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LOW BETA CW LINACS FOR INTENSE BEAMS

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Abstract

Pushed by interest in intense charged particle beams for neutron sources and neutral beams for military applications, there have been tremendous technical advances in cw linac technology in recent years. Although no one has yet broken the record for high current in a cw linac set over 35 years ago by the MTA accelerator, RFQ accelerators small enough to fit within the beam bore-hole of an MTA Mark 1 drift tube are coming close, and produce orders-of-magnitude brighter beams. A brief history of cw hydrogen linacs will be given. CW experience with the presently operating 75 mA RFQ accelerator at Chalk River will be described. An overview of the cryogenically-cooled D^- RFQ and drift-tube linac due to be installed next year at Argonne will be included.

Introduction

The story of low-beta cw linacs for intense beams is really one of accelerator technology development. There have been numerous plans to use intense high-energy proton, H^-, or D^- beams, but only the low-energy sections or prototype cavities for the high-energy section have been or are being built.

Historical Summary

Livermore (MTA)

The MTA project[1] at Livermore was the first to involve high-current cw linacs. A series of prototype accelerators was built over the period from about 1950 to 1955. The eventual goal was to build a 350 MeV >100 mA deuteron accelerator to breed plutonium for nuclear weapons.

The first prototype, Mark-I, could not reach the operating gradient required for deuterons, but in 1952 it accelerated 225 mA of protons to 15 MeV at 20% duty factor and 100 mA in a cw operating mode. This accelerator was a 9-gap, 18 m long by 18 m diameter Alvarez linac with solenoidal magnets in the drift tubes. It operated at a resonant frequency of 12 MHz, and the beam bore-hole diameter in the higher-energy drift tubes was almost 1 m (large enough to completely enclose a modern RFQ accelerator).

The final MTA accelerator, A-48, comprised a quarter-wave accelerator and two 3.6 m diameter, 6 m long, 48.6 MHz Alvarez-type cavities. It accelerated more than 100 mA cw of protons to 3.75 MeV, and 30 mA of deuterons to 7.5 MeV. Despite the problems encountered with MTA (sparking and damage to drift tubes), three cw accelerators built and operating in 5 years stands as a record, as does the peak cw current of just over 100 mA. Legacies of MTA included a new generation of higher-frequency rf amplifiers used in many subsequent accelerators, and a supply of copper-clad steel plate, without which several later accelerators would not have been considered.

Los Alamos (FMIT, LANL/Culham RFQ)

Los Alamos, in conjunction with the Hanford Laboratory, proposed to build a Fusion Materials Irradiation Test (FMIT) facility, an 80 MHz 35 MeV 100 mA deuteron linac with a liquid lithium target, as an intense neutron source for materials studies for fusion reactors. Work on the FMIT accelerator began about 1980 with plans to build the first 5 MeV section as a prototype at Los Alamos prior to committing the full facility at Hanford. Only the first 2 MeV stage, dc injector and RFQ, had been operated and components for a 2 to 5 MeV Alvarez section fabricated when, five years later, plans for the facility were halted due to escalating costs and lack of agreement on the facility's mission.

Los Alamos physicists realized early in the program that it would be extremely difficult to achieve the injector beam current and quality requirements of FMIT with conventional dc accelerating columns. Although the Radio Frequency Quadrupole (RFQ) accelerator had been invented 10 years earlier[2] and RFQ development was taking place in the USSR, it was the FMIT requirement and the resulting development work on the POP (Proof-of-Principle) accelerator that introduced the RFQ to the world accelerator community outside the USSR. Most of the RFQ's now operating or being built were designed using computer codes and design recipes developed by the team working on FMIT — another example of how cw linacs, even when they never get beyond the prototype stage, have advanced accelerator technology.

Although there are many pulsed RFQ's around the world, the FMIT RFQ, shown in Fig. 1, was the first and until recently the only high-power cw RFQ. Data from FMIT strongly influenced cw thinking and design for Chalk River's cw program, and for the early stages of the US Neutral Particle Beam (NPB) program. The FMIT RFQ operated to design cw field (vane-tip fields of 1.68 Kilpatrick) and accelerated more than 50 mA of H_2^+ (50% of design current) to full energy (2 MeV). Deuteron acceleration was not attempted to avoid activation problems. H_2^+ as a substitute was not too successful because stripping and dissociation led to large neutral and H^+ beam halos which damaged output beamline components. As was the case with MTA and cw structures at Chalk River, the FMIT RFQ experienced numerous problems with rf heating[3] (surface damage and melting of rf seals). Multipactoring problems were solved by coating interior surfaces with titanium nitride. Field enhancement (and local heating) in the cut-back region at the end of the vanes in an RFQ was first reported on FMIT.

Subsequent to FMIT, Los Alamos began another cw RFQ project, a collaboration with the Culham Laboratory to demonstrate high current, high beam quality room-temperature cw capability for the neutral particle beam (NPB) program, a component of the Strategic Defense Initiative (SDI) program. The design for the 353 MHz 2 MeV proton RFQ had been completed, but no hardware had been built when this cw RFQ program was terminated in 1988 (because of budget limitations and the decision within SDI to concentrate resources on a cryogenic demonstration). The design

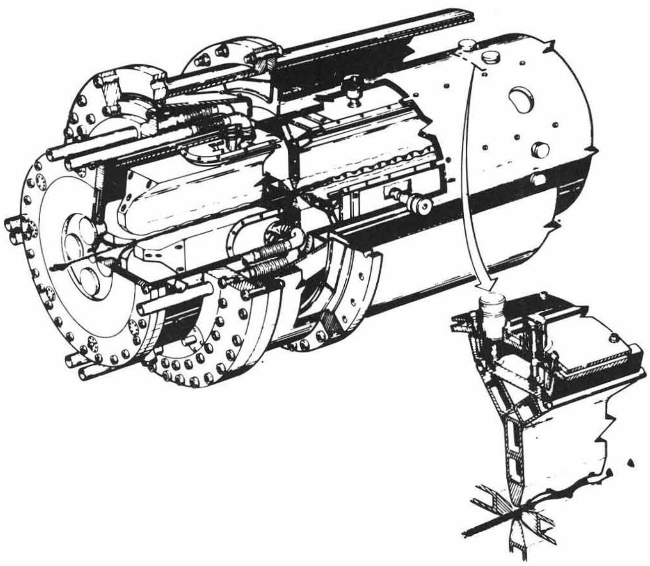

Fig. 1 Cutaway drawing showing details of the manifold-coupled FMIT cw RFQ.

broke new ground in the proposed use of high-strength copper alloys, fabrication techniques, and thermal management to control frequency shifts during rf power changes.

Chalk River (CWPL, RFQ1)

The Chalk River cw linac program started in the mid 1960's with a proposal to build a 65 mA, 1 GeV proton linac as an intense neutron source for physics research. Like MTA and FMIT, the full machine was never funded, but also like MTA and FMIT, prototype work was undertaken. This resulted in the first cw proton linac since MTA, a 750 keV dc accelerator and 3 MeV 269 MHz Alvarez Continuous Wave Proton Linac (CWPL).[4] Throughout its history, CWPL was plagued by a combination of physical and budgetary problems, and first beam was not accelerated in the Alvarez accelerator until 1981. The program was ended in 1983, having accelerated just over 5 mA (10% of design cw current). However, much was learned about the safe handling of cw beams, cooling for cw, minimizing currents in drift-tube stems[5] and design of components for cw linacs.

Interest in cw linacs at Chalk River was maintained over the 1970's and early 1980's by proposals for accelerators to breed fissile fuel for power reactors from thorium or uranium.[6] Optimization studies showed that ≈ 300 MW of proton beam power (at between 1 and 2 GeV energy) was required, and design of a prototype injector to demonstrate proof-of-principle of the first 10 MeV of such a breeder accelerator was begun in 1980. The 300 mA of cw protons was so beyond state-of-the-art (at that time the first RFQ at Los Alamos, POP, had demonstrated 30 mA in short pulse), that it was decided as an intermediate step to build a lower current cw RFQ using the existing 270 MHz cw rf amplifiers. At this frequency, and with conservative assumptions on what peak electric fields could be used, the design current limit for the RFQ was calculated to be 75 mA. This accelerator, RFQ1, accelerated first beam in 1988 and is at present the only operating high-current cw RFQ.[7]

CW Operating Experience with RFQ1

The RFQ1 accelerator comprises a 50 keV, 90 mA dc injector, a 600 keV 267 MHz RFQ and ancillary subsystems. A cutaway drawing of the RFQ is shown in Fig. 2. It is a copper-electroplated mild-steel weldment (following FMIT's lead), but with solid OFHC copper vane tips, so there is no risk of sparks between the tips damaging the plating and exposing mild steel to the rf fields. At design fields (78 kV intervane voltage, peak surface field 24.7 MV/m), structure power is 135 kW, roughly 1/3 of that for the FMIT RFQ. However, because of the higher frequency, the surface power density is 4 times that of FMIT (6.8 vs 1.6 W/cm^2). In the undercut region at the ends of the vanes, the MAFIA code predicts a surface power enhancement of more than a factor of 5 (to almost 40 W/cm^2) and temperatures of >200°C have been measured on the vane-to-tank racetrack seals in this area.[8] Other papers at this conference describe in detail the diagnostics devices,[9] and beam operations[10] on RFQ1.

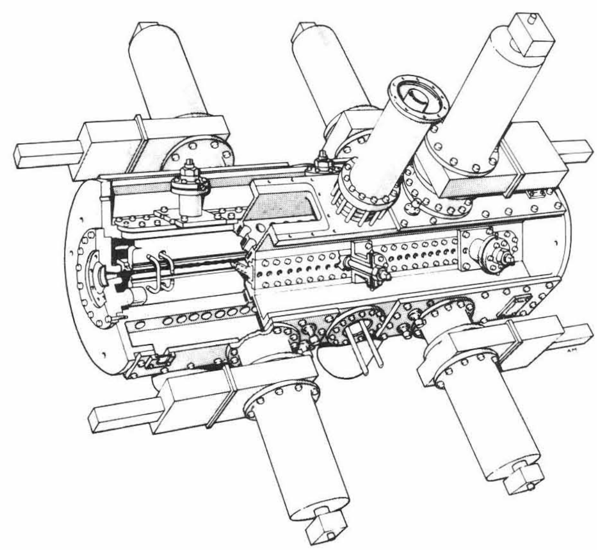

Fig. 2 Cutaway drawing of loop-coupled RFQ1 RFQ showing installation of vanes through slots in side of steel tank.

Highlights of the first two years operation on RFQ1 include:

- Acceleration of 67 mA cw, 90% of design.
- Solution of initial beam-matching problems to increase the multi-beamlet RFQ transmission from 35% to the design 85%.
- Operation with single and multi-beamlet sources.
- Motor-driven stub tuners that perform flawlessly at cw power levels approaching 8 W/cm^2.
- Arcing problems in an rf coupling loop. This loop handled up to 175 kW of cw power for two years, but now fails at less than 100 kW.
- RF loop analysis with a new code, SEAFISH, a SUPERFISH-like code able to compute complex-valued travelling-wave rf field distributions and VSWR's, and used to redesign the coupling loop.

Reliable cw operation of vane-coupling-rings (to suppress dipole fields in the RFQ) and of deformable "racetrack" vane-to-tank rf/vacuum seals.

New vanes designed to operate at higher electric field will be installed to upgrade the RFQ1 facility to 1.2 MeV.[11] These vanes are being fabricated from alumina dispersion-strengthened copper[12] (a high-strength, high conductivity copper alloy). The Los Alamos RFQ design recipes, developed for the BEAR accelerator[13] were used to maximize the energy gain over the 1.47 m long vane length that will fit in the RFQ1 tank.

CWDD, the "Next Generation" CW Linac

Grumman Aerospace Corp., assisted by the Culham Laboratory and Los Alamos National Laboratory, are presently building a cryogenically-cooled, 80 mA cw, 7.5 MeV D^- linac. The Continuous Wave Deuterium Demonstrator (CWDD) is to demonstrate proof-of-principle of the first stage of an accelerator suitable for a space-based NPB weapons system. High beam quality, space traceability, remote operation and high reliability are primary requirements. CWDD will be installed, and US Army acceptance tests performed, at Argonne National Laboratory, following which it is expected that the accelerator will be turned over to Argonne for further experiments. Installation of major components at ANL will begin in mid-1991, with demonstration of full cw beam scheduled for mid-1992.

The CWDD accelerator comprises a 0.2 MeV 92 mA dc D^- injector, a 352 MHz RFQ, to accelerate 80 mA to an output energy of 2 MeV, and a single tank 7.5 MeV output energy ramped-gradient drift-tube linac (RGDTL). A conceptual drawing of the accelerator is shown in Fig. 3. The RFQ is nearly 4 m long (4.63 λ at 352 MHz), made up of four, 1 m long units that bolt together. Each unit is fabricated from four tellurium-copper ingots, electroformed after machining to give a single monolithic structure, similar to that successfully used for the BEAR accelerator.[13]

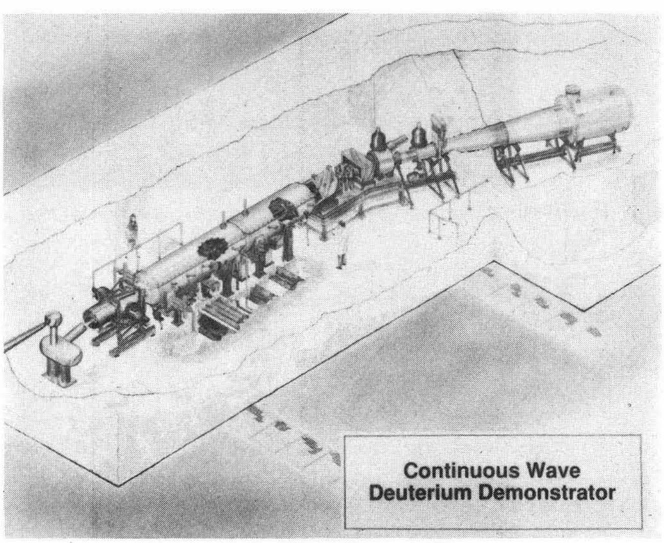

Fig. 3 Conceptual drawing of the CWDD 80 mA cw deuteron accelerator. From left: dc injector, RFQ, DTL, HEBT with bending magnet for beam analysis, beam stop.

High surface currents (typically of the order of 5000 A/m for a 300 MHz structure) flow on the interior of a 4-vane RFQ. The capacitance in an RFQ resonator is mostly between the vane tips, so the charging currents flow radially along the vane sides, and circumferentially along the connecting tank wall. As well as making a very strong, stress-free (and therefore stable) structure, electroforming gives a continuous interior surface. This means that the main rf-current path in the RFQ is free of mechanical joints, eliminating one of the most failure-prone features (joints in high rf-current regions) of all previous cw DTL and RFQ accelerators.

CWDD demands significantly higher beam quality than any previous RFQ, requiring an extensive computer analysis of effects of vane displacement errors, fringe fields and multipole fields.[14] Emittance and brightness predictions for CWDD have not been released. However, some indication of the improvements in beam quality from MTA to CWDD can be inferred from the fact that space-charge-limited beam radii in RFQ's are essentially inversely proportional to frequency. Similar scaling occurs for DTL's. By ignoring changes in focusing period, $\beta\lambda/2$, $\beta\lambda$, etc., between RFQ's and DTL's, and differences between protons and deuterons, one can use the quantity $I*f^2$ as an "indication" of relative beam brightness. Design and achieved currents (I_d and I_a), frequency (f) and "relative-brightness" factor (If^2, normalized to MTA Mark I = 1) for the linacs of this report are given in Table I. Beams have not yet got bigger, but they are very much brighter!

TABLE I
Approximate Relative Beam Brightness

Linac	f (MHz)	I_d (mA)	I_a (mA)	$I_d f^2$ (rel)	$I_a f^2$ (rel)
Mk-I**	12	200*	100	1	0.5
A-48**	48	250	100	20	8
FMIT	80	100	50	22	11
CWPL	269	50	5	126	13
RFQ1	267	75	67	186	166
CWDD	352	80		344	

* Estimate, based on pulsed performance.
** Solenoid focusing was used in the MTA DTL's, so relative brightness numbers for MTA are too generous. If the drift tube bore radius is used as the indicator of beam size, the increase from Mk-I to CWDD is over 2000, instead of the 344 suggested by the frequency ratios.

CWDD will break new ground in other areas besides effective length, fabrication methods and beam brightness. It will be the first cryogenically-cooled cw linac (supercritical neon will keep the structure temperature below 35 K) and the first RFQ to have multiple drive loops in the RFQ cavity. The cryogenic temperature simulates space operation, where liquid hydrogen would provide the cooling. The effective Q of the cavity is increased by nearly a factor of 5, decreasing the rf power required to excite the cavity.

The FMIT RFQ had multiple rf drives, but to an rf manifold. RFQ1 has provision for two drives to the RFQ cavity, but can be driven to full power with only one, and tests of a dual drive cannot begin until after delivery of a dual, klystrode-based rf amplifier, scheduled for delivery in late 1991. CWDD will, from the outset, have a 4-way split of the power from a 1 MW cw klystron to excite 4 drive loops in the RFQ.

A cryogenically-cooled Alvarez linac will accelerate the 2 MeV beam from the CWDD RFQ to a final energy of 7.54 MeV. The DTL will have a ramped-gradient, following the Los Alamos recipe,[15] to minimize longitudinal emittance growth. For the CWDD tank, this requires that the accelerating field increase linearly by 68% from the input to the output end. The ramp will be generated by detuning the two end gaps; post-couplers will be used for fine tuning and to stabilize the DTL fields. Transverse focusing in the DTL will be provided by samarium-cobalt quadrupole magnets in the drift tubes, employing a F-F-D-D lattice structure to reduce the required permanent-magnet quadrupole gradient to achievable levels. Calculated peak surface electric fields in the DTL are ≈ 26 MV/m (1.4 Kilpatrick), somewhat lower than the 1.8 Kilpatrick fields in the RFQ. At 35 K, rf power requirements are expected to be 175 kW to excite the cavity, and 440 to accelerate the beam, giving a beam loading factor $P_b/(P_b + P_c)$ of > 70%.

Conclusions

CW RFQ and DTL linac technology has matured to the point where average beam intensities, currents and brightness are within about a factor of two of peak values that are reached in low duty-factor linacs. Although no high-energy cw linac has yet been funded, the successes of the prototypes augurs well for the future. At present, cw linac development is being driven primarily by the NPB program of the US military, and critical parts of this program, particularly related to improvements in beam quality and control of beam emittance, are classified. However, it speaks volumes about the progress that is being made when experts in that community will now propose, and can then get favourable technical reviews for, a 250 mA high-energy cw proton linac on which one can do hands-on maintenance.[16]

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