Recoil Separators*

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I. Introduction

Recoil separators are devices which separate nuclear reaction products (recoils) leaving a target from the unreacted beam particles. In addition, some separators have the additional property that they can disperse the reaction products at the focal plane according to their mass/charge. If the separator optics are achromatic, it can be used to obtain particle energies by measuring time-of-flight. The separators described in this review are located at accelerator facilities where the beam energies are below 10 MeV/u. This means that the experiments are carried out at Coulomb-barrier energies or slightly above. We wish to differentiate these recoil separators from fragmentation separators, which are generally located at facilities where the projectile energies are above 10 MeV/u.

All recoil separators use electromagnetic elements such as electric dipoles, magnetic dipoles, and Wien filters to accomplish the separation of the recoils from the unreacted primary beam. In addition, magnetic quadrupole lenses are used for focussing the ions, and magnetic multipoles (usually sextupoles and octupoles) are used to correct higher order aberrations. Because heavy ions are routinely used as beams, high vacuum is necessary in recoil separators in order to avoid losses due to multiple scattering or charge-changing collisions. Typical pressures attained are 10^{-7} Torr or better.

II. General properties of Recoil Separators

Modern recoil separators are designed to separate the products from heavy-ion induced fusion-evaporation reactions. Here the yield of recoils is peaked near 0°, and thus the recoils are mixed in with primary beam particles that have not reacted as both leave the target. To obtain the maximum separation of beam and recoils, the beam particles are blocked at an early stage of the separator. The dipole magnetic and electric fields are set to pass a central particle with energy E_o, mass M_o, and charge Q_o along the central trajectory, and the quadrupole lenses are set to focus the central particles at the focal plane.

In some devices, different types of ion-optical focussing can be achieved at the focal plane. At devices similar to the Argonne Fragment Mass Analyzer [1] (FMA), for instance, the 4 quadrupoles can be varied to achieve point-to-point, point-to-parallel, and dispersionless solutions. Primary beam rejection in recoil separators is generally a strong function of the masses of target and projectile, as well as the charge state of the central particle.

We will use the FMA at Argonne National Laboratory as an example of a typical recoil separator. The ion optic scheme is shown in fig. 1, along with some of the other properties of the FMA.

III. Mass/Charge Dispersion

With 2 out of the following 3 elements: electric dipole, magnetic dipole, and Wien filter, a recoil separator can disperse recoils at the focal plane by mass/charge. When the first two are used, the energy/charge dispersion of the electric dipoles is cancelled by the magnet, leaving its mass/charge dispersion. When the last two are used, the velocity-dispersed output of the Wien filter enters the magnet, and its momentum/charge dispersion results in mass/charge dispersion at the focal plane. In the second configuration the velocity acceptance is usually only a few percent, while in the first configuration energy/charge acceptances of several tens of percent are common.

Mass dispersion is obtained in the following way: let x represent the deviation from the central trajectory in the transverse (dispersion) direction. So, to first order in the small quanties x_o (target position), θ_o (angle at target), δ_E (relative energy deviation), and δ_M (relative mass deviation),

$$x = (x|x)x_o + (x|\theta)\theta_o + (x|\delta_E)\delta_E + (x|\delta_M)\delta_M,$$
$$\text{where } \delta_E = \Delta E/E_o \text{ and } \delta_M = \Delta M/M_o$$

We want a focus in x, so the coefficient $(x|\theta)$ must equal 0. We want mass dispersion, so $(x|\delta_M)$ cannot be equal to 0. $(x|x)$ is a constant, the image magnification, usually having a magnitude of 1 – 2. So, in order to have mass dispersion, we require that $(x|\delta_E) = 0$ (energy dispersion cancellation). In the FMA this is achieved by adjusting the distance between electric and magnetic dipoles, as is shown in fig. 2. Using these concepts, excellent mass/charge resolution can be obtained. Fig. 3 shows an example from an experiment at the FMA

IV. Some Operating Recoil Separators

The longest-running recoil separator is SHIP [2] at GSI in Darmstadt, Germany, shown in fig. 4. SHIP is a velocity filter, primarily used in experiments searching for new elements, with elements 107-112 being observed there for the first time. The first ground-state proton emitter ^{151}Lu was discovered at SHIP in 1981.

The kinematic separator VASSILISSA is located at FLNR, JINR, Dubna, Russia. It uses electric dipoles for beam separation, and is shown in fig. 5. The physics program at VASSILISSA is primarily aimed at the synthesis and study of decay properties of superheavy elements formed in reactions with ^{48}Ca beams. Recent observations include alpha-decay chains from elements 114 and 116.

A number of separators use similar optics to obtain beam separation and M/Q dispersion. These include the FMA (Argonne National Laboratory), the HRIBF RMS (Oak Ridge

National Laboratory), JAERI-RMS (JAERI, Japan), HIRA (Nuclear Science Centre, Delhi, India), and CAMEL (Laboratori Nazionali di Legnaro, Italy). The HIRA and JAERI-RMS both have a split anode in the first electric dipole in order to reduce scattered beam background at the focal plane. A similar split anode has recently been installed in the FMA.

Physics programs at these installations include proton radioactivity, recoil-gamma spectroscopy, fusion and transfer cross-sections, spin distributions, isomers, accelerator mass spectrometry, and nuclear astrophysics. The JAERI-RMS and HIRA devices have been used to produce radioactive ^{7}Be beams, which have been subsequently used in secondary reactions. Two separators, the DRS at HRIBF and DRAGON at TRIUMF, are situated at laboratories where radioactive beams are available, and are used mainly for experiments in nuclear astrophysics. Fig. 6 shows a layout of the DRAGON separator.

V. Future Developments

A number of new recoil separators are on the horizon. One example comes from the field of nuclear chemistry, where the community has begun discussions on building a recoil separator optimized for doing few-atom chemistry experiments with superheavy elements. Fig. 7 shows the ion optics for a proposed design [10] for such a separator, based on the ion optics of the FMA at Argonne National Laboratory. It features large angular and charge state acceptances, with a small image size at the focal plane so that the recoils can enter the chemistry setup with high efficiency. Another example is a future separator to be constructed at the new ISAC II facility at TRIUMF. This device will be used in studies of nuclear astrophysics, nuclear structure, nuclear reactions, and heavy element synthesis with the intense radioactive beams expected from this facility. Both of these projects will benefit from the experiences obtained over the last few decades at the many laboratories worldwide using recoil separators.

VI. Conclusions

A number of new recoil separators have been placed into operation in the past 10 years. These devices have been used effectively in nuclear structure, nuclear reactions, and astrophysics experiments. In the future, improved detector technology will make recoil separators even more productive, and new ideas are emerging for the next generation of devices.

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References

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Figure Captions

Figure 1. Ion optic layout and properties of the Fragment Mass Analyzer (FMA) at Argonne National Laboratory, Argonne, USA.

Figure 2. Energy dispersion cancellation is accomplished in the FMA by adjusting the distance d.

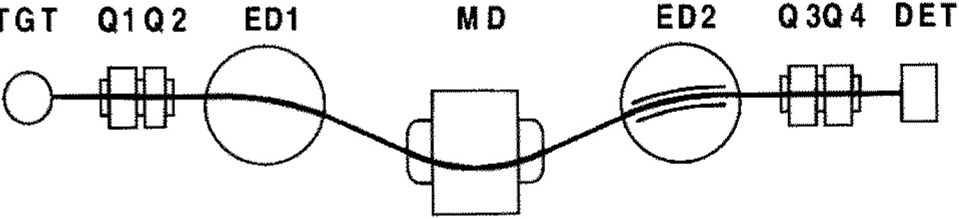
Figure 3. M/Q spectrum observed at the FMA focal plane.

Figure 4. The velocity filter SHIP, located at GSI, Darmstadt, Germany. It was designed for use in experiments on the synthesis of heavy elements.

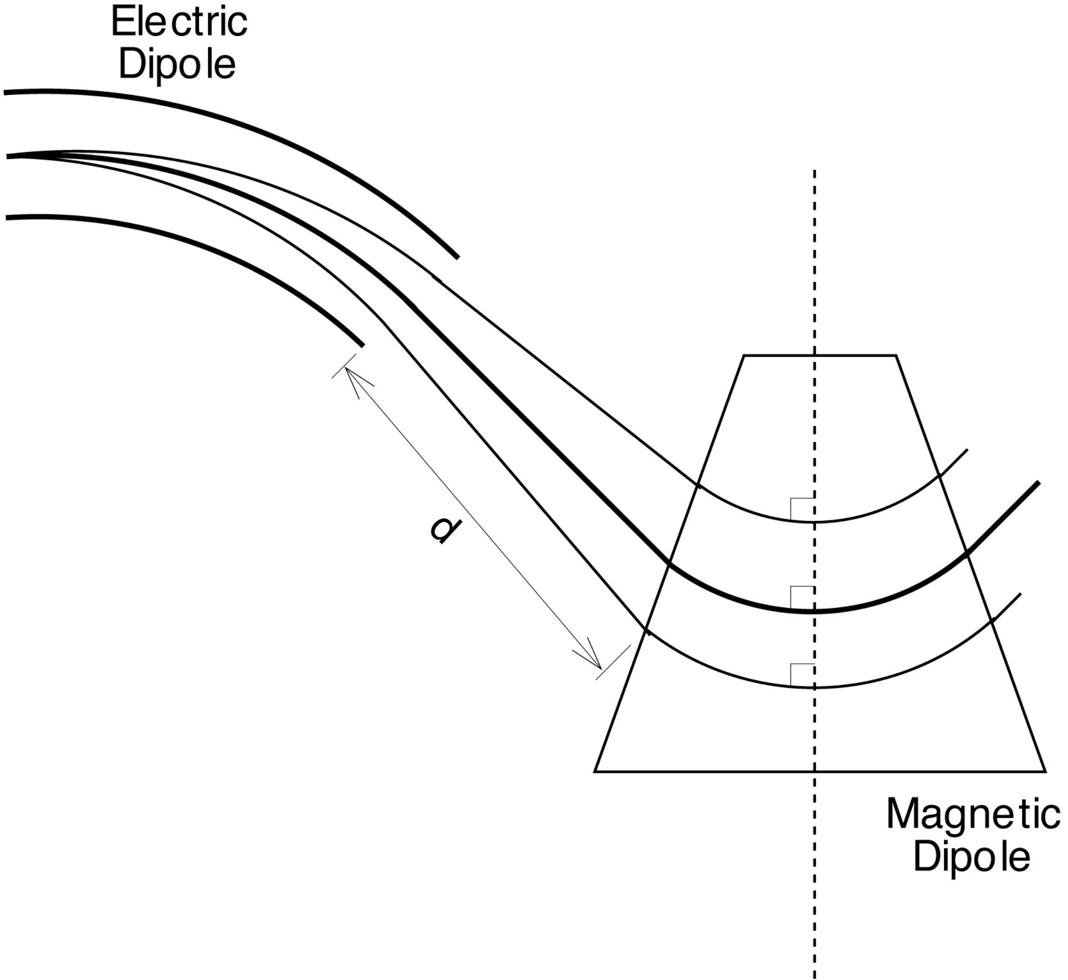
Figure 5. The kinematic separator VASSILISSA at FLNR, JINR, Dubna, Russia.

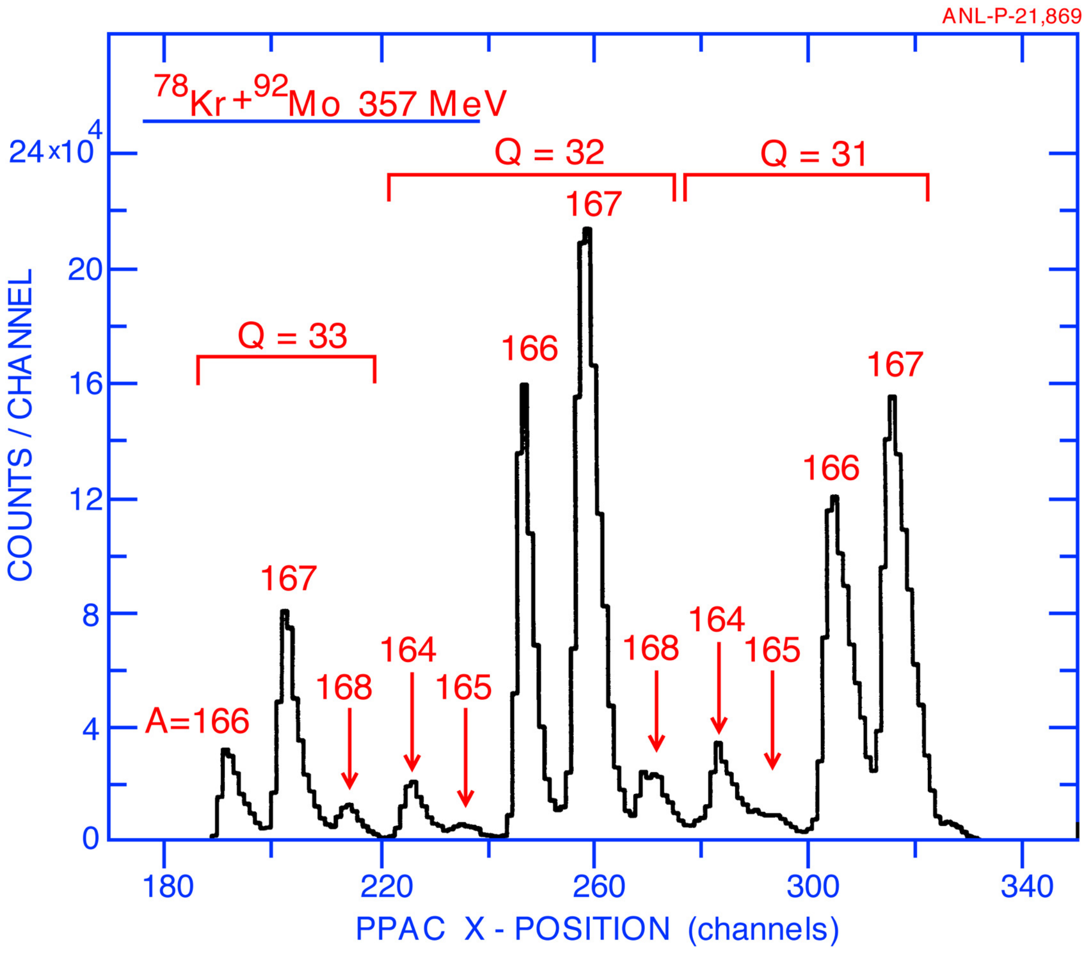
Figure 6. The DRAGON separator at ISAC, TRIUMF, Canada.

Figure 7. Vertical (y) and horizontal (x) ion optic layout for a proposed design for a recoil separator for superheavy element chemistry.

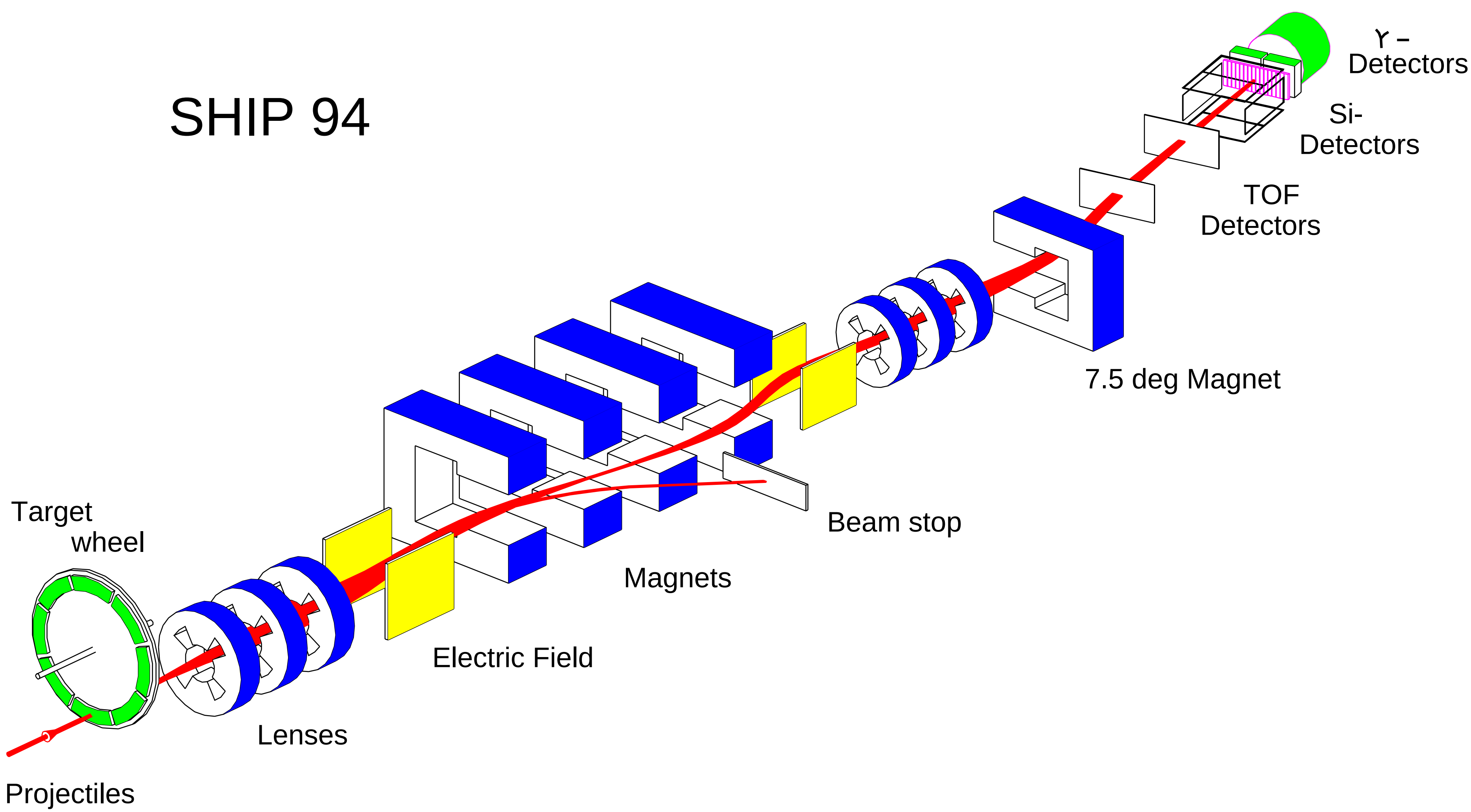


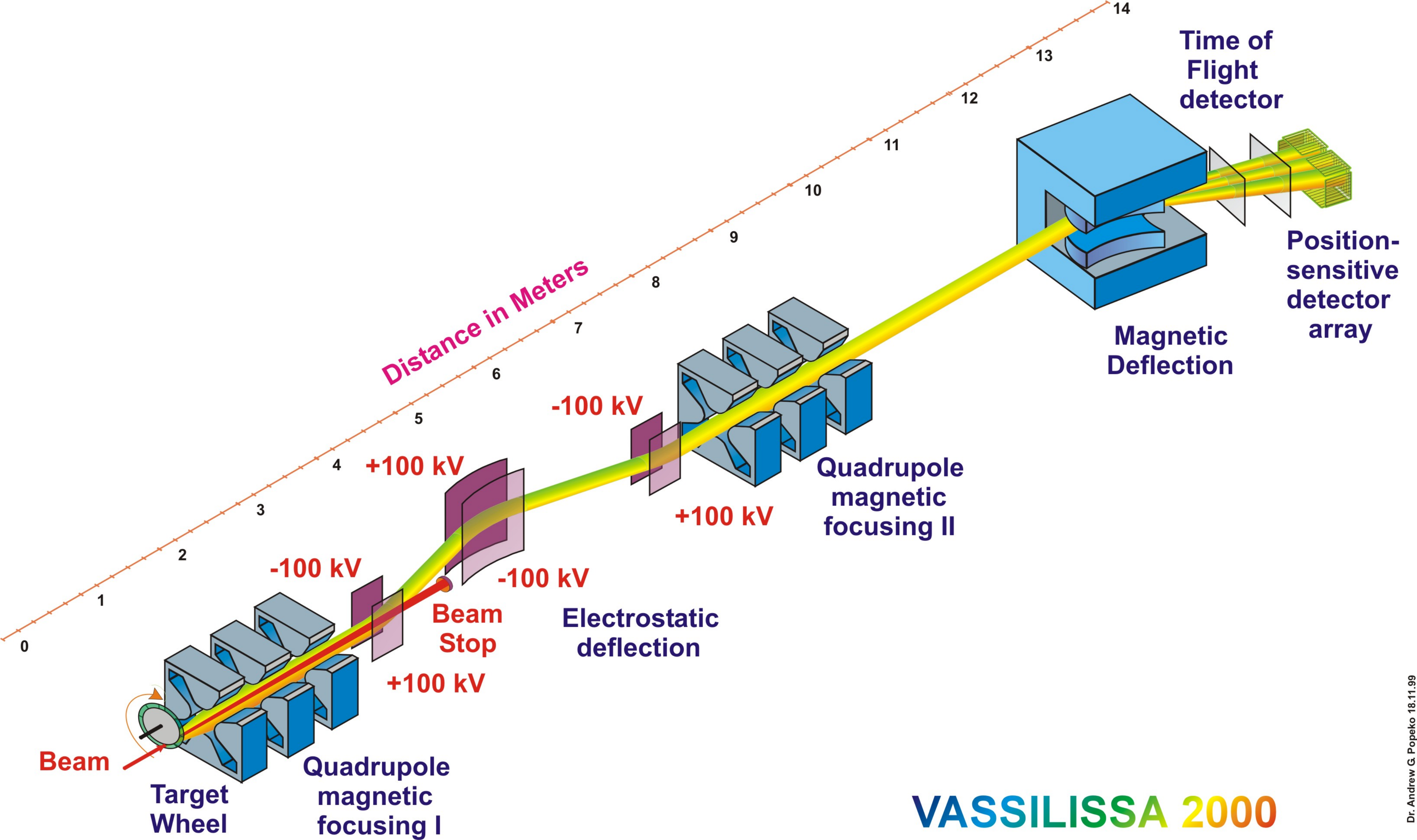
- **Solid Angle Acceptance** **5 msr**
- **Energy Acceptance** **± 20%**
- **M/q Acceptance** **± 4%**
- **M/q Dispersion** **0 → 20 mm/%**
- **Rotation Angular Range** **-5° → +45°**
- **Length** **8.2 m**


Electric
Dipole
d
Magnetic
Dipole



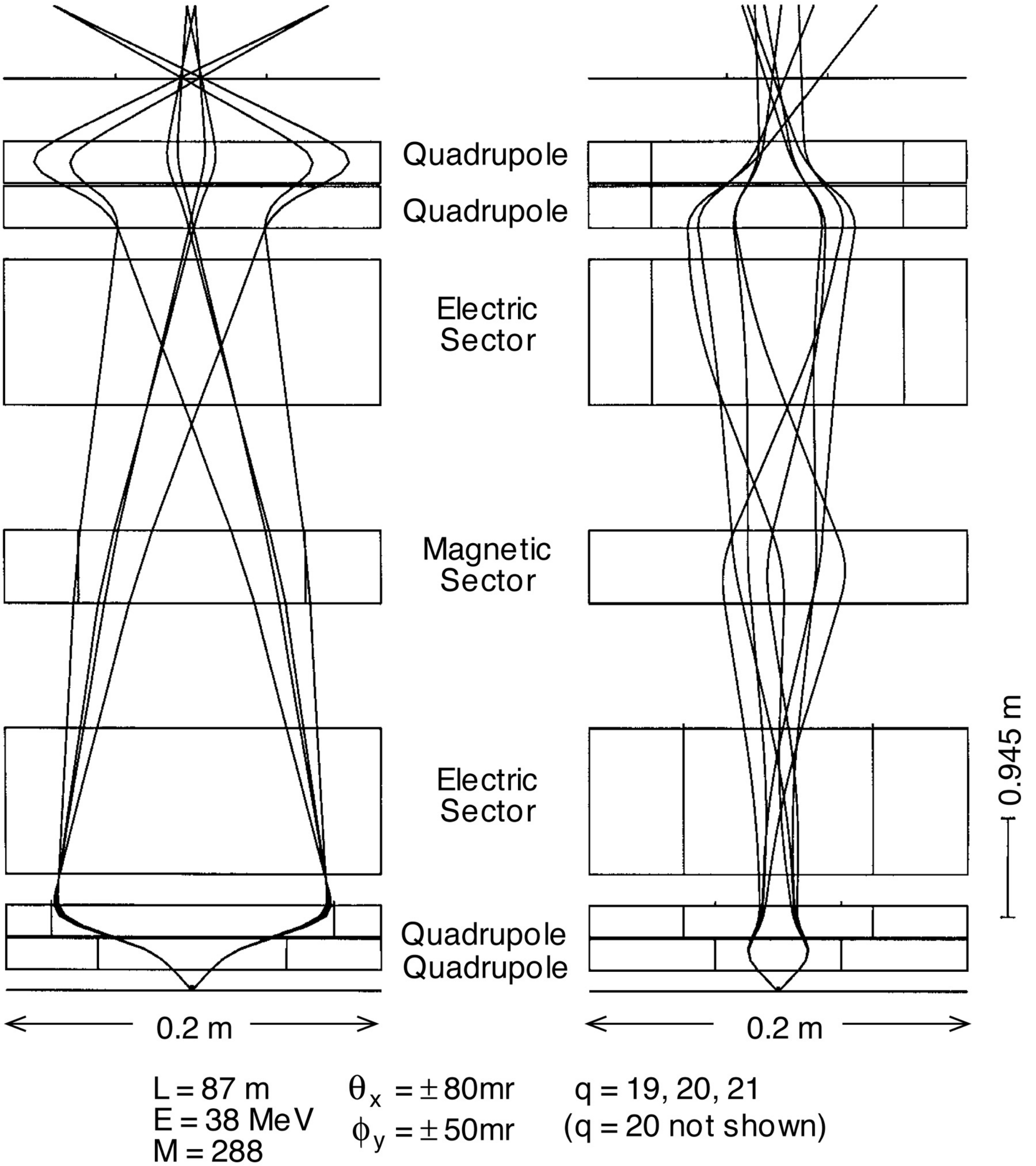
ANL-P-21,869
^{78}Kr + ^{92}Mo 357 MeV
Q = 33
Q = 32
Q = 31
A=166
167
168
164
165
166
167
168
164
165
166
167
24 x10^4
20
16
12
8
4
0
COUNTS / CHANNEL
180
220
260
300
340
PPAC X - POSITION (channels)


SHIP 94
γ –
Detectors
Si-
Detectors
TOF
Detectors
7.5 deg Magnet
Beam stop
Target
wheel
Magnets
Electric Field
Lenses
Projectiles



Distance in Meters
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Beam
Target Wheel
Quadrupole magnetic focusing I
-100 kV
+100 kV
Beam Stop
+100 kV
-100 kV
Electrostatic deflection
-100 kV
+100 kV
Quadrupole magnetic focusing II
Magnetic Deflection
Time of Flight detector
Position-sensitive detector array
VASSILISSA 2000
Dr. Andrew G. Popeko 18.11.99


DRAGON
Detector of Recoils And Gammas Of Nuclear reactions
Gas Target
Gamma Array
Magnetic Quads
Magnetic Dipole
Charge Slit Box
Magnetic Quads
Electrostatic Dipole
Mass Slit Box
Magnetic Dipole
Quads
Electrostatic Dipole
Magnetic Quads
Final Focus Box
Recoil Detectors
MCP Start


Quadrupole
Quadrupole
Electric
Sector
Magnetic
Sector
Electric
Sector
Quadrupole
Quadrupole
0.945 m
0.2 m
0.2 m
L = 87 m
E = 38 MeV
M = 288
θx = ± 80mr
φy = ± 50mr
q = 19, 20, 21
(q = 20 not shown)