The Continuous Wave Deuterium Demonstrator (CWDD) Design and Status†

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Abstract

The design of the Continuous Wave Deuterium Demonstrator (CWDD) and the status of the fabricated hardware is presented. The CWDD is a high brightness, 352 MHz, CW linear accelerator designed to deliver a 7.54 MeV, 80 mA D^- beam at a transverse normalized rms emittance of 0.11 π mm-mrad and a longitudinal rms emittance of 0.20 π mm-mrad. End-to-end beam dynamics analysis for nominal and off-design conditions is described. The tuning and predicted operational performance of the as-built device are also discussed. These results all indicate that the present design can meet the output performance specifications in the presence of combined errors at the limits of the specified engineering tolerances. Preliminary injector operations have been conducted at AEA Technologies, Culham Laboratory and at Argonne National Laboratory, where the CWDD is sited. Initial RFQ beam experiments at Argonne are projected for early 1994. DTL installation and commissioning will be completed in 1995.

I. INTRODUCTION

The Continuous Wave Deuterium Demonstrator (CWDD) is a high brightness, unfunneled, 352 MHz, CW linear accelerator designed to deliver a 7.54 MeV, 80 mA D^- beam with a transverse normalized rms emittance of 0.11 π mm-mrad and a longitudinal rms emittance of 0.20 π mm-mrad. The device, which has been built by Grumman and principal subcontractor AEA Technology, Culham Laboratory with the assistance of the Los Alamos National Laboratory, is sited at the Argonne National Laboratory. The purpose of CWDD is to demonstrate automatic control of a cryogenic, CW, high brightness deuterium accelerator. Figure 1 is a component schematic that illustrates the principle design point performance parameters that characterize the CWDD beamline. Powers are room temperature (RT) values.

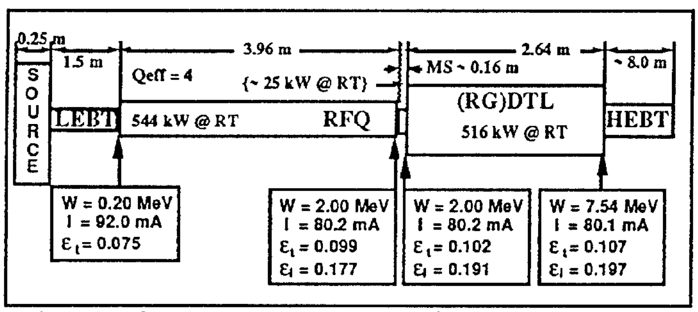

Figure 1. CWDD component schematic and key parameters.

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Figure 2 demonstrates that in an end-to-end source-to-dump beam dynamics simulation, CWDD target performance values for transverse and longitudinal emittance (the identified horizontal lines) are met at the end of the DTL accelerator where the performance will be characterized.

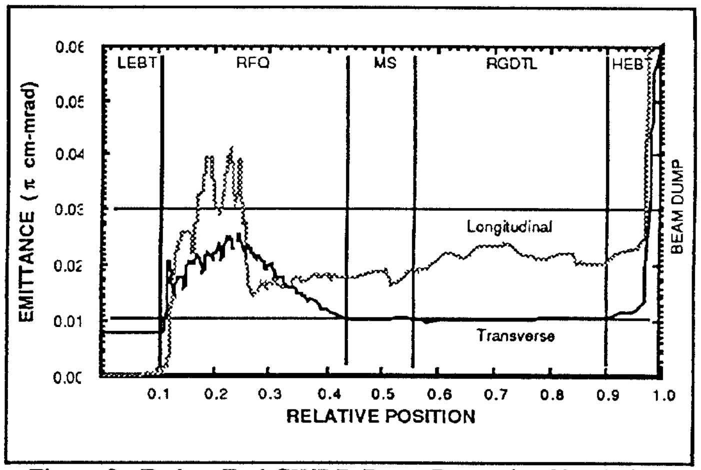

Figure 2. End-to-End CWDD Beam Dynamics Simulation.

The goal of the CWDD physics design was to meet the output performance targets for energy, current, transverse and longitudinal emittance. Below, we describe the beam dynamics of each beamline component and the current status of the associated hardware.

II. INJECTOR

The principal physics issue for the CWDD injector is the ability of the Culham negative ion volume source to meet the required CW performance specifications of both the nominal 90 mA current at 0.150 π mm-mrad, and 50 mA at the nominal 0.075 π mm-mrad emittance. Additional areas of concern are stripping and emittance growth of the negative ion beam in the accelerator column and LEBT, and problems associated with the electron component extracted from the source. An electron suppression technique to reduce the extracted electron component, and a novel electron trapping technique that uses rotating dipoles to spread the electron power load on the dump are used.

Both analytical calculations and numerical modeling using the SCHAR code have been used to model emittance growth within the LEBT solenoid and drift spaces. The resultant emittance growths for the 50 mA, 0.075 π mm-mrad case are 3.7 ± 0.5 % due to aberrations for an aligned solenoid with a K-V beam distribution, as shown on the right of Figure 3, and 2 ± 1 % due to space charge at an effective LEBT current of 1 mA. Monte Carlo calculations have been performed for stripping within the DC accelerator using an axisymmetric computer code. Assuming a gas temperature of 700 °K throughout the accelerator, the derived pressure profiles suggest that between 24% and 34% of the negative ions will

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be stripped for the range of source and accelerator operating parameters envisaged. The AXCEL code has been used to confirm, as shown on the left of Figure 3, that the DC accelerator will operate correctly as the initial LEBT lens, and that the first gap potential needed to obtain the required output beam can be varied by changing the length of the second grid.

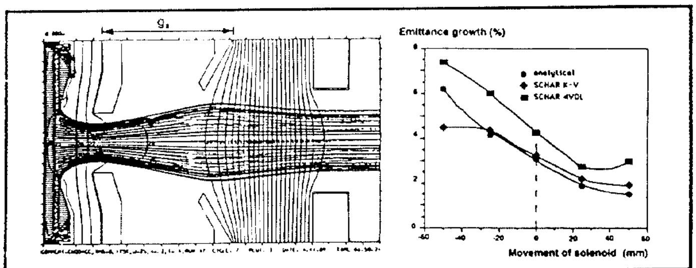

Figure 3. AXCEL & SCHAR Accelerator & LEBT Analysis

III. RFQ

The principal design parameters of the CWDD RFQ, which is shown in Figure 4, are listed in Table I. In designing the accelerator, the Kilpatrick factor was set to 1.8. Scoping studies that traded length, transmission, current limit and emittance growth were performed. Input and output RFQ energies together with the aperture, synchronous phase and energy at the internal RFQ breakpoints between the shaper, gentle buncher and accelerating sections were used to drive these trades and generate the Table I parameters.

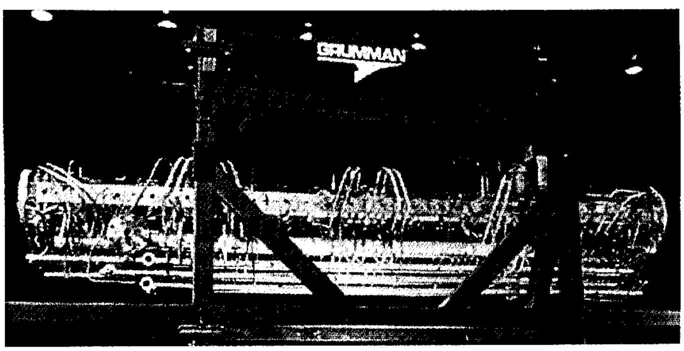

Figure 4. The CWDD RFQ.

The accelerator features include end stabilizers and a constant minimum aperture, a, where the average vane aperture, r_0, varies to reduce the length of the structure accelerating section by maintaining the accelerating field with β at a constant peak surface electric field (PSEF). The vanes have a constant radius (3/4 r_o), except in the accelerator section where the radius increases to maintain the desired resonant frequency. This yields an enhancement factor of 1.26 which has been factored into the Kilpatrick value and PSEF.

The outstanding issues for the CWDD RFQ are the longitudinal field stability of the 4.6λ device, where conventional wisdom recommends the length be maintained under 4λ, the 13% current loss and the control consequences of very high beam loading in the CW cryogenic device, and the ratio of the design current to the accelerator current limit, which is slightly higher than the 50% rule of thumb.

The high RFQ input energy is driven by deuterium operation, the high current performance requirement and the resultant high RFQ current limit. Additional advantages of high injector output energy are reduced LEBT stripping, and improved margin with respect to LEBT instability.

Table I. CWDD RFQ Design Parameters.

Injection Energy	0.200	MeV
Output Energy	2.004	MeV
Input Current	92.0	mA
Output Current	80.2	mA
Transmission	87.1	%
Current Limit	140.	mA
Final Synchronous Phase	-33.0	degree
Initial (Final) Intervane Voltage	87.7 (92.0)	kV
Maximum Vane Modulation	1.625	
Peak Surface Field	33.7	MV/m
Vane Length	3.96 (4.64)	m (λ)
Kilpatrick Factor	1.80	
Enhancement Factor	1.26	
Minimum Vane Aperture	0.257	cm
Initial (Final) Average Aperture	0.328 (0.337)	cm
Minimum Longitudinal Radius	3.499	cm
Admittance	1.153	π mm-mrad
Input Transverse Emittance	0.075	π mm-mrad
Output Transverse Emittance	0.099	π mm-mrad
Output Longitudinal Emittance	0.175	π mm-mrad
Transverse Phase Advance (I=0)	6.6 (17.7)	degree
Longitudinal Phase Advance (I=0)	5.4 (13.1)	degree

Table II. CWDD Tolerance Criteria Summary

Location	Type	Criterion
Injector to RFQ Interface	Beam Axis Misalignment	$\langle r \rangle \leq \pm 0.20$ mm
	Beam Angular Misalignment	$\langle r' \rangle \leq \pm 3.0$ mrad
	Transverse Beam RMS Size	$\langle \lvert r - \langle r \rangle \rvert \rangle \leq \pm 5\%$ ($\pm$ 10% < 5 msec)
	RMS Convergence Angle	$\langle \lvert r' - \langle r' \rangle \rvert \rangle \leq \pm 2.5$ mrad
	Beam Energy Offset	$\Delta W \leq \pm 1\%$ or ± 2 keV
Internal RFQ	RF Amplitude	$\Delta V \leq \pm 1\%$
	RF Phase	$\Delta \Phi \leq \pm 1°$
	Vane Machining Errors	$\Delta r \leq \pm 1$ mil
MS to RGDTL Interface	Axis Misalignment	$\langle x \rangle, \langle y \rangle \leq \pm 0.20$ mm
	Axis Angular Misalignment	$\langle x' \rangle, \langle y' \rangle \leq \pm 3.0$ mrad
	Beam Energy Offset	$\Delta W \leq \pm 5$ keV
	Buncher RF Amplitude	$\Delta V \leq \pm 1\%$
	Buncher RF Phase	$\Delta \Phi \leq \pm 1°$
Internal RGDTL	RF Amplitude	$\Delta V \leq \pm 1\%$
	RF Phase	$\Delta \Phi \leq \pm 1°$
	PMQ Field Strength	$\Delta K \leq \pm 5\%$ ($\pm$ 1% random)
	PMQ Tilt : Roll	$\Delta \theta \leq \pm 1\% : \pm 0.5\%$
	PMQ Transverse Alignment	$\Delta r \leq \pm 2$ mils

The impact of interface or engineering tolerance variation is traced through the entire downstream beamline. The tolerance criteria selected reflect a specified acceptable deterioration in the RGDTL output beam performance. Our guideline sought to keep the design point transmission above 86.5%, the transverse emittance growth under 5%, and the longitudinal emittance growth under 10% for off-design conditions. Additionally, we have verified that the other scenarios, in particular the potentially damaging 90 mA, 0.0150 π cm-mrad CW scenario, and the impact of higher order field components in the RFQ, can be accommodated by the engineering design also under this maximum combined off-design condition. The tolerances for the entire beamline are summarized in Table II.

IV. RGDTL AND MATCHING SECTION

Figure 5 schematically illustrates the matching section, which consists of a single buncher cavity and three PMQs (permanent magnetic quadrupoles). PMQ alignment steering uses the two magnets straddling the buncher. The MS delivers a satisfactorily matched beam to the RGDTL over the anticipated range of operating conditions. The output of this system is be a parallel beam suitable for immediate diagnosis.

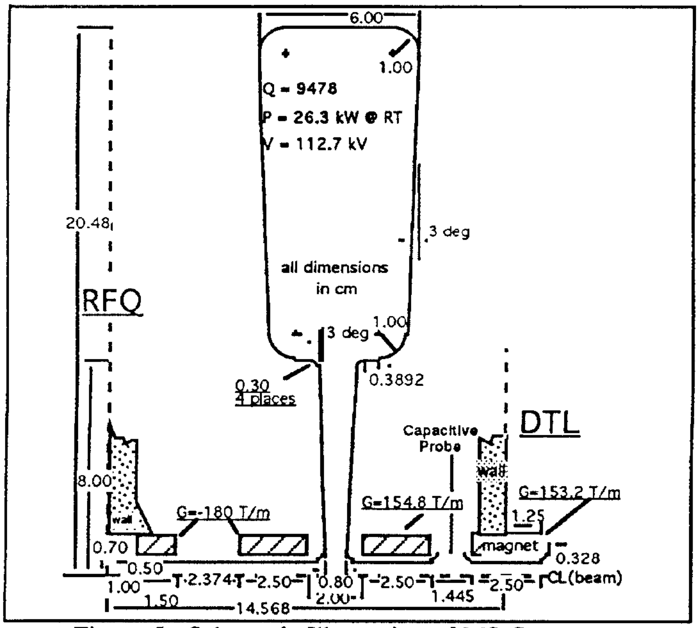

Figure 5. Schematic Illustration of MS Geometry.

The RGDTL employs a constant g/L = 0.2 for all cells which results in near optimal values for the transit time factors but complicated the manufacture. The resonant frequency is established by varying the face angles from cell to cell over the range of ~1.0° to ~5.0°. The low input energy is the minimum that leads to an acceptable engineering design for the first drift tube. This lower DTL input energy permits a higher initial DTL accelerating field which is desirable for controlling longitudinal emittance and yields a more efficient ramp section. The maximum Kilpatrick factor is 1.4 at the high energy end of the accelerator. The accelerating field is ramped from ~ 2.0 to ~ 4.0 MV/m in the 47 cell RGDTL. The linear ramp will be imposed in the single tank by detuning the DTL end cells. We used a constant ramp defined by a fixed longitudinal focusing prescription that maintains the bunch length.

We adopted a FO-FO-DO-DO lattice structure to reduce the required PMQ gradient to achievable levels. The zero current transverse phase advance in the $4\beta\lambda$ structure (~70°) does not exceed the beam stability boundary (90°). Although the tolerances and available space are tight, from the standpoint of the required magnetic properties and from mechanical or thermal design considerations, the drift tubes and the PMQs can be successfully engineered.

Finally, various commissioning analyses have been completed. For instance, Figure 6 illustrates the calculated DTL tuning diagram which will be used to set the accelerator RF phase and amplitude.

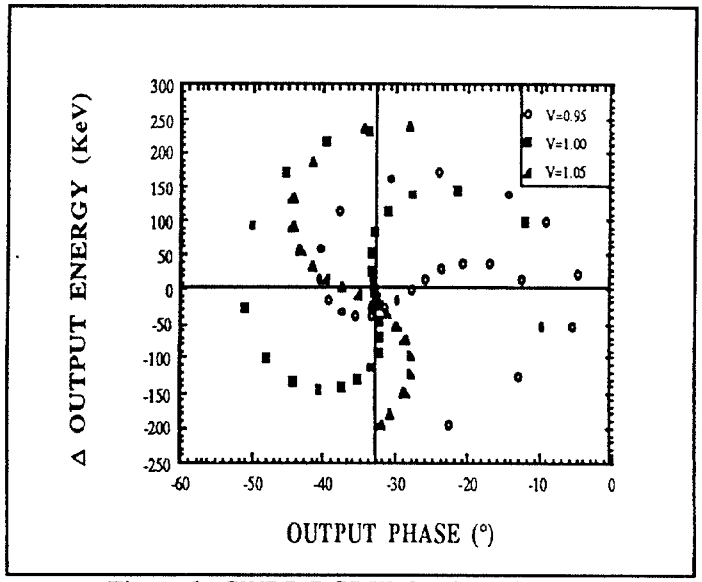

Figure 6. CWDD RGDTL Tuning Diagram.

V. HEBT, BEAM DUMP AND DIAGNOSTICS

Beam spill is the principal HEBT and beam dump physics issue. However, beam dynamics analysis indicates that it is not a serious concern for the present design over the spectrum of anticipated operating conditions. The effectiveness of the HEBT transverse emittance diagnostic and the various fast shut down diagnostics are critical. Figure 7 shows the Injector, RFQ and HEBT as presently installed at Argonne.

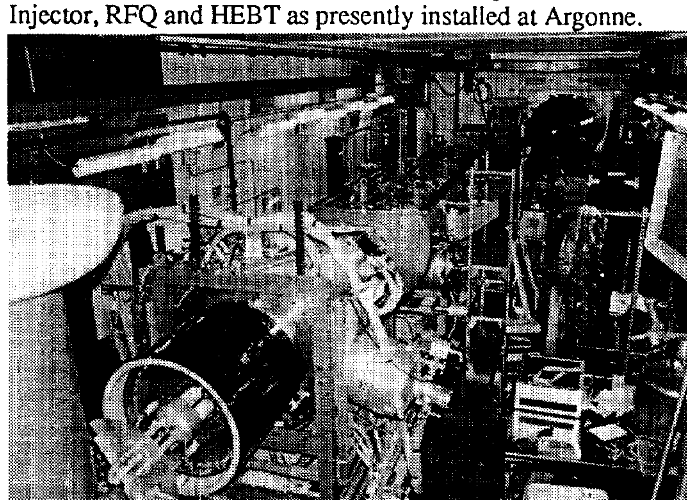

Figure 7. The present installed CWDD beamline at Argonne.

VI. CONCLUSIONS

The 352 MHz CWDD has been designed to deliver a 7.54 MeV, 80 mA CW D^- beam with normalized rms emittance values of 0.11 and 0.20 π mm-mrad in the transverse and longitudinal planes respectively. Nominal and off-design analysis of the device have been completed, and commissioning support analysis is in progress. Injector acceptance tests will be completed in August 1993, first RFQ experiments are scheduled for early 1994, and the DTL will be installed and commissioned in 1995.