同位体計測用TOF型質量分析器の開発

Development of high-resolution TOF mass spectrometer for isotope analysis

横田勝一郎

Mass analysis

Earth's MS: H+, He+, He++, O+

AKEBONO
(*Kaya et al.*, 1990)
GEOTAIL
(*Hirahara & Mukai*, 1993)

→

SCOPE & ERG
Under development
TOF型
M/ΔM= 10

Moon, Mercury, … : Na+, K+, …

KAGUYA
(*Yokota et al.*, 2005)
M/ΔM= 20

→

BepiColombo
(*Delcourt et al.*, 2009)
FM in preparation
LEF-TOF型
M/ΔM= 40

Isotope analysis: M/ΔM > 100

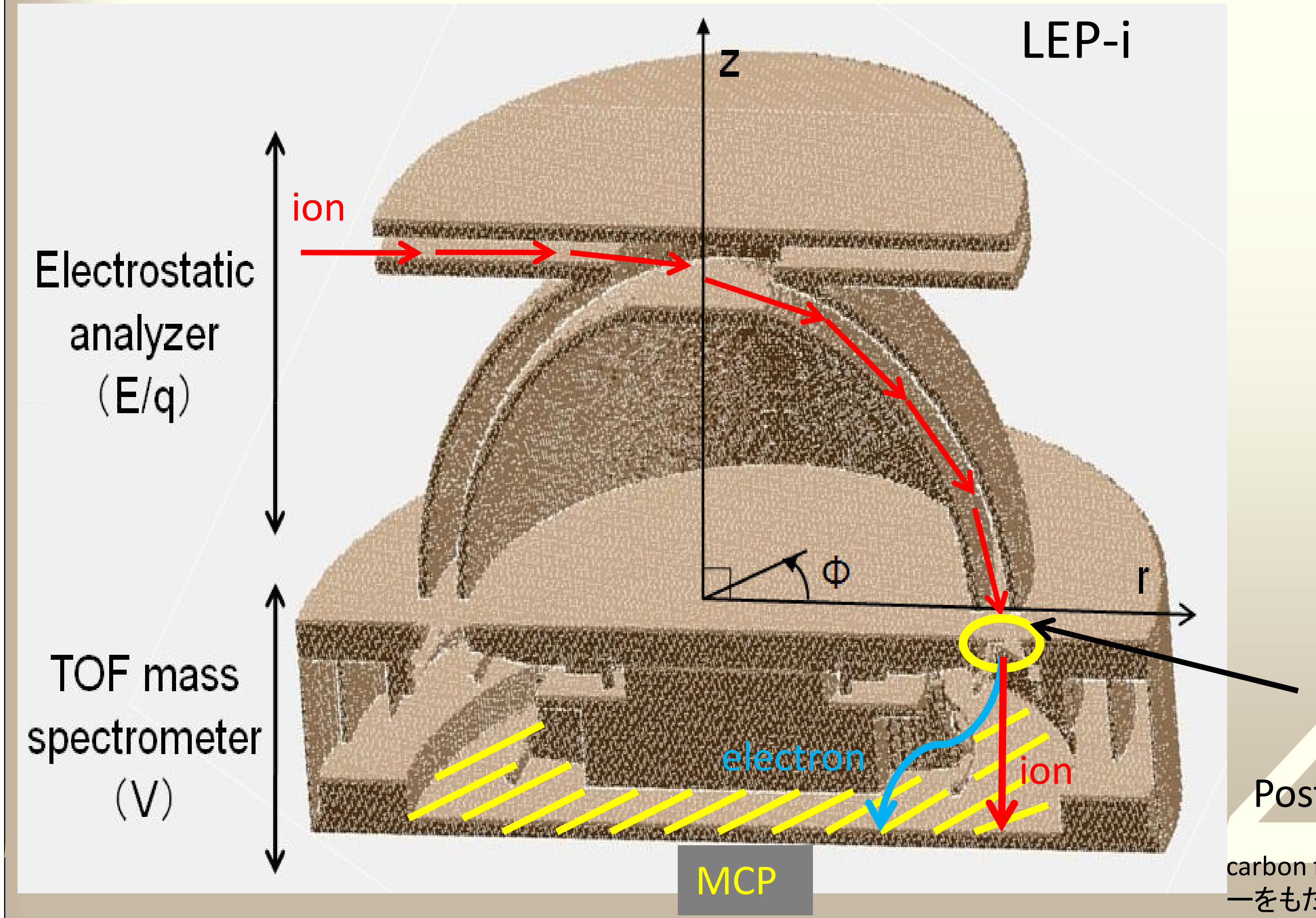
→

MELOS
Under development
M/ΔM > 100~3000

Time-Of-Flight(TOF) mass analysis

- SCOPE and ERG
  - TOF analysis
- KAGUYA and MMO
  - LEF-TOF analysis
- Isotope analyzer
  - 2段加速 Two-stage accelerator
  - リフレクトロン Reflectron
  - **MULTUM-S 2**

SCOPE & ERG (地球磁気圏探査衛星)
太陽風、地球磁気圏起源のイオンを観測する

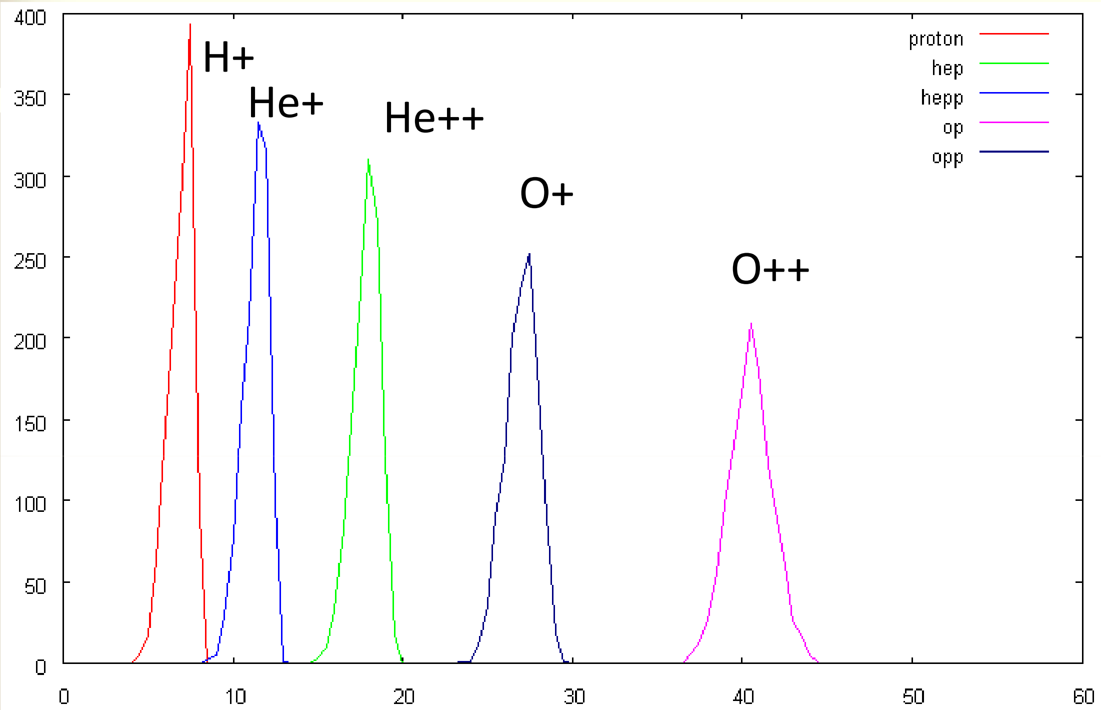


[*Uchida* 2008] modified

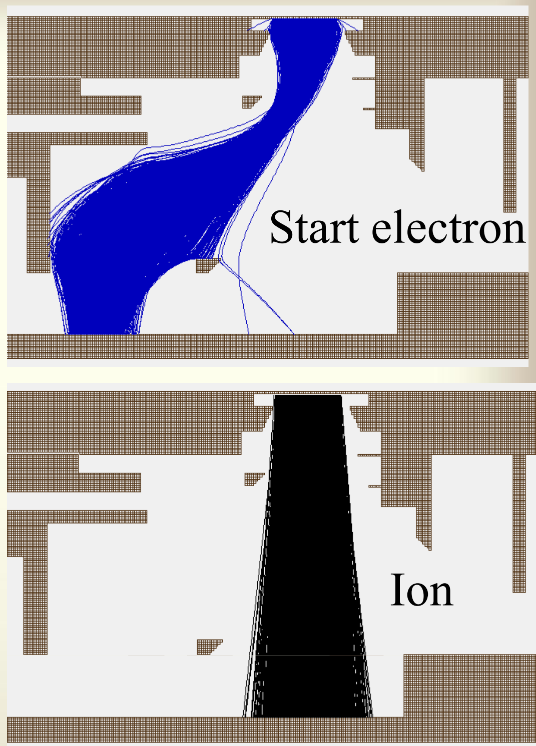
Post acceleration

carbon foilを通過できるだけのエネルギーをもたせるために+5kV加速させる

SCOPE & ERG



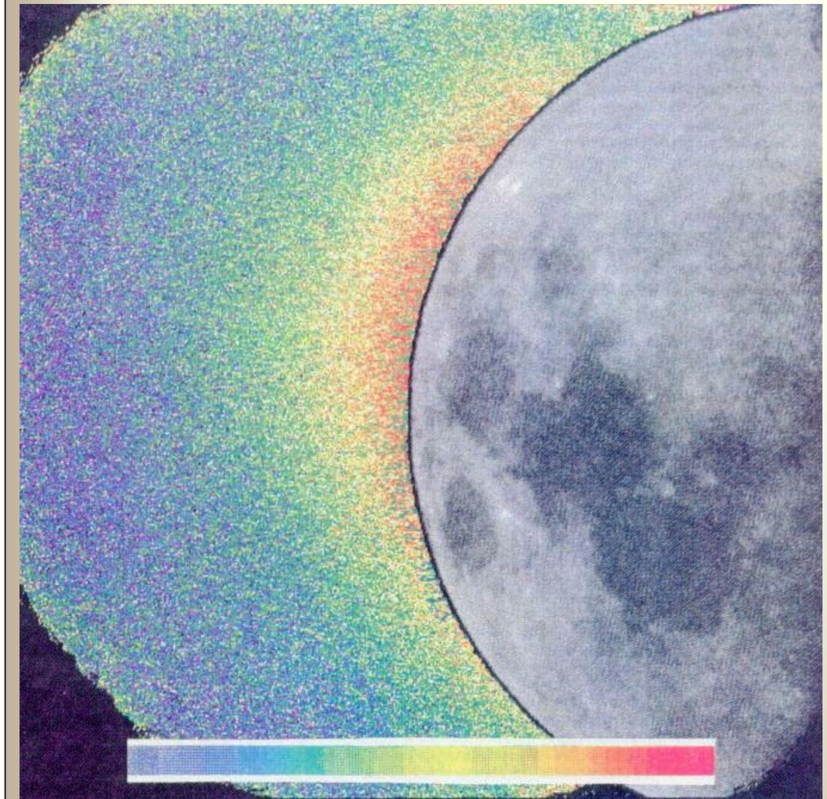
TOF (ns)



Field of view: 6 deg. x 360 deg.
Angular resolution: 22.5 deg. x 22.5 deg.
Energy range: 10 eV/q–25 keV/q
Energy resolution: 16%
Mass range: 1–64 amu
Mass resolution: $m/\Delta m = 10$ (<15 keV/q);
G-factor: 2.6e-3 cm^2 sr eV/eV

[*Shirai* 2010]

Lunar exosphere



Na exosphere

Potter and Morgan 1998

Astronomical objects with no substantial atmosphere, such as the Moon, Mercury or asteroid are surrounded by tenuous atmosphere derived from its surface materials. It is called a surface-bounded exosphere, and generated by the interaction between the surface and the solar wind, solar photon and micro-meteoroid. The lunar surface-bounded exosphere has been observed by ground-based telescopes on many occasions since its discovery. The observed exospheric components are mostly alkali atoms such as Na or K because the emission lines are much brighter than those of other conceivable components. The structure, source, and the transport mechanisms of the lunar exosphere have been discussed based on the ground-based observations.

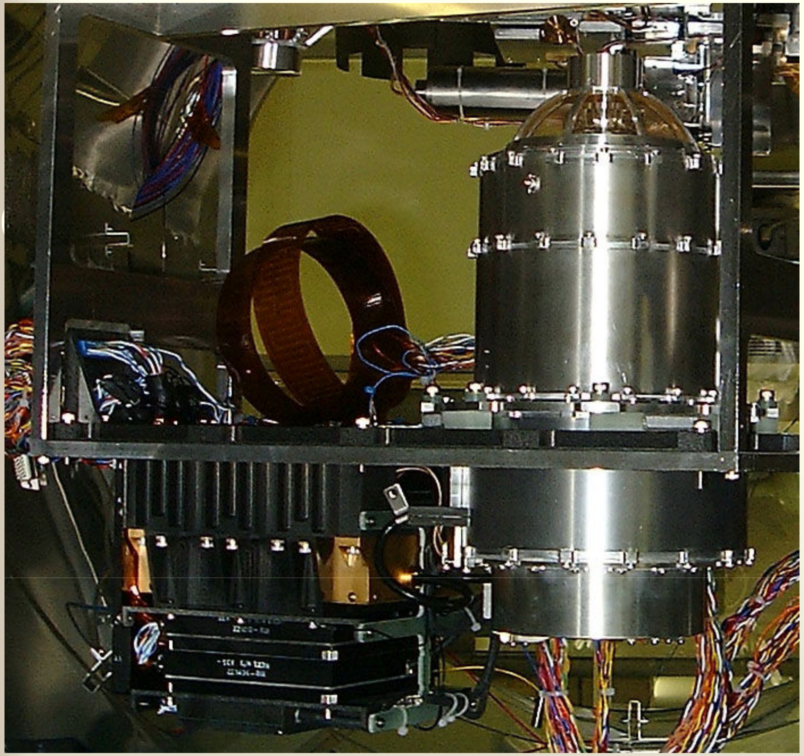
Ground-based observations found:
- Na (30/cc) and K(15/cc)
- Dependence on the SZA

Source mech.
- -UV(Photon-Stimulated Desorption)
- -SW sputtering
- -Thermal desorption
- -Micro-meteoroid

Loss mech.
- -Radiation pressure
- -Photo-ionization + Solar wind

Gardening effect (Solar wind)

Ion mass analyzer(IMA) of MAP/PACE



Field of view: 2 pi.

Angular resolution: 5.625 deg. x 5.625 deg.

Energy range: 5 eV/q–28 keV/q

Energy resolution: 10%

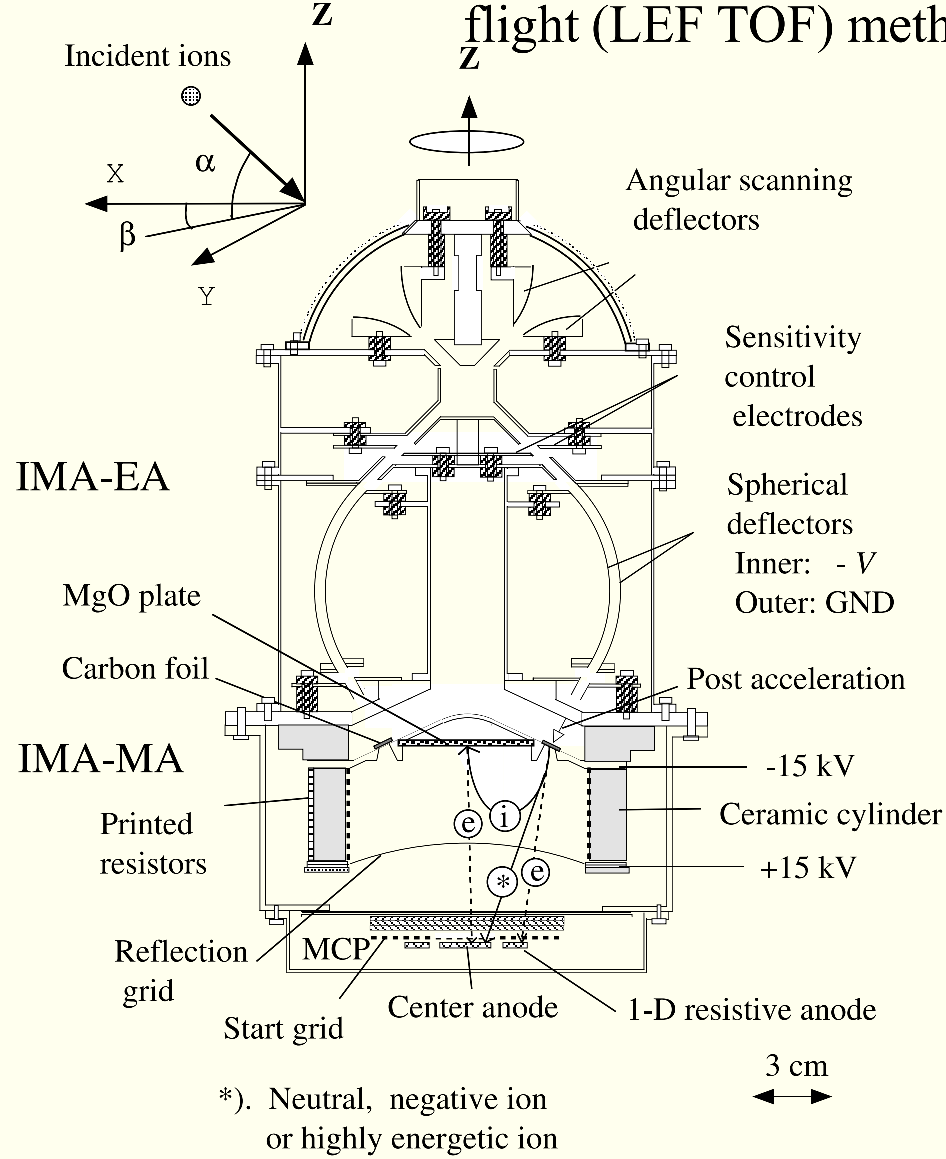
Mass range: 1–60 amu

Mass resolution: $m/\Delta m = 20$ (LEF);
$m/\Delta m = 10$ (Neutrals)

Time resolution: 1 s for 3D (32 energy steps)

G-factor: 10^-4 – 10^-6 cm^2 sr eV/eV

Linear-electric-field time-of-flight (LEF TOF) method



Yokota et al. 2005

Ion mass analyzer(IMA) of MAP/PACE

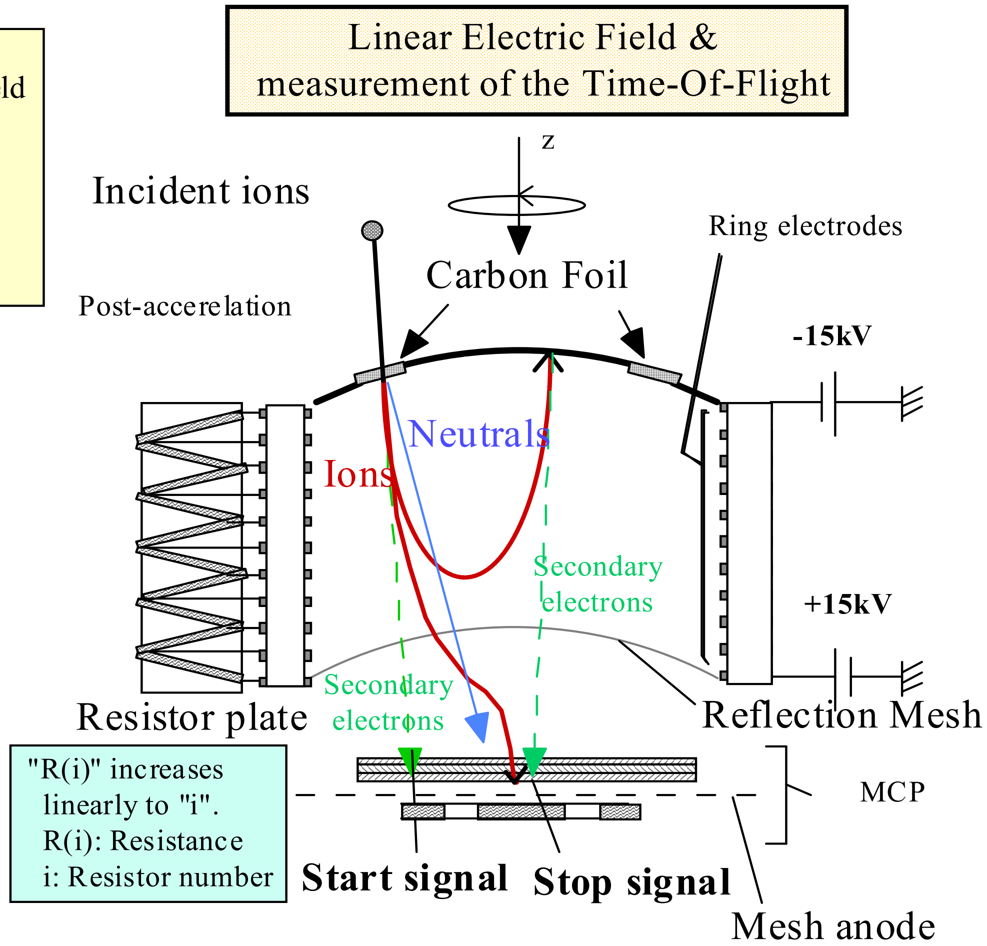
$E_z = -Cz$:Linear Electric Field

$$m\frac{d^2z}{dt^2} = qE$$

$$T_{tof} = \pi\sqrt{\frac{m}{qC}}$$

C : const
E : electric field
m: mass
q : charge
T : Time-of-Flight

Flight time of the ion is only dependent upon the mass/charge.



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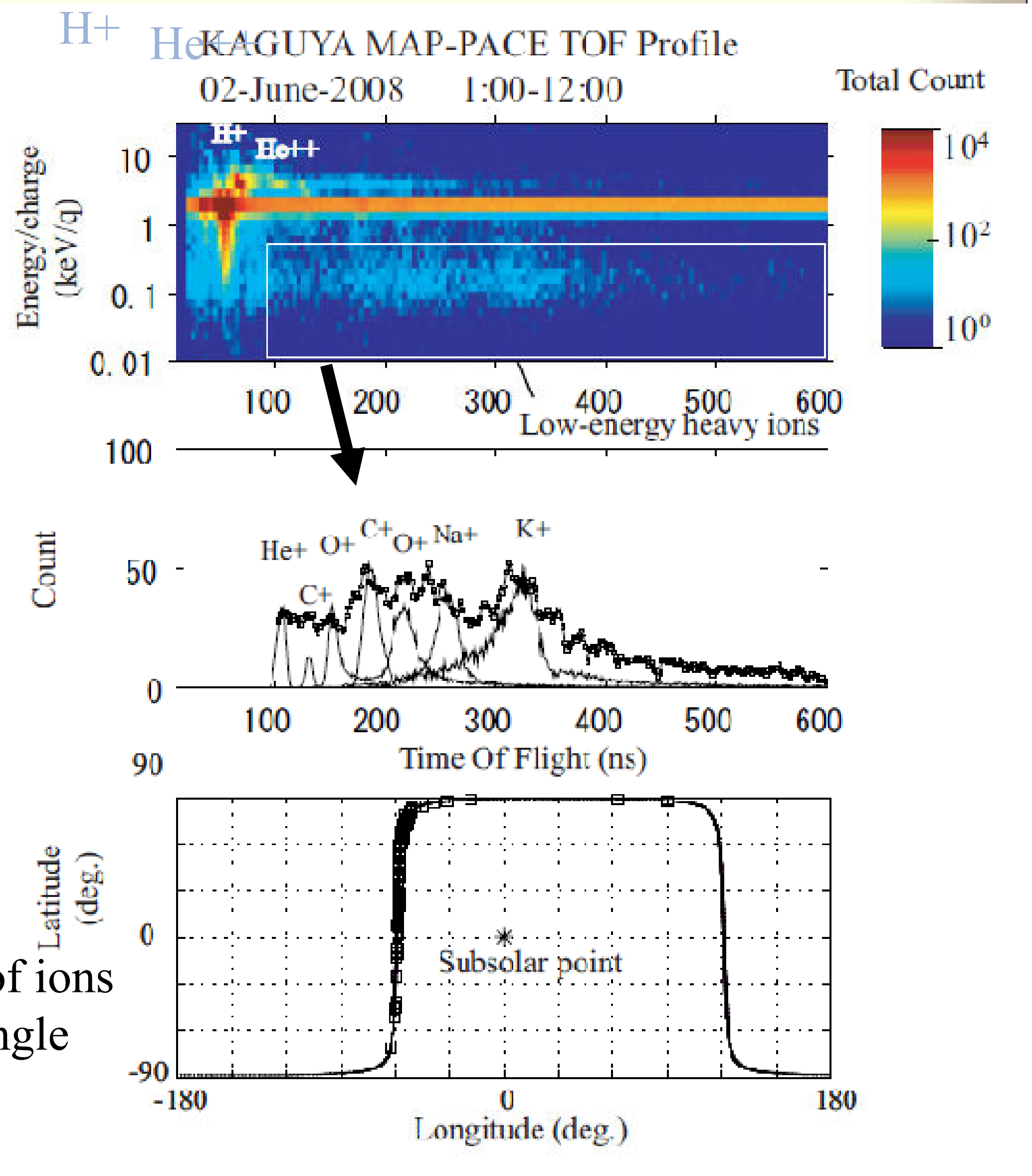
MAP-PACE IMA Observation *in the SW*

- Detected He+, C+, O+, Na+ and K+.
  - *E* ~ a few 100s eV
  - In the northern hemisphere

- Other species?
  - Ar+
  - H2O group
  - Al+

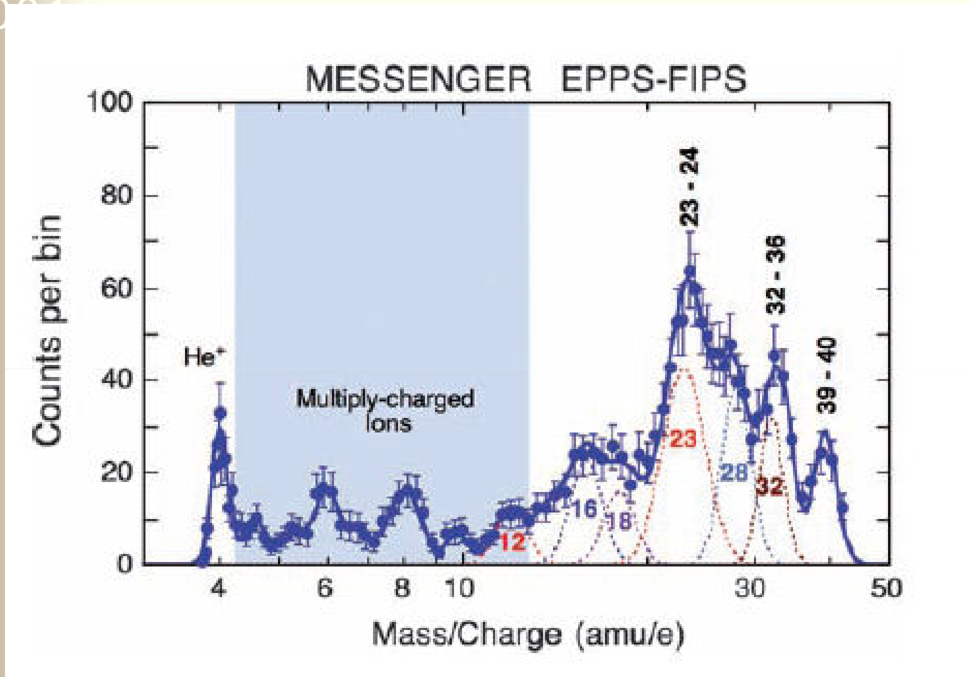


Detection points of ions in the white rectangle

Yokota et al., GRL, 2009

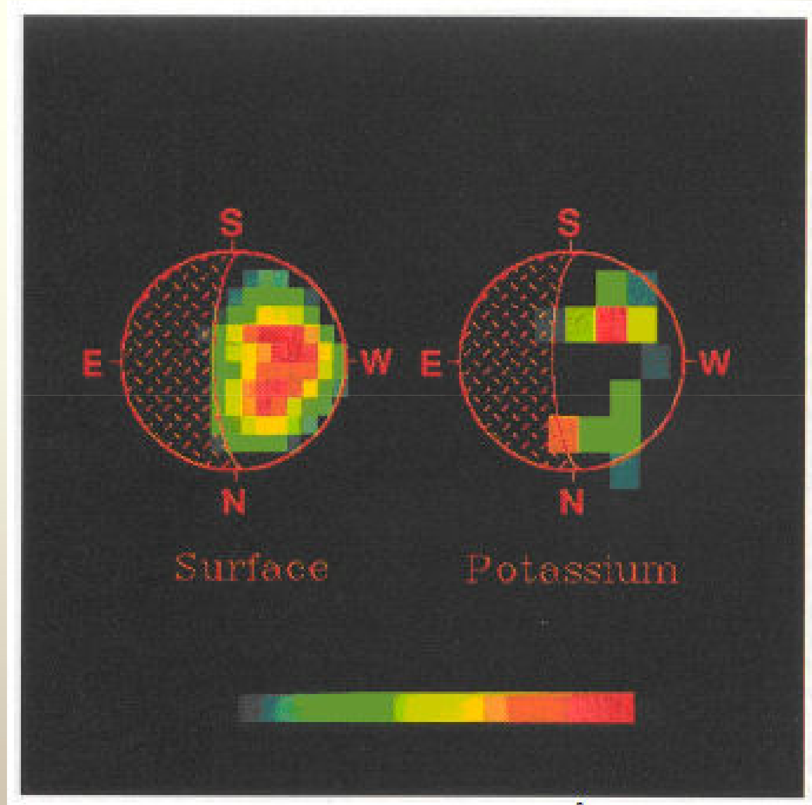
BepiColombo/MMO

Target of the ion mass analyzer



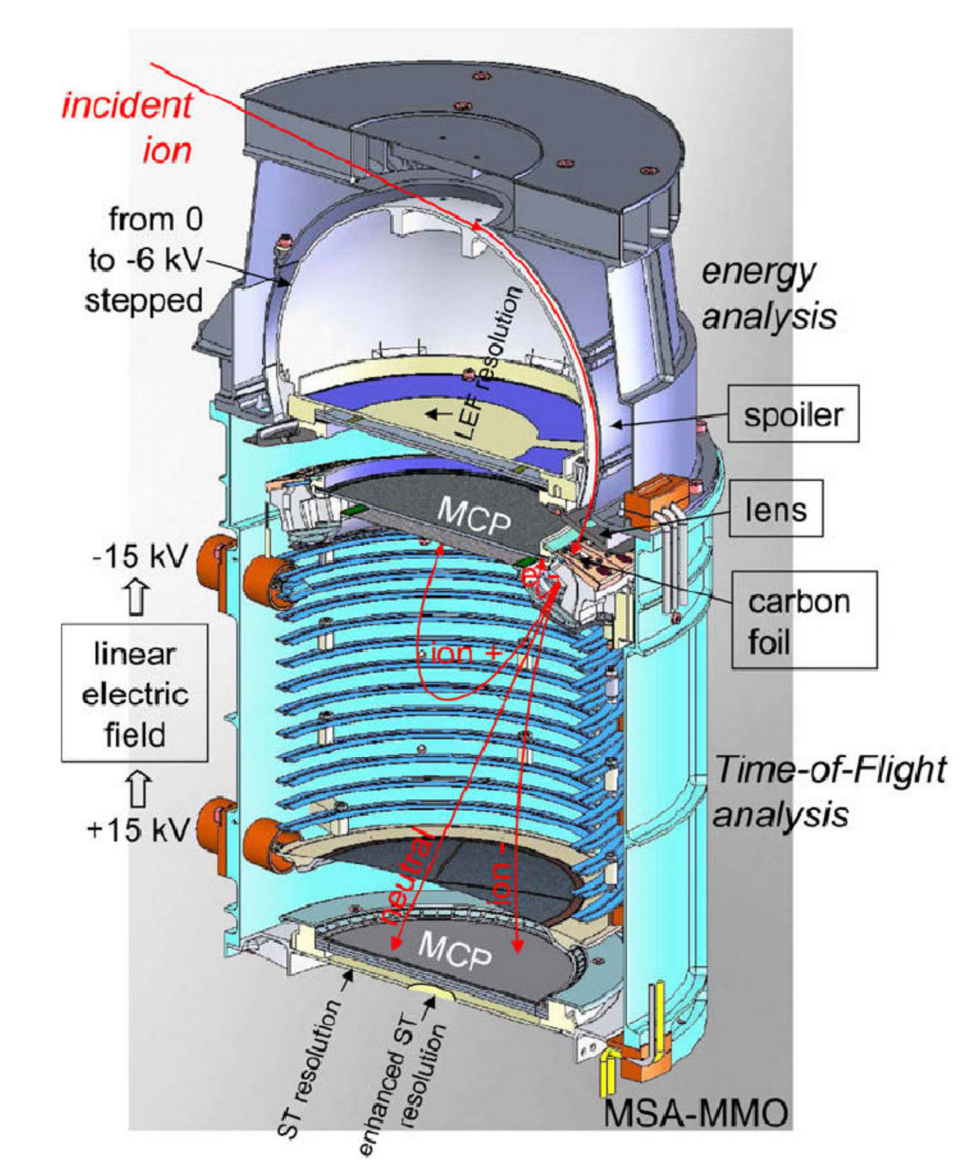
Zurbuchen et al., 2008

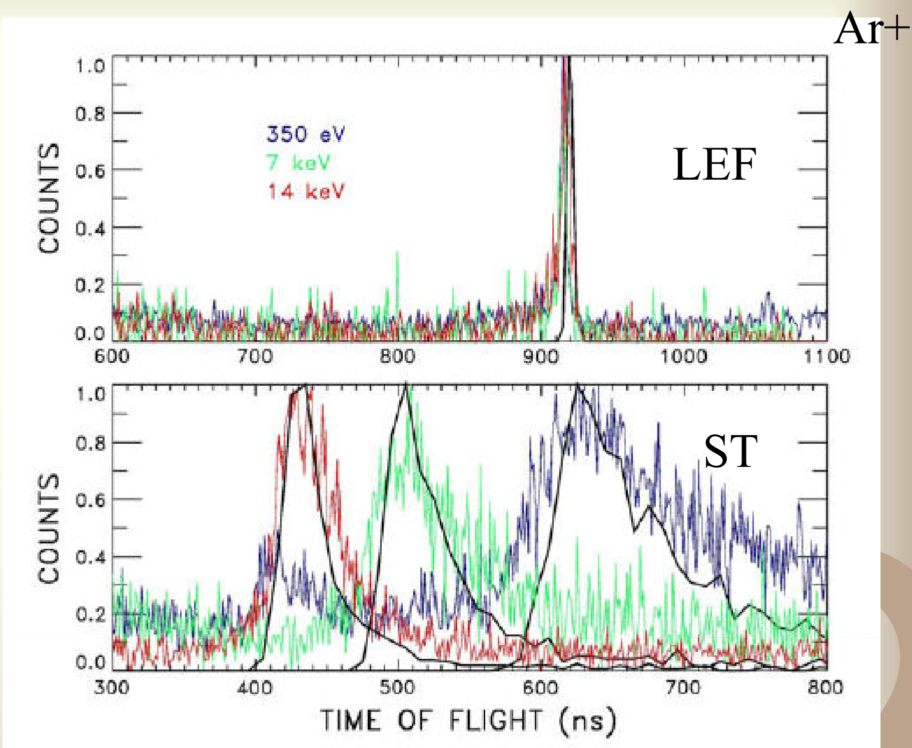
Potassium vapour in the Mercury atmosphere



Potter & Morgan, 1997

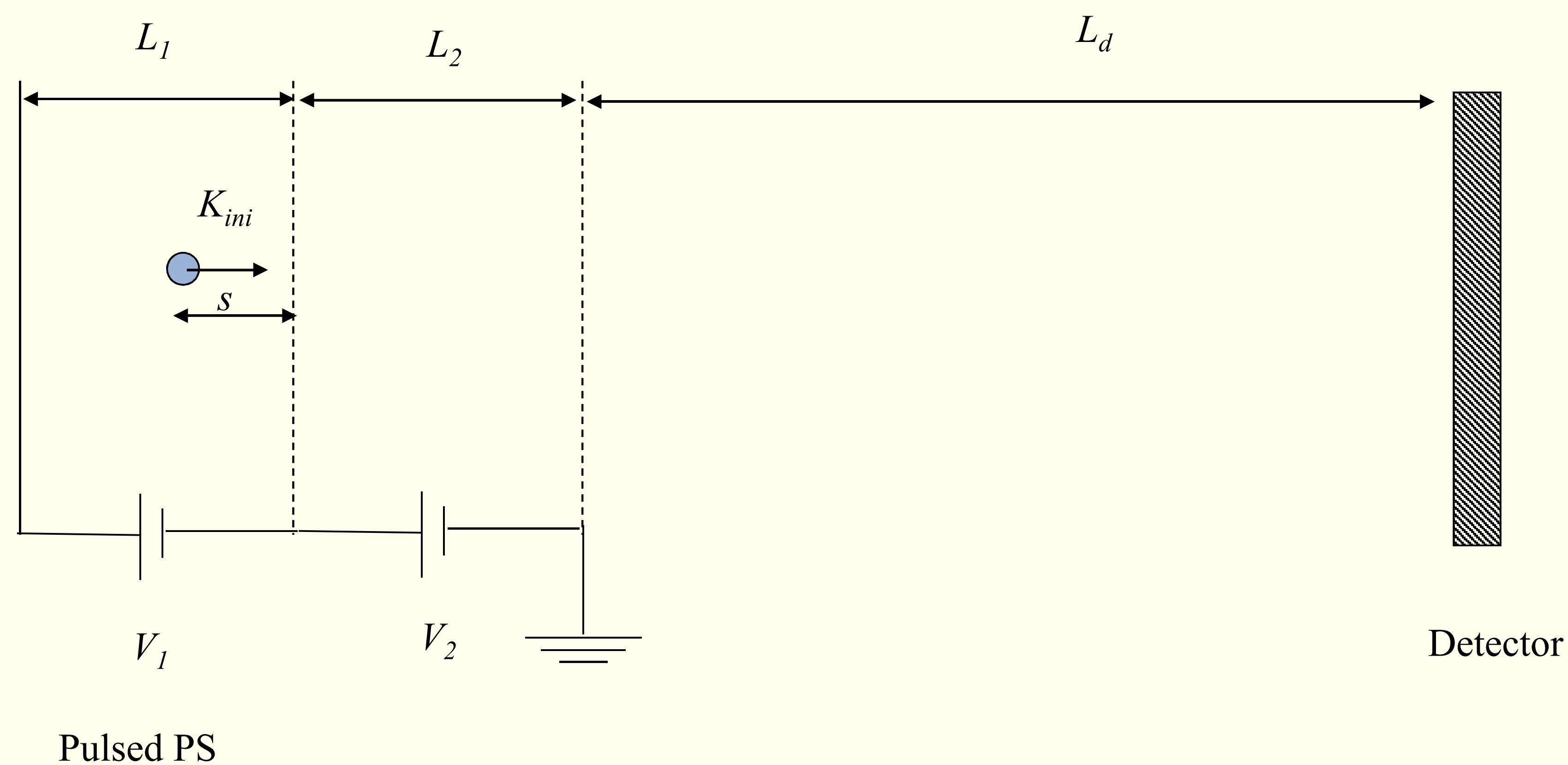
BepiColombo/MMO





Field of view: 8 deg. x 360 deg.
Angular resolution: 11.25 deg. x 11.25 deg.
Energy range: 5 eV/q–40 keV/q
Energy resolution: 10%
Mass range: 1–64 amu
Mass resolution: $m/\Delta m = 40$ (<15 keV/q);
$m/\Delta m = 15$ (>15 keV/q)
Time resolution: 4 s for 3D (32 energy steps)
G-factor: 5e-3 cm^2 sr eV/eV

2段加速型 (Two-stage accelerator)



2段加速型 (Two-stage accelerator)

飛行時間の解析解

$$T = L_0\sqrt{\frac{m}{2K_0}}\,g(\varepsilon,\delta,a_2,a_1) \qquad \text{飛行時間}$$

$$g(\varepsilon,\delta,a_2,a_1) \equiv \pm 2\frac{l_1}{a_1}\sqrt{\delta} + \frac{l_d}{\sqrt{1+\varepsilon}} + 2\frac{l_2}{a_2}\sqrt{1+\varepsilon} + 2\left(\frac{l_1}{a_1} - \frac{l_2}{a_2}\right)\sqrt{1+\varepsilon-a_2}$$

$$K_0 \equiv \langle K_{ini}\rangle + \frac{\langle s\rangle}{L_1}qV_1 + qV_2$$

$$\delta \equiv \frac{K_{ini} - \langle K_{ini}\rangle}{K_0}$$

$$\varepsilon \equiv \delta + \frac{s - \langle s\rangle}{L_1}a_1$$

$$L_0 \equiv L_1 + L_2 + L_d, \quad l_i \equiv \frac{L_i}{L_0} \qquad (i = 1,2,d)$$

$$a_1 \equiv \frac{qV_1}{K_0}, \quad a_2 \equiv \frac{qV_2}{K_0}$$

e.g. Saito et al., 1998

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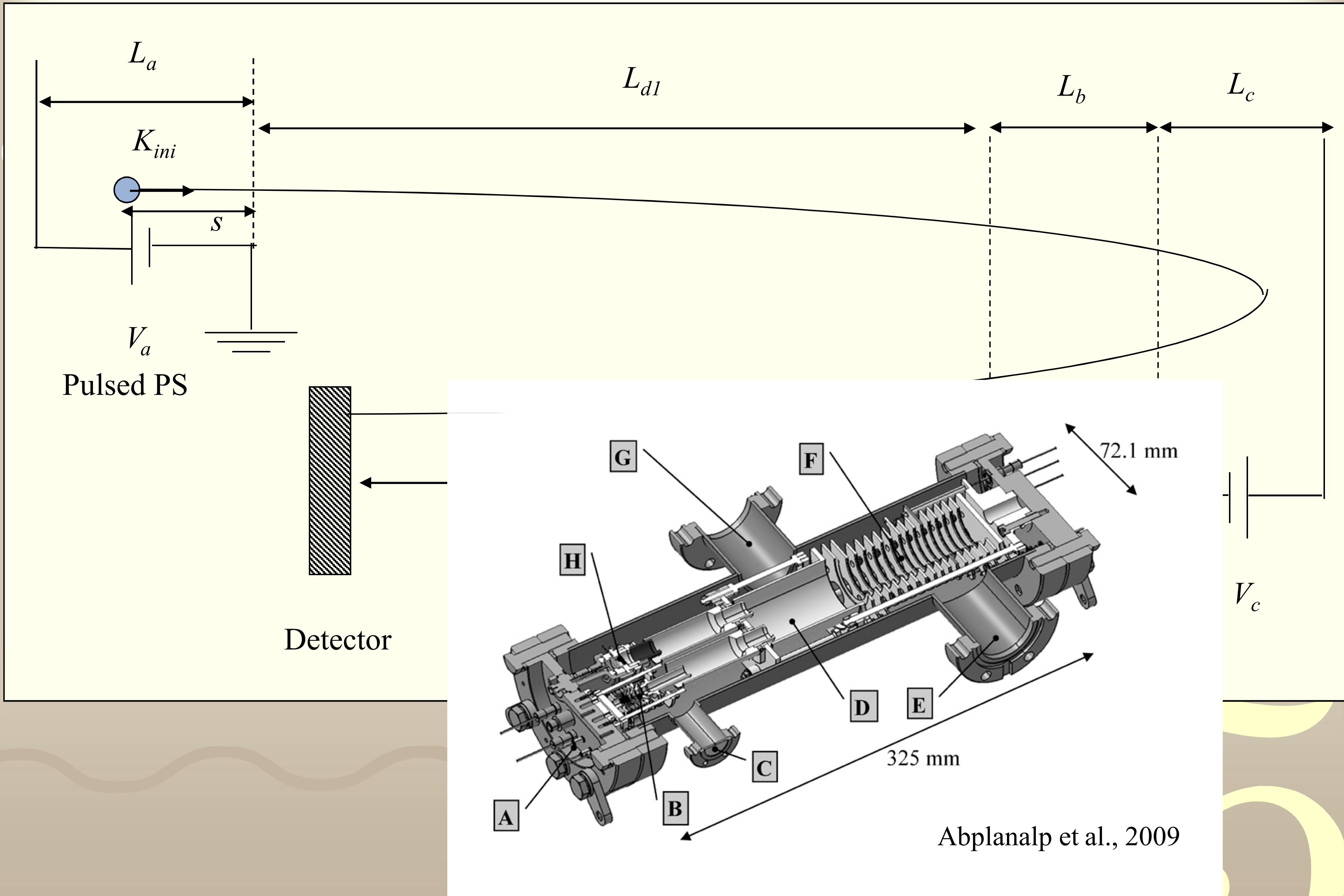
リフレクトロン型 (Reflectron)



Abplanalp et al., 2009

リフレクトロン型 (Reflectron)

Analytical solution of flight time

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$$T = L_0\sqrt{\frac{m}{2K_0}}f(\varepsilon,\delta,b,c)$$ 飛行時間

L1: 5mm
L2: 10mm
Ld: 25mm

$$f(\varepsilon,\delta,b,c) \equiv \pm 2\frac{l_a}{a}\sqrt{\delta} + \frac{2l_d}{\sqrt{1+\varepsilon}} + 2\left(\frac{2l_a}{a} - \frac{4l_b}{b}\right)\sqrt{1+\varepsilon} + 4\left(\frac{l_c}{c} - \frac{l_b}{b}\right)\sqrt{1+\varepsilon-b}$$

$$K_0 \equiv \langle K_{ini}\rangle + \frac{\langle s\rangle}{L_a}qV_a$$

$$\delta \equiv \frac{K_{ini}}{K_0}$$

$$\varepsilon \equiv \delta + \frac{s-\langle s\rangle}{L_a}V_a$$

$$L_0 \equiv L_a + \frac{L_{d1}+L_{d2}}{2} + L_b + L_c, \qquad l_i \equiv \frac{L_i}{L_0} \qquad (i = a, d1, d2, b, c)$$

$$l_d \equiv \frac{l_{d1}+l_{d2}}{2}$$

$$a \equiv \frac{qV_a}{K_0}, b \equiv \frac{qV_b}{K_0}, c \equiv \frac{qV_c}{K_0}$$

Hybrid
(Two-stage accelerator + Reflectron)

0011

$g(\varepsilon,\delta,a_2,a_1), f(\varepsilon,\delta,b,c)$ は無次元の実効的飛行時間である。エネルギーの分布εに関係なく高い質量分解能を得るには、εに関する収束が得られるような装置形状パラメータを選択すればよい。また、これらの2つの方式を併用した場合の実行的飛行時間は以下のようになる。

$$gf(\varepsilon,\delta,a_2,a_1,b,c) \equiv \pm 2\frac{l_1}{a_1}\sqrt{\delta} + \frac{2l_d}{\sqrt{1+\varepsilon}} + 2\left(\frac{l_1}{a_1} - \frac{l_2}{a_2}\right)\sqrt{1+\varepsilon-a_2}$$

$$+\left(\frac{2l_2}{a_2} - \frac{4l_b}{b}\right)\sqrt{1+\varepsilon} + 4\left(\frac{l_c}{c} - \frac{l_b}{b}\right)\sqrt{1+\varepsilon-b}$$

Isotope analyzer for MELOS

火星の大気散逸･進化を捉えるため、火星電離圏にて同位体計測を行う。

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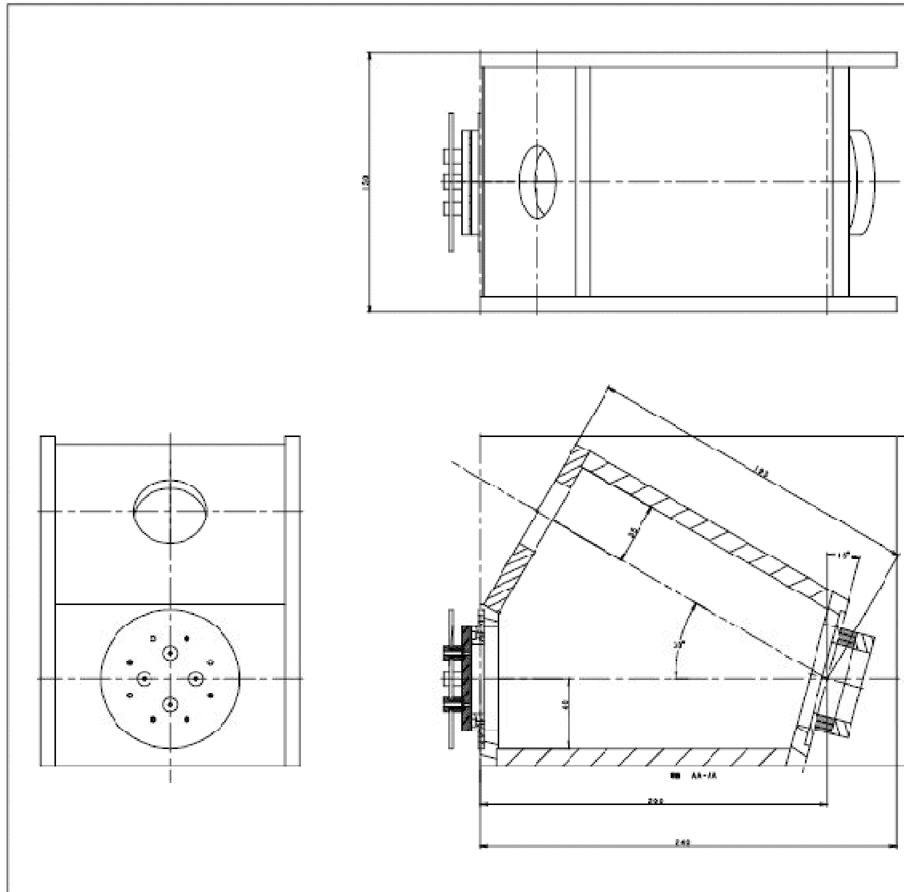
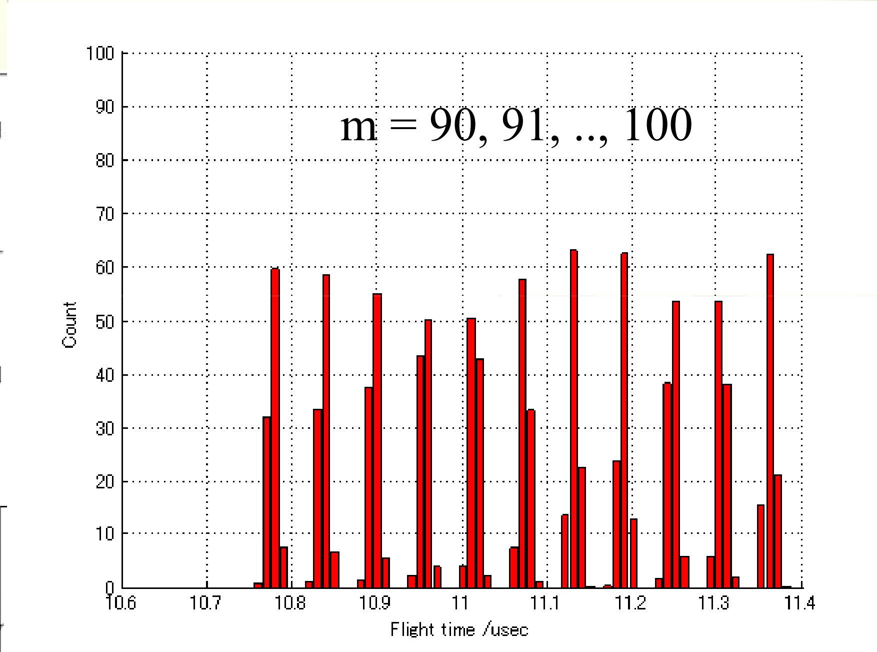
Two-stage accelerator + Reflectron



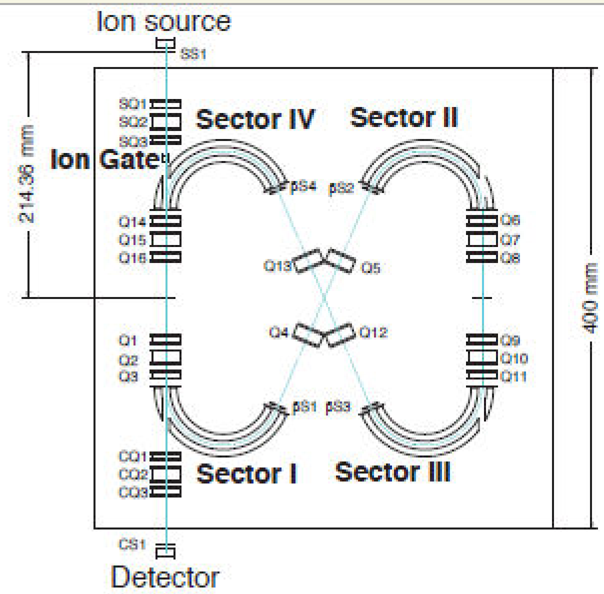


Energy range: <100 eV/q
Mass range: 1–200 amu
Mass resolution: m/Δm = 100

COとNNの分離！！

MULTUM

$$
\begin{pmatrix} x_f \\ \alpha_f \\ y_f \\ \beta_f \\ \gamma \\ \delta \\ l_f \end{pmatrix}
=
\begin{pmatrix}
\pm 1 & \underline{0} & 0 & 0 & 0 & \underline{0} & 0 \\
\underline{0} & \pm 1 & 0 & 0 & 0 & \underline{0} & 0 \\
0 & 0 & \pm 1 & \underline{0} & 0 & 0 & 0 \\
0 & 0 & \underline{0} & \pm 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
\underline{0} & \underline{0} & 0 & 0 & R(l \mid \gamma) & \underline{0} & 1
\end{pmatrix}
\times
\begin{pmatrix} x_i \\ \alpha_i \\ y_i \\ \beta_i \\ \gamma \\ \delta \\ l_i \end{pmatrix}
$$



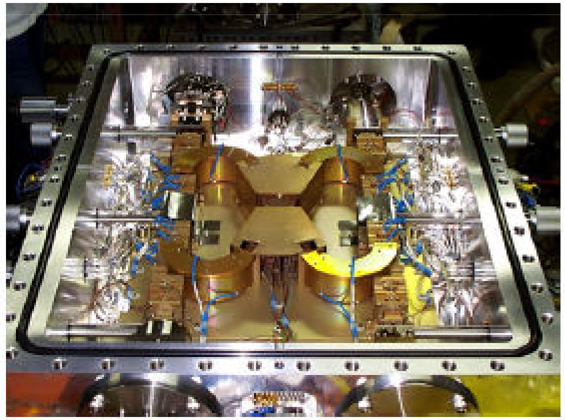


Figure 1. A Schematic drawing and a photograph of the first multi-turn ToF mass spectrometer "MULTUM Linear plus".

Toyoda., 2010

MULTUM

マルチターン型
Multi-turn TOF mass analysis

0011

MULTUM-S II
Optics 20 x 20 cm
50 x 30 x 60 cm
35 kg (with vacuum pump)

<u>性能</u>
Energy:　<1eV
M/ΔM ~4,800(11cycles) ~30,000
Transmission　5%(2cycles), 97%/cycle

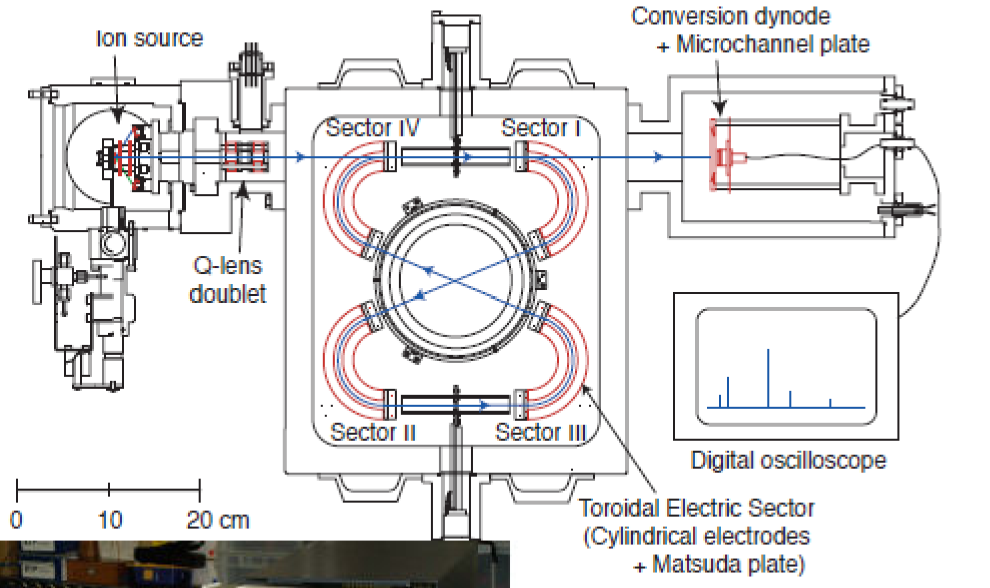


Figure 7. A photograph of the miniature multi-turn ToF mass spectrometer "MULTUM-S II".

Toyoda., 2010

2011 極低エネルギーイオンビームを使ったOpticsの性能試験
2012 マスゲート用パルス電源を宇宙用に開発

MULTUM-S Ⅱ

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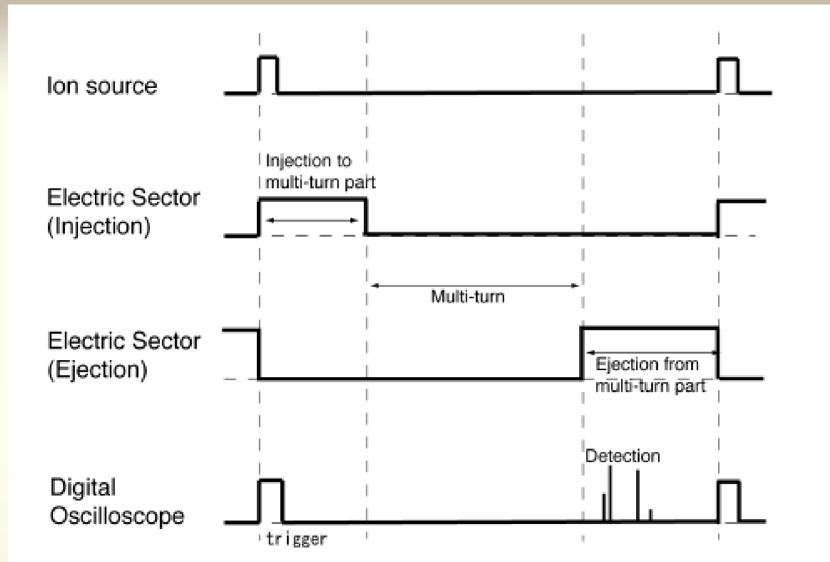

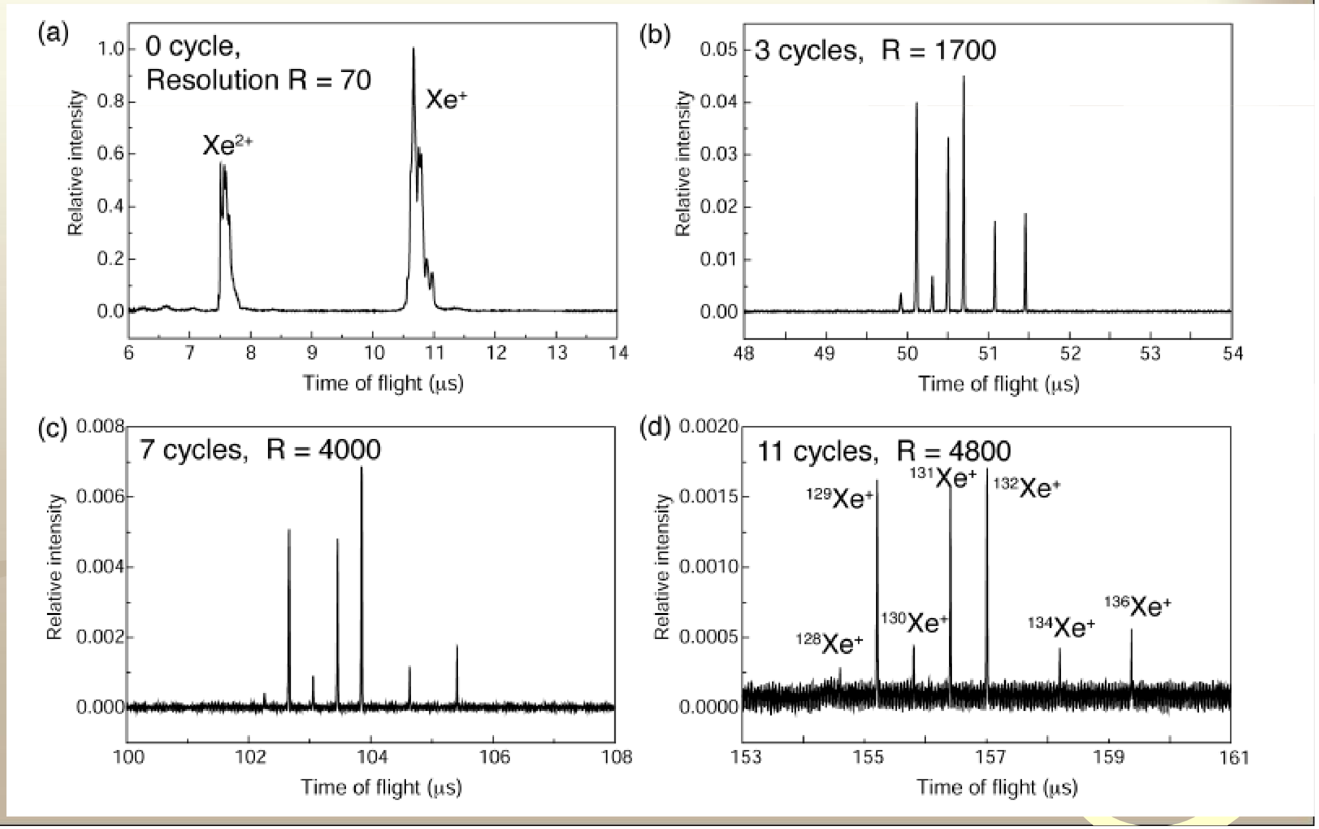

Ichihara et al., 2007

Mass analysis