DEVELOPMENT OF THE CALCULATION METHOD OF INJECTION BEAM TRAJECTORY OF RIKEN AVF CYCLOTRON WITH 4D EMIT-TANCE MEASURED BY THE DEVELOPED PEPPER-POT EMITTANCE

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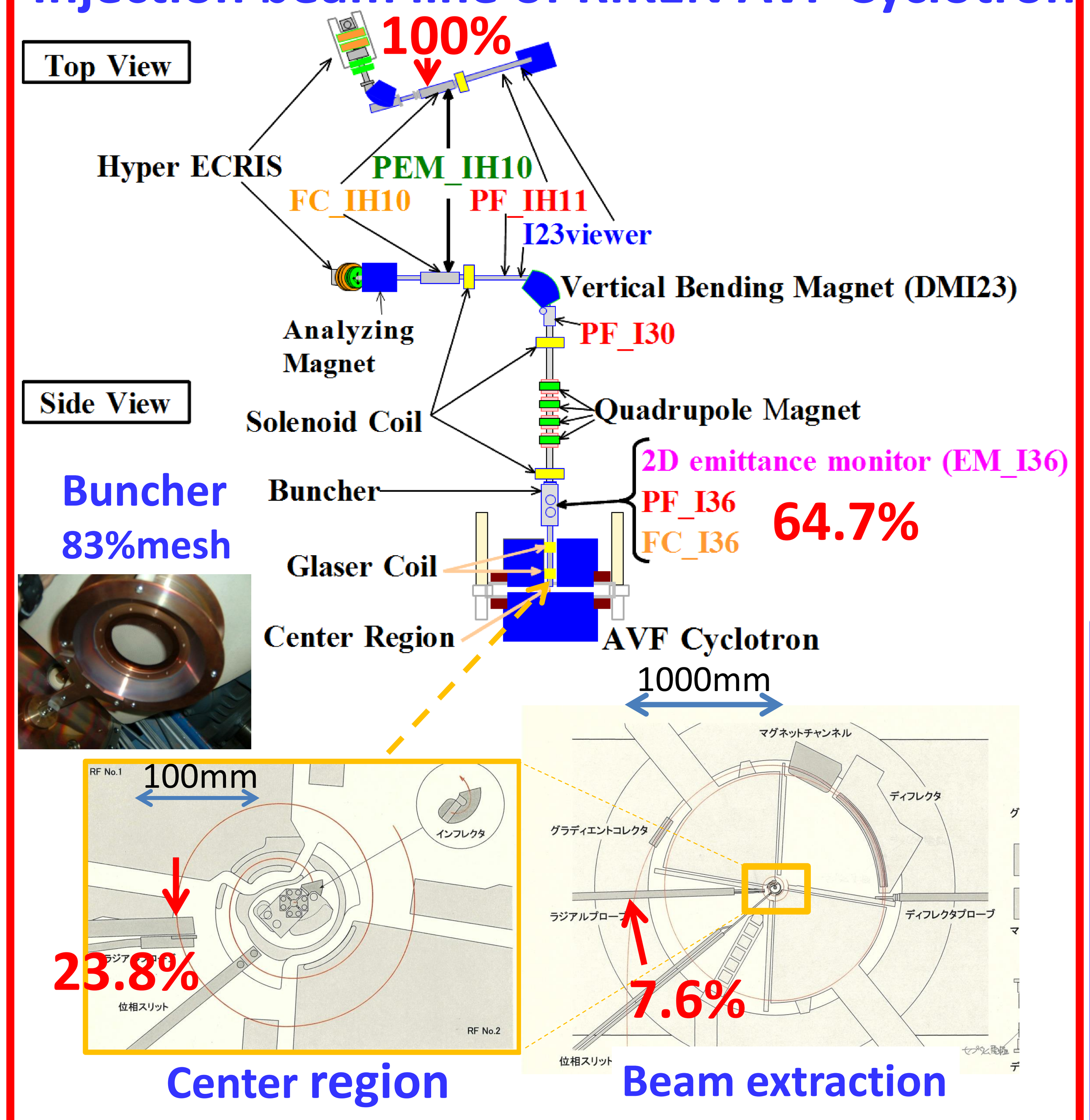
Injection beam line of RIKEN AVF Cyclotron



Red value is average transport efficiency . (Sep/11-Aug/13)

To solve the problem that transport efficiency is 23.8% in the injection line

1st step : try to understand beam transverse motion and examine cause of beam loss

→beam trajectory calculation = developing original calculation method

i) measuring 4D emittance (x, x' , y, y') by pepper-pot emittance monitor

ii) 4D emittance →Initial value for Lunge-Kutta method

iii) calculated 3D Magnetic Field Solenoid Coil, Quadrupole Magnet, Bending Magnet

iv) necessary to introduce Space Charge effect

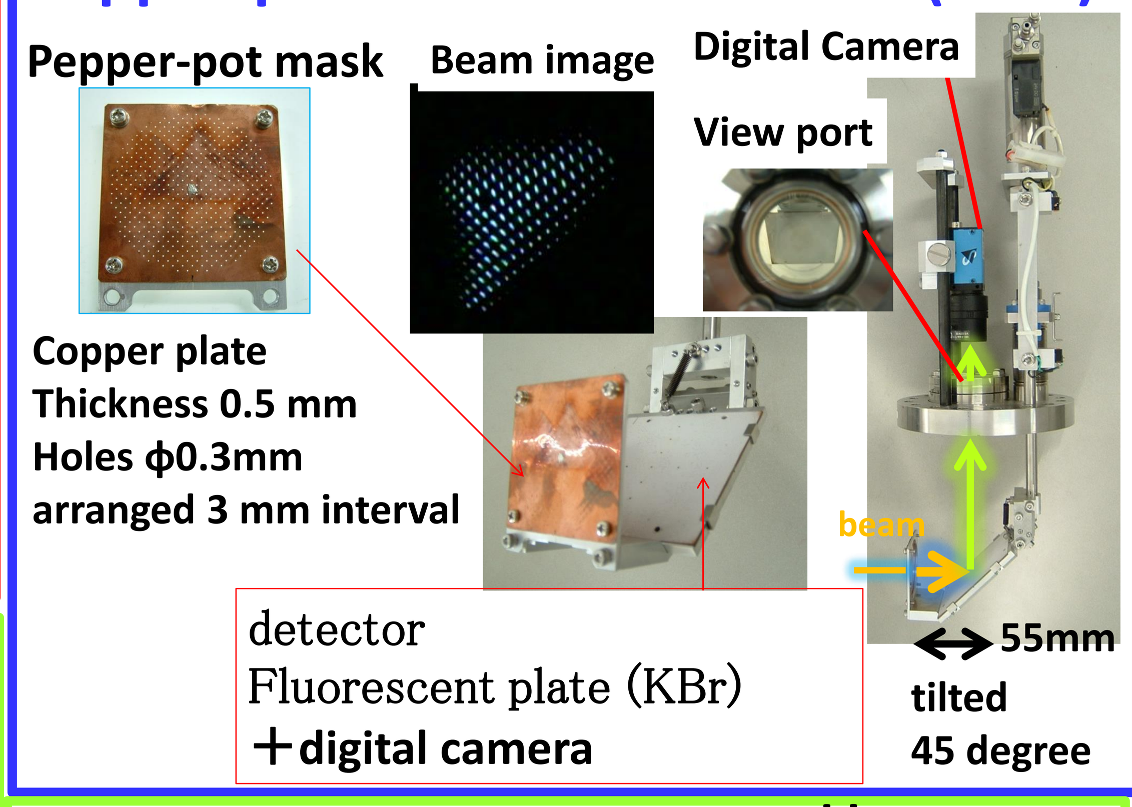
2nd step (in the future)

→Designing beam trajectories

i) constraining beam loss

ii) matching the beam acceptance of AVF Cyclotron

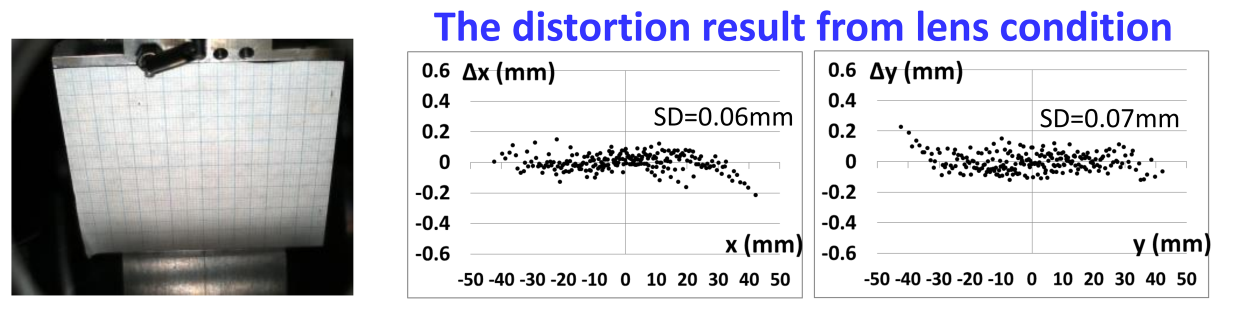
Pepper-pot emittance monitor (PEM)



Optimizing camera lens condition

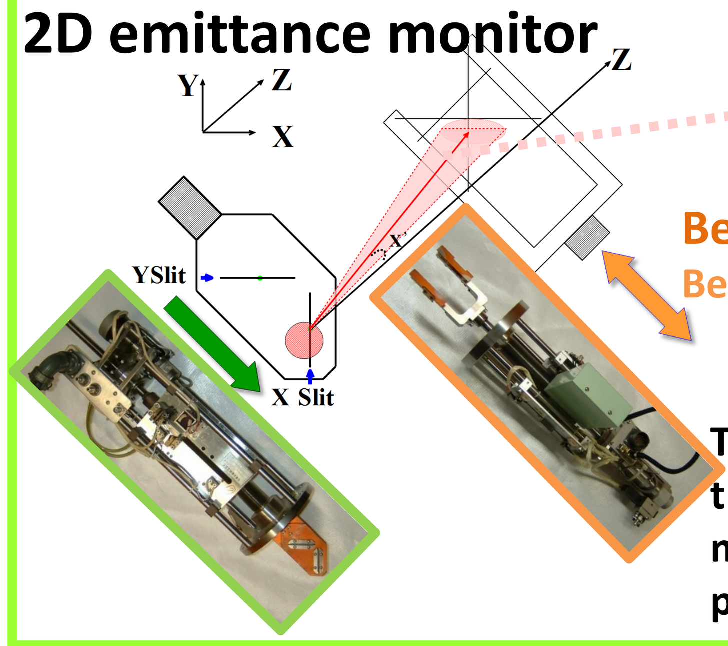
①choose 225 fiducial points at 5 mm interval in 70x70 mm²
②give real positions in the beam line to fiducial points
③measure bitmap position of the fiducial points on the digital image
④transform the bitmap coordinates to the fiducial points coordinates using the projective transform coefficient
⑤difference between fiducial points and their transformed position →distortion.

The distortion result from lens condition



GigE camera + lens (Tamron 13VM308AS)
lens condition : focal length 8mm object distance 250mm
→ image resolution 0.8mm/pixel SDx=0.06mm Sdy=0.07mm
→ angle resolution ～2mrad (if flight length is 55mm)

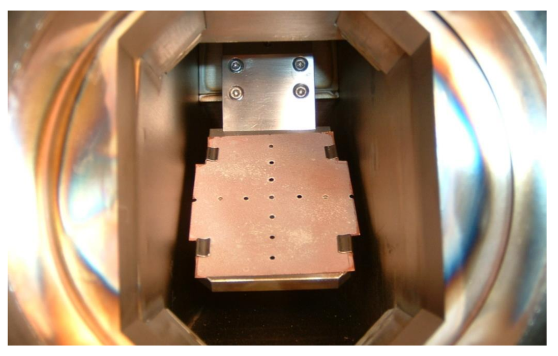
2D emittance monitor



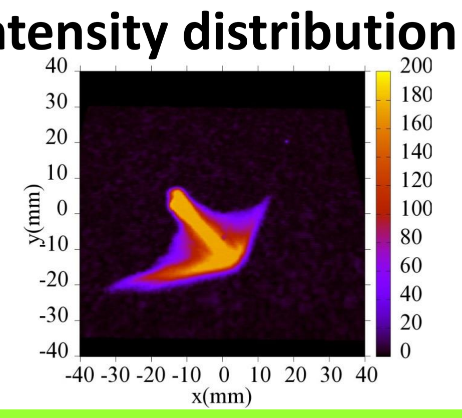
Beam profile monitor (BPM)
Beam intensity distribution

The profile of beam passing through slit in a position is measured by BPM. The position of slit at 2mm interval

I23Viewer



measured beam intensity distribution

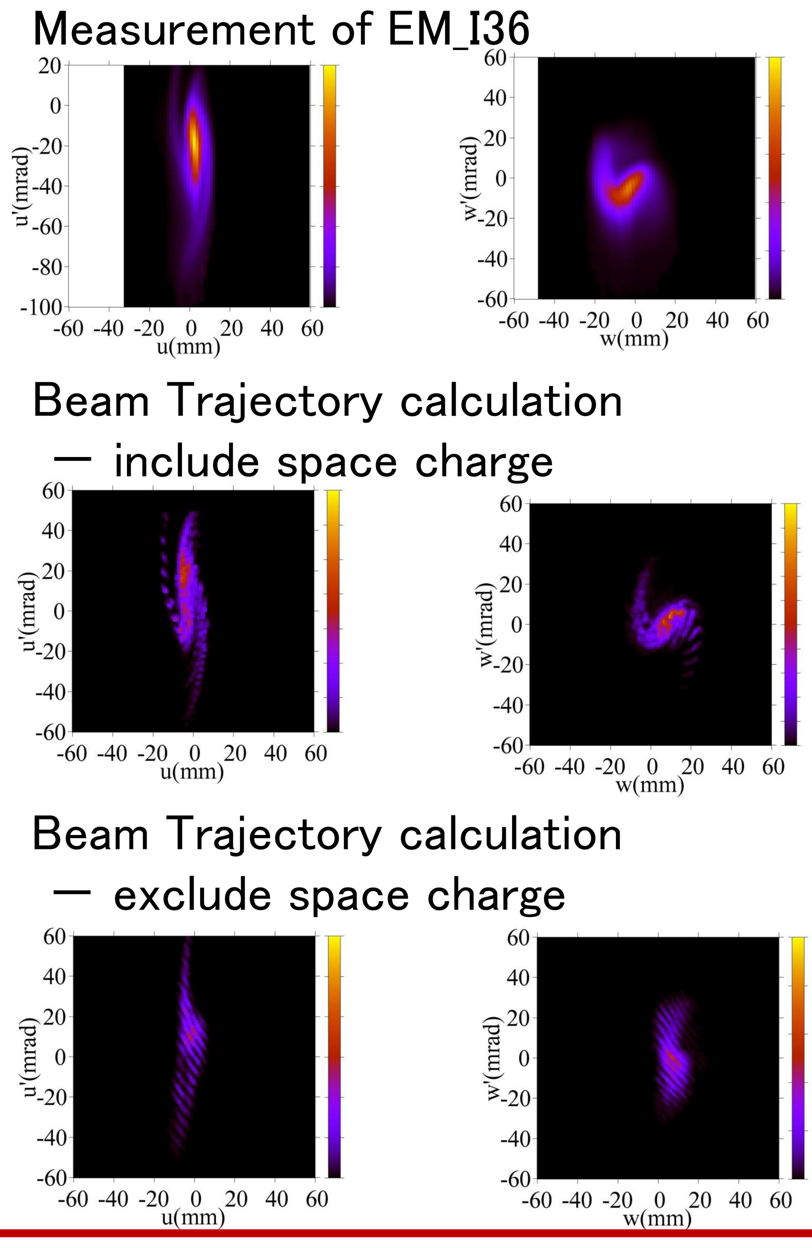


Comparison between Include and exclude Space charge effect

Measurement of EM_I36

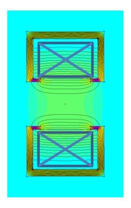
Beam Trajectory calculation — include space charge

Beam Trajectory calculation — exclude space charge



Developing beam trajectory calculation method

EOM of solenoid coil

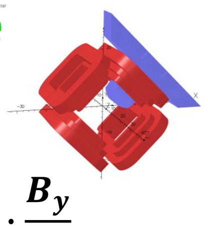


$$\frac{d^2x}{ds^2} = -2g\frac{dy}{ds} - \frac{dg}{ds}y$$

$$\frac{d^2y}{ds^2} = 2g\frac{dx}{ds} + \frac{dg}{ds}x \quad g = \frac{1}{2}\frac{q}{p}\cdot B_s$$

Magnetic field calculated by FEMM

EOM of quadrupole

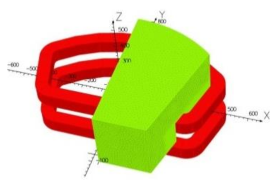


$$\frac{d^2x}{ds^2} = -kx$$

$$\frac{d^2y}{ds^2} = ky \quad k = \frac{q}{p}\frac{B_x}{dy} = \frac{q}{p}\frac{B_y}{dx}$$

Magnetic field calculated by TOSCA 3D

EOM of dipole



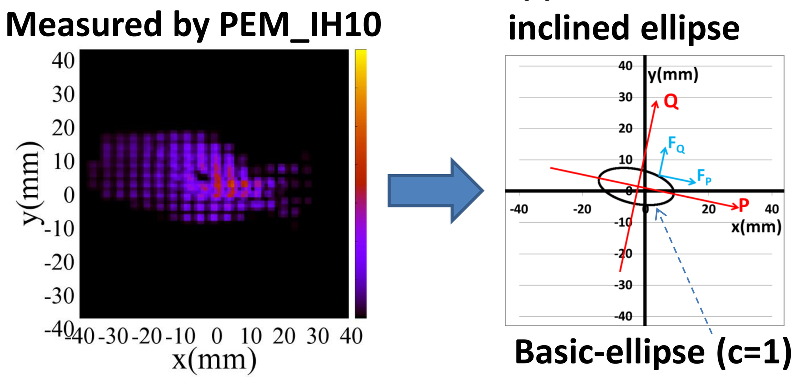
$$m\frac{d^2\vec{r}}{dt^2} = q(\vec{v}\times\vec{B})$$

$$\vec{r} = (X,Y,Z) \quad \vec{v} = \frac{d\vec{r}}{dt} \quad \vec{B} = (B_X, B_Y, B_Z)$$

Magnetic field calculated by TOSCA 3D

beam intensity distribution Measured by PEM_IH10

Approximate to inclined ellipse



Basic-ellipse (c=1)

Equation of motion for space charge effect

$$\frac{d^2x}{ds^2} = \frac{4\lambda r_p}{\beta^2\gamma^3 a(a+b)}(x - x_0)$$

If R=0, $$\frac{d^2y}{ds^2} = \frac{4\lambda r_p}{\beta^2\gamma^3 b(a+b)}(y - y_0)$$

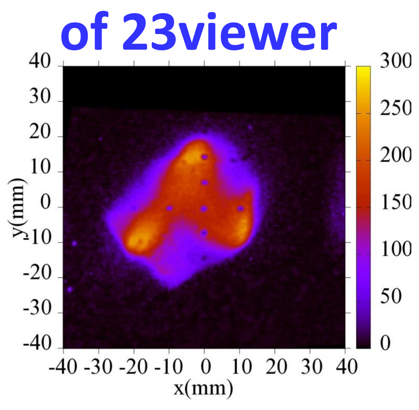
ellipse made from distribution statistically

$$\frac{(x-x_0)^2}{a^2} - \frac{2R}{ab}(x-x_0)(y-y_0) + \frac{(y-y_0)^2}{b^2} = 1 - R^2$$

$$x_0 = \langle x\rangle, y_0 = \langle y\rangle, a = RMS_x\cdot c, b = RMS_y\cdot c, R = \frac{RMS_{xy}}{RMS_x\cdot RMS_y}$$

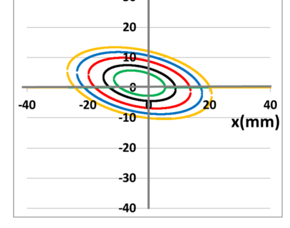
Two models for Space charge effect

Measurement of 23viewer



Multistep-ellipse

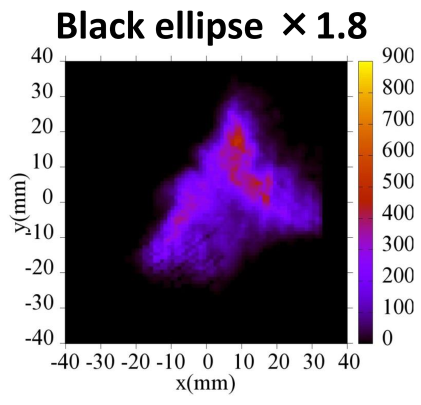
example



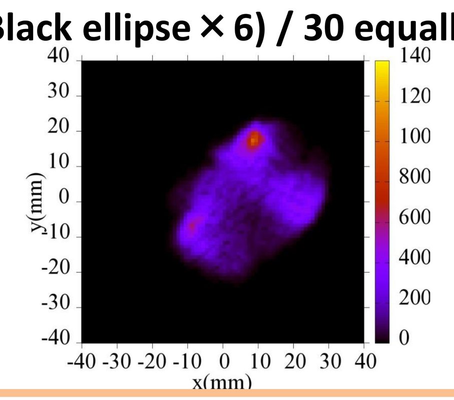
green < element < black	green–ellipse
black < element < red	black–ellipse
red < element < blue	red–ellipse
blue < element < orange	blue–ellipse
	orange–ellipse

Single-ellipse

Approximate by one ellipse
Black ellipse × 1.8



Approximate by 30 ellipses
(Black ellipse × 6) / 30 equally



Evaluation method

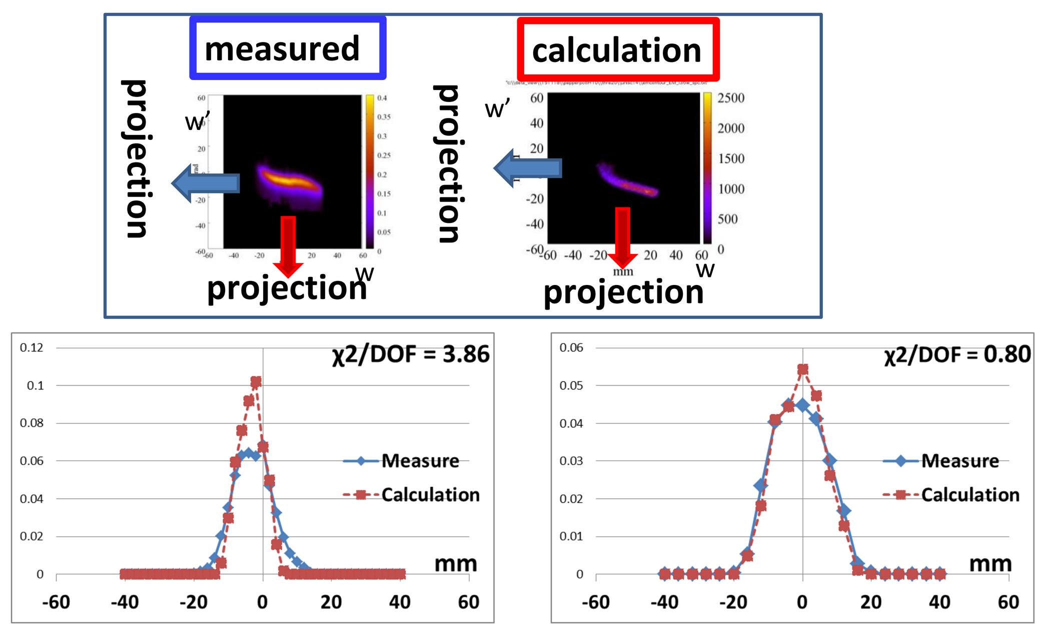
- Compare Beam Trajectory calculation with other diagnostic measurement
- Quantifying the degree of fit by χ2/DOF

$\chi^2 = \Sigma(C_i - M_i)^2/\sigma^2$

σ=10%of highest value of Measurement

normalizing area to 1

For 2D distribution, make projection to arbitrary coordinate



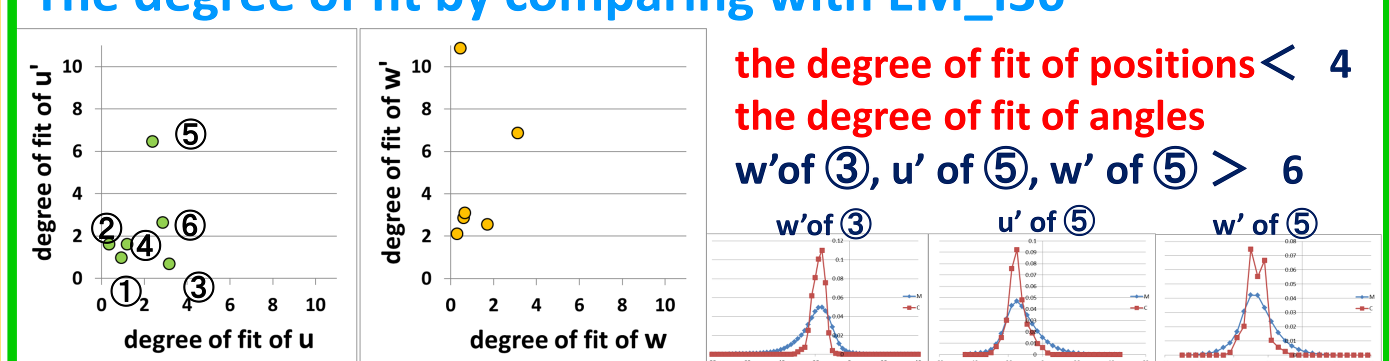
Quasi χ2/DOF is named degree of fit

Beam test for the evaluation

Test beam

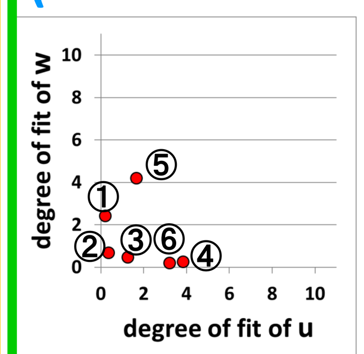
	Ion	E (keV)	Intensity(eμA)
1	$^4He^{2+}$	15.4	124
2	$^2H^+$	12.64	100
3	$^4He^{2+}$	15.4	196
4	$^4He^{2+}$	15.4	308
5	$^4He^{2+}$	15.4	187
6	$^2H^+$	12.8	214

The degree of fit by comparing with EM_I36



the degree of fit of positions < 4
the degree of fit of angles
w'of ③, u' of ⑤, w' of ⑤ > 6

The degree of fit by comparing with PF_I36 (107.5mm behind EM_I36)



all the degree of fit < 4.2
→not so large as the degree of fit of angle of EM_I36
(possible cause)
the measured angle of EM_I36 may be fault. They contain noise because the zero level of signal becomes uneven by secondary electrons made from beam.

The degree of fit by various exposure time and gain of digital camera and 2 kinds of thickness of KBr

thicness 1.9 μm — Gain (dB): High ← → Low; Exposure time (sec): long ↑ ↓ short

	15	13	11	9	7	5
1/10	1.33	0.97	0.77	0.68	0.63	0.68
1/20	0.91	0.8	0.69	0.65	0.79	1.1
1/38	0.81	0.63	0.64	0.81	1.43	1.73

thickness 34.6 μm — Gain (dB): High ← → Low; Exposure time (sec): long ↑ ↓ short

	15	13	11	9	7	5
1/10	1.68	1.38	1.1	0.93	0.51	0.51
1/20	1.19	0.94	0.67	0.49	0.64	1.04
1/38	0.72	0.56	0.5	0.79	1.52	1.86

$$\text{Thickness} \equiv \frac{\text{The weight of fluorescent agent KBr(g)}}{\text{area}(80\times 80\ mm^2)\times\text{density of KBr }(2.75g/cm^3)}$$

Conclusion

- The improved PEM and developed beam trajectory calculation method can be used in practical way.
- we can start the 2nd step
- Moreover, examine the degree of fit of various ion species, beam intensity, and energy to see measurement limit.