S^3: The Super Separator Spectrometer for LINAG Beams

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Abstract:

S^3 (Super Separator Spectrometer) is a device designed for experiments with the very high intensity stable beams of LINAG, the superconducting linear accelerator of GANIL, which will be built in the framework of SPIRAL2. These beams, which will provide in a first phase of SPIRAL2 ions with A/q = 3, can reach intensities exceeding 100pμA for lighter ions - A<40-50 - depending on the final choice of the ECR (Electron Cyclotron Resonance) ion source. These unprecedented intensities open new opportunities in several physics domains, e.g. super-heavy and very-heavy nuclei, spectroscopy at and beyond the dripline, multi-nucleon transfer and deep-inelastic reactions, isomers and ground state properties and molecular resonances. An international collaboration interested in the aforementioned physics has been formed for developing technical solutions for this new instrument. Independent letters on the various physics topics relevant to S^3 complement this letter of intent (LoI).

Scientific case

The unprecedented intensities of the LINAG accelerator, the driver of the SPIRAL2 project, open new opportunities in several physics domains. These were discussed in the "SPIRAL2 Reactions Workshop" in October 2005 and in the first meeting of the S^3 working group, in Paris, the 27-28 June 2006 (see annex 1 and 2). The main topics, which are addressed within the framework of this LoI are listed in Table I.

Table I: Physics subjects associated with this LoI.

Super-heavy elements synthesis	Very- and super-heavy elements spectroscopy and chemistry	Study of reaction mechanisms and product distributions
Multi-nucleon transfer and deep-inelastic	Spectroscopy at/beyond the proton drip line	Molecular resonances
Production and study of isomers	GT strength through charge exchange reactions	Ground state properties of nuclei

All these subjects have the common feature of requiring the separation of very rare events

Very rare events and excellent background suppression are, in fact, the central issues of this LoI. The importance of having a high intensity primary beam for observing rare events can be understood simply if one takes super-heavy synthesis as an example: Present technology allows one to use about 1pμA beam intensity of a heavy ion (^{70}Zn for instance) on a target (such as ^{208}Pb of 450μg/cm^2 thickness). Standard separators have transport efficiencies exceeding 50% for the mentioned example. Adopting a cross section of the order of 1 pb (which is the order of magnitude of the cross section for the synthesis of element 112), one arrives to a production yield for the synthesis of element 112 of about 6 events per month. This can be considered as the lower limit[1] cross section for nuclear physics studies – identification and ground state first properties. The increase of the target thickness does not help to enhance the yield, because the value of the mentioned cross section is only valid in a very tiny window in the excitation function, corresponding to an energy loss of about 5 MeV in the target. The gain in improving the separators cannot be larger than a factor 2. The only way to increase the sensitivity one or two orders of magnitude, i.e. to reach equivalent yield of 6 events per month for 0.1-0.01 pb, is to increase the beam intensity by one or two orders of magnitude.

Study of "non-limiting" topics can also be improved significantly

For a factor 10 increase of beam intensity, all experiments, which can be performed today in *one week,* could with LINAG be performed in *one day*. For a factor 100 increase of beam intensity, all experiments, which can be today performed in *one month*, could be performed in less than *one day*. Possibilities will exist for measurements of masses, lifetimes and other fundamental ground state properties of extremely exotic nuclei – today inaccessible with present yields – helping to build a better picture of the structure of nuclei at the extremes. Important measurements in other fields, such as astrophysics (study of GT strength with

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[1] It should be noted that the smallest measured cross section for the production of element 113 in RIKEN is 0.03 pb. Two events were observed after about 250 days of irradiation.

charge exchange reactions and properties of N=Z nuclei) or the production of long-lived isomers would also be enabled.

Various nuclear reactions, which could be studied with S^3 include:
i) Fusion-evaporation, ii) Fusion-fission, iii) Massive-few nucleon transfer, iv) Deep inelastic and v) Charge exchange.

All these reactions have different kinematics and, as a consequence, different requirements for the detection system. In all cases the need of a separator and/or a spectrometer with unprecedented primary beam rejection is of paramount importance.

The need of a Separator/Spectrometer with very high primary beam rejection is a common technical requirement for all these studies

The S^3 collaboration proposes a Separator/Spectrometer tailored to respond to most of the requests of each physics topic. The main requirements are listed in Table II.

Table II: Main requirements of the separator/spectrometer.

Primary beam suppression $> 10^{12}$	Reasonable angular acceptance : >100 mrad	Not only a zero degree device
Different operation modes	Adaptable to a wide energy range	Wide momentum acceptance

Moreover, the need of a target, which can withstand such very high intensities delivered by LINAG is also an important requirement to be included in the design of the Separator/Spectrometer. The size of the object point of the separator – on the target – together with the angular acceptance defines the maximum emittance to be transported. The resolution of the spectrometer is not considered as a crucial requirement at this stage of the studies. Anyhow, it has to be variable, depending on the various operating modes of the spectrometer. It will be defined at a later stage of the design.

High intensity primary beams for heavier nuclei (A>40-50) are also a priority

The acceleration of very high intensity heavier nuclei (A>40-50) by LINAG opens new possibilities, such as working in inverse kinematics. This includes the possibility of using S^3 as an in-flight mass separator and performing reactions with exotic secondary beams. This option is only possible with the implementation of a RFQ with $A/q = 6$ and the use of the most advanced ion sources. Therefore, it is strongly requested to have the highest possible intensity for the whole range of masses. An estimation of the production yields for the ion source A-Phoenix and beams accelerated by an injector optimized for $A/q = 3$ and $A/q = 6$ is shown in Annex 6.

Methodology

Beam properties:

- Beams from p to U are required in this LoI. It is evident that very light beams of p,d and ^{3,4}He are not priorities but they should not be neglected. The maximum intensity for heavy ions is 1 mA (electric).
- The energy needed ranges from 2A MeV to 14.5A MeV.
- The requested time resolution of the beam at the target position is the same as at the exit of LINAG (200 ps FWHM) for energies exceeding 3A MeV.
- The size of the beam on the target of S^3 is requested to be in the range of 2 mm (HO) x 20 mm (VE). The vertical beam profile is requested to be flat (not parabolic or Gaussian).
- It is strongly requested to have the highest possible intensity for the whole range of masses. This is also important for working in inverse kinematics. This opens the possibility to use S^3 as an in-flight mass separator and perform reactions with produced exotic species.

Target(s):

- Targets of any nature, **including actinides,** are needed in these experiments. Solid, liquid and gaseous targets will be used. Solid target design is discussed in annex 3.
- The target thickness varies from 100 µg/cm^2 to about 2 mg/cm^2. The beam is not stopped in the target.
- More than one target can be used, depending on the experiment.

Instrumentation and detectors:

The new Super-Separator-Spectrometer is proposed in this LoI.

In view of the various requests concerning the performance of the Separator/Spectrometer, two main concepts drive our design:
1) S^3 is a “two-step” machine, allowing either to filter in successive stages or to work as a Separator connected to a Spectrometer.
2) Each stage is independent and can be turned off as necessary.

The basic design of S^3 contains:
- the primary target
- the separator that reject the majority of the beam
- the secondary target or detection point
- the spectrometer or the second filtering part
- the final focal plane

The different operating modes of S^3 are briefly described below:

Two stage separator

This configuration is dedicated to experiments that need the best rejection. SHE synthesis is the best example to use this mode, as the focal plane has to be as clean as possible to avoid random correlations. Here, the second spectrometer is used as a secondary separator for a complementary rejection of unwanted particles. A combination of a Wien filter (or "SHIP-like" separator) plus a gas filled spectrometer could be envisaged. Presently we are studying a configuration for the first separator, which uses a double dipole with a dispersive intermediate plane.

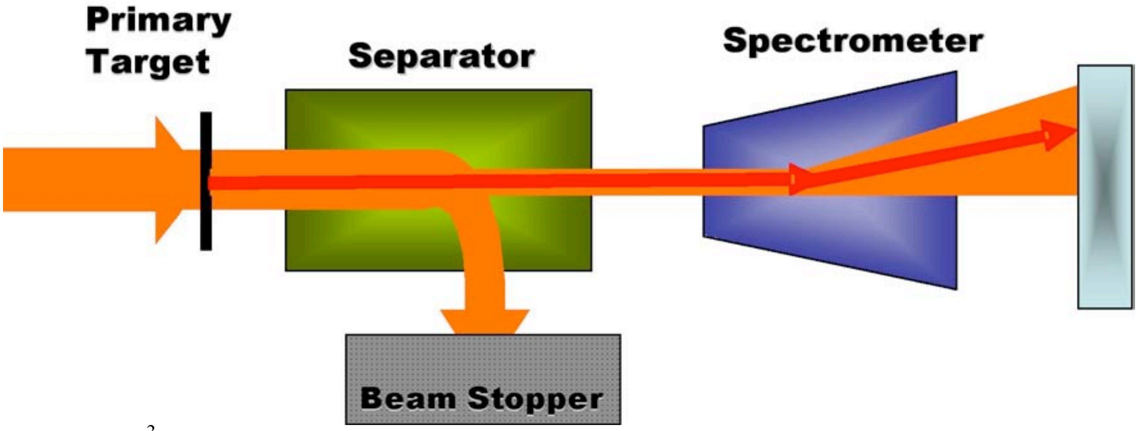


Figure 1: S^3 in a two-stage separator mode. Most of the beam is stopped in a beam dump in the middle of the first section.

Secondary reaction mode

In this mode, the interesting nuclei are still produced in the primary target point, but they can interact at the secondary target point. Obviously, this can occur only if the production rate is high enough. The beam is rejected in the first part, so that the secondary target point is in a "low intensity" zone. The spectrometer part can be used as a standard spectrometer to analyze the secondary reaction products. It could measure their momentum and scattering angle and allow their identification in mass and charge. If necessary, the spectrometer can be rotated to study angular distributions.

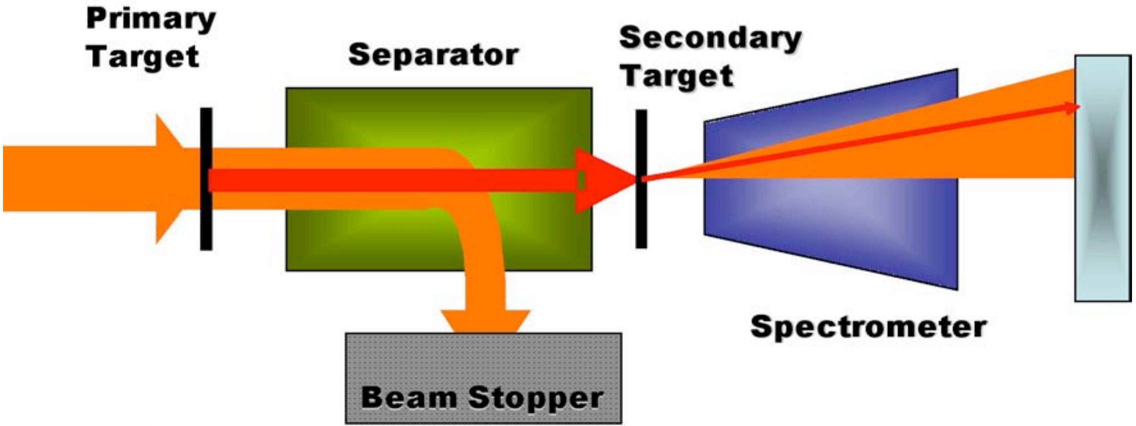


Figure 2: S^3 in a secondary-beam mode. A second target can be placed in an intermediate focal plane between the two sections.

Pure spectrometer configuration

The first part of S3 can be turned off, allowing the primary beam to be conducted up to the secondary target point. This configuration shall allow the measurement of, e.g. multi-nucleon transfer with primary beams. The emission angles of the reaction products should be measured close to the grazing angle. The Spectrometer part can be rotated, as shown in Fig.3. The beam dump is located at zero degree. This configuration implies that the secondary target point should also be useable with relatively high beam intensities.

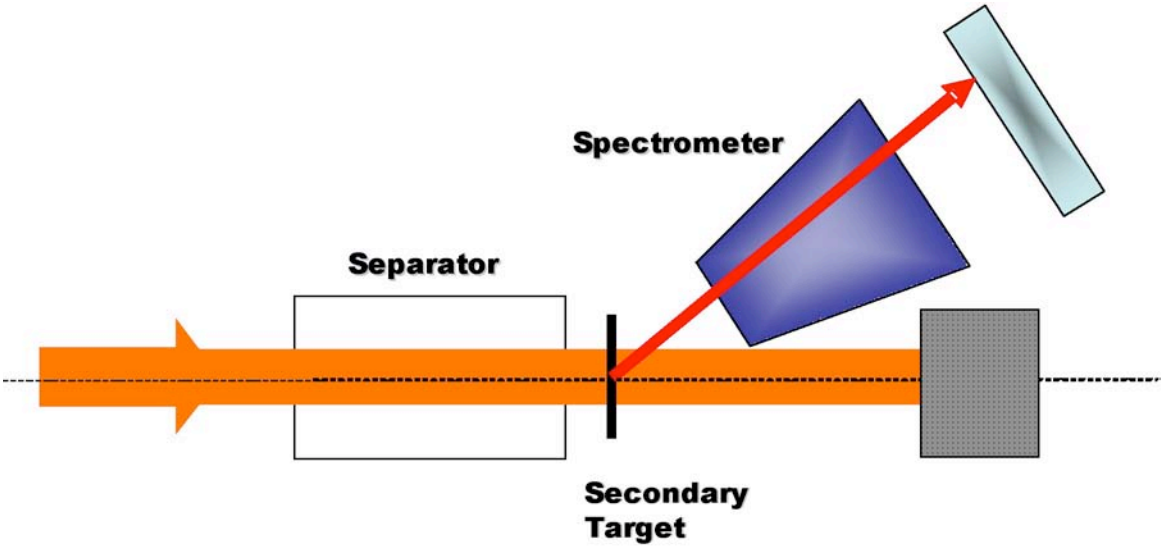


Figure 3:S^3 in the pure spectrometer configuration.

Additional features

1) The primary target point can receive actinide targets and is placed in a special room, isolated from the rest of the separator. NO ANCILLARY detection can be used in this point.
2) Preliminary studies show that an optical configuration of the Separator with a double dipole like "LISE" and very large momentum acceptance (15%) can be a very elegant solution (see annex 5).
3) The angle acceptance of the Separator is of the order of +/-75 mrad.
4) The secondary target point allows the use of ancillary detection. It is an achromatic point.
5) A **gas cell** can be placed in the Secondary target position. This allows stopping the fragments and conducting them to a **penning trap**, for mass measurements.
6) The penning trap will be placed outside the main S^3 room.
7) The Spectrometer can work also in gas filled mode.
8) The final focal plane can be dispersive (Spectrometer mode) or not (Gas filled mode).

Detection devices

S^3 can be coupled to various detection devices according to the experimental requirements. We give here selected examples of detectors that could be used with S^3:

- Prompt detection around secondary target point (note that special care has to be considered for the shielding) :

  - Gamma detection: EXOGAM2, AGATA
  - Particle detectors: MUST2, GASPARD
  - Neutron array

- Detection at the final focal plane
  - Tagging detectors: MUSETT, BEST
  - Delayed Gamma spectroscopy: EXOGAM, Germanium Box
  - Identification detectors: HARPEE-like for ΔE-E measurement
  - Particle emission decay : 4Π charged particle detector
  - Tracking detectors: Se^{-}D-like for trajectory reconstruction
  - Dedicated detection (see annex 4)

Mass measurements device

The mass measurement device will be set up behind the S^3 spectrometer section providing cleaner beams of ions produced in a fusion-evaporation reaction. This device will consist mainly of a cooler trap, a cleaner Penning trap and a high resolution Penning trap to carry out mass measurement. As the accuracy of Penning Trap spectrometer depends in the charge q of the measured ions, cooling of highly charged ions delivered by S^3 will give a significant improvement in the mass determination of very heavy nuclei. Depending on the counting rate and half-life of the nuclei of interest the mass spectroscopic technique will be either the Fourier Transform-ICR (non destructive, for long observation time and low counting rate) or either the Time Of Flight-ICR (destructive, for short half life).

Updated references for present separators, spectrometers and associated techniques can be found in the two last EMIS (International Conference on Electromagnetic Isotope Separators and Techniques related to their Applications) conference proceedings. See:

- Nuclear Instruments and Methods in Physics Research B 126 (1997)
- Nuclear Instruments and Methods in Physics Research B 204 (2003)

Theoretical support:

Several laboratories have already shown interest in designing and developing parts of S^3. As example, we can mention particular interest for the following topics (this list is NOT exhaustive):

- Optical design: GANIL, ANL, Northern Illinois University and LPHC.
- Solid target constraints and wheel: GANIL and JINR. JINR particularly could collaborate in all aspects concerning actinide targets and laboratory.
- Gaseous target: ANL and GANIL
- Magnets concept and design: ANL DAPNIA/SACM and DAPNIA/SPhN .
- Detection: CYF-Kr, IPHC, LNS and CSNSM.

Preliminary schedule of the process leading to the signature of the Memorandum of Understanding and of the construction of new equipment:

These are only “selected milestones”:

November 2006	Preliminary design study starts
June 2007	MoU between all participants
September 2007	Detailed design study starts
September 2008	Construction starts
February 2011	Start assembly of all parts
November 2011	Commissioning of S^3: first beam.

Preliminary evaluation of the cost of the equipment to be constructed as well as necessary manpower:

Equipment-only cost:

Primary Target station:	1,000 k€
Separator session	3,300 k€
Secondary Target station	500 k€
Spectrometer session	2,500 k€
Low energy facility (Gas cell and Penning trap)	1,250 k€
Detection in the final focal plane (see details in Annex 4)	1,500 k€
Total	10,050 k€

Man-power:

Manpower is evaluated taking into account the rate of 30% of CONSOLIDATED total budget. Taking into account the cost rate of 80k€/person/year, the total manpower needed is around:

50 man x year

Annex 1

Report of the working group on the new separator/spectrometer for LINAG : Super Separator Spectrometer – S^3

Workshop SPIRAL2-Reactions, October 20-21, 2005.

1. Physics case

Workshop SPIRAL2-Reactions, October 20-21, 2005.

Nuclear physics science has growth mainly as an experimental discipline guided by more and more sophisticated theories of nuclear structures and reaction mechanisms. As a consequence what has been ascertained rely on the availability of experimental facilities and techniques to emphasize the phenomena under study, compared to the unwanted background. Even with the impressive progresses done in the last years in many directions of investigation, many interesting phenomena cannot be experimentally accessed due to the very low probability to happen. The availability of intense stable beams, as foreseen in the SPIRALII project will open new opportunities in many fields of experimental nuclear physics, as witnessed by the stimulating discussions at the recent workshop in GANIL (discussion session on spectrometers).

Important examples mentioned by the participants are the studies of synthesis and spectroscopy of super heavy elements, characterized by cross sections as low as 1 pb or less, in a huge background coming from other reaction products from heavy ion collisions. On the other hand, such studies are fundamental in the challenging enterprise to look for the existence of a possible isle of stability for super heavy systems, which nowadays is a hot topics of research. Different experimental approaches are based on the distinction between direct, symmetric and inverse kinematics for the chosen heavy ion collisions, allowing for different kind of synthesis. A multipurpose instrument, designed for very intense beams, capable to work at forward angles in a broad interval of kinematics conditions, is considered an ideal tool to systematically explore the region of super heavy nuclei.

Intense beams at energies not far from Coulomb barrier are considered important also for studies of fusion evaporation reactions and consequently for studies of proton rich nuclei. These are normally limited by the decreasing cross section for the evaporation of many neutrons, depending on the excitation energy of the compound system. It is believed that the availability of a broad range of intense heavy ion beams, along the whole nuclear chart, will give a decisive improvement in the knowledge about the proton side of nuclear stability valley. A specific example, mentioned in the Workshop, is that of M ~ 80, N = Z nuclei, which can be delivered by SPIRALII. These systems are particularly suitable, via quasi-elastic reactions, for studies of n - p pairing strength, nowadays an important theoretical issue. Again one would need an instrument that works at very forward angles, with very efficient suppression of beam induced events.

Another interesting field of research that will benefit from the intense beam facility is that of transfer of many nucleons or clusters, up to now limited by small cross sections and large background. Several open questions remain both in the interpretation of nuclear structure information (e.g. rigid rotor model versus fluid at high rotational velocities, backbending, cluster pre formations and so on) and on the reaction mechanism based on the deep inelastic collision model. For these studies one needs to measure angular distributions in a broad range of angles, and a magnetic spectrograph with high energy and mass resolution, mounted in a rotating platform would be the proper tool to use.

A growing interest is nowadays given to nuclear astrophysics research, characterized by the need to measure cross sections of particular nuclear reactions at an energy close to the Gamow peak (much less than 1 MeV/u). At these energies, partly accessed by SPIRALII, the Coulomb repulsion makes the processes extremely unlikely to happen, and the need of very intense beam is straightforward. Again the broad range of beams available can allow systematic studies of star nucleo-synthesis of heavy elements and consequently of element abundances. Nevertheless it is mandatory for these applications to have very stable energy from the beam, since the reaction yields can fluctuate of orders of magnitude for small variation of energy (KeV or less).

An interest has been manifested about studies of plasma created in heavy ion collisions, due to the possible application in nuclear fusion research programmes. The very high intensity of the primary SPIRALII beams could in fact open new opportunities in this field.

Summary of the physics case

- Super heavy elements Synthesis & spectroscopy (direct, symmetric and inverse kinematics)
- Fusion and evaporation reactions
- M~80 N=Z nuclei from secondary reactions
- Massive/few nucleon transfer
- Deep inelastic reactions
- Astrophysics
- Studies of plasma created by ion collisions

2. The separator/spectrometer:

We have identified several topics involving the beam characteristics, targets and different kinds of separators and spectrometers for use in the SPIRAL2 room dedicated to high intensity beams.

Beam

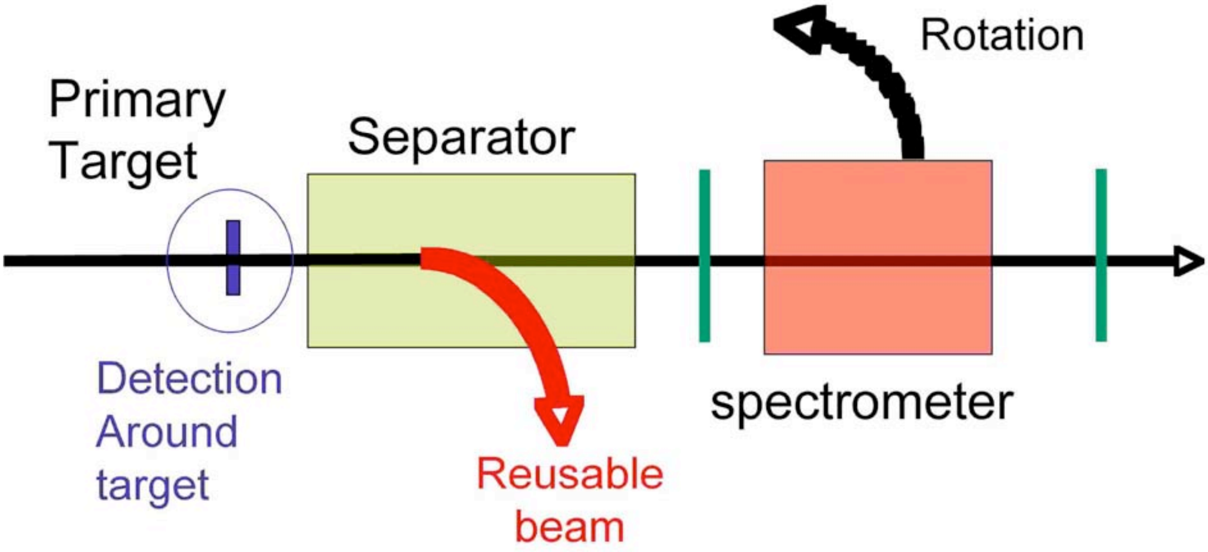
The beam energies considered in the SPIRAL2 project are from 0.75A MeV up to 14.5A MeV. The characteristics of the beam, concerning energy resolution and emittance were considered rapidly during the discussion. The remark was that energy resolution can be an important issue depending on the experiment, but it was considered that the present design fulfils the requested specification. Importantly, the time structure of LINAG (88 MHz) corresponding to a beam structure of 11.4 ns is considered as very short depending on the experiment, mainly for mass identification proposes. Therefore, it is important to make available a bunch isolator (fast chopper) and this, as soon as possible. It was also proposed the use of the LINAC for decelerating the beam exiting from the RFQ, which would allow obtaining even lower energies, mainly for the study of reactions with astrophysical interest. The present mass over charge ratio of the RFQ (1/3) allows acceleration of beams up to mass around 40 with high intensities. The possibility of installing a new RFQ, optimized to mass over charge ratio of 1/6 was discussed. This would extend the capability of having high intensities for higher masses. The French and European groups of discussion on “low energy heavy ion beams” considered this approach as a very important step forward a dedicated low energy heavy ion European accelerator. This new RFQ should, therefore, be considered as a high priority extension of the present SPIRAL2 project. Importantly, it was recalled the need of a rebuncher between the exit of LINAG and the target in front of the separator/spectrometer. This will ensure a good time resolution for all experiments.

Target

Special attention was taken during the discussions on the capability to use such very high intensities (of the order of 1 emA) on experiments. This implies the need of specific solutions for the use of thin targets in any kind of experiment proposed. Dedicated R&D should be undertaken to find solutions for this topic. Large wheels with multiple targets, large surface solid targets or gaseous and liquid targets were considered. In all cases, the target nature and chamber are crucial points and should be considered in conjunction with the conception of the separator/spectrometer.

Separator/spectrometer

The most important feature of the SPIRAL2 project is the unprecedented intensity of the beam. This would oblige a very high primary beam rejection factor of the separator/spectrometer. It is requested a rejection factor of the order of 10^{15}, which is considered as a major challenge. This high rejection level, never achieved so far, will certainly need special developments and innovative solutions. An interesting idea, to be developed, came into discussion (R. Dayras) with a proposition of a fast chopper, which could help in rejecting the primary beam. The discussion group foresees the need of specific R&D in this topic. Nevertheless, some interesting ideas were discussed and it was clear that the philosophy of using a multi-stage separator/spectrometer would provide interesting benefits in this sense. For the super-heavy and very-heavy physics, the separator can have relatively poor mass and energy resolution, not very high angular acceptance (+/- 20 mrad) but with extremely high primary beam rejection factor. For deep-inelastic and other reactions, it was proposed to have a spectrometer with variable angle and large acceptance, while having better mass and energy resolution. It is important to note that no specifications (numbers) are given in this report, because the discussion should continue within the working group. Interesting features involving the use of gas filled solenoids (H. Savajols) were also mentioned. Moreover, the possible of use of the rejected primary beam in other experiments can be a very attractive feature of the separator/spectrometer. This should be also analyzed carefully. Considering the coupling with the target, one should also consider to have a device with an acceptance compatible with a large object point. This feature should help distributing the beam over a large surface of the target and, therefore, would allow handling high beam power. A sketch of a mixed solution in two or more stages involving what we called a separator section and a spectrometer section is given in the figure below. The main features of this solution are recalled in this figure. An important feature is also that the separator and the spectrometer can be turned on and off independently.



3. Detection for the separator/spectrometer

We have identified different kinds of detection systems that could work in conjunction with the separator/spectrometer. It should be noted that the workshop discussion was very broad and open. All the detection systems mentioned here have still to be thoroughly designed for our applications. All the here-after mentioned ideas should be integrated in physics experiment projects.

Beam position monitors

The beams coming from the linear accelerator will require a precise monitoring. Due to the high intensities, the slightest misalignment of defocusing can be the cause of spurious scattering. We should be able to determine during the experiment the mean position of the incoming particle as well as the general shape of the beam. It should not disturb the downstream experimentation, thus this monitoring should be perfectly transparent. Different methods could be investigated: residual gas detectors, resonant tuning techniques, capacitive probes… If very low energy beams are delivered, a specific detection should be envisaged, especially for a precise measurement of the beam energy.

Around the target

The main characteristic of the environment around the target is the high background noise that should come from the reactions: X and γ rays, neutrons or even high fluxes of charged particle are expected. This has to be taken into account when thinking about implanting a detector around the target. *E.g.* AGATA is expected to be able to cope with beams as high a 100pnA, but would be overwhelmed by higher intensities.

If we want to collect all the benefits from high intensities, we have to design detectors that are able to sustain them. From the geometrical point of view, the farther from the target are the detection system, the lower are the rates. Thus a large target chamber could be considered. Other kinds of experiments, like the “Megajoule Laser” studying inertial confinement fusion, require high flux monitoring. It could be very profitable to have a look at the technical solutions employed there.

The identification of the light particles emitted has also been mentioned. It could use magnetic fields around the target to this purpose.

For very low energy beams, the cross sections of all the nuclear reactions will decrease and the background could be moderate, even with high intensities. This case has to be considered specifically.

Focal plane detection

Thanks to the high rejection of the separator/spectrometer, the rates at the focal plane are moderate. If the spectrometer is intended to be dispersive, the tracking of the reaction products will be mandatory to reconstruct their trajectories. Nevertheless, it should be kept in mind that we will be dealing with low energy ions and that the detection has to be developed accordingly:

- thin position sensitive detection (emissive foils : Se$^-$D like…)
- low threshold ionization chambers
- low dead zone detectors (thin entrance window silicon arrays : MUSETT project…)

A wide range of detection settings can be also be considered:

- gamma arrays for delayed spectroscopy (EXOGAM like)
- α and e$^-$ spectroscopy (BEST like)
- ions traps for laser spectroscopy or chemical analysis experiments (TASCA like)

4. Final comments

This session was a first step toward the definition of a separator/spectrometer for LINAG intense stable beams. We come to some general ideas about some possible solutions for the separator/spectrometer itself, its uses and its associated detection, but they still have to be refined and validated. Next year, another workshop will take place, devoted to the constitution of effective working groups and to the first quantitative estimations of the needs and of the means. All the people interested in are welcomed to contact the three organizers of the session.

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Annex 2

Minutes of the discussion session of the S^3 - 1st working group meeting

Paris, CISP – June 27-28, 2006

Three topics were discussed:

1- Physics issues related to S^3
2- Letters of intent for SPIRAL-2
3- Technical / design issues for S^3

1- Physics Issues

The first goal of this discussion was to straighten the physics topics, which were defined in the "nuclear reactions" workshop of SPIRAL-2 in October 2005. The criteria was to classify the topics in accordance to its uniqueness, related to the beam energies and intensities of LINAG (the linear accelerator of SPIRAL-2) and the need of unprecedented primary beam suppression of the separator/spectrometer. Following these criteria, a table of topics was built during the meeting. Working sub-groups for each topic were proposed and individuals took in charge each topic. Conveners have in charge to write the physics case for the topic in close collaboration to worldwide physicists interested in S^3.

Experiments that cannot use the full intensity of LINAG were not discarded. These experiments could take place in the intermediate focal plane of S^3, provided that arguments show the usefulness of S^3 and LINAG beams. See table 1.

CONVENERS: A first draft of ONE PAGE only is due to the 1st of September, together with a list of interested people and laboratories.

2- Letters of Intent – LoI

One letter of intent specific to the proposal of S^3 will be written and submitted to the SPIRAL-2 Scientific Advisory Committee (SAC). This letter should be done by the 2nd of October. All conveners on "Physics Issues" and "Technical Specifications" of S^3 are invited to send to Jerry Nolen (nolen@anl.gov), Antoine Drouart (adrouart@cea.fr) and Antonio C.C. Villari (villari@ganil.fr), spokespersons of S^3, the one page first draft (resumé) of their specific topic and the name of individuals and laboratories interested on S^3. The spokespersons will propose a version of the LoI for S^3 two weeks after.

Independent LoIs based on physics cases that include S^3 as experimental device will also be proposed. You are welcome to inform the spokespersons about them. They will be referenced in the main S^3 letter.

3- Technical requirements

The technical requirements of S^3 will be discussed and proposed by several sub-working groups. The topics for each working group as well as the names of conveners were proposed during the working group meeting. Table 2 lists the topics and names the conveners. Conveners have in charge to write the technical requirements for each topic in close collaboration to worldwide physicists and engineers interested in S^3.

A first draft of ONE PAGE only is due to the 1st of September, together with a list of interested people and laboratories.

Notes

If you are not involved into the S^3 collaboration but would like to, or know people who could be interested in this field, please contact Jerry Nolen (nolen@anl.gov), Antoine Drouart (adrouart@cea.fr) and Antonio C.C. Villari (villari@ganil.fr). All proposals are welcomed.

TABLE 1 – Physics issues:

Topic	Sub-topic	Need	Conveners
SHE - synthesis		High intensity High rejection	Ch. Stodel R. Dayras
S-VHE - spectroscopy	Prompt	100pnA maximum Justification needed	P. Greenless R. Herzberg Ch. Theisen M. Lopez-Martens
	Decay	High intensity High rejection Compact focal plane	P. Greenless R. Herzberg Ch. Theisen A. Lopez-Martens
	Secondary reactions (COULEX)	High intensity High rejection Compact intermediate focal plane	A. Korichi A. Lopez-Martens
	Chemistry	High intensity High rejection Compact focal plane	Ch. Stodel M. Shädel (*)
Molecular resonances		High rejection 100pnA maximum Prompt-like experiments Justification needed	M. Rousseau S. Courtin
Spectroscopy at/beyond the proton drip line	Prompt	100pnA maximum Justification needed	K. Lister F. Azaiez
	Decay	High intensity High rejection Compact focal plane	K. Lister F. Azaiez
	Secondary reactions	High intensity High rejection Compact intermediate focal plane	A. Korichi K. Lister F. Azaiez
Multi-nucleon transfer and Deep-inelastic	Prompt	100pnA maximum Justification needed	F. Cappuzzello A. Korichi A. Cunsolo F. Azaiez
	Decay	High intensity High rejection Compact focal plane	F. Cappuzzello A. Korichi A. Cunsolo F. Azaiez
	Secondary reactions	High intensity High rejection Compact intermediate focal plane	F. Cappuzzello A. Korichi A. Cunsolo F. Azaiez
Study of reaction mechanism and product distributions			A. Wieloch A. Rodin O. Dorvaux C. Schmitt
Production and study of isomers			S. Karamian J.M. Daugas (*)
Ground state properties (masses…)		High intensity Compact focal plane	G. Savard G. Audi
GT strength measurements through charge exchange reactions			F. Cappuzzello A. Cunsolo

TABLE 2 – Technical Specifications:

Topic	**Detail**	**Conveners**
Beam Specification	2 injectors, resolution, timing, diagnostics …	M. Lewitowicz
Targets	Solid, liquid, gaseous …	A. Yeremin J. Nolen A.C.C. Villari
Separator design	Includes separator and spectrograph. Includes also re-use of primary rejected beam or stripping of small part of the beam.	F. Cappuzzello A. Rodin B. Erdelyi J. Uusitalo A.C.C. Villari A. Cunsolo A. Drouart
Prompt detection	Intermediate focal plane	A. Korichi, M. Rousseau, S. Courtin
Detection	Final focal plane	B. Gall, R. Herzberg, K. Haushild, Ch. Theisen, C. Dossat, P. Greenlees
Infrastructure	(including shielding)	M. Lewitowicz (+ engineers)
Very Low Energy Facility	Gas cell, traps, chemistry …	G. Savard S. Franchoo (*) DESIR - synergy
Safety issues	Beam dumping, actinide targets …	M. Lewitowicz A. Yeremin (GANIL safety group)

ANNEX 3

Targets for S^3 : Can we work with such high intensity?

– THIS IS A WORKING DOCUMENT –

Antonio C.C. Villari

The very high intensity of LINAG beams brings unprecedented opportunities to physics around the Coulomb barrier, but also challenging issues. The first one is related to the target. How can a target "survive" under such huge beam intensity?

Here I propose some simple calculations, which seem to indicate the way to proceed, at least for solid targets. It is based on targets mounted on wheels. The difference from actual wheels is that the beam spot is multiplied by a factor of around 5 in ONE direction (not in both directions) and the speed of the wheel is significantly higher, when compared with present systems. These two assumptions seem to make it possible the use of very high beam intensities in S^3.

The simulations were done with the following assumptions and steps:

1- Only cooling by radiation is taken into account. This is justified by the fact that the thickness of the target is small (< $1mg/cm^2$), which means that conductance can be neglected. Anyhow, conductance will help cooling, therefore the temperatures can be considered as overestimated.
2- A simple radiation cooling calculation can be done considering Stefan-Boltzman black body law and supposing that the overall surface of the "illuminated" target radiates. This gives you the limiting temperature of the target for a wheel that turns at infinite speed. This is interesting to fix the maximum limits of the system and guide the following calculations.
3- The code "Stefan" written by Roland Dayras (CEA/Saclay) is used to estimate the maximum and minimum temperatures of the target while the wheel is turning. It takes into account only radiation cooling, as mentioned above.
4- In all cases, the beam profile is considered to be flat.

I) Case with GSI-equivalent wheel, and infinite rotation speed (simple black body):

Beam	Energy	Target /Energy loss	Target wheel radius	HO beam spot	T operation
70Zn	344 MeV	208Pb - 450µg/cm2 – 6.1 MeV	150 mm	2 mm	< 180°C
48Ca	250 MeV	238U – 450µg/cm2 – 3.1 MeV	150 mm	2 mm	< 500°C

The operation temperature is the ad-hoc maximum temperature allowed for the considered target. It is roughly half the fusion temperature of the target. The emissivity used is equal to 0.8. The target contains a small fraction of carbon (helping to obtain a good emissivity) The walls in front of it should also be "black". The environment is considered at the temperature of 40°C.

Fig. 1 shows the evolution of the vertical beam spot in order to obtain T operation of 180°C in the first case and 500°C in the second. If one considers a "reasonable" beam spot of the order of 20 mm, the maximum beam intensity for Pb targets is of the order of 10pμA. For U targets, this intensity can increase up to 200pμA. Note that the figures are in logarithmic scale, but the curve is LINEAR, evidently.

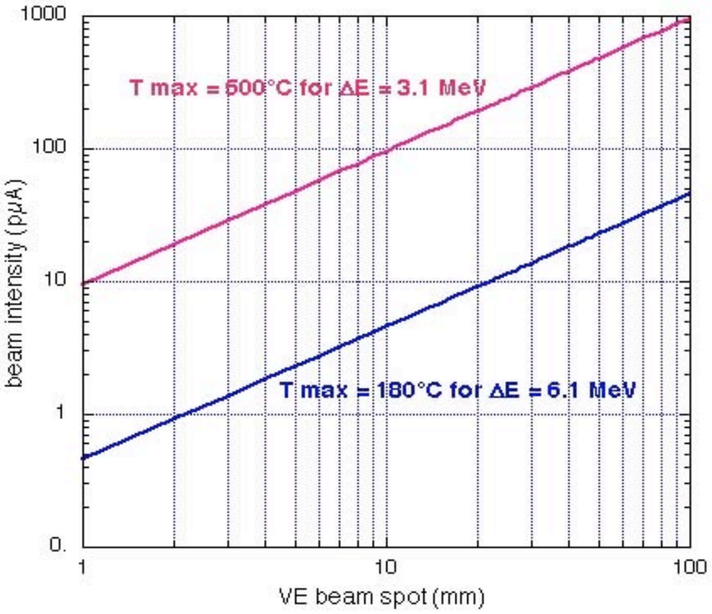


Figure 1: Beam intensity as a function of the vertical beam spot for a “GSI-equivalent” wheel spinning at infinite speed.

II) The effect of the rotation speed for “GSI-equivalent” wheel:

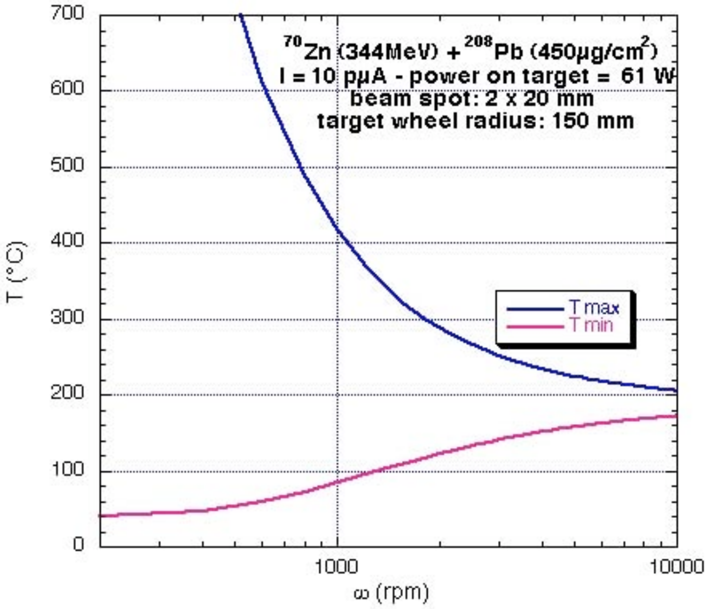


Figure 2: Maximum and minimum temperatures of the target as a function of the speed rotation

The speed of the wheel is very important. The temperature dependence as a function of the speed is shown in Fig. 2. In this simulation we assume a VE size of 20 mm. The HO size is only 2 mm. It is clearly not the correct assumption for low speed, but if one considers the fact that we have to couple this target with a spectrometer, it is nice to have a small beam spot in (X). Moreover, at high speed the HO size does not influence the maximum temperature of the target.

It is clear that a speed of the order of 10000 rpm is needed in order to have a maximum temperature of about 200°C in the Pb target. For Ca +U target and higher temperature (see Fig. 3), intensities of about 100pμA or more could be at 10000 rpm.

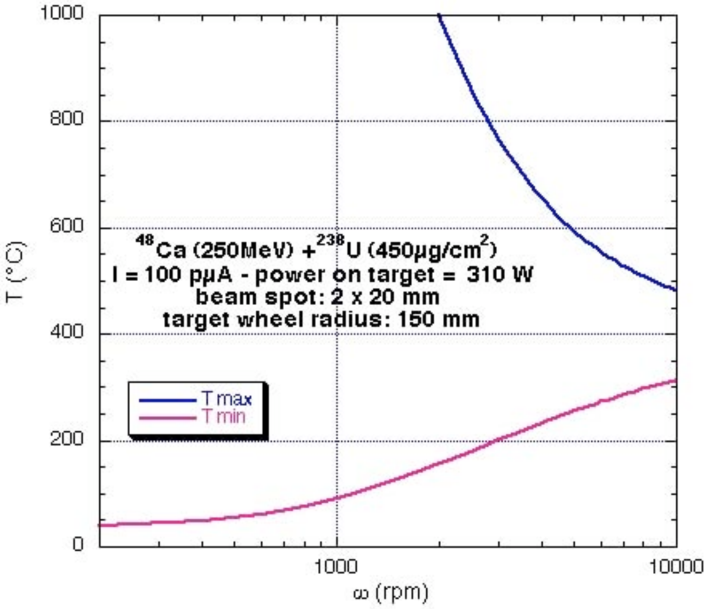


Figure 3: Same as Fig. 2 for ^{48}Ca + ^{238}U case.

III) Smaller target wheel

It would be also interesting to study a smaller target wheel when using transactinide targets. The target, in this case, could have a smaller radius, i.e. 8 cm, more likely a kind of “Dubna-type” wheel. Fig. 4 present a calculation using the following parameters:

Beam	Energy	Target /Energy loss	Target wheel radius	HO beam spot	T operation
48Ca	250 MeV	243U – 450µg/cm2 – 3.1 MeV	80 mm	2 mm	<600°C

The operation Temperature is attained for a speed of the order of 20000 rpm.

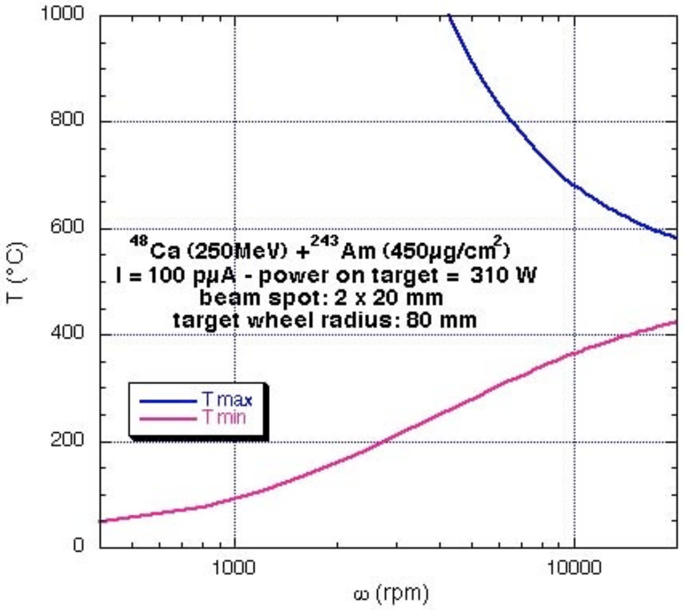


Figure 4: Same as Fig. 2 for ^{48}Ca + ^{243}Am case.

Comments:

A wheel of 150 mm radius is well suited for use with beam intensities of the order of 10 pµA with Pb targets (corresponding to a total power dumped on the target of the order of 60W). The conditions are i) the beam size of 2 x 20 mm and ii) rotation speed of a least 10000 rpm. In order to have higher beam intensities on a Pb target, larger wheels could be built, but my feeling is that the best solution would be a gaseous target. A GANIL-type target (wheel diameter of 35 cm) cannot be used with 100pµA of beam intensity on Pb targets, unless the beam spot is enhanced. But in this case the emittance in (Y) direction would be the limiting factor.

For U, a wheel of 150mm with 10000 rpm is well suited and can be used with 100 pµA beam intensity (for a beam power dumped on the target of the order of 300W). For transactinides, a smaller wheel (radius of 8 cm) could be envisaged, but with 20000 rpm.

No calculation on the resistance of the targets was done. It should be investigated if centrifugal force influences the integrity of the target. Also sputtering should be considered.

These targets require special development probably based on turbo-pump design.

ANNEX 4:

Final focal plane detection - Technical specifications

Conveners

B. Gall, R. Herzberg, K Hauschild, Ch. Theisen, C. Dossat, P. Greenlees,
Zbigniew Sosin, Andrzej Wieloch

Since we were foreseen only to write on Final focal plane some important points linked to this part should be seen elsewhere:

- In-beam spectroscopy (gamma/electrons)
- Rotating target (target temperature problem)
- Separator transmission
- Optics of the separator

The spectroscopy of heavy elements has been possible due to the progress of the tagging methods up to the present limits. For such studies, the association of the best gamma-ray detector, recoil tagging system and acquisition electronics is needed. This part of the LOI is dedicated to the tagging system needed for the S^3 project where we aim the 10 pb cross-section level for focal plane experiments.

The first element in the time-line of an event is the prompt gamma and/or electron detection at target. The recoiling nucleus is then transported in the separator to the focal plane detectors. The first information that we can get is the time of flight and the position from the TOF detector. The recoil is then implanted in the focal-plane detector, usually a silicon strip detector (SSD). When this nucleus decays, it gives access at focal plane to the emitted activity: alpha, beta, and gamma/electrons from daughter nuclei. Therefore the SSD is usually surrounded by a Tunnel of Charged Particle detector (CPT) and gamma detectors.

The TOF

The use of a TOF measurement has demonstrated power of selection brought to the detection of heavy nuclei. This can be done using Parallel Plate Avalanche Counters (PPAC) or Secondary Electron Detection device (SED). The PPAC based TOF need usually a thin window at each end in order to prevent the drift gas to go in the separator and in the focal plane. Each SED has also a thin foil where the secondary electrons are generated. These foils may stop low velocity recoils. In order to avoid dismounting TOF for these cases, an R&D programme is needed. We could imagine to work on thinner windows system or even window-less systems based on a differential pumping system or operated with the separator gas. All the proposed solutions will also depend on optics through the recoil dispersion in the separator.

The implantation detector

The size of the recoil spot on the focal plane will condition the SSD detector. Large dispersion will enable better separation between the different events but will also increase the cost of all the focal-plane detectors. The use of gas-filled separator enables a re-focussing of the different charge states into a wide area where a vacuum separator would give narrower spots

for only a few charge states on the same plane. From the point of view of dispersion as well as transmission, a gas filled separator is more adapted to this type of physics.
One of the challenges of going to lower cross-section reactions is to be able to select events out of background linked to all other implanted products. This is essential since an event is an implantation followed by the associated decay at the same position in the detector. The coincidence between the TOF and the SSD can be used to clean the data, nevertheless the operation of a high-quality stripped detector is certainly essential. For instance, the use of double-sided silicon-strip detectors (DSSSD) gives the position in x and y coordinates improving the separation power. Cooling the SSD will also improve the resolution but may need some R&D. Low threshold operations and thin dead layer will be needed. Due to the variety of radiations to be detected (alphas and electrons), preamplifiers with large dynamic range required.

The Charged Particle Tunnel

A charge particle detector surrounding the upstream part of the SSD detector is needed in order to measure the electrons and alphas emitted with the decay of the recoil nucleus. Silicon detectors are usually used. Since the decaying nucleus is implanted in the SSD, the energy deposited in the CPT depends on the implantation depth, emission angle and dead layer thickness. The CPT elements are usually made of silicon detectors. Cooling will be needed in order to improve the resolution. Due to the variety of radiations to be detected (alphas and electrons), preamplifiers with large dynamic range required. Some R&D is needed for size optimisation, detector cooling technique and preamps positioning. One may also study the possible income from the new pulse-shape analysis technique.

The focal-plane gamma-ray detector

Due to the low production cross-section of the VHE, the gamma sensitivity of the focal plane is one of the main issues. With such a setup, one may be able to observe for the first time gamma rays from a Super Heavy Element (SHE). Very Heavy Elements (VHE) and SHE emit mainly gamma rays between a few keV and 1-2 MeV. The low energy part of the spectrum may be modified by absorption in SSD and CPT. This is not a major problem since a high proportion of the gamma transition strength is going through conversion electrons detected in the CPT. Due to the low efficiency of gamma detectors with respect to particle detectors, one need a large solid-angle gamma-ray array.
One may use existing Ge detectors such as clovers in order to build a quite compact « clover box ». Due to the way the clover is built, some solid angle may be lost in the vicinity of the SSD. The optimum positioning of such detectors will come from GEANT simulation.
An array built out of planes of coaxial arrangements dedicated to a given focal plane geometry gives the best solid angle coverage. This is the idea behind the γ^3 R&D program started in 2006. The first results of GEANT simulations shows that even if the coverage is optimum, due to the used energy range, the efficiency of the array is mainly coming from the γ^3 elements right behind the implantation spot in the SSD.
One may also imagine intermediate solutions combining the use of existing detectors and γ^3 elements or the construction of detectors out of new gamma detector material such as CdTe.

4π geometry for charged particles detection

Modification of the GANIL super heavy element detection system to achieve the 4π geometry for charged particles detection. This can be done by constructing additional gaseous detector which will detect not only alpha radioactive decay chains of reaction products implanted in the silicon (Si) position sensitive detector (IMP) but also protons - the main source of the background seen by the IMP. This detector will also be able to detect spontaneous fission fragments.

Electronics and acquisition system

Recent experiments, especially with the JUROGAM+RITU association, has shown the power of the use of trigger-less electronics. Each detector information is time-stamped and sent to a Merging unit. The time of flight can therefore be set and optimised on the full statistics of a given experiment. In addition, we do not loose information due to common dead time. In parallel, the recent developments in digital electronics such as those done for the AGATA project underlines the time stamping of events and enables to run at counting rates such as 20-50 kHz without major decrease in measurement quality. In addition, this electronics exhibit a nice linearity on the whole energy range. The S^3 project should also benefit from these developments.

Reference cost estimation:

The cost is based on existing project and detectors. Two options are presented, with (a) a “gamma-cube” and (b) planar Ge detectors associated with clovers.

	(a)	(b)
TOF	50	50
Differential pumping	30	30
DSSSD & CPT	220	220
R&D	50	50
Gamma detectors	720	150
Cables & connectors	35	35
HV	70	70
Auto-fill	50	50
Mechanics	40	40
Electronics	175	135
Data acquisition	110	110
TOTAL (kEuros)	1550	940

ANNEX 5

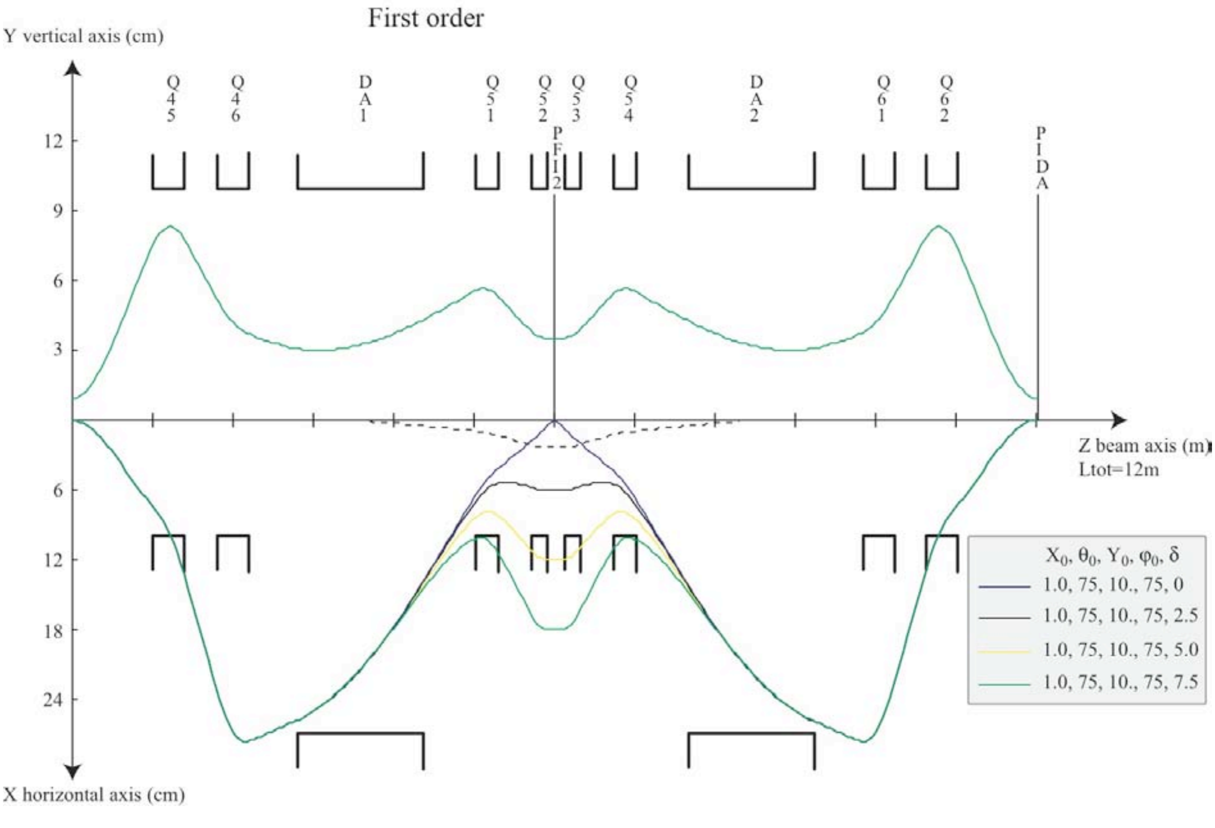
First discussion on the optical concept of the Separator session of S^3

L. Perrot, A.C.C. Villari and R. Anne

Usual recoil mass separator like SHIP or FMA could constitute the first session of S^3. However, in view of the very intense primary beams of LINAG, it was considered that separators using electrostatic devices would be extremely difficult to be used. Therefore, the first attempt reported in this discussion is to study to which extend the separator session could be a “LISE-like” facility, with the requested acceptances in moment and in angle.

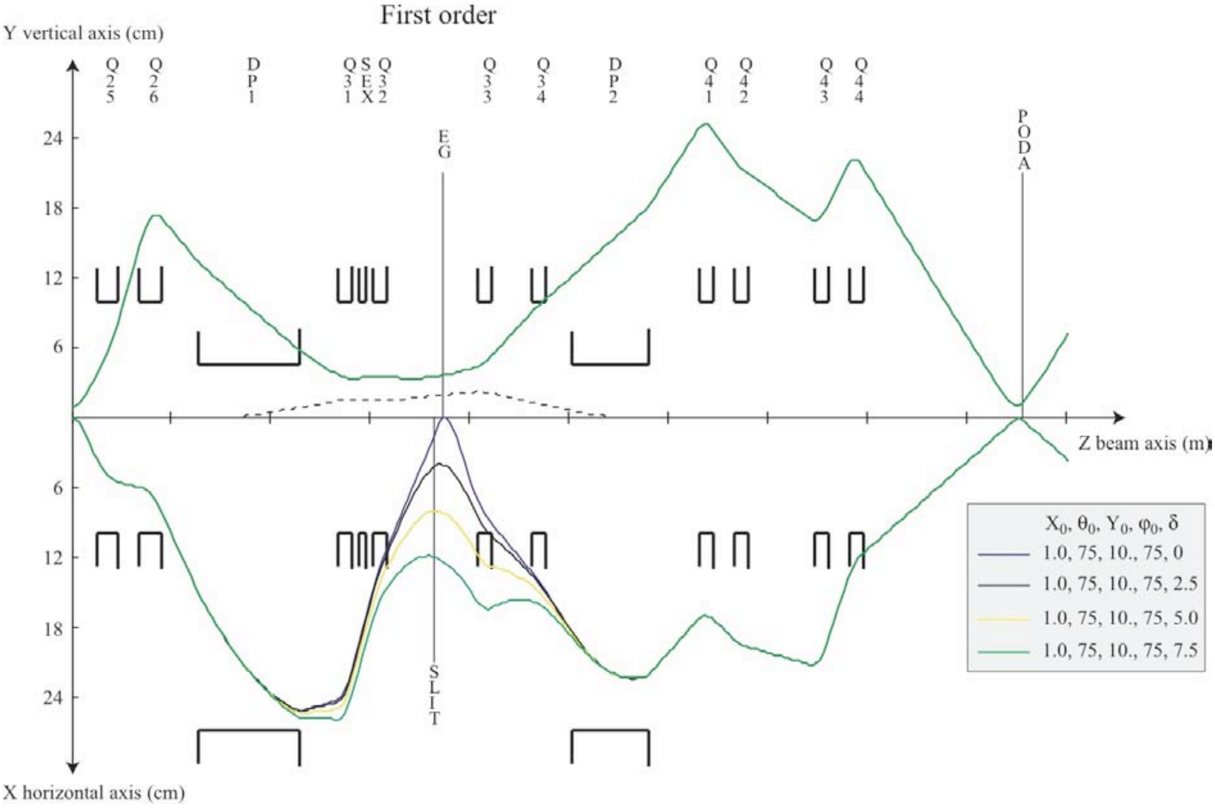
Two simple figures illustrate this optical calculations. Only first order is considered. In this phase of the calculations, it is assumed that most of the aberrations can be “hardware-corrected”.

Case 1: Simple achromatic and symmetric deviation using 45 degrees dipoles:



The green curve is the beam envelope considering angular acceptance of +/- 75 mrad and momentum acceptance of +/- 7.5 %. The different colors show the evolution of the beam size in the horizontal axis. The maximum magnetic gradient for the quadrupoles (Q46 for instance, in this test case) is of 1.43 Tesla at 28 cm radius. This is considering a maximum magnetic rigidity of 2.0 Tm. The total length of the separator 12 m. This is a very simple case, double achromatic and with magnification 1. This does not give any versatility in the image point of the separator.

Case 2: LISE-like separator, with more flexibility (a quadruplet in the exit of it) in the image focal plane.



The same as the preceding figure, where the green curve is the beam envelope considering angular acceptance of +/- 75 mrad and momentum acceptance of +/- 7.5 %. The different colors show the evolution of the beam size in the horizontal axis. The maximum magnetic gradient for the quadrupoles (Q41 in this test case) is of 0.83 Tesla at 25 cm radius. This is considering a maximum magnetic rigidity of 2.0 Tm. The total length of the separator session in this case is of about 18 m.

Conclusion:

The outcome of these simulations seems to show that this kind of separator can constitute one possible solution for the separation session of S^3. More studies are certainly necessary. The overall size of each object (quadrupoles and dipoles) is challenging but does not seem to be oversized.

ANNEX 6

Production rates in the Superheavy region

Antoine Drouart

We show in Figure 1 the expected counting rates for some SHE, with the ion source A-PHENIX and RFQ injector optimized for A/q = 3 and A/q = 6. Calculations hypothesis are the following:

- With few exceptions, we have considered only 1n, 2n and 3n channels for cold fusion, and known hot fusion reactions from Z=112 to Z=118. We notably did not take into account reactions with lighter Ca isotopes or with symmetric systems, which leads to new isotopes.
- for cold fusion reaction (^{208}Pb targets), cross section systematic has been considered.
- for hot fusion reaction (^{48}Ca beams on actinides targets) measured cross sections have been considered
- target thickness is 400µg/cm^2, set-up efficiency is 50%.

Orange and red codes indicate that delayed spectroscopy can be performed for those nuclei. Blue and green indicate that the expected count rate is sufficient for synthesis confirmation.

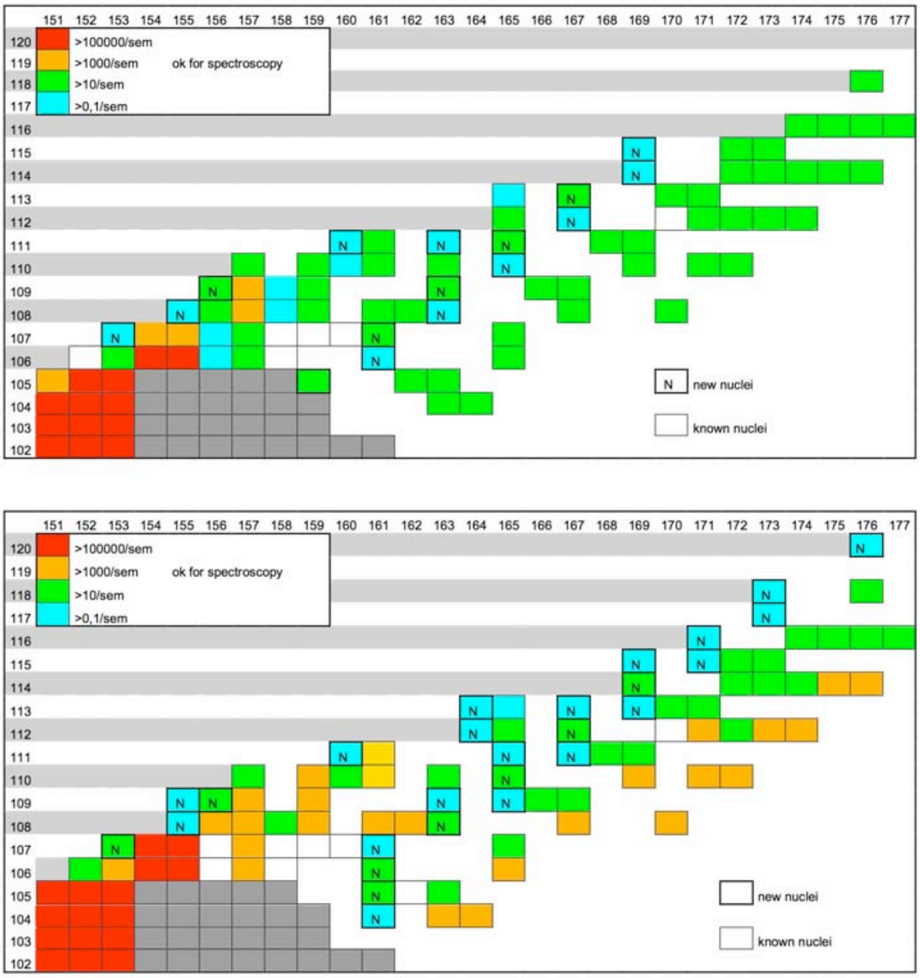


Figure 1) Counting rate supposing A-Phoenix and RFQ injector for A/q=3 (top) and A/q=6 (bottom)