Overview for RHIC complex:
Screens for electrons, protons and ions

Workshop on

Scintillation Screens and Optical technologies for transverse Profile Measurements

Krakow, Poland April 1 – 3, 2019

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BROOKHAVEN NATIONAL LABORATORY

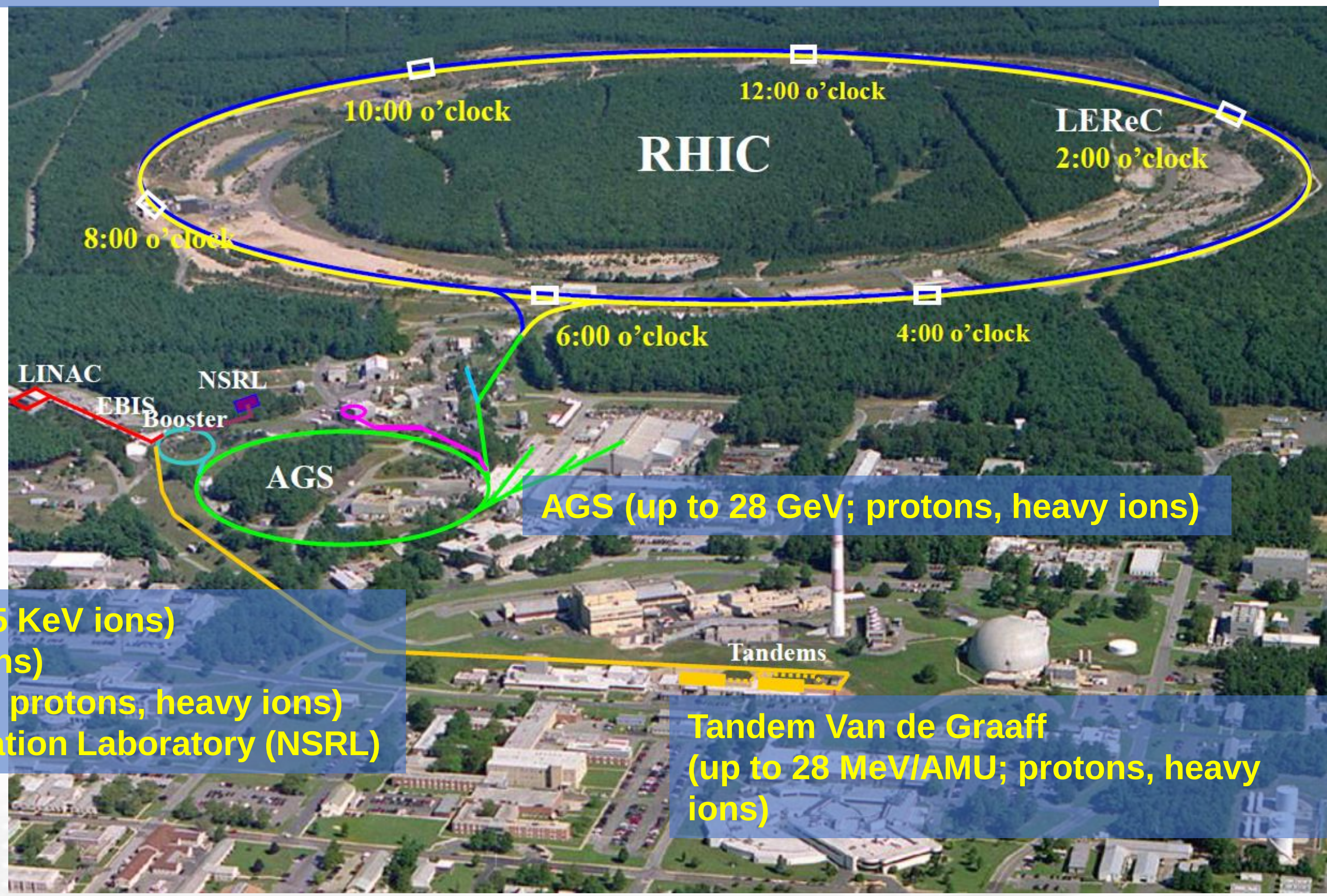
U.S. DEPARTMENT OF ENERGY

Outline

- Overview of Collider-Accelerator Facility Machines
- Facility Layout of Accelerators
- Overview of Collider-Accelerator Facility Profile Monitor Screens
- Profile Monitor Screen Details
  - Chromox (Al_2O_3 Cr_2O_3)
  - Radlin (aka PFG, P20)
  - Gadolinium (P43)
  - YAG:Ce Crystalline Screens
    - Uses, Illumination, Resolution
    - YAG Damage Incident
    - Destructive YAG Test
  - Crystalline CsI(Tl)
  - BNNT “Bucky Paper”
- Camera Network & Controls
  - Legacy Analog Video Management Server
  - GigE Cameras
  - GigE Video Network
- Conclusion

Overview of Collider-Accelerator Facility Machines

RHIC (3.85 to 255 GeV; protons, heavy ions)
- Low Energy RHIC electron Cooling (LEReC,1.6 to 2.7 MeV electrons)
- Coherent electron Cooling (CeC,18 MeV electrons)
- Electron-Lens (5 KeV electrons)



AGS (up to 28 GeV; protons, heavy ions)

EBIS (range of 14 – 25 KeV ions)
Linac (200 MeV protons)
Booster (up to 3 GeV; protons, heavy ions)
- NASA Space Radiation Laboratory (NSRL)

Tandem Van de Graaff (up to 28 MeV/AMU; protons, heavy ions)

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Overview of Collider Accelerator Facility Profile Monitor Screens

- **Tandem Van de Graaff Accelerator**
  - Chromox screens – 1.5 mm thick ceramic
  - AF995R Chromium doped Alumina Ceramic Fluorescent Screen

- **Electron Beam Ion Source**
  - CsI (Tl) scintillator screen, rectangular 80 mm by 30 mm

- **Booster & NSRL**
  - 4 Chromox screens 1.5 mm thick ceramic, located at Booster extraction and in the transfer line to AGS
  - NSRL has 7 screens: (2) Chromox, (4) Gadolinium and (1) Radlin

- **AGS**
  - Chromox and Radlin screens used to monitor slow and fast extracted beams.

- **RHIC**
  - **AGS-to-RHIC transport beam line**
  - 12 Gd_2O_2S:Tb Plunging Profile Monitor Screens.

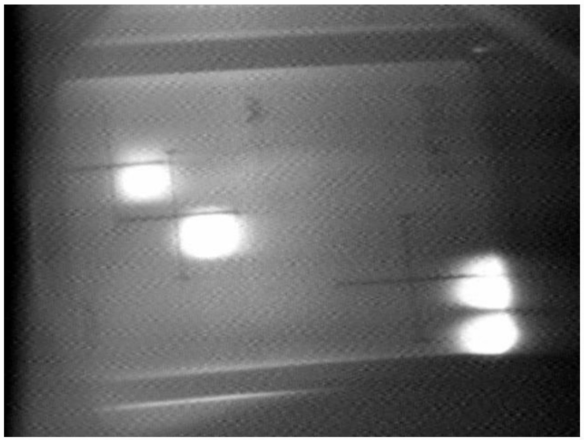
  - **Electron-Lens [1, 2]**
  - YAG:Ce monolithic 100 microns x 30mm diameter, Crytur

  - **LEReC [3] & CeC [4]**
  - YAG:Ce monolithic 100um x 30 – 60mm diameter, Crytur
  - OTR on 250um thick metalized silicon wafer (15 x 25mm)
  - BNNT “Bucky Paper” 50um x 60mm, density of 2.5 mg/cm^2 for 50 micron thickness

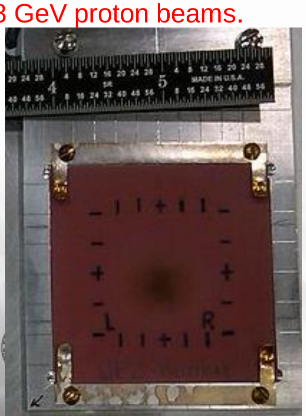
Chromox

- (Al_2O_3 99.4% + Cr_2O_3 O.5%), average grain size 10-15 microns. Morgan Advanced Ceramics
- Use for many years at the AGS fix target experiments
- Used inside Booster vacuum (10^{-11} torr), baked 200C
- Resilient to high intensity beams

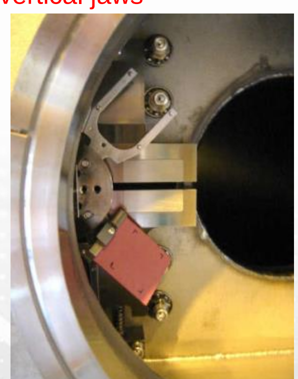
AGS 28 GeV proton beam, slow extraction over 1 sec, split 4 ways to separate fixed targets. Chromox screen 100' from extraction septum. FY96



Chromox screen removed from AtR, showing burn mark from 28 GeV proton beams.



Chromox screen in Booster, on rotary stage, near extraction collimator vertical jaws



Technical Data Sheet
Alumina doped with Chromium Oxide

Chromox

(MAC-A994R)

Description

Specialized alumina material that is doped with chromium oxide. Typically contains **99.4% Al_2O_3** and **0.5% Cr_2O_3**.

Developed in collaboration with CERN, Geneva, mainly for customized components used in particle physics research.

Prime features

- Fluorescent under UV conditions or when impacted by electrons .
- High sensitivity.
- Good thermal stability.
- High resistance to radiation.
- UHV compatibility.
- Good thermal shock resistance.
- Good thermal quenching characteristics.
- Excellent conversion efficiency.
- Readily accepts thick film metallizing with noble metals.

Typical applications

- Ceramic fluorescent screens used in accelerator beam observation.
- Particle beam targets.
- Substrates for conductor and/or resistor networks.

Specifications

- Quality Assurance to ISO 9002

MAC production capabilities

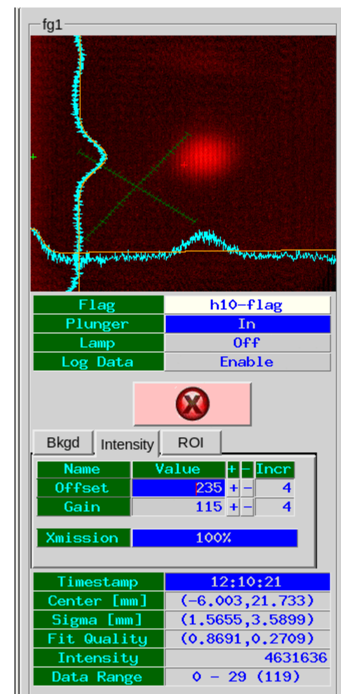
- Ground or polished surface finishes.
- Precision thick film metallizing.
- Prototype and batch production.

Physical properties*

Color	Pink
Bulk density (fired), Mg/m^3	3.85
Grain size, µm	10 -15
Porosity (apparent), % nominal	0 (fully dense)

(* Please note that all values quoted are based on test pieces and may vary according to component design. These values are not guaranteed in any way and should only be treated as indicative values. They should be used for guidance only and for no other purpose whatsoever.)

Morgan
morganadvancedceramics



3.85 GeV Au beam on Chromox screen AGS extraction to RHIC

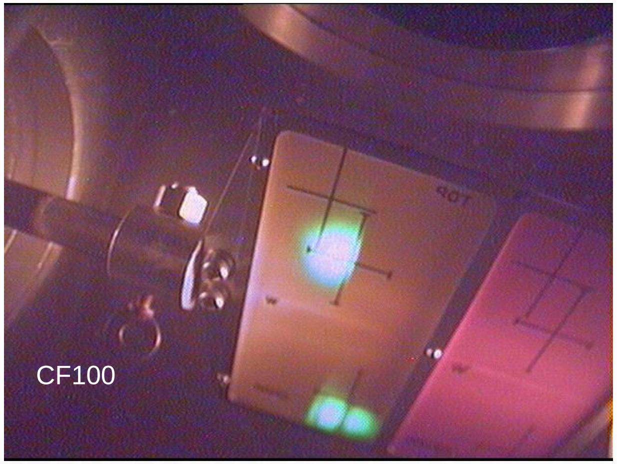
Radlin (aka PFG, P20)

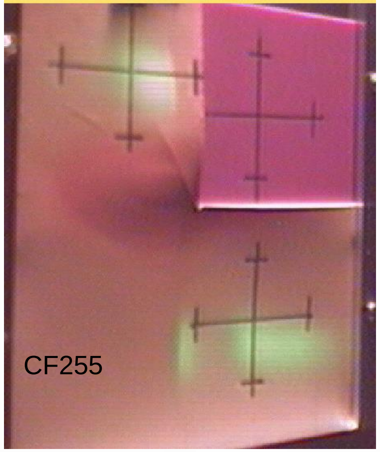
- ZnCdS:Ag Zinc cadmium sulfide, 40% Cadmium Sulfide, 60% Zinc Sulfide, <0.1% Silver, by weight. Manufactured by MCI Optonix
- Decay time: 4ms 90-10%, 55ms 10-1%

History:

- Use for many years at AGS and Booster extraction at fix target experiments.
- High sensitivity for low intensity beams.
- Not UHV compatible, or as resilient at Chromox

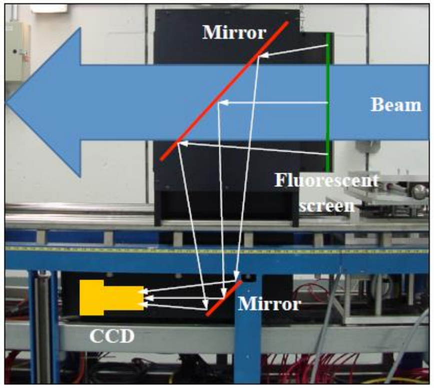
AGS slow spill extraction, 11.68 GeV/c/n Au beam split into 3, FY97
Maximum dose: 70×10^{12} protons/1s spill





Multi-position profile monitor screen plunger
Radlin screen on left for low intensity Au
Chromox screen (pink) on right for high intensity protons
Courtesy K. Brown.

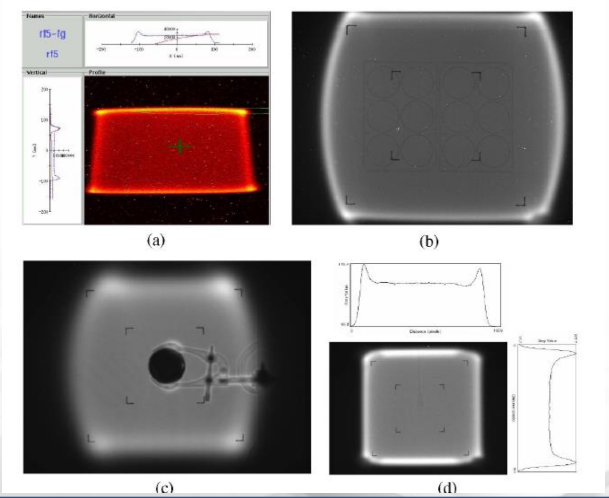
Booster NSRL Target Station
"Digital Beam Imager"



40x40 cm^2 Radlin screen and a pair of mirrors guide light to a Hamamatsu CCD camera

Reference: Overview of the NASA space radiation laboratory, C. La Tessa. BNL-113465-2017-JA

Figure bottom right shows a rectangular beam image of dimensions 20 cm^2 x 20 cm^2



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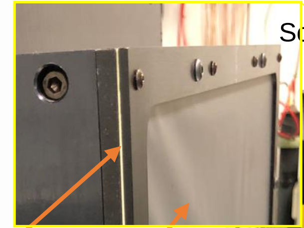
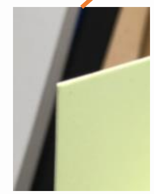
NSRL Target Station
- Camera & images

- Bragg Peaks of Ca^+ and Ne^+ beam on Radlin Target through copper wedge.
- Hamamatsu deep cooled camera with motorized lens, with microscopy software
- 40 cm square target area

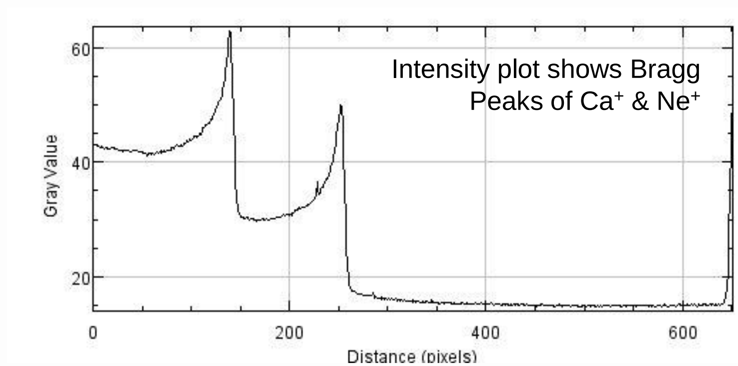


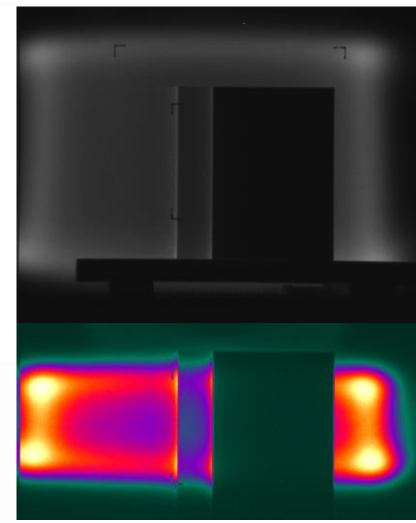
Screen & mirror assy (camera below)



Radlin coating on 0.75mm vinyl

Tedlar film (PVF)





Color & BW images of beam through copper wedge
Courtesy of Adam Rusek, NSRL, BNL

Hamamatsu ORCA-ER deep cooled CCD camera with motorized lens and microscopy software

Camera & Detector layout along beam line

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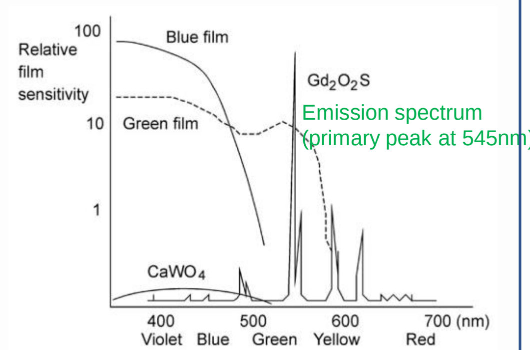
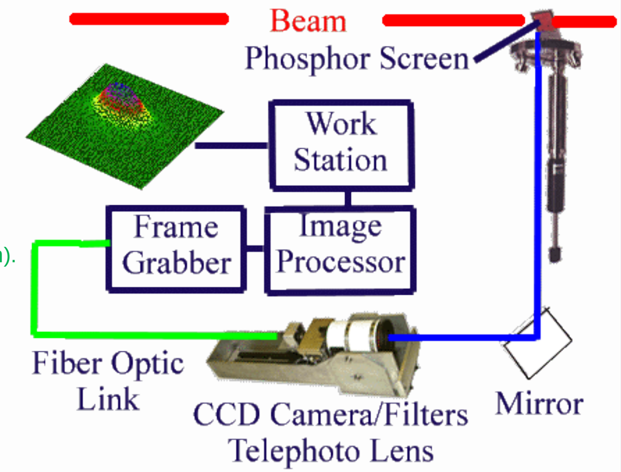
Gadolinium (P43)

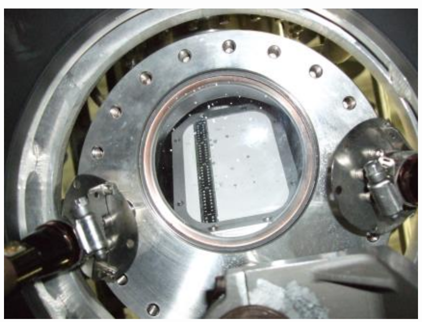
- Gadolinium oxy-sulfide doped with terbium ($Gd_2O_2S:Tb$)
- The screen consists of a 0.002“ thick coating of ($Gd_2O_2S:Tb$) phosphor on a 0.001" aluminum foil substrate with a potassium silicate binder. (courtesy R. Witkover)
- The best resolution measured was ~150 microns over a 3 m optical path.
- Used at:
  - 12 screens AGS-to-RHIC transport
  - 4 Screens NSRL
- High sensitivity, fast response (few ms’s)
- UHV compatible, not bake-able.



Source: http://www.e-radiography.net/radtech/s/specsense.htm

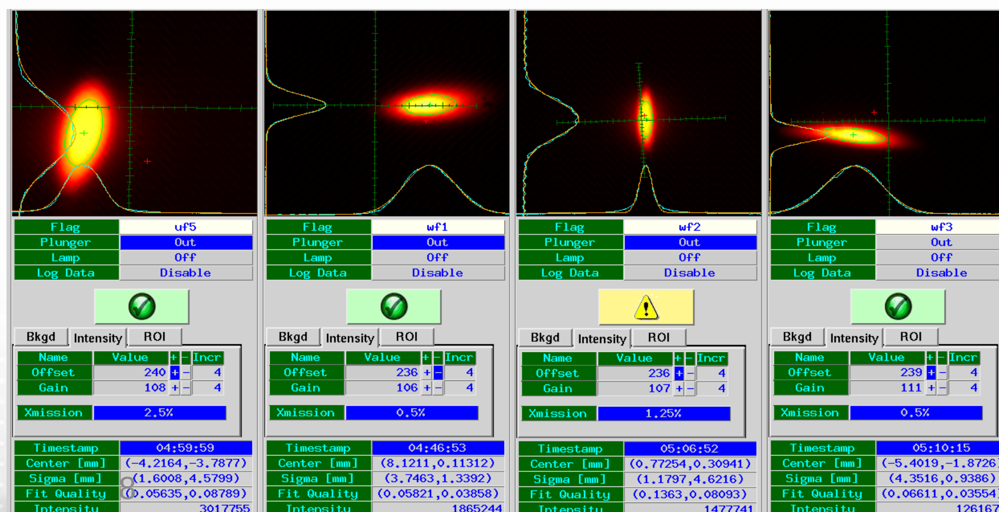


AGS-to-RHIC Profile Monitor system block diagram

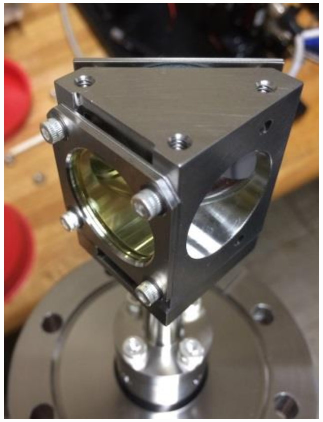


AGS-to-RHIC PM screen with ruler for resolution measurements

Au beam profiles in the AGS-to-RHIC transport



YAG:Ce Crystalline Screens

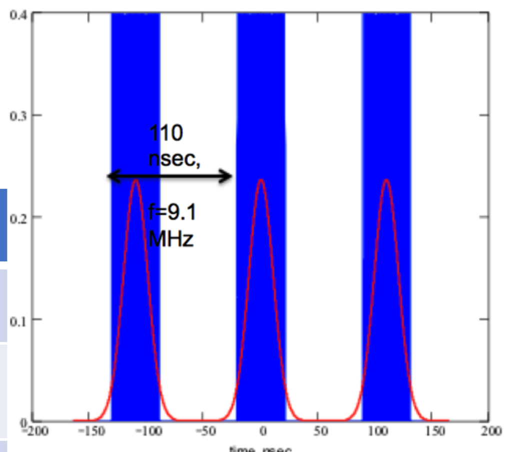


YAG Holder with rear 45º polished metal mirror

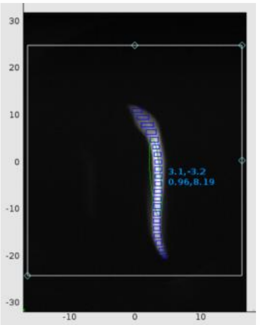
- Monochrystalline YAG, Cerium doped (Crytur)
  - Sizes: ⦰20, 30, 50, 60mm & 20 x 30mm sq
  - 100 µm thick
  - 100 nm Aluminum coating to drain charge
  - Some with fiducial markings
- Used in electron machines:

Machine	Q (pC)	I (mA)	E (MeV)	Pulse	Period
eLens		500 dc	5 keV	12 µs	1 s
CeC	500		1.5 15	200 - 400 ps 10 ps	1 s 1 s
LEReC [6]	3,900	93 pk 38 pk	1.6 – 2.6	42 ns 250 µs	1 s 10 s

LEReC Beam Pulse Structure [1]

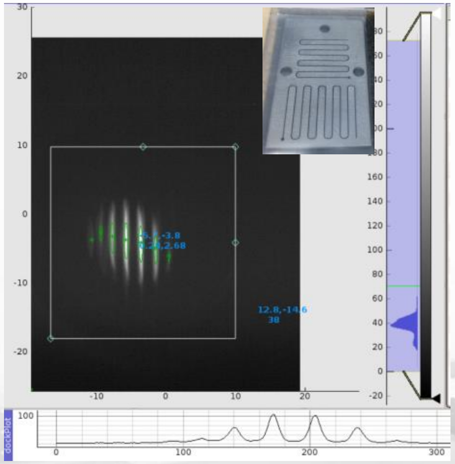


The electron beam has a nested pulse structure [5], where 80 ps bunches at 704 MHz are grouped in macro bunches and positioned to overlap with the 9.1 MHz RHIC ion beam.

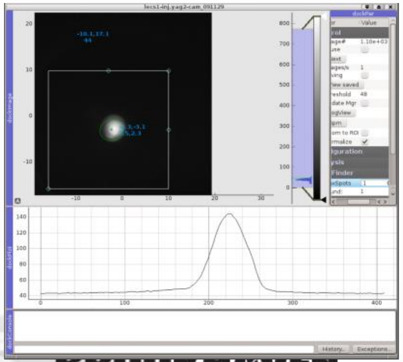


Longitudinal Energy Scan with Deflecting Cavity

- Orientation
  - Crystal normal to beam
  - Rear 45º polished metal mirror
- Applications
  - Beam profile
  - Emittance with slit masks
  - Longitudinal Phase Monitor
    - Deflecting cavity with Profile Monitor
    - Measure e-energy spread, goal 10^{-4}



Emittance with upstream slit masks



Beam Transverse Profiles

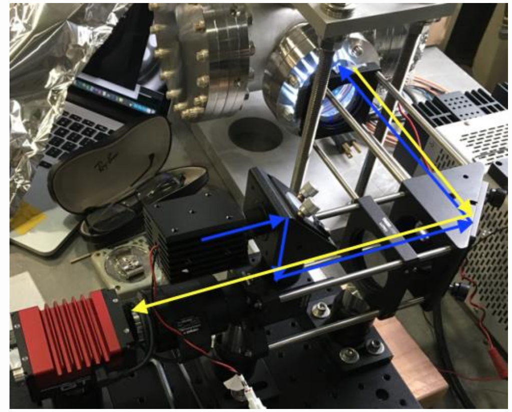
YAG:Ce Crystalline Screen Illumination

Normal & Fluorescent Illumination with RGB LED ring around lens

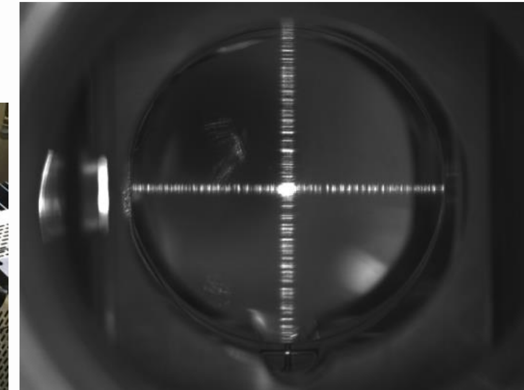
- Normal: Red + Green LEDs
- Fluorescent: Blue LED (~450nm)
- 500nm low pass filter in camera

Project fluorescent cross on YAG

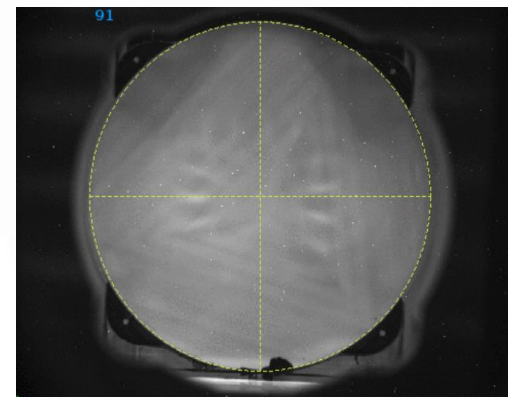
- Inject 450nm laser with Diffractive Optical Element [8]
  - Dichroic beam splitter reflects Blue / Passes YAG emission

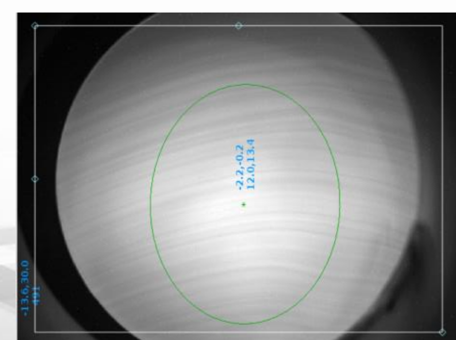


Illumination laser light path

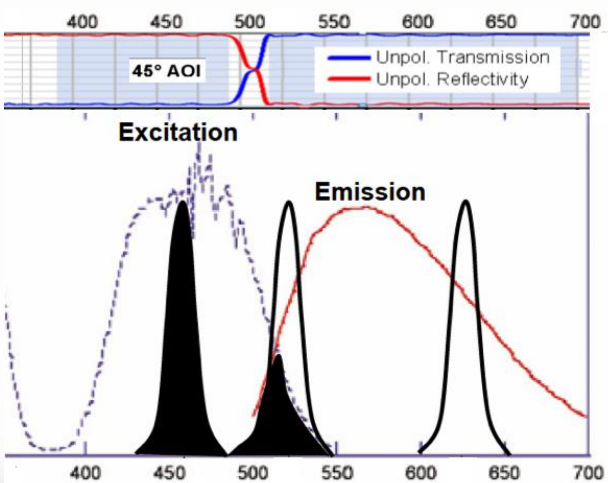


Blue laser through Diffractive Optical Element from Holoeye Photonics

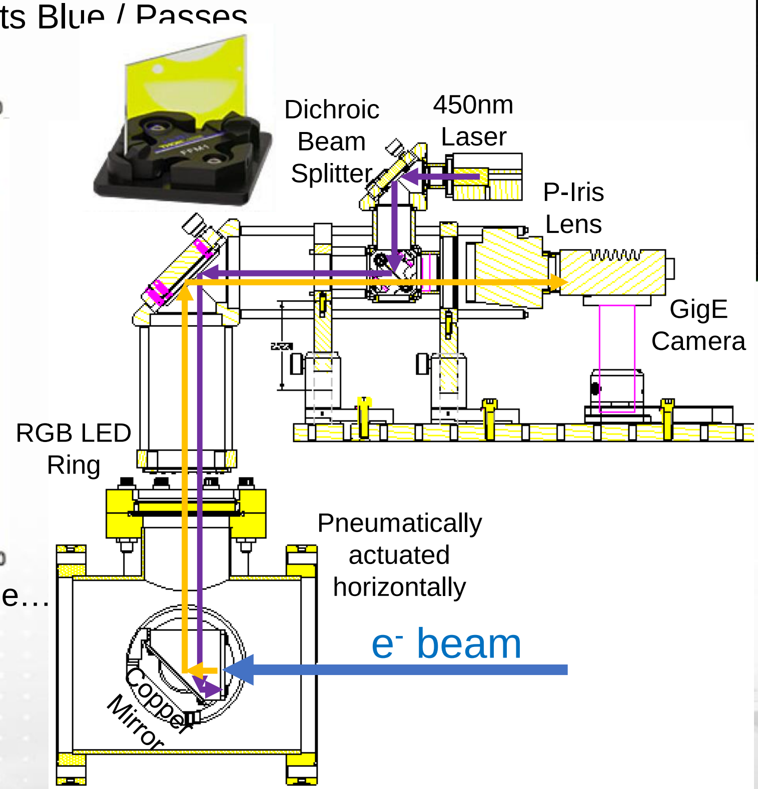




(Top & Bottom) 50mm YAG with Fluorescing under 450nm Blue illumination. Reference circle show above.



Y. Zhu, et al, "…Optical Properties of YAG:Ce…



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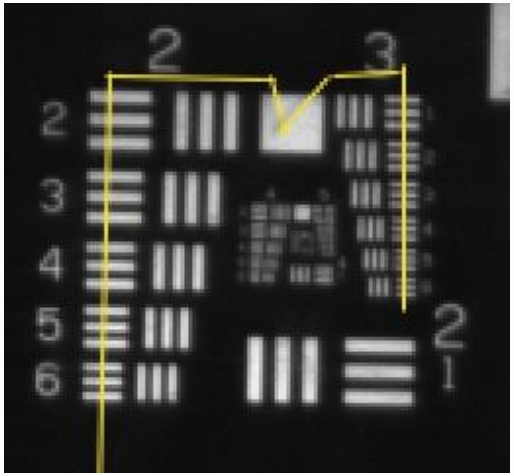
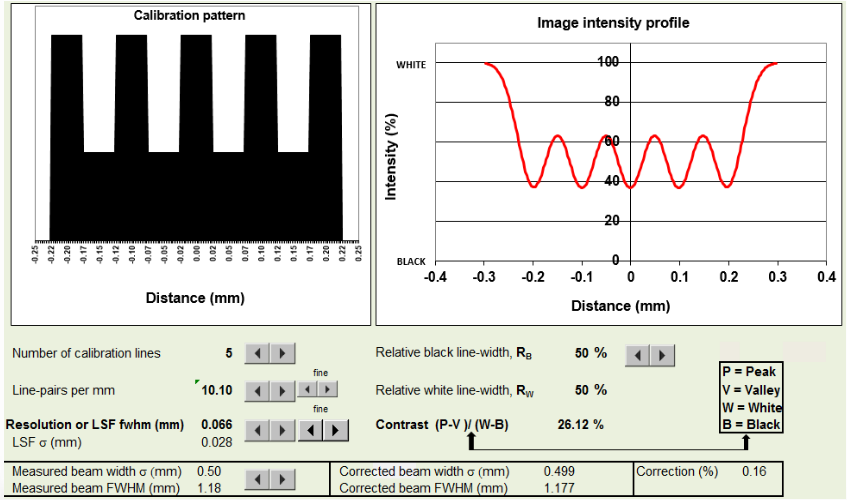
YAG:Ce Screen Resolution Tests

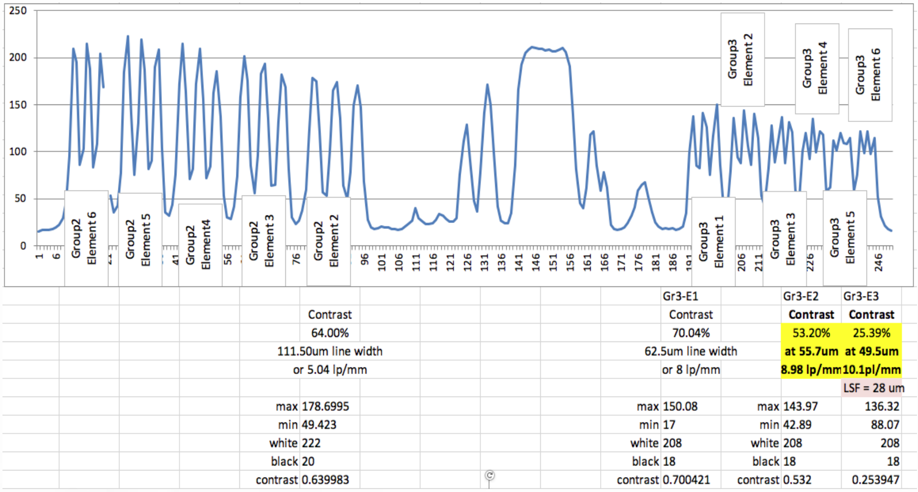
- Measured "contrast" or Modulation Transfer Function (MTF) with standard resolution target.
- MTF simulator uses pattern dimensions to find FWHM resolution corresponding to measured MTF
- MTF = 27% on 49.5µm target
  - Resolution => 66%$_{FWHM}$ (>100µm Required)
- YAG resolution limit due to secondary emissions was found by others [9] to be 30µm in 100µm YAG @ 1.5 – 2 MeV



USAF 1951 Target with line through Group 2 Elements



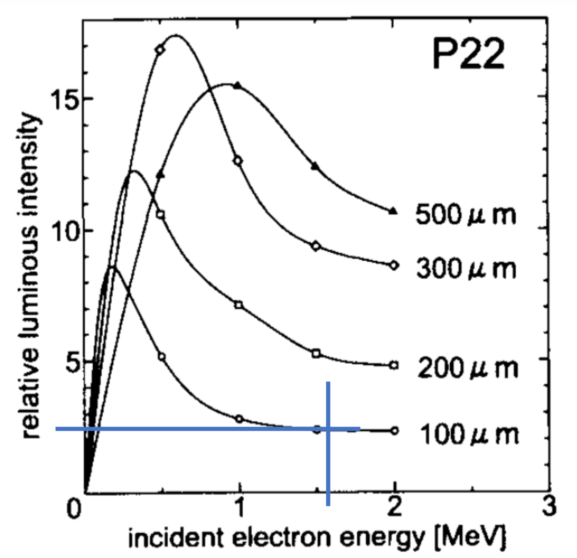
Modulation Transfer Function simulator from resolution of pattern line widths.

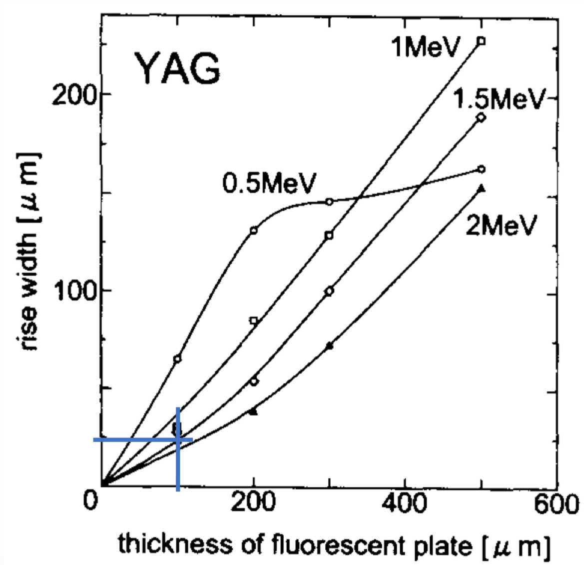


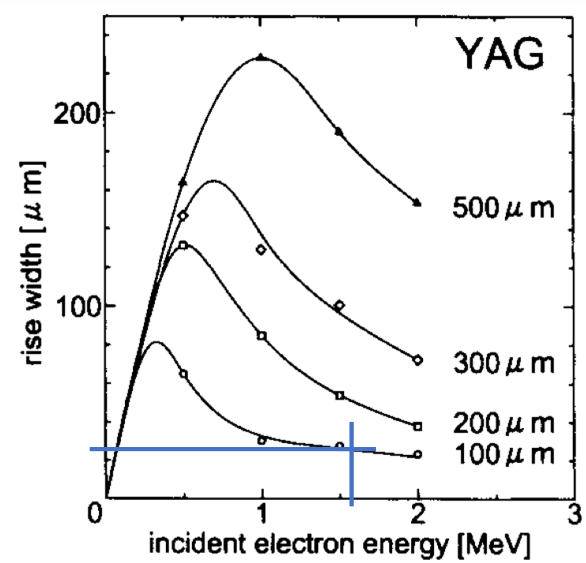
Line profile through Group 2 Elements
49.5um (10.1 line-pairs/mm) in Group 2-Element 3

YAG:Ce Screen Resolution Limit

- YAG resolution limit due to secondary emissions was found by others [9] to be 30μm in 100μm thick YAG @ 1.5 – 2 MeV
    - From a study of electron energy dependence of fluorescence in electron microscopes (1996)







Reference data [9] courtesy of Vladimir Litvinenko, BNL

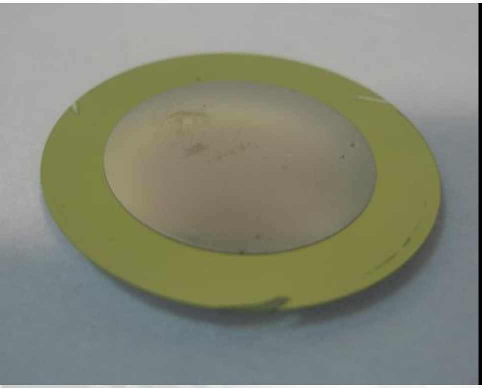
YAG Damage Incident

- Electron Lens Test Bench 2012

- 3 shots of 80μs pulse of 400~500mA beam, 5keV electron beam
- Carbon coated YAG crystal
- Result :
  - ➔ Thermal damage to the crystal
  - Partially still fluorescent during bench inspection
  - Color photo from Blue LED shows blue reflecting area (damaged) and yellow fluorescent area
  - aluminum holder shielded 5mm ring around crystal

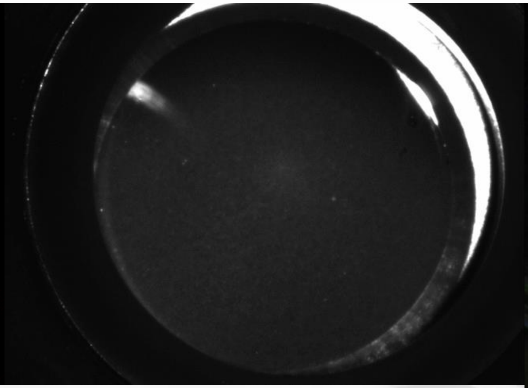
Undamaged area masked by holder

Damaged YAG removed from aluminum holder

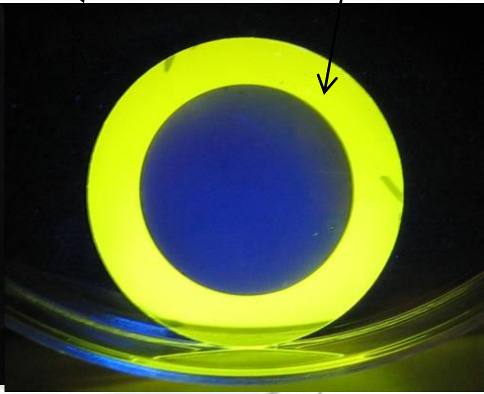


Part of YAG still sensitive to beam – dead lower center

Photo of damaged YAG in vacuum – white illumination

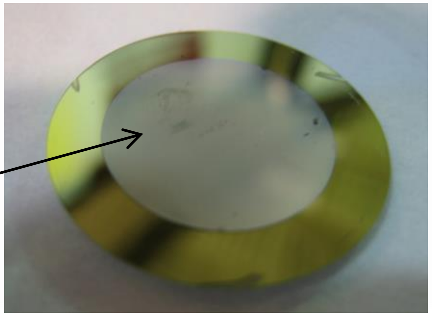


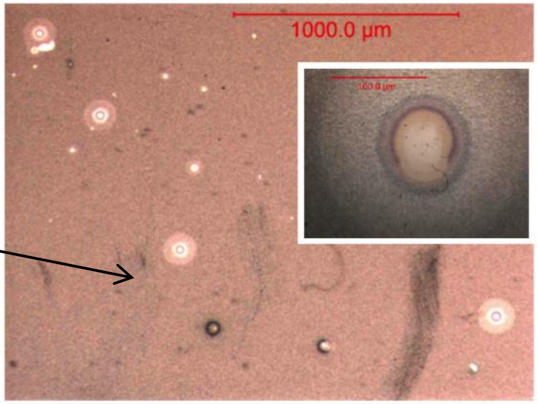
455nm illuminated YAG after removal

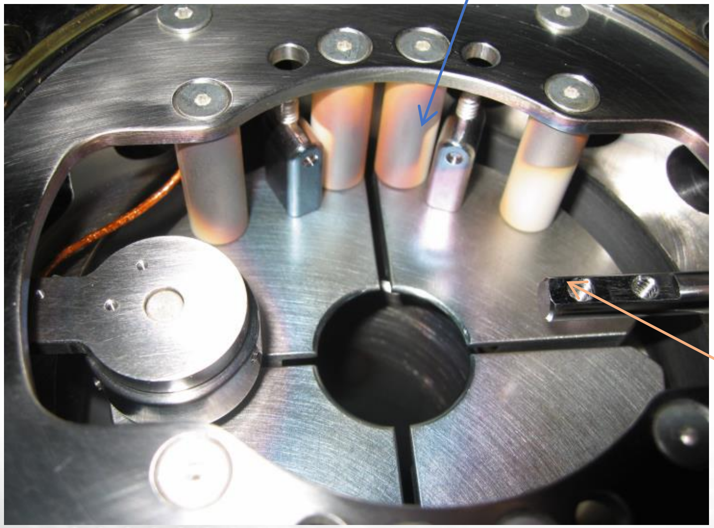


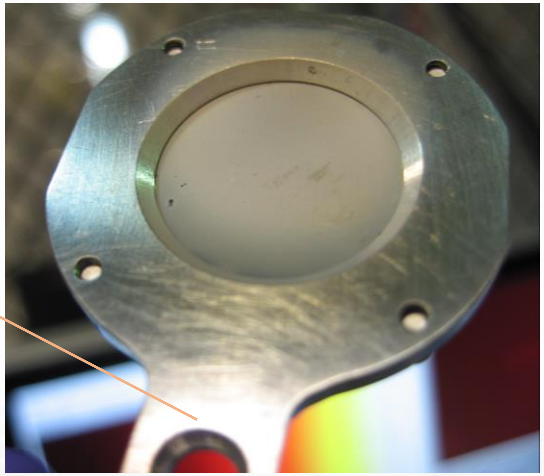
YAG Damage Analysis

- Beam struck carbon coated side but damaged the back side.
- Color: white opaque
- Surface: still smooth
- Micro damage points seen under microscope
- Metal evaporated on nearby insulators

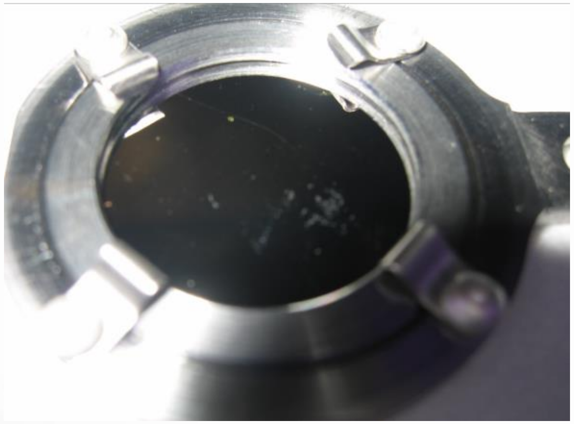






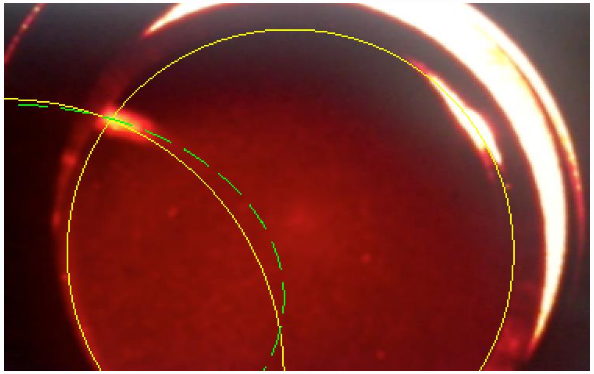


Damaged YAG in aluminum holder (**downstream side**)



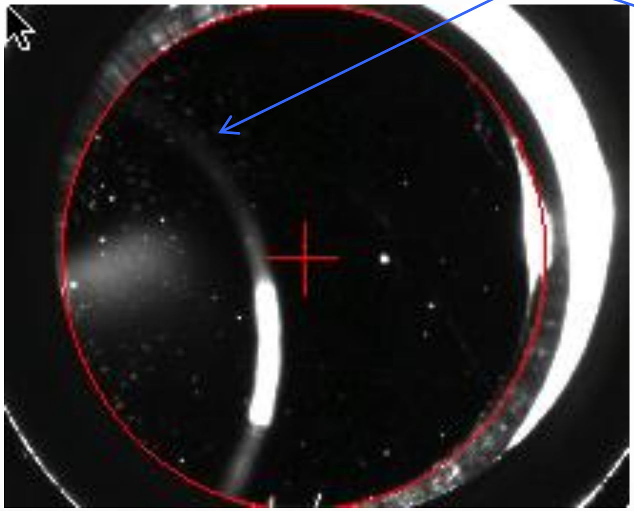
Showing carbon coated side **hit by the beam**.

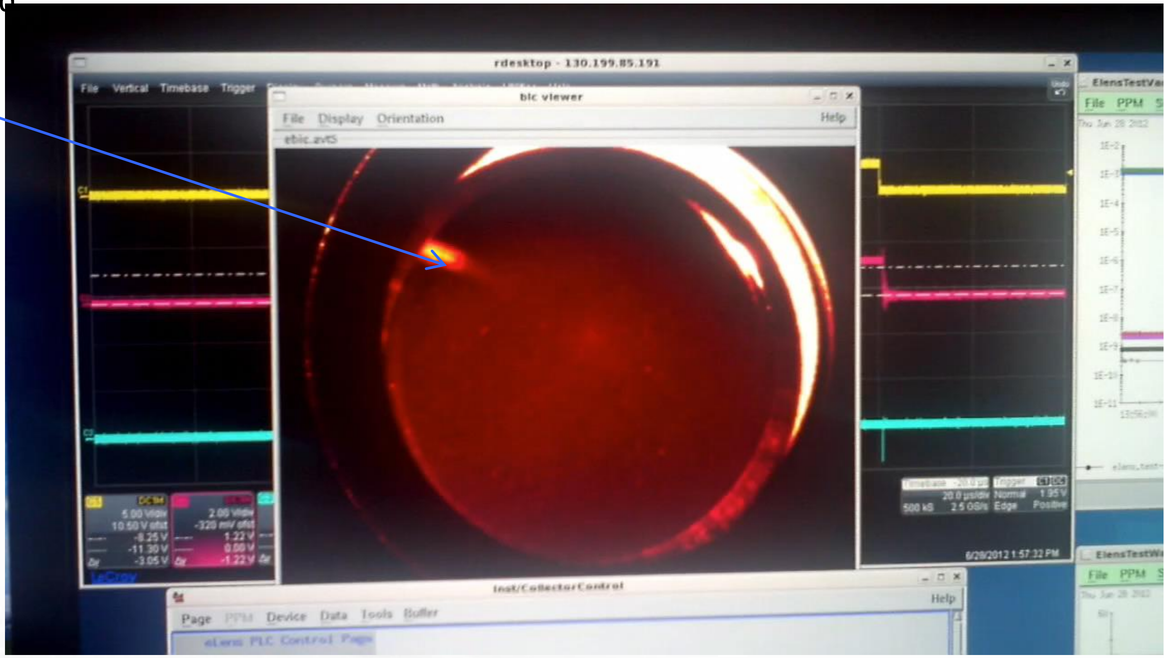
Destructive YAG Test



- Before replacing YAG, the damaging beam pulses were repeated & documented
  - 660mA pulses, 80μs long, 1Hz repetition rate
  - YAG heated so much that deflection was visible after each shot – without fracture
  - Couldn’t reproduce the same permanent surface damage…

Reflection of in polished surface of YAG





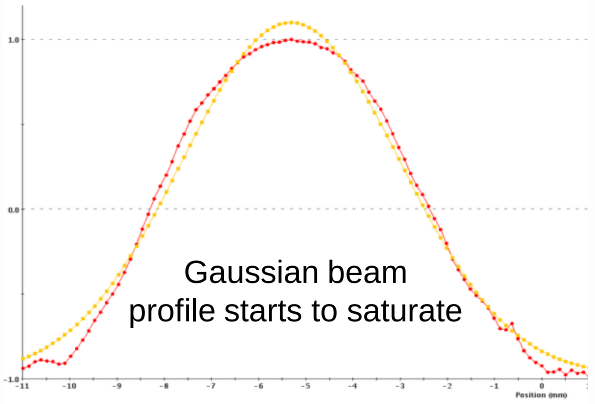
See this video on line at: http://www.youtube.com/watch?v=TOrgEd4AAAI
note: camera trigger was not properly synchronized and doesn’t show every shot.

YAG Crystal Test of Thermal Limits

- Using Electron-Lens Test Bench (2012) – 5keV beam

- Nondestructive Test of Linearity – highest exposure before distortion due to thermal limit
  - 800μs @ 100mA
  - Q_{total} = 80k nC, P = 400mW (500W_{pk})
  - Estimated single-shot Temperature = 310ºC (based on work in [7])

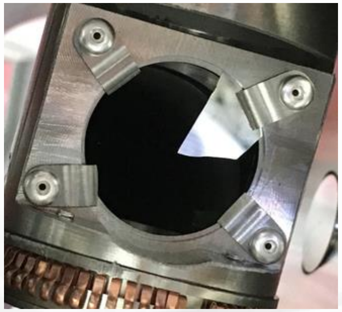
  - 40μS @ ~500mA
  - Q_{total} = 2k nC, P = 100mW (2,500W_{pk})



- Temporary Thermal Saturation
  - 1.2ms @ 100mA – profile distortion (gaussian peak flattening)

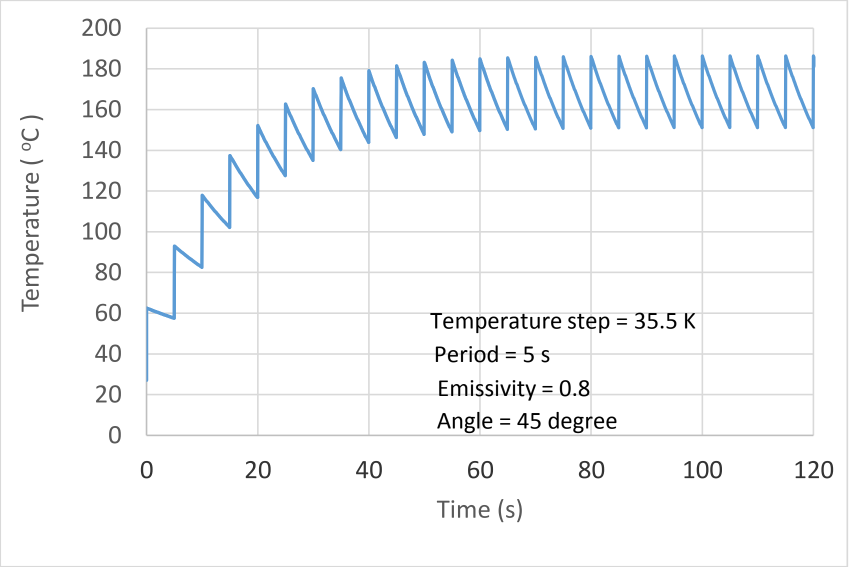
Permanent Thermal Damage (incident)
  - 80μs @ 400 – 500mA (3 shots in < 3s) – surface damage

Destructive Test of Maximum Power
  - 80μs @ 660mA – visible flexure of the crystal without fracture
  - 1.2ms @ 100mA (3 shots in < 3s) – fracture



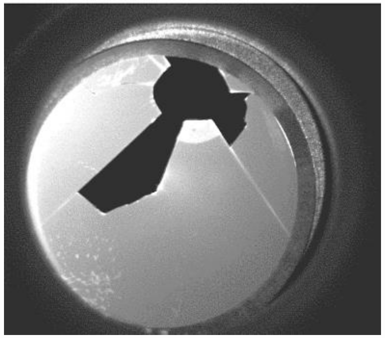
YAG Exposure Limit Simulation

- The YAG screen for Longitudinal Phase Monitor required a 250us long electron beam pulse train, 2 MeV, 35mA.
- Based on recommended maximum operating temperature of 200ºC, a steady state temperature was found [7].
  - one pulse train => +35.5ºC in the YAG
  - Assuming black body radiant cooling & 100% emissivity, steady state Temperature < 200ºC is reached with 40-50s with pulse interval of about 5 sec.

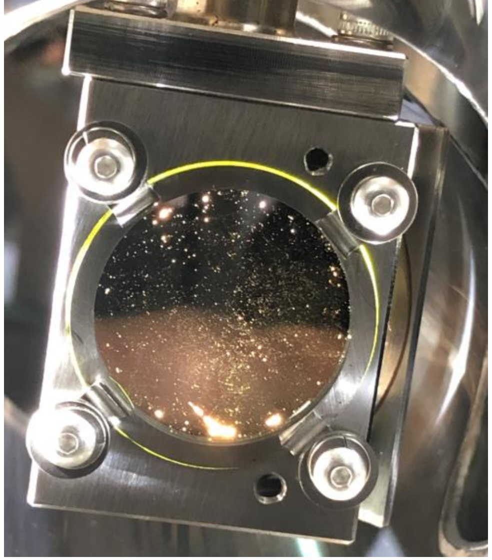


YAG:Ce Screens Casualties

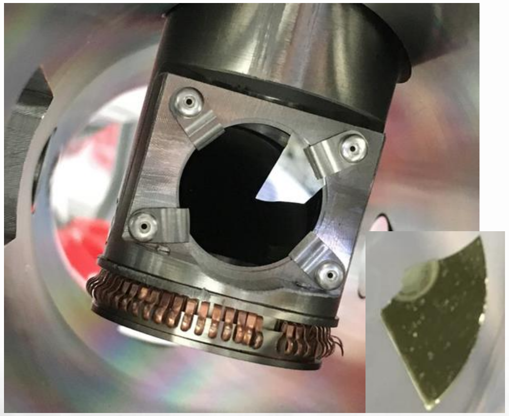
- 2012 eLens Test Bench
  - #1 dc beam due to loss of gun control
- 2017 LEReC
  - #2 dc beam due to laser leakage
- 2018 CeC
  - #3 gun dark current
  - #4 Crack (cause unknown)
  - #5 Coating damage (cause unknown)
  - #6 apparent scratches (nature unknown)



eLens: Sept 2012
DC beam

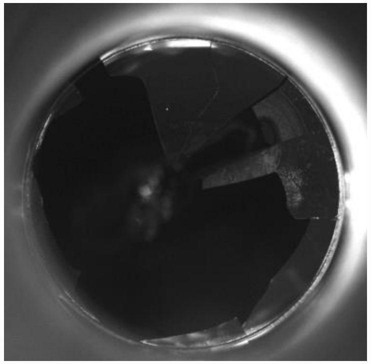


CeC: 1/14/19 – Damaged Coating
(gc2.mod.yag)

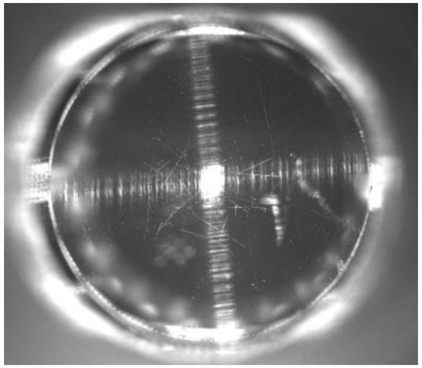


LEReC: 6/17 – Laser Leakage
(lecs1-inj.yag1-fc)

CeC: 8/18 – Crack
(ca2-acc.yag)



CeC: 5/14/18 – Dark Current
(ca2-inj.yag1)



CeC: 2017 – scratches
(ca2-dlg.yag)

Crystalline CsI(Tl) Screen

Thallium-doped Crystalline Cesium Iodide

- A profile monitor with a CsI(Tl) scintillator screen was used [10] to help separate/select Xenon isotopes for the purpose of generating isotopically pure beams of singly charged ions with modest intensity, which can be used at NSRL and also accumulated by RHIC.
- A CsI (Tl) screen has been successfully used to optimize mass resolution of the separator.
- **<u>Details</u>**
  - CsI(TI) screen vendor was Marketech International
  - No coating, just optically transparent CsI(Tl) crystal
  - Size – 80 x 40 x 3 mm
  - We used fine grounded mesh on the front crystal surface to prevent charge build-up
  - It has two decay components – fast (100 ns) and slow (1 us). We used single pulse mode.
  - We didn't study threshold energy. It was pretty impressive to have recordable signal for 14 keV energy and 100 nA/ms intensity.

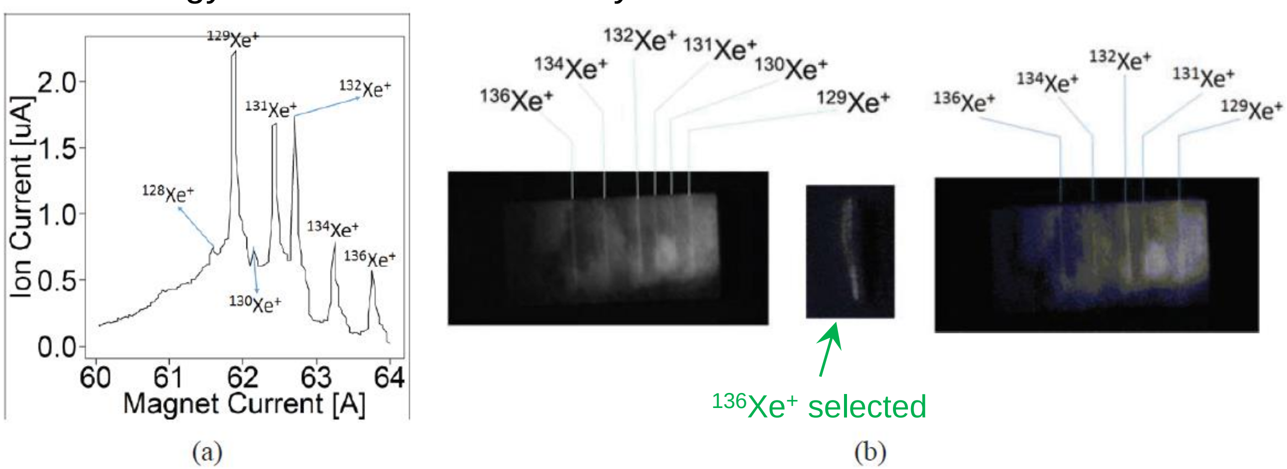


FIGURE 2. Resolved xenon isotopes (ion beam energy – 25 keV, dipole magnet input slit was fully open): (2a) – dipole magnet scan with output slit width set to 0.6 mm; (2b) – scintillator images for lower ion beam current (on the left), higher ion beam current (on the right) and $^{136}Xe^+$ ion beam selected by dipole magnet output slit (in the middle).

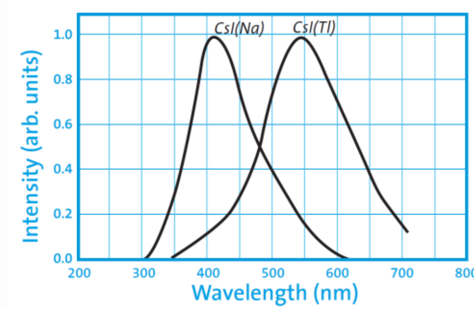


Figure 1. Scintillation emission spectrum of CsI

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Reference: "Isotope separator for external ion injection into EBIS" S. Kondrashev et al, 2018, AIP Conf Proceedings

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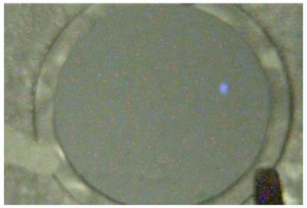
BNNT “Bucky Paper”
R&D Screen for High Power Profile Monitor

- Boron Nitride NanoTube (BNNT) pressed 50um “paper” screen
  - 2.6 mg/cm^2 density
  - Thermally conductive
  - Hi melting point at 2,973ºC
- Application: Possibly only solution for direct imaging of high power low energy beam transverse profiles.
  - Critical for LEReC – reconcile discrepancies between single MacroBunch (MB) and CW beam conditions.
  - Must confirm match of e-beam to ion-beam profiles with 38mA CW e-beam
- Tests:
  - High energy low power test at JLAB - Done
  - Low energy low power test at BNL - Done
  - Low energy high power test at BNL- planned

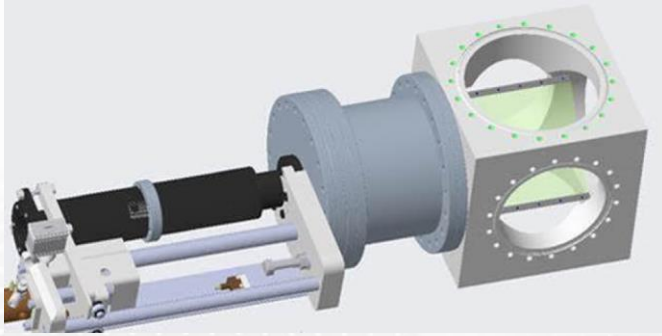
Sheets of BNNT Paper
at various stages of processing

Photos & data courtesy of
Kevin Jordan, BNNT, LLC

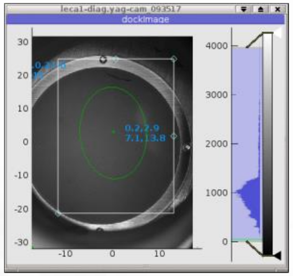
Beam Test at JLAB
11GeV, 10nA



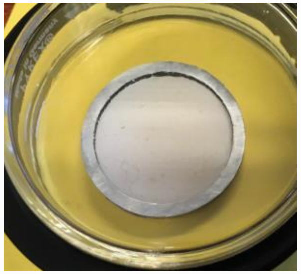
Hi power BNNT screen
profile monitor development



60mm BNNT screen
installed in LEReC



60mm BNNT screen
prepared for BNL



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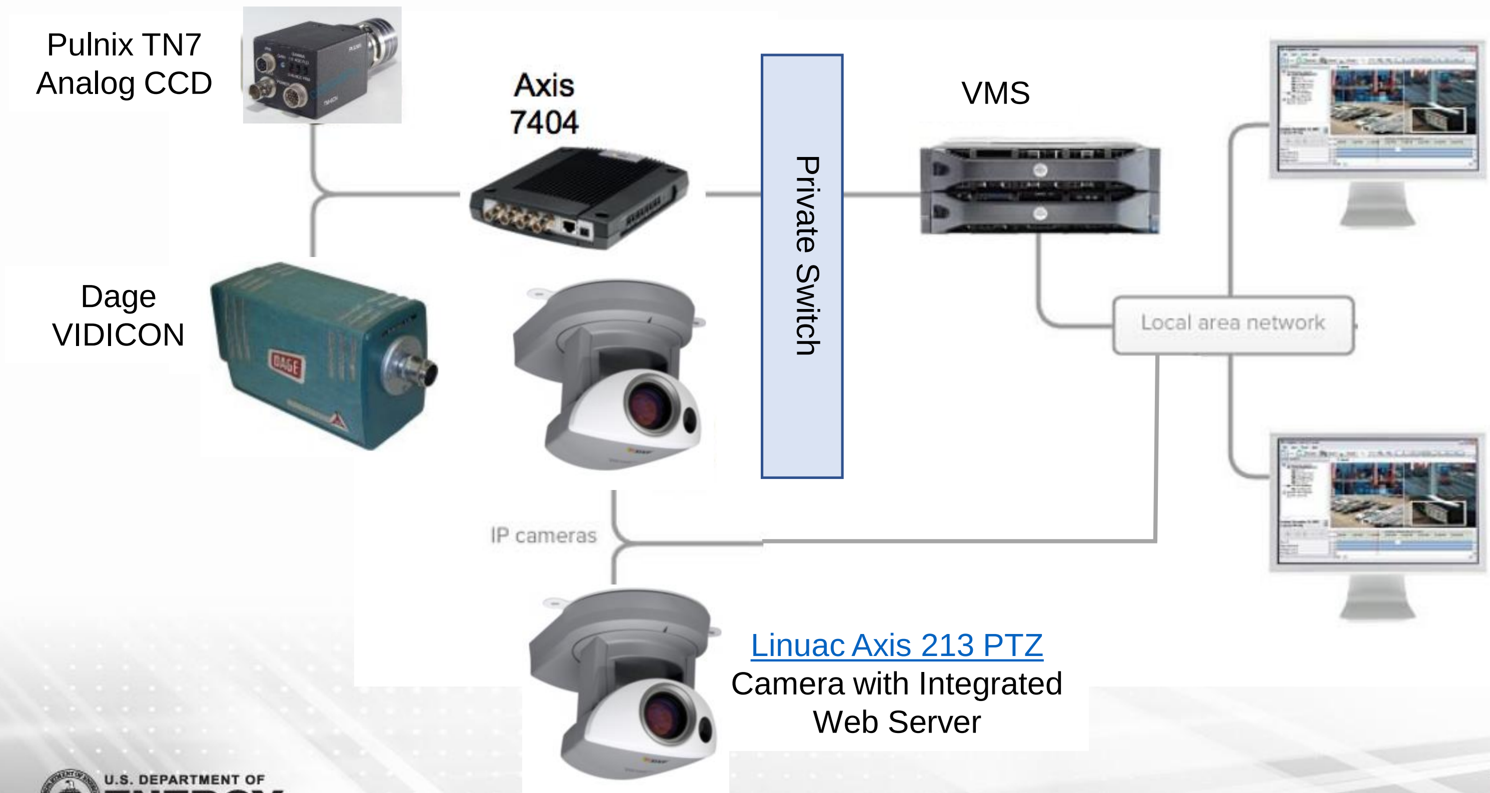
Analog & IP camera Video system

- Video Management Server (by IPVideo Corp) https://ipvideocorp.com
  - Receives video from 4-ch analog to IP converters (Axis 7404)
  - Private network feeds all converters to server
  - Continuous loop recording (MPG) for 1 week
  - Published video streams accessible via web browsers



Camera & Lens Choice and Experience

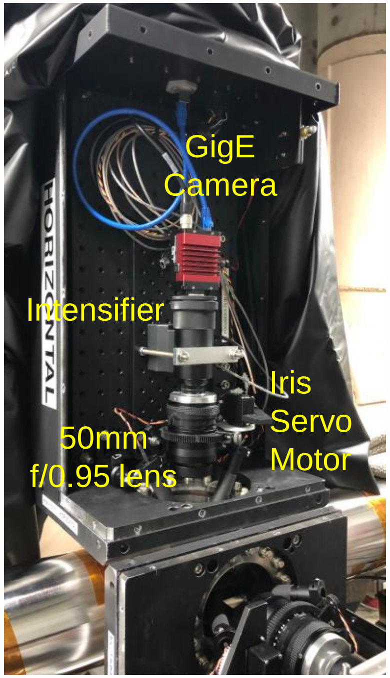
- GigE cameras for Profile Monitors
  - AVT Prosilica GT1600 – 1/1.8” ICX274 CCD sensor
    - 12 bit, 4.4um pixel, 26dB gain, 2MP, 8.8e$^-$ Dark Noise, 4,900e$^-$ Saturation
    - Manual Iris control through camera parameters (stepper controlled)
  - Edmund Optics HD P-Iris lens - 50mm, f/2.0
    - 5 MegaPIxel Imaging
    - P-Iris stepper motor control: f/2.0 – inf / 42 steps
  - Camera Failures

Qty	Failure Type	Repair Type	Possible Cause	Location
3	Iris control failures	warranty repairs	High Dose Area	Merger line
1	imaging failure (warranty repairs)	warranty repairs	High Dose Area	Merger line
1	total camera failure	paid repair @ 50% cost of camera	Unknown	Near Gun

Allied Vision Technology GT series, GigE


Edmund Optics HD P-Iris Lens

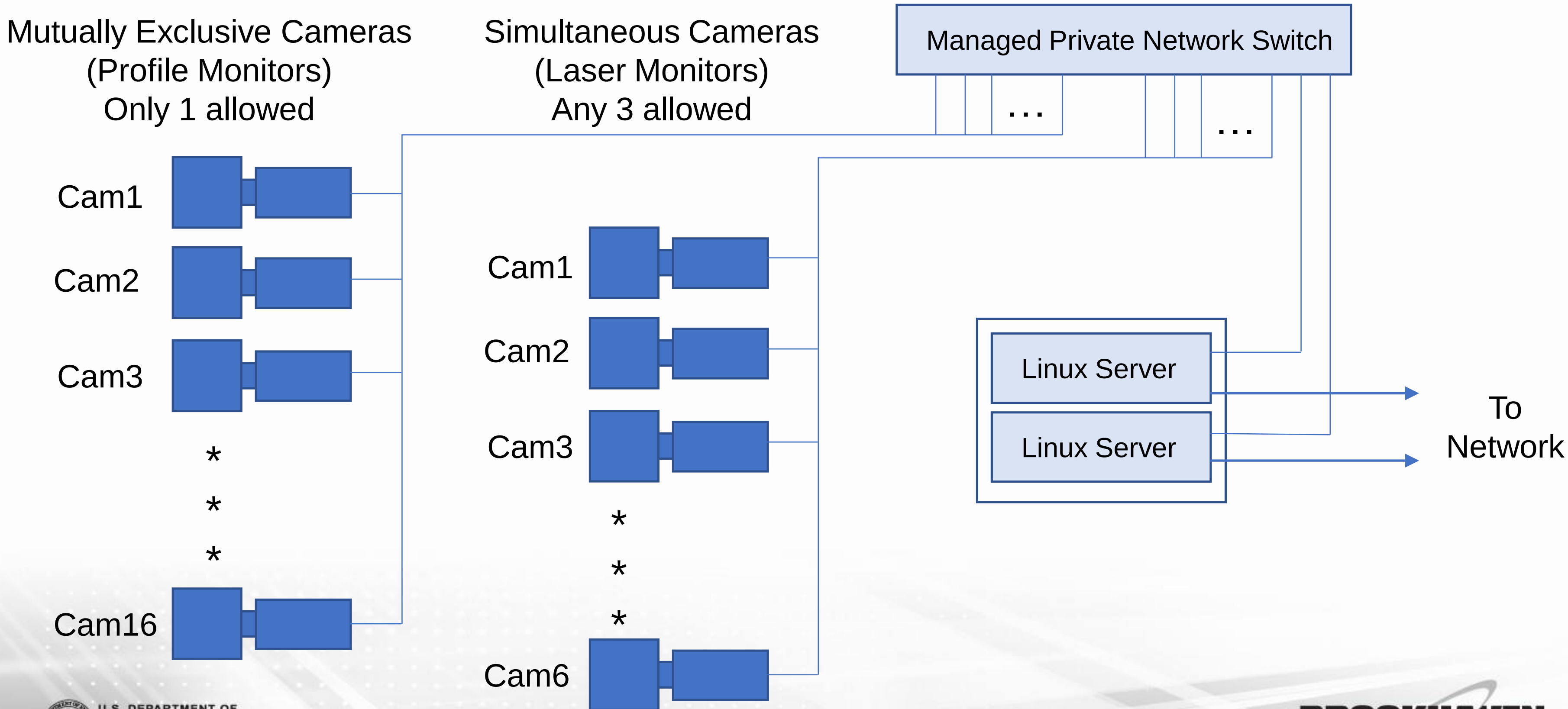
- GigE cameras for Low Light for **B**eam **I**nduced **F**luorescence (BIF) Monitor:
  - Prosilica GT1930 – 1/1.2” IMX174 CCD sensor
    - 12 bit, 5.8um pixel, 40dB gain, 2.35MP, 3.3e$^-$ Dark Noise, 32,810e$^-$ Saturation
    - Manual Iris control through camera parameters (stepper controlled)
  - Image Intensifier from Photonis – 18mm MCP, Hi-QE Green photocathode, Glass input window, P43 output phosphor on Fiber-optic plate
    - Photocathode response: 30% @ 380 - 480 nm
    - Photon Gain @ 440 nm: 9,000 - 11,000
    - Resolution: 64 linepairs/mm
- Controls
  - In-house developed driver using Aravis open source library
  - External hardware-triggered acquisition
  - Not using power of Ethernet… need control of power cycle to reset cameras



Camera + Intensifier for BIF Monitor

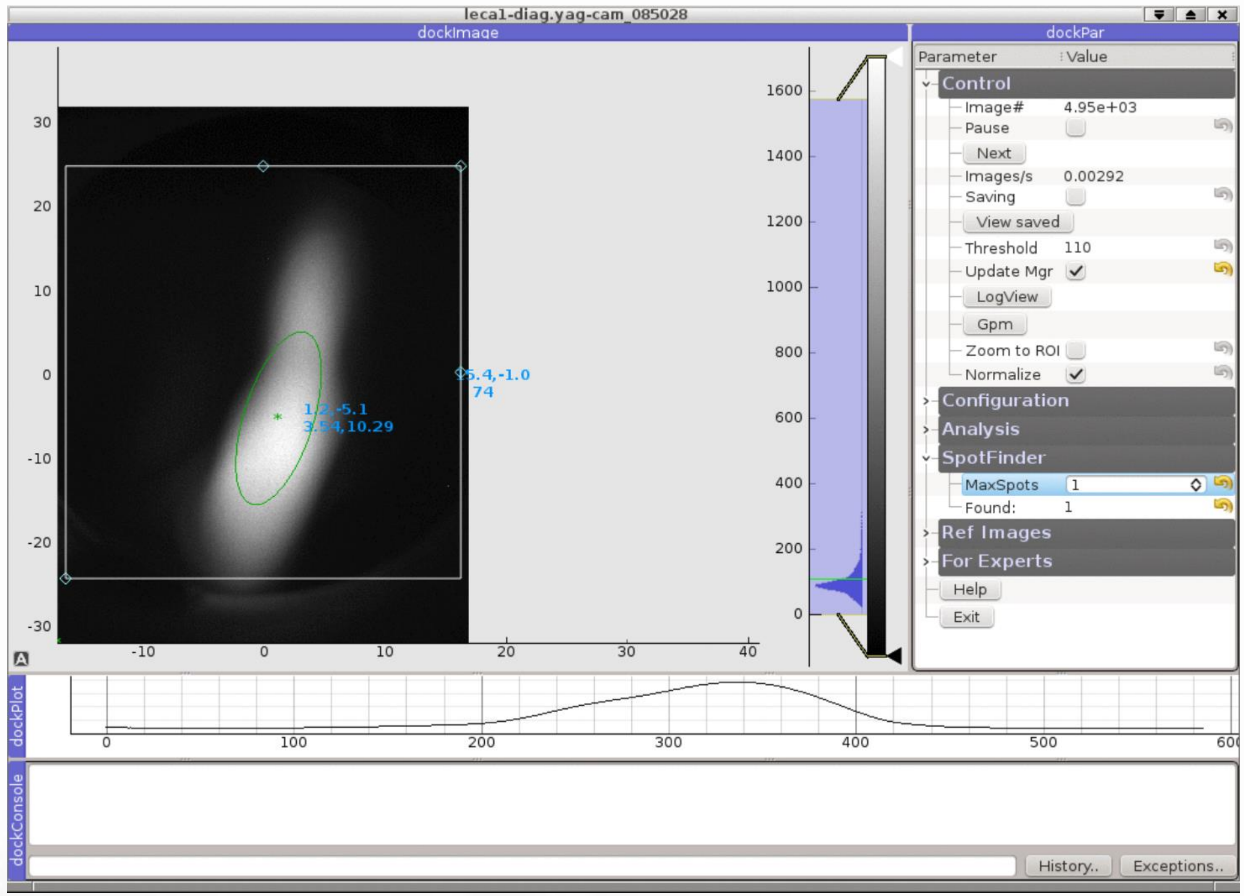
Camera Network & Controls

- Linux server runs camera managers
  - Dual NIC – 1) camera switch, 2) publishing to outside network
  - Manager software developed with open source Aravis Library
- Private network for cameras
- Hardware trigger (fan-out to all cameras) – Trigger Rate = 1 Hz
- Managed power supply chassis for individual camera power cycle



Camera Image Data & Viewer

- Image Viewer User Application
  - Images from cameras continuously analyzed and logged
  - Logged Image Data
    - Spot position (X, Y)
    - Spot size (Ellipse: W, H)
    - Fitted Sigma
    - Fitted position (X,Y)



Conclusion

A variety of scintillator screens have been used at the RHIC Facility over the years in the proton & ion beam lines that remain in service.

The new additions of integral electron machines has moved shifted focus to new monolithic YAG for pulsed beams with good results.

We continue to search to fill the need for continuous profile measurement of low energy, high power CW electron beams during operations.

Thank you for your attention

Special thanks to Kevin Jordan at BNNT,LLC and to the members of the C-AD Beam Components & Instrumentation Group at BNL.

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