LOW AND MEDIUM ENERGY BEAM ACCELERATION IN HIGH INTENSITY LINACS*

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Abstract

In the past two years accelerator builders have published papers describing mature designs of no fewer than 7 new high-performance proton linacs. These machines are typically designed to deliver multi-megawatt beams for applications in pure and applied research. All of these machines use the radio-frequency quadrupole (RFQ) linac for the first stage of acceleration to reach an energy of a few MeV. In essentially all cases, superconducting elliptical cavities have been adopted as the technology of choice for acceleration above ~100 MeV. Between the RFQ and the high-energy elliptical cavities, designers have proposed no fewer than 6 different types of accelerating structures. In many cases these structures are reaching maturity as a result of active development programs. In this paper, we review the design architectures of the "low and medium energy" portions of these machines emphasizing recent experience and developments applicable to high-current linac designs.

HISTORICAL BACKGROUND

In 1972 the 800-MeV LAMPF proton linac was commissioned in Los Alamos. The following year this machine demonstrated its design performance goal of 1 mA average current although it was a few more years before the targets could accept this 800 kW beam for production. In the 1990's the current was further increased to produce a 1 MW beam.

Two new 200 MeV linacs were also commissioned in the early 1970's, one at Brookhaven (BNL) and one at Fermilab, as injectors for synchrotrons. Except for the duty factor, the first 100 MeV all three accelerators was of very similar design, comprised of a 750-keV Cockroft-Walton electrostatic injector followed by a transport line to bunch and match the beam into a 201.25 MHz drift-tube linac (DTL). At 100 MeV the LAMPF beam enters a coupled-cavity linac structure (CCL) of the side-coupled type at 805 MHz. While no longer required to deliver such high beam powers, this linac, renamed LANSCE, continues to operate daily, essentially unmodified and unactivated, three decades later.

In 1980, a novel accelerating structure having "spatially-homogeneous strong focusing," proposed by Russian scientists I.M. Kapchiski and V.A. Teplyakov, was demonstrated in Los Alamos. This structure, renamed the radio-frequency quadrupole accelerator (RFQ), was built as a part of the Pion Generator for Medical Irradiation (PIGMI) project funded by the US National Cancer Institute. This first RFQ, accelerated 30 mA of protons from 100 to 650 keV in an rf structure 1.1 m long.

An RFQ bunches, electrically focuses and today can accelerate a beam from ~50 keV to final energies as high as ~7 MeV. The LEDA RFQ in Los Alamos delivered a 100-mA cw beam at 6.7 MeV (670 kW). The RFQ has become the standard for modern low-energy ion accelerators. It represents the enabling technology for the construction of a new generation of high intensity linacs because it so elegantly accelerates the beam through a very difficult energy range while preserving both its current and quality.

The BNL, Fermilab and more recent CERN linac, that deliver high peak currents but with relatively low average currents, have all been upgraded to improve their suitability as synchrotron injectors. Both BNL and CERN have replaced their electrostatic injectors with an RFQ while Fermilab has replaced the 100- to 200-MeV portion of their DTL with a 400-MeV side-coupled CCL.

The PIGMI project also operated a 425-MHz copper-plated DTL, containing permanent-magnet quadrupole (PMQ) lenses, at an average axial accelerating field E_0=8.0 MV/m. The US Spallation Neutron Source (SNS) linac, which is presently being commissioned in Tennessee, incorporates each of these technologies to accelerate an average current of 1.5 mA to 1 GeV.

HIGH INTENSITY LINAC DESIGNS

During the last decade numerous projects have been proposed requiring high intensity ion linac drivers [1]. Applications have included the transmutation of nuclear-waste, sub-critical energy production, neutrino factories, spallation-neutron sources, tritium production and materials irradiation to name a few. These applications would require linacs that can deliver ≥1 mA of average beam.

Typical linac designs proposed for such applications consist of three main sections:

- A "front end" consisting of an ion source and RFQ,
- Intermediate-velocity structures which accelerate the beam from ~5 to ~150 MeV ($\beta \approx 0.1$ to 0.5), and
- High velocity structures that accelerate the beam to ~1 GeV.

The primary challenges in designing a linac at such high beam currents include maximizing machine reliability while minimizing cost and the potential for radio-activation of accelerator components.

Reliability

The fact that the LANSCE DTL and CCL are in daily operation after three decades speaks for itself. While the brazed copper CCL structure is responsible for essentially no down time, some drift tubes in the DTL have begun to

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leak. Postmortem analysis shows the leaks to be associated with fabrication flaws at the stem-to-body braze joints, eroded by years of unregulated water flow. Variants on these structures can be expected to operate reliably at similar duty factors. Accelerators required to operate cw present special power management challenges and proposed designs have yet to demonstrate long-term reliability in this energy range.

Cost

The capitol cost of an accelerator is frequently characterized by 3 primary drivers:

- Structure choice,
- rf power and distribution system, and
- Power conditioning systems that convert ac power to pulsed or cw high voltage dc.

Other major cost factors, such as facility size and utility requirements, are related to these three components. The cost of both the structure and the rf system are driven by the structure's efficiency in converting rf power to beam power.

Activation

One of the most demanding requirements affecting the choice of accelerating structures is to assure that activation, resulting from beam loss, will not preclude hands-on maintenance of beam-line components during production runs. This implies a residual radiation limit of <100 mrem/hr, 30 cm from the beam pipe following a 4 hour cool-down [2]. This limit corresponds to an uncontrolled beam loss of ~1 W/m at 1 GeV. LANSCE met this requirement during high intensity operations. However radiation measurements have indicated losses up to ~0.6 W/m that are not explained by simulation. The predictable beam loss limit from all sources in new designs is typically <1 W/m.

There are several sources of beam loss in a linac. However the primary concern, with respect to structure choice, is the potential for initiating emittance and halo growth, leading to beam loss at high energy. With the adoption of large-bore elliptical superconducting cavities above β=0.5, such losses have become somewhat less of a concern. The main sources of emittance growth and halo development are beam mismatch, charge redistribution, and resonances.

In a linear transport system without space charge, all particles rotate in phase space with the same angular velocity or real-estate phase advance k_0. The evolution of such beams is said to be emittance dominated. The introduction of space charge creates nonlinear defocusing forces within the beam that react the external restoring forces of the lattice. As a consequence, the phase advance with space charge k, becomes damped or depressed in proportion to the charge density. In this case the beam evolution is said to be space-charge dominated because k of the perimeter of the beam may be only slightly affected while k at the core may be severely damped. The degree to which a beam is space-charge dominated is defined by its tune depression ratio k/k_0. A beam in a lattice designed to maintain a smaller rms beam size, will suffer a less severe tune depression and be less susceptible to emittance growth [3].

When such a beam is matched, particles leaving one region of phase space are just replaced by new particles and, while the motion can be highly nonlinear, there is no net increase in its phase-space area. If, however, the beam is not matched, particles leaving a region of phase space are not replaced. This in itself does not initially cause emittance growth, but it introduces filamentation which, as the beam propagates with a spread in angular velocity, quickly disperses, developing into the dreaded halo.

The particle distribution within a beam entering a new lattice will not be in equilibrium with the new restoring forces. Space charge will cause the particles to seek a new equilibrium distribution. Further, if the velocity distributions in the transverse and longitudinal planes are unbalanced, energy will be exchanged between planes to cause the beam to become "equipartitioned." Both of these phenomena lead to emittance and halo growth and are stimulated by mismatch or changes in the lattice.

The consequences of mismatch are further complicated by the stimulation of coherent core resonances excited by envelope oscillations. Space charge, acting on particles oscillating through the core, drives them into the halo through parametric resonances. All of these effects are amplified by a large tune depression, so for high beam currents, it is prudent to pick structures that are compatible with strong focusing lattices with short periods, capable of maintaining a small beam size.

In a typical 1-GeV linac design the intermediate energy structures control the beam during almost half of its total flight time. If this section is comprised of multiple structure types there are multiple opportunities to introduce mismatches at low energy. The most common and potentially most damaging mismatch occurs at the transition between the RFQ and the following accelerating structure where the beam velocity is low. In accelerator applications including a funnel to achieve the required beam current or where a chopper is required to facilitate synchrotron injection, additional mismatches are inevitable.

Cavity Design

We characterize a structure's efficiency by its shunt impedance, ZT^2, which relates cavity power dissipated per unit length to E_0 corrected for the transit-time factor, T.

$$\frac{P}{L} = \frac{(E_0 T)^2}{ZT^2}$$

The objective of the cavity designer is to maximize ZT^2 subject to other constraints:

- E_{peak}, the peak surface electric field, must not exceed a "reasonable" value at the design E_0. The maximum E_{peak} is related to the frequency by the "Kilpatrick criteria" and is expressed in units of E_K. A reasonable limit depends on the total area exposed to the highest voltage. RFQs are typically designed to operate at E_{peak}=1.8 E_K because a relatively small area of the vane tips are exposed to the highest voltage. DTLs are typically designed to operate at ≤1.3 E_K because a larger surface area is exposed to the highest voltages. However, recently conditioned DTLs have demonstrated excellent voltage holding capability at much higher levels.

- ρ_{max}, the maximum cavity power dissipated per unit area, must be manageable. In traditional DTLs and CCLs operating at ≤7% rf duty, power densities don't exceed 10 W/cm^2 and thermal management is tractable. In structures designed to operate cw, either E_0 or ZT^2 must typically be compromised to maintain $\rho_{max} \leq 20$ W/cm^2.
- In DTLs, there are two additional constraints. Drift tubes must be of large enough in length and diameter to accommodate quadrupole focusing lenses specified by the beam-dynamics design. In addition, if field stabilization is required, the cavity dimensions must meet the "post-coupler criterion" that relates the drift tube diameter d to the tank diameter D.

$$0.95 \geq \frac{[(D-d)/2]}{(\lambda/4)} \geq 0.90$$

DTLs

The SNS DTL, shown in fig. 1, is designed to accelerate a peak current of 38 mA from 2.5 to 86 MeV in 6 tanks. Two thirds of the 110 drift tubes contain permanent magnet quadrupole lenses (PMQs) having an integrated strength of 1.3 T. It operates at 402.5 MHz with a beam duty factor of 6%. This DTL is installed, tuned, and conditioned and to date has accelerated 38 mA of beam to 40 MeV with no measurable beam loss.

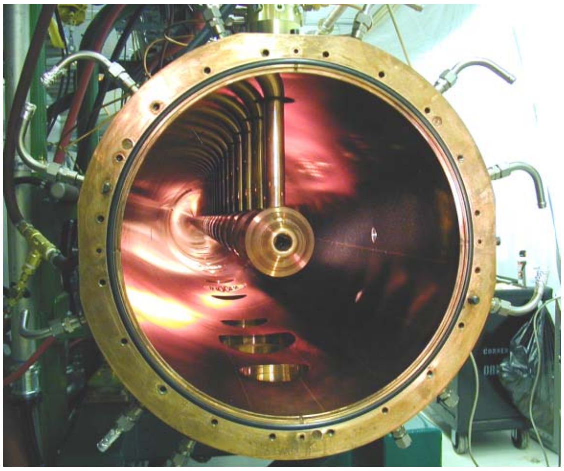

Figure 1: SNS DTL tank 3.

Each drift tube has been individually optimized for ZT^2, a feature which, in hind sight, may not be cost effective. In Fig. 2 we plot the cavity shunt impedance corrected for stems, post couplers, end walls, etc.

E_0 is ramped by a factor of 3 in tank 1 to adiabatically capture the beam longitudinally. In Fig. 3, we see that E_{peak} was conservatively held to ≤1.3 E_K. The first 3 tanks were conditioned to ~1.6 E_K in ~48 hours, indicating that a more aggressive design would be feasible.

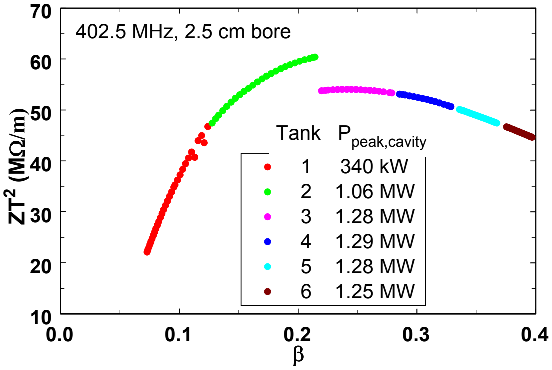

Figure 2: SNS DTL cavity shunt impedance ZT^2.

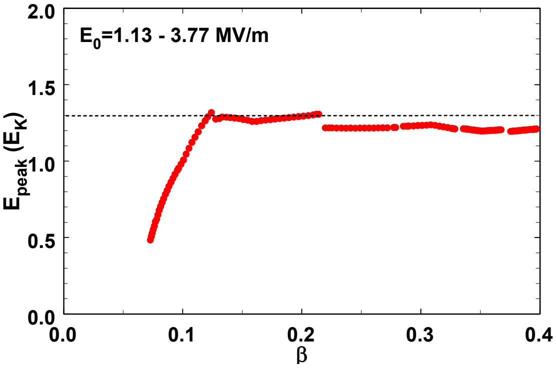

Figure 3: SNS DTL peak surface electric field E_{peak}.

In Fig. 4, we see that ρ_{max} would be quite unmanageable in cw operation but at the design 7% rf duty, the hottest spots do not exceed 3W/cm^2.

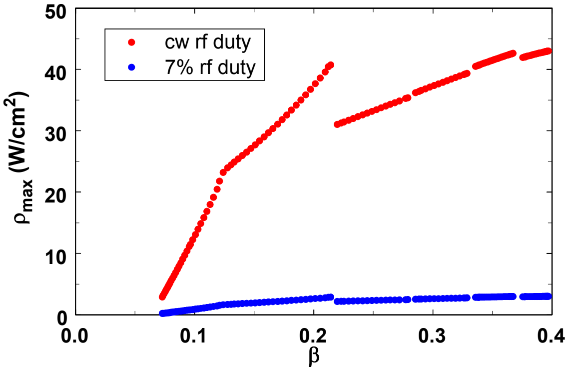

Figure 4: SNS DTL maximum power density ρ_{max}.

Classical DTLs are typically the preferred structure following the RFQ in high-current applications for three reasons.

- The real-estate ZT^2 is high implying modest power requirements and a short tunnel.
- Operating at the same frequency, E_0, and synchronous phase ϕ_s, can be tailored to match the longitudinal phase advance k_{0l}, of the RFQ and adiabatically increase the acceleration rate.
- Because of their short focusing lattice (2-4βλ), with quadrupoles in each drift tube, the transverse phase

advance k_{0t} can be tuned to match that of the RFQ and maintain a small beam size, minimizing the tune depression.

Ideally, if the DTL were "close coupled" to the RFQ and k_{0l} and k_{0t} were both continuous at the interface, the design would be, to first order, current independent, a property difficult to realize in configurations having longer lattice periods.

In the SNS linac, the requirement for a 3.6-m-long medium-energy chopping beam line (MEBT) makes it impossible to avoid a mismatch, both transverse and longitudinal, between the RFQ and DTL. The resulting halo is well demonstrated in simulations and measurements.

The SNS drift tubes are sized to contain PMQs in an FF0DD0 lattice. The beam envelope is matched to the DTL by four bunchers and the final 4 MEBT quadrupoles. To provide continuity in the longitudinal motion, ϕ_s is programmed to maintain the physical length of the beam bunch while adiabatically increasing E_0 from 1.1 to 3.6 MV/m (see in Fig. 3). The MEBT quads must be retuned to match beams of different currents.

Some designers have chosen a more conservative and flexible approach by including individually adjustable electromagnetic quadrupoles (EMQs) in the drift tubes. By increasing the injection energy in the J-Park design to 3 MeV and reducing the rf frequency to 324 MHz, the lowest frequency deemed feasible for klystron amplifiers, the initial drift tube becomes 36% longer and 56% larger in diameter, large enough to accommodate a pulsed EMQ 3 times the strength of the SNS PMQs, strong enough to accommodate an FD lattice.

ZT^2 typically scales with the square root of frequency if the bore is scaled. If, however, the bore size is held constant and the cavity geometry reoptimized, we find that ZT^2 is nearly independent of frequency and the power efficiency is not compromised.

SDTLs

Separated function DTLs or SDTLs, comprised of short tanks containing 3-5 drift tubes, have been proposed as an alternative to DTLs for accelerators having modest peak beam currents but operating up to 100% duty. Because the tanks are so short, field stabilization is unnecessary and because transverse focusing is provided by doublets or triplets located between tanks, the drift tubes are empty. The absence of internal quadrupoles, steering dipoles, diagnostics and post couplers make the SDTL tanks less costly to fabricate and simpler to align. Because the drift-tube size and shape are not constrained, the designer has more flexibility in optimizing the cavity geometry.

Figure 5 shows the cavity shunt impedance, corrected only for stems, for 5 different SDTL designs. The real-estate ZT^2 must be reduced by 30 to 40% from these values to account for the cavity packing fraction. In these designs the drift tubes have very steep face angles which have been adjusted to meet the design objectives. Figs. 6 and 7 show the corresponding values of E_{peak} and ρ_{max}.

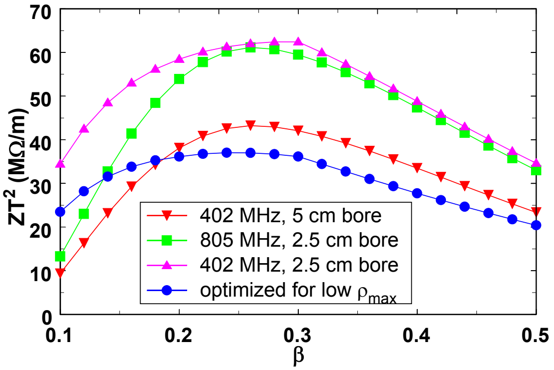

Figure 5: SDTL cavity shunt impedance ZT^2.

The pink curve shows that the rf efficiency of a 402-MHz design, comparable to the SNS DTL, having a 2.5-cm diameter bore, E_0= 3.575 MV/m, and 7 % rf duty factor, appears competitive between 5 and 85 MeV (β=0.1 - 0.4). An 805-MHz version plotted in green, having the same bore may be attractive above 20 MeV (β=0.2) although it would require twice as many drift tubes per tank. Because the transverse focusing period is long, relative to a DTL, a larger bore would be necessary to meet the same beam loss criteria, which compromises ZT^2 as indicated by the red curve.

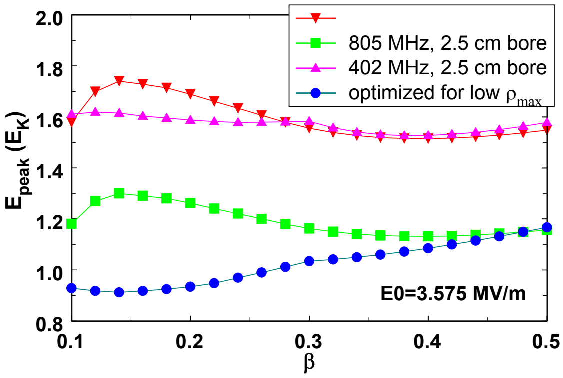

Figure 6: SDTL peak surface electric field E_{peak}.

In each of these designs, E_{peak} was constrained by controlling the face angle and nose radii. We see that in the first case, plotted in pink, E_{peak} was limited to ~1.6 E_K, reducing ZT^2 slightly below 50 MeV. None of these three designs are viable at high rf duty. The blue curve in all three figures corresponds to a design optimized for $\rho_{max} \leq$ 20 W/cm^2. In this design the drift-tube diameter was increased and the face angle reduced. Alternatively, E_0 could be reduced but in either case the total number of tanks would increase.

It is impractical to resonantly couple multiple SDTL tanks, locking their fields as we do in CCLs, because of the long space required for the external lenses at low energy. Consequently they must be driven individually, each having independent phase and amplitude control. They could be driven by individual low-power rf systems or by multiply splitting the power from a single large klystron. In the later case, phase and amplitude control would have to be implemented in full-power waveguide components. The cost of either scheme must be added to the structure cost.

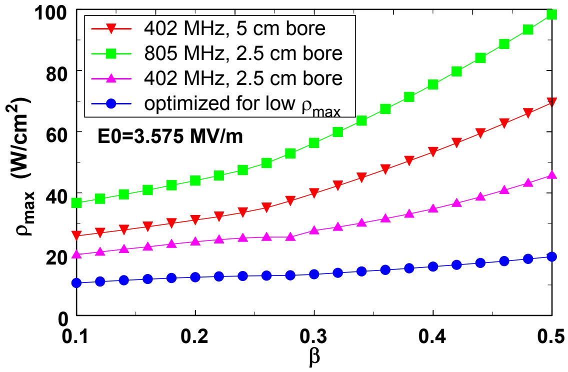

Figure 7: SDTL maximum power density ρ_{max}.

Figure 8 shows a section of the J-PARC SDTL having cylindrical drift tubes designed to operate at E_0=2.5 MV/m and 3% rf duty. This cavity has been conditioned to ~170% of its design electric field.

Figure 8: J-PARC SDTL.

CCDTLs

Coupled-cavity DTLs or CCDTLs are comprised of side-coupled CCL cavities loaded with one or more drift tubes. Low β cavities operating at 700 MHz containing multiple drift tubes proved difficult to fabricate. Segments containing 1, 2 or 3 drift-tube loaded cavities are separated by gaps nβλ long for the insertion a quadrupole lens. Coupling cavities that span gaps an odd number of βλ/2 in length proved too difficult to tune. Unlike SDTLs, multiple CCDTL segments are resonantly coupled and driven from a single power source and enjoy all of the advantages of the π/2 structure mode. In the CERN implementation, beginning at 64 MeV and operating at 350 MHz, the structure looks like a 3 or 4 gap resonantly coupled SDTL.

While the CCDTL was considered a key component of early SNS designs it was deleted for budgetary reasons when funneling was eliminated from the design and superconducting cavities were adopted above 186 MeV. Figure 9 shows the ZT^2, corrected for coupling slots, of the SNS CCDTL and CCL. While the CCDTL had a high E_0, E_{peak} was held to ≤1.5 E_K and at 7% duty, ρ_{max} was quite manageable.

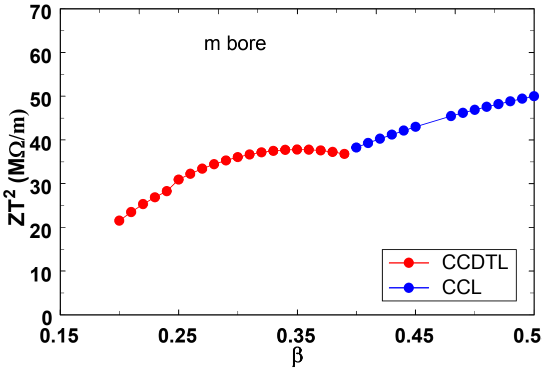

Figure 9: SNS CCDTL and CCL cavity shunt impedance.

The CCL is the most efficient structure above β≈0.4 (85 MeV) and is compatible with a strong focusing lattice. Versions have been operated cw and, because it contains no internal magnets, it is cost effective to manufacture.

SUMMARY

For high intensity applications, a strong-focusing, short-period lattice is important to reduce space-charge induced emittance growth and halo development. It is important to pick a structure with high real-estate shunt impedance. The dependence of ZT^2 on frequency for each of these structures is weak. For a duty factor of ≤10%, ZT^2 is typically constrained by E_{peak} while in high duty applications, E_0 is constrained by ρ_{max} where lower frequency structures may be more efficient at dissipating the rf power. While different structures may perform better in different velocity ranges it is typically not practical to mount the effort to design and fabricate multiple types of structures.

- The DTL offers the highest efficiency, can transport very high currents and cw models have been demonstrated. Especially with the inclusion of EMQs in preference to PMQs, DTLs are expensive to build.
- SDTLs may have a comparablr real-estate ZT^2 but their peak current is limited by the long focusing period, but they are economical to build and cw models are feasible.
- CCDTLs are attractive where funneling is required. They can accelerate high currents but have a relatively low ZT^2 at low β. With high ρ_{max}, building low β cw structures at high frequencies has proved to be very challenging.
- The CCL is the most efficient structure above β≈0.4. It can transport very high beam currents and operate cw.

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