VUV & SX Beamline Design

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Outline

1. Choice of monochromator type
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   1.2. resolution & intensity
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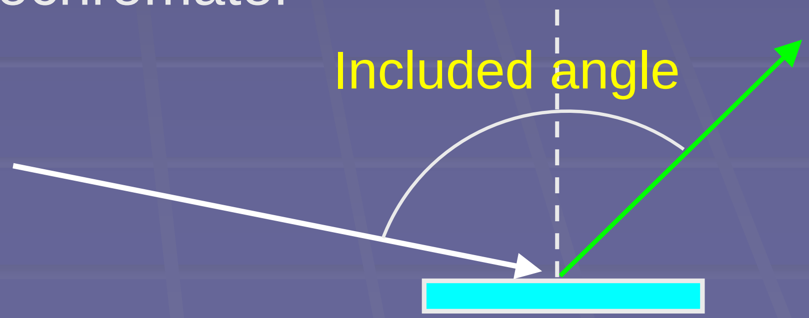
1.1. energy region

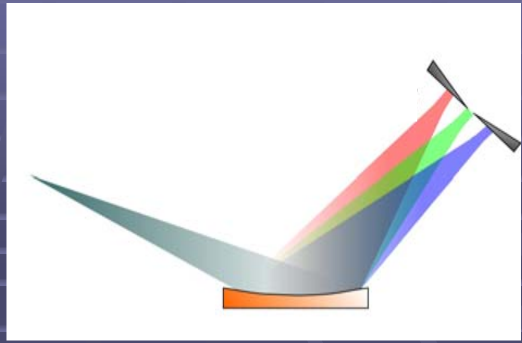
1. High-energy region (>~150 eV)
   Grazing incidence (>~85 deg) monochromator is inevitable
      *except for multilayer grating
2. Low-energy region (<~50 eV)
   (Near) normal incidence monochromator is also available

   *Medium incidence monochromator?
      Strongly affects the polarization

3. Wide-energy beamline (e.g. 30 eV – 1500 eV)
   (a) Combination of grazing and normal incidence monochromators
   (b) Variable included angle monochromator
   (c) Interchangeable gratings



1.2. resolution & intensity



1. Energy resolution depends on…

   Dispersion & Focus

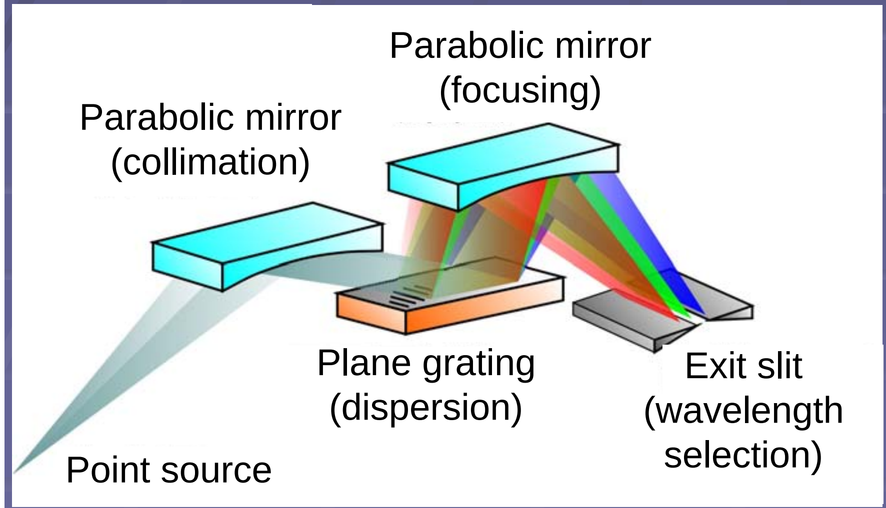
   Focus size depends on…

   Source size, demagnification, aberration, slope error,…

   Some of them drastically change according to technical progress

   No absolute solution !!

e.g. aberration-free monochromator



Perfect monochromator, in principle,
except for the reflectivity loss

Slope errors in parabolic mirrors are large

Use of cylindrical mirrors ⇒ large aberration

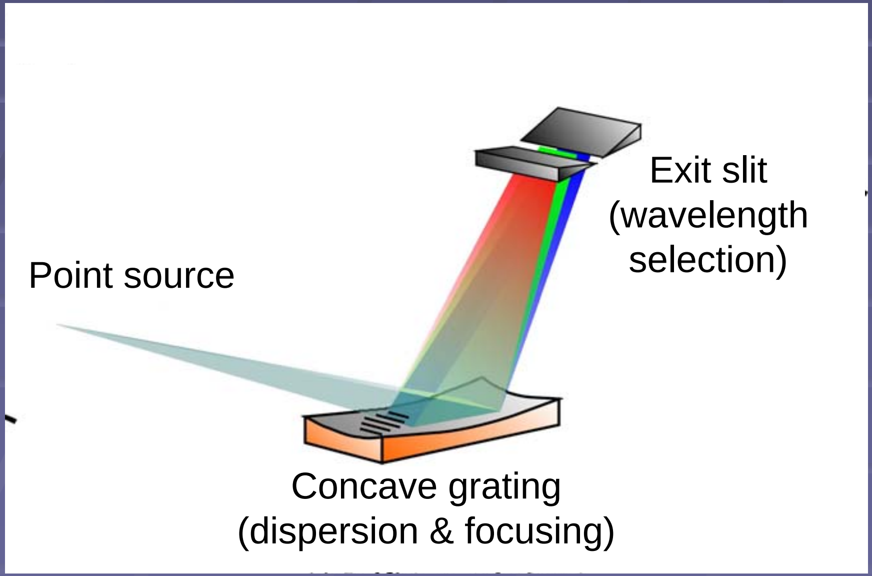
Recent progress in SR sources;
Small divergence ⇒ negligible aberration

1.2. resolution & intensity

2. Intensity depends on…

- Number of optical elements
- Incidence angle & acceptance (* larger incidence needs larger mirror)
- Diffraction efficiency of the grating
  - * High groove density ⇒ large dispersion but low efficiency

e.g. the simplest monochromator



Minimum intensity loss (no mirrors)

Focal condition depends on wavelength

Aberration might be serious

We must compromise !!

Intensity, resolution, energy range,…

1.3. some hints for the choice

1. Grating shape (plane, spherical, …)

Spherical : dispersion & focus ⇒ small number of optical elements
be careful for aberrations

2. Groove density (uniform or varied)

Varied line spacing : simpler optics (or higher resolution with the same optics)
be careful for precision in the groove parameters

3. Included angle (constant or variable)

Variable : higher degree of freedom ⇒ resolution & intensity in wide energy range
scanning mechanism is more complicated ⇒ be careful for reproducibility

4. Entrance slit

Without slit : Source size of SR itself directly affects the resolution
Higher resolution than the source-size limit is never obtained !

With slit : Higher resolution can be achieved at the sacrifice of intensity
pre-focusing optics is necessary

5. Focusing elements in monochromator (upstream, downstream, or nothing)

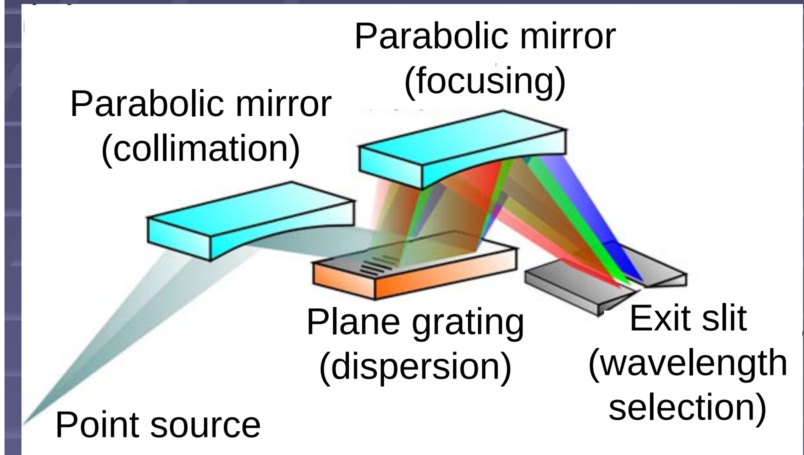
Effects of the slope errors in the focusing mirror are smaller in the upstream case

The choice depends on properties of light source, precision of mirrors, reliability of scanning mechanism, needs from applications, costs, …

1.4. examples for soft X-ray monochromator

(1) Plane grating monochromators

Collimated light illumination



Essentially no aberration

⇒ α and β can be freely chosen

⇒ Demagnification can be controlled

Precision of parabolic mirrors is relatively poor

One can use cylindrical mirrors if divergence is small enough

Diverging light illumination (SX-700)

Plane grating & post-focusing mirror (e.g. elliptical mirror) with variable included angle

Precision of elliptical mirrors is relatively poor

One can use cylindrical mirrors if divergence is small enough

Number of optical elements is reduced compared to the collimated case

Relation between α and β must be properly chosen to keep focal condition

1.4. examples for soft X-ray monochromator

(2) Spherical (or cylindrical) grating monochromators

Rowland mount

Monochromator itself consists of a grating only

But…

Relation among α, β, r, and r' must be properly chosen

"Rowland condition": $r = R \cos \alpha$, $r' = R \sin \beta$

⇒ Many optical elements and complicated scanning mechanism

DRAGON mount

Monochromator consists of a spherical (cylindrical) grating only

Fixed included angle

⇒ Simple scanning mechanism

Kinds of aberration arises, but only the defocus term can be canceled by moving the exit slit

1.4. examples for soft X-ray monochromator

(3) Varied-line-spacing (VLS) plane grating monochromators

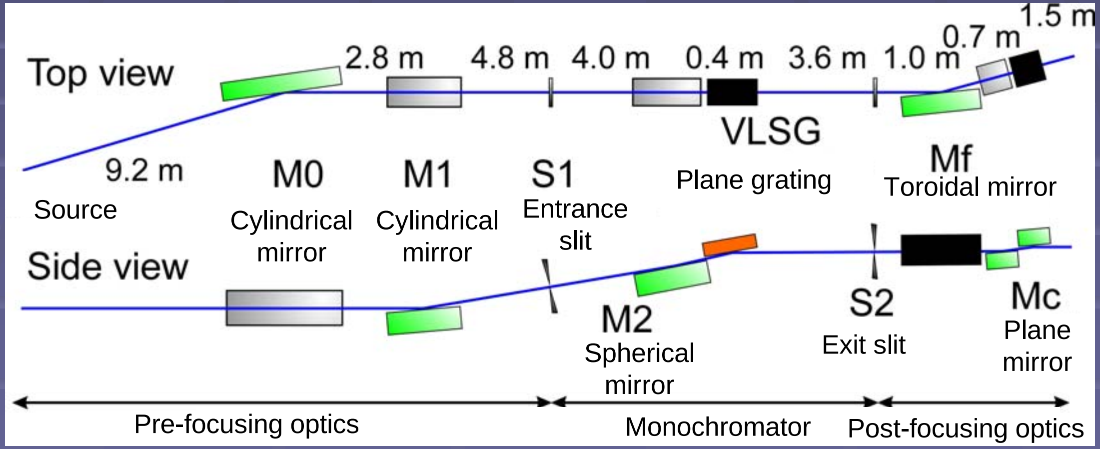
Diverging light illumination

Monochromator itself consists of a VLS plane grating only

Relation between α and β must be properly chosen

⇒ A precise variable included angle system is inevitable

Converging light illumination (Monk-Gillieson mount)



Pre-focusing mirror upstream of VLSG

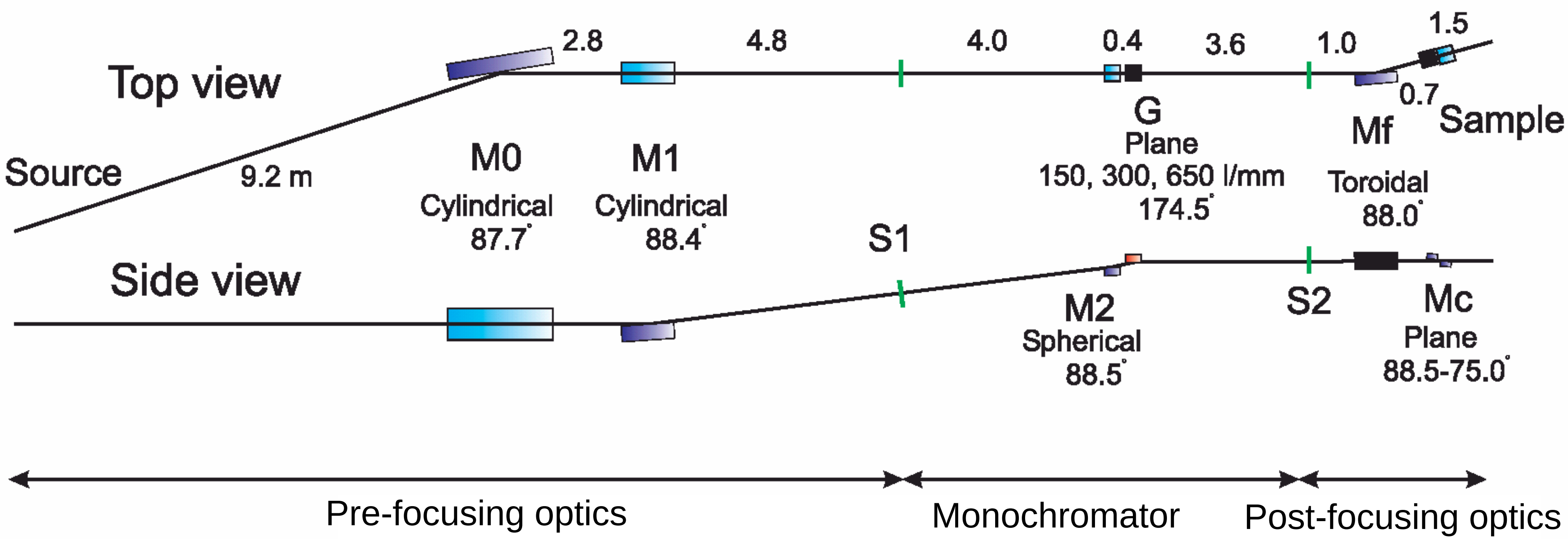
Constant included angle ⇒ Simple scanning mechanism

Moderate aberration in spite of constant included angle

Variable included angle system is also adopted recently

2.1. Optimization of the parameters

Overview of a typical soft X-ray beamline

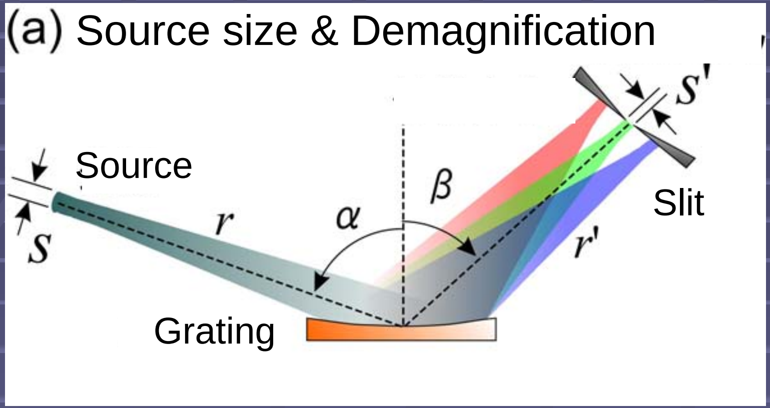


Pre-focusing optics： focuses X rays onto the entrance slit
Monochromator： from the entrance slit to the exit slit
Post-focusing optics： focuses monochromatized X rays onto sample position

Higher order suppression (Mc)：
utilizes energy dependence of reflectivity (or transmittance)

2.1. Optimization of the parameters

1. Source-size limit



Dispersion:

$$dz / d\lambda = r' nm / \cos\beta$$

Beam size at the exit slit

$$s' \text{ (lower limit)} = s\, r'/r$$

$$\Rightarrow \quad \lambda/\Delta\lambda \propto r/s$$

(a) If the source size is the same, longer monochromator gives higher resolution.

(b) If the monochromator length ($r + r'$) is the same, longer entrance arm (r) gives higher resolution. ⇒ Higher demagnification factor is better !

But…

(a') Long monochromator needs large mirrors to keep enough acceptance ⇒ higher cost, or intensity loss by reduced acceptance

(b') High demagnification factor causes large aberration. ⇒ Eventual decrease in energy resolution

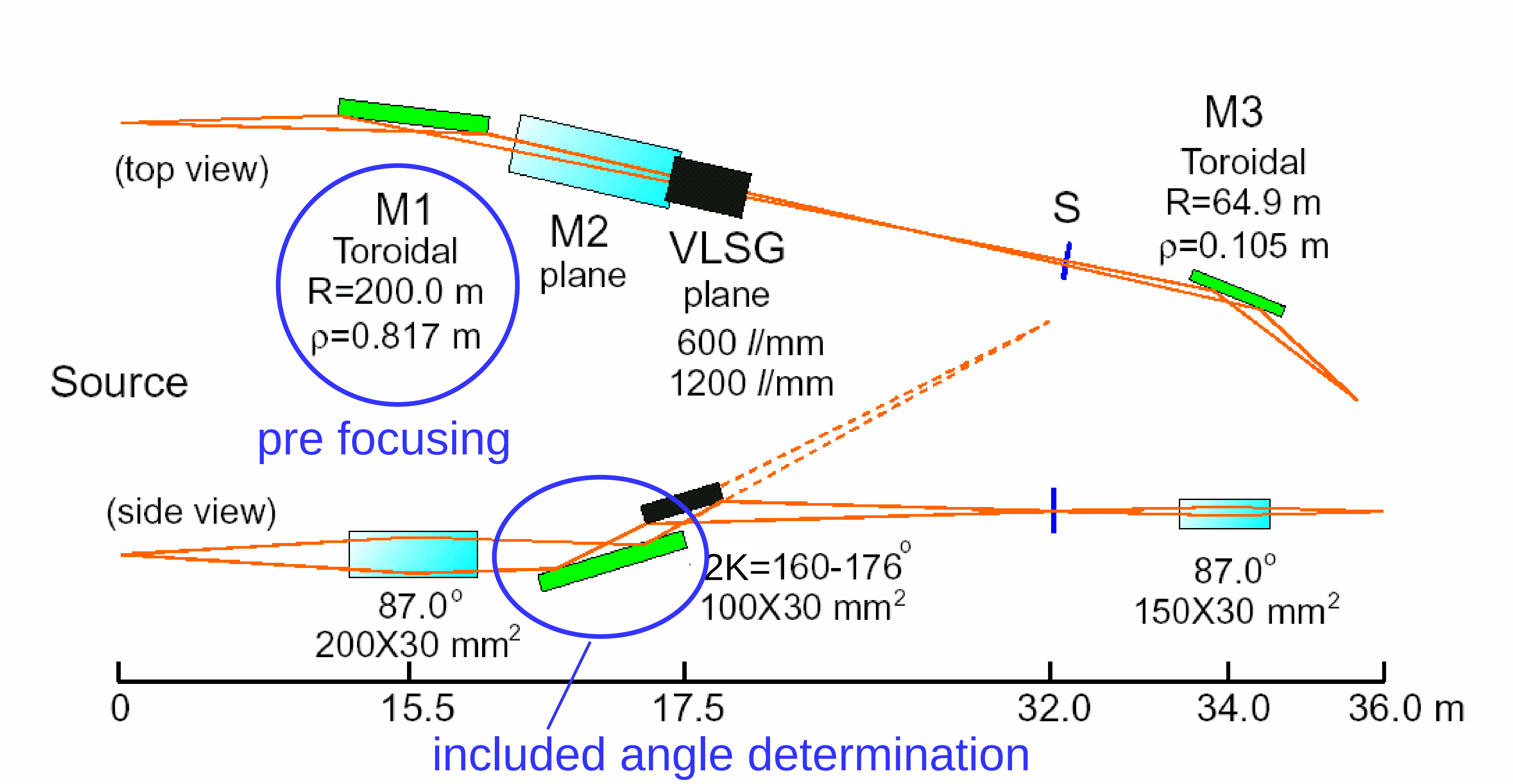
Most people choose ~1:1 demagnification optics, though it might not be the best solution.

Groove density (n) and included angle are chosen, considering the balance among dispersion, demagnification, diffraction efficiency, etc.

2.1. Optimization of the parameters

2. Monochromator parameters (mirror radius, groove parameter, etc.)
   - highly depends on the type of monochromator

Design example: Variable-included-angle Monk-Gillieson mount varied-line-spacing (VLS) grating monochromator

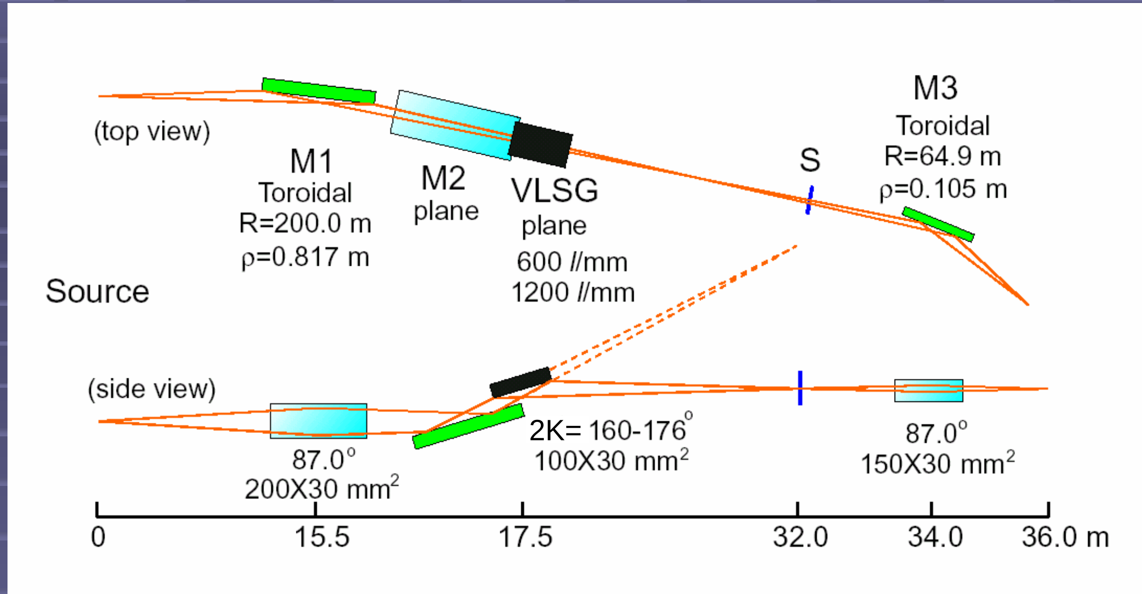


2.1. Optimization of the parameters

Parameters:

- ρ (sagittal radius of M1)
- Groove parameters of VLSG

$$N = N_0\,(1+a_1 w+a_2 w^2+a_3 w^3)$$



K. Amemiya & T. Ohta, J. Synchrotron Rad. 11 (2004) 171.

1. Choose two energies (E_1 and E_2) and respective included angles (K_1 and K_2)
2. Optimize ρ and a_1 so that the defocus vanishes at (E_1, K_1) and (E_2, K_2)
3. For other energies, included angles are set so that the defocus vanishes
4. Choose an energy (E_3) and optimize a_2 so that the coma aberration vanishes
5. Choose E_4 and optimize a_3 so that the spherical aberration vanishes

2.1. Optimization of the parameters

pA(S-FM)	21	
qA(FM-G)	1.5	
rB	15.5	
Incidence angle of FM	88	
R (radius of FM)	390	
N0(l/mm)	600	1200
Included angle @E1	168	168
Included angle @E2	175	175
Included angle @E3	170.0075871	170.0075871
Included angle @E4	170.0075871	170.0075871
E1(eV)[defocus=0]	50	100
E2(eV)[defocus=0]	500	1000
E3(eV)[coma=0]	100	200
E4(eV)[spherical=0]	100	200
λ1(Å)	247.97	123.985
λ2(Å)	24.797	12.3985
λ3(Å)	123.985	61.9925
λ4(Å)	123.985	61.9925

α1(deg)	88.08108609	88.08108609
β1(deg)	−79.9189139	−79.9189139
α2(deg)	88.4772024	88.4772024
β2(deg)	−86.5227976	−86.5227976
α3(deg)	87.45160484	87.45160484
β3(deg)	−82.5559822	−82.5559822
α4(deg)	87.45160484	87.45160484
β4(deg)	−8.2556E+01	−8.2556E+01
rA(m)	−14.9820	−14.9820
n20(mm−2)	−7.6699E−02	−1.5340E−01
n30(mm−3)	4.8778E−06	9.7556E−06
n40(mm−4)	−1.3394E−09	−2.6789E−09
ρ(m)	6.4455E−01	6.4455E−01
a1(mm−1)	−1.2783E−04	−1.2783E−04
a2(mm−2)	1.2195E−08	1.2195E−08
a3(mm−3)	−1.1162E−12	−1.1162E−12

$$N = N_0\,(1+a_1 w+a_2 w^2+a_3 w^3)$$

2.2.analytical estimation of energy resolution

N0(l/mm)	600				undulator length(m)=	4.5	
rA(m)	-14.9820	pA(m)	21		electron div.hor./ver.(urad)=	20.00	5.00
rB(m)	15.5	qA(m)	1.5		electron size.hor./ver.(um)=	350.00	20.00
n20(mm-2)	-0.0767	ρ (m)	0.6445				
n30(mm-3)	4.88E-06	Incidence angle	88				
n40(mm-4)	-1.3E-09	R (radius of l	390				
error (μ rad)	0.48	grating length(	100				

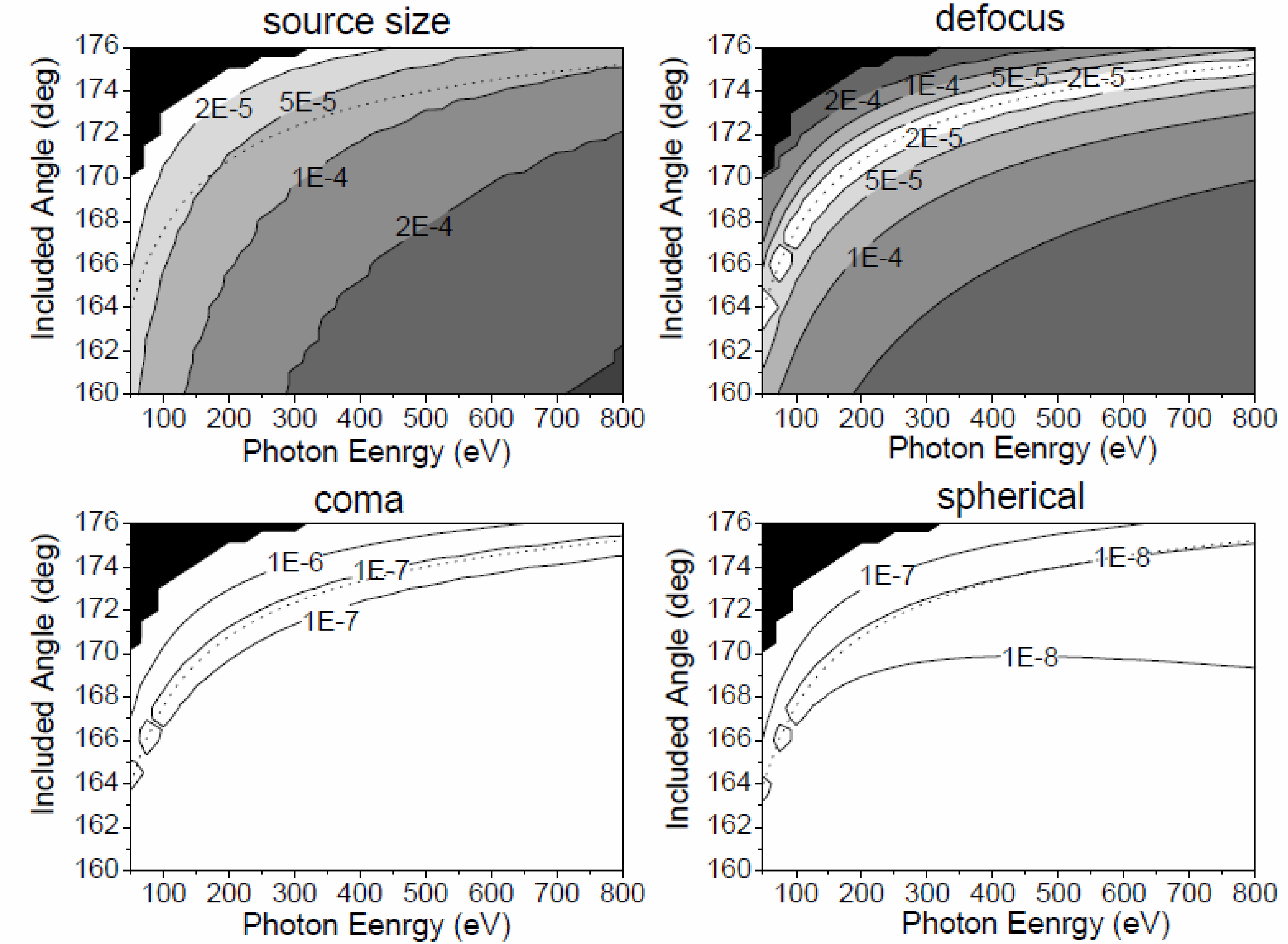
Included angle (deg)	Energy	λ (Å)	σ p(um)	Σ h(um)	Σ v(um)	σ p'(urad)	Σ h'(urad)	Σ v'(urad)	α	β	w(m)	Δ λ 20/ λ	Δ λ 30/ λ	Δ λ 40/ λ	Δ λ so/ λ	Δ λ sl/ λ	total(w/o sl	total
									α	β								
168	50	247.97	26.58	351.01	33.27	74.23	76.88	74.40	88.081	-79.92	0.037481	5.68E-17	2.61E-07	6.20E-08	1.05E-05	1.83E-05	1.05E-05	2.11E-05
169.0155705	75	165.31	21.70	350.67	29.51	60.61	63.82	60.82	87.478	-81.54	0.026383	2.46E-17	4.82E-08	7.32E-09	1.83E-05	2.58E-05	1.83E-05	3.16E-05
170.0075871	100	123.99	18.80	350.50	27.45	52.49	56.17	52.73	87.452	-82.56	0.022637	3.34E-17	0.00E+00	0.00E+00	2.29E-05	3.17E-05	2.29E-05	3.91E-05
170.8042113	125	99.188	16.81	350.40	26.13	46.95	51.03	47.21	87.529	-83.27	0.020908	0.00E+00	2.00E-08	1.49E-09	2.65E-05	3.67E-05	2.65E-05	4.53E-05
171.4465431	150	82.657	15.35	350.34	25.21	42.86	47.29	43.15	87.629	-83.82	0.019908	7.20E-17	3.10E-08	1.68E-09	2.94E-05	4.12E-05	2.94E-05	5.06E-05
171.9748591	175	70.849	14.21	350.29	24.53	39.68	44.43	39.99	87.728	-84.25	0.019257	1.34E-16	3.80E-08	1.49E-09	3.20E-05	4.53E-05	3.20E-05	5.55E-05
172.4179974	200	61.993	13.29	350.25	24.01	37.12	42.16	37.45	87.821	-84.6	0.018801	4.46E-17	4.29E-08	1.18E-09	3.43E-05	4.91E-05	3.43E-05	5.99E-05
172.7960709	225	55.104	12.53	350.22	23.60	34.99	40.31	35.35	87.906	-84.89	0.018466	5.98E-17	4.65E-08	8.52E-10	3.65E-05	5.26E-05	3.65E-05	6.40E-05
173.1233189	250	49.594	11.89	350.20	23.27	33.20	38.76	33.57	87.983	-85.14	0.01821	1.35E-16	4.93E-08	5.35E-10	3.85E-05	5.59E-05	3.85E-05	6.78E-05
173.4100546	275	45.085	11.33	350.18	22.99	31.65	37.44	32.05	88.053	-85.36	0.018009	3.85E-17	5.15E-08	2.41E-10	4.03E-05	5.90E-05	4.03E-05	7.15E-05
173.6639224	300	41.328	10.85	350.17	22.75	30.31	36.31	30.71	88.117	-85.55	0.017848	4.79E-17	5.33E-08	2.94E-11	4.21E-05	6.20E-05	4.21E-05	7.49E-05
173.8907098	325	38.149	10.43	350.16	22.55	29.12	35.32	29.54	88.176	-85.71	0.017717	1.53E-16	5.49E-08	2.75E-10	4.38E-05	6.48E-05	4.38E-05	7.82E-05
174.0948831	350	35.424	10.05	350.14	22.38	28.06	34.46	28.50	88.23	-85.87	0.017609	8.99E-17	5.62E-08	4.99E-10	4.55E-05	6.75E-05	4.55E-05	8.14E-05
174.2799478	375	33.063	9.71	350.13	22.23	27.11	33.69	27.56	88.279	-86	0.017519	4.47E-17	5.73E-08	7.03E-10	4.70E-05	7.01E-05	4.70E-05	8.44E-05
174.4486972	400	30.996	9.40	350.13	22.10	26.25	33.00	26.72	88.325	-86.12	0.017444	5.56E-17	5.83E-08	8.89E-10	4.86E-05	7.26E-05	4.86E-05	8.74E-05
174.6033869	425	29.173	9.1177	350.12	21.98	25.461	32.377	25.948	88.367	-86.24	0.01738	1.59E-16	5.92E-08	1.06E-09	5.00E-05	7.51E-05	5.00E-05	9.02E-05
174.7458606	450	27.552	8.86	350.11	21.87	24.74	31.82	25.24	88.406	-86.34	0.017326	1.46E-16	6.00E-08	1.22E-09	5.14E-05	7.74E-05	5.14E-05	9.30E-05
174.8776414	475	26.102	8.6245	350.11	21.78	24.084	31.306	24.598	88.443	-86.43	0.01728	1.26E-16	6.07E-08	1.36E-09	5.28E-05	7.97E-05	5.28E-05	9.56E-05
175	500	24.797	8.41	350.10	21.69	23.47	30.84	24.00	88.477	-86.52	0.01724	1.22E-16	6.14E-08	1.50E-09	5.42E-05	8.20E-05	5.42E-05	9.82E-05
175.1140057	525	23.616	8.2035	350.1	21.617	22.909	30.411	23.448	88.509	-86.6	0.017206	4.74E-17	6.20E-08	1.62E-09	5.55E-05	8.41E-05	5.55E-05	1.01E-04

defocus

Source size

slope error

2.2.analytical estimation of energy resolution



2.3. ray-tracing simulation

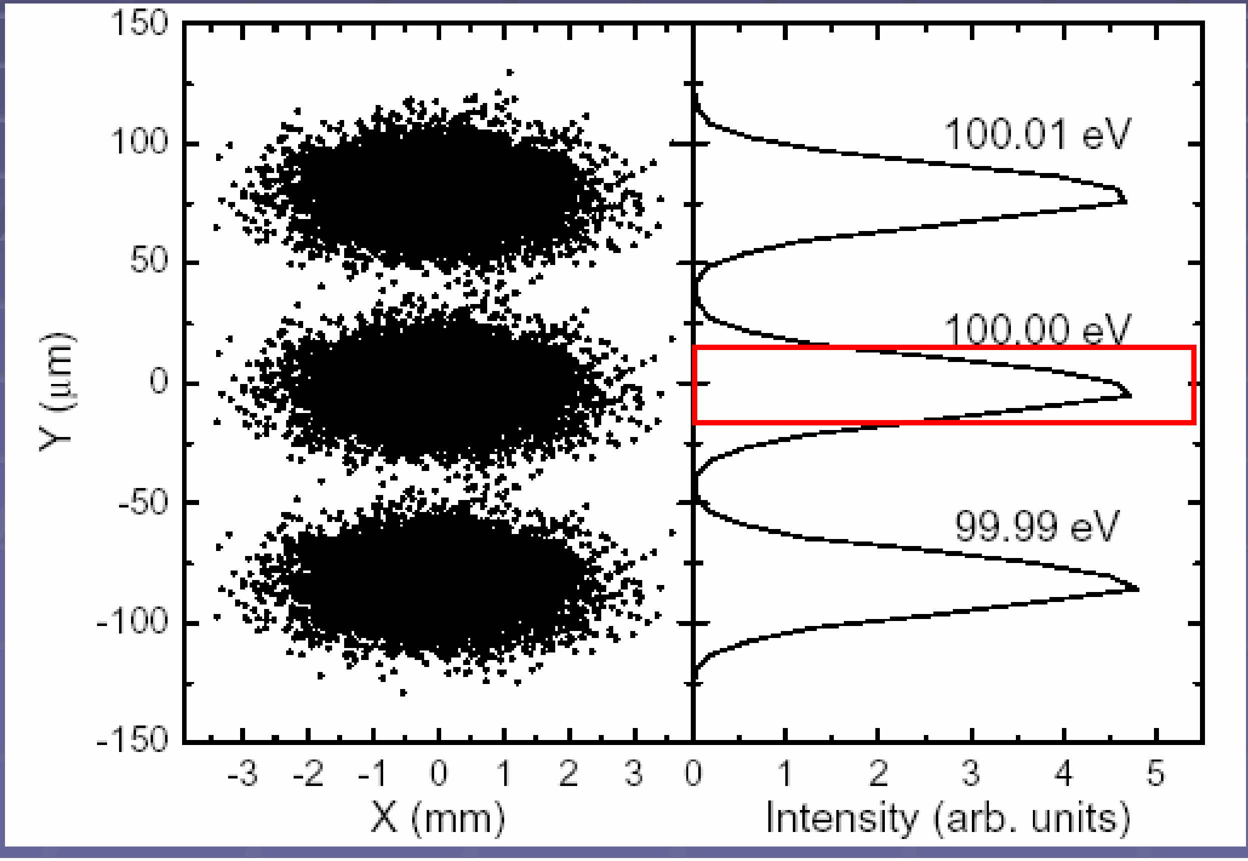
Source parameters:

σ_x = 350 μm, σ_y = 20 μm, σ_x'= 20 μrad, σ_y' = 5 μrad, 4.5 m undulator

Optimization conditions for N_0 = 600 l/mm:

E_1 = 50 eV, E_2 = 500 eV, K_1 = 164º, K_2 = 174º, E_3 = E_4 = 100 eV

Spot diagram at the exit slit

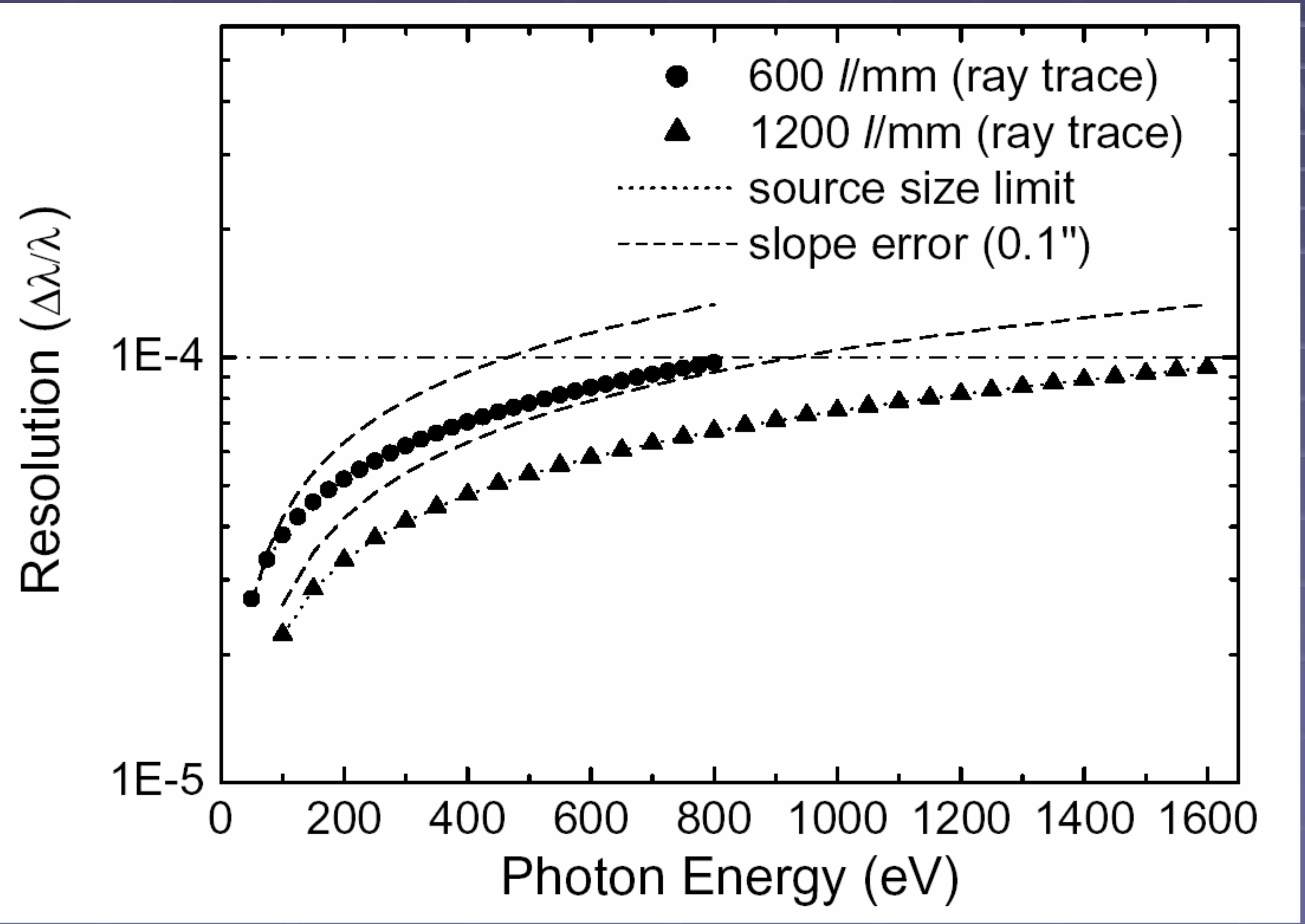


=> E/ΔE~26,000

2.3. ray-tracing simulation

Simultaneous scan mode

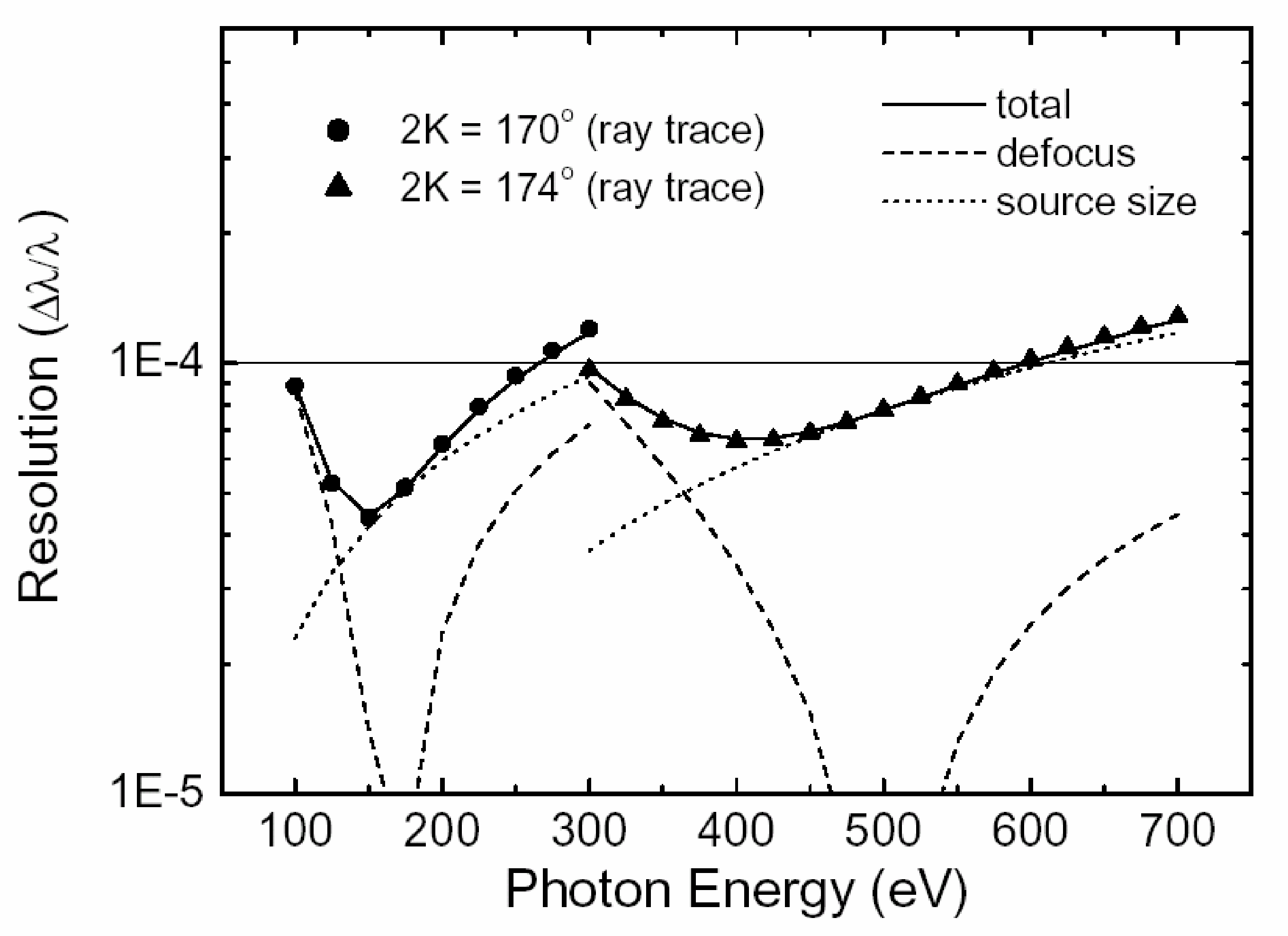
Included angle is scanned simultaneously with the grating



Source size or slope error limited resolution

2.3. ray-tracing simulation

Fixed included angle mode

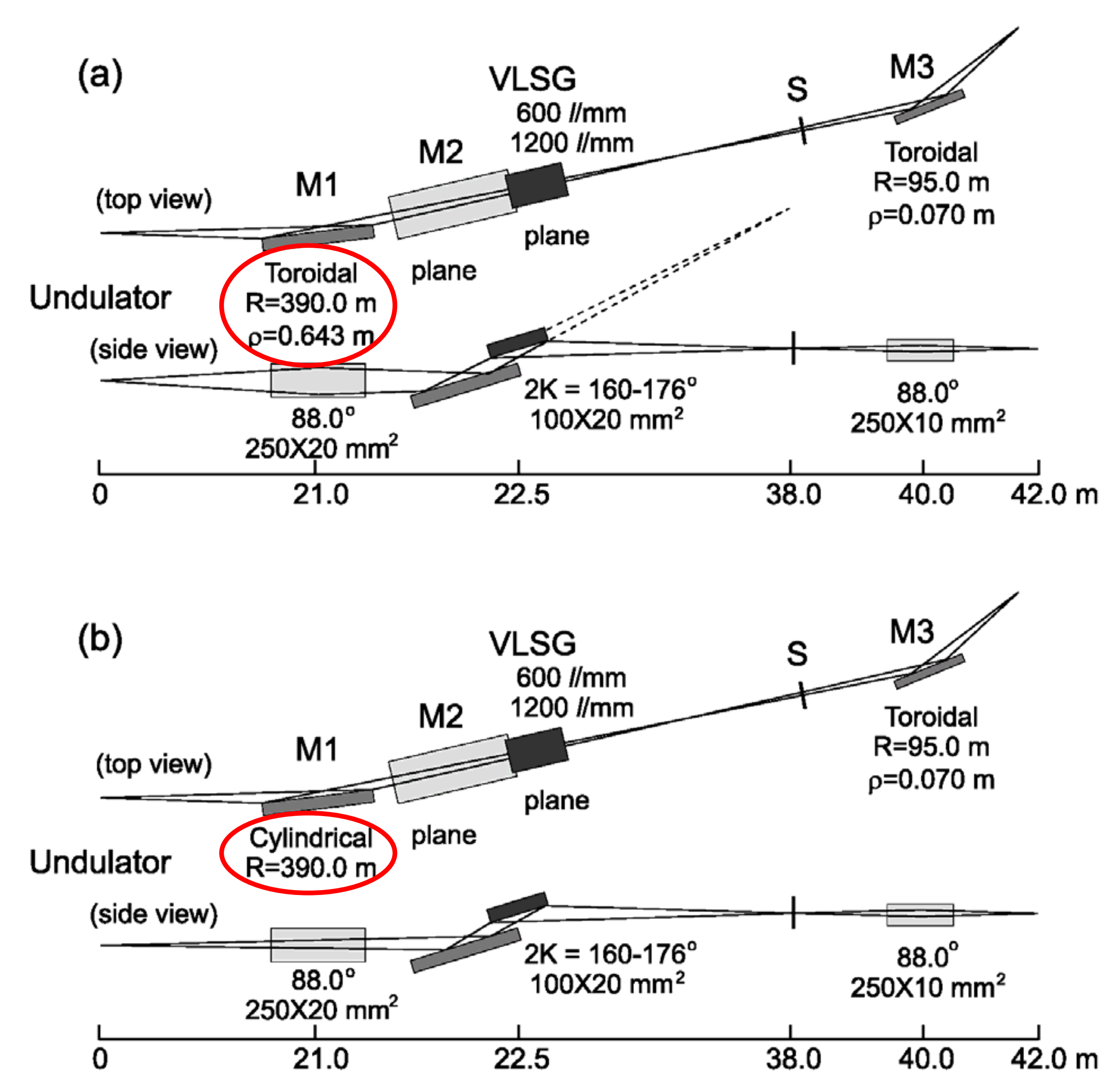


Relatively high resolution over wide energy range

* Analytical estimation is consistent with ray tracing simulation

2.3. ray-tracing simulation

Comparison with diverging illumination optics



Monk-GIllieson

converging X rays illuminate VLSG

non Monk-GIllieson

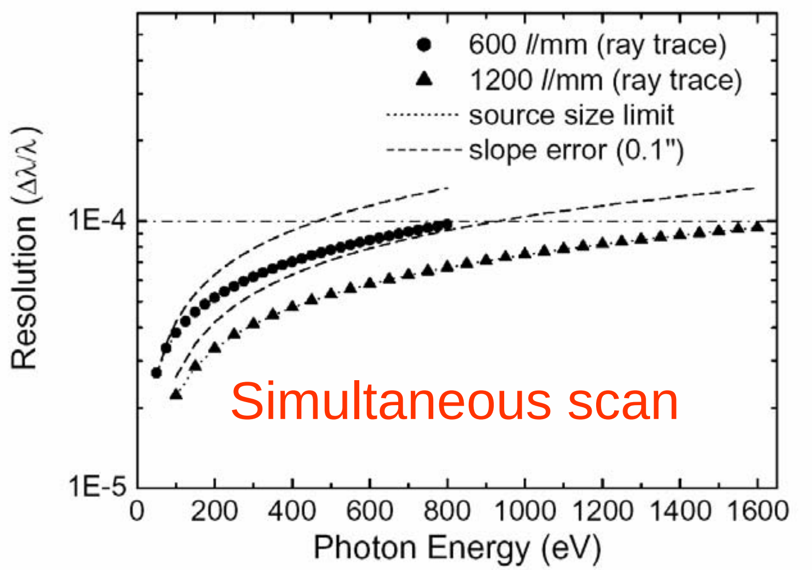
diverging X rays illuminate VLSG

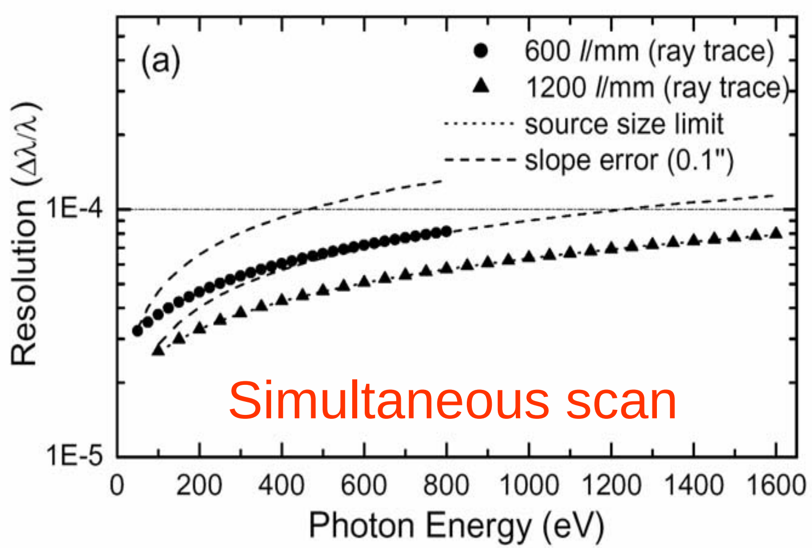
2.3. ray-tracing simulation

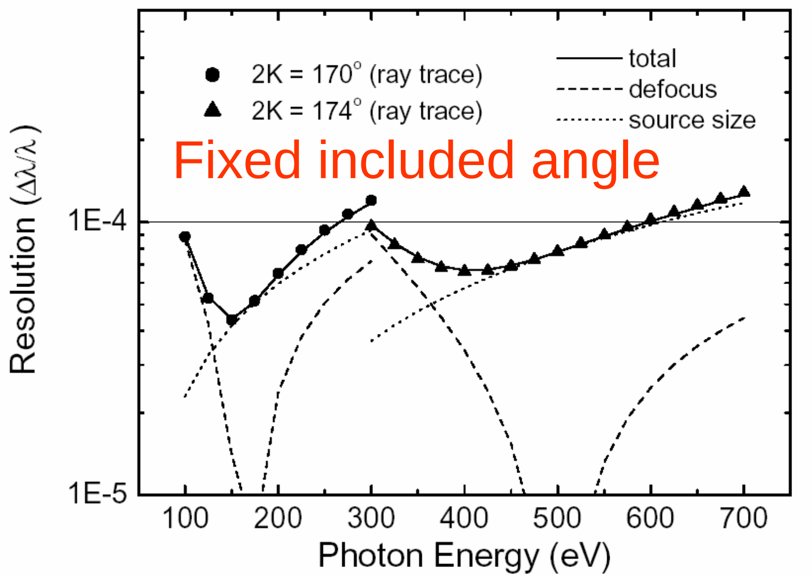
Comparison with diverging illumination optics

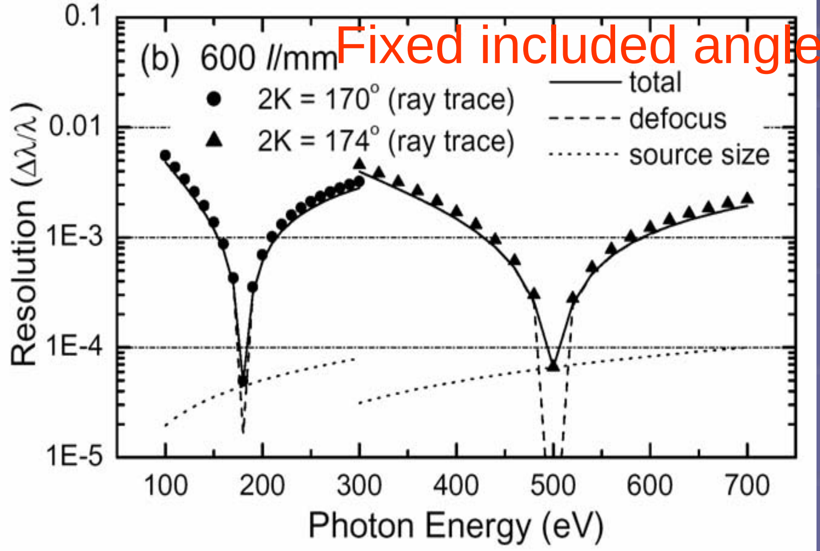
Monk-Gillieson (converging illumination)

non Monk-Gillieson (diverging illumination)





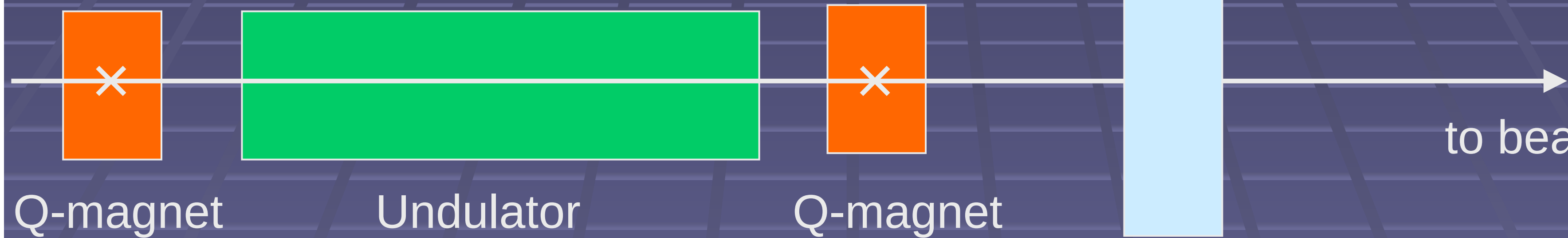




3.1. alignment

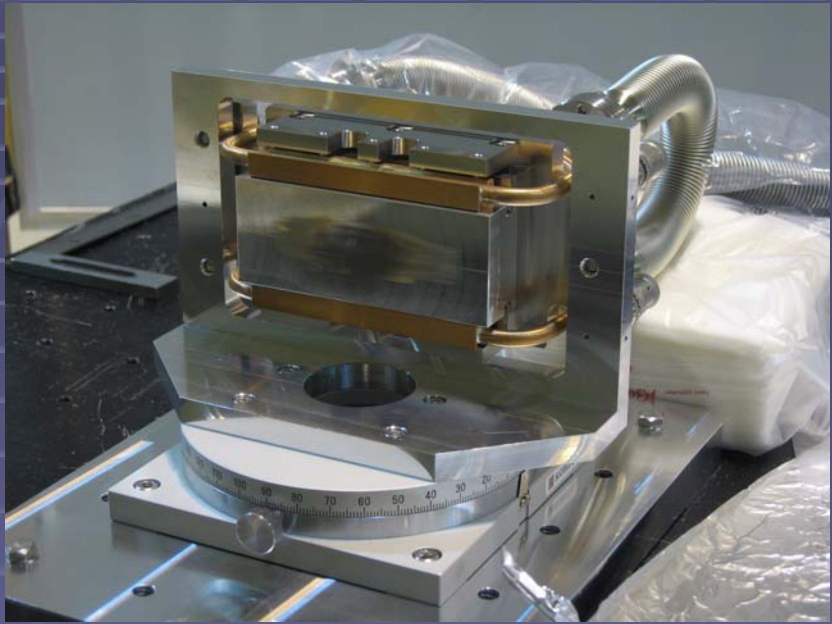
Determination of beamline center

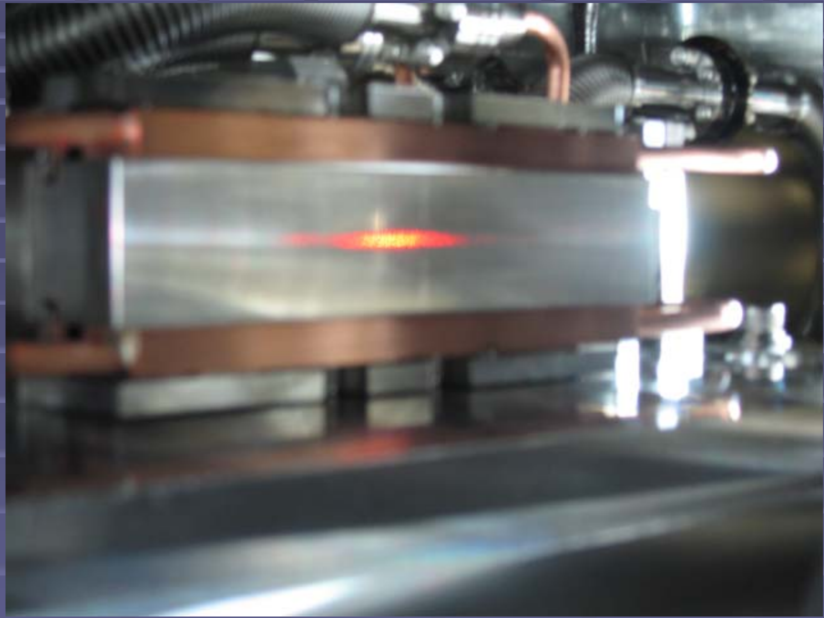
Hole on the Shield wall



Target on the Q-magnet

3.1. alignment





Grating adjustment
(roll and yaw)

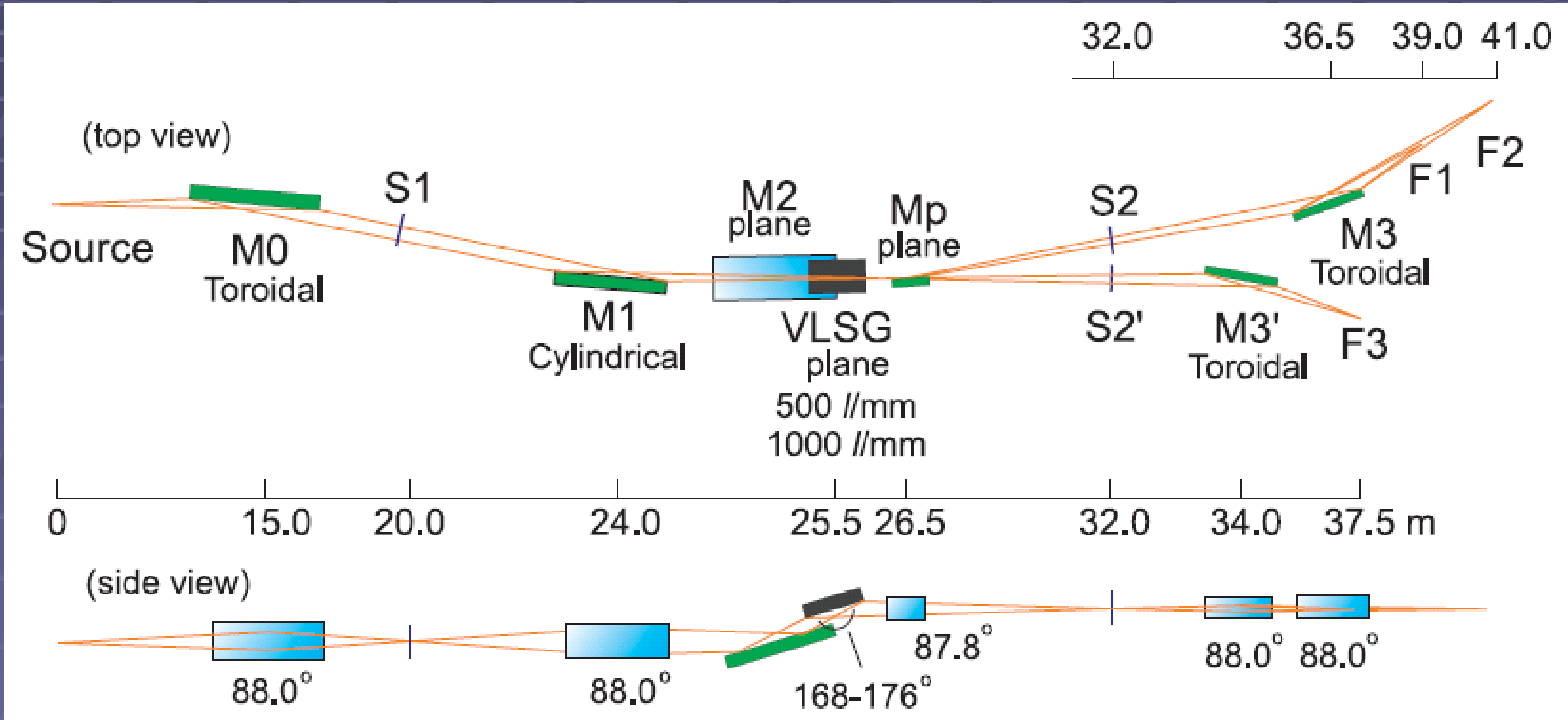
Adjusted by using
diffraction of Laser light

Mirror adjustment

Adjusted by using a dummy
mirror and Laser light

3.2. optical adjustments using SR

Example: BL-16A at the Photon Factory



M0: vertical focusing to entrance slit (S1) [r = 15 m, r' = 5 m]

M1: vertical focusing to 90 mm upstream of exit slit (S2)

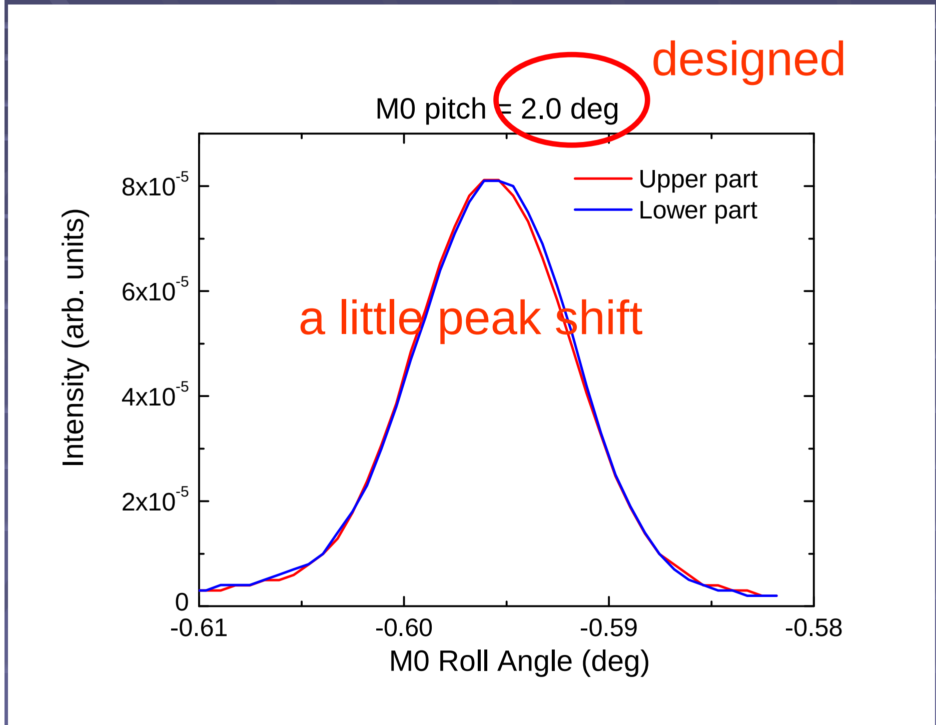
[r = 4 m, r' = 7.91 m]

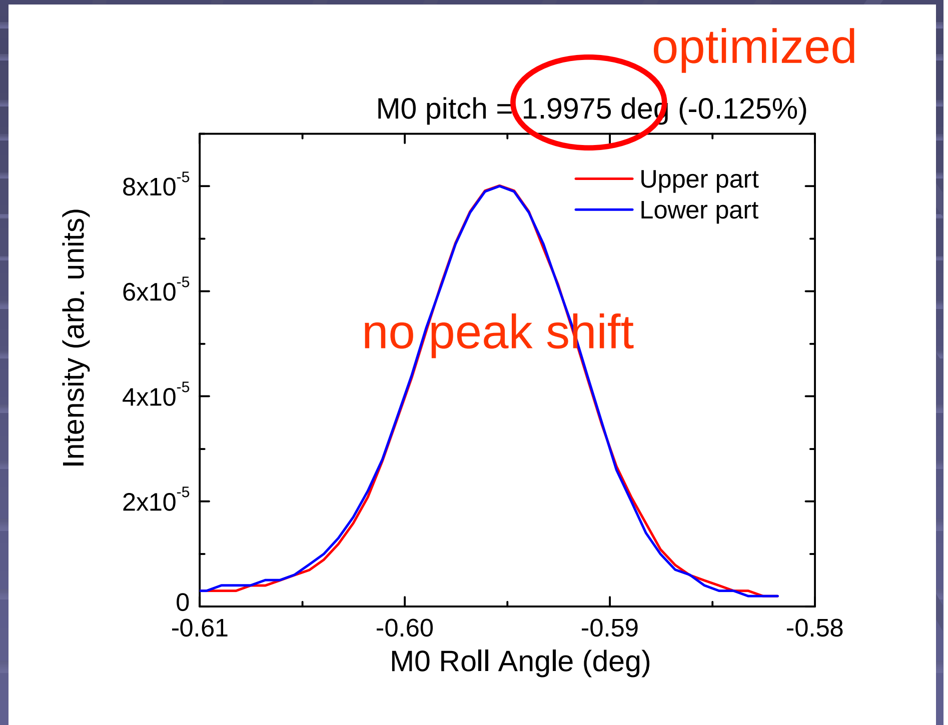
3.2. optical adjustments using SR

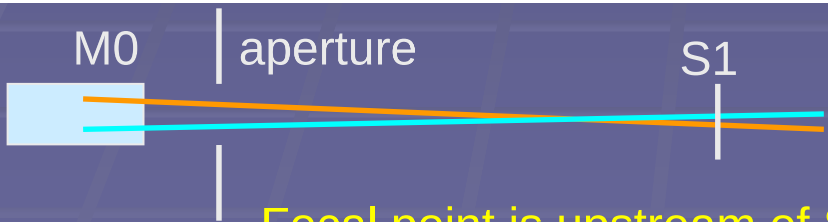
(a) Vertical focusing of M0

Light intensity was monitored downstream of S1 during M0 roll-angle scan.

Upper and Lower parts of light were taken by using an aperture.







Focal point is upstream of S1

Focal point is just at S1!

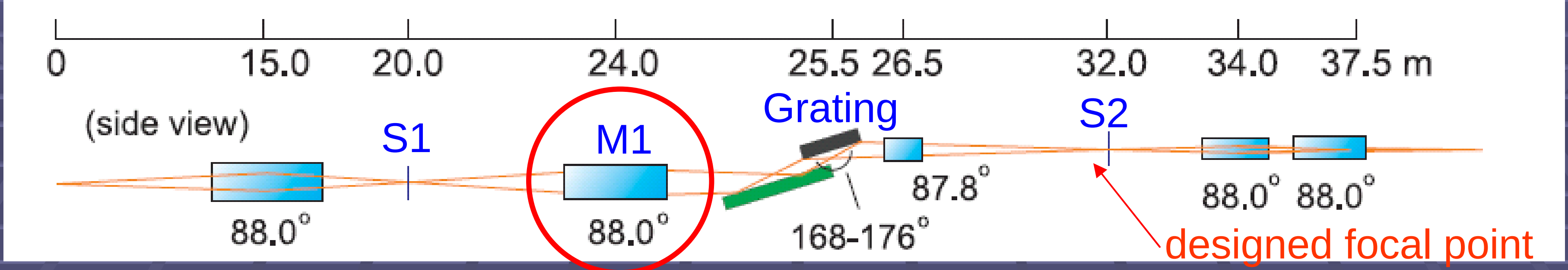
Sagittal radius of M0 is ~0.1% smaller than the designed value (262 mm).

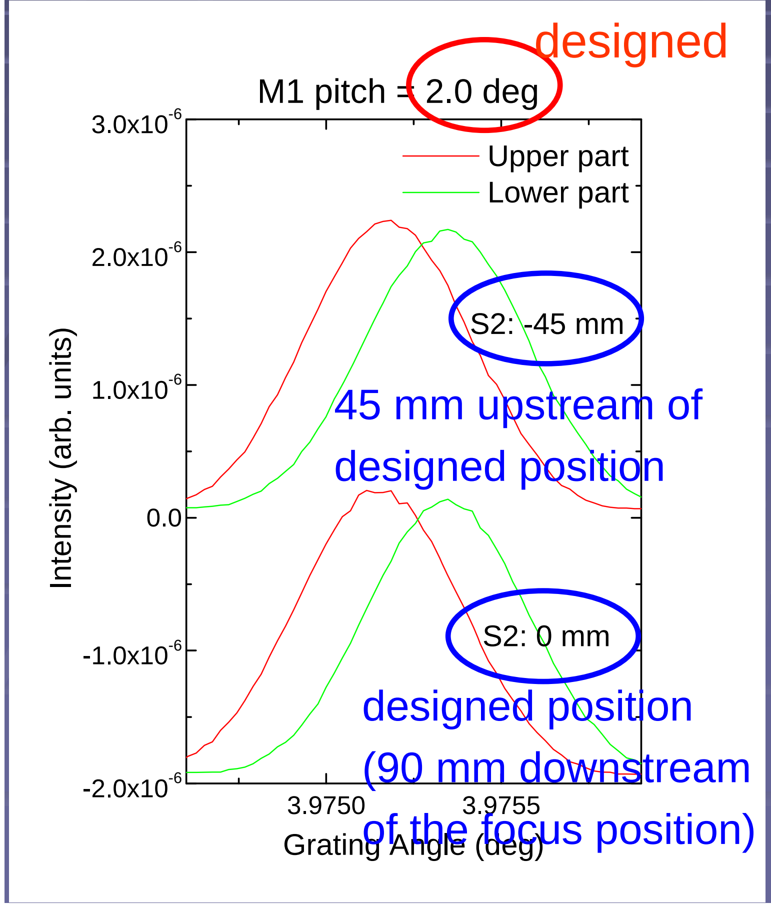
This coincides with the inspection report!

3.2. optical adjustments using SR

(2) Vertical focusing of M1

M1 is designed so that light is focused at 90 mm upstream of S2.





Zero-th order light intensity was monitored downstream of S2 during Grating angle scan.

Upper and Lower parts of light were taken by using an aperture

A peak shift between the upper and lower parts means that the focal position is upstream of S2.

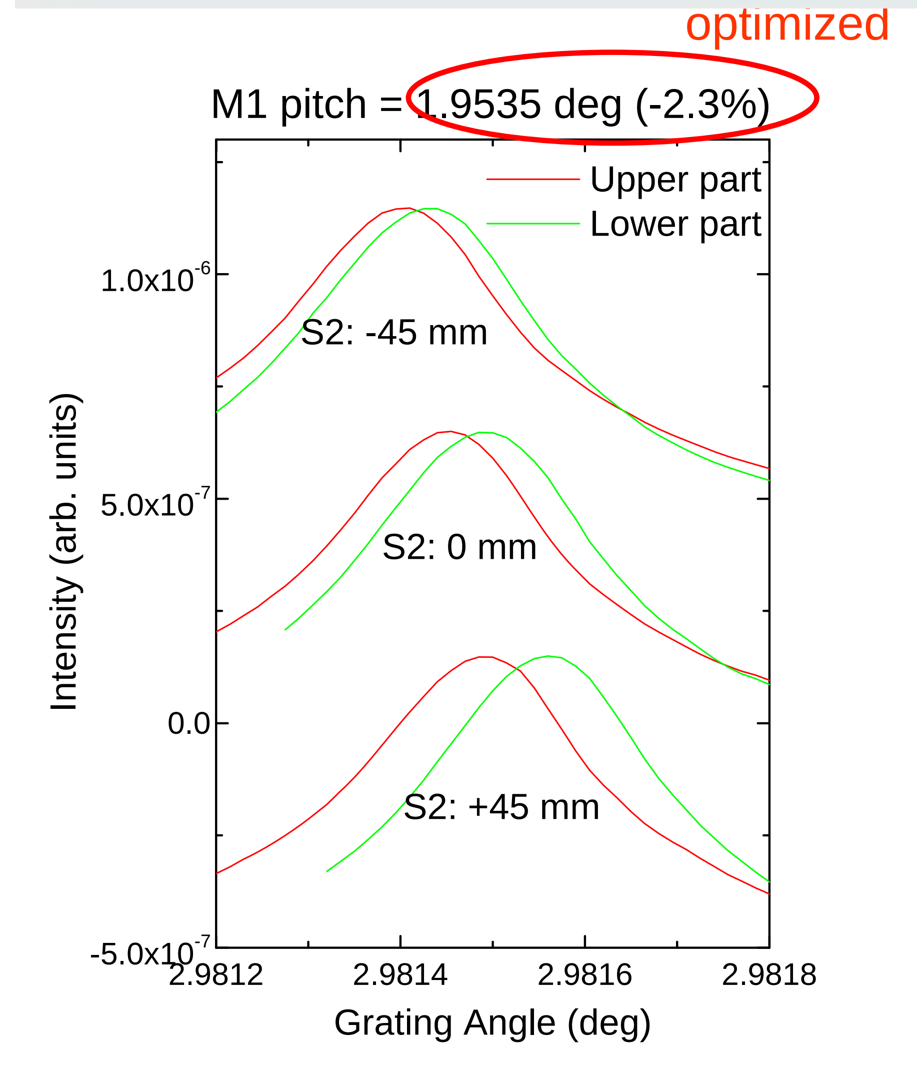
However…

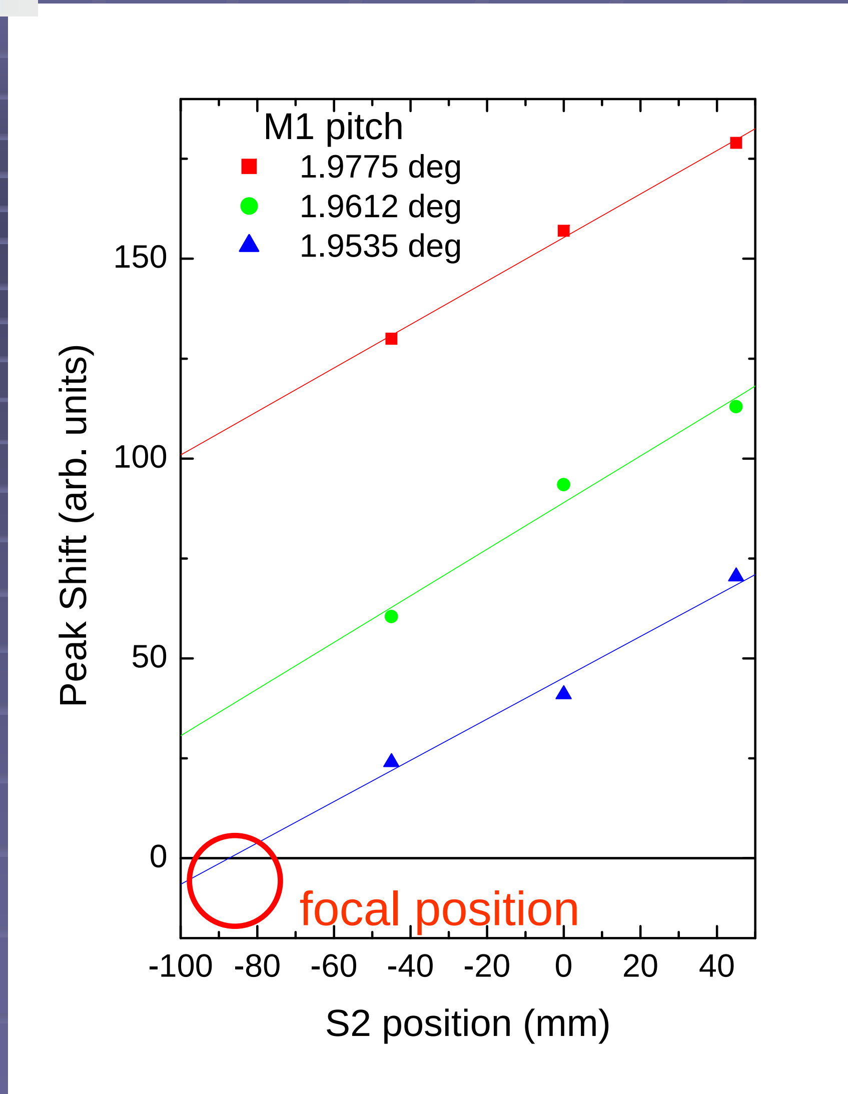
The peak shift should be reduced by ~50 % when S2 is placed at -45 mm position.

➡ Focal position is far from S2 !?

3.2. optical adjustments using SR

(2) Vertical focusing of M1



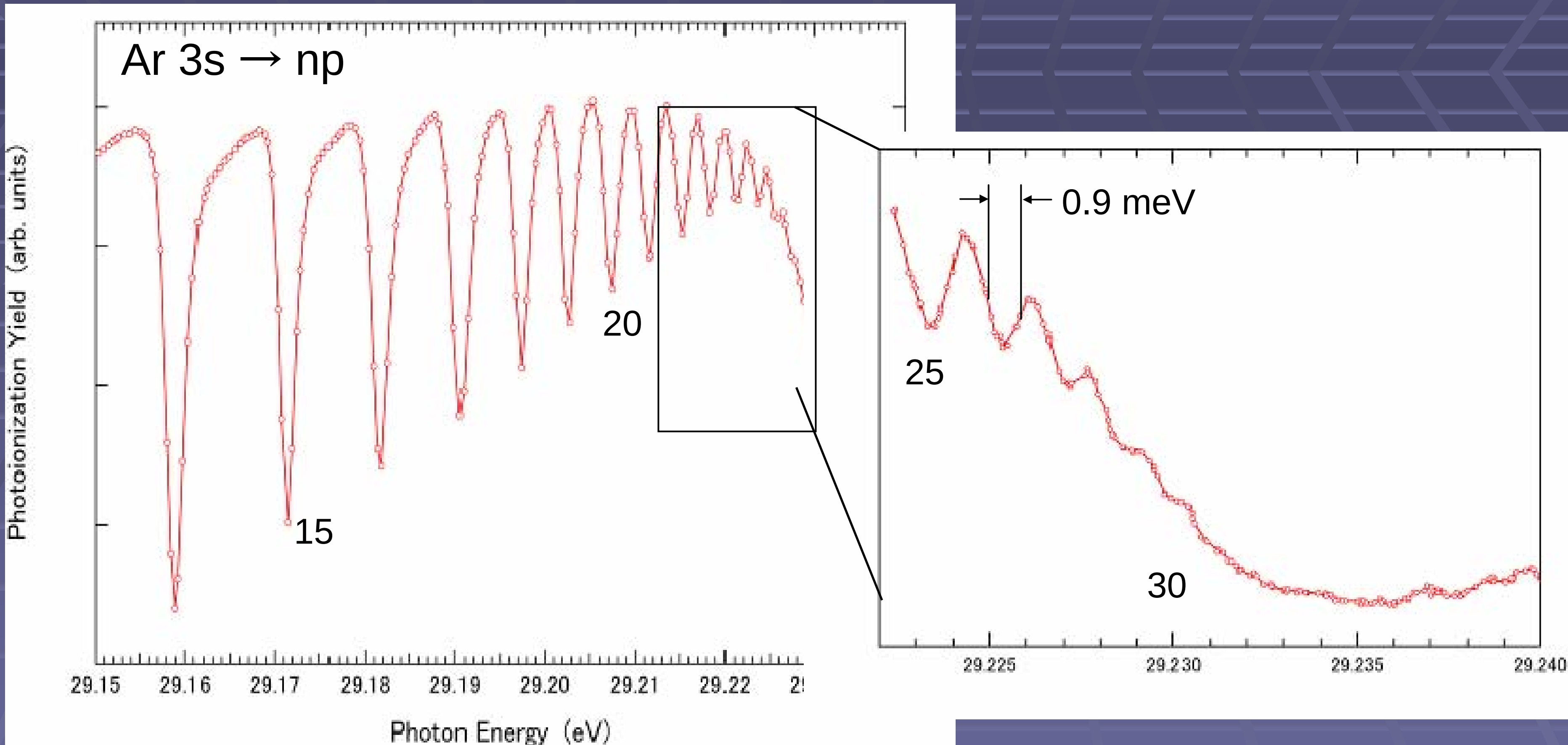


The focal point became 90 mm upstream of S2 when the pitch angle of M1 was changed to 1.9535 deg (-2.3% from the designed value).

Sagittal radius of M1 is ~2.3 % smaller than the designed value !?

3.3. experimental estimation of beamline performance

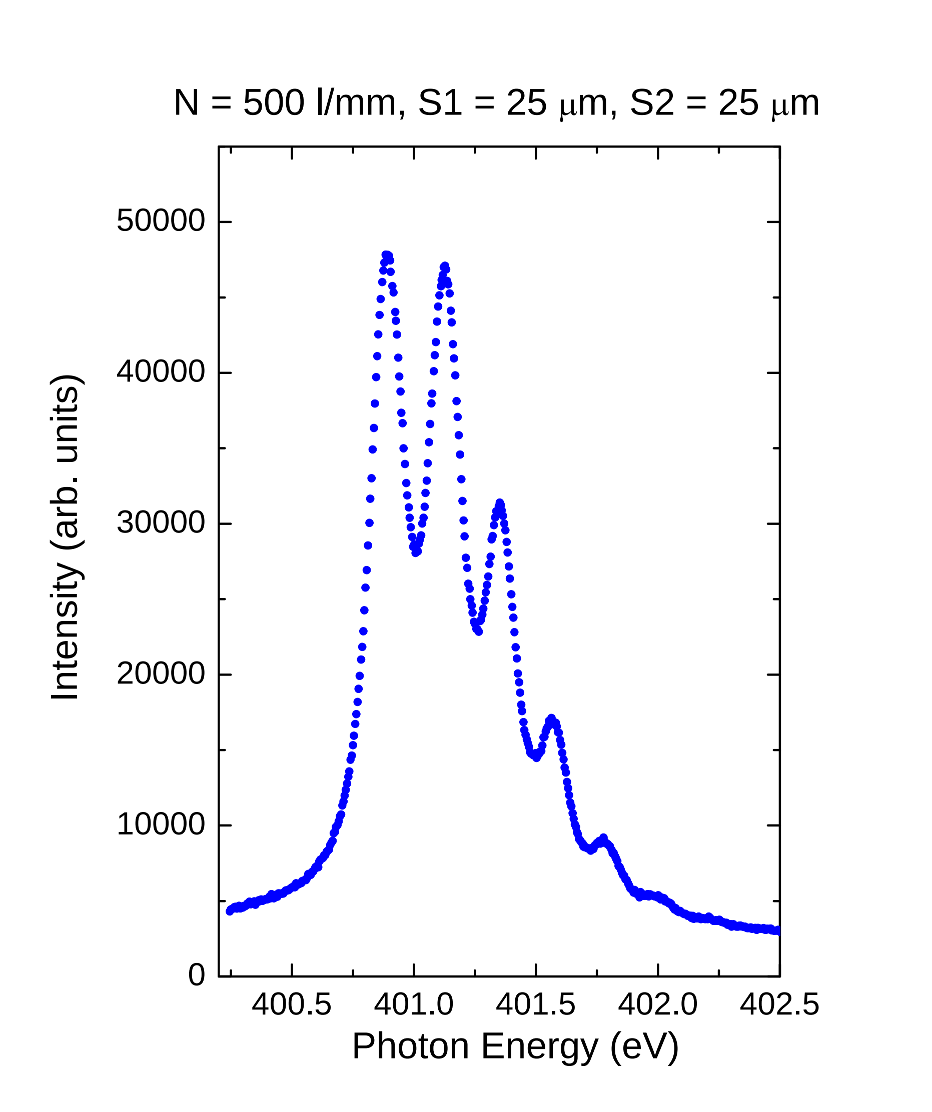
Absorption spectrum for Ar gas

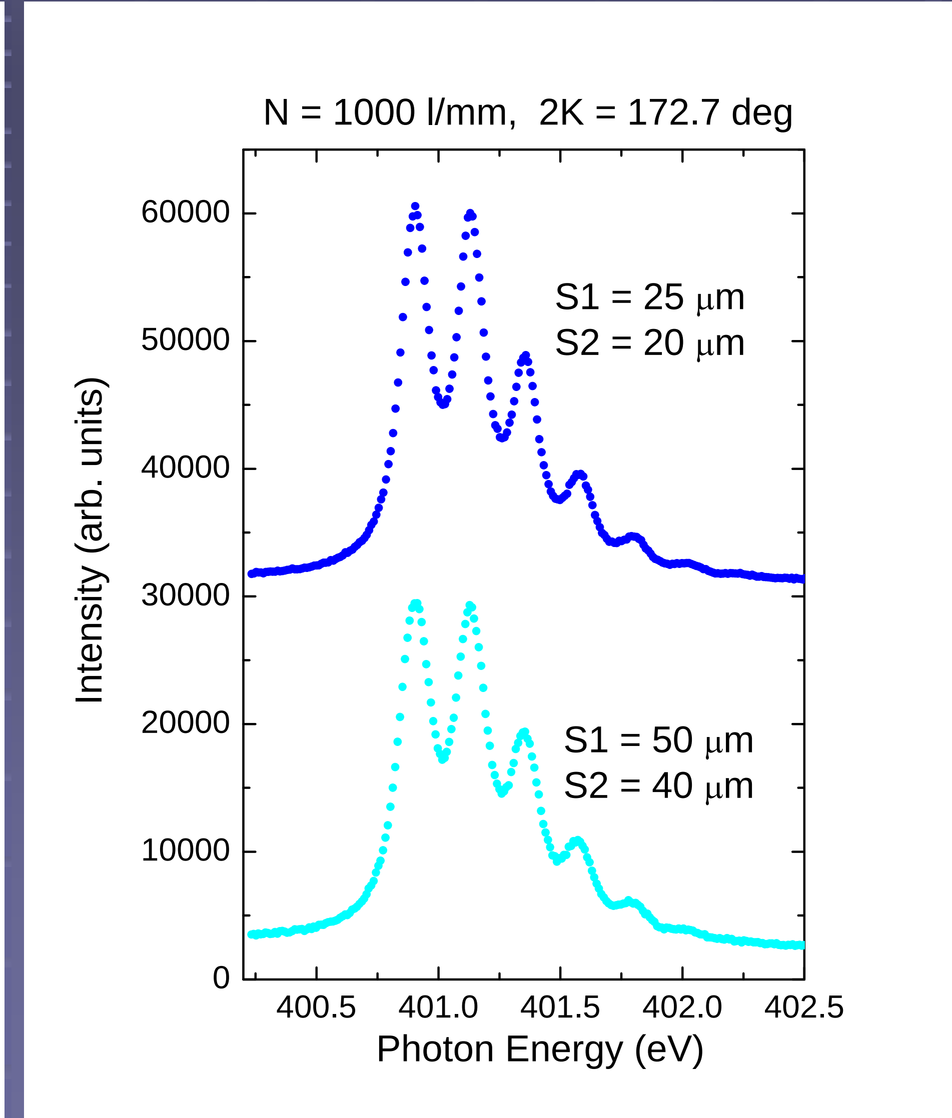


$\lambda / \Delta\lambda > 30{,}000$

3.3. experimental estimation of beamline performance

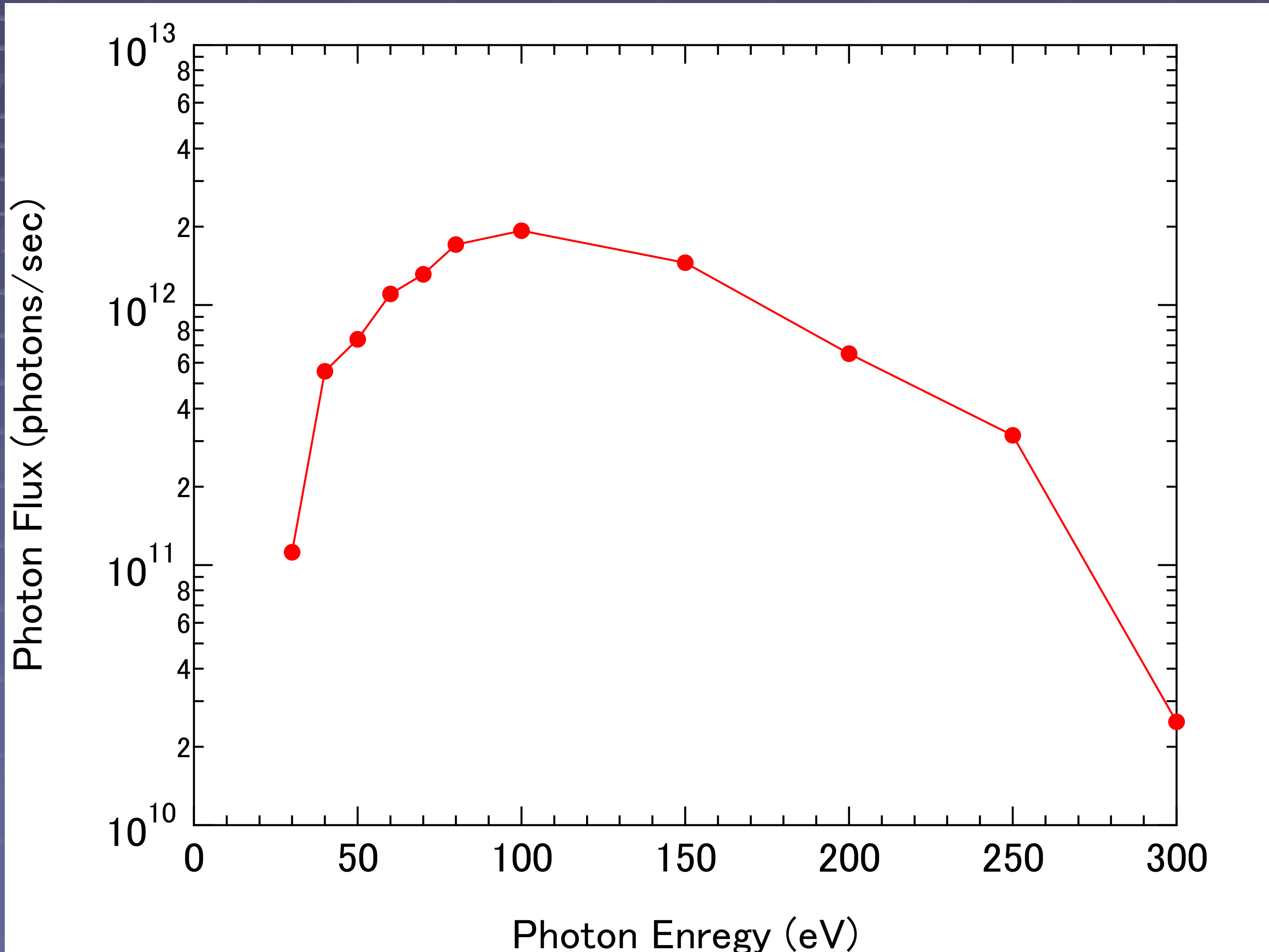
Absorption spectrum for N_2 gas





3.3. experimental estimation of beamline performance

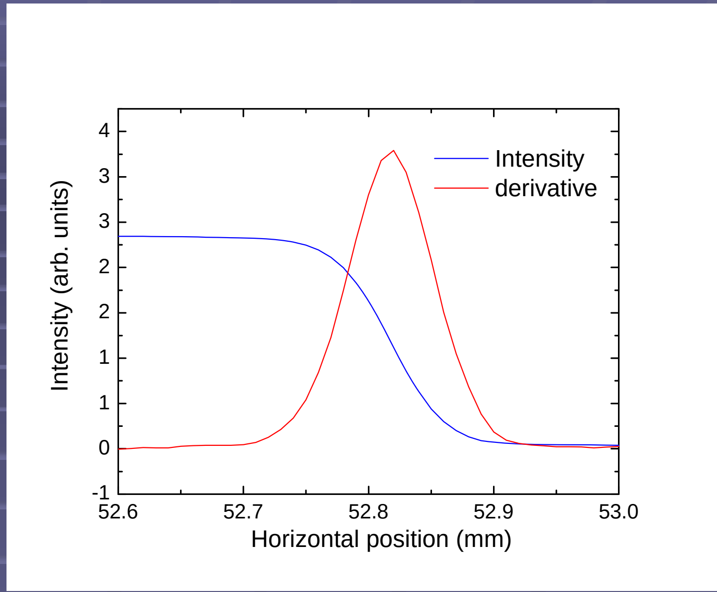
Photon Flux: photodiode is available



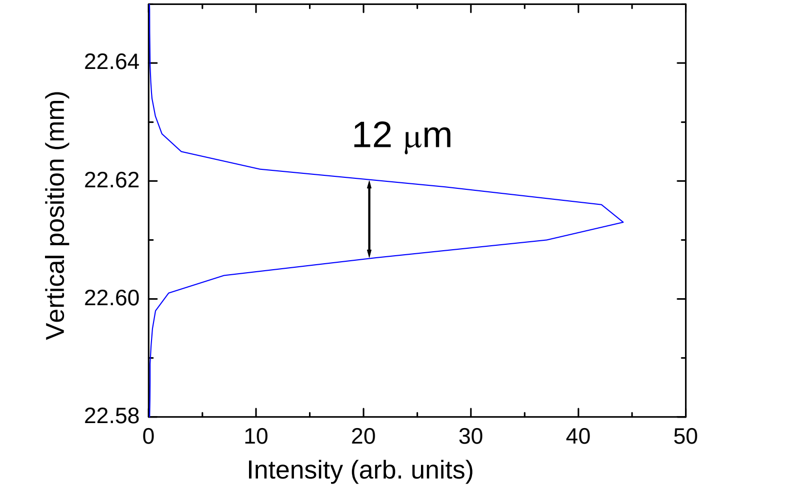
3.3. experimental estimation of beamline performance

Beam size: knife-edge scan

Light intensity is monitored at downstream of the knife edge



Vertical Size



Horizontal Size