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ESS – The European Spallation Source

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Abstract

The ESS project was presented at an international conference in the Congress Centre of the Former House of Parliament of the Federal Republic of Germany in Bonn, 16-17 May 2002. The project proposal was documented in 4 volumes, which covers why Europe needs ESS [1], the scientific case for ESS [2], the proposed technical specifications of ESS [3] and instrument suite and user support [4]. This report will mainly concentrate on how ESS differs from the US (SNS) and Japanese (J-PARC) projects and on the final selection of specific technical solutions and design details that have been made after the May 2002 presentation. In the final section of the paper possible routes to the realisation of a new next generation spallation neutron source in Europe will be presented and the predicted source strength of the ESS compared to the performance of existing facilities in Europe and the facilities SNS and J-PARC that are under construction.

1. Introduction

The aim of the ESS project is to design an affordable, technically feasible next generation neutron source that on completion will provide World leading performance for all classes of instrumentation. The project is supported by 17 institutions in 11 different European countries. The result of a close dialogue between users, instrument designers, target and accelerator experts is a facility with two complementary target stations (see Fig 1). This is a unique feature of the ESS. The Long Pulse (LP) target station receives 5 MW of beam power from 2 ms long proton pulses with a frequency of 16 2/3 Hz (300 kJ/pulse). This is ideal for broad bandwidth applications where the integrated intensity in the pulse is the important parameter. The Short Pulse (SP) target station also receives 5 MW of beam power but from 1.4 μsec proton pulses arriving at a frequency of 50 Hz (100 kJ/pulse) for applications where the peak intensity in the pulse is the key parameter.

The high total beam power (10 MW), the demand for low loss in the accelerator and the combination of short and long pulses put rather stringent requirements on both the accelerator and the target stations. But it allows for unprecedented performance, the possibility for optimally optimised complementary target stations and allows for a very balanced scientific utilisation, with virtually no compromises for any of the scientific fields that will be using the facility. The proposed design, which either meets these requirements with currently available technology or where R&D activities has been outlined, has been scrutinised by an international group of leading experts and deemed feasible.

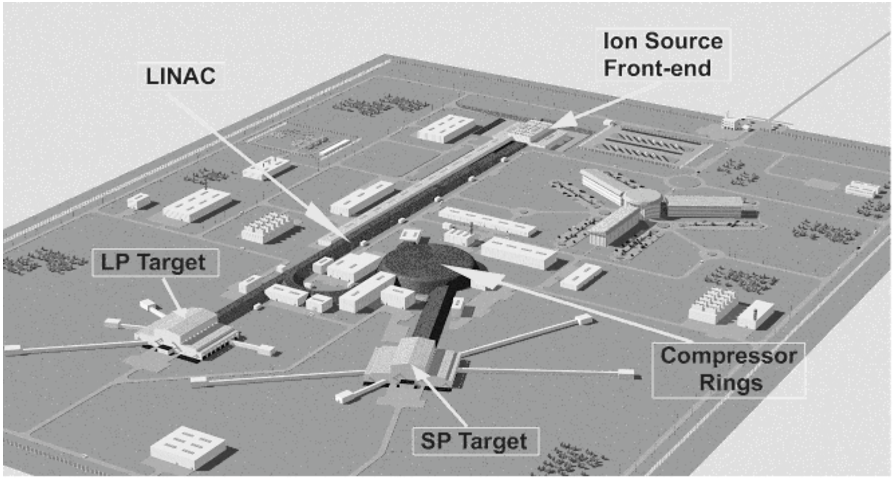

Figure 1: The proposed layout of the ESS facility with its 5MW Long Pulse (LP) and 5 MW Short Pulse (SP) target stations.

1. The ESS Linac

In the ESS proposal [3] both NC (normal conducting) and SC (super conducting) solutions, with different frequencies were described. All the described proposals were feasible and estimated to result in almost the same cost. A specific reference design has now been finally selected by the ESS accelerator team and approved by the ESS Council.

1.1 Linac layout

The layout of the accelerator system is shown in Fig 2, and the main parameters summarised in Table 1.

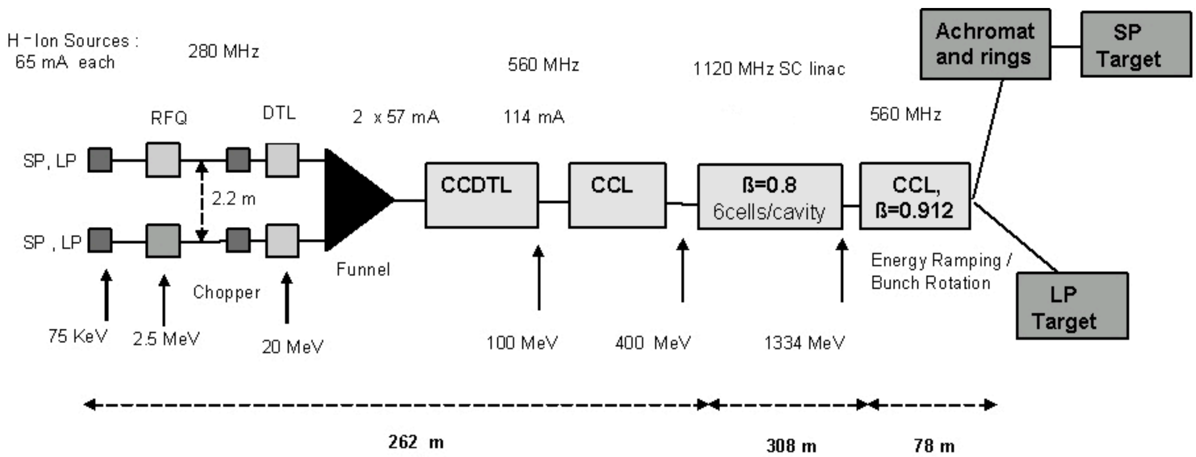

Figure 2: The ESS 1120 MHz Superconducting (SC) reference Linac.

The main difference between the ESS accelerator and the accelerators currently under construction for SNS [5] and J-PARC [6] is the requirement of simultaneously delivering both short and long pulses.[3]

In order to deliver 5 MW beam power in about 1.4 μsec to the SP target, the ESS facility needs 2 accumulator rings with 35 m mean radius in a shared tunnel. Ring injection utilises H^- stripping injection with painting in the horizontal, vertical and momentum dimensions. Each ring is filled sequentially and injection is limited to 0.48 ms and 600 turns per ring in order to limit the temperature rise in each stripping foil. The linac pulse is chopped to 70 % of the 800 ns ring revolution time at the ring revolution frequency to leave a gap for the ring extraction kicker magnets. A 100 μs gap is required for vertical deflection of the linac beam between the rings. The pulse structure in the linac is shown in Figure 3.

Table 1 :Main parameters for the ESS reference linac with its simultaneous SP&LP operation. During commissioning the LP beam will also be chopped.

	SP	LP	
Beam Data			
PRF (pulses per second)	50	16.67	
Beam pulse length(ms)	0.48/ring	2.0	
Beam duty factor	4.8%	3.3%	
Non-chopped beam current (mA)	114	114	
Chopping factor	70%	70%	100%
Final energy (MeV)	1334	1334	
Peak beam power (MW)	107	107	152
Mean beam power (MW)	5.1	3.5	5.1
Pulse gaps, ring separation (ms)	0.1		
280/560 MHz NC-Linac			
Energy range (MeV)	<400		
NC linac length (m)	262		
Peak RF power (nominal)(MW)	64	78 (100%)	
RF pulse: length (msec) / duty cycle (d.c.)	1.4/7.0%	2.3/3.83%	
Wall plug RF power (MW) (30 % RF control included)	12	8	
1120 MHz SC-Linac			
Energy range (MeV)	400 –1334		
SC linac length (m)	308		
Accel. gradient in SC cells (MV/m)	10.2		
Peak RF power (nominal) (MW)	75	107 (100 %)	
RF pulse: length (ms) / d.c.	1.4/7.0%	2.3/3.83%	
Wall plug RF power (MW) (30 / 40 % RF control included)	15 (40 %)	11 (30 %)	
AC Cryo power (MW)	2.4	1.6	

The LP target station needs a 2 ms linac pulse every 60 ms or at 16.67 Hz repetition rate with 114 mA pulse current. This can be achieved with two H^- ion sources at 65 mA each, funneled together at about 20 MeV. No beam chopping is required here, see Fig 3. The RF control system for pulsed SC cavities has to be very carefully designed as we are matched only for the 2 msec un-chopped LP pulse, but quite heavily mismatched for the 70% chopped SP. Operating at high frequencies and / or small accelerating gradients is a possible solution here.

The chopping line for the ESS linac must be able to switch the beam on and off between RF bunches resulting in elements with a rise time of less than 2 ns to avoid beam loss further down the accelerator. The beam collection system must be able to cope with up to 10 kW power, since both the SP and LP beam will be chopped initially.

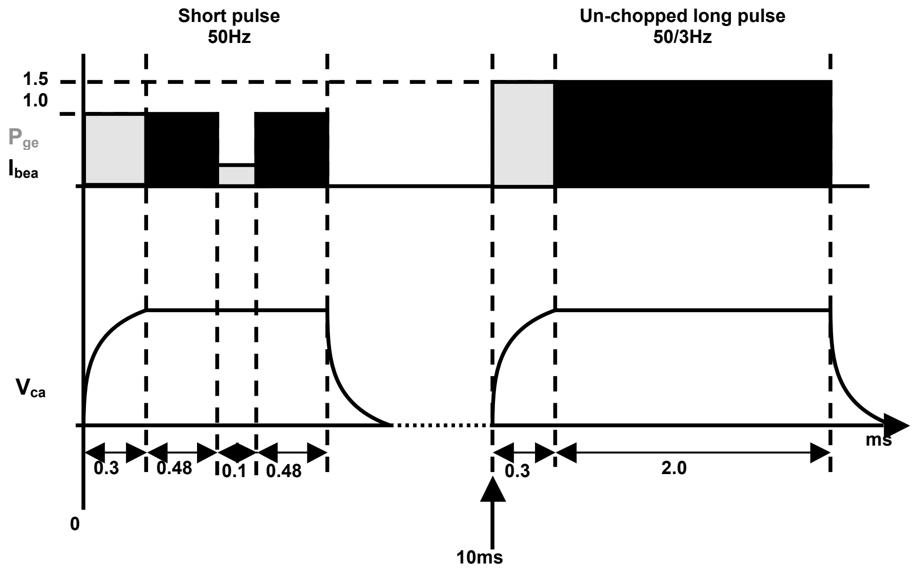

Figure 3: Pulse sequence on ESS linac, V_{ca}= Cavity voltage, I_{bea} = beam current relative to a chopped beam, P_{Ge} power from the RF generator for the SC cavities.

The ESS reference linac with 10 MW of beam power, shared between the SP and the LP target stations, cannot be a direct copy of any current or planned linear accelerator. The ESS accelerator team therefore had to find a linac design that is cost effective and that will provide the 10 MW of beam power with a high degree of certainty. The 280/560 MHz normal conducting (NC) linac design described in ESS Volume 3 [3] is a technically feasible and physically robust design with a reasonable cost estimate. Selecting 1120 MHz elliptical SC cavities above 400 MeV and using the old 280/560 MHz NC linac below 400 MeV was found to promise both good beam quality with low losses and competitive construction and operating costs. The resulting main ESS linac parameters are shown in Table 1 and Figure 2, the ESS reference linac starts with a low frequency front end, houses an innovative double chopper system, combines two H^- beams at 20 MeV and uses high frequency SC cavities for beam acceleration above 400 MeV. The SP and LP beams are separated by 10 ms.

The 1120 MHz SC linac is 308 m in length and 172 cavities are required with only one SC main coupler per cavity designed for 0.85 MW peak power. Although cavity and cryostat can be scaled from the J-PARC 972 MHz SC proton linac test-stand, R&D is required for the SC main coupler. As the cavity bandwidth and stiffness is increased with the higher frequency, an 1120 MHz SC linac is well suited to guarantee loss free injection into both ESS compressor rings whilst not being hindered by the ESS SP&LP scheme.

Operation of both long and short pulses may require two H^- ion sources in each leg of the front end. Neither the H^- ion-sources nor the chopper /collection system will be overloaded, but both beams must be combined at 20 MeV in the funnel. Progress in high intensity H^- ion-sources indicates that the ESS SP & LP requirements may be achieved with two H^- sources only, if the beams are separated by 10 ms.

1.2 Linac front end

The 280 MHz low frequency front end houses an innovative double chopper system, where one chopper element ensures a fast rise time: ±2 kV in 2 ns, 10 ns flat top. The other provides the long hold time for switching between the two rings and cleaning the front end of unwanted H^- pulses: ±6 kV in 10 ns , with flat tops up to 100µs. The second chopper also serves as the main beam collection system [7] for all deflected bunches. see Fig 4.

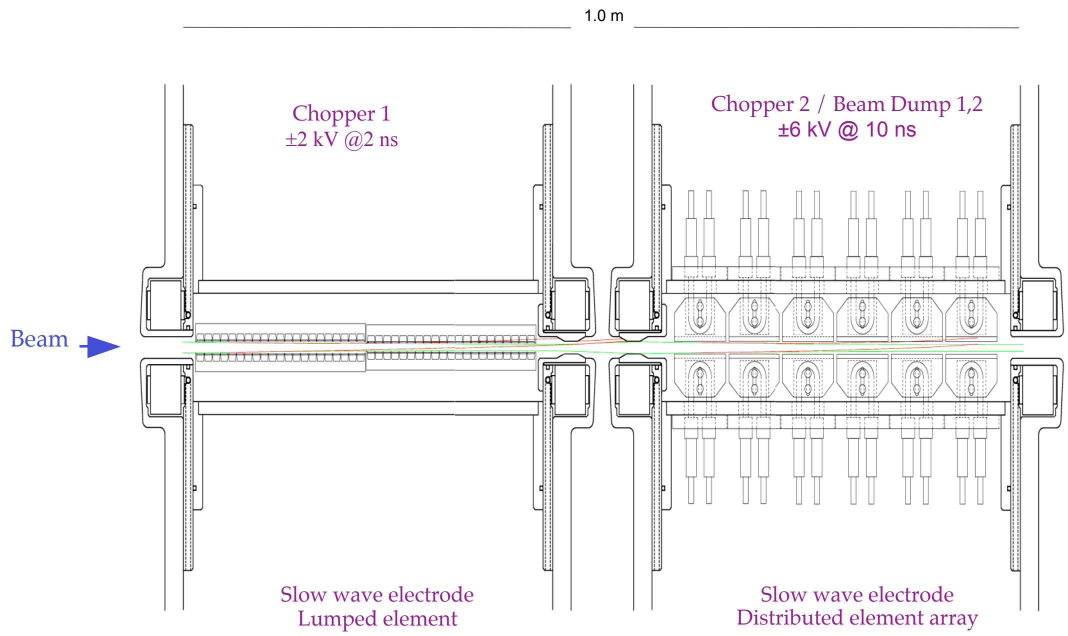

Figure 4 : The ESS double chopper system, 2 sections are necessary to dissipate 5 kW beam power at 4 positions.

The complete chopper section from RFQ to DTL entrance is about 4 m in length. Full 3D simulations from the RFQ exit to the output of the 20 MeV linacs have indicated acceptable beam filamentation and tolerable bunch centre shift due to RF field errors.

As the ESS requirements on the front end system are much more demanding than for the SNS and J-PARC facilities, a dedicated ESS front end test-stand must be built soon in order to start construction of the ESS facility in the medium term.

To replace warm parts of the ESS reference linac up to 400 MeV by SC low or medium ß structures is not considered to be a valid alternative due to the ESS linac´s RF duty cycle of only 12 % and the expected time scale for ESS even if it is delayed by a few years. The ESS accelerator team regards SC low and medium ß structures as an ongoing long term R&D programme.

From 400 MeV, 1120 MHz SC cavities accelerate the ESS beam up to its full 1334 MeV final energy. SC structures offer reduction in operating costs compared to warm NC ones, but requires a careful look at the pulsed RF control system especially for SP&LP requirements. Higher frequency SC structures are beneficial for the demanding ESS requirements and offer headroom for capital cost saving. As the ESS front end prefers low frequencies, a change in frequency from 560 MHz to 1120 MHz at 400 MeV is foreseen for the ESS reference linac.

1.3 The SC linac

The SC part of the linac uses 43 cryomodules, each housing 4 elliptical SC cavities. Each cavity consists 6 cells of ß=0.8 equipped with one SC main coupler. Doublets in the warm intersections provide the transverse focusing. The ESS cryomodule layout profits considerably from the work of the J-PARC team on their 972 MHz SC cavities. As the overall RF duty cycle is about 10 % , we limited ourselves to only 0.85 MW peak power for the un-chopped LP beam, leading to 80 kW SP&LP averaged power. Only 10 MV/m accelerating gradient inside the SC cavities are required, leading to a matched cavity bandwidth of ±2 kHz for the 114 mA LP beam. Under construction are SC main coupler at 1300 MHz, designed for either 1 MW peak [8] or 100 kW average power[9]. Higher gradients in the ESS SC linac are not in general excluded, but problems to be looked at are the SC main coupler and the pulsed RF control system under the ESS SP&LP conditions.

Detailed Monte Carlo simulations with complete 3d space charge have been performed to demonstrate the capability of the 1120 MHz ESS SC linac to handle 228 mA bunch current (114 mA pulse current) from 400 MeV onwards and by using ß=0.8 6 cell cavities only [10]. Fig 5 show the phase slip of the bunch centre for each cell of the total 172 accelerating cavities. The energy gain is changing from cell to cell, but we have stable synchrotron oscillation, leading to acceptable longitudinal filamentation at the ESS SC linac end.

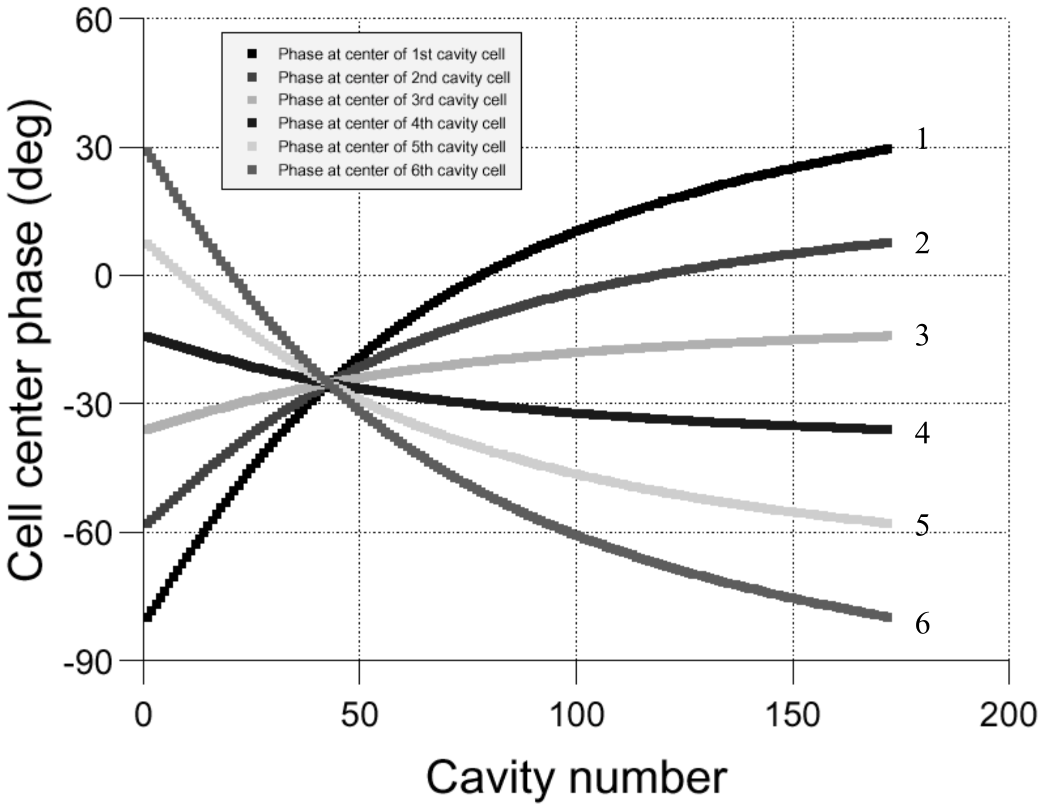

Figure 5 : Phase slip of the bunch centre in each of the six cells for the 172 SC accelerating cavities: The phase is always between ±90°, which means energy gain in each cell and therefore stable synchrotron oscillations.

For a matched 6d Gaussian “control” beam as input to the SC linac and applying no RF field errors: very little filamentation is seen at the 1334 MeV linac exit, and the energy spread at the ring injection point is limited to ± 0.5 MeV, only a quarter of the ±2 MeV constraint for loss free ring injection. Energy spread reduction is obtained by placing warm 560 MHz , ß=0.912 CCL structures 78 m behind the SC linac, and delivering a 13 MV rotation voltage to the beam. Using 1120 MHz SC structures instead will need only half the voltage, but requires sophisticated RF control to get the same energy ramping for both compressor ring pulses, which are only separated 100 μsec in time.

RF field errors along the ESS linac will lead to a shift of the beam centre in energy and phase/time, maybe leading to unacceptable large energy shifts after final bunch rotation. Assuming ±1 %, ±1° RF amplitude, phase errors in each SC cavity, randomly distributed along the 172 SC cavities, and applying the same bunch rotation voltage as used for the Gaussian " control " beam, the bunch centre is displaced by more than ± 1.0 MeV after bunch rotation in about 10^{-3} cases. Even including filamentation due to mismatch and shift of the bunch centre due to accumulated RF amplitude and phase errors in the NC and SC structures, there are less than 10^{-4} particles outside ±2 MeV. The ESS reference linac can tolerate twice as large RF errors in the SC cavities than SNS.

To achieve ±1 %, ±1 ° RF amplitude, phase errors in each SC cavity during the mismatched 1 msec SP pulse respectively, the matched 2 msec LP pulse requires a quite sophisticated RF control and an appropriate frequency detuning of each SC cavity. About 30 % RF control power is assumed for the matched LP beam and about 40 % for the mismatched SP. High power results from the 1st SNS medium ß cryomodule indicates about ±40 Hz frequency oscillations during a 1 msec RF pulse at 10 MV/m accelerating gradient even by using cold piezoelectric tuners[11]. Much less frequency detuning is observed either at a low power SC test-stand or by using warm piezoelectric tuners [12].

Detailed numerical simulations with realistic hardware components [13] and including higher order mode excitations [14] are planned to support experimental results from a high priority ESS SC test-stand with a complete 1120 MHz cryo-module and one full power klystron.

The ESS SC linac can tolerate twice as large RF errors than the SNS one but has a much more demanding RF pulse structure, which cannot be easily simulated even on high power test-stands as we are limited in approximating the different ESS SP& LP beam loading conditions. As the ESS facility is expected to be delayed by a few years, we can profit quite a lot from the ongoing SNS results and from 1300 MHz SC main coupler developments.

The ring is unchanged relative to the Bonn presentation [3], and the High Energy Beam Transport system has been detailed out [15].

2. ESS Target stations

The two ESS target stations will apart from minor details – the moderator assembly – be identical. The target stations will use liquid mercury as the target material. The main changes after the Bonn presentation[3], is a result of optimisation during detailed design work on the target systems. The enclosure concept for the ESS target station operates for optimal safety with 2 to 4 independent safety barriers depending on the exposure of the contained media and components. The cost optimised technical shielding layout of the target station is almost finished and will be published in a final report on the layout and the technical development of the ESS-target station by the end of 2003 [16]. Due to a potentially high number of target unit exchanges, a very simple flange layout has been chosen, with remote handling capabilities and sealing functions.

The main parameters for the target stations are given below:

Table 2 Target station parameters

Two target stations	**SP Short Pulse**	**LP Long Pulse**
Beam power	5 MW	5 MW
Time structure of proton pulse	2 x 0.6 μs	2.0 ms
Energy content of proton pulses	100 kJ	300 kJ
Repetition rate	50 Hz	16 $^{2}/_{3}$ Hz
Proton beam diameter at target (parabolic 2D-density distribution)	6 x 20 cm^2	6 x 20 cm^2
Target type	Flowing mercury horizontal injection	Flowing mercury horizontal injection
Number of moderators (viewed faces)	2 (4)	2 (4)
Average thermal flux	3.1 x 10^{14} n/cm^2s	3.1 x 10^{14} n/cm^2s
Peak thermal neutron flux	1.3 x 10^{17}n/cm^2s	1.0 x 10^{16}n/cm^2s
Decay time of flux	150μs	150μs

The final layout of the target station is shown in Fig 6 and described in more details in the proceedings from this years ICANS XVI meeting [16], [17] and [18]. The accelerator beam dumps has been integrated in the target stations [19] and a collimator [19] (Fig. 6) designed to ensure that accelerator failures can not result in a beam profile that could destroy the target window.

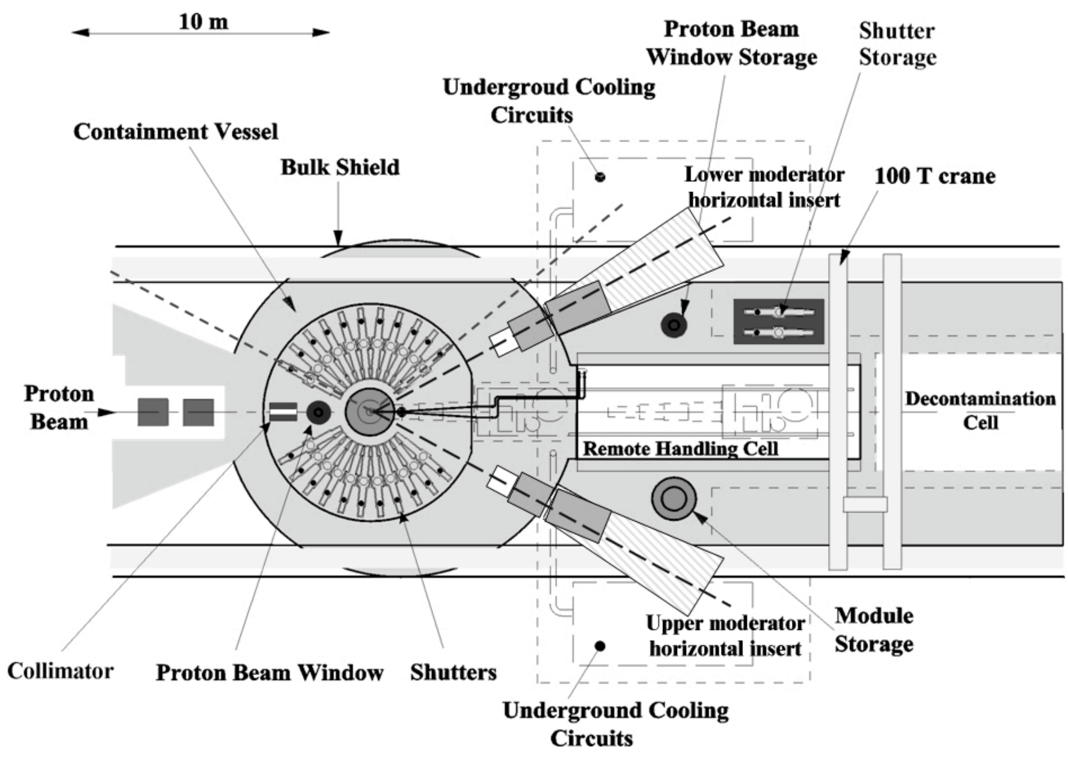

Figure 6 : Top view of the ESS target layout. [16], [17] and [18].

Each side of the target station is equipped with 11 rotating shutters, which are equidistantly separated by 11^o, and will allow vertical insertion of guides or other beam optics without heavy component handling. The rotating shutter concept avoids unshielded caves within the shielding structure and enables high positioning accuracy. The shutters will allow optic elements as close to the moderator as 1,6 m, and the insert plug in the shutter is 23 cm wide and 17 cm tall – allowing for either a guide 'bundle' or complicated optics as a bi-spectral extraction system [20] [21].

One of the major changes relative to the Bonn proposal [3] is to change the moderator mount from being vertical and an integral part of the reflector moderator module, to be horizontal and decoupled from the moderator plug. The latter design is not only simpler and easier from a maintenance point of view. It will also allow for later use of advanced cold moderators, which requires horizontal access and could offer substantial gain in performance.

The mercury target system is placed on a shielded target trolley [22] (Fig 6 and 7) carrying the complete mercury-loop which can be moved on an air cushion drive system between the target station (operation) and the remote handling cell (maintenance) without opening of the Hg-pipe work. The total mercury content will stay on the trolley for all necessary handling operations. The drain tank on the trolley is mainly used for target unit exchange.

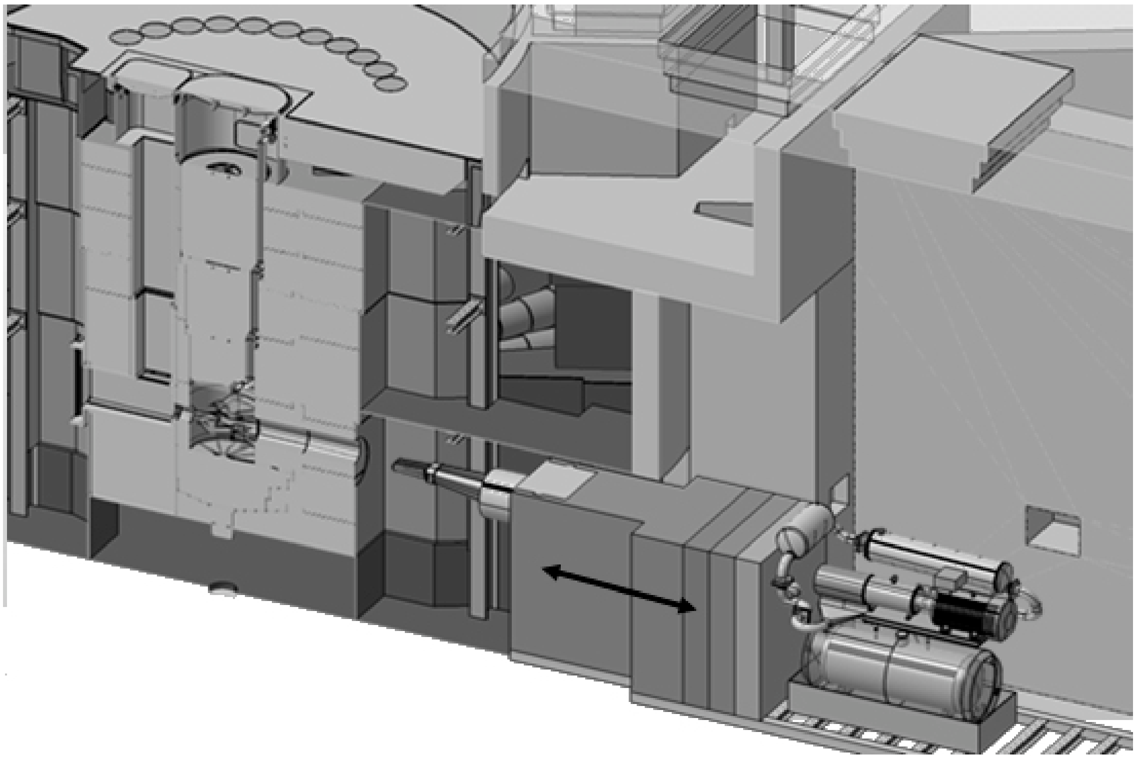

Figure 7. The target layout with the shielded Hg target trolley. The mercury pump is placed above the Hg tank on the trolley [23].

For operation of a short pulse target station above approximately 2 MW a method to mitigate the pressure pulses created in the mercury by the short intense proton pulses from the ring is required. The ESS team plays a key role in the international collaboration between mainly ESS, SNS and J-PARC to work on this problem. Helium bubbles in the mercury seem to cure the problem and technical solutions to inject such bubbles are currently being developed [24].

2.1 Moderator layout and performance

The ESS project is based on a moderator system with a joint optimization over two target stations, [3],[20],[21],[25]. Two unpoisoned moderators with four viewed faces, each serving a ~60º viewing fan, allows for 22 individual beam lines at each target station. The moderators are based on conventional techniques, cold Hydrogen and water at ambient temperature. With this moderator layout and the instrument suite proposed for the ESS [4],[21] a working group under the European Strategy Forum for large Research Infrastructure (ESFRI) demonstrated that instrumentation at ESS would not only represent between 1 and 2 orders of magnitude improvement relative to the current European facilities, but would be superior world-wide in all areas of science and instrumentation [26].

The ESS design has provisions for subsequent installation of advanced cold moderators [27]. A hot source[28] is not yet in the design, but such an option is an important outstanding question to look into. With advanced cold moderators and a hot source there is a potential for an even better performing ESS.

3. ESS instrumentation

The proposed instrument suite for the ESS is not what will finally be built, rather what we would build if the source was ready today and we had to decide on all instruments immediately. It therefore represents a conservative forecast of how instrumentation at ESS could be. The ESS instrumentation [4],[21] is thus based on an extrapolation of ISIS instrumentation for the Short pulse target station, and for the long pulse target station on the fact that neutrons can be transmitted over large distances with very low loss [21],[30] and that choppers can be used for pulse shaping, repetition rate multiplication, wavelength frame multiplication etc.[29],[30]. The selection and definition of instruments has been based on detailed performance calculations using Monte Carlo simulation techniques. One such example – an ultra high resolution powder diffractometer – is presented in these proceedings [31]. The detailed design and decision on instrumentation will be a continuous process starting after the decision to build ESS has been taken.

4. ESS safety and licensing

A key question for a facility like the ESS is to have very high safety standards at reasonable costs. Accurate estimation of radiation levels from a detailed understanding of the facility is therefore essential. The ESS safety team has developed general guidelines for ESS shielding. These guidelines contain an improved method for multi MW spallation sources to consider local (accidental) beam losses in the accelerator and compressor rings [32]. Ongoing work deals with shielding design for the floor beneath the accelerator, to avoid spreading of activity due to activation of soil and ground water and subsequent migration of activity with the ground water flow [33].

A preliminary safety study for ESS was performed on basis of such a study at SNS - the PSAR/SNS [34]. In comparing dose regulations and specific site conditions it was found, that tolerable radioactive releases in design basis accidents are at least 2 orders of magnitude smaller than those, acceptable for SNS. ESS could be build in an urban area f.i. directly adjacent to a university campus. System, reliability and source term studies for ESS lead to the conclusion, that there is sufficient potential for the required proof of reduced source terms. Far more stringent safety goals than those used in nuclear power technology seem well within reach for ESS. Hg-194 dominates the radiological consequences of ESS accidents [35].

With respect to license/authorization of multi MW spallation sources like ESS, it was found, that for several EU countries regulations were not yet established: In order to avoid delays during the construction phase, the creation of a sufficient basis for ESS licensing and authorization has to be carefully looked into by the countries proposing to host ESS. This includes examining whether a nuclear emergency plan will be required.

5. Status of the ESS proposal – the way ahead

By mid-January 2003 it became clear that a decision to build the ESS would not be forthcoming by the end of 2003, and that the project would be delayed. The ESS project in its present form will therefore be stopped by the end of the summer 2003, with all efforts documented by the end of 2003.

Some of the elements in the continuation of the ESS is to create a new organisation, which can liaise with European governments and EU to establish a 10-20 year neutron road-map for Europe, and to agree on a date when a decision on a multi MW pulsed spallation source in Europe need be taken. Another element is to set up competence centres to look into key technological questions (accelerator front ends, high power SC couplers, pitting, materials, advanced moderators etc.). Last but not least – we the future users or hosts for the facility must ensure that such a facility is kept on the political agenda. At present a four to five year delay and a staged approach starting with the LP target station first seem to be a realistic option. The web site: http://www.ess-europe.de will stay alive and be kept updated with the neutron developments in Europe.

6. Acknowledgements

The present paper is written on behalf of and with the help of a large number of participants on the ESS project. Space does not allow me to name the individual participants, but allow me to express my sincere thanks to all the 3-400 scientists, engineers or just supporters across Europe, who have put a lot of energy and all their enthusiasm into this project and have brought it to its present state. We have an outstanding proposal and science case – circumstances became such that we did not obtain funding now – but that will come. I look forward to celebrating with all the ESS-teams when the decision on a multi MW spallation source in Europe gets the go ahead in a few years time.

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