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## **Status Report For The Hypervelocity Free-Flight Aerodynamic Facility**

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### **Abstract**

The Hypervelocity Free-Flight Aerodynamic Facility, located at Ames Research Center, is NASA's only aeroballistic facility. During 1997, its model imaging and time history recording systems were the focus of a major refurbishment effort. Specifically the model detection, spark gap (light source); Kerr cell (high speed shuttering); and interval timer sub-systems were inspected, repaired, modified or replaced as required. These refurbishment efforts have fully restored the HFFAF's capabilities to a much better condition, comparable to what it was 15 years ago. Details of this refurbishment effort along with a brief discussion of future upgrade plans are presented.

### **Introduction**

During 1997, Ames Research Center (ARC) embarked upon a project to refurbish its Hypervelocity Free-Flight Aerodynamic Facility (HFFAF), NASA's only aeroballistic range. The purpose of this paper is to document this refurbishment effort. There were many motivating factors which prompted this effort, but perhaps the most influential are as follows. During the mid-1990's NASA embarked upon a "Zero Base Review Project," in response to decreasing foreseeable annual budgets. The goal of the review was to identify and consolidate/eliminate areas of redundancy and duplicative effort within the Agency, thereby allowing NASA to utilize its funding more efficiently. During the review it was observed that four NASA centers (ARC, JSC, MSFC and WSTF) were all performing some sort of hypervelocity impact testing. NASA management decided that it would consolidate all future impact testing activities at the White Sands Test Facility (WSTF). As a result, at the conclusion of 1996, ARC's impact testing activities came to an end. During this same period, NASA redefined its missions and goals as they pertain to space exploration. Specifically, NASA decided to focus much of its future space exploration effort on small, relatively inexpensive, unmanned planetary probes. Many of the envisioned probes are intended to enter a planet's atmosphere and possibly land a payload on its surface (a recent example is the Mars Pathfinder). One parameter which is essential to the success of such a probe is "dynamic stability" during atmospheric entry. In order to design a probe that is dynamically stable under such hypervelocity conditions, there are basically three options: (1) Select a design which differs minimally from designs that have proven successful in the past; (2) Design the probe using computational fluid dynamics (CFD); or (3) Design the probe using aeroballistic data. Because of the obvious limitations with Option 1, and

the current evolutionary state of suitable CFD codes, Option 3 is surprisingly still the most popular and accurate method to obtain this crucial information. Since ARC's HFFAF is the only aeroballistic facility within NASA, it stands to reason there is great potential for significant aeroballistic testing in the near future. Upon realizing this, ARC management also recognized that the reliability of the HFFAF imaging and time recording systems had degraded significantly over the last 33 years, and that a major overhaul was needed.

### **Facility Description/History**

The Hypervelocity Free-Flight Aerodynamic Facility is one of two functioning ballistics facilities located within the HFF complex. Originally constructed in 1964, the HFFAF consists of: a 2-stage light-gas gun; a sabot separation tank; a test section with sixteen photo stations, each with a pair of orthogonal imaging systems; and a combustion-driven shock tube (see figure 1). Actually the facility has an arsenal of four guns to choose from: a 0.28cal (7.1mm); a 0.50cal (12.7mm); a 1.00cal (25.4mm); or a 1.50cal (38.1mm) gun. The purpose of the facility is to examine (via shadowgraphic means) the aerodynamic characteristics and flow-field structural details of free-flying aeroballistic models.<sup>(1)</sup> For very high Mach number (i.e.  $M > 25$ ) simulation, models can be launched into a counter flowing gas stream generated by the shock tube. This "counterflow" mode of testing tends to be both technically demanding and expensive. Consequently this type of testing hasn't been performed since 1972.

During the 30 plus year history of the HFFAF, nearly all of NASA's space probes which have entered an atmosphere (i.e. Gemini, Mercury, Apollo, Shuttle, Viking, Pioneer Venus, and Galileo) have received some level of aeroballistic testing in this versatile facility (see figure 2). In addition to aeroballistic testing, the HFFAF has been configured as a shock-tube driven wind tunnel (shock tunnel). For example, from 1989 through 1994 the facility was operated strictly as a shock tunnel to perform scramjet propulsion studies in support of the National Aerospace Plane (NASP) program. During 1995 and 1996 the facility was again reconfigured, this time for hypervelocity impact testing in support of the International Space Station (ISS) Program. In conjunction with Johnson Space Center (JSC), various ISS debris shielding configurations were impacted with large diameter (i.e. 10 to 20 mm) particles at 3 to 7 km/s to help ascertain ballistic limits. By the end of 1996 the reliability of the shadowgraph imaging and timing functions had degraded to the point that the facility could no longer support a true aeroballistic program. Hence the refurbishment effort was begun to restore this unique and versatile NASA capability.

### **Model Detection Sub-System**

The first group of components to be refurbished was the model detecting sub-system. At each of the 16 photo-stations in the HFFAF test section there is a halogen light source, a variable voltage power supply, two mirrors, a photomultiplier tube/pre-amp signal conditioning unit, and an amplifier unit (see figure 3). The halogen lamp produces a beam which is directed towards the lower mirror. The mirror disperses the light into a planar sheet spanning the test section, and directs it towards the upper mirror.

The upper mirror re-focuses the light sheet onto the photomultiplier tube/pre-amp unit. The pre-amp supplies a signal to the amplifier unit. Details of the electronic design of the pre-amp and amplifier units are beyond the scope of this paper, but suffice it to say that the system is configured such that an appreciable decrease (or increase) in light intensity will produce an output (trigger) signal from the amplifier unit. Thus, if a model passes through the light sheet, a trigger signal is produced.

Soon after this project began, it became affectionately referred to as "Pandora's Box." For example, when the detection sub-system was initially examined, several of the halogen lamps were found to be burned out and in need of replacement. It was soon discovered, however, that these (100W) bulbs had been discontinued several years earlier, and replacements were no longer available. Thus, an alternative needed to be identified and obtained. Unfortunately, all of the currently available bulbs with comparable power ratings were geometrically different. This, of course, required a design modification to all of the lamp fixtures. While re-working the lamp fixtures, it was discovered that much of the wiring had degraded (cracked or burned insulation), or was no longer up to code (ungrounded, two-wire cables). Hence, all of the wiring had to be replaced. Similarly, many of the power supply units (variacs) had degraded and needed to be replaced. The mirrors were examined and many were found to be in terrible shape. The reflective coatings were badly scratched and oxidized, which adversely reduced reflectivity. Apparently thirty years of dust accumulation and removal (via compressed air or camel-hair brush) had taken its toll. Thus, all of the mirrors were recoated and polished. The next component to be examined was the photomultiplier tube at each station. The performance of several was found to have degraded significantly, and so they were in need of replacement. However, as was the case with the lamps, it was found that this particular tube had been discontinued years earlier. After months of searching, a company in the UK was found that still had a dozen of these tubes in stock. All of them were purchased. Fortunately, only two of the pre-amp units were found to be functioning improperly. These were replaced with spare units.

The final component in the model detection subsystem is the photo-beam amplifier. As alluded to previously, this unit provides a trigger pulse to the orthogonal spark gaps (lamps) in response to the signal it receives from the pre-amp (due to model arrival). This unit has several stages of amplification, along with attenuation and sensitivity adjustments by which the input signal from the pre-amp is conditioned. There is also a gating function which provides a window of opportunity wherein the unit will accept an input signal and send out the appropriate trigger signal(s). Any input signal received before, or after, this window is ignored. All of the electron tubes, pots, capacitors, connectors, etc. were tested, inspected, cleaned, and replaced as necessary.

### **Spark Gap (Light Source) Sub-System**

For this sub-system the primary components are spark gaps and power supplies. The spark gaps are the light sources for the imaging systems. The spark gaps also provide the trigger pulses for the high speed shuttering sub-system. Each photo station has one power supply and two spark gaps to provide a horizontal and vertical (orthogonal) views. The way a spark gap functions is as follows. The storage capacitors are typically charged to a value between 6 and 7 kilovolts. When a trigger pulse is

received from the photo-beam amplifier, a small arc is established between the trigger electrode and the back electrode (cathode). This increases the free electron population in the gap and allows the storage capacitors to discharge through the rear electrode (cathode) across the gap to the front electrode (anode), see figure 4. The resulting arc persists for 1 to 2  $\mu$ sec. The discharge of the storage capacitors also produces a trigger pulse which is sent to the Kerr cell shutter (this sub-system will be discussed in the next section).

For a given charging voltage the gap spacing affects both the timing of the spark and the intensity. If the gap spacing is too small the unit will tend to break down prematurely, producing a weak, inconsistent spark (the capacitors are not allowed to charge fully). If the gap is too large it will tend to take longer for the arc to establish, if at all. Once again this produces a weak spark at best. Thus, there is an optimum range which produces a consistent, strong spark. Finding this optimum range for a set of spark gaps (at a given photo station) is typically done with the aide of diode detectors and an oscilloscope. The sparks are fired and the gaps adjusted until a consistent stable setting is found for both units. Once synchronized, a pair of sparks typically fire within a few hundred nanoseconds of each other.

Each photo station has one power supply which provides the high voltage to both the horizontal and vertical spark gaps. This power supply also provides power for both the photo-beam amplifier and pre-amp. For the spark gaps and power supplies, all of the electron tubes, pots, capacitors, electrodes, connectors, etc. were inspected, tested, cleaned, and replaced as necessary. In particular, for the spark units, the storage capacitors were high-tension and bridge tested to ensure that their high voltage and energy storage capacities were within specifications.

### **Light Path Sub-System**

The primary components for this sub-system are windows and mirrors. The light path for the HFFAF is arranged in a classic off-axis configuration, or "Z" formation (see figure 3). In this configuration a Spark gap light source shines on a parabolic mirror, which collimates and directs a beam through the windows/test section onto the other parabolic mirror. The second mirror re-focuses the beam (with a shutter located at the focal point) and projects the shadowgraph image upon sheet film positioned in a film box. There are two mirrors and two windows for each view (horizontal and vertical) at each photo-station. All of the windows were inspected. Those that were damaged (scratched, pitted, etc.) were either re-polished or replaced. Similarly, all of the mirrors were inspected. Although the mirrors are routinely covered when not in use, the lower mirrors (vertical view) were found to have degraded severely after 33 years of use. Hence all of the lower mirrors were recoated and polished.

### **High Speed Shuttering (Kerr Cell) Sub-System**

The HFFAF utilizes Kerr cells as the basis of its high speed (40 ns) shuttering sub-system. Without going into excessive detail, a Kerr cell is an electro-optical shutter that uses a high-voltage gradient to induce a polarizing effect within a glass module containing a special "Kerr" fluid (for this application, the fluid is benzonitrile).<sup>(2)</sup> The glass module is positioned between two rectangular polarizers (see figure 5). The polarizers are

oriented so that when the gradient is applied, light can pass through the cell (the shutter is open). Conversely, when there is no gradient, light cannot pass through the cell (the shutter is closed).

The HFFAF high speed shuttering sub-system consists of four primary components: a high voltage (35 kilovolt) power supply; pulse generators; pulse forming networks; and the optical (Kerr) cells. The power supply drives all of the individual pulse generators. Each pulse generator contains a 100M $\Omega$  charging resistor, 4 capacitors (75 pf each), and a high voltage thyatron (high speed switch). During operation the power supply charges the capacitors to a value between 24 and 26 kilovolts. When a trigger signal is received from the spark gap (light source), the thyatron switch closes and the capacitors discharge. The pulse forming network controls the rate of discharge and the voltage gradient within the Kerr cell. The network also produces a low voltage (60 volts) output signal which can be used to stop an interval timer.

All of the charging resistors and capacitors were tested and replaced as required. The thyatron tubes were high tension tested. Many were found to be "leaky." That is, they drew excessive current while the capacitors were being charged, and reduced the final charge value. This is significant in that the final charge value determines the amount of light transmission through the Kerr cell. When the capacitors are properly charged to 24 to 26 kilovolts, the Kerr cells transmit roughly 50% of the incident light. At 20 kilovolts the transmission drops to 30%. All poor performing tubes were replaced. Interestingly, these thyatron tubes are still commercially available. However, their geometry has changed over the years. As a result, installing new tubes requires some modification. The fluid levels were checked and replenished as necessary for all of the Kerr cell modules. Lastly, the output signals from the pulse forming networks were examined by using a digital oscilloscope. The units with the smoothest, lowest noise signals were selected for the horizontal stations, which trigger the interval timers.

### Interval Timers

Interval timers are used to record the occurrence of various events of interest during an aeroballistic test. Typically, all of the timers receive a common "start" pulse at gun fire. "Stop" pulses are received from sensors at various points along the light-gas gun pump tube upon piston arrival. These times are used to calculate piston velocities. Similarly, "stop" pulses are received from the horizontal photo-station Kerr cell pulse forming networks upon model arrival. These times are used to calculate model velocities at various points along its trajectory.

The original 33 year old timers provided many years of reliable service. However, by 1996 they were becoming significantly less reliable and were becoming increasingly more difficult to calibrate. This, in part, was due to the fact that the units contained many obsolete components (i.e. germanium transistors). Hewlett Packard, the manufacturer of these units, discontinued production many years earlier and no longer stocked replacement components for the units. During the last decade, virtually all of the HFFAF spare timers were cannibalized in order to keep a minimum number operational. By 1996 the supply of spare parts had been exhausted. Hence, the counters were all replaced with current technology units. These new units have an order of magnitude improvement in accuracy.

In order for the new units to interface properly with the existing equipment, the input signals had to be conditioned appropriately. All of the input signals were examined using a digital oscilloscope. Based on this, appropriate attenuation, triggering and sensitivity levels were selected to avoid erroneous triggering (i.e. due to noise) or equipment damage.

### Film

The film that was originally used in the HFFAF was Kodak Tri-X Ortho. This film is blue sensitive and red insensitive which is well suited for the imaging system. The spark gap radiative power peaks in the UV and blue end of the visible spectrum (2000 to 4000Å), and falls off dramatically towards the red (7000Å). The Kerr cells transmit well from 3400 to 7000 Å, and the windows transmit well over this range as well. As a result, the majority of the radiative energy the film is exposed to is in the 3400 to 5000 Å range. In early 1997 it was found that Kodak no longer made Tri-X Ortho film in the sheet size required for the HFFAF film holders. Neither did Fuji or any other major film manufacturer. Thus a compatible alternative had to be found. Ultimately, Kodak T-Max 400 was selected. This film is panchromatic, or sensitive to the entire visible spectrum (3800 to 7600Å).<sup>(3)</sup> However, with the proper developing technique it has proven to give adequate contrast and resolution.

One additional obstacle that had to be addressed in order to implement the use of the new film was background lighting. During a test, the HFFAF test section room is often illuminated with red light for brief periods of time. With the old red-insensitive film this was not a problem. With the new film, however, the film boxes had to be made more-or-less "light-tight" in order to prevent fogging of the film.

### Future Plans/Upgrades

The recent refurbishment efforts have restored the HFFAF's model imaging, and time history recording systems to a condition comparable to what they were 15 years ago. These efforts will keep the facility functioning reliably and accurately for years to come. Ultimately, however, the HFFAF will need to be modernized in order to remain a cost effective, state-of-the-art national facility. Preliminary studies on future upgrades have just begun. Some of the topics/questions include whether to continue using film or to switch to digital camera technology. If film is still the media of choice, is it preferable to use a laser/pocels cell arrangement or a spark gap/Kerr cell arrangement? If digital cameras are preferable, what would be the cost of a complete set of gated CCD cameras with enough resolution to provide detailed flowfield images? When might funding become available to perform such an upgrade, and where would the funding come from? Obviously this study is in its infancy and many factors (i.e. technical, economical, and political) will come to bear as the study progresses and these questions are answered.

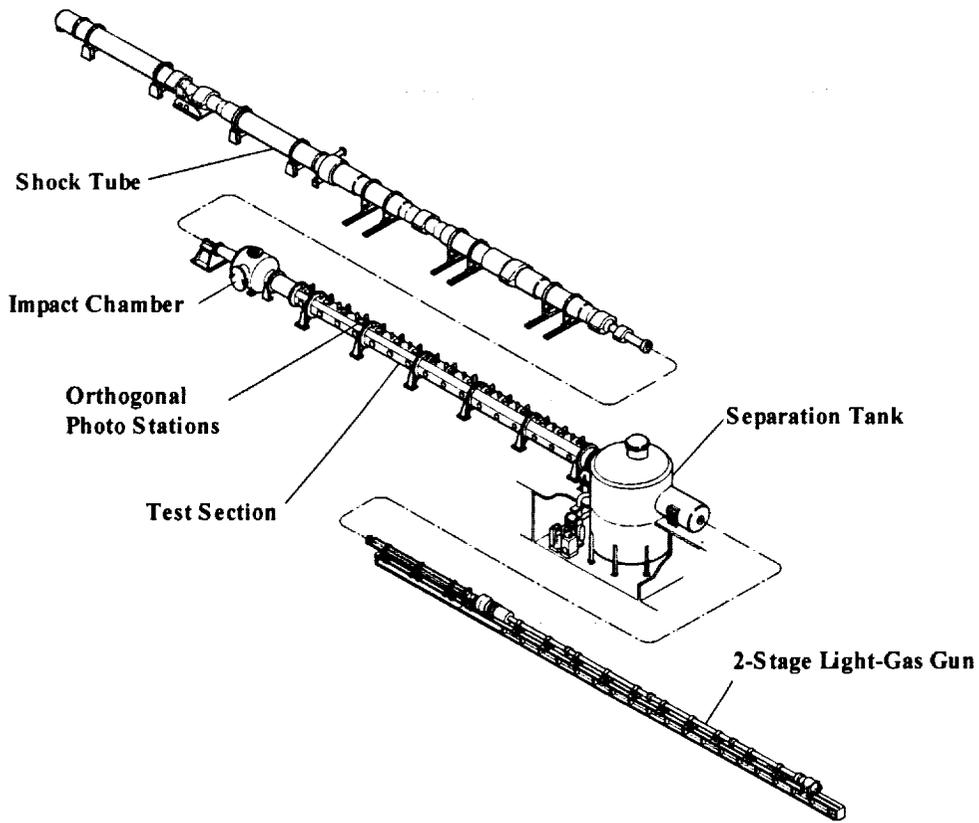
### Summary

In response to changes in the economic climate, and in anticipation of NASA's future space mission goals, the Hypervelocity Free-Flight Facility model imaging and time

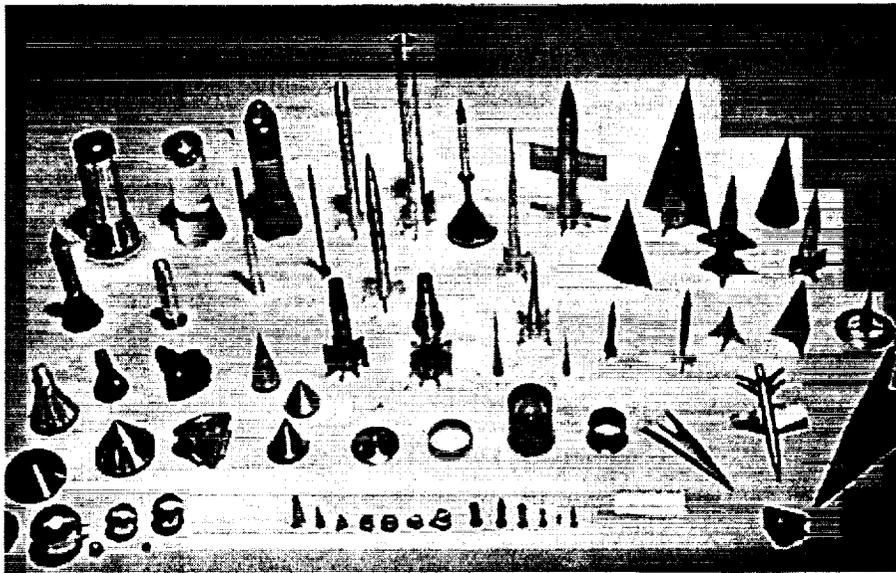
history recording systems were refurbished during 1997. Specifically the model detection, spark gap (light source); Kerr cell (high speed shuttering); and interval timer sub-systems were inspected, repaired and modified as required. Damaged windows were either polished or replaced, and mirrors were resurfaced. These refurbishment efforts have fully restored the HFFAF's capabilities to a much better condition, comparable to what it was 15 years ago. Eventually it is desirable to upgrade the imaging system to state-of-the-art (digital) technology. Upgrade feasibility studies are now underway.

### References

- 1) T.N. Canning, A. Seiff and C. S. James, *Ballistic Range Technology*, AGARDograph No. 138, 1970.
- 2) F. Kreith, and W. Z. Black, *Basic Heat Transfer*, 1st ed., Harper & Row, New York, 1980.
- 3) Kappa Scientific Corporation, *Electro Optics Catalogue*, 1964.



**Figure 1: The Hypervelocity Free-Flight Aerodynamic Facility.**



**Figure 2: A variety of aeroballistic models tested in the Hypervelocity Free-Flight Complex.**

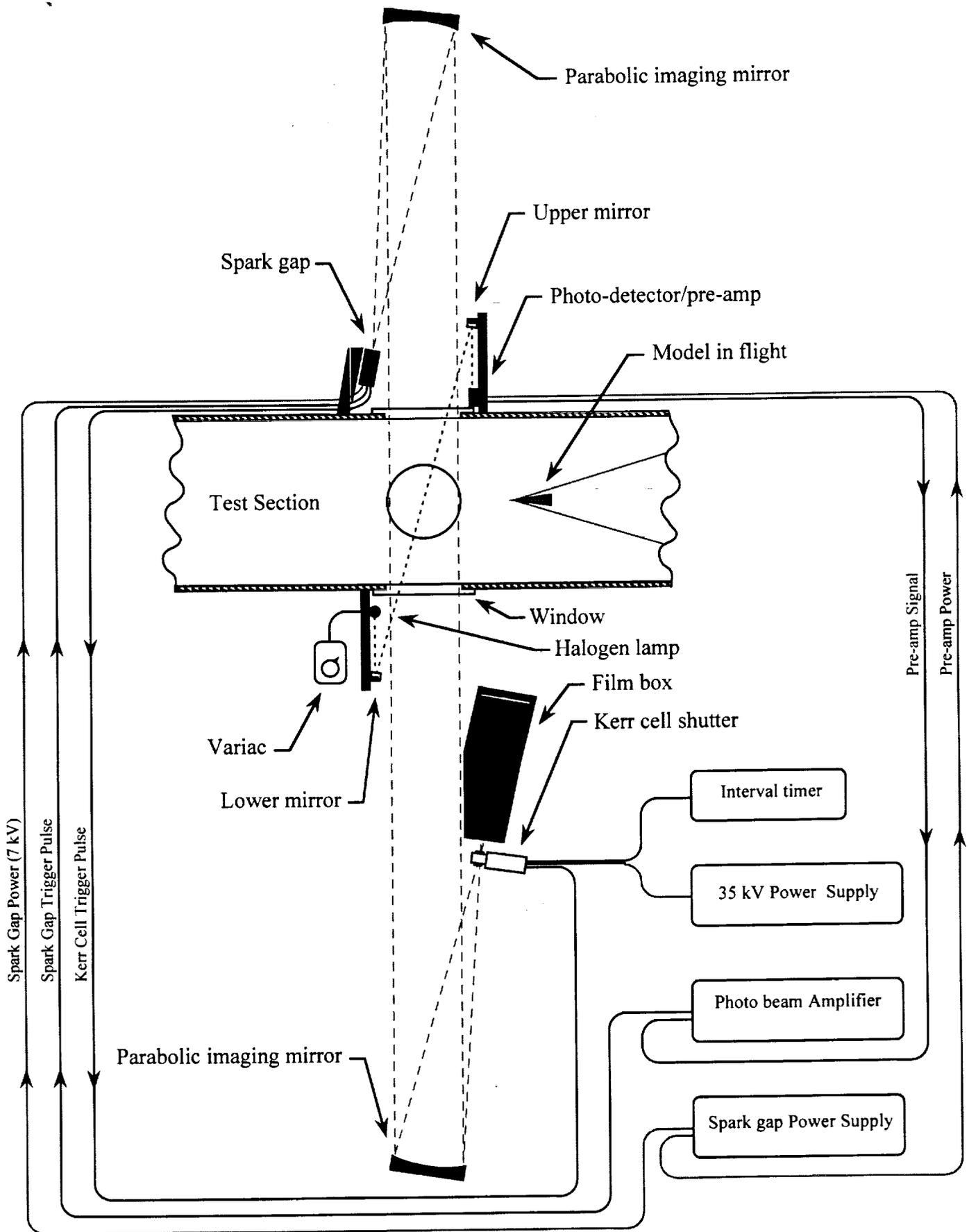
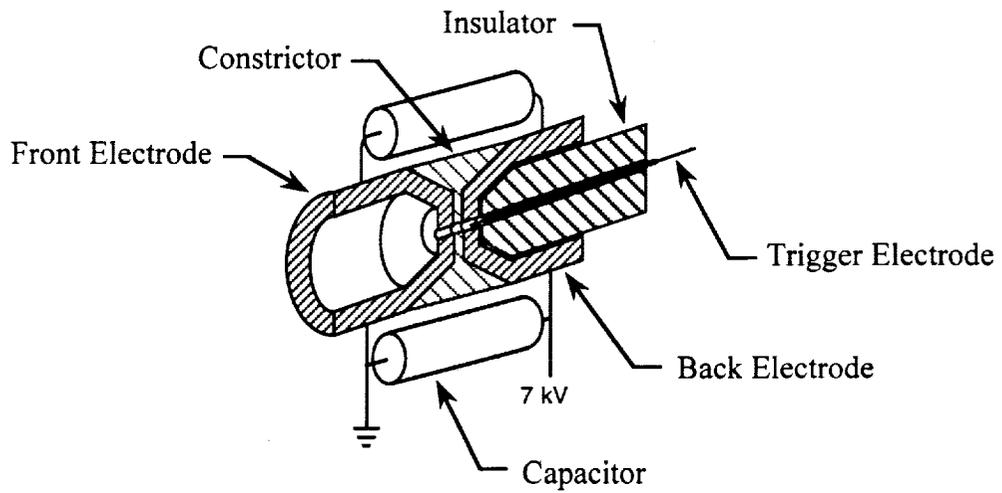
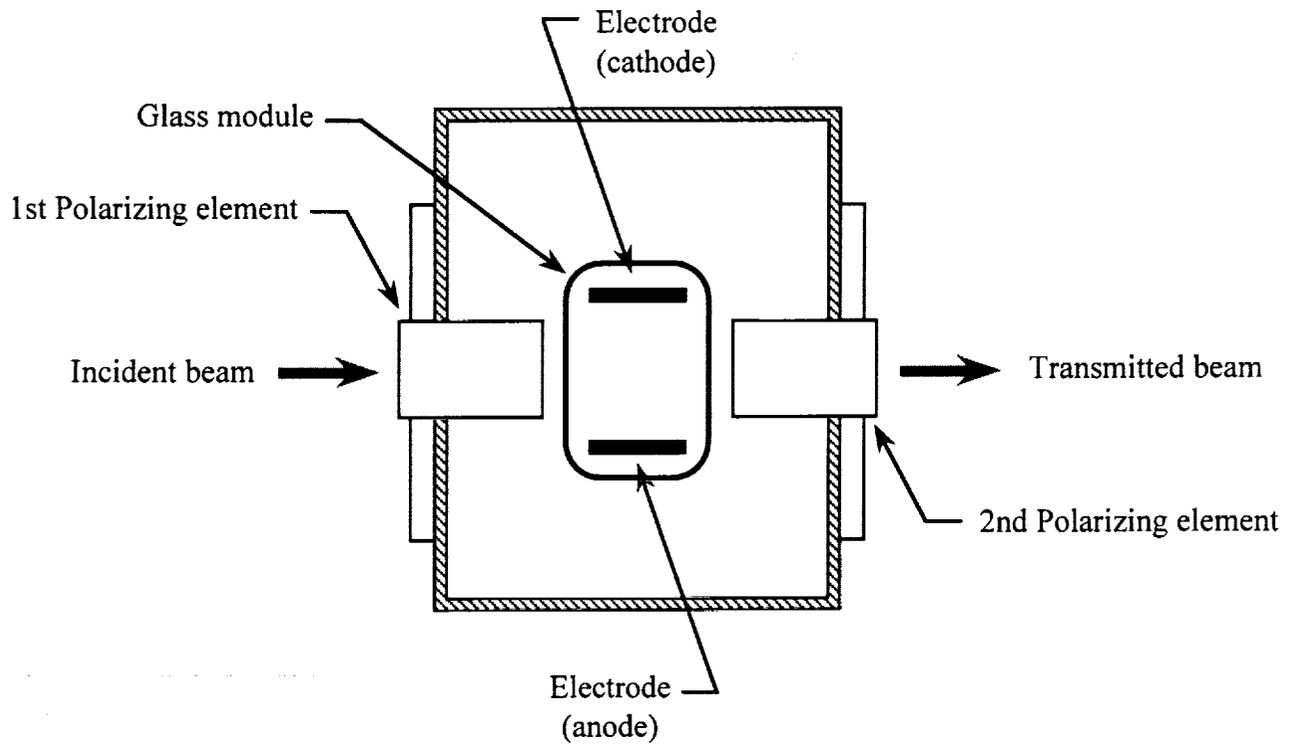


Figure 3: HFFAF Model Imaging System Layout



**Figure 4: Basic Spark Gap Electrode Configuration**



**Figure 5: Basic Kerr Cell**