

HIGH CURRENT BEAM DYNAMICS IN AN ESS SC LINAC

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Abstract

Three alternative designs of the European Spallation Source (ESS) high energy linac are described. The most promising ones are either a normalconducting (nc) coupled cavity linac (CCL) up to final energy or a change at 407 MeV to only one group of 6 cell superconducting (sc) elliptical cavities.

Fully 3d Monte Carlo simulations are presented for both options, optimized for reduced halo formation at the linac end. For the error free matched case, especially the halo formation in the longitudinal plane is more pronounced for the hybrid solution with its superconducting cavities, caused by the unavoidable phase slippage, but still quite well acceptable for loss free ring injection. Simulations however for a 30% mismatched dense core, surrounded in addition by 1.5% halo particles are showing few particles with very large amplitudes even in real space. This case represents halo formation in front to end simulations, caused by current fluctuations, filamented RFQ output distribution and enhanced by accumulated field errors.

1 OPTIONS FOR THE HIGH ENERGY PART OF THE 6% D.C. ESS LINAC

The current reference design of the ESS contains a 1.334 GeV H^- linac with a 5% duty cycle, a 50 Hz repetition rate and a peak current of 114 mA. The beam current is chopped with a 70% duty cycle [1]. The radio frequency is 280MHz for the two front end RFQs and DTLs. After funneling at 20 MeV final acceleration to 1.334 GeV is accomplished in a nc CCDTL and CCL operating at 560 MHz. A sc version of the high energy linac is also being studied. The 1 msec long linac pulse is injected into 2 compressor rings, to produce a final beam pulse length of 1 μ sec.

Any design of the ESS high energy linac must ensure loss free ring injection. This demands an unfilamented 6d phase space distribution for the linac beam.

Table 1, lists 3 high energy, 6% duty cycle, linac design options for a 107 mA, 60% chopped beam using 700 MHz structures. These were the linac parameters from the ESS study [2]. The 700 MHz linac frequency is also the same as considered for the CONCERT [3] multi-user facility. The following conclusions are valid for both 560 and 700 MHz frequencies, but they are limited to linacs with about 6% duty cycle.

For all three options, a doublet focusing system with warm quadrupoles is assumed either after 2 nc cavities [2] or after (2, 3, 4) 6-cell elliptical sc cavities. The accelerating gradient is kept constant at $E_o T = 2.8$ MV/m for the nc cavities resp. $E_o = (5$ MV/m, 8.50 MV/m, 13.7 MV/m

Table 1: Options for the high energy part of the ESS 6% d.c., 64 mA pulse current, 700 MHz linac

	Normal conducting (nc) linac	Superconducting (sc) linac	Hybrid solution
Energy range	105 - 1334 MeV: CCL	120-1334 MeV: $\beta = 0.52, 0.65, 0.8$	105-407 MeV: CCL >407 MeV: $\beta = 0.8, sc$
Total length	631 m	493 m	148 m (nc) + 267 m (sc) = 415 m
# of cavities	232	212	62 (nc) + 116 (sc) = 178
# of klystrons	116	212	31 (nc) + 116 (sc) = 147
Peak RF power per klystron	2 MW	0.4 MW, 0.75 MW	2 MW (nc), 0.75 MW (sc)
Total peak RF Power	232 MW	101 MW	137 MW
# of circulators	NONE	212	116
Cryogenic power	NONE	4 MW	3 MW

) for the 3 sc cavities. Two power coupler/ cavity are assumed for the $\beta = 0.8$ sc cavities. The synchronous phase is kept constant at -25° in the nc cells, whereas only the sc cavity midphase can be kept constant at -25° as a consequence of phase slippage. All sc cavities are assumed to be made out of 6 identical cells. The relative β dependence of the transit time factor is the same as for the SNS 805 MHz sc high $\beta = 0.76$ 6-cell cavities [4], obtained from superfish calculations where end field effects are included. The average transit time factor is smaller by at least 10% than the $\pi/4 = 0.79$ value of $\beta = 1$ sc elliptical cavities. The average synchronous phase per cavity is smaller than -37° at beginning resp. end of each sc section.

It is obvious from table 1, that a pure nc ESS linac version from 105 MeV on is the cheapest in capital cost, but not in operating cost. A sc ESS linac from 120 MeV on requires much less peak RF power, but it is in capital cost quite expensive and substantial R & D is necessary for the 50 Hz pulsed mode behaviour of $\beta = 0.52$ elliptical sc cavities [5, 6], including the ESS 2.7 msec long pulse option

[2]. The hybrid solution with its two couplers/cavity is the shortest and the cheapest one for capital plus 20 years operating time cost. By having only one coupler/cavity the ESS hybrid linac will be longer than the corresponding nc one. Detailed pulsed power tests with 2 couplers/cavity are foreseen for the 500 MHz, $\beta = 0.75$ sc cavity teststand at FZ Jülich [7]. The open questions are halo formation at the end of the ESS hybrid linac, resulting from the phase slippage and enhanced by mismatch.

2 MULTIPARTICLE RESULTS FOR THE ERROR FREE MATCHED ESS LINAC

In Fig. 1, 2 results from Monte Carlo simulations are shown for the ESS nc linac at 105 MeV injection and at the 1334 MeV final energy. All simulations are done with 10000 fully in 3d interacting particles. The 700 MHz bunch current is 107 mA, the normalized rms emittances are 0.3π mm mrad resp. $0.4\pi^\circ$ MeV. The ratio between the full and zero current tune is greater than (0.6, 0.5) transversely resp. longitudinally. The ratio between the transverse and longitudinal temperature in the rest system is 0.66 at injection and about 1.3 at the linac end. All zero current tunes are below 90° . The rms radii are about 3 mm at injection resp. 2 mm at the final energy.

The results in Fig. 1, 2 are obtained for the error free matched case. The upper row corresponds to an 6d waterbag input distribution limiting each particle coordinate to $\sqrt{8}$ of its rms value. As the ESS high intensity nc linac is designed to avoid all kind of instabilities, driven either by high space charge, temperature anisotropy or resonance crossing [8], almost no halo formation is visible at the linac end: there are no particles outside $20\epsilon_{rms}$ at the linac end. The rms emittances are changing by less than 10%.

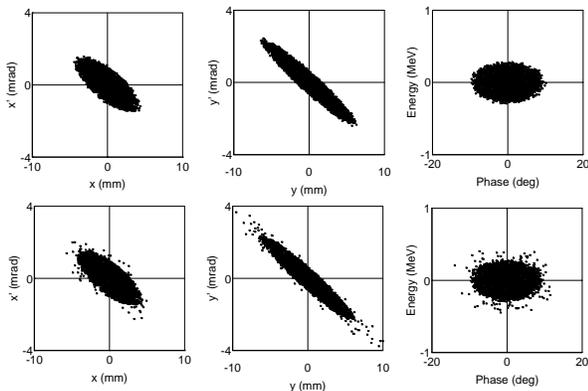


Figure 1: Input distribution for the ESS linac with matched input. Upper row without, lower row with 1.5% initial halo

In the lower row 1.5% halo particles are placed initially outside the dense core at the surface of a 6d phase space boundary with $16\epsilon_{rms}$. Each particle coordinate is now limited to 4 times its rms value and there are in each 2d phase space projection less than 10^{-2} particles outside

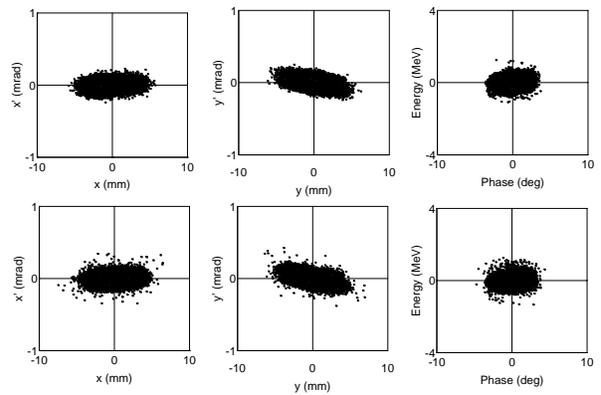


Figure 2: Output distribution for the nc linac for matched input. Upper row without, lower row with 1.5% initial halo

$10\epsilon_{rms}$. About 1% halo particles above $10\epsilon_{rms}$ are found in simulations of the 2.5 MeV ESS RFQ [9]. Phase space correlations between halo particles of a bunched beam in a periodic focusing channel are reported before [8, 10]. At the ESS nc linac end there are now about 10^{-3} particles outside $20\epsilon_{rms}$, going up in phase space to about $40\epsilon_{rms}$. But still all particles are limited to ± 10 mm at the linac end which is less than half of the assumed 22 mm aperture radius. There are less than 10^{-3} particles outside ± 1 MeV.

In Fig. 3 the output distributions are shown for the error free matched ESS hybrid linac. Again the upper row is assuming an initial 6d waterbag distribution without halo, whereas the lower row assumes a distribution with 1.5% halo. For a constant transverse full current tune of 45° in the sc cavity section the ratio between the full and zero current tune is greater than (0.6, 0.67) transversely resp. longitudinally. The ratio between the transverse and longitudinal temperature in the rest system is 0.36 at 407 MeV and about 1.1 at the linac end. All zero current tunes are below 90° . The rms radii are about 2 mm at 407 MeV resp. 1 mm at the final energy.

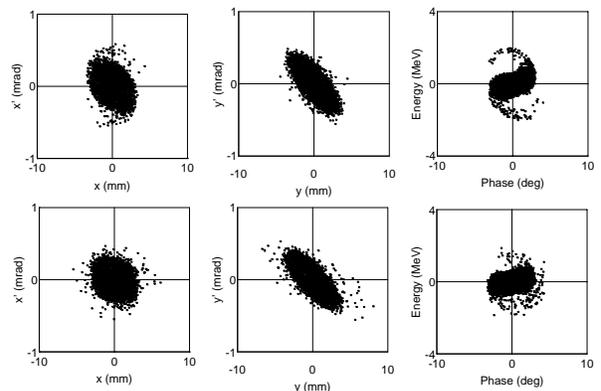


Figure 3: Output distribution for the hybrid linac. Upper row without, lower row with 1.5% initial halo

By comparing the nc output distribution in Fig. 2 with the hybrid one in Fig. 3 much more halo formation especially in the longitudinal plane is visible at the end of the ESS linac. Less than 10^{-3} particles are outside ± 2 MeV. The input distribution with initially 1.5% halo particles will lead to single particle amplitudes up to 9 mm at the ESS hybrid linac end, well outside the 6 mm boundary value of twice the beam core size, predicted by particle-core models [11]. The reason is the phase slippage especially at beginning and end of the sc section, where the beam velocity differs by $\pm 15\%$ from the cavity design velocity. In the Monte Carlo simulations all particles experience the change of the synchronous phase from cell to cell in the 6-cell cavity. As a consequence, even the rms beam radii are oscillating along the ESS hybrid linac, as the nc to sc 6d phase space matching is done for the average cavity synchronous phase.

3 MONTE CARLO SIMULATIONS OF THE MISMATCHED ESS LINAC

In Fig. 4 phase space distributions are shown at the final 1334 MeV energy for the ESS nc resp. hybrid linac, assuming a mismatched input distribution with 1.5% initial halo particles. The upper row is showing the nc and the lower row the hybrid linac output distributions. Excited is a pure high mode with 30% radial and 20% axial mismatch of the 3 bunch radii. The high mode oscillation frequency of about $160^\circ/\text{period}$ [8] causes halo formation in all 3 phase space planes as single particle have initial frequencies of half the high mode oscillation frequency.

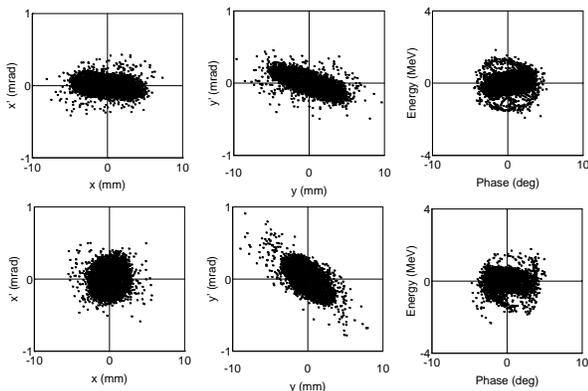


Figure 4: Output distribution for the nc linac (upper row) and the hybrid linac (lower row). The mismatched input distribution is surrounded by 1.5% initial halo.

By assuming the same 30% pure high mode excitation, but for an initial distribution without halo particles, the not shown resulting phase space distributions for both, the nc and the hybrid version of the ESS high intensity linac look quite similar to the shown distribution in Fig. 4. The only difference are somewhat less particles nearby the bunch core. But all requirements for loss free ring injection are fulfilled: the final normalized transverse rms emittance is

smaller than 0.4π mm mrad and there are about 10^{-3} particles outside $20\epsilon_{rms}$. Longitudinally there are less than 10^{-3} particles outside ± 2 MeV, which is acceptable for energy spread reduction by the bunch rotation system.

Adding initially 1.5% halo particles to the 30% mismatched dense core, the linac output distributions in Fig. 4 show a few particles with quite large amplitudes even in real space. Studies are going on for the motion of these particles in the linac to compressor ring transfer line, still effected by space charge forces [2]. Unconstrained hands on maintenance requires less than 1 W/m uncollected deposited beam power at linac end and at ring injection. This value corresponds to less than $10^{-7}/m$ uncollected particle loss for the ESS accelerator facility with its 5 MW average beam power.

In a periodic focusing system correlated field errors of $\pm 1\%$ even for same limited periods can cause noticeable mismatch later on [12]. In front to end simulations of the complete ESS linear accelerator, including the chopping and funnel lines, the halo formation at the linac end is caused by current fluctuations, filamented RFQ output distribution and enhanced by accumulated field errors. The so resulting halo formation can be estimated by assuming 30% mismatch of an unfilamented beam, surrounded by 1.5% halo particles, at the entrance of the error free high energy linac section.

4 REFERENCES

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