Conceptual Design Report
for the
THz Beamline at the Jefferson Lab Free Electron Laser

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September 9, 2004

1. Introduction.

We describe the conceptual design of an optical beamline which is designed to extract THz light emitted from a GW magnet at the Jefferson Lab Free Electron Laser immediately prior to the laser optical cavity, and deliver it to user Lab. 3 upstairs. The beamline delivers an f/8 beam of a source that appears approximately 2mm vertical ? 3mm horizontal in size. Under the present configuration, the beam is approximately 60 % vertically polarized. A plan of the JLab FEL building is shown in Fig. 1, and a schematic of the FEL itself, which is some 5 meters lower than the laboratory floor, is shown in Fig. 2. The THz extraction port location is shown in Fig. 2.

2. Design Goals.

The primary goal is to extract light emitted into a subtended angle of ~200 milliradians horizontal by ~135 milliradians vertical and transport it to Lab. 3.

The beamline is based on 150mm (6”) optics and is designed such that wavelengths up to 3mm pass without significant loss. (3mm = 0.1 THz or 3 cm^{-1}). Beam will be transported in a manner that preserves the wavefront and polarization to the greatest extent possible. Jogs in the optical transport allow for radiation shielding to be placed. The beam will be transported in vacuum, however a diamond window located at the first optical focus will separate the high machine vacuum of 1? 10^{-9} Torr from the 100 millitorr vacuum of the remainder of the optical transport line. Finally, the beam will be delivered into air in Lab. 3 using a second diamond window.

3. THz Beam Extraction.

The ring vacuum chamber and extraction port and are shown in Fig. 3. Apertures within this chamber are shown in Fig. 4 and define the opening angles. Taking the DIMAD “start-of-bend” machine lattice point as a reference, and taking 2 degrees from this as the optical beamline center line, the angles are shown in Fig. 5. A penetration with a 10” id has been made in the ceiling above the machine vault at a 2 degree angle from the straight-ahead, and 1040 mm from the dimad point, which is a machine lattice point defining the “start-of-bend” for the electron orbit. During installation it was found necessary to add a 1” spacer between the M2 and M3 mirror chambers to account for a discrepancy between the dimad point and the actual ring vacuum chamber.

4. Optical Design

The philosophy of the optical design is to use a relay optics configuration to transport the beam via reflection off metal mirrors through a series of focal points as shown in Fig. 6. Thus the beam will be focused at F1 onto a diamond window with unit magnification, then re-focussed at an intermediate point F2, and finally re-focused at F3 at a second diamond window in Lab. 3. The final focus will also be a 1:1 image of the source. Specifications of the diamond windows is given in Appendix A, while the measured transmission of one of the windows (~60%) is shown in Fig. 7.

M1 is a 1:1 ellipsoidal mirror of focal length 625 mm, which reflects the beam vertically upwards using s-polarization providing a focus at F1. M2 and M4 are an identical pair of ellipsoids with focal lengths 705 and 2426 arranged such that M2 provides a source image at F2 magnified by 3.4, while M4 reduces this image by the same factor to give a 1:1 final image on the final diamond window at F3. F3 is 1 meter above the floor in User Lab. 3. Exact specifications for the ellipsoid optical surfaces are shown in Figs. 8 & 9 and the mirror specifications are given in Appendix B.

The optical scheme was developed using the Synchrotron Radiation Workshop (SRW) code developed by Pascal Elleaume and Oleg Chubar. This code performs a full calculation of the electric field from a relativistic electron. It does not handle multiparticle coherent enhancement, but is significantly different from all the other synchrotron radiation calculations because it retains a term called the Coulomb term. In almost all cases of normal synchrotron radiation beamlines this is an unimportant term, but it is very important in the JLab case, making it essential to use this code. Initially this code failed for the JLab case due to the long wavelengths involved and close proximity of M1. However, the code was modified for us, and Oleg Chubar and Paul Dumas spent several days working with JLab staff on applying the code to the JLab situation. In addition to calculating the electric field and from this, the intensity, the code also allows one to propagate the field through optical focusing elements and apertures.

The patterns of light on M1 obtained from the SRW code for 3 different wavelengths are shown in Fig. 10. They are all calculated for 100 MeV beams. Note that the ring pattern originates from interference between the electric field generated by the magnetic field change on leaving one magnet and the one generated on entering the next magnet (Maxwell's equation

$? \; ? \; E \; ? \; ? \frac{?B}{?t}$). The more solid pattern seen particularly well on the right hand side of Fig. 10, on the other hand, is the synchrotron radiation (Maxwell's equation $? \; ? \; H \; ? \; J_{Free} \; ? \; ?_{o} \frac{?E}{?t} \; ? \frac{?P}{?t}$). Taking account of the finite electron beam emittance made no discernible difference to the patterns, changing the electron beam energy from 80 MeV to 150 MeV made a discernible but unimportant difference. In Fig. 11, radiation patterns were calculated for 1 THz light at M1, F1, M2, F2, M4 & F3. The red circles indicate the approximate sizes of the apertures at the optical elements. We also experimented with toroidal mirrors but there was no significant advantage and since we do not wish to change the anamorphic ratio, we retained ellipsoidal figures. Actually the differences between elliptical and toroidal figures are small. Finally, in Fig. 12 we show that at 0.1 THz we still catch most of the radiation, since 67.5% of it passes the first 20mm diamond window.

The mirrors are all made of machined and polished aluminum. They are all approximately 25mm thick and elliptical in shape consistent with 150mm diameter optics. Quality assurance of the surface finish (< 50 nm rms roughness) was verified by Peter Takacs in the instrumentation division of Brookhaven National Laboratory. The drawings of the mirrors are shown in Figs. 13, 14 and 15.

5. Power loading on the first mirror.

The power loading of M1 varies from a few hundred watts to a few hundred watts, see Fig. 16. Therefore M1 is cooled by a copper braid attached to a 1" diameter Cu feed-through to prevent thermal runaway. Assuming that M1 intercepts 1 kilowatt of THz power, then with a reflectivity of 99%, 10 watts could be absorbed by M1. The installed 25 ? 3 mm braid transfers this 10 Watts giving a 100^0 temperature rise to M1. A thermocouple has been attached to the mirror to monitor the situation.

6. Vacuum system.

The vacuum system is shown in Figs. 17 & 18, but we note that in initial installation we rotated the final beam by 90^0 from what is shown, so the the final beam direction is facing outward from the accelerator, and this has the effect of rotating the polarization to the vertical. Scaling these drawings reduces the legibility, but larger versions are available. M1 is in machine vacuum at all times but the diamond window at F1 can be isolated by means of a gate valve. Pumping is therefore provided between the gate valve and the window. This arrangement allows for window replacement, and for isolation for machine protection in the event of a leaky window.

The remainder of the beamline after F1 is in 100 millitorr vacuum and utilizes standard O-ring high vacuum fittings. Immediately following F1 is a remotely operable insertable beam-stop, mirror and camera arrangement, called safety shutter #1. This is identical to the "beam viewers" used throughout the FEL facility and will allow us to shut off the beam and also to position M1 so that the beam is centered on the window. Prior to M2 is a bellows.

The vacuum system is supported below M1, at the point of entry into the ceiling penetration, and between M4 and F3. Support structures are similar to those used by the other optical transport systems at the facility, including some re-cycling from our earlier FEL. They are shown in Fig. 19. Due to the poor legibility of Figs. 17-18, we show in Fig. 20, a photograph taken in May 2004 of the vacuum system without mirrors after initial installation and prior to the addition of the shielding.

7. Mirror mounting and controls.

The mirrors are all mounted on Thor Labs ® non-anodized but otherwise standard 2-axis manipulators. All the mirrors are adjustable while in vacuum. M1 and M2 are adjustable remotely using Phytron® single axis controllers, a high vacuum version being used for M1 for compatibility with machine vacuum of 10^{-9} Torr. Each controller has a stroke of 12 mm and a step size of 25.5 nm. This gives angular adjustment over the 3" base of 160 milliradians. M3 and M4 are manually adjustable while under vacuum using standard Wilson sealed rotary feedthroughs. M1 is mounted on a conflat flange, while M2, M3 and M4 are all mounted on quick-connect flanges. The mounting arrangements are shown in Figs. 21-23. A photo of M1 is shown in Fig. 24 prior to installation in July 2004. For mirrors M2, M3 and M4 it was found necessary to add springs externally to the Thor Labs ® mount.

8. Optical Beam Diagnostics.

The insertable mirror shown in Fig. 25, which is part of the safety shutter above F1, presents an image of the diamond window to a camera to allow remote adjustment of M1. Scatter from the cvd diamond window allows the beam to be observed.

Arrangements have been made for optical alignment without electron beam present in the machine, using alignment lasers, see Fig. 26. One laser located at a reverse tangent point will aim a beam at zero degrees. A second alignment laser can aim a beam at an angle of 2 degrees with respect to the zero degree line, to simulate the center of the optical axis. This is done using an insertable mirror.

9. Safety, Safety Shutters and Radiation Shielding.

There are 2 major safety issues: radiation protection from the electron accelerator, and the THz light itself.

The goal of the radiation shielding is to reduce to as low a value as reasonably achievable, the amount of radiation entering the penetration connecting Lab. 3 with the accelerator vault. Jogs in the optical beam transport allow the removal of “line of sight” between the penetration and the machine. The shielding was installed based on measurements made in Lab. 3 by the JLab radiation control group and is shown in Fig. 25. Above the FEL vacuum system is a 2’ ? 2’ shield comprising 8” of iron then 8” of borated polyethylene. In addition to this, the vertical section of pipe is surrounded by 4” borated polyethylene for the 3 feet prior to ceiling penetration.

The THz beam is treated as a Class 4 laser, meaning that the beam must be contained at all times in an interlocked exclusion zone. To ensure that the THz beam is adequately shut off during access to this zone, 2 safety shutters must operate to ensure redundancy. These are located immediately following F1 and immediately preceding F3. They work by inserting a mirror into the vacuum system to intercept the beam and reflect it through a quartz window to a water-cooled dump.

10. Beam Conditioning in Lab 3.

In Appendix C we show a scheme developed by Diyar Talbayev and colleagues at William and Mary for filtering, collimating, splitting and delaying the light emerging from the final diamond window at F3.

Appendix A

Specifications for diamond windows for NVL THz beamline project at Jefferson Lab.

Optical windows are required for the NVL THz beamline, in which light is to be extracted from the GW magnet immediately downstream of the high-reflecting laser cavity, and transported to laboratory 3.

The window material is natural type IIa (2a) or synthetic material made using condensed vapor deposition methods. No specific crystal orientation is needed, however, for synthetic material, crystalline is preferred over “diamond-like”.

Windows to be 20 mm clear aperture, wedged 1 deg. with mean thickness to withstand 2 atmospheres, so typically 500 microns running to 1000 microns.

Windows to be tested to 1 atmosphere, and to be sufficiently dense as to have a leak rate not to exceed 2 ? 10^{-10} Std. cc/sec He.

Surface flats should be within one fringe / cm of 633 nm or better, with a roughness of < 50 nm or better.

Window to be mounted on ultra-high vacuum components, bakeable to 200C and the seal to be strong enough to allow a 1 atmosphere pressure differential to be pulled on either side of the window.

All parts are to be cleaned to ultra-high vacuum standards, the use of sulfur bearing oils is prohibited during any machining.

These windows are intended to pass light from the accelerator primarily in the far-infrared region of the spectrum. The following external transmittances are required.

Frequency Range (cm-1)	External Transmittance
1-1500	>60%
1500-2750	>20%
2750-40,000	>60%

Vendors:

Mark Fraser
Harris International
35 West 45th St.
New York,
NY 10036
Phone: (212) 869-3037 Fax: (212) 302-5757

Simon Hanks
Manager Special Techniques Group UKAEA
D4/05, Culham Science Center
Abington
Oxon OX14 3DB
Phone:011-44-1235-463708 Fax: 011-44-1235-463278
simon.hanks@ukaea.org.uk

Prof. Dr. Peter Koidl
Fraunhofer-Institut für Angewandte Festkürperphysik
IR/diamond
Tullastrasse 72
D-79108 Freiburg
Germany
Tel: +49 761 5159 - 350
Fax: +49 761 5159 - 851

Appendix B

Specifications for M1 mirror for NVL THz beamline project at Jefferson Lab.

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December 5, 2003

1.0 SCOPE

1.1 This is a specificationfor fabrication and delivery of an ellipsoidal mirror for the Terahertz beamline at the Free Electron Laser facility at Thomas Jefferson National Accelerator Facility (JLab)

2.0 APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect on date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein.

Drawings: see Appendix A

3.0 REQUIREMENTS

3.1 General

The mirror described herein is to be part of the THz Beamline used to transport light from a synchrotron source to a remote experimental station. Planar mirror Ml is designed to intercept 135 mrad vertical by 200 mrad horizontal of the direct source at a distance of 625 mm and 45 degrees angle of incidence. The high incident power of up to 1 kilowatt necessitates cooling because even with a 99% reflectivity in the THz spectral region, the power absorbed will be 10 watts. Power density is not a problem because this power will be widely distributed across the reflecting surface. Cooling will be accomplished by clamping a braid to the mirror, and connected to a water-cooled copper feedthrough.

3.2 Operating Conditions.

Vacuum pressure: 10^{-9} Torr nominal (ultra-high vacuum).

Temperature: 20 C nominal, 150C during system bakeout.

Wavelength range: 0.5 microns to 1 cm

Operating Position: Reflecting surface tilted upward along length at 45 degrees to horizontal.

3.3 Geometrical Parameters

Blank size: Elliptical section see drawing, but approximately 140mm ? 200mm,

thickness 25mm.

Clear Aperture: Nominally the full extent of the reflecting surface

3.4 Tolerances

3.4.1 Reflection Surface:

Focal Lengths: Both F1 and F2 to ? 5mm.

Slope errors: Shall not exceed 75 micro-rad (15 arc sec) over any linear surface extent for surface spatial wavelengths between 500 micrometers and the maximum dimension.

Micro roughness: Shall not exceed 50 nm RMS integrated over surface spatial wavelengths between 5 microns and 500 microns as measured by a surface profilometer at any point within the C.A. This is equivalent to a total integrated scatter of 0.016% at ? = 1 micrometer into the hemisphere.

3.4.2 Rear surface

Rear surfaces shall be ground flat to within 5 micrometers, or equivalent for mounting on 3 balls.

3.5 Materials and Fabrication Methods

3.5.1 Substrate Fabrication

Mirror substrate material shall be aluminum.

3.5.2 Protective Coating

An easily strippable protective coating maybe applied to the optical surface to protect it during shipping and handling.

3.5.3 Vacuum Compatibility

The finished mirror must not produce carbon-containing contaminants at partial pressures above 1 ? 10^{-12} Torr after normal bake-out procedures in ultra-high vacuum, i.e. at pressures less than 1 ? 10^{-9} Torr. No organic or high vapor pressure inorganic materials may be on any part of the mirror after final cleaning prior to installation in the vacuum chamber. Protective coatings or packaging must be fully removable by mechanical separation or rinsing in a solvent, such as acetone, or by vapor degreasing in a treon or isopropanol system.

4.0 QUALITY ASSURANCE

4.1 Responsibility for Inspection

Unless otherwise specified in the contract or order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to JLab. JLab reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements

4.2 Figure

The vendor will provide JLab with evidence that the final polished reflecting surface meets the surface figure specification in paragraph 3.4.1. Verification may take the form of a report from an independent testing laboratory acceptable to JLab or a test at the vendor's premises witnessed by an independent testing laboratory acceptable to JLab or a test at the vendor's premises witnessed by an authorized JLab representative or by any other means acceptable to JLab.

Surface Roughness

The vendor will provide JLab with evidence that the final machined or polished surface meets the surface finish requirements in paragraph 3.4. Suggested measurement techniques are stylus profilometry or optical profilometry of representative regions of the surface. The method by which the above tests are carried out and the analysis of the data must be approved in consultation with JLab prior to the actual testing. JLab may require delivery of the raw test data for our own analysis.

Surface Defects

Cosmetic defects within in the C.A. must be minimized such that the total area of scratches, digs, voids, or other imperfections which can remove energy from the reflected wavefront be less than 0.1% of the C.A.

Vacuum Requirement Compliance

The vendor shall supply JLab with evidence that the mirror meets the vacuum compatibility requirements in paragraph 3.5.3. The nature of the test used to ensure compliance shall be a residual gas analysis in a clean ultrahigh vacuum chamber. JLab must approve the details of the test method proposed by the vendor and will offer guidance as to how the test shall be performed if so requested. Use of services of an independent testing laboratory is subject to the approval of JLab.

5.0 PREPARATION FOR DELIVERY

5.1 Preservation

The finished optical surface may be coated with a strippable plastic film as per paragraph 3.5.2, provided that film does not injure the surface in any way, and provided that removal of the film does not injure the surface in any way, and provided that removal of the film meet the UHV requirements outlined in paragraph 3.5.3. The finished piece must be thoroughly clean and free from any organic or low-vapor pressure material *or* residual polishing compound or cutting fluid.

5.2 Packaging

Each individual mirror must be packaged in it own protective container. The container must be capable of being seale<Jtightly to prevent dust and moisture from entering. The container must prevent contact of any object with any part of the clear aperture. Design of the packing container is subject to JLab approval.

5.3 Packing

Packing for shipment must insure that each mirror is insulated from severe shock and rough handling. Package markings shall indicate the fragile nature of the contents.

Vendors for JLab THz M1.

Corning NetOptix
Diamond Turning Division
69 Island Street
Keene, NH 03431 USA
Tel: 1-603-357-7662 Fax: 1-603-357-7764

Thomas Keating Ltd
Attn. Richard Wylde
Station Mills
Billingshurst
West Sussex
RH14 9SH
UK
Tel: +44-1403 787614 Fax: +44-1403 451271

KUGLER GmbH
i. A. Joachim Kopmann
Technical Sales Management
+49/7553/9200-16
http://www.kugler-precision.com

LT-Ultra
www.satzunddesign.de/lt_neu2/index.htm

Appendix C

Suggested layout for the optical bench for pump-probe spectroscopy in Lab 3,
Diyar Talbayev, Gunter Luepke, Gwyn Williams