

SORTING IN THE ESS

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INTRODUCTION

The ideal optics at the top of Fig. 1 show the ratio of the design gradient to the nominal maximum gradient E_{0d}/E_{0n} for each cavity in the three superconducting sections of the 5 MW ESS linac – spoke, medium- β , and high- β . It is reasonable to expect that, just as at the 1 MW SNS, there will be a significant scatter in the maximum achievable gradient E_{0m} of the individual ESS cavities, as measured before installation. Fortunately, SNS experience shows that high-power proton linacs are quite forgiving when the operating gradients differ from their design values. This is illustrated at the bottom of Fig. 1, where cavity gradient set values that were used to achieve a beam power of 1 MW are compared to the nominal maxima in the two superconducting sections of the SNS [1]. In the approximation that each SNS cavity was set at its maximum achievable gradient E_{0m} , then the average gradient ratio

$$f \equiv \langle E_{0m}/E_{0n} \rangle \quad (1)$$

deviated significantly from 1 in both sections, with a relative standard deviation, σ , of order 0.1.

This suggests that higher ESS performance may be achieved by deviating significantly from ideal optics, and it suggests that cavity sorting may be effective, depending on the actual production line scenarios that come to pass.

FIGURES OF MERIT

Sorting is performed on one or more measured or derived quantities, such as E_{0m} or RF power overhead. Perfection is only possible if $E_{0m} \geq E_{0d}$ at every cavity location. Important figures of merit that measure the effectiveness of sorting include output beam energy, transverse emittance growth, longitudinal emittance growth, longitudinal acceptance, halo and beam losses. A combination of these quantities could be optimised in a comprehensive sorting scheme.

The beam output energy W_{out} is perhaps the most important and most calculable figure of merit, while beam losses are the least calculable. The output energy is exactly

$$W_{out} = W_{in} + \sum_{i=1}^3 \frac{\langle E_{0m}T \rangle_i}{\langle E_{0d}T \rangle_i} \Delta W_{d,i} \quad (2)$$

where $W_{in} = 89.7$ MeV is the energy at the end of the DTL, i labels the sections, and Table 1 lists the $\Delta W_{d,i}$ values [2]. If the transit time factors T are not too distorted, a useful approximation is

$$W_{out} \approx W_{in} + \sum_{i=1}^3 \frac{f_i}{\langle E_{0d}/E_{0n} \rangle_i} \Delta W_{d,i} \quad (3)$$

The ideal optics shown in Fig. 1 lower several gradients at the beginning of each section, in order to achieve longitudinal matching. In particular, gradients entering the medium- β section are about half of the nominal, leading to the “efficiency” value of $\langle E_{0d}/E_{0n} \rangle = 0.80$ listed in Table 1. All

Table 1: Ideal design parameters in the spoke, medium- β and high- β sections of the ESS.

Parameter	spoke	medium- β	high- β
Efficiency $\langle E_{0d}/E_{0n} \rangle$	0.98	0.80	1.00
Nomin. $E_{0n}T$ [MV/m]	9.0	16.8	19.9
Cavity count N	26	36	84
Frequency [MHz]	352	704	704
Gain ΔW_d [MeV]	125.7	354.2	1428.7

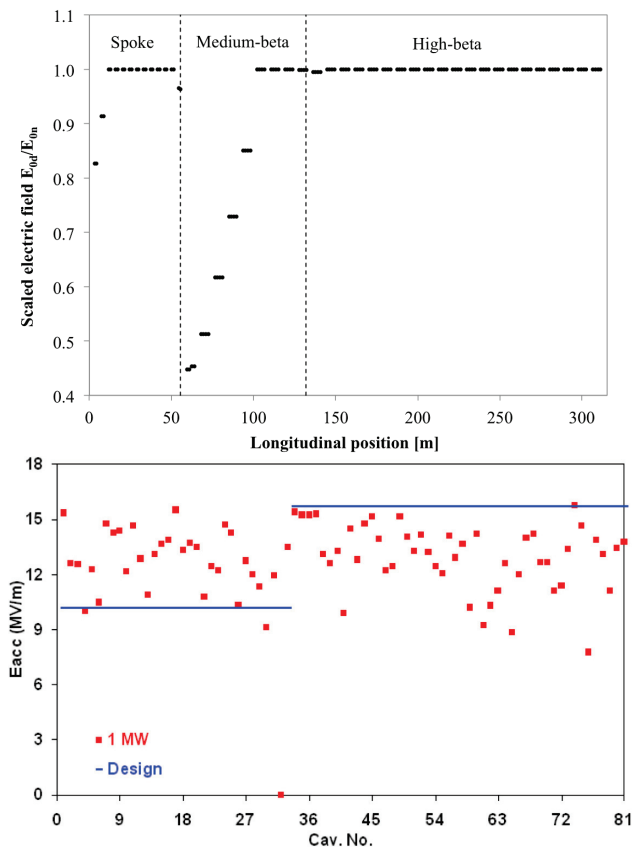


Figure 1: TOP: ideal electric field ratios in the superconducting sections of the ESS linac. BOTTOM: actual cavity gradients for 1 MW neutron production, and nominal gradients, for the superconducting sections of the SNS [1].

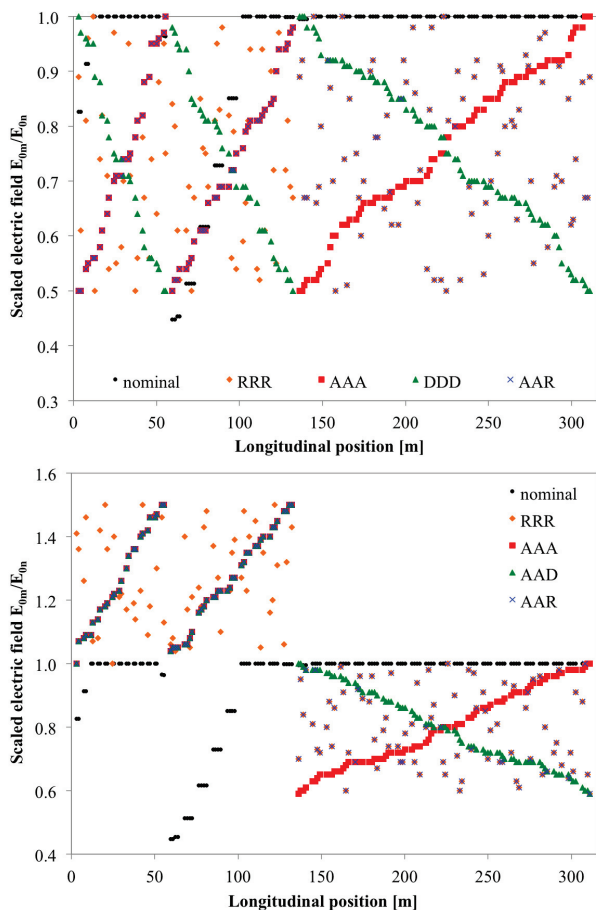


Figure 2: Cavity field profiles for various sorting strategies in scenario 1 (top) and scenario 2 (bottom).

sorting strategies, and their simulations, need to evaluate longitudinal matching.

STRATEGIES AND SCENARIOS

Consider 3 simple sorting strategies, R, A and D, assuming for simplicity – and to gauge the maximum available benefits – complete knowledge of each of the three sets of cavities, before assigning each cavity to its tunnel location. In practice the “sorting pool” is unlikely to be this deep.

R: The simplest sorting strategy is none: the cavities are distributed at *random* in each section.

A: The *ascending* strategy places the cavity with the weakest gradient first, the second weakest next, et cetera. This is expected to help longitudinal matching in the medium- β section more than in the high- β section, where the ideal field distribution is almost flat.

D: Cavities sorted with *descending* gradients may provide relatively poor performance in the medium- β section, because longitudinal matching is compromised.

These strategies are applied to 2 simple scenarios:

1. Weak spokes and ellipticals:

$$(f, \sigma) = (0.75, 0.13)$$

$$W_{out} \approx 1589 \text{ MeV}$$

2. Strong spokes, strong medium- β , weak high- β :

$$(f, \sigma)_{sp} = (1.25, 0.13)$$

$$(f, \sigma)_{mb} = (1.25, 0.13)$$

$$(f, \sigma)_{hb} = (0.80, 0.10)$$

$$W_{out} \approx 1946 \text{ MeV}$$

where the approximate output energies W_{out} have been calculated using Equation (3). Scenario 2 (similar to the SNS) is arguably more likely than Scenario 1, because the high- β elliptical cavities have the highest nominal gradient, and so present a higher potential risk.

SIMULATION RESULTS

Figure 2 shows the gradients after R, A, or D sorting is applied, section-by-section, under scenarios 1 and 2. The results summarised in Table 2 are given in more detail elsewhere [3]. The final energy is almost independent of the sorting strategy in both scenarios. No beam losses were observed in any of the simulations, which do not include other errors. The ascending strategy gives satisfactory beam quality in the spoke and medium- β sections, but has little impact in the high- β section, as expected. Beam quality is not always assured if little or no sorting is possible (so RRR applies), and the final beam energy is maximised by operating each cavity at its maximum field. Modified cavity field and phase configurations can improve the beam quality, if necessary, at the expense of final beam energy. Beam energy shortfalls can be recovered by adding cavities in the contingency space at the end of the high- β section.

Scenario 2 is very demanding on spoke and medium- β cavities, with rather high electric fields, and may not be achievable. It may be difficult or impossible to achieve the design beam energy of 2 GeV, if the average field in the high- β section is below the nominal value, without additional contingency cavities.

If the cavity phases are raised to an average of $(-15^\circ, -10^\circ, -10^\circ)$, the energy gain increases by about

Table 2: Results for scenarios 1 and 2, after applying sorting algorithm R, A or D, section-by-section.

Sorting algorithm	Beam energy [MeV]	Trans. emit. growth [%]	Longit. emit. growth [%]	Longit. halo para.
Nominal	1998	5.7	4.5	1.84
Scenario 1				
RRR	1499	20.1	3.9	2.10
AAA	1465	16.2	-0.4	1.51
DDD	1498	18.4	13.3	1.92
AAR	1464	17.6	-6.2	1.65
Scenario 2				
RRR	1965	26.7	47.5	3.20
AAA	1966	15.7	10.7	1.93
AAD	1966	15.4	16.9	1.95
AAR	1966	14.5	12.5	2.01

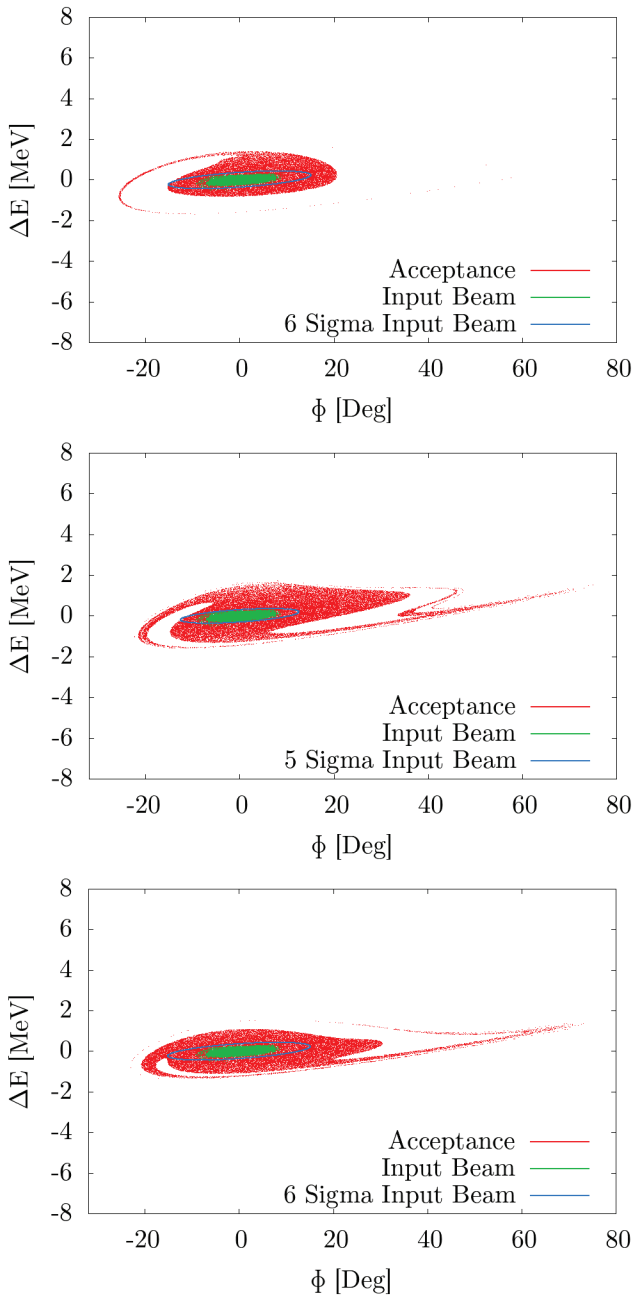


Figure 3: Longitudinal acceptance in the nominal case (top), and in Scenario 2 for RRR (middle) and AAR (bottom) sorting.

(7%, 3%, 2%) in the spoke, medium- β , and high- β sections, for a total gain of about 2.5%. Such phase increases preserve an adequate phase acceptance along the linac, but reduce the energy acceptance to about half the design value in the spoke and medium- β sections. Nonetheless, Fig. 3 shows that there is sufficient longitudinal acceptance with RRR and AAR sorting under scenario 2 to avoid forming longitudinal tails that can lead to beam losses [4]. A conservative approach is to modify the cavity phases only for longitudinal matching, guaranteeing a large end-to-end longitudinal acceptance and limiting longitudinal (and trans-

verse) emittance growth. Smoothing the longitudinal phase advance rate is especially important between the spoke and medium- β sections, where the frequency doubles and the gradient increases from 9 to 16.8 MV/m.

LOW LEVEL AND HIGH POWER RF

RF power overhead – the difference between the maximum RF amplifier output and the power delivered to the beam – can be a factor in sorting. Sufficient overhead is necessary to maintain a constant cavity field in the presence of perturbations and errors. Overheads vary systematically, even if the cavities and amplifiers in each section are identical and perfect, because the proton speed changes. Beam current fluctuations within and between pulses need a constant overhead for different RF stations [5], while Lorentz force detuning and Q -loading effects vary randomly between cavities. Significant extra power is needed in unfortunate cases – if the piezo-tuner does not work, if there is large installation error, or with a large manufacturing error. Cavities with particularly large errors can be sorted to locations that have a naturally larger power overhead. Measured values of Lorentz force detuning and Q_L may be important cavity sorting indicators.

CONCLUSIONS

The sorting algorithms discussed here assume a complete pool of cavities for each type, with the goal of exploring the potential gains. Random distributions of measured maximum achievable electric fields are assumed, around a displaced average value. A simple ascending sort effectively ensures relatively good beam performance in the spoke and medium- β sections, provided that longitudinal beam matching and phase advance smoothing are performed. Adequate beam quality is not guaranteed if the output beam energy is maximised in isolation. Cavity Lorentz force detuning and Q_L are also candidate sorting parameters, in order to optimise the cavity power overhead.

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REFERENCES

- [1] Y.Zhang *et al*, “Experience and lessons with the SNS superconducting linac”, MOZMH01, IPAC10, 2010.
- [2] M.Eshraqi, “Beam physics design of the Optimus+ SC linac”, ESS Technical Report ESS/AD/0050, 2013.
- [3] E.Sargsyan, E.Laface, S.Peggs, R.Zeng, “Cavity Sorting at ESS”, ESS Technical Report ESS-0011779, 2014.
- [4] Y.Zhang *et al*, “Measurement of Longitudinal Acceptance and Emittance of the SNS SCL”, PRST-AB 11, 104001, 2008.
- [5] R.Zeng *et al*, “Investigation to Reduce Power Overhead Required in SC RF Cavity Field Control”, IPAC13, 2013.