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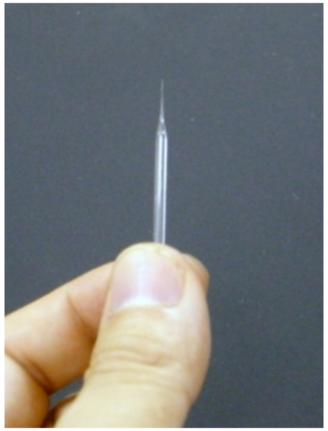
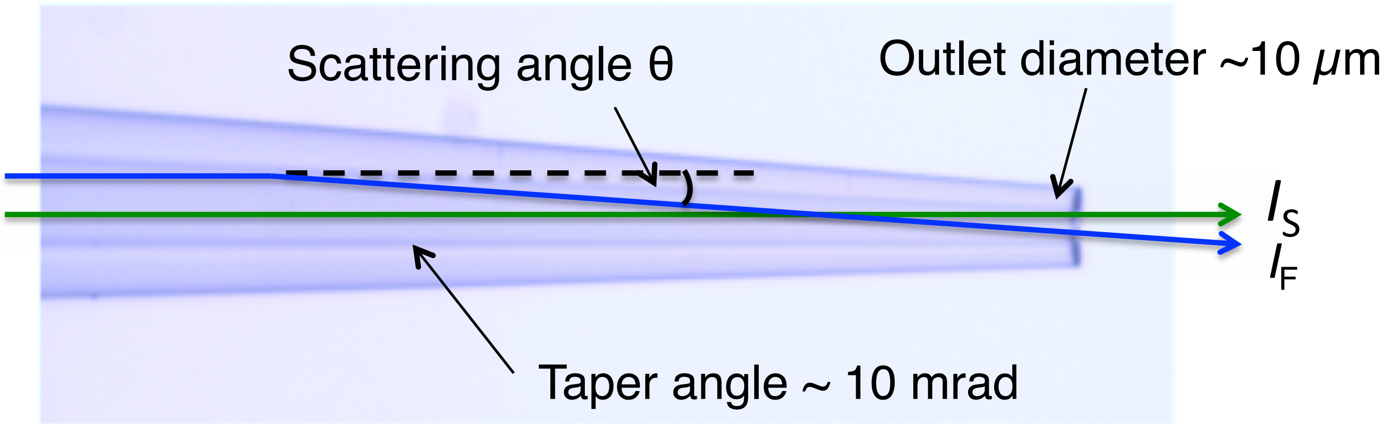
Novel Focusing Device for Ion-Driven WDM Experiments

(Investigation of MeV-beam focusing using tapered glass capillary and its application to micro-beam analysis)

J. Hasegawa and Y. Oguri, *Tokyo Tech*
S. Jaiyen and C. Polee, *Chulalongkorn Univ.*

Beam focusing using glancing-angle scattering has been applied to generate micro-beams of MeV ions.

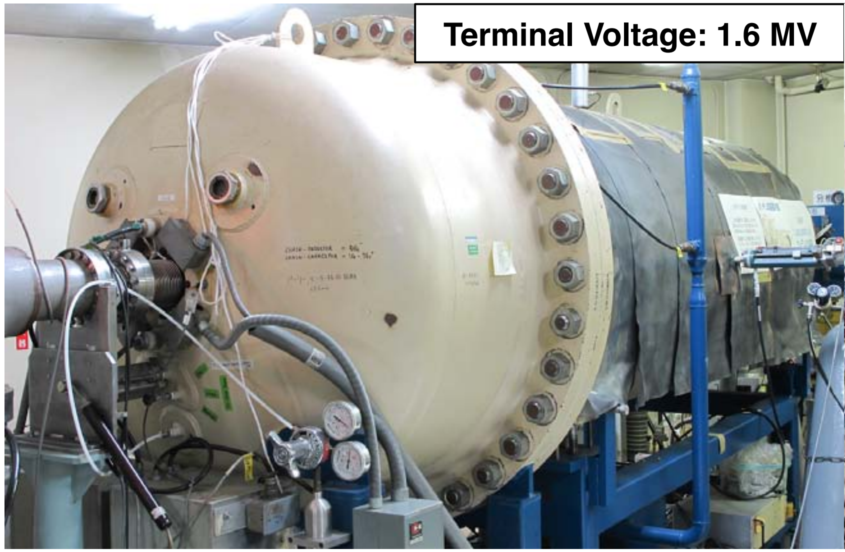




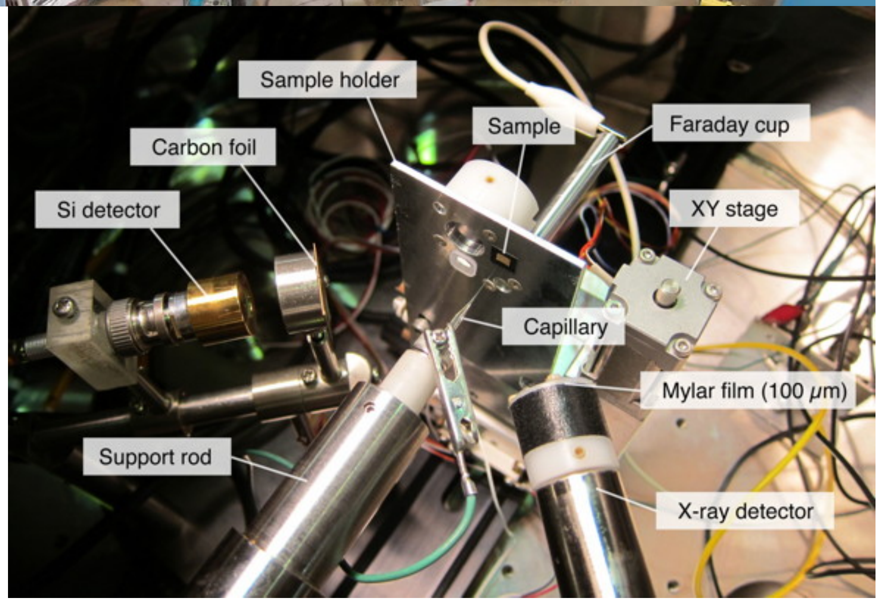
- The use of the tapered glass capillary for MeV ion focusing was proposed by Nebiki, *et al*.[1]
- Higher scattering cross section is expected at smaller scattering angle (Rutherford scattering cross section ∝ $1/\sin^4(\theta/2)$).
- MeV-ion focusing using the tapered capillary has been tested to micro-PIXE, micro-NRA, high-contrast X-ray imaging, cell surgery, and etc.
- Beam focusing ratio (= enhancement): $\eta = \frac{I_S + I_F}{I_S}$

[1] T. Nebiki, *et al*., J. Vac. Sci. Technol. A **21**, 1671 (2003).

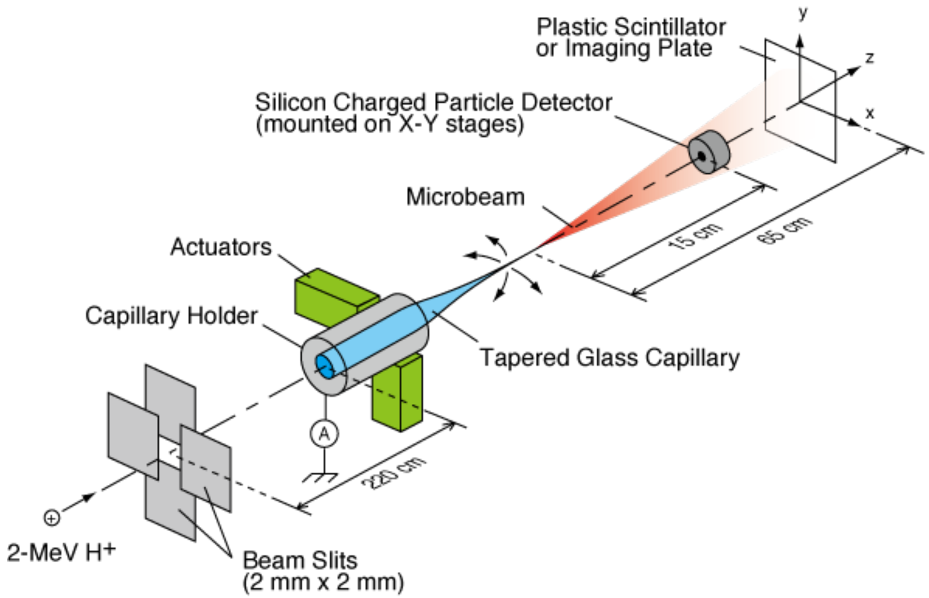
Capillary beam-focusing experiments have been performed at Tandem Accelerator Facility of Tokyo Tech.

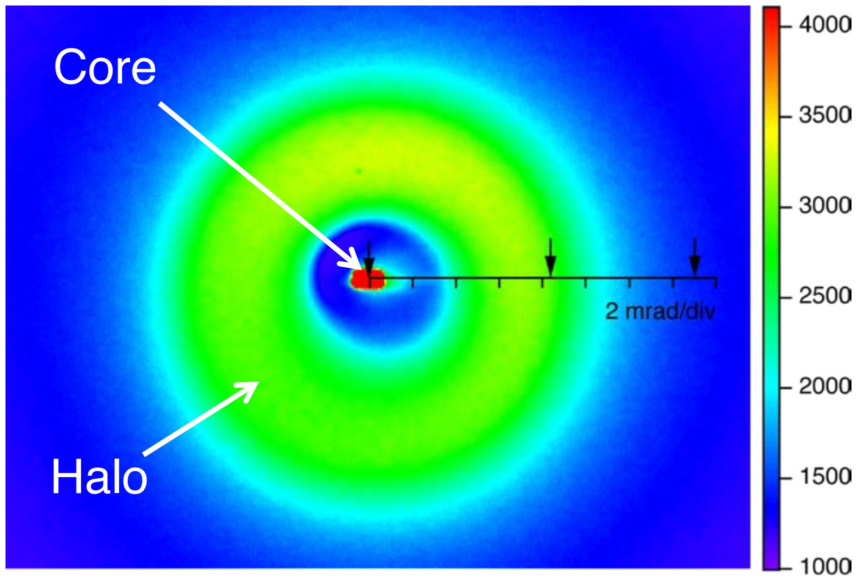


- A micro-beam irradiation stand using the tapered glass capillary is being constructed for micro-PIXE analysis.
- Low gas conductance allows us to do the analysis in air and to irradiate the samples in liquid phase or those in water.

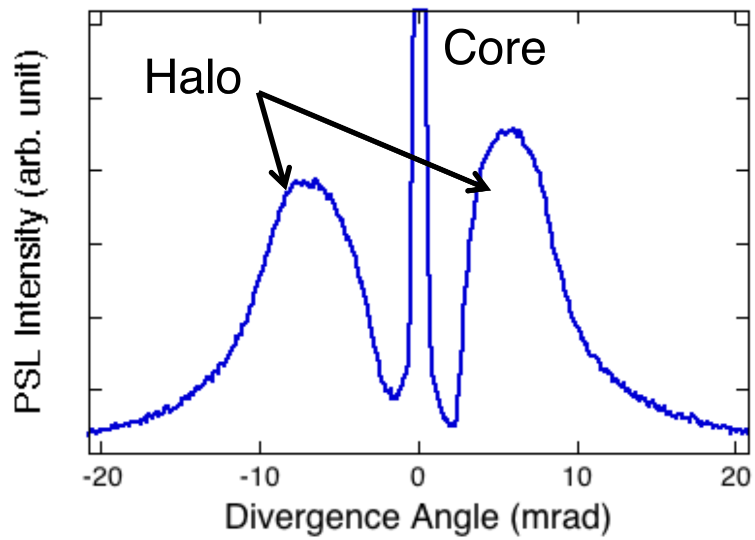


The capillary-focused beam consists of two components having different divergence angles.

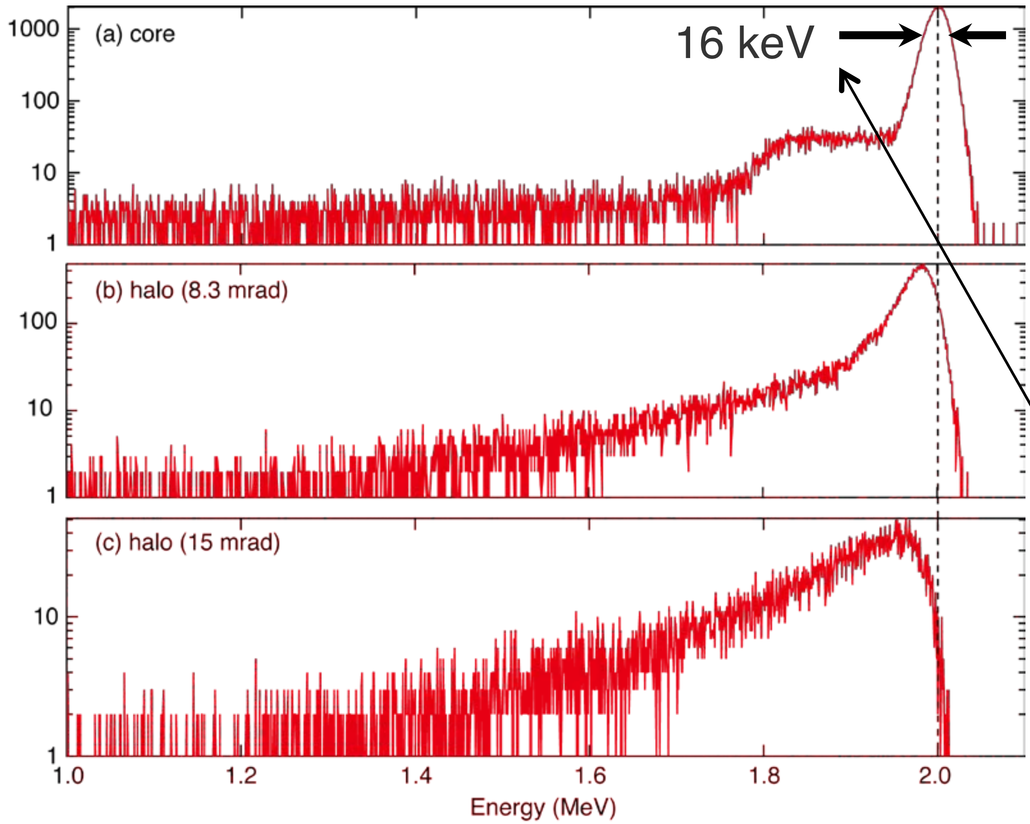


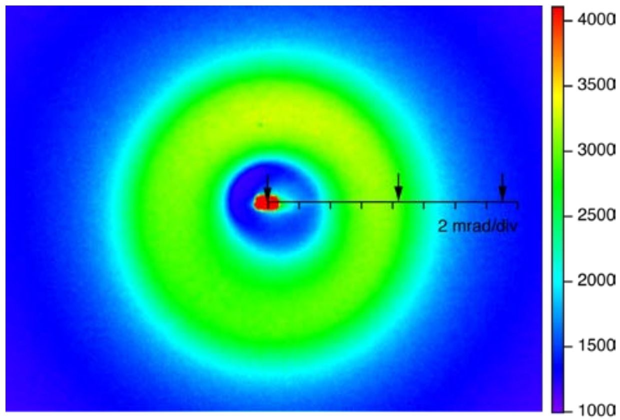


- The intense "core" component is surrounded by the "halo" component having relatively large divergence angles.
- Thanks to the clear separation between the core and the halo, the energy spectra can be measured for both components separately.



The core component consists of projectiles passing straight through the capillary.



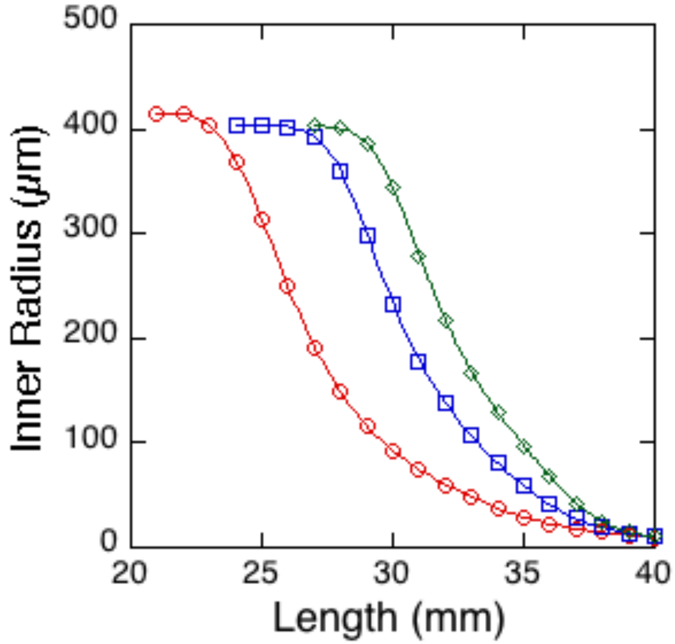


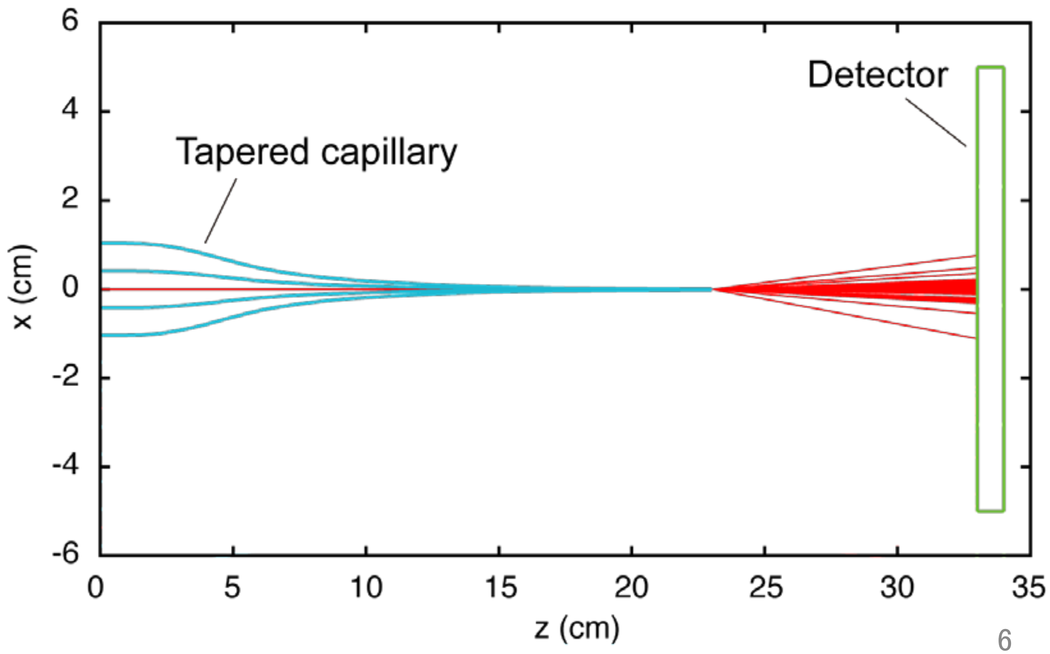
$$\sqrt{12^2 + 9.3^2} \approx 15\,\mathrm{keV}$$

- The FWHM of the peak can be explained by the energy resolution of the Si detector and the straggling in the Al foil (0.8 μm) located in front of the detector.
- The halo component was proved to consist of the projectiles scattered by the capillary inner wall.

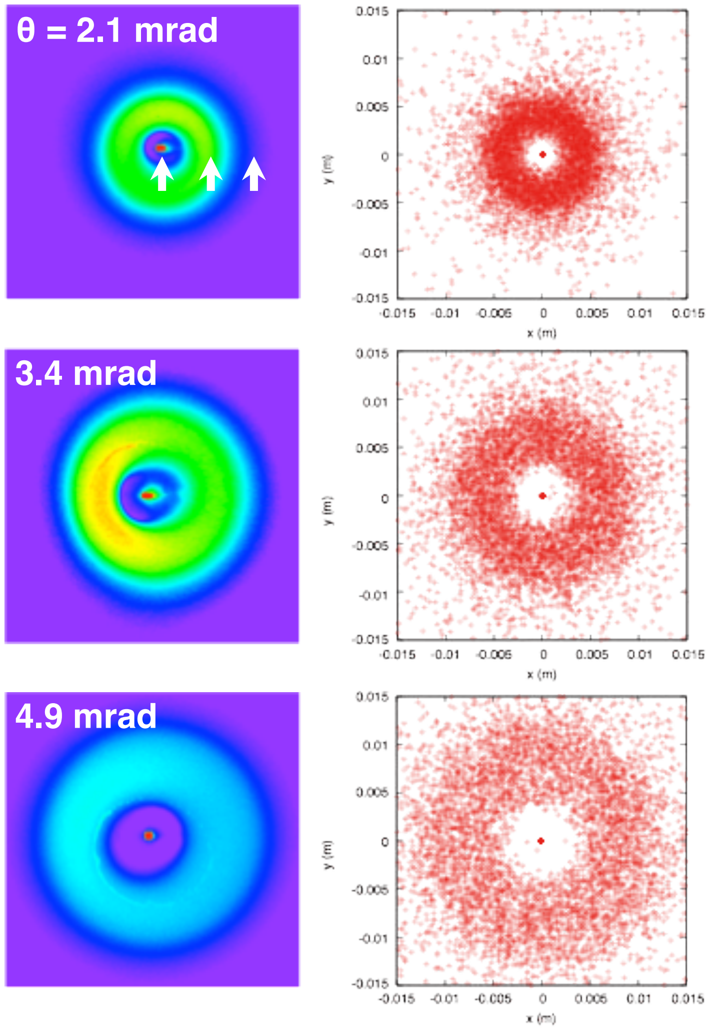
A three-dimensional Monte Carlo code was developed and used to investigate MeV ion transport in the capillary.

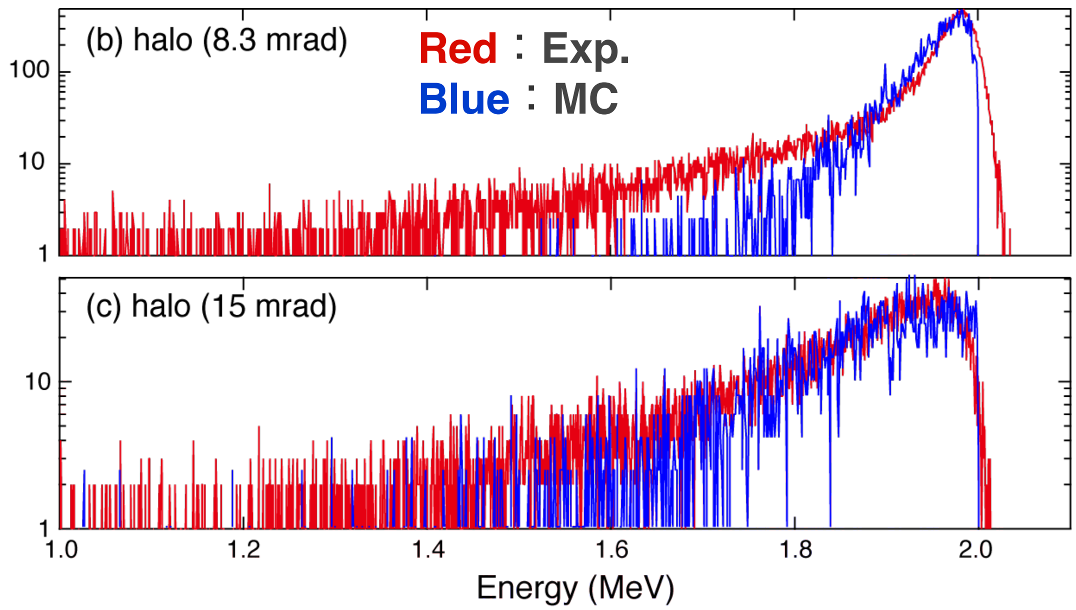
- Only elastic scattering is treated as an elementary step.
- The Rutherford potential or ZBL potential is used as an interatomic potential for the calculation of scattering cross section.
- Electronic stopping power data is imported from SRIM2008.
- The actual shape of the capillary is used to simulate the experiment.

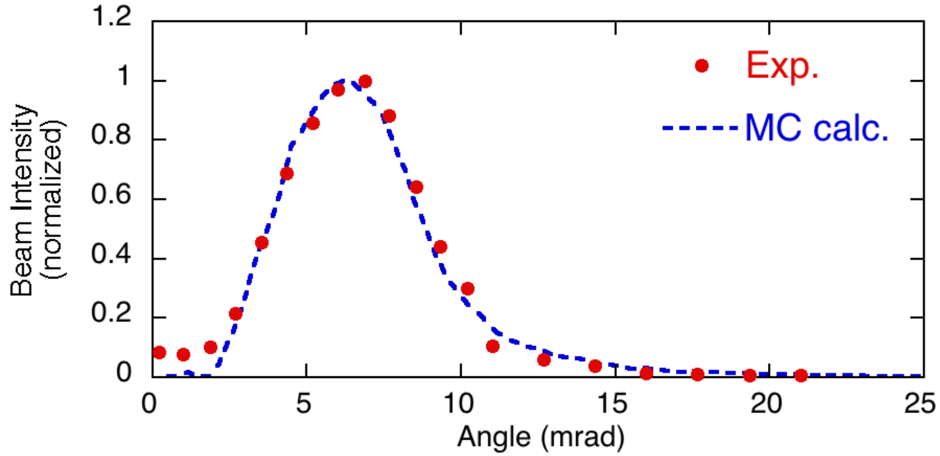




The reliability of the MC code was checked by the experiments.

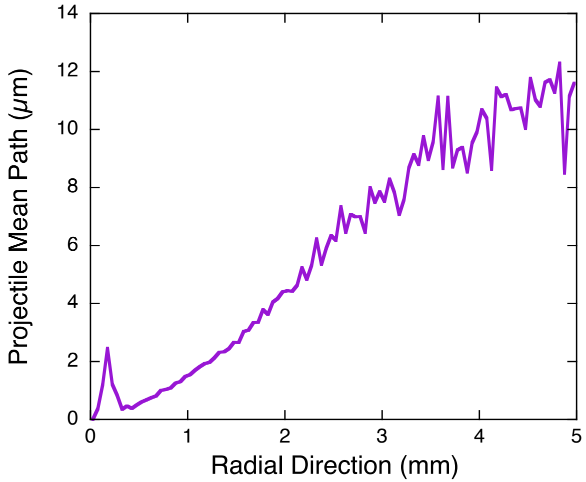


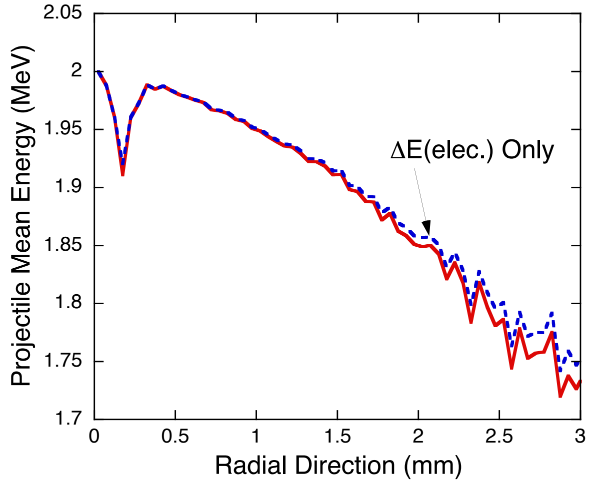


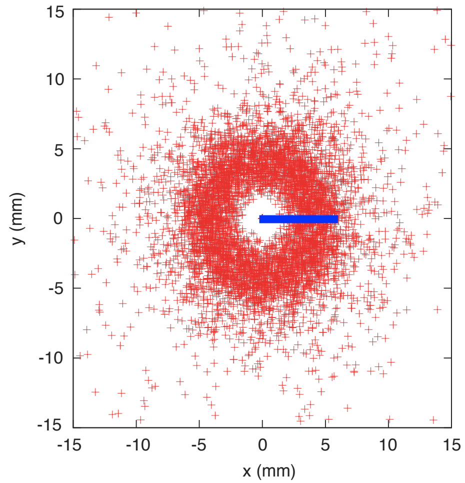


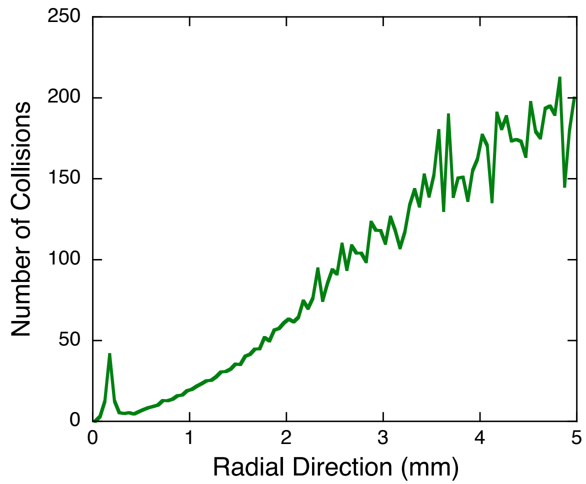
- The MC simulation well reproduced the experimental results.

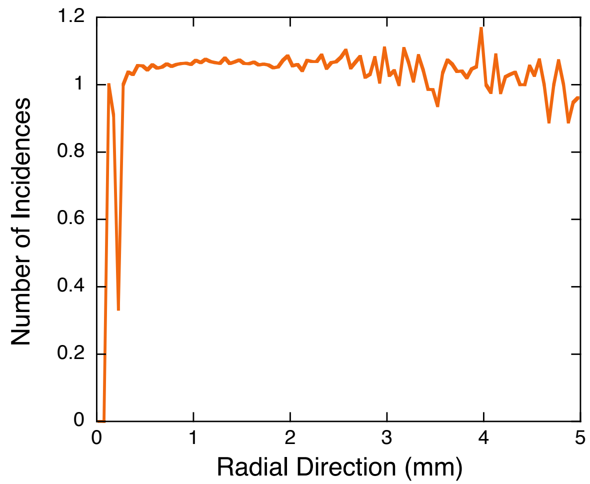
The projectiles having larger divergence angles fly longer distances in the capillary wall.







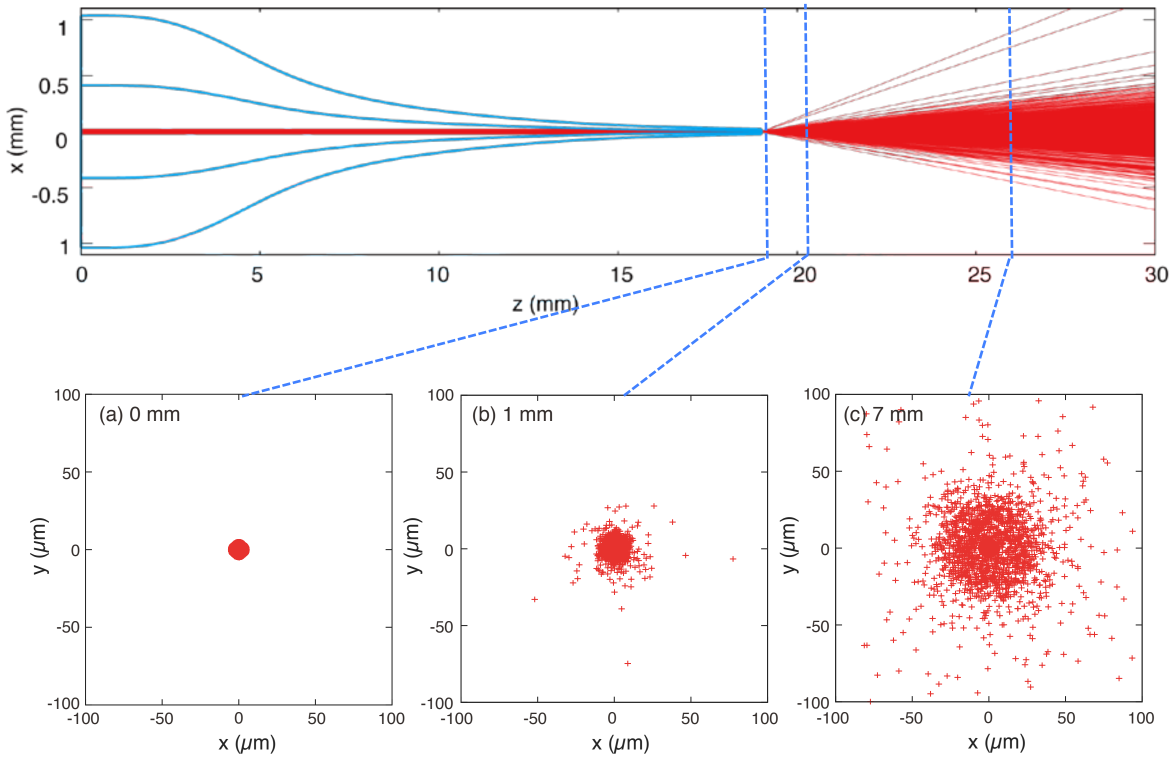


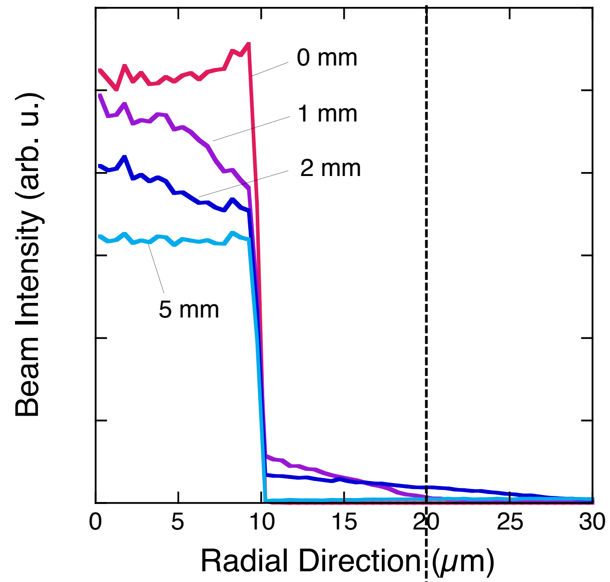


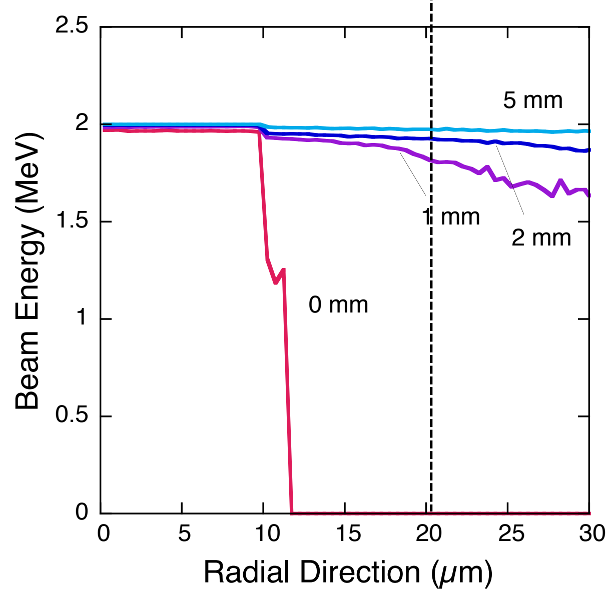
1 mm <-> 6.7 mrad

- Averaged projectile energy decreases with divergence angle, which is due to the projectile energy loss in the capillary.
- The number of bounces per projectile is almost unity.

The spot size of the capillary-focused beam strongly depends on the distance from the capillary outlet.

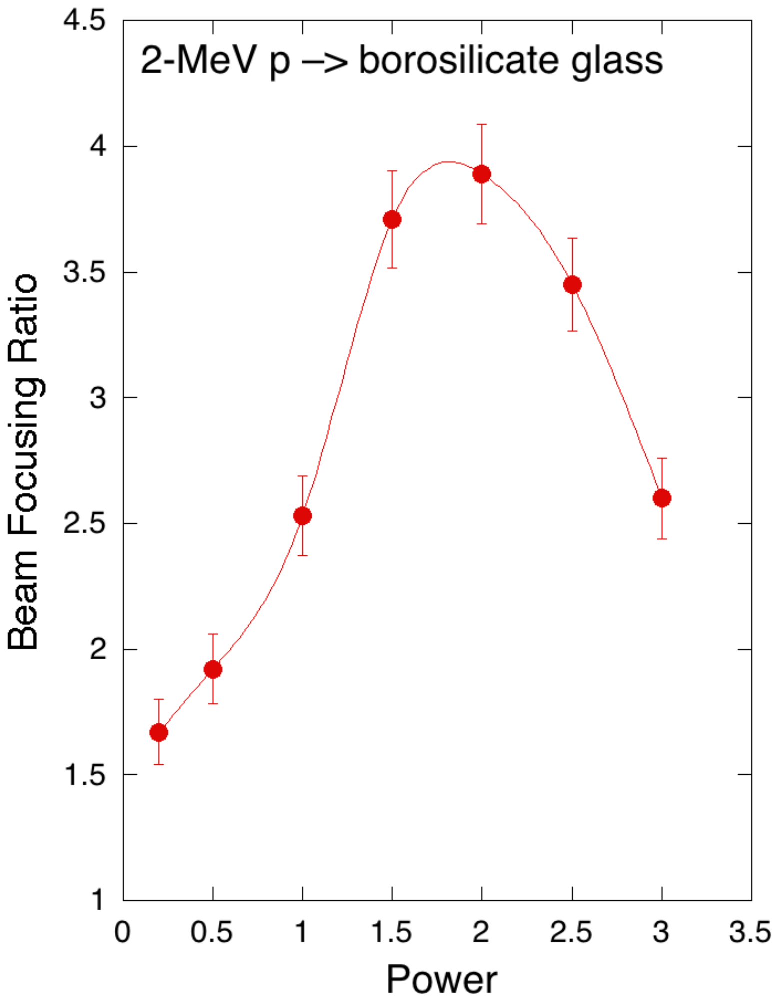


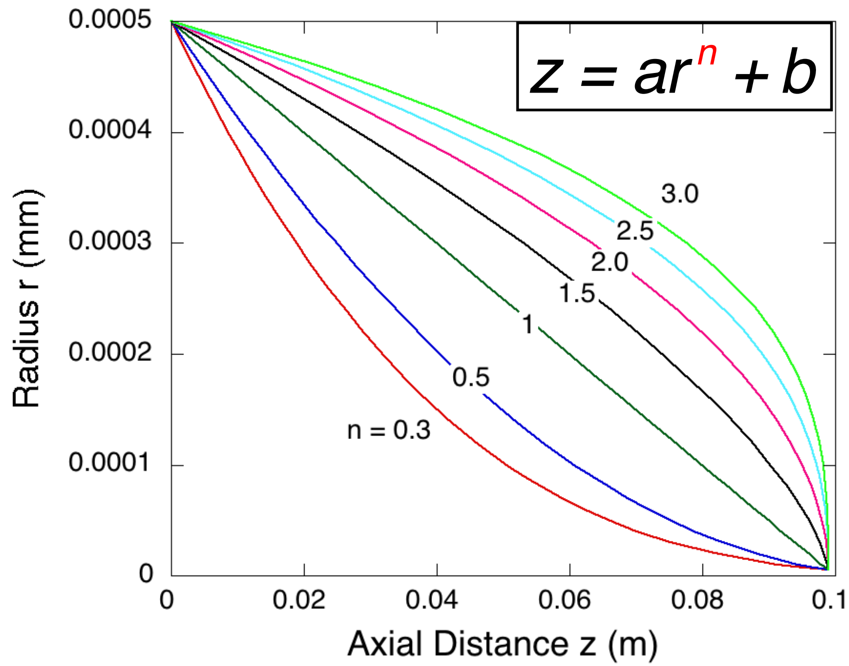




- The beam uniformity may be acceptable just after the capillary outlet.
- To use the focused (scattered) component, we need to put the target as close as possible to the capillary outlet.

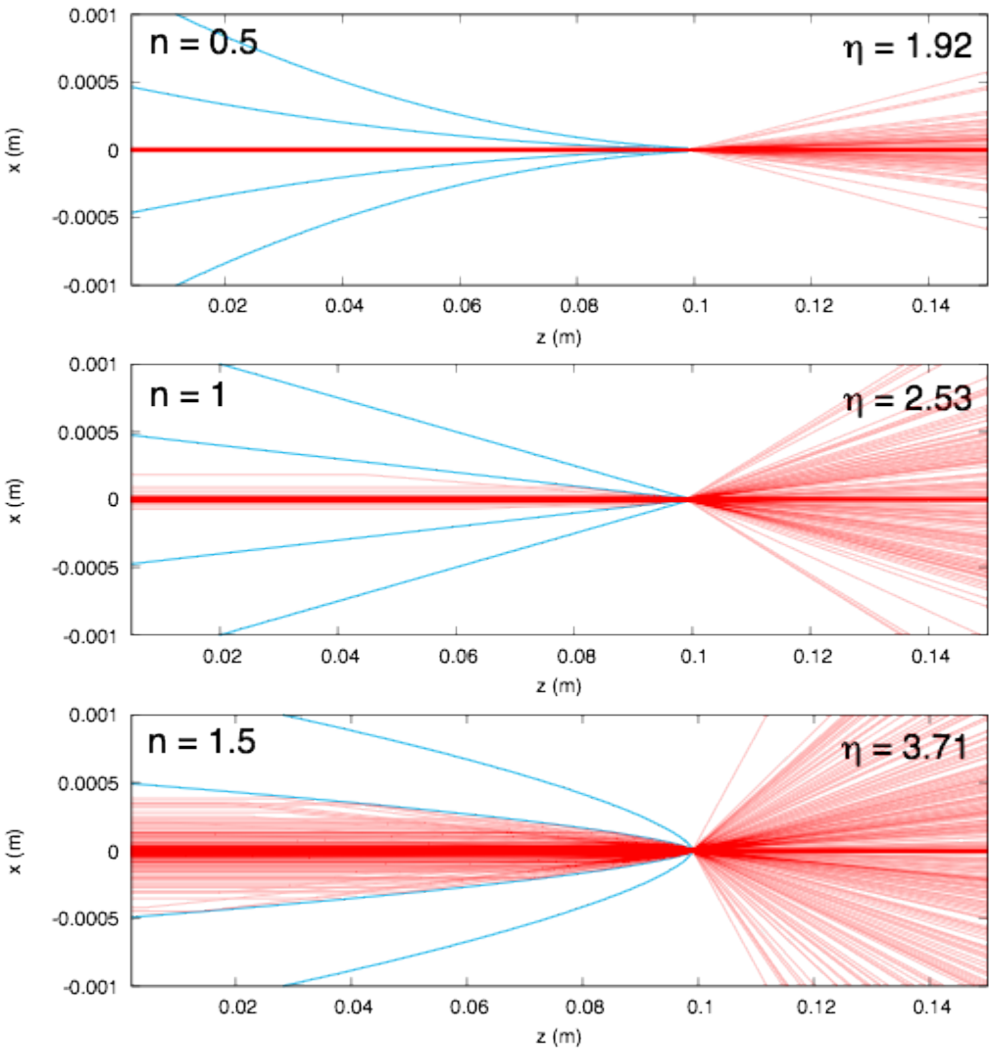
Concave inner wall improves ion transmission through the capillary.

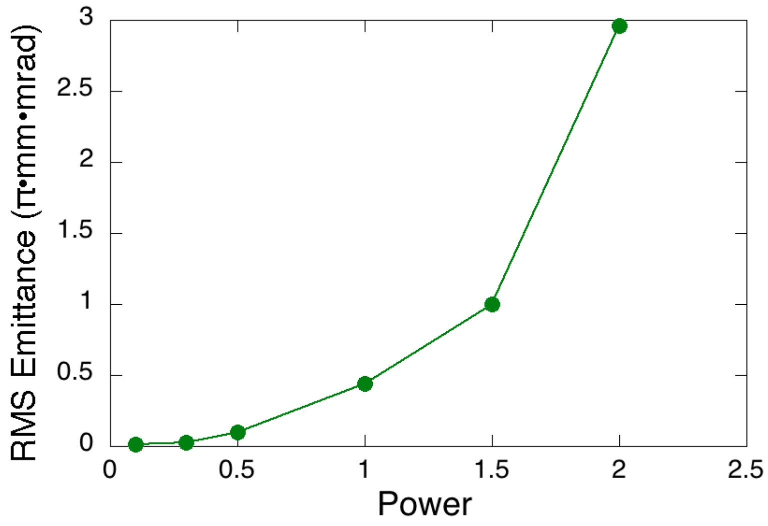




- The maximum transmission is obtained when the power index is 1.5 ~ 2.

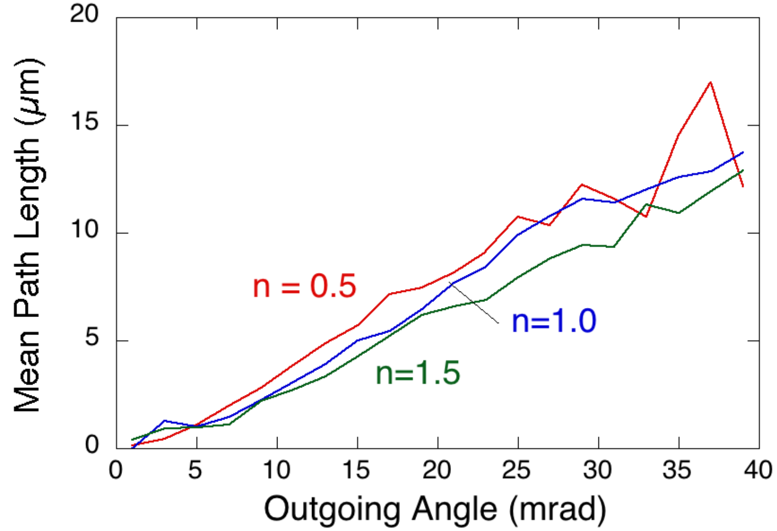
The utilization rate of the inner wall surface determines the ion transmission.

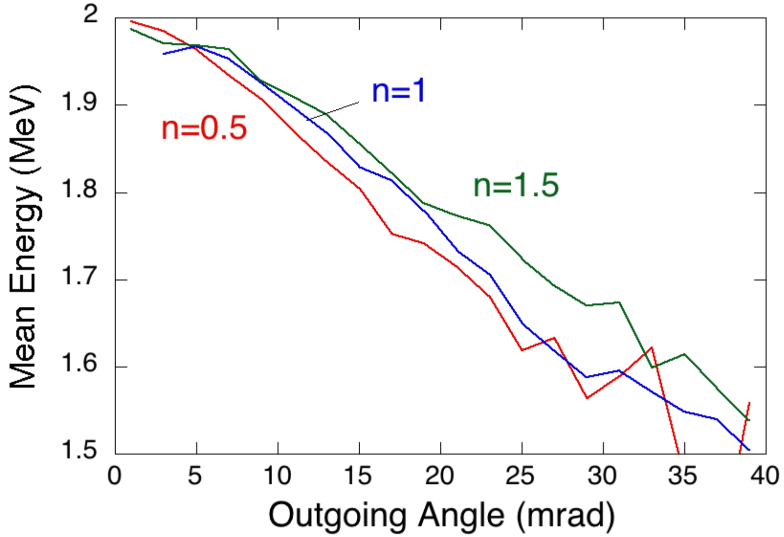


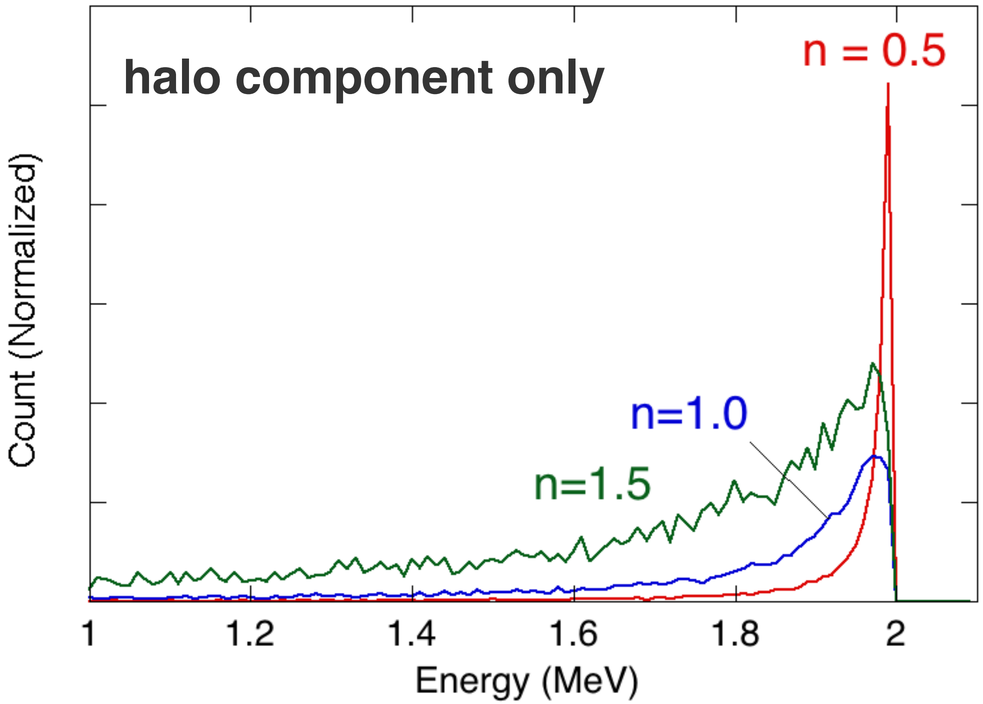


- The beam emittance increases with increasing power index of the wall shape function.

The projectile energy loss slightly deceases with increasing power index of inner wall curve.

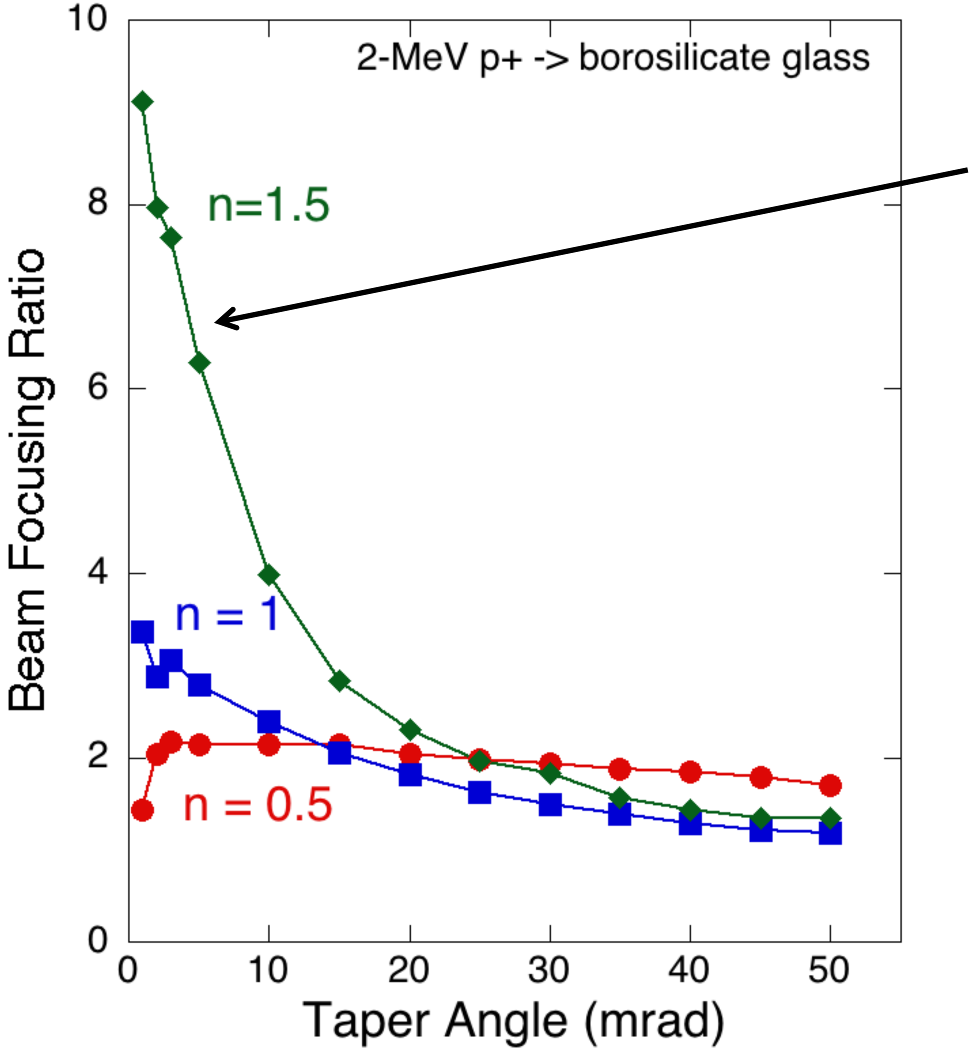






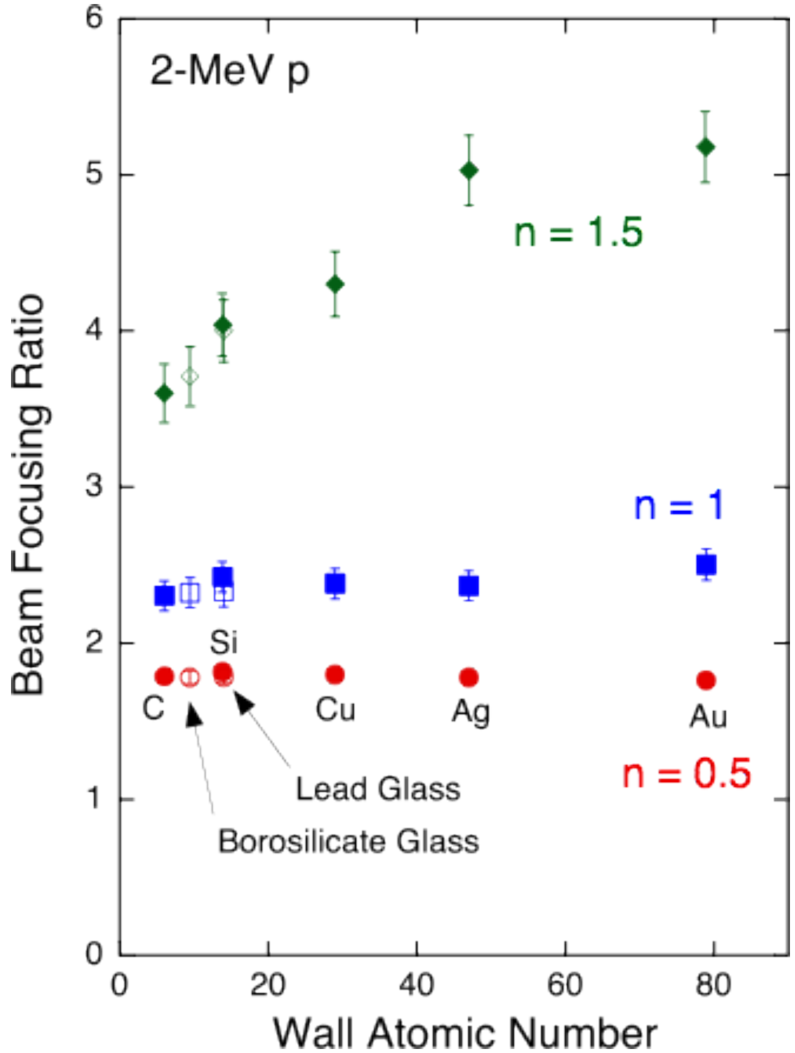
- Low-energy tail in the energy spectrum increases due to the increase in the scattered component for higher power index.

Beam focusing ratio of concave-inner-wall (n=1.5) capillary is drastically improved by decreasing taper angle.



- *η* ~ 10 is obtained with taper angles of several mrad.
- Efficient use of inner wall probably leads this enhancement.

Beam focusing ratio increases with increasing wall atomic number when concave inner wall is employed (n=1.5).



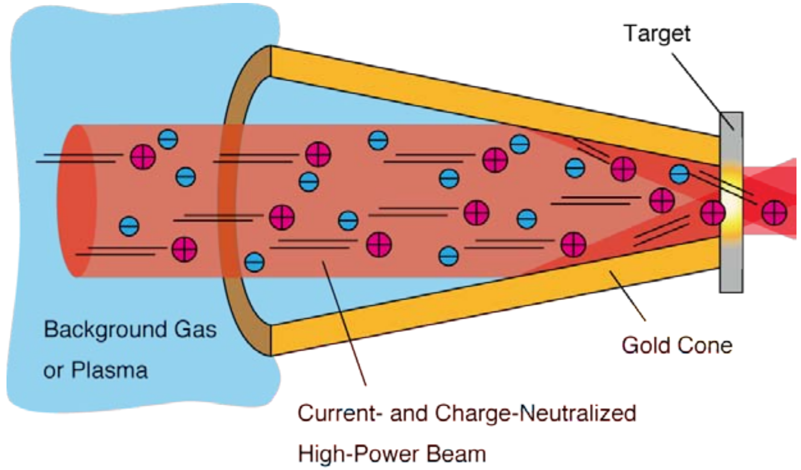
- In the case of convex inner wall (n=0.5), beam focusing ratio is almost independent of wall material.
- Beam focusing factor of composite-material (glass) capillary well predicted from the curve for single element material when the simple averaged wall atomic number is used.

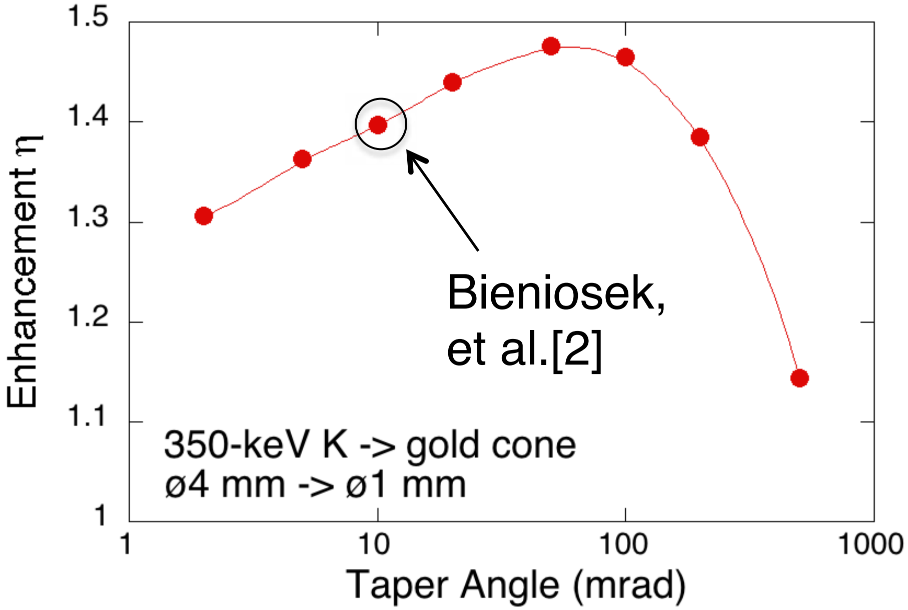
Glass	<Z>	$\langle Z^2 \rangle$
Borosilicate	9.4	9.9
Pyrex-Lead	13.8	21.2

Beam focusing using the tapered capillary (cone) might be adoptable to beam-driven WDM experiments.

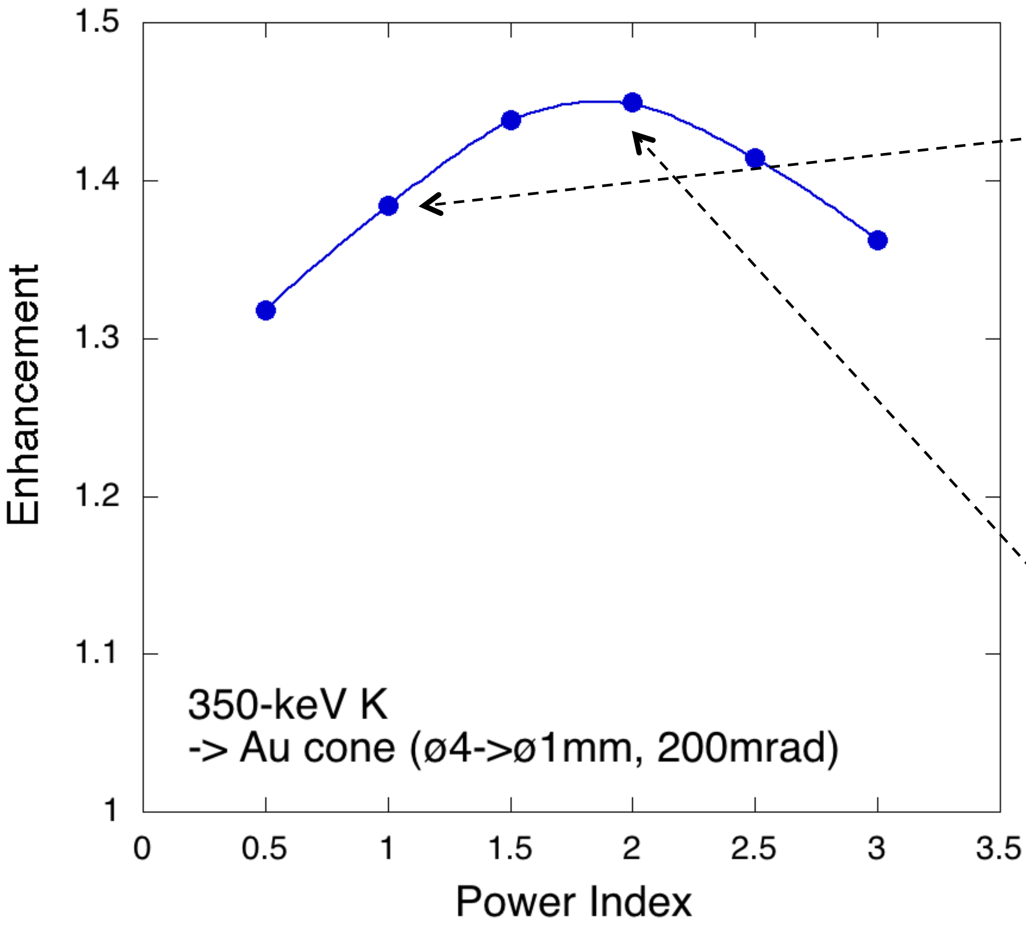
- Beam spot diameter is well defined on the target.
- No electromagnetic field is necessary for beam focusing, which enables us to use it for charge- and current-neutralized beams.
- The MC simulation predicts that the enhancement is around 1.4 for 350-keV K focused by 200-mrad gold cone, which is identical to the experimental results at LBL[2].

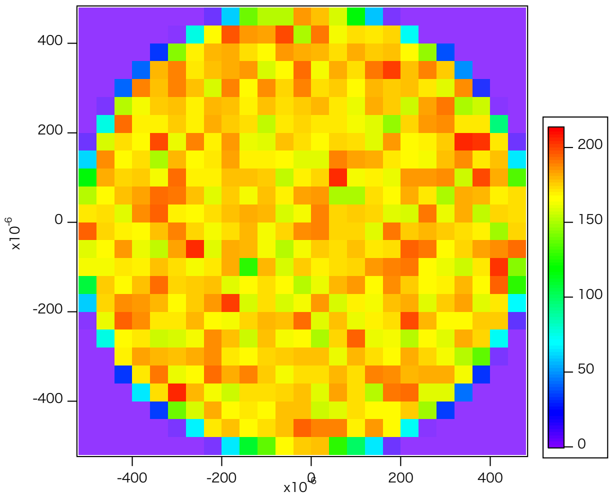
[2] F.M. Bieniosek, et al., Laser Part. Beams, **28**, 209 (2010).

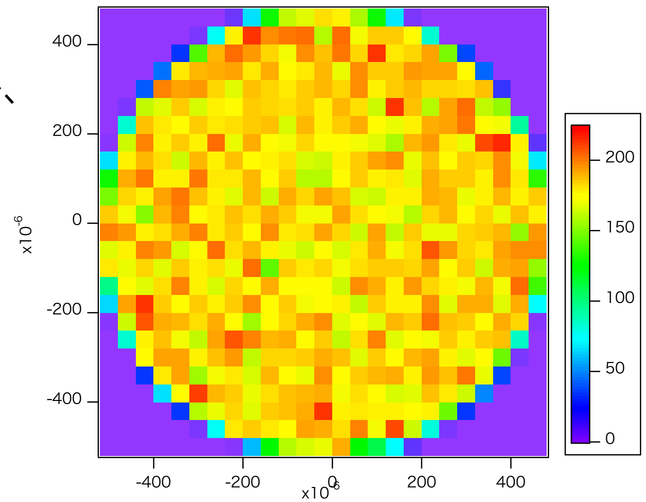




The beam enhancement reaches a maximum when the inner wall shape is parabolic.

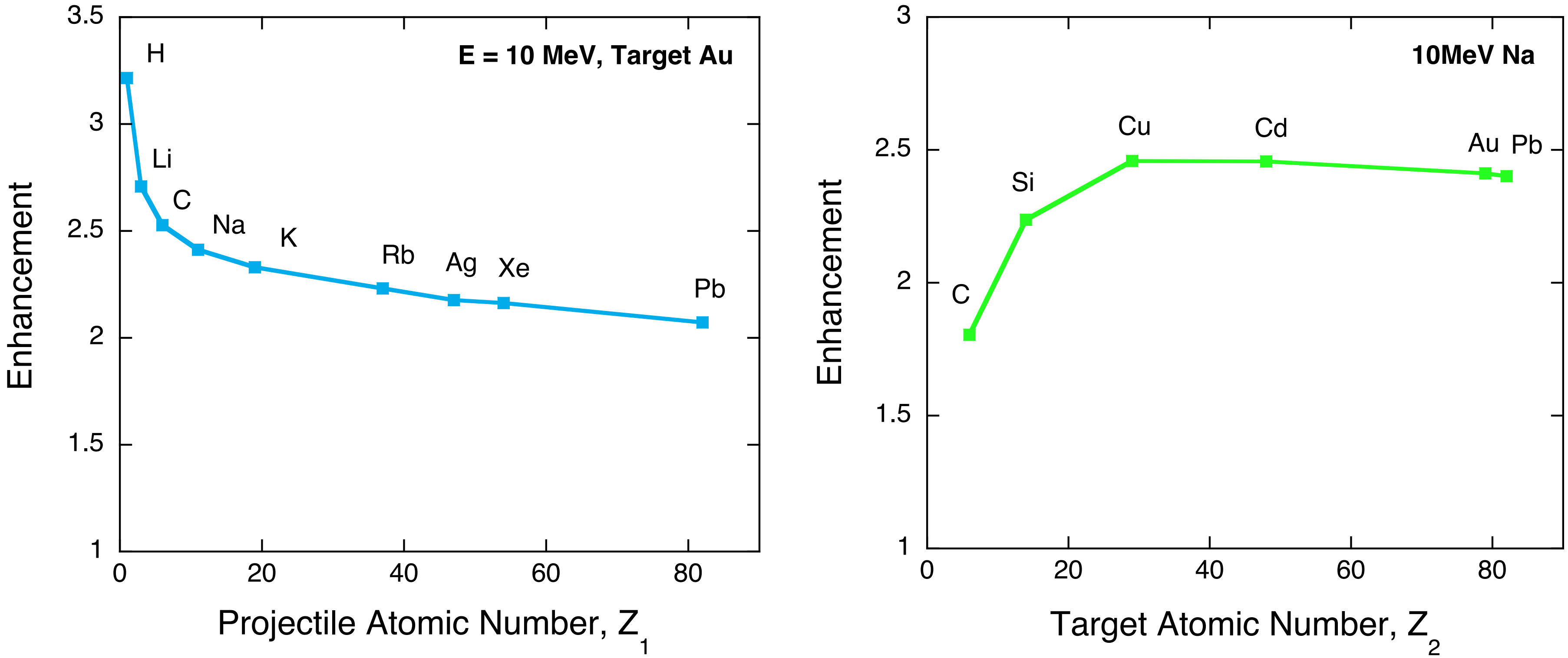






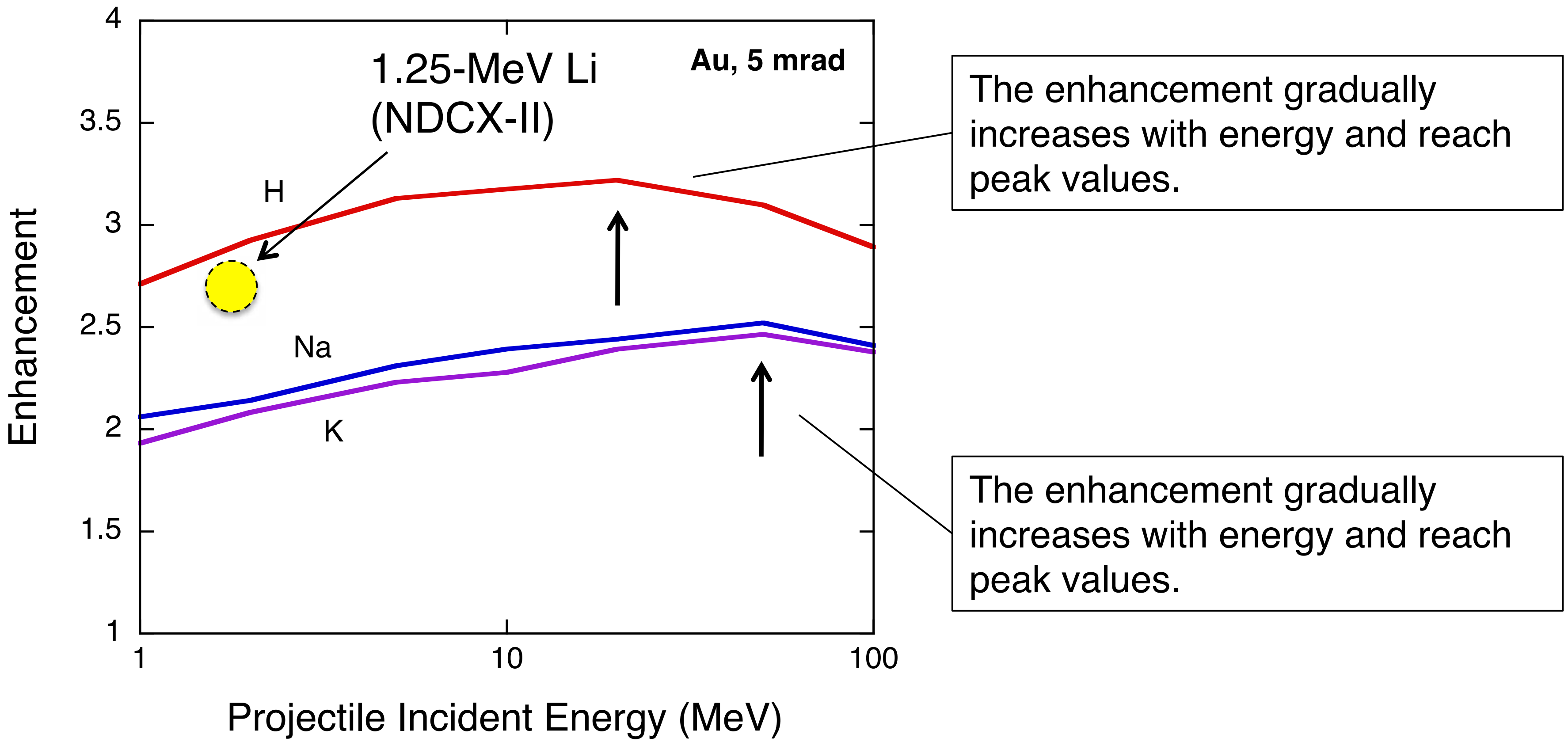
- The beam uniformity seems to get worse with the parabolic inner wall.

Dependence of enhancement on Z_1 and Z_2 was much weaker than expected from the Rutherford formula.



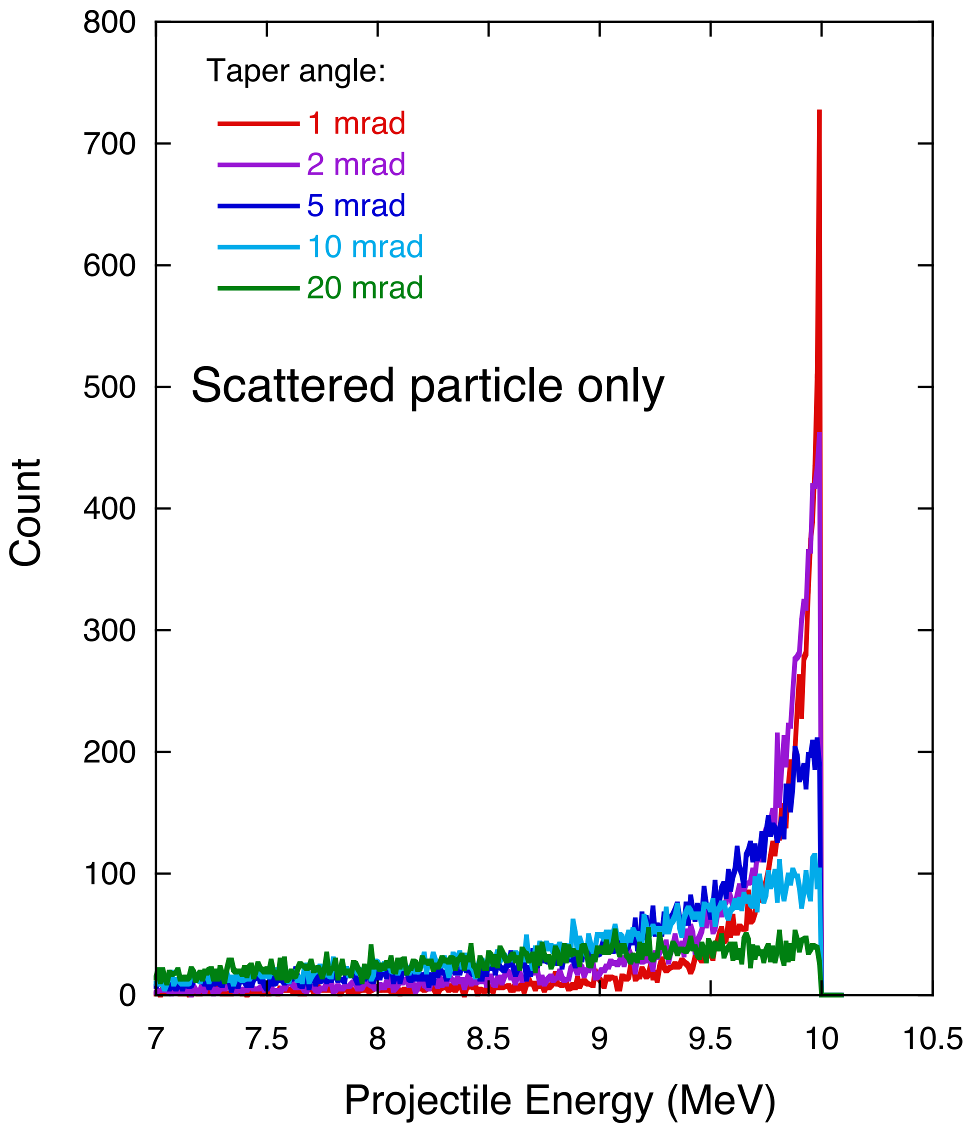
- The saturation of enhancement at higher target atomic number is probably explained by the increase in the energy loss.

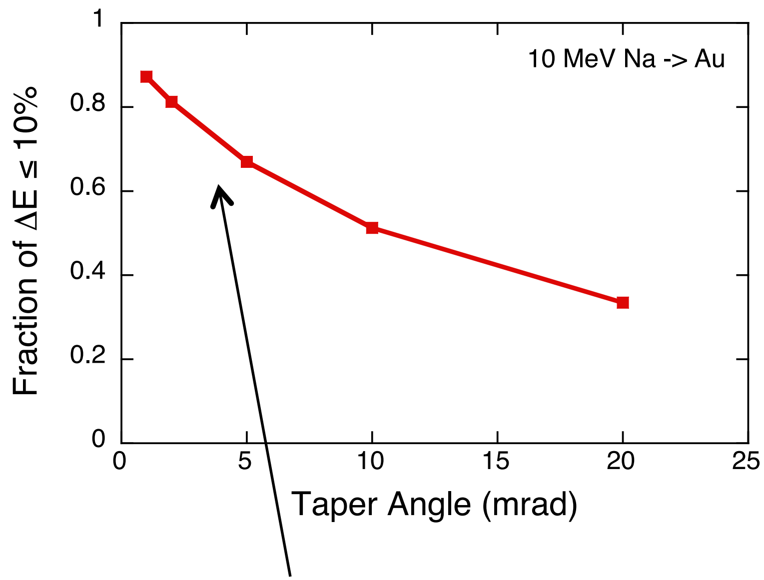
Enhancement depends weakly on the projectile incident energy.



- The increase in the enhancement in an energy region less than 10 MeV cannot be explained by scattering cross section, which is inversely proportional to the square of energy.
- The increases in the escape probability may explain it.

Sharp energy spectra of the scattered ion are available with very small taper angles.





- When the taper angle is less than 10 mrad, more than a half of scattered particles have energy losses less than 10%.

- But, the alignment of the capillary may be very severe with a taper angle less than 10 mrad.

Summary

- The focusing factor of the proton beam depends strongly on the capillary inner wall shape.
- The use of concave inner wall is effective to increase the beam transmission.
- The dependency on the wall material is smaller than expected, which may be explained by the escape probability of the projectile from the capillary wall.
- The capillary-beam-focusing scheme may be adoptable to the high-power beam focusing experiments in the MeV energy range.
- The uniformity of energy deposition in the target maybecome crucial depending on the cone parameters.