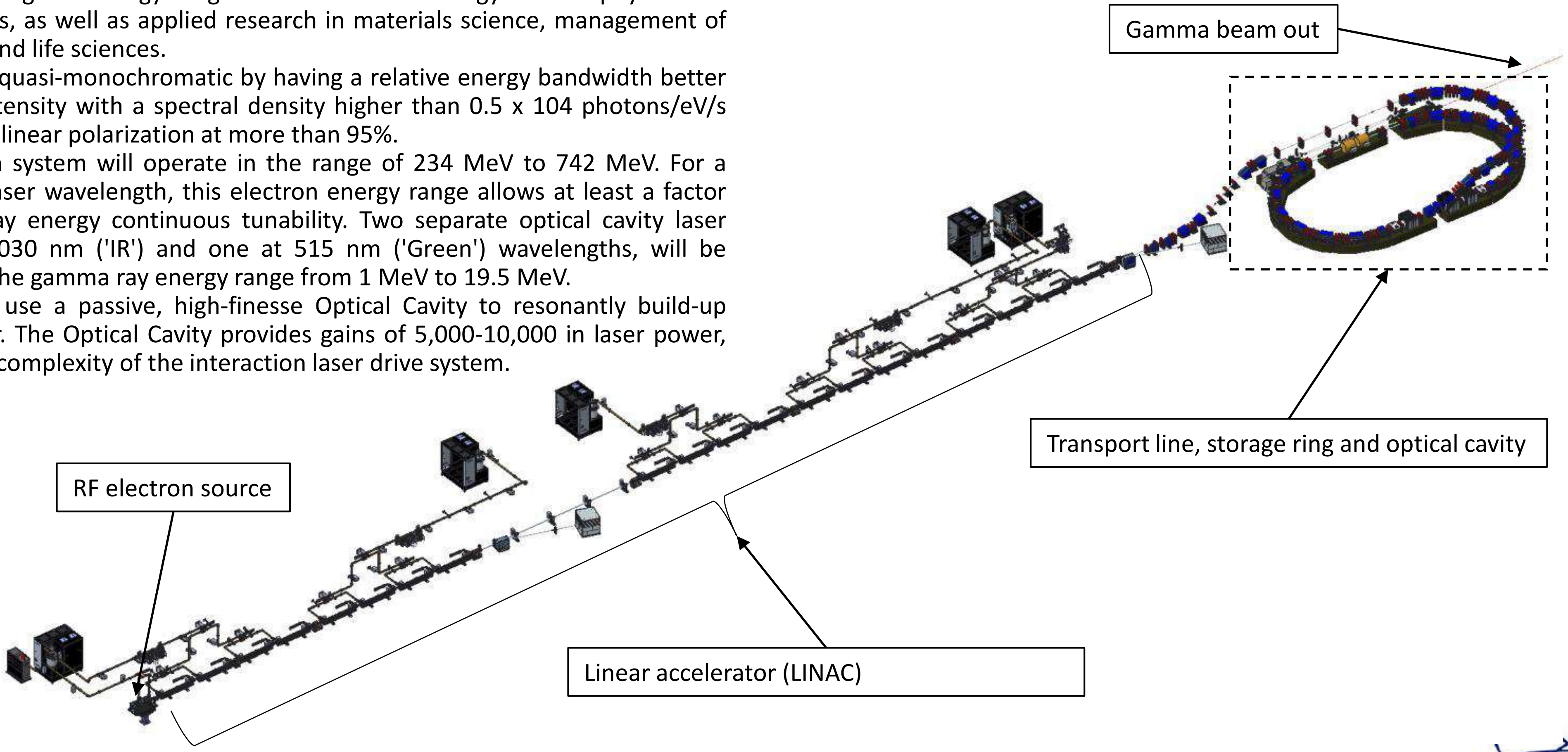
Overview of RF generation, distribution and LLRF systems for ELI/NP-VEGA project

Variable Energy Gamma (VEGA) System

VEGA System - main components

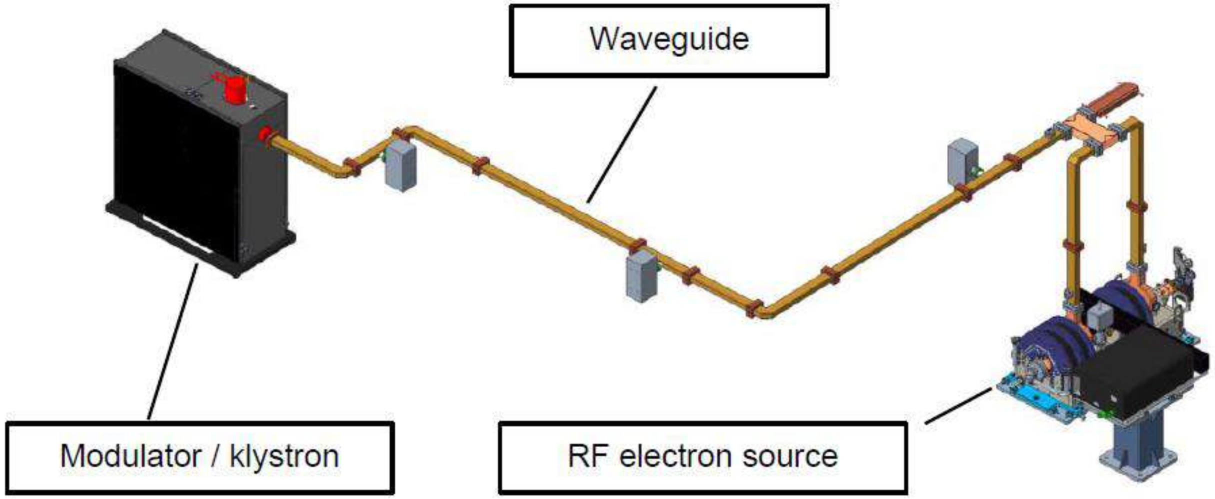
- The system will deliver gamma-rays with energy continuously variable from 1 MeV up to 19.5 MeV covering the energy range relevant for low-energy nuclear physics and astrophysics studies, as well as applied research in materials science, management of nuclear materials and life sciences.
- The beams will be quasi-monochromatic by having a relative energy bandwidth better than 0.5%, high intensity with a spectral density higher than 0.5 x 104 photons/eV/s and high degree of linear polarization at more than 95%.
- The electron beam system will operate in the range of 234 MeV to 742 MeV. For a given interaction laser wavelength, this electron energy range allows at least a factor of 10 in gamma-ray energy continuous tunability. Two separate optical cavity laser systems, one at 1030 nm ('IR') and one at 515 nm ('Green') wavelengths, will be provided to cover the gamma ray energy range from 1 MeV to 19.5 MeV.
- The laser systems use a passive, high-finesse Optical Cavity to resonantly build-up pulsed laser power. The Optical Cavity provides gains of 5,000-10,000 in laser power, which reduces the complexity of the interaction laser drive system.



Variable Energy Gamma (VEGA) System

RF electron source - components of the photocathode

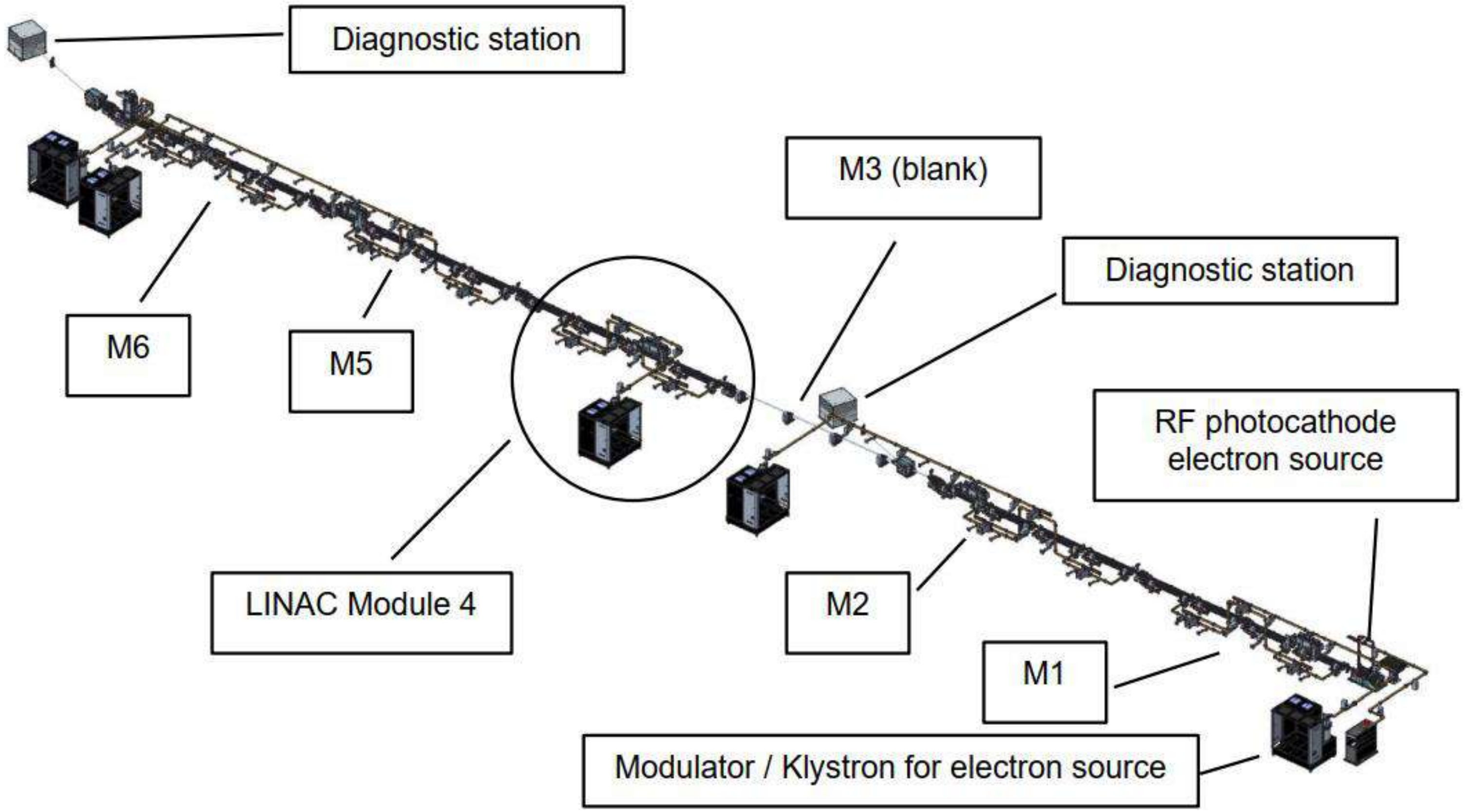
- 7.5 MW S-band klystron, model Canon E3772A.
- 1 Modulator model Scandinova K-100.
- Waveguide system, including RF diagnostic couplers for forward/reverse power.
- One photocathode RF source.
- One standing wave accelerating structure.
- One matched 3 dB hybrid to split power between RF source and accelerator structure.
- One BPM (beam position monitor) reference cavity.
- Three solenoid magnets which focus the beam through the first LINAC module.
- One RF load at the hybrid.
- Support structure.
- Injector laser system.



Variable Energy Gamma (VEGA) System

Linear accelerator (LINAC) – general description

The VEGA LINAC is designed for a top energy of 800 MeV to easily achieve approx. 750 MeV as required by specification. There are five modules of acceleration, where each module can add up to 160 MeV energy to a single bunch (of variable charge) with two beam analysis (diagnostics) stations for commissioning and tune up independently from the storage ring, one approximately at 320 MeV after LINAC module 2 and one at full energy at 750 MeV, after LINAC module 5. The diagnostic beamlines require only one bending magnet each.

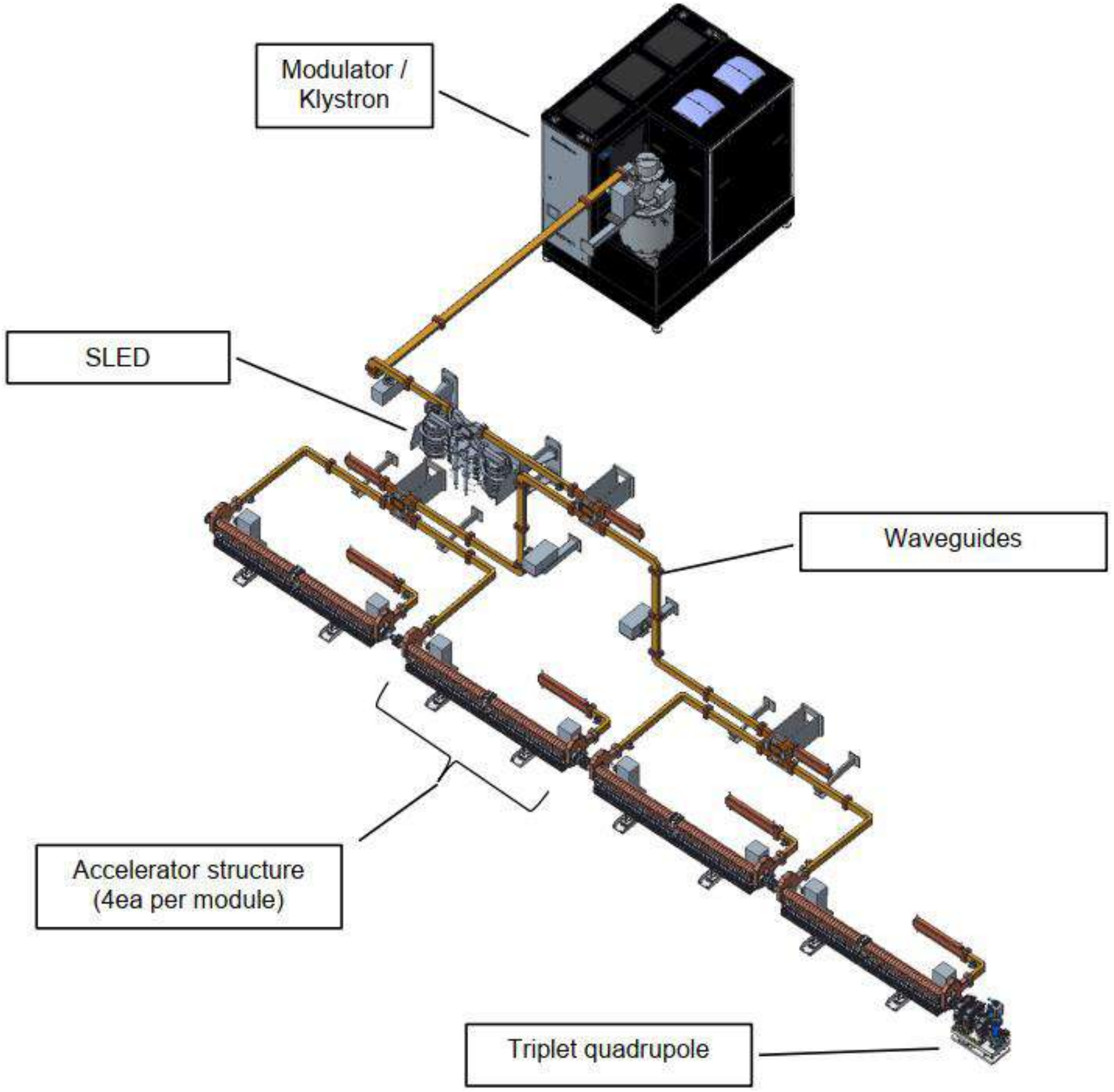


Variable Energy Gamma (VEGA) System

Linear Accelerator (LINAC) - description of one acceleration module

One accelerating module contains:

- 50 MW, 4 microsec S-band klystron, model Canon E3730A.
- Pulse modulator, model Scandinova K-300.
- SLED system (RF pulse compression).
- 4ea x 2 m long accelerator structures.
- Waveguide distribution system, including waveguide 3dB hybrids and bends.
- Several RF waveguide loads (high power RF dummy loads).
- Group of quadrupole magnets for focusing between modules (3 or 4).
- Beam position monitors within each group of magnets.
- RF power.



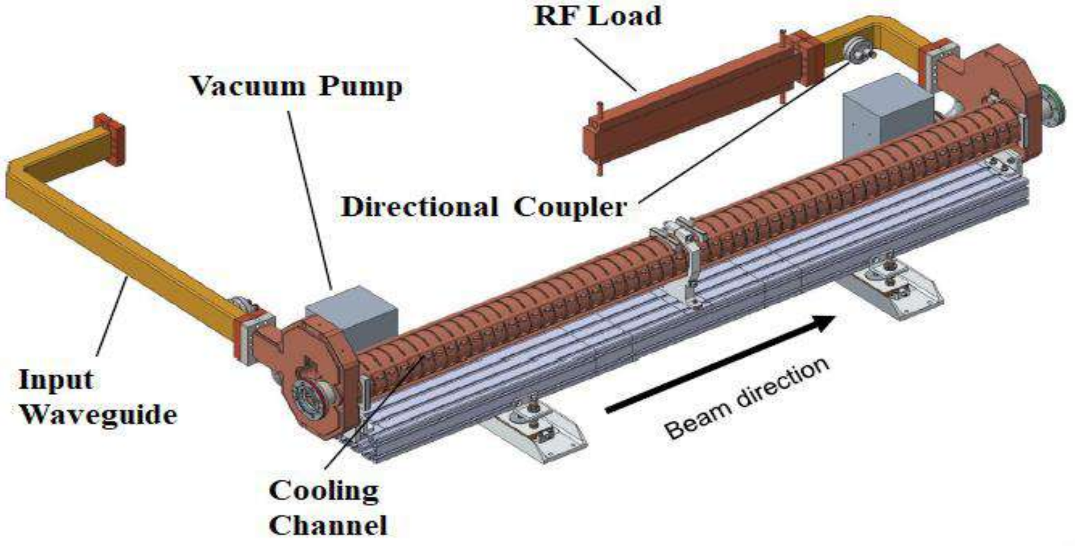
Variable Energy Gamma (VEGA) System

Linear Accelerator (LINAC) - accelerator structures

The purpose of the accelerator structures is to provide a stable acceleration of the electron beam for injection into the storage ring. There are four accelerator structures in each module and five modules, so a total of 20 accelerator structures. The waveguides and spacing of the structures are arranged and tuned so that a speed of light electron bunch remains at the peak of acceleration throughout the length of the module. After the accelerating structures have completed filling, the RF electron source is fired to launch a particle bunch near the crest of the RF wave. At the end of the module a quadrupole magnet system serves to focus the beam for acceleration in the next module.

Parameters for the VEGA Injector LINAC travelling wave RF structure

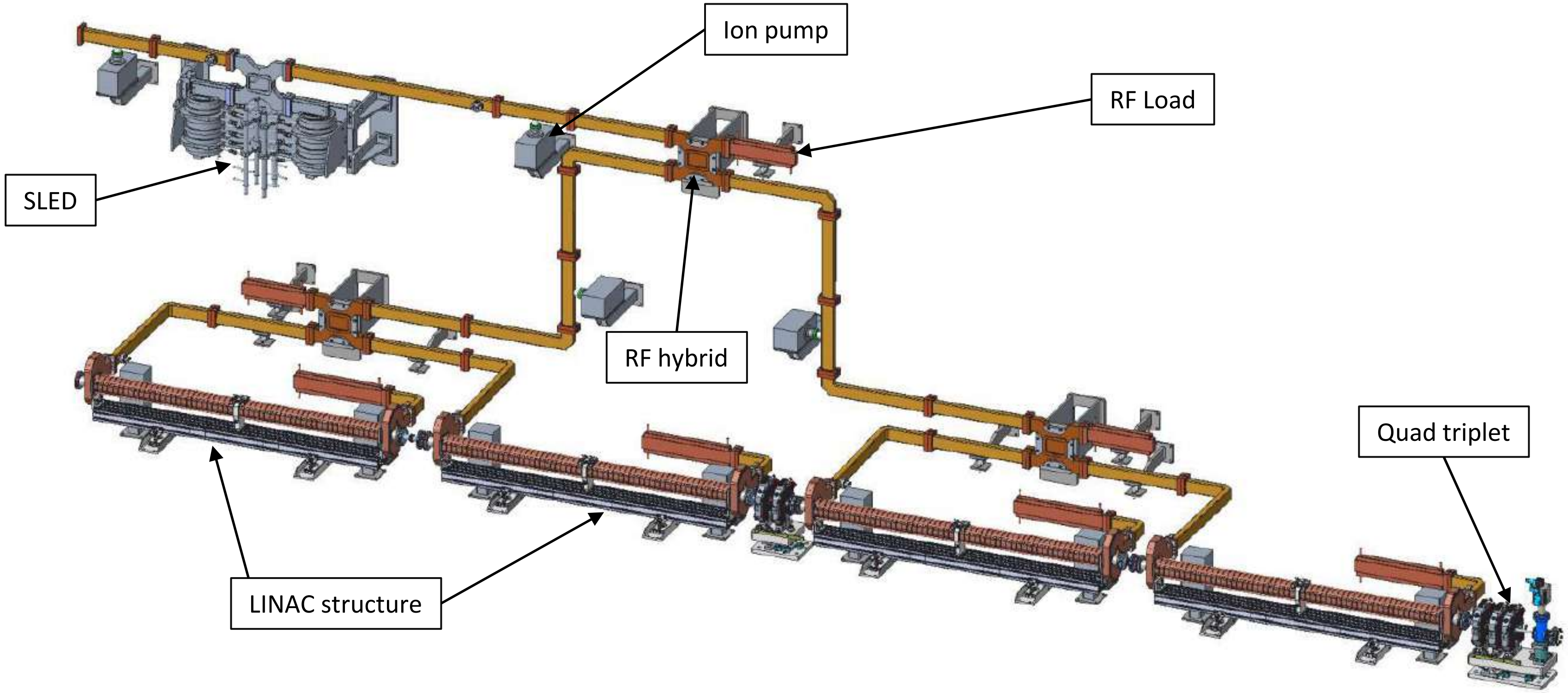
Quantity	Symbol [Unit]	Design parameter
Type of structure		Constant Impedance
Accelerator frequency	fRF [MHz]	2856
Phase advance per cell		2 π/3
Quality factor	Q0	15100
Shunt impedance	Rsh [MW/m]	65.65
Group velocity	vg/c	0.953%
Active length	L [m]	2.0
Number of cells	Ncell	56 + 2 Couplers
Attenuation constant	t	0.416
Filling time	tfill [μsec]	0.700
Nominal flat top input power	Pin [MW]	22
Max nominal acceleration	[MV]	40
Operating temperature	[degrees C]	25



Variable Energy Gamma (VEGA) System

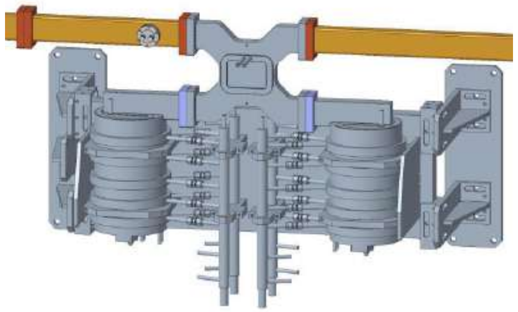
Linear Accelerator (LINAC) - Waveguide system

The waveguide system includes all flanges, bends, hybrids, pumping ports and RF couplers to detect and monitor RF properties of each module. The waveguide system is tuned upon installation to adjust the phasing of each accelerator component so that the relativistic electron beam is always near the same phase as it passes from one accelerator to the next one within a module.



Variable Energy Gamma (VEGA) System

Linear Accelerator (LINAC) - SLED cavities, klystron and modulator



The purpose of the SLED system is to accept an RF pulse from the klystron of 4 µs and compress that power to provide a shorter pulse of <1 µs but with a higher peak power. This method was developed at SLAC and is commonly used in high gradient S-band systems throughout the world. The method uses storage cavities combined with a 3dB hybrid coupler. A phase switch from the klystron dumps the stored energy through the waveguide system towards the accelerating structures.

PULSED KLYSTRON AMPLIFIER
E3730A

The purpose of the klystron and modulator system is to amplify a 4 µs pulse of lower power RF delivered from the low-level RF system, so that it has sufficient power for accelerating the electron beam in the LINAC. The klystron is a narrow band RF amplifier, and the modulator acts as a pulsed power supply to give the energy to the RF pulse. The pulse of RF travels to the SLED system described above, and then on to the accelerator structure system.

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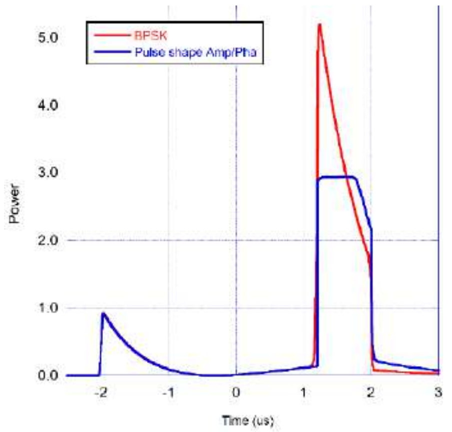
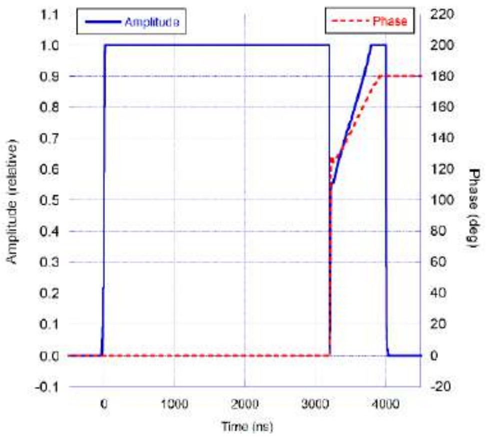
Variable Energy Gamma (VEGA) System

Linear Accelerator (LINAC) - SLED cavities, klystron and modulator





The LLRF System must control shape (phase, amplitude, rise and fall time, length) of the RF signals to each RF pulsed device independently. The low phase jitter of the RF signals and use of insulated phase stable cables are necessary.

The LINAC modules use SLED pulse compression in which the energy is stored in resonant cavities and discharged. This method can create a significant peak power due to the exponential discharge of the cavity when combined in phase with the klystron output. It is desired to “smooth out” the peak power in order to avoid RF breakdown in components such as the accelerating structures

The LLRF system must provide fast phase switching (less than 10ns) of the RF pulse signal in range from 0 to 180 degrees with magnitude control. By ramping the amplitude and phase of the klystron pulse during the last 800ns of its 4µs pulse width, the peak power is reduced while maintaining >80% of average power over the same time (blue).

Variable Energy Gamma (VEGA) System

LLRF System - LLRF distribution

Three reference RF signals (table below) are necessary for the VEGA system operation. These references, harmonically related and phase locked to high precision, will be distributed to devices that require high fidelity phase information. The fixed set of absolute reference frequencies must be provided. LLRF system is requested to control phase and amplitude independently for RF electron source (one klystron and injector laser) and for each LINAC module (five klystrons) to deliver appropriate RF signals.

Frequency	Channel	Description
2856 MHz	Injector RF	Pulsed RF to Injector Klystron
	Injector Laser	CW reference signal for frequency stabilization of Injector Laser
	LINAC-1	Pulsed RF with SLED phase shift to RF module 1
	LINAC-2	Pulsed RF with SLED phase shift to RF module 2
	LINAC-3	Pulsed RF with SLED phase shift to RF module 3
	LINAC-4	Pulsed RF with SLED phase shift to RF module 4
	LINAC-5	Pulsed RF with SLED phase shift to RF module 5
	LINAC Diagnostics	CW reference signal for LINAC BPMs and RF signal diagnostics
	Ring Diagnostics	Future CW reference signal for Storage Ring BPMs
	OC Diagnostics	Future CW reference signal for cavity feedback (diagnostic)
142.8 MHz	RF Cavity	Future CW drive signal to RF Cavity Amplifier
	Ring Feedback	Future CW reference signal for Ring Feedback and BPM Systems
71.4 MHz	Injector Laser	CW reference signal for initial phasing of frequency stabilization
	Cavity Laser	Future CW reference signal for frequency stabilization of Optical Cavity
	AC Sync	CW clock signal for AC mains trigger synchronization

Variable Energy Gamma (VEGA) System

LLRF System - Timing and Synchronization

Main parameters:

- The trigger signals must be synchronized with the RF reference signals and with the AC mains (50Hz).
- The trigger distribution system must provide TTL-level digital triggers with less than 50ps jitter, synchronized to the LLRF system.
- The triggers have a delay and pulse width resolution of one clock cycle ~14ns.
- The phasing of the RF, inside the pulse envelope, will be determined by the LLRF system.
- Timing within the RF pulse must contain sufficient sampling points resolution for measurement and controls. The system must ensure that the sampling is always synchronized pulse to pulse, as well as across the entire machine, to sub-ns.
- The injector laser pulse must be synchronized to the high power 2856 MHz RF phase, where relative timing jitter will result in electron beam energy jitter. The required precision of synchronization is about 1 degree (1 ps, rms).
- The Injector Laser feedback has two channels for frequency stabilization: 71.4 MHz circulation frequency and the 40th harmonic at 2856 MHz. This architecture allows the lock acquisition to occur at the lower (electron ring bunch spacing) frequency, but then hand-off to the higher frequency for precise phase control.

Variable Energy Gamma (VEGA) System

LLRF System – RF Diagnostics

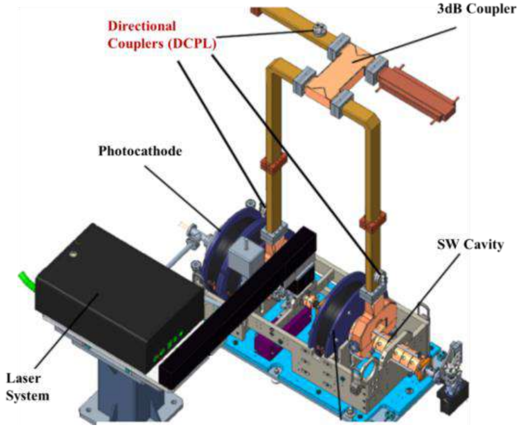
Pulsed RF signals will be collected from waveguide couplers (Directional Couplers) in the RF Electron Source and LINAC modules and routed to electronic modules for measurement of the pulse envelope, power, phase and amplitude. The RF phase measurements within the pulse are to be used in slow (software) feedback to stabilize the electron beam injection. There are:

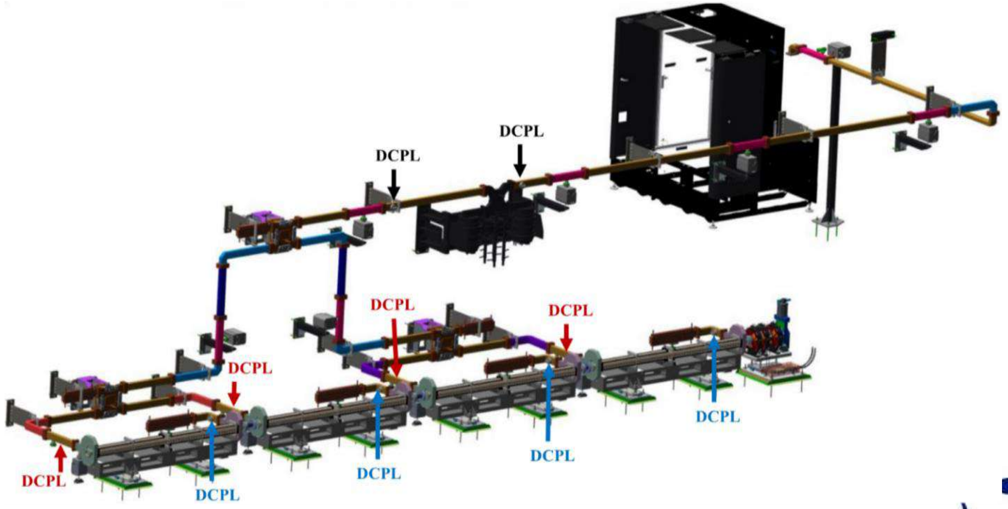
a) 3x Directional Couplers in the RF electron source at: the 3dB Coupler input, RF Gun Cavity input and SW Cavity input.
b) 10x Directional Couplers in one Linac module at: SLED Cavity input and output (2x) and Accelerating Structures input and output (8x).

That Means:

a) 6 RF channels (3x forward signals, 3x reflected signals) in the RF electron source.
b) 20 RF channels (10x forward signals, 10x reflected signals) in one LINAC module, and in total: 20 x 5 = 100 RF channels for all five LINAC modules.

The locations of the Directional Couplers for an LINAC module





Variable Energy Gamma (VEGA) System

LLRF System – LIBERA PROPOSAL

LIBERA Reference Master Oscillator (RMO) used as a source of low-phase-noise radio frequency signal (2 pcs)

RMO specifications		
Parameter	**Requered**	**Proposed**
Output frequency	2856 MHz	✓
Frequency stability (Allan Deviation)	5E-11	≤ 5E-11
Nominal output power	≥ +15 dBm ±1 dB	+18.66 dBm
Return loss	< -15 dB	-17.149 dB
Harmonics	< -50 dBc	-61.3 dBc
Spurious	< -50 dBc	-56.6 dBc
Phase Jitter	< 1 ps/h at ambient temp. stability ±1°C/h	< 0.085 ps/h at ambient temp. stability ±1°C/h
Output/input connector type Impedance	SMA-F 50 Ω	✓
Comunication interfaces	Integrated EPICS input/output controller (IOC) – EPICS IOC	✓
Size	19”	✓

Variable Energy Gamma (VEGA) System

LLRF System – LIBERA PROPOSAL

LIBERA RMO Distribution Amplifiers (RMO DA) used for amplification and distribution output RF signal from RMO Unit to RF devices (5 pcs)

RMO DA specifications		
Parameter	**Requered**	**Proposed**
Input power	+15 dBm ±1 dB	✓
Ouput power	+16 dBm ±1 dB	✓
Bandwidth	±5 MHz	✓
Harmonics and spurious components	< -50 dBc	✓
Phase noise	<60 fs (10 Hz – 10 MHz)	✓
Input, output connectors type	SMA-F (50 ohm)	✓
Input and Output frequency	1x input at 2856 MHz 2x module at 2856 MHz with 8x outputs, 1x module at 142.8 MHz with 4x outputs,	✓
Comunication interfaces	Integrated with EPICS input/output controller (IOC) – EPICS IOC	✓
Size	19”	✓

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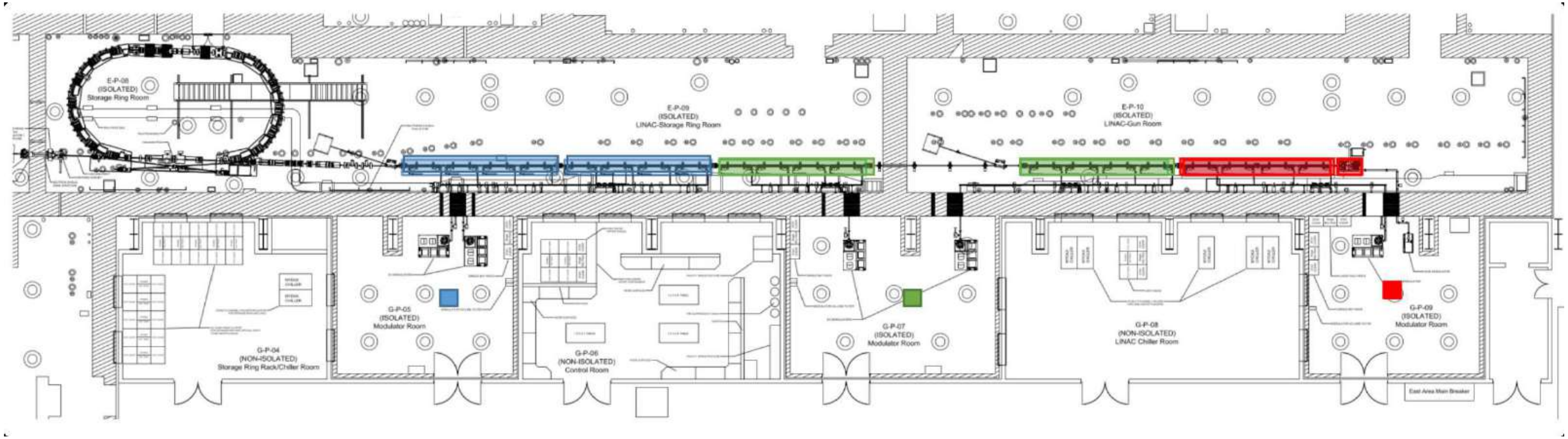
Variable Energy Gamma (VEGA) System

RMO DA – LIBERA Proposal



DA3: RMO DA with 6 output modules
- 1x module at 2856 MHz
- 1x module at 178.5 MHz (SR LLRF)
- 1x module at 119 MHz (SR LLRF)
- 1x module at 142.8 MHz (SR LLRF)
- 1x module at 142.8 MHz (
cBPMs
- 1x module at 71.4MHz (SR Optical)

DA1: RMO DA with 3 output modules
- 2x modules at 2856 MHz
- 1x module at 142.8 MHz (cBPMs)

DA2: RMO DA with 3 output modules
- 1x module at 2856 MHz
- 1x module at 71.4 MHz
- 1x module at 142.8 MHz (cBPMs)

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Variable Energy Gamma (VEGA) System

LLRF System – LIBERA PROPOSAL

LIBERA Trigger Signal Generator Unit (TSU) used for time synchronization of rf drive signals (2 pcs)

Libera Trigger Synchronization front panel

RMO DA specifications		
Parameter	**Requered**	**Proposed**
Lock to 50 Hz AC mains	✓	✓
TTL-level digital output triggers generation	✓	✓
Synchronization to LLRF signals	< 50 ps RMS	✓
Time resolution	≤ 14 ns	✓
Interface (min)	a) 1x input @71.4 MHz b) 16x output channels 3.3 LVTTL, coax LEMO c) 6x output channels 5V TTL, BNC connector	a) 1x 71.4 input b) 26x output channels 3.3 LVTTL c) 13x output channels 5V TTL
Output jitter (RMS)	24 ps (LEMO type output) 80 ps (BNC type output)	✓
Comunication interfaces	Integrated with EPICS input/output controller (IOC) – EPICS IOC	✓
Size	19”	✓

Variable Energy Gamma (VEGA) System

LLRF Modules – LIBERA PROPOSAL

LIBERA LLRF – S-band LLRF systems used to generate RF drive signals for RF devices, and to process output signals from diagnostic devices in accelerating modules of RF Electron Source/LINAC (2+5 pcs)

Libera LLRF analog front-end's front panel

Libera LLRF digital processor's front panel.

LLRF Modules specifications			
Parameter	**Requered**	**Proposed LLRF for LINAC**	**Proposed LLRF for RF Electron Source**
Operation frequency	2856 MHz	2856 MHz	✓
Amplitude resolution	0.01% RMS	0.0071% RMS	0.0067% RMS
Phase resolution	0.01° RMS	0.0043 ° RMS	0.0047 ° RMS
Temperature stable operation	≤95 fs at ambient temp. 24°C ±2°C	40.79 fs at ambient temp. 24°C ±2°C	40.79 fs at ambient temp. 24°C ±2°C
Number of inputs and outputs (min.)	20 inputs 1 drive output 6 inputs 1 drive output	22 inputs 1 drive output	11 inputs 1 drive output
Comunication interfaces	Integrated with EPICS input/output controller (IOC) – EPICS IOC	✓	✓
Size	19"	✓	✓

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Variable Energy Gamma (VEGA) System

LLRF System – LIBERA PROPOSAL

LIBERA RF Clock Transfer Units (SYNC) used for conversion of RF signals to very stable optical signals. Necessary for distribution of RF signals for distances longer than 40 m (3 pcs)

RF Clock Transfer Units (SYNC) specifications		
Parameter	**Requered**	**Proposed LLRF**
Combination of transmitter and receiver	✓	✓
Long-term stability	(max.) 100 ± 5 fspp/day	35,881
Drift compensation capability	≥ 500 ps	640 ps
Integrated added jitter (from 10 Hz to 10 MHz)	< 10 fs RMS	7.1928 ± 0.5
Comunication interfaces	Integrated with EPICS input/output controller (IOC) – EPICS IOC	✓
Size	19”	✓

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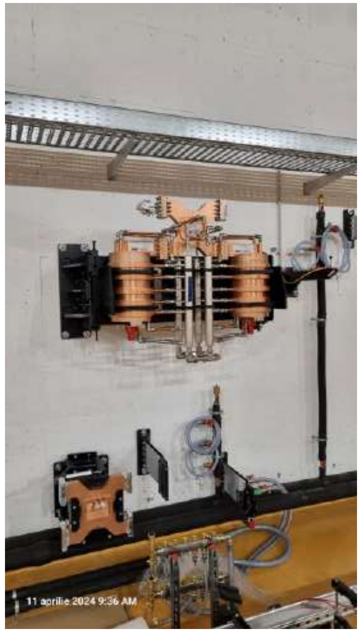
Variable Energy Gamma (VEGA) System

ELI/NP-VEGA project achievements

At the moment we have installed all the necessary utilities for the operation of the VEGA system including the vacuum and cooling systems, the power supplies and control electronics for LLRF system, the magnets and the vacuum pumps from RF Gun/LINAC. Also, the support plates for the acceleration structures were installed and we began the assembly of some components of the High Power Pulsed RF System, such as modulators, SLEDs and hybrids.

Our goal is to have all the RF Gun + LINAC components up and running by the end of the year. This includes positioning of the all acceleration structures, magnets, ion pumps, alignment and diagnostics tools as well as the High Power Pulsed RF Systems together with the waveguides.



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Variable Energy Gamma (VEGA) System

ELI/NP-VEGA project achievements

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CONCLUSIONS

- **VEGA System will be the most advance gamma-ray beam system in the world**
- **Implementation underway with completion in 2026**
- **LINAC to be commissioned in 2024**