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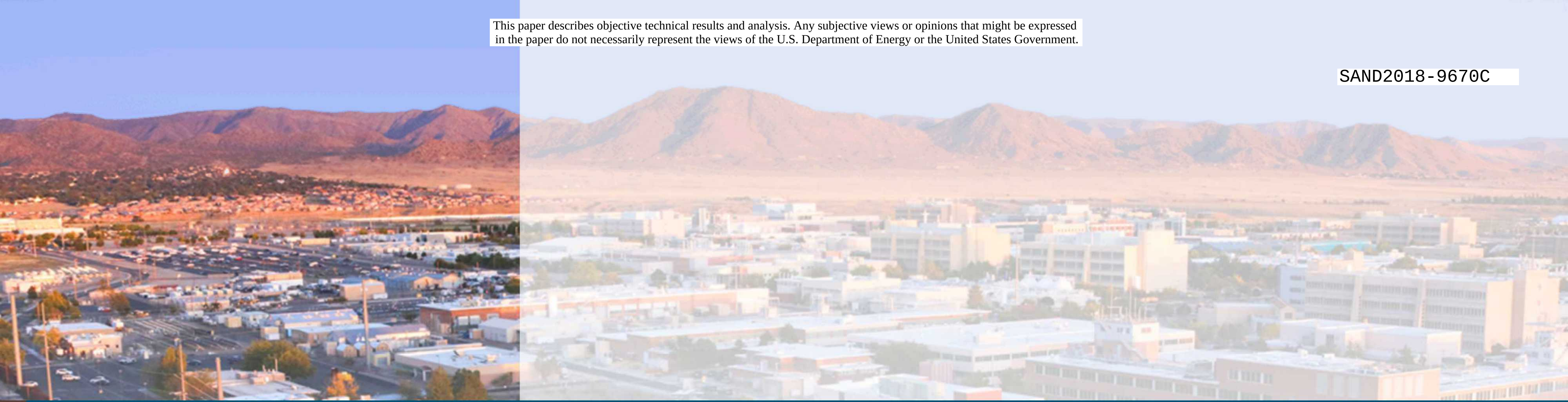

Exploring spectral, temporal, and spatial pulse shaping techniques for high energy short pulse lasers

Jens Schwarz, Patrick Rambo and Ben Galloway

8TH CONFERENCE OF THE INTERNATIONAL COMMITTEE ON ULTRAHIGH INTENSITY LASERS

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Outline

- Spectro- temporal bandwidth control in OPCPA: How to fight gain narrowing?
  - Temporally modify the OPCPA pump laser so that the resulting spectral imprint on the signal beam pre-compensates the successive gain narrowing.
  - Employ novel laser glass that supports broader spectral bandwidth.
    - As such we tested Schott BLG80.002 glass and contrasted it to the well known APG1 glass

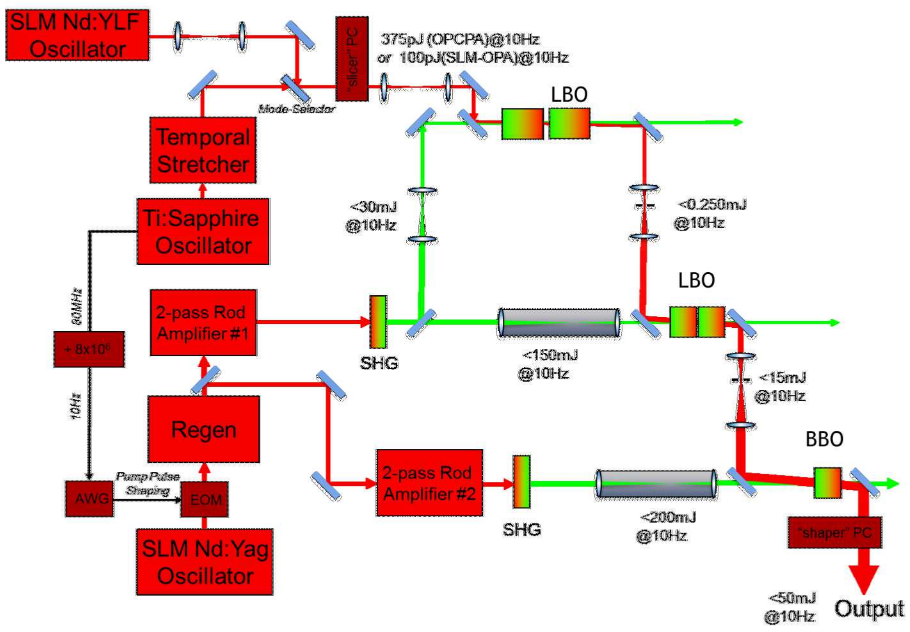
- Spatial pulse-shaping control
  - A spatial light modulator (SLM) was employed to:
    - Optimize the un-amplified seed NF via a Sandia custom feedback loop
    - Compensate edge enhancement in rod amplified beams

- Conclusion

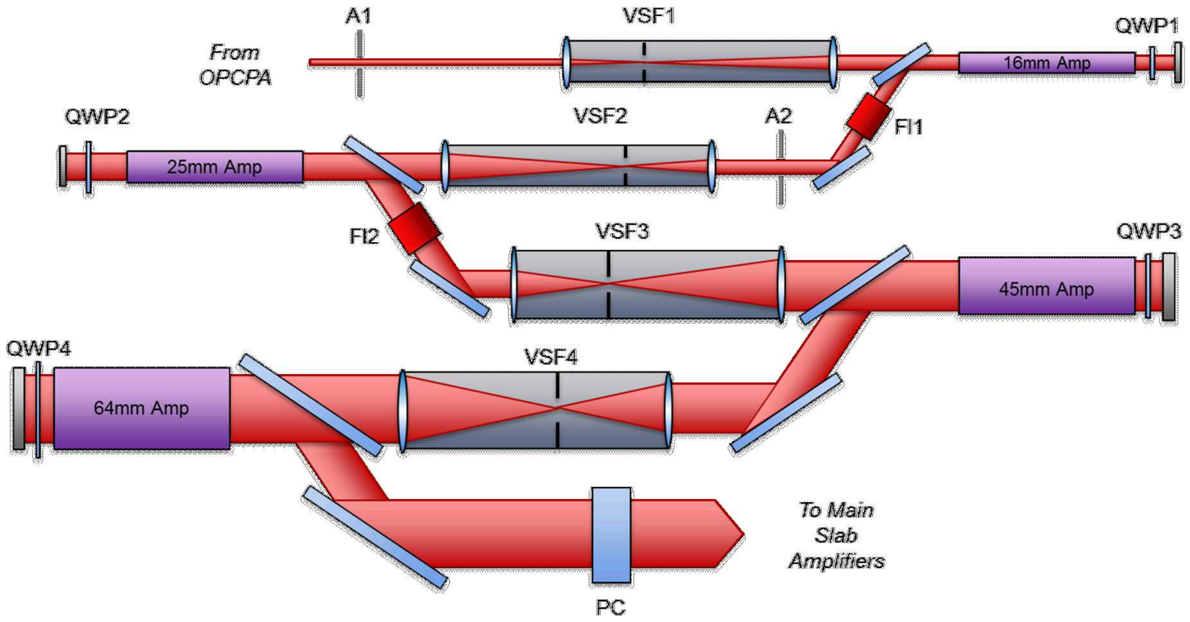
Z-Petawatt laser front end and rod amplifier stages

- The Z-Petawatt (ZPW) laser front end consists of a three stage OPCPA that provides a 2.5ns, 50mJ, 10Hz seed for four successive double passed rod amplifiers of increasing aperture (16,25,45, and 64mm).

SLM-OPA/OPCPA

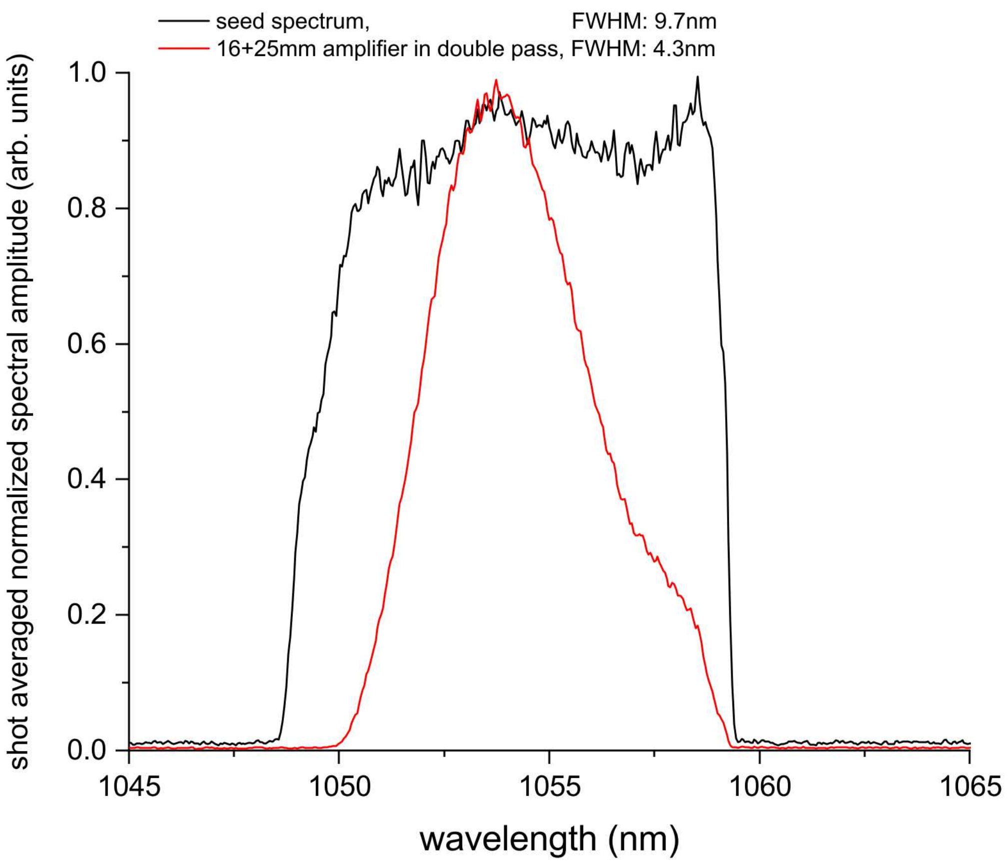


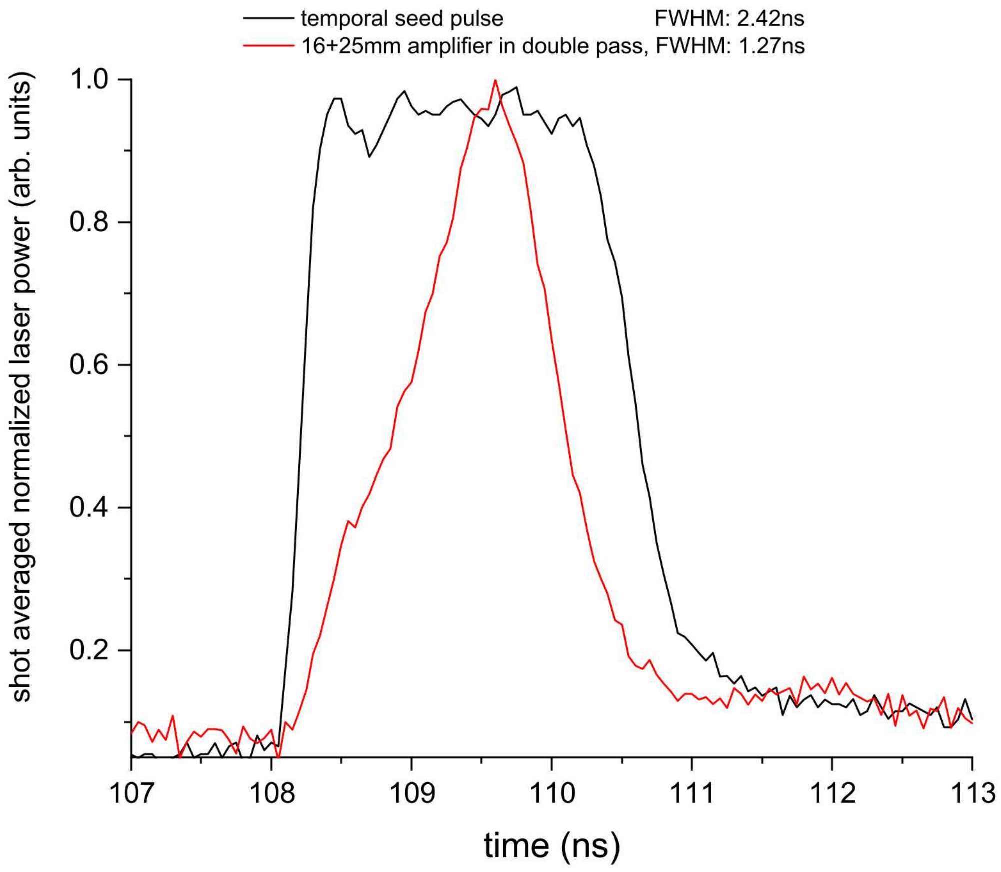
Rod Amplifiers



Gain-narrowing in rod amplifiers

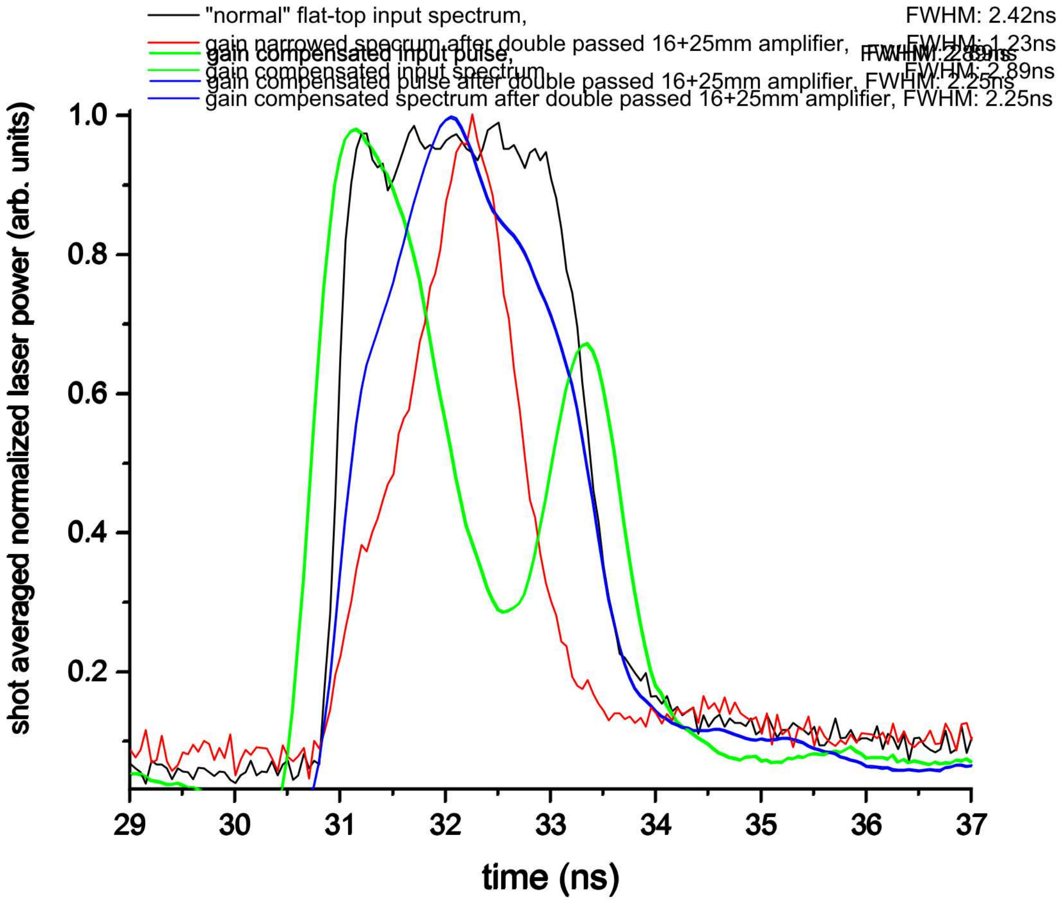
- Spectral gain-narrowing is well known in high-gain rod amplifier systems
  - In our case, the seed spectrum narrows from 10nm to 4nm after only two amplifiers.

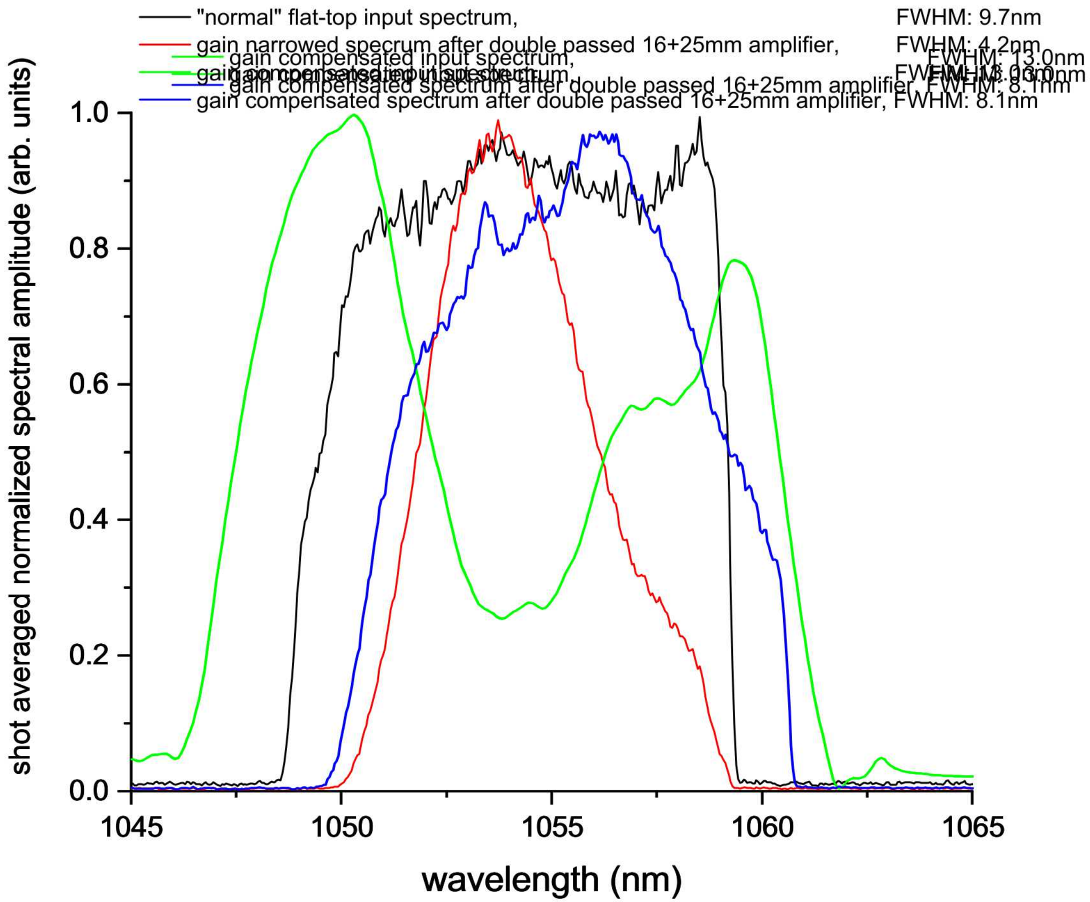




Temporal control of OPCPA pump pulse to pre-compensate seed beam

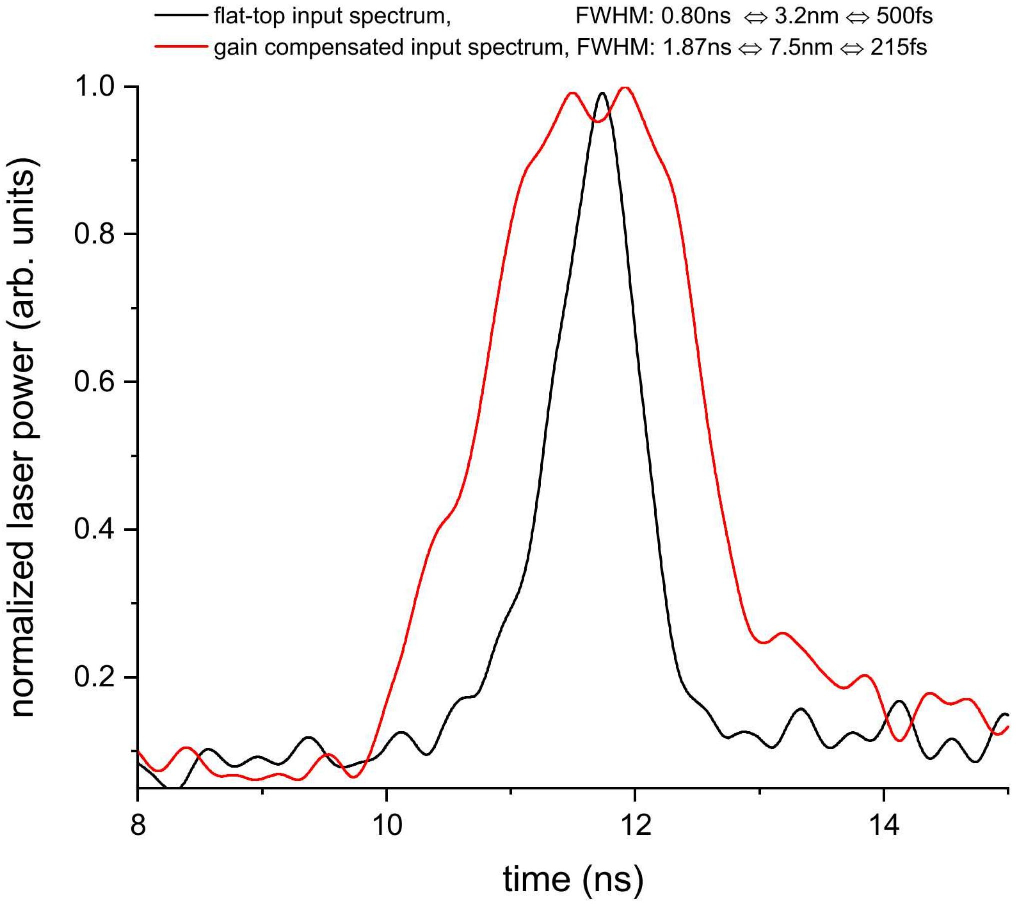
- The amplified spectrum can be broadened if one can generate a “dip” at the spectral location of the peak gain.
  - We achieve this by temporally controlling the OPCPA pump beam pulse via an AWG-EOM.





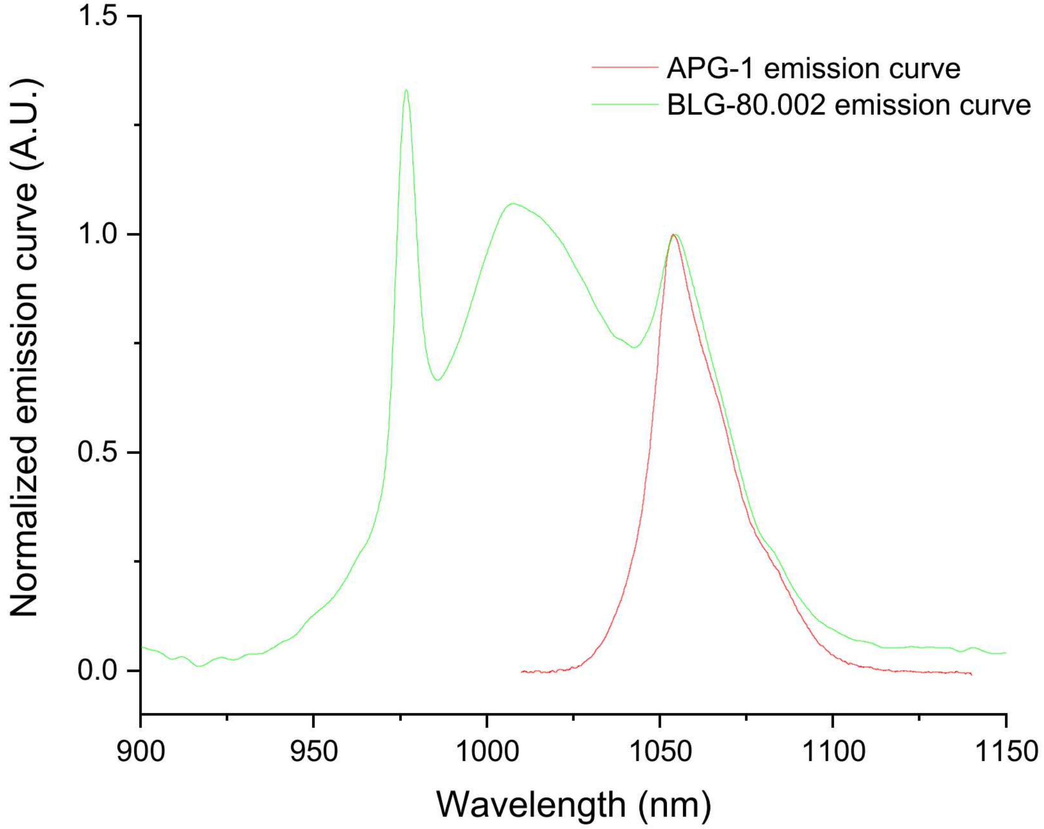
Temporal control of OPCPA pump pulse to pre-compensate seed beam

- Using the broadband rod amplified pulse as a seed for the main glass amplifier one can observe a significant increase of preserved spectrum (temporal pulsewidth).



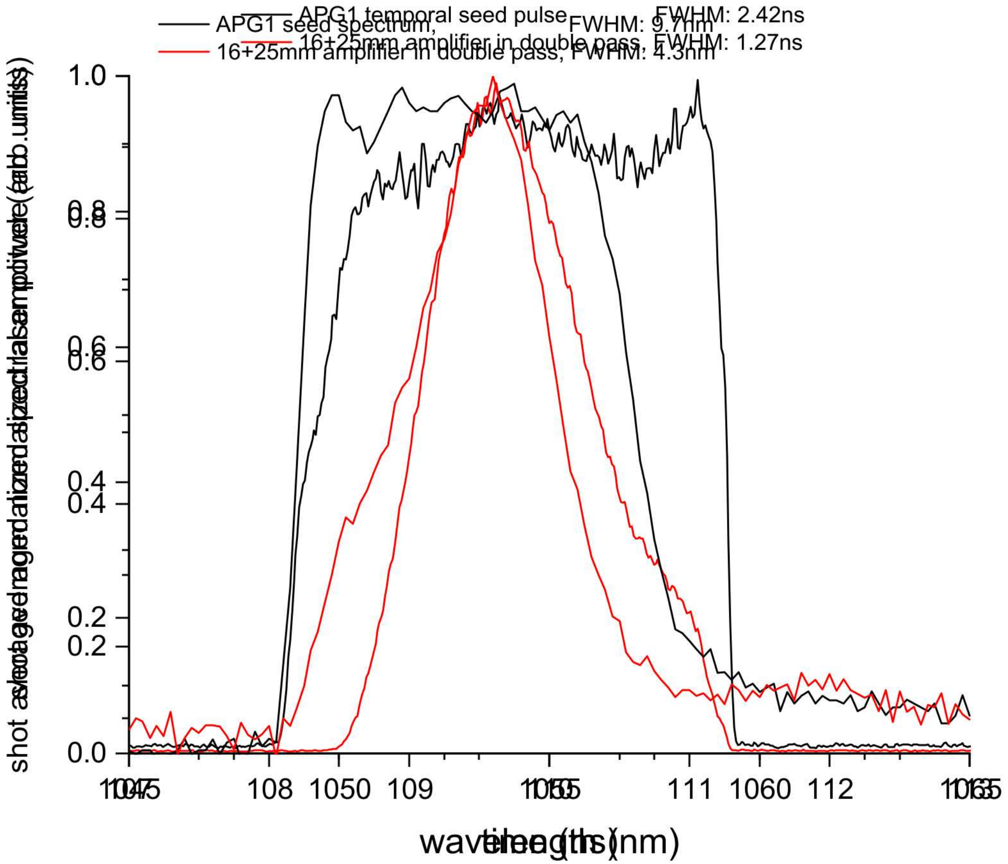
Use of novel laser glass to preserve spectral bandwidth

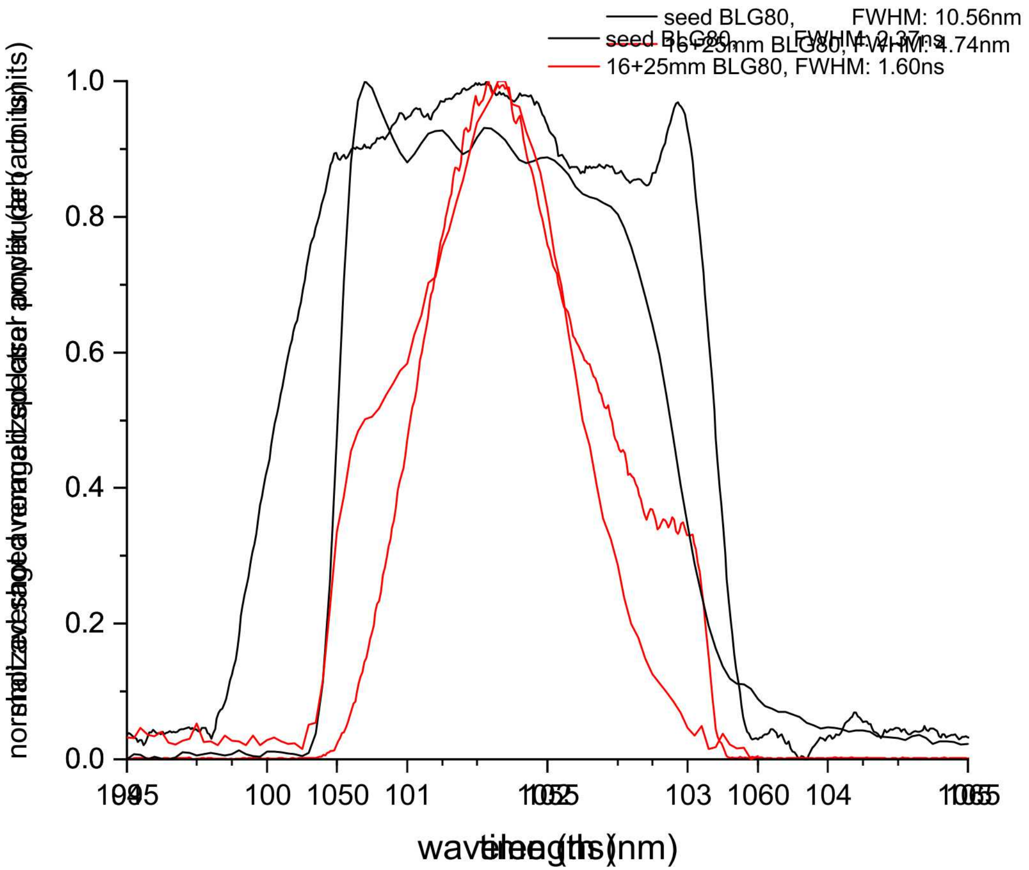
- Schott AG provided a 16mm and 25mm diameter rod of BLG80.002 for testing.
- The emission curve provided by Schott for the BLG-80.002 under evaluation is shown in green compared to the APG-1 curve in red (as normalized at the Nd ion peak near 1054nm).



APG1 vs. BLG80.002: 16+25mm amplifiers in double pass comparison

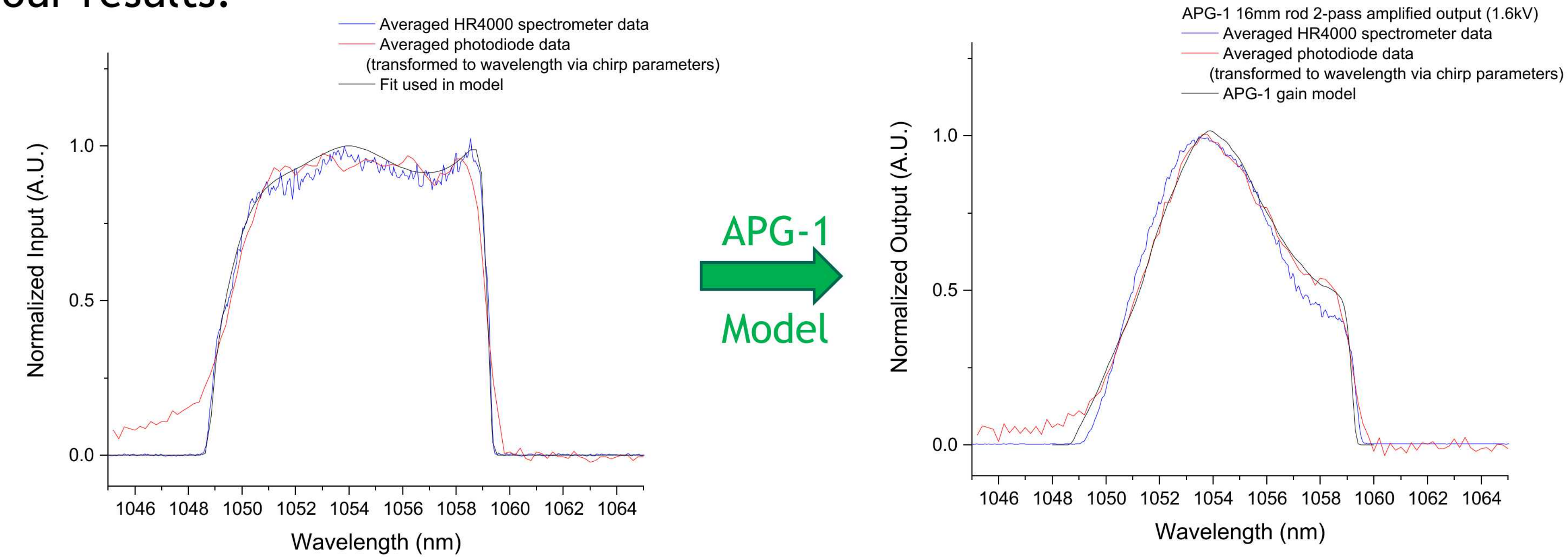
- In order to demonstrate the maximum benefit of spectral bandwidth improvement, we measured the spectral/temporal traces for the 16+25mm amp in double pass.
- The total gain was: 3530 for APG1 and 254 for BLG80.002 (both Nd 2% wt.)





Is BLG80.002 better than APG1 for our application?

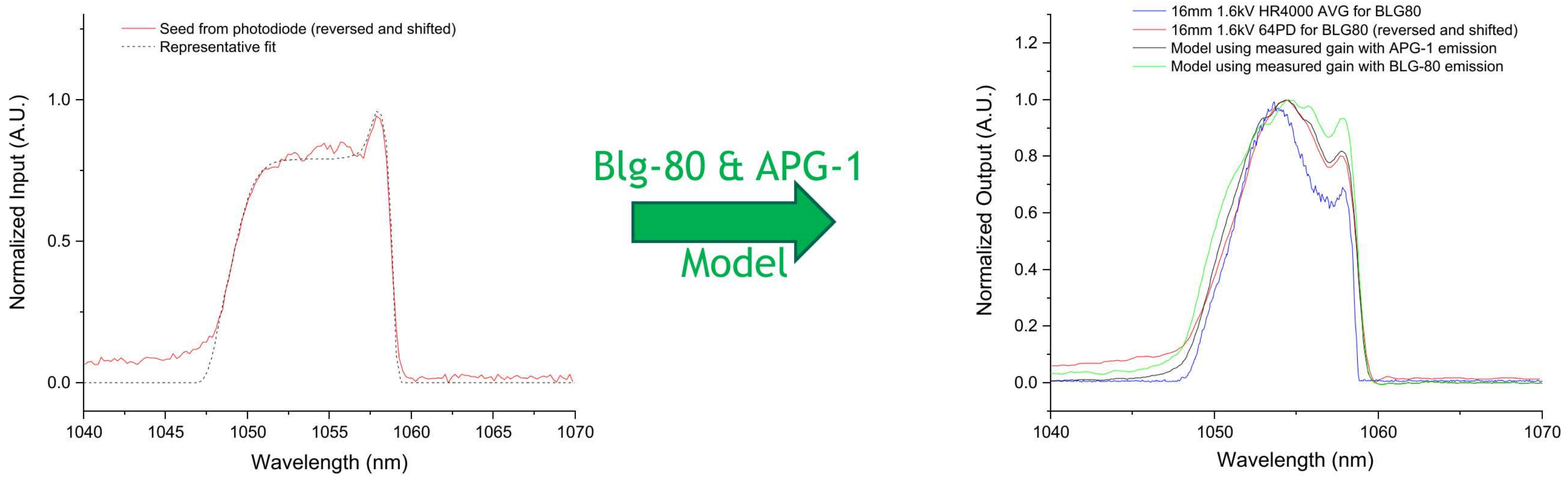
- The previous slide seems to suggest that there may be less gain narrowing for BLG80.002 versus APG1.
- However, one should keep in mind that the total gain was also a factor 14 lower for the BLG80.002 case. As a result, more gain narrowing would be expected for similar high gain.
- Based on Beer's law, we developed a simple gain narrowing model that provides more insight into our results.



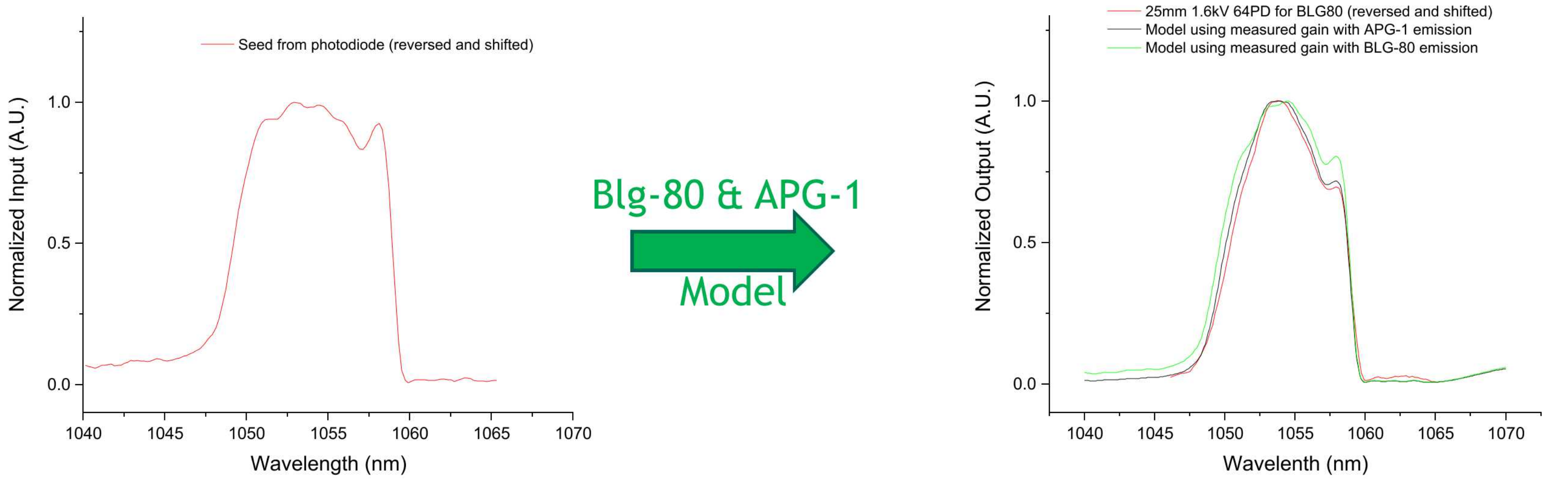
Comparison of Model with BLG-80.002 Broadband Data

- In applying the gain model, we used the spectra obtained via photodiode for the input and found that the model output agreed with the measured diode spectral data well if we used the emission data from APG-1 (black) and the measured gain (red).

16mm amp @1.6kV

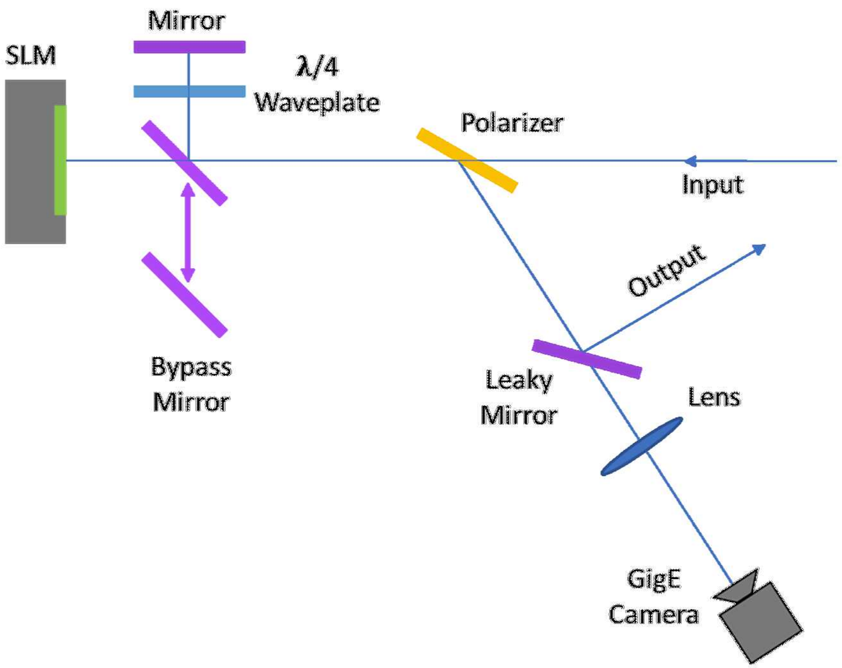


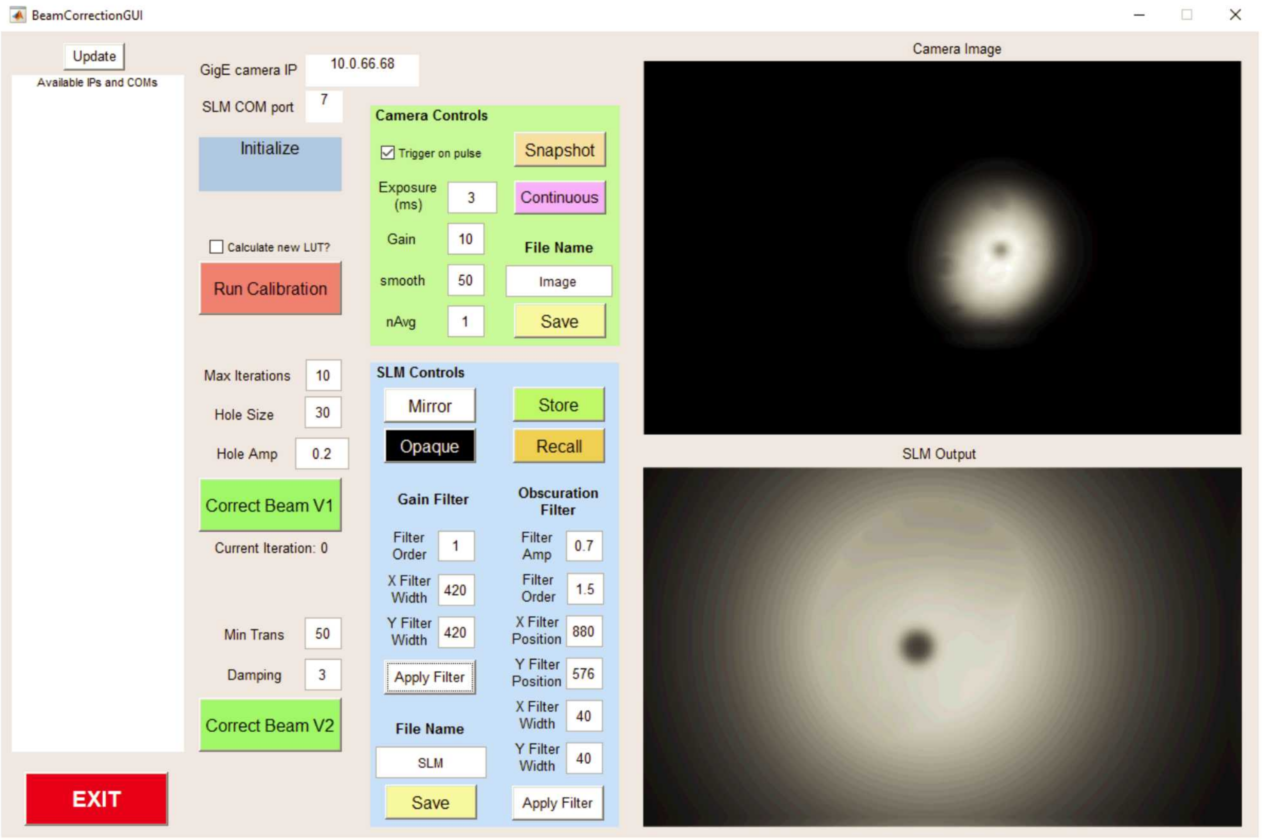
25mm amp @1.6kV



Spatial pulse-shaping using Spatial Light Modulator

- We used an SLM from Meadowlark with 1920x1152 pixel at 9.2μm x 9.2μm pixel size.
- Using Meadowlark's SDK, we generated a custom GUI using MATLAB



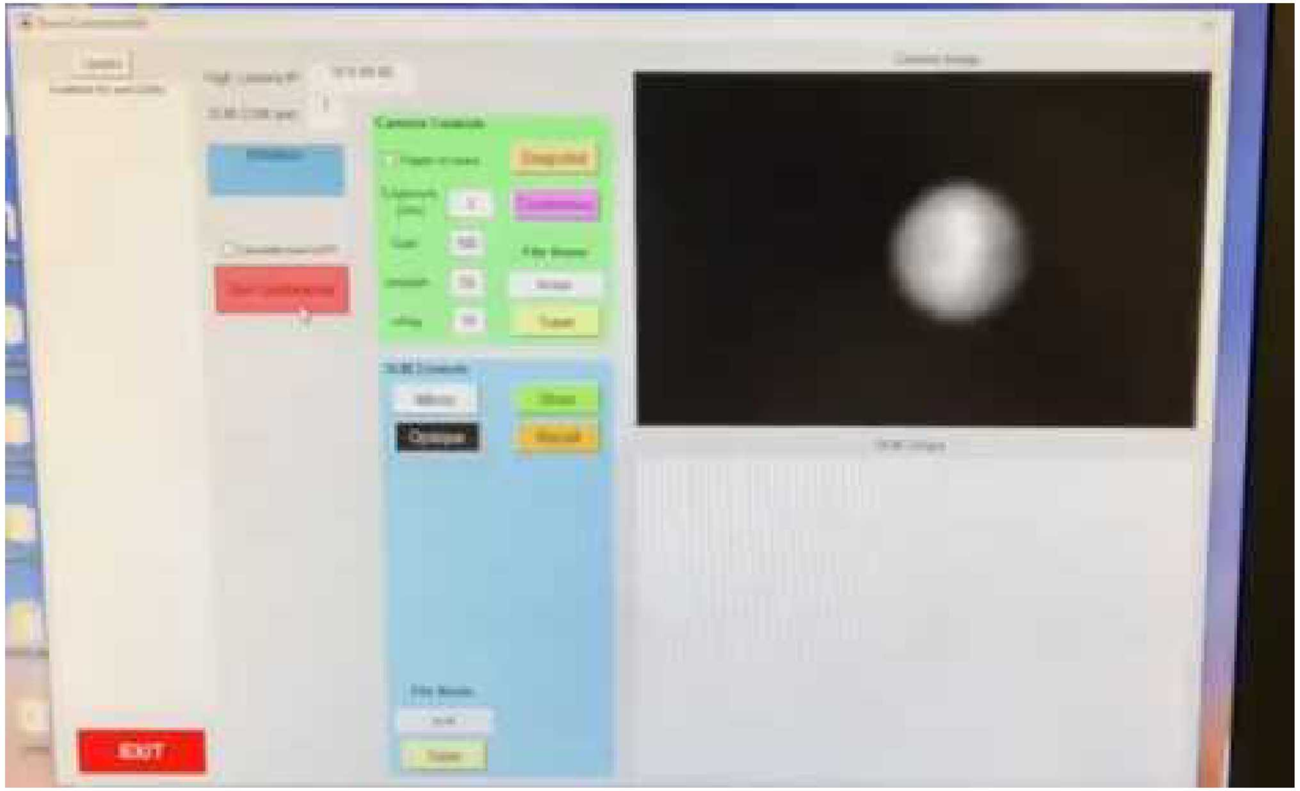


Spatial pulse-shaping using Spatial Light Modulator

- Accurate beam correction requires precise mapping between the GigE camera space and the SLM LCD.

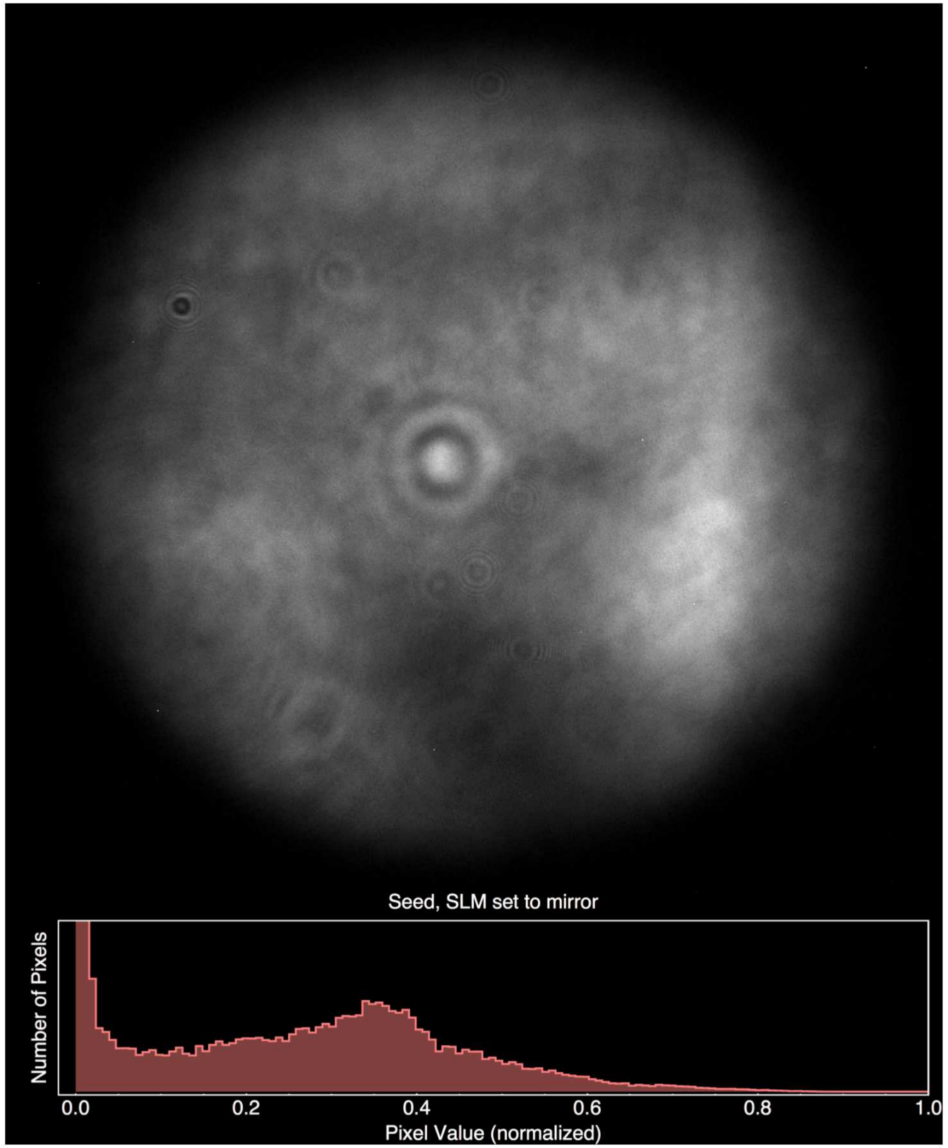
- This mapping is achieved by generating “dark spots” at the SLM and recording the corresponding images at the GigE camera.

$$\begin{pmatrix} x_{SLM} \\ y_{SLM} \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} + \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x_{CAM} \\ y_{CAM} \end{pmatrix}$$



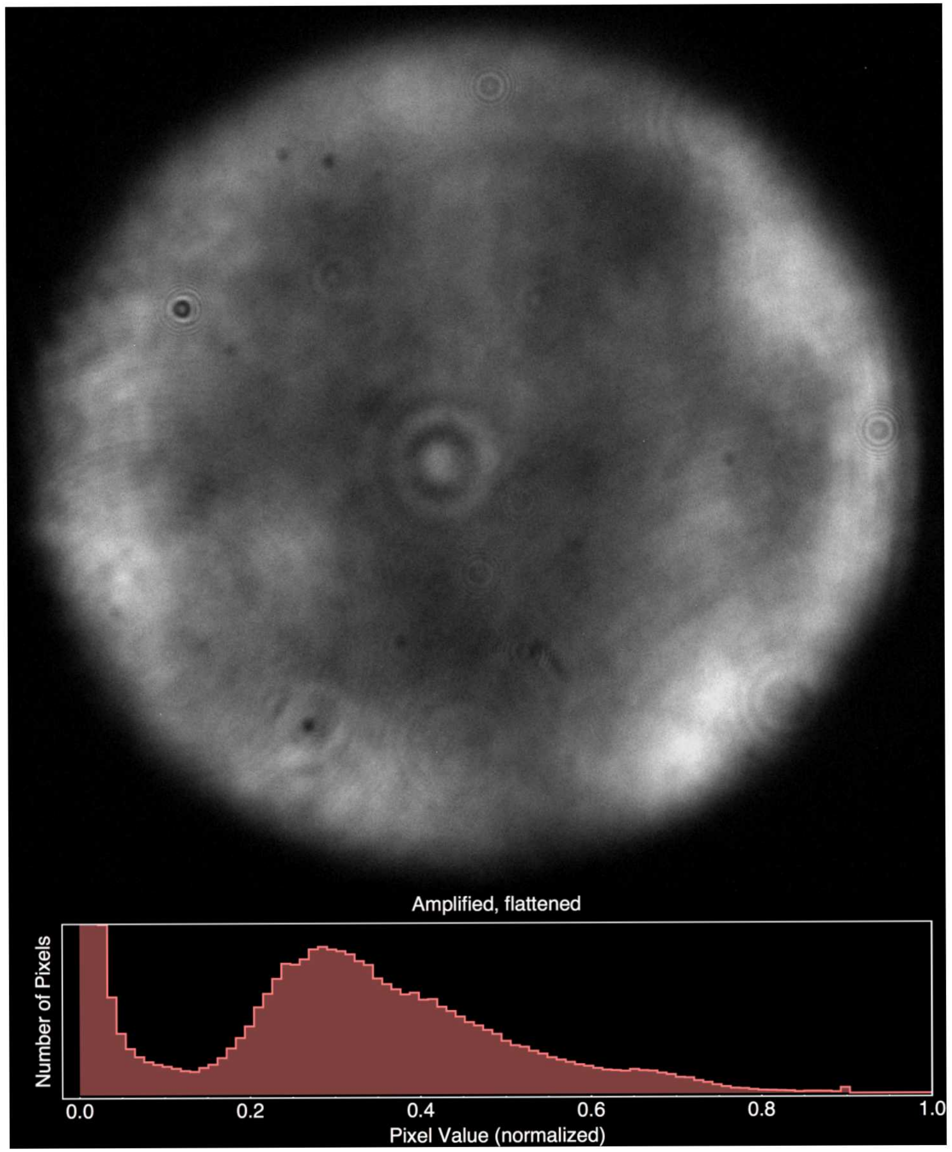
Use SLM to correct beam NF and damage spots

- The software calculates pixel by pixel the appropriate attenuation to flatten the beam.
- The maximum allowable attenuation is set by the user and allows for a variable damping factor.
- That way one can slowly iterate toward the desired NF.



Use SLM to correct for NF edge enhancements in rod amplifiers

- When using the corrected seed NF in rod amplification, one can clearly see the familiar edge enhancement.
- One can use the same SLM to correct for this gain non-uniformity by adding a custom circular obscuration with variable transmission.

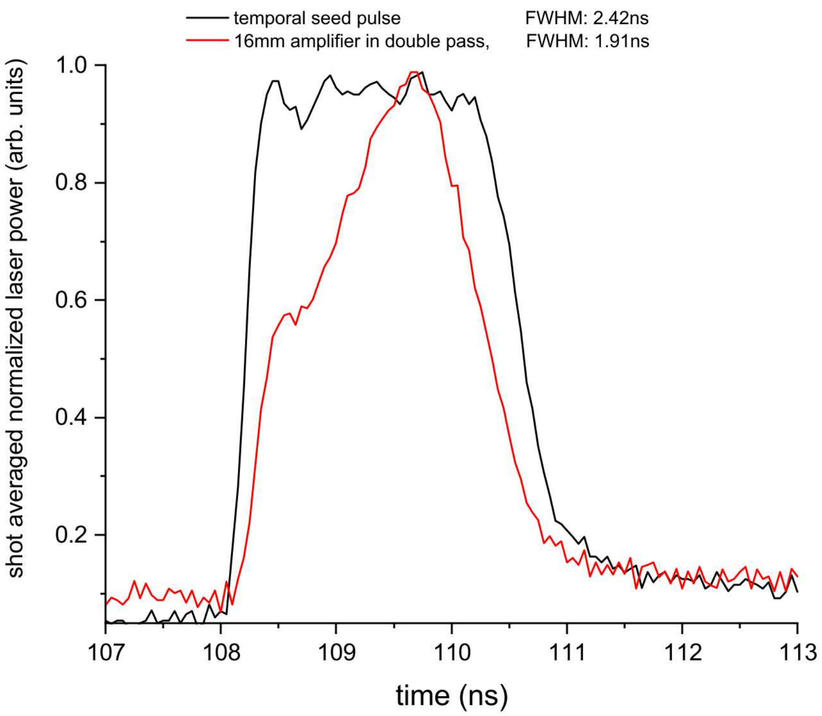


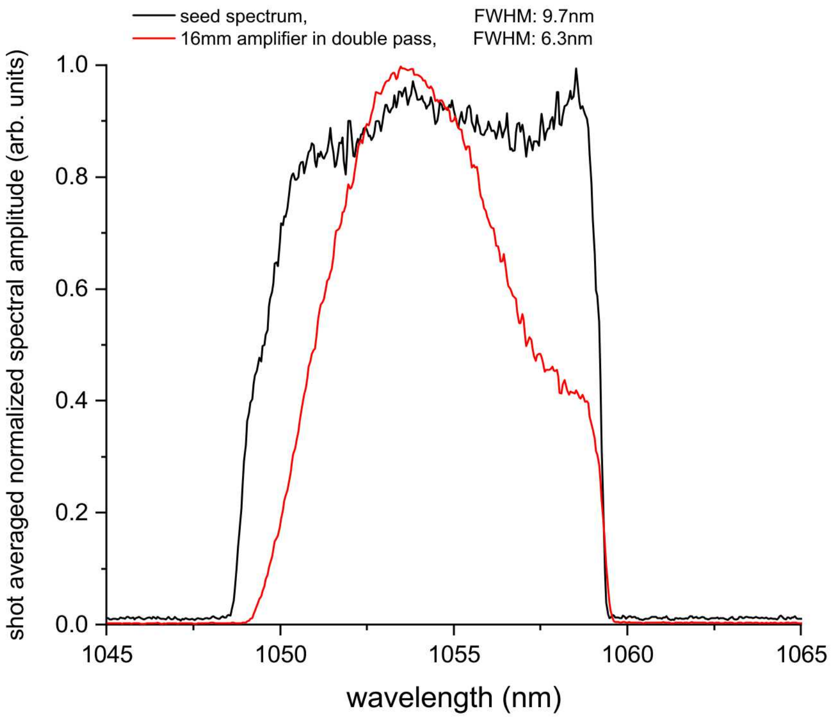
Conclusion

- We demonstrated that spectral gain narrowing in an OPCPA-rod amp system can be reduced by temporally shaping the pump beam in the OPCPA section.
  - Using this technique, we could double the output bandwidth from the rod amplifier section as well as the main slab amplifier.
- In addition, we investigated BLG80.002, a novel laser glass from Schott AG
  - Even though the emission curves seemed promising, it turns out that this glass shows no appreciable benefit for spectral bandwidth improvement **in our particular laser system**.
- We showed that a spatial light modulator (SLM) can be used to improve a laser beam NF as well as reducing “hot spots” caused by damage sites.
  - The same technique was also used to demonstrate that we can pre-compensate preferential edge gain in rod amplifiers.

16mm Rod Data for APG-1: Gain and spectrum

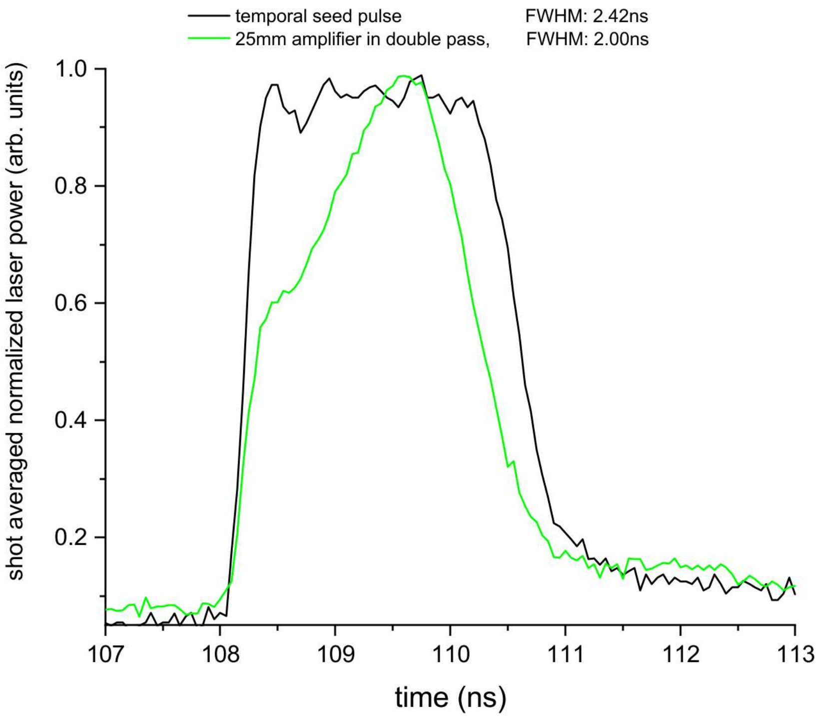
- Due to the risk of parasitic lasing due to the high APG-1 gain, the corresponding 16mm rod was tested at a flashlamp voltage of only 1.6kV (out of an available practical range of 1.6 to 2.0kV).
- A series of at least four shots was done with both the SLM-OPA and OPCPA seeds at low seed energy levels such that the corresponding gain is in the small signal regime (i.e. rod outputs were <10% of F_{sat}=5J/cm^2) .
- Gain was observed at: 143.2±10.1 (±7.0%) for the SLM-OPA seed and 106.2±2.0 (±1.9%) for the OPCPA seed

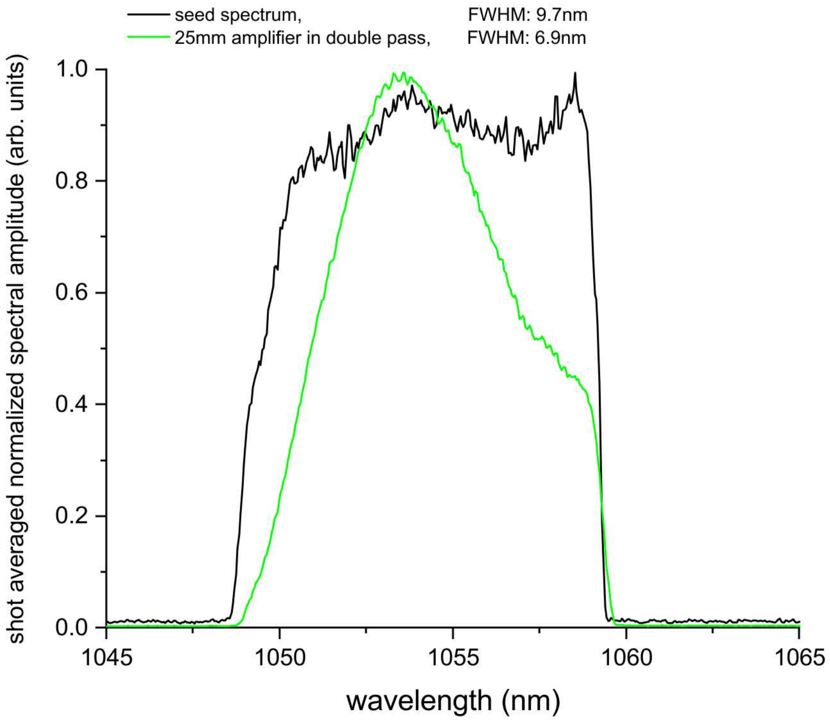




25mm Rod Data for APG-1: Gain and spectrum

- Due to the risk of parasitic lasing due to the high APG-1 gain, the corresponding 25mm rod was tested at a flashlamp voltage of only 1.6kV (out of an available practical range of 1.6 to 2.0kV).
- A series of at least four shots was done with both the SLM-OPA and OPCPA seeds at low seed energy levels such that the corresponding gain is in the small signal regime (i.e. rod outputs were <10% of F_{sat}=5J/cm^2) .
- Gain was observed at: 74.9±3.4 (±4.5%) for the SLM-OPA seed and 53.8±2.1 (±4.0%) for the OPCPA seed





Simple Beer's Law Gain Narrowing Model for APG-1

- For a multi-pass system (n passes) with 1-pass spectral gain $G(\omega)$ and losses $B(\omega)$ *:

$$I_{Out}(\omega) = I_{in}(\omega) \cdot [G(\omega)]^n \cdot [1 - B(\omega)]^n$$

…For… $\Gamma = nL/N$, $\alpha(\omega) = N\sigma(\omega)$, …and… $b_0 = [1 - B(\omega)]^n$

…where N is the population inversion, L is the gain medium length, and $\sigma(\omega)$ is the emission cross-section as a function of frequency ω.

$$I_{Out}(\omega) = I_{in}(\omega) \cdot \left[e^{N\cdot\sigma(\omega)\cdot L}\right]^n \cdot [b(\omega)]$$

$$I_{Out}(\omega) = [I_{in}(\omega)]' \cdot \left[e^{N\cdot\sigma(\omega)\cdot L}\right]^n$$

We measure the seed at the same position as the output after the system such that transmissive variation with frequency is incorporated: $[I_{in}(\omega)]' = b(\omega) \cdot I_{in}(\omega)$

$$I_{Out}(\omega) = [I_{in}(\omega)]' \cdot \left[e^{N\cdot[\sigma(\omega_0)\cdot\sigma_{Norm}(\omega)]\cdot L}\right]^n$$

We simply define the actual emission cross-section $\sigma(\omega)$ as the product of the cross-section measured at its peak ω_0 with a normalized cross-section.

$$I_{Out}(\omega) = [I_{in}(\omega)]' \cdot \left[e^{[N\cdot\sigma(\omega_0)\cdot L]\cdot\sigma_{Norm}(\omega)}\right]^n$$

$$I_{Out}(\omega) = [I_{in}(\omega)]' \cdot \left[e^{[\ln(G(\omega_0))]\cdot\sigma_{Norm}(\omega)}\right]^n$$

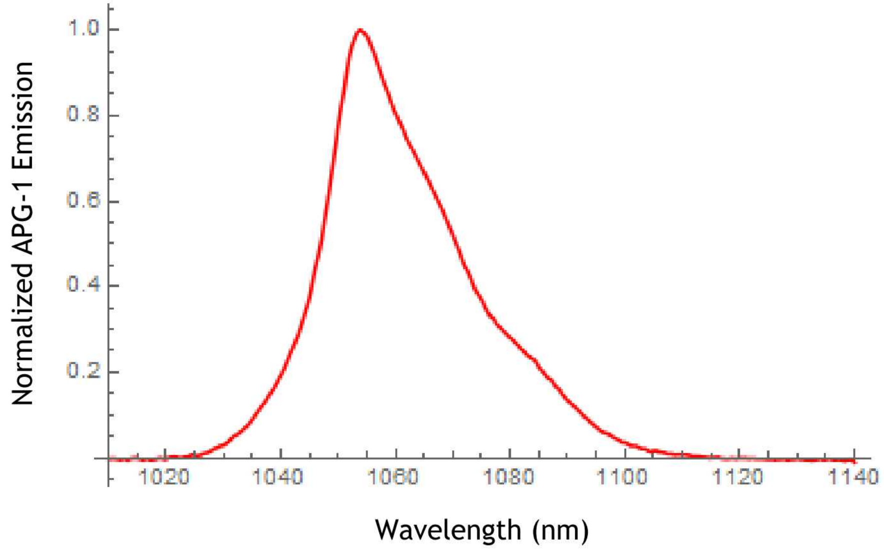
- For n=2 passes,

$$I_{Out}(\omega) = [I_{in}(\omega)]' \cdot \left[e^{[2\cdot N\cdot\sigma(\omega_0)\cdot L]\cdot\sigma_{Norm}(\omega)}\right]$$
$$= [I_{in}(\omega)]' \cdot \left[e^{[\ln(G_{2pass}(\omega_0))]\cdot\sigma_{Norm}(\omega)}\right]$$

Measured with the OPCPA seed pre-shot.

Measured on a SLM-OPA rod shot at the same pump level.

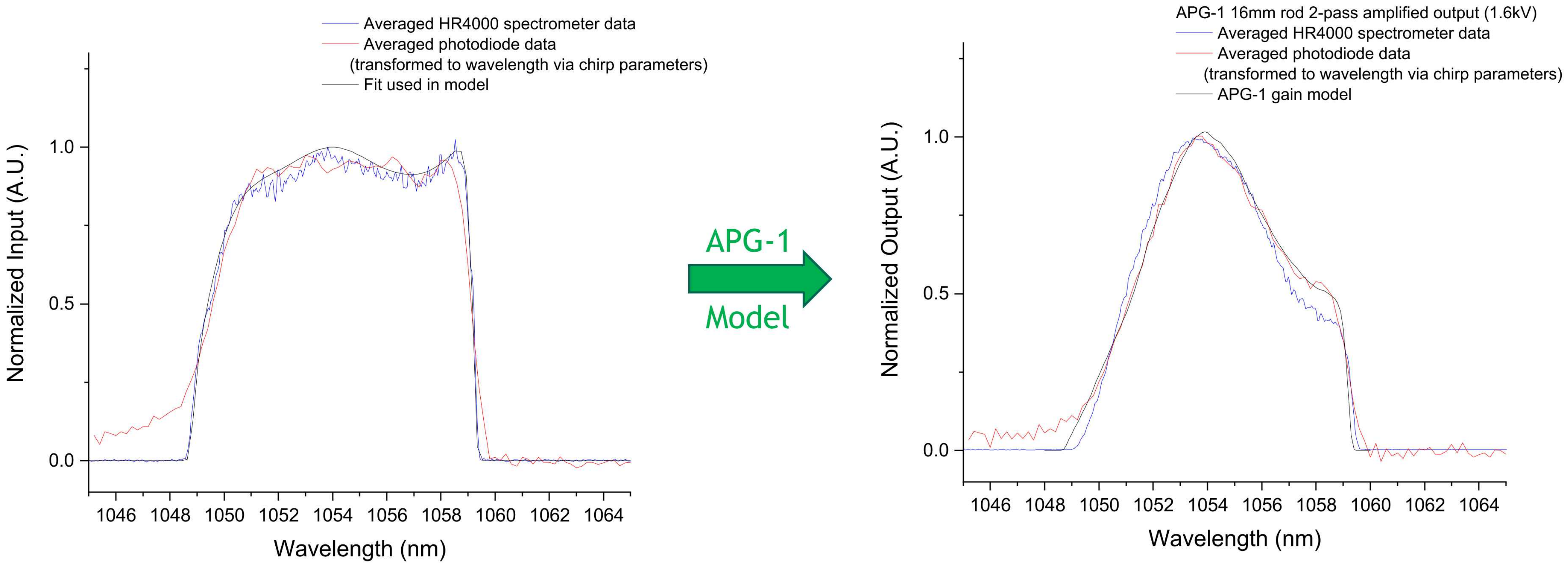
Normalized from the data provided by Schott



* See Patterson et al. JOSA B v.8 n.11 (1991)

Comparison of Model with APG-1 Broadband Data: 16mm

- Using the process described and the SLM-OPA gain data, we can model the effect of gain narrowing in the small signal regime based on the input spectrum (with the normalized model data in black).

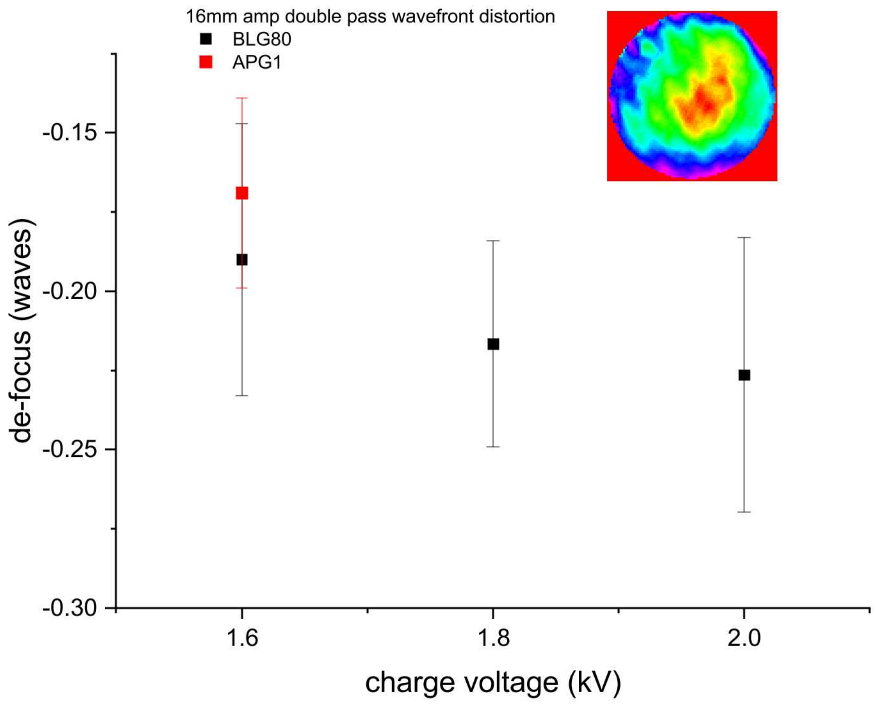


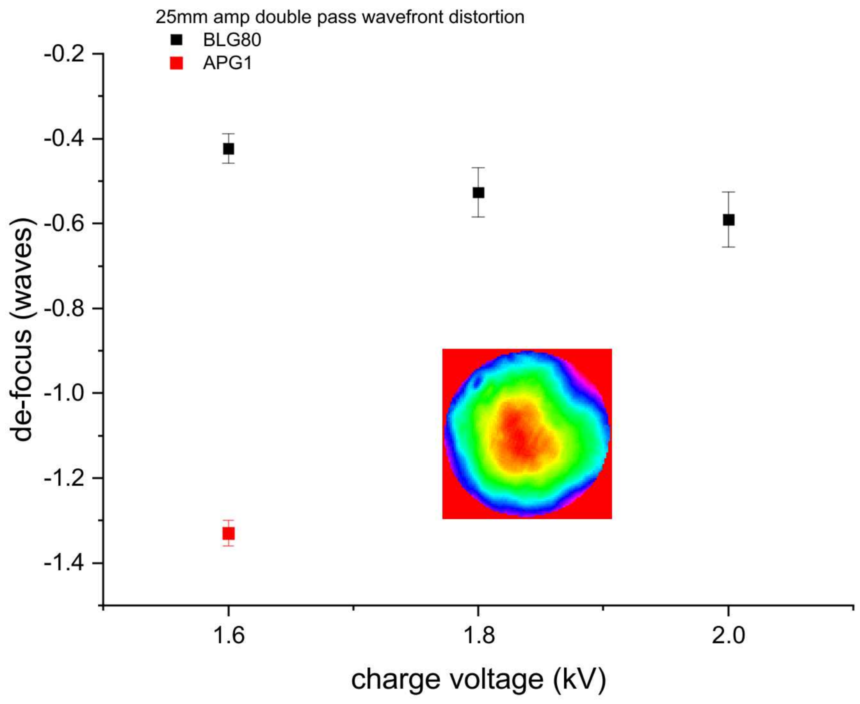
Comparison of Model with APG-1 Broadband Data: 16mm

- The previous slide demonstrates that there is good agreement between model and measurement.
- This gives us confidence in the developed model as well as the published emission curve for APG1.
- One should note that the measurement agrees better when compared to a spectrum derived from temporal data.
  - This is due to the fact that the spectrometer shows greater sensitivity to alignment errors than the photodiode setup. As a result, only temporal data was considered when comparing data with the model.
  - The spectral data is still shown, since the error is small and spectral data offers a more intuitive way of judging spectral bandwidth performance.

16mm and 25mm Rod Data for BLG-80: Thermal wavefront distortion

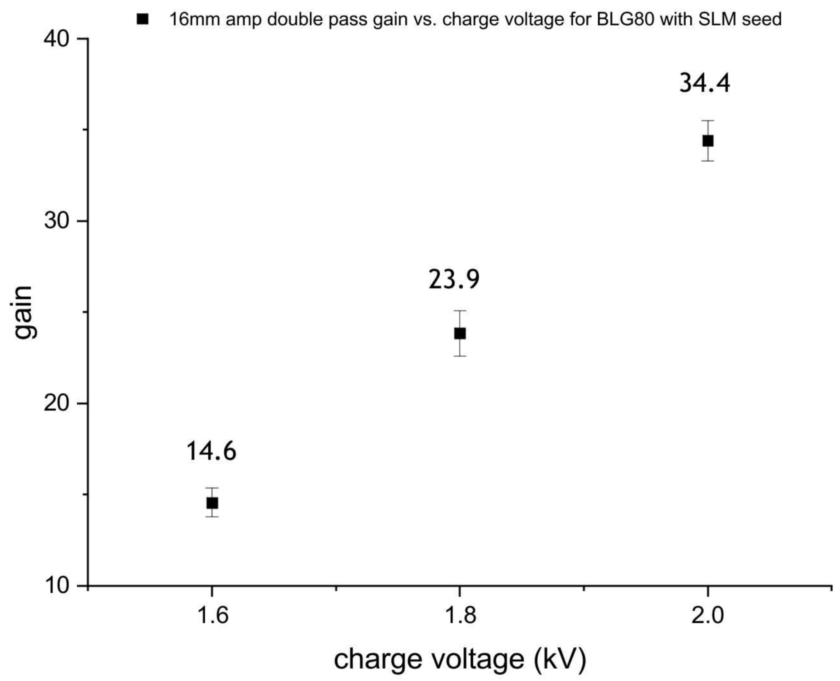
- A SID4-GE wavefront sensor from Phasics Corp. (http://phasicscorp.com/) was used to measure the on-shot thermally induced wavefront distortions. These distortions are primarily de-focus, due to the cylindrical geometry of the lasing material. As such, we have only plotted this term (Zernike #4) as a function of charge voltage. A full set of wavefront data is available for each shot if requested.

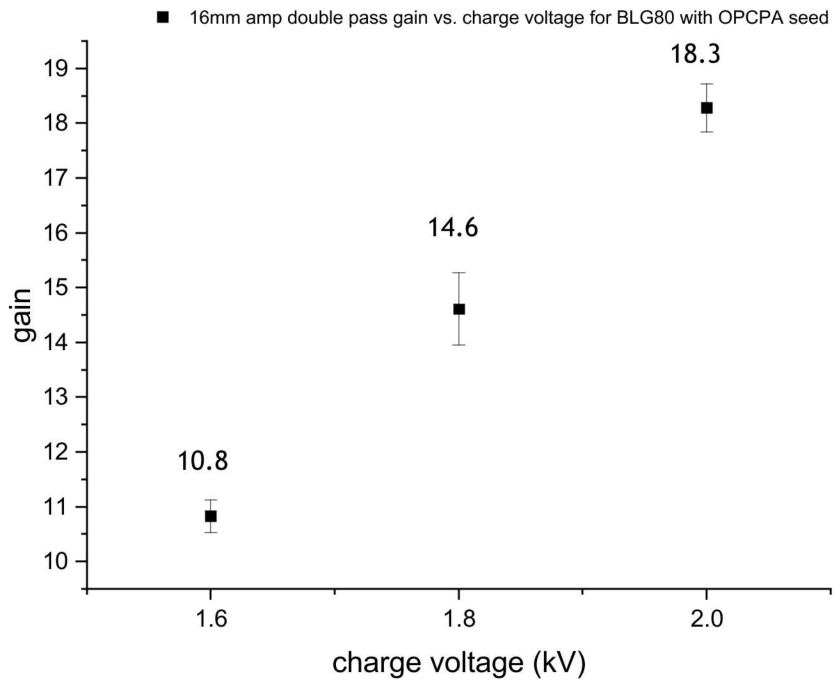




16mm Rod Data for BLG-80.002: Gain

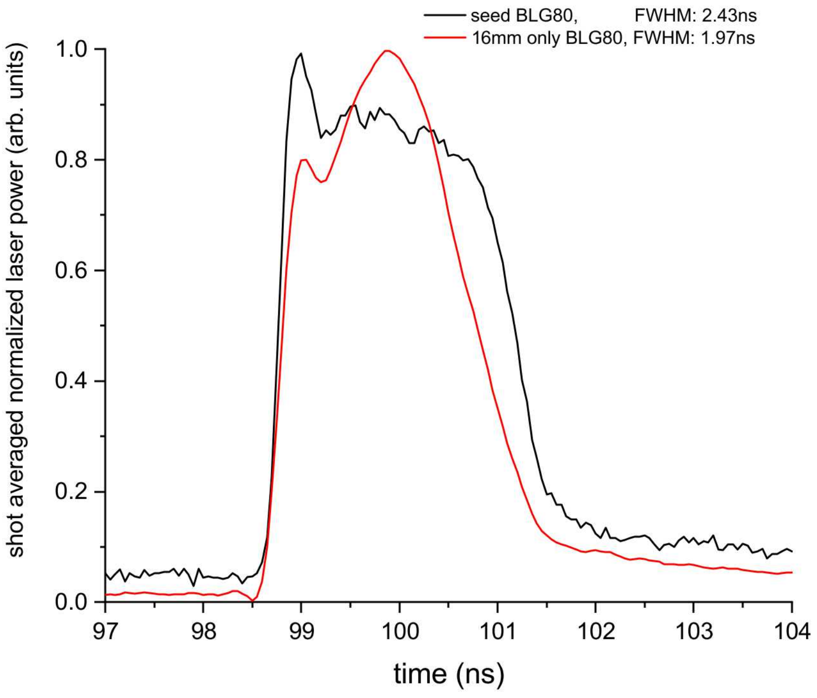
- Due to the lower gain for BLG-80.002, the corresponding 16mm rod was tested at a flashlamp voltages of 1.6kV, 1.8kV, and 2.0kV.
- A series of four shots was done with both the SLM-OPA and OPCPA seeds at low levels such that the corresponding gain is in the small signal regime.

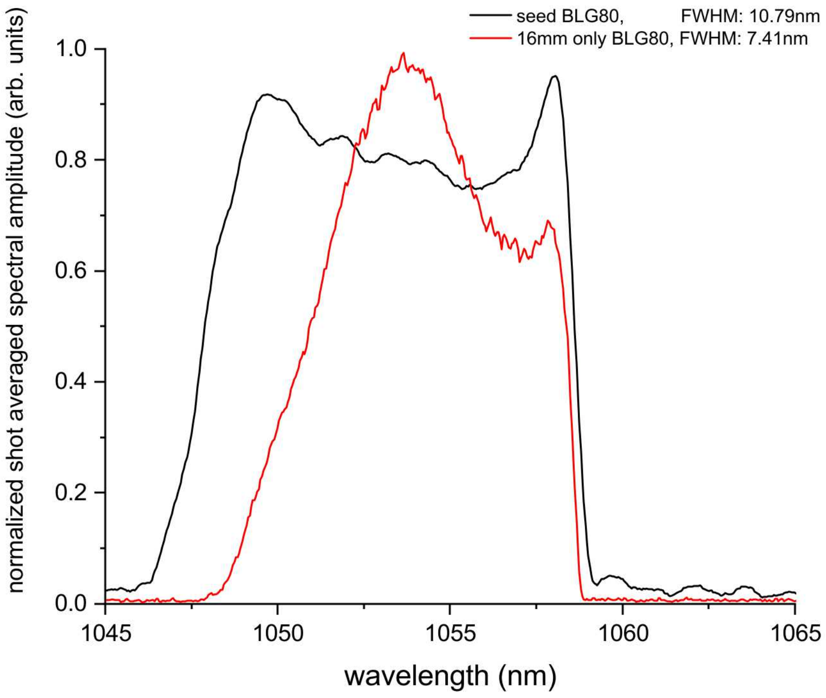




16mm Rod Data for BLG-80.002: Spectral and temporal gain (1.6kV)

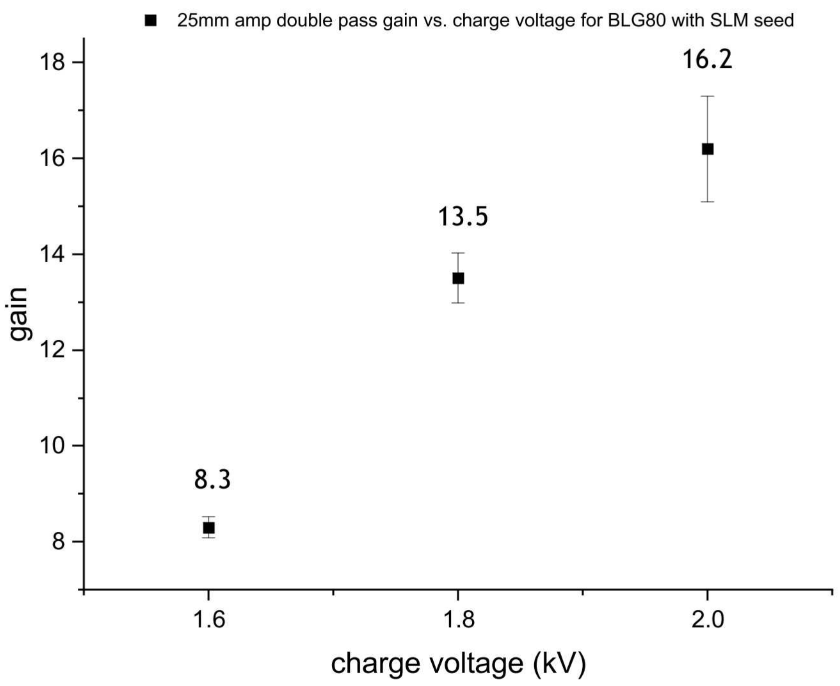
- Spectral data was obtained by an HR4000 spectrometer from Ocean Optics using grating#H6 and a slit wdith of 5 micron. The resulting spectral resolution was 0.25nm.
- Temporal data was taken via a photo-diode (DET08, 70ps rise- 250ps fall-time) from Thorlabs in combination with a TDS6124C oscilloscope from Tektronix with an analog bandwidth of 12GHz.

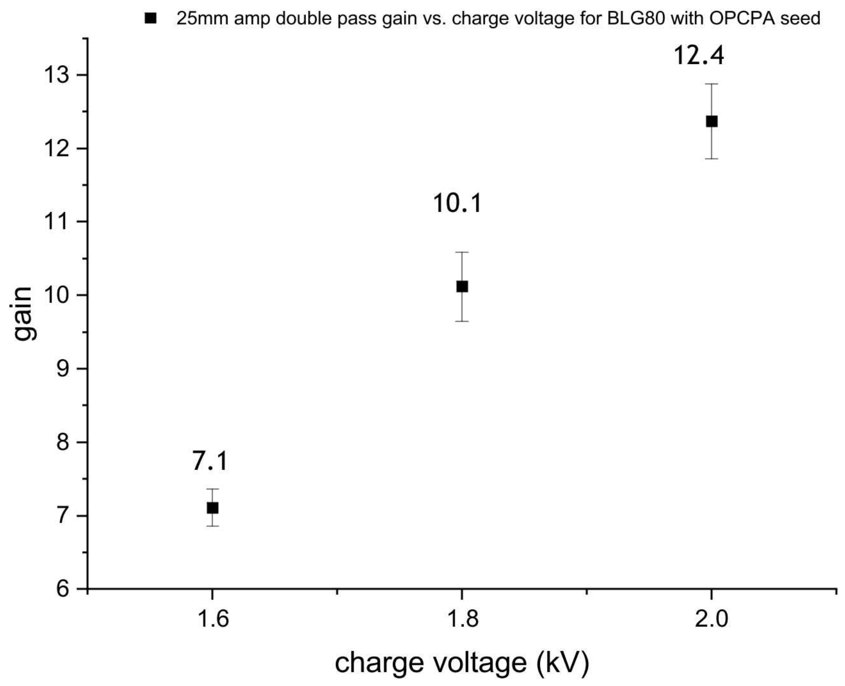




25mm Rod Data for BLG-80.002: Gain

- Due to the lower gain for BLG-80.002, the corresponding 25mm rod was tested at a flashlamp voltages of 1.6kV, 1.8kV, and 2.0kV.
- A series of four shots was done with both the SLM-OPA and OPCPA seeds at low levels such that the corresponding gain is in the small signal regime.





25mm Rod Data for BLG-80.002: Spectral and temporal gain (1.6kV)

- Spectral data was obtained by an HR4000 spectrometer from Ocean Optics using grating#H6 and a slit width of 5 micron. The resulting spectral resolution was 0.25nm.
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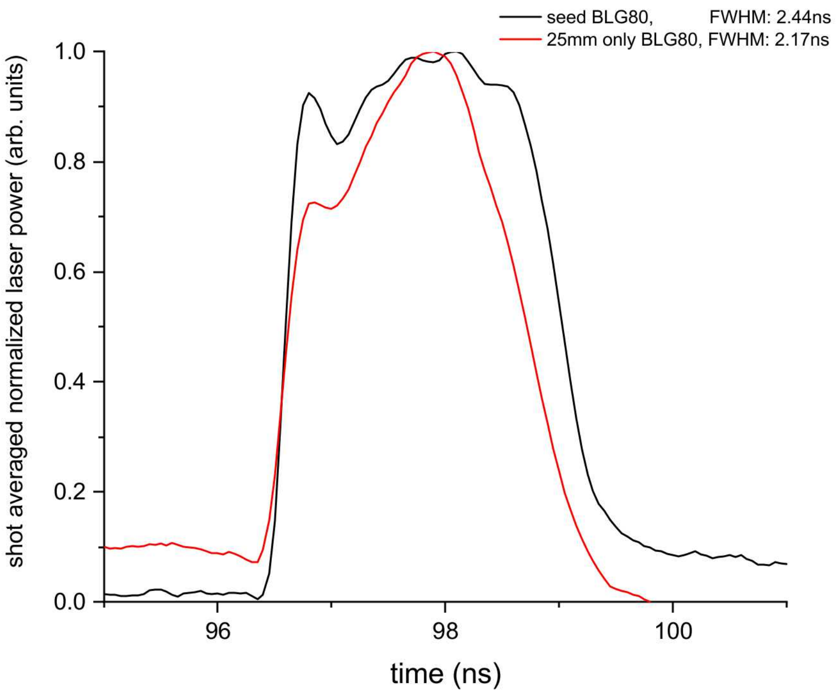
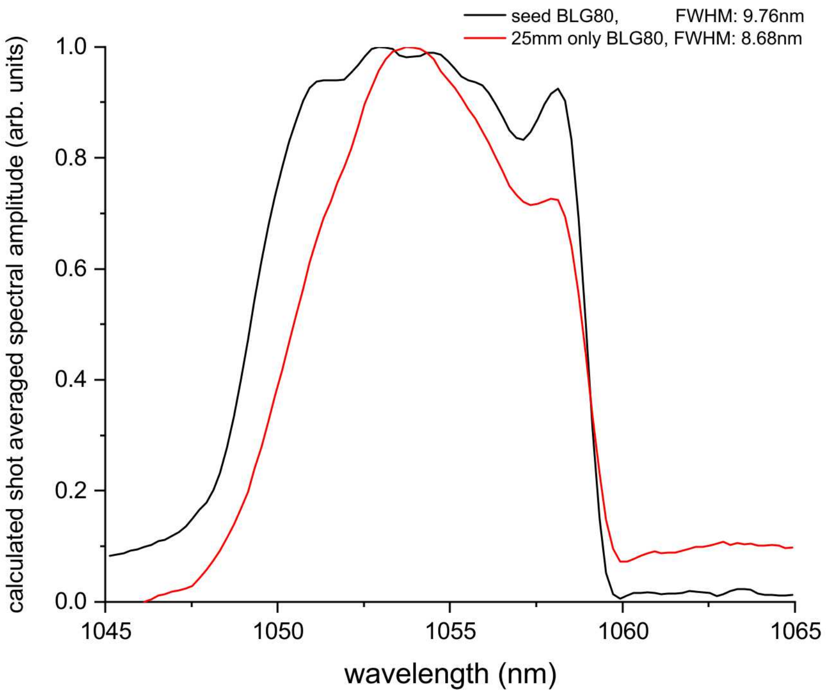
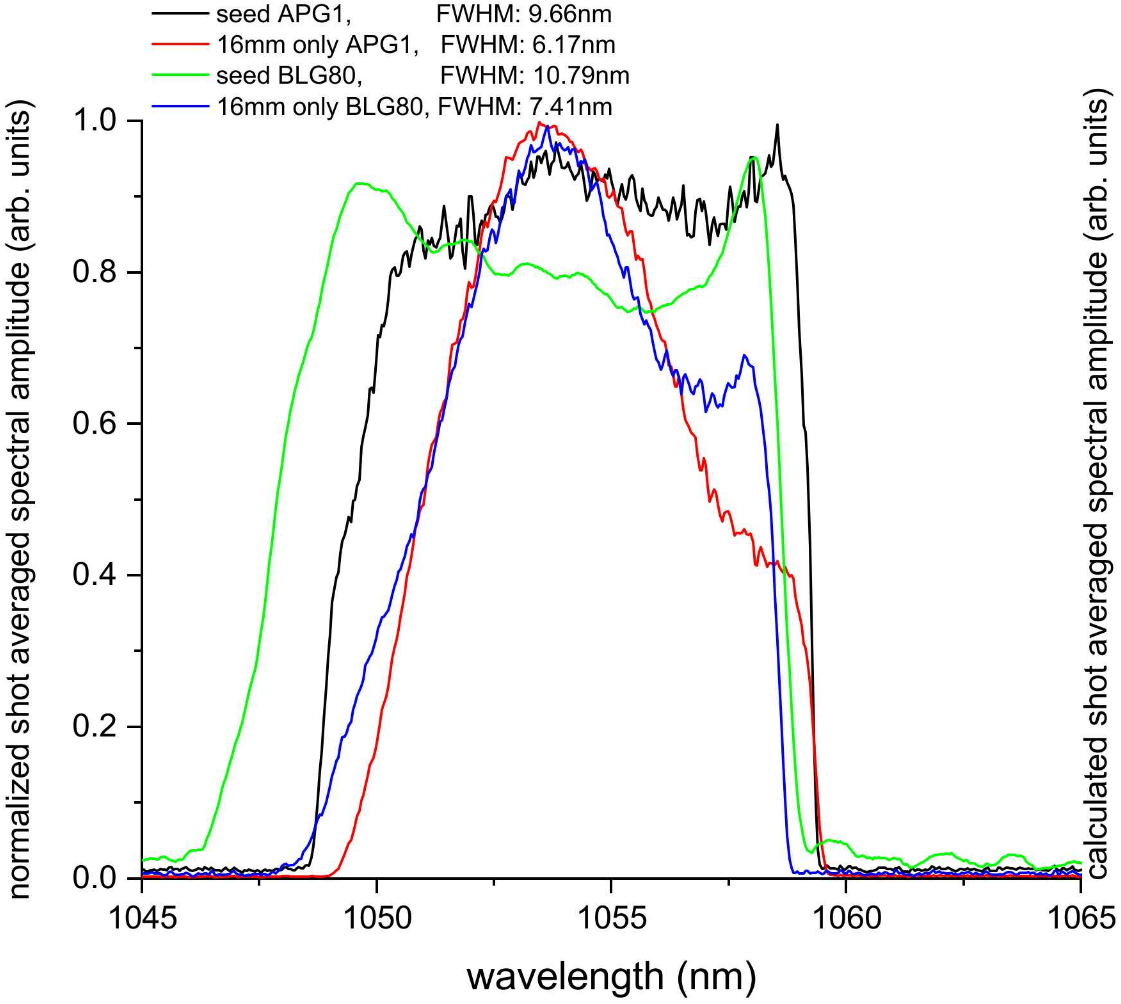


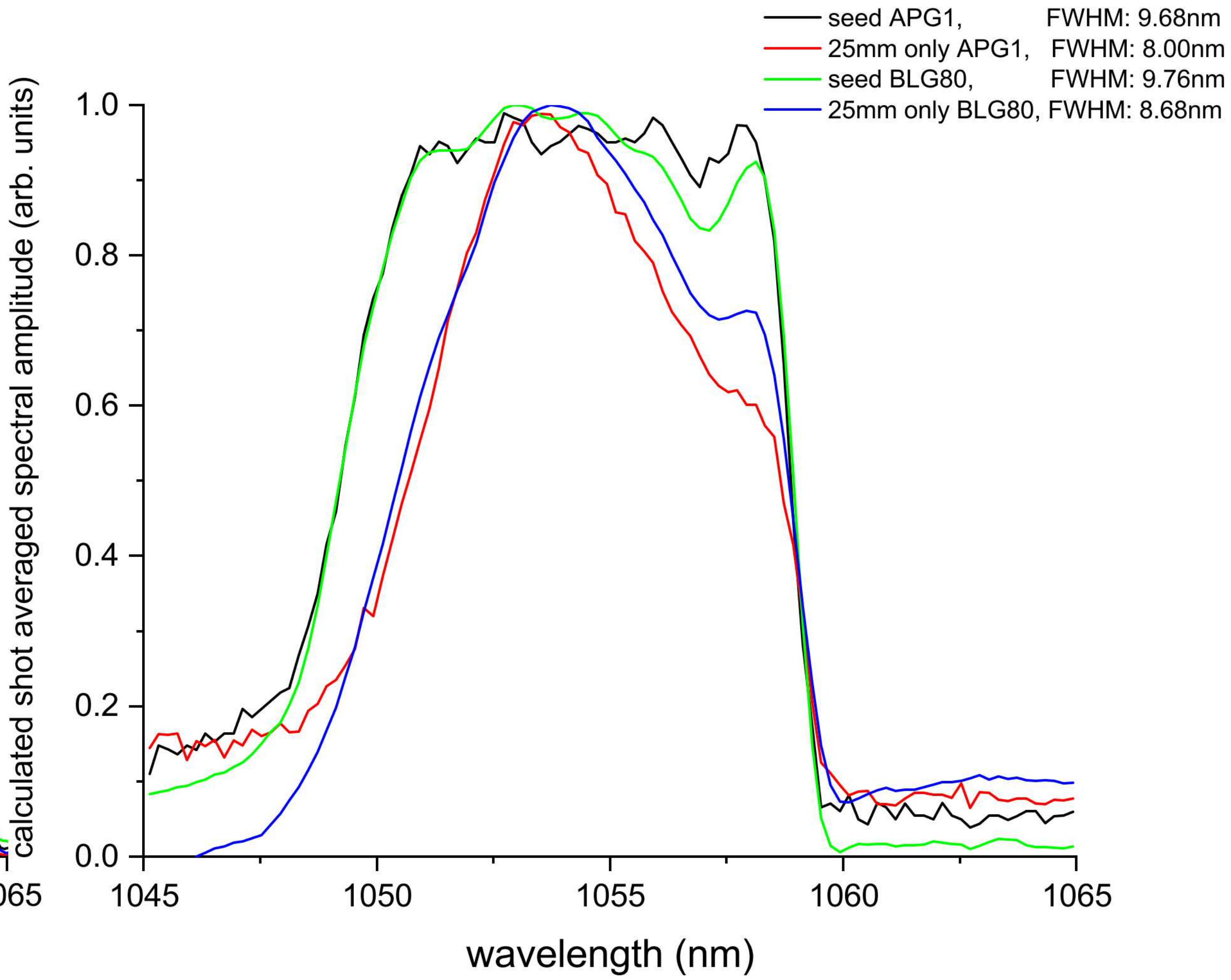


APG1 vs. BLG80.002: Spectral comparison for 1.6kV charge voltage

16mm amp in double pass



25mm amp in double pass



APG1 vs. BLG80.002: Temporal comparison for 1.6kV charge voltage

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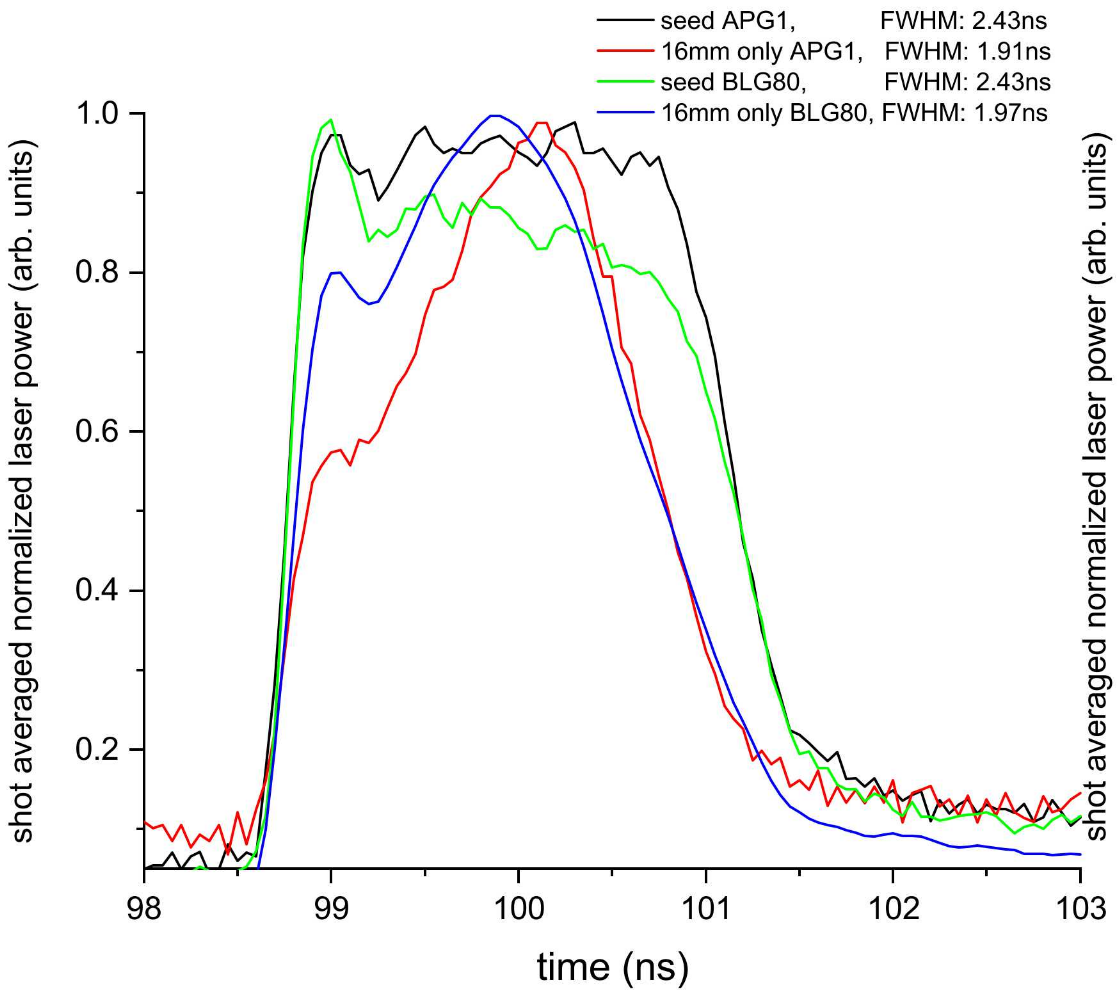
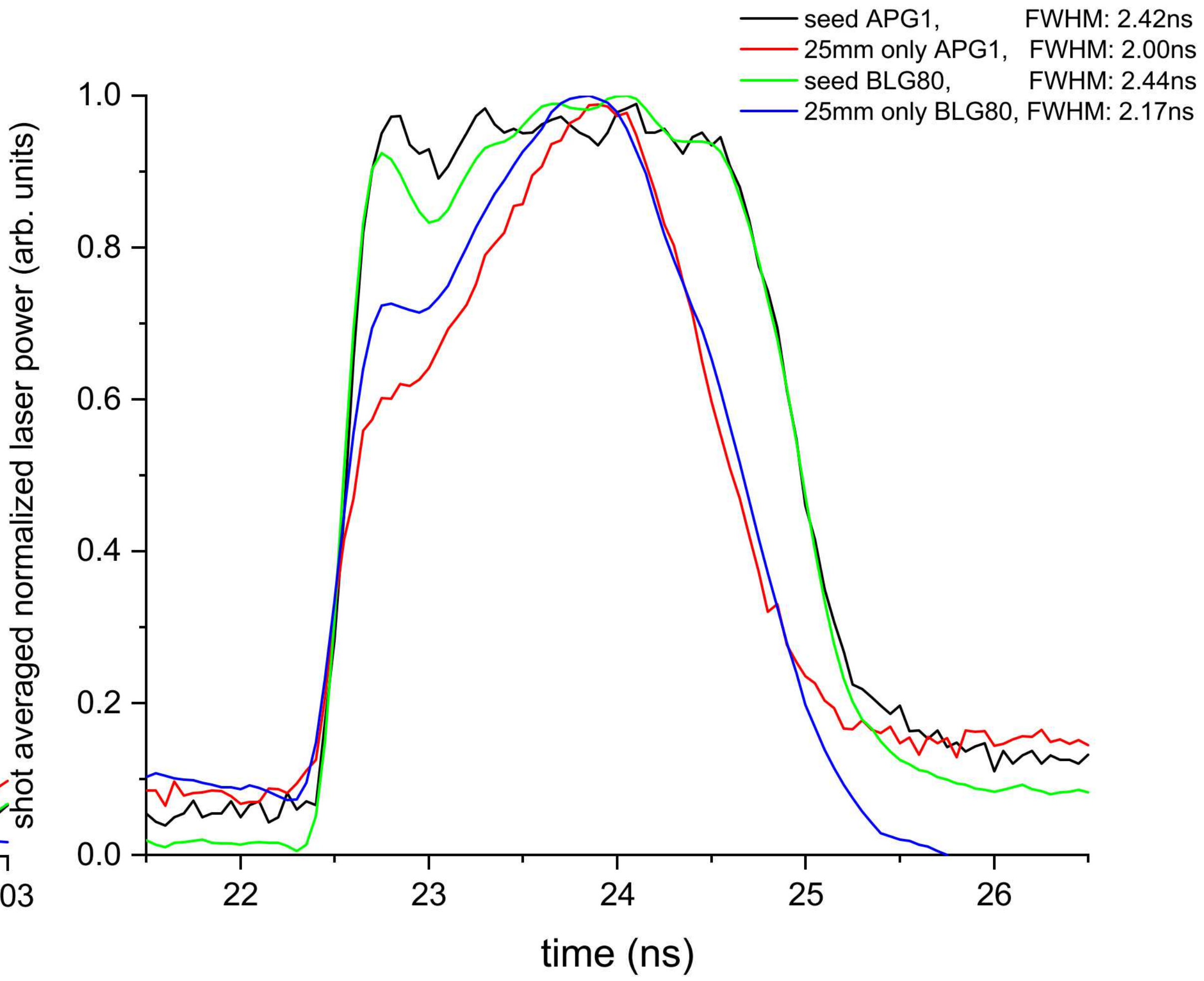
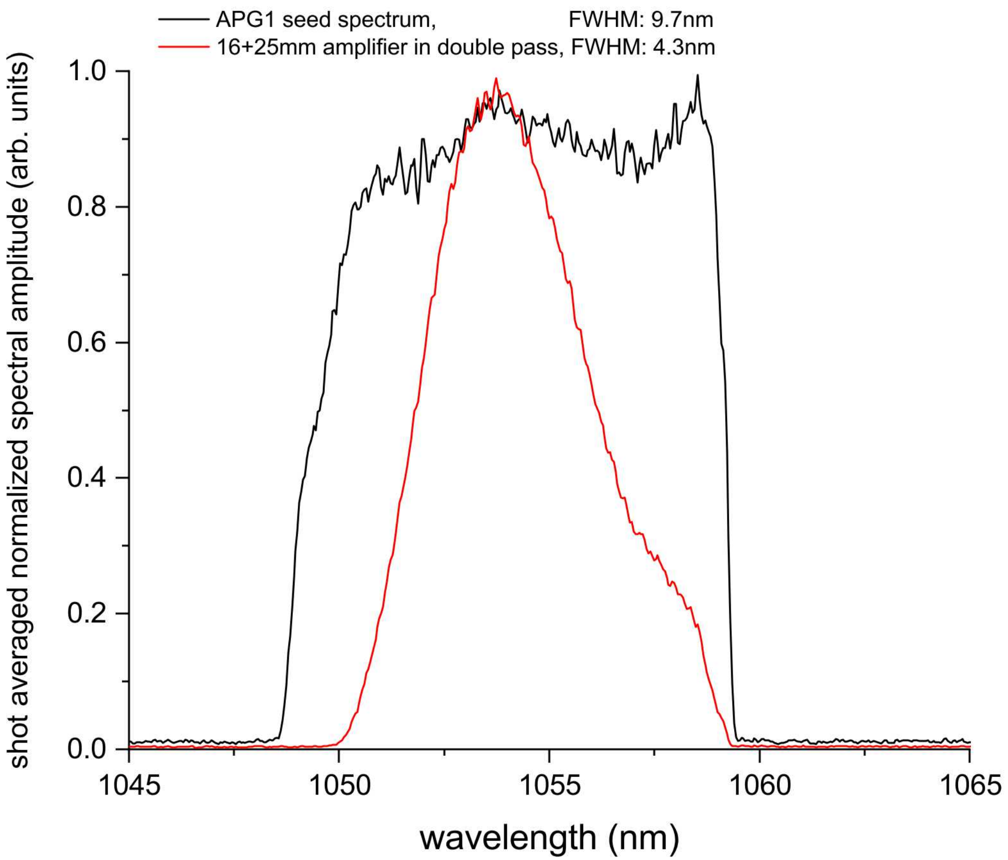


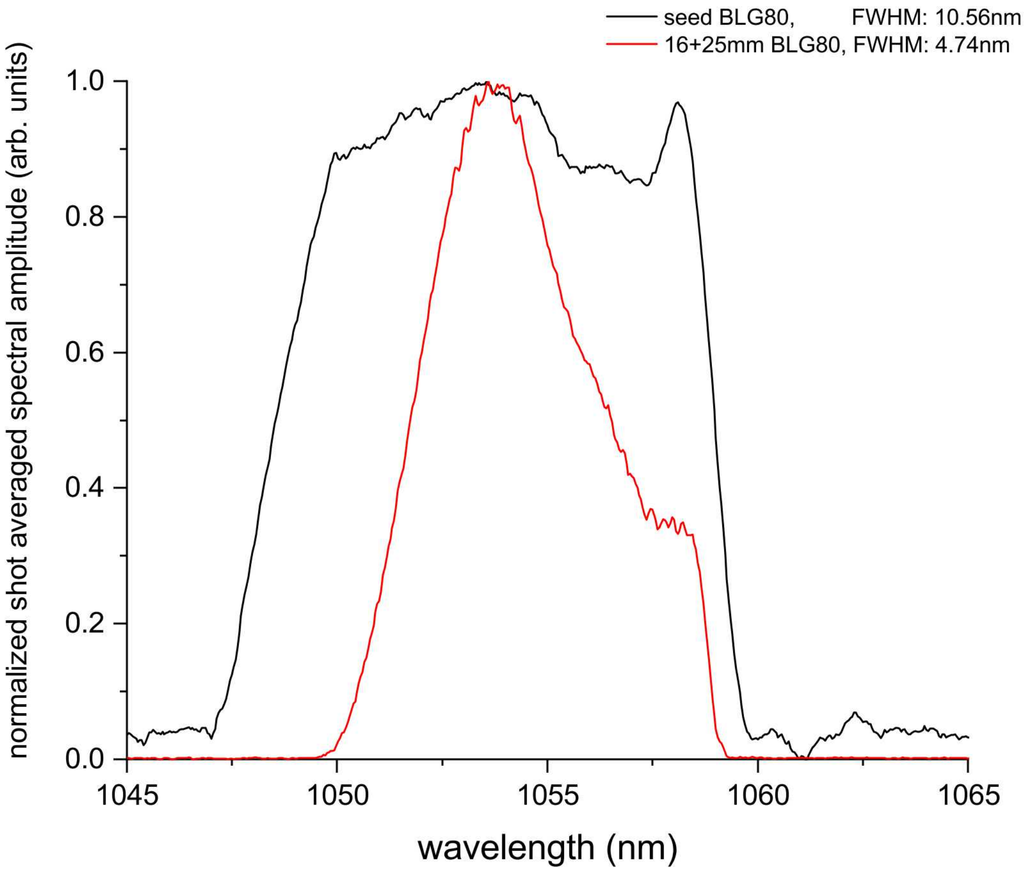
25mm amp in double pass



APG1 vs. BLG80: 16+25mm amplifiers in double pass comparison

- In order to demonstrate the maximum benefit of spectral bandwidth improvement, we measured the spectral/temporal traces for the 16+25mm amp in double pass.
- The total gain was: 3530 for APG1 (1.6kV) and 254 for BLG80.002 (2.0kV)





APG1 vs. BLG80.002: 16+25mm amplifiers in double pass comparison

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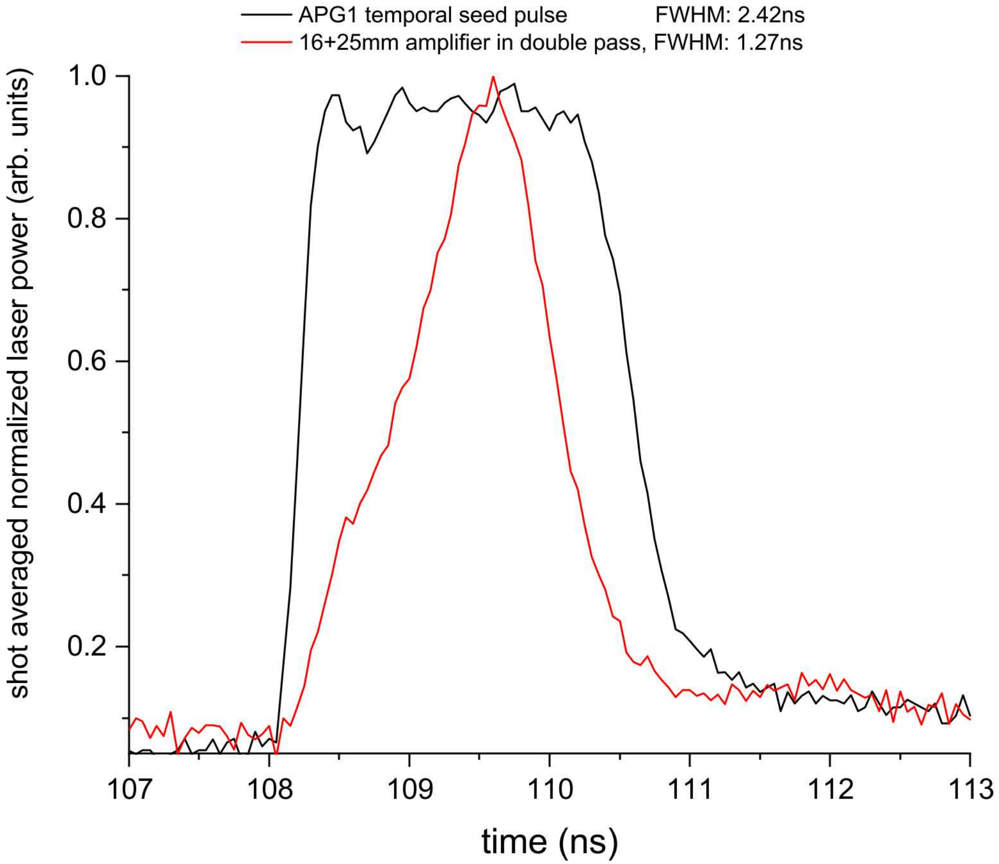
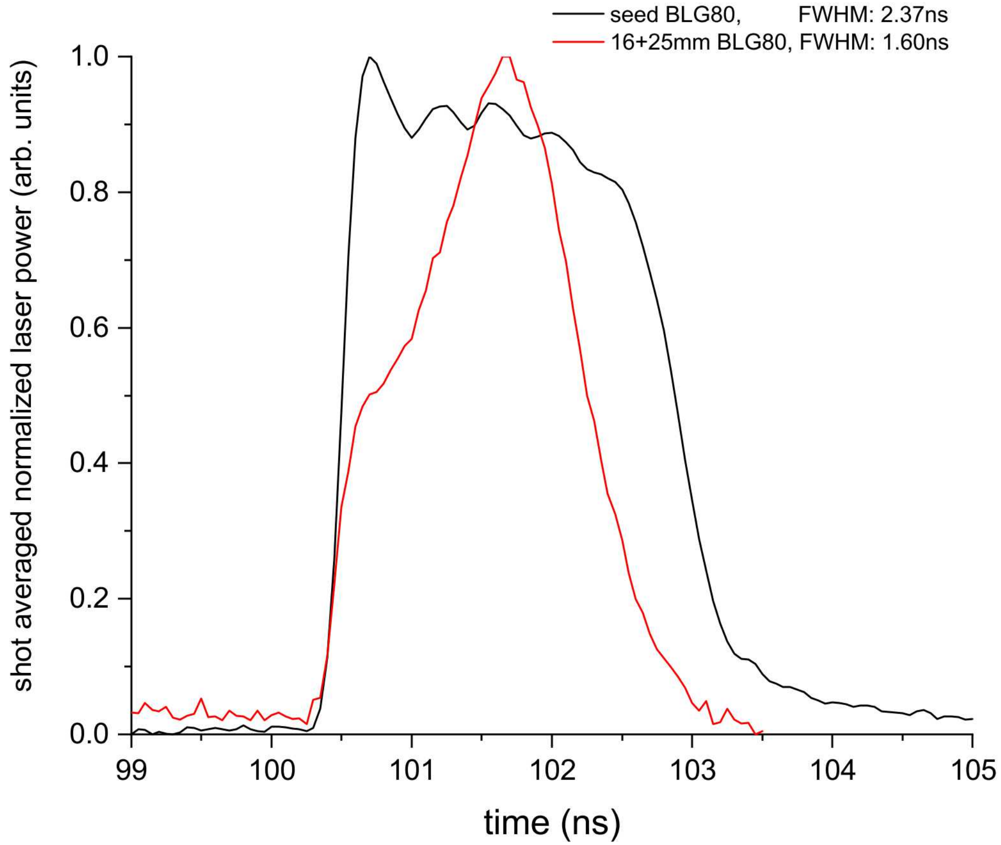


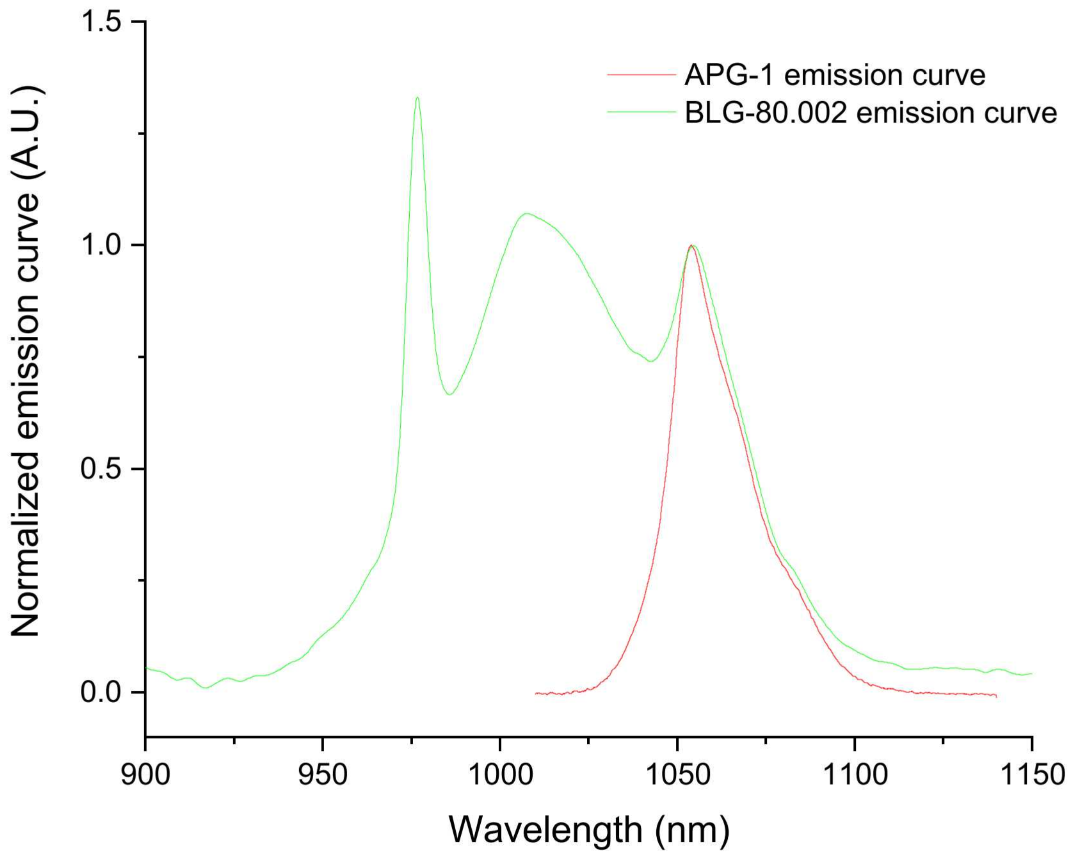


APG1 vs. BLG80.002: 16+25mm amplifiers in double pass comparison

- The previous slide seems to suggest that there may be less gain narrowing for BLG80.002 versus APG1.
- However, one should keep in mind that the total gain was also a factor 14 lower for the BLG80.002 case. As a result, more gain narrowing would be expected for similar high gain.
- In fact, this is precisely what the model calculation on the following slide show.

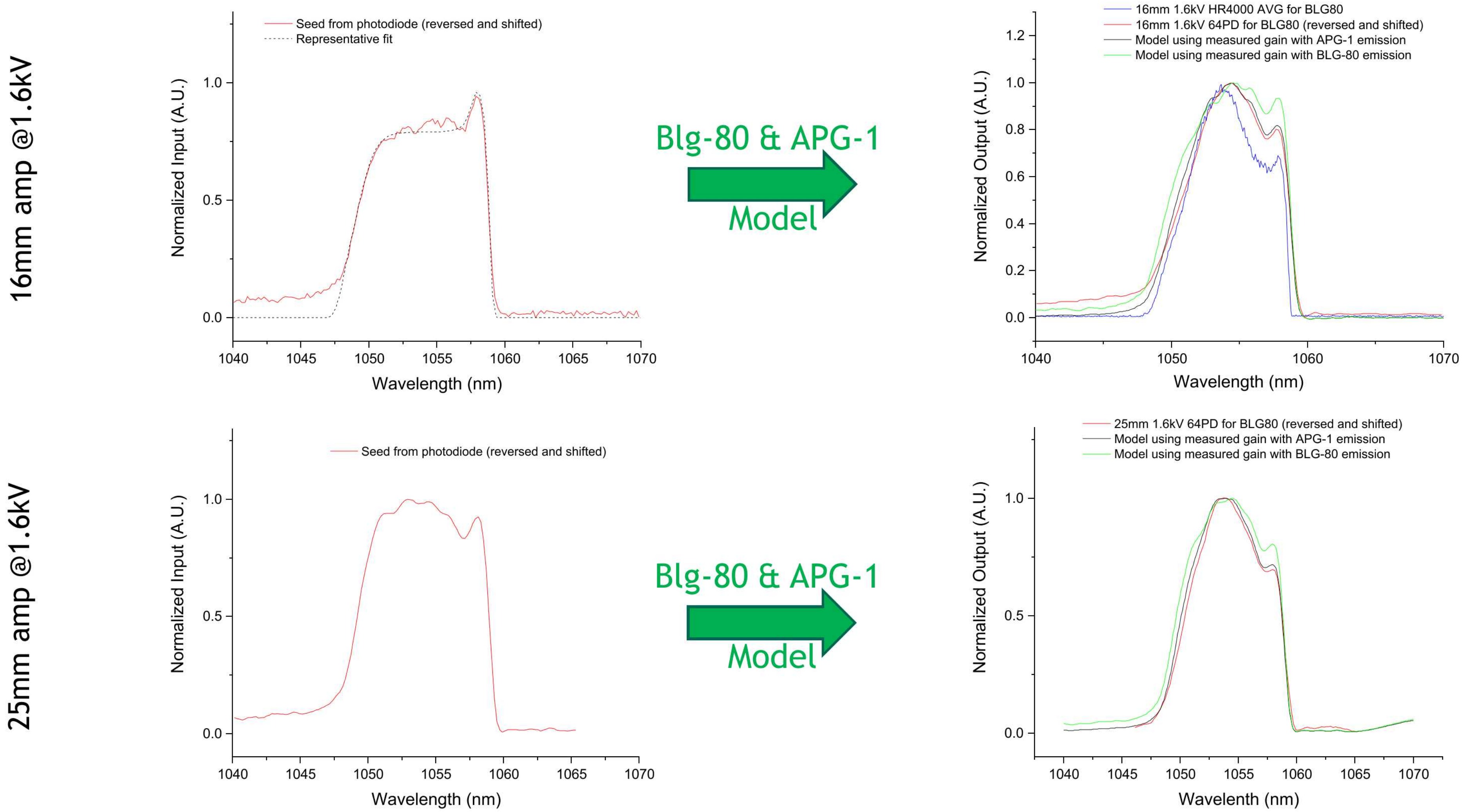
Simple Beer's Law Gain Narrowing Model for BLG-80.002

- The emission curve provided by Schott for the BLG-80.002 under evaluation is shown in green compared to the APG-1 curve in red (as normalized at the Nd ion peak near 1054nm).
- Note that in the vicinity of 1054nm, the BLG-80.002 curve is only slightly broader than APG-1.



Comparison of Model with BLG-80.002 Broadband Data

- In applying the gain model, we used the spectra obtained via photodiode for the input and found that the model output agreed with the measured diode spectral data well if we used the emission data from APG-1 and the measured gain (black trace vs. green trace).



APG1 vs. BLG80.002: Conclusion

- Based on the measurements presented, it seems that there is no significant improvement in spectrally preserved bandwidth between APG1 and BLG80.002 **for our particular laser configuration**.
- As the model shows, the emission curves for APG1 and BLG80.002 are mostly identical across our lasing bandwidth. Although BLG80.002 offers additional lasing bandwidth below 1040nm, the subtle “dip” in the emission cross-section curve at 1045nm is deep enough that the final peak largely performs like a traditional Nd:phosphate glass system.
- The previous slides show that there is a discrepancy between the BLG80.002 measured gain and the Beer’s law modeled gain using the BLG80.002 fluorescence spectrum provided by SCHOTT. Possible explanations for this discrepancy may be:
  - The rate of nonradiative energy transfer from the Nd3+ species to the Yb3+ species and its relation to the Nd3+ and Yb3+ upper state lifetimes. The fluorescence spectrum is measured in a time integrated fashion, whereas the few-ns laser pulse temporally gates the emission cross section. If the spectral emission cross-section changes in time, a discrepancy would be expected.
  - The absence/presence of the seed laser: In the ZPW gain measurements, the seed laser extracts energy at longer wavelengths from the Nd3+ species, which could partially deplete the Nd3+ excited state and consequently reduce the population of Yb3+ available for gain at shorter wavelengths. Again, the temporal dynamics play a role here, so the upper state lifetimes and the rate of nonradiative energy transfer would be useful for investigating this hyposysis.