Science & Technology Facilities Council
Daresbury Laboratory

A Staged, Multi-User X-Ray Free Electron Laser & Nuclear Physics Facility based on a Multi-Pass Recirculating Superconducting CW Linac

Peter Williams

ASTeC, Daresbury Laboratory & Cockcroft Institute, UK

8th March 2018

The Cockcroft Institute
of Accelerator Science and Technology

Science & Technology Facilities Council
Daresbury Laboratory

Outline

1. Challenge to the MHz Hard XFEL Community
2. Recirculation as a Cost Mitigation Strategy
3. Opportunity to extend science reach through Energy Recovery
4. Candidate Topologies
5. Slice Energy Spread & Peak Current Limitations from ISR
6. An Example Cost Mitigation
7. R&D to Establish Feasibility
8. Conclusions

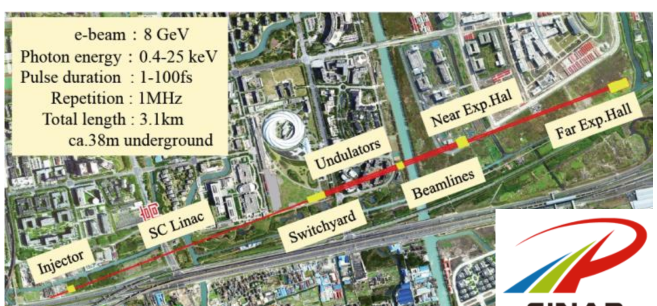
So… You Want to Build A CW MHz Repetition Rate Hard X-Ray FEL?

European XFEL CW Upgrade:

7 GeV electrons, 15 keV photons, 250 kHz

LCLS-II-HE:

8 GeV electrons, 13 keV photons, 1 MHz



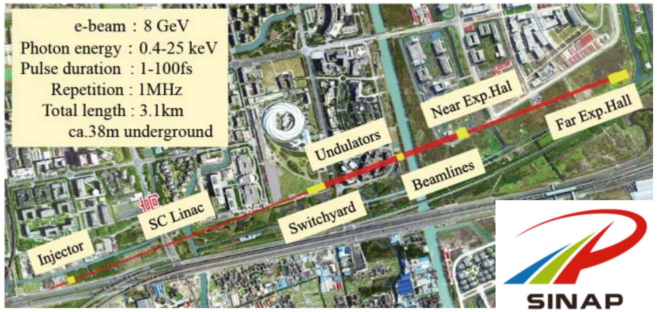
SINAP SCLF:

8 GeV electrons, 25 keV photons, 1 MHz

J. Sekutowicz et. al. “R&D Towards Duty Factor Upgrade of European XFEL Linac”, PR-AB 18, 050701 (2015)
Robert Schoenlein, “LCLS-II Science Cases”, Topical Workshop on High Repetition Rate XFEL Physics, Aug 2017, SINAP
Zhiyuan Zhu, “Overview of the SCLF Project”, Topical Workshop on High Repetition Rate XFEL Physics, Aug 2017, SINAP

Science & Technology Facilities Council
Daresbury Laboratory

So... You Want to Build A CW MHz Repetition Rate Hard X-Ray FEL?



Why do we build one single-pass linac? Are we as a community being too conservative and inefficient?

What additional capability could we enable with a more radical approach?

We should consider recirculation

Consideration of Recirculation as Cost Mitigation for a Possible UK-XFEL

- There is an ambition to build an XFEL in the UK in the coming decade (see Neil Thompson’s talk on Tuesday). Specifications are still evolving, however many are **not compatible** with normal conducting linac technology e.g. user requests have included **high repetition rate (>100kHz) ~10 keV pulses, laser/XFEL synchronisation < 1fs**

- We therefore explore superconducting linac technology as an **additional capability** option. The facility should:
  1. Satisfy **as many** specifications as possible on Day 1
  2. Maximise opportunity for further exploitation (facility lifespan ~ 30 years)

- This should be done with minimal total cost of ownership and lowest risk of:
  1. The “Day 1” facility
  2. The “Maximum Exploitation” facility

- This motivates use to consider **TWO** stages of accelerator development
  1. N-Pass*
  2. N-Pass with Energy Recovery

  * Where N = 1 (straight linac, no recirculation), 2, 3, 4 (recirculating linac)

- User request also **25 keV with 1 kHz rep rate and high pulse energy (3 mJ)** – how to include this?

Science & Technology Facilities Council
Daresbury Laboratory

Consideration of Recirculation as Cost Mitigation for a Possible UK

- There is an ambition to build an XFEL in the UK in the coming decade (see Neil Thomps are still evolving, however many are **not compatible** with normal conducting linac included **high repetition rate (>100kHz) ~10 keV pulses, laser/XFEL synchro**

- We therefore explore superconducting linac technology as an **a**
  1. Satisfy **as many** specifications as possible on Day 1
  2. Maximise opportunity for further exploitatio

- This should be done with minimal total
  1. The "Day 1" facility
  2. The "Maximum Exp

- This motivates pment
  1. N

ulation), 2, 3, 4 (recirculating linac)

ith 1 kHz rep rate and high pulse energy (3 mJ)** – how to include this?

However, my aim in this talk is to make general comments about recirculation in CW XFEL drivers – NOT any UK-XFEL project specifics

In Addition to Cost Mitigation: A Recirculating Linac Opens the Door to Extend Science Reach through Energy Recovery

CW Rep. Rate	1 MHz	10 MHz	100 MHz
Bunch spacing	1 us	100 ns	10 ns
Gun Current (100pC bunches)	100 uA	1 mA	10 mA
(Virtual) beam power at 8 GeV	800 kW	8 MW	80 MW

- Additional capability stems from the **high average virtual beam power** available (even 100 MHz would not be source limited), we should **expect future user demand** for such capability for the following :

1. Enabling **transform-limited pulses at ~10 keV** through deployment of XFELO & RAFEL
2. Industrial & scientific uses for longer wavelength high average power sources enabled by ease of access to lower energy recirculation passes: **100 eV – 1 keV** e.g. chip lithography
3. Harmonics of fundamental 10 keV MHz sources due to the high spectral brightness wrt SASE – **100 – 1000 keV**, applications in materials science
4. Inverse Compton Scattering (ICS) **narrowband (10^{-4} – 10^{-5}) gamma sources** in two regimes – ~10 MeV & multi-GeV
5. Internal target electron beam experiments – e.g. dark matter searches, isotope production

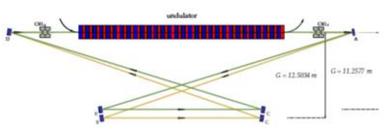
High Average Power Application 1: XFELO / RAFEL

- Enabling **transform-limited pulses at 10 keV** through deployment of XFELO (Low gain / high Q) cavity
  also enables high power in harmonics of 10 keV MHz sources – **100 – 1000 keV**

Kwang-Je Kim

An FELO for hard X-Rays; XFELO

- XFELO was first proposed by R. Collela and A. Luccio at 1983 BNL workshop by using Bragg reflectors as high reflectivity normal incidence mirrors
  - The same WS where BNP proposed SASE
  - Taking into account of the advances in accelerator (ERL)and x-ray optics, it was "resurrected" in 2008 by KJK, Y. Shvyd'ko, and S. Reiche



- Tuning is possible with the four-crystal, zigzag cavity
  - R. M.J. Cotterill (1968, ANL); KJK and Y. Shvyd'ko (2009)
- Electron beam with a constant, ~ MHz rep rate will be ideal

KJK CAS Hamburg

An X-Ray FEL Oscillator is fully coherent and stable

- Full transverse and longitudinal coherence
- Transform limited BW: $\Delta\hbar\omega =$ (3-10) meV for (0.3-1) ps pulse length
- 10^8-10^9 γ's /pulse, or 10^{14}-10^{15} γ's /second
- Complete polarization control with crossed U

→100-fold higher spectral flux, 10,000-fold higher brightness than USR

- Up to 1 keV sources could be RAFEL (high gain / low Q): E.g. Cavity using multilayer mirrors with low reflectivity: undulator length should be ~half the length of a SASE undulator so cavity perimeter ~ 60m, so round trip frequency = **5 MHz**
- Such oscillators benefit greatly from **MULTI-MHz repetition rate** bunches – i.e. 1 MHz should be seen as a lower limit

Science & Technology Facilities Council
Daresbury Laboratory

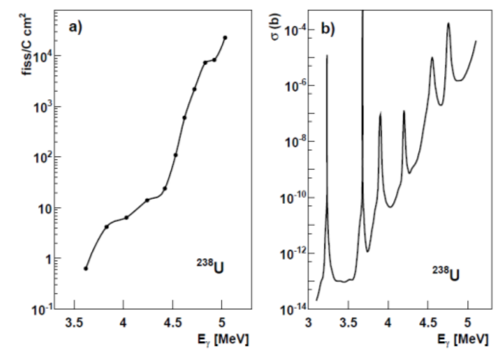
High Average Power Application 2: Narrowband Gamma Production for Nuclear Physics / Industrial Research

Inverse Compton Scattering (ICS) gamma sources in two regimes:

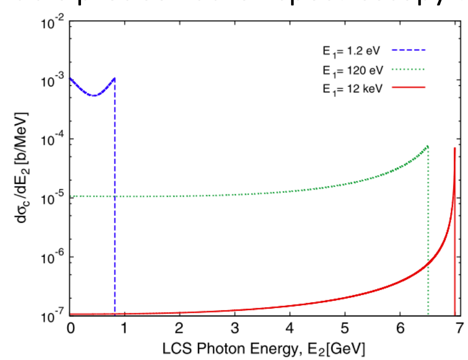
i. **~10 MeV**: Motivated by upcoming **ELI-NP** demonstrations of the utility of 10^{-3} energy spread γ's – a CW ERL could go well beyond, with **10,000 x average flux and 100 x narrower bandwidth**. Precise photonuclear / photofission studies would become possible. Real industrial applications such as nuclear resonance fluorescence, non-proliferation enforcement, radioactive waste stewardship (and even mitigation), economic production of novel medical isotopes, moderator-free thermal neutron source, narrow bandwidth positron / muon source, …

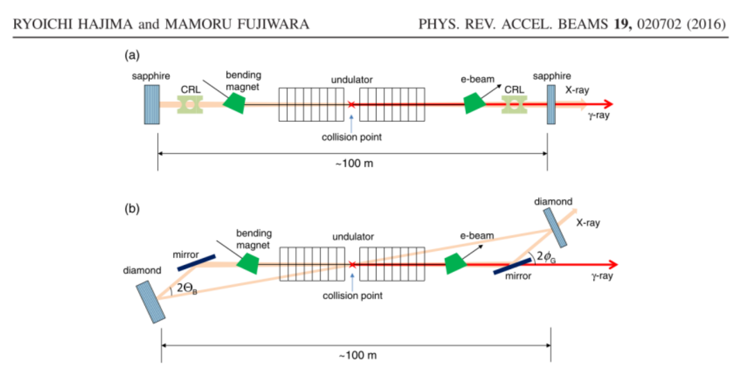
E.g. "hidden" resonances in photofission cross section as all gamma sources thus far are broadband – implications for waste management

"Perspectives for photofission studies with highly brilliant, monochromatic γ-ray beams" P. G. Thirolf et. al., EPJ Web of Conferences **38**, 08001 (2012)



ii. **Multi-GeV**: narrowband would enable precise hadron spectroscopy through electron recoil-dominated ICS self-interaction in an XFELO / RAFEL.

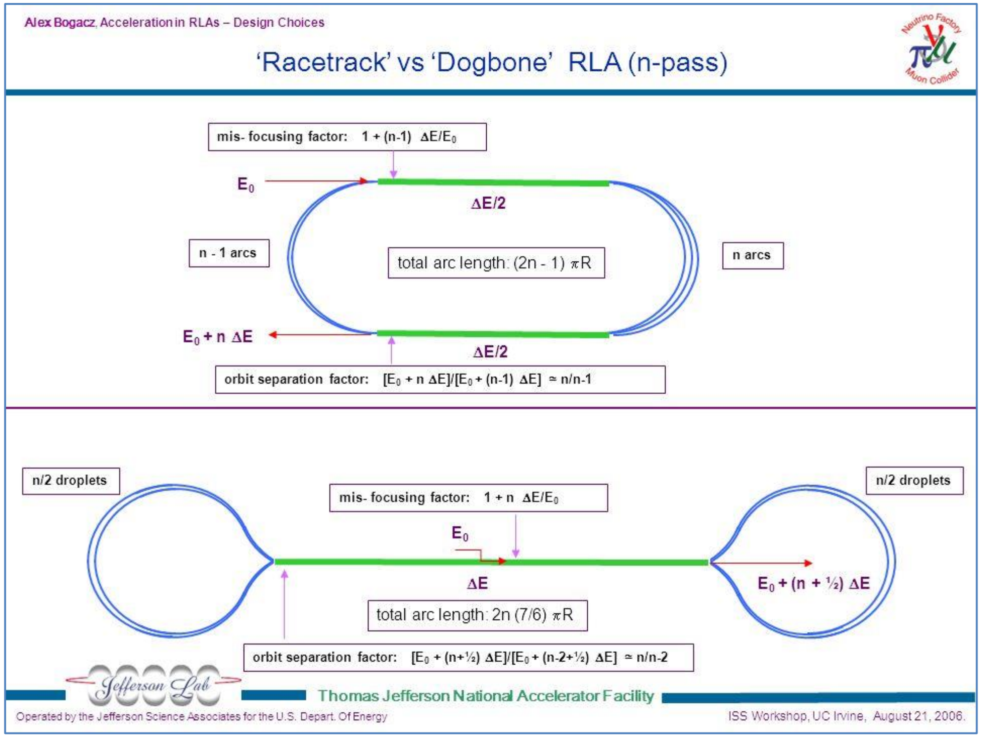




Exploring the Topological Menagerie

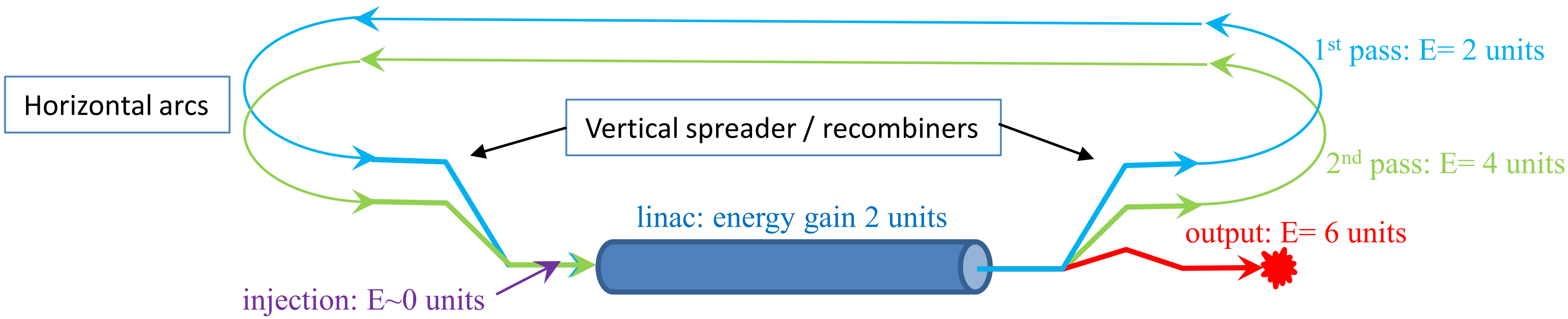
Option 1: “Dogbone” Types:

- These have been extensively considered by Alex Bogacz (JLab) in context of LHeC, Neutrino Factory and Muon Collider
- They are advantageous in the 100’s GeV, low current regime as they are more efficient in utilising RF
- We **reject** these in the context of few GeV scale with 10’s mA current as there is no way to implement ion clearing gaps in such configurations

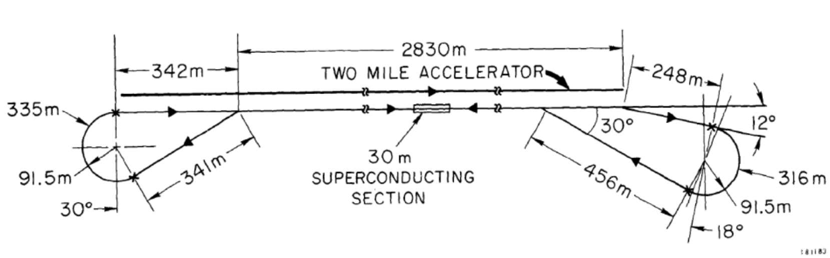


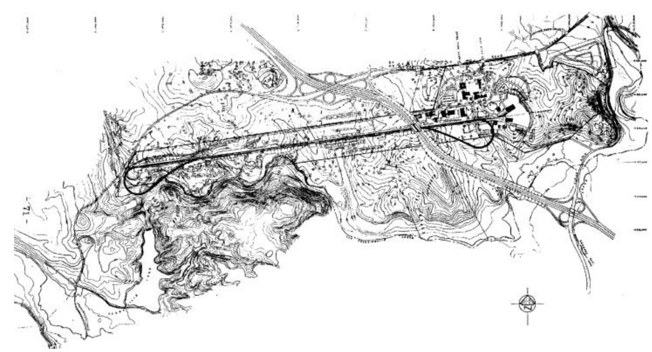
Exploring the Topological Menagerie

Option 2: <u>Monolith</u>: One linac with long bypasses (3-pass shown here)



- First considered originally for SLC in 1968! (before discovery of RF pulse compression) W. B. Herrmannsfeldt et. al. SLAC-TN-71-004, SLAC-R-139





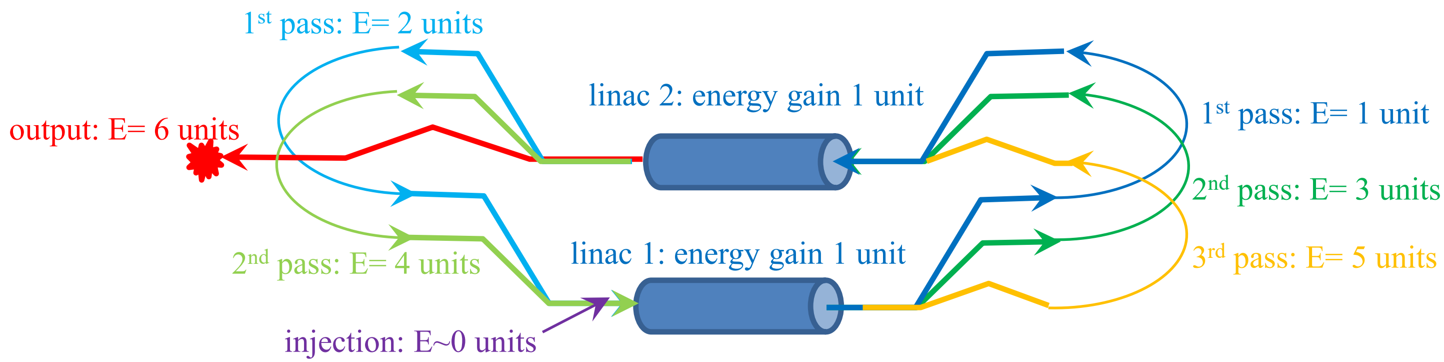
- Also used in UK NLS recirculating design

- Cryogenically simple, however tunnel packing fraction is low (or additional arc bending = no cost advantage over split types, so **reject**

Science & Technology Facilities Council
Daresbury Laboratory

Exploring the Topological Menagerie

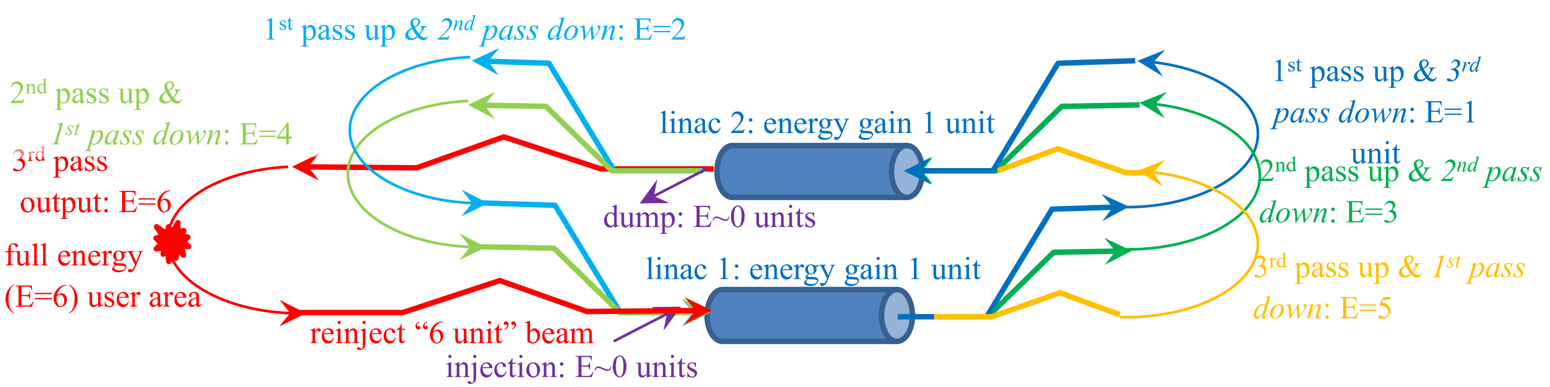
Option 3: Symmetrically bisected: Split linac into two identical half-linacs on opposite sides of a racetrack



- CEBAF-like, also used in design for PERLE / LHeC
- With respect to the monolith, this increases the packing fraction of linac to tunnel
- When we implement energy recovery, we are faced with a choice…

Exploring the Topological Menagerie

Option 3a: Symmetrically bisected: Split linac into two identical half-linacs on opposite sides of a racetrack

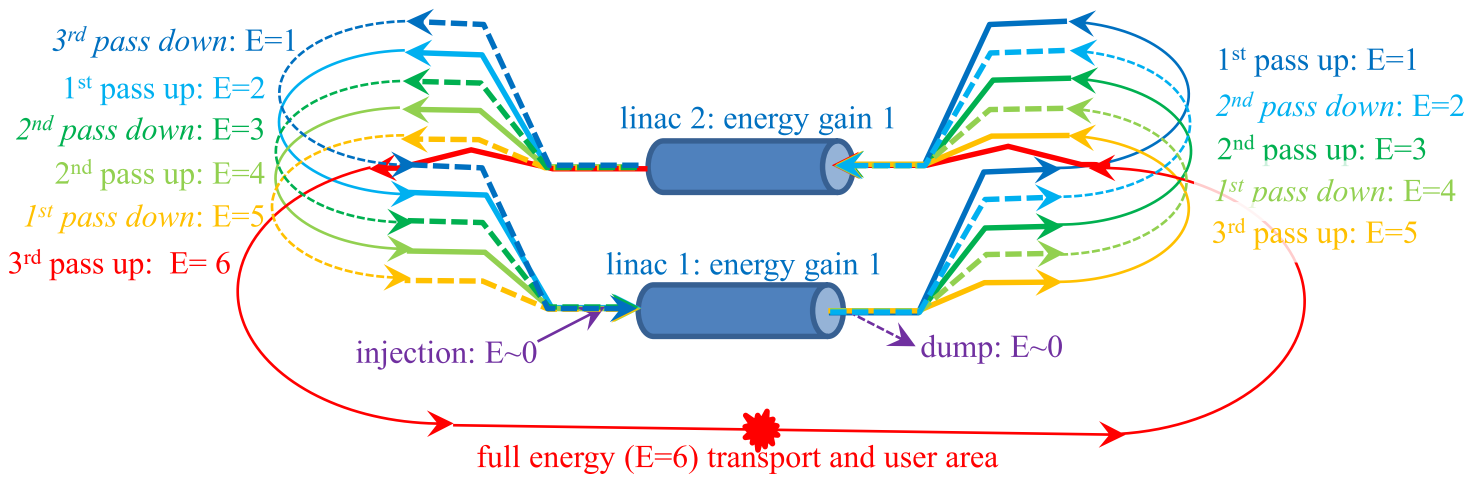


Re-inject the spent beam into L1

- Other than re-injection this involves **no additional beamlines**
- The recirculation transport **necessarily** carries both accelerated and recovered beams simultaneously as their energies are very similar (true even when lasing / interaction and SR losses included). Therefore there is **no independent control of optics and longitudinal phase space** on deceleration
- 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)

Exploring the Topological Menagerie

Option 3b: Symmetrically bisected: Split linac into two identical half-linacs on opposite sides of a racetrack

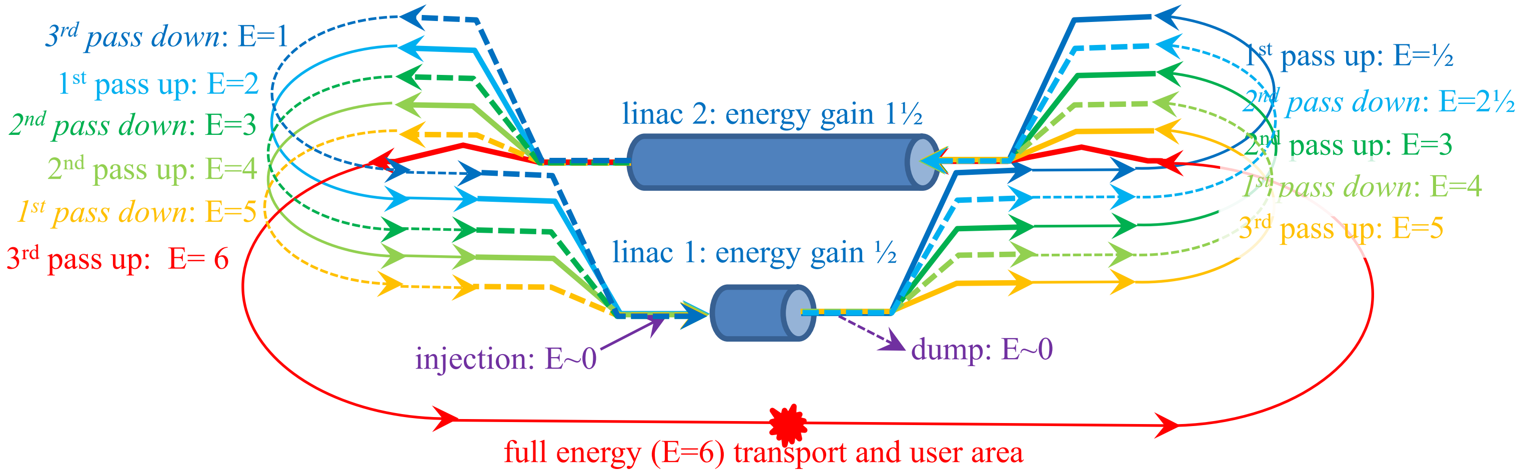


Re-inject the spent beam into L2

- The transport now carries both accelerated and recovered beams separately as their energies are distinct. This enables **individual pass-to-pass optics and longitudinal phase space control (in fact this is a necessary condition to find global longitudinal phase space solution)**
- However, L1 still has a very large **mismatch of focusing strength to beam energy** – this limits the focusing we can apply to the top energy – even with a "graded gradient" focusing technique. Beam envelops thus scale as (linac length)^2 = errors!
- The east and west **splitter / recombiners are now identical**

Exploring the Topological Menagerie

Option 4: Asymmetrically bisected (GERBAL): Split linac into two non-identical linacs on opposite sides of a racetrack, inject spent beam to **L2**



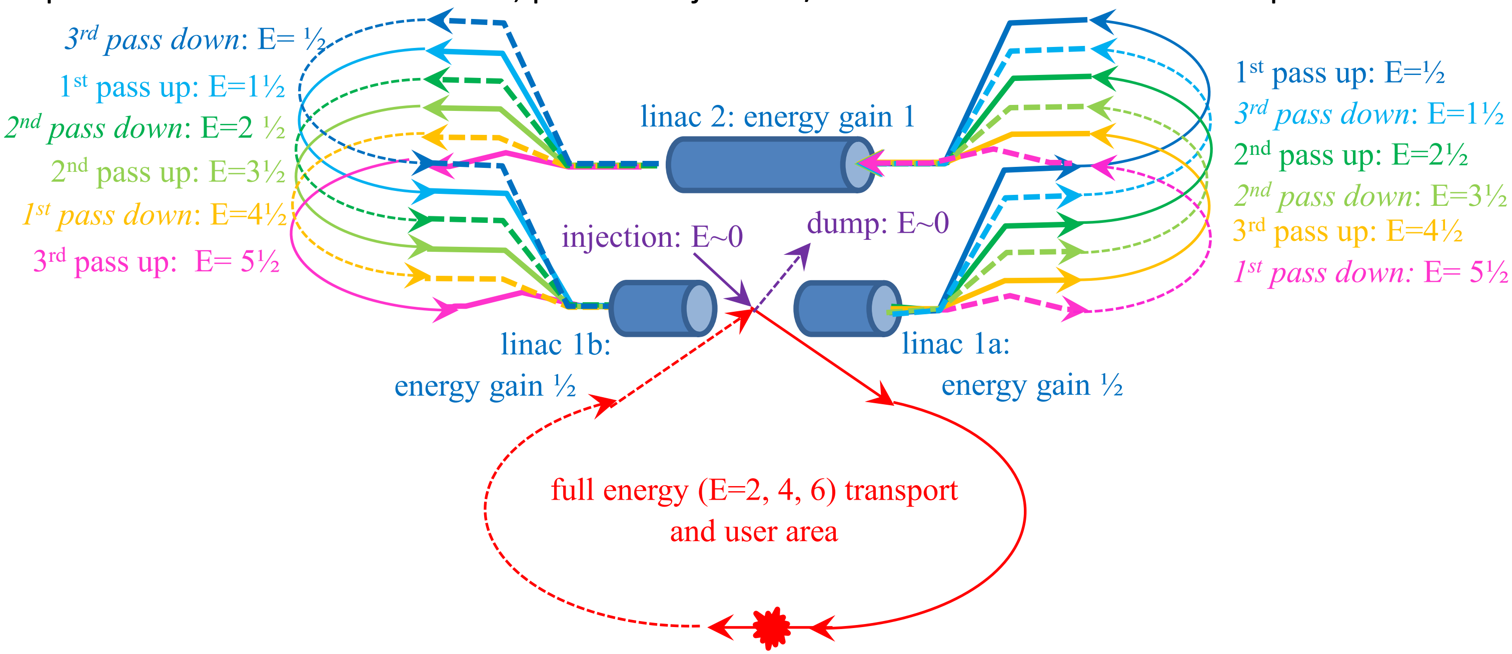
Re-inject the spent beam into L2

- Shortening the linac into which we inject / extract **mitigates the low-beam-energy-constrained focusing** at the expense of **additional tunnel and beamline length**
- Unfortunately, we again **lose the symmetry in spreader / recombiners**
- **Despite above shortcomings use this topology to illustrate the method (but remember the non-optimal tunnel packing fraction)**

"GERBAL" = Generic Energy Recovered Bisected Asymmetric Linac

Exploring the Topological Menagerie

Option 5: Symmetrised asymmetrically bisected (SYBAL): Split linac into one half-linac on one side of a racetrack and two quarter-linacs on the other side, place all injection / extraction between the two quarters

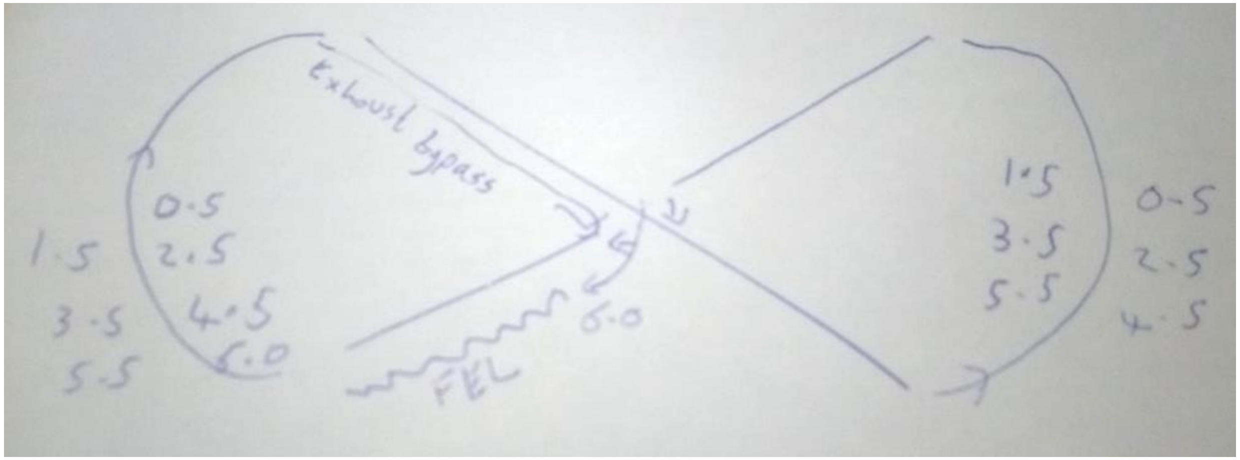


Although I use the GERBAL to illustrate – lets consider how it can be improved …

- Mitigates the low beam energy constrained focusing, but **retains tunnel packing fraction**
- **Symmetrizes all optics** in spreader / recombiners
- Complexity in the crossover region where space is limited – this can be solved by **building L1b slightly below L1a** and placing the FELs below L1a on the straight path from L1b, guide the spent beam in a bypass within the existing tunnel all the way around to L1a/L1b intersection for reinjection – **rather long bypass**

Exploring the Topological Menagerie

Option 6: Symmetrized asymmetrically bisected figure-of-eight (SYBAL-8): Split linac into one half-linac on one side of a racetrack and two quarter-linacs on the other side, place all injection / extraction between the two quarters, twist the racetrack to a figure-of-eight



Apologies for poor drawing!

- As SYBAL, but allows spent beam to **only traverse half the machine in bypass** before a hard bend for reinjection (restrictions on emittance growth / SR loss less for spent beam)
- Disadvantage is it **increases the total bend angles by twice the crossover angle**

Choosing the Right Topology

- We need to understand cost scalings for each of these in:

    1. FEL Driver Beam Energies (note the plural)
    2. Beam Current
    3. RF Frequency
    4. RF Gradient
    5. Number of Acceleration Passes
    6. Recirculation Arc Radii
    7. Major Component Capital Expenditure (SRF, Tunnel, Beamline, Cryoplant)
    8. Major Component Operational Expenditure (SRF, Cryo, Activation)

- We can then assess the implications of introducing energy recovery on each topology as stage 2

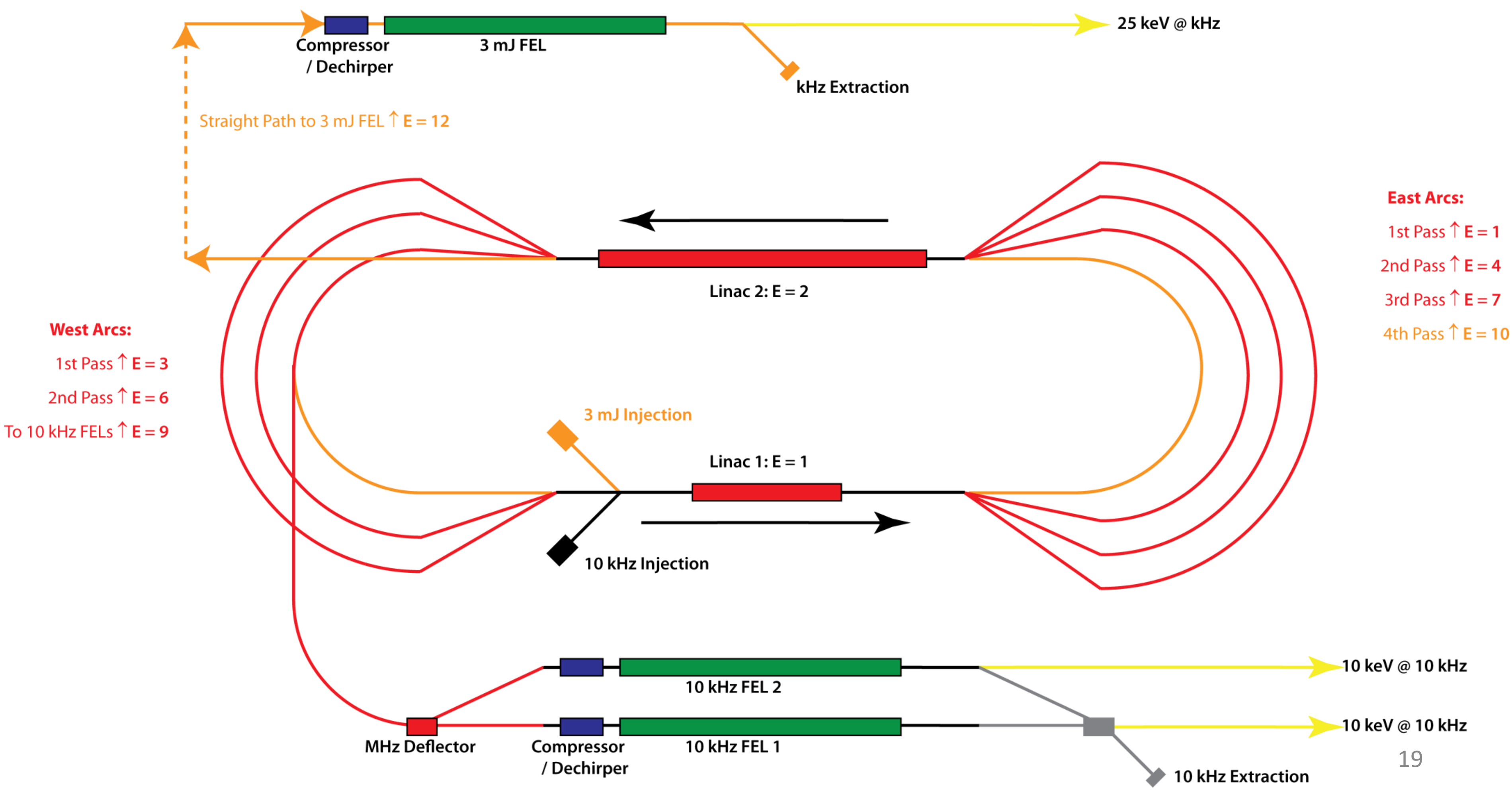
- Construct longitudinal matches for stage 1 and stage 2

- Down-select through SWOT analysis and iterate including using analytic and semi-analytic indicators of beam properties

- This process is not complete! One example solution and a cost scaling for number of acceleration passes follows…

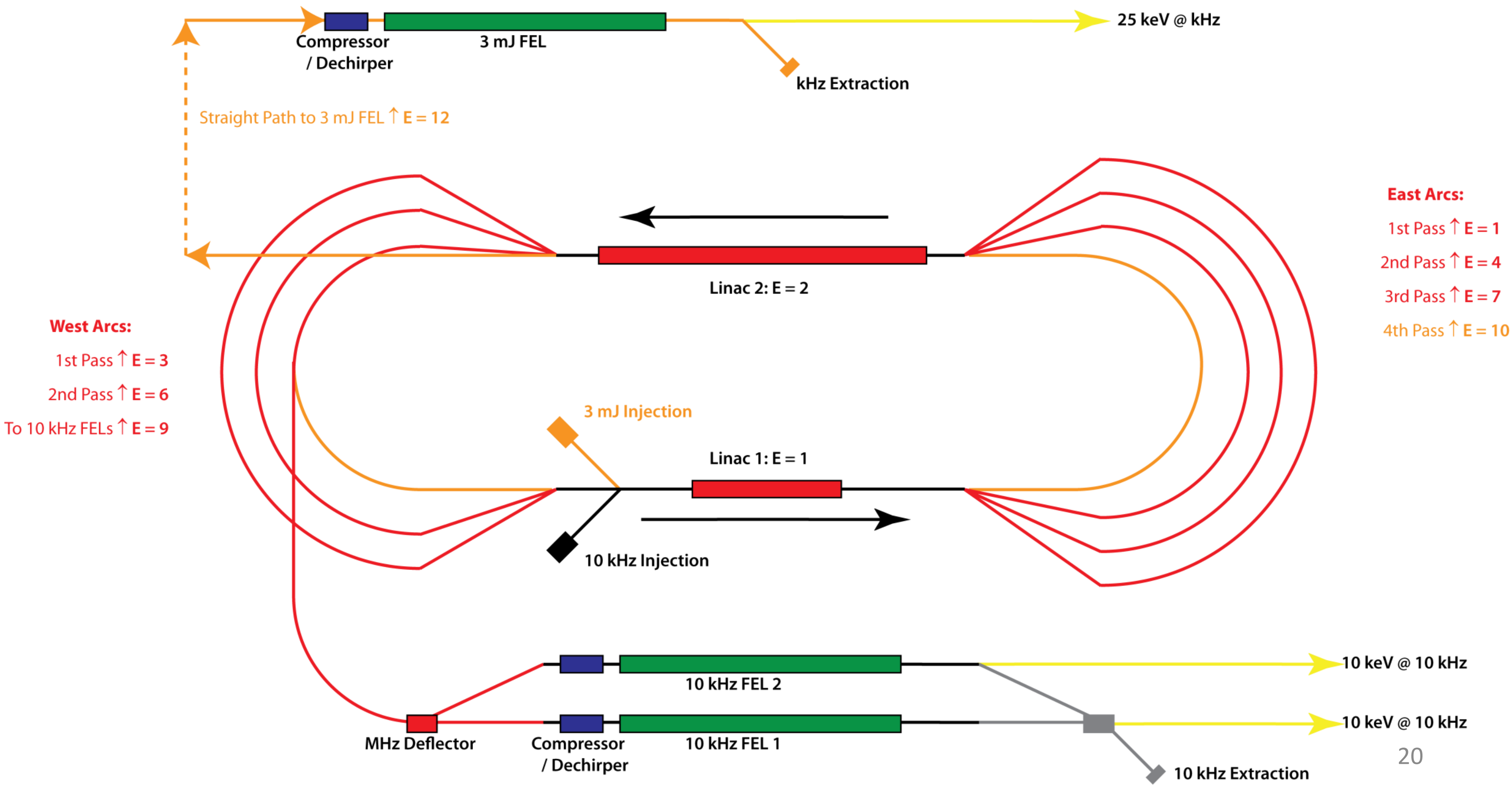
Science & Technology Facilities Council
Daresbury Laboratory

Strawman UK-XFEL Stage 1 (= 10's kHz rep rate) based on 3-Pass GERBAL



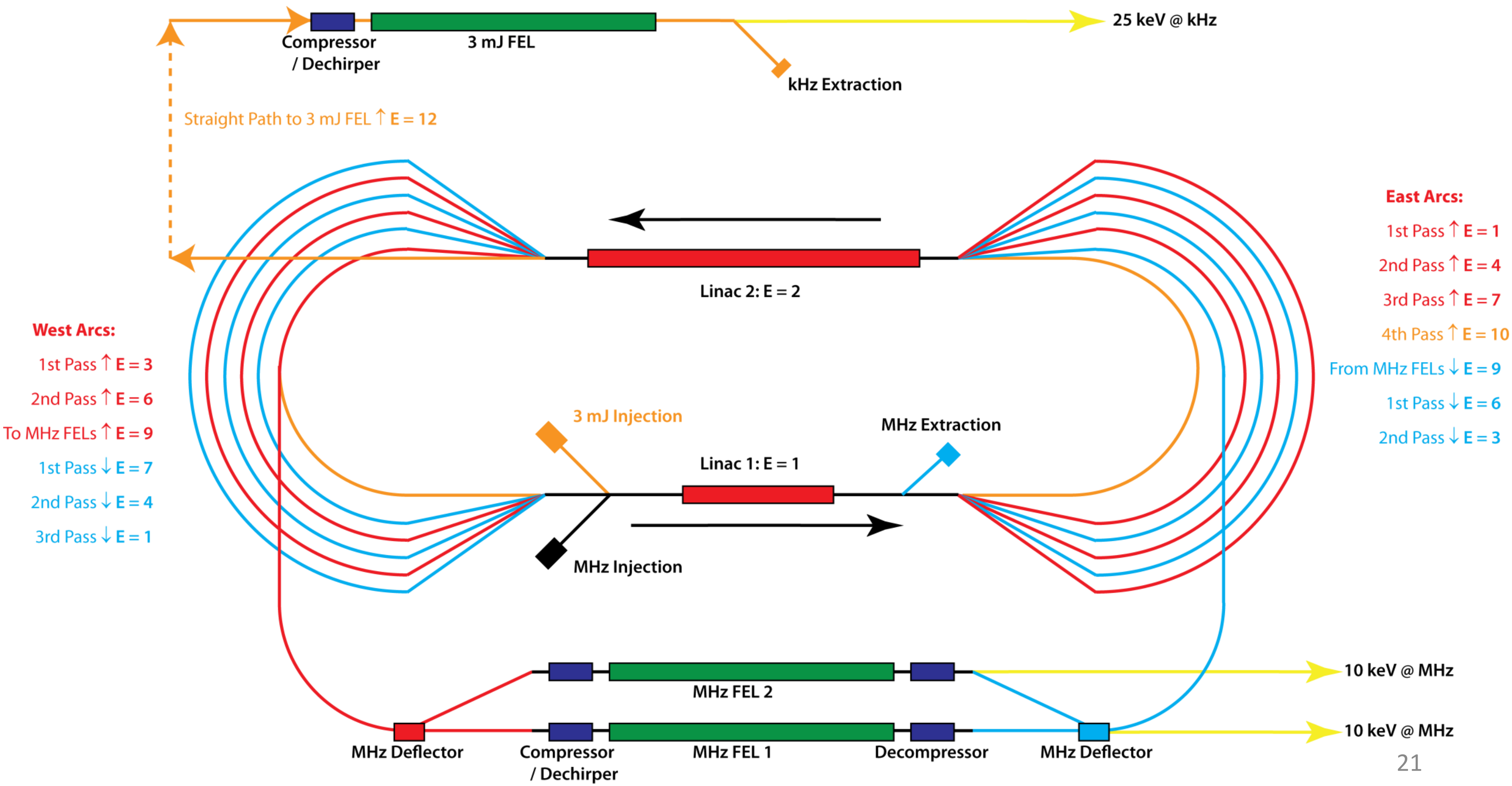
Strawman UK-XFEL Stage 1 (= 10's kHz rep rate) based on 3-Pass GERBAL

Also shown: an "afterburner" 4th pass to take low rep. rate, higher charge bunches to a 25 keV FEL



Strawman UK-XFEL Stage 2 (= 100 MHz rep rate) based on 3-Pass GERBAL

Also shown: an "afterburner" 4th pass to take low rep. rate, higher charge bunches to a 25 keV FEL



Set the Arc Size By Specifying Tolerable Slice Energy Spread AND Peak Current

- ISR usually considered in terms of quantum excitation of energy spread that leaks via dispersion into slice emittance growth, relevant formulae derivation from Matthew Sands (SLAC-121)

$$\sigma_E^2 = 1.18 \times 10^{-33} \text{ GeV}^2 \text{ m}^2 \frac{\gamma^7}{\rho^2} \qquad \Delta\varepsilon = 7.19\pi \times 10^{-28} \text{ m}^2 \text{ rad} \frac{\gamma^5}{\rho^2} \langle H \rangle$$

Where H is the usual term in the 5th radiation integral – i.e. dispersion dominated

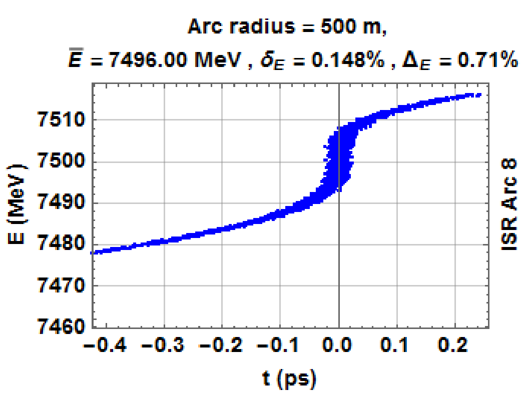
- In a ~10 GeV scale recirculated XFEL it turns out that the **longitudinal emittance degradation** is the limiting factor – i.e. we are concerned with the slice energy spread increase itself. Transversely we remain source dominated and can mitigate ISR emittance growth with isochronous, locally-symmetric arcs, C.-Y. Tsai et. al. [Phys. Rev. Accel. Beams 20, 024401]

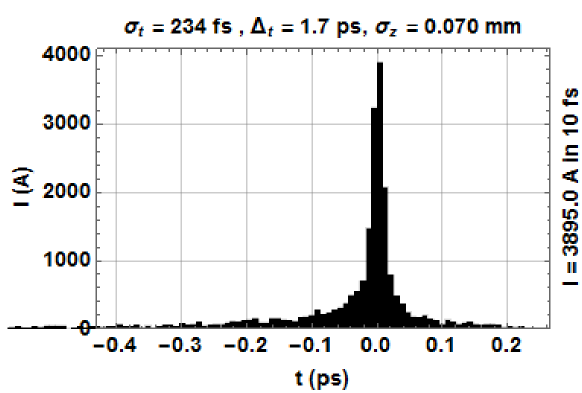
- We recast Sands formula to see the relevant scaling: arc radius required to avoid growth to a specified relative slice energy spread

$$\rho = 6.7253 \times 10^{-14} \text{m} \frac{\gamma^{2.5}}{(\sigma_E / E)}$$

For a fixed relative energy spread growth the arc radius scales as **energy to the power 2.5**

- In addition, through longitudinal phase space shearing used to compress the bunch this translates directly to **a limit on the peak current achievable** (exaggerate below by standing the bunch up in LPS and progressively reducing arc radii)

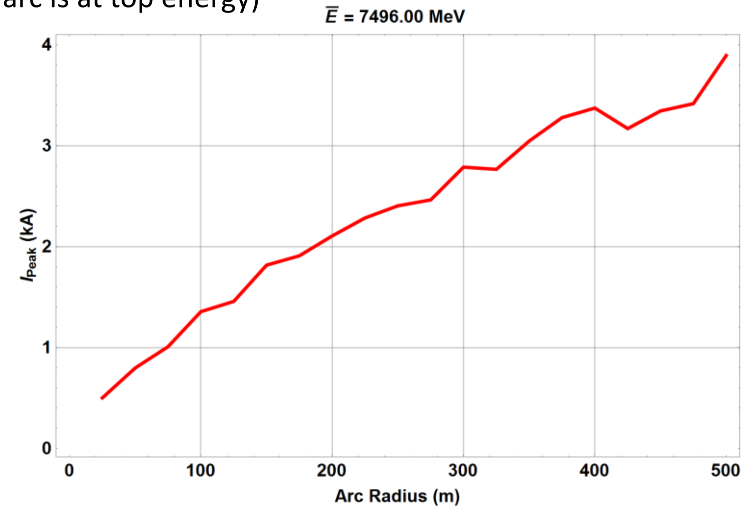




Science & Technology Facilities Council
Daresbury Laboratory

Set the Arc Size By Specifying Tolerable Slice Energy Spread AND Peak Current

- ISR peak current degradation derived from longitudinal phase space solution for the GERBAL at 7.5 GeV with 200 pC (assuming final arc is at top energy)



For this example **considering only the peak current** we should pick arc radius of 150 m to ensure ISR limit lies above 1.5 kA

(c.f. LCLS SASE 10 keV peak current of 2 kA for 200 pC)

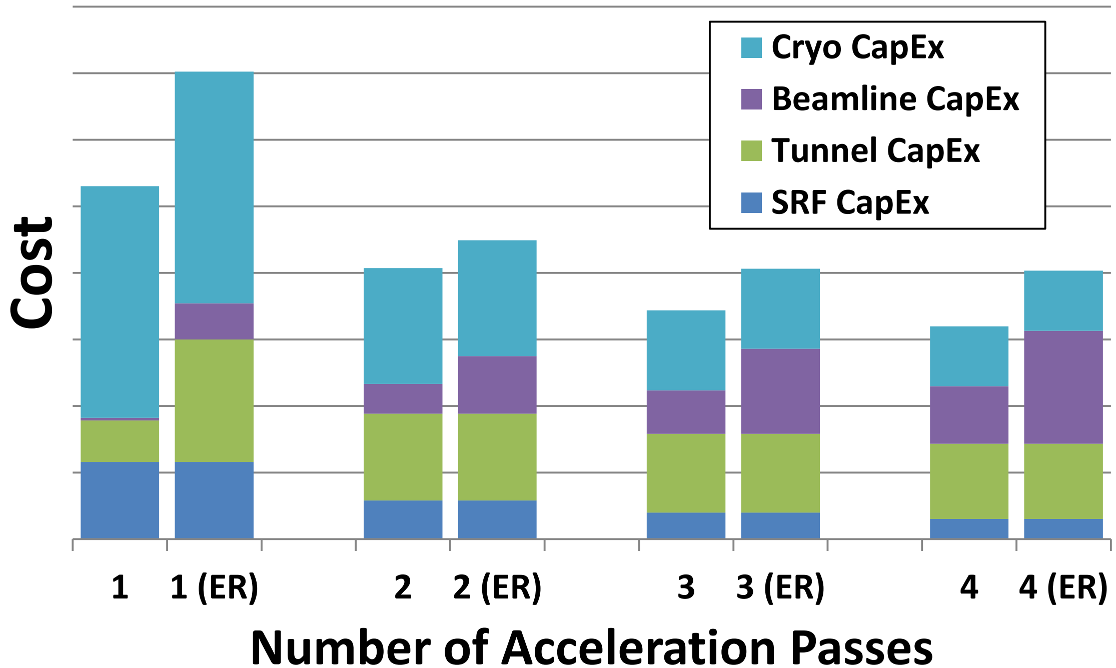
- Upside is that **microbunching instability will be suppressed** – the ISR in the arcs Landau damps it away (natural beam heater)

- What about CSR projected emittance growth? Mitigated by maintaining ps-scale bunch through recirculation and compressing **after** final arc

- Residual energy chirp then mitigated by **dechirping** (also required for single pass linacs e.g. LCLS-2) – SYBAL and SYBAL-8 configurations allow further mitigation by compressing **before** the final pass as the **final arc is not at the top energy**

- Picking a **topology**, an **energy** and **tolerable peak current and slice energy spread** sets the **arc size** required and therefore the size of the facility and therefore its cost …

Recirculating Linac as a Cost Optimisation



- Max rep. rate of 1, 2, 3, 4 = **1 MHz**
- Max rep. rate of 1 (ER), 2(ER), 3 (ER), 4 (ER) **> 100 MHz**

- Example cost scaling as a function of N: The "**1**" line is a straight linac, "**1 (ER)**" is monolith with long bypass
- For all **N > 1**, we semi-arbitrarily chose GERBAL topology and fix E = 8 GeV with arc radii of 150 m, RF frequency 800 MHz, gradient 14 MV/m, switchyard fixed length 150 m, 50 m fixed for spreader / recombiners and compressors
- Indicative cost contributions taken from previous project costings (JLAMP-X, NLS, LHeC)
- We see a **~35% saving** for a 3-pass configuration as opposed to a 1-pass configuration
- It would then cost an additional **~10%** to implement Energy Recovery "3 (ER)", enabling **additional capability** as linac would now support 100 MHz repetition rate without beam loading
- A 3-pass ER machine could thus be achieved with a cost **saving** over a 1-pass non-ER machine of **~25%**

Recirculating Linac as a Cost Optimisation

MHz
(ER),

Health warning: This cost optimisation has not been “optimised” with respect to RF freq., gradient, etc and is merely meant to be indicative. Hence no vertical axis or units!

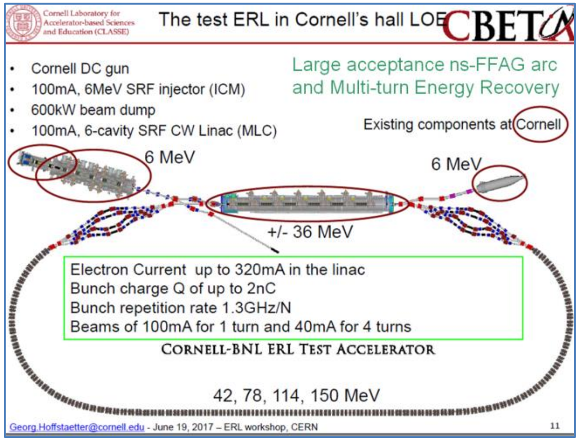
- … linac, “**1 (ER)**” is monolith with long bypass
- … and fix E = 8 GeV with arc radii of 150 m, RF frequency 800 MHz, … m fixed for spreader / recombiners and compressors
- … ious project costings (JLAMP-X, NLS, LHeC)
- W … nfiguration as opposed to a 1-pass configuration
- It w … **~10%** to implement Energy Recovery “3 (ER)”, enabling **additional capability** as linac would now supp … on rate without beam loading
- A 3-pa … e could thus be achieved with a cost **saving** over a 1-pass non-ER machine of **~25%**

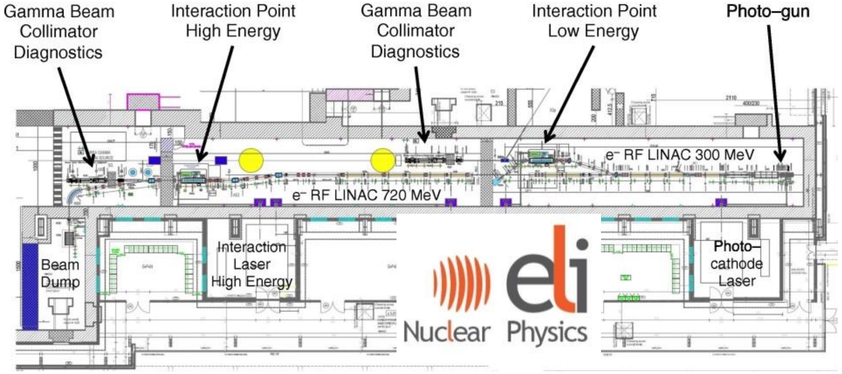
R&D to Show Feasibility

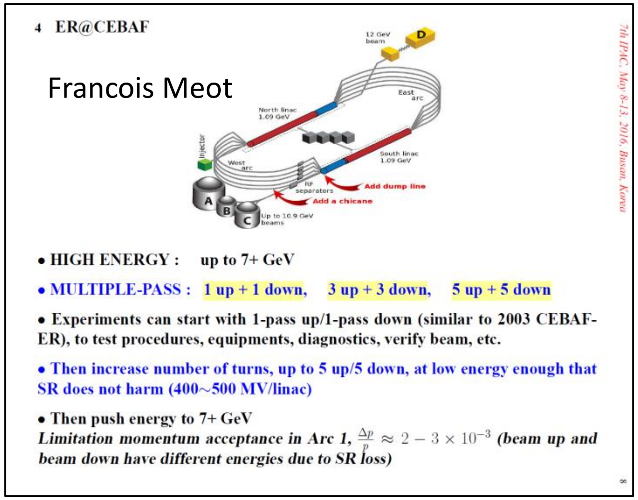
- **Recirculation + ER:** CBETA (Cornell / BNL): Will be the first multi-pass ERL (4-pass) (BINP is recuperator). Initial arc transport commissioning this month (March 2018)

- **Recirculation + ER:** ER@CEBAF (JLab): Proposal to insert two small modifications (path-length adjusted + low-energy dump) to CEBAF to produce worlds first multi-GeV, multi-pass ERL (5-pass). Arc optics can be set to transport large energy spread and therefore also demonstrate bunch compression in a multi-pass ERL (JLAB-TN-17-011)

- **Nuclear Applications:** ELI-NP (Magurele, Romania): In construction phase. Will demonstrate 2-19 MeV narrowband (10^{-3}) gamma production via ICS to investigate NRF, BRIN, BRIP

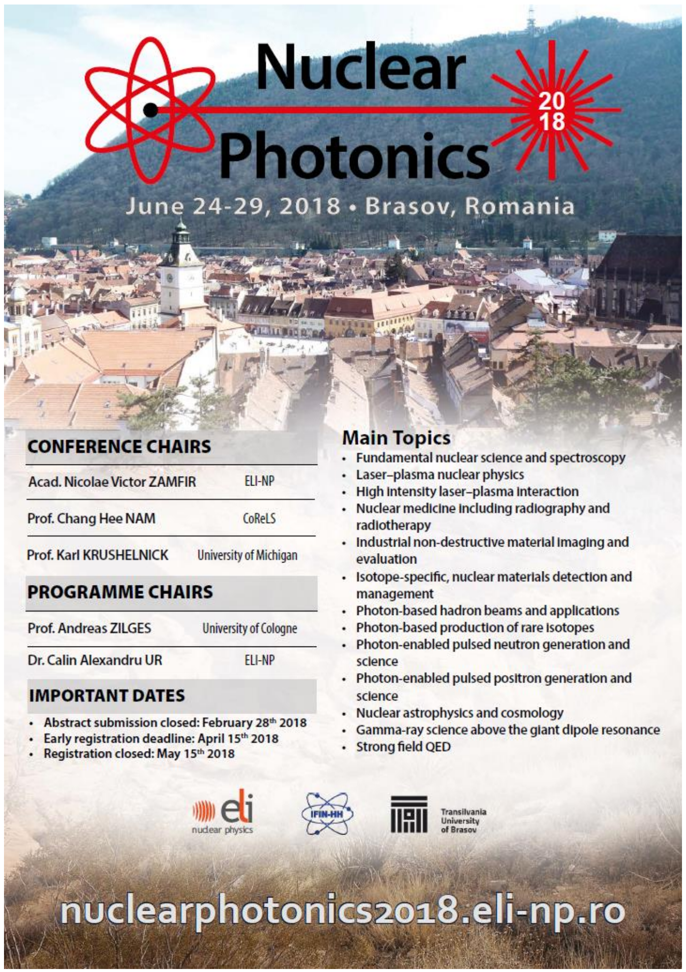






- Is there a place for a **dedicated multi-pass CW ERL industrial user facility at ~900 MeV**? Would serve as an XFEL demonstrator, but also could support high average power (10 kW) **EUV-FEL** and high average flux **ICS narrowband (10^{-5}) γ source** for NRF, medical isotope production etc. (unlike ELI-NP the laser interaction cavity would need to be Fabry-Perot as opposed to recirculator)

Conclusions



Question: Why did no-one build a 4th generation, MBA-type "ultimate" storage ring (of which the first is Max-IV) in the 1990's/2000's?
Answer from Richard Walker (Diamond) @ NOCE 2017:
"Ultimately, because no-one had the guts to take the risk"

- My view is we are now in a similar situation with XFELs and we need to re-evaluate potential opportunities opened by more radical accelerator designs
- A recirculating linac should be seen **firstly as a cost mitigation** method vs a single-pass linac. I have showed that significant savings are plausible
- But it **also opens up additional capability through energy recovery (which enables >100 MHz rep rate operation)** and any implementation should consider that as its eventual aim
- Additionally my view is that the time is right to look beyond traditional SR users towards the newly emerging field of nuclear photonics and to consider industrial uses of high average power sources

Science & Technology Facilities Council
Daresbury Laboratory

Acknowledgements

- Special thanks to Dave Douglas (Jefferson Lab) who has worked intensively with myself to develop these ideas

Thanks also to the following:

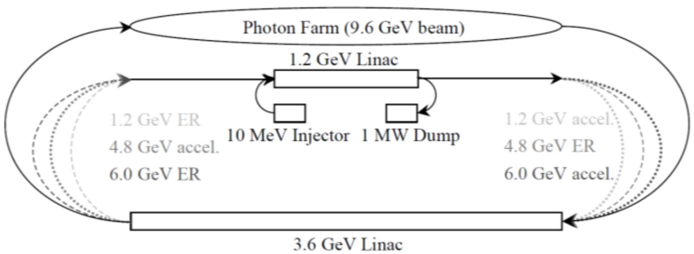
- Deepa Angal-Kalinin, Alex Brynes, Jim Clarke, Louise Cowie, Dave Dunning, Phillipe Goudket, Frank Jackson, James Jones, Peter McIntosh, Boris Militsyn, Andy Moss, Bruno Muratori, Susan Smith, Mark Surman, Neil Thompson, Alan Wheelhouse (STFC Daresbury Laboratory, UK)
- Iwan Akkermans (ASML Netherlands B.V., Veldhoven)
- Richard York (Facility for Radioactive Ion Beams, Michigan)
- Steve Benson, Yves Roblin, Todd Satogata, Mike Spata, Chris Tennant (Jefferson Lab, Newport News, Virginia)
- Ian Bailey (Lancaster University; Cockcroft, UK)
- Tessa Charles (The University of Melbourne, CERN, Geneva)
- Hywel Owen (U. Manchester; Cockcroft, UK)
- Brian McNeil (U. Strathclyde; Cockcroft, UK)

Science & Technology Facilities Council
Daresbury Laboratory

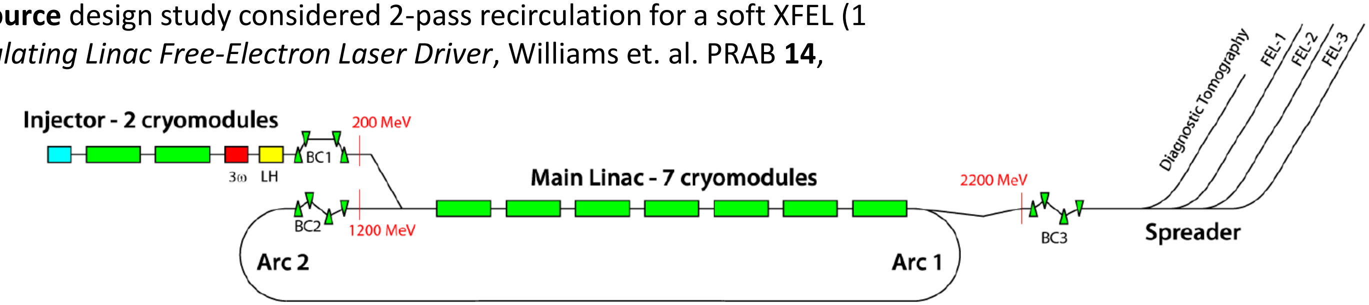
Extra Slides

History of Recirculating XFEL Proposals*

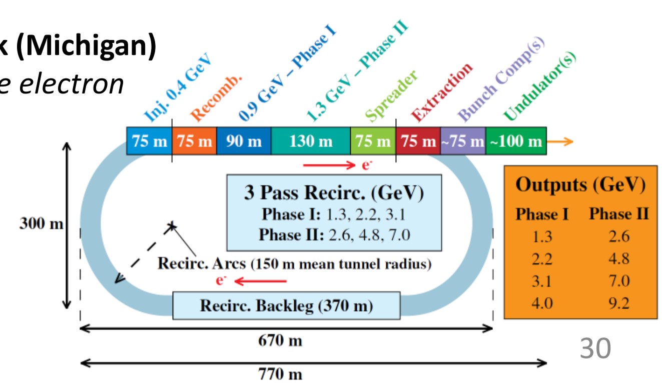
- **2001: GERBAL** considered an FEL among other spontaneous sources (*Generic Energy-Recovering Bisected Asymmetric Linac*, Douglas, ICFA-BD-NL-26, 2001)



- **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)

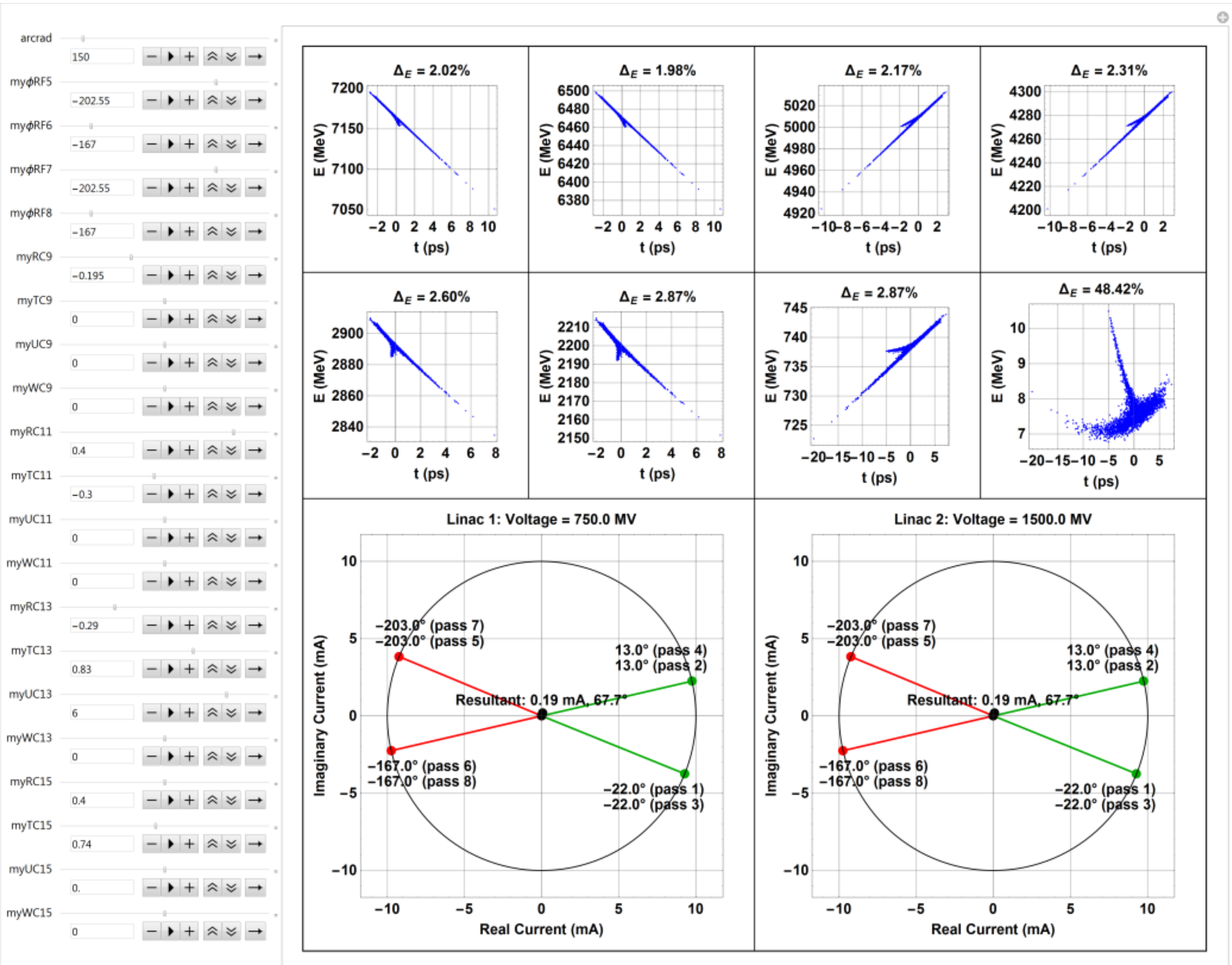


- **2014: CEBAF-X** design study to add a soft XFEL to CEBAF lead to **Richard York (Michigan)** proposed 3-pass recirculation for hard XFEL, (*5 keV upgradable to 25 keV free electron laser facility* PRAB **17**, 010705, 2014)



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

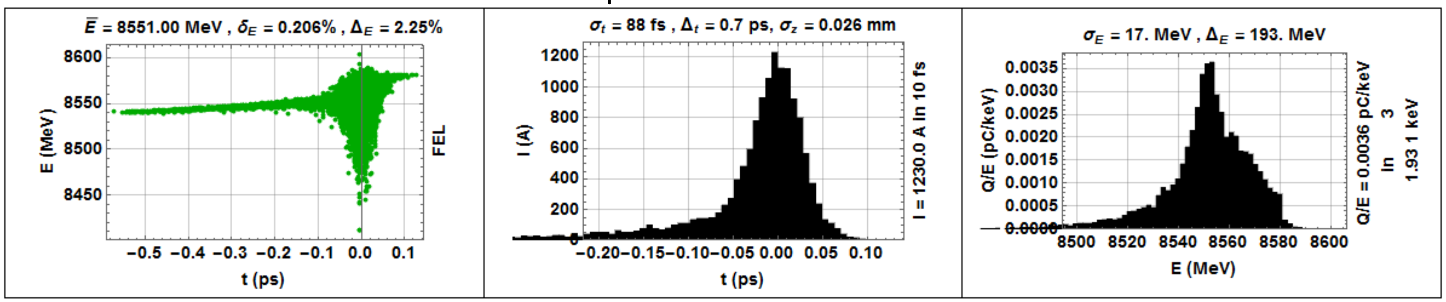
Successfully Recovering the Spent Bunch in a Multi-Pass ERL



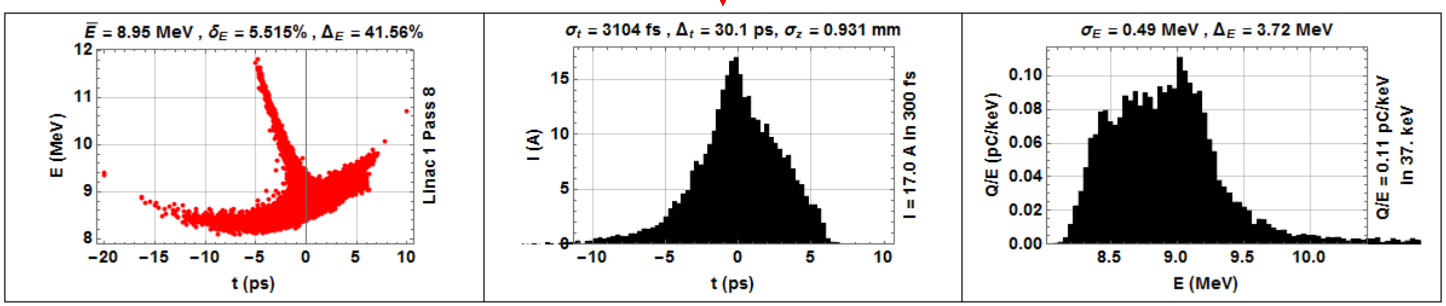
- For > 1 MHz rep rates we must ensure full energy recovery, this requires self-consistent longitudinal phase space match with RF load balancing, accelerating bunch compression and decelerating bunch decompression (and energy spread compression)
- This match must also account for bunch disruption by FEL lasing (or internal target interaction) 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)

Successfully Recovering the Spent Bunch in a Multi-Pass ERL

Spent bunch after FEL



4-pass decompression and deceleration



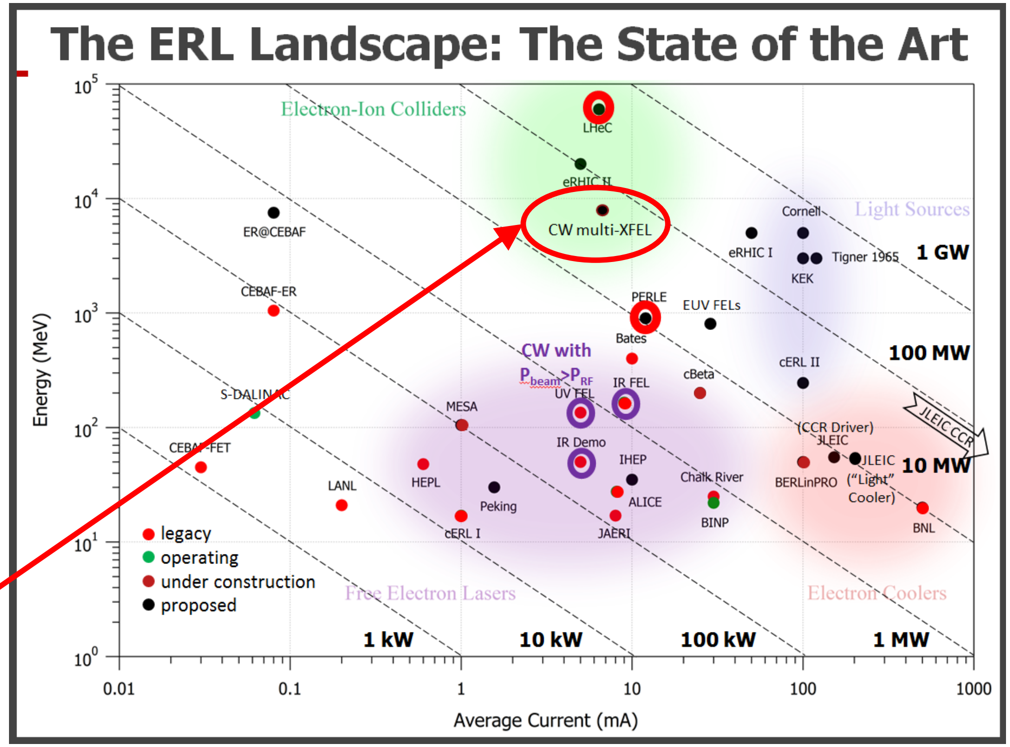
Spent bunch successfully transported to low energy dump – note the three tails, two from the injector (top and right), one from the lasing sheared from energy spread to arrival time (left) – this process is "catadioptric optics" in longitudinal phase space (we image the spent bunch onto the dump without aberration)

- More sophisticated "Caustic" analysis being developed to systematically minimise parasitic crossings

Path to Show Feasibility

- Given that our final goal is an ERL we should survey the ERL landscape

Courtesy Chris Tennant, JLab



- A **100 MHz rep rate incarnation** would be two orders of magnitude larger in beam power from that proven at JLab FEL (only true CW with P_beam > P_RF), and one order of magnitude larger that to be demonstrated on CBETA / BERLinPro / PERLE, it would be one order of magnitude less than LHeC – we assert that this is therefore a reasonable next step given relevant R&D