HIGH POWER PROTON/DEUTERON ACCELERATORS

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Abstract

High power proton and deuteron linear accelerators can give rise to a large variety of scientific applications, useful for both fundamental and applied research. Thanks to the on-going efficient development of the Superconducting RF (SRF) technology, more and more projects based on such machines have emerged during the last 2 decades. This paper will review these existing high power proton/deuteron accelerator facilities or projects, trying in particular to emphasize in each case the various specificities and challenges related to the SRF technology.

GENERAL OVERVIEW

Introduction

There is presently a clear growing demand for high-power proton or ion accelerators to better support various fields of science like particle physics, nuclear physics, or neutron-based physics. These applications typically ask for beams with very high mean power in the GeV range, which goes significantly beyond the present capability of most of existing facilities.

The panorama of high-power proton and deuteron beams is presently largely dominated by room-temperature machines as illustrated in Figure 1, with the single exception of the recently built US Spallation Neutron Source (SNS), which delivers its ~1 MW proton beam thanks to a 1 GeV SRF-based linac. In order to reach and exceed the MW range, SRF linear machines are indeed becoming more and more mandatory, leading to several new superconducting accelerators being constructed or planned.

SRF as Low as Reasonably Achievable

One of the main reasons among others for using SRF accelerators is obviously to minimize the overall power consumption and therefore decrease the operating costs. But one has to keep in mind that this statement isn't always true since it heavily depends on the operating RF or beam duty cycle (*dc*), as shown in the above simplified formula: when *dc* approaches zero, the total power consumption P_{total} is dominated by the power required by the cryogenic plant P_{cryo}, which will in turn encourage to choose a full room-temperature solution.

$$P_{\text{total}} \approx dc \times \left(P_{cav} + P_{beam}\right) + P_{cryo}\,. \tag{1}$$

This straightforward statement suggests that for a given duty cycle, one can ideally find an optimal transition energy between the normal conducting (NC) and the superconducting (SC) structures of a given linac, which will minimize its overall power consumption. This is illustrated on Figure 2 that plots the actual NC to SC transition energy for the main high-power ion SRF linacs presently existing or planned. Two main families clearly appear: the pulsed proton machines (SNS, ESS, SPL), with duty cycles in the range of a few percents and transition energies in the vicinity of 100 to 200 MeV, and the Continuous Wave (CW) machines for which the worldwide rule has clearly become since a few years "SRF As Low As Reasonably Achievable" (i.e. down to

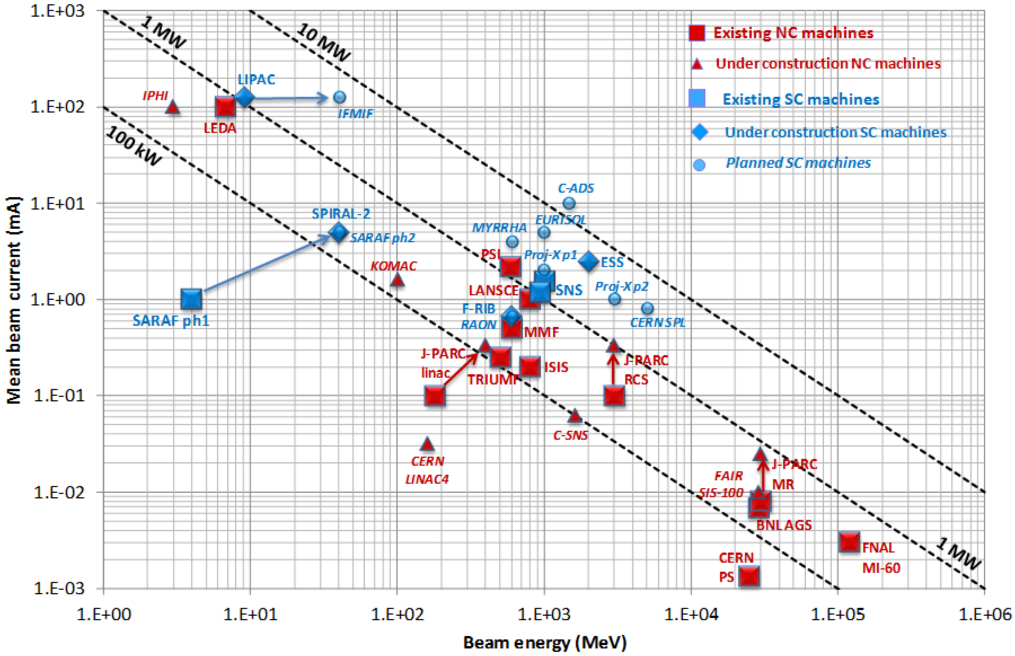

Figure 1: Panorama of high power proton/deuteron beams worldwide (non exhaustive plot).

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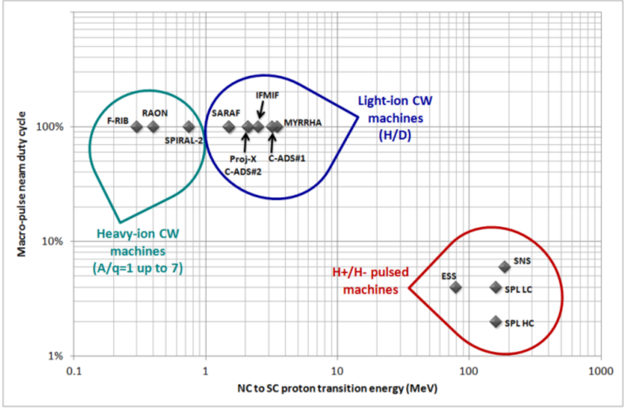

Figure 2: Beam duty cycle vs NC/SC transition energy for present high-power ion linac machines & projects.

the RFQ). It is by the way to be underlined that most present high power proton/ion linac projects plan to operate CW. Such machines were previously very difficult to envisage due to the enormous power dissipations in the copper RF cavities; they have been clearly made feasible thanks to the recent progress of SRF technology.

Panorama of SRF Cavities

The SRF accelerating cavities to be developed and used in these machines can be roughly gathered into 4 different families, each one covering a given range of beam velocity as shown in Figure 3. Right after the RFQ, low frequency (~80 MHz) Quarter-Wave Resonators (QWR) are used for very low beta acceleration of heavy ions, whereas higher frequency (~160 MHz) Half-Wave Resonators (HWR) or CH structures become preferable when considering proton or deuterons CW acceleration. Spoke cavities are then very promising as far as medium-energy range is concerned, with a lot of prototyping going on presently worldwide around ~350 MHz. Finally elliptical cavities obviously remain the more efficient structure for higher energies, from typically 200 MeV on.

This paper will try to review the state-of-the-art of proton and deuteron high-power linacs, with a special focus on the following machines or projects: SNS – the present reference – ESS, SARAF, IFMIF, Project X – the more or less “under construction” machines – SPL, MYRRHA and C-ADS – the main other on-going projects still in the design phase. Heavy-ion high-power linacs, like F-RIB, RAON or SPIRAL-2, which will actually become soon the world first operating CW high-power SRF linac for proton and deuteron acceleration, will not be included in this overview; more information on these projects can nevertheless be found in the present proceedings [1-3]

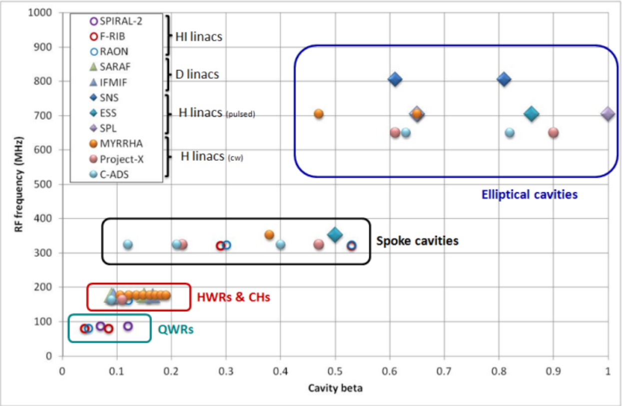

Figure 3: Panorama of SRF structures to be used for proton or deuteron acceleration in high-power linacs.

ELLIPTICAL-BASED SRF HIGH POWER PROTON LINACS

High-Power Pulsed Proton Linacs

The SNS [4,5] is presently the only operating high-energy SRF linac for protons – actually H$^-$ – and the first MW-class one. It is pulsed but at relatively high duty cycle (6% macro-pulses). Originally designed to produce a 1.44 MW proton beam on target at 1 GeV, the SNS present routine operation point is limited to 1.1 MW, with a final beam energy slightly below design value (935 MeV). The SNS is presently the second more powerful proton accelerator worldwide, the first one still being the PSI cyclotron with 1.3 MW [6].

The European Spallation Source (ESS) project [7], which is about to start its construction phase (first neutrons planned in 2019), is also based on a high-power proton linac, but with higher final energy (2 GeV) and beam power (5 MW). Operating at 4% duty cycle, its design is very similar to the SNS, including two families of elliptical SRF cavities covering the 200 MeV - 2 GeV energy range [8], as shown in Figure 4. The main noticeable difference is that the CCL copper section is replaced in ESS by superconducting Spoke cavities [9]. This can be considered as a rather risky choice since the full demonstration of the technology is still to be fully established, but this also clearly underlines the very high interest of SRF technologies for medium-energy acceleration, even in the case of pulsed operation.

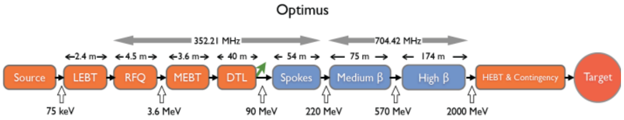

Figure 4: ESS linac architecture [7].

The CERN SPL (Superconducting Proton Linac) [10] is the third one in the family of high-power pulsed proton linacs. This 4 MW machine is especially studied as a possible proton driver for a neutrino physics facility. It would be used as an extension of the new CERN Linac4 160 MeV injector, presently under construction, to provide a possibility for direct injection into the PS2. Like for SNS and ESS, the design of the SPL 5 GeV linac is also based on SRF elliptical cavities of two different types –β=0.65 and β=1.0 in this case [11].

The SNS Operational Feedback

One of the main challenges to face for high-power proton machines is obviously the management of beam losses and of the induced activation. In the SNS, the situation is very satisfactory on this point of view, with an activation level very well contained. Nevertheless some unpredicted beam losses have been observed, which have been recently explained by the intra-beam stripping phenomenon [12]: accelerating protons instead of H^- in the SNS actually leads in 30 times reduced beam losses, underlining that proton operation should be generally favoured when possible in such machines. Moreover, due to the very high beam power density, the SNS showed that the Machine Protection System (MPS) needs to be very carefully operated, and the beam power ramping up performed with great care – 3 years have been actually needed to reach the 1 MW level in the SNS case.

All in all, the SNS machine is running extremely well, with an overall recorded availability higher than 90%. In particular, the SRF linac has proven to be extremely reliable (less than 1 trip per day), actually substantially more reliable than the normal conducting linac despite the high number of RF stations and the complexity of cryogenics. Looking in more details at the SRF linac systems downtime breakdown (cf. Figure 5) shows that most of the failures come from RF systems, as expected, and very few from the SC modules themselves. This very good behaviour of the SRF systems actually encourages the SNS team to plan a 3 MW upgrade by adding some additional cryomodules to reach 1.3 GeV while increasing the beam current. The replacement of the DTL plus CCL by SRF cavities is also being considered [14].

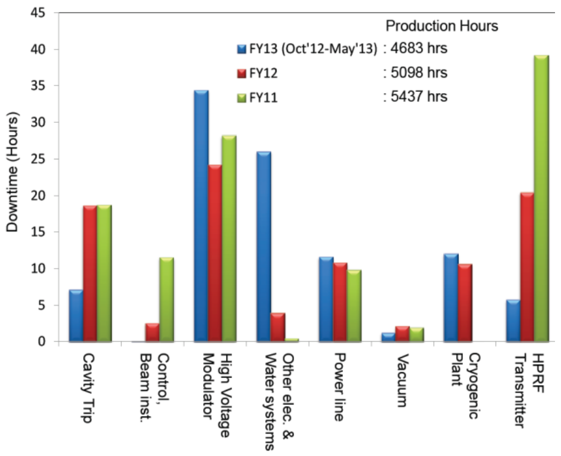

Figure 5: SNS SRF linac downtime breakdown [13].

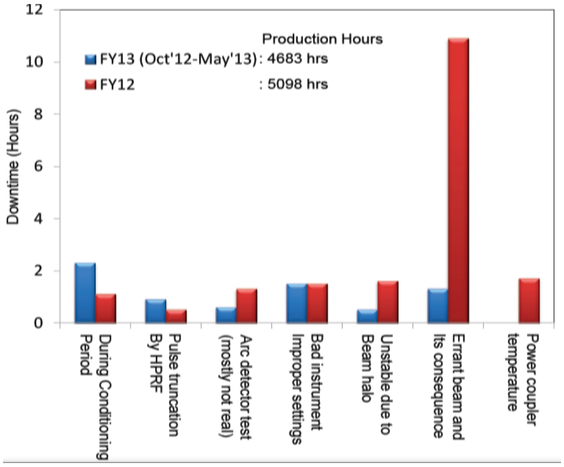

Figure 6: SNS SRF cavity trip breakdown [13].

As far as SRF cavities operation is concerned (cf. Figure 6), the recorded trips are mainly due to "errant" beam hitting the cavity surface, which can lead to gas desorption creating an environment for arcing with RF; such errant beams, usually partial beam pulses with low current or/and incorrect energy, are typically created after a MPS system trigger, which is most of the time initiated by discharge/arcing in the warm part of the linac and/or by the induced beam losses. More generally, SRF cavities performance degradation is also observed, but can be most of the time recovered by thermal cycling of the cryomodule. It is finally to be stressed that multiple cryomodule repairs have been performed in house for various reasons (coupler window leaks, helium or vacuum leaks, tuner failures, HOM couplers...).

Accelerating Gradients

One of the main design constraints for high-power proton linacs is related to the maximum accelerating gradient reasonably achievable in SRF cavities. In order to minimize the investment cost, there is obviously a tendency to push the gradients as much as possible to minimize the linac length. This is especially true in the case of pulsed operation for which the dynamic cryogenic load remains rather moderate in the overall cost balance. The ESS and SPL projects therefore logically tends to base their design on very high accelerating gradients (e.g. 20 MV/m for the ESS β=0.86 cavity in the very last "Optimus" design which is supposed to significantly decrease the machine cost [6]) at the expense of obviously increased technical risks.

The amplitude of this risk is illustrated in Figure 7 that shows the present SNS operating gradients superimposed with a few projects design goals. This plot indeed shows that the target gradients are usually very ambitious, especially in the case of pulsed machines – 25 MV/m for the SPL β=1 cavity is even higher than the X-FEL 23.6 MV/m specification [15]. It also strongly suggests that margins and operational flexibility should be a key issue to seriously consider during the design phase to secure beam operation within nominal parameters. As a matter of fact, the SNS experiences a very huge gradient variability, which is by the way the main reason why the machine final energy is presently limited to 935 MeV in "safe" standard operation. This variability is directly related to the fact that achievable gradients in the SNS are limited, especially at high duty factors. This is most of the time due to heating from electron activity (mutipacting,

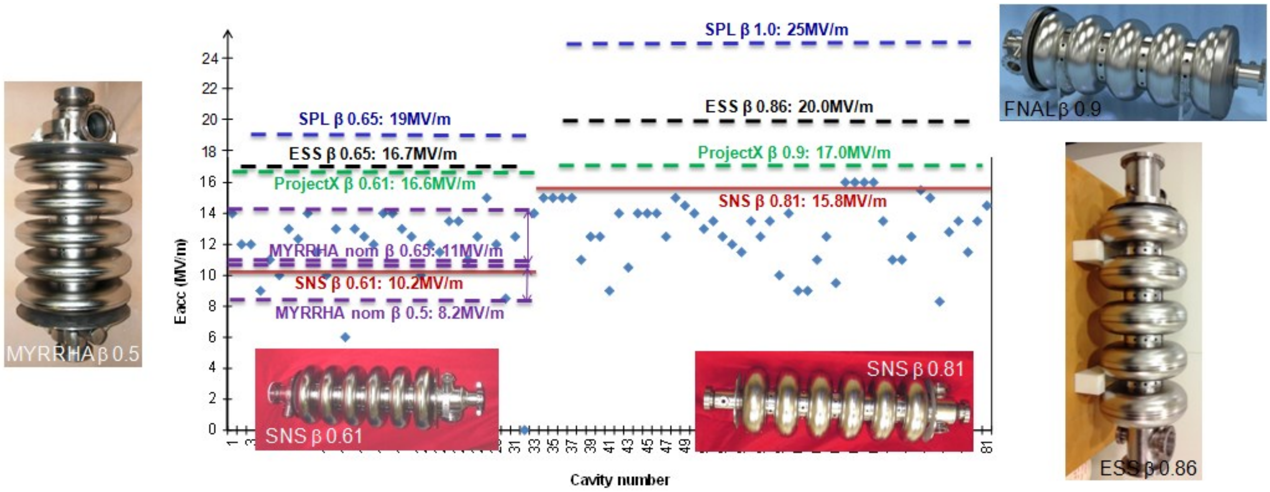

Figure 7: SNS operating gradients (blue points [14]) superimposed with a few project design goals (lines).

field emission even including collective effects within cryomodules [5]). In practice; almost every SNS run, a few cavities actually experience problems, resulting in degraded set-points (lower accelerating field) or even in a complete turn-off and therefore leading to a complete longitudinal linac retuning. Also note that this observation underlines how crucial is the SRF cavities cleanliness and surface preparation to secure optimal operation.

Power Couplers

Besides cavity gradients, the other main constraint for high-current linac designers is the maximal RF power available from the main power coupler. This power is presently a clear technological limit, in particular when dealing with pulsed operation. In the case of the SNS for example, the design limit was set to 550 kW peak power, corresponding to 48 kW mean power, but the coupler was tested up to about 2 MW in test stand. In the case of ESS, the design limit has been set to 1.1 MW peak power, which is presently considered as the safe "state-of-the-art" limit for such power couplers.

A lot of R&D is being performed worldwide on high power couplers (e.g. CEA, CERN [16], CNRS [17], FNAL...), both for pulsed and CW operation, and it's interesting to notice that most of the proposed designs are very similar. They are usually derived from the 805 MHz SNS coaxial coupler [18] – which was in turn scaled from the original KEK 508 MHz coupler [19] – with fixed coupling and in most of the cases only some differences on the cooling strategy. These very strong similarities would therefore suggest to try to concentrate the R&D effort worldwide on a single power coupler design for all planned machines (1 MW pulsed / 100 kW CW typically). This would probably lead in a more efficient development work in order to, in a second step, try to push the limits towards higher powers.

Other Components

It has now become a general agreement that High Order Modes (HOM) couplers are not mandatory for high-power proton linacs. As a matter of fact, several beam break-up analyses have shown that the HOM voltages build-up is not an issue in such machines [e.g. 20], thanks in particular to the natural damping provided by the power coupler and to the high HOM frequency dispersion from cavity to cavity. One has therefore only to check that HOMs are sufficiently away from the main machine lines, which is usually the case. Even in the case where such a very unlikely event would happen, a detuning/retuning of the concerned cavity might be sufficient to slightly move the HOM away from the beam resonance, at least for the "soft" elliptical cavities. The fact remains that no HOM couplers are foreseen for the cavities of ESS, Project X or MYRRHA; moreover, SNS is presently in the process of taking out all HOM feedthroughs (15 cavities are already operating without HOM coupler).

In pulsed operation, SRF elliptical cavities particularly suffer from the Lorentz force detuning. Contrary to SNS for which this dynamic detuning remains manageable with RF power, active detuning with piezo-actuators have become a real necessity for ESS and SPL due to the higher operating gradients. Most of the present developed tuners, usually based on the "Saclay-type" design, therefore plan to include such additional fast tuning capabilities [e.g. 21], the reliability of which clearly needs to be further improved given the quite mixed recorded performance of presently used piezo-systems in accelerator-like environment.

Finally, concerning cryomodule design, the main goal in pulsed operation is obviously to minimize static heat loads, which by the way is not the primary concern for CW operation as discussed here after. Present designs are usually inspired either from the DESY-style concept or, more often, from the CEBAF concept (e.g. SNS). Information about the ESS and SPL designs for example can be found in the present proceedings [22-24].

CW SRF HIGH POWER LINACS

Main Specificities of CW Operation

Dealing with CW beam operation slightly changes the overall picture described here before on a few points.

First of all, as already underlined, CW operation favours the use of SRF cavities down to the RFQ output or nearly: all CW high-power linac projects indeed plan to use low-beta SRF cavities (QWR, HWR, CH, Spokes) as shown in Figure 2. The point here is that these technologies, unlike elliptical SRF cavities, are not yet very mature, especially for high current operation: the only low-beta SRF cavities presently operating with a high-current beam are actually the SARAF HWR ones [25], with quite poor results as detailed here after. But besides cavities development, one of the main difficulties of such superconducting injectors is also to find the good compromise between very high compactness, which is required for beam dynamics reasons at such low velocities, and feasibility/operability in terms of beam diagnostics and maintenance especially. A complete technology demonstration is therefore clearly required for such low-beta CW SRF linacs. This is by the way what is presently being initiated in the case of Project-X (PXIE demonstrator [26]) and of IFMIF (LIPAC demonstrator [27]).

Another difference is that the peak beam current is usually much lower in CW operation compared to pulsed operation – except in the IFMIF case. This obviously leads in reduced space-charge effects on the beam dynamics point of view, but on the other hand, this also implies lower optimal RF coupling (higher Q_{ext}) and therefore narrowest cavity bandwidths. The management of microphonics thus becomes a more serious issue to be considered. For this reason, several CW linac projects plan to use piezo-based tuners for microphonics' compensation and favour a cryogenic operation at 2 K to minimize the helium bath pressure fluctuations. There is presently a general agreement for a 2 K operation down to 350 MHz spoke cavities at least. MYRRHA and Project-X are even fully 2 K down to their low frequency first cavities (162.5 MHz and 176.1 MHz respectively), although a 4.5 K operation would be theoretically more efficient in this case given the already very low BCS surface resistance at these frequencies.

Even if the peak beam current is usually lower, the mean beam current is actually often higher in CW beam operation: while SNS and ESS exhibit 1 mA and 2.5 mA average beam intensities respectively, MYRRHA is for example 4 mA, SARAF 5 mA and C-ADS 10 mA. This shows that beam loss mitigation and MPS management remain very high concerns for CW high-power proton linacs, probably even higher than for pulsed machines. Moreover, this statement is reinforced by the fact that such machines use superconducting structures at very low energies, as already underlined, in which several additional difficulties potentially complicates the beam loss mitigation compared to higher energies: the beam is larger and very "soft", tails from the RFQ need to be managed, available space for beam diagnostics and collimation is limited and last but not least, beam apertures are much smaller.

Finally CW beam operation obviously means CW RF operation. Dynamic heat loads therefore clearly dominate cryogenics operation cost: contrary to the case of pulsed operation, the SRF cavities quality factor (Q_0) is therefore an important cost driver for CW machines for which it's often preferable not to push too much the accelerating gradients so as to keep affordable cryogenic loads. More generally, CW RF operation is also considered to be more harmful as far as electron activity is concerned (multipacting, field emission) and for the thermal management of all room-temperature copper structures, especially the RFQ. On the other hand, RF power generation has somehow become simpler and more reliable than for pulsed operation thanks to the recent emergence of tens of kW solid-state amplifiers [28].

Project X and the PXIE Demonstrator

Project-X [29] is a typical example of how could look a CW high-power proton linac: as shown in Figure 8, SRF cavities of different types – HWR [30], Spoke [31,32], elliptical [33] – bring the beam from 2.1 MeV (RFQ output) up to 3 GeV in this case, including 2 frequency jumps (162.5, 325 & 650 MHz).

In order to validate the Project X concept and eliminate the already discussed technical risks related to the SRF injector, a 25 MeV front-end demonstrator (PXIE) is presently under construction (see Figure 9). Beam CW operation at 1 mA is planned to start there between 2016 and 2018.

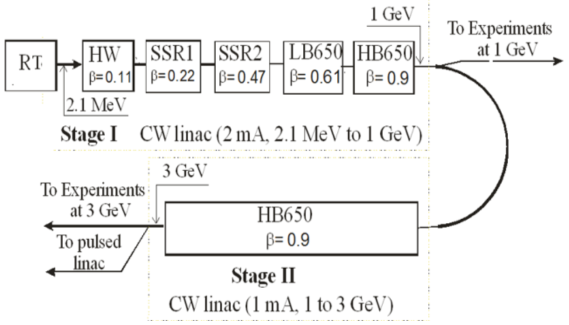

Figure 8: Acceleration scheme for Project-X.

Figure 9: HWR (left) & spoke (right) cavities for PXIE.

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SARAF, IFMIF and the LIPAC Demonstrator

As already mentioned, SARAF is presently the only facility worldwide operating an HWR cryomodule behind its RFQ with (high-current) beam. The machine is presently able to produce 1 mA CW protons at 4 MeV (2.1 mA at 2 MeV) and 4.8 MeV deuterons at 50% duty cycle but suffers from several technical problems. As far as SRF cavities operation is concerned, the main present limitations are related to the heating of the power couplers [34] and to the management of microphonics [35], which has appeared to be rather problematic given the very high sensitivity of the SARAF HWR cavities to He pressure fluctuations (60 Hz/mbar) and the difficulties encountered with the piezo-tuners operation. All in all, the simultaneous operation of all 6 cavities at nominal field was actually not achieved for long period. Given the present difficulties, a new plan is by the way foreseen for the SARAF 40 MeV upgrade by 2019, probably by means of a contract with vendor [30].

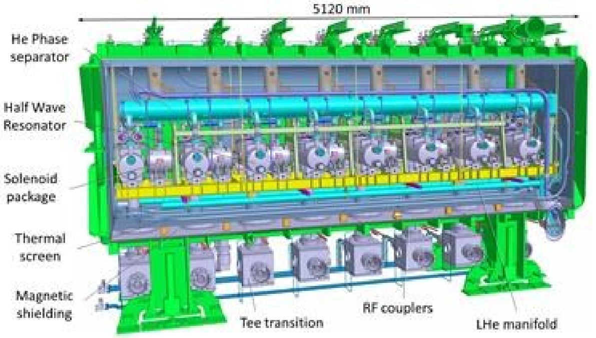

Figure 10: IFMIF/LIPAC HWR cryomodule.

Like SARAF, the IFMIF project also plans to accelerate deuterons up to 40 MeV using HWR SRF cavities. A 9 MeV demonstrator (LIPAC, first beam planned in 2016) is presently under construction, and uses a very compact concept more or less similar to the PXIE and SARAF ones (see Figure 10). But compared to the SARAF or the PXIE cases, IFMIF is carrying the additional big challenge to accelerate a 50 times higher beam current (125 mA CW)! This obviously leads in additional technical difficulties related to the beam transport tuning, to beam losses mitigation, but also to RF power distribution since 70 kW RF power needs to be safely injected inside each cavity in a compact way [36,37].

MYRRHA and the Chinese-ADS

The goal of the MYRRHA project is to demonstrate the technical feasibility of transmutation in a 100 MW_{th} Accelerator Driven System (ADS) by building by 2023 a new flexible irradiation complex in Mol (Belgium). The MYRRHA facility requires a 600 MeV accelerator delivering a maximum proton flux of 4 mA in CW operation (2.4 MW beam power), with an additional specific requirement for exceptional reliability (Mean Time Between Failures > 250 hours) since only a very limited number of unforeseen beam interruptions can be sustained by the reactor structures. To try to fulfil this very specific requirement, the MYRRHA linac design is therefore based on several redundancy schemes [38]. In particular, the 17 MeV injector [39], based on CH SRF cavities [40], is doubled to provide a hot stand-by spare able to quickly resume beam operation in case of any failure in the main one. Moreover, the MYRRHA main SRF linac [41], composed with spoke and elliptical SRF cavities from 17 to 600 MeV, is designed with significant RF power and gradient overhead throughout the 3 SC sections to ensure enhanced "fault-tolerance" capabilities: RF units failures are recovered by using a local compensation method (while stopping the beam for not more than 3 seconds) during which the RF fault is compensated by acting on the RF gradient and phase of the 4 nearest neighbouring cavities. A dedicated R&D program is presently on-going in order to try to demonstrate experimentally the feasibility of such procedures [42].

It is finally to be underlined that a very ambitious ADS program has also started in China since 2011. This Chinese-ADS project aims at building a 15 MW ADS by 2032 (1.5 GeV, 10 mA) and basically plans to use the same reliability-oriented concepts as MYRRHA, as illustrated on Figure 11. Very active R&D is presently on-going around this project [43], including in particular the planned construction of two 10 MeV front-end SRF injectors by 2015 and a lot of associated R&D on HWR, Spoke, and elliptical cavities. More information can be found in the present proceedings [e.g. 44-46].

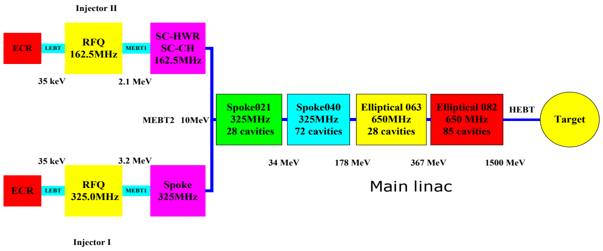

Figure 11: C-ADS linac structure.

CONCLUSIONS

This paper tries to give an overview of present SRF-based high-power proton/deuteron linac machines and projects. From this analysis a few straightforward but interesting conclusions can be derived.

First of all, it is to be stressed that such high-power hadron accelerators have been made feasible thanks to the SRF technology, leading to more and more SRF linac machines and projects. This is especially true for CW operation where SRF is to be used from the RFQ on. The next 20 years will clearly be the "golden age" for SRF high-power linacs with the probable construction of several new large machines of this kind.

Second, the main present R&D challenges can be roughly summarized as follows: on the one hand, secure high gradients operation for elliptical-based pulsed machines (ESS, SPL) and on the other hand, demonstrate the SRF injector technology for CW machines (through

PXIE, SARAF, LIPAC, C-ADS demonstrators), including Q_0 optimization. R&D on piezo-actuators, which become more and more a necessity, is also to be reinforced.

Many R&D activities are going on worldwide for high-power proton/deuteron SRF linacs, clearly leading to a very high potential for new synergies and collaborations on all SRF-related technologies in general. On these aspects, one could even think about establishing some common component designs usable for different projects: this could concern power couplers, as already mentioned, but might also be applied to larger components like full cryomodules – ESS, MYRRHA and SPL for example share the same elliptical SRF section at β=0.65... Finally, the R&D on reliability enhancement pursued for the ADS programs is also to be followed closely since it could be a potential benefit for all future projects.

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