# RF STRUCTURES FOR LINEAR ACCELERATION OF RADIOACTIVE BEAMS

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*Abstract*

The production and acceleration of secondary, radioactive ion beams differ quite substantially from the case of stable ion beams. The individual production and separation of the specific ion species, low beam currents or short lifetime of the ions as well as the needed energy variability, typically ranging from 1 to 8 MeV/u, have consequences on the layout of the accelerator.

Long living isotopes can be bred to higher charge state, like it is done at the REX/ ISOLDE project at CERN, and accelerated very efficiently with an accelerator similar to the CERN Lead Linac or the GSI High Charge State Injector. In case of short isotope lifetimes below a few milliseconds charge breeding is not feasible. Therefore, the ions produced in a low charge state have to be accepted by the accelerator. A linac designed for high mass to charge ratio, like the TRIUMF ISAC or the GSI High Current Injector with A/q < 65, which started routine operation in 1999, could serve this task. Due to the low intensities of some of the ion species a high duty cycle is required. Additionally, coincidence experiments profit a lot from a cw ion beam.

This contribution will review the basic needs for radioactive beam acceleration and the possible solutions. It covers linacs based on RFQs, quarter wave resonators and H-mode cavities. Room temperature as well as superconducting solutions are discussed. The state of the art and future perspectives will be described.

## 1 INTRODUCTION

Experiments with radioactive ion beams contain attractive features:

In nuclear physics, peripheral scattering reactions at energies just above the Coulomb barrier allow nuclear structure to be probed by the transfer reactions in direct or inverse kinematics. These transfer reactions have been a rich source of structure information with stable beams and now offer an attractive way to extend that concept towards the wide landscape of unstable nuclei.

Especially the neutron-rich ions accelerated to the Coulomb barrier should give new impulses on the discovery of super heavy nuclei.

Studying the rapid neutron capture process (r-process) and the photodisintegration process (gamma-process) with radioactive ion beams will give answers to astrophysical questions.

Therefore, quite a number of secondary beam accelerators are under design or construction at present all over the world. In finding an adequate solution for every individual case, these accelerator solutions differ considerably from each other with respect to basic parameters. This article will be restricted to linacs as they can provide solutions for the whole parameter range relevant for these experiments:

### *Mass to charge ratio*

To pre-accelerate beams with high A/q-value a high source terminal voltage is needed. To offer a large acceptance for the typically slow particle beam one has to choose a low rf frequency at the linac front end. The linac itself has to provide a high voltage due to the low charge state. Therefore, the ions are stripped to higher charge states by a stripper foil at intermediate energies in many cases. The disadvantage is a severe reduction in beam transmission.

### *Energy variability*

Most experiments require a continuous output energy variation. If the flexible energy range is extended to very low energies, long multi-cell structures become less attractive. As a result, the linac has to be built by short cavities, resulting in increased complexity as well as in high efforts on construction, maintenance and operation of the linac.

### *Duty cycle*

The duty cycle of the post accelerator depends very much on the duty cycle of the driver accelerator. For example an ISOL-facility driven by a cyclotron delivers a continuous beam. In order to accelerate as many of the produced particles as possible it is obvious to build a cw post accelerator. On the other hand long pulse lengths as well as high repetition rate lead to a longer room temperature linac, as the cooling power per cavity unit surface area is limited. The higher the duty cycle, the more attractive is the use of superconducting cavities, as they are usually only limited by the accelerating gradient.

## 2 ACCELERATOR STRUCTURES

The combination of an ion source on zero or low terminal voltage with an RFQ and an DTL has been proven during the last two decades to be a robust and cost-effective accelerator concept. The reduction of high voltage equipment around the ion source is a big advantage in case of secondary beams with their complex production processes.

### Radiofrequency Quadrupoles

The RFQ is making exclusively use of rf electric fields for beam focusing as well as for acceleration. It has a high beam transmission, 60 % - 95 % of the injected dc beam is bunched and accelerated to the nominal energy, typically. Very short cells can be realized at injection, allowing the realization of low injection energies at convenient operation frequencies.

Table 1 shows a comparison of three different RFQ versions, which together can cover the full parameter range of interest.

The 4 rod-RFQ [1] and its modified versions like [2] are cost-effective solutions for the parameter range given in tab. 1. Duty cycles up to cw are operated successfully. The highest resonance frequencies can be realized by the 4 Vane-RFQ [3]. It is very efficient for proton and light ion acceleration even to higher energies. For cw operation a superconducting RFQ version built out of bulk Niobium is under development at INFN Legnaro [4].

The IH-RFQ ($H_{210}$-mode) is suited for the acceleration of heavy ions with low charge states [5]. It allows the choice of short distances between the electrode supports even at low operating frequencies. Therefore, no direct water-cooling along the mini-vanes is needed at duty factors up to 10 % typically. The IH-RFQ was developed within the High Current Injector project at GSI [6]. The split Ring-RFQ [7] as well as the spiral-RFQ and the Split Coaxial RFQ [8] are suited for about the same parameter range.

Table 1: Parameter ranges for different RFQ types

| Type | IH-RFQ | 4 Vane-RFQ | 4 Rod-RFQ |
|---|---|---|---|
| Mode | $H_{110}$ | $H_{210}$ | Coupl. $\lambda/2$ |
| Frequency (MHz) | 20-100 | 90-450 | 50-250 |
| A/q | 10-240 | 1-10 | 1-1000 |
| Energy range (keV/u) | 0.3-500 | 1-7000 | 2-2500 |

### Drift tube linacs (DTL)

The use of multi-cell cavities results in a fixed velocity profile. Different ions characterized by their A/q-value can be accelerated by setting adequate levels for the rf-amplitudes of the cavities and for the focusing elements. Energy flexibility can be provided by applying the UNILAC concept [9]: The linac consists of few multi-cell structures that can be turned off individually and thus can provide output energies in discrete steps. At the linac end a couple of short resonators are located, which can decelerate or accelerate the beam up to half the voltage, which is gained within one multi-cell cavity. All cavities are designed to function as a transport channel for beam energies corresponding to or exceeding the RFQ exit energy.

During the last three decades H-type DTLs were developed successfully which are superior to Alvarez or Wiederoe resonators with respect to rf power economy (see fig. 1) and achievable accelerating gradient. The key to the high shunt impedance – a measure for the power efficiency of a cavity- is the implementation of a dedicated beam dynamics allowing very slim drift tubes: With the `Combined Zero Degree Structure' KONUS [10] each structure period consists of a transverse focusing quadrupole triplet, a few rebunching gaps at synchronous rf phases of about -35$^{o}$ and a main acceleration section at zero rf phase, where the beam is injected with a some percent higher energy compared to the synchronous particle of this section.

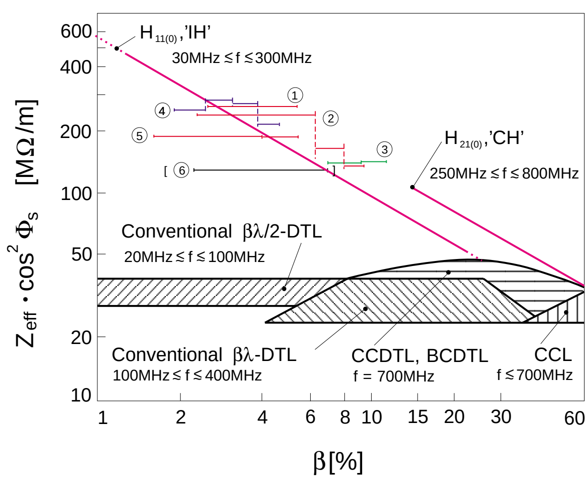


Figure 1: The shunt impedance of different linacs based on H-mode resonators compared to conventional resonators. 1. HLI-GSI, 2. LINAC III-CERN, 3. SchweIN, 4. ISOL, INS, 5. HSI-GSI, 6. TIT-Tokyo

### Short cavities

These linacs consist of cavities with two to four gaps where the drift tubes house no focusing lenses. The cavities are grouped and embedded in a periodic focusing structure, where the focusing elements can be solenoids, quadrupole singlets, doublets or even triplets. The energy variation can be provided very efficiently by readjusting the rf phases and amplitudes of each cavity. As the velocity acceptance of each short cavity is very wide, these cavities can be used over a wide velocity range. Consequently, the maximum end energy of this kind of linac depends on the mass to charge ratio of the accelerated beam.

This type of linac was at first developed to serve as a post-accelerator behind electrostatic machines like Tandems [11]. Superconducting linac versions using Quarter Wave Resonators were realized for beam velocities between β = 0.01 and β = 0.2 quite successfully [12,13]. For the velocity range form β = 0.2 up to β = 0.6 a Niobium Spoke cavity at 350 MHz is developed at Argonne, presently [14].

# 3 EXAMPLES OF RADIOACTIVE BEAM ACCELERATORS

This section will be dedicated to review some facilities currently under construction or planned. This list is by far not complete (the reader is referred to [15]). The aim is to describe the different concepts and to allow some comparisons.

### *REX/ISOLDE*

To avoid an expensive cw linac, special beam accumulation and breeding techniques were developed: The radioactive ions coming out of the primary target are collected and cooled inside a Penning ion trap and transferred to an EBIS source, where the charge state is increased to at least A/q < 4.5. The linac (see fig. 2) operated at a duty cycle of 10 % starts with an RFQ, followed by a short IH-structure and three 7-gap spiral resonators [16]. The energy of this accelerator can be adjusted between 0.8 and 2.2 MeV/u.

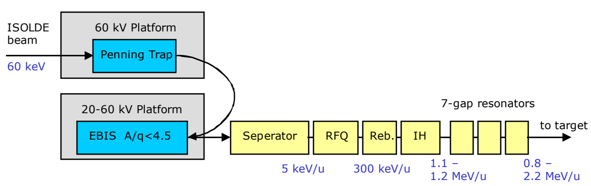


Figure 2: The REX-ISOLDE accelerator complex

### *ISAC at TRIUMF*

The post-accelerator for ISAC [17] consists of a 35 MHz four vane splitring RFQ to accelerate beams of A/q < 30 from 2 keV/u to 150 keV/u. At this energy the ions are stripped to 3 < A/q < 6. The beam is further accelerated by an IH drift tube linac at 105 MHz (shown in fig. 3) to a variable final energy between 0.15 and 1.5 MeV/u. The duty cycle is 100 %. The RFQ itself, a four-vane split-ring structure, has no bunching section, the beam is pre-bunched at 11.7 MHz by a single-gap buncher. The variable energy DTL is a separated function linac, based on the KONUS beam dynamics. It consists of five independent IH cavities providing the acceleration, quadrupole triplets outside the resonators for the transverse focusing and separated three-gap bunching cavities between the IH tanks ensuring longitudinal focusing.

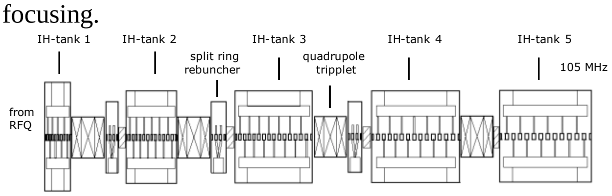


Figure 3: The ISAC drift tube linac

To accelerate the radioactive ion beams up to energies of at least 6.5 MeV/u, TRIUMF is designing ISAC II, which would use the existing RFQ. An ECR charge state booster at the front end would be added to achieve the required mass to charge ratio (A/q < 30) for masses up to 150. A new room temperature IH-DTL would accelerate the beam to 400 keV/u followed by a superconducting post-stripper linac based on Quarter Wave Resonators.

### *RIA*

The post-accelerator of the proposed RIA facility [18] will consist of an RFQ at the front end followed by sc Quarter Wave Resonators operated at 48.5 MHz. The linac will allow cw operation, the energy will be variable up to 12 MeV/u. The more challenging part of the facility will be the high intensity driver linac delivering a beam of several hundred kilowatts. The energy will be 400 MeV/u for heavy ions or 730 MeV for protons. The driver accelerator would start with an ECR ion source injecting into a room temperature RFQ and four short IH structures. An array of more than 400 sc cavities of nine different types, ranging from 58 to 700 MHz in frequency, will accelerate the beam up to the final energy.

It is also planned to accelerate multiple-charge-state beams inside the linac to increase the beam current for heavier ions, which would otherwise be limited by the state of the art in ion source technology.

### *MAFF*

The MAFF linac [19] is planned to accelerate neutron rich fission fragments produced in an inpile target ion source at the FRM II reactor. For charge breeding an ECR source will be applied (A/q < 6.5). The linac itself (duty cycle 10 %) is shown in fig. 4. It will consist of an IH-RFQ, an RFQ buncher as a matching section and three IH-tanks. The energy variation (3.7 to 5.9 MeV/u) will be done with three 7-gap IH-resonators.

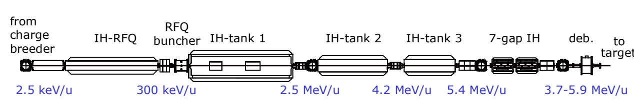


Figure 4: The planned MAFF accelerator

# 4 ACTIVITIES AT GSI

During the last decade two new linacs have been build at GSI:

- The high charge state injector (HLI) makes use of the highly charged ions that can be extracted out of an ECR ion source. With A/q < 9.5 these beams are accelerated by a 4-rod RFQ and one IH-tank up to 1.4 MeV/u with a duty cycle of up to 40%. This linac went into operation in 1992 [20].
- The high current injector (HSI) was built in 1999 [6]. It allows the acceleration of beams with A/q as high as 65, which is very attractive for the acceleration of radioactive ion beams, where low intensities prohibit stripping processes and charge breeding techniques fail because of short ion lifetimes. Moreover, the HSI is able to accelerate very intense beams, the current limit is calculated

to be i/mA = 0.25 * A/q, resulting in 10 mA $Ar^+$, which is reached in routine operation.

## *A new cw linac*

Currently GSI together with the IAP Frankfurt designs a new linac (see fig. 5) that should be optimized for the production of super heavy nuclei. To reach high luminosities - as the cross-sections are typically in the pbarn region - this linac should operate cw.

Up to an energy of 1.4 MeV/u the linac will look very much like the GSI high charge state injector (HLI): Behind the ECR ion source the particles are accelerated by a 4-rod RFQ up to 0.3 MeV/u, followed by a room temperature IH-resonator. With A/q < 7 (HLI: 9.5) cw operation will require only little additional cooling.

At 1.4 MeV/u the beam will enter the superconducting section of the linac. This part will consist of 7 CH-resonators, which will be described in the next section. The accelerating gradient inside these resonators will be above 6 MV/m even for cw operation. The linac will have a variable output energy (4.0 to 7.5 MeV/u) and an energy spread below +/-3 keV/u over the whole energy range. Therefore, the final energy adjustment (+/- 0.5 MeV/u) has to be done by short cavities (Quarter Wave Resonators).

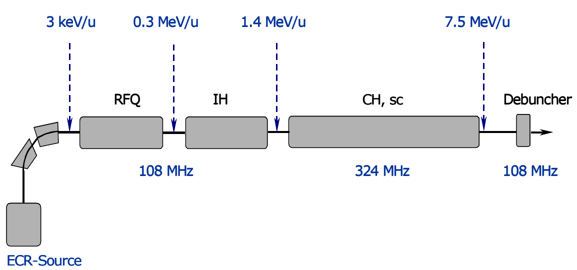


Figure 5: Proposal for a new cw linac at GSI for the production of super heavy nuclei. This machine would also be able to accelerate radioactive ion beams.

## *Cavity Development*

The high shunt impedance of IH-cavities decreases with increasing particle velocities (see also fig. 1). To accelerate particles to higher energies with adequate efficiency one has to build cavities using the next higher ($H_{211}$) mode, which is well known in accelerator physics from the 4-vane RFQ. The dangerous dipole modes observed in RFQs are short-circuited by the drift tubes. Further more, the CH-cavity exceeds by far the mechanical rigidity of IH-tanks. This opens the possibility to develop superconducting multi-cell cavities, the first ideas were presented in [21].

The work started with an analytical model that allowed a first optimization step of the fundamental cavity parameters. The consequent numerical simulations of the resonators were done using the MAFIA package.

Starting with a room temperature design the drift tubes and the shape of the stems were optimized. Special care was taken to keep the magnetic surface field well below

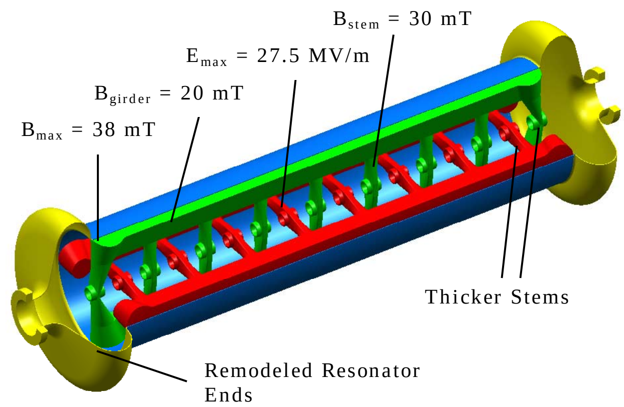


Figure 6: Three-dimensional view of a CH-mode cavity (352 MHz, $\beta$ = 0.17). The cavity dimensions can be found in tab. 2. Also shown are some field values calculated with MAFIA assuming an accelerating gradient of 6.7 MV/m: The maximum value of the magnetic (38 mT) is reached at both resonator ends, the maximum of the electric field (27.5 MV/m) on the drift tube surface.

the BCS-Limit of Niobium. By increasing the stem cross-section, the magnetic surface field could be reduced by approx. a factor of two, reaching up to 30 mT in the actual design. This optimization process caused an increase in the capacitive load and thus lowered the shunt impedance by 20 %, which is no drawback in case of a superconducting cavity. The maximum electric field (27.5 MV/m) has been found at the drift tube ends.

The girder undercuts used in room temperature IH and 4-vane cavities successfully to create the zero mode were found to be not the right choice for an sc cavity, as they lead to high magnetic surface fields in the region of the undercuts. The lowest surface fields were gained by combining two modifications: The tank cross-section of both resonator ends had to be increased. Following cavity production needs this is achieved by forming re-entrant

Table 2: Parameters and expected performance of the different prototype cavities

| | | | |
|---|---|---|---|
| frequency (MHz) | 352 | 433 | 700 |
| particle velocity (v/c) | 0.17 | 0.17 | 0.5 |
| Mode | $H_{21(0)}$ (CH) | | |
| Gap number | 18 | 18 | 10 |
| Length of the cavity (m) | 1.43 | 1.01 | 1.07 |
| drift tube aperture (mm) | 25 | 25 | 10 |
| transit time factor | 0.8-0.85 | | |
| tank radius (mm) | 185 | 130 | 105 |
| $E_{max}/E_{acc}$ | 4.1 | 3.9 | 5.2 |
| $B_{max}/E_{acc}$ (mT/(MV/m)) | 5.8 | 3.7 | 8.8 |
| $R/Q_0$ (kΩ/m) | 2.7 | 4.7 | 2.6 |
| Q-factor (4K,Nb) | $4.3\cdot10^9$ | $2.7\cdot10^9$ | $1.4\cdot10^9$ |
| diss. power (4K,Nb) (W) | 6.5 | 4.0 | 13.8 |
| shunt impedance (rt, Cu) (MΩ/m) | 44 | 68 | 39 |

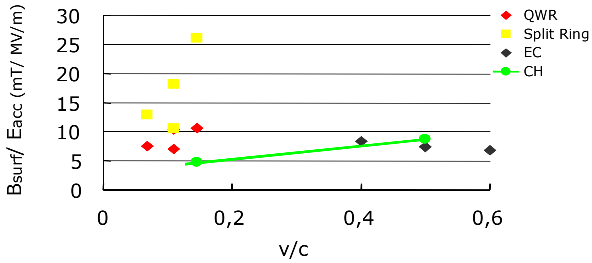


Figure 7: Magnetic to electric field ratio as a function of the particle velocity for different sc cavities. The data were taken from [22].

like resonator ends. To assure the field flatness, i.e. a constant accelerating field along the whole cavity, the local capacity at the cavity ends had to be further increased. This was attained by forming thicker stems.

Figure 6 shows the layout of the cavity, tab. 2 summarizes the results of the simulations. Comparing these parameters to that of existing sc cavities [22] reveals the potential of CH-cavities. One comparison is done in fig. 7 for a typical parameter: the maximum magnetic field on the resonator surface divided by the accelerating gradient. A small $B_{surf}/E_{acc}$ ratio indicates, that the achievable accelerating gradient will be higher.

A copper model of the cavity shown in fig. 8 was built at the IAP Frankfurt, first low-level rf measurements will take place shortly after this conference. The sc cavity will be built in cooperation with industry. Several production procedures are currently under investigation. A prototype cavity is expected to be delivered within 18 month.

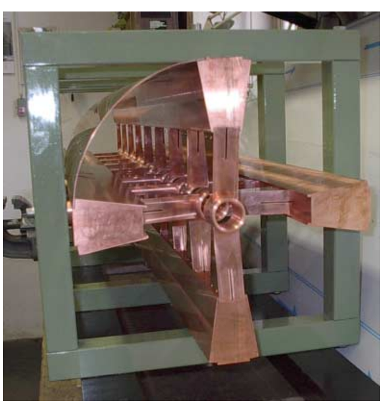

Figure 8: Photo of the CH copper model cavity.

## 5 CONCLUSIONS

Quite a large variety of linac technology for room temperature as well as for superconducting versions is available from existing accelerator laboratories. RNB specific conditions, however, such as beam production and separation processes, the limited time available for beam production and acceleration as well as the needed high beam transmission along the linac and high duty cycle causes a large variety of accelerator designs which have to be optimized for each individual application. High current heavy ion beams with high A/q-values can be efficiently accelerated by H-type cavities, RFQs as well as DTLs. They are also attractive for the acceleration of driver beams up to around 100 MeV/u. The design work of this type of cavity started recently. Our investigations indicate that CH-mode cavities are well suited to design sc resonators. The results of the numerical simulation of such a cavity are very promising. Using state of the art technology the fabrication of a superconducting CH-mode cavity is possible.

## 6 ACKNOWLEDGEMENTS

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