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PRELIMINARY DESIGN FOR A PIERCE
WIGGLER BEAMSTICK AND ADDENDUM

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Livermore
National
Laboratory

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ADDENDUM TO PRELIMINARY DESIGN FOR A PIERCE WIGGLER BEAMSTICK

Figure 1 presents the magnetic field profile on axis for the proposed VYW-8250W wiggler magnet with a 6" i.d. hole in the polepiece facing the MIT superconducting magnet. The thickness of the top polepiece has also been reduced from 0.5" to 0.375". The "dip" in the magnetic field profile that occurred with the 2" i.d. polepiece has been eliminated, and the field from the wiggler solenoid maps smoothly into the fringing field from the 7.4 T superconducting magnet. The combination of the wiggler solenoid and fringing field from the superconducting magnet produces a uniform 2.5 kG field for a length of eight inches. The field amplitude inside the iron for this geometry when the wiggler solenoid is not energized is 13 kG; hence, with the wiggler energized, the field inside the iron will be well below 12 kG.

The contribution from the superconducting magnet fringing field to the 2.5 kG flat field is represented by the crosshatched line. The top edge of the wiggler solenoid polepiece occurs at 17.375". The contribution from the superconducting magnet is significant even in the middle of the solenoid. The i.d. of the top polepiece can probably be reduced somewhat to improve the isolation of the wiggler field from the superconducting magnet, without reintroducing a dip in the field. For the field profile shown in Fig. 1, the top solenoid coil nearest to the top polepiece carries only 38 A of current, as opposed to the 46 A of current for the 2" i.d. polepiece. Hence, the top polepiece i.d. can be reduced to increase the shielding, and the current in the top coil increased to maintain the uniform field profile.

The fringing field from the MIT 7.4 T superconducting magnet is remarkably similar to the fringing field from the 10 T Bitter magnet. The wiggler solenoid design presented in Fig. 1 will work equally well with the Bitter magnet; a smooth field profile can be produced with only minor changes in the wiggler coil currents near the top polepiece.

Two results of this investigation call for further work. Firstly, the coil currents that MIT provided for the superconducting magnet produce a 7.4 T field according to our calculations rather than the 6.5 T field indicated by MIT. This discrepancy should be resolved. Our calculations were done with an analytical calculation (AIRCORE) which has always given very accurate results in the past. I wonder if MIT inadvertently provided the coil currents for 7.4 T (i.e. upper limit of the magnet with pumping on the helium reservoir) which they have been contemplating. Secondly, as indicated schematically (neither the amplitude nor the shape should be accepted as accurate) by the open circles in Fig. 1, the field increases rapidly again outside the shielding at the gun end of the wiggler solenoid. Hence, shielding will also be needed around the gun to isolate the cathode from the superconducting magnet fringe field. We recommend that a small coil be installed inside this gun shielding in order to adjust the focusing of the electron beam in conjunction with the wiggler coil closest to the gun.

MASTER

JMP

Proposed VYW-8250W Electromagnet

6" ID Top PP, 2.5 kG, 9" Coil 4 Coils

Fig. Density on Axis, Kropchuss

Schematic representation that the field rises rapidly (up to a peak of 4 kG) outside the gun end of the solenoid. (Ignore the detailed shape, it is not accurate; hand drawn from a verbal description).

PRELIMINARY DESIGN FOR A PIERCE WIGGLER BEAMSTICK

INTRODUCTION

Lawrence Livermore National Laboratory is developing a fast tunable microwave source for operation at 250 GHz and 10 kW peak output power. This report presents the preliminary design of a Pierce gun and solenoid magnet that will be compatible with a Pierce-wiggler electron beam formation system (beamstick). The beamstick will be an appropriate power source for a tunable gyro-BWO at 250 GHz. Figure 1 presents the major components of the Pierce-wiggler beamstick: the electron gun, solenoid, beam tunnel, wiggler, and vacuum valve. Figure 2 shows an artistic conception of how the beamstick will interface with the interaction magnet, modulator and gyro-BWO circuit at MIT.

SOLENOID

During the course of this design, we realized that the wiggler solenoid interacts strongly with the fringing field of the interaction magnet. Designing the proper magnetic field profile from the wiggler solenoid to the interaction circuit will require a significant design effort involving close cooperation between Varian and MIT. Table 1 lists the design goals and achieved design parameters for the wiggler solenoid. Figure 3 shows the magnetic field profile for the current design at 2800 Gauss on axis. The field is uniform within approximately 1% over a 6" length. The 2800 Gauss amplitude represents the "detuned" condition when the magnetic field is purposely set to be off resonance. We expect 2800 Gauss to be the highest on-axis magnetic field produced by the wiggler solenoid under normal operating conditions. The cross hatched line in Fig. 3 shows the field amplitude at a radius of 0.94", corresponding to the location of the magnetic wiggler strip furthest off axis. The field strength at this radial position is still under 3 kG; the magnetic wiggler strips start to demagnetize significantly in axial fields over 3 kG.

The wiggler solenoid design consists of four pairs of independently controllable coils. Each pair of coils is connected together internally with power leads brought out. Hence, the field profile can be controlled to optimize the electron beam formation and focusing.

The current solenoid design calls for iron shielding. The shielding must be extra thick in order to prevent saturation of the iron in the extensive fringing fields of the Bitter magnet used for the interaction circuit. The iron shielding has several consequences, some desirable, some not. One desirable consequence of the shielding is isolation of the wiggler axial field from the interaction circuit field. Hence, the interaction circuit field can be modified without affecting the resonance in the wiggler. Also, the shielding protects the wiggler and cathode from stray magnetic fields. This protection may be important, since the transverse fields in the wiggler are only 10 Gauss. On the other hand, the iron shielding adds 40-50 pounds extra weight over what is required for structural integrity. Also, preliminary calculations indicate that the iron may increase the compressive force between the wiggler solenoid and the Bitter magnet

by up to a factor of five.

The current shielding design needs some modification because the shielding causes a "dip" in the magnetic field amplitude between the wiggler solenoid and the Bitter magnet. We feel that the dip can be eliminated by thinning the polepiece facing the Bitter magnet, and by enlarging the hole in that polepiece.

Other details of the solenoid design are presented in appendix A.

VACUUM BALL VALVE

We have identified a ball valve design capable of isolating the Pierce-wiggler vacuum and yet compact enough to fit through the bore of the wiggler. Figure 4 displays marketing literature for a vacuum ball valve that meets the vacuum requirements of our application. The custom ball valve being constructed by Huntington Mechanical Laboratories will be based on a similar design; however, it will incorporate material which can withstand higher bakeout temperature and will be smaller diameter. The ball valve is scheduled to be delivered in late April, so we will have an opportunity to evaluate it. If the ball valve seems unsatisfactory, it will be possible to incorporate a standard gate valve or straight-through valve and still deliver the gun in June.

GUN

Table 2 lists the specifications for the electron gun. The electrostatic design of the electron gun is virtually complete. Figure 5 shows the simulated electron trajectories for the present design. The design has a microperveance of 0.276 compared to a specification of 0.272. The beam waist is 80 mils diameter, which is slightly smaller than the specified diameter of 100 mils. In our experience, the computer simulations consistently predict a smaller beam diameter than the beam analyzer measures. Hence, we expect that this electrode design will produce a beam diameter much closer to 100 mils than is indicated by the computer simulation. Some minor changes will be made to the anode to bring the voltage gradients into the 80-100 kV/cm range, which is practical for the short pulse length application of this gun. At six amps beam current, the cathode loading is 5 A/cm², which is consistent with over 1000 hours of cathode life. We are presently designing the magnetic focusing; we won't be able to assess the beam ripple until this design is complete. We expect to achieve a magnetics design on the computer with zero ripple; however, similar to the situation with the computer simulations of the electrostatic beam waist, we also expect to measure some ripple on the beam analyzer.

The electron gun design incorporates two SAES getters and a VacIon appendage pump in order to help maintain high vacuum in the gun, wiggler, and gyro-BWO beam tunnel.

WIGGLER AND BEAM TUNNEL

Figure 6 shows the preliminary wiggler and beam tunnel design. The beam tunnel inner diameter must be chosen to compromise between maximizing vacuum conductance and preventing rf interaction in the beam tunnel. At 2800 Gauss, the relativistic cyclotron frequency is 7.1 GHz for a 55 kV electron beam. In our experience, if the cut-off frequency for the fundamental mode is 20% above the cyclotron frequency, no gyrotron interaction will occur in the beam tunnel. Hence, the beam

tunnel should have an i.d. of 0.81" or less in order to prevent possible gyrotron interaction. Fortunately, this diameter is not a significant constriction on the vacuum conductance.

For obtaining the best beam quality, the radius of the wiggler should be comparable to the pitch of the wiggler helix, in this case about 0.67". For larger radius to pitch ratios, the transverse field of the wiggler develops amplitude "spikes" at the ends of the wiggler. For smaller radius to pitch ratios, the transverse field from the wiggler becomes less uniform across the diameter of the electron beam, which contributes to velocity spread. To a large extent, amplitude end spikes for large radius to pitch ratios can be eliminated by tapering the layers of magnetic strips. For example, the strips can be wound with the first layer having 5 pitches, the second layer with 4.5 pitches and the third layer with 4 pitches. The wiggler diameter of 1.5" (0.75" radius) is in the right range for good beam quality and is still large enough to slide over the 1.5" diameter vacuum valve. In our experience, when the wiggler strips are wound on a 1.5" diameter, they produce about five Gauss transverse field on axis. The strips become uniformly demagnetized about 20% in an axial field of 3 kG. Hence, to get 10 Gauss transverse field on axis, about three wiggler strips will be required. The present design can accommodate five strips if necessary.

SCHEDULE

Figure 7 presents a milestone chart for delivery of the VUV-8250 beamstick. We are making every effort to deliver the beamstick by the first week of June 1988. However, everything must work within specifications the first time in order to meet this delivery date; we have made no provision for contingencies. In particular, very little test time has been allotted for magnetic beam analyzer tests. We should not take shortcuts on these tests because they determine what measures should be taken to improve the beam ripple. Although we will continue to target delivery for the first week of June, a delivery for the third week of June would be more realistic and would have lower overall technical risk.

Figure 1. Schematic layout of Pierce-wiggler electron-beam formation system

Scale $\approx 1" = 10"$

Scale $\approx 1" = 5"$

			Artistic conception of Wiggler solenoid environ		D. Rinkle x 2014 1/18/89
			varian engineering sketch		MATERIAL		JOB ORG			
					Var1045					
					SCALE		USE		SKETCH	
REV			DATE		CHANGE		noted		VW-8250	

FIGURE 2

Design Parameters

<u>Parameter</u>	<u>Goal</u>	<u>Achieved</u>
Operating Field	2.5/2.8 kG	2.5/2.8 kG
B(R*.94,Bmag*2.8kG)	3.0 kG Max	3.0 kG Max
Inside Diameter	1.95"/2.25"	Pole Piece *1.95" Coil ID * 2.0"
Length	9.0" Max	10.25" Nom (Req'd for Field Spec)
Outside Diameter	<12"	10" Nom
Power	<2.5 kW	2.9 kW Max @2.5 kG 3.7 kW Max @2.8 kG
Current	<50 Adc	46.0 Adc @ 2.5 kG 51.5 Adc @ 2.8 kG
Weight	< 55 Lbs	126 Lbs (Has a 96 Lb Shell)
Coils	Not Spec'd	4 Individual Coils

M Anderson, 2/88

TABLE 1. SOLENOID DESIGN PARAMETERS

Proposed VYW-8250W Electromagnet

2" ID, 2.8 kG, 9" Coil Length, 4 Coils

FIGURE 3

FORGED BRASS & 304 STAINLESS STEEL High Vacuum BALL VALVES

- GUARANTEED LEAKAGE RATE
- HIGH CONDUCTANCE
- STRAIGHT THROUGH FLOW
- COMPLETE RANGE OF SIZES
- SIMPLE & EASY TO SERVICE

$\frac{1}{8}$ " to $2\frac{1}{8}$ "

For the first time a ball valve is offered specifically intended for high vacuum service. Valves are stocked in forged Brass and 304 Stainless Steel in $\frac{1}{8}$ " to $2\frac{1}{8}$ " pipe thread and tube O.D. end connections. Teflon seats and Vilon seals are standard, however, other combinations are available on request.

The valves offer straight-through flow providing maximum conductance, interchangeable end connections, unobstructed ports allowing feed through and low initial installation and maintenance costs.

Gas entrapment has been eliminated by drilling a hole in the shut-off side of the ball exposing the body cavity to either upstream or downstream pressure depending on

installation. A further advantage is the rigid stem assembly which does away with the lateral movement that has plagued users of other valves in the past.

Stem seals are easily replaced without removing the valve from the line and only three bolts need be disassembled to service the seats and body seals.

Provision is made to evacuate the area between the seat and the body up to the body seal.

Each valve is mass spectrometer helium leak checked and certified. Guaranteed leakage rate is less than 1×10^{-9} std. cc/sec.

Pneumatic & Electric ACTUATORS

PNEUMATIC ACTUATORS. Integrally-mounted valve operators using plant air source are available in either a double-action or fail-safe design. A 4-way solenoid valve, either general purpose or explosion-proof, is normally mounted on the actuator to control the air supply. A control to regulate the closing speed of the actuator is a part of the solenoid. Compact microswitch assemblies are available where remote indication of valve position is desired.

ELECTRIC ACTUATORS. A compact electric motor (brushless) actuator provides positive valve operation, plus materially lower installation cost. Only electric power is needed. Valve opening or closing is a matter of 5-6 seconds. Electrically-actuated units are supplied in weather-proof housings. Microswitch assemblies are also available where remote indication of valve position is desired.

TABLE 2. ELECTRON GUN SPECIFICATIONS

PARAMETER	SPECIFICATION
Beam Voltage	60 kV nom. 80 kV max.
Beam Current	4 A nom. 6.2 A max.
Micro-perveance	.272
Beam Diameter	.100 inches max.
Scalloping	8% max. <5% goal
Brillouin Number	2.74 or greater
Duty Factor	1% max.
Pulse Width	1 microsecond; goal of 5 microseconds with aging
Repetition Rate	10 kHz max. (rep. rate x pulse width not to exceed 1% duty)
Cathode Life	1000 hours nom.

XK-B250, V=60KV, ZA=.6950, A8250I
ITERATION 10

Rudy Garcia 02/19/88

Beam Current 4.06 A
 Reverance .276 μ pervs
 Peak Voltage Gradient ≈ 90 kV/cm

REV	DATE	CHANGE

Factors determining Magnet bore for small bore shield	Don't write x 2014 1/12/88
ENGINEER Don't write x 2014 1/12/88	MATERIAL Except for strips - Non-magnetic
SCALE 1:1 1/12/88	DESIGN NO DEG-119 1/12/88

W. Engineering sketch
 W. Varian Vx-W-850W

FIGURE 6

varian®

MILESTONE CHART

FIGURE 7

○ ORIG. START. □ REVISED START
▽ ORIG. COMPLETE △ REVISED COMPLETE
● ▼ ▲ ■ COMPLETED MILESTONES

DESIGN PHASE

- Interior Field
 - Central Field Homogeneity
 - 0.94" Off Axis Field Strength
 - Coil Operating Parameters
- Exterior Field
 - Bitter Magnet Model
 - Magnet Shell Design
 - Interior Field Homogeneity
- Interior/Exterior Crossover Region
 - Downstream Insert Diameter Selection

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MECHANICAL DESIGN

Construction Methods

- Coils
 - Aluminum Foil
 - Water Cooled
 - Eight Pies, Four Coils
- Cooling
 - Water Cooled
 - OFHC Copper Cooling Plates
 - 37 Degree Cooling Fittings
- Outer Shell (Shielding Jacket)
 - Steel End Pole Pieces
 - Steel Outer Shell
 - Kulka Terminal Strip

Design Parameters

<u>Parameter</u>	<u>Goal</u>	<u>Achieved</u>
Operating Field	2.5/2.8 kG	2.5/2.8 kG
B(R=.94, Dmag=2.8kG)	3.0 kG Max	3.0 kG Max
Inside Diameter	1.95"/2.25"	Pole Piece = 1.95" Coil ID = 2.0"
Length	9.0" Max	10.25" Nom (Req'd for Field Spec)
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Power	<2.5 kW	2.9 kW Max @2.5 kG 3.7 kW Max @2.8 kG
Current	<50 Adc	46.0 Adc @ 2.5 kG 51.5 Adc @ 2.8 kG
Weight	< 55 Lbs	126 Lbs (Has a 96 Lb Shell)
Coils	Not Spec'd	4 Individual Coils

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Proposed VVW-8250W Solenoid

2" ID, 2.8 LG, 9" Coil Length, 4 Coils

REV 1

Proposed VYW-8250W Solenoid

2" ID, 2.8 KC, 9" Coil Length, 4 Coils

REV 1
M A 005611

Proposed VYW-8250W Electromagnet

2" ID, 2.8 kG, 9" Coil Length, 4 Coils

Proposed VYW-8250W Electromagnet

2" ID, 2.8 KG, 9" Coil Length, 4 Coils

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2/26/22

Proposed VYW-8250W Electromagnet

2" ID, 2.8 kG, 9" Coil Length, 4 Coils

Distance to Center of Bitter Magnet, In
—— I=0 in VYW-8250W

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Proposed VYW-8250W Electromagnet

2" ID, 2.8 KG, 9" Coil Length, 4 Coils

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Proposed VYW-8250W Electromagnet

2" ID, 2.5 KG, 9" Coil Length, 4 Coils

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Proposed VYW-8250W Electromagnet

2" ID, 2.5 kG, 9" Coil Length 4 Coils

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TEMPERATURE SPECIFICATION
 Model VYW-8250W Electromagnet

Description: Liquid Cooled Electromagnet for use with the VUW-8250 Pierce-wiggler electron beam forming system. The electromagnet consists of four independent coils which provide the field shaping capability for the beam forming system when energized with the proper currents.

ABSOLUTE RATINGS : See Notes 1, 2

Parameter:	I	T(in)	Q	Delta P	P	R1(20)	R2(20)	R3(20)	R4(20)
Units :	Acc	C	gpm	psid	psig	Ohms	Ohms	Ohms	Ohms
Maximum :	55	35		40	200	0.293	0.293	0.293	0.293
Minimum :			1.6			0.256	0.256	0.256	0.256
Notes :	11		8,9	9		3	3	3	3

OPERATING PARAMETERS: See Note 11

Parameter:	I1,4	I2,3	Rop1	Rop2	Rop3	Rop4
Units :	Acc	Acc	Ohms	Ohms	Ohms	Ohms
Maximum :	51.47	47.82	0.376	0.367	0.367	0.376
Minimum :						
Notes :	10	4	4	4	10	4

Dimensions : Per Outline Drawing No. TBD

Mounting Position : Any

Coolant : Water (Or equivalent flow of other coolant, Note 8 and 9)

Finish : Black, Acrylic Paint per Varian Spec P13-7-01

Weight : 126 Lbs

QUALITY CONFORMANCE INSPECTION (PRODUCTION):

Test	Conditions	Symbol	Min	Max	Units	Notes
Hydrostatic Pressure	Outlet closed, 200 psig applied, 5 minutes (min)		No Leaks			7,8
Pressure Drop	Flow rate = 1.6 gpm water	Delta P		40	psid	9

	Symbol	Min	Max	Units	Notes
Insulation Test potential 500 Vdc		50		megohms	5
Resistance Time = 30 Seconds					
Non-operating, Q=1.6 gpm Water, 20 C	R1(20)	0.256	0.293	Ohms	3
Resistance, All	R2(20)	0.256	0.293	Ohms	3
Coils in Series	R3(20)	0.256	0.293	Ohms	3
	R4(20)	0.256	0.293	Ohms	3
Operating Resistance	Rop1		0.376	Ohms	4,11
Q = 1.6 gpm Water	Rop2		0.367	Ohms	4,11
I1, I4 = 51.47 Ade	Rop3		0.367	Ohms	4,11
I2, I3 = 47.82 Ade	Rop4		0.376	Ohms	4,11
Field Polarity I = 50 Ade		Aiding			6

Notes:

1. Abbreviations and symbols used in this specification are as follows:

- I = Operating current, Ade (Numbers indicate coil)
- P = Hydrostatic pressure, psig
- Delta P = Pressure drop, psid
- Q = Coolant flow rate, gpm
- R(20) = Non-operating resistance corrected to 20 C, ohms (Numbers indicate coil)
- Rop = Operating resistance, ohms (Numbers indicate coil)
- Rt = Non-operating resistance, coils at temperature T(in), ohms
- T(in) = Temperature of coolant at inlet of magnet, C
- T1 = Temperature at measurement point 1, C
- T2 = Temperature at measurement point 2, C

2. The maximum ratings are not to be exceeded under any service conditions. Operation beyond these ratings will shorten the service life and may lead to early failure of the magnet. Any change in operating conditions that makes the magnet operate at a lower temperature (e.g. lower current, higher flow rate, lower inlet temperature, more efficient coolant) will result in lower power consumption, longer service life and higher reliability.

3. This measurement is made with coolant flowing, but with no power applied to the coils. When the temperature has stabilized, the resistance of the coils and the coolant temperature are measured. The resistance at 20 C is obtained by correcting the readings with the following formula:

$$R(20) = R_t \times \frac{243.1}{(T(in) + 228.1)} \quad \text{Ohms}$$

The resistance of the unit can be extrapolated to any temperature, T2 if the resistance is known at temperature T1 by the formula:

$$R(T2) = R(T1) \times \frac{(T2 + 228.1)}{(T1 + 228.1)} \quad \text{Ohms}$$

4. This measurement is made with minimum coolant flowing at the maximum inlet temperature and the indicated currents applied to the respective coils. When the unit has stabilized, the voltage reading across the coils is divided by the current to determine the operating resistance. When operated in this mode the unit will not exceed the maximum resistance value given nor the maximum coolant pressure drop.

5. The magnet shell and cooling system constitute ground for insulation resistance measurements. The test voltage shall be brought evenly up to the maximum specified in the time given.

6. All magnetic fields are to be aiding when the coils are connected in series.

7. No sign of leakage allowed after five minutes at pressure P.

8. Minimizing coolant corrosion and freezing damage: Do not allow coolant to freeze in the magnet. Remove all coolant before shipping or storing or when coolant freezing is anticipated. Do not operate the unit with inlet temperature below the local ambient dew point so that condensation forms on the unit. It is recommended that the maximum coolant flow rate be limited to less than 2.5 gpm to prevent cavitation and resultant corrosion acceleration due to high coolant velocity. Small traces of high purity water left in a stored unit will cause accelerated corrosion in copper. Dry the unit thoroughly before storage, especially if high purity water was used in testing or operation.

9. Liquid coolants other than water can be used to cool the unit. Please contact Varian XED Magnet Engineering to determine the required flow rate and pressure drop required for any specific coolant desired other than water.

10. Consult the Pierce-wiggler electron forming system data to determine current requirements to form the beam properly.

11. Operating Parameters show how the unit will operate under one specific energizing current condition at the maximum inlet coolant temperature and minimum coolant flow rate. The unit is capable of operating continuously at 55 Adc in all coils under the minimum coolant flow and maximum inlet coolant temperature without damage. However, at 55 Adc, the operating resistances will be higher than shown under Operating Parameters due to the increased operating temperature.