# SUMMARY OF WG5 ON ERL APPLICATIONS– ERL 2015

V. Litvinenko, Stony Brook University, Stony Brook, NY, USA
O. Brüning, CERN, Geneva, Switzerland

*Abstract*

In this paper we present a brief summary of material presented and discussed at ERL 2015 workshop, Working Group 5 (WG5), Applications. Because of the brevity of the paper we can only scratch the surface of the material covers in many excellent presentations. The goal of the WG5 was to discuss applications, which require an ERL or can benefit from an ERL. We also aimed to discuss strengths and weaknesses of ERLs as accelerator used for those applications.

As examples of possible weaknesses we identified the difficulty with radiation protection/beam loss monitoring (when ERLs compared with storage rings) and the need to bend electrons and suffer SR losses and effects (when ERLs compared with straight linacs).

As example of obvious advantages we identified the ERL's energy efficiency, its ability of providing fresh beam with very high power as well as to preserve polarization of the accelerated beam.

We also discussed a set of critical parameters, which ERLs should demonstrate to become of interest for various applications.

## INTRODUCTION

The list of applications, which were presented as part of WG5 thematic (e.g. some of them were presented as plenary talks) included the following [1-16]:

- High energy and nuclear physics, including γ-ray sources;
- Light sources and FELs;
- Material science and technology;
- Industry, including XUV lithography.

First, we have heard about three operational ERLs. JLab ERL after operating record breaking high power IR and UV FELs [17] continues to have user applications including THz radiation and the dark photon search. A detailed review [3] of ALICE ERL operation and user program – THz radiation, IR FEL, Thomson scattering, injector in FFAG ring EMMA - was a clear demonstration of the usefulness of ERL, which was initially built as a test facility. Unique four-pass ERL at Novosibirsk did not have a dedicated presentation at the workshop. Nevertheless its user program using high power THz and FIR FEL radiation [18] is well known and was acknowledged in a number of talks. In addition, a lot of excitement came from the KEK, where a commissioning of ERL prototype is in full swing [19] and BNL, where SRF gun became operational initiating the R&D ERL commissioning program [20].

Most of the WG5 talks were focusing on the future accelerators and applications.

## LIGHT SOURCES AND FELS

H. Kawata from KEK presented an illuminating talk [5] on scientific potential of the ERL based (both incoherent and coherent) light sources. He presented a compelling case that ERLs would offer far superior performance when compared with existing storage ring-based light sources. In ERL based-light sources, the high repetition rate, short pulse, high spatial coherence and high brightness will enable the filming of ultrafast atomic-scale movies and determination of the structure of heterogeneous systems at a nano-scale. He concluded that unique capabilities of ERL-based light sources will drive forward a distinct paradigm shift in X-ray science from *"static and homogeneous"* systems to *"dynamic and heterogeneous"* systems. In other words, ERL can provide a conceptual change in X-ray science from *"time- and space-averaged"* to *"time- and space-resolved"* analysis.

T. Atkinson from HZB presented design of ERL-based Femto-Science Factory [2], which promised outstanding performance (see Fig. 1) while operating very short electron bunches (from 5.6 fsec upwards).

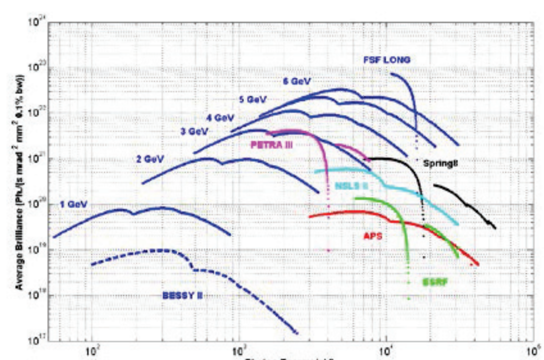


Figure 1: Spectral brightness of various light sources [2].

N. Nakamure (KEK) presented a very interesting design of 800-MeV ERL based FEL, which would serve as a new generation 13.5 nm light source for a chip-production industry [4]. Such facility (see Fig. 2) would generate 10 kW of average power in a 100-meter long SASE FEL with tapered undulator. The EUV FEL power would be split and delivered to chip manufacturing stations. Potentially this ERL technology can revolutionize the chip industry and become one of the main ERL usages.

Y. Jing (BNL and Stony Brook University), presented an overview of existing/past ERL-based FELs (JLAb, ALICE, Novosibirsk and JAERY) and discussed their future potential of ERL-based X-ray FELs [6]. He discussed challenges of preserving the beam quality while propagating the beam through the ERL arcs, as well as

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design of bunch of compressors which minimize damage to the beam from coherent synchrotron radiation (CSR).

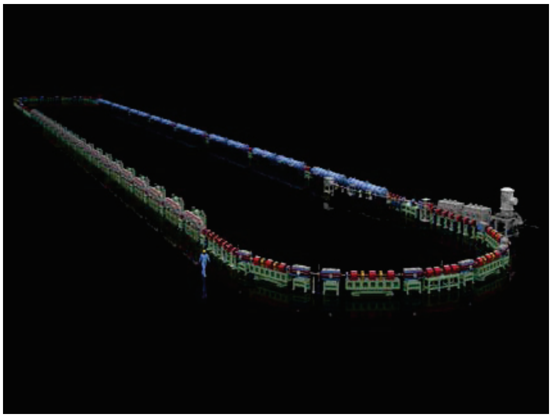

Figure 2: 3D-rendering of EUV source design [4] for industrial applications.

Using an example of an ERL designed for the eRHIC electron-ion collider, he showed that the electron bunch can be accelerated, compressed and used in a single path SASE FEL [6,21 (see Fig. 3). Furthermore, he illustrated how ERL driven FEL can be used for X-ray FEL oscillators [22,23].

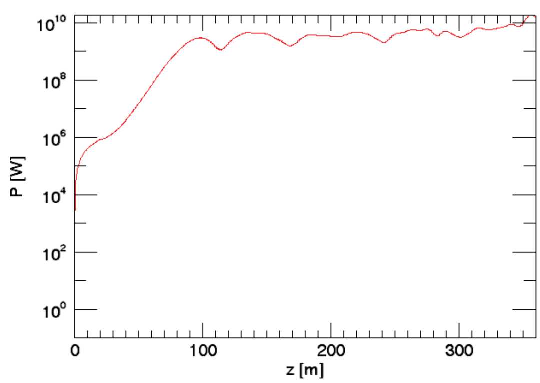


Figure 3: Power evolution in ERL driven SASE FEL operating at 1 Å. Such FEL saturates after 100 m of the FEL wiggler.

I. Konoplev (JAI) presented a concept of a compact ultra-high flux X-ray and THz source [13], based on unique two-cavity SRF system strongly coupled at fundamental frequency (Fig. 4). One of the cavities is used for accelerating the beam and the other is for decelerating. A unique feature of this design is that HOMs of two cavities are intentionally detuned to suppress TBBU instability. The X-ray radiation in such ERL system will be generated using Compton scattering of a laser light, while THz radiation will use a Smith-Purcell type.

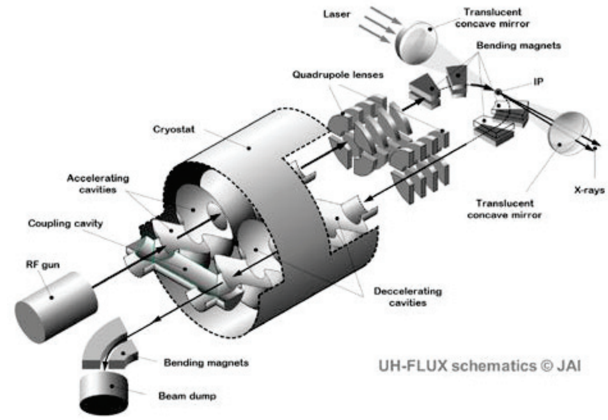


Figure 4: Conceptual layout of uh-flux system [13].

## HIGH ENERGY AND NUCLEAR PHYSICS, INCLUDING γ-RAY SOURCES

V. Ptitsyn presented two compelling designs of high energy ERL-based electron-hadron colliders [1]: eRHIC [21] and LHeC [22]. In eRHIC (Fig. 5), 21.2 GeV 16-pass ERL would be used to collide polarized electrons with 250 GeV polarized proton or 100 GeV heavy ion circulating in one of RHIC super-conducting rings. This next generation QCD-facility promises a range of discoveries ranging from observing gluon saturation to solving proton spin puzzle. [21]

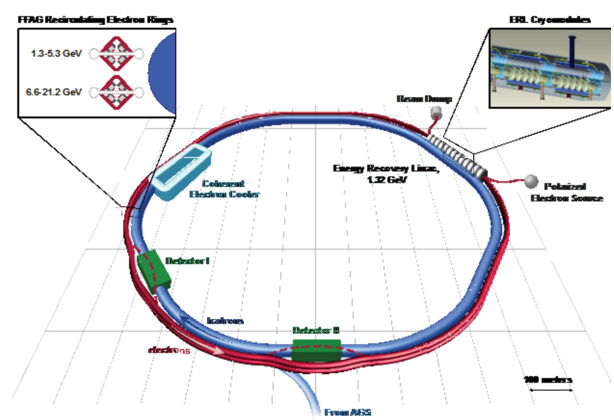


Figure 5: Layout of eRHIC collider.

LHeC would use a 3-pass 60 GeV ERL (see Fig. 6) to accelerate and to collide polarized electrons with one of he 7 TeV proton beams circulating the LHC. This collider program aims at the energy frontier of high-precision physics and beyond-the-standard-model physics [22]. It also would allow high precision studies of Higgs properties.



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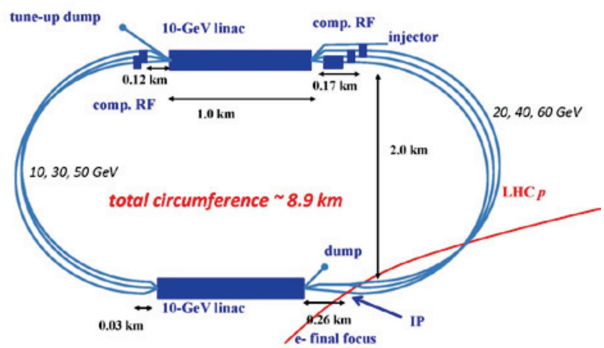


Figure 6: Layout of LHeC ERL.

One of the co-authors from this summary presented a concept of lepton ERL scalable to TeV energies using proton beam for transporting the energy from decelerating linac to an accelerating one [8] (see Fig. 7). Such scheme allows to practically eliminating losses for synchrotron radiation, which limit traditional lepton ERL schemes to few tens of GeV.

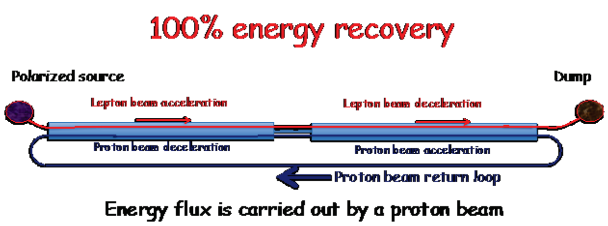


Figure 7: Schematic of TeV-scale lepton ERL.

E. Jensen (CERN) presented plans for 900 MeV three-path ERL facility at CERN (Fig. 8), which would be used for a number of applications beyond serving as a test bed for LHeC [7]: quench test of the superconducting magnets, testing beam instrumentation for future accelerator facilities, and generating γ-ray beams.

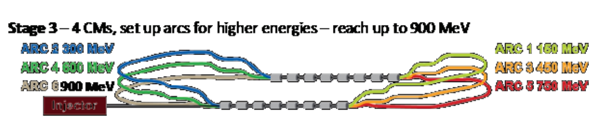


Figure 8: Schematic of CERN ERL facility.

There were two talks on how ERL can be used for cooling hadron beams. I. Pinayev (BNL) presented talk on using an ERL for coherent electron cooling (CeC) on hadron beam in eRHIC, which had to increase the RHIC hadron beams' brightness by about three orders of magnitude [11]. He also presented the Proof-of-Principle CeC experiment system (see Fig. 9), which is under commissioning at RHIC IP2 straight section [23].

J. Kewisch presented a concept of low energy (2.7 to 5 MeV) ERL for cooling RHIC ion beams when operating at low energies below 10 GeV/u [14] (see Fig. 10).

R.Heine described a 155 MeV MESA ERL/RL, which is under construction at Mainz, Germany [9] under the nuclear physics research program. This facility will operate both in ERL and RL (recirculating linac) modes accelerating polarized electron beam (see Fig. 11).

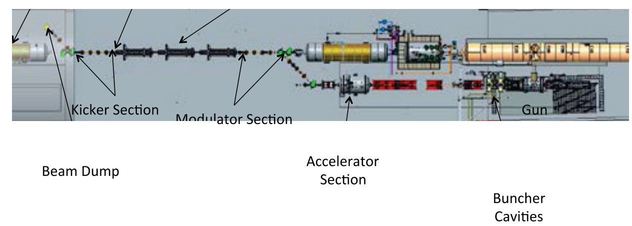


Figure 9: CeC Proof-of-Principle system at IP2 of RHIC.

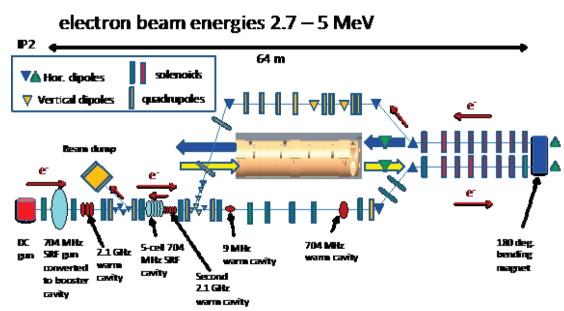


Figure 10: CeC Proof-of-Principle system at IP2 of RHIC.

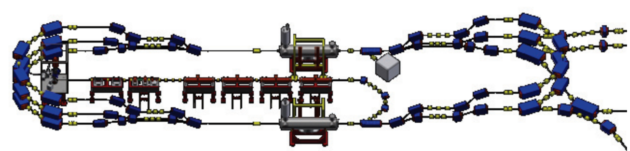

Figure 11: Layout of MESA ERL.

Generating Compton back-scattered γ-ray beams using ERLs was a prominent theme in many presentations. ERL-based Compton γ-ray sources [24] have significant advantage when compared with that based on storage rings [25] or linacs [26]. R. Hajima (JAEA) presented a detailed design as well as a first experiment on ERL-based γ-ray source at KEK [10] (see Fig. 12). He presented an example of how such sources can be used for detection of illicit radioactive materials using existing HIγS facility at Duke University [24].

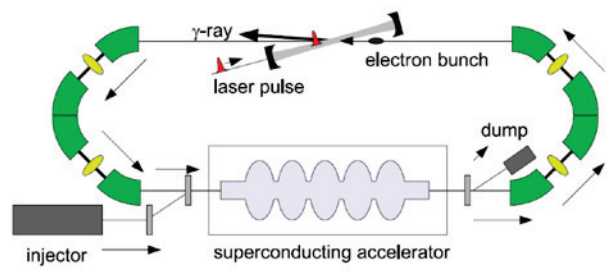


Figure 12: ERL based Compton γ-ray source.

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V. Yakimenko gave an overview talk on ERL-based intense mono-energetic γ-ray sources [12]. He presented quite an exhausting list of potential applications for such sources ranging from security applications and isotope production to generating polarized positron beams for colliders (see Fig. 13).

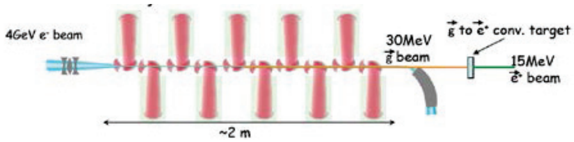


Figure 13: Possible scheme for generating polarized positrons using polarized Compton γ-ray source.

B. Dunham (Cornell U) continued the trend describing how they would use a proposed 4-path ERL for generating intense beams of 50-200 KeV Compton X-rays for material studies and structural engineering [15]. M. Perelstein (also Cornell U) continued discussion of potential application of the propose ERL and shared with us his opinion that such ERL with 300 MeV electron beams can be used in search for dark photon search and used for discoveries in physics beyond the standard model [16].

## TABLE OF PARAMETERS

We asked participants of WG5 to send us list of ERL parameters, which are either critical or sufficient for specific application. We have a number of responses and results that are presented in the table below. We want to thanks everybody who responded to our call for information. *Important disclaimer: this table by no means is representative of the whole set of parameters needed for the specific application – it is just a snap-shot of a public opinion represented in WG5.*

Table 1: Range ERL and Beam Parameters Important for Various Applications

| Application/ ERL parameter | eA/ep colliders | XUV/XRay FELs | γ-ray sources | SR sources | Nuclear Physics | THz/IR FELs | Electron cooling | CeC |
|---|---|---|---|---|---|---|---|---|
| Energy, GeV | 20-60 | 0.65-10 | 0.1-10 | 3-7 | 0.2 | 0.01 – 0.2 | 1.6-5 MeV | 0.1-0.2 |
| # of passes | 3-16 | 1-4 | x | 1-2, 12 | 3 | 1-3 | 1 | 3 |
| Beam current, mA | 5-50 | 10-50 | 100 | 10- 100+ | 1 | 2-20 (within macropulse if pulsed) | 50 | 100 |
| Peak current, A | | 500 - 5000 | 1000 | ~ 100 | ? | 20-200 | 0.35 | 10 |
| Charge per bunch, nC | 1-5 | 0.05 – 1 | ~ 1 | 0.01-1 | pC | 0.05-0.2 | 100 | 10 |
| Norm Emittance, mm mrad | 5-50 | 0.1 – 1 | ~ 1 | 0.1-1 | | 2-20 | 2.5 | <5 |
| Bunch length, mm | 4-10 mm | 10– 100 μm | 100 μm | 3-100μm | | 0.1 – 0.5 | 15-35 | 200 |
| Energy spread | $10^{-3}$ $10^{-4}$ | $10^{-3} – 10^{-4}$ | $10^{-3} – 10^{-4}$ | $10^{-4}$ | | $10^{-2} – 10^{-3}$ | $5\cdot10^{-4}$ | $5\cdot10^{-4}$ |
| Electron Polarization | >80% | No | ? | No | Yes | No | No | No |
| Return arc energy acceptance | | 1-5% | 10% | 10-3 | | Few percent | | |



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## CONCLUSIONS

Presentations and discussions at WG5 clearly demonstrated that ERL brings new and unique capabilities in many application areas: from fundamental science to industry and national security. With ERL technology maturing, we expect more and more application area to pop-up in near future. The fact that a number of ERL are either under construction, commissioning or in other advanced development phases, makes this period very exciting but also very raveling of real challenges posed by ERL technology.

## ACKNOWLEDGMENTS

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