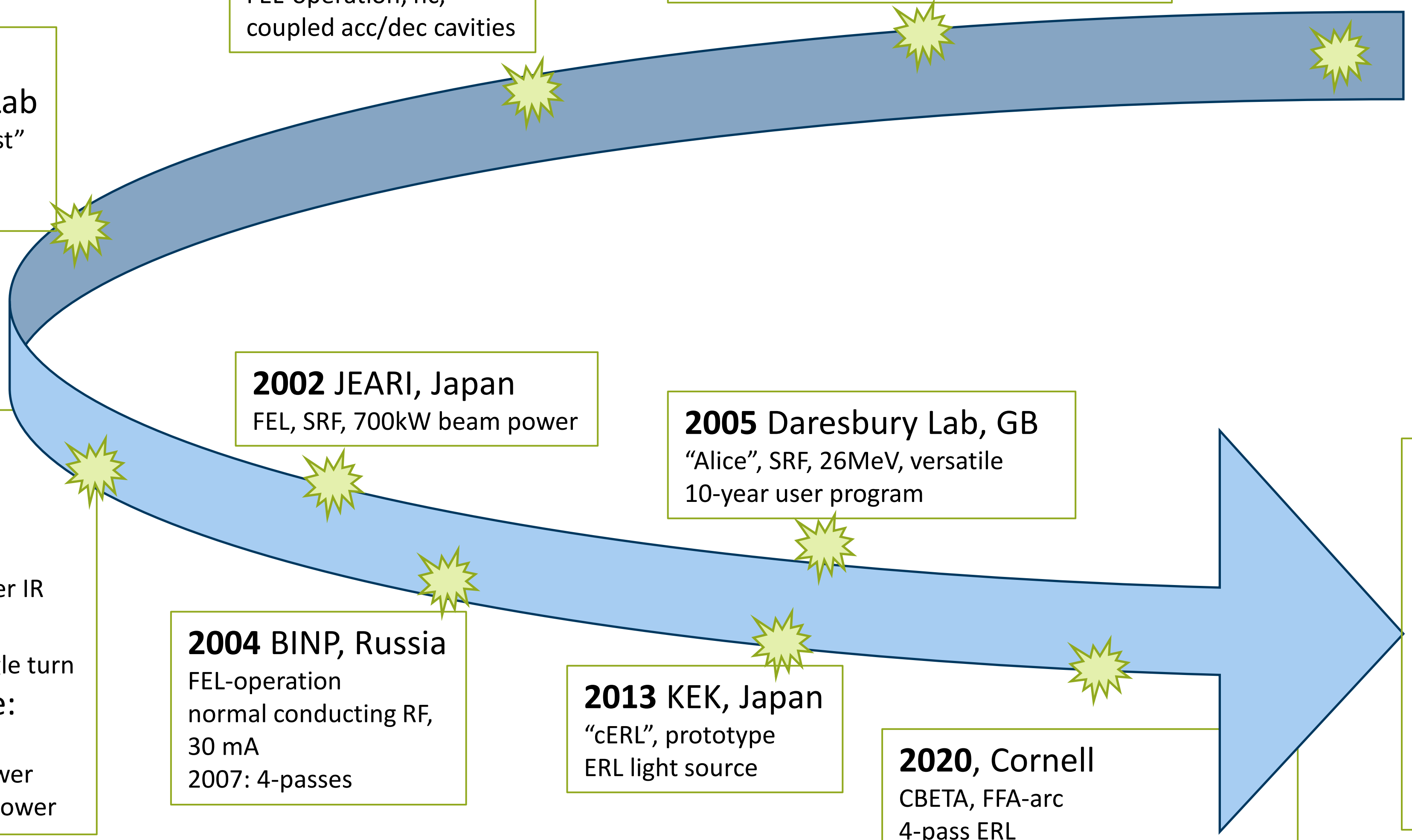
ERL challenges and potential ERL-based colliders

Andrew Hutton

Jefferson Lab

SOME ENERGY RECOVERY LINAC HISTORY AND ACHIEVEMENTS



1965 M. Tigner
“A possible apparatus for electron clashing-beam experiments”

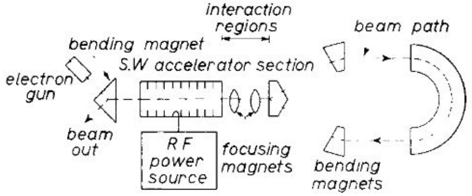


Fig. 3.

1987 High Energy Physics Lab Stanford University
SRF cavities, proof of principal experiment

1987 Los Alamos
FEL-operation, nc,
coupled acc/dec cavities

1992
Jefferson Lab
“Front End Test”
SRF, first CW
recovery

2002
Jefferson Lab
“IR-Demo”
SRF, 5mA, 48MeV,
2.1kW beam power IR
2003
CEBAF, 1 GeV, single turn
2007 Upgrade:
9mA, 150MeV
1.1MW beam power
with ~300kW RF power

2002 JEARI, Japan
FEL, SRF, 700kW beam power

2004 BINP, Russia
FEL-operation
normal conducting RF,
30 mA
2007: 4-passes

2005 Daresbury Lab, GB
“Alice”, SRF, 26MeV, versatile
10-year user program

2013 KEK, Japan
“cERL”, prototype
ERL light source

2020, Cornell
CBETA, FFA-arc
4-pass ERL
(80mA injector, $\varepsilon = 0.3$mm mrad)

under construction:
MESA, Germany
particle physics application

PERLE, France
testfacility (FCC-ee)

bERLinPro, Germany
SRF/ERL technology test
facility

Courtesy Bettina Kuske

Study for an ep / eA collider using the LHC / FCC

CDR Study assumptions:

-Assume parallel operation to HL-LHC / FCC-hh

-TeV Scale collision energy

➔ 50-150 GeV Beam Energy

-Limit power consumption to 100 MW ➔ 40-120MW

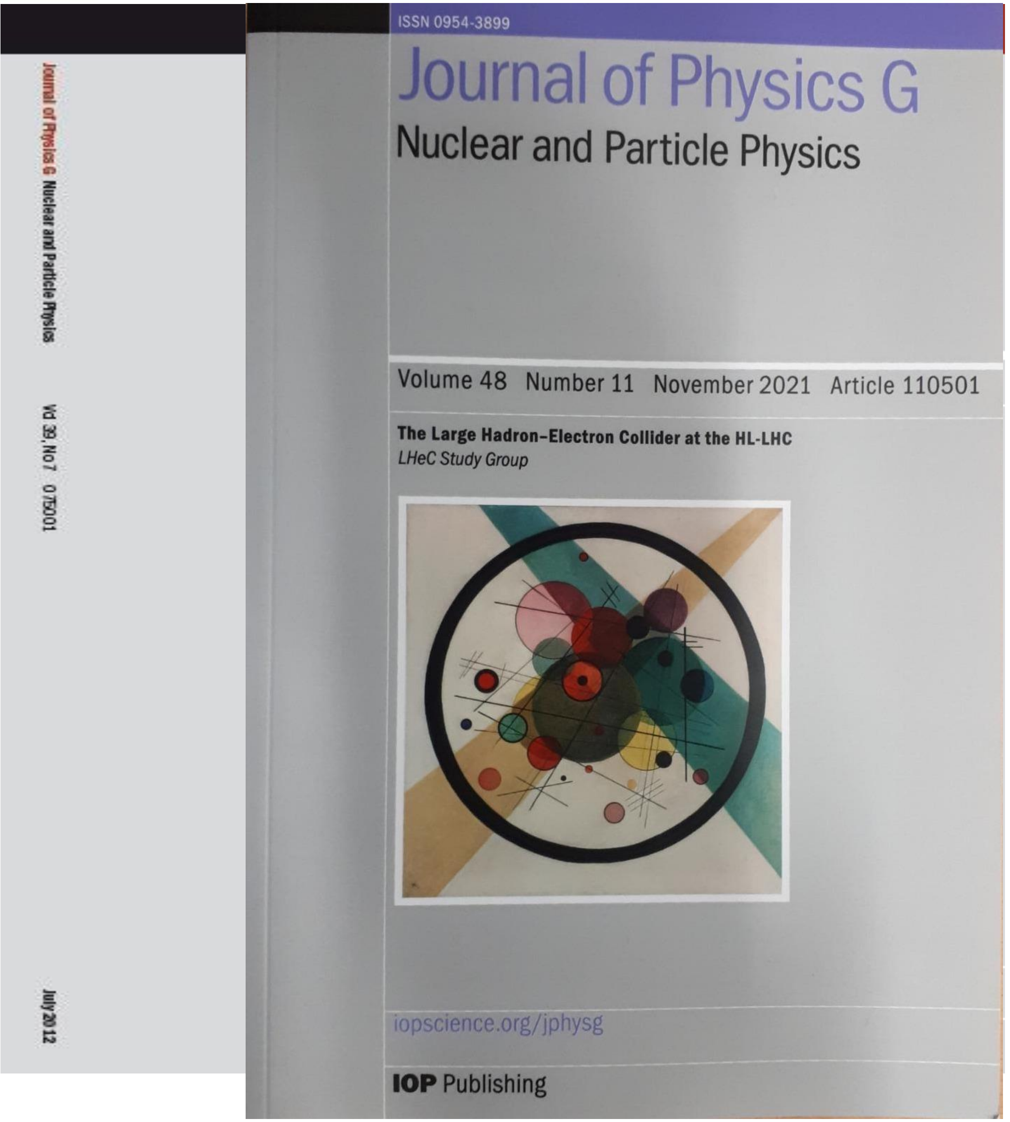
➔ (beam & SR power < 70 MW)

➔ 60 GeV beam energy ➔ 50GeV

-Int. Luminosity > 1000 * HERA

-Peak Luminosity > 10^{33} cm^{-2}s^{-1}

Higgs @ 125GeV ➔ > 10^{34} cm^{-2}s^{-1}



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The Large Hadron–Electron Collider at the HL-LHC

LHeC Study Group

iopscience.org/jphysg

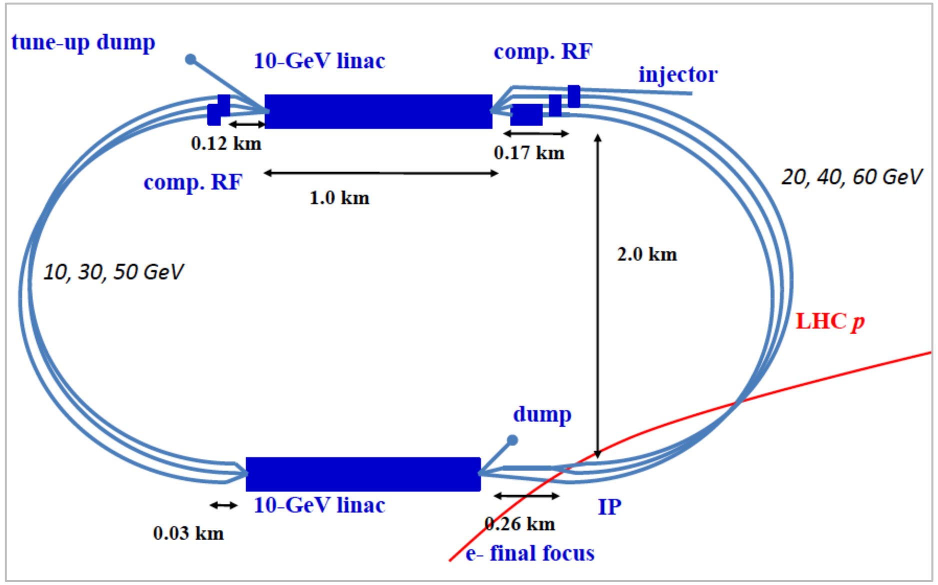
IOP Publishing

Courtesy Oliver Brüning, CERN

Application: LHeC / FCC ERL Configuration

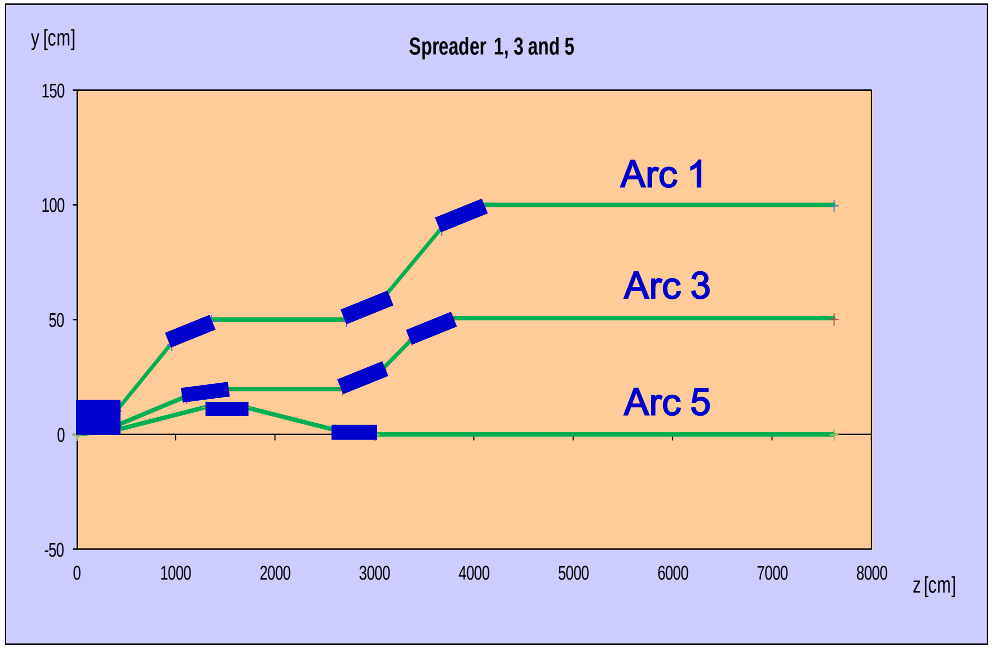
* LHeC CDR, arXiv:1206.2913

🟩 Racetrack design: 3-turn Recirculating SRF Linac and ERL operation



Operation in parallel with LHC/HE-LHC/FCC-hh

- TeV scale collisions ➔ 50-60 GeV e-beam energy
- power consumption O(100 MW) ➔ ca. 50/50 SR and TI



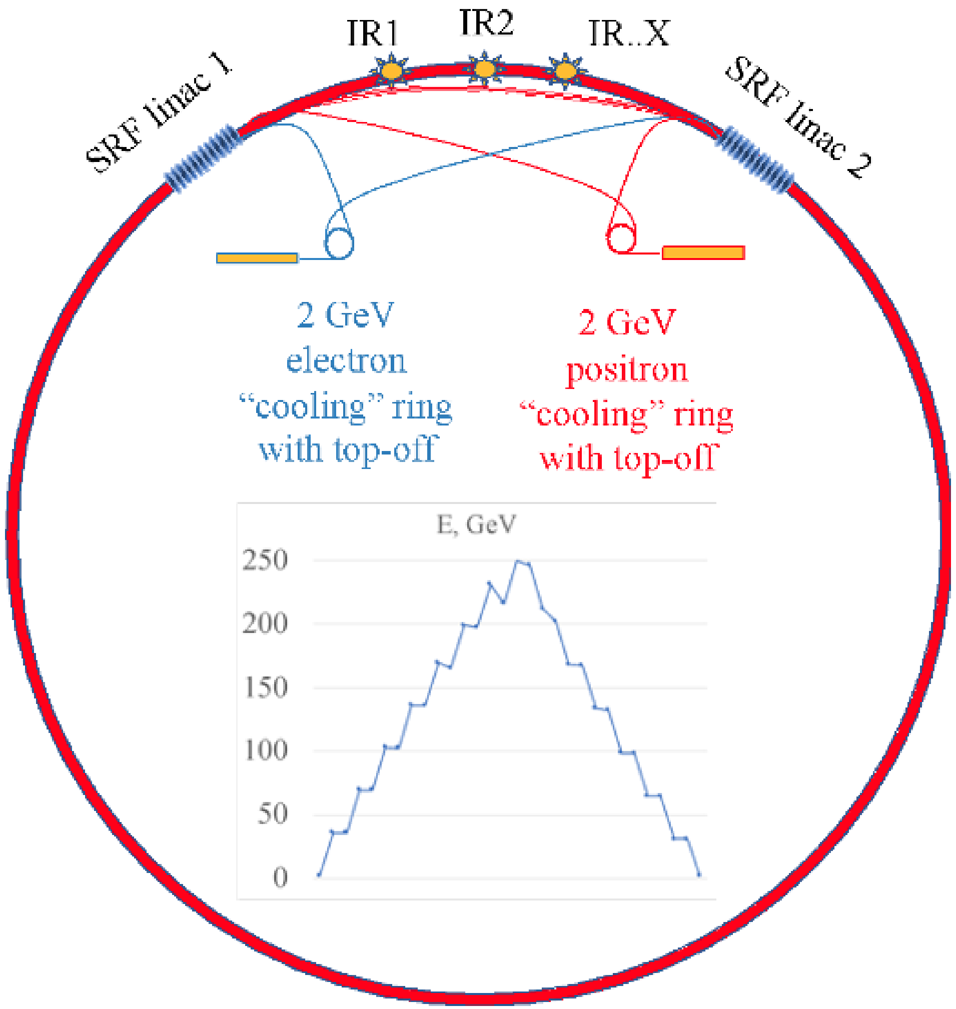
➔ Two 1km long SRF linacs

➔ 3 separate return arcs at each end of the linac, matched for the beam energies

➔ Each beam passes 6 times through the SRF: 3 passes with acceleration and 3 with passes deceleration ➔ 6 times I_e in SRF!

courtesy H.Burkhardt, CERN

Circular Energy Recovery Collider Concept: CERC proposal



- Two 11 to 90 GeV SRF linacs in 4 pass configuration
- 1/3rd of power consumption as compared to circular collider
- CM Energy reach of 600 GeV in 100 km circumference tunnel
- Damping rings for emittance reduction and recycling of beams

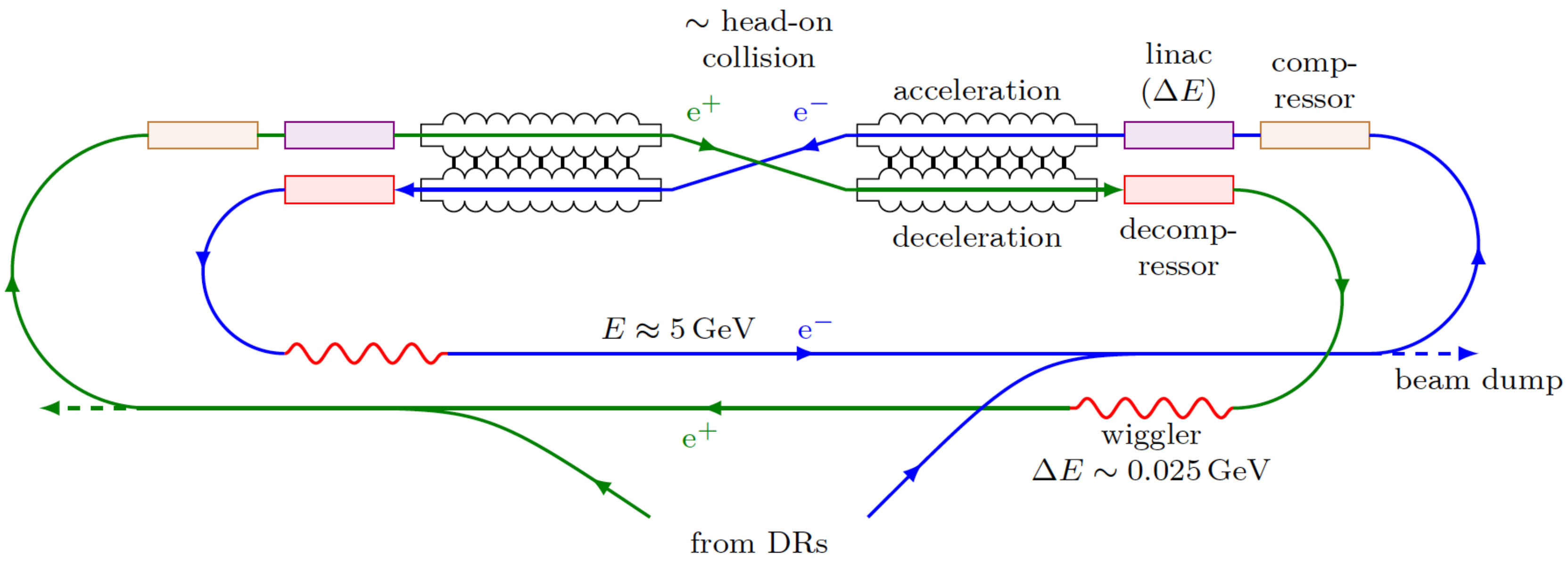
https://arxiv.org/abs/1909.04437

Physics Letters B, 804 (2020) 135394

- Maximum Power of 300 MW per beam @ 120 GeV and 2.47 mA

V. Litvinenko BNL and Stony Brook University; T. Roser BNL; M.C. Llatas BNL

Energy Recovery Linear Collider Concept: ERLC proposal



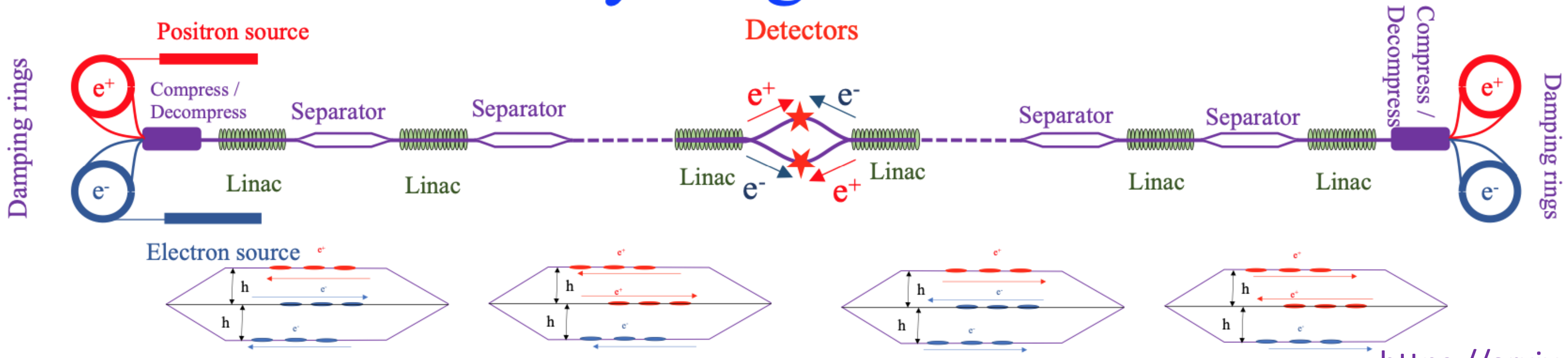
V. I. Telnov. JINST 16 (2021) P12025

- ERLC consists of two parallel superconducting linacs connected to each other with RF-couplers, so that the fields are equal at any time
  - One line is for acceleration, the other for deceleration.
- Damping is provided by wigglers (no damping rings) at the “return” energy about E~5 GeV
- The energy loss per turn δE/E~1/100
- Damping is needed to reduce the energy spread arising from collision of beams

Baseline Layout

ReLiC – Recycling Linear Collider

Snowmass 2021



V.I. Litvinenko et al., https://arxiv.org/abs/2203.06476

- Flat beams cooled in damping rings with "top off" to replace burned-off particles
- Bunches are ejected with collision frequency, determined by the distance between beam separators
- Beams are accelerated **on-axis** in SRF linacs collide in one of detectors
- After collision at the top energy, they are decelerated in the opposite linacs
- Bunch trains are periodically separated from opposite beam, with accelerating beam propagating **on-axis**
- Decelerated beams are injected into cooling rings
- After few damping times the trip repeats in the opposite direction and beams collide in a detector located in the opposite branch of the final separator …..

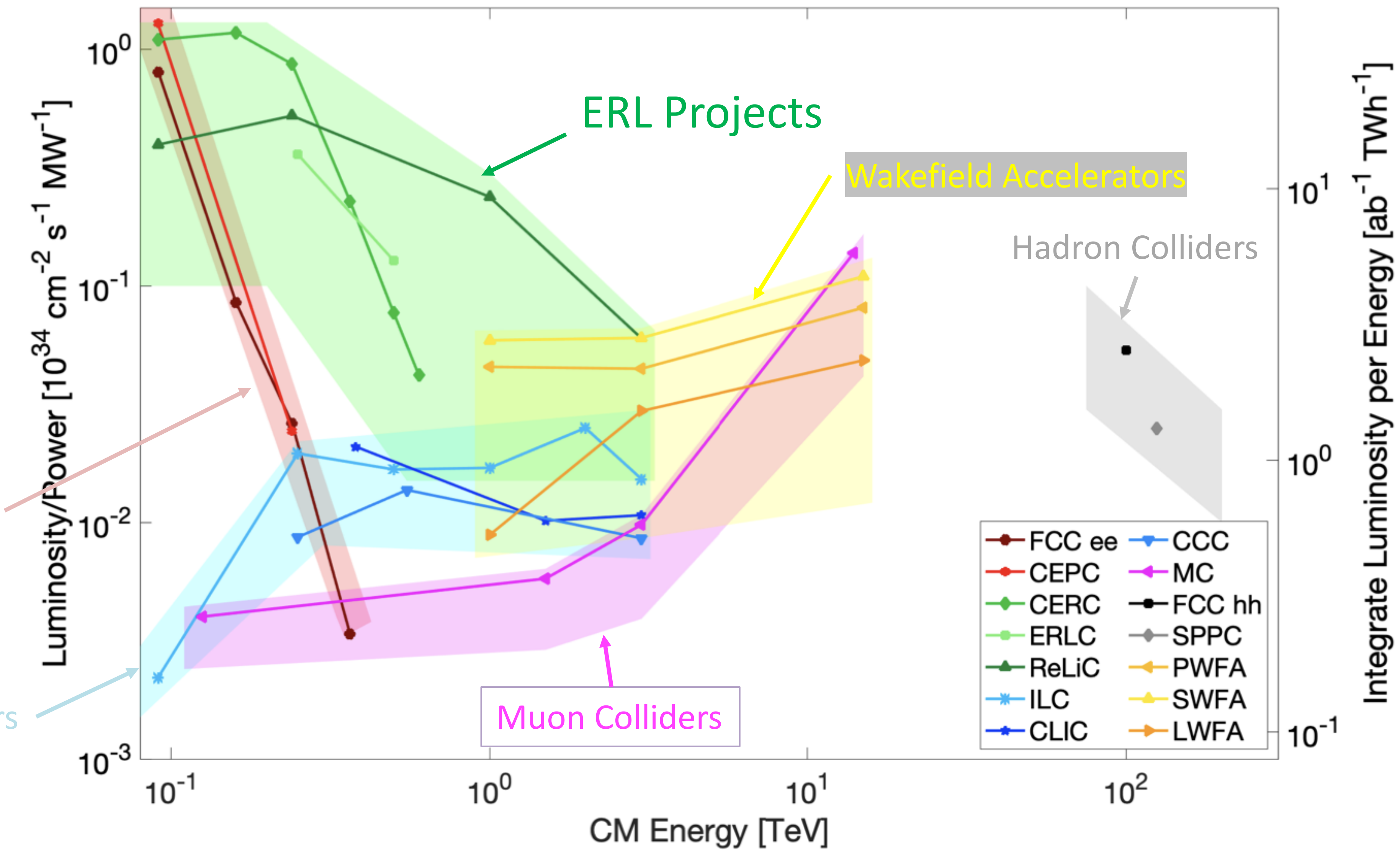
$$F_x = \pm e\left(E_x + \frac{v_z}{c} B_y\right) = \left\{ \begin{array}{c} 0, \mathit{acclerating} \\ 2eE_x, \mathit{decelerating\ postions} \\ -2eE_x, \mathit{decelerating\ electrons} \end{array} \right\}$$

ReLiC collider recycles polarized electrons and positrons

- Reusing electron and positron beams beam cooled in damping rings provides for natural polarization of both beam via Sokolov-Ternov process. Depolarization in the trip between damping ring is minuscular, which would provide for high degree of polarization. With lifetime ~ 10 hours, necessary replacement of electrons and positrons is at 1 nA level – this is major advantage of ReLiC

Report of the Snowmass'21 Implementation Task Force

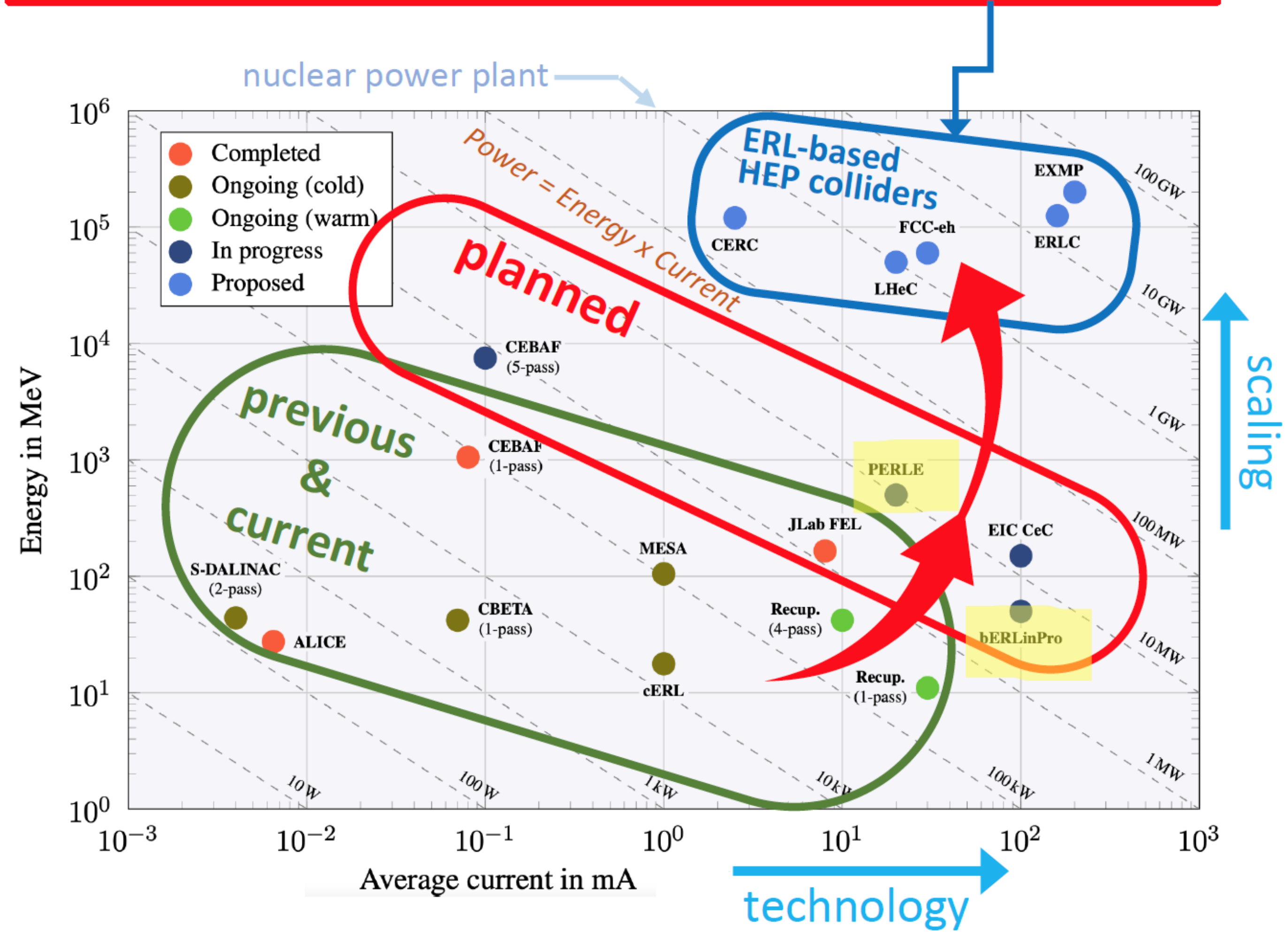
- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh
- Data points were provided by proponents of the respective machines
  - No independent checks



https://arxiv.org/abs/2208.06030

ERL R&D Goals

ERL to enable high-power beams that would otherwise require one or more nuclear power plants



- Primary goal is to provide high luminosity at high energies with improved sustainability
- Increase in energy requires a large financial investment not R&D
- The technology axis requires targeted R&D
- Decrease in cryogenic power requirements
  - Improve cryogenic plant efficiency
  - Operation at 4.5 K
  - Nb_3Sn technology

  } Included in SRF Roadmap
- Increase in bunch current
  - Reduce reflected power (FRTs)
  - High efficiency over a wide power output
  - Magnetrons
- Increase in bunch charge
  - Extract higher order modes (HOMs) from cavities

Cryogenics


Jefferson Lab CHL 2

- Requires 4.2 MW at 300 K to produce 4.6 kW cooling power at 2 K
  - Not as efficient as it could be, partially because the cold box is old technology
  - The warm helium compressors are the least efficient components of the system (50-60%) and stand to gain the most from R&D
  - R&D not being pursued anywhere in the world

Cryogenics

- The cryogenic plant is the largest contributor to the electrical efficiency of an ERL facility, driven by the dynamic heat load in the superconducting cavities
- The Coefficient of Performance (COP) is often (but not universally) used to quantify the efficiency of the cryoplant
  - Lower COP value is better
- It is defined as the grid power in watts to provide one watt of cryogenic cooling
  - Jefferson Lab COP ~ 860 @ 2 K and 240 @ 4.2 K
  - Carnot efficiency = 150 @ 2 K and 72 @ 4.2 K

Room for Improvement!

- In a typical cryoplant, additional power is required for the cryo-support systems (e.g., guard vacuum, purifier), heat shields, cryo-controls, and conventional utilities (e.g., cooling water, instrument air), none of which are included in the COP
- For the overall energy efficiency, it is the total power from the grid for a given cooling capacity in the SRF cavities that is important

Components of Cryogenic Efficiency

- R&D is being carried out on the contributing components to improve the overall efficiency
- R/Q is determined by the cavity shape alone
  - The cavity shape has been exhaustively optimized – unlikely to see big improvements
- Q_0 is inversely proportional to the cavity surface resistivity and depends on the operating temperature (2 K or 4.5 K)
  - Included in the SRF Roadmap as this affects all SRF projects

“Gated” RF

- Superconducting ERLs have always been CW, but Valery Telnov proposed a “gated” scenario for the ELRC where the RF is on for two seconds and off for four seconds
    - This reduces the cryogenic load by a factor 3
- Establishing the required bunch pattern in this design would be complicated with ramp-up and ramp-down of the beam, and the gated RF makes this easier
- It is likely, but not demonstrated, that the cryostat would provide a thermal buffer and the cryoplant would only see the average power
- The only caveat is that the liquid helium should not boil, a condition that is assured if the cavity is being used with the peak gated RF power equal to the CW power for which it was designed

- This operating mode should be tested soon as it could have a large impact on future facilities, but no facility is currently planning to carry out a test

RF Power

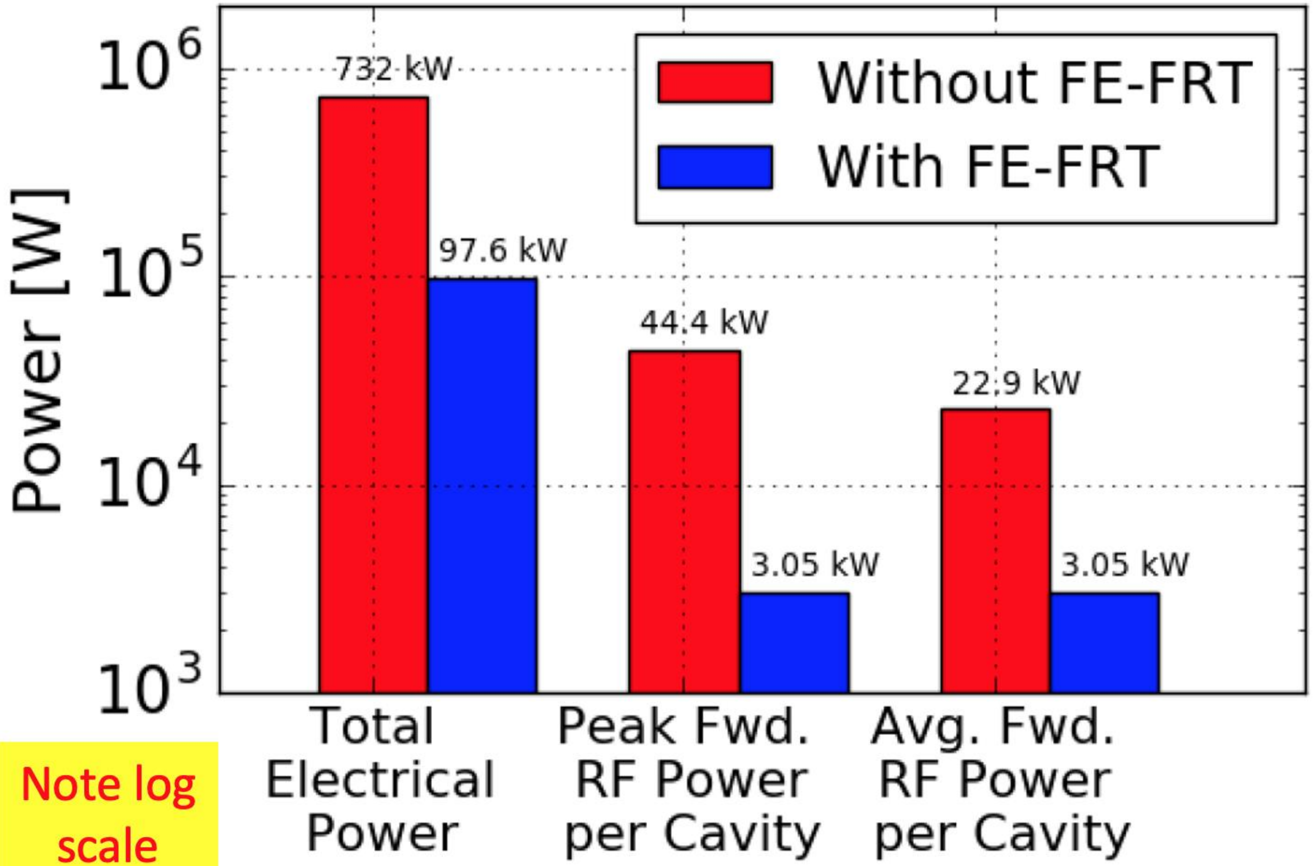
- Fundamental power coupler R&D usually aims for high power delivery, but not for ERLs where the load is small
- The RF power P consumed by a detuned cavity to maintain a voltage V with zero beam loading is given by:

$$P = \frac{V^2}{8\frac{R}{Q}Q_L}\frac{\beta+1}{\beta}\left[1+\left(\frac{2Q_L\Delta\omega}{\omega_0}\right)^2\right]$$

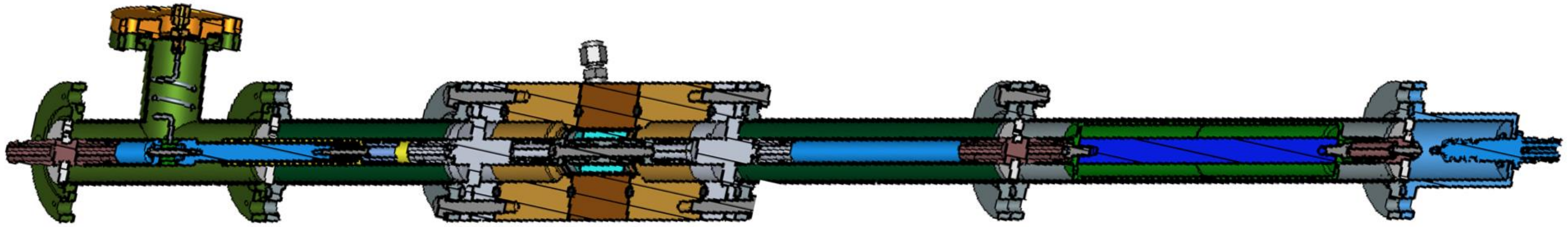
  - where Q_L is the loaded quality factor, β is the coupling factor, R/Q is the shunt impedance in circuit definition and Δω is the detuning of the SRF cavity from the nominal frequency ω_0
- Microphonics (vibrations of the cavity) move the resonant frequency of the cavity outside the bandwidth of the RF source, increasing Δω leading to reflection of the RF power
  - To mitigate this, all ERLs to date have reduced Q_L to minimize the total RF power
  - Better to minimize Δω

→ Fast Reactive Tuners

FerroElectric Fast Reactive Tuners (FE-FRTs)



Note log scale



- FerroElectric Fast Reactive Tuners (FE-FRTs) are being developed to minimize reflected RF power by compensating the cavity frequency change due to microphonics
- The change in tuning is achieved using an external magnetic field to change the permittivity of a special ceramic
- The FE-FRTs can respond to fast transients (up to 10 MHz)
- Simulations show that the reflected RF power can be reduced by about an order of magnitude
- R&D part of iSAS

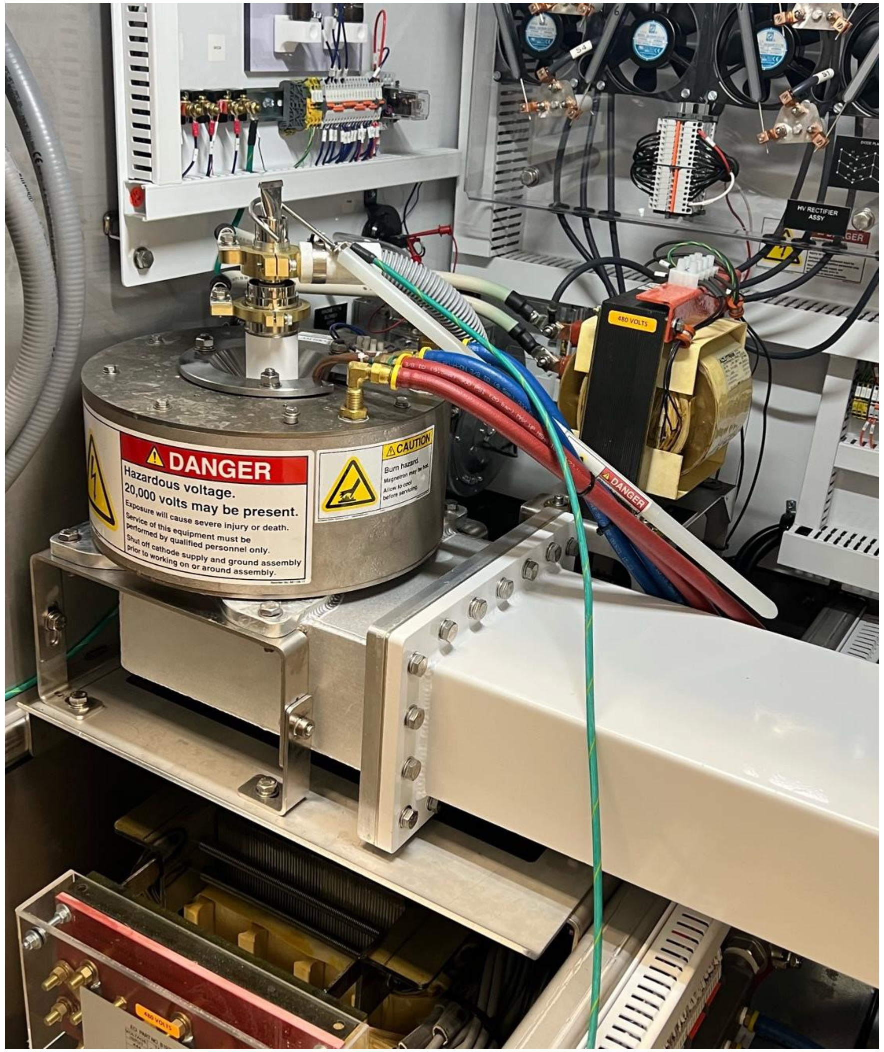
RF Sources

- An ERL needs power sources for initial commissioning with once-through beam, but will mostly be used at much lower power (particularly if the cavities are equipped with FE-FRTs)
- Klystrons have high power, high gain, and excellent phase and frequency stability but the electrical power from the grid is virtually independent of the output power
  - Lower efficiency at lower output power
- Solid State Amplifiers (SSAs) have many transistors combined to provide high efficiency (~70%) at maximum power, but transistors have reduced electrical efficiency when operated at low power
- Since most klystrons and SSAs are operated below the maximum output, the electrical efficiency is reduced in operation
- SSAs with high efficiency over a broad range of output power should be the next R&D goal

Solid State Power Amplifiers at the CERN PS

Magnetrons

- Magnetrons are high power (kW to MW), high efficiency (~90%) RF sources which suffer from inferior phase and frequency stability because they are natural oscillators rather than amplifiers
- High efficiency make magnetrons a dynamic R&D topic
- The best approach appears to be via injection locking to stabilize the phase and fast amplitude response which moves power into sidebands that are reflected from the cavity
- Progress is being made, but magnetrons are not ready for prime time yet



75 kW, 915 MHz Magnetron under test at Jefferson Lab

Higher Order Modes (HOMs)

- ERLs with a high beam current and/or high bunch charge must manage the resulting large HOM power, because the HOM energy from the accelerating and decelerating beams is additive
- The HOMs must be extracted from the cavities to minimize beam instabilities and to reduce heating of the superconducting cavity walls
  - The higher frequencies can be handled using beamline absorbers; ideally, they should be situated outside the cryostat at room temperature
- Lower frequency HOMs are trapped in the cavities
  - Coaxial or waveguide couplers are used to extract them
- HOMs have been extracted to 80 K in cryostats with multiple cavities

- Extraction of HOMs to room temperature is being actively studied in iSAS

Outlook

- ERLs have already demonstrated impressive efficiency in routine operation
- These advantages need to be enhanced with targeted R&D and demonstrated at higher energies in a multi-turn configuration
  - This is the role of bERLinPro, PERLE and iSAS
- R&D recommendations
  - Improved cryogenic plant efficiency
  - “Gated RF” tests
  - SSAs with high efficiency over a broad range of output power
  - Magnetrons
- ERLs provide higher luminosity for the same site power, a major advantage for future high-energy colliders