Technical Report

for the Design, Construction,
Commissioning and Operation of *LaSpec*
(within the NUSTAR collaboration)

Laser Spectroscopy
of Short-Lived Nuclei
at FAIR's Low Energy Branch

LOI Identification N° 9

FAIR- PAC:
APPA [ ]
NUSTAR [X]
QCD [ ]

Date: 14.12.2005

Technical Report for the Design, Construction, Commissioning and Operation of LASPEC

Abstract:

A multi-purpose laser spectroscopy station for the study of stopped, cooled, and bunched radioactive species is presented in full technical detail. The station will be installed on the low-energy beamline of the Super-Fragment Separator (S-FRS) and will permit, by a variety of optical techniques, the model-independent determination of isotopic and isomeric nuclear spin, magnetic dipole moments, electric quadrupole moments and changes in mean square charge radii. To realize fully the opportunity afforded at the LEB the LASPEC collaboration proposes to study radioactive atoms and ions with a variety of fluorescence, resonance ionization and polarization based spectroscopic techniques. The range of experimental approaches reflects the universal capabilities of the LEB and will ensure that, whilst capable of complimenting research at existing ISOL facilities, the new laboratory will provide an unparalleled opportunity to study the most exotic, and short-lived, nuclear species to the limits of nuclear stability.

Spokesperson: Paul Campbell
Email: pc@mags.ph.man.ac.uk,
Telephone : +44 (0)161 275 4157

The LASPEC Set-Up

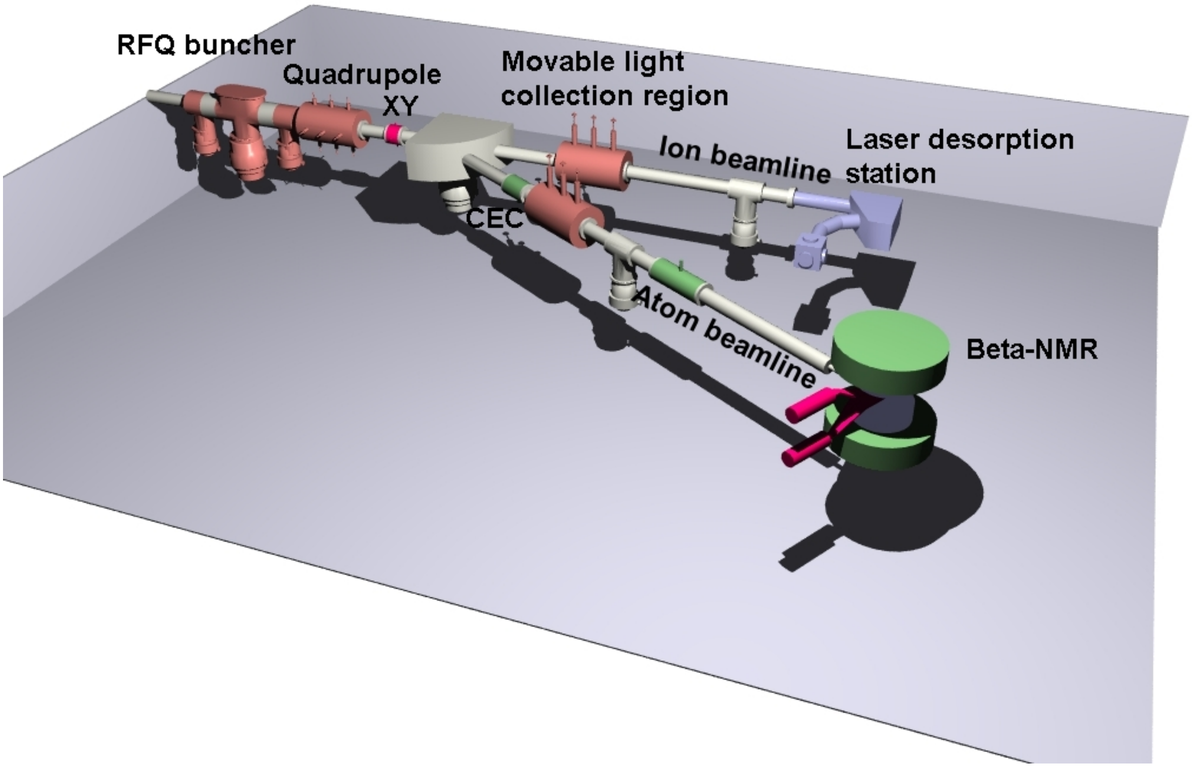

Figure 1: Overview of the proposed LASPEC set-up including RFQ buncher, collinear ion beam spectroscopy, collinear atomic beam spectroscopy and optical pumping, laser-desorbed resonance ionization and β-NMR.

Spokesperson:
Paul Campbell, pc@mags.ph.man.ac.uk, Tel.: +44 (0)161 275 4157

Deputy:
Wilfried Nörtershäuser, W.Noertershaeuser@gsi.de, Tel.: +49 (0)6159 71 2459

Contact person @ GSI
Wilfried Nörtershäuser, W.Noertershaeuser@gsi.de, Tel.: +49 (0)6159 71 2459

Members of the LASPEC Collaboration

BELGIUM

K. Flanagan, M. Huyse, I. Koudriavtsev, G. Neyens, P. Van Duppen
Katholieke Universiteit Leuven, Afd. Kern- en stralingsfysica, B-3001 Leuven.

FINLAND

J. Äystö, A. Jokinen, T. Kessler, I. Moore, K. Peräjärvi
JYFL University of Jyväskylä, Jyväskyla, P.O. Box 35.

FRANCE

F. Le Blanc, D. Lunney
IN2P3, CNRS, F-91405 Orsay.

GERMANY

Ch. Geppert, Th. Kühl, C. Scheidenberger, M. Tomaselli
Gesellschaft für Schwerionenforschung mbH, D-64291 Darmstadt.

D. Habs, M. Sewtz, J. Szerypo, P.G. Thirolf
Ludwig-Maximilians-Universität München, D-85748 Garching.

K. Blaum, G. Huber, W. Nörtershäuser, M. Seliverstov, K. Wendt
Johannes Gutenberg-Universität, D- 55099 Mainz.

J. R. Crespo López-Urrutia, J. Ullrich
MPI Kernphysik, D-69117 Heidelberg.

C. Zimmermann
Eberhard-Karls-Universität, D-72076 Tübingen.

GREAT BRITAIN

J. Billowes, P. Campbell
University of Manchester, Manchester M13 9PL.

SWITZERLAND

A. Dax
CERN, CH-1211 Geneva 23

USA

D. Schneider
Lawrence Livermore National Laboratory, US-CA 94550-9234 Livermore.

B. A. Bushaw
Pacific Northwest National Laboratory, Richland WA 99352.

Table of Contents

A Introduction and Overview:

Laser spectroscopy of radioactive isotopes and isomers is an efficient and model-independent approach for the determination of nuclear ground and excited state properties. Hyperfine structures and isotope shifts in electronic transitions exhibit readily accessible information on the nuclear spin, magnetic dipole and electric quadrupole moments as well as root-mean-square charge radii [1, 2]. The dependencies of the hyperfine splitting and isotope shift on the nuclear moments and mean square nuclear charge radii are well known [2],

$$A_{\mathrm{hfs}} = \frac{\mu_I \ \mu_{\mathrm{N}} \ B(0)}{I \ J}$$

$$B_{\mathrm{hfs}} = e \ Q_s \left(\frac{\partial E}{\partial z} \right)_0$$

$$\delta \nu^{AA'} = K \ \frac{M_A - M_{A'}}{M_A M_{A'}} + \frac{2 \pi Z}{3} \ \Delta \left| \Psi(0) \right|^2 \delta \left\langle r^2 \right\rangle^{AA'}$$

and the theoretical framework for the extraction of nuclear parameters is well established [2]. These extracted parameters provide fundamental information on the structure of nuclei at the limits of stability. Vital information on both bulk and valence nuclear properties are derived and an exceptional sensitivity to changes in nuclear deformation is achieved. Laser spectroscopy provides the only mechanism for such studies in exotic systems and uniquely facilitates such studies in a model-independent manner.

At FAIR the Super Fragment Separator (SFRS) will provide a rich spectrum of isotopes that are not and will not be available at any other facility. From the view of optical spectroscopic research the proposed facility will afford unique access to regions of particular nuclear interest that would otherwise remain inaccessible. The proposed research of the ***LASPEC*** collaboration is thus not in competition with that of other facilities but will rather study complementary or entirely new cases. As highlighted in the LOI these cases include the study of isotopes of refractory elements, high-K isomers and a vast region of heavy, neutron-rich isotopes.

The accuracy of laser-spectroscopic-determined nuclear properties is very high. Requirements concerning production rates are moderate; collinear spectroscopy has been performed with production rates as few as 100 ions per second [3] and laser-desorption resonance ionization mass spectroscopy (combined with β-delayed neutron detection) has been achieved with rates of only a few atoms per second [4]. At FAIR it will be possible for our collaboration to greatly extend our knowledge of nuclear sizes, deformation and electromagnetic moments far into the neutron-rich side of the upper part of the nuclear chart.

The ***LASPEC*** collaboration intends to construct a number of complementary experimental devices which will provide a complete system with respect to the physics and isotopes that can be studied:

- **Collinear laser spectroscopy on ions**
  Collinear laser spectroscopy of atoms and ions has been the workhorse for high-precision laser spectroscopy on short-lived isotopes for many years. Although the absorption lines of ions are typically in the deep blue and ultraviolet regions of the spectrum, suitable laser light can often be produced and a highly robust and universal spectroscopy provided. Collinear ion spectroscopy on cooled and bunched beams has recently been demonstrated [3] and this variant of the technique will be immediately and powerfully applicable at the new facility.
  A new development immediately applicable for the ***LASPEC*** collaboration involves optical pumping of cooled ions. This has been recently demonstrated within a radiofrequency quadrupole cooler-buncher device. With the use of a pulsed, high-repetion rate tunable laser system this technique enables the manipulation of the population of ionic states to

preferentially select a state via which an efficient transition may be chosen for collinear laser spectroscopy.

- **Optical pumping and collinear laser spectroscopy on atoms**
  Ion beams can be efficiently neutralized by charge exchange processes (experimentally achieved using a beamline cell containing a low pressure alkali-metal vapour). This offers the possibility of laser spectroscopy on a fast beam of atoms, which have absorption wavelengths that are more readily accessible than those of ions. Different types of optical and particle detection will be employed. Polarized beams of atoms and ions can be produced by optical pumping. This opens the possibility of β-asymmetry detection and β-NMR.

- **β-NMR**
  β-NMR is a well-established method for the determination of nuclear magnetic dipole and electric quadrupole moments. The technique has been especially favoured for light elements [5] but has also been applied to a range of cases where high precision has been required to explore the nuclear structure (such as measuring small admixtures of intruder components in a wavefunction). It combines optical pumping with nuclear magnetic resonance and β-decay asymmetry spectroscopy. Recently the method has been used to determine the quadrupole moment of ^{11}Li to high accuracy using yields of only a few thousand ions/s [6]. The method can be used for all β-decaying (non-zero spin) isotopes with half-lives between approximately 5 ms and 20 s. Generally, β-NMR is able to deliver quadrupole moments with higher accuracy then those obtained from standard laser spectroscopy. However, laser spectroscopy and hyperfine structure investigations are necessarily the first step prior to attempting optical pumping.

- **Resonance Ionization Laser Ion Source (RILIS)**
  Resonance ionization of atoms combined with the detection of the produced ions is a very efficient method in the study of rare isotopes [7]. During the last decade, it has been used for a broad range of applications, *e.g.*, laser ion sources to produce ion species which were not accessible by other methods [8, 9], in-source laser spectroscopy [10], and ultra-trace detection of cosmogenic and radio-toxic isotopes [11]. Its most prominent features are the efficient ionization process with resonant intermediate and autoionizing states, the elemental, isotopical, and sometimes even isomeric selectivity [12] and the large detection efficiency for the produced, charged particles.
  At the FAIR facility's Low Energy Branch (LEB), a resonance ionization laser ion source (RILIS) will add to the selectivity inherent in the production method of the super-FRS and ion catcher device. The RILIS will be used to enhance the production of isotopic (or even isomeric) enriched or pure ion beams. There are several possibilities to implement RILIS and they are closely related to the ion catcher device developments, whether it be a gas-filled stopper cell or a superfluid helium catcher as demonstrated by Huang and colleagues [13]. Laser resonance ionization within an ion catcher is an attractive option for a smaller device such as a superfluid helium catcher, or a cryogenic gas catcher. A natural development to a laser ion source is the installation of a laser ion source trap (LIST) [9]. This device may be coupled to the exit nozzle of the ion catcher. One possible design of a LIST is based on a typical segmented and gas-filled radio-frequency ion trap. Any neutral species that exit the ion catcher may be selectively ionized with counter propagating high-repetition rate pulsed lasers. All options are being actively pursued by members of the *LASPEC* collaboration and this development is closely related to that of the beam distribution working group of the LEB.

- **Laser-Desorption Resonance Ionization (LDRIS)**
  Radioactive ions or atoms can be deposited on an appropriate catcher, laser desorbed, and studied during a secondary (and resonant) laser ionization [14]. When used in conjunction with Time-Of-Flight (TOF) mass-separation [15] and decay-tagged photo-ion detection an

extremely sensitive spectroscopy can be achieved. For cases with very low production yields, the technique is superior to fluorescence detection. Such spectroscopy has previously, and notably, been used to study isotopes where the radioactive species was deposited in chemical or cluster form. It was also used for cases where the species of interest was not directly available but precursor nuclei could be deposited [16]. At FAIR the technique will be applied to the study of heavy neutron-rich elements (Pb, Bi, Pt, Au…) and will provide an opportunity to extend the investigation of these elements beyond the neutron-deficient cases previously studied at ISOLDE [16-20].

- **Spectroscopy in an Electron Beam Ion Trap (EBIT)**
  Spectroscopy of highly-charged ions inside an EBIT is an interesting option for the LASPEC collaboration. It can be performed in collaboration with the MATS group as an EBIT is an integral part of their experimental set-up. The spectroscopy will study ground state properties of nuclei via, for example, precision measurements of the hyperfine splitting of the atomic ground state, and will provide stringent tests of QED in strong electric and magnetic fields.

As the varying experimental approaches place different demands on the experimental station we propose to build two beamlines. A short beamline for collinear laser spectroscopy of ions will be optimized for the best vacuum conditions and minimal laser scattering. A second, longer beamline will be used for optical pumping of ions and atoms. This line will house the charge exchange cell and the β-NMR station.

The LASPEC collaboration has sought to, and has succeeded in, gathering a collection of members expert in each of the spectroscopic fields. The opportunities offered by a universal laser facility at LEB will be met by this strong and varied collaboration.

B Systems

1.1 Segmented Radio Frequency Quadrupole (RFQ) for Cooling and Bunching

The capabilities of the LASPEC station, at the lowest production rates, will be limited by the number of background events (*e.g.*, from stray light, collision-induced fluorescence in optical detection or non-selective ionization processes in particle detection). Many of these background rates can be effectively reduced by *bunching* the ion beam and all spectroscopic concerns can be improved by a *cooling* of the ion beam. The improvement in experimental signal-to-noise ratio following a combination of cooling and bunching can be dramatic (2 to 3 orders of magnitude). Segmented radiofrequency quadrupole (RFQ) cooler bunchers, provide a transverse and longitudinal confinement of ions in a low pressure gas cell. Collisions between the radioactive ions and light buffer gas atoms act to cool the ensemble as it is collected. The devices are highly efficient and have proved their adaptability (and are now becoming standard elements for trapping systems). From a spectroscopic perspective cooler-bunchers improve the ion beam quality in terms of both spatial and phase spatial extent and act to reduce critical concerns in the causes of background.

The first stage of LASPEC will be a second-generation cooler-buncher. The system will be operated at cryogenic temperature which offers a potential gain of two orders of magnitude over a room temperature system. This cooler-buncher will be jointly constructed and used with the MATS collaboration and its costs are fully included in the MATS technical report.

a. **Simulations**
   i. Detectors
      N/A – no new simulation required
   ii. **Beam**
      see MATS report

b. **Radiation Hardness**
   As the beam intensities reaching this post stopper device are modest, radiation hardness is not an issue.

c. **Design**
   The design will be based on the existing RFQs at ISOLTRAP [21], JYFLTRAP [22], SHIPTRAP, and LEBIT [23]. To adapt the system to the new requirements will require 6 months.

d. **Construction**
   The construction phase is expected to take about one year.

e. **Acceptance Tests**
   Before installation of the RFQ cooler, off-line tests will assure that the required performance is reached. Since the cooler is being purpose built within the MATS and LASPEC collaborations, no formal acceptance tests as such are specified.

f. **Calibration**
   Calibration with respect to voltage and RF frequency will be done with stable ions from an off-line ion source.

g. **Requests for test beams**
   At the first development stage no test with radioactive ions is needed. For the final commissioning a radioactive test beam is required.

1.2 Collinear Laser Spectroscopy

a. Simulations

i. Detectors

N/A – no new simulation required

ii. Beam

N/A – determined by the gas stopper

b. Radiation Hardness

All the components in the proposed LASPEC project have been demonstrated to be radiation hard from experience at the ISOLDE facility, CERN. A primary concern - a photonic radiation background contributing to the experimental background counting rates - has been demonstrated to be fully controllable. Not stated in every case, this is true for all other sub-projects as well.

c. Design

The design of the collinear laser spectroscopy apparatus closely follows that of existing and proposed facilities adjusted for the size constraints in the LEB experimental hall. The layout is as shown in Fig. 1. Other proposed facilities, particularly the ISOLDE cooler-buncher, will become operational during the R&D phase of the LASPEC project and will serve as perfect prototypes for the new facility.

d. Construction

The construction of the collinear laser line is estimated to take less than 4 months (including the delivery of all components). The LASPEC collaboration intend this sub-project to be the earliest on-line and the first to study low-energy beams from the LEB gas stopper.

e. Acceptance Tests

see g, below

f. Calibration

see g, below

g. Requests for test beams

Although essential calibration, efficiency and stability testing of the LASPEC facility could be undertaken on any previously studied isotope chain the cases of the Be, Ti, Zr and Th isotopes have been selected for primary study. These cases are of general interest to many users of the LEB and, aside from providing calibration over the range of nuclear masses, will be the first to afford new physics results from the project.

Prior to the completion and commissioning of the gas catcher an off-line ion source will be used to commission, and provide benchmarks, for the laser line.

1.3 Optical Pumping, and Fast Atomic Beam Laser Line.

a. Simulations

i. Detectors

ii. Beam

N/A

b. Radiation Hardness

see 1.2

c. Design

For optical pumping a beamline of at least 4 m length is required. The beamline will include a charge exchange cell for a creation of an atomic beam, ion deflectors and a weak longitudinal magnetic field produced by coils outside of the beam tube. To observe the resonance condition and for performing collinear spectroscopy on neutral species, an optical detection region identical to that constructed for the collinear laser-ion spectroscopy is required.

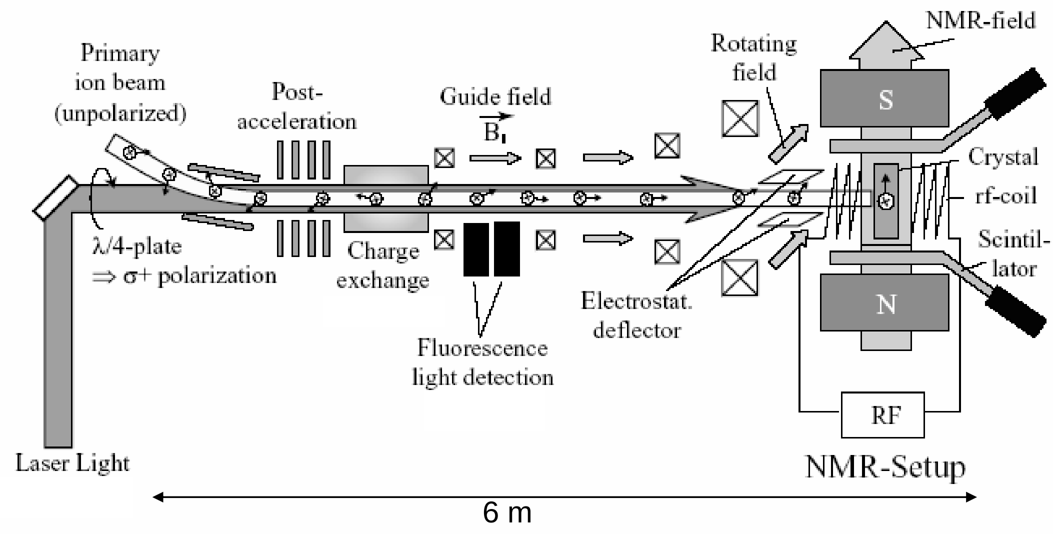

Figure 2: Schematic layout of the beamline for optical pumping, including a β-NMR set-up.

d. Construction

The construction of this laser line will run simultaneously to that of the ion spectroscopy line but is estimated to require a further two months of construction (6 months in total). The line will be commissioned in the same manner as the ion line using a variety of beams from on- and off-line sources.

e. Acceptance Tests

N/A

f. Calibration

N/A

g. Request for test beams

see 1.2

1.4 Beta-Asymmetry-Detected Nuclear Magnetic Resonance (β-NMR)

a. Simulations

i. Detectors

ii. Beam

N/A

b. Radiation Hardness

see 1.2

c. Design

There are three possible designs for the β-NMR experiments:

1. A conventional magnet with a high homogeneity (better than 10^{-5}) over a volume of 1 cm^3 and a very stable power supply. The maximum field to reach should be around 5000 Gauss. The gap between the magnet poles should be at least 12 cm, to allow the installation of beta-telescopes that stop beta-rays of up to 10 MeV. The magnet is located at the end of the collinear beamline for optical pumping as shown in Fig. 1 and Fig. 2. This allows the implementation of atoms as well as ions into the detector without the need for re-ionization of atoms. A crucial point in such a set-up is the conversion of the longitudinally polarized beam into transversal polarization which is necessary in this case.
2. A conventional magnet could also be used under a 90° geometry. Electrostatic deflection of an ion beam after optical pumping gives the necessary polarization change for the magnetic moment. Optical pumping of atoms is still possible if the atoms are afterwards re-ionized with, *e.g.*, a cold helium target. This technique is already applied at the ISAC separator at TRIUMF. Such a set-up has a larger space requirement than the one described above.
3. A solenoid at the end of the beamline. This removes all needs for a change of the polarization. The ion or atom beam would enter through a hole in the rear beta detector and be implanted into the crystal in the center.

All three designs are working at different ISOL facilities. The design (1) as shown in Fig. 2 is in operation at the ISOLDE facility / CERN, while the latter two designs are both implemented at the ISAC facility / TRIUMF [24]. Each design has its advantages and a decision about the final choice will be made in the near future.

d. Construction

The construction of the β-NMR set-up will be started after the installation of the laser beamlines. It will require approximately four months of construction and installation. The line will be commissioned in similar manner as the laser lines using a variety of radioactive beams.

e. Acceptance Tests

N/A

f. Calibration

N/A

g. Requests for test beams

see 1.2

1.5 Resonance Ionization Ion Source (RILIS)

a. Simulations

i. Detectors

ii. Beam

Identical to 1.2

b. Radiation Hardness

see 1.1

c. Design

The design of the resonance ionization laser ion source (RILIS) closely follows that of existing nuclear structural facilities. Two choices of laser system exist, both operating at high repetition rates in the 10 kHz range: a tunable dye laser system to provide the pumping and ionizing laser light as is used at the ISOLDE facility, or an entirely solid state system more recently installed at the ISAC facility in TRIUMF. Either system can be readily installed, with the Universities of Jyväskylä and Mainz having expertise in the use of the high repetition rate solid state titanium sapphire as well as the dye lasers. These lasers can also be used for laser desorption, optical pumping of cooled ions within the RFQ cooler-buncher device and resonance ionization spectroscopy. Several options exist for installation of RILIS depending on the developments of the ion catcher device. One such setup in which resonance ionization is performed in an RF multipole (LIST) is shown in Fig. 3.

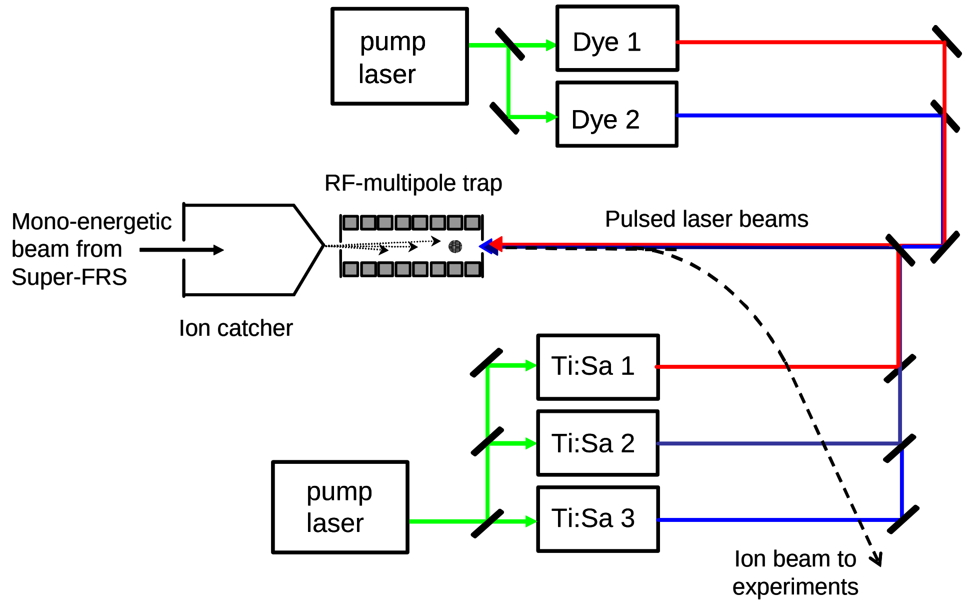

Figure 3: Resonance Ionization Laser Ion Source

d. Construction

The construction of a laser ion source will run simultaneously to both the ion and fast atom beam laser lines. The Universities of Jyväskylä and Mainz have the necessary expertise needed in the development of RF multipole devices for the development of a LIST. This construction can be done at the institutes involved and can be transferred to the LEB during the construction phase of the collinear laser beamlines.

e. Acceptance Tests

N/A

f. Calibration

N/A

g. Requests for test beams

see 1.2

1.6 Laser-Desorption and Resonance Ionization Spectroscopy (LDRIS)

a. Simulations

i. Detectors

ii. Beam

Identical to 1.2

b. Radiation Hardness

see 1.2

c. Design

The Laser-Desorption-RIS set-up is shown in Fig. 4. In this technique the low energy ion beam is directed towards (by electrostatic kickers) and is implanted into a graphite catcher foil. The neutralized implants are subsequently desorbed from the surface by intense laser light and are allowed to move to a second laser interaction region where the atoms are selectively resonantly ionized. The ionization spectroscopy may either be applied directly to the implanted species or, by use of a suitable decay period between implantation and desorption, to the study of daughter isotopes in the decay chain. Experimentally the synchronisation of the desorption and ionising laser pulses is readily matched to time structures achieveable with commercial low repetition rate lasers. A new technique, utilising the high repetition rate lasers described in section 1.5 is however foreseen and will be developed for use at the LEB.

The highest spectroscopic sensitivity possible with the technique is achieved when the produced ions are both time of flight separated and decay tagged. A shielded cabin housing ^{3}He neutron detectors is proposed for the LDRIS application at the LEB. These counters will permit the tagging of beta-delayed neutron emitters and will be vital in extending laser spectroscopic studies into the extreme neutron-rich production region of the S-FRS.

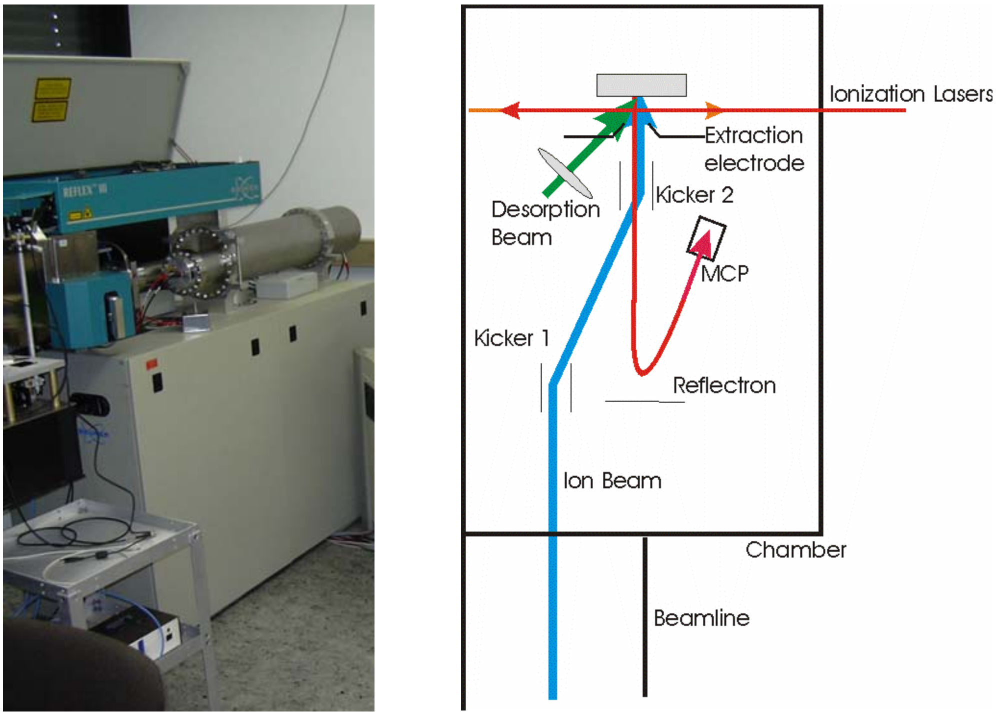

Figure 4: (left) Existing MALDI-TOF apparatus at the University of Mainz (right) Scheme for LDRIS at the LEB beamline

d. Construction

The set-up already exists at the University of Mainz (Fig. 4) and can be readily moved to GSI. Low as well as high repetition rate lasers for desorption and subsequent resonant ionization in the desorption plume will also be supplied from Mainz University. Thus, the implementation of this system causes little additional costs. As soon as the collinear spectroscopy beamline is built, the apparatus can be added as final component.

e. Acceptance Tests

N/A

f. Calibration

N/A

g. Requests for test beams

see 1.2

1.7 Laser Spectroscopy in an Electron Beam Ion Trap (EBIT)

(Optional)

A charge-breeding EBIT will be included in the MATS set-up within the Super-FRS low-energy experimental area. The device is equipped with an optical diagnostic port that can be used for visible and laser spectroscopic diagnostics. The spectroscopic instrumentation developed at the Max-Planck Institute for Nuclear Physics (Heidelberg) permits the measurement of isotopic shifts in the visible and x-ray wavelength ranges, and can thus be used to provide information about nuclear size effects, spin, and other relevant data. A drawing, taken from the MATS Technical Report, is shown in Fig. 5. It can produce hydrogenlike ions at least up to Xe^{53+}, and He-like ions across the periodic table. The EBIT can produce test beams of stable isotopes independently of the accelerator facility, and thus offer possibilities for laser spectroscopic measurements, calibrations and tests during off-line periods.

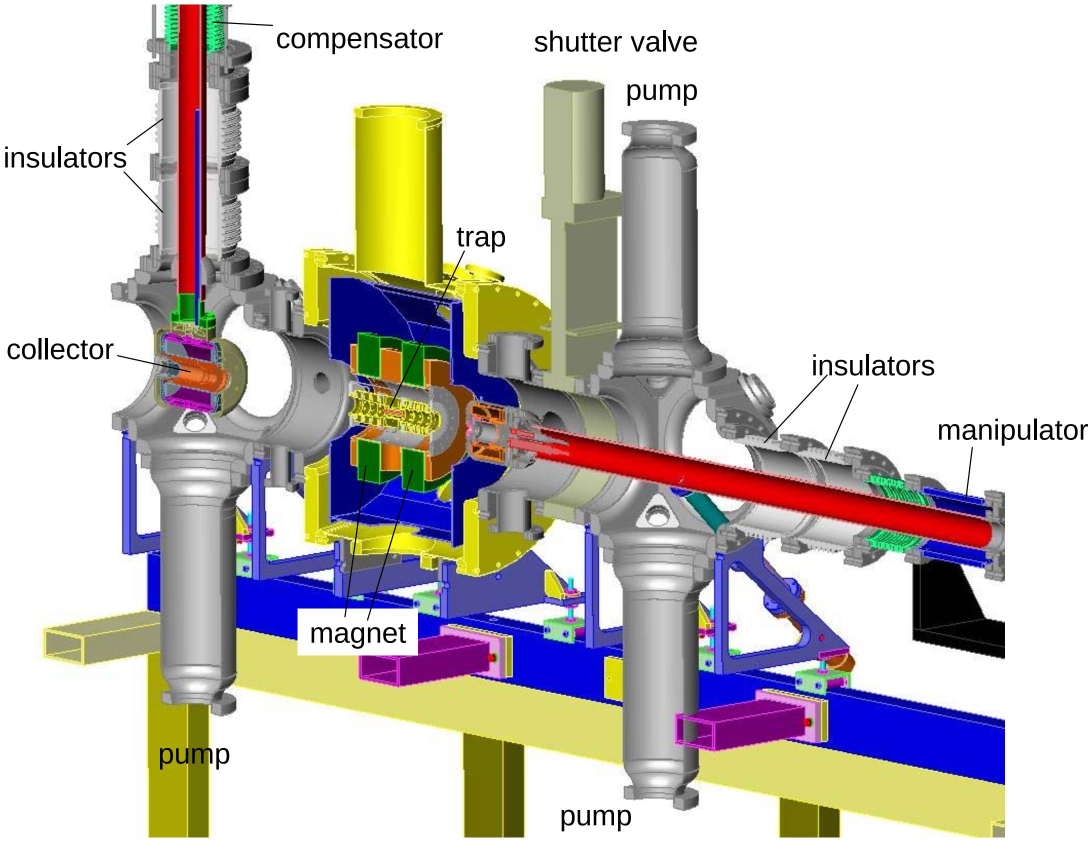

Figure 5: Scheme of the Heidelberg design on which the proposed charge breeding EBIT for MATS will be based.

1.8 Laser Housing

a. Simulations

i. Detectors

N/A

ii. Beam

N/A

b. Radiation Hardness

The laser housing must be well shielded against radiation from the experimental hall. It must be accessible at all times during experiments.

c. Design

In the laser hut a number of lasers will be operated. The following cw laser systems already exist at GSI:

Pump Lasers:
- 2 Argon-Ion Lasers, each of these includes a heat exchanger
- 1 Verdi 8 W (frequency-doubled Nd:YAG)

Tunable Lasers:
- 1 Titanium:sapphire (Ti:Sa) laser
- 1 Dye Laser
- 1 amplified diode laser system

With these lasers the whole visible spectrum + near IR can be covered (~400-1000 nm). The amplified diode laser system is restricted to wavelengths for which single-frequency diodes and broad-area diode lasers (BAL) are available. Currently we are acquiring another pump laser and a frequency doubler. These systems will then extend the range of available wavelengths into the uv region (~200-400 nm). Additionally, a frequency comb will provide frequency determination at a unprecedented level of accuracy.

Fiber transport of the laser beams from the laser housing to the beamline will be investigated. Photonic Crystal fibers offer the possibility to transport high powers with a good TEM_{00} mode quality over almost the whole visible spectrum.

Some R&D will be necessary for laser stabilization. Although many stabilization techniques are available, most are rather specialized or limited to a specific frequency region. Universal interferometric stabilization, such as fringe-offset-locking, do however exist and a similar method will be investigated and used in combination with a frequency comb.

Pulsed lasers for resonance ionization will also be operated inside the laser housing. Some pulsed lasers are already at GSI, others will be supplied by the University of Mainz during measurement campaigns. The latter have moderate requirements for cooling water and power supplies.

A floor space of 60 m^2 is required.

d. Construction

N/A

e. Acceptance Tests

N/A

f. Calibration

N/A

g. Requests for test beams

N/A

2 Trigger, DACQ, Controls, On-line/Off-line Computing

The main trigger used for these experiments is the release of the ion bunch out of the RFQ structure (if running in bunch mode). All other triggers, *e.g.*, readout start for photomultiplier or for firing of pulsed lasers will be based on this master trigger. But it might be necessary to have some slow-controls, *e.g.* of primary beam intensity, for signal normalization. Those should be preferably analog signals or count rates to be fed into the ADC's or scalers.

The DACQ and computing requirements of the ***LASPEC*** collaboration are self-contained and minimal. With respect to data acquisition they are restricted to DAC controlled voltages, scalers, ADC's, simple trigger schemes related to the master trigger (release of the ionic ensemble from the gas stopper) and GPIB communication. These can all be controlled from either the PCI slots of standard PC's or, alternatively, from a small CAMAC or similar control system. All laser controls are self-contained and are integral to the lasers within the laser housing. Ion optical control is restricted to electrostatic beam steerers and electrostatic quadrupole elements.

3 Beam/Target Requirements

3.1 Beam specifications

The ***LASPEC*** project intends to take a wide range of exotic species and will require a wide range of beam species and projectiles. The parameters of the beam received by the ***LASPEC*** stations will be determined by the gas stopper. Thus, there are no special requests for the primary beam except those set by the injection parameters of the gas stopper and the required beam intensity.

The ***LASPEC*** sub-project will receive separated and cooled ionic ensembles (either in a bunched or continuous mode) from the gas stopper. The ensembles are to be accelerated to energies of a few tens of keV, feasibly as high as 60 keV, and are assumed to possess,

- an energy spread of less than one electron volt,
- an emittance of $< 5\ \pi$ mm mrad,
- high isotopic purity.

3.2 Running Scenario including exemplary beam time planning in a year

The ***LASPEC*** collaboration would aim to secure 14 days of beam time per year.
Allocated beamtime would typically be divided into 5 day long continuous running periods. Within an individual period the collaboration would aim to study as large a number of isotopes and isomers as possible and would use “cocktail beams” in order to minimise the experimental time lost to beam changes. Each 5-day period would be dedicated to a particular form of spectroscopy. As the majority of the preparation, initial tests, commissioning and calibration can be performed with an off-line ion source (OLIS), beamtime allocations will be used almost exclusively for experimental measurements.

4 Physics Performance

In order to measure nuclear moments and changes in charge radii to an accuracy limited only by atomic calibration parameters, the spectroscopic frequency intervals, of typically GHz magnitude, must be measured to a precision of a few MHz. The experimental lineshapes in collinear spectroscopy typically exhibit a full-width half-maximum of less than 50 MHz. A beam energy drift and stability of better than 0.5 eV per hour must be maintained (and monitored to a precision of 0.1 eV). The LASPEC collaboration aims to achieve these levels of operational performance.

The desired performance of the collinear laser spectroscopy station has been defined for the case of the Zr isotopes. Such isotopes are not accessible at standard ISOL facilities, and first measurements on the system have only recently been achieved at the Jyväskylä gas-stopper-based IGISOL facility [25]. At FAIR, the Super-FRS's production yields will be expected to permit spectroscopy in the Zr chain from lighter than the N=Z=40 isotope ^{80}Zr to ^{106}Zr. At initial performance levels the following are expected to afford a publishable optical resonance:

Production yield Super-FRS ^{80}Zr ($t_{1/2}$ =4.1 s)	1.9×10^{5} ions/s
1% reaching the LASPEC experimental stations	1.9×10^{3} ions/s
Detection efficiency	1×10^{-3}
Measurement time	10 min

For the case of lead, the investigated isotope chain ($^{190\text{-}214}$Pb) could be extended into the neutron-rich region up to ^{220}Pb (production rates of ~1500/s, hence still 15 ions/sec at the LASPEC station at 1% efficiency of the catcher and cooler). Such yields will still be sufficient for resonance observation using laser-desorption-RIS:

Production yield Super-FRS ^{220}Pb ($t_{1/2}$ =2.7 s)	1.5×10^{3} ions/s
1% reaching the LASPEC experimental stations	15 ions/s
Detection efficiency	0.1 – 1 %
Measurement time	3 hours

In a 3 hour maximum measuring time it will be possible to extend measurements in the chains of Tl, Hg, Au, Pt and Ir typically 7 isotopes further from stability. In the case of gold the figure rises to 10 new isotopes.

C Implementation and Installation

1. Cave and Annex Facilities, Civil Engineering, Cranes, Elevators, Air Conditioning (Temperature and Humidity Stability requirements), Cooling, Gases

a. Access, floor plan, maxim. floor loading,, beam height, crane hook height, alignment fiducials

A floor plane is shown in Fig. 6. The whole set-up covers approximately 52 m^2 floor space. No extra-ordinary crane, beam height or floor loading issues. A crane, capable of carrying 1-2 tons of equipment, should be available.

The laser laboratory should be located close to the ***LASPEC*** and MATS experimental set-up in the Annex building. As mentioned under A 1.7, approximately 60 m^2 of floor space is needed. To improve laser stability this housing must be air conditioned and should have access limited to well trained people for safety reasons.

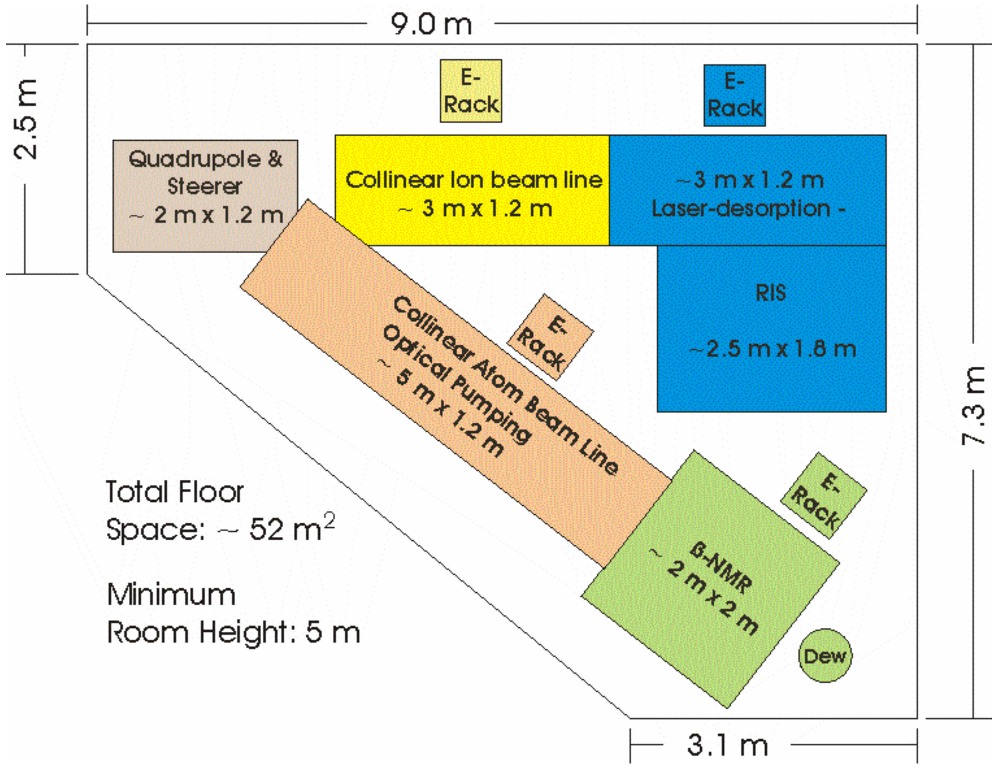

Figure 6: Floor plan for the *LaSpec* experimental set-up in the low-energy-beamline experimental hall.

b.

Electronic racks

Collinear Laser Spectroscopy

1 electronic rack capable of taking three standard crates.

Optical Pumping + β-NMR

2 electronic racks, one for the power supplies needed for the retardation plates in the optical pumping and spectroscopy section, and one for the β-NMR electronics.

RILIS

1 crate needed for electronics associated with temporal control of the pulsed lasers.

Laser-Desorption RIS

1 electronic rack capable of taking three standard crates.

Sum: 4 Electronic racks with approximately 12 crates
Total power consumption: 12 Crates × 0.8 kW ≈ 10 kW

c. Cooling of detectors (heat produced = heat removed!)

Collinear Laser Spectroscopy

no detector cooling is required outside of the laser housing.
cooling water for 5 turbomolecular pumps.

Optical Pumping + β-NMR

The β-detectors do not need cooling.

Cooling might be needed for the implantation crystal (to avoid relaxation effects). For this, the crystal will be mounted on the cold finger of a continuous flow cryostat, based on liquid He or liquid N_2 cooling. Thus, access for dewars as close as 1 m to the set-up is needed.

RILIS

No detector cooling is necessary.

Laser-Desorption RIS

No detector cooling is necessary.

Laser Housing

laser housing must be air-conditioned

2 water exchange coolers capable of sinking 30 kW each (this assumes two gas lasers operational inside the laser housing)

1 water exchange cooler capable of sinking at least 10 kW (based on the two pump lasers used for RILIS at the University of Jyväskylä , one gas and one Nd:YAG)

d. Electrical power supplies

RFQ

15 kW for high power supplies and pumps at the beamline, this may be joined with MATS collaboration (see 1.1).

Collinear Laser Spectroscopy

5 turbomolecular + 3 roughing pumps: 7 kW

Optical Pumping + β-NMR

high voltage power supplies (remote controlled) for retardation plates in the collinear beamline section (tune of beam velocity): 2 kW

power supply for the charge exchange cell: 2 kW

power supply for the magnet (delivered with the magnet system, remote controlled): 15 kW

RF Generators: 3 kW

RILIS

HV power supply necessary for temporal control electronics, 6kV 20mA sufficient. Electrical specifications for lasers included in laser housing (below).

Laser-Desorption RIS

Power supply MALDI-TOF system
2 HV power supplies for electrostatic kicker

Total LEB hall: ~ 50 kW (+ 10 kW for electronic racks, see b)

Laser Housing (Annex-Building)

Air-conditioning: 4 kW
3 three-phase electrical supplies, 70 A (2 gas lasers, 1 Nd:YAG)
variety of laser laboratory equipment (current supplies, RF supplies, stabilization systems, temperature regulations, temperature stabilized oven, heat exchanger)
Estimation: 5 × 16 A (18 kW)

Total laser lab (Annex building): ~ 22 kW, + 3 three-phase supplies (70 A/phase)

e. Gas systems

Special gas mixture needed if gas vapour pump laser used, but self-contained with laser. In general no gas system required apart from 1 bar compressed air delivery for valves and movement of Faraday cups.

f. Cryo systems

Collinear Laser Spectroscopy

No cryo systems required.

Optical Pumping + β-NMR

The use of a superconducting magnet is being considered (liquid He).
The use of a continuous flow cryostat using liquid He or N_2 for crystal cooling is also considered. If this is used, we will also need to build a cold trap (LN_2) system to avoid catching dirt on the cooled crystal surface.

RILIS

No cryo systems required.

Laser-desorption RIS

No cryo systems required.

2. Detector –Machine Interface

a. Vacuum

RFQ: The RFQ vacuum (without external gas load for buffer-gas cooling) should be at the level of 10^{-7} to 10^{-8} mbar. Typical vacuum in the laserspectroscopy beamlines will be on the order of 10^{-7}. Low conductance apertures are required at several places to maintain a good vacuum in the pipes in the close vicinity to buffer gases (RFQ) and alkali vapour (charge exchange cell).

b. Beam Pipe

The beamlines for laser spectroscopy will be constructed for direct connection to a switching station for the gas stopper delivery. A 100 mm diameter beam pipe is typically used for the beam transport system.

c. Target, in-beam monitors, in-beam detectors

Beam analysis elements (Faraday cups, channeltrons) will be included in the set-up.

d. Timing

The timing structure will be limited to bar synchronisation with ion bunch releases from the gas stopper or the RFQ.

e. Radiation environment

LASPEC will typically operate with very low yields of radioactive isotopes. The ion beam energy will be only a few 10 keV.

f. Radiation shielding

Radiation shielding is mainly required for the laser housing since this must be accessible at any time during a beamtime.

3. Assembly and installation

a. Size and weight of detector parts, space requirements

For the set-up a total space of ~ 52 m^2, as indicated in Fig. 6 is required. During the final installation, additional 10 m^2 of floor space will be required for storage and handling.

b. Services and their connections

For the valves a permanent pressurized air line is needed. Detector needs only simple feed-throughs to provide signal transfer, *etc*.

c. Installation procedure

Functional blocks like the RFQ or the optical detection region will be assembled and tested at the different institutes involved. The final installation in the cave will be done after all parts are tested and specified. The different beamlines and experiments will be built subsequently. After complete installation of the first experiment (collinear ion beam line), test experiments with the off-line ion source can be started. Soon after this, first test measurements with ions delivered by the gas catcher can be performed.

D Commissioning

a) Magnetic field measurements

No stray magnetic fields must be present in the vicinity of the laser line. Penning trap magnets from MATS have to be well shielded.

b) Alignment

The alignment of the laser line follows exactly that for any section of beam pipe. Standard optical geodesic instrumentation should be available.

c) Test runs

Test runs may be attempted as soon as beam is available from the gas stopper and these tests will be important in investigating the performance of the stopper. Native to ligand fraction, energy spreads, energy stability and bunching efficiencies will be readily determinable using the ***LASPEC*** apparatus.

E Operation

a) of each of the sub-projects

With respect to the Super-FRS, all ***LASPEC*** projects will operate at fixed conditions for periods of several days. Experimental concerns are limited to the manipulation of low energy ionic ensembles from the gas stopper and to the production, transport and detection of laser light. Both aspects are decoupled from the operation of the production facility and will be performed by members of the ***LASPEC*** collaboration.

b) auxiliaries

N/A – no auxillary dependencies.

c) power, gas, cryo, etc

As outlined in section C.

F Safety

a. General safety considerations

Specific to these experiments

- Of primary concern for both categories will be the operation and transport of class IV lasers and laser light. The laser beams will be transported within beam tubes inside the experimental hall. Inside the laser laboratory laser goggles will be required.
- The charge exchange cell will be operated with alkaline metals and proper safety requirements have to be fulfilled.
- High voltages are operated at several places

b. Radiation Environment

The ***LASPEC*** device is set-up within a radiation control area. But all experiments take rather small amounts of radioactive beam, no extraordinary safety requirements concerning radioactivity are required.

The laser housing must be accessible at all times during the run and must therefore be well enough shielded against radiation from other running experiments.

c. Safety systems

Interlock systems for the operation of the high power pump lasers must be installed. Doors with limited access (door codes *etc*.) are needed.

G Organisation and Responsibilities, Planning,

a. WBS- work package break down structure

RFQ

- Simulation studies and definition of the dimensions
- Design of the cryogenic RFQ ion beam cooler and buncher based on the system at LEBIT/MSU
- Ordering, machining, and assembling of the vacuum components and RFQ structure
- Commissioning tests of vacuum and voltage.
- Determination of the performance (cooling time, emittance, and efficiency) with stable ions from the off-line ion source
- Implementation into the MATS set-up and acceptance tests with ions from the low energy branch gas cell

Collinear Spectroscopy

- Design of the collinear spectroscopy beamline including the RFQ and switch-yard
- Construction of the movable light collector region and the particle detectors
- Purchasing and machining of beam pipe parts
- Detector Tests
- Installation at the LEB
- Commissioning with stable ions from an off-line ion source (OLIS)

Optical Pumping

- Design of the beamline, including charge exchange cell
- Construction of the Charge Exchange cell
- Purchasing and machining of beam pipe parts
- Installation at the LEB experimental hall
- Commissioning with OLIS

β-NMR

- Conceptual studies on magnet type and specification of magnet
- Design of vacuum chamber, cooling system, and β-telesope
- Purchasing of magnet, machining of vacuum chamber
- Installation at the LEB experimental hall
- Commissioning

RILIS

- Conceptual design studies for the Resonance Ionization at the catcher
- Laser ion source trap design, coupling to gas or liquid helium catcher
- Construction of the LIST
- Off-line tests and characterization at Jyväskylä university
- Transfer to and installation at LEB

Laser-Desorption RIS

- Design of the kicker system for beam implantation and beamline connection
- Off-line tests at Mainz university
- Installation at the collinear beamline
- Tests with OLIS

b. Structure of experiment management

The project is part of the NUSTAR collaboration at the FAIR facility. Thus, the NUSTAR management structures are available and used for information exchange between the projects and collaborations. LASPEC has representatives (partly joined with the MATS collaboration) in all working groups within NUSTAR that are relevant to the laser spectroscopy set-up:

LASPEC has a spokesperson (P. Campbell) and a deputy spokesperson (W. Nörtershäuser). W. Nörtershäuser is also GSI contact person. The responsibilities for the different subprojects of LASPEC are distributed in the following way (marked in bold is the main responsible or sub-project leader):

(1) RFQ (joined with MATS)
D. Lunney, A. Jokinen + MATS members

(2) Collinear Laser Spectroscopy:
P. Campbell, I. Moore

(3) Optical Pumping, and Fast Atomic Beam Laser Line
P. Campbell, G. Neyens, **W. Nörtershäuser**

(4) β-NMR:
G. Neyens, W. Nörtershäuser

(5) RILIS
J. Äystö, **I. Moore**, K. Wendt, Y. Kudryavtsev

(6) Laser-desorption RIS
G. Huber, F. Le Blanc, **M. Seliverstov**, K. Wendt

(7) Laser Housing
Th. Kühl, **W. Nörtershäuser**

c. Responsibilities and Obligations

- The **University of Leuven** is particularly interested in the optical pumping, the β-NMR set-up and the RILIS developments. 1 PostDoc and possibly one 1 PhD student could be supplied. Additionally it is intended to provide equipment for the β-NMR set-up as well expertise in resonant ionization in buffer gas cell systems.
- The **University of Jyväskylä** will contribute to the RILIS set-up. Furthermore, they provide expertise in the set-up of RFQ cooler and buncher (joined with MATS). They intend to apply for funding at an appropriate time: this could cover a PostDoc position, who would dedicate 40% of his/her time to the LASPEC set-up. JYFL is also strongly interested in pursuing developments related to RILIS within a cryogenic/superfluid helium ion catcher and will invest manpower, equipment and money at an appropriate stage.
- **IN2P3 at Orsay** intends to contribute to the beamlines and equipment with an amount that cannot be specified in the moment. They will as well contribute to the buncher system (joined with MATS). Workshop and design time is guaranteed.
- The **University of Mainz** is particularly interested in the possibilities of resonance ionization. They will provide the existing set-up for laser-desorption-RIS and – during measuring campaigns – high-repetition solid-state lasers. A contribution of 1.5 PostDoc man years and 1 PhD student is considered. At appropriate time funding will be requested for equipment and personnel. Additionally possibilities for laser spectroscopy in the MATS Penning traps will be investigated and collinear spectroscopy on atoms and ions pursued.
- Contribution of the **Max-Planck Institute for Nuclear Physics** is summarized in the MATS report. It considers mainly the set-up and operation of the EBIT.
- The **University of Tübingen** provides expertise in cw-laser construction and stabilization as well as high-resolution laser spectroscopy. We intend to apply for funding of a PostDoc position for a 3 year period.

Table 1: Money-Responsibility Matrix

	Institutes										
Contribution	UL	UJ	OR	GSI	UMz	MPIK	UT	UM	CERN	LLNL	PNL
RFQ[(1)]		X	X		X			X			
Collinear Spectroscopy		X						X	X		
Optical Pumping	X			X	X		X				
β-NMR	X			X			X				
RILIS		X			X			X	X		
Laser-desporption RIS			X		X						
Laser system					X		X				X
EBIT Spectroscopy [(1,2)]						X				X	
Investigator / year				0.1			0.3	0.3	0.15		0.1
PhD / year	1			1	1			1			
PostDoc / year	0.5	0.4		0.5	0.5		1	0.3			

Abbreviations:
UJ - University Jyväskylä; UL - University Leuven; OR –Orsay, CSN – CSNSM / IN2P3; GSI - GSI Darmstadt; UMz - University Mainz; MPIK - Max-Planck Institut for Nuclear Physics, Heidelberg; UM - University Manchester; CERN – CERN, Geneva; LLNL -Lawrence Livermore National Laboratory, Livermore; PNL - Pacific Northwest National Lab

(1) joined with MATS; (2) optional.

- Andreas Dax at **CERN** is willing to contribute with approximately 15% of his time to the project. He is generally interested in laser spectroscopy with pulsed and cw lasers.
- The **University of Manchester** is particularly interested in the collinear ion spectroscopy. 30% of a PostDoc position will be covered over three years, 1 PhD position will also be supplied. We also intend to contribute with equipment/money to the set-up of the collinear ion beam line.
- Bruce Bushaw at the **Pacific Northwest National Laboratory** offers help in frequency-doubler design and laser stabilization issues.
- **GSI Darmstadt** will contribute with 1 PostDoc and 1 PhD position. A frequency-doubler and a frequency comb will be purchased for ongoing projects. Also the maintenance and upgrade costs for the existing laser systems will be covered during this time.

d. Cost and Manpower Estimates

see Appendix.

e. Schedule with Milestones

The schedule is summarized in Table 2.

f. Organisation

see organization of NUSTAR and section G.b of this technical report

Table 2: Schedule for Design, Construction, Installation and Commissioning of the *LaSpec* set-up.

	Year	1				2				3			
	Quarter	1	2	3	4	1	2	3	4	1	2	3	4
Project	Milestone												
RFQ	Construction	🟧	🟧	🟧									
	Tests				🟪								
Resp.:	Installation					🟥	🟥						
JYFL	Tests with OLIS							🟦	🟦				
IN2P3	On-Line Experiments								▨	▨	🟩	🟩	🟩
CIB	Design	🟧	🟧										
	Optical Detect. Region				🟧	🟧							
Resp.:	Particle Detector			🟧									
UM	Installation						🟥	🟥					
	Tests with OLIS							🟦	🟦				
	On-Line Experiments								▨	▨	🟩	🟩	🟩
LDRIS	Design	🟧											
	Construction		🟧	🟧									
Resp.:	Tests				🟪								
UMz	Installation								🟥				
IN2P3	Tests with OLIS									🟦			
	On-Line Experiments										▨	🟩	🟩
Optic.	Design	🟧	🟧	🟧									
Pump.	Charge Exchange Cell				🟧								
	Optical Detect. Region			🟧									
Resp.:	Beampipe					🟧	🟧						
UL	Beamline Installation								🟥	🟥	🟥		
GSI	Tests with OLIS										🟦	🟦	
	On-Line Experiments											▨	🟩
b-NMR	Design	🟧	🟧										
	Magnet Purchase			🟧									
Resp.:	Cooling-System				🟧								
UL	Vacuum Chamber					🟧	🟧						
GSI	Installation									🟥	🟥		
	On-Line Experiments											▨	🟩
RILIS	Design	🟧	🟧										
	Construction			🟧	🟧								
	Tests at Jyväskylä					🟪	🟪						
Resp.:	Installation									🟥	🟥	🟥	
JYFL	Commissioning												▨
UMz	On-Line Experiments												🟩
LASER	R & D	🟧	🟧	🟧	🟧								
	Installation					🟥	🟥	🟥	🟥	🟥	🟥		
	operation						🟩	🟩	🟩	🟩	🟩	🟩	🟩

Legend:				
	Design & Construction	🟧	Tests, off-site	🟪
	Installation	🟥	Commissioning (OLIS)	🟦
	Commiss. (radioactive beam)	▨	Operation	🟩

H Relation to other Projects

LASPEC belongs to the LEB sub-collaboration of NUSTAR. With respect to desired beam parameters (particularly the need for cooled and bunched beam) the project has very similar requirements to those of the MATS project. These projects have common members and will cooperate as has been indicated, *e.g.*, in the case of the RFQ. Combining the techniques employed by these communities might mutually open up new possibilities, *e.g.*, preparation of isotopic or isomeric pure beams for laser spectroscopy in Penning traps or – in the other direction – delivery of isomeric pure states via resonance ionization as it has been demonstrated recently at ISOLDE [26]. The RILIS sub-project of **LASPEC** is closely related to the beam distribution working group of the LEB.

I Other issues

J References and Acknowledgements

1. Kluge, H.-J. and W. Nörtershäuser, Spectrochimica Acta B, **58** (2003) 1031-1045.
2. Otten, E.W., *Nuclear radii and moments of unstable isotopes*, in *Treatise on heavy-ion science*, D.A. Bromley, Editor. 1989. p. 517-638.
3. Campbell, P., H.L. Thayer, J. Billowes, P. Dendooven, K.T. Flanagan, D.H. Forest, J.A.R. Griffith, J. Huikari, A. Jokinen, R. Moore, A. Nieminen, G. Tungate, S. Zemlyanoi, and J. Äystö, Physical Review Letters, **89** (2002) 082501.
4. Sebastian, V., Dissertation, Johannes Gutenberg - Universität: Mainz (1999).
5. Neugart, R., Hyperfine Interactions, **127** (2000) 101-110.
6. Borremans, D., Dissertation, Katholieke Universiteit Leuven (2004).
7. Payne, M.G., L. Deng, and N. Thonnard, Review of Scientific Instruments, **65** (1994) 2433-2459.
8. Köster, U., V.N. Fedoseyev, and V.I. Mishin, Spectrochimica Acta B, **58** (2003) 1047-1068.
9. Blaum, K., C. Geppert, H.-J. Kluge, M. Mukherjee, S. Schwarz, and K. Wendt, Nuclear Instruments and Methods in Physics Research B, **204** (2003) 331-335.
10. Weissman, L., U. Köster, R. Catherall, S. Franchoo, U. Georg, O. Jonsson, V.N. Fedoseyev, V.I. Mishin, M.D. Seliverstov, J.V. Roosbroeck, S. Gheysen, M. Huyse, K. Kruglov, G. Neyens, and P.V. Duppen, Physical Review C, **65** (2002) 024315.
11. Lu, Z.-T. and K. Wendt, Review of Scientific Instruments, **74** (2003) 1169-1179.
12. Fedoseyev, V.N., G. Huber, U. Köster, J. Lettry, V.I. Mishin, H. Ravn, and V. Sebastian, Hyperfine Interactions, **127** (2000) 409-416.
13. Huang, W.X., P. Dendooven, K. Gloos, N. Takahashi, J.P. Pekola, and J. Äystö, Europhysics Letters, **63** (2003) 687-693.
14. Sauvage, J., N. Boos, L. Cabaret, J.E. Crawford, H.T. Duong, J. Genevey, M. Girod, G. Huber, F. Ibrahim, M. Krieg, F.L. Blanc, J.K.P. Lee, J. Libert, D. Lunney, J. Obert, J. Oms, S. Péru, J. Pinard, J.C. Putaux, B. Roussière, V. Sebastian, D. Verney, S. Zemlyanoi, J. Arianer, N. Barré, M. Ducourtieux, D. Forkel-Wirth, G.L. Scornet, J. Lettry, C. Richard-Serre, and C. Véron, Hyperfine Interactions, **129** (2000) 303-317.
15. Maul, J., T. Berg, K. Ebrhardt, I.Hoog, G. Huber, S. Karpuk, G.Passler, I. Stachnov, N. Trautmann, and K. Wendt, Nuclear Instruments and Methods in Physics Research B, **226** (2004) 644-650.
16. Le Blanc, F., J. Obert, J. Oms, J.C. Putaux, B. Roussière, J. Sauvage, J. Pinard, L. Cabaret, H.T. Duong, G. Huber, M. Krieg, V. Sebastian, J. Crawford, J.K.P. Lee, J. Genevey, and F. Ibrahim, Physical Review Letters, **79** (1997) 2213–2216.
17. Le Blanc, F., D. Lunney, J. Obert, J. Oms, J.C. Putaux, B. Roussière, J. Sauvage, S. Zemlyanoi, J. Pinard, L. Cabaret, H.T. Duong, G. Huber, M. Krieg, V. Sebastian, J.E. Crawford, J.K.P. Lee, M. Girod, S. Péru, J. Genevey, J. Lettry, and I. Collaboration, Physical Review C, **60** (1999) 054310.
18. Fedosseev, V.N., D.V. Fedorov, R. Horn, G. Huber, U. Koster, J. Lassen, V.I. Mishin, M.D. Seliverstov, L. Weissman, and K. Wendt, Nuclear Instruments and Methods in Physics Research Section B, **204** (2003) 353-358.
19. Andreyev, A.N., K.V.d. Vel, A. Barzakh, A.D. Smet, H.D. Witte, D.V. Fedorov, V.N. Fedoseyev, S. Franchoo, M. Górska, M. Huyse, Z. Janas, U. Köster, W. Kurcewicz, J. Kurpeta, V.I. Mishin, K. Partes, A. Plochocki, P.V. Duppen, and L. Weissman:, European Physical Journal A, **14** (2002) 63-75.
20. De Witte, H., A.N. Andreyev, I.N. Borzov, E. Caurier, J. Cederkall, A. De Smet, S. Eeckhaudt, D.V. Fedorov, V.N. Fedosseev, S. Franchoo, M. Gorska, H. Grawe, G. Huber, M. Huyse, Z. Janas, U. Koster, W. Kurcewicz, J. Kurpeta, A. Plochocki, K. Van de Vel, P. Van Duppen, and L. Weissman, Physical Review C, **69** (2004) 044305-6.

21. Herfurth, F., J. Dilling, A. Kellerbauer, G. Bollen, S. Henry, H.-J. Kluge, E. Lamour, D. Lunney, R.B. Moore, C. Scheidenberger, S. Schwarz, G. Sikler, and J. Szerypo, Nuclear Instruments and Methods in Physics Research A, **469** (2001) 254-275.
22. Nieminen, A., J. Huikari, A. Jokinen, J. Äystö, P. Campbell, E.C.A. Cochrane, and E. collaboration, Nuclear Instruments and Methods in Physics Research A, **469** (2001) 244-253.
23. Schwarz, S., G. Bollen, D. Lawton, P. Lofy, D.J. Morrissey, J. Ottarson, R. Ringle, P. Schury, T. Sun, V. Varentsov, and L. Weissman, Nuclear Instruments and Methods in Physics Research B, **204** (2003) 507-511.
24. Levy, C.D.P., R. Baartman, K. Jayamanna, R. Kiefl, T. Kuo, M. Olivo, G.W. Wight, D. Yuan, and A.N. Zelenski, Nuclear Physics A, **701** (2002) 253-258.
25. Campbell, P., A. Nieminen, J. Billowes, P. Dendooven, K.T. Flanagan, D.H. Forest, Y.P. Gangrsky, J.A.R. Griffith, J. Huikari, A. Jokinen, I.D. Moore, R. Moore, H.L. Thayer, G. Tungate, S.G. Zemlyanoi, and J. Äystö, European Physical Journal A, **15** (2002) 45-48.
26. Van Roosbroeck, J., C. Guenaut, G. Audi, D. Beck, K. Blaum, G. Bollen, J. Cederkall, P. Delahaye, A. De Maesschalck, H. De Witte, D. Fedorov, V.N. Fedoseyev, S. Franchoo, H.O.U. Fynbo, M. Gorska, F. Herfurth, K. Heyde, M. Huyse, A. Kellerbauer, H.-J. Kluge, U. Koster, K. Kruglov, D. Lunney, V.I. Mishin, W.F. Mueller, S. Nagy, S. Schwarz, L. Schweikhard, N.A. Smirnova, K. Van de Vel, P. Van Duppen, A. Van Dyck, W.B. Walters, L. Weissman, and C. Yazidjian, Physical Review Letters, **92** (2004) 112501-4.