IEX Status Report

IEX Project Working Group

Presented by A. Xiao

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Introduction

- What's IEX?
  - Electromagnetic undulator
  - Generates a variety of polarizations (linear – H/V, circular – CW/CCW)
  - At the energy range of 250 eV(h) to 3 keV – "Intermediate Energy x-ray" (IEX)

- How does IEX different from other insertion device?
  - Fully designed and manufactured at APS
  - First insertion device has quasiperiodic capability
  - 4.8 long
  - Strong magnetic field
  - Multiple correction coils (13)
  - Magnet operation always follows hysteresis loop

User Operation Requirement

Courtesy of Jessica L. McChesney

User Operations

- Polarization Selection – LP, HP, RCP, LCP
  switch in any order (no fast switching required, minutes)
- Quasiperiodicity – ON, OFF
  (no fast switching, minutes)
- Energy scans (50 eV or less)
  - scanning in one direction is OK
- Energy steps (arbitrary energy selection)
  - absolute energy reproducible ("gap scan" on conventional devices to modify lookup table)

Need always to follow the hysteresis loop!

Beam Optimization by beamline scientist (may require machine ops time, as determined)

- Polarization Refinement
- Quasiperiodicity Refinement
- Absolute Energy Calibration

Two beamlines, need different correction tables!

Mode	Energy (eV)	K values
Circular Polarization	440-3000	5.271-0.694
Horizontal Linear	250-3000	5.271-0.694
Vertical Linear	440-3000	3.863-0.694

Strong magnetic field!

Beam Dynamics Issues

Error source:

- Static field error – imperfect magnet structure
- Dynamical field error – beam orbit oscillation inside the device

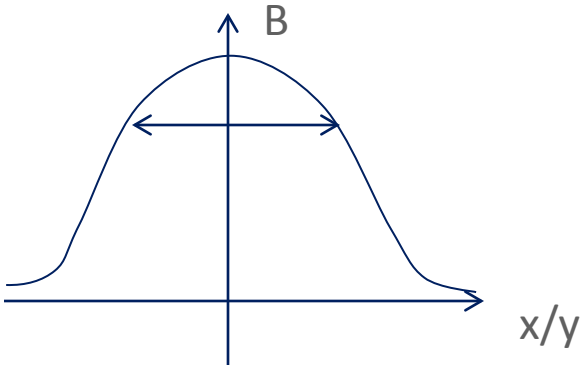
Non-linear kick strength (planar ID example)

$$\Delta x'(x) = -\frac{L_w}{(E/e)^2}\left(\frac{\lambda_w}{2\pi}\right)^2 B_{y0}^2 \frac{d}{dx}F^2(x)$$

Roll-off of magnetic field.

K^2

$$F(x) = B_y(x)/B_y(0)$$



Perturbations

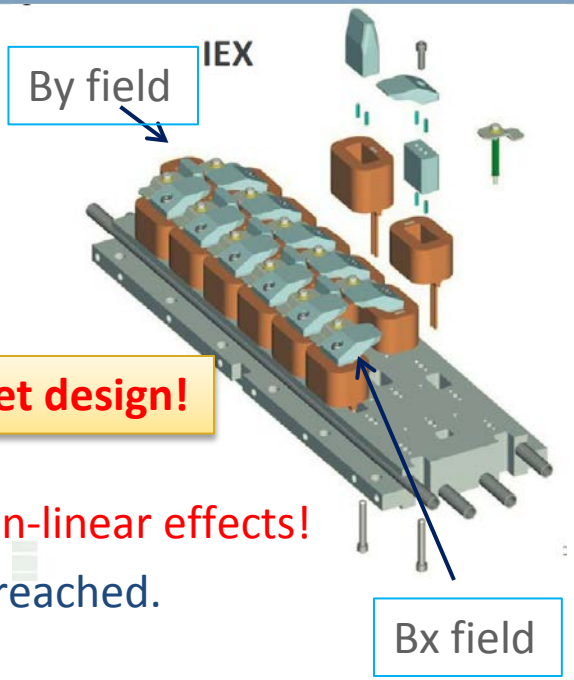
- Orbit
- Tune, beta-beating, coupling
- Injection efficiency, beam lifetime, etc.

Local correction scheme needed!

IEX	CPU
Period length: 12.5 cm	Period length: 12.8 cm
Total length: 4.8 m	Total length: 1.8 m
Max. By field: 0.45 T	Max. By field: 0.23 T
Max. Bx field: 0.33 T	Max. Bx field: 0.23 T

$$\Delta x'(x) = -\frac{L_w}{(E/e)^2}\left(\frac{\lambda_w}{2\pi}\right)^2 B_{y0}^2 \frac{d}{dx}F^2(x)$$

Big Challenge for magnet design!



The initial technical design was failed due to the intolerable non-linear effects!

After several design – simulation iterations, a final design was reached.

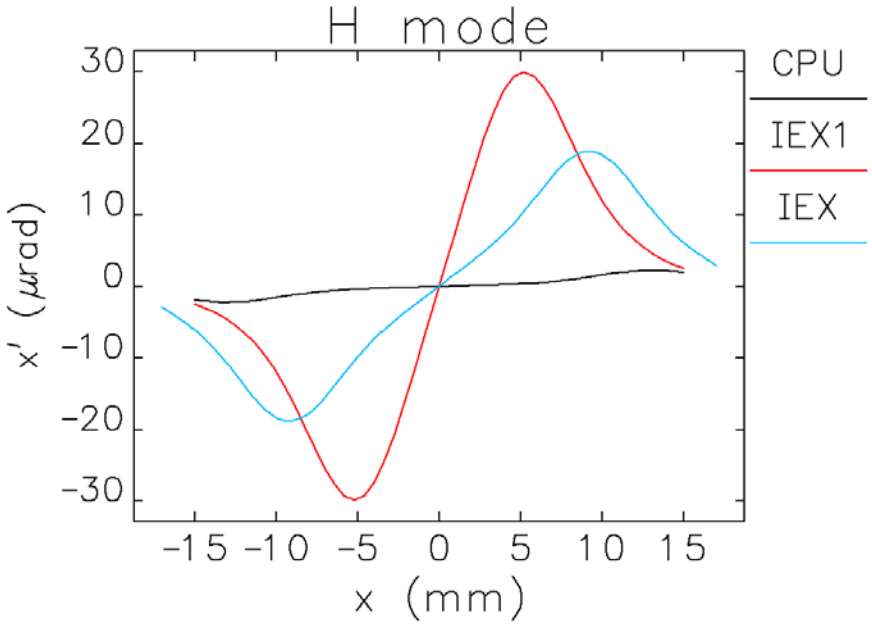
Simulation results show:

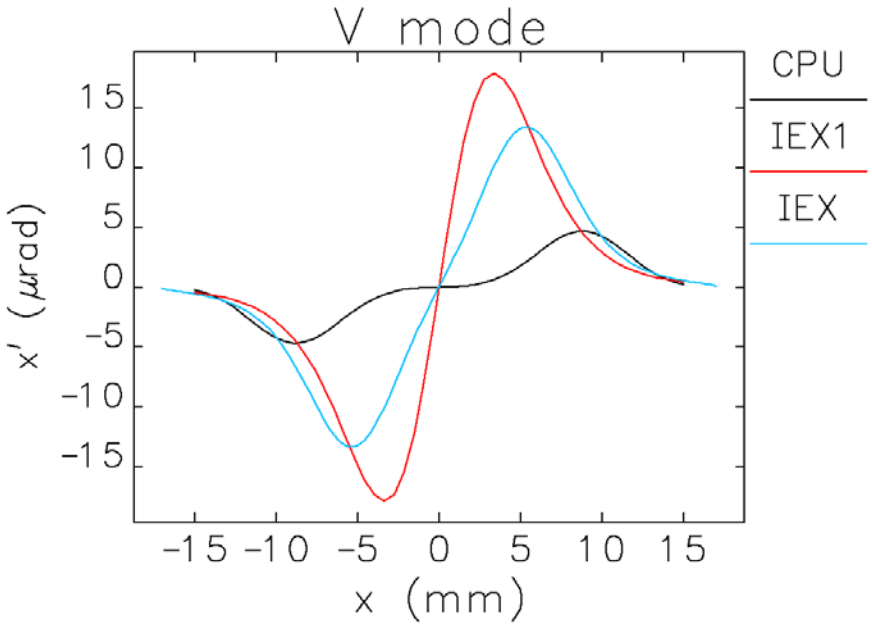
- There is no observed dynamic aperture and momentum aperture decrease
- IEX DOES reduces APS error tolerance margin!
- Among all IDs, IEX is the strongest beam perturbation source

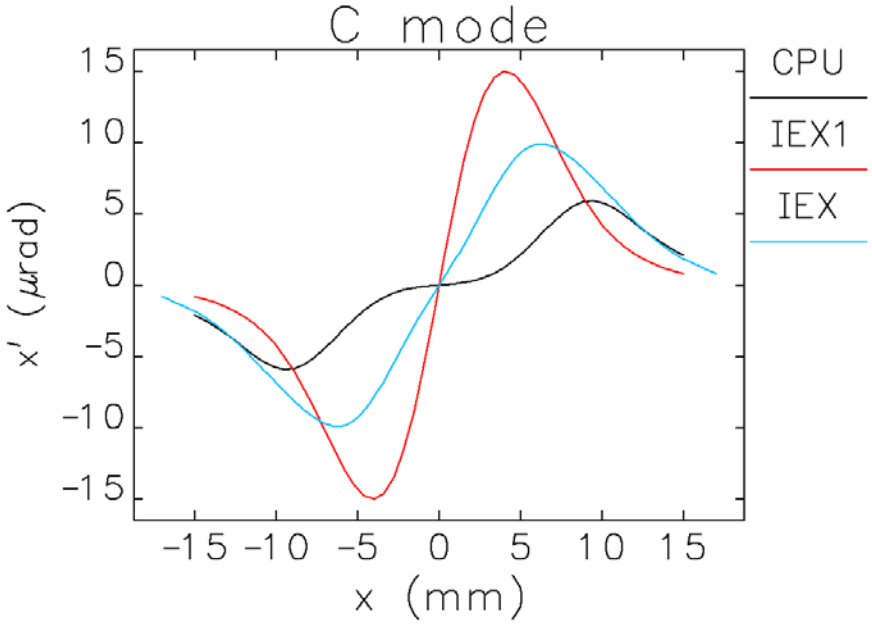
Put tight tolerance on all following works:

- Magnet manufacture, measurement, correction scheme, PS, control, installation, alignment, etc.

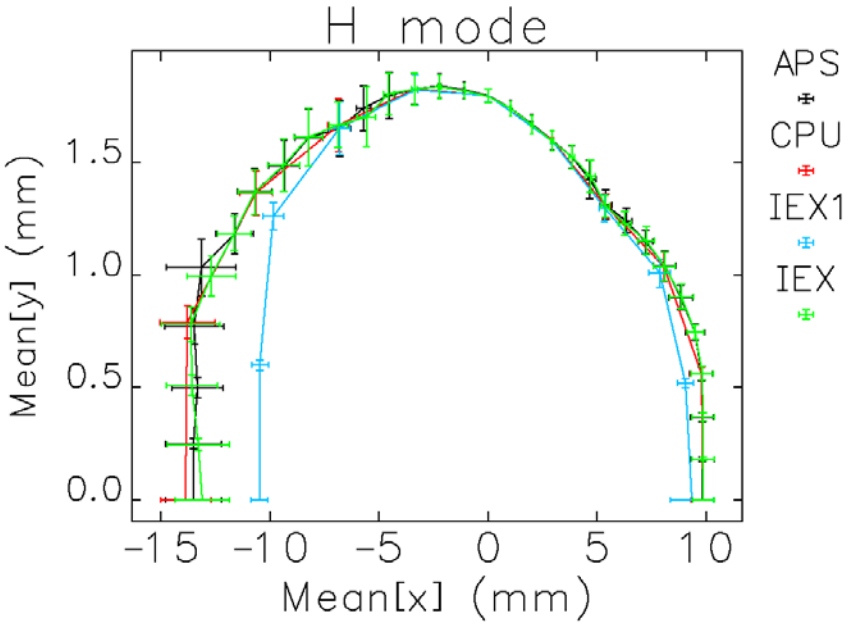
Non-linear kickmap (y=0)

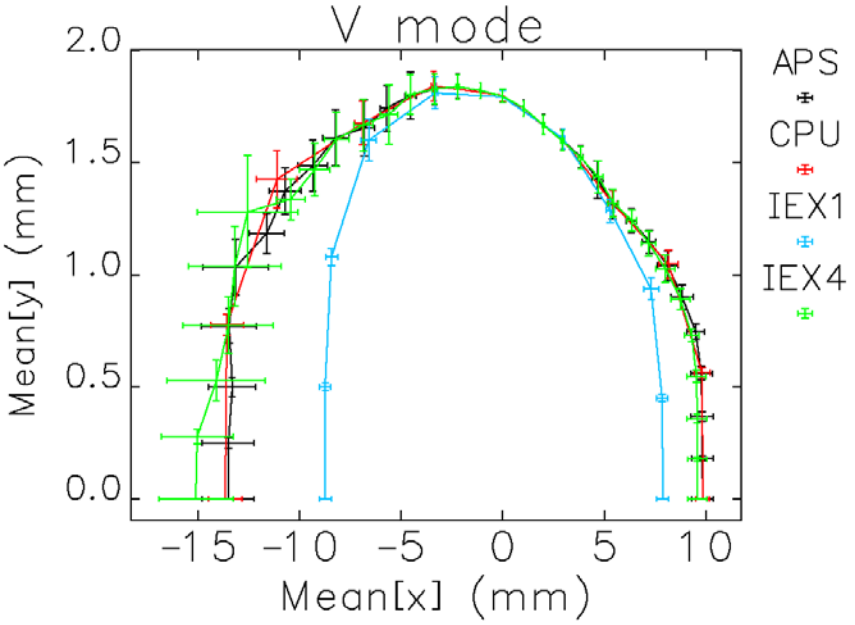


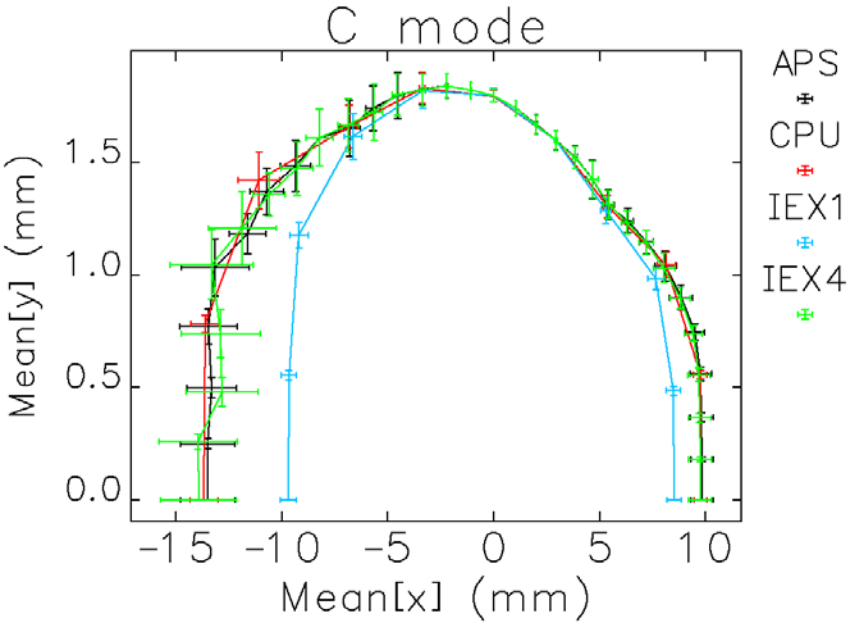




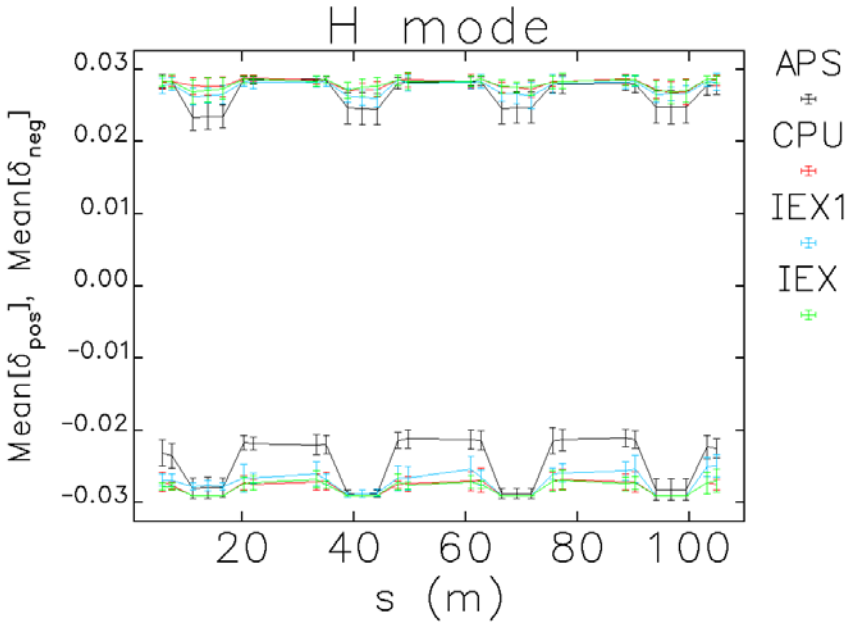
Dynamic Aperture

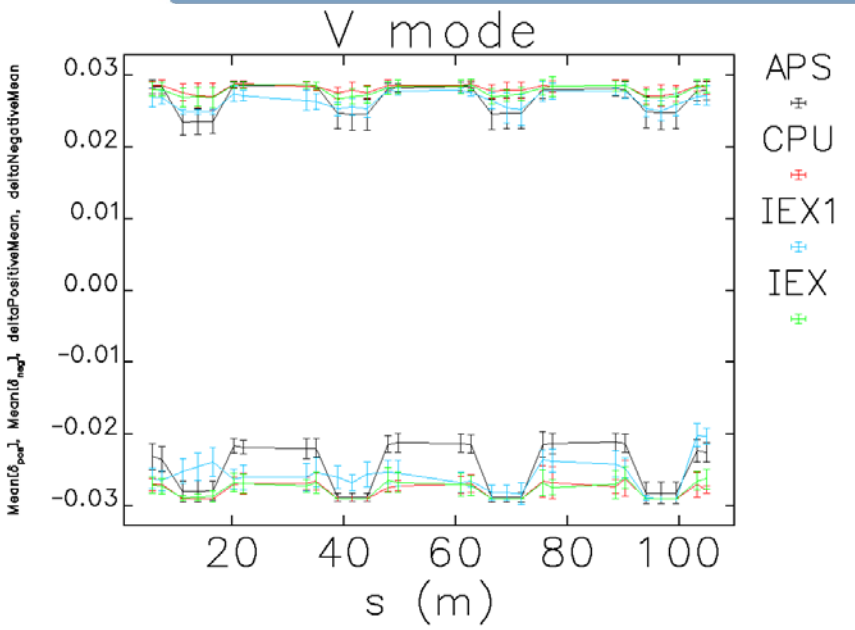


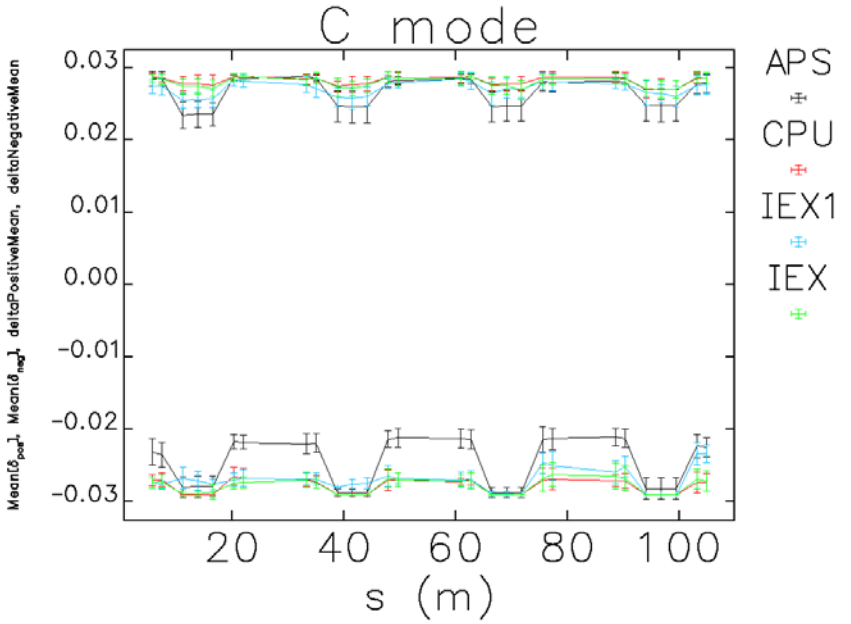




Momentum Aperture

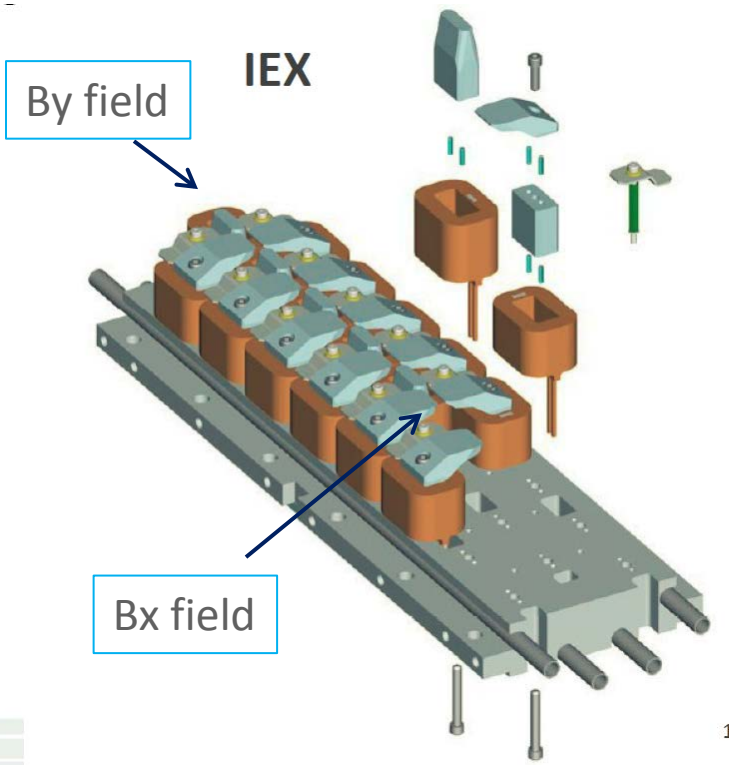


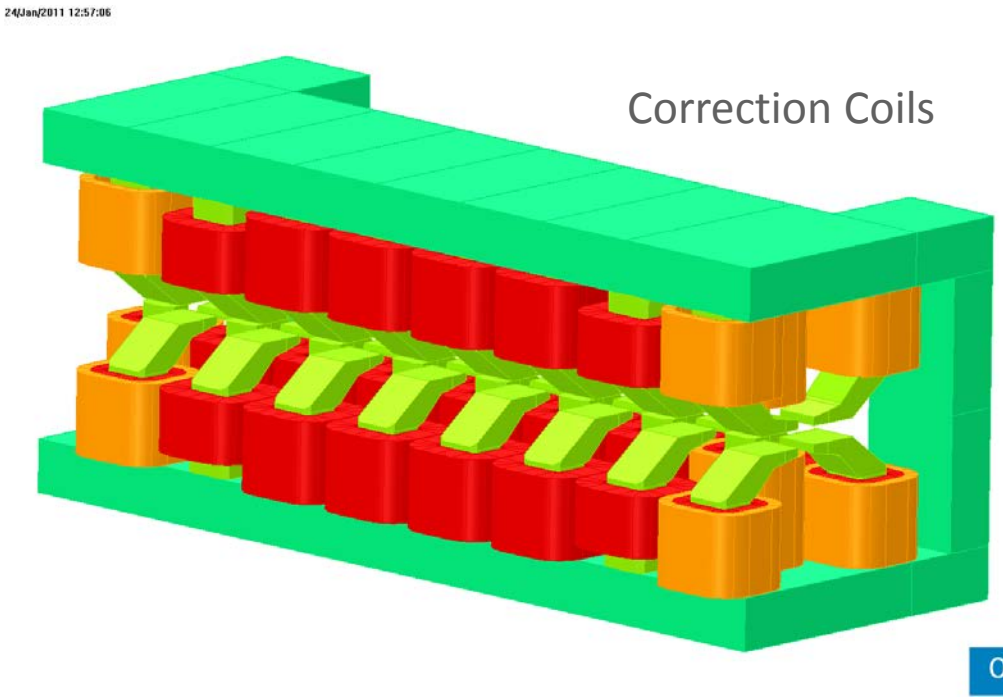




IEX Magnet Design

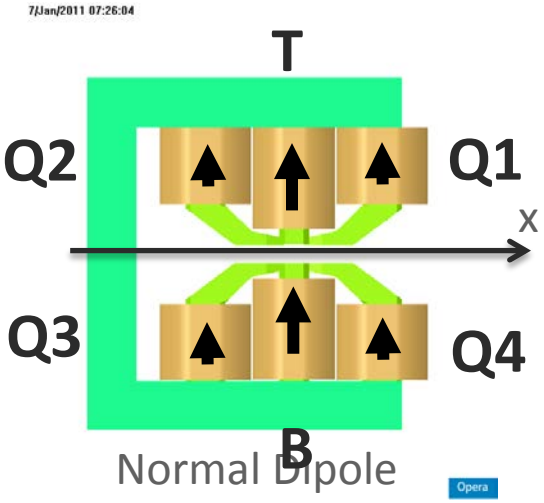
Courtesy of Mark Jaski

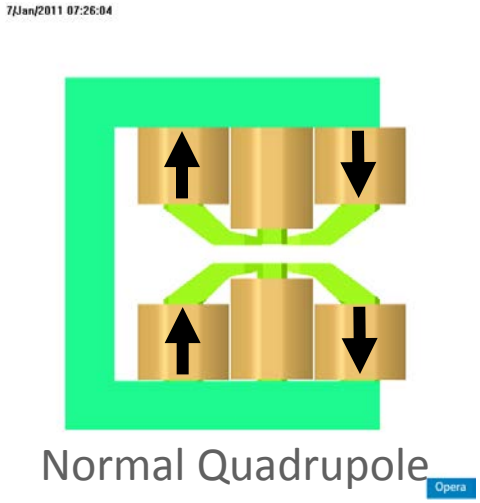


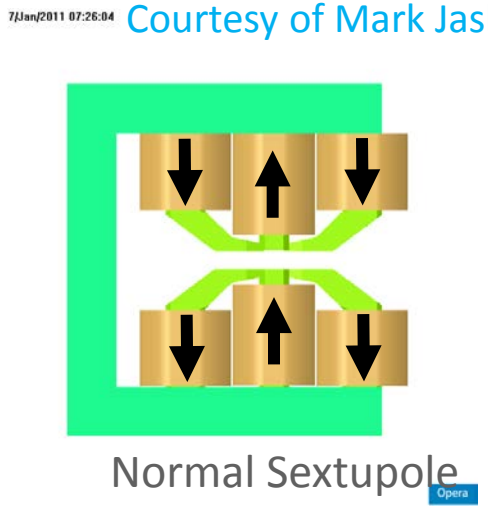


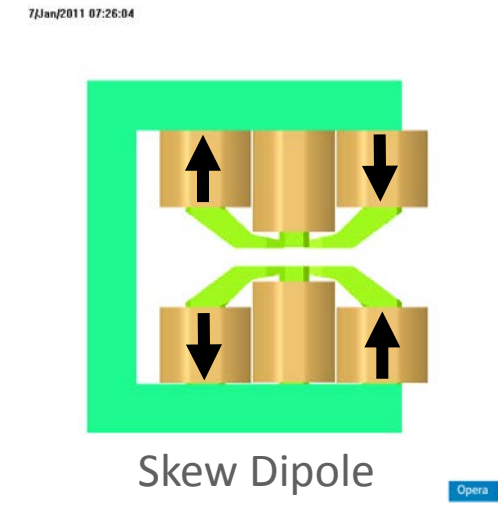
End Coil Multi-pole Field Configurations

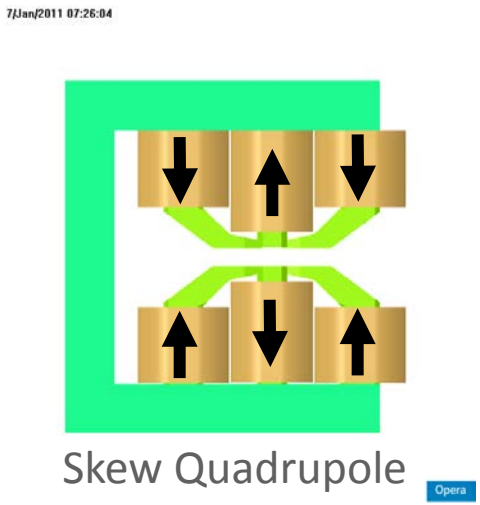
Courtesy of Mark Jaski

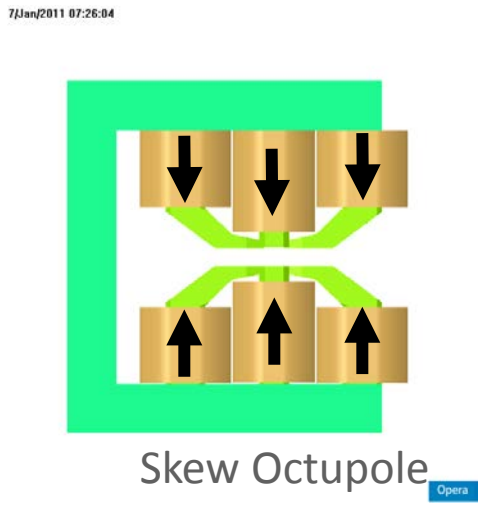






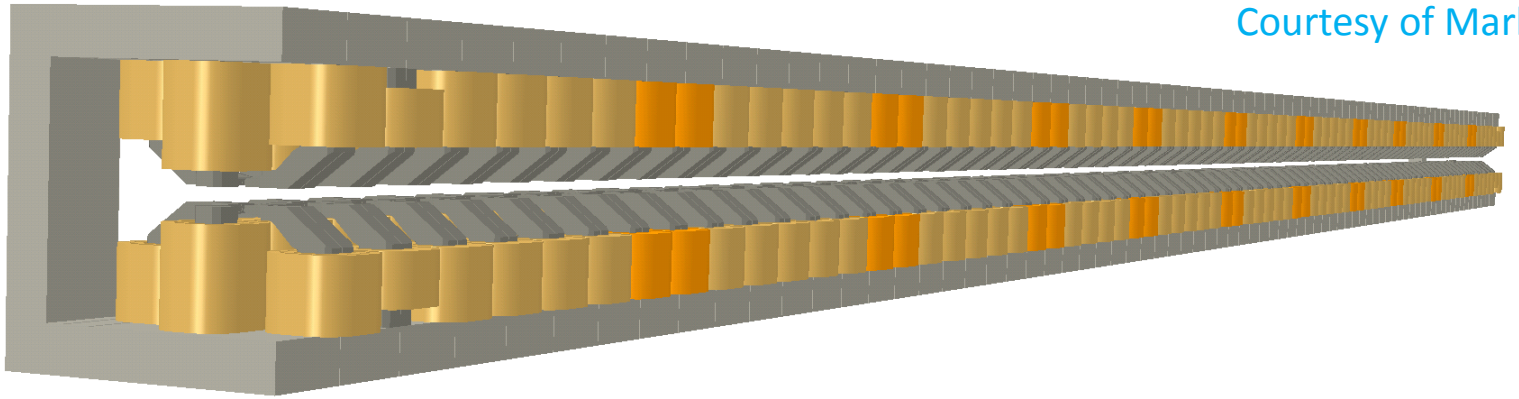






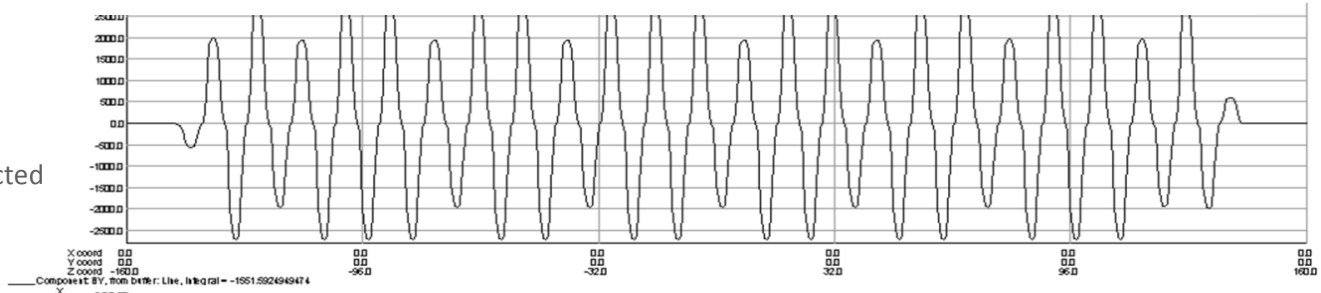
Electromagnet IEX Device Can Be Periodic or Quasiperiodic

Courtesy of Mark Jaski

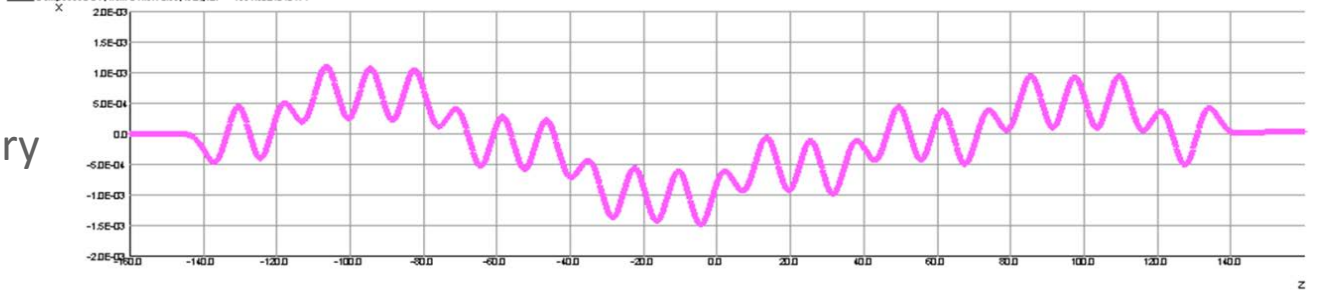


Quasi-periodic Field

The field is reduced at selected poles[1]



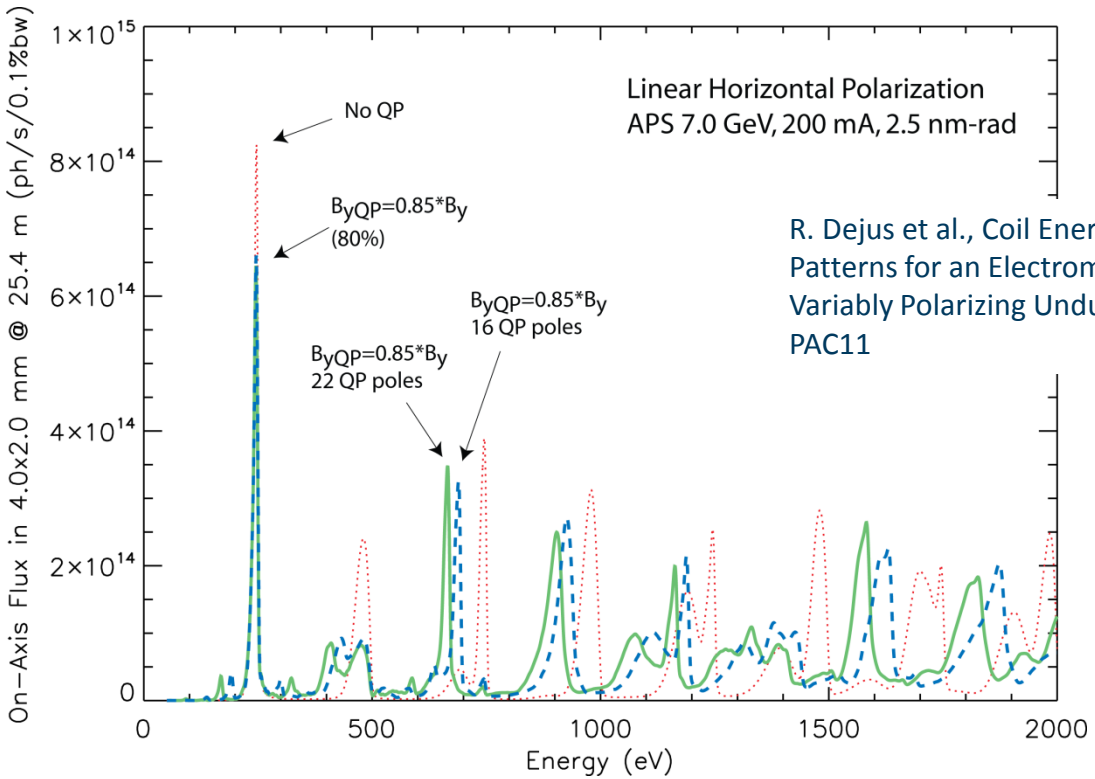
Quasi-periodic Electron Trajectory



Total: 2 By coils + 2 Bx coils + 2x6 correction coils + 1 earth coil = 17 PS!

[1]S. Sasaki, Overview of Quasi-periodic Undulators, PAC09

Quasi-periodicity Suppresses the Higher Harmonics



R. Dejus et al., Coil Energizing Patterns for an Electromagnetic Variably Polarizing Undulator, PAC11

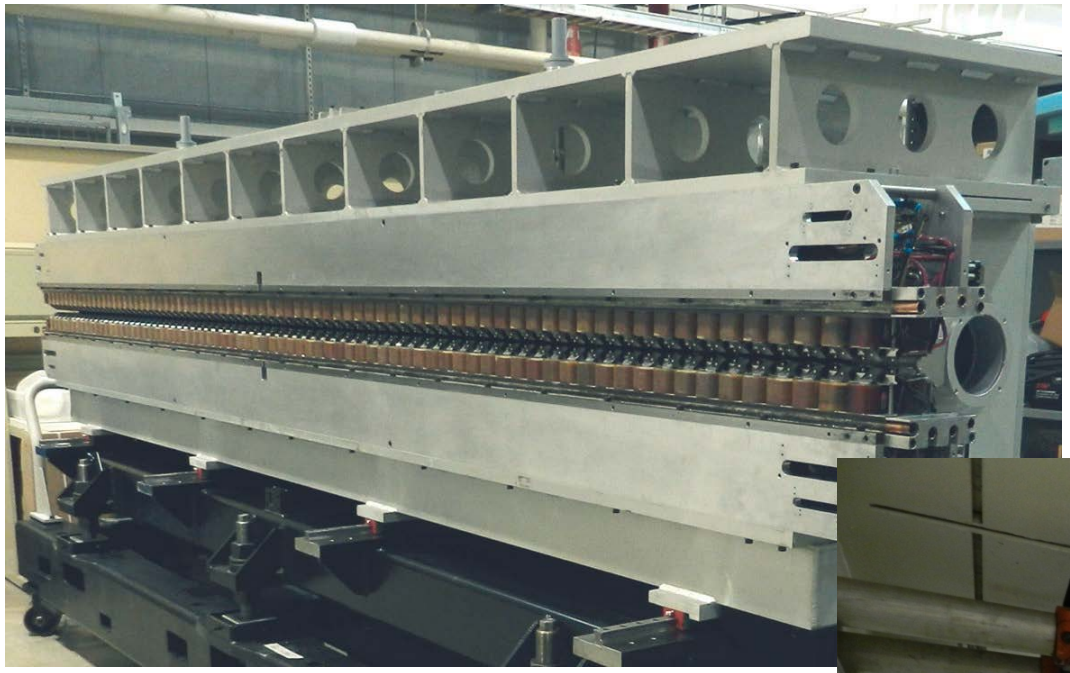
Flux in linear horizontal polarization mode at 250-eV first-harmonic energy for two different QP patterns with reduced magnetic field at the QP poles (85% of regular field). The higher harmonics are shifted to lower energies with the QP turned on. The energy shift is smaller for the 16-pole pattern (blue dashed curve). The flux of the third harmonic is reduced to ~ 8% and the second harmonic is reduced to less than 50% for both patterns. The first harmonic is reduced by ~ 20%.

Assembly

Courtesy of M. Jaski

IEX Magnet

Courtesy of M. Jaski



Magnet Measurement

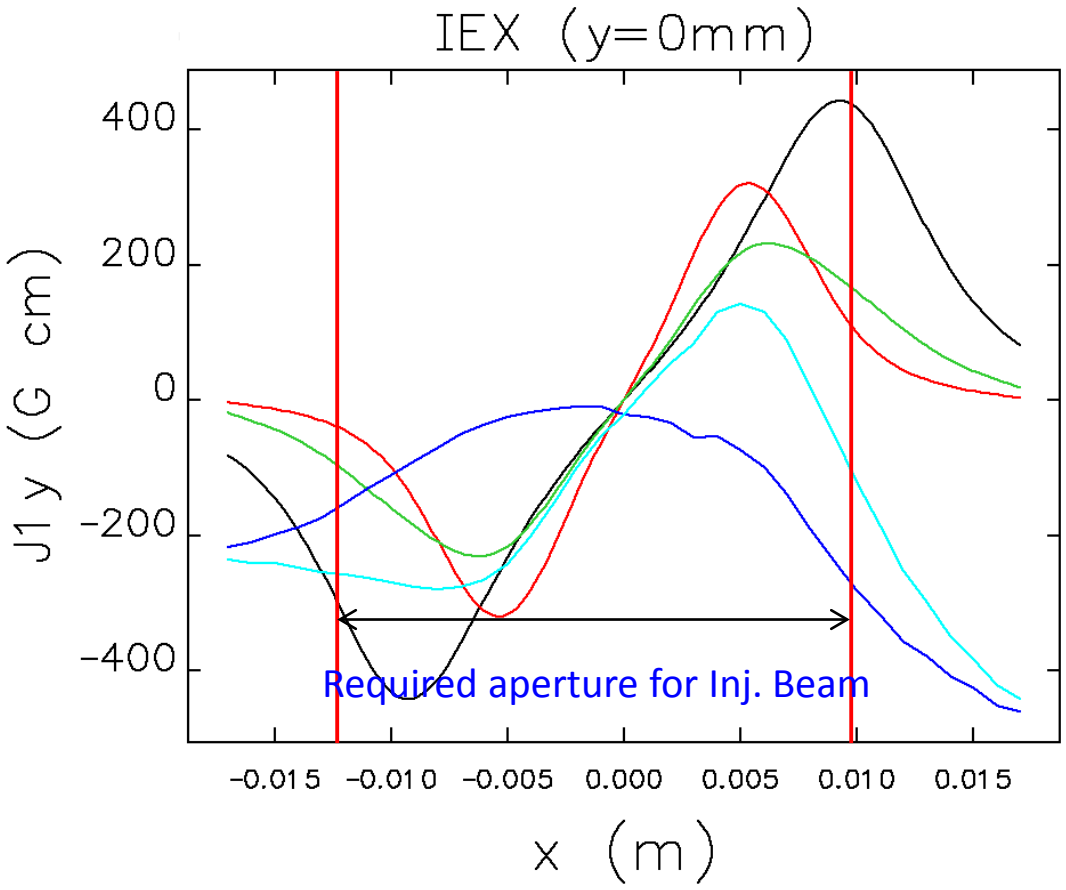
Ensure IEX is built within required tolerance!

- Measure correction coils response function (12)
- Measure main field
  - Ensure field errors are within specification
  - Ensure main field roll-off is within specification
  - Straighten beam orbit inside the magnet using earth coil
  - Generate correction “look-up” table
  - 3 operational modes, 2 directions (hysteresis loop), Quasi on/off
  - Roll-off measurement need measurement over a large x-y window
    $|x| < 18$ mm @ y=0, -1, 1, -2, 2 mm

Huge amount of work!
Measurement was done very precisely!

IEX – Field Integrals

H: H polarization mode
V: V polarization mode
C: Circular polarization mode



Dynamic Field Integral

Meas. Static Error

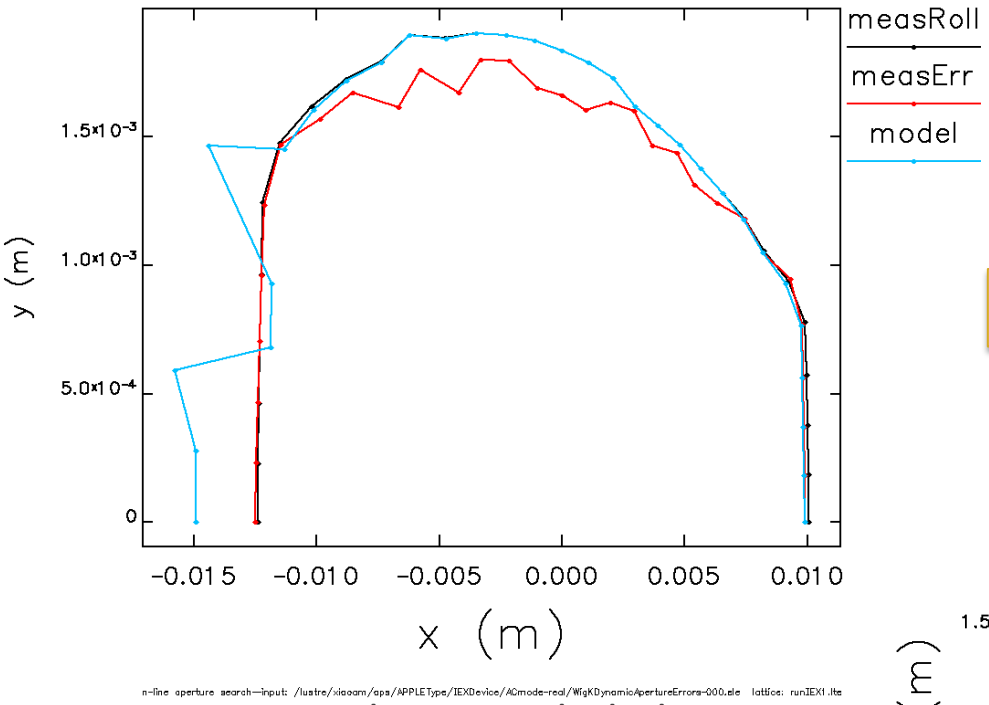
Total

Simulation condition:

1. Fit measurement data with: strength, roll-off, alignment errors
2. Correct tune, beta-beating for IEX without static errors
3. APS lattice, 8 random seeds

IEX - DA

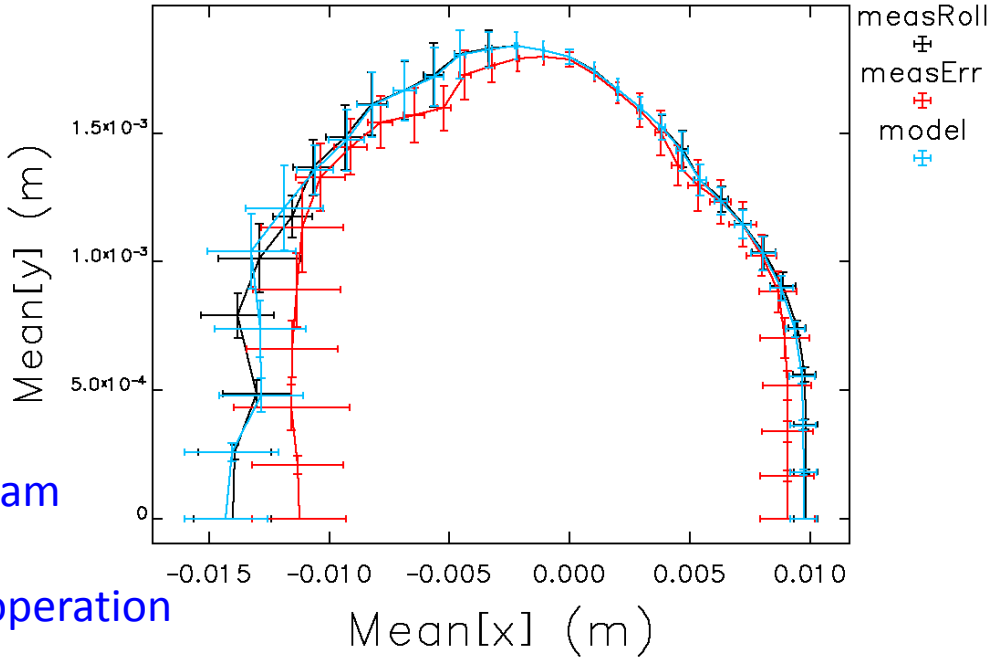
Black – only include roll-off error
Red – include measured static errors
Cyan – model from magnet design



No optical error included

Delicate correction needed to restore DA!

Include optical error

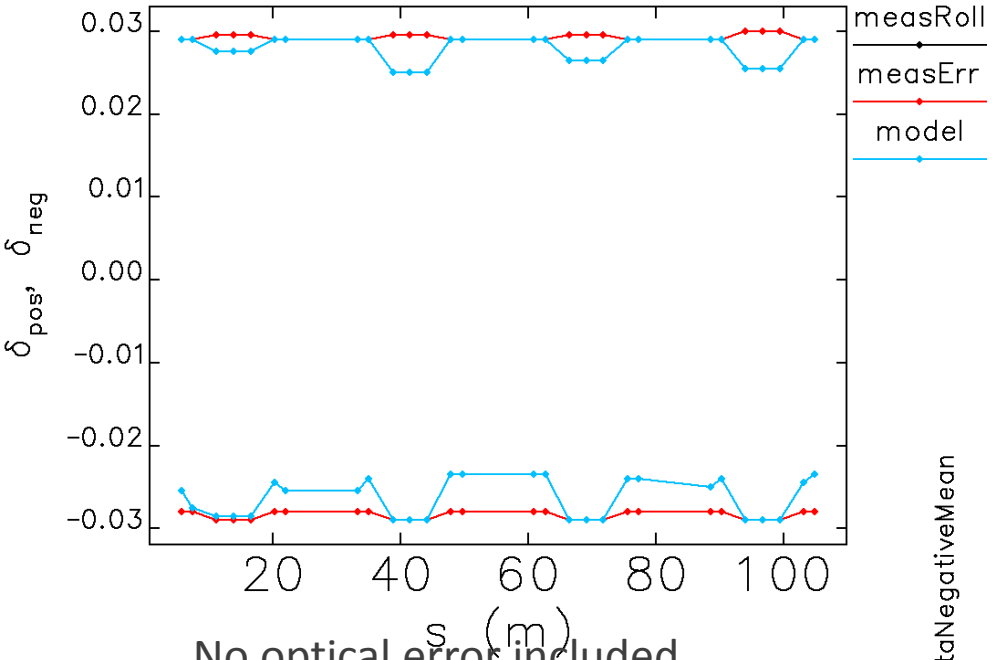


Shrinking DA observed*:

1. May have to live with tune variation
2. Reduce horizontal beta?
3. Final optimization will be done with beam

* similar as measured with beam in APS operation

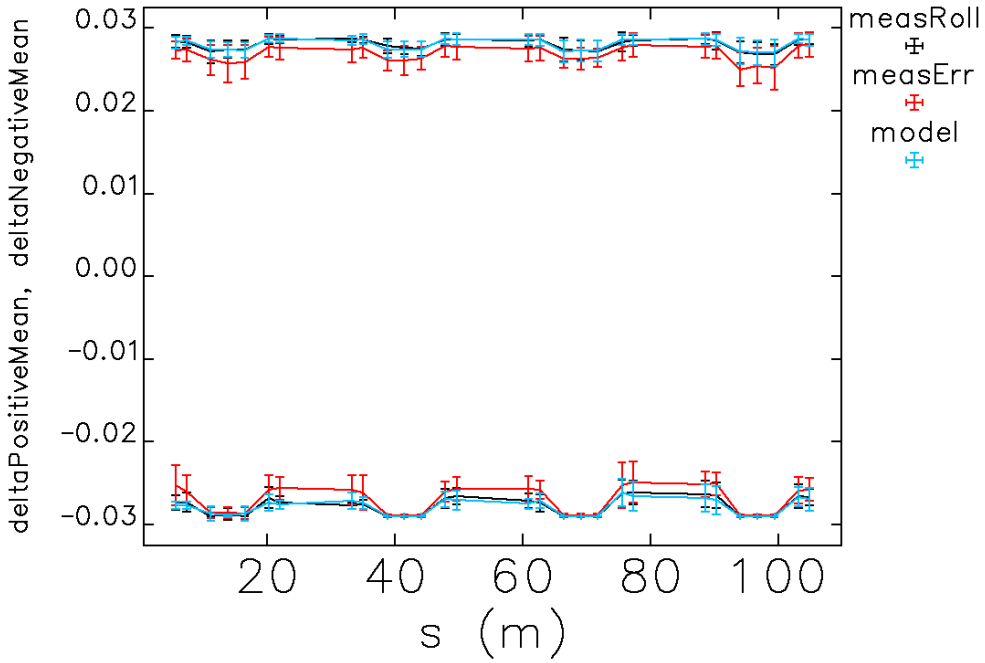
IEX - MA



No optical error included

The beam lifetime is OK.

Include optical error

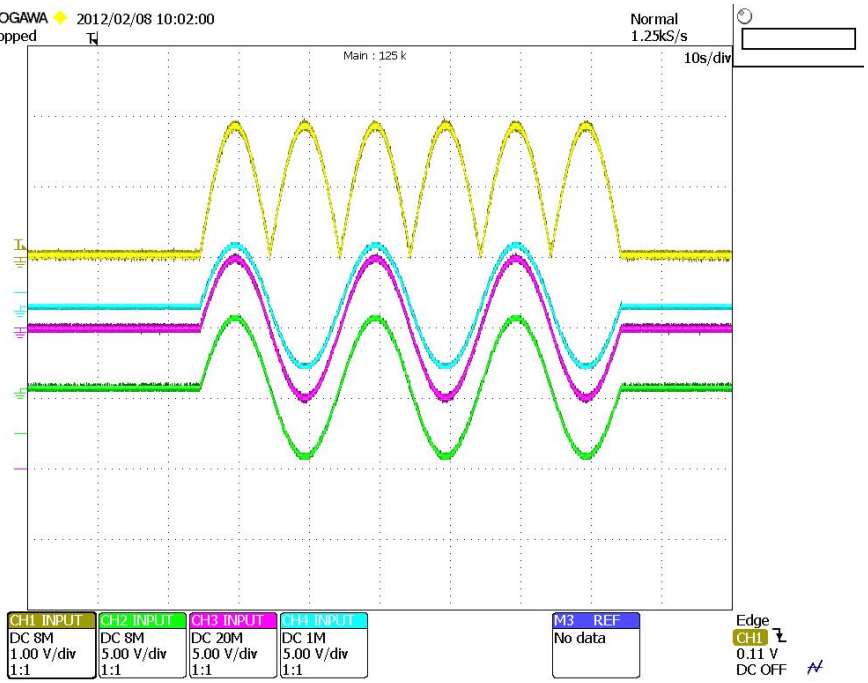


IEX PS System

- Need convenient way to degaussing and condition the magnet
- 17 power supplies, better synchronization to reduce beam perturbation
- Reducing PS over shooting during the ramp

Reducing perturbation from IEX as much as possible!

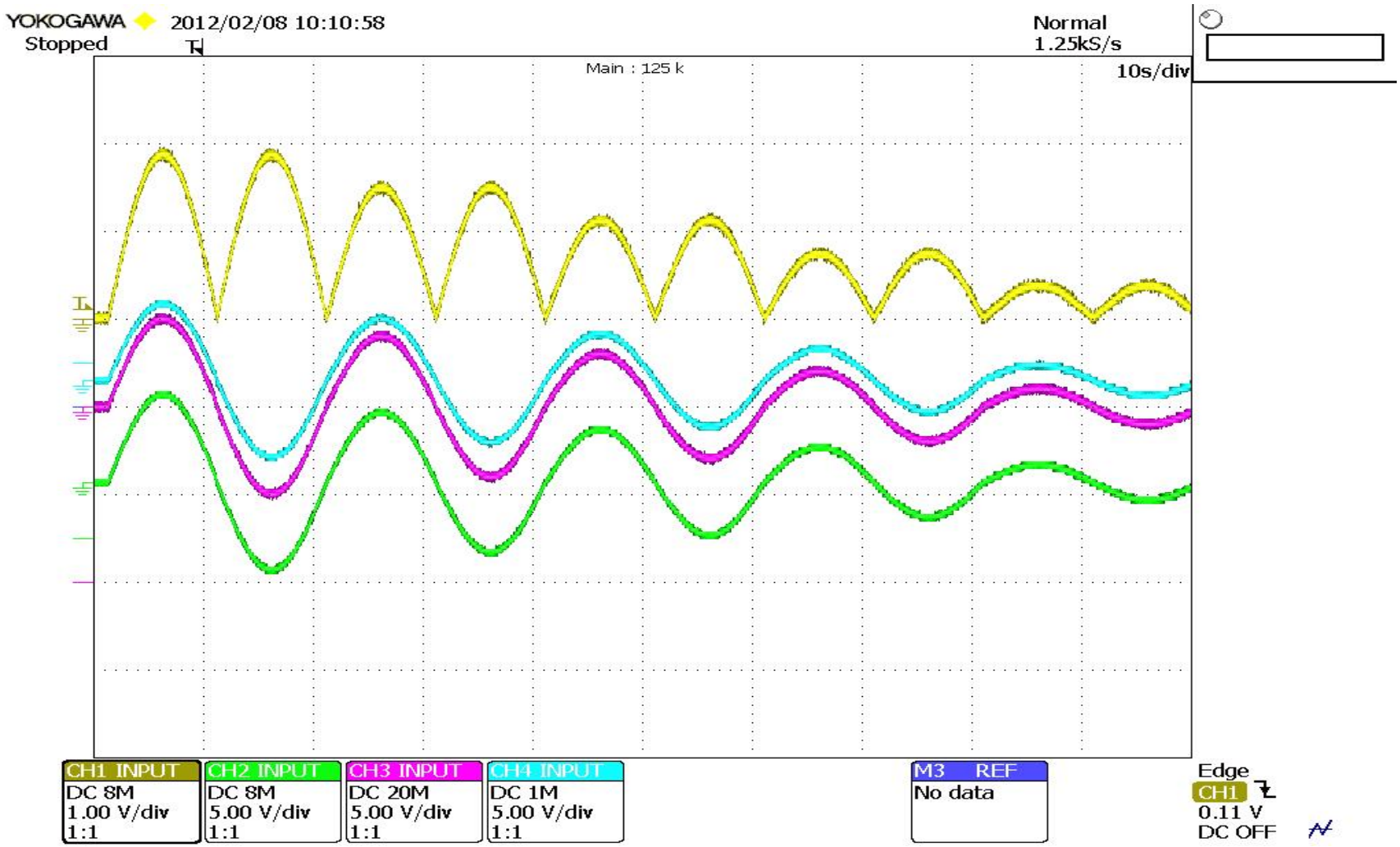
Simultaneous PS condition



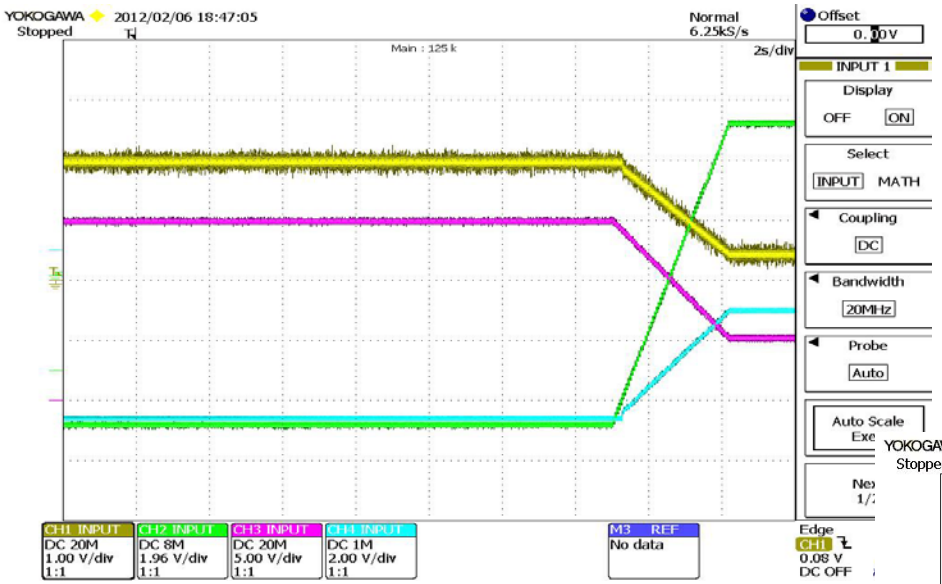
Courtesy of Boris Deriy

Simultaneous PS Degaussing

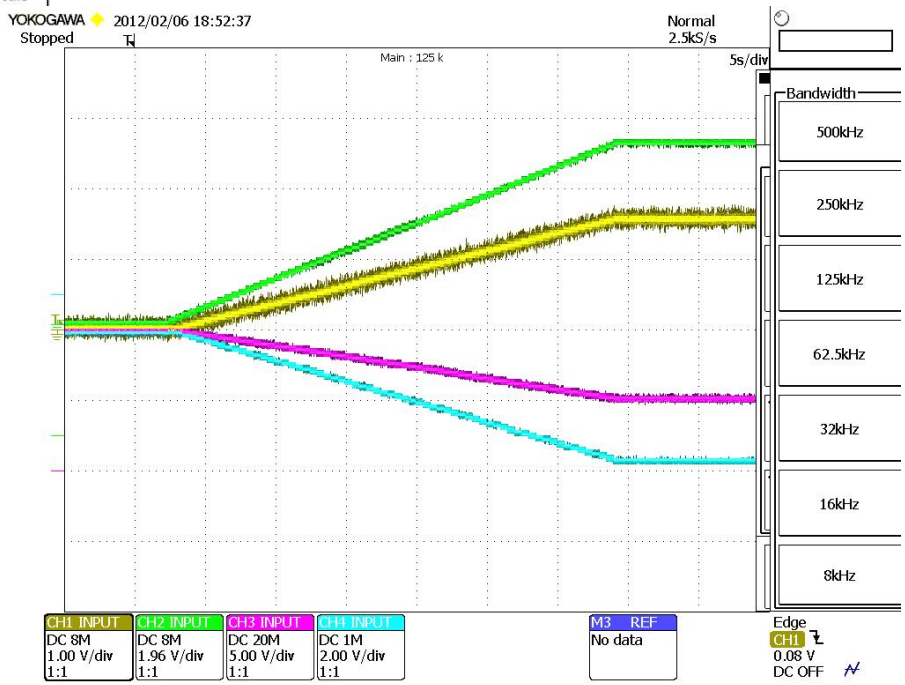
Courtesy of Boris Deriy



Simultaneous Ramping and Ramping Rate Change

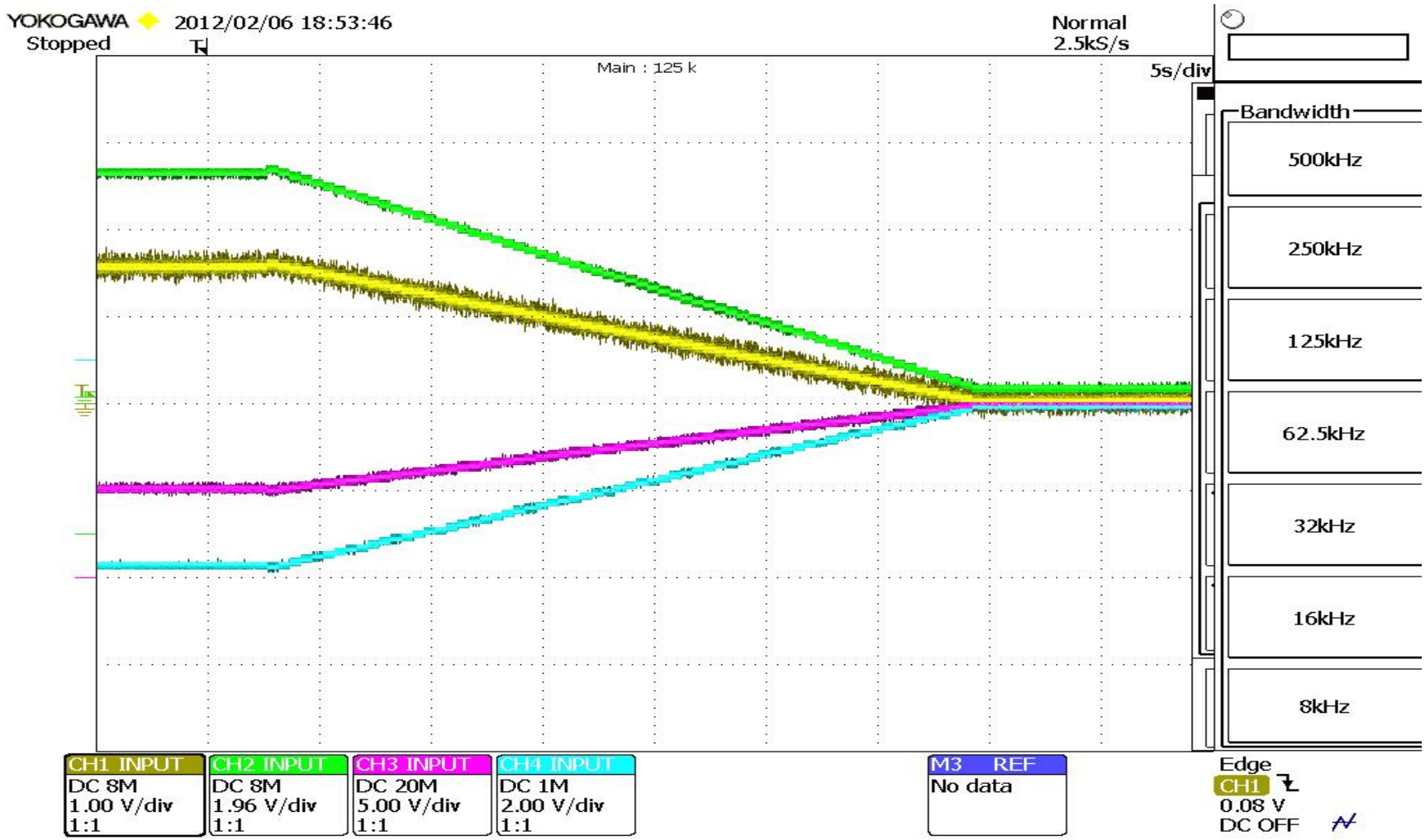


Courtesy of Boris Deriy



Shutdown on Interlock

Courtesy of Boris Deriy



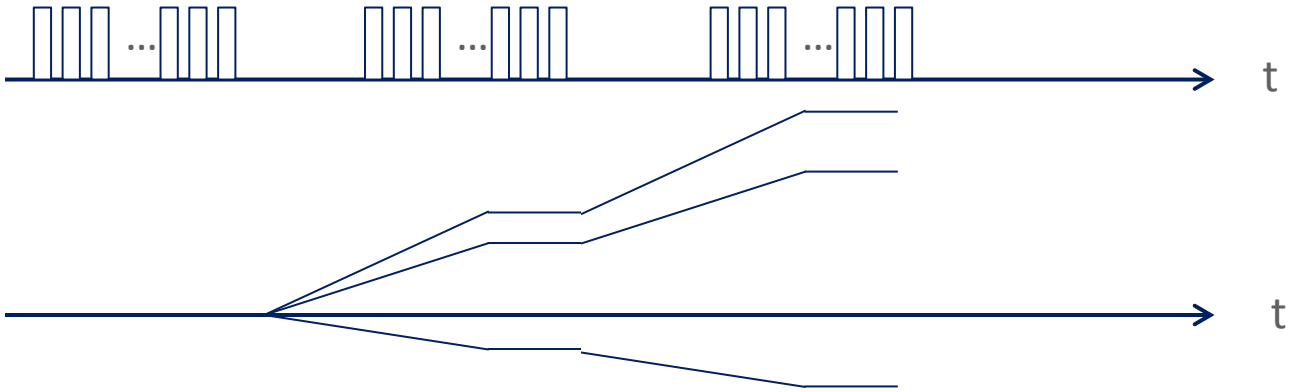
IEX Control

- IEX Correction
  - Reads SDDS corrector lookup tables into IOC

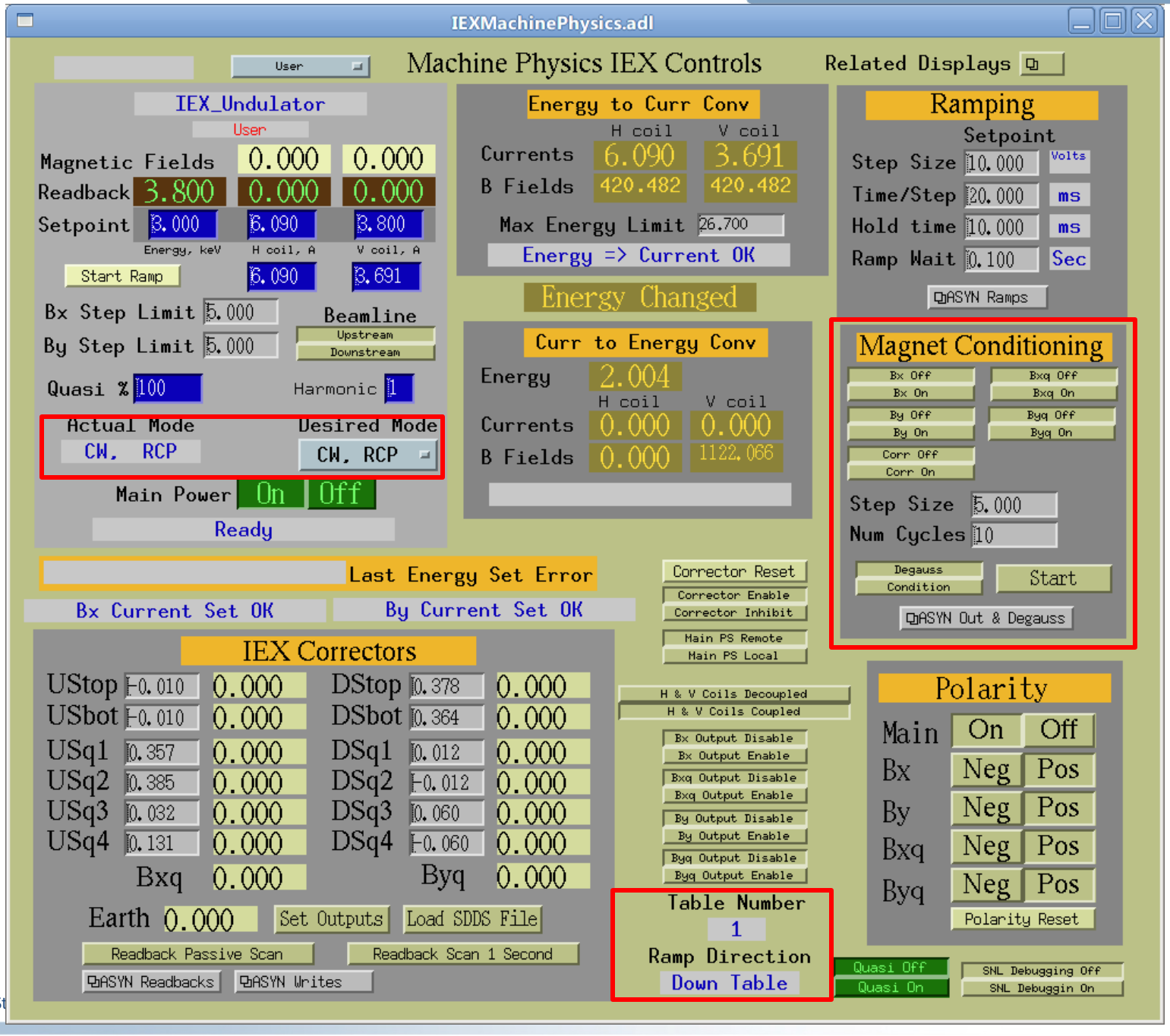
    3 (modes) x 2 (beamlines) x 2 (Quasi on/off) x 2 (ramping directions) = **24** pages!
  - Corrector Lookup

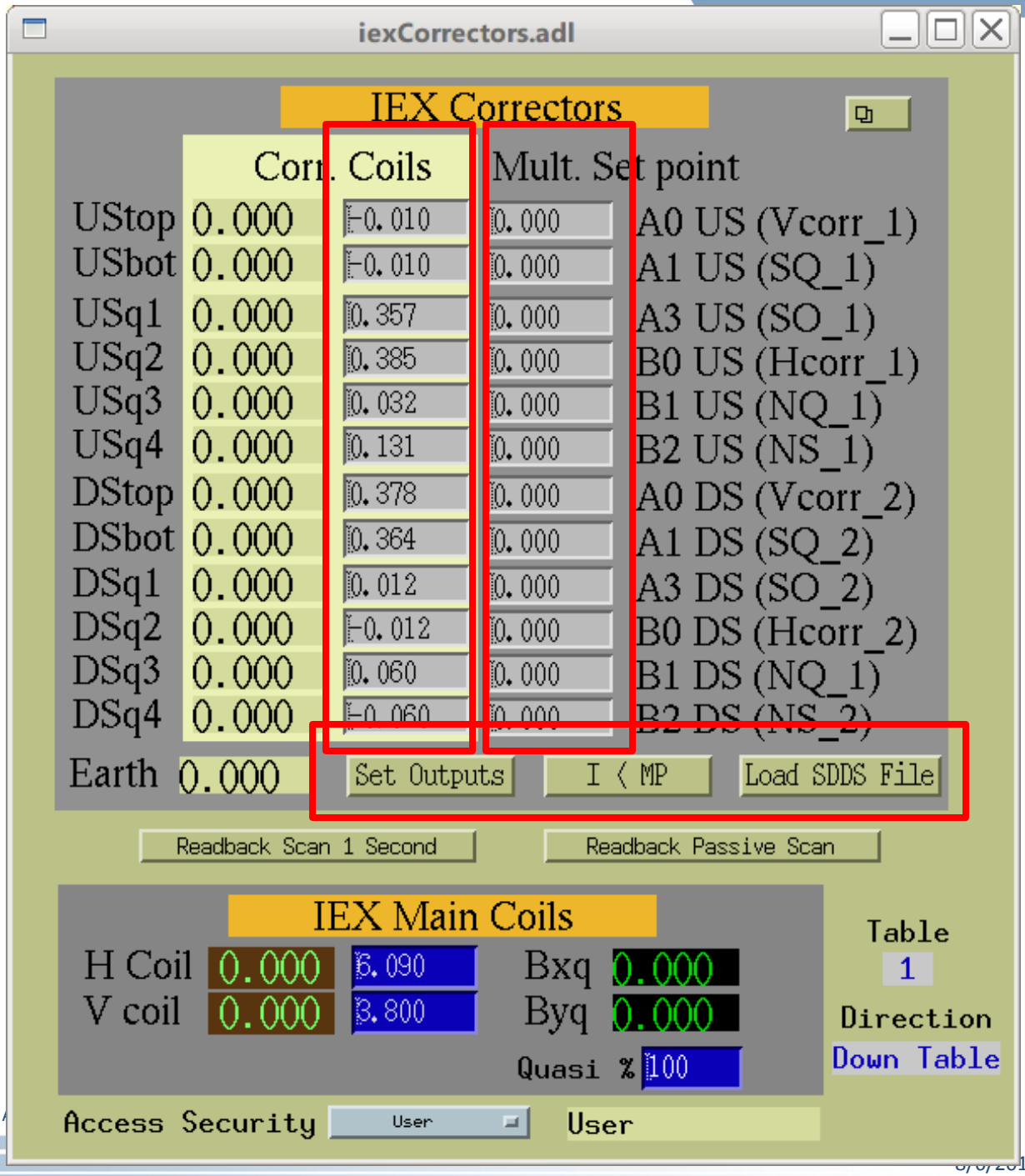
    Corrector current lookup from table data for each main coil current
  - MP2I

    Multipole to corrector coil current converter
- PS ramping

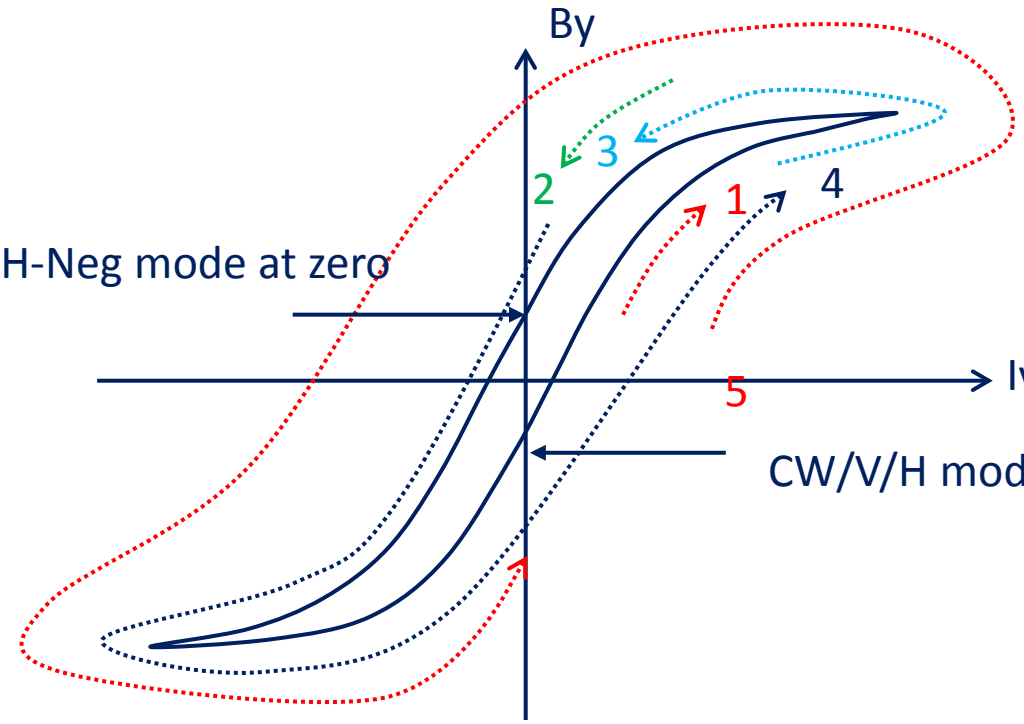


- Event driven using a finite state machine program


IEXMachinePhysics.adl
User
Machine Physics IEX Controls
Related Displays
IEX_Undulator
User
Magnetic Fields 0.000 0.000
Readback 3.800 0.000 0.000
Setpoint 3.000 6.090 3.800
Energy, keV
H coil, A
V coil, A
Start Ramp
6.090
3.691
Bx Step Limit 5.000
By Step Limit 5.000
Beamline
Upstream
Downstream
Quasi % 100
Harmonic 1
Actual Mode
CW, RCP
Desired Mode
CW, RCP
Main Power On Off
Ready
Energy to Curr Conv
H coil V coil
Currents 6.090 3.691
B Fields 420.482 420.482
Max Energy Limit 26.700
Energy => Current OK
Energy Changed
Curr to Energy Conv
Energy 2.004
H coil V coil
Currents 0.000 0.000
B Fields 0.000 1122.066
Ramping
Setpoint
Step Size 10.000 Volts
Time/Step 20.000 ms
Hold time 10.000 ms
Ramp Wait 0.100 Sec
ASYN Ramps
Magnet Conditioning
Bx Off
Bx On
Bxq Off
Bxq On
By Off
By On
Byq Off
Byq On
Corr Off
Corr On
Step Size 5.000
Num Cycles 10
Degauss Condition
Start
ASYN Out & Degauss
Last Energy Set Error
Bx Current Set OK
By Current Set OK
Corrector Reset
Corrector Enable
Corrector Inhibit
Main PS Remote
Main PS Local
IEX Correctors
UStop -0.010 0.000 DStop 0.378 0.000
USbot -0.010 0.000 DSbot 0.364 0.000
USq1 0.357 0.000 DSq1 0.012 0.000
USq2 0.385 0.000 DSq2 -0.012 0.000
USq3 0.032 0.000 DSq3 0.060 0.000
USq4 0.131 0.000 DSq4 -0.060 0.000
Bxq 0.000 Byq 0.000
Earth 0.000
Set Outputs
Load SDDS File
Readback Passive Scan
Readback Scan 1 Second
ASYN Readbacks
ASYN Writes
H & V Coils Decoupled
H & V Coils Coupled
Bx Output Disable
Bx Output Enable
Bxq Output Disable
Bxq Output Enable
By Output Disable
By Output Enable
Byq Output Disable
Byq Output Enable
Table Number
1
Ramp Direction
Down Table
Polarity
Main On Off
Bx Neg Pos
By Neg Pos
Bxq Neg Pos
Byq Neg Pos
Polarity Reset
Quasi Off
Quasi On
SNL Debugging Off
SNL Debuggin On


iexCorrectors.adl
IEX Correctors
Corr. Coils
Mult. Set point
UStop 0.000 -0.010 0.000 A0 US (Vcorr_1)
USbot 0.000 -0.010 0.000 A1 US (SQ_1)
USq1 0.000 0.357 0.000 A3 US (SO_1)
USq2 0.000 0.385 0.000 B0 US (Hcorr_1)
USq3 0.000 0.032 0.000 B1 US (NQ_1)
USq4 0.000 0.131 0.000 B2 US (NS_1)
DStop 0.000 0.378 0.000 A0 DS (Vcorr_2)
DSbot 0.000 0.364 0.000 A1 DS (SQ_2)
DSq1 0.000 0.012 0.000 A3 DS (SO_2)
DSq2 0.000 -0.012 0.000 B0 DS (Hcorr_2)
DSq3 0.000 0.060 0.000 B1 DS (NQ_1)
DSq4 0.000 -0.060 0.000 B2 DS (NS_2)
Earth 0.000
Set Outputs
I < MP
Load SDDS File
Readback Scan 1 Second
Readback Passive Scan
IEX Main Coils
H Coil 0.000 6.090
V coil 0.000 3.800
Bxq 0.000
Byq 0.000
Quasi % 100
Table
1
Direction
Down Table
Access Security
User
User

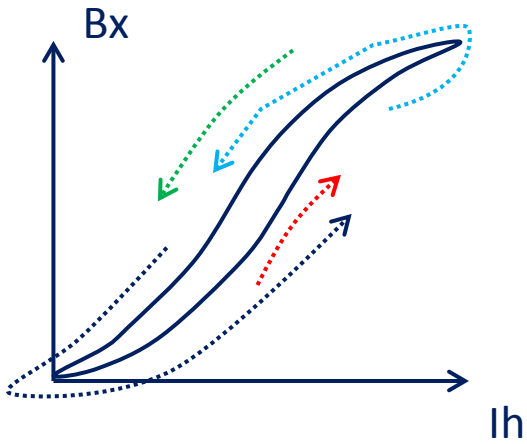
IEX Ramping States



CW and H mode:

1. By up -> up
2. By down -> down
3. By up -> down
4. By down -> up
5. By goes to zero

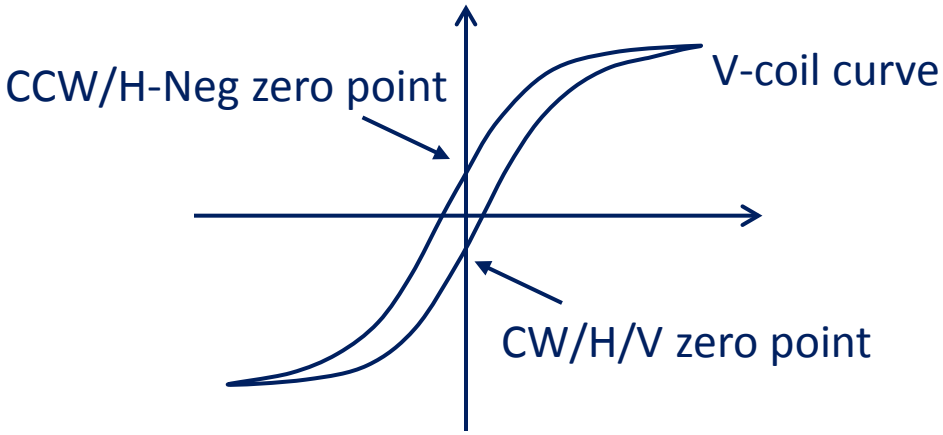
V mode (H coil only)

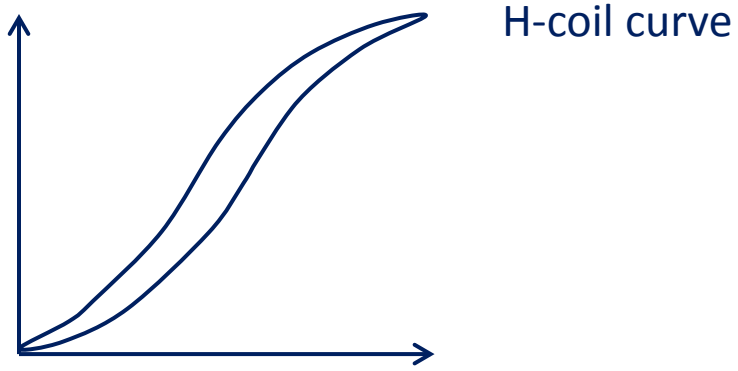


Similar ramping states for other modes (V, CCW, H-Neg)

IEX Mode Change Example (V mode, H-coil only)

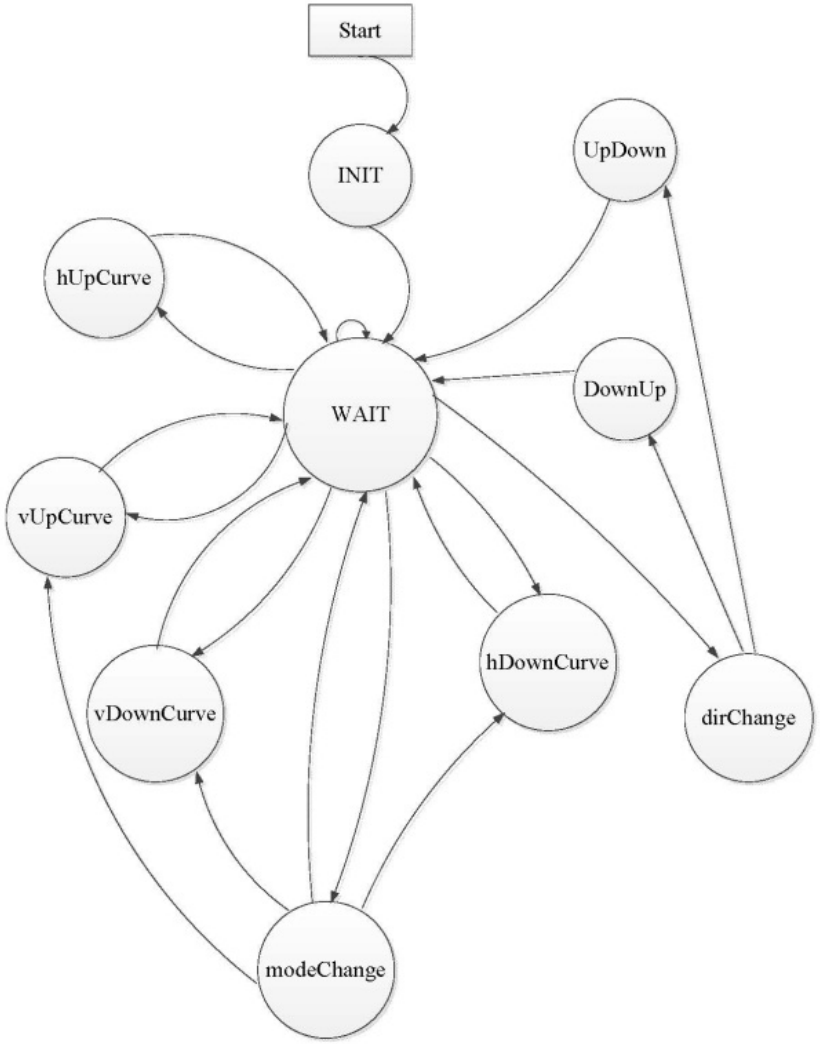
Start	End	Execute
At zero	CW or H mode	Do nothing
At zero	CCW or H-Neg mode	Ramp v-coil up to max then down to zero
At uphill curve	CW or H mode	Ramp h-coil up to max then down to zero
At uphill curve	CCW or H-Neg mode	Ramp h-coil up to max then down to zero Ramp v-coil up to max then down to zero
At downhill curve	CW or H mode	Ramp h-coil down to zero
At downhill curve	CCW or H-Neg mode	Ramp h-coil down to zero Ramp v-coil up to max then down to zero





IEX State Program Diagram

Courtesy of Marty Smith



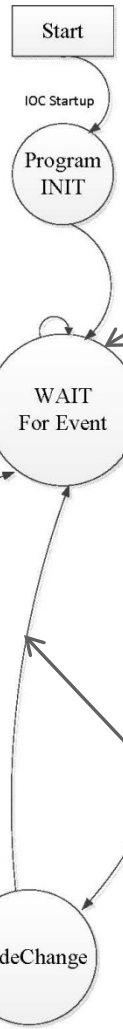
- Initializes control program
- Implements
  - Ramping algorithms
  - Device mode changes
  - Power on/off for main coils
- Modular program
  - Easier to debug
  - ~3400 lines of code

IEX Mode Change Example

Courtesy of Marty Smith

Soft IOC starts up

Program initializes variables



Program waits for events

vDownCurve conditions:

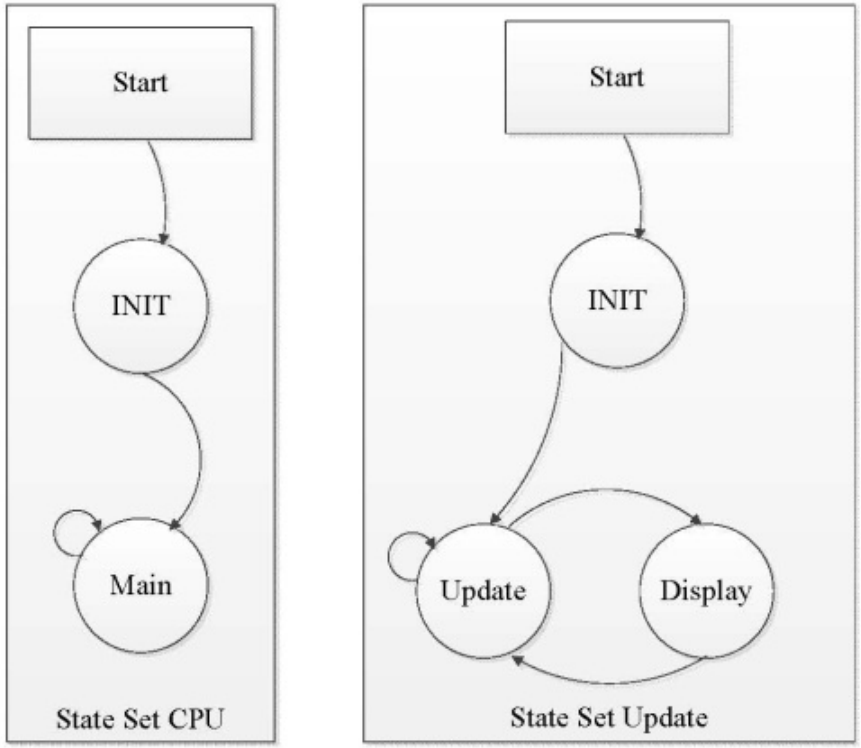
- Main coil power on
- Not in V-Mode
- On the down curve already
- V coil set point > 0
- Going to mode: CCW or H, Neg

Mode change event (User Initiated)

H & V current = 0

CPU State Program Diagram

Courtesy of Marty Smith



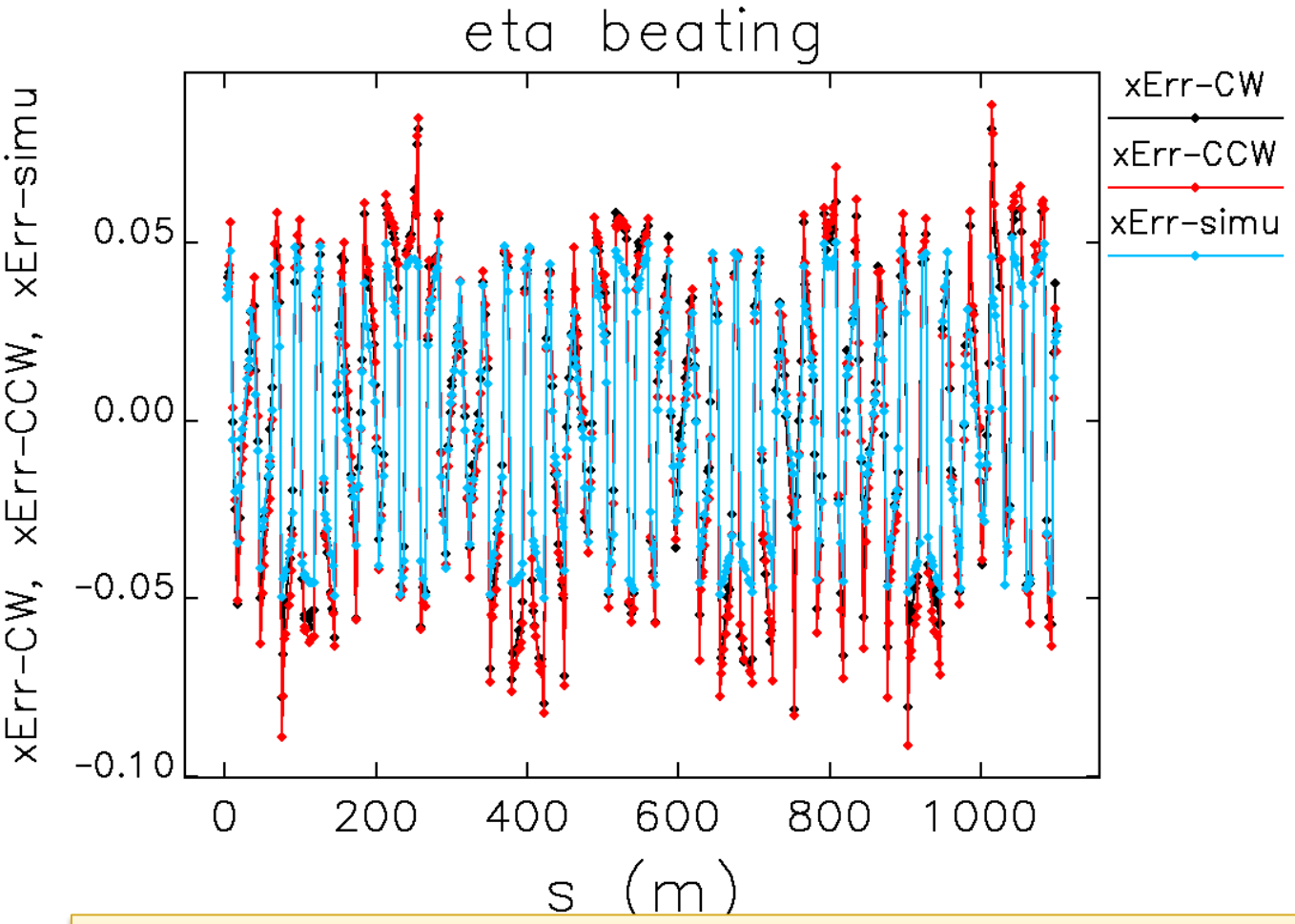
- Initializes control program
- Implements
  - Ramping algorithms
  - Device mode changes
  - Power on/off for main coils
- Program
  - ~1700 lines of code

IEX Commissioning

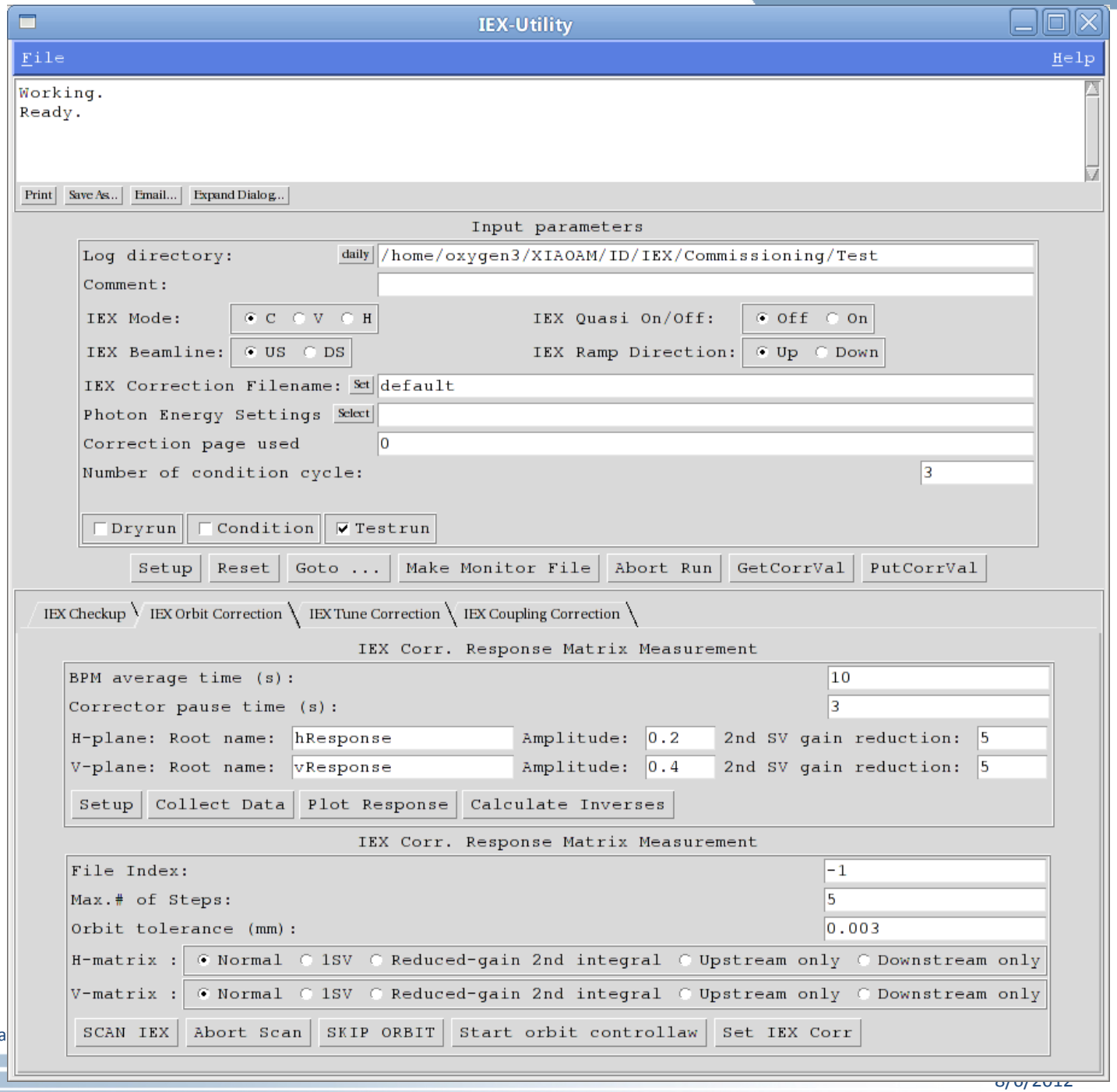
- Started from the beginning of this run
- Preliminary testing IEX system – Done with success
  - PS + control system, beam response to correctors, basic IEX operational functions, etc.
- IEX perturbation assessment – Done with success
  - Good agreement with simulation results
  - IEX's quality is as good as we expected
- Preliminary beam perturbation correction for circular mode – Done with success
  - Tune, coupling, and orbit perturbations

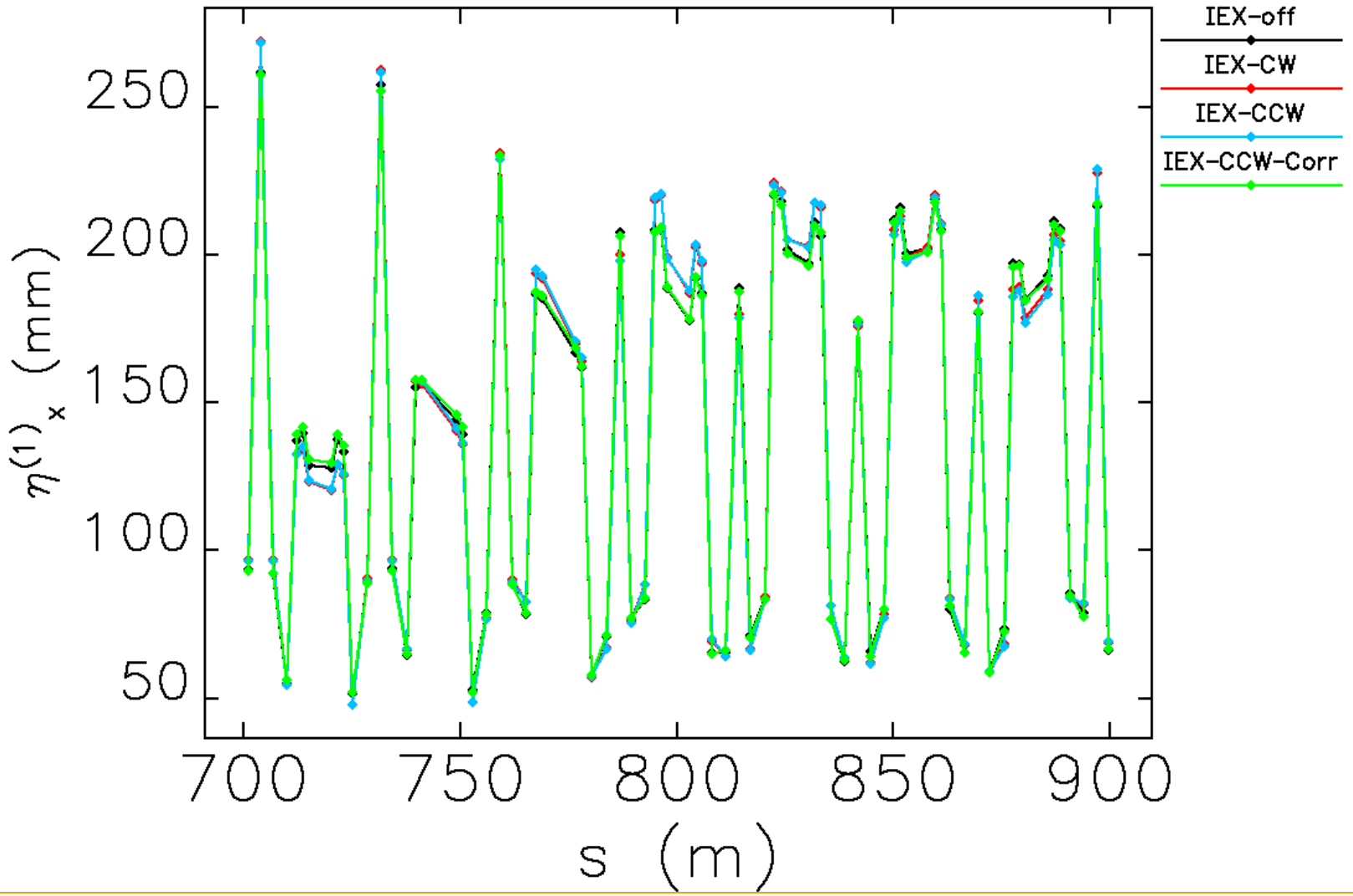
- Testing control and correction software – >70% done
- Stress testing PS and Control system – Under testing

Mode	Δnux_meas	Δnux_simu	Δnuy_meas	Δnuy_simu
CW	-0.0059	-0.003	0.0018	0.0007
CCW	-0.0040	-0.003	0.0018	0.0007

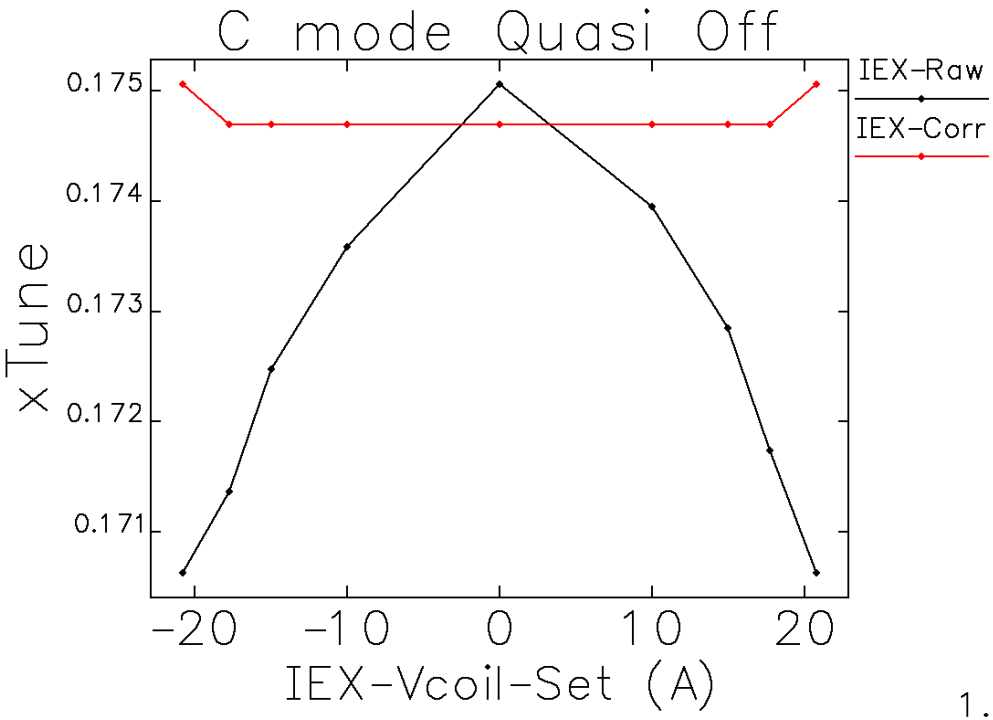


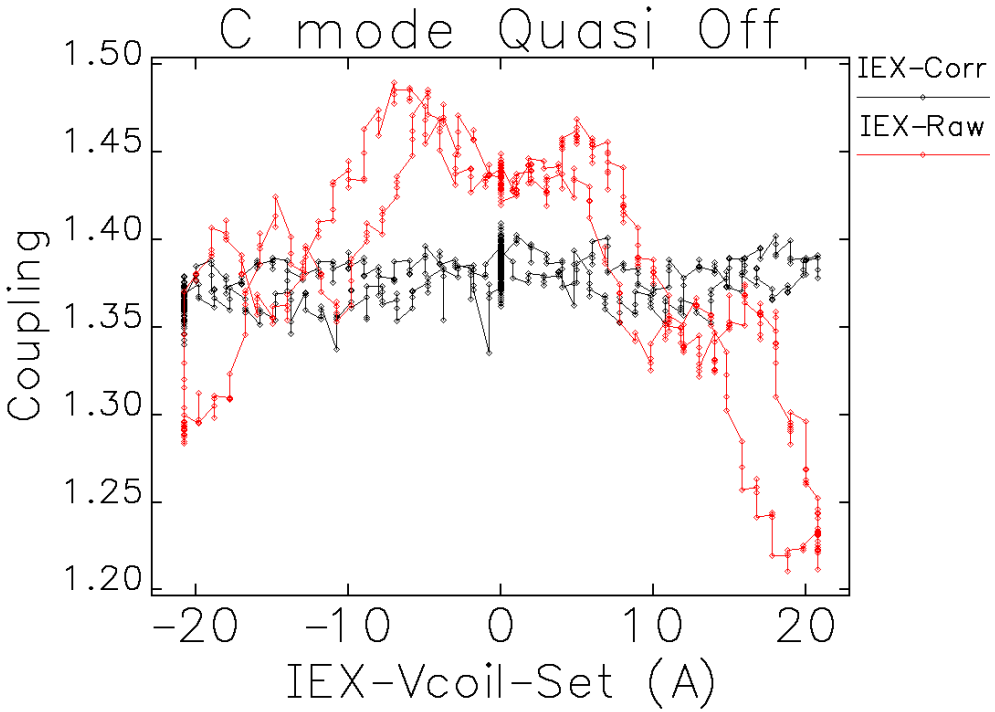
Good agreement between simulated and measured perturbations!

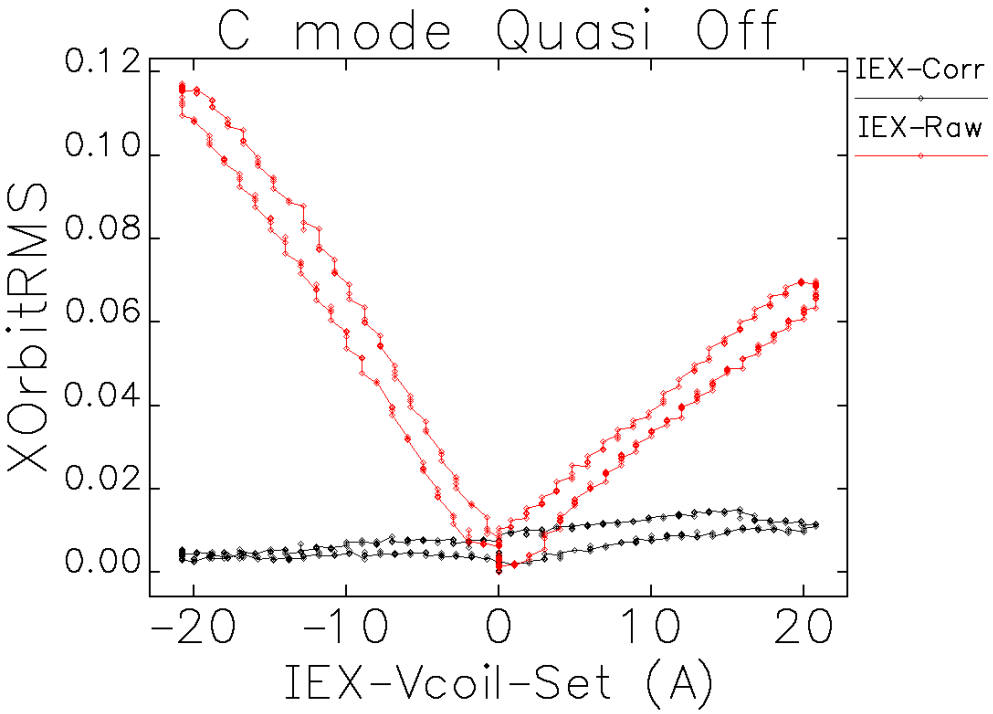

IEX-Utility
File
Help
Working.
Ready.
Print
Save As...
Email...
Expand Dialog...
Input parameters
Log directory:
daily
/home/oxygen3/XIAOAM/ID/IEX/Commissioning/Test
Comment:
IEX Mode:
C
V
H
IEX Quasi On/Off:
Off
On
IEX Beamline:
US
DS
IEX Ramp Direction:
Up
Down
IEX Correction Filename:
Set
default
Photon Energy Settings
Select
Correction page used
0
Number of condition cycle:
3
Dryrun
Condition
Testrun
Setup
Reset
Goto ...
Make Monitor File
Abort Run
GetCorrVal
PutCorrVal
IEX Checkup
IEX Orbit Correction
IEX Tune Correction
IEX Coupling Correction
IEX Corr. Response Matrix Measurement
BPM average time (s):
10
Corrector pause time (s):
3
H-plane: Root name:
hResponse
Amplitude:
0.2
2nd SV gain reduction:
5
V-plane: Root name:
vResponse
Amplitude:
0.4
2nd SV gain reduction:
5
Setup
Collect Data
Plot Response
Calculate Inverses
IEX Corr. Response Matrix Measurement
File Index:
-1
Max.# of Steps:
5
Orbit tolerance (mm):
0.003
H-matrix :
Normal
1SV
Reduced-gain 2nd integral
Upstream only
Downstream only
V-matrix :
Normal
1SV
Reduced-gain 2nd integral
Upstream only
Downstream only
SCAN IEX
Abort Scan
SKIP ORBIT
Start orbit controllaw
Set IEX Corr

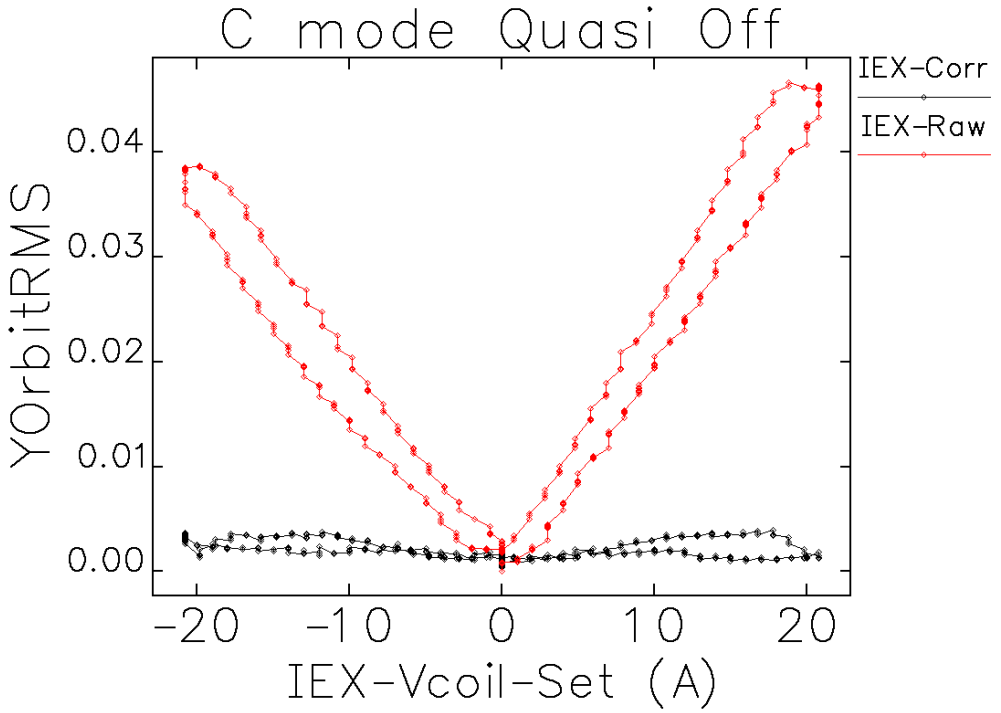


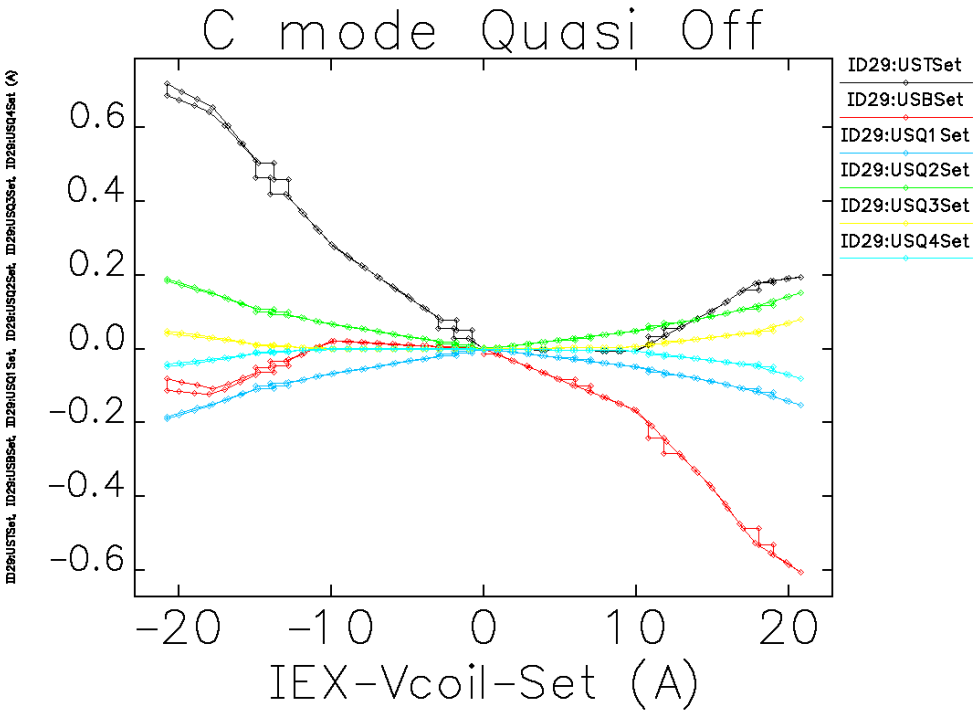
After tune correction, black and green line has good agreement – optical function restored!

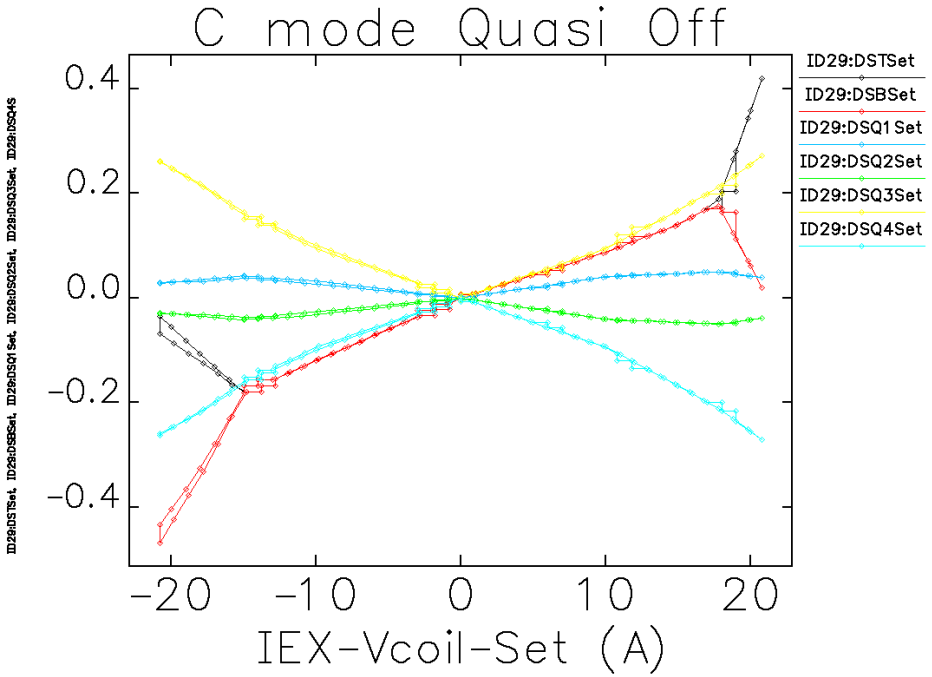

C mode Quasi Off
IEX-Raw
IEX-Corr
xTune
0.175
0.174
0.173
0.172
0.171
-20
-10
0
10
20
IEX-Vcoil-Set (A)


C mode Quasi Off
IEX-Corr
IEX-Raw
Coupling
1.50
1.45
1.40
1.35
1.30
1.25
1.20
-20
-10
0
10
20
IEX-Vcoil-Set (A)


C mode Quasi Off
IEX-Corr
IEX-Raw
XOrbitRMS
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-20
-10
0
10
20
IEX-Vcoil-Set (A)


C mode Quasi Off
IEX-Corr
IEX-Raw
YOrbitRMS
0.04
0.03
0.02
0.01
0.00
-20
-10
0
10
20
IEX-Vcoil-Set (A)


C mode Quasi Off
ID29:UST Set, ID29:USB Set, ID29:USQ1 Set, ID29:USQ2 Set, ID29:USQ3 Set, ID29:USQ4 Set (A)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-20
-10
0
10
20
IEX-Vcoil-Set (A)
ID29:USTSet
ID29:USBSet
ID29:USQ1 Set
ID29:USQ2Set
ID29:USQ3Set
ID29:USQ4Set


C mode Quasi Off
ID29:DST Set, ID29:DSB Set, ID29:DSQ1 Set, ID29:DSQ2 Set, ID29:DSQ3 Set, ID29:DSQ4S
0.4
0.2
0.0
-0.2
-0.4
-20
-10
0
10
20
IEX-Vcoil-Set (A)
ID29:DSTSet
ID29:DSBSet
ID29:DSQ1 Set
ID29:DSQ2Set
ID29:DSQ3Set
ID29:DSQ4Set

Summary

- IEX is one of the most challenge insertion devices have been built and installed to APS
- A quick and smooth start of IEX commissioning resulting from the hard and flawless work of the entire team
- Preliminary commission results show beam perturbations from IEX are
  - Very close to the simulation results
  - Can be greatly reduced by using local correctors
  - IEX's quality is as good as we expected
  - Still, IEX is the MOST strong beam perturbation source among all existing IDs
  - It DOES reduce the entire machine's tolerance margin
- Future commissioning plan
  - Stability test of the PS and control system
  - Generate experimental correction table for all IEX operational modes
  - Investigate possibility of device degaussing and conditioning with beam