Tunable coherent optical source for gamma-ray generation at LLS

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1. Background

The generation of gamma-ray radiation by laser backscattering of high-energy electrons in accelerator facilities is a well known technique. A vital component of this technique is the laser system, which must provide an optical beam with the required characteristics in terms of optical power, photon energy (frequency), spatial beam quality, and practical design for integration with the electron storage rings.

So far, the laser sources for such facilities worldwide have been based on conventional Nd:YAG type or argon-ion systems. Such lasers operate at a fixed frequency, so they offer no freedom to vary the energy of the optical photons. The ability to freely control the photon energy can offer several advantages and opens up new possibilities for conducting a wide range of novel high-energy experiments in accelerator facilities.

Conventional Lasers Since the invention of the laser in 1960, there have been major advances in the development of a wide variety of laser systems. However, the vast majority of such conventional systems (e.g. Nd:YAG, argon-ion, He-Ne, semiconductor, etc.) can operate only at a fixed frequency (wavelength), hence also providing photons of fixed energy. On the other hand, there has also been significant progress in the development of conventional lasers that are *tunable*. The wavelength range of the most widely established tunable laser systems is shown in Fig. 1 (a). However, as can be seen from the figure, the tuning range available to such sources is restricted to a few hundred nanometers at best. In addition, the spectral coverage of these systems is limited mainly to the visible and near-IR. This means that substantial portions of the optical spectrum in the UV, visible and IR can not be accessed, even by conventional tunable laser sources. To overcome this important obstacle, it is vital to deploy alternative technologies for the generation of tunable radiation in new spectral regions.

Optical Parametric Oscillators A key technology capable of overcoming the limitations of conventional lasers is the *optical parametric oscillator* (OPO). These are novel optical instruments that can provide tunable radiation over an exceptionally wide frequency range, not available to traditional lasers. They can operate from wavelengths in the visible (400 nm) to the mid-IR (12 μm), can be configured in compact, portable, solid-state formats, and are easy to operate. As such, they offer great potential for a wide range of applications requiring variable optical frequency and photon energy. Figure 1(b) shows the tuning range of three OPO systems developed by the Applicant and his research team, which can be compared with the tuning range of existing conventional tunable lasers in Fig. 1(a). A photograph of an OPO instrument developed by the Applicant is shown in Fig. 2.

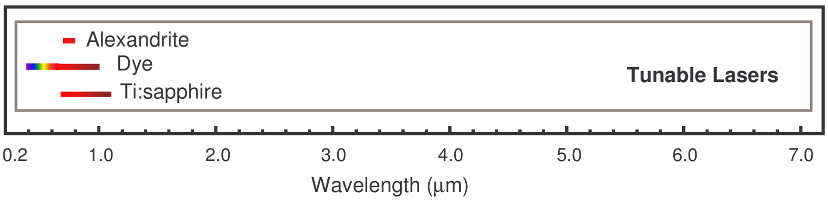

Figure 1(a). The tuning range of the most widely established conventional tunable lasers.

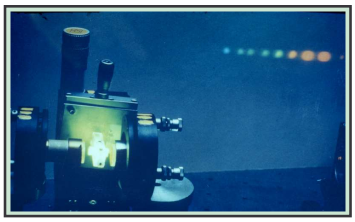

Figure 2. Photograph of an Optical Parametric Oscillator based on the crystal of β-BaB_2O_4.

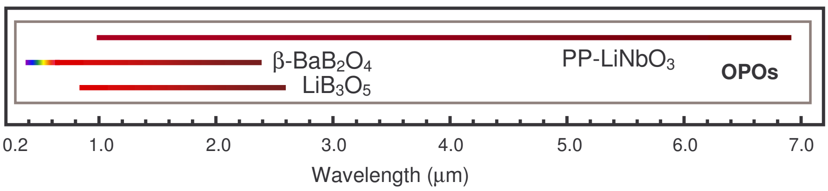

Figure 1(b). The tuning range of a number of OPO systems developed to date.

2. OPO in the Context of LLS

The unique properties of the OPO highlighted above make it a highly attractive alternative to conventional Nd:YAG or argon-ion lasers for gamma-ray generation in electron accelerator facilities. In the context of the LLS facility, the development of an OPO system will be an important breakthrough because:

- It will enable the generation of gamma-rays through laser backscattering, currently not available at the LLS facility.

- It will provide tunability control of optical photon energy on either side near the maximum gamma-ray energy, E_γ(max)=37.5 MeV. This tunability could be very useful in the experimental verification of theoretical calculations near E_γ(max), which will be of interest for some studies.

- The longer mid-IR wavelengths, hence lower photon energies, will produce higher gamma-ray intensities (at lower gamma-ray energies) compared to ALL other laser backscattering facilities (except HIGS), which use Nd:YAG or argon-ion lasers. This will make the LLS facility particularly useful for lower-energy/higher-intensity gamma-ray experiments.

- The OPO will be able to deliver large optical powers (several watts). Therefore, under similar operating parameters (σ_c, I_e, L, S), the OPO will be able to provide higher gamma-ray intensities through higher optical powers.

- The OPO will deliver an excellent spatial quality in a diffraction-limited optical beam with minimum divergence and suitable cross-section, enabling collimation, manipulation, and propagation over long distances with standard optical elements. The all-solid-state design of the OPO will also ensure excellent output beam stability, with minimum variations in optical power, spatial beam quality, temporal stability, beam size and shape, and beam positioning over long distances.

- The OPO represent a new optical instrument, which has not been previously deployed in any other accelerator facilities throughout the world. Therefore, in addition to it usability, it will represent a world-first addition to such a facility, which will also enable novel scientific advances in high-energy accelerator physics.

- The OPO system will be developed by indigenous expertise in Spain.

3. Proposed Program

Our goal is to develop a practical source of coherent variable-energy photons based on a high-power OPO for gamma-ray generation through laser backscattering at the LLS facility. The system will be a state-of-the-art instrument operating in the 1.5 to 5 μm wavelength range in the mid-IR, where no other conventional laser sources with similar operating characteristics are available. The OPO will, therefore, be capable of providing optical photons with controllable energies in the range of 0.82 eV to 0.25 eV. The optical beam will be of the highest spatial quality (M^2 ~1), with minimum divergence. This will allow diffraction-limited propagation over long distances without significant beam spreading, and will permit collimation and manipulation of the optical beam to the desired characteristics without difficulty. The intensity profile will be Gaussian (TEM_{oo}) and the beam diameter at the exit of the OPO instrument will be ϕ~2 to 5 mm ($1/e^2$ intensity points), depending on the exact focusing and resonator configuration. The instrument will be designed in a compact, all-solid-state design, which will be capable of being conveniently deployed and integrated with the electron storage ring at the LLS facility.

We propose two different OPO device configurations, which could be developed, depending on the exact operating requirements:

- (b) a *pulsed* OPO, with a nanosecond time structure in the output optical radiation.
- (a) a *continuous-wave* (cw) OPO with no time structure in the output and a steady state flow of optical photons in time.

To achieve the required performance parameters, we will develop either OPO system using the nonlinear crystal of periodically-poled $LiNbO_3$ (PPLN) as the optical gain element. For pulsed operation, the OPO will use a high-energy Q-switched Nd:YAG laser as the pump source, whereas for cw operation it will be necessary to use a cw Nd:YAG laser. Both lasers will operate at a wavelength of 1.064 μm. By suitable design of the phase-match grating on the PPLN crystal, we will be able to achieve wavelength tuning over the 1.5-5 μm range from either OPO system. In order to obtain the high spatial quality in the output beam, the OPO cavity in either system will be designed in a stable resonator. The output beam will also be linearly polarized. The OPO systems will be designed and developed in a compact, rugged, and stable configuration suitable for integration with the electron storage ring at the LLS facility. The OPO systems will be "user-friendly", requiring some basic training of personnel for day-to-day operation.

The predicted performance characteristics of the pulsed OPO system are summarized in Table 1. The corresponding performance of the cw OPO system is summarized in Table 2.

It is also important to note that while the proposed design relates to the development of OPO systems operating in the mid-IR, alternative designs can also be implemented to provide continuous tuning in other wavelength regions, particularly from 400 nm in the visible to 1.5 μm in the near-IR.

Pump Laser	Nd:YAG (Q-switched)
Wavelength	1.064 μm
Pulse Energy	500-1000 mJ
Pulse Duration	10-50 ns
Repetition Rate	1Hz-100 Hz
OPO Design	Singly Resonant (PPLN)
Wavelength Coverage	1.5-5 μm
Photon Energy	0.82-0.25 eV
Pulse Energy	>50 mJ
Pulse Duration	10-50 ns
Repetition Rate	1 Hz-100 Hz
Spatial Quality	$M^2 \sim 1$
Spatial Profile	Gaussian (TEM_{00})
Polarization	>99% Linear
Footprint	30x40 cm

Table 1. Characteristics of the nanosecond pump laser and the pulsed OPO for gamma-ray generation at the LLS facility.

Pump Laser	Nd:YAG (cw)
Wavelength	1.064 μm
Output Power	30-100 Watts
OPO Design	Singly Resonant (PPLN)
Wavelength Coverage	1.5-5 μm
Photon Energy	0.82-0.25 eV
Output Power	2-10 W
Spatial Quality	$M^2 \sim 1$
Spatial Profile	Gaussian (TEM_{00})
Polarization	>99% Linear
Footprint	30 x 40 cm

Table 2. Characteristics of the cw pump laser and the cw OPO for gamma-ray generation at the LLS facility.

This project is unique in that the coherent optical source will be developed with the expertise available in Spain, with the Applicant having already demonstrated a strong international track record in the field. It is fully expected that the development of an OPO system for LLS will bring about an added capability to this facility and, in the long term, will have a major impact on a wide range of high-energy physics applications, not only in Spain, but also at international level.

4. Budget

It is anticipated that with the involvement of an experienced post-doctoral researcher in OPO design and development, the proposed program can be implemented in 2 years. While the inclusion of a post-doctoral fellow may place additional budgetary burden on this program, this is vital for the successful outcome of the project. There is also another personnel cost relating to the fabrication costs for mechanical components for the OPO, which will require the assistance of a mechanical technician. The other major cost relates to the procurement of a suitable pump laser. Consumables costs relate to the purchase of optical components (PPLN crystal, cavity mirrors, focusing and propagation optics, etalons and diffraction gratings), micromechanical components (translation and rotation stages) and coating costs for the PPLN crystal and the optical components. Most of the necessary diagnostics is already available in the Applicant's laboratory.

The approximate budgetary breakdown for the pulsed OPO is shown in Table 3. The corresponding breakdown for cw OPO is summarized in Table 4.

Table 3. Budgetary breakdown for pulsed OPO.

(All figures include VAT)

Personnel:	
Post-doctoral Fellow (2 years)	€60.000
Mechanical Technician	€20.000
Equipment:	
Pump Laser (500 mJ Q-switched Nd:YAG)	€80.000
High-Energy Power / Energy Meter	€4.000
High-Energy Optical Isolator (2 units)	€5.000
Precision Temperature Controller and Oven	€5.000
Consumables:	
PPLN Crystal (> 1 mm thick)	€6.000
Specialist OPO Mirrors	€8.000
Etalon, Diffraction Grating	€4.000
Coating Costs for PPLN Crystal	€3.000
Propagation and Focusing Optics (Beam-steering mirrors and lenses)	€3.000
Coating Costs for Propagation and Focusing Optics	€3.000
Precision Micromechanical Mounts	€8.000
Total:	**€209.000**
Overhead Charges (at 14.7%)	€30.723
Grand Total:	**€239.723**

Table 4. Budgetary breakdown for cw OPO.

(All figures include VAT)

Personnel:	
Post-doctoral Fellow (2 years)	€60.000
Mechanical Technician	€20.000
Equipment:	
Pump Laser (100 W cw Nd:YAG) (already available in Applicant's laboratory)	€0
High-Energy Power / Energy Meter	€4.000
High-Energy Optical Isolator (2 units)	€5.000
Precision Temperature Controller and Oven	€5.000
Consumables:	
PPLN Crystal (> 1 mm thick)	€6.000
Specialist OPO Mirrors	€8.000
Etalon, Diffraction Grating	€4.000
Coating Costs for PPLN Crystal	€3.000
Propagation and Focusing Optics (Beam-steering mirrors and lenses)	€3.000
Coating Costs for Propagation and Focusing Optics	€3.000
Precision Micromechanical Mounts	€8.000
Total:	**€129.000**
Overhead Charges (at 14.7%)	€30.723

Grand Total:	**€147.963**