# Saturation of YAG Beam Profile Monitors Measured at ATF

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## *1.1 YAG properties*

- YAG:Ce crystals ($Y_3Al_5O_{12}$) are widely used as a scintillating material for electron microscopy:

***Relevant Characteristics of YAG:Ce***

| | |
|---|---|
| Index of Refraction | 1.82 |
| Wavelength of Peak Emission [nm] | 550 |
| Density [g/cm$^3$] | 4.57 |
| Radiation Length [cm] | 3.5 |
| Photon Yield [#ph/MeV] | 8x10$^3$ |
| Scintillator Efficiency [%] | 15 |
| Cerium Concetration [% of yitrium] | 0.18 |

- Advantages for using YAGs for electron beam profile measurements: vacuum-friendly, semi-infinite life time, excellent resolution:

## *1.2 Motivation for the Experiment*

- Vitaly observed inadequate behavior of a YAG crystal while running at ATF: the beam image was very smooth and did not respond well to the small changes in quadrupole settings.

  Later, with the OTR screen, he observed smaller beam image, with the well defined structure in it, perfectly responsive to the e-beam optics.

- Alex Lumpkin in his paper described the "size-blurring" effect on the YAG beam profile monitor at APS. He also compared YAG data with the OTR, and his data show image degradation, which starts at the charge densities of about ~ .02 pC/μm$^2$.

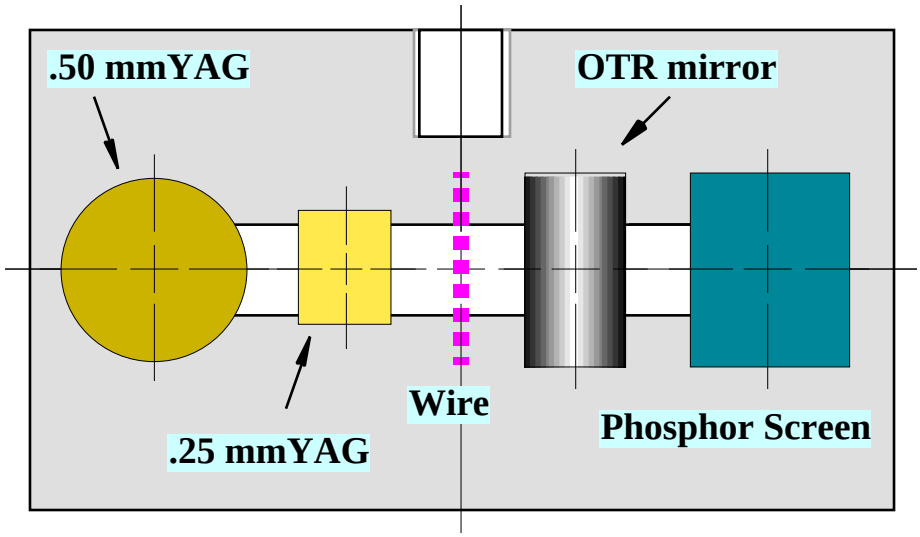
  In the case of ATF beam (Q = 1 nC) it corresponds to the beam size of $\sigma_x = 90\mu m$.

- The beam required for VISA experiment is smaller (60 μm), and a reliable performance of Beam Profile Monitors is necessary for proper beam matching into the undulator.

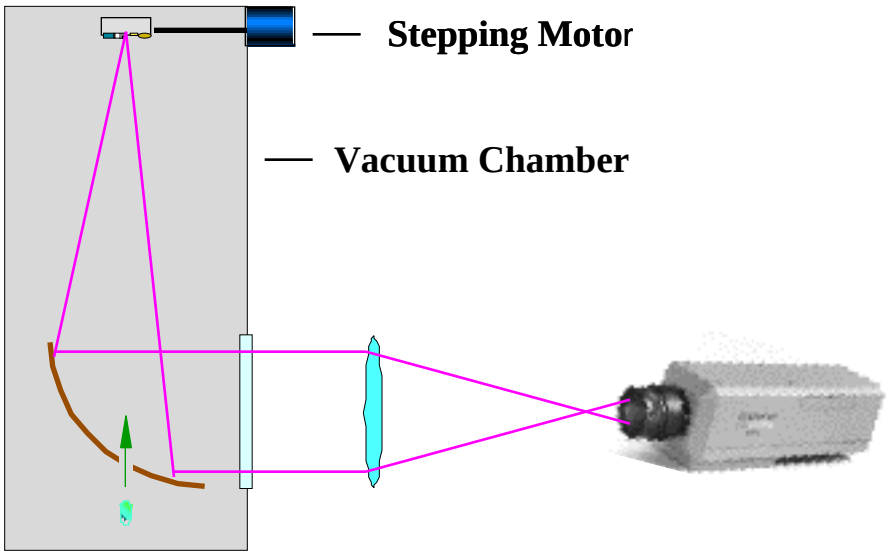
- Goal: to test a YAG performance as a beam profile monitor at ATF with respect to the OTR, phosphor screen and wire scan based techniques.

## *1.3 Experimental Set-Up*

- The target was constructed, which contained five diagnostics, including two YAG crystals, 0.25 mm and 0.50 mm thick, respectively:

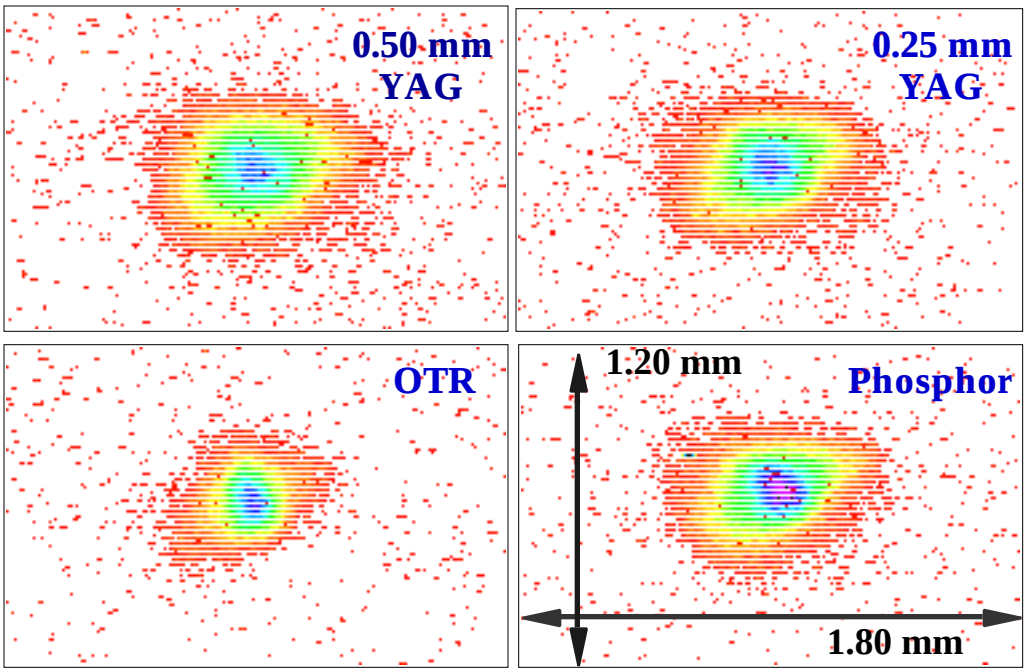


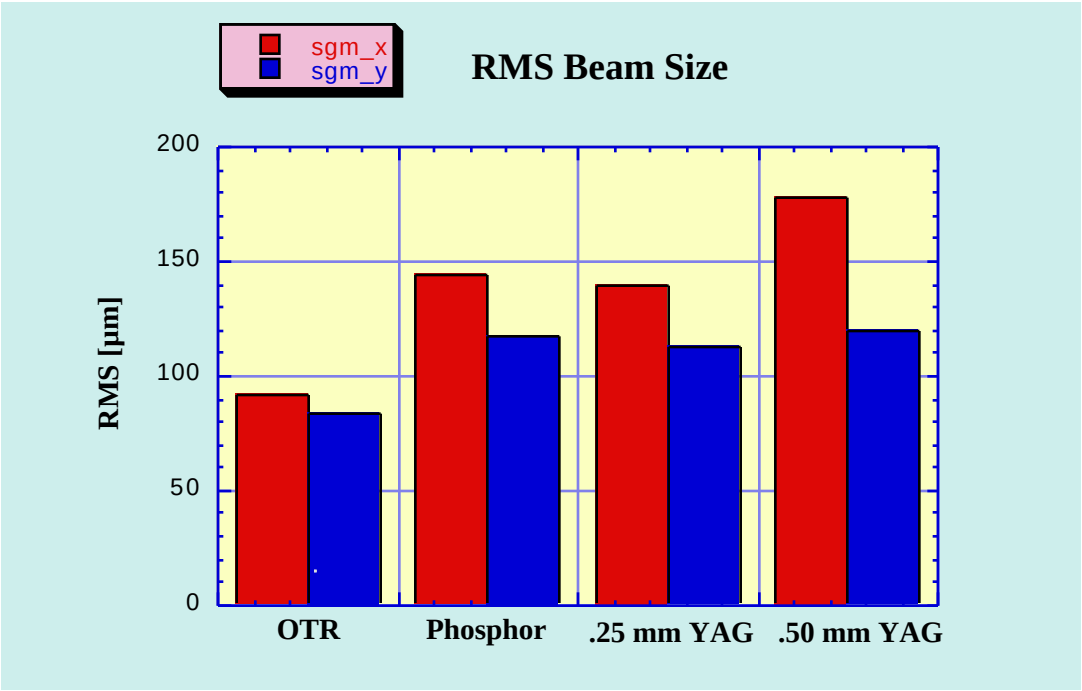

- With the parabolic mirror and a lens, the light from the target was imaged into the focal plane of a CCD camera:



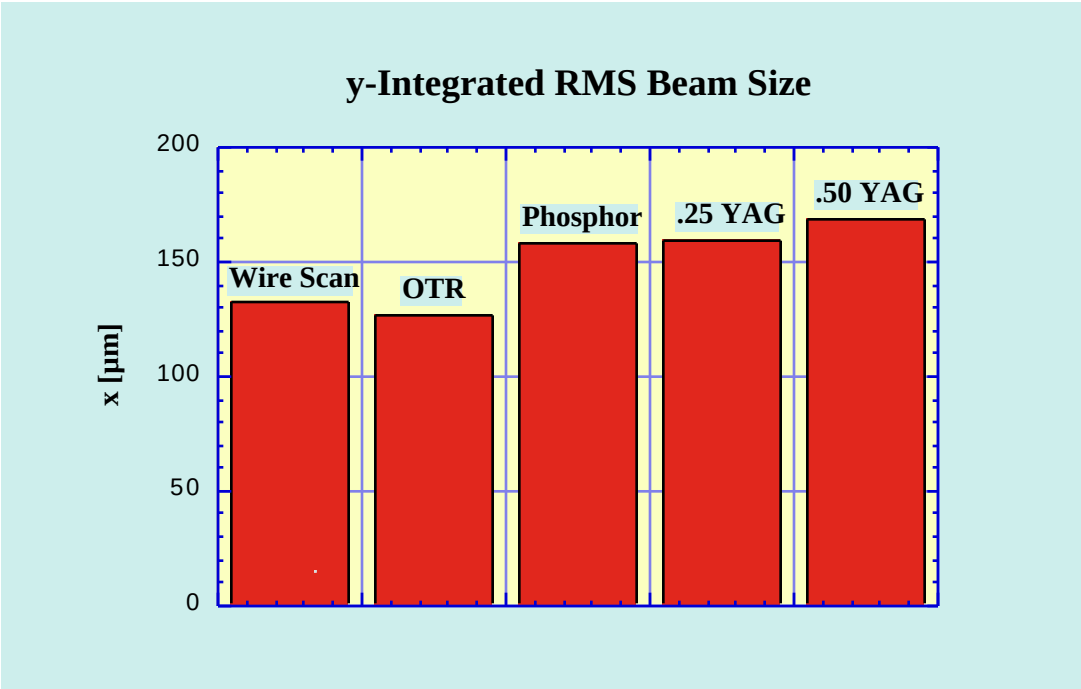
## 2.1 Data

- We observed a significant “size-blurring” of the beam on all scintillating monitors:

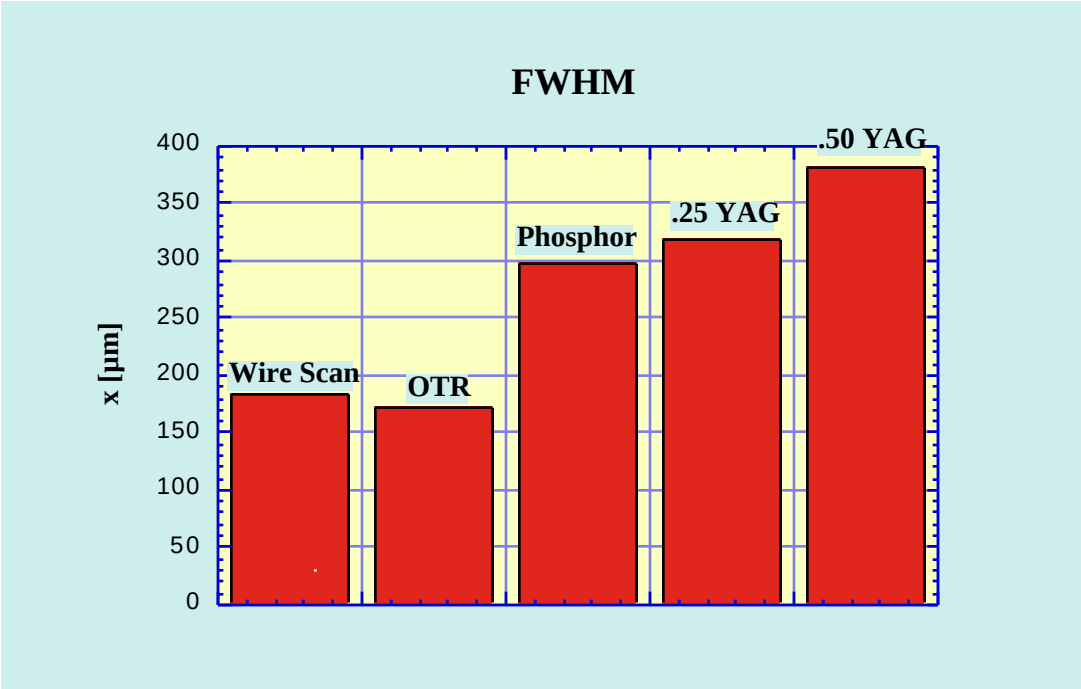


- To compare with the wire scan results, we have to integrate images over the y-coordinate:

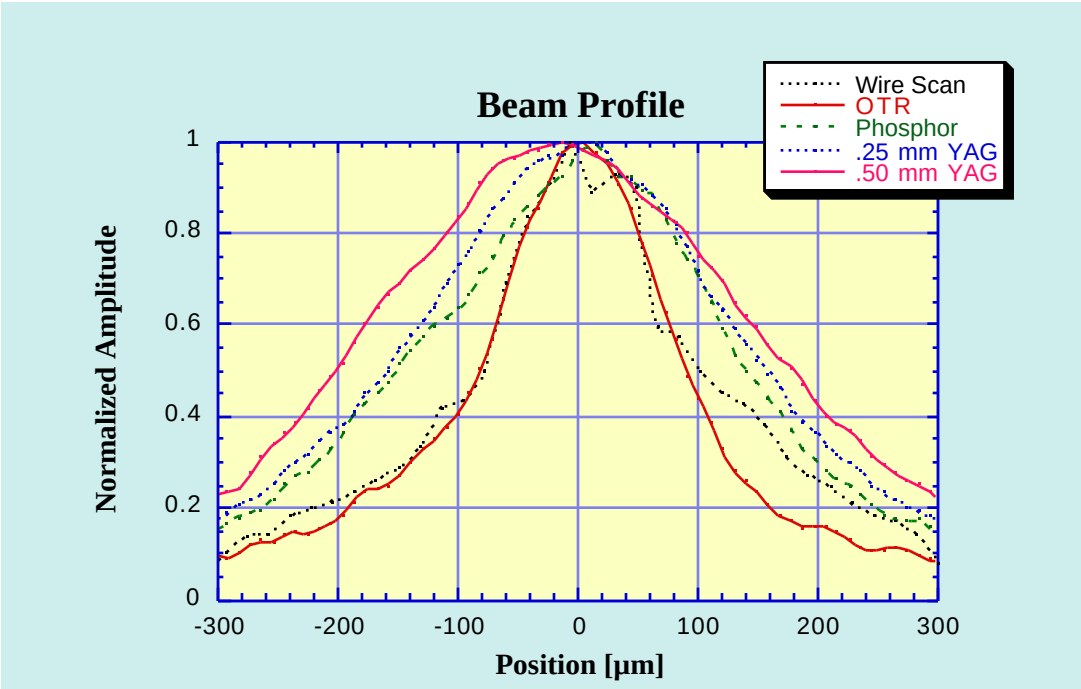



- As the beam strongly deviates from Gaussian shape, the difference in the FWHM is even more significant:



## *2.2 Possible Mechanisms*

(1) "Size-blurring" is due to the noise and measurement errors (which adds quadratically):




- Overall, we are looking into quadratic error of

  $\sigma_0$ ~100 μm

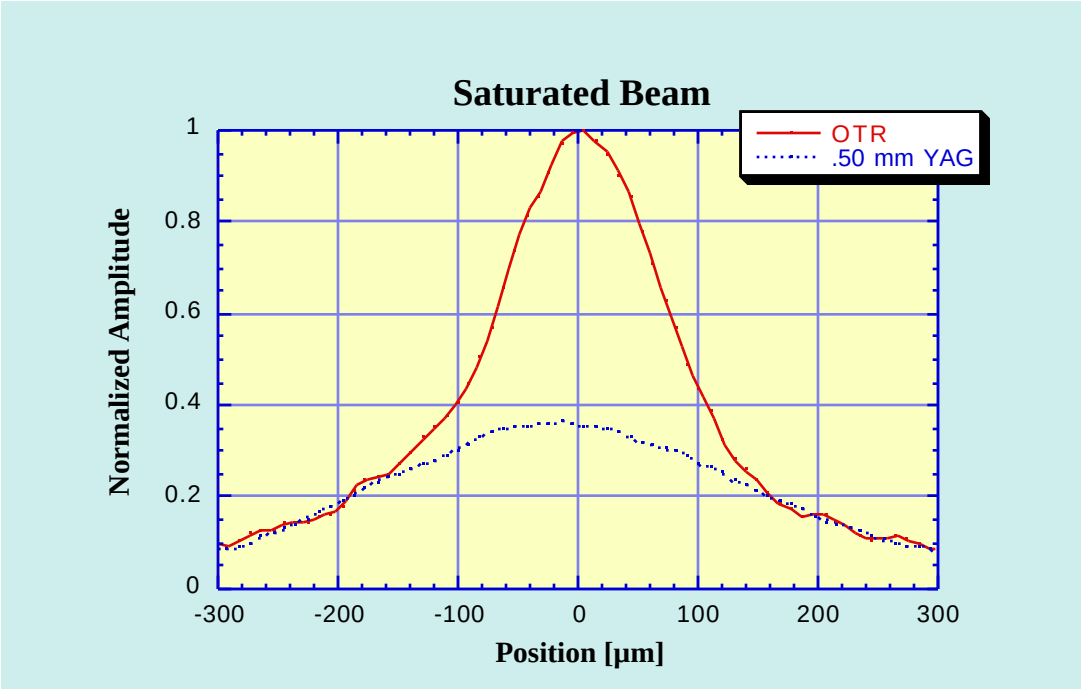
The causes could include:

- Limits on optical resolution of the system (aberrations in the lenses, misalignment, background subtraction in the framegraber, etc.).

- Depth of focus and multiple reflections issues attributed uniquely to YAG.

- Limited resolution for high energy electrons or/and due to the secondary electrons (< 30 μm spot sizes measured with YAG were reported by Lumpkin).

(2) Alternatively, the effect can be due to the saturation in the YAG crystal, which is intensity dependent. Then, at the tails of the beam, where the charge density is small, there should be an agreement between YAG and OTR:

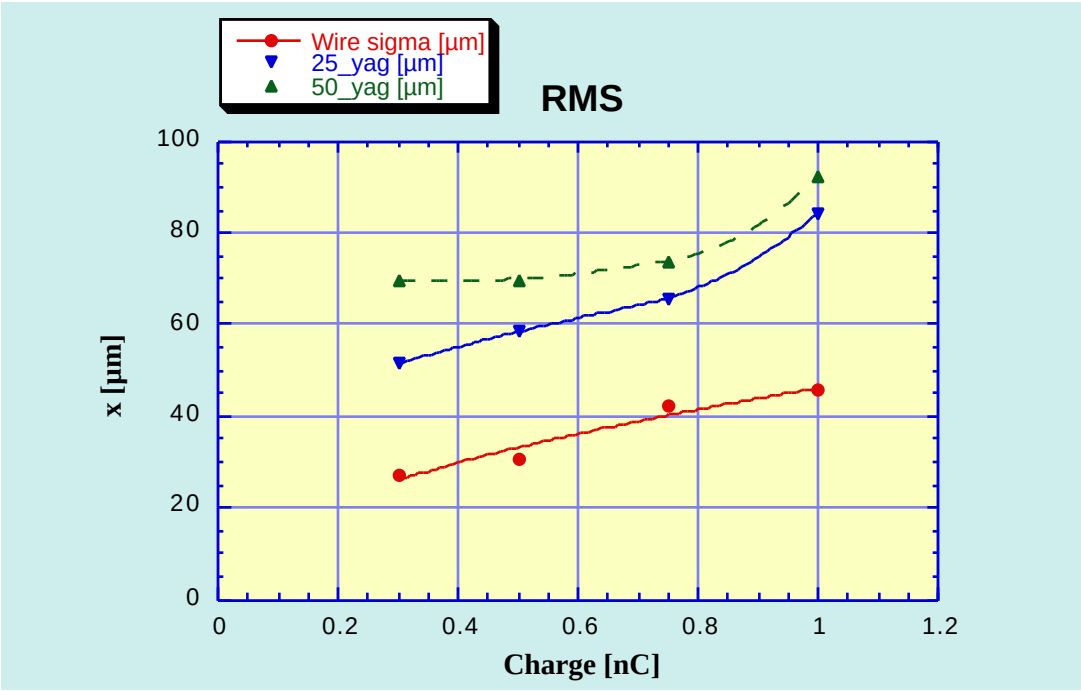


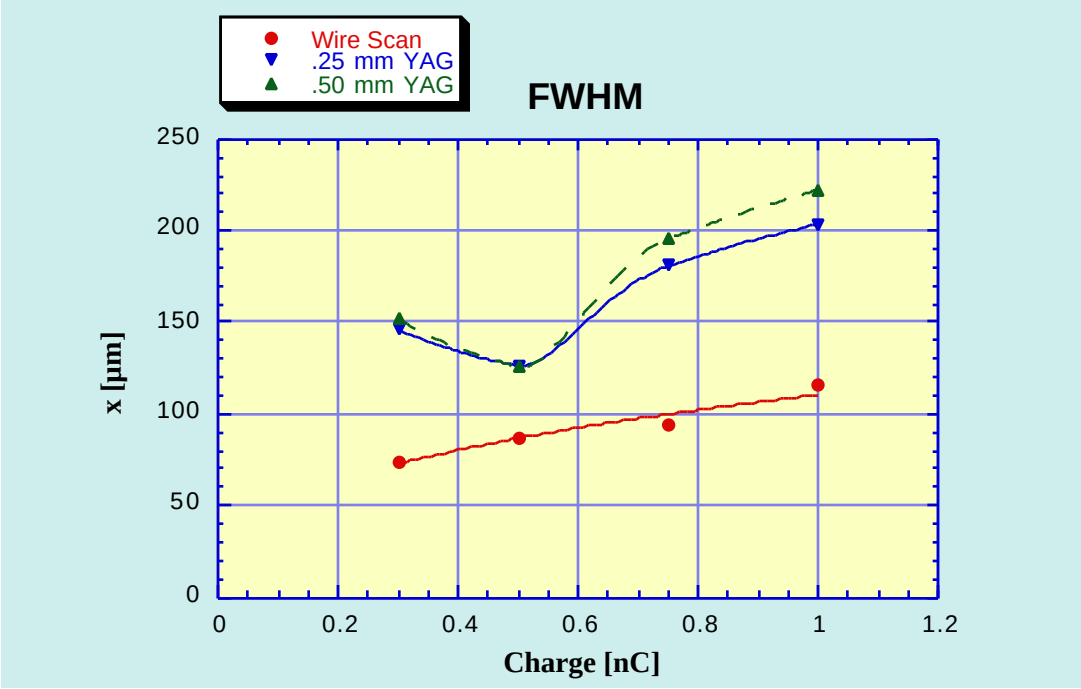

It follows from the plot, that the effect becomes important at charge densities

$$\frac{dQ}{dA} \sim 0.01 \text{ pC/}\mu\text{m}^2$$

## *3.1 Second Experiment*

- With the smaller beam, we compared YAG performance and a wire scan for different charges:



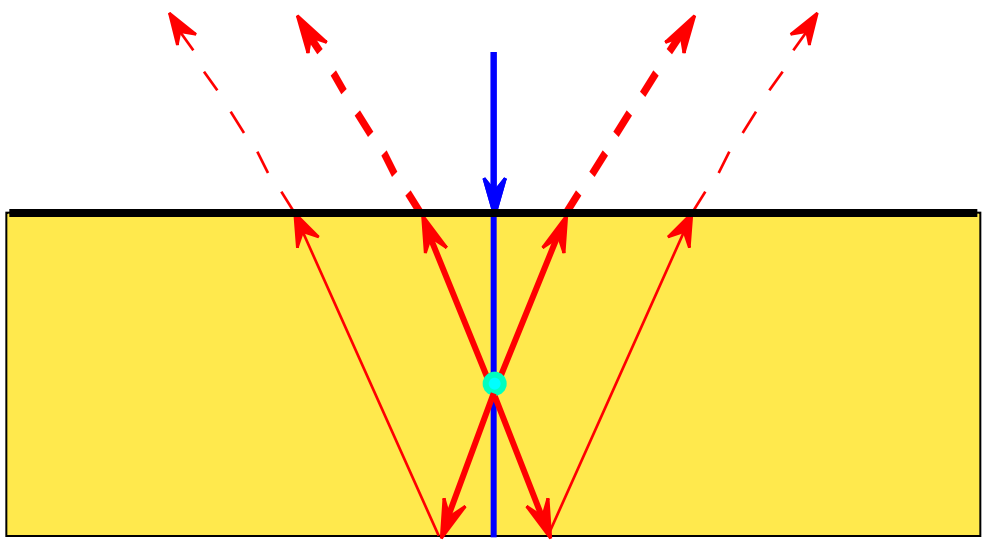



## *3.2 Taking Out the Known Errors*

- The wire has a width of 25 μm, which adds as $\sigma_w \sim 8.5\ \mu\text{m}$.

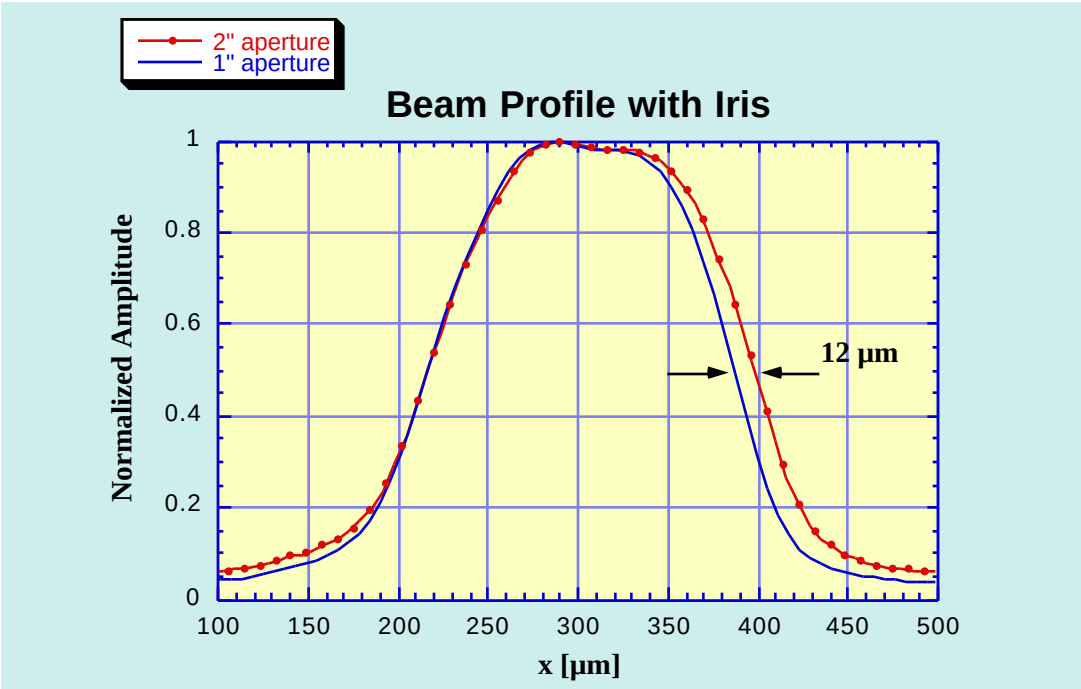
- From the YAG data we can "symmetrize" the data to compensate for overfocusing in one plane.

- The depth of focus and back wall reflections are calculable problems:

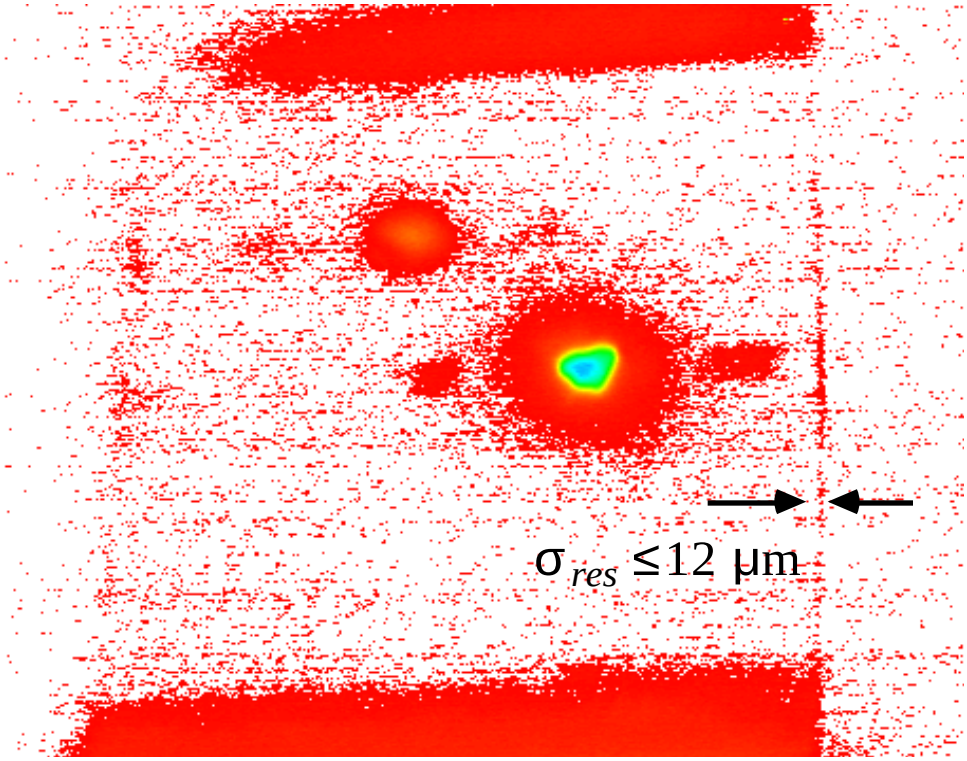


- With our angular acceptance of 19°, while camera is focused on the front surface, the effective resolution of the YAG is $\sigma_f \sim 43\ \mu\text{m}$ (for .50 mm YAG).

- We also did the measurement, by placing an aperture into the beam path, to cut the acceptance angle:

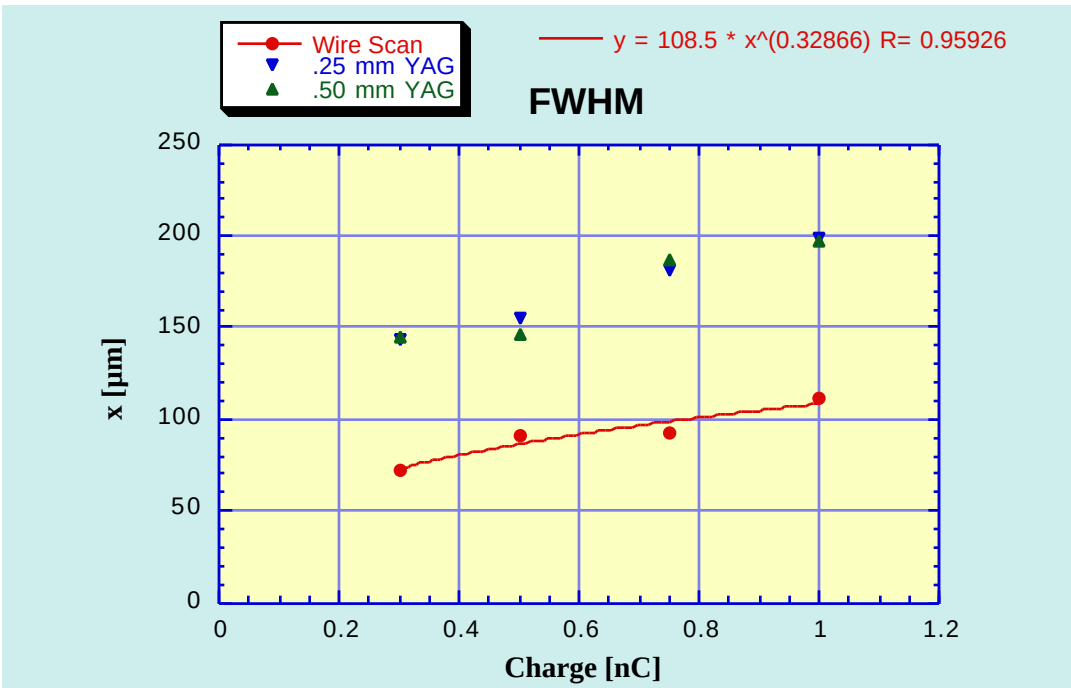



- Resolution of the rest of the optical system can be found by looking at the light coming out at the Brewster's angle, and scattered of the crystal edge:



## *3.3 Signs of Saturation*

- Now we can subtract all the known effects, described above, and we are still left with a big discrepancy between the YAG screen and wire scan measurements:



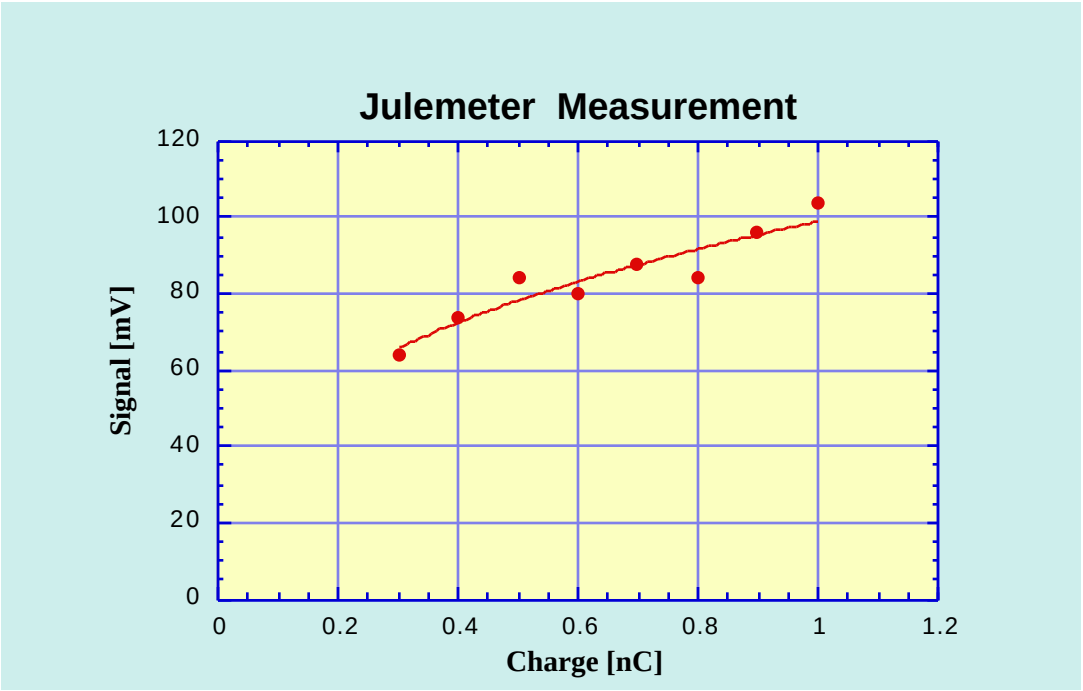

- One can see the charge dependent behavior, that has to be attributed to saturation.

- We can also calculate the expected energy from the YAG:

$$E_{rad} = E_0 \left(1 - e^{-x/X_0}\right) \approx .47\text{MeV} \qquad \Delta\Omega \approx 0.026$$

$$E_T = \left(8 \times 10^3 \hbar\omega\right) \left(N_e E_{rad}[\text{MeV}]\right) \frac{\Delta\Omega}{4\pi} \approx 180 \text{ nJ}$$

- Using julemeter, we measured the actual energy measurement (for .25 mm YAG):




- The detector is calibrated to $2.33 \times 10^{8} \frac{\mathrm{V}}{\mathrm{J}}$ . With the 50% efficiency @ 560 nm, the measured energy value is:

$$E_{\text{measured}} \quad 2 \text{ nJ}$$

- Even considering possible misalignment and γ-ray losses, there is at least an order of magnitude difference between the measured and predicted values, which also indicates saturation.

## *4.1 Saturation model*

- We can calculate the density of the scintillating sites available in the crystal (considering the 15% efficiency):

$$n_{ce} = .0018 \frac{3r}{m_p M} \approx 2.5 \times 10^{19} \text{ cm}^{-3}$$

$$n_s = .15 \; n_{ce} \approx 3.7 \times 10^{18} \text{ cm}^{-3}$$

- The demand density in our case can be estimated as

$$\left.\frac{dE}{dx}\right|_{rad} \approx 19 \frac{\text{MeV}}{\text{cm}} \qquad \Phi_e \approx 5 \times 10^{13} \text{ cm}^{-2}$$

$$n_d = \left(18 \times 10^3 \frac{\text{ph}}{\text{MeV}}\right) \frac{dE}{dx} \Phi_e \approx 1.7 \times 10^{19} \text{ cm}^{-3}$$

- Peak demand exceeds supply by a factor of $a \equiv \frac{n_d}{n_s} \approx 4.6$

- Now we can write an equation, for the response of a system approaching saturation:

$$\frac{dn}{dn_d} = \frac{n_s - n}{n_s}$$

- The normalized solution is

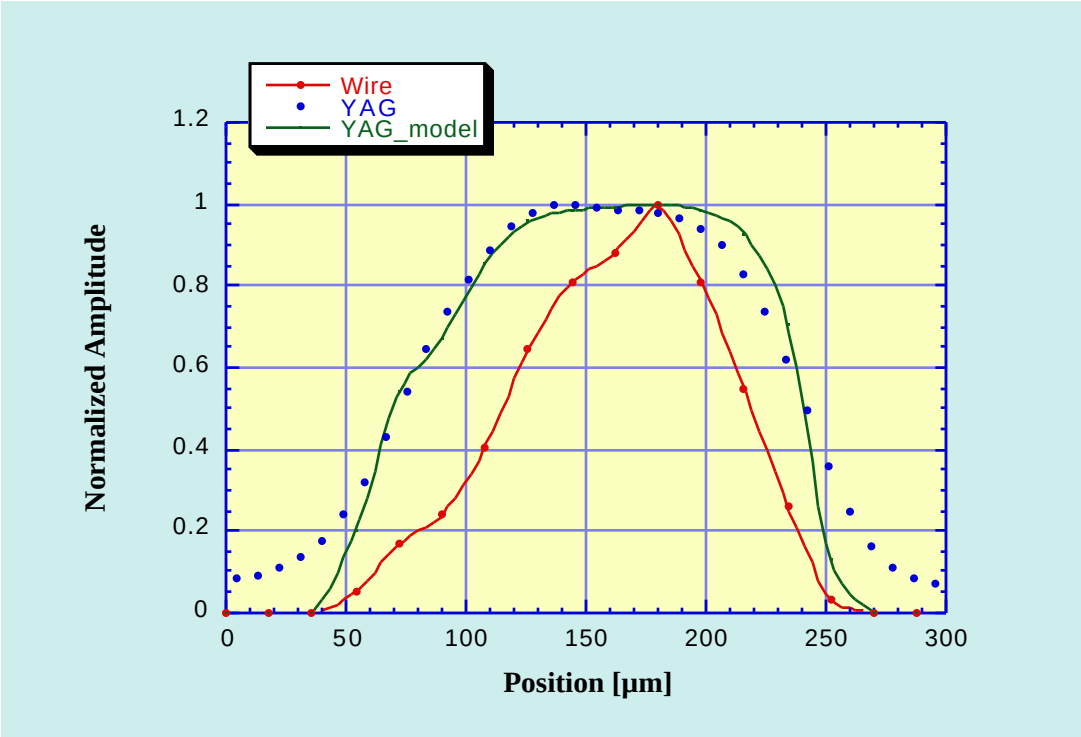
$$R(x) = 1 - e^{-x}, \quad \text{where} \quad x \equiv \frac{n_d}{n_s} \quad \text{and} \quad R(x) \equiv \frac{n}{n_s}$$

## *4.2 Data Analysis Based on the Model*

- The actual intensity seen on the YAG screen can be written then (all the units are normalized to unity):

$$I(r) = \frac{1 - \exp\left(-a \;\; I_b(r)\right)}{a}$$

- With this model we can generate the YAG image properties, based on the wire scan data:

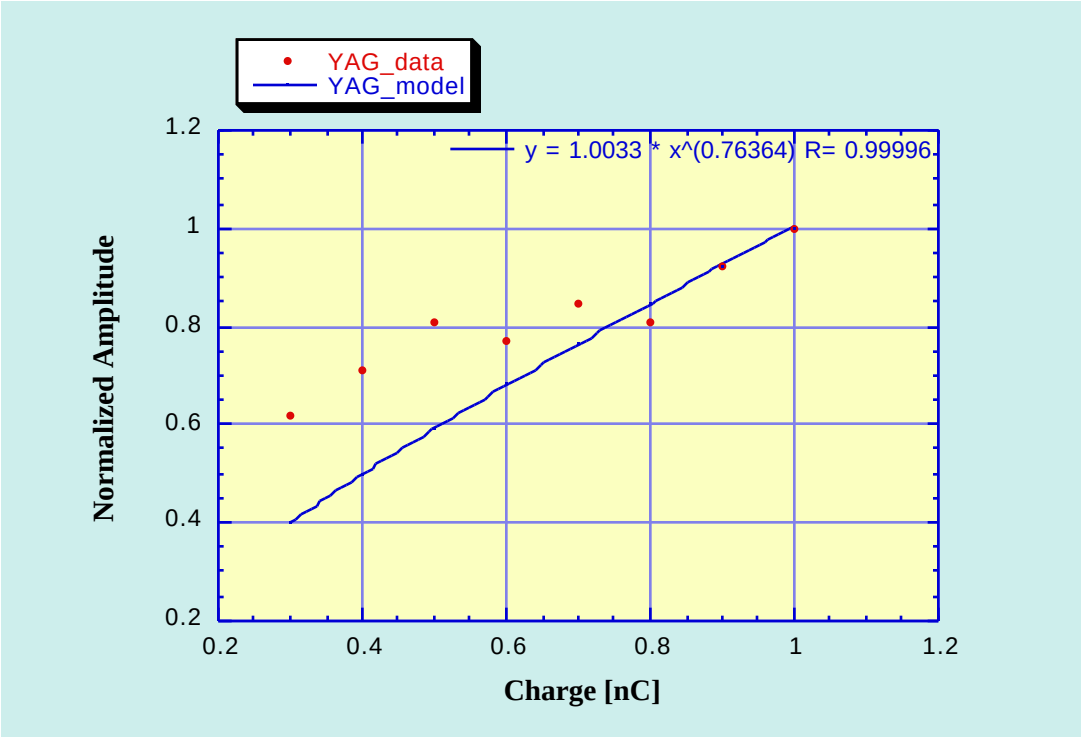



- Also, knowing from wire scan, that the beam width changes as

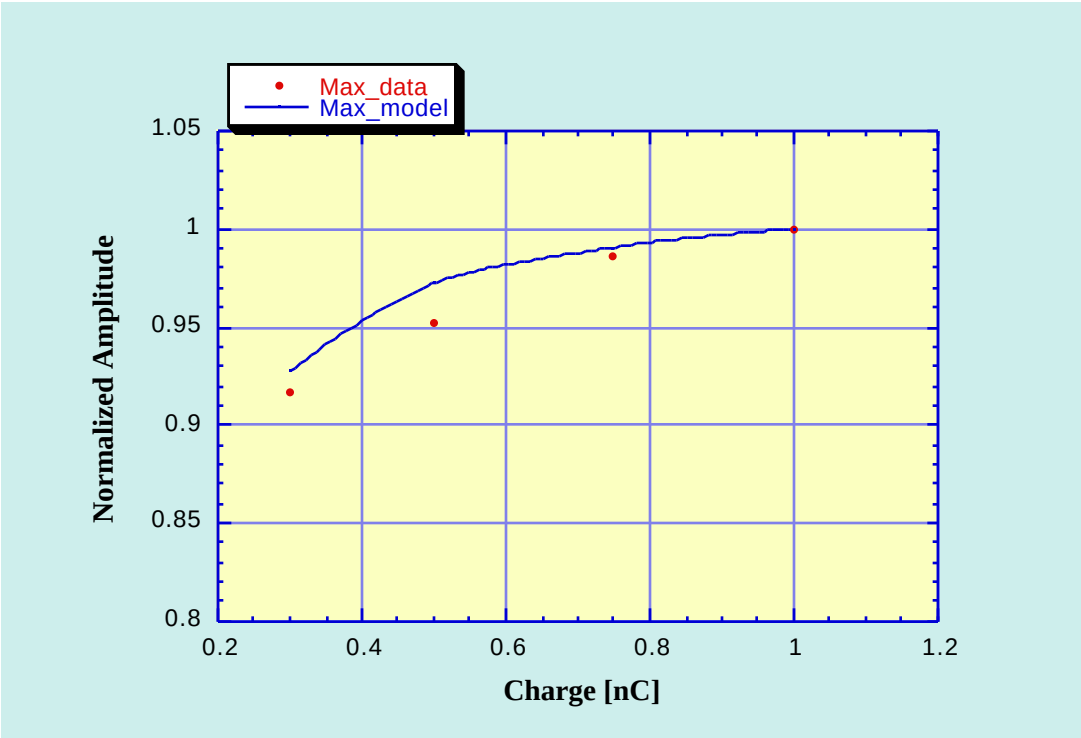
$$\sigma_x \quad Q^{1/3}$$

we can analyze the charge dependent behavior of YAGs:

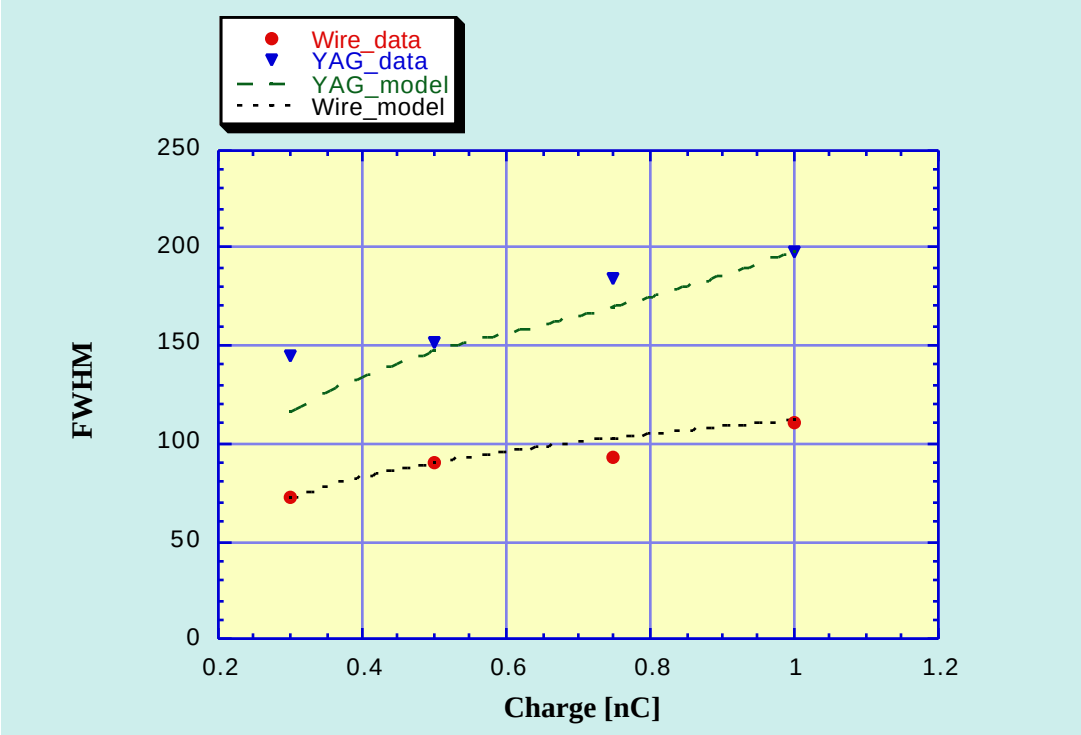
- Total energy radiated, as a function of charge




- Maximum intensity on the YAG:



- And the beam spot size as a function of charge:




- The comparison let us believe, that we are on the right path, and the described model indeed resemble all the important features of observed phenomena.

## *5.1 Conclusion*

- YAG:Ce crystals saturate. Their use as a beam profile monitors should be limited to charge densities not exceeding

$$\frac{dQ}{dA} \leq 0.01 \text{ pC/}\mu\text{m}^2$$

  for the energy range ~ 100 MeV. For higher energies, the limit can be even lower.

- Alternative methods (OTR) are more reliable for high brightness sources.

- It is possible, that groups relying on YAGs for their emittance measurements have better beam than they measured.

## *Acknowledgment:*

We would like to thank, Igor Pogorelsky and Compton group at ATF for letting us use their equipment; also Erik Johnson and Bill Graves, for motivating discussions.