Planning for a STANDARD in-Flight RNB Experiment

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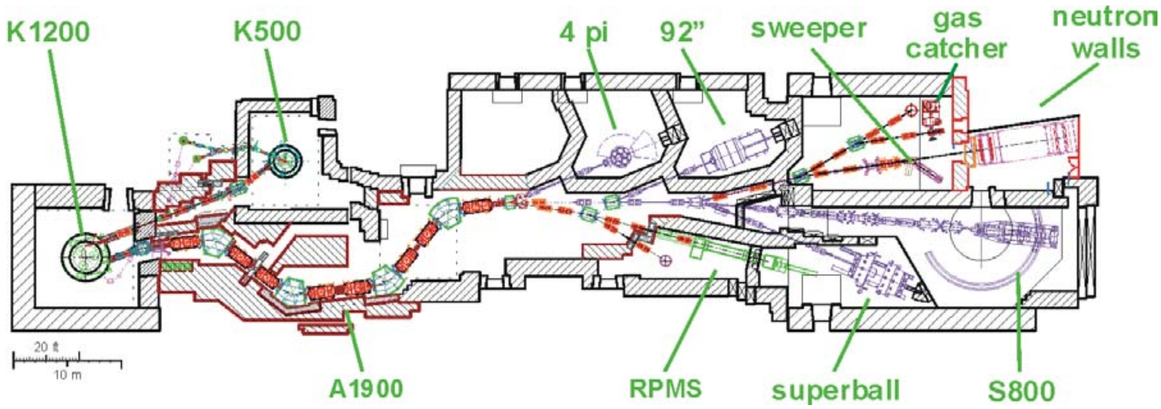
This document is meant to outline the steps that are necessary to produce a rare-ion beam using a projectile fragment separator with the specific example of the NSCL-A1900. Planning for other uses of a separator generally will require some additional interaction with NSCL personnel and are not described here. The procedure we describe represents important planning that does not require a physical presence at the NSCL. However, without such prior planning it is unlikely that a successful experiment will be completed without a LARGE amount of effort by the NSCL staff. In addition, a schematic sequence of steps for tuning the separator is given. Suggestions for improvements in this document are solicited and should be directed to the author (e.g., via electronic mail to morrissey@ nscl.msu.edu).

A1900 Device

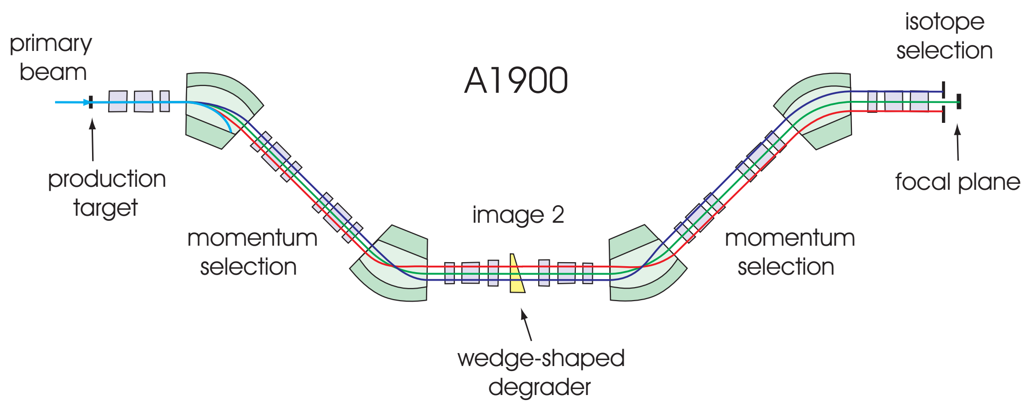
The A1900 is a magnetic separator/beam analysis device designed to work in tandem with the K500/K1200 superconducting cyclotrons at the National Superconducting Cyclotron Laboratory at Michigan State University. The basic operation of the device has been described previously [DJM:03] and the design is based on experience with its predecessor the A1200 [BMS:91] and is similar to devices at GANIL, RIKEN and GSI [BMS:91a]. We will not describe the device in detail here, but rather only give some necessary information. As indicated in figure 1, this device starts after a short section of beam line from the large cyclotron that is used to position the primary beam on the target. The A1900 has additional magnetic components that can be used to separate nuclear reaction products and a dedicated set of electronics for on-line identification of the fragments. The device is fixed at zero degrees as is typical for such energy-loss momentum-achromats, although the primary beam can be inflected so that it strikes the target with an angle of a degree or so. Heavy shielding is positioned from the target box up to Image-2 and large distances to separate experimental vaults provide low background environments for secondary beam experiments.



The A1900 consists of a series of twenty-four superconducting quadrupoles arranged in eight triplets, four superconducting dipoles (each with NMR readout), and sixteen sets of sextupole and octupole correction coils. It is mirror symmetric about the center and has two additional dispersive images as shown in figure 2. The particles are dispersed in horizontal position in proportion to their momenta at these three images. The power supplies for the magnets are usually controlled by a set of computer programs (BARNEY/MOE) running in conjunction with the EPICS control software system. The 'BARNEY' program contains reference ion-optical calculations that are scaled to the desired momentum using the excitation functions of the magnets. The position of the beam can be determined by inserting scintillating screens in the path of the beam that are viewed by video cameras. Viewers exists at all the important positions along the path of the beam. The A1900 operates as a fragment separator in an achromatic ion-optical mode in which the dispersion is at its maximum in the middle (Image-2 where the momentum can be measured) and then cancelled at the final focus. Formally there is one target position (Z015TL) at the correct solid angle acceptance for the reaction products but there are three other target ladders in the same vacuum chamber that can also position material in the path of the beam. The A1900 has a maximum Bρ acceptance of +/-2.5 % determined by the size of the beamline. The acceptance can be lowered by inserting a slotted plate at Image-2 or by a continuously adjustable slit system at Image-3. The numerical values of these acceptances are given in the table at the bottom of figure 2. The A1900 was initially operated in the summer of 2001 and a broad range of experiments has been performed since inauguration.

NSCL

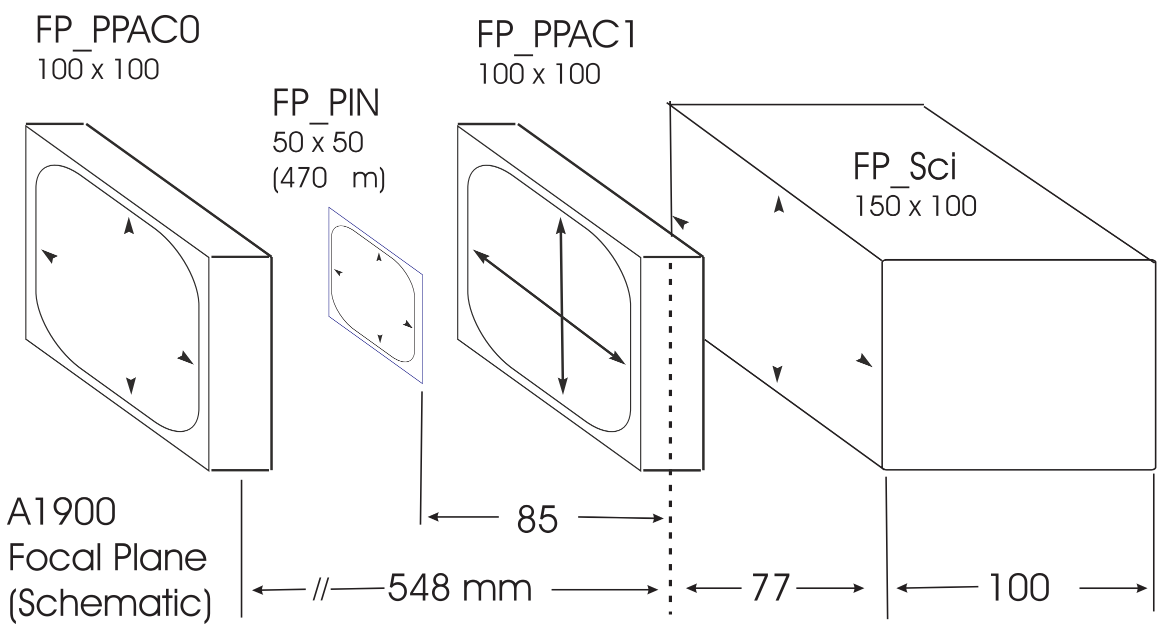
High Acceptance Fra gment Separator



	p/p	d	B max	rel. accept.
A1200 (1991-99)	3%	0.8 msr	5.4 Tm	1
A1900 (2001-)	5%	8 msr	6 Tm	18.3
RIA (HR)	6%	10 msr	~8 Tm	25

A1900_03 stolz@nscl.msu.edu 2002-10-08

The device has a dedicated set of charged particle detectors, electronic modules and computer front-end to facilitate rapid identification and tuning of secondary fragments. The standard detectors are mounted on remotely positioned plates in a common vacuum with the beam. An external detector is available to monitor the primary beam intensity via scattered particles from the target. A thin plastic scintillator is located at Image-2 for time-of-flight measurements. The positions and thus the momenta of fragments traversing the device are also measured at intermediate image and at the focal plane in pairs of two-dimensional parallel plate avalanche counters (PPACs), as shown in the schematic diagram below. The PPAC's at the focal plane are relatively simple and are read out using charge division whereas the PPAC's at Image-2 are significantly larger and have a specialized readout. In addition to the PPAC's, the focal plane is instrumented with a variety of detectors on separate drives. In the usual configuration a single PIN diode is used to give a ΔE signal (50x50 mm^2, ~500 μm thick) and a 100 mm thick plastic scintillator is used to give a signal proportional to (TKE- ΔE). There is an additional drive to insert a stack of thin silicon PIN diodes (50x50 mm^2, various thicknesses) instead of the single ΔE silicon PIN detector.



If necessary, a large gas filled ion-chamber (100x100 mm^2) can be exchanged for the silicon detectors. Dedicated gas handling systems are available for the gas-filled detectors. The detector subsystems at the focal plane and Image-2 can be changed in ~4 hours but the beam line must be vented. Additional experimental equipment can be placed into the target, image and focal plane vacuum chambers but space is extremely limited. Such installations generally require more time to remove the standard detectors.

Planning Procedure

This section contains information on the initial planning of the experiment. Once the physics goals and consistent secondary beam requirements have been established, then the optimum target and device settings can be calculated. However, it is not always possible to use the absolute "best" target or degrader wedge, and some compromise is usually necessary. Thus, the experimenter after selecting a specific secondary fragment should decide what levels of beam purity, beam intensity, kinetic energy and spread are really consistent with the "physics" justification of the experiment. It is important to recognize that these compromises are very often necessary because physical or other constraints on the separator may limit one or all of the beam parameters. If the compromises seem unacceptable, then the experimenter must decide if the A1900 is the appropriate device to use.

Reaction Mechanism

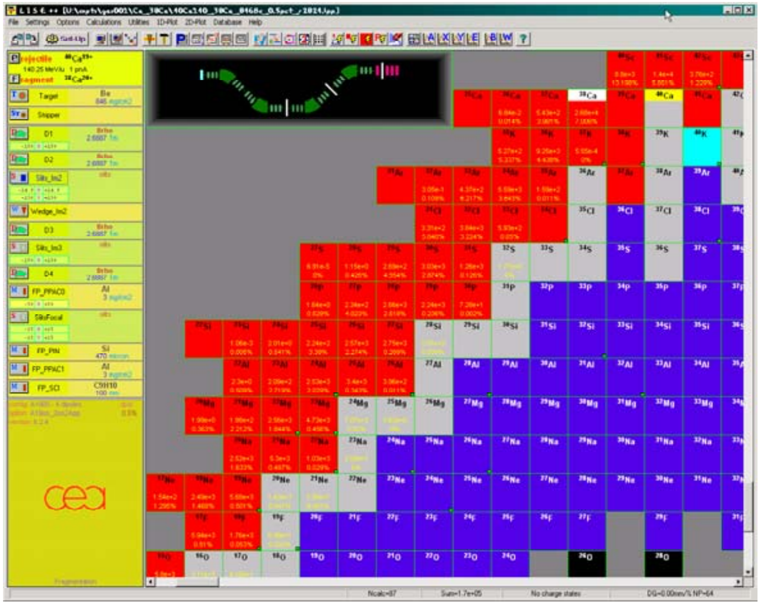
Projectile fragmentation yields a broad range of reaction products with a range of velocities. The A1900 and other similar devices use the combination of a primary selection of a group of reaction products with a single p/q value (within some bandpass) from this broad distribution, followed by passage through a wedge that introduces a differential energy loss (effectively a velocity shift depending on the nuclear charge of the passing isotope), and another selection stage with a second p/q to produce a single or limited range of isotopes. Thus, the purity of a given secondary beam will depend on the relative difference in p/q of neighboring reaction products and on their differential energy loss [JPD86, KHS87]. Broad charge state distributions that occur at lower bombarding energies for higher Z ions may complicate the selection of single isotopes. Note that the fragments produced in the target are lost in each step of the selection process, and purity is always traded against intensity. As a simple example, five fragments with m/q=3 (+/-1.5%) are produced by the fragmentation of ^{18}O with E/A=80 MeV, and each can be uniquely separated by the A1900, but the fragmentation of ^{78}Kr with E/A=70 MeV leads to ~150 reaction products for a given Bρ setting, within +/-1.5%, and the optimal wedge passes ~10 isotopes to the focal plane each with a different intensity. The fragments often pass through detectors with foils at Image-2, resetting the charge state distribution that can lead to significant losses of the heaviest ions.

Target Selection

The targets needed to produce secondary fragments are generally millimeters thick and the distributions of the resulting linear momenta of the fragments are broadened by both the nuclear reaction and by differential energy loss. If the fragment has the same atomic number as the primary beam then the differential energy loss is small. However, in most cases the beam and fragment have different Z's and lose energy in the target at different rates. Thus, fragments produced in the front and the back of the target can emerge outside the momentum acceptance of the separator. In addition, angular straggling can push fragments outside the angular acceptance of the device. Therefore, low Z targets have been generally favored for the production of secondary beams. Such targets are also have the advantages of a larger number of nuclei per unit areal density and reduced widths of charge state distributions of heavy ions. The NSCL has an inventory of beryllium (Z=4) targets for the A1900 device.

Yield Predictions

Various data and computer codes are available to assist the user and consultation with NSCL staff is recommended. The **INTENSITY** and **LISE/LISE++** codes have been independently developed to help prospective experimenters identify the best production (primary) beam and its energy, the best target material and its thickness, to supply a given secondary fragment. The Nuclear and Atomic physics contained in the two codes is essentially the same; the differences lie in the computer platform and user interface. The INTENSITY code runs on the VMS system and utilizes screen management tools to guide the user through the development of the experiment [JAW92]. On the other hand, the LISE code runs on a windows-PC with a graphical interface [DB03], see figure 4. In addition, the LISE code can produce graphical displays of product distributions that can be directly compared to the on-line data. For example, a figure with fragment energy-losses in a specific thickness silicon detector versus their time of flight can be displayed and printed.



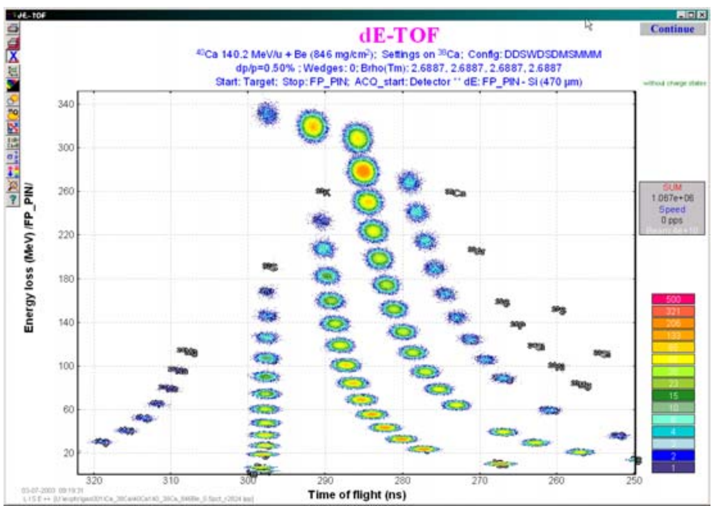
These codes combine our best-effort estimates of the underlying nuclear, atomic and ion-optical physics necessary to predict the production rates. Some of the necessary information is, in fact, unknown and some discrepancies with the predictions should be expected. It should be remembered that Suemmerer, et al., originally parameterized the nuclear cross sections from the summary of relativistic heavy-ion data and the results are probably not appropriate at 30 MeV/A [KS90]. The empirical predictions have been updated [KS00] and the comparisons to the measured production rates generally have been good. The production of light nuclei, A < 40, can be expected to be within a factor of 3 or so, even for the most exotic nuclei. On the other hand, discrepancies seem to grow somewhat with heavier beams, particularly for heavy exotic fragments. The production rates of certain light nuclei are affected by special nuclear structure considerations, for example, tritons from a ^{7}Li beam, may be grossly underestimated by the average cross sections.

Detailed descriptions of how to use the codes are available. An abstracted version of the procedure to use the LISE code is given here to demonstrate the tradeoffs in designing an experiment, but the reader should refer to the detailed documentation. Usually, the experimenter needs to cycle through the following steps:

1. Select a primary beam from the K500/K1200 beam list, or one that is close (very close?) in atomic number to one on the list. Also note the maximum intensity available for this beam. Higher energy beams are usually better due to increased kinematic focusing of fragments into the device, although the intensity decreases with E/A (higher E/A requires a higher charge state in the second cyclotron). The beam should lie to the right of the desired fragment in the "chart of nuclides" slightly above and to the right is also acceptable. A primary beam to the left of the desired fragment is generally not useful because it will require a pickup

reaction to reach the desired isotope. However, in clear distinction to higher energy reactions, transfer products have been observed in reaction at E/A = 50 - 100 MeV previously with the A1200.

2. Survey the (calculated) total fragment yield as a function of target type and thickness using only p/q selection (magnetic analysis) with the proper device acceptances. The LISE code has the option to load the standard configurations of the six or so most important fragment separators at laboratories around the world. Note that experienced fragmenters set a nominal primary beam rate of 1 pnA and then quote a normalized secondary rate per pnA. The resulting yield from only one section of magnetic analysis is the maximum rate with the worst purity and provides important information for subsequent calculations with the degrader/wedge. A rule of thumb is that the target thickness should correspond to an energy loss of approximately 15% (or less) for the primary beam. LISE provides a graphical display of all the fragments that will pass through the separator with a given Bρ value and as stated, this is worst-case purity of the secondary beam. At this point the experimenter should verify that the "best" primary beam is actually available (or can be made available) from the K500/K1200.



3. Determine if the optimal target is available with the correct thickness; the experimenter is generally responsible for non-standard targets. Also note that heating of the target by the primary beam can potentially limit the choices although the A1900 target holders are large water-cooled devices to help dissipate heat. The targets generally become activated during long production runs and may have to decay before it is convenient to transport them. Low mass targets also tend to produce radioactivities with shorter half-lives and therefore have shorter "cool down" times.

4. Calculate the beam purity and intensity after passing through an energy-loss degrader (a.k.a. wedge). A good starting point for this calculation is a wedge that is ~20% of the range of the desired fragment. It is usually sufficient to calculate the fragment distributions for wedges already in existence as the distributions

vary slowly as a function of thickness. Note that the wedges are shaped to the dispersion of the A1900 separator in order to preserve the achromaticity of the separator; meaning higher rigidity fragments should pass through more material [JPD86, KHS87]. The technique developed at GANIL to curve (uniformly thick) metal foils to produce the thickness variation is generally used at MSU and shaping forms are available. Pressed plastic *wedges* have also been used in the past. Low Z materials are preferred due to multiple scattering and charge state effects; aluminum is most commonly used but plastic is also acceptable. Other light materials have proven impractical.

5. At this point, if the purity of the secondary beam can not be brought up to specifications dictated by the "physics," even with narrowed momentum acceptances, etc., then the experiment should be rethought. As an aside, secondary beams can be passed to the RPMS, the NSCL reaction product mass separator, that incorporates a Wien filter. Previously, the separation of mixed secondary beams from the old A1200 by the RPMS Wien filter has been accomplished in several cases.

6. Some auxiliary planning should be done before attempting to carry out the experiment. It is important in secondary beam experiments to decide how the fragments will be identified during data taking. Possible choices are continuous monitoring via a ΔE/TOF system for low intensity beams or batch mode identification in which the experiment is interrupted, the beam intensity lowered, and the purity checked. It is important that this identification be done at the position that the secondary beam is used and not necessarily at the A1900 focal plane to be sure that the effects of the beam line acceptances are included.

7. It is the policy of the NSCL that the purity and intensity of the secondary beam should be demonstrated before the data taking run.

Run Execution

Most A1900 experiments involve the two-step process of the identification of the secondary fragments and subsequent use. Therefore, the A1900 has a dedicated set of "nominal" detectors, electronics modules and DAQ codes to routinely identify and characterize separated fragments. It is our intention that this setup remains in-place so that the device can be readily, reliably and reproducibly tuned (our three *R's*). These detectors remain in the beamline vacuum and are remotely moved into and out of the beam path. The identification process usually relies on identification of fragments in a ΔE/TOF diagram with auxiliary information on angles, etc., from the focal plane, and dispersive image positions. For example, such a distribution of fragments from the reaction of ^{40}Ca with a beryllium target (E/A = 140 MeV) is shown in figure 6.

Position information is obtained from two-dimensional PPAC detectors mounted on plates at Image-2 and the Focal Plane. The PPACs are operated in a charge division mode and an anode-timing signal is also available. The energy loss is usually measured in a PIN diode at the focal plane that can be replaced with a large area ion chamber. A large stopping scintillator can also be installed at the Focal Plane. The TOF can be measured in several ways; the most unambiguous timing is obtained between a thin plastic scintillator at Image-2 and a scintillator at the focal plane. Other options include combinations of timing signals from ΔE's or scintillators at the focal plane and the cyclotron rf.

General Operation

Successful operation of the A1900 requires a user that is familiar with the general features of the NSCL control system. For most purposes the user only needs to recognize that interactions with two different kinds of device controllers are necessary: magnet power supplies are connected to distributed local VME-based processors that communicate over a local network, and are controlled by interactive software; devices with discrete motions or states, e.g., target ladders or wall plugs, go through a system operated by programmable logic controllers (PLCs). The BARNEY code can easily control all of the equipment in a seamless way.

Standard ion-optical reference calculations are imbedded into the BARNEY code for easy scaling to the desired rigidity. The ion-optical modes for production and separation of fragments at the focal plane have been scaled over a wide Bρ range with excellent success. Transport and tuning of secondary beams to other experimental vaults requires some retuning of the A1900 and also may mean a slight reduction in rate. Note that selection of a fragment in the separator requires controlling the Bρ value at the 0.1% level, but transporting the fragments does not require such high accuracy. Therefore, once the proper Bρ values to select a given fragment have been obtained, all of the subsequent magnets in the transport system are easily scaled and do not needed to be fine-tuned for further fine adjustments of the A1900.

The tuning of the A1900 and identification of secondary fragments is, in essence, a small nuclear physics experiment. The user is well advised to contact the beam-physics group at the NSCL to make sure that the necessary targets and degraders are ready at the beginning of the run. This is complicated by the fact that the A1900 is the first part of the beam transport system and access is limited but is facilitated by using the standard detectors, electronics, and data acquisition codes.

Actual Operation

A secondary beam experiment invariably wants to have a specific (single) ion, whereas the separator gives a distribution. The identification of secondary fragments requires skills that could be characterized as belonging to an artist, at least, to an artisan. When viewed from this perspective the following sequence of events seems to occur:

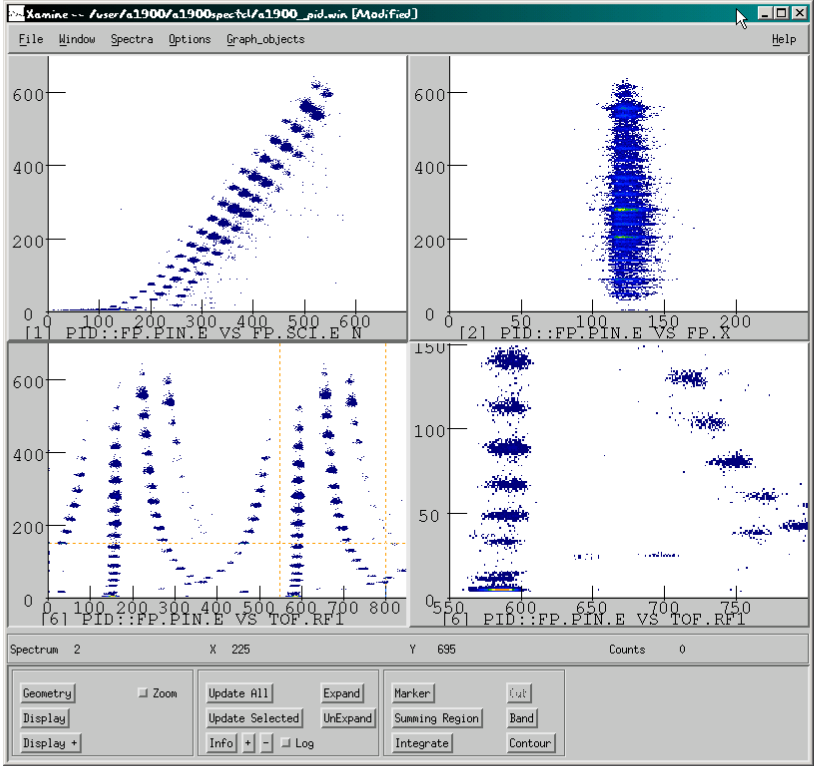
1. The beam-physics group tunes the primary beam onto the A1900 target. A smaller spot size with a level and straight beam translates into larger fragment yields.

2. The BARNEY program is used to load the settings for the primary beam into the magnet power supplies.

3. The primary beam is tuned through the system, sometimes after passing through a degrader to put the beam into a Bρ similar to that of the final fragments. This primary beam is usually viewed on phosphorescent screens with the normal (CCD) cameras.

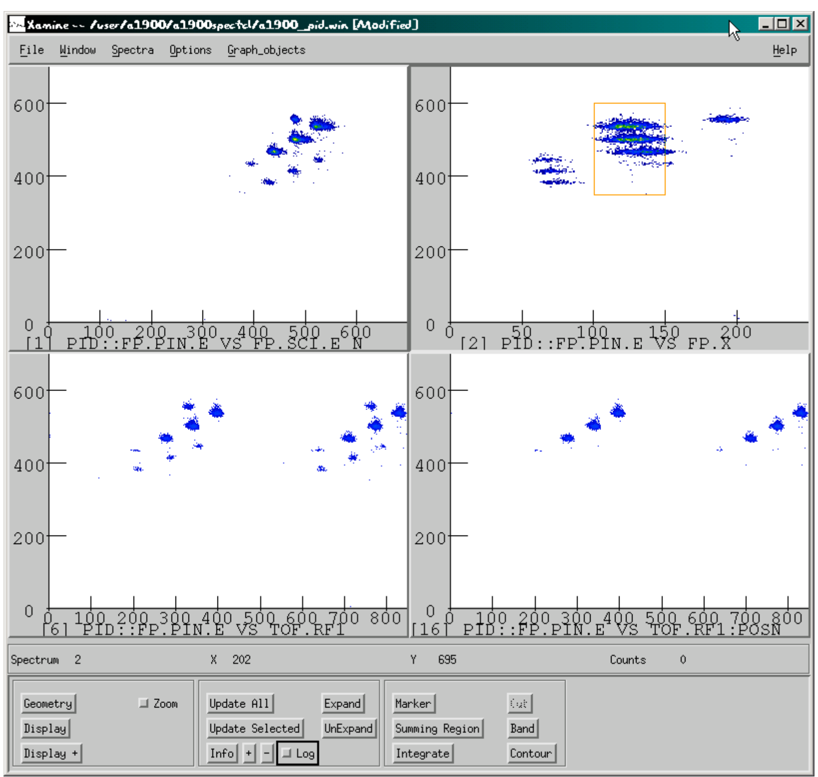
4. The intensity of the primary beam is reduced to a few hundred ions per second and the electronic detectors are inserted into the beam path for calibration and testing. Note that the intensity of the primary K500/K1200 beam can be adjusted by factors of ~3 over a total range of $\sim 10^7$. The energy loss and TOF of the primary beam in the detector system should be noted for reference. Perspicacious users compare these values to the results of prior or at least simultaneous calculations.

5. The production target is inserted and the broad spectrum of secondary fragments is surveyed in the ΔE/TOF domain at the A1900 focal plane. No wedges and no detectors are used at Image-2. Because of the selection of a constant value of Bρ, these diagrams have certain features that are characteristic of the A/q of the fragments. Depending on the beam energy and the mass range, it is often desirable to observe the lowest mass fragments as their distribution has "holes" corresponding to unstable nuclei giving a unique pattern, see figure 6, below. Again, the actual values of the energy loss and TOF of identified nuclei are noted for later reference. The identification often requires on-line correction for TOF-broadening by software or by physically narrowing the acceptance to +/-0.5%. The most conscientious users prepare detailed calibrations of the energy-loss and TOF measurements in order to predict the isotopic distribution after the wedge is inserted.



6. After the secondary fragment has been correctly identified then the Bρ values of the A1900 should be scanned to determine the maximum production rate. . Recall that the Image-2 timing and PPAC detectors will affect the ionic charge state whenever the detectors are in the ion's path. It is often useful to set the A1900 to the Bρ value that will be used in the second half with the wedge and note the position of the desired fragment in the PID spectrum (without the wedge being present).

7. The degrader wedge is inserted and the sections of the A1900 are set for the calculated Bρ of the desired fragment. At this point a relatively small number of fragments will (should) pass to the focal plane and it is crucial to have calculations and calibrations for comparison … After the desired fragment has been identified, the Bρ values of the section(s) after the wedge should be adjusted to center the desired fragment on the focal plane. The Bρ of the first half can be



carefully adjusted to maximize the rate.

8. After any small adjustments to the A1900, particularly those to find the maximum rate as a function of Bρ, the secondary beam should be ready to transport to other experimental areas. This transport usually only requires setting the fields in the transport system and minor tuning. The transport efficiency has been in the range of 30 to 95% and such factors must be included in planning for experiments. As a fine point, for beam transport the fragment focus is usually repositioned (relaxed) to the exit of the switching dipole immediately after the A1900 focal plane (the so-called extended focal plane), see figure 1. This is the location of the defining slits for fragment transmission. Therefore, because the fragment identity is correlated with position at the focus, the setting of the slits and bend angle in this dipole after the A1900 are also critical to transporting a single fragment to an experimental vault. Undesired fragments are readily transported with only slightly incorrect settings.

Other Documents

Several other documents have been prepared that describe the calculations and operation of the equipment. For the planning of experiments, the scientific basis of the fragment yield calculations has been described by Winger, et al. [JAW92]. The LISE code can be obtained over the web and comes with a practical guide maintained by Oleg Tarasov.

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