Potential uses of ERL-based γ-ray sources*

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Abstract

We get idea of using γ-rays for nuclear photofission of ^{238}U at use Giant Dipole Resonance into rare neutron-reach nuclei from the SPIRAL II project, which proposed useof 10-20 MeV Bremsstrahlung γ-rays generated by 45 MeV electron beam /http://ganinfo.in2p3.fr/research/developments/ spiral2/index.html/. Here we explore possibility of using a Compton γ-ray source for such a process.

Collider accelerator department at BNL proceeds with development of high current (up to 1 ampere), high brightness (down to 1 mm mrad normalized emittance) and high-energy (20 GeV electron beam energy is proposed for eRHIC) Energy Recovery Linacs (ERL). These electron beams are perfectly suited for generating photon beams with tremendous average power, approaching a megawatt level. The photon energy range extends from sub-eVs from Free-Electron Lasers (FEL) to 10 GeV from Compton process. In this paper we focus on is a γ-ray source for production of rare isotopes.

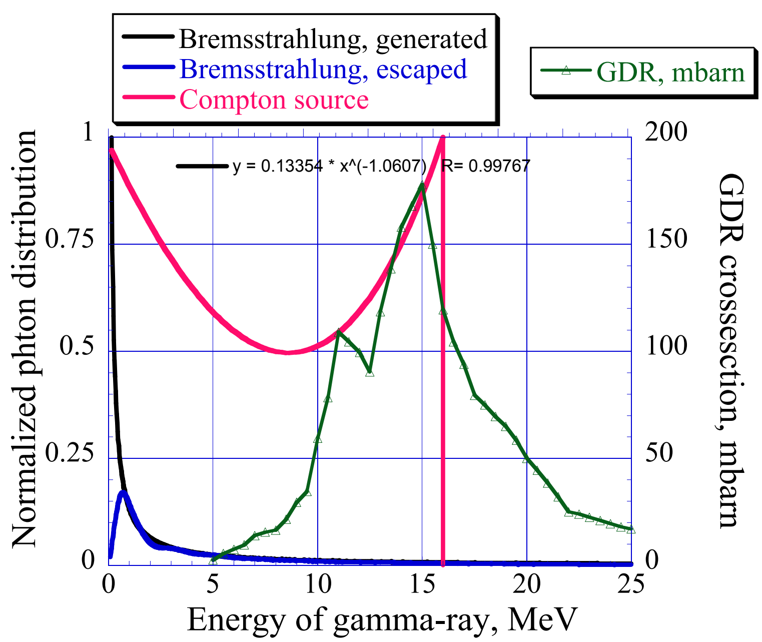

Figure 1. Plots of the normalized photons (γ-ray) distribution as function of their energy for: a) Bremsstrahlung γ-ray sources driven by 45 MeV electron linac (adopted from [13], where calculations were done for 4 mm thick ^{238}U target), both generated γ-rays (black curve) and those escaped from the target (blue) b) Compton γ-ray source [14] source with maximum energy of photon 16 MeV. The graph has also shows photon cross-section of GDR in U^{238} (adopted from [13]).

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1. Introduction.

Recent progress in developing high-energy high-current ERLs [1-4] and high average power lasers – both conventional and FELs [5-8] - opens a unique opportunity of new class of high power Compton γ-ray sources. Intense Compton γ-ray sources [9,10] are sources of choice when one needs a well-collimated high-quality γ-ray beams [11]. Compared with a traditional Bremsstrahlung γ-ray source [12], a Compton γ-ray sources have the hard edge, where most of its power is concentrated. It makes them significantly more energy efficient, which is important for high average power sources. In contrast, most of the γ-rays generated in Bremsstrahlung process have very low energy, and only very small portion of them is generated at high energies. Fig. 1 illustrates this fact by showing overlap of γ-ray spectra of Compton and Bremsstrahlung γ-ray sources with cross-section of giant dipole resonance (GDR) in ^{238}U. Even though high power γ-ray sources can be used for multiple scientific and industrial applications (such as a potential polarized positron source for International linear collider [15], study of parity violation in weak-strong coupling effects, nucleosynthesis in supernova explosion [16] or transmutation of used nuclear fuel [17]), following [13] we focus this paper on using photofission for generation of rare isotopes far away from the island of stability. These rare isotopes can be used for a large range of fundamental and application researches, discussion of which goes far beyond the scope of this paper. Scientific case for RIA (radioactive isotope accelerator) and similar information can be found elsewhere [18]. Here we focus on the choice of accelerator and laser parameters for the 100 kW CW γ-ray source suitable for such task.

Let's briefly discuss, why storage ring [9,10] can not be used for such a source? The answer is rather straight forward: 100 kW CW beam of γ-ray with energies ~ 20 MeV comprises of about 10^{17} γ-rays per second. With typical number of electrons in an amp-class storage ring being N_e~ 10^{11}, each electron has to radiate about a million γ-rays and also loose ~10,000 GeV per second, which blows-up its energy spread to $\sigma_E = \sqrt{N \cdot \langle \Delta E^2 \rangle} \geq 1\ GeV$ (here we used typical damping time in GeV-range storage ring is ~ 10 msec, with $\langle \Delta E^2 \rangle^{1/2}$~10 MeV). There is no question that such beam with energy spread ~ 100% will die quickly. Hence, there is need for another high current electron accelerators, i.e. an ERL.

2. Compton γ-ray source.

Energy of Compton γ-rays generated in head-on collision with ultra-relativistic electrons ($E_e = \gamma mc^2, \gamma >> 1$) depends on the energy if the laser photons $E_{ph} = \hbar\omega$ and angle of back-scattering θ (measured from the direction of the electron beam):

$$E_\gamma = \hbar\omega \cdot \frac{1+\beta}{1+r-(\beta-r)\cdot\cos\theta};\ r = \frac{\hbar\omega}{\mathbf{E}}; \beta = 1/\sqrt{1-\gamma^{-2}}$$
$$E_\gamma \cong \frac{4\gamma^2\hbar\omega}{1+(\gamma\theta)^2+R};\ R = \frac{4\gamma\hbar\omega}{mc^2};\ E_{\gamma\max} = \frac{4\gamma^2\hbar\omega}{1+R}. \quad (1)$$

where R is the recoil and $E_{\gamma\max}$ or simply $E_{\max}$ is the maximum energy of Compton γ-rays. Hence this energy determines choice of the laser and accelerator parameters we will use it as the main measure for the source.

Energy dependence of the cross-section of ^{238}U Giant Dipole Resonance, which is of interest for this paper, can be approximately described by broad (semi-Gaussian) peak centers at about 14.5 MeV and with RMS width of about 3.5 MeV. Using analytical expression for spectrum of the Compton γ-ray sources $\rho_\gamma(E)$, $\int_0^{E_{\max}} \rho_\gamma(E)\cdot dE = 1$ [14], we calculated efficiencies of photofission of U^{238} using such a source:

$$Eff_\gamma = \int_0^{E_{\max}} \rho_\gamma(E)\cdot\sigma_{GDR}(E)dE;$$
$$Eff_{energy} = \int_0^{E_{\max}} \rho_\gamma(E)\cdot\sigma_{GDR}(E)\frac{dE}{E_{\max}}; \tag{2}$$

as a function of the $E_{\max}$. Fig. 2 shown the results calculated using Mathematica [19]. Both measures of effectiveness (2) peak at about $E_{\gamma\max}$=16 MeV, which will use as optimum energy for such Compton source.

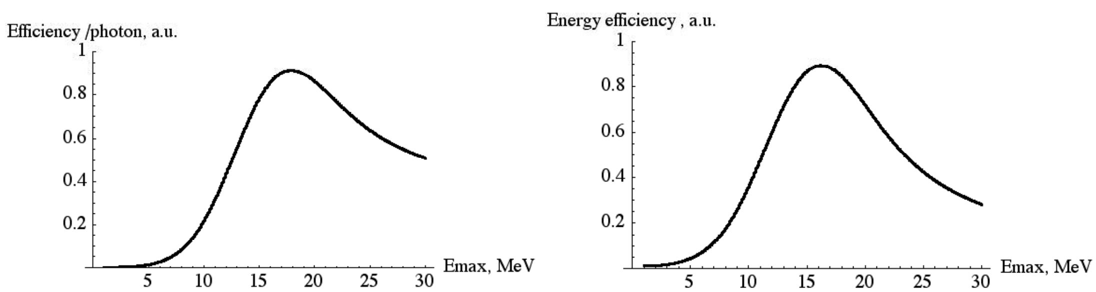

Fig. 2 Efficiencies (left -per photon and right – energy efficiency) of photofission as function of maximum photon energy from the Compton source. Both per photon and energy efficiencies peak about 16-17 MeV.

Using equation (1) we can calculate what should be laser wavelength as a function of electron's energy $E_e = \gamma mc^2$

$$\lambda = \frac{4\gamma^2 c}{hE_{\gamma\max}}\left(1 - \frac{4E_{\gamma\max}}{E_e}\right). \tag{3}$$

which is shown in Fig. 3. As follows from eq. (1), collimating of the γ-ray beam allows to cut low energy tail at any desirable energy $E_{\gamma c}$ by installing a collimator with opening angle of:

$$\theta_c = \frac{r_c}{L_c} = \frac{1}{\gamma}\sqrt{\frac{4\gamma^2\hbar\omega}{E_{\gamma c}} - 1 - \frac{4\gamma\hbar\omega}{mc^2}}. \tag{4}$$

Angular spread of electron beam (see Fig.4) can contribute into the energy spread of collimated γ-ray beam, but modern electron accelerators allows to achieve essentially mono-energetic γ-ray beams in this energy range (i.e. tens of MeV) with FWHM energy spread below 1% [9,10]. Hence, for the GDR excitation this effect is essentially negligible.

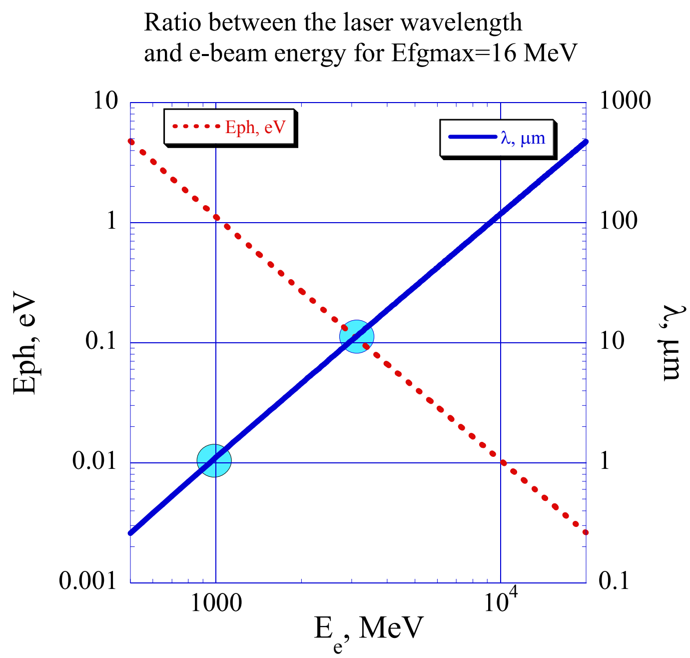

Fig. 3 Plot of the laser wavelength as function of the electron beam energy required to generate beam with $E_{\gamma\,\max}$=16 MeV. Two points on the graph are of special interest: the use of the wavelength ~10 μm (CO_2 laser) requires e-beam with energy about 3 GeV, the use of the wavelength ~1μm (YAG laser or an FEL) requires e-beam with energy about 1 GeV. In both case the recoil is rather small: R~0.02 and R~0.065 correspondently.

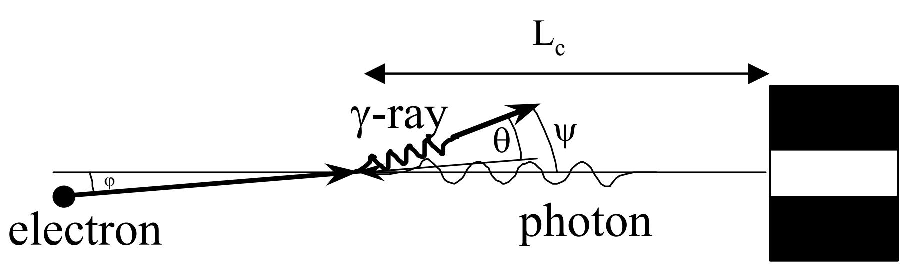

Fig. 4 Spectra of γ-ray beam can be truncated at the low energy side by simple collimation.

Because GDR cross-section diminishes below 5 MeV, the $E_{\gamma c}$=5 MeV is a natural choice. The opening angle of the collimator (i.e. the divergence of the γ-ray beam) will be 0.26 mrad for (3 GeV, 10 μm) case and 0.85 mrad for (1 GeV, 1μm) case. Such pencil-size γ-ray beams can be propagated for a long distance and used in a dedicated radioactive isotope facility. It is also important to notice that such collimated beam (with γ-ray energies from 5 MeV to 16 MeV) caries 90% of the generated beam energy (see Fig.5). Taking into account that in the case of small recoil (R<<1) the average energy of generated γ-rays is a half of the $E_{\max}$, 100 kW of the collimated beam will require generating of about 8.7 10^{16} γ-ray per second in the Compton source.

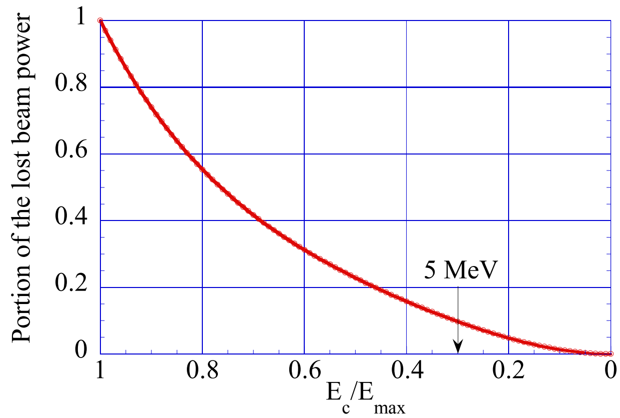

Fig. 5 Portion of the collimated γ-ray beam power as function of the ratio between the cut-off energy and the maximum energy of the γ-rays.

The rate of the γ-rays can be easily calculated [14] using standard collider formula:

$$\dot{N}_\gamma = \frac{f_{col} \cdot N_e \cdot N_{ph} \cdot \sigma_{tot}}{A}, \tag{5}$$

where $\sigma_{tot} \cong \frac{8\pi r_e^2}{3}(1-R)$ [20] is the total Compton scattering cross-section and $A = \lambda R_L/2 + 2\pi\beta\varepsilon$ is cross-section area of area of colliding ea of colliding beams (R_L is the Rayleigh range, ε and β are the emittance and β-function of electron beam). We assume that beams are round that that laser beam is a single Gaussian mode. As we can see in next chapter, beam size of electron beam from a 1-3 GeV ERL can be significantly smaller that the focal spot of the laser beam. Hence one can use $A = \lambda R_L/2$ and reduce (5) into a practical fomula:

$$\dot{N}_\gamma \approx 4.18 \cdot 10^{17} \frac{I[A] \cdot P[W]}{f_{col}[Hz] \cdot R_L[m]}. \tag{7}$$

One of the most remarkable features of the Compton sources that the target – the electron beam – moves with the speed of light and is, in-practice, indestructible. In contrast, a Bremsstrahlung target will definitely melt and evaporate if one will try to generate a hundred kilowatt watt in sub-mm γ-ray beam from it. Instead, electrons beam will acquire an energy spread within the range $\{E_e - E_{\gamma\max}, E_e\}$, which is about 1.6% for 1 GeV electrons and just above 0.5% for 3 GeV electrons. In the next paragraph we will discuss how the remaining energy of the electron will be recovered in the energy recovery linac. All the above advantage make electron beam the target-of-choice for very high power γ-ray sources.

3. Energy recovery linac.

Even though Tigner suggested idea of energy recovery linac in 1965, it took almost till the end of 20th century for this technology to be practical. After initial successes of ERLs [1, 21] many laboratories started developing variety ERLs projects [22]. Collider-Accelerator department at Brookhaven National Laboratory is focused on developing high-current high-energy ERLs [4,24] for application in its high-energy nuclear physics program. The key components of such ERLs are high current SRF gun [25] – see Fig. 6, and 5-cell SRF linac [26], shown in Fig. 7.

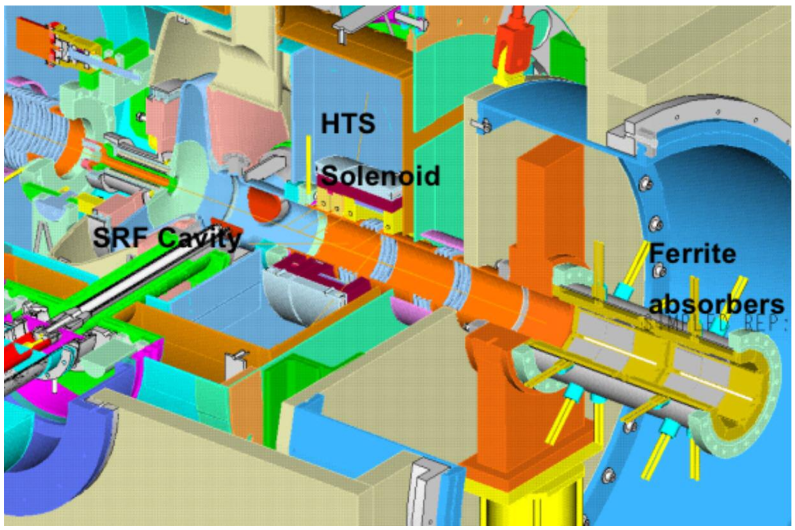

Fig. 6. A cut-off view of BNL's 2 MeV 703.75 MHz SRF gun with exchangeable cathodes. Beam moves from left to right.

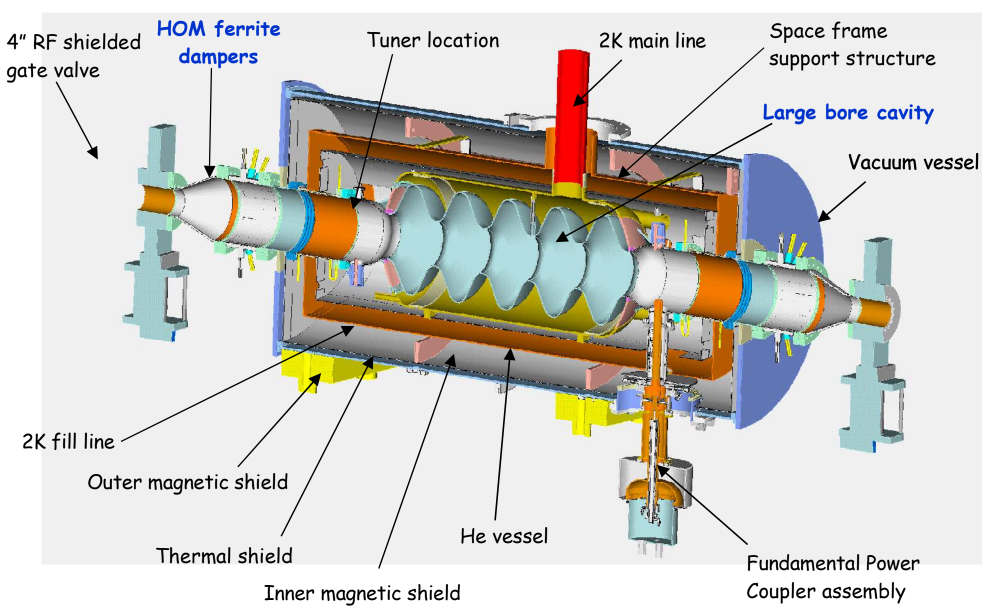

Fig. 7. A cut-off view of BNL's 20 MeV 703.75 MHz 5-cell SRF linac.

The key for ERL operating at ampere level of beam currents is the new type of single-mode SRF linacs with large bore cavities and vacuum pipes, which allow to dump heavily all higher order modes (HOMs). These HOMs are responsible for the main current limitations - the transverse multi-pass beam-break-up (BBU) instability, which can present an insurmountable problem for operations of a multi-pass ERL. The design of the 5-cell SC BNL cavity is optimized to reduce the quality factor of HOMs and to push BBU threshold beyond the ampere level. Multi-pass BBU in 2-pass ERL (shown in Fig. 9) was simulated using codes GBBU [29] and TDBBU [30] resulted in the BBU threshold between 2.5 and 5 Amps [27-28].

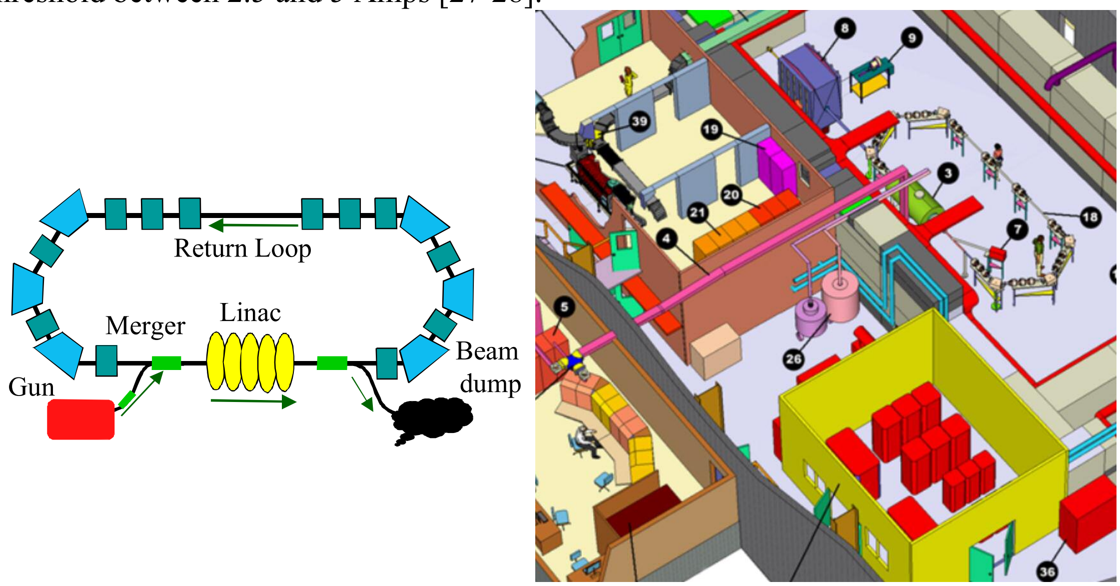

Fig. 8. Sketch of one-turn ERL and layout of R&D ERL in Bldg.912 at BNL.

Table 1: Electron beam parameters of the R&D ERL injector.

Charge per bunch, nC	0.7	1.4	5
Injection energy, MeV	2.5	2.5	3
Max. beam energy, MeV	20	20	20
Average beam current, A	0.5	0.5	0.05
Bunch rep-rate, MHz	700	350	9.38
Normalized emittance ex/ey, μm	1.4/1.4	2.2/2.3	4.8/5.3
RMS energy spread, %	0.35	0.5	0.97
RMS bunch length, psec	18.5	21	31

Note: normalized emittance is defined as $\varepsilon_n = \gamma\varepsilon/\sqrt{1-\gamma^{-2}}$.

Figure 8 shows sketch of one-turn ERL and the layout of 20 MeV R&D ERL facility, which is presently under construction with plan to be commissioned in 2009. ERL operates as follows: electrons are generated in 2 MeV SRF gun (8), are injected into the ERL via a merger, are accelerated in 5-cell SRF linac (3) to 20 MeV, pass through the loop (18) where they experience delay for an integer and a half of RF cycles, re-enter the SRF linac (3), where they are decelerated to 2 MeV, and then are directed into the beam-dump (7). Principles of multi-pass ERL operation are similar, with only exception that electron pass through linac multiple times. Table 1 shows expected beam parameters in the R&D ERL. More advanced and elaborate injectors (like one shown in Fig.9) are under consideration for electron cooling of hadron beams in Relativistic Heavy Ion Collider (RHIC) and it future electron-hadron option eRHIC [24]. They will provide even better electron beams. Layout of two-pass version of the BNL ERL with 4.7 MeV 1 and1/2 cell SRF gun is shown in Fig. 9.

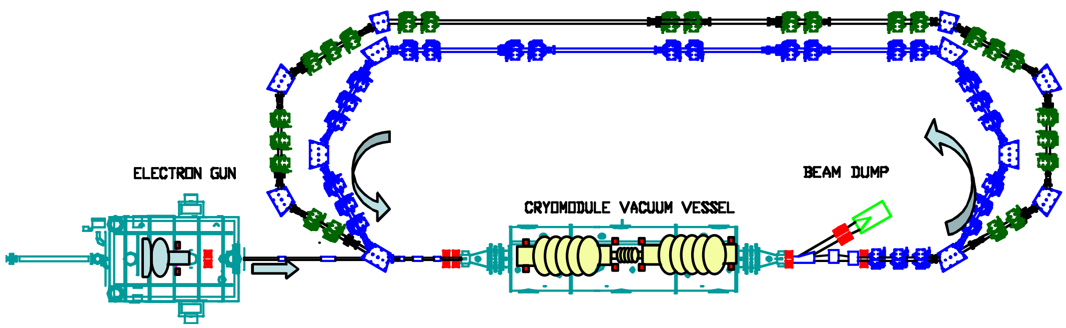

Fig. 9. Layout of 2-pass 54.5 MeV ERL for RHIC electron cooling.

Let's return to issue of the e-beam size in the Compton source interaction region (IR). For $R_L \sim \beta$ and a case of 1GeV (γ~2000) ERL and λ ~ 1μm, one can easily see from Table 1, that even with 5 nC charge per bunch, emittance contribution into the area of the beam overlap $A = \lambda R_L/2 + 4\pi\varepsilon$ is less than 3%. In the other case of interest - 3GeV (γ~6000) ERL and λ ~ 10 μm – it is at 0.1% level. Hence, beam quality provided by ERL is excellent for these Compton sources and allows use of relaxed e-beam optics with β as high as $10 R_L$ or $100 R_L$, correspondently, without any noticeable reduction in performance.

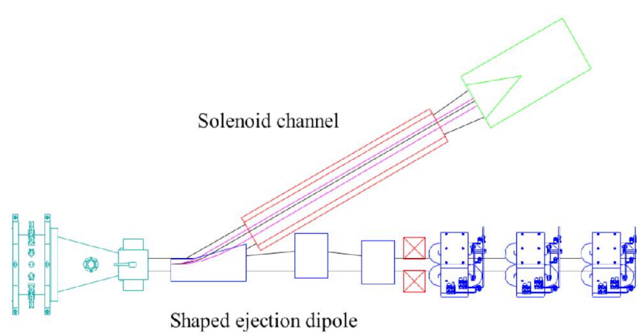

Fig. 10. Layout of the beam dump (green) with 80% energy acceptance, located at the exit of the SRF linac [31].

One of the main advantages of the ERLs is a possibility to accelerate the beams to very high energy, use them, decelerate and to dump them at energies well below 10 MeV to avoid activation of the beam-dump and the environment. This feature is absolutely critical when beams with megawatt level of power are dumped. Thus our goal is to dump electrons with energies at or below 5 MeV.

The largest ERL under consideration for eRHIC [3] will have 500 MeV 2-pass ERL pre-accelerator and the 4-pass ERL with maximum energy as high as 20 GeV. We suggest similar schematic, shown in Fig. 11, to be used for an ERL generating intense γ-ray beams. Electron gun will generate 5 MeV ($\gamma_i \sim 11$) electrons, which will be accelerated in 2-pass ERL pre-accelerator to energy of about 100 MeV, and will be further accelerated to 3 GeV (1 GeV if FEL is used), collided with the laser beam in the IP to generate γ-ray beam, and then will be decelerated down to 5 MeV and dumped.

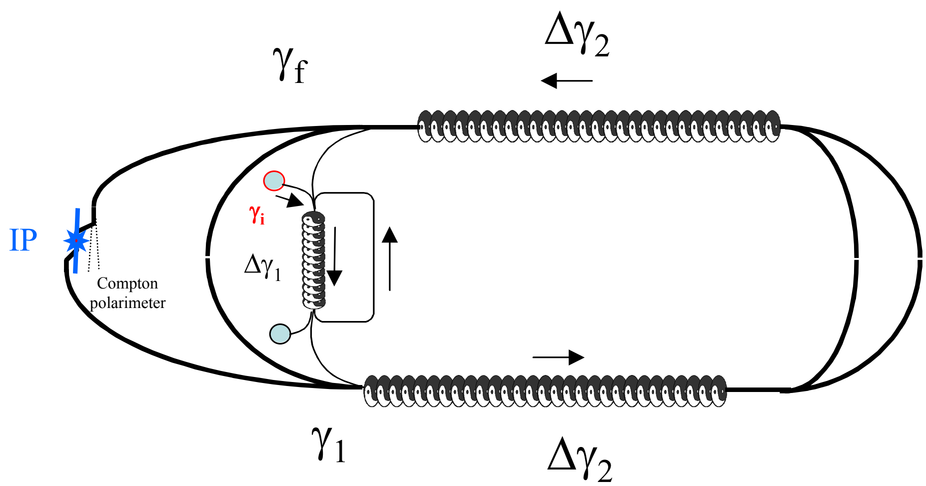

Fig. 11 Schematic layout of a two-stage ERL for generating intense γ-ray beams.

In the generation process, the average loss of 8 MeV for each electron, which generated a γ-ray, should be compensated by RF power in main linacs. Furthermore, total energy spread of electrons after generating γ-rays of 16 MeV exceeds the energy at the dump of 5 MeV. Hence, electron bunch length should be stretched on the way down to the damp by about a factor of ten. It will reduce its energy spread below 2 MeV before the beam retuns in the pre-accelerator. Beam with total energy spread of 2 MeV can be successfully decelerated in 2-pass 100 MeV ERL and damped with peak energy of electron below 5 MeV [31]. Low RF frequency of SRF linacs and large energy acceptance beam dump (Fig. 10) of the BNL's ERL provide large longitudinal acceptance ~ 1 MeV·nsec. This makes it possible to consider BNL type ERL as an efficient driver for megawatt class γ-ray facility, or as we discuss in next section, also for a high power FELs used in such a source.

4. Lasers

Both conventional and free-electron laser can be used for a megawatt class γ-ray facility. From many possible options we present here two. First option is based on CO_2 laser system, which is under development at Accelerator Test Facility (ATF), BNL [5]. Operation of CO_2 laser with 10 J, 5 psec pulses has been demonstrated at the ATF. Fig.12 shows possible IP using ten beams from ten CO_2 amplifiers, injected into ring cavity using Ge window controlled by YAG laser. A 100-pulse train with nearly constant amplitude has been alreadt experimentally demonstrated at ATF [5].

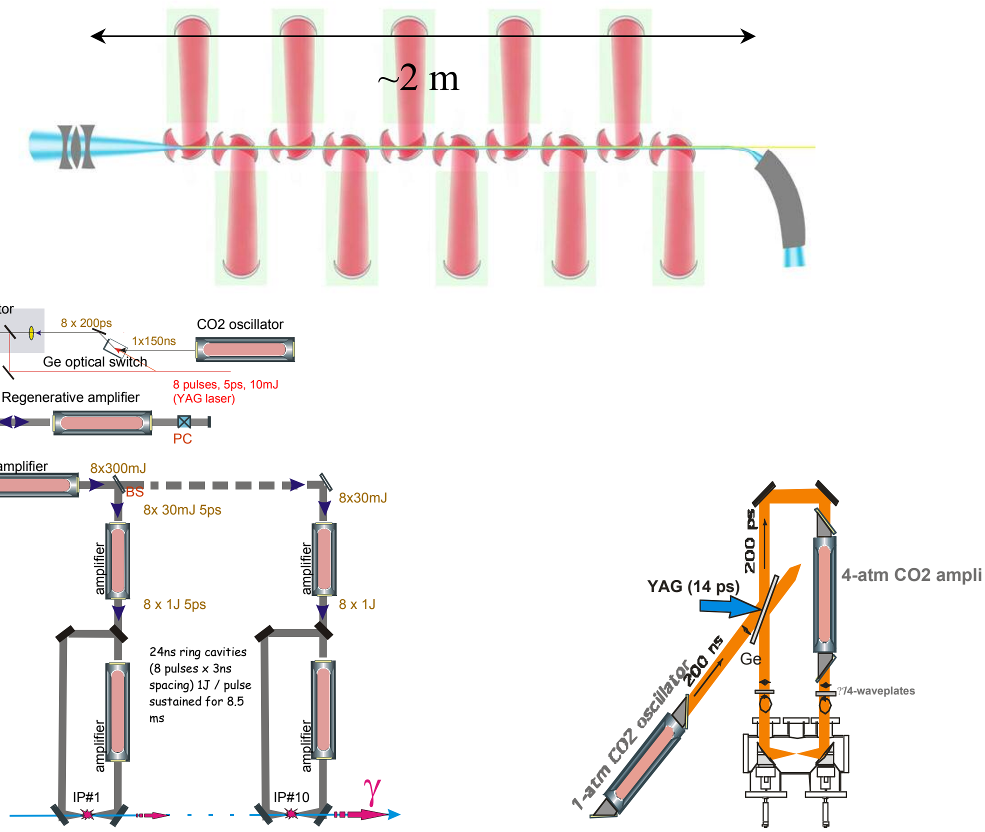

Fig. 12. Schematic layout of the γ-ray source IP with tens CO_2 beams within ring cavities (top), detailed schematic of the system (bottom left) and injection scheme into the cavity (bottom right).

Table 2. Expected CO_2 laser beam parameters at IP.

Wavelength, μm	10.6	Rep-rate, Hz	500
Number of beams	10	Collision frequency, MHz	10 x 0.25
Energy per pulse, J	2	Rayleigh range, cm	0.2
Number of reflection in the cavity	500	Pulse length, psec	5

Other attractive source of the laser will be an FEL, with its flexibility both in the wavelength and its time structure. There is significant progress in high average power

FELs and they had reached average out-coupled power well above 10 KW CW [32]. FELs also offer an attractive option of using intra-cavity power of the FEL [9-10] or use optics-free version of FEL [33,34,8]. The optics-free version of FEL, shown in Fig. 13, is capable of generating 30 KW of average power at wavelength of 30 μm. Similar system with two pass 100 MeV ERL (Fig.9) will be capable of generating 100 kW of average power at wavelength of 1 μm and average intra-cavity powers in megawatt range.

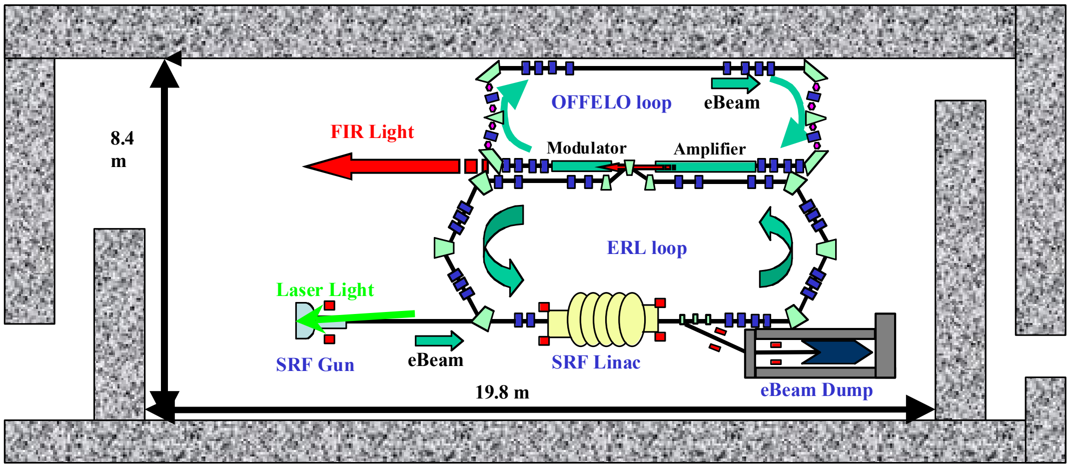

Figure 13. Optics free FEL layout based on BNL R&D ERL in existed shielded cave [8].

5. Source parameters and potential use for production of rare isotopes.

Using parameters of ERL and lasers we discussed, one can consider two following scenarios for a high power γ-ray source with parameters listed in Table 3 and Table 4. The main difference between these two sources in the rep-rate of the γ-ray pulses: it comes in burst of 500 pulses with rep-rate of 500 Hz for the CO_2 laser option and it is CW train with 70 MHz rep-rate for FEL option. Naturally, options within this range can be also considered.

Table 3: γ-ray source – the CO_2 laser option.

Laser wavelength, , μm	10.6	Collision frequency, MHz	10 x 0.25
Laser parameter	as in Table 2	Charge per bunch, nC	10
ERL energy, GeV	3	Average beam current, A	0.0025
γ-ray energy, MeV	16.04	Bunch rep-rate (in bursts), MHz	700
γ-ray flux, ph/sec	$1.04 \cdot 10^{17}$	Normalized emittance, μm	<10
Total power in γ-ray beam, kW	133	RMS bunch length at IR, psec	5
Power in 5-16 MeV beam, kW	**120**	β at IR, m	1

Table 4: γ-ray source – the FEL option.

FEL wavelength, μm	1	Intra-cavity power, MW	6
ERL energy, GeV	0.93	Average beam current, A	0.7
Bunch/Collision frequency, MHz	70	Charge per bunch, nC	10
γ-ray energy, MeV	16.14	Normalized emittance, μm	<10
γ-ray flux, ph/sec	$1.12 \cdot 10^{17}$	RMS bunch length at IR, psec	5
Total power in γ-ray beam, kW	144	β at IR, m	1
Power in 5-16 MeV beam, kW	**130**	Rayleigh range at IR, cm	0.2

Simple scaling of the SPIRAL 2 simulation [13] suggests that such γ-ray beam will generate from 10^{16}/sec to $0.5 \cdot 10^{17}$/sec photofission of ^{238}U per second, some of which will create exotic neutron-reach isotopes. In contrast with SPIRAL 2 proposal, where ^{238}U target has double use for generating γ-ray and for fission, fission target for the Compton source can be optimized to maximize the yield of the rare isotopes. Such optimization goes well beyond the scope of this paper.

Even though average posers of γ-ray beams in Tables 3 and 4 are rather high and such sources amy serve well as a part of a future rare-isotope facilities, there is definite potential to increase the γ-ray beam intensity even further towards a megawatt level.

Naturally, γ-ray source with high intensity will find many other applications, from studying rare processes in nuclear physics [17,35] to medical [36] or industrial applications [37].

Conclusions.

In this paper we presented a possible way of generating γ-ray beams with average power ~ 100 kW and using them for generating high flux of the rare neutron-reach isotopes. This method of generating neutron-reach isotopes can be competitive with more traditional methods of rare isotope production: Isotope Separator On-Line (ISOL) where high intensity proton beam (~ 1 GeV) on high Z target - and Fragmentation Facilities (FF) where high intensity (~ 300 MeV/n) heavy ion beam on "thin" target to generate fragments [18,13]. Similarly to these two methods, isotopes created by γ-ray beam can be stopped, extracted or accelerated.

In addition, source of γ-rays with such enormous power will find many other industrial, medical and scientific applications.

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