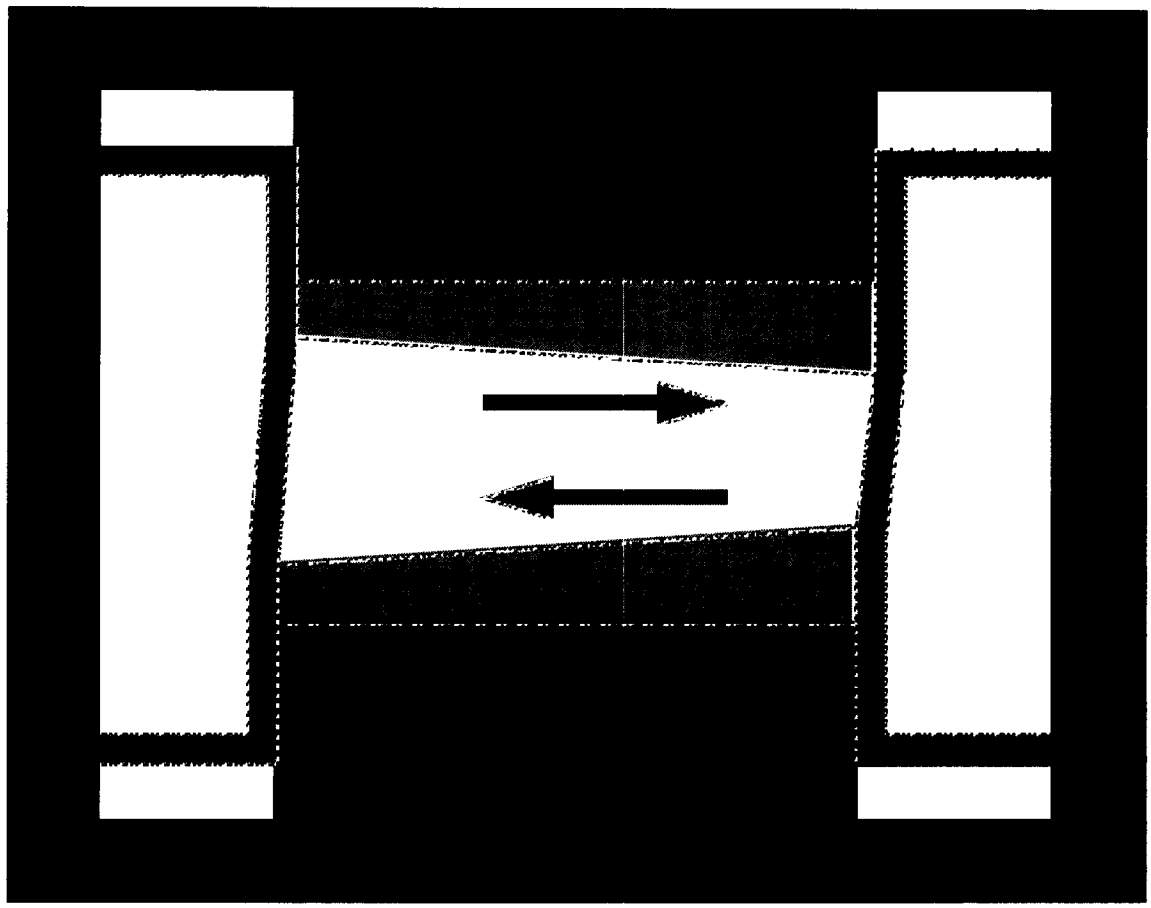
Mechanical and Magnetic Tolerances in Recycler Prototype Magnets

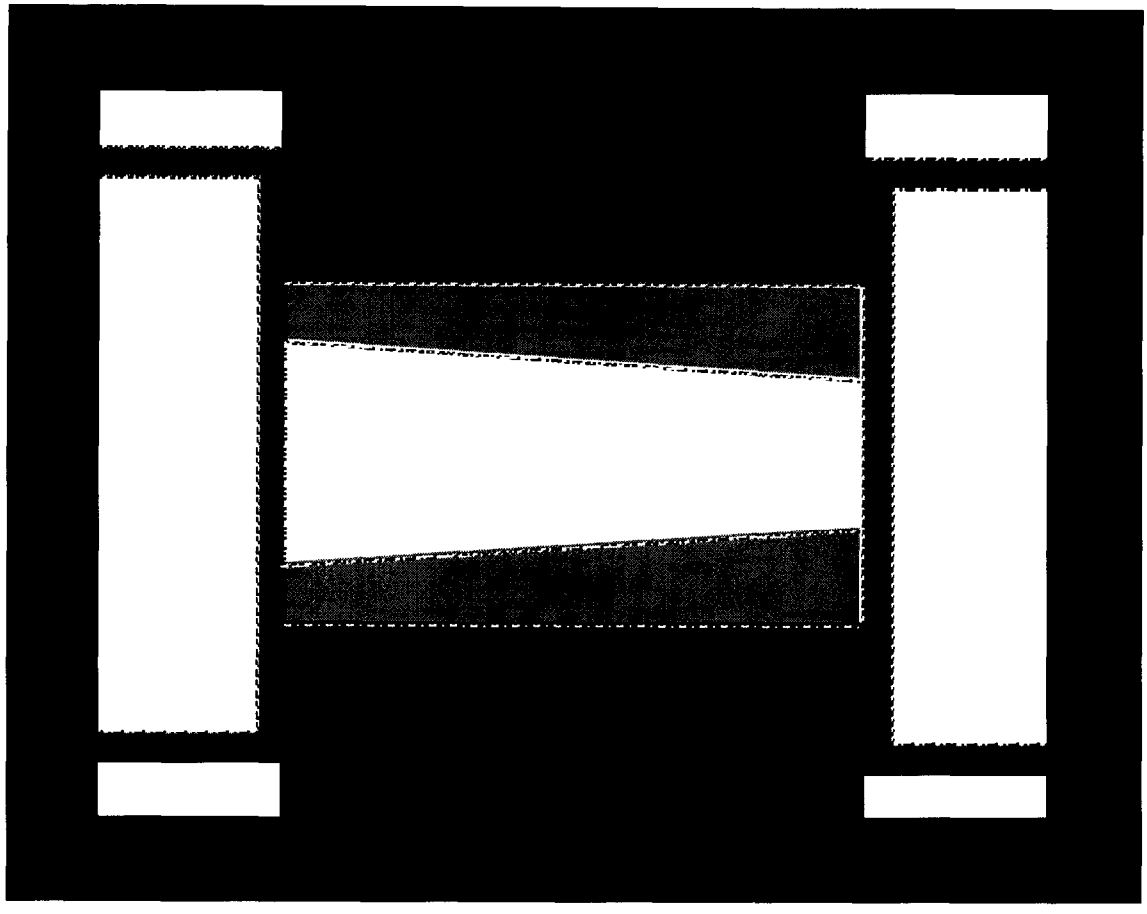


Bill Foster

20 Nov. 1996

Main Injector note #MI-194

RGP Standard Configuration



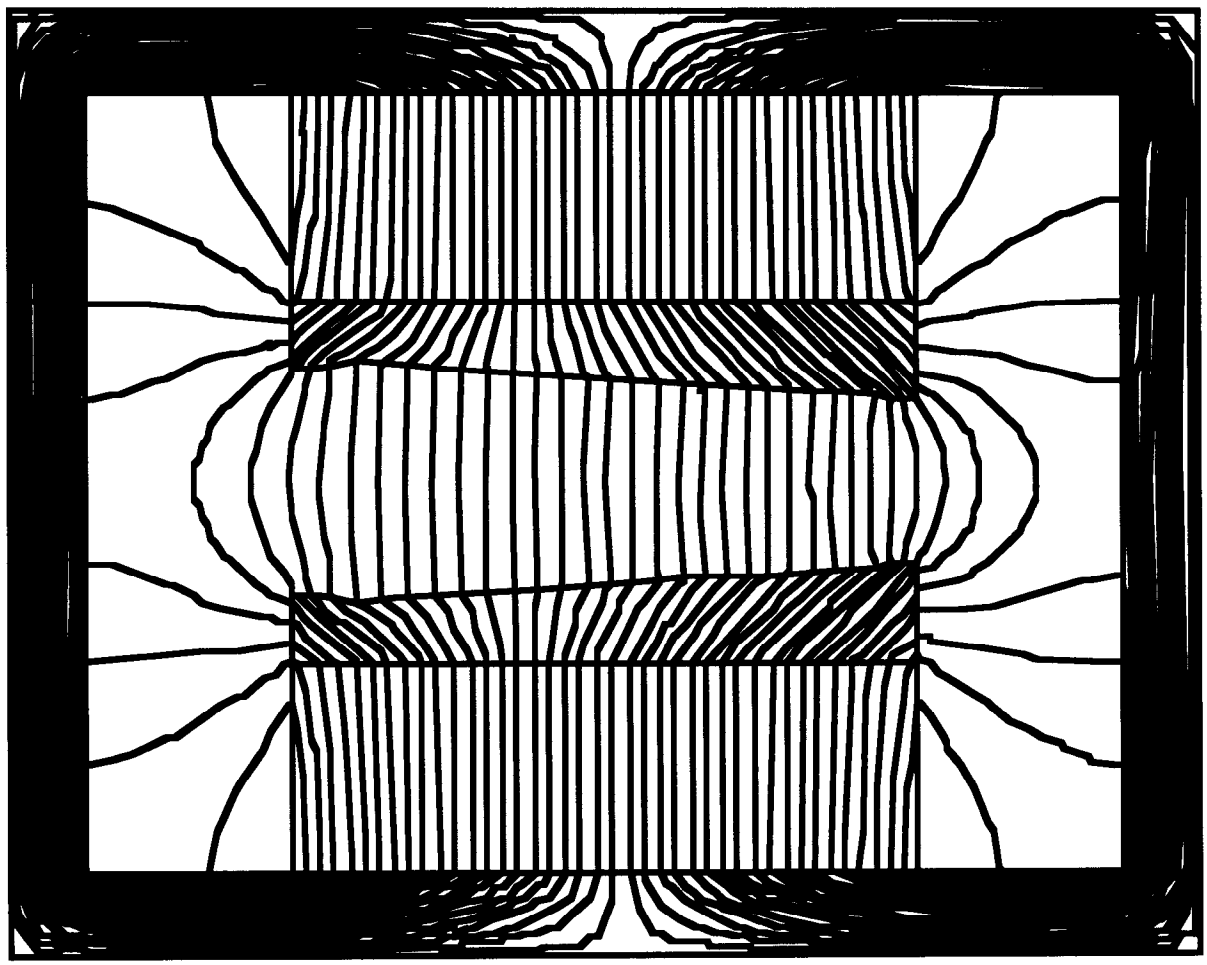
NORMAL		units@1"
Dipole	a0	10000.
Quad.	a1	610.04
Sextup.	a2	15.10
Octupole	a3	0.01
10-pole	a4	-0.13
12-pole	a5	-0.13
14-pole	a6	0.03
16-pole	a7	0.17
18-pole	a8	-0.04
20-pole	a9	-0.19
22-pole	a10	0.04

SKEW		units@1"
Dipole	a0	0.00
Quad.	a1	-0.02
Sextup.	a2	0.00
Octupole	a3	0.01
10-pole	a4	-0.01
12-pole	a5	-0.03
14-pole	a6	0.02
16-pole	a7	0.04
18-pole	a8	-0.04
20-pole	a9	-0.05
22-pole	a10	0.05

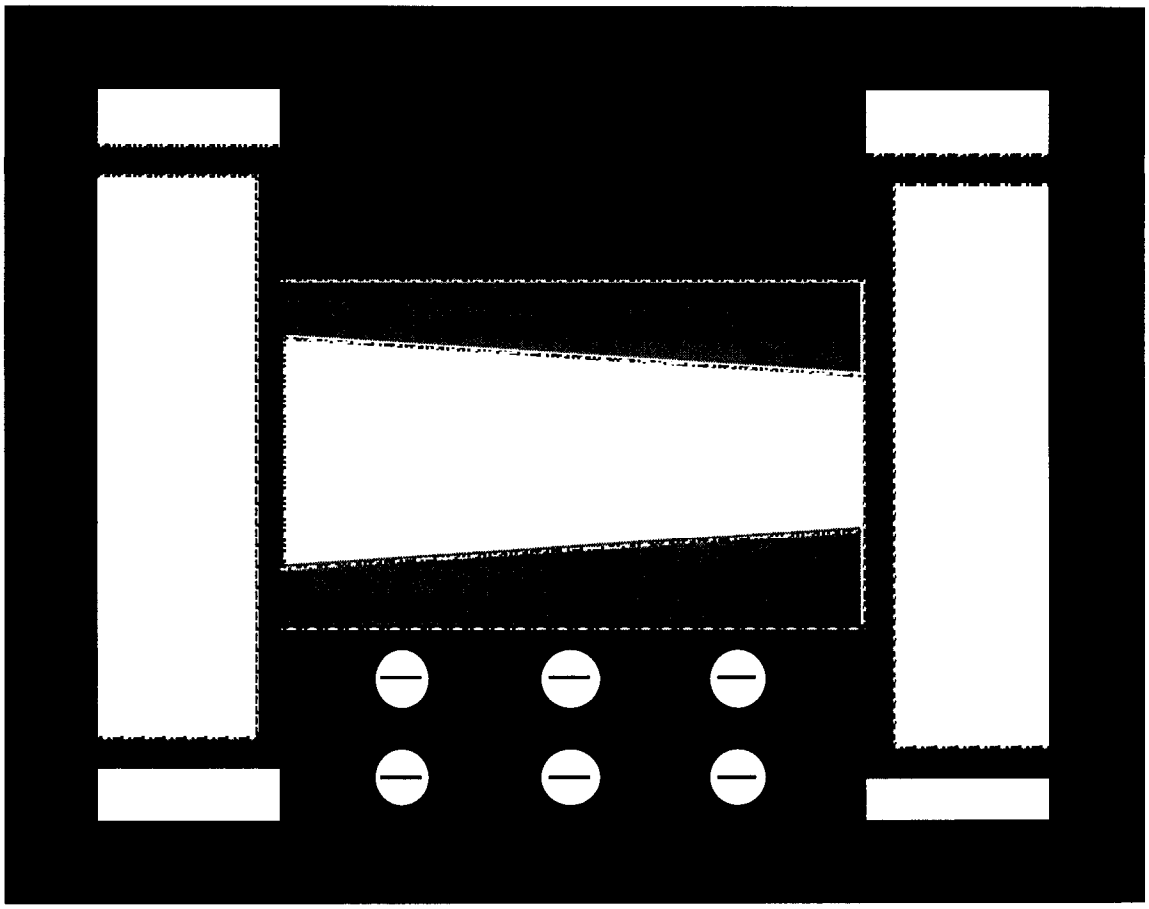
POISSON INPUT FILE FOR RECYCLER PROTOTYPE (ARCF9) DESIGN

```
Recycler Proto Arc Dipole (ARCF9)
&reg nreg=        15,
Xmin =  -6.25000   ,
Xreg1=  -5.00000   , Kreg1=        6,
Xreg2=   5.00000   , Kreg2=      106,
Xmax =   6.25000   , Kmax=       112,
Ymin =  -5.00000   ,
Yreg1=  -1.75000   , Lreg1=       19,
Yreg2=  0.000000   , Lreg2=       39,
Yreg3=   1.75000   , Lreg3=       59,
Ymax =   5.00000   , Lmax=        78,
 Rint=0.85,RNorm=1.00,NTERM=11,
 ktype=1,Angle=360.,NPTC=      1440,
 npoint=        9 &
&po x= -6.250000, y= -5.000000 &
&po x= -6.250000, y=  5.000000 &
&po x=  6.250000, y=  5.000000 &
&po x=  6.250000, y= -5.000000 &
&po x=  5.750000, y= -5.000000 &
&po x=  5.000000, y= -5.000000 &
&po x= -5.000000, y= -5.000000 &
&po x= -5.750000, y= -5.000000 &
&po x= -6.250000, y= -5.000000 &
&reg mat=2, npoint=        34 &
          POLETIP
&po x= -3.030000, y= -1.750000 &
&po x= -3.030000, y= -1.075456 &
&po x= -2.800000, y= -1.075456 &
&po x= -2.600000, y= -1.140741 &
&po x= -2.400000, y= -1.160518 &
&po x= -2.200000, y= -1.146142 &
&po x= -2.000000, y= -1.131797 &
&po x= -1.800000, y= -1.117687 &
&po x= -1.600000, y= -1.103795 &
&po x= -1.400000, y= -1.090106 &
&po x= -1.200000, y= -1.076712 &
&po x= -1.000000, y= -1.063501 &
&po x= -0.800000, y= -1.050466 &
&po x= -0.600000, y= -1.037602 &
&po x= -0.400000, y= -1.024904 &
&po x= -0.200000, y= -1.012370 &
&po x=  0.000000, y= -1.000000 &
&po x=  0.200000, y= -0.987793 &
&po x=  0.400000, y= -0.975750 &
&po x=  0.600000, y= -0.963874 &
&po x=  0.800000, y= -0.952166 &
&po x=  1.000000, y= -0.940630 &
&po x=  1.200000, y= -0.929270 &
&po x=  1.400000, y= -0.918091 &
&po x=  1.600000, y= -0.906915 &
&po x=  1.800000, y= -0.895929 &
&po x=  2.000000, y= -0.885138 &
&po x=  2.200000, y= -0.874547 &
&po x=  2.400000, y= -0.864558 &
&po x=  2.600000, y= -0.839600 &
&po x=  2.800000, y= -0.794449 &
&po x=  3.030000, y= -0.794449 &
&po x=  3.030000, y= -1.750000 &
&po x= -3.030000, y= -1.750000 &
&reg mat=        6, npoint=5 &
                 TOP BRICK
0
&po x= -3.030000, y= -1.750000 &
&po x= -3.030000, y= -3.750000 &
&po x=  3.030000, y= -3.750000 &
&po x=  3.030000, y= -1.750000 &
&po x= -3.030000, y= -1.750000 &
&reg mat=        2, npoint=        7 &
          FLUX RET TOP
&po x=  5.000000, y= -4.500000 &
&po x= -5.000000, y= -4.500000 &
&po x= -5.000000, y= -3.750000 &
&po x= -3.030000, y= -3.750000 &
&po x=  3.030000, y= -3.750000 &
&po x=  5.000000, y= -3.750000 &
&po x=  5.000000, y= -4.500000 &
&reg mat=2, npoint=5 &
          FLUX RET RIGHT SIDE
&po x=  5.750000, y= -4.500000 &
&po x=  5.000000, y= -4.500000 &
&po x=  5.000000, y=  0.000000 &
&po x=  5.750000, y=  0.000000 &
&po x=  5.750000, y= -4.500000 &
&reg mat=2, npoint=5 &
          FLUX RET LEFT
&po x= -5.750000, y= -4.500000 &
&po x= -5.000000, y= -4.500000 &
&po x= -5.000000, y=  0.000000 &
&po x= -5.750000, y=  0.000000 &
&po x= -5.750000, y= -4.500000 &
&reg mat=2, npoint=        34 &
          POLETIP
&po x= -3.030000, y=  1.750000 &
&po x= -3.030000, y=  1.075456 &
&po x= -2.800000, y=  1.075456 &
&po x= -2.600000, y=  1.140741 &
&po x= -2.400000, y=  1.160518 &
&po x= -2.200000, y=  1.146142 &
&po x= -2.000000, y=  1.131797 &
&po x= -1.800000, y=  1.117687 &
&po x= -1.600000, y=  1.103795 &
&po x= -1.400000, y=  1.090106 &
&po x= -1.200000, y=  1.076712 &
&po x= -1.000000, y=  1.063501 &
&po x= -0.800000, y=  1.050466 &
&po x= -0.600000, y=  1.037602 &
&po x= -0.400000, y=  1.024904 &
&po x= -0.200000, y=  1.012370 &
&po x=  0.000000, y=  1.000000 &
&po x=  0.200000, y=  0.987793 &
&po x=  0.400000, y=  0.975750 &
&po x=  0.600000, y=  0.963874 &
&po x=  0.800000, y=  0.952166 &
&po x=  1.000000, y=  0.940630 &
&po x=  1.200000, y=  0.929270 &
&po x=  1.400000, y=  0.918091 &
&po x=  1.600000, y=  0.906915 &
&po x=  1.800000, y=  0.895929 &
&po x=  2.000000, y=  0.885138 &
&po x=  2.200000, y=  0.874547 &
&po x=  2.400000, y=  0.864558 &
&po x=  2.600000, y=  0.839600 &
&po x=  2.800000, y=  0.794449 &
&po x=  3.030000, y=  0.794449 &
&po x=  3.030000, y=  1.750000 &
&po x= -3.030000, y=  1.750000 &
&reg mat=        6, npoint=5 &
                 TOP BRICK
0
&po x= -3.030000, y=  1.750000 &
&po x= -3.030000, y=  3.750000 &
&po x=  3.030000, y=  3.750000 &
&po x=  3.030000, y=  1.750000 &
&po x= -3.030000, y=  1.750000 &
&reg mat=        2, npoint=        7 &
          FLUX RET TOP
&po x=  5.000000, y=  4.500000 &
&po x= -5.000000, y=  4.500000 &
&po x= -5.000000, y=  3.750000 &
&po x= -3.030000, y=  3.750000 &
&po x=  3.030000, y=  3.750000 &
&po x=  5.000000, y=  3.750000 &
&po x=  5.000000, y=  4.500000 &
&reg mat=2, npoint=5 &
          FLUX RET RIGHT SIDE
&po x=  5.750000, y=  4.500000 &
&po x=  5.000000, y=  4.500000 &
&po x=  5.000000, y=  0.000000 &
&po x=  5.750000, y=  0.000000 &
&po x=  5.750000, y=  4.500000 &
&reg mat=2, npoint=5 &
          FLUX RET LEFT
&po x= -5.750000, y=  4.500000 &
&po x= -5.000000, y=  4.500000 &
&po x= -5.000000, y=  0.000000 &
&po x= -5.750000, y=  0.000000 &
&po x= -5.750000, y=  4.500000 &
&reg mat=1,cur=1., npoint=2  &
PANIDRA CURRENT LINE
&po x=  3.030000, y=  1.750000 &
&po x=  3.030000, y=  3.750000 &
&reg mat=1,cur=1., npoint=2 &
PANIDRA CURRENT LINE
&po x= -3.030000, y=  3.750000 &
&po x= -3.030000, y=  1.750000 &
&reg mat=1,cur=1., npoint=2  &
PANIDRA CURRENT LINE
&po x=  3.030000, y= -1.750000 &
&po x=  3.030000, y= -3.750000 &
&reg mat=1,cur=1., npoint=2 &
PANIDRA CURRENT LINE
&po x= -3.030000, y= -3.750000 &
&po x= -3.030000, y= -1.750000 &
```

Recycler Prototype (ARCF9) Magnetic Field Map



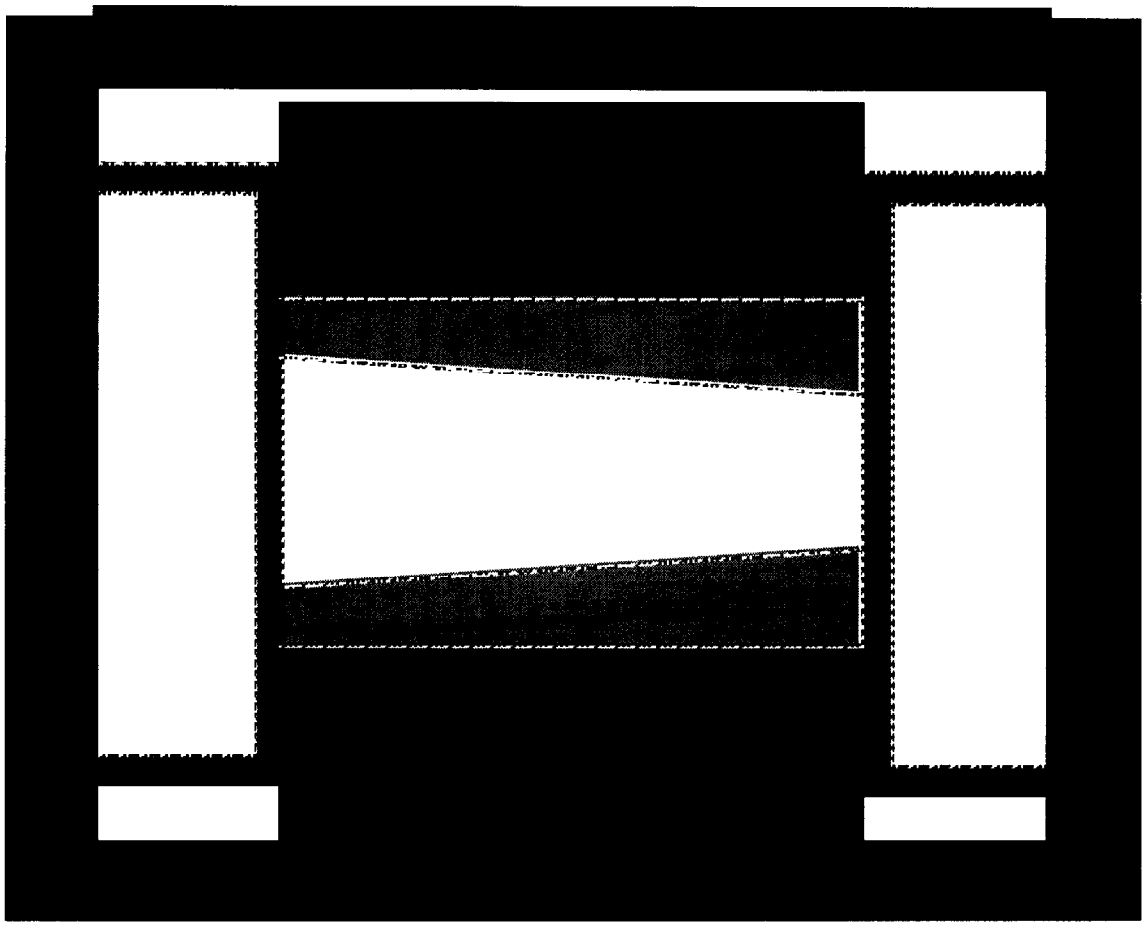
Bottom Bricks 10% Weak



POLE STRENGTH MISMATCH Top Brick 10% Weak							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000.	3.81	0.00	**3.81**
1	Quad.	610.04	-0.02	609.99	-11.62	-0.05	**-11.60**
2	Sextup.	15.10	0.00	15.05	3.62	-0.05	**3.62**
3	Octupole	0.01	0.01	0.00	-4.22	-0.01	**-4.23**
4	10-pole	-0.13	-0.01	-0.13	0.25	0.00	0.26
5	12-pole	-0.13	-0.03	-0.13	-0.51	0.00	-0.48
6	14-pole	0.03	0.02	0.03	-0.01	0.00	-0.03
7	16-pole	0.17	0.04	0.17	0.01	0.00	-0.03
8	18-pole	-0.04	-0.04	-0.04	-0.04	0.00	0.00
9	20-pole	-0.19	-0.05	-0.19	-0.08	0.00	-0.03
10	22-pole	0.04	0.05	0.03	0.04	-0.01	-0.01

A 10% Weakness of Top Pole Generates 11.6 Units of Skew Quad (& others)

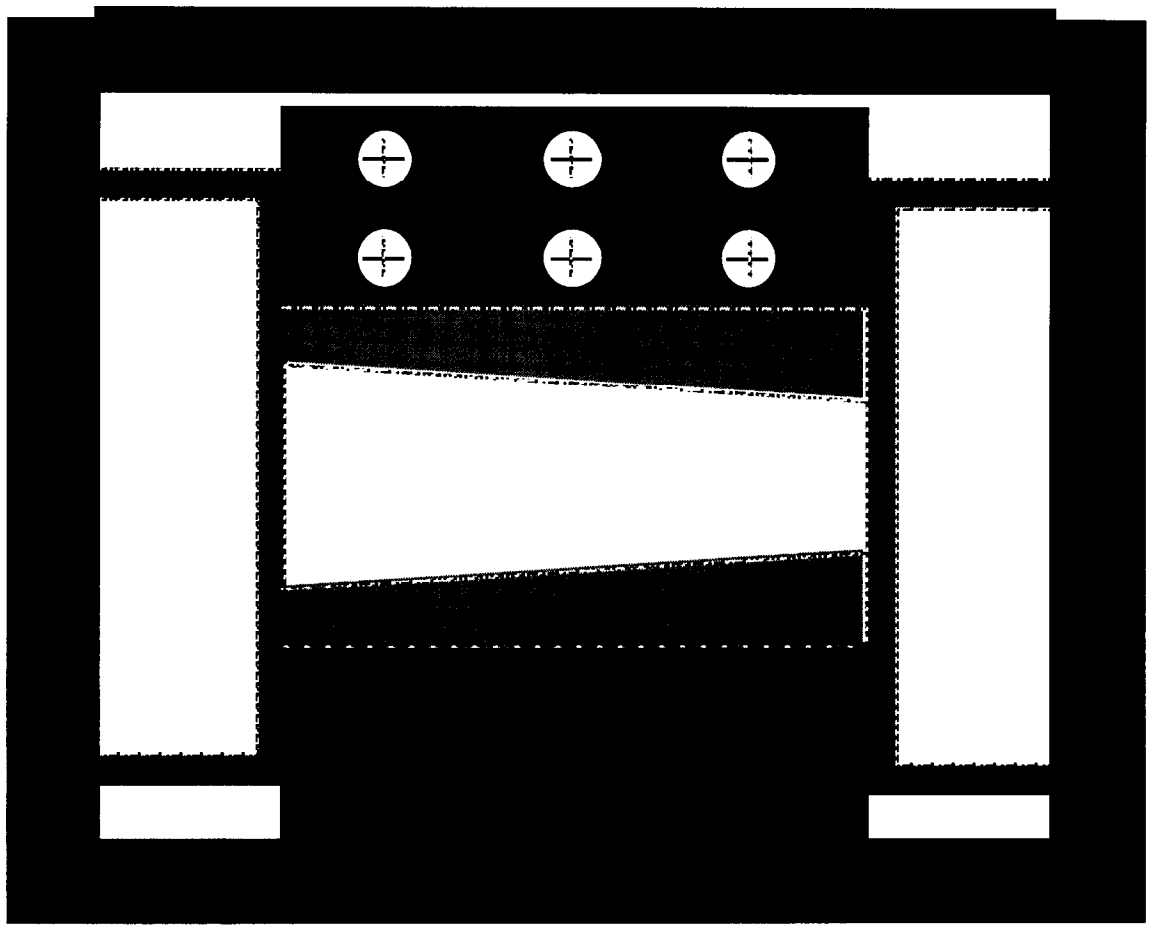
0.100" Gap Above Top Brick



0.1" Gap Above Top Brick No Correction of Top Brick Strength							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000.	1.18	0.00	**1.18**
1	Quad.	610.04	-0.02	610.00	-3.84	-0.04	**-3.82**
2	Sextup.	15.10	0.00	15.08	1.10	-0.02	**1.10**
3	Octupole	0.01	0.01	0.01	-1.38	0.00	**-1.39**
4	10-pole	-0.13	-0.01	-0.13	0.06	0.00	0.07
5	12-pole	-0.13	-0.03	-0.13	-0.19	0.00	-0.16
6	14-pole	0.03	0.02	0.03	0.01	0.00	-0.01
7	16-pole	0.17	0.04	0.17	0.03	0.00	-0.01
8	18-pole	-0.04	-0.04	-0.04	-0.04	0.00	0.00
9	20-pole	-0.19	-0.05	-0.19	-0.06	0.00	-0.01
10	22-pole	0.04	0.05	0.03	0.04	-0.01	-0.01

A 0.100" Gap Above Top Pole Generates -4 Units of Skew Quad (& others)

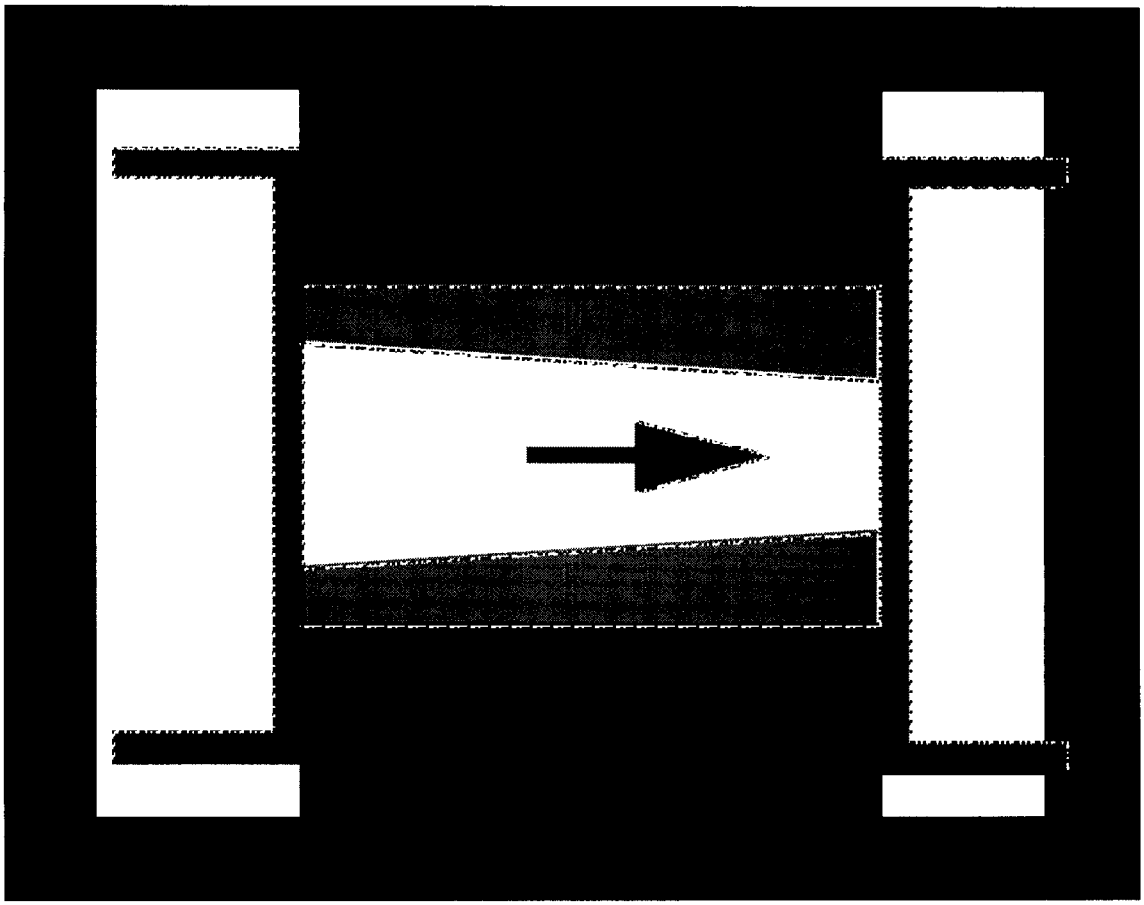
0.100" Gap Above Top Brick,
(Compensated by Re-Balancing Top/Bottom)



0.1" Gap Above Top Brick Top Brick Strength Increased 3% to Correct Skew Quadrupole							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000.	-0.10	0.00	**-0.10**
1	Quad.	610.04	-0.02	610.05	0.06	0.01	**0.08**
2	Sextup.	15.10	0.00	15.10	-0.11	0.00	**-0.11**
3	Octupole	0.01	0.01	0.01	0.04	0.00	**0.03**
4	10-pole	-0.13	-0.01	-0.13	-0.03	0.00	-0.02
5	12-pole	-0.13	-0.03	-0.13	-0.03	0.00	0.00
6	14-pole	0.03	0.02	0.03	0.02	0.00	0.00
7	16-pole	0.17	0.04	0.17	0.04	0.00	0.00
8	18-pole	-0.04	-0.04	-0.04	-0.04	0.00	0.00
9	20-pole	-0.19	-0.05	-0.19	-0.05	0.00	0.00
10	22-pole	0.04	0.05	0.04	0.05	0.00	0.00

NO SIGNIFICANT MULTIPOLES AFTER REBALANCING

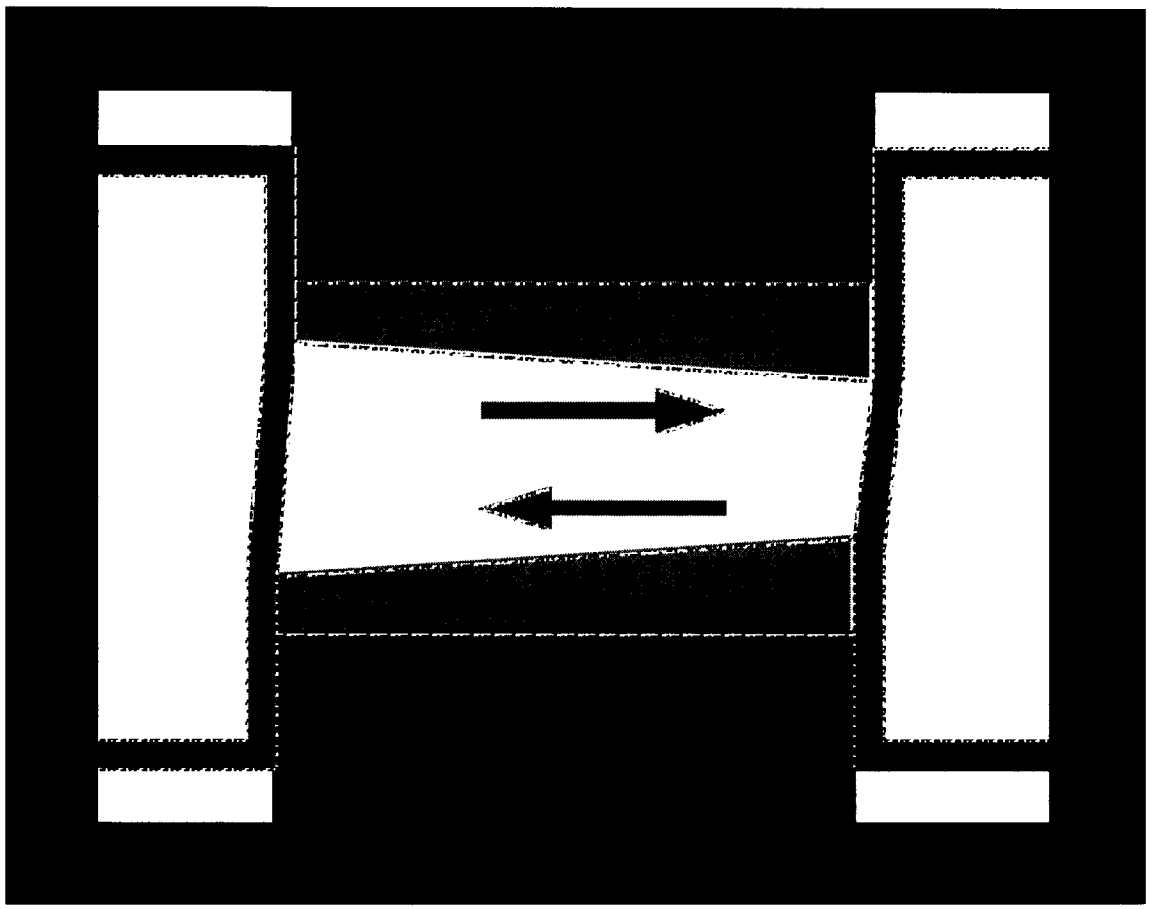
0.1" Right Shift of Poles & Bricks



Poles & Bricks Shifted Off-Center All Poles & Bricks Shifted Right by 0.100"							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000.	0.00	0.00	0.00
1	Quad.	610.04	-0.02	610.52	-0.02	**0.48**	0.00
2	Sextup.	15.10	0.00	15.19	-0.01	0.09	-0.01
3	Octupole	0.01	0.01	0.12	0.01	0.11	0.00
4	10-pole	-0.13	-0.01	0.08	0.01	0.21	0.02
5	12-pole	-0.13	-0.03	-0.05	-0.03	0.08	0.00
6	14-pole	0.03	0.02	-0.10	-0.02	-0.13	-0.04
7	16-pole	0.17	0.04	-0.06	0.05	-0.23	0.01
8	18-pole	-0.04	-0.04	-0.05	0.02	-0.01	0.06
9	20-pole	-0.19	-0.05	0.11	-0.05	0.30	0.00
10	22-pole	0.04	0.05	0.11	-0.03	0.07	-0.08

A 0.100" Shift of magnet guts generates 0.5 Units of Gradient Error.

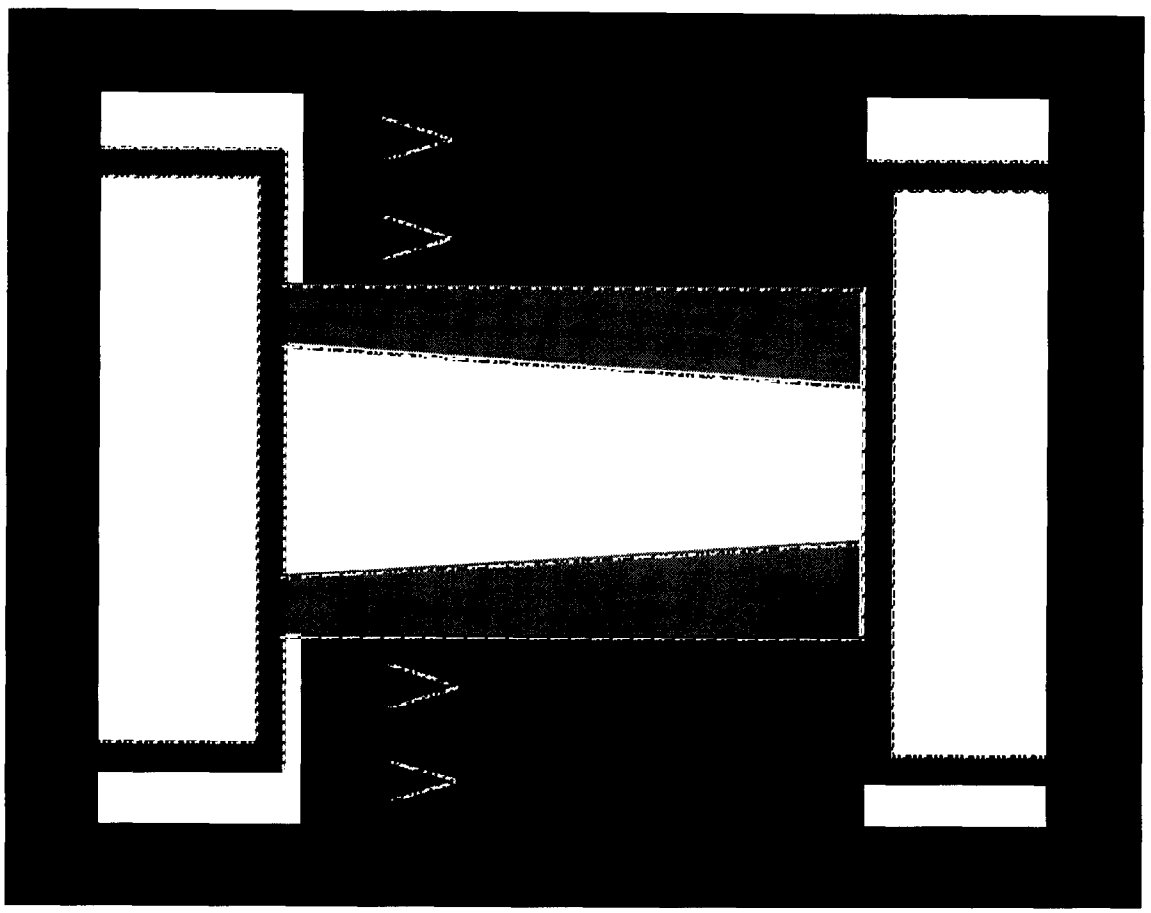
0.020" Skew Shift of Poles & Bricks



Poles and Bricks Skew Shifted by 0.020" Top Pole Shifted Right by 0.010", Bottom Left by 0.010"								
Multipole Defect		Nominal Design		Errors from Defect		Change		
		Normal	Skew	Normal	Skew	Normal	Skew	
0	Dipole	10000.	0.00	10000.	-0.97	0.00		<--
1	Quad.	610.04	-0.02	609.92	-0.01	-0.12	0.01	
2	Sextup.	15.10	0.00	15.12	-1.09	0.02	**-1.09**	<--
3	Octupole	0.01	0.01	0.15	-0.09	0.14	-0.10	
4	10-pole	-0.13	-0.01	0.05	-0.25	0.18	**-0.24**	<--
5	12-pole	-0.13	-0.03	-0.11	-0.07	0.02	-0.04	
6	14-pole	0.03	0.02	-0.18	0.02	-0.21	0.00	
7	16-pole	0.17	0.04	-0.04	0.04	-0.21	0.00	
8	18-pole	-0.04	-0.04	0.13	-0.07	0.17	-0.03	
9	20-pole	-0.19	-0.05	0.11	-0.05	0.30	0.00	
10	22-pole	0.04	0.05	-0.09	0.02	-0.13	-0.03	

A 0.020" Skew Shift Generates 1 Unit of Skew Dipole and Skew Sextupole

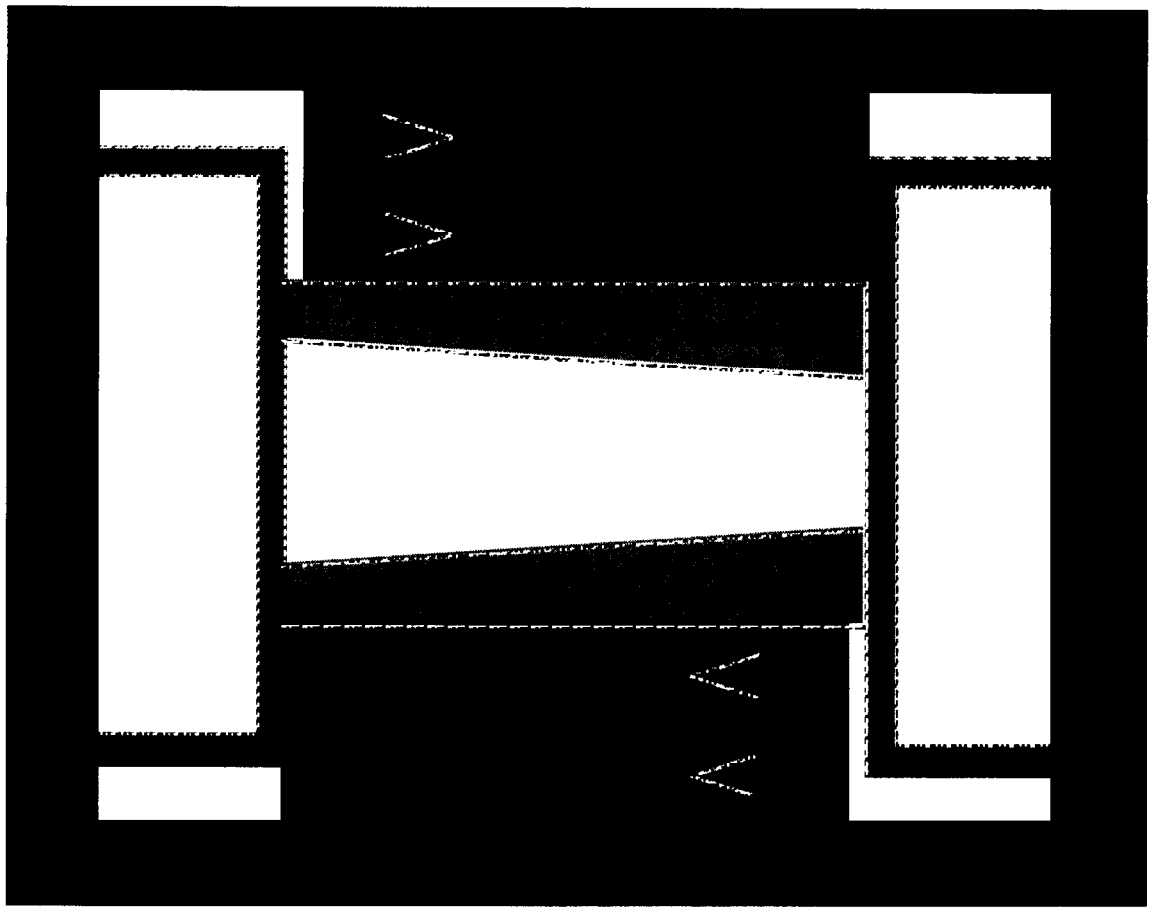
Bricks 0.1" Small and Shifted Right



Bricks Undersized 0.1" and Shifted Off-Center All Bricks Shifted Right by 0.050" (so 0.100" gap opens at left).							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000	0	0.00	0.00
1	Quad.	610.04	-0.02	610.73	-0.02	**0.69**	0.00
2	Sextup.	15.10	0.00	14.96	0	**-0.14**	0.00
3	Octupole	0.01	0.01	-0.01	0.01	-0.02	0.00
4	10-pole	-0.13	-0.01	-0.12	-0.01	0.01	0.00
5	12-pole	-0.13	-0.03	-0.13	-0.03	0.00	0.00
6	14-pole	0.03	0.02	0.03	0.02	0.00	0.00
7	16-pole	0.17	0.04	0.17	0.04	0.00	0.00
8	18-pole	-0.04	-0.04	-0.04	-0.04	0.00	0.00
9	20-pole	-0.19	-0.05	-0.19	-0.05	0.00	0.00
10	22-pole	0.04	0.05	0.04	0.05	0.00	0.00

A 0.1" Right Shift of Bricks Generates 0.69 units of Gradient Error.

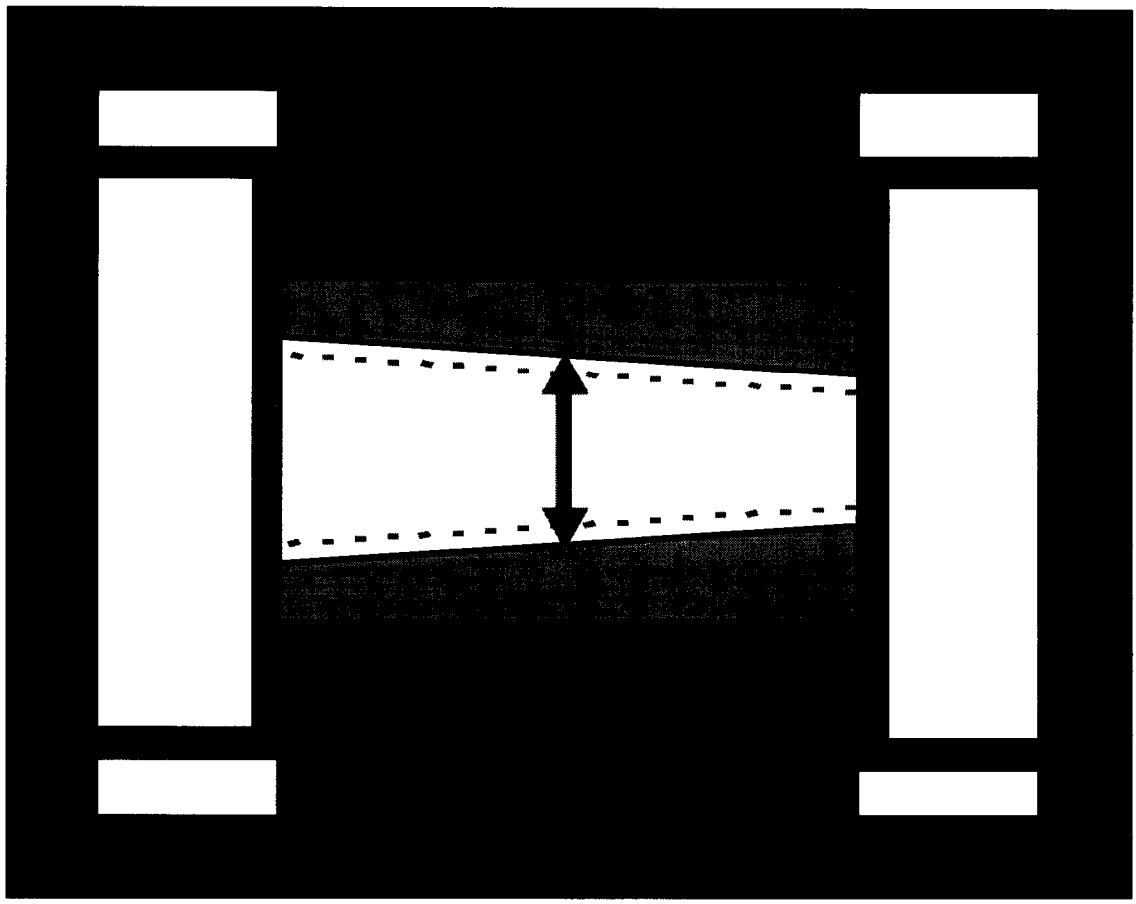
Bricks 0.1" Small and Skew Shifted



Bricks 0.1" Small and Skew Shifted Top Bricks Shifted Right by 0.050", Bottom Left by 0.050"							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000.	-0.61	0.00	**-0.61**
1	Quad.	610.04	-0.02	610.05	0.08	0.01	0.10
2	Sextup.	15.10	0.00	15.00	0.06	-0.10	0.06
3	Octupole	0.01	0.01	0.01	-0.01	0.00	-0.02
4	10-pole	-0.13	-0.01	-0.13	-0.01	0.00	0.00
5	12-pole	-0.13	-0.03	-0.13	-0.03	0.00	0.00
6	14-pole	0.03	0.02	0.03	0.02	0.00	0.00
7	16-pole	0.17	0.04	0.17	0.05	0.00	0.01
8	18-pole	-0.04	-0.04	-0.04	-0.04	0.00	0.00
9	20-pole	-0.19	-0.05	-0.19	-0.05	0.00	0.00
10	22-pole	0.04	0.05	0.04	0.05	0.00	0.00

A 0.1" Skew Shift of Bricks Creates a 0.6 unit Skew Dipole.

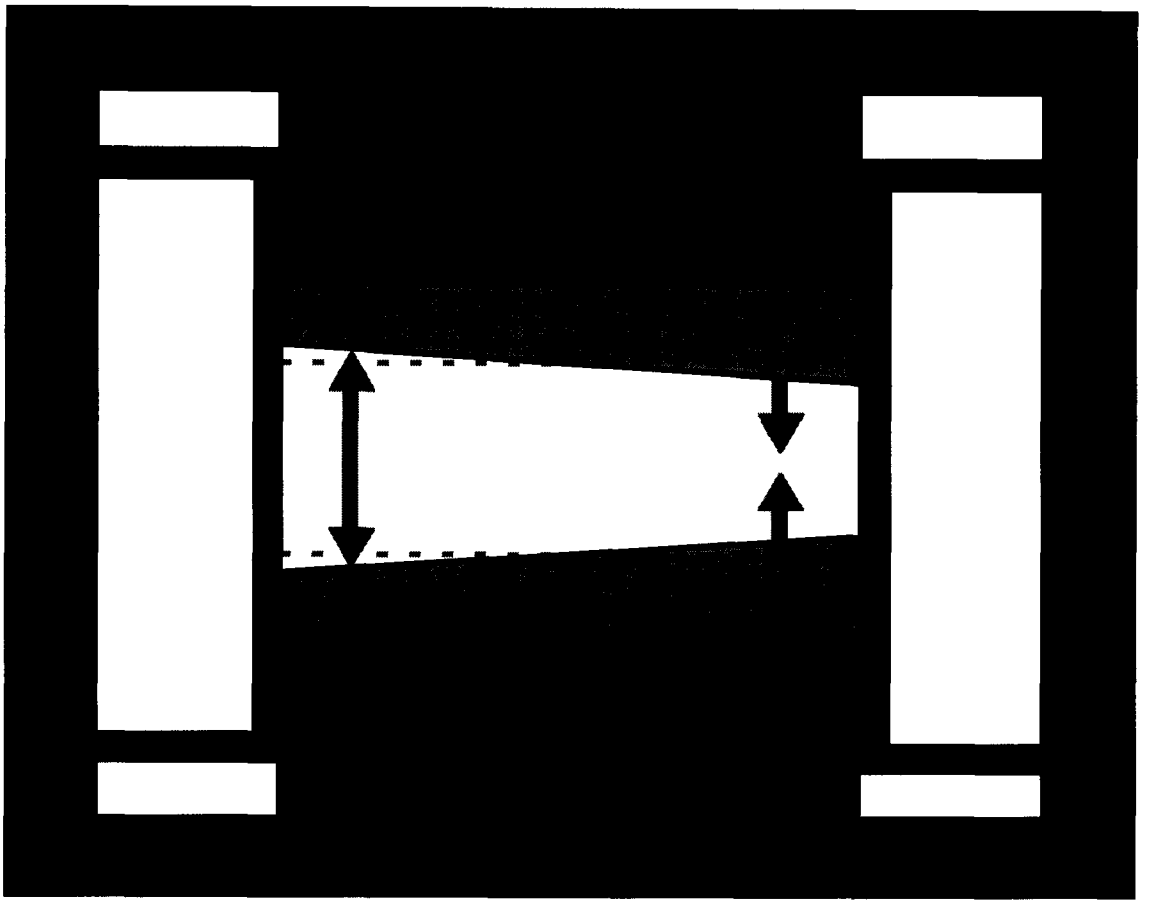
Oversize Vertical Gap Between Poles



Gap too big by 0.010" Bottom Pole Face 0.005" low, Top 0.005" high							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000.	0.00	0.00	0.00
1	Quad.	610.04	-0.02	607.01	-0.02	**-3.03**	0.00
2	Sextup.	15.10	0.00	14.79	-0.01	-0.31	-0.01
3	Octupole	0.01	0.01	0.01	0.01	0.00	0.00
4	10-pole	-0.13	-0.01	-0.15	-0.01	-0.02	0.00
5	12-pole	-0.13	-0.03	-0.12	-0.04	0.01	-0.01
6	14-pole	0.03	0.02	0.01	0.02	-0.02	0.00
7	16-pole	0.17	0.04	0.17	0.04	0.00	0.00
8	18-pole	-0.04	-0.04	-0.03	-0.03	0.01	0.01
9	20-pole	-0.19	-0.05	-0.17	-0.05	0.02	0.00
10	22-pole	0.04	0.05	0.02	0.02	-0.02	-0.03

A 0.010" Oversize Magnet Gap generates a -3 unit Gradient Error.

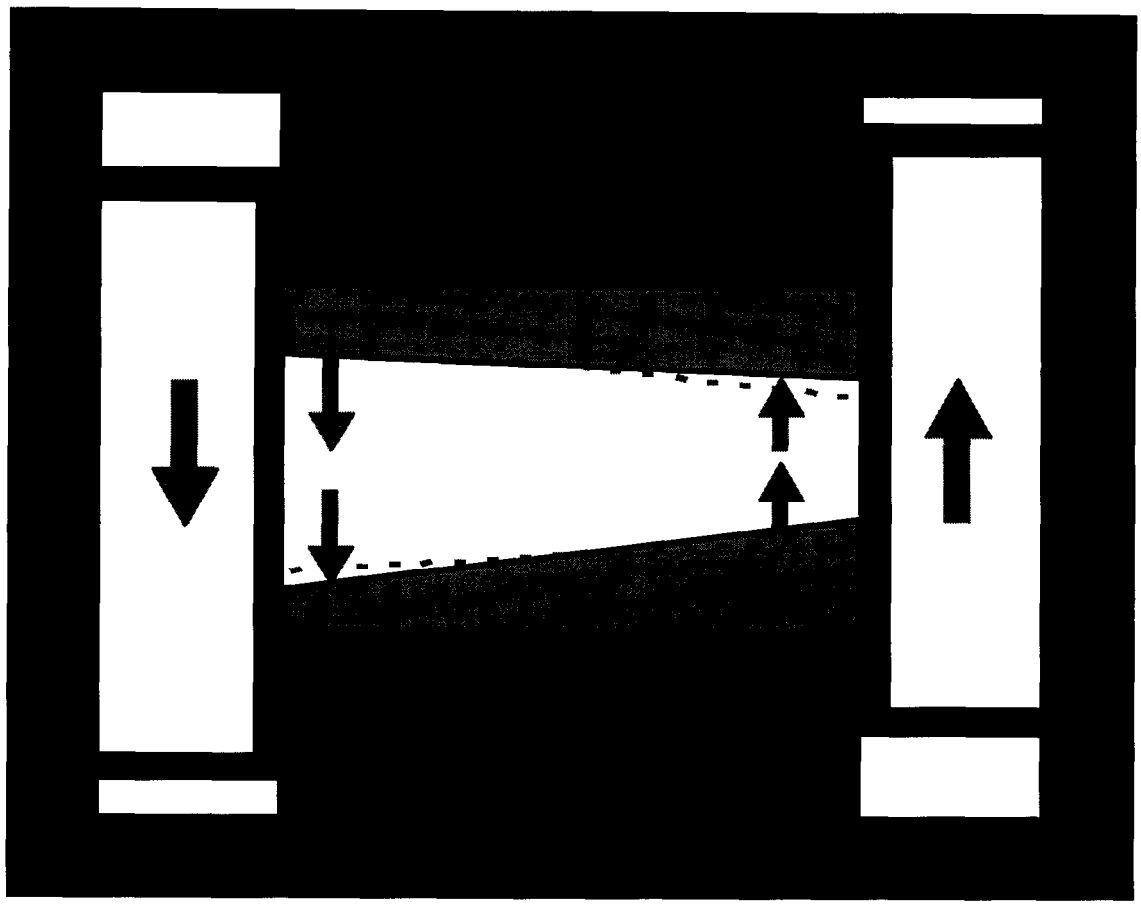
Slope Error on Pole Faces



MULTIPOLE CHANGE FROM 0.002" Misalignment of pole tips Right Side Gap is 0.001" under nominal, Left side 0.001" above nominal							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000	0	0.00	0.00
1	Quad.	610.04	-0.02	611.68	-0.02	**1.64**	0.00
2	Sextup.	15.10	0.00	15.303	0	0.20	0.00
3	Octupole	0.01	0.01	0.026	0.01	0.02	0.00
4	10-pole	-0.13	-0.01	-0.131	-0.01	0.00	0.00
5	12-pole	-0.13	-0.03	-0.129	-0.03	0.00	0.00
6	14-pole	0.03	0.02	0.03	0.02	0.00	0.00
7	16-pole	0.17	0.04	0.171	0.041	0.00	0.00
8	18-pole	-0.04	-0.04	-0.04	-0.04	0.00	0.00
9	20-pole	-0.19	-0.05	-0.191	-0.05	0.00	0.00
10	22-pole	0.04	0.05	0.039	0.05	0.00	0.00

A 0.002" Pole Face Alignment Error Generates 1.6 units Gradient Error

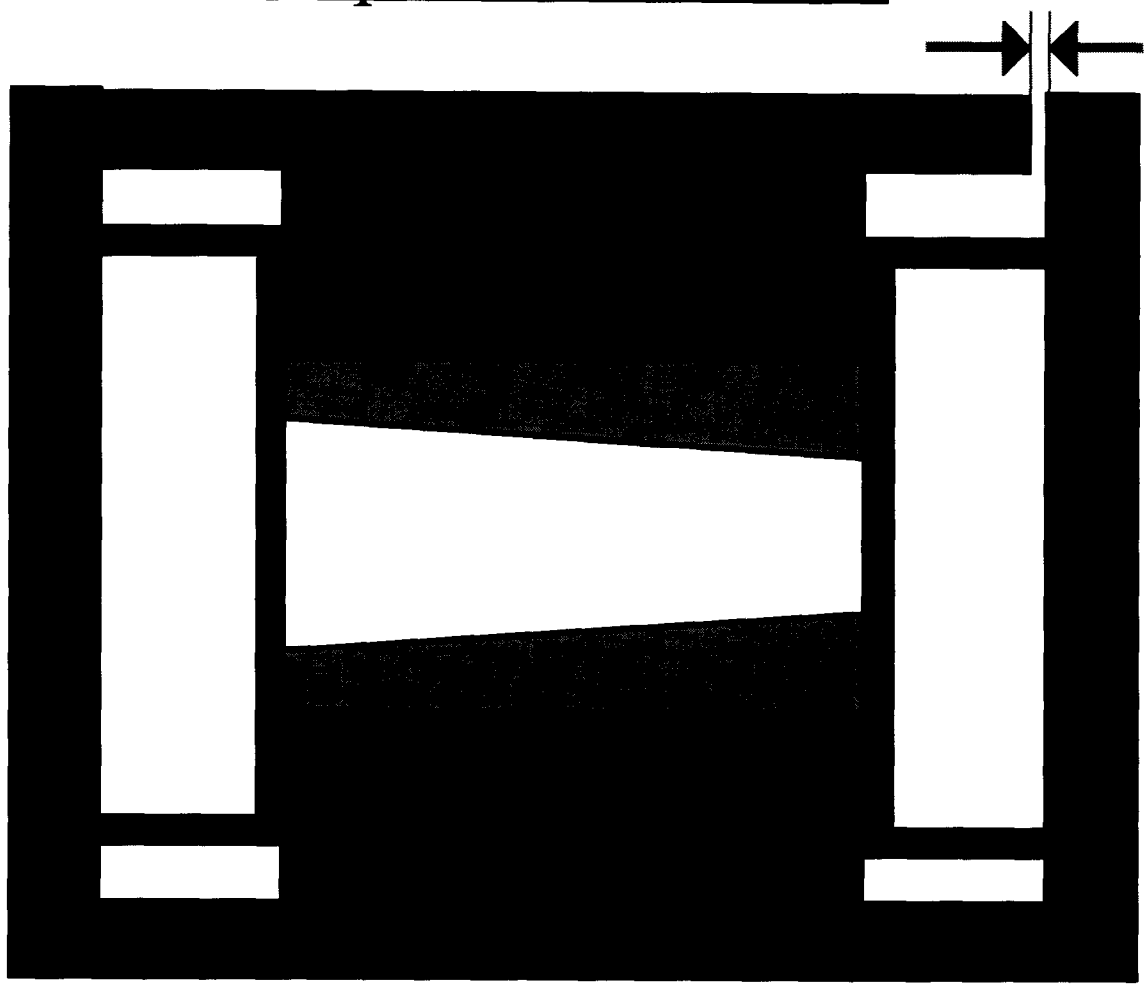
"Parallelogram" Error on Pole Faces



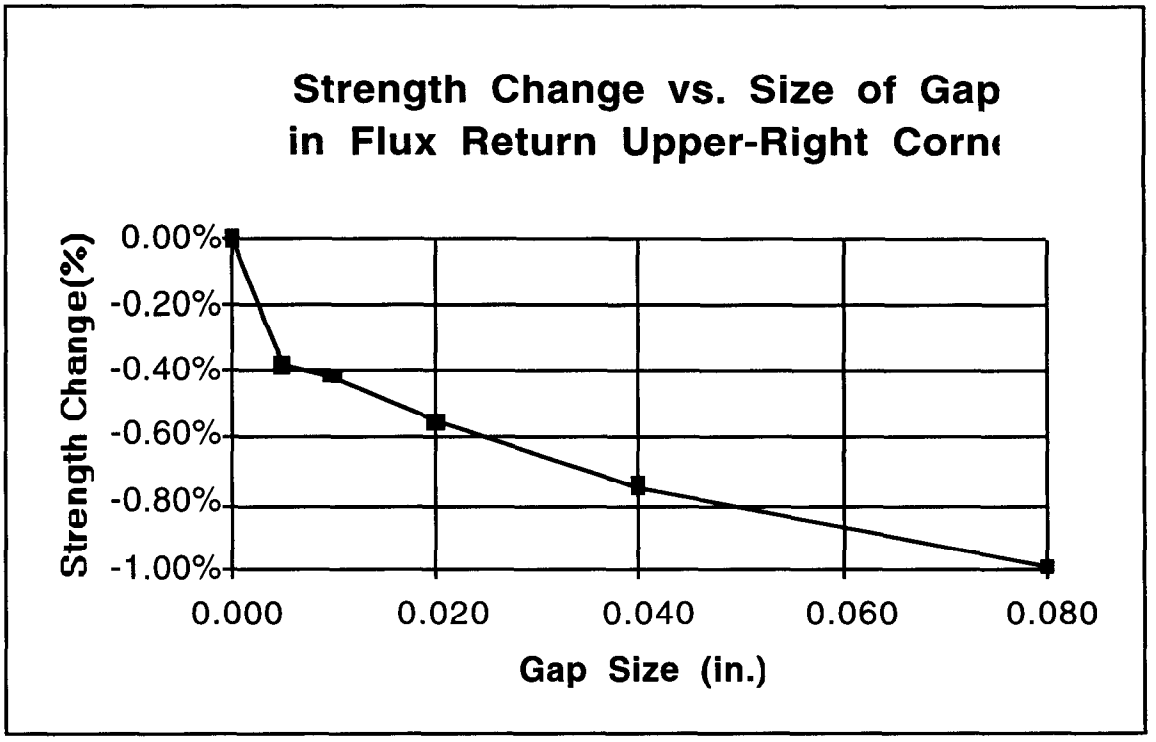
0.010" Vertical Parallelogram Error Left polefaces 0.005" low, Right 0.005" high							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000	-16.21	0.00	**-16.21**
1	Quad.	610.04	-0.02	610.04	-2.08	0.00	**-2.06**
2	Sextup.	15.10	0.00	15.1	0.14	0.00	0.14
3	Octupole	0.01	0.01	0.01	0.02	0.00	0.01
4	10-pole	-0.13	-0.01	-0.13	0.04	0.00	0.05
5	12-pole	-0.13	-0.03	-0.13	-0.03	0.00	0.00
6	14-pole	0.03	0.02	0.03	0.02	0.00	0.00
7	16-pole	0.17	0.04	0.17	0.04	0.00	0.00
8	18-pole	-0.04	-0.04	-0.04	-0.04	0.00	0.00
9	20-pole	-0.19	-0.05	-0.19	-0.04	0.00	0.01
10	22-pole	0.04	0.05	0.04	0.05	0.00	0.00

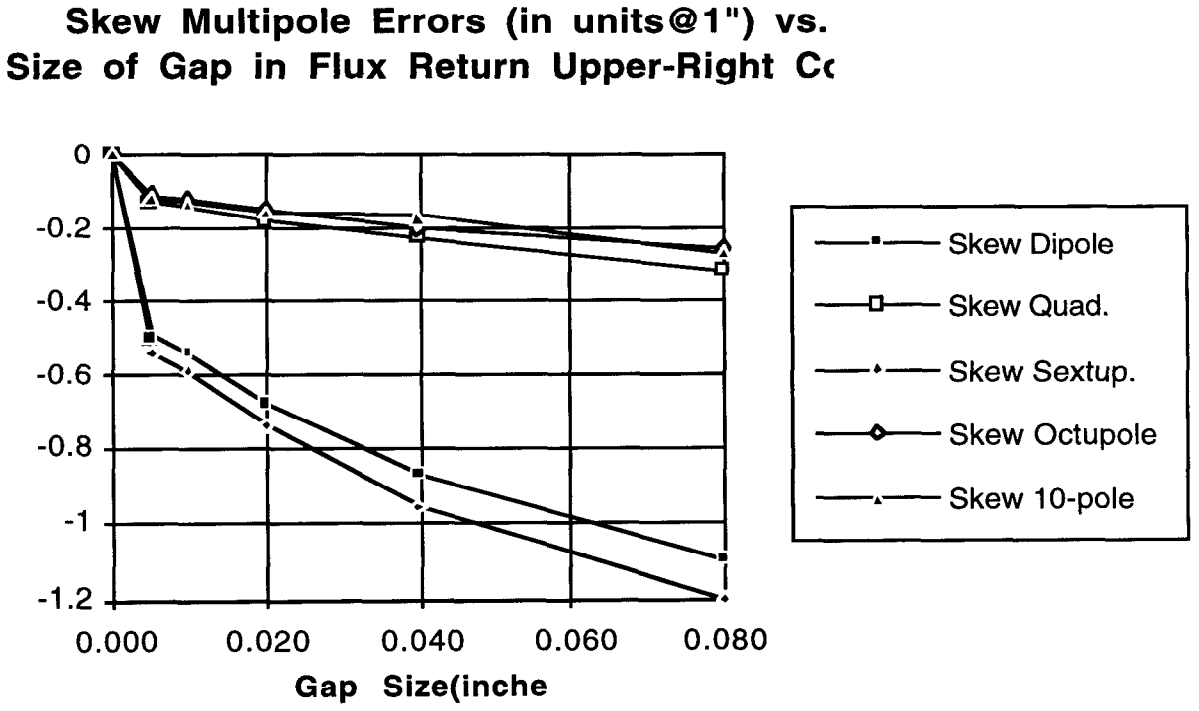
A 0.010" "Parallelogram" Error makes -16 units Skew Dipole & -2 Skew Quad

Gaps In Flux Return



Gap in Flux Return 0.010" Gap in Upper-Right Corner Joint of Flux Return							
Multipole Defect		Nominal Design		Errors from Defect		Change	
		Normal	Skew	Normal	Skew	Normal	Skew
0	Dipole	10000.	0.00	10000.	-0.54	0.00	**-0.54**
1	Quad.	610.04	-0.02	610.02	-0.16	-0.02	**-0.14**
2	Sextup.	15.10	0.00	15.09	-0.59	-0.01	**-0.59**
3	Octupole	0.01	0.01	0.01	-0.11	0.00	**-0.12**
4	10-pole	-0.13	-0.01	-0.13	-0.14	0.00	**-0.13**
5	12-pole	-0.13	-0.03	-0.13	-0.06	0.00	-0.03
6	14-pole	0.03	0.02	0.03	0.01	0.00	-0.01
7	16-pole	0.17	0.04	0.17	0.04	0.00	0.00
8	18-pole	-0.05	-0.04	-0.05	-0.05	0.00	-0.01
9	20-pole	-0.19	-0.05	-0.19	-0.04	0.00	0.01
10	22-pole	0.03	0.05	0.02	0.04	-0.01	-0.01


Strength Change vs. Size of Gap
in Flux Return Upper-Right Corn
Strength Change(%)
0.00%
-0.20%
-0.40%
-0.60%
-0.80%
-1.00%
0.000
0.020
0.040
0.060
0.080
Gap Size (in.)


Skew Multipole Errors (in units@1") vs.
Size of Gap in Flux Return Upper-Right Cc
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
0.000
0.020
0.040
0.060
0.080
Gap Size(inche
Skew Dipole
Skew Quad.
Skew Sextup.
Skew Octupole
Skew 10-pole