WG-B beam dynamics in LINACS

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WG-B

- 23 talks + 2 quick presentations
- 12 Project represented : SARAF,IFMIF,ESS,C-ADS, C-SNS, FRIB, JPARC,UNILAC ,LINAC4,SNS, XIPAF,LANSCE
- Simulations : emittance reconstruction from profile measurements/ online modelling/space charge compensation/

Important topics 1/2

- Reports /feedback from operational experience and comparison with expectation (lessons learnt)

- Benchmark between model and experiment

- Resonances
  - as design guidelines
  - benchmark between model and experiment.

Important topics 2/2

- To match or not to match? And if yes what?
- Loss maps and their importance at the different stages (design, commissioning/implementation, power ramp-up)
- Low Energy Beam transport beam dynamics
  - need to extend our knowledge of the transition between plasma and extraction.
  - Need to find a correct way to track in a bending magnet

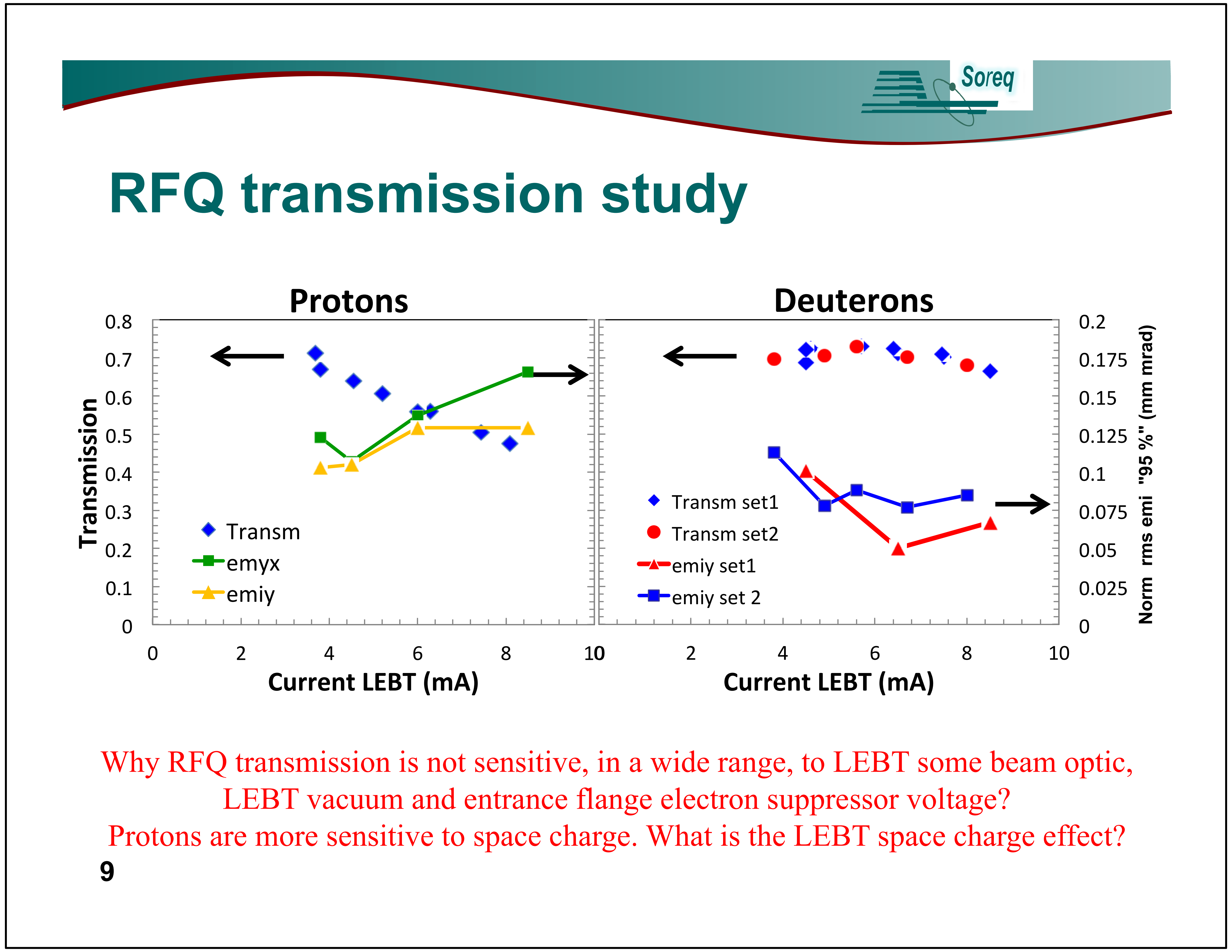
Reports /feedback from operational experience and comparison with expectation (lessons learnt)

- Talks on this topic distributed over WG-B and WG-D
  - WG-B
    - TUAM1Y01: SARAF, THPM1Y01: C-ADS Injector-II
  - Plenary
    - MOAM1P20: LINAC4, MOAM4P40: SNS
  - WG-D
    - TUPM2Y01: CSNS, TUPM6Y01: C-ADS Injector-I, TUPM8Y01: C-ADS Injector-II, THAM2X01: KOMAC, THAM3X01: SNS
- We don’t elaborate on talks in WG-D

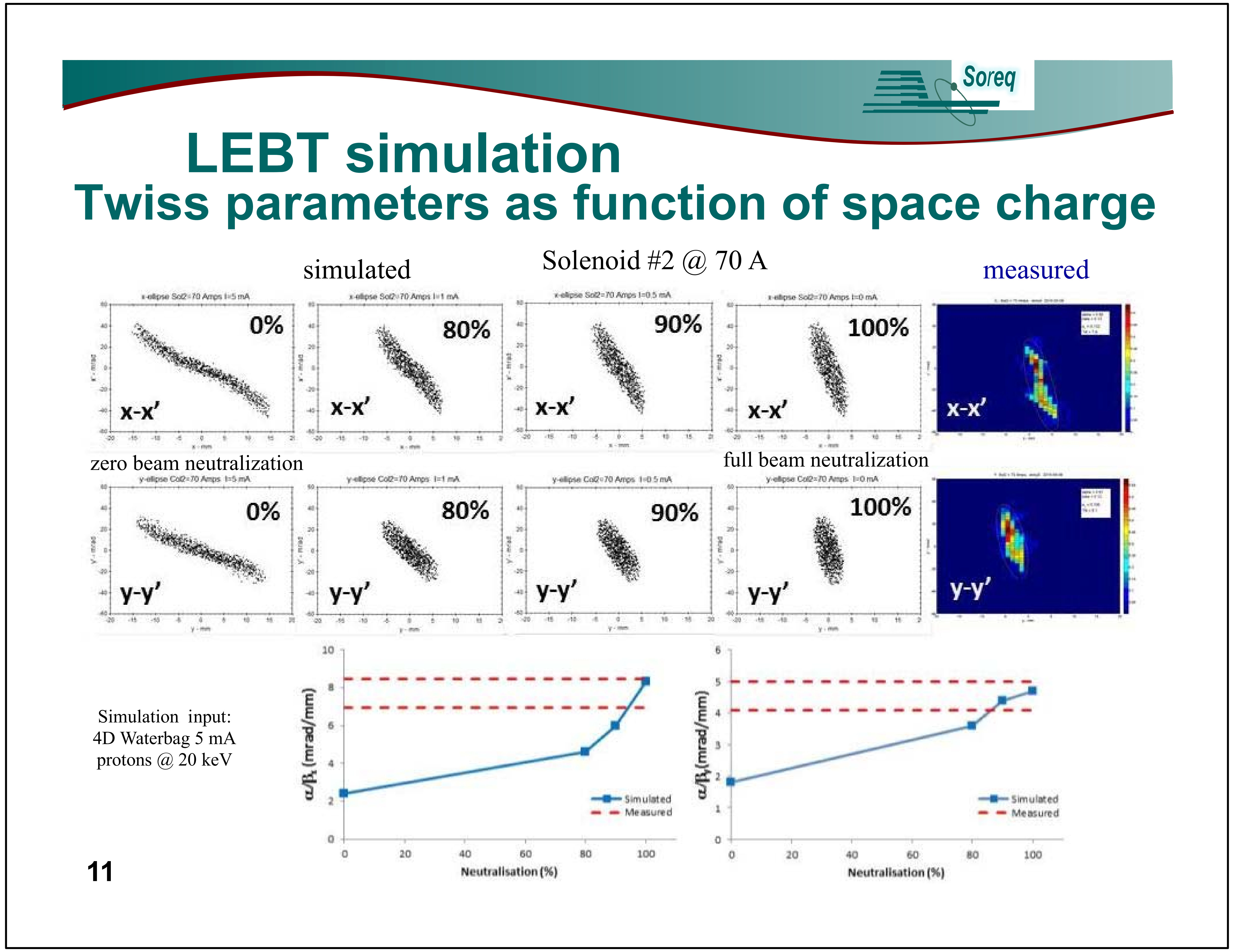
D. Berkovits

Operational Experience: SARAF

Unexpected behavior of RFQ transmission observed



Simulation study initiated to understand dynamics in LEBT (study on-going)



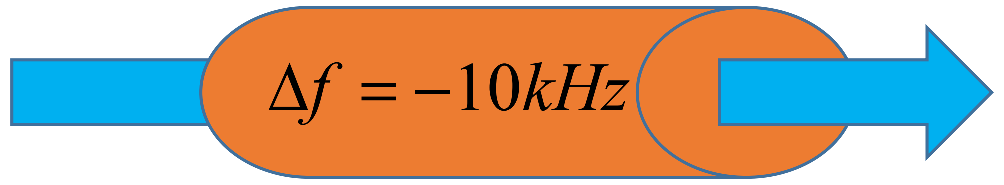
R. Huang

Operational Experience: C-ADS Injector-II

Frequency shift of 10 kHz observed at C-ADS Injector-II RFQ

Background

- In the beam experiment on the demo Injector II of the CIADS, when the 10 mA CW beam passed through the RFQ , large power reflection from the power coupler can shut down the generator, due to the interlock system.
- The feedforward is adopted to maintain the amplitude of the fields in the RFQ when the beam passes. Even if $\Delta P_f = P_b$, the beam loss in the following SC section is still significant, because the field is smaller than the designed value.
- The RFQ had to be detuned by amount of 10 kHz to minimize the reflection power, therefore, minimize the generator power, which means the optimum detuning of the RFQ under the 10 mA CW beam is 10 kHz.



- This large optimum detuning of RFQ is against the previous experience in normal conducting acceleration.

Theoretical explanation for it has been proposed

Effective RF Phase

- The effective impedance angle can be termed to be the effective RF phase.
- Detailed treatment on the effective RF phase will involve the field integration. For simplicity and consistency. To be consistent with it, we'll estimated the effective RF phase as the following way,

$$\phi_h = -\arctan\left(\frac{\left|\sum_n A_{10,n}\sin\phi_n\right| + \frac{N}{2\sum_n L_n}\sum_n A_{0,n} m_n L_n}{\sum_n A_{10,n}\cos\phi_n} \right)$$

- With the parameter of the RFQ, we'll obtain $\phi_h \approx -78.5^o$
- The beam-inducing detuning evaluated with ϕ_h is,

$$\Delta f' \approx -7.8\text{kHz}$$

- The beam-inducing field phase variation

$$\Delta\phi \approx 4.2^o$$

Resonances

- As design guidelines
  - Design study is active (especially in China) with new projects are proposed/approved
  - Resonance theory has been revisited as design guidelines for high intensity linacs
    - TUAM4Y01: C-ADS Injector-I, THPM1Y01: CIADS, THPM3Y01: Overview
  - New guideline(?): Equipartitioning is strong against error
    - TUAM6Y01: J-PARC
- As benchmark between model and experiment
  - Attempt for experimental verification of model-predicted resonance on-going
    - TUAM6Y01: J-PARC

Y. Liu

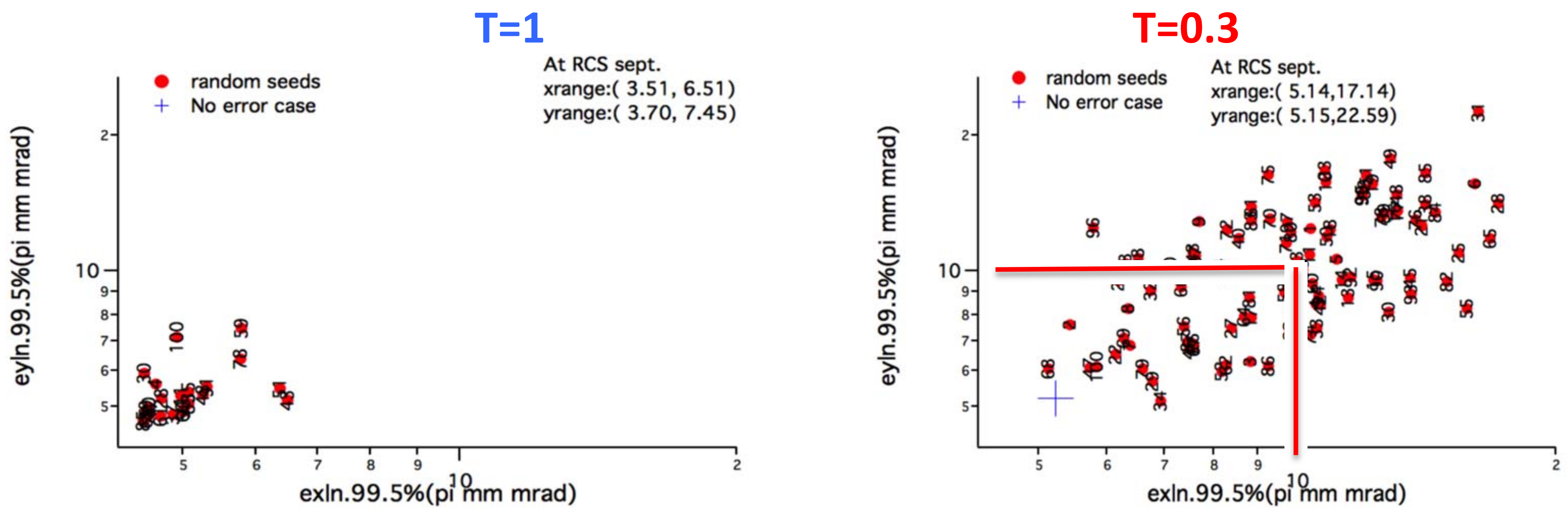
Resonance: J-PARC

Equipartitioned setting is less sensitive to errors

Property of off-EP Setting T=0.3: Lattice Stability 9

Lattice Stability problem found in error study

- Simulation with IMPACT
- Q alignment error ± 0.1mm
- RF amplitude error ± 1%, phase error ± 1^0
- 100 seeds



Very different sensitivity to errors!
Transverse emit-99.5% 10 π mm mrad: more than half of the seeds exceed for T=0.3

Attempted to observe model-predicted coupling resonance: trend looks consistent

Experiment Setup and Scheme of Measurement

Fit/simu.@MEBT2:MARK

exp.

	Nom.	T_{S+A}=0.5		T_{S+A}=0.7		T_{S+A}=0.9		T_{S+A}=1.3	
	$\varepsilon_{rms.n.}$(mm)	ε_{rms}(t3d)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)
H	0.38	0.45	18.8	0.37	−1.1	0.39	4.3	0.33	−13.4
V	0.35	0.55	58.7	0.37	7.0	0.38	9.9	0.32	−8.5
L (Relative only!)	0.34	0.26	−24.2	0.33	−1.9	0.32	−4.1	0.39	15.9
$\varepsilon^3_{rms.n.}$(mm^3)	0.0440	0.0628	42.8	0.0457	3.9	0.0483	10.0	0.0404	−8.2

simu.

	Nom.	T_{S+A}=0.5		T_{S+A}=0.7		T_{S+A}=0.9		T_{S+A}=1.3	
	$\varepsilon_{rms.n.}$(mm)	ε_{rms}(t3d)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)	$\varepsilon_{rms.n.}$(mm)	$\Delta\varepsilon/\varepsilon$(%)
H	0.27	0.33	22.2	0.29	7.4	0.31	14.8	0.24	−11.1
V	0.27	0.35	29.6	0.29	7.4	0.31	14.8	0.24	−11.1
L	0.38	0.34	−10.5	0.35	−7.9	0.31	−18.4	0.45	18.4
$\varepsilon^3_{rms.n.}$(mm^3)	0.0277	0.0393	41.8	0.0294	6.3	0.0298	7.5	0.0259	−6.4

--Emittance growth happened for exp. cases (could be well reproduced by introducing errors, but emittance ratio does not change in simulation)
--Neglecting absolute measured longitudinal emittance, look at the relation between each other.

Trend of emittance relation looks consistent!

Open question: Can equipartioning be a design guideline to be robust against errors?

Resonance: C-ADS Injector-I

Resonance condition used as design guideline

2. SC section design consideration

Longitudinal instability

Mismatch parametric resonance

$$k_{mm}L=\pi$$

⇩

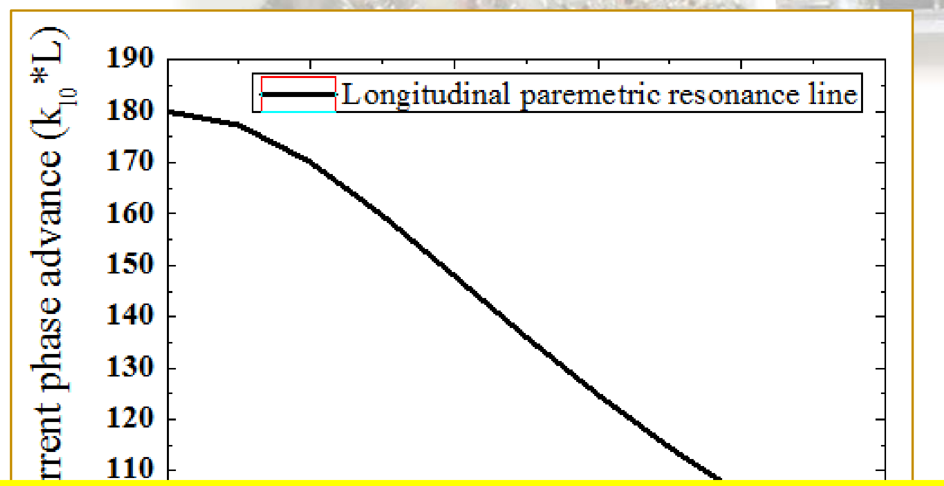
$$k_{10}=k_{mm}\Big/\sqrt{1+3\eta_l^2}=\pi/L\Big/\sqrt{1+3\eta_l^2}$$

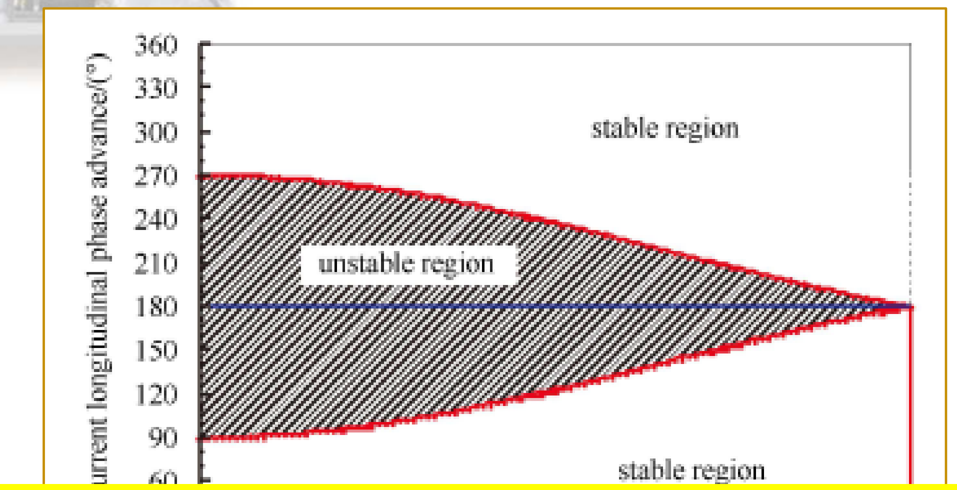
When filling factor is considered

$$\varepsilon=\frac{\sigma_{10}}{2}\frac{\sin(\pi l_{eff}/L)}{\pi l_{eff}/L}$$

L : *Periodical length*

L_{eff} : *Longitudinal effective length*





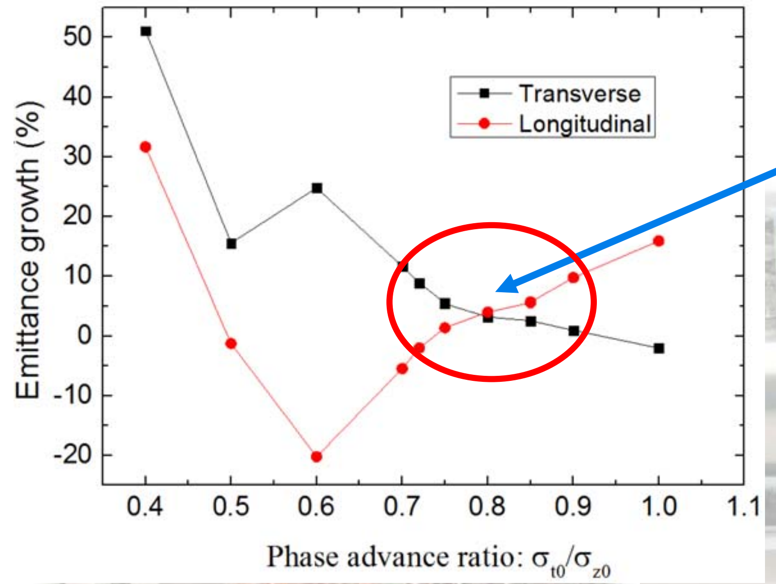
However all these effect could be avoided by keeping the zero current longitudinal phase advance smaller than 90 degree!!!

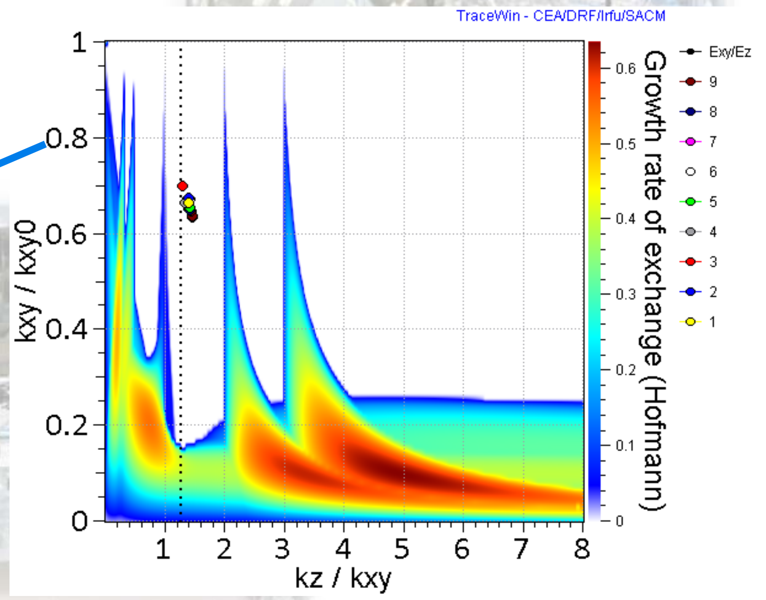
Near equipartitioned setting selected as less sensitive to error

3. Lattice design

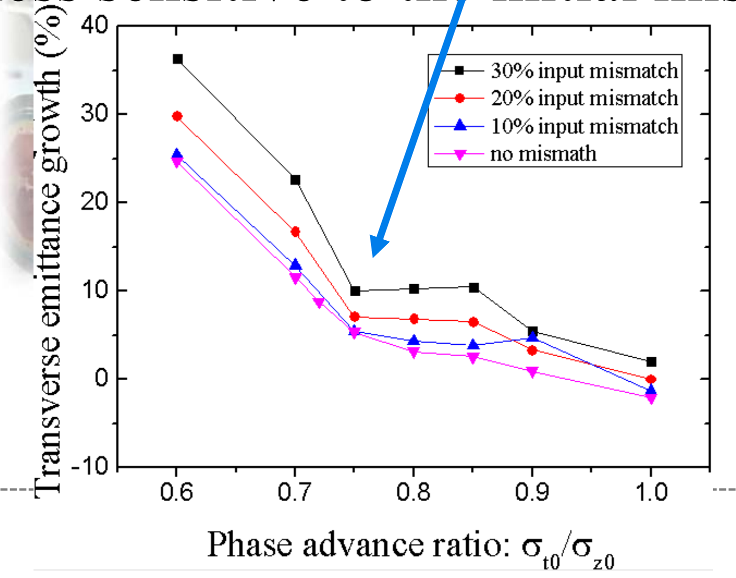
Footprint area selection

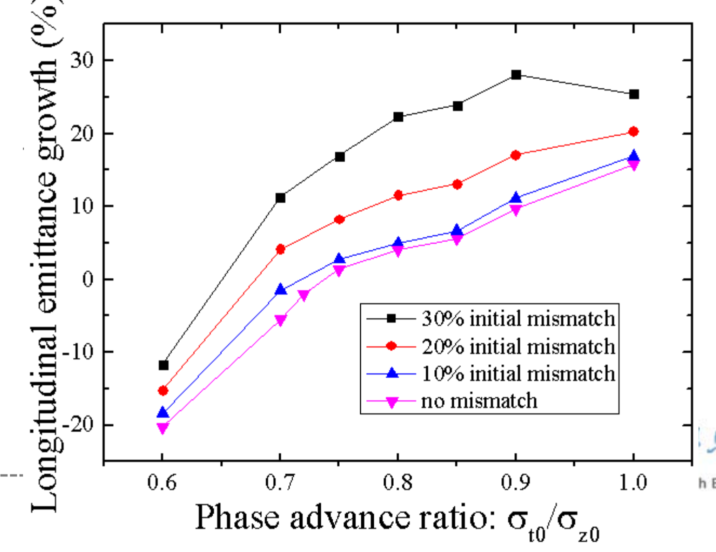
The working points were chosen between the $k_z/k_t=1$ and $k_z/k_t=2$ stop bands.





The one less sensitive to the initial mismatch was chosen for the nominal design.





C. Plostinar

Resonance: Overview

The ISIS Experience

- ISIS simulation model tuning:
  - Avoid mismatches
  - Avoid resonances/instabilities
  - Minimise emittance growth
- ISIS Linac tuning
  - Real-life machine tuning has different aims
  - Reduce losses
  - Control activation to allow hands-on maintenance (crucial for an old machine)
  - In reality the beam core could be mismatched, but the transmission increased

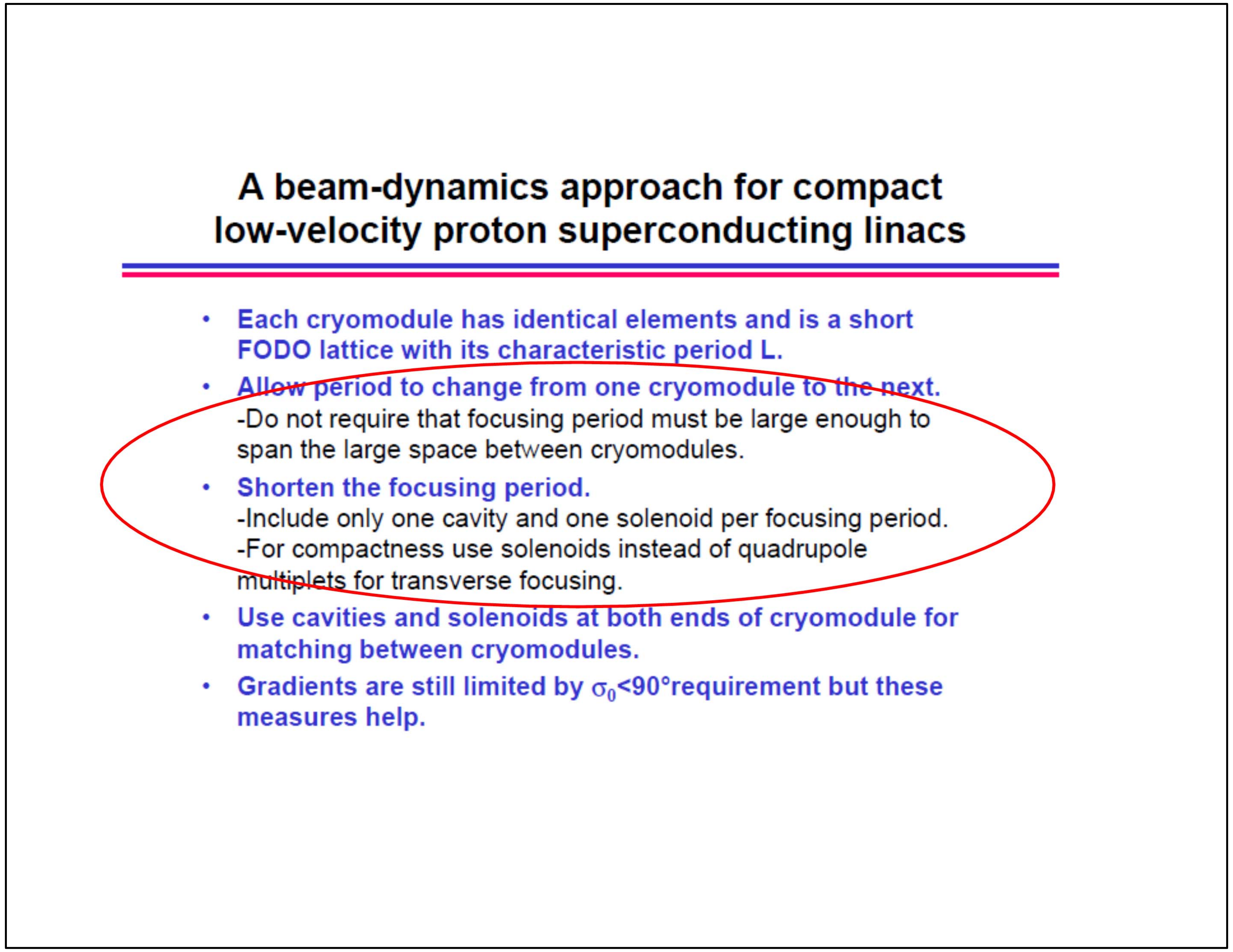
A better understanding of space-charge resonances is emerging, but experimental evidence and impact remain limited

Open questions

- Existing facilities show discrepancy between simulation models and machine operation
  - How this can be improved?
- What is figure of merit in design/operation?
  - Emittance growth tolerated?

I. Hofmann

Resonance Discussion



- Interpretation of 90 degree limit in longitudinal direction discussed
- Ambiguity in definition of a period
- Longitudinal period can be defined separately from transverse
- It may matter in designing superconducting linac

Resonance Discussion

Spiral2 — Emittance exchanges

Classical beam physics

Difference coupling resonances

Emittance exchange when

$n\,\nu_x - m\,\nu_z = p$

(beam footprint with space charge)

To avoid emittance exchange choose

$n\,\nu_x - m\,\nu_z \neq p$

EQP believers (linac)

Equipartition

Emittance exchange when

$\varepsilon_x\,\nu_x - \varepsilon_z\,\nu_z \neq 0$

To avoid emittance exchange choose

$\varepsilon_x\,\nu_x - \varepsilon_z\,\nu_z = 0$

EQP rule applied without any physical justification !
Our beams being far to be thermodynamical systems, the EQP theorem DO NOT apply

The emittance exchanges are induced by the coupling resonances

- Which is correct physics view between difference coupling resonance and equipartition?
- Which of tune diagram and Hofmann diagram better describe physics?

Benchmark between model and experiment

- This topic is intertwined with other topics
  - Model capability of reproducing experiment may limit the capability of matching
  - Model capability of reproducing experiment (beyond RMS) could be limited by front-end model
- Benchmark with RMS beam size
  - WEPM2Y01: SNS
- Benchmark with coupling resonance
  - TUAM6Y01: J-PARC
- Benchmark with beam spill (beyond RMS)
  - WEPM4Y01: LANL

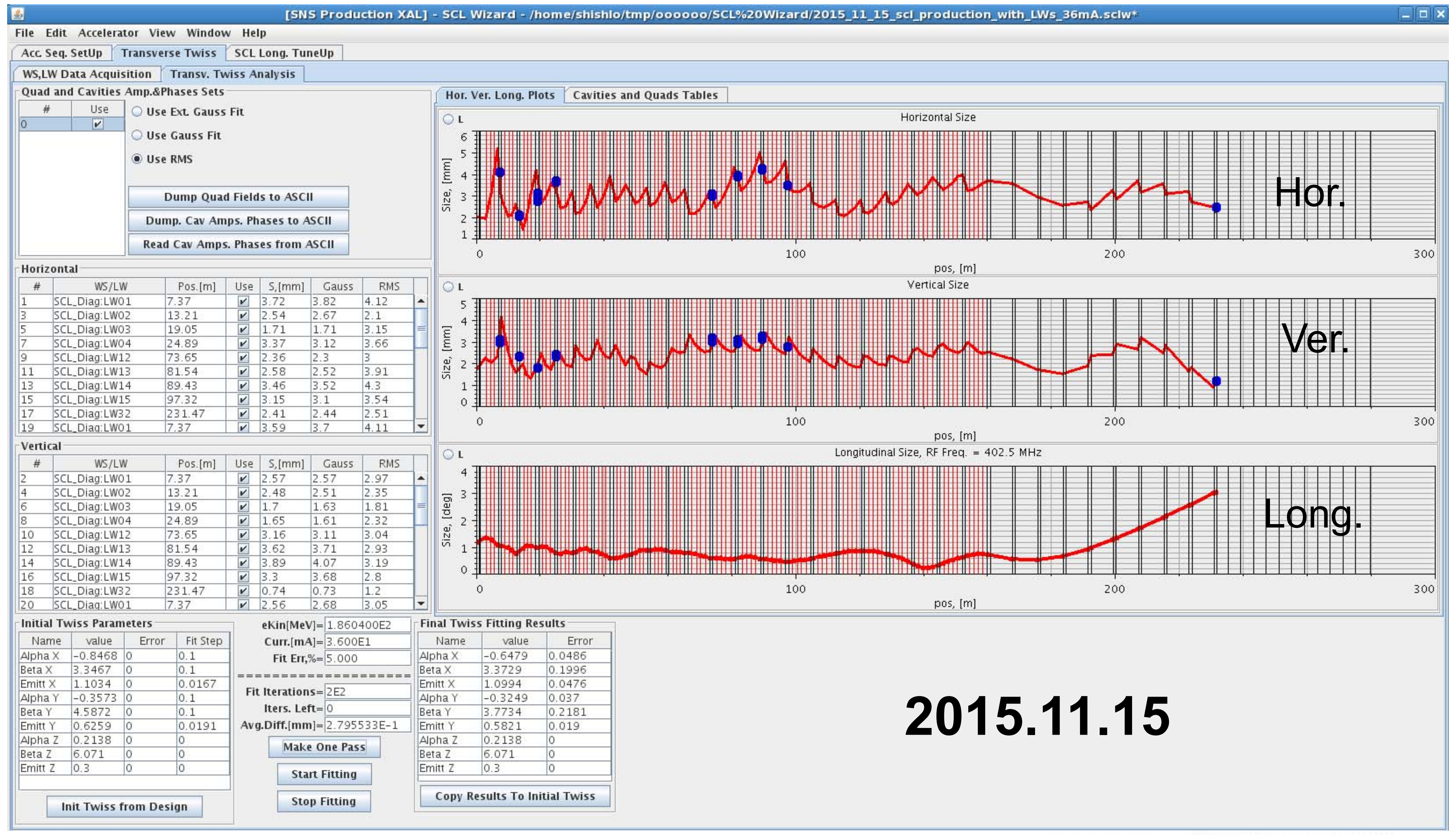
A. Shishlo

Model Benchmark: SNS

Succeeded in reproducing RMS behavior after detailed study and tuning

Further study required to understand “shoulders” in profile

Successful SCL Optics Control

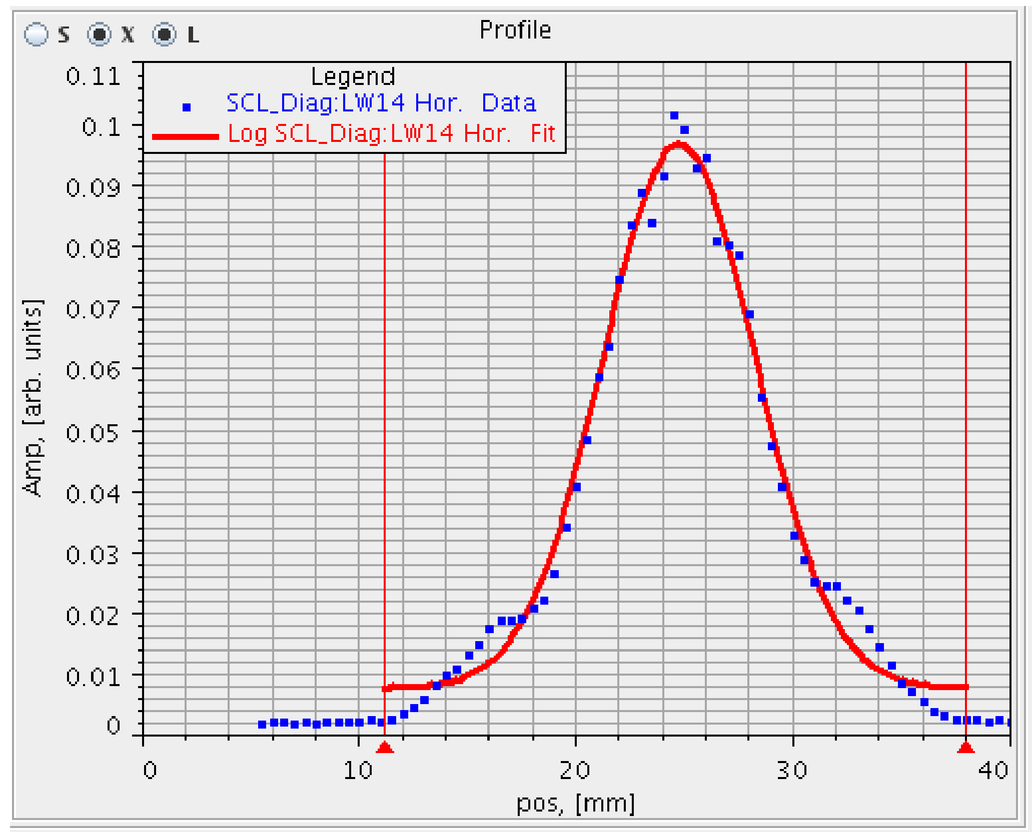


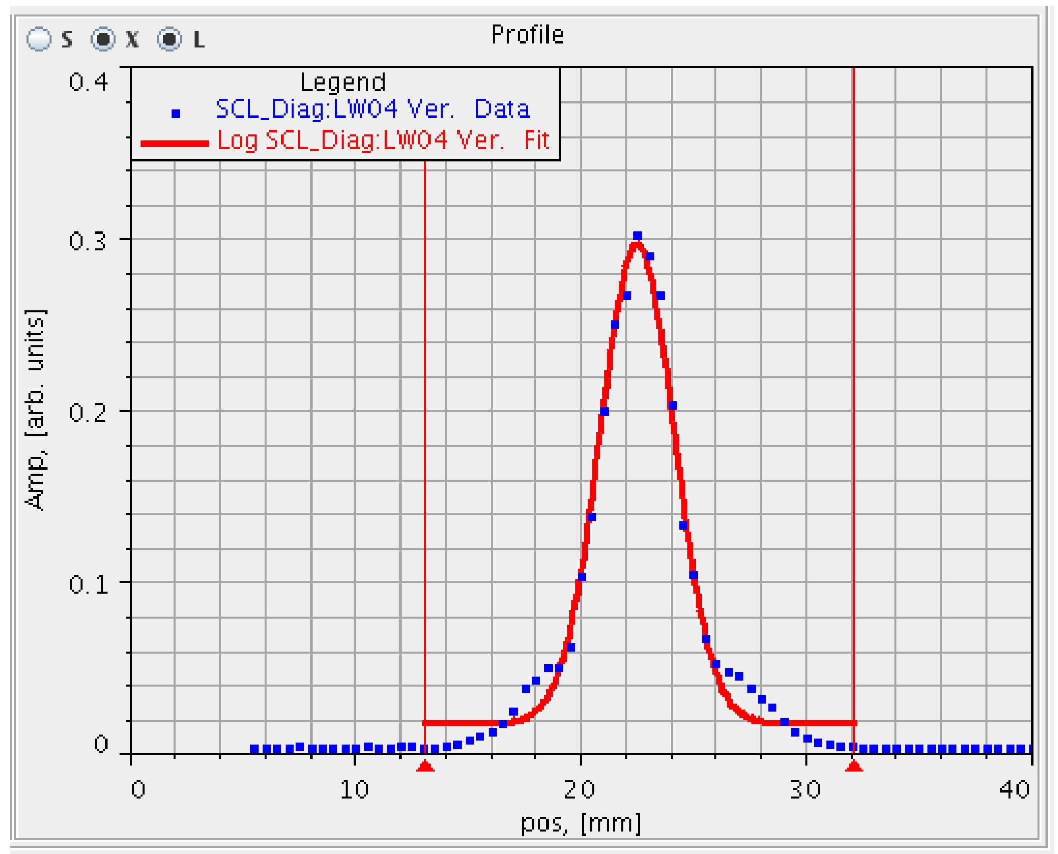
2015.11.15

Now we can reproduce RMS sizes along the whole SCL

Problem Non Gaussian Profiles

- Some LW profiles demonstrate big “shoulders”
- We can try to do transverse matching, but results may be different from expectations
- May be we need to check Warm linac settings and use multi-particle PIC code for optics planning



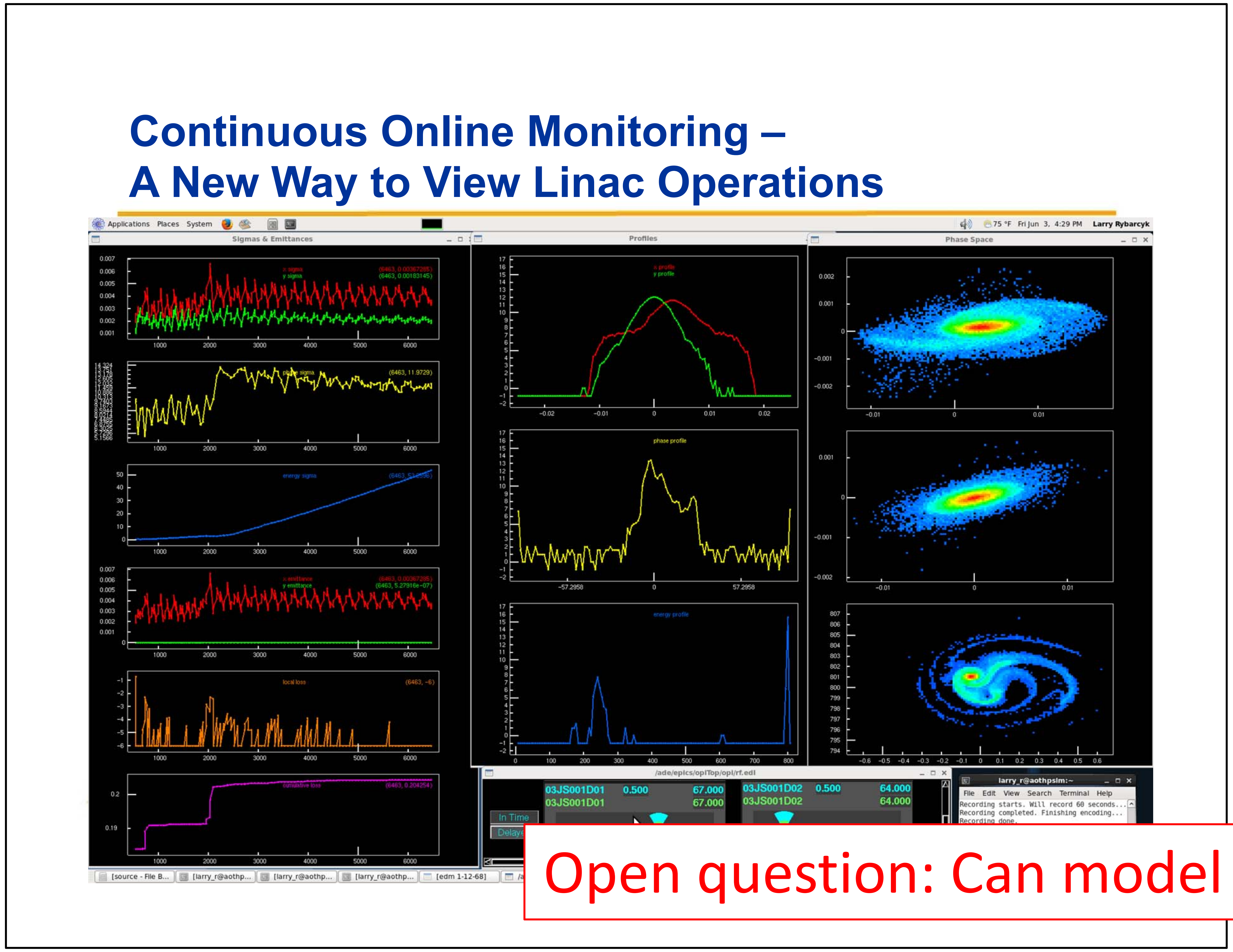


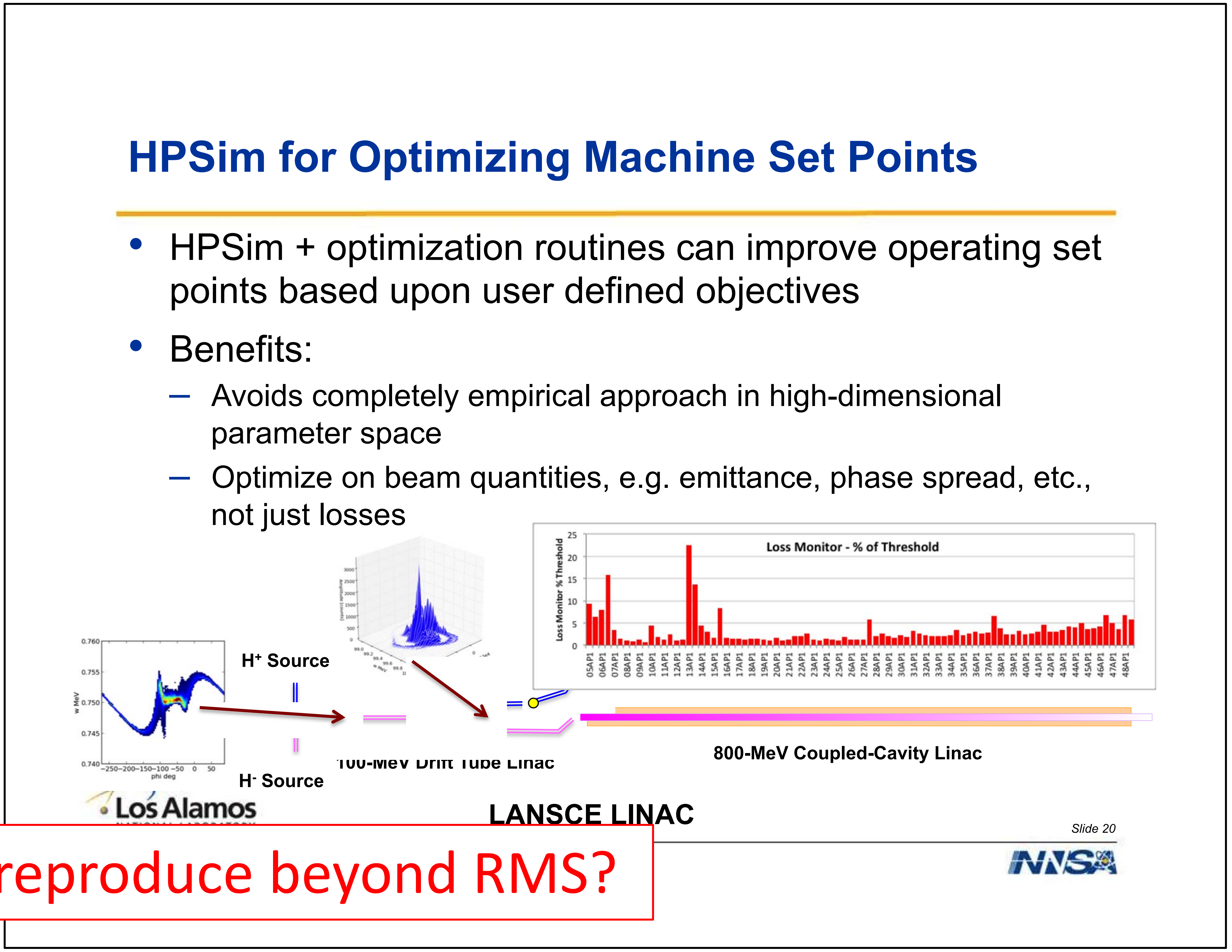
L. Rybarcyk

Model Benchmark: LANL

PIC-based online model developed

Model based tuning beyond RMS will be tested shortly





Open question: Can model reproduce beyond RMS?

Important topics

- To match or not to match? And if yes what?

- Low Energy Beam transport beam dynamics
  - need to extend our knowledge of the transition between plasma and extraction.
  - Need to find a correct way to track in a bending magnet

- Loss maps and their importance at the different stages (design, commissioning/implementation, power ramp-up)

To match or not to match?

And if yes what?

findings

- -At SNS the phenomenon of intra-beam stripping, which was not accounted for in the d esign phase, forced to take an empirical approach and set the quadrupoles in the high energy part of the linac to half the nominal value. In this way the losses could be minimised. Side effect is that the beam core is not matched. The fact of not matching has not prevented the machine from reaching the nominal specs (power 1.4 MW). A large acceptance of the ring is instrumental
- -at SNS there is no longitudinal matching yet, due to the fact that simulations and measurements do not give the same results and therefore simulations cannot be used as guideline for matching.
- -at LINAC4 during the commissioning much effort has been put at each stage to prepare simulations (tools, machine model, input beam from measurements after the source). Simulations have been key to a swift beam commissioning and information from measurements and simulations combined allows for obtaining a matched beam at each stage)
- -UNILAC reported that matching was the key to achieving world record intensity uranium beam TUAM1YO1 THPM9YO1
- -at IFMIF EVEDA it has been identified that loss control is a more important quality factor than emittance conservation as the beam goes on a target. Halo matching is the strategy. To study halo matching runs with 10^9 particles are necessary
- -LANL/LANSCE empirical matching is necessary to deliver the beam.
- -JPARC : matching and simulations are guidelines, no empirical tuning.
- -Chinese ADS/Chinese SNS : good agreement between measurements and simulations

Considerations on Matching High Intensity Linacs

- If the beam is sent to a target, the emittance growth **in not** the primary figure of merit
- To keep a hands-on maintenance, minimizing the machine activation **is mandatory**
- Accelerator matching method achieved by beam dynamics simulations should be **transposed directly** to the real machine tuning phase.

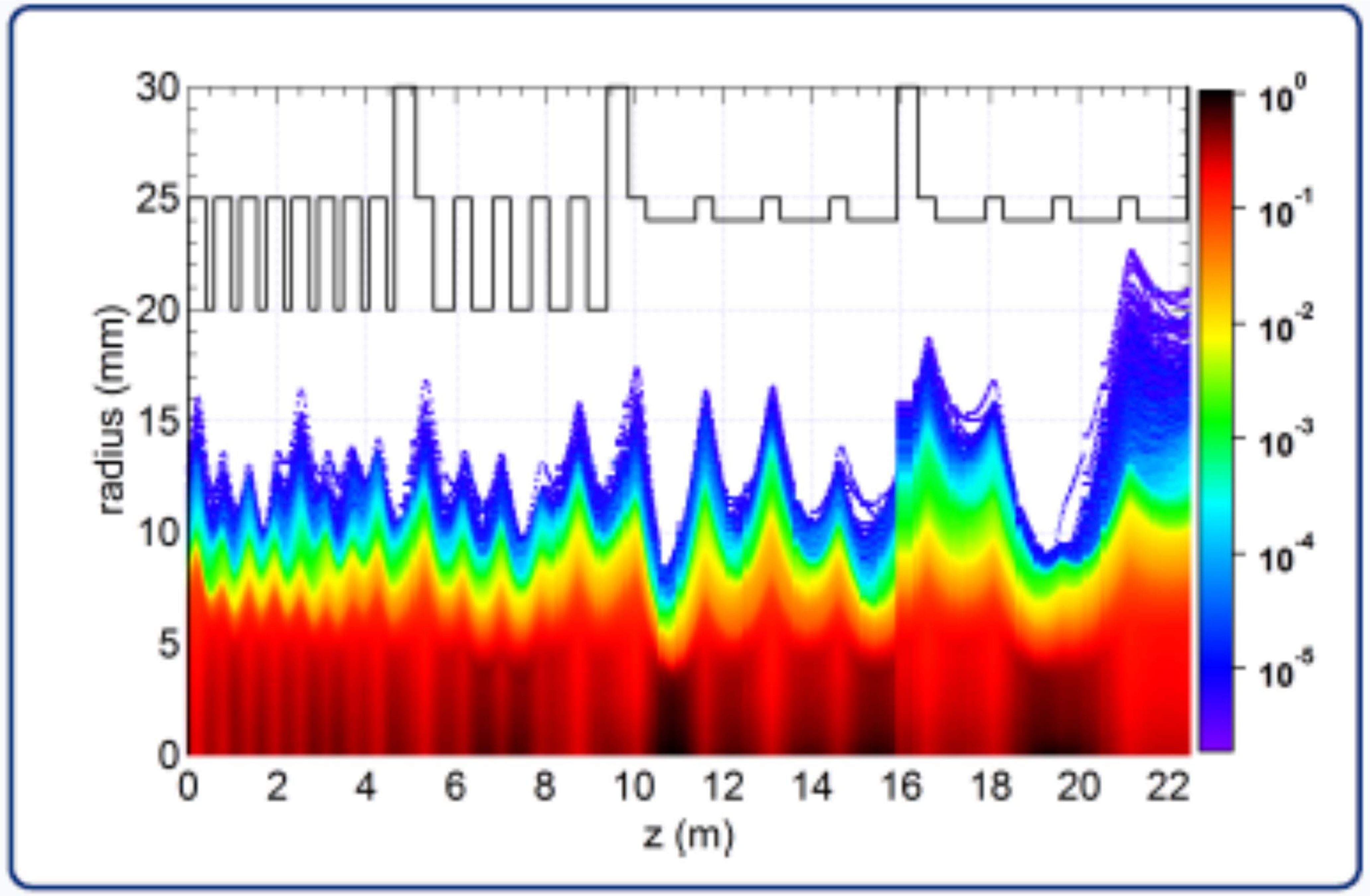
TUAM2YO1

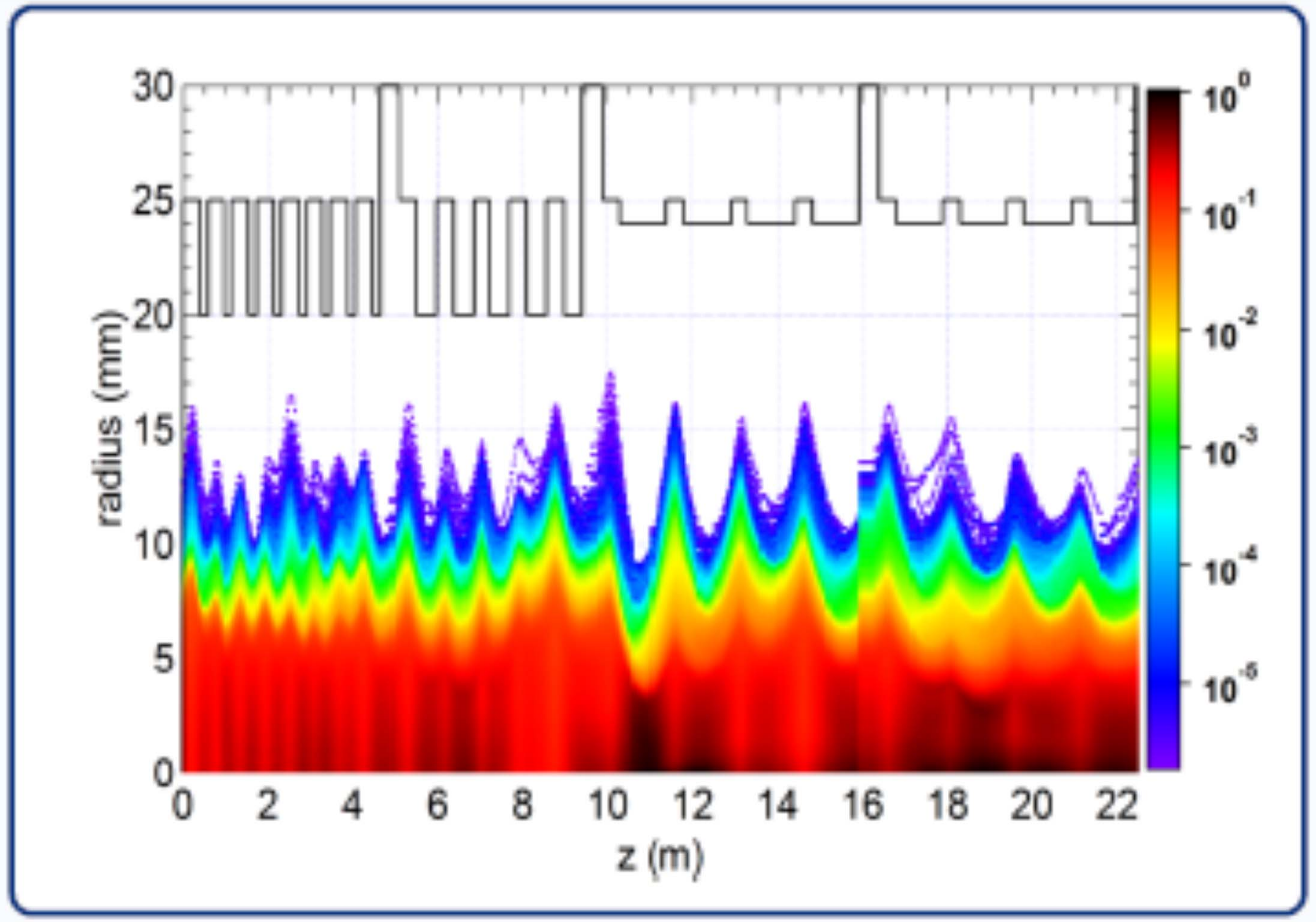
Linac Matching

- Minimization of beam extent
- Directly minimization of

Real Machine tuning

- Minimization of beam losses
- Loss detection at 10^{-6} of

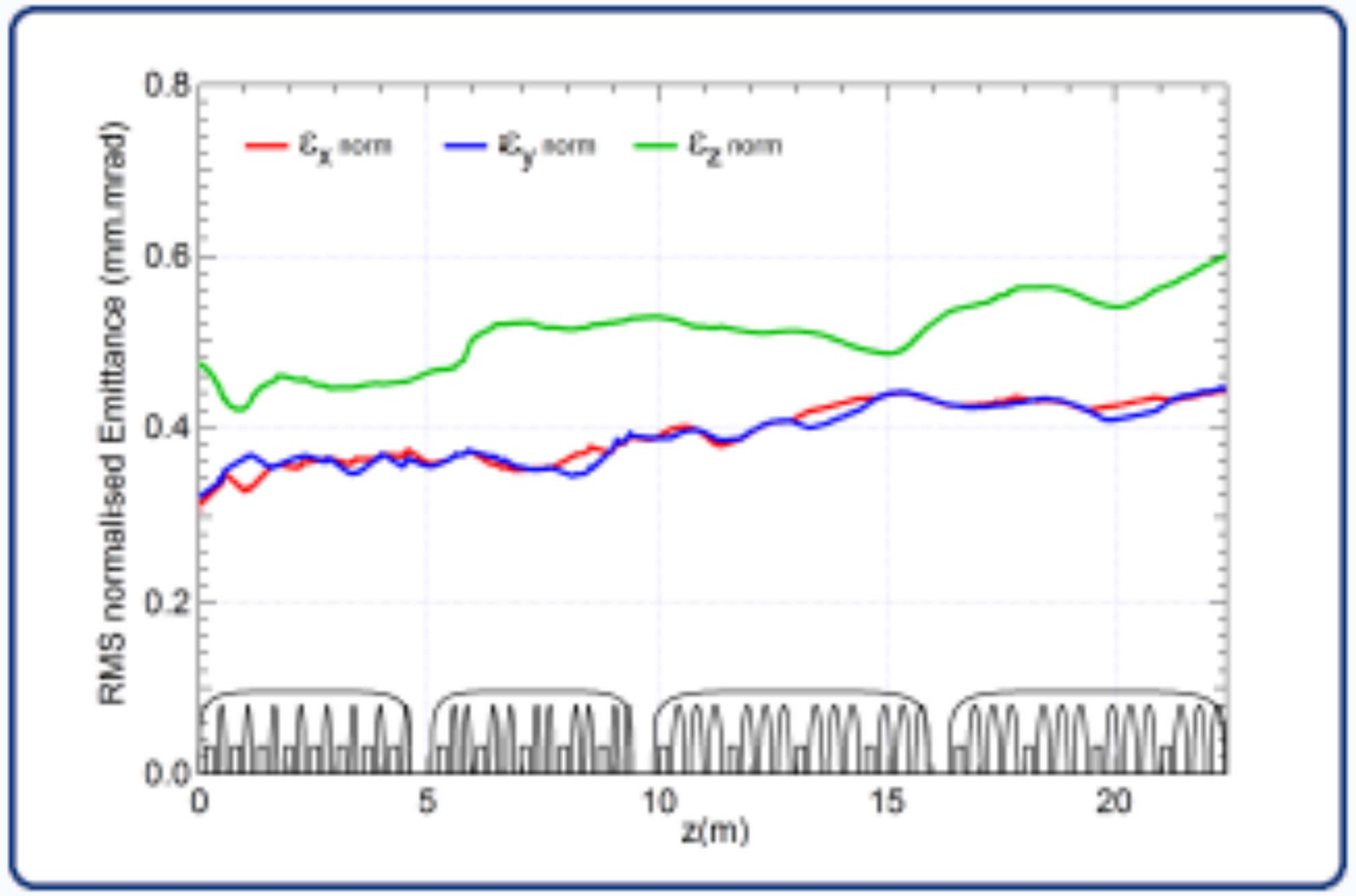


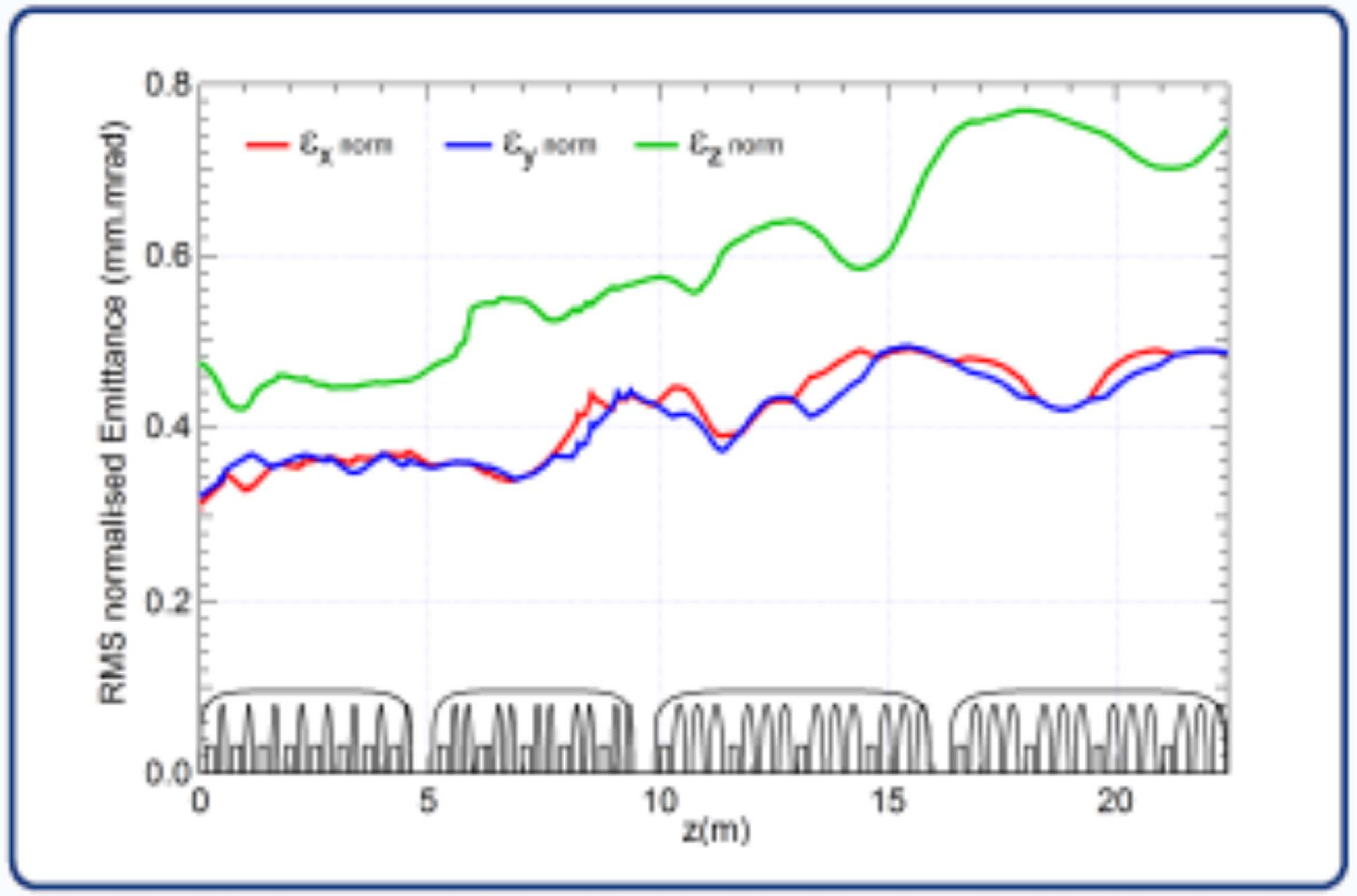


Emittance/RMS matching

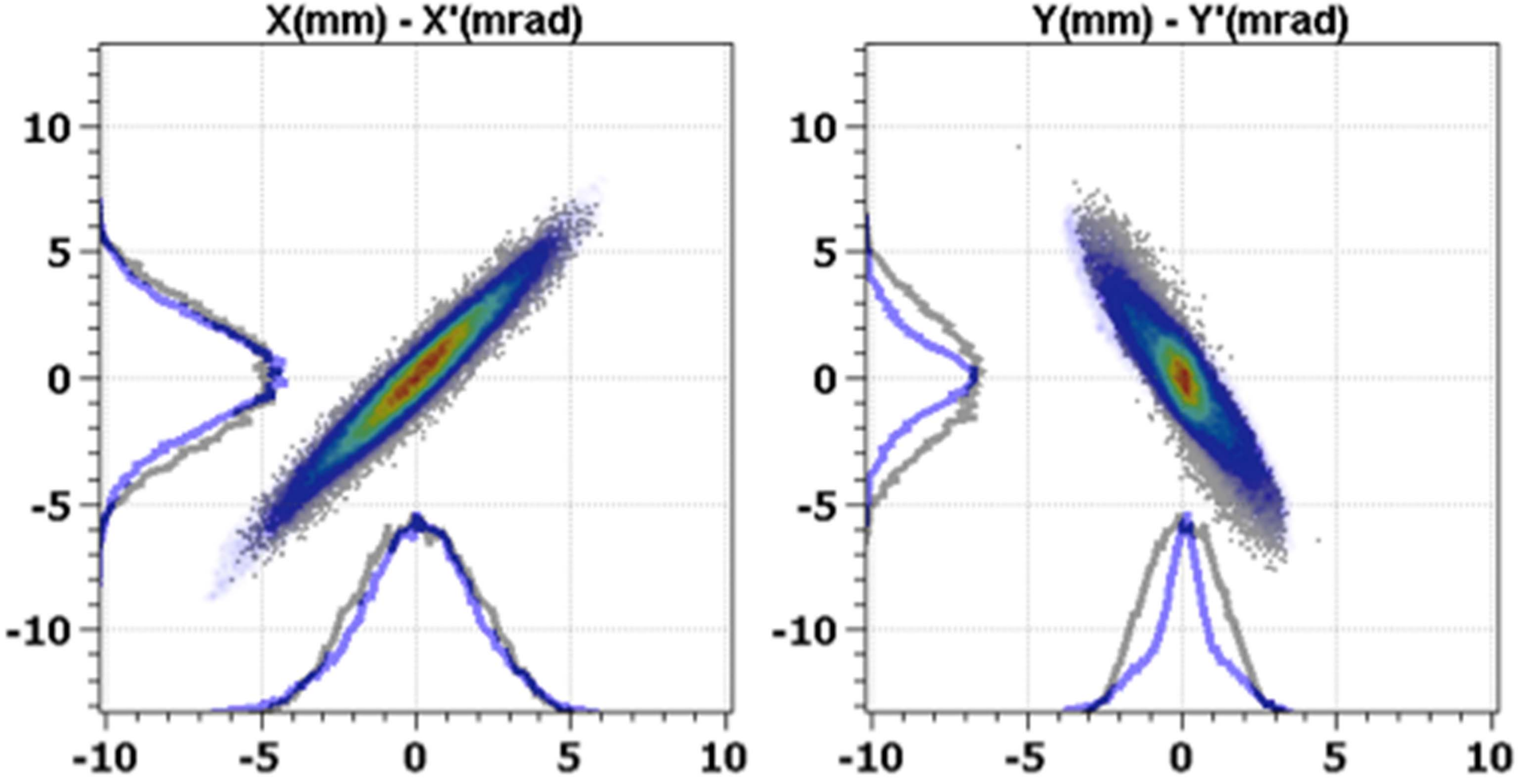
Halo matching

TUAM2YO1





Comparison of expected and measured beams

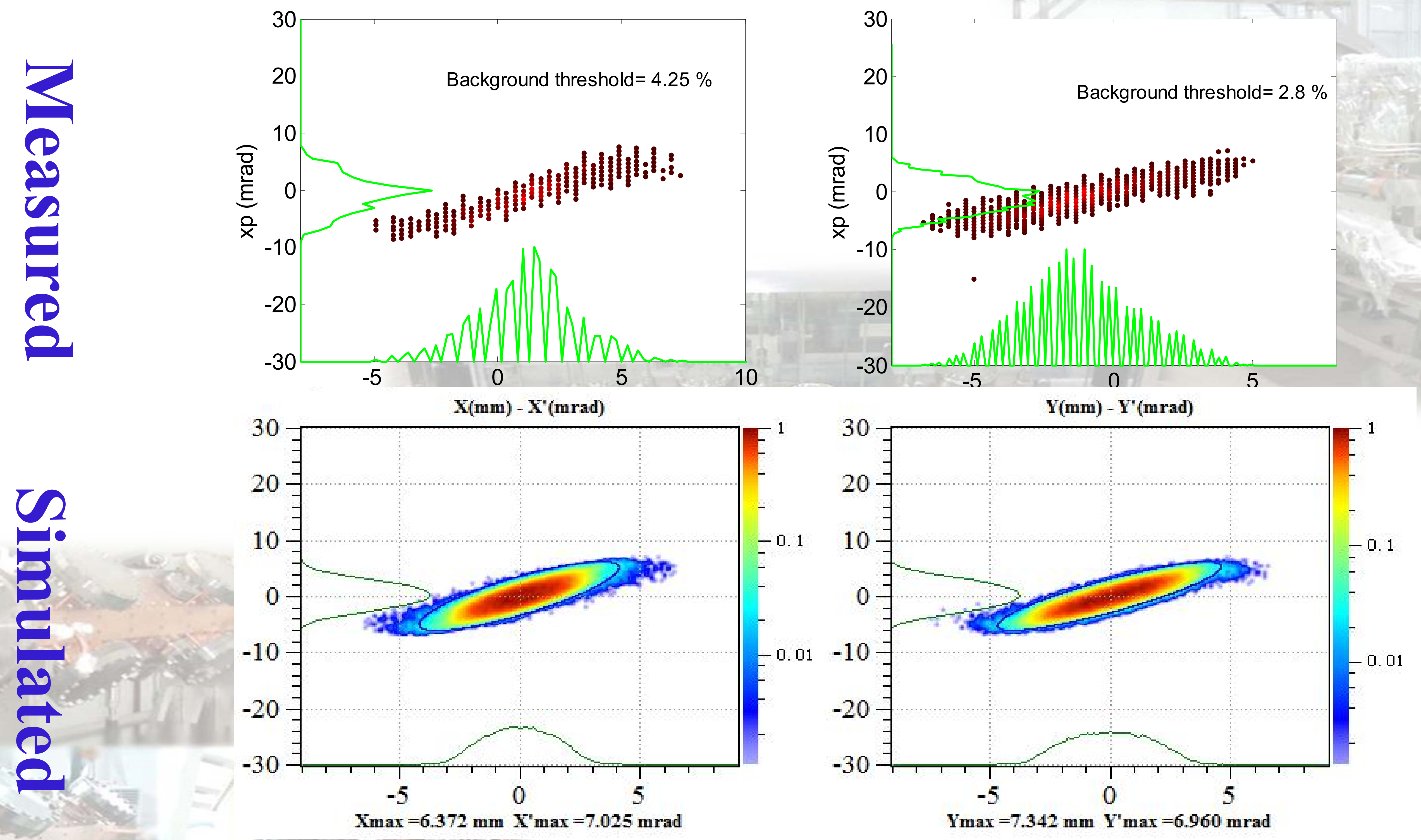


WEPM1YO1

Comparison of phase space plots of the expected beam (grayscale) and measured at 50 MeV (colour scale) after the DTL.

6. Experiment results

Transverse emittance measurement results V.S simulation at the exit of CM1 with nominal design



TUAM4YO1

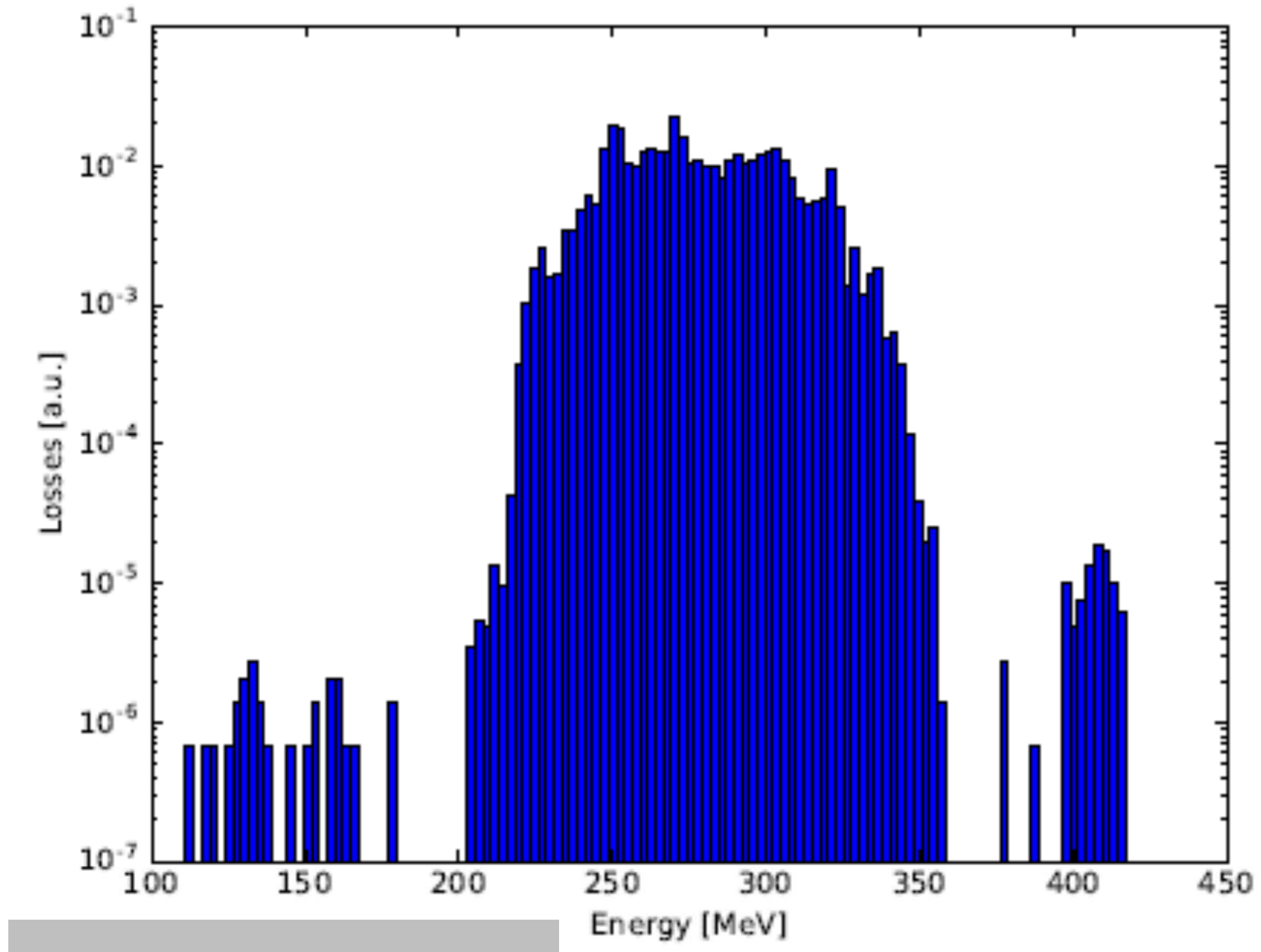
Parameters		αx/αy	βx/ βy (mm/mrad)	$E_{n,rms,x/y}$ (π mm.mrad)
CM1 exit	Simulation results (errors not included)	-1.53/-1.55	1.20/1.63	0.20/0.25
	Measurement (Double slits)	-2.12/-1.97	1.56/1.81	0.29/0.27
RFQ exit	Simulation results (4D WB input)	-1.31/1.46	0.12/0.13	0.20/0.20
	Measurement (Quads scan: with SC)	-1.22/1.10	0.16/0.10	0.16/0.24

Discussion on matching

- People feel that some kind of control/understanding of the beam parameters evolution is necessary to fully exploit the potential of a linac.
- Simulations are an extra diagnostics tool (HPSIM- WEPM4YO1)
- Issue seems to be a good knowledge of the input beam although C-SNS obtain good agreement also with a Gaussian beam input distribution.
- Questions and outlook : is it possible to find guidelines so that both the rms is matched AND the halo is contained ?

Loss maps - limit of 1W/m

Energy distribution of losses



- Losses in Med.-β and beginning of High-β
- Clear cut at Med.-β input energy (216 MeV)
- Frequency jump challenging

TUAM3YO1

Loss map are an important diagnostic tool to check linac design robustness BUT they depend on the combination of error used during the error studies statical runs. In the convener's opinion looking at the acceptance budget and bottlenecks is a more effective way to look at the problem. Simulations cannot reproduce quantitatively the actual losses.

Low Energy Beam Transport beam dynamics

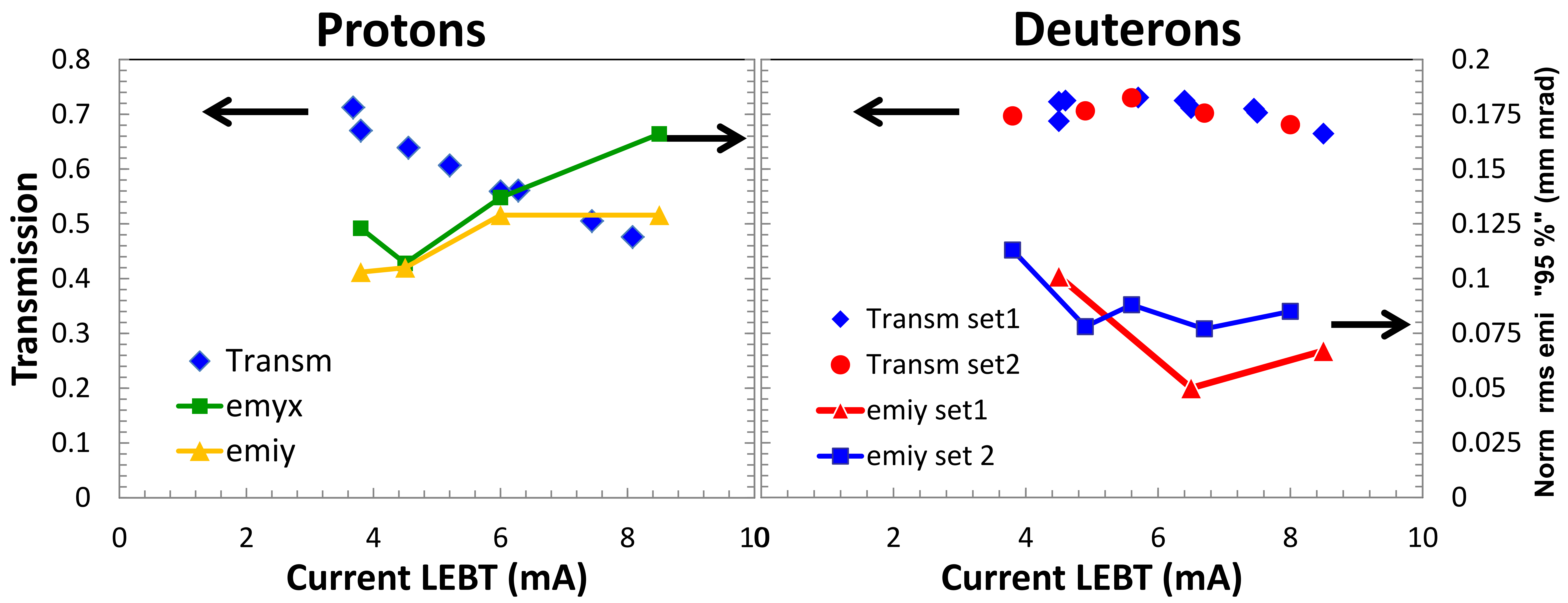
This is where we seem to need a lot of effort

findings

- SARAF : preinjector transmission about 70% RFQ transmission not sensitive to the lebt parameter change. Not understood why. Also there might be incertitude from the calculation of the space charge in bending magnets at the low energy end
- Linac4 : pre-injector transmission about 70% due to emittance at the RFQ input exceeding the acceptance. Not yet understood what is the mechanisms of emittance formation in the source/plasma/extraction area. Simulation of this part do not match measurements. At xx (comunian) simulations strarting from the plasma meniscus. How to obtain the condition at the plasma meniscus is not clear . Good insight in Bilbao
- Ingredients : neutralisation, multicharge and separation, space charge in bending magnet , asymmetric beam , strongly non-uniform distribution for beams coming out of ECR.

RFQ transmission study

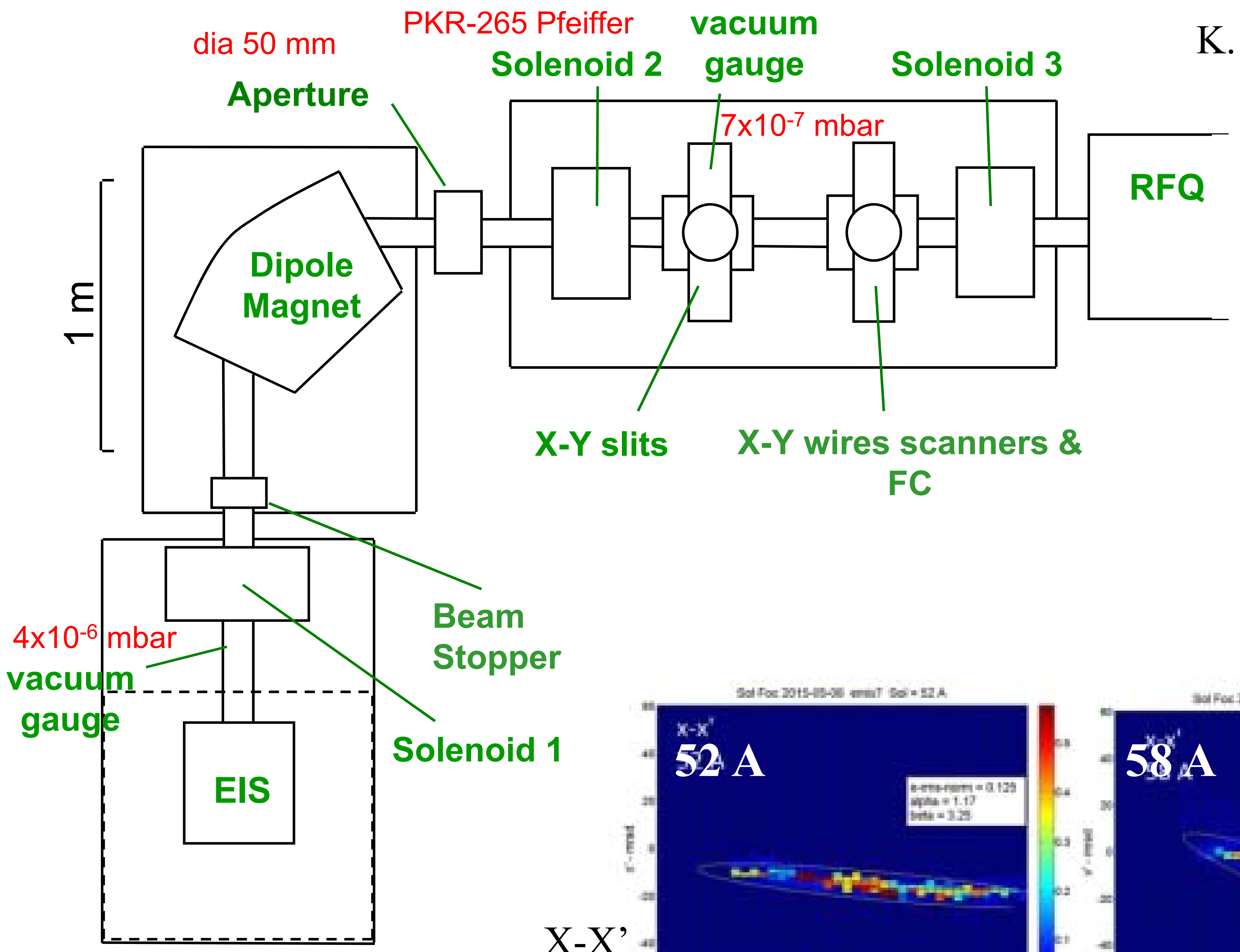
TUAM1YO1



Why RFQ transmission is not sensitive, in a wide range, to LEBT some beam optic, LEBT vacuum and entrance flange electron suppressor voltage?

Protons are more sensitive to space charge. What is the LEBT space charge effect?

Study of LEBT beam matching to RFQ



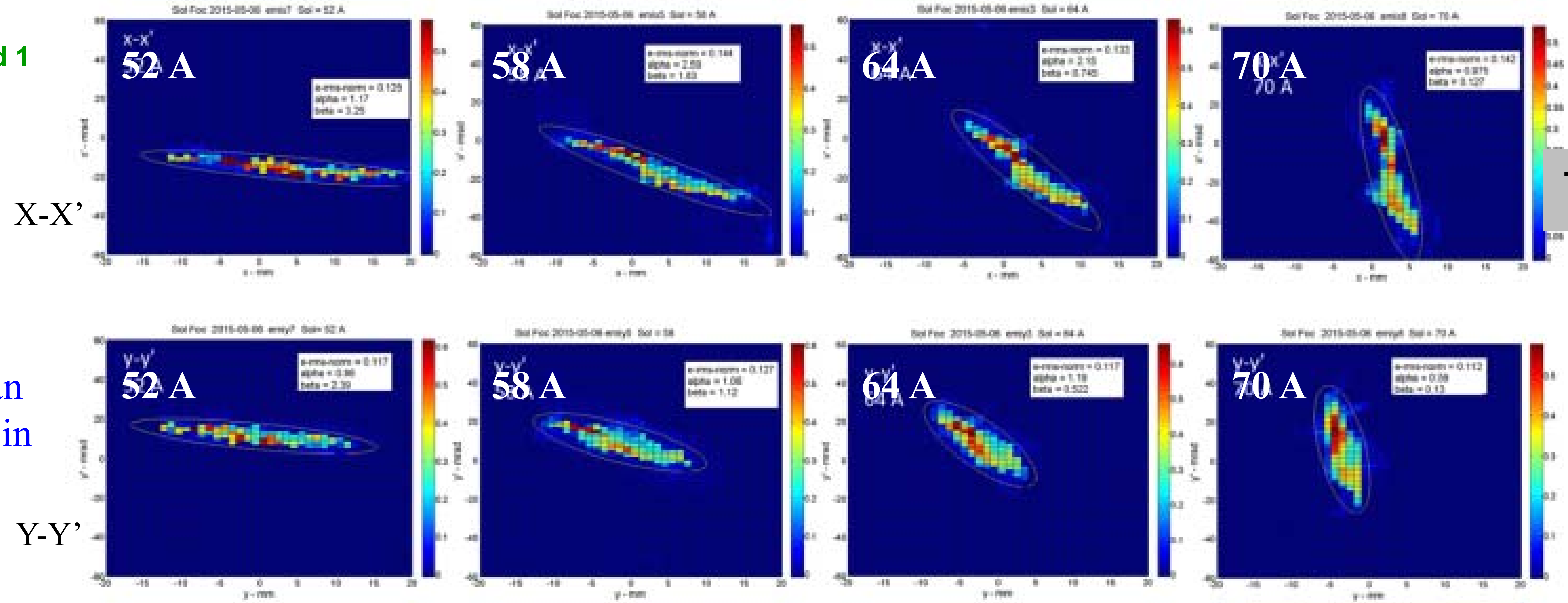
K. Dunkel, PAC 2007

phase space measured by slit and wire for 20 keV 5 mA protons beam as function of solenoid #2 current.

Results: rms norm. emittance is constant

ε_x=0.14±0.01 ε_y=0.12±0.01 π mm mrad

space charge neutralization time ~0.2-2 ms << pulses of 20 ms

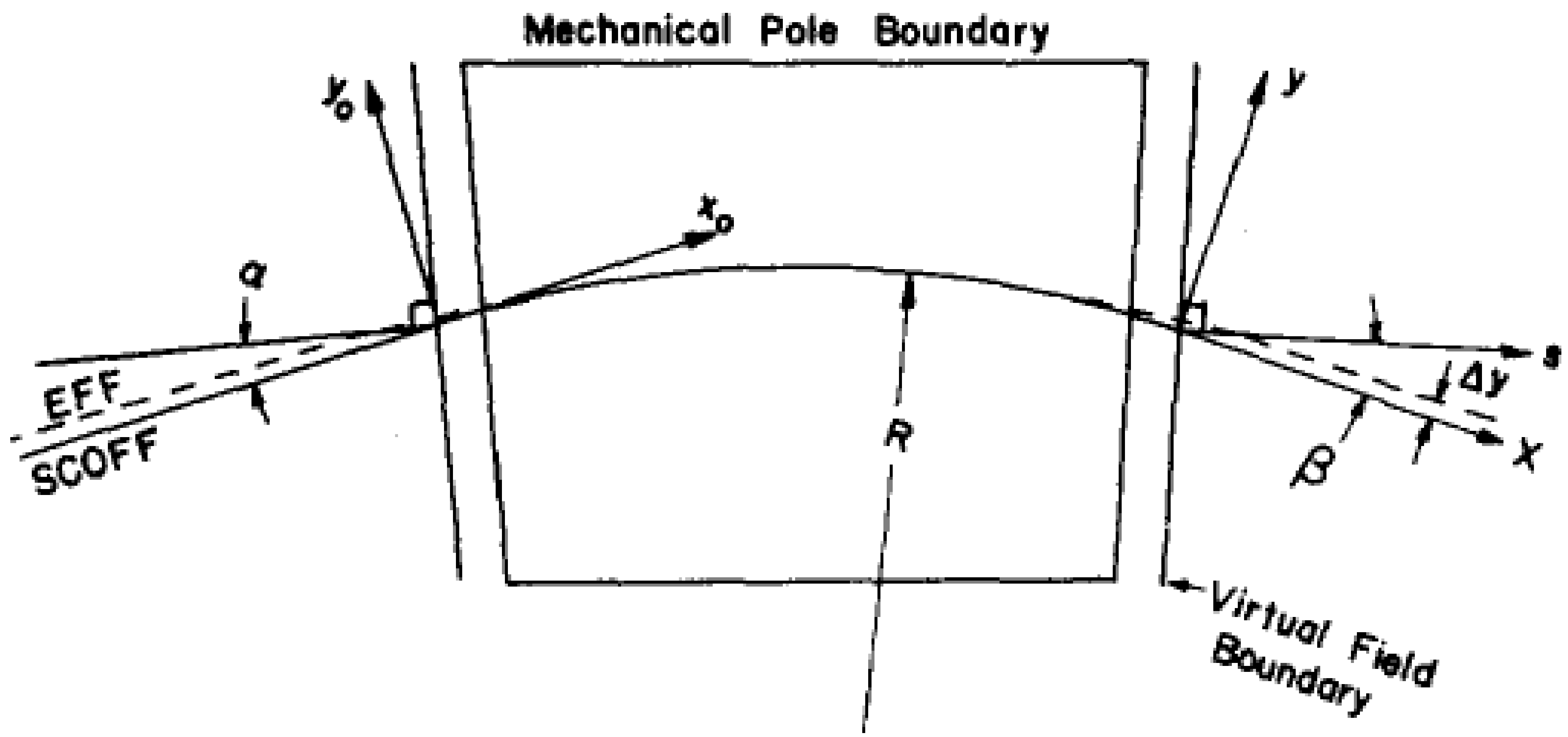


TUAM1YO1

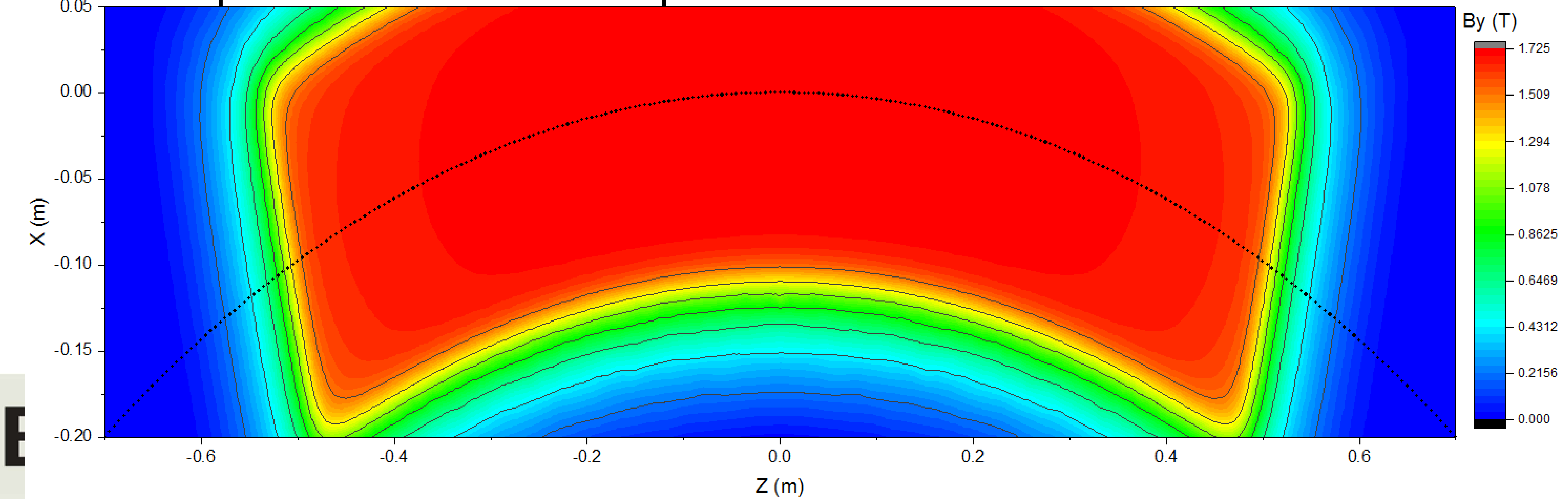
A. Shor and L. Weissman accepted for publication in JINST 2016

Orbit Displacement due to Dipole Fringe Field

- H. A. Enge, RSI,1964
  Due to fringe field effect of dipole, displacements of the beam center line at both entrance and exit (a "zeroth-order" effect)



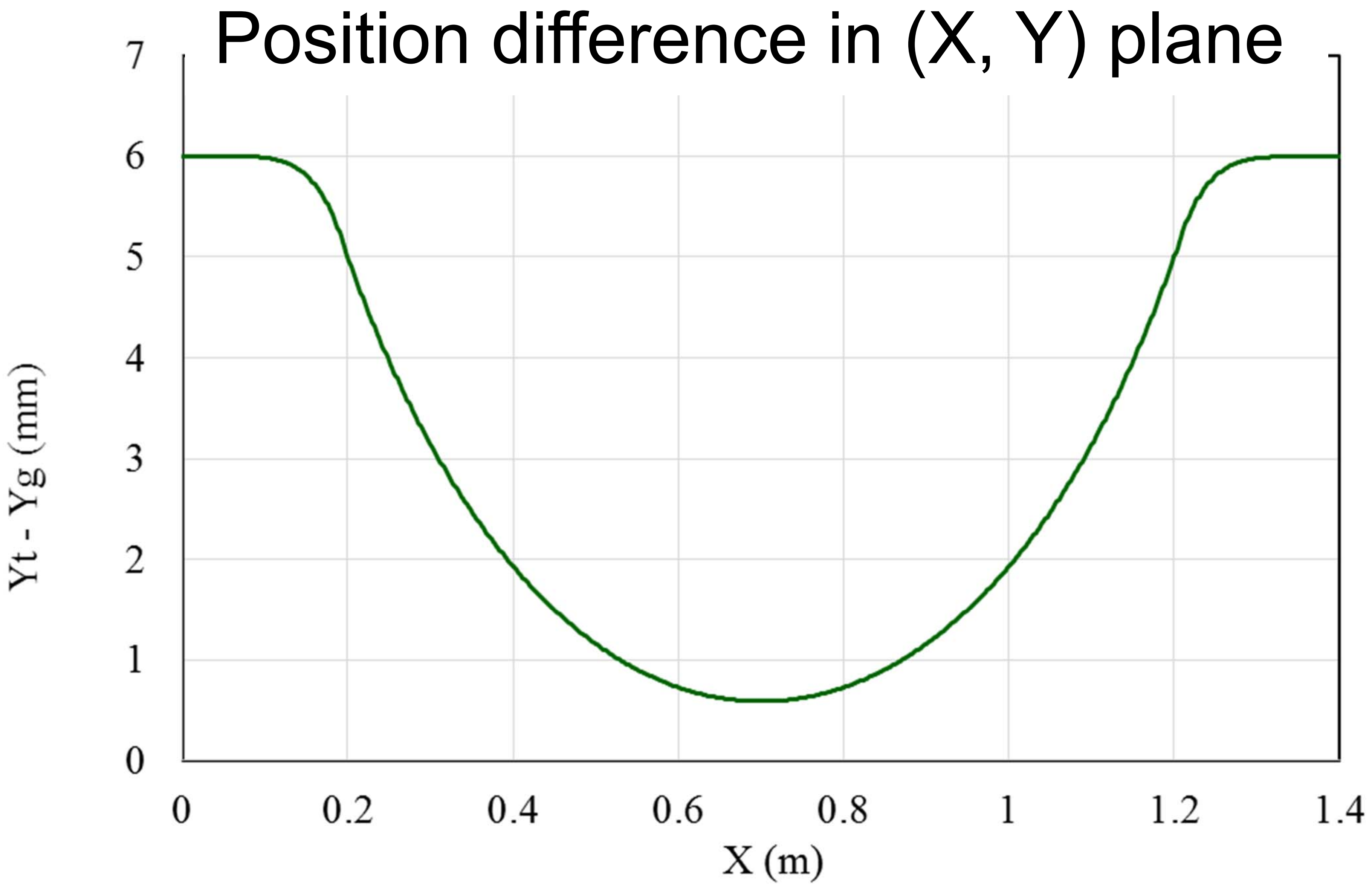
Midplane field of the 45º dipole in the first 180 bender with orbits

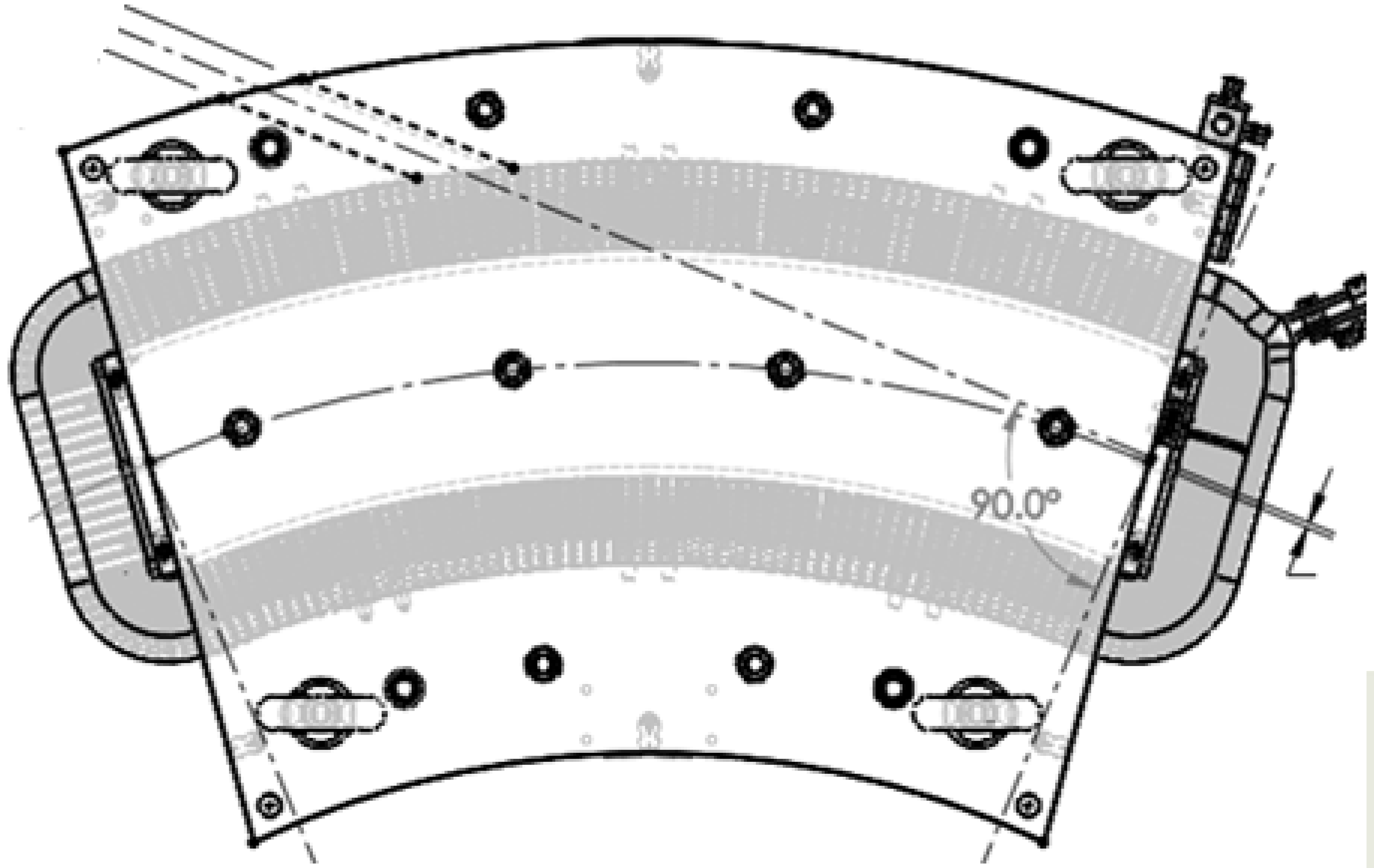


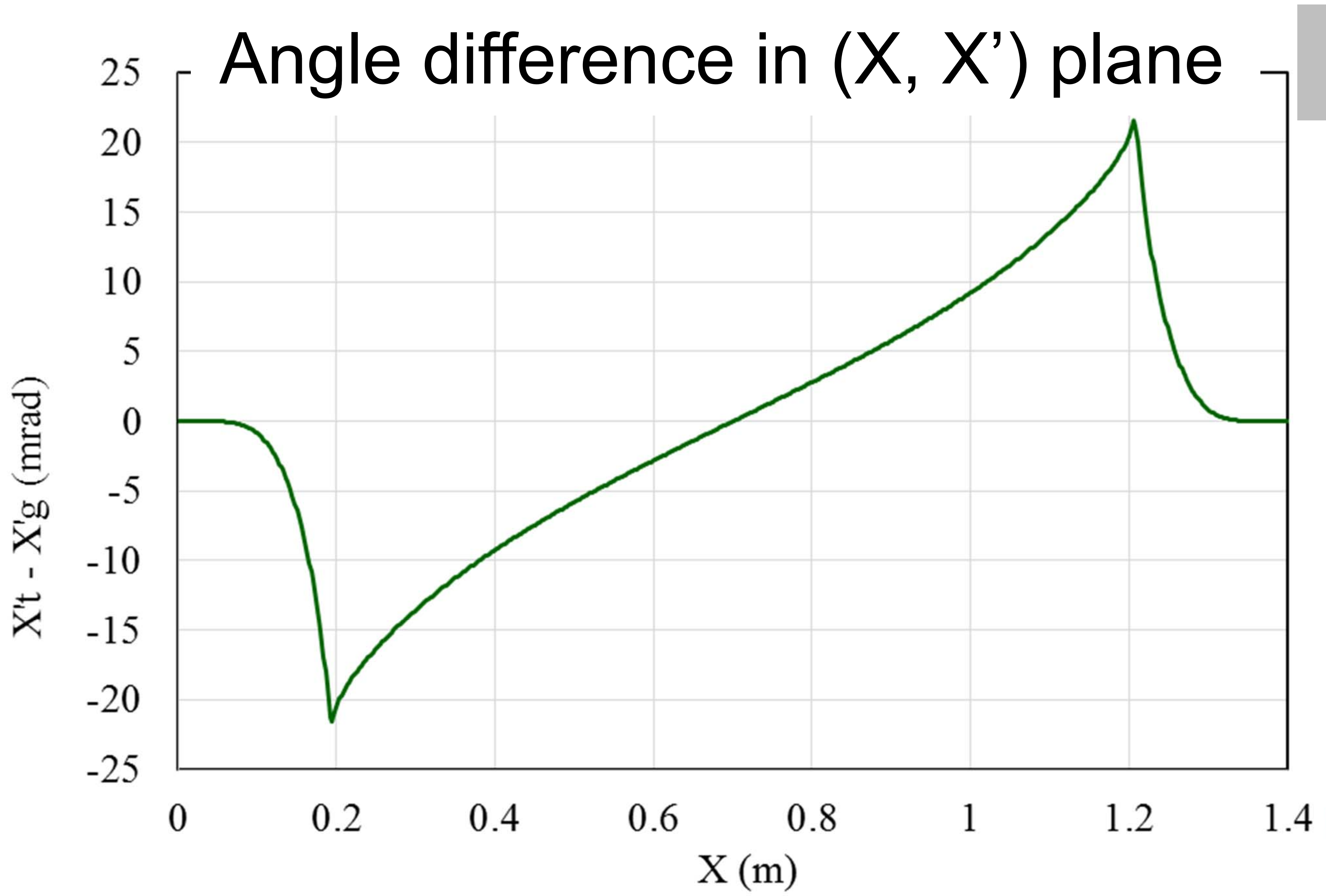
TUAM5YO1

Orbit Difference in the Midplane of 45º Dipole

- Orbits difference between 3D map field and hard-edge model of dipole
- A few different excitation currents used to take account of saturation
- Displacement of magnet implemented into fabrication drawings



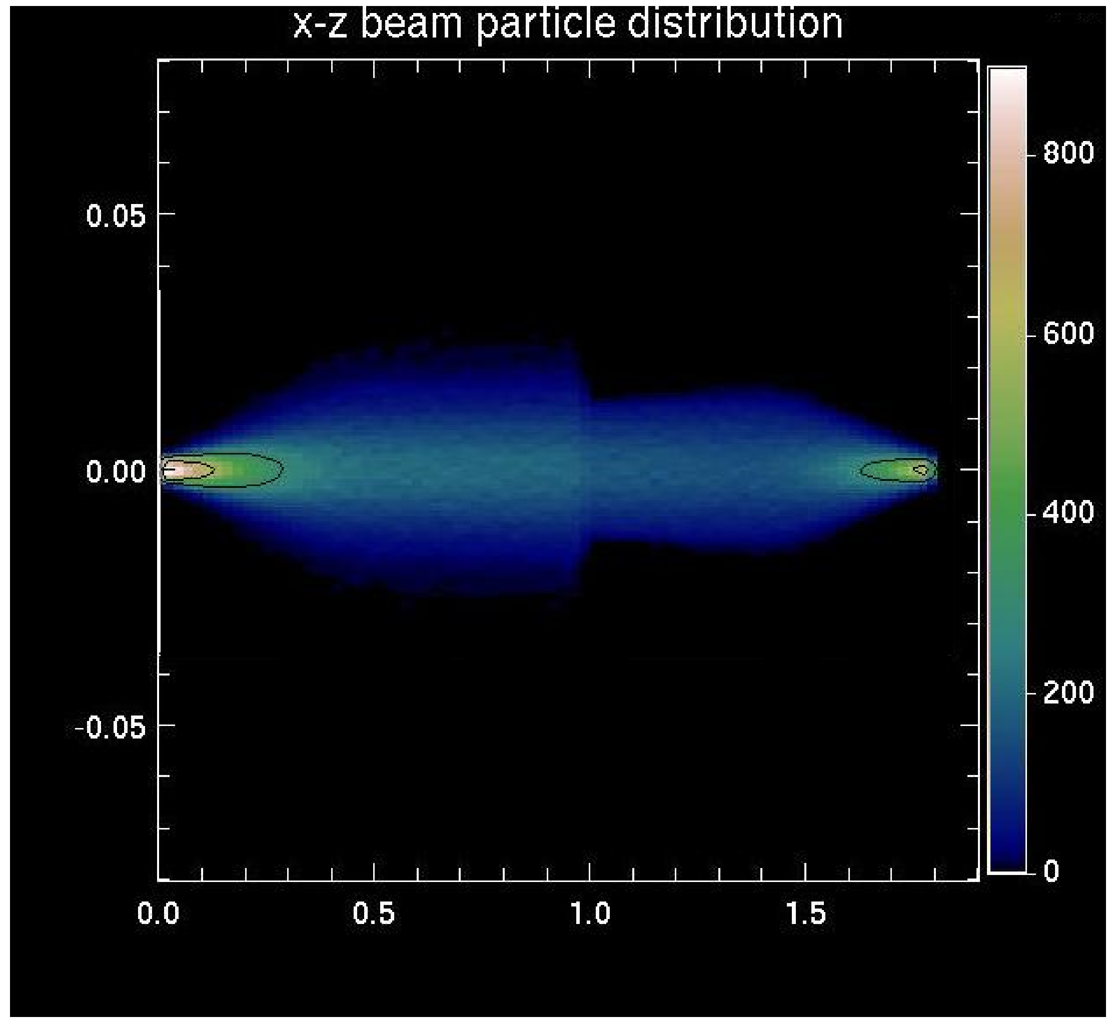


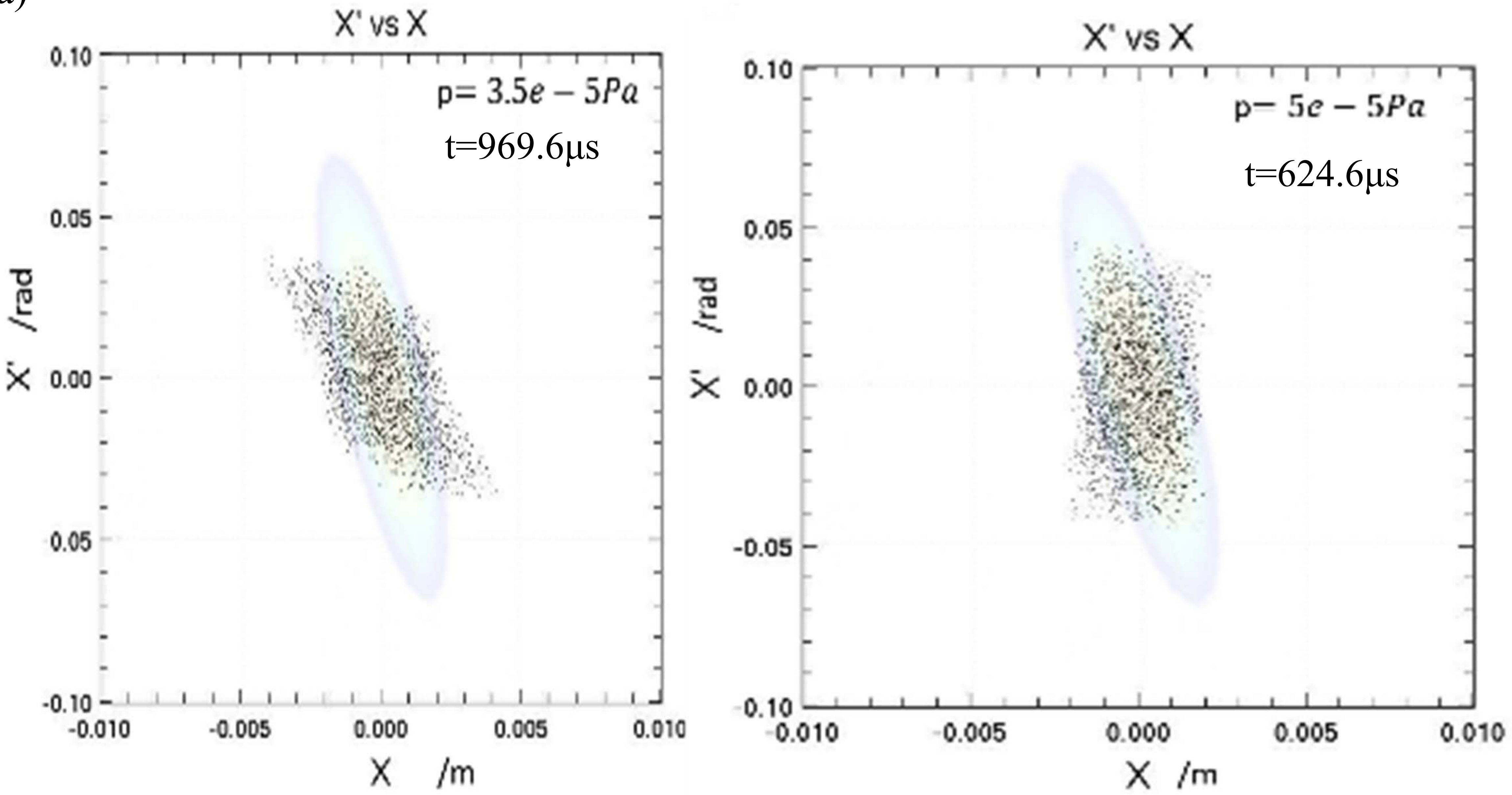


TUAM5YO1

Simulation Results

(beam envelop at t=969.6, pressure=3.5e-5pa)





(phase space at the LEBT exit, the shadow represents the acceptance of the RFQ)

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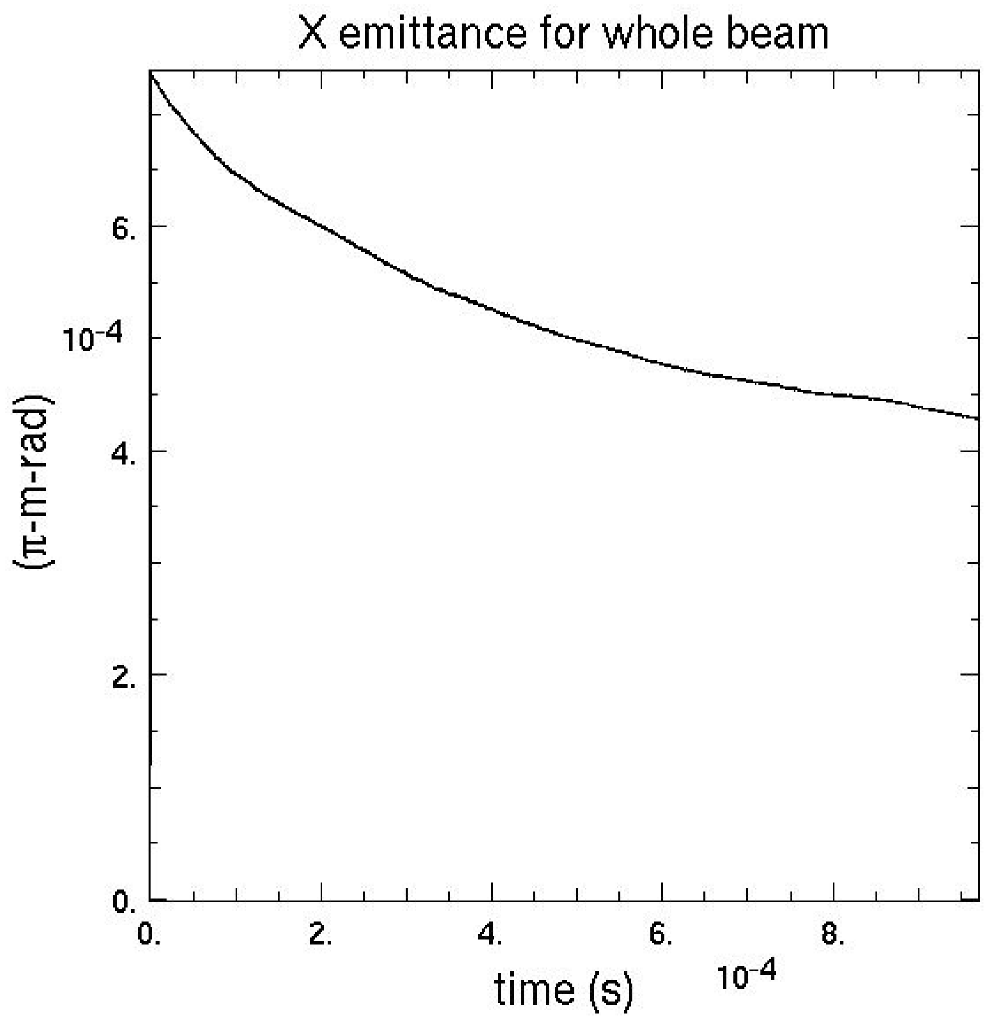


Argon gas injection:

pressure range 3.5e-5Pa~5e-5Pa

SCC build-up time > 800µs

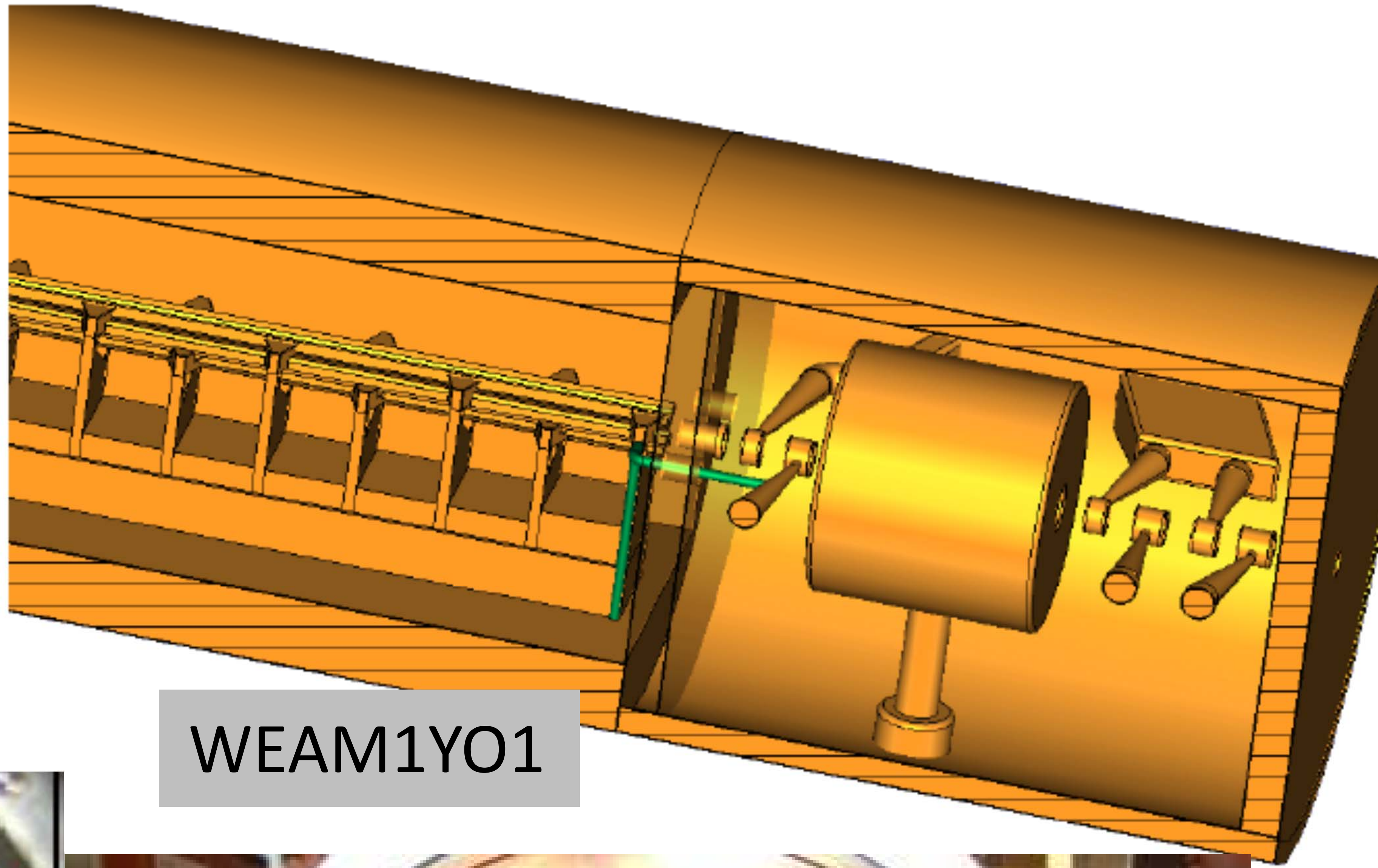
Discussion on LEBT

- We have several tracking codes to describe the Low energy beam transport
- None of them is properly interfaced with a plasma-code
- We miss
  - Validation of the codes (for complex system including multiple charge states and bending magnets)
  - More insight in neutralisation (i.e. cross sections and other crucial parameters)
  - Information on the input beam at the “meniscus” and/or description of plasma

Questions and outlook : how can we integrate the simulation of the source in the simulation of the rest of the linac?

Open questions

- Is it possible to find guidelines so that both the rms is matched AND the halo is contained?
- How can we integrate the simulation of the source in the simulation of the rest of the linac?
- Can equipartioning be a design guideline to be robust against errors?
- Existing facilities show discrepancy between simulation models and machine operation , How this can be improved?
- What is figure of merit in design/operation? Can some emittance growth be tolerated?



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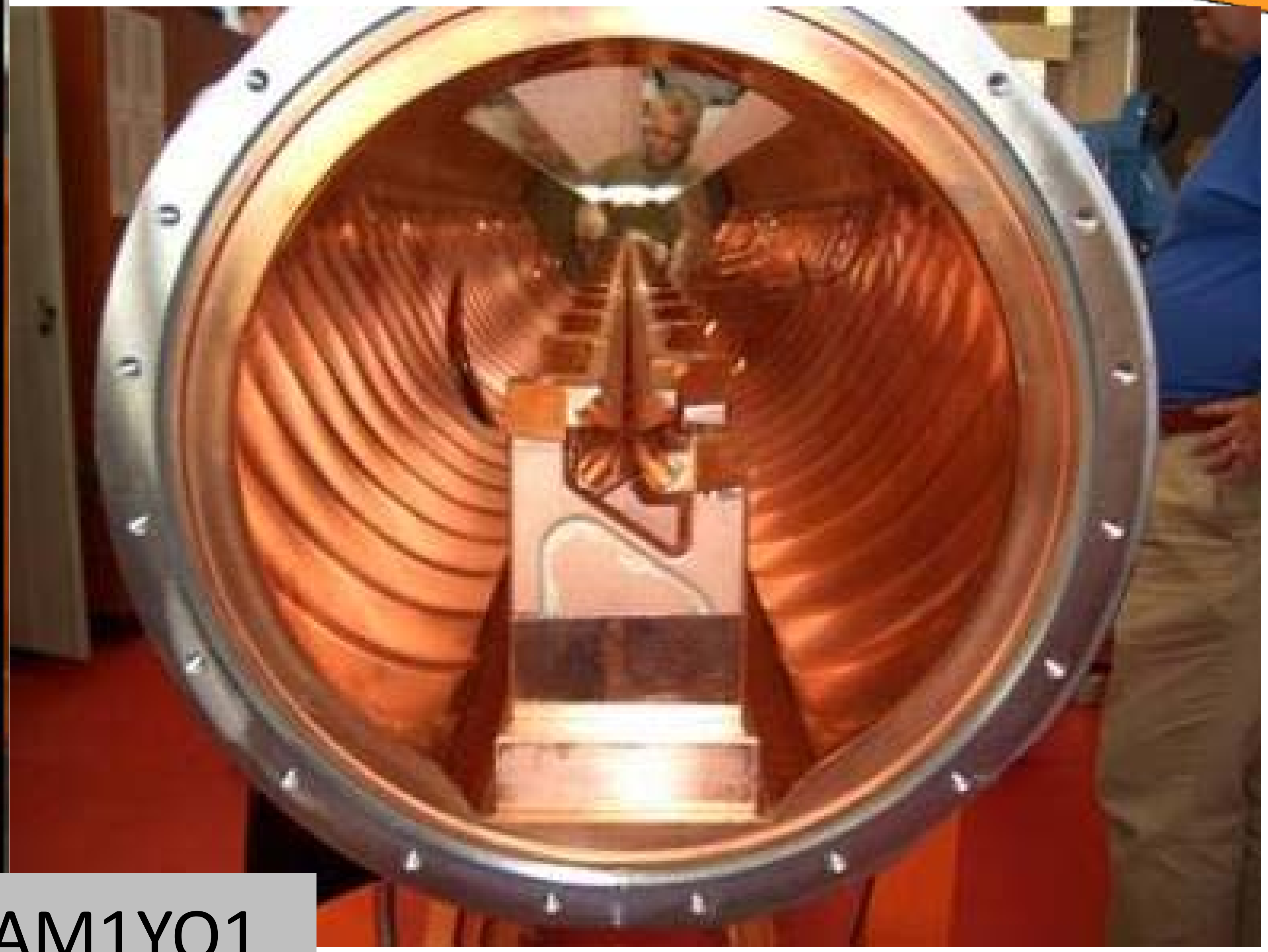

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