Hybrid Asymmetric Linear Higgs Factory (HALHF)
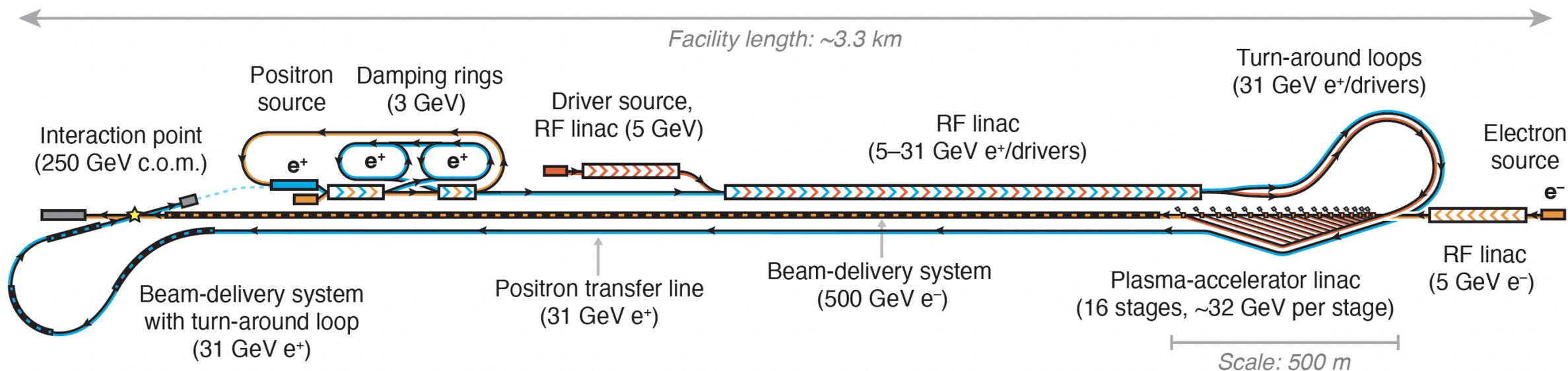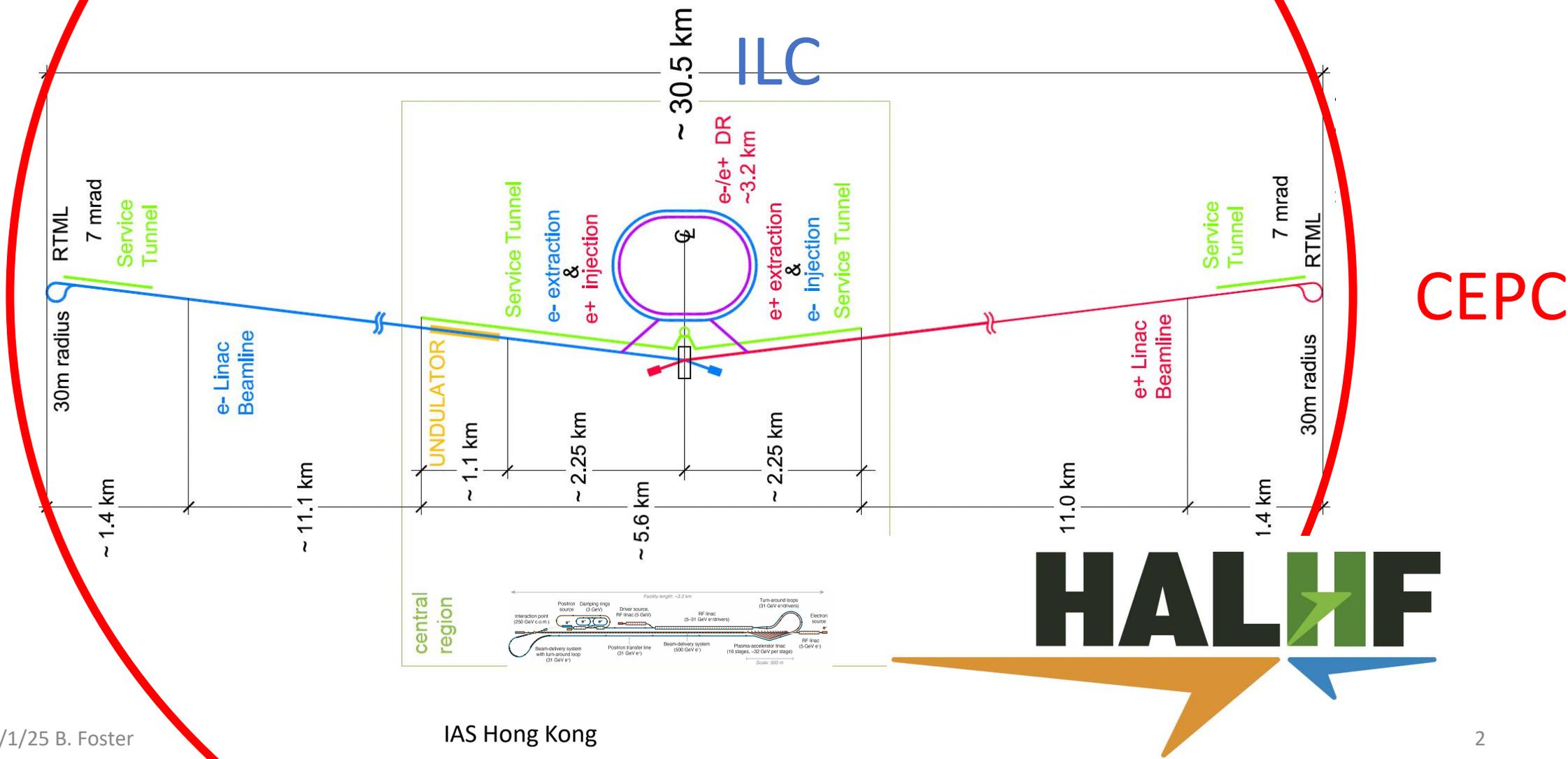
Brian Foster for the HALHF Collaboration

Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D'Arcy and Foster, arXiv:2312.04975

Hybrid Asymmetric Linear Higgs Factory (HALHF)

Hybrid Asymmetric Linear Higgs Factory HALHF

- For decades plasma acceleration has promised very high gradients => cheap LCs. HALHF for first time tries to make this a reality.

- The basic idea is – there are enough problems with a PWFA e^- accelerator; e^+ is even more difficult. Bypass this for e^+e^- collider by using conventional linac for e^+.

- For this to be attractive financially, conventional linac must be low energy => asymmetric energy machine (31 x 500 GeV).

- This requirement led to (at least for us) unexpected directions – the more asymmetric the machine became, the better!

Recent Progress

Workshops in Oslo (April) and Erice (October)

HALHF Status

HALHF workshop 3 – 8.10, Erice dedicated to reassessing baseline in light of comments from colleagues and progress in design.
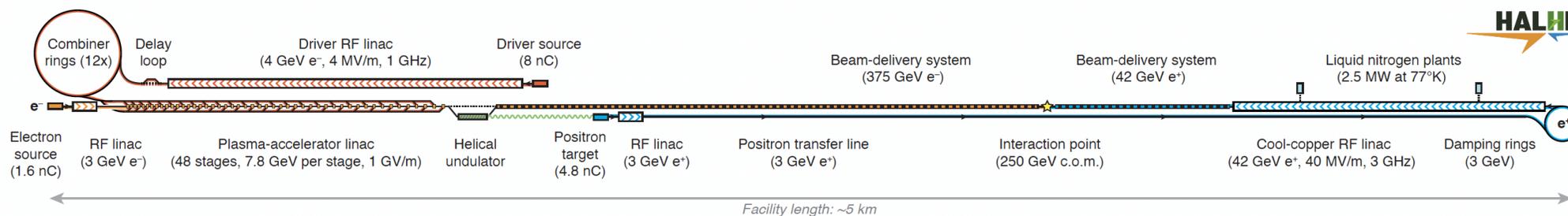
Original Baseline:

Principal problems:

1) "Turn-around" too small to retain required beam quality & scales badly with energy;

2) "Dual-Purpose" linac difficult to design and inflexible.
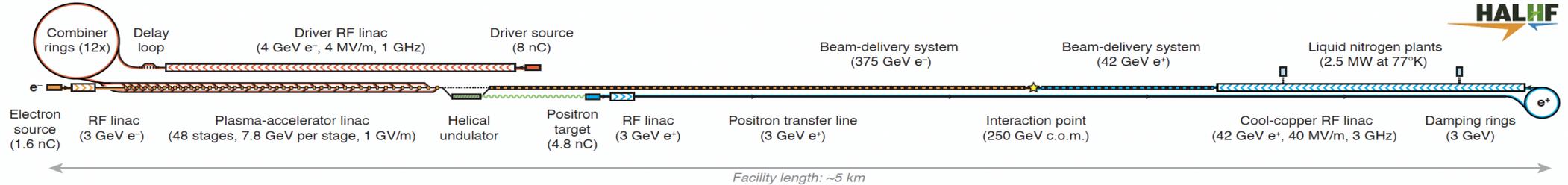
New Baseline (not yet official):
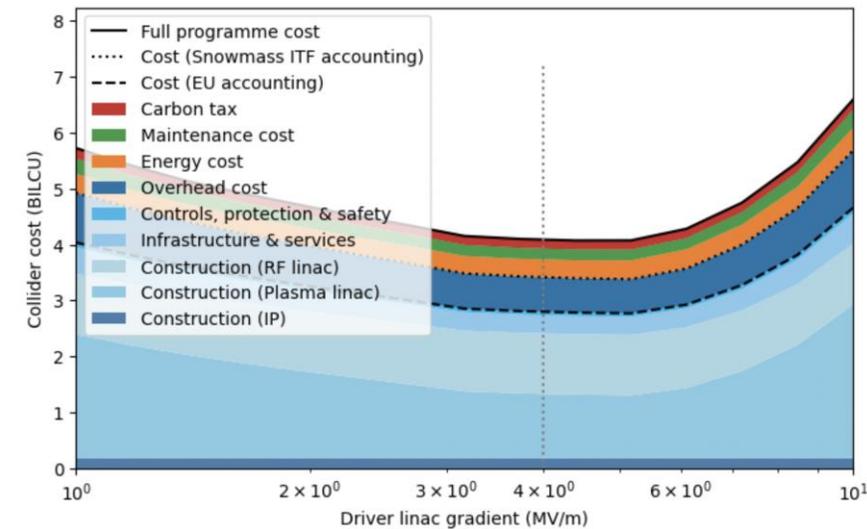
Problems with the original design

The laundry list

> **Transverse instability, tolerances** are too tight.

> **Beam ionisation** of the higher-order ionisation levels for argon (chosen to avoid ion motion).

> **Cross-plane emittance mixing** (Diederichs *et al.*): large horizontal emittance leaks into vertical emittance.

> **Plasma-cell cooling**: too much cooling required per length (~90 kW/m).

> **Radiation reaction** at high energy: large induced energy spread (%-level).

> **Bunch pattern** may not be compatible with PWFA: too much temperature increase? Effect on wakefields? Confinement?

> Exceeded the **Oide limit** in the final focusing magnets.

> **High-energy turn-arounds**: too much energy loss to synchrotron radiation.

> The required **delay chicanes** are (transversely) large and costly. Strong bending magnets (SR is problematic).

> **Combined RF accelerator** has too high gradient given its high power.

> Required **driver bunch length** is too short: problematic beam loading in the RF linac (beam current too high).

> The **instantaneous luminosity is too low**

> **High positron bunch charge**: problematic for production and for collisions.

> Need **polarised beams** for physics.

> Unknown if we can **preserve spin polarization** of electrons in plasma stages and interstages.
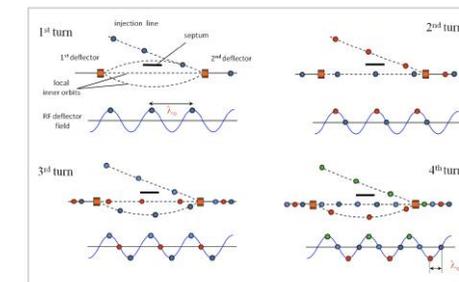
HALHF Status

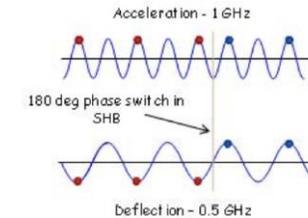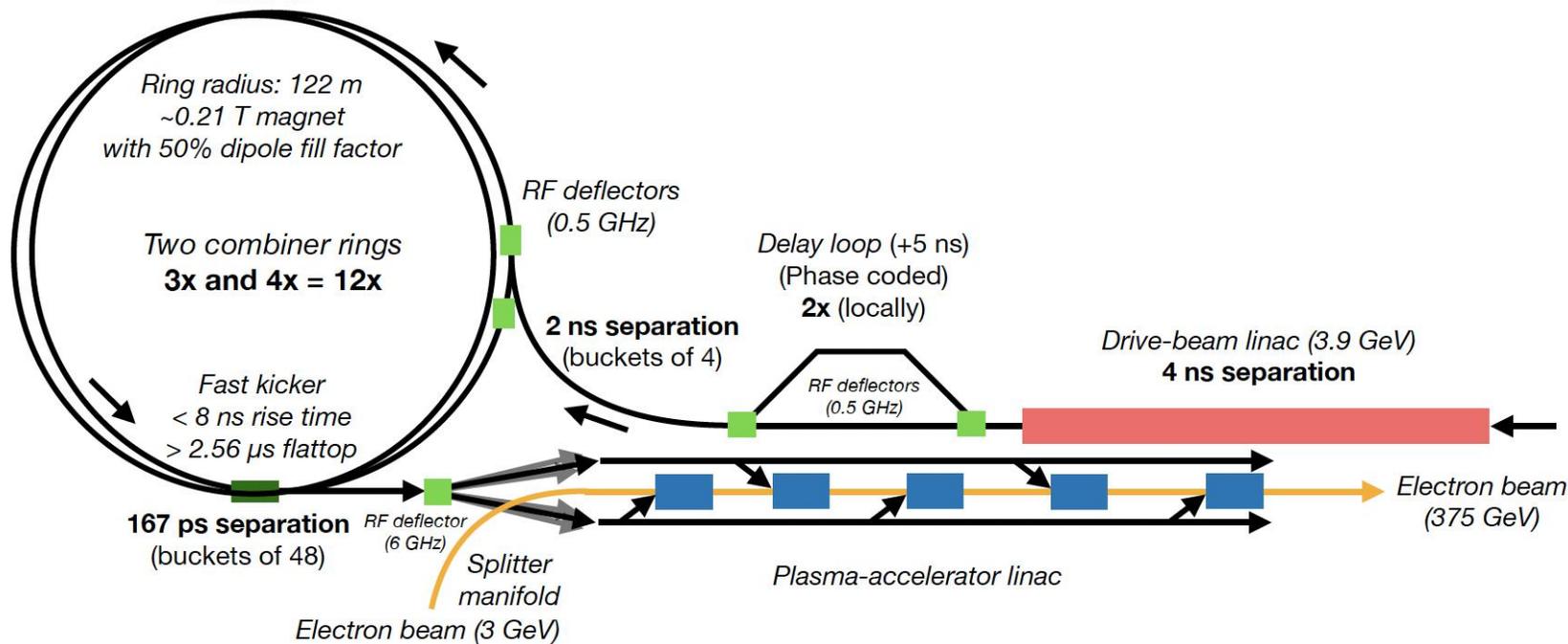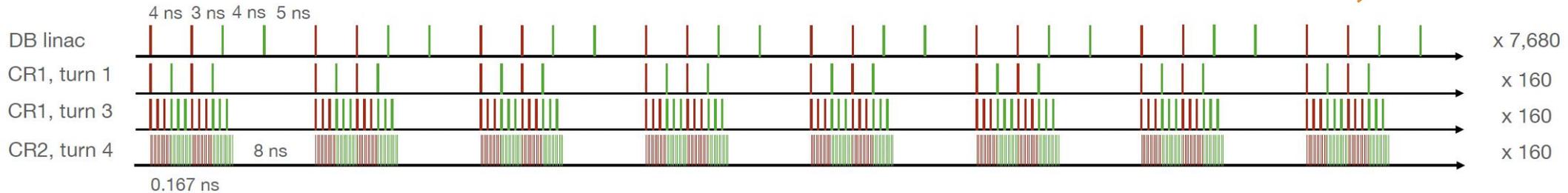**Summary of changes in new baseline – not yet official:**

> Two separate RF linacs (for more flexibility)
> > L-band (1 GHz) CLIC-like drive-beam linac — 4 MV/m, 4 ns spacing, 8 nC
> > S-band (3 GHz) cool-copper positron linac (warm-copper backup option) — 40 MV/m (25 MV/m), 16 ns spacing
> Drive train compression (for reduced peak power in klystrons)
> > Introduction of delay loop — 2x (requires phase coding)
> > Introduce combiner rings —12x compression of full train, 24x compression of driver stage-trains
> Lower energy asymmetry — around 9x between e^+ and e^-
> Positrons:
> > Fewer positrons – 3×10^{10} (4.8 nC)
> > Polarized positron source (helical undulator) — at the end of the PWFA linac
> PWFA stages:
> > More stages: 48 stages
> > Lower gradient — 1 GV/m
> > Lower density — 6×10^{14} cm^{-3}
> > Higher driver charge — 5×10^{10} (8 nC)
> > Higher transformer ratio — $T=2$
> Higher collision rate — 160 bunches per burst @ 100 Hz = 16 kHz (to have similar luminosity to ILC)

Bunch pattern

Bunch train pattern and combiner rings

From CLIC CDR (2013)

Recent Progress

Toward a self-consistent plasma linac

Start-to-end simulations (by Ben Chen, Uni Oslo)

> Multi-stage PWFA linac (here 33 stages)

> Nonlinear plasma-lens optics for stage coupling (SPARTA project, ERC)

> Flat-beam issue (Diederichs et al. 2024) suppressed with vertically flat driver

> Ion motion suppresses transverse instability.

> Longitudinal self-stabilization from compression between stages

> Full simulation (minor simplifications only):
  — PIC simulation in stages (HiPACE++)
  — Particle tracking in interstages (ELEGANT)

Staging optics with nonlinear plasma lenses (SPARTA project).

Preliminary start-to-end simulations
Source: B. Chen (University of Oslo)

Bunch pattern

(a)

(b)

PIC simulation with HiPACE++, He @ 6×10^{14} cm^{-3} ; driver and main beam (orange) 8 & 1.6 nC. Excess ion density on axis (green)

Corresponding current profile has peak current ~ 4–5 kA, with a ramped driver current and an initially Gaussian witness (colliding) beam.

Plasma Cell

- Getting the heat out of the plasma cells given the power required for colliders is a BIG problem;

- Very little is known about plasmas at these temperatures in PWFA - T > 100 keV - although rather a lot at ITER!

- Depending on details of bunch structure, extreme cooling is needed – ~ 100 kW/m – 10* higher than CLIC -> urgent R&D required!

143,01 C Max
135,16
127,31
119,46
111,61
103,76
95,907
88,056
80,206
72,355
64,504
56,654
48,803
40,952
33,102 C Min

sapphire
CVD diamond
ceramic
liquid-cooling channels

0,00   20,00   40,00 (mm)
10,00   30,00

Beam-Delivery System

Reiterating the summary – key points on HALHF BDS for CERN strategy contribution

- HALHF BDS design strongly benefits from ILC & NLC BDS designs
  - NLC BDS with renewable spoilers, integrated with ILC BDS design (polarimeters, spectrometers, etc.), is the most close design meeting HALHF parameters
    - Engineering design of renewable spoilers is to be further advanced
  - ATF@KEK Final Focus test is the most essential demonstration – no other demonstrations are needed
- Optional design improvements for HALHF BDS are possible
  - Distributed collimation inside and in between of plasma sections will help
  - This distributed collimation will also ease assumptions for renewable BDS collimators
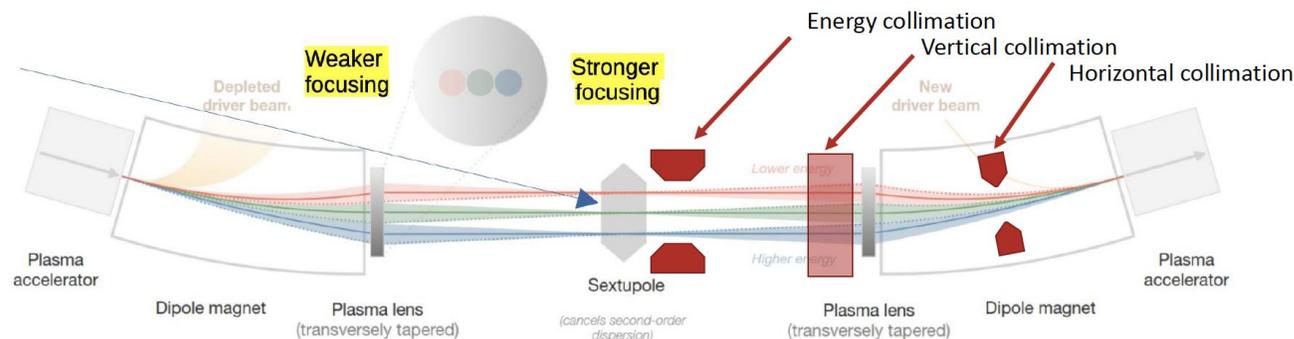- Discussion of HALHF upgrades to TeV and multi-TeV opened plethora of ideas
  - Final Focus is scaling nicely to multi-TeV energies
  - The most unfavorable scaling is for energy collimation, but novel ideas such as distributed collimation in plasma sections and nonlinear energy collimation will likely revert the scaling and allow to design a compact BDS for multi-TeV advanced collider

HALHF Workshop 2024, A. Seryi

This design was essential for NLC, where short inter-bunch spacing made it impractical to use survivable spoilers.
This concept is now being applied to LHC collimator system.

Distributed collimation in plasma sections – for HALHF design

Towards an advanced LC

- Technology being developed for HALHF could also enhance a "conventional" LC design – part of "LCVision":

- Assume: ILC has been built,
-> 2x125GeV linacs available

- Goal: upgrade electron arm to 500GeV with plasma
-> 125x500GeV -> 500GeV COM; $\gamma \sim 1.2$
-> upgrade a Higgs factory to a tth / Zhh factory

- Use electron linac for drive and witness beam:
run a lower gradient but higher current, upgrade RF on electron arm

- Use space for undulator source between electron ML and BDS to install plasma booster

- Feed boosted electrons into existing BDS (laid out for 500GeV)

(B. List)

10 TeV Wakefield Collider Summary

Working Groups

- System integration and optimization
- Beam sources (incl. damping rings)
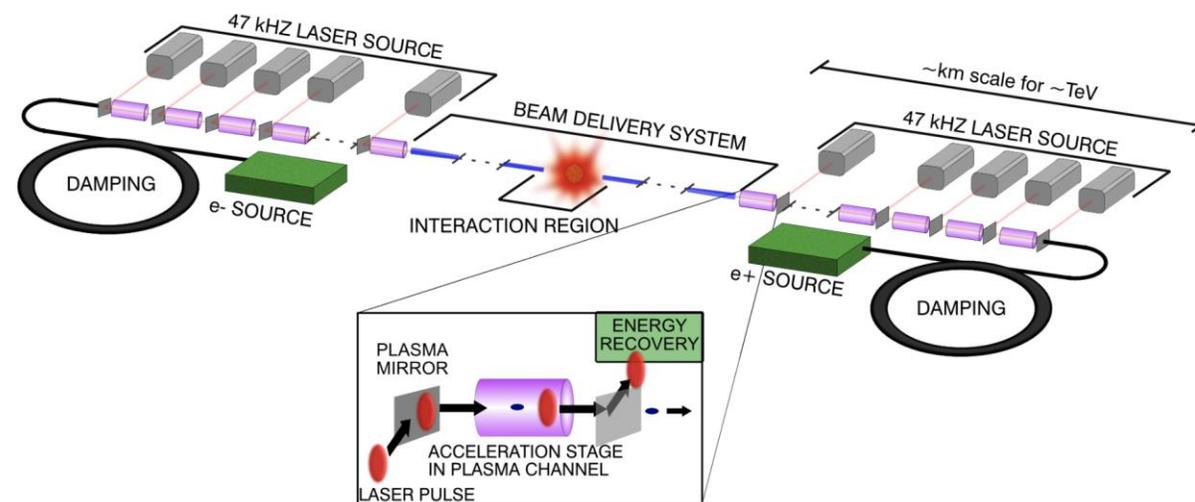- Drivers
  - Laser
  - Beams - SWFA
  - Beams - PWFA
- Linacs
  - LWFA
  - SWFA
  - PWFA
- Beam delivery system
- Beam-beam interactions
- Beam diagnostics
- Machine-detector interface
- HEP detector
- HEP physics case
- Environmental impact
- Simulations/computing/AI

Green = Broader accelerator community

Orange/blue/purple = AAC specific

Red = HEP and broader community

10 TeV Wakefield Collider Summary

Challenges

- Inefficient acceleration of positrons in plasma
  - Proposed solution: Take advantage of large VBF cross-section and utilize gamma-gamma or e^-e^- collisions instead.
- Extreme beamstrahlung at high collision energies and beam densities
  - Proposed solution: 1) Collide ultrashort bunches to mitigate beamstrahlung and 2) Embrace the broad luminosity spectrum so long as significant fraction of the colliding particles are close to 10 TeV CM.
- Detector design and background modeling for high energy collisions
  - Proposed solution: Development of new Particle-in-Cell codes, benchmarked against GUINEA-PIG and CAIN, to accurately model backgrounds for high-energy gamma-gamma, e^-e^-, and e^-e^+ collisions.

Summary & Outlook

- Despite ~ 0 funding, HALHF is making rapid progress;
- Hope to finalise new baseline tomorrow;
- Regular monthly HALHF accelerator meetings;
- In parallel, physics & detector studies continue (J. List, coord.) first indications boost does not impact physics reach;
- Next workshop in DESY, 27-28.2.25;
- Short-term goal: input to European Strategy and to comprehensive global LC plan, LCVision;
- Longer-term goal: pre-CDR & funding to start R&D programme;
- Contribute to 10 TeV design.