On-line nonlinear chromaticity correction at Rhic store

(RHIC beambeam team: M. Bai, J. Beebe-Wang, J. Bengtsson*, R. Calaga*, **W. Fischer**, **Y. Luo**, C.Montag, N. Malisky, **S. Tepikian**, **D. Trbojevic**, T. Roser, ...)

1. General descriptions
2. On-line correction algorithm
3. On-line correction implementation

New chromacity correction scheme

1) In the coming RHIC run, the number of arc sextupole power supplies will be doubled, from 12 to 24.

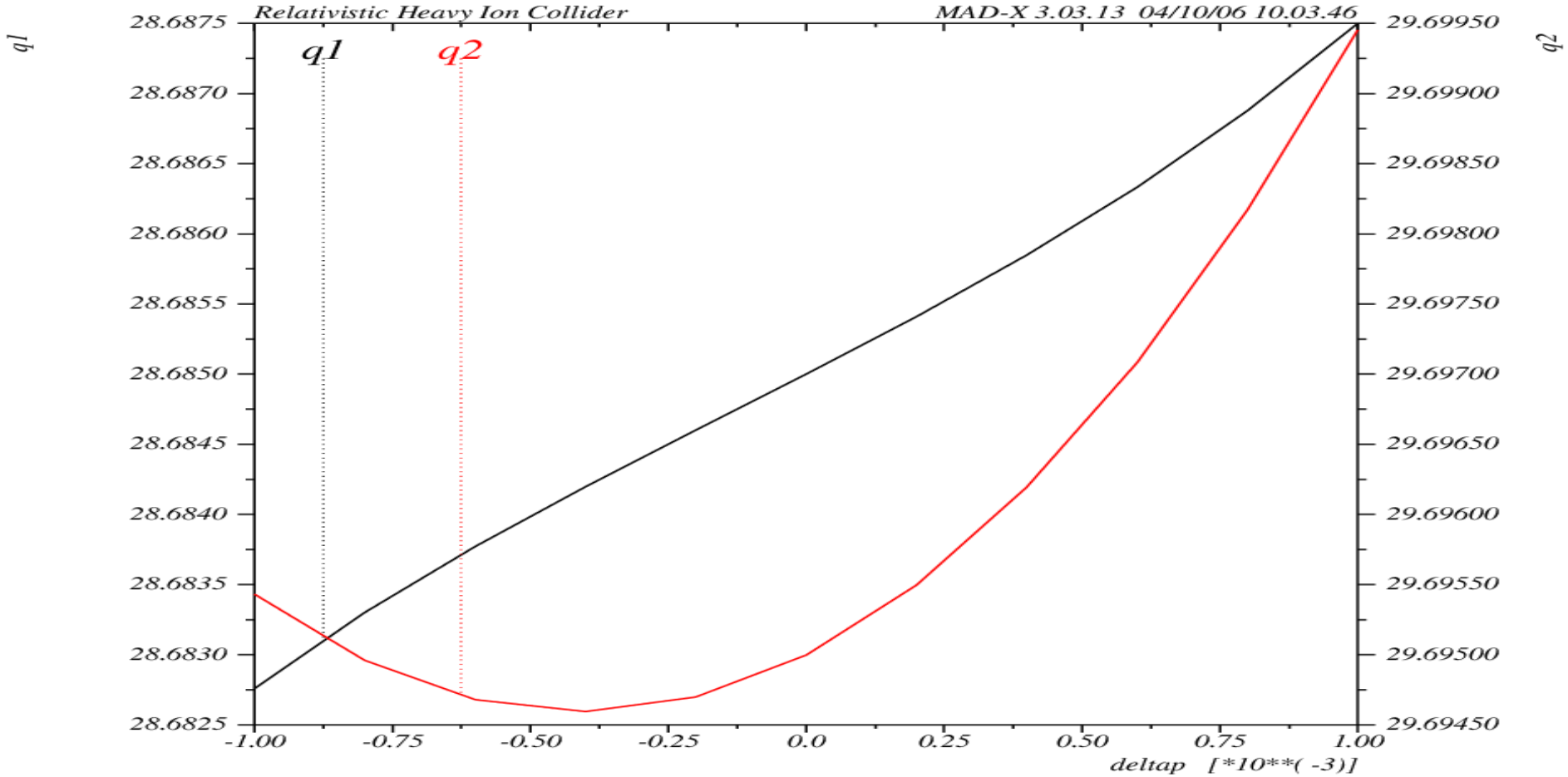
2)This will enable us use multi-families for nonlinear chromaticity correction and 3Qx correction.

In early runs:
SF, SD, SF, SD, SF, SD, SF, SD, SF, SD, SF, SD

In future runs(According to W. Scandale andS. Tepikian, AP-Note-45)
Outer arcs:
SFPO,SDPO,SFMO,SDMO,SFPO,SDPO,SFMO,SDMO,SFPO,SDPO,SFMO,SDMO
Inner arcs:
SDPI, SFPI, SDMI, SFMI, SDPI, SFPI, SDMI, SFMI, SDPI, SFPI, SDMI, SFMI

3) However, the chromaticity correction scheme is not limited to 8 families.

Nonlinear chromaticities with two sextupole families



* NAME	ORDER1	ORDER2	ORDER3	ORDER4	VALUE
$ %s	%d	%d	%d	%d	%le
"Q1"	0	0	0	0	0.6849997259
"Q2"	0	0	0	0	0.6949996997
"DQ1"	1	0	0	0	1.851720927
"DQ2"	1	0	0	0	1.924986083
"DQ1"	2	0	0	0	1445.184394
"DQ2"	2	0	0	0	2023.158067
"DQ1"	3	0	0	0	724818.9722
"DQ2"	3	0	0	0	-431422.3753

Off-line chromaticity correction for further dynamics study

1) Solution with MAD8:

Use **Harmon module** in MAD8 to minimize nonlinear chromaticities, then import the matching results to MADX for further studies.

2) Solutions with MADX:

Define your own matching objectives in a '**user macro**', then use optimizing method like Simplex, Lddiff, Migrad, and Jocobian to do matching. Sometime this procedure is time-consuming.

3) Solution with Tracy-II

Write **your own codes with Tracy-II accelerator library**. You need know Tracy-II and at least C programing, nonlinear optimization, numerical recipe.

On-line nonlinear chromaticity correction stratedge

1) Our goal, minimize nonlinear (**2nd**) chromaticities

We can measure Q' , Q'' with Rf freq. Wiggling.
Do a polynomial fitting, then we get different oders of chromaticities.
Before this excise, globally decouple the machine first.

2) Can we depend on **off-line matching for on-line use**

Of course, if your off-line optics model predicts the real machine well.
(on-line measuring Q'/Q''-->off-line matching-->feed in correction)

3) Then, we have to turn to **direct on-line matching** (correction)

Then how to implement this multidimensional nonlinear matching?

4) Matching objective choosing

- First thought: **Chromaticities Q', Q'', even Q'''**.

  There are orders of differences in different orders of chromaticities, which gives difficulty to optimizer.

- Smart choice: **Off-momentum tunes**

  Match the off-momentum tunes onto the projected tunes only contributed from first order chromaticities.

  To do so will **minimize all nonlinear chromaticities**.

  And matching objectives are of same order. It will be **easier for optimizer** to handle.

5) Optimizer: algorithm

$$\mathbf{A\ x = b}$$

- **Measure** off-momentum tune response **matrix A**

  How to: change each sextupole family strength to get off-momentum tune changes, calculate derivatives **A**ij

- **Set** your wanted off-momentum tune changes **b**

- **Solve** the equation **A x= b**, **x** gives sextupole strengths changes

  Problem of multidimensional nonlinear optimization
  Newton-Ralphson Method is used
  SVD to calculate **A_invert**
  Parabolic interpolation to searching minimum error function

- Actually we are doing **on-line nonlinear matching**.

6) Off-line testing of this method

```
//---a correction loop
for(j=1;j<=Njacob;j++){
  cout<<"    "<<endl;
  cout<<">>>Iteration: "<<j<<endl;
  cal_Jacobian();
  invert_Jacobian();
  dsvbksb(U, w, V, n_constr, n_vari, dy, dx);
  parabolic();
  get_dy_chi2();
  if(chi2 < chi2_tol) break;
}
```

Implemented with Tracy_II.

One example:

2.4*10^(-3)

```
Numerical chromaticity calculation:
  chromx1, chromy1 :        5.62865          4.96
  chromx2, chromy2 :         201.64        2438.29
  chromx3, chromy3 :         412775        47942.1
chi2=4.81197e-05
```

Before corr.

1.9*10^(-4)

```
Numerical chromaticity calculation:
  chromx1, chromy1 :        1.03069        1.02738
  chromx2, chromy2 :       -656.004        446.819
  chromx3, chromy3 :        -109878        26584.4
Final chi2=3.07547e-07
```

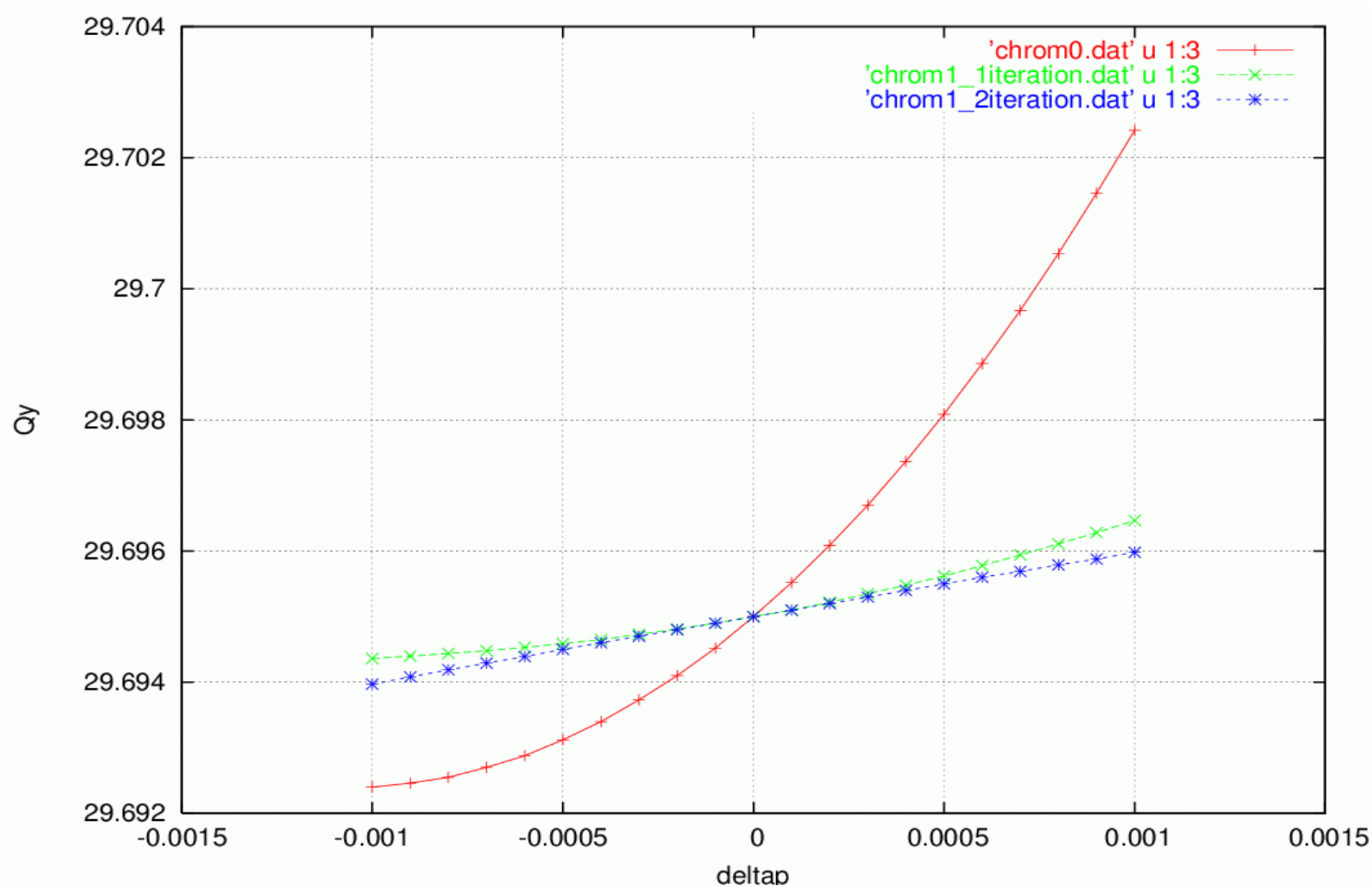
1 iteration

6*10^(-6)

```
Numerical chromaticity calculation:
  chromx1, chromy1 :       0.999338       0.999314
  chromx2, chromy2 :       -27.2574        7.54546
  chromx3, chromy3 :       -13494.6         1270.8
Final chi2=3.63347e-10
```

2 iterations

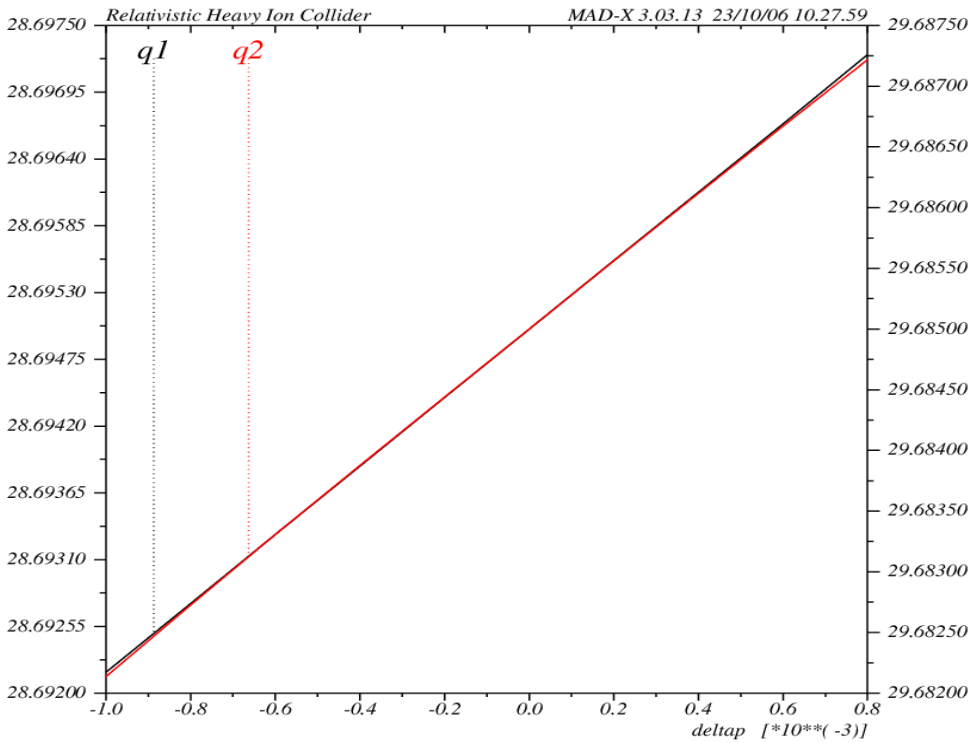
Off-momentun Qy changing during minimization



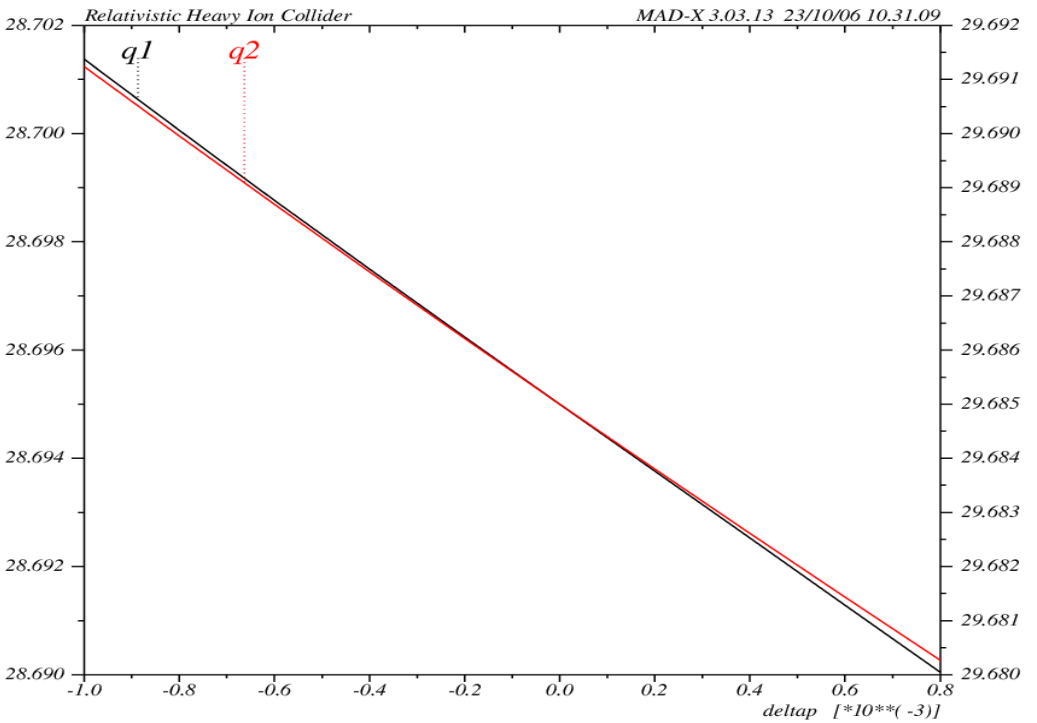
7) How can I change Q', while I don't want change too much Q'' ?

- Recipe I: with known **A**, calculate your **x**.
- Recipe II: simply scale all the eight family strength up or down.
  - But, please be gentle while doing that.

1% change will give you 1 unit Q' change.



Q'=1



Q'=-10, decreased 10%

On-line correction implementation

1) Need set up **a small team** to implement it.

S. Tepikian to help the matrix measurement and send back the correction strengths. Y. Luo responsible for the optimizer. May need an on-line GUI for this application.

2) **Key point** is how to get correct Jacobian matrix **A**

Off-line calculation, if we are luck

On-line measurement, if we are not luck

3) Need to **verify the technique** to measure **A** on line

High-resolution PLL, BBQ? 245MHz?

10^{-4} is required for 10% change in (k2dl).

First try at injection in ion run, then use it at store in pp run.

3Qx resonance correction at Rhic store

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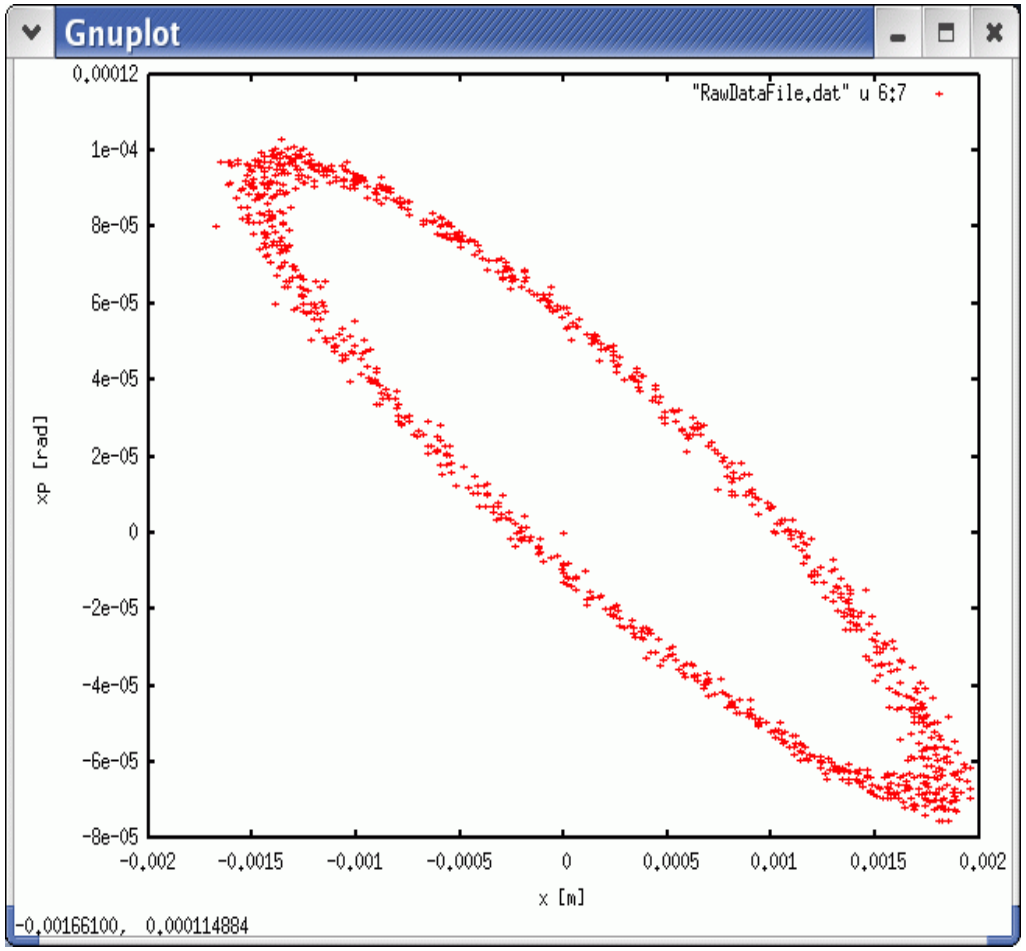
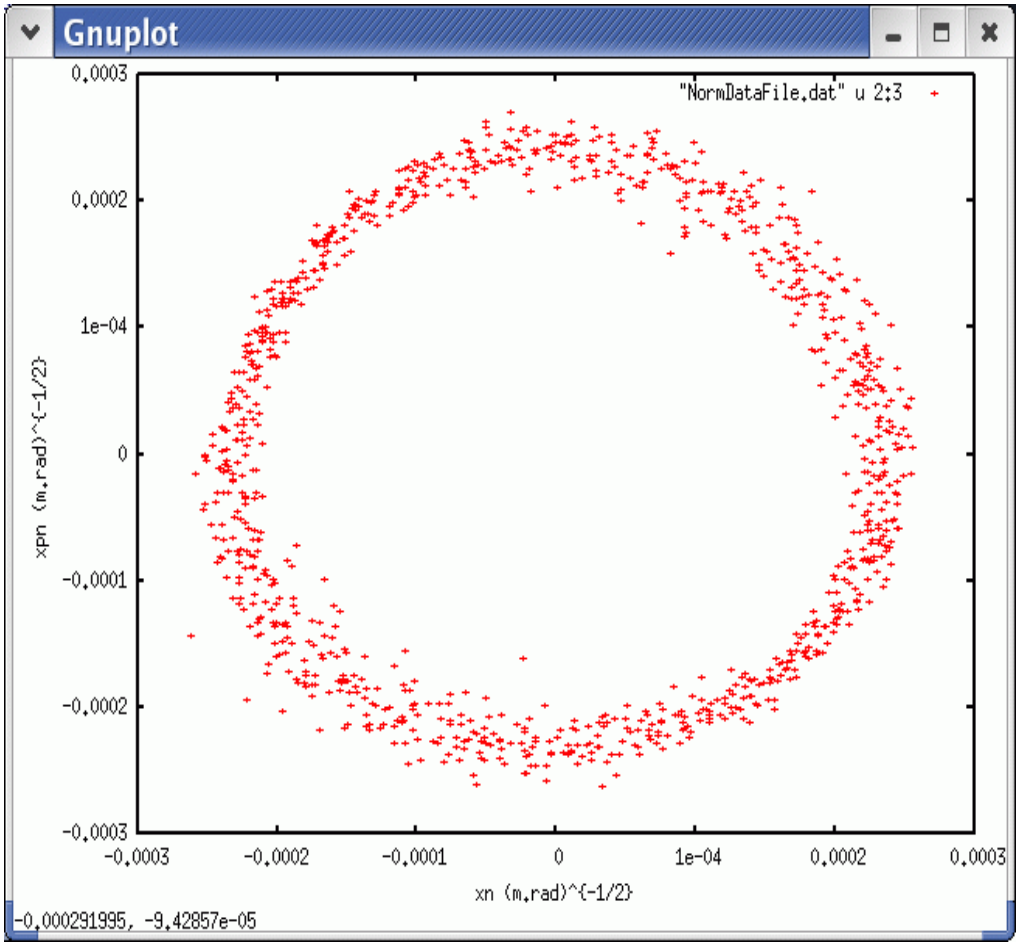
1. Analysis of BPM data taken from last run
2. Off-line measurement/correction simulations
3. Discussions

Analysis of BPM data taken from last run

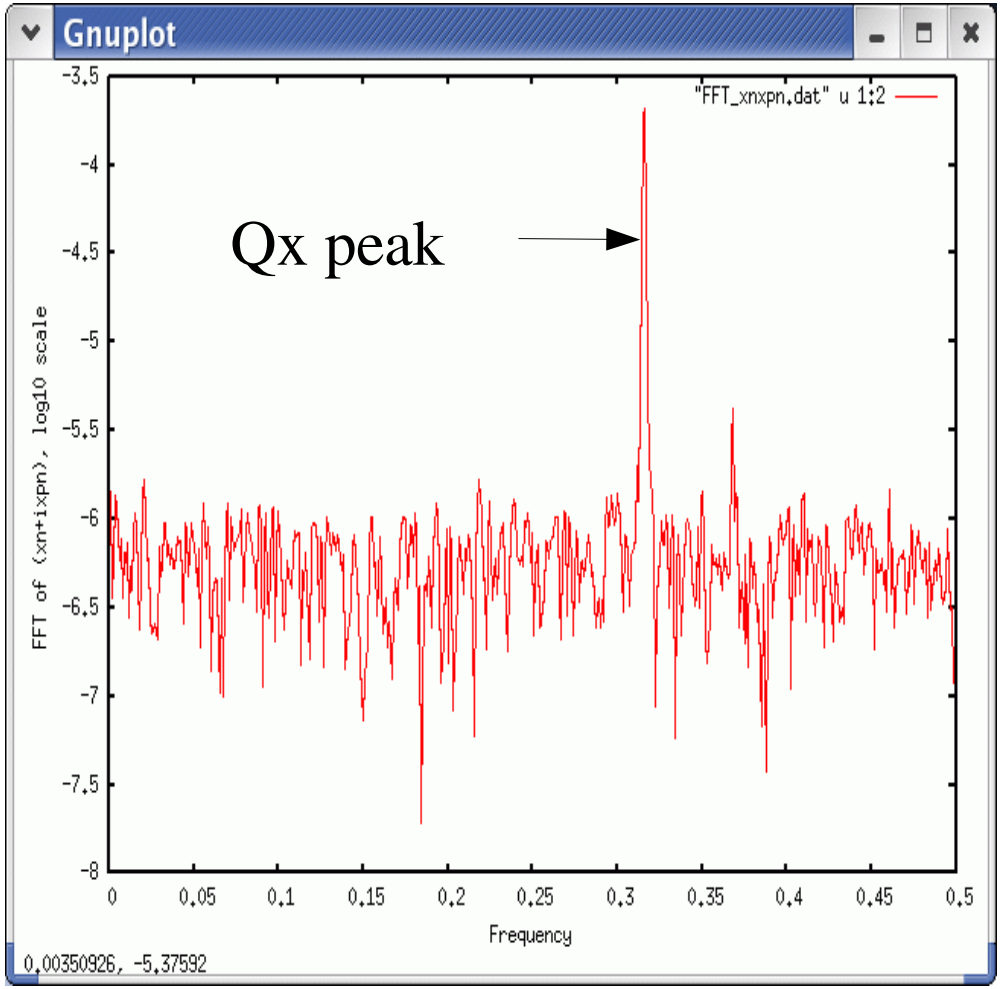
1) The procedure of BPM TBT data analysis



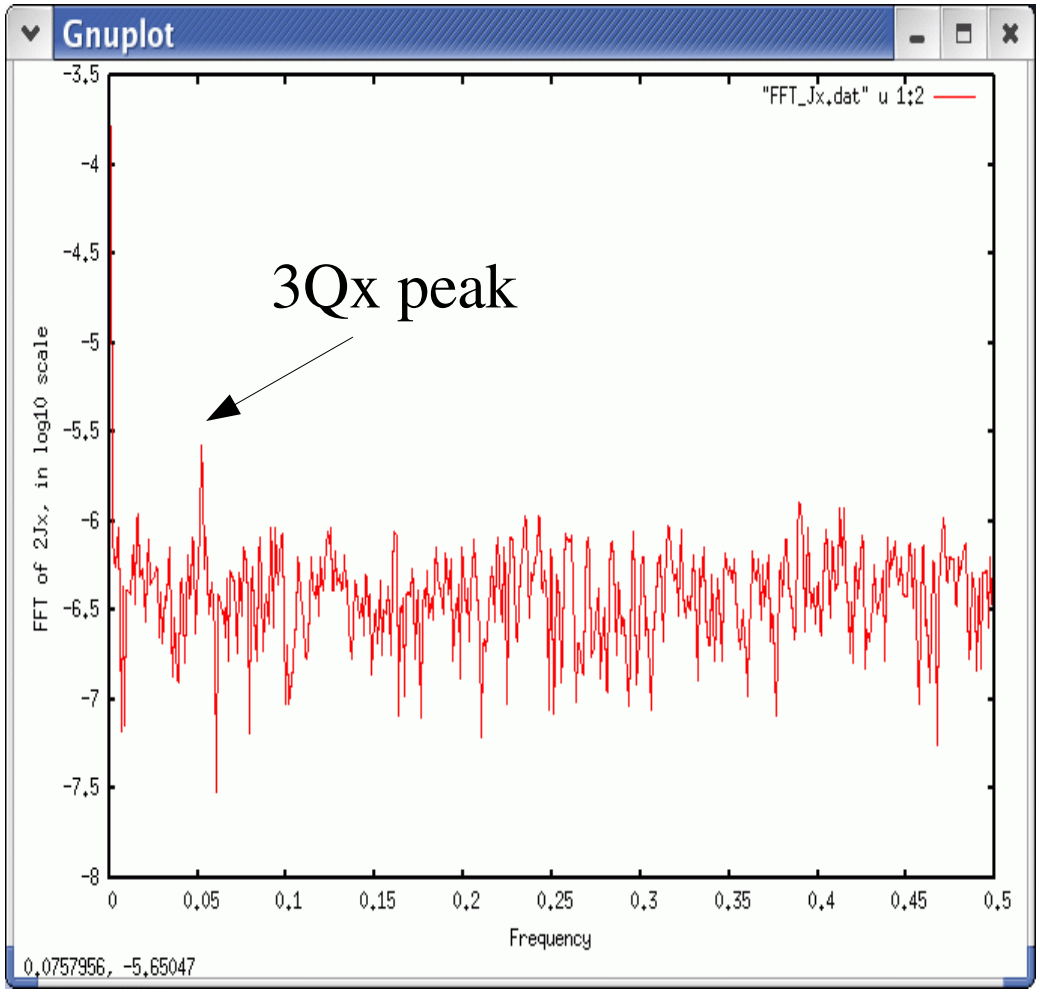


From real space to normalized space

Spectrum analysis:



FFT of xn to get Qx



FFT of (2Jx) to see 3Qx

|h30000| ~(Amp_3Qx)/(Jx0**1.5) Phase~(Phi_3Qx – 3* Phi_xn)

2) Data taken on May_02_2006 (Qx~0.685)

Name	dh3000_c	dh3000_s	Xmax	Qx	X_max	3Qx	Jx(3Qx)	Ratio	Angle
File 10:	0.5	0	skipped.						
File 11:	0.5	0	skipped.						
File 12:	0.5	0	skipped.						
File 13:	1.0	0	0.00168577	0.683998	0.000240667	0.0524408	2.15928e-09	153.08	271.39
File 14:	1.0	0	0.00170533	0.68399	0.000243171	0.052193	1.15666e-09	79.4699	288.717
File 15:	1.0	0	0.00170741	0.684006	0.000244213	0.0517291	7.26476e-10	49.5589	335.636
File 16:	1.5	0	0.00173482	0.684	0.000247567	0.0512418	2.39889e-09	156.484	9.72573
File 17:	1.5	0	0.00171731	0.683999	0.000245438	0.0523234	3.89972e-09	260.844	269.725
File 18:	1.5	0	0.00172885	0.684004	0.000246308	0.0526707	1.86694e-09	124.057	251.04
File 19:	-0.5	0	0.00169614	0.684007	0.000241131	0.0517578	3.85151e-09	272.61	315.553
File 20:	-0.5	0	0.00168085	0.683981	0.000238821	0.0523137	2.30367e-09	167.101	232.606
File 21:	-0.5	0	0.00169376	0.684006	0.000240741	0.0522986	2.61611e-09	185.214	229.231
File 22:	-1.0	0	skipped						
File 23:	-1.0	0	0.00167237	0.683988	0.000237491	0.0522581	2.58645e-09	190.916	237.815
File 24:	-1.0	0	0.00167741	0.684012	0.000237276	0.0522162	2.75053e-09	202.843	267.001
File 25:	-1.5	0	0.00166531	0.684	0.000235945	0.0510611	1.7526e-09	131.904	354.61
File 26:	-1.5	0	0.00165467	0.68399	0.000235179	0.0528024	2.09877e-09	159.332	190.488
File 27:	-1.5	0	0.00165444	0.683978	0.000235771	0.0528373	1.96115e-09	147.498	190.267
File 28:	0	0.5	0.0016515	0.683998	0.000232777	0.0528867	1.16589e-09	91.2411	234.668
File 29:	0	0.5	0.00165183	0.683998	0.000234156	0.0527743	2.45371e-09	188.632	218.98
File 30:	0	0.5	0.00165072	0.683993	0.000234061	0.0526043	2.4634e-09	189.762	222.958
File 31:	0	1.0	0.0015081	0.684004	0.000215208	0.0518888	5.12732e-10	51.0786	241.192
File 32:	0	1.0	0.00151783	0.683997	0.000216404	0.0513623	2.12984e-09	207.983	4.14186
File 33:	0	1.0	0.00153884	0.68401	0.000219182	0.0515484	2.26277e-09	212.422	321.396
File 34:	0	1.5	skipped.						
File 35:	0	1.5	skipped.						
File 36:	0	1.5	skipped.						
File 37:	0	-0.5	0.00152873	0.683994	0.000218074	0.0517068	1.50567e-09	143.496	254.394
File 38:	0	-0.5	0.00153201	0.684007	0.000216677	0.051546	2.00273e-09	194.483	299.453
File 39:	0	-0.5	skipped.						
File 40:	0	-1.0	skipped.						
File 41:	0	-1.0	skipped.						
File 42:	0	-1.0	skipped.						
File 43:	0	-1.5	skipped.						
File 44:	0	-1.5	skipped.						
File 45:	0	-1.5	0.00166979	0.684009	0.000239965	0.0519994	3.53127e-09	254.15	304.63

3) Data taken on Apr_14_2006

Name	dh3000_c	dh3000_s	Xmax	Qx	X_max	3Qx	Jx(3Qx)	Ratio	Angle
File 36:	0	0	0.00297153	0.690996	0.000436717	0.0735941	3.78208e-09	44.7863	223.069
File 37:			0.00369441	0.690979	0.000544897	0.0730962	2.12182e-09	13.0116	36.4479
File 38:	1.0	0	0.00217099	0.694995	0.000316798	0.0863564	1.82412e-10	5.63835	311.155
File 39:			0.00213692	0.694996	0.000313068	0.0875477	1.45221e-09	46.6502	289.231
File 40:	1.5	0	0.00201574	0.694995	0.000294823	0.0867692	1.23558e-09	48.0329	320.181
File 41:			0.00227617	0.694996	0.000332586	0.0848703	2.59348e-09	70.2017	329.087
File 42:			0.0026511	0.695005	0.000386518	0.0839577	9.48823e-10	16.2839	112.232
File 43:			0.00268548	0.69501	0.00039301	0.0844263	6.61329e-10	10.8391	345.477
File 44:	2.0	0	0.00275631	0.695002	0.000402429	0.0843821	2.23883e-09	34.1825	14.5944
File 45:			0.00272771	0.695	0.000399282	0.0852021	4.16256e-09	65.067	317.716
File 46:			0.0019377	0.69499	0.000282477	0.0798877	9.90152e-10	43.4268	19.9144
File 47:			0.0019167	0.695008	0.000279895	0.0851938	1.4357e-09	65.0528	226.066
File 48:	2.5	0	0.0019167	0.695008	0.000279895	0.0851938	1.4357e-09	65.0528	226.066
File 49:			0.00193978	0.694997	0.00028243	0.0865211	7.11376e-10	31.3183	259.351
File 50:			0.00192259	0.694996	0.000279799	0.0861069	5.76207e-10	25.9756	211.555
File 51:			0.00255773	0.694994	0.000372471	0.0862871	9.62148e-10	18.4099	127.141
File 52:			0.00252855	0.695002	0.000368044	0.0843297	1.78573e-09	35.6671	38.1786
File 53:	0	0	0.00185141	0.695004	0.000270656	0.0858297	5.37618e-10	26.977	127.151
File 54:			0.00185109	0.694998	0.000269784	0.0893451	8.75099e-10	44.1883	350.417
File 55:			0.00249893	0.695	0.000364506	0.0867348	1.51041e-09	31.0485	332.856
File 56:			0.00249888	0.694989	0.000363592	0.0861624	1.1165e-09	22.9554	217.438
File 57:	-1.0	0	0.0018403	0.694997	0.000268212	0.0863205	8.14352e-10	41.9468	232.701
File 58:			0.00182312	0.695	0.000265581	0.0845138	5.28351e-10	28.0239	32.6315
File 59:			0.00238655	0.69501	0.000347973	0.084888	1.84132e-09	43.4643	233.543
File 60:			0.00242989	0.695003	0.000354079	0.08065	1.2548e-09	28.0828	80.231

Data taken on Apr_14_2006

File 61:	-2.0	0	0.0018194	0.695014	0.000264983	0.0865007	9.1358e-10	48.354	152.669
File 62:			0.00183538	0.694991	0.000267696	0.0844475	2.14319e-10	11.0931	52.1006
File 63:			0.00227271	0.694999	0.000331935	0.0859032	8.21327e-10	22.3121	279.919
File 64:			0.00226636	0.694994	0.000329652	0.0848188	2.33936e-09	64.575	324.504
File 65:	-3.0	0	0.0016861	0.694997	0.000245782	0.0804818	5.90951e-10	39.5471	60.9275
File 66:			0.0016742	0.69501	0.000244257	0.0803065	1.44092e-10	9.78995	267.352
File 67:			0.00225122	0.69499	0.000328406	0.0881239	7.86685e-10	22.0421	289.74
File 68:			0.00225087	0.695011	0.000328251	0.0855834	8.14864e-10	22.8754	331.544
File 69:	0	0	0.00185584	0.694997	0.000269036	0.0858631	5.2601e-10	26.665	231.953
File 70:			0.00185854	0.695002	0.000270033	0.0868104	6.90737e-10	34.5319	358.654
File 71:			0.00242669	0.694999	0.000352422	0.0844604	9.60407e-11	2.16721	121.296
File 72:			0.00245518	0.694997	0.000357242	0.0854728	2.64359e-09	57.5865	314.194
File 73:	0	1.0	skipped.						
File 74:			skipped.						
File 75:			skipped.						
File 76:			skipped.						
File 77:	0	0	0.00197726	0.69499	0.000290124	0.086538	1.10258e-09	44.8076	153.428
File 78:			0.00194266	0.695004	0.000284058	0.0806221	8.55458e-10	36.6876	97.9655
File 79:			0.00253207	0.695006	0.000370812	0.0849497	1.09811e-09	21.328	211.18
File 80:			0.00256455	0.694999	0.000374652	0.0861782	6.59683e-10	12.3515	239.797
File 81:	0	-0.5	0.00227517	0.695012	0.000333683	0.0862436	1.23887e-09	33.0892	174.19
File 82:			0.00225841	0.695008	0.000331632	0.0851582	7.83791e-10	21.3877	202.997
File 83:			0.00291668	0.694993	0.000426264	0.0848501	1.21053e-09	15.4724	220.818
File 84:			0.00293199	0.694993	0.000429487	0.085513	4.80458e-09	60.3486	273.021
File 85:	0	-1.0	0.00266384	0.694999	0.000390186	0.0804906	1.58894e-09	26.4669	148.683
File 86:			0.00255296	0.694993	0.000372934	0.0848751	8.59256e-10	16.3855	163.9
File 87:			0.00336119	0.694999	0.000491418	0.0856577	3.80268e-09	31.7853	192.459
File 88:			0.0033636	0.694993	0.000491593	0.0862454	1.60483e-09	13.3744	206.565
File 89:	0	0.5	0.0031163	0.694986	0.000454578	0.0849323	2.0737e-09	21.8904	10.4519
File 90:			0.0029821	0.694988	0.000433675	0.0867069	2.68923e-09	32.6899	252.002
File 91:			0.00372102	0.694985	0.000541045	0.0854724	1.49992e-09	9.37661	307.966
File 92:			0.0037418	0.695003	0.000542079	0.0844825	6.30632e-09	39.0202	305.196

4) Summary of AC dipole TBT data analysis

- We saw **not small fluctuations** in the h30000 amplitude and phase even under the same machine condition, which might due to the invalid AC dipole BPM TBT data.

- Measurement of 3Qx driving term with AC dipole was **not fully verified** in last run.

- According to M. Bai: **malfunction of AC dipole** low-level signal generator (software) which affected the shaking frequency and amplitude.

- Off-line simulation is needed to guide the beam experiments.

Off-line measurement/correction simulations(not completed)

1) 'Measurements' with different oscillation amplitudes

```
==========================================================================================
Amplitude Ratio and h30000 Phase versus oscillation amplitude:
Code:  RHIC_3Qx_sim.cc
Input: rhic_blue_2family.lat
Beam parameters:  (28.685, 29.695), (1.0, 1.0), (0.9,0.9,5,5,5,5), Amp at IP6, no IR nonlinear
==========================================================================================

          Amp      [        xn_Qx_amp_phase        ]  [      2Jx_3Qx_amp_phase          ] [ |h30000|- phi   ]
Case  1:  0.1mm    0.684994  0.000106955   -109.092  0.0549812  1.40945e-10   36.0557     115.068  363.331
Case  2:  0.2mm    0.684976  0.000212957   -108.832  0.0549286  1.20532e-09   56.688      124.613  383.185
Case  3:  0.3mm    0.684944  0.000317923   -108.549  0.0548329  4.38552e-09   65.9154     136.165  391.563
Case  4:  0.4mm    0.684906  0.000422209   -108.308  0.0547188  1.00982e-08   71.7978     133.751  396.723
Case  5:  0.5mm    0.684782  0.000627825   -107.785  0.054346   2.98993e-08   74.1193     120.216  397.474
Case  6:  0.8mm    0.684518  0.000932068   -106.914  0.0535531  1.08267e-07   77.7578     132.705  398.499
Case  7:  1.0mm    0.684407  0.00103166    -106.65   0.0532218  1.41467e-07   74.8079     127.542  394.757

Annalytical calulation:

h_30000: A =   7.69, phi =   45.9, c =   5.34, s =   5.52
h3000_phi = 405.950 ( or 45.950 )
```

The simulated measurement results repeat very well, disregarding oscillation amplitude changes. At injection, with 2mm amplitude at Q3(betx=48), we can see the 3Qx peak.

2) 'Measurements' with slightly shifted oscillation frequencies

```
==========================================================================================
Amplitude Ratio and h30000 Phase versus driving freq
Code:  RHIC_3Qx_sim.cc
Input: rhic_blue_2family.lat
Beam parameters:  (28.685, 29.695), (1,1) , (0.9,0.9,5,5,5,5),    Amp=0.5mm,  no IR nonlinear
==========================================================================================

           Tune      [        xn_Qx_amp_phase        ]  [       2Jx_3Qx_amp_phase         ] [ |h30000|- phi   ]
Case  1:   28.681    0.680827  0.000517174   -108.252   0.0424799  2.01102e-08   64.0764    144.692  388.834
Case  2:   28.683    0.682842  0.000521434   -108.181   0.0485274  1.82789e-08   72.4528    128.342  396.995
Case  3:   28.684    0.683849  0.000523513   -108.123   0.0515467  1.83308e-08   75.0975    127.201  399.468
Case  4:   28.685    0.684855  0.000525556   -108.057   0.0545637  1.84987e-08   75.9319    126.905  400.104  <--
Case  5:   28.686    0.68586   0.000527562   -107.985   0.0575787  1.84709e-08   75.3966    125.315  399.351
Case  6:   28.687    0.686864  0.000529529   -107.907   0.0605921  1.81081e-08   74.1796    121.534  397.901
Case  7:   28.689    0.688165  0.000179892    22.2291   0.0666145  1.64626e-08   72.1431    108.215  5.45577
```

If the shaking frequency is not too far from Qx (less than 0.002), the simulated measurement results are acceptable. In beam experiments, we kicked beam with frequency Qx+/- 0.001.

3) 'Measurements' with different chromaticity settings.

```
==========================================================================================
Amplitude Ratio and h30000 Phase versus chromaticity settings:
Code:  RHIC_3Qx_sim.cc
Input: rhic_blue_2family.lat
Beam parameters:  (28.685, 29.695), (0.9,0.9,5,5,5,5),  Amp=0.5mm, no IR nonlinear
==========================================================================================

            Chrom       [        xn_Qx_amp_phase       ]  [      2Jx_3Qx_amp_phase        ] [ |h30000|- phi   ]
Case  0:    0.5       0.684856  0.000525621   -108.065   0.0545689  1.84382e-08   75.8682   126.448   400.062
Case  1:    1.0       0.684855  0.000525556   -108.057   0.0545637  1.84987e-08   75.9319   126.905   400.104
Case  2:    1.5       0.684853  0.000525492   -108.05    0.0545585  1.85581e-08   75.9906   127.356   400.14
Case  3:    2.0       0.684851  0.000525428   -108.043   0.0545533  1.86166e-08   76.0439   127.801   400.172
Case  4:    2.5       0.684849  0.000525364   -108.035   0.054548   1.86741e-08   76.0919   128.239   400.198
Case  4:    3.0       0.684848  0.0005253     -108.028   0.0545428  1.87308e-08   76.1344   128.671   400.219
```

The simulated measurement results are not sensitive to the chromaticity settings. In the beam experiment, we always used very low chromaticities. Simple change chromaticity will not change h30000 too much.

4) Simulation of correction results with T matrix.

(effects to nonlinear chromaticities, n*ot confirmed yet*)

5) Simulation of 3Qx correction with IR b2 correctors

(*haven't done yet...*)

Discussions

1) **Observables**: Driving term and beam decay

In the last run, both driving term h30000 and beam decay were used as observables to 3Qx resonance correction.

However, I personally like driving term. It is quantized It tells us the relative amplitude and phase of h30000. We really depend on it for correction purpose.

Beam delay lacks direct and clear connection to 3Qx resonance correction. It can be as a final adjustment of our intended h30000 correction.

h30000 driving term measurement with AC dipole MUST be verified in the next run. It is **the key** to 3Qx correction.

2) Driving term's **amplitude and phase**

In the last run, we continuously changed h30000's cosine and sine parts to check the height of 3Qx peak in FFT of Jx. However, we found intolerable fluctuations in the heights.

May we also check the measured h30000's phase to get the minimization direction. **Phase information** is more important.

3) **Separate** nonlinear chromaticity and 3Qx corrections

Chromaticities come from the sextupoles in the dispersion region. If there is no dispersion at one sextupole, it doesn't contribution to chromaticities. However, any sextupole will definitively contribute to the resonance driving terms.

Sextupoles in the dispersion-free region are '**harmonic sextupoles**'. Using harmonic sextupoles for the resonance correction does not affect chromaticity.

Can we use **b2 IR correctors** as semi-'harmonic sextupoles' for 3Qx correction? If YES, then we can split nonlinear chromaticity correction and 3Qx correction. **Simulation** are needed.

4) **Combine** nonlinear chromaticity and 3Qx corrections

If we really have to use arc chromatic sextupoles for 3Qx correction, we have to include the nonlinear chromaticity correction in this correction procedure.

For example, combine h30000 term into nonlinear chromaticity response matrix. Will verify this with **simulations**.

Operationally, we think that first-order sextupole geometric correction should be good enough. And we may only be able to measure 3Qx driving term. To measure other driving terms still is a problem.

5) Plans

Final goal is to do 3Qx correction in the pp run at store.

Can we have beam experiment time in the ion run to verify driving term measurement?

More careful work needed:

- Reliable measurement of h30000. (M. Bai, Y. Luo)
- Correct h30000 driving term. (J. Bengtsson, N. Malisky, Y. Luo)
- Using IR b2 correctors or other sextupoles. (R. Calaga, Y. Luo)
- Simulations concerning 3Qx. (Y. Luo, R. Calaga,...)