The RHIC Hydrogen Jet Luminescence Monitor

PAC 07

Thomas Russo C-AD

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Introduction

- From the Web: Luminescence is the emission of light at temperatures below that required for incandescence. The production of light without heat.
- Light is produced when electrons in a substance are excited to higher levels, then fall (de-excited) emitting photons.
- There are many types of luminescence such as chemo-, bio-, electro-,photo etc.
- Each substance emits a unique spectra depending on level of excitation and resulting de-excitation.

Example of Electroluminescence

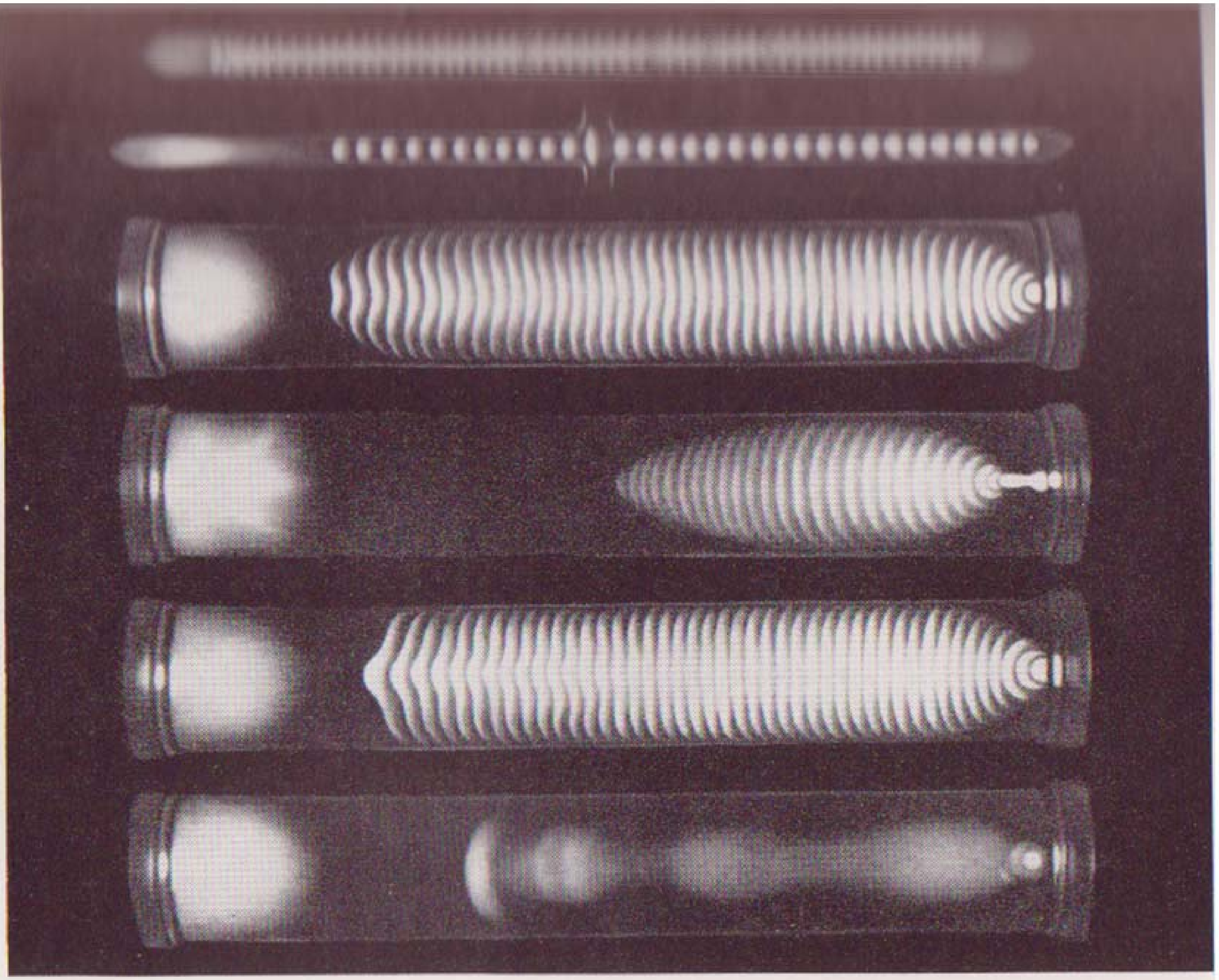
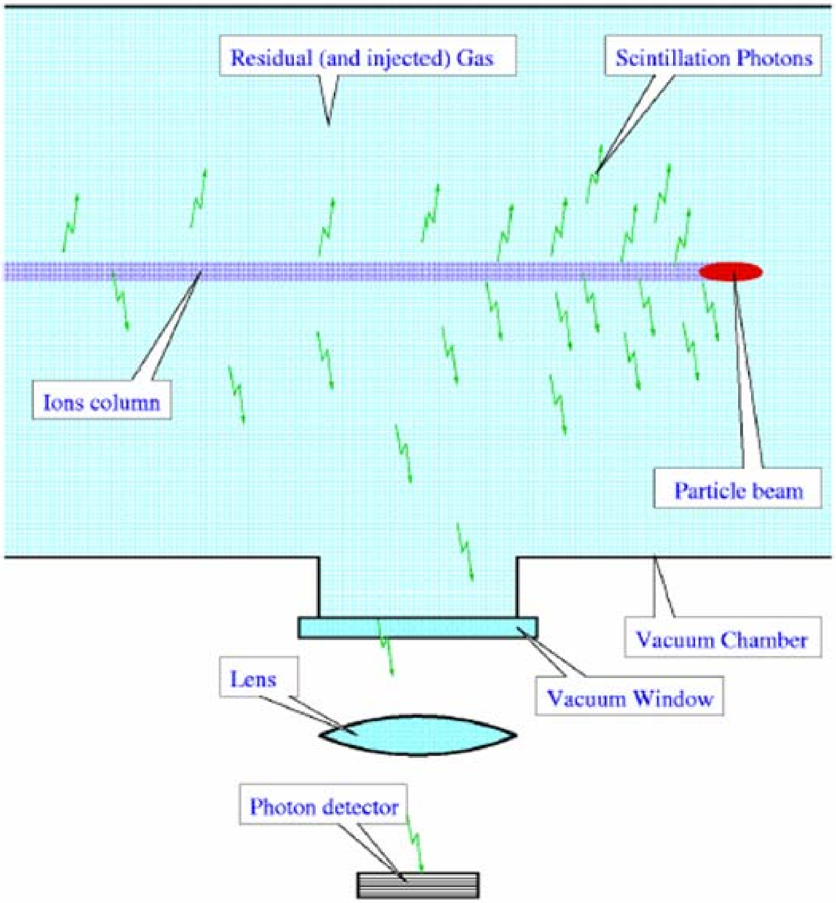


FIG. 27. Luminescent stratification in vacuum tubes. From W. De la Rue and H. Müller in the *Phil. Trans.* for 1883. These striations were described in 1711 by Edward Nairne, one of the first (1770) foreign members of the American Philosophical Society.

Gas Scintillation

Courtesy Mike Plum

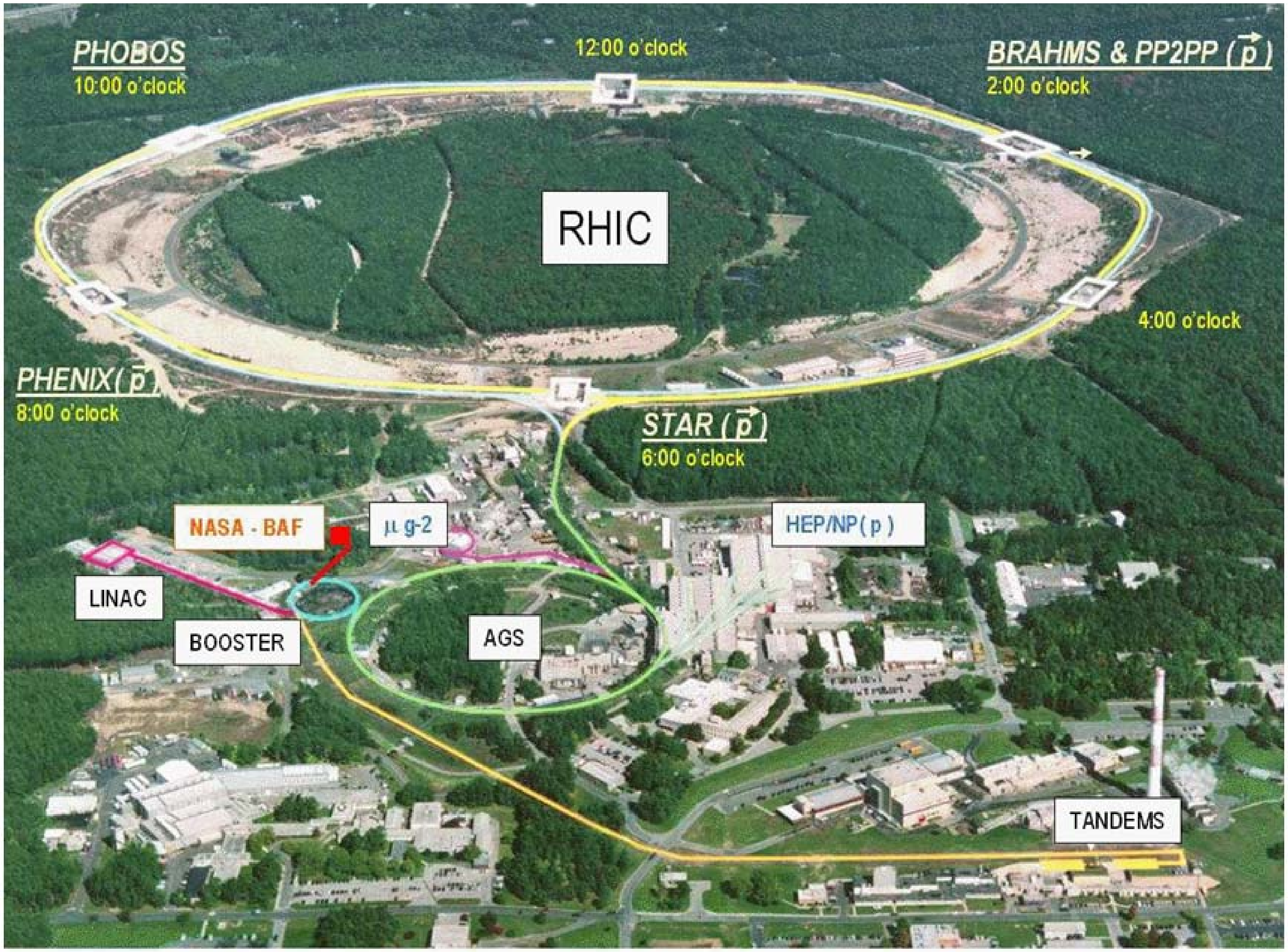


- **Gas molecules in the beam pipe, from either residual or injected gas, interact with the passing particle beam.**
- **Electrons are promoted to excited states.**
- **When the electrons fall to lower energy orbitals, photons are emitted.**
- **Photons are collected to measure the profile.**

Experiment

- Particle Beam – The Relativistic Heavy Ion Collider (RHIC) produces two counter rotating 100GeV polarized proton beams.
- Gas Source – A hydrogen gas jet polarimeter located in the 12 o'clock area of RHIC.
- Detector – The Balmer series for atomic hydrogen is well documented and image intensifiers used for astronomical purposes are readily available.
- In addition, we would try to observe light from other possible sources or "impurities" within the jet, such as oxygen, H_2, or water molecules. This would allow us to parasitically monitor the composition of the jet beam.
- The jet is only use during polarized proton operation. Heavy-ion beams would be subject to destruction caused by the higher pressure when the jet is in operation and by the production of electron clouds.
- Motivation – This measurement has never been made before…

RHIC Photo



PHOBOS
10:00 o'clock
12:00 o'clock
BRAHMS & PP2PP ($\vec{p}$)
2:00 o'clock
RHIC
4:00 o'clock
PHENIX($\vec{p}$)
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
NASA - BAF
µ g-2
HEP/NP (p)
LINAC
BOOSTER
AGS
TANDEMS

Parameters Page

Table 2. General Beam Parameters for the Collider

Element	Proton	Deuterium	Oxygen	Silicon	Copper	Iodine	Gold
Atomic Number Z	1	1	8	14	29	53	79
Mass Number A	1	2	16	28	63	127	197
Rest Energy (GeV/u)	0.93827	0.93781	0.93093	0.93046	0.92022	0.93058	0.93113
Injection:†							
Kinetic Energy (GeV/u)	28.3	13.7	13.7	13.7	12.6	11.3	10.8
Energy, ã	31.2	15.6	15.7	15.7	14.5	13.1	12.6
Norm. Emittance (ðmm·mrad)	20	10	10	10	10	10	10
Bunch Area (eV·s/u)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Bunch Length (m)	2.58	4.1	4.1	4.1	4.6	5.32	5.62
Energy Spread ($\times 10^{-3}$)	±1.26	±1.63	±1.63	±1.63	±1.59	±1.52	±1.49
No. ions/Bunch ($\times 10^{9}$)	100	100	8.3	5.6	2.7	1.5	1.0
*Top Energy, @ transfer:**							
Kinetic Energy (GeV/u)	250.7	124.9	124.9	124.9	114.9	104.1	100.0
Energy, ã	268.2	134.2	135.2	135.3	124.5	112.9	108.4
rms Bunch Length (m)	0.10	0.17	0.17	0.17	0.18	0.19	0.19
Energy Spread ($\times 10^{-3}$)	±0.83	±1.35	±1.35	±1.35	±1.41	±1.46	±1.49
*Top Energy, @ 10 h:**							
rms Bunch Length (m)	0.14						0.22
Energy Spread ($\times 10^{-3}$)	±1.25						±1.78
Norm. Emittance (ðmm·mrad)	29						43
Bunch Area (eV·s/u)	1.2						1.1

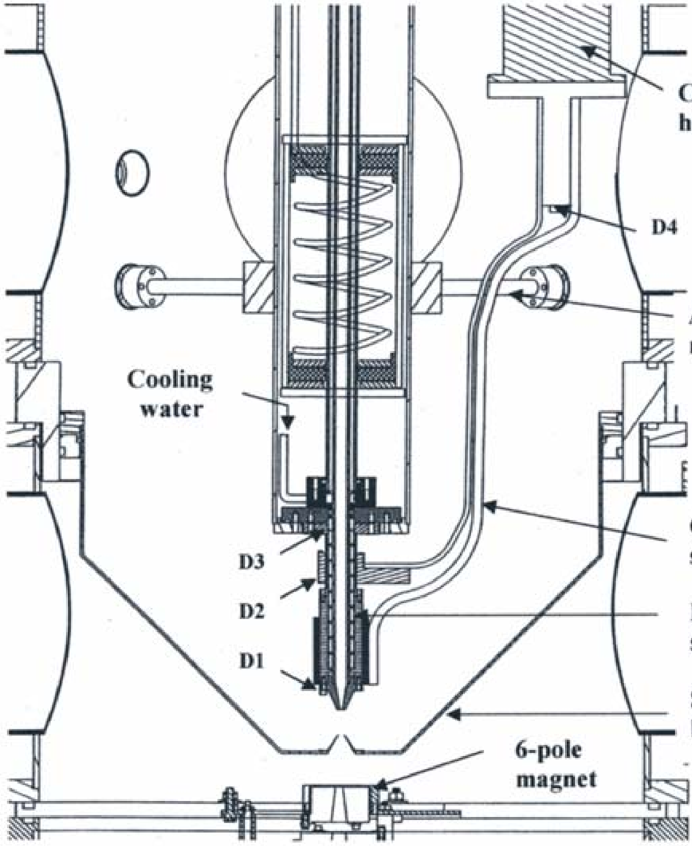
†Acceleration rf System $h = 360$, $V_{rf} = 300$ kV, except 170 kV @ p
*Storage rf System $h = 2520$, $V_{rf} = 6$ MV

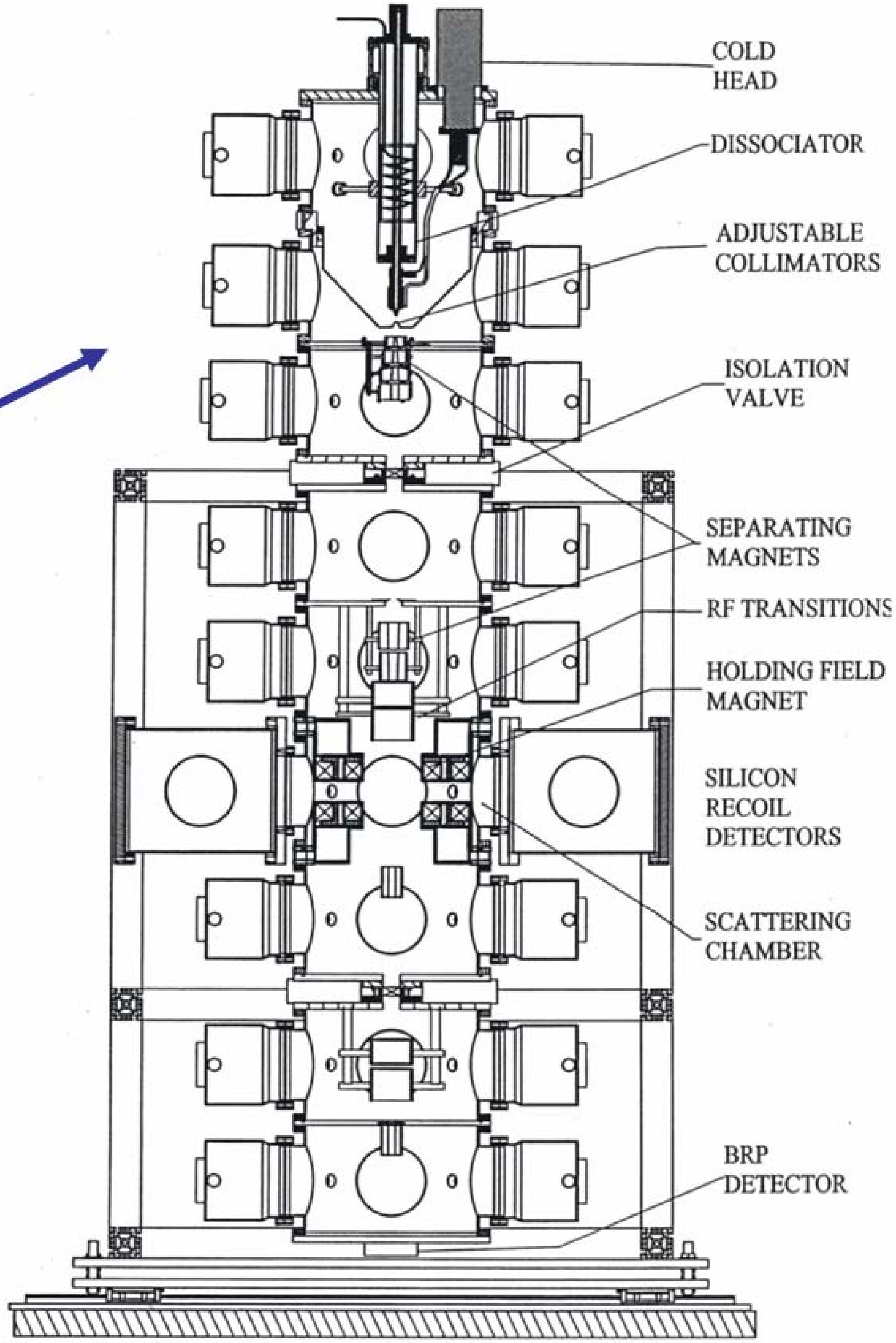
Hydrogen Jet Polarimeter Operation

- The Hydrogen Jet was developed as a method of absolute calibration of the existing carbon Coulomb Nuclear Interaction (CNI) polarimeters.
- 9 Identical vacuum chambers stacked vertically make up the polarimeter. The top 5 chambers make up the Atomic Beam Source (ABS). Followed by the Scattering Chamber and Breit-Rabi Polarimeter.
- Atomic hydrogen is produced in the dissociator thru RF discharge at ~21 MHz at 180 watts. Atomic hydrogen exits the 2mm nozzle cooled to 60K°.
- A series of collimators, sextupoles, and additional RF stages select the spin orientation needed for measurement.
- There are Helmholtz coils provide a weak field in the scattering region that contains the low energy scattered protons. Silicon Detectors are mounted to the sides of the polarimeters.

H - jet polarimeter.

Courtesy Y. Makdisi





Dissociator

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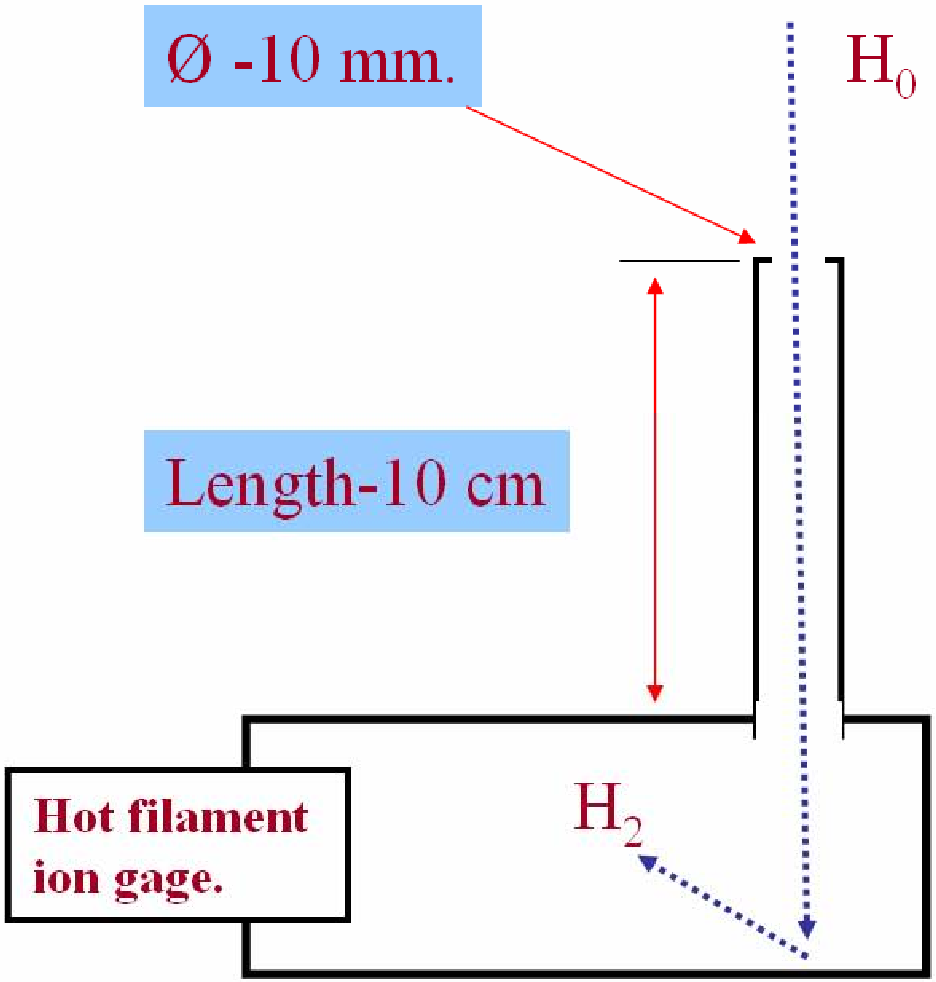
Hydrogen Jet Polarimeter Operation (2)

- Produces a beam of atomic polarized H^o 5.5 mm in diameter FWHM in the scattering region.
- Particle density 1x10^12 atoms/cm^2
- Velocity 2x10^5cm/s
- $H_o/(H_o+H_2)$ purity of 98.5% (percentage of un-disassociated molecular H_2) as measured by a modified quadrupole mass spectrometer.
- Polarization measured 95.8% out of a theoretical maximum of 96.1%
- Entire polarimeter structure can be moved +/- 10mm to measure the polarization of the individual beams. Also provides another measurement of the jet diameter.
- Dilution of the H_o with H_2 lowers the effective polarization to 92.4%+/- 1.8. H_2 is the primary source of systematic error in this system. Having an online diagnostic of the H_2 would be very helpful……

Compression tube calibration.

1. Hydrogen mass-flow controller MKS. Full range: 0.0-1.0 scc/min. Absolute accuracy 1-2%.
2. Conventional technique: pressure drop in calibrated volume.
3. Independent AB intensity measurement from the well known TMP pumping speed.

Courtesy A. Zelenski

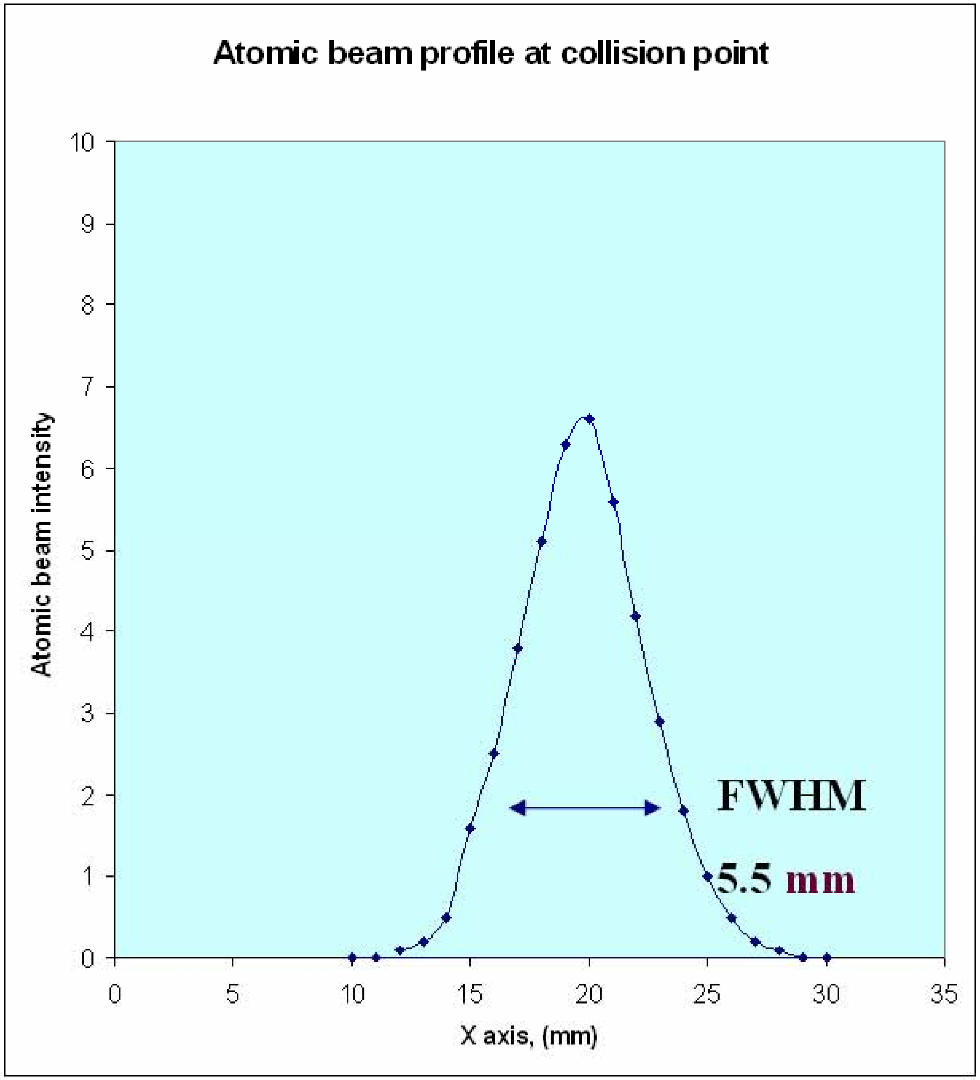


Atomic beam profile at the collision point.

- Atomic beam profile was measured with a 2.0 mm in diameter compression tube FWHM=5.0 mm

- 5 cm upstream the beam profile FWHM is about 4.5mm and 120 mm downstream FWHM is about 7.0 mm

- In assumption, that beam velocity is $2 \cdot 10^5$ cm/s, the H - jet thickness at the collision point is about $1.2 \cdot 10^{12}$ atoms/cm^2.



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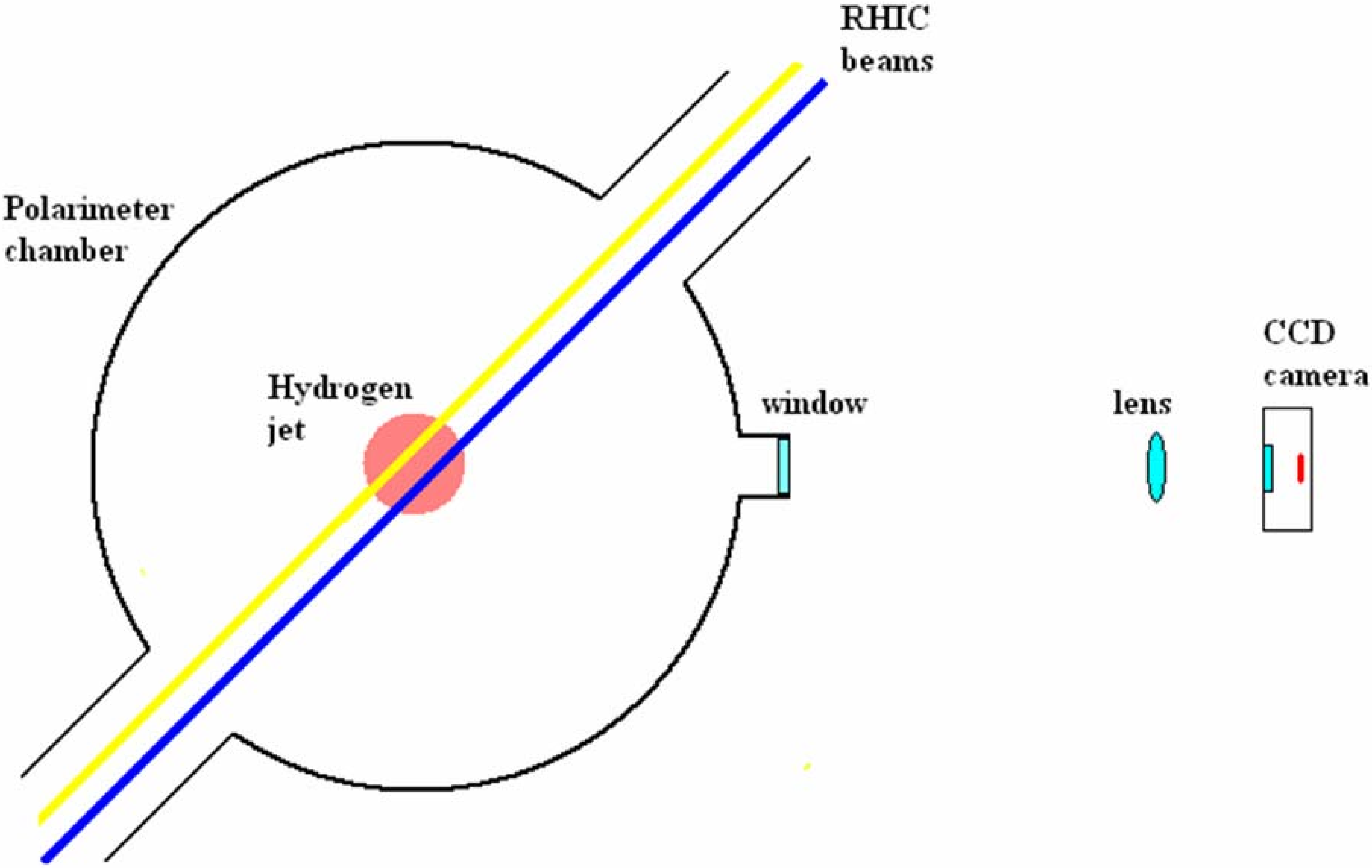
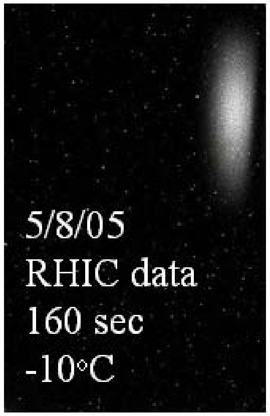
Initial Tests

- The only modification to the polarimeter itself was the replacement of a single blank off flange with a quartz window. We wanted minimal potential interruption to the operation of the polarimeter. We had to look in at a 45 degree angle due to the presence of the silicon detectors.
- We made a few unsuccessful attempts with various devices that were unable to distinguish whether the jet was on or off. Due to either high background or radiation damage………
- A camera that was designed for astronomical purposes was "temporarily" mounted to the side of the polarimeter.
- High sensitivity for the hydrogen spectral lines Alpha 656.2nm, Beta 486.1, Gamma 434.0 nm, H_2 320 nm lower end of the scale.
- This camera utilizes a Peltier cooled CCD imager.
- This camera successfully produced images of the jet and polarized proton beam interaction.

Image Successfully Captured by the Cooled CCD Camera

Courtesy T.Tsang



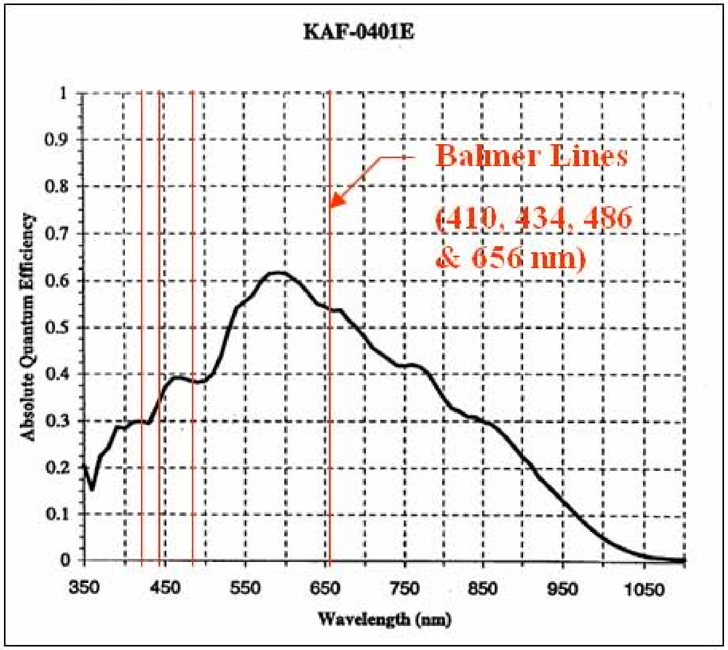


The Camera

Meade Pictor 416 XTE

Kodak KAF-0401E CCD:

- 768 x 512 pixels (6.9mm x 4.6mm)
- 1 pixel = 9.0 µm square
- Thermoelectric Temperature Control to –20 deg C
- 16 bit A/D Conversion



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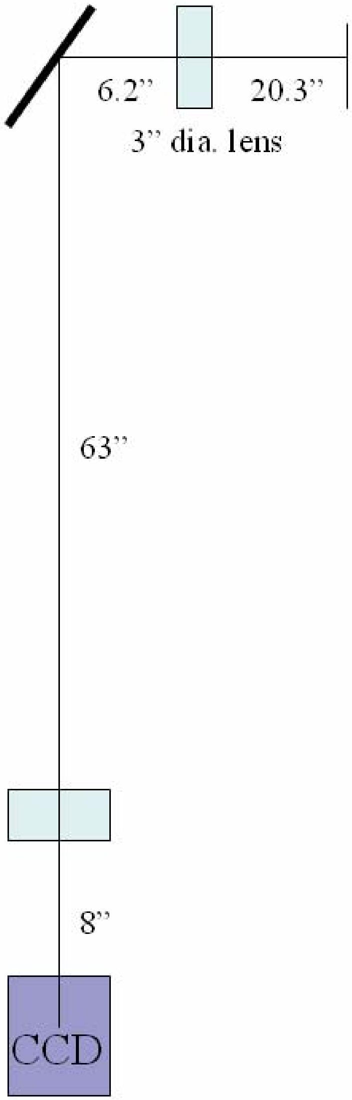
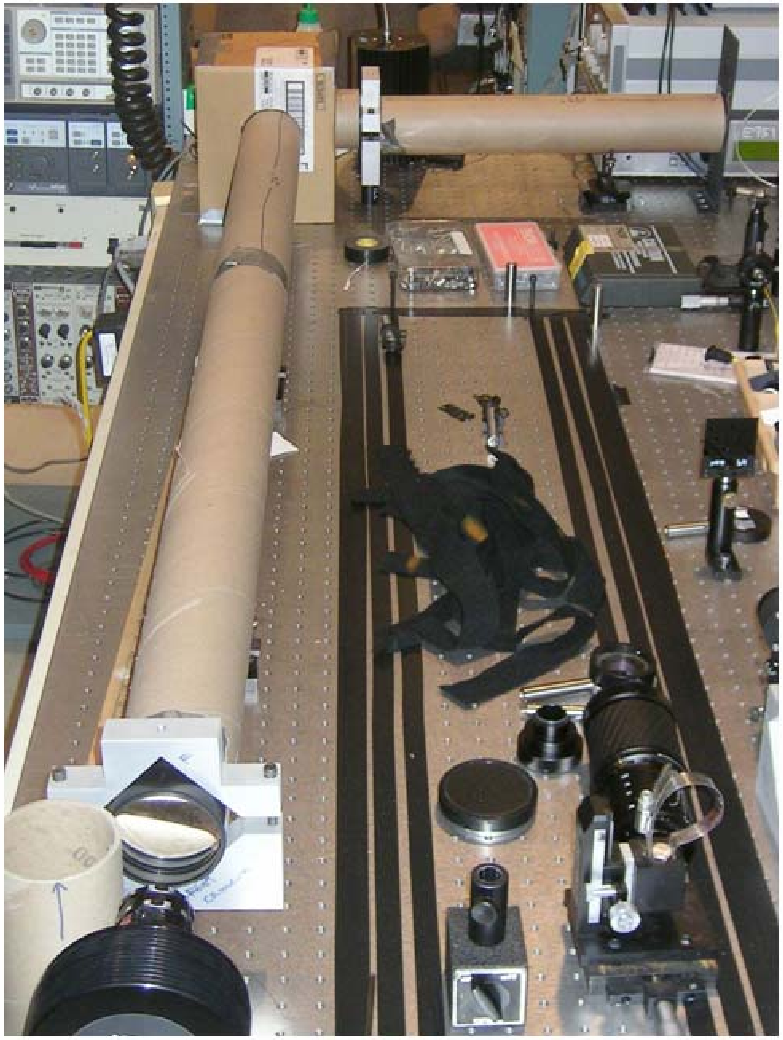
Test Bench Measurements

- After the initial images were collected, the camera was moved to the lab for calibration.
- Goal – learn more about the camera operation on the bench including the image orientation and sensitivity.
- Goal – to interpret the number of photons and interaction cross section in the photo taken 5/8/05
- Goal – mock up optics close to what would be required for a permanent installation.
- Unfortunately we learned the CCD had been damaged and we could not accurately interpret the number of photons.

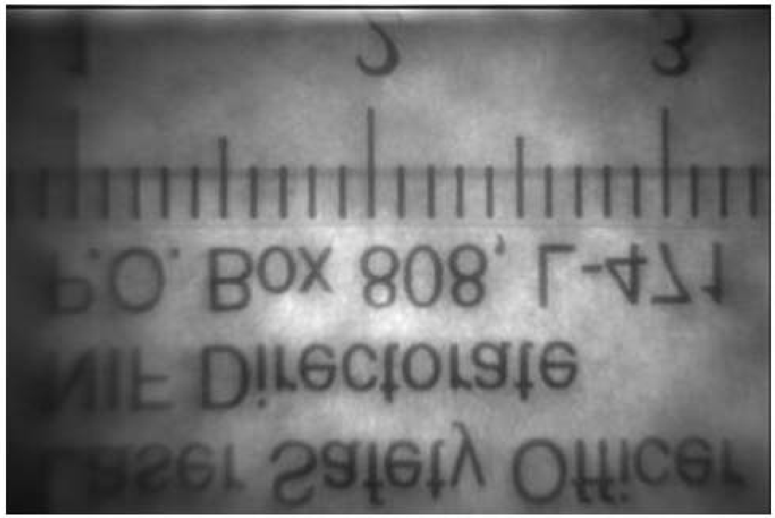
Lab layout of H_2 jet imager





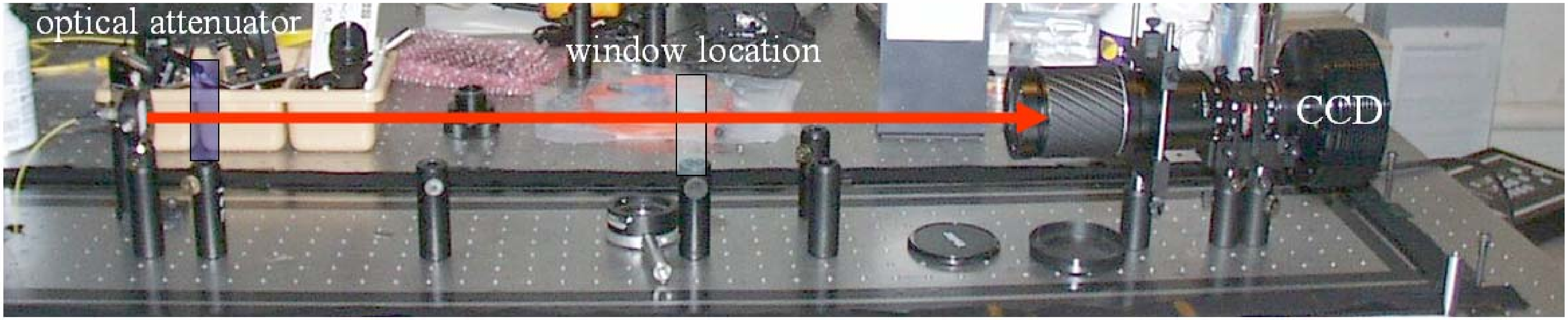
Courtesy T. Tsang
image target

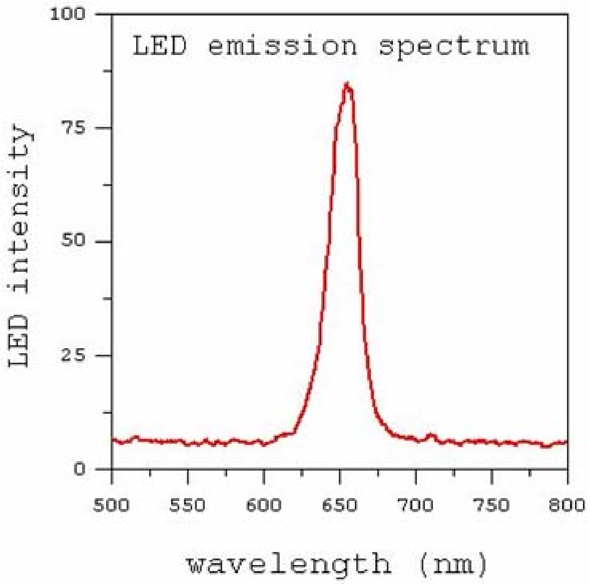
Pictor 416 XTE CCD 0.2 sec 0°C

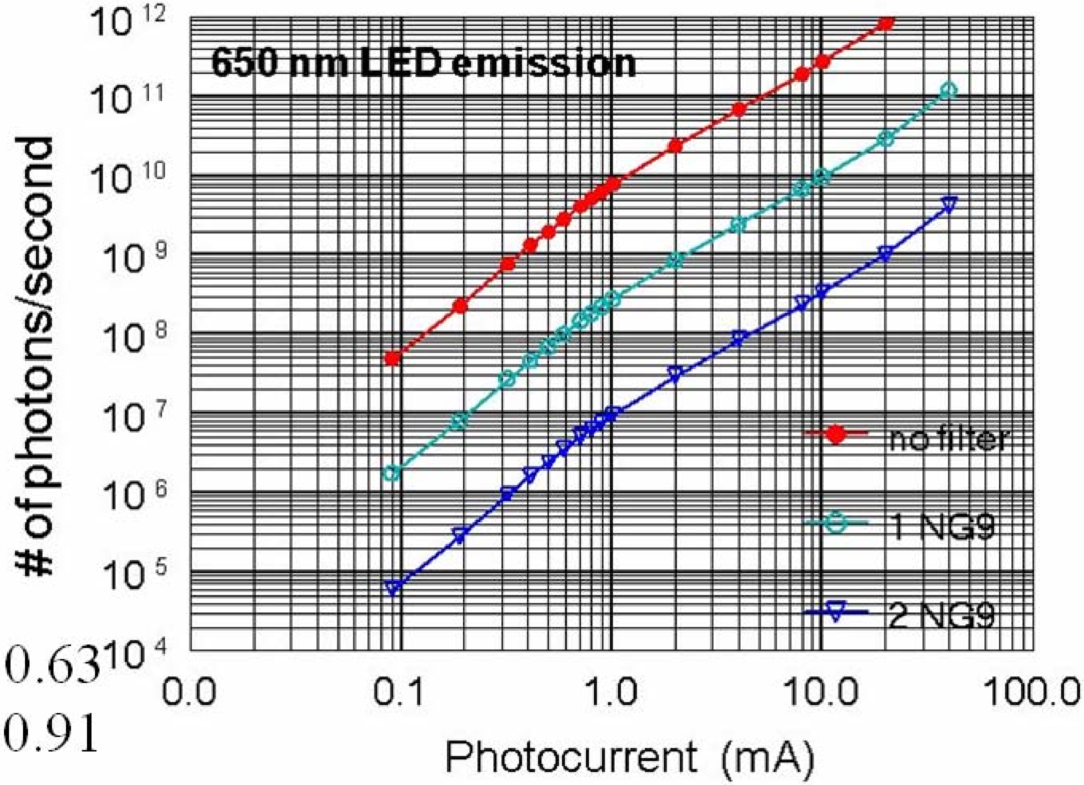


measured light throughput: 0.815

Calibrated LED light source: current-driven, fiber-coupled





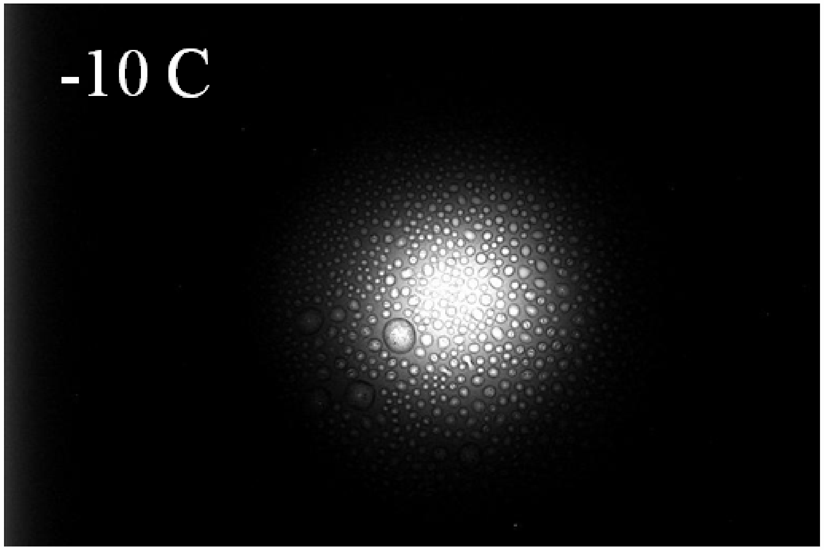


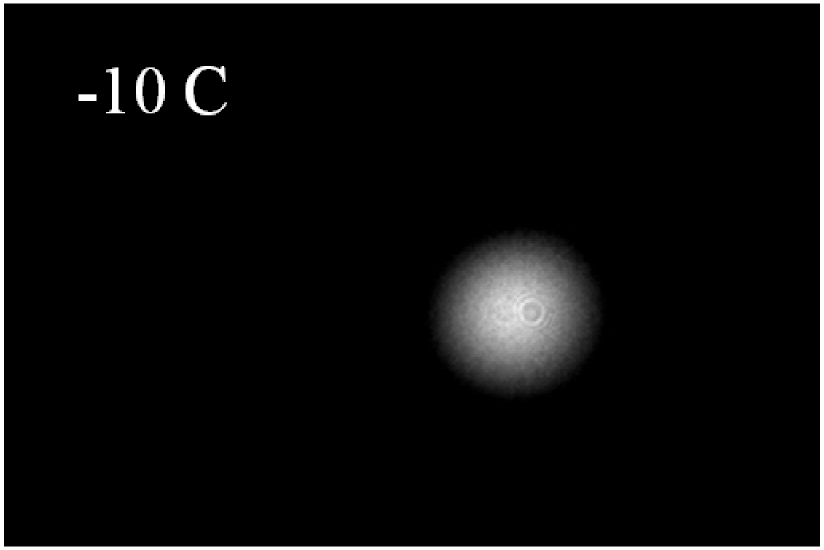
zoom lens transmission = 0.63

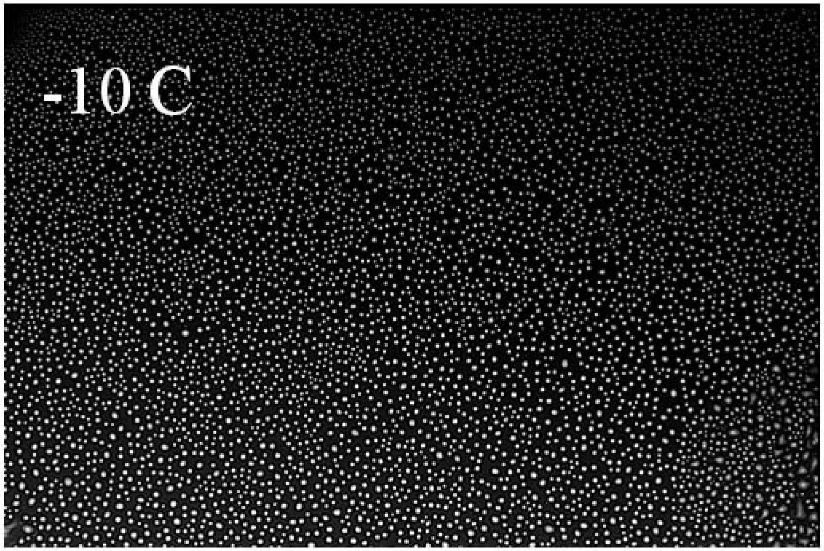
MDC glass window transmission = 0.91

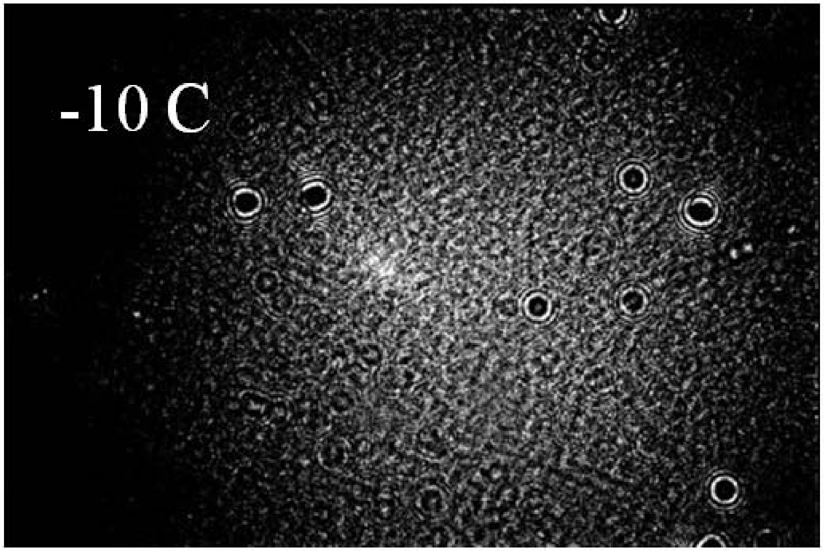
Pictor 416 XTE CCD received 10/20/05

Pictor 416 XTE CCD received 11/18/05









Temp can't go below –10 C

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array size 6.90 mm x 4.60 mm

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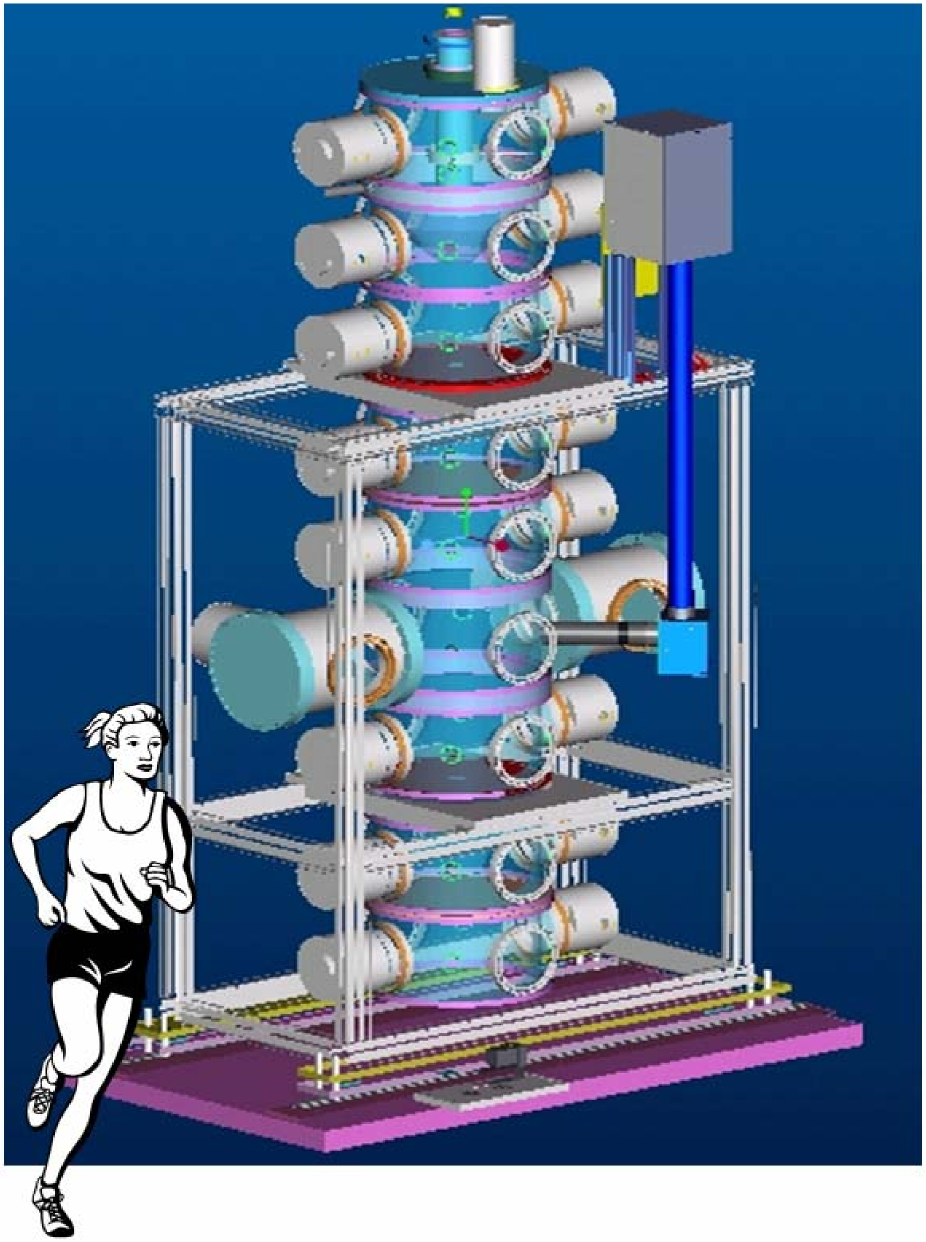
Optics Design

- The camera was returned to the manufacture for repair 3rd time – and it was decided to upgrade the imager and replace the desiccant assembly. At this time we upgraded the software.
- The camera needed to be relocated up 1.5m from the beam centerline to reduce radiation damage. Gives a total optical length of ~2.5m.
- Field of view needs to be several cm with a magnification of .25 to view both of the RHIC beams (room for alignment error).
- Eye relief needed to be several cm to allow for the addition of a filter wheel for 656nm, 486nm, and 320nm for the atomic line.
- The light-tube and enclosure were made from optical quality flat-black anodized aluminum.
- There is a complementary cooling system for the camera utilizing a fan and labyrinth.
- All functions were remote controllable from outside the ring.

RHIC H-jet beam profile imaging system



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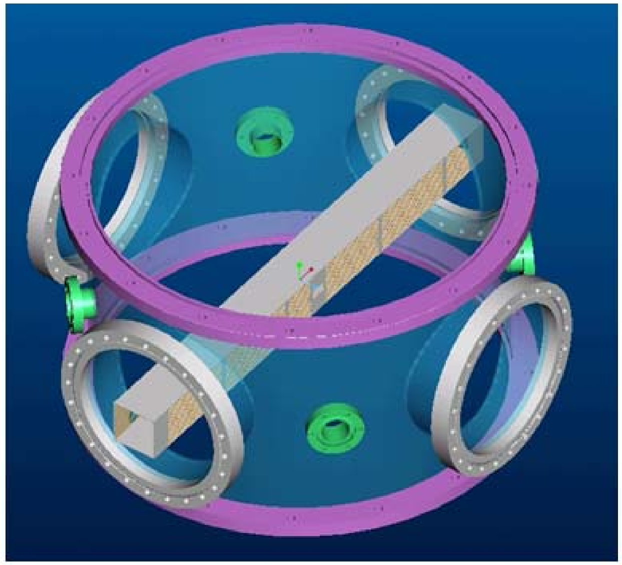

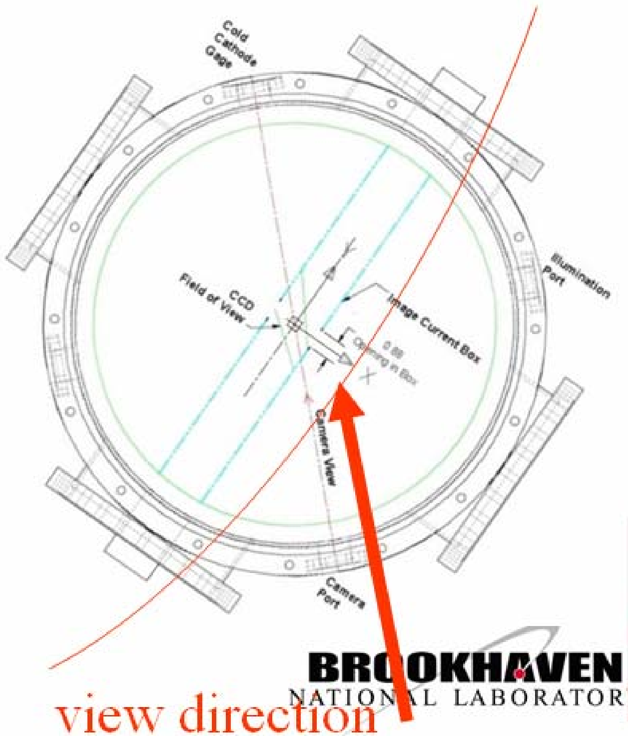

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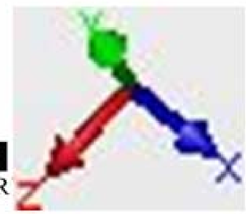
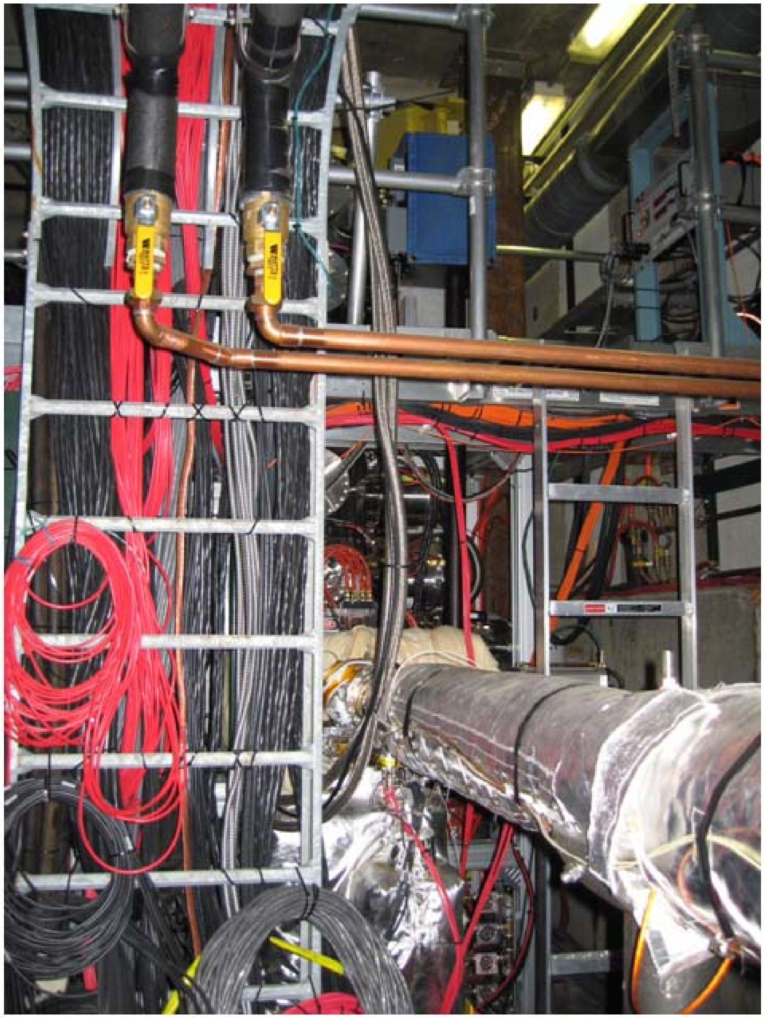


Photos Showing the Polarimeter in RHIC



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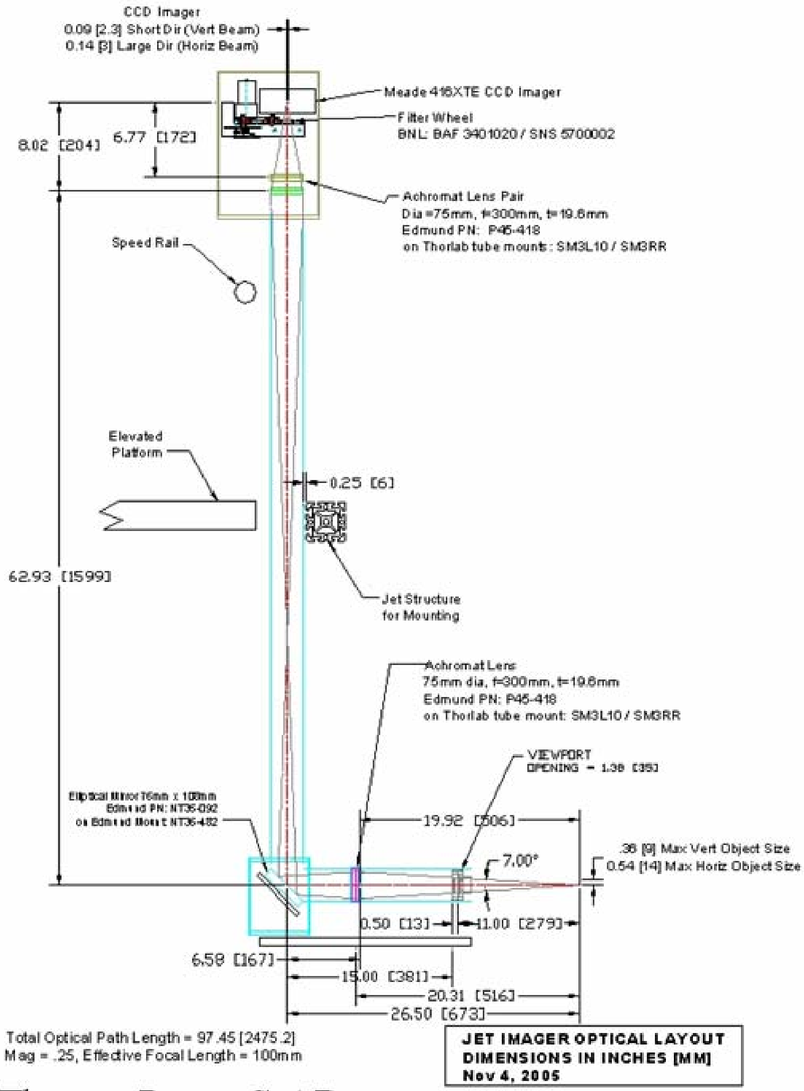
Alignment Issues

- Challenge – aligning the system without opposing viewport or target in the center upon which to focus.
- We developed an accurate CAD model. We used this model to align the camera to internal structures of the polarimeter.
- In this case we focus on the "near" and "far" wires then develop a mathematical center...

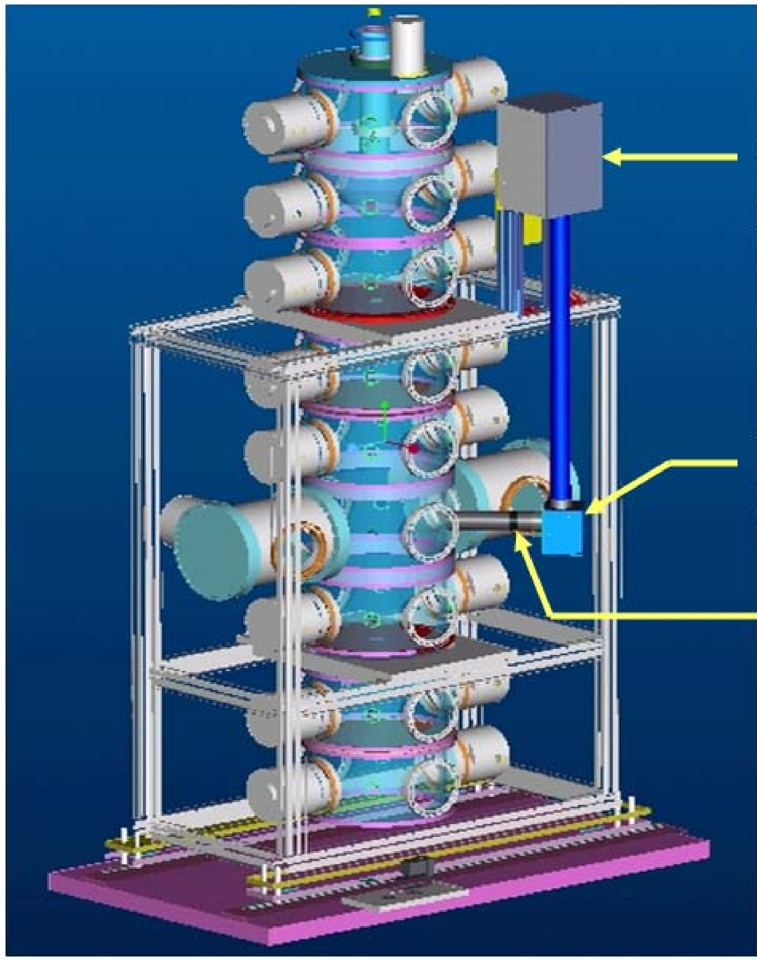
RHIC Jet Beam Profile Imaging System

Courtesy S. Bellavia

- Optical Layout



- 3-D Model



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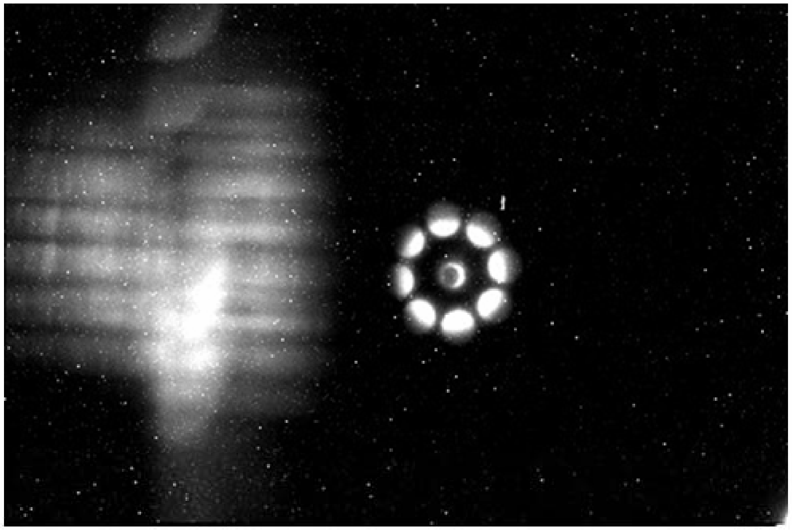
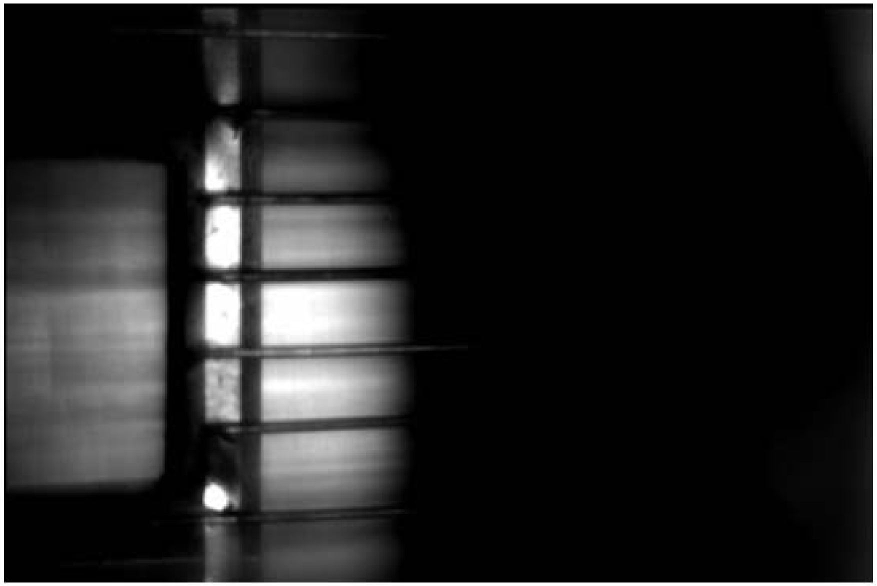
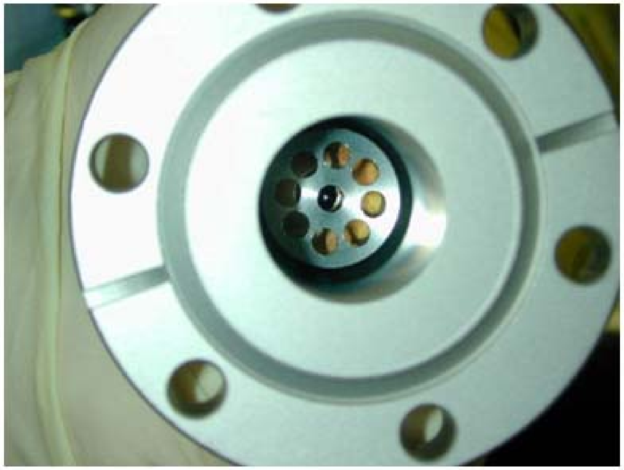
Alignment and Initial Images

Below is a photo of the "far" wires being used for alignment. Photo on the right of the back wall and "mystery" light source.
Lower right is the culprit……
Cold Cathode Gauge……







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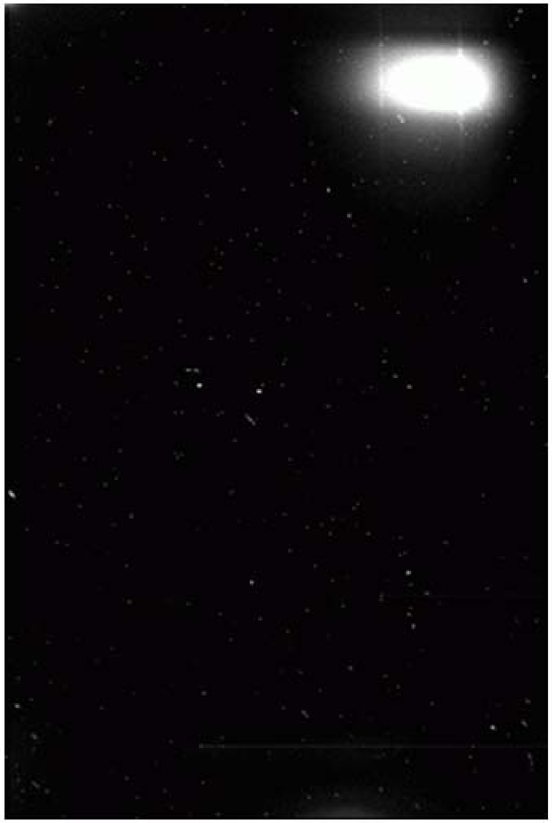
Images

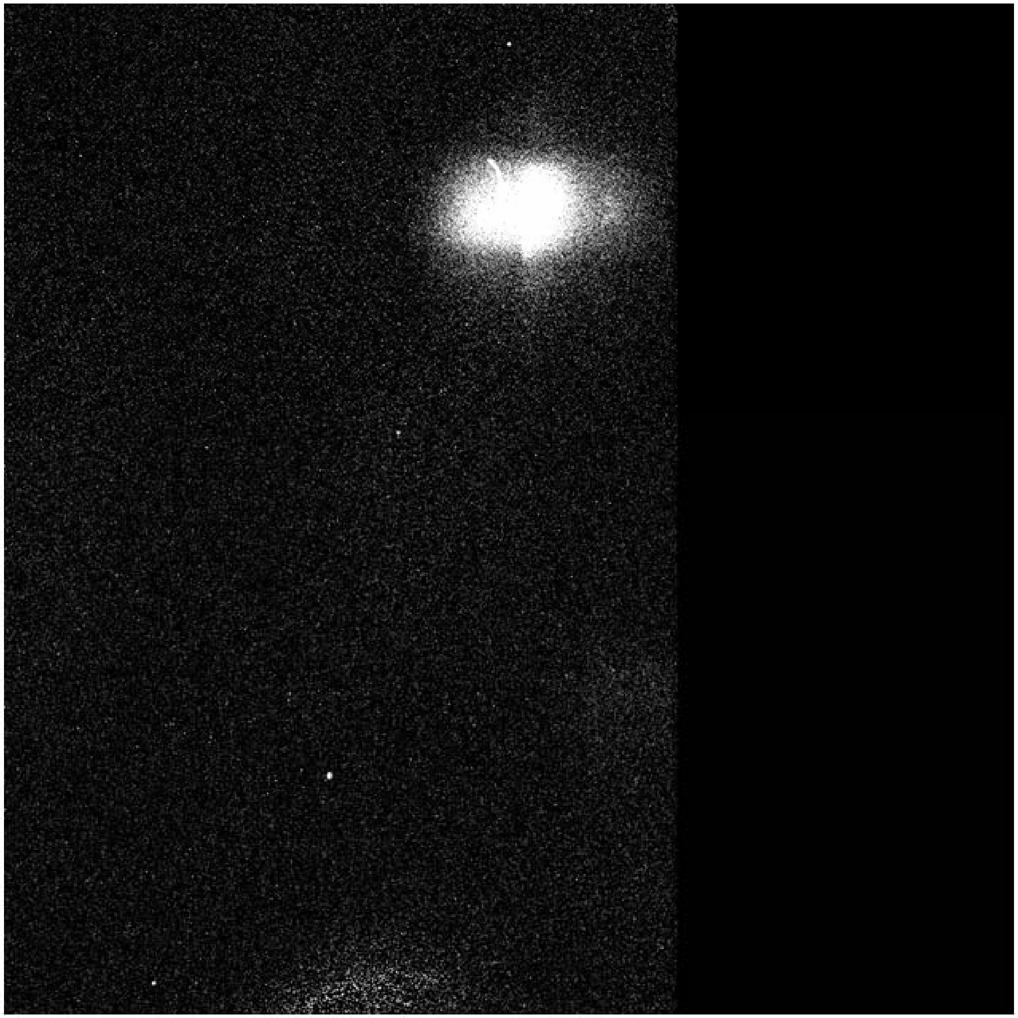
- The next two slides show moving images of the RHIC beams.
- The first is a series of images (30 second integration each) taken every few minutes during a 20 minute RHIC fill.
- The second animation is a sequence of 70 images. The luminescence from the Blue beam appears as the upper image and occurs before the Yellow due to the filling order. The "flash" is the insertion of a carbon target polarimeter which is roughly 70 meters away.

This is a series of images (30 second integration each) taken every few minutes during a 20 minute RHIC fill.

courtesy of Thomas Tsang.



This gif animation is a sequence of 70 images. The luminescence from the Blue beam appears as the upper image and occurs before the Yellow due to the filling order. The "flash" is the insertion of the polarimeter.



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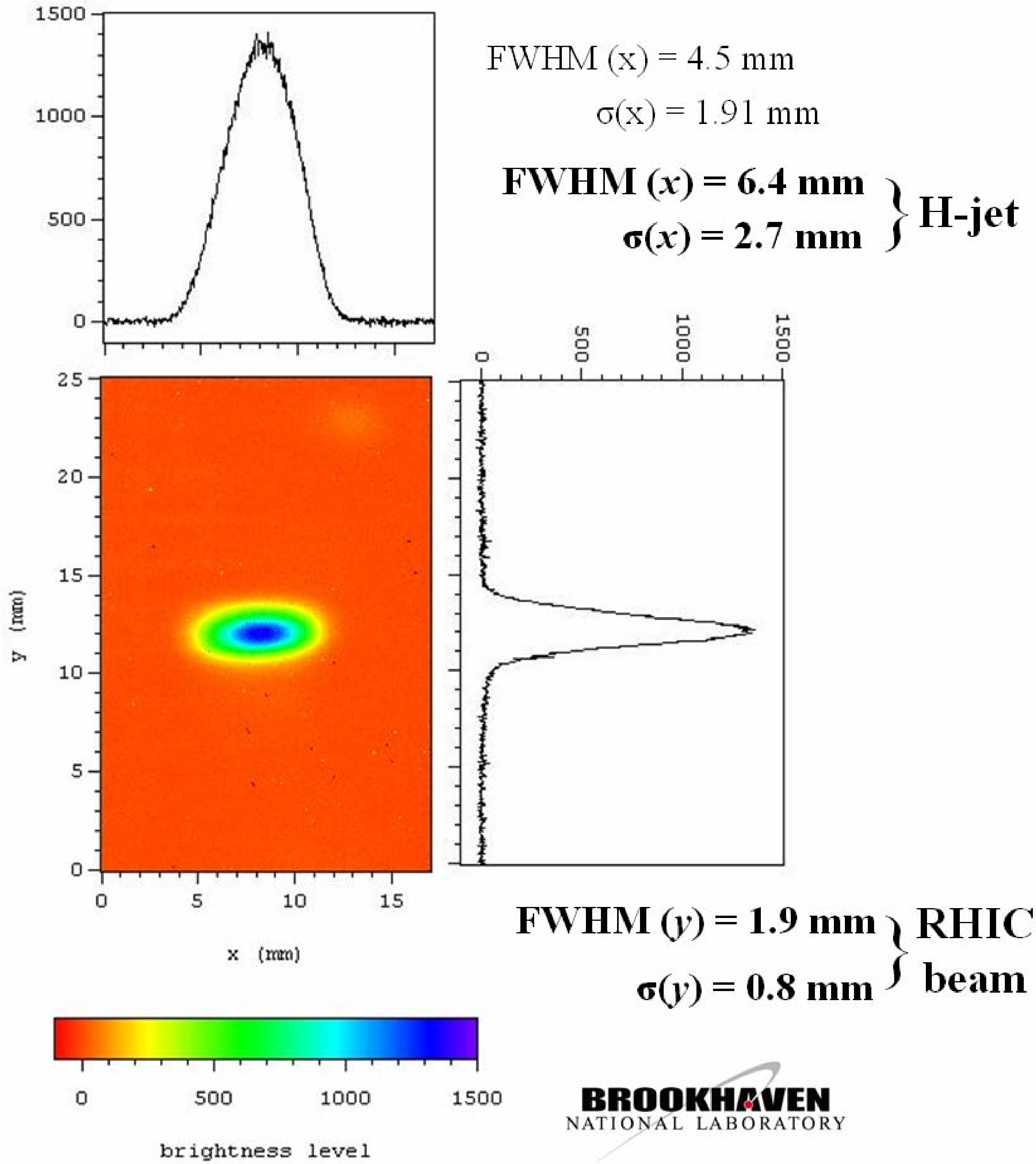
RHIC Yellow beam profile after 656 nm red filter

Data of Feb. 28, 2006

Courtesy T. Tsang



486 nm filter: H-β line gives similar result

320 nm filter shows no jet image

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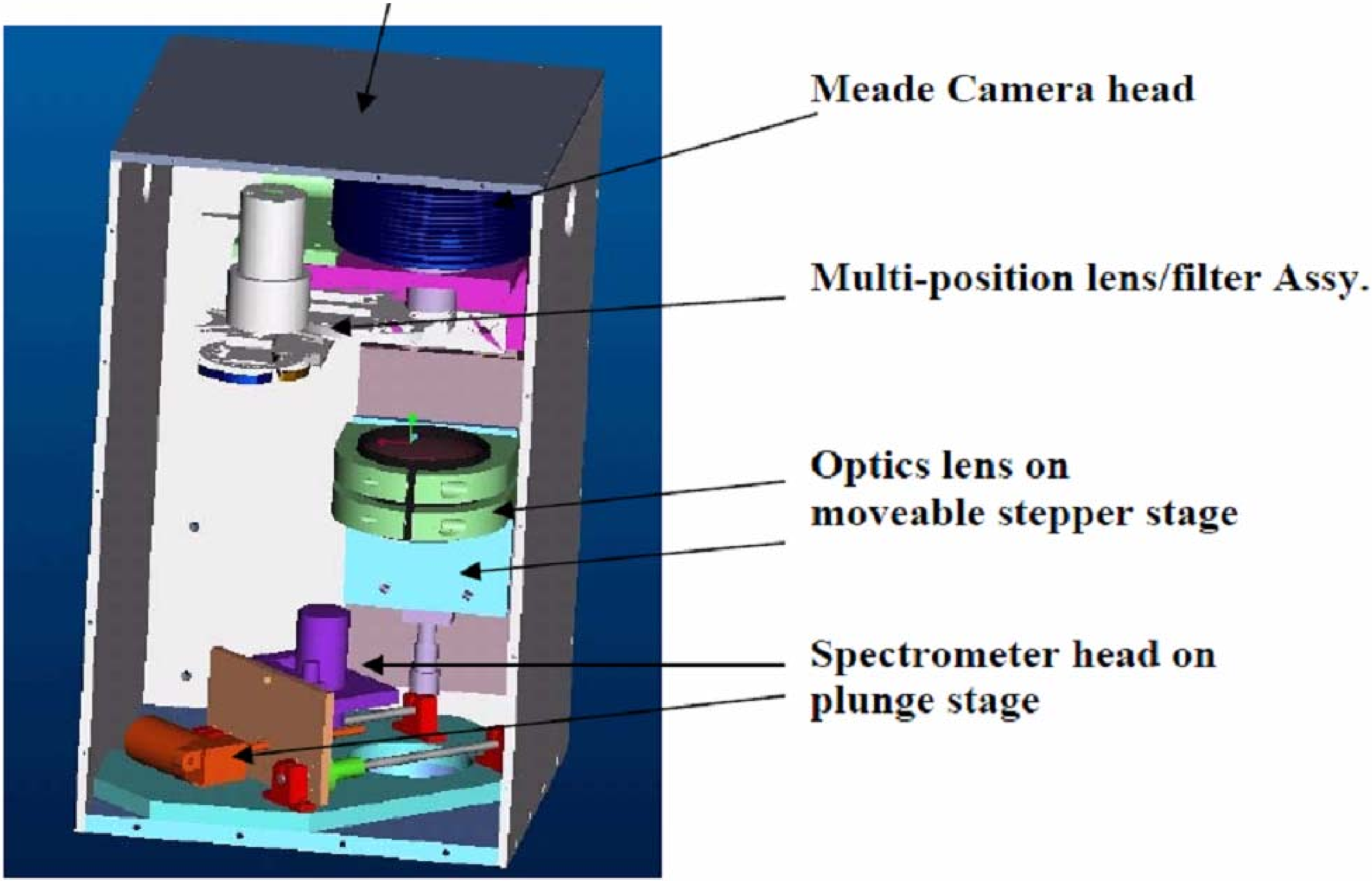
Additional Light Monitors

- There were additional attempts made to characterize the light emitted from the gas/beam interaction.
- Two light spectrometers from Ocean Optics (HR2000 and a QE65000) were taken to the lab and characterized.
- These are designed to detect spectra from 200to1100nm simultaneously.
- The first was damaged within a few days from radiation.
- The second, although located in a lower background region and coupled by fiber did not provide meaningful data.

Modified Camera Box for Plunging Stage with Spectrometers

Courtesy S. Bellavia



Results

- The jet cross section has been measured by compression tube and by physically moving the across the polarized beam. We have a third independent measurement of the jet cross section provided by the luminescence monitor.
- Results for beam height agree with the IPM predictions of what we should see in the interaction region in most cases to better than a factor of 2. Scanning the beam vertically known distances and calibrating the optics yield even closer results.
- This commissioning run provided a set of data for the number of photons incident on the CCD. But we are off from prediction---the instruments may be damaged.
- In all cases the instruments were effected by radiation. Camera dark current increased everyday.
- Putting in the 320 nm filter showed no light from the diatomic hydrogen line.
- More work is needed……………….

Future

- Try to get the spectrometers operational – this will provide an online monitoring tool for the jet operation. H_2 impurity as well as oxygen and water can be monitored. Use fibers to relocate these instruments.
- Develop a modification so that complete end to end sensitivity of the system can be measured and verified during operation. May involve removing – relocating the cold cathode gauge and installing another window directly across from the light view port. We have to be careful not to negatively effect jet operation.
- Develop a sheet jet that can simultaneously obtain measure profiles of the beam in the x and y planes.
- Continue to try and refine the models and understand how much light should be produced.

Thanks

- Peter Thieberger and Dejan Trbojevic for their guidance during this project.
- Thomas Tsang for his meticulous bench measurements.
- Steve Tepekian for his image post processing efforts.
- Steve Bellavia and Dave Gassner for optics and controls respectively.
- Joe Saetta, Alan Weston, Bob Sikora, and Al Ravenhall – their skill during assembly significantly contributed to the overall success of this experiment.
- Yousef Makdisi, Anatoli Zelenski, and George Mahler for guidance with the jet polarimeter.

Recommended Reading

- A History of Luminescence from the Earliest Times until 1900 by E. Newton Harvey – 1957. No mention of RHIC.
- Optical System Design for High-Energy Particle Beam Diagnostics by Bingxin Yang
- Luminescence Beam profile monitor for the RHIC Polarized Hydrogen Jet Polarimeter – Nick Luciano et al, PAC 2005
- Gas Scintillation Cross Section, Lifetime, and Profile Measurements at the PS – Mike Plum et al – July 2000
- Luminescence monitor web site (by Dave Gassner) can be found here:
- http://www.rhichome.bnl.gov/RHIC/Instrumentation/Systems/Jetcam/Jetcam.html