

GAMMA-RAY SOURCE FOR NUCLEAR RESONANCE FLUORESCENCE BASED ON COMPTON STORAGE RING*

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Abstract

This paper describes an intense gamma-ray source based on the Compton scattering of laser photons by the electrons circulating in the storage ring. Gamma-ray energies fall in the range from 1 MeV to 5 MeV. This source is an ideal tool for nuclear waste management by the nuclear resonance fluorescence method. The Compton ring is also a very promising tool for application in novel technologies for express cargo inspection to prevent nuclear terrorism. A crab-crossing scheme in the ring lattice can be expected to permit a gamma-beam intensity of up to 5×10^{13} gammas/s with the latest laser and accelerator technologies.

INTRODUCTION

Nuclear waste is a by-product from sources such as the nuclear fuel cycle and disposed medical isotopes. When the international nuclear industry endeavored to establish a plan for long-term energy production, one of the most pressing challenges it faced was to find adequate methods for nuclear waste disposal. The cost of disposing of nuclear waste depends strongly on the activity, isotopic composition, etc. of the spent fuel to be discarded. Specifically, it can vary from a few thousand USD to several tens of thousands of USD per drum per year [1].

One of the most promising methods for measuring the abundance of difficult-to-identify isotopes is nuclear resonance fluorescence (NRF). In the NRF method, monochromatic gamma-rays excite the transition between nuclear states, and detectors register the re-emitted gamma-rays. The spectrum of nuclear transition is unique for each isotope, comprising what is known as the “isotopic fingerprint.”

This method requires a tunable source of gamma-rays ranging from 1 MeV to 5 MeV with a gamma-ray beam of high spectral intensity (flux of about 10^{10} gammas per second per 0.1 % of spectral width).

The newest accelerator and laser technologies will enable the development of such a source based on Compton scattering [2, 3]. In Compton storage rings, the intense and dense bunches of relativistic electrons scatter off the intense laser pulses.

This paper proposes a Compton source for the NRF analysis of nuclear waste based on the electron storage ring [4, 5]. Intense bunches circulating for hours inside

the storage ring have the capacity to produce gamma-ray beams of high intensity. The bunch intensity and density, meanwhile, are only slightly dependent on the parameters adopted for the injection of electrons into the storage rings. The storage-ring-based source can detect practically all of the isotopes present in nuclear waste, and thus is suitable for express nuclear waste management. The device is also compact, and thus can be installed at seaports and aviation terminals for the scanning of cargoes (prevention of nuclear terrorism).

COMPTON STORAGE RING

To obtain an intense gamma-beam, we need to collide an intense electron bunch with an intense laser pulse. As it is well known, the yield of the scattering process is determined by numbers of colliding particles, frequency of the collisions and the geometry of the interaction (there is strong dependence of the yield on the lengths of the colliding beams under non-head-on collision). In storage rings, the length of the electron bunch is proportional to the square root of the momentum compaction factor. This presents a challenge, however, as the instabilities of the electron bunches prevent us from designing a Compton ring lattice with very low compaction. At a reasonable momentum compaction factor from the point of the electron beam instabilities, the electron bunch length are considerably larger than the length of the laser flash. This drastically decreases the intensity of the gamma-ray beam.

There are several optional approaches available for enhancing the performance of the source. It may be possible to increase the yield by proportionally increasing the electron bunch charge. The success of this, however, may be limited by the bunch instabilities. The energy in the laser pulse is limited by the available lasers and the attainable enhancement of the laser power in the optical resonator. An increase in the frequency of collisions, i.e., an increase of the average current circulating in the ring, will commensurately shorten the length of the optical resonator and increase the power load on the mirrors as a result.

A much more fruitful approach would be the reduction of the sizes of both the electron bunches and laser pulse at the collision point (CP), and reduction of the collision angle. A reduction of the electron bunch dimensions at CP will increase the yield, but this enhancement will be negligible when the laser pulse waist is larger than the bunch height at CP. To attain intense sources, the crossing angle must be large enough to permit the gamma-ray beam to bypass the mirrors of the optical resonator.

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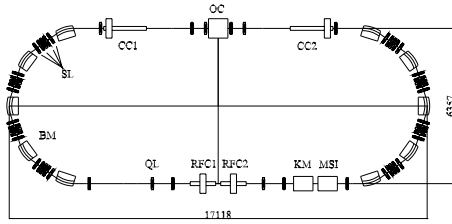


Figure 1: Ring layout. BM, bending magnets; QL, quadrupoles; SL, sextupoles; RFC, rf-cavities; CC, crab-cavities; OC, optical cavity; MSI and KM, injection magnets.

The advantageous method of the yield enhancement for Compton gamma-ray sources is so called “crab-crossing” scheme [6, 7, 8]. To maximize the yield in this scheme, the electron bunches should be rotated in the crossing plane using crab-cavities at an angle equal to half of the crossing angle. Evaluations show that the yield in Compton storage rings may increase several times due to crabbing.

Ring Lattice

The following were the main considerations and requirements for the design of the ring lattice:

- The electron beam energy falls within the range of 240 MeV to 530 MeV (gamma-ray energy from 1 MeV to 5 MeV at a laser photon energy 1.164 eV);
- The technologically realizable collision angle must be no less than 10 degrees;
- An intense electron beam and an intense laser pulse are both necessary to obtain the required gamma-ray beam intensity of greater than 10^{13} gammas/s.
- A lattice with a relatively large momentum compaction factor is required, as the electron bunches must be long enough to avoid electron bunch instabilities;
- A crab-crossing scheme must be available to enhance the yield;
- The storage ring must be reasonably compact.

A ring that met these requirements was designed. The lattice of the Compton ring and amplitude functions of the ring are presented in Fig. 1, Fig. 2.

The ring is a race-track type with a circumference $C = 41.508$ m (harmonics number $h = 90$ at rf frequency $f_{rf} = 650$ MHz). The arcs of the ring are similar to a quasi-FODO lattice, where bendings are D-elements of the lattice. A lattice of this type allows the device to reach a horizontal beam emittance of $\epsilon_x \approx 1.4 \times 10^{-8}$ m at maximal electron energy (intrabeam scattering is disregarded). The

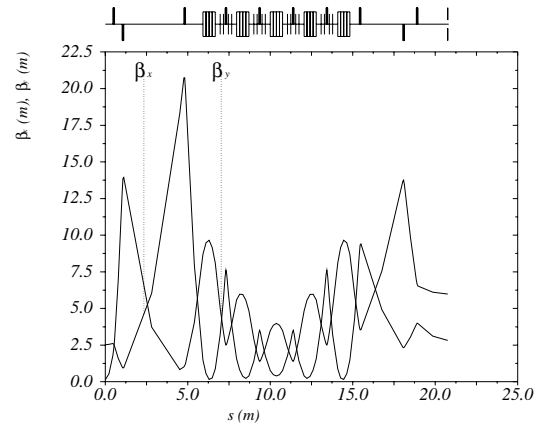


Figure 2: Horizontal and vertical amplitude functions over half of the ring from the collision point to the opposite azimuth

Table 1: Main Ring Parameters

Parameter	Unit	Value
Energy of electrons	MeV	240–530
Ring circumference	m	41.508
Hor betatron number Q_x		5.16
Vert betatron number Q_y		2.22
Momentum compaction factor		0.015
rf frequency	MHz	650
Harmonics number		90
Number of bunches in orbit		15
Bunch-to-bunch spacing	ns	9.23
rf voltage	MV	1
Hor amplitude function at CP	m	2.53
Vert amplitude function at CP	m	0.13
Crossing angle	deg	10
Energy of laser photons	eV	1.16
Laser waist at CP (rms)	μm	20

momentum compaction factor is quite large ($\alpha_1 = 0.015$), hence the size of the longitudinal beam is large as well (the initial beam length is approximately 3.5 mm at the maximal electron energy, with intrabeam scattering taken into account). The accelerating voltage, $V_{rf} = 1$ MV, is supplied by two single normal-conducting cavities and guarantees a sufficient quantum lifetime at intense Compton scattering.

The crab-cavities voltage, V_{cc} , was set to equal 0.5 MV (normal conducting cavities), the phase advance of the horizontal betatron oscillations between the cavities is equal to π . At the maximal electron beam energy $E_e = 530$ MeV, the chosen values of the amplitude functions in collision plane and crab-cavity voltage provide the optimal crabbing angle.

The main ring parameters are listed in Table 1.

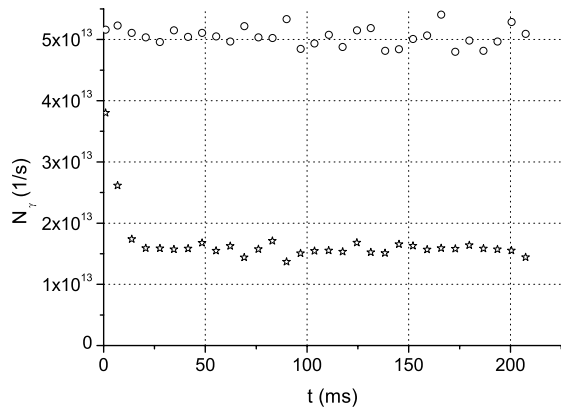


Figure 3: Gamma beam intensity at crab crossing (circles) and normal crossing (stars).

Simulation of the Ring Performance

A simulation of the electron beam dynamics in the ring during interaction with the laser pulses validated the feasibility of the ring for NRF applications.

We have carried out a simulation of Compton scattering in a designed lattice in two operation modes, a normal mode and a mode with crab-crossing. The simulation accounts for the crab-cavity effect as a longitudinally dependent kick.

The simulation results are presented in Fig. 3.

As seen in the figure, the lengthening of the electron bunch leads to a rapid decrease in the gamma-ray beam intensity at normal crossing, while the intensity of the Compton scattering at crab-crossing stays more or less constant under collision. The steady-state gamma-beam intensity at crab-crossing is about three times larger than at the normal crossing.

Fig. 4 shows the phase space of the electron bunch under crab-crossing at the azimuth of the collision point.

As one can see, the “average” crabbing angle is equal to half of the crossing angle, as required.

RESULTS AND CONCLUSION

In this paper we have presented the meritorious points of electron storage rings as sources of gamma-rays. We have also described a detailed scheme for such a ring and reported the results of a simulation of the electron beam dynamics of the source.

The proposed lattice of the Compton ring meets the requirements of a dedicated gamma-ray source for the nuclear resonance fluorescence method. A crab-crossing scheme for the colliding electrons and laser beams suppresses the loss of gamma-beam intensity caused by the lengthening of the electron bunch and allows the gamma-ray source to attain high brightness. At a total gamma-beam intensity of about 5×10^{13} gammas/s, the spectral

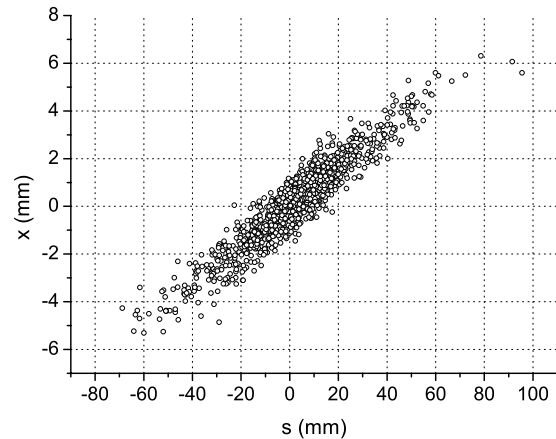


Figure 4: Phase space at azimuth of interaction point.

flux exceeds 10^{10} gammas/keV. A source of this type would be an appropriate device for nuclear waste analysis, cargo inspection, and similar procedures.

From the presented results, we conclude that a Compton source for NRF applications, a system based on the electron storage ring, can be constructed using present-day techniques.

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