Devices for High-Efficiency Slow Extraction at J-PARC Main Ring

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KEK / J-PARC

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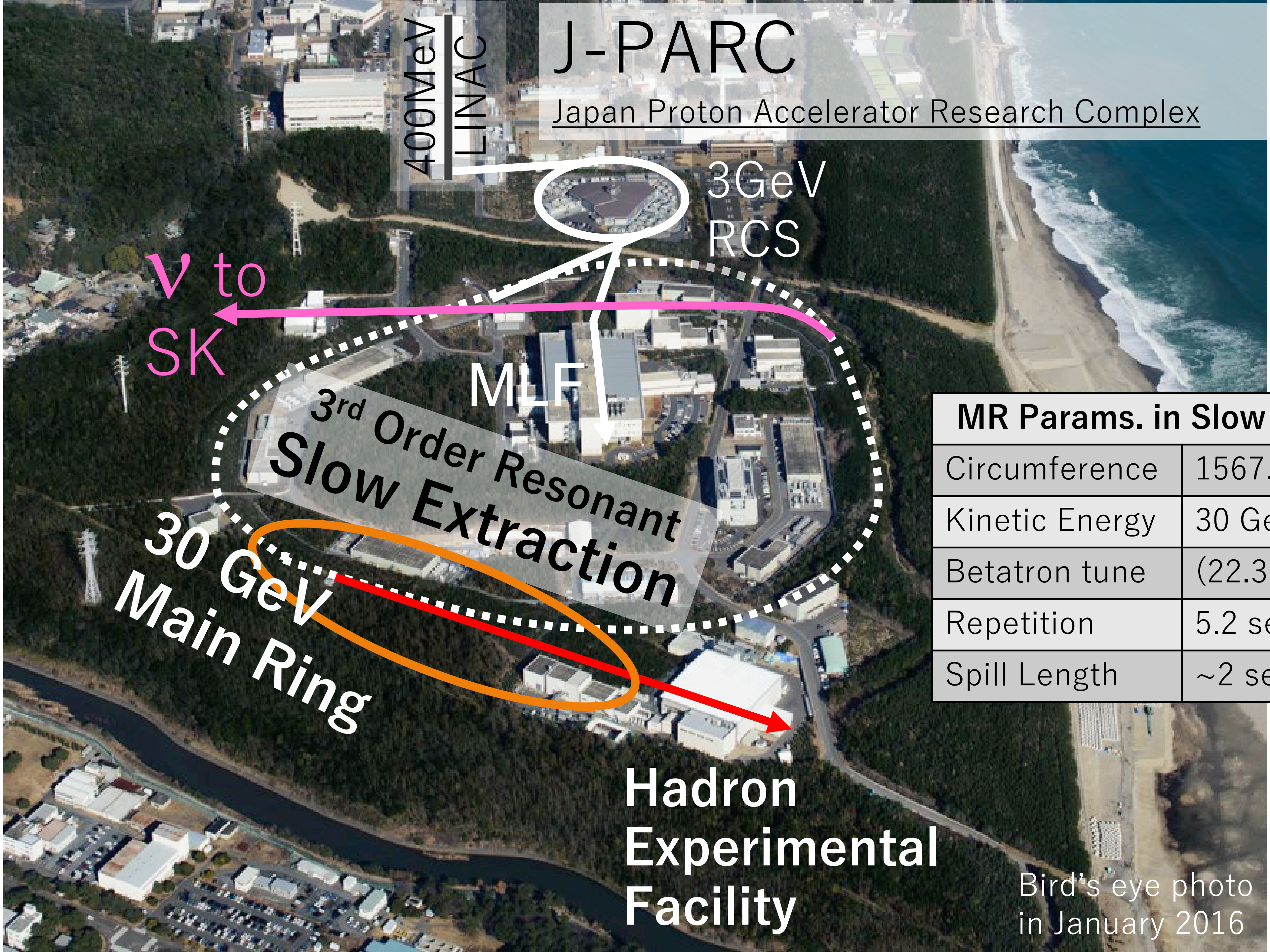
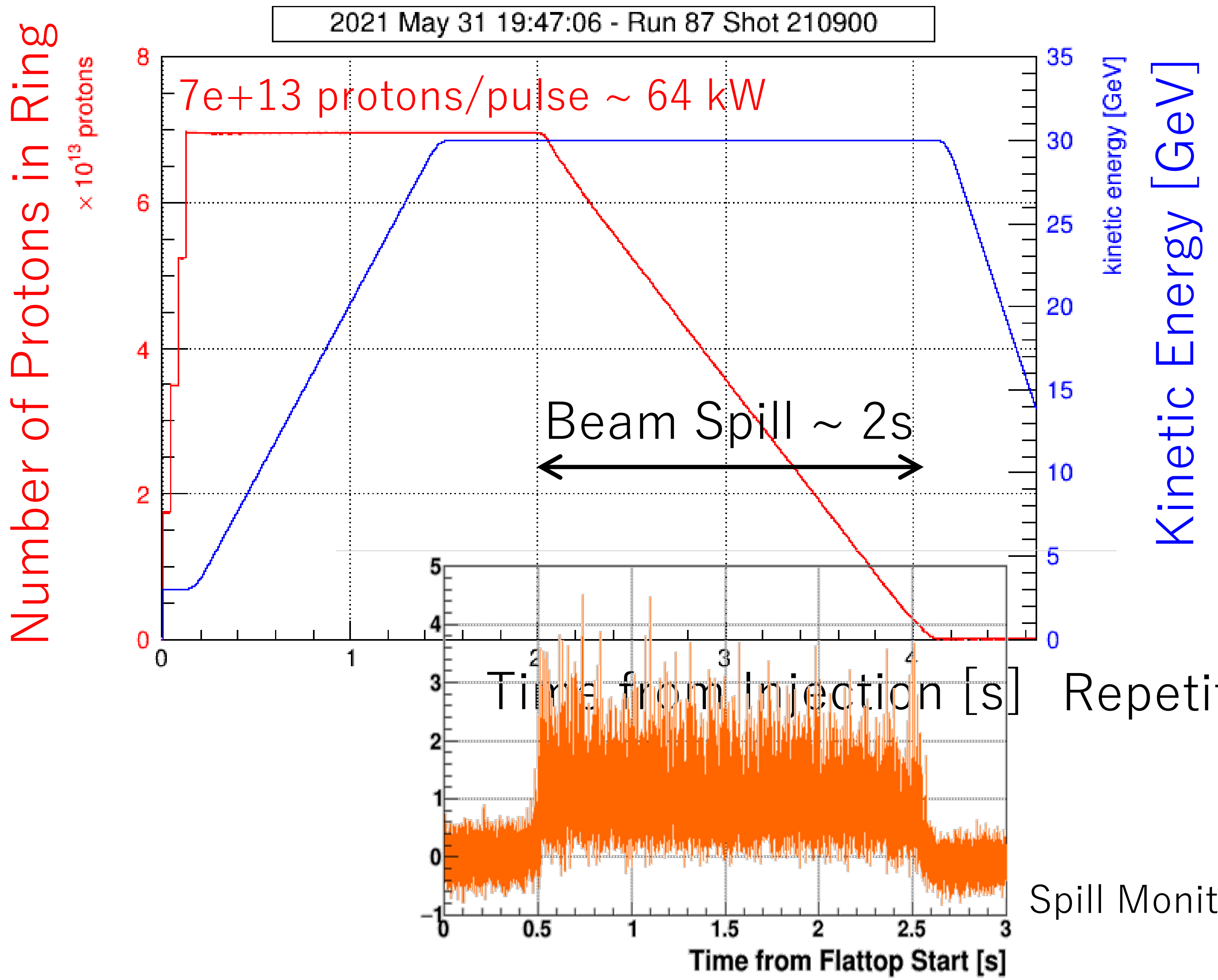
Outline

- Slow Extraction at J-PARC Main Ring
- Devices for Slow Extraction
  - Electrostatic Septum (ESS)
  - Beam Diffusers at the upstream of ESS
  - Beam Collimators at the downstream of ESS
- Future plans
- Summary



MR Params. in Slow Extraction	
Circumference	1567.5 m
Kinetic Energy	30 GeV
Betatron tune	(22.333, 20.78)
Repetition	5.2 sec
Spill Length	~2 sec

Slow extraction at J-PARC MR



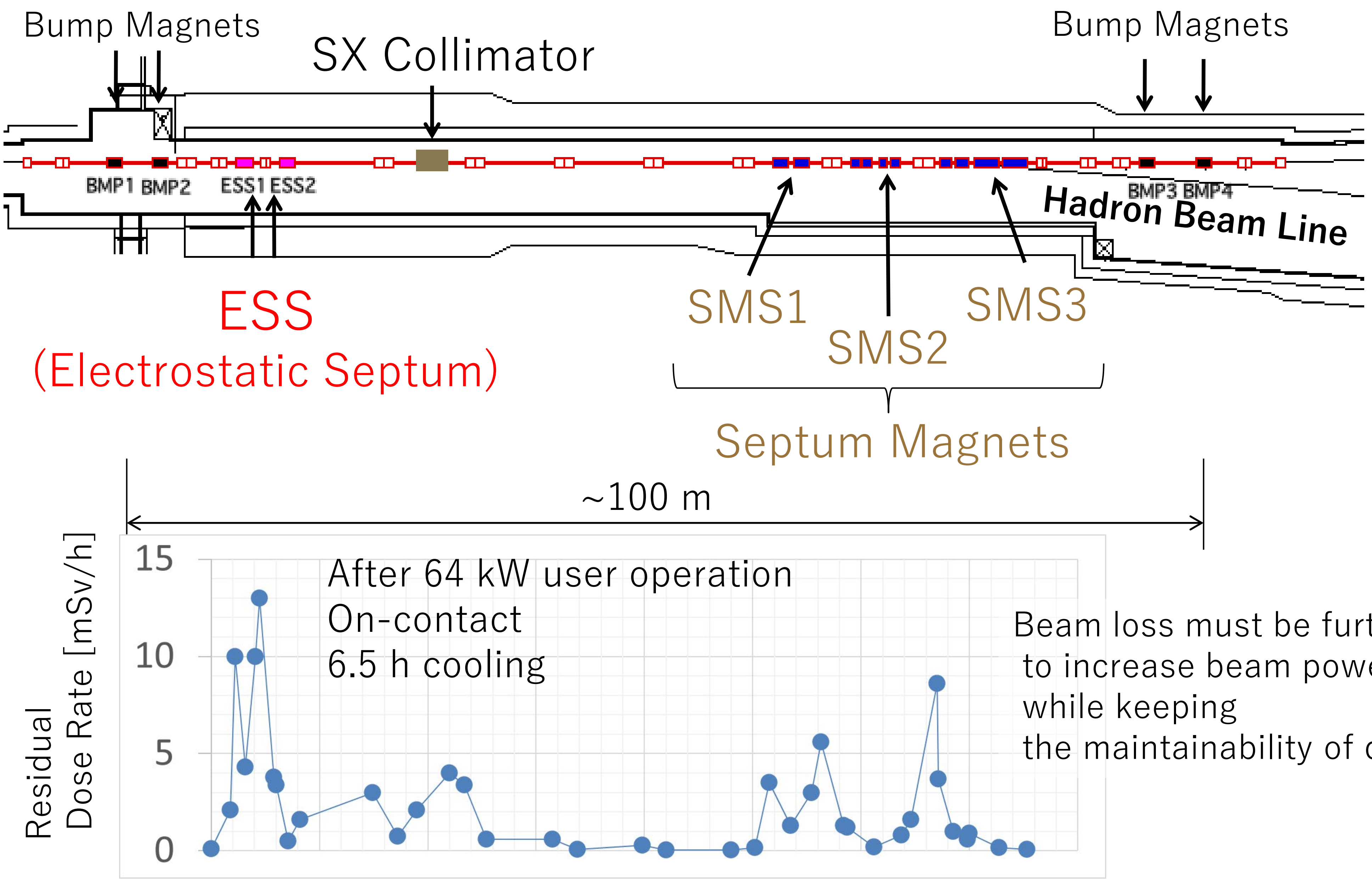
Spill Monitor Signal

Beam Power: 64 kW
Extraction Efficiency: ~99.5%

Users need more beam power

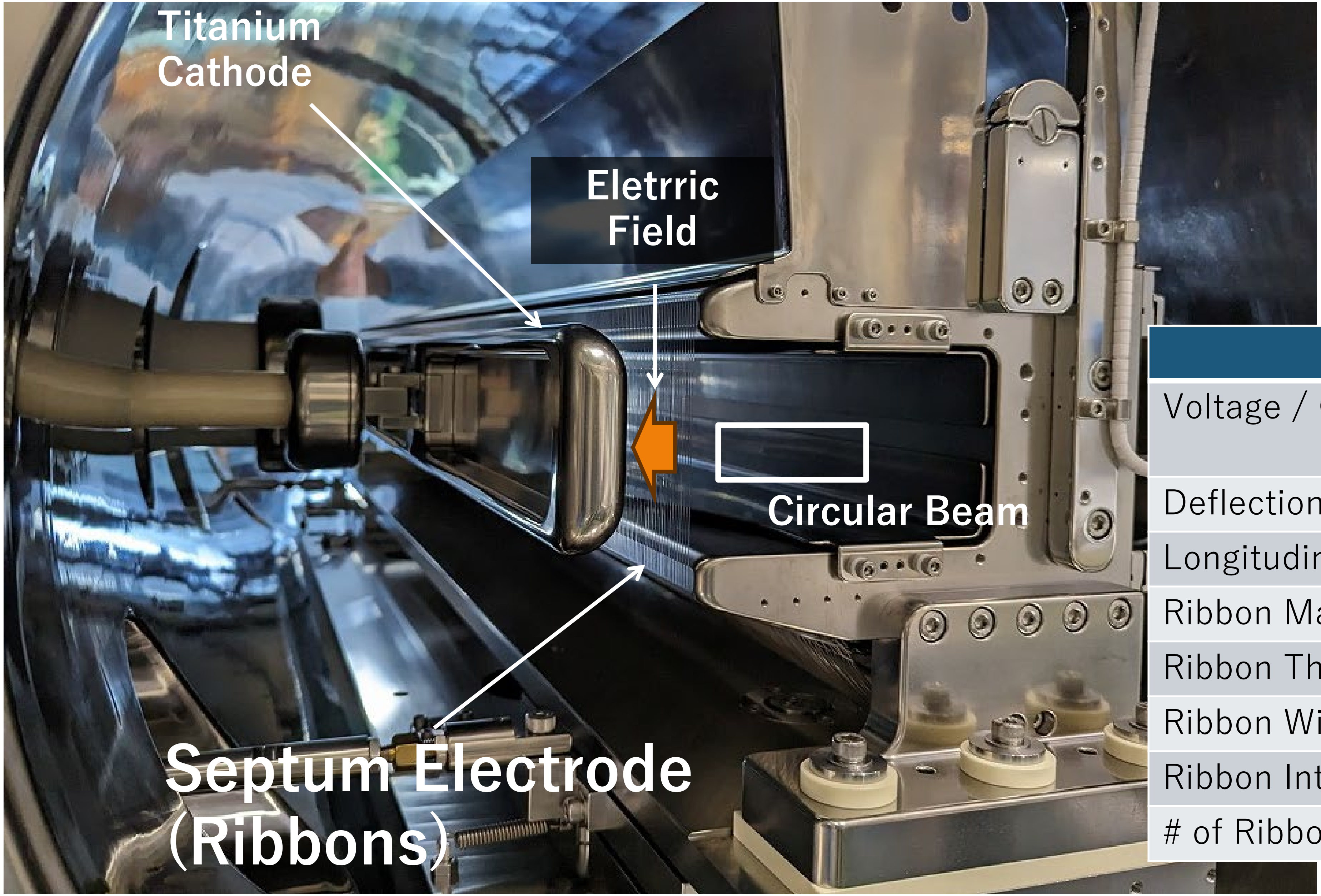
Repetition: 5.2 s

Straight Section for Slow Extraction



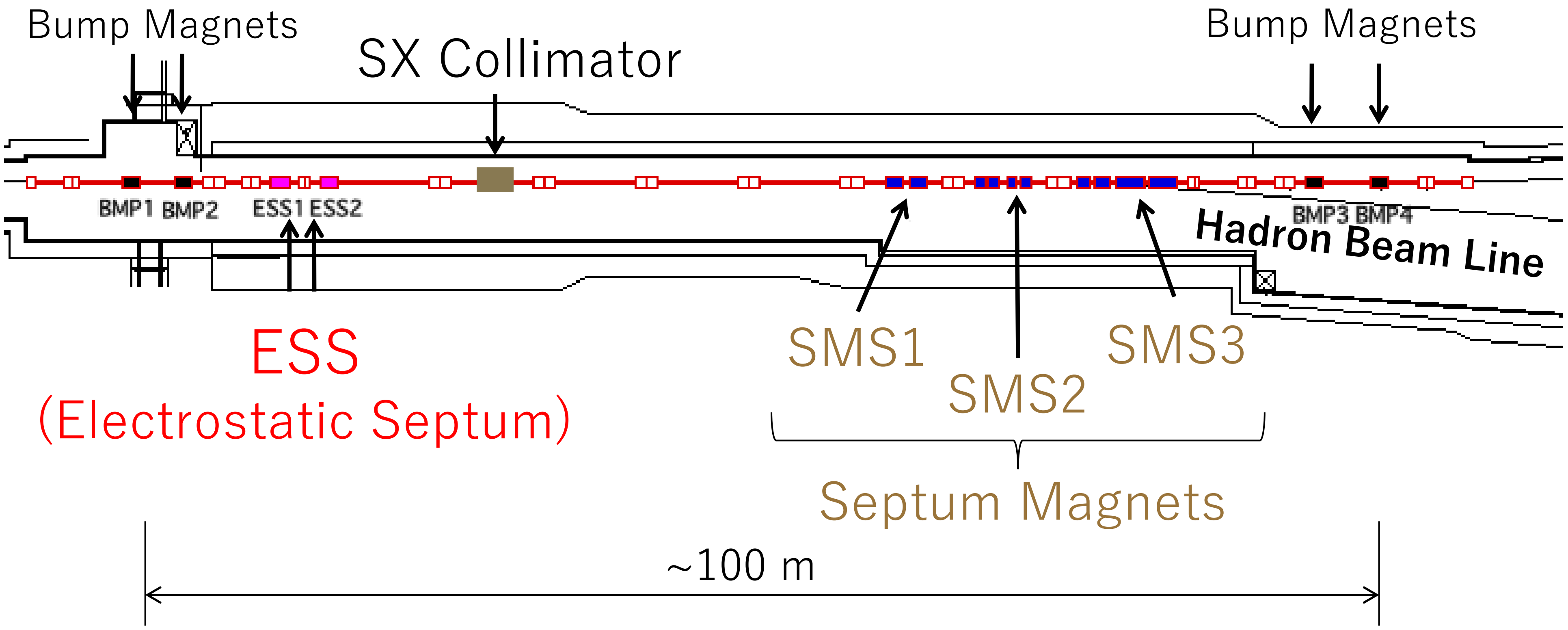
Beam loss must be further reduced to increase beam power while keeping the maintainability of devices.

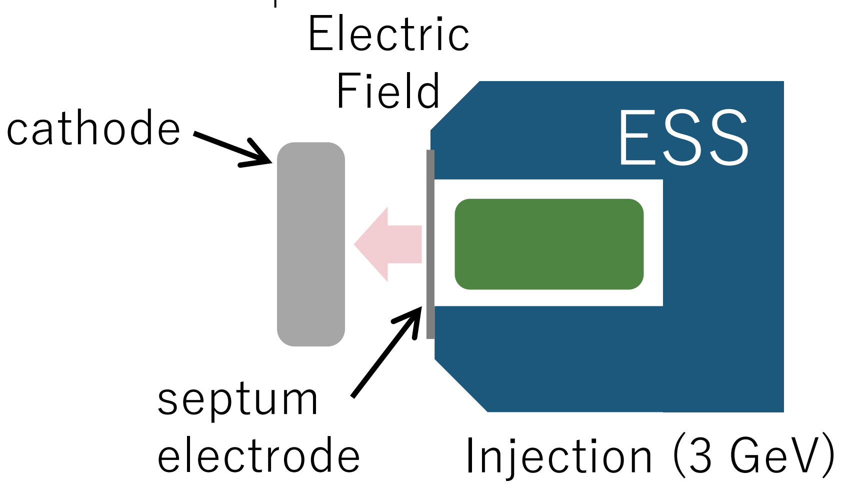
Electrostatic Septum (ESS)



	ESS1,2
Voltage / Gap	104 kV / 25 mm = 4.2 MV/m
Deflection Angle	- 0.2 mrad
Longitudinal Length	1.5 m
Ribbon Material	W-26 Re
Ribbon Thickness	30 μm
Ribbon Width	1 mm
Ribbon Interval	3 mm
# of Ribbons	495

Straight Section for Slow Extraction





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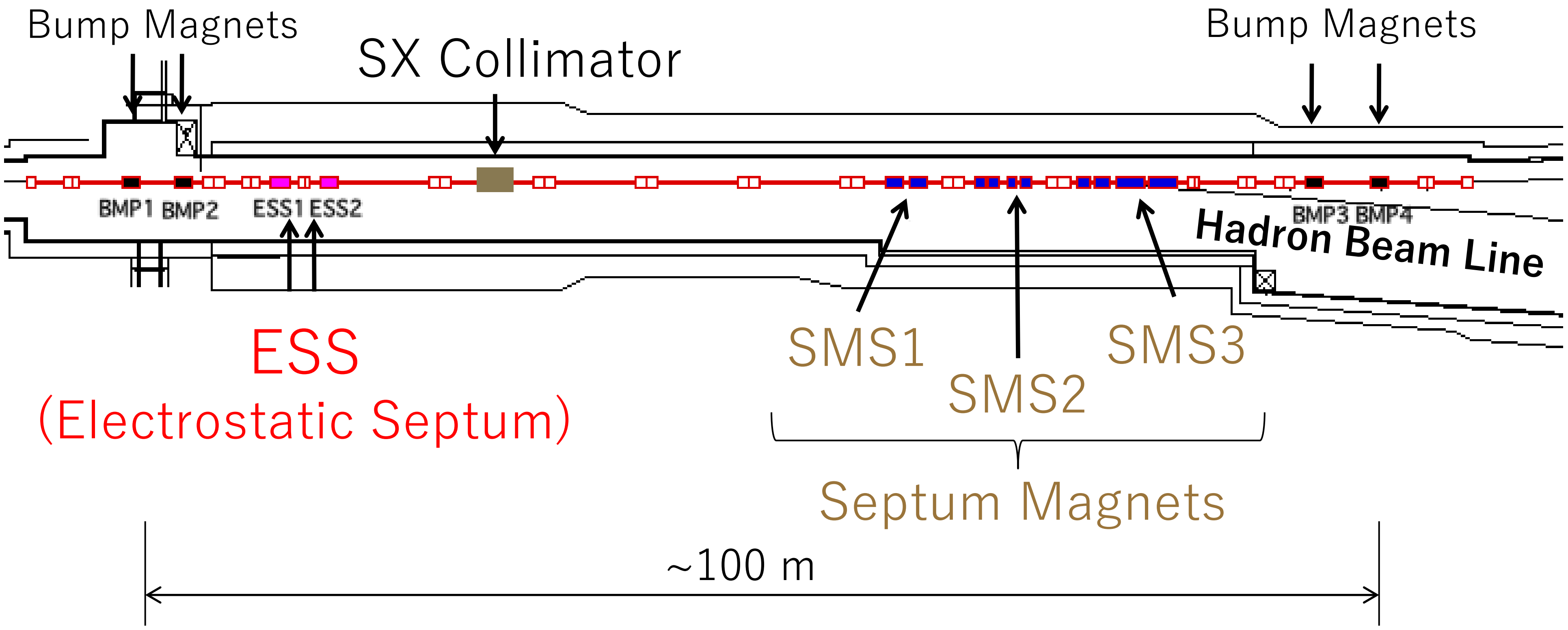

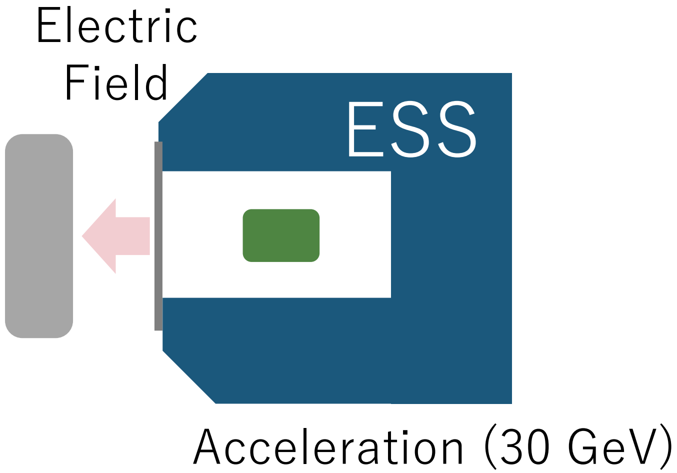

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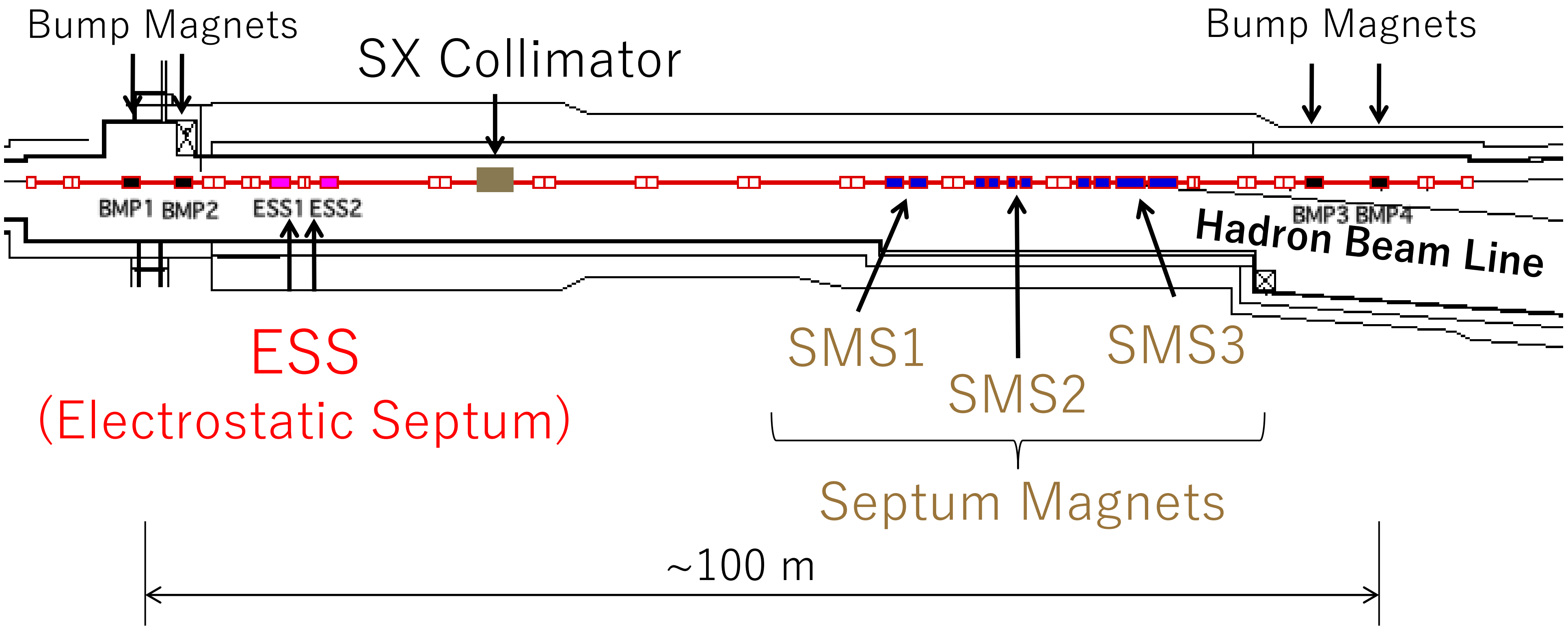

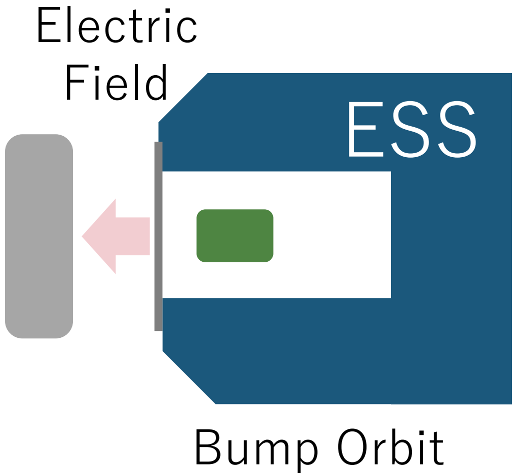

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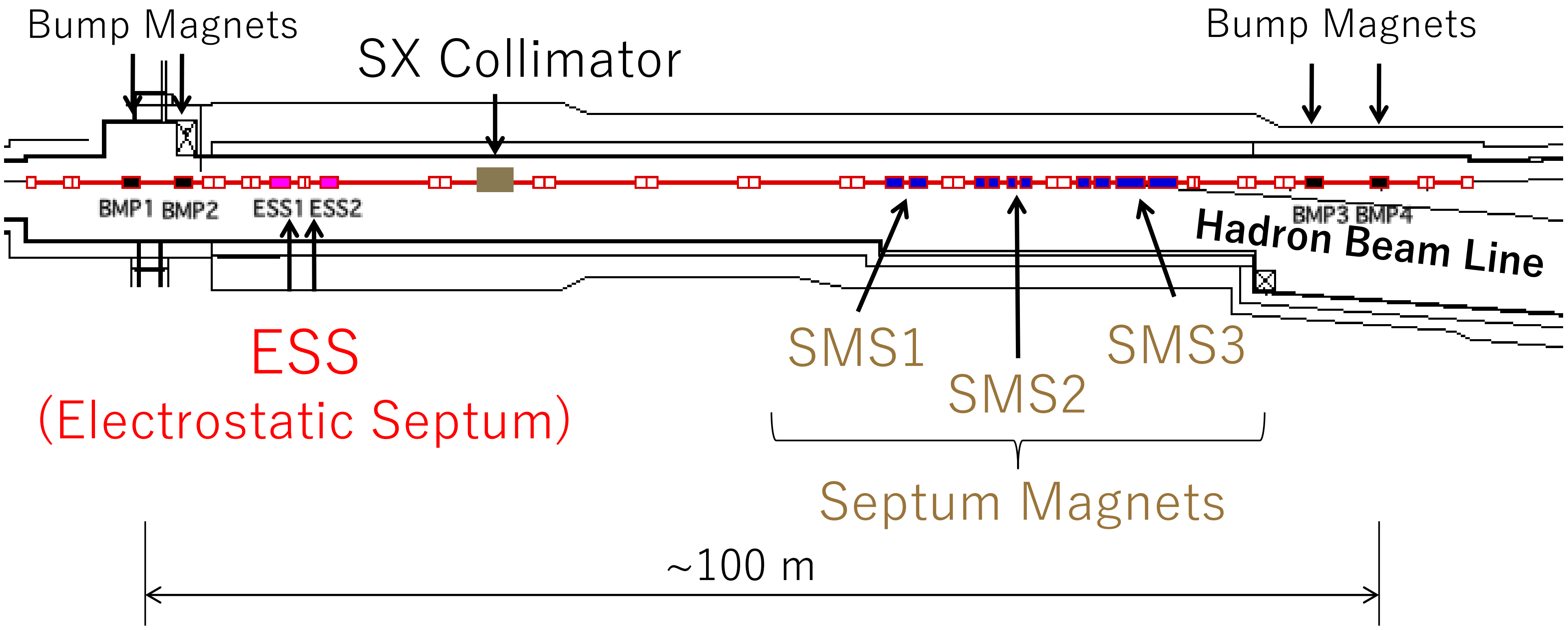
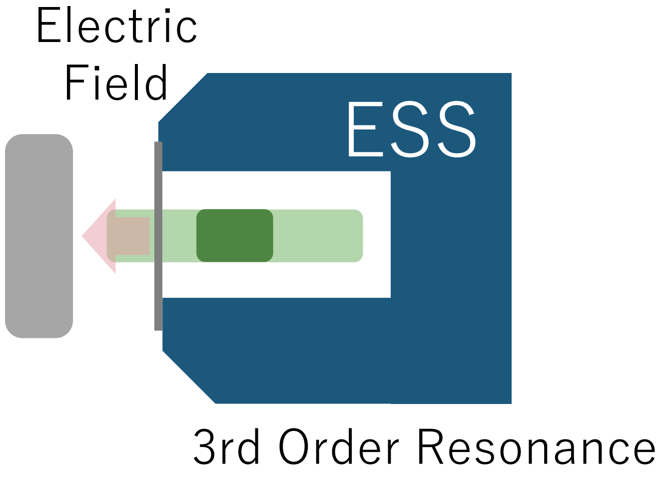


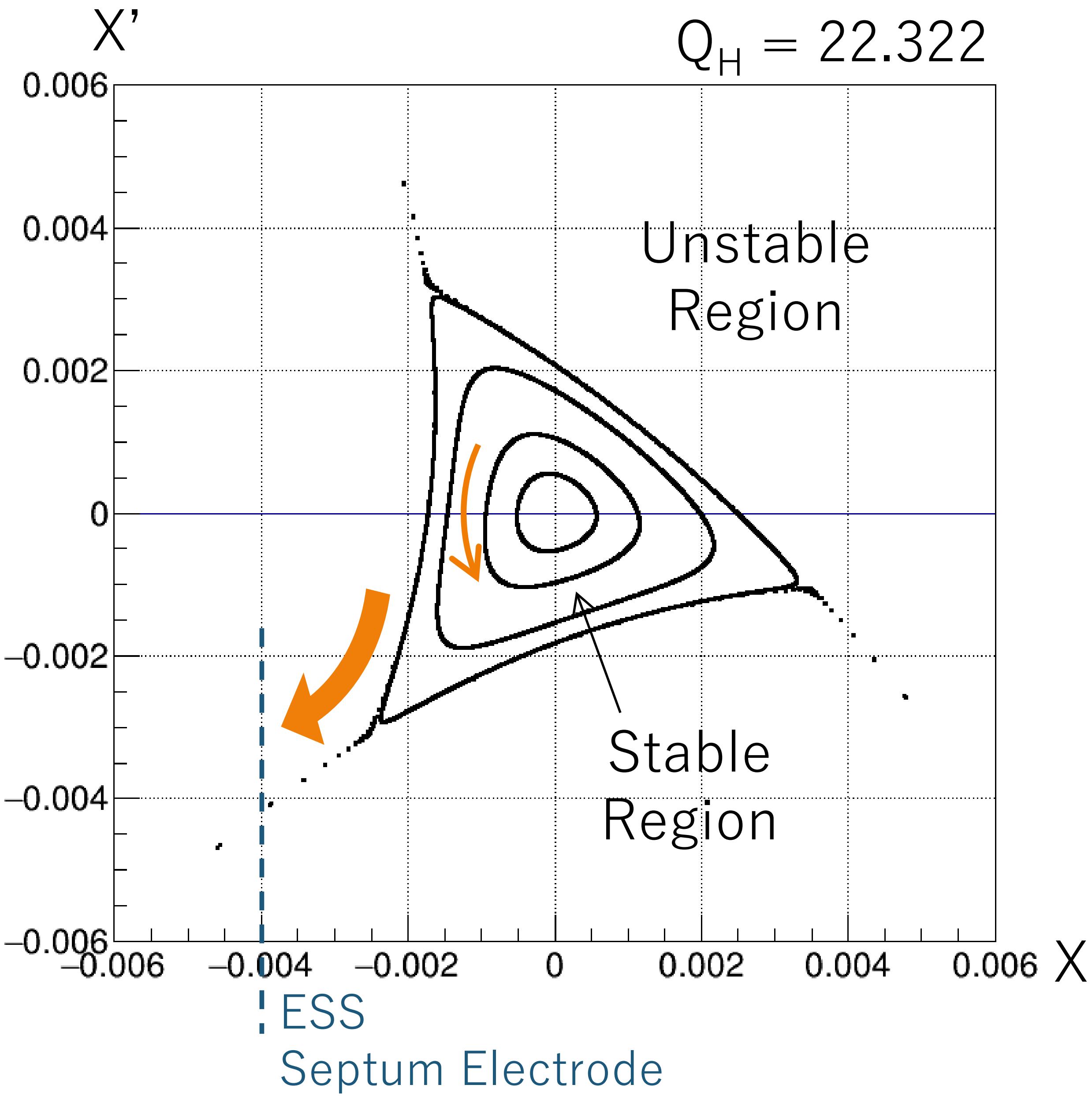


Beam loss at the septum electrode is inevitable

- How to reduce the beam loss at ESS
- How to localize the radioactivation

are the main issues in the slow extraction

Particle motion with third order resonance

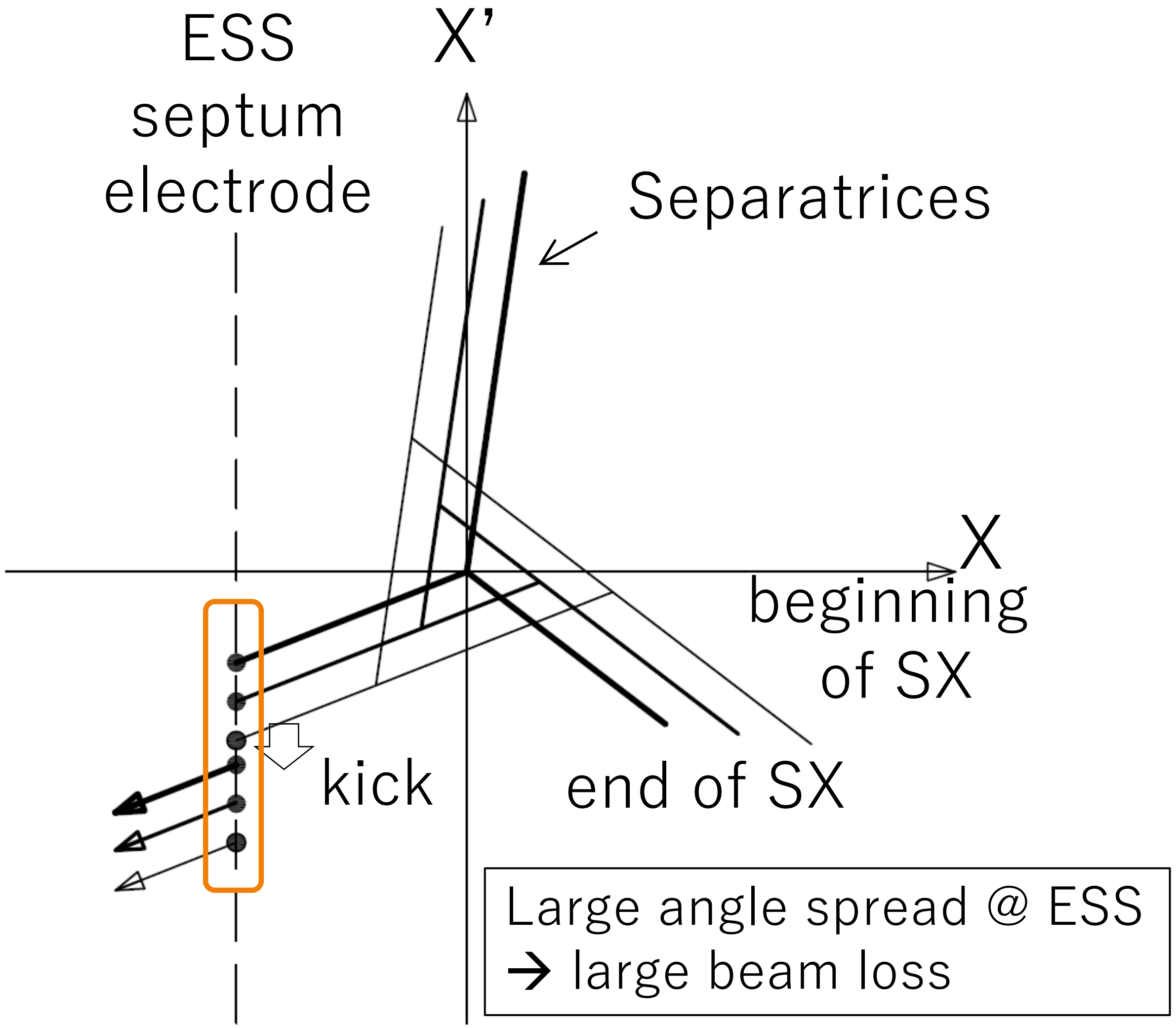


3rd order resonance is excited using 8 sextupole magnets distributed in the MR

Phase space is separated into stable and unstable regions

Particles in the unstable region increase their amplitude and are finally kicked by the ESS.

Dynamic Bump Scheme



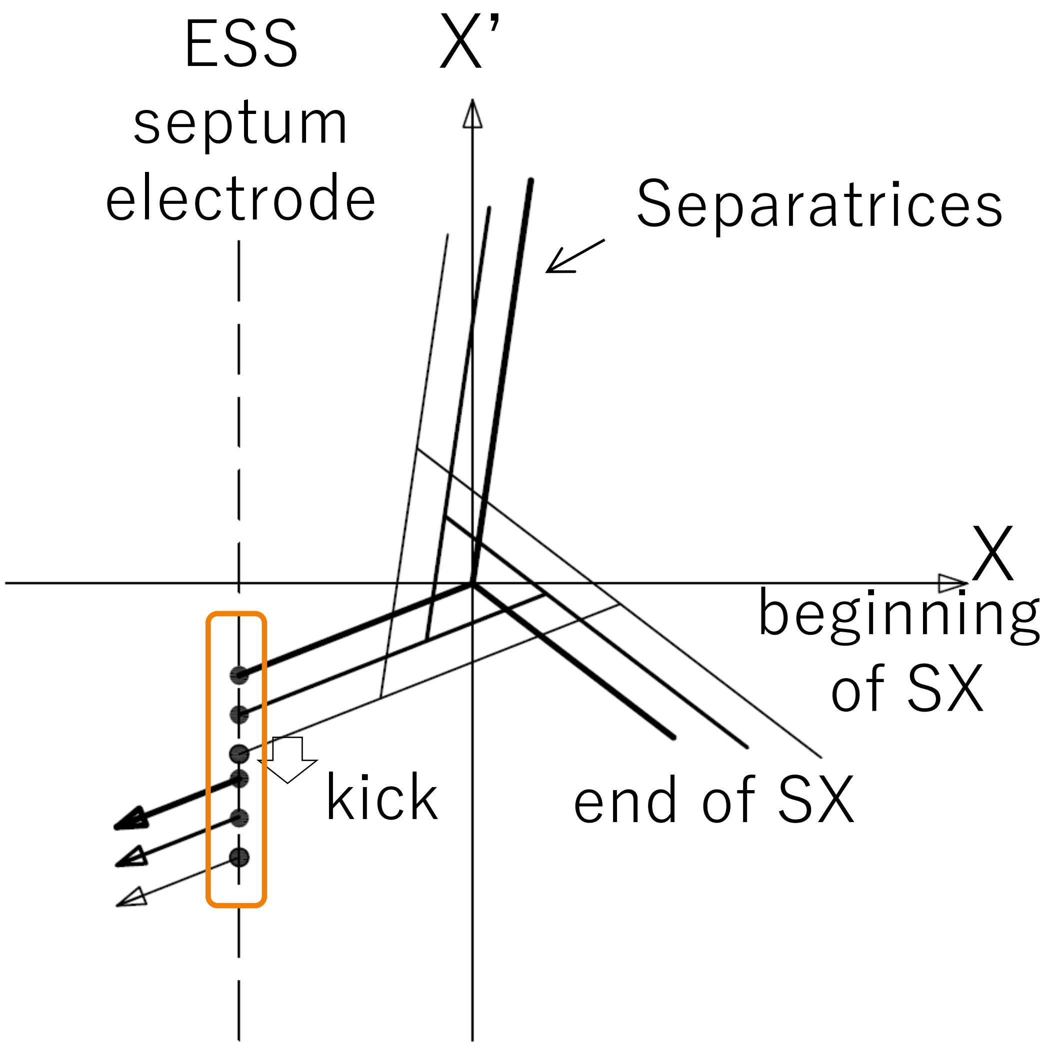
Fixed Bump

We gradually ramp
the horizontal betatron tune
closer to 22.333
and reduce the stable area

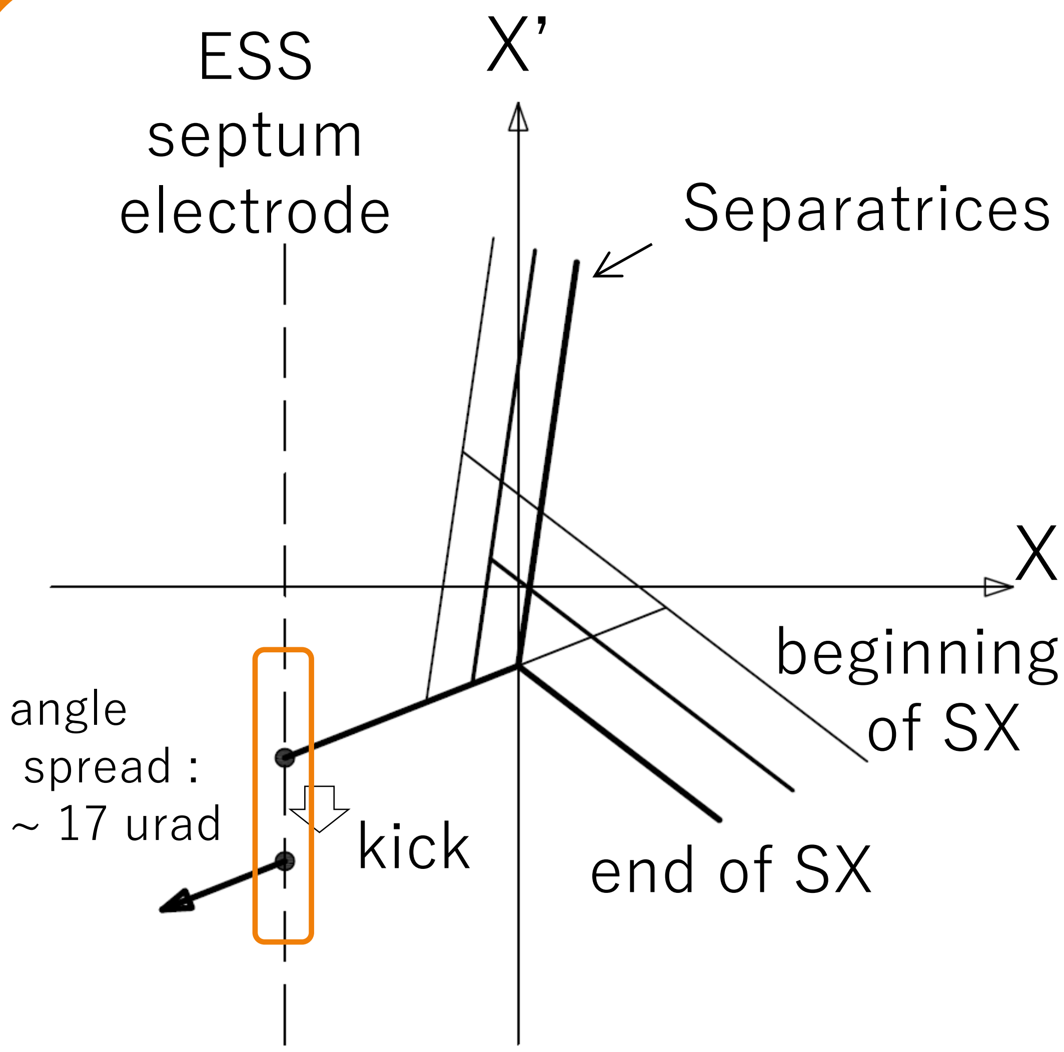
If the bump orbit remains fixed,
the particles have a large angle spread
when they reach the septum electrode.

This causes large beam loss
at the septum electrode.

Dynamic Bump Scheme



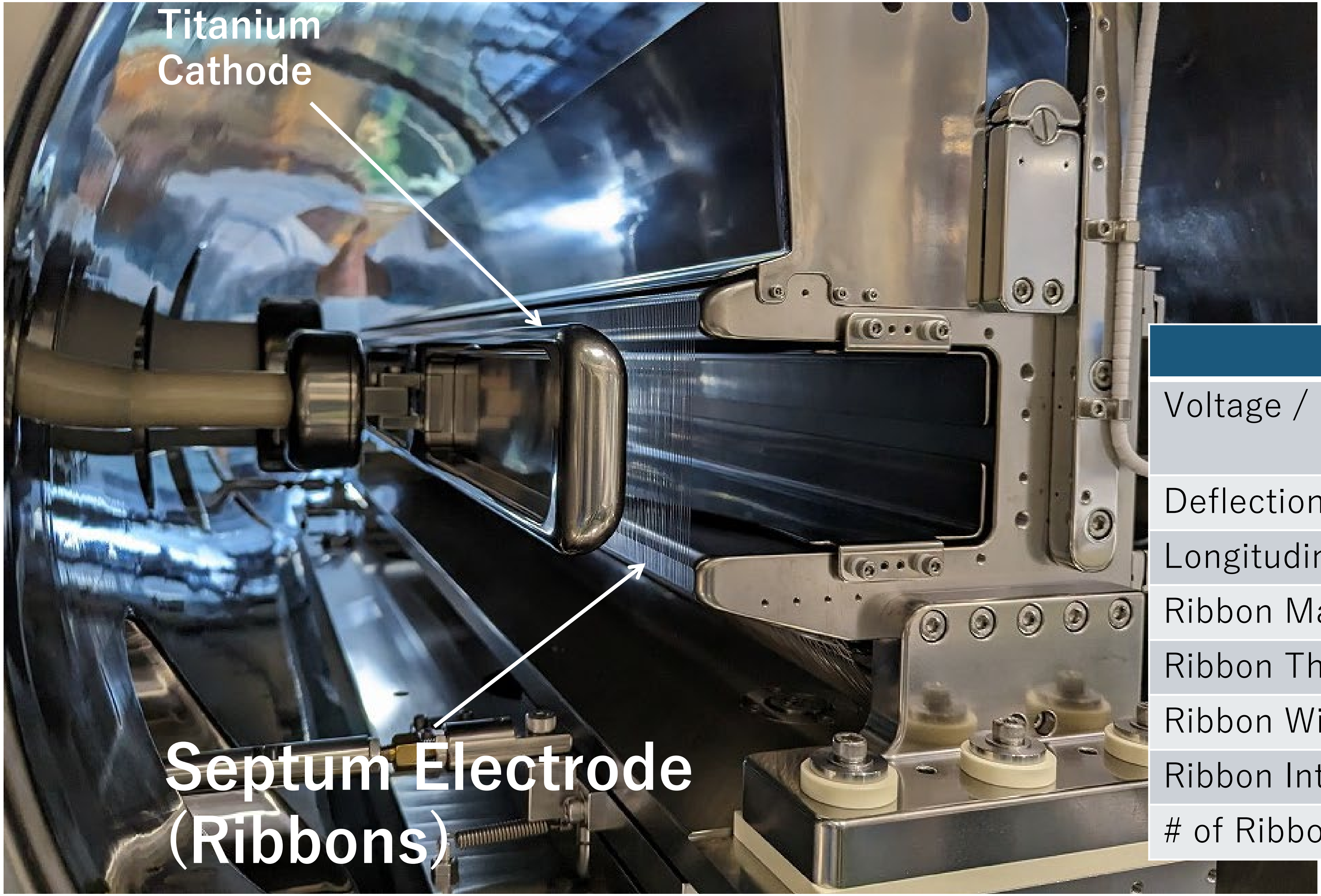
Fixed Bump



Dynamic Bump

Devices for Slow Extraction
1) Electrostatic Septum

Electrostatic Septum (ESS)



	ESS1,2
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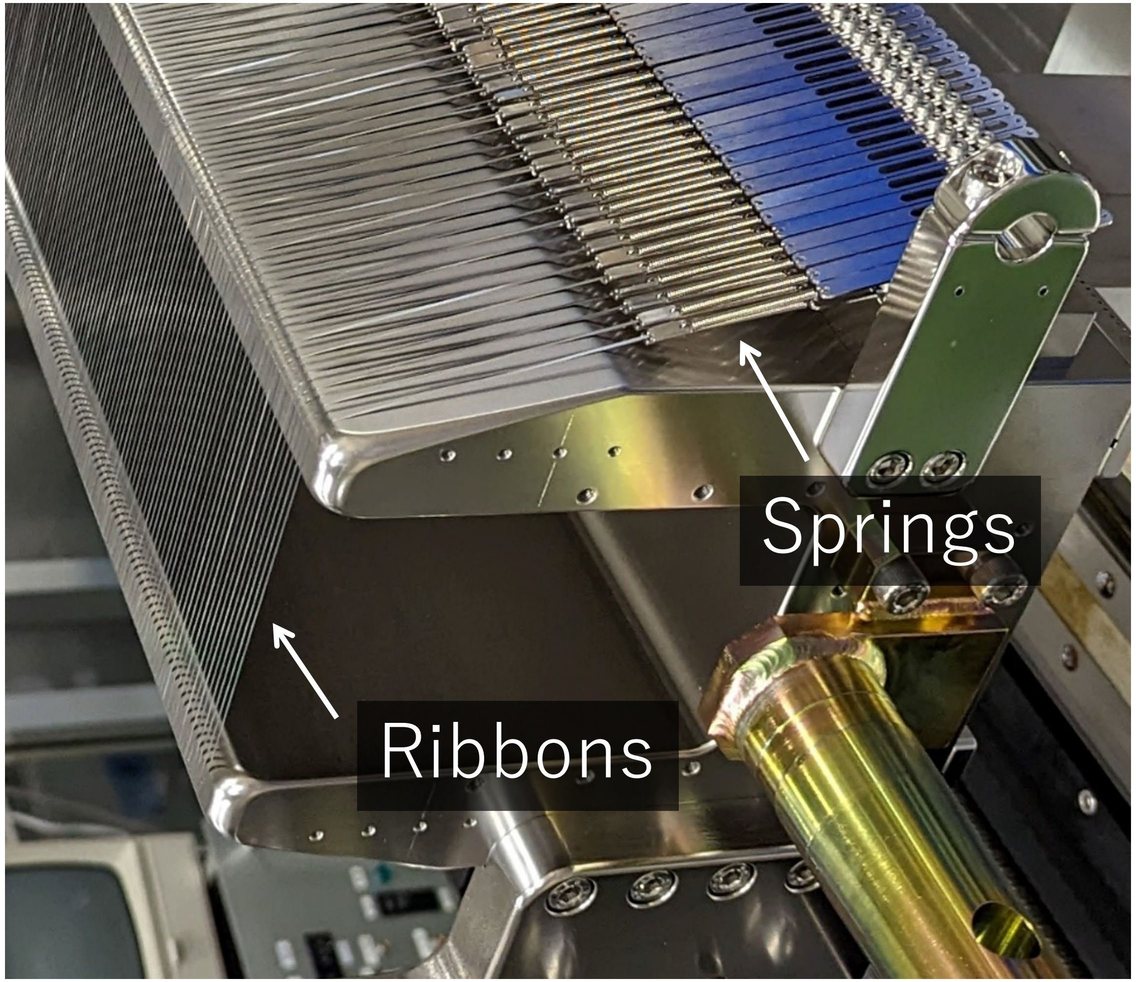
Why Ribbons?

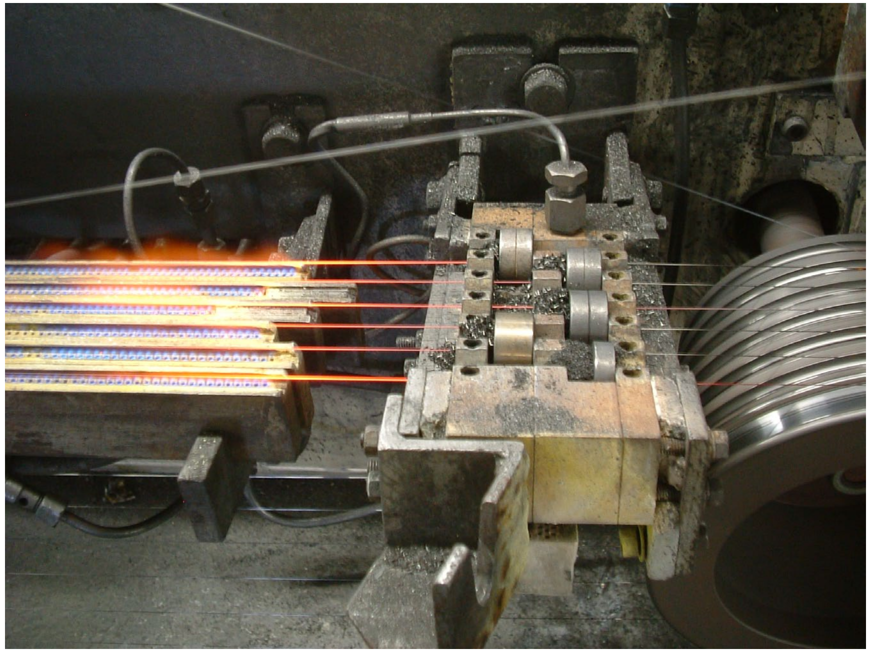
Making the septum thin is
important to reduce beam loss.

With the ribbon shape,
it is possible to increase the cross-section area
and the breaking load
while reducing the thickness of the septum.

The ribbons are pulled by springs with loads of 1 kgf
・To reduce ribbon deflection due to electric field
・To quickly pull out the ribbon when it breaks



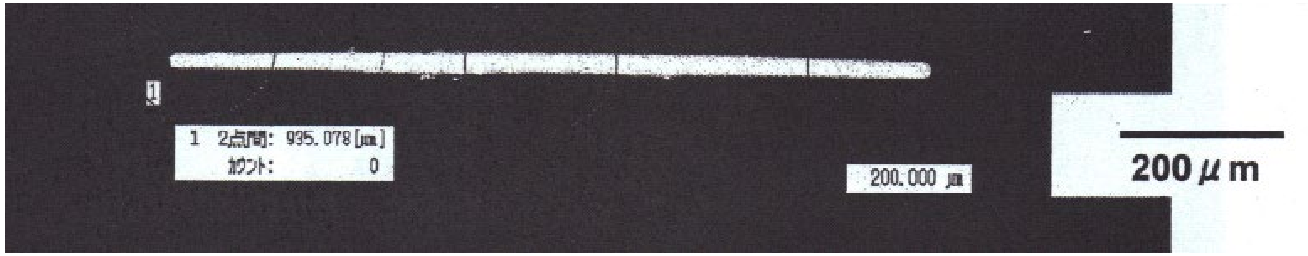
Ribbons for Septum Electrode



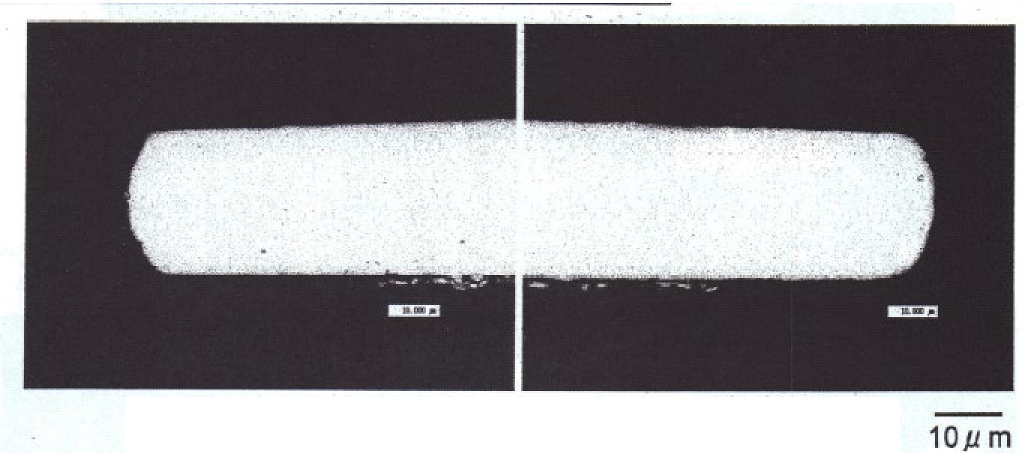
Material: W-26 Re
Made by rolling & annealing

Tensile strength test of the manufactured ribbons
Breaking load: 4~4.5 kgf
→ satisfy the requirement

Cross section



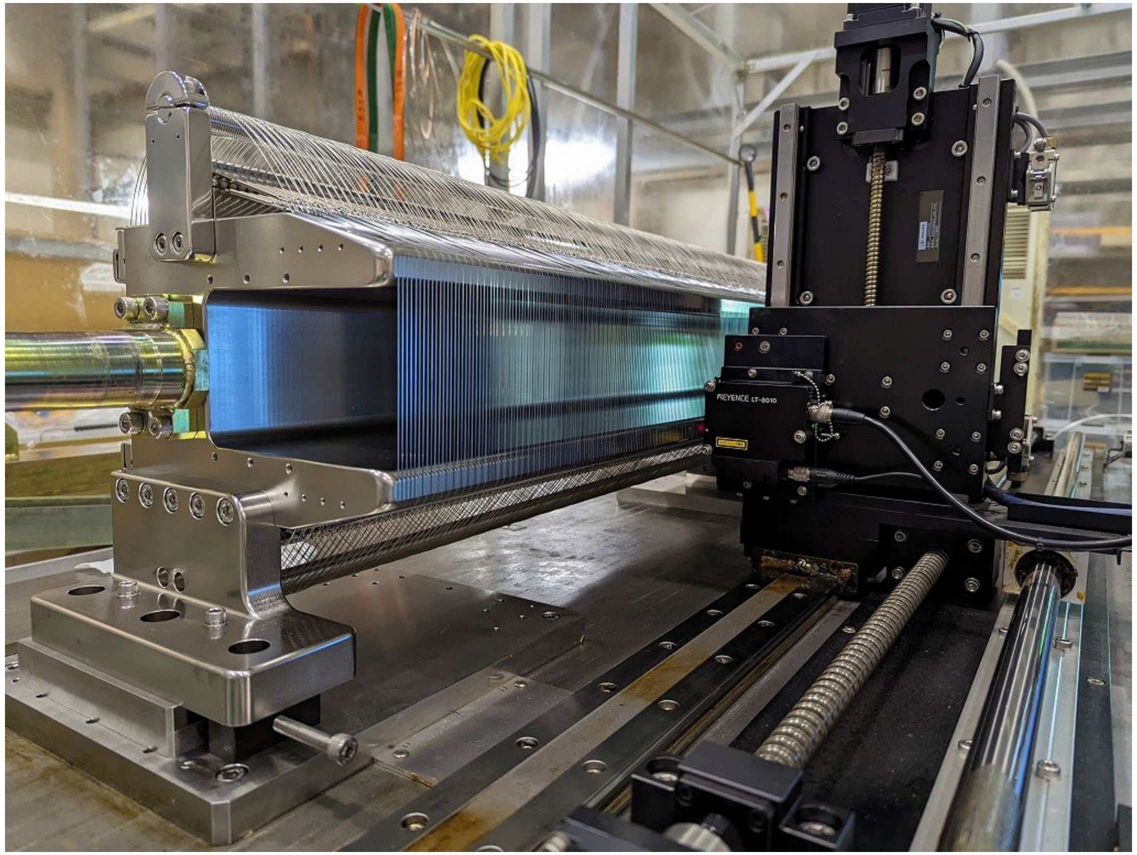
1 mm



30 μm

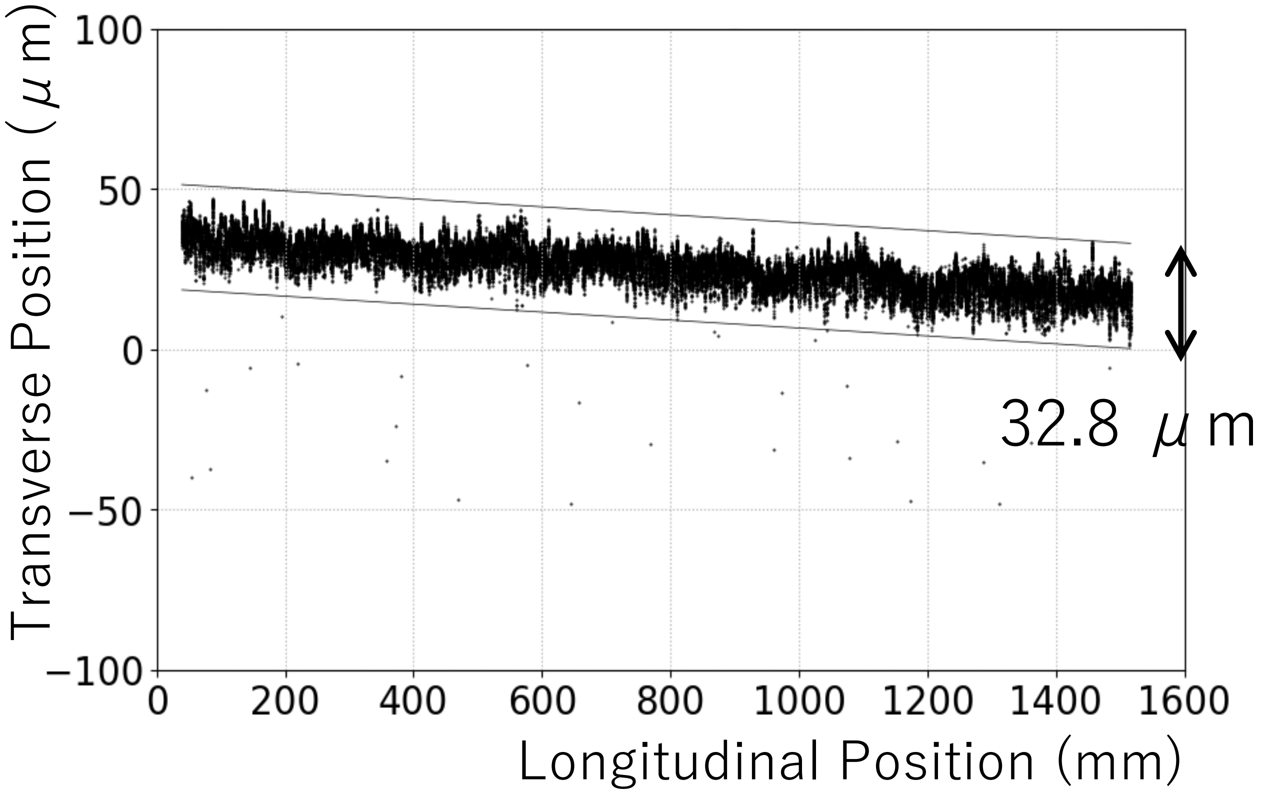
Electrolytic polished to remove burrs

Alignment of the Ribbons

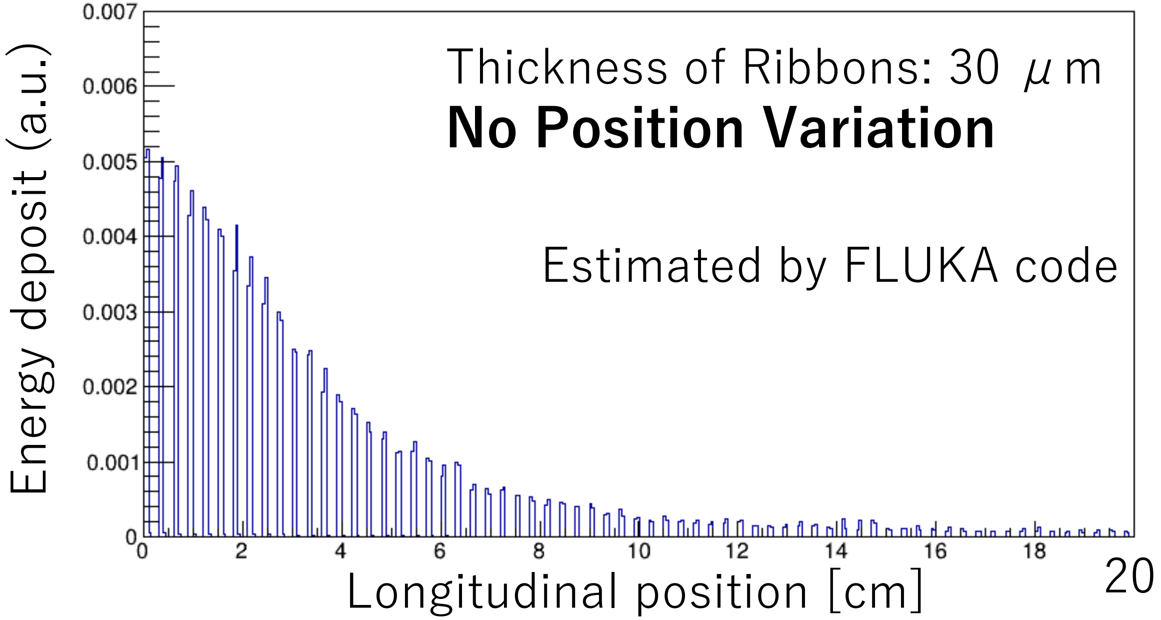


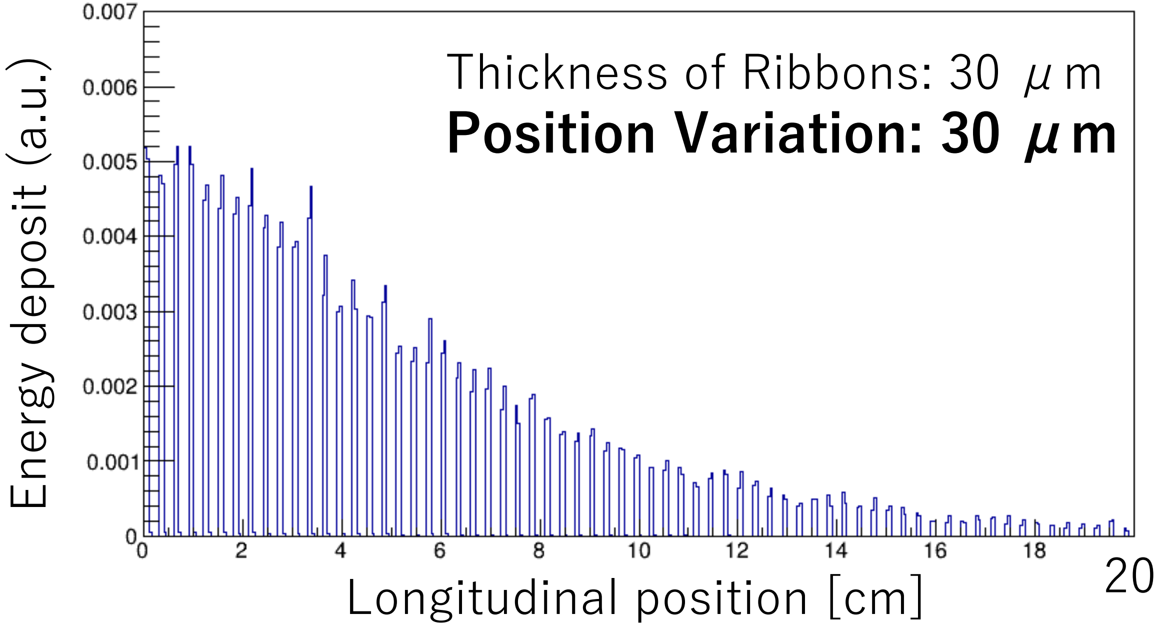
We measured the positions of the ribbons using a laser displacement sensor

We replaced the ribbons that were twisted or misaligned

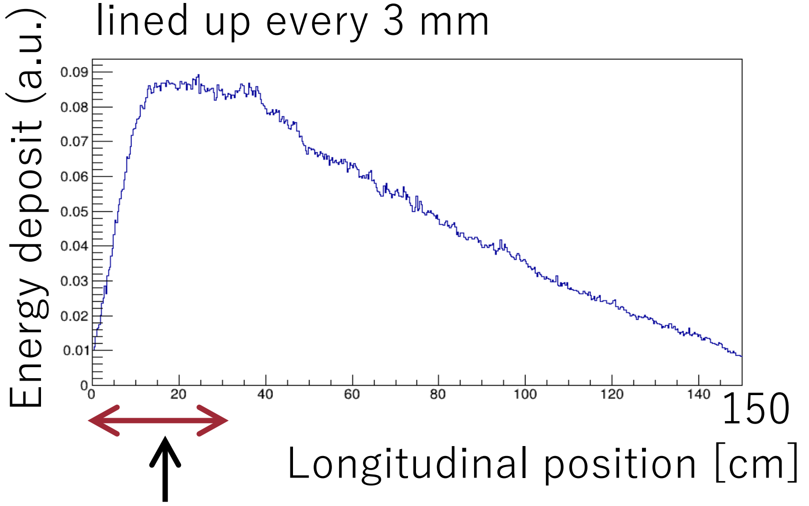


Energy Deposit on Ribbons





Reference:
If they are not thin ribbons
but 200cm x 200cm x t 1mm boards
lined up every 3 mm



λ_int x 3 ~ 30 cm for tungsten

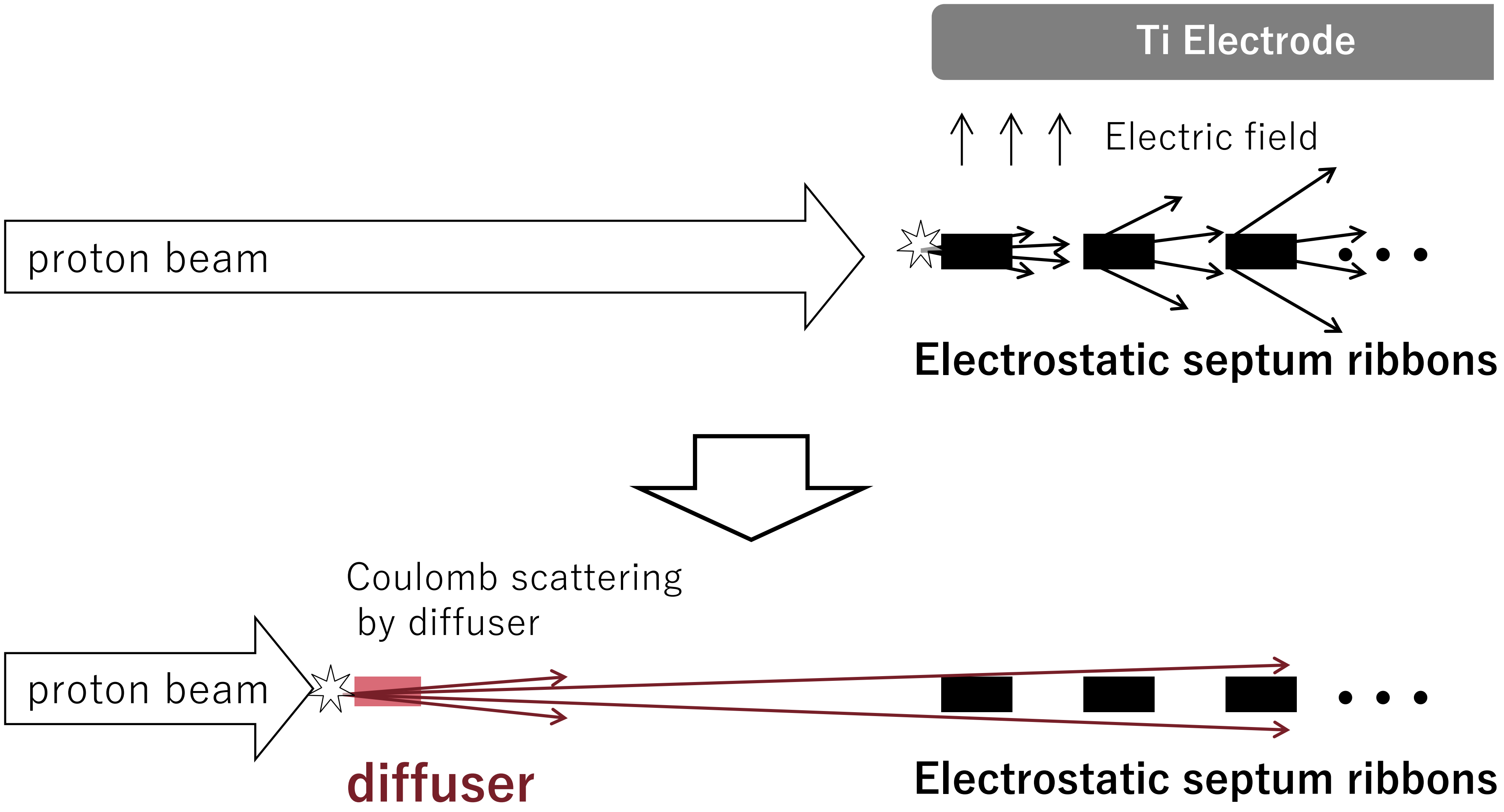
Temperature rise of the most upstream ribbon with 100 kW beam:

- 1 pulse with no cooling → **ΔT = ~ 160 ℃**
- Thermal equilibrium: at **T = 227 ℃** with only radiation cooling

Devices for Slow Extraction
2) Beam Diffusers

Beam diffuser for loss reduction

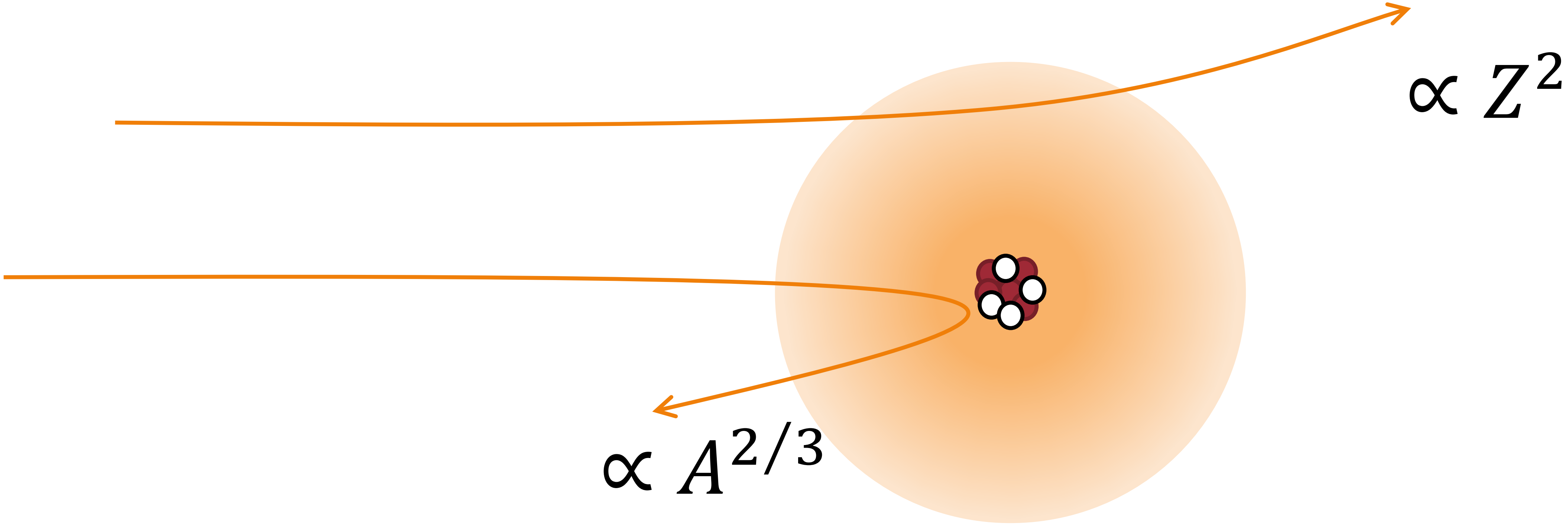
Top view



Tantalum
Thickness: 0.1~0.2 mm, longitudinal length: 0.5~2 mm

Diffuser material

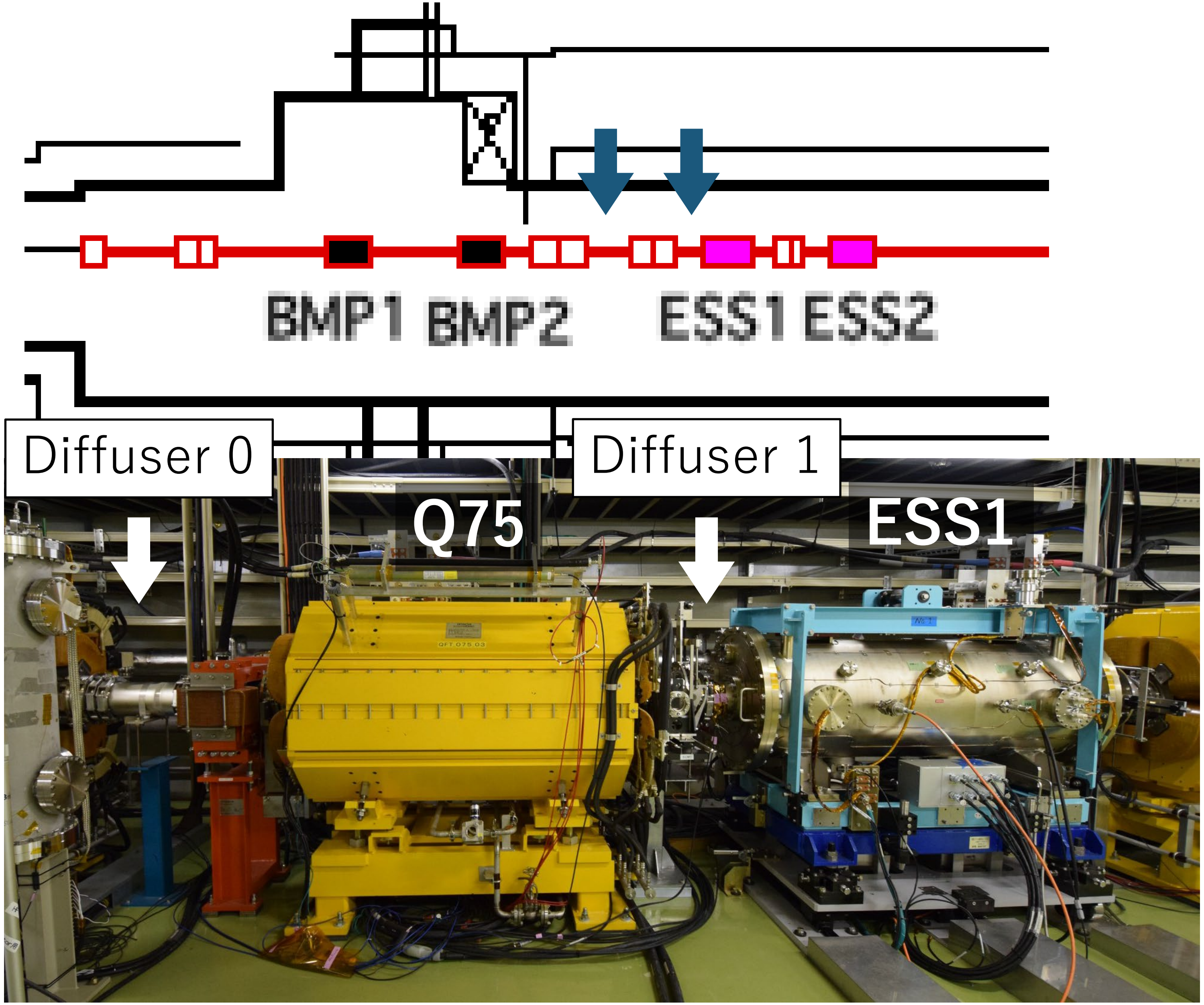
use multiple Coulomb scatterings to diffuse the angle distribution



large angle nuclear collisions are harmful because it induces beam loss at the diffuser

With high-Z material, the length of the diffuser can be made short
→ Large-angle nuclear collisions can be suppressed
We chose tantalum (Z=73, A=181) for the diffuser material

Places for Diffusers

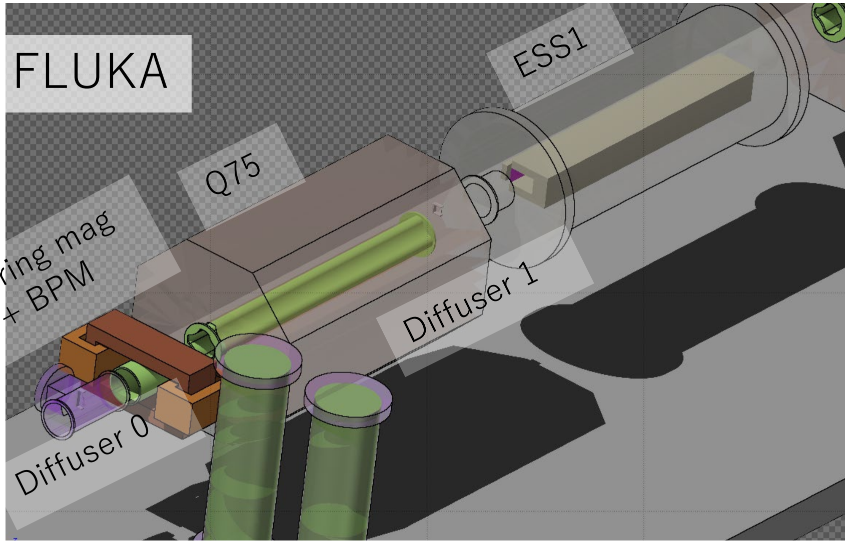


We searched for the optimal diffuser size for these two locations using FLUKA code.

Optimized sizes of diffusers

	Diffuser 0 phase ~5°		Diffuser 1 phase ~0.7°		beam loss
	thickness [um]	length [mm]	thickness [um]	length [mm]	
No diffuser	-	-	-	-	1
diffuser 0 only	200	0.5	-	-	0.42
diffuser 1 only	-	-	100	2	0.47
diffuser 0 and 1	200	0.5	100	2	**0.35**

using FLUKA



Diffuser at large phase advance
can be shorter in longitudinal length
but needs to be thicker

Installed Beam Diffusers

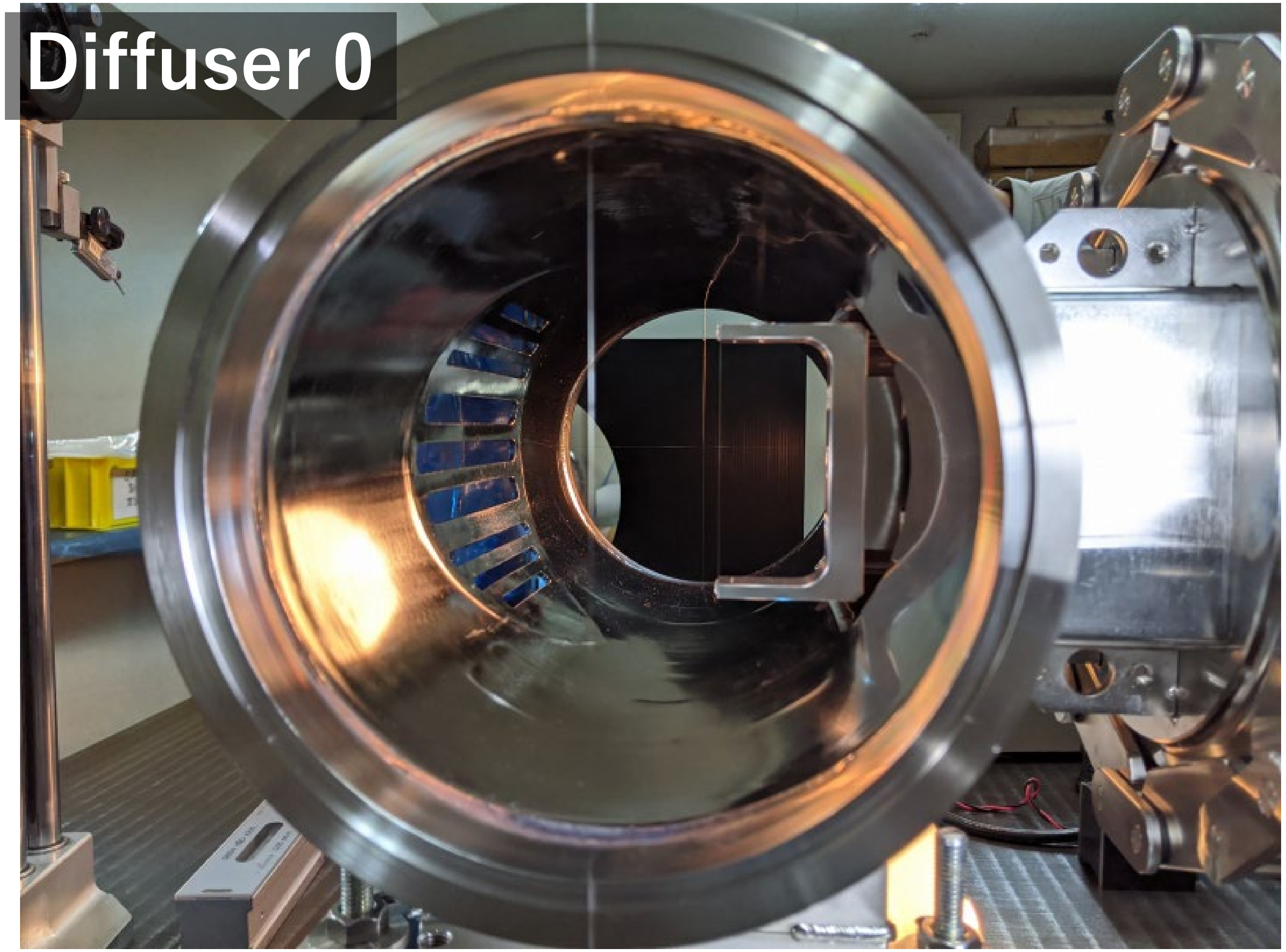
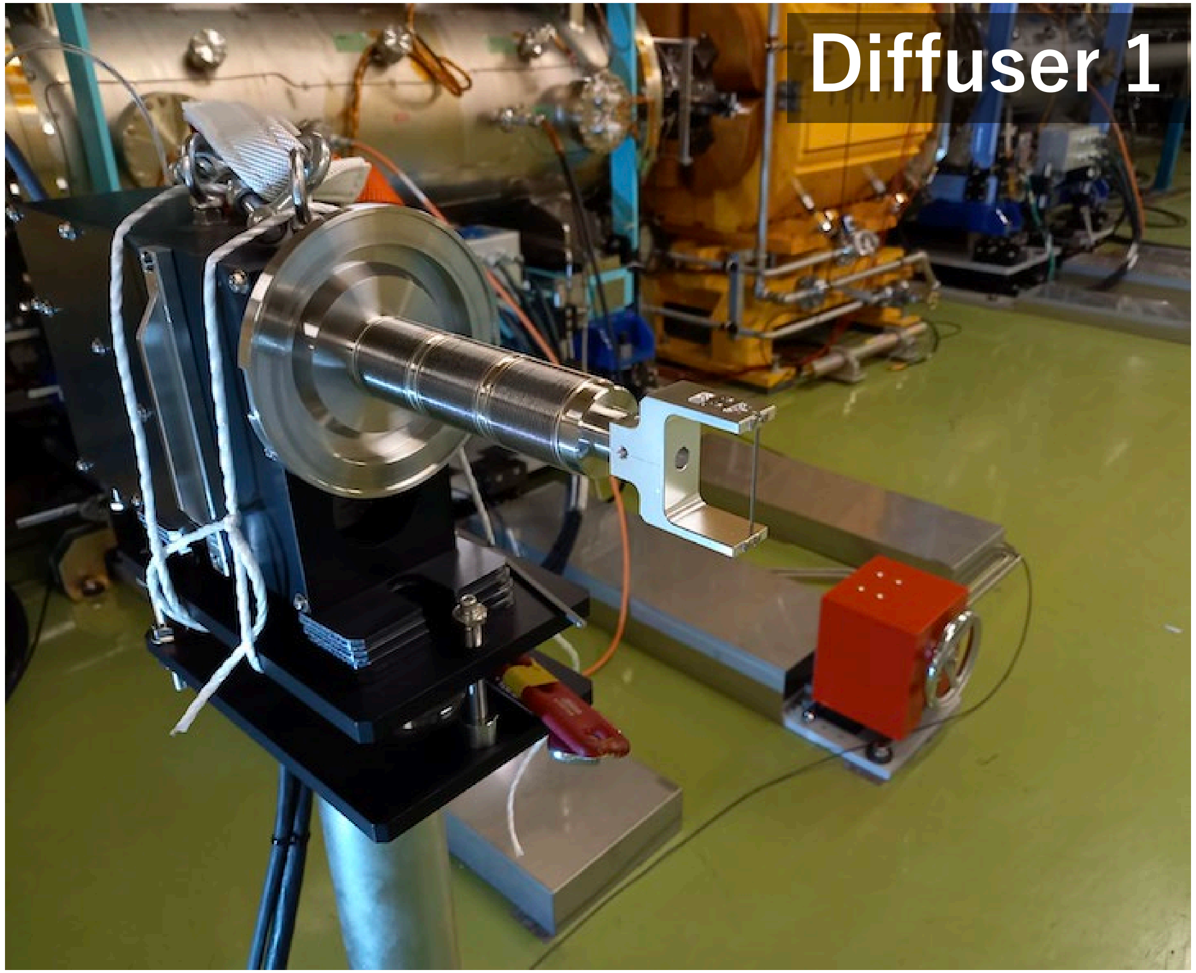
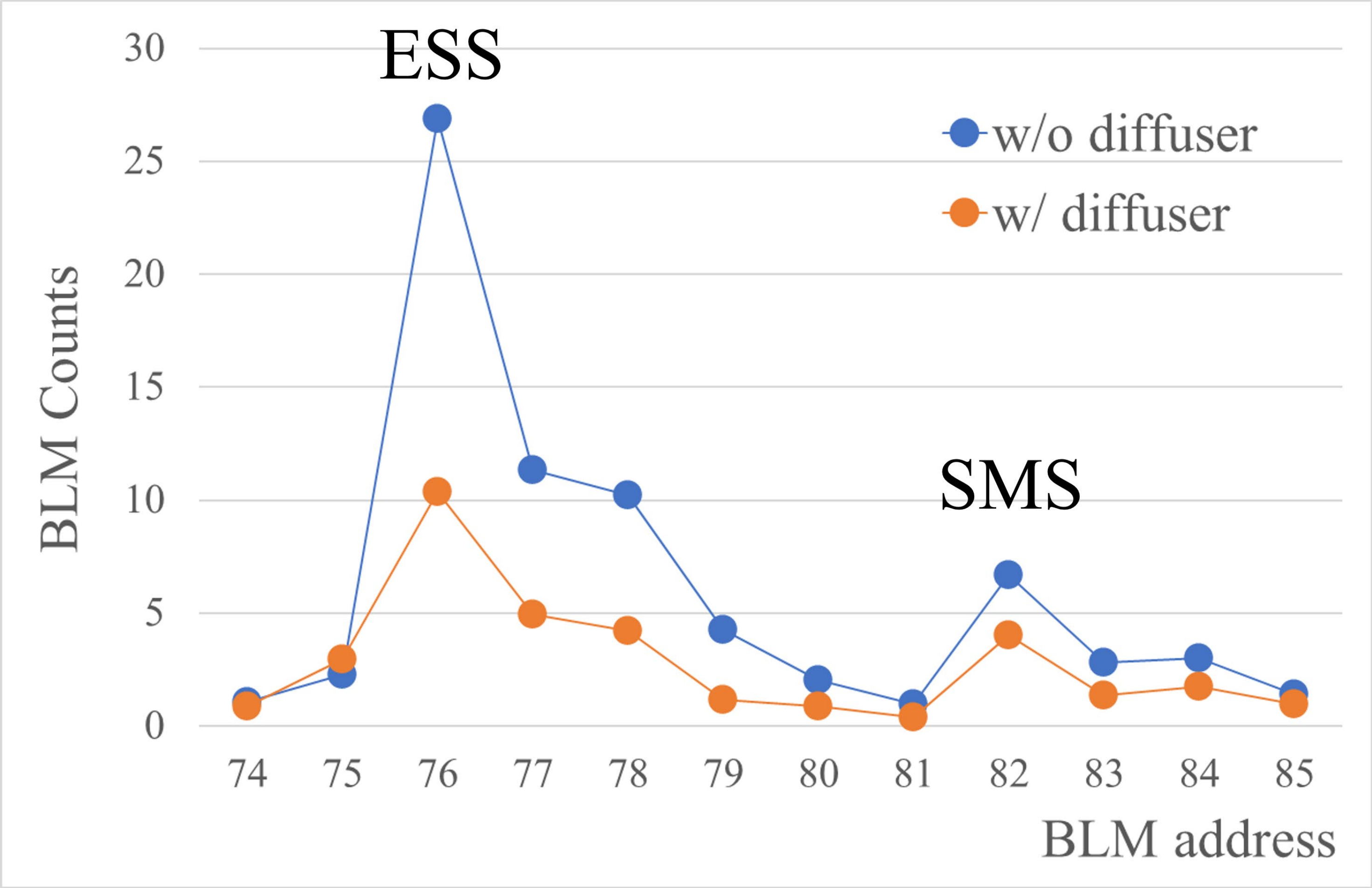


Photo from downstream



Beam loss distribution with diffuser 0

2021-02-18 16:00-17:00
Beam power: 10 kW

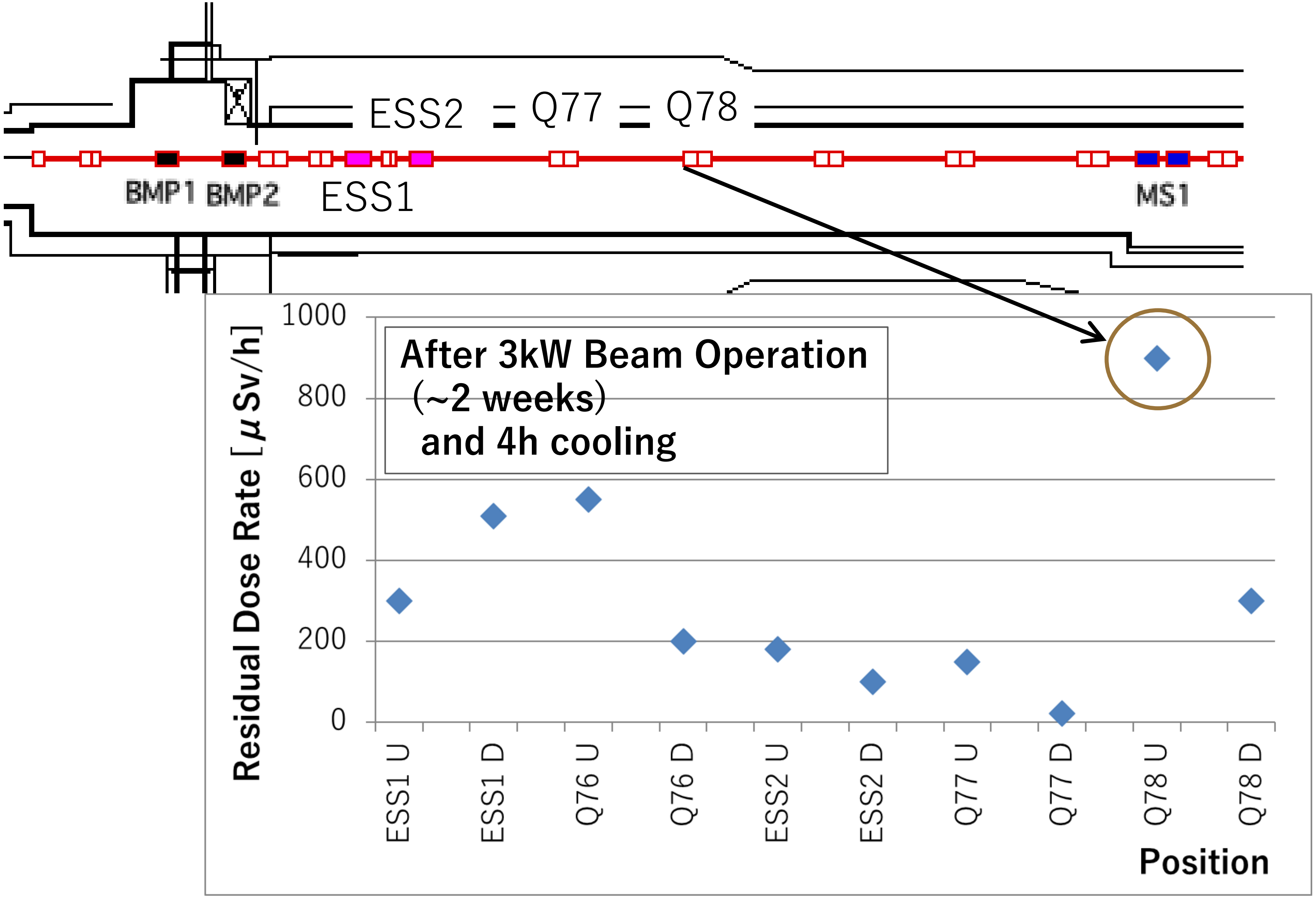


Beam loss was reduced to factor ~0.4 with diffuser 0 only (in good agreement with simulation)

- Diffuser 1 test
- Test with high-power beam will be done in the next beamtime

Devices for Slow Extraction
3) Collimator

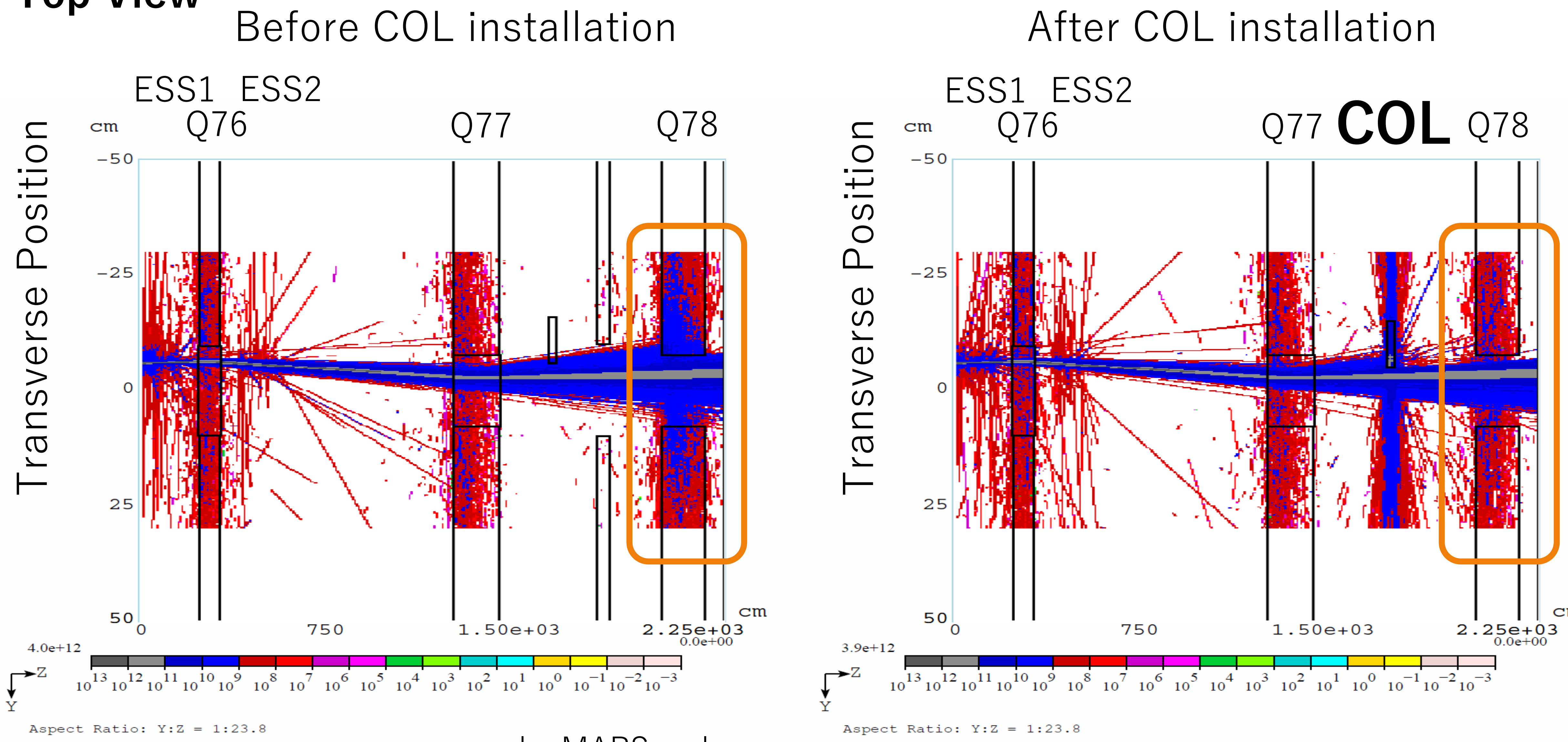
Residual Dose in the Upstream Part of the Straight Section



A steering magnet and a BPM are located just upstream of the Q78
They must be in a maintainable condition

Simulation for Collimator at the downstream of ESS

Top View

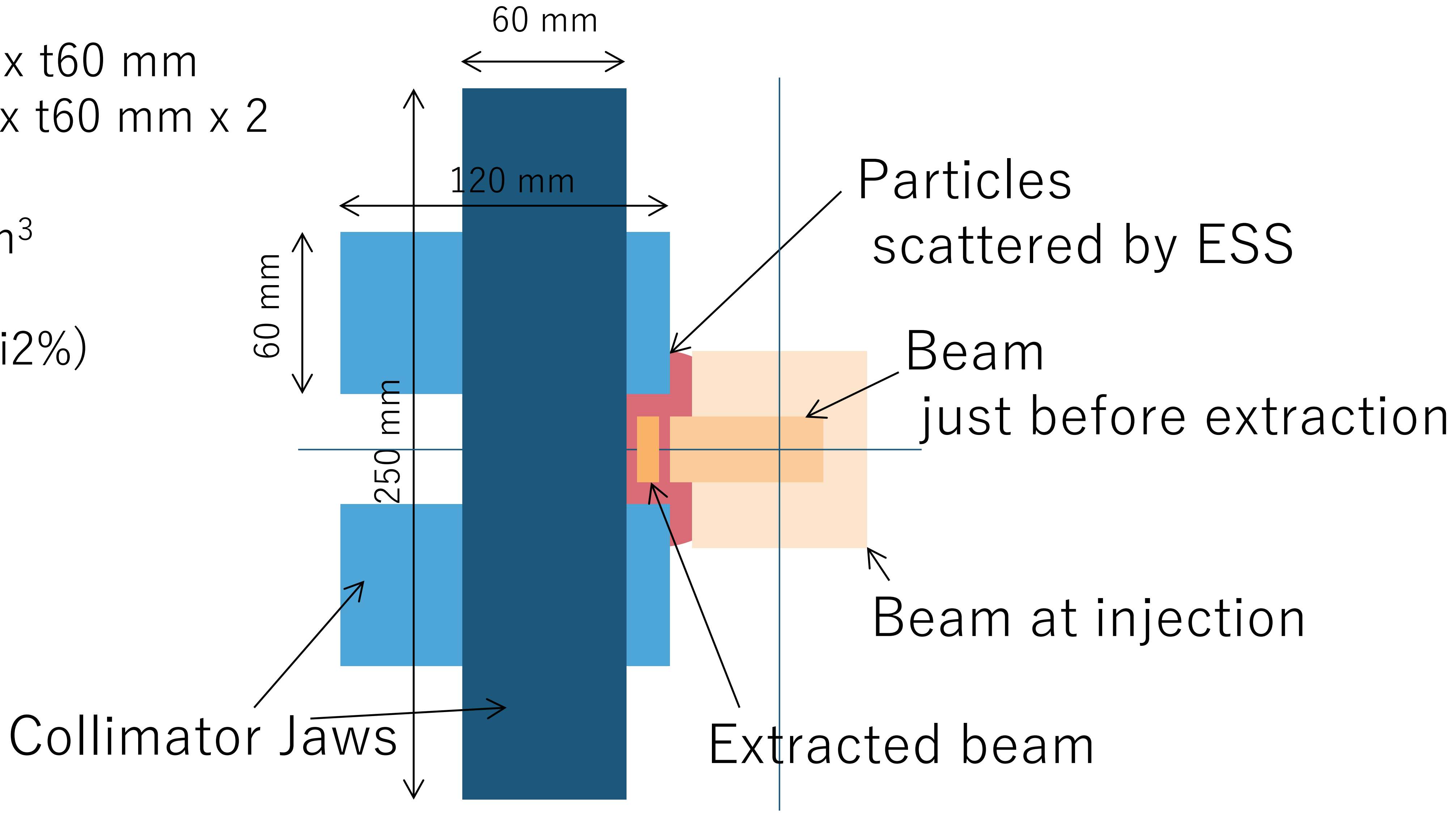


by MARS code

Configuration of the Collimator

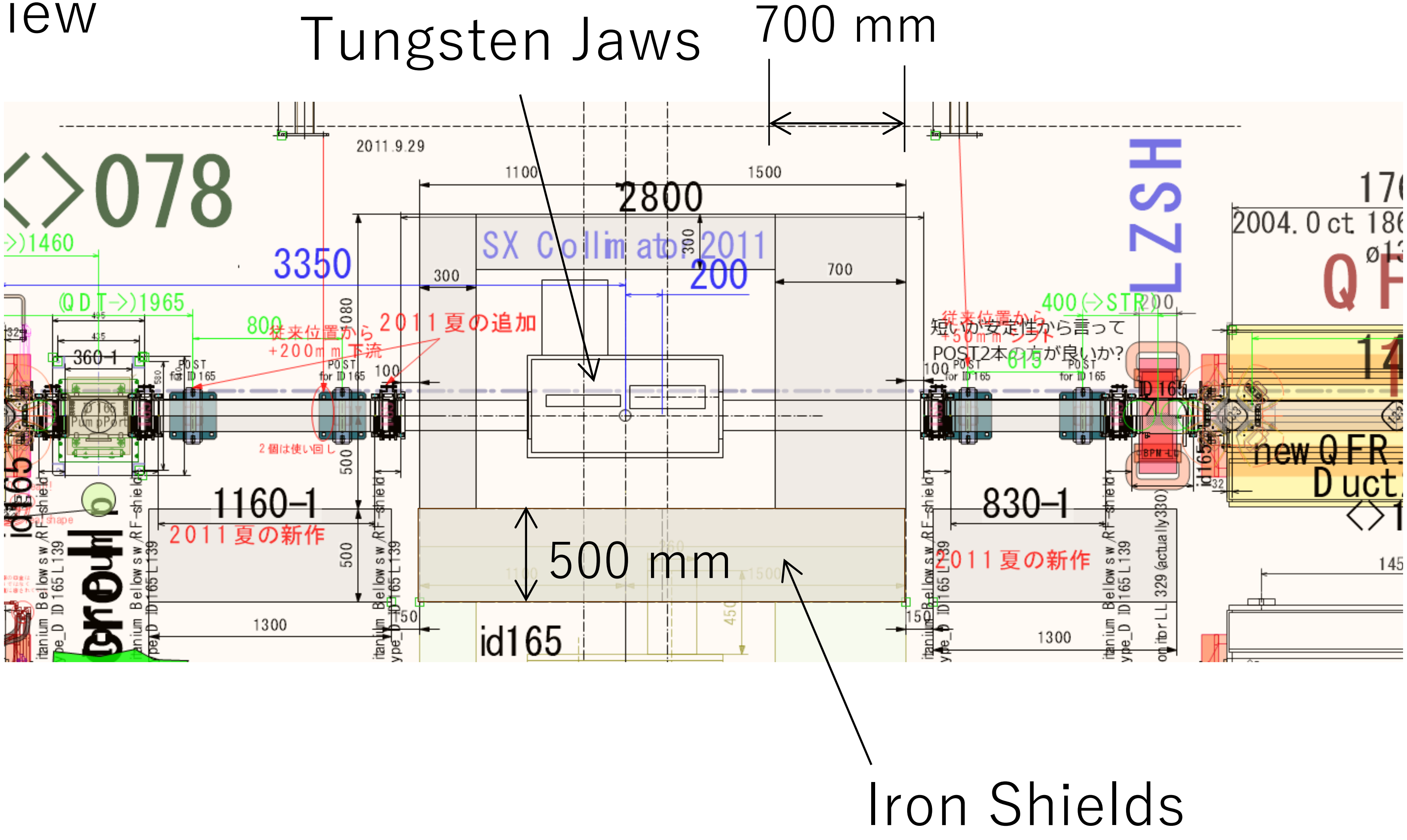
Hcol : 400 x 250 x t60 mm
Vcol : 400 x 120 x t60 mm x 2

Density: 18 g/cm^3
Tungsten alloy
(W95%-Cu3%-Ni2%)

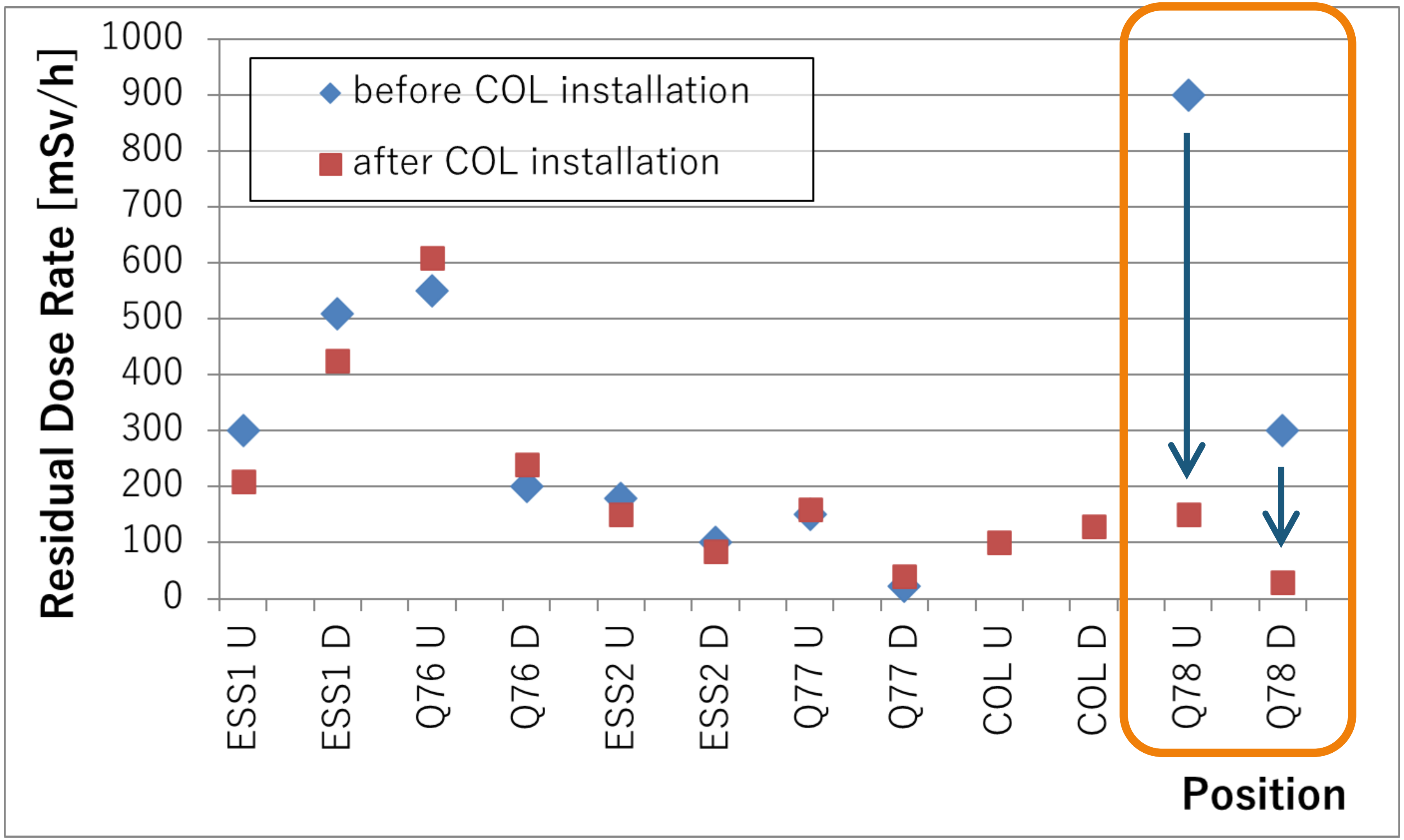


Iron Shields around Collimator

Top View



Residual Dose before and after Collimator Installation



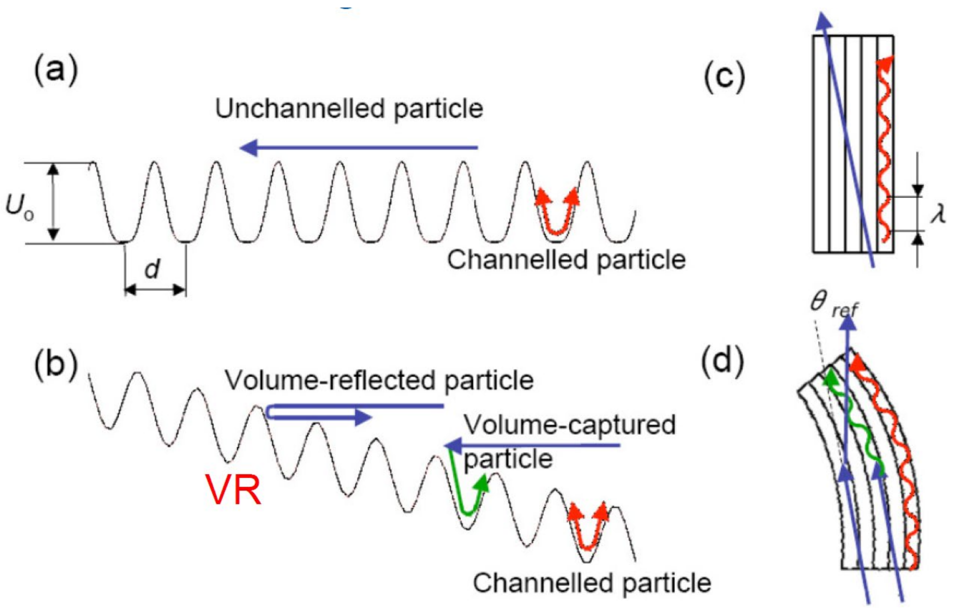
Future Plans

Bent Silicon Crystal

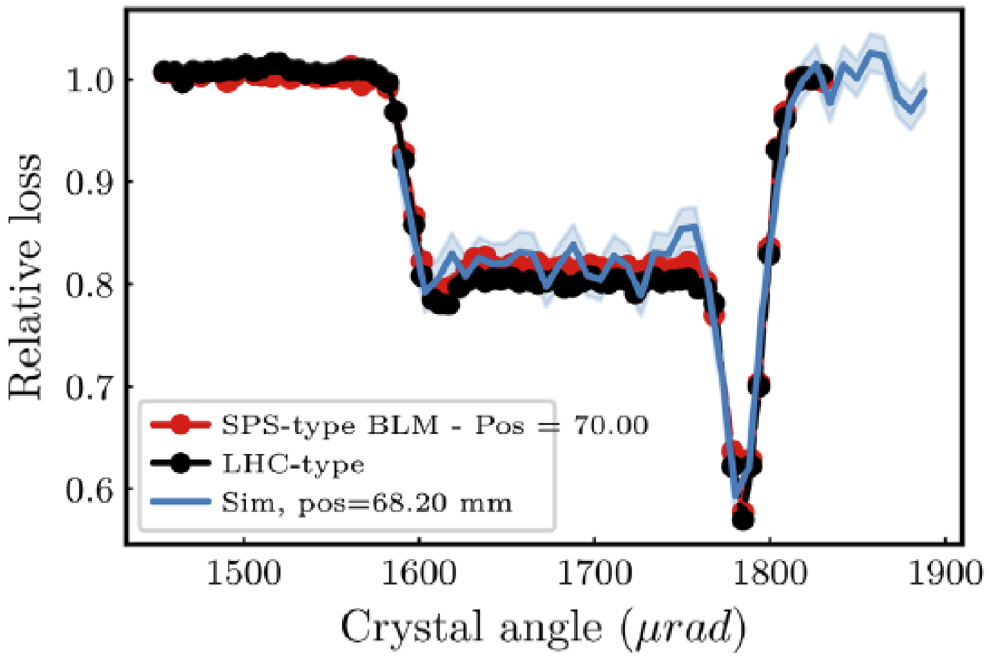
Beam loss may be further reduced by using bent silicon crystals instead of beam diffusers.

At CERN SPS 400 GeV slow extraction the effectiveness of the bent silicon crystal has already been confirmed.

We are considering replacing diffuser 0 with bent silicon crystal in the future.



W. Scandale *et al.*,
"Deflection of 400 GeV/c proton beam with bent silicon crystals at the CERN Super Proton Synchrotron",
PRAB 11, 063501 (2008)



F. M. Velotti *et al.*,
"Septum shadowing by means of a bent crystal to reduce slow extraction beam loss",
PRAB 22, 093502 (2019)

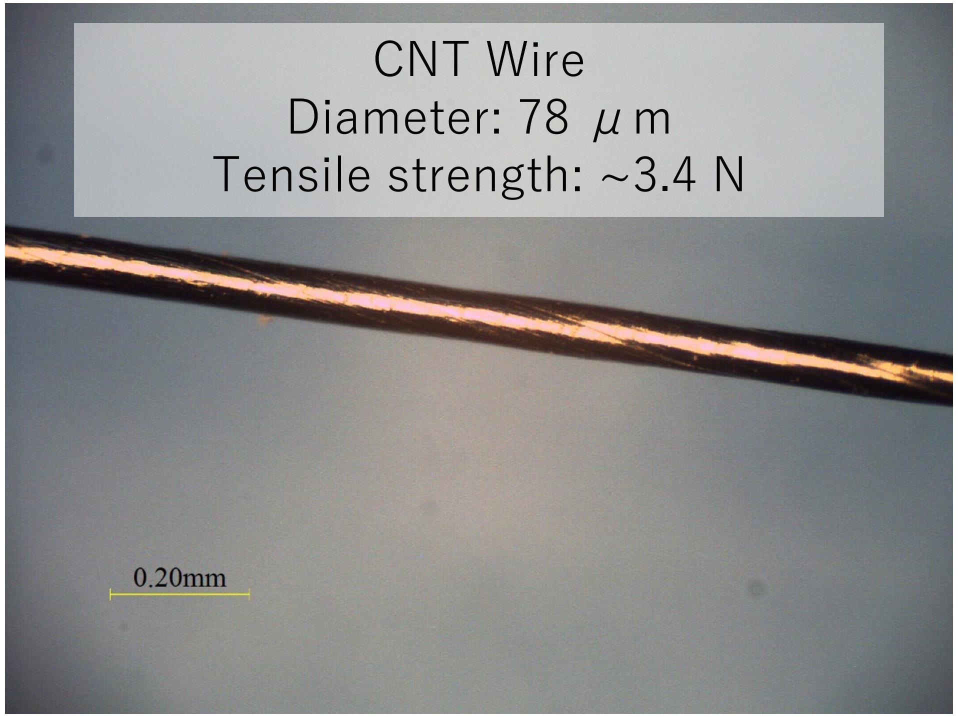
Low-Z Material for Septum Electrode

If septum electrodes can be made from low-Z materials, beam loss can be significantly reduced.

Carbon nanotubes (CNT) wires were considered one of the candidates,
but several negative results have already been reported.

J. Borburgh *et al.*, "Experimental Results of Low-Z Materials as a High Voltage Septum Anode",
29th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), Padova, Italy, 2021, pp. 446-449.

We are now considering the possibility of
using copper-coated CNT wire for the septum electrodes.



Summary

Electrostatic septa with thin ribbon septum electrode were developed, and a high extraction efficiency of 99.5% with 64 kW beam power in slow extraction was achieved with the help of dynamic bump scheme.

We also installed a beam collimator to suppress the activation of equipment downstream of the electrostatic septum and confirmed the expected effect.

We plan to conduct a beam test of the beam diffusers for the beam loss reduction installed upstream of the ESS.
We are also considering replacing beam diffusers with bent silicon crystals to achieve further beam loss reduction.

We plan to start searching for low-Z materials which are suitable for septum electrodes.