Case Study

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1 Introduction

This case study will cover different aspects which are important to select, design, develop, or to operate an ion source. The different scenarios indicate the large variety of existing ion sources, which are also the result of very different applications: cancer therapy, material modification, space thrusters for rockets are only a few of these applications. Some general aspects of different ion sources and some basic aspects are given in [1], [2], some important material properties and techniques are summarized in [3].

The most important fact in this contribution is, that its content is to be developed by the audience instead by the lecturer. Our time table does not allow to cover all issues which should be addressed in detail, but at least all critical points should be mentioned, respectively developed in a table of content. This table of content is given below, but it should be checked for completeness. Select issues you would like to investigate in more detail by yourself. A main issue of this case study should be to have a lively work, giving enough pleasure for the participants to motivate them for a long period to work on ion sources.

After this introduction of one hour, we do have five hours available to work on the individual project, three hours are available to present the results for all groups. If I do assume nine projects, twenty minutes are foreseen for each group. There will be another hour for the conclusion based on these presentations.

The first problem is to separate all of you into groups. In your papers you will find the information to which group you have been assigned to.

The second problem is already the task for each group, namely to decide how to organize. The list of topics will be presented below. Each group should work on their task, covering all aspects of importance.

I would like to mention, that there are a few specialist around, which might be very helpful in solving the task. The problem could be to involve these specialists for your work. They are not informed to be helpful to you. Try to attract them by offering a beer, as in regular life. Any other help is accepted. Google©, Wikipedia©, YouTube© or any other tool provided by the internet is ok.

One person for the protocol should be elected, responsible for the documentation.

It would be nice to have a CD or a DVD, attached later to the proceedings to summarize the results. The participants of each group will be anonymous for that compilation.

Different projects are going to be investigated:

1. Ion source for hadron therapy. 100 particle-μA of p, He, C. Ion source, low energy beam line, linac, synchrotron. Pulsed operation, 1 Hz 1 ms. HIT[4], NRoCK[1] in Germany, CNAO in Italy, HIMAC and HIBMC in Japan[5] are possible keywords for that.

2. Ion source for atom/nuclear physic experiments with low cross section, velocity in the range of 1-10MeV/u, required elements ^{50}Ti, ^{48}Ca. High duty cycle linac. SHE, GSI, Riken, Dubna, MSU are possible keywords for that. See also [6],[7] (in German).

3. Ion source for material science, required elements U, Pb, Au, optional N, Ar. High duty cycle linac. See for example [8],[9].

4. Ion source for antiproton production, p, 100mA, 100MeV. Low duty cycle 1 Hz, 1 ms pulse length. The AA (Antiproton Accumulator) at Cern[10], Fair[11], might be possible keywords.

5. Ion source for heavy ion acceleration within LHC. Required elements Xe, Au, Pb, U for a linac with maximum $m/q < 8.5$. Low duty cycle 1 Hz, 1 ms pulse length. See also [12], [13].

6. Ion source for negative ion acceleration[14], [15]. Low duty cycle 1 Hz, 1 ms pulse length. See also [16].

7. Ion source for heavy ion acceleration. 100% duty cycle. Required elements Xe, Au, Pb, U for an existing cyclotron. See for example [17].

8. Laser ion source INSTEAD OF a linac (LIS and synchrotron). Pulsed operation 1 Hz, 1 ms. ICIS brightness award of 2011, Phelix are possible keywords. See also [18], [19], [20], and [21].

9. Ion source for radioactive ion beams. SPIRAL2 is a possible keyword. See also [22], [23], [24].

Assume that you are responsible solving the task of setting up the ion source, beam line, and whatever might be necessary to generate enough ions for the specific application. This includes planning, construction, building, commissioning, operating.

The following aspects are to be considered (add missing tasks!):

- Physical design
- Simulation
- Costs for investment, personal, operation.
- Parts commercial available or own design?
- Space requirements?
- Safety issues (electrical, chemical, radiation, ...)
- Diagnostic (requirements?)
- Control system (requirements?)
- Operator training
- Operation (assume operating times of 24 h per day, 7 d per week).
- Documentation (artificial intelligence (AI) project?)
- Service (spare parts?)
- Further development (test bench required?)

[1] Remarkable: The 'Nordeuropäisches Radioonkologisches Centrum Kiel' has been canceled due to financial reasons.

The first thing you should start with is to create a project time schedule, including resource planning and cost estimate. At that point it is clear that there is no reliable information available about anything. Not more than 20 minutes should be paid for that. We will probably get an uncomplete list. Please keep these estimates unchanged in your documentation. Because of the restricted time it will not be possible to develop detailed plans. It would be fine, if at least the list of topics would be complete.

Select any item of this list to go into more detail, which will depend on the personal flavor.

When all participants have gained in experience after the course, a second project planning should be made, again including resource planning and cost estimates. It might be useful to all participants for their further work to compare the initial version with the version after this course.

Of course you could copy the first version of your overall plan, but this would make the work dispensable...

2 Example

Figure 1: Ion source, beam line with mass separation, and entrance into a linear accelerator.

An ECRIS (Electron Cyclotron Resonance Ion Source) should be taken as an example. This source and its specific properties are well described in [25].

This type of ion source has a magnetically confinement of the plasma, where the plasma electrons are heated by rf in the GHz range. The magnetic field for the source is provided by two coils, operated in mirror mode. To increase the radial confinement, a hexapole made by permanent magnets is added. Typical coil currents are in the 1000 A range which is a necessary electrical power in the 20 to 50 kW for each coil (depending on the number of turns). Each coil produces heat which has to be cooled off the device. Figure 1 shows the setup of the ion source and ion beam spectrometer behind a fence, due to security reason. Several power supplies are located in the basement.

The plasma is ignited by providing the correct gas pressure. A typical value for the pressure might be 10^{-6}mbar, measured however outside the source. To provide higher charge states with substantial density the plasma is heated by rf, generated by a 14.5 GHz klystron with a maximum power of 10 kW. Because the losses from the plasma are in the plasma loss lines only, the power density might be such as high, that cooling is not only absolutely necessary, but also a critical issue. The location, where the plasma can touch the plasma chamber it will be lost, as shown in Figure 2 and 3 for two different operating modes: for gaseous ions like Neon, and metal ion generation like Nickel.

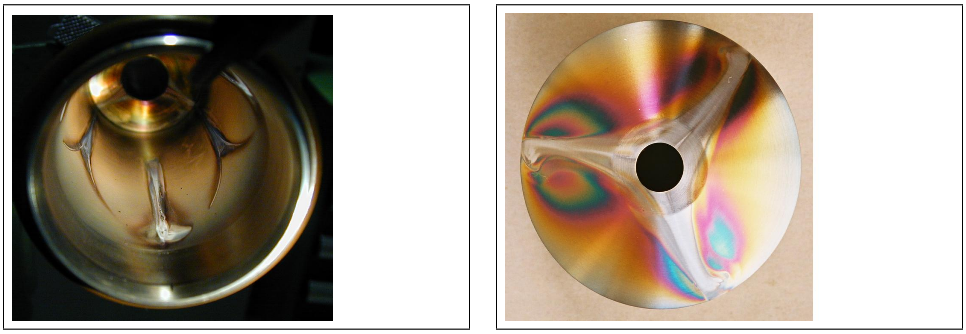

Figure 2: Plasma loss within the plasma chamber and at the extraction electrode for Neon operation[26].

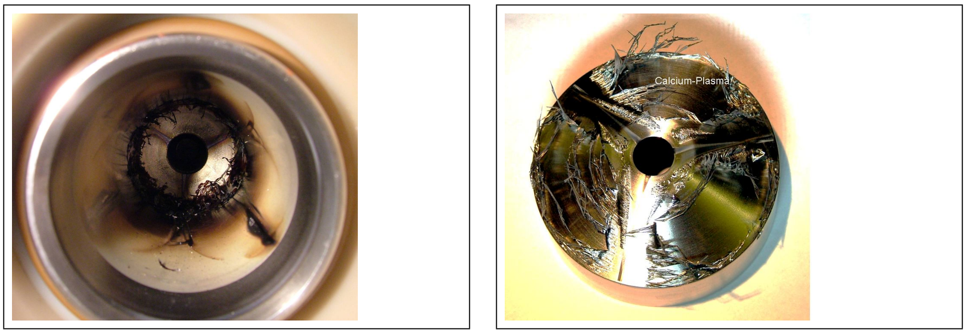

Figure 3: The same as in Figure 2, but for metal operation, here Ni[26].

The source is operated either in dc mode, or in a pulsed mode, the so-called afterglow mode[27],[28]. The ion beam is extracted by biasing the ion source to a positive voltage. Because the correct ion beam velocity is defined by the geometry of the first rf-accelerator with 2.5 keV/u, the maximum required extraction voltage (for the design ion $^{238}U^{28+}$) is 21.25 kV. The total extracted beam will be in the range of a few mA. A power supply with a maximum voltage of 25-30 kV and a maximum current of 20-30 mA seems to be a good choice. The extraction voltage should be stabilized up to 10^{-4} to 10^{-5} not to increase the horizontal emittance within the magnetic spectrograph for mass-to-charge selection. For higher intensities an accel-decel extraction system should be used not to destroy the space charge compensation and to minimize the load of the extraction power supply.

Typical questions could be:

⋆ The gas pressure, respectively the gas flow should be regulated to stay constant over a long time. Which kind of regulation system should be used?

⋆ The rf-power (forward power as well as the reflected power) should be controlled for best possible matching condition.

⋆ The extraction voltage and the extraction current is to be monitored.

⋆ Voltage and current of the mirror coils are also subject to be monitored.

⋆ For all regulation circuits, the regulation process should be done inside each power supply, not using the control system.

⋆ How to analyze the extracted ion beam? By an electric or magnetic spectrometer, by a Wien filter?

2.1 Physical Design

Describe the general layout how to operate an ion source. How does the ion source work? Which hardware is required (power supplies, ...)? Vacuum requirements? What is the required infrastructure?

2.1.1 Power Supplies

Which power supplies are required? Interlock system?

2.1.2 Vacuum System

What is the best suited vacuum system? Rotary pumps, cryogenic pumps, diffusion pumps, getter pumps?

2.1.3 Infrastructure

Estimate necessary electrical power, cooling media, pressed air. ..

2.2 Operating of the Ion Source

What is the concept to operate the ion source? How many people with which qualification are necessary? Assume a maximum working time of 8 hours a day. Assume furthermore, that everybody will have holiday and there might be a slight chance of illness. It will depend on the specific condition of the operating. Assume that an accelerator might be such as expensive, that it has to be operated round the clock, seven days a week.

2.3 Safety Issues

The apparatus has to operate reliable. The components should be save against possible malfunction. A spark, possibly triggered in the extraction system should not destroy any other component. Examples of what can happen:

- A liquid helium detector had a malfunction in a super conducting ECRIS. A too low level of the cooling medium in this super conducting device was not detected, and the current leads burned immediately without the necessary cooling to keep the superconductivity. A total dismounting of the source was necessary to repair the incident, which took the source out of operation for one year.

- A high voltage spark destroyed the sensor for the injected rf power, which caused the rf generator to increase the rf power to maximum value, which destroyed the plasma chamber. At least six month no operation, if there would be no spare part available.

- The weight of an ion source or any other beam line component can be enormous, which has to be fixed securely, especially in regions with a high risk of earth quakes (LBNL Berkeley, RIKEN Tokyo, ...).

But, more important is the fact that nobody will suffer in an accident with the device:

2.3.1 Mechanical Safety

In regions with a risk of earthquake the mechanical installation might become very important. If a heavy load part of an ion source would fall down, it not only will destroy itself...

2.3.2 Electrical Safety

Especially high voltage power supplies can act like an electric chair, if safety issues are not taken serious. Also rf generators, especially leaking rf transmission lines, can cause serious hazards.

2.3.3 Chemical Safety

Chemical danger might occur during operation, especially if hazardous materials have to be used. It could become necessary to prevent gases or liquid materials from leaking the ion source or a safety surrounding.

2.3.4 Radiation Safety

Radiation can be caused by the material to be ionized. But there might be other sources of radiation. Within an ECR source electrons are accelerated to high energies. When these electrons are going lost for some reason, they are stopped in the plasma chamber wall, causing X-rays. The energy as well as the intensity of these X-rays depends on the specific operation mode, and may be subject of sudden change during operation, therefore.

2.4 Control System

A control system is required to run the ion source. Which information is necessary to have a reliable picture of the actual status of the ion source? All parameters need to be controlled and have to be modified at any time.

2.5 Operating Program

The operating program should show all important information and should give the possibility to modify the actual state.

2.6 Data Acquisition

It is useful to store all data for documentation. The following example is not from the ECRIS as above, but from the other terminals at GSI, one equipped with a PIG ion source, the other with a high current source.

Figure 4: Ion beam current protocol for 24 hours. The beam intensity is measured non destructive by an ac beam transformer [30]. The histogram at the bottom indicate the number of operator interactions. The top line informs about the individual device which has been interacted with, see a magnified view in Fig. 5.

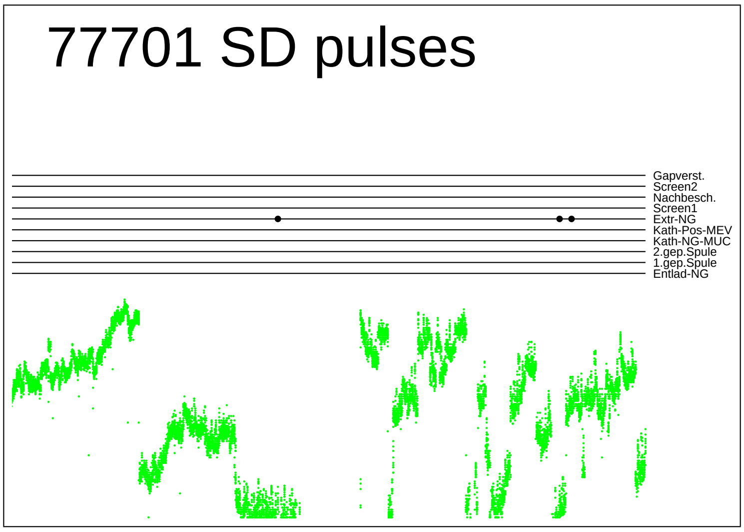

Figure 5: Magnified section of Fig. 4 with all operator interactions.

At GSI as many data as possible are stored automatically and can be displayed by an ISOC-program (Ion Source Operating Control program), see Fig. 4.

2.7 Diagnostic

Which kind of beam diagnostic is necessary to operate and to optimize the ion source?

Is it necessary to create a charge state spectrum? Is it necessary to measure the beam energy? Is it necessary to measure beam intensity or beam emittance?

To measure the beam intensity a Faraday cup is typically used. Such a Faraday cup should be designed such, that secondary particles do not influence the measurement. Electrostatic and magnetic screened Faraday cups are available. Instead of measuring the charge, the magnetic field of the ion beam can be measured. Both, dc and ac beam transformers are available commercially [30]. Figure 6 shows the mass spectrometer and the beam line schematically. Another example of an injection beam line is shown in Figure 7, where two ion sources are feeding the rf-accelerator sequentially. The left beam line is shown magnified on the right side of the figure.

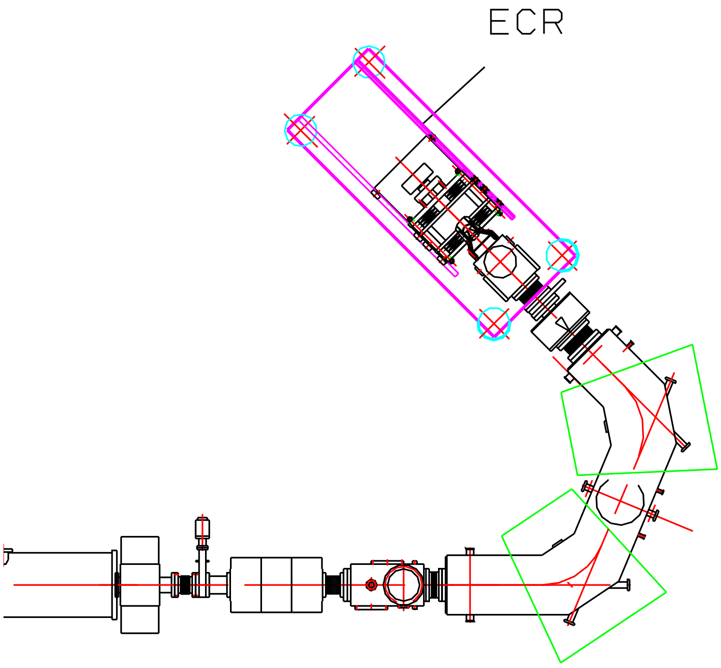

Figure 6: Ion source, beam line with mass separation, and entrance into a linear accelerator.

For trouble shooting an expert system could be of great value, especially if the ion source should be operated for years, and the specialists will leave the project crew for other applications after commissioning. Programs for artificial intelligence was a highlight when PROLOG (PROgramming in LOGic) was invented. Up to now no serious application for ion source applications have been developed for my knowledge beside service instructions for single components.

2.7.1 Real Time Data

Beam transformers have the advantage that they are measuring the beam current non destructive and simultaneously. Therefore they are perfectly qualified to measure the transmission,, see Figure 8.

If there are noise signals on the beam, the flight time can be extracted from such a measurement, see Figure 9.

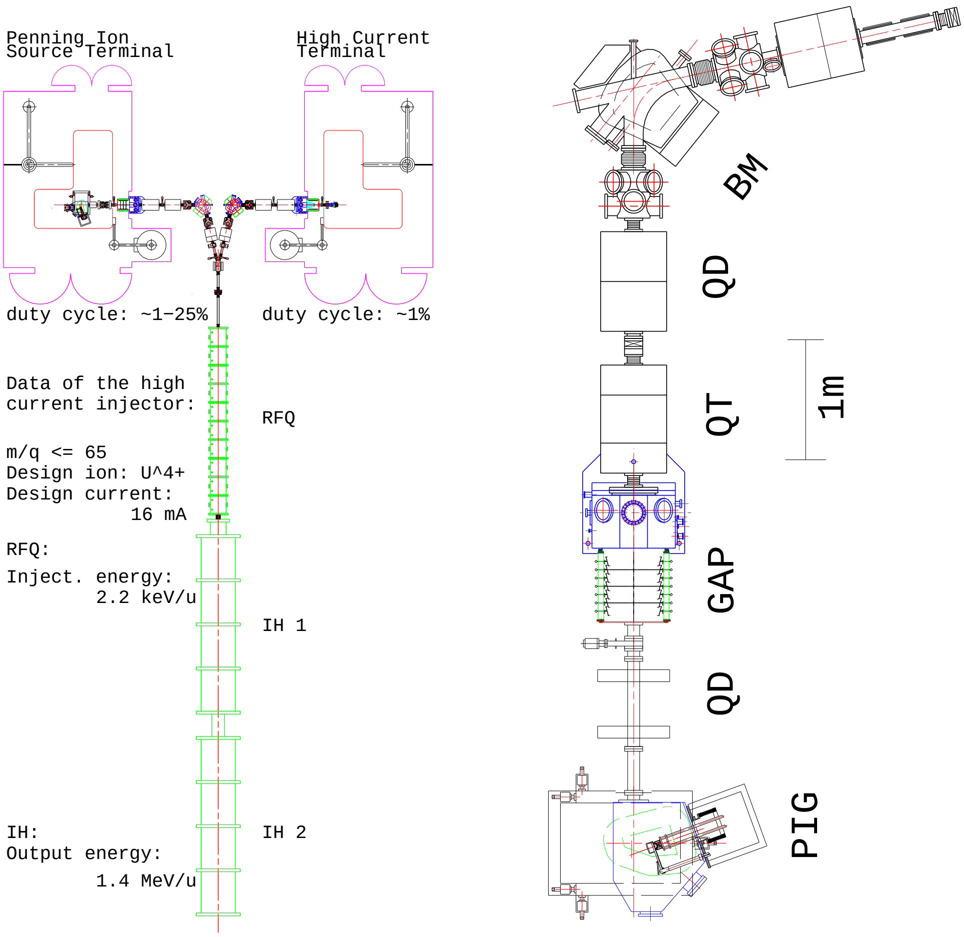

Figure 7: Ion source terminals at GSI, together with beam line, mass-to-charge separation, and injection into the first rf-accelerator [31],[32].

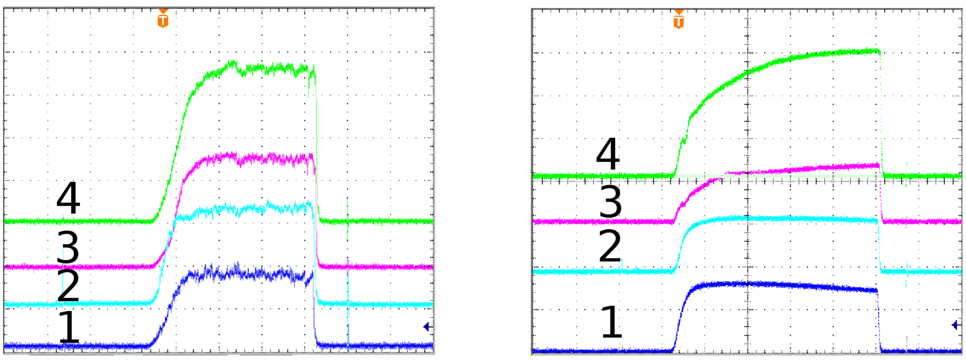

Figure 8: Comparison of beam pulses (200μs/div) along the LEBT (Low Energy Beam Transport) for a multi cusp source (right, N_2^+) and for a vacuum arc ion source (left, Ni^{2+}). CH 1: full beam current behind dc post acceleration (left:10 mA/div, right 20 mA/div), CH 2: full beam current in front of bending magnet (left:5 mA/div, right 20 mA/div), CH 3: separated beam behind bending magnet (left:2 mA/div, right 5 mA/div), CH 4: beam current in front of RFQ (left:1 mA/div, right 2 mA/div)[33].

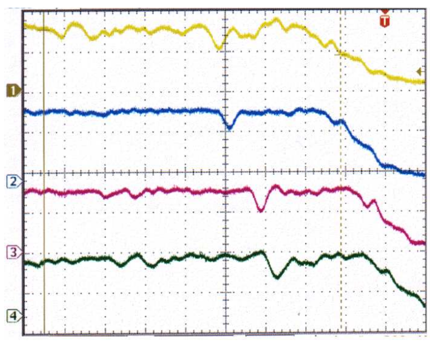

Figure 9: Enlarged time scale (10μs/div) CH 1: full beam current behind dc post acceleration (^{58,62}Ni$^{+,2+,3+,\cdots}$, CH 2: second beam transformer before m/q-separation, CH 3: separated beam after m/q-separation, CH 4: beam current in front of RFQ.

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