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DESIGN CONSIDERATIONS FOR A PROTON LINAC FOR A COMPACT ACCELERATOR BASED NEUTRON SOURCE

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Abstract

New neutron sources are needed both for Canada and internationally as access to reactor-based neutrons shrinks. Compact Accelerator-based Neutron Sources (CANS) offer the possibility of an intense source of pulsed neutrons with a capital cost significantly lower than spallation sources. In an effort to close the neutron gap in Canada, a prototype Canadian compact accelerator-based neutron source (PC-CANS) is proposed for installation at the University of Windsor. The PC-CANS is envisaged to serve two neutron science instruments, a boron neutron capture therapy (BNCT) station and a beamline for fluorine-18 radioisotope production for positron emission tomography (PET). To serve these diverse applications of neutron beams, a linear accelerator solution is selected, that will provide 10 MeV protons with a peak current of 20 mA within a 5% duty cycle. The accelerator is based on an RFQ and DTL with a post-DTL pulsed kicker system to simultaneously deliver macro-pulses to each end-station. Several choices of linac technology are being considered and a comparison of the choices will be presented.

INTRODUCTION

A Canadian consortium of neutron users, BNCT researchers and technical experts is proposing a compact accelerator-based neutron source (CANS) that would be hosted at the University of Windsor. The PC-CANS (prototype Canadian CANS) is a relatively low-cost facility that would serve the local community of neutron users, allow the development of BNCT in Canada and supply 18F for PET at the University of Windsor hospital. It is envisaged that the PC-CANS could serve as a model to set up other similar CANS facilities across Canada and serve as a technical development centre towards a more powerful facility, C-CANS (Canadian CANS) that would be a national-scale facility and could be located elsewhere. A schematic of PC-CANS is shown in Fig. 1. Briefly, it consists of a proton linear accelerator with a peak intensity of 10 mA at 5% duty factor (0.5 mA average current) to 10 MeV for a peak/average beam power of 100/5 kW. For neutron time-of-flight (TOF) considerations, repetition rates are in the range from 20 Hz to 200 Hz. For upgrade potential and engineering margin the linac is designed for a peak intensity of 20 mA. The beam intensity limitation is chiefly due to present target technology that is foreseen to be developed in a staged way. In Stage 1, and assuming the addition of a pulsed switchyard, the 10 MeV beam is shared between three end-users delivering simultaneously 2 kW average power to the neutron Target-Moderator-Reflector (TMR) and BNCT stations with 1 kW to the 18F station. In Stage 2 the full current would be delivered in dedicated mode to the neutron or BNCT station at 5 kW average power. In Stage 3, after further target technology development, the full linac capability of 20 mA/1 mA would produce 10 kW average power on the neutron TMR.

A conceptual design study has been completed [1,2] that supports the funding proposal submitted to the Canada Foundation for Innovation (CFI). The conceptual design includes a study of accelerator options, design considerations of the TMR system, and studies towards a small angle neutron scattering (SANS) and multi-purpose neutron imaging end-station. This paper summarizes the work that has been done to characterize the linac system of PC-CANS.

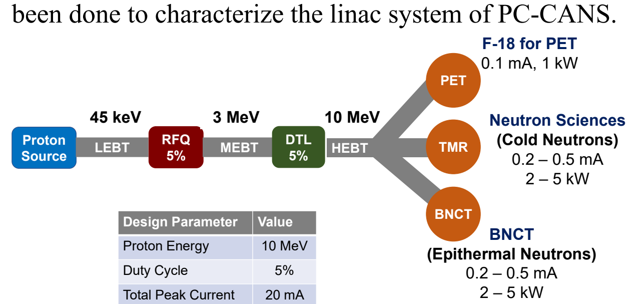

Figure 1: Schematic layout of PC-CANS [2].

LINAC CONSIDERATIONS

The pulsed low duty cycle high intensity scheme for the PC-CANS favours a normal conducting linac. Important optimization parameters are capital and operating cost, low losses for hands-on maintenance, footprint and ease of operation given the non-laboratory setting. The PC-CANS parameters allow some flexibility in the technical choice as the space charge forces are not extreme and the RF duty factor at ~7% (for 5% beam duty factor) reduces RF power density in the structures. Several facilities have been built or proposed in this regime with microwave frequencies ranging from 300-400 MHz, though lower frequency linacs [3] have been proposed for higher beam intensities (100 mA) requiring larger acceptances. The present PC-CANS studies consider 352 MHz as the baseline since this

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is a common microwave frequency and standard linac cost optimization would favour the highest frequency that supports the beam dynamics. Variants using a low frequency RFQ (ie 176 MHz) and frequency jump in the DTL to 352 MHz have not been considered to date in order to maintain a common RF technology for ease of operation/maintenance/spares.

Commercial ECR sources are available in this intensity range. A source potential of 45 kV is suitable for moderate space charge applications like PC-CANS. The choice is a compromise between considerations of beam space charge effects that may increase the transverse emittance at low energy and limiting initial energy to promote efficient bunching in the RFQ, where the longitudinal emittance and length favours decreasing injection energy. A short LEBT consisting of two solenoids is assumed in the design. A handover energy of 3 MeV between RFQ and DTL is chosen where the RFQ length is modest and the initial cell length of the DTL allows efficient acceleration for a reasonable DTL bore size of 20 mm.

RFQ DESIGN

The RFQ, bunches, focuses, and accelerates simultaneously an unbunched proton beam from source potential, 45 keV to 3 MeV. The RFQ vane parameters are modelled in PARMTEQ [4] with the main cell parameters shown in Fig. 2. The present variant has 295 cells, a length of 3.3 m, with 78 kV vane voltage, a transverse focussing factor of B=5.5 and a computed transmission of 97.7% for 20 mA beam intensity. The estimated peak RF power loss is 400 kW (28 kW average at 7% duty factor) based on similar RFQs that have been realized [5]. The input/output beam parameters from the PARMTEQ study (Table 1) are used as the input to the DTL study described in the next section with transverse and longitudinal emittances of 5 x RMS.

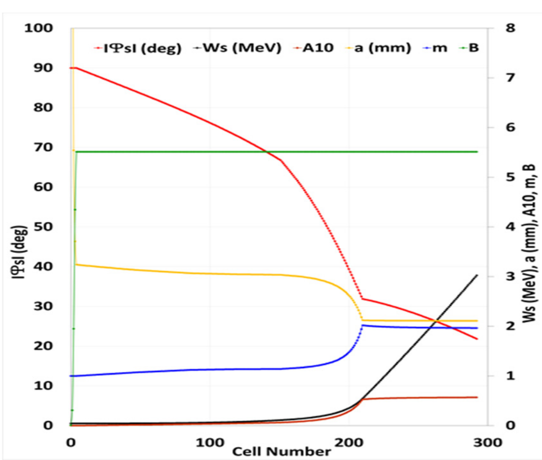

Figure 2: Main vane parameters for the PC-CANS RFQ.

DTL DESIGN

Seven DTL variants have been considered: two Alvarez structures and five CH-DTL structures. Both LANA [6] and PARMILA [7] are used for multi-particle modelling while Trace-3D [8] is used for rapid prototyping and matching. Each variant is first modelled in Trace-3D to set the approximate matching conditions and tank lengths.

Table 1: Input and output beam parameters from PARMTEQ. The outputs at 5 x RMS were used in the DTL study.

	α	β	units	$\varepsilon_{\text{un-norm rms}}$	$\varepsilon_{\text{norm rms}}$	units
x_{in}	0.9055	2.492	cm/rad	2.553	0.025	cm-mrad
y_{in}	0.9055	2.492	cm/rad	2.553	0.025	cm-mrad
x_{out}	-0.671	10.267	cm/rad	0.316	0.0255	cm-mrad
y_{out}	0.707	13.767	cm/rad	0.316	0.0268	cm-mrad
z_{out}	0.423	723.102	deg/MeV	0.137	0.137	MeV-deg

Next the variant is independently modelled in LANA and PARMILA. A common DTL bore of 20 mm is used. All simulations assume a beam intensity of 20 mA.

RF power is a cost driver for PC-CANS and so shunt impedance is an important consideration. Alvarez structures at this frequency and energy range have shunt impedances of 45-50 MΩ/m [5] while CH structures with inherently smaller drift tubes have shunt impedances of ~85 MΩ/m [9]. The difference means that CH structures can operate at comparatively higher gradients with shorter RF structures for the same RF power. Conversely Alvarez structures have transverse focussing built into the drift tubes while CH structures require external focussing which add length and cost to the linac. The choice of gradient is an optimization between cavity power and overall length – the higher the gradient the shorter the RF structure but also the higher the consumed RF power. Figure 3 shows how the required RF power changes as a function of the effective shunt-impedance for various assumed gradients for an effective voltage of 8 MV and an energy gain of 7 MeV for 20 mA beam loading. The vertical lines show the approximate shunt impedances for the Alvarez and the CH structure in this velocity range.

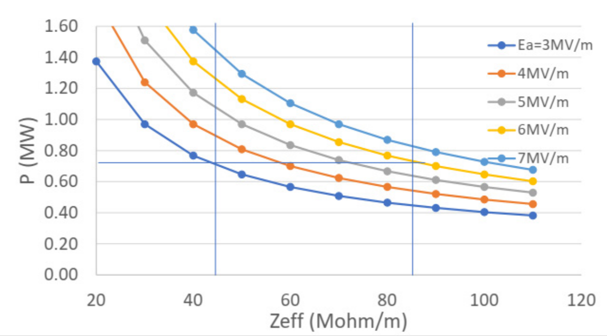

Figure 3: Peak RF power loss as a function of accelerating gradient and shunt impedance for V_{eff}=8 MV and beam intensity of 20 mA. The two vertical lines correspond to the approximate shunt impedance of the Alvarez (45 MΩ/m) and the CH structure (85 MΩ/m) over this energy range.

MEBT

In all cases, except for Variant 1, a common MEBT is used to match the beam from the RFQ to the DTL. The MEBT geometry consists of 4 quadrupoles with a two gap 352 MHz buncher either between Q1 and Q2 or between

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Q2 and Q3 depending on the longitudinal matching optimization for a particular variant. The length of the MEBT is 84 cm.

Alvarez Variants

The Alvarez linac operates in TM010 mode with 2π phase shift between accelerating gaps. The drift tubes can host either quadrupole electro-magnets or permanent magnets to provide strong transverse focus during acceleration typically in a FODO lattice. Longitudinal focusing is achieved by choosing a negative synchronous phase defined by the gap structure.

For the PC-CANS Alvarez variants, a field gradient of E_0=3.4 MV/m, corresponding to a Kilpatrick value of 1.8, is chosen. This gives a length of the Alvarez tank at 2.6 m. This variant requires 26 gaps (25 drift tubes) to produce 7 MeV of acceleration with an effective voltage of 8.1 MV. For lower gradients (longer tanks) the number of cells (gaps) scales with the length. Longitudinal focussing is realized by using a synchronous phase of -30 degrees while transverse focussing is accomplished by installing PMQs in every second drift tube with an alternating (FODO) gradient of ±64 T/m. This produces a transverse phase advance of 55-70 degrees at 20 mA over the whole energy range.

Variant 1: In this Alvarez variant the MEBT is eliminated and replaced by a 15.5 cm drift. Adjustable quadrupoles in the first four drift tubes are used to match the beam to the downstream FODO section. In this case the sixth drift tube is the first FODO quadrupole.

Variant 2: In this Alvarez variant the MEBT (as described above is added to match the beam from the RFQ to the DTL. The FODO structure is maintained for the whole length of the tank.

The beam envelopes for the two Alvarez variants are shown in Fig. 4.

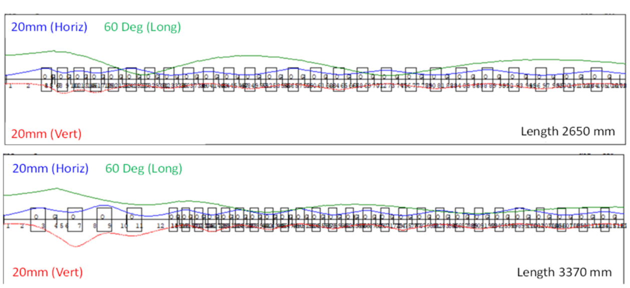

Figure 4: Trace 3D envelops of Alvarez Variant 1 (no MEBT) and Variant 2 (with MEBT). In Variant 1 the first four quadrupoles in the drift tubes are adjusted to match to the downstream FODO.

The multi-particle phase space plots at the exit of PARMILA and LANA for Variant 1 are shown in Fig. 5. There is good agreement between the two codes. The transmission is 100%. There is evidence of distortion of the transverse phase space from longitudinal coupling since, in the absence of a MEBT, the beam debunches before the DTL and the phase spread is quite large in the initial gaps.

The final phase space plots for the Alvarez Variant 2 (with MEBT) are shown in Fig. 6 for PARMILA and LANA, respectively. Note that the distortion in the transverse and longitudinal phase space is less due to the better

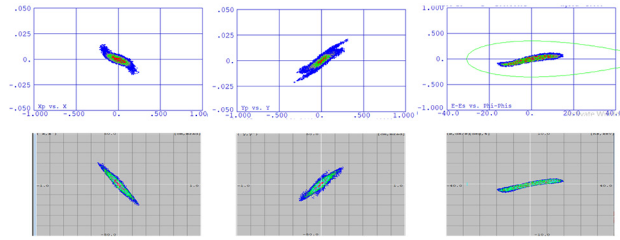

Figure 5: PARMILA (top) and LANA (bottom) output (on the same scale) for the Alvarez Variant 1 with no MEBT. Shown are the x:x' (cm,rad) and y:y' (cm,rad) and φ-ΔW (deg,MeV) phase spaces.

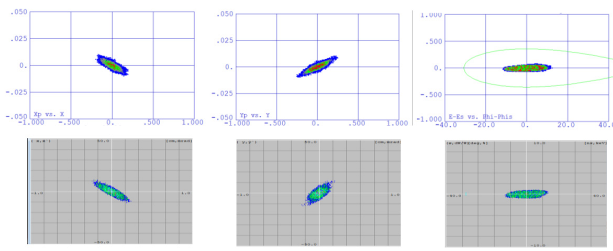

Figure 6: Comparison of PARMILA (top) and LANA (bottom) output (on the same scale) for the Alvarez variant with MEBT. Shown are the x:x' (cm,rad) and y:y' (cm,rad) and φ-ΔW (deg,MeV) phase spaces.

control of the longitudinal phase space with the addition of the buncher.

With no buncher between the RFQ and DTL the longitudinal matching suffers but the overall cost is reduced. Other variants like customized exit cells in the RFQ and customized gap placement in the Alvarez will be considered to improve the longitudinal acceptance of the no buncher case.

CH Variants

In the CH structure the drift tubes are small with no magnetic focussing in the RF tanks. The CH structure operates in the pi-mode with gap-to-gap separation of βλ/2. Longitudinal focussing is achieved either with a negative synchronous phase structure or with a combined bunching and zero degrees structure (termed KONUS [10]). Transverse focussing is achieved periodically either with quadrupole triplets in long tank variants or with quadrupole doublets in short tank variants. The KONUS structure has less transverse defocusing and so affords longer tanks.

Variant 3: This CH-DTL variant adopts a KONUS structure with an aggressive electric field gradient of E_0=6.6 MV/m corresponding to a Kilpatrick of 1.8. Here two tanks are required with one triplet between tanks to achieve transverse focussing. The MEBT is used to match the beam to the first tank that operates at 0 degrees synchronous phase. The structure synchronous energy is lower than the beam energy so that the beam is accelerated in the 2^{nd} quadrant of the longitudinal phase space. In the second

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tank the first three gaps are designed to provide a strong longitudinal focussing with a synchronous phase of -60 degrees and then the rest of the drift tubes are designed with a synchronous phase of 0 degrees.

The two DTL tanks have a combined length of 1.42 m with 13 gaps (12 tubes) in the first tank and 16 gaps (15 tubes) in the second tank. The length of the triplet is kept short at 37 cm to reduce longitudinal debunching. The total length of the DTL including MEBT, RF tanks and triplet is 2.61 m. The beam envelops from Trace-3D are shown in Fig. 7.

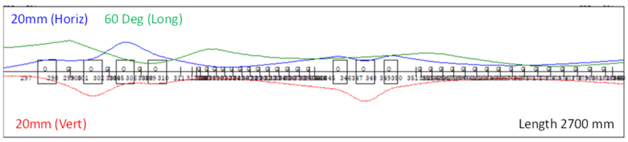


Figure 7: CH-DTL envelop simulated in Trace-3D for Variant 3.

Variant 4: This CH-DTL variant adopts a structure at -25 degrees synchronous phase with an electric field gradient of E_0=6 MV/m. The DTL tanks are optimized in length to reduce transverse and longitudinal emittance growth giving the number of cells in Tank1, 2, 3 as 12, 9 and 12 respectively. The output phase space at 10 MeV as simulated in LANA and compared in PARMILA with results plotted in Fig. 8.

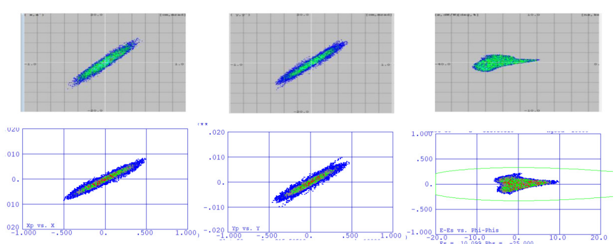


Figure 8: The output phase space at 10 MeV as simulated in LANA (upper) and PARMILA (lower) for 20 mA, E_o=6 MV/m, 3 tanks, CH linac variant with -25 degrees synchronous phase. Shown are the x:x' (cm,rad) and y:y' (cm,rad) and φ-ΔW (deg,MeV) phase spaces.

Variant 5: This CH-DTL variant adopts a field gradient of E_0=5 MV/m with four DTL tanks. The number of cells and synchronous phase for each tank are 9, 8, 10, 12 and -30, -30, -25, -25 respectively.

Variant 6: This CH-DTL variant adopts a field gradient of E_0=5 MV/m with three DTL tanks. The number of cells and synchronous phase for each tank are 14, 11, 15 and -28, -27, -28 respectively.

Variant 7: This CH-DTL variant adopts a synchronous phase of -25 deg, a field gradient of E0=6 MV/m with five short DTL tanks. In this case quadrupole doublets of length 24 cm are used to provide periodic transverse focussing. The number of cells for each tank are 5, 5, 6, 6, and 7 respectively. The Trace-3D envelops for this variant are shown in Fig. 9.

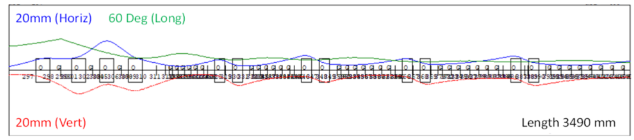


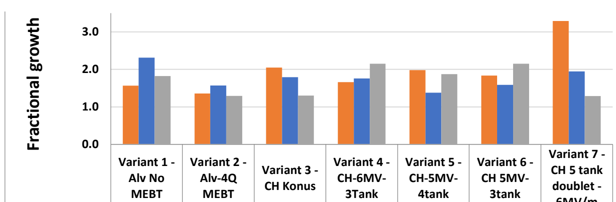
Figure 9: Trace-3D simulation of the CH short tank variant with doublets between tanks and E_0=6 MV/m.

Simulations Results

All variants are run in multi-particle simulation code LANA assuming a MEBT of 84cm (except for Variant 1), triplets of 37 cm or doublets of 24 cm. Except in the acceptance study the input beam parameters for the study use the PARMTEQ output parameters with 5 x RMS emittance values. For each variant the output emittance growth for both the 99% and RMS phase space containment ellipse are calculated by comparing the final emittance with the initial emittance. In all cases the beam intensity is 20 mA.

All simulated variants with nominal emittance produce reasonable beam dynamics with 100% transmission of the particle ensembles. There are variations in the amount of emittance growth produced for each variant. A summary of the fractional emittance growth for both transverse and longitudinal planes for the various variants at the 99% level are given in Fig. 10.

The Alvarez with MEBT (Variant2), KONUS (Variant3) and 5 tank CH with doublets (Variant7) have the smallest longitudinal emittance growth. The smallest transverse emittance growth is with the Alvarez with MEBT (Variant2) with the doublet solution (Variant7) producing the largest growth given that the beam has the largest average size during acceleration.



	Variant 1 - Alv No MEBT	Variant 2 - Alv-4Q MEBT	Variant 3 - CH Konus	Variant 4 - CH-6MV-3Tank	Variant 5 - CH-5MV-4tank	Variant 6 - CH 5MV-3tank	Variant 7 - CH 5 tank doublet - 6MV/m
eps_x (99%)	1.57	1.36	2.05	1.66	1.98	1.83	3.29
eps_y (99%)	2.31	1.57	1.79	1.76	1.38	1.59	1.94
eps z(99%)	1.82	1.29	1.30	2.15	1.87	2.15	1.29

Figure 10: Fractional emittance growth at the 99% level for the various variants for the nominal input emittance.

An estimate of the longitudinal acceptance of each option is done by performing repeated runs with sequentially larger longitudinal emittances and looking at the relative emittance growth for both 99% ellipses. The results are shown in Fig. 11 for 99% fractional growth. The nominal transverse emittance is adopted and the size of the initial longitudinal emittance is normalized to the nominal longitudinal input emittance. The results show that the Alvarez with MEBT rebuncher (Variant2) is the most robust of the variants with reasonable performance even up to 6 times the nominal longitudinal emittance with the KONUS variant (Variant3) second with good performance up to 3 times nominal emittance. The CH variants using negative synchronous phase structures give a 2-3 times margin while the `no MEBT' version of the Alvarez (Variant1) is the

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most restrictive due to the mismatch coming from the RFQ. Some improvement may be expected by customizing the final cells of the RFQ and the initial cells of the Alvarez.

In a similar study the transverse emittance was sequentially increased looking at the transmission through the DTL. The results are presented in Fig. 12. The Alvarez

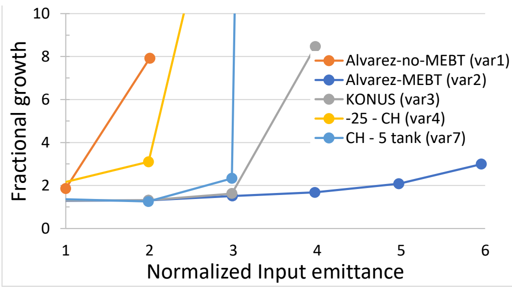

Figure 11: Fractional growth in the longitudinal emittance for 99% ellipse for five DTL variants (1,2,3,4,7) as a function of initial longitudinal emittance normalized to the baseline input emittance.

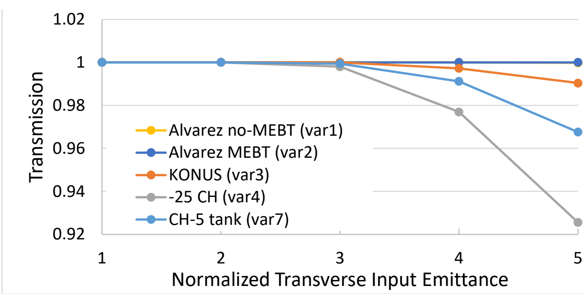

Figure 12: DTL transmission for variants 1,2,3,4,7 as a function of relative transverse input emittance.

variants have the most dynamic aperture yielding 100% transmission for up to 5 times the nominal input emittance. All variants deliver nearly 100% transmission up to 3 times the nominal emittance. The study also shows that the transverse emittance growth actually improves with the larger emittance due to reduced space charge.

The length of the RF sections and the full length (including any MEBT and excluding any HEBT) of each variant are highlighted in Fig. 13. The total peak power required (with and without 20 mA of beam loading) is given in Fig. 14. The RF length is directly related to the chosen gradient while the linac length is impacted by the number of focusing sections required. Total power is reduced for lower gradients but may require additional triplets in the CH variants.

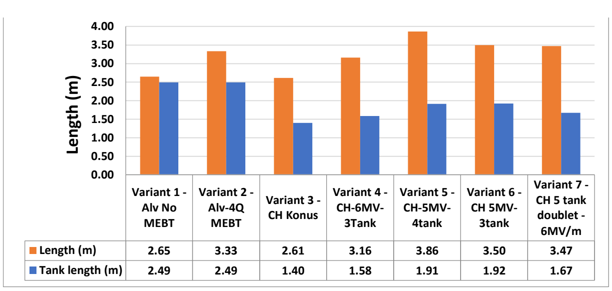

Figure 13: Relative DTL lengths (including MEBT and excluding HEBT) and lengths of the RF sections only.

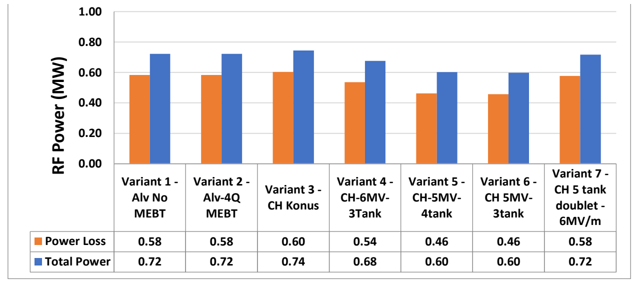

Figure 14: Relative total peak power required with and without beam loading for the different variants.

The Alvarez no-MEBT variant is about the same length as the KONUS CH-variant due to the significantly higher gradient in the CH simulation. Also, the total power is about the same for the two variants. The actual choice of the gradient will come from a cost optimization of structure and RF power. In all cases the average dissipated power is acceptable due to the modest duty factor.

CONCLUSION

Several DTL variants are compared. These include an Alvarez DTL, CH-DTLs operating in negative synchronous phase, and a CH-DTL operating in zero-degree synchronous phase (KONUS). The findings show that all variants yield reasonable beam quality with the Alvarez with MEBT offering the best overall acceptance and beam quality. Further studies are in progress. The next steps are performing sensitivity and error analysis on a few most promising linac variants, and initiating the RF simulations and refining the costing models.

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