Solenoid-based spectrometers

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Background Information (Solenoid Optics)

Operational Experiences (Mainly *BigSol*)

Recent Developments

Some New Concepts

IRIS Workshop March1,2010

Solenoid Optics:

Act as a simple, thick lens with focal length as a function of length and axial field, B_z^2L (the integral) and ion Bp:

In order1: $f = 4(Bp)^2 / \langle B^2_z L \rangle$

Hence we can change image location (which also impacts angular and transverse magnification) as we would for any lens:

$$1/f = 1/i + 1/o$$

$M_T = -i/o$ (hence dispersion is variable and have similar dispersion along z axis)

$M_T M_A =$ Constant

$f/\# = f/D =$ can be "fast" (f/2)

Dispersion: Both transverse and axial can be used.

Pre-1970's: Used mostly for electrons (basis for electron microscope) as can use permanent magnets or electromagnets w/ electrons (Ruska Nobel prize)

1970's onward: Superconducting magnets (as suggested by J. Nolen, MSU) permit use of solenoids for MeV energy ions.

Work at Orsay (Schapira et al; SOLENO): Exotic decay studies (14 C decay, etc.) using sc solenoid spectrometer

UM-ANL-UND: 3.5T solenoid at ANL ATLAS and later at UND

Early Orsay papers on solenoid HI spectrometers:

NUCLEAR INSTRUMENTS AND METHODS 162 (1979) 181-192 ; © NORTH-HOLLAND PUBLISHING CO.

MAGNETIC QUADRUPOLE AND SOLENOIDAL SPECTROMETERS

H. LAURENT and J. P. SCHAPIRA

Institut de Physique Nucléaire, BP no. 1, (91) Orsay, France

General optical properties of magnetic quadrupole spectrometers (QS) are reviewed, together with experimental purposes for nuclear physics: background reduction, magnetic rigidity filtering for extreme forward angles measurements, light charged particle discrimination, ionic charge state separation, time of flight mass spectrometry and fast collection of radioactive nuclear reaction products. Possibility of alternative devices such as superconducting quadrupoles or solenoid spectrometers are discussed.

Nuclear Instruments and Methods in Physics Research 224 (1984) 337–346
North-Holland, Amsterdam

SOLENO, A SUPERCONDUCTING SOLENOIDAL COIL USED AS A SPECTROMETER FOR NUCLEAR CHARGED PARTICLE STUDIES AROUND ZERO DEGREES

Jean-Paul SCHAPIRA, Faiçal AZAIEZ, Simone FORTIER, Sydney GALES, Eid HOURANI, Jaana KUMPULAINEN * and Jean-Marie MAISON

Institut de Physique Nucléaire, BP no. 1, 91406 Orsay, France

Received 14 November 1983

Related UM-ANL project (RSI paper) based on Orsay work:

1682 Rev. Sci. Instrum. 58 (9), September 1987

Tests of a large air-core superconducting solenoid as a nuclear-reaction-product spectrometer

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(Received 6 February 1987; accepted for publication 23 March 1987)

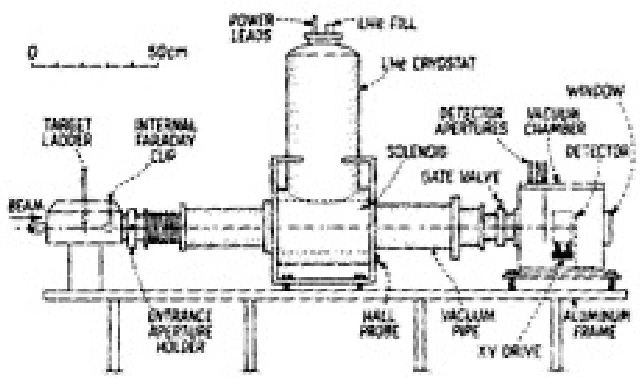
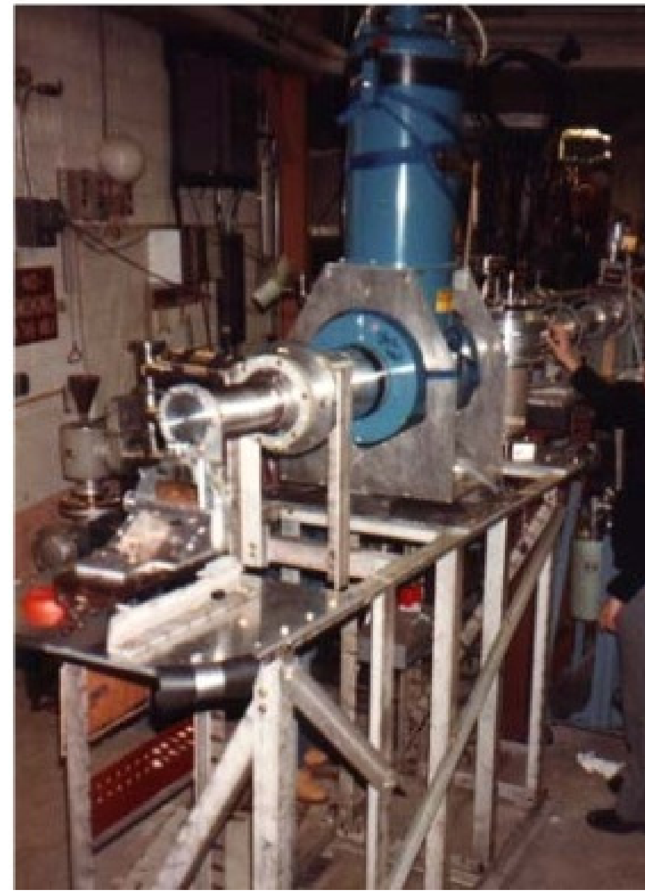
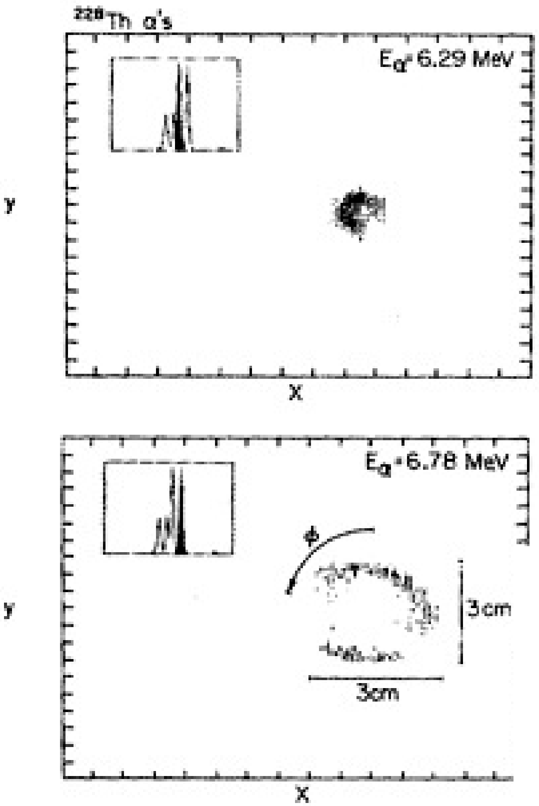


FIG. 4. The layout of the Univ. of Michigan 20-cm bore solenoid spectrometer.



Images at focal plane
(radial dispersion):



Lots of stuff !!

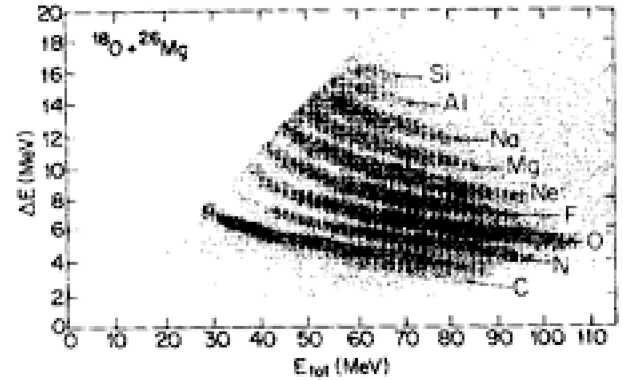


FIG. 12. A $\Delta E - E$ spectrum for 106-MeV ^{18}O + ^{26}Mg, obtained with the gas proportional counter detector.

Small angle HI transfer data:

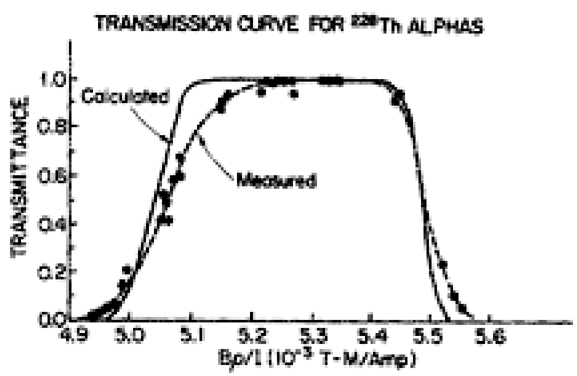


FIG. 9. Measured and calculated solenoid-spectrometer transmission curve for α particles emitted from a ^{228}Th source (E_α = 5.34–8.78 MeV) located at the target position with angular acceptance of 5°–6°.

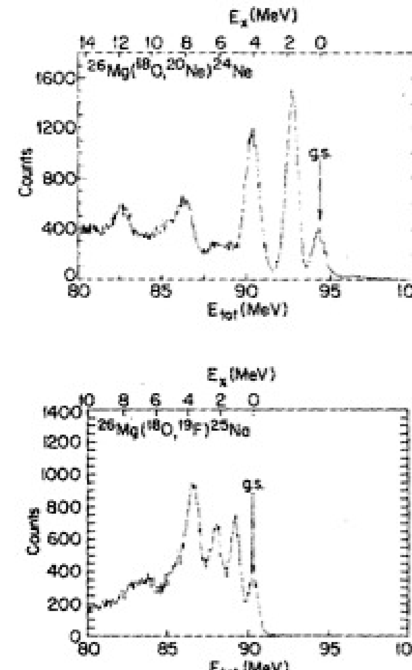
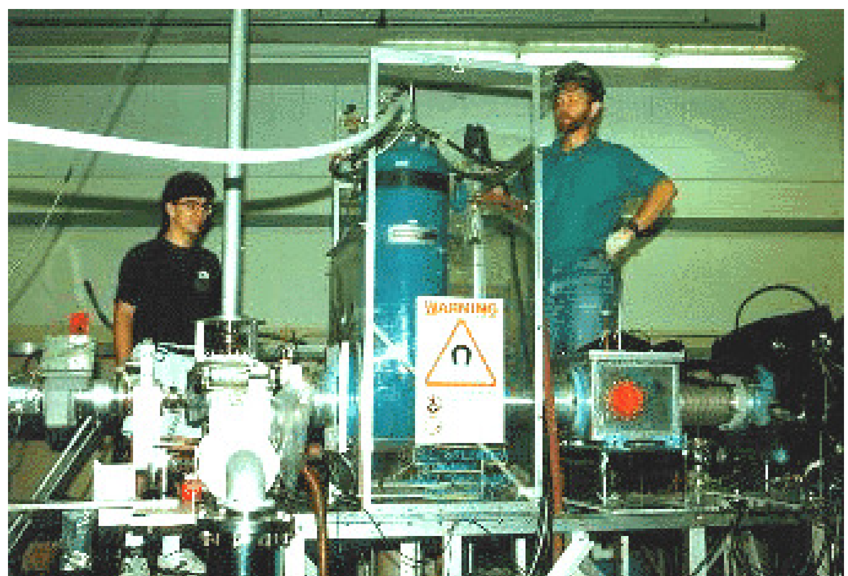


FIG. 15. Top: Energy spectrum for $^{26}Mg(^{18}O, ^{20}Ne)$ ^{24}Ne at 100 MeV. The angular acceptance was θ = 3°–6° ($d\Omega$ = 25 msr). Bottom: Energy spectrum for $^{26}Mg(^{18}O, ^{19}F)$ ^{25}Na at 100 MeV. The angular acceptance was θ = 5°–6° ($d\Omega$ = 8.5 msr).

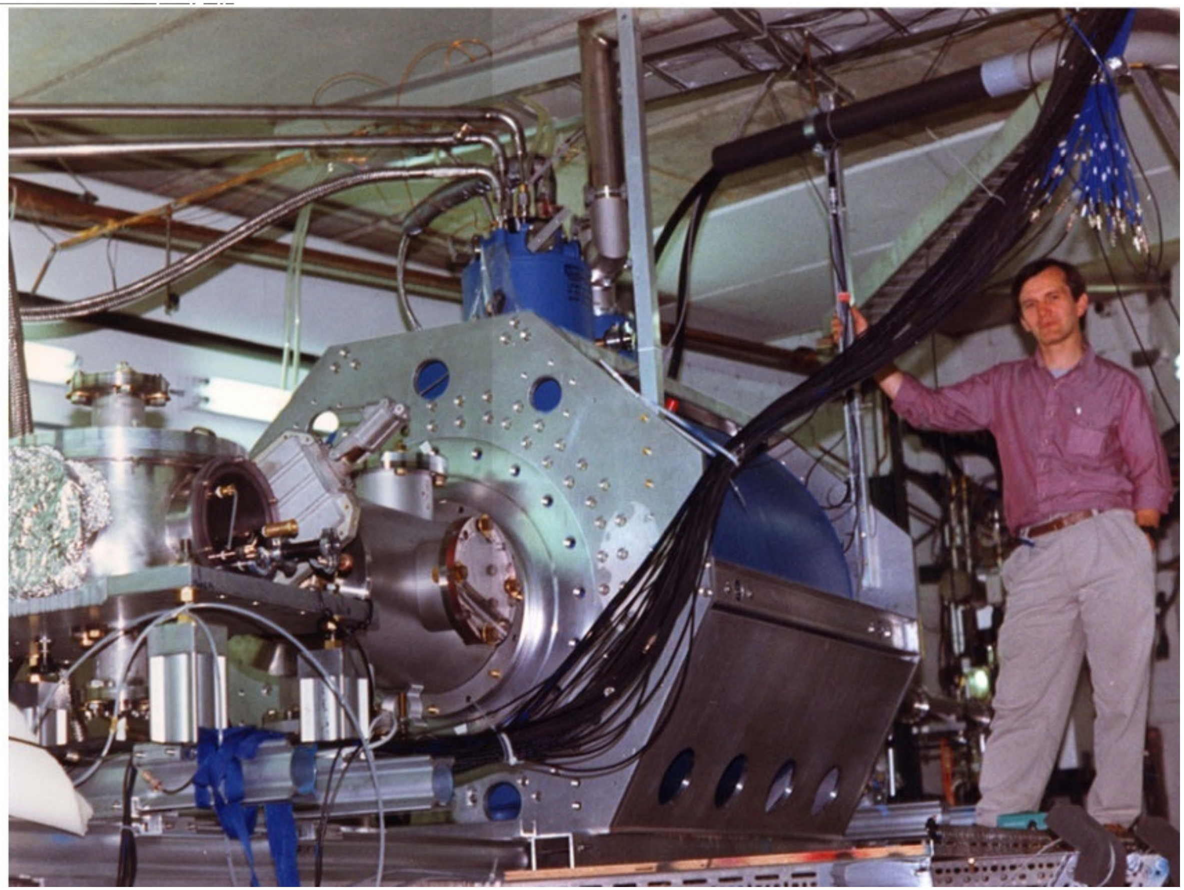
3.5 T solenoid ("LiLSol") at ANL used as small angle multi-nucleon spectrometer (dE-E-ToF) for 18O induced reactions(R.Stern,UM Phd; Rev.Sci.Instrum. 1987):

Problem: Tho demonstrated techniques there was high count rate of "unwanted" ions (>10^4/s) (17,18F,19O, 21Ne,…) =radioactive ions= RNBs!…so…

Moved to U. Notre Dame FN tandem as dedicated LE RNB production device, one of first operational high-intensity RNB devices (1985-1992):



Led to design and construction of a "portable (!)" 40 cm bore, 7T sc magnet ("BigSol") for use at MSU NSCL as both a specialized RNB production device (isomer beams e.g. 200 nsec 18Fm) and as a multi-particle spectrometer (1990s)



Material from ToD thesis (and related NIM paper)[a]:

A SUPERCONDUCTING-SOLENOID ISOTOPE SPECTROMETER FOR PRODUCTION OF NEUTRON-RICH NUCLEI

$$(^{136}Xe +^{nat} C,\ E/A = 30MeV/u)$$

by

Thomas W. O'Donnell

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Physics)
in The University of Michigan
2000

a) This and other theses etc available at UM *TwinSol* web site:
www.physics.lsa.umich.edu/twinsol/

As lens, can pick object and image distance for given E/A and solid angle (MT,MA, dispersion then set):

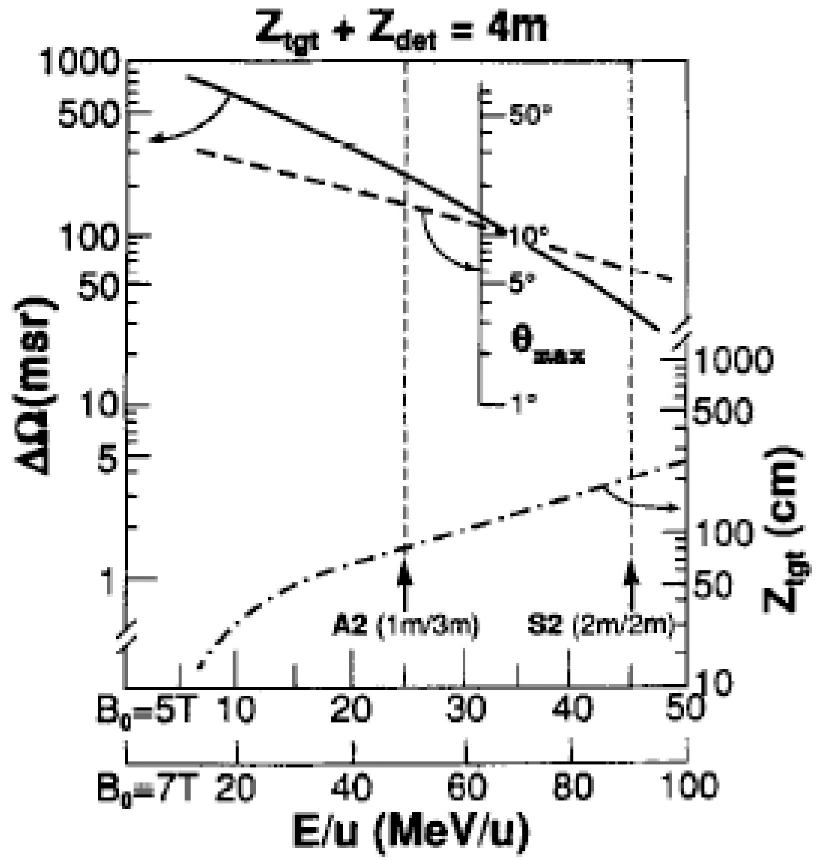
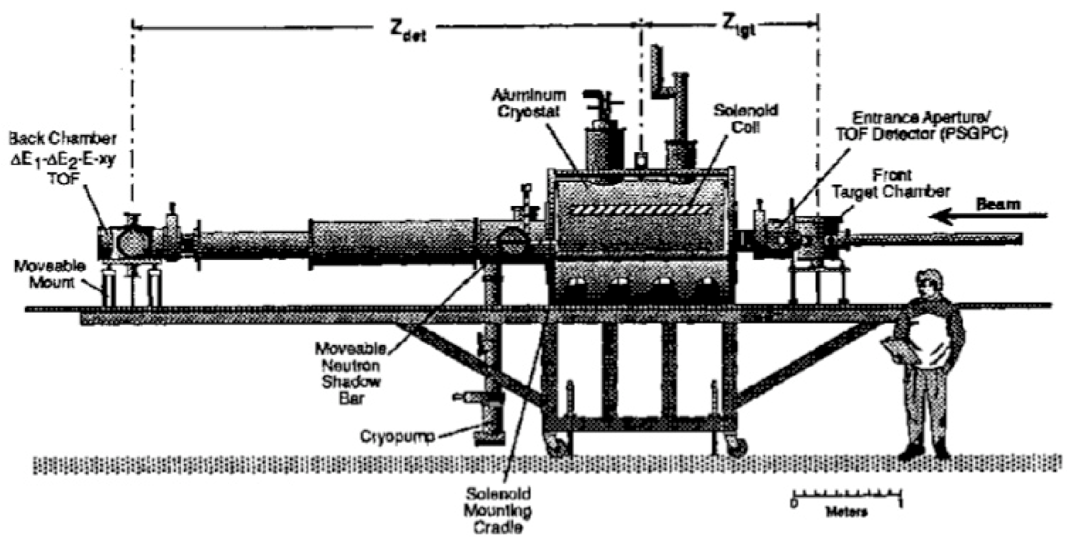


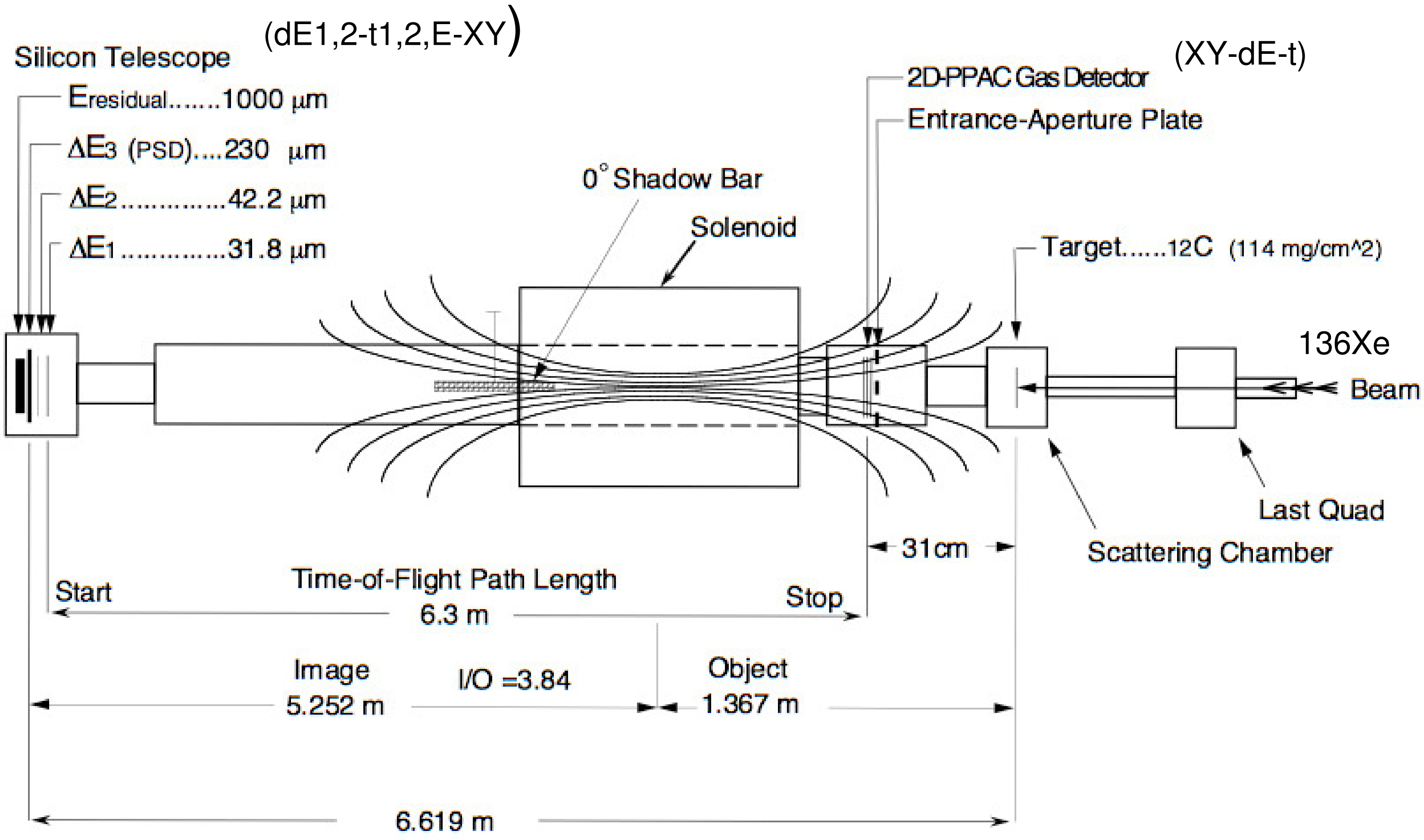
Fig. 2. Typical operating characteristics (dΩ and Θ_{max}) at B_{oz} = 5 T and 7 T for various combinations of Z_{tgt} and Z_{det} (see fig. 1). The initial tests corresponded to $Z_{tgt} \approx 1.5$ m and $Z_{tgt} + Z_{det} \approx 3.5$ m.

Configuration of BigSol at MSU NSCL as a multi-particle spectrometer for study of fragment yield 136Xe+ natC, E/A= □30 MeV/u (T. Odonnell, UM PhD 2000-available on line):

Here we set up for long focal length and hence long flight path (6.6 m) for ToF, but still few cm^2 image size to permit use of thin+thick+PSD silicon detectors at focal plane (an advantage of solenoid along with uniform trajectories for sub-nsec ToF):



(note wheels!)



UM BigSol Isotope Spectrometer, NSCL

(Schematic, not to scale.)

Specifically, *a key goal here was to find particle identifiers which would combine signals in such a manner that q would be eliminated (be canceled out) from the calculations.* The (not immediately obvious) constructed space ended up being a fairly simple Z-identifier vs. an A-identifier.

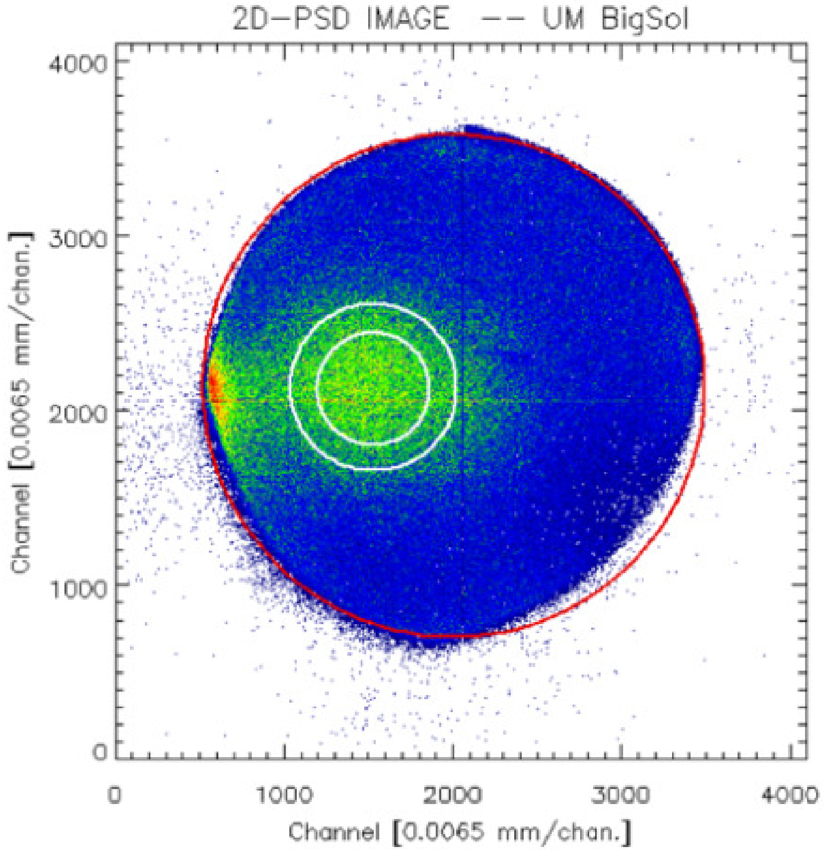
Large-area front PPAC XY (trajectory, dE, and fast timing < 1 nsec) together with silicon detectors dE1-t1,dE2-t2,E-XY at focal plane permits good fragment identification without any pre-gating (hence all events used including several q states):

Table 6.1: University of Michigan 'BigSol Isotope Spectrometer' at NSCL.

• Beam	
Ion:	$^{136}Xe^{24+}$
Kinetic energy:	30 MeV/u (4 GeV)
Intensity:	$\approx$ 4.6 enA (1.2e^{+09}particles/s), after attenuation by 10-100X
Accelerator:	K1200, National Superconducting Cyclotron Laboratory (NSCL).
• Target	
Material:	^{nat}C in layered graphite foils.
Aerial Density:	114 mg/cm^2
• Solenoid field	
Current-to-rigidity:	80 amps $\approx$ 1.36 T-m ($\int B \cdot dl$)
Maximum Current:	170 amps
• Solenoid entrance (object)	
Apertures:	$0.7° \leq \theta_{lab} \leq 3.1°$ or $2.2° \leq \theta_{lab} \leq 6.2°$, and $\Delta\phi_{lab} \approx 2\pi$
Timing-stop & θ_{lab} detector:	Position-sensitive parallel plate avalanche counter (2-D PPAC), iso-octane gas.
Counting rate:	$\leq 35 - 50$ kHz (PPAC)
• Solenoid focal-plane (image)	
ΔE_1 & time-start signal	31.8μm Si
ΔE_2:	42.2 μm Si
Si-PSD:	230 μm Si
$E_{residual}$:	1000 μm Si
Counting rate:	$\leq$ 500 Hz (at ΔE_1)
Logic:	Trigger and timing start on ΔE_1 event, timing stop on delayed PPAC anode signal.
• Spectrometer dimensions:	
Target to focal-plane distance:	6.62 m
image/object (i/0) distance:	5.25/−1.37 m (asymmetric mode)
Time-of-flight distance:	6.31 m

Precise ion-optics of solenoid (if aligned) with minimal aberrations permits accurate XY gating (to < 1mm) to select Bp bites in silicon PSD:

Here image is 25 mm diameter and Bp bite is a few mm Wide.



..but..

Figure 7.1: Typical 2D PSD image showing $B\rho$ selection software gates at solenoid focal plane. See text for details.

Front PPAC XY image for a given isotope (can measure differential cross section *if* transmission calculated OK)

Note: Spiral angle image of FC support can confirm Bp.

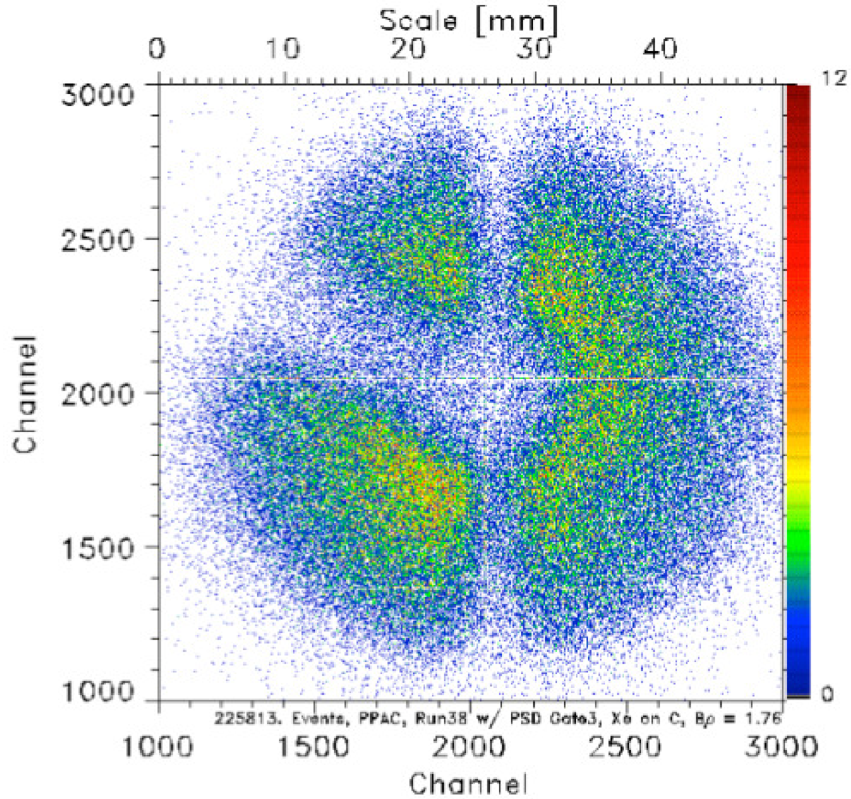


Figure 7.2: 2D entrance PPAC image with 0.7° − 3.1° aperture. PPAC spectra shown here has been gated by a software aperture on the Si-PSD *focal*-plane detector.

Problem: At FP XY can correspond to two different orbits, one crossing axis, one not (so need good E-t)

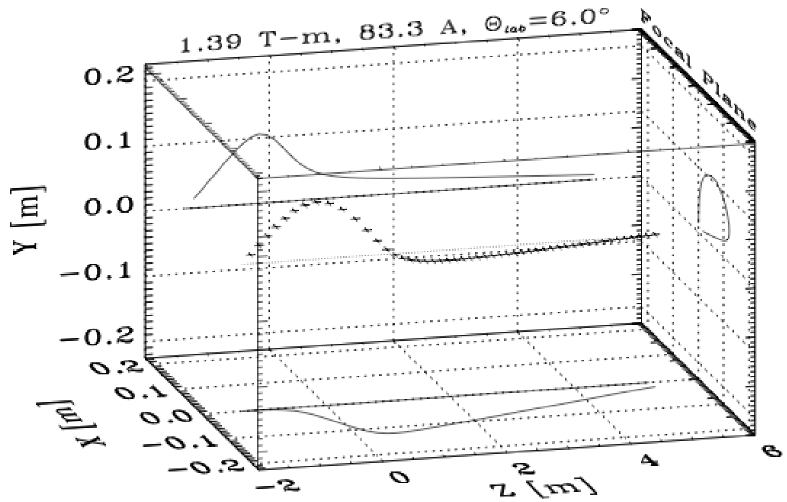


Figure 5.6: 3D box plot of simulated solenoid orbit. $\theta_{lab} = 6.0°$, $B\rho = 1.39$ T-m. Ion DOES cross axis yet reaches the SAME focal-plane position as for Fig. 5.7, illustrating double-valued $B\rho$ of solenoids as function of θ_{lab}.

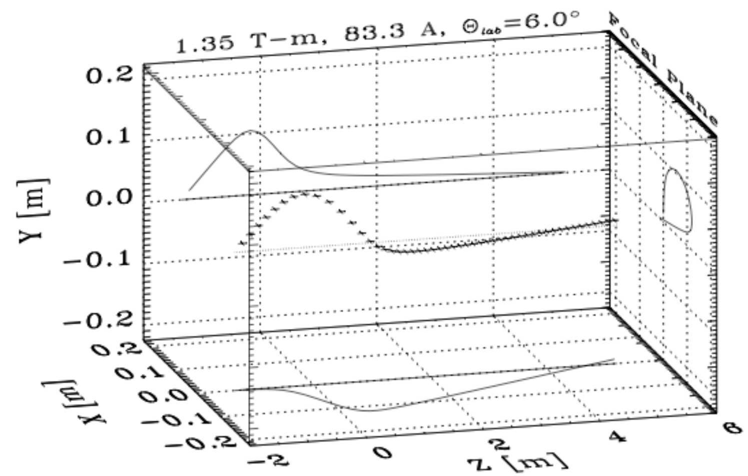


Figure 5.7: 3D box plot of simulated solenoid orbit. $\theta_{lab} = 6.0°$, $B\rho = 1.35$ T-m. Ion DOES cross axis to reach SAME focal-plane position as for Fig. 5.6.

Thus transmission efficiency somewhat complicated and depends on good alignment wrt beam axis, beam emittance etc. (but if those known can simulate orbits well due to simple ion-optics)

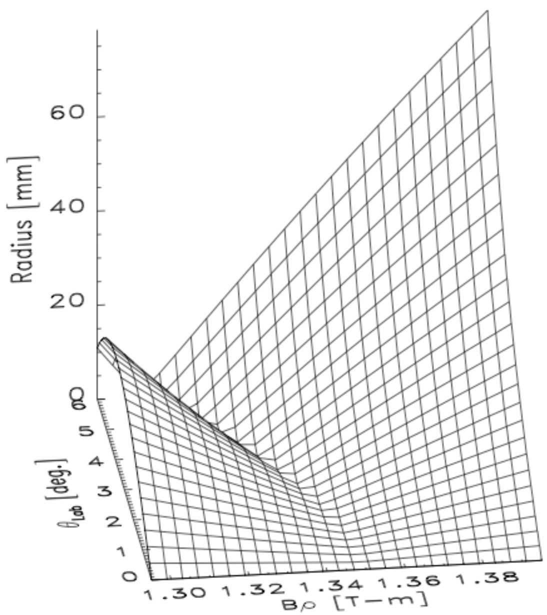


Figure 5.9: Acceptance map. Full thick-coil field model: Like Fig. 5.8 but with r^{-3} dipole-fit model for far field.

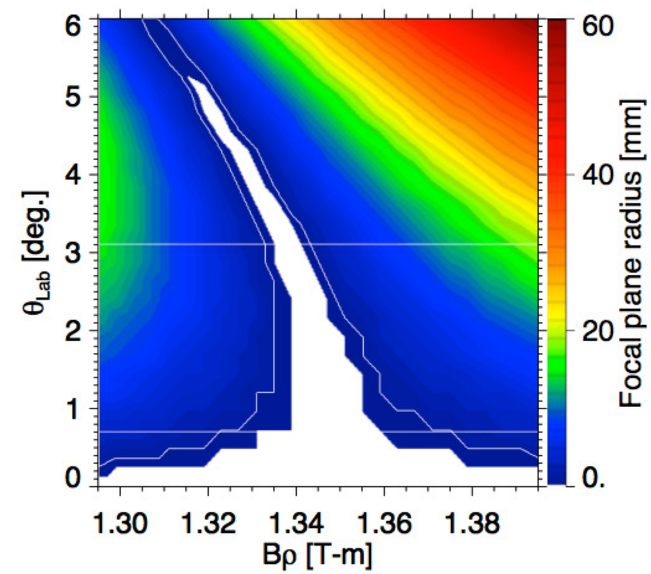


Figure 5.12: Contour map showing same information as in earlier wire-frame plot of Fig. 5.8, but now the radial-hit position of ions is represented by contours. Spectrometer acceptance for ideal, on-axis primary beam is shown together with the cuts caused by physical apertures (lines drawn at constant θ_{lab}) and cuts caused by software focal-plane apertures (lines drawn at constant-height contour). Acceptance is the INTERIOR region formed by these four aperture (cut) lines.

136Xe+natC, 30 MeV/u at small thetas:

Large acceptance: *Be careful what you wish for !:*

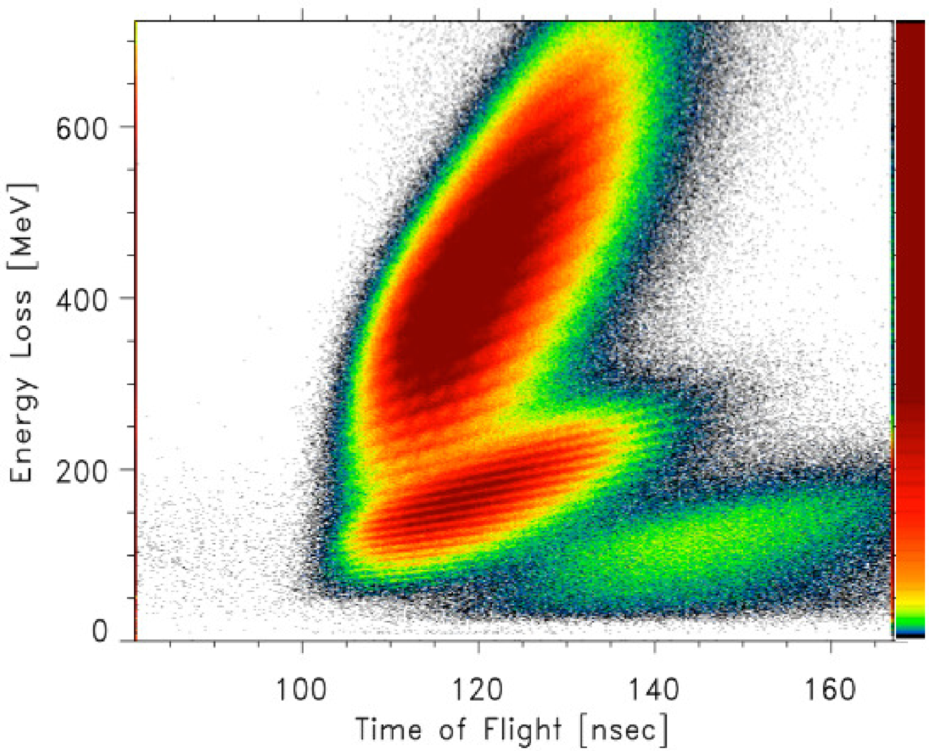
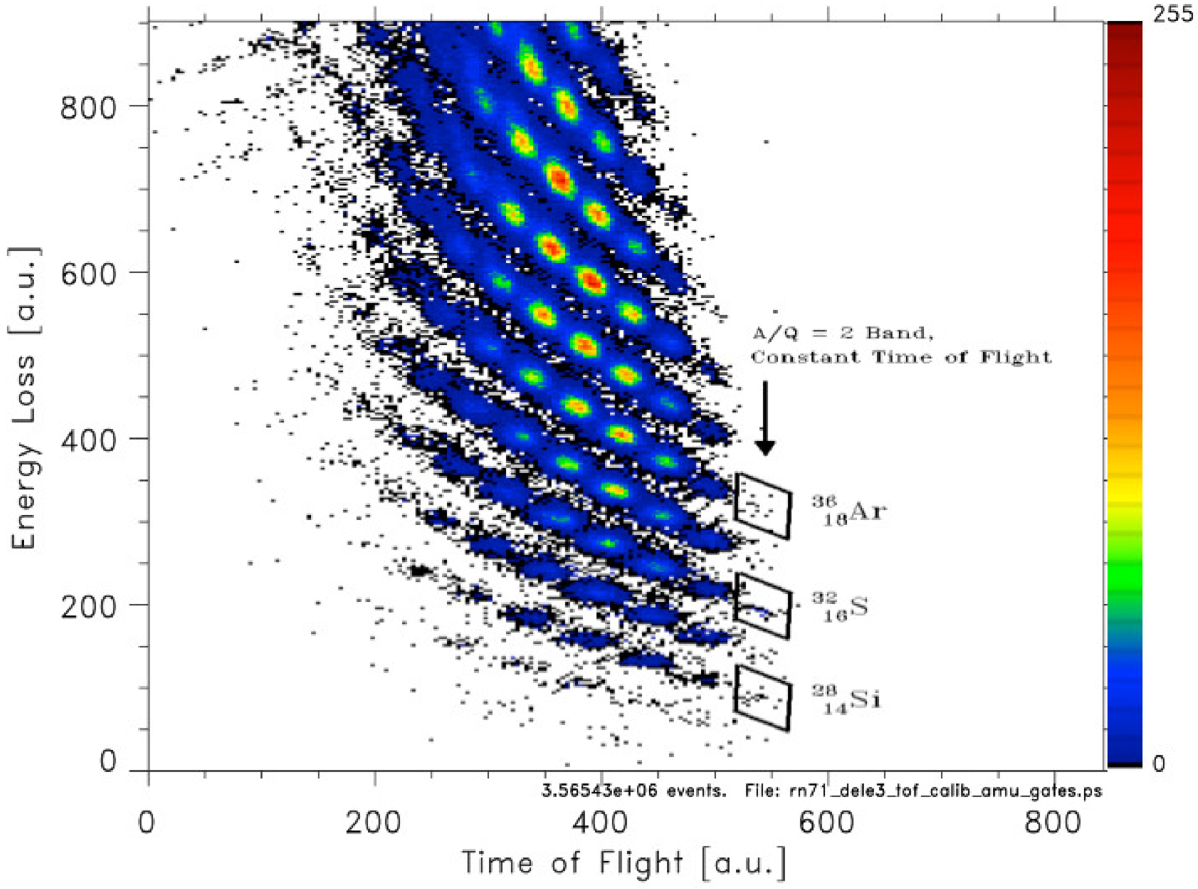


Figure 7.4: ΔE vs. ToF at 1.36 T-m. Full data, without software $B\rho$ bite restriction.

So major problem is to i.d. everything.

Critical: Have available calibration beams (known Z,A,E) .
In cyclotron we use analog beams (same q/A and B π)



F. Becchetti: Solenoid-based spectrometers, IRIS Workshop March1,2010

Developed Fourier transform technique to remove spurious events (yet keep all good events)

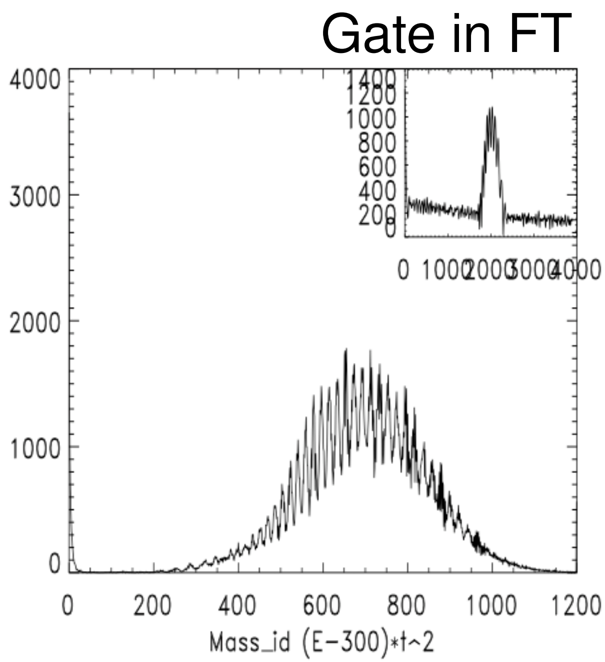
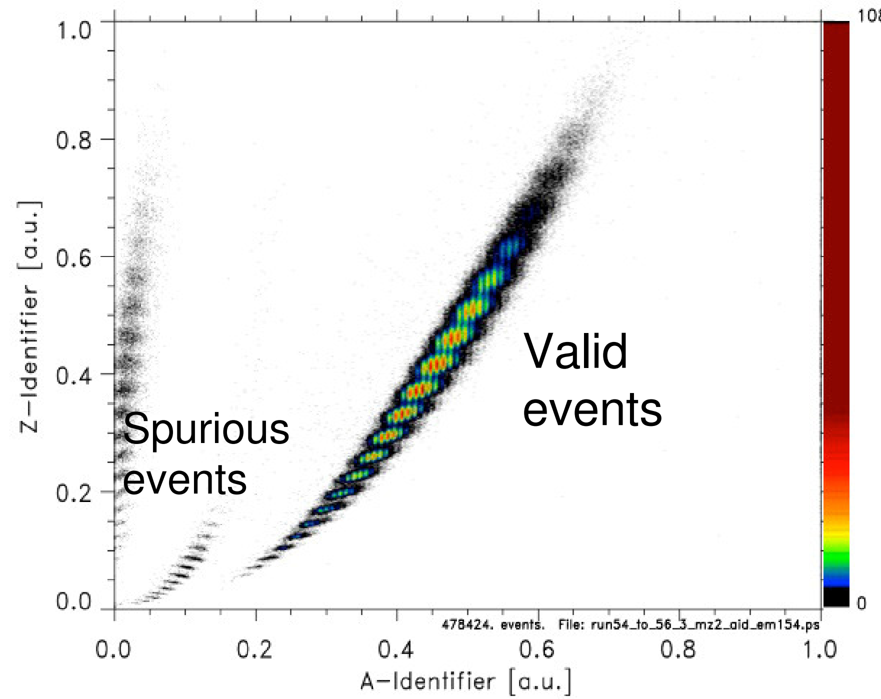


Figure 7.10: Projection of A-identifier and its Fourier transform used to objectivel
assess effect of parameter on resolution (here set to 300).

Figure 7.11: 2D Z-identifier vs. A-identifier matrix after initial optimization of E calibration. Note 'bad' data points have been *automatically* (i.e., objectively) displaced from region of interest.



With care can add runs taken at different field settings (40Ar band shown here)

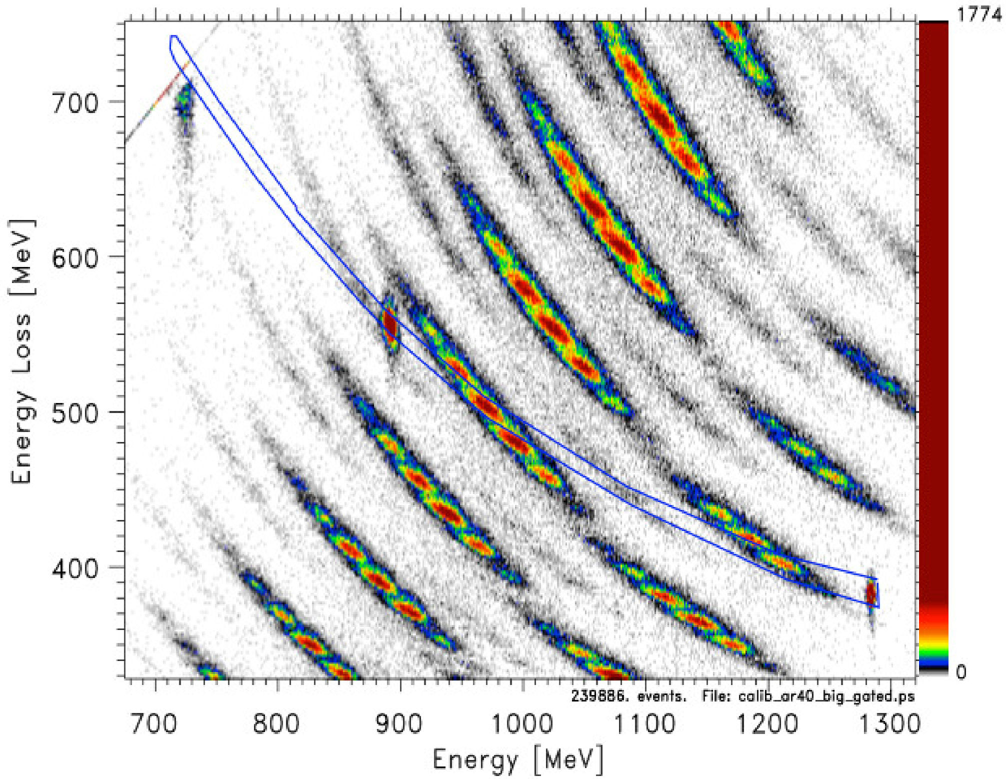


Figure 7.8: Blowup of Fig. 7.7 for ^{40}Ar MZ^2-band region. Two different magnetic-rigidity runs (about 1.36 and 1.76 T-m) are combined here to accomplish full tiling calibration.

Generating Z,A "identifiers" leads to relatively clean Z,A spectra where all events have been used…I,e, none thrown away in gates.. (dE1,dE2,E are correlated and should not be pregated)

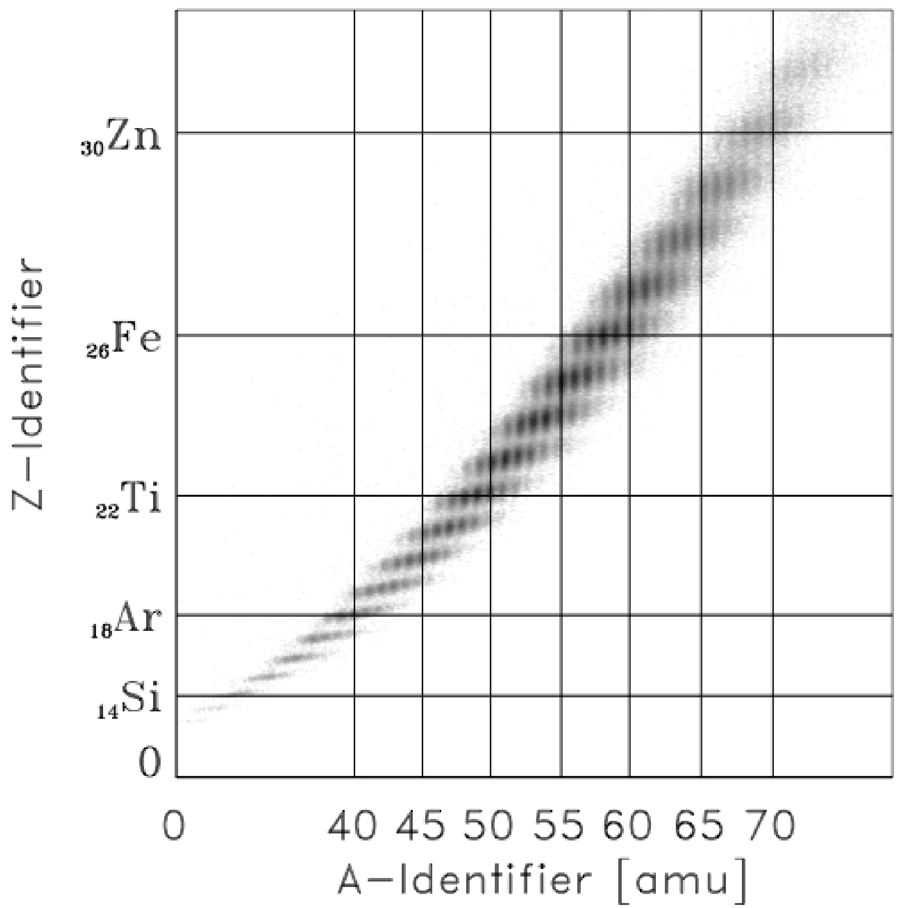
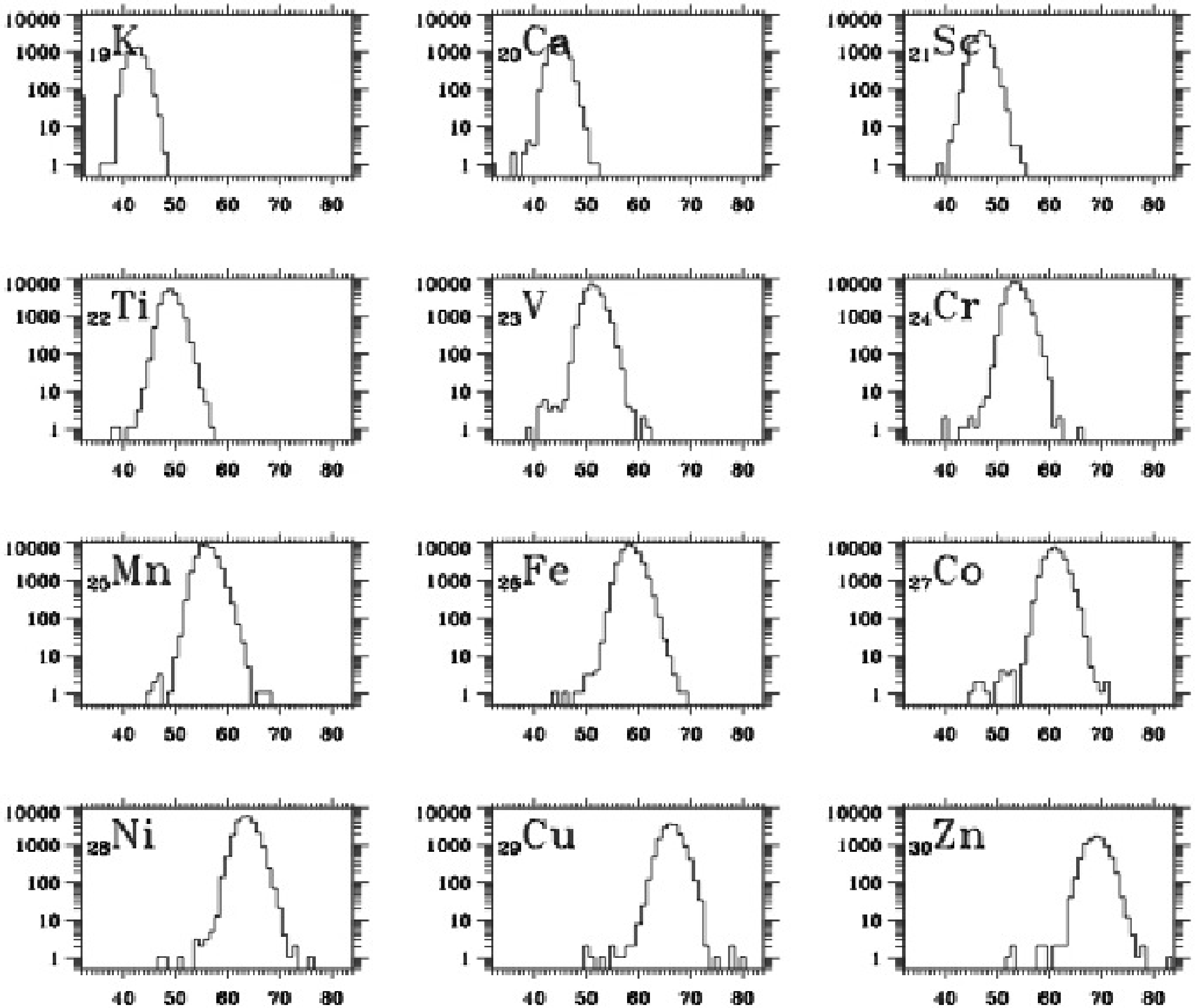
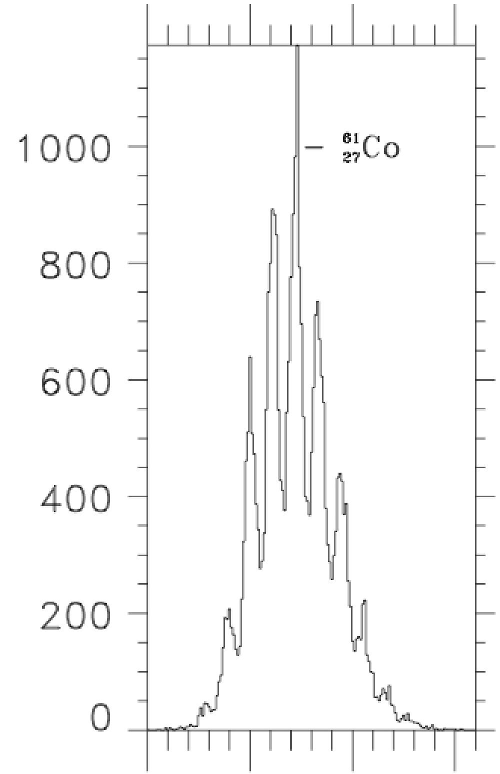


Figure 9.5: 2D Z-identifier vs. A-identifier. Identical to Fig. 9.4 but grey scale and having absolute, calibrated values of Z-identifier and A-identifier shown. Data from 4-5 charge states are positively identified by Z and A values independent of their q-states. Data includes neutron-rich nuclei up to and beyond the most n-rich produced at the time of this experiment.



19K
20Ca
21Sc
22Ti
23V
24Cr
25Mn
26Fe
27Co
28Ni
29Cu
30Zn
10000
1000
100
10
1
40 50 60 70 80



1000
800
600
400
200
0
$^{61}_{27}$Co

65,66,68 +Co?

^

But: Large-area front PPAC available at the time (resistive XY) limited count rate w/o degrading ToF to 10^4/sec. This limit (and beam time allocated for experiment including set up time) N,Z of fragment spectra:

Improved system : Utilize fast segmented PPAC or MCP+foil based detectors for trajectory measurements. This could increase rates x10-x100 or more. Also, may be possible and sufficient to measure trajectory only at exit of magnet (less neutron/other background) and larger silicon detectors array at focal plane.

System at MSU NSCL had to be used in a "portable" mode (moved in/out of beam line including LHe lines etc.) Also device limited to fragment energies < 20 MeV/u (I.e. below NSCL > 2000 upgrade energies). Hence moved to dedicated beam line at TAMU cyclotron:

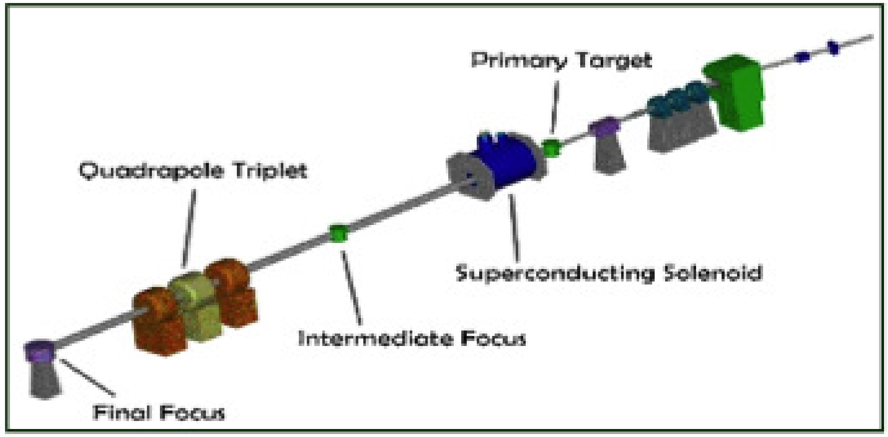


Figure 1. Schematic diagram of the Superconducting Solenoid Rare Isotope Beamline.

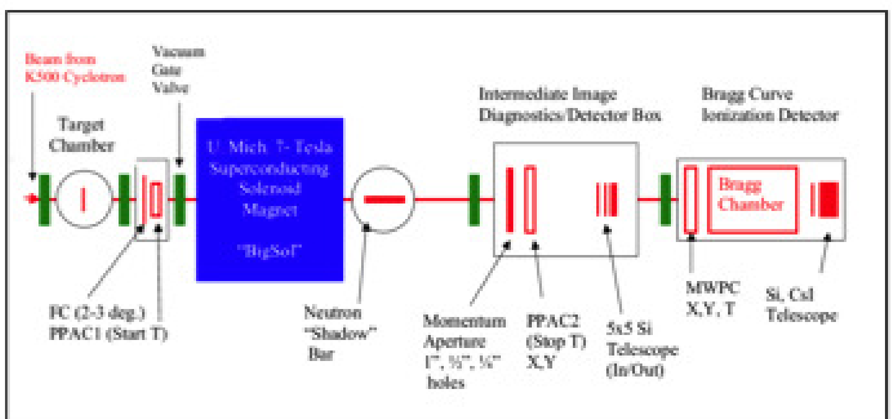


Figure 2. Schematic diagram of the experimental setup of the first part of the Big Sol Line.

Recent TAMU experiment using BigSol:

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Vol. 18, No. 4 (2009) 1036–1043

World Scientific
www.worldscientific.com

NEW EXPERIMENTAL APPROACH FOR HEAVY AND SUPERHEAVY ELEMENT PRODUCTION

M. BARBUI[a], T. MATERNA[b], P. SAHU[b], A. WIELOCH[c], F. D. BECCHETTI[d], G. CHUBARYAN[b], M. CINAUSERO[a], T. W. O'DONNELL[d], D. FABRIS[e], H. GRIFFIN[d], K. HAGEL[b], S. KOWALSKI[b,f], M. LUNARDON[e], Z. MAJKA[c], S. MORETTO[e], R. MURTHY[b], J. B. NATOWITZ[b], G. NEBBIA[e], S. PESENTE[e], G. PRETE[a], L. QIN[b], V. RIZZI[a], Z. SOSIN[c], G. SOULIOTIS[b], G. VIESTI[e], R. WADA[b], J. WANG[b]

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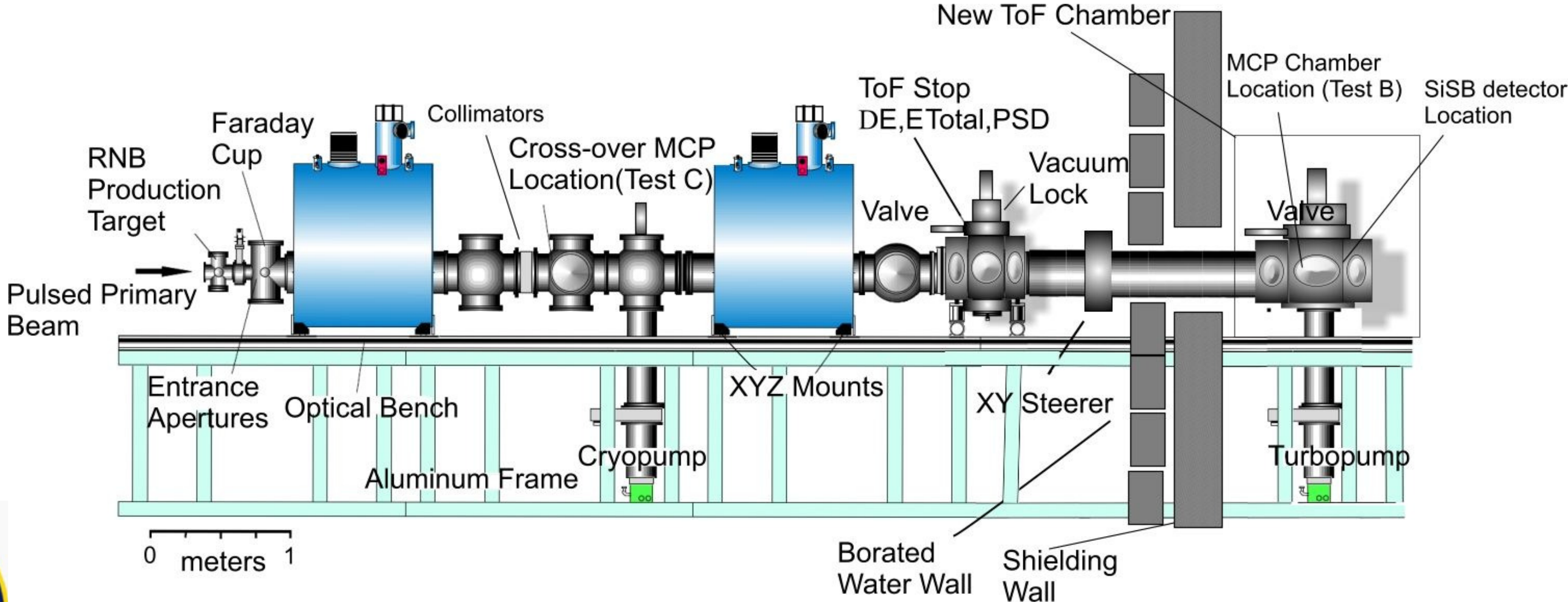
Ideal system ?: Two solenoid magnets ?? .

TwinSol : Designed and constructed as joint UM-UND project (1995-) mainly as LE RNB production device, but on occasion used as a spectrometer system with front reaction chamber added for particle-particle coincidence.

Special feature: Low-loss croystats and operate in persistent mode (no LHe system needed).



Two magnets can be used in multiple modes with or w/o cross over at center (latter for ToF detector, E-loss absorber, etc.). Opposing B reduces fringe field.

Again long-flight path ToF possible with minimal time dispersion. Multiple scattering chamber locations possible .

Recent Twinsol set up as 8 M ToF system (RNBs) w/MCP at cross over focus:

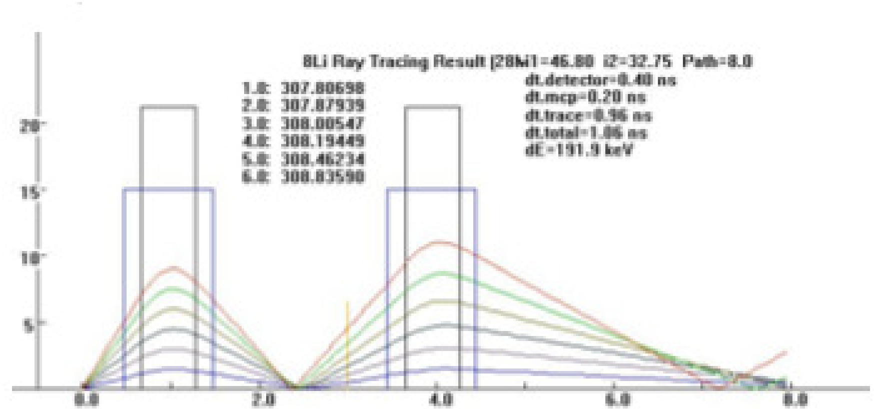


Figure A.11: Ray-trace calculation of a 28 MeV ^{8}Li beam in *TwinSol* with a long flight path (8 m).

Also have run in parallel hi-Bp mode:

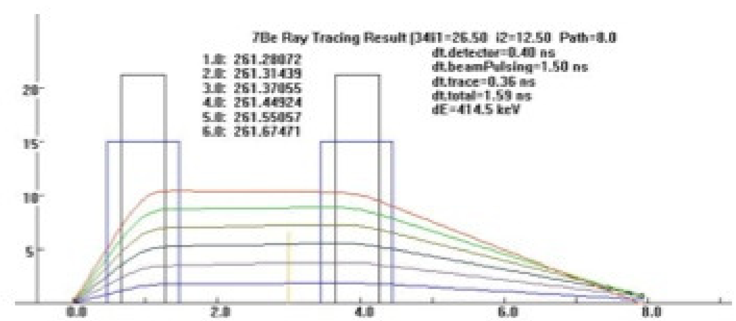


Figure A.12: Ray-trace calculation of 34 MeV ^{7}Be in parallel mode (8 m flight path).

Upgrade options for use as multi-fragment spectrometer:

A) Add radial electric field lens or similar (UM RSI paper)

B) Run gas filled mode (but destroys ToF-XY): See ANU work

C) Compensating Eloss absorbers (UM NIM paper)

D) Long magnets for harmonic charge focussing (UM RSI paper) ?

Ideal configuration depends on intended use and Z,A,q of ions to be detected.

e.g. neutrons an issue?? Don't need zero degrees, rather 1 to 10 degrees?? ?? (Solenoids run at zero degrees..but need angles away from zero for dispersive focii).

Large-aperture, axially symmetric ion-optical lens systems using new types of electrostatic and magnetic elements

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(Received 4 November 1988; accepted for publication 27 March 1989)

Focusing of multiply charged energetic ions using solenoidal B and radial E lenses

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(Received 28 July 1986; accepted for publication 17 October 1986)

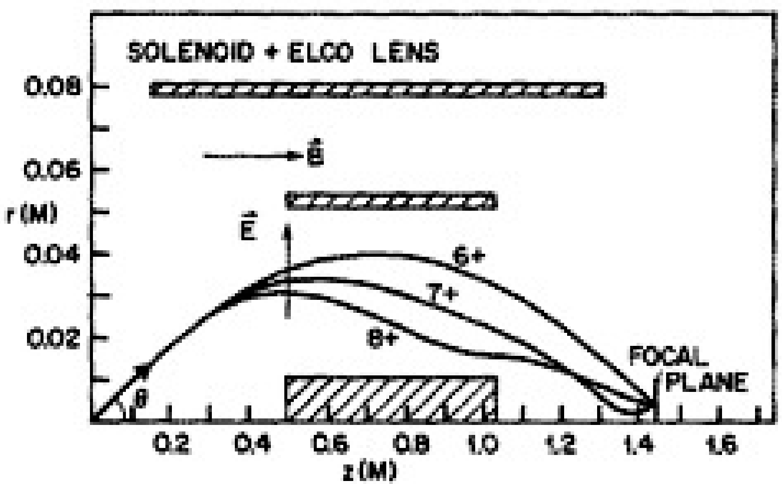

FIG. 3. Calculated ion orbits for a combined magnetic solenoid and radial-electric-field (ELCO) lens system with parameters adjusted to focus a range of charge states for 60 MeV ^{16}O, $\theta = 5°$. Other properties are given in Table I. (Note different horizontal and vertical scales.)

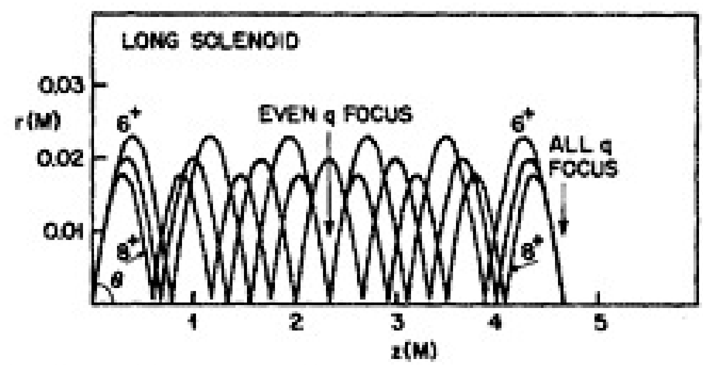

FIG. 1. Calculated orbits for ^{16}O ions ($E = 60$ MeV), $\theta = 5°$, in charge states $q_i = 1^+, 2^+, ..., 7^+, 8^+$, in a long, uniform, solenoid lens. The solenoid length and field strength are such that after $n = q_{max} = 8$ orbits [Eq. (1)], all charge states are brought to a first-order focus. The parameter r is distance from the solenoid axis as the particles spiral through the magnet. Other properties are given in Table I. (Note different horizontal and vertical scales.)

And new magnets can have built in cryo-coolers, and have active shields (tho latter is $$..i.e. 0.7 M$ vs. ca. 0.4 M$).

(For magnet shown, can be split-coil design for use also as an ion trap or other applications needing side access. In UM queue for submission to US NSF)

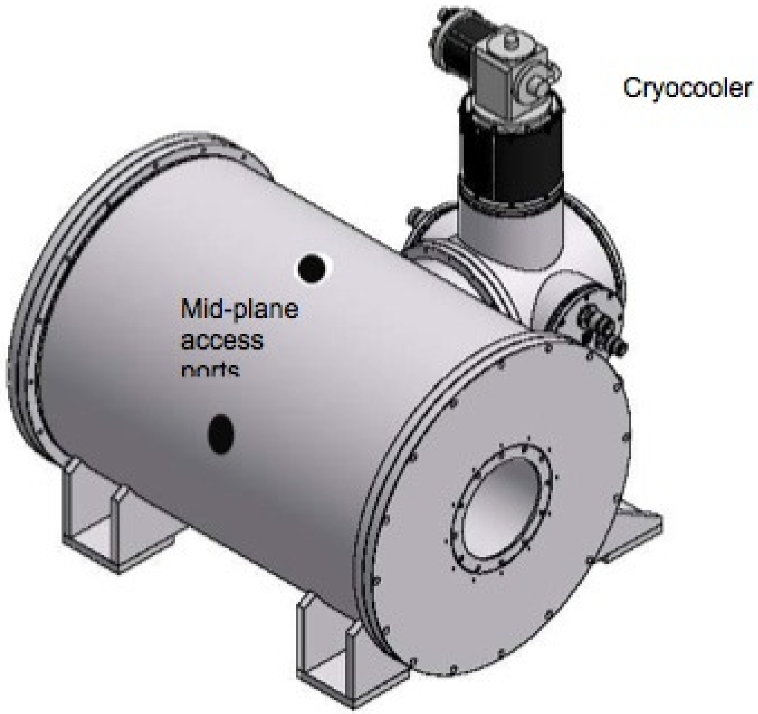

Figure 1. A schematic diagram of the proposed magnet system (power supplies, ion-optics instrument insert and atomic-physics instrument insert not shown).

Just Kw's needed, no LHe

Group mainly involved with this (and UM has worked with) is at ANU 14UD and they describe recent work in a timely paper (submitted to NIM):

SOLITAIRE: A New Generation Solenoidal Fusion Product Separator

M.D. Rodríguez, M.L. Brown, M. Dasgupta [*], D.J. Hinde, D.C. Weisser, T. Kibèdi, M.A. Lane [1], P.J. Cherry [2], A.G. Muirhead, R.B. Turkentine, N. Lobanov, A.K. Cooper, A.B. Harding, M. Blacksell, P.M. Davidson [3]

Department of Nuclear Physics, Research School of Physics and Engineering, The Australian National University, ACT 0200, Australia

Small bore (20 cm), short f.l. (so need high B..a limitation)

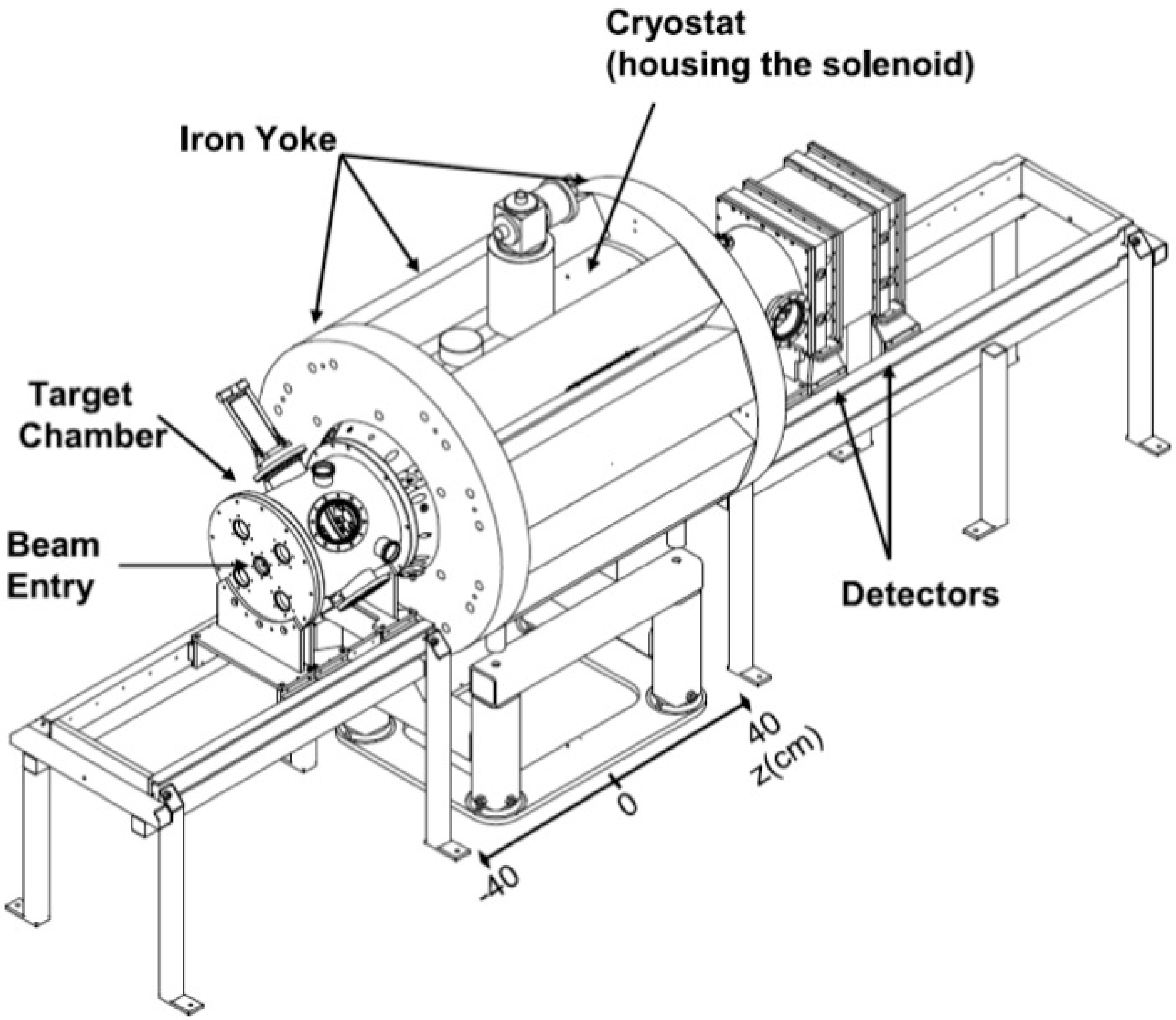

Fig. 1. External view of SOLITAIRE.

With a short focal-length system, if avg q is low, one needs a very high field to focus ERs.

In this experiment they apparently couldn't get an optimal focus of the ions (note scale..so limits dets. used).

Also gas-filled negates use of ToF for most part.

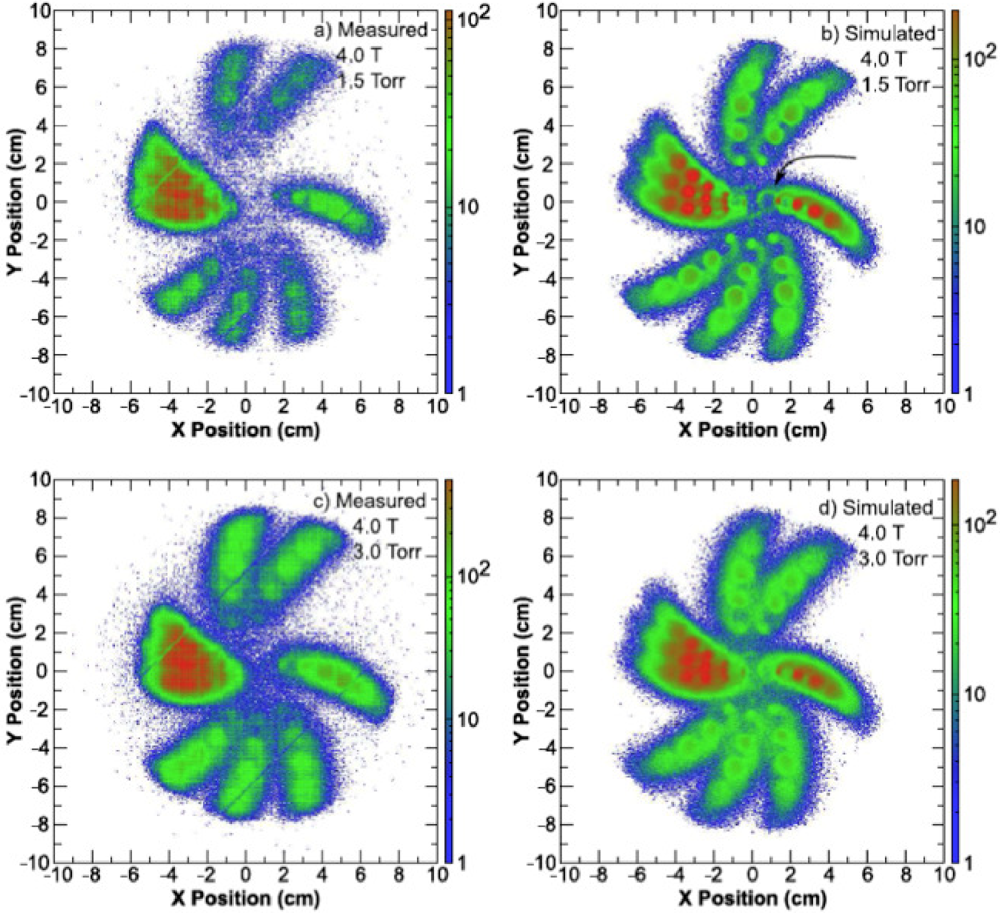

Fig. 4. Image at the detector plane of the elastically scattered particles measured (left spectra) and simulated with SOLIRTE [26] (right spectra), for ^{58}Ni+^{58}Ni reaction with E_{Lab} = 220 MeV, at different B_z and different He pressure in the gas cell.

Usual problem: Where is scattered beam going ??

Yoke has pluses/ minuses..Can also use active magnetic shield (but $$)

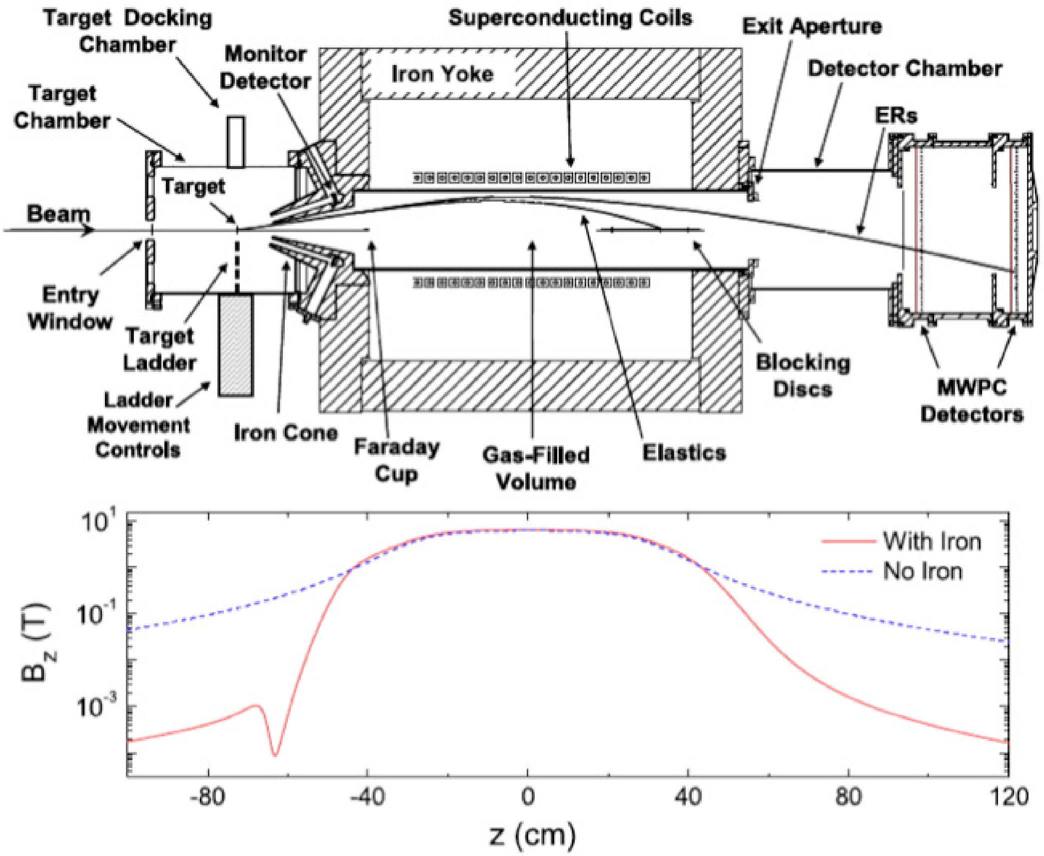

Fig. 2. Upper: cross section of SOLITAIRE. The radial component of the trajectories of the ERs and elastically scattered particles through the device are shown schematically. Lower: calculated magnetic field distribution along the axis of SOLITAIRE for a central field of 6.5 T. The field profile with and without the iron yoke is shown by the full and dashed lines, respectively.

Conclusions:

Solenoid-based systems can be cost- and space-effective and provide a multi-mode, multi-functional spectrometer system.

Given their relative simplicity and modest costs together with rapid construction possible, this does not necessarily exclude also having a more elaborate spectrometer system as funds and space become available.

Some references : *www.physics.lsa.umich.edu/twinsol/*

Thank you

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