ILC Damping Ring Wiggler Prototype comparison of FEA predictions with Magnetic Measurements

Steve Gottschalk
STI Optronics Inc

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Main goals

- Reduce DRW cost
- Design the DRW to produce small dynamic multipoles
  - Caused by wiggle amplitude, $K/(k_w*\gamma)=0.934*B(T)*\lambda^2{}_w(cm)/(2\pi*\gamma)$
    - Quadratic rolloff causes quadrupole
    - Fourth order rolloff causes octupole
    - Sixth order rolloff causes duodecapole
  - They are energy dependent. Tuning after assembly is energy independent.
  - Best is to tune random errors, not add band aids when poor design causes dynamic multipoles
- Apply methods to other ID's

Summary

- Damping rings are used to reduce beam emittance by synchrotron radiation cooling. The damping time depends on the B^2 integral. Damping ring wigglers (DRW) are used to do this.
- For one iteration of the ILC DRW the period was quite large, about 400mm.
- The radiation being emitted in the ring is **100's of kW**. Standard SR have parasitic radiation, but not here. Superconducting wigglers will quench quite easily. EM wigglers will require huge amounts of power. PM wigglers are one solution. However, the amount of magnet required for the wigglers is an issue. Standard wigglers use wide poles. For small period devices that is acceptable, but the cost is prohibitive for large periods. In addition, if the poles are wide, the magnetic force grows. For a 10 period wiggler, wide poles have **100,000 lbs** force while narrow poles reduce this to **50,000 lbs**, which is "typical" of wigglers already made.
- The narrow pole, optimized DRW has a cost that is about **60% of the cost** of a wide pole DRW.
- The risk is that the field quality will be insufficient.
- This SBIR showed that with careful analysis, design, manufacturing and QA that the present state-of-the-art is able to achieve the required quality.

FEA Requirements

- Must be parametric
  - Geometry
  - Material
- Automation
- Global optimizer
  - Tightly integrated with parametric and automation
- Well tested and robust

Outline

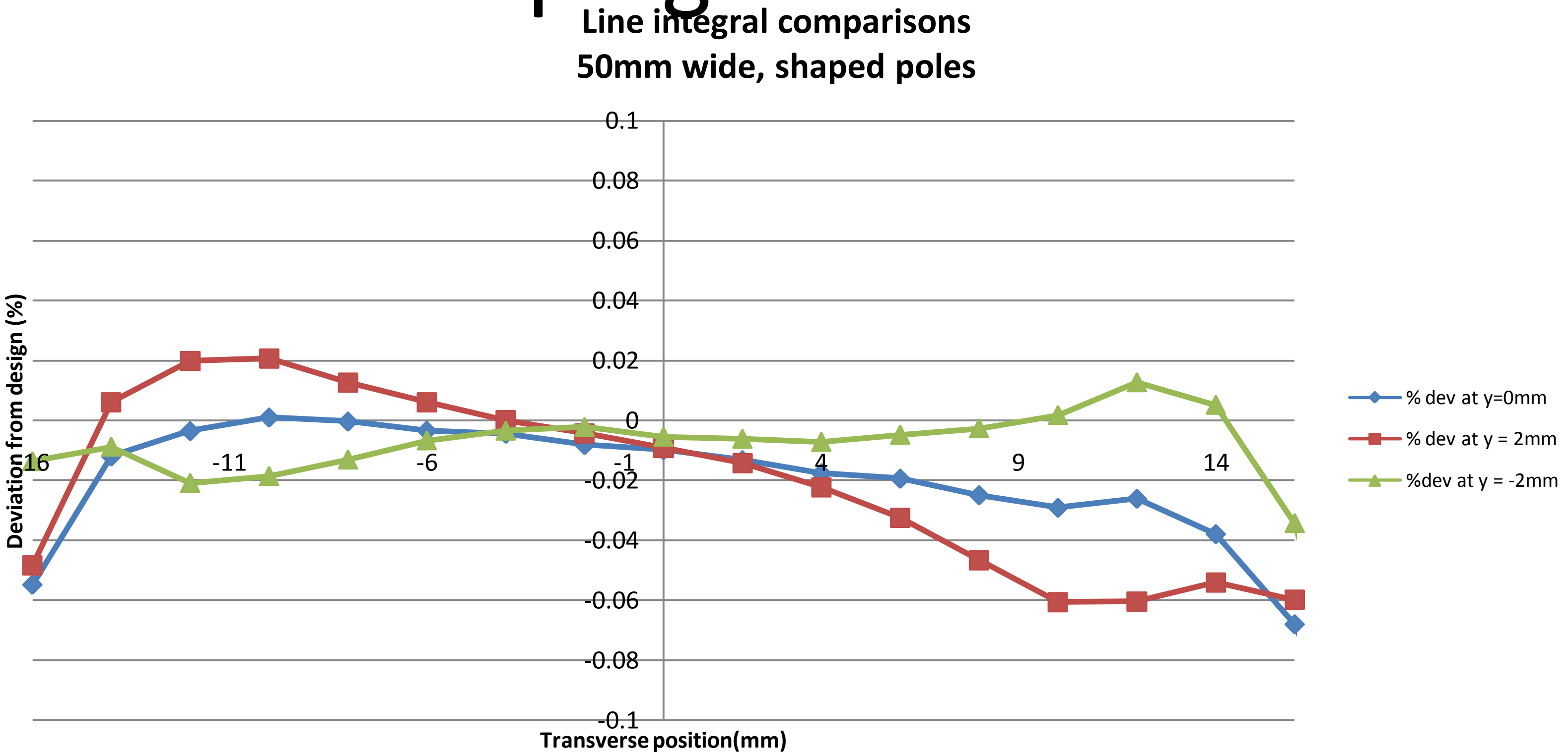
- Specifications and summary of comparisons with FEA
- FEA based cost saving estimates
- FEA results
- Measurements and data analysis
- Conclusion

SPECIFICATIONS AND SUMMARY OF COMPARISONS WITH FEA

ILC-DRW Specifications

Property	SBIR Value	Comments
Period	400mm	ILC-DW specification. Largest period ever made.
Peak field	1.8Tesla	ILC-DW specification. Causes substantial pole saturation
Gap	20mm	ILC-DW Specification
Axial field shape	Square wave to maximize integral of B^2	Minimize damping time. The thick poles achieve B^2 integrals = $0.67*B^2*(\lambda_w/2)$.
Half-period integral	250,000 G-cm	Result of maximizing B^2 integral. Standard wiggler integral < 90,000 G-cm, undulators < 10,000 G-cm
Beam energy	1 GeV	ILC-DW Specification
Wiggle amplitude	5mm peak-to-peak	Wigglers <0.3mm, undulators much less
Pole axial length	120mm	Maximized B^2 integral

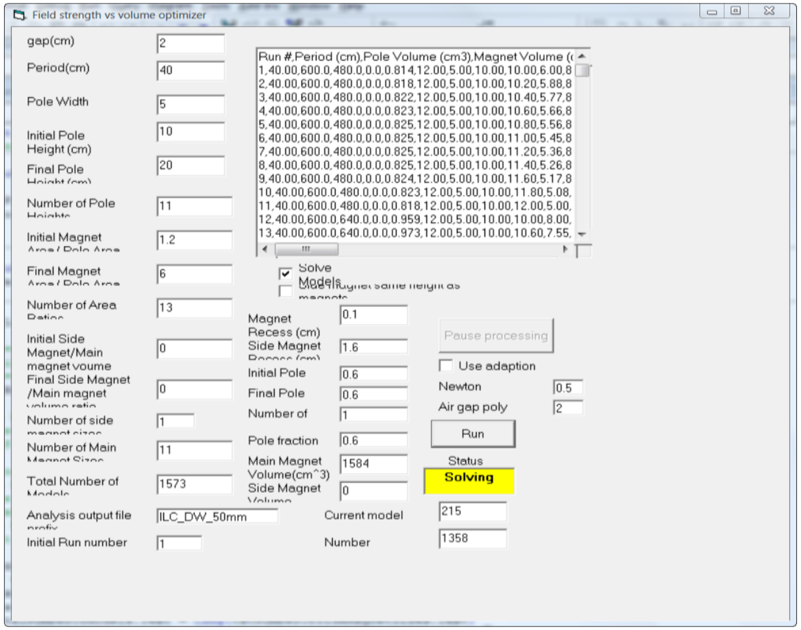
Comparisons with FEA show Pole Shaping Achieved Goals



Volume	B field P-to-P	Int P-to-P	Int RMS
32mm x 4mm x 190mm	0.07%	0.09%	0.0218%
32mm x 0mm x 190 mm	0.035%	0.07%	0.0193%

FEA BASED COST SAVING ESTIMATES

3D parametric code used to calculate B for many magnet and pole sizes



gap(cm) 2
Period(cm) 40
Pole Width 5
Initial Pole Height (cm) 10
Final Pole Height (cm) 20
Number of Pole Heights 11
Initial Magnet Area / Pole Area 1.2
Final Magnet Area / Pole Area 6
Number of Area Ratios 13
Initial Side Magnet/Main magnet voume 0
Final Side Magnet /Main magnet volume ratio 0
Number of side magnet sizes 1
Number of Main Magnet Sizes 11
Total Number of Models 1573
Analysis output file prefix ILC_DW_50mm
Initial Run number 1

```
Run #,Period (cm),Pole Volume (cm3),Magnet Volume (c
1,40.00,600.0,480.0,0.0,0.814,12.00,5.00,10.00,10.00,6.00,8
2,40.00,600.0,480.0,0.0,0.818,12.00,5.00,10.00,10.20,5.88,8
3,40.00,600.0,480.0,0.0,0.822,12.00,5.00,10.00,10.40,5.77,8
4,40.00,600.0,480.0,0.0,0.823,12.00,5.00,10.00,10.60,5.66,8
5,40.00,600.0,480.0,0.0,0.825,12.00,5.00,10.00,10.80,5.56,8
6,40.00,600.0,480.0,0.0,0.825,12.00,5.00,10.00,11.00,5.45,8
7,40.00,600.0,480.0,0.0,0.825,12.00,5.00,10.00,11.20,5.36,8
8,40.00,600.0,480.0,0.0,0.825,12.00,5.00,10.00,11.40,5.26,8
9,40.00,600.0,480.0,0.0,0.824,12.00,5.00,10.00,11.60,5.17,8
10,40.00,600.0,480.0,0.0,0.823,12.00,5.00,10.00,11.80,5.08,
11,40.00,600.0,480.0,0.0,0.818,12.00,5.00,10.00,12.00,5.00,
12,40.00,600.0,640.0,0.0,0.959,12.00,5.00,10.00,10.00,8.00,
13,40.00,600.0,640.0,0.0,0.973,12.00,5.00,10.00,10.60,7.55,
```

☑ Solve Models
☐ Side magnet same height as magnets

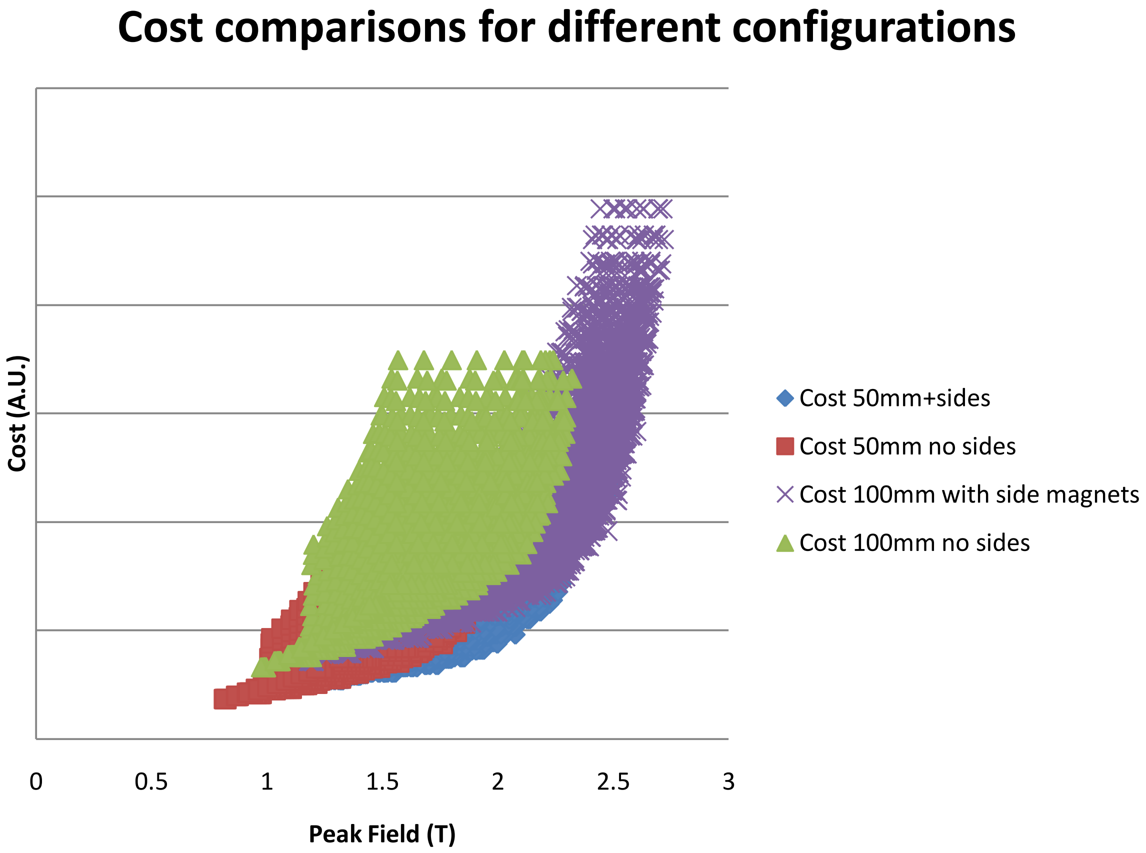
Magnet Recess (cm) 0.1
Side Magnet Recess (cm) 1.6
Initial Pole 0.6
Final Pole 0.6
Number of 1
Pole fraction 0.6
Main Magnet Volume(cm^3) 1584
Side Magnet Volume 0
Current model 215
Number 1358

☐ Use adaption
Newton 0.5
Air gap poly 2
Status **Solving**

- STI custom VB code (2000)
    - Automates MagNET objects
    - Create models, meshes, solves, post-processes
    - Object oriented, easy to understand
    - Output is CSV file with details
    - Easy to change outputs to reflect other figures of merit as the application requires

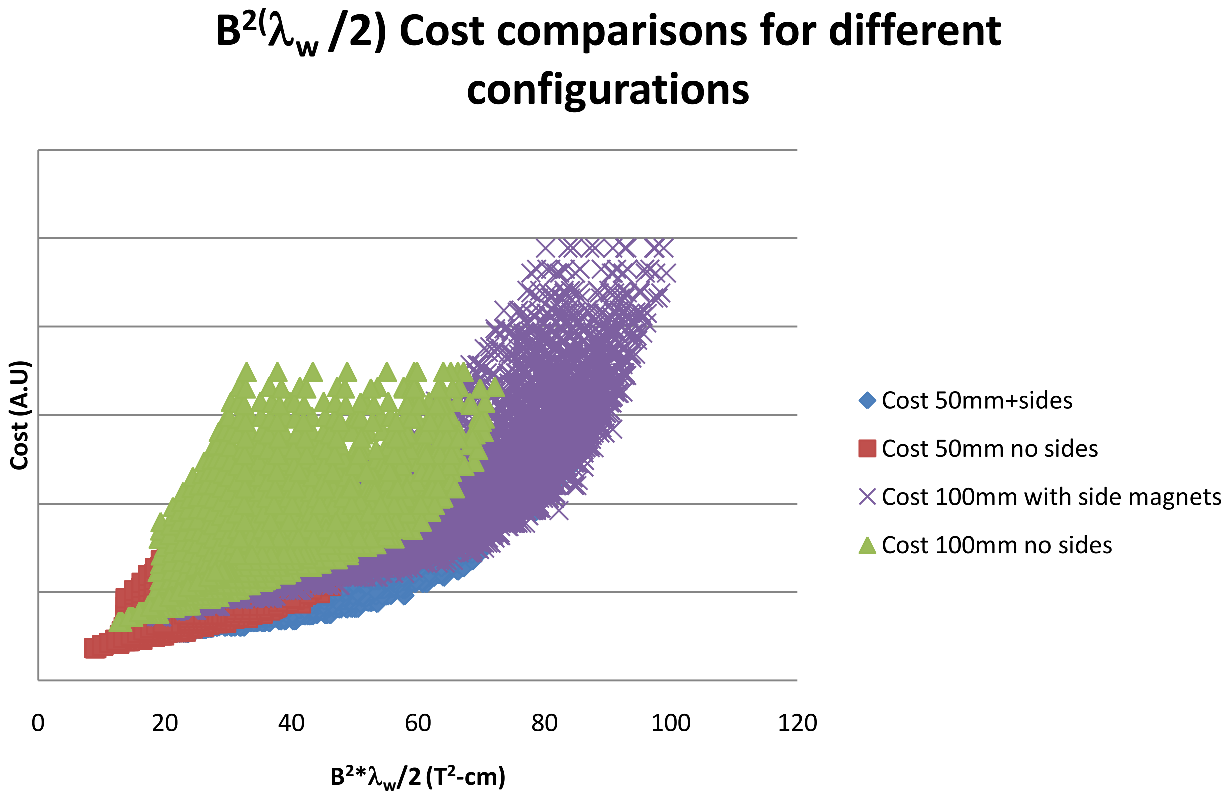
- Fixed gap and period
- Varied topology
    - Allowed designs with and without side magnets
- Varied geometry
    - Poles, main magnets, side magnets, transverse, vertical overhangs
- Recorded all parameters, on-axis peak field, By(x,0,z).
- Solved approximately 10,000 models

Costs (A.U) for different configurations



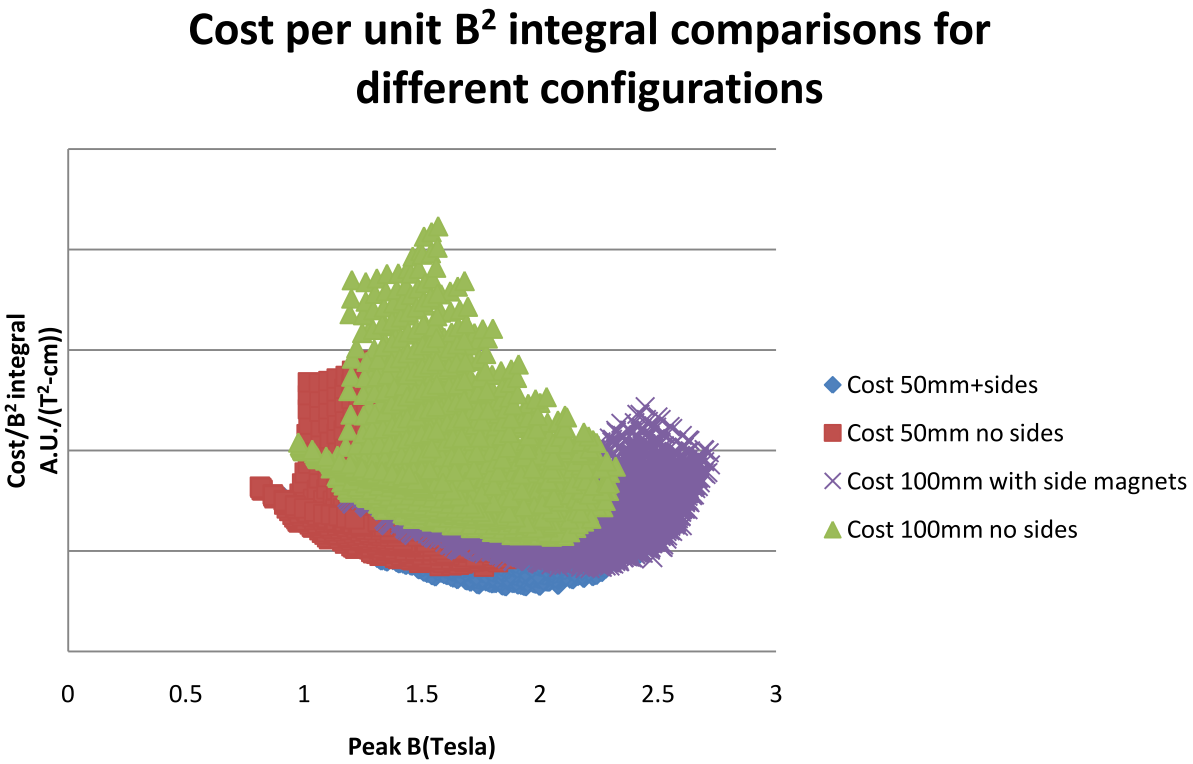
- Highly non-linear cost vs. field strength
  - Poles are heavily saturated. Small dB requires lots of dV.
  - Typical of all large period wigglers
  - Common for 1% dB /B to require 30% dV/V

Costs (A.U.) vs. $B^2*\lambda_w/2$



- Alternative is improvement in damping time, e.g. B^2 integral

System cost trades



Cost per unit B^2 integral comparisons for different configurations

- Useful to optimize *system* cost, e.g. Cost/B^2 integral. Implies overall length can be adjusted

Summary of optimum configurations based on FEA

Figure of merit	Value	Minimum cost configuration
Peak field	< 1.5 Tesla	50mm wide poles no side magnets
Peak field	1.5 – 2.3 Tesla	50mm wide poles with side magnets
Peak field	2.3 – 2.6 Tesla	100mm wide poles with side magnets
Peak field	>2.6 Tesla	Not analyzed, no conclusions
B^2 integral	< 25 T^2-cm	50mm wide poles no side magnets
B^2 integral	25 – 70 T^2-cm	50mm wide poles with side magnets
B^2 integral	70 – 120 T^2-cm	100mm wide poles with side magnets
B^2 integral	>120 T^2-cm	Not analyzed, no conclusions

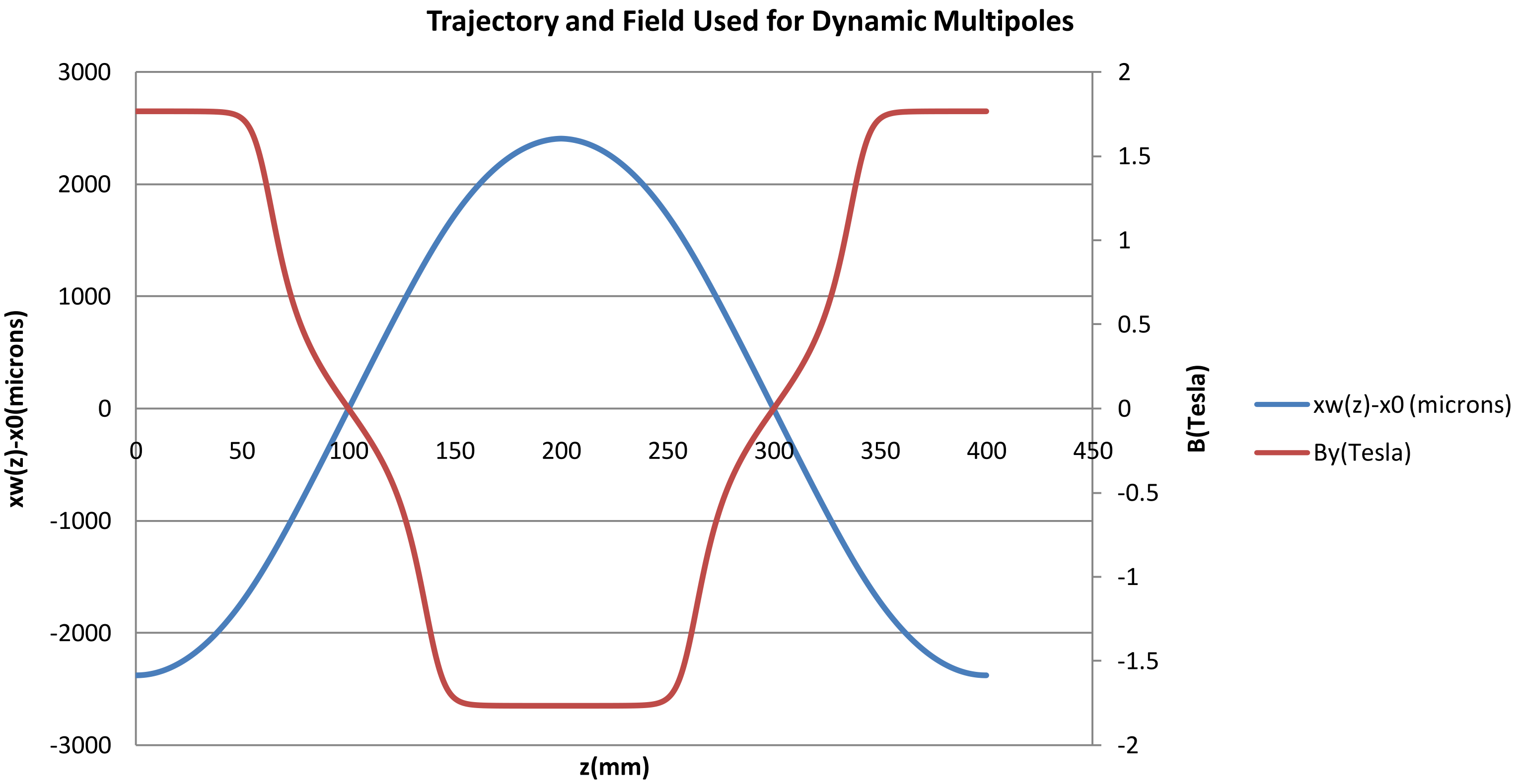
FEA RESULTS

Several approaches used

- Quarter period model
  - 2D pole axial width, axial chamfers on magnets, poles
  - 3D to get magnet and pole heights
  - 3D for pole shaping
  - See 2005 workshop for details
- Full model
  - Magnet homogeneity sorting
  - BH curve sensitivity
  - Geometry sensitivity
  - Used to compare FEA with measurements
- Codes are general and have been used to optimize other figures-of-merit

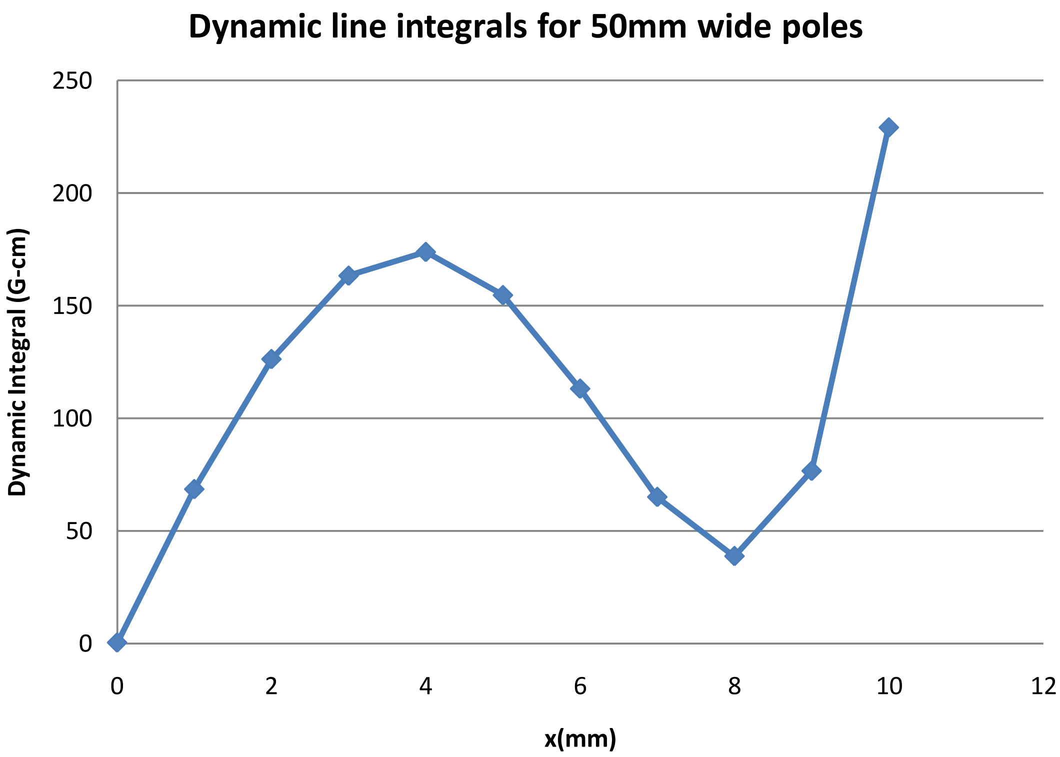
QUARTER PERIOD FEA

2D FEA to get pole axial shape



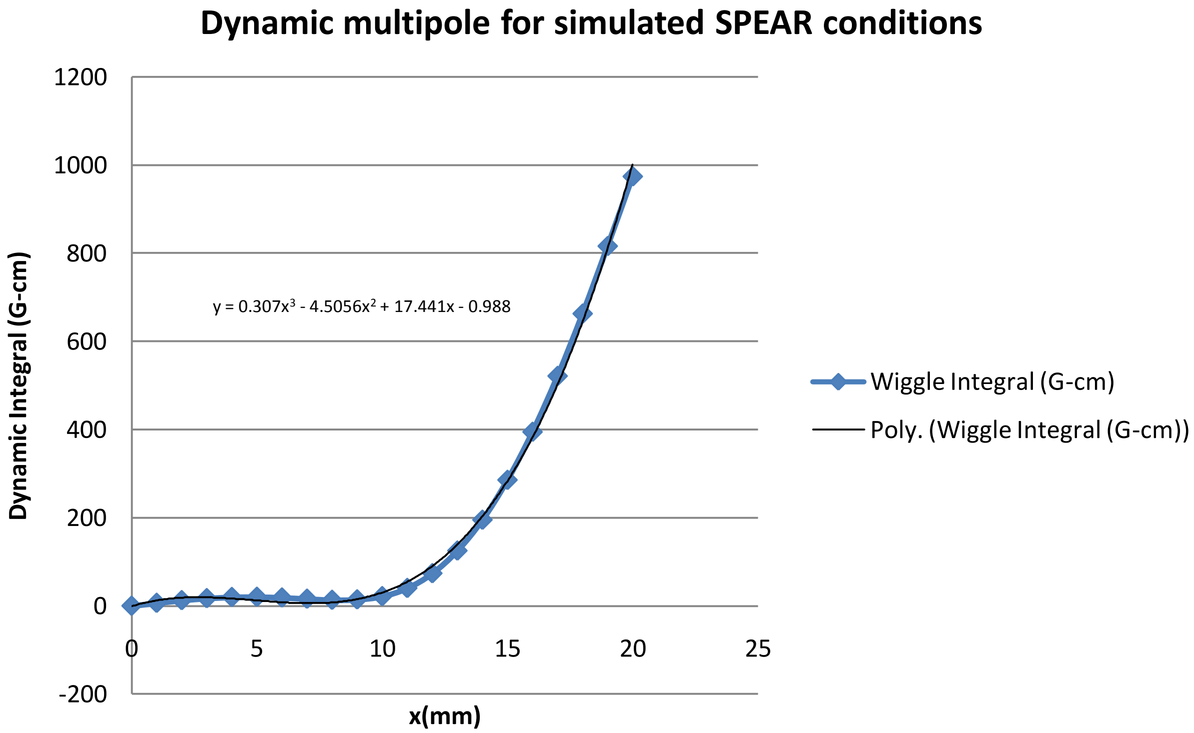
- Maximize B^2 integral to minimize damping time
- Result is very long pole
  - Standard insertion device has poles 40-25% of $\lambda_w/2$, magnets 60%-75% of $\lambda_w/2$
  - DRW has poles that are 60% of $\lambda_w/2$, magnets are 40% of $\lambda_w/2$

Optimization produced 13X lower dyanamic multipoles



- Flat pole has 3200 G-cm dynamic multipole
- Used OptiNET (Infolytica) global optimizer, parametric geometry, special dynamic multipole post-processing code to minimize peak-to-peak dynamic multipole variation.
- See presentation at 2005 workshop for process.

SPEAR BL11 dynamic multipole reduction



- BL11 dynamic octupole was 0.38 kG/cm2
- This design produces 0.0307 kG/cm2 for same wiggle amplitude (0.310mm)

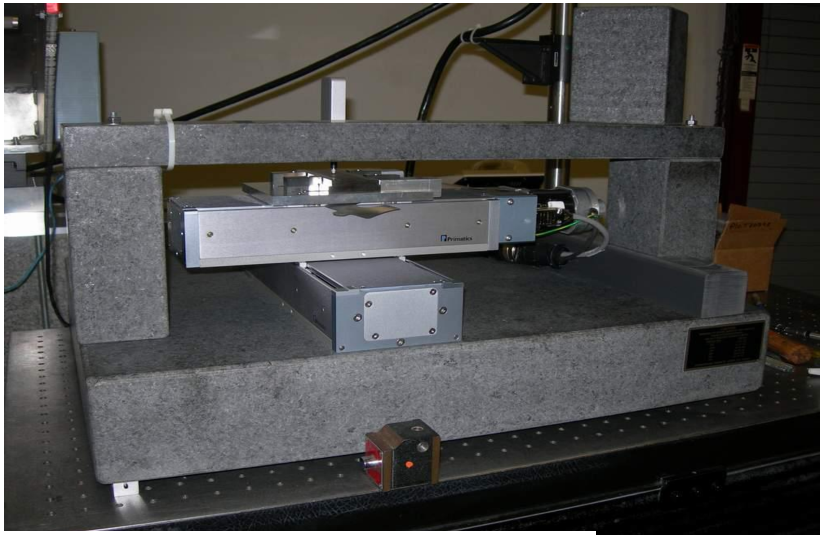
Pole shapes studied

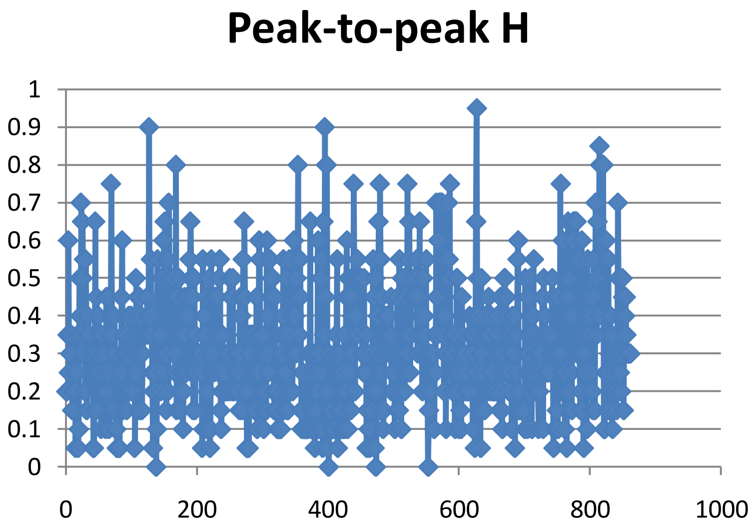
- Poles and magnets
  - Flat
  - Stepped with flat bottom
  - Stepped with curved bottom
  - Curved edge stepped with flat bottom
  - Curved edge with curved bottom
  - Pocket in pole with the above 5 choices. Pocket axial extent varied
- All shapes are feasible and can be manufactured using 3-4 processes.
- All were evaluated with OptiNET and custom pre and post processing codes

Optimum pole/magnet configurations

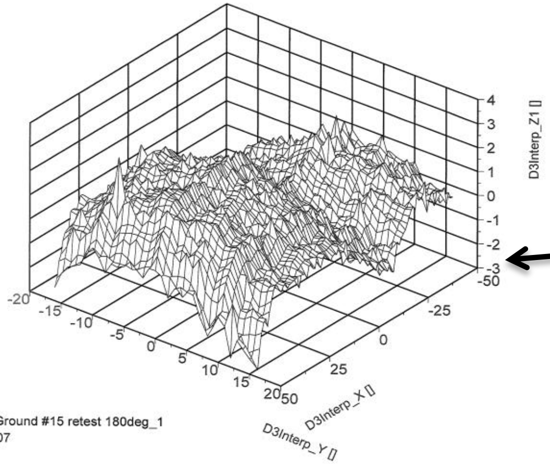
- 50mm wide poles
  - Stepped with curved bottom
  - Curved edge with curved bottom. Slightly better, higher risk, not used on prototype
- 60mm wide poles
  - Curved edge stepped with flat bottom
- 70mm wide poles
  - Stepped with flat bottom
- 100mm wide poles
  - Flat

Pole pseudo-CMM machine





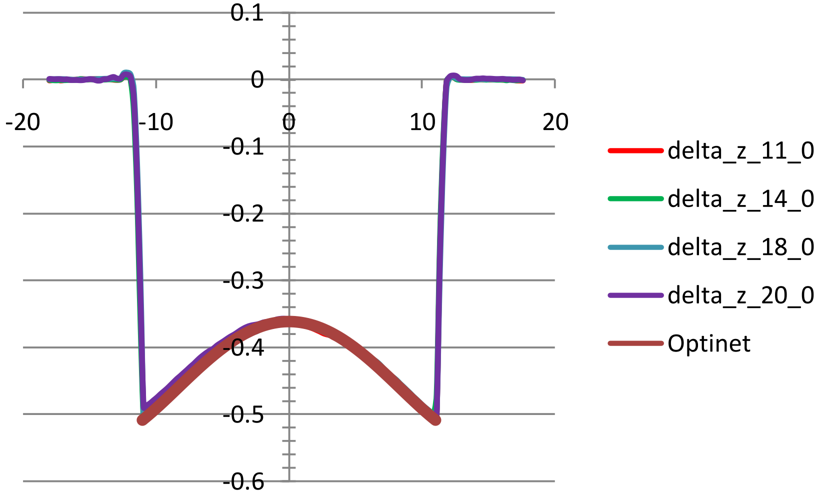
Gage block test of CMM (3X repeats). Devs probably dust

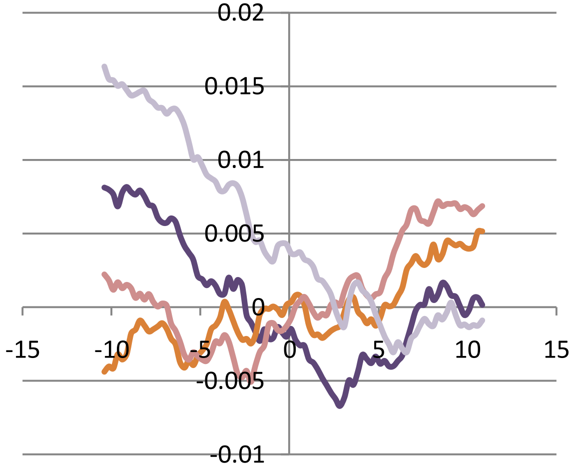


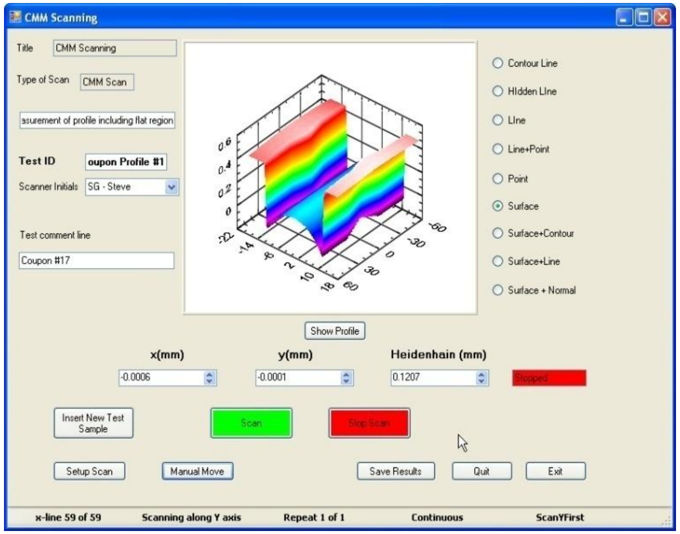
1919-SK005-50mm Ground #15 retest 180deg_1
Scan Date: 11/16/2007
Scan Time: 16:26:46
Tilt Corrected Range: 6.4 [microns]

Test of coupon flatness after grinding and before profiling

Pole coupon results







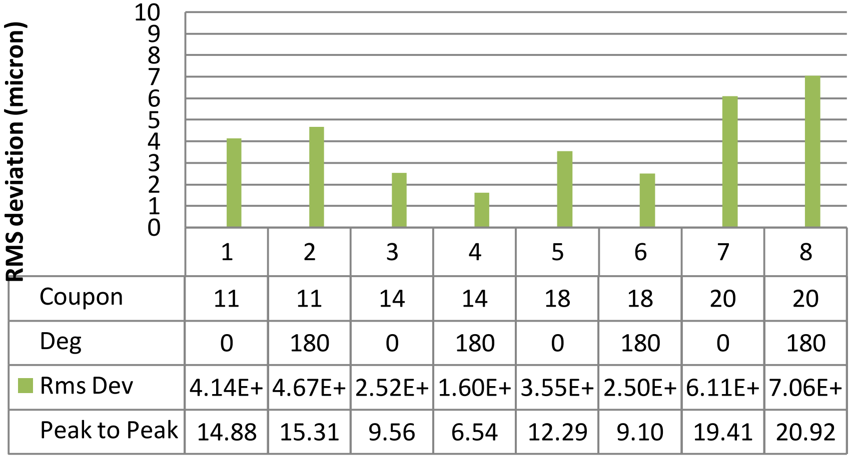
Title: CMM Scanning
Type of Scan: CMM Scan
asurement of profile including flat region
Test ID: oupon Profile #1
Scanner Initials: SG - Steve
Test comment line: Coupon #17

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

x(mm): -0.0006
y(mm): -0.0001
Heidenhain (mm): 0.1207
Stopped

x-line 59 of 59 | Scanning along Y axis | Repeat 1 of 1 | Continuous | ScanYFirst

RMS Deviations of coupon profiles
Profile #7 50mm wide

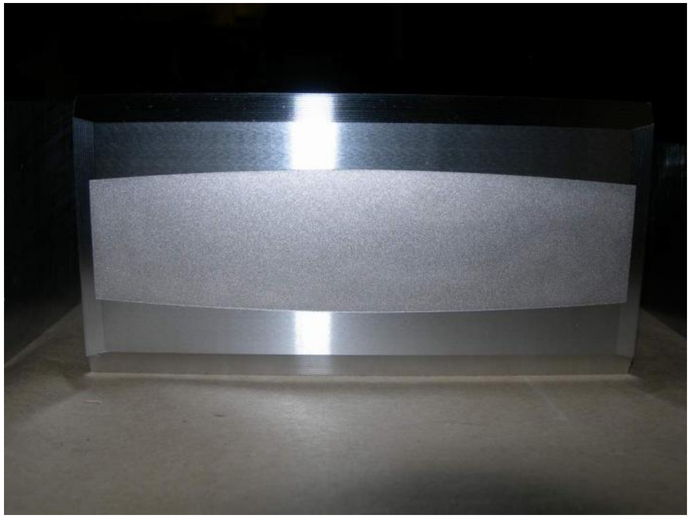


	1	2	3	4	5	6	7	8
Coupon	11	11	14	14	18	18	20	20
Deg	0	180	0	180	0	180	0	180
🟩 Rms Dev	4.14E+	4.67E+	2.52E+	1.60E+	3.55E+	2.50E+	6.11E+	7.06E+
Peak to Peak	14.88	15.31	9.56	6.54	12.29	9.10	19.41	20.92

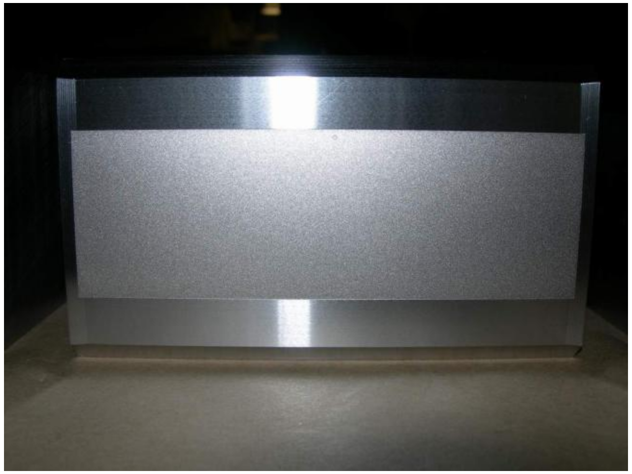
Pole pictures

50mm

60mm



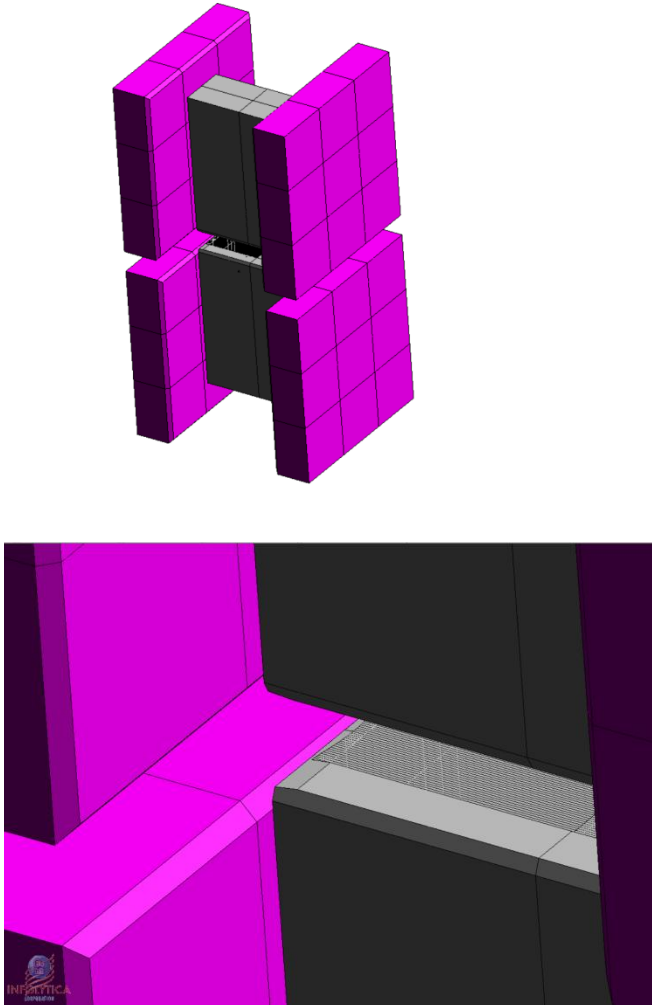
70mm



- All have different optimum step widths and depth
- All have different optimum transverse chamfer

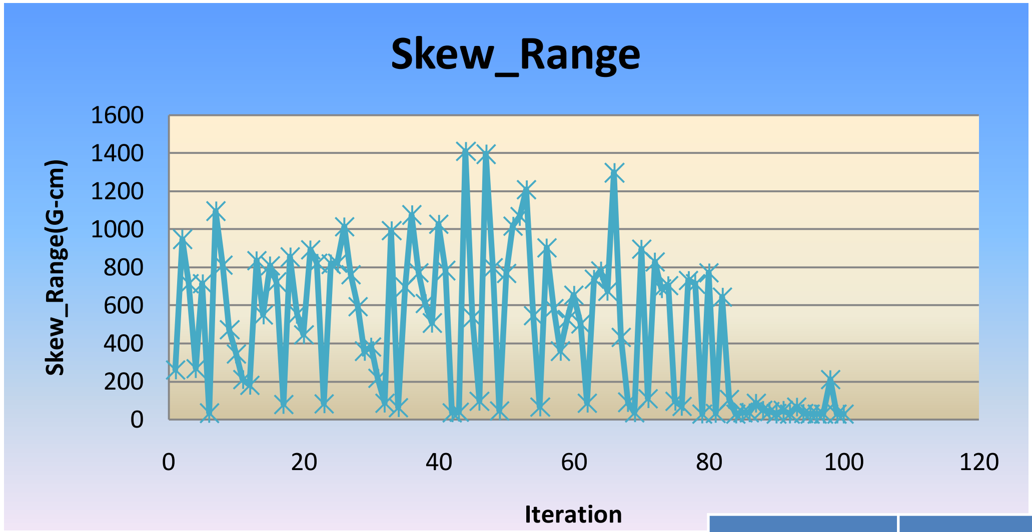
FULL FEA OF PROTOTYPE

Full FEA model

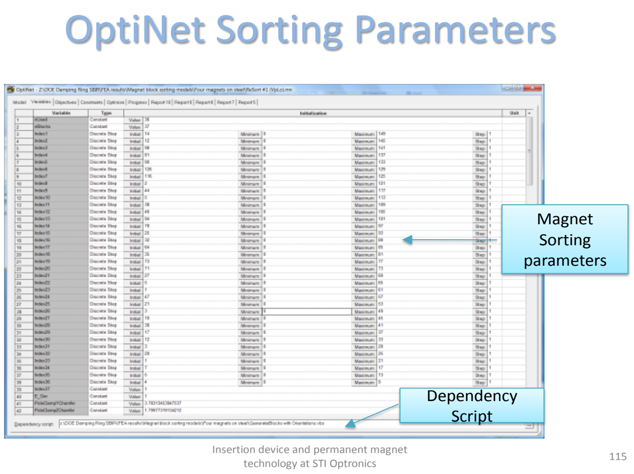


- FEA implied that a full-sized prototype was needed
  - Approximate profile sensitivity using FEA is 5-10 G-cm/micron for dynamic multipoles
  - Actual profile accuracy using small STI pseudo-CMM is about 5 micron RMS, 10 micron P-to-P
  - Rough estimate is then 25-50 G-cm RMS, 100 G-cm P-to-P
  - Ideal peak-to-peak dynamic multipoles are 250 G-cm
  - “Rule-of-fives” in QA is that you need 5X better quality measurements than are specified
  - Only a *full sized* prototype could ever meet this requirement.
- Budget constraints implied only one prototype could be built with capability to handle many configurations.
  - Full optimization would require different magnet shapes for each pole width.
  - 3X more expense for magnets
  - Different mechanical assembly for each pole width
  - Different assembly tooling for each pole width
- Did not add side magnets
  - Code can handle them, but budget could not
  - Higher risk since shaped poles hadn’t been proven
  - Prototype does allow adding side magnets in the future

FEA based magnet sorting



- Main result is the magnets *must be sorted on a brick-by-brick basis*
- See 2007 workshop presentation for details


OptiNet Sorting Parameters

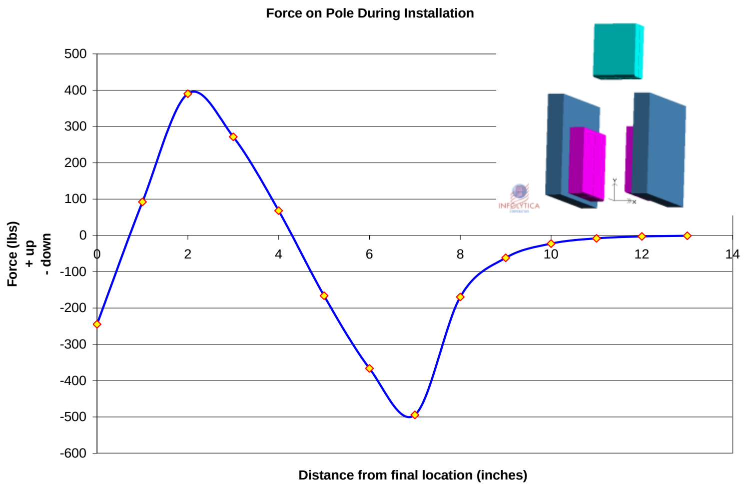
Insertion device and permanent magnet technology at STI Optronics

115

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

FEA TO ASSIST ASSEMBLY PROCESS

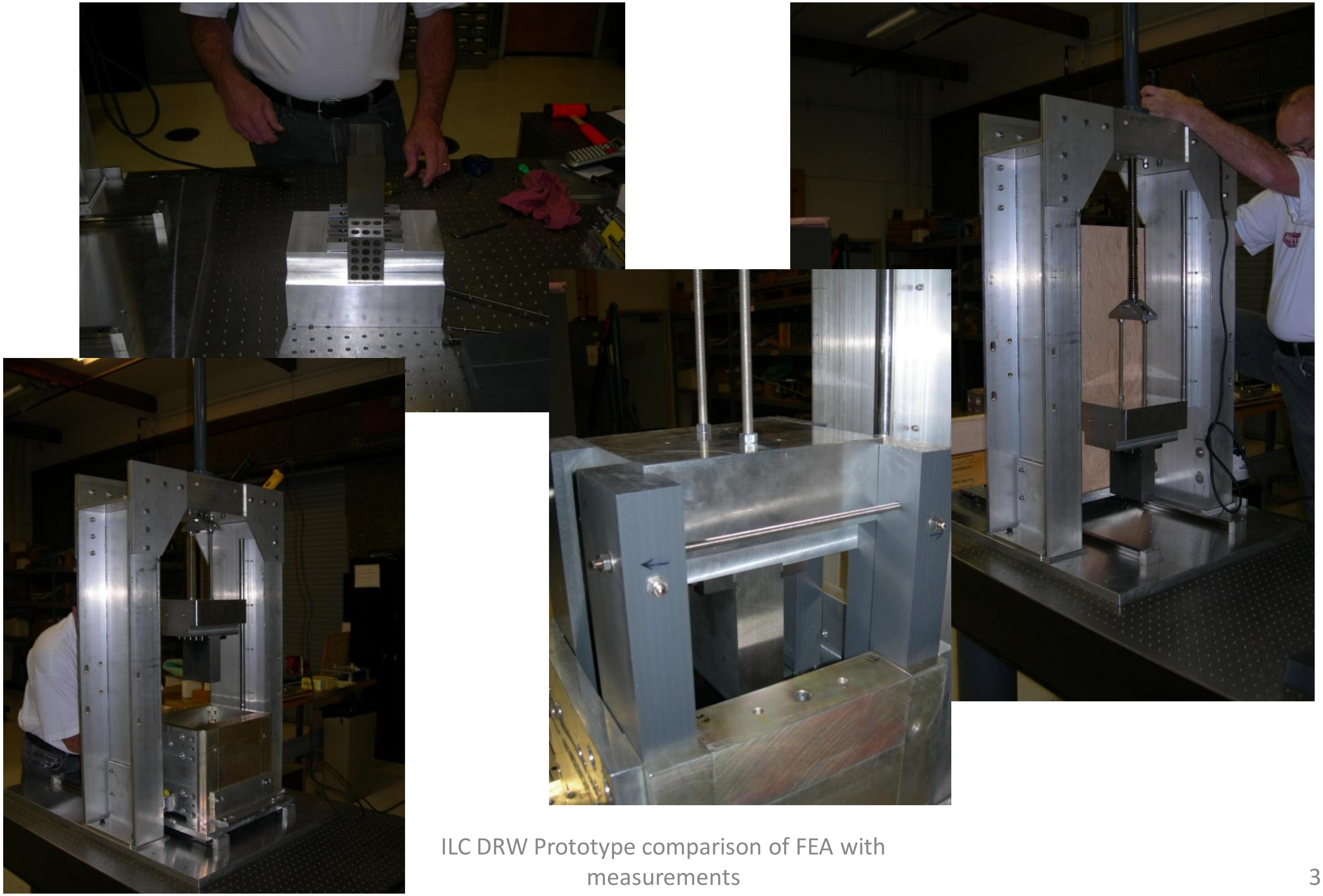
FEA Force calculation



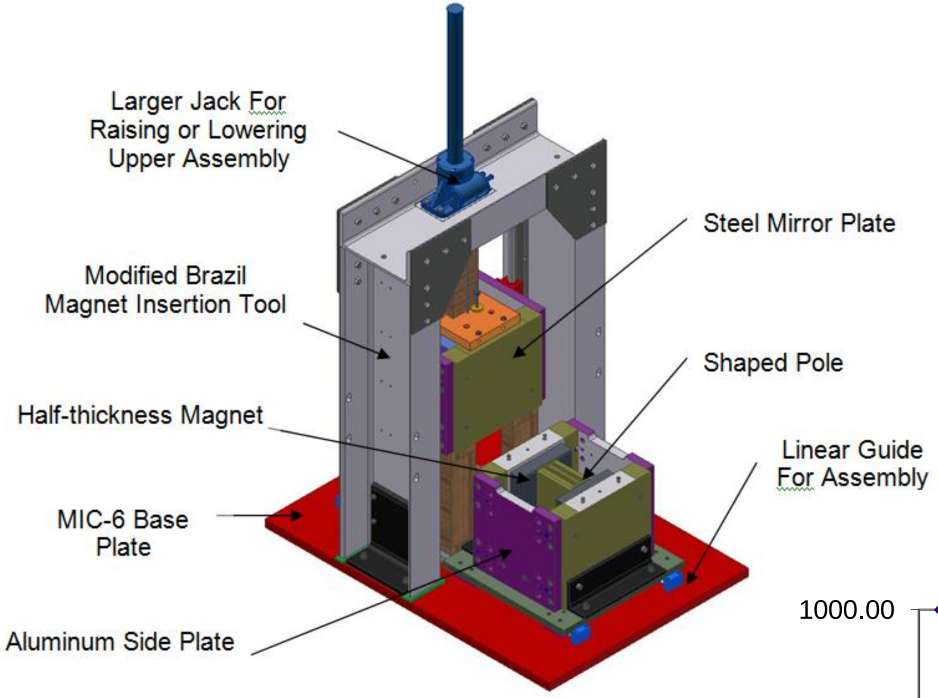
Extremely important that force reverses at 0.75” otherwise pole is a deadly projectile

- MagNet uses optimized Maxwell Stress
- Requires air space around object
  - We parametrically vary the air gaps and extrapolate to zero gap to insure maximum accuracy
- Tested on earlier devices and predicted behavior is correct
- Must be used on ILC-DRW due to large, dangerous forces
- Used to carefully script entire assembly process

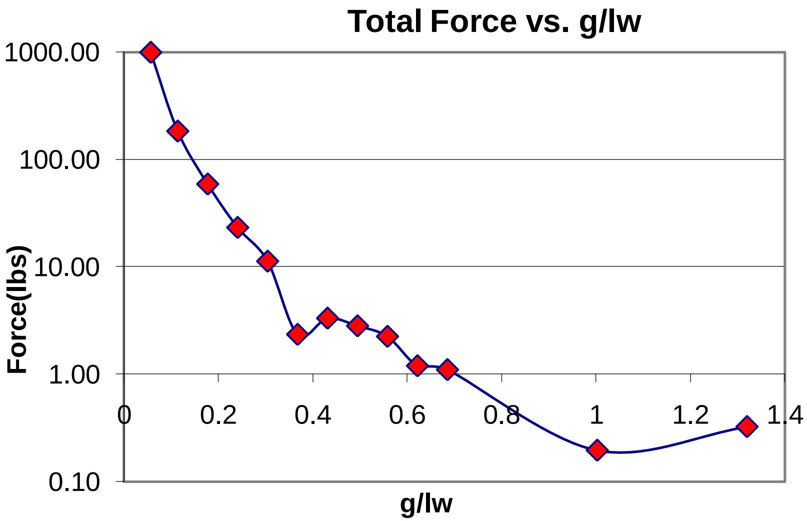
Pole installation pictures



Force during full assembly

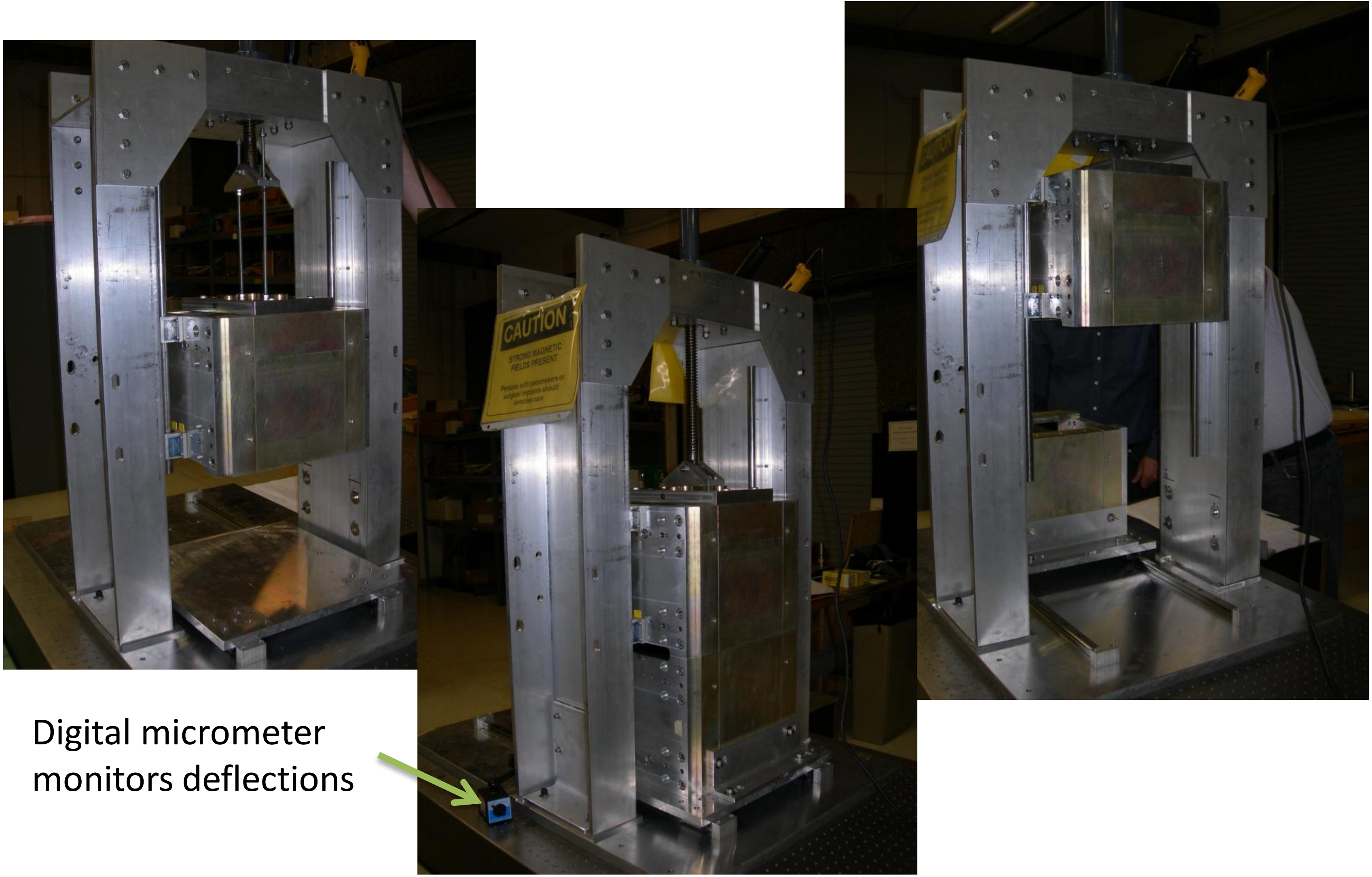


Forces on assembly include steel. Multi-period DRW with periodic BC has 2.5X higher forces



One ton jack used to safely install each half. Note this force is for 50mm wide pole

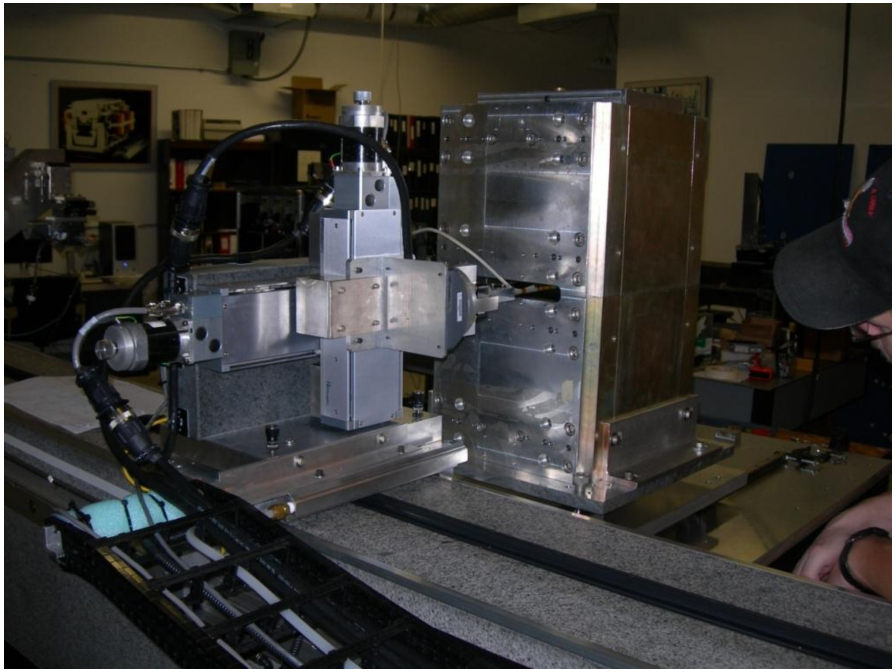
Full assembly pictures

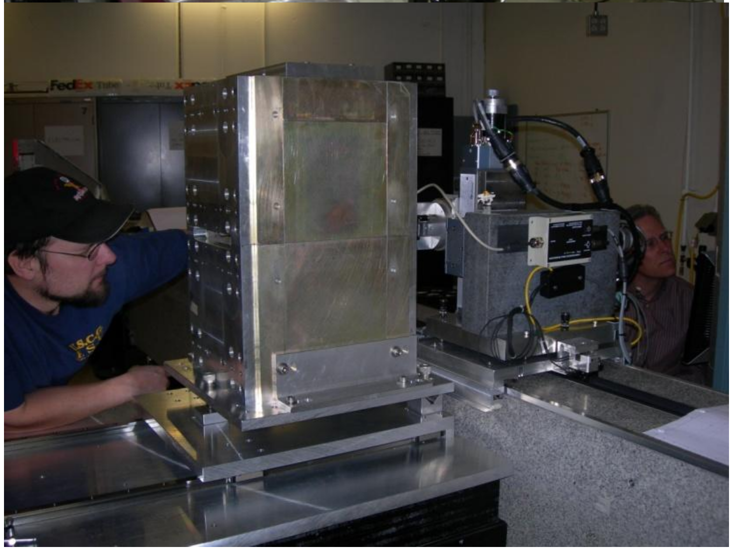


Digital micrometer monitors deflections

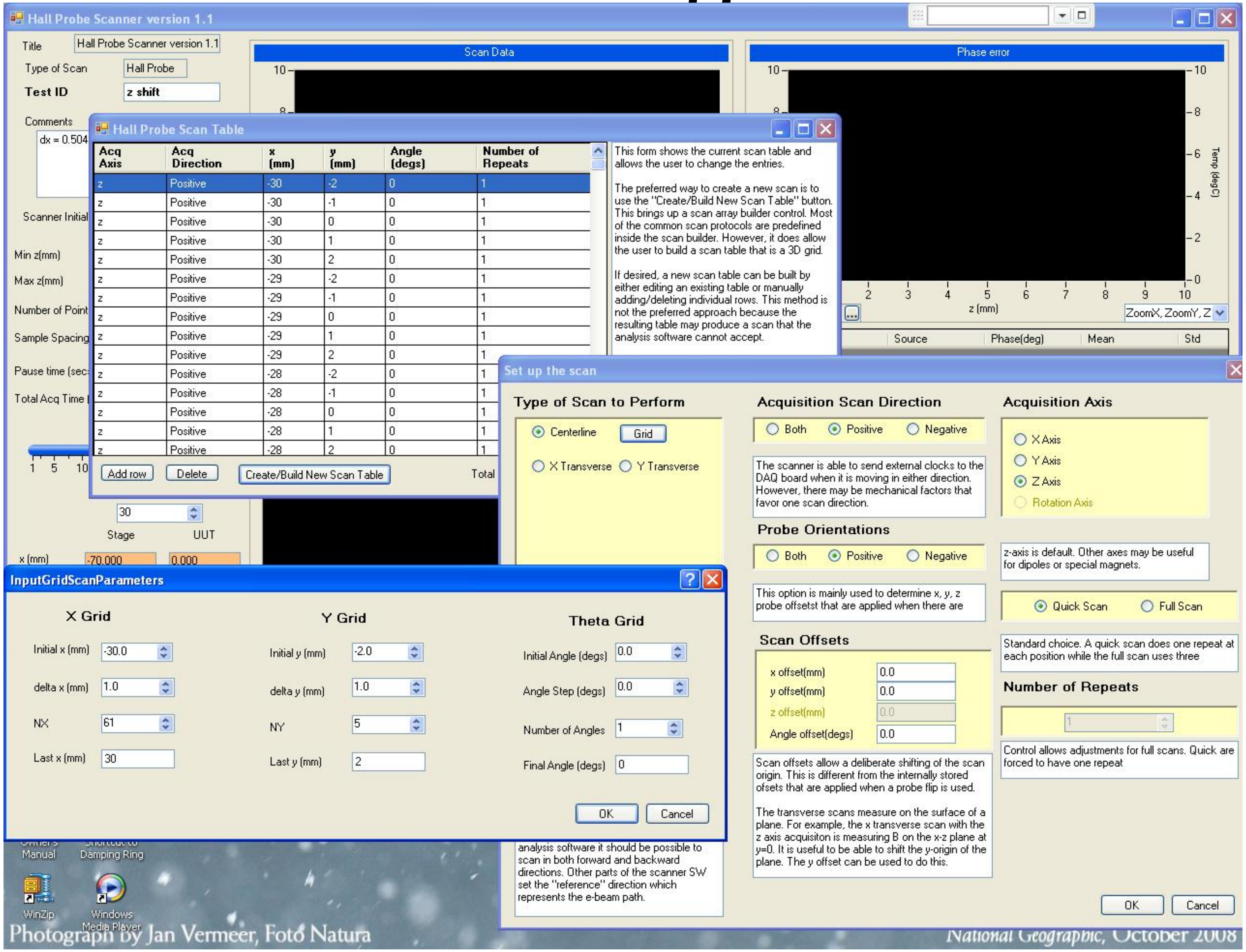
MEASUREMENTS AND DATA ANALYSIS

Prototype scanning





Scanning SW



Title: Hall Probe Scanner version 1.1

Type of Scan: Hall Probe

Test ID: z shift

Comments: dx = 0.504

30

x (mm): Stage -70.000, UUT 0.000

Hall Probe Scan Table

Acq Axis	Acq Direction	x (mm)	y (mm)	Angle (degs)	Number of Repeats
z	Positive	-30	-2	0	1
z	Positive	-30	-1	0	1
z	Positive	-30	0	0	1
z	Positive	-30	1	0	1
z	Positive	-30	2	0	1
z	Positive	-29	-2	0	1
z	Positive	-29	-1	0	1
z	Positive	-29	0	0	1
z	Positive	-29	1	0	1
z	Positive	-29	2	0	1
z	Positive	-28	-2	0	1
z	Positive	-28	-1	0	1
z	Positive	-28	0	0	1
z	Positive	-28	1	0	1
z	Positive	-28	2	0	1

Add row | Delete | Create/Build New Scan Table | Total

This form shows the current scan table and allows the user to change the entries.

The preferred way to create a new scan is to use the "Create/Build New Scan Table" button. This brings up a scan array builder control. Most of the common scan protocols are predefined inside the scan builder. However, it does allow the user to build a scan table that is a 3D grid.

If desired, a new scan table can be built by either editing an existing table or manually adding/deleting individual rows. This method is not the preferred approach because the resulting table may produce a scan that the analysis software cannot accept.

Set up the scan

Type of Scan to Perform

● Centerline Grid

○ X Transverse ○ Y Transverse

analysis software it should be possible to scan in both forward and backward directions. Other parts of the scanner SW set the "reference" direction which represents the e-beam path.

Acquisition Scan Direction

○ Both ● Positive ○ Negative

The scanner is able to send external clocks to the DAQ board when it is moving in either direction. However, there may be mechanical factors that favor one scan direction.

Probe Orientations

○ Both ● Positive ○ Negative

This option is mainly used to determine x, y, z probe offsetst that are applied when there are

Scan Offsets

x offset(mm): 0.0
y offset(mm): 0.0
z offset(mm): 0.0
Angle offset(degs): 0.0

Scan offsets allow a deliberate shifting of the scan origin. This is different from the internally stored ofsets that are applied when a probe flip is used.

The transverse scans measure on the surface of a plane. For example, the x transverse scan with the z axis acquisiton is measuring B on the x-z plane at y=0. It is useful to be able to shift the y-origin of the plane. The y offset can be used to do this.

Acquisition Axis

○ X Axis
○ Y Axis
● Z Axis
○ Rotation Axis

z-axis is default. Other axes may be useful for dipoles or special magnets.

● Quick Scan ○ Full Scan

Standard choice. A quick scan does one repeat at each position while the full scan uses three

Number of Repeats

1

Control allows adjustments for full scans. Quick are forced to have one repeat

OK | Cancel

InputGridScanParameters

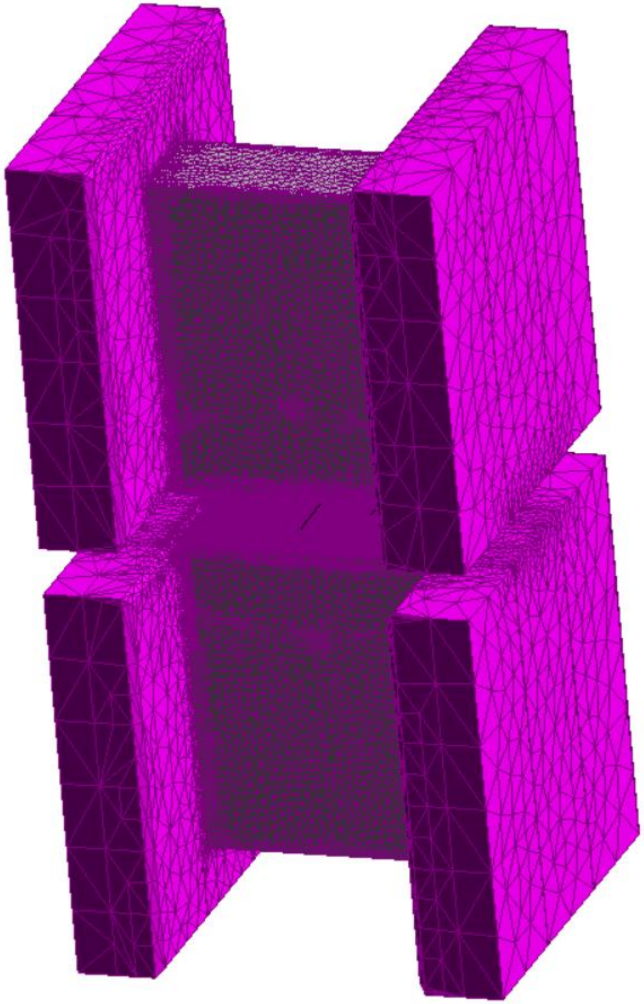
X Grid		Y Grid		Theta Grid	
Initial x (mm)	-30.0	Initial y (mm)	-2.0	Initial Angle (degs)	0.0
delta x (mm)	1.0	delta y (mm)	1.0	Angle Step (degs)	0.0
NX	61	NY	5	Number of Angles	1
Last x (mm)	30	Last y (mm)	2	Final Angle (degs)	0

OK | Cancel

Still not finished with FEA!

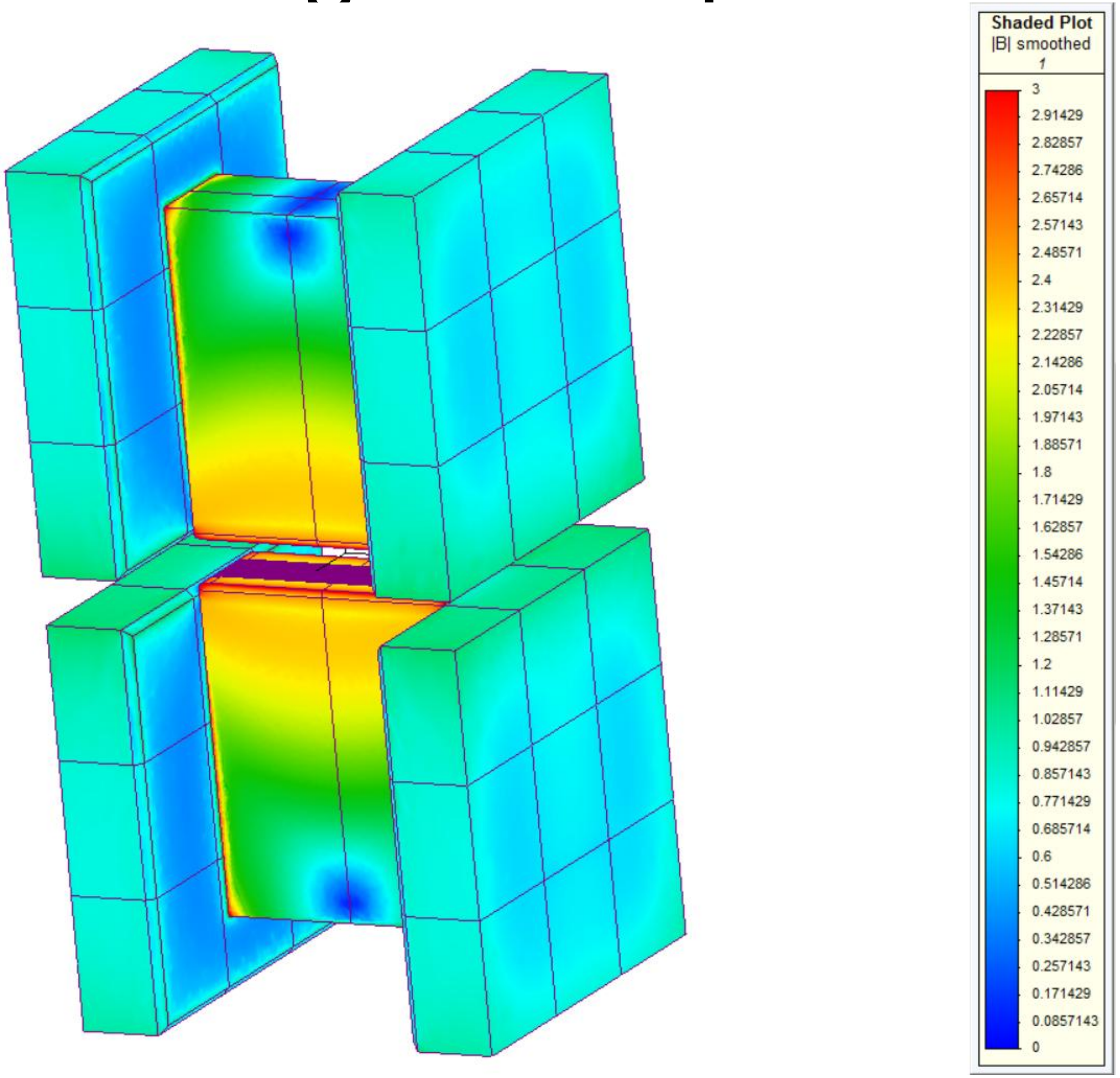
- Needed even higher accuracy
- Account for finite air space (70 microns) between magnet and poles
  - Magnets had coating so physical space was smaller
  - Used FEA to determine effect
- Adjusted magnetic gap in FEA to match actual, built gap. Things deflect.
- Did not incorporate measured pole shapes

Refined 3D FEA details

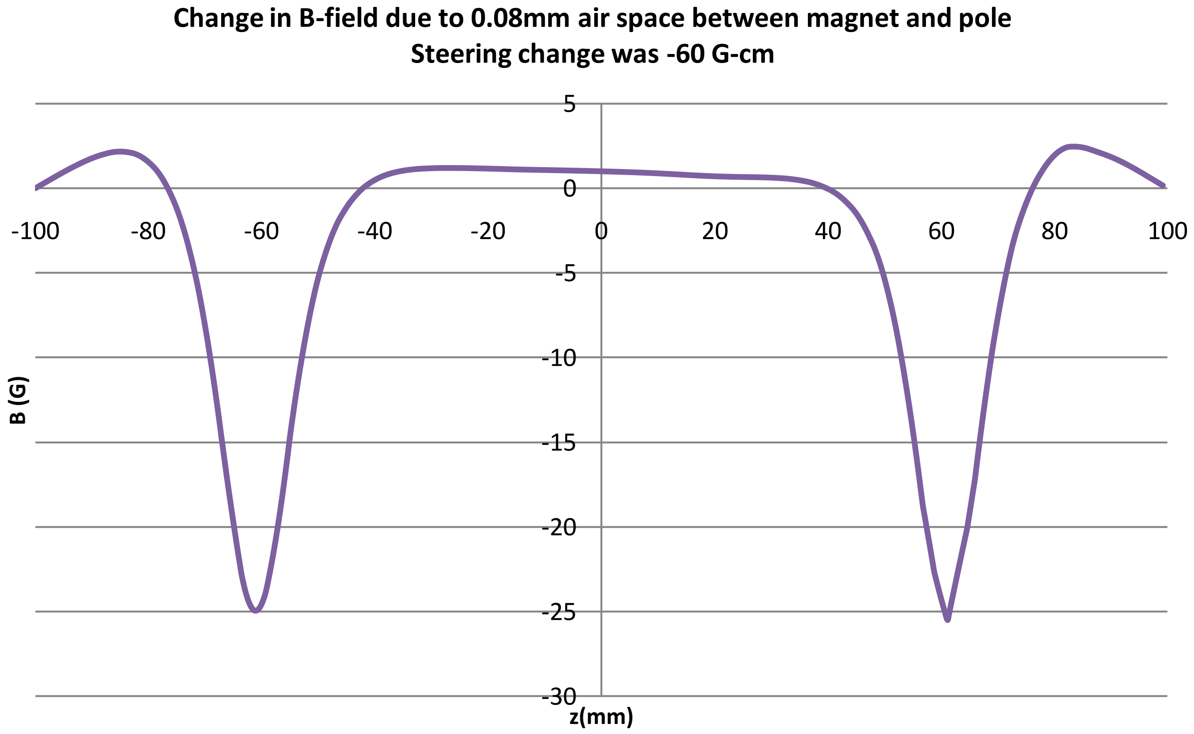


- Newton convergence 0.05%
  - Successive approximation gave same answers, took 5-10X longer
- Air regions used 3rd order elements
- Rest used 2nd order elements
- Dynamic multipoles can change by 120 G-cm (0.05%) for different *measured* BH curves
- Final, adapted mesh (h-method)
  - Tetrahedra 6,330,036
  - Field nodes 9,079,376
  - Solution time 40 hrs (3 adaptions) on Dell Precision 490, dual XEON 5160, 3GHz, 4 GB RAM, Vista 64 OS
- BH curve extrapolated from measured 79 kA/m to 300 kA/m

Field shows significant pole saturation



FEA Sensitivity to pole-magnet air space



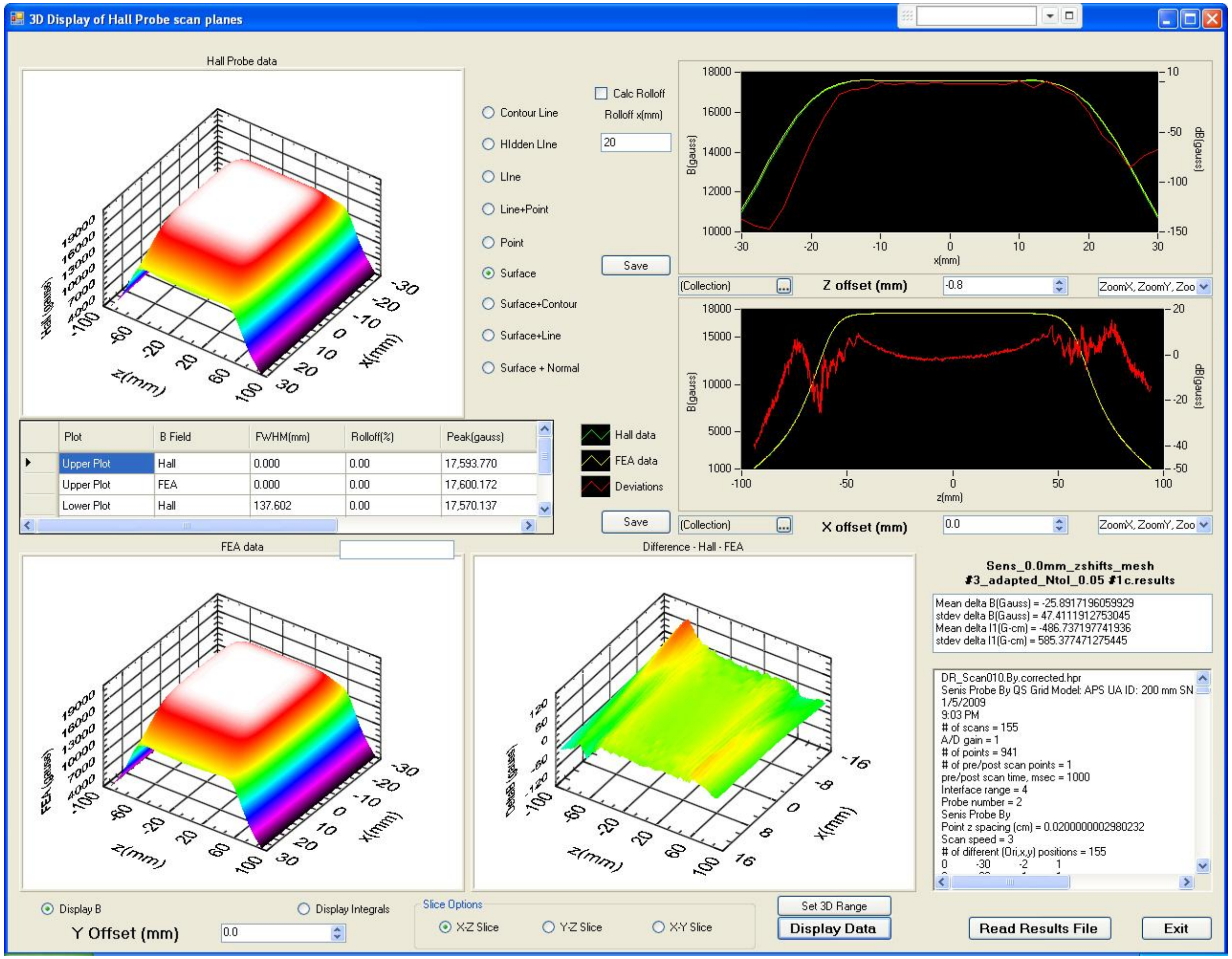
- Physical pole axial length was slightly smaller. Deviations between measurements and FEA indicated needed to include this in analysis

Data analysis

Parameter	Value	Units
Air space	0.0700950924341504	mm
Taper	1.927874735840963E-02	%
Cant	5.199473664717784E-02	mrad
X shift	-0.2766589729255725	mm
Y shift	0.2433049726089509	mm
Z shift	-0.2549652902216381	mm
Alpha	0.3868679428146524	deg
Beta	0.1006526101511226	deg
Gamma	-0.6652153429615457	deg

- Wrote special Fortran95 post processing code to compare FEA with measurements
- Varied above parameters to minimize deviation
  - Rigid body transformation of coordinates between FEA and scanner
  - Taper and cant as well
  - Used 3D tensor spline interpolation of FEA data, no interpolation of measurements
- Found at least four local minima so should use global optimizer

Comparison of FEA to measurements



● Surface

☐ Calc Rolloff

Rolloff x(mm): 20

Z offset (mm): -0.8

X offset (mm): 0.0

● Display B

Y Offset (mm): 0.0

● X-Z Slice

Plot	B Field	FWHM(mm)	Rolloff(%)	Peak(gauss)
Upper Plot	Hall	0.000	0.00	17,593.770
Upper Plot	FEA	0.000	0.00	17,600.172
Lower Plot	Hall	137.602	0.00	17,570.137

Sens_0.0mm_zshifts_mesh #3_adapted_Ntol_0.05 #1c.results

```
Mean delta B(Gauss) = -25.8917196059929
stdev delta B(Gauss) = 47.4111912753045
Mean delta I1(G-cm) = -486.737197741936
stdev delta I1(G-cm) = 585.377471275445
```

```
DR_Scan010.By.corrected.hpr
Senis Probe By QS Grid Model: APS UA ID: 200 mm SN
1/5/2009
9:03 PM
# of scans = 155
A/D gain = 1
# of points = 941
# of pre/post scan points = 1
pre/post scan time, msec = 1000
Interface range = 4
Probe number = 2
Senis Probe By
Point z spacing (cm) = 0.0200000002980232
Scan speed = 3
# of different (Ori,x,y) positions = 155
0       -30      -2      1
```

CONCLUSION

Shaped poles work

- Shaped poles can significantly reduce costs of large period wigglers
- Agreement between measurements and state-of-the-art FEA at the 0.02 – 0.07% level
- Absolutely must include magnet inhomogeneity
- Better results are possible
  - *Measure* BH curves to larger H values
  - Better pole fabrication
- Adding side magnets and re-optimizing pole shape will further improve dynamic multipoles
- Good agreement in 3D implies FEA can be used to generate symplectic coefficients
- ***But*** Still will need to tune the wiggler
  - Every ID ever built has needed some sort of tuning
  - On 60+ ID's STI built, the best initial kick error was 0.18%. This is 450 G-cm *per pole*
  - Random accumulation would be unacceptably large producing significant trajectory, multipole, phase and other errors
  - *Must tune*