# International Workshop on Energy Recovery Linacs (ERL 22)

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# Book of Abstracts

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**Beam Dynamics and Instrumentation / 2**

## Evidence of intrabeam scattering in high brightness electron linacs

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So far, IBS has not been observed in single pass electron accelerators because charge density orders of magnitude higher than in storage rings would be needed. We show that such density is now available at high brightness electron linacs for free-electron lasers (FELs).We report measurements of the beam energy spread in the FERMI linac in the presence of the microbunching instability, which are consistent with a revisited IBS model for single pass systems. We criticaly review experimental and numerical results in the literature in the light of most recent understanding of IBS-dominated dynamics, including a systematic characterization of the FERMI seeded FEL brilliance vs. electron beam optics, benchmarked with an IBS-MBI semi-analytical model. We also show that neglecting the hereby demonstrated effect of IBS in the parameter range typical of seeded VUV and soft x-ray FELs, results in too conservative a facility design, or failure to realise the accessible potential performance.

**Electron Sources / 3**

## The high repetition rate thermionic injector

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At Eindhoven university a high repetition rate thermionic injector is being built. The injector is capable of supplying electron bunches at a repetition rate of 1.5 GHz, which can be used for x-ray generation.

The electron source generates a continuous beam with a high current and low emittance through thermionic emission. The continuous electron beam is then chopped into a pulsed beam by a combination of a dual mode elliptical RF cavity and a knife-edge. The dual mode cavity uses both the fundamental mode (1.5 GHz) and its second harmonic (3.0 GHz) to increase the duty cycle of the chopping process to approximately 30% with a minimal loss of beam quality. Finally, a second dual mode elliptical RF cavity compresses the pulse length of the bunches, preparing the beam for injection into an X-band linear accelerator.

The first part of the injector is capable of operating at an emission current of 10 mA with a sub-50 nm rad transverse rms emittance. Construction of the elliptical chopper cavity has completed and is currently being implemented, after which the properties of the electron bunches after chopping will be measured.

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## HOM-Damping Studies in a Multi-Cell Elliptical Superconducting RF Cavity for the Multi-Turn Energy Recovery Linac PERLE

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Higher order modes (HOMs) damping is a crucial issue for the next generation of high-current accelerators. Beam-induced HOMs can store sufficient energy in the superconducting RF (SRF) cavities giving rise to beam instabilities and increasing the heat load at cryogenic temperature. To limit these effects, the use of HOM couplers on the cutoff tubes of SRF cavities becomes crucial to absorb beam-induced wakefields, consisting of all cavity eigenmodes. These couplers feature probe or loop antennas designed to couple ERL optics-related dipole cavity modes and to reject the fundamental mode sufficiently. The study presented here focuses on a 5-cell 801.6 MHz elliptical SRF cavity designed for PERLE (Powerful Energy Recovery Linac for Experiments), a multi-turn ERL currently under study and to be hosted at IJCLab in Orsay. Several coaxial coupler designs are firstly analyzed by means of equivalent circuit models. A subsequent coupler optimization is made on a 3D geometry of the coupler to enhance the damping of dipole HOMs of the 5-cell cavity. The broadband performance of HOM damping and power deposition is also confirmed by the time-domain wakefield and the frequency-domain simulations. In addition, the thermal behavior of the HOM couplers is investigated. A comparison between various HOM-damping schemes is carried out to guarantee an efficient HOM power extraction from the cavity.

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## Multi-objective Beam Line Optimization for the Commissioning of MESA

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The Mainz Energy-recovery Superconducting Accelerator (MESA) at the Institut für Kernphysik der Johannes Gutenberg-Universität Mainz will be commissioned in 2023. Detailed simulations of possible beam optics can be helpful to prepare for this process in order to speed up actual commissioning. The particle tracking code OPAL was chosen as a toolbox to perform these simulations as it handles space charge effects and low energy dynamics ($v<c$), especially in the longitudinal phase space, with high precision. A genetic optimization algorithm was developed to explore the pareto efficient solutions of many possible optic settings, providing efficient solutions regarding certain objectives. A special emphasis was put on the longitudinal beam dynamics in MESA in order to improve the energy spread at the Interaction points of the experiments.

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## A Plan of CW XFEL at Pohang Accelerator Laboratory

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The PAL-XFEL based on S-band normal conducting linac has demonstrated excellent timing stability and unprecedented peak brightness, outperforming other XFEL facilities since its start of user service operation in June 2017. Based on superconducting RF technology, CW XFEL will be on the horizon, increasing the average brightness by four orders of magnitude from pulsed XFEL; LCLS-II in the USA in 2023 and SHINE in China in 2025. And an X-ray FEL Oscillator, which is a fully coherent X-ray source, is under study in the USA by making full use of CW superconducting linac. Acknowledging this significant change, we (PAL) propose a plan to build a CW XFEL and an XFELO. A basic parameter study will be presented together with the current status of PAL-XFEL.

**Uses and Applications / 7**

## Circular-Linear energy recovery accelerator to probe the energy-frontier

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Energy-frontier particle accelerators are among the most exciting, complex, challenging, and expensive research instruments performing high precision measurements confirming the fundamentals of the physics and broadening new research horizons. Currently the highest energy machines, from multi-GeV to several TeV, (ILC, FCC, CLIC) capable of searching for the most basic building blocks of matter are either driven by circular or linear accelerators. The circular machines, having the centre-of-mass (CM) energy values reaching 200 GeV (for leptons) and above, experience beam energy loss and quality dilution, for example, due to synchrotron radiation, limiting the overall CM energy achievable and requiring a constant energy top-up to compensate the loss and the beam quality dilution. Linear colliders overcome these limitations, while the finite capabilities of generating high average current beams limits the luminosity. This is partially compensated by the quality of the colliding beams. Most of the accepted state-of-the-art designs, while reaching the energies required, have very large footprint and show the same signs of limitations and drawbacks and in this work, we suggest a novel design of circular-linear accelerator based on the merging of the weakly emitting, low-energy storage rings and energy recovery linear accelerators. To enable the operation of such a system and in particular the energy recovery from spent, high-intensity beams the use of the dual-axis asymmetric cavities is suggested. The merging of circular and linear systems, and applications of dual axes cavities, aim to maintain high beam quality, high luminosity, and high energy efficiency, while simultaneously offering a flexible energy management. The concept presented can be potentially used to reach ultimate energy frontiers in high-energy physics as well as to drive next generation light sources combining tools for fundamental and applied studies. The numbers which will be presented are for illustration purpose and can be improved further.

**Facility Reports / 8**

## ERL Operation of the Superconducting Darmstadt Electron Linear Accelerator S-DALINAC – a Facility Report*

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The superconducting Darmstadt linear accelerator S-DALINAC [1] is a thrice-recirculating accelerator for electrons at TU Darmstadt. Since its establishment in 1991, the S-DALINAC was mainly developed and operated by students. Besides the conventional acceleration scheme serving various nuclear-physics experiments, the accelerator can also be operated as an energy-recovery linac (ERL). Following the first operation as a once recirculating ERL [2], the S DALINAC achieved high-transmission multi-turn energy recovery in August 2021 [3]. Dedicated beam dynamics simulations, as well as beam diagnostic devices designed for ERL operation, are essential to operate an accelerator as an ERL. This contribution will give an overview of the facility with a focus on the ERL activities. Options for a successor ERL will be discussed.

*Work supported by DFG (GRK 2128, project ID 264883531), BMBF (05H21RDRB1), the State of Hesse within the Research Cluster ELEMENTS (Project ID 500/10.006) and the LOEWE Research Group Nuclear Photonics.

[1] N. Pietralla, Nuclear Physics News, Vol. 28, No. 2, 4 (2018).
[2] M. Arnold et al., Phys. Rev. Accel. Beams 23, 020101 (2020).
[3] F. Schließmann, Contribution to this conference

**Beam Dynamics and Instrumentation / 9**

## Multi-pass ERL Driven FELs and Light Sources

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Any proposal for an accelerator facility based upon a multipass energy recovery linac (ERL) must possess a self-consistent match in longitudinal phase space, not just transverse phase space. We therefore present a semianalytic method to determine self-consistent longitudinal matches in any multipass ERL. We apply this method in collider scenarios (embodying an energy spread minimizing match) and FEL scenarios (embodying a compressive match), and discuss the consequences of each. As an example of the utility of the method, we prove that the choice of common or separate recirculation transport determines the feasibility of longitudinal matches in cases where disruption, such as synchrotron radiation loss, exists. We show that any high energy multipass ERL collider based upon common recirculation transport will require special care to produce a self-consistent longitudinal match, but that one based upon separate transport is readily available. Furthermore, we show that any high energy multipass ERL FEL driver based upon common recirculation transport requires a larger resultant rf beam load than the one based on separate transport, favoring the separate transport designs.

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## CEBAF 5-pass

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The 5-pass energy recovery project at CEBAF (ER@CEBAF) would become the first facility to have the energy reach to demonstrate ERL performance in the multi-GeV range. This increment in peak energy from the 1 GeV CEBAF-ER demonstration to the target $\sim$ 7 GeV brings incoherent synchrotron radiation-induced energy loss, presents an invaluable opportunity for multi-pass beam break-up studies, and enables the experimental exploration of multi-pass, multi-GeV energy recovery. We update the current project status, studies on RF optics optimization, longitudinal match, and modifications to CEBAF.

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## STATUS AND PERSPECTIVE OF THE ENERGY RECOVERY LINAC AT HZB

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Since end of the year 2020 the energy recovery linac (ERL) project bERLinPro of Helmholtz-Zentrum Berlin (HZB) has been officially completed. But what is the status of this facility, the next scientific goals in the framework of accelerator physics at HZB, what are the perspectives? To reflect the continuation of this endeavor and the broadening of applications of this machine from high current SRF based energy recovery concept up to an ultrafast electron diffraction (UED) facility producing shortest electron pulses, the facility is now named Sealab, Superconducting RF Electron Accelerator Laboratory. In this contribution, an overview of lessons learned so far, the status of the machine, the coming set up and commissioning steps with an outlook to midterm and future applications will be given. In summary, Sealab will expand, including the ERL application, and become a general accelerator physics and technology test machine to employ injector parameter space and UED as a first application study case. It will also be an ideal testbed to investigate new control schemes and contribute by studies to the European ERL Roadmap for high energy physics programme.

**Beam Dynamics and Instrumentation / 12**

## Proposed Test of the Two Beam BPM at RHIC

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The essence of the ERL operation implies that at least two beams (accelerated and decelerated) are co-propagating in the same vacuum vessel and each beam has its own trajectory. The existing beam position monitors measure only "average" trajectory but not that of an individual beam, unless the time separation between bunches is so large that one can resolve individual bunches.

It was proposed to use phase information of the pick-up signal to extract information on the orbit "difference". We are planning to conduct experiments at RHIC to test the proposed idea. The approach and experiment set-up are described in the paper.

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## The VSR Demo Module design – a spaceframe-based module for cavities with warm waveguide HOM absorbers

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The VSR (Variable pulse length Storage Ring) demo module is a prototype for the superconducting upgrade of HZB's BESSY II. The module houses two 1.5 GHz superconducting cavities operated at 1.8K in continuous wave (CW) mode. Each cavity has five water cooled Waveguide HOM Absorbers with high thermal load (450 W), which requires them to be water cooled. This setup introduces several design chal-lenges, concerning space restriction, the interconnection of warm and cold parts and the alignment. In order to provide support and steady alignment an innovative space frame was designed. The transition from cold to warm over the partially superconducting waveguides made a more complex design for shielding and cooling system necessary. With the design completed, we are now in the purchasing and production phase.

**SRF / 14**

## SRF photo-injector and Booster modules at bERLinPro: Assembly and commissioning status

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The energy recovery linac (ERL) at Helmholtz-Zentrum Berlin (HZB) is in the final stage of assembly and follow-up commissioning of the injector beam line. This injector consists of a 1.4\lamba/2 cell SRF photo-injector and a three two cell Booster cryomodule, the latter based on a modified design of the Cornell injector cavity shape. The injector was designed for a final beam current of 100 mA and an injection energy of 6.5 MeV into the 50 MeV recirculator. Currently, we are working on assembling and commissioning of the first cryo-module, being the SRF photo-injector, which already ran in 2018 [1], received a major overhaul of mainly the SRF cavities between 2019 to 2021, so that first beam is expected towards early 2023. In parallel, preparations to assemble the Booster cryo-module are on-going as well as final preparation of the injector beam vacuum system, which receives upgrades to also serve as an ultrafast electron diffraction (UED) beam line in addition to the foreseen accelerator research program and ERL studies at HZB. In this contribution, the development and current work on the SRF photo-injector will be presented in addition to latest results of the high power conditioning of the 120 kW Booster couplers.

**Uses and Applications / 15**

## ERL based EUV-FEL light source for lithography

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In extreme ultraviolet (EUV) lithography, high volume manufacturing recently started using a laser-produced plasma (LPP) source of 250-W power at 13.5 nm. However, development of a high-power EUV light source is still very important to overcome stochastic effects with a high throughput. The required EUV power to realize the 3-nm node and beyond with a high speed of future scanners is estimated to be more than 1 kW [1]. We have designed and studied an ERL-based EUV-FEL for future lithography [2-6] and showed that it can provide EUV power of more than 1 kW for ten scanners simultaneously. It is also upgradable to a "Beyond EUV" FEL light source that performs much finer pattering with shorter wavelength light (~6.7 nm). In addition, it can variably control the polarization of the EUV light, which might be utilized for high-NA lithography. Switching to the EUV-FEL light source from the LPP source can greatly reduce electric power consumption per scanner or 1-kW EUV power and it is suitable for sustainable semiconductor technologies and systems [7]. In this talk, I will present the ERL-based EUV-FEL light source for future lithography and the related activities.

[1] S. Inoue, Proc. of 4th EUV-FEL Workshop, Akihabara, Tokyo, Japan (2019).
[2] N. Nakamura et al., Proc. of ERL2015, Stony Brook, New York, USA, pp.4-9 (2015).
[3] N. Nakamura, R. Kato, T. Miyajima, M. Shimada, T. Hotei and R. Hajima, Journal of Physics: Conf. Series 874 (2017) 012013.
[4] H. Sakai et al., Proc. of SRF2017, pp.13-18 (2017).
[5] R. Kato, Proc. of 4th EUV FEL Workshop, Akihabara, Tokyo, Japan (2019).
[6] H. Kawata, N. Nakamura, H. Sakai, R. Kato and R. Hajima, J. Micro/Nanopattern. Mater. Metrol. 21(2), 021210 (2022).
[7] https://www.imec-int.com/en/expertise/cmos-advanced/sustainable-semiconductor-technologies-and-systems-ssts.

**SRF / 16**

## SRF performance on the Compact ERL at KEK

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A superconducting Compact Energy Recovery Linac (cERL) was constructed in 2013 at KEK to demonstrate energy recovery concept with low emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL. cERL consists of 500 kV DC photocathode gun, the injector cavities, the main linac cavity, which made energy recovery, recirculation loop and the beam dump.Under long-term beam operation, we met several SRF performance degradation like field emission and thermal breakdown. In this presentation, we will present how to keep SRF performance and overcome these issues to give the stable beam operation and show the long-term performance of SRF cavites of injector and main linac cryomodule until now.

**Facility Reports / 17**

## Facility report of Compact ERL (cERL) at KEK

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Compact ERL (cERL) is a test facility, which was constructed on the ERL Test Facility in KEK. Its aim was to demonstrate energy recovery concept with low emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL. In 2016 and 2018, we successfully operate the CW 1 mA beam in the energy recovery condition. Recently, this cERL was operated to promote a variety of the industrial applications such as SASE-IR-FEL operation for future ERL based EUV-FEL production, THz operation and Rare Isotope (RI) production for medical application. In this presentation, we will present the status of the studies to realize the stable high-current, low-emittance CW beam and report some industrial and medical applications with this beam in cERL.

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## Energy Recovery Linac Design and Studies for Electron Cooling of EIC Hadron Beams

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The baseline scheme for hadron beam cooling in the Electron Ion Collider (EIC) calls for Coherent electron Cooling (CeC) of the hadrons with non-magnetized electrons at high energy (150 MeV electrons), and additional cooling via conventional bunched beam cooling using a precooler system. The electron beam parameters for these concepts are at or beyond the current state of the art, with electron bunch charges of the order of 1 nC and average currents on the order of 100 mA and require an Energy Recovery Linac (ERL)-based accelerator to produce such beams. Using specifications provided by BNL and Jefferson Lab, physicists and engineers at Xelera Research are working on a complete design of an ERL system capable of satisfying such a cooler. This work includes designs for the injector, merger, multi-pass Linac, merger into the cooling section, demerger into the return line (which includes 180-degree arcs), and final extraction of the energy-recovered beam, beam breakup simulations, tolerance studies, start-to-end simulations, and beam halo studies.

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## BriXSinO high-flux dual X-ray and THz radiation source based on Energy Recovery Linacs

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We present the detailed design of a compact light source named BriXSinO. BriXsinO is a dual high flux radiation source Inverse Compton Source (ICS) of X-ray and Free-Electron Laser of THz spectral range radiation conceived for medical applications and general applied research. The accelerator is a push-pull CW-SC Energy Recovery Linac (ERL) based on superconducting cavities technology and allows to sustain MW-class beam power with just one hundred kW active power dissipation/consumption. Moreover, the BriXSinO layout allows performing two pass beam acceleration experiments.

ICS line produces 33 keV monochromatic X-Rays via Compton scattering of the electron beam with a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz. The THz FEL oscillator is based on an undulator imbedded in optical cavity and generates THz wavelengths from 15 to 50 micron.

**Uses and Applications / 20**

## ERL for Photonuclear Reactions

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The electromagnetic interaction of atomic nuclei with photons is a well-understood process that provides model-independent access to their properties. Consequently, photonuclear-reaction studies below and above the particle separation threshold have been a driving force in the study of the nuclear force for decades. Around the turn of the century, the field experienced a renaissance with the availability of intense, quasi-monochromatic, polarized photon sources in the MeV energy range based on the laser-Compton backscattering (LCB) process. Next-generation LCB facilities based on Energy Recovery Linacs (ERLs) have the potential to greatly enhance the reach of fundamental nuclear physics research. In addition, they are an important step towards technological applications of photonuclear processes.

This contribution will introduce the important reaction mechanisms of photons with atomic nuclei, in particular nuclear resonance fluorescence[1]. After discussing the advantages and disadvantages of contemporary photon sources, the potential of ERL-based facilities will be discussed based on current research efforts.

[1] A. Zilges *et al.*, Prog. Part. Nucl. Phys. **122**, 103903 (2019)

**Beam Dynamics and Instrumentation / 21**

## Challenges of a Twice-Recirculating ERL Mode

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In a multi-recirculating energy-recovery LINAC (ERL), electrons are accelerated several times in the same LINAC and are decelerated afterwards in the very same LINAC just as often. Even in the case of a twice-recirculating ERL, there are challenges compared to a single-recirculating ERL: When low injector energies are used, phase slippage leads to significantly different energy gains per LINAC pass for the beam to be accelerated for the first time and the beam to be accelerated for the second time. If the cost-efficient sharing model is used, the once-accelerated and the once-decelerated beam share the same recirculation beamline. This case poses a particular challenge for finding a transverse confinement due to the lack of degrees of freedom for the once-decelerated beam: the beam optics adjusted to the once-accelerated beam must also ensure the guidance of the once-decelerated beam. The presence of phase slippage and the low number of degrees of freedom requires a sophisticated setup of the machine, which had to be determined in advance via beam dynamics simulations. We address challenges of a twice-recirculating ERL mode in the sharing model by presenting experiences and measured data obtained during the successful realization of that mode at S-DALINAC in 2021.

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## A High Brightness Beams Test Facility (HB2TF)

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We present a proposal related to the development of a High Brightness Beams Test Facility (HB2TF) at the INFN-LASA laboratory close to Milan (Italy).

The Test Facility will allow to carry out experiments with the high current high brightness CW electron beam in frontier areas of accelerator physics.

The Test Facility setup will comprise a high-performance laser driven DC Gun (using Cs2Te photocathodes) followed by a normal conducting RF buncher-acceleration section to provide 1 MeV 5 mA CW electron beam. The engineering design of a Superconducting RF booster linac able to increase the electron energies up to 5-10 MeV maintaining beam current up to 2.5 mA is part of the proposal even if its financing and realization will be delegated to future requests.

The proposal is aimed to pool different experiences and capabilities so far available in research groups at the LASA laboratory along with the contribution from accelerator groups in other INFN sites and in foreign labs.

**Beam Dynamics and Instrumentation / 23**

## Beam Dynamics Challenges of a Far-Future ERL-Based Collider - The Ghost Collider

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In a recent paper, Valery Telnov proposed a linear collider based on twin axis cavities [1]. In a subsequent presentation, Erk Jensen proposed a modification with intra-bucket energy recovery [2], which eliminates higher order mode excitation. Interestingly, this means that there is no need for large aperture SRF cavities and high-power HOM couplers. The Ghost Collider adopts these ideas, and adds the concept of four-beam collisions (initially proposed by Joel LeDuff [3]) to remove beam-beam interactions and disruption. This concept brings up a series of new beam dynamics problems

which make optimization of the parameters difficult. The presentation will describe the concept, which has a series of beam-dynamics challenges to be solved before the concept can advance.

[1] V.I. Telnov, JINST 16 (2021) no.12, P12025
[2] E. Jensen https://indico.cern.ch/event/1040671/?view=nicecompact
[3] Status Report on D. C. I, The Orsay Storage Ring Group, IEEE Transactions on Nuclear Science, Vol. NS-26, No.3, June 1979

**SRF** / **24**

## Design of the 9-cell superconducting cavity for EUV light source accelerator

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KEK has been designing the 10 mA class ERL-EUV light source accelerator. The main linac uses 9-cell superconducting cavities with beamline HOM damper. The target accelerating gradient is 12.5 MV/m. The 9-cell cavity is designed from experience of the KEK compact ERL (cERL) main linac. The cERL main linac was designed to suppress the HOM-BBU with beam current of 100mA by enlarging the iris diameter to 80mm. This resulted into the high ratio of the peak surface electric field and the accelerating field (Ep/Eacc) of 3. The accelerating gradient is limited from 8.5 to 10 MV/m during the CW beam operation due to field emission. The EUV can accept lower BBU limit than cERL because the target beam current of the EUV is 10 mA. The iris diameter is set to 70mm to lower Ep/Eacc around 2. The target accelerating gradient can be achieved if the surface peak electric field is equal to cERL. EUV end cells were designed to minimize HOM Q factor in the above condition. The optimal shape was designed by matching HOM frequencies of the two end cells and center cells calculated individually. The absorption heat of HOM damper is estimated to about 10 W. The AlN is known as high damping efficiency at cryogenic temperature. The HOM damper was designed using complex permittivity data measured at 80 K for AlN. The performance of the HOM damper combined with the cavity is capable of operating the beam at 10 mA. In this presentation, we will describe the EUV cavity and HOM damper design.

**SRF** / **25**

## Horizontal test of Superconducting RF gun #2 at KEK

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Superconducting radio-frequency (SRF) electron guns are attractive for delivery of beams at a high bunch repetition rate with a high accelerating field. KEK has been developing the SRF gun to demonstrate basic performance. The SRF gun consists of 1.3 GHz and 1.5 cell SRF gun cavity and K2CsSb

photocathode coated on 2K cathode plug. In the vertical test, the surface peak electric field and the surface peak electric field reached to 75 MV/m and 170 mT respectively. The SRF gun was installed to horizontal multipurpose cryostat equipped with a superconducting solenoid, photocathode preparation chamber and beam diagnostic line. Unfortunately, the peak surface gradient dropped to 42 MV/m. This was probably due to particulate issued that entered the cavity during assembly. We suspect that it was caused particulate are come into the cavity during assembly. In this presentation, we will describe the high gradient performance in vertical and horizontal test and individual test for each beam line components.

**Uses and Applications / 26**

# Strong Hadron Cooling in EIC with an ERL

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IntraBeam Scattering (IBS) and other diffusion mechanisms in the EIC Hadron Storage Ring (HSR) degrade the beam emittances during a store, with growth times of about 2 hours at the two nominal proton energies of 275 GeV and 100 GeV. Strong Hadron Cooling (SHC) maintains good beam quality and high luminosity during long collision stores. A novel cooling method – Coherent electron Cooling (CeC) – is chosen as the baseline SHC method, due to its high cooling rates. An Energy Recovery Linac (ERL) is used to deliver an intense high-quality electron beam for the cooling. In this talk, we discuss the beam requirements for SHC-CeC in HSR and describe the current status of the ERL design, as well as the challenges and the R&D topics that are being pursued.

**Facility Reports / 27**

# TRIUMF e-Linac facility and ERL upgrade

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The TRIUMF electron linear accelerator (e-Linac) was conceived to be one of the two main drivers for the upcoming Advanced Rare Isotope Facility (ARIEL). The e-Linac has been commissioned up to 10 kW of average beam power at 30 MeV, for both CW and pulsed beam. It is envisioned for this facility to eventually be upgraded to an Energy Recovery Linac (ERL), with a preliminary design having already been developed by former PhD student Chris Gong. This design includes a recirculating ring, a free electron laser and an additional particle gun feeding into the main linac. ARIEL is projected to come online by 2025, tripling the amount of rare isotope beams produced at TRIUMF. Until then, the e-Linac will be operated as a multi-user facility to take full advantage of the scientific potential of this facility. The FLASH experiment, making use of the medium energy section, will irradiate test samples with short, high intensity doses of radiation for cancer research. The DarkLight experiment, operating in the high energy section, will search for a so-called "dark photon", a potential force

carrier for dark matter motivated by the Atomki anomaly. The high- brightness Thz infrared photon source project, tied closely with the ERL upgrade, will demonstrate the production of high intensity broadband radiation and establish a dedicated material science user community at TRIUMF. ARIEL and these external projects will all depend significantly on the reliability of the e-Linac, which is a main focus of the Accelerator Division in the coming years. In light of this, I am working on a project directly relevant to the ERL community, which studies the migration of dust and mitigation of field emission in SRF cavities.

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## The European ERL Roadmap

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Following the European Strategy process in 2019, five Roadmap Panels were set up to prepare the technologies needed for future accelerators and colliders: high-field magnets, SRF, muon colliders, plasma wakefield accelerators and Energy Recovery Linacs (ERLs). The ERL Roadmap Panel, consisting of ERL experts from around the world, first developed a comprehensive overview of current and future ERLs. From this a gap analysis was carried out to evaluate the necessary R&D, which led to the development of the Roadmap. The European ERL Roadmap focused on three main aspects: 1) the continuation and development of facility programs for which no additional funds are needed (S-DALINAC in Darmstadt and MESA in Mainz); 2) technology development for room-temperature HOM damping and twin-axis SRF cavities; 3) the timely upgrade of bERLinPro for 100mA current, and 4) the construction of PERLE at Orsay as a dedicated 10MW beam-power multi-turn facility. The Roadmap also describes a vision for future energy-frontier electron-positron and electron-hadron colliders, and describes a high-quality ERL program for 4.4K SRF technology at high Q0. The presentation will address the ERL Roadmap process and results in detail.

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## Director's Welcome

A welcome to Cornell and the ERL 22 workshop by the laboratory director

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## Workshop Welcome

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A welcome to the workshop

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## Facility Report CBETA

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## Facility Report MESA

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## Facility Report PERLE

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## CBETA Instrumentation: From Beam Diagnostics to Machine Protection

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## Using Polynomial Chaos Expansion to determine solenoid misalignment during bERLinPro commissioning

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## Beam Dynamics and Performance Studies of PERLE

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## High Bunch Charge Operation with Small Emittance

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## Multi-Turn Performance Studies and Beam Dynamics Issues

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## Implications of beam filling patterns on the design of recirculating energy recovery linacs

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## High-energy high-luminosity e+e− collider using ERL

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## GeV muon beams with picometer-class emittance from electron-photon collisions

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## ion collisions in gas-jet targets of the dark-light type

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## Compton Backscattering sources

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## Novel Nuclear experiments at MESA

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## Progress on 2D protective coating for photocathodes

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## Progress on spin polarized electron beam sources for high current

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## Single-crystal alkali antimonide photocathode: High efficiency in the ultra-thin limit

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## PERLE electron source status and requirement for LHeC

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## Photocathodes for high average current electron beam: state-of-the-art and new perspective

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## High voltage DC gun for high intensity polarized electron source

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## DC gun for Low Energy RHIC cooler (LEReC) project

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## Long term operational experience of running Cs2Te cathodes in HZDRs SRF gun

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## Low frequency 113MHz SRF gun with room temperature photocathode for Coherent electron cooling experiment (CeC-X)

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## Commissioning of the SLAC Linac Coherent Light Source II electron source

**SRF / 56**

## Overview Nb3Sn cavity progress (for CW machine)

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## Achieving stable cw operation in vector sum

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## Iterative Learning Control for Beam Loading Compensation

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## High gradient ”turn key” SRF systems for small scale ERLs like MESA

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## Fast Reactive Tuner developments at CERN

**SRF / 61**

## High power coupler conditioning for the ERL injector Booster module

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# ERL Introductory Talk

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## SRF Operations, microphonic control at CBETA

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## SRF systems for the EIC hadron cooling

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