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6-arc configuration

PERLE Collaboration Meeting

Peter Williams, Daresbury Laboratory / Cockcroft Institute

3rd June 2020

The Cockcroft Institute of Accelerator Science and Technology

~~6-arc configuration~~

1. Common Vs Separate Transport
2. Filling Patterns and RF Stability

PERLE Collaboration Meeting

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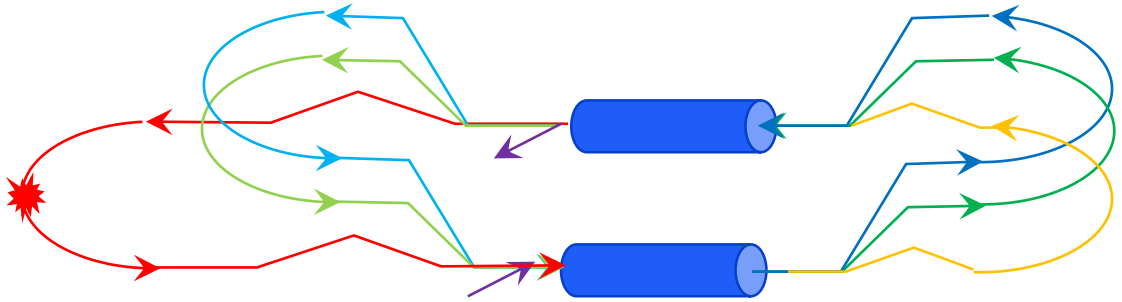
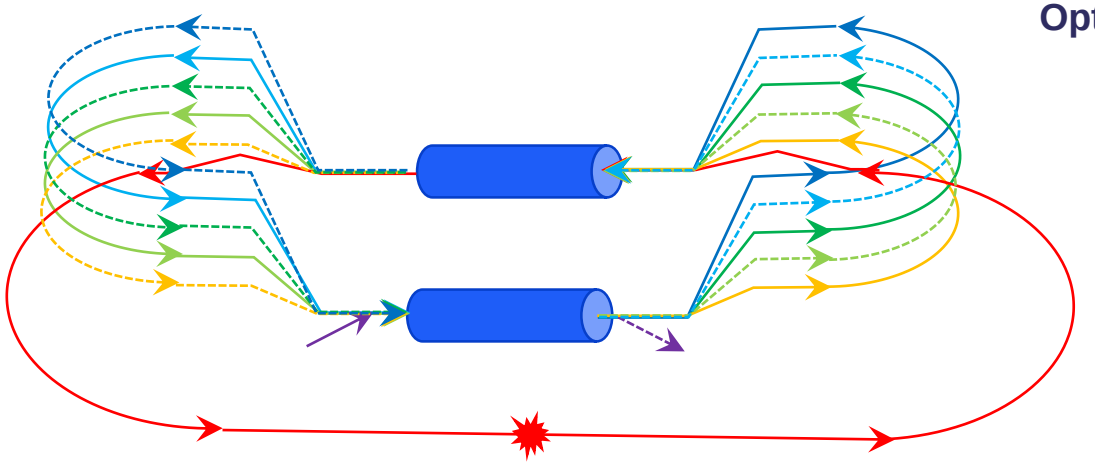
1. Common Vs Separate Transport

In a Multi-Pass ERL, One Can Choose Common or Separate Recovery Transport



Option 1: **Re-inject the spent beam into injection linac = Common Transport**

- 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 complication is that the east and west **splitter / recombiners are optically different** (energy ratios 1:3:5 and 2:4:6 respectively)



Option 2: **Re-inject the spent beam into opposite linac = Separate Transport**

- 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**
- The east and west **splitter / recombiners are identical**
- In both cases L1 has a large **mismatch of focusing strength to beam energy** –limiting the focusing at the top energy – even with a “graded gradient” technique. Beam envelops thus scale as (linac length)^2 = errors! – BUT can mitigate this with **asymmetric linacs** or by **moving inj / ext part-way through L1** if needed
- **The price is more transport beamline**

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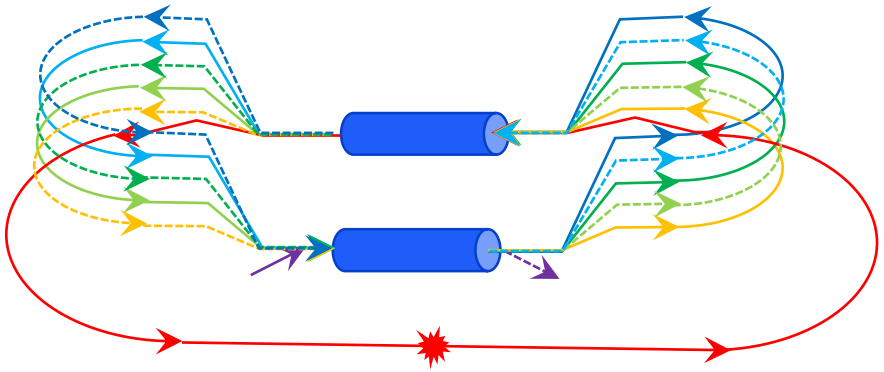
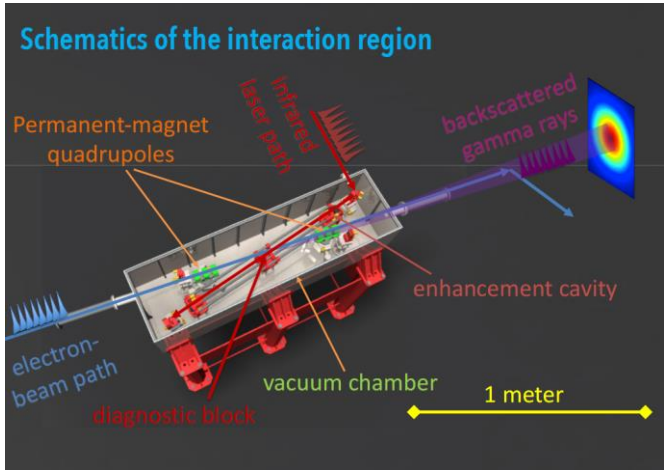
Pursuing this question as part of UK "Light Source" projects DIANA and/or UK-XFEL



OPTION 1: DIANA

- **Standalone Inverse Compton Scattering gamma source = DIANA (Daresbury Industrial Accelerator for Nuclear Applications):** ~ 1 GeV, multipass SC-ERL building on the ALICE ERL-FEL experience (2003 – 2016), use existing infrastructure as much as possible. Scale ~£100M. for Nuclear Physics, Security and Civil Nuclear Decommissioning industries, isotope production



- **Can also serve as high average power EUV-FEL driver for lithography and/or test for future UK-XFEL**

- **1-100 MeV Tuneable, Narrowband Gamma Source with spectral flux exceeding HIGS / ELI-NP by factor of 100.** Table shows gamma properties for 10mA current in Fabry-Perot bowtie resonator – Joe Crone, Hywel Owen (Manchester), Bruno Muratori (DL)

Parameter	340 MeV			680 MeV			1020 MeV		
γ-ray Peak energy (MeV)	2.05			8.17			18.27		
Flux per Shot (ph)	4076			4750			5027		
Bandwidth	raw	0.5%	0.1%	raw	0.5%	0.1%	raw	0.5%	0.1%
Flux	4.08×10^{11}	6.24×10^{9}	4.05×10^{9}	4.75×10^{11}	6.24×10^{9}	4.08×10^{8}	5.03×10^{11}	6.24×10^{9}	4.11×10^{8}
Average Brilliance (ph/s mm^2-mrad^2)	-	2.79×10^{14}	1.81×10^{13}	-	1.12×10^{15}	7.32×10^{13}	-	2.52×10^{15}	1.66×10^{14}
Peak Brilliance (ph/s mm^2-mrad^2)	-	3.77×10^{16}	2.45×10^{15}	-	1.51×10^{17}	9.88×10^{15}	-	3.40×10^{17}	2.24×10^{16}
Spectral Density (ph/s eV)	-	2.41×10^{5}	7.81×10^{4}	-	6.01×10^{4}	1.96×10^{4}	-	2.67×10^{4}	8.79×10^{3}

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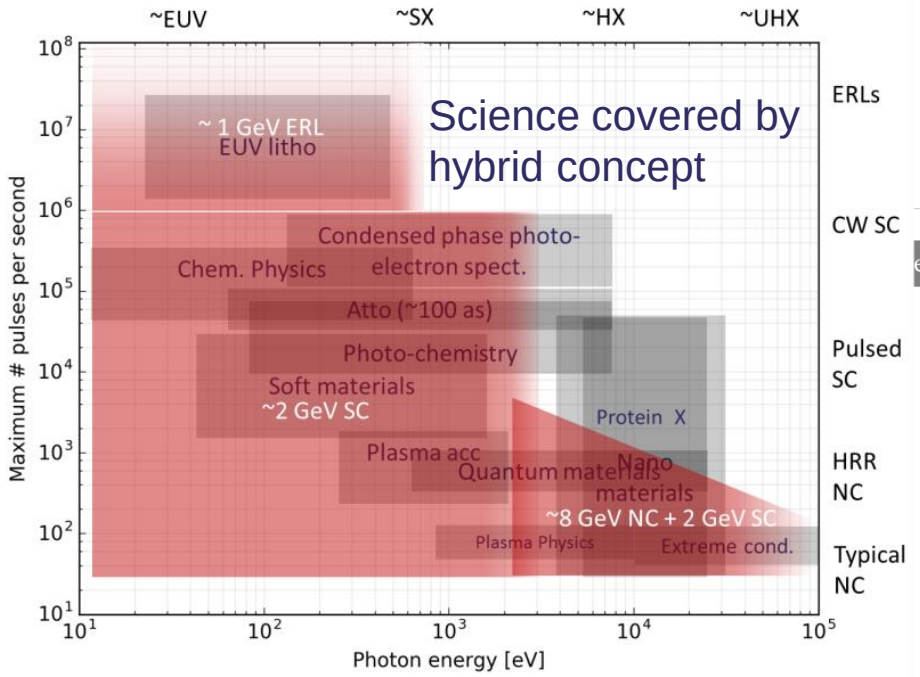
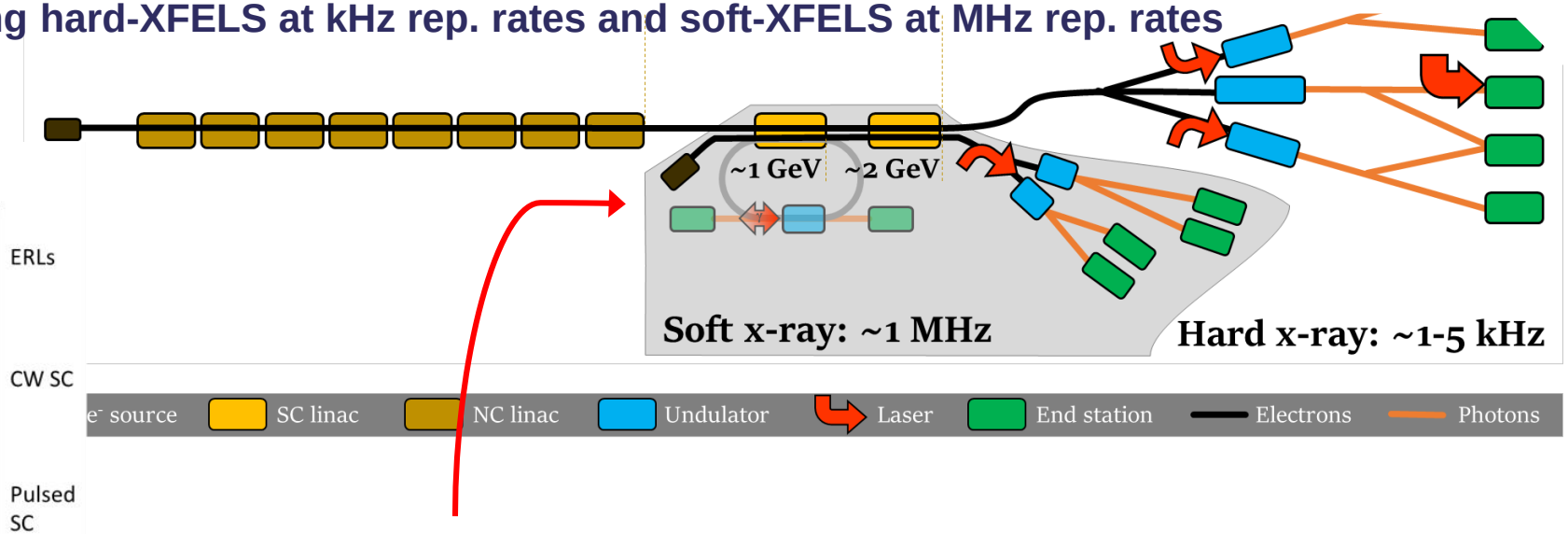
OPTION 2: UK-XFEL

- **To be published Summer 2020: UK-XFEL Science Case – 1-year effort of UK scientific community exploring potential of a UK based XFEL facility of ~£1Bn scale**

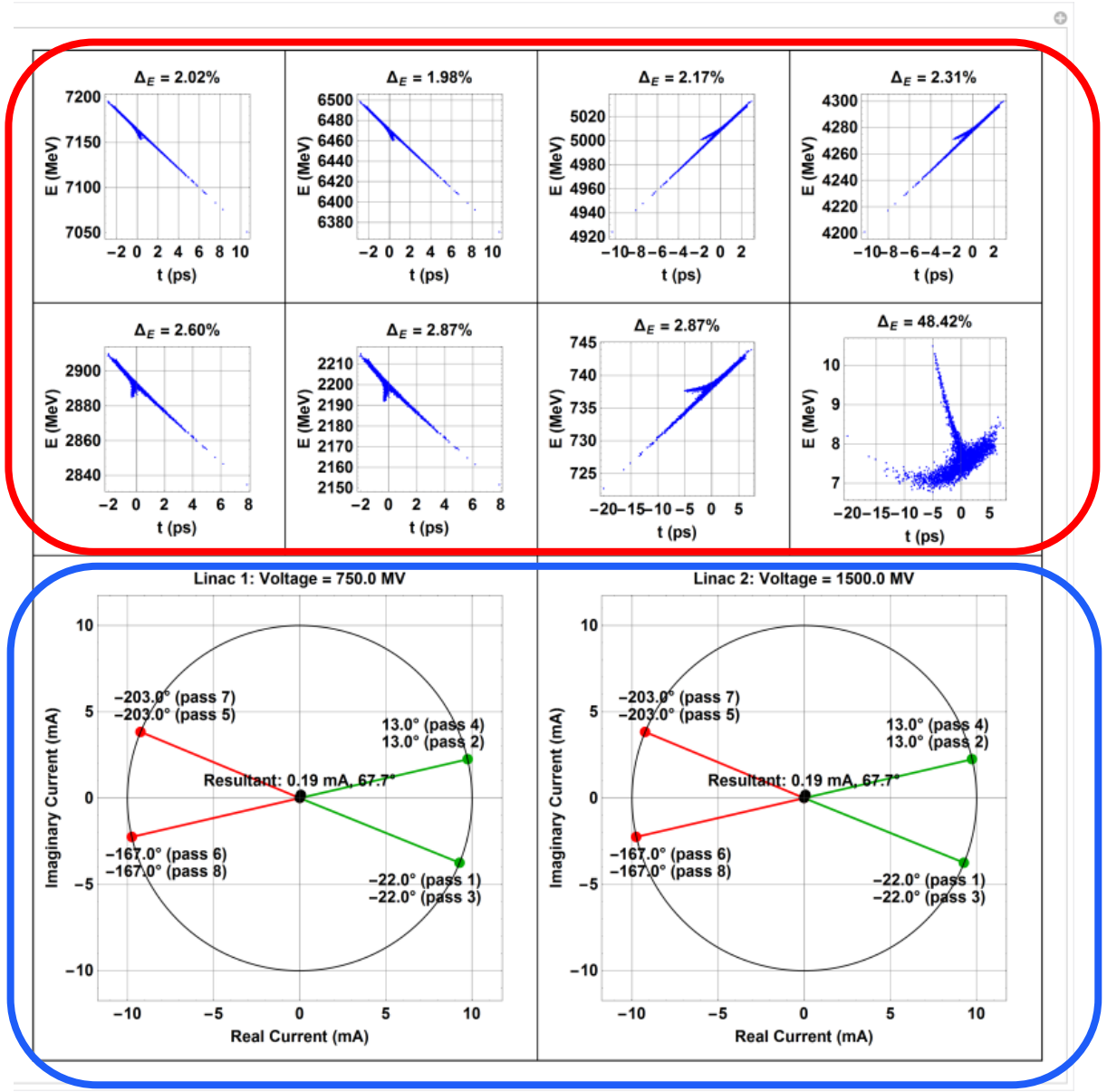
- **Some SC-RF based sections are preferred – below is shown example hybrid NC/SC machine concept: 8 GeV NC linac + 2 GeV SC linac driving hard-XFELS at kHz rep. rates and soft-XFELS at MHz rep. rates**





- **Case includes science that could be addressed by incorporating a ~1 GeV ERL into the larger UK-XFEL facility.** Soft X-ray FEL to go to high average power = lithography & seeding. Drive ICS gamma source – incorporate DIANA nuclear applications

Driving an XFEL places stringent demands on the Longitudinal Match … But actually this applies to an IP (Compton or e-A) ALSO (e.g. PERLE & LHeC)



- In an XFEL one must **chirp and compress** on acceleration to drive FEL gain ⇒ one must decompress and dechirp on deceleration = **energy compression** to fit into aperture
- Top half: 4-step energy compression of a lased bunch
- Bottom half: Satisfying the additional constraint of RF load balancing for efficient ER ⇒ chirp flipping from one pass to the next
- When we don't have an XFEL, we commonly want a flat bunch with smallest energy spread possible – e.g. MESA: essentially we're asking for the same thing but rotated in LPS
- **But** we also have **irreversible processes** going on that alter our perfect balance in LPS = wakefields, ISR loss, ISR energy spread, CSR, Lasing / Beam-beam at IP = chirp, curvature, structure
- These **break the symmetry** between the accelerating and decelerating halves of our solution implying **different longitudinal matching for accelerating and decelerating beams of the same energy to ER efficiently**
- **This cannot be fixed by compensating RF in a common arc!**
- … Am I right? Or can we get away with it … need a test case…
- Could this be contributor to beam loss at S-DALINAC and CBETA?

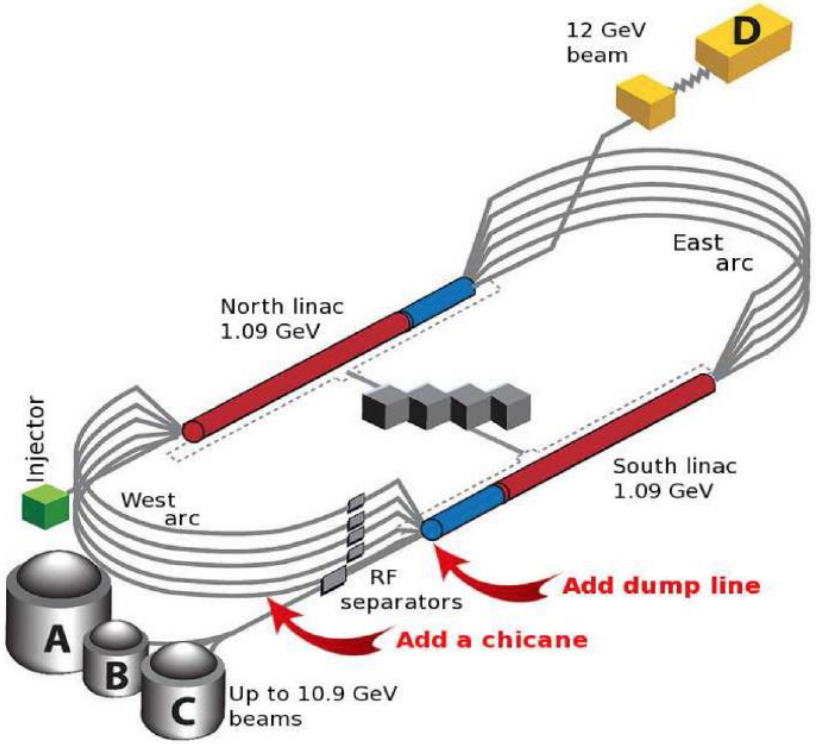
Using ER@CEBAF to Push Longitudinal Matches Off-Crest Until They Break

- Additional chicane and ER dump being installed on CEBAF (even now I think)

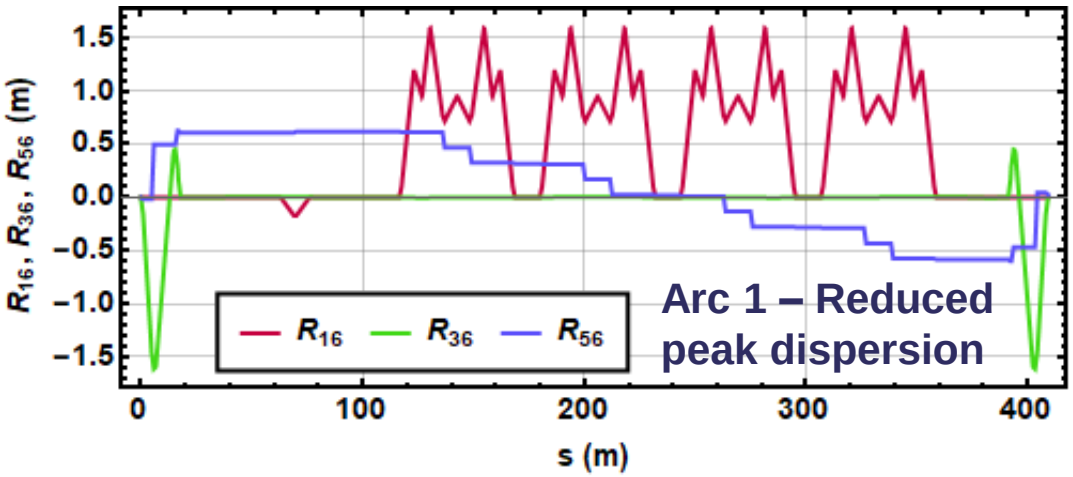
- Even the nominal solution necessitates reduction of the top energy to ~7 GeV to ensure SR loss doesn't break the symmetry such that accelerating and decelerating beams don't fit in the energy acceptance

- Our approach (in order of difficulty):

1. Maximise the energy acceptance by reducing arc dispersion as much as possible
2. See how much Off-Crest Matching **helps** and/or **is needed** to cope with non-linear effects for a Collider IP Multipass ERL (PERLE / LHeC / DIANA / UK-XFEL)
3. Produce an Off-Crest Longitudinal Match to Imitate a Multi-Pass XFEL…
4. …show that the limits can be mitigated with separate transport



- To imitate an XFEL we need to perturb the "minimal dispersion" in the arcs to generate the R56, T566 needed



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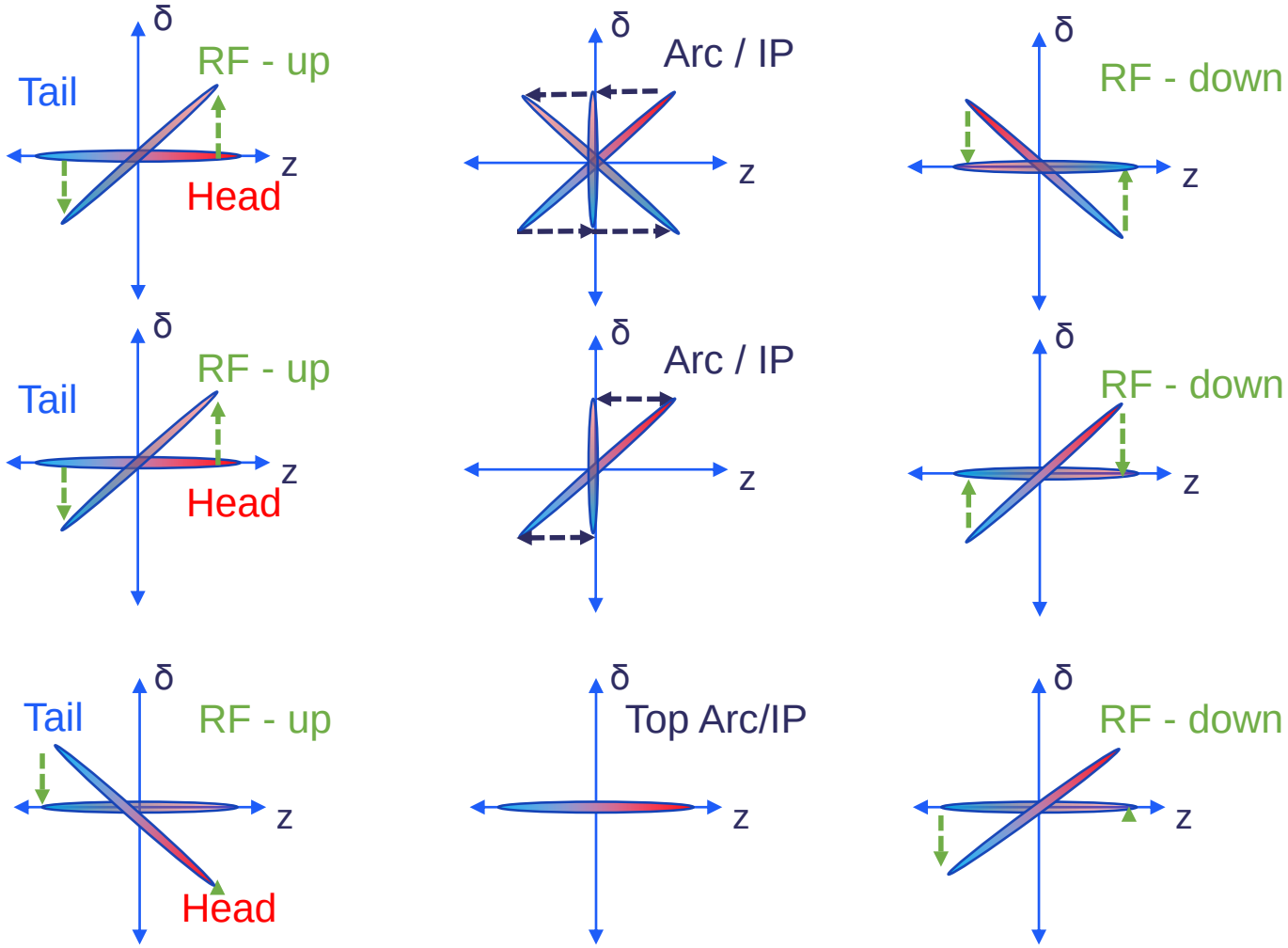
Using ER@CEBAF to Push Longitudinal Matches Off-Crest Until They Break

- Compressive matches for **common** transport only found with **parasitic compression** (over compression).

- Compressive matches for **separate** transport available **without** parasitic compression due to additional degrees of freedom

- **Non-compressive matches with synchrotron radiation** – CEBAF has no RF compensation, can we energy match for common transport with off-crest acceleration / deceleration? Combined with the path length symmetry from shared arcs results in a chirped bunch in the low energy arcs - energy acceptance? Would be no issue in a separate transport version of CEBAF - bunch could be decelerated on alternate sides of trough resulting in a parallel bunch



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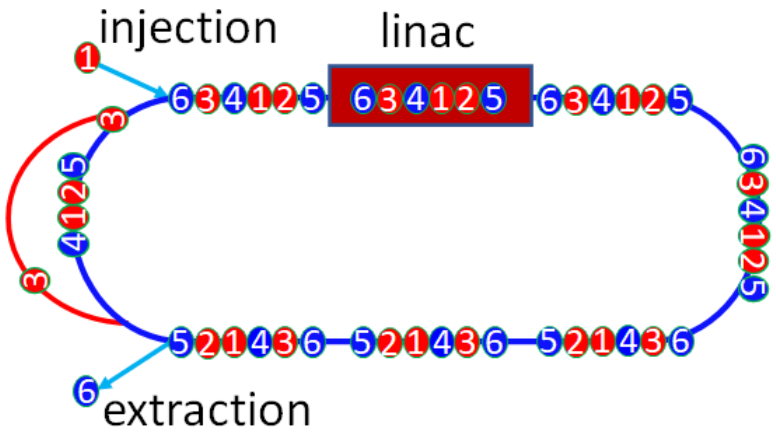
- Additional complication in CEBAF: In high energy arcs, individual control of dipoles is necessary due to SR losses within the arc. ER@CEBAF loses 14MeV to SR, ~2MeV alone in top energy arc

2. Filling Patterns & RF Stability

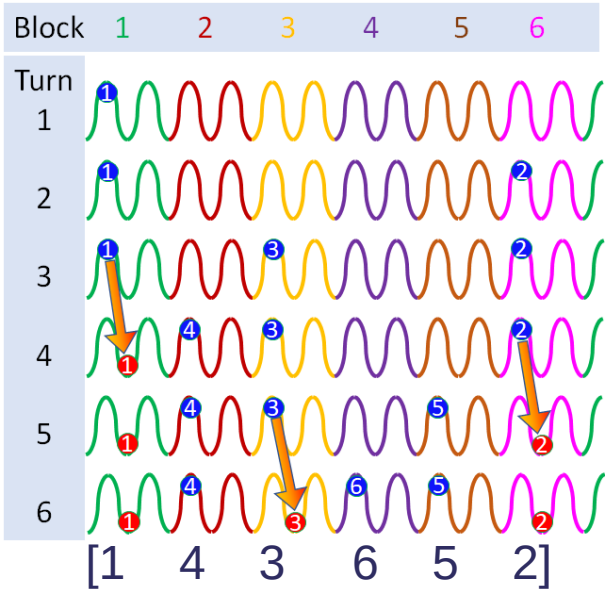
Filling Patterns – Defining the Ordering of the Bunches

- The order in which we fill up and circulate bunches will profoundly affect the **beam loading** and therefore the RF stability and **overhead RF power required (and therefore cost)** even if we perfectly energy recover

- E.g. In a 6-turn ERL we build up a "packet" of 6 bunches ordered by the "block" of RF cycles which we choose to place them in. In the diagram 8 packets fill the ERL.



Filling pattern **[1 4 3 6 5 2]**



- Our first **8 bunches** from the injector become "bunch 1" of each packet and WLOG we choose to place those in "block 1". This completes "turn 1".

- Our second 8 bunches from the injector become "bunch 2" in each packet, in the example left we **choose by fixing the turn 1 path length** to place that in "block 6". This completes "turn 2".

- Our third 8 bunches become "bunch 3". We fix turn 2 path length such that they fall in block 3.

- Our fourth 8 bunches become "bunch 4". These fall in block 2. Half-integer path length introduced in turn 3 such that bunch 1 flips phase.

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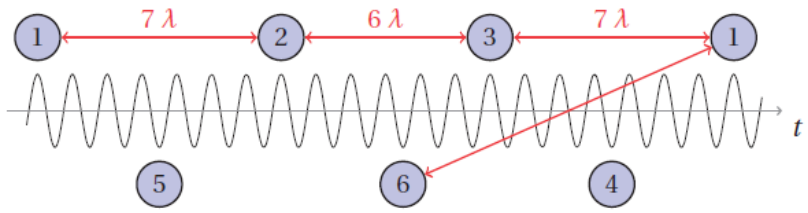
Filling Patterns vs Turn Number

- *Dario Pellegrini briefly considered this as part of his thesis, terming them "bunch recombination patterns". His solution for LHeC was, in our language, "filling pattern [1 4 3 6 2 5]", (he labels by turn number, we use curly brackets to differentiate that convention = {1 5 2 6 3 4})*

- *He only considered BBU, not RF control stability and overhead, settling for a pattern that worked in that context rather than analyzing all patterns systematically*

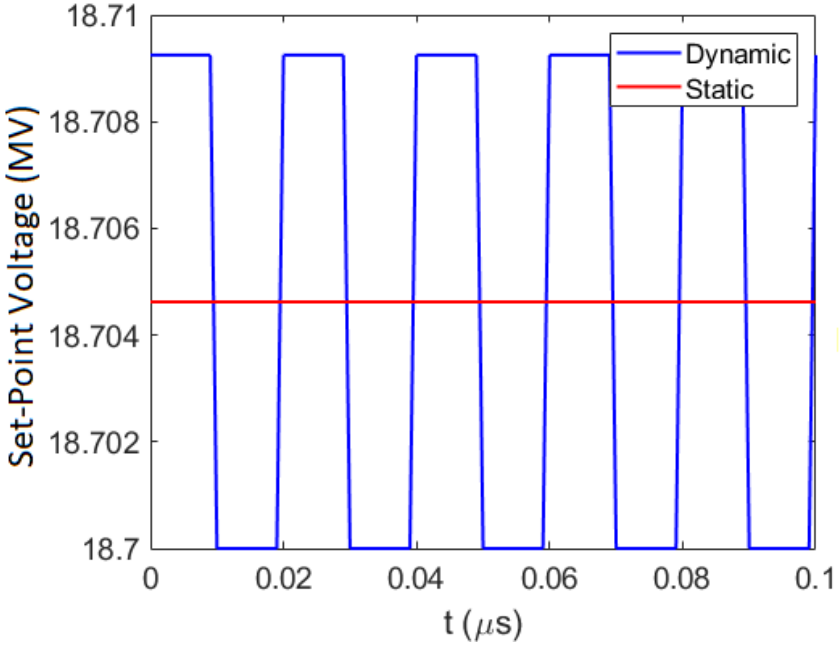


LLRF Set Point

- We include in our analysis the effect of **dynamic** and **static** set points – the behavior of the feedback voltage for LLRF:

- **Dynamic set point** – feedback voltage changes according to anticipated beam loading – a feed-forward

- **Static set point** – constant feedback voltage.



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Filling Patterns - Injection and Bunch Sequence

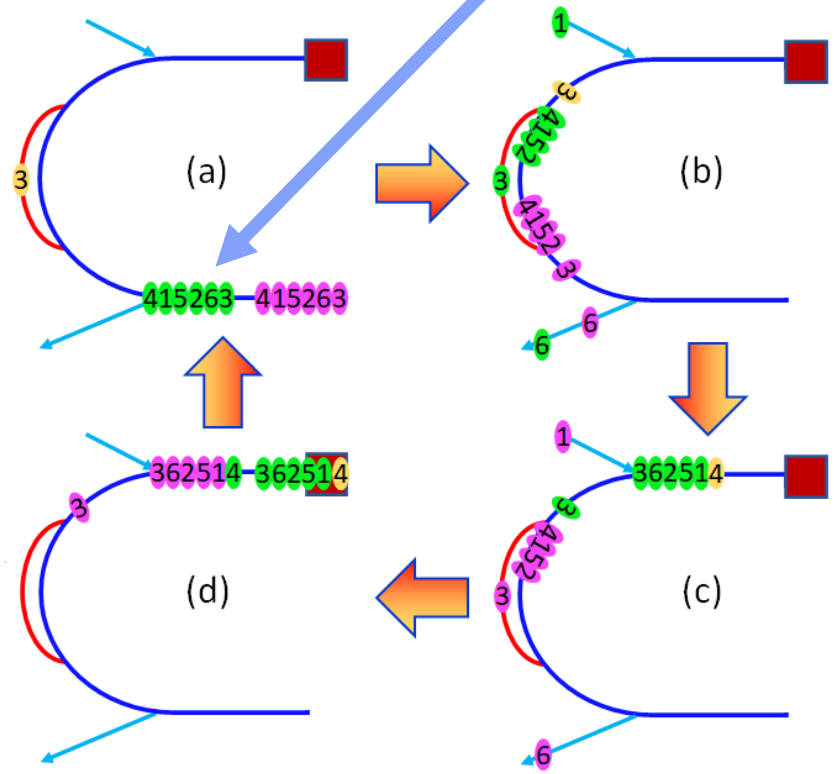
Depending on the injection mechanism: **Sequence Preserving (SP) vs First-In-First-Out (FIFO) .**

SP:

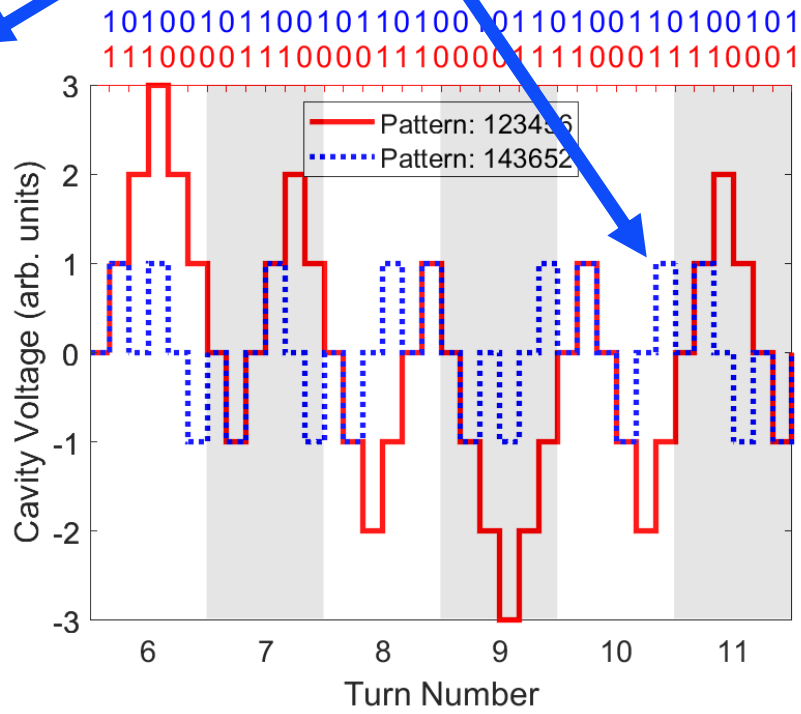
- New bunch injected to the **empty block** between packets.
- Cavity always sees same **turn number** {415263} .
- Optimal SP pattern **maintains up-down-up-down** (or acc-dec-acc-dec) beam loading pattern.
- Need empty RF bucket(s) between packets → **reduced machine fill factor** compared to FIFO.

FIFO:

- New bunch is injected to the **position of dumped bunch**.
- Cavity beam loading pattern repeat with 6-turn period.
- **Cannot maintain up-down-up-down** beam loading pattern, but optimal patterns (example [143652]) can limit beam loading to 1-up-1-down.
- **No empty RF blocks.**



Turn #	[143652]
1	011001
2	011010
3	010110
4	100110
5	100101
6	101001
7	011001
8	011010
9	010110



Filling Patterns - Results & Ongoing Work

In **on-crest acceleration**:

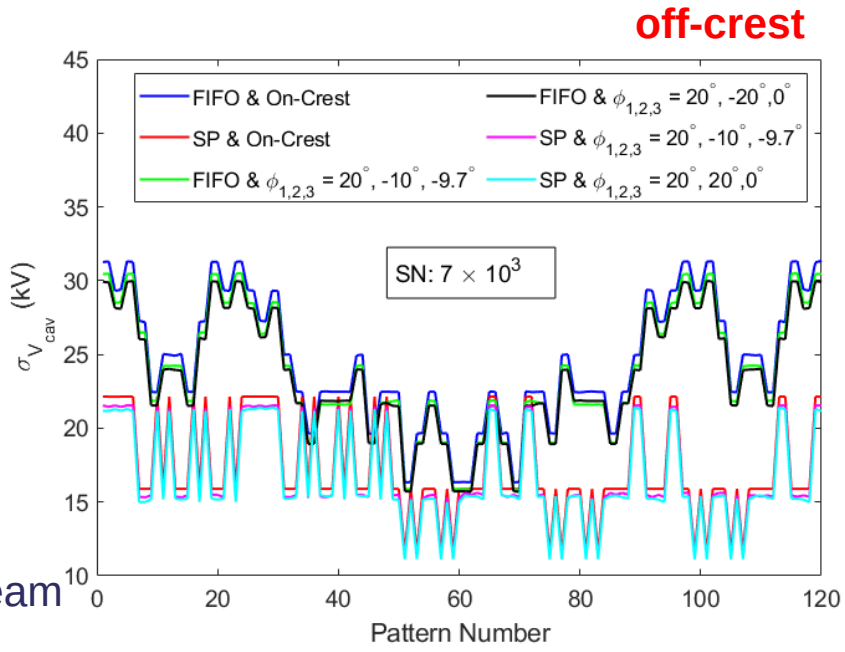
- Performance affected markedly by filling pattern chosen, particularly for FIFO
- Clear advantage of dynamic set point
- Sequence Preserving (SP) preferred over FIFO, because of lower V_{cav} .

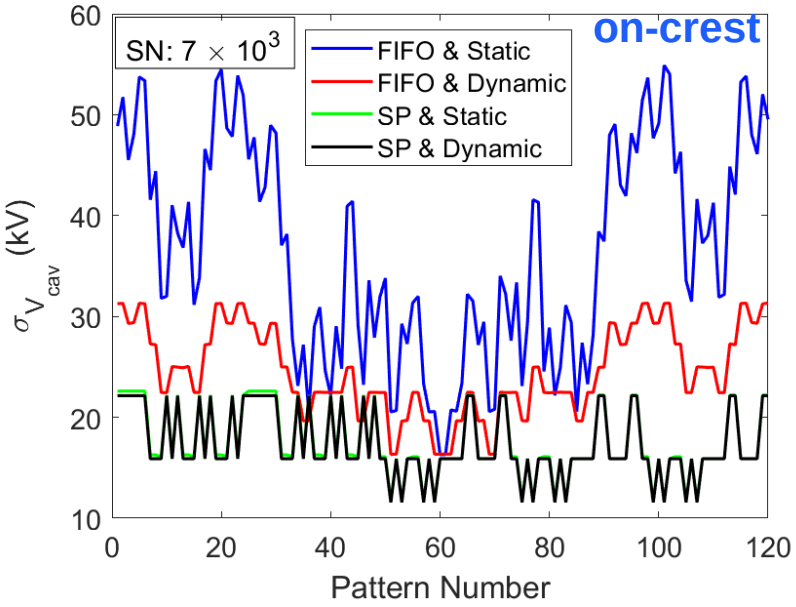
Moving **off-crest by up to 20°:**

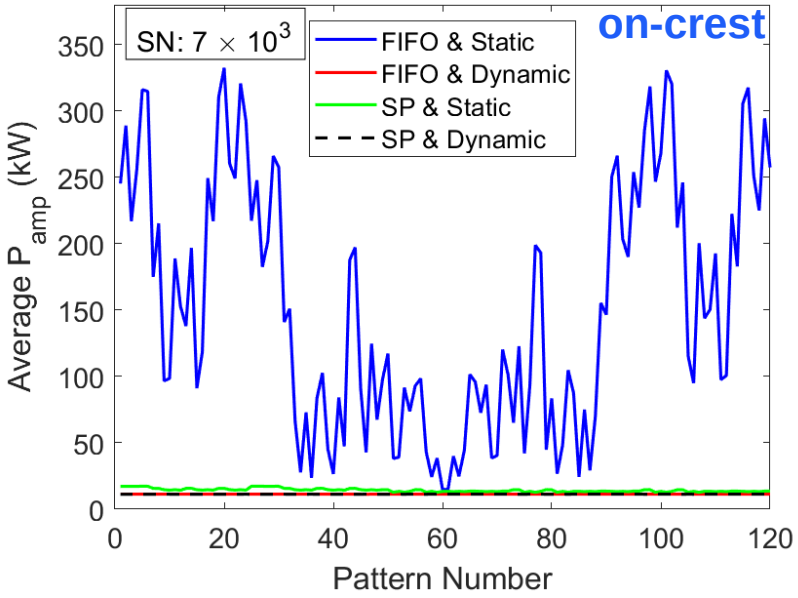
- Small phase jitter increase
- Change in cavity voltage and amplifier power negligible

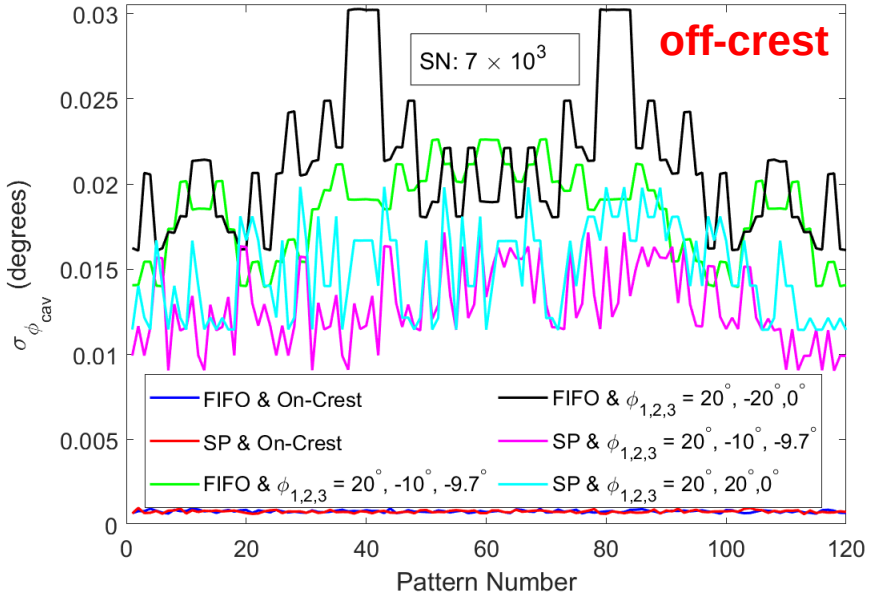
On-going work - Effects of filling patterns on BBU

- Analytical model is being developed
- Beam loading code is being extended to simulate HOMs and interaction with beam









Conclusions

- Motivated by UK-XFEL / DIANA, we are studying issues relevant to all multipass ERLs
- Exploring the implications of choosing common vs separate transport, testing some of these ideas at ER@CEBAF
- Exploring how choice of filling patterns can affect performance of ERLs

Acknowledgements

- DIANA / UK-XFEL: Joe Crone & Hywel Owen (U. Manchester), Bruno Muratori (STFC - Daresbury)
- ER@CEBAF Longitudinal Matches: Gus Perez-Segurana (U. Lancaster), Yves Roblin & Alex Bogacz (JLab)
- Filling patterns: Rob Apsimon & Sadiq Setiniyaz (U. Lancaster)

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