Final Report

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**Division of High Energy Physics
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Experimental Research on the Laser Cyclotron Auto-Resonance Accelerator “LACARA”

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submitted by:

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Abstract. The Laser Cyclotron Auto-Resonant Accelerator LACARA has successfully operated this year. Results are summarized, an interpretation of operating data is provided in the body of the report, and recommendations are made how the experiment should be carried forward. The Appendix A contains a description of the LACARA apparatus, currently installed at the Accelerator Test Facility, Brookhaven National Laboratory. This report summarizes the project, extending over three grant-years.

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Final Report Summary
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I. Introduction. This series of grants began in 1991, and for the first 9 years three experiments were done using the IFEL concept. Initial experiments resulted in the first test of the IFEL concept at Columbia in 1990-2, followed by another study completed at ATF (1997), and finally an experiment done at Yale (2000) to test the large orbit theory of the IFEL. Following these experiments we undertook research on multi-bunch wakefield acceleration at ATF, and developed a new diagnostic for measuring bunch length (2001-4). Beginning in 2005, the LACARA experiment was assembled and tested at ATF (the “dry” superconducting solenoid was constructed in the preceding years by Omega-P, Inc.). Dielectric wakefield work was continued in the period 2004-8 with the collateral support of the CRDF, which funded experimental work at the Kharkov Institute of Physics and Technology. This final report will emphasize the LACARA project, particularly in the final year when operation was successfully accomplished (2008).

II. LACARA Research.

Research carried out in the last year of this grant brought the LACARA accelerator to operation on July 14, 2008. Although further work should be done to carry the project to a satisfactory conclusion, one may summarize by saying that in the past four years the LACARA apparatus has been assembled at the Accelerator Test Facility at Brookhaven National Laboratory, and has been operated with modest success.

The last yearly report (November, 2007, see Appendix A) described in detail the different systems (magnet, bunch transport line, optical transport line, beam dumps and spectrometers, etc.), and so the main body of this report will summarize activity in the past year and the results we have obtained through operations including October, 2008. A formal publication of results will follow when matters are brought to a satisfactory level of understanding, taking advantage of the capabilities of the present equipment.

Several systems were found to need upgrading early in 2008: among them were: 1) Magnet table alignment and reproducibility of positioning; 2) Phase control in the rf gun (ATF responsibility); 3) Alignment of the CO₂ laser pulse with the electron bunch; 4) Synchronization of the optical pulse with the charge bunch; 5) Extending the range of the energy spectrometer (ATF); 6) Power measurement and pulse characterization of the CO₂ laser pulse (ATF). The first three of these required some additional hardware and construction and were largely completed by April; items 4 and 5 were in place by the time of our first run in July (#5 was obtained through the efforts of another group), and #6 (in our judgment) requires additional attention now.

Before the synchronization equipment was in place, a run was made which used a broad laser pulse having low power (40GW, 200psec). This pulse is easier to synchronize than the typically 6psec long each, train of three high power laser pulses (estimated at 200GW each at present by ATF). While theory suggested that some

acceleration should be observable, in fact none was found, thus the need for synchronization equipment. However, it also may have been that the laser power was lower than claimed by ATF (see below). Various factors delayed the next run to July (equipment, manpower).

The experimental run of July 2008 resulted in useful data. The first data to show the effect of the laser upon the bunch was the case of linear polarization of the laser field. The bunch was synchronized to one of three laser pulses in a sequence, each pulse estimated at that time to be about 200GW (or effectively 100GW in the wanted circularly- polarized mode). The results are shown in Figure 1. A shift in energy of the distribution by $\sim 0.4\text{MeV}$ was obtained, together with an overall broadening of the energy distribution by $\sim 1.4\text{MeV}$. This is a modest effect. The circularly-polarized data in Fig. 2 shows that a sense of electron gyration about the field lines is favored and the case of +5T indicates a small net energy increase and appreciable energy spread. However, the energy gains achieved, as well as the spreads, are much lower than predicted.

LACARA ACCELERATION FOR LINEARLY-POLARIZED LASER

initial beam energy $\approx 56.5\text{ MeV}$, laser power $\leq 200\text{ GW}$, B-field $\approx 5\text{ T}$

top trace: laser off; bottom trace: laser on; higher energy at left

Energy gain reaches about 2 MeV; energy loss reaches about 1 MeV.
Gain at peak of distribution $\approx 0.4\text{ MeV}$, standard deviation $\approx 0.7\text{ MeV}$.

Figure 1. Energy spectrum of bunch electrons for a linearly polarized laser pulse. The claimed laser power is $\sim 200\text{GW}$, but our analysis (below) suggests it was about $\frac{1}{2}$ this value.

Figure 2. Energy spectrum of electrons for a circularly-polarized laser pulse. Right circular polarized case at the right side. The interaction with the -5T is due to $\sim 15\%$ of the total radiation remaining in the left polarized component.

It was decided that before the next run, optimum alignment of the beam, bunch, and magnetic field should be obtained, and a quantitative measure of laser pulse power should be repeated. (It should be noted that ATF plans to obtain a more intense single pulse of light by using an isotope to broaden the gain spectrum of one of the CO_2 amplifiers, but this will probably not occur before 2009.) The longitudinal behavior of the laser profile in Lacara was measured in 2006, and was reported in the yearly report for that year: it was fit by a Gaussian envelope, but it was not entirely symmetric about that axis. In Figure 3 below, we show a transverse intensity pattern of the laser spot; some asymmetry is apparent. It should be noted that any non-Gaussian mode behavior would be “filtered out” of the beam in its passage through the optical transport line.

Data on the behavior of the waist of the laser beam are shown in Fig. 4 (waist size $w(z)$ versus z , in mm); although the waist in one transverse dimension appears to be Gaussian (Fig 4a for w_x), the other component (Fig. 4b for w_y) does not substantiate this fit, as the minimum beam radius w_0 in Fig 4a is 1.8mm, whereas for Fig. 4b it is 1.4mm.

Fig. 3. Gaussian laser spot. Note it is not exactly symmetrical.

Fig. 4a: $w_x(z)$. The Gaussian fit to the waist behavior is good.

Fig 4b: $w_y(z)$. The Gaussian fit to the waist behavior is not so good.

However, w_0 in each case corresponds to the center of the magnet, a desirable thing. Here we should point out that the design of the optical system had a constraint other than that the beam should have a small waist centered inside the magnet. The light beam was introduced into the bunch line through an opening in the dipole magnet that forms the aperture of the optical system. Thus the waist at that position must clear the aperture. This set the design waist size of the beam at $\sim 1.6\text{mm}$ and the Rayleigh Range = $z_R = 76\text{cm}$. Any change from this would cause loss of additional laser energy at the aperture, and thus it is not possible to “vary” z_R . The different behavior of w_x and w_y may be caused by asymmetry of the aperture that is located between the jaws of the dipole for beamline #2. Finally, while the above is indicative of the best behavior of the laser, it does happen that some shots on certain days do not have a good Gaussian quality for various reasons: thus the variability of data may be caused in part by these problems.

Our early studies of the energy gain in LACARA showed the behavior in Fig. 5 where the beam diameter is taken to be 150 micrometers. The expected energy gain (laser power = 40GW) is appreciably larger than we obtained. So, we began a more thorough study of this problem, using also the new experimental data on the energy spread induced by the interaction to help guide the analysis.

Fig. 5. Energy gain (MeV) vs. B (T), Energy: green = 61MeV; blue = 56MeV; red = 51MeV. Magnet operates at 5T for this run; laser = 40GW.

The LACARA code was used to tentatively identify the problem with the equipment that is causing the energy gain to be much smaller than originally predicted by the code. The problem is very likely that the particles cannot be injected precisely along the magnetic axis. The bunch is initially aligned with the magnetic axis of the solenoid at lower fields (1-2T), but it was found that at the field we must use ($\sim 5T$), the axis shifted approximately $\pm 150\mu\text{m}$ in one direction and $\pm 500\mu\text{m}$ in the other: it is the latter appreciable shift that likely gives trouble. It is not possible to align the bunch motion better, which means that the bunch is entering the solenoid and traversing a region where the field lines have been “bent”. This might be caused by a slight shifting of one or both of the two windings in the cryostat when the magnetic field is large. The present code does not allow for this misalignment to be modeled; however a similar effect will occur if the bunch diameter is increased to the same dimensions as the offset described above. Then many electrons in the bunch find themselves off the solenoid axis and interact with magnetic lines that are canted with respect to the solenoid axis. The results of this modeling, for parameters used in the experiment, are shown in Fig. 6a and 6b. A dramatic falloff of energy gain and spread occurs for the larger bunch sizes (the initial emittance is a constant in these calculations, and so the transverse velocity spread of the particles decreases as the bunch size increases-- thus it is the increase of bunch size that causes this effect). Results comparable to experimental values (see Fig. 1) are obtained for a laser power of 50GW right circularly polarized (100GW linear polarized),

Fig. 6a: Energy gain (red) and energy spread (blue) versus bunch RMS size (the beam is round). Laser power is 50Gw.

Fig. 6b: Energy gain and spread versus CO₂ laser power, fixed bunch size of $\sigma_x = 453$ microns and $\sigma_y = 268$ microns.

which is about one-half of what was claimed to have been available in the experiment. While it is not possible to argue for an accurate connection between the code model and the actual experiment, the results of the new simulations suggest that the behavior of the magnetic axis is causing LACARA to perform below expectations. Alignment of the laser beam is satisfactory, so another run might be done to determine if the bunch motion along the magnetic field can be improved.

Returning to the data shown in Fig. 2, a certain energy spread and no average energy gain was found for the left-polarized sensitive -5T result. This interaction occurs because approximately 15% of the light is left-polarized, and interacts with the bunch at this field value. Thus the interaction should be explained if we look at Fig. 6b and extrapolate to 7.5GW: no energy gain and small energy spread consistent with the data are found. Thus there is additional evidence that the laser power should be ~ 50 GW right-circularly-polarized during the run, smaller than was indicated by ATF.

σ_{ini} , um	Laser power, GW	Offset, mm	Θ , mm	Offset, MeV	Θ , MeV
268	50	2.24	31.54	0.28	2.03
268	150	6.71	53.73	0.84	3.45
268	300	13.06	74.2	1.64	4.76
360	50	5.74	29.1	0.72	1.87
360	150	16.8	50.3	2.11	3.23
360	300	31.9	71	4.01	4.56
453	50	3.13	22.9	0.40	1.47
453	150	9.33	40.6	1.17	2.61
453	300	18.2	59.3	2.28	3.81

Table I. Results (see last two columns at right) of code simulations of predicted LACARA performance at the output of the energy spectrometer. The “effective” bunch input size (due to magnet problem) and laser power yield “offset” (average energy gain) and “ Θ ” (RMS energy spread) when converted by the spectrometer calibration.

A set of comprehensive simulations (Table I) was done to improve the model with respect to how it handles emittance. We found that it was necessary to have a symmetric bunch ($\sigma_x = \sigma_y$) for a reliable result. These calculations followed the bunch through the magnetic transport system from the magnet to the energy spectrometer downstream. It was possible to then compare the computed behavior of the bunch (with given input size, emittance, energy, energy spread) with the spectrum that was actually observed. For these computations, three different input bunch sizes were taken, along with three different laser pulse powers. Again, larger bunch sizes (the actual one is 150micron) are chosen (Fig. 7) to model the magnetic axis problem that we described above. The best fit is the red curve with crosses (seventh row in Table I), obtained for 50GW right circular polarized light (100GW linear polarized light for Fig. 1) and an “effective” bunch diameter of 453microns. From this study, there is a good indication that the ATF laser power is less than claimed: it may be that some of the laser pulse energy is going into a low-level “plateau” that underlies the three prominent observed pulses, or there may be additional low-level pulse features not detected in the overall power output waveform that would sap power from one of the peak pulses. Further work must be done to check these conjectures. Nevertheless, if the laser power were to increase to 300GW, the analysis we have done would predict an electron bunch energy gain $> 2\text{MeV}$ (last row, Table I), and that would definitely be worth exploring. As of this writing, it would appear that another run at ATF is needed, with energy and power measurements as well. If the

Fig. 7. Predicted electron energy distribution on our spectrometer. Red curves: 50GW laser; blue curves, 150GW laser (circular polarization). The sizes in microns chosen for the bunch are: smooth curves, 268; box curves, 360; crossed curves, 453.

power of the ATF laser is increased and a single large laser pulse is provided in the next few months, we may be able to obtain important increases for the bunch energy gain in LACARA and be able to interpret it satisfactorily with help from an improved code. We

also plan to study effects of artificially high emittance to model the problem with the magnet.

An important result of our analysis since the recent LACARA run at ATF has been the appreciation that the straightness of the solenoid's magnetic axis is a very important matter for the successful performance of this accelerator concept. The next question is what can be done about correcting the magnetic axis of the solenoid, assuming that remains our firm conclusion. The misalignment may cause the field lines to become canted $\sim 1\text{mrad}$ (on the average) with respect to the geometric axis and the desired bunch motion. It is possible that a transverse magnetic field $\sim 50\text{Gauss}$ might correct this, possibly to zeroth order. A large Helmholtz coil apparatus could be constructed and mounted so that the correction field is transverse to the cryostat axis and oriented so that it opposes the error field. However, if the field lines are "bowed", then two pairs of Helmholtz coils would be required. Thus, correcting the magnetic orientation of the solenoid would be an important undertaking involving magnet design and placement as well as additional Further LACARA code development must be done to ensure complete confidence in the computational model before construction of the correcting field components is undertaken. The scope of this effort would require new manpower and further support from the DOE (to Yale, in this case).

III. Dielectric Wakefield Accelerator Research DWA research this past year has focused on the two-channel rectangular structure, which has been designed and will be shortly constructed and operated at the Argonne Wakefield Accelerator facility. The two channel design permits separation of the drive and witness bunch trains, realizes a significant transformer ratio ($\sim 15\text{-}20$), and permits continuous coupling of energy from the drive to the witness bunches. Work on this project is supported by a DoE SBIR grant to Omega-P., Inc., for which one of us (TCM) is a consultant. In the course of our studies of this device, we found an important flaw in the 2-channel structure: a lack of symmetry that allows potentially troublesome transverse forces to deflect or distort the witness bunch at certain locations. This flaw can be eliminated by using a symmetric 3-channel structure that has two co-moving drive bunches. It was found that the witness bunch in this structure enjoys dynamical stability when at least two acceleration modules are provided, and that a Terahertz model (dimensions $\sim 2\text{mm}$ wide X 0.6mm tall) will develop accelerating wakefields $>350\text{MV/m}$ using two SLAC- type drive bunches. On the other hand, a *coax* configuration using the simpler two-channel concept will provide axial focusing for the witness beam; yet, it needs an annular drive bunch (see Fig. 8a), and – most likely in a TeV collider application -- a carbon nanotube fabric for supporting the inner dielectric component at each end of the structure module. The focusing force on the test (or "witness") bunch where the axial accelerating force is maximum, is radial toward the axis (Fig. 8b).

We have also found that, due to the potentially large transverse forces that appear at certain locations along the witness channel, our 5-zone DWA can operate as a novel "fast" ($\sim 1\text{nsec}$) kicker for GeV-level bunches, such as are found in light sources.

Further information about these designs and the ongoing experimental project can be obtained by consulting the publications in part V, or via the reports and publications of the Omega-P group.

Fig. 8a: A coaxial two-channel dielectric wakefield accelerator. This design chooses parameters appropriate to the Argonne Wakefield Accelerator facility.

Fig. 8b: Axial and transverse forces on the witness bunch, at $r = 0.8\text{mm}$ from the central axis of the coax; witness bunch is located at $z = 86\text{mm}$ behind the drive bunch which is located at $z = 100\text{mm}$. Notice the axial force is focusing there (negative force for positive radial displacement). The transformer ratio is 10. The wakefields are destroyed at the left by the slower-moving “quenching wave” which arises from the input boundary.

IV. Personnel:

1. Dr. Sergey Shchelkunov, Postdoctoral Research Scientist, 2/15/07 through 2/28/08.
2. Prof. Thomas Marshall, 2/15/07 through 8/14/08 (part-time)

V. Recent Publications and Presentations:

At the Advanced Accelerator Workshop, Santa Cruz CA, July 27- August 2, 2008, and in the Workshop Proceedings (to be published, AIP Conference Proceedings Series) these first three:

1. *“First Experimental Results for LACARA”*, S.V. Shchelkunov, T.C. Marshall, M.A. LaPointe, V. Yakimenko, I.V. Pogorelsky, J. Park, and J.L. Hirshfield.
2. *“Two-Channel Rectangular Dielectric Wakefield Accelerator Structure Experiment”*, G.V. Sotnikov, T.C. Marshall, S.V. Shchelkunov, A. Didenko, and J.L. Hirshfield.
3. *“A Symmetric Terahertz Dielectric-Lined Rectangular Structure for High Gradient Acceleration”*, T.C. Marshall, G.V. Sotnikov, S.V. Shchelkunov, and J.L. Hirshfield.
4. *“A Three-Channel Terahertz Dielectric Wakefield Accelerator That Develops High Gradients”*, G.V. Sotnikov, T.C. Marshall, S.V. Shchelkunov, and J.L. Hirshfield, *Strong Microwaves in Plasmas*, Institute of Applied Physics, Nizhny-Novgorod, Russia, (2009) [to be publ.]

Appendix A. The LACARA Apparatus (from the 2007 yearly report)

The LACARA schematic showing the different subsystems.

We divide the LACARA setup in the following main constituents:

1. The solenoid, which provides the magnetic field in which the interaction between the electron beam (e-beam) and the high power CO₂ laser occurs
2. The electron transport line, which is a) to deliver the electron beam to the solenoid, and to shape the electron beam prior to its entry into the magnetic field so as to achieve the e-beam acceleration when it interacts with the CO₂ laser beam, and b) to guide the accelerated and/or non-accelerated e-beam to the spectrometer after the e-beam leaves the solenoid.
3. The spectrometer, which measures the electron beam energy gain and spread
4. The Laser transport line, which is to a) deliver the high power CO₂ beam (with energy ~8-10 J, and the pulse length ~5-10 psec) to the solenoid (interaction region) and to shape the CO₂ laser beam so that it accelerates the electron beam, and b) to dispose of the CO₂ laser beam after it leaves the solenoid (interaction region)
5. The alignment hardware, which provides means for achieving the alignment between the electron beam, magnetic field, and CO₂ laser beam.
6. The control and data acquisition/ processing system, which provides the remote control over the experimental setup components, and collects and/ or processes the experimental data.
7. The auxiliary hardware, which provides suitable working conditions for the components that form the setup as per items #1-6 above (e.g. a chiller for the solenoid cooling head, or ion-pumps for the Laser transport line, and/or similar items).

As of now, all the main components have been assembled and also tested (separately from each other). In the series of paragraphs below, a detailed description of each main component/ system is given together with their latest modifications and the results of the tests.

1. The solenoid provides a guiding magnetic field up to 6 T at 77 amps over the length of 0.96 m. The unit's flange-to-flange length is 1371 mm. Its windings have operational temperature of 4.2 K⁰, and are chilled by a Sumitomo SRDK-408 cryocooler head through a thermally conductive mount, which is in the middle of the coil. There are 8 control points to monitor the temperature of the coil as well as the conductive mount and the layered thermal shielding around the coil. The total time for cooling down from the room temperature is about 4.5 days. This magnet was constructed at CVIP, PA. The solenoid was energized up to the 5.95 T several times prior to its installation to the beam line as well as after. A procedure to align the magnet with the electron beam was developed [described in Appendix 1], and the successful transmission of the e-beam was reported at different field values, and in particular at 5.85 T, where one should expect the maximum acceleration to occur if the CO₂ laser beam is present [see Appendix 1]. During the tests conducted in October-November, 2006, the stability of the magnet support table was questionable, however; this may result in a non-repeatable solenoid position from one run to another. To eliminate this problem, presently a set of precision micrometers has been installed so as to monitor the solenoid position relative to the beam line at all times.
2. The electron transport line is a collection of items between two dipoles, with the space between those commonly referred as the 2nd beam line. The main items/components are: quadrupoles, steering magnets, beam position monitors (BPMs) and the supports for them. To focus the electron beam, there is one quadrupole triplet in front of the LACARA solenoid, and one triplet after the solenoid. The positions of quadrupoles were chosen as a result of numerical optimization so as to have the e-beam best suited for LACARA. Individual quadrupoles within each triplet were aligned with accuracy better than $\pm 20 \mu\text{m}$; and all the quadrupoles were aligned with a respect to the common straight line with an accuracy of $\pm 35 \mu\text{m}$ [see Appendix 2]. For this installation, we used the available ATF quadrupoles, but supplied the supports for them as well as positioned and aligned the quadrupoles. There are three BPMs before the solenoid and three BPMs after, each aligned with an accuracy $\sim 0.5 \text{ mm}$ with respect to the beam line axis. Most of the BPMs follow the standard ATF design and allow monitoring the position of the e-beam as well as its size. We supplied parts (YAG screens, mirrors, pneumatic actuators, cameras, lenses, and power supplies) for roughly two BPMs, and manufactured supports for about 70% of BPMs. We also aligned the BPMs as well as any other chamber (including the dipoles), which is present now on the 2nd beam line. The steering magnets are mostly located right behind the BPMs and are there to correct the e-beam trajectory. Out of 6 units, we supplied 2 (with supports). Among the major components is also a strip line (provided by ATF) to record the moment when the e-beam arrives at a given

location. The electron transport line was tested and it was found that the electron beam sizes were as expected [see Appendix 2, and photos therein]. It should be noted that to form the electron beam suitable for LACARA, one must utilize the entire lattice (2 dipoles and 17 quadrupoles) situated between the ATF LINAC and the LACARA solenoid (note that in total, there are 3 dipoles and 23 quadrupoles being active during this experiment). The behavior of the e-beam is well understood, and the procedure is in hand to achieve the required e-beam parameters at the entrance to the solenoid (note that depending on the gun condition, optimizations may take from 0.5 to 2 days).

3. The spectrometer, presently, is formed by the 2nd dipole, the quadrupole triplet, which follows the 2nd dipole, several steering magnets, and a scintillating screen inside a chamber whose design is similar to that of a regular BPM. All these items were in place before we assembled LACARA, and we presently are adopting this setup for our purposes: to achieve a required energy resolution we must adjust the currents in the quadrupoles. The current values are chosen as a result of numerical simulations. The dipole must be wired to an additional power supply to allow calibration and beam steering (the power supply will be provided by ATF). The total distance between the dipole (bending magnet) and the screen is [see Appendix 3] about ~4.5 m, which limits then the energy acceptance to about 3-4 MeV only. This 3-4 MeV energy acceptance is sufficient for initial LACARA runs/tests to demonstrate the CO₂-beam – e-beam interaction. Since the expected peak energy gain (25 MeV) for this experiment is far larger than the energy acceptance of the present spectrometer, we are planning to design and install a new spectrometer. This new spectrometer [see also Appendix 3], in essence, is a large format screen placed in a sufficiently large vacuum chamber with dimensions, which allow monitoring all the electrons within energy range from about 50 MeV to 85 MeV; thus, this new spectrometer will also allow capturing on the single screen both accelerated and non-accelerated bunches. Its design/installation is subject to two conditions: a) the acceleration is demonstrated with the present spectrometer, and b) sufficient budget. The new spectrometer will also require adequate shielding, the configuration of which is subject to a very limited available space.
4. The laser transport line is formed by a set of components fully described in Appendix 4. The important components are a set of mirrors, a lens, and a vacuum window together with motors that position the mirrors. Most of the mirrors are planar copper mirrors which fold the laser light path so that it clears all obstacles, and is brought to a designated location. One of the mirrors is a convex mirror that together with the lens forms a telescope that focuses the light at the mid-plane of the solenoid. The lens as well as the vacuum window are sodium chloride which is the best material for transmitting high intensity, high energy pulses of laser light. The interaction with the bunch occurs in vacuum, but the light is delivered from its source via an air-filled conduit, so the vacuum window is essential and must be positioned where the light flux does not exceed its failure limit. All mirrors and the lens are installed in mounts that can be adjusted to provide precise beam positioning. The line has been tested, and was found to deliver a nearly-Gaussian beam focused at the middle of the solenoid with waist size at the focal plane close to the desired 1.6mm in such a way that power transmission is not limited by

apertures. Due to the particular design of the ATF CO₂ laser system, the CO₂ energy measurements are available only when the CO₂ laser is delivered to the 1st (STELLA) beam line; consequently, a need has arisen for the LACARA group to install a setup to handle the energy measurements for the CO₂ laser when it is delivered to our 2nd ATF beam line. Possible solutions are presented in Appendix 4; however, it is expected to have the energy measurement system available only few months from now, and thus in the near future we must conduct several runs without the CO₂ pulse energy measurements.

5. The alignment hardware is a collection of items and parts that provide means for achieving the alignment between the electron beam, magnetic field, and CO₂ laser beam. The following is the list of items manufactured/ purchased by the LACARA group for these tasks: a) the magnet support table; b) forward alignment HeNe laser setup; c) backward alignment HeNe laser setup; d) beam-line irises on kinematic stages; e) alignment targets for quadrupoles, BPMs, and vacuum chambers, f) a periscope imaging optical system to monitor the alignment beam on the in-vacuum mirrors; g) an alignment unit in front of the entrance dipole to provide fine alignment between the CO₂ laser and the beam-line and several other functions; h) two sets of irises and auxiliary mirrors on the breadboard and on side-support after the alignment unit (see item g) to align the CO₂ laser and forward alignment HeNe laser with each other; and i) a monitor, after the solenoid, with a composite screen to monitor either the electron beam or the CO₂-laser pulse. More details are given in Appendix 5. As of now, all these items have been tested, and any problem adversely affecting their performances (e.g. the unpredictable pitch backlash of the magnet table, or its poor vertical adjustment accuracy, etc) has been eliminated [see Appendix 5]. Item h) requires an additional work to improve the overall performance of the entire setup, and item i) requires an additional installations: the planned completion date is the middle of January 2008.
6. The control and data acquisition/ processing system is built around a single PC computer (the LACARA control computer) which runs LabView (v8.0) and Mathcad (v11). The LabView based application is used to remotely control and collect data from units such as the solenoid power supply (CS-4), the step-motor controller for the solenoid support table (VP-9000), and similar devices as provided in Appendix 6. All data are placed in a common database, and also recorded in uniquely labeled files. One of the LabView-based applications (main console) maintains a constant dialog with all other applications, as well as with the ATF main control computer (HAL) so that up to a certain extent and operator can exercise control over ATF main functions using the LACARA control computer. It is, however, convenient to process certain data streams using the Mathcad based applications, and the dialog between LabView and Mathcad is established via a set of common files. There are also several hardware devices which we consider as part of the control system, even though some of them are not wired to the control computer (see App. 6). The control system was crucial to obtain and process data to achieve an alignment between the solenoid and e-beam as it was described in paragraph 2 above. Presently, a plan is to extend the control system with several software applications to collect data from the oscilloscopes measuring the gun voltage and bunch charge, and to adjust the gun IQ-modulator settings to suppress

the gun phase drifts (typically in the second half of a day, the gun phase drifts occasionally by several degrees in the course of 15 minutes). Factors that contribute to errors that arise from this gun phase shift include: a) different initial bunch energy; b) increased energy spread; and c) initial transverse sizes (e.g. at the solenoid entry point) which differ from requirements. Thus, this new extension of the control system is essential for the collection of error-free data about the bunch acceleration by the laser.

7. The auxiliary hardware is a collection of power supplies, chillers, ion-pumps, different sorts of gauges and similar items required to provide suitable working conditions for the main LACARA components. All auxiliary units have been tested and found operational. The full list of items is given in Appendix 7. Below are described a few, but the most notable auxiliary units are: a) the bipolar power supply, CS-4, for the magnet can drive up to 100 Amps of DC current in either direction, has a built-in quench protection system, and data communication ports, and is wired to the LACARA control system; b) the cooler compressor, CSW-71, cools the cryocooler head, SRDK-408, of the solenoid, and uses compressed helium as a coolant (25.4 liters at about 235 psig). The compressor is detached from the magnet, and requires 208 VAC at 60 GHz with steady power 7.5 kW and overloads up to 8.3 kW, and must be cooled by means of an external chiller with about 9 liters/min flow rate; c) the external water chiller, UC-080, with 11kW cooling capacity at 50 psi cools the magnet cooler compressor.

Appendix A1

The successful transmission of the electron beam was observed at different values of the magnetic field, and in particular at 5.85 T [see Fig. A.1.1], where one should expect the maximum acceleration to occur if the CO₂ laser beam is present. This was the result of the application of the alignment procedure as reported at e.g. AAC2006 [article #].

The procedure is shortly described below, and even though the full operating solenoidal field during the acceleration with the CO₂ laser beam must be ~6T, it was demonstrated that the alignment can be performed at much lower fields (with the CO₂ laser beam being off). It must be noted that the solenoid is aligned with the electron beam, but not the opposite. Three beam position monitors (BPM) are required: two BPMs before the magnet (downstream), and one BPM after the magnet (upstream). To accurately determine the position of the solenoid (and thus to move it then by a measured amount) one shall: 1) establish the electron axis without the magnetic field (e.g. by using a HeNe laser); 2) change the magnetic field, but keep the electron beam at the same position on the first monitor (BPM #1); 3) observe the shifts of the electron beam at two other BPMs: one before the solenoid, and another after the solenoid; 4) repeat for several more values of magnetic field, and deduce from the obtained data the solenoid position relative to the e-beam [as documented in article #, AAC2006]

The beam position monitors to perform this alignment followed the standard ATF design for BPMs, and were installed as a part of electron transport line.

Fig. A.1.1 The electron beam at the beam position monitor(BPM 4) after the solenoid when the solenoid is energized to 5.85 T

By comparison the solenoid position for the best transmission at low (less than 0.5T), medium (around 2.5T), and high (around 5.5T) fields, it was found that the solenoid axis is as straight as not less than 150 μm vertically, and 500 μm horizontally. The comparison was performed for the data sets acquired in different days; however, shortly after the data was accumulated, the stability of the magnet support table was questioned, resulting in a fact that in actuality the straightness of the magnet axis could be better than the aforementioned 150 and 500 μm . To eliminate the table stability problem, a set of precision micrometers has been installed so that to monitor the solenoid position relative to the beam line at all times. The improved setup has not been tested yet; estimated run time to complete this test is ~ 4 days.

Appendix A2

The electron transport line was tested and it was found that the electron beam sizes were as expected [Fig. A.2.1]. Thus, the behavior of the e-beam is/was well understood, and the procedure is in hand to achieve the required e-beam parameters at the entrance to the solenoid (note that depending on the gun condition, optimizations may take from 0.5 to 2 days).

The items along the 2nd beam line were placed to satisfy the needs of the LACARA experiment [see Fig.A.2.2.] We installed (except the Compton Chamber [see item #8 in Fig.A.2.2]) and aligned all the items. Note that some items, such as quadrupoles, were supplied by ATF; for a detailed account of items manufactured and supplied by the LACARA group, see paragraph #2, and/or caption to Fig.A.2.2

BPM 1 (after e-beam leaves the first dipole & before the first quadrupole triplet)

BPM 4 (after the LACARA solenoid & before the second quadrupole triplet; the solenoid is off)

BPM 2 (after the first quadrupole triplet)

BPM 5 (after the second quadrupole triplet)

BPM 3 (before the LACARA solenoid)

BPM 6 (before the e-beam enters the second dipole)

Fig. A. 2.1 The electron beam spot at beam position monitors

the bending magnet for this spectrometer; however, the dipole performances must be thoroughly evaluated to prove that they are suitable for such a task. The screen and chamber design, the details of the imaging system, the configuration of shielding are to be developed. The design, manufacturing and installation are subject to two conditions: a) the acceleration is demonstrated with the present spectrometer, and b) sufficient budget.

Fig. A.3.1 The present spectrometer is formed by the 2nd dipole, the quadrupole triplet (pos. 36), which follows the 2nd dipole, several steering magnets (not shown) and a scintillating screen inside a chamber (pos. 17). The energy acceptance is limited to about 3-4 MeV only, which is sufficient for initial LACARA runs/tests to demonstrate the CO₂-beam – e-beam interaction.

Appendix A4

The components of the laser transport line were manufactured or purchased, and installed by the LACARA group. The main components are copper mirrors, a NaCl lens, and a vacuum-proof NaCl window.

Most of the mirrors (8 pieces) are plain copper mirrors (with diameters of up to 6 inch), and are to fold the CO₂ laser path so that the laser light clears all the obstacles, and is brought to a designated location. Two mirrors are convex. One of them together with the NaCl lens (5 inch in diameter, see Fig.A.4.1) forms a telescope that focuses the CO₂ beam at a desired distance with the required spot size ($w \sim 1.6\text{mm}$). The other is installed in the so-called laser-beam dump that picks up the CO₂-beam after it has interacted with the electron beam, and scatters the laser beam so that there are no back-reflections to the CO₂ laser-source.

The interaction between the electron beam and the CO₂ laser (with energy $\sim 8\text{-}10\text{J}$, and the pulse length $\sim 5\text{-}10\text{ psec}$) happens in vacuum, but the CO₂ laser is delivered from its source via a normal air-filled conduit, so a vacuum window is required [see Fig. A.4.2]. It has the diameter of 4.5 inch, and is chosen to have the laser fluence at the window below the damage threshold.

Fig.A.4.1. NaCl lens on a 4-degree-of-freedom positioning stage that slides along a rail to control focusing (the secondary alignment HeNe laser can be seen on the lens surface)

Fig. A.4.2. NaCl window (the secondary alignment HeNe laser can be seen on the window surface)

All mirrors are in mounts, which allow precise CO₂ laser-beam positioning. Since most of the mirrors are heavy, their mounts, normally commercially available, were retrofitted to provide stability. Two of mounts are vacuum-compatible, and equipped with piezomotors [see e.g. Fig A.4.3] that provide the step-size from 20 to 30 nm, which may result in a very fine accuracy ($\sim 5 \mu\text{m}$) of laser positioning at the focal plain ($\sim 6.5 \text{ m}$ away from the last mirror). In actuality, the positioning is limited by the overall resolution of the imaging system built on the basis of a pyro-viewer, and presently may not be better than $\sim 170 \mu\text{m}$; it however is sufficient for experimental needs.

Fig.A.4.3 A mirror inside a vacuum-compatible mount that is equipped with piezomotors

Fig. A.4.4 The pyro-viewer is open, and the bright spot in the middle of the TV-screen is an image of the CO₂ beam

In a series of tests, the CO₂ laser-beam emerging after the laser transport line was folded and directed toward a pyro-viewer [see e.g. Fig. A.4.4]. It was demonstrated that the laser beam was focused at the point corresponding to the magnet center. The CO₂ beam profile was mapped along the Z-axis (the direction of propagation), see e.g. Fig.A.4.6. There was a good approximation in the X-direction of the measured profile by

a Gaussian beam with the waist ~ 1.8 mm at the focal plain [see Fig.A.4.7]. Any approximation by a Gaussian beam in the Y-direction was somewhat questionable. However, an additional investigation using a 13mm-tall aperture, and a 23mm-tall aperture showed that at the focal plain the vertical waist was ~ 1.4 mm.

Fig.A.4.5 CO₂-laser image (at the focal plain) after it has been processed by the frame-grabber

Fig.A.4.6 Example of the CO₂-laser beam's transversal distribution along the horizontal axis, after its image has been processed by the frame-grabber (see also Fig.A.4.5)

Fig. A.4.7 The CO₂ laser beam horizontal waist (mm) vs. distance (m). Note that the measured profile (red dots) can be approximated by a Gaussian beam (blue curve) with the waist ≈ 1.78 mm at the focal plain; the point "0" corresponds to the "would-be" center of the magnet (in this particular case the CO₂ beam was focused by -15mm before the magnet center)

The test results demonstrated that the laser transport line delivers the CO₂ beam as planned, namely a) the power transmission is not limited by apertures; b) the beam can be focused in the middle of the solenoid; c) the waist size at the focal plain is close to the planned 1.6 mm (the difference in horizontal and vertical sizes/waists is caused not by the laser transport line, but by the fact that the CO₂ beam is different when it emerges from the CO₂ source; however, the difference is acceptable for the experimental needs).

The table below presents the major components of the laser transport system

1	Copper mirrors	There are about 13 mirrors with different diameters ranging from 1.5 to 6 inch. Seven (7) mirrors are used to deliver the CO ₂ beam to the NaCl window, and two more in-vacuum mirrors are used to direct the laser beam along the beam-line. One mirror is used as a part of the so-called beam dump to prevent back-scattering. The other mirrors serve to provide auxiliary functions, such as the beam-imaging. Most of the mirrors are plain.
2	NaCl lens	One (1) lens with the diameter of 5 inch is used to focus the CO ₂ beam (it functions in pair with one of the copper (defocusing) mirrors, which is convex)
3	NaCl window	One (1) window is used. It has the diameter 4.5 inch, and is installed inside of a holder which provides vacuum-proof sealing
4	Breadboards	There is one large breadboard (48 X 48 inch) which accommodates lots of mirrors, as well as an optical rail which supports the lens. It also holds some of the alignment irises [see Appendix 5]. There are also several small breadboards which are used to support the items installed around the beam-line.
5	Optical rails	There are two (2) optical rails, one of which is used to support the defocusing convex mirror, and the other is used to support the lens – the components which form the telescope and need to have their positions adjusted relative to each other.
6	Mounts	Each mirror [see above] has a mount that allows two-degree angular adjustment. Two of the mounts are vacuum-compatible and are equipped with picomotors.
7	Kinematic stages	There are 11 kinematic stages equipped with micrometers
8	Bases/ magnetic bases	There are about between 5 and 10 bases of different kind
9	Picomotors	There are 4 picomotors (with a single controller [see Appendix 6]) that are to provide a fine accuracy of laser beam positioning
10	Irides	Irides are rated as a part of the alignment hardware [see Appendix 5]
11	Vacuum cubes, chambers and tubing and bellows	There are two vacuum cubes which accommodate two in-vacuum mirrors, the mirrors' mounts and picomotors. There are several other vacuum chambers, such as 3,4 or 5-way crosses which are used to attach vacuum gages [see Appendix 6], vacuum pumps [see Appendix 7], or feedthroughs. The vacuum tubing/bellows has total length of about 6.5 m.
12	Adjustable/ fixed support	There are about 10 different structures which function as fixed or adjustable supports, e.g. for the vacuum cubes [see above], vacuum tubing, etc

Recently it has been found that due to the particular design of the ATF CO₂ laser system, the optical energy measurement is available only when the CO₂ laser is delivered to the 1st beam line (STELLA); consequently, a need has arisen for the LACARA group to install an energy measurement setup to handle the energy measurements for the CO₂ laser when it is delivered to the 2nd beam line (LACARA). It is expected to have the

energy measurement system available only in a few months from now, and thus, we must conduct several runs in the near future without the CO₂ pulse energy measurements. As for the possible options, we are considering either to use a system similar to that used by the STELLA experiment, or to employ a strategically positioned (and properly insulated from external disturbances) thermocouple (a case study will be required to prove the feasibility of this technique).

Appendix 5

During the series of tests, it was found that the magnet support table [see Fig. A.5.1] under its full load had poor performances when the magnet pitch or magnet elevation were changed. In particular the pitch backlash was not repeatable ($\pm 40\%$ of discrepancy), which was caused by the spring loaded screw tips (in the table's suspension mechanism) acting against the spring force exercised by the bellows at either end of the solenoid, when the solenoid stayed connected to the beam line. To eliminate this problem each solenoid flange is presently equipped with two precision micrometers to monitor constantly the vertical as well as horizontal flange shifts. Together with (previously used) fine-step motors, this arrangement demonstrates now a sufficient accuracy.

Normally to align items such as quadrupoles, beam profile monitors and other chambers, it is sufficient to use one alignment laser (a HeNe laser with the red light, with several attenuators to control intensity, and several mirrors to direct the light as required). This *forward* alignment laser permits to align the items sequentially in the space between the 1st and 2nd dipoles, starting from the 1st dipole and going downstream [see e.g. Fig.A.2.2], and thus, complete Electron transport line. However, the Laser transport line, which was installed after the elements of Electron transport line had been aligned, was installed sequentially starting at the 1st dipole and then going upstream and up, etc. Such an installation required *backward* alignment laser together with a set of attenuators and mirrors [see e.g. Fig.A.2.2, pos. 36-37]. Now, both

forward and *backward* alignment laser setups are in constant use.

Fig. A.5.1 Magnet support table with the solenoid on the top of it

Every time an alignment laser is used, the beam line axis is given by and verified at the two beam-line irises (with one before the 1st dipole, and the second iris after the 2nd dipole). Because of the need to install additional items in the spaces occupied by irises, we had to either move or reinstall them on kinematic stages. During the re-installation of the downstream iris, the third auxiliary iris was used; as for the upstream iris, it was simply replaced by a new one on a kinematic stage. The irises in their new positions and on their new supports give the same beam line axis with accuracy of better than $\pm 10\text{ }\mu\text{m}$ for the downstream iris and of better than $\pm 5\text{ }\mu\text{m}$ for the upstream iris.

During the alignment every item is normally equipped with a target whose center is somehow related to the center of the item. To align the quadrupoles, we used a round photosensitive screen installed in holders with each holder made specifically to fit each quadrupole. We collected the data for two holder's positions opposite to each other within 5° , so as to exclude a measurement error caused by the non-concentricity of the holder and/or the photosensitive screen. The targets for vacuum chambers (e.g. for BPM crosses) typically were/are made out of rigid plastic or paper, round and with concentricity ($\pm 250\text{ }\mu\text{m}$) to insure 0.5 mm accuracy when installed in the chamber flanges and aligned with the alignment laser.

To monitor the (alignment) laser beam position on the in-vacuum mirrors, we installed a periscope-like setup in front of the NaCl window [see e.g. Appendix 4]. It includes a mirror (on a kinematic stage), and an optical 10X telescope (in a removable mount). The setup allows imaging the mirrors (and their mounts) situated about 4-5 m away from the window, and to identify the laser spot position without need for viewports.

The alignment unit in front of the entrance dipole is installed in place of the upstream alignment iris, when the laser transport line is connected to the beam-line. This unit comprises an in-vacuum target and numerous auxiliary parts to do the following: 1) align the beam-line with the accuracy $\pm 5\text{--}8\text{ }\mu\text{m}$; 2) serve to align the NaCl lens with the forward alignment laser (when it goes through the NaCl window); 3) serve to tune the position of the secondary alignment laser that comes from the terawatt CO₂ room (where the CO₂ source is located) and which is pre-aligned with the CO₂ laser beam itself; 4) serve to fine-tune the alignment of CO₂ beam; 5) provide an independent path to introduce the forward HeNe laser to the beam-line by-passing the NaCl window (thus other users may use the forward alignment laser independently of the setting of the LACARA laser transport line and will not overexpose the NaCl window that is normally capped to the atmospheric water vapor).

There are two irises on the breadboard [see also Appendix 4 above] to help insure that the alignment HeNe laser and CO₂ pulse move along the same path. Once the electron transport line and laser transport line are connected to each other, these irises will serve also to aid in establishing the beam line axis when required. The irises have a composite structure: each iris is a collection of two units, with the first unit being an iris that has a large OD to transmit the CO₂ light when opened, and the second unit being an iris with zero-aperture so that it can be aligned precisely with the alignment laser light (having a small transverse dimension). The first unit is installed permanently, and its position can be corrected by precision micrometers, if necessary. The second unit is attached to the first by a magnetic stage. Precise machining insures that the centers of both units are at the same point in space. Also, a set of several irises (and auxiliary optics to fold the laser beam path) is installed after the alignment unit (this setup also uses an IR

camera provided by ATF). The setup serves to fine-tune the alignment between the beam-line and the CO₂ laser beam. The setup was successfully tested, and soon (by Jan/15/08) will be permanently integrated into the laser transport line.

We need to redesign and install the monitor after the solenoid, equipping it with a composite screen to monitor either the electron beam or the CO₂-laser pulse; this unit will serve to check and finalize (if needed) the alignment between the beam-line and the CO₂ laser beam, as well as to divert a small portion of the CO₂ energy to obtain the synchronization signal. The planned completion date is the middle of January 2008.

Appendix 6

The control hardware and software purchased, installed or developed by the LACARA group is listed in the table below along with the description of main functions/features.

Control hardware		
1.1	VP-9000	Motor controller that drives up to 4 step-motors, and can be controlled either locally (via a panel), or remotely (by a computer)
1.2	LSCI-218	Temperature monitor that can monitor the temperature as low as 4K at up to 8 control points and can be controlled either locally (via a panel), or remotely (by a computer)
1.3	8753 picomotor driver	Picomotor controller with its auxiliary hardware to drive up to 4 picomotors. Note: it is controlled remotely via a computer by DCN utility (supplied by the manufacturer)
1.4	USB range extender with USB-RS232 adapters	Connects a remote USB 2.0 hub to the control computer over the length of 35 m; the USB hub is equipped with the RS232 adapters to communicate with external devices such as CS-4 [see Appendix 7] or VP-9000 [see above], etc
1.5	Vacuum gauges and flow-meters	* Presently there are 3 vacuum gauges, one to monitor the vacuum in the solenoid tank, and two (including MKS I-MAG) to monitor the vacuum in the Laser transport line; * There is one flow meter, MA10312, to monitor the water-flow rate through the helium compressor CSW-71
1.6	Synchronization unit	The unit is to check the synchronization between the electron beam and the CO ₂ laser beam. It functions together with the strip-line [see Fig. A.2.2 in Appendix 2]. The unit is based on an in-vacuum mirror attached to the stem of the after-solenoid BPM, and a CO ₂ –sensitive photodiode. (Note: to correct the synchronization, the available ATF hardware will be used)
1.7	Other control devices	The LACARA group purchased several devices with extended options to insure that these devices have built-in controls for reliable operation. Those options were, e.g.: a) Quench and power failure protection for the power supply CS-4 [see Appendix 7] b) Overheating protection for the helium compressor CSW-71 c) Precision temperature control for the water chiller UC-080 d) Built-in current protection for all the vacuum controllers
Control software		
2.1	Shell(VP-9000)_1	* Communicates with the motor controller VP-9000; configures the motor controller; reads data, etc. (LabView application)
2.2	Shell(LSCI-218)_1	* Communicates with the temperature monitor LSCI-218; reads data. Note: to configure the monitor one uses LSCI-218 TempMon (all are LabView applications)
2.3	Shell(CS-4)_1	* Communicates with the bipolar power supply CS-4; reads data. Note: to configure the supply one uses CS-4_MPS (all are LabView application)

2.4	Shell(ATF.HAL)_2	<ul style="list-style-type: none"> * Communicates with the ATF master computer (HAL); * Set/reads the currents in all dipoles and quadrupoles; * Operates and reads beam profile monitors; * Has three AI-algorithms to assist an operator in a speedy collection of data e.g. as required to align the solenoid * LabView application
2.5	CaptureDataType1_2_3 & CaptureDataType1and2	<ul style="list-style-type: none"> * Both communicate with 2.1-2.4 to collect and preprocess data * the first utility prepares data files to be processed by MCDReadType2 [see below] to align the solenoid * the second one is for the record keeping of various data streams * both are LabView applications
2.6	MCDReadType2	<ul style="list-style-type: none"> * Processes the data prepared by CaptureDataType1_2_3 to perform the solenoid alignment later with Shell(VP-9000)_1 * Mathcad based application

Appendix A7

The auxiliary hardware installed by the LACARA group is listed in the table below along with the description of main functions/features of every component/item.

1	CS-4, bipolar DC power supply	<ul style="list-style-type: none"> * Provides up to 100 Amps of current of either DC polarity with adjustable rates for energizing * Has a quench protection * Has external power failure protection * Has data ports for connection to a computer
2	CSW-71, helium compressor unit	<ul style="list-style-type: none"> * Cools the magnet cryocooler head, SRDK-408 * Uses compressed helium (407 liters at normal pressure) as a coolant * Requires up to 8.3 kW of external power * Has compact dimensions: 450 mm x 500 mm x 684 mm
3	UC-080, water chiller	<ul style="list-style-type: none"> * Cools CSW-71 (see above) * Has 11 kW cooling capacity at 49 psi, with max. flow rate 22 l/min.
4	High-bay to experimental hall water line(s)	<ul style="list-style-type: none"> * Connects UC-080 and CSW-71 (over 57 m distance) * Filters the water and monitors/regulates its flow rate
5	Ion-pumps	<ul style="list-style-type: none"> * Equipped with controllers (all purchased by the LACARA group) * Include one 8 l/sec compact pump, one 20 l/sec pump, and one 140 l/sec pump * All pump are on custom made support to fit to the available limited space
6	Optical breadboard enclosure	<ul style="list-style-type: none"> * Protects the optical setup from dust and air flows * Has all custom made panels to fit in a limited space
7	High load winch and rail for Laser	<ul style="list-style-type: none"> * To handle the mirror chambers of the Laser transport line

	transport line	
8	Heating for Laser transport line	<ul style="list-style-type: none"> * To bake the Laser transport line * Has strategically located temperature monitors to monitor the baking process