Comparison of Optical Transition, Diffraction, and Thermal Radiation

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U.S. DEPARTMENT OF ENERGY
Office of Science

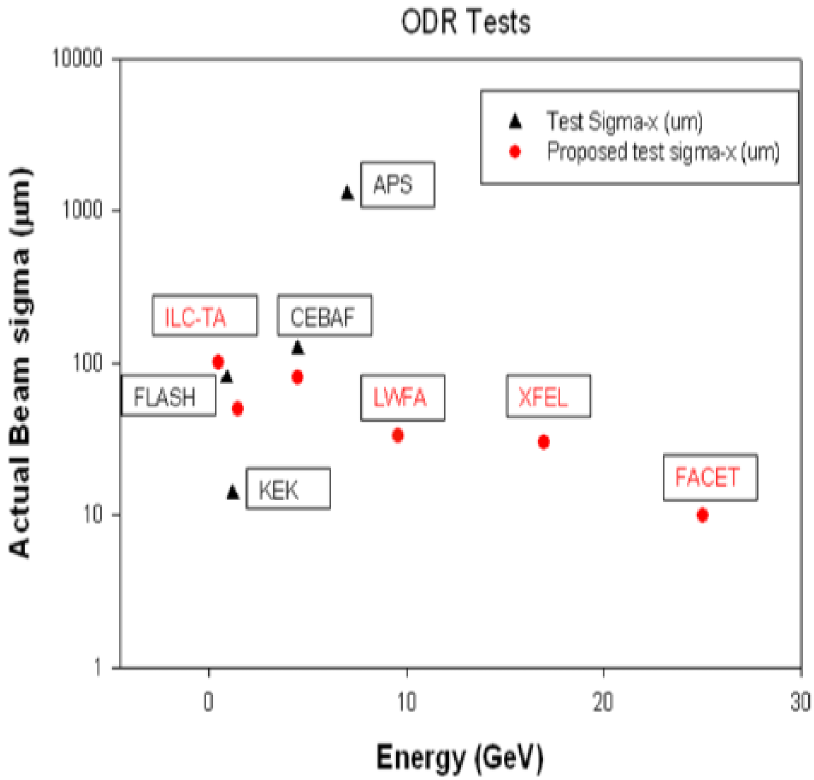
SLAC NATIONAL ACCELERATOR LABORATORY

About Myself

- **Oakland University** – Rochester, MI
  - B.S. **Physics**
  - B.S.E. **Mechanical Engineering**
- Physics Graduate Student at **Stanford**
- Previous Experience
  - **Manufacturing Engineering** Company – FATA Automation/Aluminum
  - REU at **Michigan State (NSCL)** in **Nuclear Physics**
  - REU at **Cornell** in **Accelerator Physics**
  - **Theoretical Radiation Biophysics** at Oakland
  - **Tutoring** and **Teaching** Physics, Math, and Engineering at Oakland
  - **SLAC's** ATLAS group at **CERN** in HEP

Goals and Motivation

- See if **Optical Diffraction Radiation** is a legitimate beam diagnostic tool at FACET
  - **Calculations** and **experiment**
  - Motivation is a **less invasive** spot size measurement
  - Measurements performed at other laboratories
- Compute the effects of **Optical Thermal Radiation** to see if it can interfere with OTR beam size measurements



Optical Transition Radiation (OTR)

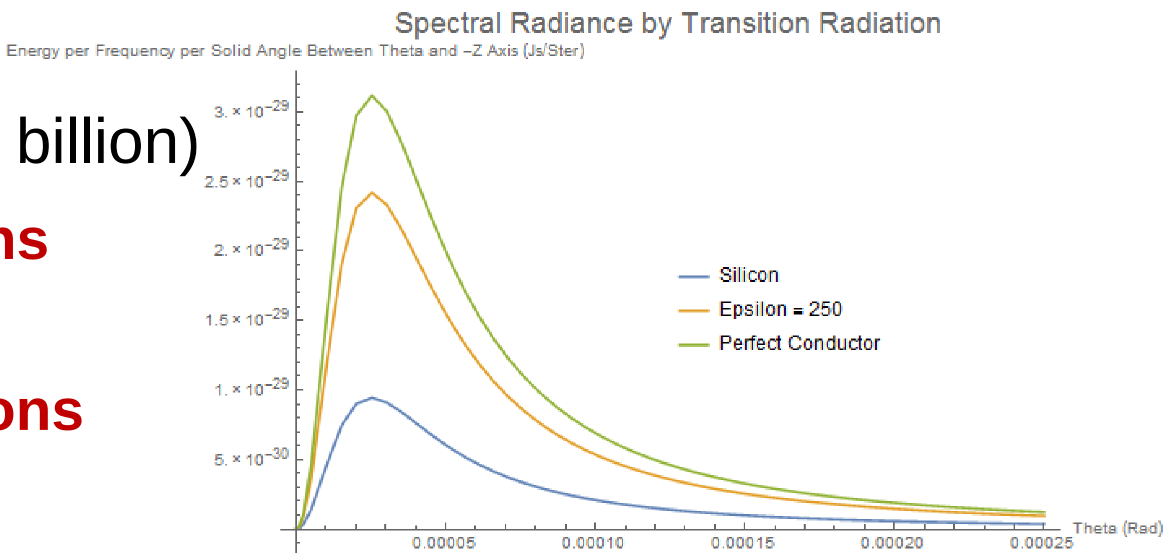
- Spectral Intensity of Optical Transition Radiation (OTR)

$$\frac{dW}{d\Omega d\omega} = \frac{e^2\beta^2\sin^2\theta\cos^2\theta}{\pi^2 c(1-\beta^2\cos^2\theta)^2} \times \left(\frac{(\epsilon-1)(1-\beta^2+\beta\sqrt{\epsilon-\sin^2\theta})}{(1+\beta\sqrt{\epsilon-\sin^2\theta})(\epsilon\cos\theta+\sqrt{\epsilon-\sin^2\theta})}\right)^2$$

- For a perfect conductor, $\varepsilon \to \infty$

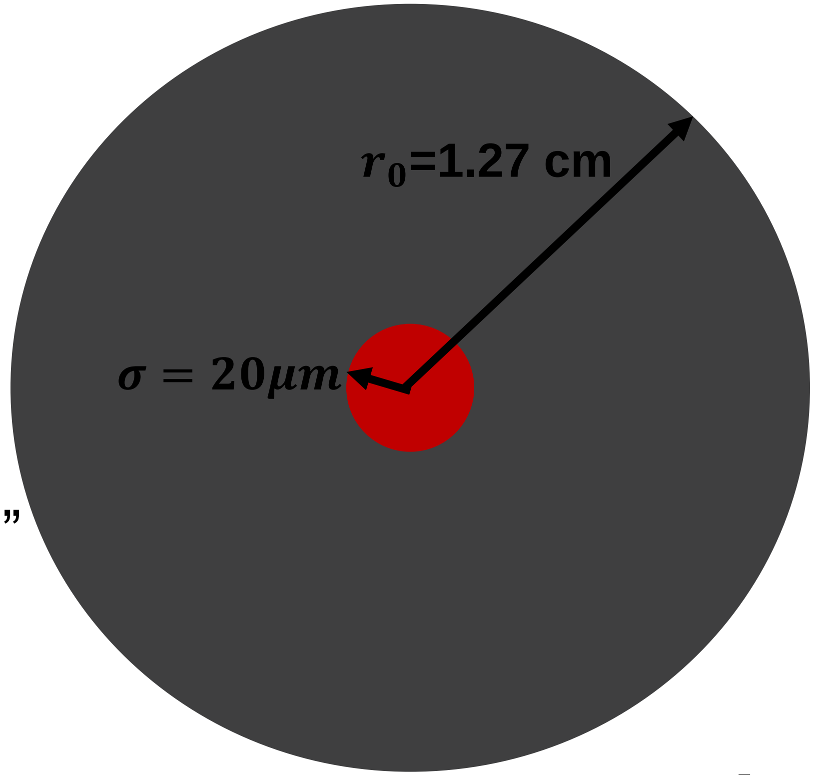
$$\frac{dW}{d\Omega d\omega} = \frac{e^2\beta^2\sin^2\theta}{\pi^2 c(1-\beta^2\cos^2\theta)^2}$$

- Total Intensity (N=20 billion)
  - **3.39×10^9 photons for titanium**
  - **0.856×10^9 photons for silicon**



Optical Thermal Radiation – Statement of Problem

- How does the radiation given off by **OTR** compare to the **thermal radiation** from the heated foil in the visible range?
- Will this interfere significantly with measurements from cameras?
  - Analyze **Steady State**
  - Analyze **“flash”** immediately after energy deposition
- Assumptions
  - Neglect Radiation for Steady State
  - Negligible Conduction for “flash”
  - Uniform Temperature



Optical Thermal Radiation (Steady State)

- **Total Power** *P* delivered to a point on a screen of thickness δ = 25 μm for a beam with 10 billion electrons, *N*, and a pulse repetition rate, *PRR*, of 10 Hz is **< 1 mW**

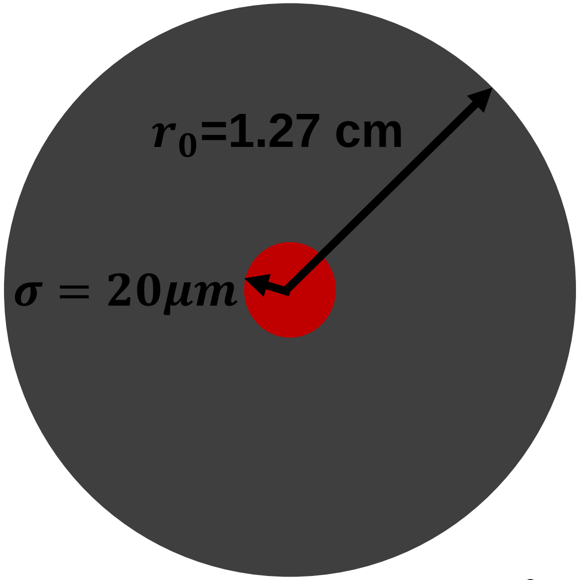
$$P = -\rho \frac{\mathrm{d}E}{\mathrm{d}x} \times N \times PRR \times \delta$$

- **Temperature difference** between foil and surroundings is **< 0.1 K**

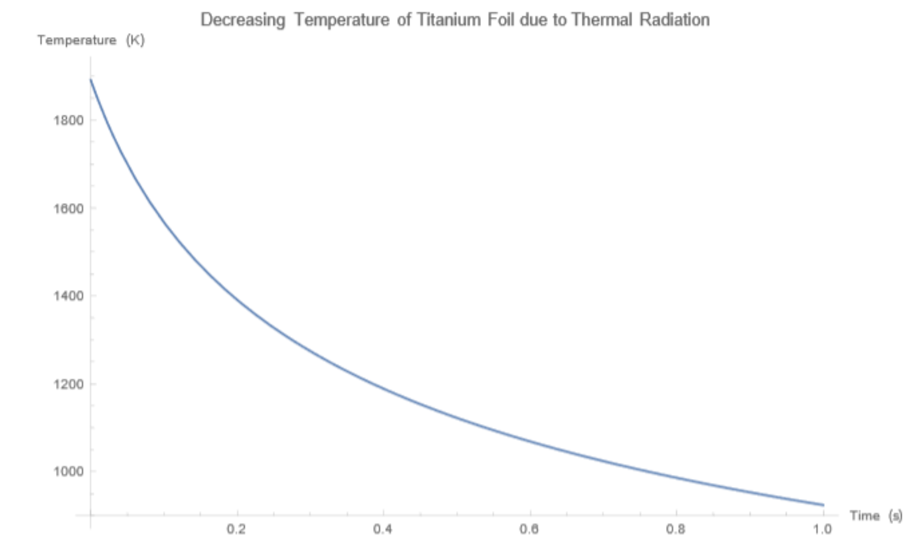
$$T_o - T_i = \frac{S\sigma^2}{4K}$$

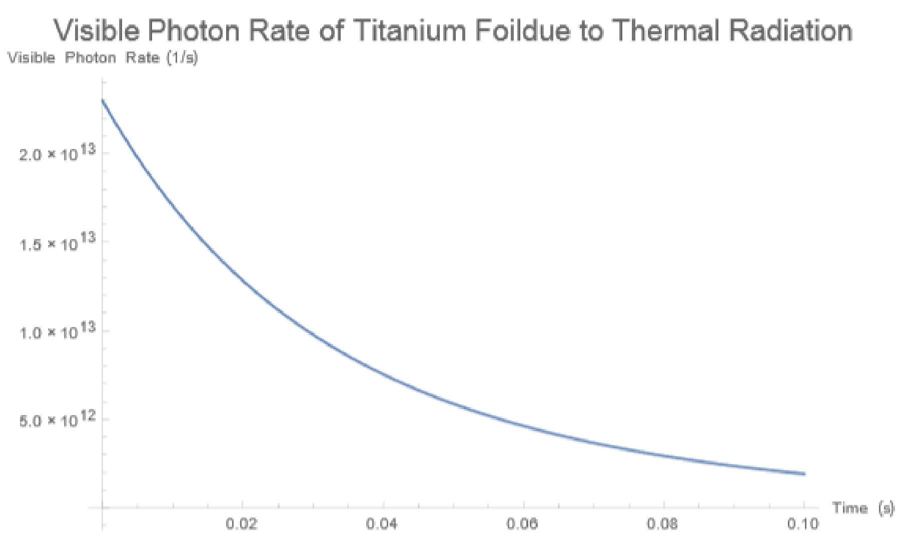
- **Temperature difference** between foil and beam spot is **< 1 K**

$$\Delta T = P' \frac{ln(\frac{r_o}{\sigma})}{2\pi k}$$



Optical Thermal Radiation





- How much light from a “**flash**?”
- Neglect radiation on foil due to surroundings
- Ignore conduction and start at a temperature just below melting

$$T(t) = T_h \left(1 + \frac{6\epsilon\sigma}{\delta\rho c_p} T_h^3 t\right)^{-\frac{1}{3}}$$

- Takes a **“long time”** to cool down

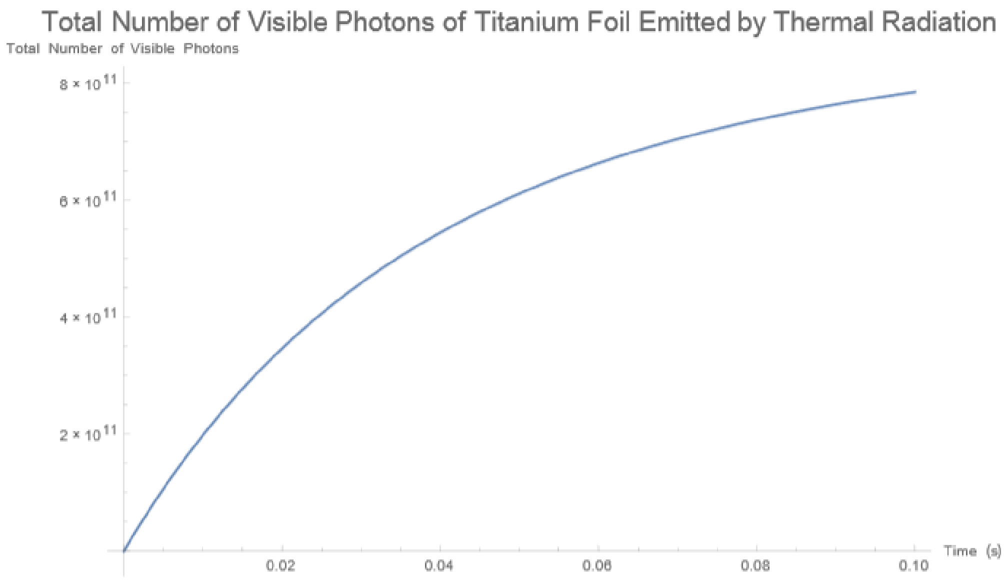
$$n(t) = 4\pi^2\sigma_r^2 c\lambda_{avg} \int_0^t \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T(t')}} - 1} d\lambda dt'$$

Optical Thermal Radiation

- For a small time interval, say 10 ms, number of photons can be approximated

$$n(t) \approx 4\pi^2\sigma_r^2 c\lambda_{avg} \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} d\lambda \times t$$

  - **$\mathbf{0.11 \times 10^9}$ for titanium**
  - **$\mathbf{0.018 \times 10^9}$ for silicon**
- OTR ~**10 times** more intense than thermal for titanium
- ~**40 times** more intense for silicon

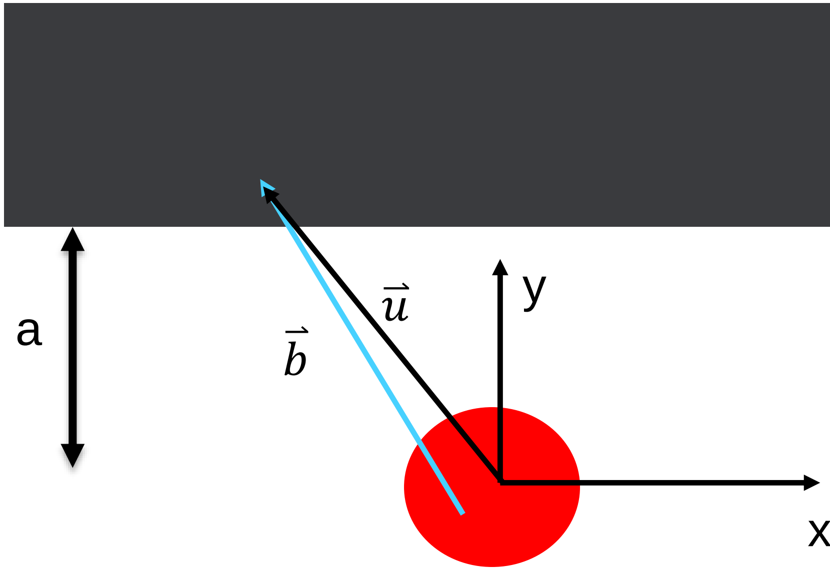


Optical Diffraction Radiation (ODR)

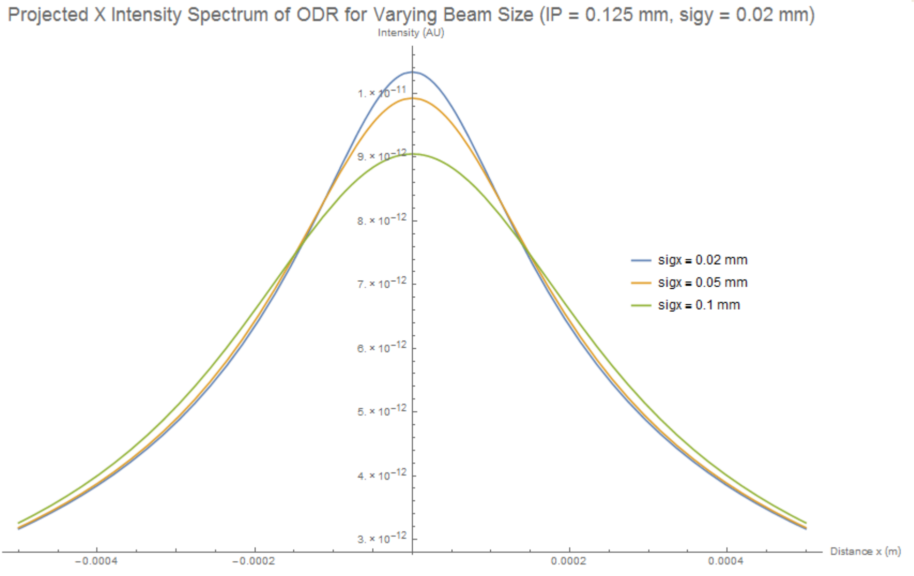
- The optical diffraction radiation (ODR) due to an incident beam passing near a **flat edge**

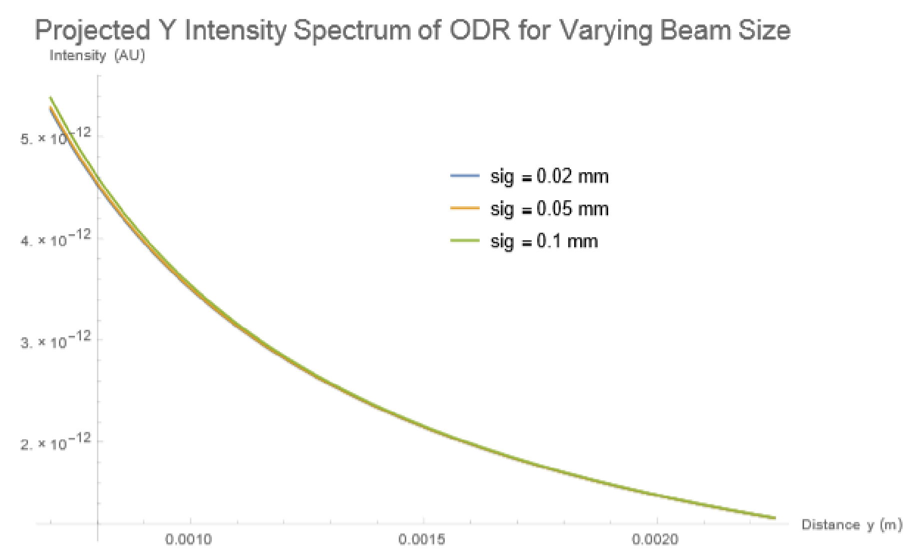
$$\frac{dI}{d\omega}(u_x, u_y, \omega) = \frac{e^2}{\pi^2 c \beta^2} \frac{1}{(\gamma\lambda)^2} \frac{N}{2\pi\sigma_x\sigma_y} \int\int K_1^2 \left(\frac{1}{\gamma\lambda} \sqrt{(u_x - x)^2 + (u_y - y)^2} \right) e^{-\left(\frac{x^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}\right)} dx dy$$

- *a* is the **impact parameter** – shortest distance from the foil to the center of the beam



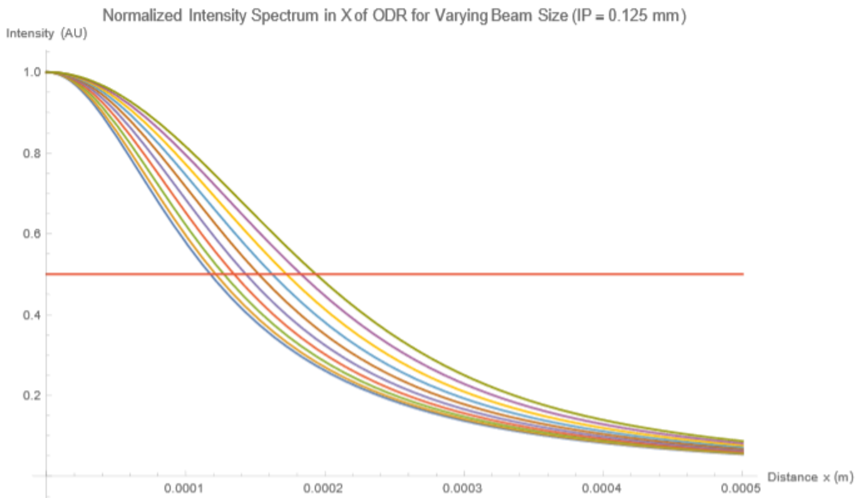
Optical Diffraction Radiation

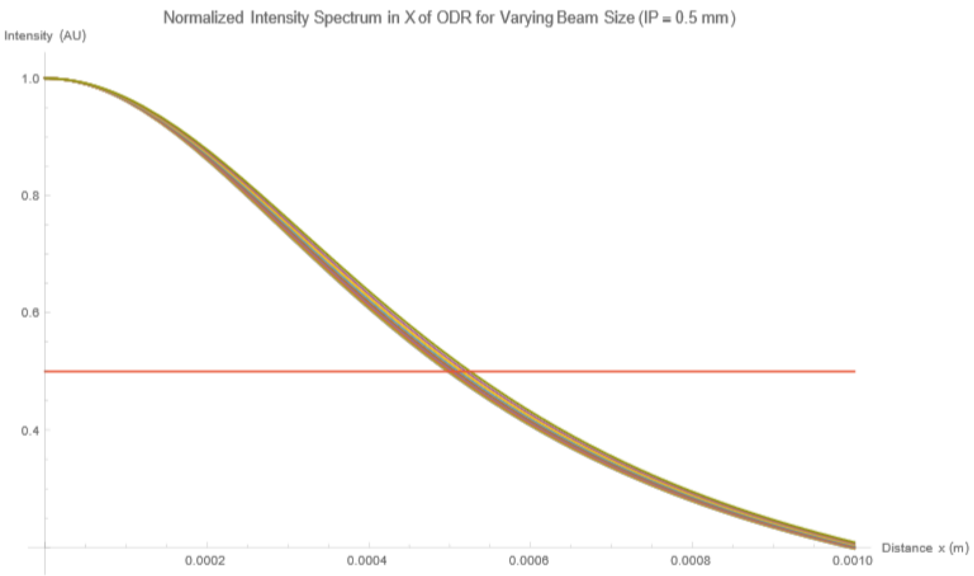




- Top – **x intensity** for varying beam size
  - **IP = 0.125 mm**
  - σ_y = 0.02 mm
- Bottom – **y intensity** for varying beam size
  - **IP = 0.125 mm**
  - σ_y = 0.02 mm

Optical Diffraction Radiation

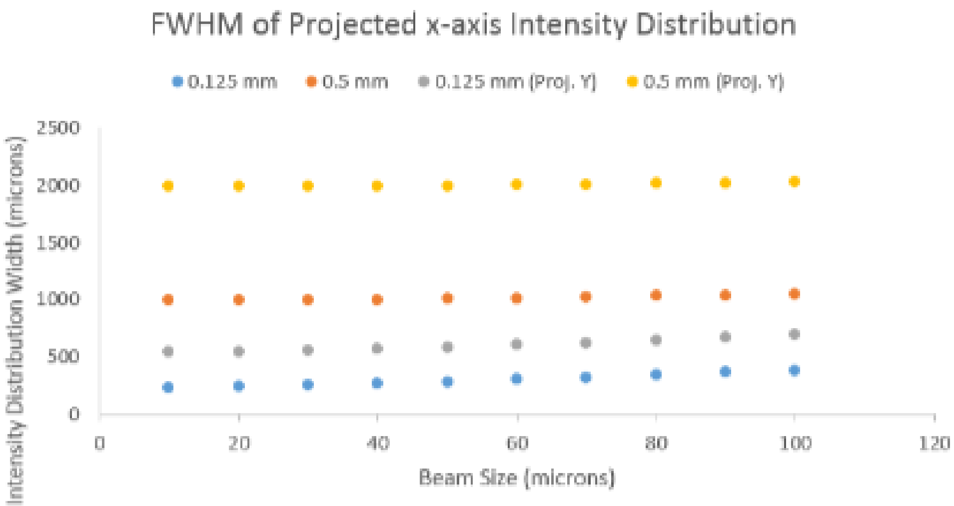


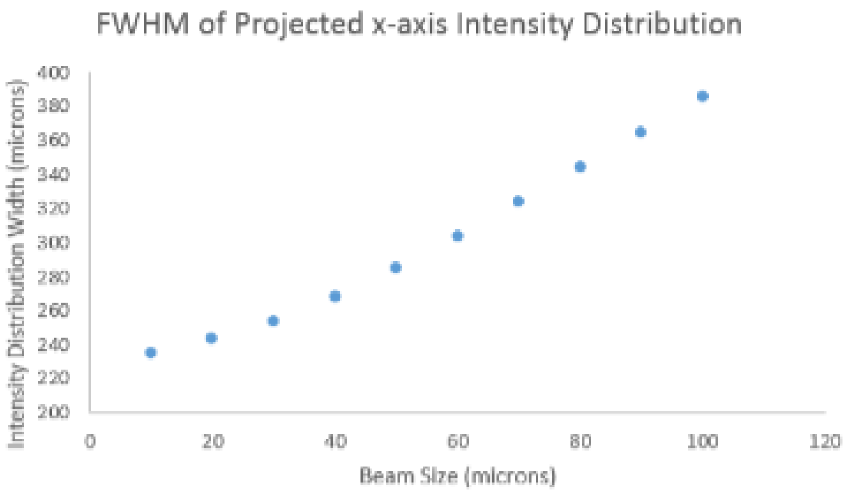


- Top – **x intensity** for varying beam size
  - **IP = 0.125 mm**
  - σ_y = 0.02 mm

- Bottom – **x intensity** for varying beam size
  - **IP = 0.5 mm**
  - σ_y = 0.02 mm

Optical Diffraction Radiation





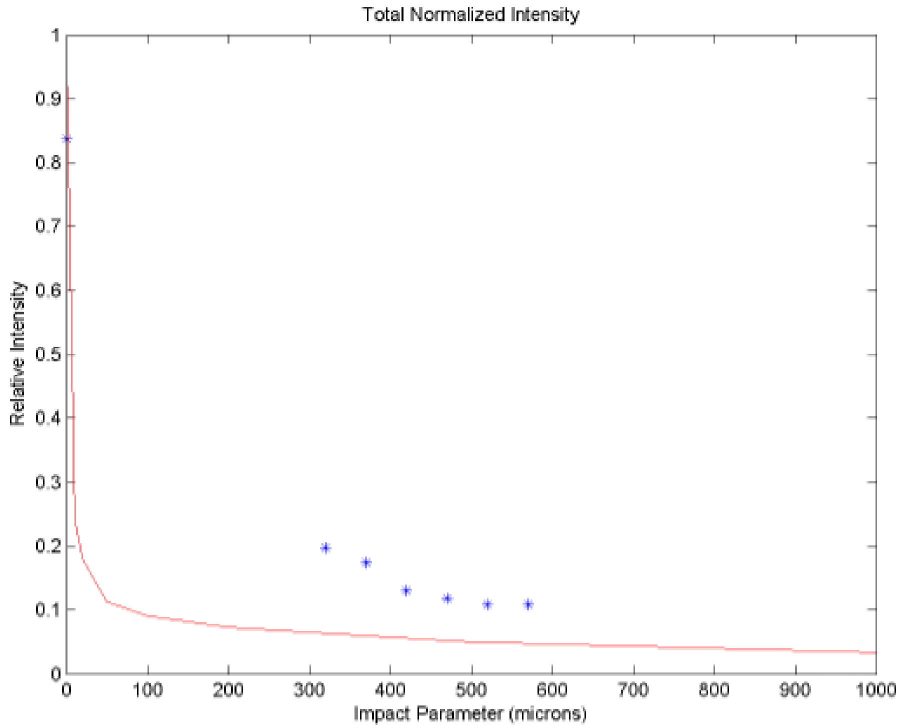
Beam Size (microns)	Width (microns) IP = 125 microns	Width (microns) IP = 500 microns	Width (microns) IP = 125 microns, Proj. Y	Width (microns) IP = 500 microns, Proj. Y
10	235	994	540	1986
20	244	996	546	1987
30	254	999	556	1988
40	268	1003	570	1992
50	285	1008	588	1996
60	304	1015	606	2002
70	324	1022	625	2008
80	344	1030	646	2014
90	365	1039	670	2022
100	386	1050	692	2030

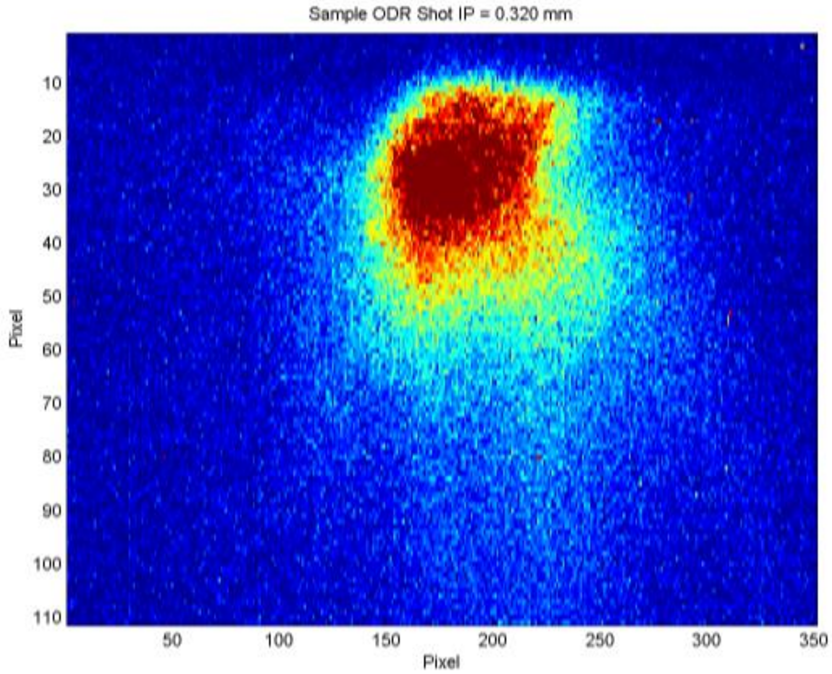
Calculation Conclusions

- OTR calculations for silicon and titanium complete.
  - Silicon is about **¼ the intensity** of titanium
- Optical thermal radiation is not a major factor in **steady state**
- At worst cast scenario, **OTR dominates** optical thermal radiation in both silicon and titanium
- ODR should be successful in measuring **large beam size**
- ODR may not be successful for measuring **smaller beam size**
- Calculation of ODR’s **polarization components** may be necessary

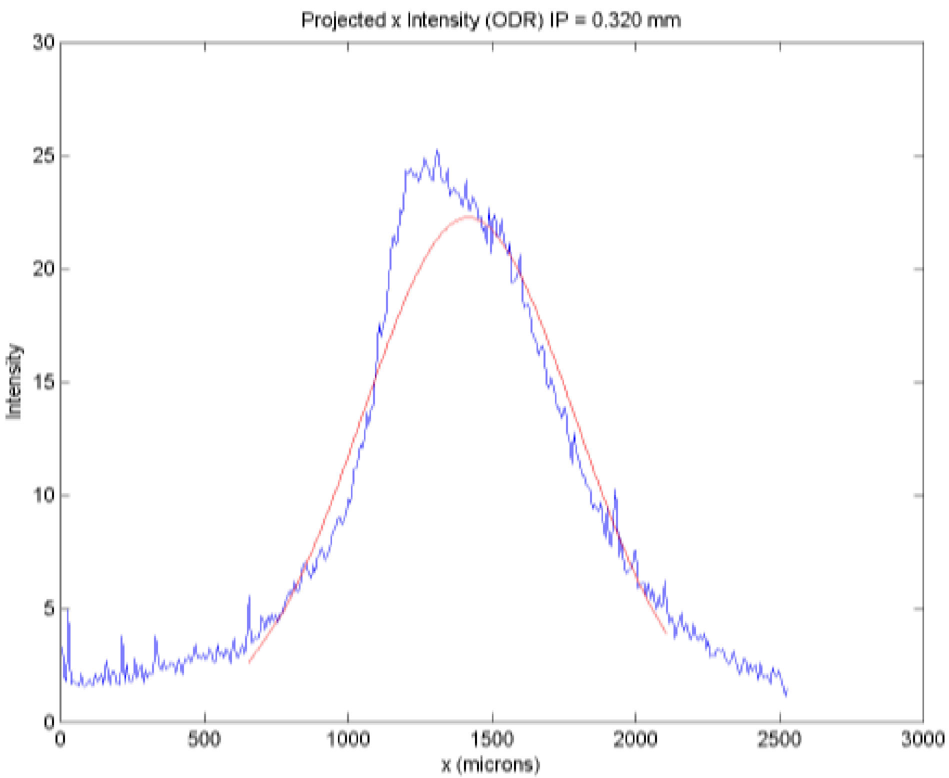
Optical Diffraction Radiation Measurements

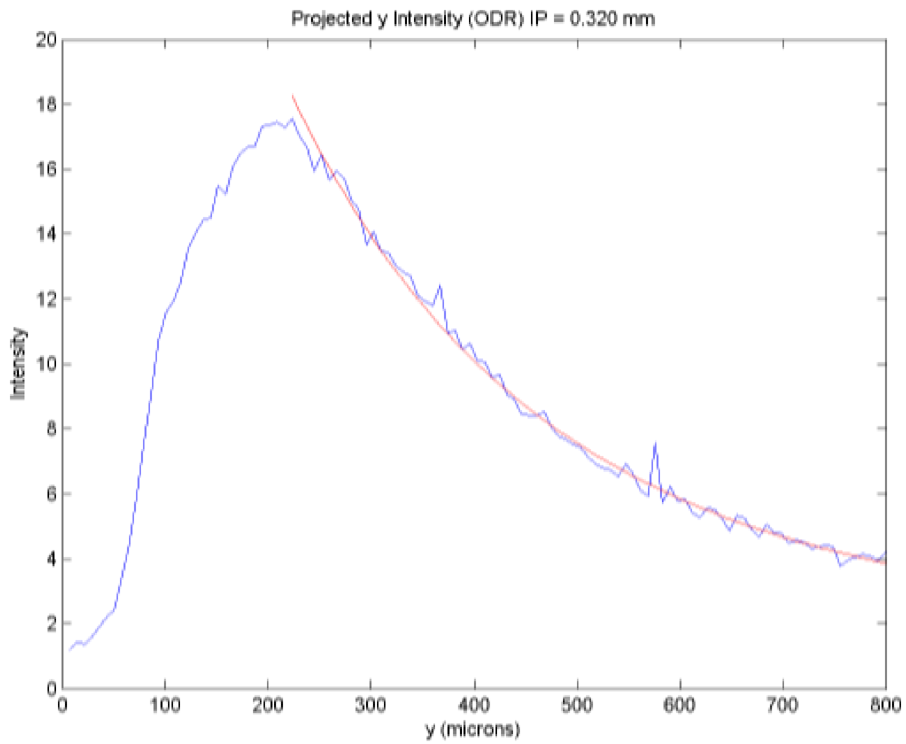
- Data was taken during on a day with a **poor beam quality** with limited time. Most analysis was impractical.
- Did we see **ODR**, or did we see **beam tail OTR**?
  - My job to convince you we saw ODR





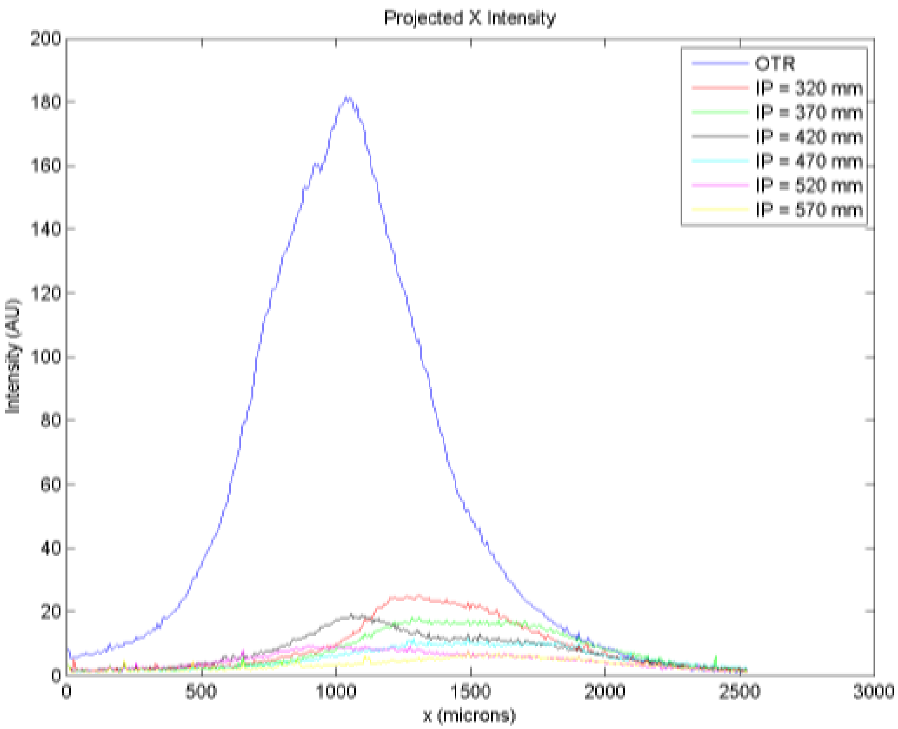
Measured X and Y Intensity Spectrums

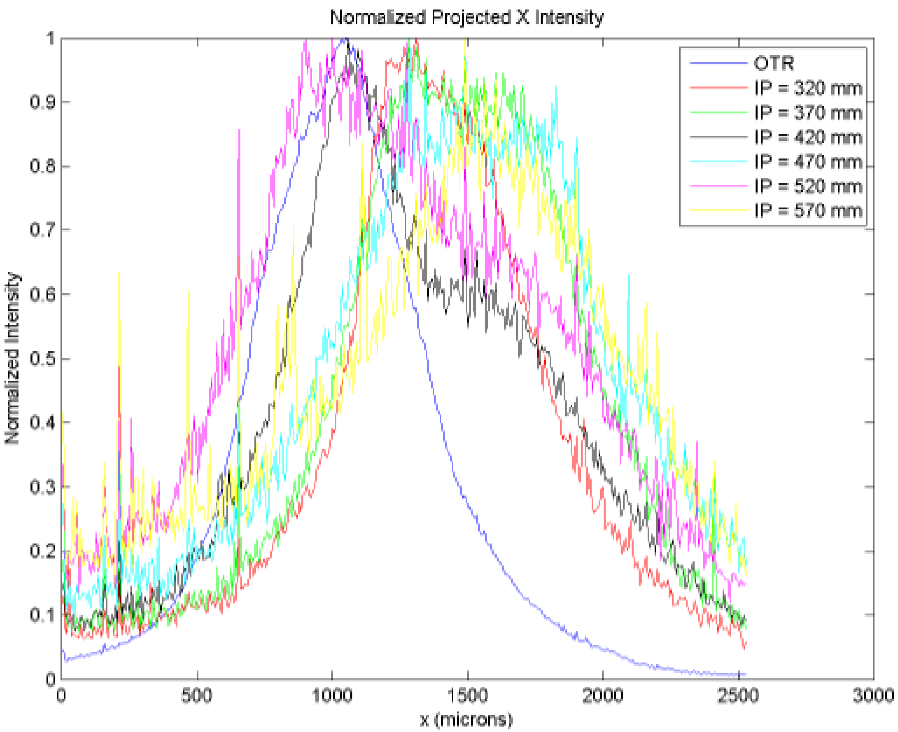




- X Spectrum should be approximately **Gaussian**
- Y Spectrum should have a **Gaussian tail**
  - Why does the leading edge not have a sharp slope?

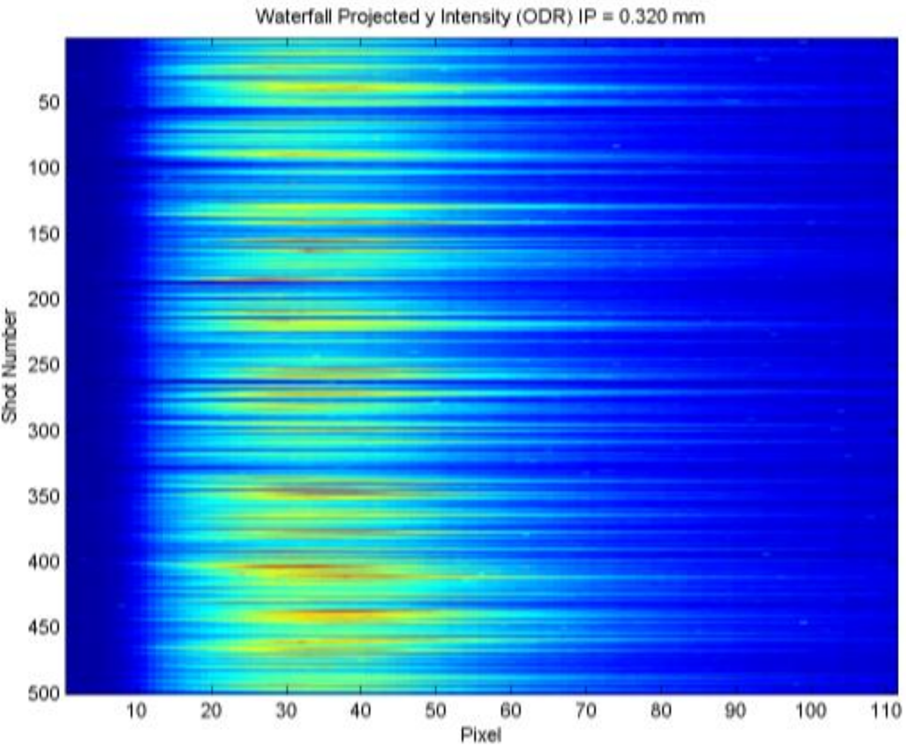
Measured X Intensity Spectrum

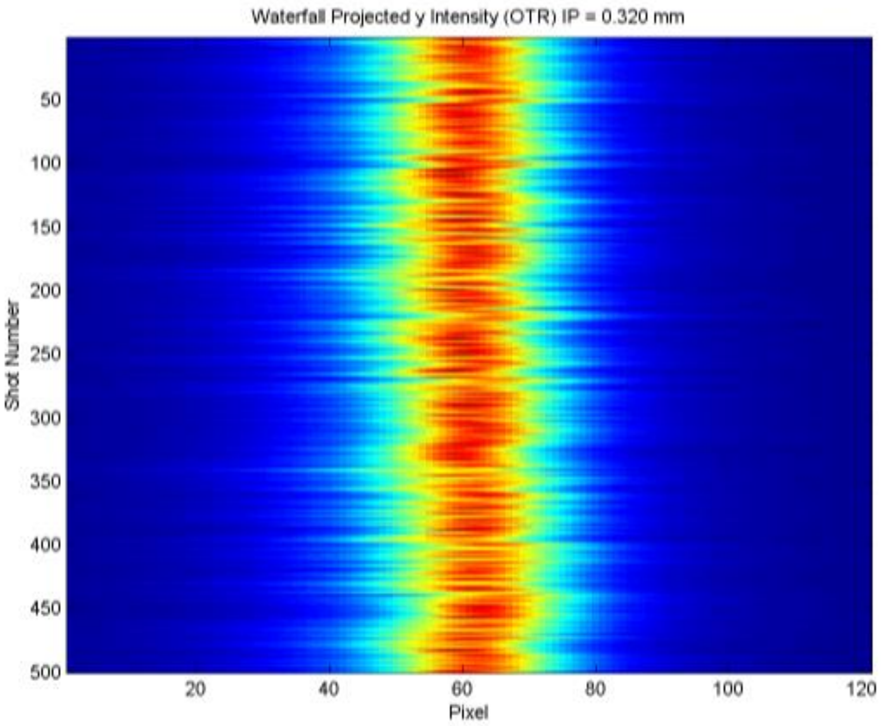




- X intensity spectrum **decreases** with impact parameter
- Width of X intensity **increases** slightly with impact parameter

Waterfall Plot of Y Intensity

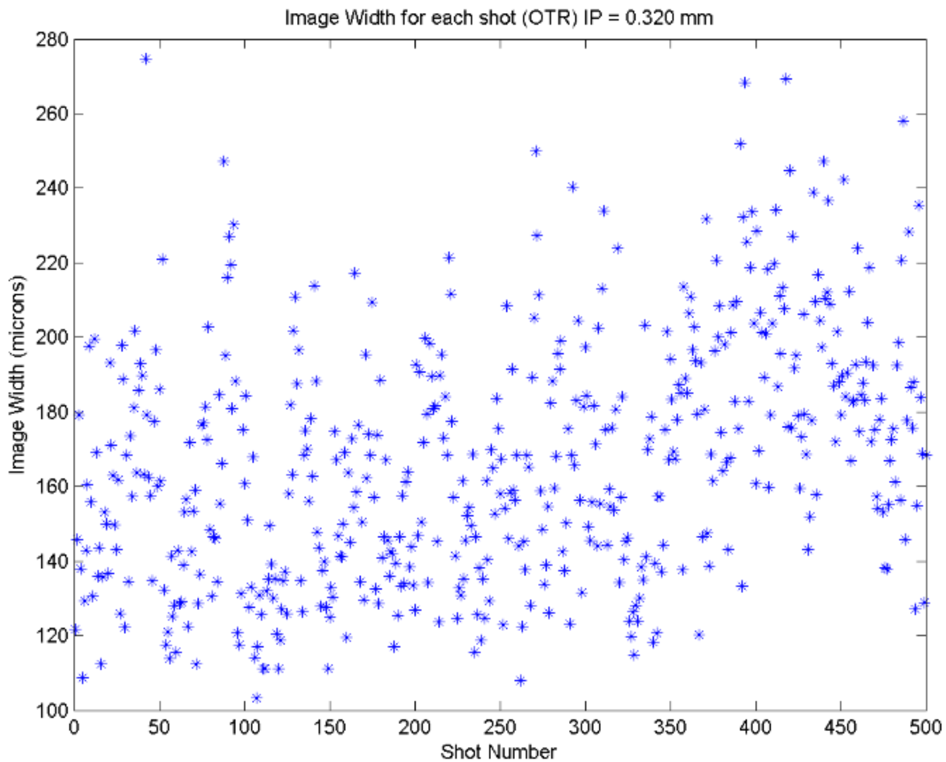




- Left is ODR. Right is OTR.
- Waterfall Plots of Y Intensity

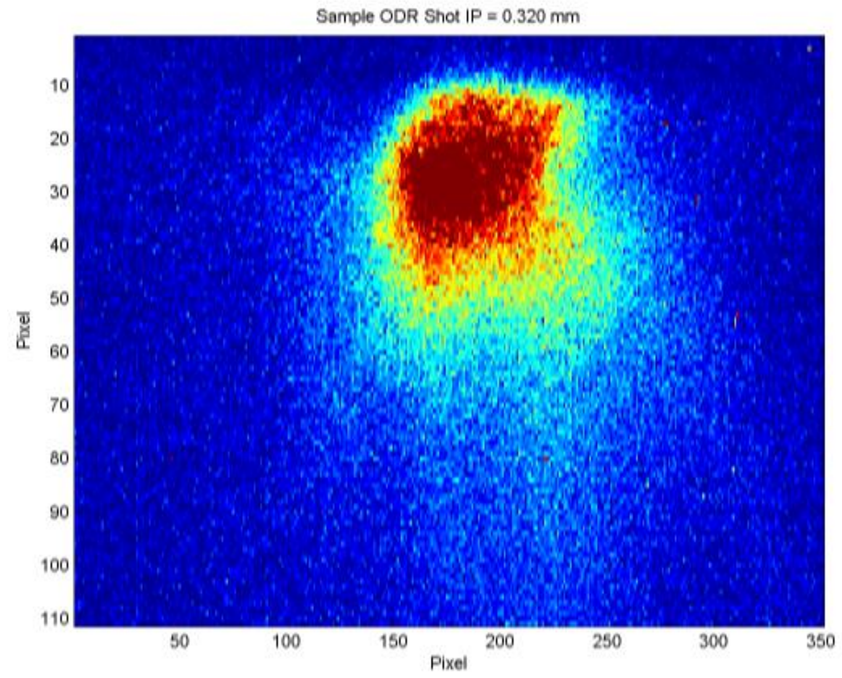
Measurement Conclusion and Future Work

- **ODR was observed experimentally at FACET**
- Analysis was not much use with poor beam quality
- In the future, take data with a good quality beam
- Vary **beam size** and more range in varying **impact parameter**



Conclusions and Future Plans at Stanford

- **Learned** much about FACET and still have much to learn
- Also developed many **useful skills** including data taking, calculations, and surviving tunnel work
- **Contributed** to many aspects including thermal radiation issues and OTR/ODR measurements/calculations
- Taking full advantage of Stanford's rotation system
  - Joined **LUX/LZ Dark Matter** search
  - One more Spring quarter rotation



References

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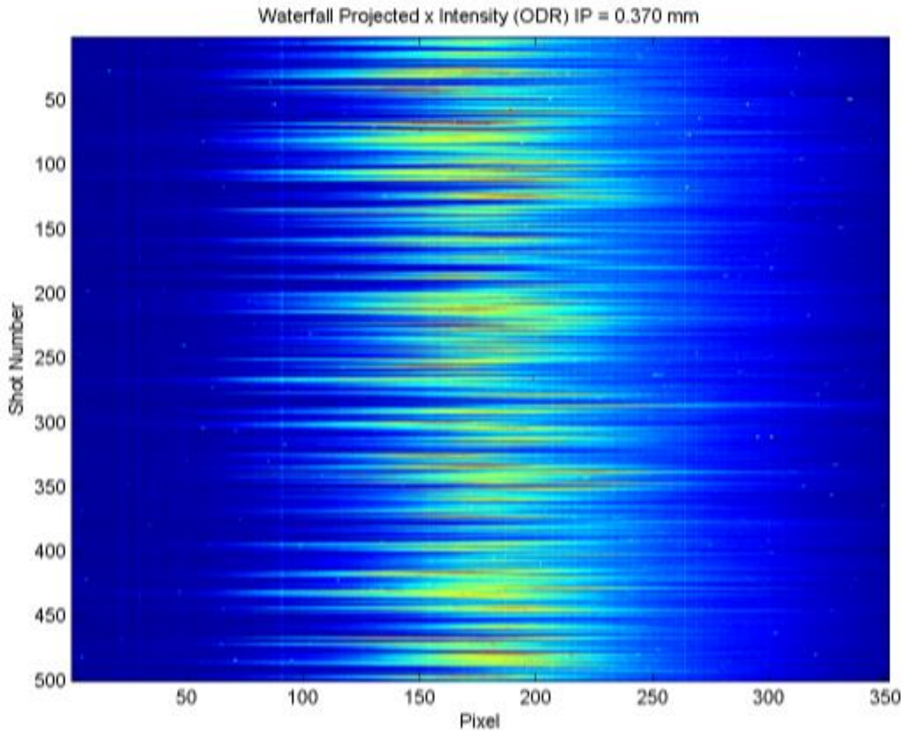
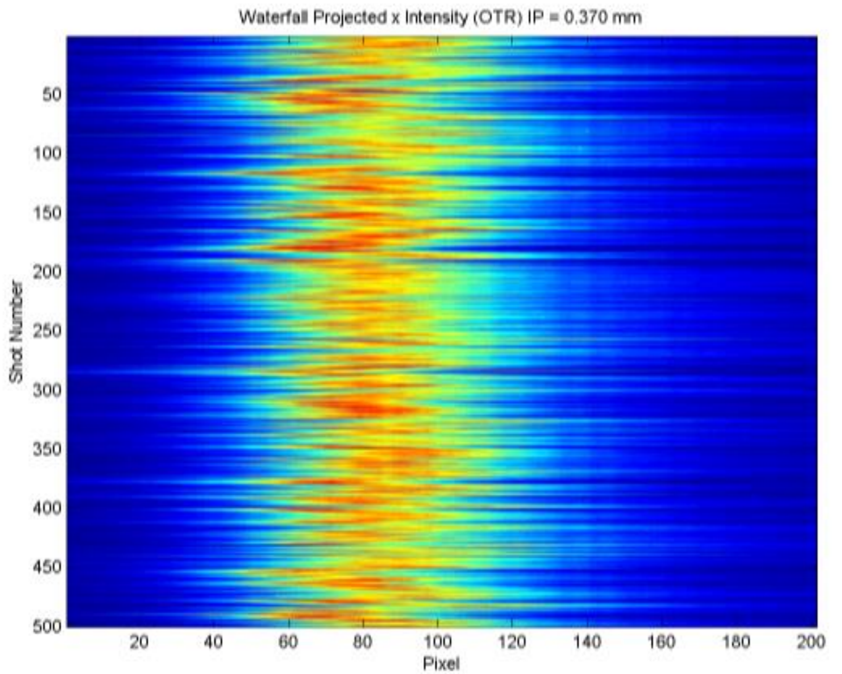
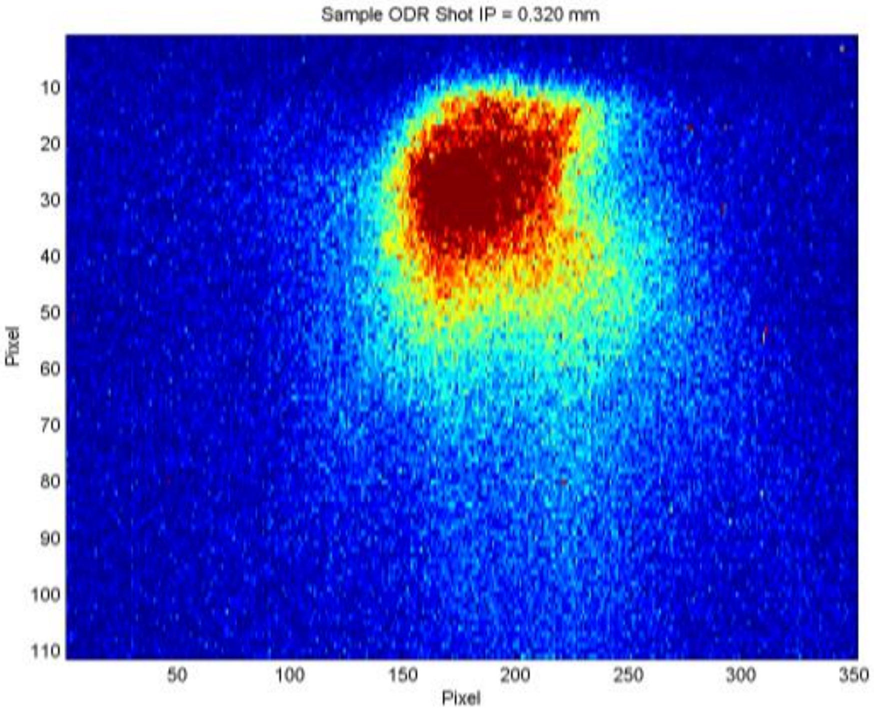
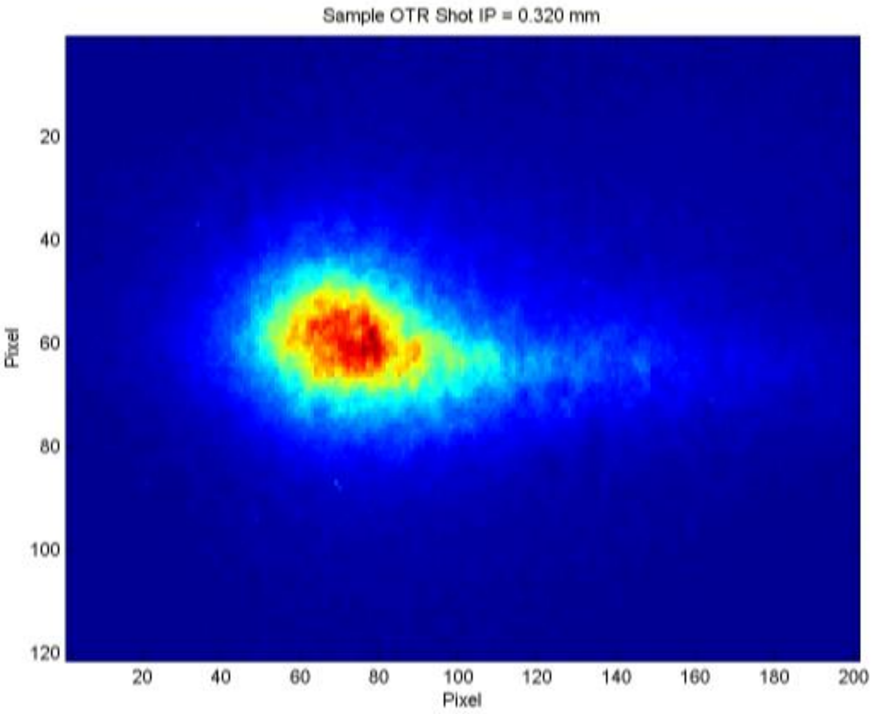
Supplemental Slide 1



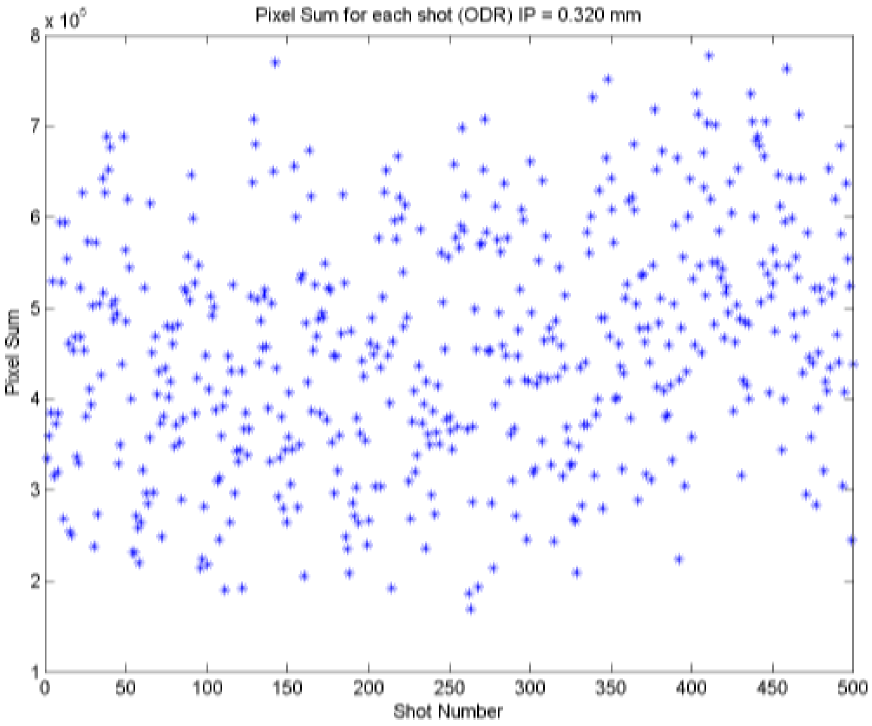


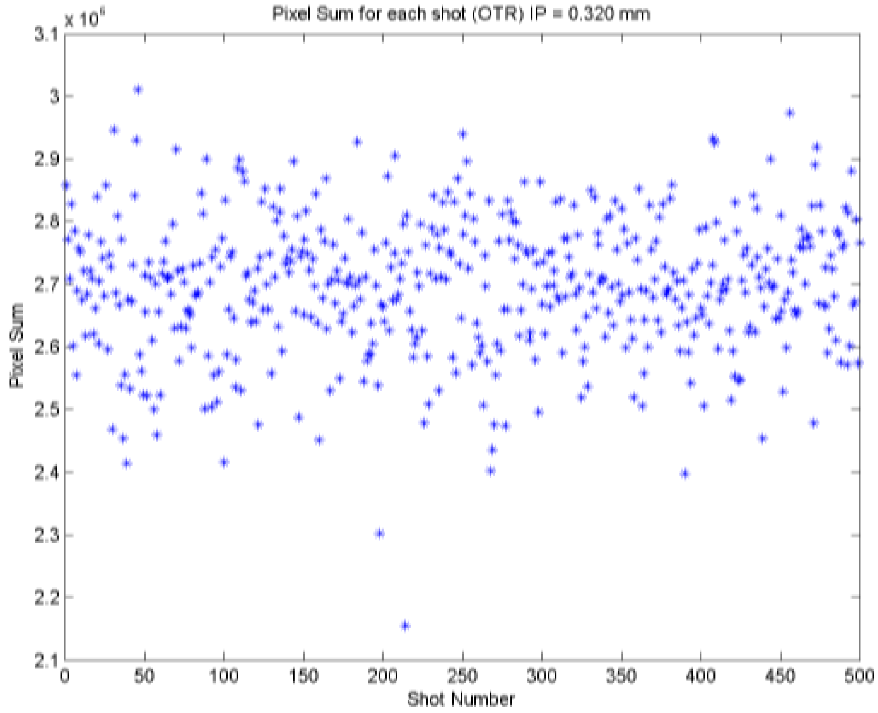
Supplemental Slide 2



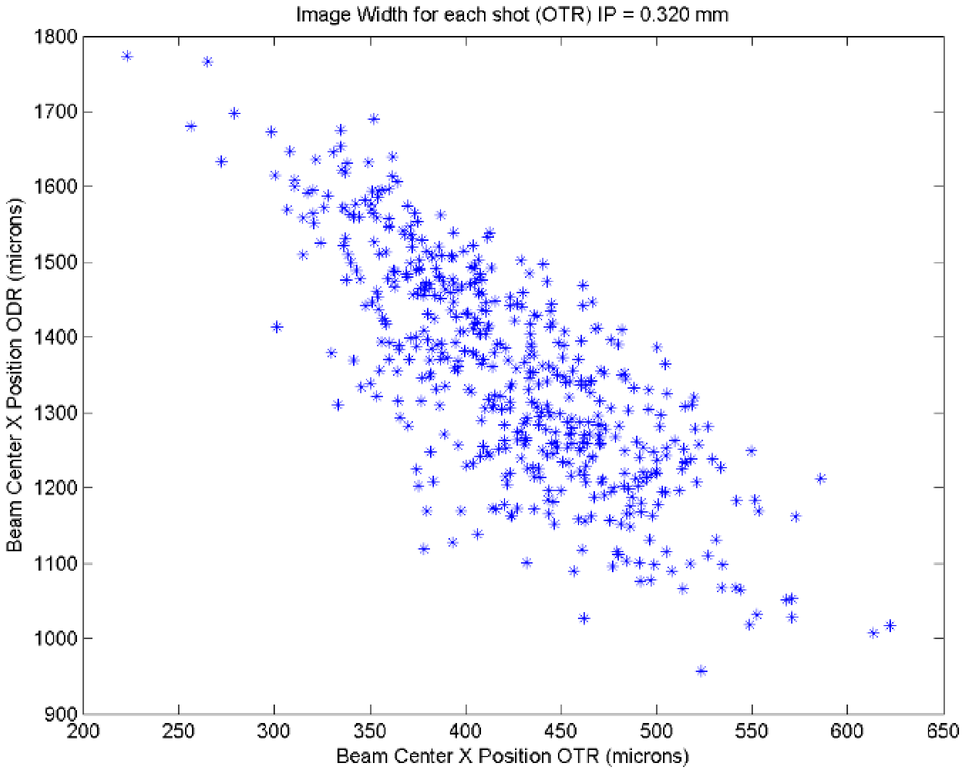


Supplemental Slide 3





Supplemental Slide 4



Supplemental Slide 5