國家同步輻射研究中心
National Synchrotron Radiation Research Center

Bendable KB Type Focusing Mirrors Designed for TPS IR Beamline

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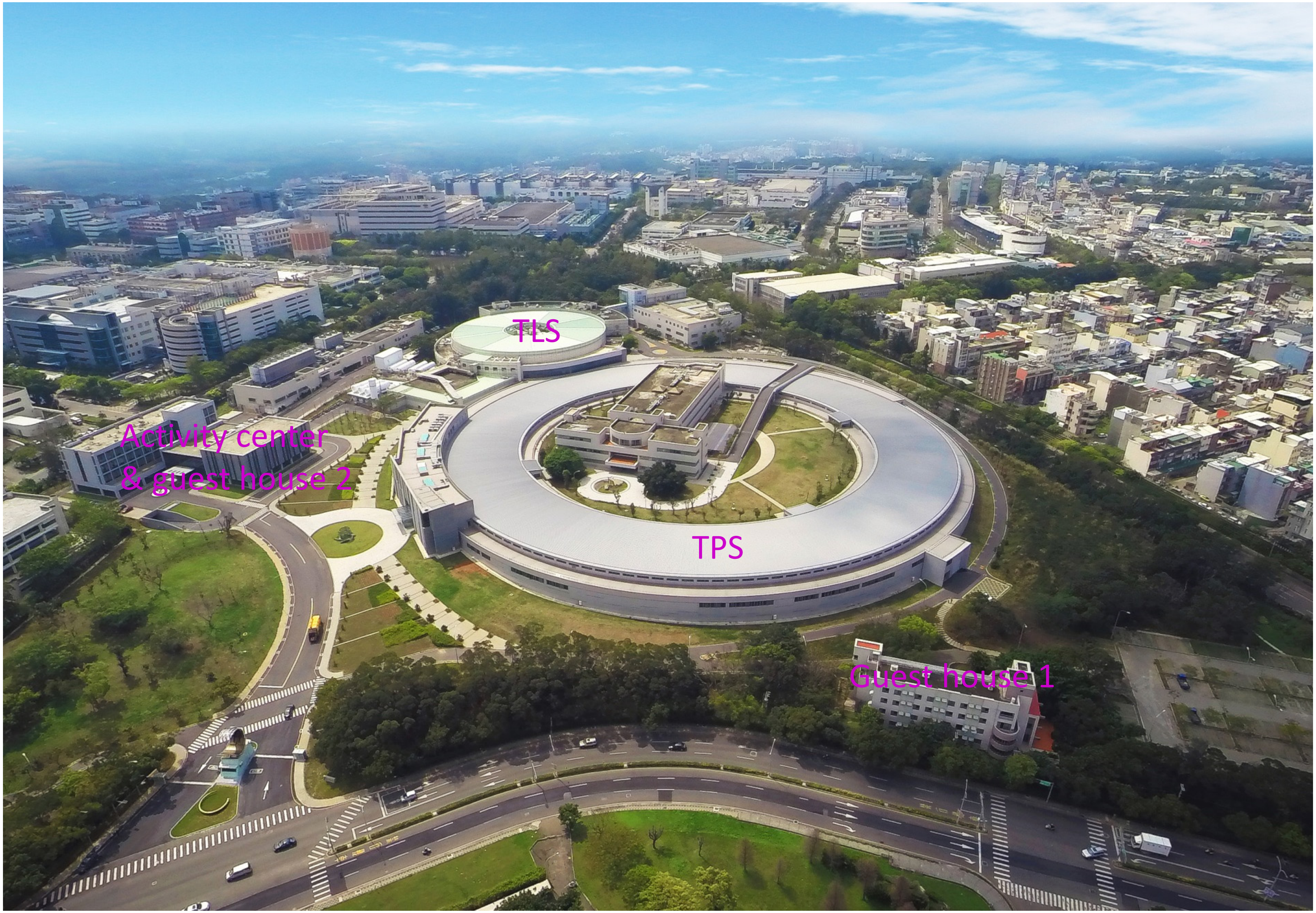
NSRRC

Outline

1. Introduction
2. Ideal KB type mirror surface profile equations derived with drawing method
3. Equations derived for bending flat mirror to fit ideal mirror surface profiles
4. Optimized width profile equations with FEM analysis iteration
5. Engineering Design
6. Conclusions

NSRRC Site Aerial View



NSRRC TLS 14A FTIR Microscopy Beamline

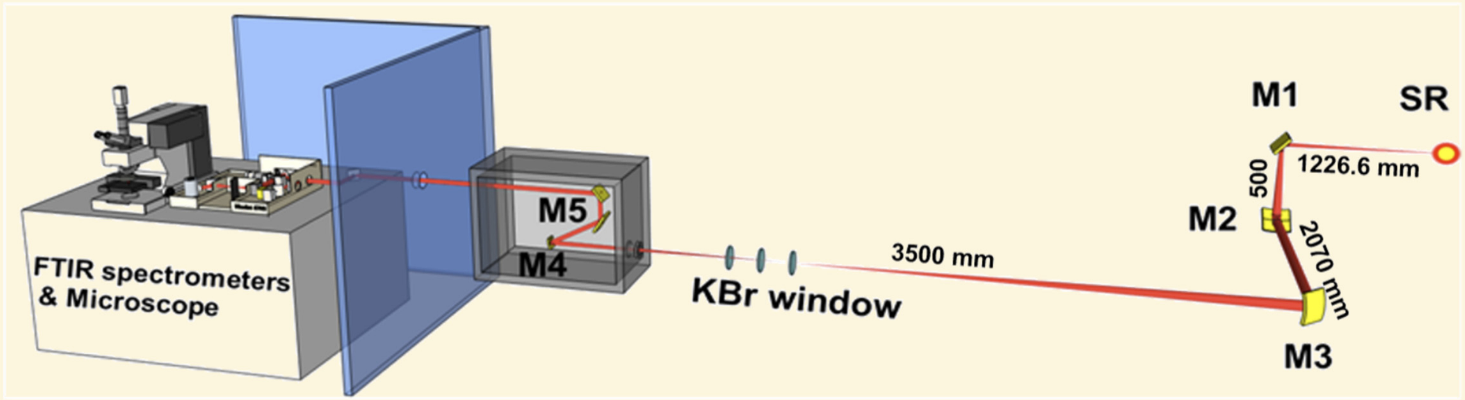


Figure 1. The optical layout of the NSRRC TLS 14A IR beamline.

Pre-focusing mirror design :

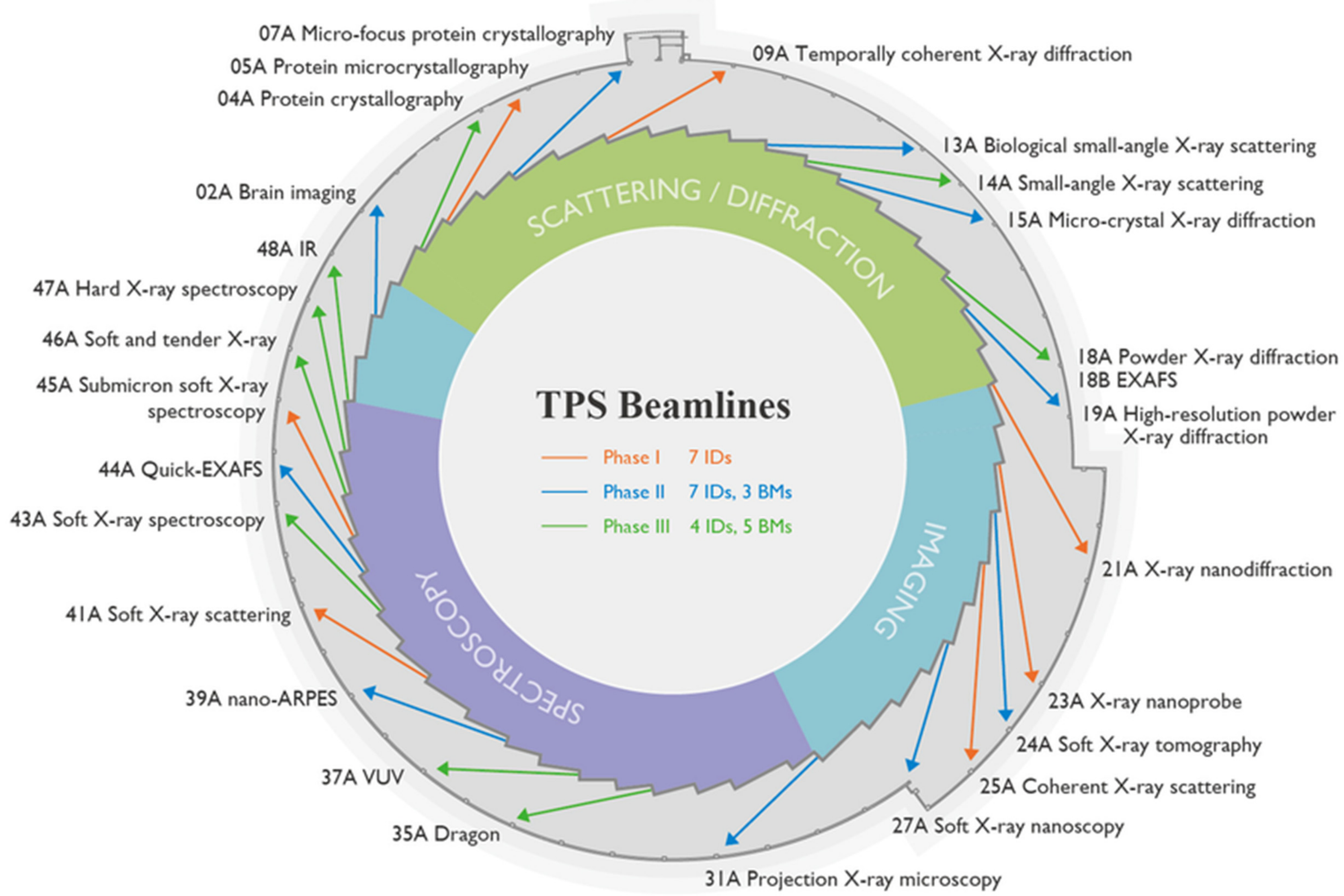
- S.-J. Chen, C. K. Kuan,S. Y. Perng, D. J. Wang, H. C. Ho, T. C. Tseng, Y.-C. Lo, C. T. Chen, “New focusing mirror system for synchrotron radiation infrared beamlines”, Optical Engineering, Vol. 43 No. 12, 2004

Excellent research articles published

- R. R. Reisz*, T. D. Huang, E. M. Roberts, S. R. Peng, C. Sullivan, K. Stein, A. R. H. LeBlanc, D. Shieh, R. S. Chang, C. C. Chiang, C. Yang, and S. Zong, “Embryology of Early Jurassic Dinosaur from China with Evidence of Preserved Organic Remains”, Nature 496, 210 (2013). (IF: 43.070)
- Y.-C. Lee*, C.-C. Chiang, P.-Y. Huang, C.-Y. Chung, T. D. Huang, C.-C. Wang, C.-I. Chen, R.-S. Chang, C.-H. Liao, R. R. Reisz*, “Evidence of preserved collagen in an Early Jurassic sauropodomorph dinosaur revealed by synchrotron FTIR microspectroscopy”, Nature Communications, 8, 14220, (2017). (IF: 12.124)

However, TLS is scheduled to be shut down after TPS phase III due to the budget consideration

TPS Beamline Map



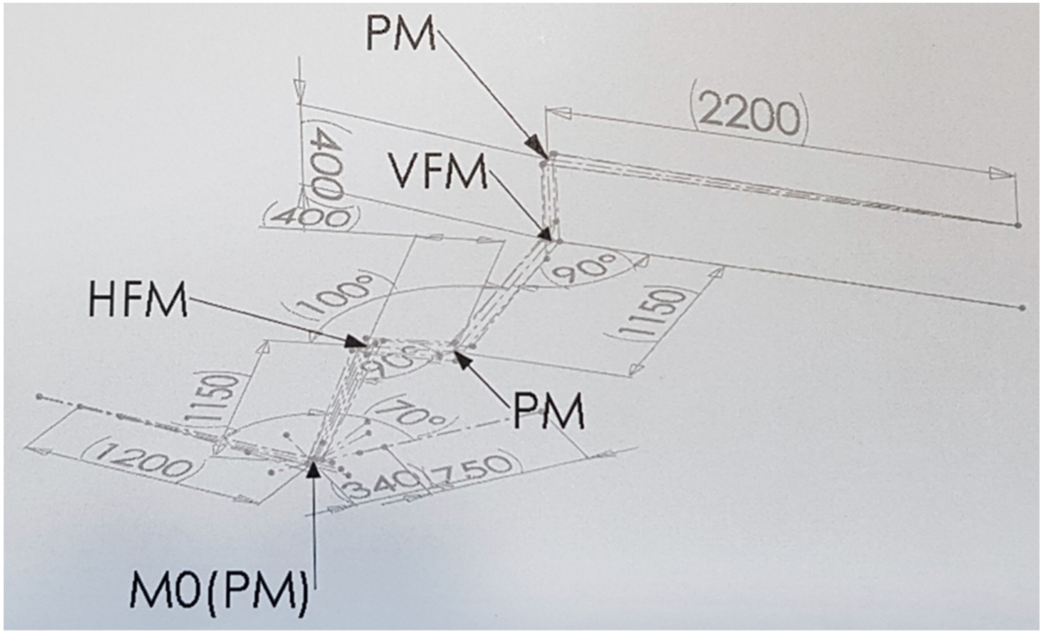
Phase I & II beamlines are mostly opened to users and phase III beamlines are under design.

A new IR beamline is scheduled at phase III.

With different conditions from TLS, The TPS IR beamline has to be re-design!

TPS IR Pre-Focusing Period Design

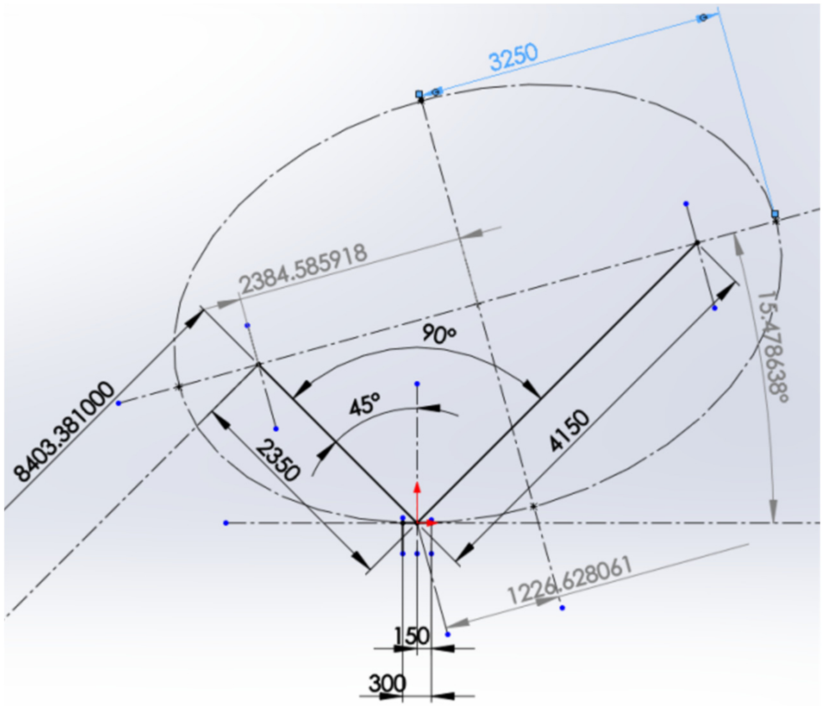
- The TPS IR beamline adopts the similar design as TLS by using K-B type focusing mirrors in the pre-focusing period.
- Two Stainless flat mirror plates are to be bended to the desired surface profile.
- In experience, a 5th order polynomial surface profile is enough and also for the manufacturing consideration.

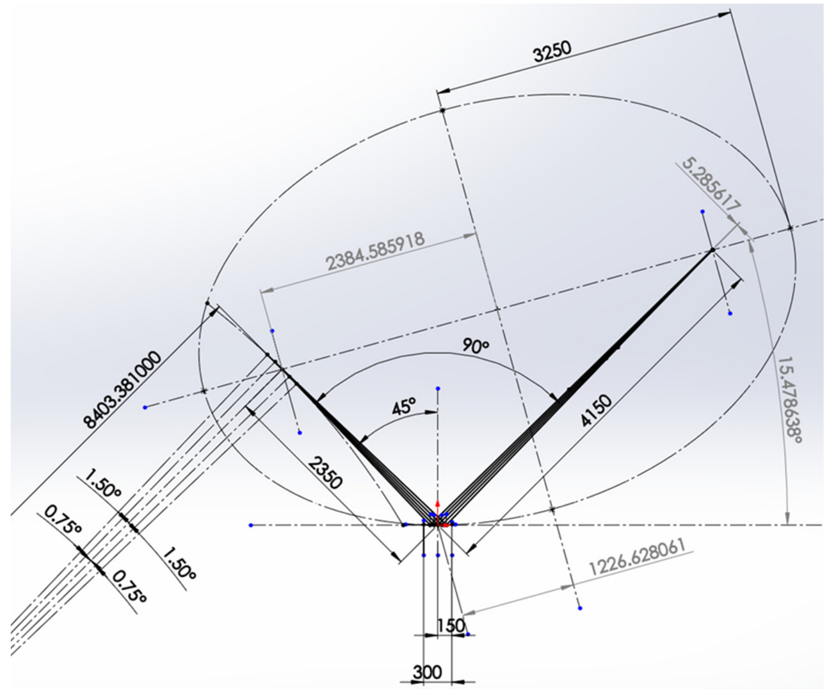


For the frontend space consideration

- **HFM** is located 2350mm from the center of the light source and 4150mm from the focus point.
- **VFM** is located 3900mm from the center of the light source and 2600mm.
- The beam divergence angles of horizontal and vertical are 50mrad and 25mrad from the focus point , respectively .
- The light-reflecting areas of HFM and VFM are about 166mm x 66mm (maximum) and 77mmx138mm respectively.

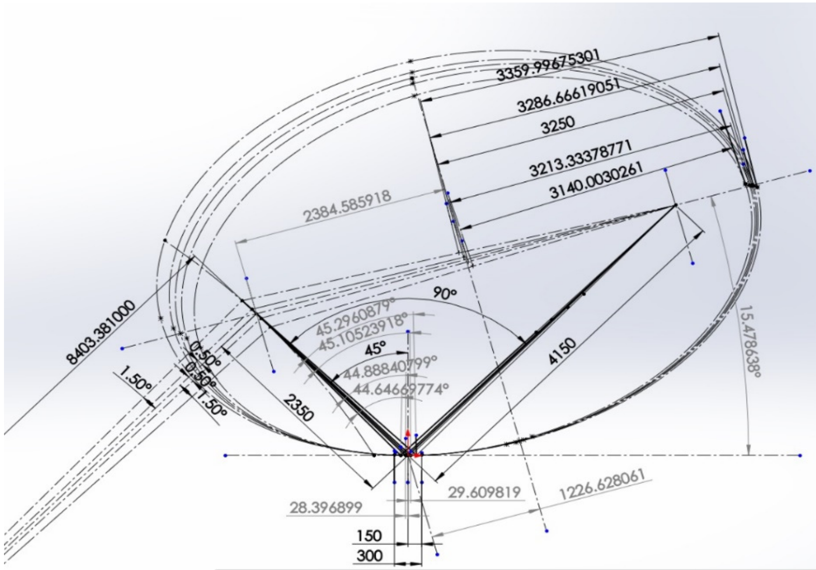
Bending Magnet Arc Light Source

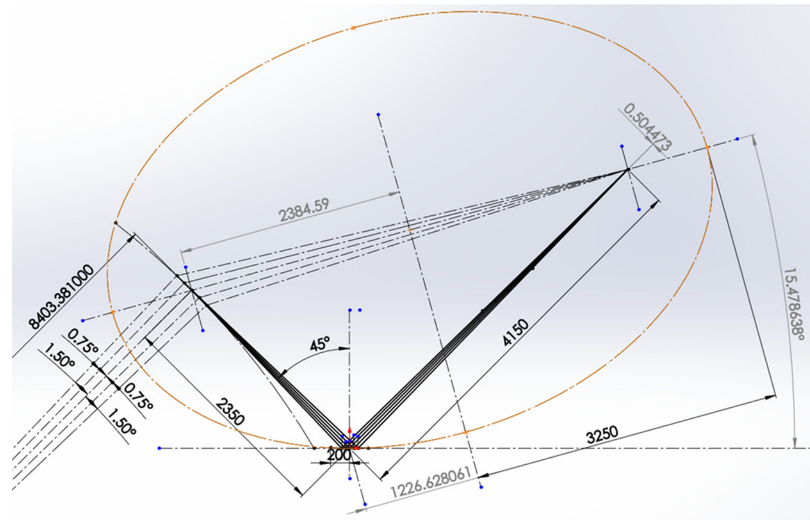


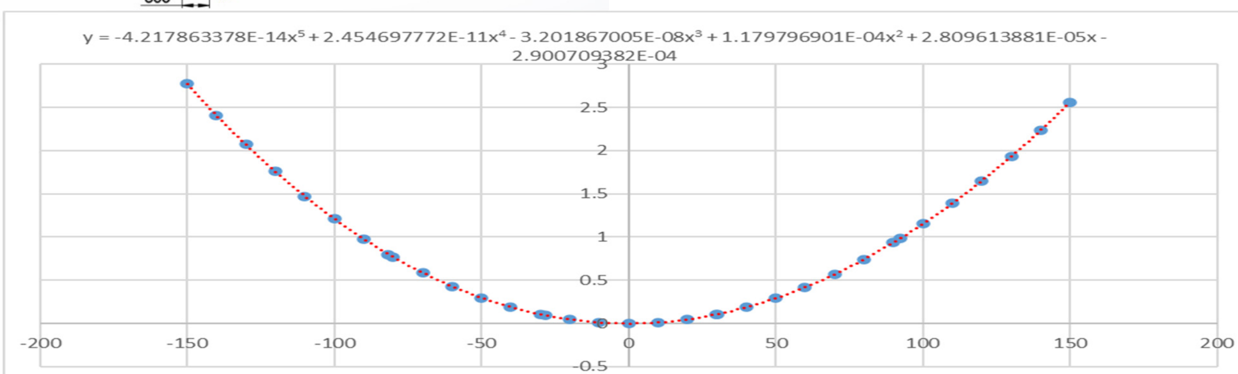


- For an ideal point light source, by using an elliptical mirror, the light from one focus will be reflected and concentrated in another focus.
- This phenomenon is will adopted in VFM because it can be regard as from a point source without considering the electron beam size.
- For HFM, the light source is an arc section from bending magnet, the light will not concentrate in another focus and the profile should be modified.
- in TLS mirror design, a fourth-order RungeKutta numerical method was used to find out the coefficients of the modified polynomial equation. — Complicated！！
- The Drawing method was adopted any try to easily find out the profile polynomial.

HFM Surface Profile Polynomial Correction First Attempt







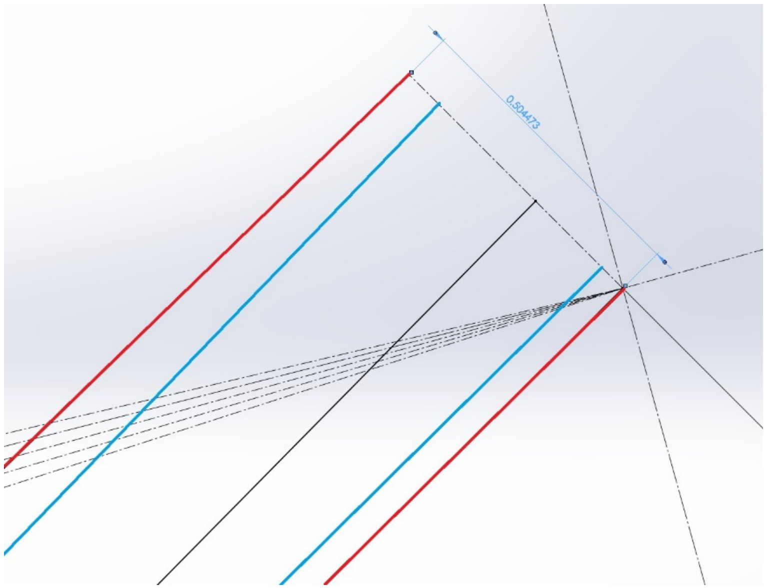
- At first, 5 ellipses were setup according to the arc divergence angle.
- The crossed sections were jointed to form a new profile and fitting to get a new polynomial :

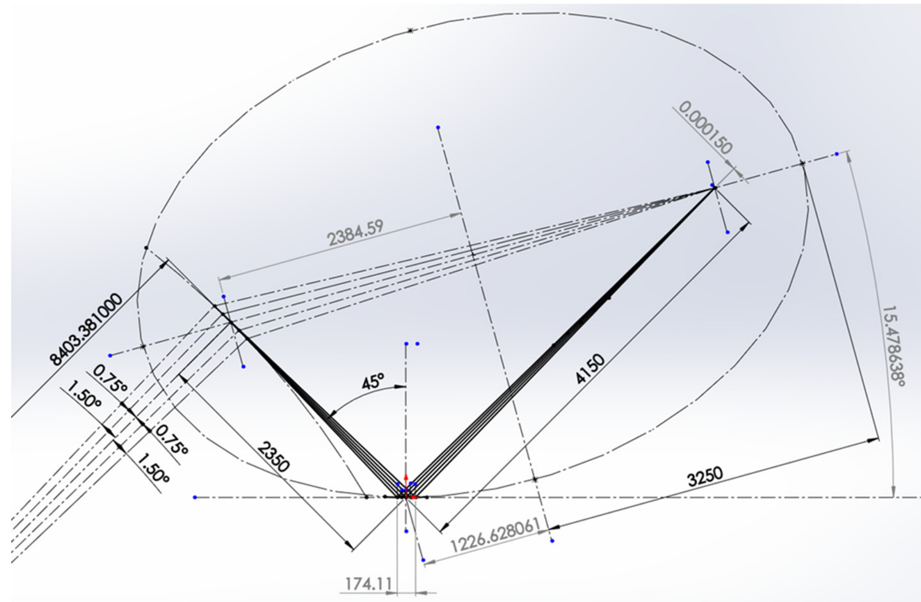
$$y_1 = -\ 4.217863378E\text{-}14x^5 + 2.454697772E\text{-}11x^4 - 3.201867005E\text{-}08x^3 + 1.179796901E\text{-}04x^2$$

From the drawing, the focusing size is reduced to 0.5mm.

Not bad but still not good enough !

HFM Surface Profile Ideal Polynomial Equation





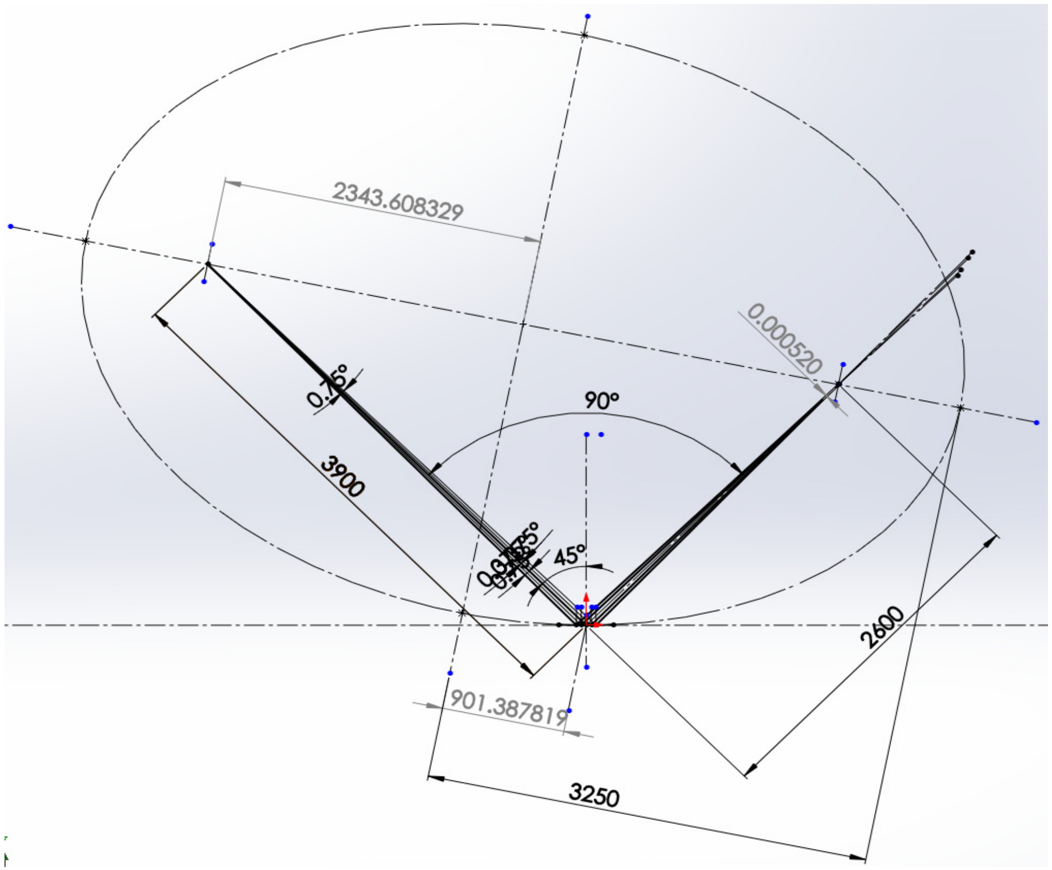
From the above polynomial equation, It is observed with the drawing :

- Coefficient of 2nd order term control the 4 lines concentration
- Coefficient of 4th order term enlarge the outside 2 lines concentration rate
- Coefficient of 3rd order term control 4 lines inclination
- Coefficient of 5th order term enlarge the outside 2 lines inclining rate

With these conditions, an ideal HFM surface profile polynomial can be obtained :
（ the drawing focusing area in only 0.15um ）

$$y_H = -4.92E\text{-}14x^5 + 3.953E\text{-}11x^4 - 3.4673E\text{-}8x^3 + 1.178178E\text{-}4x^2$$

VFM Surface Profile Ideal polynomial equation



VFM surface profile polynomial can be found from an ideal elliptical section fitting :
(the drawing focusing area in 0.52um)

$$y_v = 3.998784046E\text{-}16x^5 + 3.090696309E\text{-}12x^4 + 5.136405406E\text{-}9x^3 + 1.133183483E\text{-}4x^2$$

Equations for Bending Single Flat Mirror Plate to Fit Desired Mirror Surface Profile

Although the ideal mirrors surface profile equations were obtained, the design requirement is to use a single force to bend a stainless flat mirror plate and to from the desired shape.

- Let the requirement 5th order profile polynomials equation is : $y(x) = c_2x^2 + c_3x^3 + c_4x^4 + c_5x^5$
  (The constant and 1st order terms of face curve polynomial are translation and rotation, do not affect the analysis of face shape can not be neglected.)
- From the flexure equation : $\kappa(\text{curvature}) \approx \frac{d^2y}{dx^2} = \frac{M}{EI} \Rightarrow M = EI(2c_2 + 6c_3x + 12c_4x^2 + 20c_5x^3)$
- Since the moment distributed of a same thickness plate from a single force is constant, a different width design is required to obtain the desired face shape.
- So, in principle, the flat plate with a 3rd order polynomial width distribution can get a surface profile polynomial of 5th order, but because the high order terms are not included in the calculation, to prevent the error accumulation, a 4th order polynomial width distribution can get a better approximation value.
- Let the width distribution polynomial equation as follows : $b(x) = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4$
- The moment of inertia is : $I_t(x) = \frac{b_t(x){h_0}^3}{12} = \frac{I_0}{b_0}(b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4)$
- The bending moment is $M = E\frac{I_0}{b_0}(b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4)(2c_2 + 6c_3x + 12c_4x^2 + 20c_5x^3)$

$$= E\frac{I_0}{b_0}[2c_2b_0 + (6c_3b_0 + 2c_2b_1)x + (12c_4b_0 + 6c_3b_1 + 2c_2b_2)x^2 +$$

$$(20c_5b_0 + 12c_4b_1 + 6c_3b_2 + 2c_2b_3)x^3 + (20c_5b_1 + 12c_4b_2 + 6c_3b_3 + 2c_2b_4)x^4 + \cdots]$$

- The bending moment is constant, let the coefficient of the variable terms to zero and get the coefficients of width polynomial as following:

$$6c_3b_0 + 2c_2b_1 = 0 \Rightarrow b_1 = -3c_{32}b_0 \ (c_{32}=c_3/c_2)$$

$$12c_4b_0 + 6c_3b_1 + 2c_2b_2 = 0 \Rightarrow b_2 = -3c_{32}b_1 - 6c_{42}b_0 \ (c_{42}=c_4/c_2)$$

$$20c_5b_0 + 12c_4b_1 + 6c_3b_2 + 2c_2b_3 = 0 \Rightarrow b_3 = -3c_{32}b_2 - 6c_{42}b_1 - 10c_{52}b_0 \ (c_{52}=c_5/c_2)$$

$$20c_5b_1 + 12c_4b_2 + 6c_3b_3 + 2c_2b_4 = 0 \Rightarrow b_4 = -3c_{32}b_3 - 6c_{42}b_2 - 10c_{52}b_1$$

Modified Equations for Mirror Plate with Bending Arms to Fit Desired Surface Profile

- **However, the above calculation is the ideal situation of a single flat mirror plate bended with equal moment.**
- The real design of the focusing mirror has to be assembled with bending arms to apply the torque, the actual inertial moment is complex and difficult for theoretical analysis.
- A flexible way is to make the moment of inertia of the mirror structure same as a single plate, the mechanism of the bending arm is another pseudo bending moment. With the same applied force, the pseudo moment distribution will be the same, so the desired surface curve profile can be approached by the plate width modification iteration without to know the real pseudo moment distribution.
- The mirror width curve parameters calculated from the above initial calculations can be used to establish a basic model for finite element analysis by using Solidworks and COSMOS software .
- The surface center curve from the FEM simulation is polynomial fitting as :

$$y_s(x) = s_2x^2 + s_3x^3 + s_4x^4 + s_5x^5$$

$$\kappa_s(\text{curvature}) \approx \frac{d^2y_s}{dx^2} = \frac{M_s}{EI_t} = 2s_2 + 6s_3x + 12s_4x^2 + 20s_5x^3$$

$$M_s(x) = E\frac{I_0}{b_0}(b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4)(2s_2 + 6s_3x + 12s_4x^2 + 20s_5x^3)$$

- A single force only affects the 2nd order term, the surface polynomial desired is :

$$y_r(x) = s_2x^2 + c_3x^3 + c_4x^4 + c_5x^5$$

Modified Equations for Mirror Plate with Bending Arms to Fit Desired Surface Profile

- The correction of other terms of the surface polynomial requires modifying the coefficient of the width curve polynomial so that the inertial moment of the new width curve polynomial becomes :

$$I_n(x) = \frac{b_n(x){h_0}^3}{12} = \frac{I_0}{b_0}(b_0 + b_{1n}x + b_{2n}x^2 + b_{3n}x^3 + b_{4n}x^4)$$

$$\kappa_r(\text{curvature}) \approx \frac{d^2y_r}{dx^2} = \frac{M_s}{EI_n} = 2s_2 + 6c_3x + 12c_4x^2 + 20c_5x^3$$

- With the assumption of the same bending moment, then

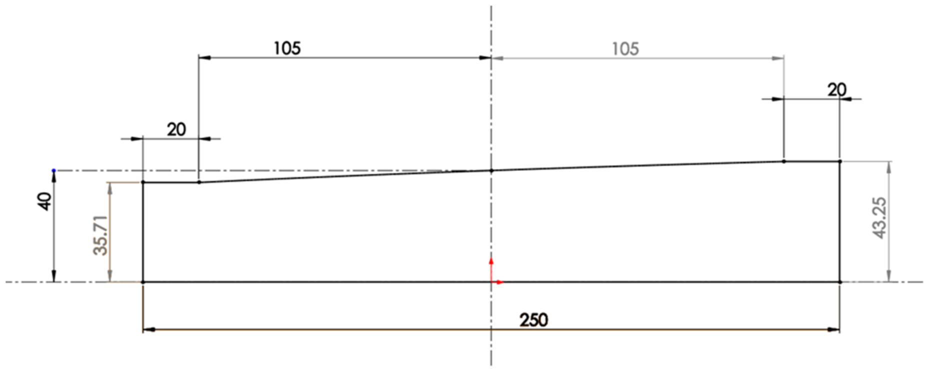
$$(b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4)(2s_2 + 6s_3x + 12s_4x^2 + 20s_5x^3)$$
$$= (b_0 + b_{1n}x + b_{2n}x^2 + b_{3n}x^3 + b_{4n}x^4)(2s_2 + 6c_3x + 12c_4x^2 + 20c_5x^3)$$

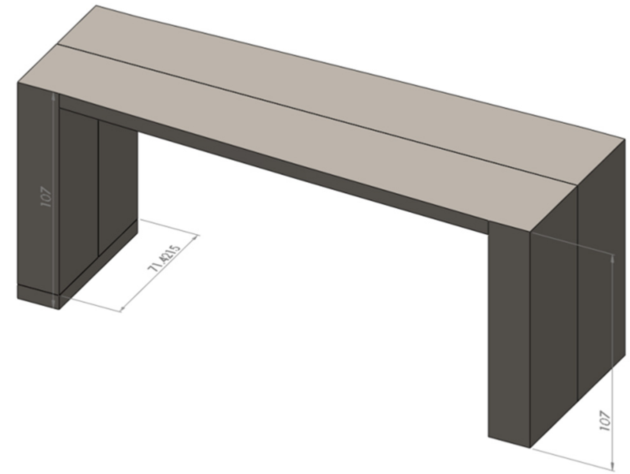
- **The New coefficients of the width distribution can be obtained from the old ones combined with the data from the FEM simulation : (Skip the high order terms)**

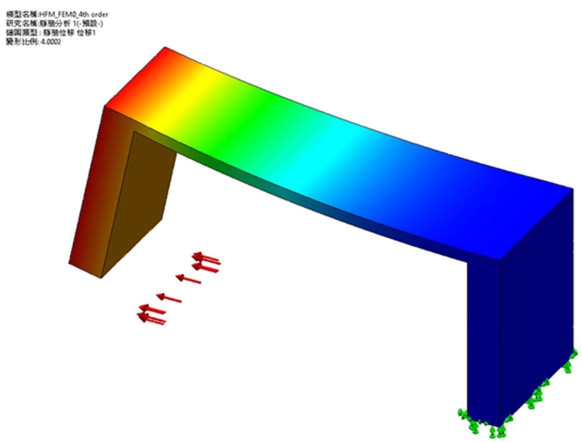
$$\boldsymbol{b_{1n} = b_1 + 3b_0(s_3 - c_3)/s_2}$$
$$\boldsymbol{b_{2n} = b_2 + 3(b_1s_3 - b_{1n}c_3)/s_2 + 6b_0(s_4 - c_4)/s_2}$$
$$\boldsymbol{b_{3n} = b_3 + 3(b_2s_3 - b_{2n}c_3)/s_2 + 6(b_1s_4 - b_{1n}c_4)/s_2 + 10b_0(s_5 - c_5)/s_2}$$
$$\boldsymbol{b_{4n} = b_4 + 3(b_3s_3 - b_{3n}c_3)/s_2 + 6(b_2s_4 - b_{2n}c_4)/s_2 + 10(b_1s_5 - b_{1n}c_5)/s_2}$$

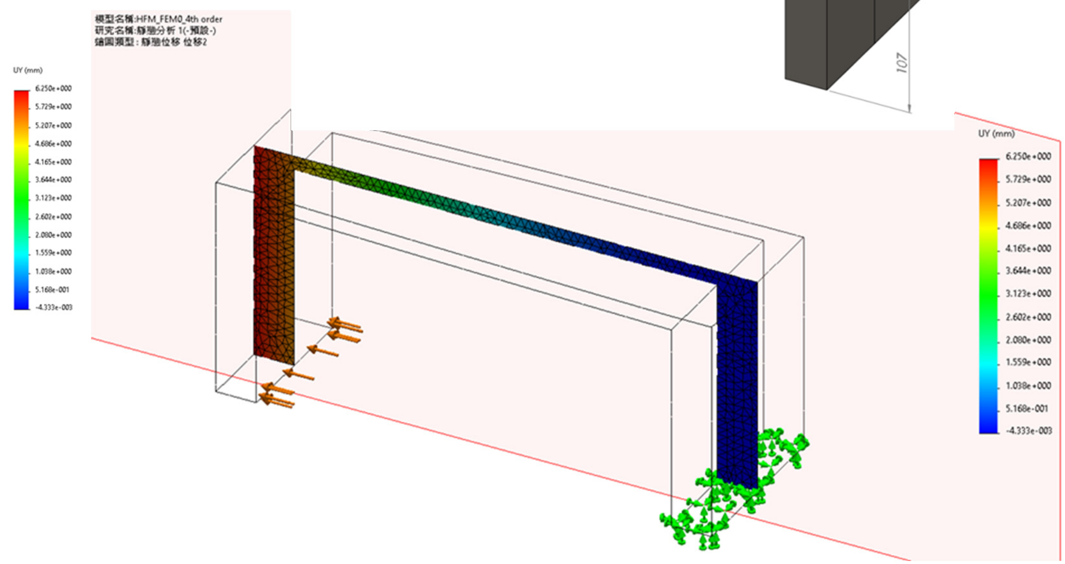
HFM First FEM Analysis

At first, a bending mirror model was built with the width coefficients derived from the single mirror plate without bending arms and applied for FEM simulation.









F_0=115.34kgf

b_0=80mm, h_0=7mm

b_{10}=0.0706304141

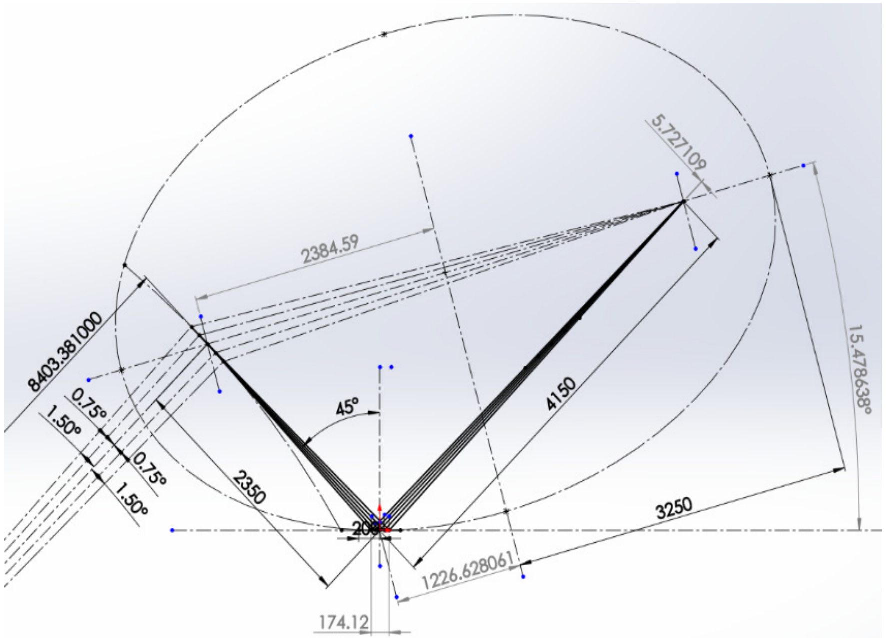
b_{20}=-0.0000986904777

b_{30}=1.04756612E-7

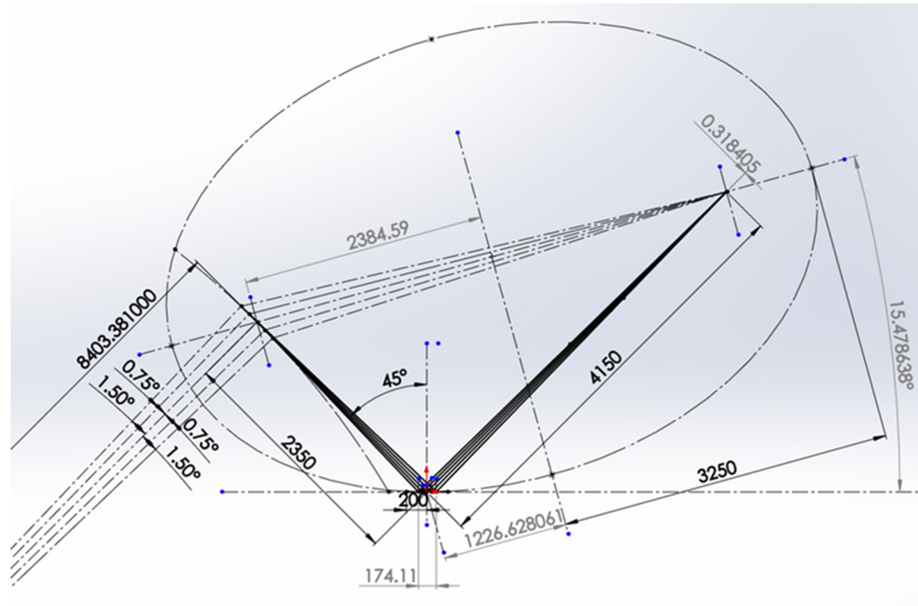
b_{40}=3.87224983E-10

$$y_0 = 1.841849055\text{E-}13x^5 - 9.223772983\text{E-}11x^4 - 3.775903127\text{E-}08x^3 + 1.178178\text{E-}04x^2$$

HFM Second FEM Iteration Analysis



Focusing size of initial FEM polynomial



Focusing size of the 1st FEM optimized polynomial

New parameters for simulation :

F_1=116.575kgf

b_{01}=80mm, h_1=7mm

b_{11}= 0.0642766966

b_{21}= -0.00065255328

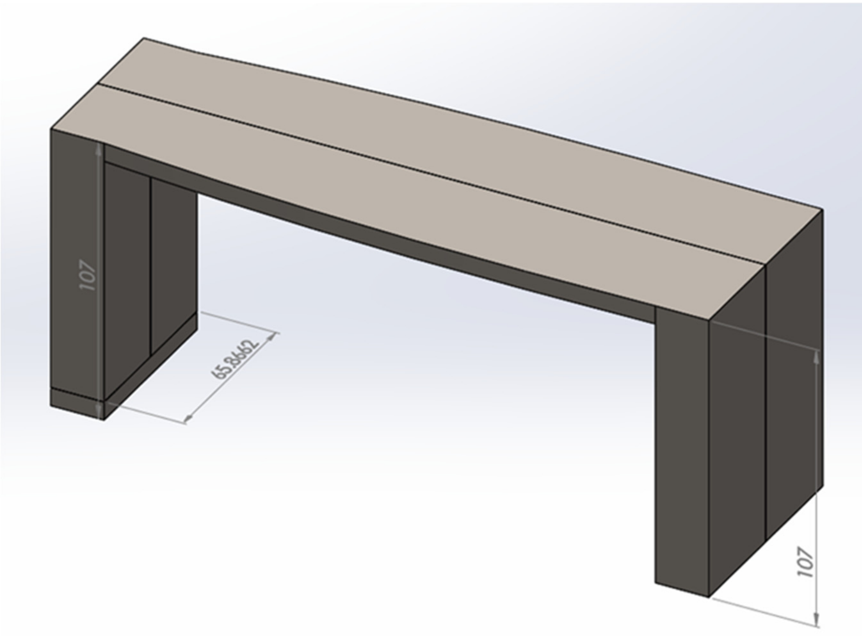
b_{31}=7.53946116*E-7

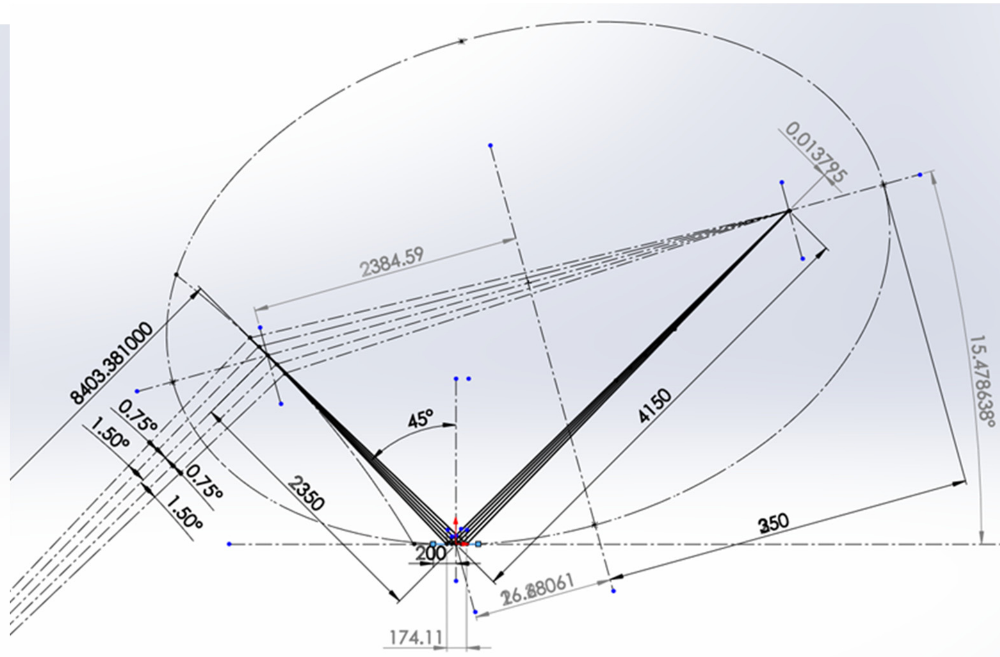
b_{41}= 4.14176349*E-9

New profile equation from fitting :

$$y_1 = -8.733021600E\text{-}14x^5 + 3.704793792E\text{-}11x^4 - 3.537329605E\text{-}08x^3 + 1.178178E\text{-}04x^2$$

HFM 4th FEM Iteration Analysis





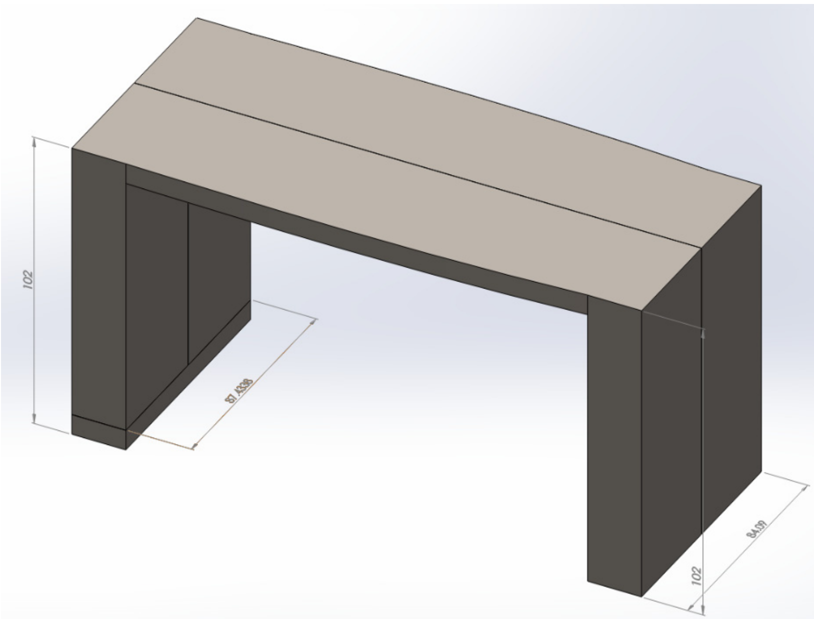
（ the drawing focusing area in 13.8um ）

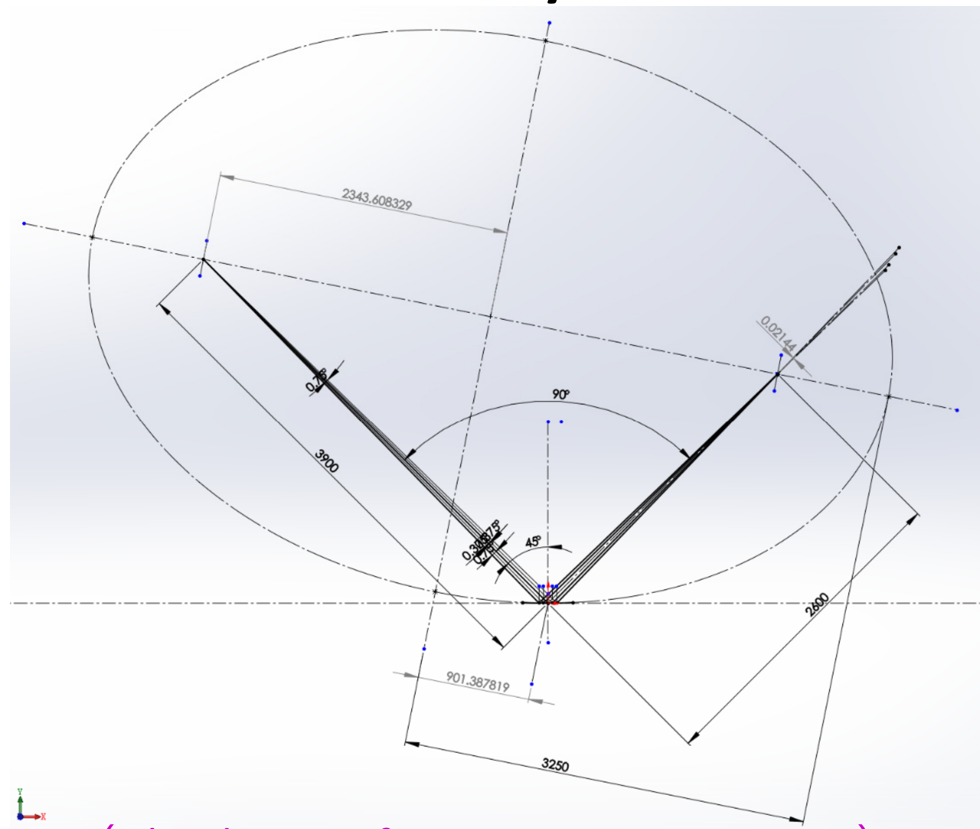
F_4=116.324kgf
b_{04}=80mm, h_4=7mm
b_{14}= 0.061753965
b_{24}=-0.000652769462
b_{34}=8.29455727E-7
b_{44}=4.17384912E-9

Optimized profile equation from fitting :

$$y_4 = -6.256419631E\text{-}14x^5 + 3.938009232E\text{-}11x^4 - 3.452010438E\text{-}08\,x^3 + 1.17828E\text{-}04x^2$$

VFM 3th FEM Iteration Analysis





(the drawing focusing area in 21.4um)

$F_3 = 116.324kgf$

$b_{03} = 90mm,\ h_4 = 7mm$

$b_{13} = -0.00753142942$

$b_{23} = -0.00058733453$

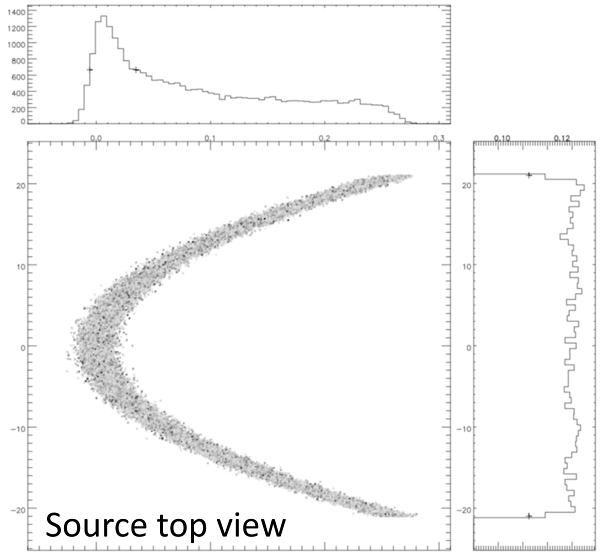
$b_{33} = -1.6795816397E\text{-}6$

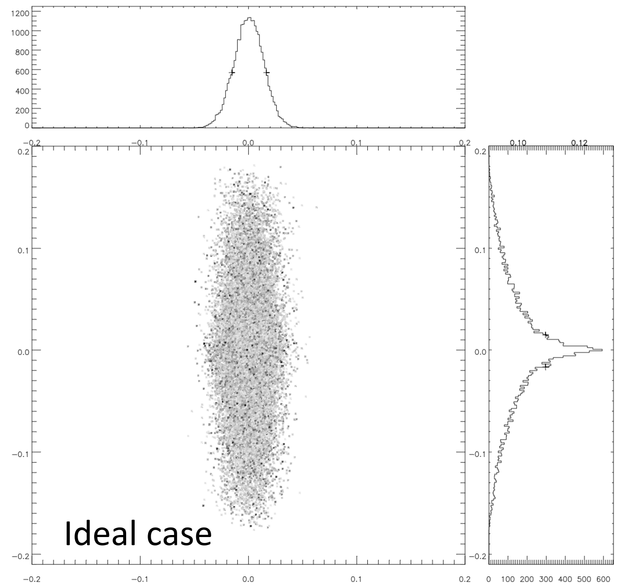
$b_{43} = 1.080632164E\text{-}10$

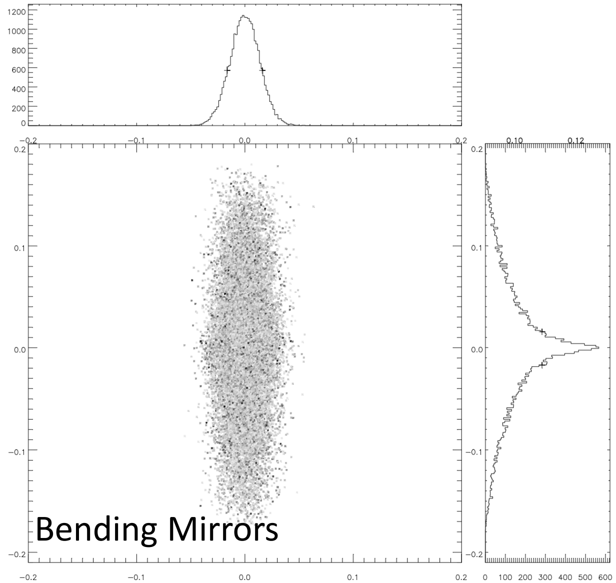
Optimized profile equation from fitting :

$$y_3 = -2.557394017E\text{-}14x^5 + 6.402854459E\text{-}12x^4 + 5.608805821E\text{-}09x^3 + 1.132978470E\text{-}04x^2$$

Shadow Simulation Result

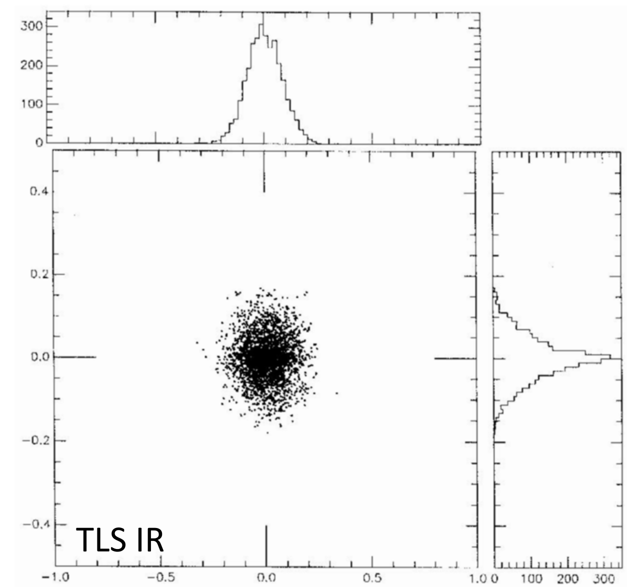






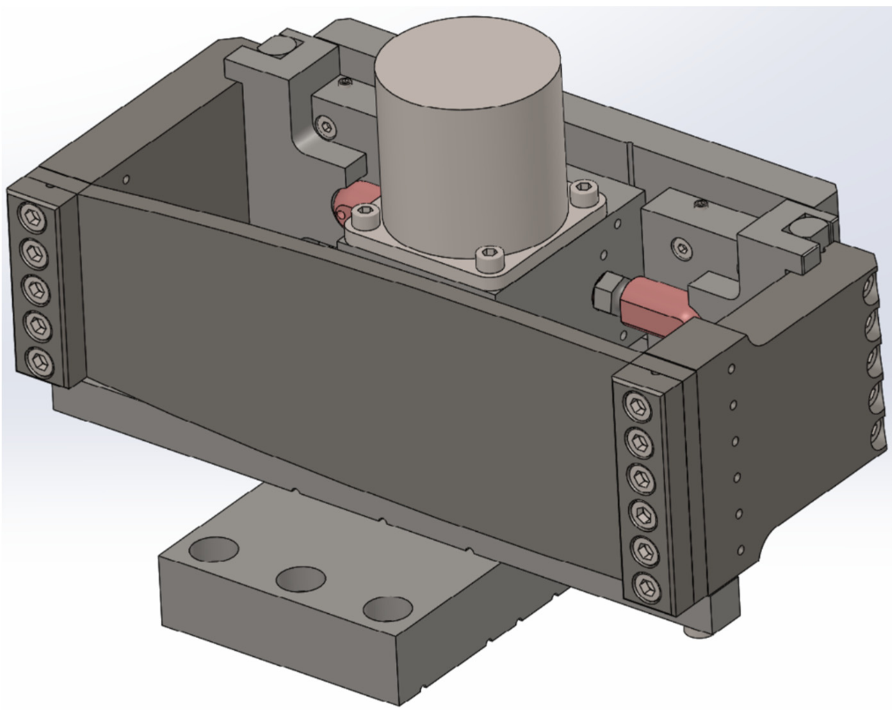
From the Shadow simulation

- The focusing point distribution of the bending mirrors is quite the same as the ideal profile.
- The size in horizontal direction is about only 1/5 of the vertical direction shows more better concentration.
- Compared to TLS IR, the situation is also the same.

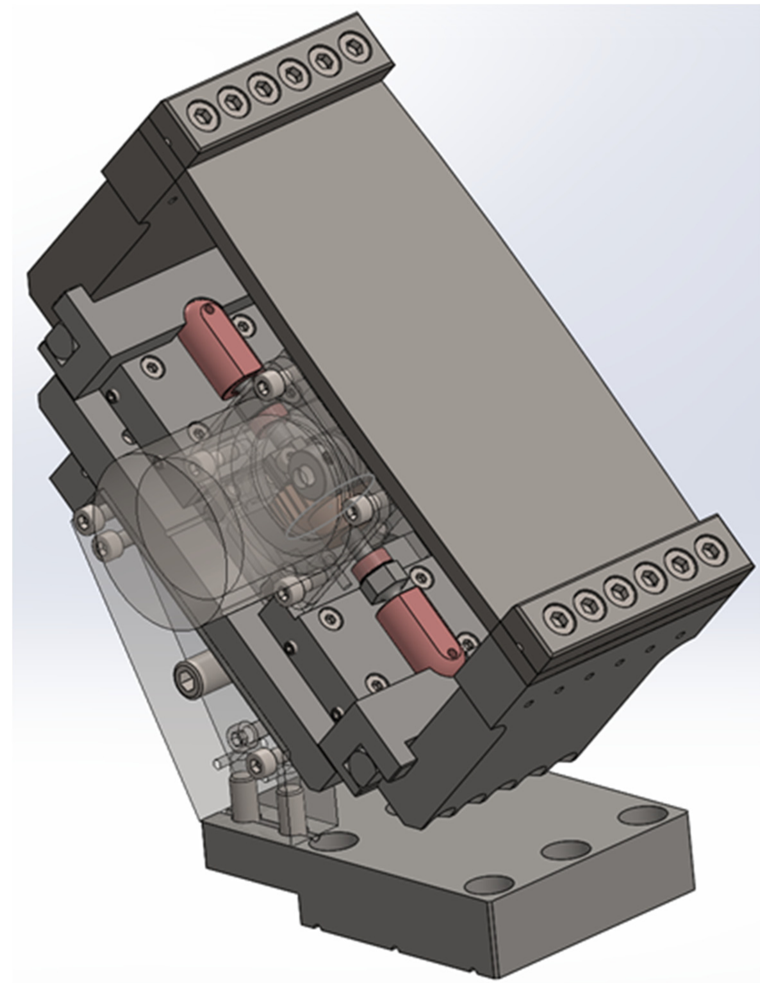


Thanks Dr. Hok-Sum Fung in the Experimental Technique Group NSRRC for the shadow simulation works

TPS IR Beamline Focusing Mirrors Engineering Design



Horizontal Focusing Mirror



Vertical Focusing Mirror

Conclusions

- By using the drawing method, a fine way to define a correction polynomial equation for focusing arc source is identified. The shadow simulation result shows good condition.
- By using the pseudo moment and FEM simulation iteration procedures, the width equation of a plane mirror can be found in order to define a desired mirror surface shape with pure bending moment (one single force).
- With Exact Beamsize correction in the vertical direction, The VFM focusing might be further improved if demanded.
- The Engineering design is on the way. However, domestic mirror polishing vendor in Taiwan seems a problem.

Thanks for your attention!