MAFF — SAFETY ASPECTS OF A REACTOR-BASED RIB FACILITY

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Abstract

The Munich Accelerator for Fission Fragments MAFF is under design at the new research reactor FRM-II. The safety concept of this instrument is outlined with emphasis on the reactor part, not the post-accelerator part. Although a large installation, MAFF is one among many instruments sharing the FRM-II. Therefore the main general safey goal is minimizing the feedback of potential failures to the reactor. In particluar, in-pile parts of MAFF must not affect reactor safety. This causes constraints, e. g. for the layout of the target/ion source assembly. Some potential failure szenarios are discussed as well as techniques for radioactivity handling.

1 INTRODUCTION

The new Munich high-flux reactor FRM-II has been technically completed in August 2001 and is since awaiting the final authorisation for nuclear operation. At a thermal power of 20 MW, it will have a maximum neutron flux of $\approx 8 \cdot 10^{14}$ cm^{-2}s^{-1} and provide in a first stage a total of 20 experiments in the reactor experimental hall and the adjacent neutron guide hall. One of them is the Munich Accelerator for Fission Fragments MAFF [1, 2] which aims at delivering very intense beams (up to $\sim 3 \cdot 10^{11}$ s^{-1}) of neutron-rich isotopes at an energy of 30 keV (low energy beam) and at energies variable between 3.7 and 5.9 MeV·A (high-energy beam) to perform experiments at the Coulomb barrier. The beam intensities expected after the first mass separator are given in figure 1.

Apart from typical nuclear physics experiments (e. g. nuclear spectroscopy of exotic nuclei close to the r-process path), the low-energy beam is interesting for a range of possible applications, such as the production of tracer-free radiopharmaceuticals.

MAFF focuses, however, on the high-energy beam, which is well suited for fusion experiments in order to produce neutron-rich, super-heavy elements, e. g. in the range $106 \leq Z \leq 120$ if a ^{208}Pb target is used, with predicted lifetimes in the order of up to several years [3]. The use of neutron-rich projectiles results in higher fusion cross sections and longer lifetimes of the super-heavy fusion products [4].

2 MAFF at the FRM-II

Contrary to most other Radioactive Ion Beam (RIB) facilities, MAFF does not use a driver accelerator but produces radioactive ions by thermal neutron induced fission of ^{235}U, diluted as UC_2 in porous graphite. The target is placed in in-pile position in the FRM-II. The fission products are then ionized (1^+) and extracted from the reactor beam tube, mass pre-separated and beam splitted before passing a gas-filled emittance improver (RFQ or funnel) and a high-resolution mass separator. One beam can then be used directly for experiments (low-energy beam), the other one will be transported into an external experimental hall, transferred to higher charge states in a charge breedig device, ECRIS or EBIS (Electron Beam Ion Source), and accelerated to its final energy in a compact LINAC before it is directed towards one of several experimental areas (cf. fig. 2).

In a first stage only the low-energy beamline will be set up.

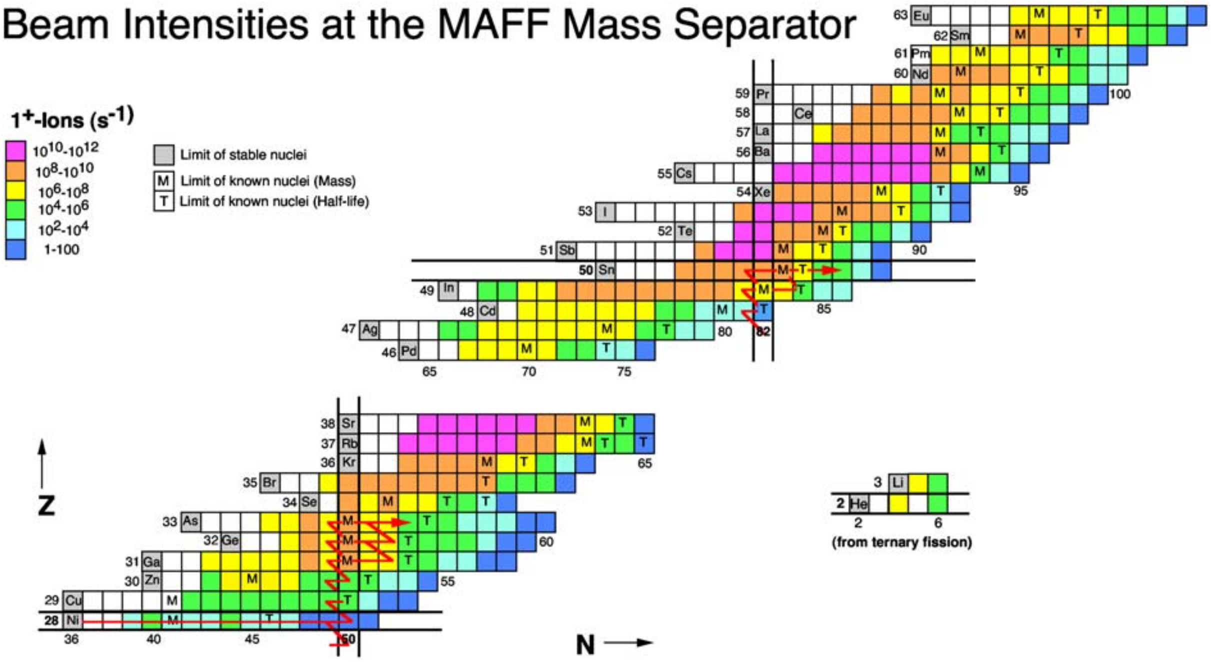

Fig. 1: Beam intensities of MAFF expected at the first mass separator.

3 FRM-II SAFETY

The safety concept of the FRM-II is described in detail in [5]. Here we concentrate on some aspects which are relevant also for MAFF and eventually other experiments at the reactor.

The FRM-II has been designed to withstand an earthquake up to an intensity of $I_{\rm MSK} = 6.5$ without major damage. Even in case of an airplane crash which directly hits the reactor hull, a catastrophic failure which means melting-down of the fuel element and release of activity to the environment must not occur.

Several precautions have been taken to achieve this goal: The reactor containment consists of 1.8 m reinforced concrete to prevent penetration and the reactor pool is mechanically decoupled from the hull to absorb or at least attenuate vibrations.

There is a total of two (even three if one counts each of the doubled neutron windows in the beam tube locking plates) barriers against a loss of reactor pool water: the reactor beam tubes and their locking plates. Both barriers are designed to remain intact if an earthquake occurs, in case of an airplane crash at least one of the barriers (the outer one) shall preserve its integrity. In this way a melting down of the fuel element with subsequent release of activity can be avoided, even if the primary cooling circuit fails.

As a general design rule passive barriers are used wherever possible. A few exceptions are e. g. the pumps of the primary cooling circuit (although the remaining decay heat after shutdown can be dissipated by natural convection) and the ventilation flaps in the reactor building that close in case of activity leaks. All structures in the vicinity of the barriers must possess sufficient stability to prevent damage to the barriers.

4 THE INTEGRATION OF MAFF INTO THE FRM-II SAFETY CONCEPT

As there will be a total of 20 instruments installed at the FRM-II, the general safety rule applies that any adverse feedback of an instrument to the reactor must be avoided in order not to affect all other instruments. Additionally, any release of activity should be minimized and must remain within the limits conceded for normal reactor operation — even in case of accident or failure scenarios. In particular no

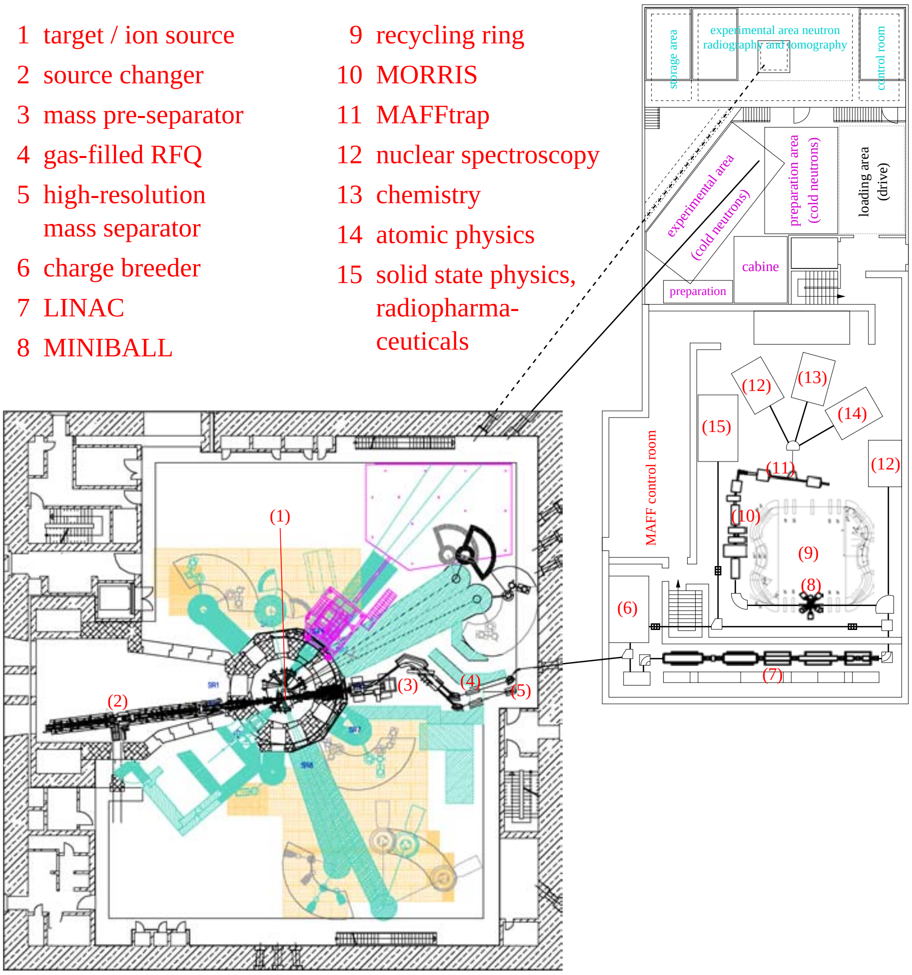

Fig. 2: The layout of MAFF at the FRM-II.

third party must be affected.

One has to admit that operating MAFF might cause problems to the reactor if no special precautions were taken. These potential problems as well as their solutions are analyzed in the following:

4.1 The target/ion source system

The target/ion source system is located in in-pile position in the center of the through-going beam tube in a high neutron flux of $\sim 10^{14}$ cm^{-2}s^{-1}. It is mounted on a trolley and inserted into the reactor beam tube from the source-changer side (neutron tunnel). In order to achieve fast diffusion of the fission fragments out of the target and subsequent ionization, it has to be operated at high temperature of up to 2400° C. The surrounding beam tube is made of zircaloy. This material has a melting temperature of 1850° C.

The high fission cross section of ^{235}U for thermal neutrons ($\sigma_\mathrm{f} \approx 585$ b) allows, however, a very compact target design which not only helps in reducing diffusion times of the fission fragments, but also minimizes the heat capacity of the target. The fission power dissipated in the target amounts to no more than 3 kW at nominal fission rate (10^{14} fiss/s). Even if the hot target drops and touches the beam tube, this is not sufficient to cause real damage to the zircaloy beam tube as long as it is placed in the heavy water vessel [6]. Moreover, the target is surrounded by several heat shields to achieve the desired central temperature also at lower power levels in case of small uranium contents. At nominal fission rate, the heat shields will be replaced by a mesh of refractory metal (W or Re). Thus, if the target cracks and drops, it cannot touch the beam tube.

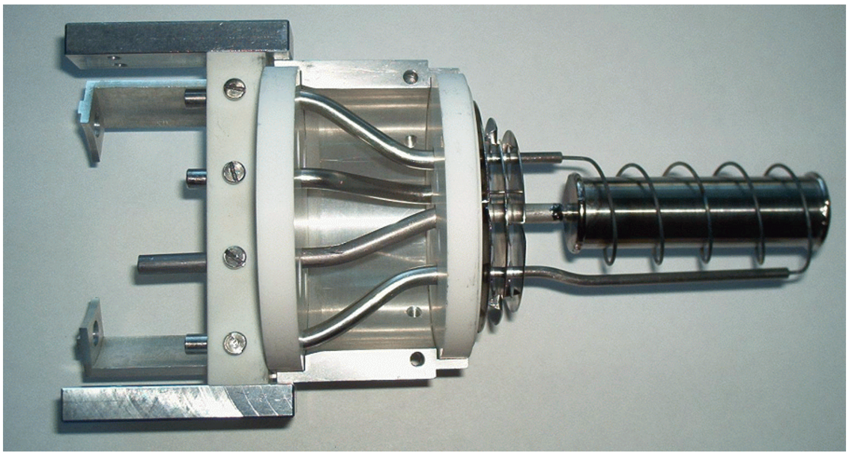

Fig. 3: A prototype of the MAFF target/ion source unit, shown without heat shields.

4.2 Ion beam extraction — the barrier design

In contrast to most other instruments that extract neutrons out of the reactor, MAFF cannot use aluminium windows as passive second and third barriers. Hence the first barrier (the reactor beam tube) has been constructed in accordance to stricter specifications so that it will withstand an airplane crash. The one barrier that has to remain intact in this case was thus shifted from the second to the first one. Active elements (shutters) will be used as second barrier, they must be doubled in order to avoid the consequences of a single failure.

A safety analysis has been performed investigating potential failure scenarios. An increase in pressure in the reactor beam tube, e. g. may be due to one or a combination of the following reasons:

- a leakage in the reactor beam tube leading to an ingress of water
- a leakage at one of its sealings (ingress of He gas or water)
- a leakage in the He cryopanel (ingress of cold He gas)
- a leakage in the vacuum system or the beamline outside the reactor (ingress of air)

Whether these leakages may be caused by some external event (earthquake, airplane crash), are due to a maloperation or occur spontaneously is irrelevant for the measures that will be talken. In any case fast closing valves will be activated to separate the reactor beam tube from the vacuum system and the external beamline. In this way a water leak is closed and no activity from the target will be released.

A special construction will be used on the beam extraction side of the through-going beam tube: Similar to the target/ion source unit also the system of ion optical lenses for beam extraction is mounted on a trolley. In order to withdraw this trolley from the reactor beam tube, it is necessary to open a large cross section in the beamline that cannot be shut by fast closing valves within milliseconds. On the other hand, no large open cross section is required for beam extraction during normal operation of MAFF. Hence, some kind of “piggy-back valve” is under design which allows to slowly open and close a large cross section to move the trolley. At the same time, a small opening can be closed very fast by a commercial fast closing valve, sitting on the valve head of the large shutter.

It should be emphasized that the construction of the reactor beam tube prevents a spontaneous rupture which would allow a massive ingress of water resulting eventually in the formation of a shock wave that could destroy adjacent systems, e. g. the shutters. Given the actual design, only small leakages in the beam tube are possible, with the exception of a very hypothetic scenario that will be discussed later.

A rupture opening a large cross section is possible, however, along the external beamline in case of an airplane crash. Then the ingressing medium is air, a compressive medium which does not form shock waves.

An additional “barrier” (although not in the strict sense) against an ingress of air due to some maloperation at the experiment is the ion beam cooler. It is filled with noble gas at a rather high pressure (~ 0.1 mbar) compared to the reactor beam tube on one side and the experiment on the other side ($p \approx 10^{-6}$ mbar). Together with its differential pumping stages, this ion beam cooler decouples both vacuum regions.

The hypothetic scenario which has been discussed at the FRM-II is a so-called steam explosion resulting from a fragmentation of the fuel element and a very rapid release of thermal energy to the surrounding water. In this case it is assumend that all reactor beam tubes will be destroyed without exception by a shock wave. Concerning MAFF, this shock wave may also affect the fast closing valves, and therefore an additional shutter is positioned between the reactor bassin and the fast closing valves. This shutter closes only with a delay of several seconds to let the shock wave pass by and then shutting off the water flow. It is evident that the reactor may not be operated with this valve closed.

4.3 Radioactivity handling

A major part of the fission products leaving the target during operation of MAFF are not ionized. Without additional measures, they would spread within the reactor beam tube unless they are pumped away by the vacuum system to be stored in delay tanks until they finally can be released. The amount of radioactivity which has to be handled by the vacuum system would be enormous, however, requiring very large and heavily shielded delay tanks. Moreover, the radiation from the reactor has to be well shielded, which means small open cross sections in the beam tube and thus a very reduced pumping capacity within the reactor beam tube.

Both problems can be overcome by the use of an in-pile cryopump. As this cryopump is subject to a dedicated article [7], it will not be discussed in detail here. This cryopump not only provides sufficient pumping capacity at the location of the target/ion source, it also reduces the activity that must be handled by the external vacuum system by approximately a factor of 1000. The non-ionized volatile fission fragments are frozen out on the cryo panels and are thus fixed in a well-shielded area. Apart from few isotopes, their half-lives are short in comparison to the reactor period of 52 days. Therefore most of them decay into non-volatile species and remain fixed on the cryo panels even after the cryopump has been warmed up.

Thus only a small fraction (~ 0.1 %) of the total gaseous activity must be handled by the vacuum system (cf. fig. 4). Here, too, cryopumps will be used in all places close to the reactor beam tube where the gas load is not too high to avoid saturation of the pumps (i. e. everywhere apart from the differential pumping stages around the gas-filled ion beam cooler). They offer the advantage that those parts which require maintenance are not contaminated, contrary to turbomolecular pumps.

Apart from the time it takes to regenerate a cryopump, moreover, the pumping lines can remain closed during operation which facilitates the requirements for integrity of the pumping system in case of catastrophic events.

After a reactor cycle has ended, the cryogenic pumps will be regenerated and the evaporated activity be pumped to delay tanks where it will remain long enough to release only a sufficiently low residual activity. As a special technique to further reduce the gaseous activity, the contents of the delay tanks will be circulated by roughing pumps with the pumping oil acting as a filter for some of the fission products. Most of the remaining activity forms aerosols with the pumping oil which can then be filtered off. The delay tanks will be kept at slight depression throughout operation.

A special part of radioactivity handling is the manipulation of the spent target/ion sources after the reactor cycle has ended. With a radioactive inventory of 10^{14}–10^{15} Bq it cannot be handled manually. The source trolley will be drawn back remotely controlled into the beamline in the neutron guide tunnel. In the source exchanger the spent target will be taken off from the trolley, placed in a vacuum tight and shielded transport container, and a new target/ion sorce will be installed.

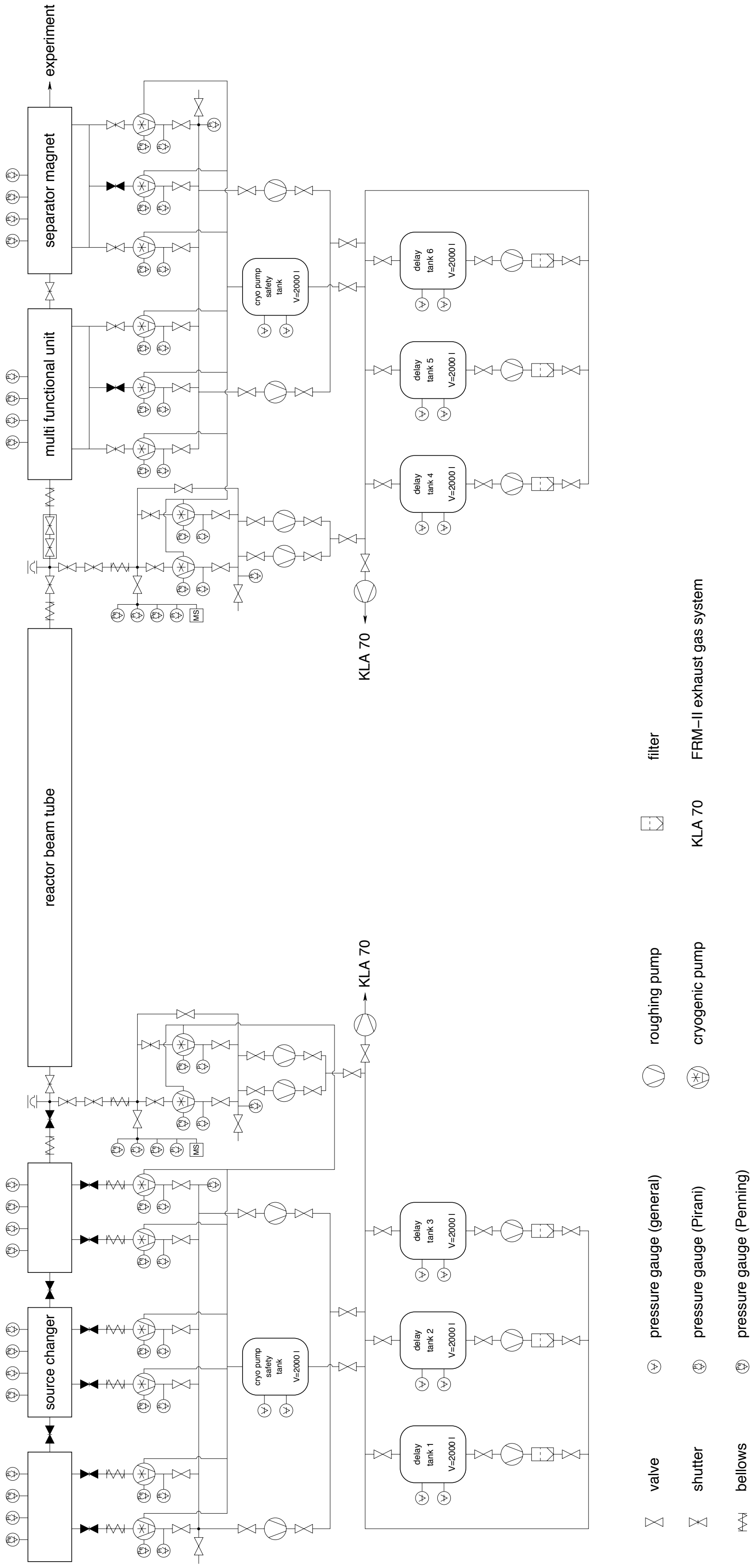

Fig. 4: The MAFF vacuum system.

Whereas there will be shielding around the target changing mechanism, it is not feasible to shield all the beamline in the neutron guide tunnel. Therefore, a manually driven mechanical back-up system for moving the trolley has been foreseen which can be operated from outside the tunnel if the electric drives fail that usually actuate the trolley.

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