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ESS AD Technical Note
ESS/AD/0030

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Analysis of the DTL-to-Spokes Transition Energy

17 February 2012

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Memo to: File **17 February 2012**

From: J. Stovall & M. Eshraqi

Subject: Analysis of the DTL-to-Spokes transition Energy

Introduction. In our initial end-to-end beam dynamics simulations of the ESS DTL we see a significant emittance increase just following the transition from the Drift Tube Linac (DTL) to the Spoked Resonator Cavity section (Spokes) of the linac. We believe that this is the result of a discontinuity in relative longitudinal restoring forces in the two structures characterized by the real-estate phase advance, k_{0l}. In the baseline design the transition energy occurs at 50 MeV following the third tank of the DTL. In this study we have investigated two options for reducing the discontinuity in k_{0l} and we have evaluated the potential cost and benefits of increasing the transition energy.

Option 1. The DTL has been designed to make full use of the rf power available from 3 klystrons to accelerate 75 mA of protons to a final energy of 50 MeV. We assume that the power available from each klystron is 2.8 MW. Reserving 30% for control overhead and waveguide losses leaves 2.15 MW to excite each cavity and accelerate the beam. Applying certain design philosophies and constraints we have arrived at a baseline DTL design having the following properties.

Table 1. Baseline DTL properties

Tank	No of Cells	Length (m)	W_{out} (MeV)	Power (MW)
1	66	7.47	19.20	2.13
2	29	5.75	34.88	2.12
3	24	5.93	50.26	2.15
Total	120	19.42	50.26	6.40

By reducing E_0, the average axial accelerating field, we can lengthen the DTL and increase its final energy W_{out}. Doing so reduces k_{0l} at the end of the DTL reducing somewhat the discontinuity in restoring forces between the two structures.

Figure 1 shows in green the output energy, W_{out}, as a function of the cumulative length, L, for the Spoke section. In this study we have assumed 3 Spoke cavities per cryostat. In red we show the output energy of the 3-tank DTL as a function of increased length, L, of the DTL, relative to the baseline design, where we have reduced E_0 while maintaining the 2.15 MW power constant in each tank. In blue we plot the number of additional drift tubes required against the right-hand ordinate.

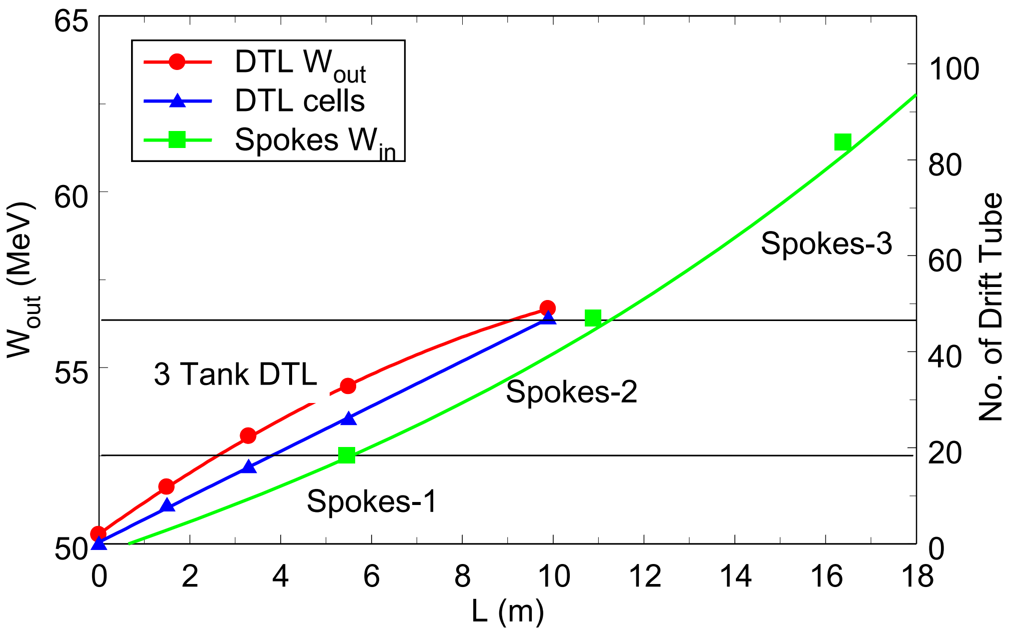

Figure 1. Energy options for a DTL designed to operate at reduced E_0

To replace one 3-cavity Spoke cryomodule and inject the second at its design energy of 52.5 MeV, we would have to reduce E_0 in the DTL from 3.3 to ~2.9 MV/m. We can see in this figure that this would increase the length of the DTL by ~2.5 m but, by removing one cryostat, would reduce the overall length of the linac by 3 m. While saving one 3-cavity cryostat, the DTL would require 19 additional drift tubes. In this scheme we would eliminate three 400 kW rf transmitters.

To replace two Spoked cryomodules and inject the second module at its design energy of 56.4 MeV, we would have to further reduce E_0 in the DTL to ~2.3 MV/m. In this case we would increase the length of the DTL by ~9 m. Removing 2 cryostats would reduce the overall length of the Spoked section by 11 m for a net savings of only 2 m. While saving two 3-cavity cryostats, the DTL would require ~47 additional drift tubes. In this scheme we would eliminate six 400 kW rf transmitters.

Figure 2 shows the longitudinal zero-current real-estate phase advance k_{0l}, in both the DTL and the first 4 focusing periods of the Spoke linac. In periods 2, 3 & 4 of the Spoke structure k_{0l} is constrained to ≤14°/m in the design process to assure that we don't approach a resonance that occurs at σ_{0l}=90°/period. We see, in the baseline design, that there is a factor of 2 discontinuity in k_{0l} between the two structures or 13°/m. By reducing E_0 and extending the DTL to replace one spoked cryostat we can reduce the discontinuity in k_0 to 9°/m, not a dramatic improvement. By replacing 2 cryo-modules we can reduce the discontinuity to 5°/m, still not a dramatic improvement considering that the DTL would be considerably longer.

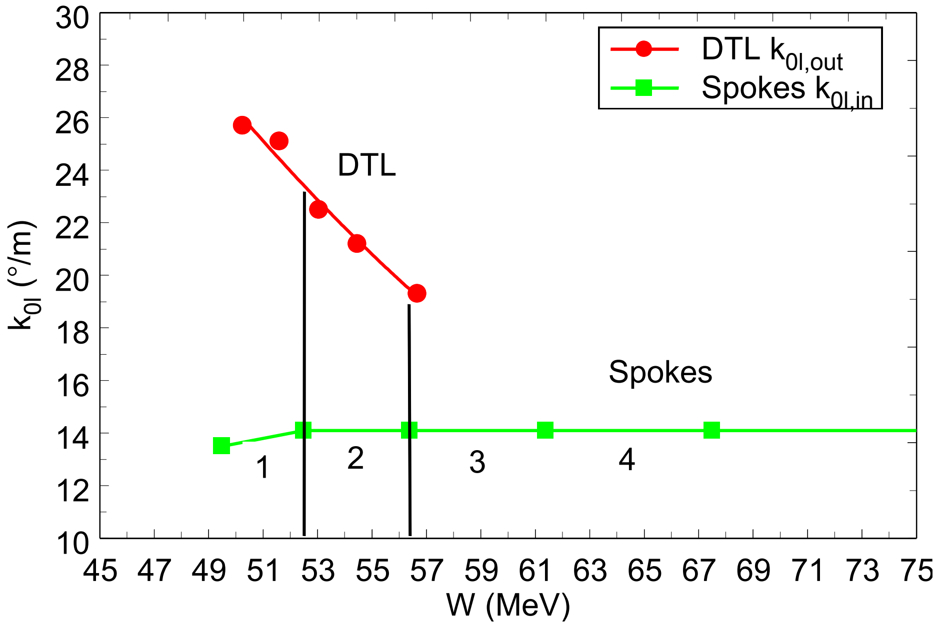

Figure 2. k_{0l} in the DTL and Spoke cryostats

Option 2. Applying the same design philosophy as we used in the baseline design we can add tanks to the DTL to increase its energy while maintaining a high rate of acceleration. Table 2 shows the properties of the baseline DTL extended to 5 tanks having a final energy of almost 80 MeV.

Table 2. Properties of the baseline DTL extended to 5 tanks

Tank	No of Cells	Length (m)	W_{out} (MeV)	Power (MW)
1	66	7.47	19.20	2.131
2	29	5.75	34.88	2.124
3	24	5.93	50.26	2.149
4	21	5.98	64.99	2.126
5	20	6.32	79.81	2.206
Total	160	31.46	79.81	10.74

Figure 3 shows in green the output energy W_{out}, as a function of the cumulative length of the first 6 Spoked cryomodules (3 cavities/cryostat). In red we show the output energy of the 4^{th} and 5^{th} DTL tanks as a function of increased length of the DTL, relative to the baseline design.

In this scenario we see that by adding one DTL tank, having a final energy of 65 MeV, we can replace ~11 Spoked cavities and their associated transmitters, reducing the net length of the linac by ~15 m. Adding a second DTL tank would eliminate an additional 5 cavities and reduce the overall length by 3 additional meters.

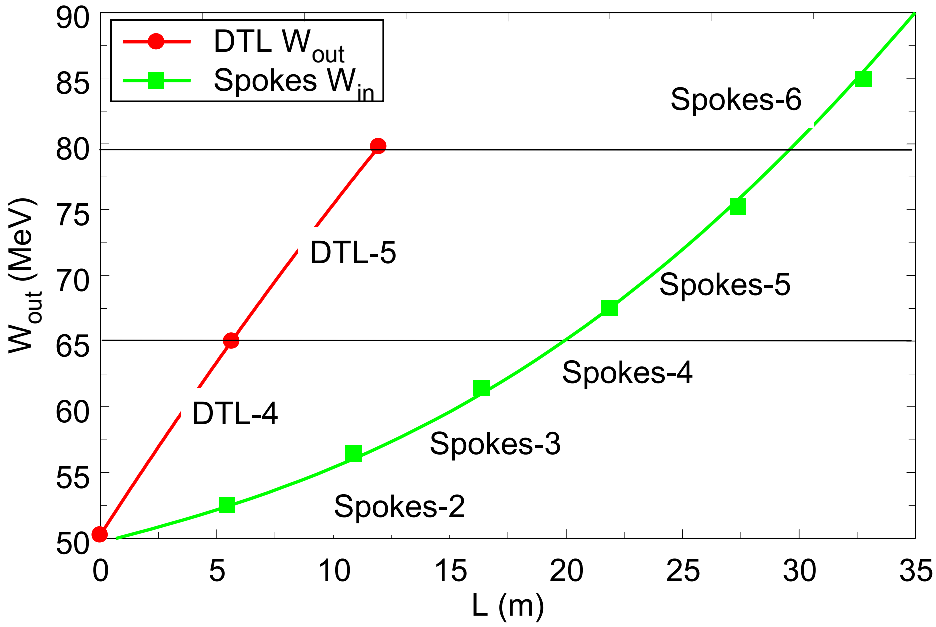

Figure 3. Energy options for a 5 tank DTL

The red curve in figure 4 shows k_{0l} at the exit of DTL tanks 3, 4 and 5. The green curve shows k_{0l} in the first 11 periods of the Spoke linac. By extending the baseline DTL by one tank, displacing almost 4 focusing periods of the Spoke structure we can reduce the discontinuity in k_0 to 6°/m. By extending the DTL to 5 tanks, we would further reduce the discontinuity to ~3°/m.

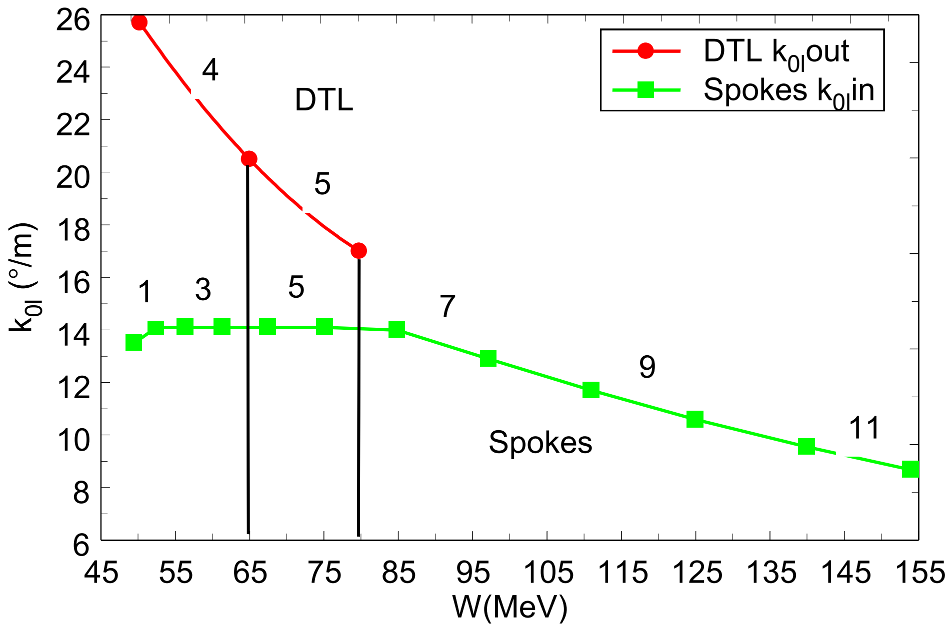

Figure 4. k_{0l} in the DTL and Spokes

To calculate the power savings we assume that each DTL tank uses the entire 2.15 MW available and that it is 50% beam loaded. This means that $P_{beam}=P_{cavity}$=1.075 MW/tank while operating with a peak beam current of 75 mA. We can then calculate the total average electrical power,

$$P_{DTL,ave}=N*(P_{beam} + P_{cavity})*0.04/0.44 \approx 195 \text{ \& } 391 \text{ kW}$$

Where N is the number of DTL tanks, the rf duty factor is 4% and the rf power supply is assumed to be 44% efficient.

Similarly we can calculate the power dissipated in the Spoke cryostats,

$$P_{spokes,ave} = P_{beam}*0.04/0.44+M*P_{cryostat}= 107 \text{ \& } 211 \text{ kW},$$

In this case we have assumed 2-cavity cryostats that require 2 kW of cryo power each to cool and that the cavities themselves dissipate no rf power. M is the number of cryostats and, like the DTL, the rf duty factor is 4% and the rf power supplies are assumed to be 44% efficient.

The net extra power required for a 5 tank DTL accelerating beam to 80 MeV would only be ~180 kW. It is interesting to note that a DTL-to-Spokes transition energy of 80 MeV occurs where the real estate rate of energy gain is approximately equal in both structures. As a result it also corresponds to the shortest tunnel. Adding an additional DTL tank would not change the tunnel length.

Summary. We can summarize the options described above in the following table.

Table 3. Properties a linac having an increased transition energy between the DTL and Spokes

Option	**$W_{transition}$ (MeV)**	**Δk_{0l} (°)**	**ΔL_{total} (m)**	**Δno. of drift tubes**	**Δrf power systems**	**$\Delta P_{installed}$ (MW)**	**$\Delta P_{operating}$ (kW)**
baseline	50.0	12.5	0	0	0	0	0
1a	52.5	9.0	-3	19	-3	-1.2	-190
1b	56.4	5.0	-2	47	-6	-2.4	-480
2a	65.0	6.5	-15	21	-10	-1.6	+88
2b	80.0	3.0	-18	41	-14	-0.8	+180

Conclusion. We conclude that simply lengthening the DTL by reducing E_0 is not very attractive. However, replacing 16 spoke cavities (eight 2-cavity cryostats) with 2 DTL tanks appears to be very cost effective.

- the discontinuity in k_{0l} is reduced to ~3°/m by replacing 16 Spoke cavities with 2 DTL tanks.
- The linac is shortened by 18 m
- 16 rf transmitters are replaced with 2 klystrons.
- the operating power is increased by only ~180 kW (average electrical)

By matching k_{0l} we expect to improve the overall beam quality and benefit from a current independent design. We are unaware of any calculations or analysis that support the 50 MeV transition energy of the base line design.

Addendum

Option 3. Another option, which was under study during the preparation of this note, is to reduce the number of spoked resonators per cryo-module, therefore increasing the averaging longitudinal restoring force in this structure. Assuming a constant maximum phase advance per period, σ_{0l} of 75°/period, a shorter cryo-module will result to a higher real estate phase advance of ~18°/m for a period length of ~4 meters. If the design of the DTL is fixed, then the phase advance in DTL will follow the red line in fig 5. The discontinuity in k0l at the transition would be ~4 deg/m at 65 MeV and less than 2 deg/m at 80 MeV.

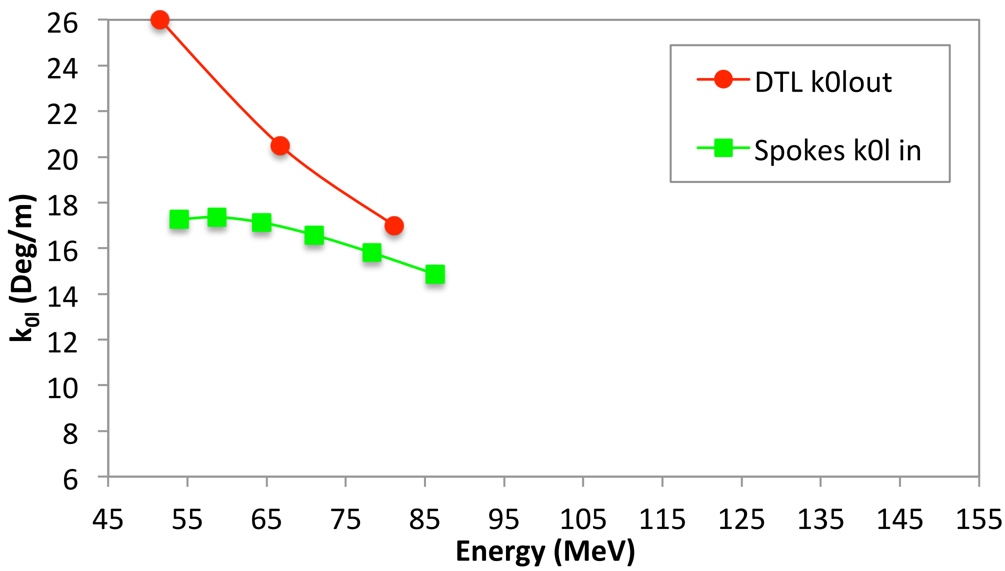

Figure 5. k_{0l} in the DTL and 2 cavity spokes

However, it is worth mentioning that increasing the energy out of DTL requires further optimization of the design beta in spoke resonators. This will increase k_{0l} to ~18 deg/m.

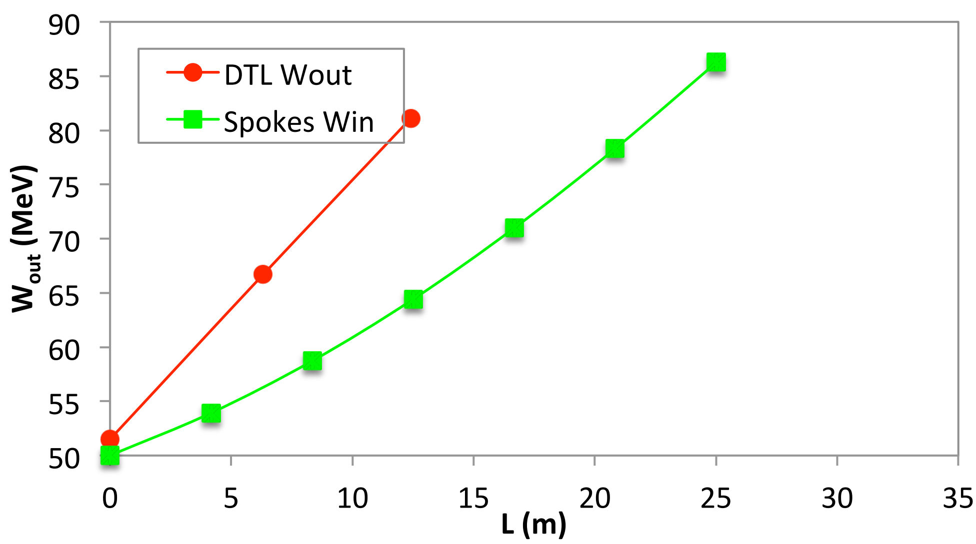

Figure 6. Energy options for a 5 tank DTL

In summary, by reducing the number of cavities per cryo-module from 3 to 2 in the spoke section we can reduce k_{0l} thereby reducing the discontinuity in the longitudinal restoring forces between the DTL (4 or 5 tank) and a spoke linac. By increasing the DTL-to-Spoke transition energy we can further reduce or even eliminate this discontinuity. Increasing the transition energy reduces the overall length of the linac by ~6 m and ~8 m respectively for a transition energy of 65 and 80 MeV. Increasing the transition energy would increase the operating power consumption by 88 & 180 kW respectively.