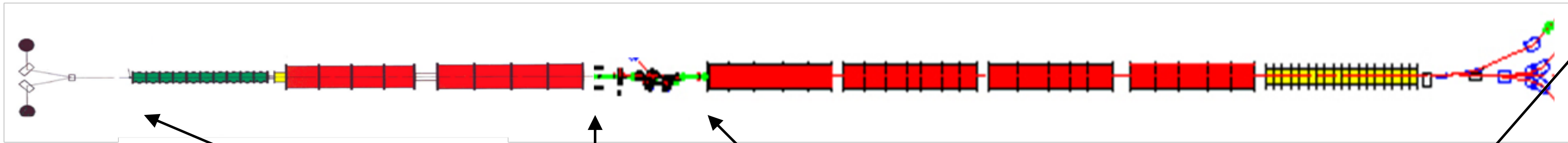
1.4 MeV/u
β = 0.054

11.4 MeV/u
β = 0.16

Set-up for Measurements



UNILAC at GSI : Requirements (Uranium)



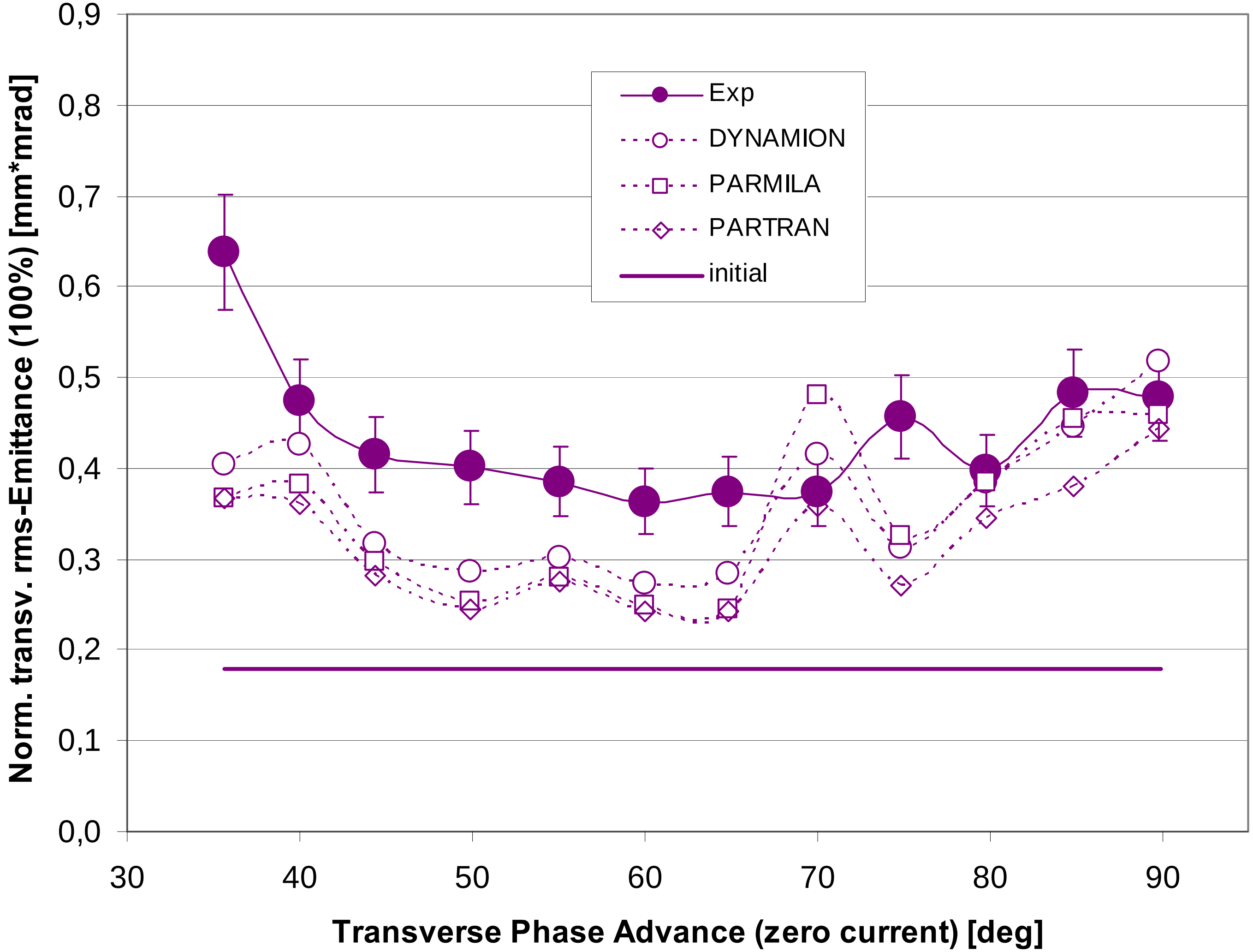
	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection	SIS 18 injection (Future)	SIS 18 Injection
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$	$^{238}U^{28+}$	$^{238}U^{73+}$
El. Current [mA]	16.5	15	12.5	8.4*	15	4.6
Part. per 100μs pulse	$2.6 \cdot 10^{12}$	$2.3 \cdot 10^{12}$	$2.8 \cdot 10^{11}$	$1.9 \cdot 10^{11}$*	$3.5 \cdot 10^{11}$	$4.2 \cdot 10^{10}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4	11.4	11.4
$\Delta W/W$	-	$\pm 4 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8	0.8-1.1	0.8
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5	-	

Design: 4.6 mA, Status 2001: 0.37 mA, Status today: 2.0 mA

Benchmarking efforts at GSI

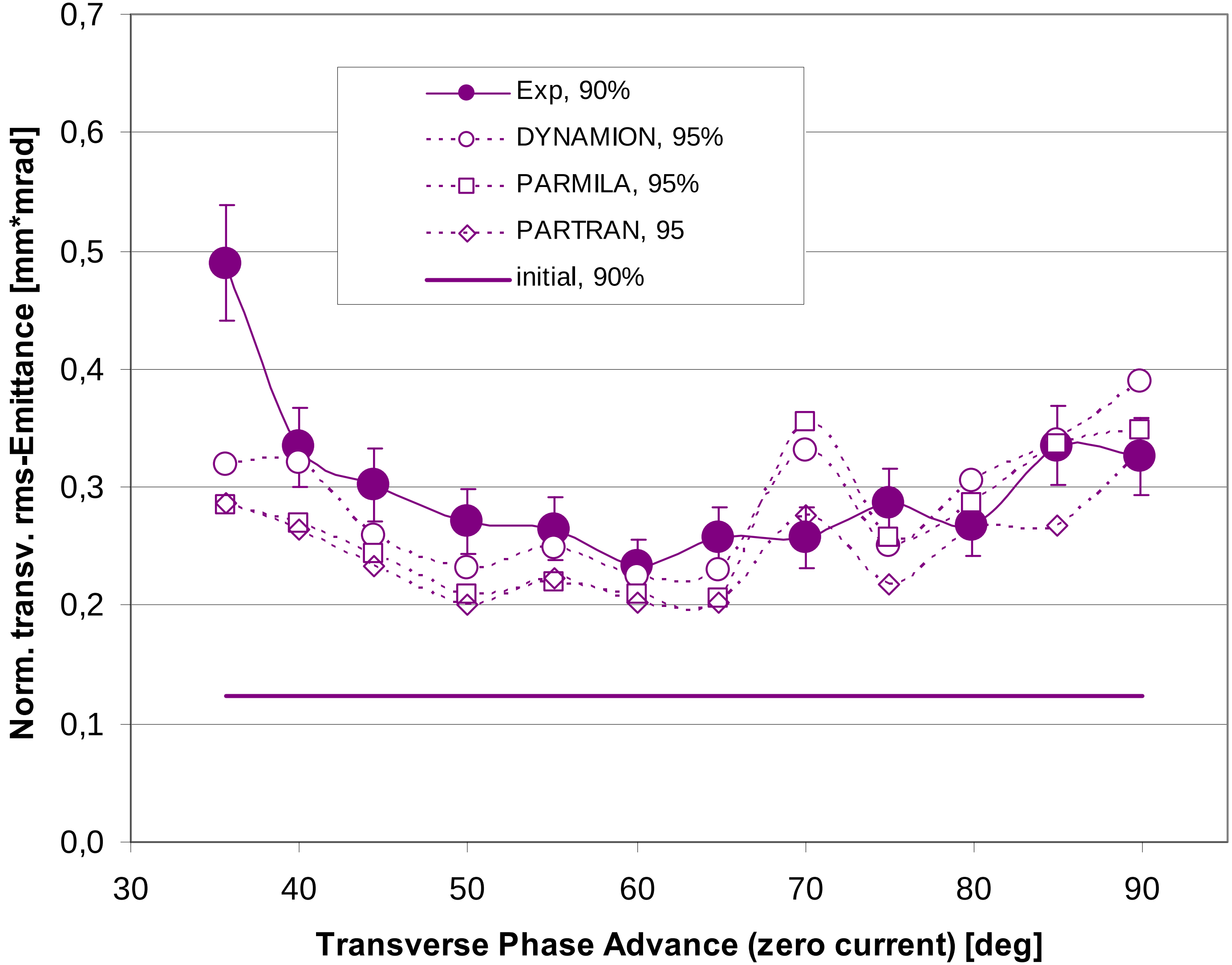
- **It needs to better understand the UNILAC for higher beam current requirement of FAIR project.**
- **GSI waged a campaign of measuring the output beam emittance, varying the zero current phase advance from 35° to 90°.**
- **Efforts to compare the experiment with simulation of codes.**
- **Three different codes have been used: DYNAMION (GSI), PARMILA, PARTRAN (France).**

Code benchmarking effort comparing exp (100%) and simulation (100%)



- **Comparison of 100% rms emittance suffers from noise in measurement data**

Code benchmarking effort comparing exp (90%) and simulation (95%)



- **Gap between experiment and simulation narrows.**

Code benchmarking effort comparing exp (95%) and simulation (95%)

- **Coming soon!!**