Recoil separators for studies of super-heavy nuclei

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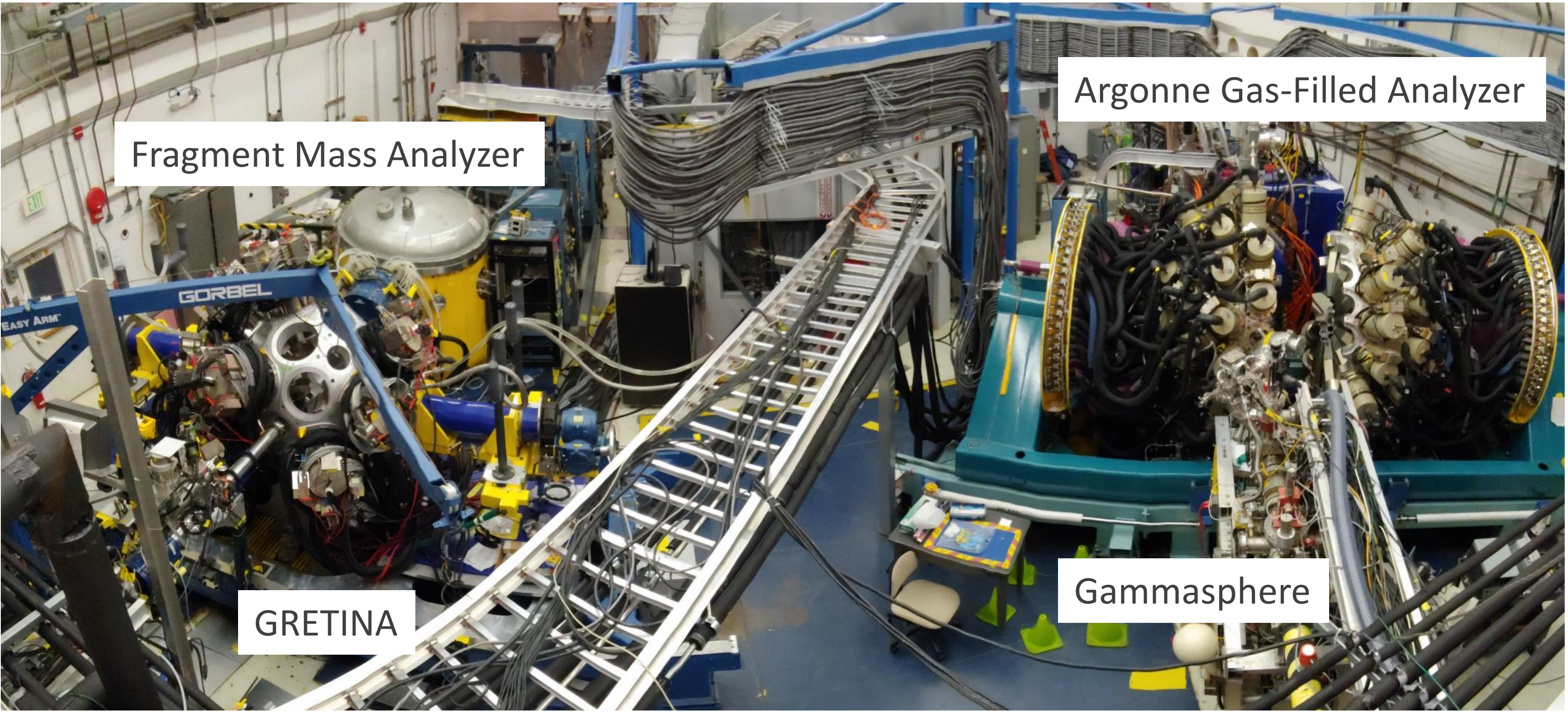


Outline

- Recoil separators for SHN studies
- Vacuum (mass) separators versus gas-filled separators
- Examples of existing separators
  - Argonne Fragment Mass Analyzer (FMA)
  - Argonne Gas-Filled Analyzer (AGFA)
- Recoil separators under construction for SHN studies
  - Gas-Filled Separator (GFS) at Dubna
  - Superconducting Super Separator (S^3) at GANIL
- Cool beams of SHN
- Conclusions

Requirements for studies of SHN

- Targets (radioactive)
- Intense beams
- Long beam times
- Efficient detection

Studies of SHN require a recoil (mass) separator
to separate reaction products from a primary beam
and to collect them at a focal plane for further studies.

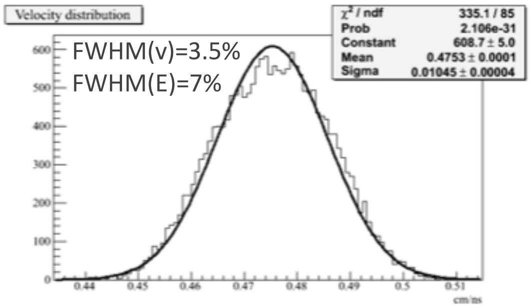
Experimental approaches to SHN studies

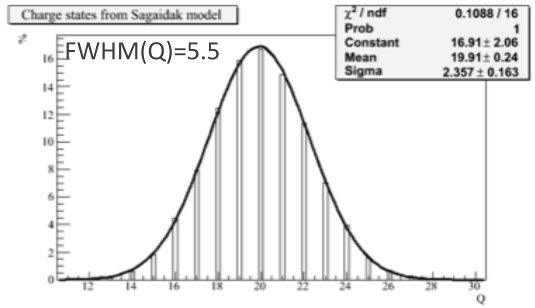
- Search for new elements
- Spectroscopy of SHN
  - in-beam
  - decay
- Chemistry of SHE
- Precision mass measurements
- Laser spectroscopy
- …

Specific choice of a recoil separator depends on a foreseen experimental program.

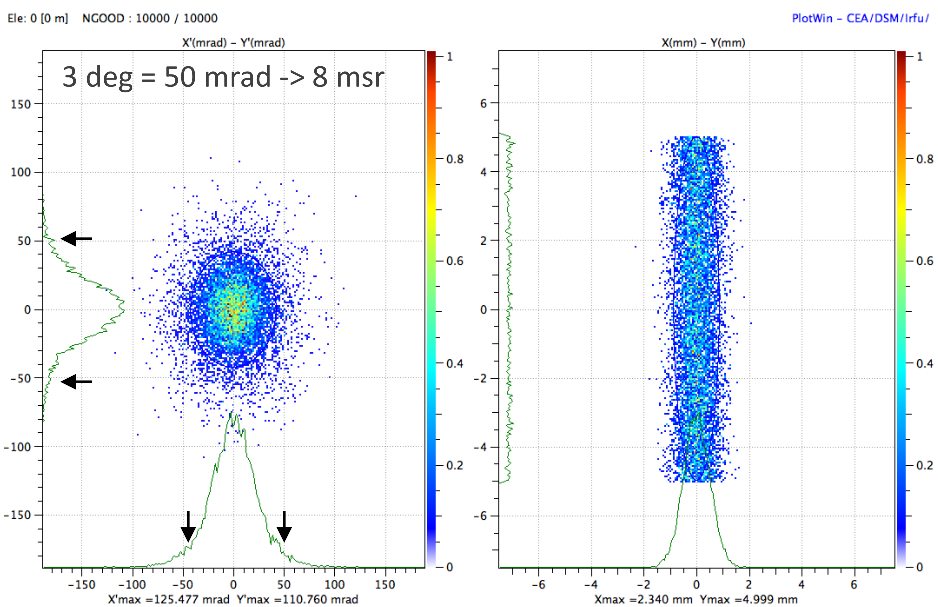
$^{48}Ca + ^{248}Cm \rightarrow ^{292}116 + 4n$

0.3 mg/cm^2 Cm oxide





Neutron emission
Target thickness



Sigma_X' [rms] = 24.4161 mrad
Sigma_Y' [rms] = 24.2556 mrad
Sigma_X [rms] = 0.4998 mm
Sigma_Y [rms] = 2.8824 mm

Important separator design parameters

- Transmission (depends on a reaction)
  - Solid angle
  - Energy acceptance
  - M/Q acceptance
- Mass resolution
- Electric and magnetic rigidity
- Beam suppression
- Focal plane size

Recoil separators currently used for studies of SHN can be roughly divided into two groups:
vacuum (mass) separators and gas-filled separators

Vacuum vs Gas-Filled separators

- ☺ M/Q measurement
- ☺ physical M/Q separation
- ☺ good beam suppression (for symmetric reactions)

- ☹ no mass resolution
- ☹ no separation
- ☹ poor beam suppression (for symmetric reactions)
- ☹ not suitable for very asymmetric reactions

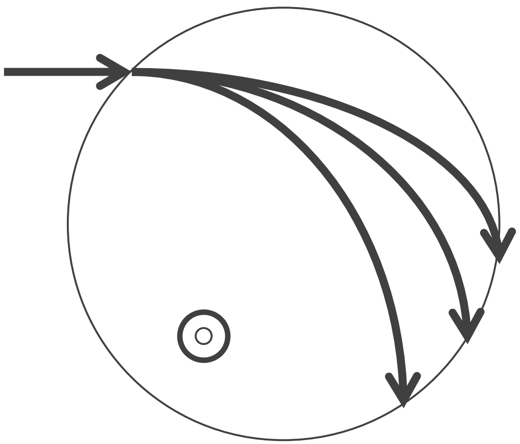
- ☹ low efficiency
- ☹ long flight path
- ☹ more complex
- ☹ more expensive

- ☺ high efficiency
- ☺ short flight path
- ☹ simple
- ☹ less expensive

Very much complementary devices!

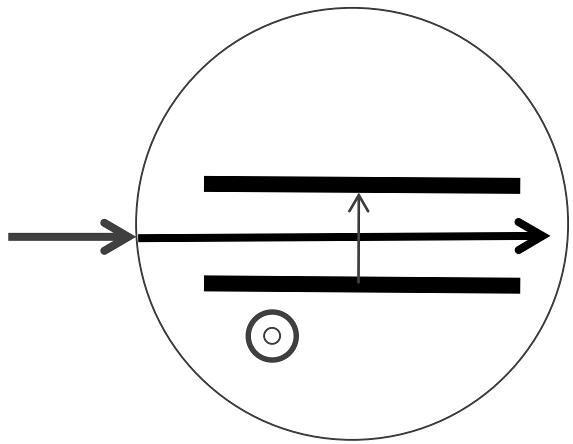
Principle of Operation

vacuum



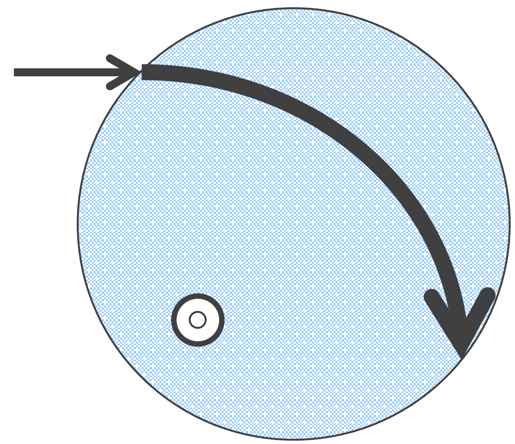
$B\rho_i = p/q_i$

velocity filter



$v = E / B$

gas



$B\rho = p/q_{ave}$

$q_{ave} \sim (v/v_0)\, Z^{1/3}$

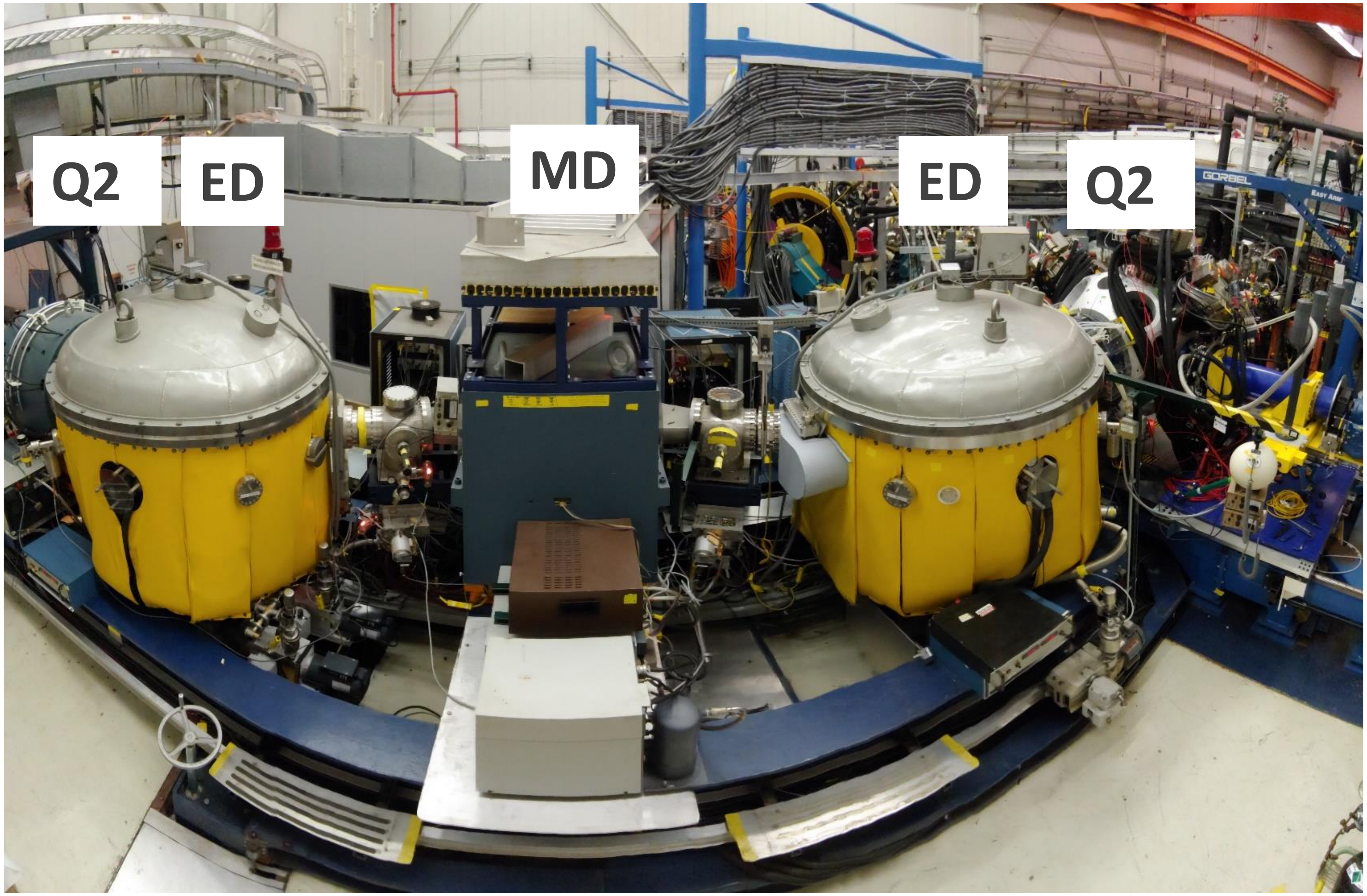
$B\rho \sim 0.0227\ A/Z^{1/3}$ [Tm]

Existing and planned separators for SHN studies

laboratory	vacuum separators: velocity filter	vacuum separators: recoil mass separator	gas-filled separator
GSI	SHIP		TASCA
DUBNA	VASILLISSA		DGFRS
	SHELS		DGS
LBNL			BGS
RIKEN			GARIS II
ANL		FMA	AGFA
Jyvaskyla		MARA	RITU
GANIL		S3	VAMOS*
IMP Lanzhou			SHANS

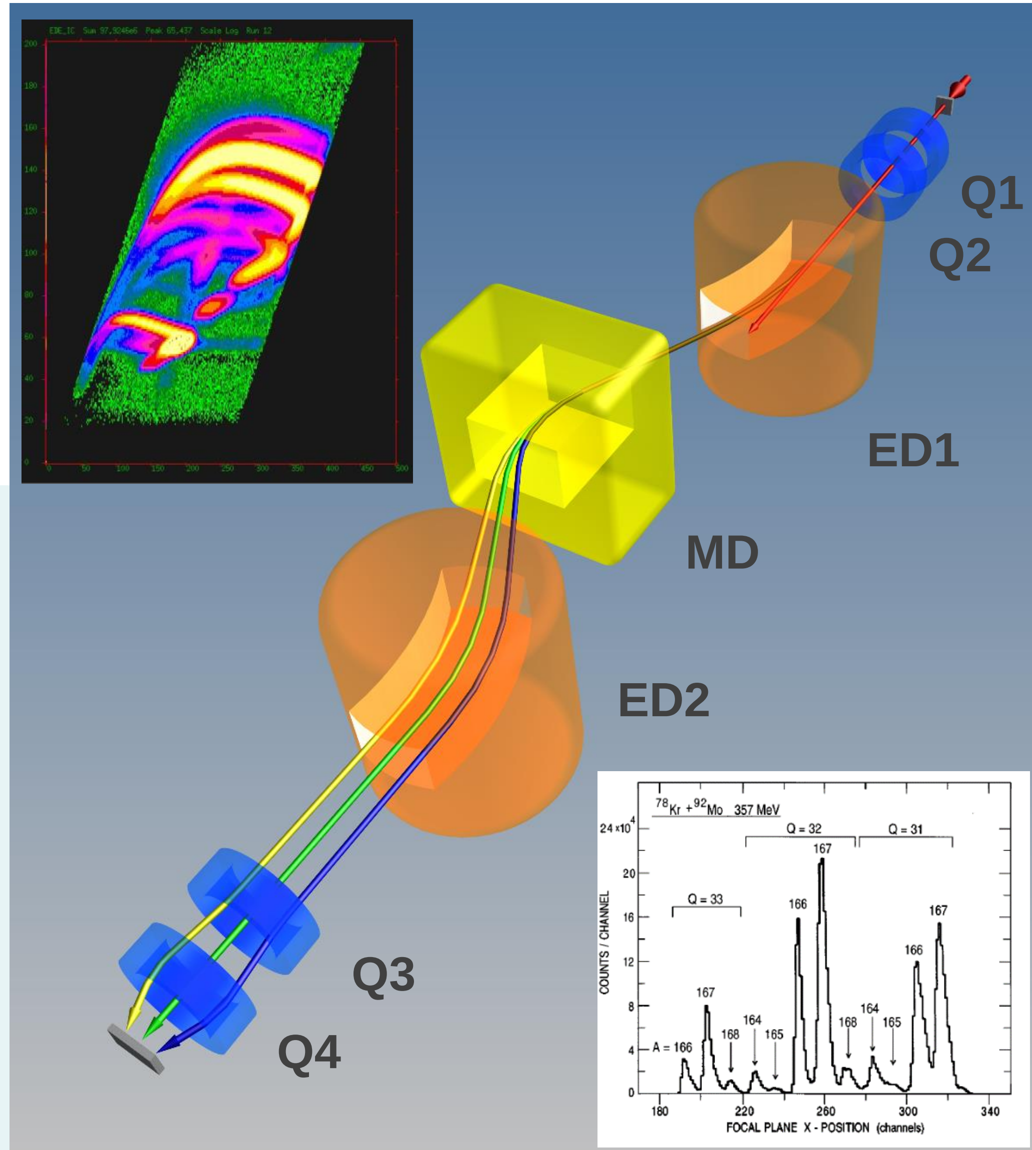
Active SHE searches
Starting
Under design/construction
*gas-filled mode of operation

Argonne Fragment Mass Analyzer

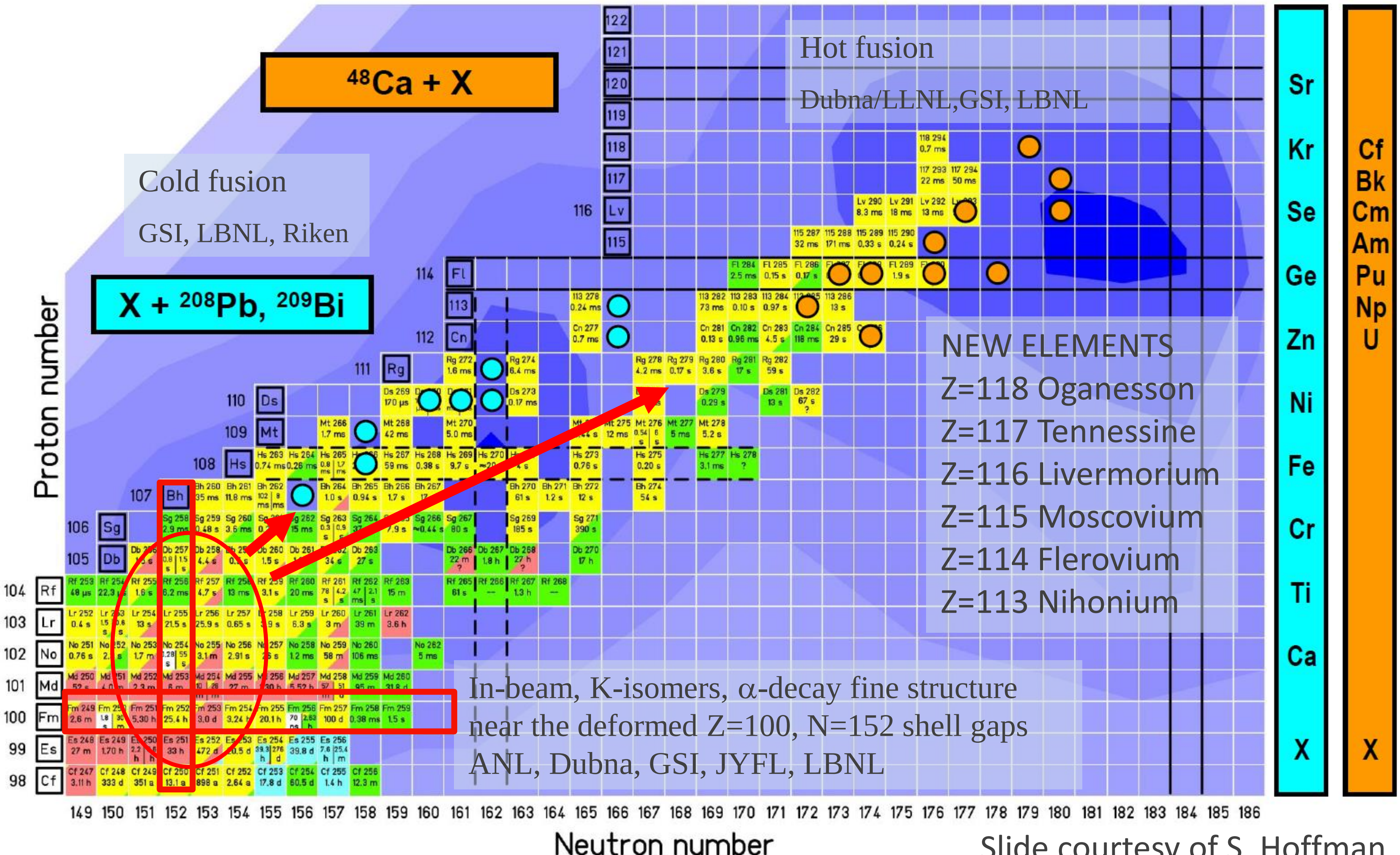


FMA parameters

- Mass resolution: $\delta M/M \sim 1/350$
- Angular acceptance: $\Delta\Omega$=8 msr
- Energy acceptance: $\Delta\mathcal{E}/\mathcal{E}$=+/-20%
- M/Q acceptance: $\Delta(M/Q)/(M/Q)$=10%
- Flight path 8.2m
- Max($B\rho$)=1.1Tm
- Max($E\rho$)=20MV
- Can be rotated off 0 degrees
- Can be moved along the axis
- Different focusing modes



Super-heavy nuclei



Slide courtesy of S. Hoffman

AGFA concept
D. Potterveld, ANL

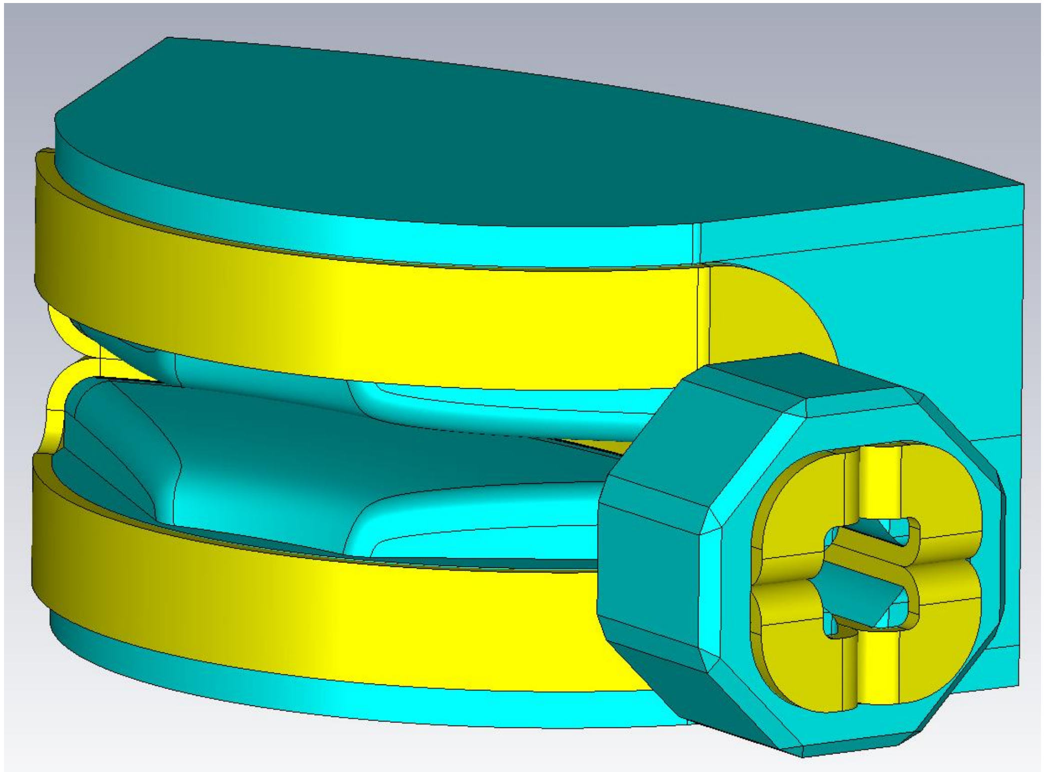
Use Combined Function bending magnet
- Overlapping bending, focusing fields
- Fewer magnets, ultra-compact design

$Q_v D_m$ design

2.5 Tm max Bρ
38^o bend

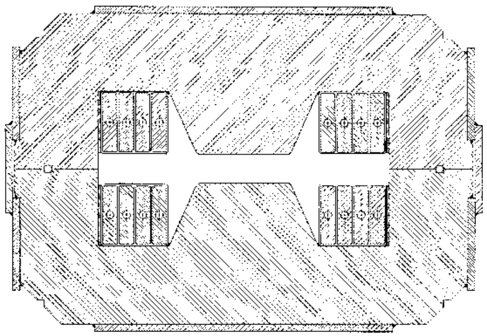
22.5 msr @ 80 cm
(44 msr @ 40 cm)

4.2 total length @ 80 cm
(3.9 m @ 40 cm)



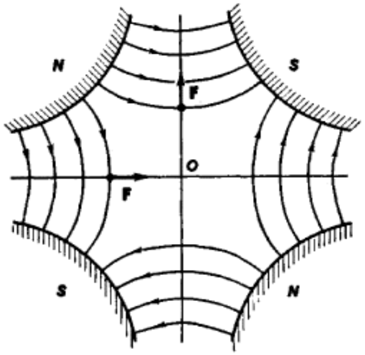
Combined function magnet

Dipole magnet



Constant field

Quadrupole



Midplane: $B_y = B_0 \cdot x$

More complex pole shapes generate higher order terms

Combined function: $B_y = B_0 + B_1 \cdot x + B_2 \cdot x^2 + \; B_3 \cdot x^3 + \cdots$

Dipole edge rotation provides additional focusing

Comparison of gas-filled separators

Separator and Location	Config.	Solid angle (msr)	Bend Angle	Max. B-rho (Tm)	Length (m)	Target Dist. (cm)	Dispersion (cm/%)
BGS LBNL	$Q_v D_h D$	45	70^o	2.5	4.6	35	1.80
TASCA GSI	$D Q_h Q_v$	13	30^o	2.4	3.5	15	1.0
RITU Jyväskylä	$Q_v D Q_h Q_v$	10	25^o	2.2	4.7	40	1.0
Garis II Riken	$D Q_h Q_v D$	20	45^o	2.4	5.1	<40	0.78
GFS Dubna	$D Q_h Q_v$	10	23^o	3.1	4.3	<40	0.63
AGFA ATLAS	$Q_v D_m$	22	38^o	2.5	4.2	80	0.59
AGFA ATLAS	$Q_v D_m$	44	38^o	2.5	3.9	40	0.61

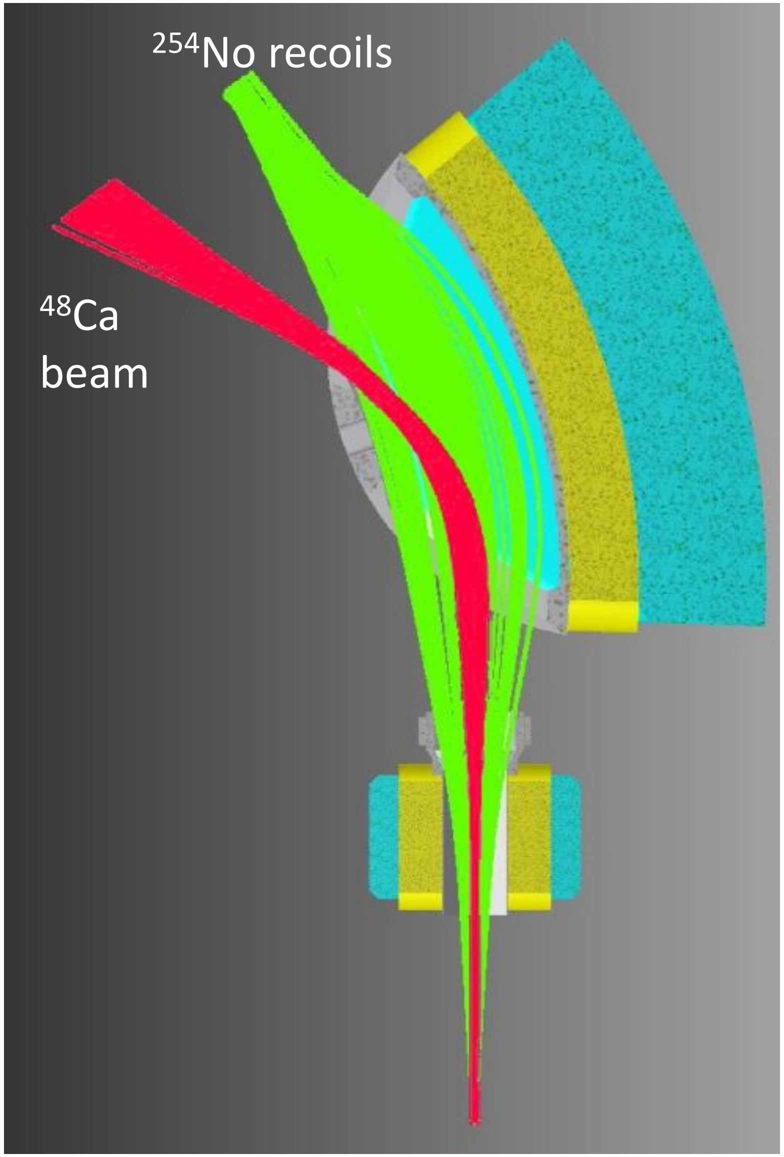
Monte-Carlo simulation results

$^{48}Ca + {}^{208}Pb \rightarrow {}^{254}No + 2n$

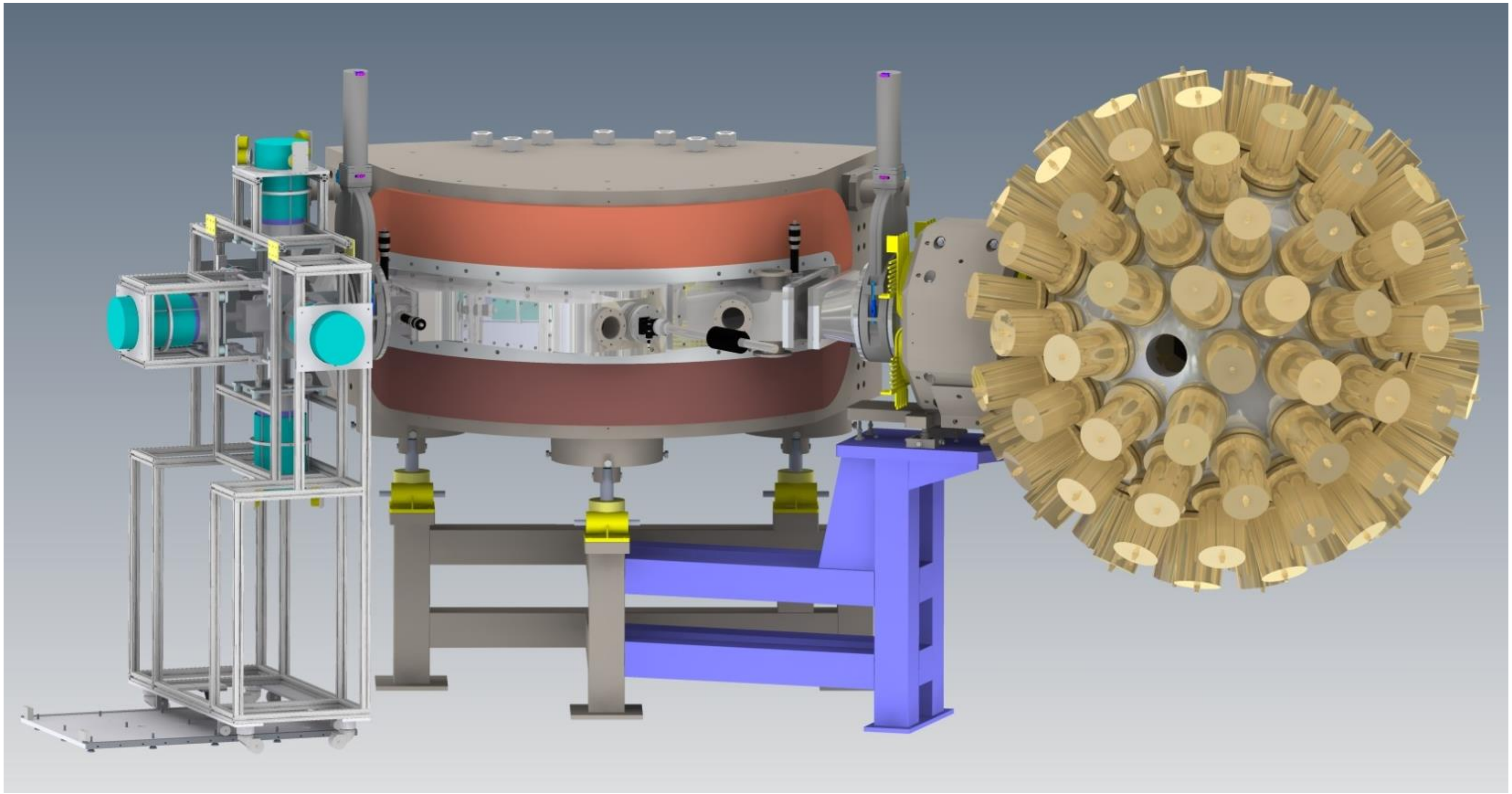
$E_{beam} = 220$ MeV

- 1 Torr He
- 5 x 2 mm beam spot
- ^{254}No angular distribution: σ = 51 mrad
- ^{48}Ca stripped in C foil: <q> = 17.1

- 89% of ^{254}No transported to focal plane
- 71% fall within a 64 x 64 mm^2 DSSD
- Solid angle to DSSD is 22.5 msr.
- Beam is well separated.



AGFA - Argonne Gas-filled Fragment Analyzer

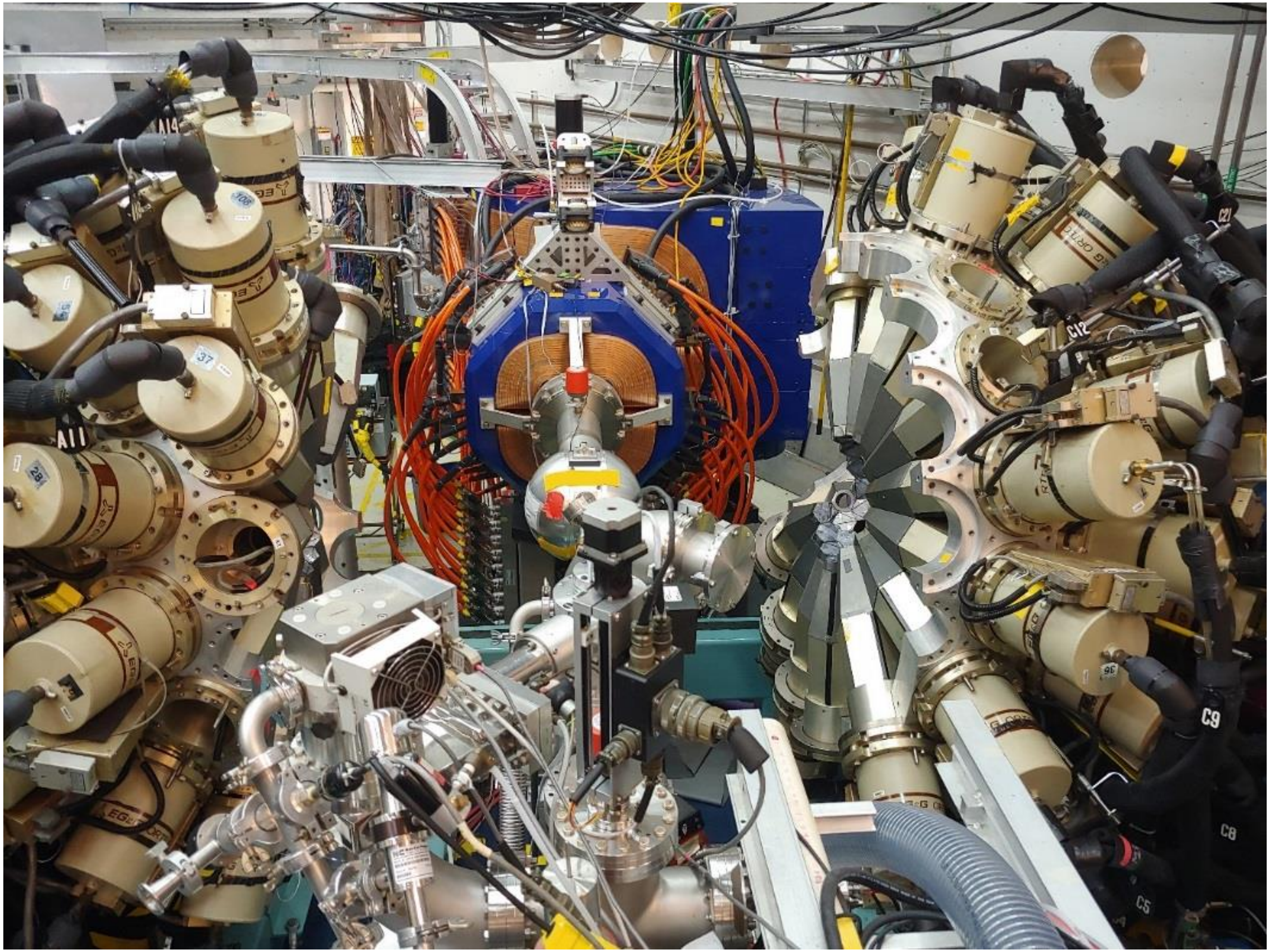


Large target-separator distance - prompt γ-ray spectroscopy with a 4π Ge array

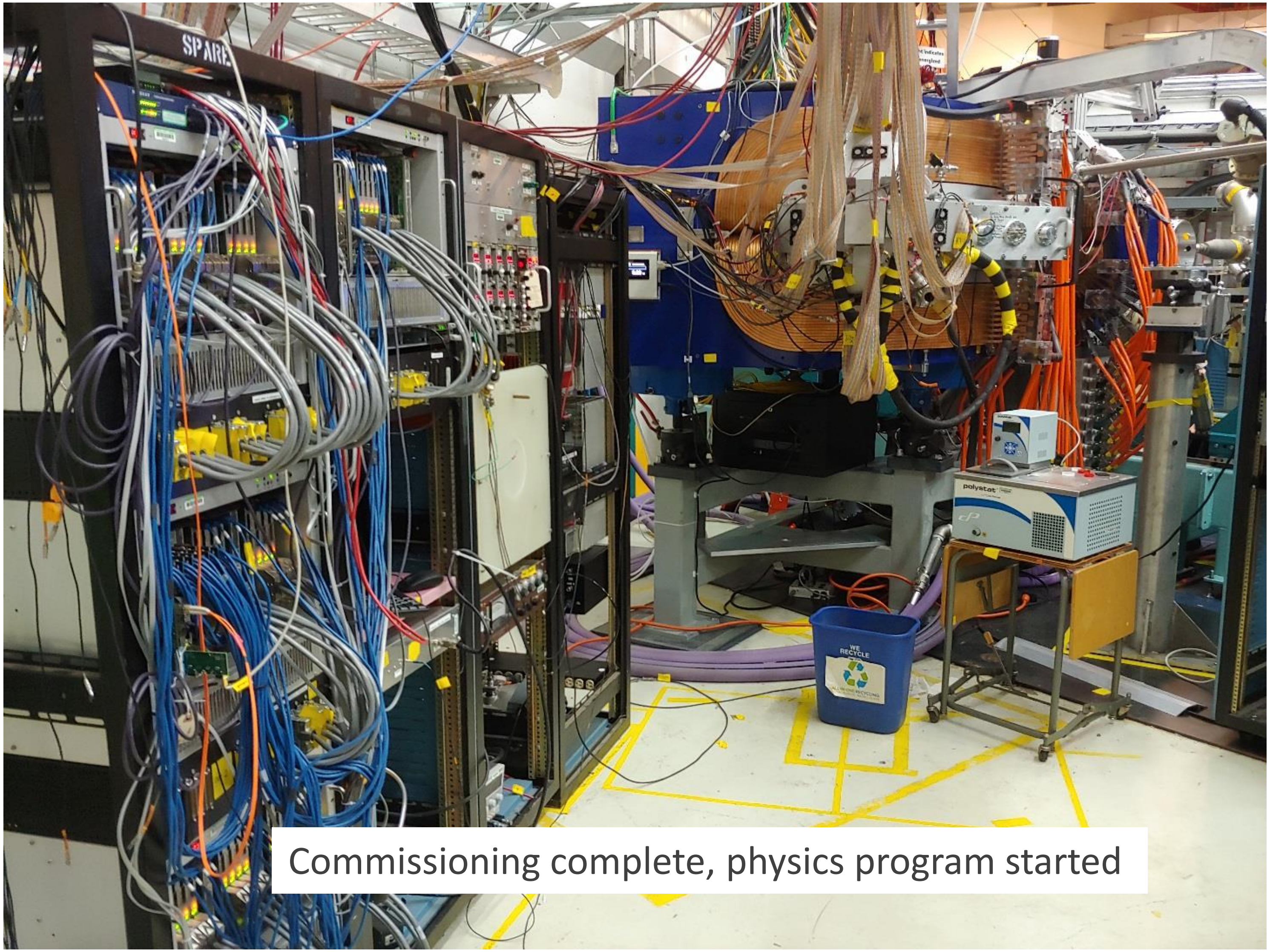
Compact focal plane – efficient decay spectroscopy

Short flight path – fast activities

AGFA and Gammasphere

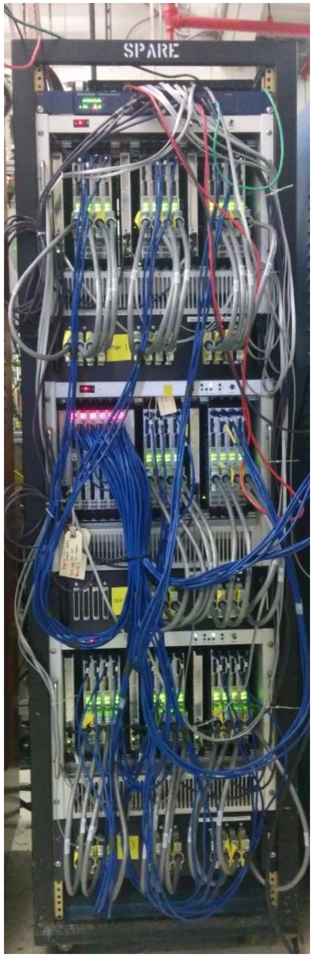


AGFA focal plane

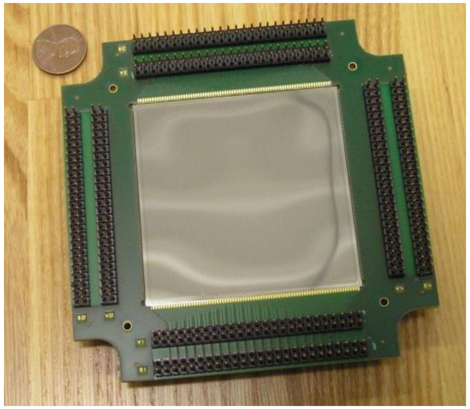


Commissioning complete, physics program started

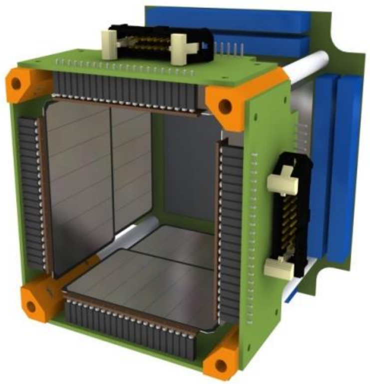
High-granularity Fast Implantation-Decay Station



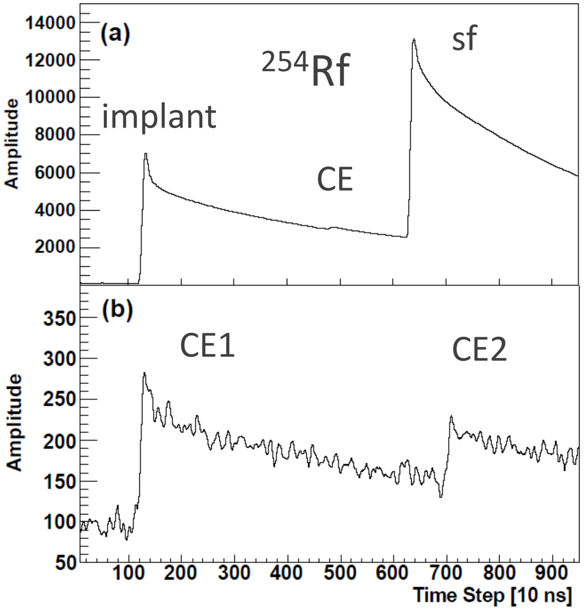
Digital DAQ

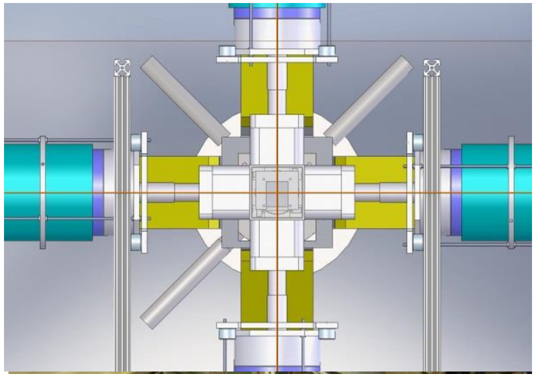


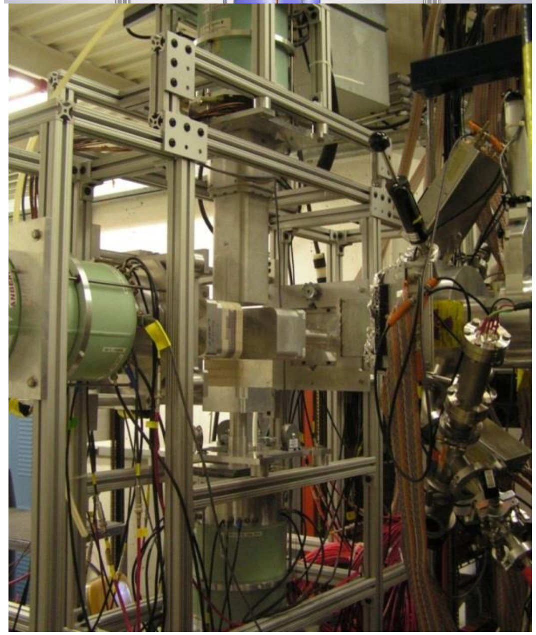
160X160, 64mmX64mm DSSD



Si tunnel
8 SSSD's







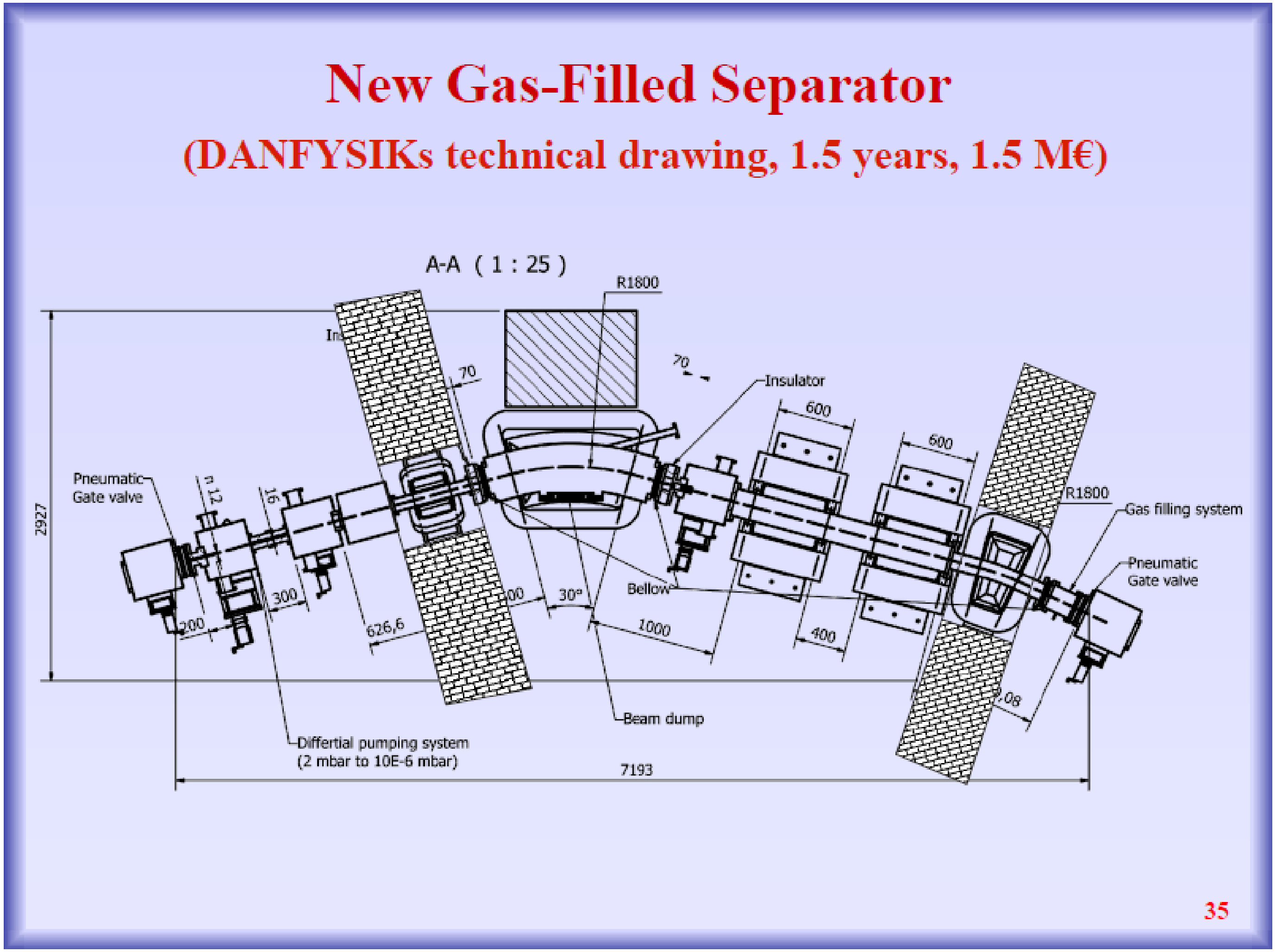
X-Array, 5 clovers
in box geometry

AGFA Cost

- Quad - 240 k$
- Dipole - 350 k$
- Vacuum chamber - 170 k$
- Power supplies – 125 k$
- Support stand – 50 k$
- Utilities
- Vacuum equipment
- Differential pumping
- Gas handling system
- Detectors
- Target wheel system
- …

1-2 M$
1 year design
1 year manufacturing
1 year installation

New Dubna Gas-Filled Recoil Separator

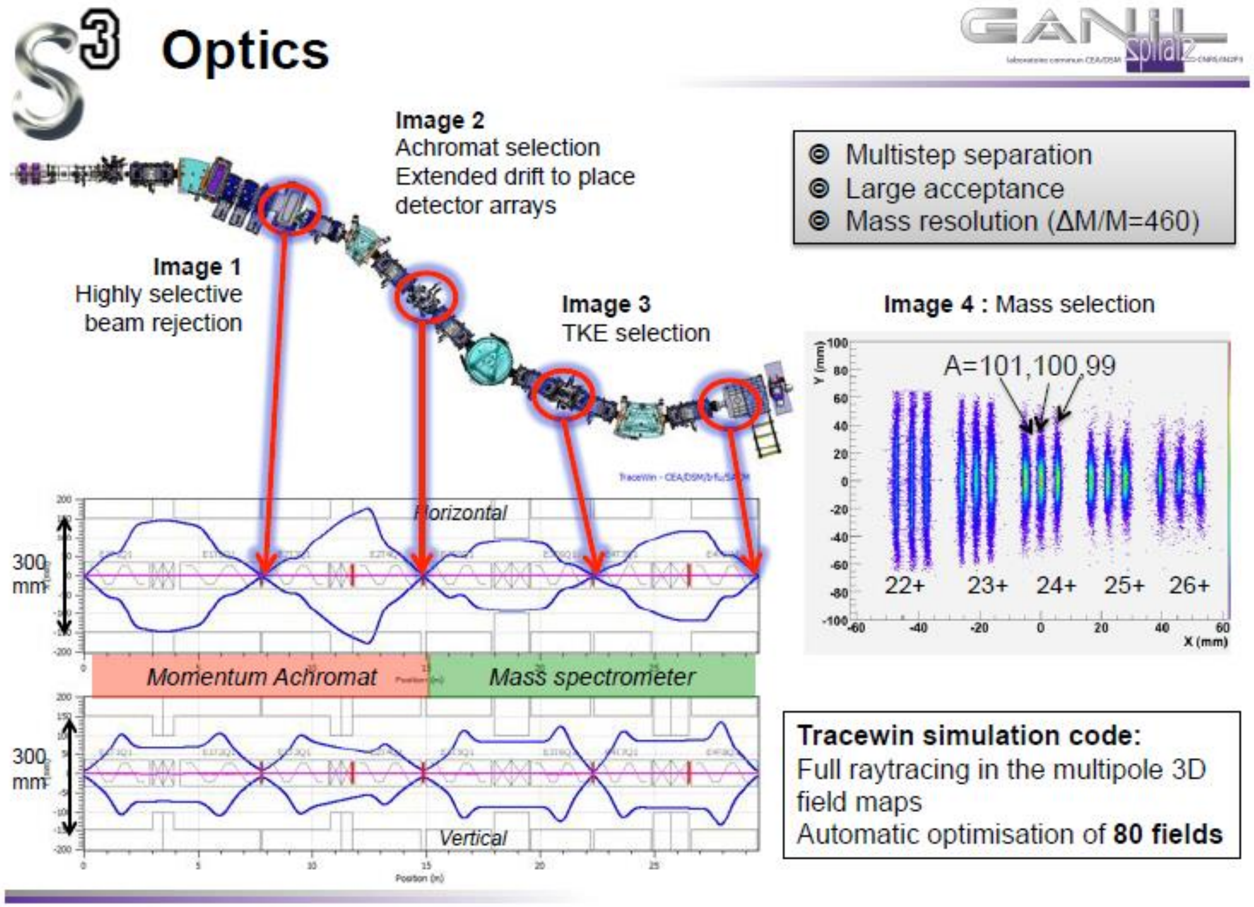


$Q_V D Q_H Q_V D$

Slide courtesy: A. Popeko

Superconducting Super Separator – S^3

$Q^3MDQ^3Q^3MDQ^3$-$Q^3MDQ^3Q^3EDQ^3$

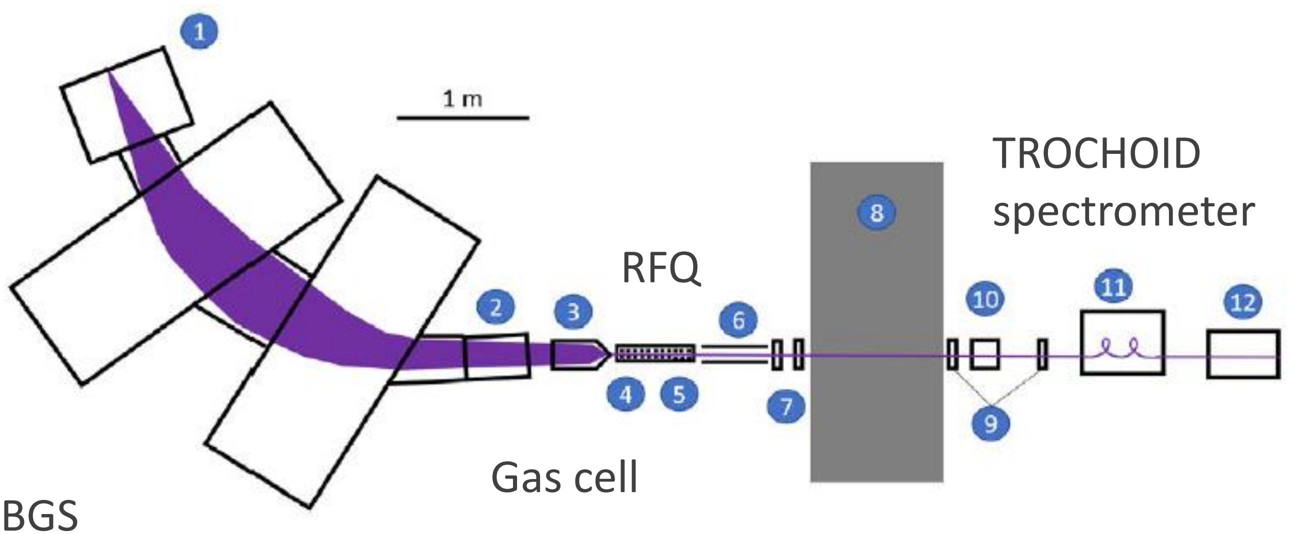


Two stage separation, large M/Q acceptance, good mass resolution
Complex, expensive

Slide: courtesy H. Savajols

Cool SHN beams

- GSI/SHIP
  - SHIPTRAP
  - Laser spectroscopy
- RIKEN/GARIS II
  - MRTOF
- LBNL/BGS
  - FIONA



J.M. Gates et al., PRL 121, 222501 (2018)

Conclusions

- Recoil separator is a MUST for SHN studies
- Design/construction/commissioning takes 3-5 years (best case scenario)
- Choice of a separator depends on foreseen research
- Gas-filled separator would be **my** first choice based on superior transmission and relative simplicity

Thank you for your attention!