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5MW, 350/700 MHz ESS LP linacs, 2 ms pulse every 60ms: with or without funnel

K.Bongardt: gratefully acknowledged are many fruitful discussions with Feri Mezei and Peter Tindemans

Summary

The anticipated 5 MW ESS H^+LP linac should be based on the accepted common European linac frequencies of 350/700 MHz to benefit from synergy with other discussed European multi MW linac projects. But special for ESS is the anticipated pulse structure as well as an upgrade possibility towards 7.5 MW beam power.
In order to allow for easier comparability, all discussed linacs have 2 ms pulse length and 16.67 Hz repetition rate, the optimized pulse structure for the ESS LP source, base for the overwhelming neutron performance, shown in Figure 1. (*F. Mezei*, *New perspectives from new generation of neutron sources*, *C.R.Physique 8, No7-8, p. 909, 2007& H. Schober et al, Tailored Instrumentation to Long Pulse Neutron Spallation Sources, NIMA 589, p.34,2008.) Choosing different pulse structure could be of advantage for same applications, but on average more beam power is required.*

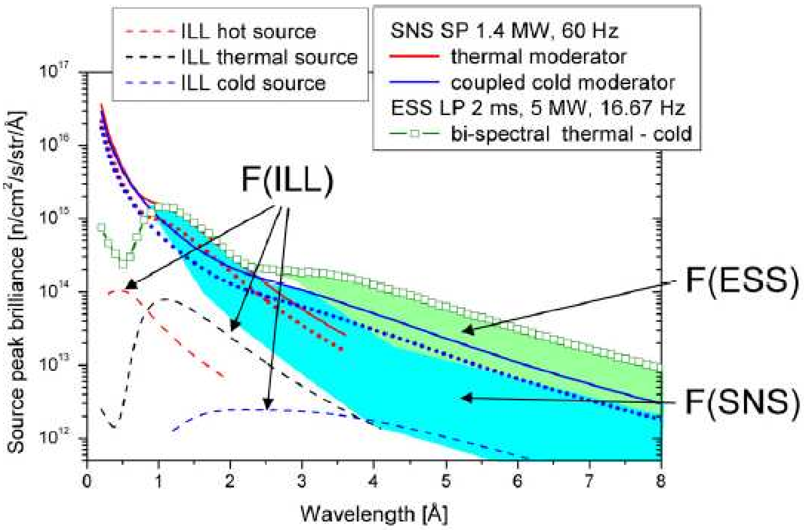


Figure 1 : Figure-of-merit F for various neutron sources for the typical variety of neutron scattering experiments using more or less monochromatic neutron beams of thermal and cold neutron. Principle of novel bi-spectral moderator was successfully demonstrated in the new guide hall at Helmholtz Zentrum Berlin, formerly HMI.

Based on the well attested (ESS Technical Advisory Committee; accelerator section chair R. Garoby) ESS SC linac option from 2002/3, which includes a 20 MeV funnel section and 180 mA bunch current afterwards, a 150mA,1GeV ESS LP linac is on the official ESS-PP web page since February 2008, http://www.ess-neutrons.eu/index.php/documentation *(page 3 contains lay-out). This 5 MW linac with* *its 209m long SC part, low gradient of only 7.7 MV/m simplifies pulsed RF control and reduces particle loss/activation and is upgradeable to 7.5 MW because of separate warm focusing quads in the SC part.*

This paper compares this design with some recent outlines of alternative designs and provides an overview of the key differences (see especially the summary table on page 8). Technical and cost arguments still seem to be in favour of this 150 mA, 1 GeV, upgradeable 5 MW ESS LP linac, compared to those alternatives. A much shorter SC part, leading to cheaper linac cost, is only one key issue. Another issue is better brightness of the neutron beam and lower cost of the target. It is therefore indeed a solid basis for the design review and update.

Introduction

The 150 mA, 1 GeV 5 MW H^+ linac shown in Figure 2 is a derivative of the10 MW ESS H^- SC Linac option with a 180 mA bunch current after the 20 MeV funnel, but superconducting (SC) elliptical cavities are foreseen only above 400 MeV. Components for all sections, including the funnel, are successfully tested with pulsed beams, but not at ESS conditions. For a 150mA pulse current the dissipated RF power between 200 to 400 MeV is less than half of the needed beam power. The SC linac period shown in Figure 3 requires only a small gradient of 7.7MV/m to get 600 MeV energy gain after 209m; separated warm quads for focusing allow an energy upgrade by adding later more cryomodules. Not considered for cost reduction is RF power splitting between SC cavities as this is problematic even for 1ms long pulses and at 5 Hz repetition rate, see Figures 5 and 6. Scaled from the well document cost analysis for the 10 MW ESS SC linac option 2002, which without contingency came down to 370 MEuro_2002, such a 5 MW ESS LP costs about 350 MEuro_2008, including a 15 % contingency and general inflation from 2002 to 2008, but without specific increases in raw material costs.

Several other ESS linac designs have recently been presented, e.g. at PAC 2009, Vancouver by the Spanish and Swedish ESS groups. These designs are quite similar: lowering the H^+ pulse current to 60 mA leads to a final energy of 2.5 GeV, but they require high gradients of 15 MV/m and long cryostat housing for focusing quads to get an acceptable linac length. How to get a 50 % power upgrade is not clear, as the couplers are peak power limited. Also, for evaluation by the ESFRI Site Review Group in 2008, the ESS-B group presented a 90 mA, 1.334 GeV linac with a 321m long SC part with 3 different sections. It was shown at EPAC 2008 and has either 4 MW beam power when the proton pulse length is 2ms or 5 MW with 2.5ms pulses. The cost estimate of that linac was 500 MEuro_2008 which included a 15 % contingency, general inflation and adjustment of raw material costs from 2002 to 2008. (see ESS Bilbao - Executive Summary 2008, p.5&6). But it is not exactly clear which beam power (or pulse length) is chosen. Quite likely the cost figure corresponds to 4 MW beam power, as the SC linac option 2002 was only costed for 2 ms pulse length.

1) The 150 mA, 1 GeV ESS LP linac: with funnel, no SC spokes

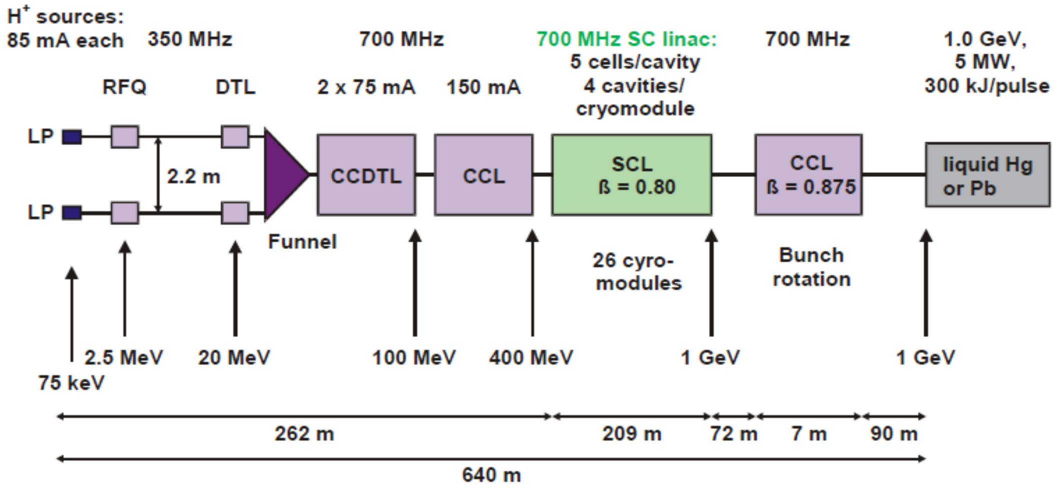
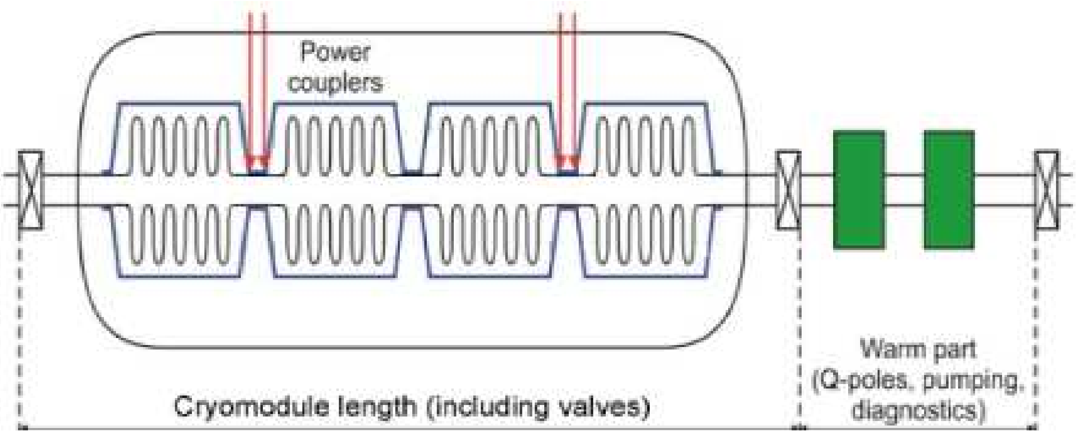


Figure 2: The key elements and sections of the approximately 471m long ESS LP accelerator. Two H^+ ion sources are shown; the funnel section creates the single beam entering the main accelerator part, which is normal conducting up to 400 MeV and then superconducting; there is a dedicated transfer system to the LP target, including bunch rotation for energy spread reduction.

The H^+ linac with a 150 mA pulse current is a derivative of the 10 MW ESS H^- SC Linac option with a funnel at 20 MeV; only high ß SC elliptical cavities are foreseen. Components for all sections, including the funnel, are successfully tested with pulsed beams, but not at ESS conditions.

The dissipated RF power, between 200 to 400 MeV per proton, is less than half of the needed beam power. The shown H^+ linac uses a small gradient of only 7.7MV/m in the SC cavities, simplifies pulsed RF control and reduces particle loss/activation, and separated warm focusing quads outside the cryostat allow for an energy upgrade.



6.12m 1.9m

Figure 3: 8.02m long SC linac period at 700 MHz: 5 cells/cavity, gradient of 7.7 MV/m.

There are two RF feed-troughs/module and separated warm focusing quads allow an energy upgrade by installing additional cryomodules, as also envisaged for the SNS power upgrade. Details of the SC lattice period are listed in the ESS Update Report 2003. Using 5cells /cavity leads to simplified construction of the SC cavities, improves efficiency for a wider energy range and reduces the length of the cryomodules, but a 20 % higher accelerating gradient is required compared to 6 cells/ cavity and unchanged energy gain /cavity.

Each SC cavity has one coupler and is connected to a compact klystron of 1.2 MW peak and 50 kW average power, including a 30 % surplus for the pulsed RF control system, and a 0.3 ms start-up time. Only a 4 % RF duty cycle is required. This important aspect avoids multi MW vector modulators for power splitting, problematic even for 5 Hz rep rate and pulse length of 1 ms (see figures 4 and 5), a figure not optimal for neutron performance in the majority of circumstances.

At high rep rate and/or for long pulse length, amplitude and phase correlations between SC cavities inside one cryomodule limit the accelerating gradient: SNS high ß SC cavities are specified for 16 MV/m, but they don't reach this on average for 1ms and at 30 Hz repetition rate; only 10 MV/m is achievable in some cavities. The RF control system is much easier than without RF power splitting, as SC cavities are always somewhat different from each other. The small accelerating gradient of 7.7 MV/m in the SC cavities results in less amplitude and phase correlations and therefore an easier start-up procedure with reduced particle loss. Activation in the SNS SC linac is noticeable for more than 50 kW beam power, inspite of much larger aperture.

Depending on the ESS upgrade plan, the transition energy and ß value for the 5-cell SC cavity will be optimized. As an example, 5-cell SC cavities at ß= 0.8 are efficient from 0.3 GeV to 1.5 GeV, resulting in 7.5 MW power. Added must be 24 more cryomodules for an additional length of 192 m. The needed AC power of about 65 MW for such a ESS H^+ facility with one 7.5 MW LP target is about half of the 107 MW AC power for 10 MW full ESS H^- facility, serving SP and L P targets .Included are about 33MW AC power for the 7.5MW H^+ linac.

Based on the well documented cost analysis of 370 MEuro_2002, without contingency , for the 10 MW ESS SC linac option 2002, this 5 MW ESS LP costs about 260 MEuro_2002 (without contingency) or 350 MEuro_2008, including 15 % contingency and inflation from 2002 to 2008, but without specific increases in raw material costs. Large cost savings occur in the 209m long SC part, only one power coupler / SC cavity is needed because of the reduced RF duty cycle: 4 % instead of 11 %. The numbers of cryomodules and RF systems are almost identical but they have reduced peak power and no power splitters. The 2.5 MeV chopper lines, the separated 20 MeV H^+ linac and the medium ß SC linac are no longer required.

Applying a funnel scheme leads to a robust ESS LP linac design with high, but acceptable pulse/bunch currents and low accelerating gradient in SC cavities. RF field control in pulsed SC cavities is therefor much easier and particle loss will be reduced. Warm focusing quads outside the cyrostat allow lateron energy upgrade by adding more cyromodules. Only one teststand for the high ß SC cryomodule is needed. Synergy is possible with other discussed European multi MW linacs at 350/700MHz, but still most components will be special for the 2 ms pulsed ESS linac. A detailed cost estimate that includes for example specific increases in the costs of raw materials from 2002 to 2008, is not available for this 150 mA, 1 GeV linac. Scaling from the well documented ESS SC linac option 2002, however, leads to a smaller cost figure than quoted for the ESS-S and. ESS-B linac designs, both with a much longer SC part.

2) The 60 mA, 2.5 GeV ESS-S linac, no funnel, with SC spoke

Figure 4 shows the 5 MW, 2.5 GeV ESS-S linac, presented at PAC Vancouver 2009: reduced pulse current of 60 mA and 4 different SC sections. For the gradient of 15.5 MV/m in the high ß SC cavities, the 100m long transport line must be filled with cyromodules, 254m long SC part to reach energy gain of 1.84 GeV.

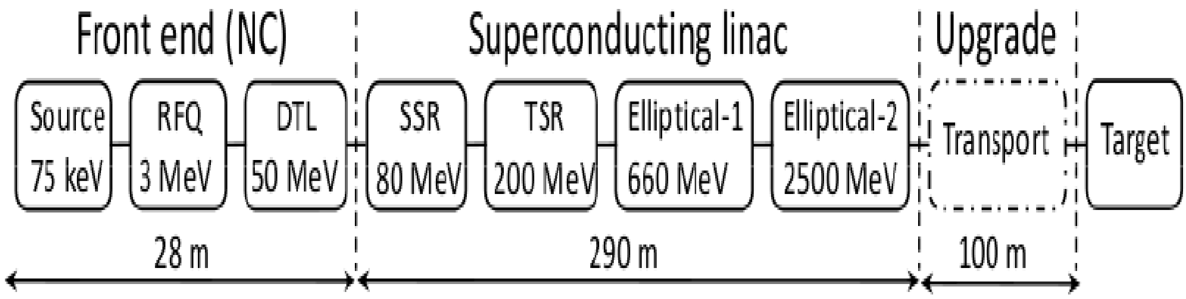


Figure 4: 5 MW, 418m long ESS-S linac, PAC09
http://trshare.triumf.ca/~pac09proc/Proceedings/papers/tu6pfp083.pdf.

The ESS-S linac shown in Figure 4, as well as the quite similar ESS-B linac differ in many aspects from the linac design shown in Figure 2: a low pulse current of only 60 mA, and the absence of a funnel leads to short bunches at 2.5 GeV, complicating beam transfer to the LP target. Bunch rotation (BR) is mandatory to reduce energy spread before final transfer to the LP target. The SC part of 390 m is almost twice as long as the SC part of the linac shown in Figure 2 in spite of the higher gradient (more than doubled) in the high ß SC part.

While the slight increase of the rep rate from 16.67 Hz to 20 Hz is now technically possible, reducing the pulse current but also the bandwidth in the SC linac; but there are some disadvantages for science: it will shorten the neutron time gap from 60 ms to 50 ms. It should also be noted that a linac energy well above 3 GeV reduces the brightness of the neutron beam and increases the target costs. The best balance between these pros and cons is an issue for the design review and update. But the basis once more clearly should be the16.67 Hz rep.rate as for the 2002/2003 ESS design. Choosing a different pulse structure could be of advantage for some applications, but on average more beam power is required to get the overwhelming neutron performance of Figure 1. The for the ESS LP source suggested bi-spectral thermal-cold moderator concept is based on a novel beam extraction system *(F. Mezei and M. Russina, Patent application of 23.01.2002, Deutsches Patent- u*. *Markenamt, 102 03591.1, http://neutron.neutron-eu.net/FILES/VolII.pdf*).
The first example of this novel extraction system has been installed and successfully tested in the new guide hall at Helmholtz Zentrum Berlin, formerly HMI.

Even higher gradients than 15.5 MV/m are reached in high ß SC cavities like the elliptical 2, but only at 1 ms pulse length and 5 Hz rep rate; see results in Figure 5 for modified DESY-TTF multicell cavities. In contrast, this is not the case in the 1 ms, but 30 Hz SNS high ß SC linac. Both ESS groups prefer long cryomodules housing focusing quads to get acceptable linac length; the layout is not yet available. How to achieve a 50 % power upgrade is not obvious, as SC power couplers are not designed to handle 50 % more pulse current. Low current and high gradient means small bandwidth and large frequency detuning, but preferred for loss free SC linac operation is just the opposite, i. e. large bandwidth and small frequency detuning.

Two kinds of SC spoke cavities are proposed to accelerate the beam from 50 to 200 MeV. However, SC spoke cavities have not been tested in a pulsed mode, even without beam. Such pulsed SC spoke test is anticipated for the Fermilab HINS project in 2010.
http://trshare.triumf.ca/~pac09proc/Proceedings/papers/tu5pfp060.pdf.

To get a cost reduction by using 5MW, 700 MHz klystrons at 4 % RF duty cycle, RF power splitting between 4 high ß SC cavities is proposed for an updated ESS-B linac version (see ESS-B Proposal for Baseline Completion, May 2009, p.12). But SC cavities are not identical and present RF vector modulators are not suited even for 1 ms pulses at 5 Hz rep.rate, recently demonstrated at KEK, Japan with their high ß, 4 cavity STF test-stand. Figures 5 and 6 show recent results of modified 1.3 GHz multicell cavities with improved stiffening: amplitude and phase behavior due to RF power splitting between 4 cavities /cryostat at 1 ms pulse duration and 5 Hz rep rate. Individually each SC cavity reaches a gradient above 20 MV/m, but an average gradient of only 17.2MV/m is achievable with 4-fold RF power splitting.

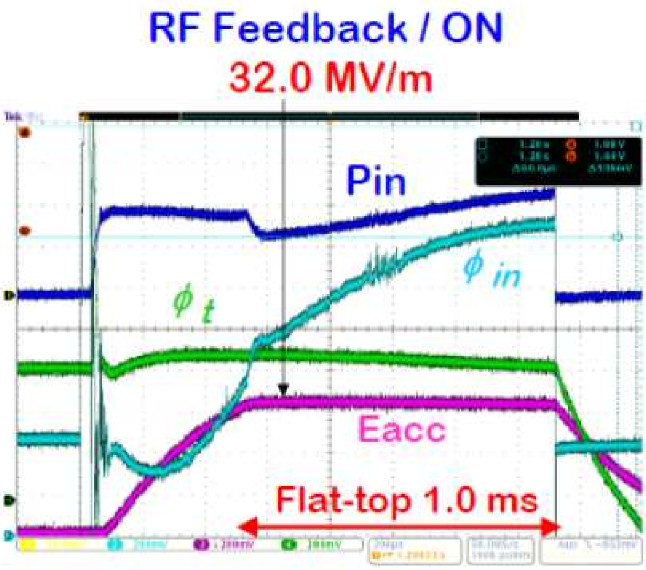


Figure 5: excellent stability of single cavity phase, green line, and gradient, pink line .Obtained are 32 MV/m for 1 ms pulse and at 5 Hz rep.rate.

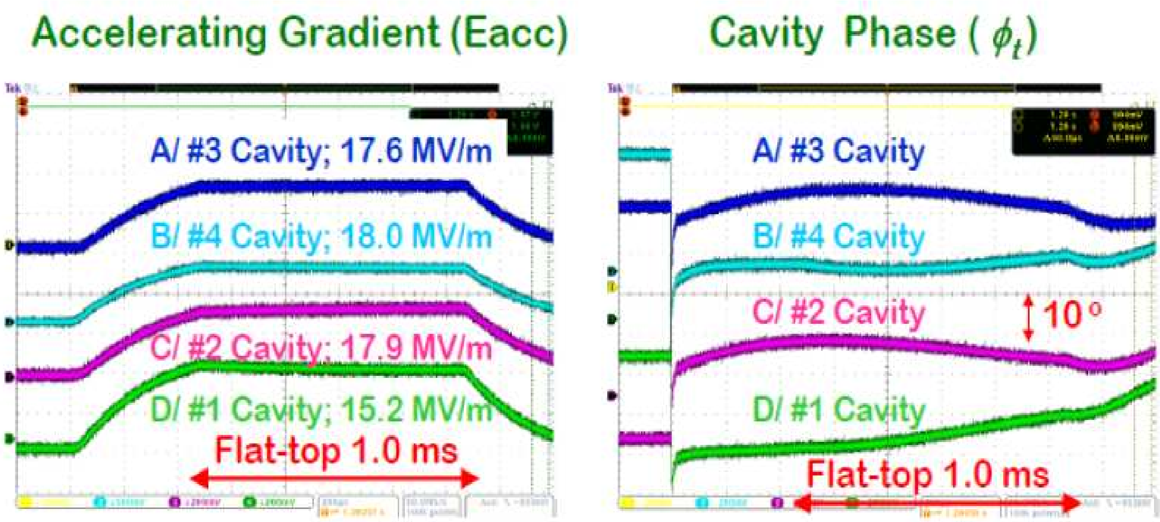


Figure 6:4 cavities connected to one klystron , reduced gradient below 18 MV/m; much less stability for gradient & phase; strong fluctuation from cavity to cavity.

3)Comparison of 5 MW ESS LP linacs, 2 ms pulse every 60 ms: 350/700 MHz , with or without funnel

	high current, low energy: with funnel	**ESS-S:low current, high energy: without funnel**
Pulse current, energy total length , SC part	150mA,1GeV, 471m ,202m	60mA, 2.5GeV, 418m ,390m
Structures from 50-200 MeV	700MHz : warm CCDTL & CCL	350MHz: single& triple SC spoke
700 MHz SC linac: energy, gradient, power	>400MeV,7.7MV/m 1.2MW per coupler	> 200 MeV, high ß: 15.5MV/m, 1MW per coupler
Pulsed SC cavity, bandwidth& detuning; pulsed RF control system	large bandwidth, small detuning; relaxed RF control system reduce loss and activation	SC spokes: unknown pulsed behavior; SC elliptical: small width, large detuning; ambitious RF control system
RF power splitting in SC linac	Not foreseen in SC linac	Problematic even for 1 ms , 5 Hz
350 MHz SC test stand	None	two, single & triple spoke
700 MHz SC test stand	one, high ß	two, medium &high ß
Transport to LP target	1 GeV: short & compact line with RF cavity for BR	2.5GeV:longer line, bunch rotation (BR) is mandatory
Energy upgrade	Yes: separate quads allow to add more cryomodules	No: cryostat with quads, 50% more current will overload the SC couplers
capital costs,15% contingency	~350 MEuro-2008	ESS-B linac,2008,likely at 4 MW: ~500 MEuro-2008