Low Level RF Test System for the Compact X-Ray Light Source at ASU

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Abstract: A compact femtosecond X-Ray Light Source (CXLS) for time-resolved scientific and medical studies is being constructed at Arizona State University. The CXLS X-rays will be generated by the inverse Compton scattering (ICS) collision of 200 mJ, 1 ps, IR laser pulses with 300 fs electron bunches with energy up to 35 MeV. The electron beam is accelerated via a photoinjector and three standing-wave 20-cell linac sections driven by two klystrons delivering up to 6 MW 1 µs pulses at 9.3 GHz with a pulse repetition rate of 1 kHz. For initial testing of the CXLS klystrons a hybrid digital-analog low-level RF (LLRF) driver has been developed which allows for inter-pulse phase and amplitude corrections based on feedback from waveguide-couplers. The micro-controller based system can also be programmed to adjust continuously in advance of predictable drifts.

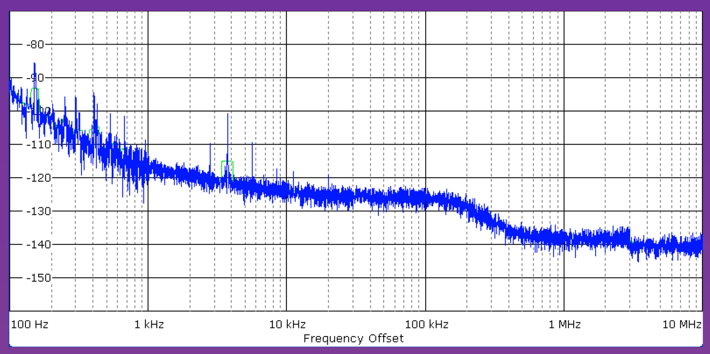


Figure 1: Single sideband phase noise plot of the 9.3 GHz seed signal from the master oscillator (MO). Wenzel Golden-Frequency Source which provides outputs at 76.65625 MHz, 2.325 GHz, 6.975 GHz, and 9.3 GHz. The signal has single-sideband noise figures of, -116, -122, -126, and -136 dBc/Hz, at 1, 10, 100, and 1000 kHz.

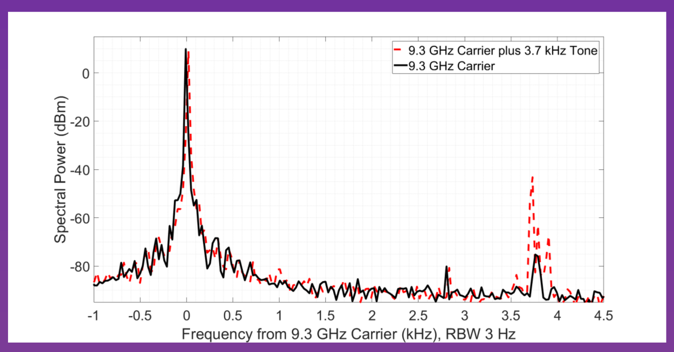


Figure 2: Demonstrating acoustic noise mixed up to the carrier frequency. Most of the noise peaks seen in the plot of Fig. 1 are likely of mechanical/acoustic origin that has been mixed up to the carrier frequency. Here the spectrum around the carrier has been plotted with a 3.7 kHz tone from a laptop speaker either on or off.

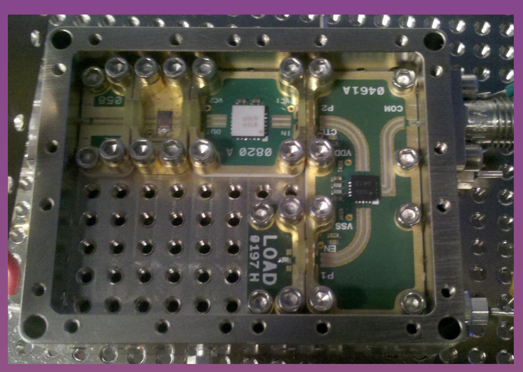


Figure 3: Klystron drive chain during construction (circuit blocks from X-Microwave). Integrated RF switch (ADRF5020) used to turn on and off the seed signal. In the event of arcing RF-power to the klystron can be shut off within ~40 ns. As there are two klystrons each powering different cavities the relative phase and amplitude of these sources must be tuned to ensure the electron bunches are accelerated as desired. Amplitude modulation is accomplished with a voltage controlled variable attenuator (VVA) (HMC812ALC4) with a 30 dB attenuation range. The phase shifter (HMC247) has a range of ~300°.

Figure 4: Top unit, Stanford Research Systems DG645 provides the trigger pulses to start and stop the drive signal. Bottom unit, FS740 with rubidium oscillator which disciplines the MO and DG645 via a 10 MHz reference. Long term timing is provided by the timing signals picked up from the GPS network.

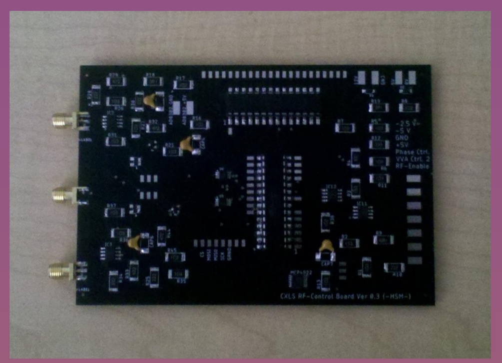


Figure 5: Microcontroller test board for controlling the drive chain, adjusting phase and amplitude in response to feedback from AD8302 gain and phase measurement ICs.

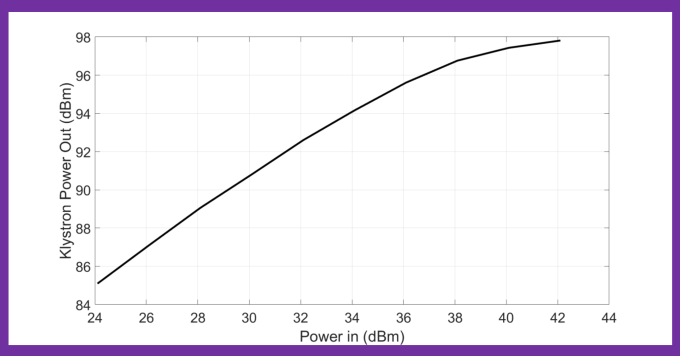


Figure 6: Klystron power out as a function of input power. To reach 6 MW (97.78 dBm) requires an input of 42 dBm.

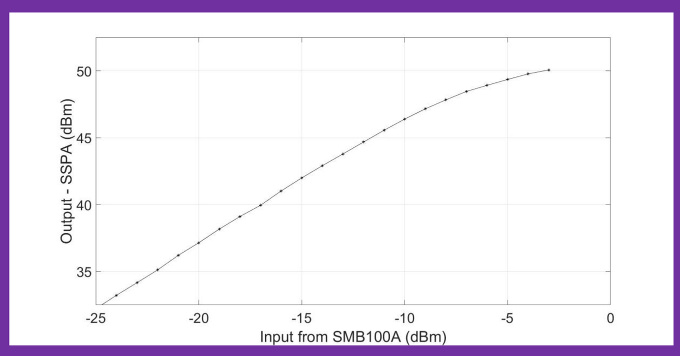


Figure 7: Calibrating the solid state power amplifier (SSPA). The output of the drive chain is ~0 dBm after insertion loss of the chain of around 10 dB (with the VVA set to minimum). Just -15 dBm is sufficient to get the klystron to full power.

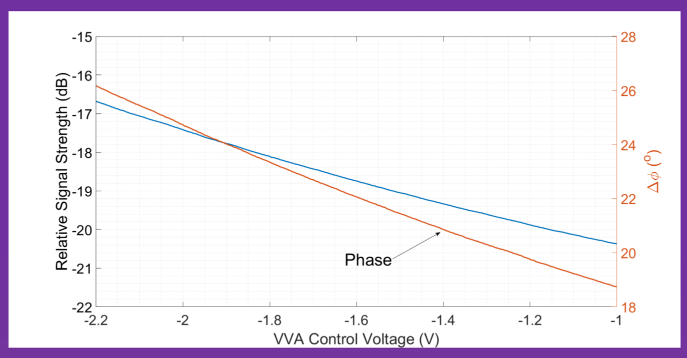


Figure 8: Measurements of the undesired changes of phase which occur as the amplitude attenuation is adjusted in the drive chain. From initial measurements the VVA requires ~250 µs settling time. Power output close to the desired operating point of the klystron as a function of input is ~257.6 kW/dBm. The accuracy of the VVA is ±0.05 dBm which correlated to ±12.9 kW or ~±0.2% of the peak amplitude. Changing attenuation with the VVA causes phase changes, ~2°/dB.

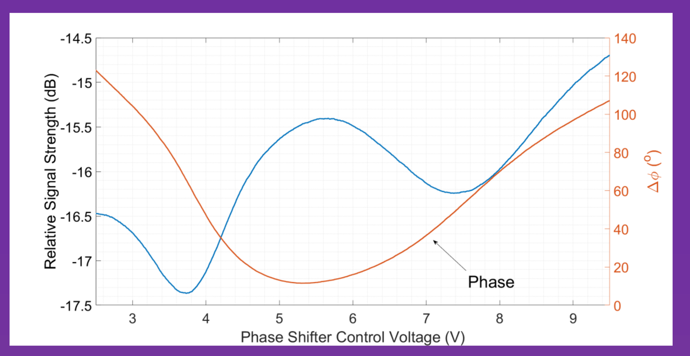


Figure 9: Measurements of the undesired changes in attenuation which occur as the phase is adjusted in the drive chain. The phase shifter affects levels of attenuation at different rates de-pending upon the control voltage. Phase control of below 0.2° at 9.3 GHz has been verified with this setup. If necessary for ultra-fine slow tuning, a servo-adjusted mechanical attenuator between the SSPA and Klystron controlled by the LLRF control-board would allow changes of less than ±0.005 dB.

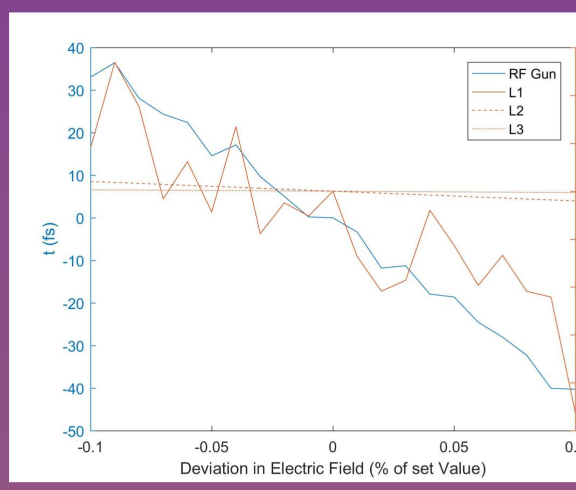


Figure 10: GPT simulations of delays in electron bunch arrival times at the end of the beam line in response to error in the accelerating field of the different accelerating cavities.

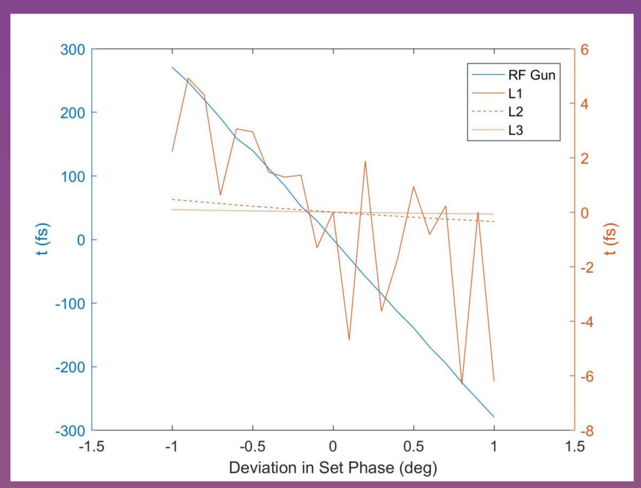
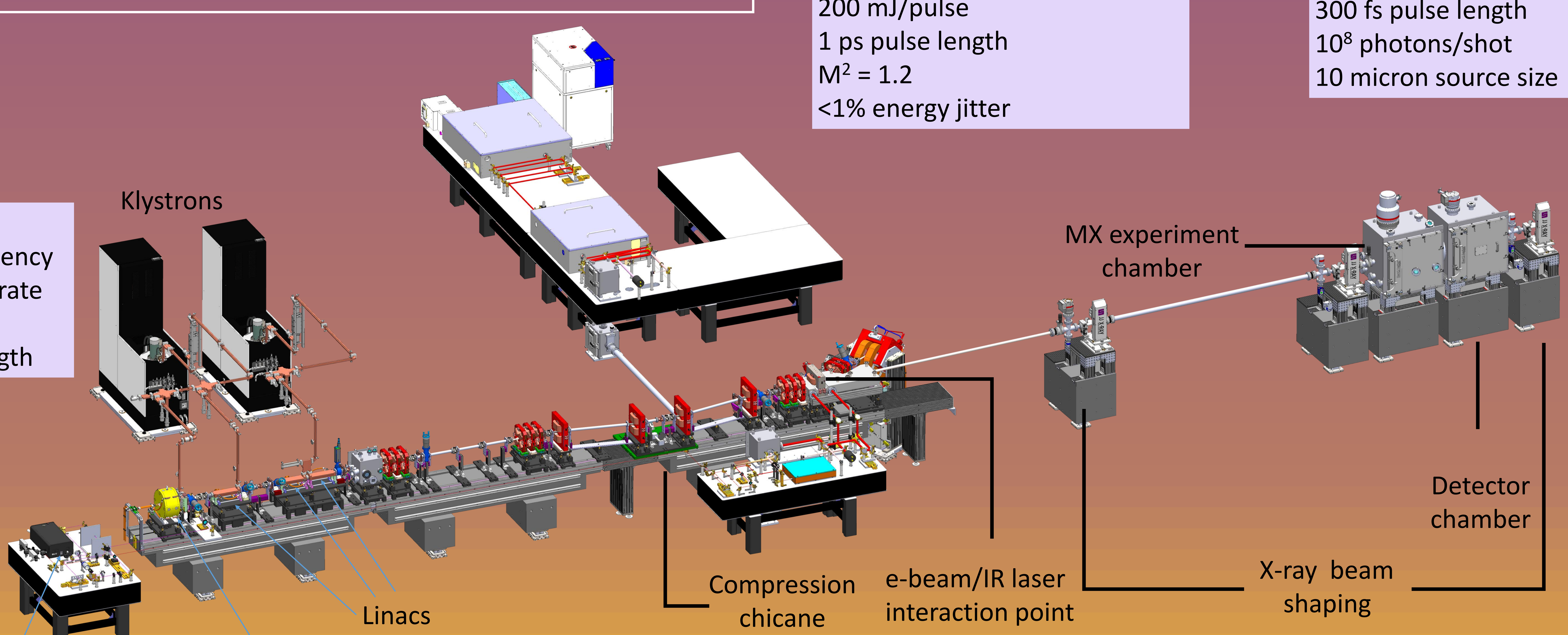


Figure 11: GPT simulations of delays in electron bunch arrival times at the end of the beam line in response to error in the phase of the accelerating field of the different accelerating cavities.

IR laser
Yb:YAG thin disk regen amplifier
200 mJ/pulse
1 ps pulse length
$M^2 = 1.2$
<1% energy jitter

Femtosecond x-ray output
Tunable 1 – 35 keV photon energy
Tunable linear/elliptical polarization
300 fs pulse length
10^8 photons/shot
10 micron source size

Electron Linac
9.3 GHz RF frequency
1 kHz repetition rate
200 pC/bunch
300 fs bunch length



Klystron 1 drives 2 RF structures, the mode-launcher-gun and linac L1. Electrons are generated at the RF gun photocathode using a UV laser and are accelerated to 4 MeV in the 4.5 cells gun accelerating structure. The UV laser also provides a trigger for the ICS IR-laser. Linac L1 is a standing-wave 20 cell RF cavity structure, 0.35 m long that increases electron energy 4 to 12 MeV. Klystron 2 power two linacs (L2 and L3) through a power dividing hybrid with the result being a final electron energy of 35 MeV. The LLRF system described will be upgraded to a fully digital system based on the LCLSII upgrade in collaboration with SLAC.