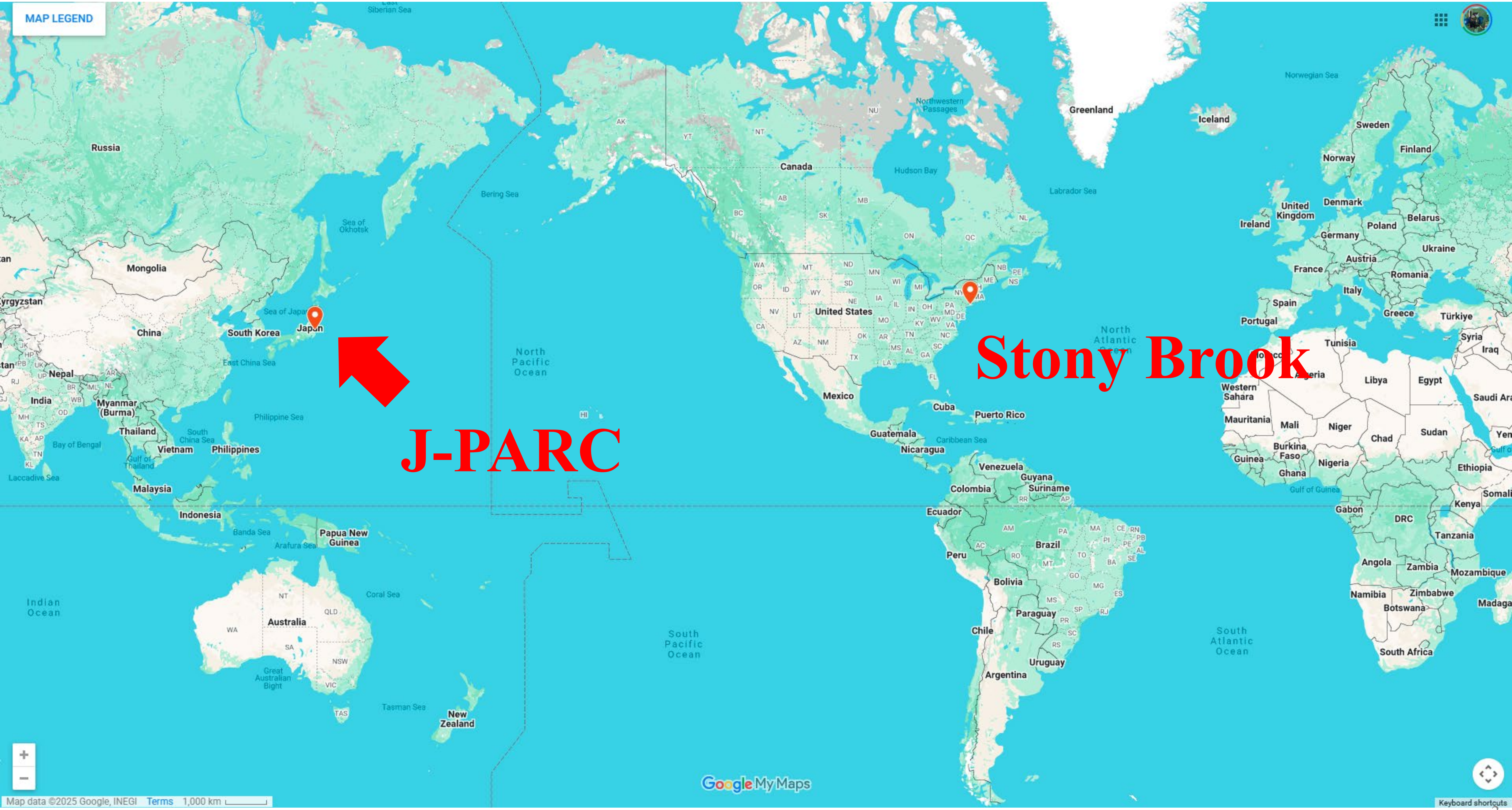
Crystals and Beam Diffusers for Higher Extraction Efficiency at J-PARC

Ryotaro Muto
KEK/J-PARC

Outline

- Brief Introduction of J-PARC Main Ring and Its Slow Extraction
- Beam Test Results of Beam Diffusers
- Simulation Studies on Bent Silicon Crystal
- Summary


J-PARC
Stony Brook
MAP LEGEND
Russia
Mongolia
China
South Korea
Japan
Sea of Okhotsk
Bering Sea
North Pacific Ocean
Philippine Sea
East China Sea
Nepal
India
Myanmar (Burma)
Thailand
Vietnam
Philippines
Bay of Bengal
Laccadive Sea
Malaysia
Indonesia
Banda Sea
Arafura Sea
Papua New Guinea
Coral Sea
Australia
Indian Ocean
Tasman Sea
New Zealand
South Pacific Ocean
Canada
Hudson Bay
Greenland
Iceland
Labrador Sea
Norwegian Sea
United States
Mexico
Cuba
Puerto Rico
Guatemala
Nicaragua
Caribbean Sea
Venezuela
Guyana
Suriname
Colombia
Ecuador
Peru
Brazil
Bolivia
Paraguay
Chile
Uruguay
Argentina
North Atlantic Ocean
South Atlantic Ocean
Sweden
Norway
Finland
United Kingdom
Ireland
Denmark
Poland
Belarus
Germany
Ukraine
Austria
France
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Italy
Spain
Portugal
Greece
Türkiye
Tunisia
Syria
Iraq
Libya
Egypt
Western Sahara
Mauritania
Mali
Niger
Chad
Sudan
Burkina Faso
Guinea
Ghana
Nigeria
Ethiopia
Gulf of Guinea
Gabon
DRC
Kenya
Tanzania
Angola
Zambia
Mozambique
Namibia
Zimbabwe
Botswana
South Africa
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1,000 km
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J-PARC
~2 h by car or train
from the center of
Tokyo
Tokyo
MAP LEGEND
Sendai 仙台
Niigata 新潟
Fukushima 福島
Koriyama 郡山
Iwaki いわき
Hitachi 日立
Utsunomiya 宇都宮
Takasaki 高崎
Nagano 長野
Toyama 富山
Kanazawa 金沢
Tokyo 東京
Yokohama 横浜
Kashiwa 柏
Choshi 銚子
Mount Fuji 富士山
Shizuoka 静岡
Hamamatsu 浜松
Nagoya 名古屋
Kyoto 京都
Osaka 大阪
Kobe 神戸
Okayama 岡山
Wakayama 和歌山
IBARAKI
TOCHIGI
GUNMA
SAITAMA
TOKYO
CHIBA
KANAGAWA
YAMANASHI
NAGANO
NIIGATA
FUKUSHIMA
TOYAMA
ISHIKAWA
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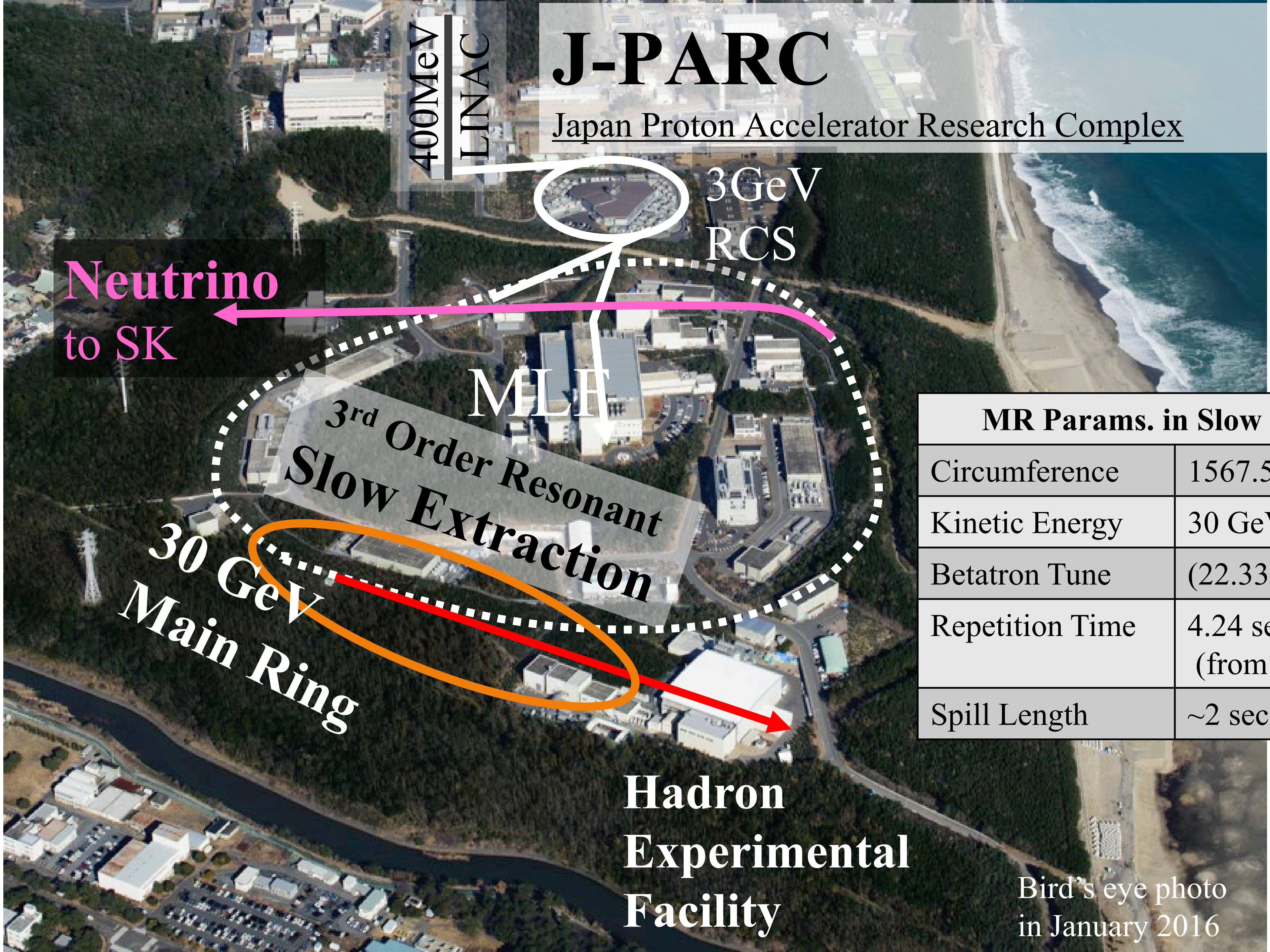
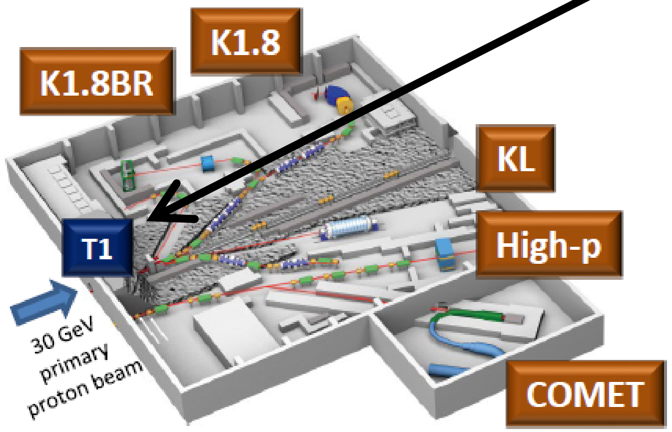


MR Params. in Slow Extraction	
Circumference	1567.5 m
Kinetic Energy	30 GeV or 8 GeV
Betatron Tune	(22.333, 20.78)
Repetition Time	4.24 sec (from 2024 Mar)
Spill Length	~2 sec

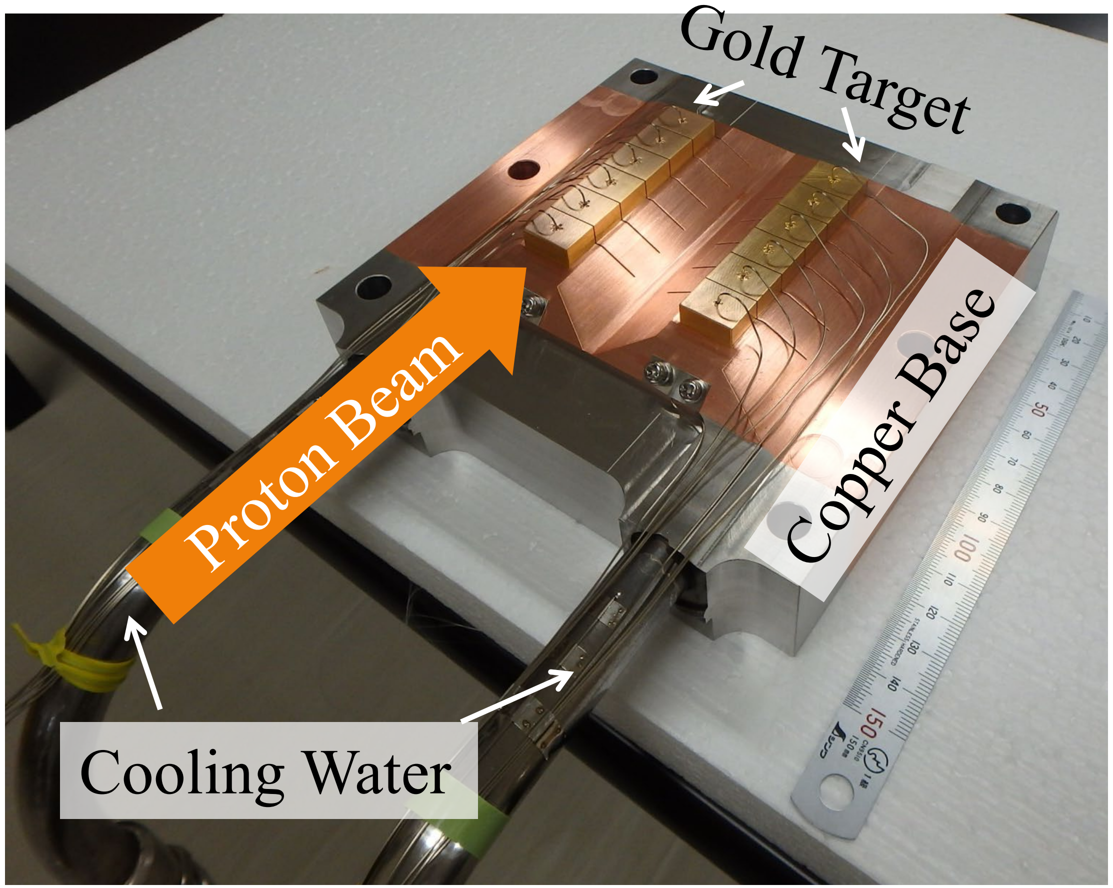
Hadron Experimental Facility & Its Extension Plan

Acceptable Beam Power: 115 kW

Present HEF (2009～)

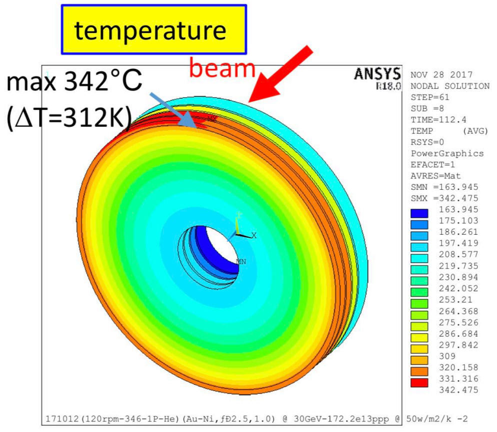


1 production target (T1)
1 secondary-charged beamline (K1.8/K1.8BR)
1 neutral beamline (KL)
1 primary beamline (High-p)
1 muon beamline (COMET)



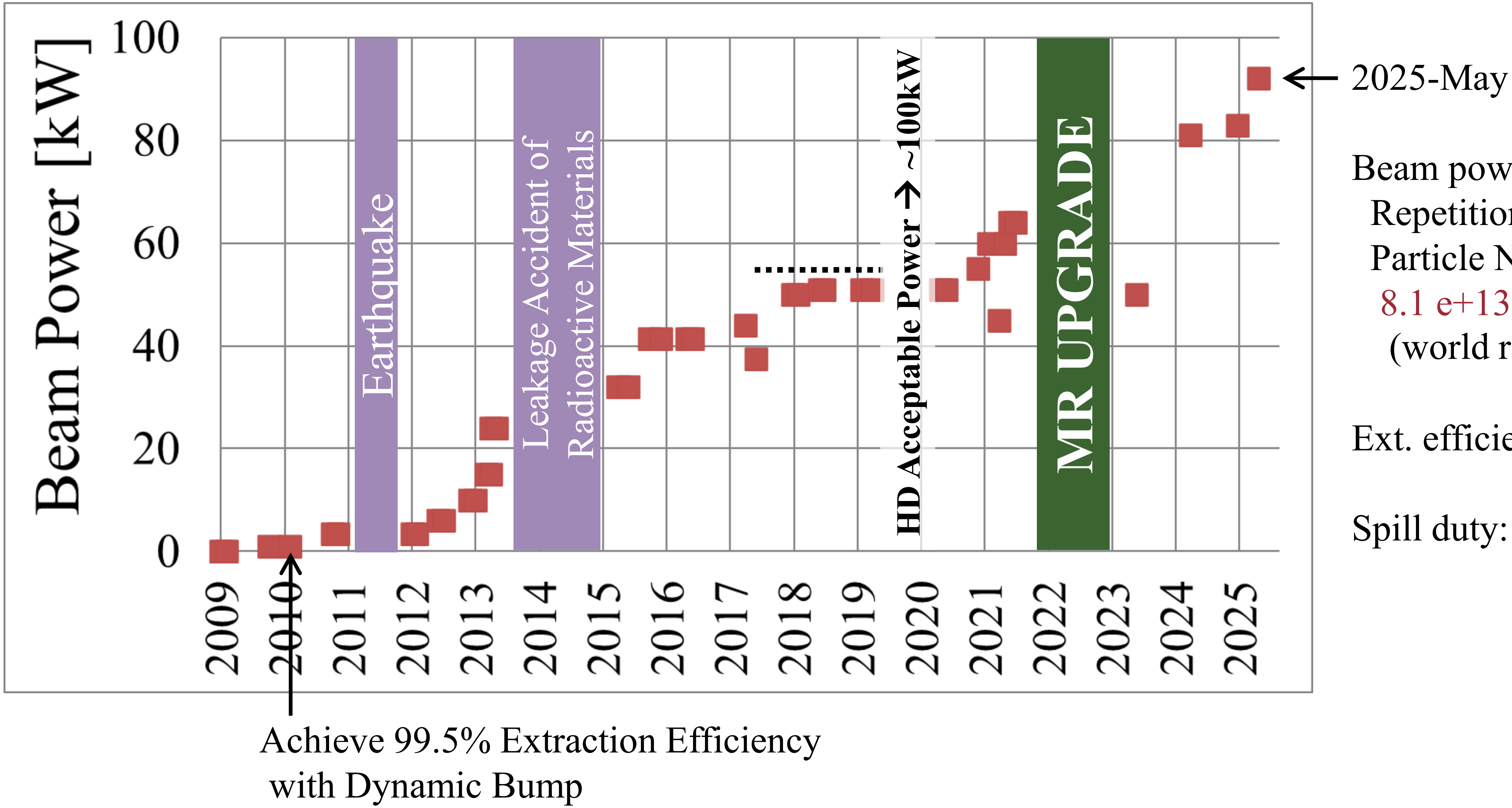
New Production Target (under development)

He gas cooled (assuming 50 W/m²/K)



Acceptable Beam Power: **>150kW**

Beam Power Trend of J-PARC Slow Extraction



Beam power: **92 kW**
Repetition: 4.24 s
Particle Number:
8.1 e+13 protons/pulse
(world record)

Ext. efficiency: ~**99.6%**

Spill duty: ~**83%**

Issues on J-PARC MR Slow Extraction

Beam Power

- Beam Loss Reduction

  Crystals and Beam Diffusers for Higher Extraction Efficiency at J-PARC (Mon) Ryotaro Muto

- Suppress Beam Instability at Debunch Timing

  Studies on collective phenomena related to slow beam extraction (Tue) Masahito Tomizawa

  Analysis of Beam Instability During Debunching at J-PARC Slow Extraction (Poster) Keita Itahashi

Spill Structure

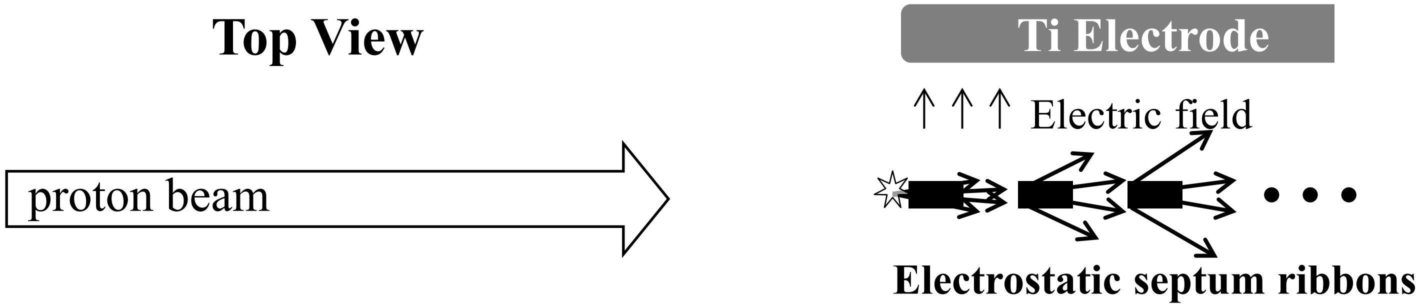
Studies on spill quality improvement at J-PARC (Wed) Ryotaro Muto

Optics Correction

Precise evaluation of time-varying quadrupole field errors in the J-PARC Main Ring (Wed) Takashi Asami

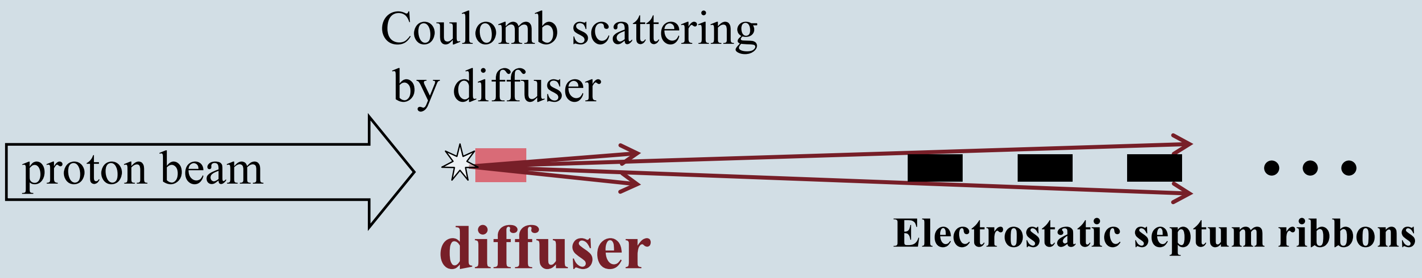
Beam Diffuser and Bent Silicon Crystal for Beam Loss Reduction

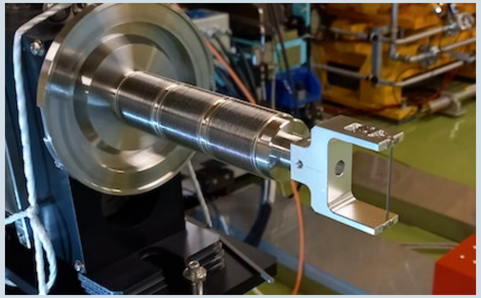
Beam Diffuser and Bent Silicon Crystal



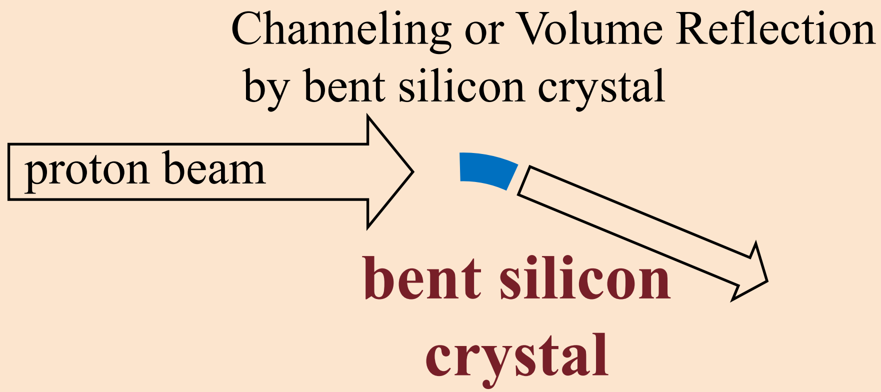
W-Re alloy

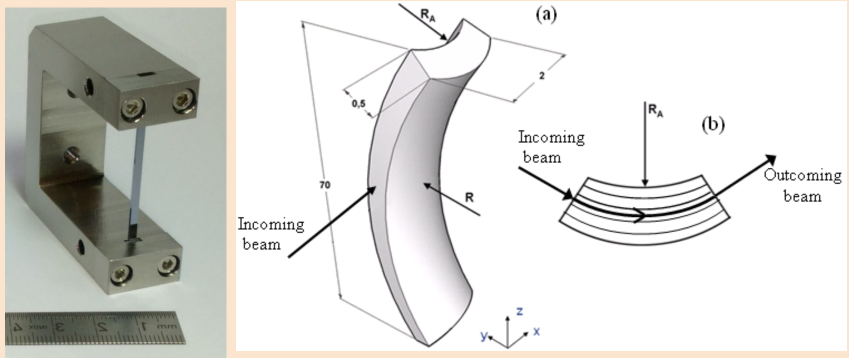
Each ribbon : 30 um thick, 1 mm long
In total : 495 ribbons in 1.5 m length,
effective thickness : 60 um





Beam diffuser
in the J-PARC MR

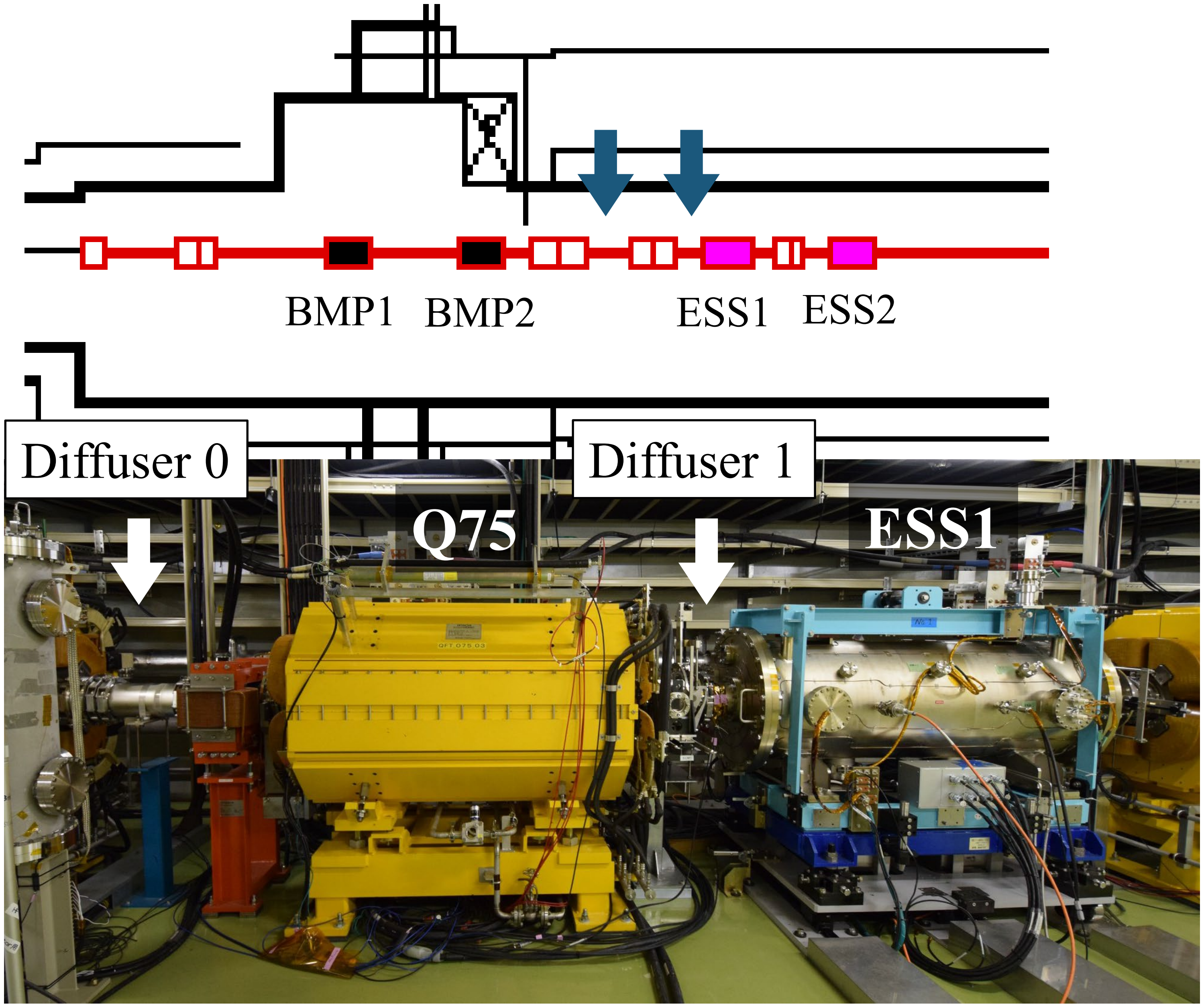




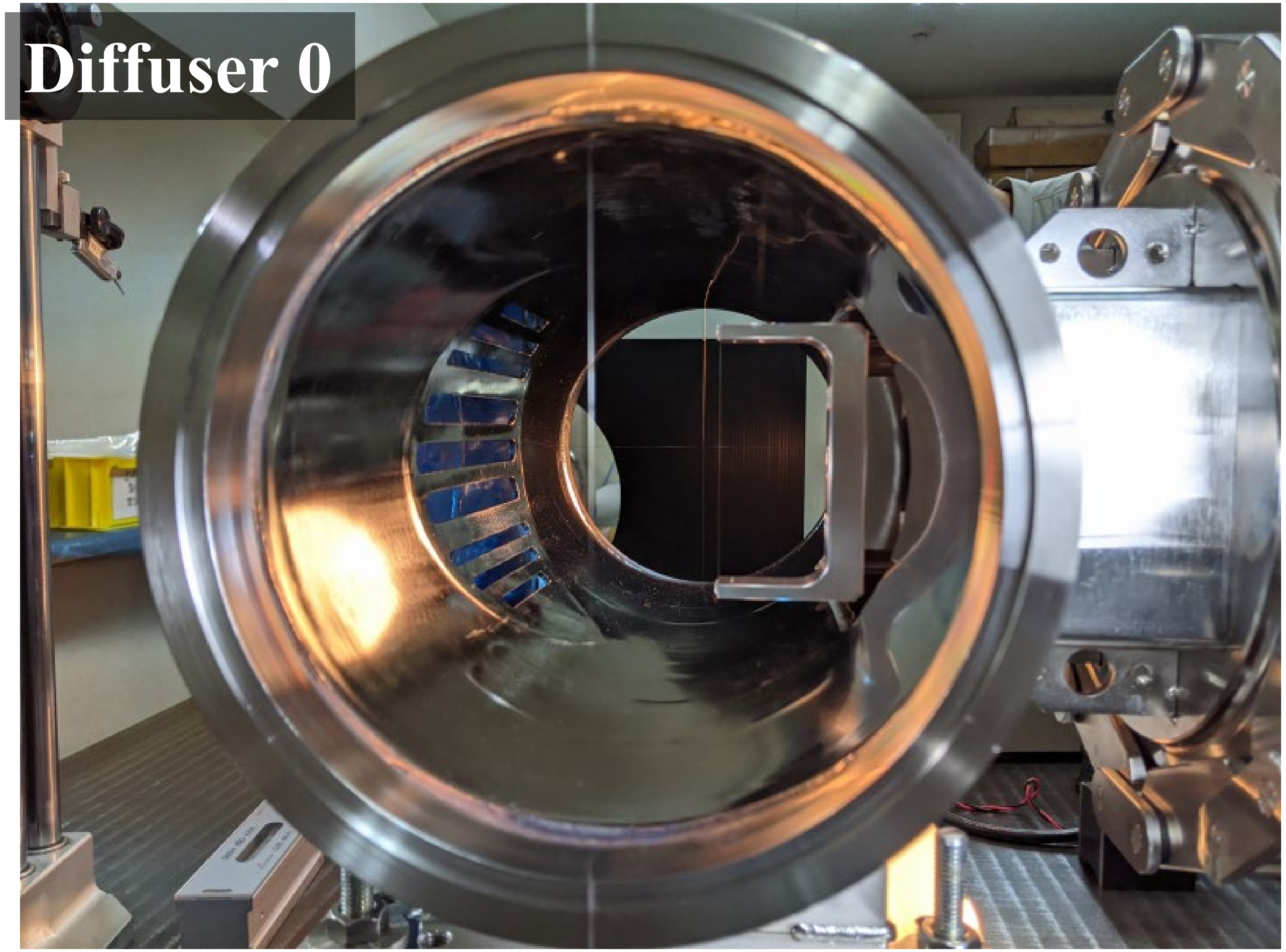
Bent silicon crystal developed for CERN LHC
beam collimation

Beam Diffusers

Locations for Diffusers



Installed Beam Diffusers



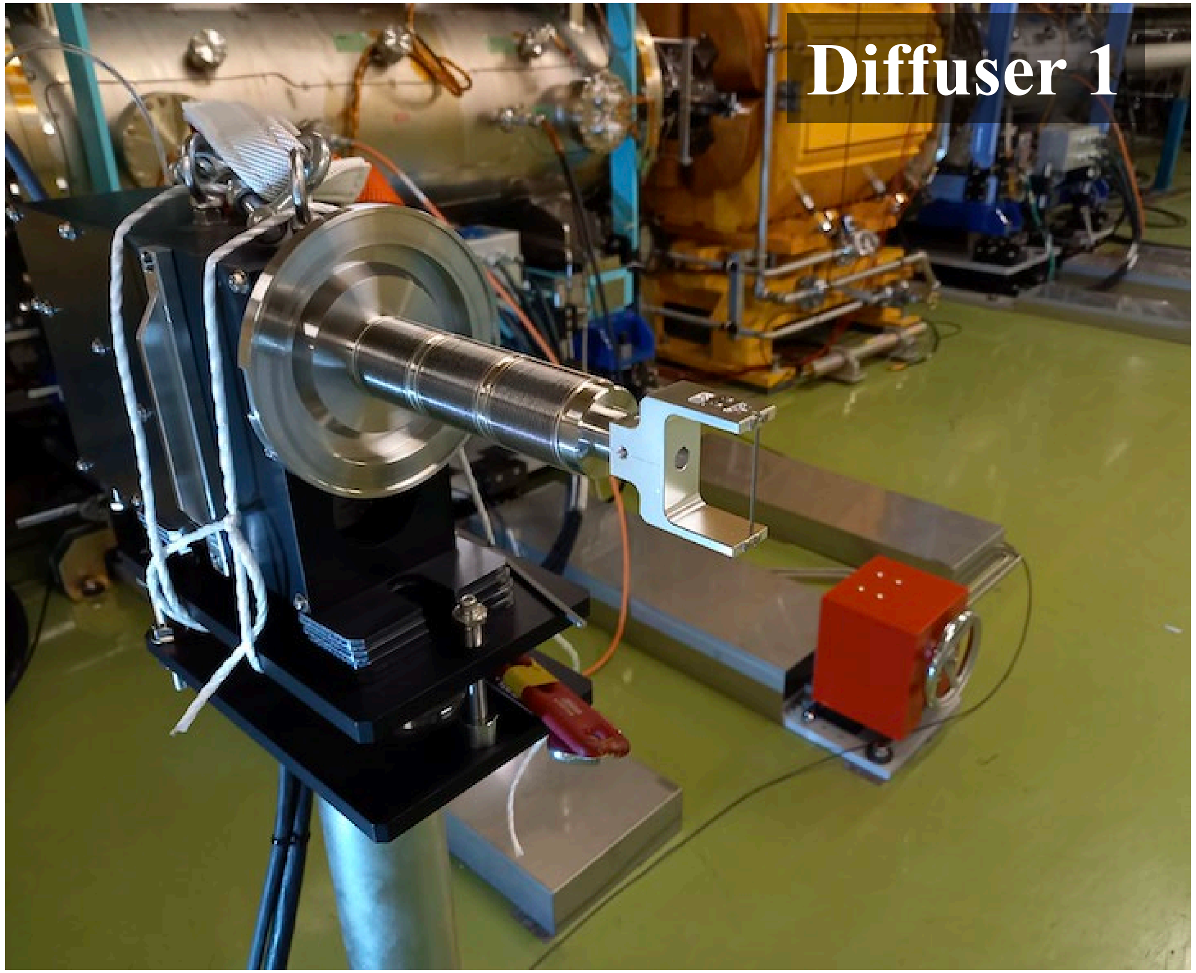
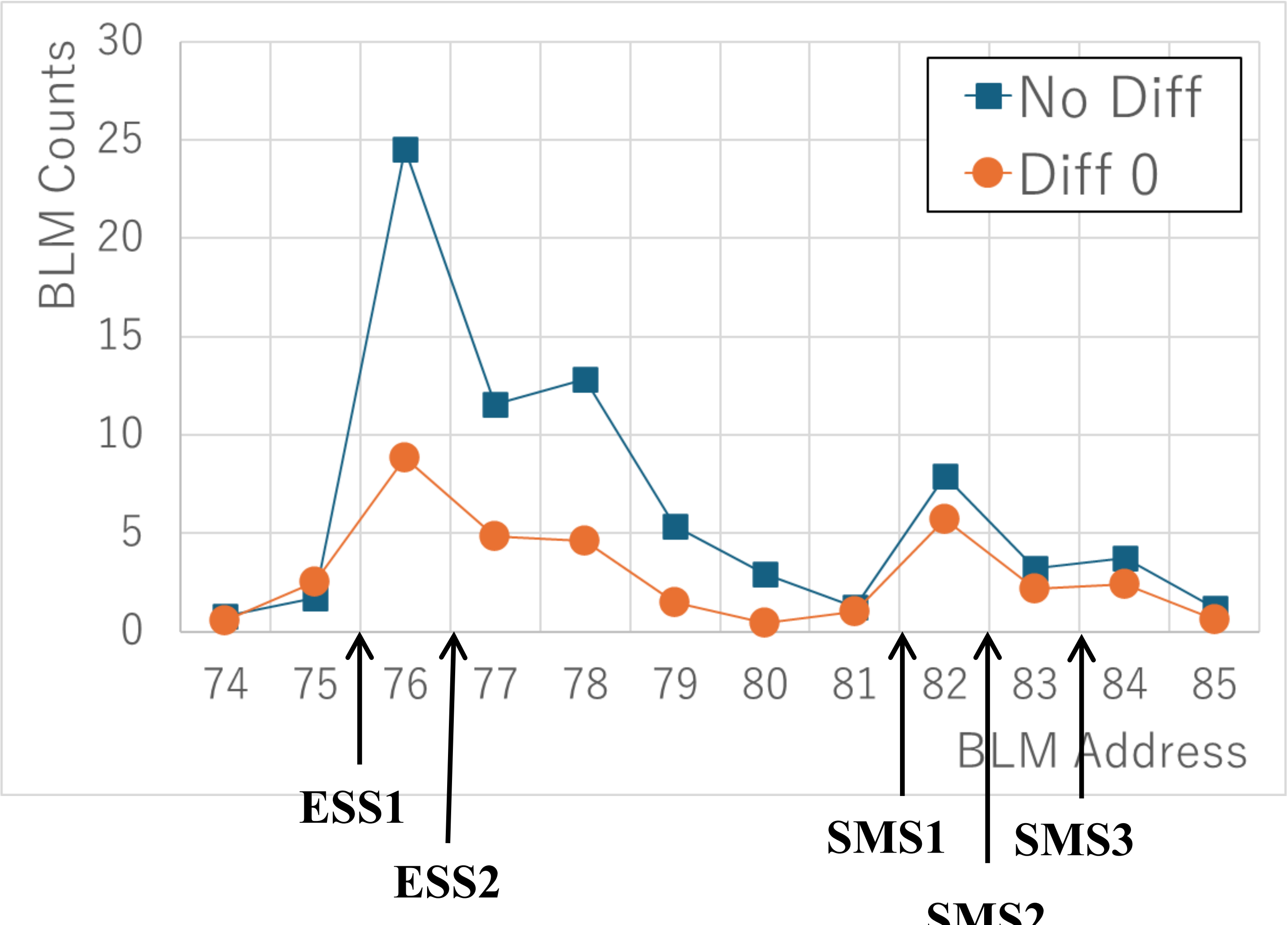
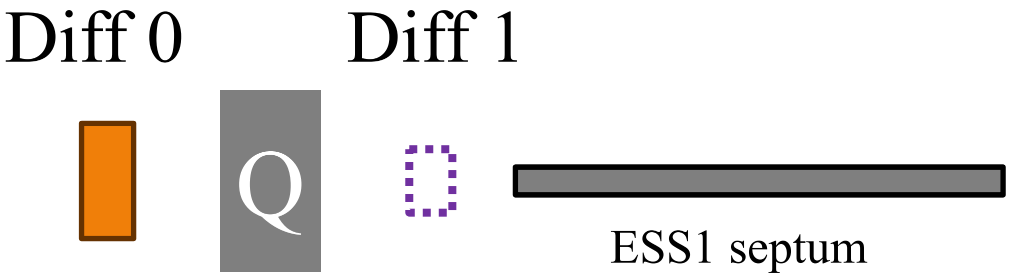


Photo from downstream

Beam Loss Distribution with Diffusers

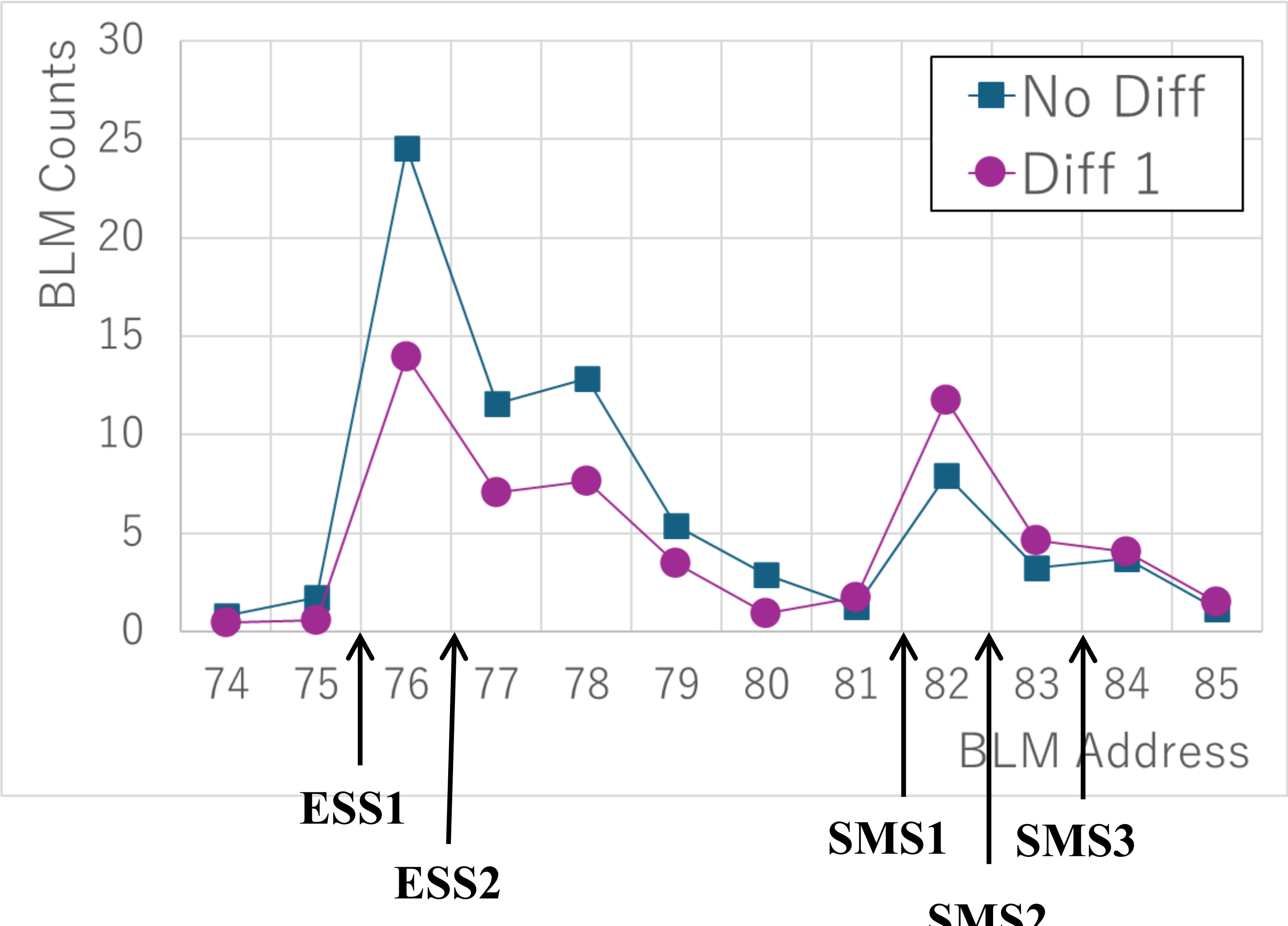
10 kW Beam

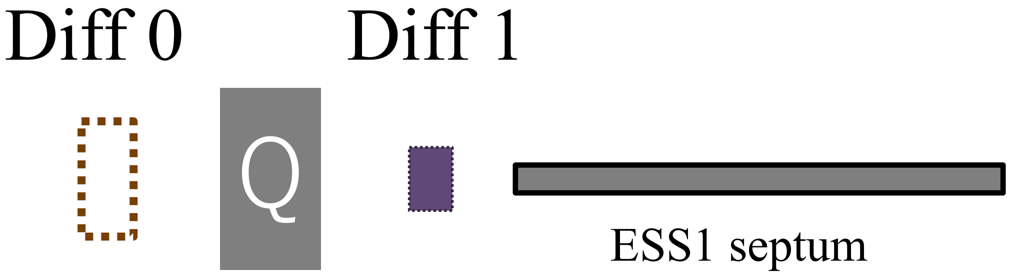




Beam Loss Distribution with Diffusers

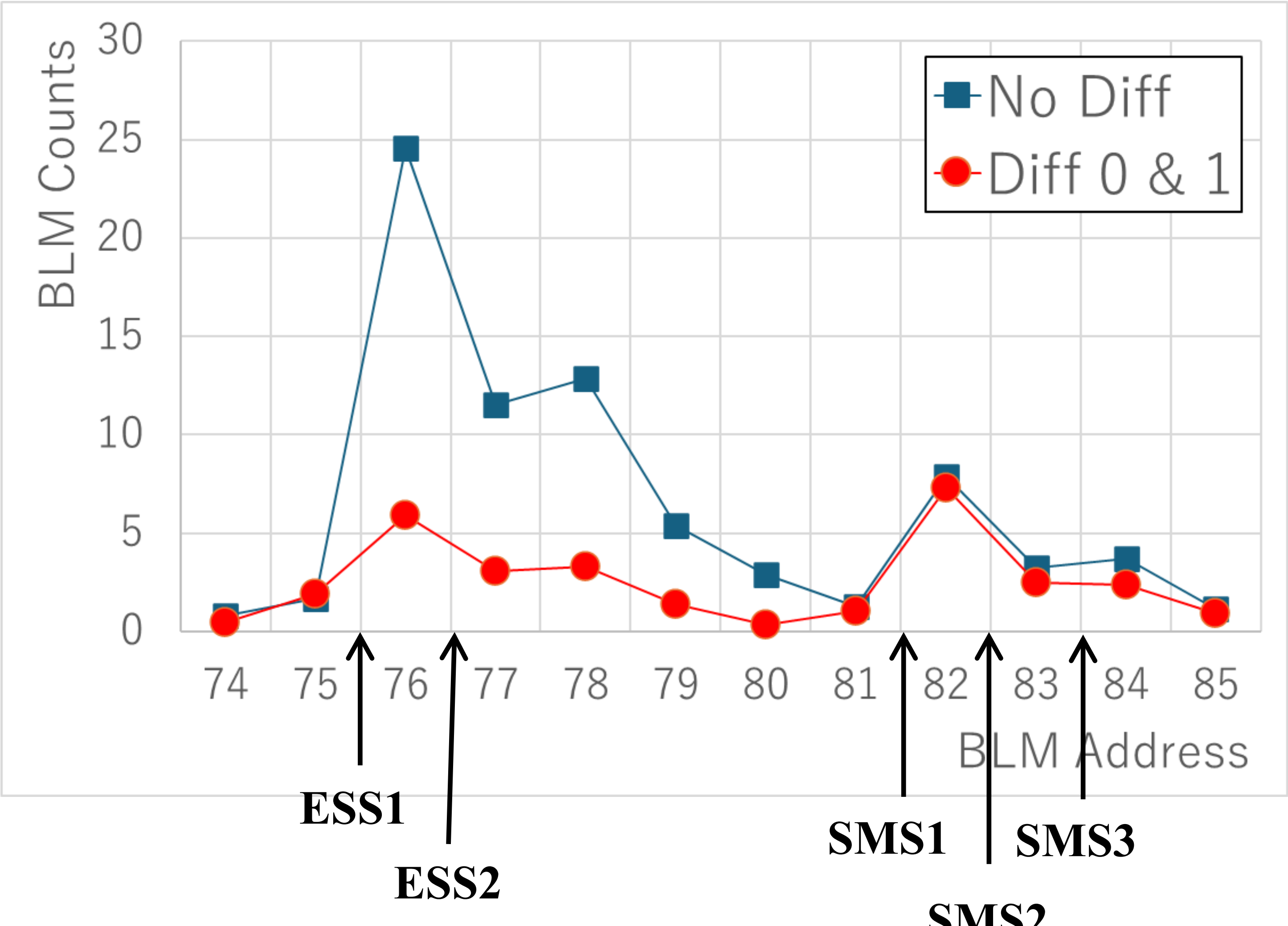
10 kW Beam

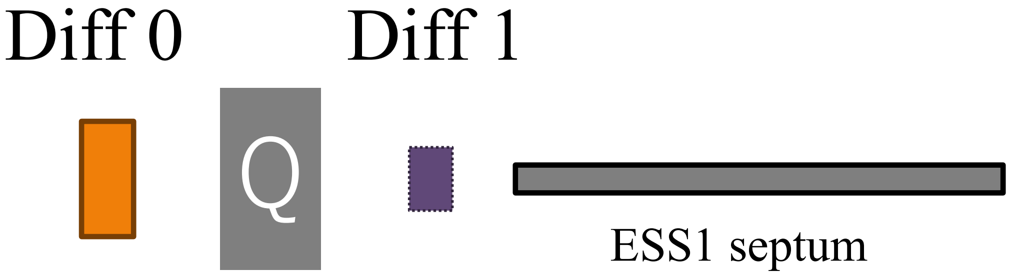




Beam Loss Distribution with Diffusers

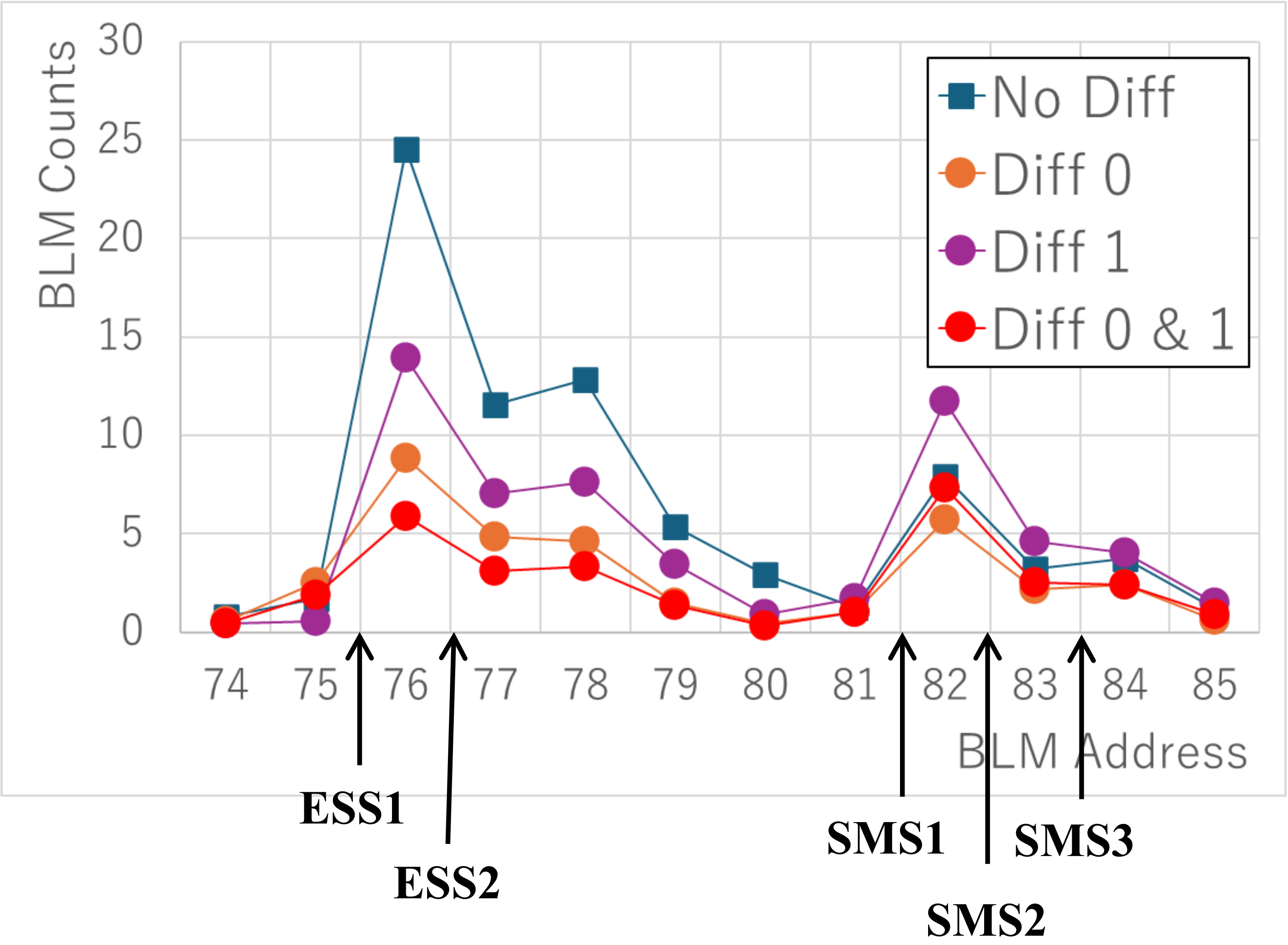
10 kW Beam





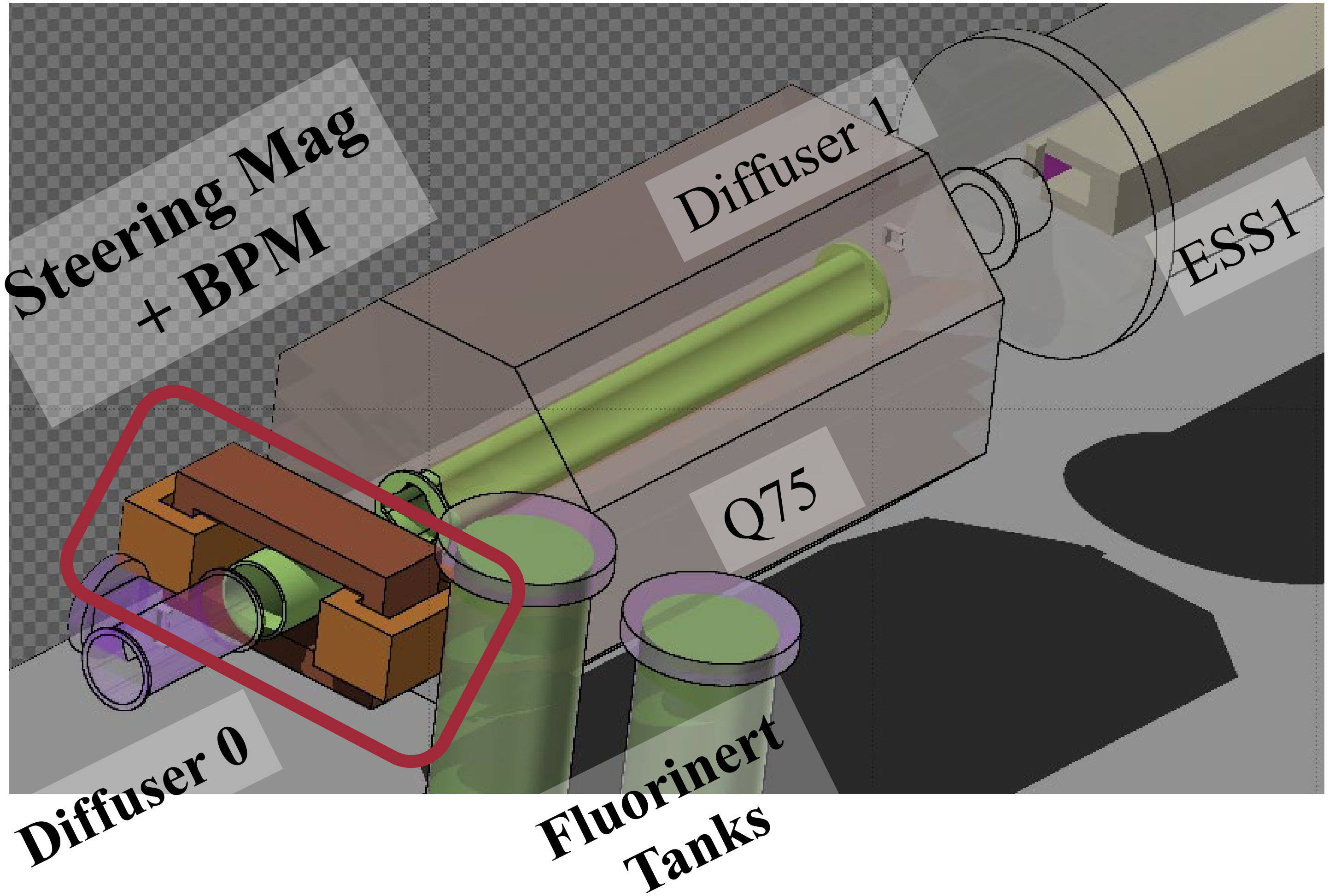
Beam Loss Distribution with Diffusers

10 kW Beam



	Loss around ESS	(sim)	Loss around SMS
No Diff	1	1	1
Diff 0	0.40	0.42	0.61
Diff 1	0.58	0.47	1.21
Diff 0 & 1	**0.28**	**0.35**	**0.72**

Issue on Diffuser 0

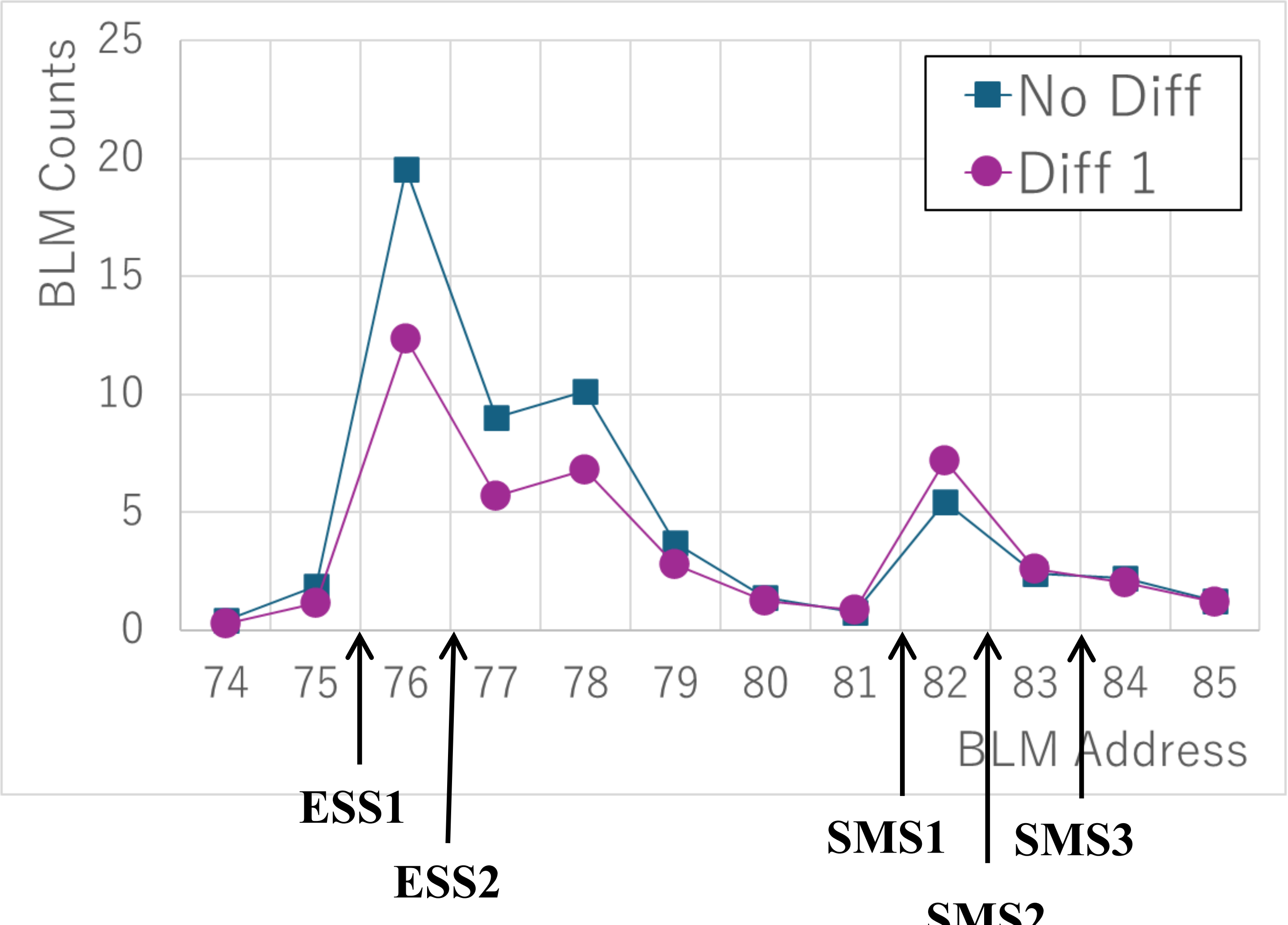


There are steering mag + BPM
at the just downstream of
Diffuser 0

For the continuous operation,
we chose NOT to use Diffuser 0

Beam Loss Distribution with Diffusers

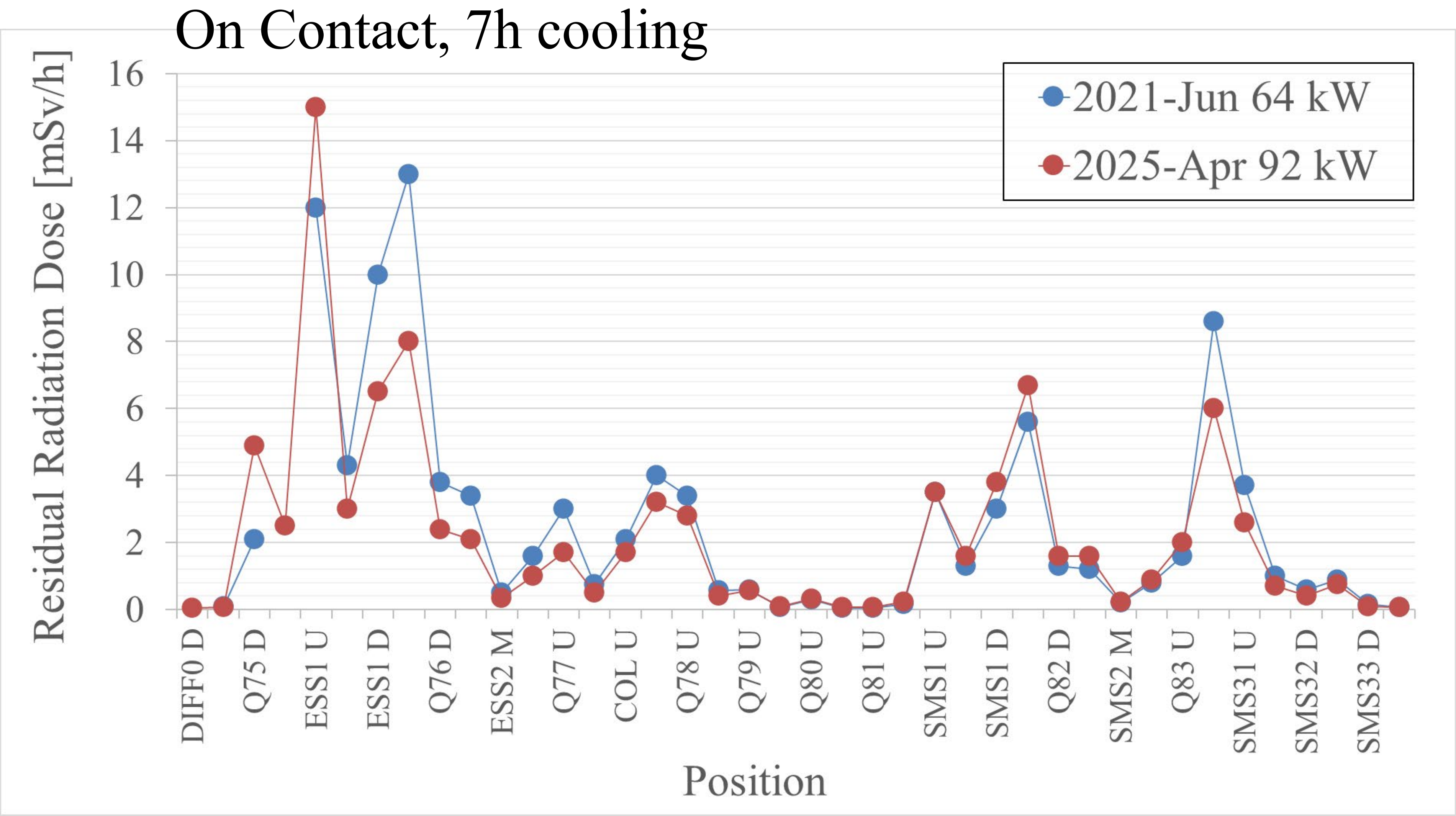
81 kW Beam



	Loss around ESS	Loss around SMS
No Diff	1	1
Diff 1	**0.65**	**1.12**

At present, we use Diffuser 1 for 92 kW continuous beam operation

Residual Rad. Dose after 92 kW Op. with Diff. 1



The distribution of residual radiation dose rate was in good agreement with the expectation from the beam loss distribution.

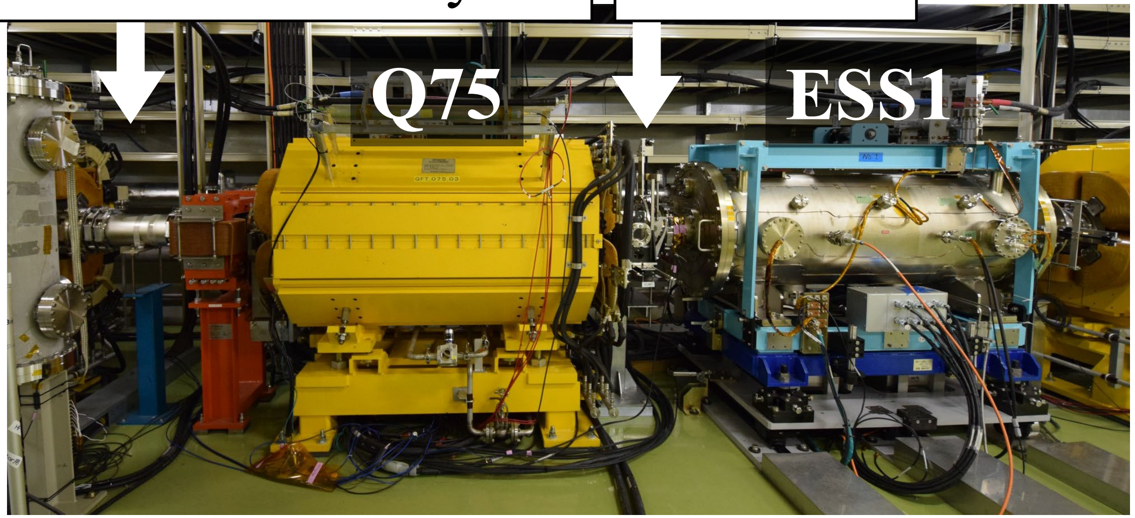
~ 0.85 mSv/h at 1 m from beam line around ESS1 (7h cooling)

Bent Silicon Crystal

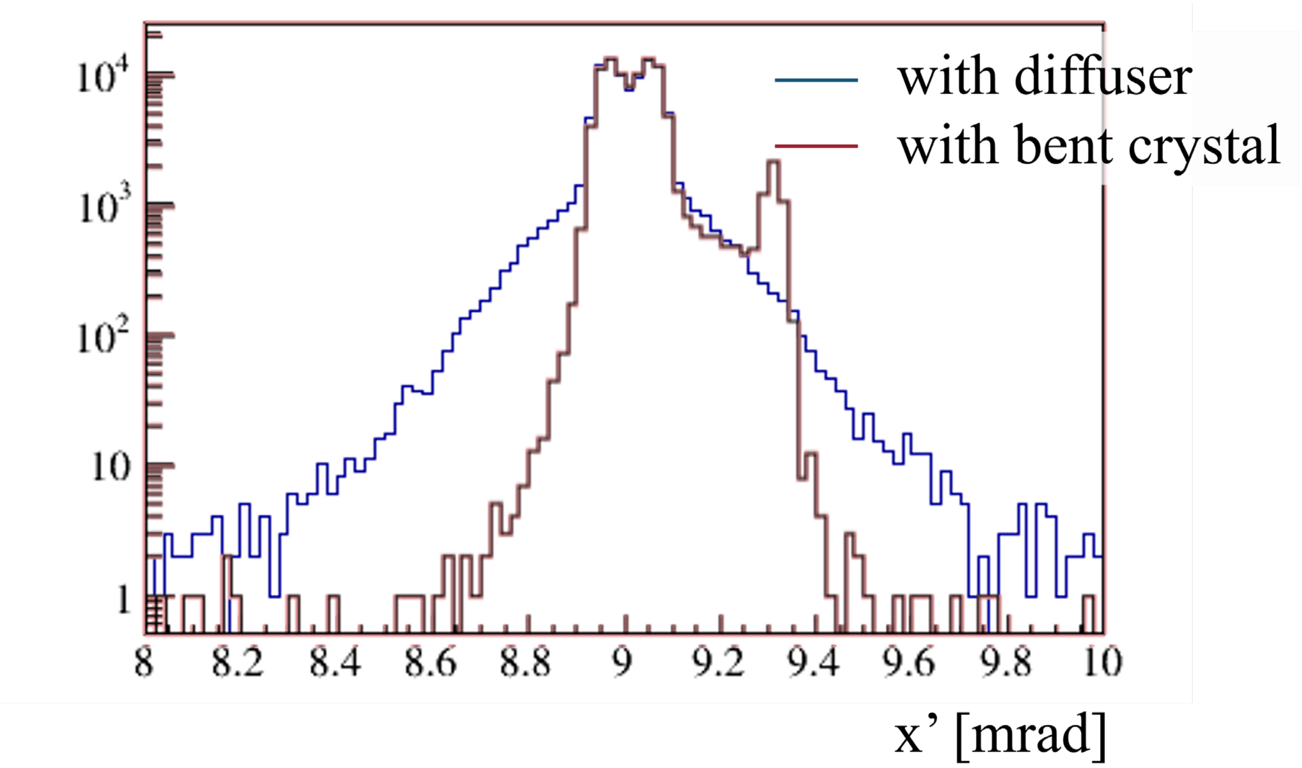
Location of the Bent Silicon Crystal

Diffuser 0
→ Bent Silicon Crystal

Diffuser 1



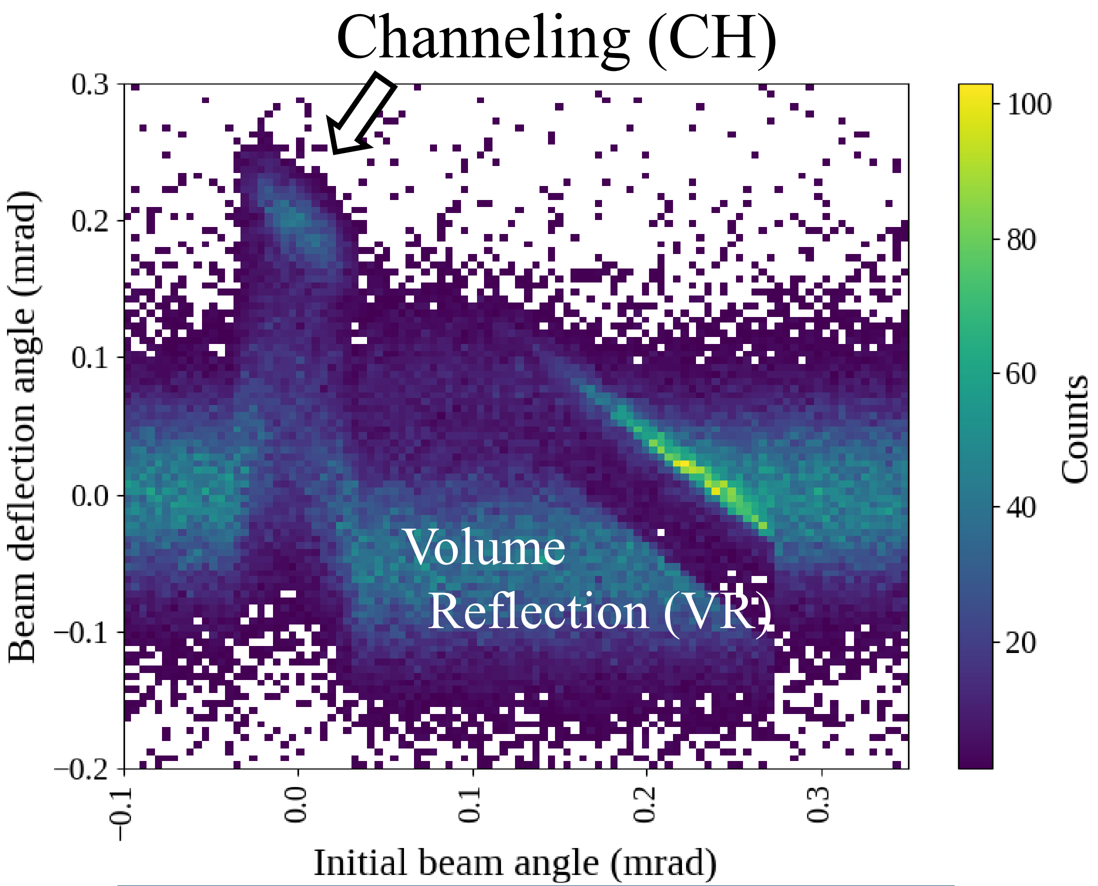
The angular spread comparison
between diffuser and silicon crystal

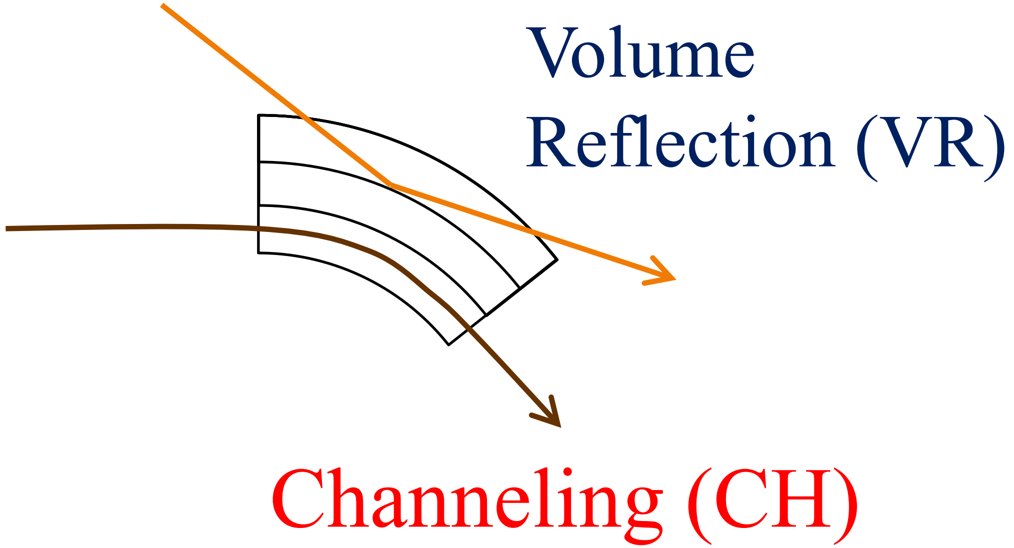


The angular spread produced by a bent silicon crystal is much smaller than that produced by a tantalum diffuser

Optimization of the Dimension of the Crystal

FLUKA simulation for 30 GeV proton deflection by bent silicon crystal

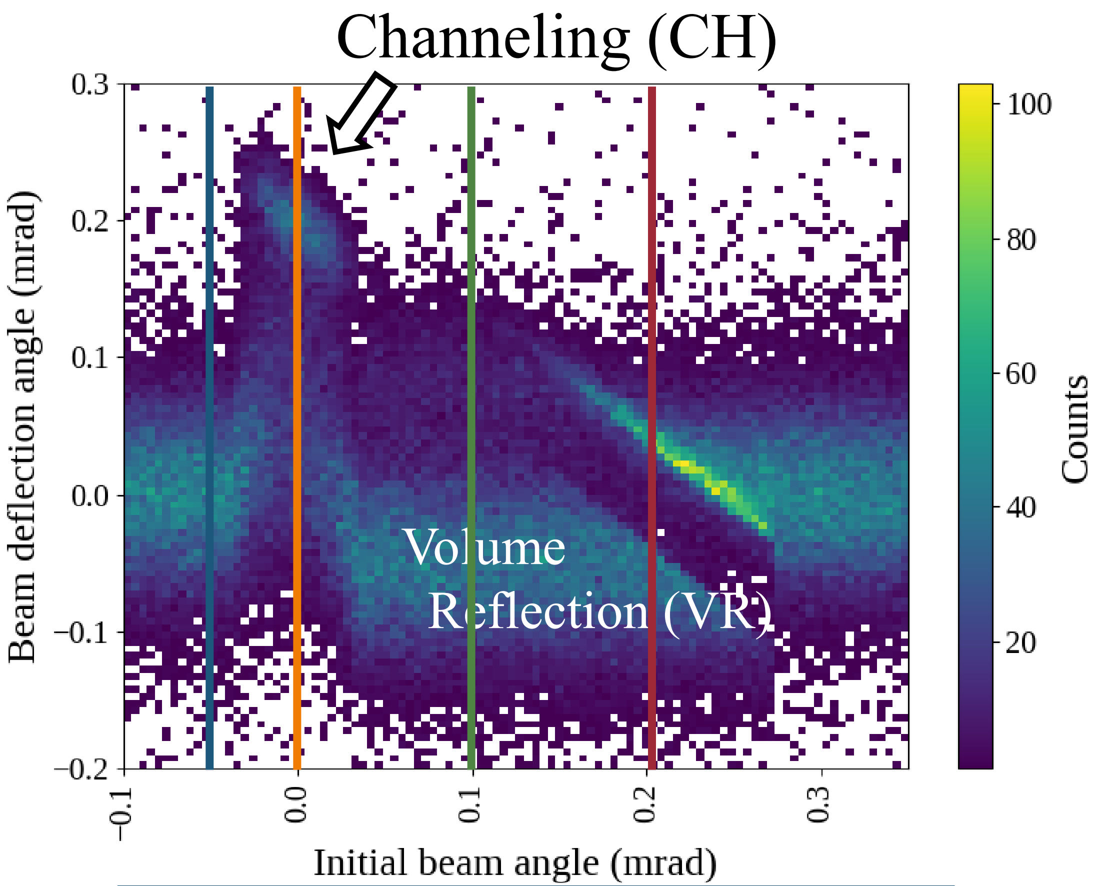


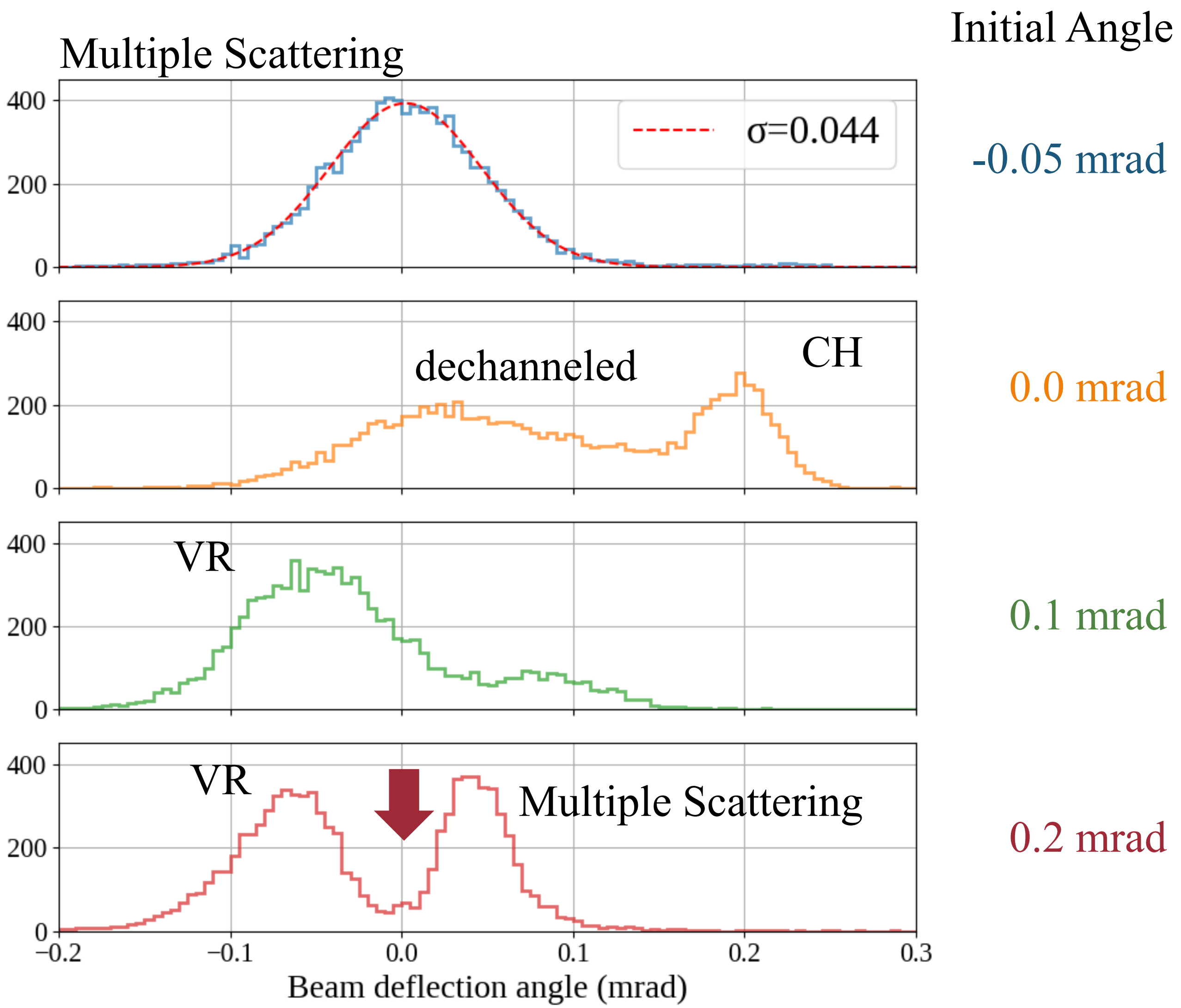


Bent Silicon Crystal Dimensions	
Longitudinal Length	1.0 mm
Bending Angle	0.2 mrad

Optimization of the Dimension of the Crystal

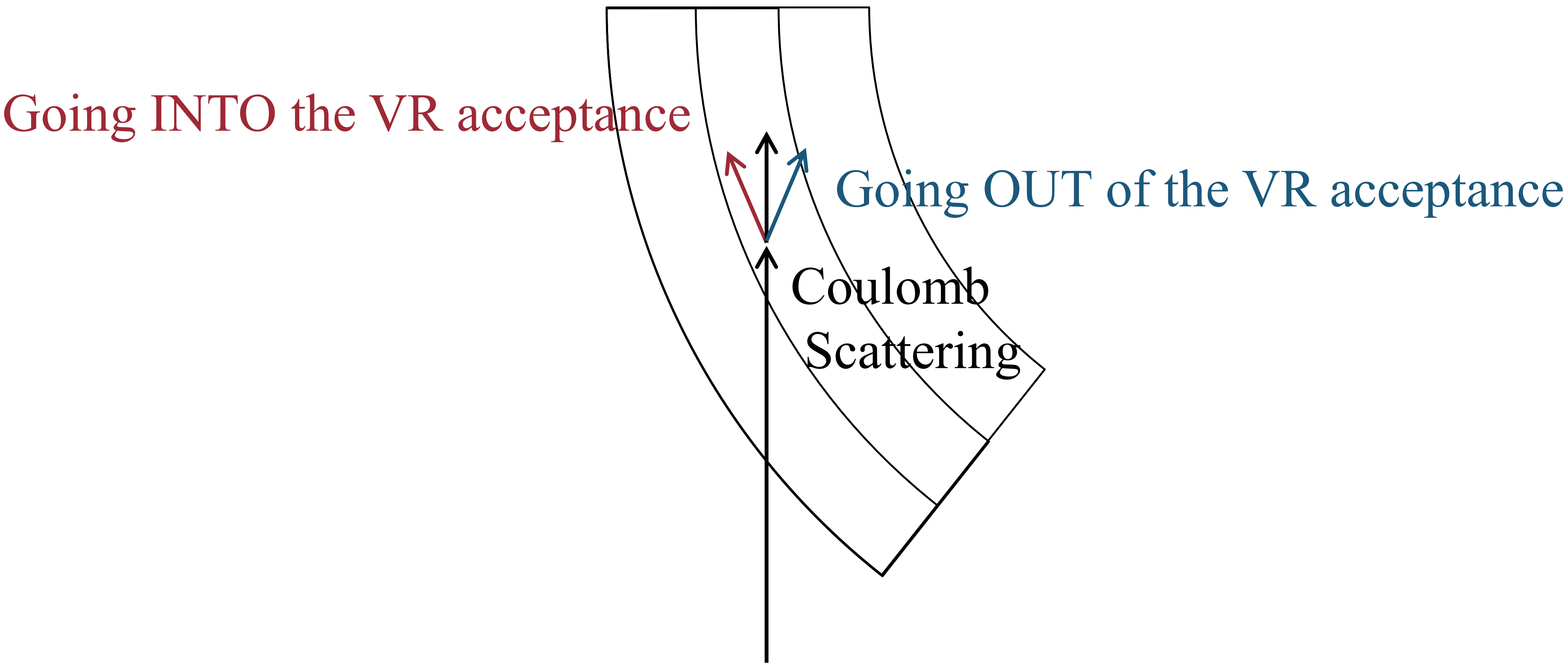
FLUKA simulation for 30 GeV proton deflection by bent silicon crystal



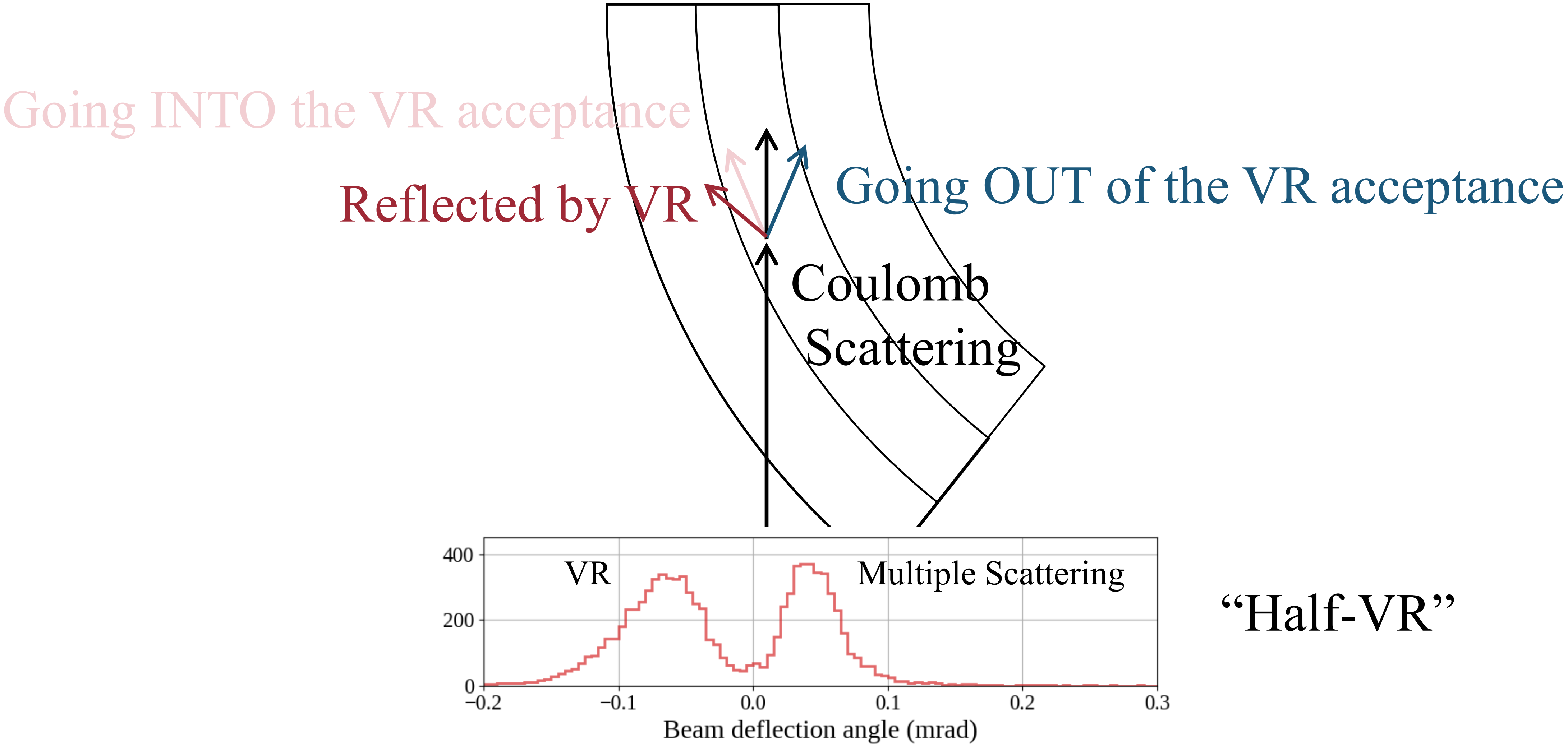


Bent Silicon Crystal Dimensions	
Longitudinal Length	1.0 mm
Bending Angle	0.2 mrad

Situation around the Edge of the VR Acceptance

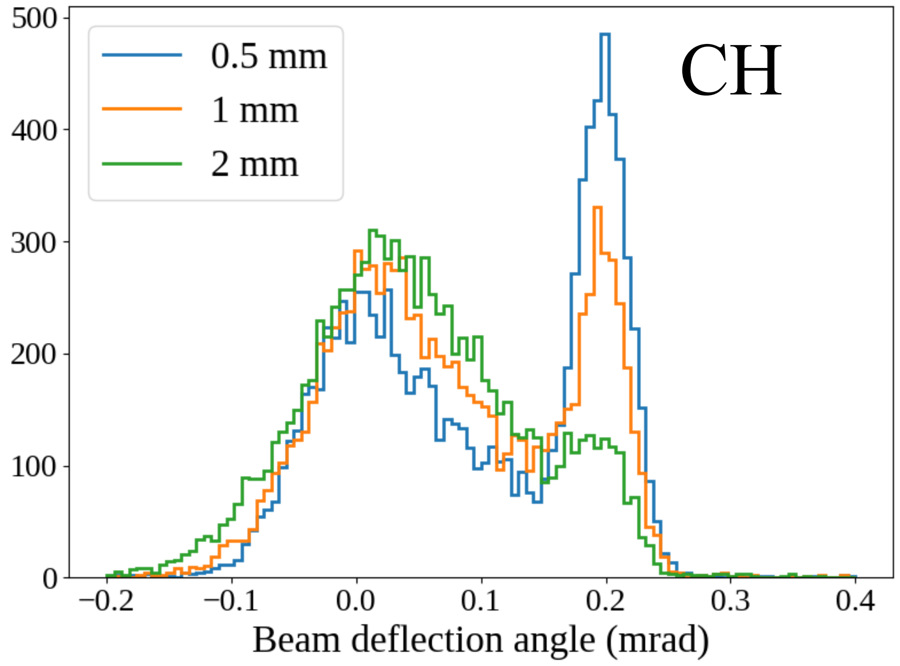


Situation around the Edge of the VR Acceptance



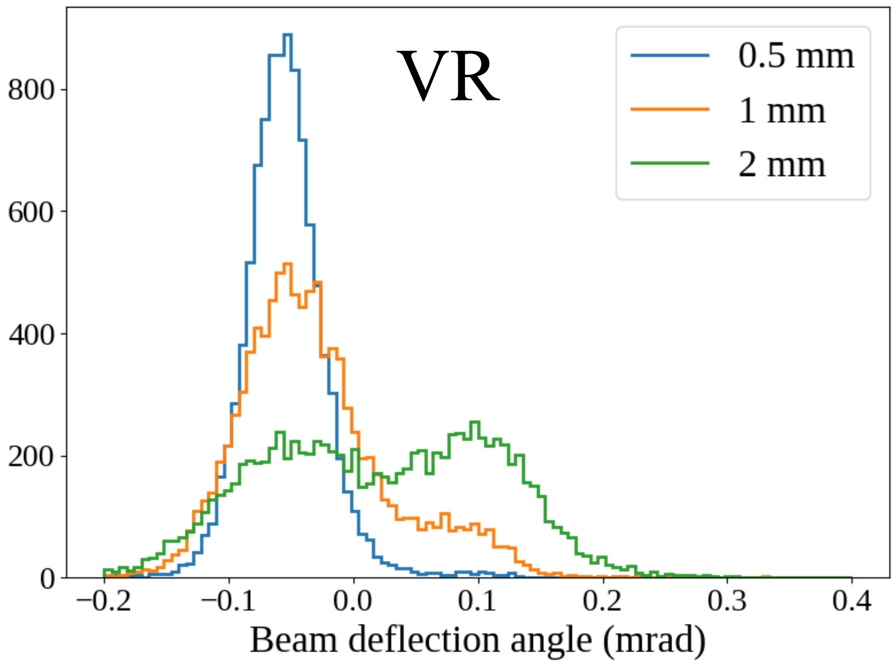
"Half-VR"

Deflection angle dependence on the length of the crystal



Shorter is better

(dechanneling rate is smaller)



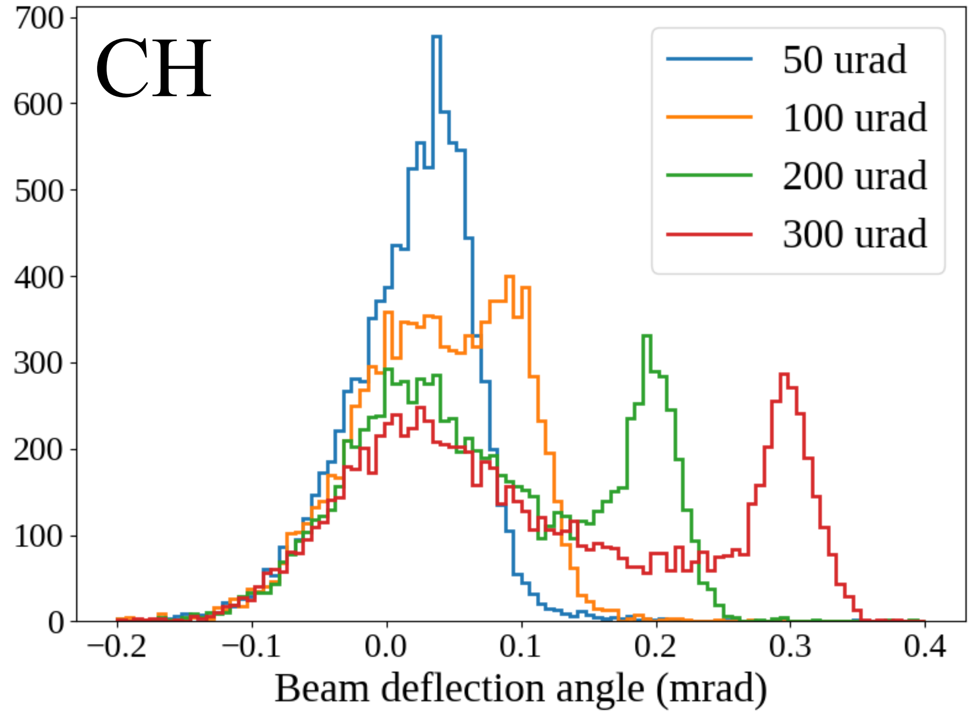
Shorter is better

(Angle spread
from Coulomb scattering
is smaller)

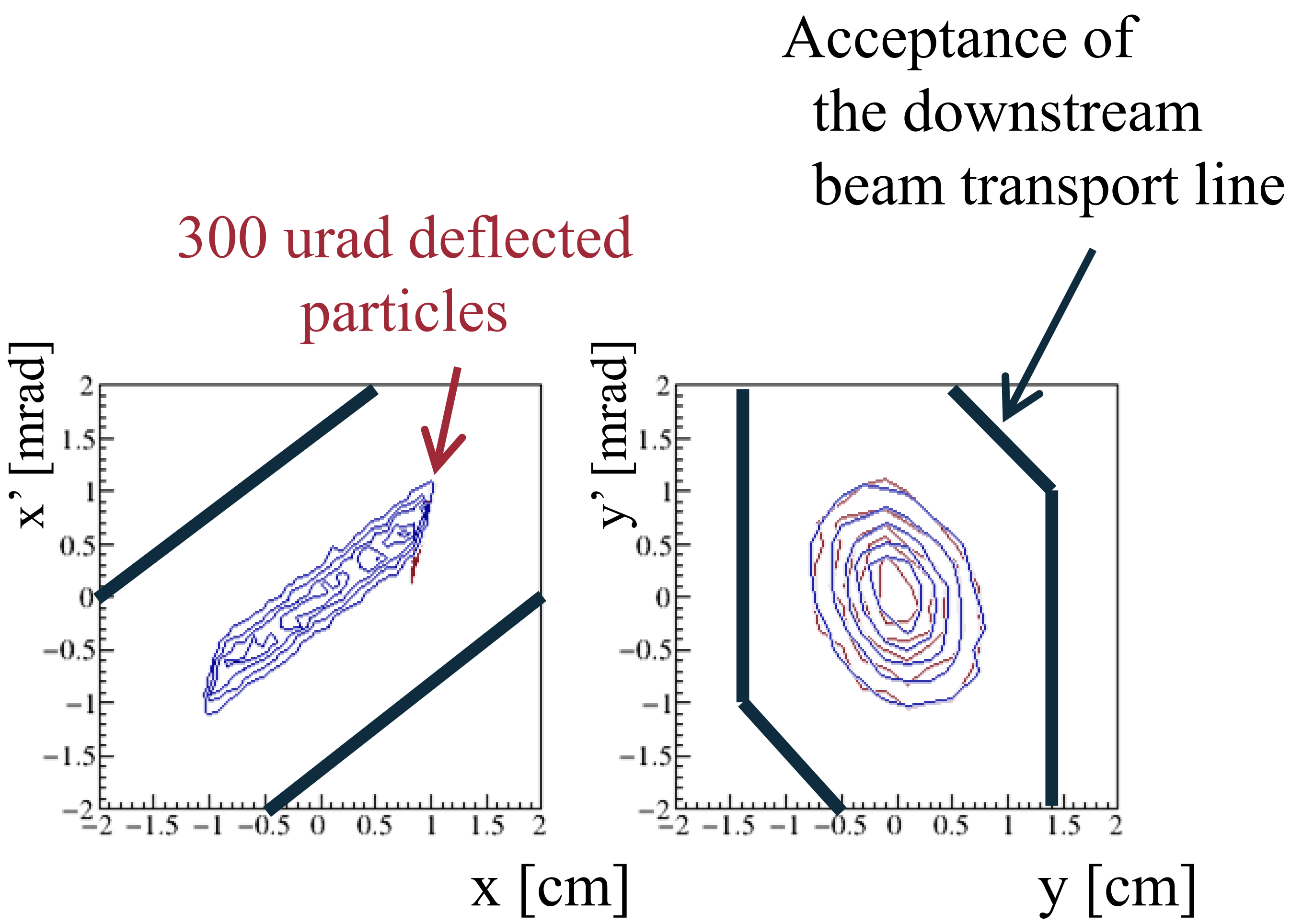
Whether CH or VR is used,
the crystal should be short.

→ We assume that we can manufacture the bent silicon crystal with 1 mm length.
(width = 0.2 mm)

Deflection Angle Dep. on the Bending Angle of the Crystal



Larger is better



Estimation of the Beam Loss Reduction

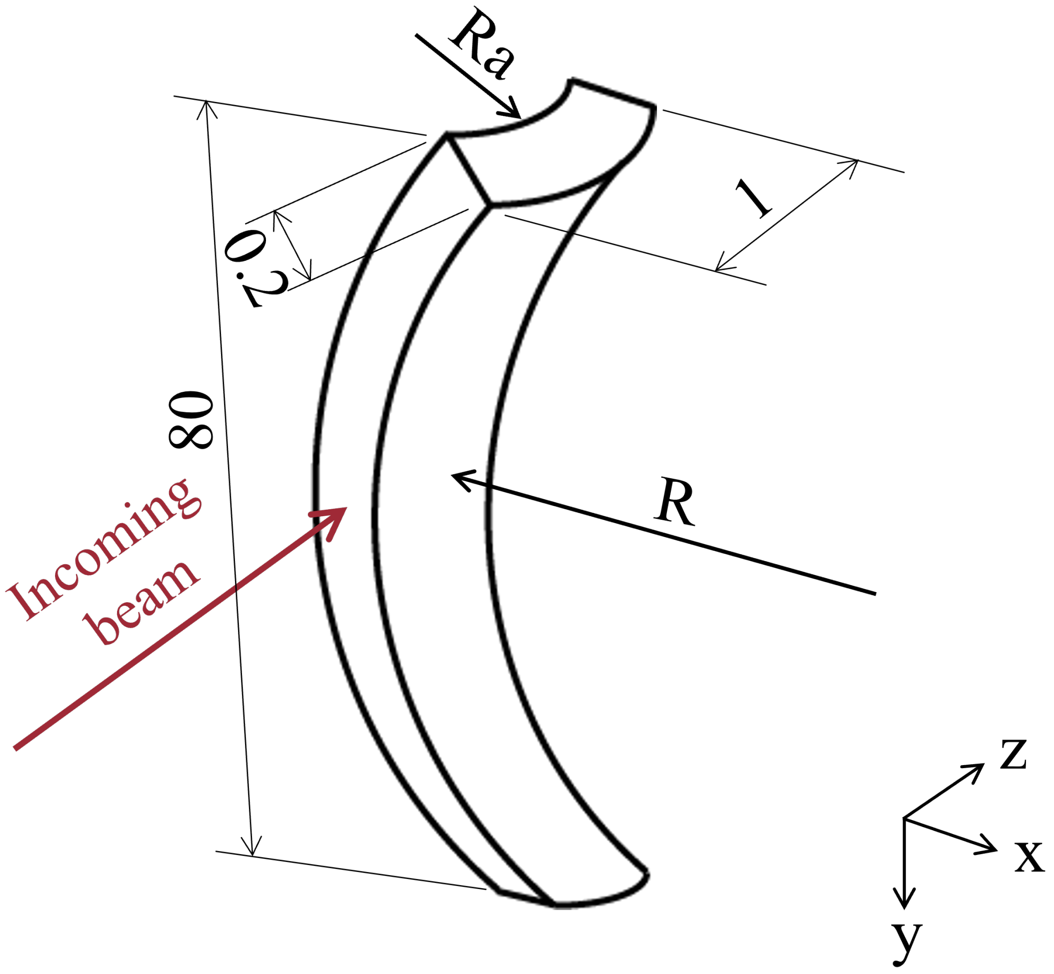
Bent Silicon Crystal Dimensions	
Longitudinal Length	1.0 mm
Bending Angle (for CH)	0.3 mrad
Width	0.2 mm

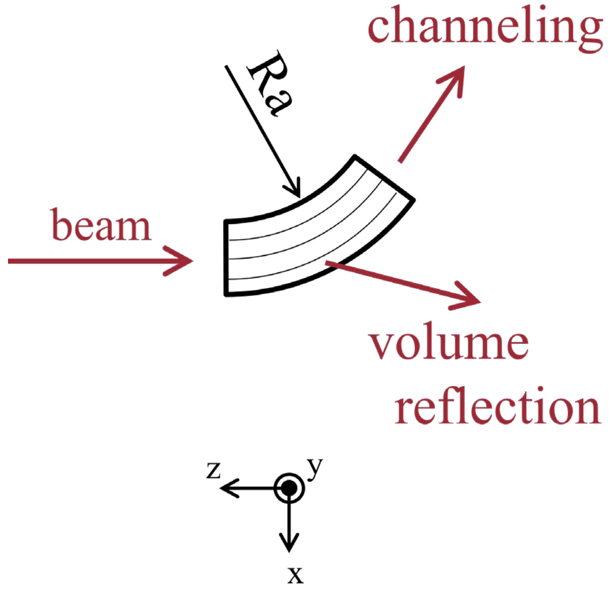
Beam Loss Estimated by FLUKA for 30 GeV proton

Configuration	Beam Loss
No mitigation	1.00
CH	0.48
VR	0.53
Half-VR	0.24

How to Bend Crystal

Anticlastic Deformation





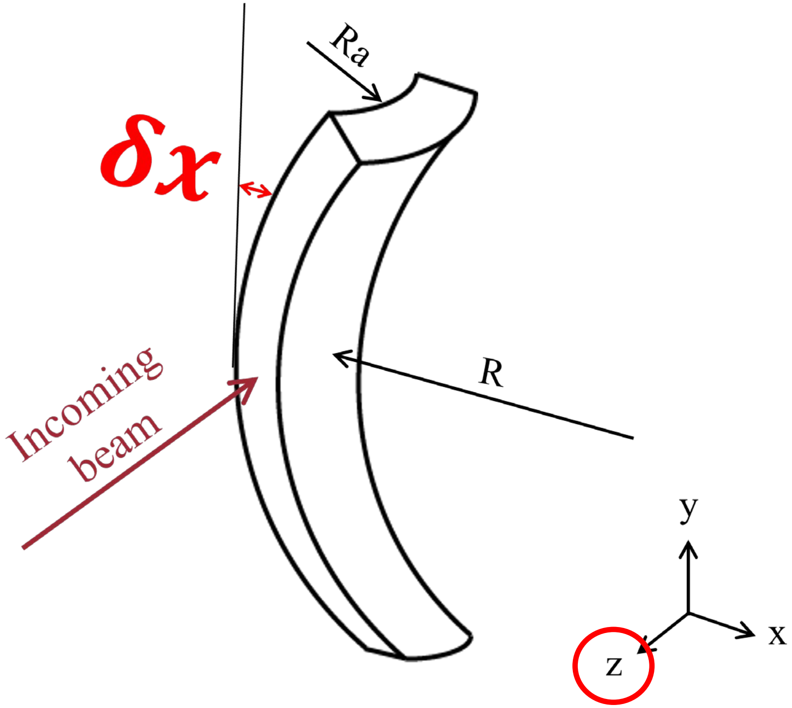
R is applied to produce Ra

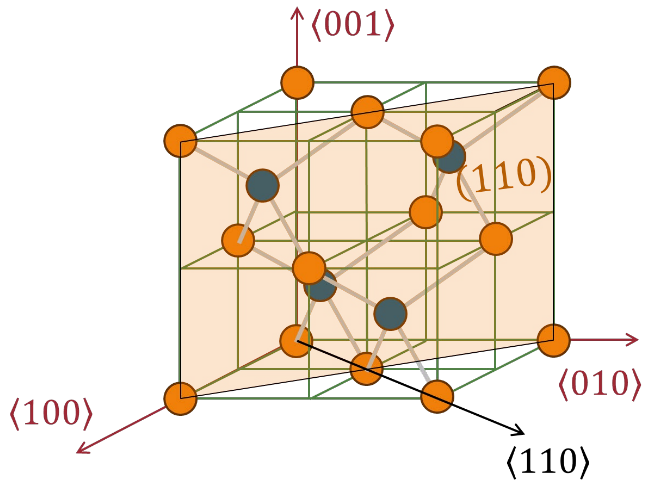
Crystal is anisotropic
→ Ra/R depends on the crystal orientation

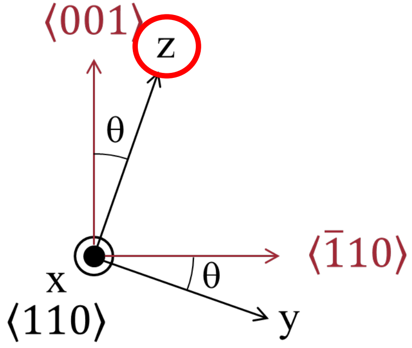
How to Bend Crystal

Vertical beam size is non-negligible
especially with 8 GeV beam

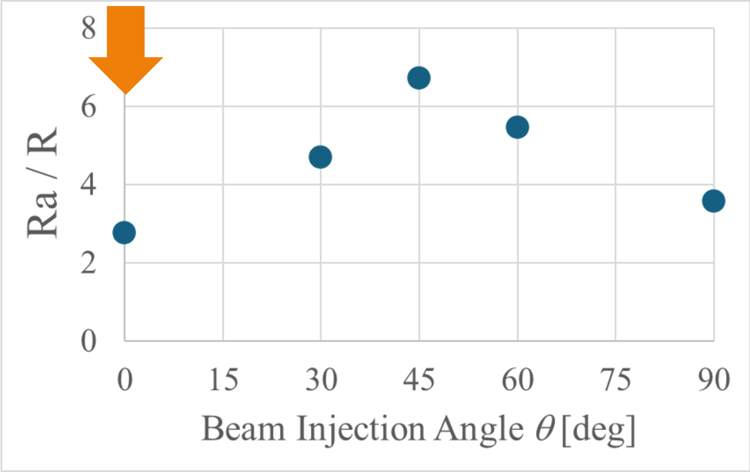
→Small δx is preferred
→ Large R is preferred
→ Small Ra/R is preferred







θ = 0 is preferred (Ra/R = 2.8)



← Ra/R = 3.6

estimation
using ANSYS (FEA)

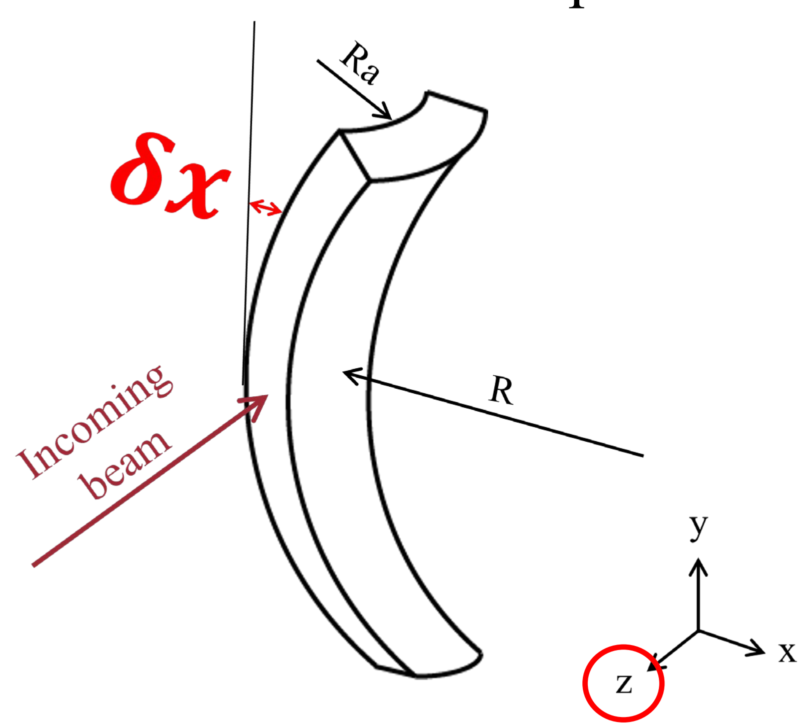
How to Bend Crystal

Vertical beam size is non-negligible especially with 8 GeV beam

→Small δx is preferred

→ Large R is preferred

→ Small Ra/R is preferred

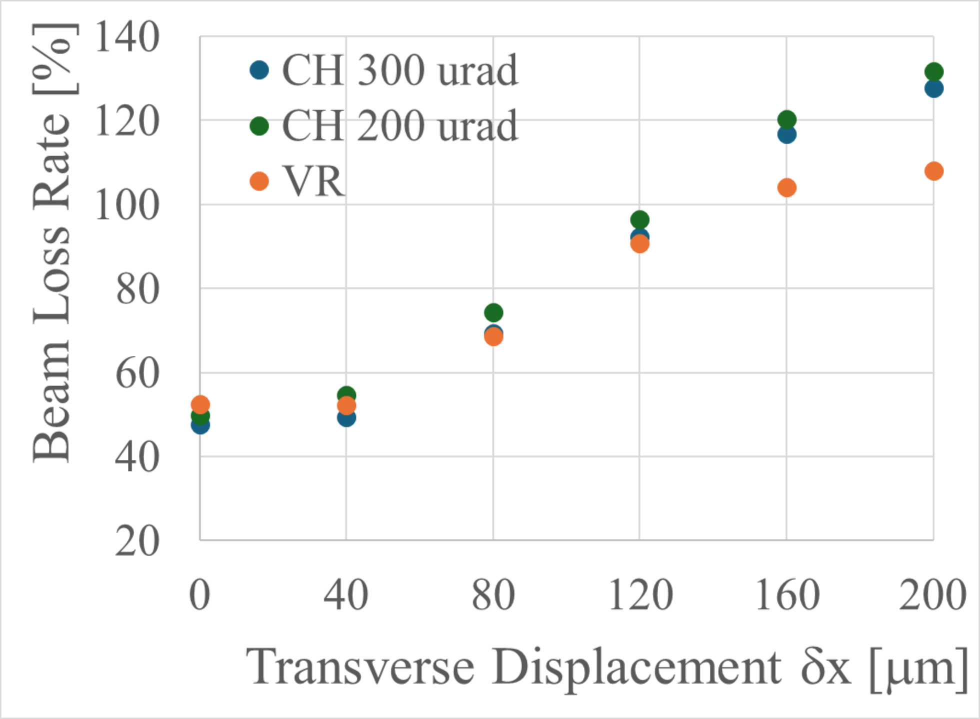


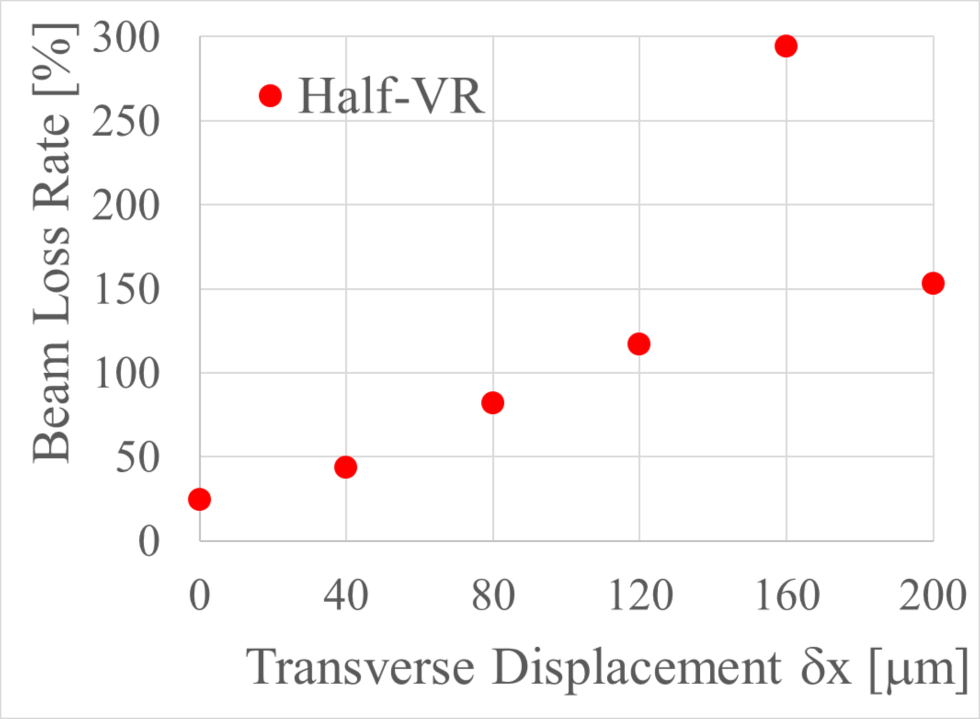
Vertical beam size (30 GeV):
~ 7 mm (1 RMS)

Bending angle	R [m]	δx for 1 RMS vertical pos	δx for 2 RMS vertical pos
300 urad	1.2	**40 um**	**160 um**
200 urad	1.8	**27 um**	**109 um**
100 urad	3.6	**14 um**	**54 um**

Crystal Width: 200 um

Effect of the δx





For **CH**, there is no large difference between bending angle of 200 urad and 300 urad.

→ **200 urad** is better because δx is smaller for the same vertical position

For **VR** and **Half-VR**, the bending angle only affects the acceptance, and **100 urad** is sufficient. (especially because Half-VR is very sensitive to δx)

Estimation of the Beam Loss Reduction

With a Gaussian beam profile in the y-direction, the beam loss rate for each δx(y) was multiplied to estimate the beam loss reduction effects.

Configuration	Bending Angle	Beam Loss
No mitigation	-	1.00
CH	200 μrad	0.50 → **0.57**
VR	100 μrad	0.53 → **0.54**
Half-VR	100 μrad	0.24 → **0.31**

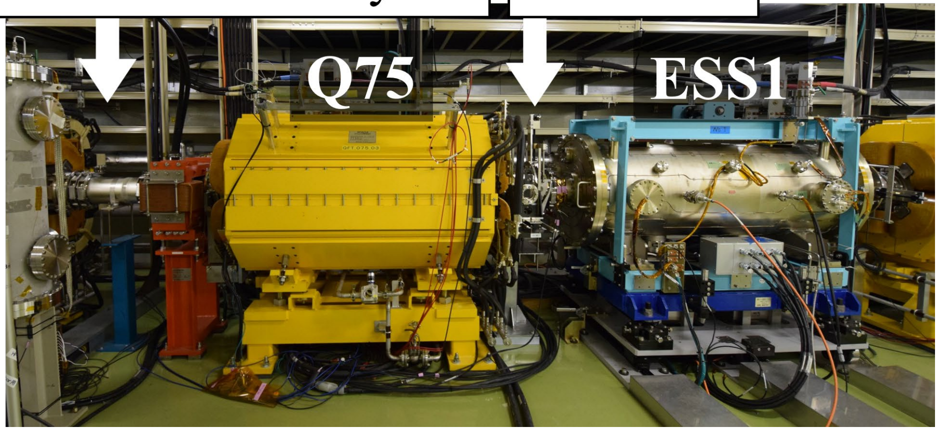
Estimation of the Beam Loss Reduction

With a Gaussian beam profile in the y-direction, the beam loss rate for each δx(y) was multiplied to estimate the beam loss reduction effects.

Configuration	Bending Angle	Beam Loss
No mitigation	-	1.00
CH	200 μrad	0.50 → **0.57**
VR	100 μrad	0.53 → **0.54**
Half-VR	100 μrad	0.24 → **0.31**
CH + diff 1	200 μrad	**0.27**
VR + diff 1	100 μrad	**0.26**
Half-VR + diff1	100 μrad	**0.20**

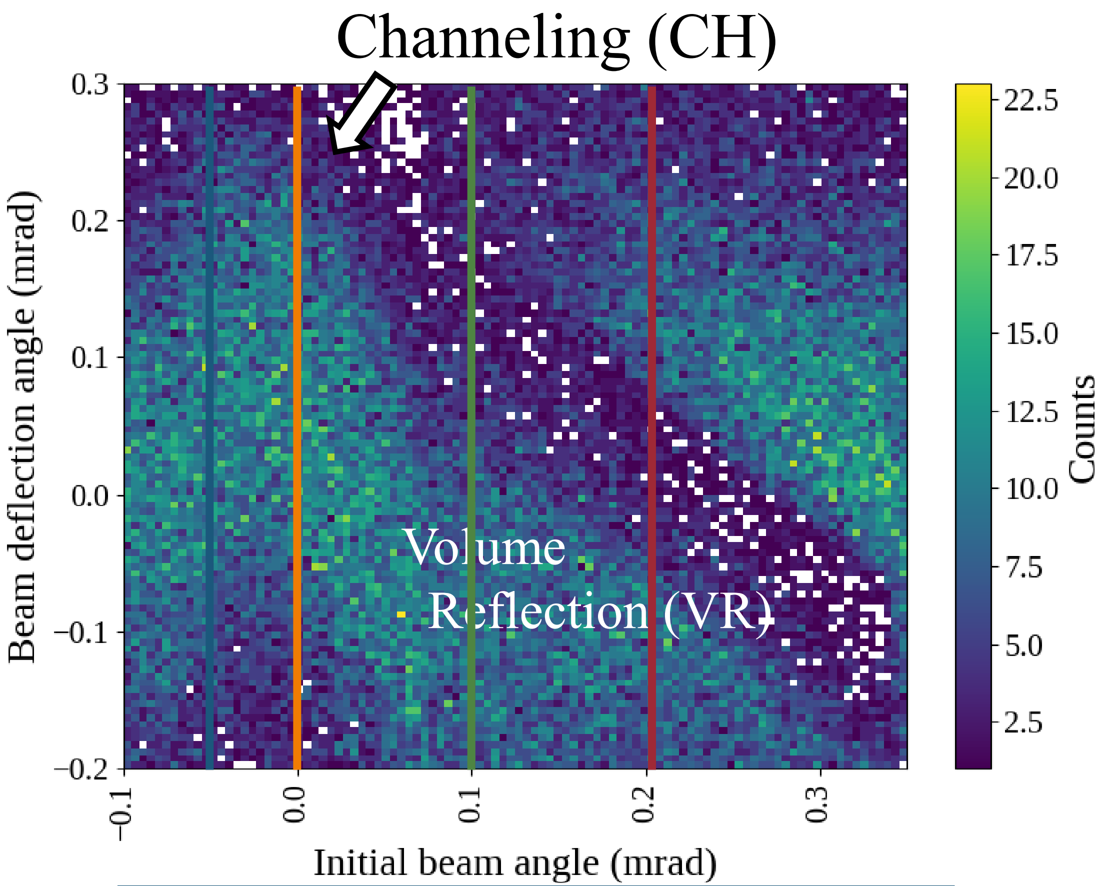
Diffuser 0
→ Bent Silicon Crystal

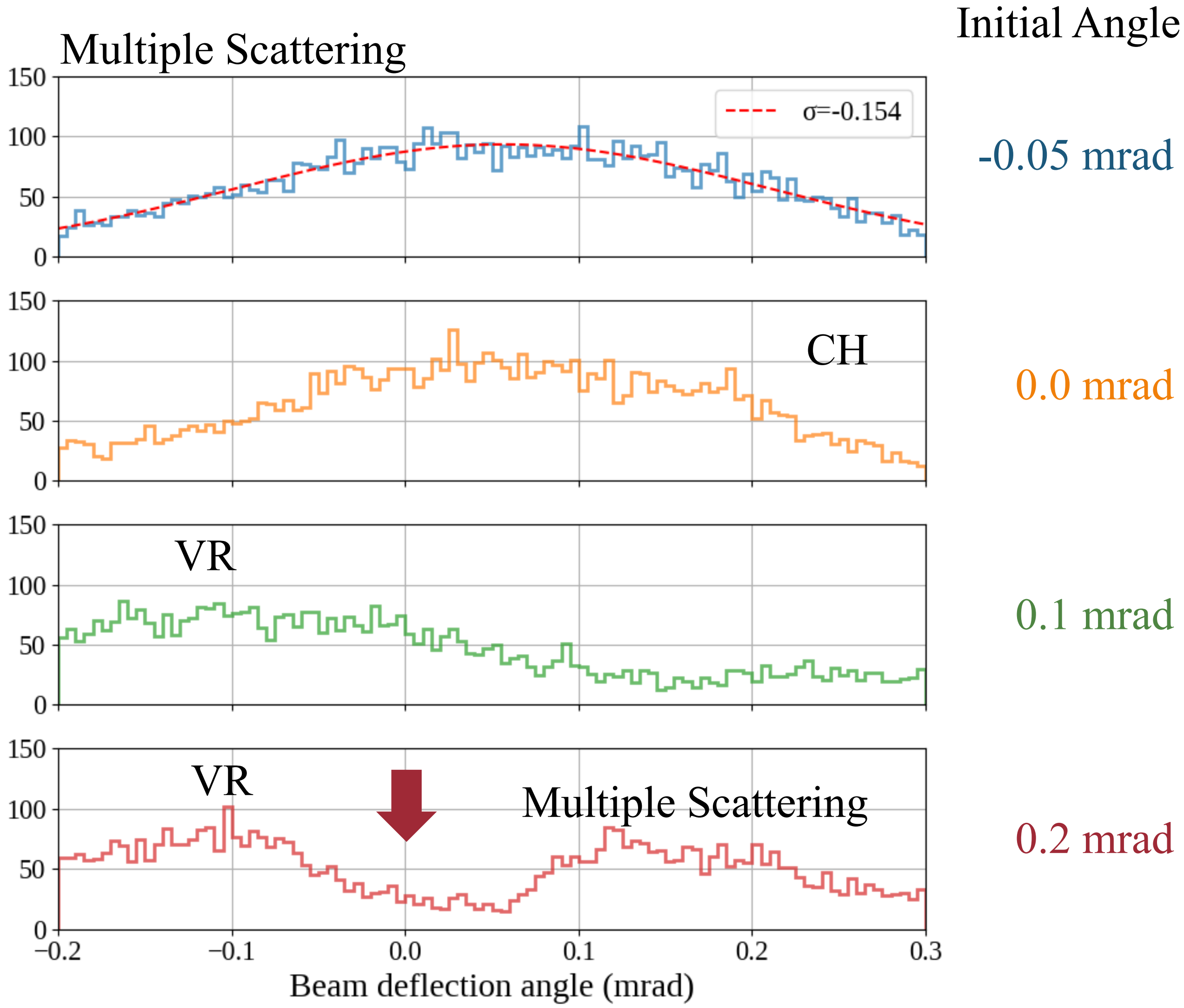
Diffuser 1



for 8 GeV Beam

FLUKA simulation for 8 GeV proton deflection by bent silicon crystal





Bent Silicon Crystal Dimensions	
Longitudinal Length	1.0 mm
Bending Angle	0.2 mrad

for 8 GeV Beam

Multiple scattering RMS angle by 1 mm length silicon

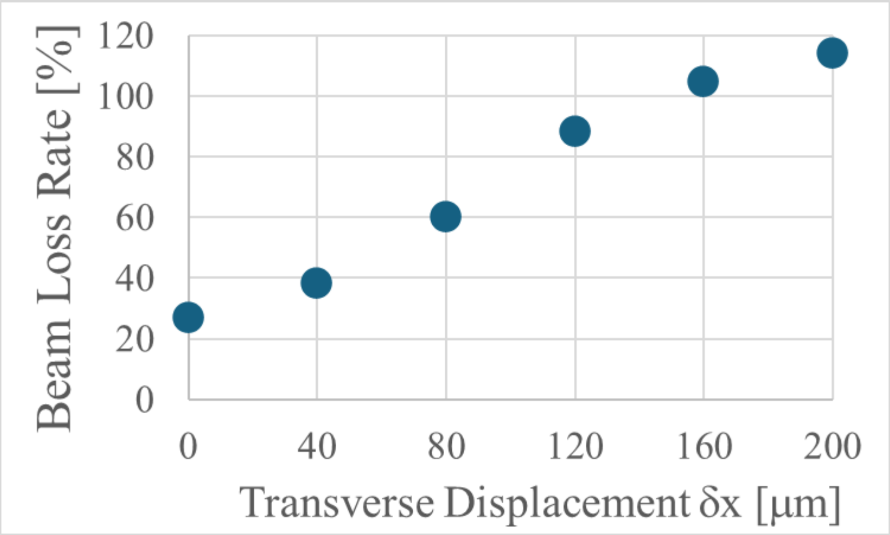
	8 GeV	30 GeV
Θ_{rms} [mrad]	**154**	44

for 8 GeV Beam

Multiple scattering RMS angle by 1 mm length silicon

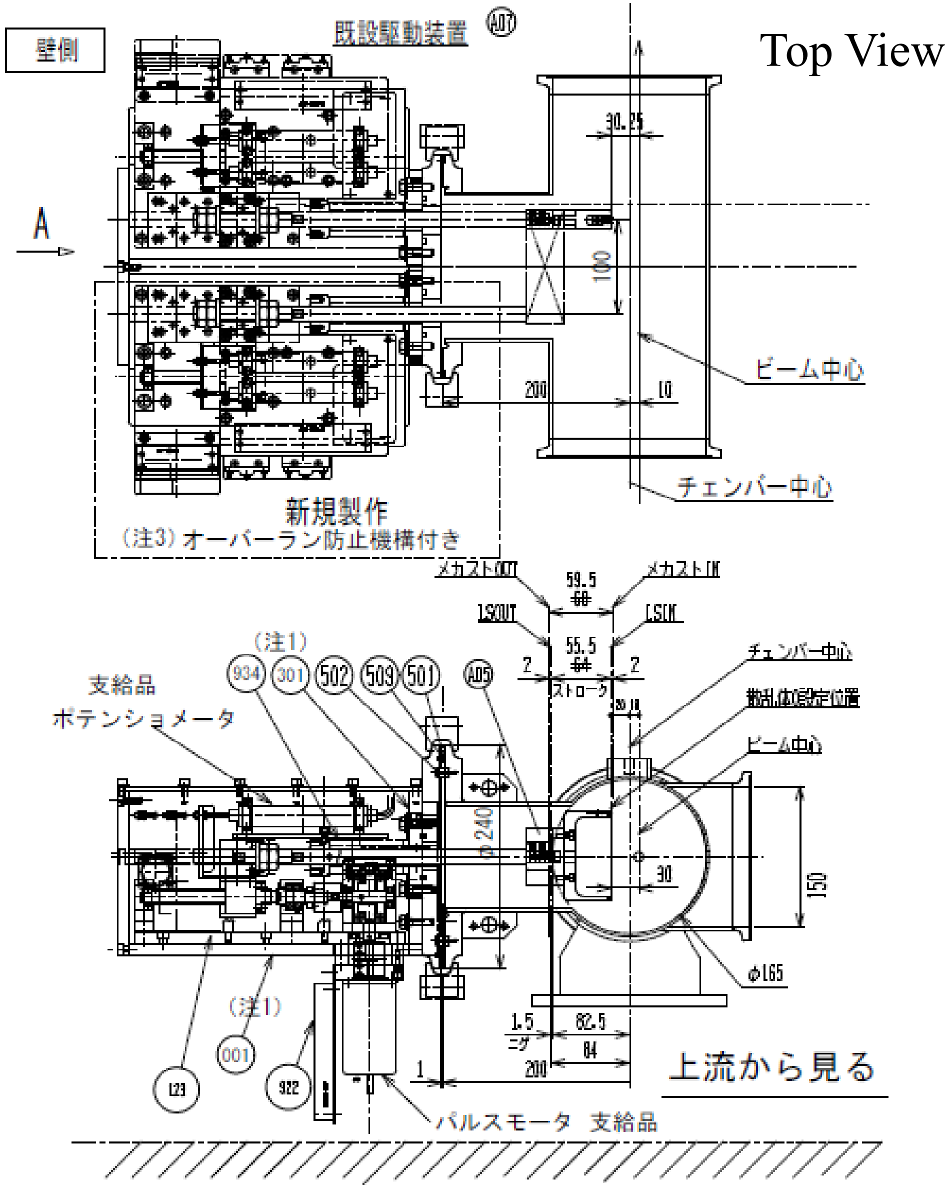
	8 GeV	30 GeV
Θ_{rms} [mrad]	**154**	44
Θ_{rms} for Diffuser 0 [mrad]	-	**166**

δx dependence of beam loss rate for VR with 100 urad bending angle



→Beam Loss Rate
~ 46% for VR
~ 34% for Half-VR

Goniometer for Crystal



Goniometer is now under fabrication

It has two axes for
insertion and angle adjustment of the crystal

The distance between the two axis is 100 mm
→ Angle resolution is < 10 urad

Summary

- J-PARC MR Slow Extraction currently operates with Diffuser 1
  beam power: ~92 kW, extraction efficiency: ~99.6%

- For higher extraction efficiency
  we are considering to replace Diffuser 0 with a bent silicon crystal

- Beam loss estimation was done

- Next step: crystal fabrication