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List of acronyms and abbreviations

AECR	Advanced Electron Cyclotron Resonance Ion Source
ATOMKI	Magyar Tudományos Akadémia Atommagkutató Intézet
CAPRICE	Compacte A Plusieurs Résonances Ionisantes Cyclotron Electroniques
CB	Charge Breeder
CCD	Charge Coupled Device
CSD	Charge State Distribution
ECR	Electron Cyclotron Resonance
ECRIS	Electron Cyclotron Resonance Ion Source
EEDF	Electron-Energy Distribution Function
GANIL	Grand Accélérateur National d'Ions Lourds
GSI	Gesellschaft für SchwerIonenforschung
HIISI	Heavy-Ion Ion Source Injector
HLI	Hoch-Ladungs Injektor (High Charge State Injector)
HTO	High Temperature Oven
IEDF	Ion Energy Distribution Function
ISOL	Isotope Separation On-Line
JYFL	Jyväskylän Yliopiston Fysiikan Laitos
KVI-CART	Kernfysisch Versneller Instituut-Centre for Advanced Radiation Technology
LCO HT	Large Capacity Oven High Temperature
LEBT	Low Energy Beam Transport
LPSC	Laboratoire de Physique Subatomique et de Cosmologie
MCP	Multi-Channel Plate
MIVOC	Metal Ions from Volatile Organic Compounds
SPIRAL2	Système de Production d'Ions RAdioactifs en Ligne de 2^{e} génération
STO	Standard Temperature Oven
TPG	Table Plasma Generator
UCLM	Universidad de Castilla-La Mancha

EXECUTIVE SUMMARY

This deliverable report describes the status and outcome of the hands-on trainings. According to the planning 93% of all scheduled trainings have been successfully accomplished. 59 persons were instructed.

INTRODUCTION

The objective of the hands-on training is to promote the transfer of the optimised and the most useful methods between the participating institutes. This improves not only the expertise of the staff but day-to-day operation of facilities as well. New practices and information will optimise the use of facilities and gives an opportunity to ECRIS community to progress toward the use of best practices. The most important hands-on-training subjects were defined among the partners and further extended. The trainings and the organising institutes are listed in the following:

- Low-temperature plasma diagnostics (UCLM)
- ECR charge-breeder techniques (LPSC)
- Low-energy beam-transport design and emittance measurements (KVI-CART)
- MIVOC method and/or Highly charged plasma diagnostics (JYFL, two separate but simultaneous trainings)
- Microwave-based techniques to improve the performances of the ECRISs (GSI)
- Iron-beam production with ECR4 ion source using oven technique (GANIL)
- Measurements of ECR plasma parameters by Langmuir-probe (ATOMKI)
- Nickel-beam production with the CAPRICE ECRIS using the GSI standard oven (GSI)

Detailed information on the training programmes and schedules can be found on the MIDAS-website: https://wiki.jyu.fi/display/ensar2/Hands-on-training

The overall schedule of the trainings is shown in the following table:

Title of hands-on-training	Course #	Host lab	Start date	Duration	Participants	Status	Report
Metal-beam production with Phoenix V2 ion source	1	GANIL	15 Nov 2016	3 days	5 (+1)	accomplished	available
MIVOC Method	1	JYFL	5 Dec 2016	2.5 days	3	accomplished	available
Highly Charged Plasma Diagnostics	1	JYFL	5 Dec 2016	2.5 days	5	accomplished	available
MIVOC Method	2	JYFL	7 Dec 2016	2.5 days	4	accomplished	available
Highly Charged Plasma Diagnostics	2	JYFL	7 Dec 2016	2.5 days	3	accomplished	available
Measurements of ECR plasma parameters by Langmuir-probe	1	ATOMKI	10 May 2017	2 days	4	accomplished	available
Microwave-based techniques to improve the performances of the ECRISs	1	GSI	12 Dec 2017	3 days	4	accomplished	available
ECR Charge breeder techniques and low temperature oven	1	LPSC	23 Jan 2018	3 days	4	accomplished	in progress
Microwave-based techniques to improve the performances of the ECRISs	2	GSI	27 Feb 2018	3 days	4	accomplished	available
Nickel-beam production using the oven technique with CAPRICE ECRIS	1	GSI	13 Mar 2018	3 days	5	accomplished	in progress
Measurements of ECR plasma parameters by Langmuir-probe	2	ATOMKI	20 Jun 2018	2 days	4	accomplished	available

Low-temperature plasma diagnostics	1	UCLM	25 Sep 2018	3 days	5	accomplished	available
Low-energy beam-transport design and emittance measurements	1	KVI-CART	9 Oct 2018	3 days	4	accomplished	in progress
Low-energy beam-transport design and emittance measurements	2	KVI-CART	16 Oct 2018	3 days	4	accomplished	in progress
Low-temperature plasma diagnostics	2	UCLM	4 Dec 2018	3 days		scheduled	

At present the number of accomplished intended training courses is 14 out of 15 (93%) and 59 persons out of expected 63 (94%) were instructed.

The outcome and achievements from trainings are resumed here:

- GANIL training motivated us to extend training programme. Upon request two extra oven trainings were organised at LPSC, and at GSI, respectively.
- The participants expressed the desire to extend the exchange of ideas and knowledge.
- Collaboration experiments between partners are proposed and encouraged, even if not within the scope of MIDAS: e.g., RF measurements at LPSC supported by personnel and equipment from GSI and training has motivated new R&D using Optical Emission Spectroscopy: GSI and GANIL
- Discussion about the new 18 GHz ECRIS: HIISI.
- Solutions for technical problems in other laboratories have been found during the training
- Trainings are useful in helping to create and accelerate new personal contacts. This is very important especially for young researchers.

In the next sections the trainings are described in details.

Section 1 Low temperature plasma diagnostics (UCLM)

Description

The participants gained practical knowledge about the design and mounting of optical systems, ion mass spectrometry and timing synchronisation between events and data acquisition. This knowledge will be very useful for a wide range of ion-source experiments where complex measurements and constraining timing conditions are frequently encountered.

During the Workshop the assistants actively participated in the development and use of two diagnostics techniques in a 2.45 GHz hydrogen plasma source [1]: Ultra-fast Photography and Ion Mass Plasma Spectroscopy.

The Ultra-fast Photography diagnostics uses a novel system of transparent electrode that keeps the electromagnetic coupling properties of the microwave excitation system while allowing the observation of the full plasma chamber volume. An ultra-fast image acquisition system with a combination of MCP (Multichannel Plates) and CCD cameras is used to obtain plasma pictures with 1 µs exposure times. Special attention is dedicated to the synchronism between the plasma discharge and the ultra-fast acquisition system to guarantee the proper timing.

The Plasma Ion-Mass Spectroscopy diagnostics uses a quadrupole mass spectrometer for plasmas that allows obtaining mass spectra of all ions present in the plasma with mass between 1 and 300 amu. Once the ion species has been identified, the system can obtain the Energy Distribution Function for each ion species with a resolution of 100 ns allowing to make a case for the synchronisation between the plasma discharge and the instrument.

REMARKS AND CONCLUSIONS

In general terms, both diagnostics deployed during the Hands-on-Training worked very well showing original results to the participants. As shown in Figure 1, a split in the energy distribution can be observed with the plasma ion-mass spectrometer, as well as with the previous coil setup. The quality of the images obtained with the image intensified CCD frame camera, as shown in Figure 2, have to be improved due to the weakness of the light coming from the plasma and to the age of the camera.

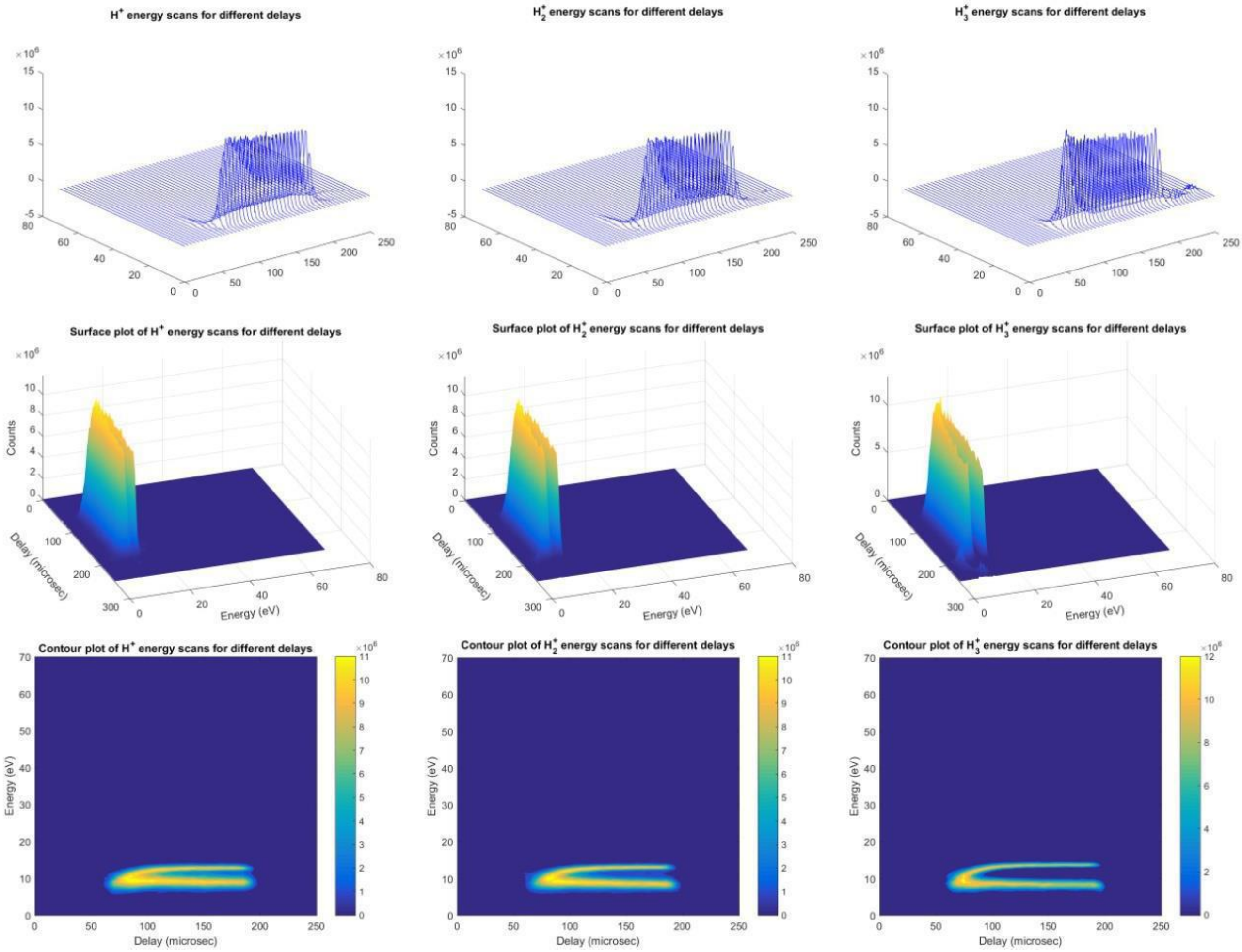

Figure 1: Example of data obtained in a sequence of measurements of IEDF temporal evolution for H^+, H_2^+ and H_3^+ ions during the training.

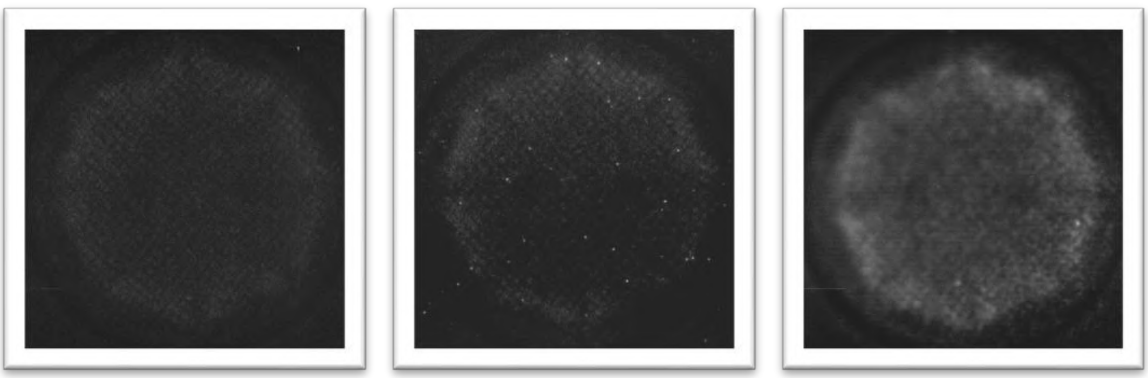

Figure 2: Typical pictures of the breakdown process with 5 µs of exposure time. The delay of 50 µs (left), 60 µs (middle) and 70 µs (right) is measured from the rising slope of the incoming microwave pulse.

The participants confirmed that the techniques have opened a different point of view on the experimental possibilities of their experimental facilities. The participants also suggested some methods to improve the diagnostics with a special emphasis on the data treatment. Some possibilities of collaboration were discussed with respect to the ERINS (follow-up of ENSAR2) proposal that is currently under preparation. One interesting suggestion is to purchase some plasma diagnostic equipment to be shared by the groups.

Section 2 ECR charge breeder techniques (LPSC)

Description

Charge breeding

The participants gained practical knowledge about the ECR charge-breeding techniques. In this method, the implementation of two beam lines and two ion sources is necessary. The hands-on-training focused on the beam capture and the measurements done to qualify the process: efficiency measurement, charge-breeding time, charge-state distribution, ΔV curve for gaseous or alkali ions. The participants actively switched on the test bench, tuned the optics and the parameters to improve the efficiency. They used the beam diagnostics and performed the specific charge-breeding measurements.

Oven

The participants gained knowledge on the low-temperature oven technology dedicated to the production of low-temperature vapour pressure metals. The technology and the steps to design and build the oven were presented. Then, the participants acquired practical knowledge on making a calcium beam on PHOENIX V3 [2] ion source and tried to optimise the high charge-state production at high microwave power.

Plan of activities

First day

Oven activity (morning)

The participants will follow an introductive seminar on the low-temperature oven technology. Then, the participants will vent the source, install a Ca load in the oven, plug it into the PHOENIX V3 source and set the LEBT under vacuum.

Charge breeding with gaseous 1+ beam (afternoon)

The participants will attend an introductive seminar about the objective of the training, about the ISOL method, about the devices used on a charge-breeding test bench, and more specifically the LPSC ones (ion sources, diagnostics, optics) and about the charge-breeding process. Then, they will get the safety instructions mandatory to work in the test area. The participants will switch on the test bench, they will start both 1+ and CB ion sources. Then they will inject the 1+ gaseous beam in the Charge Breeder and optimise the parameters to improve the efficiency of one charge state. In the evening, The 1+ source of the 1+/N+ beam line will be replaced for alkaline charge breeding on the third day.

Second day:

Oven Activity

The participants will start the oven using different buffer gas (He, O_2) and make a Ca beam. The participants will optimise the charge-state distribution to high charge state, move the oven toward the ECR zone to try to find an optimum, calculate the beam-line transmission vs the high voltage and possibly measure beam emittance provided the Allison scanners are available at the time of the training. At the end of the day, the Ca oven will be removed and the Ca consumption will be derived from the metal weighting.

Third day:
Charge breeding with alkaline 1+ beam
The participants will make experiments injecting an alkaline 1+ beam and optimising the parameters to improve the efficiency of one charge state. They will make comparative measurements changing parameters (1+ ion beam current, support gas...) and analyse the results.

SECTION 3 LOW-ENERGY BEAM TRANSPORT DESIGN AND EMITTANCE MEASUREMENTS (KVI-CART)

DESCRIPTION

The training workshop addressed two topics related to low-energy beam transport. The first one covered the design of low-energy beam-transport lines, both theoretically and practically. Important concepts such as phase space, beam emittance and space-charge forces were introduced. The participants got hands-on experience with simulation tools used for beam-transport design. The second topic concerned measuring beam emittances. After giving a brief overview of emittance measuring methods, the one used at KVI-CART, the pepperpot method, was focused on. Participants got hands-on experience with this device and studied how the beam emittance depends on the tuning of the ion source and the optical elements in the beam-transport line.

PLAN OF ACTIVITIES

First day: The participants attended an introduction seminar on the objectives of the training followed by an introduction to the theory of beam transport and the use of simulation software. They then used the simulation software to design a low-energy beam transfer line between an ECR ion source and a cyclotron.

Second day: The workshop started with a seminar on beam emittances and devices to measure them. The rest of the day was devoted to practical training including operating the KVI-CART AECR ion source [3] and beam transport line. The pepperpot emittance meter was discussed in detail, including its construction, operation and reconstruction of the 4D phase space from the measurements.

Third day: The last day was entirely devoted to hands-on training. The participants used the KVI-CART AECR ion source to produce an ion beam, tune the low-energy beam line and measure the beam emittance with the pepperpot emittance meter. They performed a series of measurements to investigate the effect of different ECRIS parameters, e.g., the gas pressure and injected RF power, and the tuning of the beam-transport line on the beam emittance. The workshop ended with an evaluation and feedback session.

SECTION 4 MIVOC METHOD AND/OR HIGHLY CHARGED PLASMA DIAGNOSTICS (JYFL)

DESCRIPTION

The participants gained practical knowledge about the metal ion-beam production using MIVOC method [4] and about visible light spectroscopy of highly charged plasma. It was also demonstrated how to detect electron cyclotron instabilities that often limit the performance of ECR ion sources. The hands-on-training in order to get familiar with the MIVOC method covered the safety issues, loading and handling of the MIVOC chamber, material feeding into ECR ion source and its operation. In the case of plasma diagnostics the visible light spectroscopy was used to identify most intensive signals emitted by highly charged ions. The effect of optical filters was demonstrated as well. Operation of diagnostics techniques, namely microwave-sensitive diode and bremsstrahlung power flux detector, of plasma instabilities was introduced as well. The objective is that after training the participant is able to bring the MIVOC method into use in his/her home laboratory and the participant understands limitations and also possibilities of the method. After training he/she also understood the basics of visible light spectroscopy, its possibilities and limitations in the case of highly charged plasmas and recognised the symptoms of plasma instabilities.

REMARKS AND CONCLUSIONS

Figure 3 shows a Fe spectrum obtained during the training. After the practical training, a short summary discussion was performed. As a next step, the discussion focused on the 18 GHz HIISI ECRIS [5] under construction at JYFL. A lot of interest was shown in the unique insulated permanent magnet solution and the cooling of the plasma chamber. Different heat loads of the permanent magnets and mechanical limitations of present configuration were explained.

The visible light spectroscopy was performed with different spectrometers in terms of resolutions. The difference between high-resolution spectrometer [6] and pocket size, easy to use spectrometer (Ocean optics) can be easily seen from the comparison data presented in Figure 4.

It was shown how to produce a spectrum from the measured data and how the data can be used for particle species identification. The task was to determine the gas mixture in mystery-gas bottle (unknown plasma), as shown in Figure 5, and to find typical plasma impurities. The mystery gas was a mixture of argon (~20%) and neon (~80%). Usually plasma impurities like hydrogen, oxygen and nitrogen can be found. In addition, emission lines originating from iron can be seen with high-bias voltages due to the sputtering process.

After the analysis part of the training, a very fruitful conversation about the training took place with good ideas for improving the optical emission spectroscopy setup further and also about phenomena, which could be studied with the optical spectrometers. The possible collaboration to perform the optical spectroscopy and interest to purchase optical spectroscopy equipment by other laboratories were discussed.

Diagnostics methods suitable for detecting kinetic plasma instabilities were shown. Finally, the stabilising effect of double frequency heating was demonstrated by first triggering the instabilities in single frequency heating mode by increasing the magnetic-field strength beyond the threshold value and then providing 5 - 30 W of additional microwave power at 11.53 GHz from a TWT-amplifier. The stabilising effect of the secondary frequency was confirmed by monitoring the temporal variation of the scintillator signal (bremsstrahlung power flux) and O^{6+} beam current shown in Figure 6.

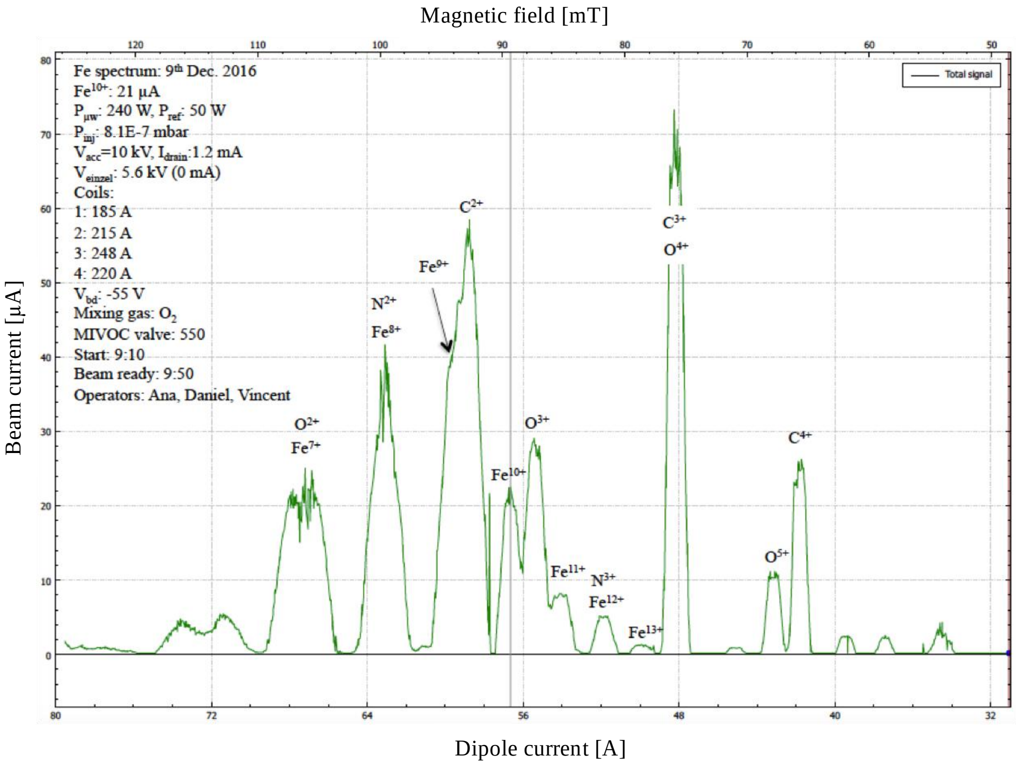

Figure 3: Iron spectrum produced by using MIVOC method with the JYFL 6.4 GHz ECRIS.

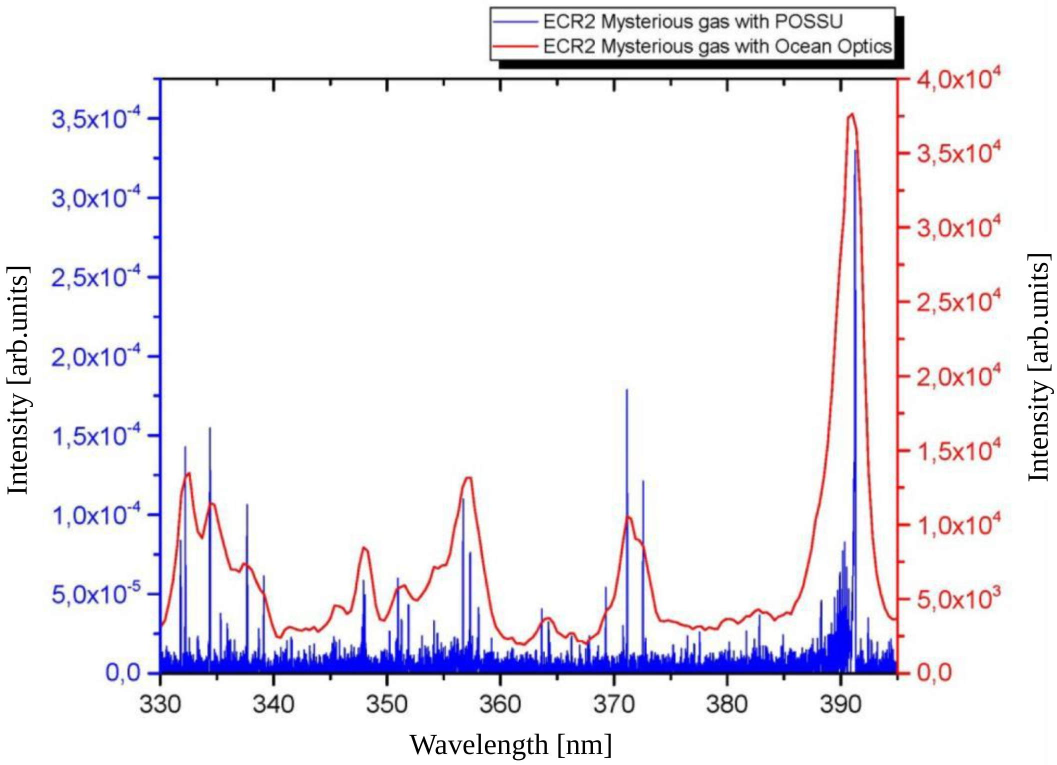

Figure 4: Comparison between Ocean optics spectrometer and high-resolution POSSU spectrometer

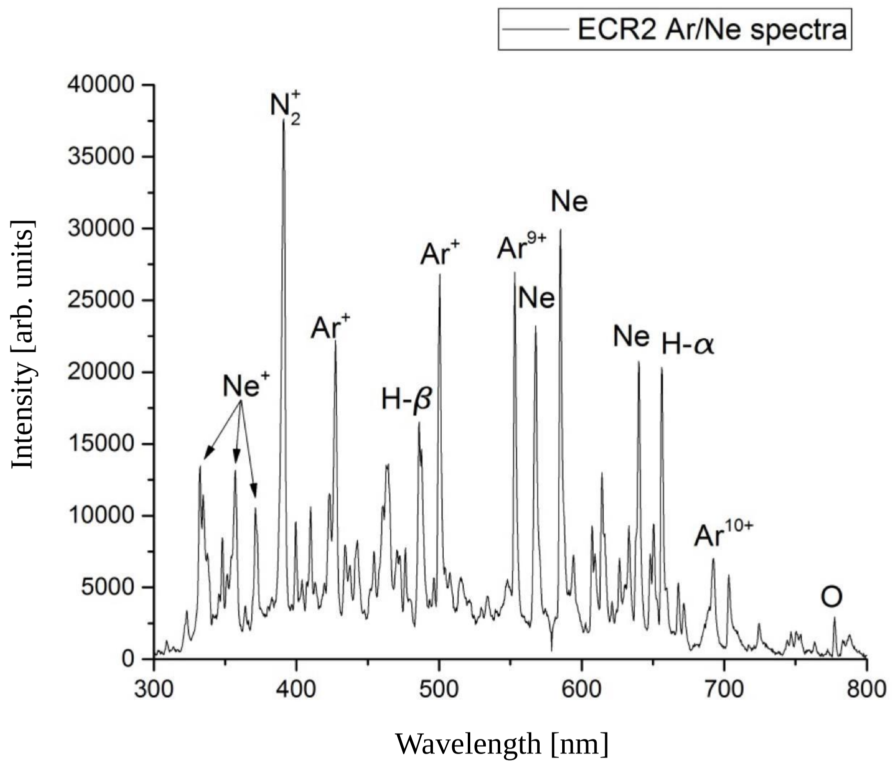

Figure 5: Emission spectrum from unknown gaseous plasma

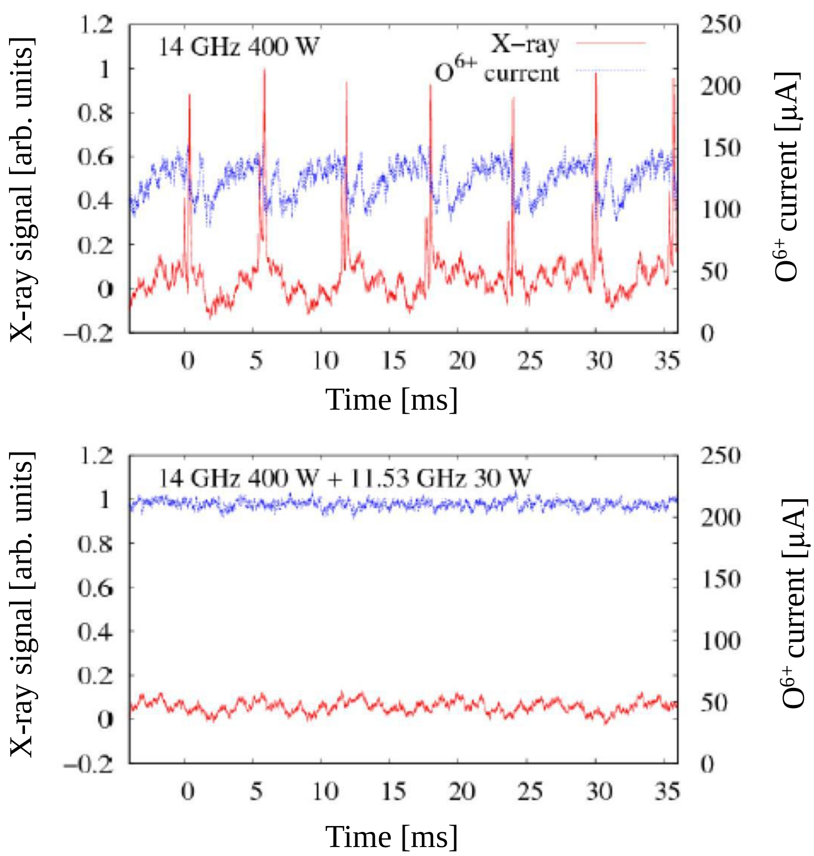

Figure 6. Stabilising effect of two-frequency heating.

Section 5 Microwave-based techniques to improve the performances of the ECRISs (GSI)

Description

The participants gained practical knowledge about the handling of microwave devices and components to be used to increase the production of highly charged ion current of ECRISs. During the training the main issues about microwave generators, resonance cavities and coaxial/waveguide components were explained to instruct the participants about the suitable components for the assembly of microwave lines for plasma generation. The participants got instructions about microwave measurement devices, i.e. Network Analyser, Spectrum Analyser and Power Meter, and they performed microwave characterisation of active and passive devices. The training included the operating of the ECRIS under different operation modes like frequency tuning by sweeping the microwave frequency and double frequency heating by combining two microwave generators. The participants actively switched on the ion source, controlled it, tuned the main parameters and analysed the effects of the tuning on the extracted ion current. At the end of the training, the participants were able to identify the necessary microwave components to assemble a microwave line to run an ECRIS under the above-mentioned operating modes. They understood how to handle frequency generators, and high-power microwave amplifiers, and how to use them for the performance optimisation of ECRISs.

Remarks and conclusions

After getting instructed about the main microwave components and measurement instruments, the participants operated the ECRIS under different operation modes like frequency tuning by sweeping the microwave frequency and double-frequency heating by combining two microwave generators. They first tuned a single frequency generator and analysed the effect of the frequency tuning on the extracted current of different charge states, see Figure 7. After identifying the frequency where the highest intensity of high charge states occurred, they compared the charge-state distributions, as shown in Figure 8, at this frequency and at the normal operation frequency of the CAPRICE ECRIS, 14.5 GHz [7]. Then, they combined a second microwave generator to analyse the ECRIS performance, in terms of intensity of Ar^{11+}, when the double-frequency technique is applied. The result is reported in Figure 9 showing a comparison between the two mentioned techniques.

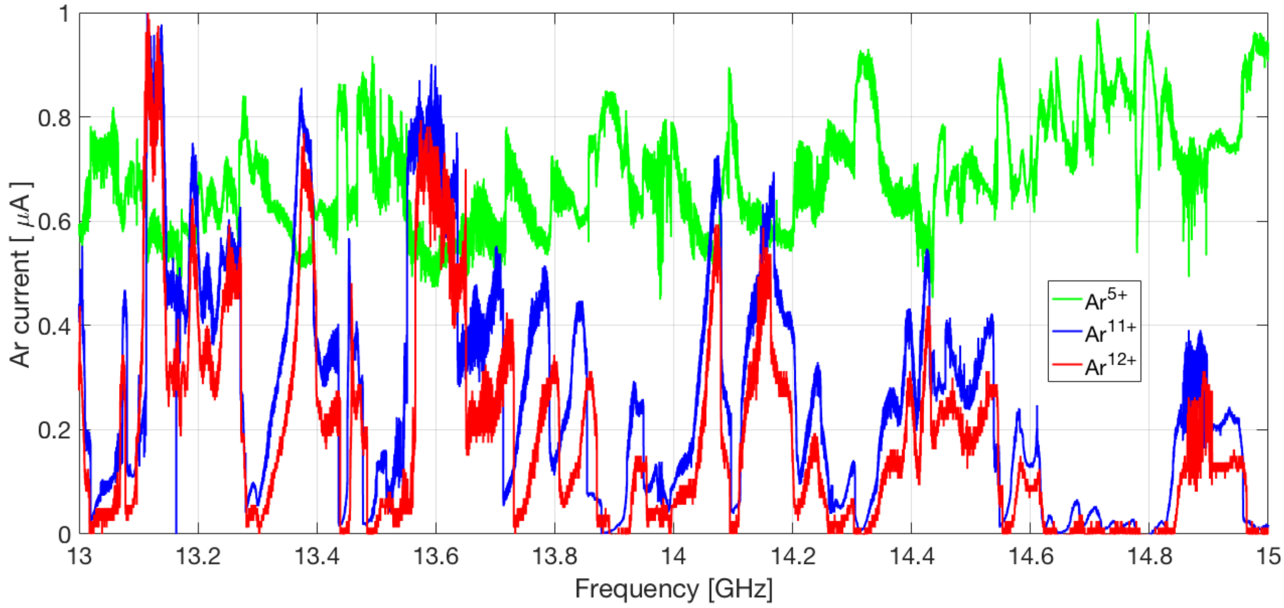

Figure 7: Normalised ion-current evolution with the microwave frequency.

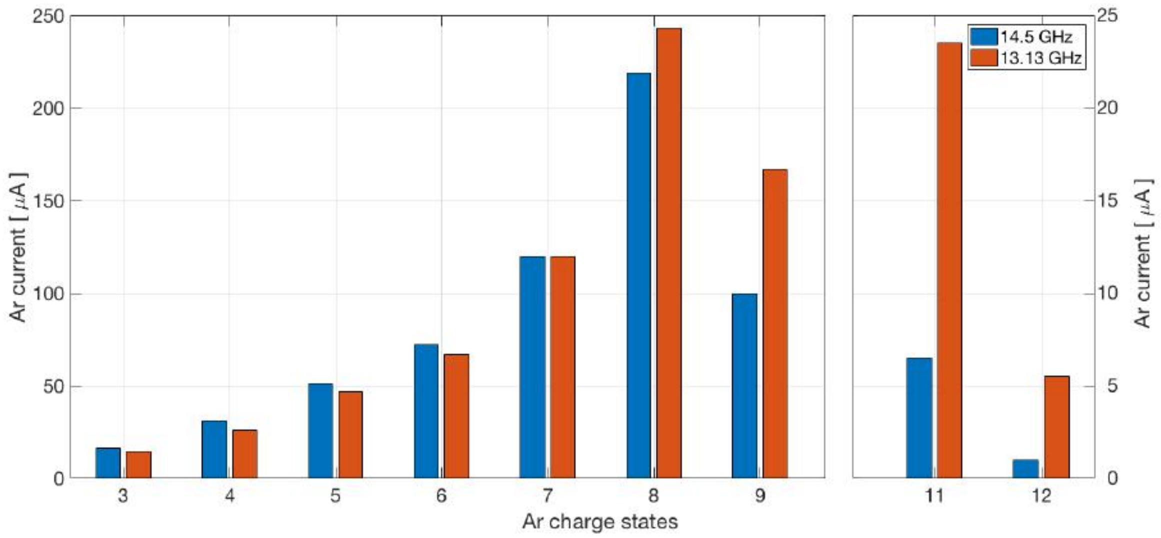

Figure 8: Charge-state distribution of Ar for two different microwave frequencies.

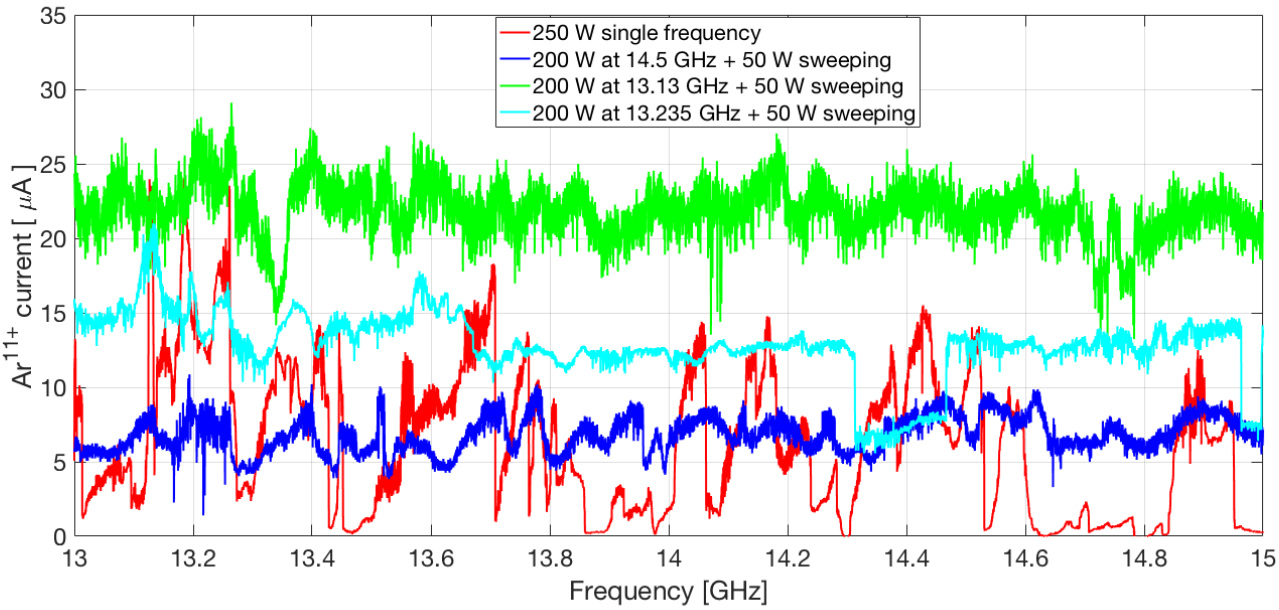

Figure 9: Ar^{11+} current when applying the frequency tuning or the double-frequency heating.

Active discussions and questions arose during the training. As an outcome, the participants were successfully trained for running microwave-based techniques to improve the performances of the ECRISs.

Section 6 Iron-beam production with ECR4 ion source using oven technique (GANIL)

Description

The ion source Phoenix V2 [8] is being commissioned for the SPIRAL2 facility. The nominal intensity of 50 µA $^{40}Ar^{14+}$ at 60 kV is expected in the next few months. Then, the first metallic beam $^{58}Ni^{19+}$ at 61 kV will be optimised and validated by producing a stable beam intensity of 19 µA (1 pµA).

The participants gained practical knowledge in nickel load preparation and mounting of the resistive oven (1600°C). The start-up and the optimisation of the ion source for nickel was practiced as well.

Remarks and conclusions

The GANIL LCO HT Oven shown in Figure 10 has been successfully mounted and heated up to 1500°C in the test vacuum vessel and then filled with nickel material and inserted into the ECR4 ECRIS. A beam intensity of ~5 µA of Ni^{19+} has been produced after about 2 hours of operation and a current up to 10 µA was achieved after one day of operation/optimisation of the ECRIS. Several fruitful discussions based on the different ovens and hot screen expertise of the participants took place during the training.

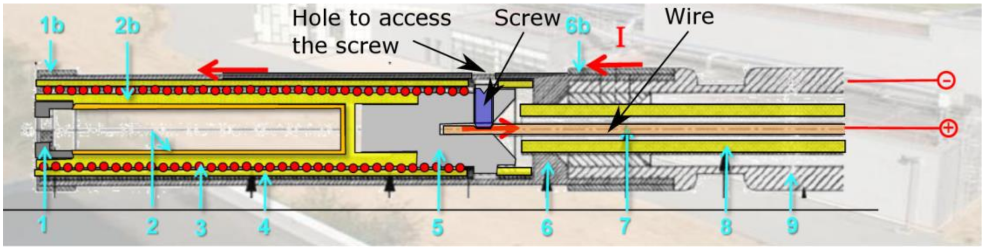

Figure 10: GANIL LCO HT: (1) half cap; (2) alumina crucible; (3) tungsten wire; (4) alumina insulator; (5) molybdenum connector; (6) tantalum tube; (7) molybdenum electrical conductor; (8) alumina insulator; (9) stainless steel oven holder.

Section 7 Measurements of ECR plasma parameters by Langmuir-probe (ATOMKI)

Description

The participants gained practical knowledge about the measurements of certain plasma parameters with small-size electrostatic probes (Langmuir-probes). Among the various methods, Langmuir probes are among the most important ones available for local plasma diagnostics. In the Atomki ECRIS Laboratory two plasma devices are available. The Table Plasma Generator (TPG) is a plasma device operating in a wide range of frequency producing low-charged plasmas. There are no mirror coils, just a long radial permanent-magnet hexapole magnet, and there is no beam extraction at all. However, it is very easy and fast to install any probes into it; the plasma is fully visible with the naked eye. The other device is a classical 14.3 GHz ECRIS [9] with B-minimum geometry and with beam extraction for producing highly-charged plasmas and beams. Langmuir-probes can be installed into both devices. The measuring system consists of Langmuir-probe (optionally movable), power supply, remote control unit, control software, analysing software. The results of the measurements are several plasma parameters at the position of the probe, like floating potential, plasma potential, electron temperature, electron density, electron-energy distribution function, effective temperature. The effect of setting ECRIS parameters (microwave frequency and power, gas type and pressure, etc.) to the plasma can also be studied by this method. In the first half of the training days, the simplest (small size cylindrical) probes are applied. In the second half, other types (double probe, emitting probe) were used.

Remarks and conclusions

The participants got knowledge about the Langmuir Probe plasma diagnostic device and how to operate it to analyse the ECRIS plasma parameters like the electron density, as shown in Figure 11, and the EEDF, as shown in Figure 12. Different settings of the ECRIS were used to investigate the effect on the plasma parameters. The participants took an active part, while controlling the measurement device, to record the data and to analyse the results.

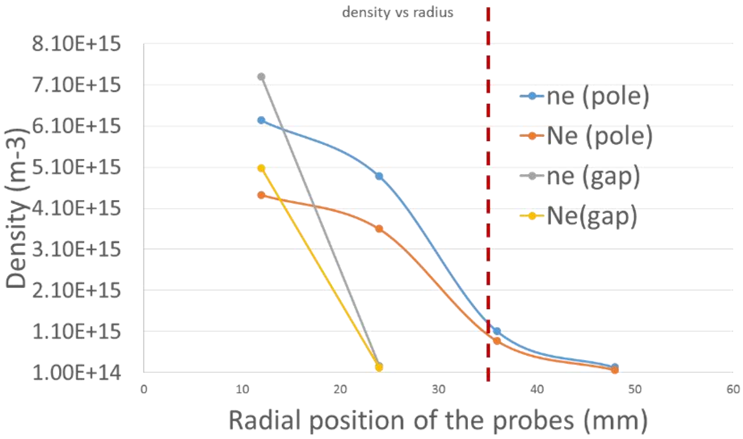

Figure 11: Electron Density (*ne* and *Ne* are obtained with different analysing techniques) as a function of the plasma chamber radius at different azimuthal positions. The red-dashed line shows the radial position of the resonant surface, between the solenoids, for the microwave frequency of 10.3 GHz.

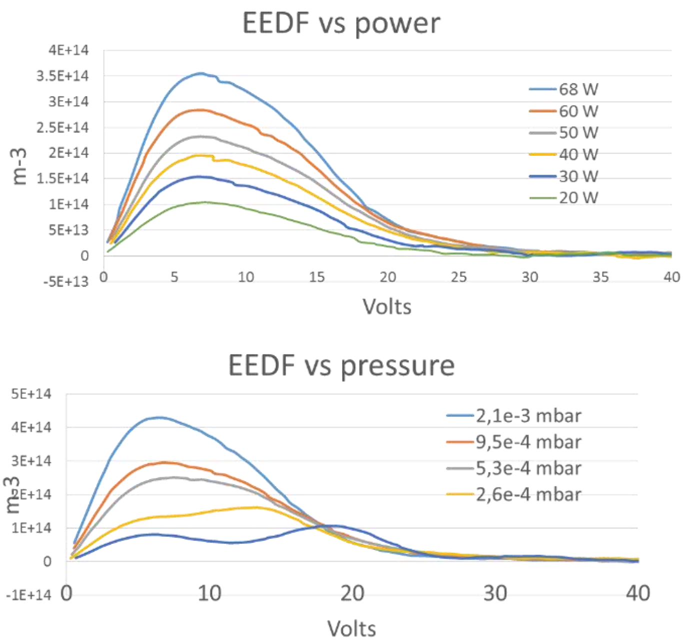

Figure 12: Electron-Energy Distribution Function (EEDF) versus microwave power (top) and gas pressure (bottom)

SECTION 8 NICKEL BEAM PRODUCTION WITH THE CAPRICE ECRIS USING THE GSI STANDARD OVEN (GSI)

DESCRIPTION:

One result of the hands-on-training at GANIL (Caen, France) in November 2016 on "Iron production with the oven method" was that the same training in another laboratory of the MIDAS collaboration was desirable. For this reason, an oven training has been organised at GSI as well. The participants gained practice in operating the GSI standard oven with the CAPRICE-type ECRIS at the ECRIS test bench. The arrangement of the CAPRICE ECRIS and the LEBT at this test bench is identical to that at the High Charge State Injector (HLI) at the GSI accelerator facility. The assembling procedure of the oven was demonstrated in the oven service area. After filling the oven with natural

Ni material a pre-processing was done by controlled melting of the Ni material in an external vacuum recipient. After cooling down to room temperature the oven remains under vacuum by means of a lock system during transport to the ion source. This approach further allows the mounting of the oven and insertion into the ion source without breaking the vacuum. The participants gained practice in the start-up process of the ion source and in the operation and the optimisation for different charge states.

Remarks and conclusions

The participants got a presentation about "The GSI oven concept" (link to website see above) and the arrangements in the dedicated oven service area. There all components of the GSI standard temperature oven and the GSI high temperature oven were exposed, including the ancillary equipment of the ovens. The procedure of cleaning and reusing some parts of the ovens was demonstrated including the use of special tools and special materials for the mounting of the different versions of the STO depending on the particular chemical element or chemical compound to be handled. Finally, the mounting of one complete item of the STO was accomplished by active practicing of the participants. In order to demonstrate the problem of an outburst of material, the STO was intentionally filled with too much material. In this case the molten Nickel crept through the aperture ring and became solid again which is clearly visible in a video recording taken during the complete heating process. The trainees got practical experience in the whole procedure of pre-processing the oven, transport an insertion into the ion source without breaking the vacuum by means of a lock valve system.

A lively discussion ensued among the participants about experiences with the oven technique in daily routine operation. It was agreed that the only way to ensure a stable and repeatable ion-source operation with the oven technique requires skilled personnel with appropriate technical background and with long term experience. A good documentation is mandatory concerning the construction, the mounting and dismounting, and about the operating procedure including special handling for every element. It was also discussed that problems may result from the composition of the evaporated material, e.g., impurities like ^{27}Al in ^{54}Cr sample material. Such conditions may lead to severe difficulties in providing a pure beam of one selected ion species and sometimes can be hardly detected.

Conclusions

After accomplishment of 14 training courses (out of 15) it turned out that hands-on-trainings are a favourable tool to promote the transfer of the optimised and the most useful methods among the partners. On-site training proved to offer an inspiring environment for experts, young physicists and engineers to improve their expertise by the courses offered by the partner institutes. The feedback from the colleagues who participated in hands-on-trainings was very positive. Many fruitful discussions were stimulated leading to new ideas for improved methodology and techniques.

In addition to the individual transfer of knowledge, it can be concluded that it is absolutely recommended to collect and summarise the outcome of the training courses in reports in order to maintain and to further disseminate the knowledge. This is achieved within the present networking activity by means of a dedicated website:(https://wiki.jyu.fi/display/ensar2/Website+for+European+collaboration+on+ECR+ion+sources%2C+MIDAS-NA), which comprises all necessary information of the NA including the reporting of the training courses.