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Conceptual Design of a 50-100 MW Electron Beam Accelerator System for the National Hypersonic Wind Tunnel Program

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Conceptual Design of a 50-100 MW Electron Beam Accelerator System for the National Hypersonic Wind Tunnel Program

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ABSTRACT

The National Hypersonic Wind Tunnel program requires an unprecedented electron beam source capable of 1-2 MeV at a beam power level of 50-100 MW. Direct-current electron accelerator technology can readily generate high average power beams to approximately 5 MeV at output efficiencies greater than 90%. However, due to the nature of research and industrial applications, there has never been a requirement for a single module with an output power exceeding approximately 500 kW. Although a 50-100 MW module is a two-order extrapolation from demonstrated power levels, the scaling of accelerator components appears reasonable. This paper will present an evaluation of component and system issues involved in the design of a 50-100 MW electron beam accelerator system with precision beam transport into a high pressure flowing air environment.

INTRODUCTION

The design of a Medium Scale Hypersonic Wind Tunnel (MSHWT) facility is being explored to address deficiencies in present ground test capabilities above Mach 8. The MSHWT facility would create prototypic hypersonic flight conditions at Mach 8-15 at an equivalent altitude of 30,000 m for several seconds. Conventional techniques involving isentropic expansion from a high pressure, high temperature source can not support this hypersonic parameter space and operation time without introduction of substantial high temperature material challenges. Radiative energy addition, a concept proposed by Princeton University[1], provides a potential means to extend wind tunnel technology above Mach 8 while preserving prototypic flight conditions in the test section. For an output section that allows 50-100 cm diameter test objects, approximately 50-200 MW will need to be added to the air flow from an external power source. Electron beam accelerators were proposed[2] as the most cost efficient means of delivering this extraordinary power to a precise location in the wind tunnel expansion nozzle. Generating a 1-2 MeV electron beam at this power level would represent a two order of magnitude increase in the power demonstrated by an electron beam accelerator system. There are approximately 1000 industrial accelerators operating around the world at a total installed capacity of approximately 100 MW. The beam power of the MSHWT accelerator system would match the combined output power of electron accelerators installed world-wide.

An artist's concept of the MSHWT facility is show in Figure 1. A T&E facility with the capability to support testing of a 0.5-1.0 m test object will require the approximate system performance parameters shown in Table 1. A Mollier diagram showing the RDHWT energy addition concept is in Figure 2. The accelerator system requirements are driven by the required enthalpy addition by the electron beam (path 2-3 in Figure 2) and the design of the expansion nozzle where the electron beam injects into the high density air flow. The electron beam injection into the nozzle is shown in Figure 3.

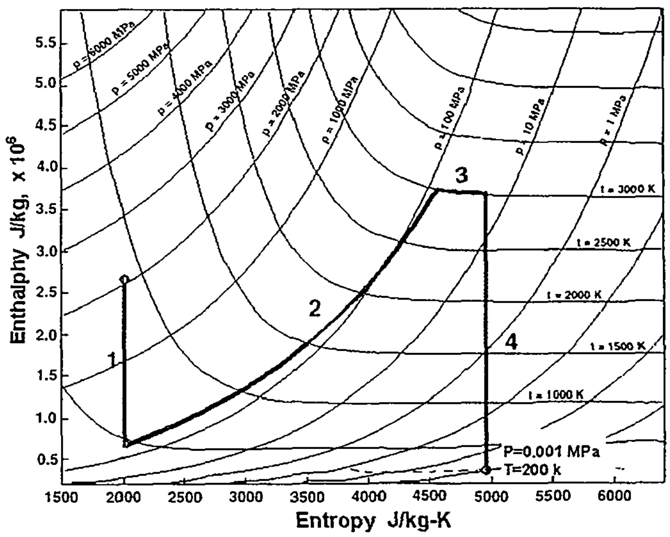

Figure 2. Mollier diagram. Paths: (1) isentropic expansion from plenum, (2-3) radiative energy addition, (4) final isentropic expansion to 200 K and 0.001 MPa at Mach 12.

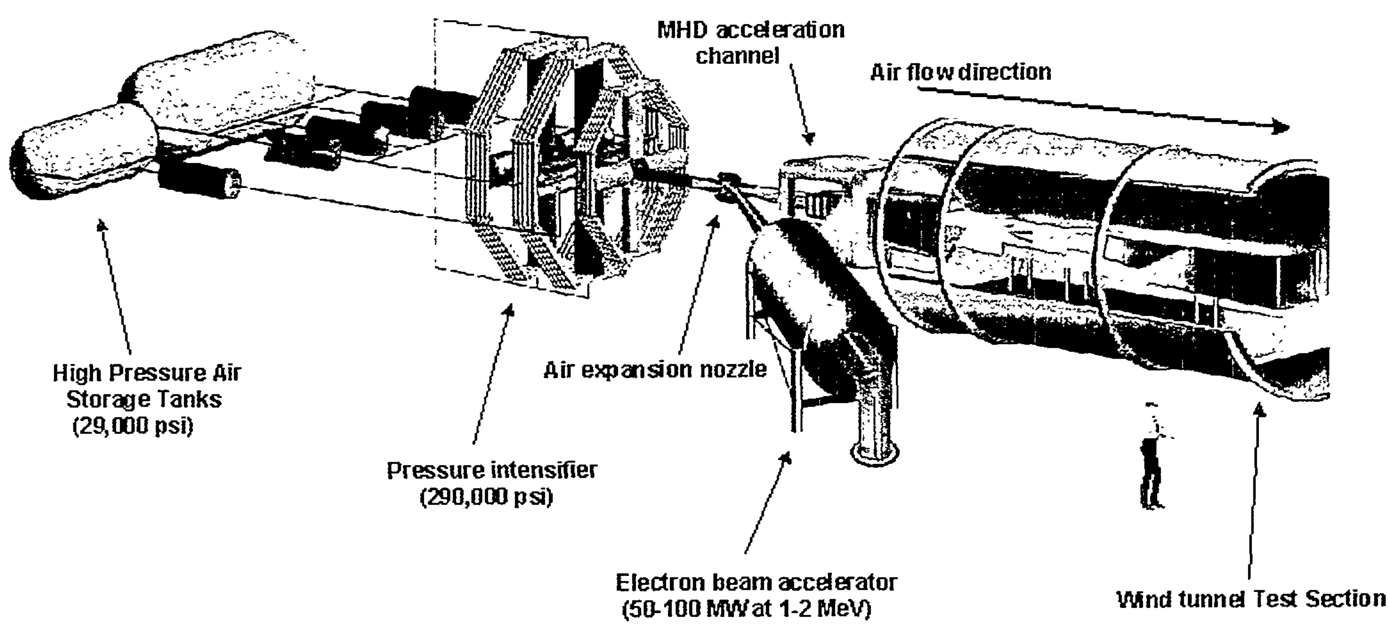

Figure 1. Artist's concept of the MSHWT ground test facility.

Table 1. MSHWT facility conceptual design parameters.

Test section parameters:		***Heated core flow parameters:***	
Velocity (pure air):	Mach 8-15	Mass flow rate:	15 kg/s
Dynamic pressure (q):	500-2000 psf	Throat Diameter :	0.3-0.6 cm
Static pressure:	1200 Pa	Static pressure @ EIR	100 MPa
Temperature:	225 K	Temperature@ EIR:	600-3000 K
Total Enthalpy:	3.6 M J/kg	Density @ EIR:	100-900 kg/m^3
Test section diameter:	0.5 m		
Operation time:	$\leq$ 120 s	***Accelerator system requirements:***	
Plenum parameters:		Enthalpy addition:	3.3 M J/kg
Pressure:	2300 MPa	Power addition:	50-200 MW
Temperature:	750 K	Beam energy:	1-2 MeV
Density:	1200 kg/m^3		

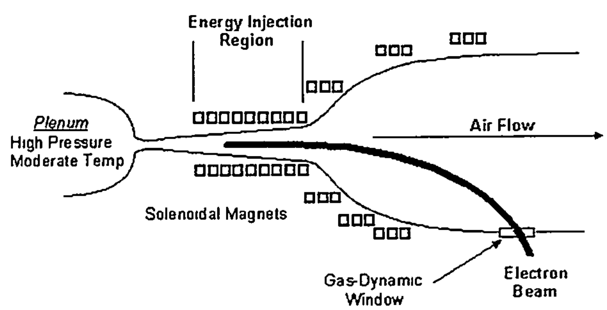

Figure 3. Cross-section of the plenum and expansion nozzle. The electron beam enters the wind tunnel through a gas-dynamic window and is guided and compressed into the Energy Injection Region (EIR) by a solenoidal magnet array.

MSHWT ACCELERATOR SYSTEM ANALYSIS

An accelerator system block diagram is shown in Figure 4. The MSHWT accelerator is comprised of five subsystem components: (1) high voltage DC power supply, (2) electron injector and accelerating column, (3) beam transport section, (4) aerodynamic window, (5) nozzle magnet system.

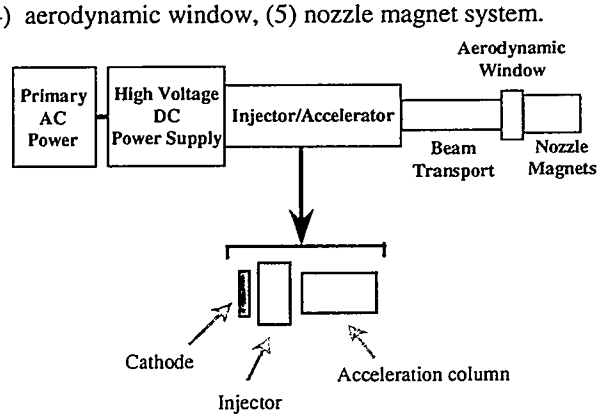

Figure 4. MSHWT accelerator subsystem components.

Scaling to power levels in the 50-200 MW range will require a careful review of the physical limitation of each component in the path from the birth of the electrons at the cathode through the acceleration and transport of the beam into the high pressure expansion nozzle.

High Average Power Accelerator Technology

Industrial uses for accelerator technologies span a wide range of applications[3,4]. However, due to the throughput volume and efficiency of most radiation processing applications, there has never been a requirement for a single module with an output power exceeding approximately 500 kW. The development of reliable accelerator systems has taken decades of R&D and field installation experience. The MSHWT facility requires an electron beam accelerator two orders of magnitude larger than any demonstrated system. Extrapolating any technology base by this magnitude can introduce new challenges in the physics, engineering feasibly, and ultimately the reliability of individual components and the integrated system.

The approach in this conceptual design was to select a demonstrated accelerator technology base with the greatest potential to scale to the power levels required by the MSHWT facility with reasonable risk. The system energy efficiency and cost were secondary considerations. However, in the final analysis the approach discussed in this paper is likely optimized from a scalability, efficiency, and cost standpoint.

Selection of an Accelerator Technology Base

There are three major classes of electron beam accelerator systems that have the capability to scale to several megawatt outputs at beam energies in the MeV range. They are: Radio-Frequency (RF), Direct-Current (DC), and repetitive pulsed accelerator systems. Each technology base has intrinsic and practical limitations. Table 2 summarizes the accelerator technology reviewed in this paper.

Table 2. Example high average power accelerator systems with ≥ 1 MeV capabilities.

Accelerator Class • Example system (Company)	Technology base	Energy (MeV)	Power (kW_{ave})[2]	Efficiency (%)
RF				
• Surebeam (Titan-Beta Corp.)	S-band (2856 MHz) conventional RF LINAC system with Klystron power amplifiers.	1-10[1]	150	10-15
• Rhodotron (IBA, Belgium)	107 MHz CW coax RF cavity with multi-pass beam circulation. Commercial power tetrodes.	1-10[1]	500	40-50
DC				
• Dynamitron (IBA, Belgium)	RF inductively coupled rectifier stack.	1-5	200	65
• Nissin accelerator (Nissin HV, Japan)	Cockcroft-Walton.	1-5	200	80-90
• Electron series (Efremov, Russia)	Air-core inductively coupled rectifier stack.	1-5	500	80
Pulsed-repetitive				
• RHEPP II (Sandia Nat. Laboratories)	Magnetic pulse compression w/ magnetically insulated transmission line transformer.	1-3	1000	50

Notes: 1. Practical upper limit due to nuclear activation of materials.; 2. Demonstrated or estimated capability with limited new design.

The MSHWT application requires energy addition that is relatively constant with respect to the time scales involved in the dynamic flow in the expansion nozzle. Conventional RF LINAC accelerator technologies typically operate with pulsed outputs at a rate of 200-300 pulses-per-second (pps). These RF systems would need to operate CW for this application. Although this is possible, existing RF LINAC technology has an output efficiency of approximately 10-40% due to the relatively inefficient Klystron or magnetron high frequency power sources and cavity losses. Although lower frequency RF cavity accelerators like the 107 MHz Rhodotron are capable of higher efficiencies (approximately 50%) and operate CW, single modules are likely limited to the few MW range due to intrinsic space charge issues. Pulsed accelerator technologies such as Sandia's RHEPP technology[5] can produce few MeV beams and has a relatively weak cost scaling relationship with output power. Although present RHEPP technology is pulsed at approximately 100 pps, systems could likely be designed to operate at a frequency compatible with the MSHWT application. However, the efficiency of this and other high average power pulse compression approaches is limited to typically 50-60%.

There are several types of DC accelerator technology. Although DC technology is limited to approximately 5 MeV, this should be adequate for any MSHWT facility or future T&E facility application. Inductively coupled rectifying transformer systems offer simplicity of design, robustness, and a significant capability to scale in power. The efficiency of these systems at high power levels can be very high (> 90%). For these reasons, inductively coupled rectifying transformer concepts were selected for further analysis in the MSHWT facility conceptual design.

High Voltage DC Power Supply

Generating 50-100 MW of electrical power at 1-2 MV is non-trivial. Several concepts were studied under contract by the Delta Division of the Efremov Institute in St. Petersburg, Russia. The Delta group was selected due to their industrial experience with inductively coupled rectifying transformer accelerator systems. Several topologies were studied conceptually in this work. Although significant analysis remains, several viable concepts evolved. Figure 5 shows a three-phase, iron-core, rectifying transformer concept for a 2 MeV, 100 MW power supply. This approach uses a three-phase transformer and a grounded iron core. A 2 MeV accelerator column and differential pumping system for a foil-less window is shown to the left of the HV power supply. This concept can be extended to multi-phase configurations, as shown in the 1 MeV unit under construction in Figure 6, to reduce output voltage ripple and the required current per phase. Although the high voltage output must be insulated from the grounded core in this design concept, the coupling of flux from the primary windings around each vertical core to the high voltage secondary is very high. Closed core concepts can have electrical efficiencies > 95%. This is a critical attribute at extremely high output power levels. The power supply and accelerator are insulated with SF_6 and N_2 at 1.2 MPa and would use commercially available 25 kV, 5 A diodes in the rectifier assembly.

The rectifying power supply concepts are capable of operation for several seconds to minutes. Extended operation is primarily a cooling issue. For a projected power supply efficiency of approximately 98%, a 100 MW unit would require a 2 MW cooling system.

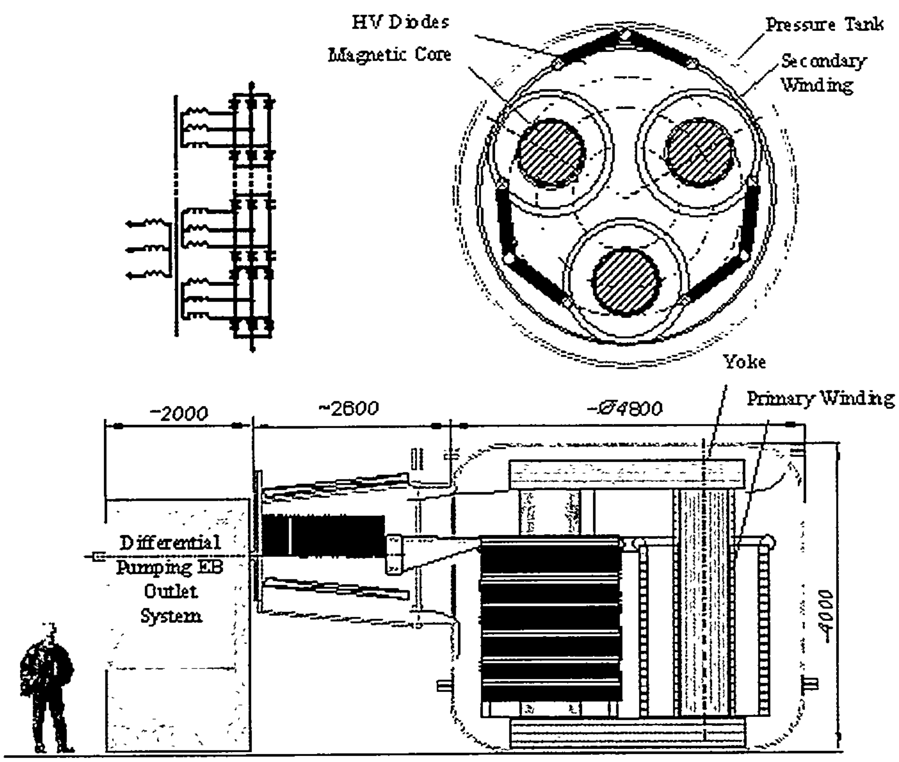

Figure 5. A 2 MeV, 100 MW DC power supply concept. The 3-phase rectifying transformer feeds the accelerator column. Both the DC supply and accelerator are SF_6 insulated. Dimensions are in centimeters.

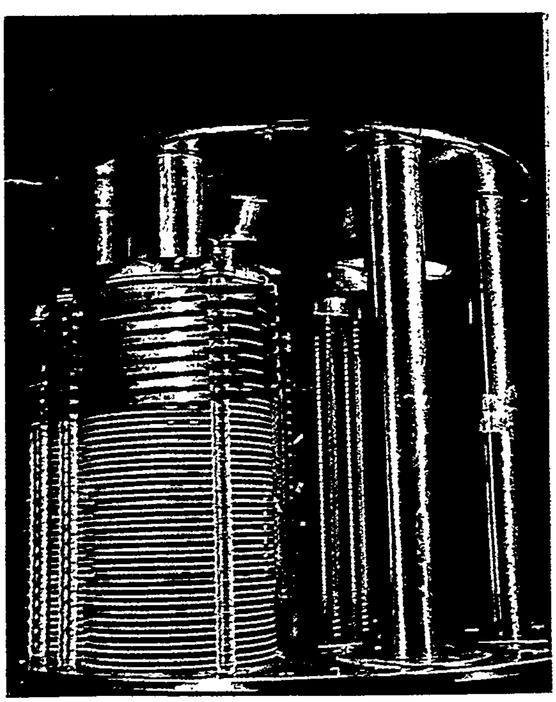

Figure. 6. 1 MeV, 100 kW DC power supply using two three-phase rectifying transformers. This concept can be extended to 6 or 12 phase.

Injector physics

A 2 MeV, 100 MW accelerator module will require 50 amps of beam current. Cathode current density and space charge limitations in the injector will complicate the design of this component. Cathode materials are well developed from a long history in industrial accelerator applications. A thermionic cathode is well suited to this application due to its current density capability and long lifetime. The cathode emission current density can be expressed as,

$$j_c = A_{mat} T^2 \exp(-11.6E3\ \phi_W / T) \quad A/cm^2 \qquad (1)$$

where, A_{mat}= material properties in $A/cm^2 K^2$
ϕ_W= work function
T= operating temperature in K

For an operating temperature of 1900 K, j_c=9.3 A/cm^2. LaB_6 is resistant to cathode poisoning, can operate at pressures as high as 10^{-5} Torr, and has a demonstrated lifetime of 1000's of hours. With the current density limit defined, the design of the injector can proceed.

Industrial injectors typically operate at < 50 keV, allowing for a fairly compact design. For a LaB_6 cathode operating at a conservative 7 A/cm^2, 7.14 cm^2 or a 3 cm diameter emitting surface is required. Using an accelerating potential of 50 keV, this 2.5 MW device will need to have very low losses. Although the injector hardware in this system will represent less than 1% of the cost of the system, it presents a significant technical challenge and sets a primary constraint on the power limitation of the accelerator module.

A Pierce type injector is shown in Figure 7. When the perveance of the injector is below approximately 1 μperv, aperture effects are small and the device can support a total current consistent with the non-relativistic planer Child-Langmuir equation,

$$j_o = \frac{4\varepsilon_o}{9}\,[2q/m_e]^{1/2}\,\frac{V_o^{3/2}}{d^2} \quad \mathrm{A/m^2} \qquad (2)$$

where, V_o = injector voltage
d = injector accelerating gap

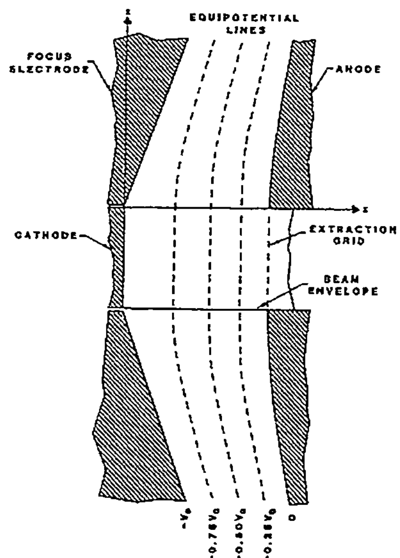

Figure 7. Low perveance injector. The solid cylindrical beam is extracted with low divergence due to minimal distortion of the electric field at the extraction aperture. This is a standard injector configuration for industrial systems.

For a 50 kV, 5 cm injector gap, the space charge limit from Eq. (2) is approximately 1 A/cm^2 in a low perveance injector design. This is an insufficient current density for the MSHWT application. The perveance of a 50 kV, 50 A injector with a cathode operating at 7 A/cm^2 is 15.6 μperv. This will require a numerically designed high perveance injector geometry. Figures 8 and 9 show a high perveance injector design operating at 50 keV and 50 A with a beam output diameter less than 3 cm. The conceptual design was generated by a Poisson solving code developed at Sandia. This simulation does not include an axial magnetic field, which may improve the beam divergence. A low divergence multi-MW injector will require additional modeling and experimental development.

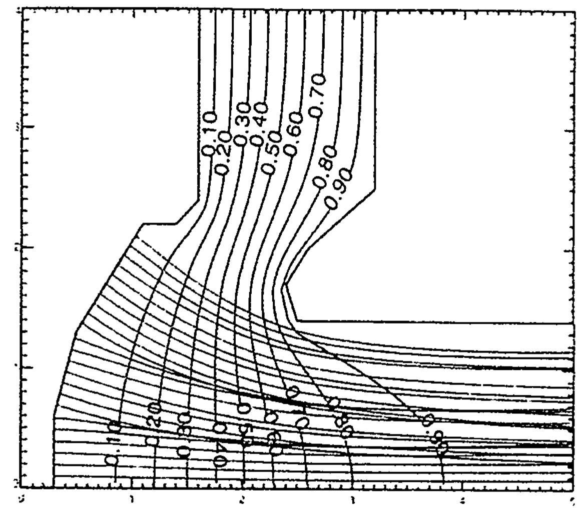

Figure 8. 50 keV, 50 A injector. Space charge constraints requires a large emission area cathode. Dimensions are in cm.

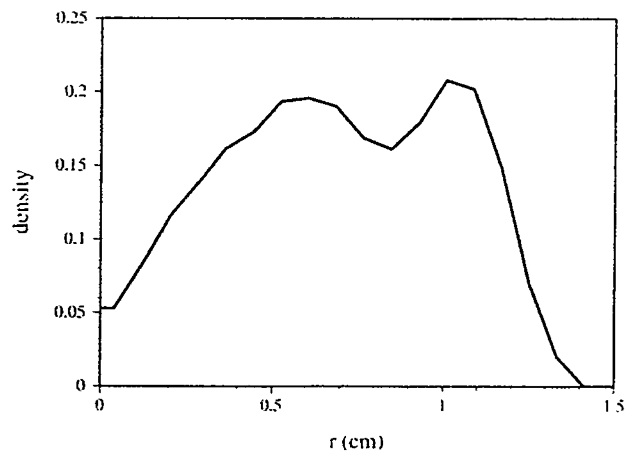

Figure 9. Relative beam current density at the output of the 50 A injector. The current uniformity can be modified by changing the cathode surface and field shaping electrode.

Accelerator column physics

After initial acceleration to 50 keV in the injector, the next accelerating gap can also limit total current due to space charge effects. Eq. (2) can be modified to account for the injected 50 keV beam that enters the first accelerator column gap (see Figure 10). Enhanced flow is described by Eq. (3).

$$j_{enh} = j_o\,F(\chi) \quad \mathrm{A/cm^2} \qquad (3)$$

where $F(\chi) = \chi^{3/2}\,[(1-1/\chi)^{3/4} + 1]^2$ and $\chi = -\varphi_2 / (\varphi_1 - \varphi_2)$. φ_1 is the beam energy entering the gap and φ_2 is the beam exit energy (injection energy + gap energy).

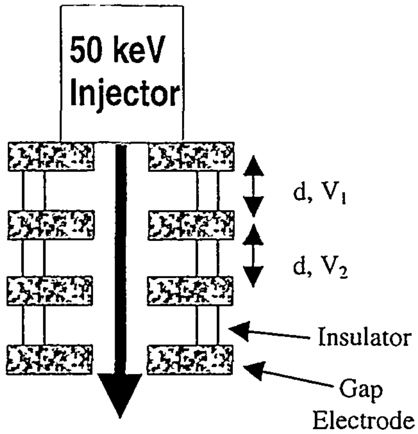

Figure 10. Injector and initial gaps in the accelerator column.

Industrial accelerator columns routinely operate with electric field gradients of 1-1.5 MV/m on the ceramic insulators. For an accelerating gap in the column of d_1=5 cm, a gap voltage of V_1 = 60 kV (1.3 MV/m), and a beam diameter of 3 cm, the non-enhanced space charge limited current is only 9.7 A. For a 50 keV injected beam and a gap potential of $V_1 = 60$ kV, $\chi = 2.2$ and $F(\chi) = 8.5$. This allows a maximum current in the 3 cm diameter beam of I_o=(9.7 A)(8.5) = 82 A. The injected 50 keV significantly enhances the flow in the first column gap. A similar gain is seen in the second gap d_2. For a beam entering at 110 keV, χ = 2.8 and $F(\chi)$ = 14. The maximum current space charge will allow in gap d_2 is I_2 = (9.7 A)(14) = 136 A. As the beam accelerates past 500 keV and becomes relativistic, the space charge limit raises significantly. Based on this space charge analysis, it is reasonable to envision a 100 MW module at 2 MeV or a 50 MW module at 1 MeV.

In practice, there will be beam optics issues that impact the peak current capability of this accelerator column. At these power levels, beam losses in the column must be extremely low to prevent damage to the accelerating gaps and ceramic insulators. The divergence of the injector must be very low and beam halo that could impact the gap electrodes must be extremely well controlled. These issues could limit a system of this size to several amperes instead of 10's amperes. However, the MSHWT accelerator system will require that the cathode, injector, and accelerating column be immersed in an externally supplied axial magnetic field to mitigate magnetic mirroring effects. This axial solenoidal field will also serve to confine the beam as it leaves the finite divergence injector and accelerates through the column. The axial magnetic field is a key requirement to extend the beam current into the 10's of ampere regime. The impact of the magnetic field in the accelerator on the beam optics will need to be modeled in detail in order to design the column accelerating gaps.

Beam transport from the cathode to the nozzle

Figure 11 shows a conceptual layout of the accelerator system for a MSHWT facility. This application requires that the electron beam travel from its origin at the vacuum

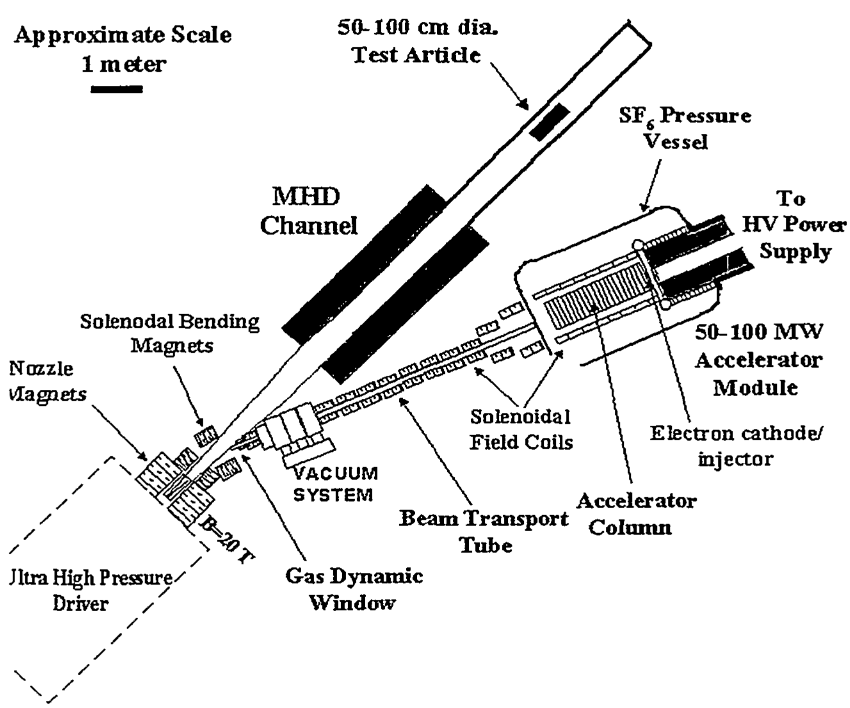

Figure 11. 50-100 MW electron accelerator module with beam transport system that injects into the MSHWT high pressure nozzle.

insulated thermionic cathode in the injector to a high pressure expansion nozzle within the wind tunnel chamber. Transport of the 1-2 MeV beam from the accelerator module to the tunnel chamber will occur in a vacuum beam line with an external solenoidal magnetic field.

The beam will exit the high vacuum environment of the transport region through a gas-dynamic window where it will then be guided and compressed into the expansion nozzle. The transport region from the gas-dynamic window to the entrance of the expansion nozzle will require modeling to evaluate the magnitude of gas breakdown in the approximate 1 atm environment that extends for about 0.3 m. As the beam enters the high pressure nozzle, electron scattering and space charge issues will dominate the physics concerns in this Energy Injection Region (EIR). At these high power levels, high energy electrons can not be allowed to impact the wall of the nozzle. The scattering beam must be compressed radially as it enters the nozzle using a series of multi-Tesla solenoidal magnets. Collisional effects in the high pressure nozzle have been modeled using Cyltran[6] to set the magnitude of the solenoidal B-field in the EIR. Cyltran is a Monte-Carlo Particle-In-Cell code that accounts for the collision of electrons with gas atoms in this region. Figure 12 shows the resulting electron orbits in the transport region and nozzle. A 20 Tesla magnetic field was required to minimize beam loss to the nozzle walls. Further modeling in the EIR will be required as Cyltran does not account for beam self-fields or the effects of electron induced gas chemistry. Space charge and plasma effects need to be evaluated in the transport and nozzle region.

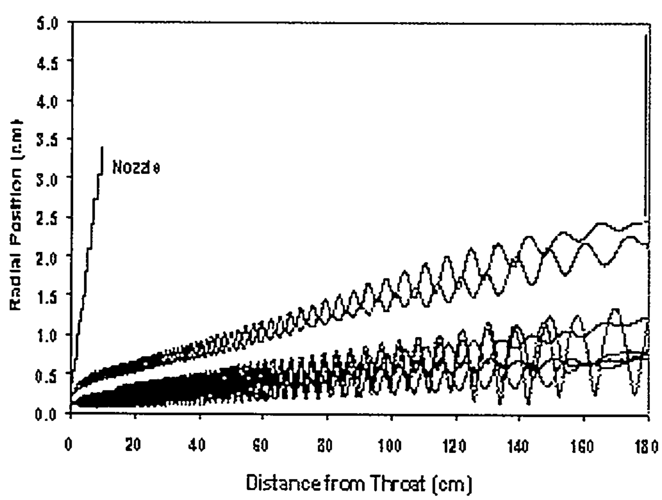

Figure 12. Cyltran modeling of electron trajectories in a 1 MeV beam entering the wind tunnel and traveling into the high pressure expansion nozzle. The nozzle profile is exaggerated due to the expanded vertical scale.

Once the peak B-field strength is set in this region of the MSHWT system, the B-field profile back to the cathode can be designed. The 20 T magnetic field is sufficiently high to reflect back all the 1-2 MeV electrons entering this field if those electrons are born in a zero-field region. This mirroring effect can be estimated by considering the electron's gyrofrequency and conservation of energy as the particle converts azimuthal velocity to axial velocity. The maximum solenoidal B-field that an electron can propagate into (starting from a zero field) can be estimated as,

$$B_{max} = \frac{2 c_0 m_e \gamma\beta}{q_e r} \tag{4}$$

where, B_{max} = B-field strength (T)
r = beam radius (m)

For a 1 MeV electron beam starting with a 0.5 cm diameter outside the solenoid, mirroring will occur at a field strength above approximately 3.8 T. To overcome this effect the electrons must be immersed in a continuous solenoidal B-field back to cathode source. Determining the magnitude and profile of the axial magnetic field back to the cathode will require numerical modeling techniques. The minimum field strength needed at the cathode can be estimated as,

$$B_o/B_m = \sin^2\theta \tag{5}$$

where,
B_o = minimum field strength
B_m = maximum field strength
θ = divergence angle

The thermionic source in our injector will create a plasma at a temperature of < 1eV. However, the high perveance injector configuration and imperfect electric field grading will produce a beam with a perpendicular velocity component of a few milli-radian divergence. If we assume 5 mrad and use B_{max}= 20 T, B_o will need to be on the order of 0.1 T. Minimizing the divergence in the injector will be important to reducing the cost of the integrated magnet system.

Gas-dynamic window

Conventional foil windows will not survive the heating from beam current much above a few mA/cm^2. A foil-less gas-dynamic window will be required to transition the beam from the vacuum line into the approximately 1 atm environment just downstream of the expansion nozzle. An exit aperture of approximately 1 cm diameter will be required to inject beam into the wind tunnel chamber. This can be accomplished through conventional differential pumping techniques or potentially through other less developed techniques that can reduce the overall high volume vacuum pumping requirements and system cost. A steam injection concept[7] is shown in Figure 13. Steam injected next to the exit aperture can dramatically improve the pumping efficiency due to essentially 100 percent water vapor content. A pressure reduction from approximately 1 atm to approximately 10 Torr can occur in this stage, leading to reduced pumping requirements in subsequent stages.

Other techniques such as plasma portholes[8], that essentially replace the steam injection stage with a high temperature, high viscosity, low density plasma, also offer an advantage in reduced pumping requirements.

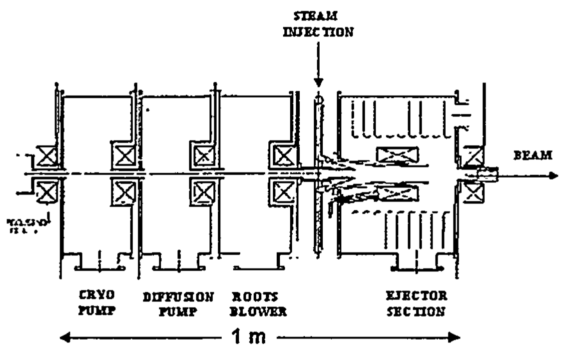

Figure 13. Steam injection concept for a gas-dynamic window.

Solenoidal magnet system

The magnet designs in the nozzle region will require careful interfacing to the high pressure mechanical hardware. A maximum field strength of approximately 20 Tesla will be required to confine and compression the beam in this region. A magnet inner bore diameter of approximately 20-30 cm will be required to accommodate the mechanical structure for the high pressure nozzle. Magnets of this class have been demonstrated at the National High Magnetic Field Laboratory. However, further definition of the integrated magnetic field for the MSHWT accelerator is required before individual magnet designs can be evaluated in detail.

ACCELERATOR SYSTEM COST ESTIMATE

Several aspects of the MSHWT accelerator system will need to be developed prior to final design of this state-of-the-art facility. The rough cost estimate based on this MSHWT accelerator concept will include consideration of the development required to mature several areas of this system. This cost estimate includes both a 50 MW and 100 MW MSHWT facility system. The beam energy for both cost estimates is assumed to be 2 MeV. If operation is required at 1 MeV, this may reduce the accelerator module power level due to space charge limitations. Lower beam energy will tend to reduce the cost of this system. The cost of a high power accelerator system can be approximated as,

$$C = 1.7 \times \sqrt{E \times \sqrt{P}}$$

where,

C = cost in $M
E = beam energy in MeV
P = output power in MW

This estimator does not include costs associated with the development of accelerator system components, the solenoidal magnet system, or the gas dynamic window. Primary cost components and development areas for this MSHWT facility design include:

- 50-100 MW, 2 MeV DC power supply
- 2.5 MW, 50 keV injector
- 2 MeV accelerator column
- Gas-dynamic window
- Beam transport system prior to the nozzle
- Nozzle magnet system and interface to high pressure nozzle hardware.

This cost estimate *includes*:

- 5% project management loading
- 7% technical integration loading
- 2% documentation loading

The high voltage power supply and accelerator costs are based in part on scaling relationships from commercial systems as provided by the Delta division of the Efremov Institute. The high field magnet costs for the nozzle were generated from estimates provided by the National High Magnetic Field laboratory. The gas-dynamic window cost estimate is based on work from a previous project at Sandia National Laboratories. The ratio of development, management, design, installation, and test costs are based on typical ratios seen in high technology R&D programs.

This cost estimate does *NOT* include:

- AC primary distribution system
- Facility or infrastructure
- Global control or access control systems

Appendix 1 summarizes the cost elements in the MSHWT accelerator system.

SUMMARY

Demonstrated industrial DC accelerator technology forms the basis of the MSHWT accelerator concept described in this report. Scaling issues in extrapolating this technology base have been examined at a conceptual level. This work has not identified any fundamental physics that would prevent a system of this magnitude from being developed and fielded into a reliable hypersonic ground test facility. However, several areas of this system require further analysis and may require development. The next phase of this system design needs to include analysis and simulation in key risk areas such as the injector, accelerator column, beam transport in the non-vacuum environment, and the multi-Tesla magnet system. A full system simulation is required from the immersed cathode to the expansion nozzle to develop design parameters for the magnetic confinement fields. The beam optics in the accelerator will be impacted by the applied solenoidal magnetic field, magnetic mirroring effects, self-fields (space charge), and collisional scattering.

ACKNOWLEDGEMENTS

The MSHWT facility thermodynamic system requirements were generated by Robert Anderson, Prof. Gary Brown, and Prof. Richard Miles of Princeton University. The artists concept shown in Figure 1 was generated by the Arnold Engineering and Development Center in Tullahoma, TN. The Mollier diagram shown in Figure 2 was generated at Princeton University. The required beam conditions, magnetic field requirements, and the Cyltran run shown in Figure 12, were generated by Ron Lipinski of Sandia National Laboratories (SNL). The injector simulations shown in Figures 8 & 9 were generated by Barry Marder, SNL. Preliminary concepts and cost estimates for the high voltage power supply were generated under a Sandia contract to the Delta Division of the Efremov Institute in St. Petersburg, Russia.

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APPENDIX I

CONCEPTUAL DESIGN COST ESTIMATE

50 MW - 2 MeV MSHWT Facility Accelerator System

Subsystem	Estimated Costs ($M)				Contingency	Subsystem
	System Development	Design	Hardware	Install/test	(based on risk)	Cost
(1) 50 MW - 2 MeV Accelerator						
Accelerator/Power supply	5	2	3	1.5	40%	
SF6 Gas/Vacuum System	0	0.5	0.5	0.5	15%	17.8
(2) Solenoidal B-Field System						
Transport section	0.5	0.25	0.25		25%	1.3
Nozzle section	1	0.75	2	0.75	40%	6.3
DC Power Supplies	0	0.5	1	0.5	25%	2.5
						10.1
(3) Gas-dynamic Window						
Window	0.75	0.25	0.5	0.125	25%	2.0
Vacuum pumps	0	0.125	1	0.25	25%	1.7
						3.8
(4) Global Control/Diagnostics	0.5	0.75	0.5	0.5	25%	2.8
Cost elements (no cont.)	7.25	4.375	8.25	3.625		
(5) Project Management	1.7					1.7
(6) Technical Integration	2.4					2.4
(7) Documentation	0.7					0.7

Total System Cost Estimate	39.3

CONCEPTUAL DESIGN COST ESTIMATE
100 MW - 2 MeV MSHWT Facility Accelerator System

Subsystem	Estimated Costs ($M)				Contingency	Subsystem
	System Development	Design	Hardware	Install/test	(based on risk)	Cost
(1) 100 MW - 2 MeV Accelerator						
Accelerator/Power supply	6	4	6	4	40%	
SF6 Gas/Vacuum System	0	0.5	1	0.5	15%	30.3
(2) Solenoidal B-Field System						
Transport section	0.5	0.25	0.25		25%	1.3
Nozzle section	1	0.75	2	0.75	40%	6.3
DC Power Supplies	0	0.5	1	0.5	25%	2.5
						10.1
(3) Gas-dynamic Window						
Window	0.75	0.25	0.5	0.125	25%	2.0
Vacuum pumps	0	0.125	1	0.25	25%	1.7
						3.8
(4) Global Control/Diagnostics	0.5	0.75	0.5	0.5	25%	2.8
Cost elements (no cont.)	8.25	6.375	11.75	6.125		
(5) Project Management	2.3					2.3
(6) Technical Integration	3.3					3.3
(7) Documentation	0.9					0.9

Total System Cost Estimate	53.5

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