Variable Energy Gamma (VEGA) System at ELI-NP

IFIN-HH/ELI-NP

Variable Energy Gamma (VEGA) System – overview

- 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.

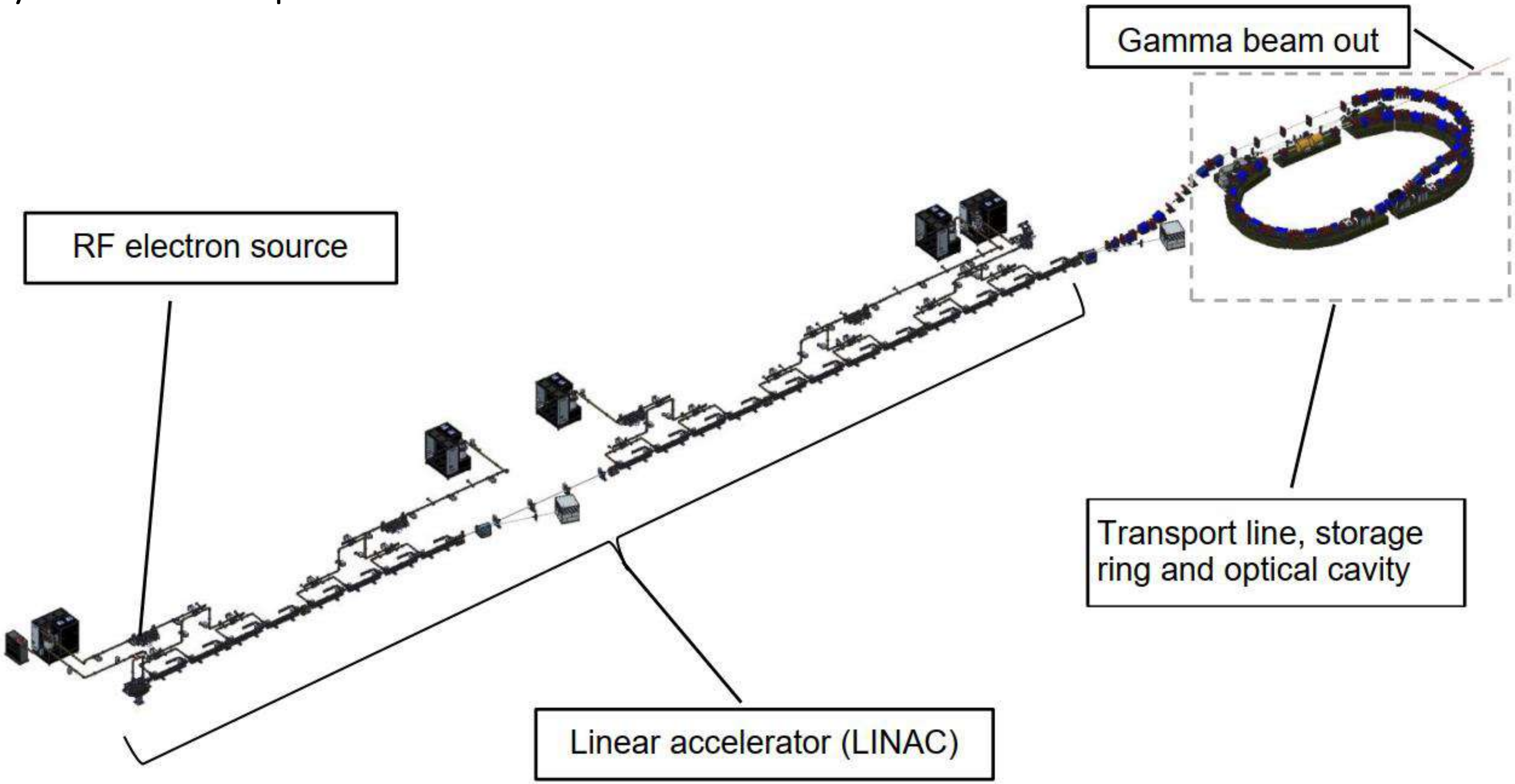
Variable Energy Gamma (VEGA) System – overview

Main Parameters to be achieved:

Quantity	Unit of measurement	Specification
Maximum Photon Energy	[MeV]	≥ 19.5
Tunability of the Photon Energy		Steplessly variable
Linear Polarization of Gamma-Ray Beam	[%]	≥ 95
Divergence at Full Width Half Maximum (FWHM) of Beam Spot	[rad]	$\leq 1.5 \times 10^{-4}$
Average Relative Bandwidth of Gamma-Ray Beam (FWHM)	[m]	$\leq 5.0 \times 10^{-3}$
Total Photon Flux		$\geq 1.0 \times 10^{11}$
Time-Average Spectral Density at Peak Energy	[1/s]	$\geq 5.0 \times 10^{3}$
Average Spectral Off-Peak Gamma-Ray Background Density	[1/(s eV)]	$\leq 1.0 \times 10^{-2}$
Angular Spectral Flux Density	[1/(s mrad^2 0.1%W)]	≥ 1.0 x 109

Variable Energy Gamma (VEGA) System – overview

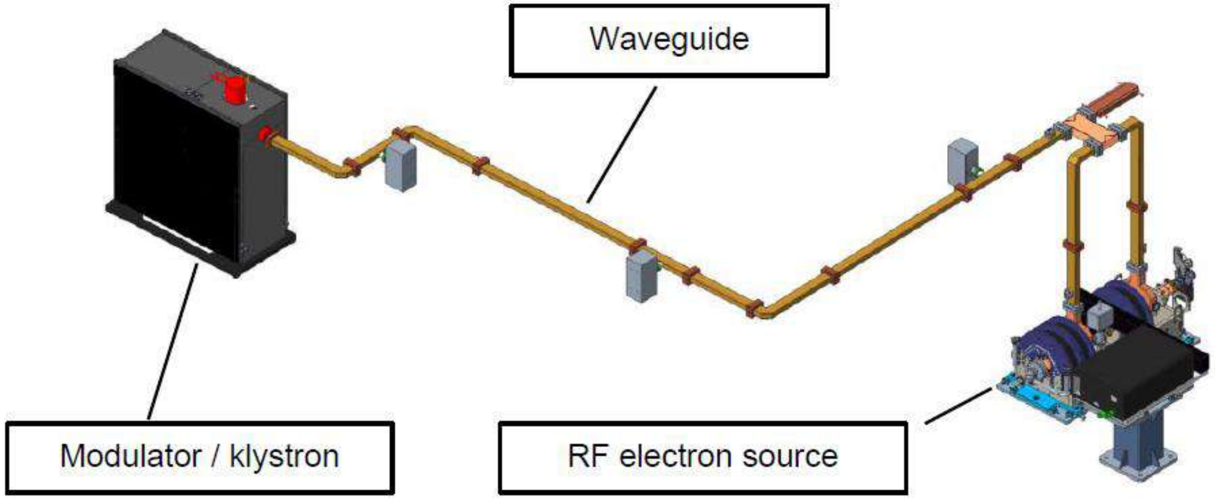
VEGA System - main components



Variable Energy Gamma (VEGA) System – overview

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 – overview

RF electron source - klystron and modulator

These devices provide the RF energy to bring the standing wave electron source and accelerator structure up to full accelerating field prior to the laser pulse that triggers emission of electrons to be accelerated.

Klystron parameters

Parameter	Value
Frequency	2856 MHz
Maximum peak output power	7.5 MW
Nominal RF pulse length	5 µs
Maximum repetition rate	50 Hz
Maximum average output power	10 kW

Modulator parameters

Parameter	Value
Modulator peak power	17.6 MW
Modulator average power	18.5 kW
Operational voltage range	160 kV
Operational current range	110 A
Repetition rate	1-50 Hz
Pulse length	0.1-5 µs
Amplitude stability	±0.01%
Rate of rise	100-150 kV/µs
Pulse to pulse time jitter	<±4 ns
Pulse width time jitter	<±8 ns

Variable Energy Gamma (VEGA) System – overview

RF electron source - Injector laser system

Electron bunches are generated in the RF electron source by illuminating a photocathode by ultraviolet (UV) picosecond pulses from the injector laser.

The injector laser system has the following components:

- a CW mode-locked oscillator at IR wavelength.
- a regenerative amplifier that selects one pulse and amplifies it.
- a harmonics generating module that converts it to UV with wavelength of about 260 nm via second and fourth harmonics generation in nonlinear crystals.

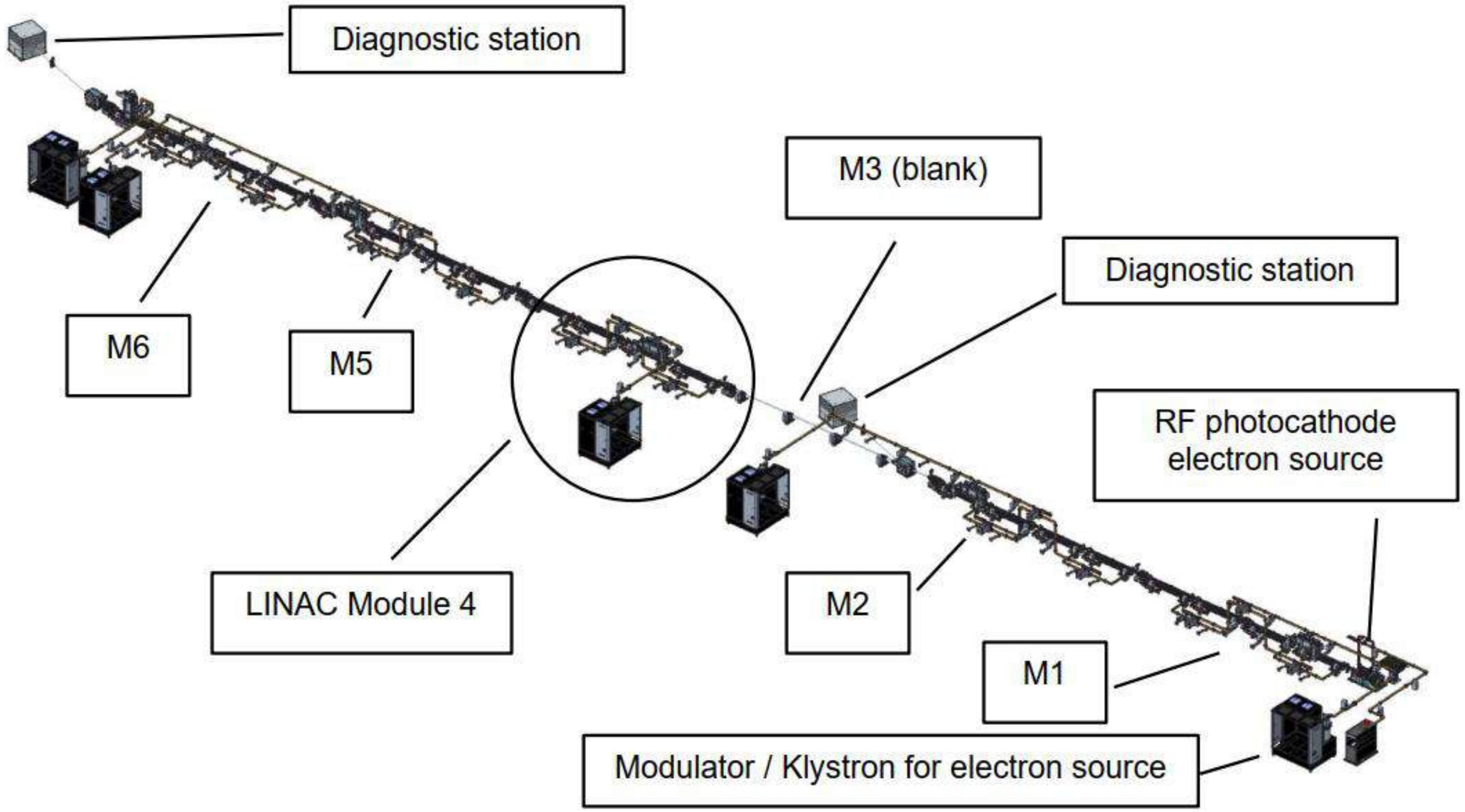
Specifications and parameters for the PHAROS injector laser

Param	Unit	Information	VEGA Specification	PHAROS Value
λIL	nm	Injector laser wavelength	255 - 265	257.5
Ehν	eV	UV photon energy	4.68 – 4.86	4.815
fOSC	MHz	Oscillator repetition rate	71.40	71.40
EIL	mJ	Injector laser pulse energy	0-135	0-135
τIL	ps	Injector laser pulse width	5	5 (nominal) (2-10 range)
fIL	Hz	Injector laser repetition rate	Single shot-50Hz	Single shot-1000Hz
dOP	mm	Beam diameter on photo-cathode during operation	4	4

Variable Energy Gamma (VEGA) System – overview

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.

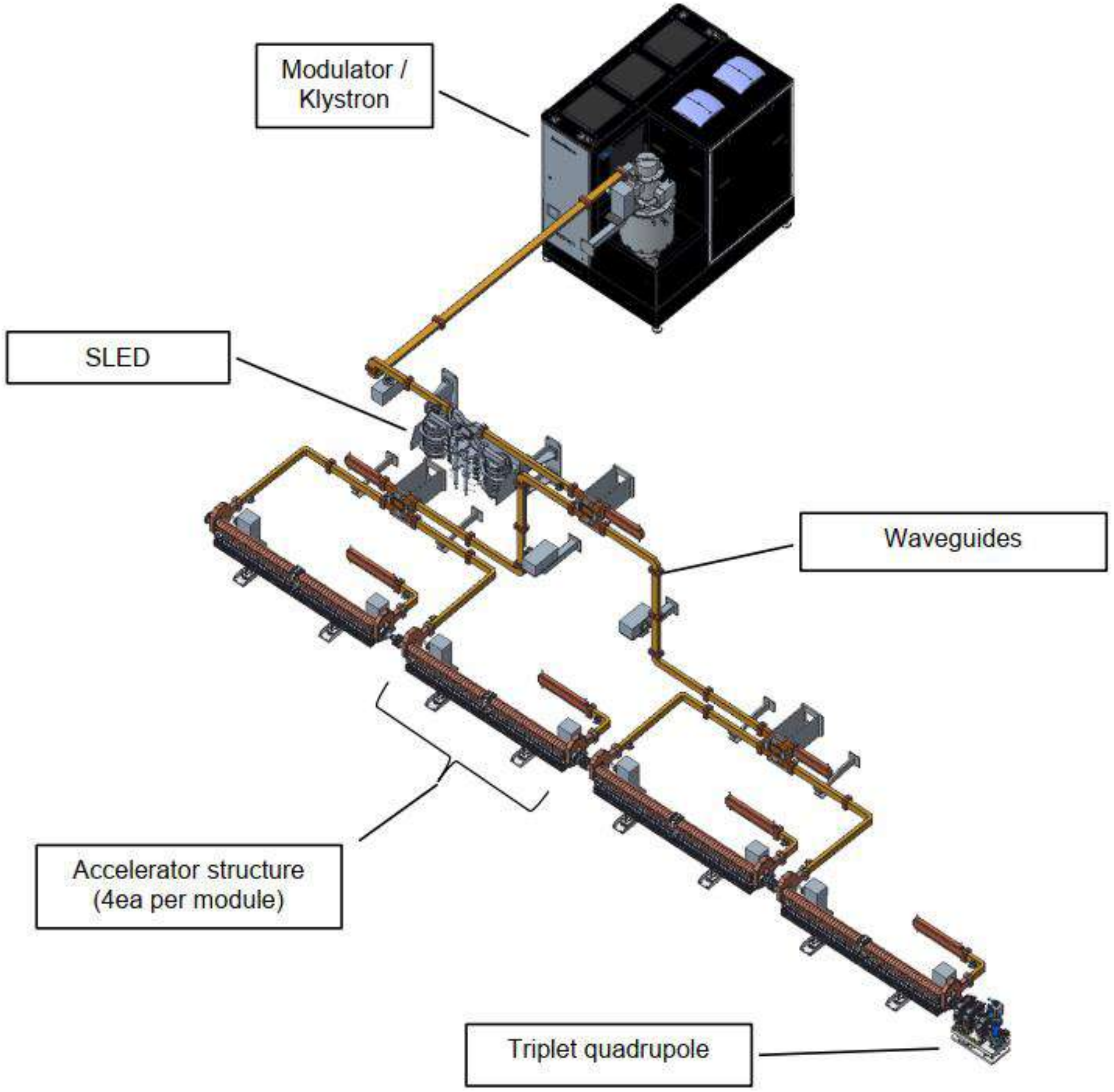


Variable Energy Gamma (VEGA) System – overview

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 – overview

Linear Accelerator (LINAC) - klystrons and modulators

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.

Klistron parameters

Parameter	Value
Frequency [MHz]	2856
Maximum peak output power	50 MW
Nominal RF Pulse length	4 µs
Maximum repetition rate	50 Hz
Maximum average output power	10 kW
LTI reference	SP000108

Modulator parameters

Parameter	Value
Modulator peak power	110 MW
Modulator average power	32 kW
Operational voltage range	340 kV
Operational current range	360 A
PRF range	0-50 Hz
Pulse length (flat top)	0.1-4 µs
Top flatness	±0.1%
Rate of rise	250-325 kV/µs
Pulse to pulse time Jitter	<±5 ns
Pulse width time jitter	<±8 ns

Scandinova Modulator K-300

Pulsed klystron amplifier E3730A

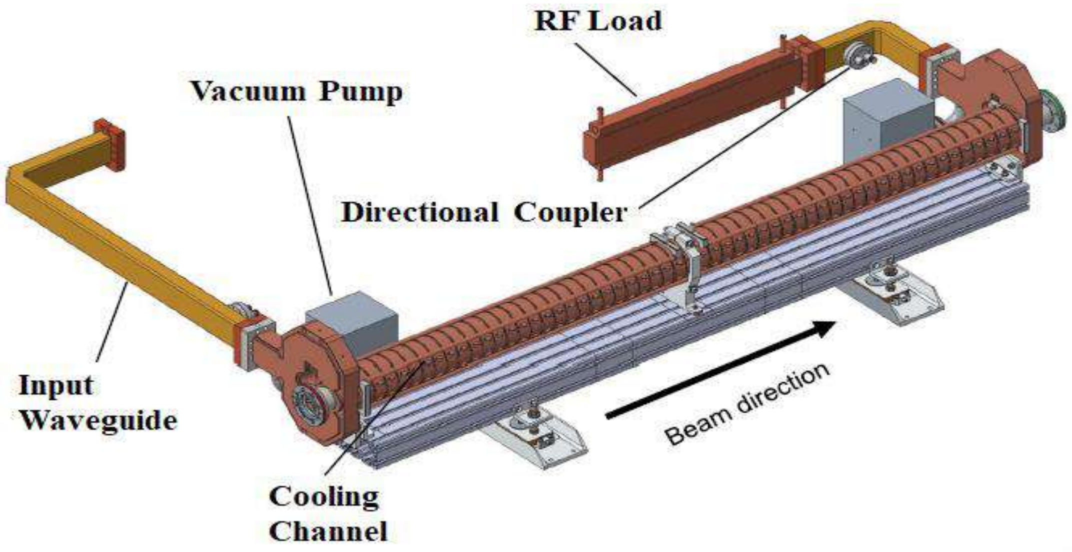
Variable Energy Gamma (VEGA) System – overview

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 [msec]	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 – overview

Linear Accelerator (LINAC) – precision cooling

Most of the cooling of the VEGA systems is performed utilizing the house water system. The accelerator structures and the SLED system must have precise temperature control controlled to higher precision (±0.05° C) and therefore have dedicated chillers for this precise control.

RF heat load and cooling of SLED and accelerator structures

Module Component	**Operating Temperature**	**Heat load to H2O (Maximum)**	**Temperature Precision**
SLED	25°C	2.06 kW	±0.05° C
One accelerator structure	25°C	1.125 kW	±0.05° C
One accelerator load	House Water	<1.0 kW	±2° C
LTI Reference		TN000288	

Precision 3-channel chiller for RF electron source and LINAC modules

Specifications for the precision chiller system

Parameter	**Value**
Cooling capacity [loop 1, loop 2, loop 3]	3000 W, 3000 W, 4000 W
Fluid set point range	+ 15° C to +30° C
Temperature stability	± 0.05° C
Vendor and model (equivalent could be used)	Mydax 3MP34W
LTI reference	SP000107

Variable Energy Gamma (VEGA) System – overview

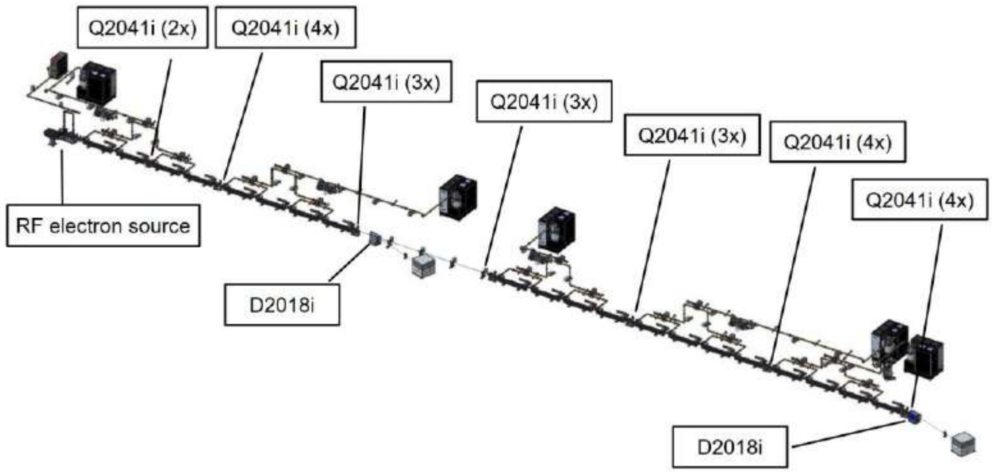
Linear Accelerator (LINAC) – LINAC magnets

The VEGA LINAC contains groups of quadrupole magnets that focus the electron beam and dipole magnets at two locations that can divert the electron beam into a diagnostic beamline

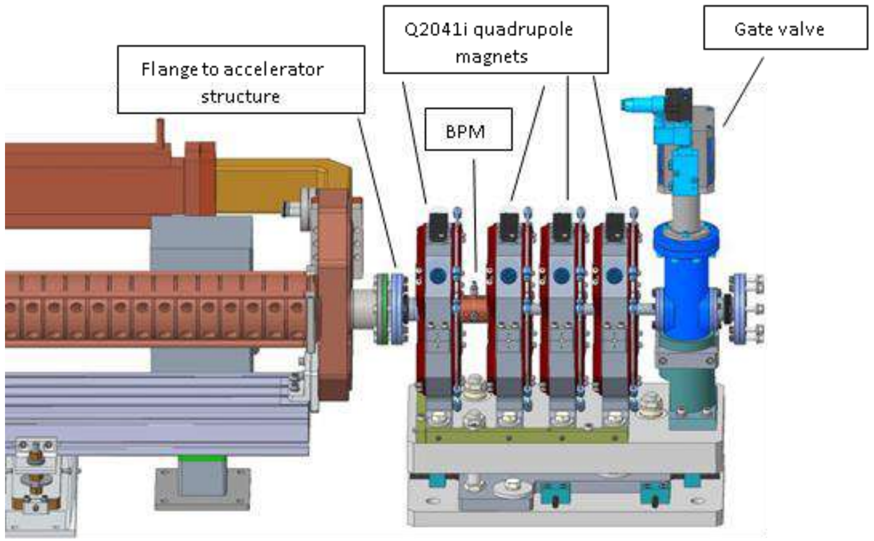
Magnet types used in the VEGA LINAC

Magnet type	Qty. [Pcs]	Pole gap [mm]	bend angle [°]	Leff [m]	Design field	IOp [A]	P/magnet [kW]	LTI Ref.
D2018i	2	20	18	0.524	1.63 T @109 A	23-100 (107)	0.2-3.7 (4.3)	TN000297
Q2041i	23	20	n/a	0.052	50 T/m @13 A	1-12 (13)	0.0-0.1 (0.2)	TN000115

Locations of different magnet types in LINAC



Focusing magnet grouping for modules



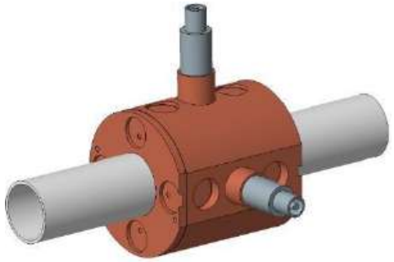
Variable Energy Gamma (VEGA) System – overview

Linear Accelerator (LINAC) – LINAC instrumentation

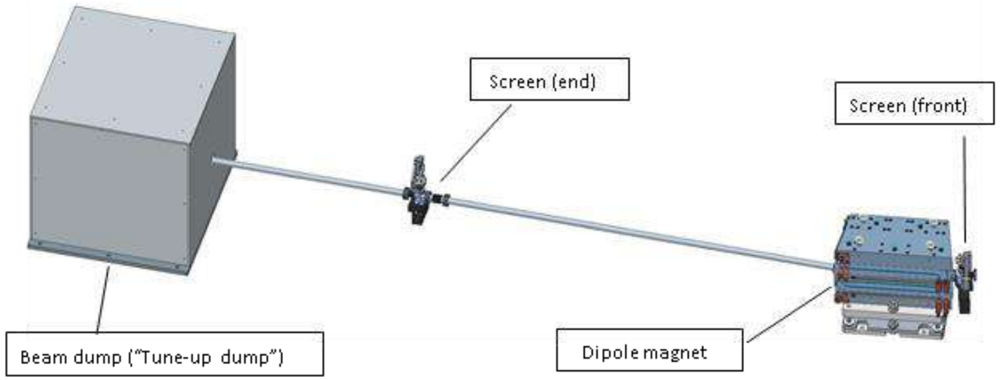
The location, number and functionality of LINAC instrumentation are described below:

- BPMs: There will be one BPM before the first structure and at the end of each module. There are six modules including the gap through the wall, therefore, the total number of BPMs is 7.
- Screens: The intercepting fluorescent screens are used to detect beam size as well as the centroid. There will be one right after the electron source, and one each at the start and the end of the two diagnostic stations. The front screen at the diagnostic station is used to measure emittance, and the second one is used for momentum spread measurement. The total number of screens is 5.
- Current monitor: The current monitor will be located right after the electron source to measure individual bunch charge. Total number is 1.

LINAC BPM



View of LINAC diagnostic stations

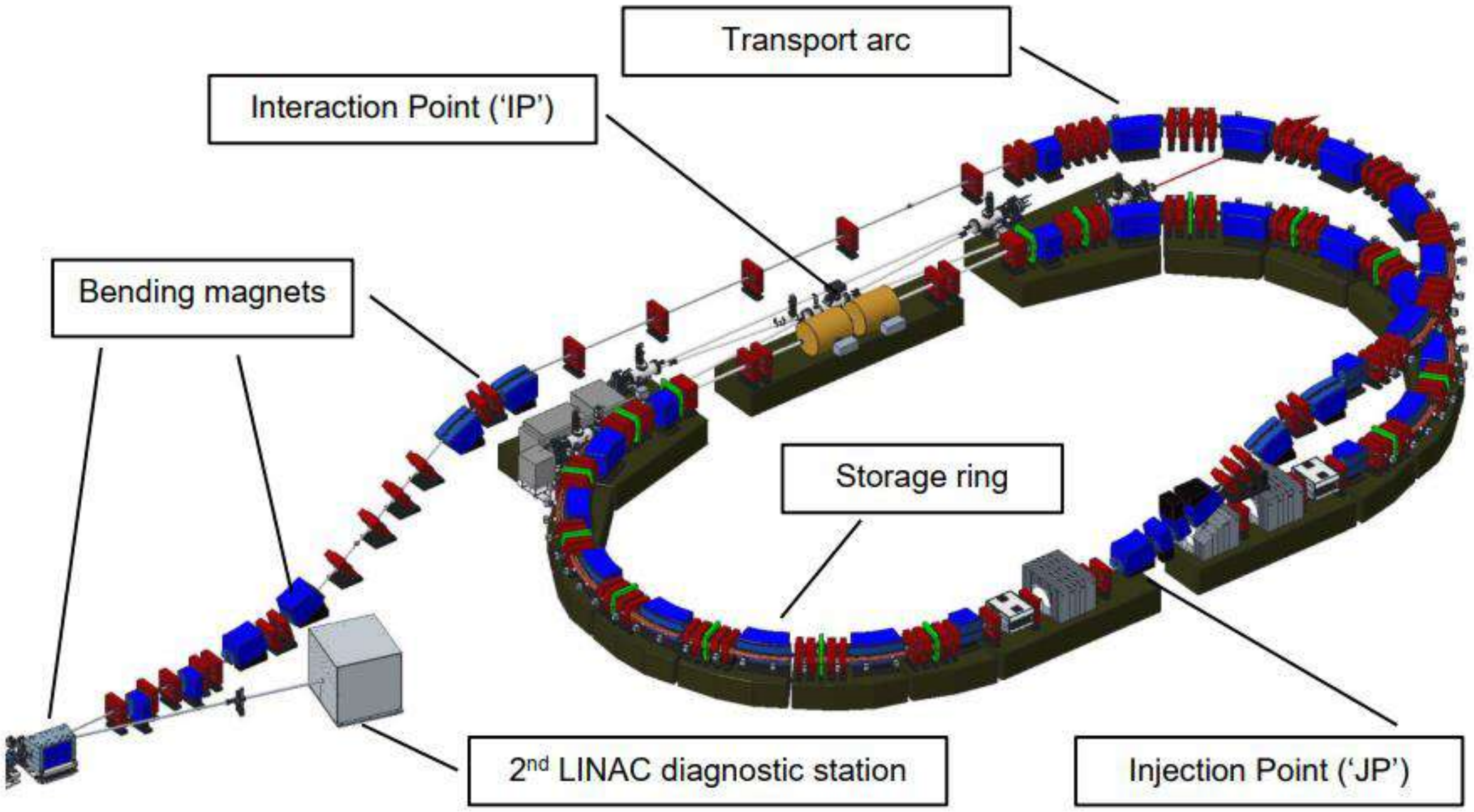


Burgoz Integrated Charge Monitor

Variable Energy Gamma (VEGA) System – overview

Transport line

The purpose of the transport line lattice is to accept the beam from the LINAC and transport it for injection into the storage ring. After the LINAC and final analysis station, the beam is bent horizontally by 2.0 degrees and then is bent vertically (above the optical cavity and interaction region) towards an arc of magnets, which serve to orient the beam so that it can be injected on the opposite side of the storage ring in the 'JP' (inJection Point) region. After traversing the arc, the beam is bent down towards the injection septum, where it is injected beside the circulating electron bunch.



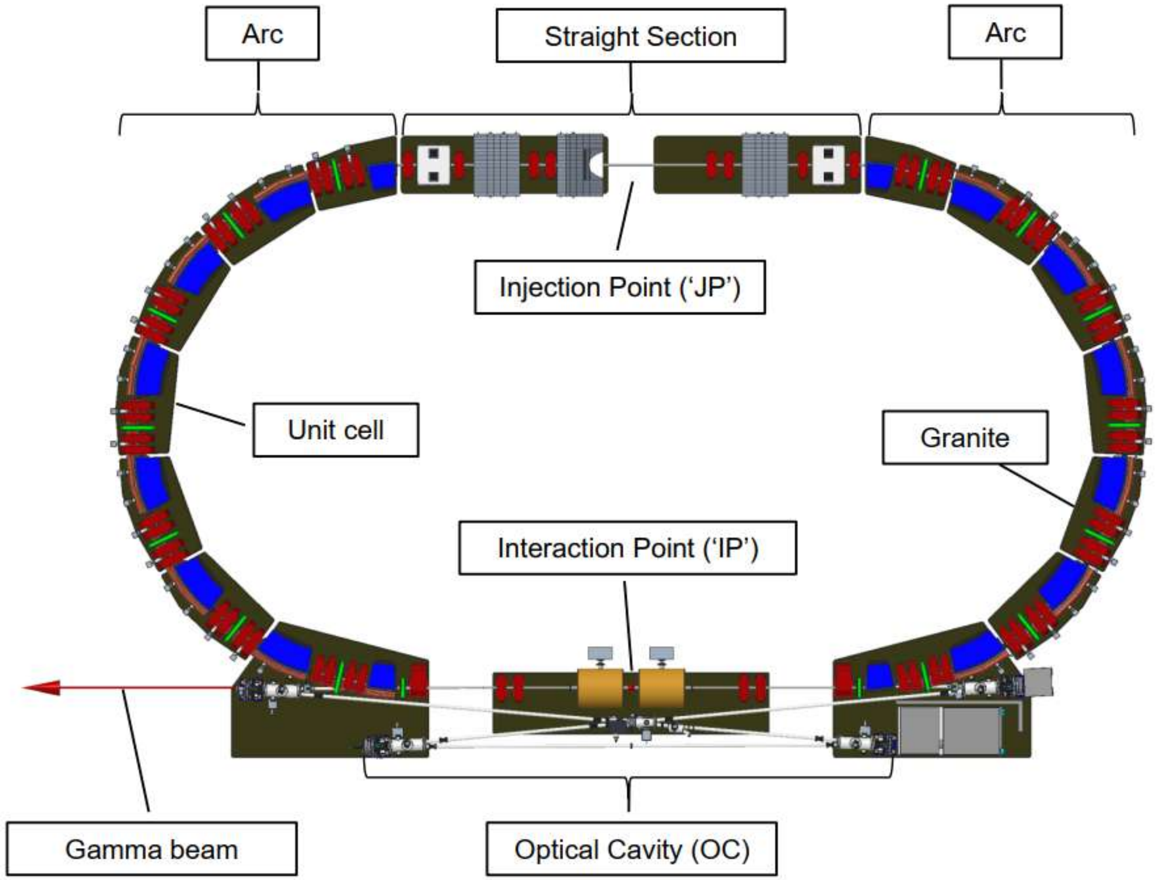
Variable Energy Gamma (VEGA) System – overview

Storage ring - system parameters

The storage ring operates in steady state with quasi-constant current, where the charge is topped up regularly to compensate both for inherent losses and possible losses due to Compton scattering (gamma ray generation). Integrated beam dumps intercept any lost electrons and minimize the generation of unwanted secondary radiation.

Parameters for the VEGA storage ring

Parameter	Symbol	Value
Electron Energy [MeV]	Ee	742
Charge per Bunch [nC]	eNe	2.8
Revolution Frequency [MHz]	frev	8.925
Average Bunch Current [mA]	Bunch Iavg	200/8
Momentum Compaction Factor	α	0.0086
Energy damping time Ring [ms]	τδ	5.2
Average beam current [mA]	Iavg	200
RF Cavity Frequency [MHz]	fcav	142.8
Harmonic Number	h	16
RF Cavity Voltage [MV]	Vcav	0.16
RF Momentum Acceptance	(Δp/p0)max	2.9%
Synchrotron Tune	νs	0.00217
RMS Energy Spread	σE /Ee	0.0534%
RMS Bunch Length [mm]	σs	11.3
Shunt Impedance (1 cell) [MΩ]	Rsh	6.1
Generator Power [kW]	Pgen	7.9
Coupling Coefficient	β	1.9
Cavity tuning angle [degrees]		-69
Synchronous Phase [degrees]	ϕs	6.71



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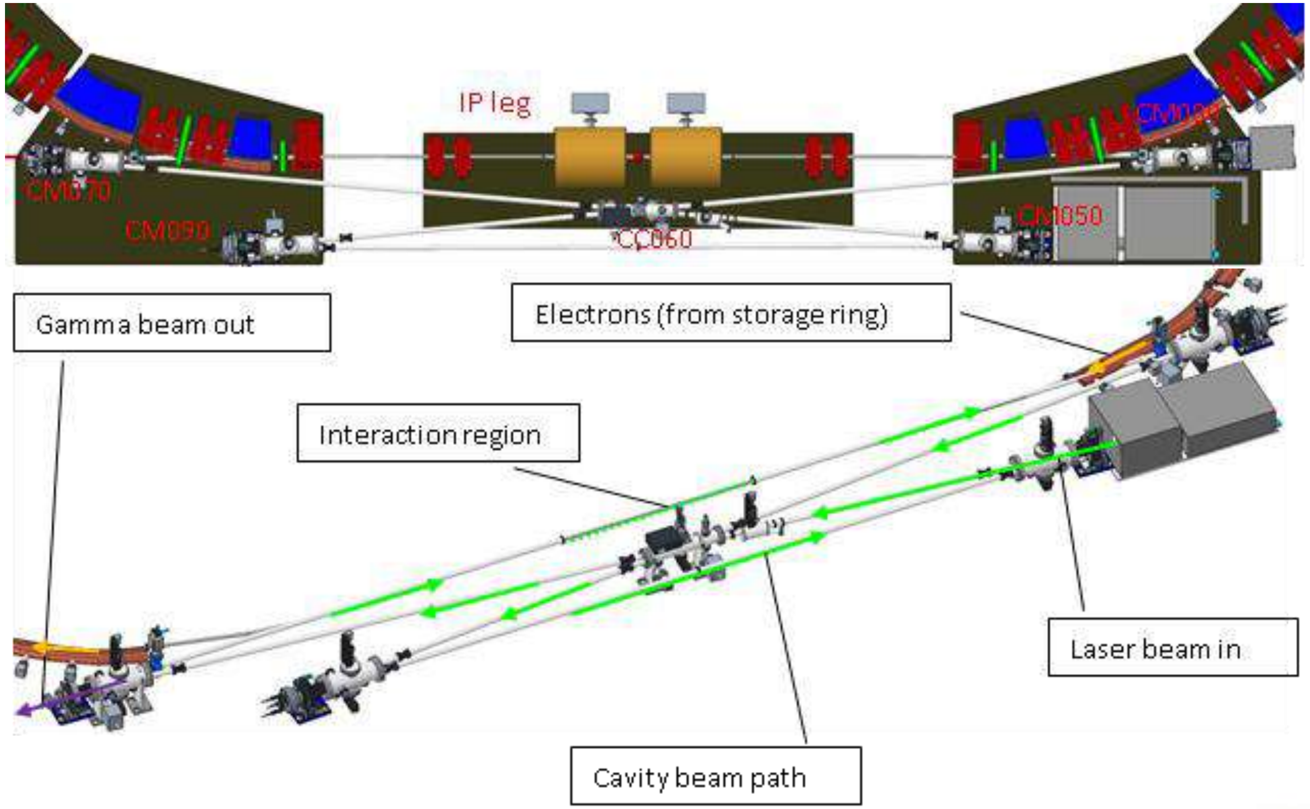
Variable Energy Gamma (VEGA) System – overview

Storage ring - optical cavity (OC) design parameters

The high power laser pulses are stored in a low-loss power-enhancement optical cavity continually fed by a CW mode-locked laser. The laser pulses are made to backscatter off the electron bunches to generate gamma rays in the interaction region of the storage ring and cavity.

Optical cavity design parameters

Parameter	Unit	VEGA IR	VEGA Green
Wavelength	nm	1030	515
Cavity length	m	33.6	
Free spectral range	MHz	8.925	
Distance between mirrors in IP leg	m	10.0	
Separation between IP and opposite leg	m	0.75	
Rayleigh range on IP leg	m	1.0	
Mirror radius (IP leg)	m	4.72	
Mirror radius (Second leg)	m	8.42	
Number of pulses stored in OC		8	
Finesse		~30,000	>20,000
Cavity power	kW	up to 100	up to 50
Drive laser operating power	W	20	10
Drive laser repetition rate	MHz	71.4	



Variable Energy Gamma (VEGA) System – overview

Storage ring - cavity laser parameters

Two configurations of the optical cavity, one using a 1.03 µm laser wavelength ("IR") and the other using a wavelength of 0.515 µm ("Green") will be provided. By choosing the energy of the electron beam (continuously tunable from 234 to 742 MeV) and the laser wavelength (two discrete choices, IR or green), the gamma ray energy can be tuned continuously from 1.0 MeV to >19.5 MeV.

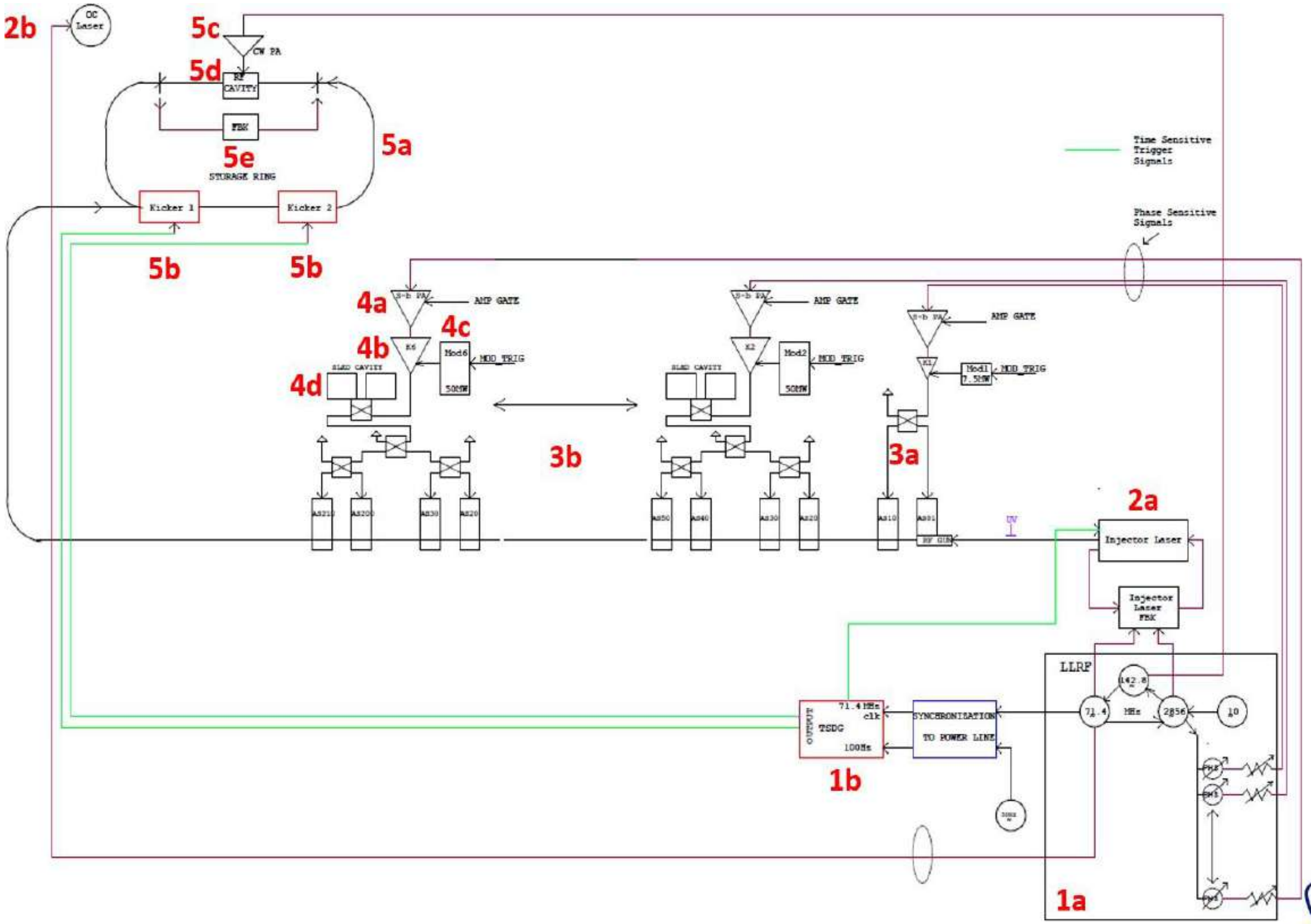
Parameters for the cavity laser

Parameter	Unit	Information	IR configuration	Green config.
lCAV	nm	Cavity laser wavelength	1030	515
PCAV	W	Cavity laser design power	>35	>15
tCAV	ps	Cavity laser pulse width	20±10	
fCAV	MHz	Cavity laser repetition rate	71.4	
dCAV	mm	Beam diameter at the output at 1/e2 level	~3.5	
M2		Output beam quality (TEM00)	<1.3	
C	%	Beam circularity	> 90%	

Variable Energy Gamma (VEGA) System – overview

Control system

1. **Timing and RF Generation Circuitry:**
   a) Low Level RF (LLRF).
   b) Trigger Delay Signal Generator (TSDG).
2. **Laser Systems:**
   a) Injector Laser.
   b) Optical Cavity.
3. **High Power Pulsed RF Systems:**
   a) Injector.
   b) LINAC.
4. **Control Components for RF Systems:**
   a) S-Band Driver Amplifiers.
   b) High Power Klystrons.
   c) Modulators.
   d) SLED System.
5. **The Storage Ring Control Elements:**
   a) Storage Ring Magnets.
   b) Kicker (Fast Deflecting) Magnets.
   c) VHF Power Amplifier.
   d) RF Cavity.
   e) Ring Feedbacks.



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Variable Energy Gamma (VEGA) System – overview

LLRF System - Master Oscillator

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. Any frequency tuning, for instance to the RF accelerating structures, will be accomplished by tuning the load itself through precision thermal control.

LLRF master RF clocks

Frequency	Sub-harmonic	System
2856 MHz (F1)	1	• RF Photocathode (photocathode gun cavity and SW cavity) • LINAC (TW accelerating cavities)
142.8 MHz (F2)	/20	• Future RF Cavity in Storage Ring (CW)
71.40 MHz (F3)	/40	• Injection Laser rep rate (feedback reference frequency) • Trigger Synchronization to AC mains • Future Optical Cavity (OC) Laser rep. rate (feedback reference frequency) • Future Interaction or Collision rate

Parameters for Master Oscillator

Parameter	Value			Units
Harmonics (not worse than)	-20			dBc
Spurious (not worse than)	-60			dBc
Phase Noise	F1	F2	F3	
@ Offset 100Hz	-115	-109	-75	dBc/Hz typ.
1 kHz (not worse than)	-145	-139	-85	dBc/Hz typ.
10 kHz (not worse than)	-160	-154	-100	dBc/Hz typ.
100 kHz (not worse than)	-165	-159	-125	dBc/Hz typ.
1 MHz (not worse than)	-165	-159	-145	dBc/Hz typ.
Phase Jitter	< 1.0			ps, rms

Variable Energy Gamma (VEGA) System – overview

LLRF System - LLRF distribution

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.

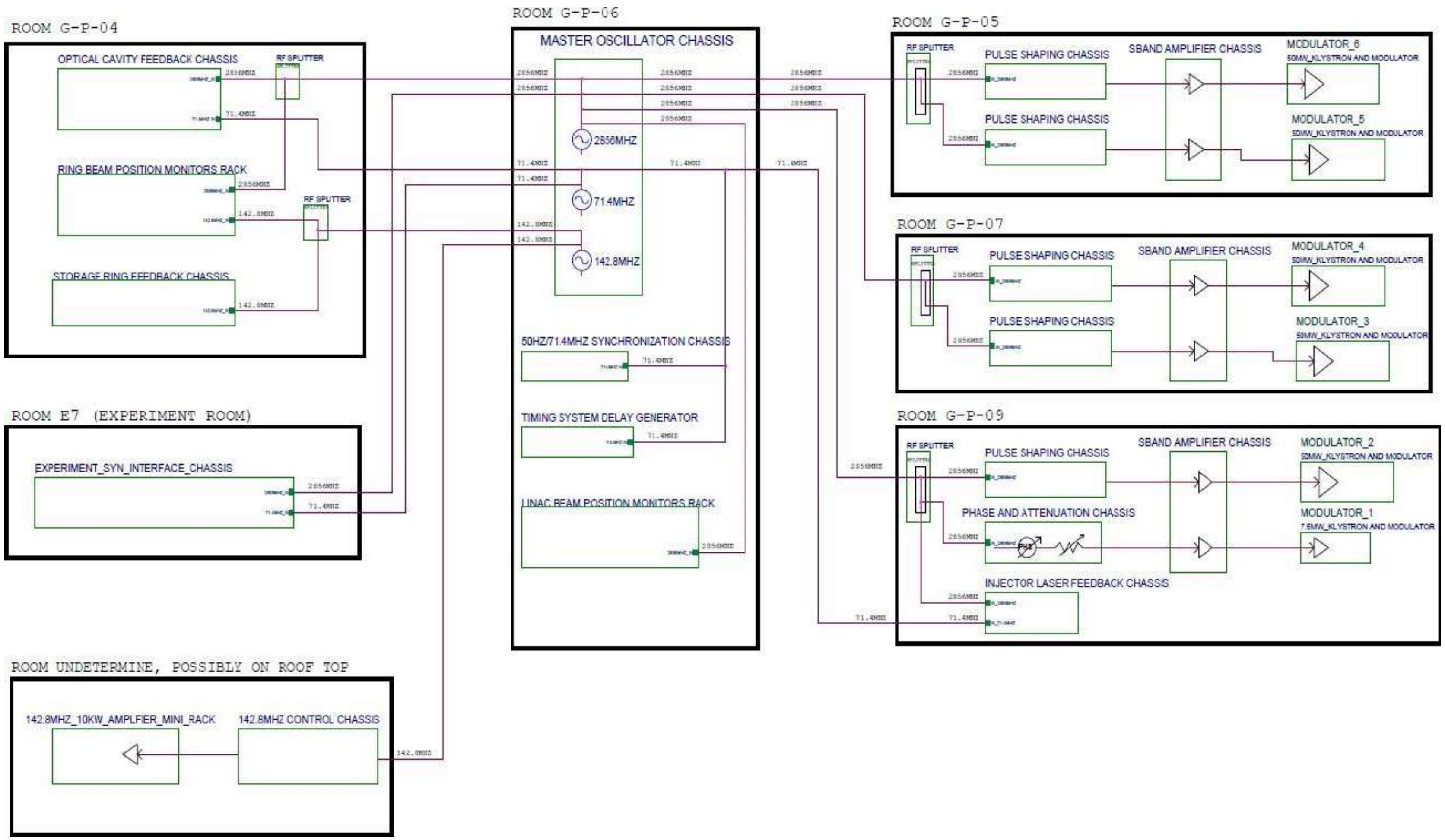
LLRF channels

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 – overview

LLRF System

LLRF distribution



Variable Energy Gamma (VEGA) System – overview

LLRF System - Timing and Synchronization

Main parameters:

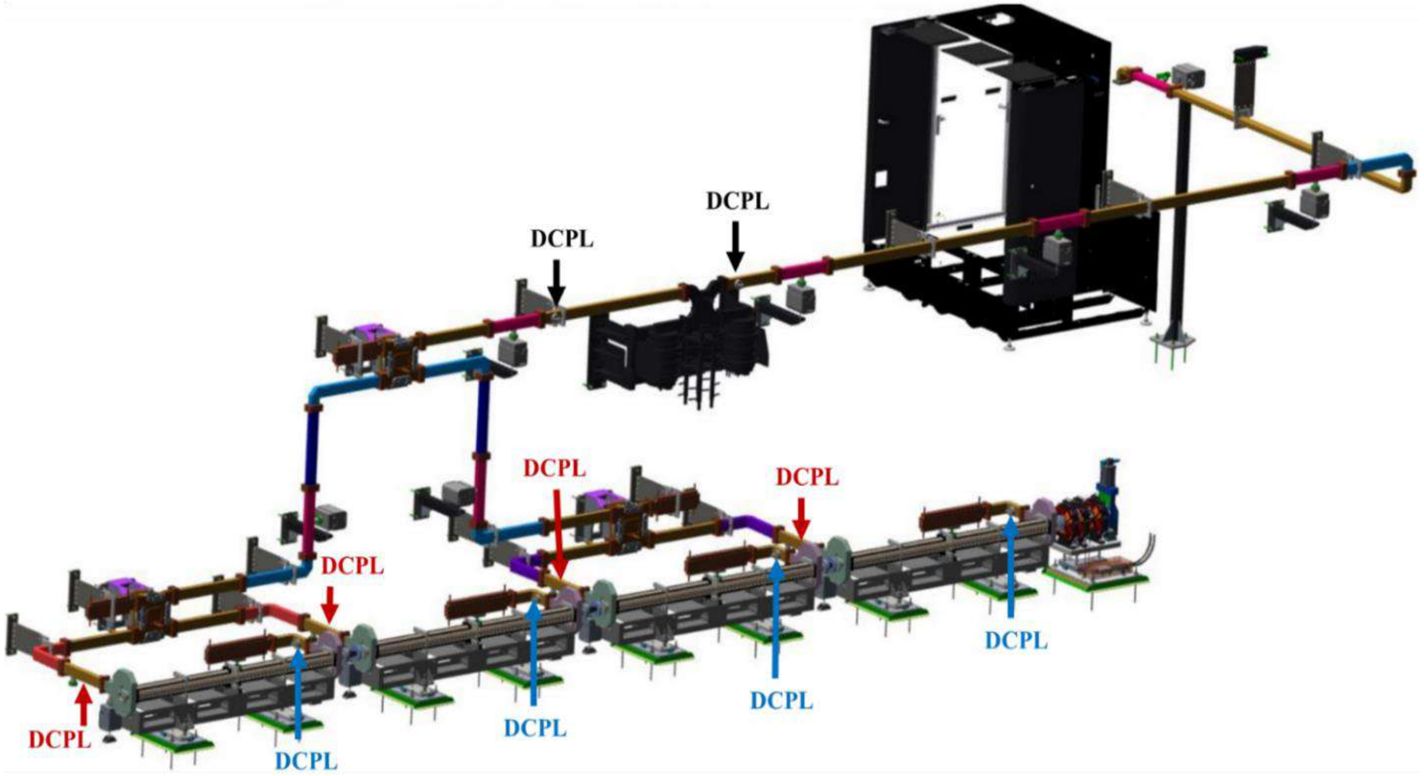
- The trigger signals must be synchronized with the RF reference signals and with the AC mains (50Hz).
- The trigger distribution system must provide TTL-level digital triggers with less than 50ps jitter, synchronized to the LLRF system.
- The triggers have a delay and pulse width resolution of one clock 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 – overview

LLRF System – RF Diagnostics

Pulsed RF signals will be collected from waveguide couplers (Directional Couplers) in the 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.

The locations of the Directional Couplers for an LINAC module



Variable Energy Gamma (VEGA) System – overview

LLRF System – RF Diagnostics

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), at 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.

There are no RF probes in the RF gun cavity and SW cavity, and there are no RF probes in the TW cavities in LINAC modules.

Parameters of directional couplers:

a) Coupling factor for forward power ports: -60 ±1 [dB].

b) Coupling factor for reflected power ports: -60 ±1 [dB].

c) VSWR / Return loss (forward direction): < 1.05 / -32.2 [dB].

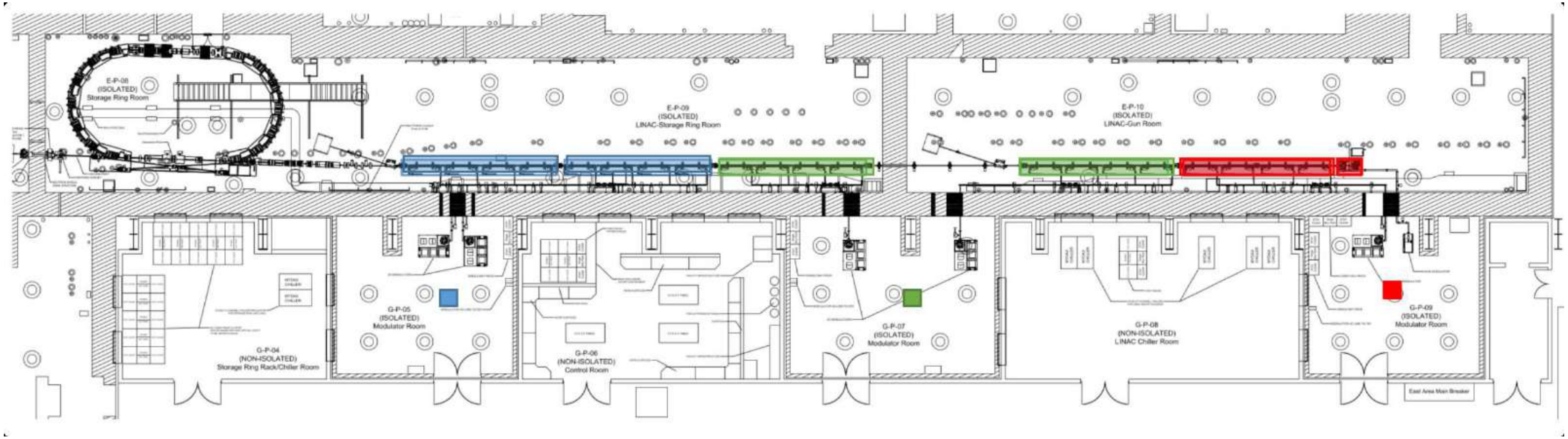
d) Directivity: > 31 [dB].

Directional Coupler for the VEGA Injector System. RF connector: N-type, 50 ohms.

Variable Energy Gamma (VEGA) System – overview

LLRF System – location proposal

- Installation of the racks at 3 locations much closer to the RF structures (Rooms GP07, GP09 and GP05).
- The RF cable distance is expected to be < 25 m, also considering the possibility to apply the LLRF control on the signals with shorter cables.
- The selected rooms are better controlled +/1 °C/h than GP06 and GP08 (+/ 3 °C/h). Resulting in 0.5 ps/h.
- The location of the racks within the rooms should be selected in order to avoid the interference with the modulators and to minimize RF cable length.
- The MO signal needs to be distributed among the 3 rooms, preferred RMO installation within the rack in room GP 07.



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Variable Energy Gamma (VEGA) System – overview

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**