Design and Prototype Testing of the Girder System for TPS

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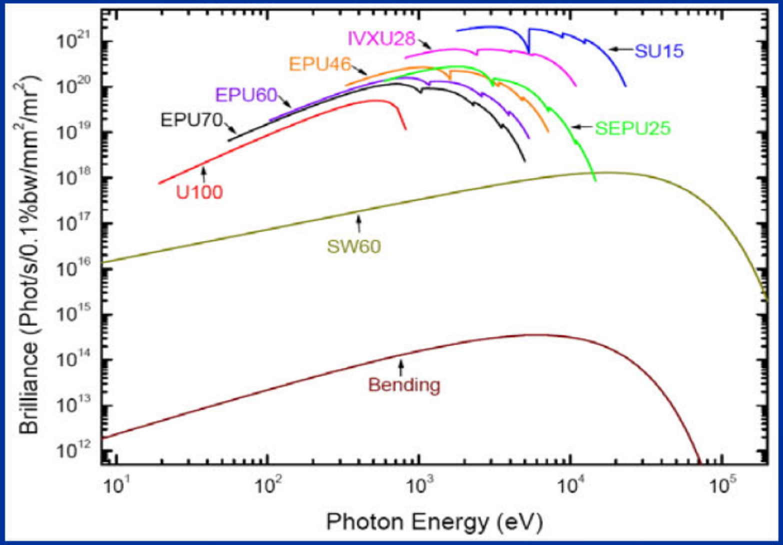
NSRRC

Outline

- Introduction
- Design of the girder system
- Prototype fabrication and testing
- Conclusion

TPS (Taiwan Photon Source)
A brilliant and of low emmittance ring



Major parameters of the TPS

Energy (GeV)	3.0~3.3
Beam current (mA)	400
Circumference (m)	518.4
Nat. emittance (nm-rad)	1.7
Cell/symmetry/structure	24 / 6 /DBA
β_x / β_y / η_x (m) LS centre	10.59/ 9.3 /0.11
RF frequency (MHz)	499.654
RF voltage (MV)	5.0
Harmonic number	864
SR loss/turn, dipole (MeV)	0.98733
Long Straights Standard Straights	11.72m*6 7m*18
Betatron tune ν_x / ν_y	26.22 / 12.28
Synchrotron tune ν_s	6.7×10^{-3}
Bunch length (mm)	2.34
Dipole B/L (Tesla)/(m)	1.3789 / 0.95
Mom. comp. (α_1, α_2)	2.0×10^{-4}, 2.3×10^{-3}
Nat. energy spread σ_E	9.53×10^{-4}
Damping time ($\tau_x/\tau_y/\tau_e$ ms)	10.5 / 10.5 / 5.25
Nat. chromaticity ξx / ξy	-78.2 / -32.5

Design goals of the girders system for TPS

- Firm support and precise positioning of magnets
- High nature frequency above 30 Hz
- Whole ring automatic alignment

  (To align the girders precisely and quickly with less manpower)

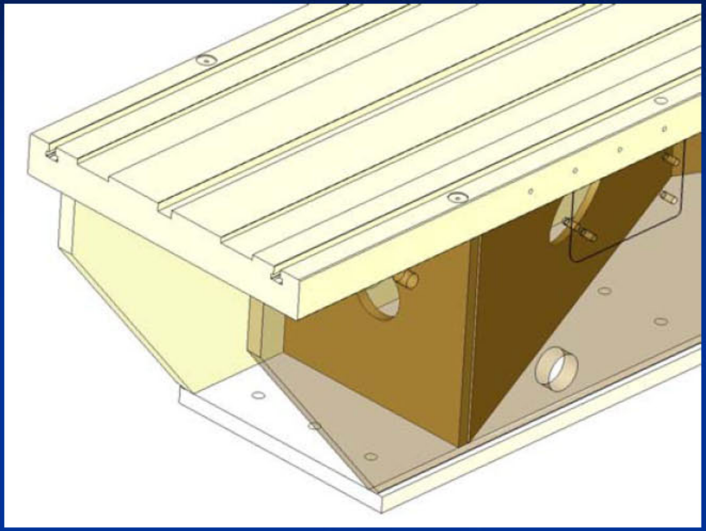
- Precise resolution (μm)
- Beam based girder alignment (optional)

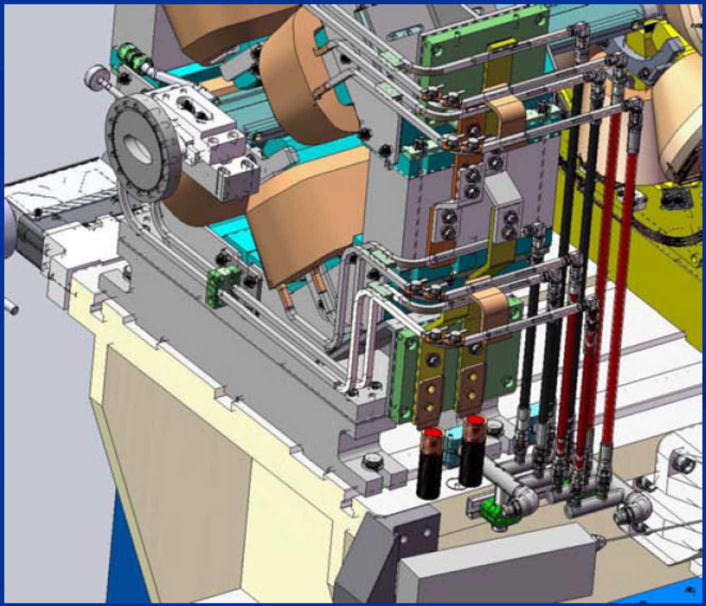
A 6-axis motorized adjusting mechanism demanded !

(considering the deformation of the floor and limited space in the tunnel also frequent earthquake in Taiwan)

Girder body deign considerations

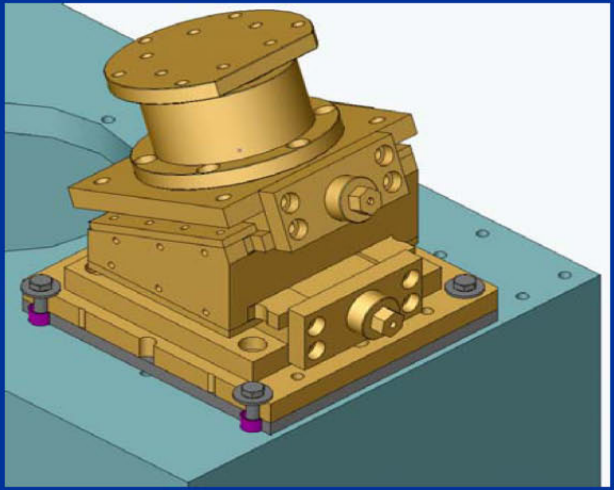
- Table type girder to reduce the total girder quantities
- Precisely machined reference channels to keep the magnets pre-aligned on the girder accurately
- Precisely machined alignment fiducials on the girder to increase the alignment efficiency
- Inclined steel plates inside the girder body to reduce the weight and increase stiffness
- Weight of magnets on a girder : 6000kg (estimated)
- Weight of the girder body : 3500kg(estimated)

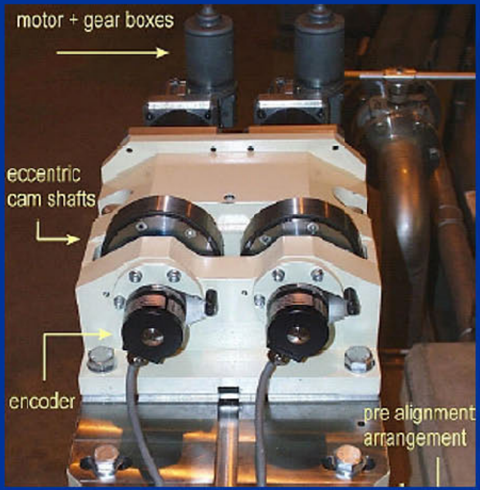




Existing Adjusting mechanism

- Wedge type adjusting mechanism (used At TLS)
  high stiffness(face contact) but poor adjustability (often manual)
- Cam type adjusting mechanism (used at SLS, Diamond)
  good adjustability but low stiffness(point or line contact)





Problems of existed cam mover type girder design

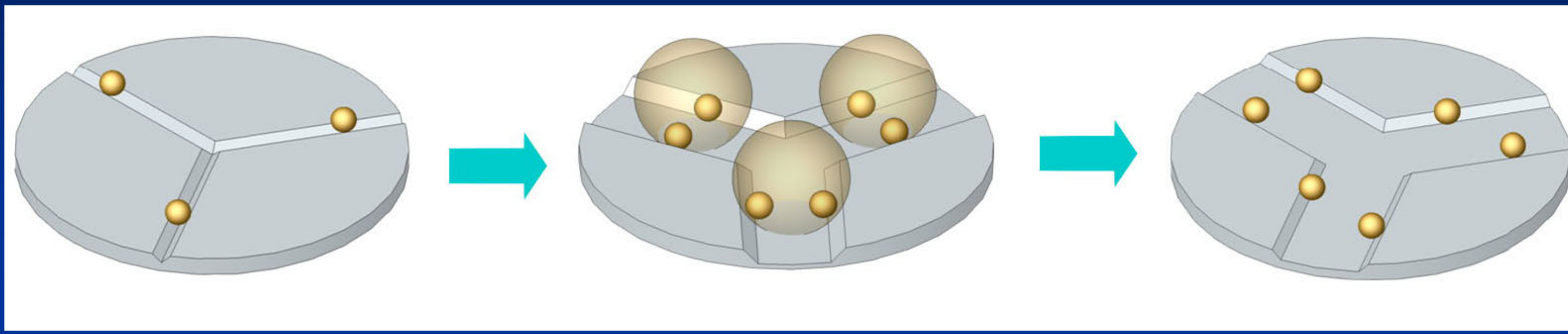
- 2 pedestals
- 5 degrees adjustment
- Higher deflection of girder body
- Lower natural frequency

Natural frequency of the girder in synchrotron facilities

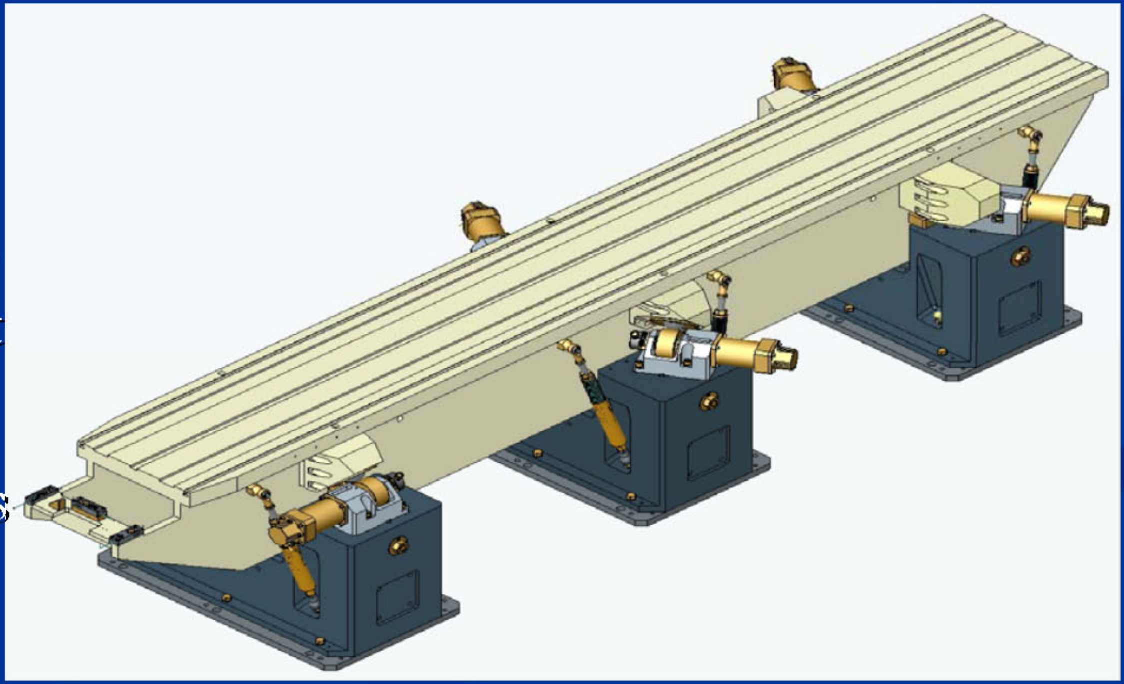
Facilities	Girder Adjusting Method	1^{st} natural f.(Hz)	Mag. in Hori. Dir.	Mag. in Verti. Dir.
SLS	Cam Mover /2 pedestals 5 degree	15.5		
Diamond	Cam Mover/2 pedestals 5 degree	16.3	9.7(1~100Hz)	
SOLEIL	3 jacks support +4 locking system	42		
MAXlab(DESY) (for ALBA)		15~16		
ESRF		6.8		
SSRF	Wedge mechanism (same as TLS)	23		
APS		10.5		
ALS		6.4		
BESSYII		5.6		
SPEAR III		15.5		
SPRING-8		19(H)/27.8(V)		

- No matter what type of adjusting mechanism is adopted, the first natural frequency of the girder system among most synchrotron facilities is less than 30Hz.
- Only that of SOLEIL is higher than 30Hz because of a locking system which enforces the stiffness of the girder system.
- A 6-axis motorized cam type automatic tuning girder system with locking system is thus proposed.

Cam mover type mechanism modification and an original girder Concept Design



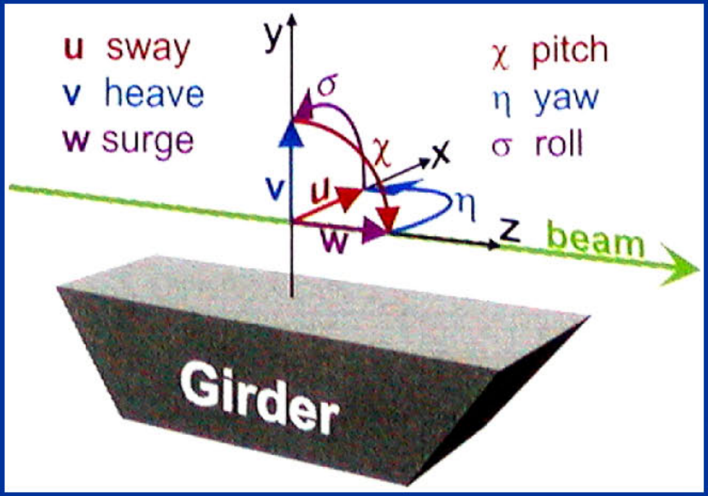
- 6 stands type kinematic mounting girder design
- Ball transfer units point contact with eccentric cam
- Spring with damper weight compensating system
- Polymer concrete pedestals



* Presented at MEDSI 2006

Single girder system adjusting algorithm

- To determine how to adjusting the girder in each direction by movers directly is not easy.
- An algorithm is required to transfer the directional adjusting magnitude to the motor's steps.
- The coordinate systems should be established both at girders and movers at first, than we can do this transformation.



Pitch (around x): $$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\chi & -\sin\chi \\ 0 & \sin\chi & \cos\chi \end{pmatrix} \quad (1)$$

Yaw (around y): $$R_y = \begin{pmatrix} \cos\eta & 0 & \sin\eta \\ 0 & 1 & 0 \\ -\sin\eta & 0 & \cos\eta \end{pmatrix} \quad (2)$$

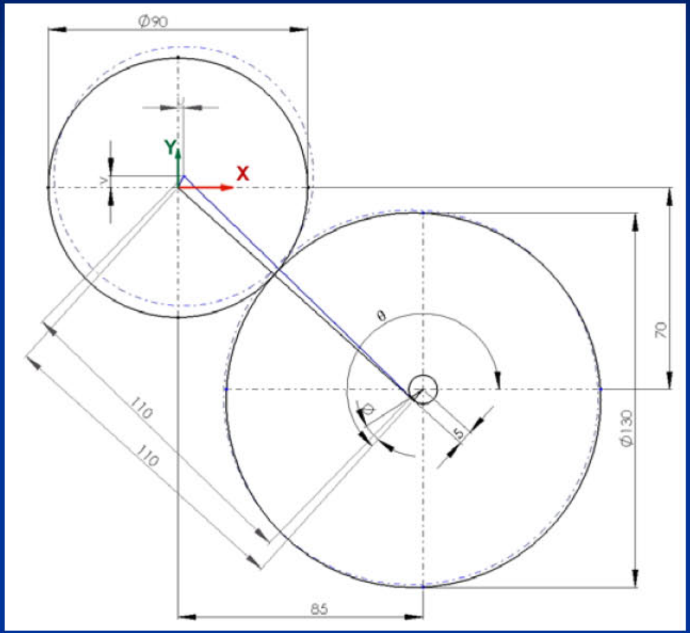
Roll (around z): $$R_z = \begin{pmatrix} \cos\sigma & -\sin\sigma & 0 \\ \sin\sigma & \cos\sigma & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3)$$

Combined roataion $$R = R_x R_y R_z \quad (4)$$

Combined displacement $$T = \begin{pmatrix} u \\ v \\ w \end{pmatrix} \quad (5)$$

Sway	translation u along x-axis
Heave	translation v along y-axis
Surge	translation w along z-axis
Pitch	rotation around x-axis by angle χ
Yaw	rotation around y-axis by angle η
Roll	rotation around z-axis by angle σ

Algorithm to transfer the directional adjusting magnitude to the motor's steps



$$d = \sqrt{(85 + r\cos(\theta_0))^2 + (-70 + r\sin(\theta_0))^2}$$

$$= R_{ball} + R_{cam} = 45 + 65 = 110(mm)$$

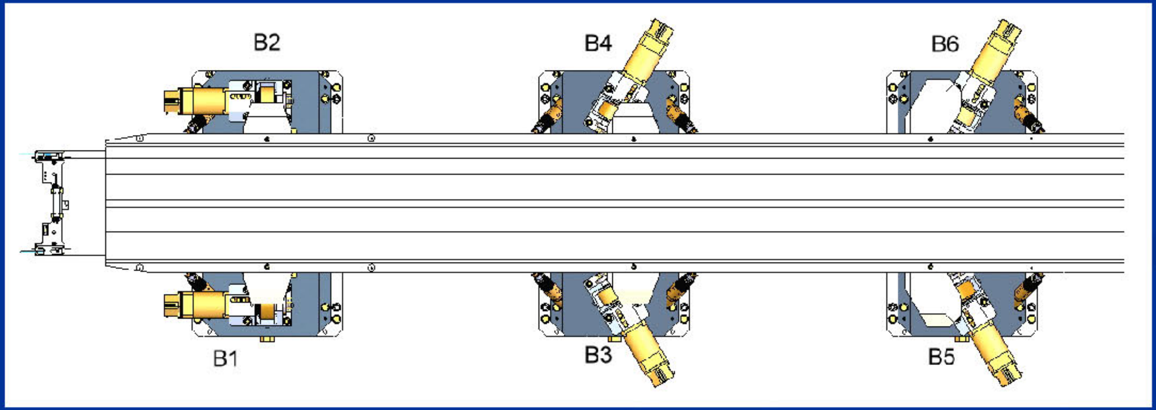
Starting angle of the cam θ_0 is 227.925

$$d = \sqrt{[(85 + r\cos(\theta + \phi)) - u_{mover}]^2 + [(-70 + r\sin(\theta + \phi)) - v_{mover}]^2}$$

$$= 110(mm)$$

then

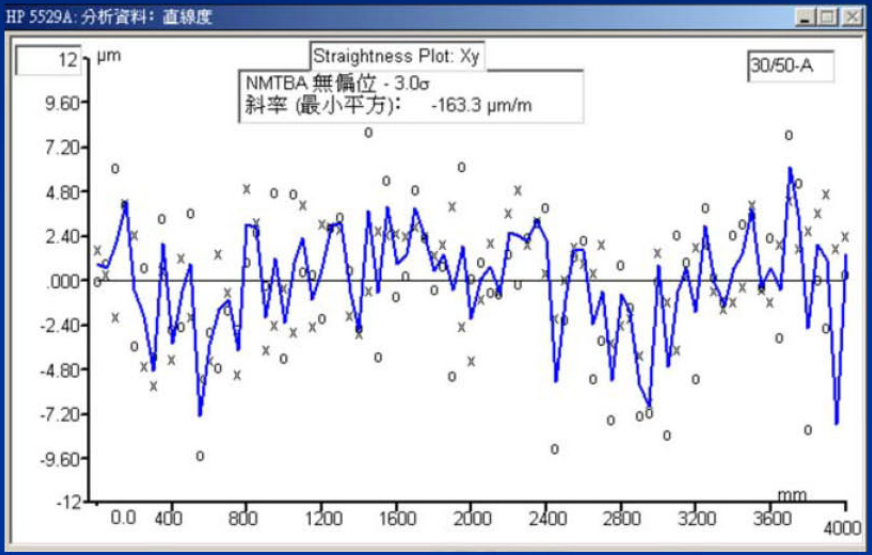
$$\begin{cases} T_{B1\_mover} = R_y(\eta = 180^o)T_{B1\_girder} \\ T_{B2\_mover} = R_y(\eta = 0^o)T_{B2\_girder} \\ T_{B3\_mover} = R_y(\eta = 120^o)T_{B3\_girder} \\ T_{B4\_mover} = R_y(\eta = 60^o)T_{B4\_girder} \\ T_{B5\_mover} = R_y(\eta = 300^o)T_{B5\_girder} \\ T_{B6\_mover} = R_y(\eta = 240^o)T_{B6\_girder} \end{cases}$$



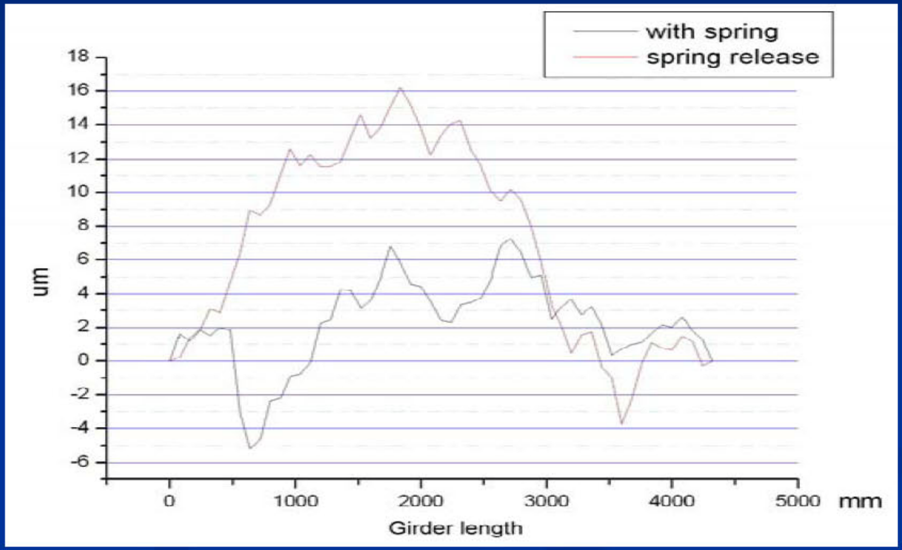
Prototype fabrication and testing

- Machining accuracy and ability testing
- Vibration testing
- Adjustability testing

Machining accuracy and ability testing



Girder reference channel surface flatness measured by a HP 5529A laser at factory.



Girder reference channel surface flatness measurement by autocollimator after installed

* surface flatness machining within 15mm is available in Taiwan local factory

Natural frequency preliminary testing result

Natural frequency			Without magnets	With magnets
Steel pedestal	With spring force	X direction	30.2	26.5
		Y direction	40.2	38.1
		Z direction	29.2	31.5
	Spring released	X direction	43.1	26.9
		Y direction	45.8	39.1
		Z direction	40.1	32.3
Polymer concrete Pedestal	With spring force	X direction	19.2	16.3
		Y direction	35.2	24.6
		Z direction	19.7	18.3
	Spring released	X direction	29.6	22.5
		Y direction	37.0	30
		Z direction	27.7	21.1

(the total weight with magnet is about 9000 Kg)

Problem of point contact type cam

Hertz Contact Stress

$$a = \sqrt[3]{\frac{3F}{8}\frac{\left[\left(1-\mu_1^2\right)/E_1\right]+\left[\left(1-\mu_2^2\right)/E_2\right]}{\left(1/d_1\right)+\left(1/d_2\right)}} = 1.546mm$$

$$b = \sqrt[3]{\frac{3F}{8}\frac{\left[\left(1-\mu_1^2\right)/E_1\right]+\left[\left(1-\mu_2^2\right)/E_2\right]}{\left(1/d_1\right)+\left(1/\infty\right)}} = 1.843mm$$

asuume $F = 2500kgf$

$\mu_1 = \mu_2 = 0.27$: poission ratio of steel

$E_1 = E_2 = 20000kg/mm^2$: Young's modulus of steel

$d_1 = 90mm$: Ball Bearing Diameter

$d_2 = 130mm$: Mover Cam Diameter

$$p_{MAX} = \frac{3F}{2\pi ab} = 419kg/mm^2$$

$$p_{MAX} \propto \sqrt[3]{F} \rightarrow \text{for } p_{max} \le 180kg/mm^2 \Rightarrow F \le 303kgf$$

800Kgf load appied, 900 cycling test lasting for 42 hours，frictional wear is obvious on the cam surface (SKD11，Rc 58).

Contact design improvement

Hertz Contact Stress

$$a = \sqrt[3]{\frac{3F}{8}\frac{\left[(1-\mu_1^2)/E_1\right]+\left[(1-\mu_2^2)/E_2\right]}{(1/d_1)+(1/d_2)}} = 11.225\,mm$$

$$b = \sqrt[3]{\frac{3F}{8}\frac{\left[(1-\mu_1^2)/E_1\right]+\left[(1-\mu_2^2)/E_2\right]}{(1/d_1)+(1/\infty)}} = 1.843\,mm$$

asuume $F = 2500\text{kgf}$

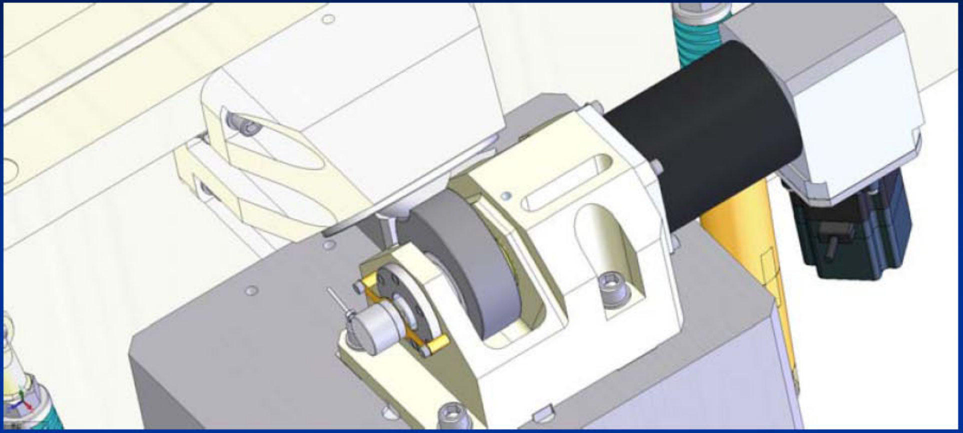
$\mu_1 = \mu_2 = 0.27$: poission ratio of steel

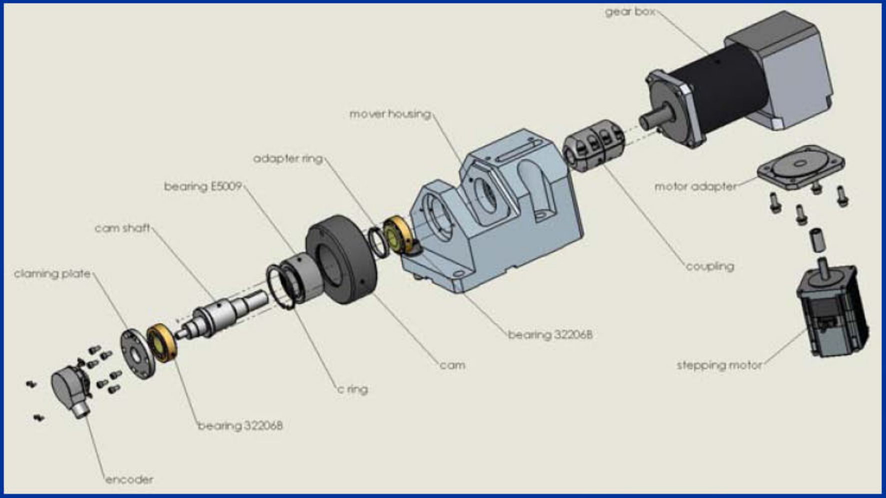
$E_1 = E_2 = 20000\,kg/mm^2$: Young's modulus of steel

$d_1 = 90\,mm$: Ball Bearing Diameter

$d_2 = -90.4\,mm$: Mover Cam Diameter

$$p_{MAX} = \frac{3F}{2\pi ab} = 57.8\,kg/mm^2 \le 180\,kg/mm^2$$





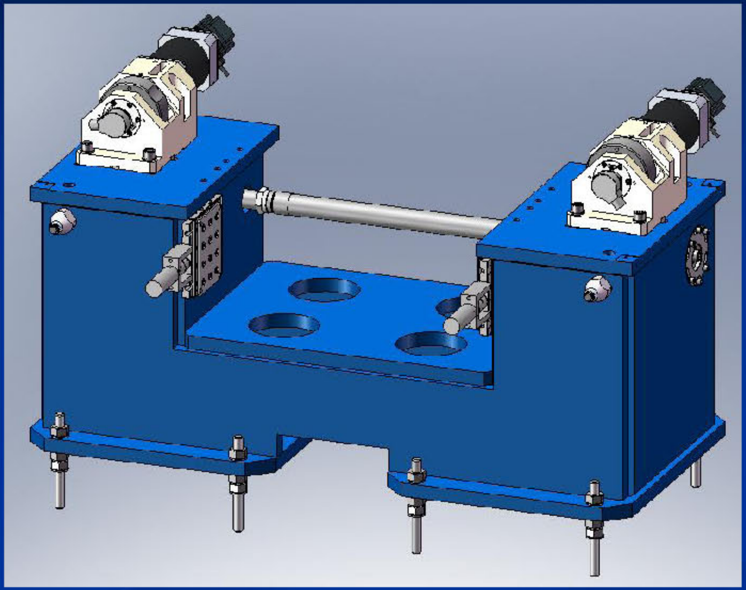
- Kinematic mounting situation preserved.
- The contact position of the ball and the cam remains the same for adjusting algorithm.
- the contact situation changes from point contact to line contact.
- the stress is reduced drastically to 12.4% and far beyond the elastic limitation of the cam.

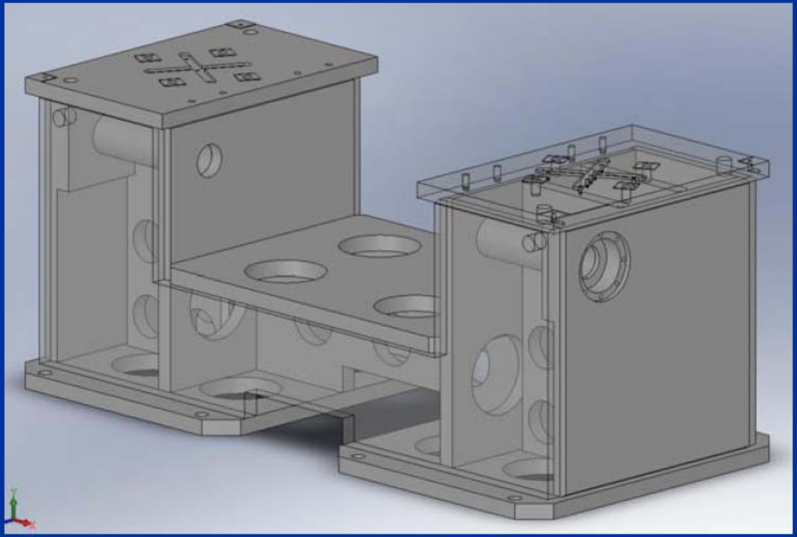
Conditions	NF_X	NF_Y	NF_Z
Old cam	25.08	37.26	29.02
New Cam	24.2	34.5	29.0

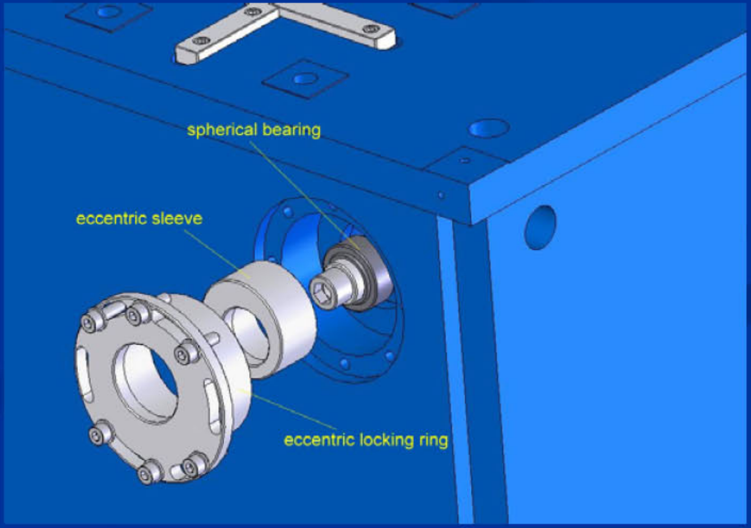
* The total weight is about 10,000Kg

Pedestal and locking mechanism design

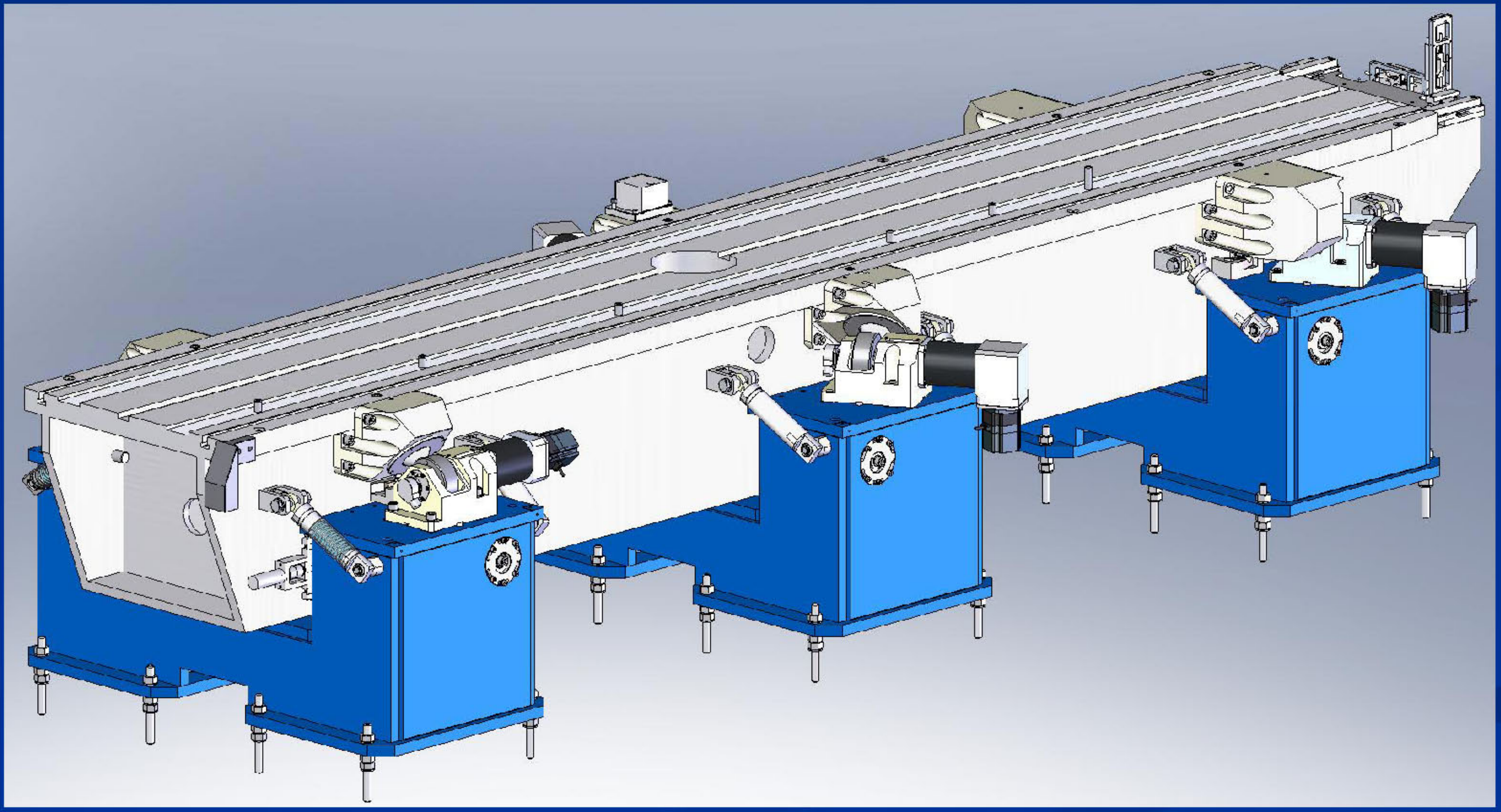
- A strong foundation for the cam mover.
- 4 alignment fiducials on the sides of top plate to align the pedestal
- After aligned the pedestal will be anchored to the ground with 8 M20 bolts and then grouted with no shrinkage concrete
- A recess cutting at the bottom to accommodate the main cooling pipes of the magnets
- A hard stop shaft for the girder across the pedestal body limits the girder adjusting range to ±0.5mm
- Locking stage on both sides to hold the girder after fine adjustment





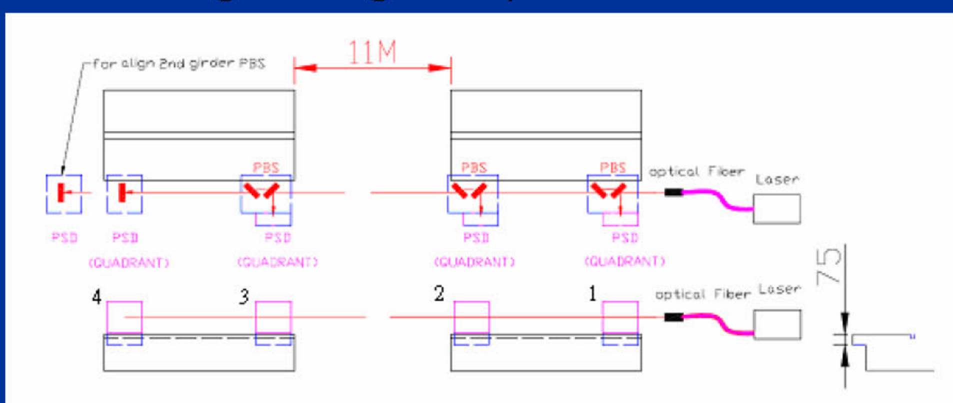


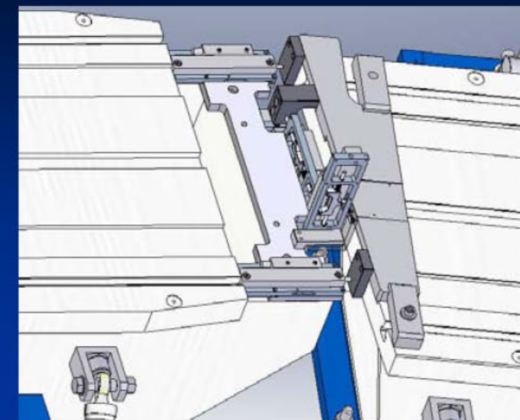
A kinematic mounting prototype girder system with 6 cam movers on 3 pedestals

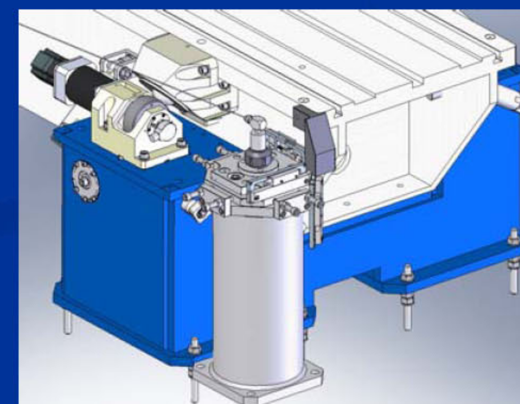


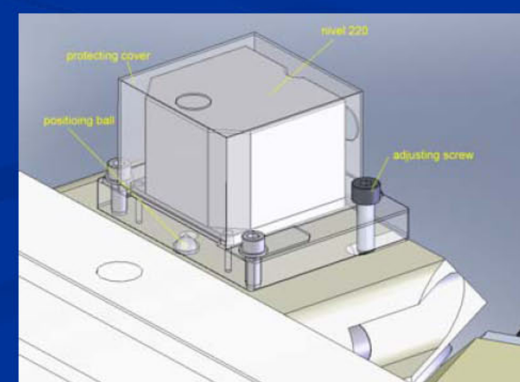
Sensor system design

- 3 major sensor systems to detect the relative position between girders.
- 5 touch sensors between the consecutive girders to detect the relative sway, heave, surge and yaw variations
- A tilting sensor mounted on each girder to detect the roll and pitch variations
- 3 touch sensors installed on each pillar at side of straight section to detect the relative sway, heave, and surge variations
- A laser PSD system can detect the relative sway, heave, pitch and yaw variations between the girders aside the straight section
- With these sensor systems, a feedback controlled whole ring automatic alignment girder system is thus fulfilled.

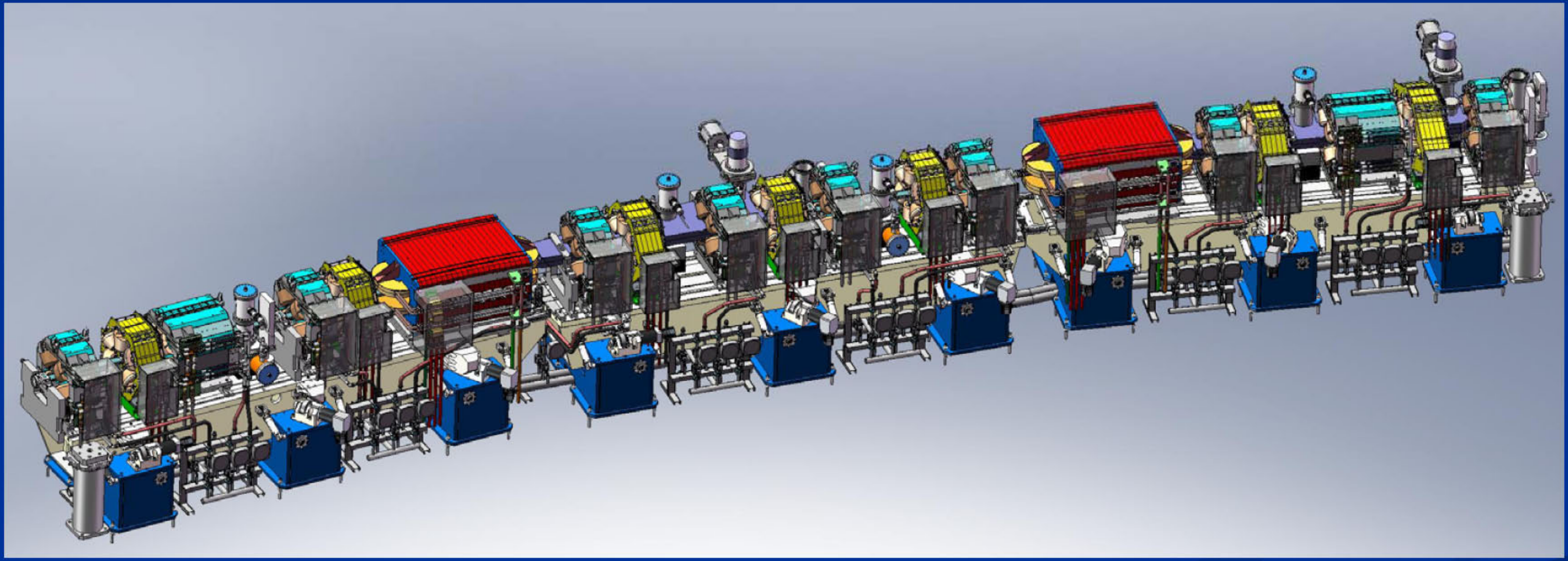








One section of 1/24 ring concept design



Girder system survey and auto-alignment procedure

1. Initial survey installation network establishing
2. Pedestals installation and adjustment
3. Girder section (6 girders) installation
4. Local survey – laser tracker local network
5. Girder section alignment
6. Local re-survey – laser tracker local network
7. Vacuum components & others installation
8. Repeat 3~7 till 12 sections installation completed
9. Whole ring survey – laser tracker network
10. Global auto-alignment – vertical
11. Global auto-alignment – horizontal

Global Alignment Algorithm

1. Girder Initial coordinate data establishing $G_{nm}(X,Y,Z)_0$ - Whole ring survey (laser tracker network) n : girder ID, m : points on girder [Left (L), or Right(R)],
2. Establish sensors deviation data between girders $S_{n(n+1)}(X,Y,Z)_{0,}$
3. Establish girders new coordinate data $G_{nm}(X,Y,Z)_{1,}$, each point calculated from the adjacent points (left and right) initial data with the sensors deviation data

$$G_{nL}(X,Y,Z)_1 = \{[(1\text{-}W)(G_{(n\text{-}1)R}(X,Y,Z)_0+E_0)+ W(S_{(n\text{-}1)n}(X,Y,Z)_0+E_{S(n\text{-}1)n})]+ [(1\text{-}W)(G_{nR}(X,Y,Z)_0 +E_0)\text{-} W(S_n(X,Y,Z)_0+E_{Sn})]\}/2$$

$$G_{nR}(X,Y,Z)_1 = \{(1\text{-}W)(G_{nL}(X,Y,Z)_0 +E_0)+ W(S_n(X,Y,Z)_0+E_{Sn})]+ (1\text{-}W)[G_{(n+1)L}(X,Y,Z)_0+E_0]\text{-}W[S_{n(n+1)}(X,Y,Z)_0+E_{Sn(n+1)}]\}/2$$

4. Least square fitting lattice best fitting pattern $P_{nm}(X,Y,Z)_1$
5. Calculate deviations between $G_{nm}(X,Y,Z)_1$ and $P_{nm}(X,Y,Z)_1$,

$$D_{nm}(X,Y,Z)_1 = G_{nm}(X,Y,Z)_1 - P_{nm}(X,Y,Z)_1$$

6. According to $D_{nm}(X,Y,Z)_1$, calculate motor adjusting steps of each girder
7. Adjust girders
8. Let $G_{nm}(X,Y,Z)_0 = P_{nm}(X,Y,Z)_1$
9. Iteration procedures 2~8 till least square fitting minimized (10^{-6} typically)

Girder position lattice pattern Least Square Fitting algorithm (straight line method)

- Let a line equation $X+AZ=B \Rightarrow [1,A][X,Z]^T=B$ approximate girder1
- Calculate orthogonal distance between girder 1 and this line

$L_{G1R}= [1,A][X,Z]^T_{G1R}-B$, $L_{G1L}= [1,A][X,Z]^T_{G1L}-B$

- The line equation approximate girder2 is $[1,A][R][X,Z]^T=B$,

(Since there is 7.5° rotation between girders according to the lattice design)

- Calculate orthogonal distance between girder 2 and this line

$L_{G2R}= [1,A][R][X,Z]^T_{G2R}-B$, $L_{G2L}= [1,A][R][X,Z]^T_{G2L}-B$

- Calculate orthogonal distance between girder n and the approximate line

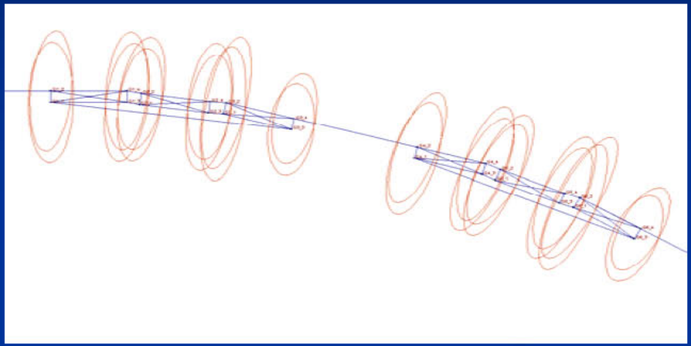
$L_{GnR}= [1,A][R]^n[X,Z]^T_{GnR}-B$, $L_{GnL}= [1,A][R]^n[X,Z]^T_{GnL}-B$

- Least square fitting all distances to find the value A & B
- The lattice fitting pattern of girder points P_{nm} is the orthogonal projection points of the original girder points

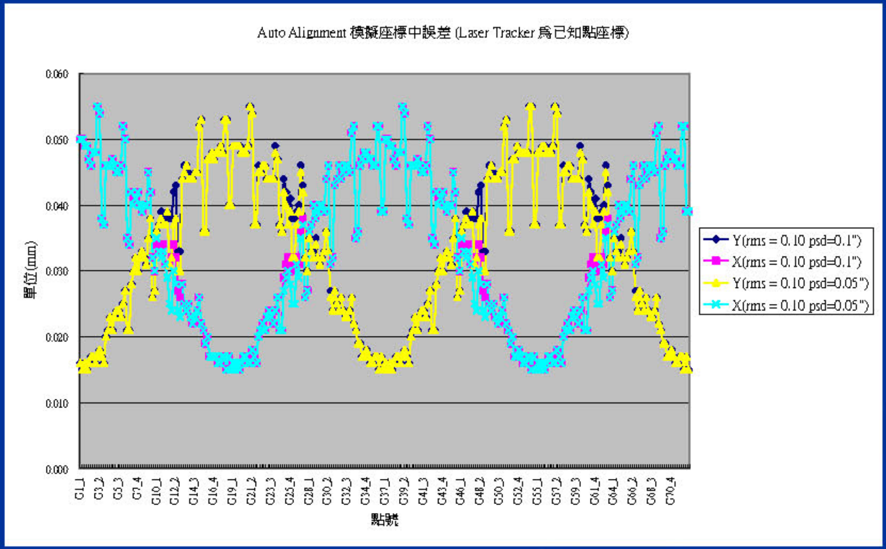
Auto-alignment accuracy simulation (with STAR*NET Software)

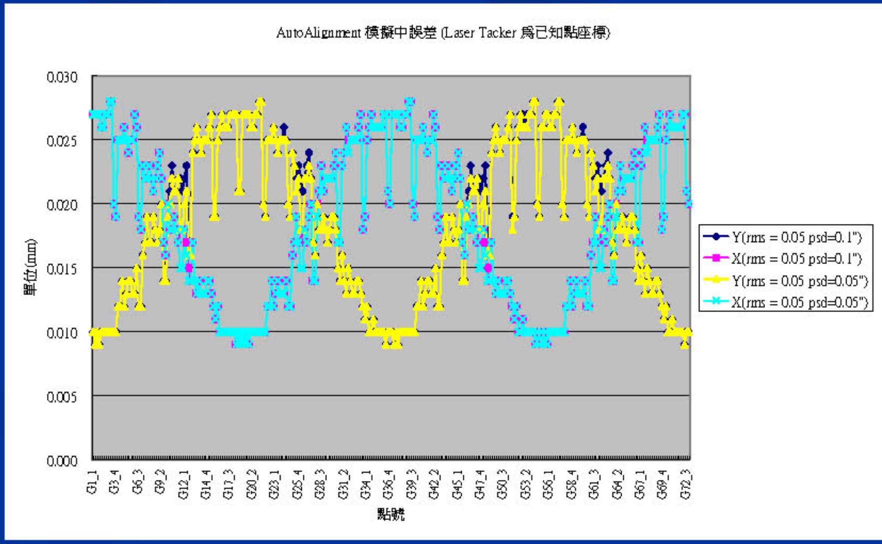
Conditions：

1. RMS survey errors of the fiducials on the girder are 0.10mm in transverse dir. and 0.05 mm in longitudinal dir. respectively.
2. RMS errors between consecutive girders measured by touch sensor is 2μm .
3. Distance RMS errors between long section girders measured by disInvar is 0.01mm ，and angle RMS errors is 0.05” by laser PSD system．

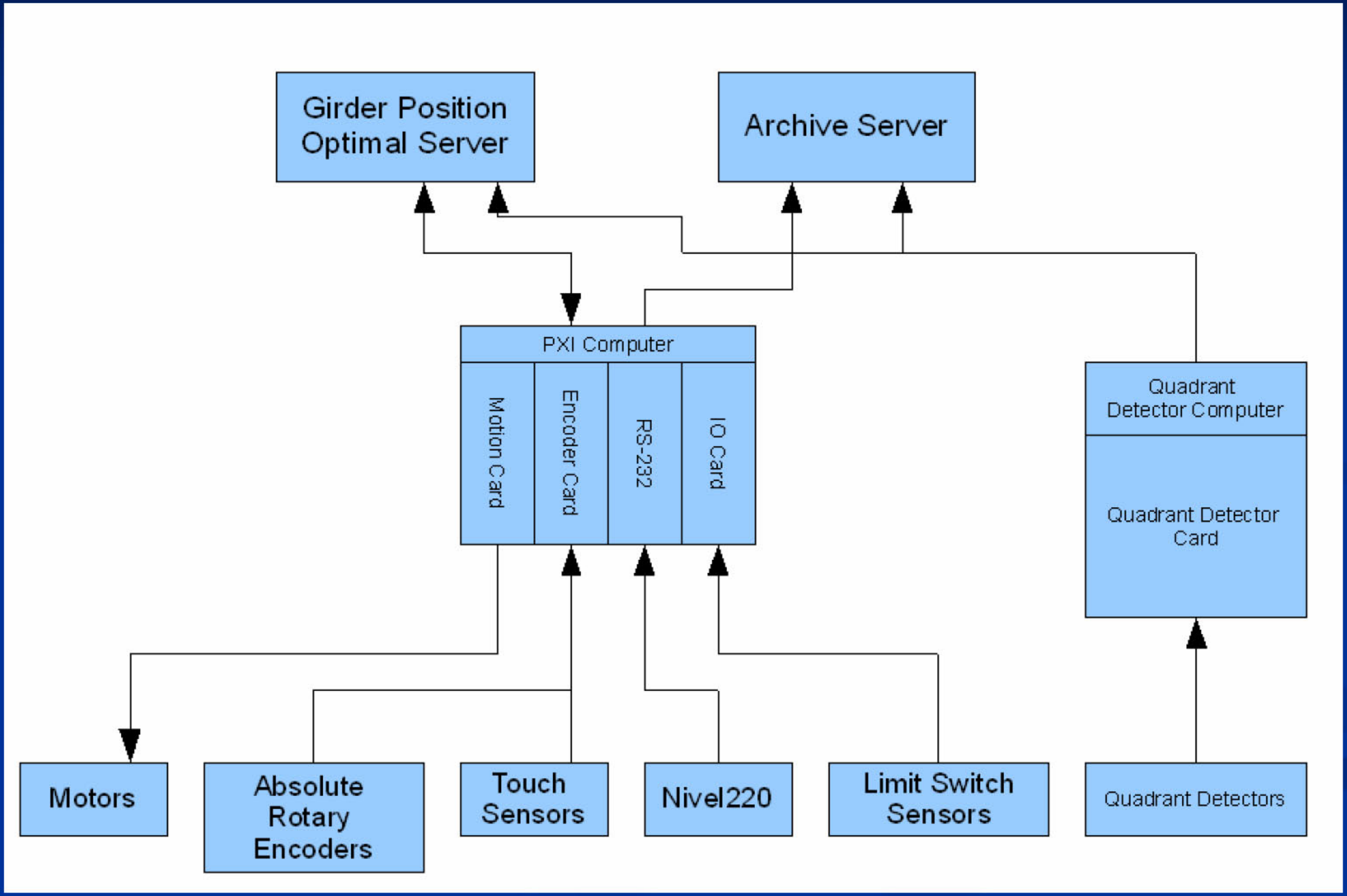


* Alignment accuracy within 50μm is possible

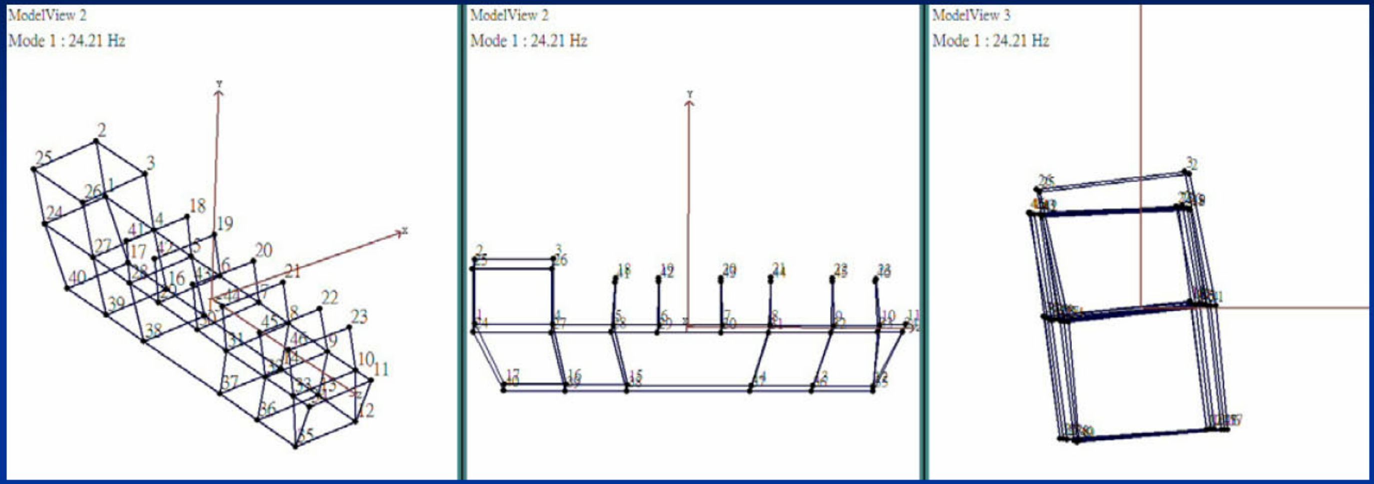


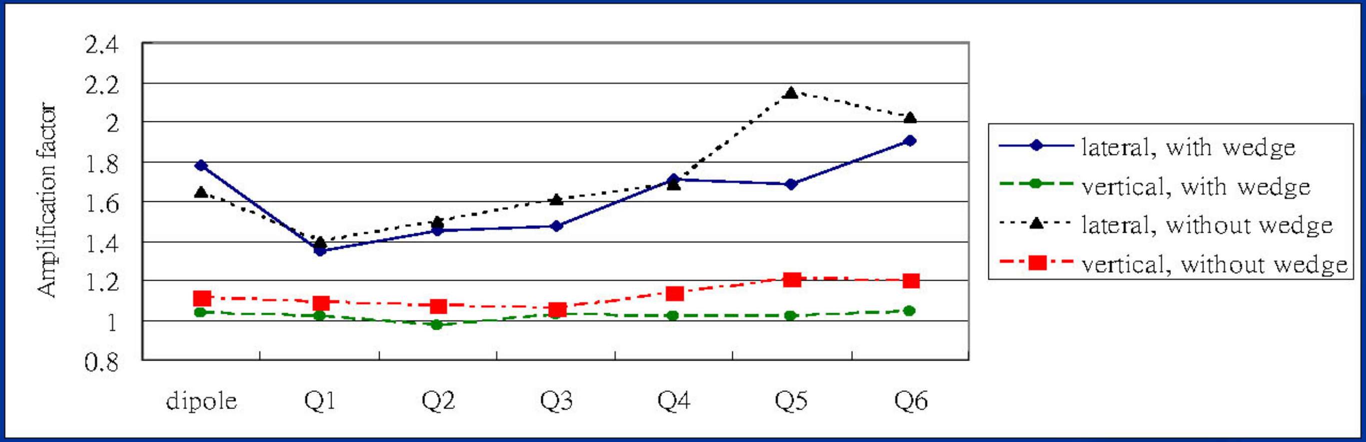


Control system layout



Modal and amplification factor testing





The amplification factors of girder to ground integrated from 4 ~ 100Hz are about 2.1 in horizontal transverse direction and 1.2 in vertical, while with the locking system they are reduced to 1.9 and 1.1 respectively.

*** Detailed description will be presented at MSDEI 2008**

Adjustability testing

(a) Initial position

Touch Sensors (Between Girder1 and Girder 2 Unit:um)			
Touch1(X1):	-4.6	Touch4(Z1):	1.2
Touch2(X2):	0.0	Touch5(Z2):	0.2
Touch3(Y):	4.2		

Touch Sensors (Between Girder 2and Girder 3 Unit:um)			
Touch1(X1):	9.0	Touch4(Z1):	-0.4
Touch2(X2):	0.0	Touch5(Z2):	0.0
Touch3(Y):	-3.8		

Gider2 Attitude (Unit: mm, mrad)			
X	-0.0035	Pitch	0.0020
Y	0.0044	Yaw	0.0050
Z	-0.0005	Roll	0.0110

(b) 100μm transverse direction(x) movement

Touch Sensors (Between Girder1 and Girder 2 Unit:um)			
Touch1(X1):	-101.3	Touch4(Z1):	-0.3
Touch2(X2):	0.0	Touch5(Z2):	0.4
Touch3(Y):	1.7		

Touch Sensors (Between Girder 2and Girder 3 Unit:um)			
Touch1(X1):	-99.0	Touch4(Z1):	-0.5
Touch2(X2):	0.0	Touch5(Z2):	-0.4
Touch3(Y):	-1.0		

iider2 Attitude (Unit: mm, mrad)			
X	-0.1013	Pitch	0.0010
Y	0.0017	Yaw	0.0009
Z	0.0000	Roll	0.0160

(c) Return to initial position (-100μm movement)

Touch Sensors (Between Girder1 and Girder 2 Unit:um)			
Touch1(X1):	-3.5	Touch4(Z1):	-2.5
Touch2(X2):	0.0	Touch5(Z2):	1.4
Touch3(Y):	4.4		

Touch Sensors (Between Girder 2and Girder 3 Unit:um)			
Touch1(X1):	3.4	Touch4(Z1):	-1.2
Touch2(X2):	0.0	Touch5(Z2):	0.1
Touch3(Y):	-4.4		

Gider2 Attitude (Unit: mm, mrad)			
X	-0.0035	Pitch	0.0020
Y	0.0044	Yaw	0.0050
Z	-0.0005	Roll	0.0110

- Without feedback coupling within 10% (could be better)
- With feedback resolution 1um in translation and 1urad in rotation

Resolution testing

X(μm)	Set value	0	1	2	3	4	5	6	7	8	9	10
	Displacement	0	0.3	1.4	2.4	3.5	4.4	5.8	6.4	7.4	8.4	9.5
Y(μm)	Set value	0	1	2	3	4	5	6	7	8	9	10
	Displacement	0	0.3	1.3	2.3	3.6	4.6	5.7	6.8	7.7	8.9	9.5
Z(μm)	Set value	0	1	2	3	4	5	6	7	8	9	10
	Displacement	0	0.5	1.6	2.3	3.2	4.6	5.3	6.3	7.4	8.2	9.5

- With feedback control 1um resolution is achieved
- 0.5um resolution is possible

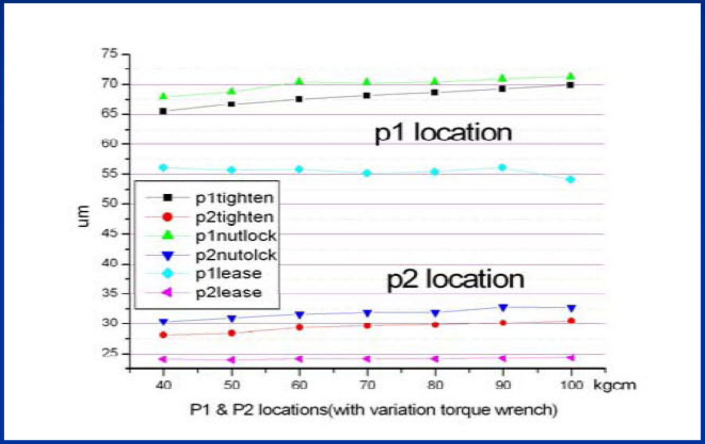
Lateral load and retrievability testing

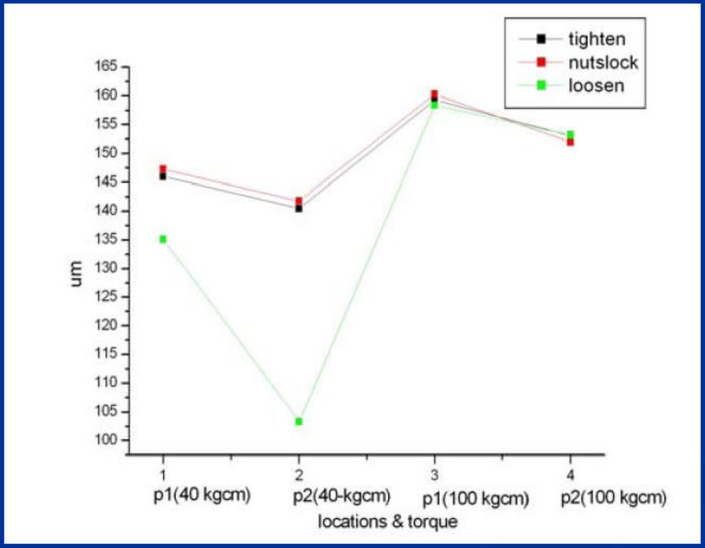
Direction	Load (Kgf)	Sensor X between girder 1,2	Sensor X between girder 2.3	Sensor Z1 Between girder 1,2	Sensor Z2 Between girder 1,2	Sensor Z1 between girder 2,3	Sensor Z2 between girder 2,3
X_center	0	-0.2	0.2				
X_center	50	-0.9	2.4				
X_center	100	-1.8	5.7				
X_12	0	0	0				
X_12	50	-9.1	-5.2				
X_12	90	-17.4	-10.4				
X_12	100	-					
X_12	release	-3.4	-4.1				
X_23	0	0	0				
X_23	50	3.2	10.1				
X_23	100	8	24.7				
X_23	release	1.1	0.2				
Z	0			-0.8	-0.1	0.2	-0.3
Z	50			-2.4	-1.8	5.3	5.3
Z	100			-4.1	-3.8	10.7	10.7
Z	release			-1.6	-0.5	2	2.1

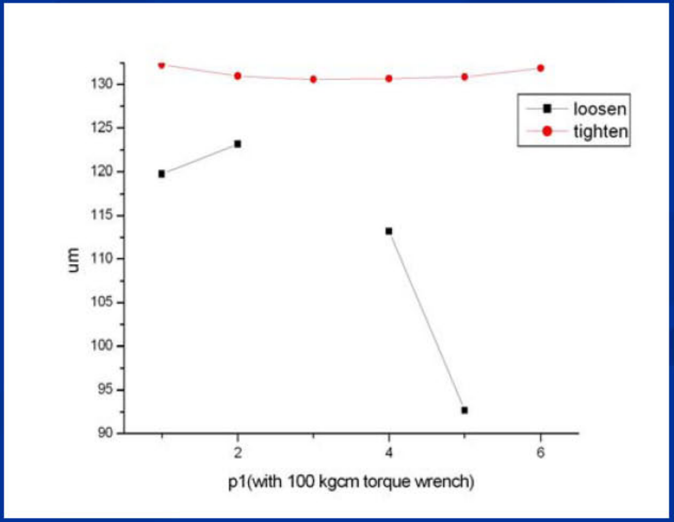
Natural frequency improvement wedge locking system test

	Y	X	Z
spring 24rs	36.6211	26.3672	30.7617
wedge	34.4238	26.3672	30.7617
200kg-cm	43.9453	32.2266	38.0859
300kgcm	43.2129	32.2266	38.0859

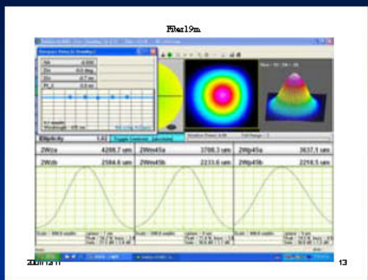
Magnet base installation repeatability testing

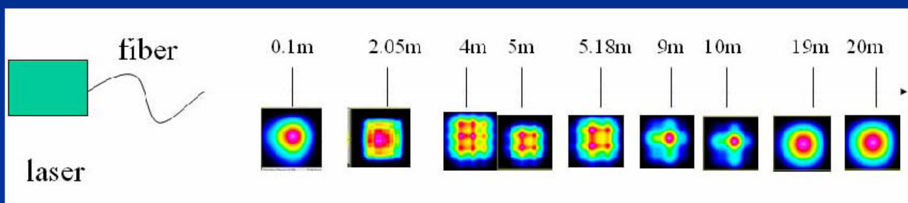






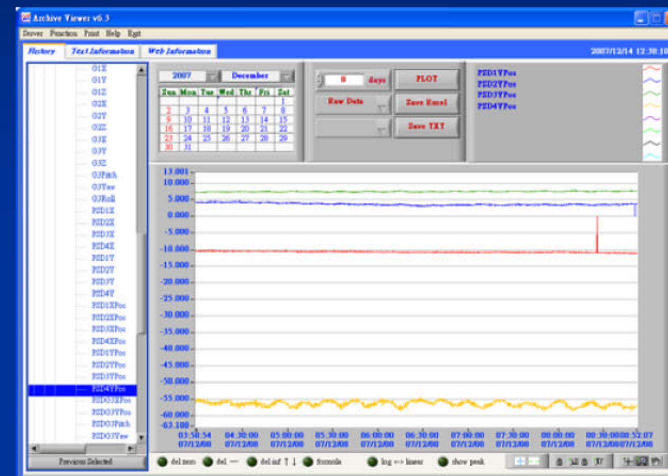
Laser PSD system testing

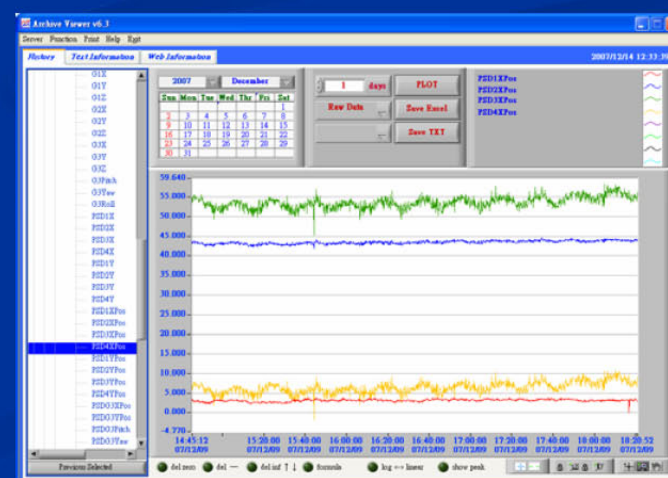


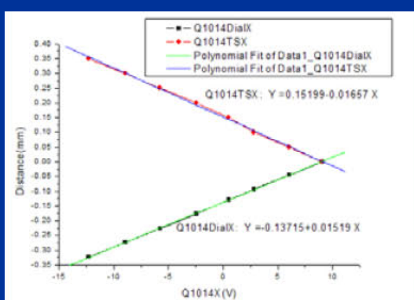


Laser properties measurement

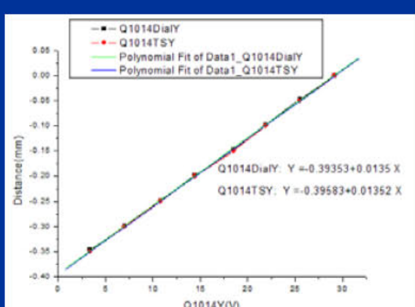
After thermally shielding the system
Stability could be maintain at 2μm P-P







PSD calibration

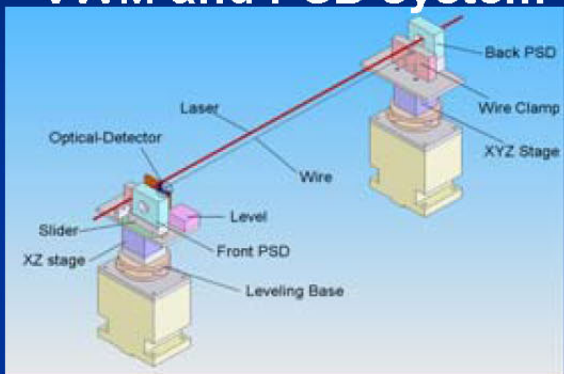


PSD center alignment

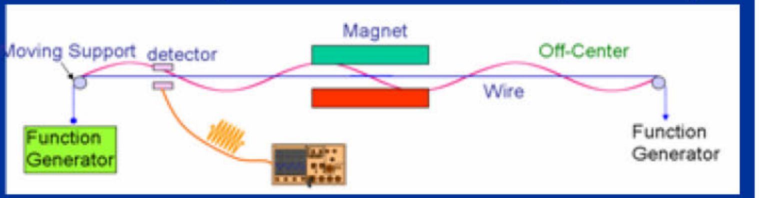
*** Detailed description will be presented at MSDEI 2008**

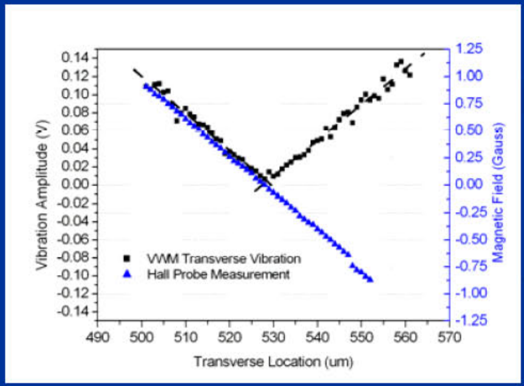
Multiple Quadruple Magnetic Center Alignment on the Girder

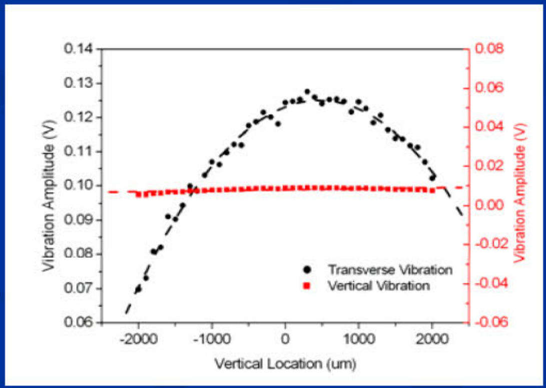
VWM and PSD system



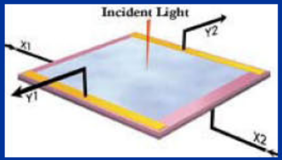
Vibrating Wire Method (VWM)







Position Sensing Detector (PSD)



$$y = \frac{L_y}{2}\frac{Y_1 - Y_2}{Y_1 + Y_2} \qquad x = \frac{L_x}{2}\frac{X_1 - X_2}{X_1 + X_2}$$

VWM and PSD system provide a new method to ensure the alignment of Quadrupole magnetic centers on girder to within 20 μm transverse positioning errors. The future goal of this new system is to improve the accuracy and repeatability for Sextupole Magnetic center measurement to within 30 μm, so that the alignment of Quadrupole and Sextupole magnets could all be verified on girder using the proposed system.

* Presented at APAC 2007

Conclusion

- A magnet girder system has been deigned for the TPS project
- A girder pre-prototype system was fabricated and installed at NSRRC for testing
- Tests and improvements had been done:
  - 6 ball contacting type kinematic mounting adjustment mechanism design and improvement
  - A hard Stopper deign to prevent miss-function of control system and sudden impact such as the earthquake
  - Single girder adjusting algorithm and programming and the resolution is 1μm
  - Modal analysis and testing ability established
  - A laser PSD system prototype designed, established and tested. The system stability is within 5μm/day P-P with a thermal shielding protection.
  - The magnet base installation repeatability in within 2μm with a same side pushing force.
  - A locking stage mechanism could raise the first natural frequency high than 30Hz
  - The global alignment algorithm established and a preliminary feasibility simulation shows a positive convergence.
  - A Vibrating Wire Method magnet alignment module developed
- Tasks still in progressing
  - Feedback controlled locking system to prevent further displacement after fine adjustment
  - Global feedback control testing
  - Final design modification according to the lattice and interface agreement with magnets and vacuum system for a real section of 1/24 ring this year.

Thank you for your attention !