Component description	RF Electron Source (electron gun subassembly) for VEGA system
Component manufacturer	LTI
Component part number	GA000001
Component serial numbers	SN006 (RF Electron Source) M1700-3 (Scandinova K100 Modulator K1) 19D101 (Canon E3772A,A Klystron K1) M1700-2 (Scandinova K100 Modulator K2) [Note: M1700-2 will be shipped to ELI-NP as the electron source modulator] 19E103 (Canon E3772A,A Klystron K2) L191325 (Light Conversion Pharos Injector Laser)
Component ID	ES000
Customer	IFIN-HH/ELI-NP
Test date(s)	Dec 22, 2020 through Jan 22, 2021
Test engineer(s)	R. Loewen, W. Guo, B. Woo
Reference documents	DR000007 ELI-NP VEGA FINAL TECHNICAL DESIGN REPORT

1 Component description

The RF electron source (RF gun subassembly contract deliverable for VEGA) creates the electron bunch for the LINAC where it is accelerated to the correct energy for injection into the storage ring. The main components for the Electron Source (ES) assembly are the Modulator/Klystron, the RF electron source and paired accelerator, and the injector laser system (see Figure 1). A picture of the installed RF electron source during test is appended for reference.

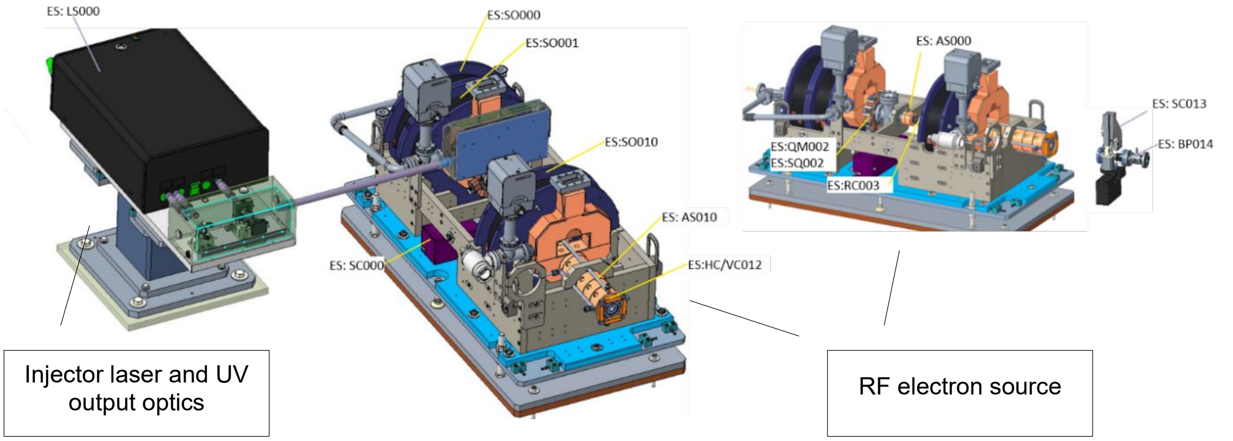


Figure 1. Components of the VEGA RF electron source assembly. The modulator and klystron are not shown.

2 Test setup

In addition to the RF electron source, a short electron LINAC and transport line was assembled and aligned within the radiation test enclosure at Lyncean. The LINAC includes a pair of powered structures to boost the beam energy by about 16 MeV to a total of 29 MeV, as well as one unpowered structure to provide a bunch charge calibration. The transport line was used to provide a dispersive region for measuring the beam energy and energy spread as well as steer the beam to a dump.

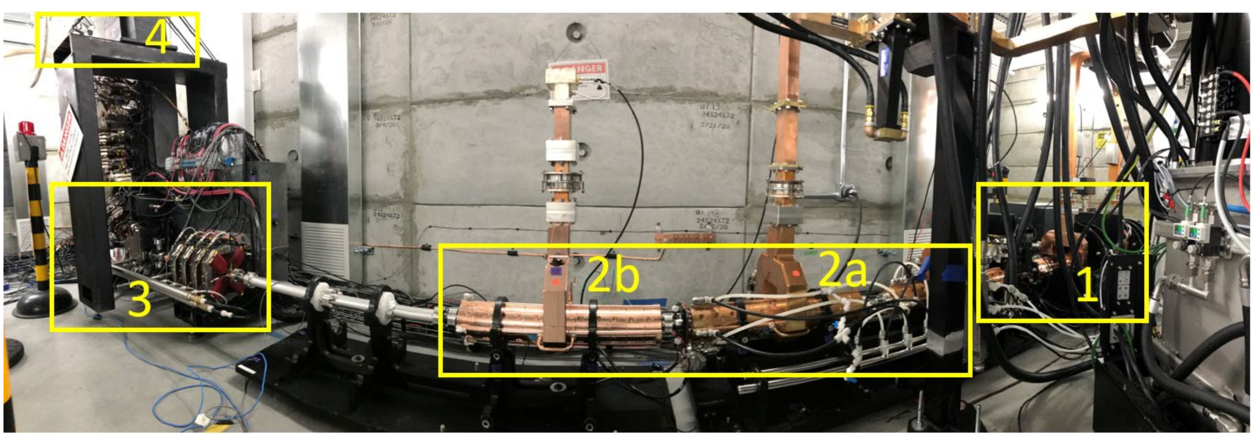


Figure 2. Electron beam line for testing RF electron source [1]. The LINAC [2] is composed of a pair of accelerators [2a] powered by a 5.5 MW klystron station and an unpowered structure [2b] for calibrating the electron beam charge. A set of quadrupole magnets and profile monitor screens are used at the beginning of the transport assembly [3] for emittance measurements, while another profile monitor after the first (vertical) bend is used to measure the beam energy properties. The residual beam passing through screens is transported to a lead brick dump [4].

Other diagnostics include vacuum monitors using ion pump controller channels, radiation meters, and power meters to measure forward and reverse pulsed RF waveforms along the high-power RF waveguide system. The BPM (beam position electronics) were only partially commissioned for these tests and were not necessary for orbit correction since the beam is being dumped and not aligned for injection to a storage ring.

3 Test procedure

3.1 RF Conditioning

Since we installed new accelerator components, the first task is RF conditioning to high power. There are two modulator/klystron stations, one for the electron source (K1) and one for the accelerator pair (K2), which are identical K100 Scandinova modulators and both fit with 7.5 MW peak power E3772A Canon klystrons. The accelerator pair (K2) operated at a reduced klystron HV setting that corresponds to 5.5 MW peak power to limit the acceleration module to 16 MeV. This setting verifies that the RF electron source exit energy is 13 MeV by setting a configuration of the transport bends to 29.2 MeV (a previously tested configuration).

3.2 Clean the cathode

After conditioning, the copper cathode will have some gas surface coating that reduces the quantum efficiency and limits charge extraction. We remotely insert a focusing lens to create a higher fluence (~1 mJ/mm^2) beam that is raster scanned over the normal laser spot. This step requires some care since there is a narrow range of fluence that effectively cleans the cathode surface without damaging it and creating dark current.

3.3 Center laser position on cathode and set beam energy

By periodically oscillating the solenoid magnets at the cathode, we track beam motion on downstream screen and find the magnetic center, or laser spot position. Then the electron bunch is accelerated and phased by first doing a Schottky scan to set the electron source phase, and then peaking the energy to set the accelerator phase. The beam energy is set by measuring the beam orbit after the first transport bend with a known magnet configuration.

3.4 Measure emittance

After choosing an operating charge intensity and tuning the energy and energy spread of the beam, we use the straight-ahead screen after the (four) matching quadrupoles at the start of the transport line to measure beam sizes while scanning one of the matching quad strengths. The emittance and optical beam parameters are calculated by fitting the waist size and divergence.

4 Test results

4.1 RF Conditioning

The electron source conditioning (K1) was paced by the vacuum waveguide and not the electron source or accelerator structure itself. After six days of methodically increasing RF power and pulse width, the system exceeded nominal operating power, which was set to 6.5 MW (above the design spec of 5.5 MW). The higher power will marginally benefit the performance of the electron source by increasing the field gradient at the cathode. The conditioned power was slightly higher still, at ~7 MW at 5.5 µs modulator pulse width (also longer than the 4.5 µs operational design). After conditioning, the electron source was stable at 6.5 MW klystron power with no additional breakdowns. Vacuum level of the electron source reduced throughout the testing period to high ~1e-9 Torr scale and is expected to improve over time to 1e-10 scale.

The electron source and paired structure have independent precision temperature settings to adjust the resonant frequency. Both showed excellent RF match (Figure 3) and stability.

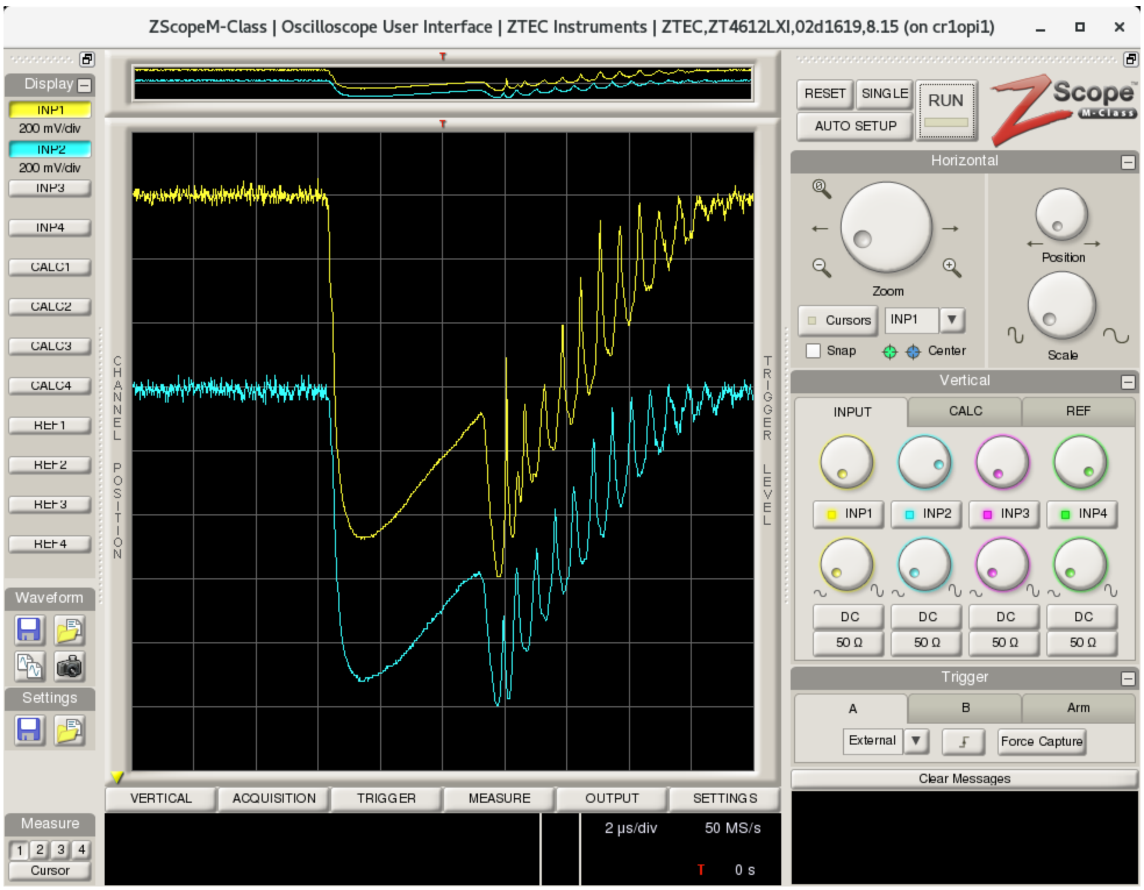


Figure 3. Reflected RF power from the electron source (ch1, ES:AS001) and paired Accelerator Structure (ch2, ES:AS010) at 6.5 MW power from klystron measured using logarithmic RF power meters. Each box on the scope (200 mV) is 8dB. After the initial reflection (standing wave structures) the exponential fill time approaches the steady-state match of < -15dB. The temperature settings are 32.2 C and 29.2 C for the electron source and structure. Note that the klystron drive RF pulse width is wider than the modulator pulse width, and the beating on the trailing edge is normal, due to excitation of other modes in the structure during discharge of the RF.

4.2 Clean the Cathode

After conditioning, the copper cathode was cleaned by slowly increasing laser power while focusing the beam and scanning (Figure 4). We adjusted the lens position to minimize future risk of damage by requiring a high intensity setting on the laser (~80%) to reach the threshold for cleaning, while allowing some room to increase fluence if needed. After minimal cleaning, the charge level reached ~300 pC, which is already sufficient for operation.

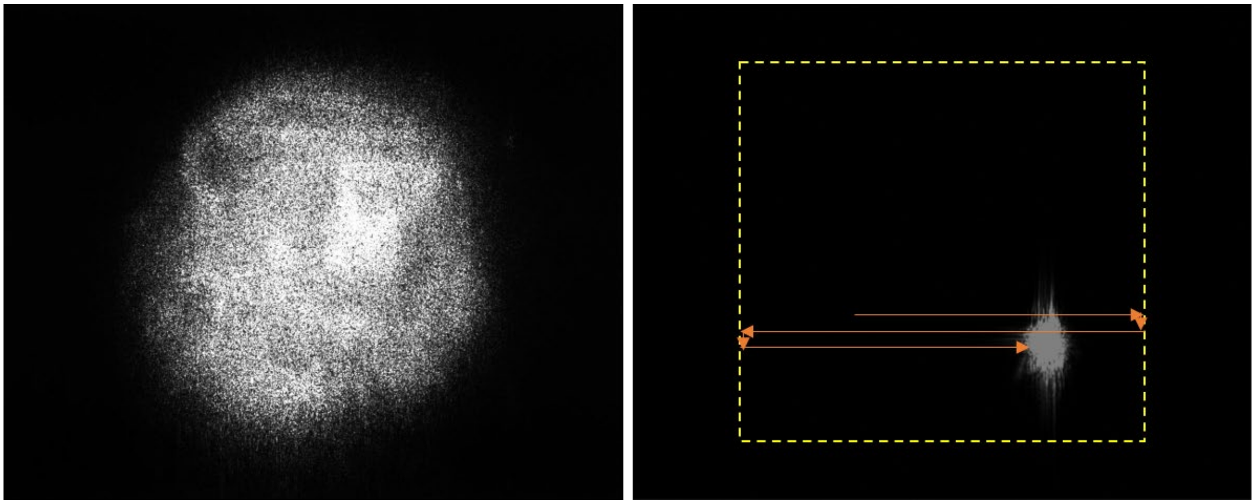


Figure 4. Cathode imaging camera (ES:SC000), with unfocused beam (left) and focused beam for cleaning (right). The UV imaging plane is at the cathode surface, and approximately 1:1. The unfocused collimated beam has a 4 mm (apertured) diameter. A firmware script on the motor controller scans a square area overlapping the unfocused laser spot, which takes about two minutes.

4.3 Center laser position on cathode and set beam energy

The laser spot was adjusted only slightly to center the beam in the solenoid field. A Schottky scan next measures the intensity of the beam vs. RF phase (fig below). The charge intensity can be adjusted between 50 pC and 300 pC, the expected operational range of the VEGA system. Note that the RF electron source and paired structure always operates at nominal klystron power of 6.5 MW.

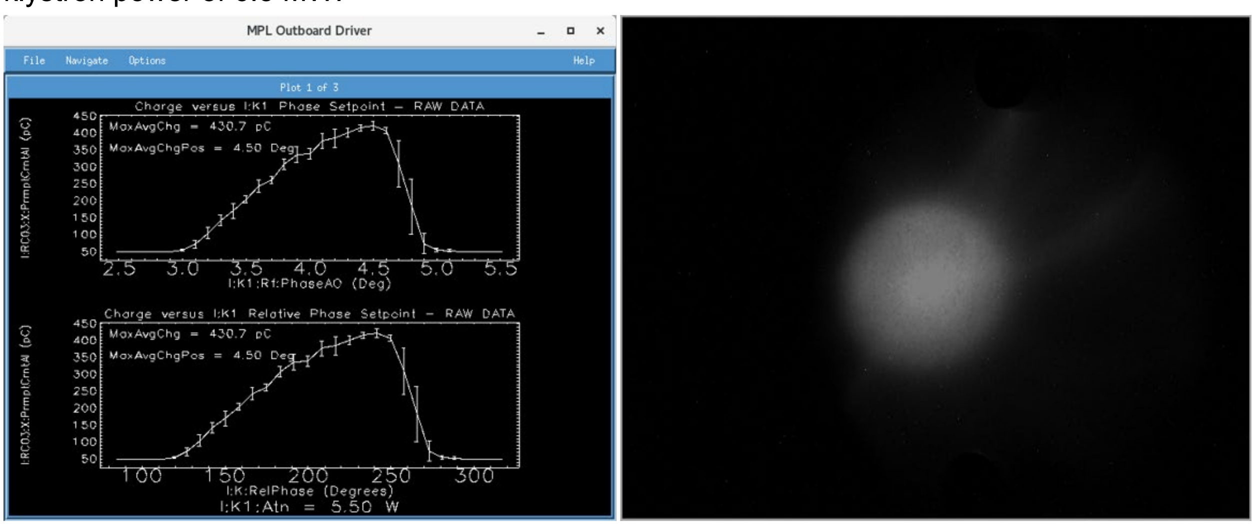


Figure 5. On the left is a Schottky scan, where klystron phase is varied while beam intensity is measured from a reference cavity (ES: RC003). The intensity was calibrated using the unpowered accelerator structure. On the right is the electron beam imaged on the first screen after the RF electron source (ES:SC013) at a charge of ~300 pC corresponding to the calculated operating phase of the Schottky scan.

Next the beam energy is set by measuring the beam position on a screen after the first transport bend with a magnet configuration of 29.2 MeV. The second pair of accelerators had to have reduced klystron power (~90% of saturation) which is consistent with the RF electron source running at higher power than design (6.5 MW instead of 5.5 MW). Both the energy and energy spread are tuned by adjusting the second klystron power and phase.

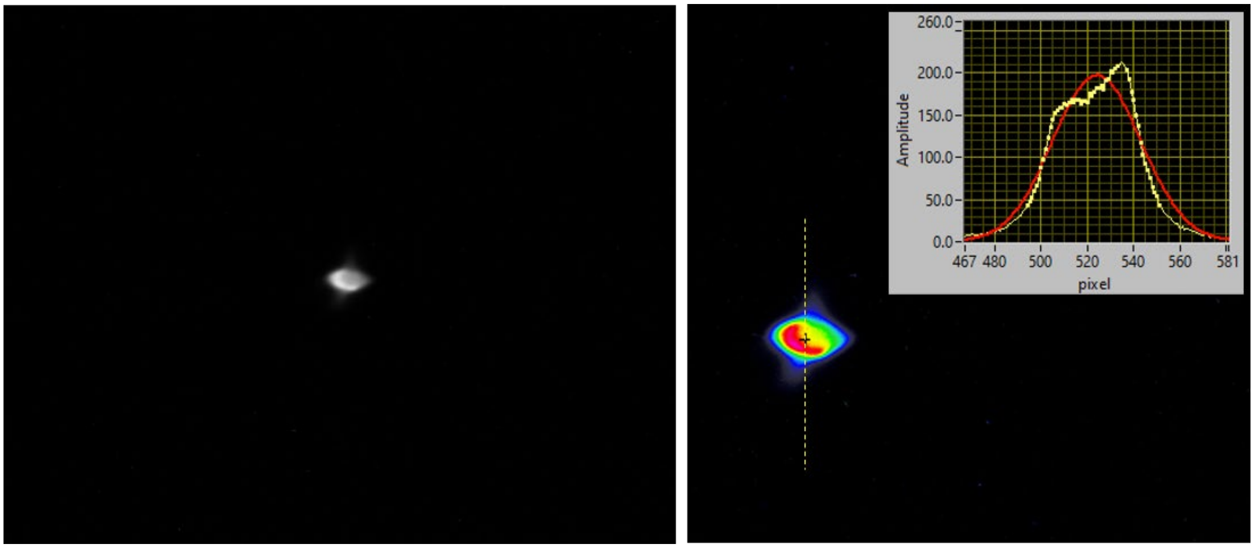


Figure 6. On the left is the electron beam tuned up using a profile monitor in the dispersive part of the transport line, after the first vertical 45-degree bend. Vertical beam size is dominated at this point by energy spread ("down" on screen is higher energy). On the right is a fit of the beam size where the FWHM is 45 pixels (*10.2 microns/pixel) = 460 microns. The dispersion, η, is 0.20 m, which yields a full energy spread of 2.3e-3.

4.4 Measure emittance

The charge intensity was set to a nominal operating value of 200 pC for checking emittance. 200 pC represents the expected steady-state operation in VEGA for top-up injection (up to 300 pC can be used for filling the storage ring). By varying one of the quadrupoles after the LINAC, the beam can be focused in one dimension at a screen location before the first bend. (The VEGA diagnostic stations will have the same layout: one screen after a bend to tune energy and one screen before the bend to do emittance scans.)

Each plane, horizontal and vertical, is measured independently. The method of the measurement relies on the optics model and magnet calibration (analogous to specifying a lens focal length in a laser M^2 measurement). The fits of the electron waist position, size, and divergence simultaneously yields the beam optical properties (so called Twiss parameters, or Courant Snyder parameters, α and β) and emittance (ε). There is a known asymmetry in the optical beam properties due to RF focusing in the accelerator and electron source structure couplers. (This asymmetry is not a problem for matching since several quadrupoles are used to focus the beam.)

Due to optical asymmetry, the emittance does not have to be the same in each plane. The differences we measure (Figure 7) may also be due to small errors in the model, for example calibration of magnet strengths. At low beam energy, which is only used for this test, the electron beam is especially sensitive. (At VEGA, the beam energy will be about 160 MeV when the emittance is measured and matched.) The average normalized emittance is expected to be

2-3 mm mrad, in line with LTI's previous RF electron source performance. Overall, this RF electron source behaves very similar to the one operating in the Lyncean Compact Light Source.

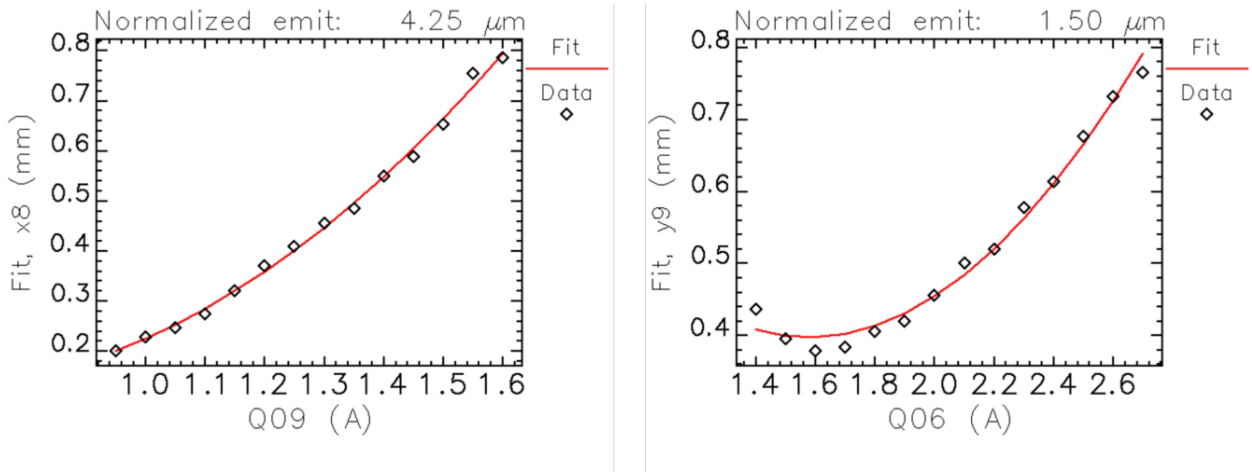


Figure 7. Emittance scans for each plane, horizontal (left) and vertical (right), including fits. The average emittance, which is preserved in weakly coupled systems, is consistent with previous RF electron source performance.

4.5 Specification Table

The following table is reproduced from the TDR with the right two columns added for the factory test. The relevant measured specifications have been confirmed.

Para meter	Unit	Information	Comment	Value (Specification)	Measured	Test comment
E_{source}	MeV	Electron source energy	fixed	13	~14	Estimated from 6.5 MW klystron[1]
f_{RF}	MHz	Accelerator frequency	All LINAC	2856	2856	By design
G	MV/m	Acceleration gradient [max]	LINAC Structure	20	n/a	Will be measured with VEGA LINAC
E_{max}	MeV	Energy at end of first module	ES + Module 1	160	n/a	Will be measured with VEGA LINAC
$\gamma\varepsilon_x$ inj	μm	Source emittance [normalized]	Specification	<5.0	4.25 x 1.5	at 200 pC charge intensity
$\gamma\varepsilon_x$ inj	μm	Source emittance [normalized]	Simulated	2.5	n/a	
σ_z	mm	Bunch Length rms	Specification	<1.0	0.81	2.7 ps deduced by energy spread[2]
σ_z	mm	Bunch Length rms	Simulated	0.48	n/a	
σ_δ	mm	Relative Energy Spread rms	Specification	<0.003	0.0023	FWHM
σ_δ	mm	Relative Energy Spread rms	Simulated	0.0005	n/a	

[1] Exact beam energy can't be measured directly and only inferred from the power setting of the modulator and the beam energy measurement in the transport arc using the beam deflection as a spectrometer.
[2] See following section for relationship between energy spread and bunch length.

Bunch length calculation

When the electron bunch is phased at maximum energy, as illustrated in Figure 6, the bunch length σ_τ may be deduced from the full width at half max (FWHM) energy spread (dE/E) based on the following formula:

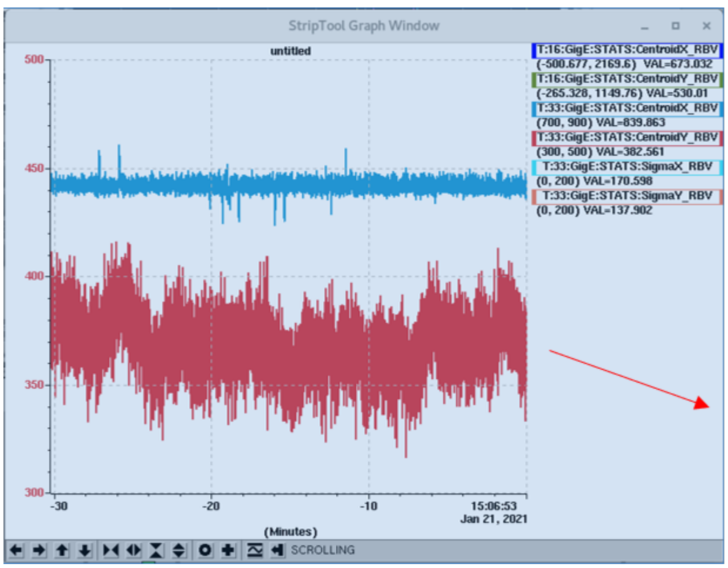
$$\frac{dE}{E} = \omega^2 \sigma_\tau^2$$

where ω is given by the RF (2*π*2856MHz).

5 Beam energy stability

During the RF Electron Source commissioning there was an opportunity to confirm the energy stability of the system as it was configured at Lyncean. Although the VEGA system will have a different LINAC, the timing electronics and feedback system will be very similar.

Using the same dispersive screen insert for the energy tune-up (Figure 6), the centroid of the bunch was tracked over a time of approximately 30 minutes at an acquisition rate of 10 Hz (sampling individual shots from the 30 Hz trigger rate). The relative energy jitter is calibrated the same way as the energy spread calculation, yielding dE/E = 6.5e-4 rms.



	T:33:GigE:STATS:CentroidY_RBV []
Minimum	315.68201
Maximum	415.67499
Sum	6744122
Points	18305
Mean	368.43059
Median	368.50201
RMS	368.64865
Std Deviation	12.677943
Variance	160.73025
Std Error	0.093705254
Skewness	-0.050563661
Kurtosis	0.075472587

Figure 8. Pulse energy jitter measured on the dispersive screen. A σ of 12.7 pixels (*10.2 microns/pixel) = 130 microns. The dispersion, η, is 0.20 m, which yields an energy spread due to jitter of 6.5e-4 rms.

The goal is to have the total energy spread <0.3% rms. If this jitter is added together in quadrature with the beam energy spread (rms) = $\sqrt{((2.3e\text{-}3/2.35)^2+(6.5e\text{-}4)^2)}$ = 0.12% rms. This satisfies the target, even at FWHM (= 0.28%).

The contribution to the pulse energy jitter has two main sources: Injector laser timing and klystron voltage. The 6.5e-4 rms measurement already confirms that <u>any one source</u> is less than this sum. Therefore, each of the two modulator/klystron voltages satisfies the <0.1% amplitude stability as stated in GD000005 Scandinova K100 Modulator System Specification.

5.1 Injector Laser Timing Jitter

The electronics feedback for the CLS timing system (used for the RF electron source test) is very similar to the VEGA electronics. The 2856 MHz reference frequency is locked to a n^{th} harmonic of the laser oscillator, which was 64.909 MHz for the RF Electron Source test (n=44) compared to the 71.4 MHz VEGA system (n=40). The specification is to have a frequency stabilization of <1 ps, or equivalently 1 deg of 2856 MHz rms noise. The electronics for the feedback system is required for the RF source test and was shown to meet specification. The following figure is a measurement of the frequency noise error signal as demonstrated in the lab, not during the high-power test, but the value is consistent with the measured beam stability. Once installed at VEGA, the electronics will be re-tested at the 71.4 MHz oscillator frequency.

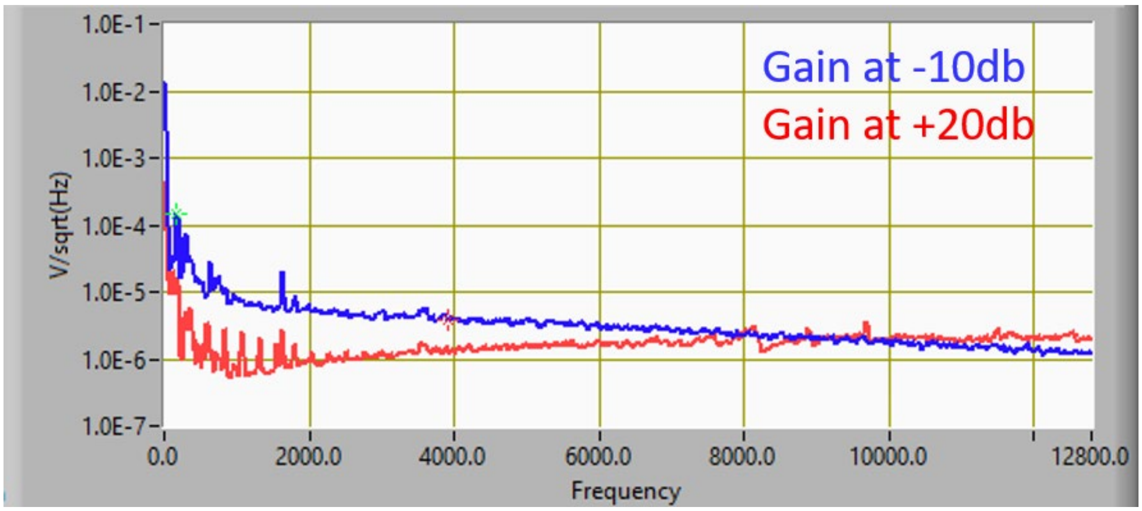


Figure 9. Error signal from frequency stabilized injector laser oscillator (measured on a SR785 acoustic spectrum analyzer) at two different gain settings of the electronics. Higher servo gain reduces the residual noise up to the unity gain frequency of around 10 kHz. By integrating the amplitude noise spectrum, the rms V noise is 0.33 mV which, when converted to phase by using a mixer at 2856 MHz, yields 0.23 deg phase (rms).

6 Appendix: Figure of RF electron source during test