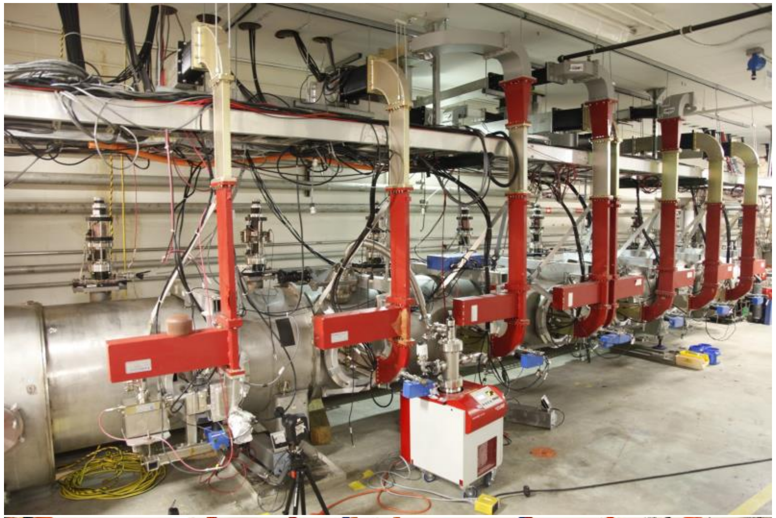
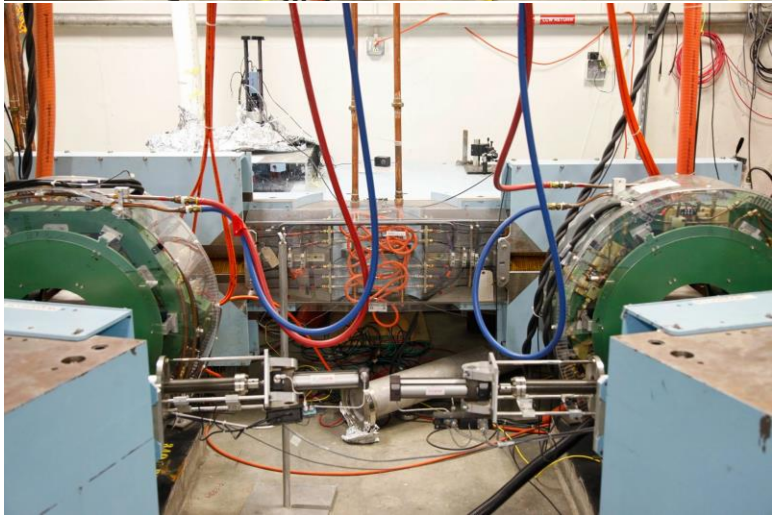
WHY PERLE?

An Accelerator Test Facility Supporting the LHeC





University of Liverpool, November 2017

Steve Benson, Alex Bogacz, David Douglas, and Chris Tennant

for the Jlab PERLE Study Group

Saturday, November 11, 2017

QUESTIONS WE HOPE TO ANSWER…

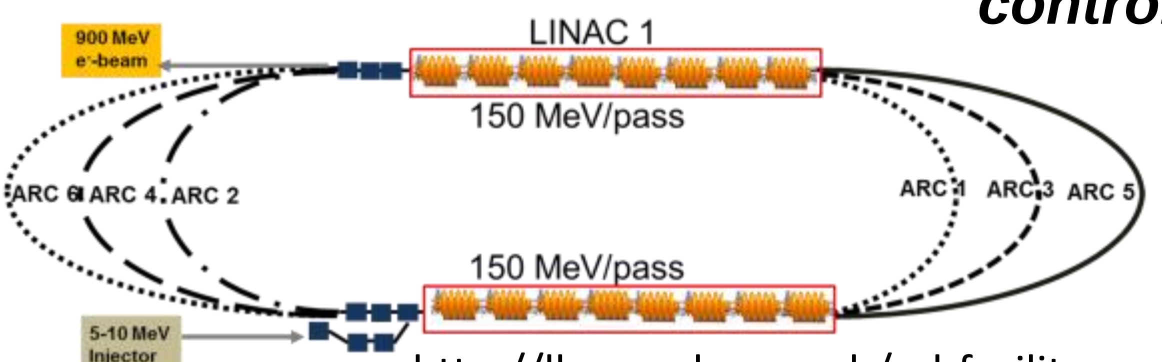
- What is an ERL, and why would anyone want one?
- How do ERLs work?
- Where did they come from, and what performance do they offer?
- Applications: The Next Generation
- What Challenges Await, and why PERLE?
- What *is* PERLE? – Design overview and status

OVERVIEW

PERLE is a GeV-scale accelerator system invoking a unique combination of parameters, technology, and design choices

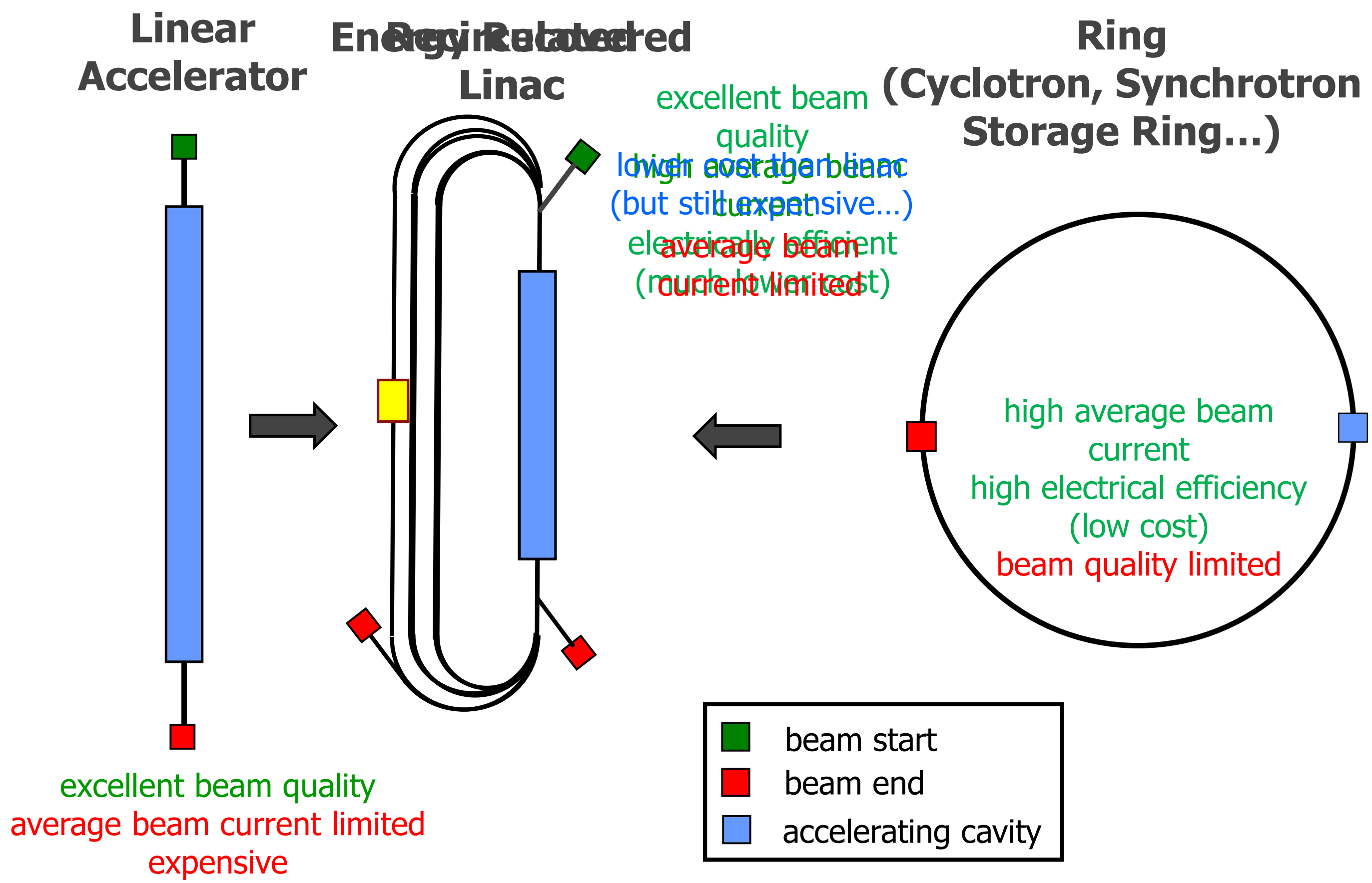
- Very high “virtual” beam power
- Moderately high current and bunch charge
- Conventional accelerator transport system design
- Common beam transport for acceleration and recovery
- Extremely large dynamic range (ratio of full to final energy)
- Multiple passes

PERLE thus encounters (and offers opportunity to controllably study) virtually every effect of interest in the next generation of ERL design

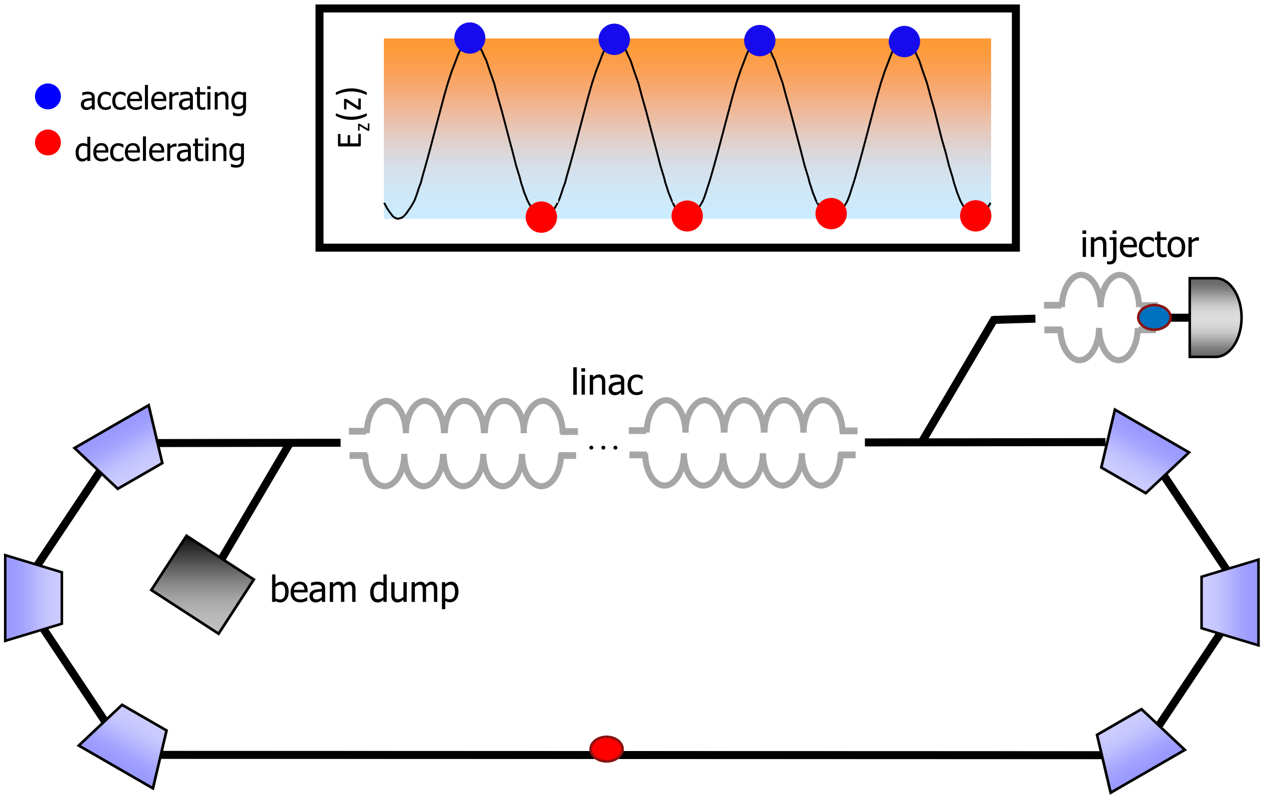


http://lhec.web.cern.ch/erl-facility

ACCELERATOR ARCHITECTURES



GENERIC ERL



SO… WHAT IS AN "ERL"… AND WHY SHOULD YOU WANT ONE?

- ***An ERL is an non-equilibrium accelerator system based on a superconducting RF (SRF) linac and a time-of-flight spectrometer (a "recirculator")***
  - the linac accelerates/decelerates the beam
  - the spectrometer (recirculator) is used to create phase space correlations
    - providing beams of specified properties to users,
    - allowing RF power extraction from beam after users are fed
  - desire for electrical *and* cost efficiency motivates use of SRF and multiple recirculations
- ***ERLs are desirable because they provide***
  - (nearly) linac quality/brightness beam at (nearly) storage ring beam powers:
    - $P_{beam} >> P_{RF}$
    - beam quality *source* limited: $\varepsilon_{beam} < \varepsilon_{ring\ equilibrium}$
  - high power beam with reduced RF drive $\Rightarrow$ cost savings!
  - radiation control: beam is dumped at low energy
    - can mitigate intractable (i.e. expensive) environmental/safety concerns

COMPARISON TO "CONVENTIONAL" ACCELERATORS

- Linac quality beam at near storage ring power (energy × current); wall-plug efficiencies approaching that of storage rings…
- Flexible time structure (as in linac…)
  - single bunch to CW bunch train, and everything in between
- Independent manipulation of various portions of phase space at will and independently of other sub-spaces (as in linac) – they are fully 6 dimensional systems!
  - Transverse matching to desired spot sizes
  - Longitudinal matching to desired bunch length/energy spread (transverse longitudinal coupling)
  - H/V, transverse/longitudinal coupling – phase space exchanges
- high beam brightness + high beam power/current + SRF + recirculation $\Rightarrow$ access to (and treachery from) many phenomena:
  - Source limitations, space charge, BBU, CSR, μBI, ions, scattering effects, halo,…

ERLs thus provide considerable potential entertainment value… and are a cost optimum architecture for many applications and across a range of parameter space

“HOW” ARE ERLS…?

*That is – how do they **work**, and how do you **use** them?*

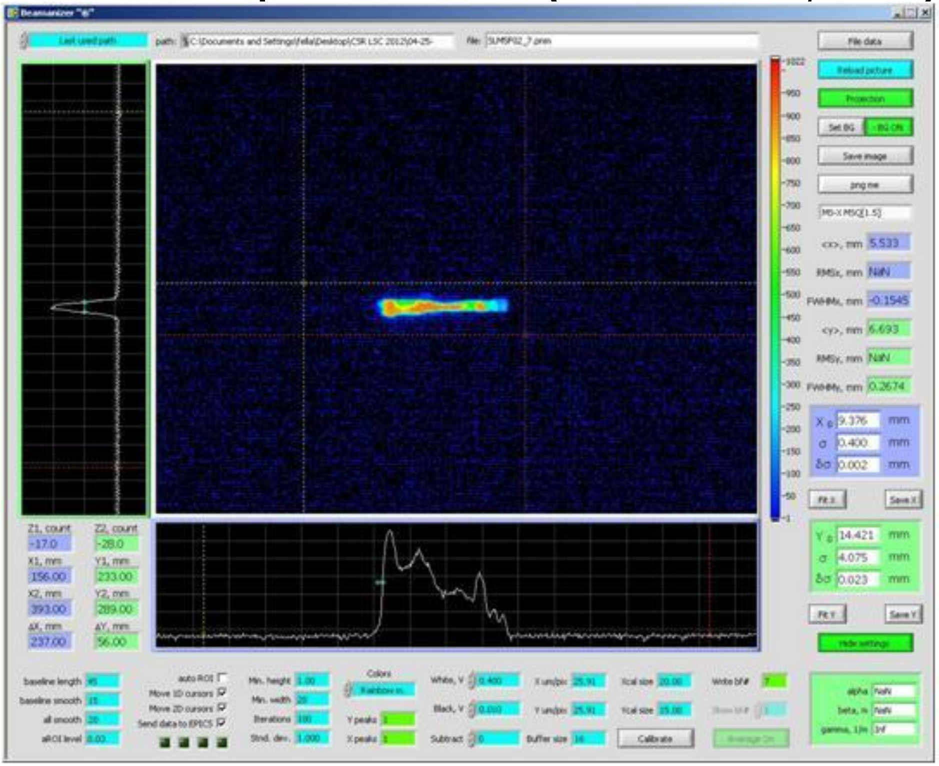
- It would be nice to only have to accelerate/decelerate a beam, but getting funding usually requires that the beam gets *used* by somebody… (*and, yes, the speaker is a machine guy…* ☺)
- At some point – typically full energy – the beam hits a target, makes light, drives a reaction of some kind, interacts with *something*, which generally
    - takes energy out
    - degrades the phase space

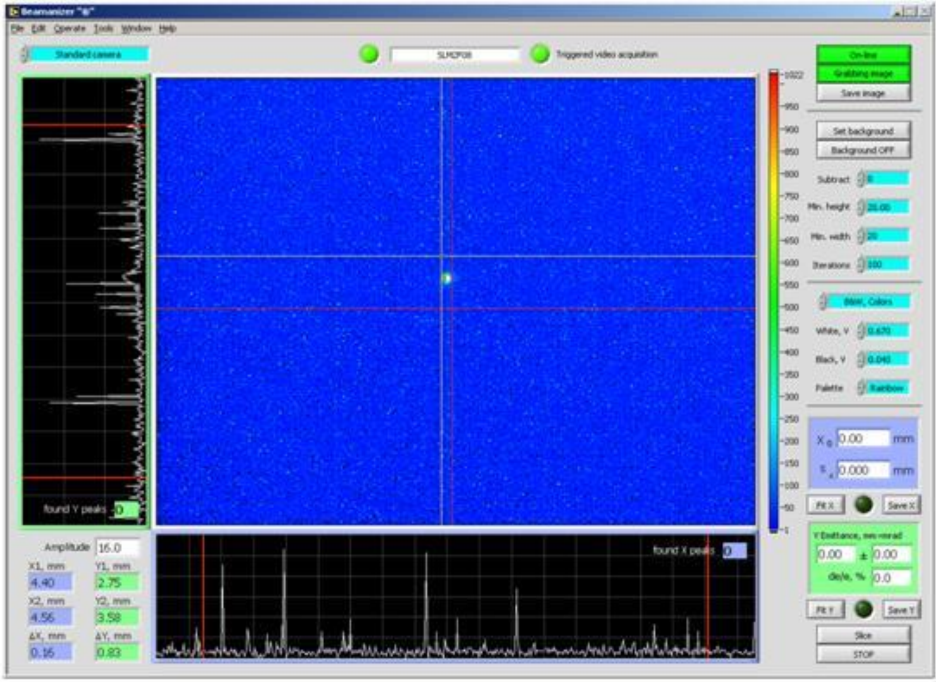
As a result, ERL operation is ***not*** just a matter of riding the RF crest up in energy and RF trough back down…

…which leads to numerous interesting “opportunities”!

UNIQUE ERL PROPERTIES

- No “closed orbit”
- No dynamical equilibrium (beam is in machine<<damping/excitation time)
- No need for long-term stability (finite length system…)
- Multiple beams (at least 2, maybe 4, 6, 8,…) in dynamically





CONTEXT: WHY BUILD AN ERL?

(La responsabilità scientifica degli scritti inseriti in questa rubrica è completamente lasciata dalla Direzione del periodico ai singoli autori)

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

While the storage ring technique for performing clashing-beam experiments (1) is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant or superficially more complex may prove more tractable.

In order to be useful for clashing-beam work an acceleration device must produce beams of small cross-section or beams of high enough quality that they may be focused to a small spot in the interaction region or regions. Such beams are well known to be produced by linear radio-frequency accelerators. Figure 1 depicts a rudimentary type of arrangement for performing a clashing beam experiment with standard traveling wave linacs. For purposes of illustration let us consider two linacs having energy gains of 500 MeV each and producing continuous beam currents of 50 to 100 milliampere. (As we shall see currents of this order would be necessary to obtain useful interaction rates at this energy.) Under these conditions the rf power necessary to establish the accelerating field in the guides would be of the order of 100 megawatt in a standard

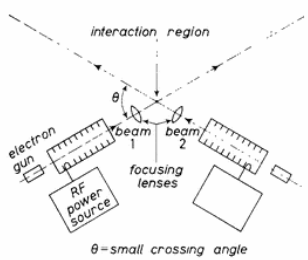


Fig. 1.

design while an additional 25 to 50 megawatt would be carried away by each beam. Although in principle it may be possible to produce and handle this large power the sheer brutishness of the scheme robs it of all appeal.

With some modification we may be able to retain the basic advantages of the linear device while avoiding the

(*) Work supported in part by the United States National Science Foundation.

(1) See for instance G. K. O'Neill: *Phys. Rev.*, **102**, 1418 (1956).

economic consequence of this particular arrangement. First, by the introduction of superconducting accelerator sections one may avoid the high power necessary to establish the accelerating field. With this technique one might hope to achieve an energy gain of about 11 MeV per meter for a rf power investment of about 12 watt per meter at an operating frequency of about 1000 megacycles per

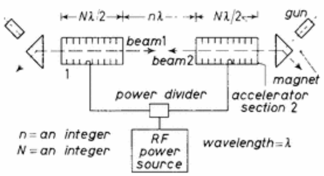


Fig. 2.

second (2). One is still faced with the problem of the power wasted in the beam. By the use of an artifice this problem may also be solved. Consider the arrangement shown in Fig. 2. The accelerator sections are now placed coaxially with the electron guns placed to one side to avoid damage by the incoming beam from the opposite accelerator. Further let us assume that the accelerators have exactly the same energy gain and the same beam current, operate in the standing wave mode at the same frequency and are phase-locked together. The distance between conjugate points in the opposite accelerator sections must be an integral number of wavelengths at the operating frequency.

We see that under these conditions it can be arranged that electrons leaving accelerator 1 arrive at accelerator 2 at just the right phase to be decelerated in accelerator 2, thus giving back their energy to the field. The same holds for electrons in beam 2 entering accelerator 1. Another way to describe the situation is to say that the two currents cancel in the steady state. In this case the energy stored in the beams is supplied only once, during the transient period while the beams are being turned on.

One difficulty with such a device is that the two beam currents must be made equal very precisely. For example at 500 MeV, 100 mA and constant r.f. power, the currents must be kept equal to about one part in ten thousand to maintain the energy constant to one per cent even when the accelerators are heavily overcoupled to the generator. While this problem might be solved by the use of sophisticated electronic feedback circuitry there appears to be another configuration which, if designed properly, ought to make the currents track well and has the added attraction of eliminating one of the accelerator sections. A schematic drawing of this arrangement is given in Fig. 3. In this configuration the beam is turned back upon itself and re-enters the accelerator where it gives back its energy to the

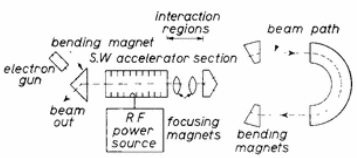


Fig. 3.

accelerating field provided that the path length through the magnet system has been correctly chosen. As shown the magnet system would work only for monoenergetic particles. In practice the magnet system would have to be somewhat more complex to accommodate the energy spread in the beam.

The interaction rate that we might

(2) H. A. Schwettman, P. B. Wilson, J. M. Pierce and W. M. Fairbank: *The Applications of Superconductivity to Electron Linear Accelerators*, in *Advances in Cryogenic Engineering*, vol. **10** (1964).

FIGURES OF MERIT

- “multiplication factor”: P_{beam}/P_{RF}
- “dynamic range”: $P_{beam}/P_{dump}=E_{beam}/E_{dump}$
- both measure efficiency of acceleration and recovery
  - multiplication factor defines how much “free” acceleration is provided
  - dynamic range characterizes the fraction of full beam power that is “wasted” in the dump

A BRIEF HISTORY

- ERL Tin
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- FEL
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  - S-D

Klystron Power Required when Configured

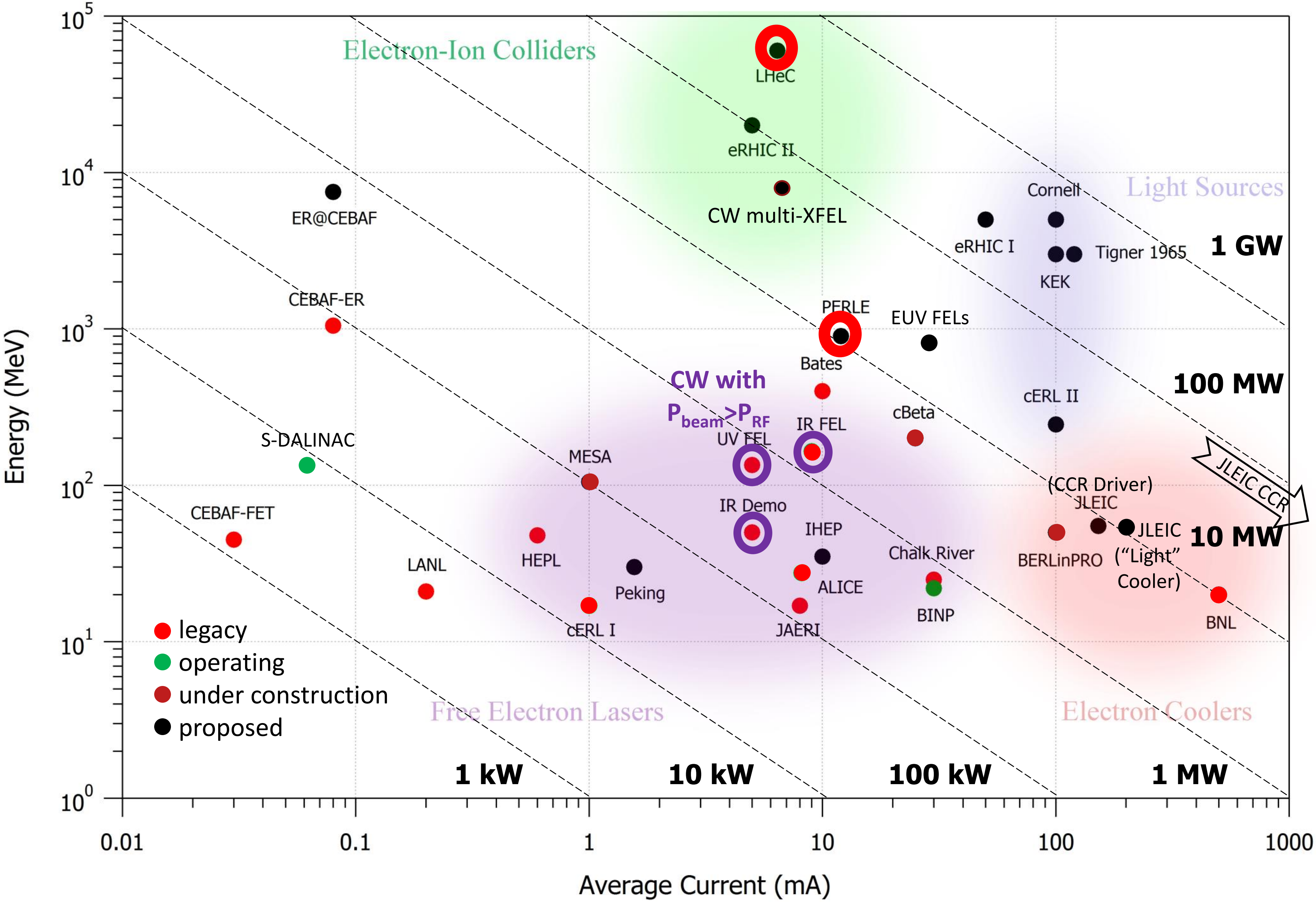
FEL 1986 Oral Presentation

… tion of the FEL", Symposium on High Average Power Free Electron Lasers, JLab, 27 Sept. 2017

THE "ERL LANDSCAPE" (C. TENNANT, ERL'17)

- Summarizes ERLs to date, including
  - *Legacy* (decommissioned) *ERLs*
  - *Operating facilities* (There's only one… the S-DALINAC at Darmstadt…)
  - *Systems under construction* (MESA, C-BETA, bERLinPRO)
  - *Proposed machines* (including PERLE and LHeC)
- **Shows that only three (legacy) SRF systems have operated CW with P_{beam}/P_{RF}>>1**
  - JLab IR Demo, IR Upgrade, UV Demo ⇔ all 1-turn FEL drivers
  - Note that other legacy or operating systems did **not** achieve CW (Chalk River*, MIT*, LANL*, HEPL, JAERI, ALICE) and/or P_{beam}/P_{RF}>1 (CEBAF-FET, CEBAF-ER, BINP*, KEK cERL, BNL test ERL, S-DALINAC) *NCRF linacs
- Facilities in operation/under construction have varied architectures, capabililites, & access different phenomena

The ERL Landscape: The State of the Art



PRIOR/PRESENT/NEXT-GENERATION COMPARISON

	JLab ERLs (legacy)	S-DALINAC (in operation)	bERLinPRO	Cbeta	PERLE
Gun technology	DC	thermionic	SRF	DC	DC
total # passes	2	2* *tests continue	2	8	6
recirculation architecture	conventional	conventional	conventional	FFAG	conventional
acceleration/recovery multipass transport	linac only	linac only* *tests continue	linac only	common	common
RF frequency (GHz)	1.5	3	1.3	1.3	0.8
nominal bunch charge (pC)	135	very low	77	77	320
design current (mA)	10	very low	100	40	20
total current in linac (mA)	9.1	very low	200	320	120
energy (GeV)	0.165	~0.0425* *tests continue	~0.05	~0.15	0.5-1
beam power (MW)	1.25 ($>>P_{RF}$)	low ($<P_{RF}$)	10 ($>>P_{RF}$)	6 ($>>P_{RF}$)	10-20 ($>>P_{RF}$)
energy at dump (MeV)	11	2.5	5	5	5
E_{full}/E_{dump}	15-20	17	10	30	100-200

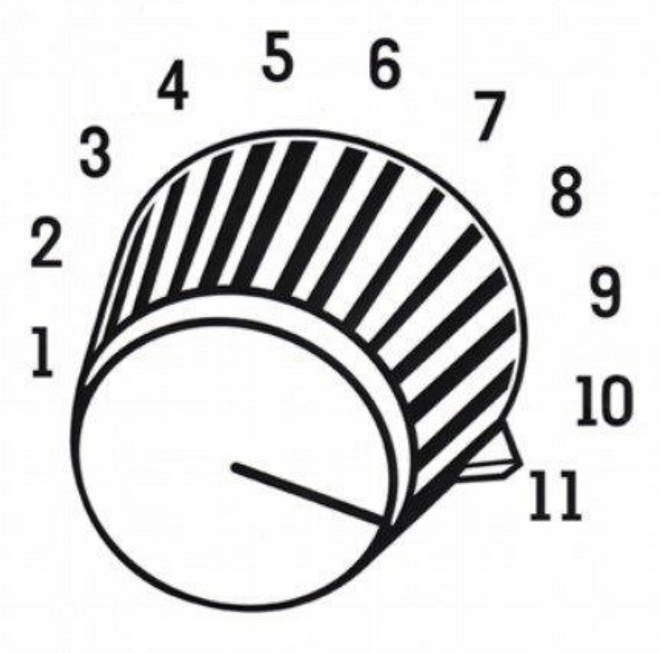
CW SRF ERLS: STATE OF ART

- **3 SRF systems have operated CW with $P_{beam} >> P_{RF}$**
  - all were 1 pass up/1 pass down, with commthe linacon transport in only
    - CEBAF-ER used common transport in (both) linacs and one arc, and ran CW – but at (very) low CW current ($P_{beam} < P_{RF}$)
    - BINP runs multiple passes (NCRF, $P_{beam} < P_{RF}$)
- **CW beam power at MW levels**
  - Bunch charges ~100 pC } ~ 10 mA } ~ 1 MW
  - Rep rates ~100 MHz
  - Energy ~100 MeV
- **Modest beam brightness** (ε ~10 mm-mrad x 50 keV-psec)
- Injection energy 5 – 9.2 MeV } P_{beam}/P_{dump} ~ 15-20
- Full energy 20 – 165 MeV

APPLICATIONS FOR ERLS: USES TO DATE

Great for producing high power electron beams…!

- ✓ Test facilities (JLab FET, CEBAF-ER, BNL ERL, KEK cERL, S-DALINAC, Cβ, bERLinPRO,…)
- ✓ FEL drivers (HEPL, ALICE, JLab IR Demo, IR Upgrade, UV Demo)
  - 14 kW IR, 100+ W UV
- THz sources (JLab)
  - kW levels of THz
- Compton sources (cERL)
- ✓ Internal target (DarkLight, MAGIX)



TEST FACILITIES

Chalk River Reflexotron (smallest ERL)

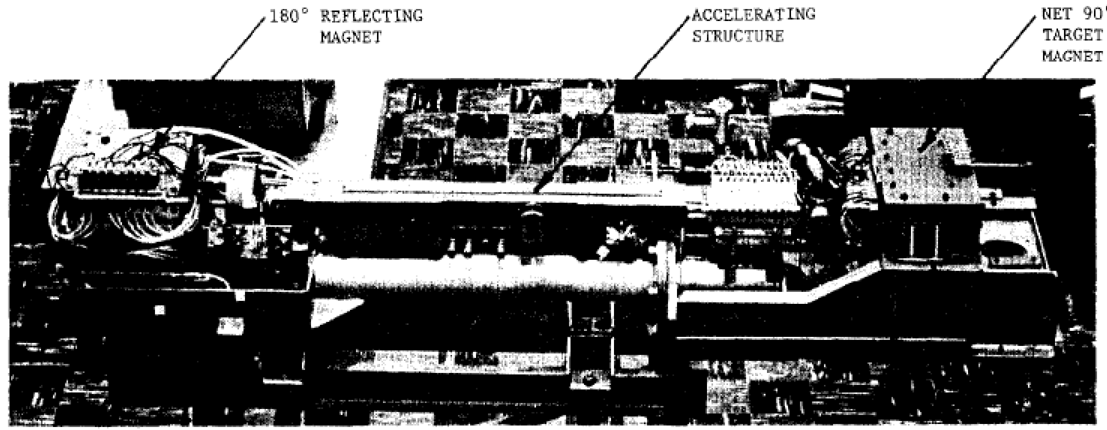
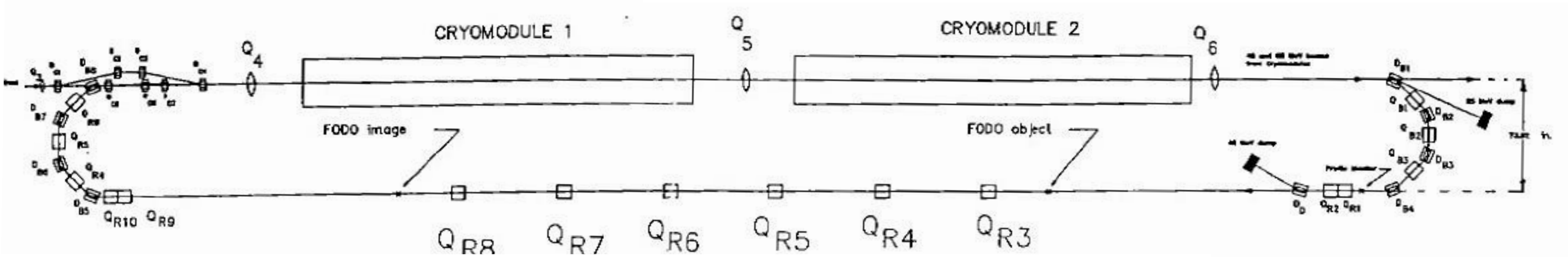
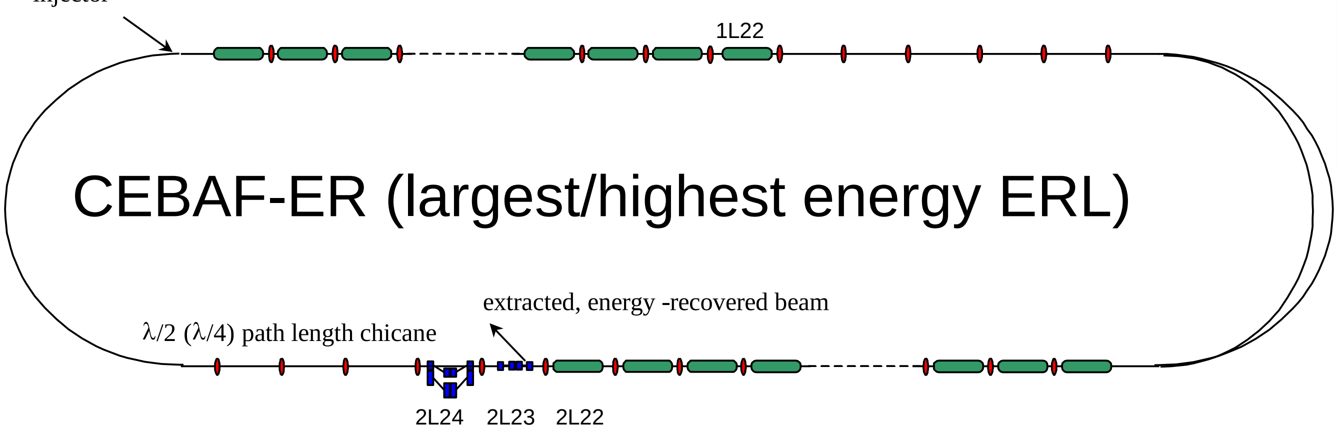


Figure 1. The 25 MeV electron accelerator attached to its strongback.

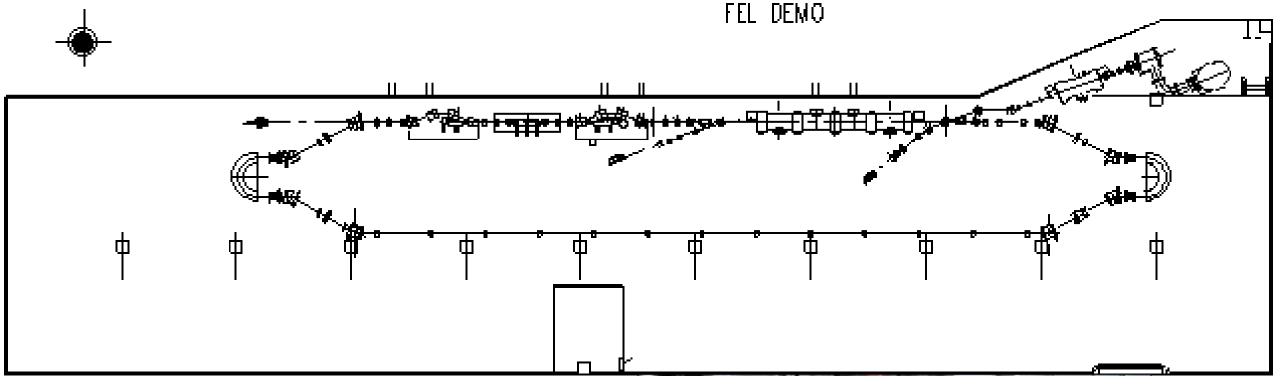
CEBAF-FET (1st CW ERL, BBU test)



CEBAF-ER (largest/highest energy ERL)



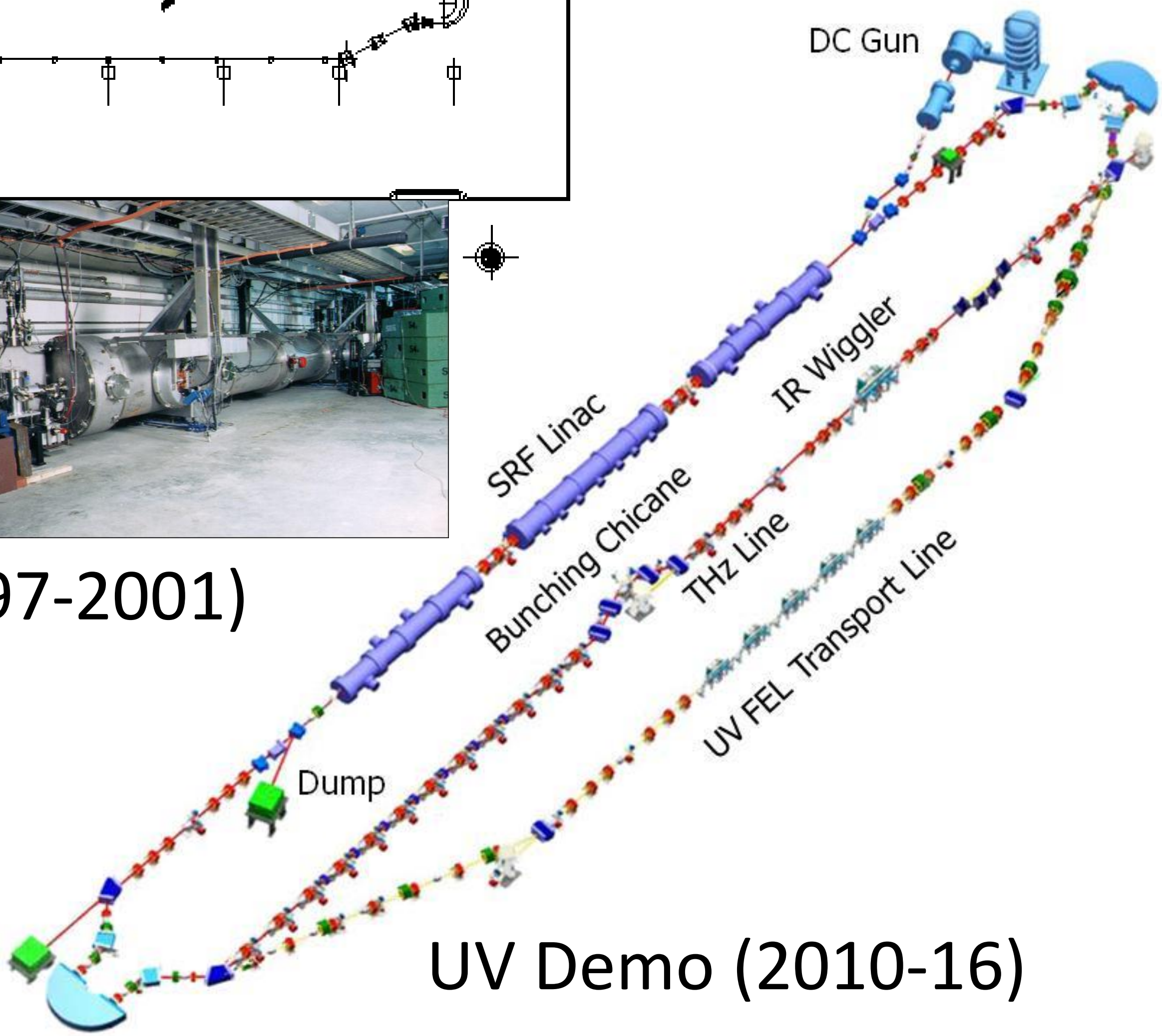
FEL DRIVERS



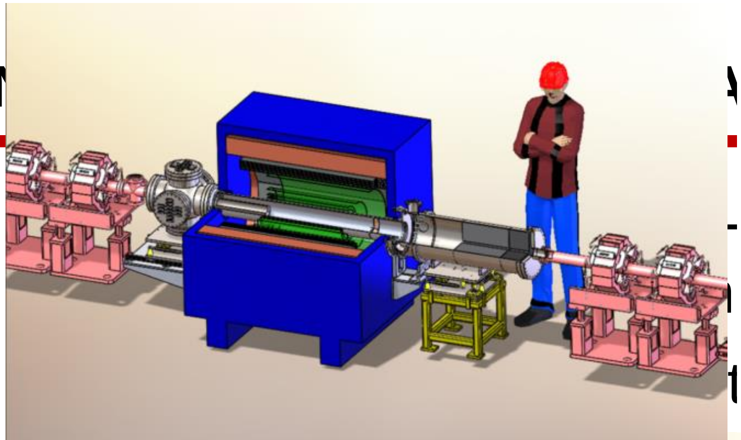
JLab IR Demo (1997-2001)

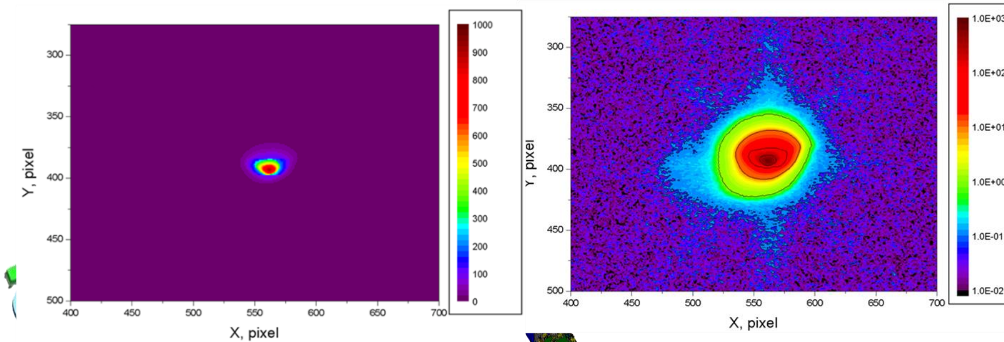
- 1+ kW in THz
- 10+ kW in IR
- 100+ W in UV

JLab IR Upgrade (2003-16)



UV Demo (2010-16)





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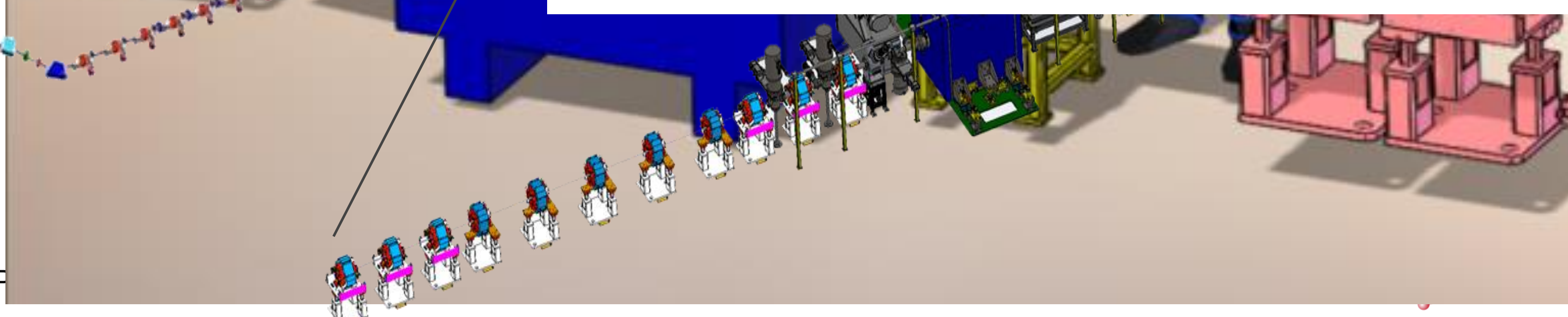

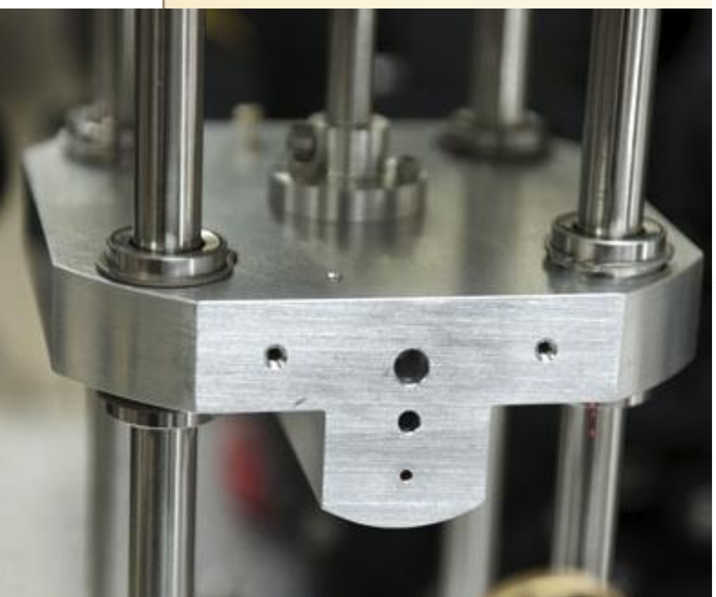

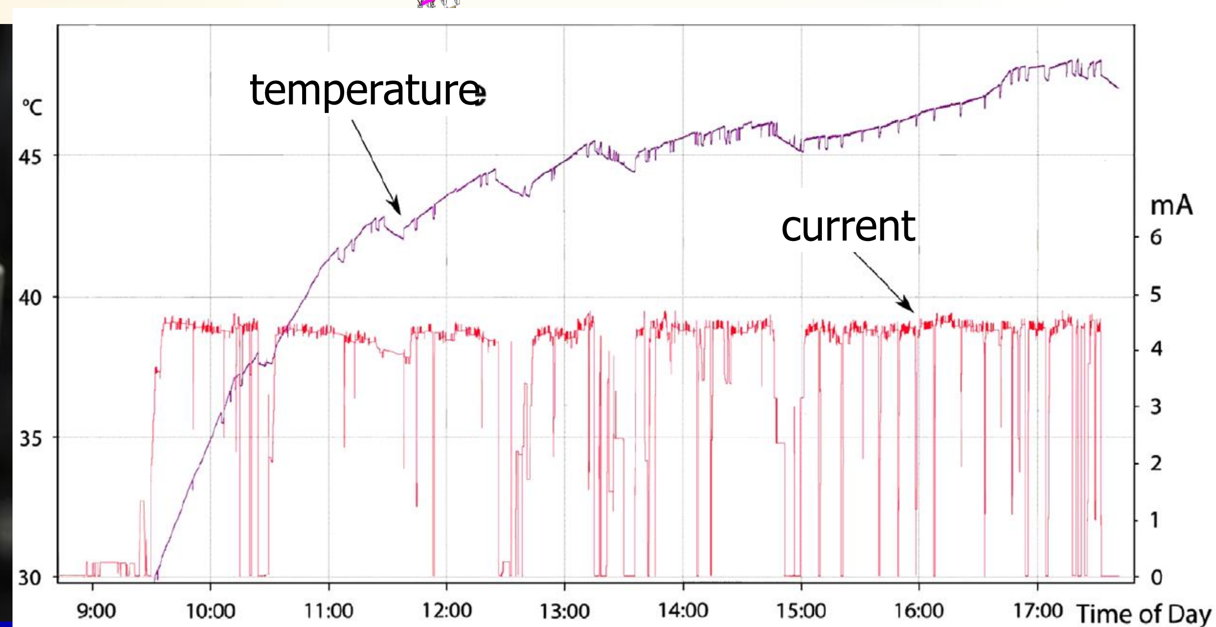

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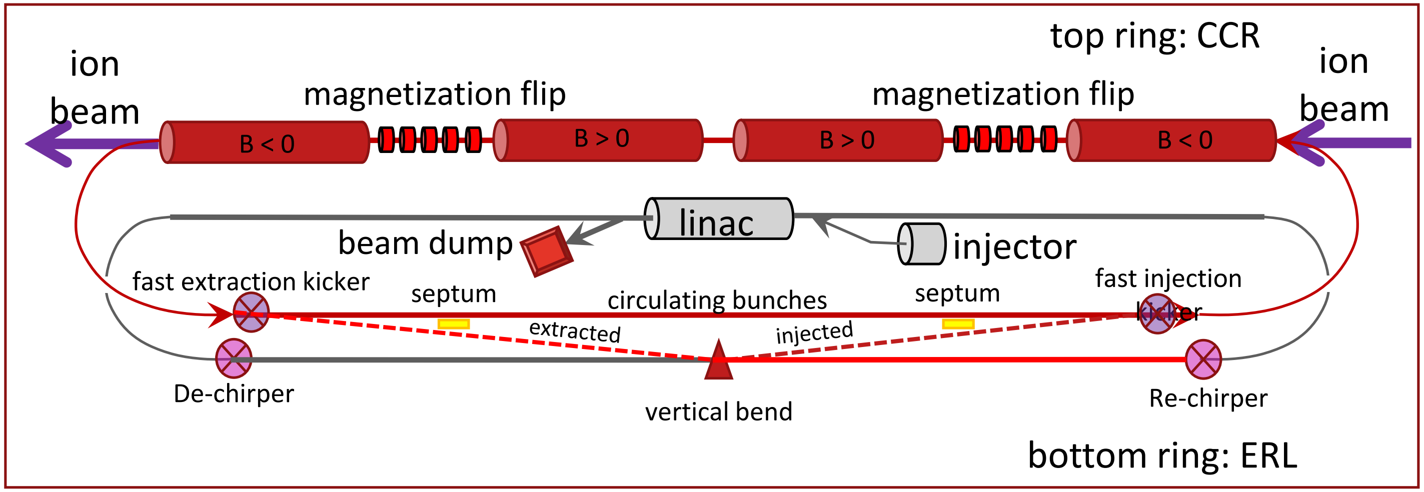
Time of Day

APPLICATIONS – THE NEXT GENERATION

- Test facilities
  - ERL technology scaling: bERLinPro
  - Ring-ERL collider development: C-BETA, PERLE
- Photon sources
  - FELs over large range of wavelengths – THz to EUV/X-ray – and very high powers (10s of kW – few MW…), THz sources (multi kW comes free from FEL drivers…);
  - Inverse Compton/gamma sources – to 1 GeV…!
- Internal target systems: MESA/MAGIX, DarkLight
- ✓ Electron cooling systems for colliders (JLEIC, eRHIC)
- Isotope production
- ✓ ***Colliders*** (eRHIC, LHeC)
  - **leverage source-limited beam quality at very high electron energies (10+ GeV)**
  - ***PERLE provides test facility LHeC technology***

JLEIC COOLER CONCEPT: ERL-DRIVEN STACKING RING

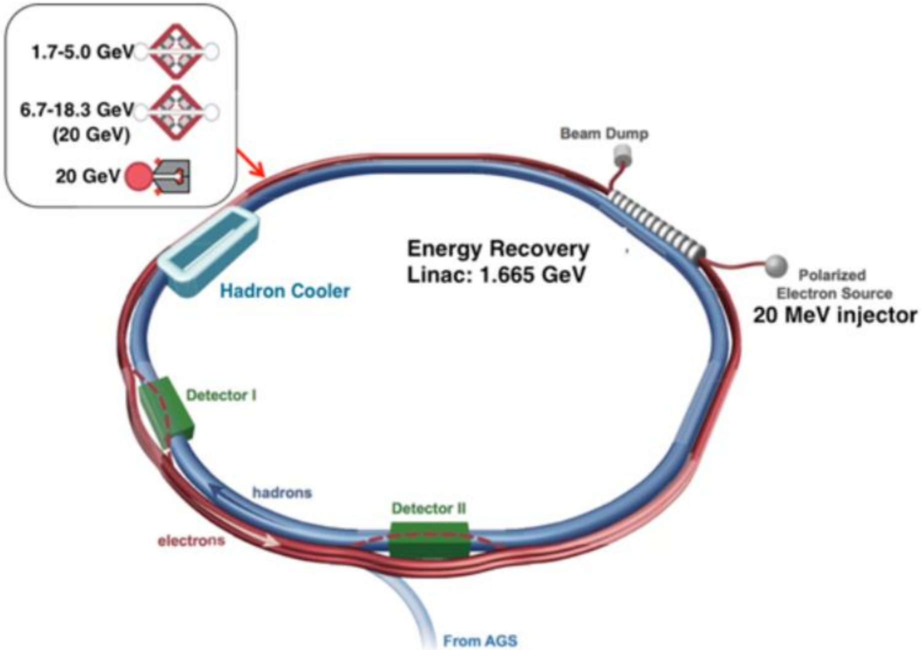
- “Magnetized” (CAM-dominated) beam for efficient cooling
- Same-cell energy recovery in SRF cavities
- Uses harmonic kicker to inject and extract from CCR
- High charge, “low” rep-rate injector w/ subharmonic bunching/acceleration
  - ERL provides capability for full 6D phase space match from injector to cooler



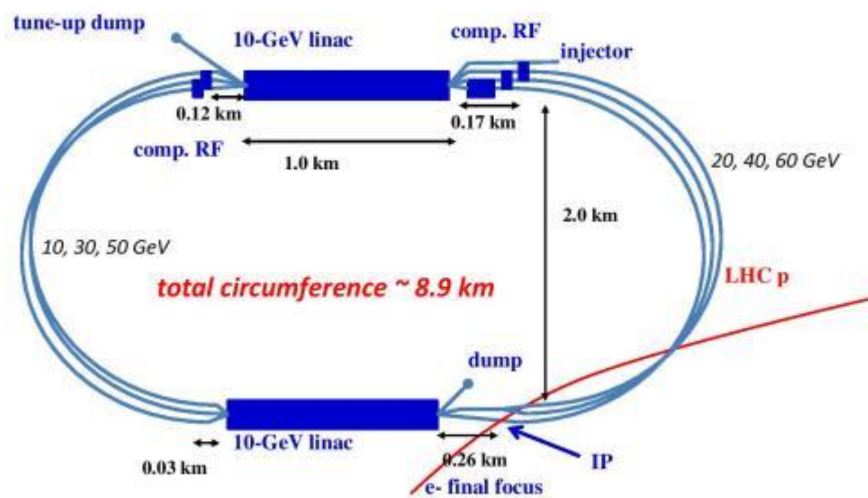
Jefferson Lab

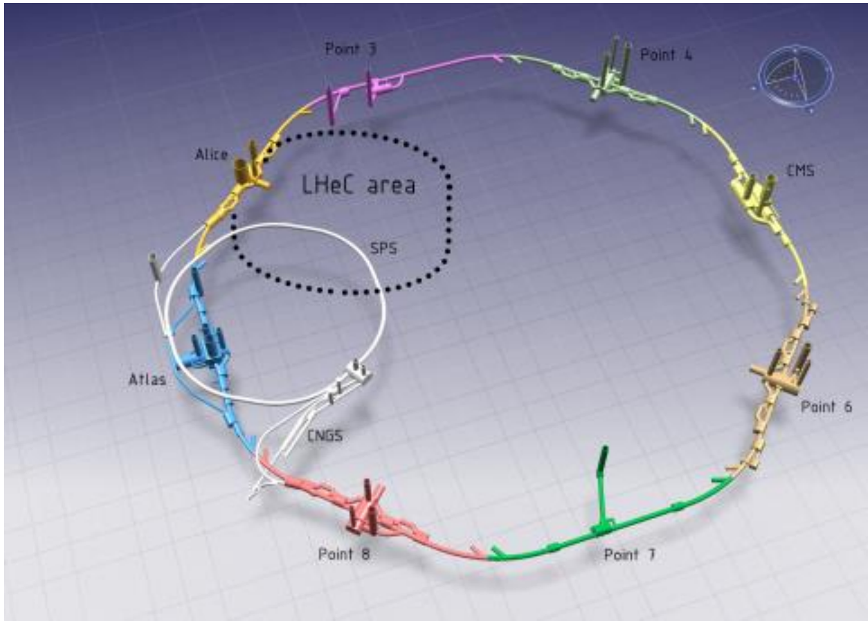
COLLIDERS

eRHIC



LHeC





V. Ptitsyn *et al.*, Proc. IPAC 2016

- sequential many-pass (FFAG) ERLs
- 20 GeV e- for collisions with ions

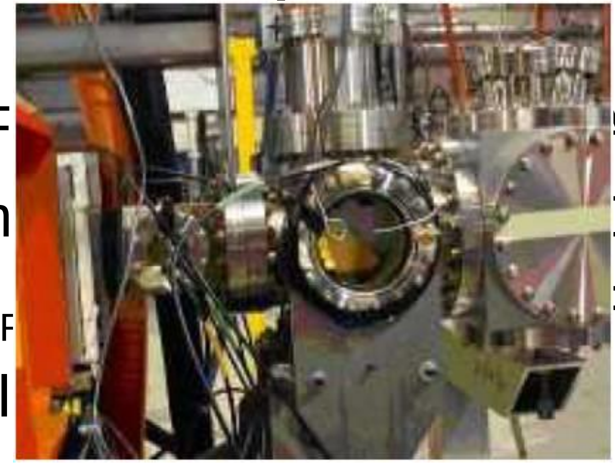
    - twin 10 GeV linacs ⬄ 3 pass up, 3 pass down ERL = 60 GeV e-
      http://lhec.web.cern.ch/figures

CHARACTERISTICS OF NEXT GENERATION

- Extremely bright, very high power sources and injectors
  - Cornell injector at state-of-art for CW current, charge, brightness (5-10 MeV, 75 mA)
  - How to merge beams?
- Multiple turns
- Very high virtual beam power (10+ MW – 1+GW)
- High bunch charge (>1 nC)
- Use of "exotic" beams
  - CAM-dominated ("magnetized") beams for coolers
  - Polarized beams in colliders
- Recovery of severely degraded beams
  - FELs ⬄ minimal transverse degradation, large growth in momentum spread
  - Internal target
    - gas – large emittance, energy spread
    - solid – very large emittance, energy spread
- Long lengths of "common" transport
  - cost/complexity optimum lies toward shorter linacs, more turns, multiple beams/beam line
  - multiple turns in cooler stacking rings

CHALLENGES AND RISKS

Reviev  ***of all 10 SRF ERLs operated to date***
offers



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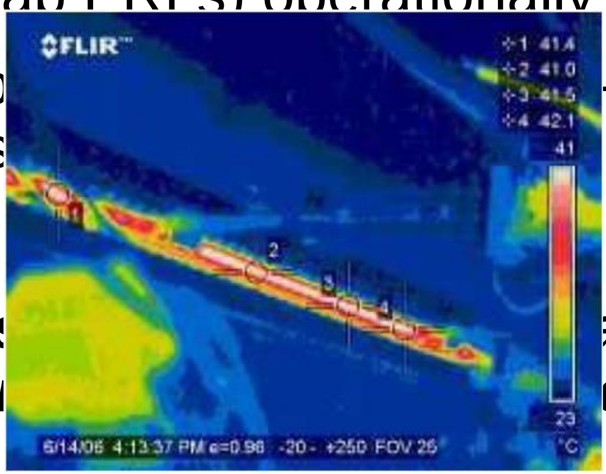

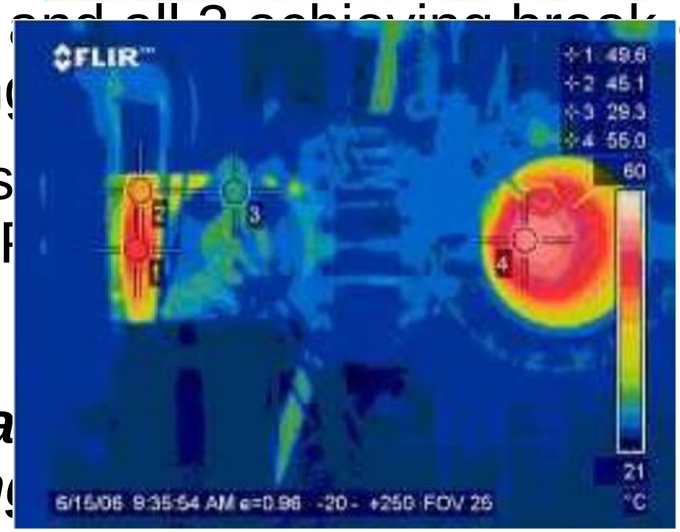

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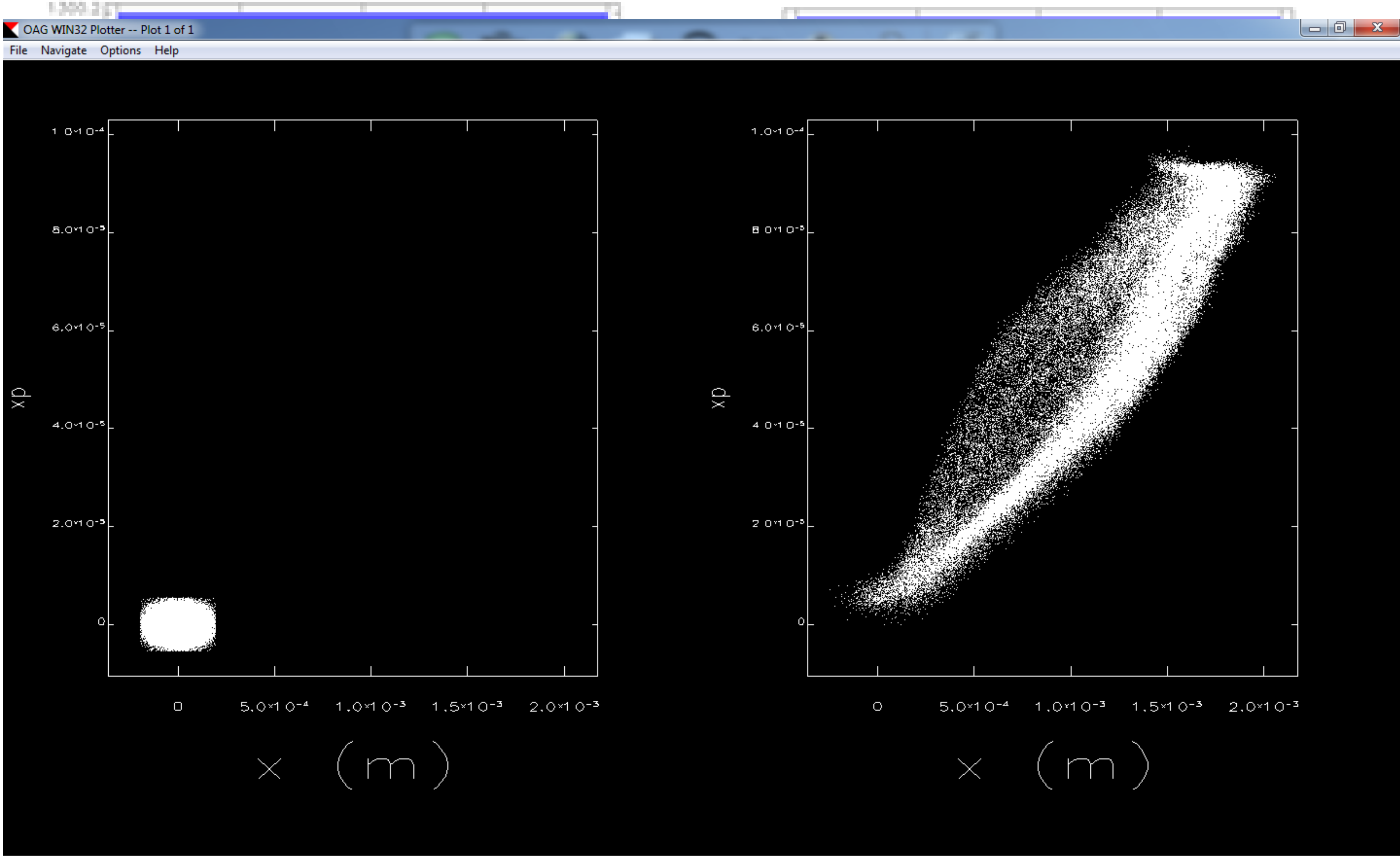
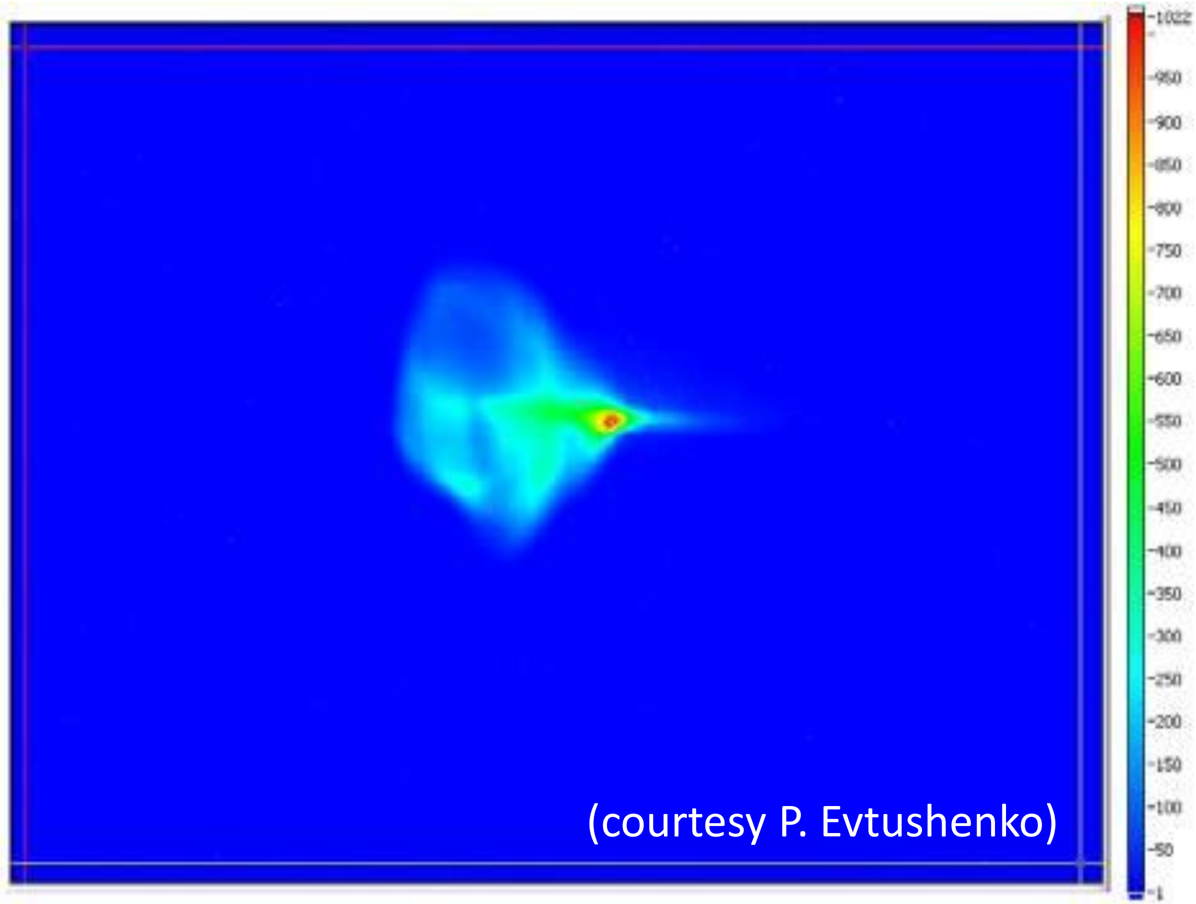
"OPPORTUNITIES"



MORE OPPORTUNITIES!

"Real beams do not occur in distributions named after dead mathematicians – instead, they look like the profile of a two-humped camel passing in front of an obelisk…"

(P. O'Shea)

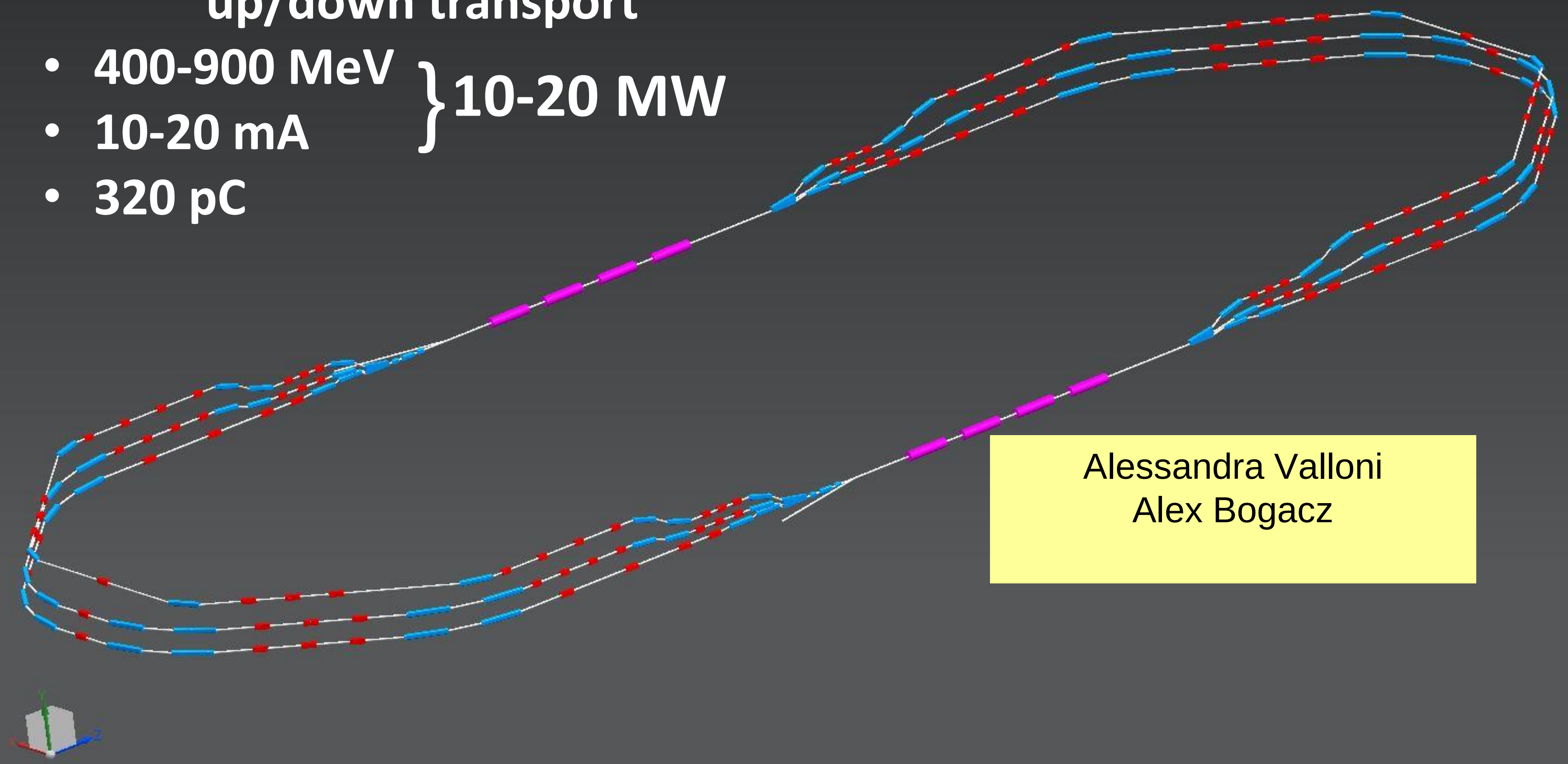


Jefferson Lab

WHAT IS PERLE, AND WHAT DOES IT OFFER?

- Split linacs,
  75-150 MeV gain/pass
- 3 pass up/down; common
  up/down transport
- 400-900 MeV
- 10-20 mA
- 320 pC

} 10-20 MW



Alessandra Valloni
Alex Bogacz

RISK ASSESSMENT: CF. SRF SYSTEMS WITH $P_{BEAM}>P_{RF}$

Scale-up/exploratory capability is provided with limited number of "reach" parameters/novel methods; use of common multipass transport is new for high-power systems.

- *Source/Injector*: within state of art (cf. Cornell)
- *Linac*: conventional SRF
- *Current*: ~2x scale-up of demonstrated full-energy beam current; ~7x scale-up of demonstrated current in linac (cf. JLab)
- *Energy*: 3-6x high power state of art (cf. ~150 MeV @ Jlab)
- *Full Beam Power*: 10x scale-up of demonstrated (cf. JLab IR Upgrade)
- *Transport Architecture,* N_{pass}: **high-power multipass is novel**
- *Use of common multipass transport for acceleration and recovery*: **common recovery transport is novel**
- *Dynamic range*: 5x scale-up of demonstrated range (cf. JLab IR Upgrade)
- *Bunch charge*: modest increase (cf. 270 pC recovered CW, JLab IR Upgrade)

RELEVANT DYNAMICS/TECHNOLOGY R&D/VALIDATION

PERLE moves the community to the 10 MW level in several areas!

- High charge/brightness bunch
  - Beam quality preservation with space charge/LSC, CSR, mBI…
- High current/charge/power beam ⇔ beam stability
  - BBU, other impedance/wake effects
- High current/power beam ⇔ power flow management
  - Halo formation and control
  - High power THz, RF heating, resistive wall,…
- Machine operations:
  - Choice of working point
  - Control algorithms for common transport & halo control
  - Diagnostic & Control in new beam power regime
    - Large dynamic range (LDR) diagnostics, measurement methods

PERLE AS A TESTBED: "OPPORTUNITIES"

- Use of conventional transport technology allows flexibility in working point and possibility for detailed measurements
  - explore phenomena across very large energy range
  - characterize accelerator lattice and evolution of beam,
  - operate with varying numbers of passes to establish N_{pass} scaling
- "low" RF frequency
  - explore system cost-of-ownership optimum (T. Powers, SRF'15)
  - validate SRF design/BBU modeling in new frequency range (800 MHz)
- high bunch charge, high brightness, moderately high current DC source:
  - within demonstrated capabilities, but must validate injector models (space charge/LSC, CSR, μBI at low energy) and merger designs
- moderately high current, very large dynamic range (E_{full}>>E_{dump}), multipass operation
  - new operating regime – validate BBU scaling with N_{pass} at high current across large dynamic energy range
- very large dynamic range
  - explore impact of magnet field quality (severe and as yet generally unrecognized constraint on ERL performance – D. Douglas, BIW'10)

CHARACTERISTICS ⇔ OPPORTUNITIES (CONTINUED)

- Very high beam power
  - explore halo formation/control mechanisms
  - explore/validate collimation schemes for very high power/high energy CW operation
  - assess impact of ion accumulation, IBS, Touschek scattering, beam/gas scattering
  - validate machine protection systems for high-power non-equilibrium systems
- High beam brightness
  - validate models for CSR and μBI,
    - explore CSR emittance compensation/microbunching gain suppression
    - characterize CSR shielding
  - investigate LSC effects at very high power
- Common multi-pass transport:
  - explore multipass longitudinal matching – e.g. linearization of phase space, monochomatization of longitudinal phase space (e.g. D. Douglas & C. Tennant, AIP Conf. Proc. 1563),
  - validate use of common transport
    - multipass/multibeam matching
    - localized error correction v. global error compensation in ERLs (completely novel topic)

WHY, THEN, PERLE?

- Evolution of ERL performance can be characterized by increases in
  - full-energy beam power
  - multiplication factor
  - dynamic range E_{full}/E_{dump}
- Present state of art (for “true” ERLs – those with multiplication factor >1):
  - P_{beam} ~ 1.25 MW
  - P_{beam}/P_{RF} ~ 10
  - E_{full}/E_{dump} ~ 10
- PERLE calls a factor of 10 increase in each of these, and is thus a natural step towards LHeC (100x and beyond…)

May (or, will…?) encounter unanticipated effects… what might these be?

6 OPEN QUESTIONS ADDRESSED BY PERLE

PERLE will validate the use of ERL technology in large-scale, high power, high energy, high brightness applications by answering several questions that remain open after operation of current state-of-art systems

1. *There have been few successful (P_{beam}>>P_{RF}) demonstrations of CW SRF ERL operation*

- See “ERL Landscape” - the statistics are not encouraging
  - no successful demonstrations with multiple passes
  - no demonstration of common acceleration/recovery
- Large system designs to date rely on both of these, despite two decades of operational experience characterizing heightened risk and degree of difficulty.

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2. *Limits to Demonstrated Stability*

- Existing SRF systems have directly demonstrated BBU stability at only a modest fraction (<20%) of the full (in linac) current needed for LHeC
  - threshold currents *have* been *indirectly* measured at higher values
  - there is no actual demonstration with beam that multipass systems will be sufficiently resistant to BBU at the order-of-magnitude higher current
  - sensitivity of instability threshold to linac length, dynamic range, and number of passes not systematically measured
- PERLE will provide an additional datum on linac length, and can directly measure the dependence on N_{pass} and turn-to-turn transport
  - can then more reliably extrapolate to determine sensitivity to length

3. *Scaling dynamic range (E_{full}/E_{dump}) from 10 to 100(+)*

- Critical design parameter
  - defines sensitivity to magnetic field errors
    - error effects at high energy **magnified** by adiabatic antidamping during energy recovery
  - field tolerances scale inversely with dynamic range
    - high energy machine (or ones with large range) needs higher quality magnets.
  - This is a largely neglected topic… with ***significant*** cost implications in large scale systems

ERLs are, after all, simply time-of-flight spectrometers…

4. *Power scaling and halo*

- Existing systems operated at "only" 1 MW full beam power without a precise understanding and control of beam halo.
- Extrapolation to 10 MW involves suppression of localized losses to/below few parts per million;
  - higher power requires lower fractional loss.
- ***There are no demonstrated solutions for this***
  - no experience with collimation systems at loss rates observed in CW linacs
  - some guidance was provided by DarkLight (where we ***quenched*** the linac with halo…)
  - additional halo effects become significant at higher CW powers (e.g. 10 MW? See Cornell ERL design study…)
    - adiabatically antidamp during recovery/exceed dump acceptance, Touschek and intra-beam scattering, beam-gas scattering, ion trapping,…

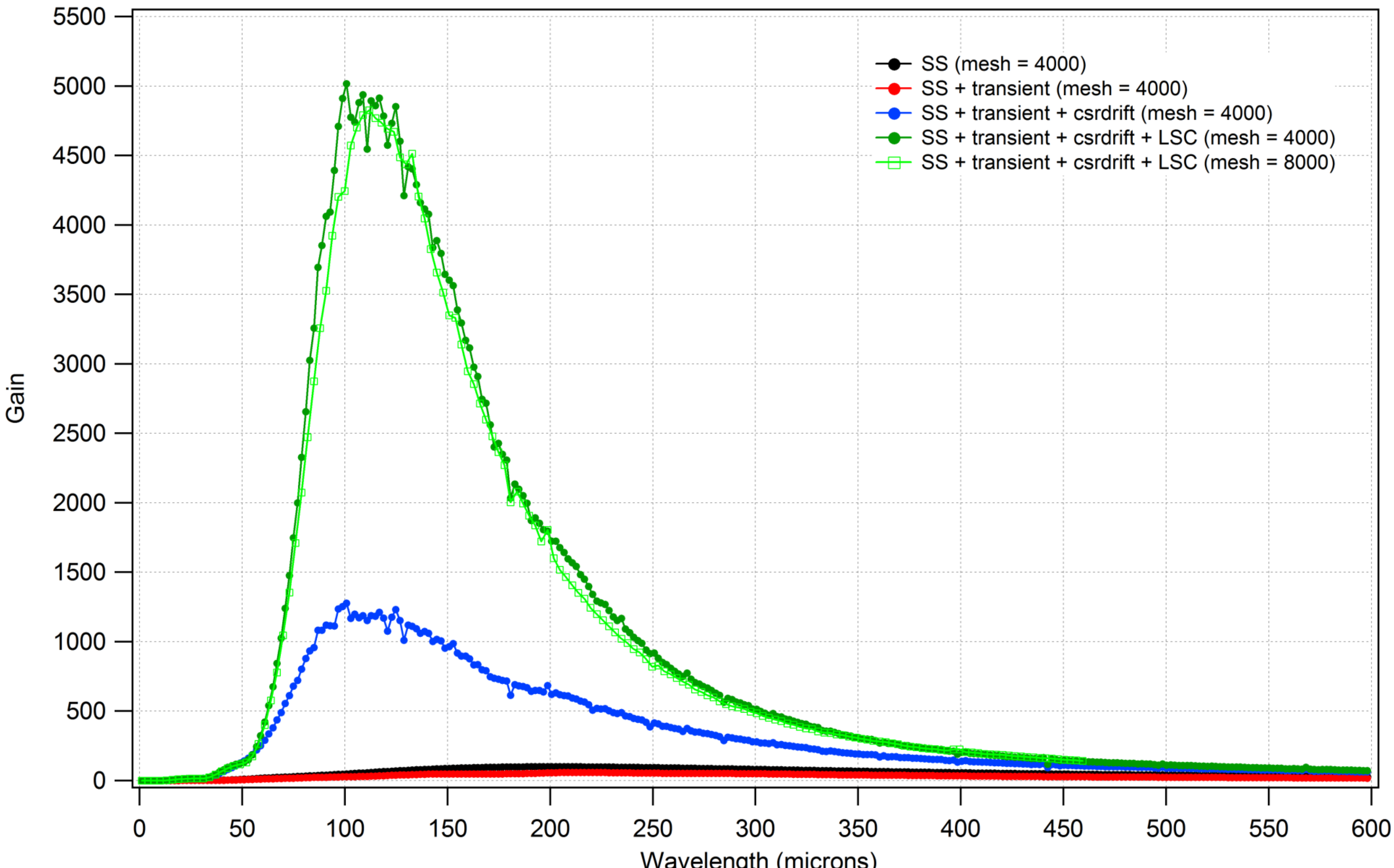
5. “*Power-flow management*”

- heating from many collective effects already problematic at lower beam powers
  - RF heating, resistive wall, THz emission,…
- these have greater impact at higher power/energy
- No systems now in operation/under construction can study these effects in a multipass architecture
  - beam power/brightness too low (MESA)
  - insufficient operational flexibility (C-BETA)
- PERLE is the ***only*** multipass system proposed or under construction that offers *both* intensity and flexibility

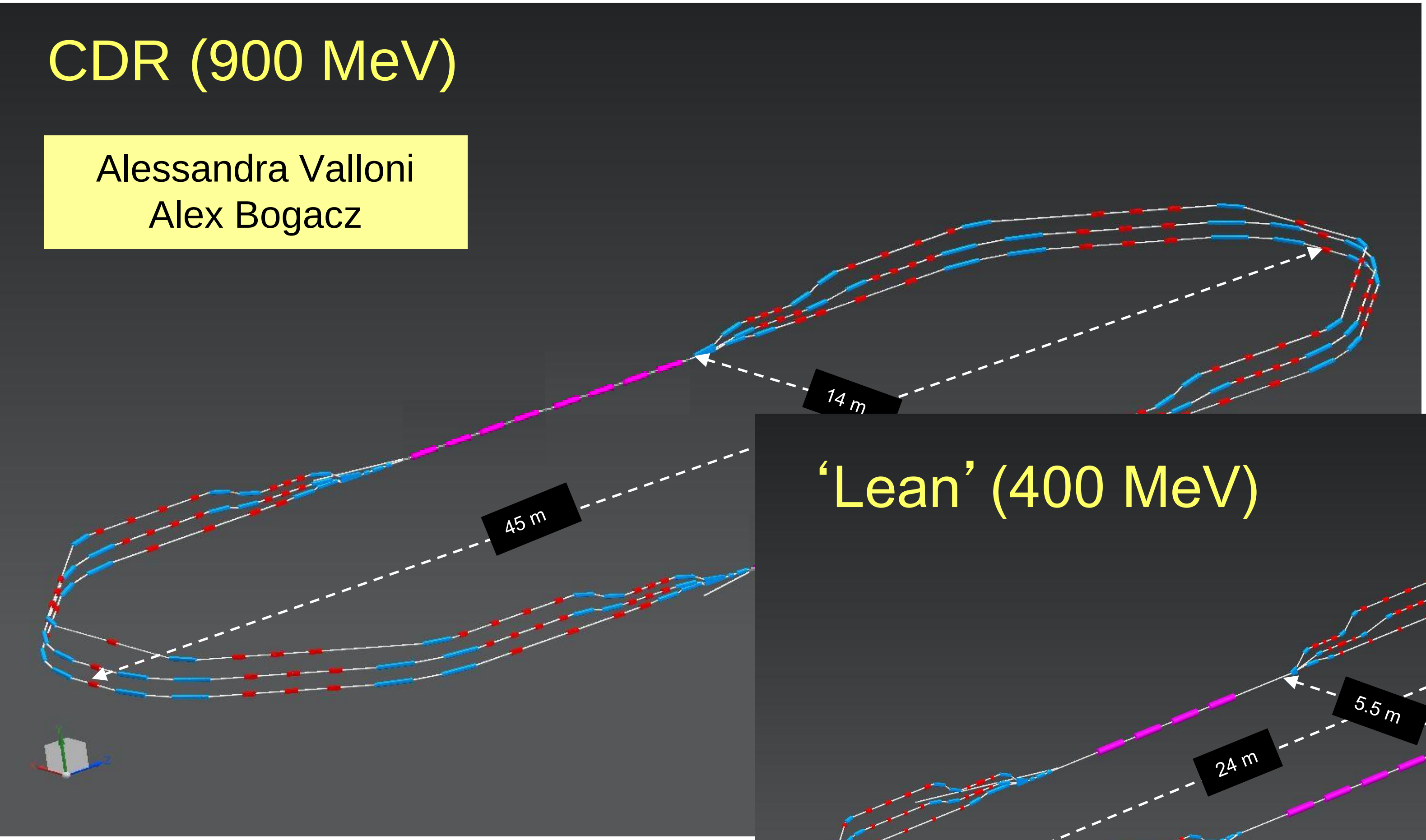
6. *Beam quality preservation throughout acceleration/recovery cycle*

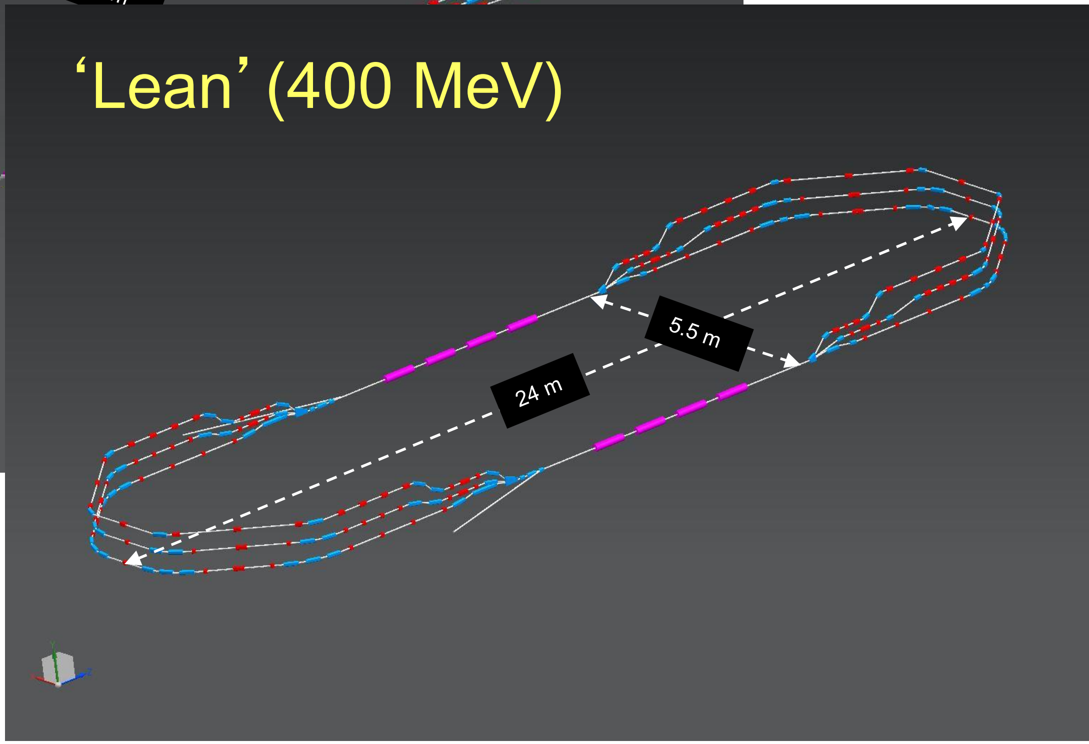
- Maintaining beam quality – in presence of collective effects - a significant challenge for modern machines
- Space charge/LSC, CSR, and microbunching instability have serious impact on performance
  - can preclude meeting user requirements
  - in worst case can inhibit high power operation
- PERLE probes the regions of parameter space where these effects are observable
  - offers opportunity to benchmark models
  - can explore mitigation methods.

DESIGN STATUS



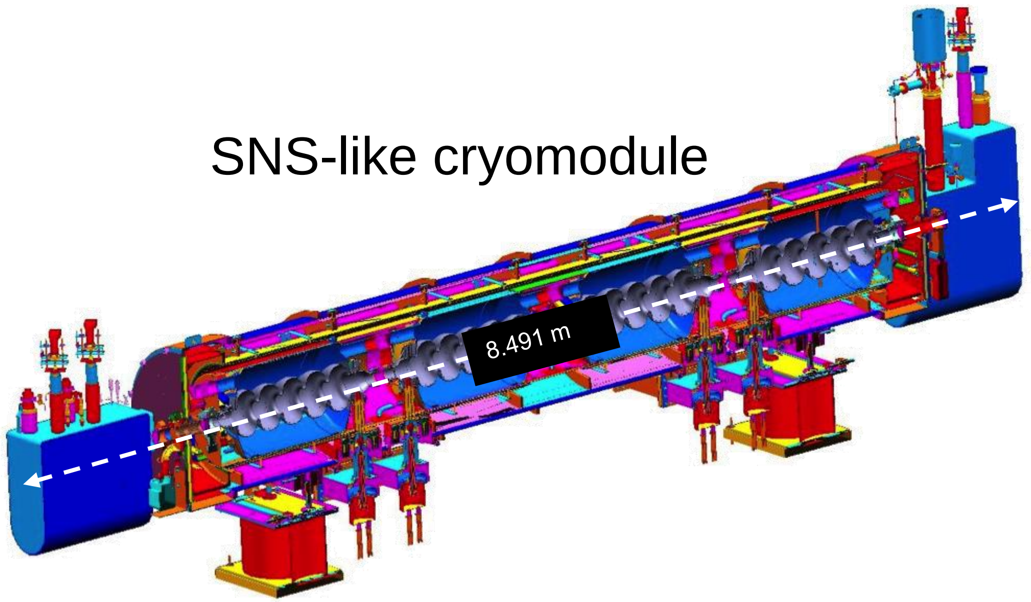
PERLE Downsizing





LINAC, CRYO-MODULE – LAYOUT

SNS-like cryomodule



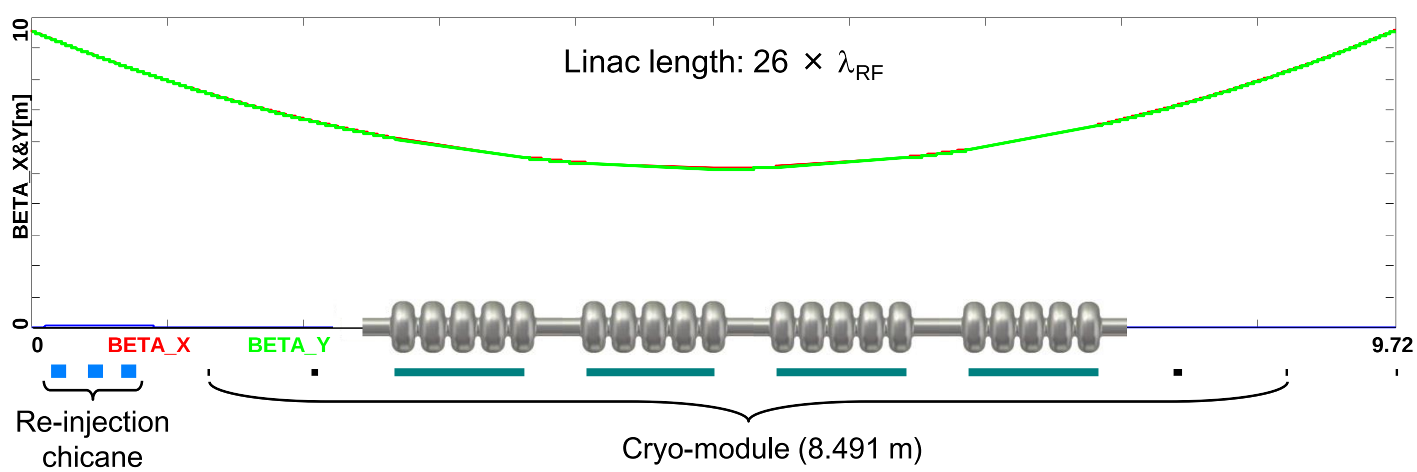
801.58 MHz RF, 5-cell cavity:

λ = 37.40 cm

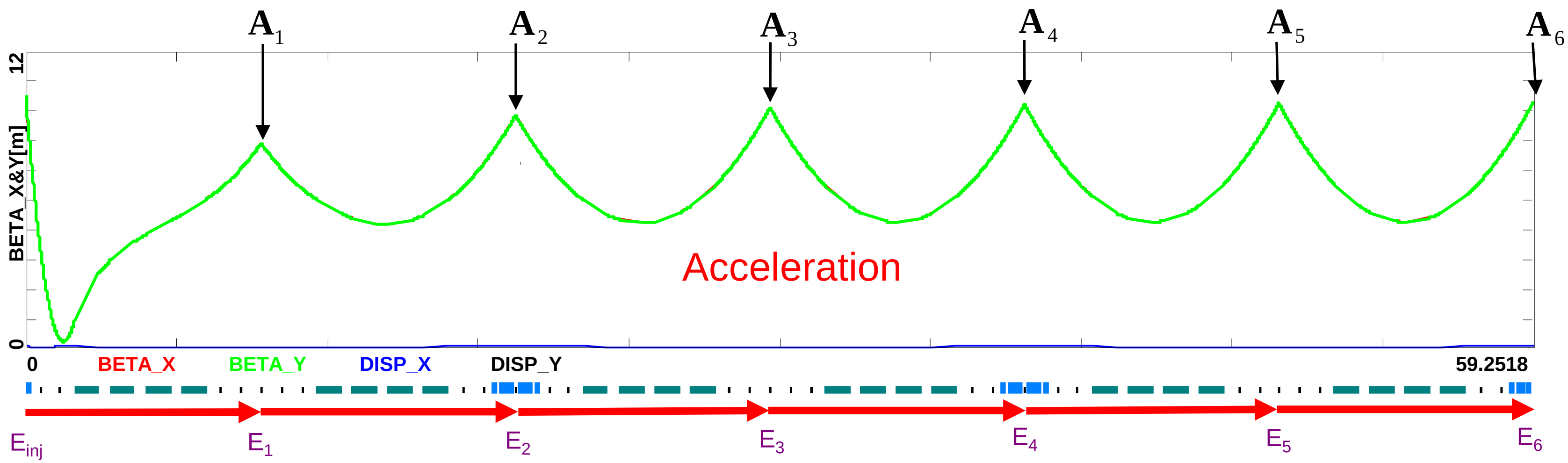
L_c = $5\lambda/2 = 93.50$ cm

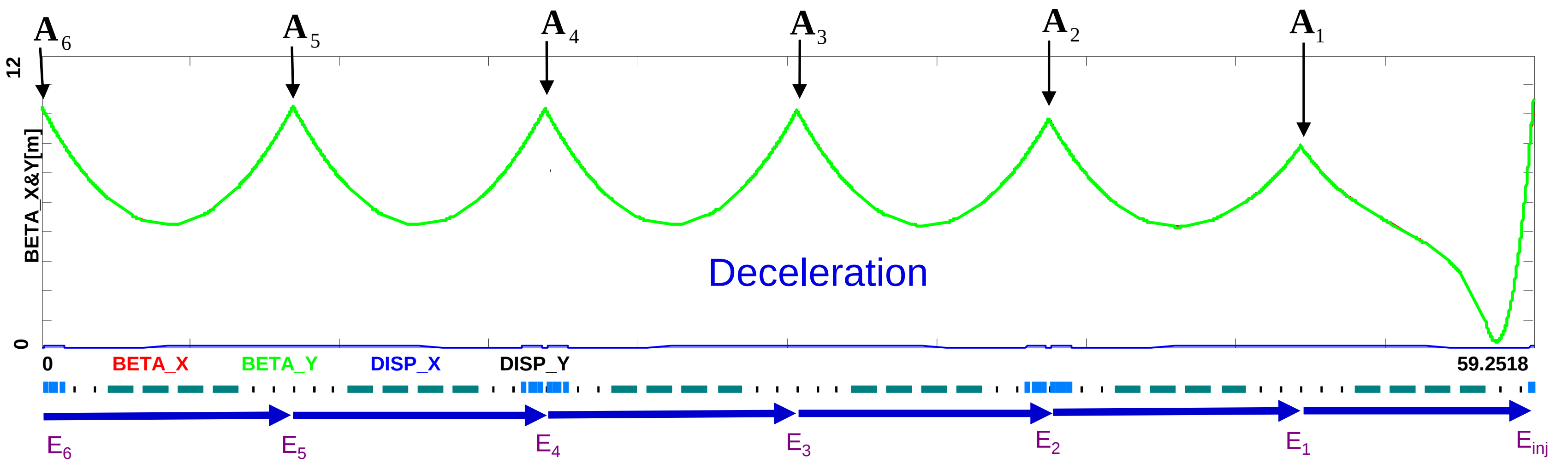
Grad = 17.5 MeV/m (16.4 MeV per cavity)

ΔE= 65.5 MeV per Cryo-module

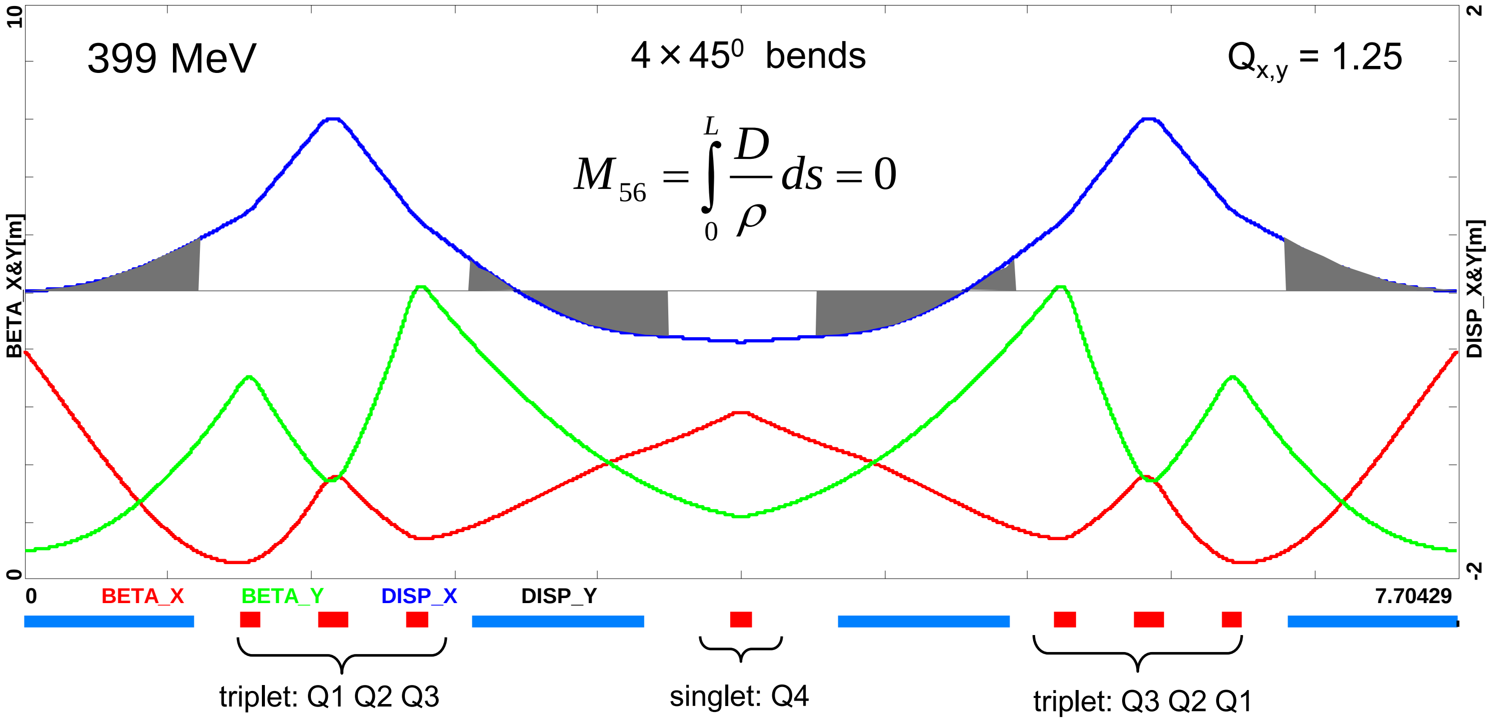


Multi-pass ER Optics





Flexible Momentum Compaction Arc



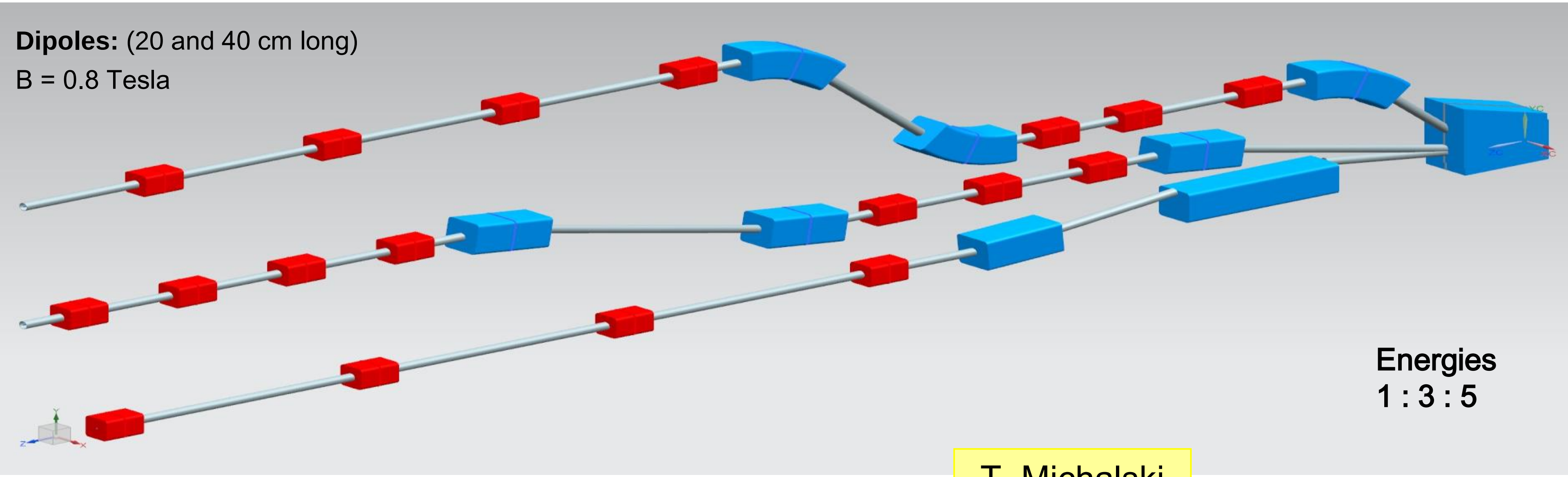
Dipoles: (91.2 cm long)

B = 1.2 Tesla

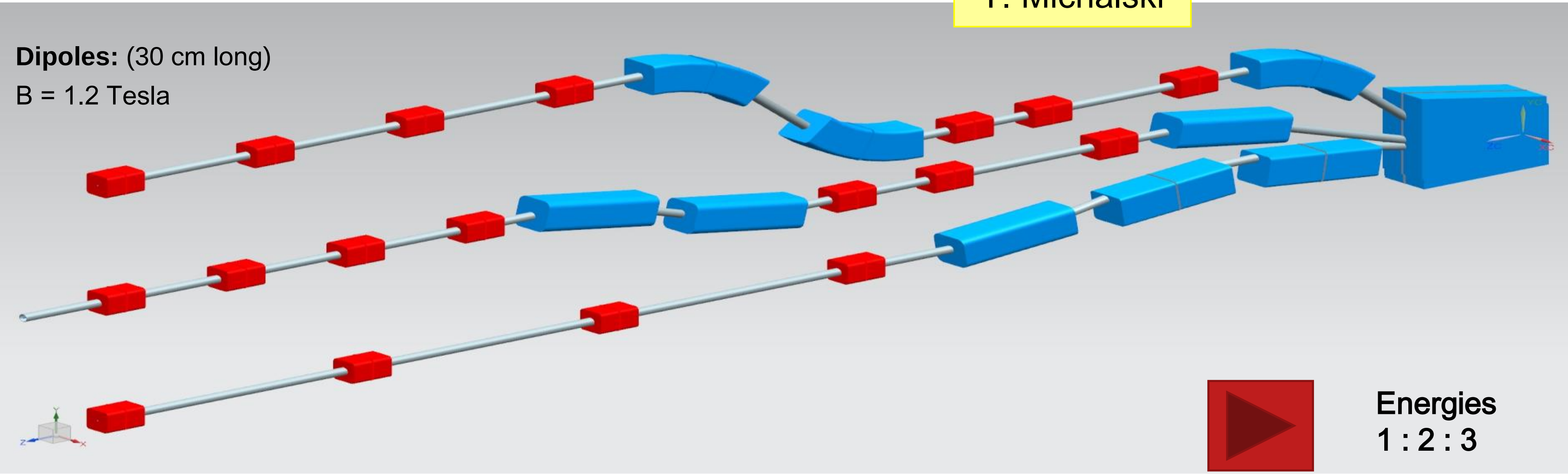
Quadrupoles:

Q1	L[cm] =10	G[T/m] = - 23.6
Q2	L[cm] =15	G[T/m] = 28.2
Q3	L[cm] =10	G[T/m] = - 22.4
Q4	L[cm] =10	G[T/m] = 8.6

Vertical Switchyard CEBAF-like Architecture



T. Michalski



SUMMARY

- PERLE uniquely combines beam energy, current, power, brightness, and operational flexibility
- It can therefore support testing throughout an unmatched region of ERL parameter space, informing and providing a technology base for designs of future generations of machines including
  - high energy colliders – in particular, LHeC!
  - non-equilibrium systems for electron cooling
  - high power/short wavelength FEL drivers
- Significant design progress has been posted
  - Linear system design maturing
  - Initial dynamics assessment underway

Thank you for the opportunity to visit, present, and discuss this very important machine with you!

NON-EQUILIBRIUM SYSTEM "TECHNICAL READINESS LEVELS"

At one level the LHeC ERL is analogous to a stealthy high-performance aircraft built out of advanced composites

The state-of-art JLab ERLs (the only CW systems to achieve RF drive "break-even"…) are at the state of the art in this technology:

Jefferson Lab

AEROSPACE ANALOG HISTORY OF ERLS