USING FINITE ELEMENT ANALYSIS AND A GLOBAL OPTIMIZER TO SORT MAGNETS AND COMPENSATE FOR MAGNET INHOMOGENEITY

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Second Special Workshop on Magnet Simulation for Particle Accelerators
PAC07
June 26-27, 2007

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FEA Makes Sense with Modern Codes and Fast Computers

- Accurate (Tested against measurements)
  - 0.1% (S. Gottschalk, et al, SRI95, PAC99)
- Precise (Tested against measurements)
  - 0.005% rolloff (S. Gottschalk, et al, SRI95, PAC99)
  - 6 ppm – PM Dipole (S. Gottschalk, et al, FEL 2002)
- Fast
  - 2-6 minutes quarter period FEA ($x>0$, $y>0$, $z \le \lambda_w/4$)
  - 6-10 minutes half period (all x, all y, $-\lambda_w/4 \le z \le \lambda_w/4$)
- Can determine arbitrary cost functions such as trajectories and multipoles
  - ILC DRW multipoles in this talk

Examples using FEA based sorting

- Wigglers
  - Subject of this talk
- Undulators
  - JLAB IR undulator
- PM quads
  - Minimize strength dependent magnetic CL shifts and skew quad rotation during BBA
  - NLC quad (PAC2005 papers)
  - Triplets delivered to Columbia RAFEL

Signature function FEA

- Build a parametric model (wiggler, quad, dipole, etc)
- Change properties of ‘test’ magnet(s) or pole(s)
- Subtract magnetic fields to get signature
- Effects included by this method
  - Non-linear pole
  - Non-unit, anisotropic magnet permeability
  - Spatially varying reversible demagnetization
- Signatures found for
  - Mx, My, Mz
  - Size
  - Mechanical shifts, tilts
  - Temperature
  - Pole placement errors (mainly for PM quads, dipoles)
  - Pole shape errors

Inhomogeneity model

- Inhomogeneity is dominant source of field errors on state-of-the-art PM devices (author opinion!)
- Very hard to measure inhomogeneity directly (author opinion!)
- Experimentally smaller magnets appear to be more homogeneous
- Build a real magnet from smaller pieces.
  - Accuracy increases as number of discrete pieces grows
- Each piece has a different strength and angle, but is otherwise uniform.
- Use FEA for accuracy and elimination of simplistic assumptions.

Outline

- Motivation and Review
- LNLS Wiggler Sorting Example
- ILC Damping Ring Example
- Conclusion

Motivation and review

Motivation

- Magnets are not perfect.
  - Typical strength variation is 1.5%
  - Typical angle variation is 1.5 degrees
- Designs with low permeability are especially critical
  - Pure REPM, no steel poles, mu=1.05-1.10 in magnets
  - EPU's even worse because banks of magnets slide and non-unit permeability does produce non-superimposition.
  - High field wigglers. Strong increase when mu < 100.
- Hybrids with high permeability poles are less susceptible.
  - Vertical angle errors 20X less important, K. Robinson, et al, JQE QE-23, 1497, 1987, also confirmed by FEA calculations

Sorting techniques at our disposal

- Ignore problem
  - Very risky. Rebuilding an ID is expensive and without an understanding the problem could get worse!
- Simple sums based on Helmholtz data (STI 1979-1994, others)
  - Classic is S-W pairing for strength and (in-out) and (up-down) pairing for angles.
  - One issue is weights to assign to each one
  - No determination of cumulative errors that produce steering and trajectory errors
- More sophisticated is angle and trajectory sums (STI 1994-2003)
  - Estimate angle and trajectory errors by summing up Mx, My and Mz down length of wiggler
- Full FEA based optimization (STI 2003-present)
  - Calculate signature functions and convolve them
  - Directly calculate fields for each sort

Sorting algorithms

- Brute force permutations (STI, others)
  - Only useful for small problems and even then the number of iterations is huge, 1,000 to 10,000
- Simulated annealing (R. Carr, B. Divaccio, STI and others)
- Genetic algorithms (way too confusing to be practical plus it’s really inefficient)
- Evolutionary optimizer (STI)
  - OptiNet from Infolytica released 2003.
  - Very efficient, consistent and convergent answers with 100 iterations.
  - Optimization variables are MagNet (Infolytica) parameters (parametrics released 1998)

Advantage of commercial code

- Tested and robust
- Easy to use
- Flexible
  - Library of pre-programmed functions
  - Easy to use scripting to make custom codes
  - Can weight the goals based on specifications/performance requirements
- Technical support

Design codes that integrate into OptiNet

- All are parametric
  - Central and end field ID designers (hybrid, REPM, straight and wedged)
  - EPU designers (central and end with ESRF, ELLETTRA and STI ends)
  - 3D pole shaper (many configurations)
  - 3D shim designer (central and end field)
  - EM coil designers (mainly for gap dependence)
  - PM Quadrupoles (many configurations and options)
  - EM quadrupoles
  - Others

Pre and post processing codes

- Demagnetization fields vs. temperature and gap
- Minimum pole permeability
- End field steering and trajectory
- Dynamic multipoles (field integral along wiggle trajectory)
- Wiggler axial harmonics
- Transverse rolloff
- Static multipoles (normal and skew)
- DR axial field profile ‘squareness’ (integral of B^2)
- Equal two-plane focusing with curved poles
- Phase slippage between undulator sections as the axial gap changes
- Temperature dependent quad strength changes
- Quad centerline shifts vs. magnet retraction
- Skew quad rotation vs. magnet retraction
- Quad multipoles vs. magnet retraction
- Dipole multipoles
- Sextupole multipoles
- Others

LNLS Wiggler Sorting Example

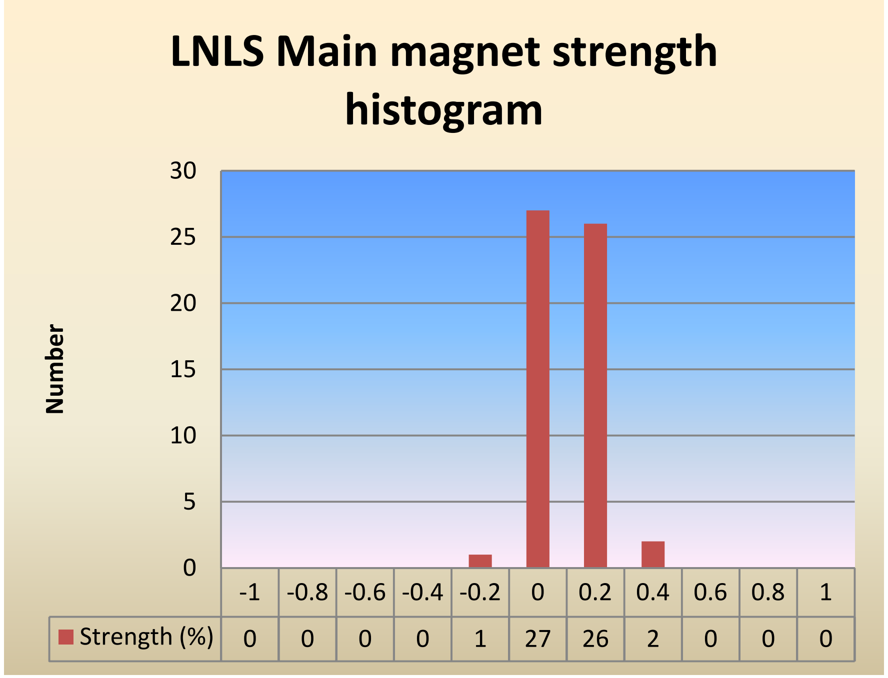
LNLS Wiggler Parameters

- Period 180mm
- Gap 22 mm
- Peak field 2.06 T
- Length 3.0m
- Initial survey of field errors for previous devices showed no problems

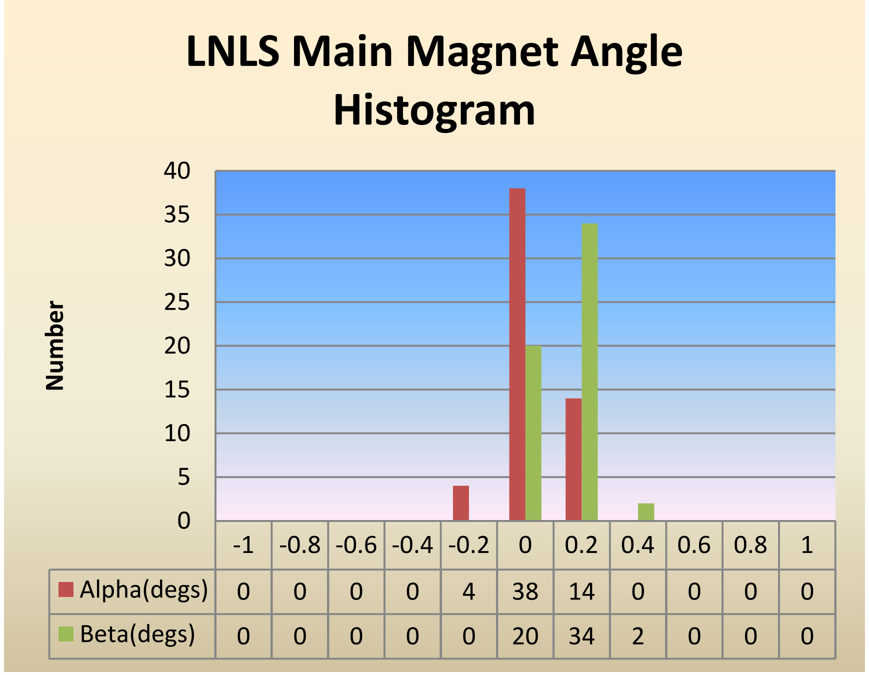
Device	Peak Field (T)	Gap (mm)	Period (mm)	Untuned Skew Quad (G)
SRRC W20	1.86	22	200	140
APS W85 – 2 units	1.67	11.5	85	9, 110
APS U55	1.36	10.5	55	140
SRRC U9 – Wedged pole	1.28	18	90	34

One shim used to get <20 G quad all gaps

LNLS Wiggler had extremely good strength and angle histograms



	-1	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8	1
🟥 Strength (%)	0	0	0	0	1	27	26	2	0	0	0



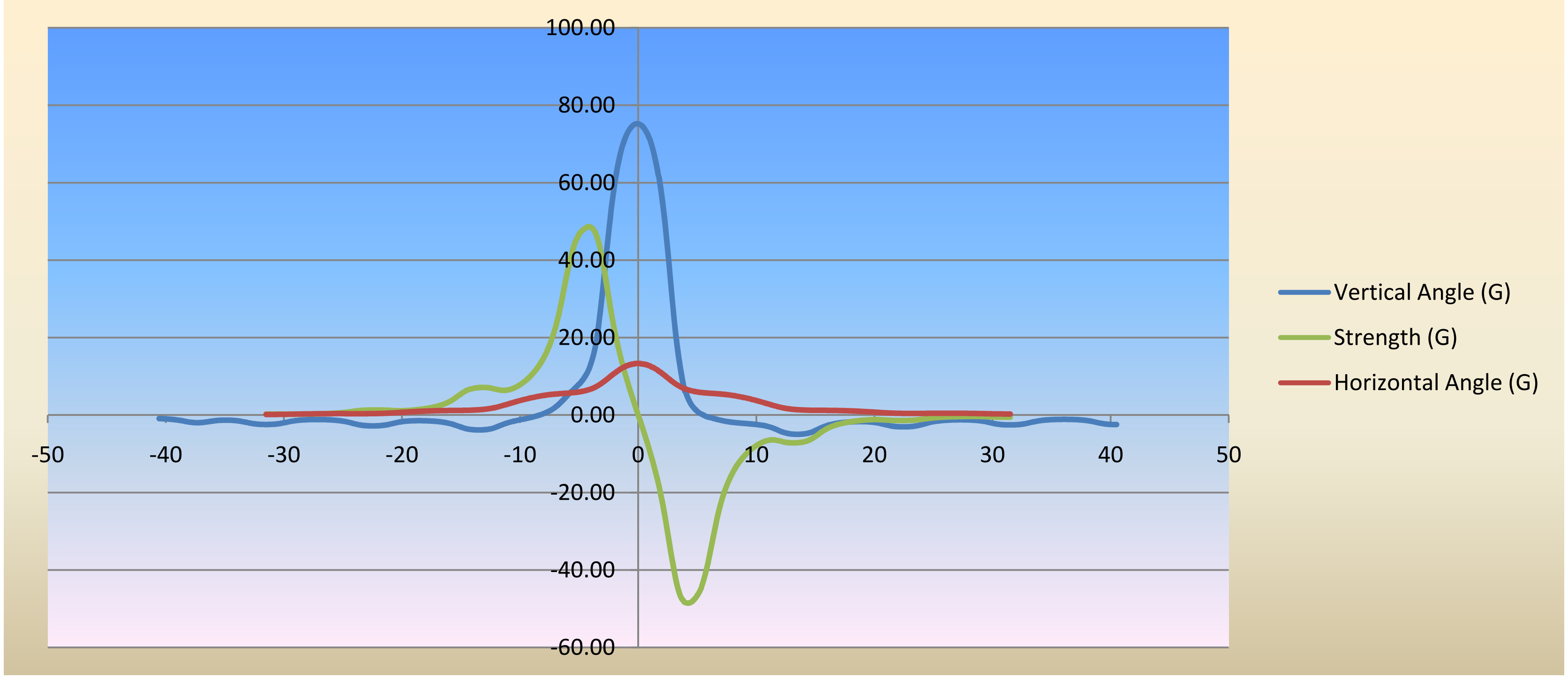
	-1	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8	1
🟥 Alpha(degs)	0	0	0	0	4	38	14	0	0	0	0
🟩 Beta(degs)	0	0	0	0	0	20	34	2	0	0	0

Magnets are about 10X better than specs
Mechanical tolerances were also 5X better than specs
Pieces used to make main magnets were large, but underlying strength and angle distributions were narrower, i.e. 0.1%, 0.1 deg

Additional tests for magnet inhomogeneity

- Magnet paper – passed
- Surface Hall probe scans – passed
- Hall probe checks of field symmetry - passed

Signature functions
Used for FEA post-processing

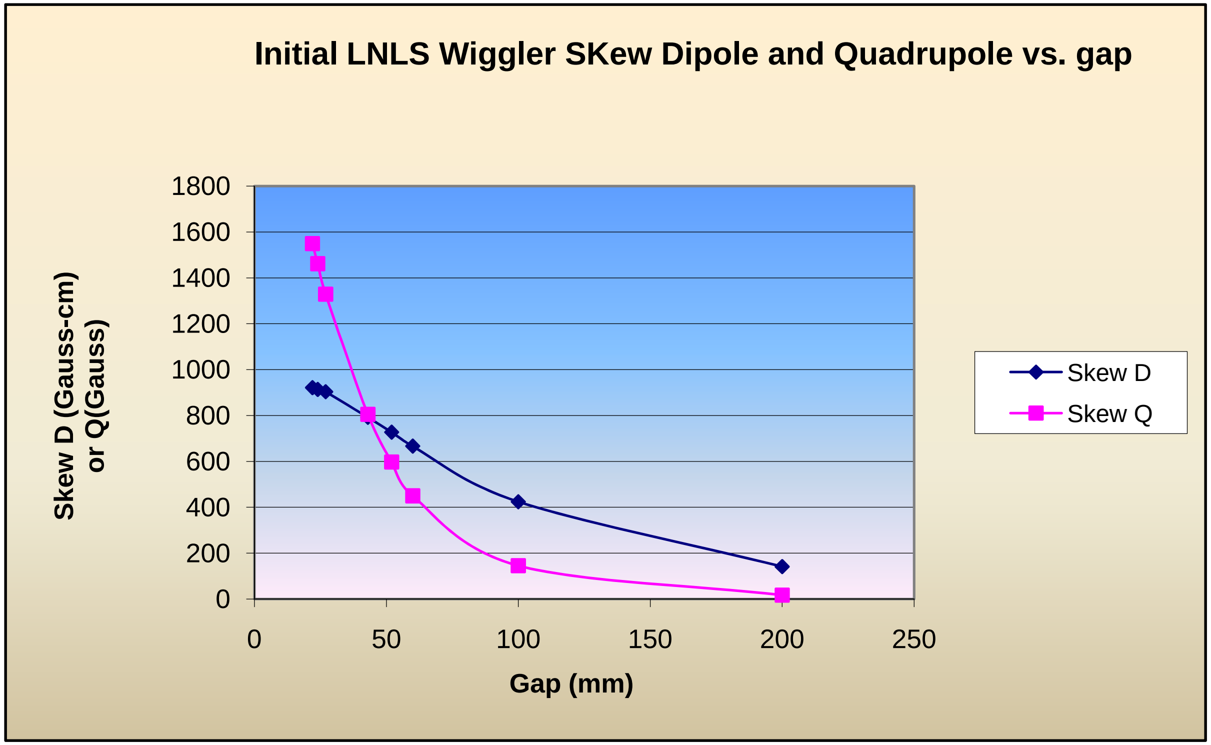


Effect	Peak (Gauss)	Integral (G-cm)
Strength	48.7	0
Vertical Angle	75.2	272
Horizontal Angle	13.3	190

Multi-stage LNLS sorting

- Stage 1 – Use simulated annealing code to minimize ‘angle’ and ‘trajectory’ errors. Not FEA convolution
  - Used for 35 ID’s so is well tested and reliable
  - Run 10 sorts. Any one is acceptable.
- Stage 2 – Post process sorts and convolve FEA signature functions
- Stage 3 – Look at results and pick the ‘best’ one.

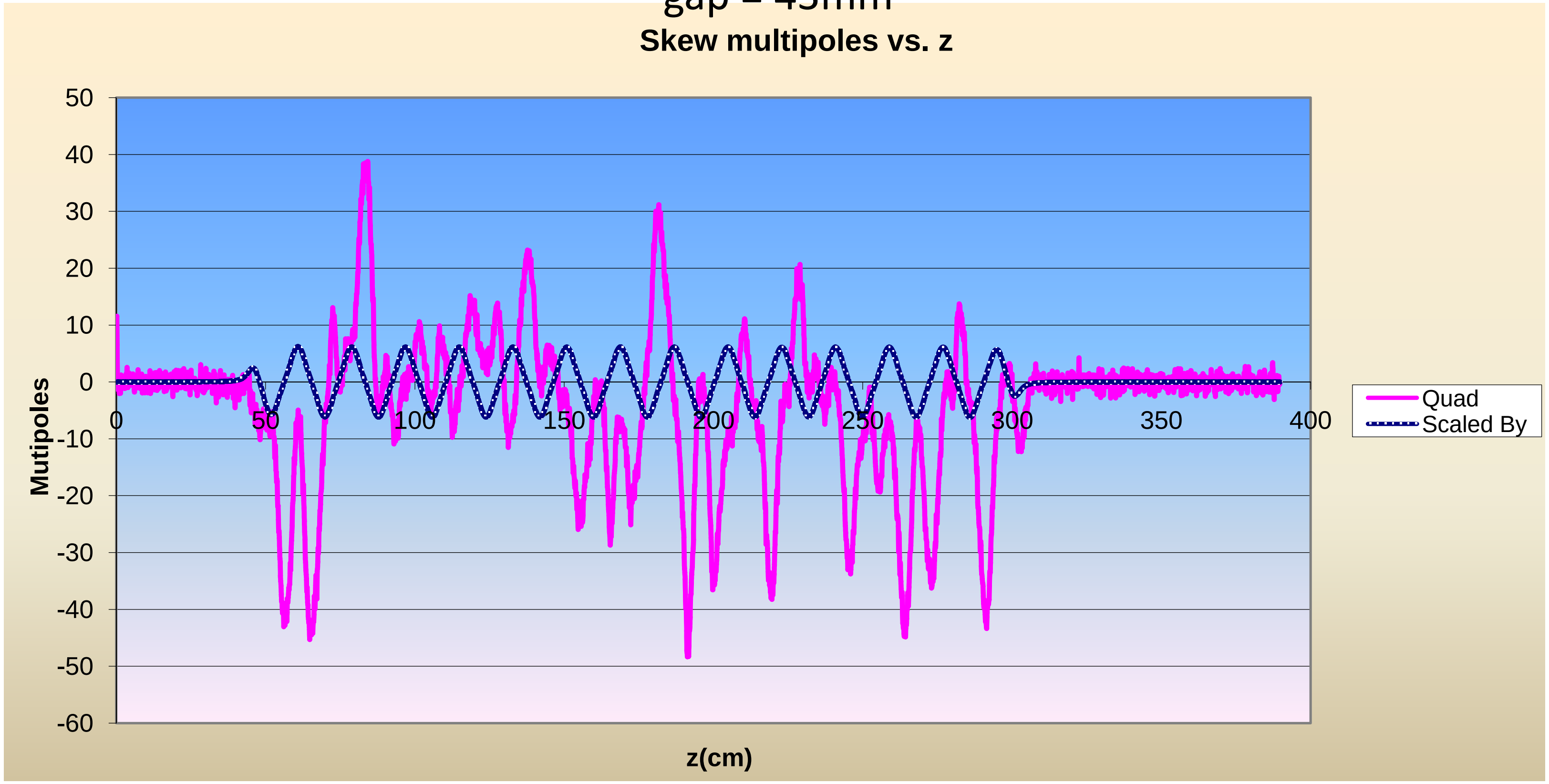
Did this work?



- Normal steering and trajectory were fine, but skews were terrible
- None of 40 ID’s built and measured by STI for skews had this large of a skew field error
- What caused this?

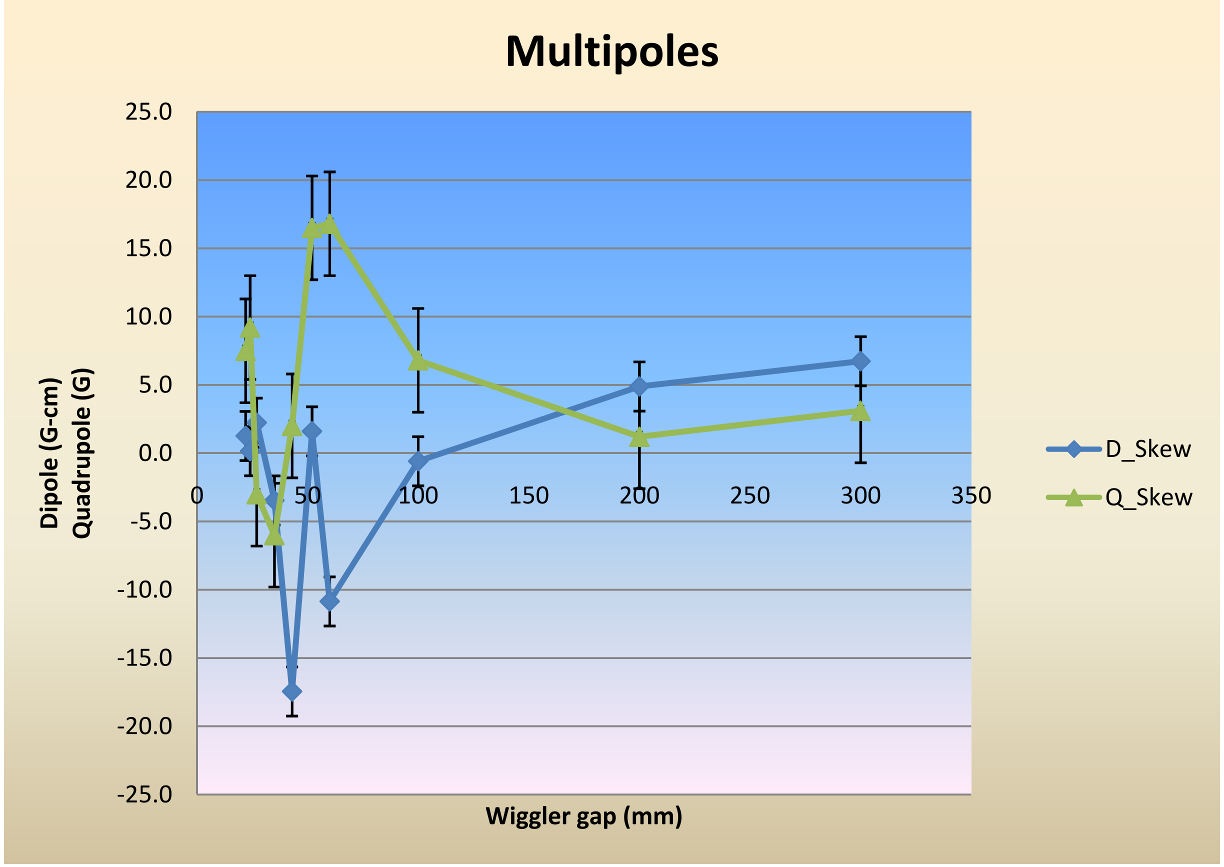
Magnet Inhomogeneity

gap = 43mm



- Skew quads (and dipoles) were located at magnet centers
- Magnitude is much bigger than Helmholtz data would predict

This was fixed by lots of tuning, but not easy



- Air core coils too weak
- Steel core EM skews wouldn’t fit in space allowed
- Magic fingers still require shimming, violate several specs
- Tuned by shimming and other methods

- Multipoles after tuning are 100X smaller, met all specs

Need something better

- Effect is small, < 0.1%, 0.1deg and hard to measure or control
- Large magnets more likely to have problem
- These are made from multiple pieces so sorting is challenging
- Example below for ILC DR may be helpful
- Measurements (later this year) will tell if it works

ILC Damping Ring Wiggler Example

DOE SBIR- Phase II

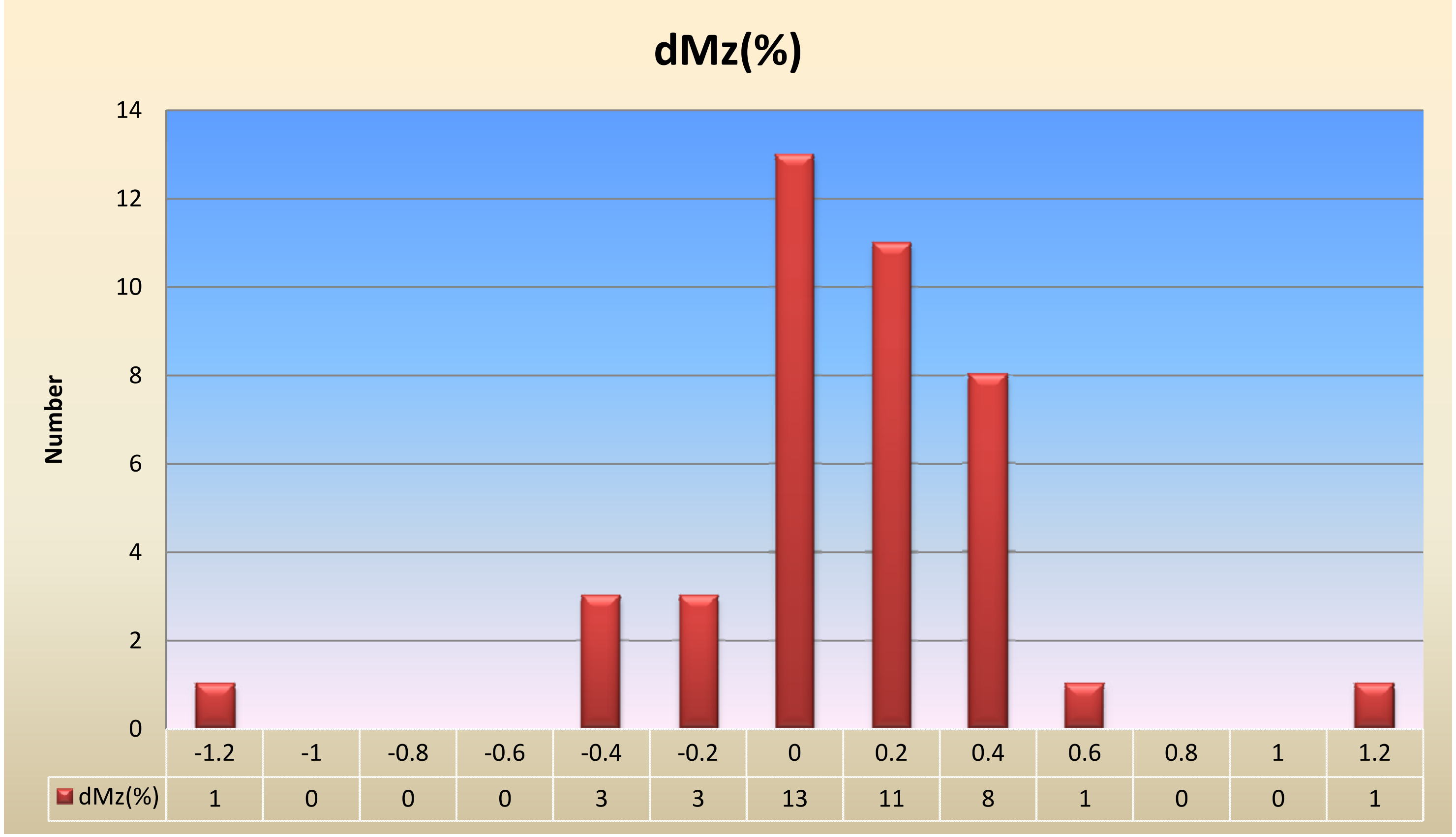
ILC DR Wiggler parameters

- Period 400mm !!
- Poles are huge. Magnets made from 9 pieces/magnet like SRRC W20
- Making a full-sized, half-period prototype
- Peak field 1.8T, flat topped, maximized B^2 integral
  - Pole axial thickness 120mm, different widths and shapes
  - Magnet axial thickness 80mm
- Energy 1 GeV
- Wiggle amplitude is 5mm!
- See PAC05 workshop presentation for details

FEA Model

- Multi-piece magnet
  - 4 half magnets, 36 bricks total with 4 orientations/brick
  - 3D, shaped pole
- Choose bricks
- Calculate B
  - Fully non-linear with 3D, shaped, VP poles
  - Measured Mx, My, Mz for each brick
  - All interactions included
  - Signature functions not needed
- Evaluate goal function, objectives

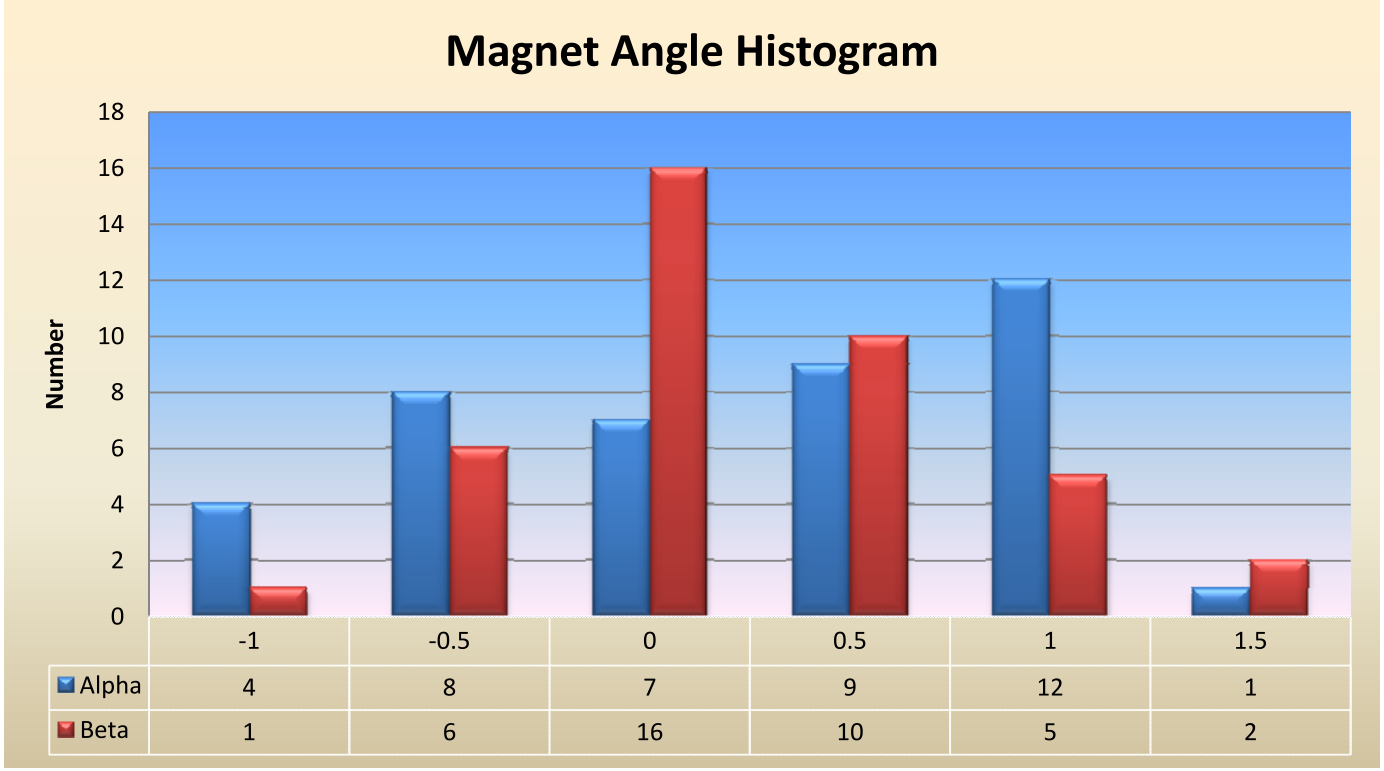
ILC Magnet strength histogram



	-1.2	-1	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8	1	1.2
🟥 dMz(%)	1	0	0	0	3	3	13	11	8	1	0	0	1

Magnets are in spec. The distribution is quite narrow, essentially 0.5% covers all but two magnets

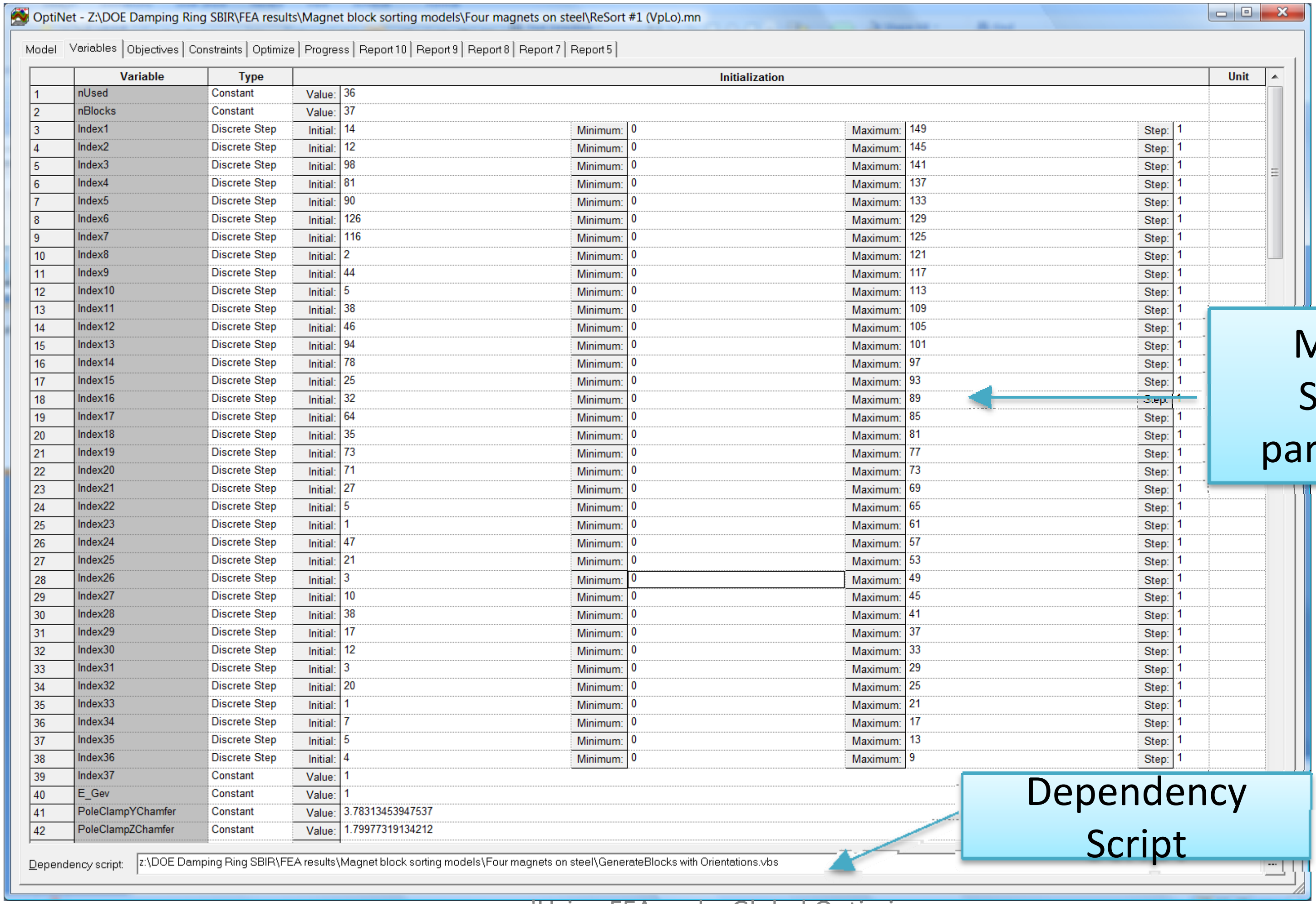
ILC Magnet angle histogram



	-1	-0.5	0	0.5	1	1.5
🟦 Alpha	4	8	7	9	12	1
🟥 Beta	1	6	16	10	5	2

- Angles are all in-spec. No correlation between the angles.

OptiNet Sorting Parameters



OptiNet - Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\Four magnets on steel\ReSort #1 (VpLo).mn

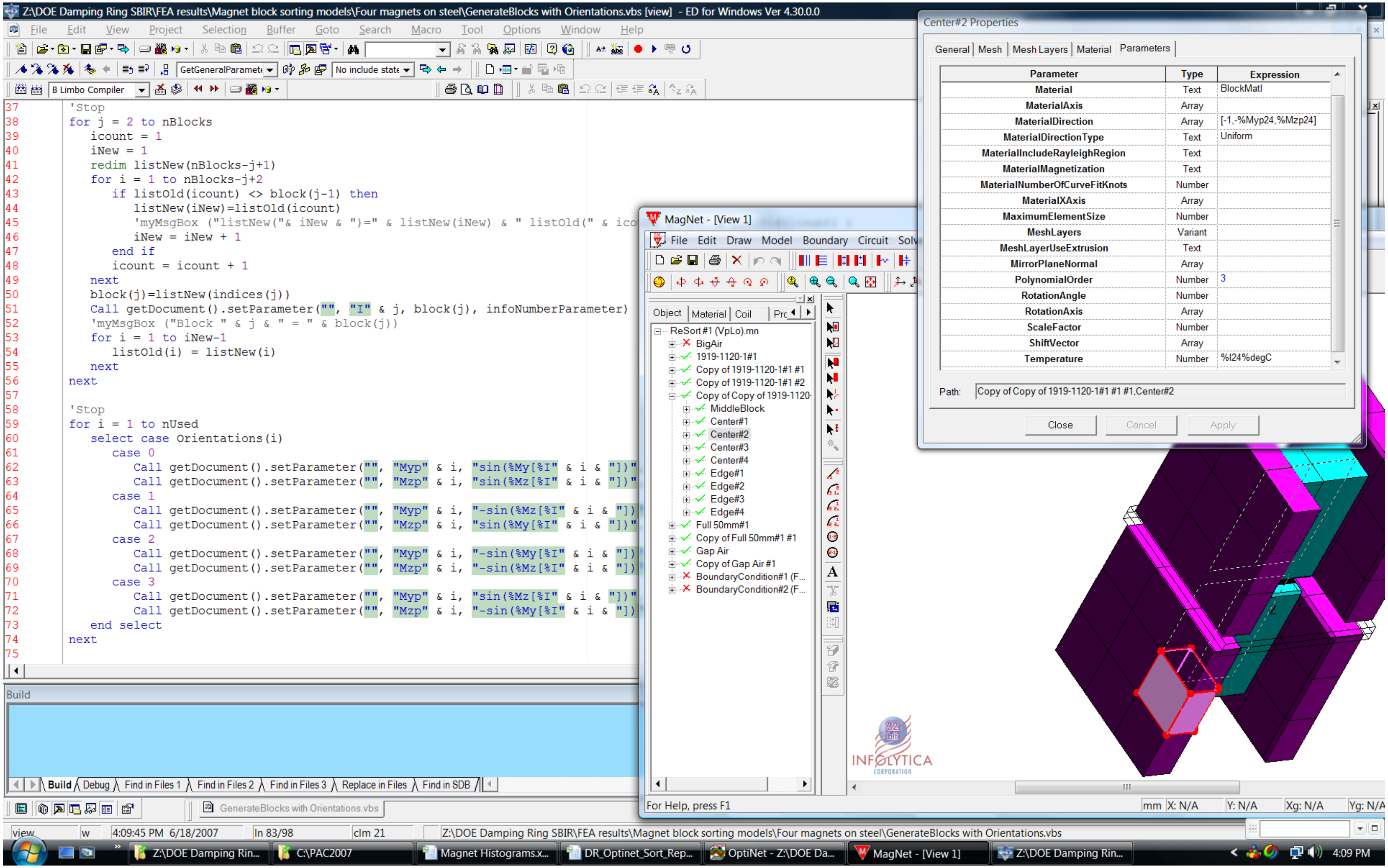
	Variable	Type	Initialization								Unit
1	nUsed	Constant	Value:	36							
2	nBlocks	Constant	Value:	37							
3	Index1	Discrete Step	Initial:	14	Minimum:	0	Maximum:	149	Step:	1	
4	Index2	Discrete Step	Initial:	12	Minimum:	0	Maximum:	145	Step:	1	
5	Index3	Discrete Step	Initial:	98	Minimum:	0	Maximum:	141	Step:	1	
6	Index4	Discrete Step	Initial:	81	Minimum:	0	Maximum:	137	Step:	1	
7	Index5	Discrete Step	Initial:	90	Minimum:	0	Maximum:	133	Step:	1	
8	Index6	Discrete Step	Initial:	126	Minimum:	0	Maximum:	129	Step:	1	
9	Index7	Discrete Step	Initial:	116	Minimum:	0	Maximum:	125	Step:	1	
10	Index8	Discrete Step	Initial:	2	Minimum:	0	Maximum:	121	Step:	1	
11	Index9	Discrete Step	Initial:	44	Minimum:	0	Maximum:	117	Step:	1	
12	Index10	Discrete Step	Initial:	5	Minimum:	0	Maximum:	113	Step:	1	
13	Index11	Discrete Step	Initial:	38	Minimum:	0	Maximum:	109	Step:	1	
14	Index12	Discrete Step	Initial:	46	Minimum:	0	Maximum:	105	Step:	1	
15	Index13	Discrete Step	Initial:	94	Minimum:	0	Maximum:	101	Step:	1	
16	Index14	Discrete Step	Initial:	78	Minimum:	0	Maximum:	97	Step:	1	
17	Index15	Discrete Step	Initial:	25	Minimum:	0	Maximum:	93	Step:	1	
18	Index16	Discrete Step	Initial:	32	Minimum:	0	Maximum:	89	Step:	1	
19	Index17	Discrete Step	Initial:	64	Minimum:	0	Maximum:	85	Step:	1	
20	Index18	Discrete Step	Initial:	35	Minimum:	0	Maximum:	81	Step:	1	
21	Index19	Discrete Step	Initial:	73	Minimum:	0	Maximum:	77	Step:	1	
22	Index20	Discrete Step	Initial:	71	Minimum:	0	Maximum:	73	Step:	1	
23	Index21	Discrete Step	Initial:	27	Minimum:	0	Maximum:	69	Step:	1	
24	Index22	Discrete Step	Initial:	5	Minimum:	0	Maximum:	65	Step:	1	
25	Index23	Discrete Step	Initial:	1	Minimum:	0	Maximum:	61	Step:	1	
26	Index24	Discrete Step	Initial:	47	Minimum:	0	Maximum:	57	Step:	1	
27	Index25	Discrete Step	Initial:	21	Minimum:	0	Maximum:	53	Step:	1	
28	Index26	Discrete Step	Initial:	3	Minimum:	0	Maximum:	49	Step:	1	
29	Index27	Discrete Step	Initial:	10	Minimum:	0	Maximum:	45	Step:	1	
30	Index28	Discrete Step	Initial:	38	Minimum:	0	Maximum:	41	Step:	1	
31	Index29	Discrete Step	Initial:	17	Minimum:	0	Maximum:	37	Step:	1	
32	Index30	Discrete Step	Initial:	12	Minimum:	0	Maximum:	33	Step:	1	
33	Index31	Discrete Step	Initial:	3	Minimum:	0	Maximum:	29	Step:	1	
34	Index32	Discrete Step	Initial:	20	Minimum:	0	Maximum:	25	Step:	1	
35	Index33	Discrete Step	Initial:	1	Minimum:	0	Maximum:	21	Step:	1	
36	Index34	Discrete Step	Initial:	7	Minimum:	0	Maximum:	17	Step:	1	
37	Index35	Discrete Step	Initial:	5	Minimum:	0	Maximum:	13	Step:	1	
38	Index36	Discrete Step	Initial:	4	Minimum:	0	Maximum:	9	Step:	1	
39	Index37	Constant	Value:	1							
40	E_Gev	Constant	Value:	1							
41	PoleClampYChamfer	Constant	Value:	3.78313453947537							
42	PoleClampZChamfer	Constant	Value:	1.79977319134212							

Dependency script: z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\Four magnets on steel\GenerateBlocks with Orientations.vbs

Magnet Sorting parameters

Dependency Script

SCREEN SHOT SHOWING HOW SORTING INCLUDED IN FEA MODEL



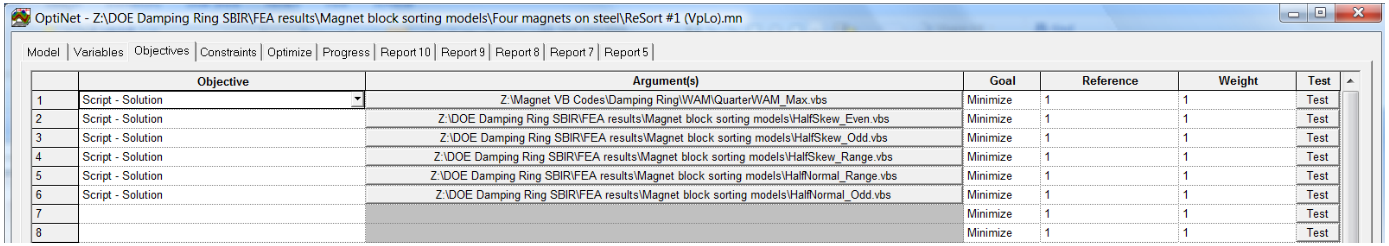
```
'Stop
for j = 2 to nBlocks
   icount = 1
   iNew = 1
   redim listNew(nBlocks-j+1)
   for i = 1 to nBlocks-j+2
      if listOld(icount) <> block(j-1) then
         listNew(iNew)=listOld(icount)
         'myMsgBox ("listNew("& iNew & ")=" & listNew(iNew) & " listOld(" & ico
         iNew = iNew + 1
      end if
      icount = icount + 1
   next
   block(j)=listNew(indices(j))
   Call getDocument().setParameter("", "I" & j, block(j), infoNumberParameter)
   'myMsgBox ("Block " & j & " = " & block(j))
   for i = 1 to iNew-1
      listOld(i) = listNew(i)
   next
next

'Stop
for i = 1 to nUsed
   select case Orientations(i)
      case 0
         Call getDocument().setParameter("", "Myp" & i, "sin(%My[%I" & i & "])"
         Call getDocument().setParameter("", "Mzp" & i, "sin(%Mz[%I" & i & "])"
      case 1
         Call getDocument().setParameter("", "Myp" & i, "-sin(%Mz[%I" & i & "])
         Call getDocument().setParameter("", "Mzp" & i, "sin(%My[%I" & i & "])"
      case 2
         Call getDocument().setParameter("", "Myp" & i, "-sin(%My[%I" & i & "])
         Call getDocument().setParameter("", "Mzp" & i, "-sin(%Mz[%I" & i & "])
      case 3
         Call getDocument().setParameter("", "Myp" & i, "sin(%Mz[%I" & i & "])"
         Call getDocument().setParameter("", "Mzp" & i, "-sin(%My[%I" & i & "])
   end select
next
```

Parameter	Type	Expression
Material	Text	BlockMatl
MaterialAxis	Array	
MaterialDirection	Array	[-1,-%Myp24,%Mzp24]
MaterialDirectionType	Text	Uniform
MaterialIncludeRayleighRegion	Text	
MaterialMagnetization	Text	
MaterialNumberOfCurveFitKnots	Number	
MaterialXAxis	Array	
MaximumElementSize	Number	
MeshLayers	Variant	
MeshLayerUseExtrusion	Text	
MirrorPlaneNormal	Array	
PolynomialOrder	Number	3
RotationAngle	Number	
RotationAxis	Array	
ScaleFactor	Number	
ShiftVector	Array	
Temperature	Number	%I24%degC

Path: Copy of Copy of 1919-1120-1#1 #1 #1,Center#2

Sorting objective functions

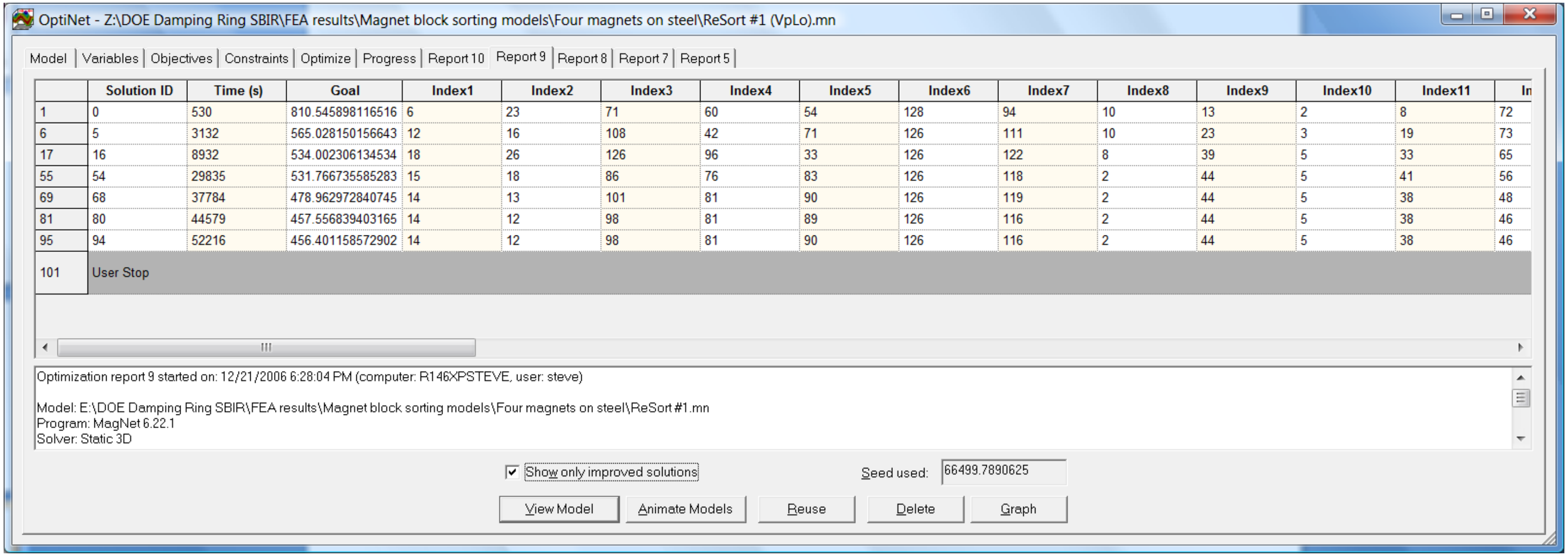


OptiNet - Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\Four magnets on steel\ReSort #1 (VpLo).mn

	Objective	Argument(s)	Goal	Reference	Weight	Test
1	Script - Solution	Z:\Magnet VB Codes\Damping Ring\WAM\QuarterWAM_Max.vbs	Minimize	1	1	Test
2	Script - Solution	Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\HalfSkew_Even.vbs	Minimize	1	1	Test
3	Script - Solution	Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\HalfSkew_Odd.vbs	Minimize	1	1	Test
4	Script - Solution	Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\HalfSkew_Range.vbs	Minimize	1	1	Test
5	Script - Solution	Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\HalfNormal_Range.vbs	Minimize	1	1	Test
6	Script - Solution	Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\HalfNormal_Odd.vbs	Minimize	1	1	Test
7			Minimize	1	1	Test
8			Minimize	1	1	Test

- The goal is to reduce all multipoles.
  - Goal is weighted sum of objectives
  - Objectives can be pre-programmed or user supplied
- The line integrals over a half-period plus a dynamic multipole are used
- Dynamic multipole sample B field over 25mm aperture
- Multipole range is simply the (max-min) over a 20mm aperture
- Even integrals are (I(+x)+I(-x))/2
- Odd integrals are (I(+x)-I(-x))/2

Sorting goal summary



	Solution ID	Time (s)	Goal	Index1	Index2	Index3	Index4	Index5	Index6	Index7	Index8	Index9	Index10	Index11	In
1	0	530	810.545898116516	6	23	71	60	54	128	94	10	13	2	8	72
6	5	3132	565.028150156643	12	16	108	42	71	126	111	10	23	3	19	73
17	16	8932	534.002306134534	18	26	126	96	33	126	122	8	39	5	33	65
55	54	29835	531.766735585283	15	18	86	76	83	126	118	2	44	5	41	56
69	68	37784	478.962972840745	14	13	101	81	90	126	119	2	44	5	38	48
81	80	44579	457.556839403165	14	12	98	81	89	126	116	2	44	5	38	46
95	94	52216	456.401158572902	14	12	98	81	90	126	116	2	44	5	38	46
101	User Stop														

Optimization report 9 started on: 12/21/2006 6:28:04 PM (computer: R146XPSTEVE, user: steve)

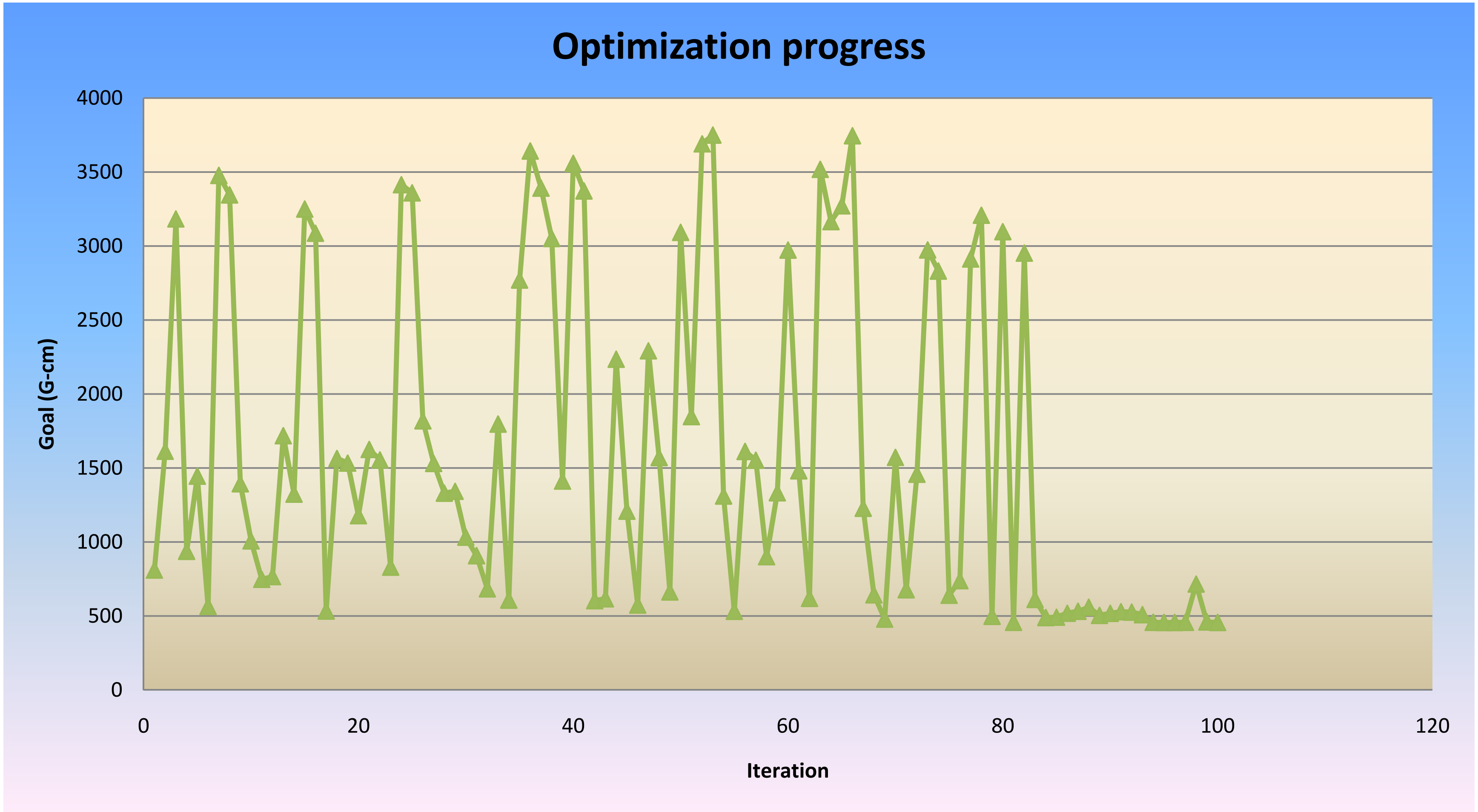
Model: E:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\Four magnets on steel\ReSort #1.mn
Program: MagNet 6.22.1
Solver: Static 3D

☑ Show only improved solutions

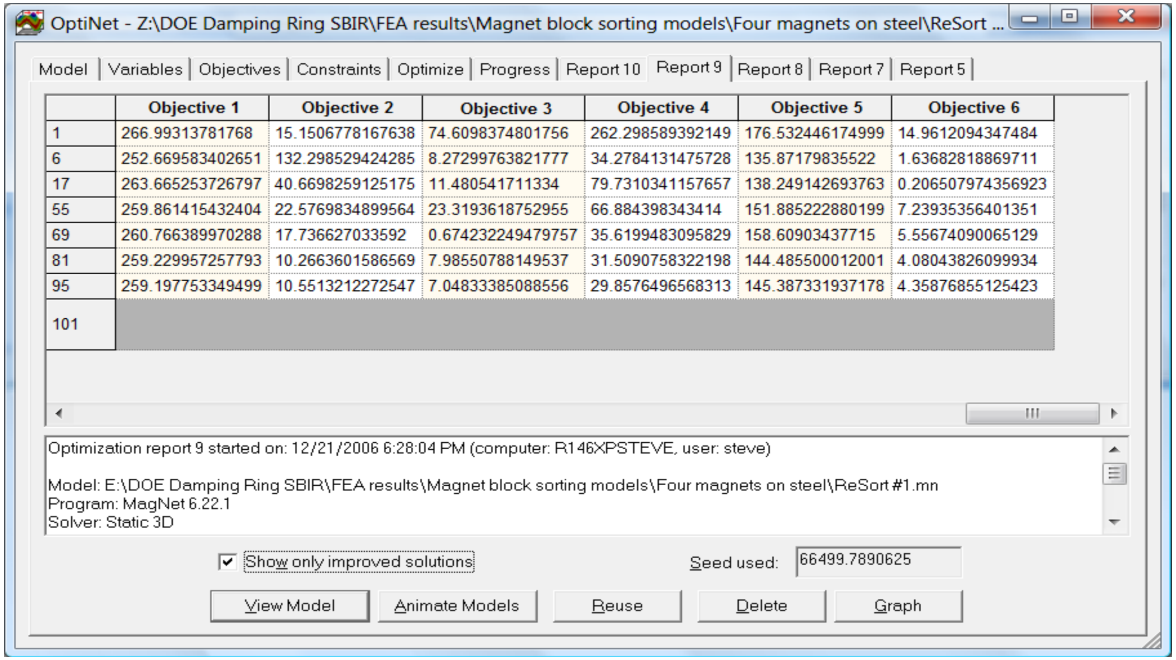
Seed used: 66499.7890625

- Table shows sorts that improved the goal function. Other sorts were 10X worse

Goal Function During Optimization Demonstrates Importance of Magnet Homogeneity



Undesirable Multipoles Improved by Sorting



OptiNet - Z:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\Four magnets on steel\ReSort ...

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5	Objective 6
1	266.99313781768	15.1506778167638	74.6098374801756	262.298589392149	176.532446174999	14.9612094347484
6	252.669583402651	132.298529424285	8.27299763821777	34.2784131475728	135.87179835522	1.63682818869711
17	263.665253726797	40.6698259125175	11.480541711334	79.7310341157657	138.249142693763	0.206507974356923
55	259.861415432404	22.5769834899564	23.3193618752955	66.884398343414	151.885222880199	7.23935356401351
69	260.766389970288	17.736627033592	0.674232249479757	35.6199483095829	158.60903437715	5.55674090065129
81	259.229957257793	10.2663601586569	7.98550788149537	31.5090758322198	144.485500012001	4.08043826099934
95	259.197753349499	10.5513212272547	7.04833385088556	29.8576496568313	145.387331937178	4.35876855125423
101						

```
Optimization report 9 started on: 12/21/2006 6:28:04 PM (computer: R146XPSTEVE, user: steve)

Model: E:\DOE Damping Ring SBIR\FEA results\Magnet block sorting models\Four magnets on steel\ReSort #1.mn
Program: MagNet 6.22.1
Solver: Static 3D
```

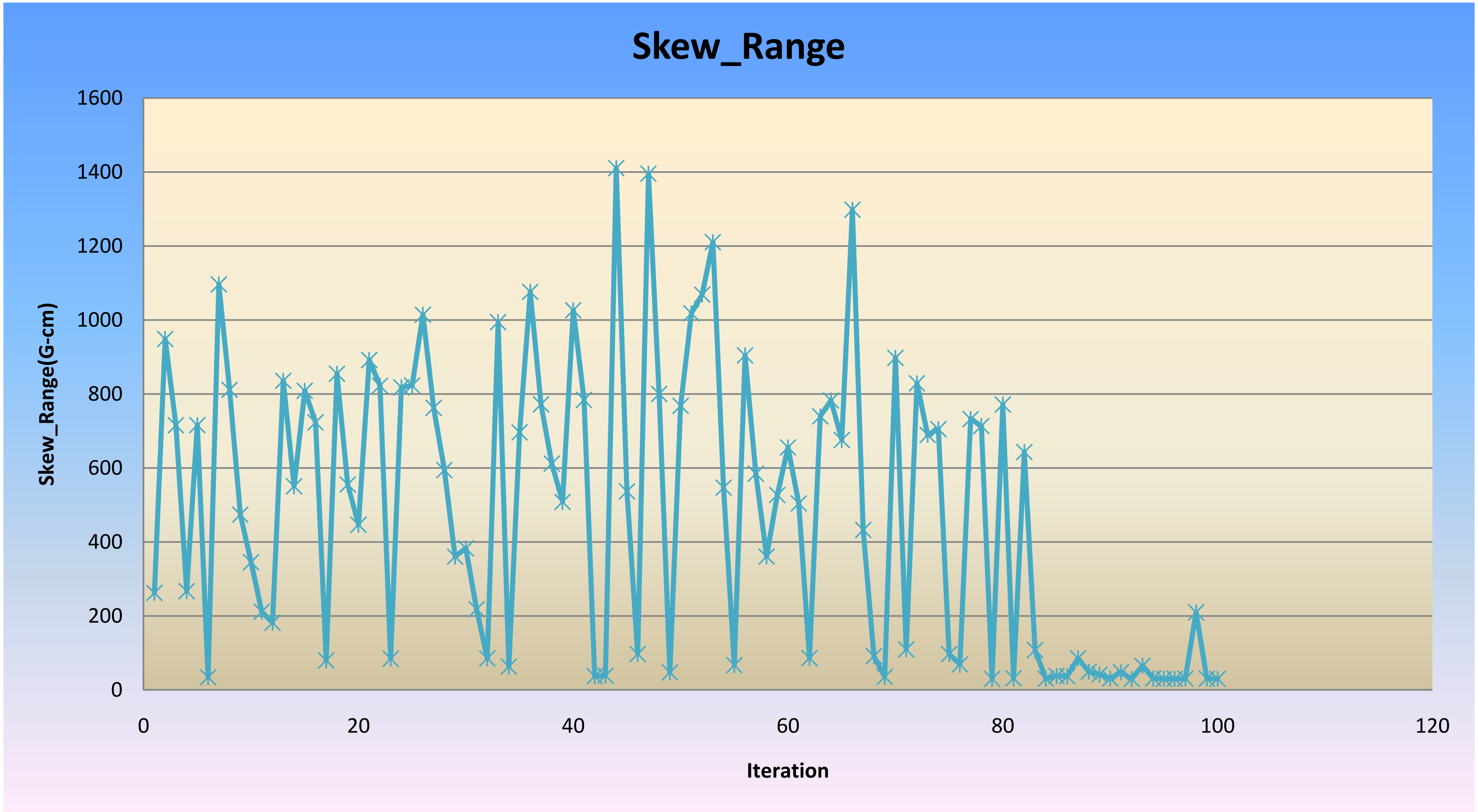
☑ Show only improved solutions

Seed used: 66499.7890625

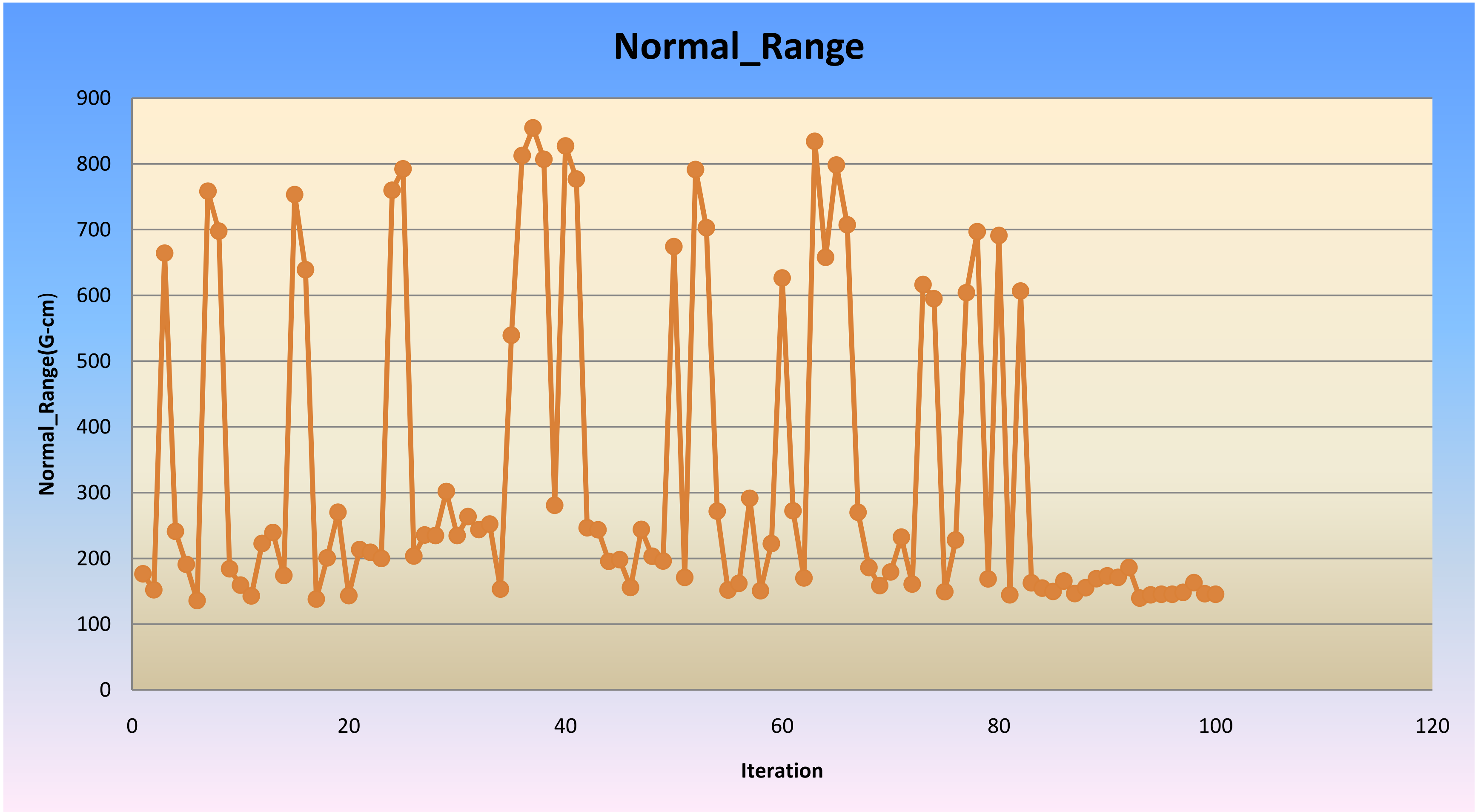
Half-period integral about 250,000 G-cm!

Objective	Function	x range	Ideal value	Final value (G-cm)
1	Dynamic multipole	25 mm	Finite	259
2	Even skew	20 mm	Zero	11
3	Odd skew	20 mm	Zero	7
4	Skew range	20 mm	Zero	30
5	Normal range	20 mm	Finite	145
6	Odd normal	20 mm	Zero	4

Skew multipole Improvement



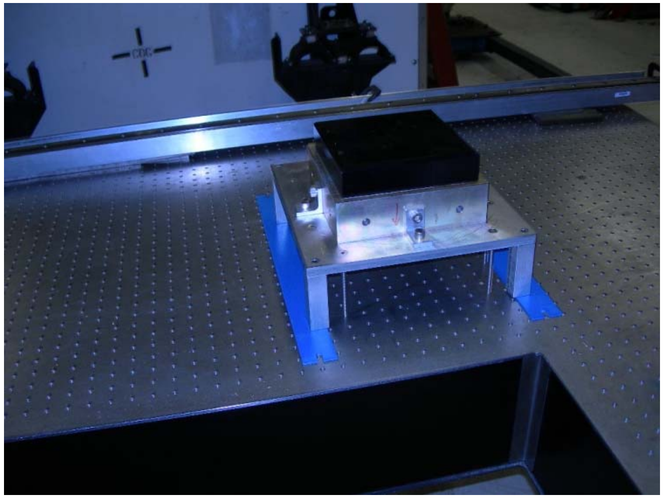
Normal Multipole Improvement

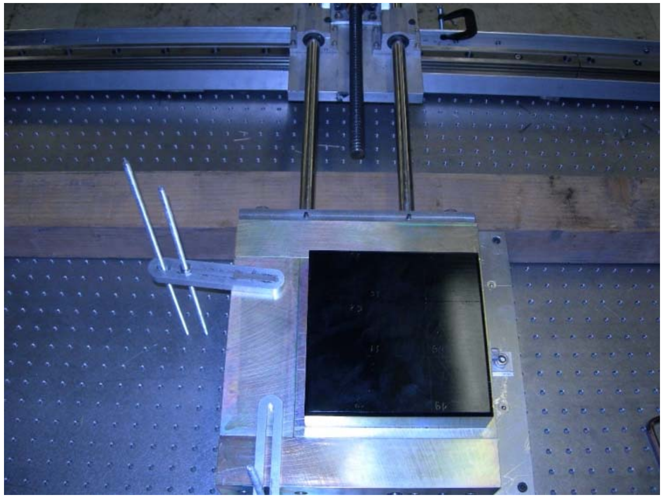


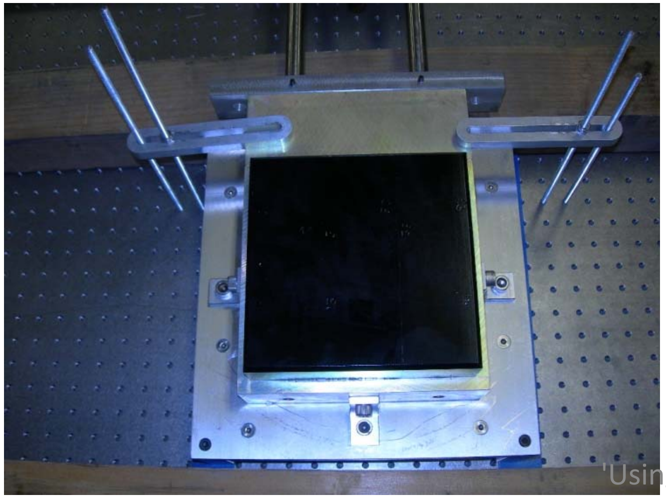
Optimization Summary

- Without sorting a random mix of small magnets would still meet 1.5%, 1.5 deg specs
- Without sorting skew multipoles could be gigantic even when normal multipoles are small and vice-versa
- Optimizatoin reduced undesirable multipoles to numerically insignificant levels

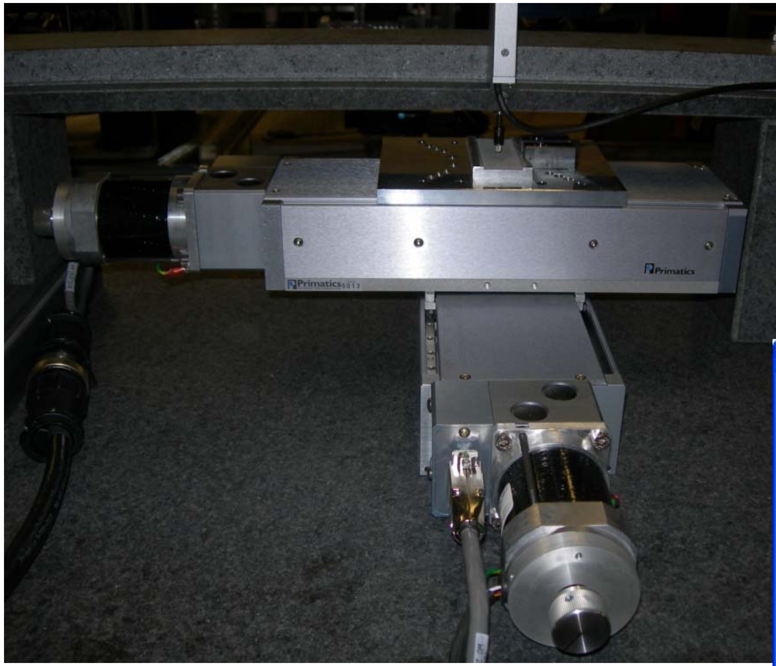
ILC DRW Magnet pictures



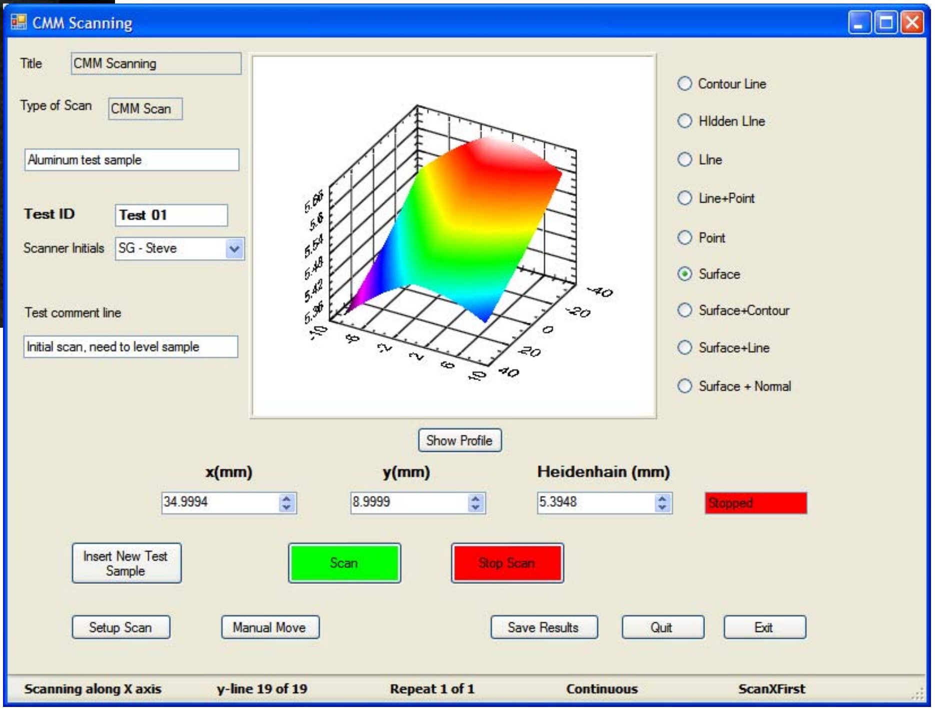




Pole Profile CMM pictures



- Scanner SW written to collect data in variety of protocols
- Separate post-processing code for QA
- Data stored in database


CMM Scanning

Title: CMM Scanning
Type of Scan: CMM Scan
Aluminum test sample
Test ID: **Test 01**
Scanner Initials: SG - Steve
Test comment line: Initial scan, need to level sample

○ Contour Line
○ HIdden LIne
○ LIne
○ Line+Point
○ Point
● Surface
○ Surface+Contour
○ Surface+Line
○ Surface + Normal

x(mm)	**y(mm)**	**Heidenhain (mm)**	
34.9994	8.9999	5.3948	Stopped

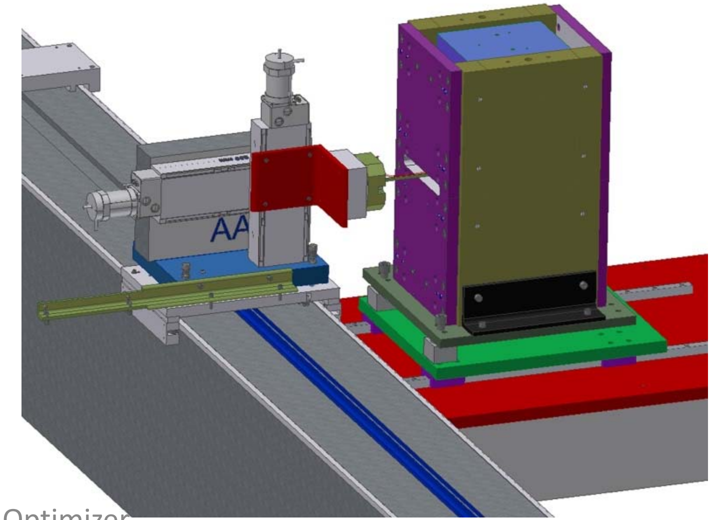
Scanning along X axis **y-line 19 of 19** **Repeat 1 of 1** **Continuous** **ScanXFirst**

- Used to test pole profile
- Stages with < 1micron accuracy
    - Interferometer calibrated
- Resolution 0.1micron
- Heidenhain metrology gage, 50 nm resolution, 100nm accuracy

Scanner pictures

- Once poles are inspected the stages will be moved to the 7-m bench for magnetic field scanning
- Half-period prototype will be tested for 6 pole shapes and results compared to FEA

- CMM Stages will be moved to 7-m scanner
- Lab temp controlled to 0.1 degC



ILC DRW Status

- Assembly tooling, etc made based on FEA forces as parts move into position
- Magnets have been received and waiting for poles
- Scanning will start soon

Conclusions

- Inhomogeneity is really important for larger magnets
- Use FEA to guide sorting
- Newer, faster computers allow more realistic calculations
  - Full FEA
  - Signature convolution
- Planning to revisit homogeneity scanning on new scanner