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Arguments to choose the Frequency for a new 180 MeV Linac and the associated Front-End Test Stand at RAL

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1 Introduction

This document intends to list all arguments for and against certain frequency choices which could be used for a 180 MeV linac at Rutherford. The most serious contenders are schemes involving: a) 200/400 MHz, b) 400/800 MHz, c) 235/704 MHz, d) 352/704 MHz, and e) 324 MHz

2 Beam Funnelling

In case the ion source fails to deliver the required currents and duty cycles a beam funnel could help to achieve the necessary beam intensity.

Up to now there have been two experiments for a beam funnel after an RFQ. One of them is well documented and was constructed as a one-leg funnel at 5 MeV with a 425 MHz strongly collimated (40 %) input beam [4], [5]. It was found that 25-40 mA beams can pass the funnel structure with 100 % transmission without a major transverse or longitudinal emittance increase (within measurement precision). However, no reference was made to the used duty factor (which leads to assume that the duty factor was very low) or if the longitudinal beam properties satisfied the conditions for injection into a higher frequency RF system. Other critical points are the cooling of the funnelling device and the beam dynamics after the funnel. Any development of beam halo can only be measured after several focusing periods and was not assessed in the experiment. Since the beam will not see a constant field along the length of a bunch, different portions of the bunch will experience different deflection forces, which will yield transverse oscillations after the funnel device.

More recent efforts towards funnelling which will be detailed in the following fall in two categories: a) funnelling at an energy of around 20-30 MeV (so far theoretical work), b) low energy RFQ funnels (theoretical and experimental work)

For recent high-power proton linac studies (e.g. ESS [1] [2], CONCERT [3]) a merging of the beams at an energy of 20-30 MeV is suggested to avoid beam blow-up through space charge. Furthermore, the space charge forces in the two chopper lines would be relaxed putting less constraints on the beam dynamics design in this area. The required frequency doubling demands that the subsequent accelerating structure is reasonably efficient at the higher frequency. For high-intensity linacs this limits the frequency after the funnel to ≈ 400 MHz if one wants to avoid a high number of single RF sources (see section 4). Neither CCDTL, SDTL nor traditional DTL structures are practical at higher frequencies for this energy. Higher energies for beam funnelling are excluded because of the required voltages for the funnelling device.

The 2nd scheme is studied by IAP suggesting beam funnelling within a funnel-RFQ [6]. With this device every eventual beam loss will take place in the RFQ, at low energy. Up to now these funnels still suffer from emittance growth (≈ 60 %) but given enough time for R&D they represent an interesting option for the 352/704 MHz and 400/800 MHz option: in case of too low source currents one could replace the source and RFQ part with a half-frequency front-end instead of building two complete legs including source, RFQ, chopper line, and first DTL tank. Since the RFQ basically defines the longitudinal phase space, the risk of additional phase and energy jitter is much lower than for scenarios with two frequency jumps at later stages in the linac.

Taking into account the arguments which relate frequencies and structures in section 4 we have the following options for accelerator designs with or without beam funnel:

- Funnel at 20-30 MeV with a frequency doubling at the funnel. This option demands an upper frequency limit of $\approx$ 400 - 450 MHz after the funnel yielding the following possibilities: 200/400 MHz, 176/352 MHz, 162/324 MHz. All of these options imply a relatively low frequency for acceleration from the funnel up to the final energy of 180 MeV. This results in a long and expensive accelerator and is so far only adopted by JPARC.
- RFQ funnel with one frequency doubling at the funnel and the possibility for a 2nd frequency doubling at a convenient energy. This yields to more flexibility in the accelerator design and enables a high frequency for the high-energy section of the linac.

Beam funnelling is an interesting and challenging R&D project that is a fundamental requirement for all schemes looking at heavy ion fusion. However, it also represents a major complication for the beam dynamics and adds a work-intensive research field to the design of a high-intensity linac or a front-end test stand. It also introduces a major source for beam mismatch and particle loss that has to be studied very carefully.

3 RF systems

324 MHz is for the JPARC [13] project and is supposed to be the lowest frequency where klystrons are still efficient. The devices for this project are delivered by Japanese companies. Outside of Japan, however, this frequency is not used.

352 MHz was the frequency of the CERN LEP RF system and has thus led to a variety of projects adopting this frequency. The 1.1 MW CW Thales klystrons have been in operation for many years and their properties are well known. During the last 10 years many projects chose this frequency because there was a chance of recuperating klystrons, waveguides, and cavities from CERN. Even though this source is more or less exhausted by now, a lot of R&D effort is still made for 352 MHz cavities, fast phase shifters, klystron pulsing, etc. 702 MHz klystrons are under investigation by CERN for use in Linac4 [7] and the SPL [8]. They are also required for a 702 MHz test stand for superconducting cavities at CEA and for the European PDS-XADS reference scenario [20]. The most likely supplier will again be Thales.

The RF system for the ISIS linac is based on a 200 MHz RF system and Thales offers powerful diacrodes (TH628) for this frequency that have been demonstrated to deliver 4.5 MW in pulsed operation for 0.5 ms pulse length. These devices are also being studied for a possible upgrade of the LANSCE RF system, based on 200 MHz.

400 MHz is the frequency of the SNS linac up to $\approx$ 90 MeV as well as for the LHC RF system. SNS is using 2.5 MW klystrons [9] while LHC is using 300 kW klystrons due to the low power consumption of the LHC superconducting cavities [10]. 800 MHz klystrons have been developed for the SNS in two varieties: 5 MW and 550 kW for the CCL and the superconducting linac part, respectively.

235 MHz is not available "off the shelf" but Thales offered to modify the existing diacrode (TH628) for a price of 200-300 kEuros. The device would then cost 100-200 kEuros per item.

In conclusion: 400/800 MHz klystrons are available from the US, 352/704 MHz klystrons are available from Europe with a small possibility of getting odd pieces of equipment for free from CERN. 200 MHz diacrodes and tubes are available from Thales, 324 MHz klystrons are available from Japanese industry.

4 Beam dynamics and structure choices

For low energy beam acceleration with normal conducting accelerating structures the classic Alvarez DTL is still the most efficient structure. This stems from the fact that for low energy acceleration the focusing periods are short but the transverse focusing has to be very strong. The only way to satisfy both requirements is to include the focusing quadrupoles in the accelerating structure which is done in case of the Alvarez DTL. Since the size of the quadrupoles (and therefore the drift tubes) does not change with the frequency this means that high frequencies yield higher RF losses than low frequency structures (at least for a certain energy range, compare Fig. 4, [11].

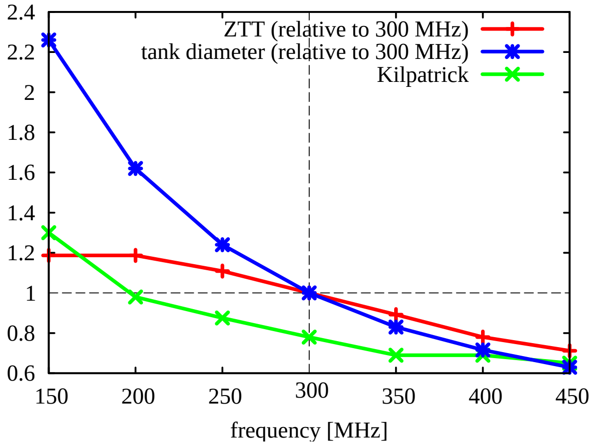

Figure 1: ZTT, Kilpatrick, and tank diameter versus frequency for a DTL cell at: 15 MeV, gap/$\beta\lambda$ = 0.3, drift tube face angle: 10 deg, drift tube diameter: 160 mm, $E_0 = 2.5$ MV/m.

Due to $\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$ the focusing force of the magnetic quadrupoles becomes more effective at higher energies and one can take the quadrupoles out of the accelerating structure and use CCDTL or SDTL tanks for further acceleration. Having removed the space requirements for the quadrupoles one can then also double or triple the frequency in order to shorten the linac and to increase the maximum electric field gradient that can be used in the cavities. Before doing this, however, several factors have to be taken into account: a) the spacing between adjacent gap centres of neighbouring coupled cavity (CCDTL, or CCL) tanks has to be an odd multiple of $1/2\beta\lambda$ and they have to provide enough space to accommodate the quadrupoles ($>$ 20 cm). These distances have to bridged by coupling cavities which, if they exceed $3/2\beta\lambda$, consist of multiple coupling cells which become expensive and impractical, meaning that there is a certain energy/frequency limit for the use of these structures. In Linac4, for instance, the CCDTL can only be used from 40 MeV onwards at a frequency of 352 MHz using a $3/2\beta\lambda$ distance between tanks because at lower energies there is not enough space for the quadrupoles. b) SDTL tanks are either individually powered or they use an expensive waveguide system to split power from klystrons to the single tanks. This means that these structures are only effective if one finds a cheap solution for the power supplies (e.g. power splitting cavities, which are up to now only proposed as power combining cavities [12]), or if one uses a high number of cells per SDTL tank and thus accepts compromises on the beam dynamics performance.

In addition to the above arguments the number of frequency jumps is limited by the development of phase and energy jitter which is due to the gradient and phase variations in the RF system. Four fold frequency jumps have been realised in the past (e.g. LANSCE) but have been accompanied by severe beam loss after the transition. For the 235/704 MHz scheme the triple frequency jump has been studied using "state of the art" tolerances for the RF system (0.5 deg, 0.5 % rms errors) with the conclusion that the transition is feasible but that it will result in emittance growth and final phase/energy jitter and that is just about acceptable [11]. This means that the maximum frequency jump within the planned 180 MeV linac should not exceed a factor of three. Otherwise the tolerances for the RF system become extremely challenging.

Any design based on 352 or 400 MHz has to use permanent magnet quadrupoles in the first DTL tank if the DTL input energy is 2.5 or 3 MeV. The current "frequency/energy" limit for electromagnetic quadrupoles is set by the Japanese JPARC [13] project with 324 MHz at 3 MeV. SNS is using permanent quadrupoles for the whole DTL up to $\approx$ 90 MeV, which means that there is no "knob" to rematch the beam in case the "paper design" does not coincide with the evolution of the real beam. There is also very little margin to change the beam currents, since the lattice is designed for a specific current. CERN chose to use permanent quadrupoles only in the first DTL tank which allows them to use a DTL from 3 MeV onwards, but still retains the possibility to adapt the overall lattice to different beam currents and beams of different shape and/or orientation than used in the “paper design”.

A low frequency front-end (200 or 235 MHz) enables the use of a rod RFQ and builds thus on experience that is already present at ISIS. Higher frequencies demand a vane RFQ and offer the possibility to explore this technology and benefit from a wide range of existing designs, especially at 352 MHz. If the test stand is meant to be generic for a variety of high-intensity front-ends one has to study if a rod RFQ is at all suitable for a high duty cycle machine.

Low frequencies in the front-end ease the task of the low-energy beam chopper [14], [15] which has to provide a deflecting field of up to several kV that rises between two subsequent bunches. For this reason a front-end based on 200 or 235 MHz puts less constraints on the beam chopper than a 352 or 400 MHz based system. On the other hand the chopper for the new 180 MeV ISIS linac only has to chop 35 bunches out of a bunch train of 118. This means that even if one or two bunches are lost at each transition from “chopped” to “un-chopped” operation, the whole scheme will not be jeopardised. Due to the relatively low duty cycle of the new ISIS linac (1.5 %) and the relatively easy chopping scheme (35 out of 118) the RAL chopping line can accept much more losses than for instance the CERN scenario where 3 out of 8 bunches have to be chopped at duty cycles of up to 10 %. No matter at which frequency the RAL test stand will operate, it will offer the possibility to explore how precise the RAL chopping scheme can work and future high-intensity linac applications (like spallation sources and neutrino factories) will be able to base their machine design on the experience with the RAL front-end test stand.

5 Politics and collaborations

Choosing a 400, 800 MHz based RF system means that possible collaborations are limited to the SNS, a project that is already fully designed and under construction. Since SNS has no more R&D needs regarding the RF system a possible collaboration will be one sided: Rutherford needs something and SNS can give something.

The same arguments apply for schemes based on 324 MHz and JPARC.

Choosing a 200 MHz front end means that the RAL development stands alone with little technical overlap to any other high-intensity linac project except a planned upgrade of the LANSCE linac which uses newly designed 200 MHz RF tubes and power supplies! No work is planned there on the 200 MHz accelerating structures.

The same holds for a 235 MHz front-end. However, for the high energy part of the envisaged 235/704 MHz linac one could profit from developments at CERN and elsewhere in Europe. The section from 90 to 180 MeV could be an exact copy of the Linac4 design at CERN.

A 352/704 MHz based design offers the widest range of possible collaborations and technical overlaps with other projects. 352/704 MHz linacs are being designed for CERN, GSI [16], CEA [17], the Indian Proton Driver Project [18], PEFP (Korea) [19], PDS-XADS (Europe, 25 participants!) [20]. Furthermore, with the CERN front end test stand being developed in parallel with the RAL test stand, one has the unique opportunity to test two different design strategies for a low energy beam chopper at the same time. After the tests both labs can pick the best technological solutions of both approaches. It has to be stressed that this does not represent a duplication of R&D effort but that we are really looking at two completely different designs. This does also open a possibility for RAL to test the complete RAL chopper line at CERN in case the UK funding does not suffice to construct source + RFQ + chopper + diagnostics.

6 Conclusions

There are four realistic scenarios for a 180 MeV linac at ISIS:

200/400 MHz : **pros:** only scheme that offers the possibility of a medium energy beam funnel, 200 MHz is already used at ISIS, 200/400 MHz diacrodes/klystrons are available, possible collaboration with Los Alamos on 200 MHz RF based on diacrodes, **cons:** long and expensive linac, no collaborations on 200 MHz accelerating structures, it is unlikely that the 400 MHz accelerating structures from SNS is suitable, → high R&D effort for RAL (in house development of: RFQ, DTL, ion source, chopper line).

400/800 MHz : **pros:** copy the SNS design, RF systems are available, short linac, possibility of RFQ funnel, **cons:** one-sided collaboration with one single partner in the US, by the time RAL could start building the SNS design is already 15 years old, questionable SNS chopping scheme, inflexible design due to permanent magnet quadrupoles in DTL, no medium energy funnel → low R&D effort for RAL (in house development of ion source, chopper line, and possibly DTL).

235/704 MHz : **pros:** eases chopper design, possibility to copy 704 MHz CCL from CERN, active R&D program in Europe on 702 MHz, alternative high-intensity front-end at an alternative frequency, possibility for RFQ funnel **cons:** 235 MHz diacrodes need to be developed (can be done by Thales), R&D for 235 MHz accelerating structures has to be done at RAL, triple frequency jump, no medium energy funnel → medium R&D effort for RAL (in house development of ion source, chopper line, RFQ + DTL up to 90 MeV).

352/704 MHz : **pros:** RF systems are available, accelerating structures can be copied from Linac4, many international R&D programs study accelerating structures (normal and superconducting) at these frequencies, RF test stands are under construction, many European collaborations are possible, two chopper line designs (CERN, RAL) can be tested and compared, existing RFQ designs, possibility of collaborating with India/Korea on 352 MHz RFQs (two existing devices), complete RAL chopper line could be tested at CERN, short linac, possibility of RFQ funnel **cons:** less original approach, no medium energy funnel → little R&D effort for RAL (in house development of ion source, chopper line)

324 MHz : with or without frequency jump: **pros:** RF systems and accelerating structures can be copied from JPARC, **cons:** single partner for collaboration, by the time the RAL linac will be built the JPARC technology will no longer be 'cutting edge' → little R&D effort for RAL (in house development of ion source, chopper line).

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scheme	RF systems	collaborations	beam dynamics	RAL R&D	pros/cons
176/352/704 (funnel)	existing klystrons for 352/704 MHz, existing tubes or diacrodes for 176 MHz	CERN, GSI, IAP, CEA, Orsay, INFN, India, Korea, Russia	4 fold frequency jump: high energy/phase jitter, difficult funnel section	LEBT, MEBT, funnel, RF control, beam steering after funnel	large parts of Linac4 can be copied, a lot of international R&D work, existing technology for RF, cavities, magnets, funnel prevents ion source shortcomings, difficult funnel, high jitter, rod RFQ can be used
200/400/800 (funnel)	existing klystrons for 400/800 MHz, existing tubes or diacrodes for 200 MHz	SNS	see above	LEBT, MEBT, RFQ, funnel, RF control, beam steering after funnel, electromagnetic quadrupoles	klystrons from SNS, 200 MHz is known at ISIS, difficult funnel, high jitter, funnel prevents ion source shortcomings, rod RFQ can be used
352/704	existing	CERN, GSI, IAP, CEA, Orsay, INFN, India, Korea, Russia	straight forward	ion source, LEBT, MEBT	large parts of Linac4 can be copied, R&D on RF and accelerating structures is done by CERN and other EU labs, SC technology is being developed, well known technology, once the test stand is completed one can choose between the CERN/RAL approach for the chopper line
200/400	existing	SNS (on 400 MHz RF)	straight forward	in house design for linac and all components	long linac, inefficient structure above 90 MeV, all designs have to be done in house, no collaborations on major issues, more conservative than SNS
400/800	existing	SNS	straight forward	ion source, LEBT, MEBT, 400 MHz DTL with el.magn. quads	the whole linac can be copied from SNS, or modified to use el.magn. quads, technology will be 'old' by the time RAL needs it, one-way collaboration with one partner, inflexible design
(162)/**324**(648)	existing for 324 MHz	JPARC	straight forward	ion source, LEBT, MEBT, everything for 162 or 648 MHz	collaboration with only one partner, long linac if used w/o freq. jump, techn. will be 'old' by the time RAL needs it
235/704	existing for 704 MHz, R&D for 235 MHz can be bought	CERN, Orsay, CEA, INFN	tricky but feasible	ion source, LEBT, MEBT, RFQ, 235 MHz linac up to 90 MeV	SCL (90-180 MeV) can be copied from Linac4, rod RFQ can be used, original scheme that eases chopping