# Energy Recovery Linac Facilities

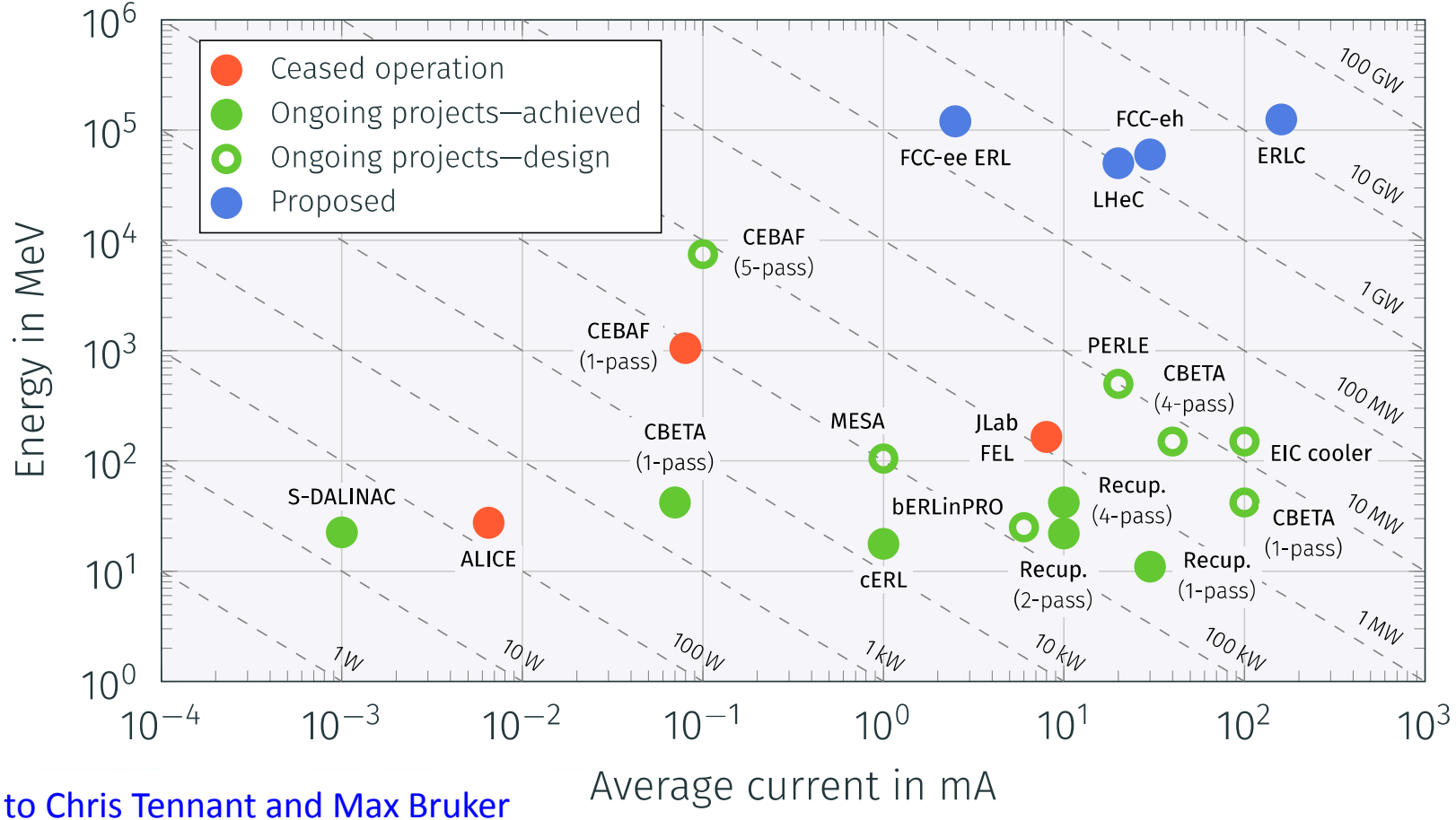
Andrew Hutton

# Overview

- Landscape
- Facilities that have ceased operation: ALICE, JLab FEL, CEBAF 1-Pass
- Ongoing Facilities: s-Dalinac, bERLinPro, cERL, Recuperator, CBETA
- Facilities in Progress: MESA, PERLE, CEBAF 5-Pass, EIC Cooler
- Parameters

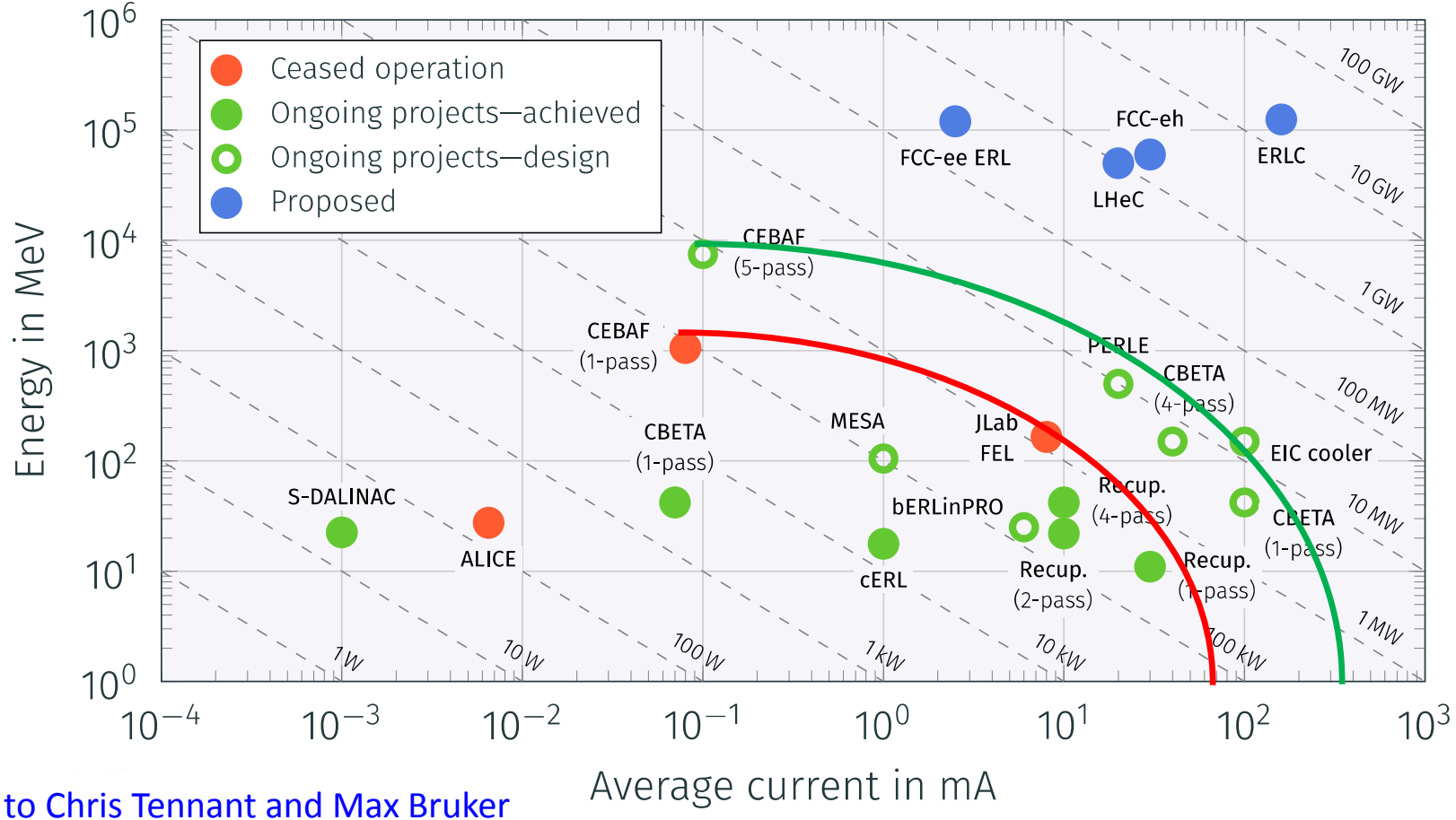
- Thanks to the ERL Panel members and many others who sent me information about their projects
  - But any errors are all mine!

# ERL Landscape




Thanks to Chris Tennant and Max Bruker

# ERL Landscape




Thanks to Chris Tennant and Max Bruker

# Facilities That Have Ceased Operation
## (but still hold a record for something)

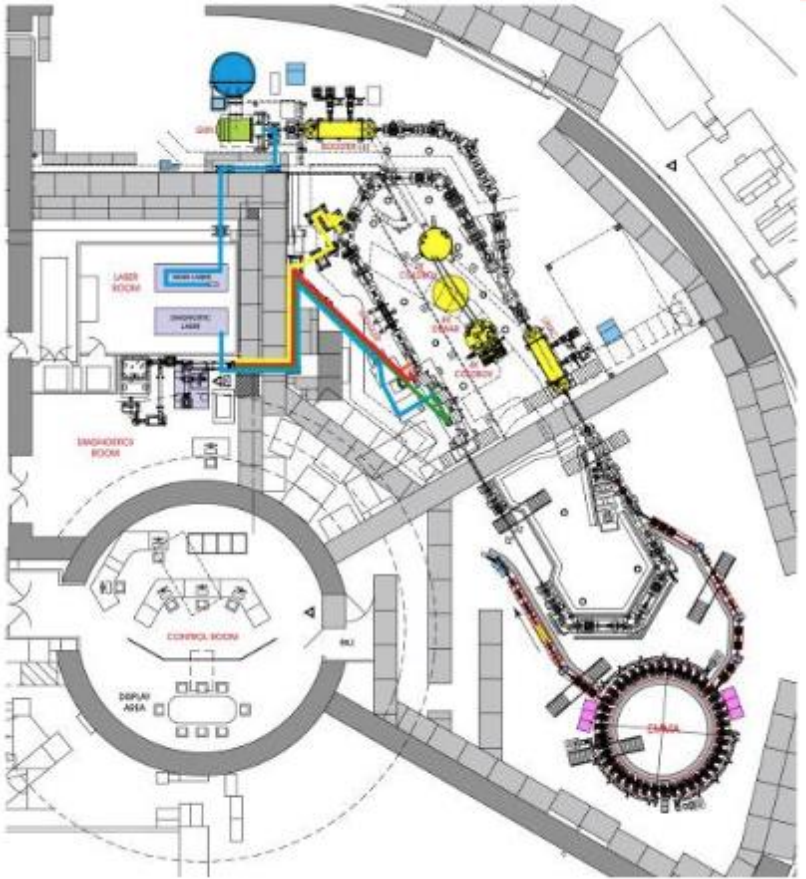
ALICE, Jefferson Lab FEL, CEBAF 1-Pass

# ALICE

- Where: STFC, Daresbury
- Energy: 27.5 MeV
- Beam Power 0.18 kW

Why it is important:

- First ERL in Europe



# Jefferson Lab FEL

- Where: Jefferson Lab, USA
- Energy: 165 MeV
- Beam Power 1300 kW

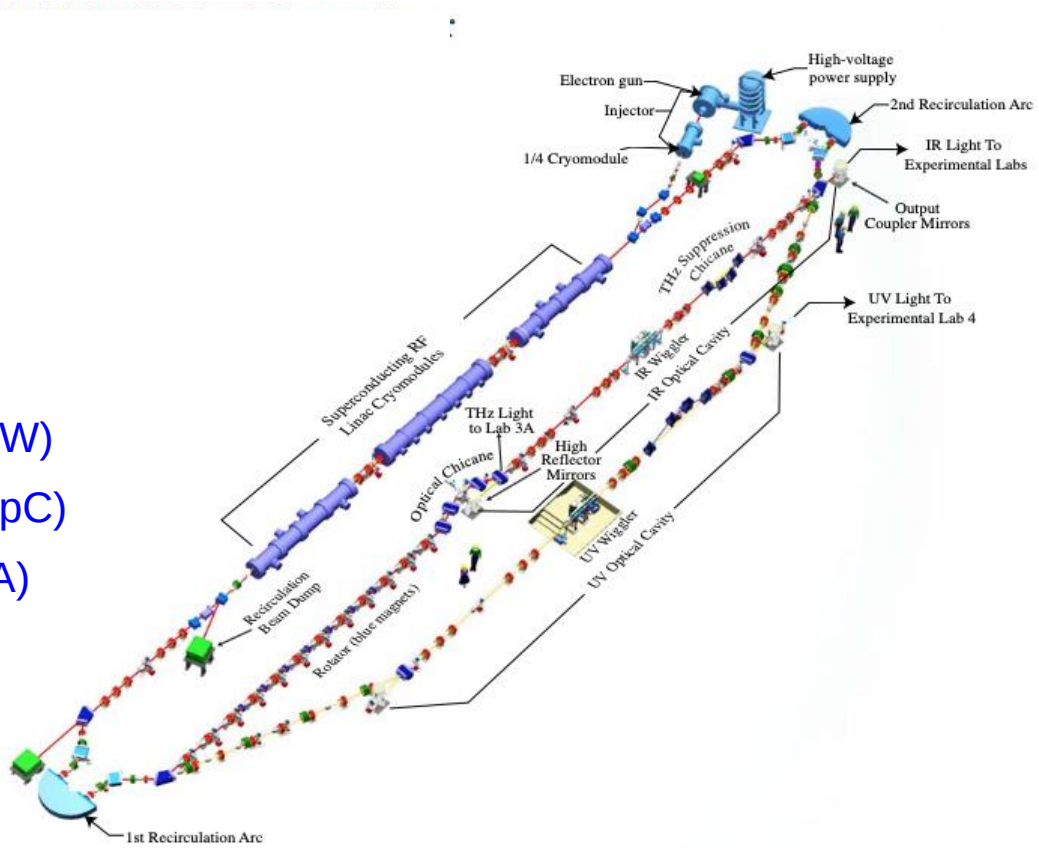
Why it is important:

First SRF ERL

Record beam power for SRF ERL (1.3 MW)

Record bunch charge for SRF ERL (270 pC)

Highest beam current for SRF ERL (9 mA)

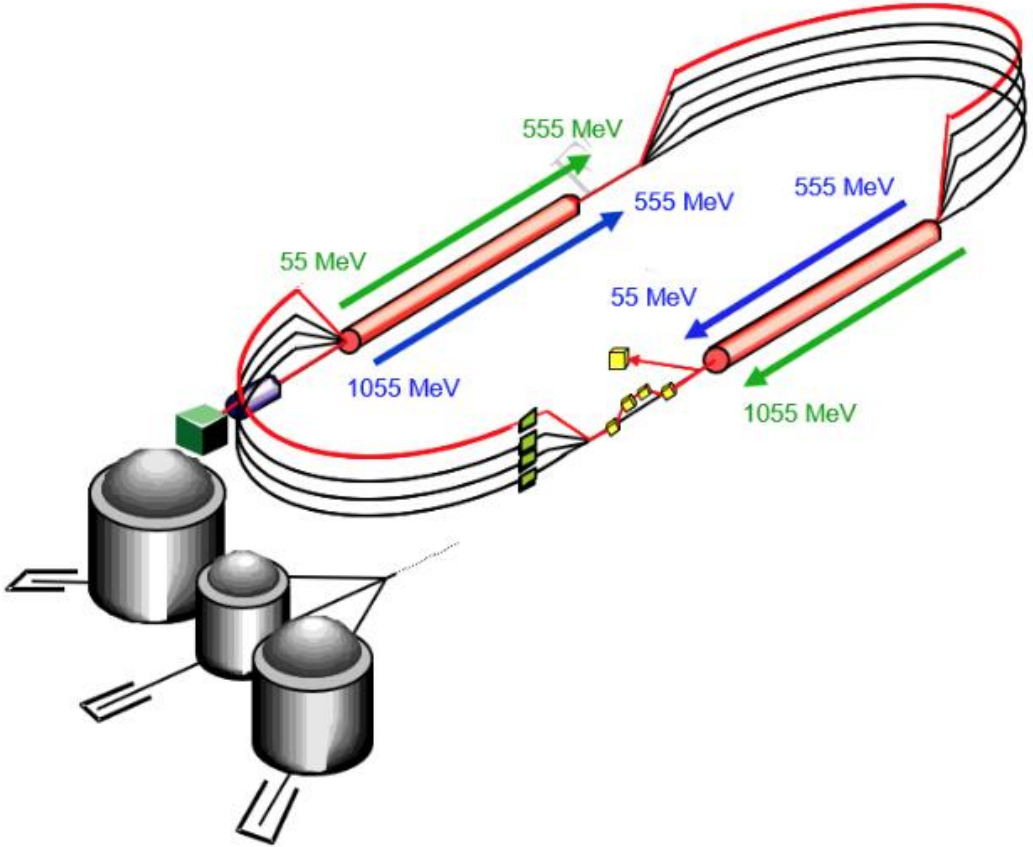


# CEBAF 1-Pass

- Where: Jefferson Lab, USA
- Energy: 1045 MeV
- Beam Power 104.5 kW

Why it is important:

- Highest energy achieved



## Ongoing Facilities

s-DALINAC, bERLinPro, cERL, Recuperator, CBETA

# S-Dalinac 1 / 2 pass

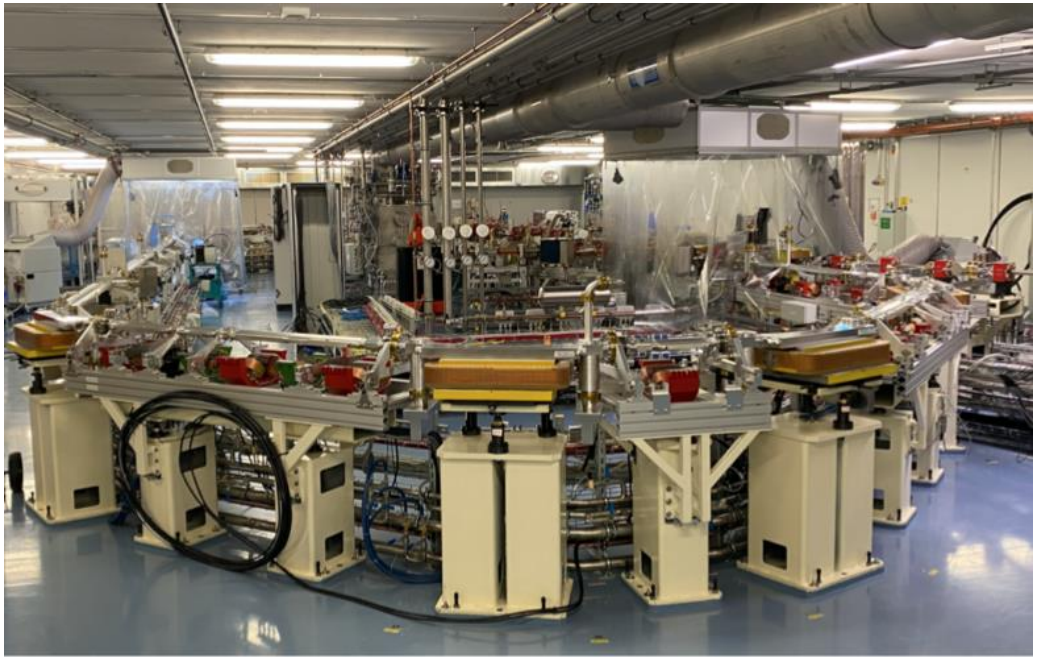
- Where:  Technische Universität Darmstadt, Germany
- Energy: 22.5 MeV / 34.2 MeV
- Beam Power  2.6 kW

Why it is important:

- Single pass operation since 1991
- Two pass operation in progress
- Being continually improved with student participation

# bERLinPro

- Where: Helmholtz-Zentrum Berlin, Germany
- Design Energy: 25 MeV
- Achieved Beam Power: 150 kW
- Design Beam Power: 2.5 MW

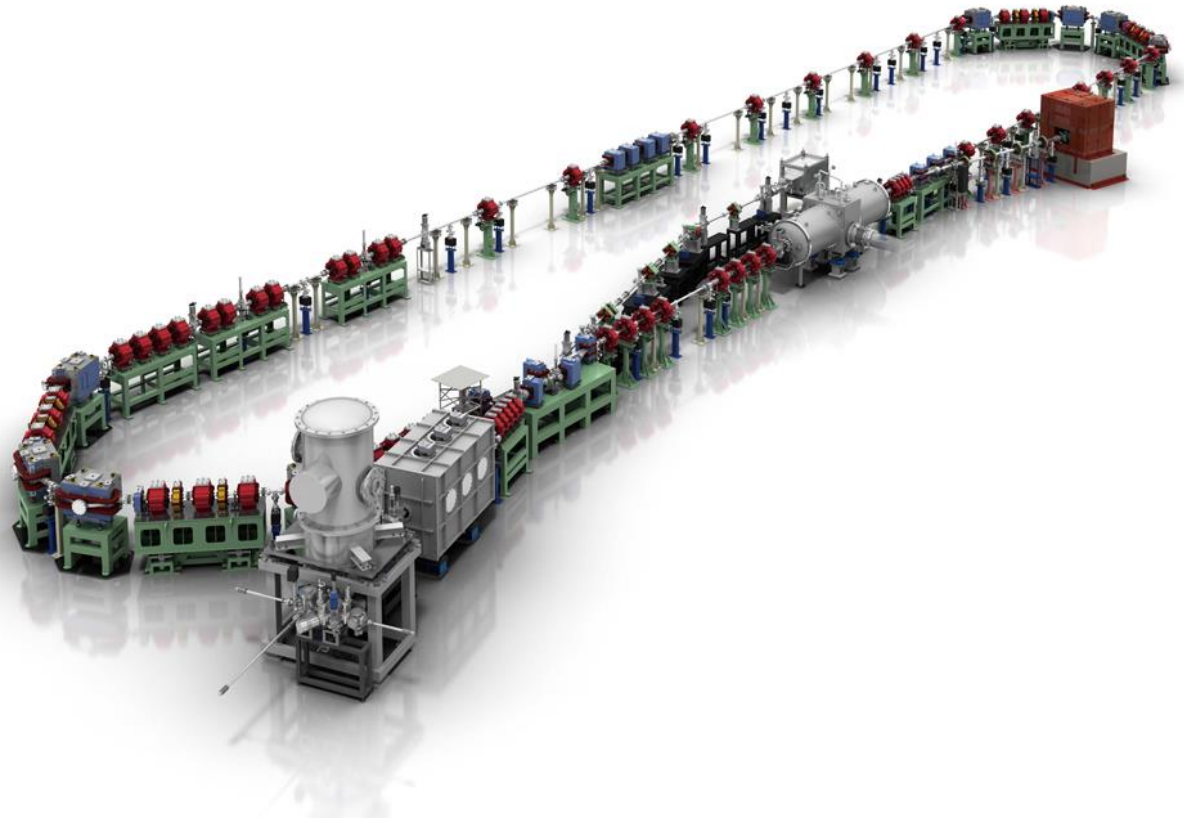


- Why it is important:
- Highest gun current proposed (100 mA)
- SRF gun development

# cERL

- Where: KEK, Japan
- Energy: 17.6 MeV
- Achieved Beam Power: 16 kW

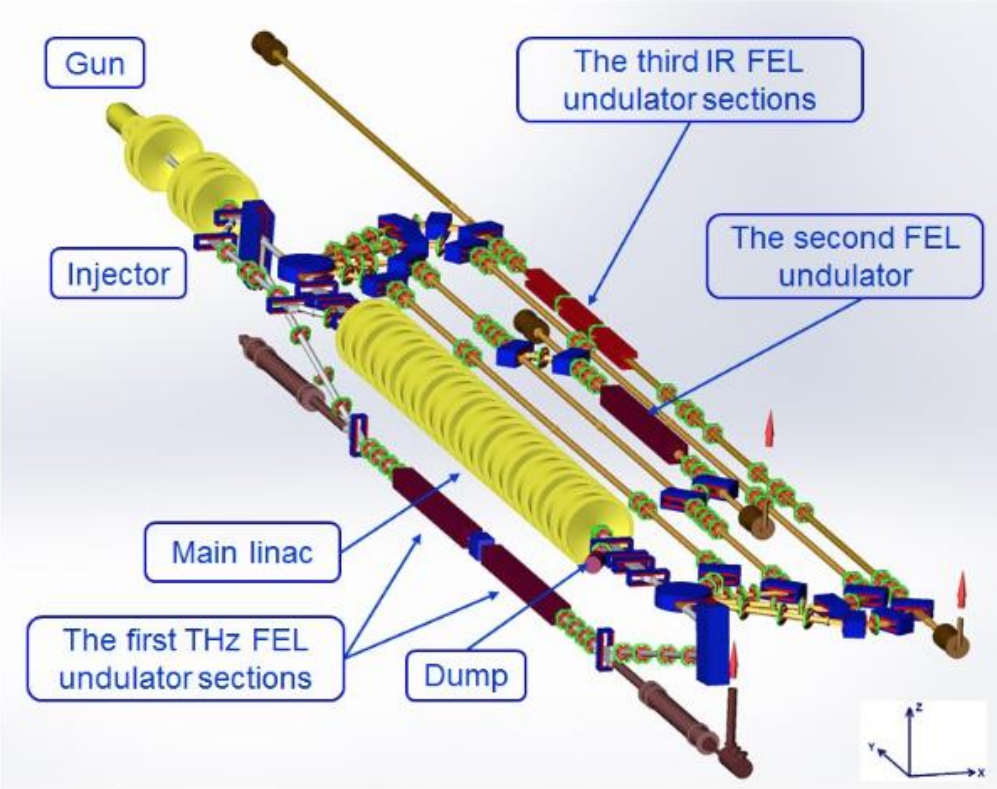
- Why it is important:
- Highest gun voltage (500 keV)
- Future UV-FEL



# Recuperator

- Where: BINP, Novosibirsk, Russia
- Energy: 40 MeV
- Achieved Beam Power: 200 kW

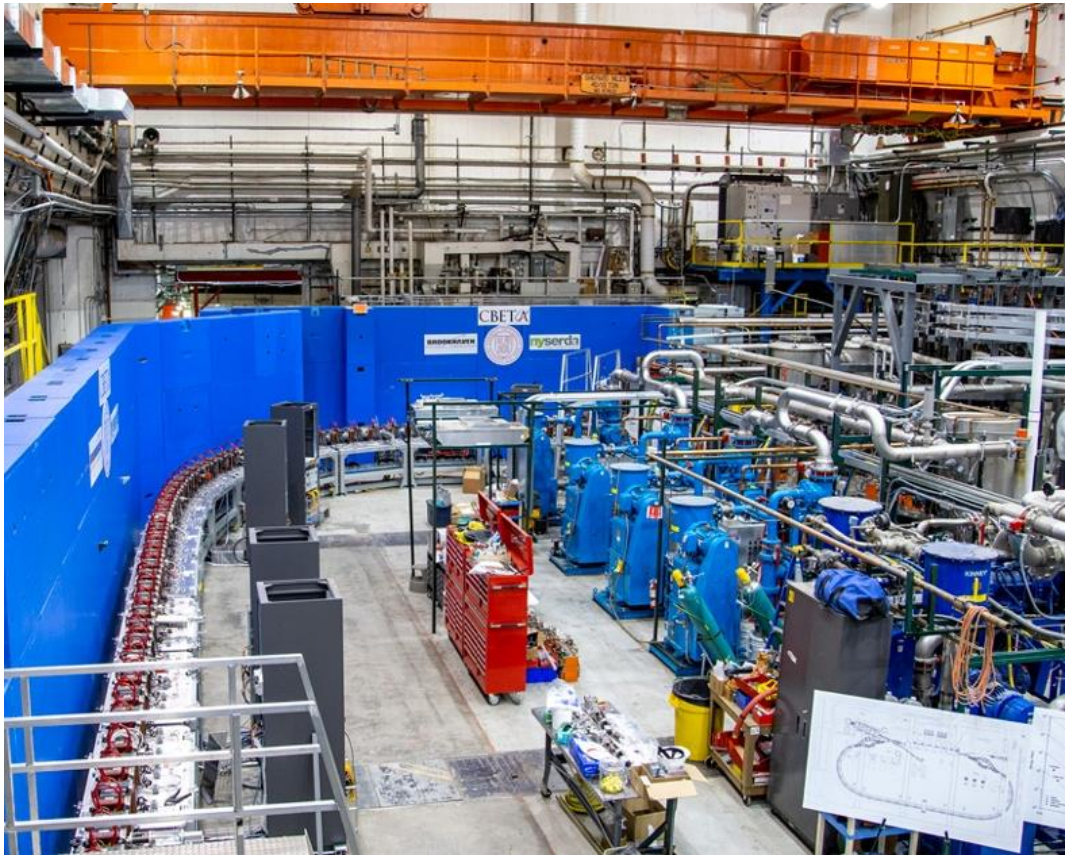
- Why it is important:
- Highest current (10 mA) and bunch charge (1.5 nC) in ERL mode
- Operates 3 FELs at different energies
- Only non-SRF ERL



# CBETA 1 / 4 pass

- Where: Cornell University, USA
- Energy: 42 / 150 MeV
- Achieved Beam Power: 3 kW / 0.3 W
- Design Beam Power: 4.2 / 6 MW

- Why it is important:
- Highest gun current achieved (75 mA), but not in ERL mode
- Highest number of passes achieved in SRF ERL
- First ERL facility with FFAG arcs



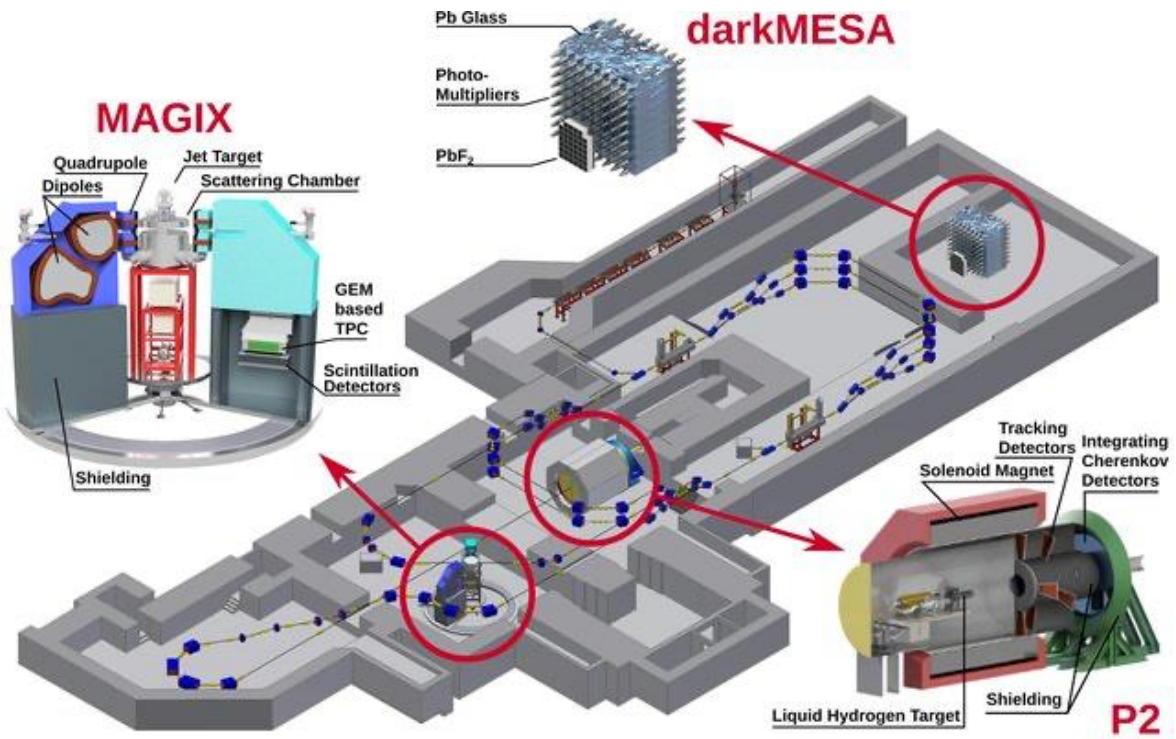
## Facilities in Progress

MESA, PERLE, CEBAF 5-Pass, EIC Cooler

# MESA

- Where: U Mainz, Germany
- Energy: 105 MeV
- Beam Power  210 kW

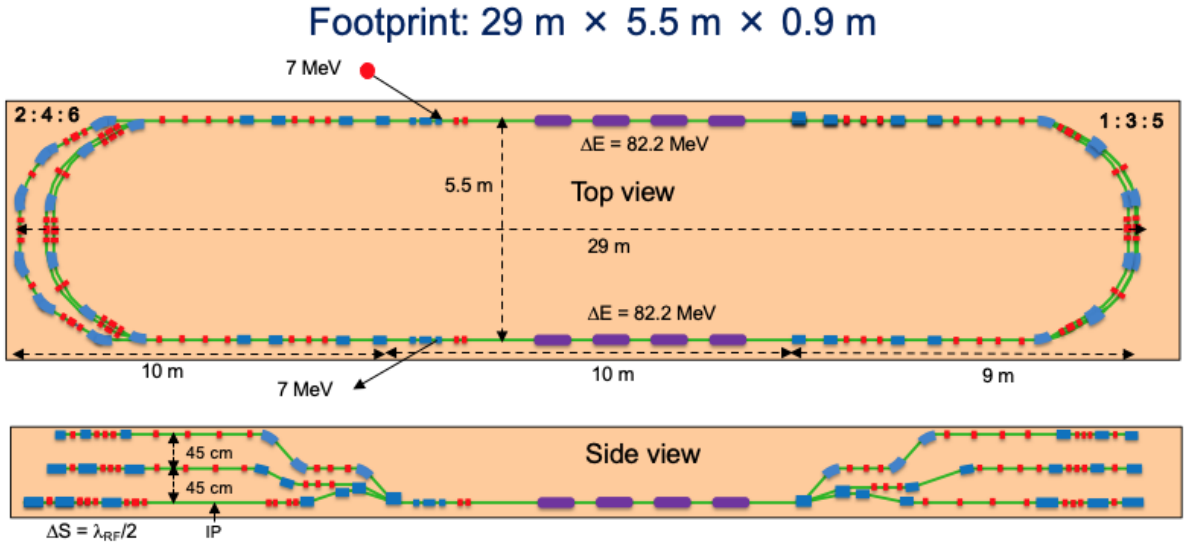
- Why it is important:
- First completely instrumented ERL facility for particle and nuclear physics



# PERLE

- Where: IJCLab, Orsay, France
- Energy: 500 MeV
- Beam Power  10 MW

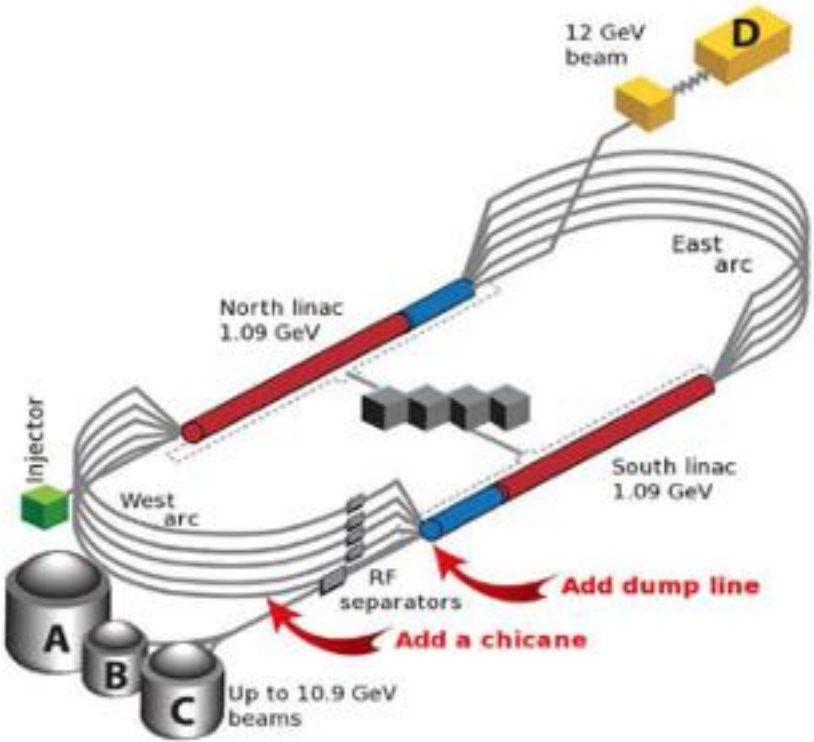
- Why it is important:
- First high power, high energy facility in Europe
- Test-bed for future high-power ERL facilities, specifically developing LHeC and FCC-ee technologies



# CEBAF 5-Pass

- Where: Jefferson Lab, USA
- Energy: 7584 MeV
- Beam Power: 0.75 MW

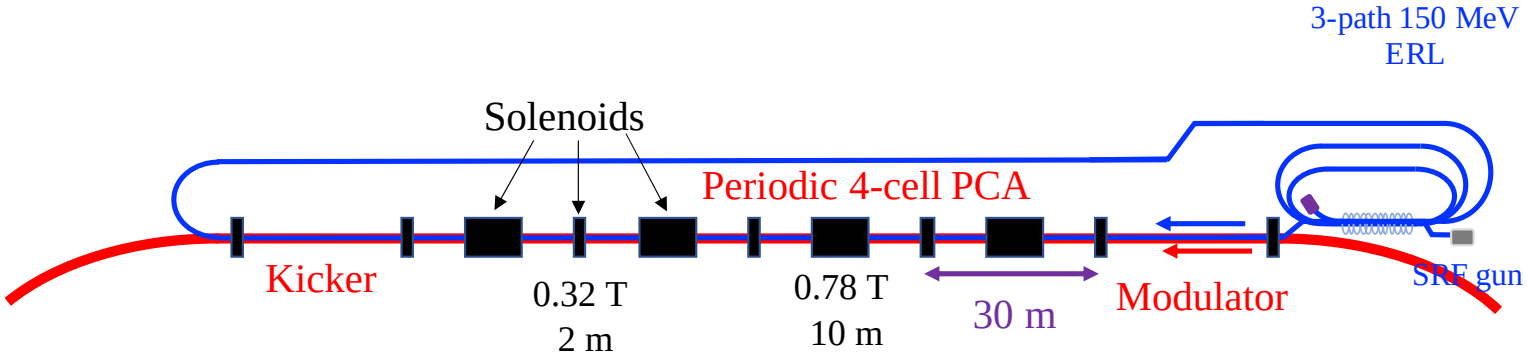
- Why it is important:
- Highest energy multi-turn ERL proposed
- Highest number of passes proposed (5)



# EIC Cooler

- Where: Brookhaven National Lab, USA
- Energy: 150 MeV
- Beam Power: 14.7 MW

- Why it is important:
- Highest power multi-pass ERL proposed
- Highest beam current proposed (98.5 mA)



## Future Facilities

LHeC, FCC-eh, FCC-ee ERL and ILC ERL
will be presented by Oliver Brüning

# Summary

- ERLs have been developing for decades with ever improving specifications
- They are now almost ready to move from small machines (but with considerable beam power) to the large machines that will be required for the high energy frontier
- PERLE is will be an important step in demonstrating all of the technologies needed for the LHeC
- There are three other design studies DIANA in STFC, DICE in Darmstadt and BriXSino in Milano at various stages of development that show the continued interest in ERLs
- As part of the ERL Panel, the parameters of the principal ERL facilities have been collected
  - Preliminary values are given here, but they are subject to correction as the Panel moves forward

| | | | Completed Facilities | | | Ongoing Facilities - Parameters Achieved | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | ALICE | JLab FEL | CEBAF 1-Pass | s-Dalinac 1/2 Pass | bERLinPro | cERL | Recuperator | CBETA 1/4 Pass |
| | | | STFC, UK | Jefferson lab, USA | Jefferson Lab, USA | TU Darmstadt, Germany | HZB, Germany | KEK, Japan | BINP, Russia | Cornell, USA |
| **ERL** | **Top energy** | **MeV** | 27.5 | **165** | **1045** | **22.5/34.2** | **25** | **17.6** | **40** | **42/150** |
| | **Beam power** | **kW** | **0.18** | **1300** | **104.5** | **2.6** | **150** | **20** | **200** | **2.9/0.3** |
| Source | Gun Energy | keV | 350 | **100** | 100 | 125/250 | <3500 | **500** | 300 | 350 |
| | Bunch charge | pC | 60 | **270** | 0.06 | | 77 | 0.77 | **1500** | 5 |
| | Current | mA | 5 | 8.5 | 0.1 | 0.0012 | <6 | 0.9 | **10** | 0.07, 2x10^-6 |
| | Polarization | | No | No | No | Yes/No | No | No | No | No |
| Injector | Beam energy | MeV | 6.5 | **9** | 25/45 | 2.5/3.8 | 6 | 3 | 1.5 | 6 |
| | Emittance | $\mu$m | 2.5 | 8 | 0.05 | | ≤ 1 | 0.29, 0.26 | 20 | 0.3 |
| Acceleration | Energy gain/linac | MeV | 20 | 156 | 2 X 500 | | ~ 28 | 14.6 | 10 | 6 |
| | RF Frequency | MHz | 1300 | 1497 | 1497 | 3000 | 1300 | 1300 | 180 | 1300 |
| | Bunch repetition rate | MHz | 0.000001 | | 1497 | | | | 5.6, 7.5, 3.8 | |
| | Total Linac Current | mA | 10 (peak) | 17 | 0.2 | 0.004, 0.0002 | < 12 | 1.8 | 10, 30, 70 | 0.28, 8x10^-6 |
| | Harmonic frequency | MHz | 81.25 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | Macropulse length | $\mu$sec | 100 | CW | CW | | CW | CW | CW, copper | CW |
| | Bunch charge | pC | 60 | **270** | 0.06 | | 77 | 0.77 | 1500 | 5 |
| | Normalized Emittance | $\mu$m | 3 | 10 | 0.05 | | ≤1 | 0.42/0.26 | 20 | 0.3 |
| | Gradient | MV/m | 11 | 12 | 12 | | 14 | 5.8 - 8.3 | 0.4 | 16 |
| | Quality factor | x $10^{10}$ | 5.00E+09 | 1 | 1 | | 1 | 0.25 - 0.6 | 4 x 10^-6 | |
| | RF controls | | Analog, DLLRF | Analog | Analog | | | | | |
| | Beam loss | nA | not measured | 100 | | | <10^-5 | <0.01% | | |
| | Multi-pass | | 1 + 1 | 1 + 1 | 1 + 1 | (1 + 1) / (2 + 2) | 1 + 1 | 1 + 1 | 1+1, 2+2, or 4+4 | (1 + 1) /( 4 + 4) |
| Arcs | Optics design | | | Bates bends | Achromatic, isochronous | | | DBA | 180-degree achromatic bends | FFAG |
| | Beam loss | % | 2 | <1 x 10^-4 | | | | <0.01% | 1% | |
| Interaction Regio | βx, βy | cm | 20 | ~6, ~6 | N/A | N/A | N/A | N/A | ~300 | N/A |
| | Beam size | $\mu$m | 50 | 50 | N/A | N/A | N/A | N/A | | N/A |
| | Beam Divergence | $\mu$rad | EM | Not measured | N/A | N/A | N/A | N/A | | N/A |
| | Magnets | | | Standard, warm | N/A | N/A | N/A | N/A | undulators and quadrupoles | N/A |
| Dump | Dump beam energy | MeV | < 10 | 11 | 25/45 | | 6 | 3 | 1.5 | |
| | Dump power | kW | 30 | 100 | 4.5 | | < 60 | 2.7 | 15 | 0.42, 0.012 |
| | Max CW current recovered | mA | 100% | 8.5 | 0.1 | | | 0.9 | 20 | 0.07, 2x10^-6 |
| Comment | | | First European SRF ERL | Highest power achieved Highest current and bunch charge achieved in SC ERL mode; Highest Injector energy | Highest energy achieved | | Highest gun current proposed | Highest gun voltage achieved in ERL mode | Highest current and bunch charge achieved in ERL mode | Highest gun current achieved, 75 mA, but not in ERL mode. Highest number of passes achieved |
| | | | | Interaction Region at 100 MeV, 0.6 mA | | | | | | FFAG Arcs |

# Completed Facilities

- Completed Facilities only include those that have a record performance in some parameter

# Ongoing Facilities

- Ongoing Facilities include some that are temporarily without funding

# Facilities in Progress

- Facilities include all active proposals that are partially or fully funded

| | | | Facilities in Progress - Target Values | | | |
|---|---|---|---|---|---|---|
| | | | **MESA** | **PERLE** | **CEBAF 5-Pass** | **EIC Cooler** |
| | | | U Mainz, Germany | IJCLab, France | Jefferson Lab, USA | BNL, USA |
| **ERL** | **Top energy** | **MeV** | **105** | **500** | **7584** | **22.3/54.1/150** |
| | **Beam power** | **MW** | **0.21** | **10** | **0.758** | **2.2/5.3/14.7** |
| Source | Gun Energy | keV | 100 | 350/200 | 100 | 400 |
| | Bunch charge | pC | 1 | 500 | 0.06 | 1000 |
| | Current | mA | 2 | 20 | 0.1 | 98.5 |
| | Polarization | | Yes | Yes & No | Yes | No |
| Injector | Beam energy | MeV | 5 | 7 | 84 | 5.6 |
| | Emittance (normalized) | $\mu$m | < 1 | 6 | 0.05 | < 3 |
| Acceleration | Energy gain/linac | MeV | 2 x 25 | 2 x 82 | 2 x 750 | 17.3/49.1/145 |
| | RF Frequency | MHz | 1300 | 801.58 | 1497 | 591 |
| | Bunch repetition rate | | | | | 98.5 |
| | Total Linac current | mA | 8 | 120 | 1 | 197 |
| | Harmonic frequency | MHz | N/A | N/A | N/A | 1773 |
| | Macropulse length | $\mu$sec | CW | CW | CW | CW |
| | Bunch charge | pC | 1 | 500 | 0.06 | 1000 |
| | Emittance | $\mu$m | <1 | 6 | 0.05 | < 3 |
| | Gradient | MV/m | 12.5 MV/m | 21 | 12 - 17.5 | 20 |
| | Quality factor | x $10^{10}$ | >1.25 | >1 | 1 | |
| | RF controls | | MTCA (digital) | | Analog/digital | TBD |
| | Beam loss | nA | <10^-5 | | | TBD |
| Arcs | Multi-pass | | 2 + 2 | 3 + 3 | 5 + 5 | 3 + 3 |
| | Optics design | | MBA | Flexible Momentum Compaction | Achromatic, isochronous | R56 canceling bending, Bates |
| | Beam loss | % | <10^-3 | | | TBD |
| Interaction Regio | βx, βy | cm | ~1m | | N/A | 40/40 |
| | Beam size | $\mu$m | 100 | | N/A | 1330, 550/200 |
| | Beam Divergence | $\mu$rad | 100 | | N/A | 4 |
| | Magnets | | Copper | | N/A | Copper |
| | Dump beam energy | MeV | 5 | 7 | 84 | 5.6 |
| Dump | Dump power | kW | 5 | 140 | 8.4 | 551.6 |
| | Max CW current recovered | mA | 0.999mA | | 0.1 | |
| Comment | | | | | Highest energy proposed<br>Highest number of passes proposed | Highest beam power proposed<br>Highest beam current proposed<br>Highest dump beam power proposed |

# Future ERL-Based Collider Projects/Proposals

| | | | ERL-Based Energy Frontier Collider Projects | | | |
|---|---|---|---|---|---|---|
| | | | **LHeC** | **FCC-eh** | **FCC-ee ERL** | **ILC-ERL** |
| **ERL** | **Top energy** | **GeV** | **50** | **50** | **45.6** | **250** |
| | **Beam power** | **MW** | **1000** | **1000** | **48** | **40,000** |
| | **Luminosity Estimate** | **MW** | **$10^{34}cm^{-2}s^{-1}$** | **$10^{34}cm^{-2}s^{-1}$** | **$10^{36}cm^{-2}s^{-1}$** | **0.5 x $10^{36}cm^{-2}s^{-1}$** |
| Source | Gun Energy | keV | 220 - 350 | 220 - 350 | N/A | |
| | Current | mA | 20 | 120 | 3.7 | 91 |
| Injector | Beam energy | MeV | 7 | 7 | 2,000 | |
| Acceleration | RF Frequency | MHz | 801.58 | 801.58 | 750 | 1300 |
| | Total Linac current | mA | 720 | 720 | 29.6 | 320 |
| | Bunch charge | pC | 500 | 500 | 12,500 | 800 |
| | Normalized emittance | $\mu$m | 30 @ 500pC | 30 @ 500pC | 4, 0.008 | 20/0.035 |
| | Gradient | MV/m | 19.73 | 19.73 | 20 | 20 |
| | Quality factor | x $10^{10}$ | >1 | >1 | ~1 | 3 |
| | Multi-pass | | 3 + 3 | 3 + 3 | 4 + 4 | 1 + 1 |
| Interaction Region | βx, βy | cm | 7 - 10, 7 - 10 | 7 - 10, 7 - 10 | 15/0.08 | 25/0.03 |
| | Beam size | $\mu$m | 6, 6 | 6, 6 | | 4.5/0.006 |
| Dump | Dump power | kW | 840 | 840 | N/A | ~100 |