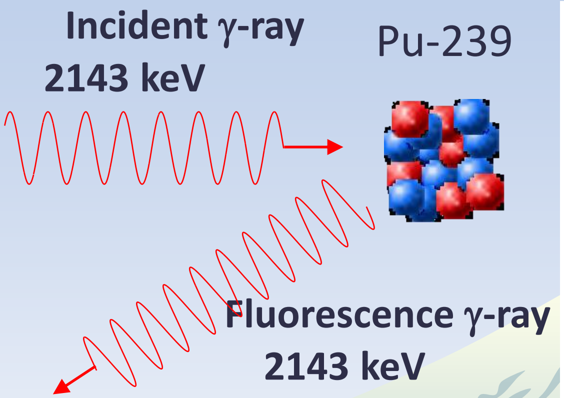
Compact several MeV Gamma-Ray source based on Compton scattering

Junji Urakawa (KEK, Japan) at PosiPol2012 for new proposal to MEXT
Peter Gladkikh (NSC KIPT)

Application of gamma-ray : gamma-ray can interact with nucleon

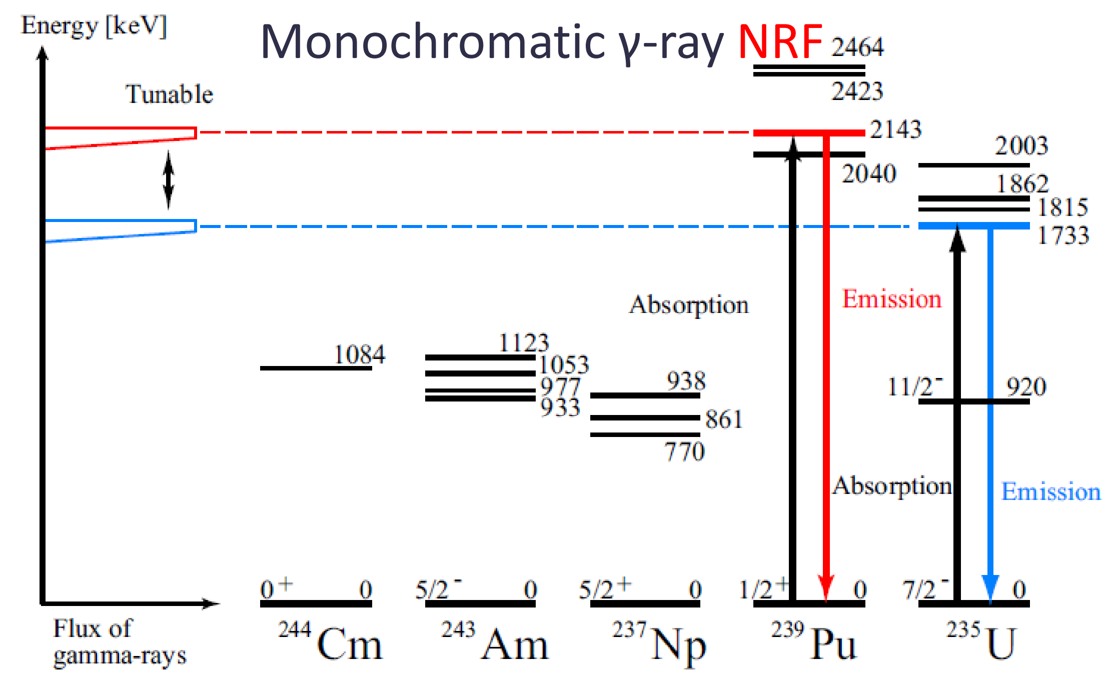
Nuclear **R**esonance **F**luorescence through specific reaction with particular isotope）

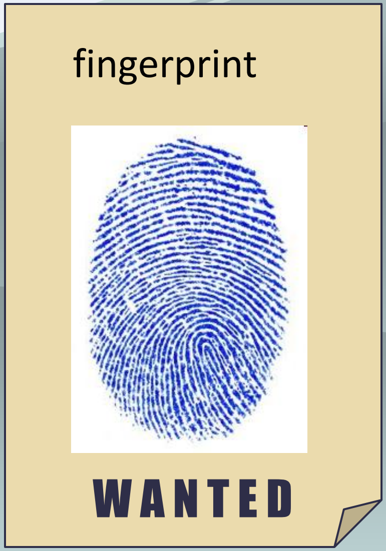


Incident γ-ray
2143 keV

Pu-239

Fluorescence γ-ray
2143 keV





Changeable and monochromatic γ-ray beam → **Selective nuclear reaction**

R. Hajima, T. Hayakawa, N. Kikuzawa, E. Minehara, J. Nucl. Sci. Tech. 45, 441 (2008).

From NIMA 621 (2010) 105-110, reported by Eugene Bulyak et al.,

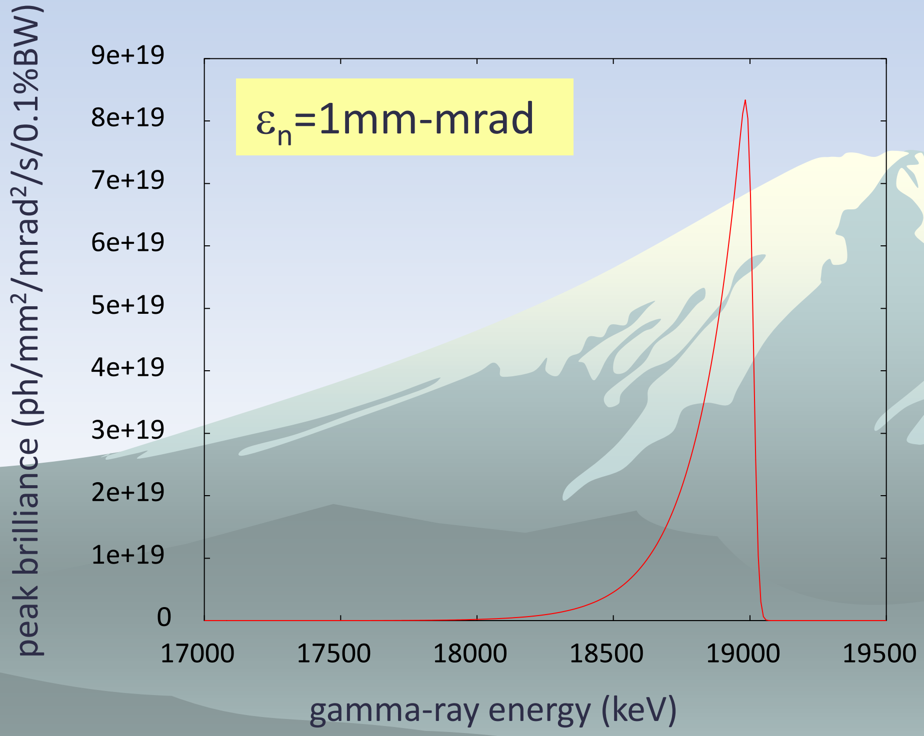
Nuclear waste is a by-product from sources such as the nuclear fuel cycle and disposed medical isotopes. The cost of disposing of nuclear waste depends strongly on the activity of isotopic composition of the spent fuel to be discarded. Specifically, it can vary from a few thousand USD to several tens of thousands of USD per drum per year [1].

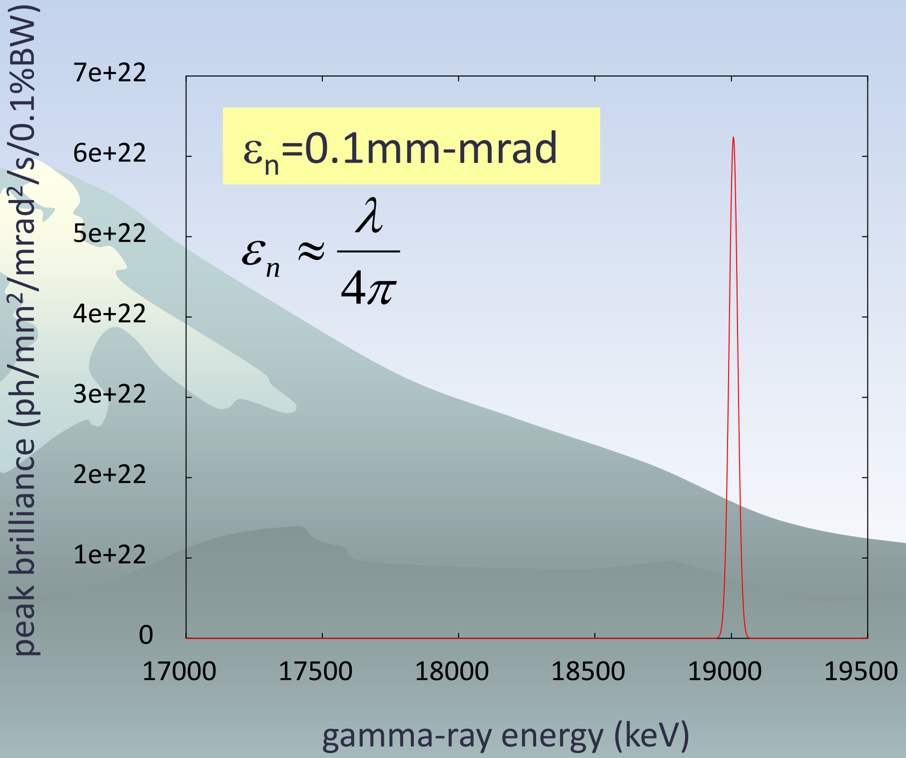
Nuclear waste management by the nuclear resonance fluorescence method is extremely important.

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 emitted gamma-rays. The spectrum of nuclear transition is unique for each isotope, comprising what is known as the “isotopic fingerprint.”

Decrease the emittance → improve the monochromaticity of γ-ray

Calculation of γ-ray brightness on the axis of 1-GeV （use analytic formula）





$$\varepsilon_n \approx \frac{\lambda}{4\pi}$$

$$\hat{B}_x = \frac{4\times 10^{-15}}{\pi^2}\frac{\gamma_0^2}{\varepsilon^2}\frac{N_e N_\lambda}{\Delta\tau}\frac{r_0^2}{w_0^2}\exp\left\{\frac{\chi-1}{2\chi\Delta u_\perp^2}\left[2+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\left[1-\Phi\left\{\frac{\chi-1}{\sqrt{\delta\omega^2+\delta\gamma^2\chi^2}}\left[1+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\right] \times \frac{\eta e^{1/\mu^2}[\Phi(1/\eta)-1]-\mu e^{1/\mu^2}[\Phi(1/\mu)-1]}{\mu^2-\eta^2}, \tag{50}$$

calculation by using a formula in [1].

[1] F.V. Hartemann et at. Phys. Rev. ST AB 8, 100702 (2005).

Requirements for ring lattice.

The main parameters of the gamma-beam generated in the Compton ring are intensity and spectrum. The gamma-beam intensity is determined by:

- **Electron bunches population and stored laser flash energy;**
- **Electron beam size at collision point and laser beam waist;**
- **Collision angle;**
- **Electron bunch lengthening because of the growth of the beam energy spread.**

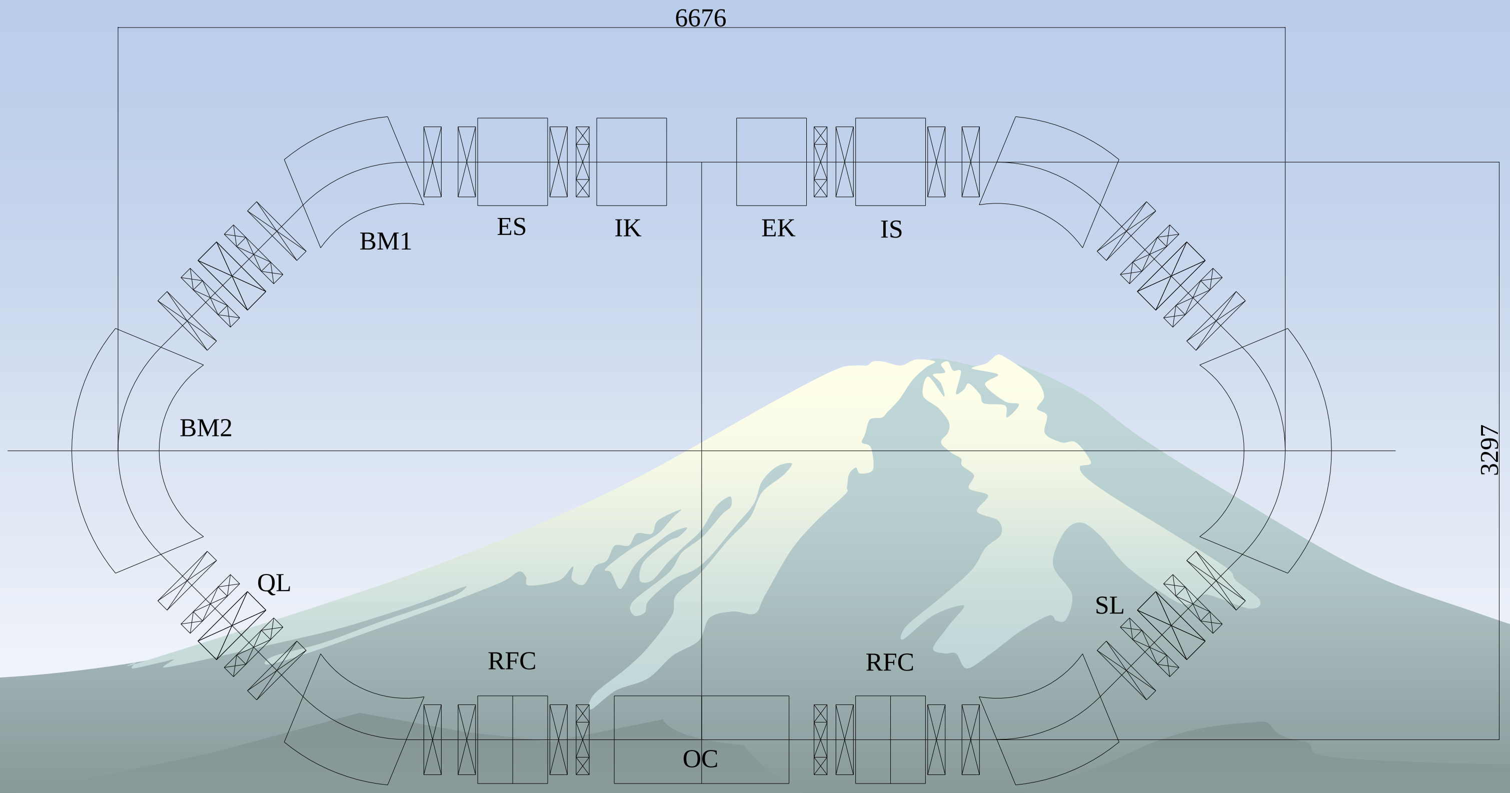
To obtain high gamma-yield we need the lattice with low beam emittance, low beta-functions at the collision points and low momentum compaction factor. Low momentum compaction allows us to avoid the gamma-yield decreasing because of the electron bunch lengthening under intensive Compton scattering. Width of the collimated spectrum from the Compton ring is determined by statistical sum of two components.

The first one is associated with the electron beam divergence. When the electron beam divergence becomes comparable with the natural divergence of the Compton radiation, collimated spectrum significantly widens. The second reason of the collimated spectrum widening can not be less than doubled beam energy spread.

Problems becomes challenging on lattice design of the compact rings, where obtaining both low beam emittance and low momentum compaction is problematic.

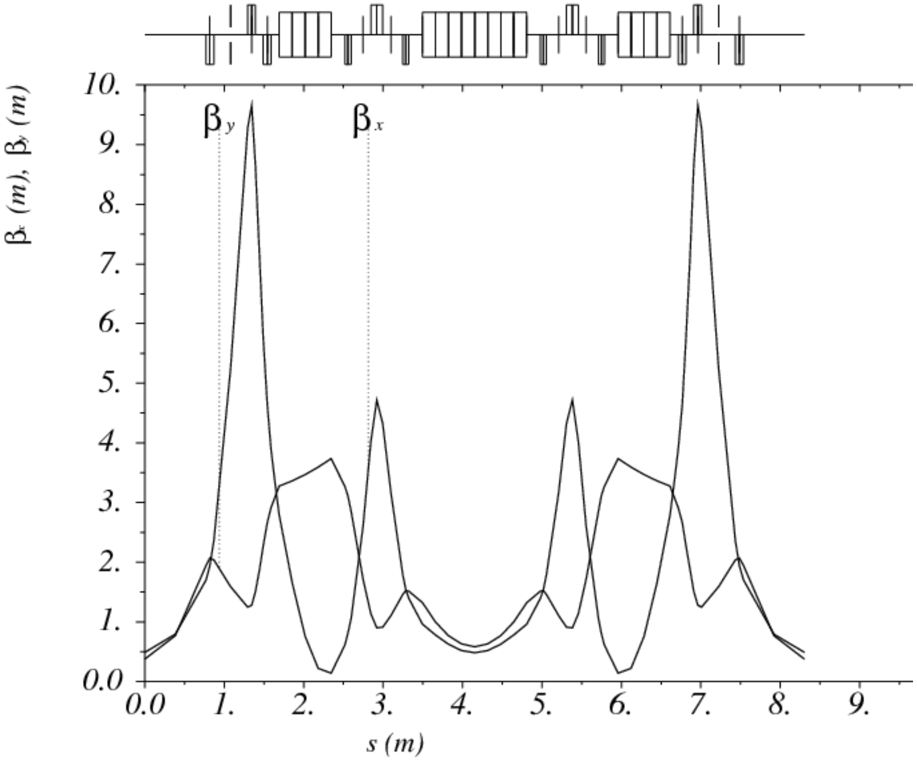
To resolve the problems we propose the gamma-source composed of high-repetition (300 Hz Linac), low emittance linac-injector with high bunch population and compact storage ring with quite low natural beam emittance. To avoid significant widening of the gamma-beam spectrum during gamma-generation we assume pulse operation mode, when generation time is much less than pulse repetition cycle of the linac.

Ring layout

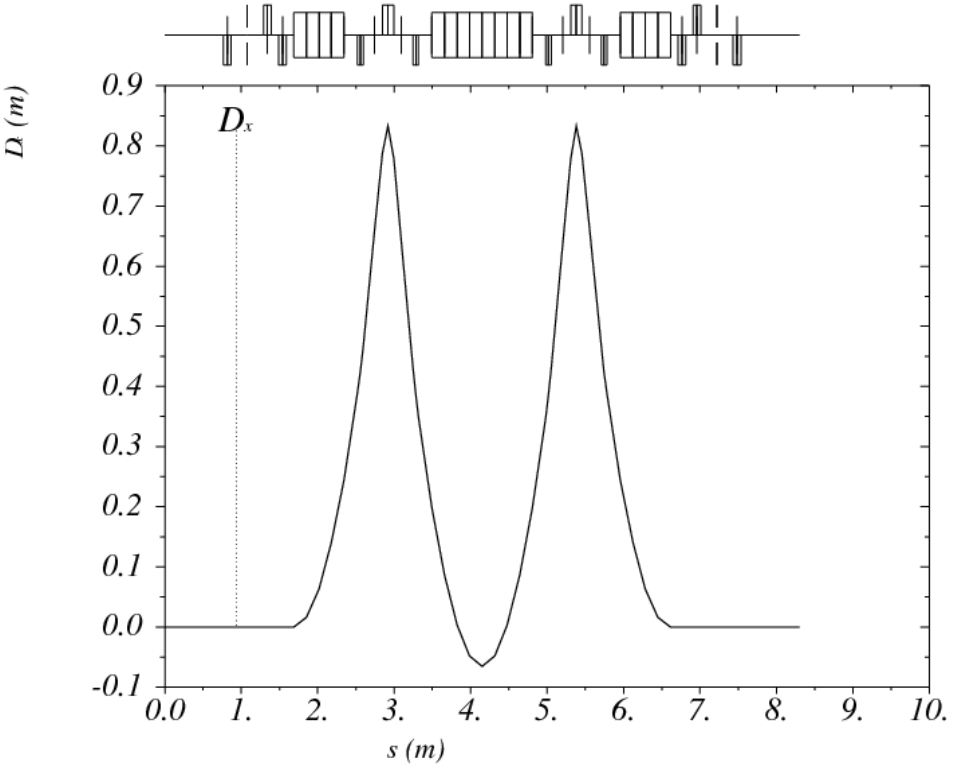


Ring layout. BM1, BM2 are bendings with bending angle 45 and 90 ,respectively; QL, SL quadrupoles and sextupoles; RFC rf-cavities; OC optical cavity; IS, IK injection septum and kicker; ES, EK extraction septum and kicker.

One can say, that presented lattice is some modification of three-bend-achromat lattice. Triplets of the quadrupole lenses in ring arcs provide both low beam emittance and momentum compaction factor. Beam focusing at the interaction point provides by the quadrupole triplets in long straight sections. Correction of the natural chromaticity in horizontal plane provides by sextupoles of arcs. In these sextupoles we also assumed bending-coils for the orbit correction. The vertical chromaticity is corrected by sextupole field generated by the pole shape of the bendings. Two rf-cavities provide accelerating voltage of 0.8 MV. The beam injection is assumed in the horizontal plane and electron beam after generation will be extracted down in the vertical plane.



Amplitude functions of single Super-period

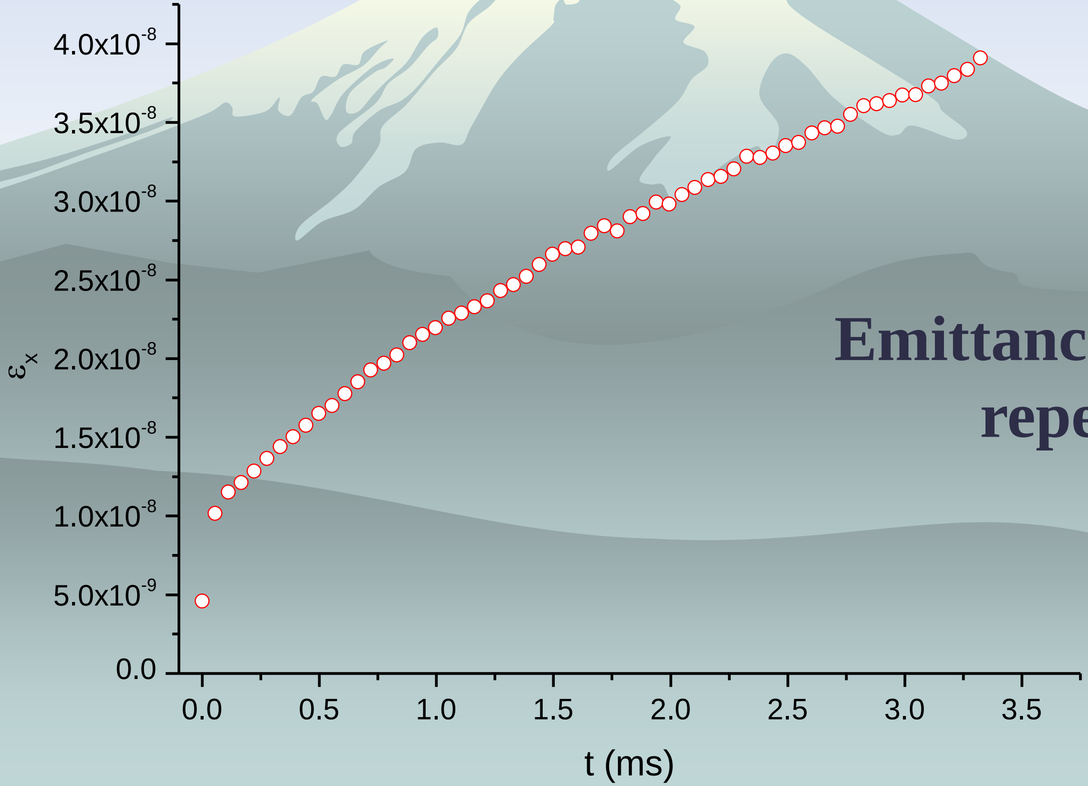


First order dispersion of single Super-period

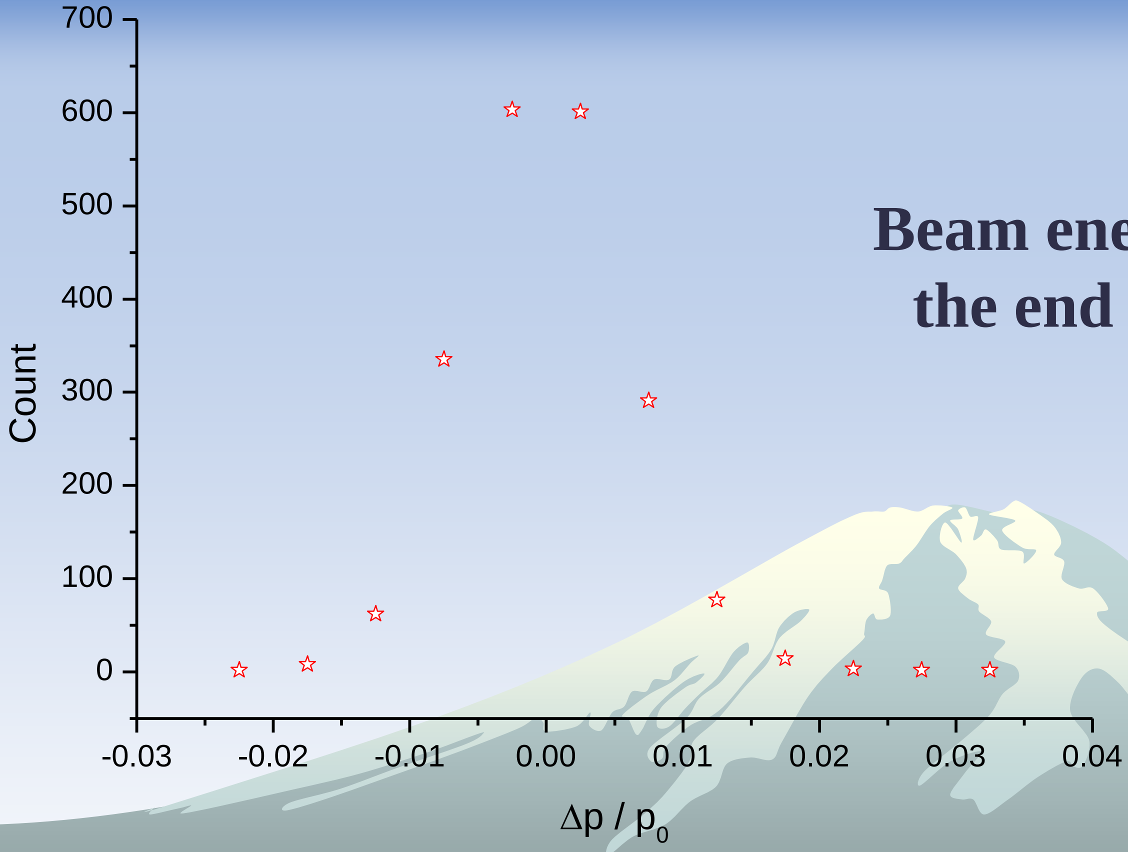
Parameter	Value
Electron beam energy range, MeV	90 – 450
Circumference, m	16.604
Bunch number	18
Bunch charge, nC	0.5
Bunch-to-bunch spacing, m	0.923
Bending field, T	1.8
RF – cavities number	2
Tunes, Q_x, Q_y	3.389; 2.185
RF voltage, MV	2*0.4
Momentum compaction factor	0.02
Natural emittance at maximal energy, nm*rad	70
Amplitude functions at collision point, m	0.49; 0.38
Laser photons energy, eV	2.328
Laser flash energy, mJ / flash	30
Laser waist, microns	20
Gamma – rays energy range, MeV	0.29 – 7.22
Gamma – yield, gamma’s / s	1.2 – $1.6*10^{13}$
Spectral density of collimated spectrum, gamma’s / keV / s	$5*10^9$ – $8*10^{10}$
Collimated spectrum FWHM, %	0.7 – 1.3

Simulations of the Compton scattering

We can roughly evaluate the degradation time of the electron beam as equal to the beam damping time. At chosen bending field the synchrotron damping time is approximately 7 ms at maximal beam energy and pulse repetition cycle 3.33 ms. Nevertheless, even during such short time collimated spectrum is being significantly widened because of both beam emittance and energy spread growth.

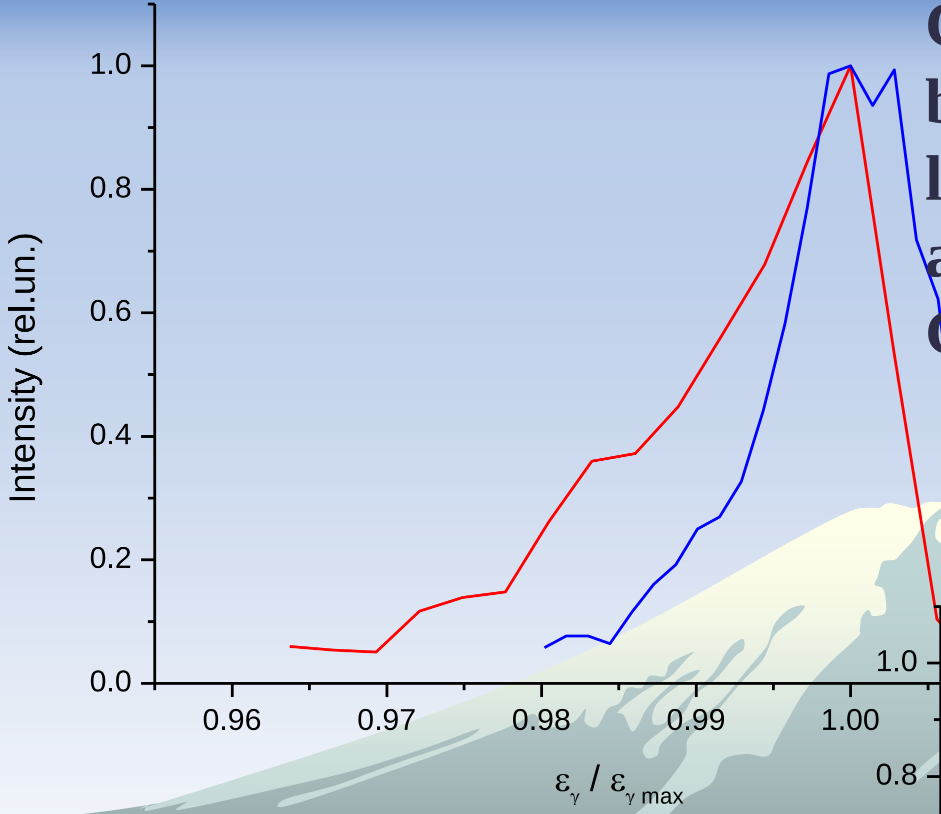


Emittance growth during repetition cycle



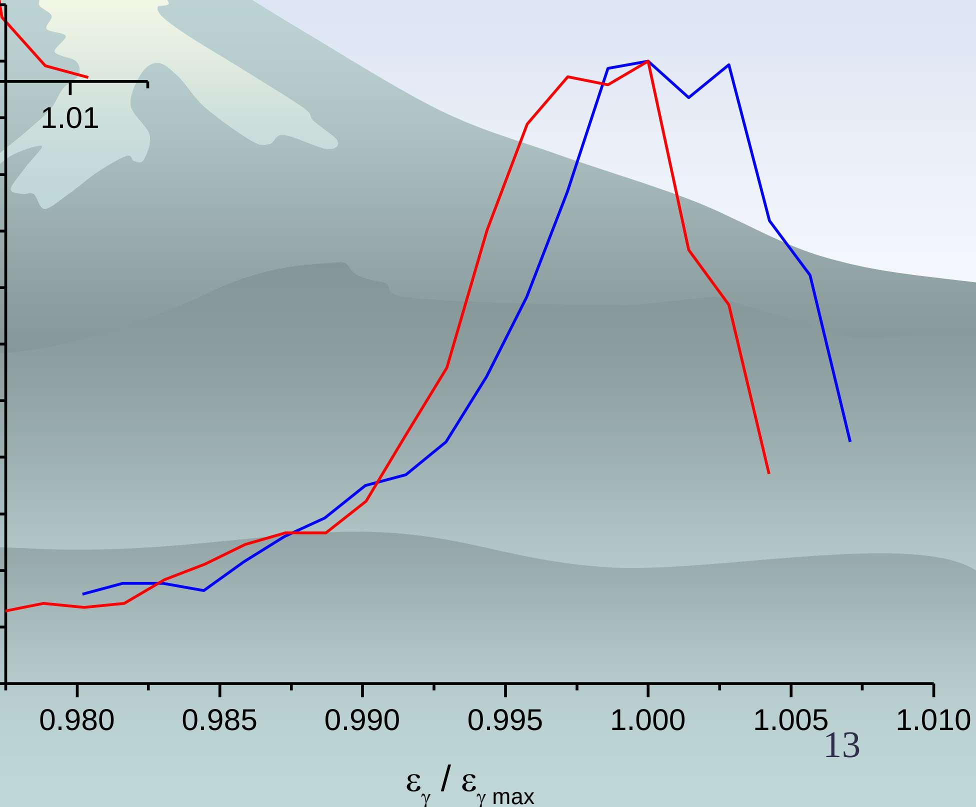
Beam energy distribution at the end of repetition cycle

As a result FWHM of the collimated spectrum is several %.
To obtain narrow spectrum we assume the gamma-beam generation during a short time just after beam injection into the ring (from 250 to 500 μs dependently on the electron beam energy).
The simulation results of the Compton scattering in proposed lattice are presented when normalized emittance of the injected beam is equal to 1*10-6 m*rad.



Collimated spectra at electron beam energies Ee = 450 MeV (red line, collimation angle 0.1 mrad) and 100 MeV (blue line, 0.4 mrad). Generation time 500 µs.

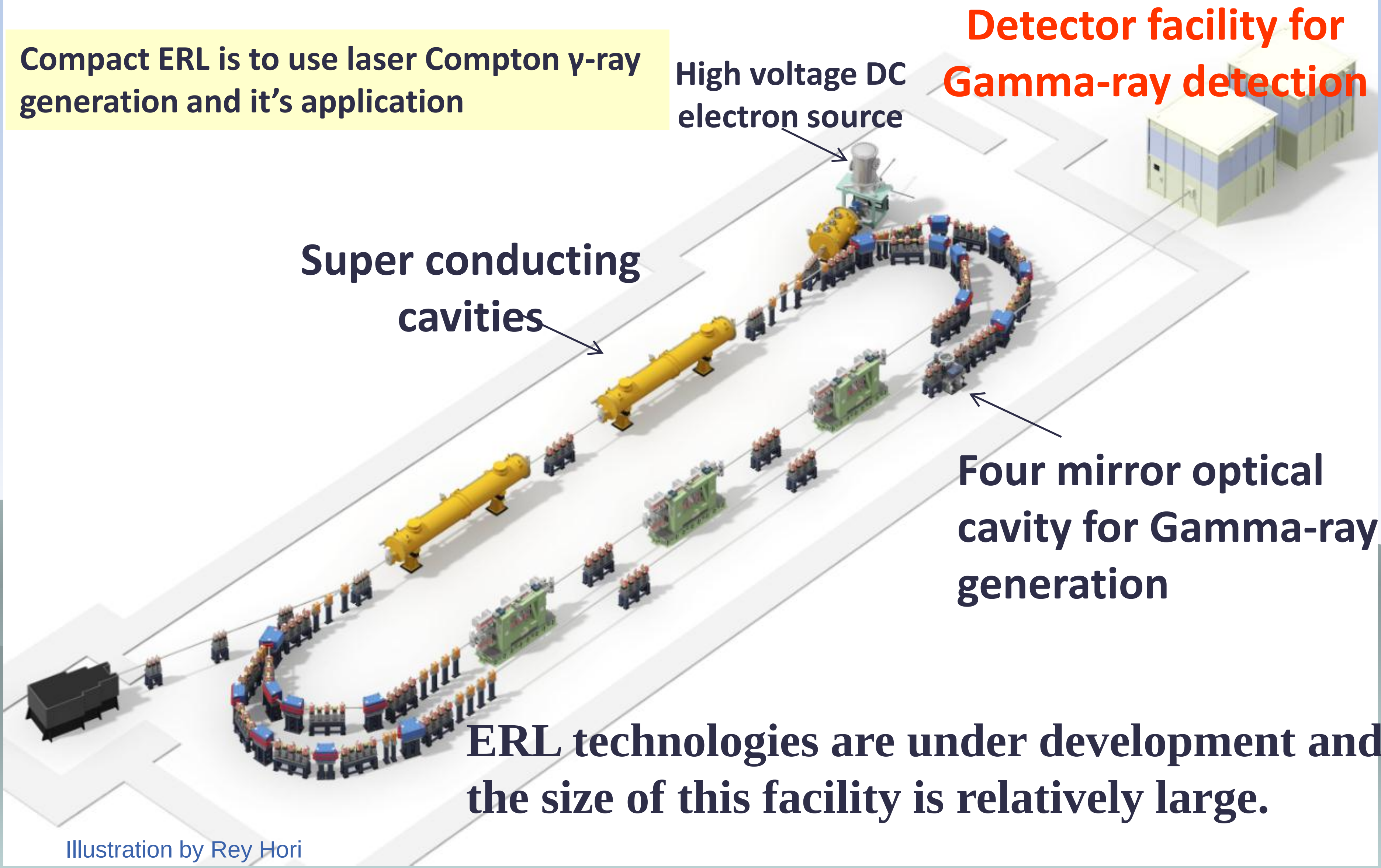
Collimated spectra at electron beam energy 100 MeV. Collimation angle 0.4 mrad. Generation times 250 µs, total gamma-yield 1.2*10^{13} / s (red line) and 500 µs, 1.5*10^{13} / s (blue lines).



From the last figure one can see that we can obtain narrower spectrum reasonably decreasing the generation time (in fact, it is difficulty to detect clear widening effect in the figure because of poor statistics since enough good statistics requests us a lot of simulation time.)

Demonstration experiment for ERL

Compact ERL is to use laser Compton γ-ray generation and it's application



High voltage DC electron source

Detector facility for Gamma-ray detection

Super conducting cavities

Four mirror optical cavity for Gamma-ray generation

ERL technologies are under development and the size of this facility is relatively large.

Illustration by Rey Hori

3. Summary

Compact system is necessary because many nuclear waste are stocked in cooling pool at many places. We are considering transportable extremely high brightness γ source which includes 300Hz Linac, Compton ring and laser system.

We need more design studies and development of necessary technologies for NFR measurements and nuclear waste management.

Our proposal is under the process to select new project at MEXT.