Dependence of RFQ beam parameters on RF power

V.Kapin, K. Seiya,
P.Karns, B.Schupbach, M.Wesley

23-May-2019

PS Physics Meeting

See also previous talks:

[1] V.Kapin, “RIL Upgrade”, Beams-doc-6117-v1, 21-Feb-2018
[2] V.Kapin, “Simulation Study of RIL: Update” , Beams-doc-6601-v1, 15-Aug 2018
[3] V.Kapin, “RIL Simulation: MEBT” , BeamDocs_6886-v1, 31-Oct 2018
[4] V.Kapin, “Simulations for RFQ & Extractor Tuning Range”, BD-7007, Feb-2019

RIL Study: Directions and Status

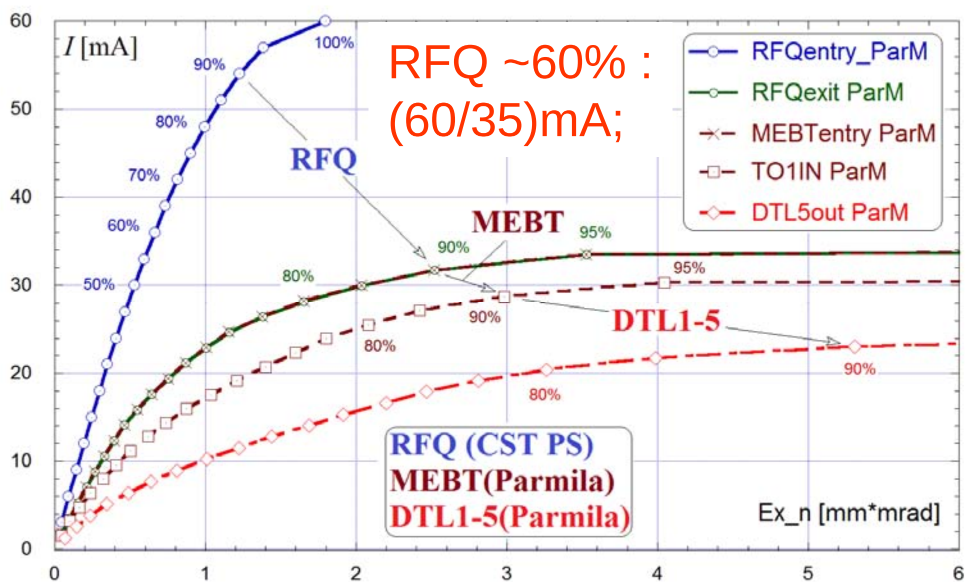
S.Y.Tan (Jun/2017):

- Beam **transmission** in RIL is <u>rather poor</u> during normal ops [VK:~40% (25mA/60)]
- the best (transm.) efficiency that was seen just after installation (Jun/2013) was 65 mA at L:ATOR and 36 mA at L:T01IN (2013-tests: I_{RFQ}->40mA measured)
- The goal is to improve transmission (at 28mA @L:TO1IN)

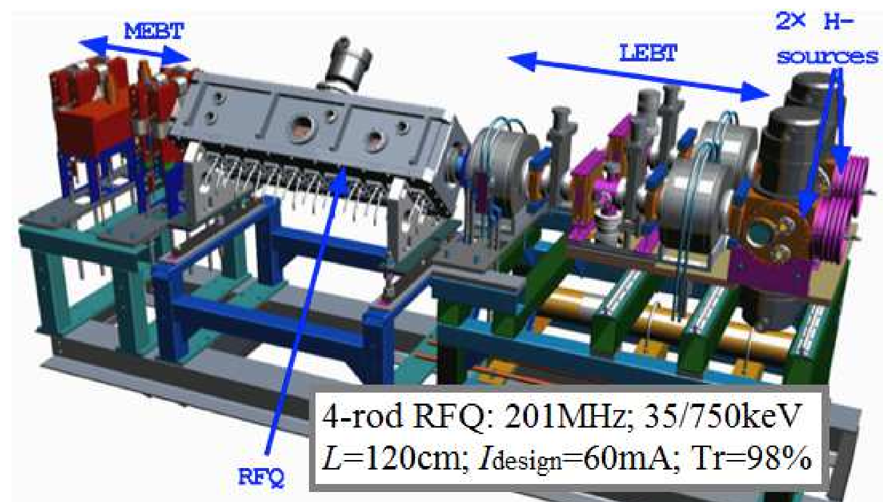
Feb-2018 discussion: "**beam quality**" (W.Pellico) => VK: "$I_{beam}=f(\varepsilon_{norm})$" along LINAC

Mar-2019 K.Seiya PS(Linac): need for **30mA @ Linac exit** (Beams-Doc-7330)

Old 2018 simulations[2]: RFQ&MEBT&DTLs



Derivative dI/dε always drops along linac!
Realistic fields in RFQ & MEBT with CST/PS



Diagnostics:

Tests ~2013: Emitt & Toroid @ RFQ_{exit}

Now: only at MEBT exit Emitt.& toroid

MEBT: 4Qs+4HD+4VD+2RF-gaps

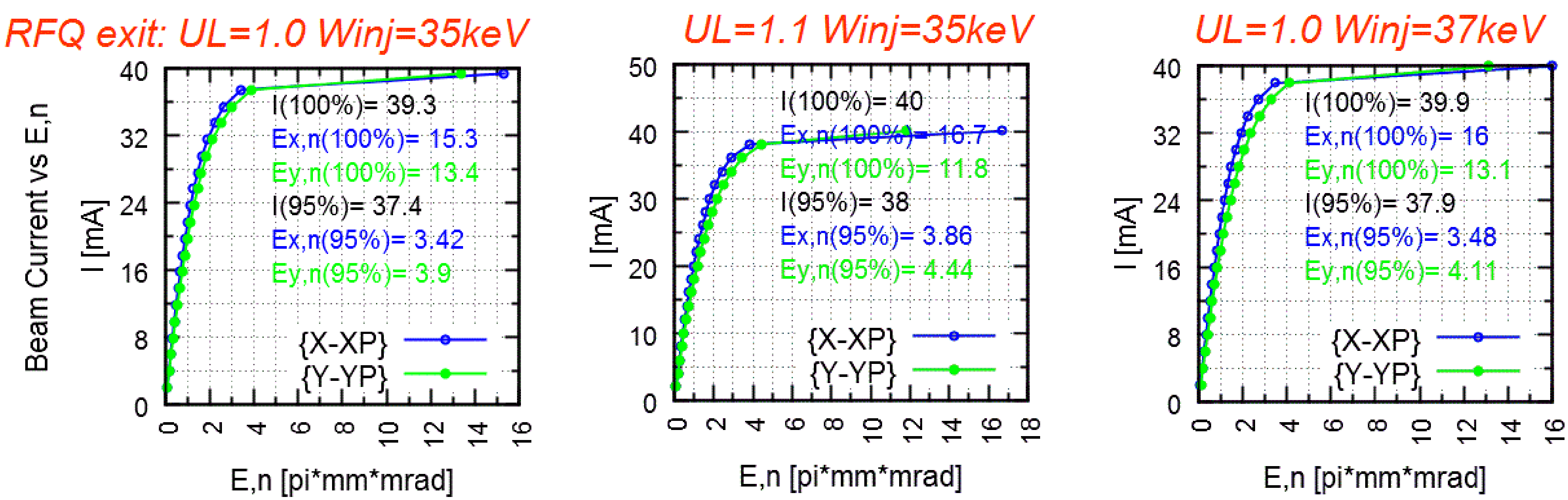
Refining simulation model for 4-rod RFQ

Refined RFQ model: *I* exit ~40mA @ Iinj =60mA (~67%)

- very near to achieved experimental maximum ~ 40mA !!!

Model refinement includes:

- Calculated effective RFQ acceptance (set of RF phases) [4]; a really matched beam (while E=5xErms, not 6 as Gaussian $\mathcal{E}_{95\%} = 6 \times \mathcal{E}_{rms}$)
- Size of simulation area adjusted (increased) to take all injected particles
- Even slightly higher I_{exit} with electrode voltage coeff 1.1 & Winj=37mA



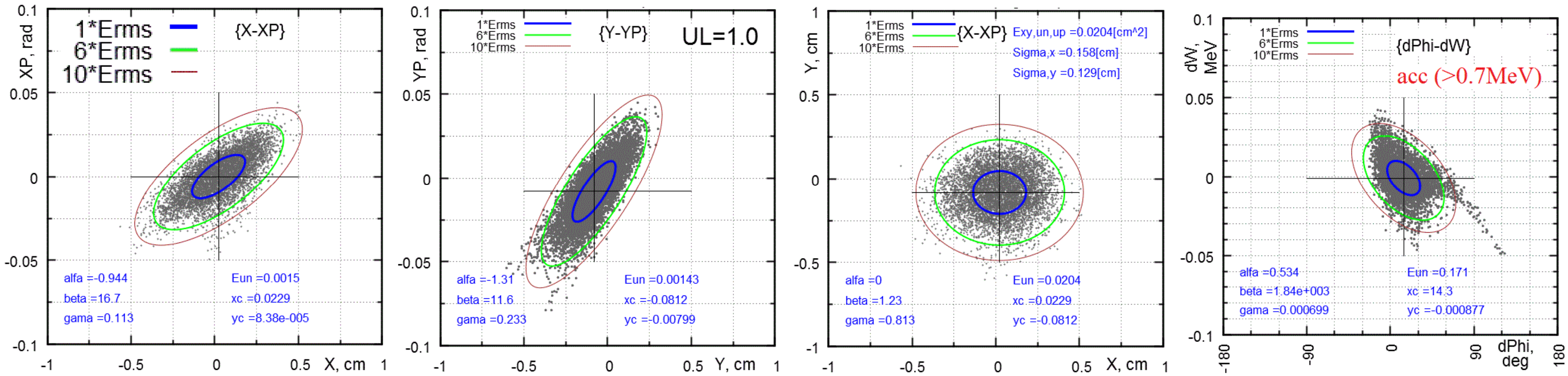
To understand RFQ - need to simulate dependence on ***RF power*** *& Winj beam*

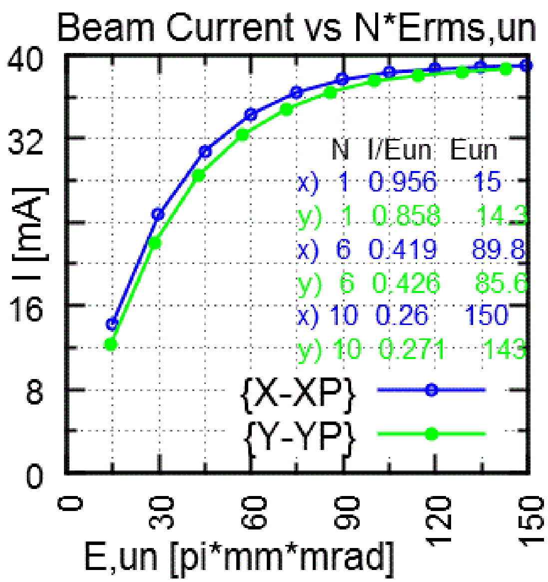
RFQ: $\mathcal{E}_{rms,x\&y}$ growth ~20%.

4-rod RFQ exit: phase spaces with RMS-ellipses

Phase-spaces {X-X'}; {Y-Y'}; {X-Y} & {dPhi-dW} and NxRMS ellipses (N=1,6,10)

Emittance dilutions: $\mathcal{E}$rms,x&y growth ~20%; many particles outside of 6xErms (exactly =95% for ideal Gaussian)





Essetial percentage of particles (I beam) are at large E,un => Potential beam losses at MEBT, DTLs, ….. Booster

Note values for N=1,6,10 E=NxErms:

X-XP: j=0.96(N=1); j=0.42 (N=6); j=0.26(N=10)

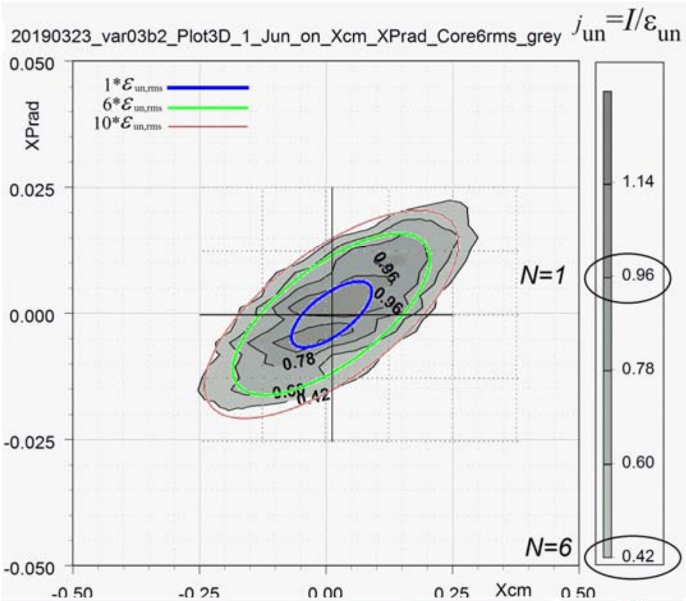
Y-YP: j=0.86(N=1); j=0.43 (N=6); j=0.27(N=10).

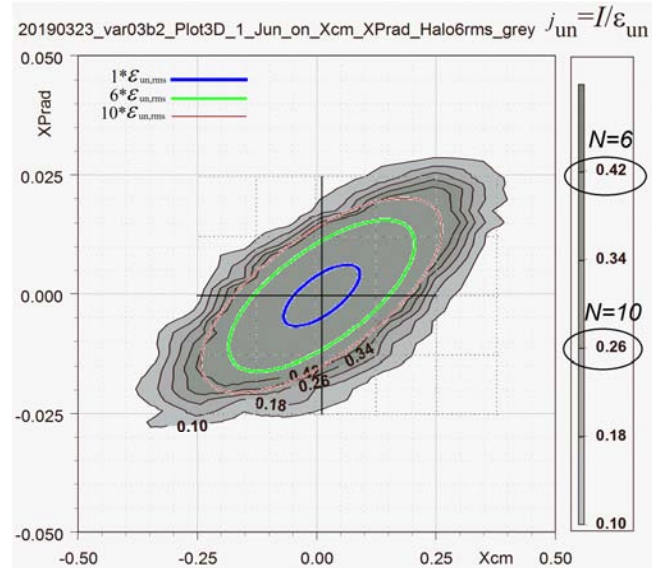
(used later – see counter plots)

Note. Dot plots could not visualize density distribution – Every dot => different number of particles => 3D plots

(Bad) beam quality vs rms-ellipses with 3D plots - 1

Usual dot plots could not visualize density; ***beam core (left)*** *and* ***beam halo (right)***





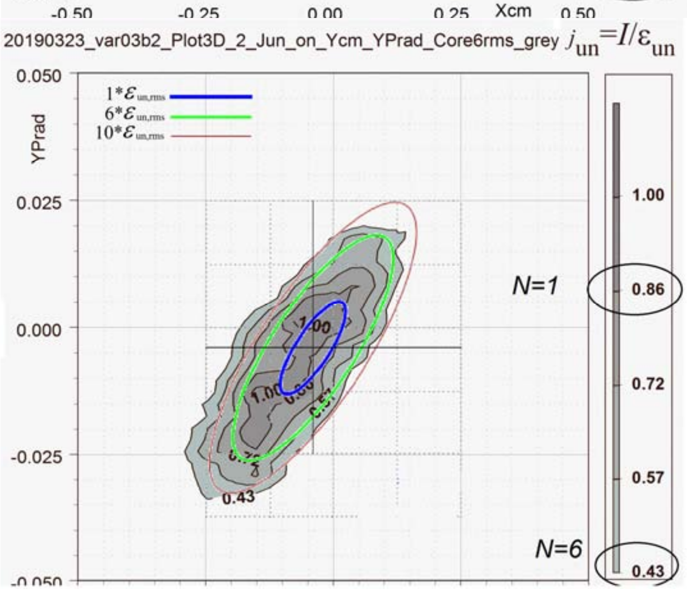
NxRMS, N=1,6,10

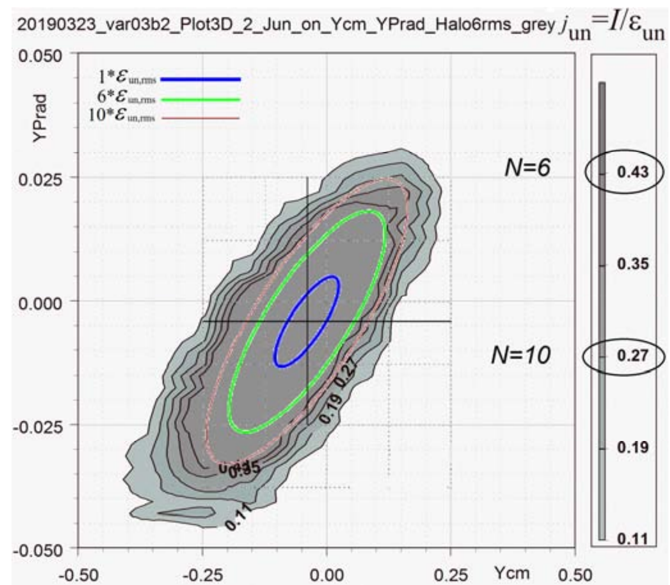
X-XP – upper row

N=1: j=0.96

N=6: j=0.42

N=10 j=0.26





Y-YP – lower row

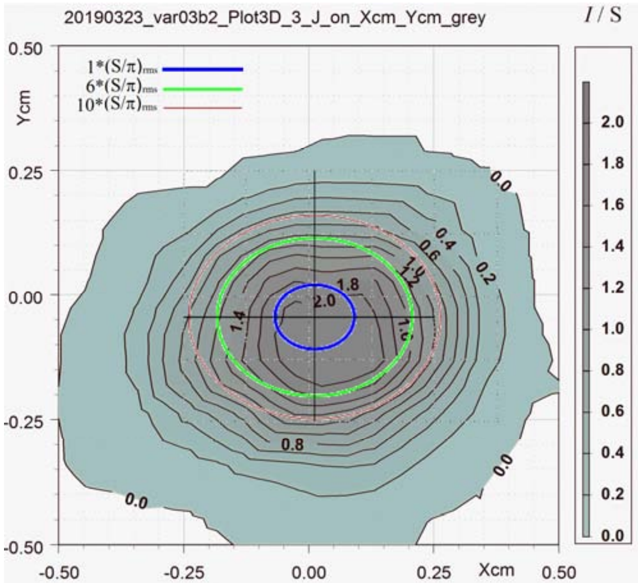
N=1: j=0.86

N=6: j=0.43

N=10: j=0.27

V.Kapin, RFQ, May-2019

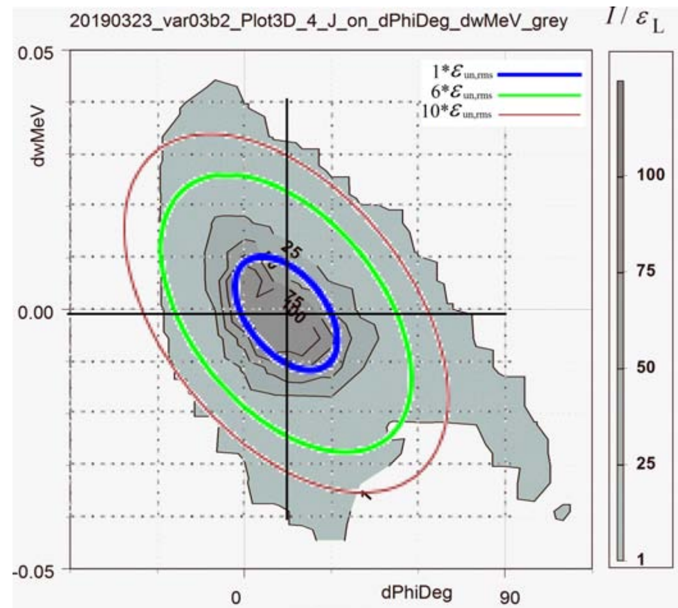
(Bad) beam quality vs rms-ellipses with 3D plots - 2



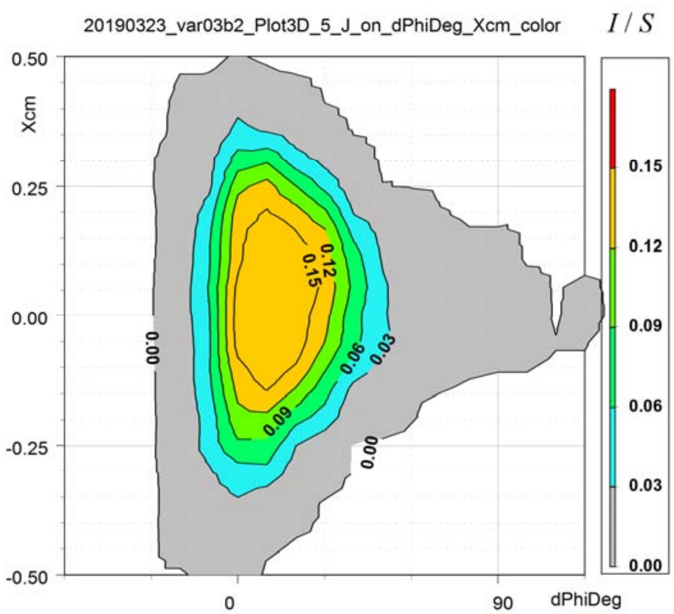
NxRMS, N=1,6,10

Y-X – left;

ϕ-dW -> right

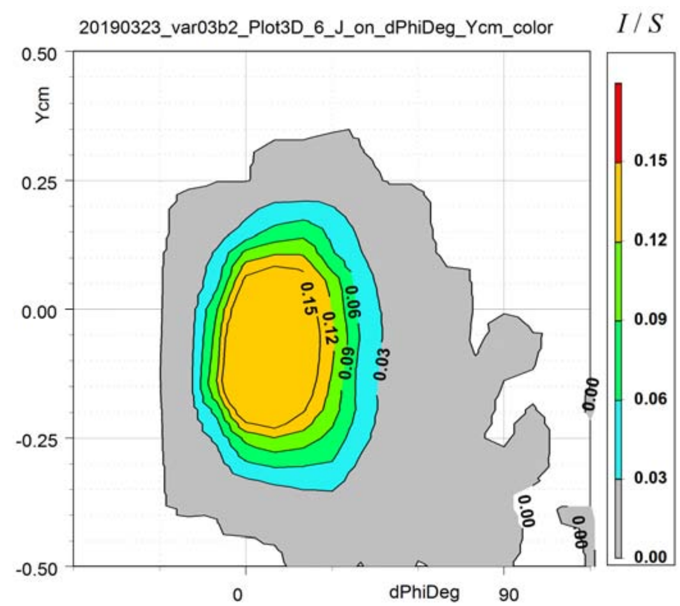


Schempp-type
4-rod RFQ =>
intrinsic field
Distortions =>
Bad beam quality =>
Losses in MEBT &
Linac & Booster [1]



X-ϕ – left

Y-ϕ – right



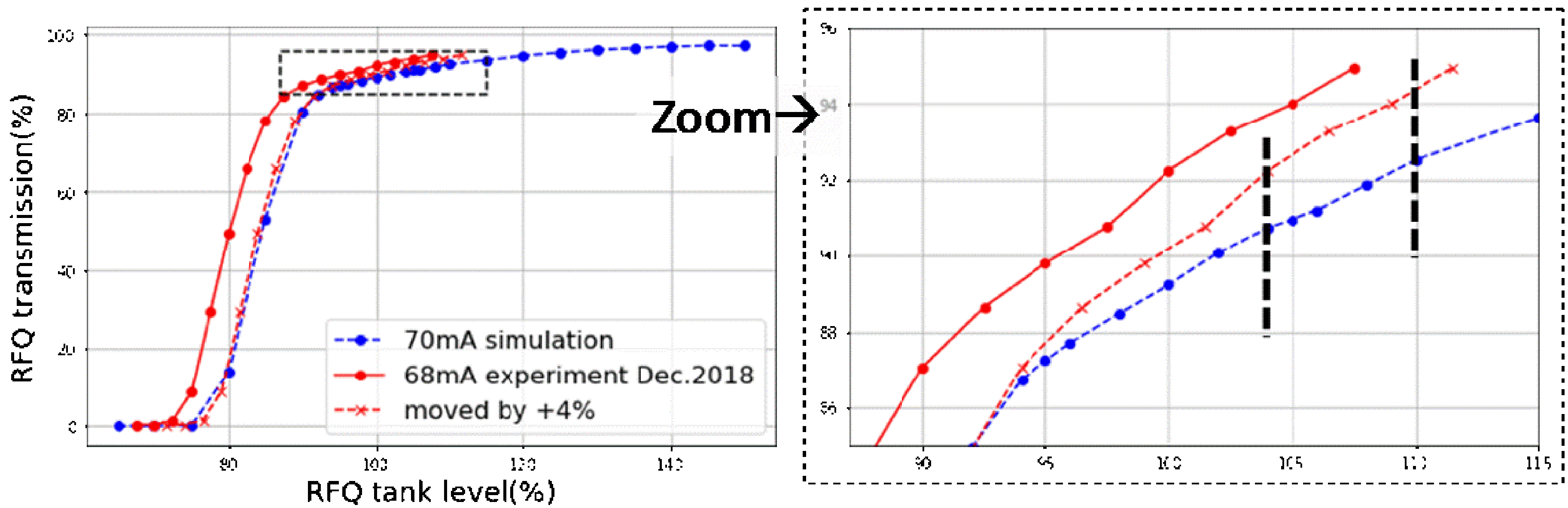
V.Kapin, RFQ, May-2019

JAERI RFQs: Beam Transmission vs Prf

Several (~4) RFQs (4-vane) built and studied at J-PARC since 1990th

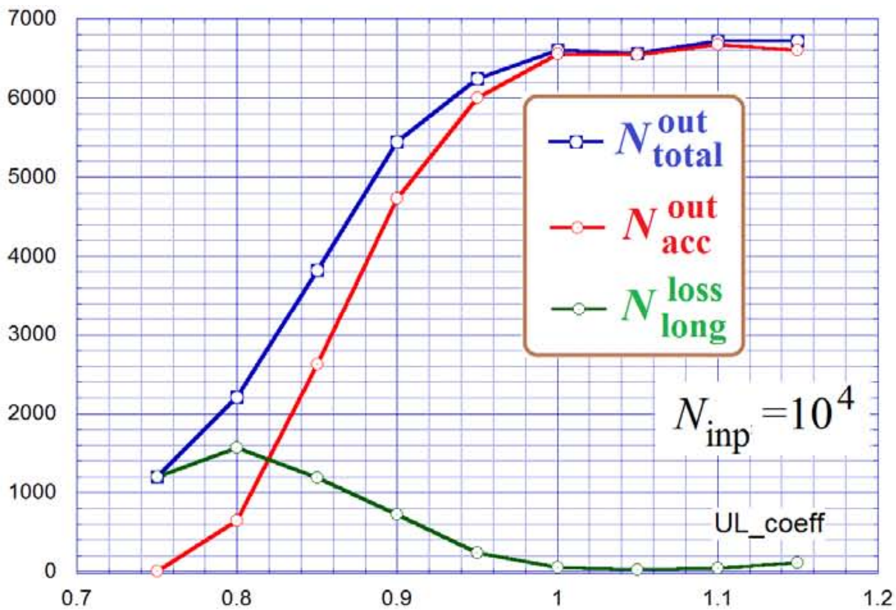
Important: there beam toroids at RFQ entry and RFQ exit

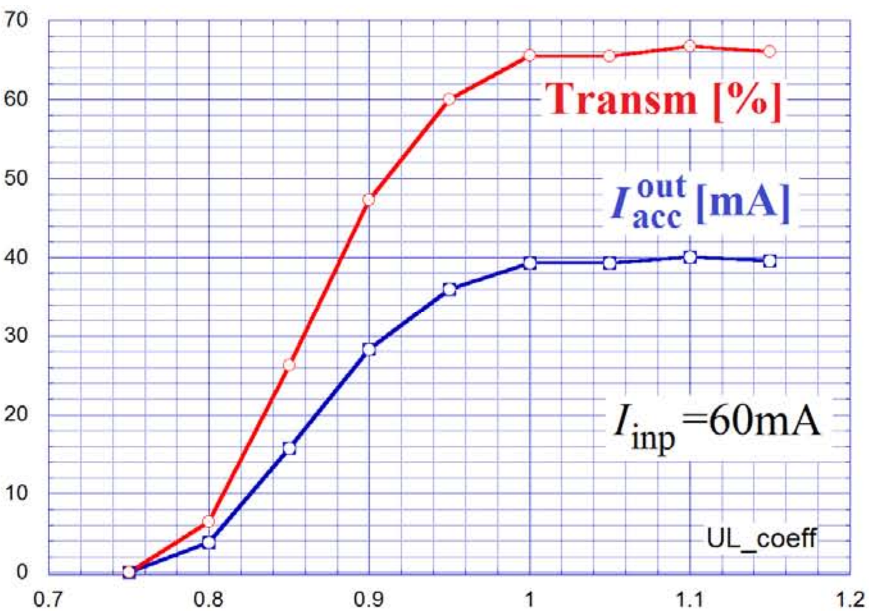
Example: Comparison of RFQ simulations vs Measurements



Prf – the most important parameter greatly affected on RFQ beam parameters;
It must be correctly tuned !

CST Simulations: “Matched” Beam vs UL (RF-power) for 60mA

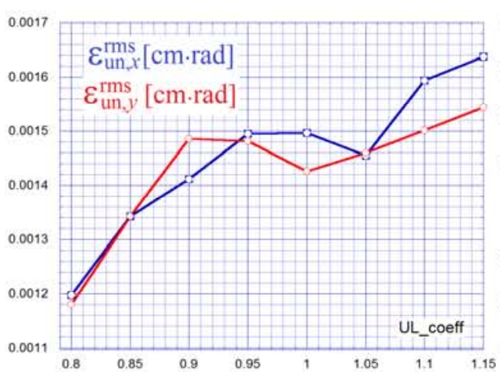


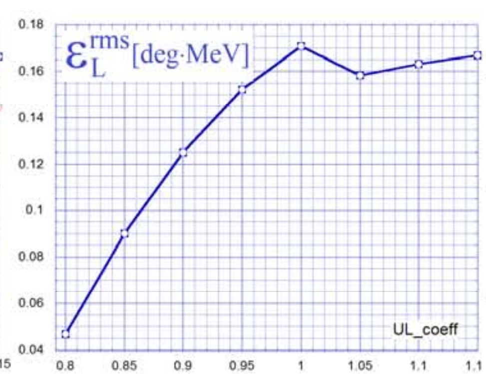


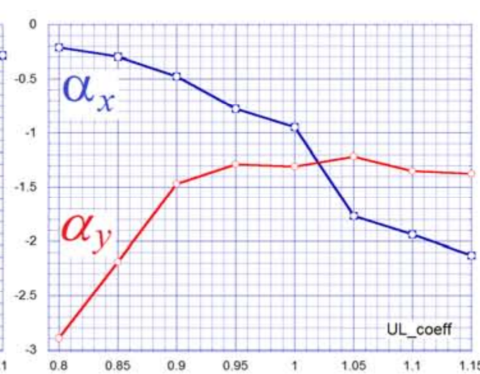
UL – “inter-vane voltage”

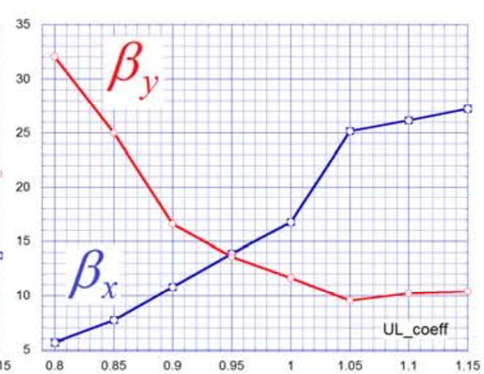
UL threshold=~0.8

ε & Twiss: $\varepsilon_{x,y}$=40%up ε_L=0.04÷0.17 α_x=[-2.5;-0.5] α_y=[-2.9;-1.2] β_x=5÷28cm β_y=9÷32cm



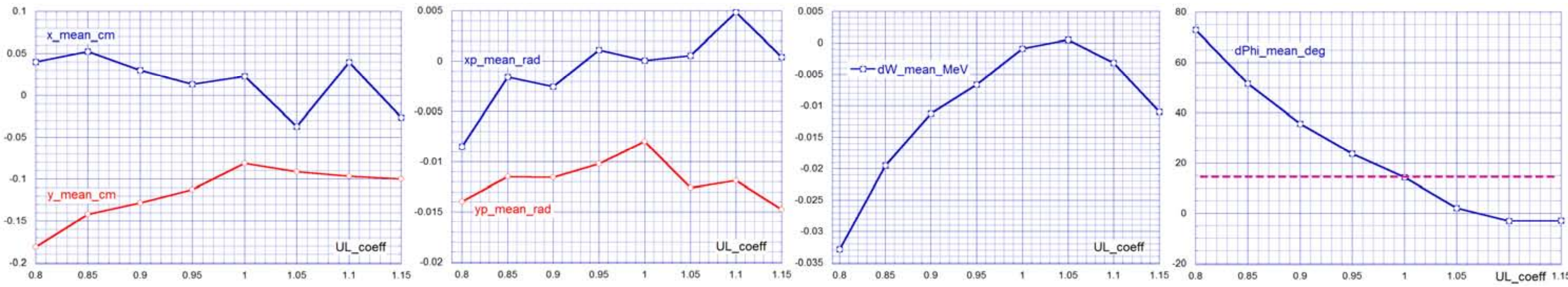




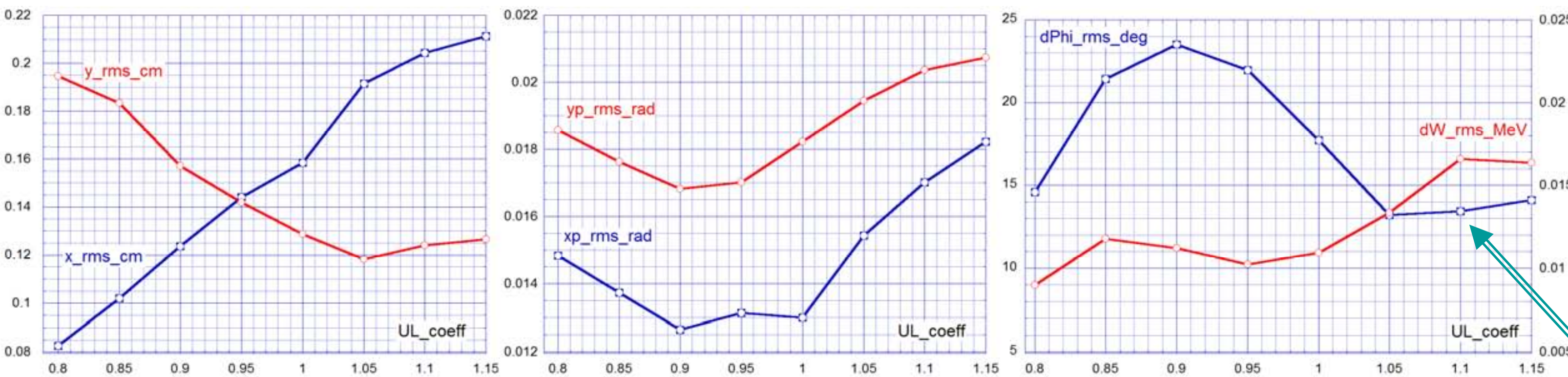


Exit beam vs UL: **means** and **rms** of coords

Mean: *X*=±0.5mm *Y*=[-1.8;-0.8]mm *X'*=[-8;+5]mrad *Y'*=[-8;-15]mrad *W*=[-33;0]keV ϕ~[0÷80°]

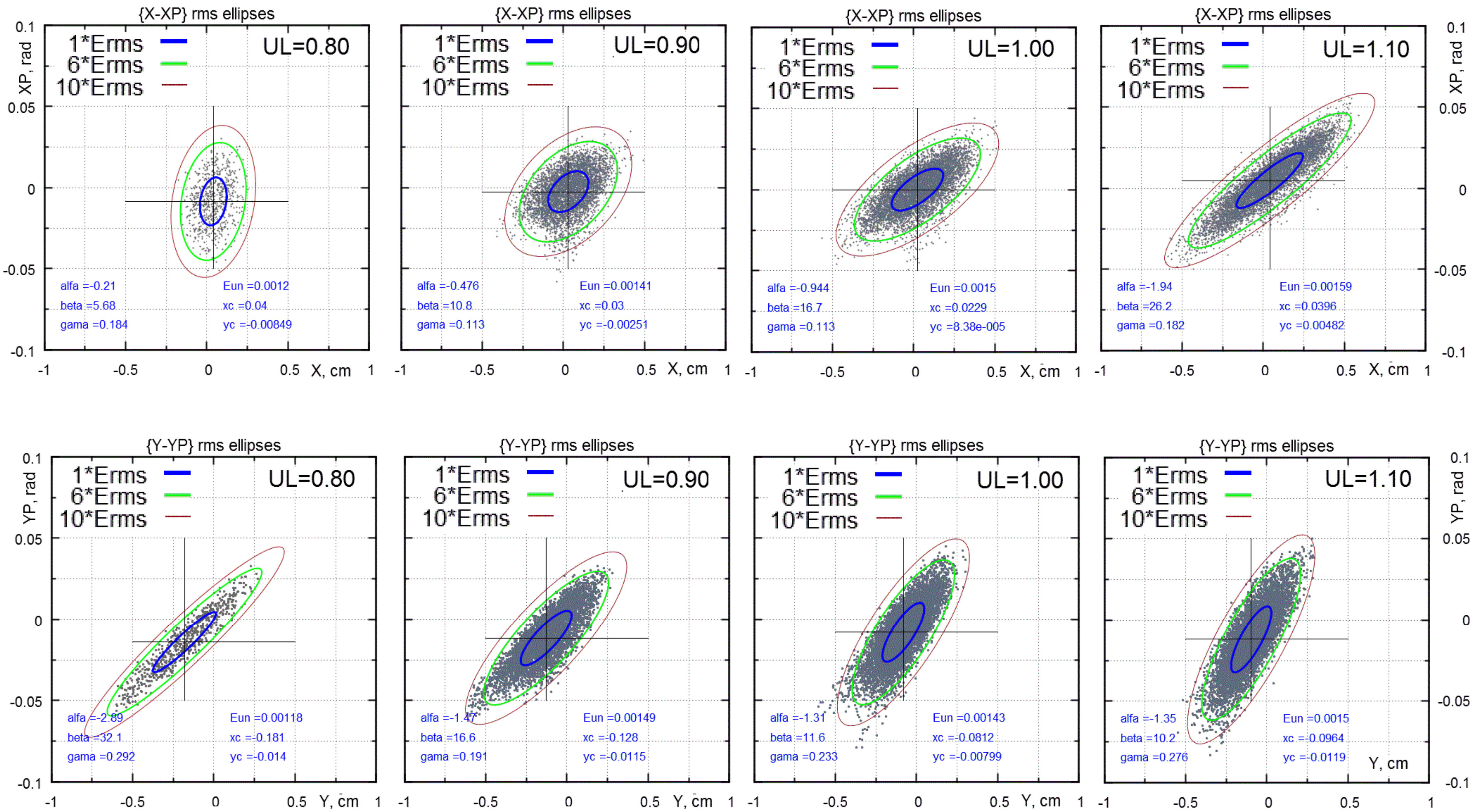


RMS: *X*=0.8÷2.1mm *Y*=1.1÷2.0mm *X'*=12÷18mrad *Y'*=17÷21mrad *W*=9÷17keV ϕ=13÷24°

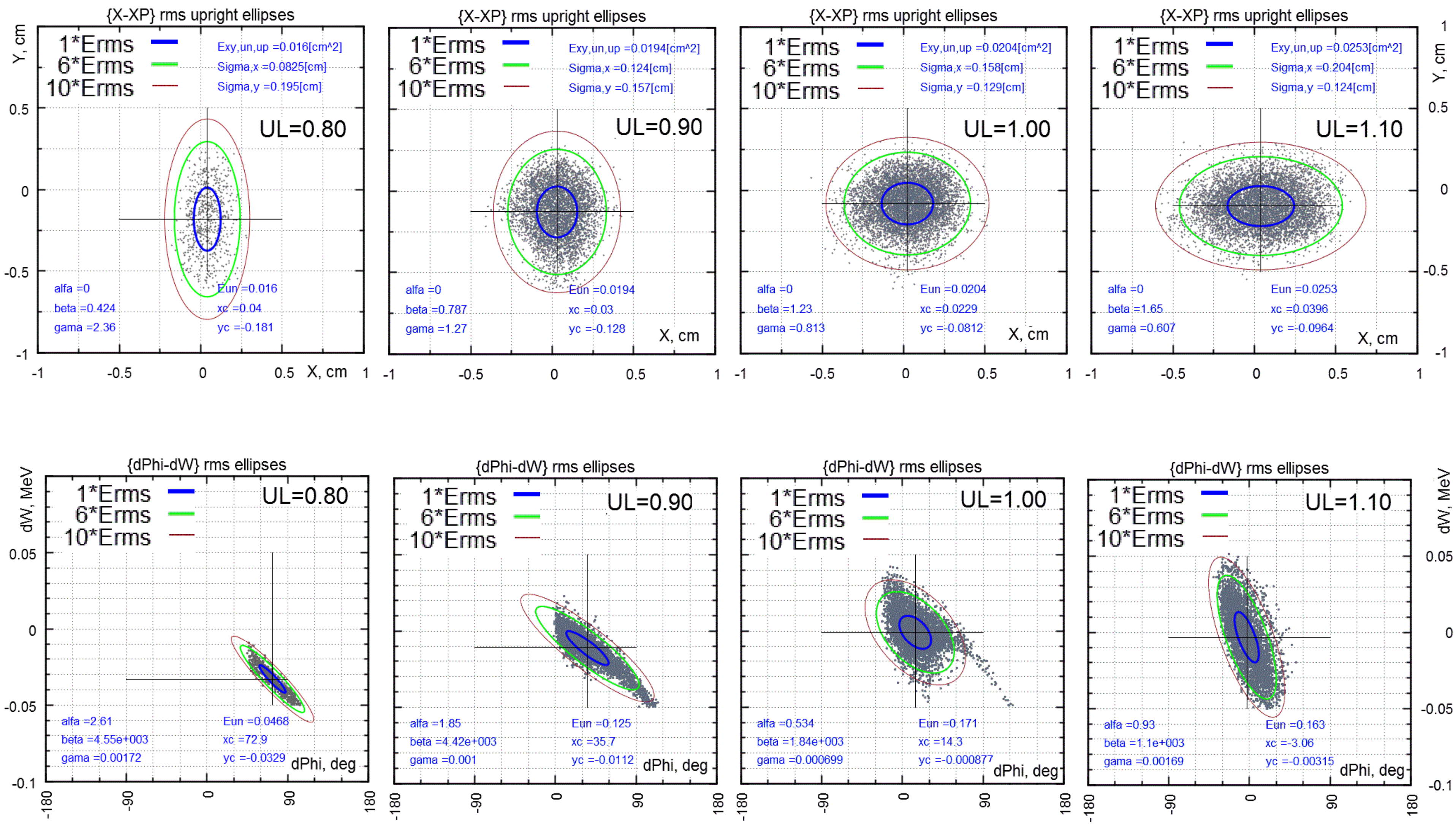


Note. Bunch length "frozen" at UL>1 (similar to plot in Tan's paper)

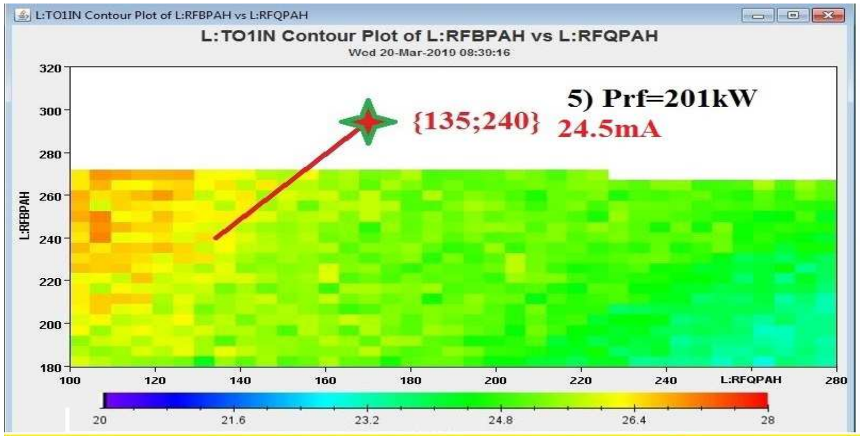
{X-XP} & {Y-YP} evolutions vs UL=0.8,0.9,1.0,1.1

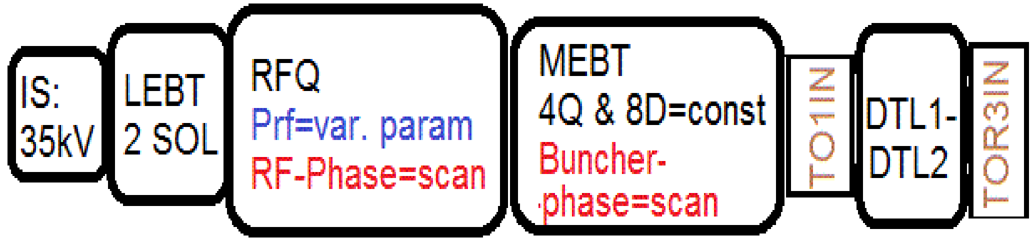


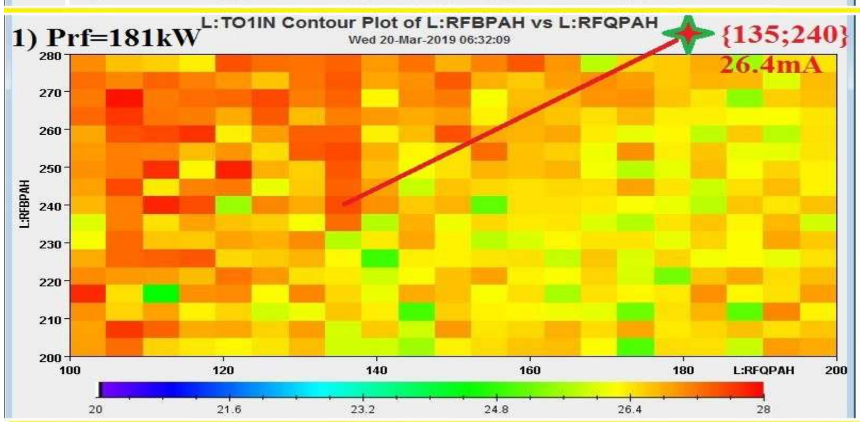
{X-Y} & {Phi-dW} evolutions vs UL=0.8,0.9,1.0,1.1

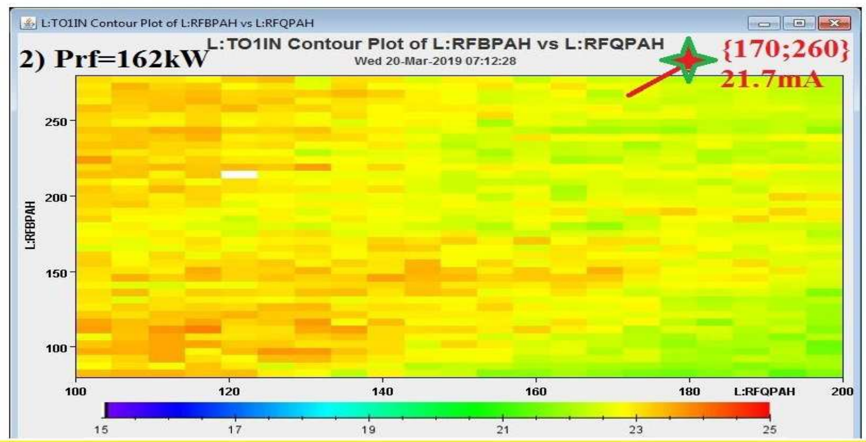


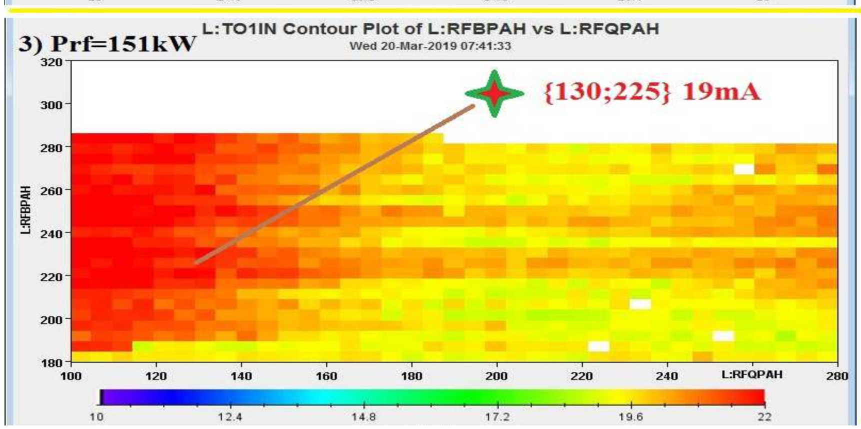
Experimental study vs Prf (~ UL^2): TO1IN current

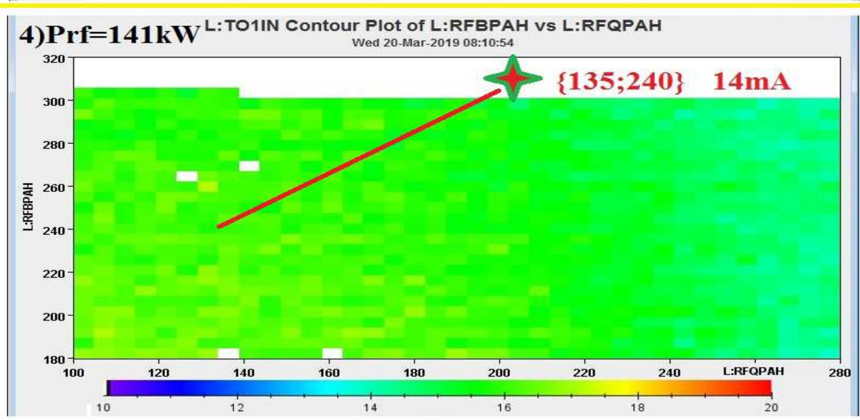




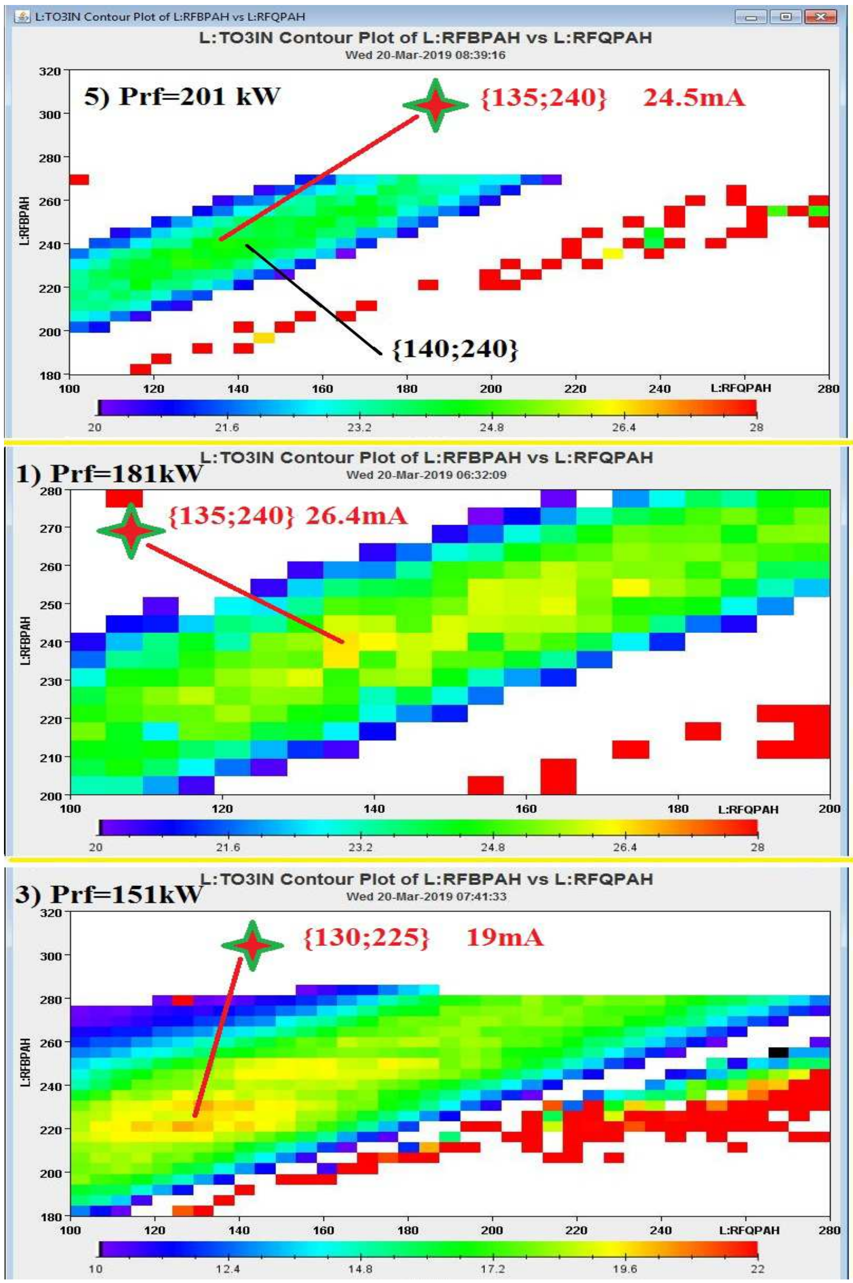


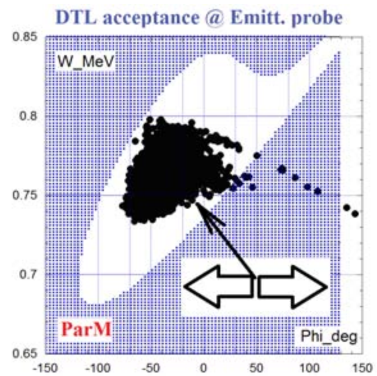




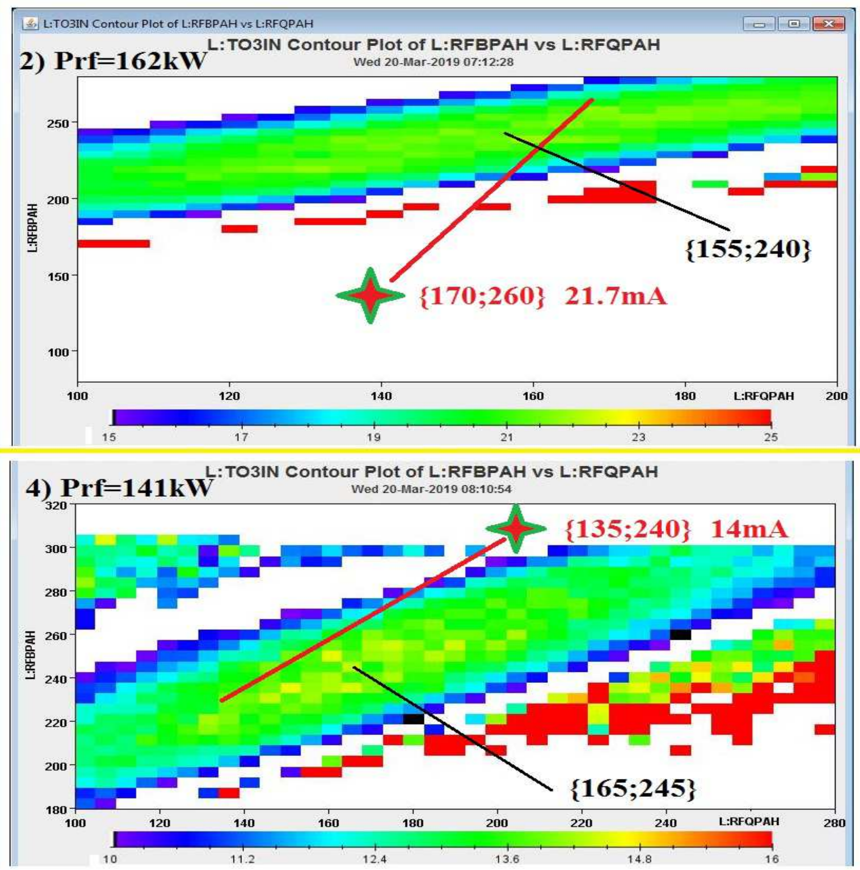


Experimental study vs Prf (~ UL^2): TO**3**IN current

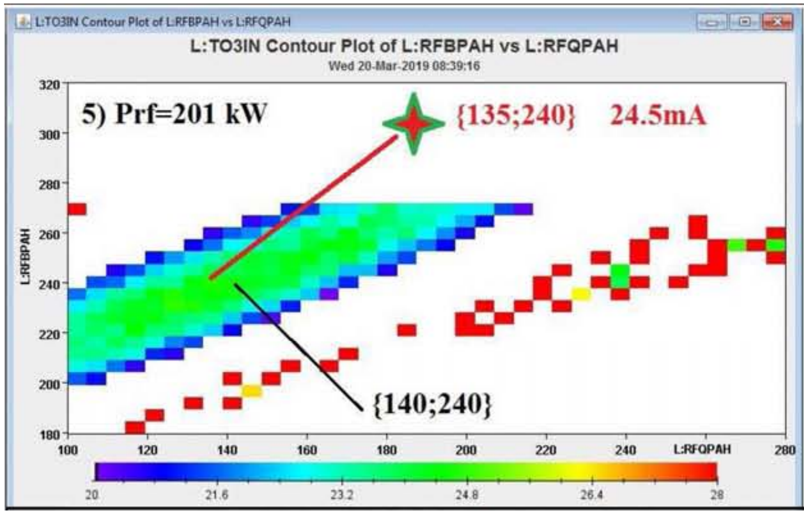




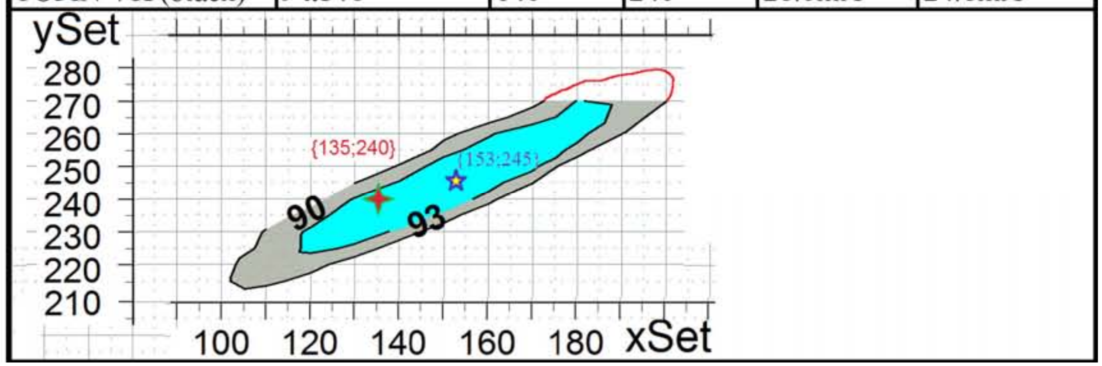
RFQ-Phase variation
Moves L-emittance
Along L-acceptance =>
There can be an optimum
(a bell-shape "regular"
DTLTransm=*f* (RFQphase)

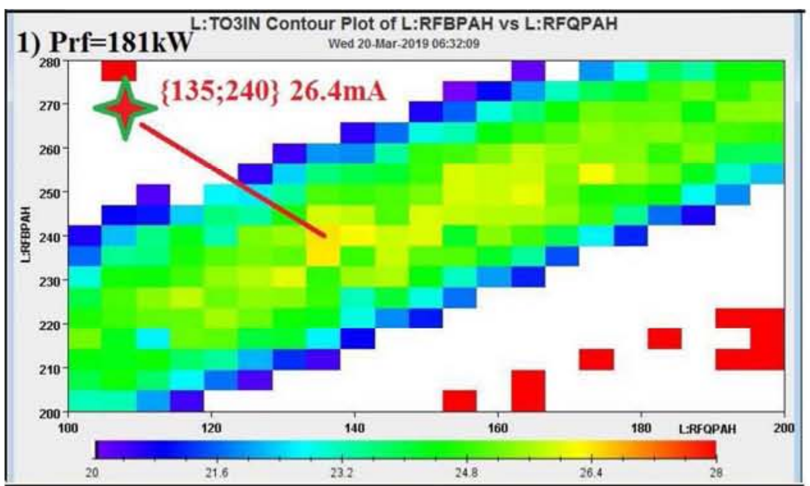


Opt RFQ phases via Tr.=I_3 / I_1 with Contour Plots (1)

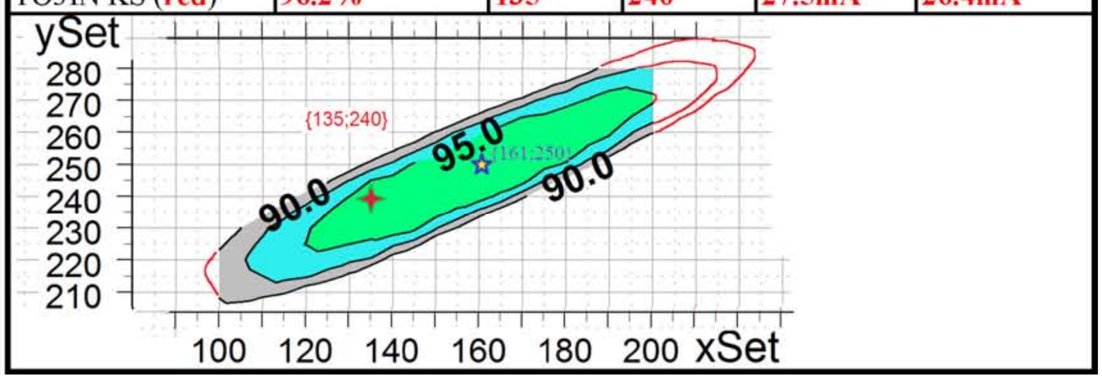


5) Prf=201kW	Trans, %	xSet	ySet	I_1 [mA]	I_3 [mA]
Transm-**Mean**(Max)	**~94.5%** (94.8)	**153** (155)	**245** (245)	**25.5** (25.6)	**24.1** (24.3)
TO3IN KS (**red**)	**93.6%**	**135**	**240**	**26.3mA**	**24.6mA**
TO3IN VK (black)	**94.5%**	140	240	26.0mA	24.6mA



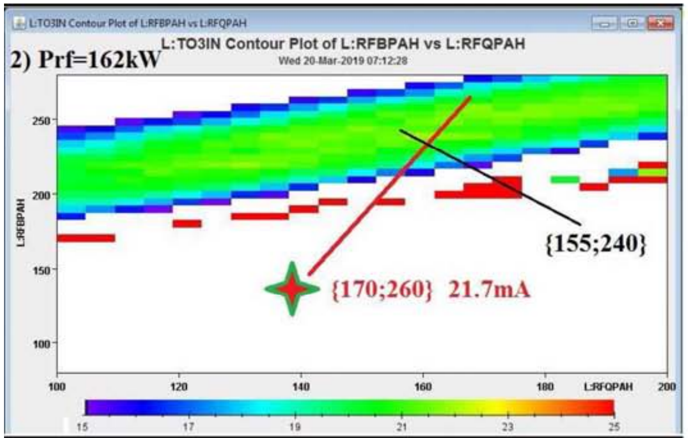


1) Prf=181kW	Trans, %	xSet	ySet	I_1 [mA]	I_3 [mA]
Transm-**Mean**(Max)	**~97.0%** (97.5)	**161** (150)	**250** (245)	**26.7** (26.6)	**25.9** (26.0)
TO3IN KS (**red**)	**96.2%**	**135**	**240**	**27.5mA**	**26.4mA**

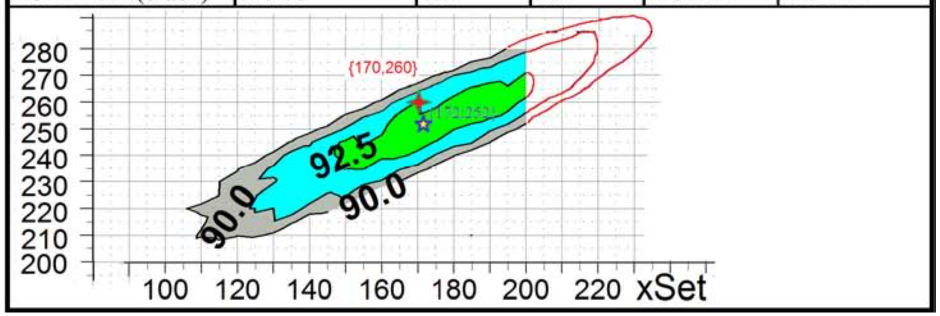


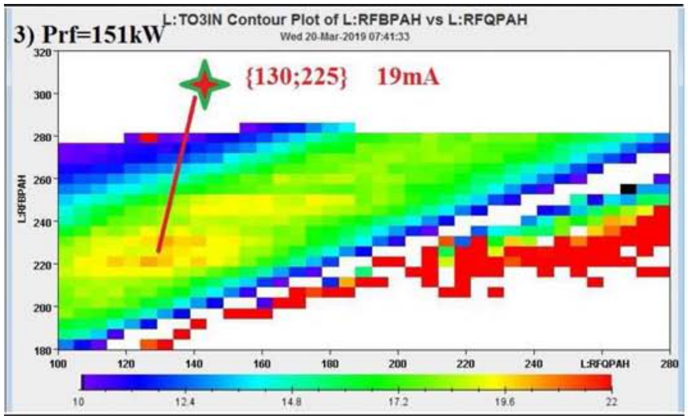
“Mean” = an ellipse mean phase

(2)

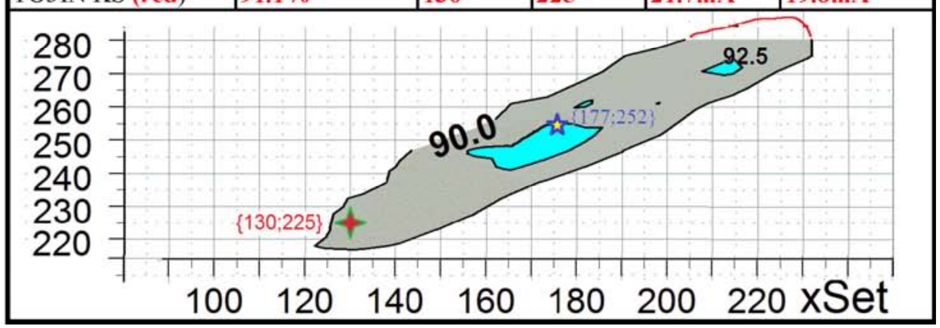


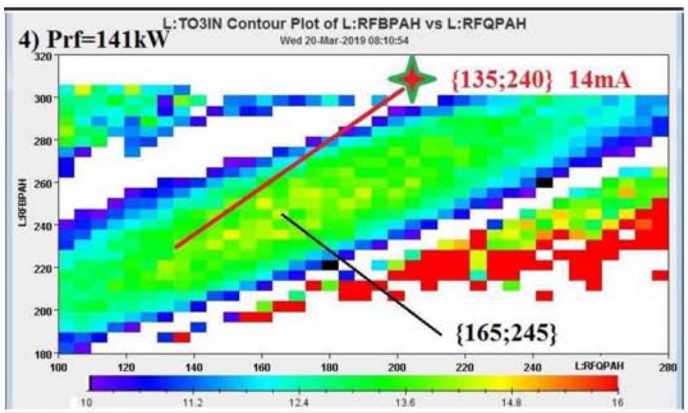
2) Prf=162kW	Trans, %	xSet	ySet	I_1 [mA]	I_3 [mA]
Transm-**Mean**(Max)	**~95.5%** (96.1)	**172** (175)	**252** (250)	**22.3** (22.3)	**21.2** (21.4)
TO3IN KS (**red**)	**95.1%**	**170**	**260**	**22.9mA**	**21.7mA**
TO3IN VK (black)	95.8%	155	240	22.4mA	21.5mA



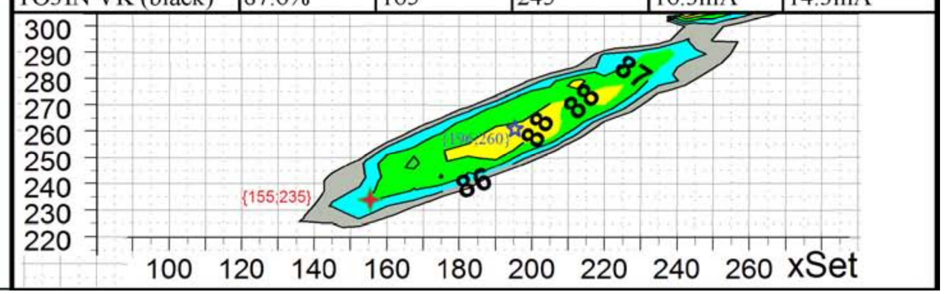


3) Prf=151kW	Trans, %	xSet	ySet	I_1 [mA]	I_3 [mA]
Transm-**Mean**(Max)	**~92%** (93.8)	**177** (175)	**252** (250)	**~20** (20.7)	**~18.5** (19.4)
TO3IN KS (**red**)	**91.1%**	**130**	**225**	**21.7mA**	**19.8mA**

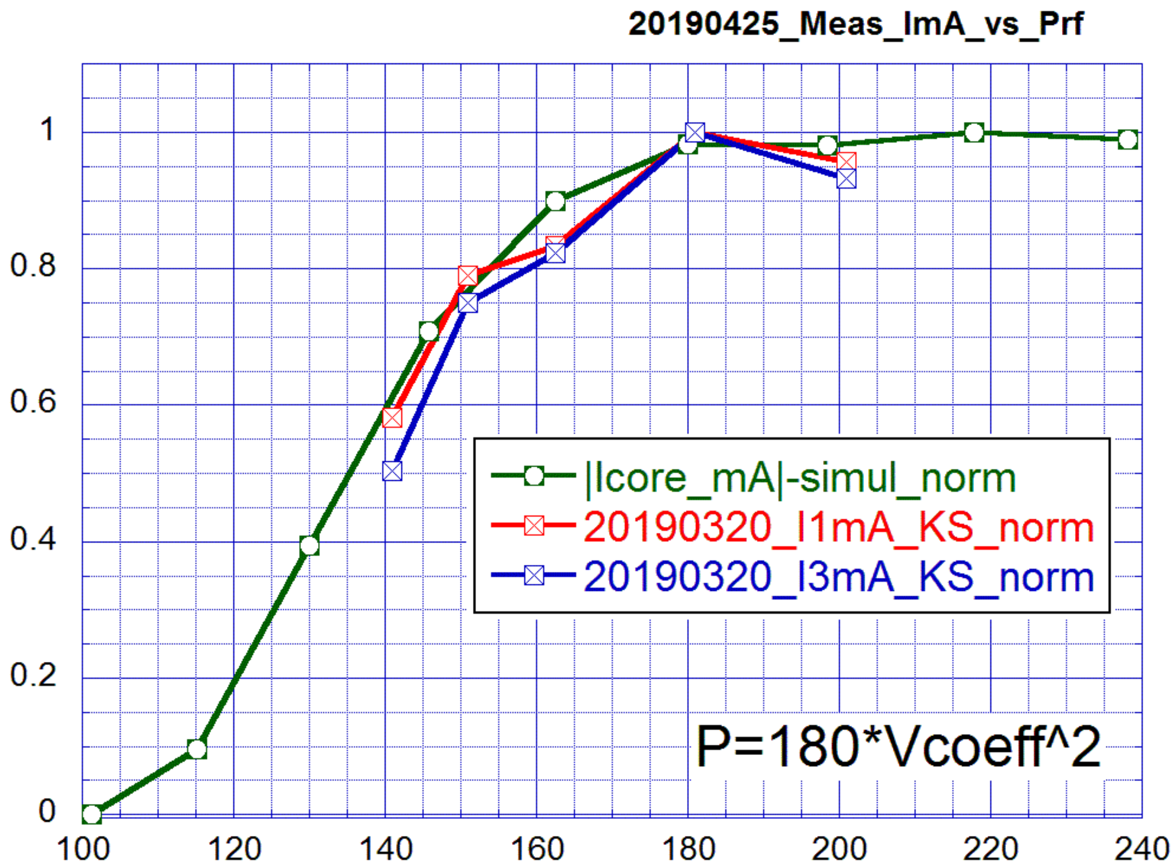




4) Prf=141kW	Trans, %	xSet	ySet	I_1 [mA]	I_3 [mA]
Transm-**Mean**(Max)	**~87.8** (88.9)	**196** (190)	**260** (255)	**15.6** (16.2)	**13.7** (14.4)
TO3IN KS (red)	**83.2%**	**135**	**240**	**16.0mA**	**13.3mA**
TO3IN VK (black)	87.6%	165	245	16.3mA	14.3mA



I RFQ vs UL dependence (Simul vs experim.)

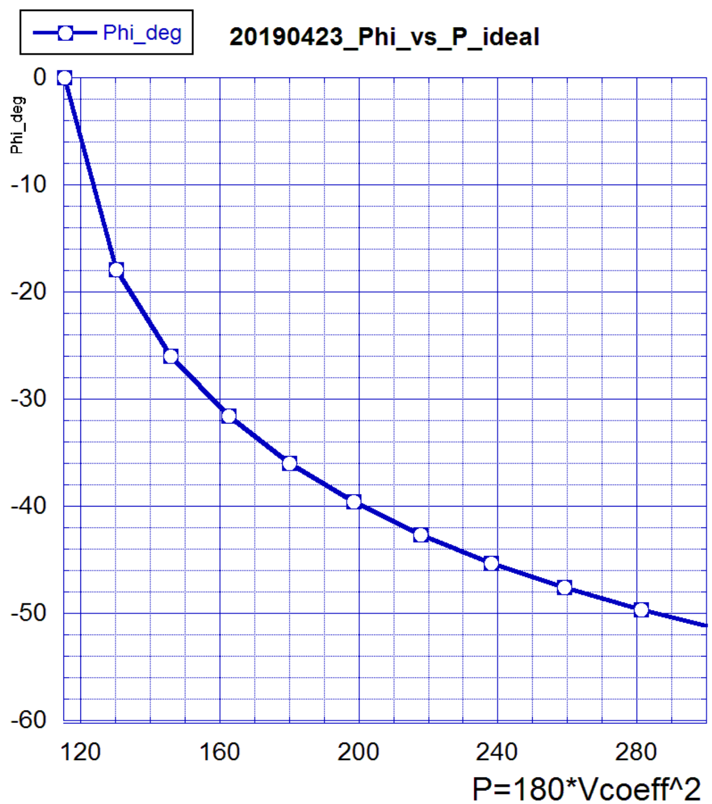


RFQ – exit (simul);
DTL1 – entry (TO1IN)
DTL3 – entry (TO3IN)

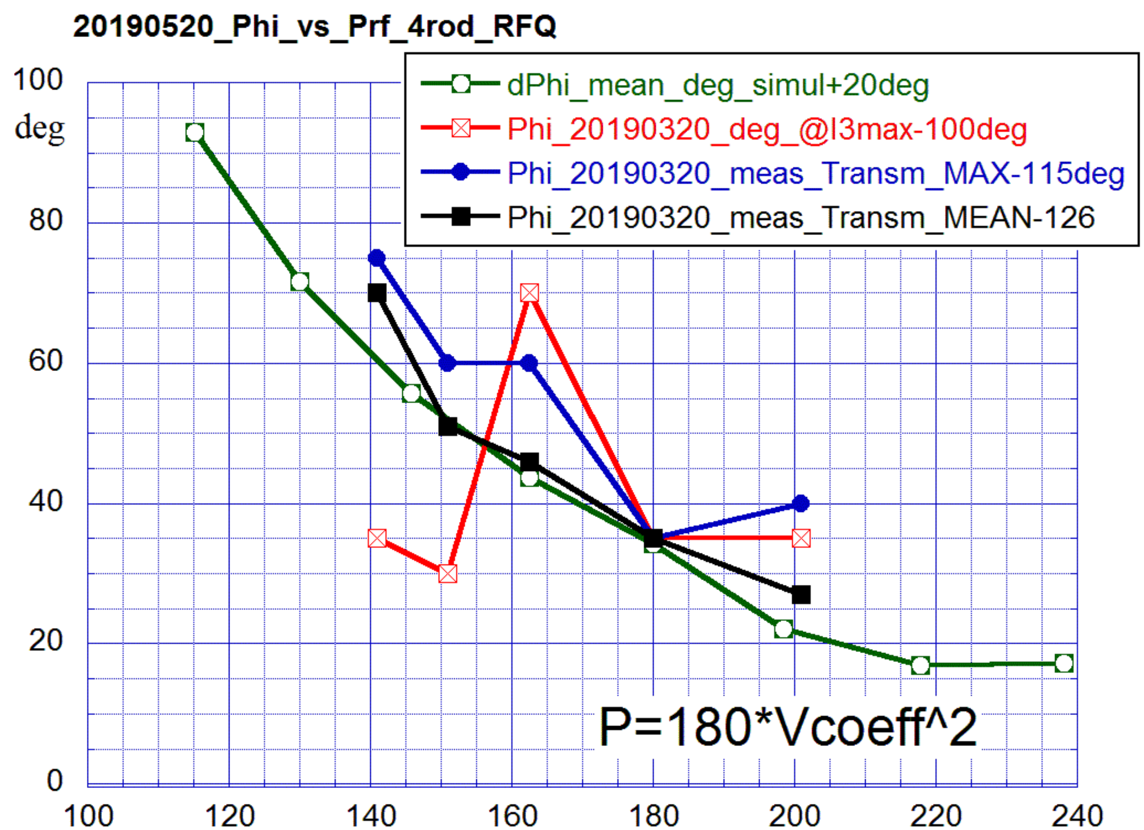
- Looks as our Prf=180kW (UL=1.0) is close to nominal RFQ electrode voltage
- Lower current at 200kW(UL=1.05) – could be explained as "MEBT is tuned well for nominal Prf=180kW, and not tuned for 200kW"

Compare experimental with Phi_mean vs Prf

Typical Ideal $V*\cos(\phi s)$=const



FNAL 4-rod RFQ CST/PS-simul (Winj=35kV) and Experim. data by 3D-I3 and Transm. Countor Plots

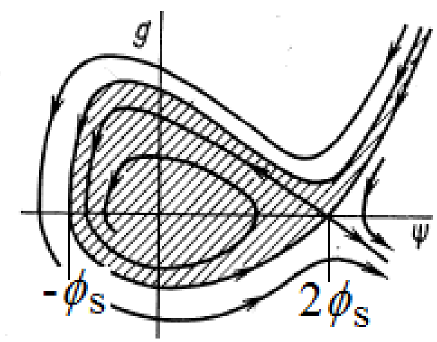


dϕ/dP decreases vs Prf

Let's assume 180kW => UL=1.0

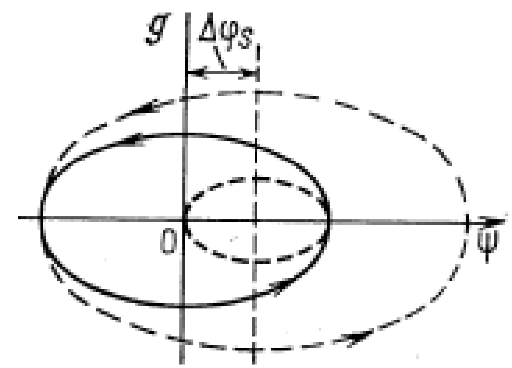
Conclusion

- Refined CST model is close to max exp. RFQ beam current
- Comparison of simulations & measurements of $f\,(P_{rf})$ suggests that P_{rf}=180kW is close to a nominal value
- Might be post-processing with “contour plot centers” provides a better RFQ phases to match into DTL1-2 (?) => avoid possible coherent beam oscillations within separatrix which may cause emittance growth



DTL: Long-acceptance;

$\mathcal{E}$-growth due to ϕ-jump

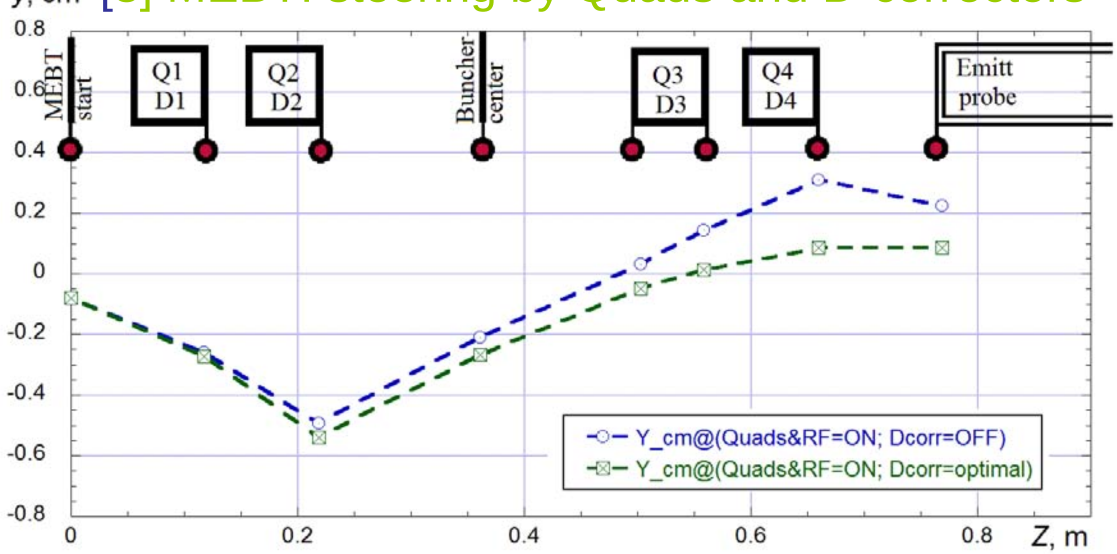


Further Plans

- define corresponding sets of “solutions” for MEBT Quads q1,..q4 – for every UL & Winj => a guide for “manual” tuning
- simulations for updated MEBT at UL&Winj-variable (+ Bill’s collimator at DTL entrance) => “schedule” of beam losses
- Consider a possible mechanical & magetic (PM) compensation of vertical beam centroid offsets (RFQexit)

---

[3] MEBT: steering by Quads and D-correctors



Vert offsets Yc&Y’c @ RFQexit:

• Beam Steering by Quads & Dipoles (+RF-gaps=f(ϕ))

• Beam focusing (matching) must be done by Quads

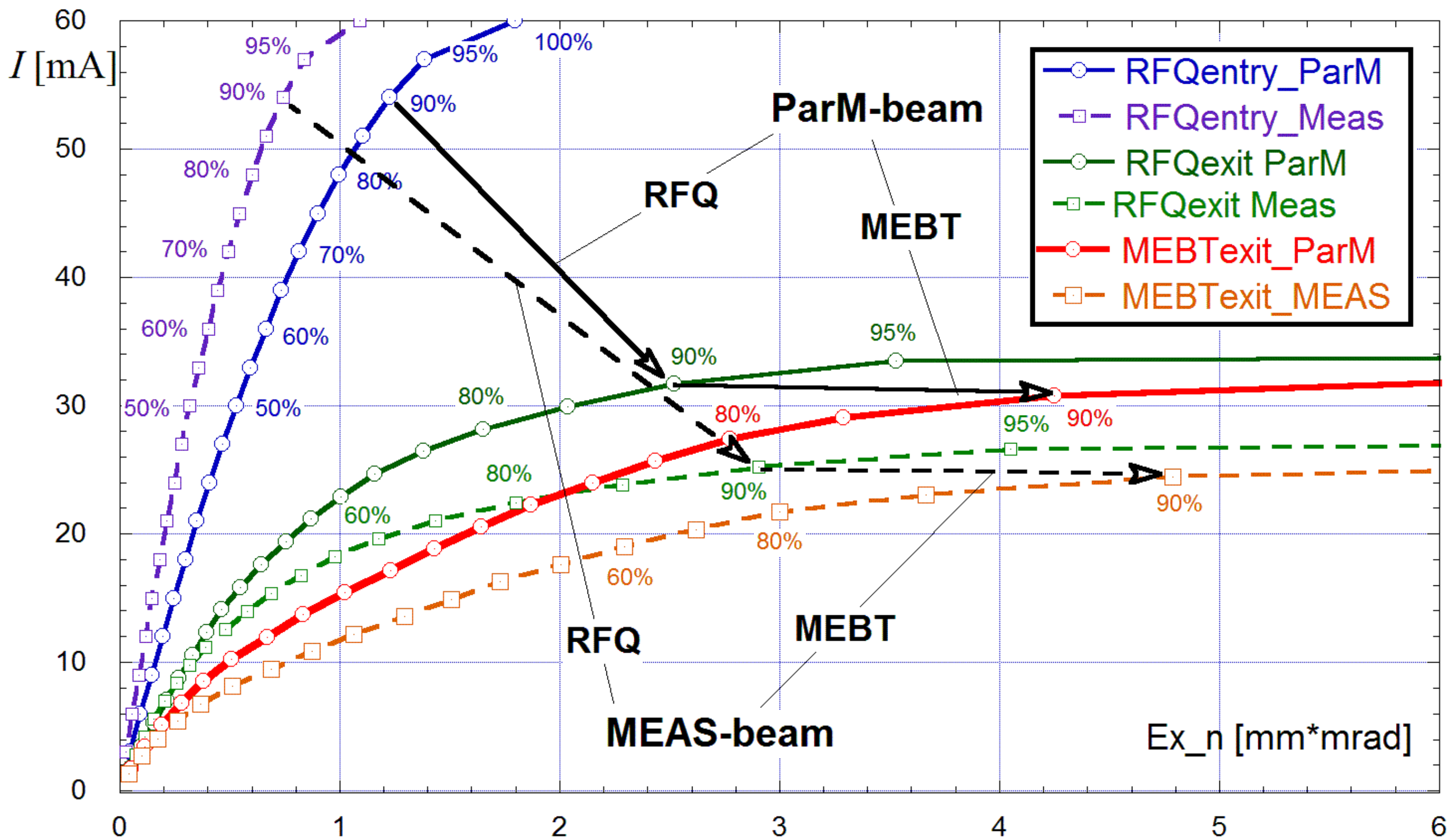
=> Quads affect on both focusing & steering

centroid is focused w/o dipole fields (blue) and with dipole fields (green)!

Supporting slides

[3]: Beam quality drop in RFQ+MEBT by CST

“ParM”-beam vs “Meas”-beam

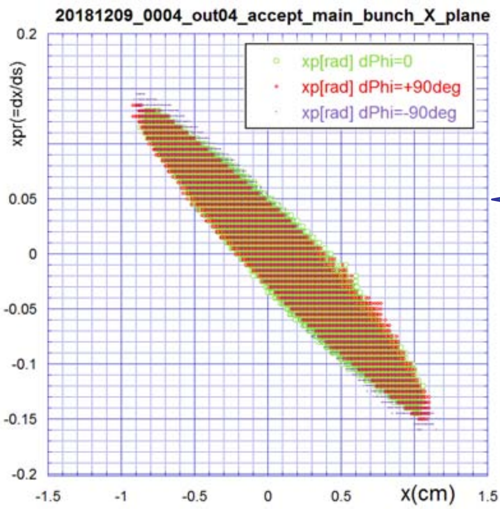


❖ drop of the phase space density dI/dE (curve slope) within RFQ+MEBT

❖ MEBT by CST: essential growth of 90%-emittance values

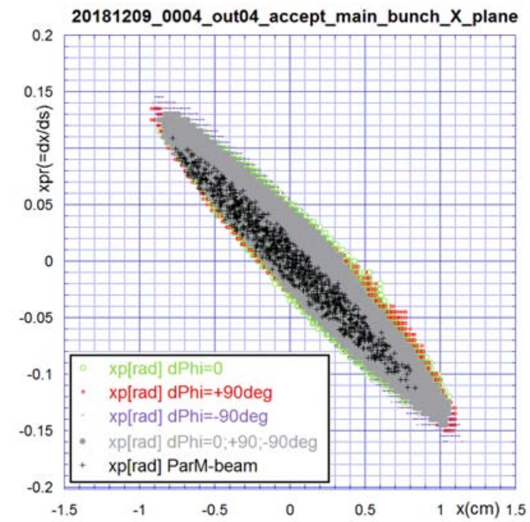
❖ Example: I-drop@Ex-n=1.0 MEAS: RFQ (60mA->18mA) &MEBT(18mA->12mA)

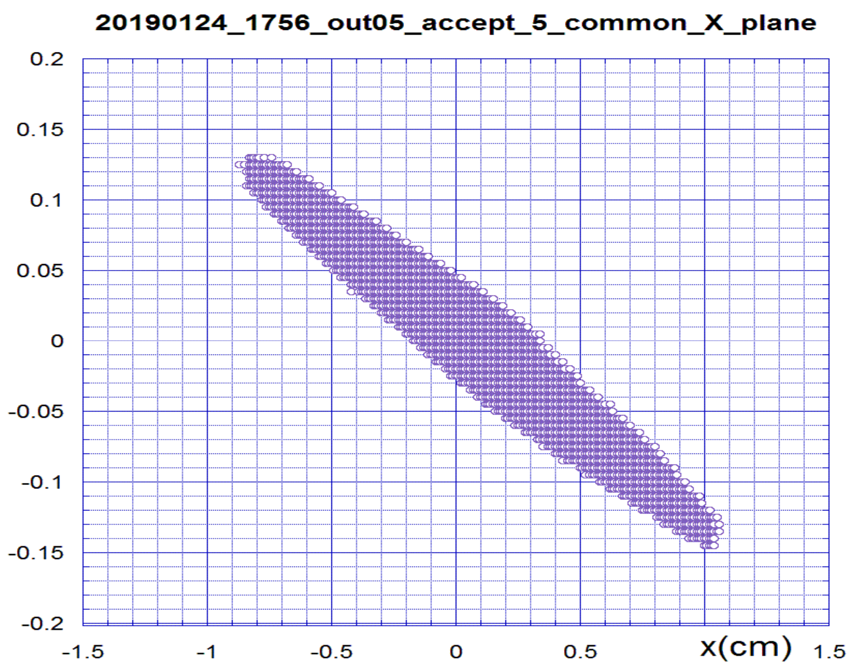
CST/PS: Transv. Acceptance X-plane (*I* beam=0)



Overlap of partial acceptances: Phi=0,+90;-90

Effective acceptance + ParM beam (within! & twice larger)

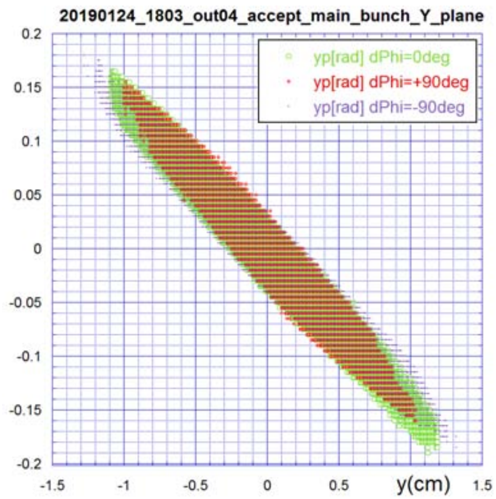




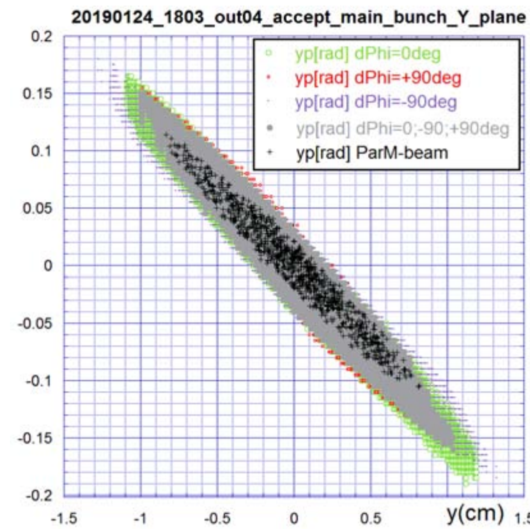
xp[rad] dPhi=0;+90;-90deg

```
!==================================================================!
!                                                                  !
! Acceptance for filter #5 (Nfiles<4>)-----------------------------!
!                                                                  !
! Array <PARMILA_inp_accept_5> [cm;rad;cm;rad;rad;MeV]:            !
! Acceptance_plane=<X>                                             !
! beta_gamma_beam= 0.86328121E-02                                  !
!                                                                  !
! Start SUBROUTINE write8_RMS_parameters:-----------!              !
!                                                   !              !
! MEAN values: -------------------------------------!              !
! x_mean_cm      =    105.832E-03 [cm]              !              !
! xp_mean_rad    =     -4.689E-03 [rad]             !              !
!---------------------------------------------------!              !
! RMS values:  --------------------------------------!             !
!  sigma_x_cm         =      481.513E-03 [cm]       !              !
! sigma_xp_rad       =      68.777E-03 [rad]        !              !
!---------------------------------------------------!              !
! Emittances: --------------------------------------!              !
!  at beta_gamma_beam  =        8.633E-03 [-]       !              !
!                                                   !              !
! ex_rms_un_cm_rad    =        8.964E-03 [cm.rad]   !              !
! beta_x_cm           =       25.866E+00 [cm]       !              !
! alfa_x              =        3.557E+00 [-]        !              !
! gamma_x_inv_cm      =      527.723E-03 [1/cm]     !              !
! ex_rms_norm_cm_rad  =       77.381E-06 [cm.rad]   !              !
!---------------------------------------------------!              !
!==================================================================!
```

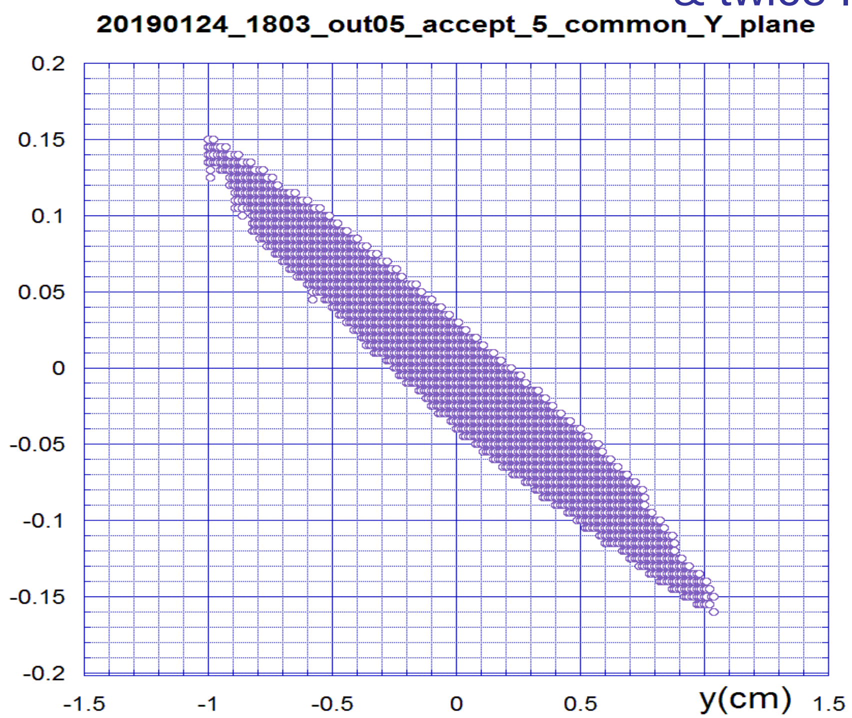
CST/PS: Transv. Acceptance Y-plane (*I* beam=0)



Overlap of partial acceptances: Phi=0,+90;-90

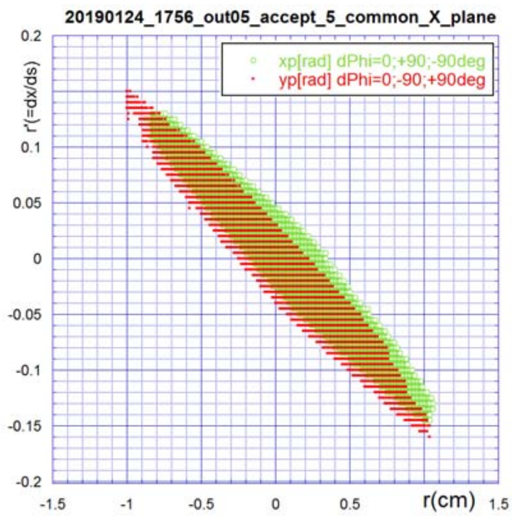


Effective acceptance + ParM beam (within! & twice larger)

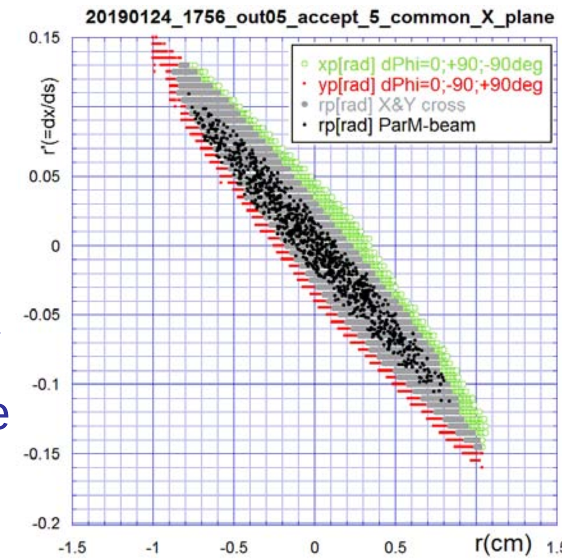



```
!==========================================================!
!                                                          !
! Acceptance for filter #5 (Nfiles<4>)---------------------!
!                                                          !
! Array <PARMILA_inp_accept_5> [cm;rad;cm;rad;rad;MeV]:    !
! Acceptance_plane=<Y>                                     !
! beta_gamma_beam= 0.86328121E-02                          !
!                                                          !
! Start SUBROUTINE write8_RMS_parameters:----------!       !
!                                                  !       !
! MEAN values: ------------------------------------!       !
! y_mean_cm      =     14.631E-03 [cm]             !       !
! yp_mean_rad    =     -4.835E-03 [rad]            !       !
!--------------------------------------------------!       !
! RMS values:  ------------------------------------!       !
! sigma_y_cm         =     505.615E-03 [cm]        !       !
! sigma_yp_rad       =      73.391E-03 [rad]       !       !
!--------------------------------------------------!       !
! Emittances: -------------------------------------!       !
!  at beta_gamma_beam  =        8.633E-03 [-]      !       !
!                                                  !       !
! ey_rms_un_cm_rad    =        9.021E-03 [cm.rad]  !       !
! beta_y_cm           =       28.338E+00 [cm]      !       !
! alfa_y              =        3.990E+00 [-]       !       !
! gamma_y_inv_cm      =      597.053E-03 [1/cm]    !       !
! ey_rms_norm_cm_rad  =       77.881E-06 [cm.rad]  !       !
!--------------------------------------------------!       !
!==========================================================!
```

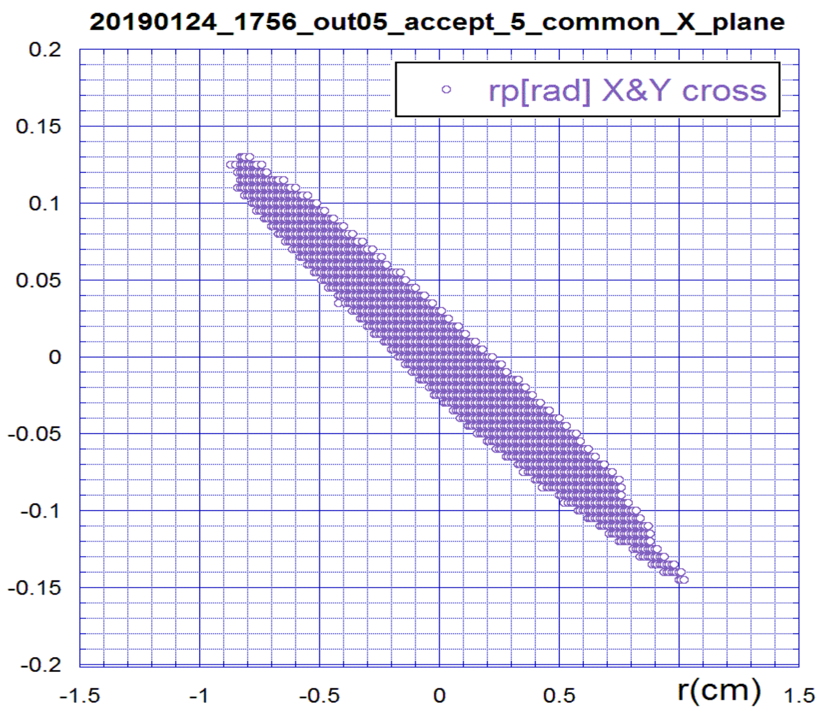
CST/PS: Effective Acceptance X&Y-plane (*I* beam=0)



Overlap of X & Y - effective Acceptances

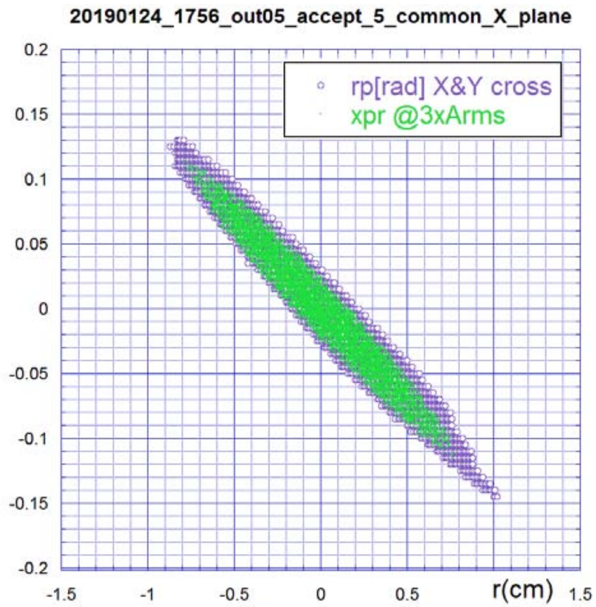


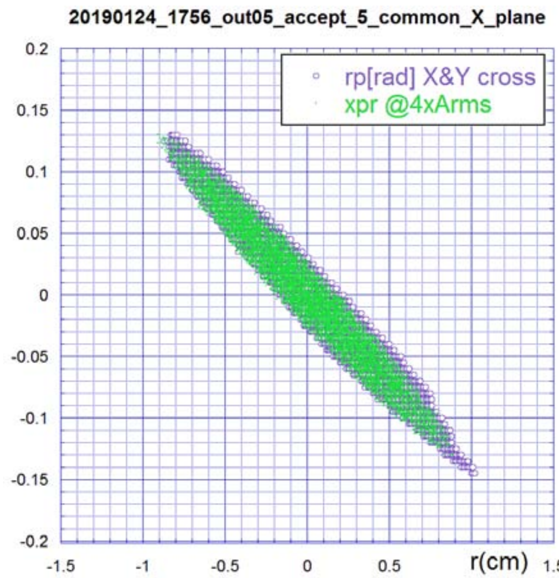
Effective X&Y acceptance
+ ParM beam (within!
& larger – 0.59 vs 0.30)

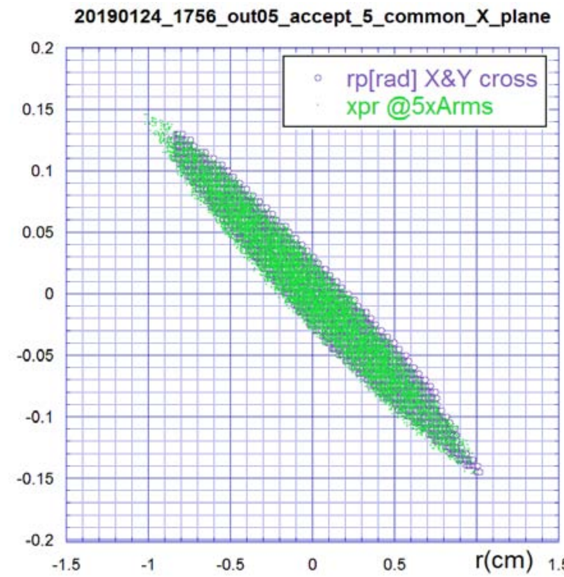


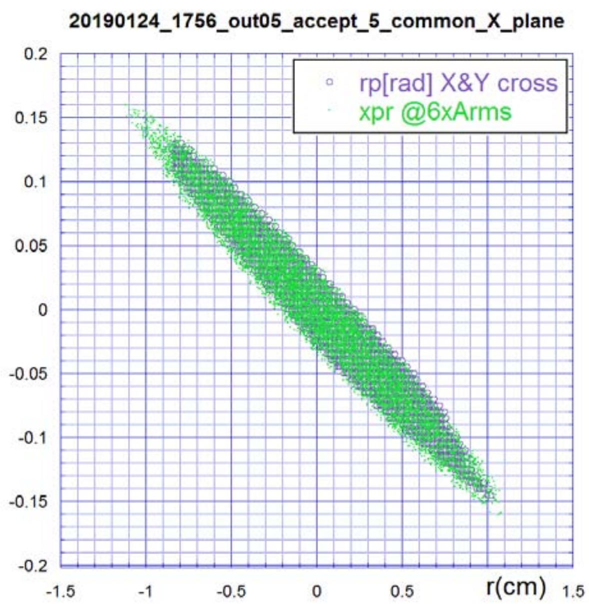

```
!==========================================================!
!                                                          !
! Acceptance for filter #5  (Nfiles<4>)-------------------!
!                                                          !
! Array <PARMILA_inp_accept_5> [cm;rad;cm;rad;rad;MeV]:    !
! Acceptance_plane=<X>                                     !
! beta_gamma_beam= 0.86328121E-02                          !
!                                                          !
! Start SUBROUTINE write8_RMS_parameters:----------!       !
!                                                  !       !
! MEAN values: -----------------------------------!       !
! x_mean_cm     =     46.718E-03 [cm]              !       !
! xp_mean_rad   =     -3.318E-03 [rad]             !       !
!-------------------------------------------------!       !
! RMS values:  ------------------------------------!       !
!  sigma_x_cm        =     461.966E-03 [cm]        !       !
! sigma_xp_rad       =      66.771E-03 [rad]       !       !
!-------------------------------------------------!       !
! Emittances: -------------------------------------!       !
!  at beta_gamma_beam  =       8.633E-03 [-]       !       !
!                                                  !       !
! ex_rms_un_cm_rad    =       6.847E-03 [cm.rad]   !       !
! beta_x_cm           =      31.169E+00 [cm]       !       !
! alfa_x              =       4.393E+00 [-]        !       !
! gamma_x_inv_cm      =     651.141E-03 [1/cm]     !       !
! ex_rms_norm_cm_rad  =      59.109E-06 [cm.rad]   !       !
!-------------------------------------------------!       !
!==========================================================!
```

Parmila: Generate matched beam (Etot=NxErms)









N=6 recommended by Parmila manual

Next:

a) find N-optimal via running CST/PS for Ex=Ey
b) Try run for different Ex & Ey including centroid offsets
c) Similar dependences for ParM (now N=6)