Science & Technology Facilities Council
Daresbury Laboratory

Why PERLE? An ERL Demonstrator for LHeC

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On behalf of **Dave Douglas**, Jefferson Lab

With thanks to **Chris Tennant**, Jefferson Lab

Jefferson Lab
Thomas Jefferson National Accelerator Facility

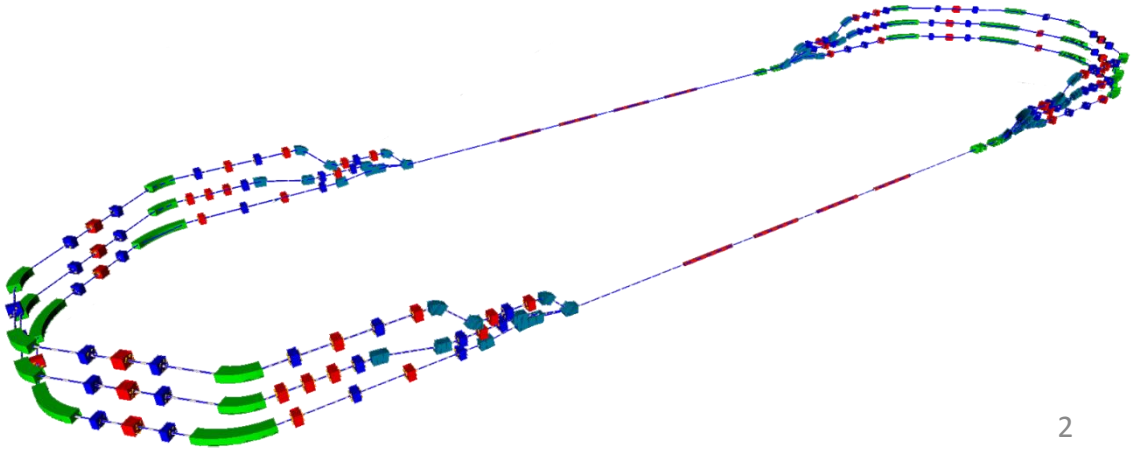
Science & Technology Facilities Council
Daresbury Laboratory

The Cockcroft Institute
of Accelerator Science and Technology

Why PERLE?

1. The need for PERLE:
   I. What do we want for the LHeC / FCC-eh that motivates an ERL?
   II. What is so different about ERLs?
   III. How have ERLs developed and where are we now?
   IV. What must ERLs demonstrate to show LHeC capability?
   V. How will PERLE address these questions / aspirations?
   VI. What additional opportunities can PERLE exploit?

2. Critique of the current PERLE design and some example ways forward



Why only an ERL will do for LHeC

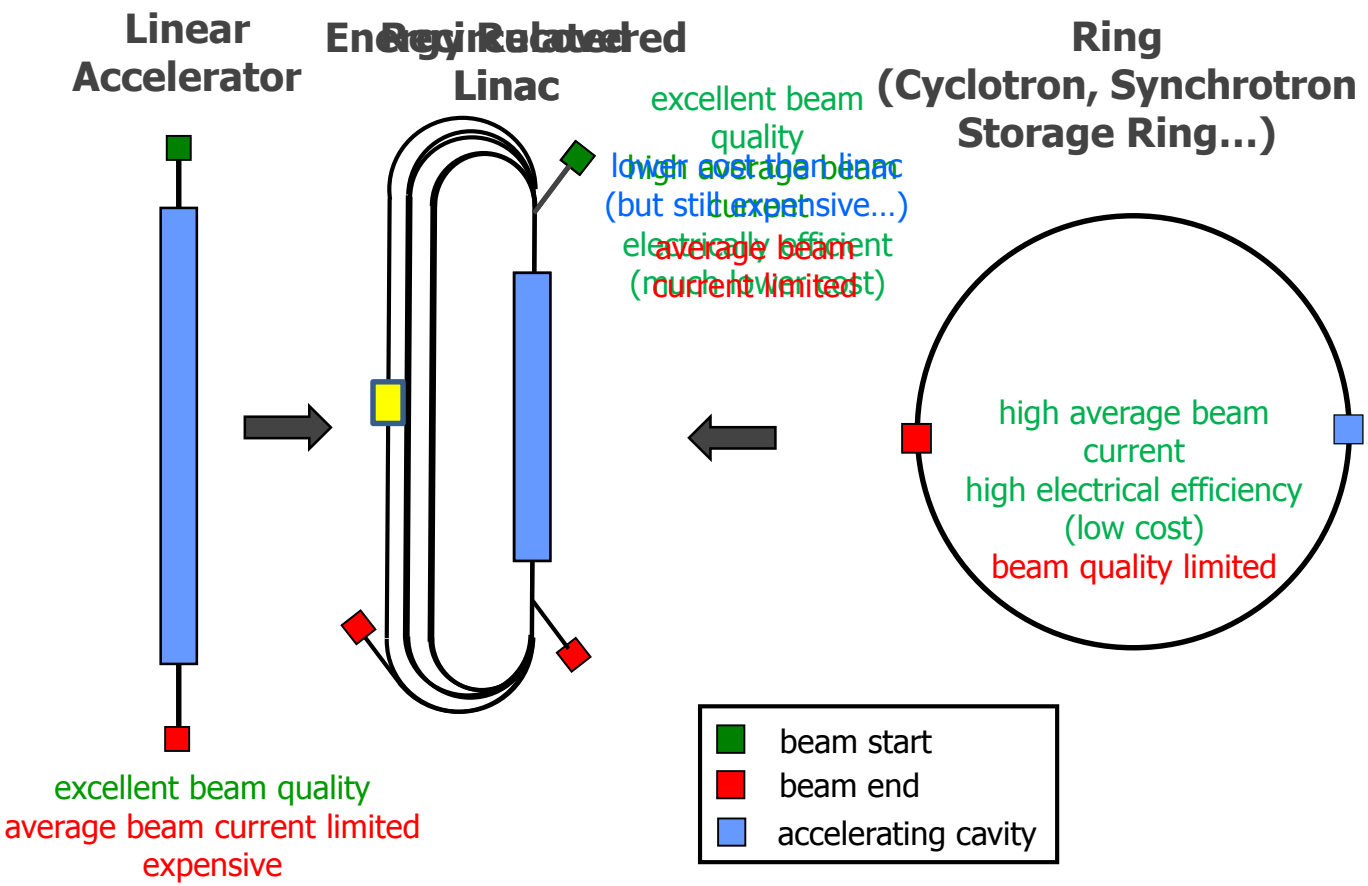
10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma\square^*_{x,y}$ [μrad]	80	40
Beam Current @ IP[mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

Oliver Bruening, PERLE collaboration meeting, Daresbury, January 2018

- A 27km ring will have normalised emittance **at least order of magnitude greater**
- ERL also capable of **withstanding stronger beam-beam**

ERL provides (nearly) linac brightness beam at (nearly) storage ring beam powers with storage ring energy consumption… ***the only chance to get to 10^{34} luminosity***

What is so different about ERLs?



Why are ERLs so hard?

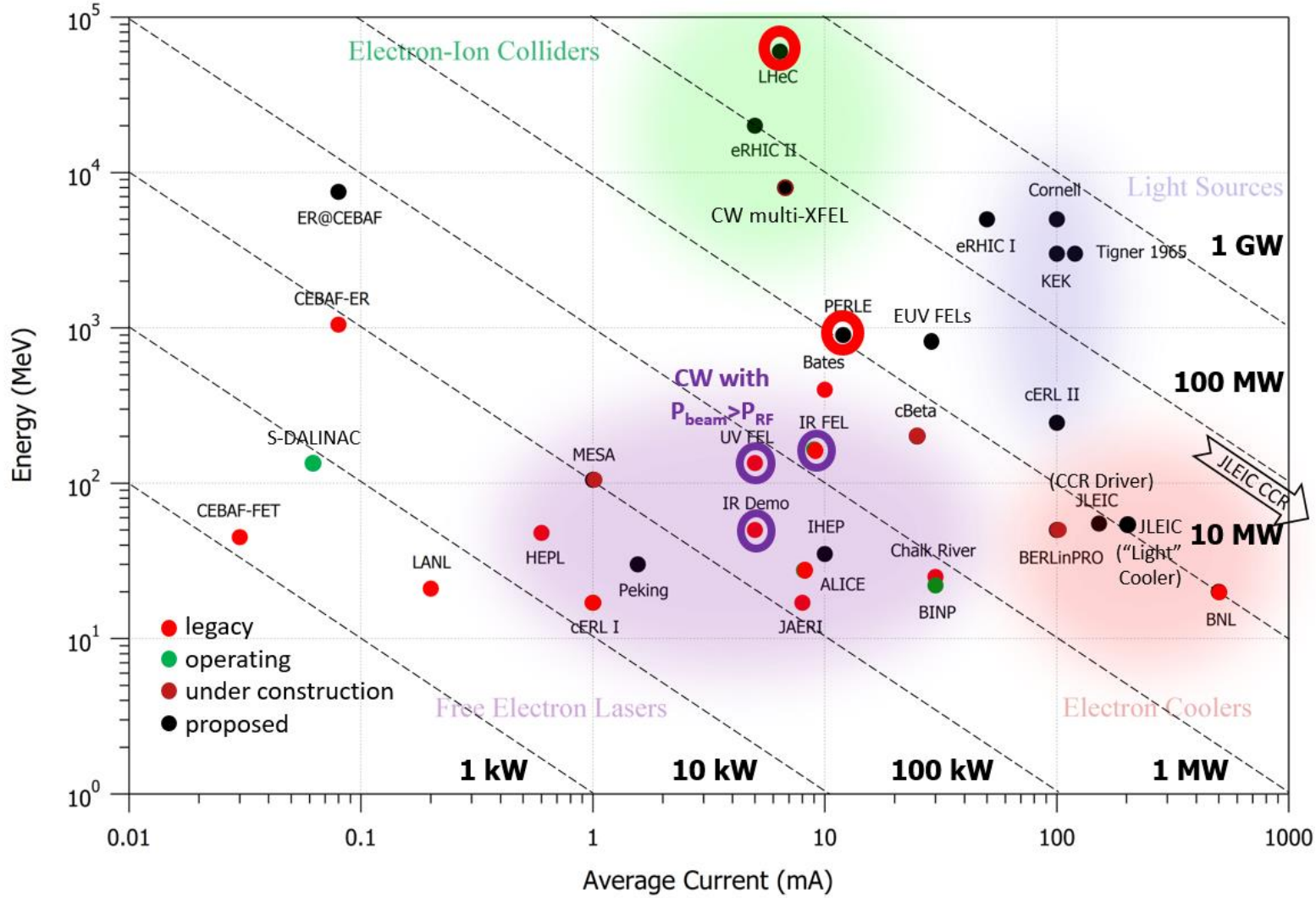
We are cocking a snook at Nature:

"Thanks for the offer of equilibrium dynamics, but we can handle these MW (GW) beams just fine on our own"

Or put another way – whenever you see an optics plot for an ERL, it represents a wish not a definition!

Or put another way – the beam and the lattice are different!

ERL Landscape: Current State of the Art



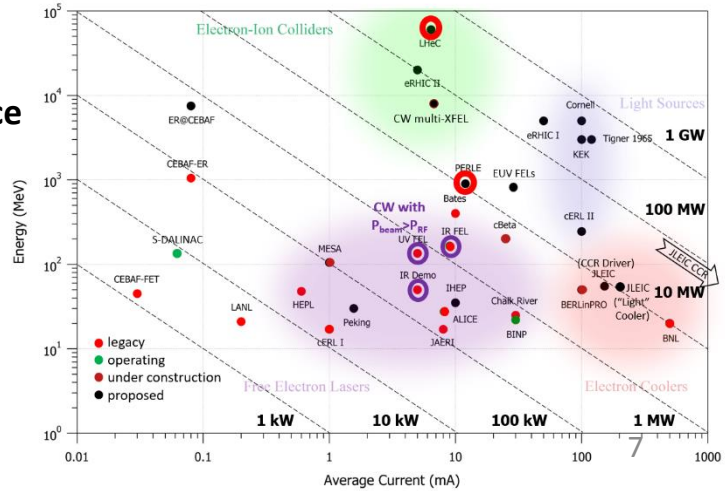
ERL Landscape: Current State of the Art

- Gives summary of
  - *Legacy systems* (now decommissioned)
  - *Operating facilities* (there is only one presently operating SRF system, the Darmstadt S-DALINAC)
  - *Systems under construction (MESA, C-BETA, bERLinPRO)*
  - *Proposed machines*

- **Only three (legacy) SRF systems have operated CW with P_{beam}/P_{RF}>>1**
  - JLab IR Demo, IR Upgrade, UV Demo; all single-pass up/down 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

- Two points to note:
  - **PERLE sits very close to "EUV FELs" in this plot, possible high-value application as semiconductor lithography source**
  - **The path from PERLE to LHeC passes directly through "CW multi-XFEL" with one order of magnitude in beam power separating each from the next**



The need for PERLE – legacy projects have not demonstrated enough

Reviewing the history of all 10 SRF ERLs operated to date offers insight…

- 2 limited to pulsed running by SRF spec / performance (JAERI, ALICE)
- 2 (probably) longitudinal-match limited (HEPL, CEBAF-FET)
- 3+ were source-limited to $P_{beam}<P_{RF}$ (CEBAF-FET, CEBAF-ER, S-DALINAC)
- 1+ was probably magnet field-quality limited (CEBAF-ER)
- 1 was loss (halo)-limited (cERL), and all 3 achieving break-even (Jlab ERLs) operationally challenged by halo
- Longitudinal matching involved more than riding crest up, trough down
- RF drive/controls more complex than naively expected; power requirements defined by transient management
- Power flow management – things getting very warm – was an issue in CW systems with $P_{beam}>P_{RF}$

Lesson learned: charge- and beam-power-dependent phenomena pose critical challenges when power scaled up!

How the current version of PERLE addresses the need

Scale-up and exploratory capability is provided with ***limited number of "reach" parameters / novel methods****; use of common multi-pass 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 scale-up** 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)

Question for the PERLE design – is this too many "reach" parameters?

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*
   - no successful demonstrations with multiple passes
   - no demonstration using common acceleration/recovery recirculation transport
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, and models have been reliable… but…
  - sensitivity of instability threshold to linac length, dynamic range, and number of passes not systematically measured

  PERLE will extend reach of data on all relevant parameters
- RF drive **dynamics** tested/validated only in single-turn / low dynamic range systems

3. *Scaling dynamic range (E_{full}/E_{dump}) from 10 to 100(+)*
   - defines sensitivity to magnetic field errors
     - error effects at high energy **magnified** by adiabatic antidamping during energy recovery

4. *Power scaling and halo control*

- Existing systems operated at "only" 1 MW full beam power without understanding and control of beam halo.
- Extrapolation to 10 MW involves suppression of localized losses to/below few parts per million ***There are no demonstrated solutions for this***

5. *"Power-flow management"*

- heating from many collective effects already problematic at lower beam powers
  - RF heating, resistive wall, THz emission,…
- PERLE is the ***only*** multipass system proposed or under construction that offers *both* intensity and flexibility to study

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

- Space charge/LSC, CSR, and microbunching instability have serious impact on performance
- PERLE probes the regions of parameter space where these effects are readily observable

Applications of PERLE: a golden opportunity

- The opinion of the authors of this presentation, based on many years of involvement with ERL projects are that the strategy of building a pure test facility is not optimal. Applications are needed to provide focus and fully justify the significant investment.

- We define applications as "societal uses of PERLE itself, not as a precursor machine"

- PERLE is fortunate in that it is timely, unique and has a plethora of potential unique applications with an already established need, most prominently…

1. ~10 kW average power EUV FEL for industrial semiconductor lithography

2. ~2 MeV Inverse Compton gamma source for nuclear resonance fluorescence, novel medical isotope production, nuclear photonics

Having started to explore these in the CDR, what is the justification for not pursuing?

Both these applications need 900 MeV – can user communities be enlisted to reach this? Can an upgrade path be defined?

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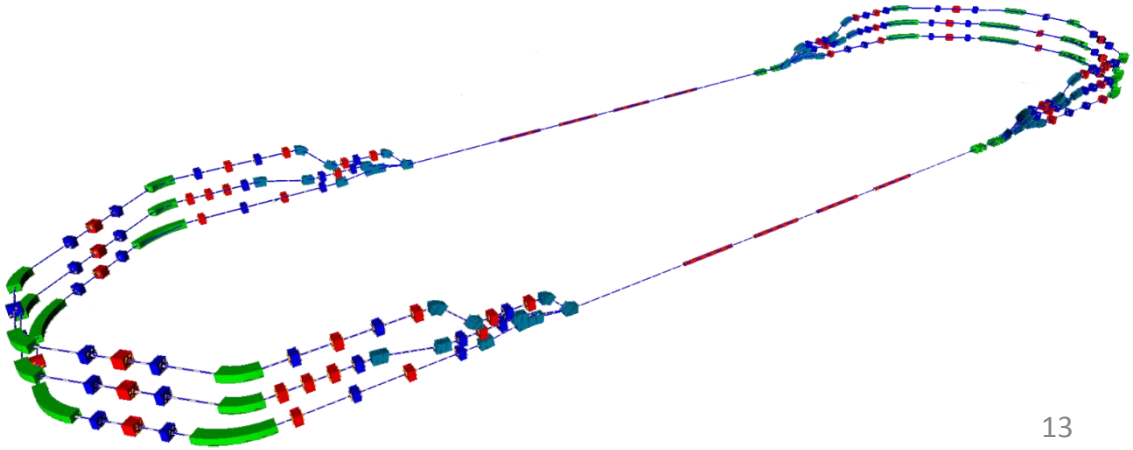
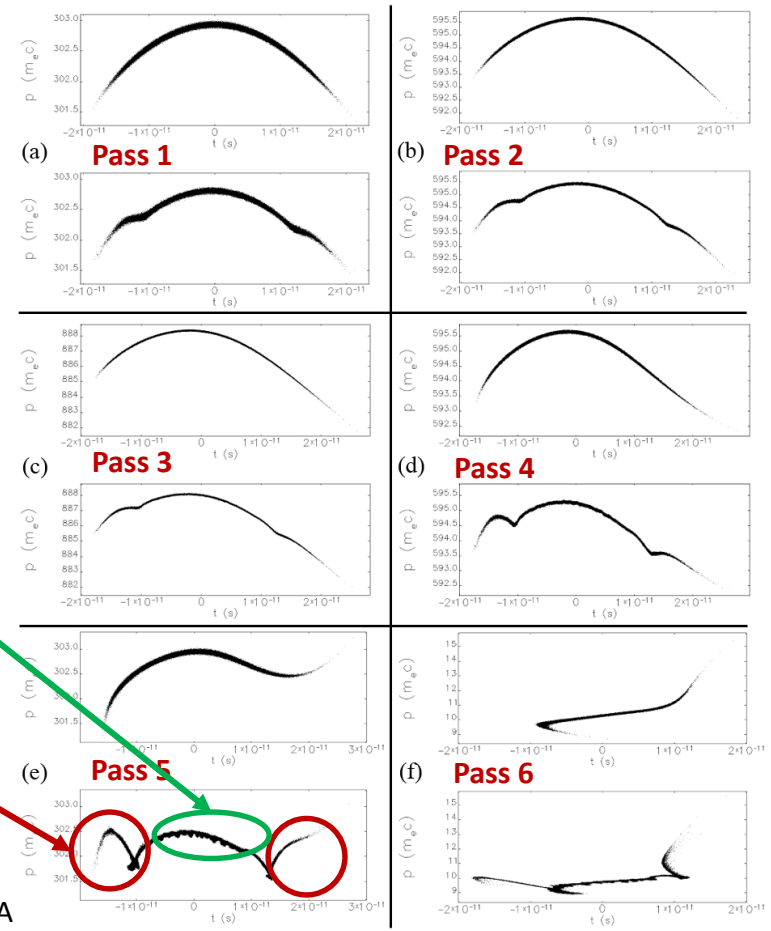


Issue to be resolved with the current PERLE design: CSR-wake driven phase space distortion (Chris Tennant: JLab)

- Longitudinal wake due to Coherent Synchrotron Radiation included in Elegant tracking
- Effect masked at high energy, evident and problematic at low energy during recovery
- "Wings" seen are feature of how CSR modifies the Gaussian longitudinal tails as opposed to the core flat-top = a sensitive function of the exact longitudinal phase space on injection
- Possible to use "Caustic" analysis (Tessa Charles) to mitigate?

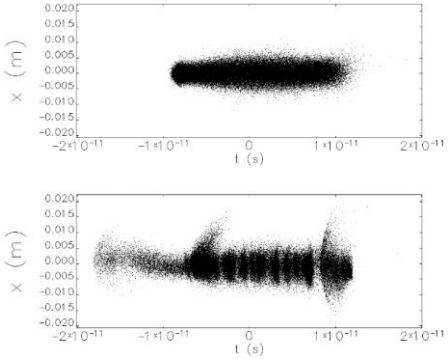


Parameter	Value
Injection Energy (MeV)	5
Maximum Energy (MeV)	450
Linac Gain (MV)	75
Normalized Emittance (mm-mrad)	6
Average Beam Current (mA)	12.8
Bunch Charge (pC)	320
RMS Bunch Length (ps)	6.67
RMS Energy Spread (keV)	10
RF Frequency (MHz)	801.6

Chris did this for 320 pC (= 12.8 mA @ 25 ns spacing) – and remember these effects go as Q^2…

Issue to be resolved with the current PERLE design: CSR-driven microbunching instability (Chris Tennant: JLab)

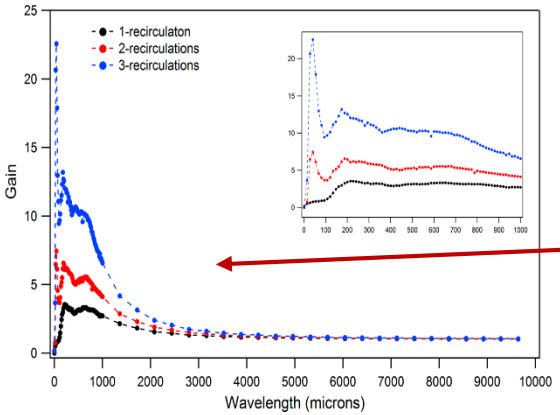
- Longitudinal phase space of bunch after six recirculations without (top) and with (bottom) CSR



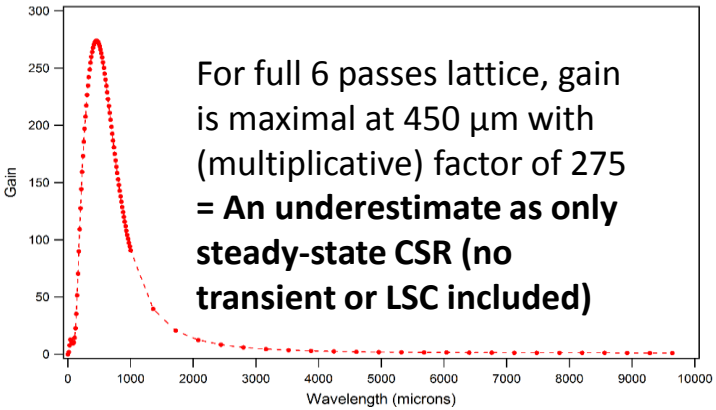
- uBI is the amplification of density modulations from shot-noise / laser via "plasma oscillations" in longitudinal phase space (although both SC and CSR impedances drive it – and crucially CSR doesn't "turn-off" at high energy)

- Left to amplify, bunch will radiate copiously at uBI peak frequency = emittance degradation

- Estimate gain factor using semi-analytic Vlasov solver (Cheng-Ying Tsai) – calculates cumulative amplification factor through entire lattice transport using matrix method. Expressed as a function of initial modulation frequency



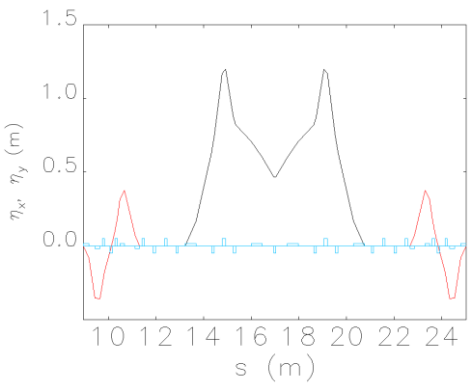
Gain accelerating from pass-to-pass

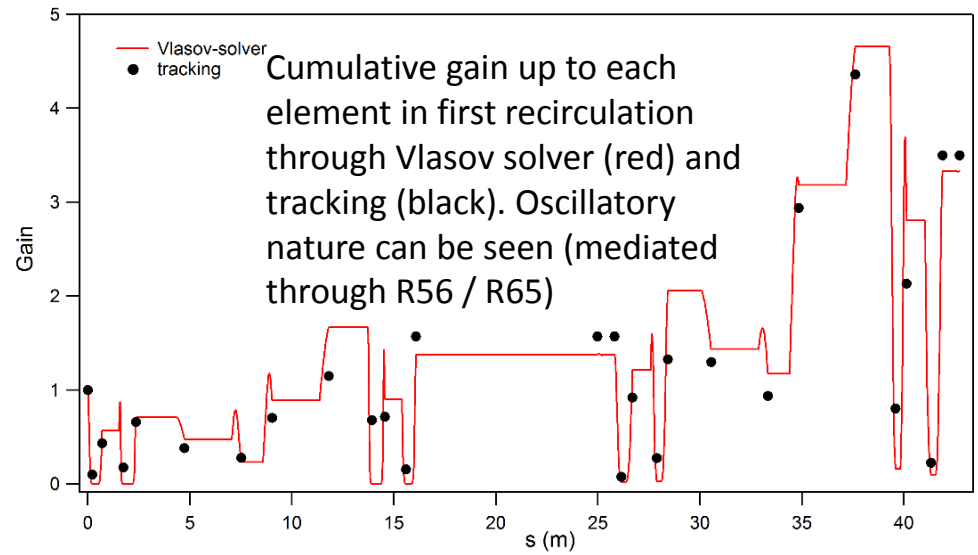


For full 6 passes lattice, gain is maximal at 450 µm with (multiplicative) factor of 275 **= An underestimate as only steady-state CSR (no transient or LSC included)**

Issue to be resolved with the current PERLE design: CSR-driven microbunching instability (Chris Tennant: JLab)

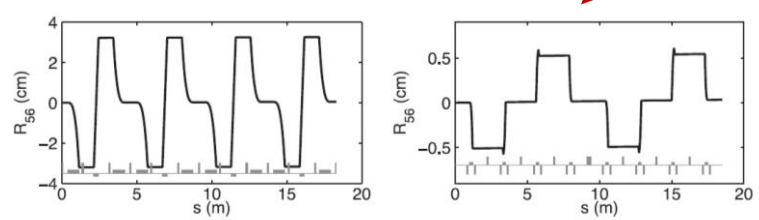
- Vlasov results (frequency domain) checked with tracking (time domain) showing good agreement
- Suspect this is due to large modulation in R56 as isochronicity is achieved through cancellation of large terms (spreaders and arcs)





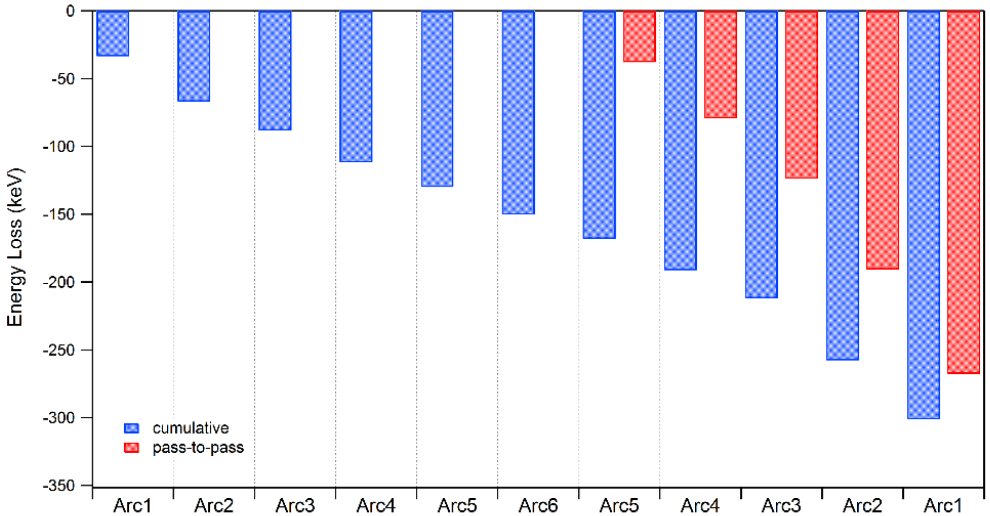
Cumulative gain up to each element in first recirculation through Vlasov solver (red) and tracking (black). Oscillatory nature can be seen (mediated through R56 / R65)

- Possible to mitigate (down to factor of 1) by replacing FMC arcs with **uBI minimising arc** (small dispersion, locally isochronous, integer multiples of pi phase advance between dipoles) [PR-AB 19, 114401; PR-AB 20, 024401] and **single step spreaders** (rather than staircase)



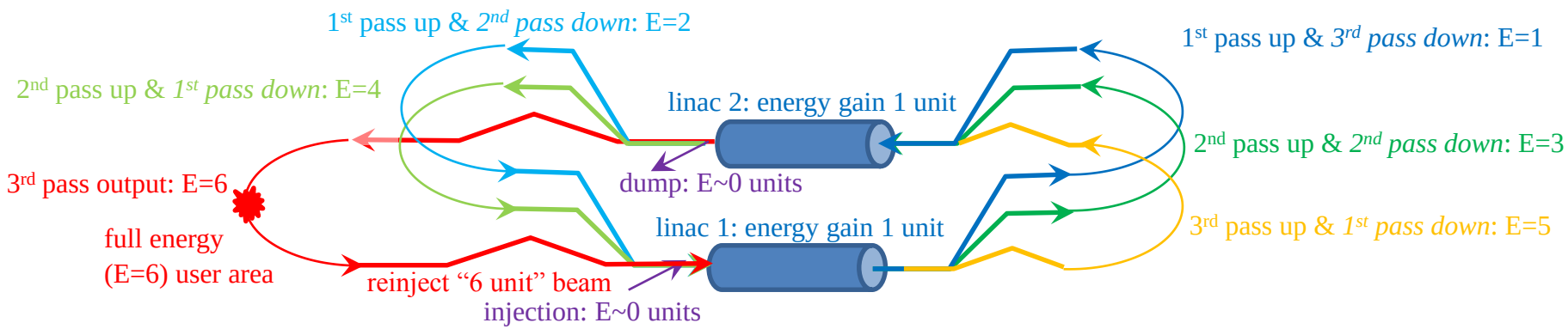
Issue to be resolved with the current PERLE design: SR pass-to-pass energy losses (Chris Tennant: JLab)

- If the **choice** is made to use **common transport** of the accelerated and decelerated beam we must create an inventory of various energy loss mechanisms to ensure that the **adequate momentum acceptance is available**
- Here we consider the combined effect of coherent and incoherent synchrotron radiation
- The total power radiated away is 3.8 kW (= 300 keV × 12.8 mA). And in particular, Arc1 must accommodate and cleanly transport the nearly unperturbed first pass accelerating beam as well as the exhaust beam on its last pass
- The energy differential between the two energy centroids is 270 keV which corresponds to 0.34% at 80 MeV/c. For the 1.25 m dispersion in Arc1 (see Fig. 4) this means beam will sample an aperture of 0.43 cm
- More generally, **is it an acceptable risk** to have **absolutely nowhere** in the machine to **independently adjust** the orbit, or the transverse match, or anything else, in what is (remember) **a machine without a natural equilibrium**?
- PERLE does not **have** to have fully common transport – alternatives choices could be made…



Risk mitigating alternative to the current PERLE Design: Separate the accelerated from the decelerated beam?

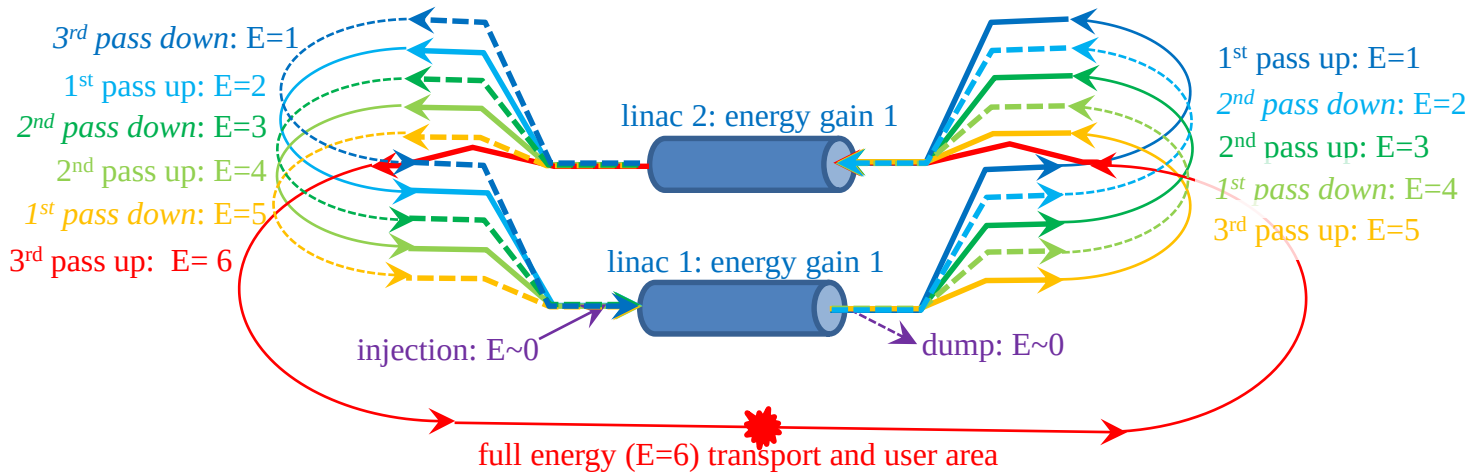
Existing PERLE topology is <u>symmetrically bisected with L1 reinjection:</u>



- This involves **minimal number of beamlines**
- The recirculation transport **necessarily** carries both accelerated and recovered beams simultaneously as their energies are very similar (true even when interaction and SR losses included). Therefore there is **no independent control of optics and longitudinal phase space** on deceleration
- User area constrained (although "paperclip" 540-degree turn would provide 2 – see additional slide)
- A lesser design complication is that the east and west **splitter / recombiners are optically different** (energy ratios 1:3:5 and 2:4:6 respectively)

Risk mitigating alternative to the current PERLE Design: Separate the accelerated from the decelerated beam?

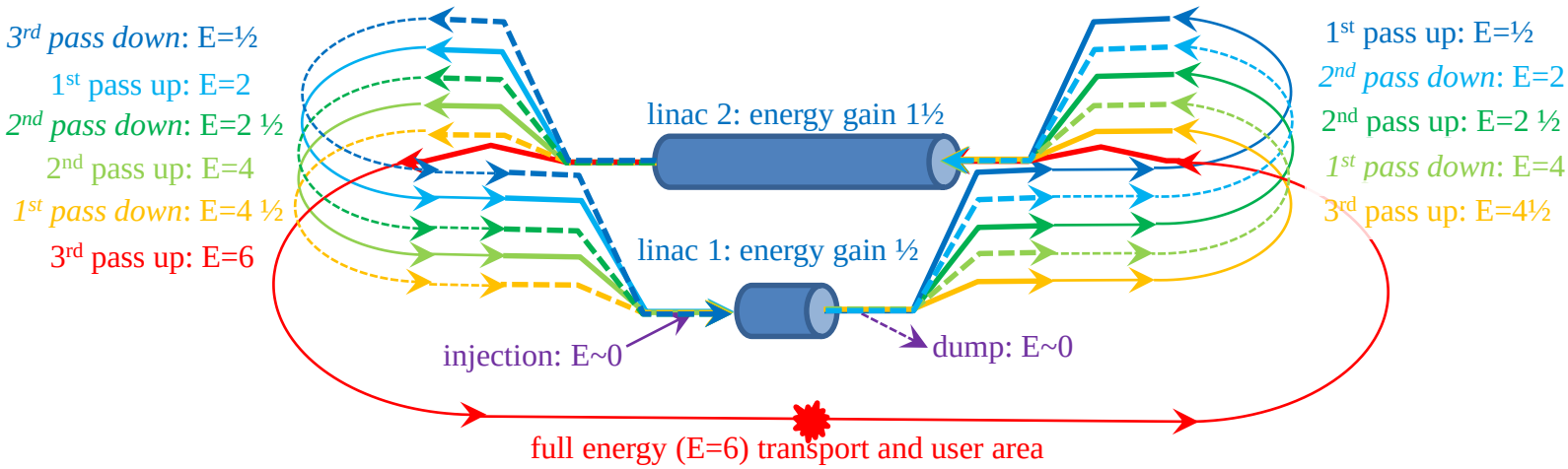
Alternative Topology 1: Symmetrically bisected with reinjection to L2:



- Accelerated and recovered beams now carried separately. Enables **individual pass-to-pass orbit, optics and longitudinal phase space control** **(in fact this is necessary to find *global* LPS solution)**
- L1 still has a large **mismatch of focusing strength to beam energy** – this limits the focusing we can apply to the top energy. Beam envelops thus scale as (linac length)^2 = errors!
- In the case of full LHeC**, eliminates need for SR compensating linacs** – can instead be done on injection -> mitigates low energy optics mismatch
- For PERLE, provides **one long straight user area**
- East and west **splitter / recombiners are now identical** for PERLE, nearly so for LHeC

Risk mitigating alternatives to the current PERLE Design: Separate the accelerated from the decelerated beam?

Alternative Topology 2: Asymmetrically bisected with reinjection to L2:

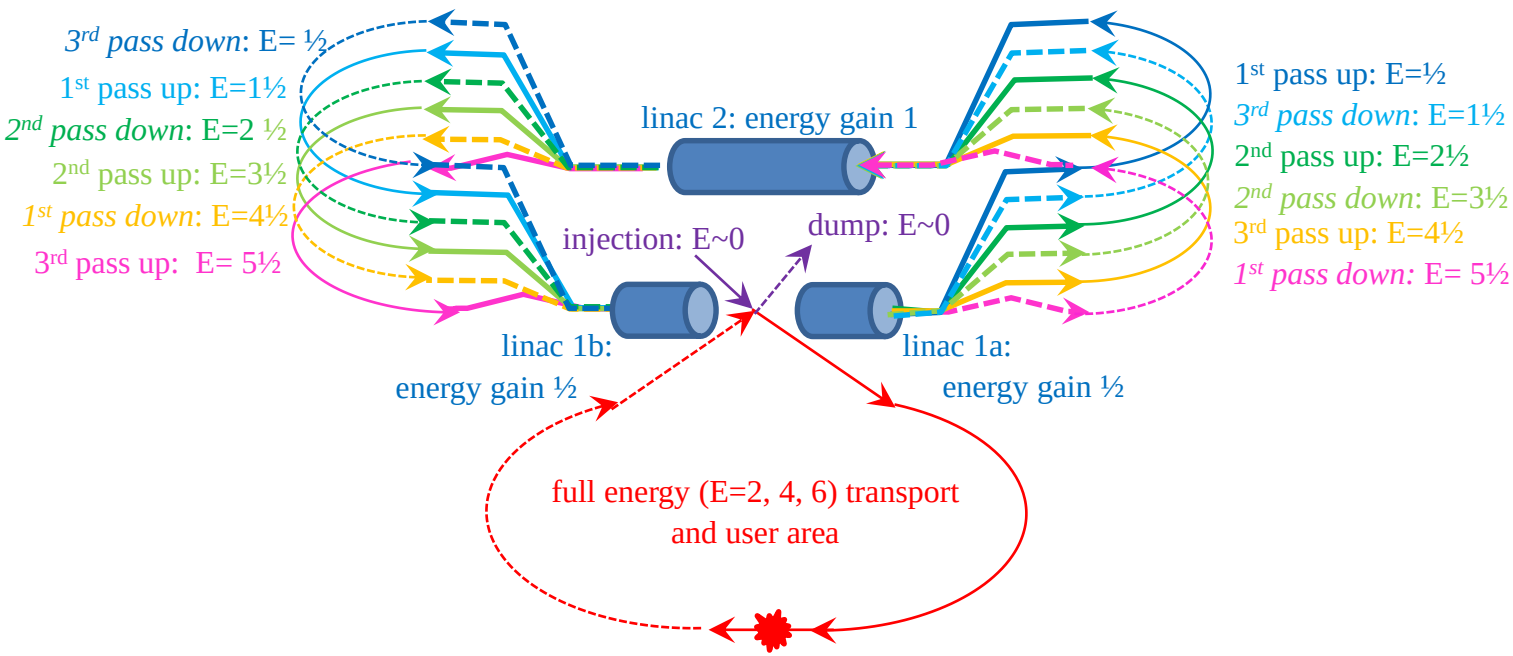


- Shortening the linac into which we inject / extract futher **mitigates the low-beam-energy-constrained focusing** at the expense of **additional beamline length**
- Unfortunately, we **lose the symmetry in spreader / recombiners**

Invented by Dave Douglas as the "GERBAL" = Generic Energy Recovered Bisected Asymmetric Linac

Risk mitigating alternative to the current PERLE Design: Separate the accelerated from the decelerated beam?

Alternative Topology 3: Symmetrised asymmetrically bisected (SYBAL):



- Mitigates the low beam energy constrained focusing, but **retains beamline packing fraction**
- **Symmetrizes all optics** in spreader / recombiners
- **Complexity** in the crossover region where space is limited (can be mitigated with "paperclip" or "figure-of-eight" – see additional slide)

Conclusions / Recommendations #1

- **PERLE is essential to show credibility of ERL solution for LHeC as it uniquely combines beam energy, current, power, brightness, and operational flexibility**
- **But is PERLE doing too much in one step?**
- **Further design work is necessary to answer this,** and should aim to minimise risk based on learning of past ERL projects
    - Produce a longitudinal match – show there is enough momentum aperture
    - Use the dynamic range to define the magnet field quality specs – adiabatic anti-damping of errors on deceleration!
    - Explore topology, detailed consideration of separate transport vs common transport – remember optics = wish, not definition!
    - Include in these studies mitigation methods for e.g. CSR / uBI
    - Study BBU, consider introduction of phase space rotators for each pass so any low thresholds that develop can be avoided operationally with flexibility
    - Consider implications of 25 mA with regards to halo, ion trapping

Conclusions / Recommendations #2

- #1 is **necessary, but is it sufficient to justify what needs to be a significant investment?** Remember, ALICE ambition was much more limited than PERLE, yet cost ~£30M (now handily = €30M ☺) capital over the 10 year operation

- PERLE sits in a unique parameter range that is also perfect to drive a ~10 kW average power EUV FEL, **and** a high flux MeV Compton gamma source (synergy here with ThomX), but only if further refinement of the design with respect to that which needs to be done for "just" an ERL demonstrator

  - Revisit previous considerations of these applications – talk to industry / potential user communities
  - Study how they could be included into PERLE in future – don't rule them out by choices made now, for example…
  - Have a defined path to 900 MeV
  - Produce longitudinal match for applications = off-crest acceleration / deceleration, bunch compression / decompression / linearization
  - Consider upgrade to higher brightness injector (~0.5 mm mrad @ ~300 pC)

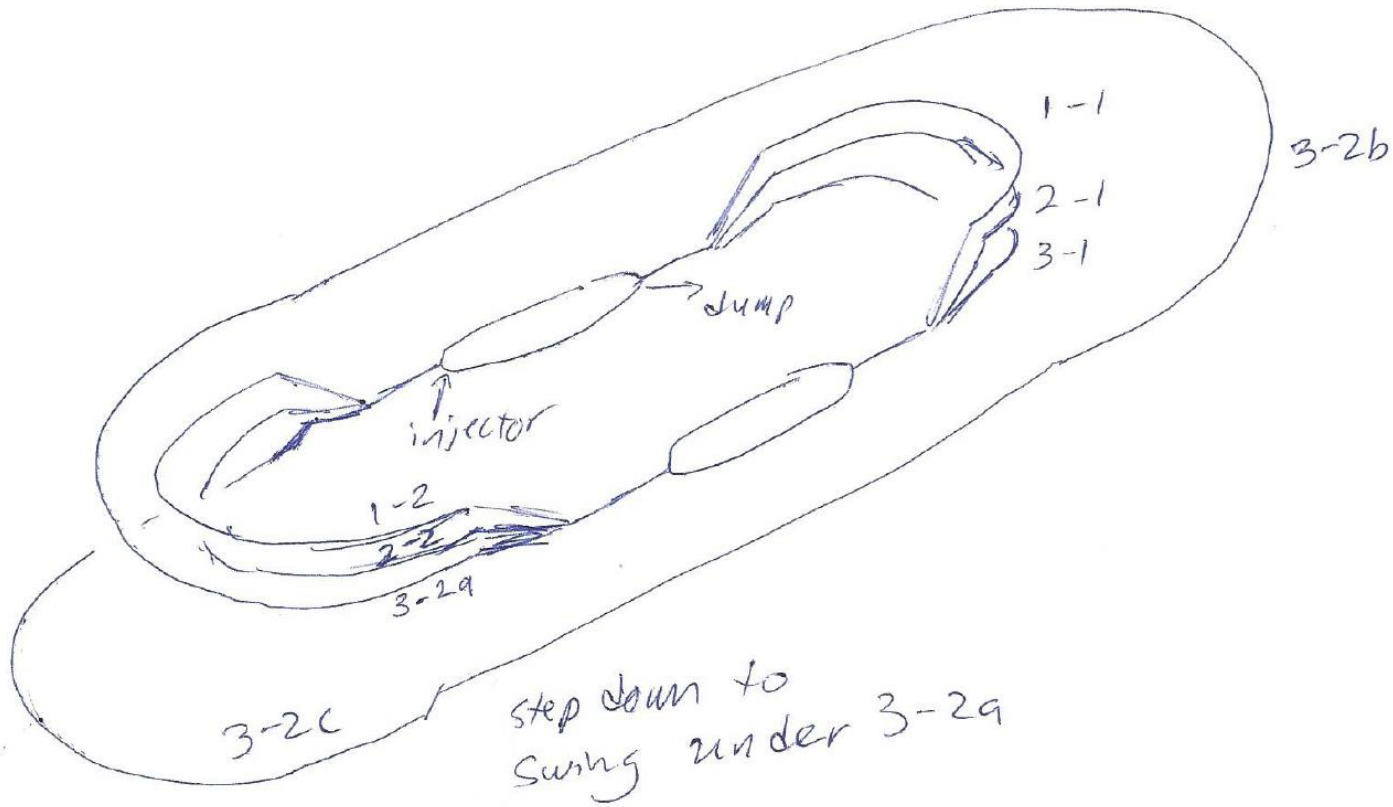
Conclusions / Recommendations #3

- International ERL community needs more coherent approach: Advocate complementary projects e.g. **ER@CEBAF**. Aim should be to **take ERLs from *"alternative unproven technology"* to DEMONSTRATED NEW CAPABILITY OF ACCELERATORS**

- LHeC project should give consideration as to whether there is need for an **additional step** beyond PERLE on the path to LHeC – a "CW multi-XFEL" (being studied as an option for UK-XFEL – see additional slide)

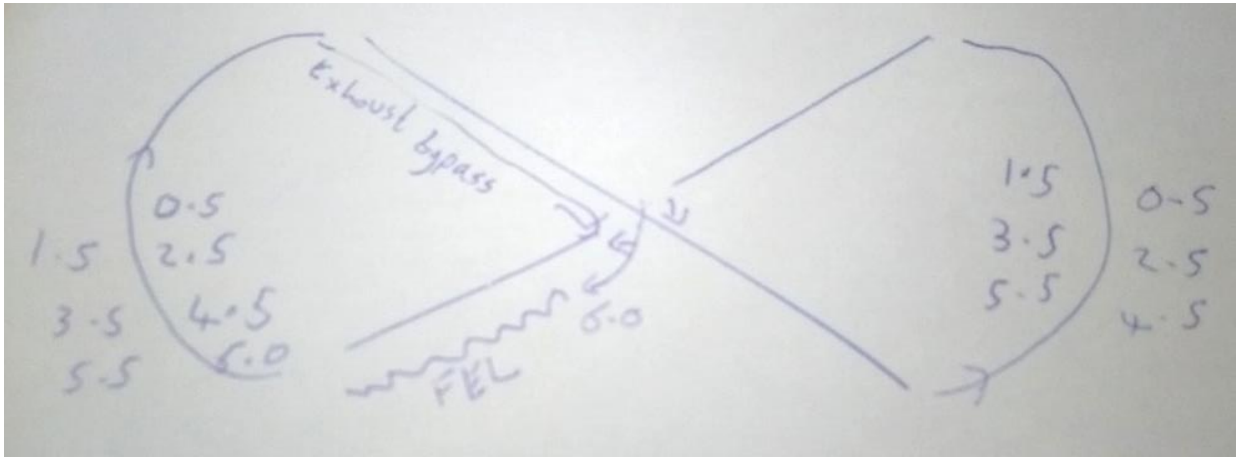
Extra Slides

More Possible Topologies – The Paperclip



Common transport, but 540-degree rather than 180-degree provides two long straight user areas

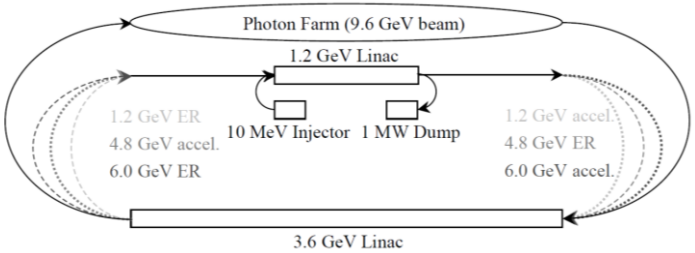
More Possible Topologies – The Figure-of-Eight



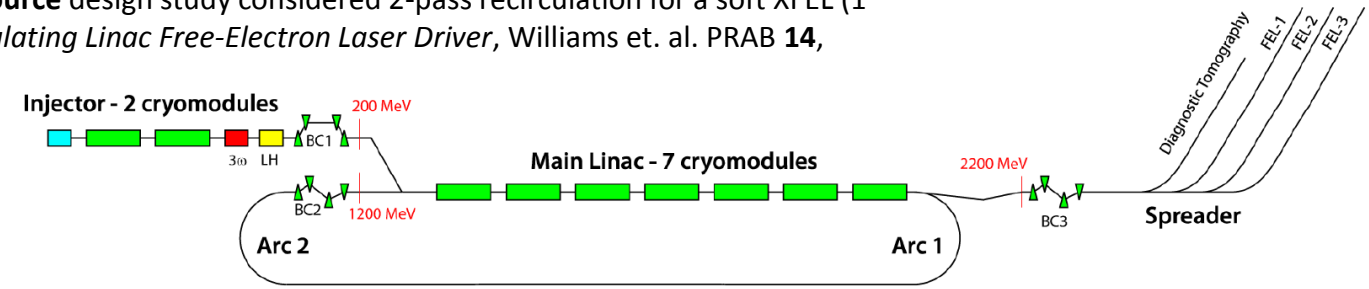
Linacs built with vertical separation, SYBAL type (one full linac and two half linacs with gap between at full linac crossover point) with scissor angle, separate transport without need for additional footprint, however more bending

History of Recirculating XFEL Proposals*

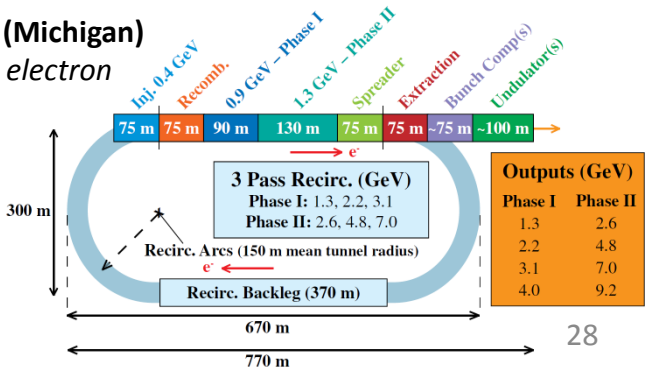
- **2001: GERBAL** considered an FEL among other spontaneous sources (*Generic Energy-Recovering Bisected Asymmetric Linac*, Douglas, ICFA-BD-NL-26, 2001)



- **2010: UK New Light Source** design study considered 2-pass recirculation for a soft XFEL (1 keV) at 1 MHz, (*Recirculating Linac Free-Electron Laser Driver*, Williams et. al. PRAB **14**, 050704, 2011)

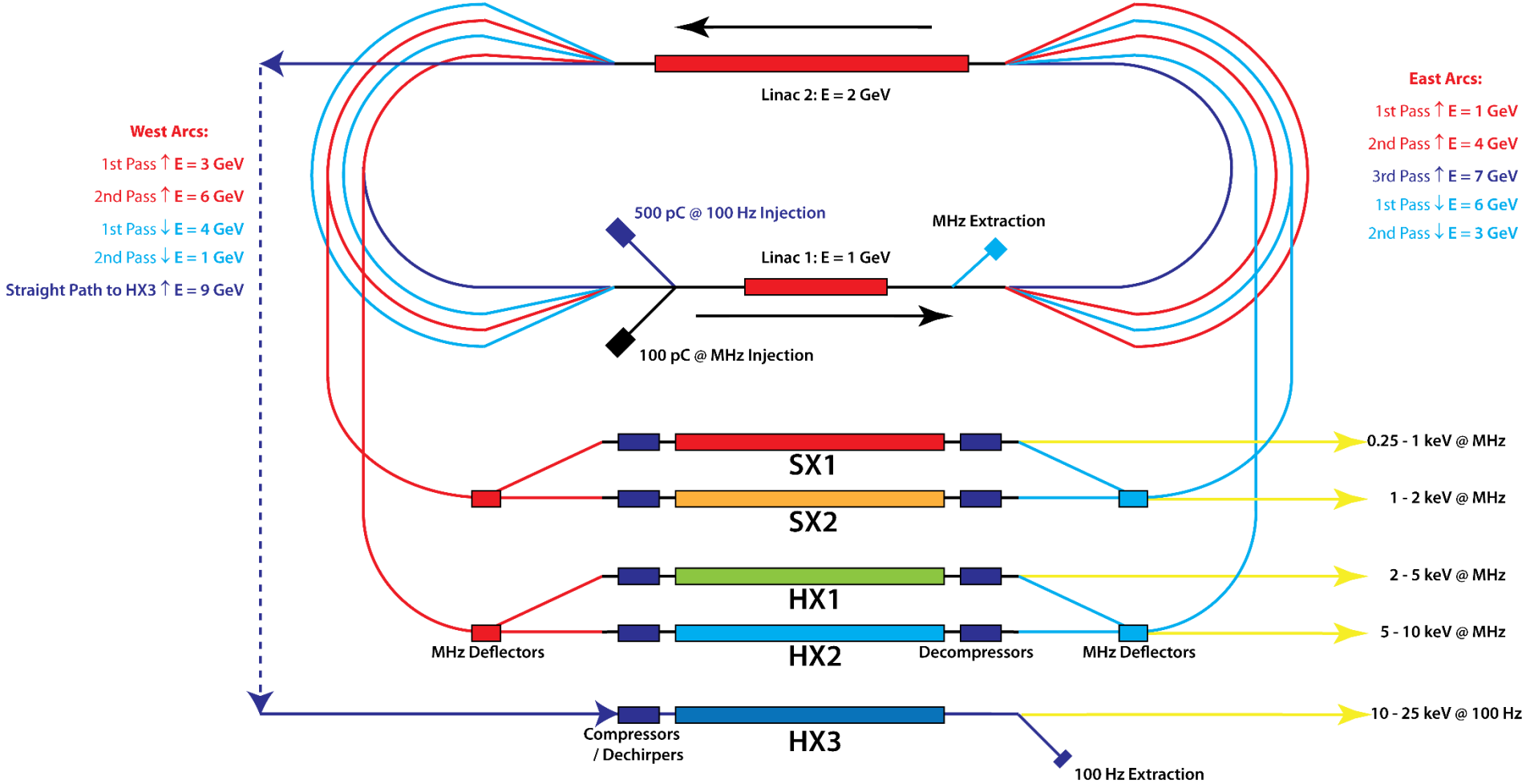


- **2014: CEBAF-X** design study to add a soft XFEL to CEBAF lead to **Richard York (Michigan)** proposed 3-pass recirculation for hard XFEL, (*5 keV upgradable to 25 keV free electron laser facility* PRAB **17**, 010705, 2014)

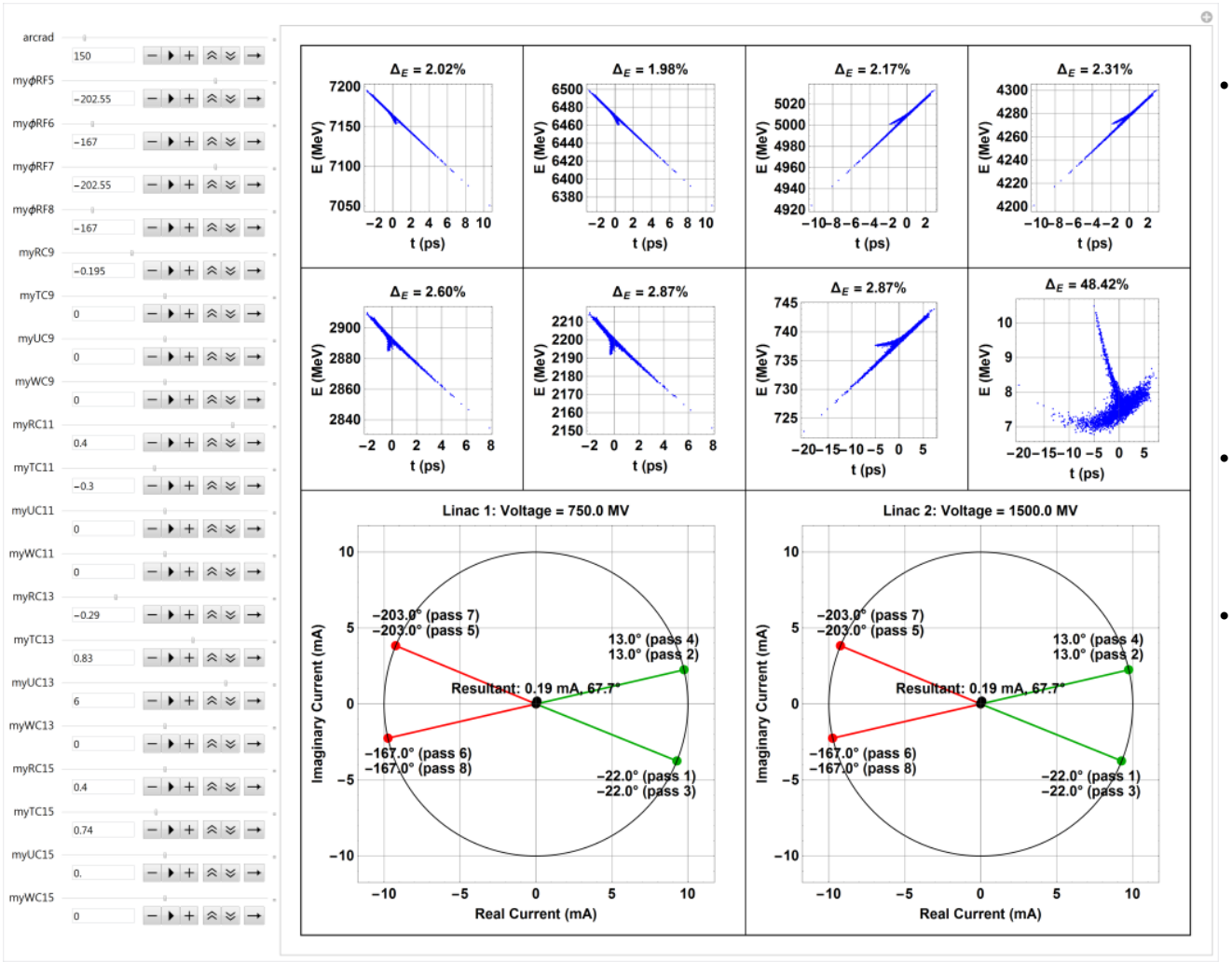


* To my knowledge, all other considerations of recirculation addressed only spontaneous sources or longer wavelength FELs

Strawman UK-XFEL based on Multi-Pass ERL: A possible stepping stone from PERLE to LHeC?



Example of Successfully Recovering the Spent Bunch in a Compressive Multi-Pass ERL-FEL



- For > 1 MHz rep rates with bunch compression / decompression we must ensure full energy recovery, this requires self-consistent longitudinal phase space match with RF load balancing, accelerating bunch compression and decelerating bunch decompression (and energy spread compression)
- This match must also account for any bunch disruption by IP / FEL lasing / internal target and ISR losses
- Global optimization of linear and higher order longitudinal transport terms in the arcs, together with pass-to-pass off crest phase achieves this (here we show a 4-pass GERBAL implementation as example)