6-arc configuration

PERLE Collaboration Meeting

Peter Williams, Daresbury Laboratory / Cockcroft Institute

3rd June 2020
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1. Common Vs Separate Transport
2. Filling Patterns and RF Stability

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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 envelopes 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
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)
Pursuing this question as part of UK “Light Source” projects DIANA and/or UK-XFEL

**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
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.

- 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.

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.
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.
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 #**

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<tr>
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</tr>
<tr>
<td>9</td>
<td>010110</td>
</tr>
</tbody>
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**Diagram:**
- Diagram (a) shows SP pattern with 6-turn period.
- Diagram (b) depicts FIFO pattern with 6-turn period.
- Diagram (c) illustrates the cavity beam loading pattern for both SP and FIFO.
- Diagram (d) compares the machine fill factor for both SP and FIFO patterns.
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 $V_{\text{cav}}$

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
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