SLAC NATIONAL ACCELERATOR LABORATORY

ATF

Emittance Measurements and Related Experimental Results

Outline

- emittance measurements
  - charge dependence
  - coupling correction
- kicker issues
- BS3X issues
- vertical dispersion correction with correctors
- beta matching in EXT upstream of OTRs
  - in inflector
  - in coupling correction section
- other issues
- Summary, Continuing Work, Mitigation

Emittance Measurement

Issues:

- do we believe the OTR measurements?
- how stable/reproducible are the measurement results?
- what about charge and bunch length correlations?

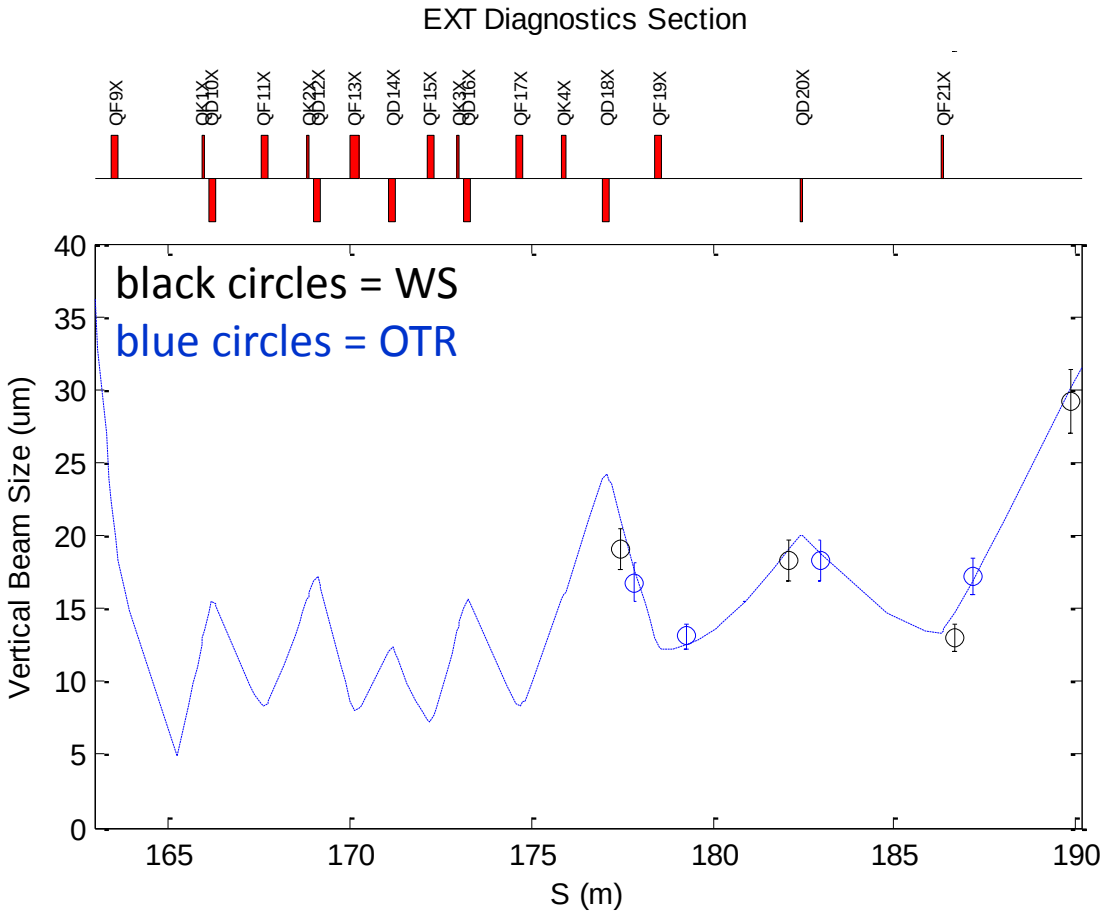
OTR Vertical Emittance Measurement

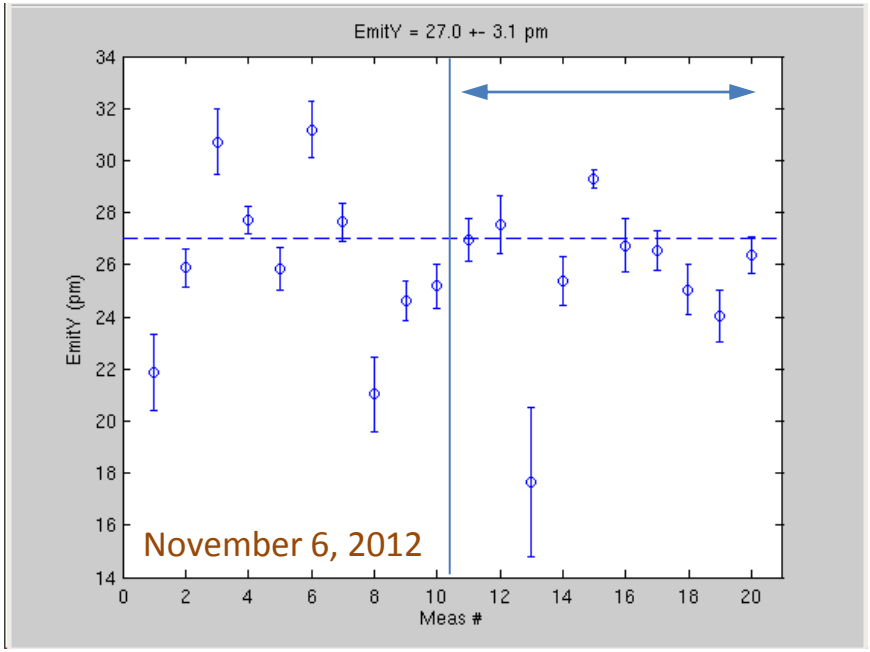
December 14, 2011 07:44

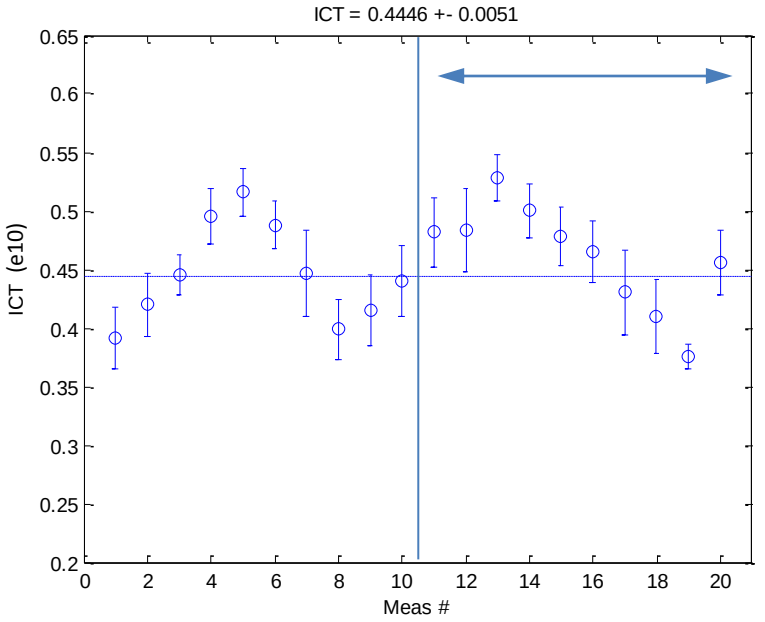
Wire Scanner Measured Vertical Beam Sizes

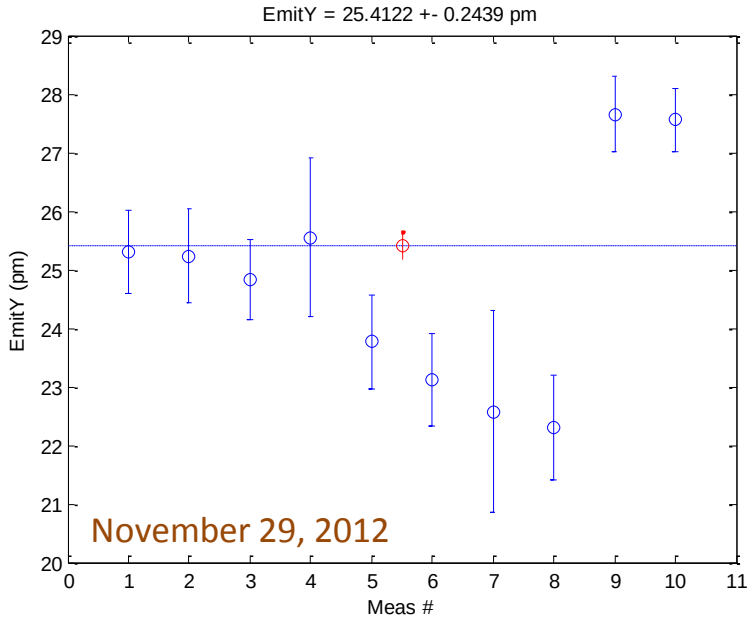
December 14, 2011 09:30

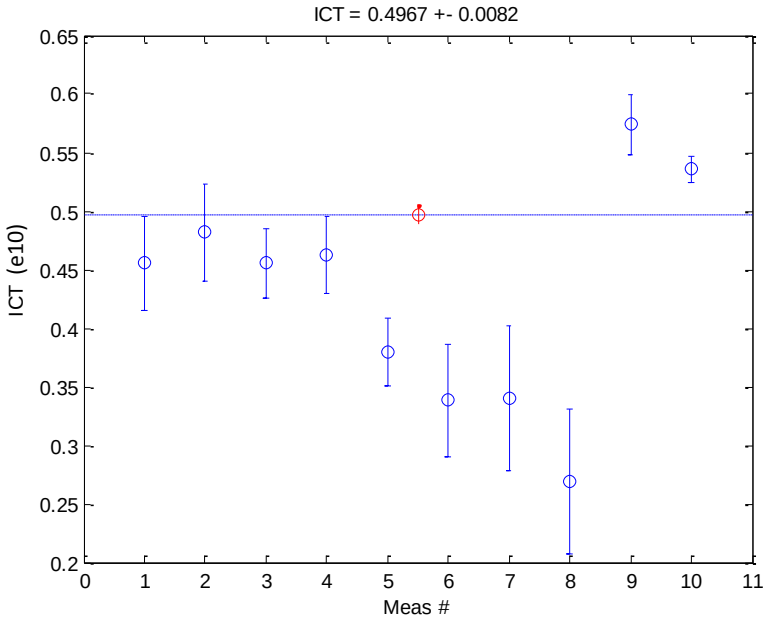
(MW1X σ_y value ignored)

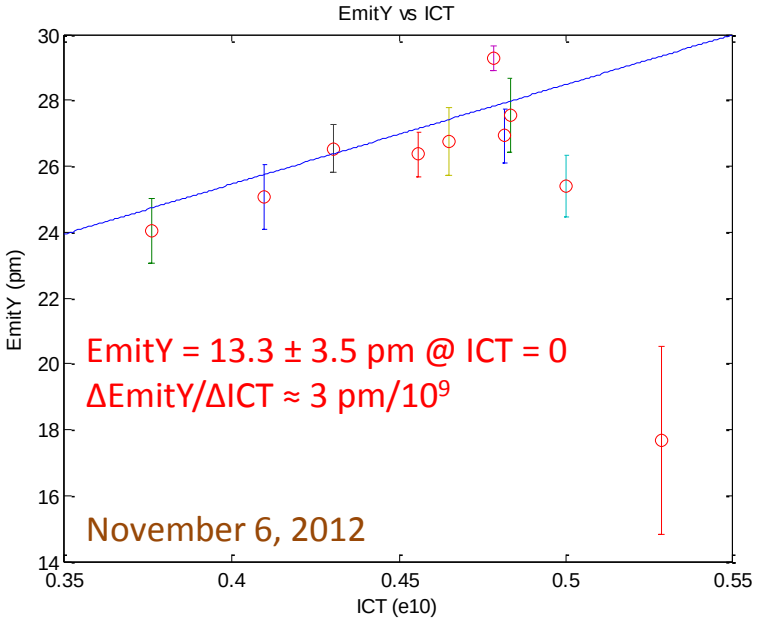


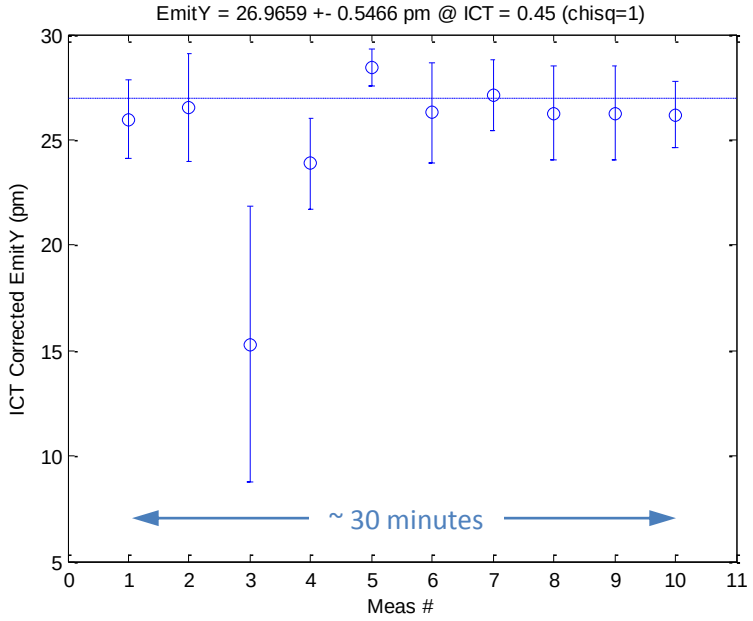

EmitY = 27.0 +- 3.1 pm
EmitY (pm)
Meas #
November 6, 2012

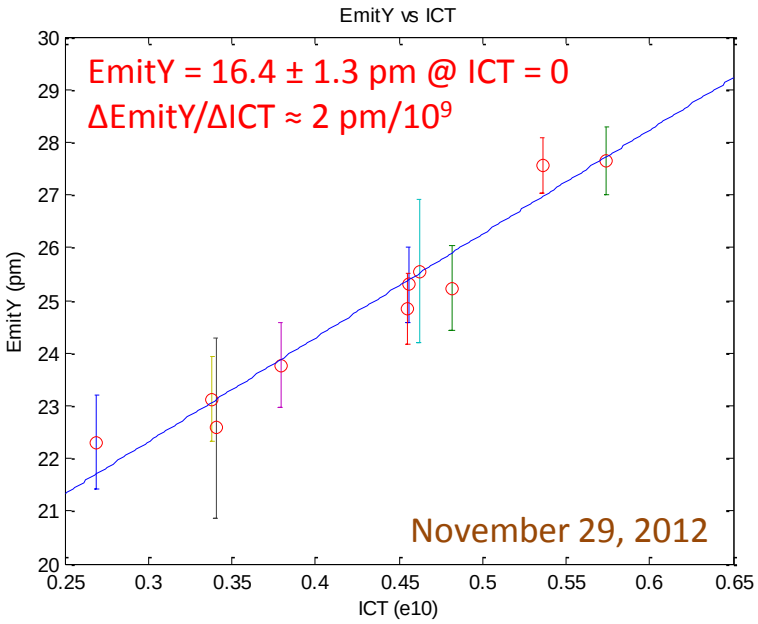

ICT = 0.4446 +- 0.0051
ICT (e10)
Meas #

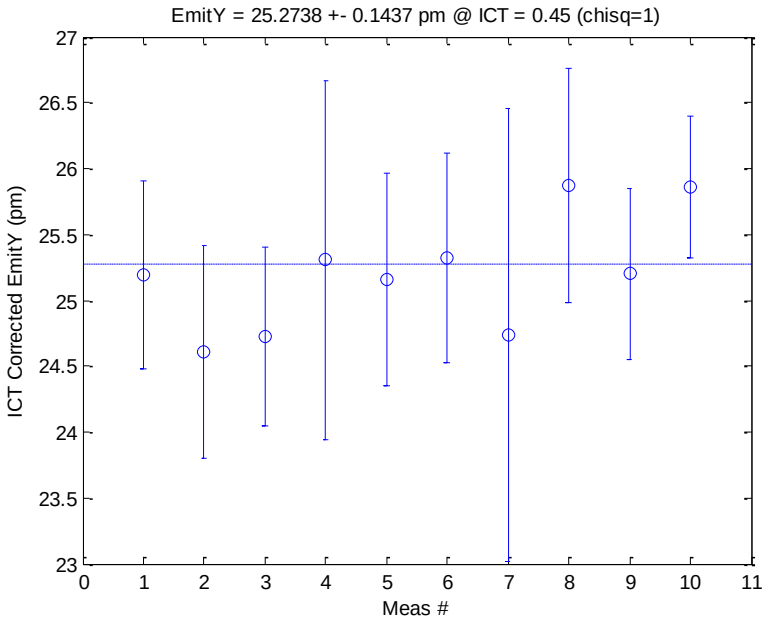

EmitY = 25.4122 +- 0.2439 pm
EmitY (pm)
Meas #
November 29, 2012


ICT = 0.4967 +- 0.0082
ICT (e10)
Meas #

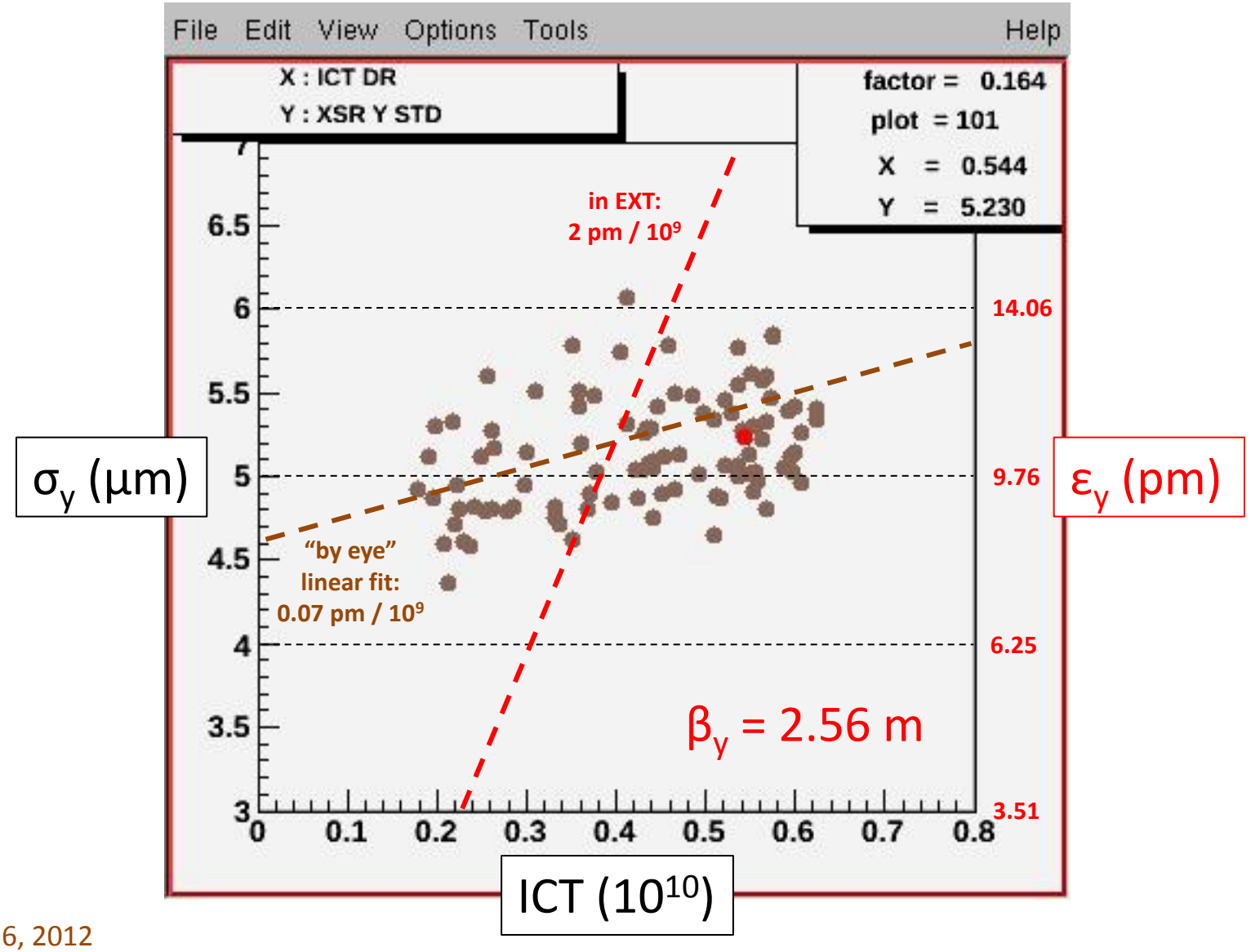

EmitY vs ICT
EmitY (pm)
ICT (e10)
EmitY = 13.3 ± 3.5 pm @ ICT = 0
ΔEmitY/ΔICT ≈ 3 pm/10^9
November 6, 2012


EmitY = 26.9659 +- 0.5466 pm @ ICT = 0.45 (chisq=1)
ICT Corrected EmitY (pm)
Meas #
~ 30 minutes


EmitY vs ICT
EmitY (pm)
ICT (e10)
EmitY = 16.4 ± 1.3 pm @ ICT = 0
ΔEmitY/ΔICT ≈ 2 pm/10^9
November 29, 2012

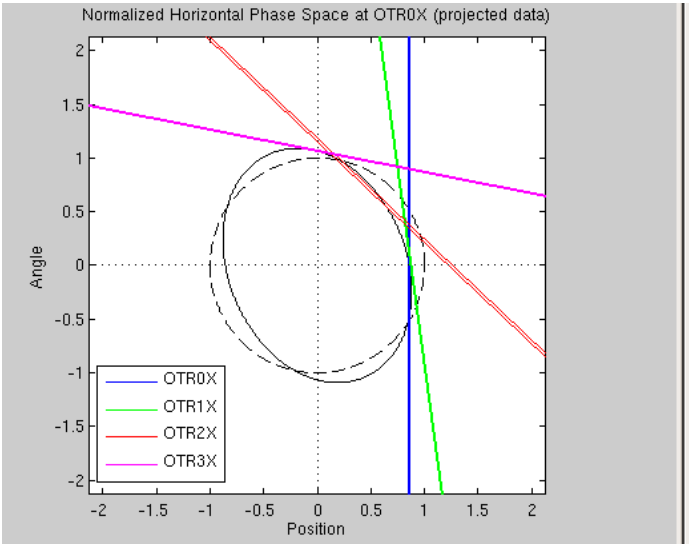

EmitY = 25.2738 +- 0.1437 pm @ ICT = 0.45 (chisq=1)
ICT Corrected EmitY (pm)
Meas #

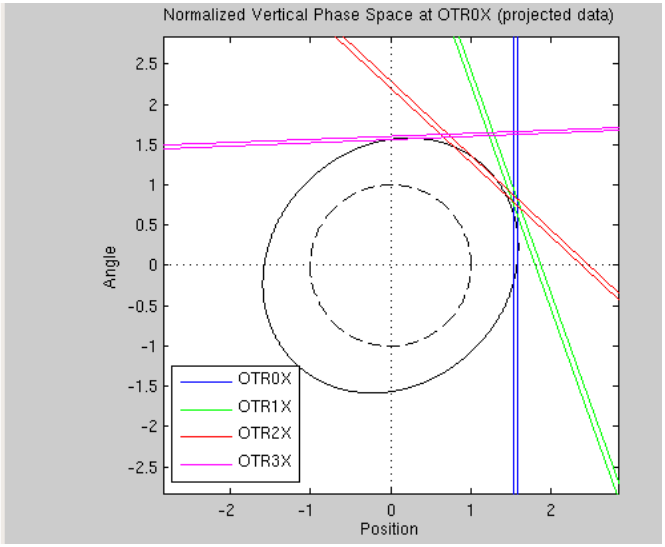
DR XSR σ_y vs ICT



November 6, 2012

Emittance vs Bunch Length (December 21 2012 owl)

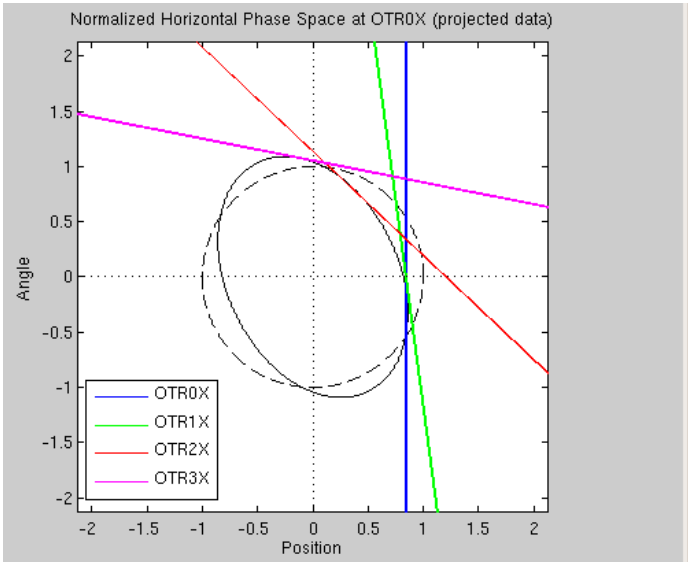


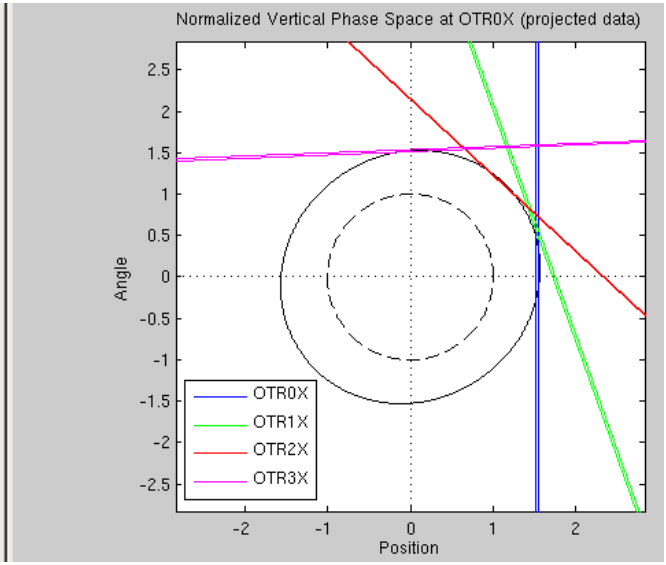


ICT = 5×10^9

DR RF = 0.29 MV

ε_x	=	1.87	nm
B_x	=	1.05	
εB_x	=	1.96	nm
ε_y	=	30.1	pm
B_y	=	1.01	
εB_y	=	30.4	pm





ICT = 5×10^9

DR RF = 0.20 MV

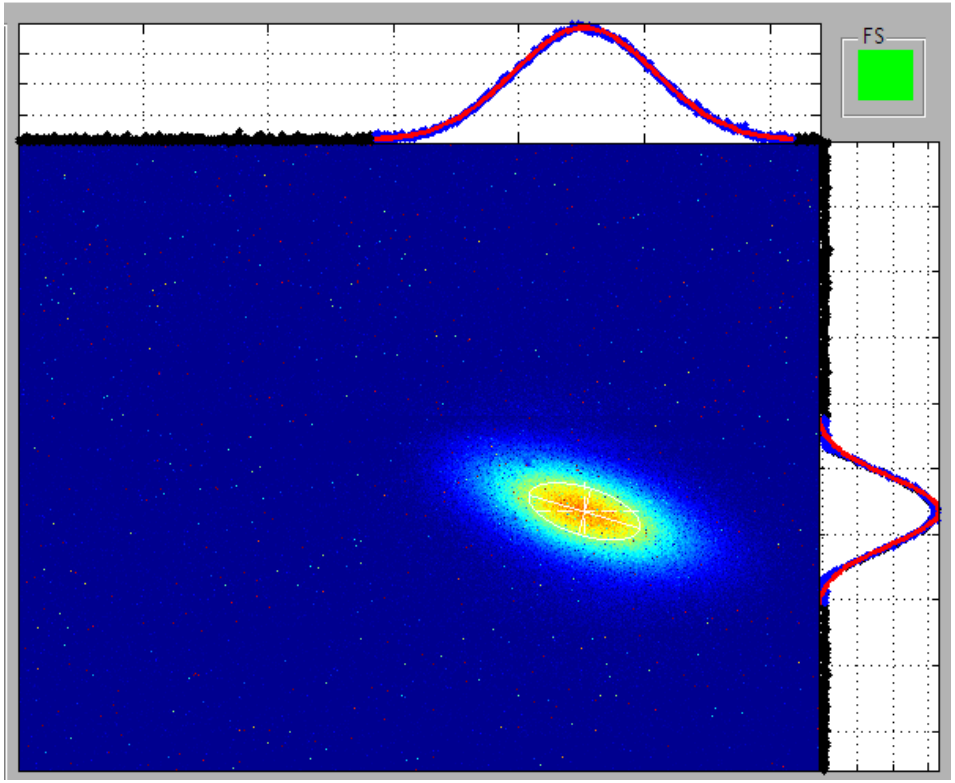
ε_x	=	1.77	nm
B_x	=	1.08	
εB_x	=	1.93	nm
ε_y	=	28.8	pm
B_y	=	1.00	
εB_y	=	28.9	pm

Coupling Correction

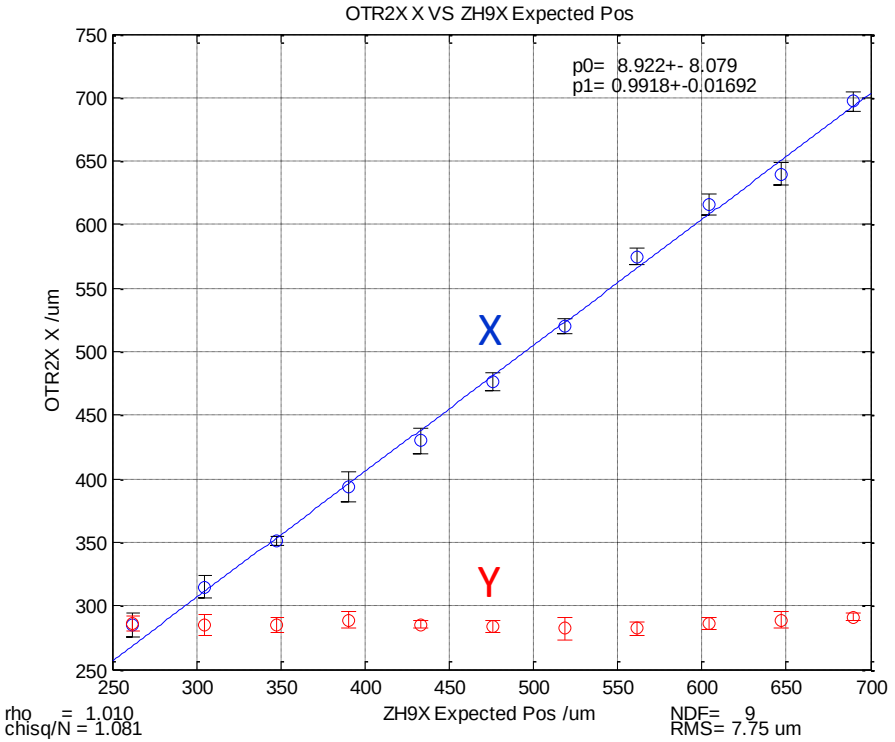
Issues:

- do we believe the OTR beam tilt measurements?
- do measured beam tilts respond to coupling correction?

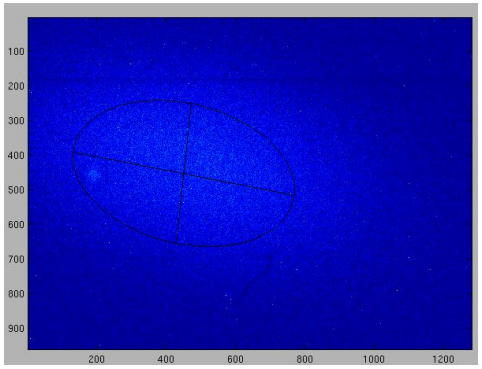
OTR2X beam tilt … is it real?



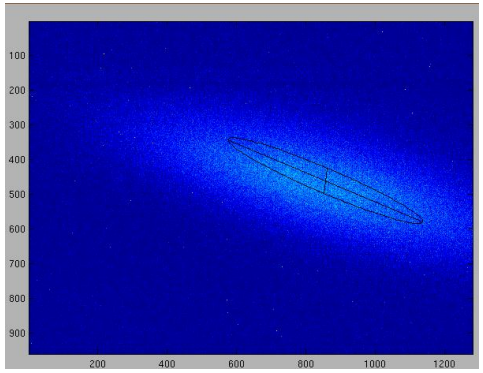
Check measured response to ZH9X



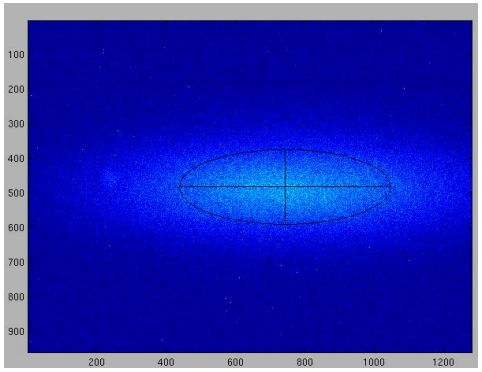
OTR0X before corrections



OTR0X after dispersion correction



OTR0X after coupling correction



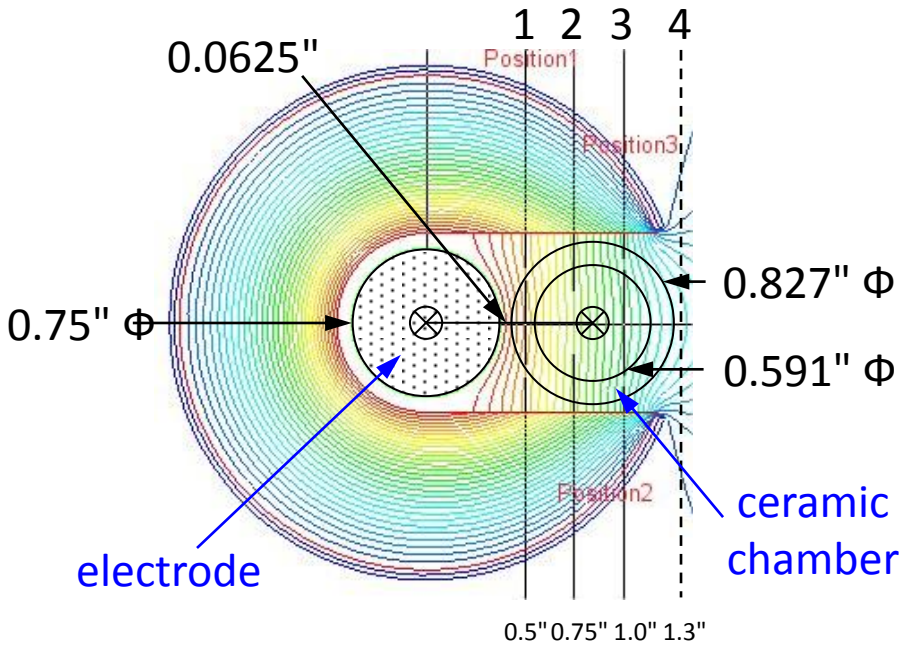
Extraction Kicker

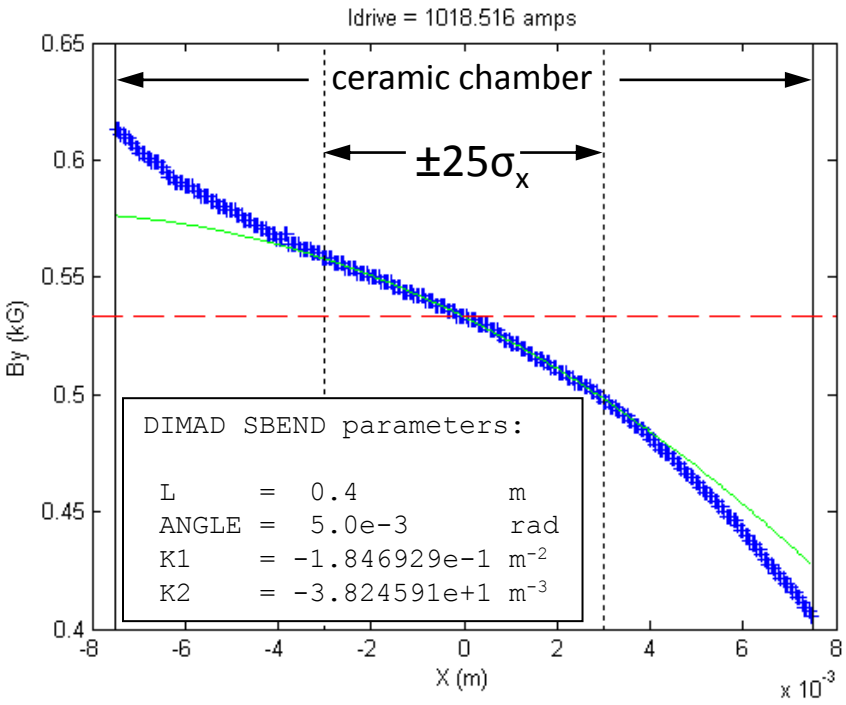
Issues:

- multipole fields (quadrupole/sextupole): are they real?
- what's the correct voltage?
- is the kicker rolled?
- what's inside? (field linearizer? metal or plastic electrode restraint?)

Field Simulation (May 26, 2005)

C. Pappas, SLAC

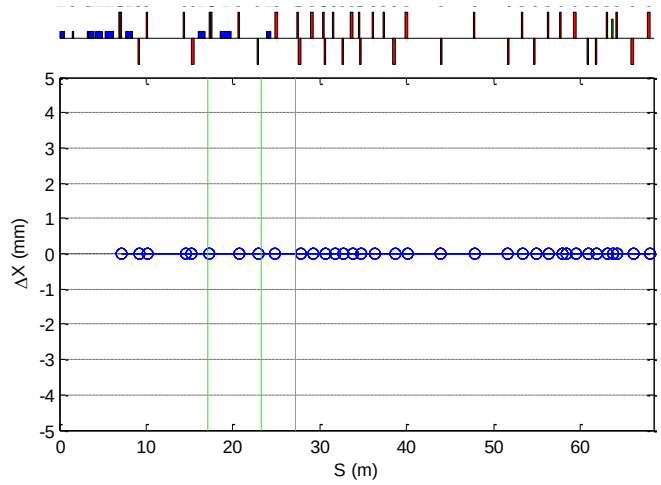


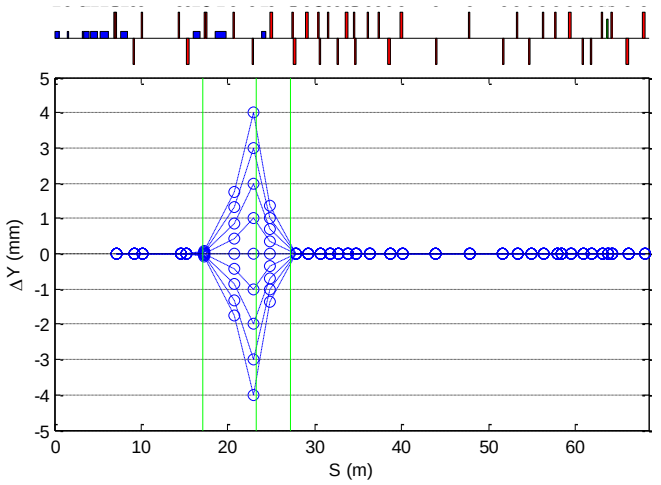


scale: 1.14" (figure) ≈ 0.75" (actual)

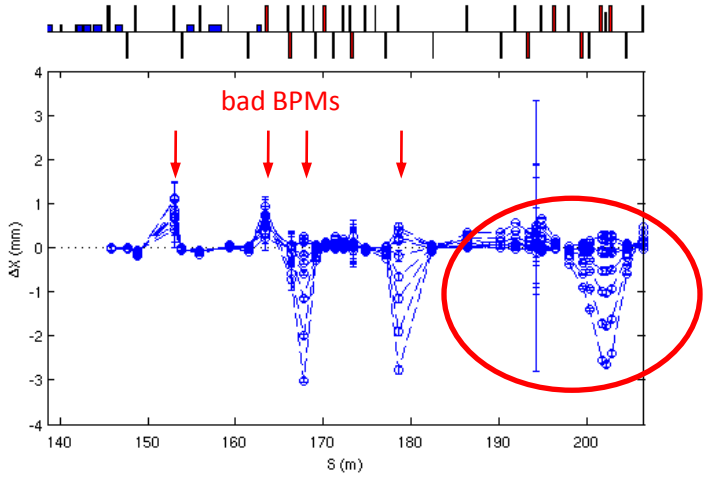
Orbit Bump Study (February 2010): bump vertically through KEX2

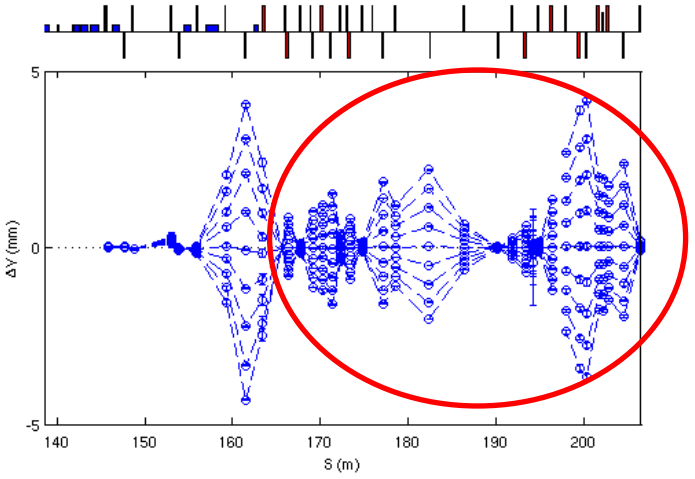
what we expected to see (no kicker multipoles) …





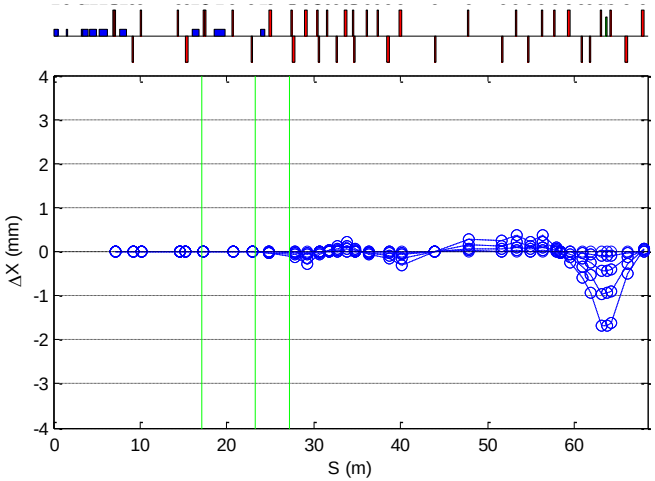
… what we observed

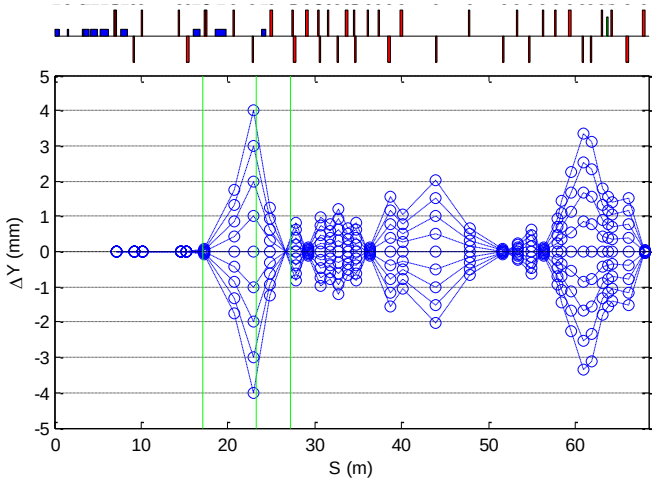




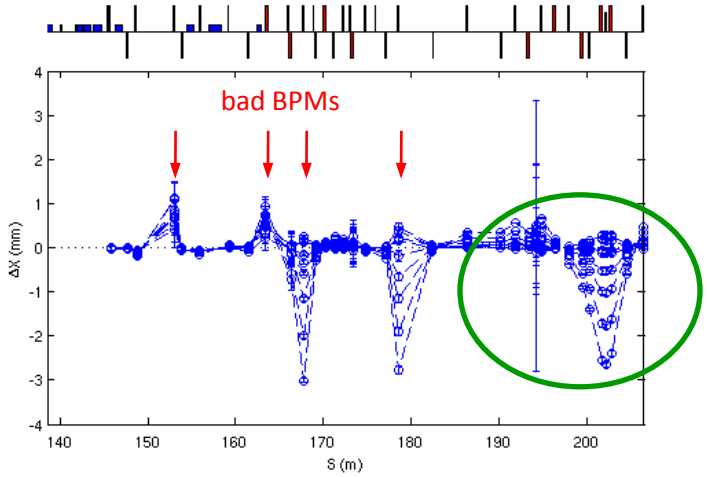
Orbit Bump Study (February 2010): bump vertically through KEX2

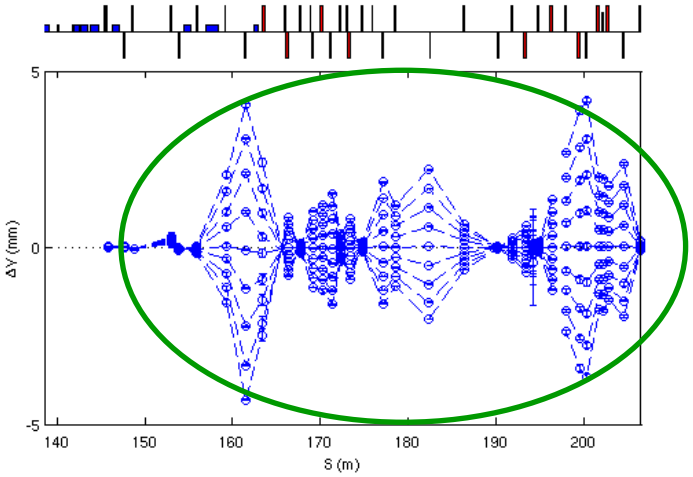
what we expected to see (with predicted kicker multipoles) …

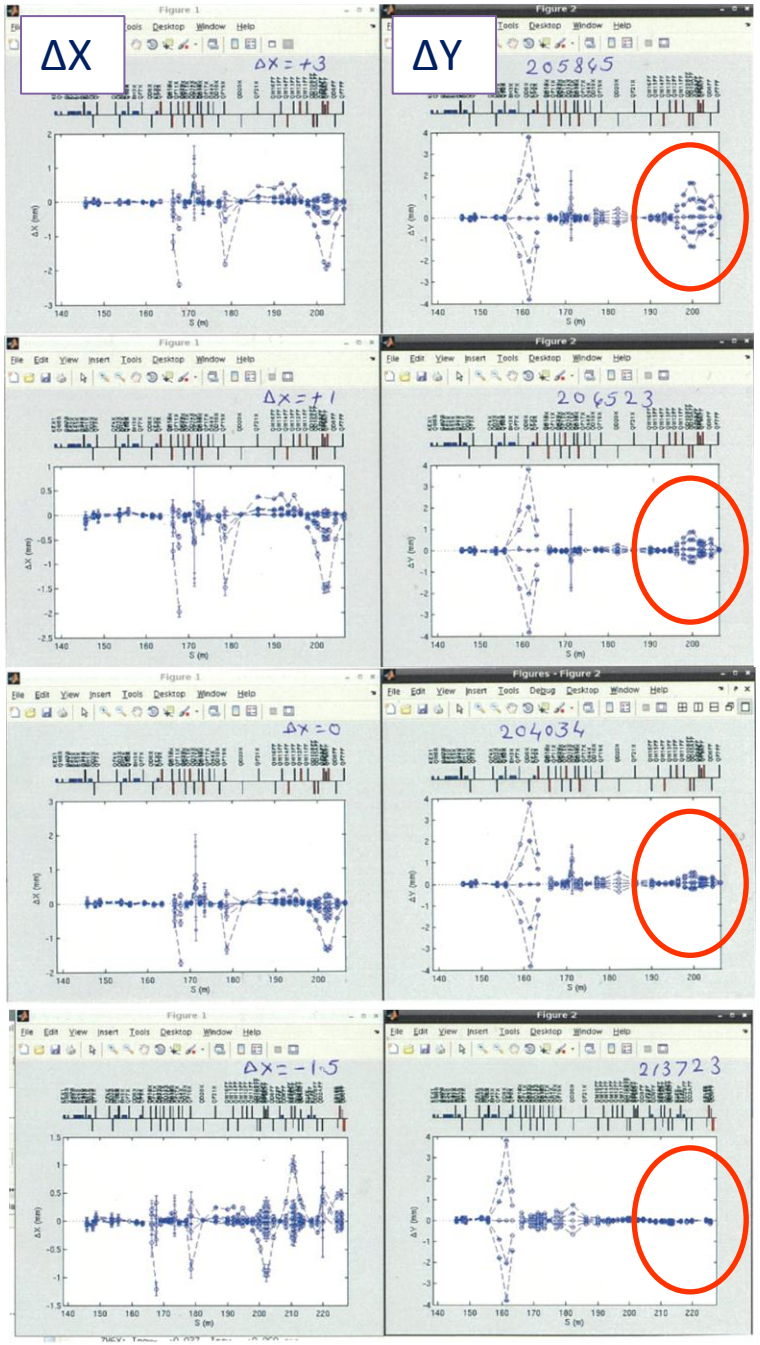




… what we observed







ΔX = +3 mm

ΔX = +1 mm

ΔX = 0

ΔX = -1.5 mm

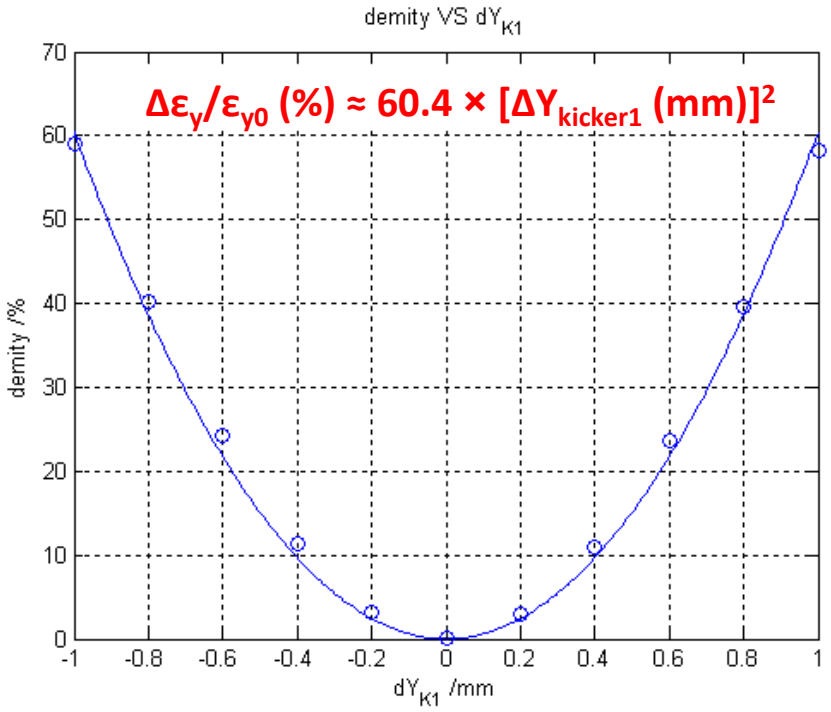
set ZH3X/ZH4X/ZH5X X-bump; scan ZV5X/ZV6X/ZV7X Y-bump; find X-bump setting where Y-bump closes

at this point the quadrupole field seen by the beam in KEX2 has the value predicted by POISSON for the vacuum chamber center

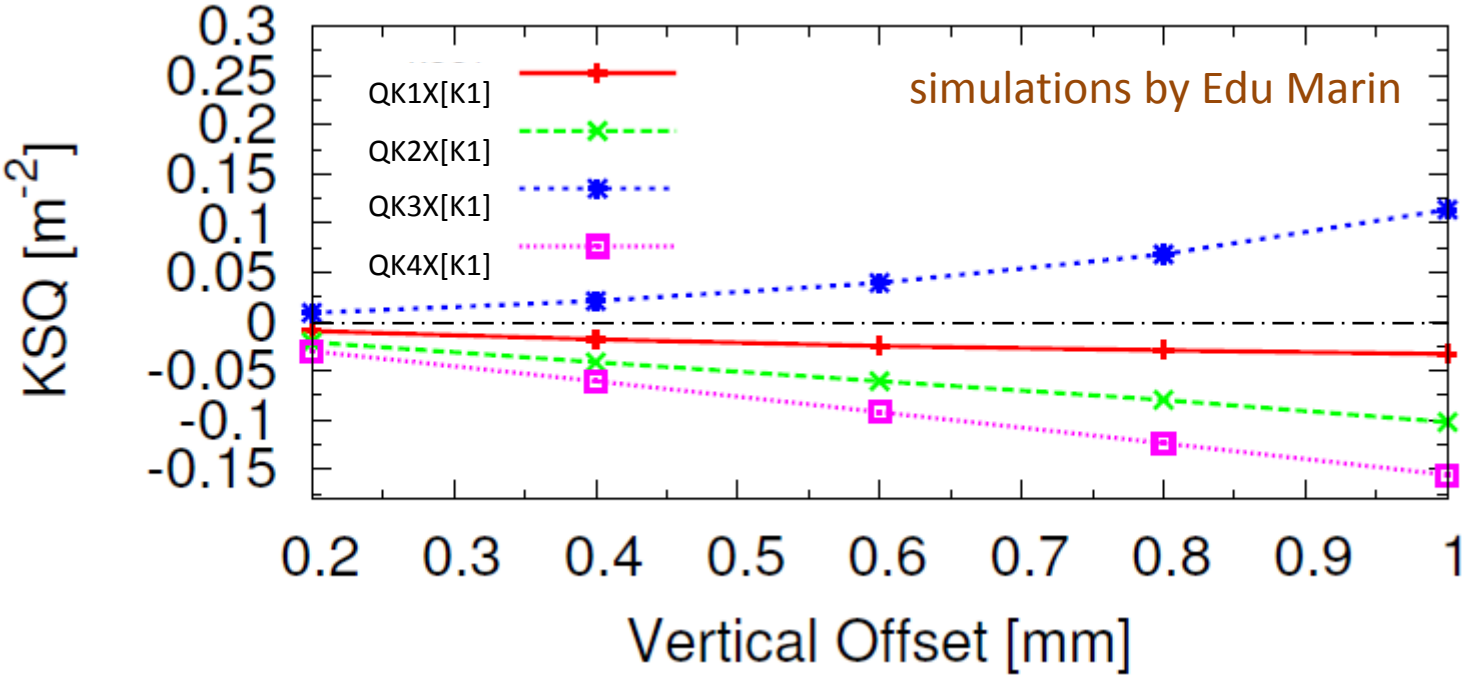
we observed that BSM background increased at X-bump = -1.5 mm, so we set X-bump back to zero … KEX2 horizontally misaligned?

should scan X-bump and observe BSM background to locate center of KEX2 vacuum chamber (in X)

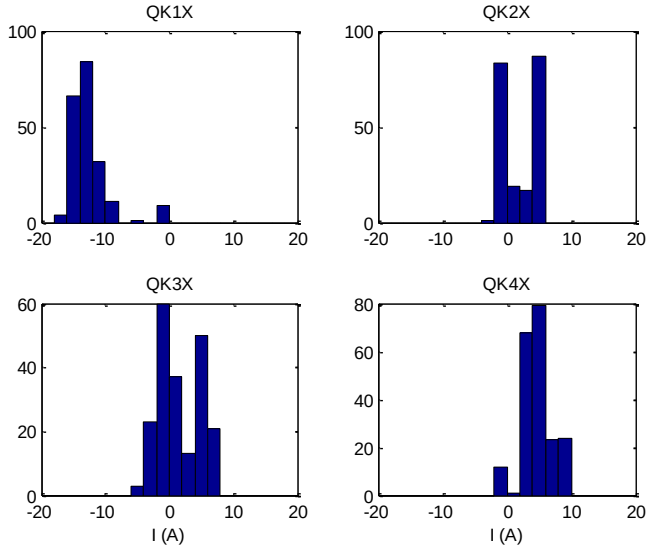
Vertical emittance growth (η_y corrected)



12 pm -> 20 pm @ +- 1 mm

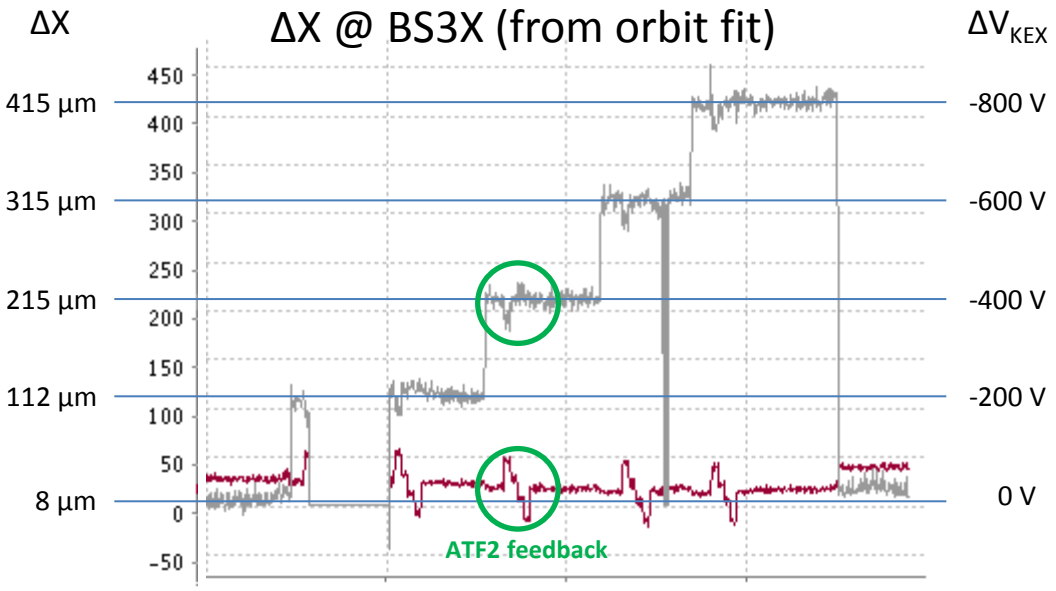


Nov/Dec 2012 QK*X SET-file values



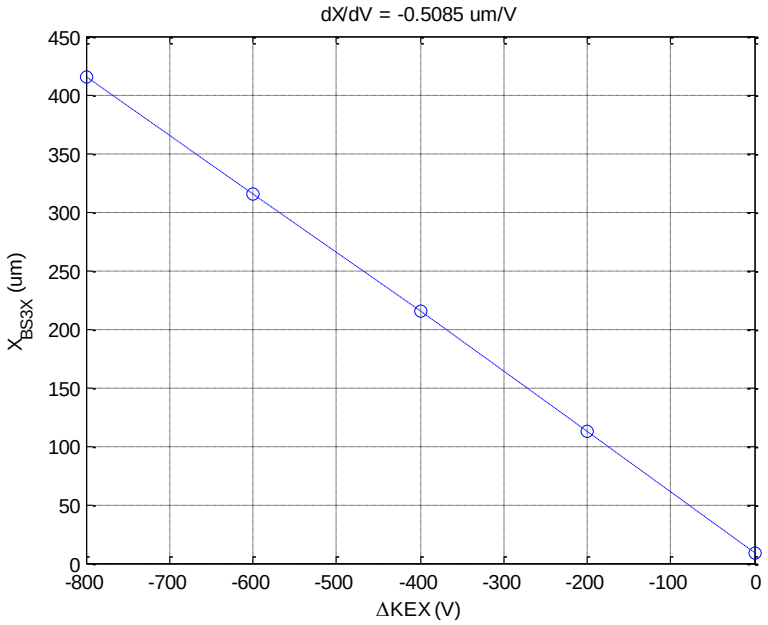
Simulation of vertical offset in KEX1

- coupling due to sextupole component blows up vertical emittance
- coupling corrected with QK skew quads (after vertical dispersion correction)
- pattern of QK strengths is not what we observe (QK1X is relatively weak)
- more in Edu Marin's presentation …



measurement: 2012/12/07 Owl Shift

Horizontal orbit position at BS3X center estimated by back-propagation from EXT BPM measurements (QF1X-QF4X)
… courtesy of Yves Renier



$$\Delta x = R_{12}\Delta\theta\ ,\ \Delta\theta = c\Delta V\ ,\ c = \frac{1}{R_{12}}\left(\frac{\Delta x}{\Delta V}\right)$$

R12 = 4.7329 mm/mrad
dX/dV = -0.5085 mm/kV
dθ/dV = -0.1074 mrad/kV
θ_0 = -5 mrad ⇨ V_0 = 46.5 kV
(SLAC NDR KEX: 0.1158 mrad/kV)

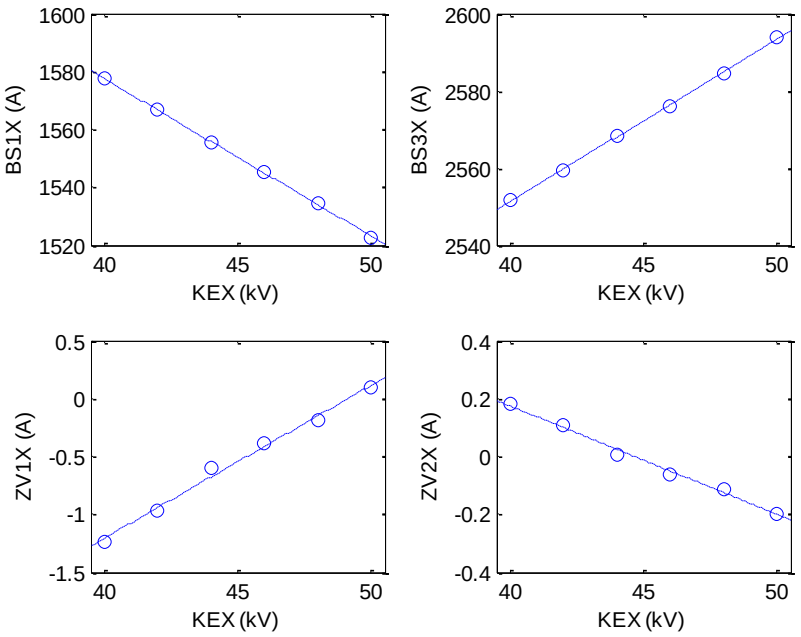
EXT Orbit (Corrected) vs KEX Voltage
December 13, 2012 Day Shift

Kicker & Septum Orbit Data

In order to make same EXT orbit, we must set to the following Septum and vertical steering settings

KEX	BS1X	BS3X	ZV1X	ZV2X
46000	1545.49A	2576.02A	-0.391A	-0.062A
48000	1534.29A	2584.62A	-0.181A	-0.112A
50000	1522.69A	2593.62A	+0.099A	-0.197A
44000	1555.29A	2568.42A	-0.601A	+0.003A
42000	1566.69A	2559.42A	-0.961A	+0.108A
40000	1577.49A	2551.52A	-1.241A	+0.183A

KEX1 steers vertically?
inferred roll is ~100 mrad (!)
… or something else?

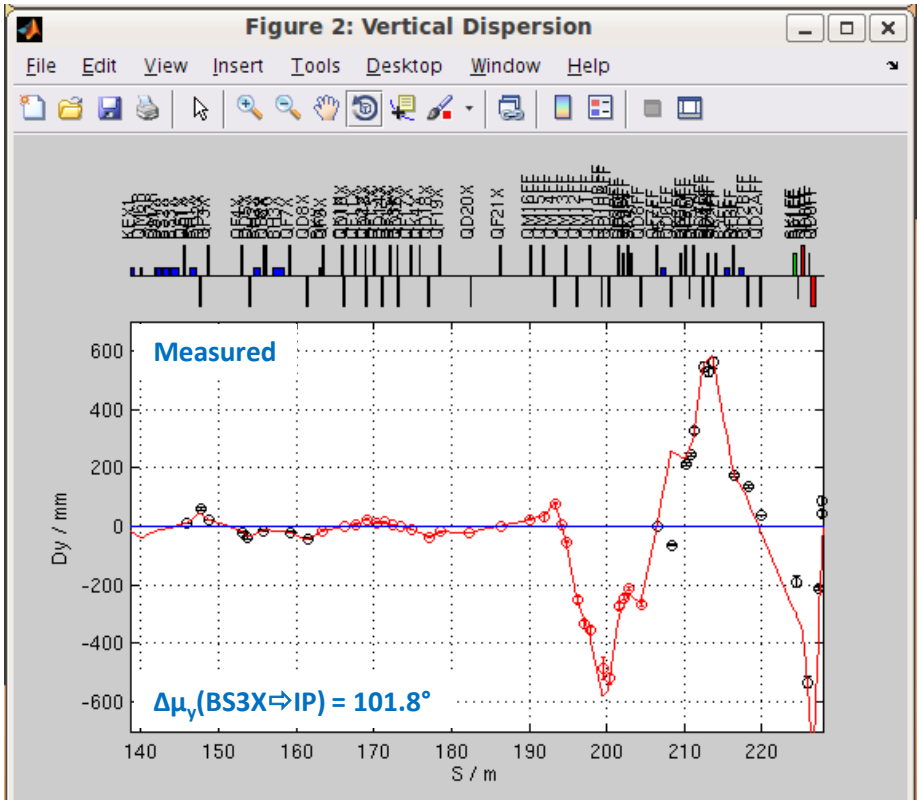


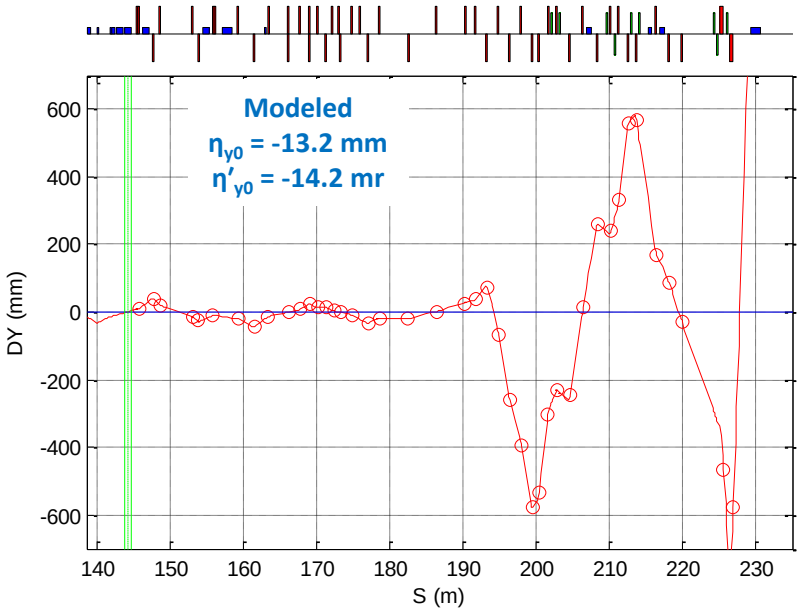
BS3X Skew Quadrupole (?)

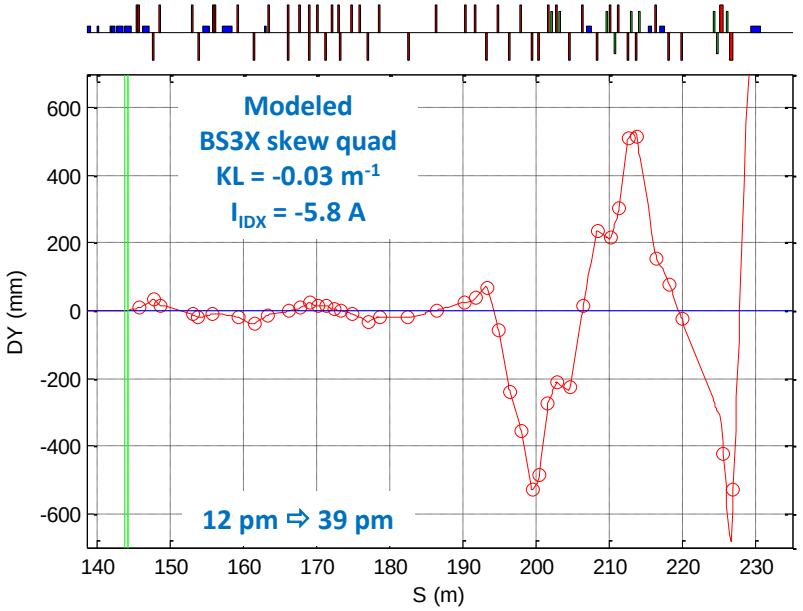
Issues:

- origin of observed anomalous vertical dispersion in EXT/FF?
  – measured vertical dispersion in DR at extraction point is small
- we have had problems with BS3X in the past
  – BS3X had to be physically rolled ~ -4 mrad (March 17, 2010)

NOTE: η_x = 179 mm @ BS3X







zoom in …

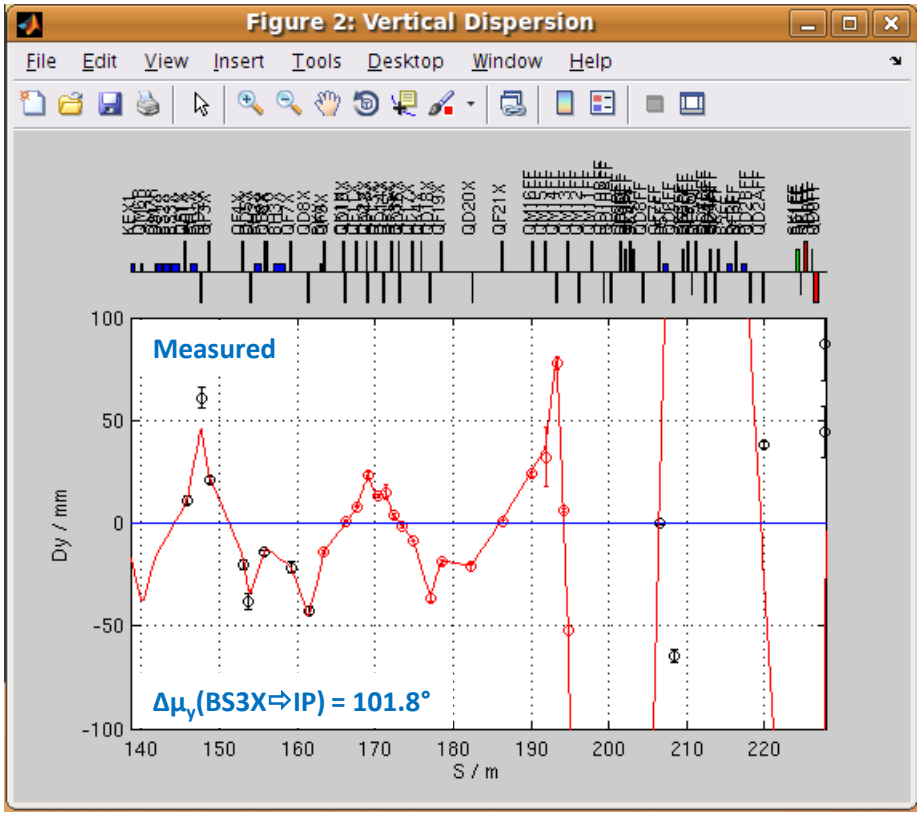
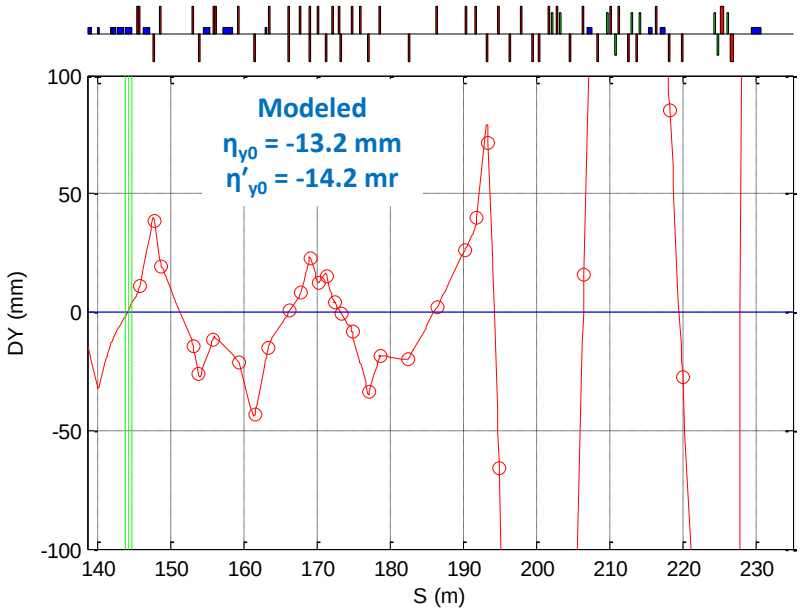
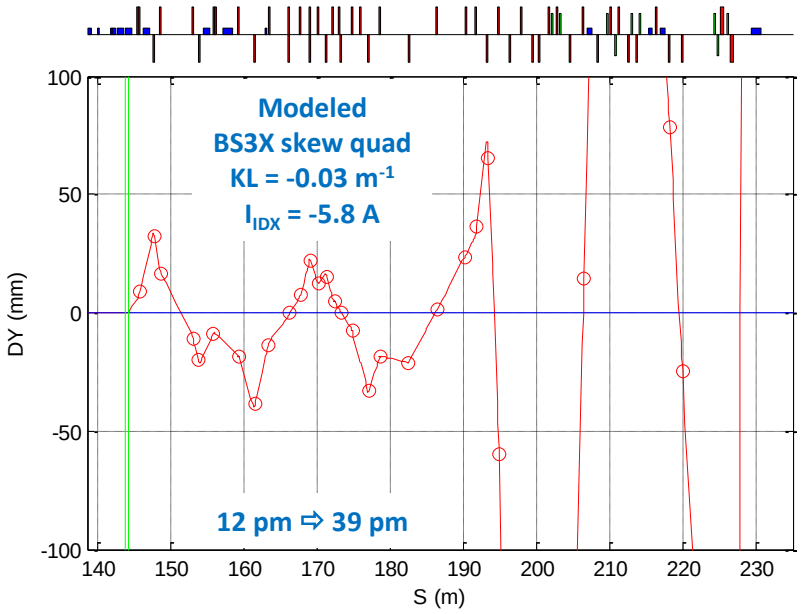
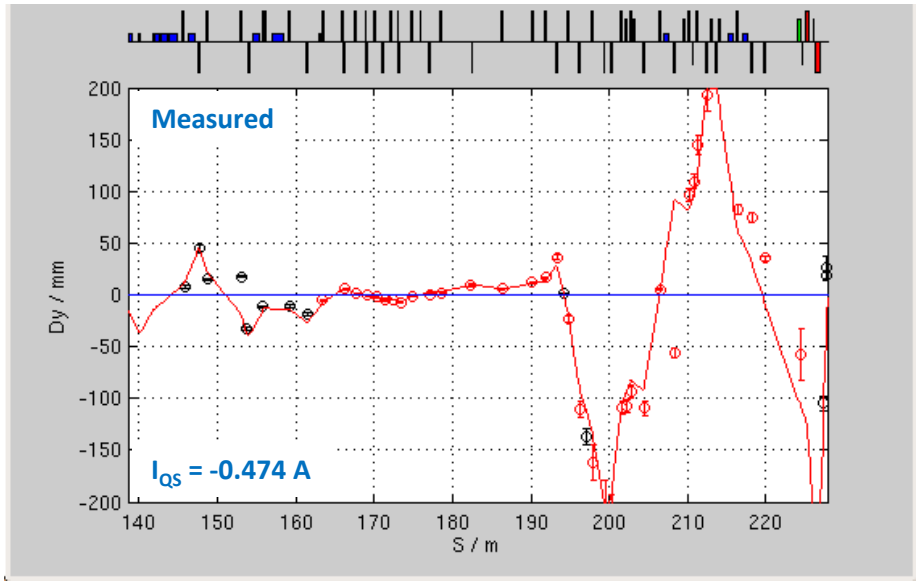


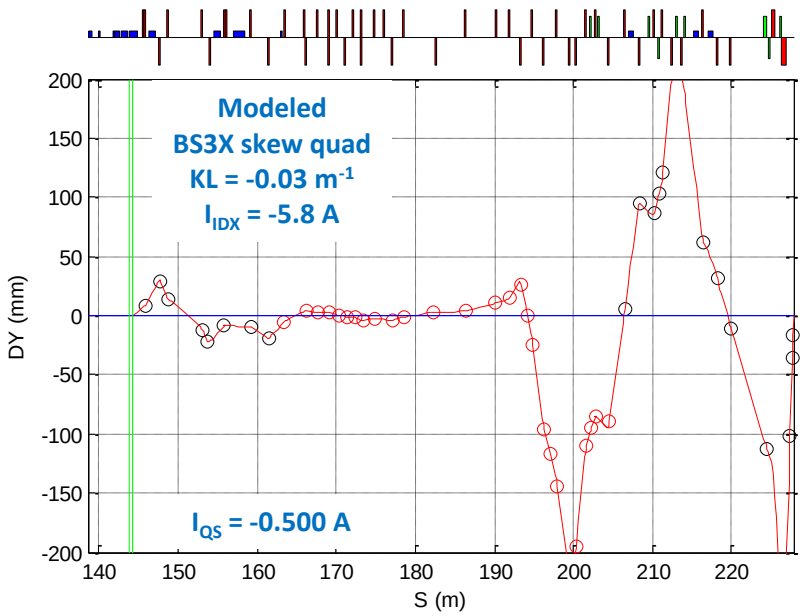
Figure 2: Vertical Dispersion
File Edit View Insert Tools Desktop Window Help
Measured
Dy / mm
S / m
Δμ_y(BS3X⇨IP) = 101.8°


Modeled
η_y0 = -13.2 mm
η'_y0 = -14.2 mr
DY (mm)
S (m)

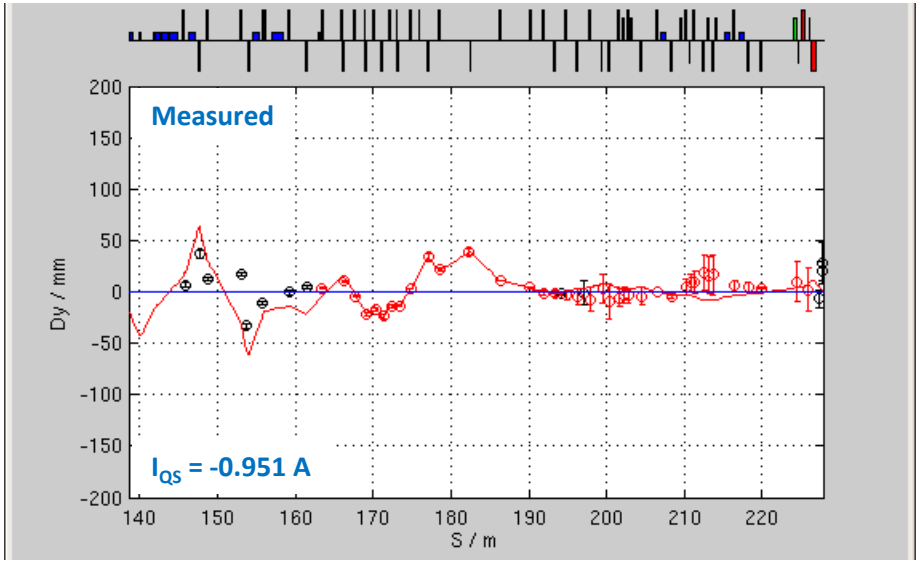

Modeled
BS3X skew quad
KL = -0.03 m^-1
I_IDX = -5.8 A
12 pm ⇨ 39 pm
DY (mm)
S (m)

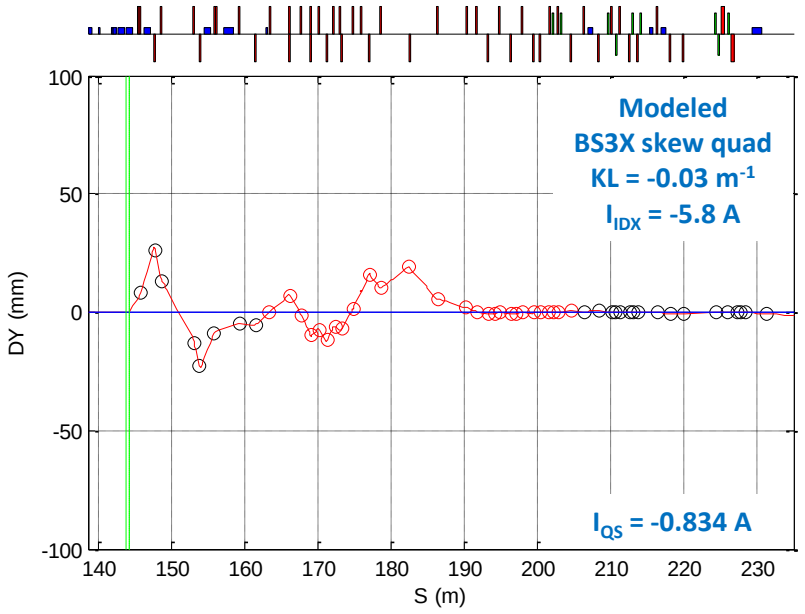
either use QS Σ-knob to correct EXT (IP-phase) …





… or use QS Σ-knob to correct FF (FD-phase)



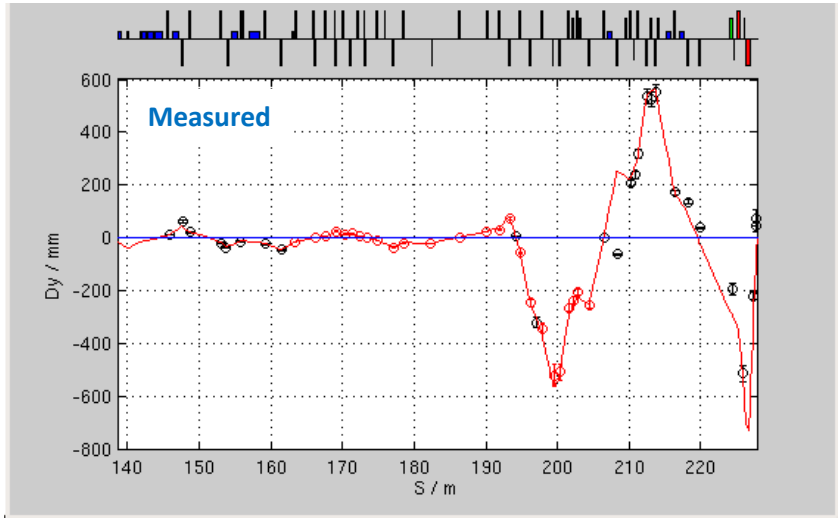


BS3X Skew Sextupole (?)

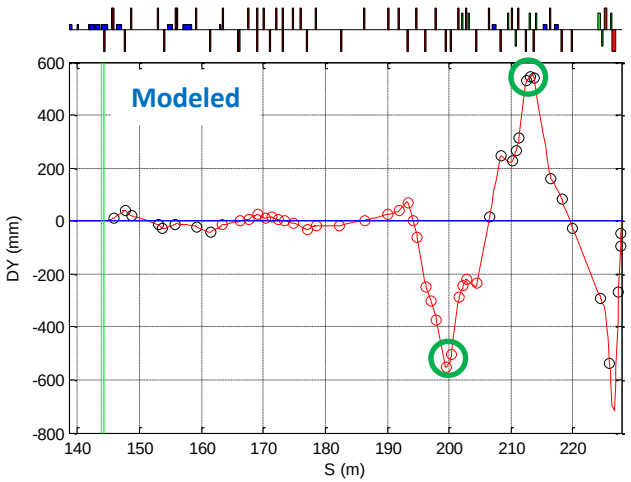
Issues:

- anomalous vertical dispersion amplitude depends on extraction kicker voltage
- X position dependent skew quadrupole field ⇨ skew sextupole

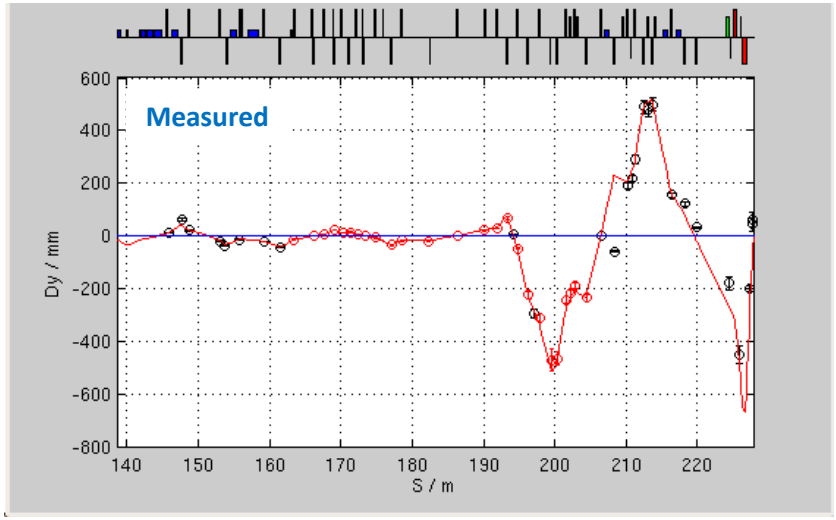
ΔKEX = 0 (KEX = 50000 V)



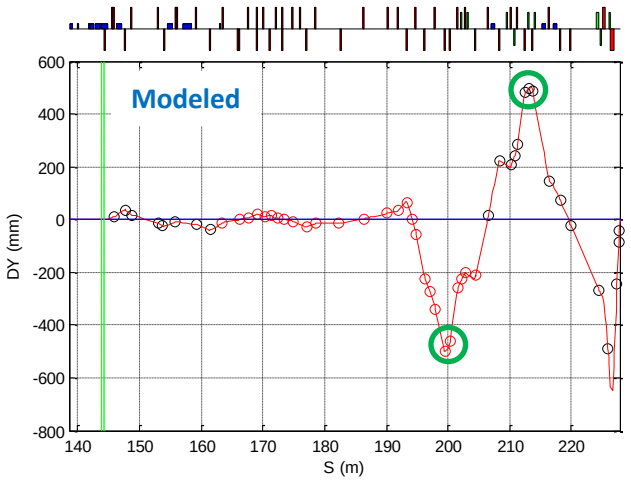
$KL_{BS3Xskew} = -0.03517\ m^{-1}$



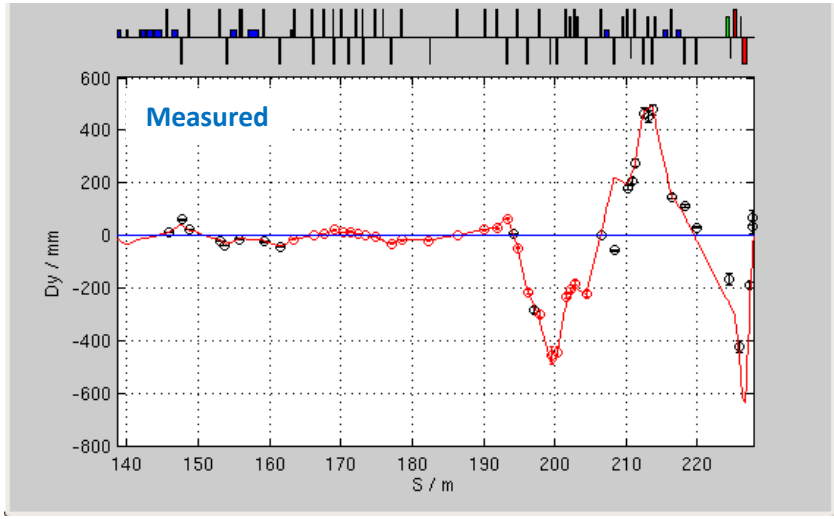
ΔKEX = -200 V



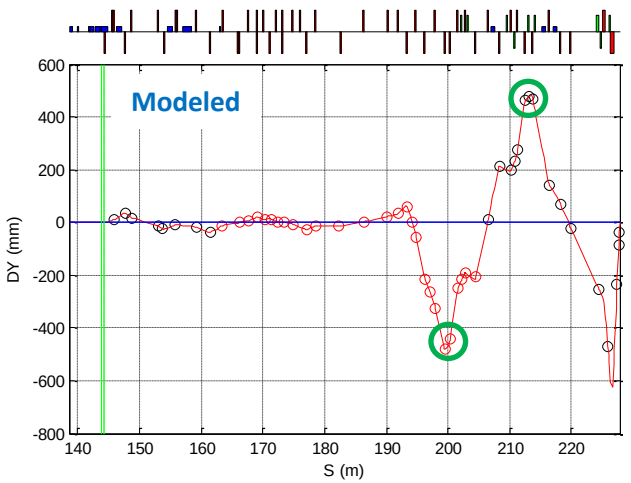
$KL_{BS3Xskew} = -0.03215\ m^{-1}$



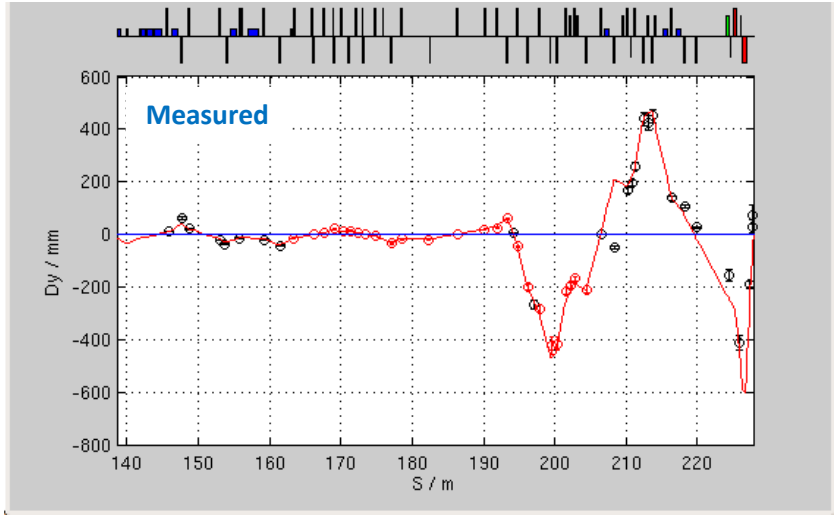
ΔKEX = -400 V



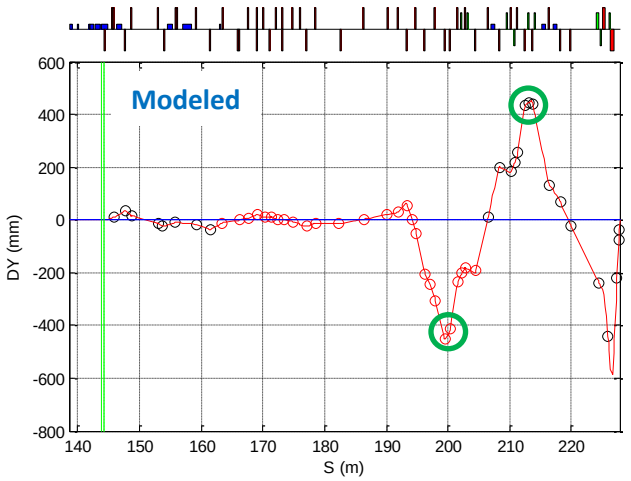
$KL_{BS3Xskew}$ = -0.03094 m^{-1}



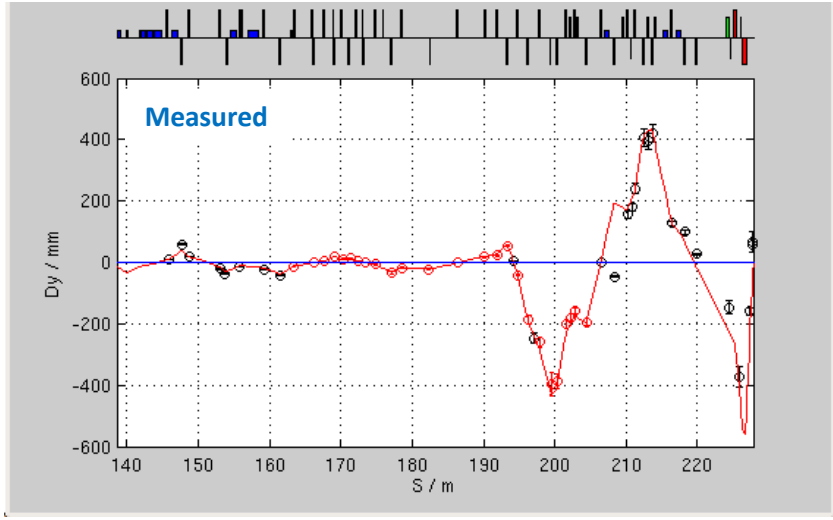
ΔKEX = -600 V



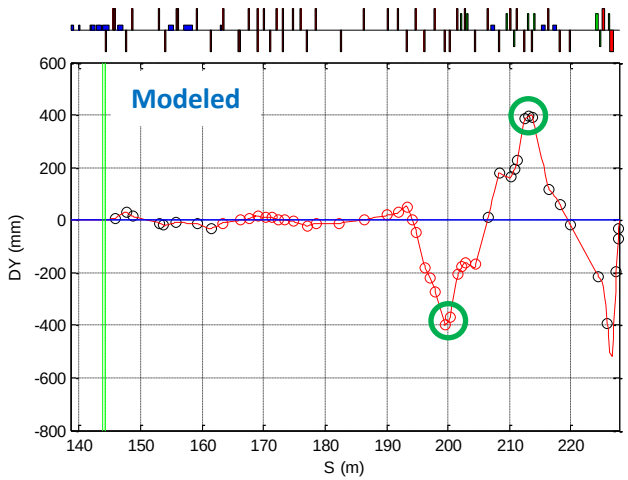
$KL_{BS3Xskew}$ = -0.02913 m^{-1}



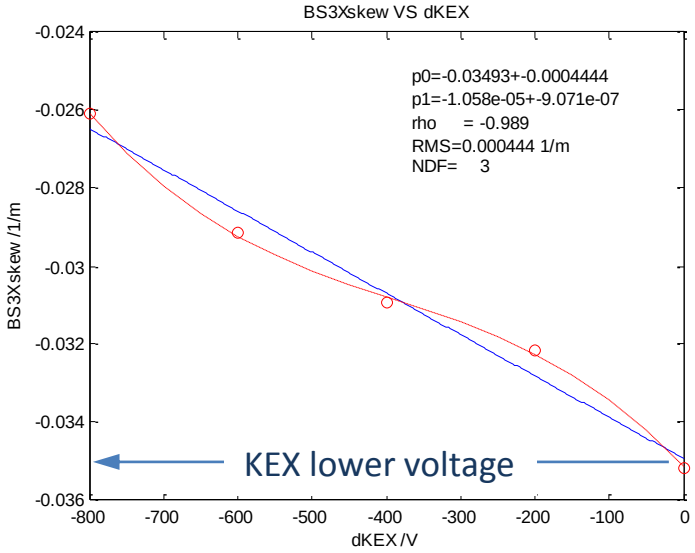
ΔKEX = -800 V



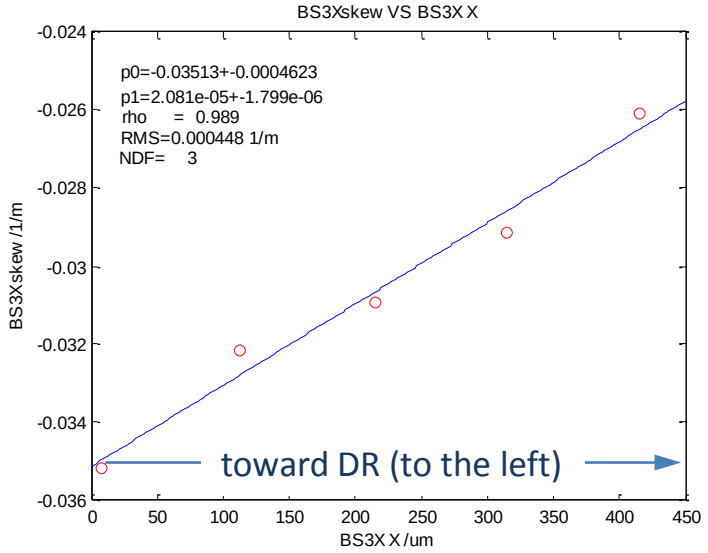
$KL_{BS3Xskew}$ = -0.02610 m^{-1}



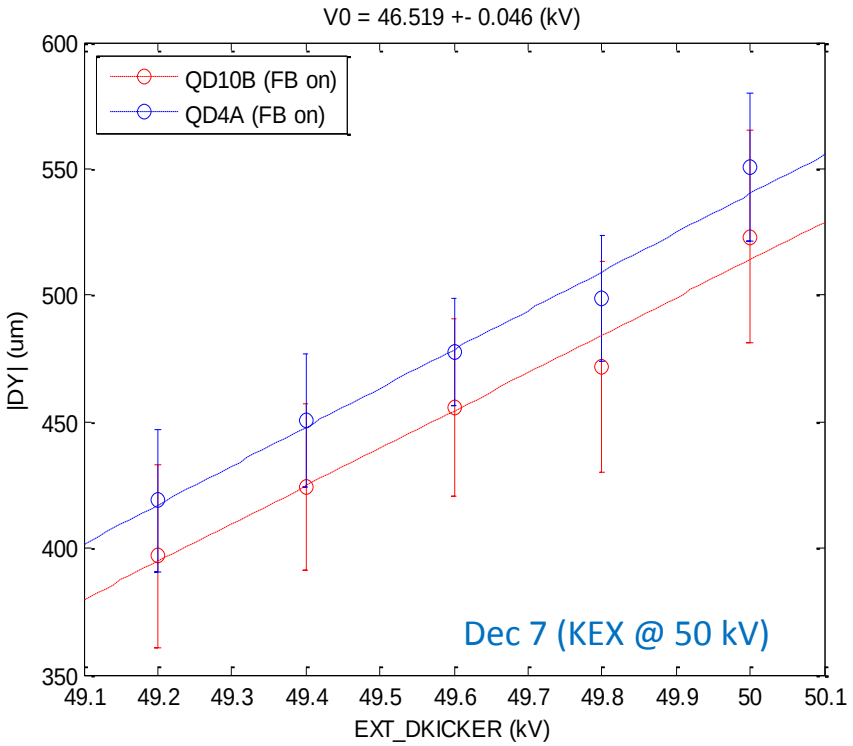
BS3Xskew = 0 @ KEX = 46.7 kV

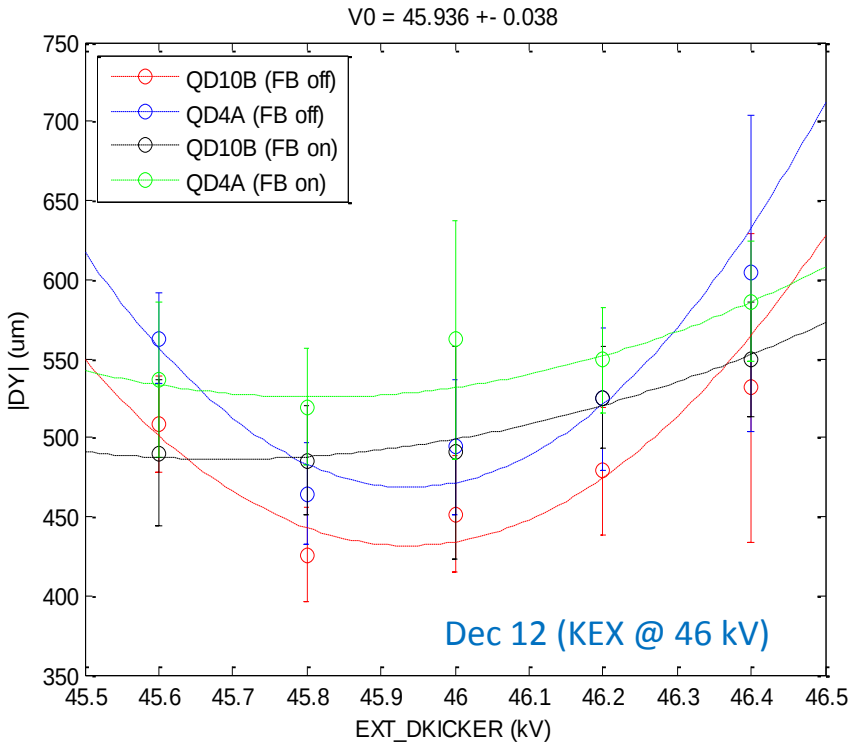


BS3Xskew = 0 @ BS3X X = +1.7 mm



Set EXT Kicker Voltage to 46 kV



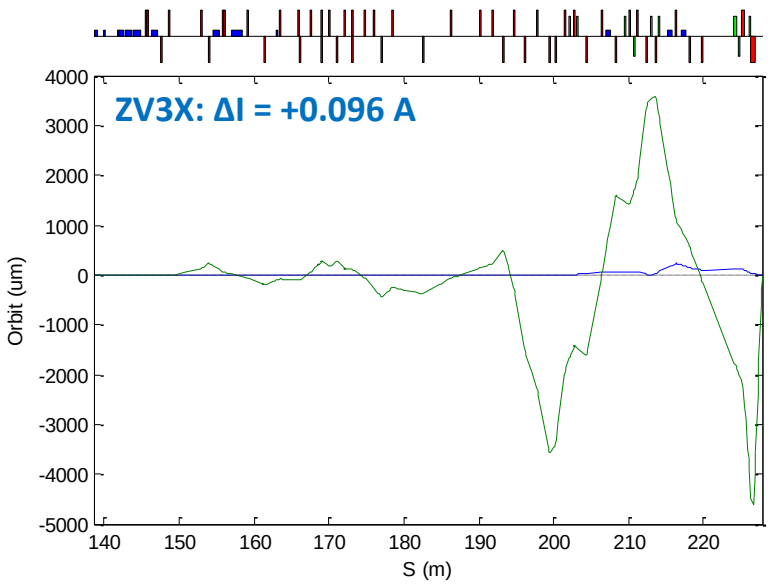


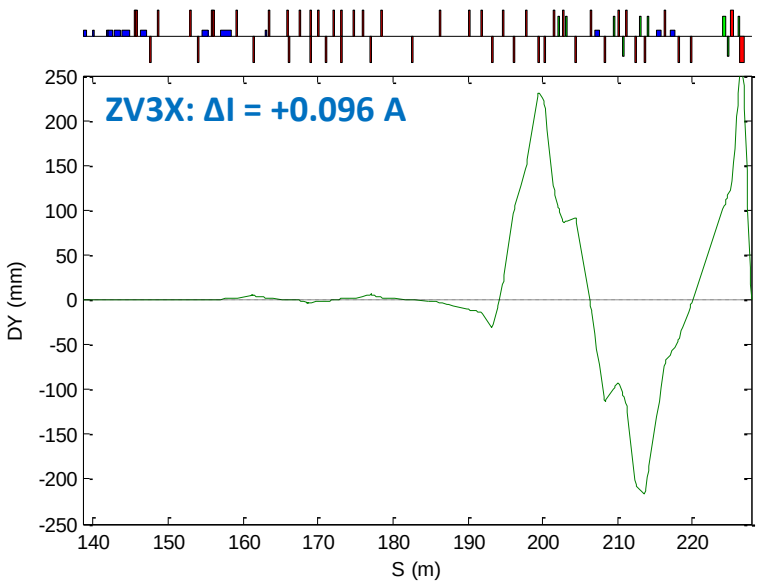
Vertical Dispersion Correction

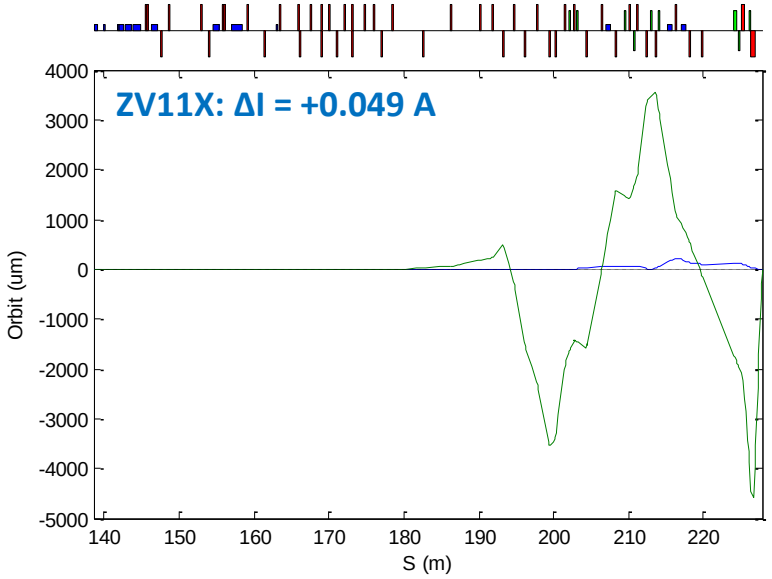
Issues:

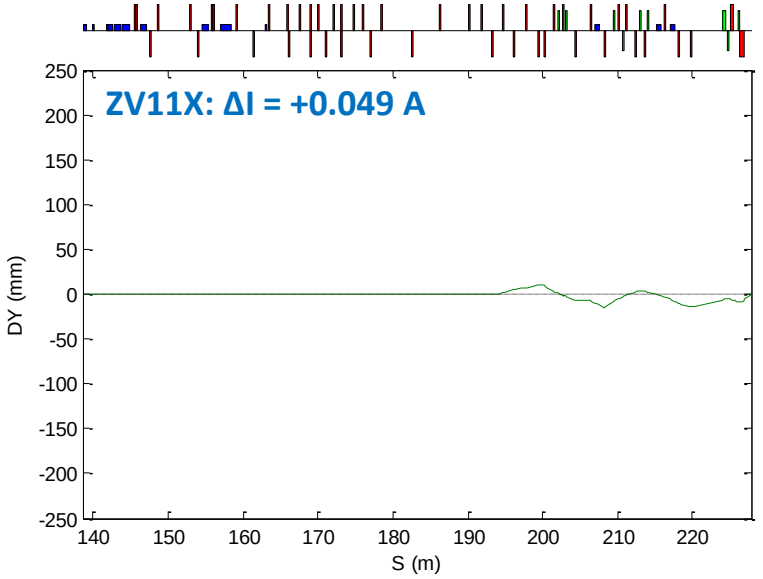
- can't simultaneously correct vertical dispersion in EXT (at OTRs … IP-phase) and in FF (FD-phase) using the QS Σ-knob
- presence of KEX2 prevented use of vertical dipole correctors for "other phase" vertical dispersion correction
  - – emittance growth when off axis vertically in KEX2 (sextupole)
  - – but … KEX2 is now gone (using BKX dipole instead)
- can now use both QS Σ-knob and vertical dipole correctors for vertical dispersion correction

Simulation


ZV3X: ΔI = +0.096 A
Orbit (um)
S (m)

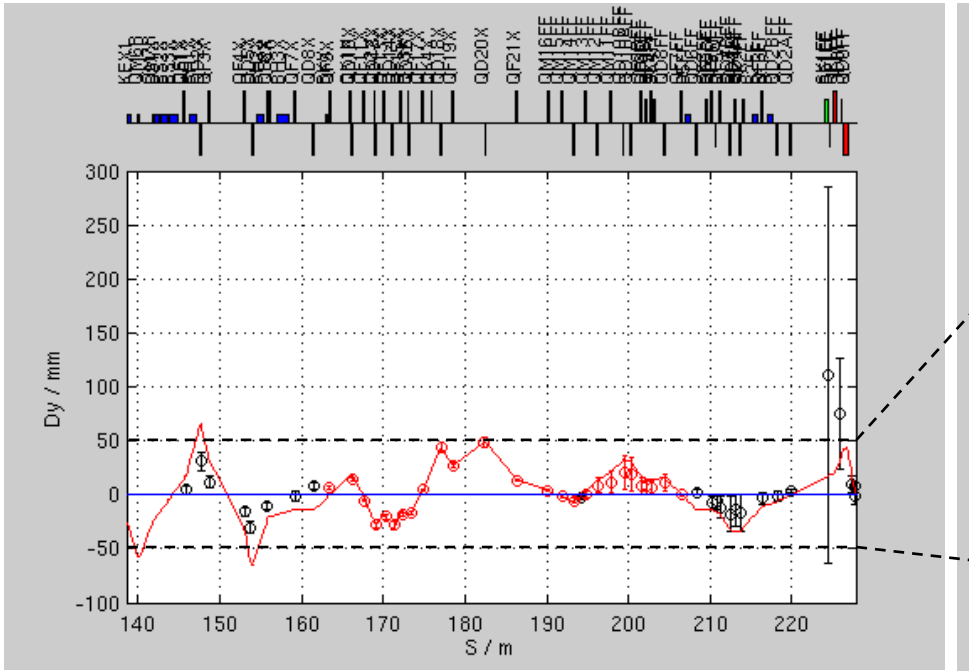

ZV3X: ΔI = +0.096 A
DY (mm)
S (m)


ZV11X: ΔI = +0.049 A
Orbit (um)
S (m)

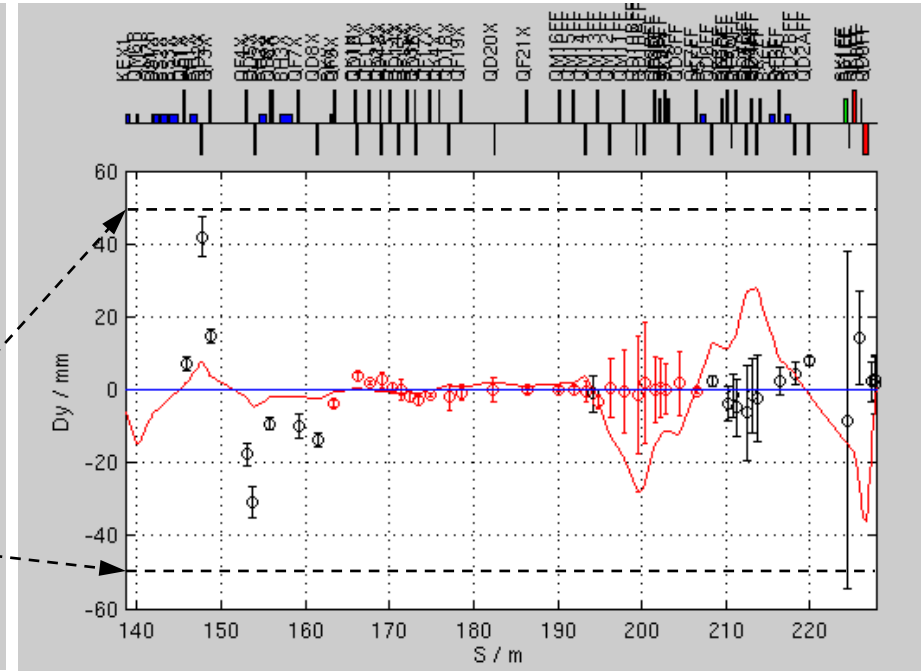

ZV11X: ΔI = +0.049 A
DY (mm)
S (m)

Monday Day Shift, December 17, 2012

before correction



after correction



QS*X : -1.050 A ⇨ -0.113 A (ΔI = +0.937 A) … correct IP-phase η_y

ZV3X : +0.172 A ⇨ +0.047 A (ΔI = -0.125 A) … correct FD-phase η_y

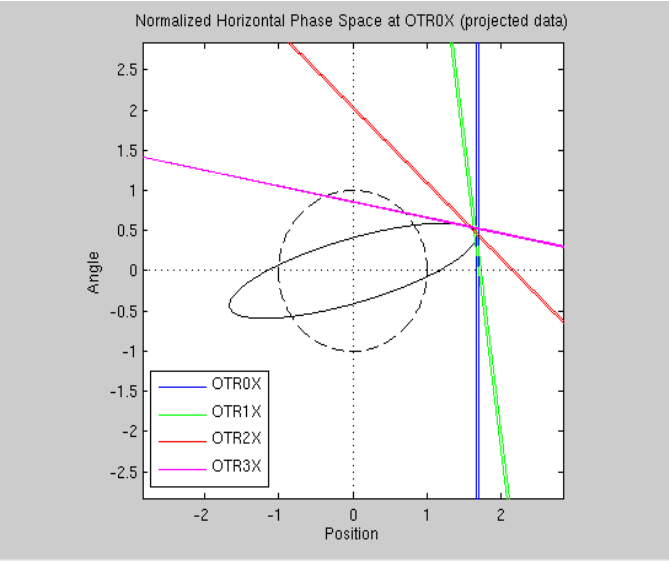
ZV11X : +0.201 A ⇨ +0.229 A (ΔI = +0.028 A) … correct FF orbit

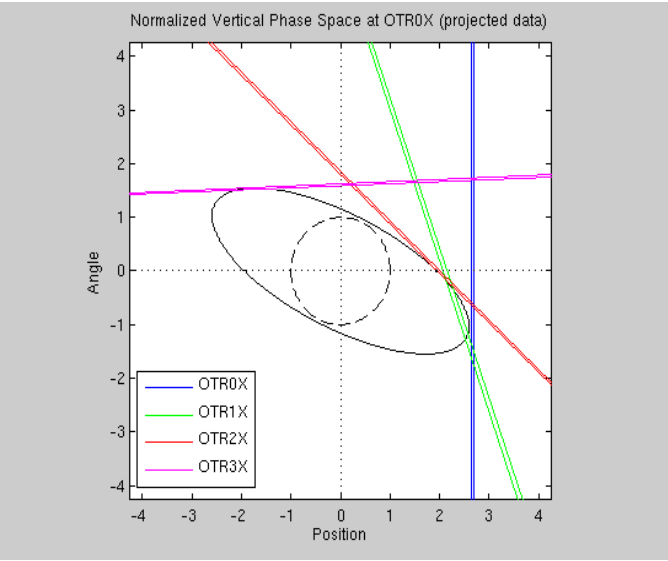
Beta Matching

Issues:

- beta matching to FF using FF matching quads can't be verified easily (QMs are downstream of OTRs)
- changing the matching quad strengths can be painful (steering, …)
- matching in EXT inflector wasn't possible given the constraints of the double kicker system
  - but … KEX2 is now gone (using BKX dipole instead)
  - still need to hold dispersion fixed
- matching between inflector and OTRs means changing optics of coupling correction system
  - maybe not so bad given coupling correction algorithm (see following presentation by Edu Marin …)

Beta Matching (December 11 2012 swing)

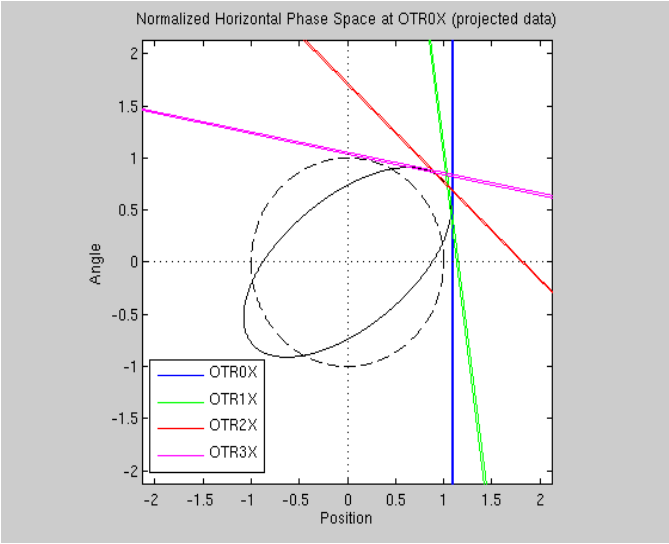


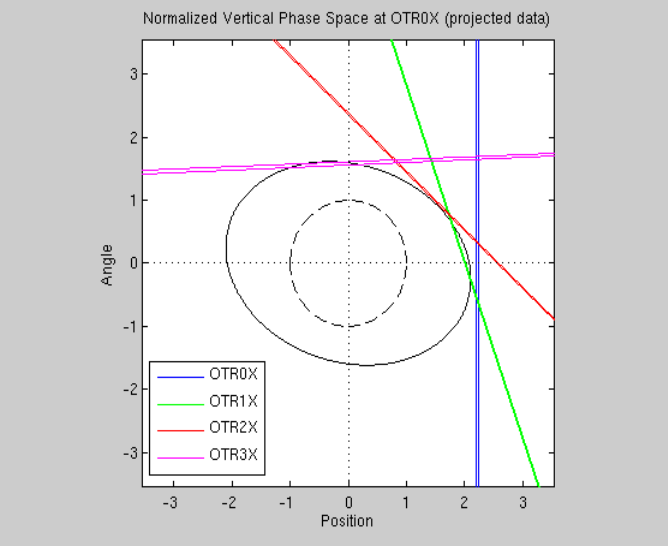


before β-match

ε_x	=	1.37	nm
B_x	=	2.26	
εB_x	=	3.11	nm
ε_y	=	36.1	pm
B_y	=	1.52	
εB_y	=	55.1	pm

(set12dec11_1908)





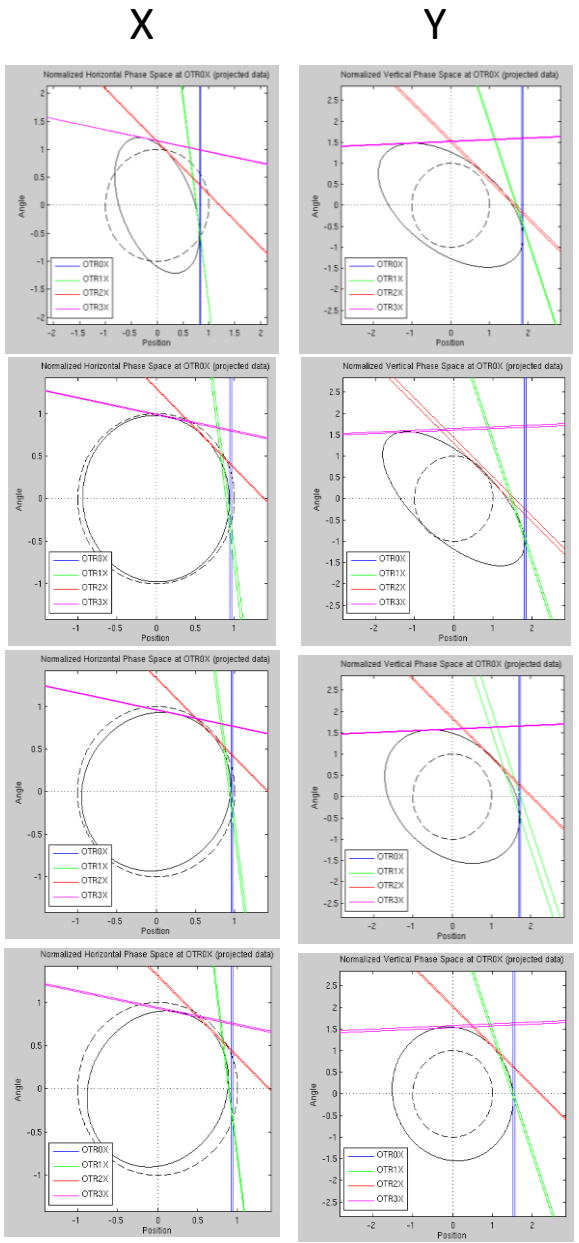
after β-match

ε_x	=	1.60	nm
B_x	=	1.24	
εB_x	=	1.99	nm
ε_y	=	40.6	pm
B_y	=	1.05	
εB_y	=	42.6	pm

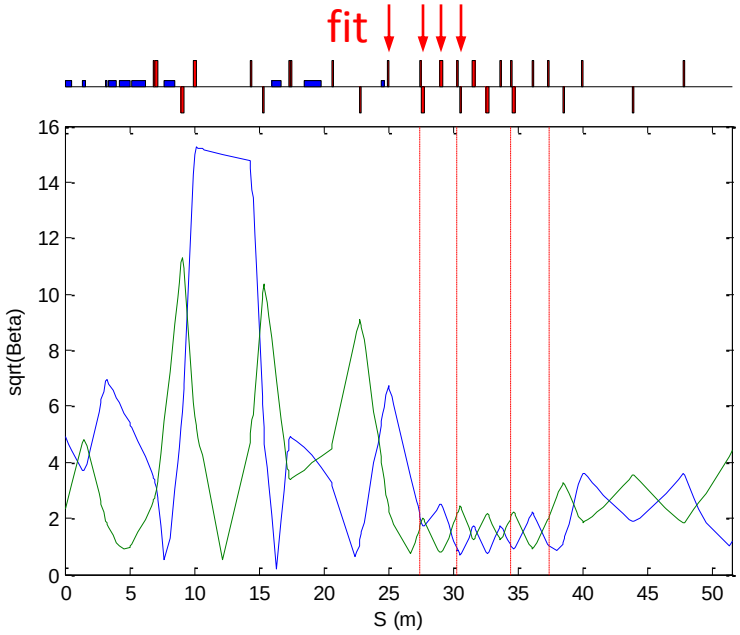
QF9X	: 36.027 ⇨	32.936 (	-8.6%)
QD10X	: 56.860 ⇨	66.116 (	+16.3%)
QF11X	: 46.638 ⇨	35.836 (	-23.2%)
QD12X	: 46.230 ⇨	48.314 (	+4.5%)

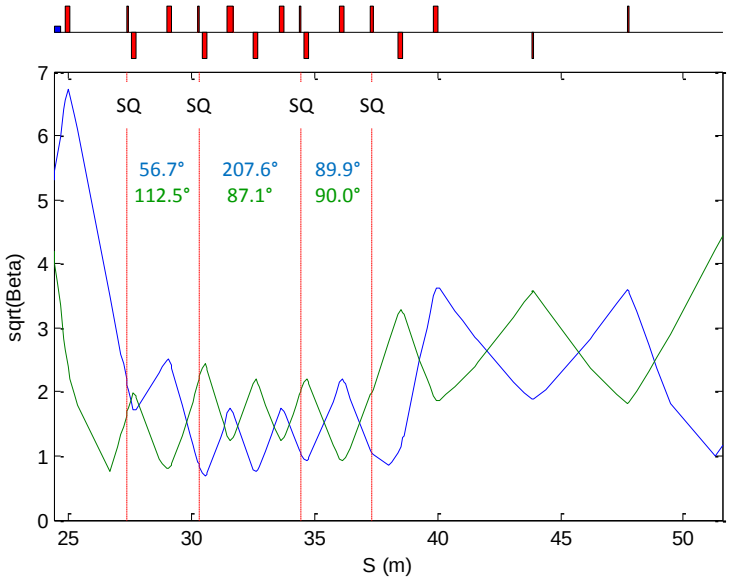
(set12dec11_2012)

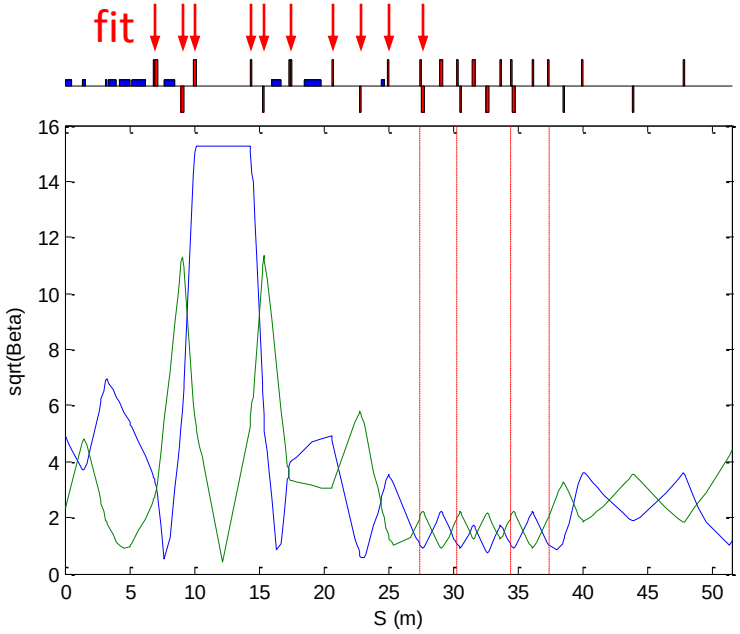
Beta Matching (December 12 2012 owl)

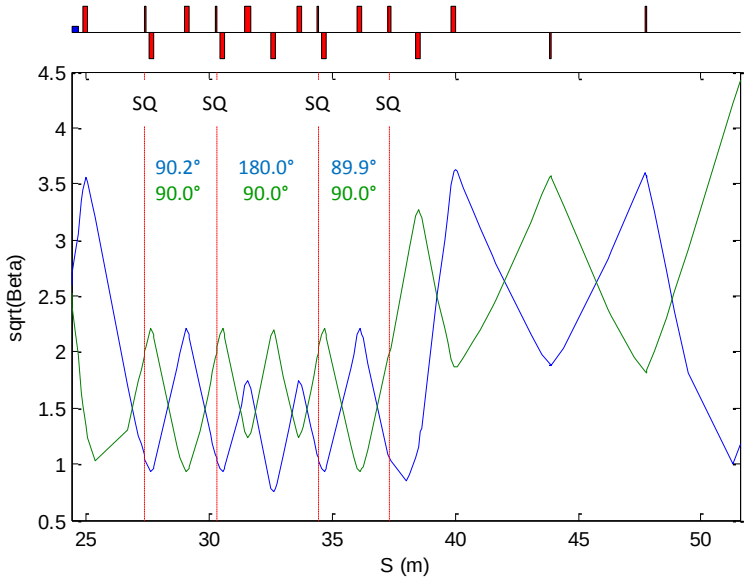


name	match0	match1	match2	match3	design
file	054152	061717	080625	084346	
EmitX	1.7894	1.8228	1.7587	1.5860	
BmagX	1.1946	1.0013	1.0026	1.0076	1.0000
EmBmX	2.1376	1.8251	1.7633	1.5981	
BetaX	4.7239	6.0386	6.4327	6.2257	6.3052
AlphaX	-2.8890	-4.2795	-4.6550	-4.5596	-4.4943
EmitY	28.4846	25.7572	30.8175	28.2300	
BmagY	1.2000	1.3489	1.0554	1.0034	1.0000
EmBmY	34.1808	34.7439	32.5253	28.3262	
BetaY	9.1308	9.4923	7.1151	6.0766	6.1903
AlphaY	4.4037	4.8369	3.2854	2.6087	2.5763
QF1X	50.682	50.947	50.812	50.812	49.024
QD2X	42.865	43.035	43.312	43.312	42.865
QF3X	30.497	30.724	30.800	30.800	30.498
QF4X	30.863	30.710	30.636	30.636	30.864
QD5X	41.940	42.083	41.995	41.995	41.940
QF6X	52.983	52.753	52.692	52.692	51.556
QF7X	54.600	54.524	57.931	57.931	54.601
QD8X	26.862	26.850	27.005	27.005	26.863
QF9X	34.701	36.133	36.027	36.027	34.702
QD10X	52.965	51.764	56.860	56.860	52.964


fit
sqrt(Beta)
S (m)


SQ
SQ
SQ
SQ
56.7°
112.5°
207.6°
87.1°
89.9°
90.0°
sqrt(Beta)
S (m)

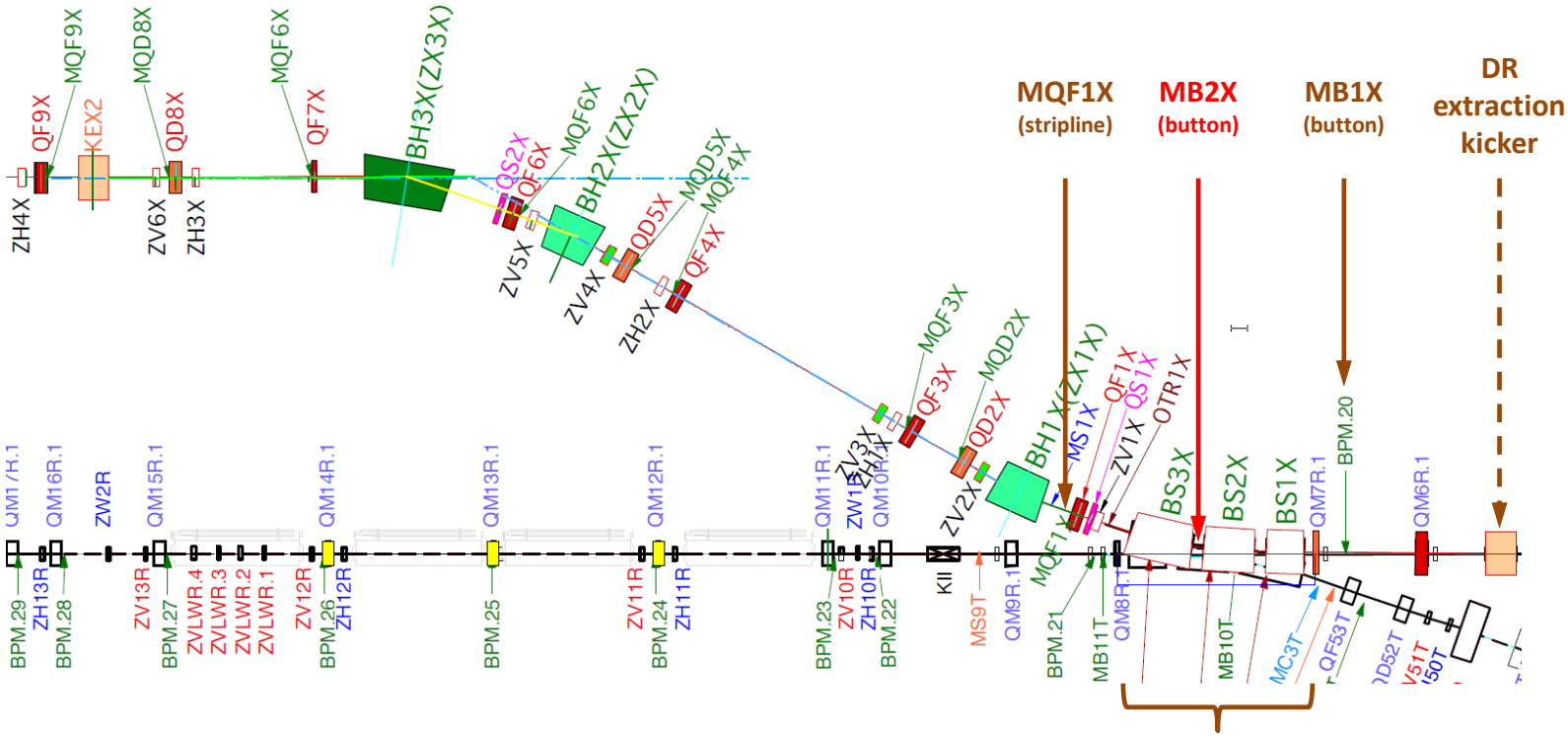

fit
sqrt(Beta)
S (m)


SQ
SQ
SQ
SQ
90.2°
90.0°
180.0°
90.0°
89.9°
90.0°
sqrt(Beta)
S (m)

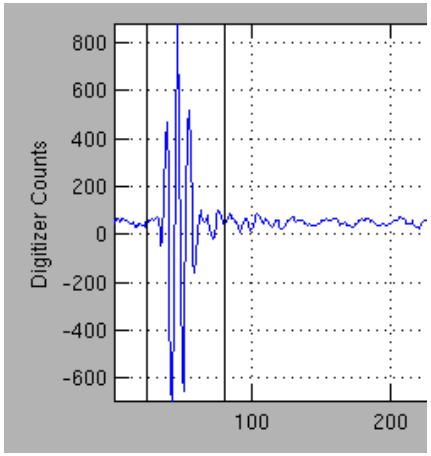
MB2X

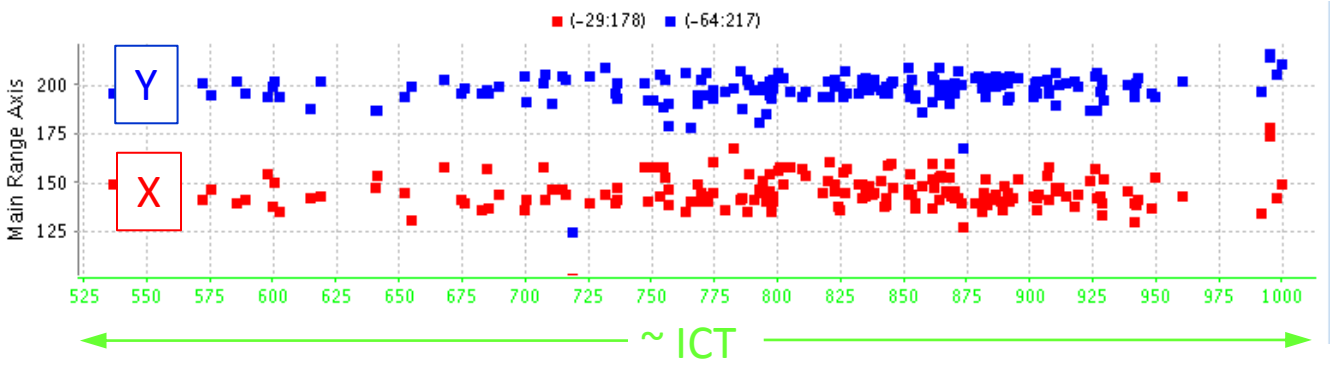
Issues:

- we were blind to the extraction trajectory between KEX1 and QF1X
- two special button-type BPMs exist in this area
  - MB1X at location of DR BPM 20 (between QM6R1 and QM7AR)
  - MB2X between septa BS2X and BS3X
- Glen hooked MB2X up to a spare channel in the stripline BPM DAQ system



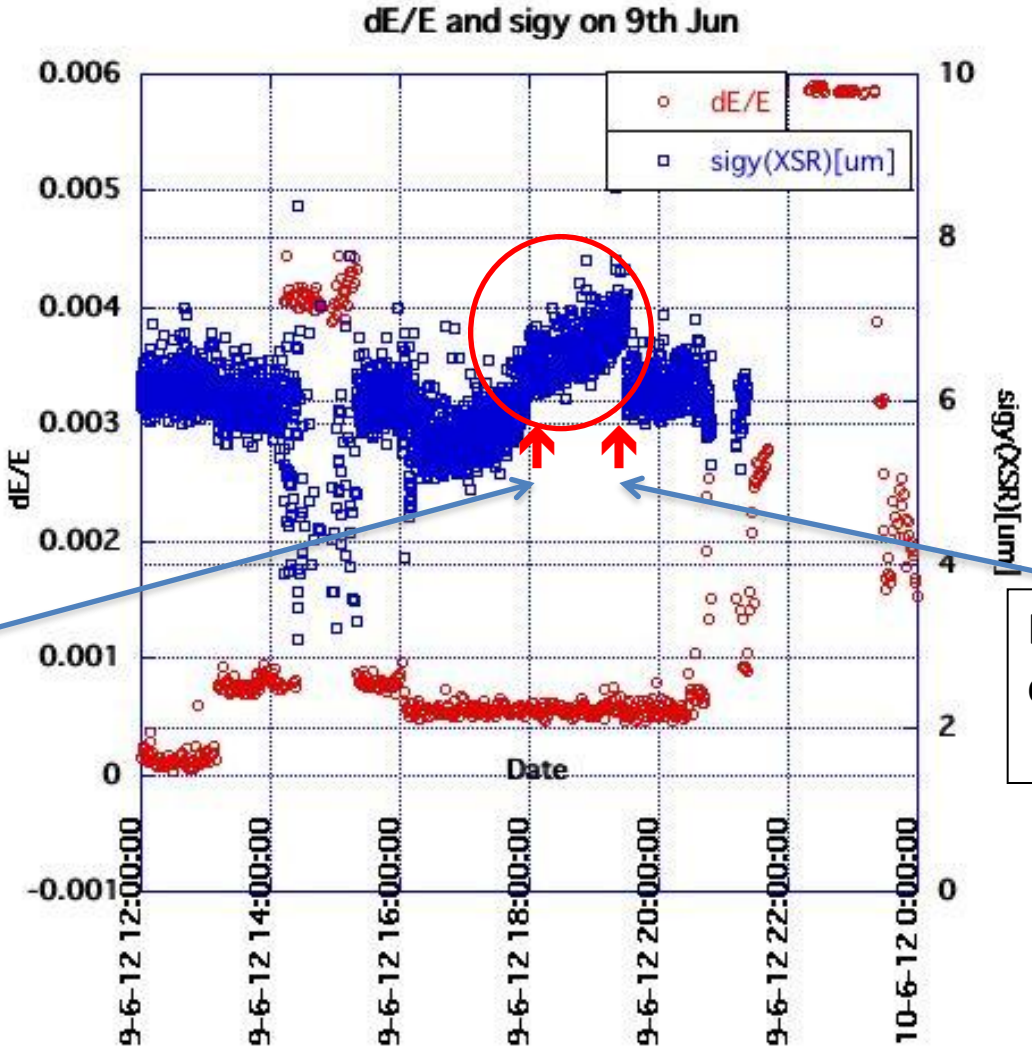
MB2X: top left button (stripline BPM system)





Additional Issues

Effect of DR orbit feedback



emittance increase due to orbit feedback?

DR FB ON

DR FB OFF and DR correctors were reset.

Summary, Continuing Work, Mitigation

Summary (1)

- multi-OTR EXT emittance measurements are reliable and stable
  - measured beam tilt (coupling) values are believable and correspond to real X-Y coupling
- extracted vertical emittance is strongly dependent on bunch charge
  - 2-3 pm per 10^9 … much larger than observed in DR (< 0.1 pm per 10^9 … IBS prediction?)
  - OTR camera gains were adjusted for low charge … optimized? other OTR systematics?
  - best vertical emittance observed during November-December running was 21 pm @ 10^9 e-/bunch
- extracted vertical emittance appears to be independent of DR RF voltage (bunch length)
- measured beam tilt (coupling) values are believable and correspond to real X-Y coupling
  - zeroing all 4 measured beam tilts minimizes projected vertical emittance
- observed KEX1 quadrupole/sextupole field components agree with (a) POISSON field simulation
  - tracking simulations indicate that vertical beam offset in KEX1 might not be a source of emittance growth
  - not sure exactly what's inside either SLAC kicker
- KEX1 calibration measured with two independent methods
  - for 5 mrad (nominal) kick at 1.269 GeV: 46.5 kV (from orbit dependence); 46.7 kV (from vertical dispersion)

Summary (2)

- anomalous vertical dispersion in EXT/FF is well modeled by a skew quadrupole field at BS3X
  - strength of inferred skew quadrupole depends on horizontal beam position in BS3X, consistent with a skew sextupole field there with strength $K_2L = 16\ m^{-2}$ … for comparison, K_2L for SD4FF is ~ $15\ m^{-2}$
- both phases of vertical dispersion (IP and FD) can be corrected with a combination of QS Σ-knob and vertical dipole correctors ZV3X and ZV11X beta matching can be done more reliably using EXT inflector quads and/or coupling correction section quads
  - leave FF matching quads alone
- button-type BPM MB2X (between extraction septa BS2X and BS3X) is now reading out through the stripline BPM DAQ system
  - still needs to be calibrated
  - could imagine setting KEX1 to nominal voltage and using X reading as “gold” value

Continuing Work

- model horizontal orbit sensitivity of vertical emittance due to assumed BS3X skew sextupole field
  - after coupling correction, does pattern of QK strengths match observations?
- model horizontal orbit sensitivity of vertical kick due to assumed BS3X skew sextupole field
  - can we reproduce Okugi-san's vertical steering (ZV1X and ZV2X) vs KEX1 voltage measurement?
- model the propagation of projected vertical emittance around the (coupled) Damping Ring
  - if ε_y = 12 pm at XSR source point (mid-store), is it 12 pm at the extraction kicker (last turn)?
- put KEX1 on a mover and try to measure vertical emittance vs KEX1 Y position?

Mitigation?

- reduce Damping Ring vertical emittance
  - use new DR laserwire to confirm XSR measurements
- run at low charge … 10^9 e-/bunch or less
  - performance of diagnostics?
- understand charge dependence of vertical emittance
  - why is charge dependence of ε_y at OTRs > 20 times what is observed in DR?
  - is this a wakefield? why doesn't ε_y depend on DR RF voltage?
- we've been measuring vertical emittance blowup in EXT since before ATF2 was proposed
  - the only part of the system common to both ATF and ATF2 is the DR extraction system (6 m of beamline starting at KEX1 and ending at BS3X)
  - maybe we should rip open the entire system and physically look for anything wrong?
- fix the slow DR circumference (energy) drift
  - should be better now that DR air conditioner is working again
  - install a small 4 dipole chicane for circumference adjustment (controlled by an energy feedback)?

Extra Slides

Horizontal EXT Emittance Measurements

Date	N_{wire}	Emit (nm)	BMAG
Dec 14 2010	4	1.784 ± 0.130	1.10 ± 0.04
Dec 9 2010	4	1.686 ± 0.102	1.08 ± 0.05
Nov 2010 (?)	EXT kicker controller replaced		
May 18 2010	4	1.905 ± 0.078	1.08 ± 0.03
Apr 21 2010	4	1.212 ± 0.065	1.26 ± 0.03
Mar 17 2010	BS3X rolled ~4 mrad (CCW)		
Feb 25 2010	4	1.868 ± 0.336	1.15 ± 0.12
Feb 17 2010	4	negative	
Feb 3 2010	4	1.626 ± 0.095	1.10 ± 0.06
Jan 28 2010			

Vertical EXT Emittance Measurements

Date	N_{wire}	Emit (pm)	BMAG
Dec 14 2010	5	27.6 ± 1.8	1.09 ± 0.04
Dec 9 2010	4	29.3 ± 3.1	1.05 ± 0.02
Nov 2010 (?)	EXT kicker controller replaced		
May 18 2010	5	11.7 ± 2.3	1.43 ± 0.25
Apr 21 2010	5	15.4 ± 2.0	1.78 ± 0.17
Mar 17 2010	BS3X rolled ~4 mrad (CCW)		
Feb 25 2010	5	22.08 ±0.9	1.19 ± 0.03
Feb 25 2010	5	38.33 ± 1.1	1.10 ± 0.02
Feb 17 2010	5	22.6 ± 1.4	1.15 ± 0.04
Feb 3 2010	5	16.1 ± 0.7	1.06 ± 0.03
Jan 28 2010	5	31.6 ± 1.2	1.03 ± 0.01

OTR Vertical Emittance Measurement

December 14, 2011 07:44

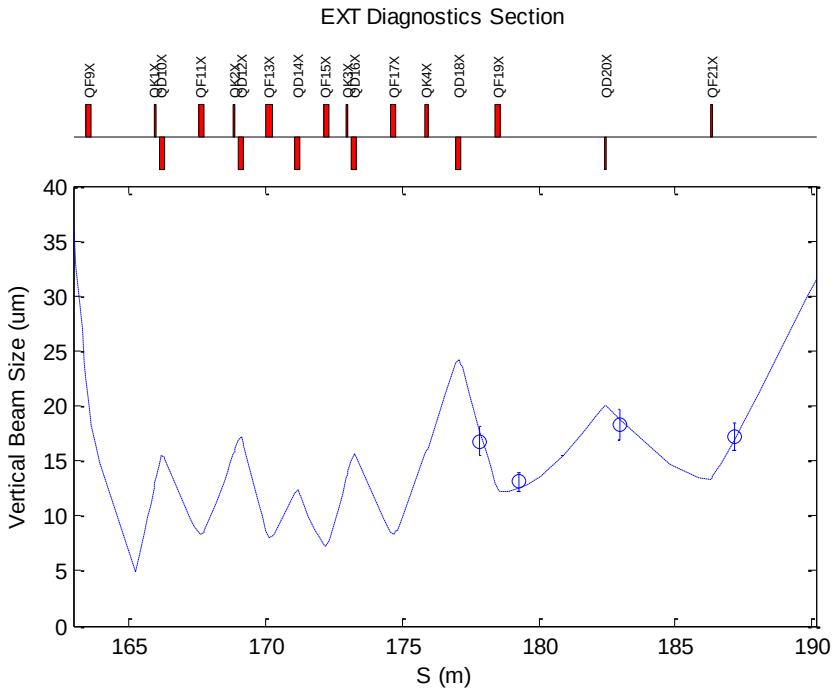
name	sigt	sigd	sig
OTR0X	17.00	2.54	16.80
OTR1X	13.44	2.90	13.12
OTR2X	19.18	5.77	18.29
OTR3X	17.53	3.26	17.22

Vertical emittance parameters at OTR0X

energy	=	1.2817			GeV	
emit	=	49.7560	+-	3.8167	pm	
emitn	=	124.7989	+-	9.5732	nm	
emitn*bmag	=	139.1183	+-	14.3102	nm	
bmag	=	1.1147	+-	0.0582		(1.0000)
bmag_cos	=	-0.0976	+-	0.0000		(0.0000)
bmag_sin	=	0.4310	+-	0.0000		(0.0000)
beta	=	6.2274	+-	0.6272	m	(6.1903)
alpha	=	3.0722	+-	0.3470		(2.5763)
chisq/N	=	1.0000				

Propagated vertical spot sizes

OTR0X =	17.6 um	(16.8	+-	1.4)
OTR1X =	12.5 um	(13.1	+-	0.9)
OTR2X =	18.8 um	(18.3	+-	1.3)
OTR3X =	16.9 um	(17.2	+-	1.3)



Wire Scanner Vertical Emittance Measurement

December 14, 2011 09:30

(MW1X σ_y value ignored)

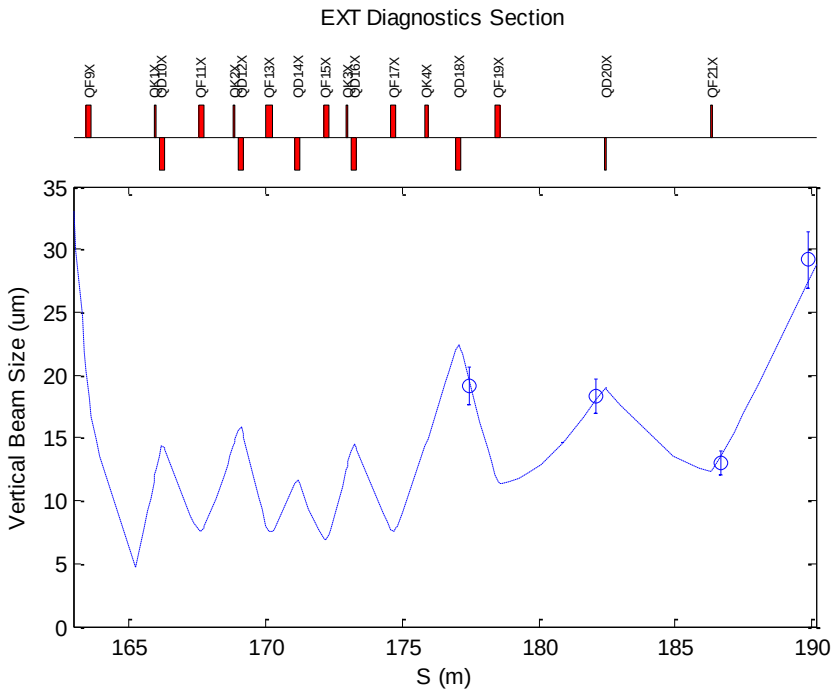
sigt	sigd	sigw	sig
19.50	2.76	2.50	19.14
19.40	5.81	2.50	18.34
13.60	3.18	2.50	12.98
29.50	3.70	2.50	29.16

Vertical emittance parameters at MW0X

energy	=	1.2817		GeV		
emit	=	42.9533	+- 3.4254	pm		
emitn	=	107.7395	+- 8.5918	nm		
emitn*bmag	=	114.9045	+- 10.4024	nm		
bmag	=	1.0665	+- 0.0409		(	1.0000)
bmag_cos	=	0.3468	+- 0.0000		(	0.0000)
bmag_sin	=	-0.0229	+- 0.0000		(	0.0000)
beta	=	8.8918	+- 0.9843	m	(	6.1903)
alpha	=	3.6762	+- 0.4276		(	2.5763)
chisq/N	=	1.0000				

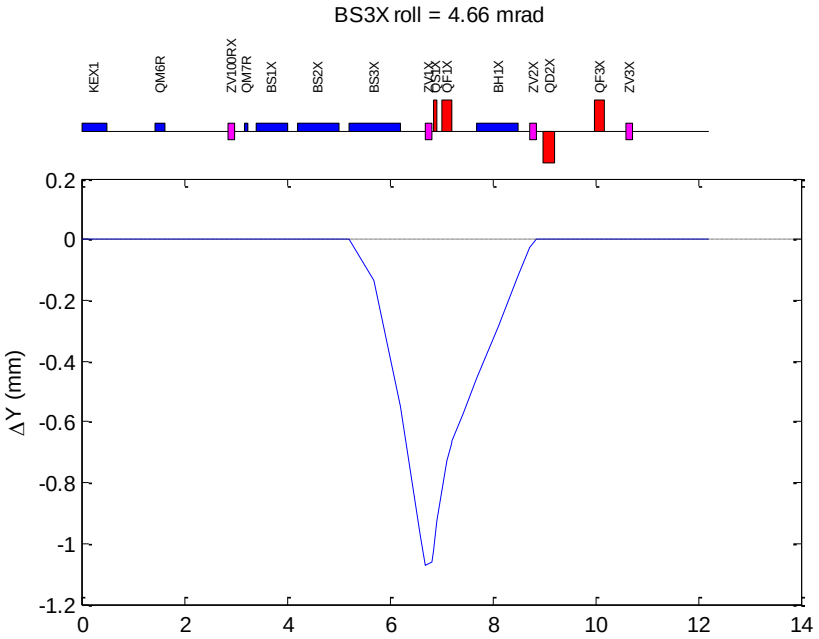
Propagated vertical spot sizes

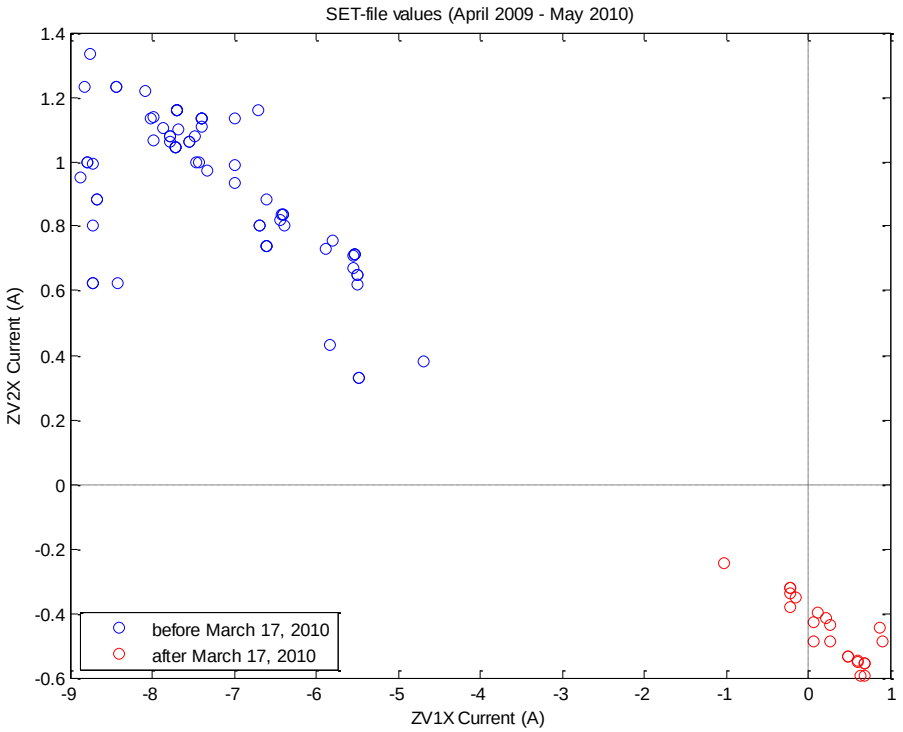
MW0X =	19.5 um	(	19.1 +-	1.4)
MW2X =	18.0 um	(	18.3 +-	1.4)
MW3X =	13.5 um	(	13.0 +-	1.0)
MW4X =	27.5 um	(	29.2 +-	2.2)



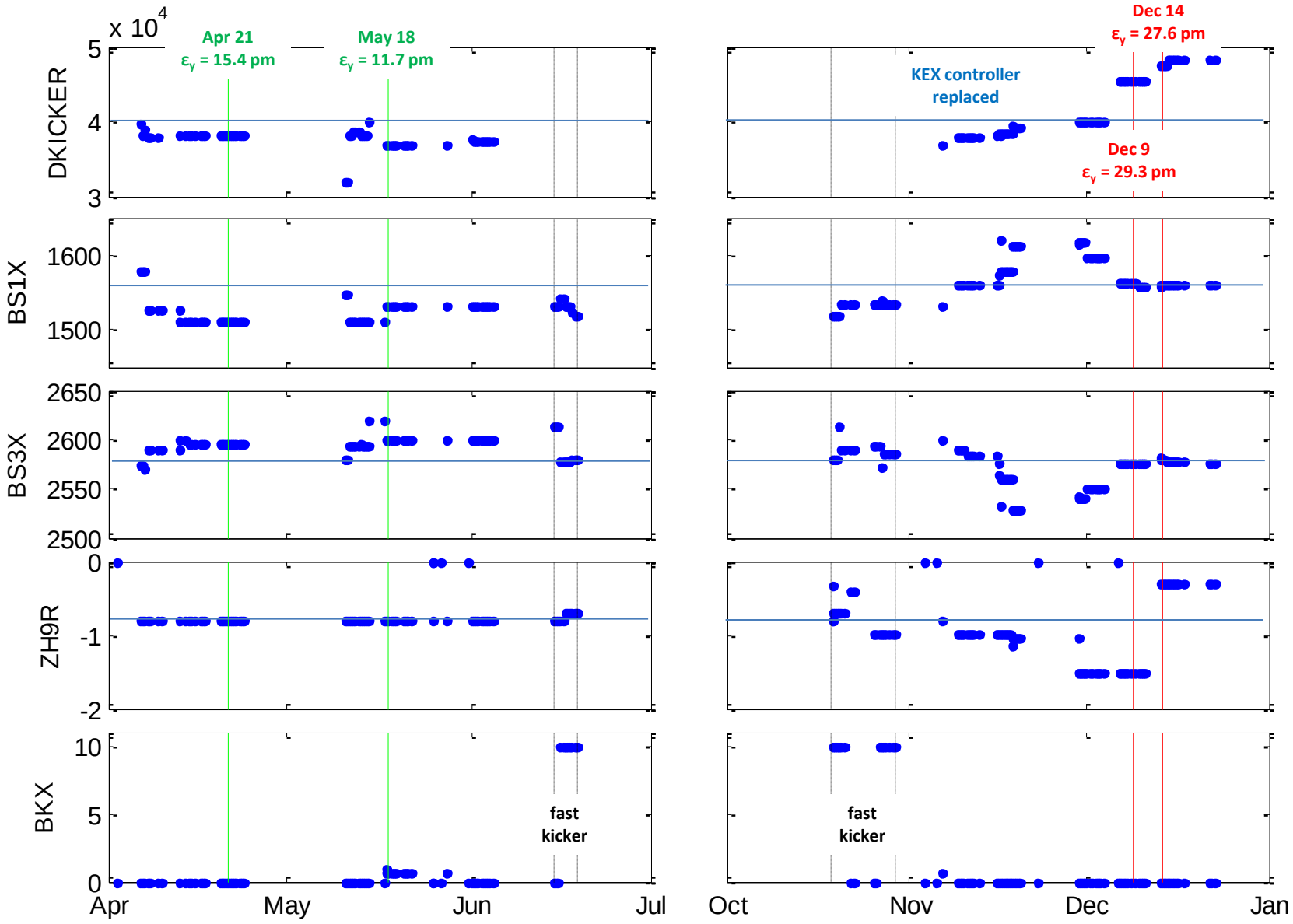
Observed that first 2 EXT vertical correctors (ZV1X and ZV2X) needed to be strong to properly launch into EXT (since before EXT rebuild for ATF2 …)

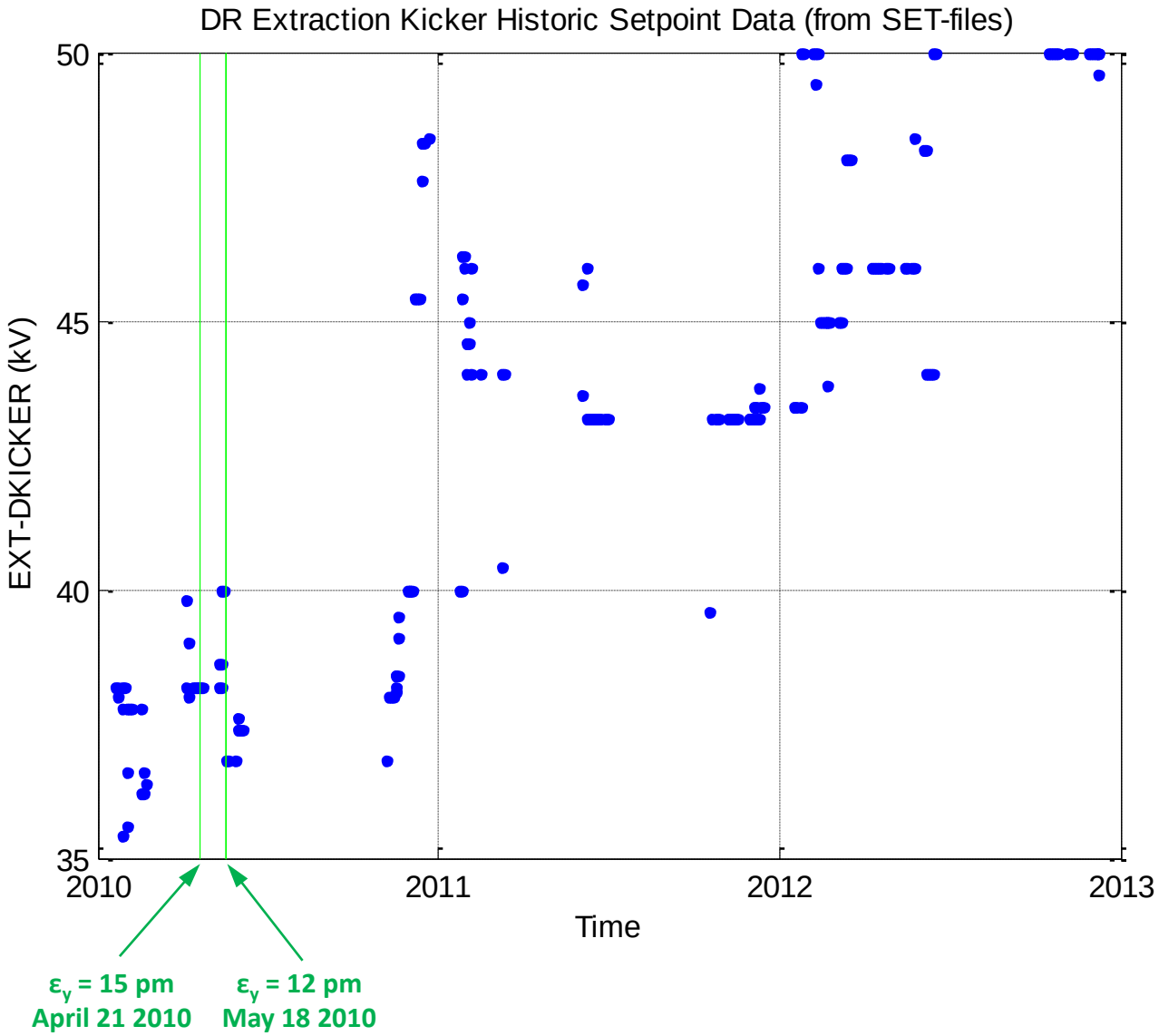
- hypothesize that correctors are compensating for a kick error in extraction channel
- simulate error kick by rolling individual elements; use ZV1X and ZV2X to correct orbit
- find error that gives best fit to actual ZV1X/ZV2X values → BS3X septum magnet roll
- BS3X was physically rolled ~ -4 mrad (March 17, 2010) to relieve ZV1X and ZV2X
- projected vertical emittance in EXT before coupling correction was improved (~20-40 pm before → ~10-20 pm after)





SET-file History (Apr-Dec, 2010)




DR Extraction Kicker Historic Setpoint Data (from SET-files)
EXT-DKICKER (kV)
50
45
40
35
2010
2011
2012
2013
Time
εy = 15 pm
April 21 2010
εy = 12 pm
May 18 2010