1.5 m In-Vacuum Undulators for NSLS-II

Magnetic Field Analysis Report

This document presents the magnetic field measurement results of the 1.5m IVUs before and after *Shimming* adjustments and *Magic Fingers* corrections. IVUs performances such as first and second field integrals, electron orbit deviations and phase errors have been measured at various gap values. Three 1.5m IVUs have been measured at BNL IDs Laboratory: **IVUn1** (S/N: A12008), **IVUn2** (S/N: A12009) and **IVUn3** (S/N: A12010). IVUn3 is installed in the NSLS-II storage ring at sector 5-ID without any in-house correction to provide synchrotron radiation to the beamline SRX (Submicron Resolution X-ray Spectroscopy) and the IVUs n1 and n2 will be installed at sector 17-ID for AMX (Automated Macromolecular Crystallography) and FMX (Frontier Macromolecular Crystallography) beamlines, which share the same straight section.

The photons generated by a single electron add up coherently along the electron trajectory in order to do so the oscillatory motion of the electron has to be in phase with the emitted photons along the whole device. The spectral properties of the synchrotron radiation produced by an ID depend mainly on the quality of the magnetic field. Amplitude and phase of the magnetic field must be within small tolerances over the complete length of the device. The field quality is quantified by the so-called phase error. It is calculated using the Phase Function Φ(z) as defined below:

$$\Phi(z)=\frac{2\pi}{\lambda}\left[\frac{L}{\beta}-(z-z_1)\right]$$

which describes the phase lag between an electron and the front of the emitted wave train directed along the nominal axis z. Where L is defined as follows:

$$L=\int_{z_1}^{z}\sqrt{1+X'^2}\,dz \qquad X'=-\frac{e}{\gamma m_0 c}\int_{-\infty}^{z}B_y(z)dz\,; \qquad \beta=\sqrt{1-\frac{1}{\gamma^2}}$$

where By is the vertical magnetic field, λ is the radiation wavelength, m0 is the electron rest mass, e is the electron charge, c is the speed of light, γ is the Lorentz factor and λu is the undulator period. So the phase error is obtained by sampling the phase function at λu/4 and subtracting the linear fit of Φ(z).

All devices underwent rigorous magnetic tuning before they are installed in the storage ring in order to optimize the magnetic field and consequently the phase error. The *Shimming* technique is a very effective way to correct field deviations and small magnetic errors, which can cause unwanted destructive interferences and degradation of the radiation quality.
Magic Fingers is an other corrective technique used. It consists of small cylindrical permanent magnet blocks located at the ends of the device. The best arrangement of the *Magic Fingers* is used to reduce the residual field integral errors and the random error distributions such as those arising from the magnetic imperfections of the magnet blocks but also of their dimensional and positioning errors.

IVUn1

IVUn1 - Shimming and Magic Fingers @ gap 6.2 mm

Figure 1 shows the horizontal (blue line) and vertical (green line) electron trajectory before and after the *Magic Fingers* correction. The electron trajectory is calculated from the magnetic field measurement at gap 6.2 mm. The first field integral describes the deflection angle of the electron beam and the second field integral the displacement respect to the magnetic undulator axis. It is calculated at 900 mm from the centre of the device. After the *Magic Fingers* the horizontal first field integral Ix is reduced to 4 G cm, before it was 58 G cm and the vertical component Iy is reduced to 10 G cm, before it was 258 G cm. As shown in the Fig. 1 the maximum horizontal and vertical displacements are just of few micron after the *Magic Fingers*.

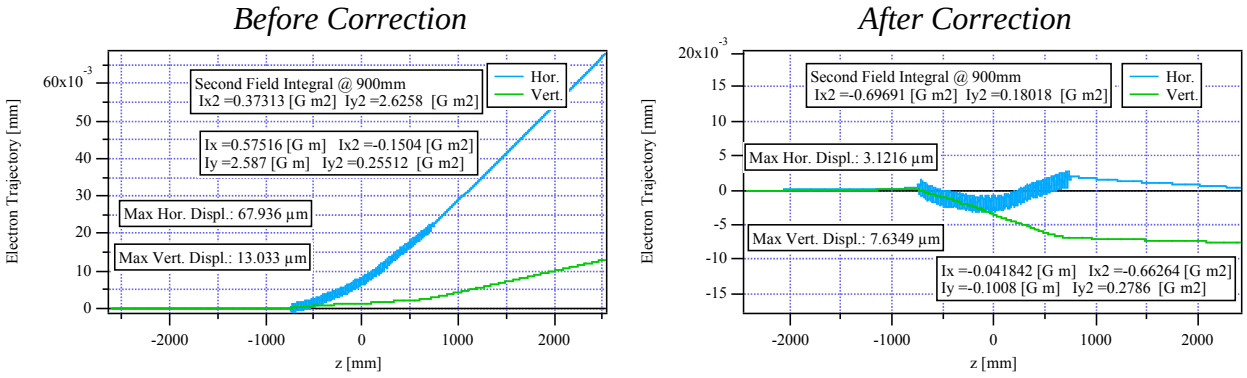

Figure 1: Electron Orbit

Figure 2 shows the phase error (red line) before and after the *Shimming*. The residual phase error after the parabolic fit (blue line) is shown at top of the graph (green line). It describes the phase error values when the taper of the device is removed.

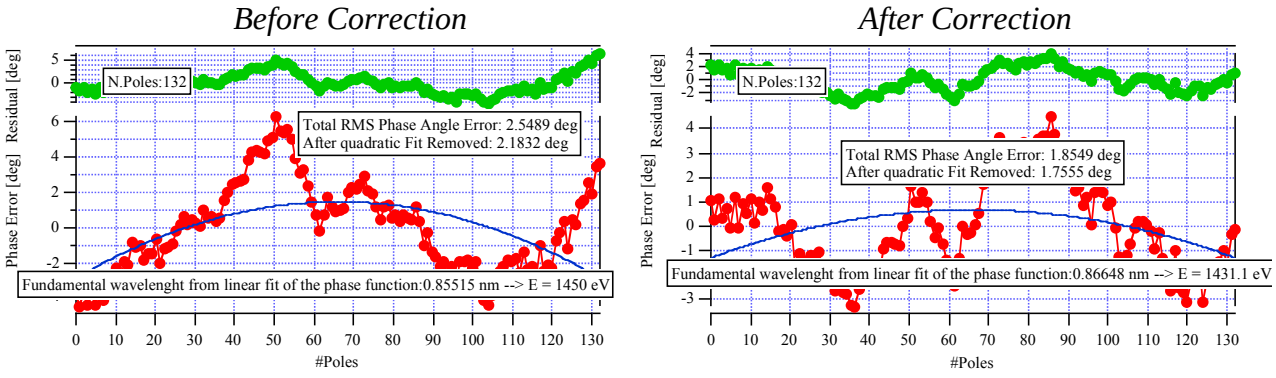

Figure 2: Phase Error

The RMS phase error is the figure of merit of the undulator spectral performance. As shown in the Fig. 2 it is about 1.85° at gap 6.2 mm after *Shimming* and 2.5° before the correction.

IVUn1 - Shimming and Magic Fingers @ gap 5.7 mm

The figures below show the magnetic field results at minimum gap 5.7 mm. As shown in the Fig. 3 (Left) the amplitude of the vertical magnetic field is 1.1388 T. It is defined as the average of the absolute values of the magnetic field peaks in the periodic part of the device, omitting 4 end-peaks at each end of the undulator. Figure 3 (Right) shows the vertical peaks distribution. The magnetic field variation is of about 1.5%, the absolute residual field error is 36 G with a residual taper of 3.8 G/m.

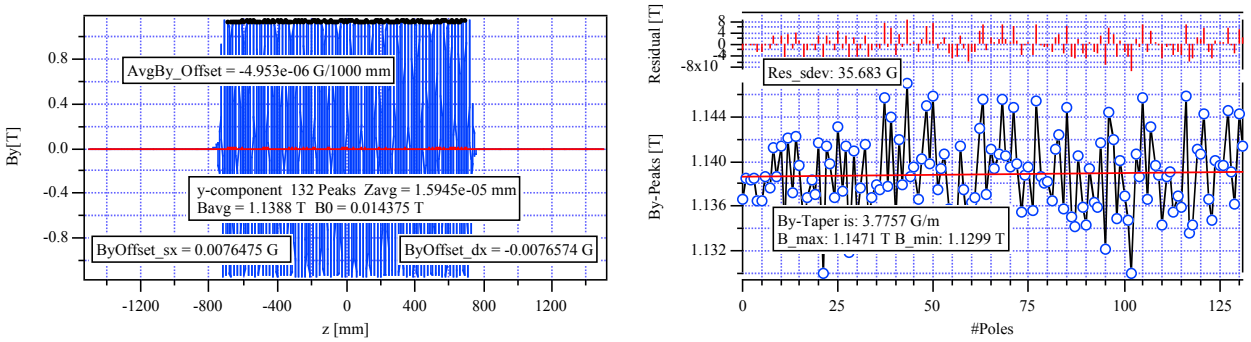

Figure 3: [Left] Vert. (blue line) and Hor. (red line) magnetic field. [Right] Vertical peak distribution

The Fig. 4 shows the period length distribution and the averaged electron angles. The period length of the device is 20.987 mm with a relative error of about 1.4%. The angular deviation is confined around +/- 5 µrad in the period part of the device, excluding the terminations.

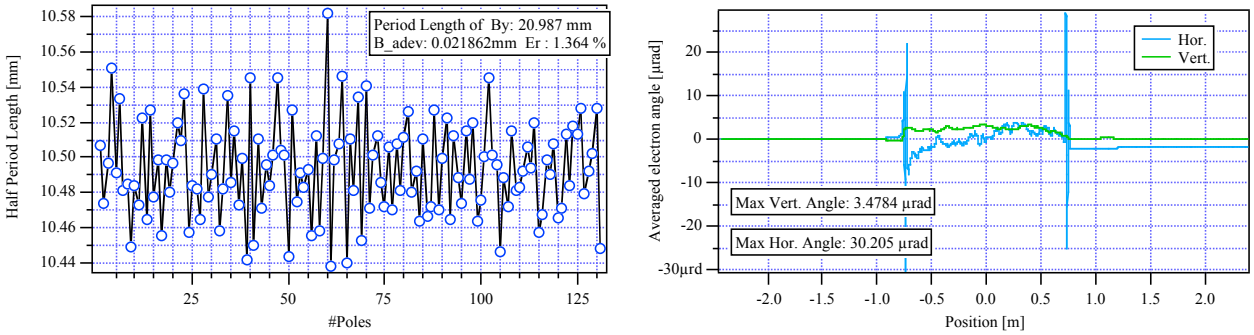

Figure 4: [Left] Half Period length . [Right] Averaged Electron Angle

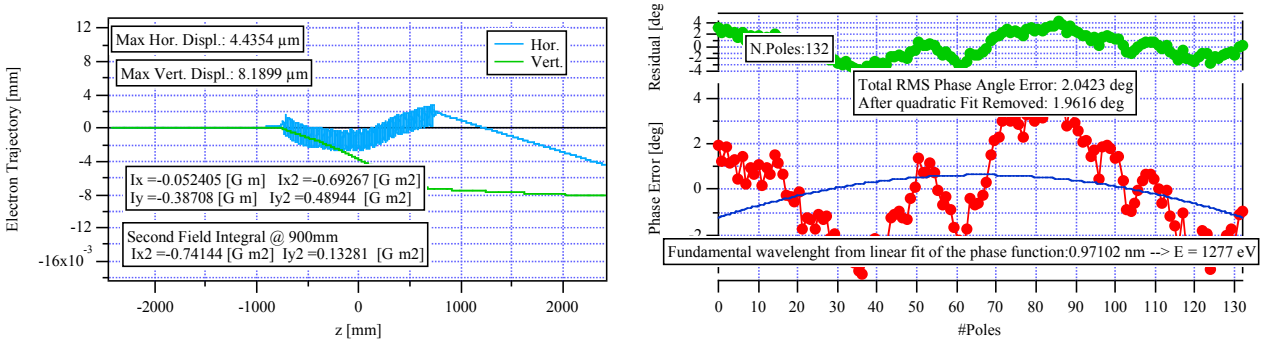

Figure 5: [Left] Electron Trajectory . [Right] Phase Error

The Fig. 5 shows the electron trajectory and the phase error at gap 5.7 mm. The RMS phase error is 2.0° and there is not a significant change after the taper correction, it is just of 0.04°.

IVUn1 - Final measurements after Shimming and Magic Fingers for each gap

The table below shows the final measurements at various gap values after *Shimming* and *Magic Fingers*. From these results, we can conclude that the methods applied so far to correct the magnetic field are effective not only at the gap of optimization but also at larger gap values.

Table 1: IVUn1 - Final magnetic measurements

File Name	B [T]	Gap [mm]	K	Energy H-1 [eV]	Iy[Gm]	I2y[Gm2]	Ix[Gm]	I2x[Gm2]	Phase Error [deg]	MaxAngX[µrad]	MaxAngY[µrad]	MaxDispX[µm]	MaxDispY[µm]
X0_Y0_gap5.7.txt	1.13885	5.7	2.12737	1309.93	-0.387111	0.132814	-0.0524047	-0.741444	2.04226	30.2047	3.47839	4.43545	8.18985
X0_Y0_gap6.0.txt	1.07602	6	2.01001	1415.23	-0.193669	0.154449	-0.0273059	-0.69483	1.90596	28.9444	3.30107	3.02483	7.49876
X0_Y0_gap6.2.txt	1.03622	6.2	1.93565	1487.48	-0.100804	0.180183	-0.0418418	-0.696909	1.85488	28.2058	3.2788	3.12164	7.63495
X0_Y0_gap6.7.txt	0.94303	6.7	1.76158	1675.08	0.00666451	0.244884	-0.0456253	-0.603733	1.7085	26.4627	2.88123	3.13308	6.67174
X0_Y0_gap7.0.txt	0.891174	7	1.66471	1791.6	0.0230145	0.174717	-0.125884	-0.686512	1.68124	25.5488	3.12839	3.24495	8.76029
X0_Y0_gap7.2.txt	0.858495	7.2	1.60367	1869.79	0.0757906	0.153549	-0.154005	-0.684584	1.6481	24.9346	2.99268	3.42748	9.12982
X0_Y0_gap7.7.txt	0.783027	7.7	1.4627	2065.04	-0.0435143	0.0413283	-0.101922	-0.5927	1.60323	23.3278	2.70757	3.24601	7.34217
X0_Y0_gap8.0.txt	0.741684	8	1.38546	2180.93	-0.0982467	-0.0096016	-0.069983	-0.516434	1.57434	22.4481	2.41019	3.22987	6.16802
X0_Y0_gap8.2.txt	0.715697	8.2	1.33692	2257.03	-0.129741	-0.0856863	-0.0909619	-0.595127	1.4979	21.9959	2.58403	3.58027	7.39272
X0_Y0_gap8.7.txt	0.655558	8.7	1.22458	2442.62	-0.164565	-0.17979	-0.192294	-0.726023	1.37523	20.7788	2.87866	4.22491	10.3342
X0_Y0_gap9.0.txt	0.622537	9	1.1629	2549.93	-0.19027	-0.182238	-0.200612	-0.602055	1.27853	19.9671	2.52597	4.60672	9.02532
X0_Y0_gap9.2.txt	0.601587	9.2	1.12376	2619.86	-0.212443	-0.228577	-0.0540885	-0.461545	1.41344	19.5904	2.09233	5.27823	5.48166
X0_Y0_gap9.7.txt	0.552979	9.7	1.03296	2787.14	-0.178927	-0.232352	-0.140252	-0.534599	1.23009	18.406	2.2514	4.97562	7.47857
X0_Y0_gap10.0.txt	0.526088	10	0.982732	2882.29	-0.207873	-0.23172	-0.0999874	-0.437957	1.29164	17.8465	2.06421	5.28115	5.84539
X0_Y0_gap11.2.txt	0.432484	11.2	0.80788	3222.49	-0.264062	-0.256738	-0.0691675	-0.428784	1.09864	15.6238	1.99034	6.33451	5.39704
X0_Y0_gap12.2.txt	0.36882	12.2	0.688955	3454.29	-0.261552	-0.287206	-0.161949	-0.386995	0.891253	14.0563	1.78806	6.80033	6.12497
X0_Y0_gap13.2.txt	0.315339	13.2	0.589053	3642.21	-0.193451	-0.209625	-0.109745	-0.326933	0.741005	12.6151	1.66665	4.95947	4.89587
X0_Y0_gap14.2.txt	0.270125	14.2	0.504593	3791.43	-0.203007	-0.194291	-0.146259	-0.333435	0.681911	11.5059	1.66346	4.88635	5.54231
X0_Y0_gap15.2.txt	0.23166	15.2	0.432742	3908.17	-0.163673	-0.115012	-0.168958	-0.322441	0.529073	10.2128	1.52755	3.45184	5.79685
X0_Y0_gap20.0.txt	0.111983	20	0.209185	4182.59	-0.131503	-0.0173821	-0.129235	-0.166104	0.408049	6.47867	1.12632	2.20561	3.54846
X0_Y0_gap30.0.txt	0.0249675	30	0.0466392	4269.46	-0.0269446	0.198022	-0.0989719	-0.073862	0.582617	3.28103	0.684373	2.00354	2.21896
X0_Y0_gap40.0.txt	0.00535104	40	0.00999575	4273.89	0.094852	0.314018	0.0389792	0.122516	0.652596	2.79845	0.73159	4.74196	1.77223

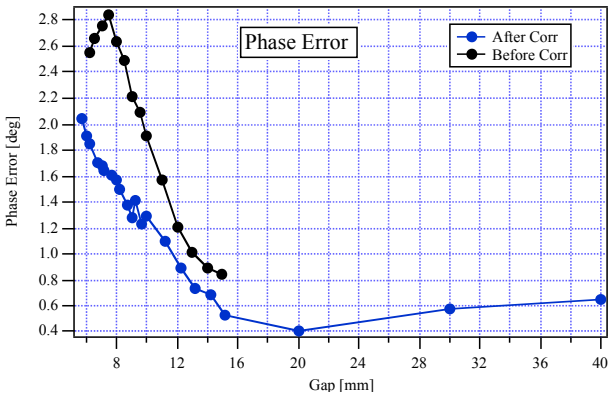

Figure 6: Phase Error before and after corrections

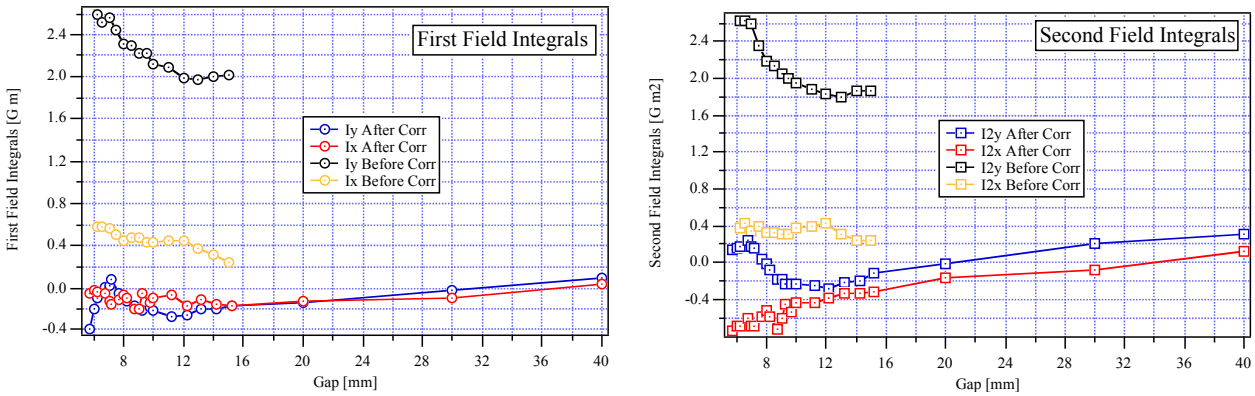

Figure 7: [Left] First Field integrals versus gap. [Right] Second Field Integrals versus gap

From Fig. 6 and Fig. 7 is evident a significant improvement of the magnetic field quality in terms of phase error and field integrals.

IVUn2

IVUn2 - Peak field distribution before and after Shimming

The IVUn2 magnetic field was affected from a strange peak distribution as shown in Fig. 8. It was present both on the upper and lower magnetic girder.

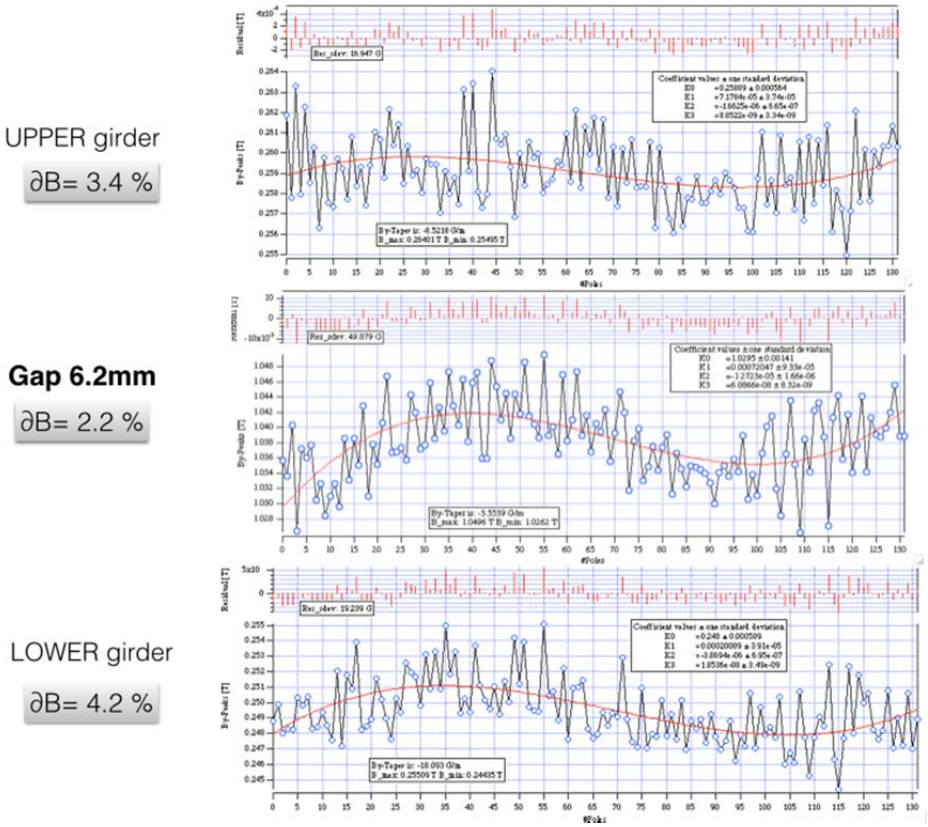

Figure 8: IVUn2 - Peak field distribution before Shimming

After *Shimming* the peak field distribution has been corrected as shown in Fig. 9.

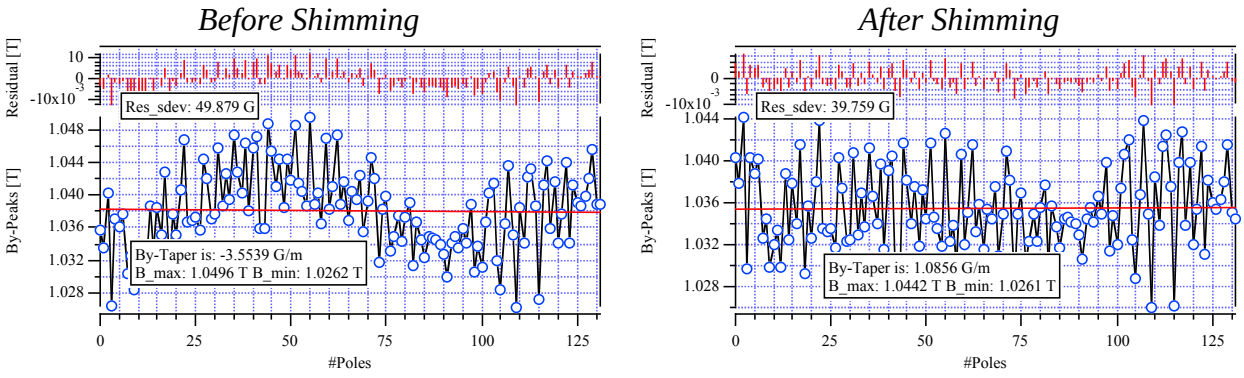

Figure 9: Peak field distribution

IVUn2 - First Field Integrals corrected - Magic Fingers Step by Step

Figure 10 shows the horizontal (red line) and vertical (blue line) of the first field integrals in G cm versus the transverse axis in mm for different *Magic Fingers* configurations.

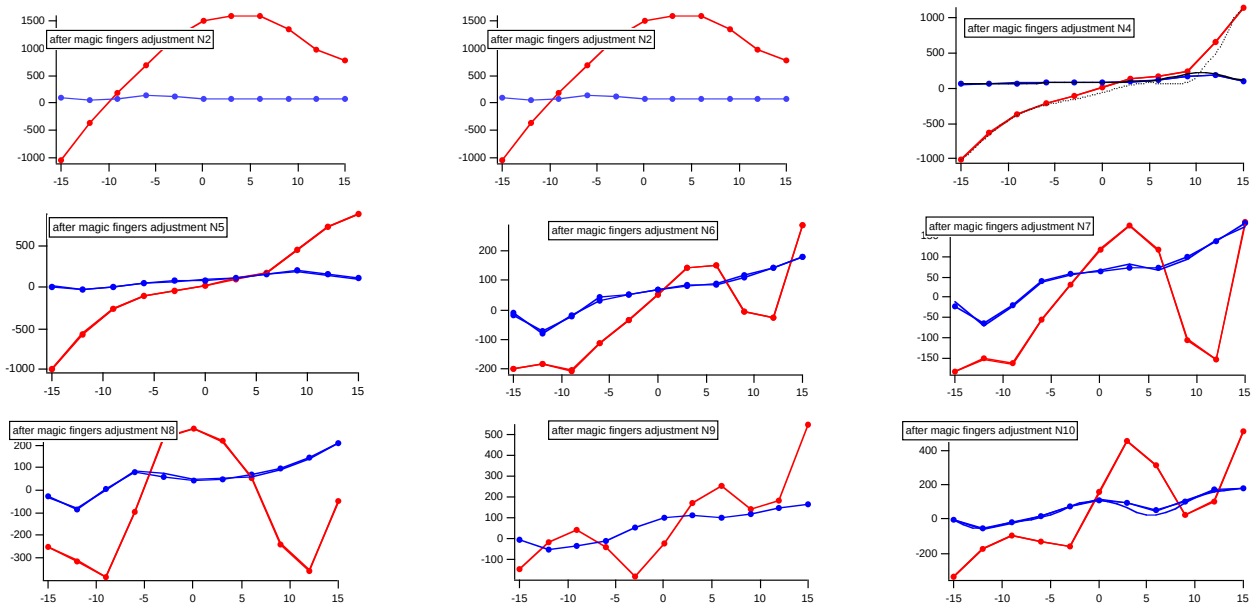

Figure 10: Magic Fingers Step by Step

The final first field integrals of the optimized *Magic Fingers* configuration are shown in Fig. 11.

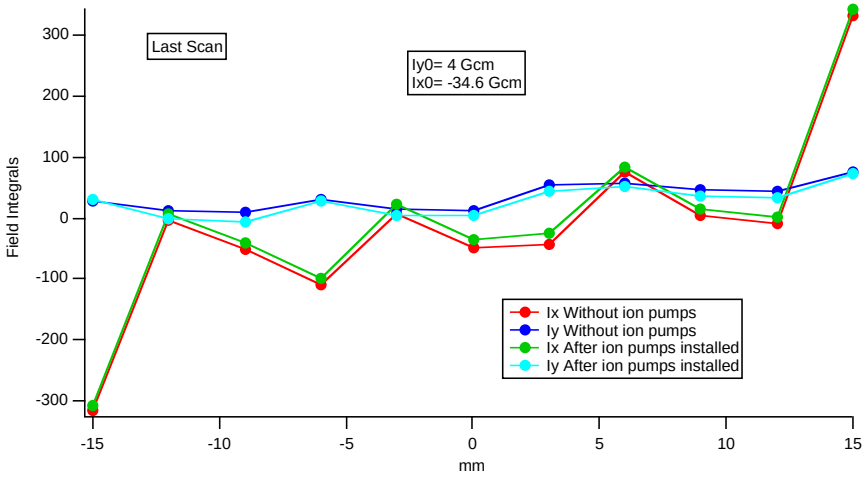

Figure 11: Final Magic Fingers Configuration

The field integral variation without and with the ion pump installed is about 8 G cm on-axis for the vertical component and about 12 G cm for the horizontal component as shown in Fig.11.

IVUn2 - Shimming and Magic Fingers @ gap 6.2 mm

The figures 12 and 13 show the electron trajectory and the phase error at gap 6.2 mm respectively before and after correction.

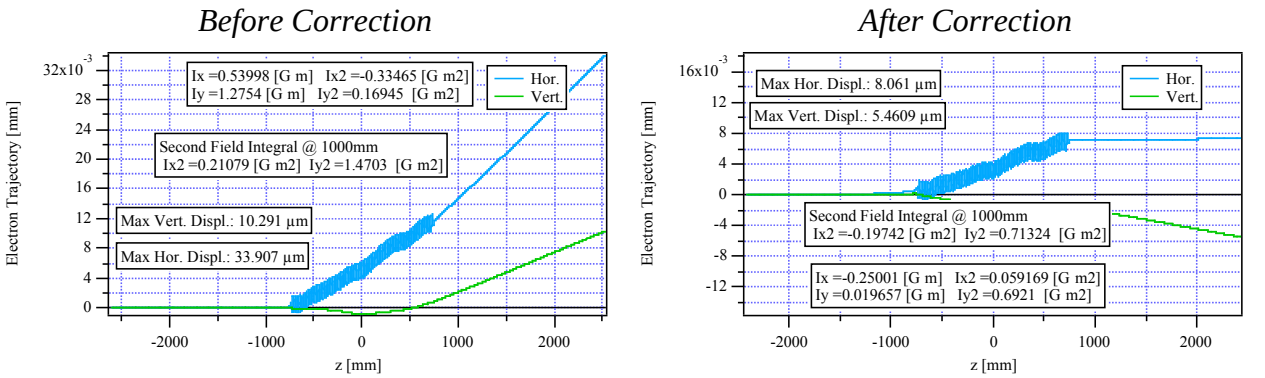

Figure 12 : Electron Orbit

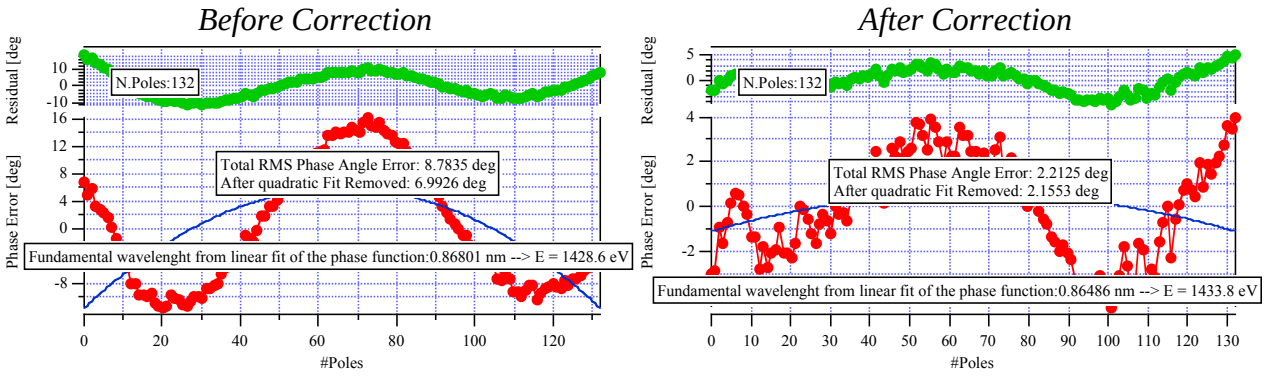

Figure 13: Phase Error

The Phase error after *Shimming* is reduced to 2.2°, previously it was 8.8°.

IVUn2 - Shimming and Magic Fingers @ gap 5.7 mm

The figures below show the magnetic field results at minimum gap 5.7 mm.

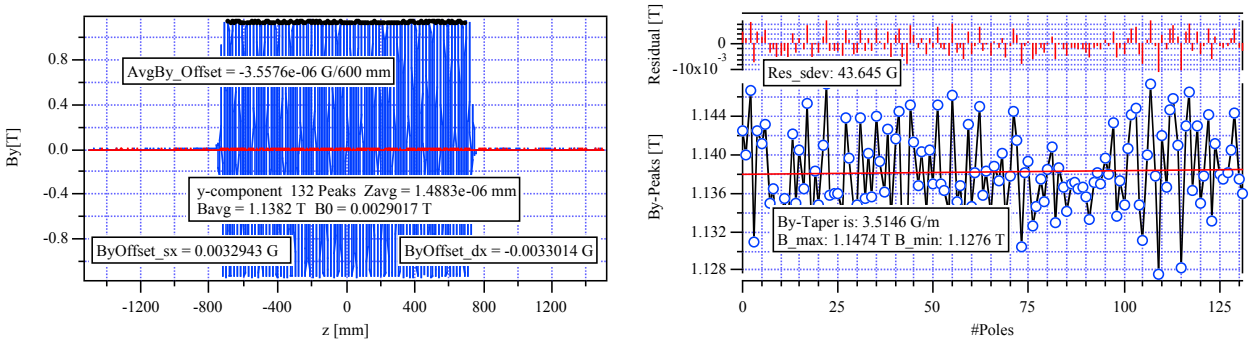

Figure 14: [Left] Vert. (blue line) and Hor. (red line) magnetic field. [Right] Vertical peak distribution

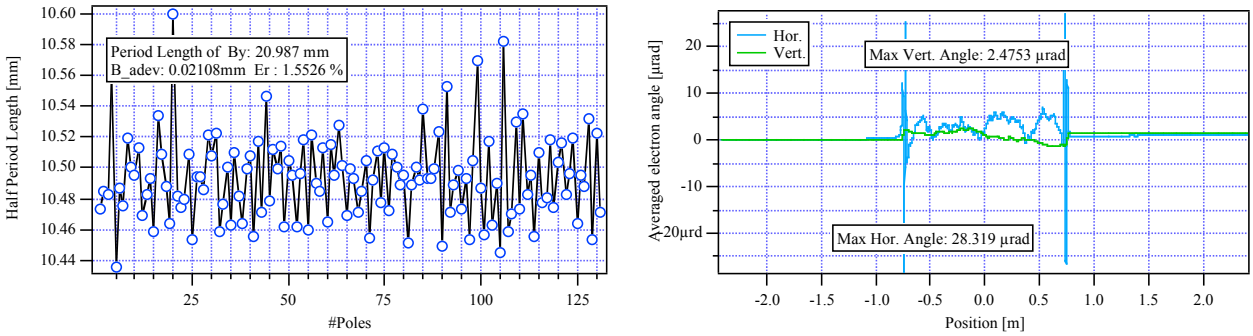

Figure 15: : [Left] Half Period length . [Right] Averaged Electron Angle

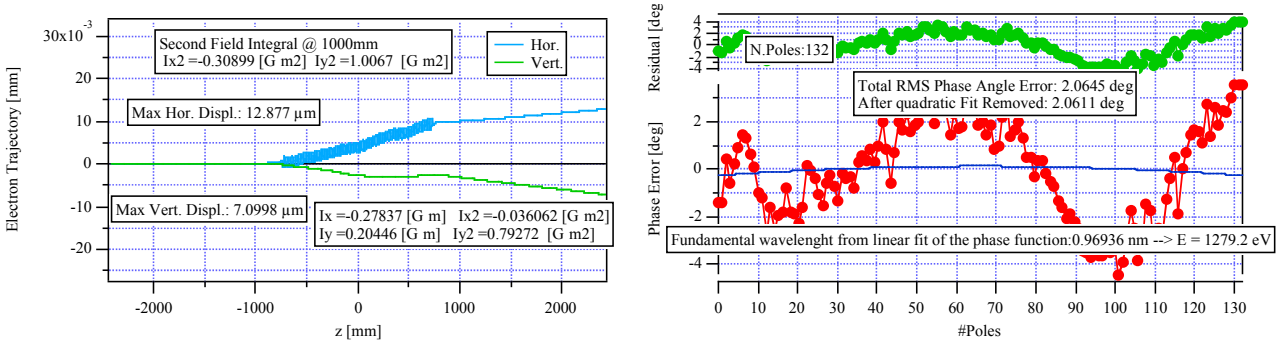

Figure 16: [Left] Electron Trajectory . [Right] Phase Error

IVUn2 - Final measurements after Shimming and Magic Fingers for each gap

Table 2: IVUn2 - Final magnetic measurements

File Name	B [T]	Gap [mm]	K	Energy H-1 [eV]	Iy[Gm]	I2y[Gm2]	Ix[Gm]	I2x[Gm2]	Phase Error [deg]	MaxAngX[µrad]	MaxAngY[µrad]	MaxDispX[µm]	MaxDispY[µm]
X0_Y0_gap5.7.txt	1.13817	5.7	2.23241	1165.74	0.204482	1.00672	-0.278366	-0.308995	2.06452	28.3191	2.47534	12.8771	7.09977
X0_Y0_gap6.0.txt	1.0752	6	2.10889	1262.7	0.101529	0.790487	-0.220973	-0.104917	2.177	27.0976	2.00657	9.22983	4.15845
X0_Y0_gap6.2.txt	1.03554	6.2	2.03111	1329.08	0.0195296	0.713236	-0.250007	-0.197424	2.21251	26.3303	2.08225	8.06099	5.46091
X0_Y0_gap6.7.txt	0.942492	6.7	1.8486	1502.79	-0.100064	0.605028	-0.244109	-0.174286	2.42453	24.5903	1.95694	7.44219	5.29557
X0_Y0_gap7.0.txt	0.89071	7	1.74704	1611.42	-0.147024	0.606497	-0.244697	-0.167273	2.47677	23.6422	1.92304	7.41356	5.07124
X0_Y0_gap7.2.txt	0.858022	7.2	1.68293	1684.76	-0.0203025	0.681927	-0.220996	-0.213912	2.44925	22.9869	1.96336	7.83743	5.25638
X0_Y0_gap7.7.txt	0.782702	7.7	1.53519	1868.6	0.0481204	0.623852	-0.124667	-0.0777642	2.28458	21.7205	1.6826	7.0841	2.57448
X0_Y0_gap8.0.txt	0.741393	8	1.45417	1978.6	0.0827615	0.615829	-0.243131	-0.246501	2.23432	20.9626	2.00994	7.23697	5.96917
X0_Y0_gap8.2.txt	0.715317	8.2	1.40302	2051.46	0.0489123	0.586985	-0.216664	-0.180176	2.15998	20.3316	1.79977	6.59684	4.80969
X0_Y0_gap8.7.txt	0.655337	8.7	1.28538	2229.11	0.11789	0.609012	-0.238982	-0.235367	1.98151	19.1288	1.91373	7.73996	5.63224
X0_Y0_gap9.0.txt	0.622288	9	1.22056	2332.87	0.113738	0.50639	-0.191505	-0.202394	1.87742	18.5979	1.88327	6.54364	4.65941
X0_Y0_gap9.2.txt	0.601361	9.2	1.17951	2400.64	0.196058	0.607932	-0.169992	-0.229823	1.82462	17.9219	1.80901	8.67106	4.81737
X0_Y0_gap9.7.txt	0.552735	9.7	1.08413	2563.86	0.157103	0.540832	-0.242375	-0.253261	1.65541	16.9669	1.86455	7.56666	5.8775
X0_Y0_gap10.0.txt	0.525832	10	1.03137	2657.28	0.238524	0.623377	-0.223335	-0.286006	1.59581	16.185	1.89661	9.50316	5.9444
X0_Y0_gap11.2.txt	0.432354	11.2	0.84802	2994.02	0.16226	0.483241	-0.124544	-0.147646	1.18135	14.2762	1.52594	7.0887	3.19025
X0_Y0_gap12.2.txt	0.368688	12.2	0.723144	3226.85	0.209879	0.533317	-0.0850734	-0.138867	0.921423	12.6751	1.54329	8.22827	2.53726
X0_Y0_gap13.2.txt	0.315176	13.2	0.618186	3417.56	0.364066	0.744935	-0.0999135	-0.20807	0.765814	10.9889	1.69542	12.6235	3.53654
X0_Y0_gap14.2.txt	0.269949	14.2	0.529478	3570.13	0.259484	0.619371	-0.0583393	-0.192657	0.558109	10.0013	1.61871	9.93381	2.84238
X0_Y0_gap15.2.txt	0.231574	15.2	0.454209	3689.94	0.292236	0.609164	-0.0460885	-0.198145	0.450728	9.05582	1.61213	10.2318	2.64935
X0_Y0_gap20.0.txt	0.111951	20	0.219581	3974.75	0.399133	0.736141	-0.0472779	-0.255054	0.31737	5.29001	1.70749	12.8814	3.27276
X0_Y0_gap30.0.txt	0.0249372	30	0.0489118	4065.71	0.338874	0.633884	0.130798	-0.0835985	0.152926	3.43823	1.34932	11.0129	1.22111
X0_Y0_gap40.0.txt	0.00543695	40	0.010664	4070.34	0.48098	0.733855	0.116354	-0.0714588	0.15439	3.20376	1.06616	13.9376	1.01785

IVUn3 (as delivered)

IVUn3- Magnetic Field Analysis @ gap 6.2 mm

The figures below show the magnetic field results at gap 6.2 mm.

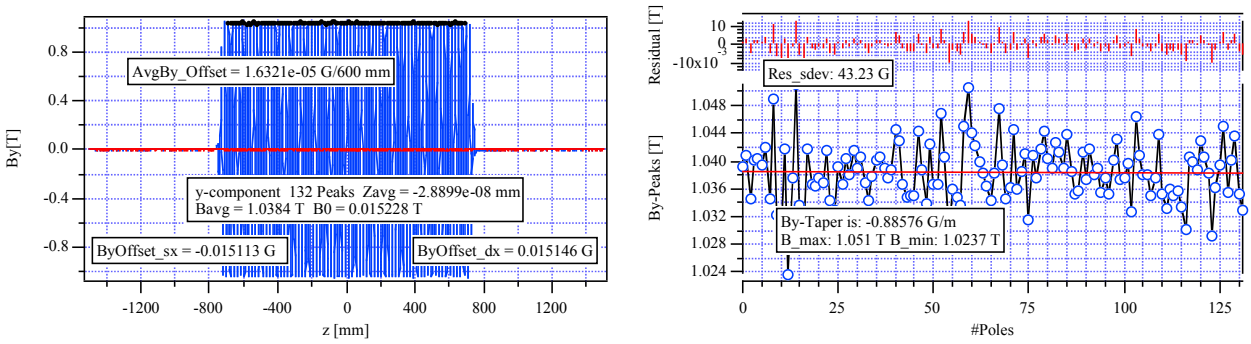

Figure 17: [Left] Vert. (blue line) and Hor. (red line) magnetic field. [Right] Vertical peak distribution

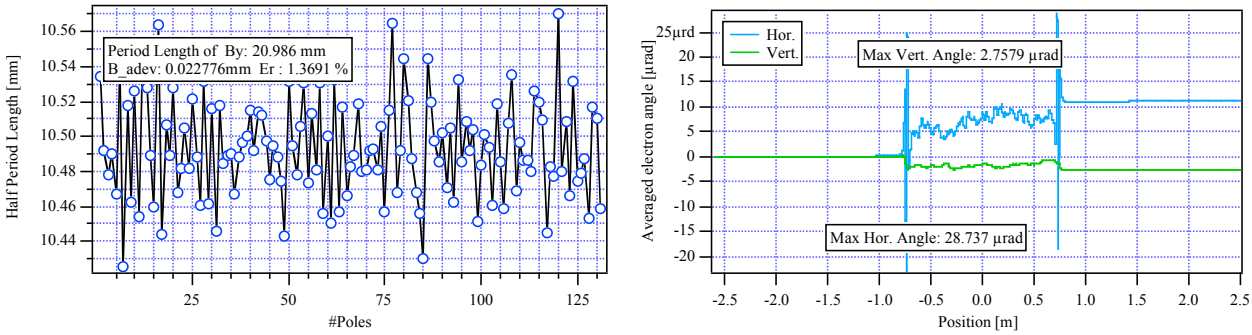

Figure 18: : [Left] Half Period length . [Right] Averaged Electron Angle

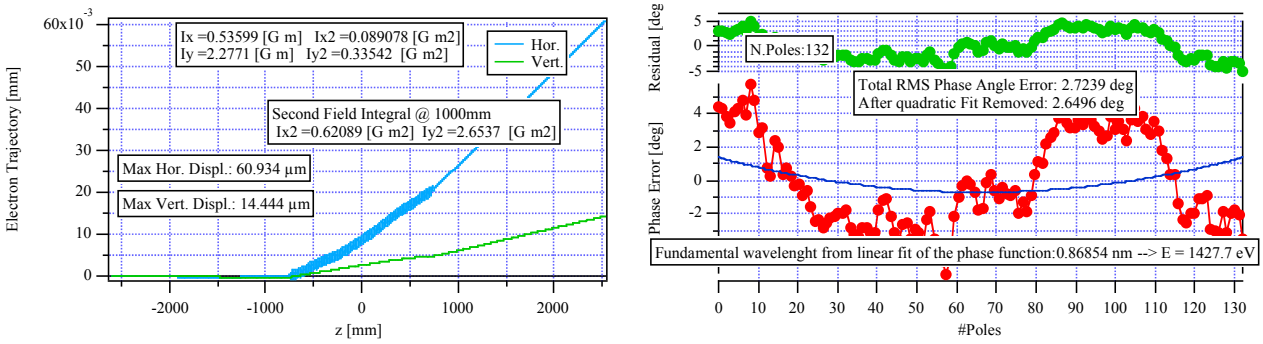

Figure 19: [Left] Electron Trajectory . [Right] Phase Error

IVUn3 - Final measurements for each gap

Table 3: IVUn3- Final magnetic measurements

File Name	B [T]	Gap [mm]	K	Energy H-1 [eV]	Iy[Gm]	I2y[Gm2]	Ix[Gm]	I2x[Gm2]	Phase Error [deg]	MaxAngX[µrad]	MaxAngY[µrad]	MaxDispX[µm]	MaxDispY[µm]
X0.0_Y0.0_gap6.2.txt	1.03843	6.2	1.93979	1483.35	2.2771	2.65369	0.535987	0.620889	2.72387	28.7373	2.75786	60.9337	14.4437
X0.txt_Y0.txt_gap20.txt	0.112292	6.8	0.209761	4182.09	1.91465	2.37003	0.764031	0.833229	2.53199	23.9708	3.84286	52.5705	19.6764
X0.txt_Y0.txt_gap9,5.txt	0.573216	7	1.07077	2716.7	1.77194	2.1548	0.659283	0.725336	2.42521	22.2477	3.31066	48.0617	17.1042
X0.txt_Y0.txt_gap8,5.txt	0.680513	8	1.2712	2364.03	1.50022	1.62215	0.670743	0.732332	2.08585	17.6852	3.37598	38.6667	17.4606
X0.txt_Y0.txt_gap40.txt	0.00539387	8.5	0.0100758	4273.88	1.39491	1.45403	0.625347	0.714087	1.88182	16.4773	3.15062	35.4946	16.6375
X0.txt_Y0.txt_gap14.txt	0.279301	9	0.521735	3762.07	1.32291	1.26868	0.652334	0.665396	1.7206	15.5279	3.28358	32.4399	16.5629
X0.txt_Y0.txt_gap30.txt	0.025006	9.5	0.0467112	4269.44	1.3481	1.23241	0.564761	0.601476	1.5147	14.5651	2.90332	32.4972	14.6612
X0.txt_Y0.txt_gap11.txt	0.447797	10	0.836485	3166.34	1.34882	1.228	0.625219	0.679625	1.39815	13.4963	3.19569	32.4131	16.3463
X0.txt_Y0.txt_gap7.txt	0.893454	11	1.66897	1786.28	1.36527	1.21043	0.623122	0.692165	1.10583	12.5479	3.16317	32.4619	16.3159
X0.txt_Y0.txt_gap6,8.txt	0.927407	13	1.7324	1709.23	1.34897	1.15108	0.437476	0.439286	0.65055	11.3368	2.28147	31.546	11.0656
X0.txt_Y0.txt_gap8.txt	0.743486	14	1.38883	2175.75	1.31662	1.10002	0.46018	0.461202	0.535775	10.7988	2.35948	30.7307	11.6584
X0.txt_Y0.txt_gap9.txt	0.624146	15	1.16591	2544.61	1.31247	1.05276	0.339367	0.282109	0.375636	10.3633	1.73374	30.041	7.88702
X0.txt_Y0.txt_gap10.txt	0.527309	20	0.985013	2877.94	1.2763	1.07313	0.107166	0.102166	0.1192	8.78198	0.771803	29.8032	2.62497
X0.txt_Y0.txt_gap13.txt	0.326089	25	0.609134	3605.25	1.21054	1.03084	0.121692	0.0564154	0.0623021	7.63142	0.647	28.4788	2.29065
X0.txt_Y0.txt_gap15.txt	0.239487	30	0.447362	3885.31	1.09583	0.878876	-0.0717886	-0.117548	0.123419	6.4975	1.13205	25.1998	2.15842
X0.txt_Y0.txt_gap25.txt	0.0530314	35	0.0990626	4253.23	1.08857	0.894647	-0.118414	-0.139583	0.167857	6.07657	1.30671	25.1851	3.25286
X0.txt_Y0.txt_gap35.txt	0.0115584	40	0.0215911	4273.1	1.016	0.869268	-0.216979	-0.30948	0.373004	5.48793	1.71061	23.8294	6.43033

IVUs Phase Error Performance

The RMS phase error was introduced as a figure of merit of the undulator spectral performance and radiation quality. Figure 10 shows the RMS phase errors of the three IVUs as a function of gap. IVUn1 and IVUn2 have the best performance at minimum gap with a phase error value of about 2°, while IVUn3 have a phase error of about 2.7°. However all three devices sit within the NSLS-II specifications.

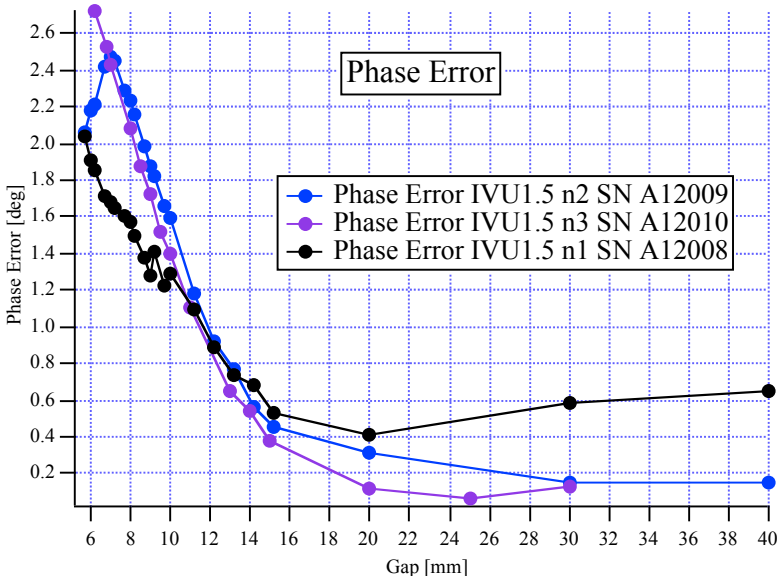

Figure 20: Phase Error