Expert Team 6

Realizations of the full physics program with plasma wakefield upgrades of the initial LCF

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1. Introduction – communities and projects involved

2. Status of projects underway – HALHF, PEEP, 10 TeV

3. Upgrades to existing LC

4. Summary

Introduction

Three WFA communities need to be involved:

1. Electron beam-driven PWFA
2. Laser-driver LWFA
3. Proton beam-driven WFA

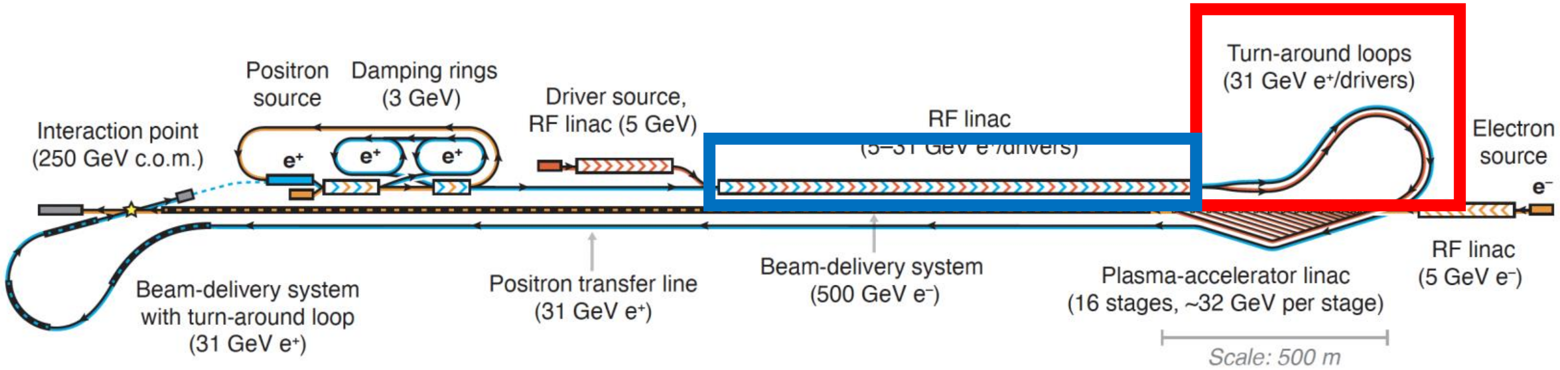
Information Zoom held on 1st Nov. 2024. 16 Attendees from Europe, US, China.

1. Is covered by the coordinators – HALHF, 10-TeV – HALHF workshop 3 – 8.10, Erice;
2. Direct applications to LC limited by laser efficiency – but much work to understand plasma properties can be done with lasers;
3. AWAKE @ CERN has applications to colliders, but not e^+e^- LC.
    - PEEP Workshop @ CERN, 30.9 – 1.10; see also arXiv:2401.14765v3
    - Enthusiasm among this community for collaboration with HALHF and the LC Vision process.

HALHF Status

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

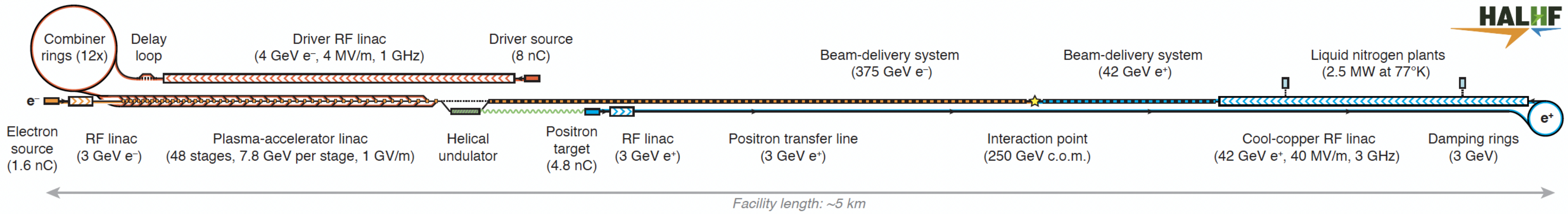
Original Baseline:



Principal problems:

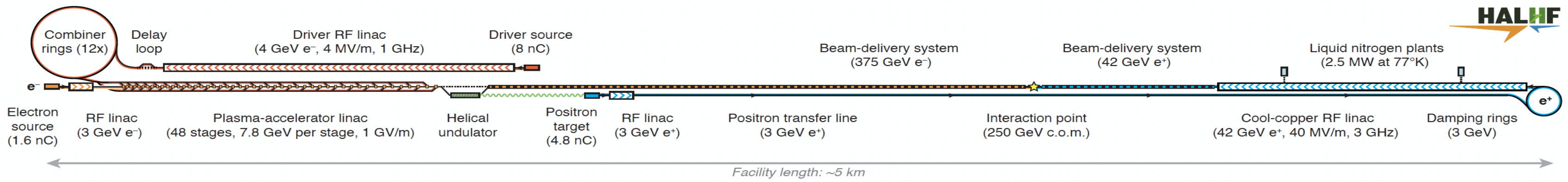
1) “Turn-around” too small to retain required beam quality & scales badly with energy;
2) “Dual-Purpose” linac difficult to design and inflexible.

New Baseline (not yet official):



Summary of changes:

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)

HALHF Summary

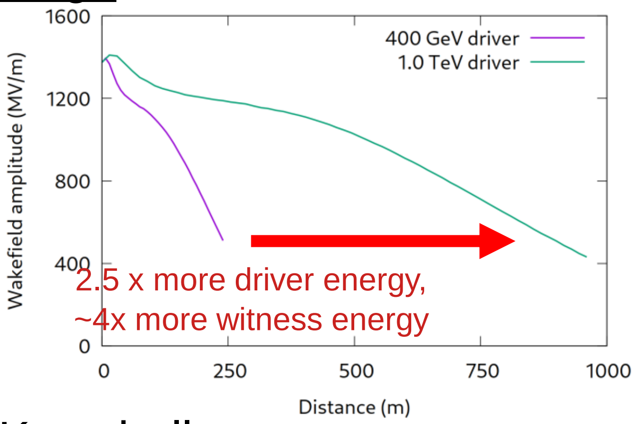
- Length: ~5 km — Power: ~106 MW
- Energy and charge asymmetry = 3
- Optimization pulled toward CLIC (power source) + PWFA (transformer) + cool copper (positrons)
- Much freedom in selecting positron RF linac — can select “best of both worlds”
  - Cool or warm RF both work, but cool copper is cheaper (by 25%). Baseline, but “loosely attached”.
  - To avoid mixing designs, we will not call it “C^3 technology” and instead call it “cool copper technology”
- PWFA simulations work very well—moving toward a full 48-stage PWFA linac simulation.
- $\boxed{\text{Main pressing PWFA R\&D topic is rep rate / plasma temperature / cooling}}$
- Open questions: cool-copper design, positron target, damping rings, BDS, 2 IPs, flat-beam electron source

Proton-driven wakefield acceleration

ALiVE: Advanced Linear collider for Very high Energy

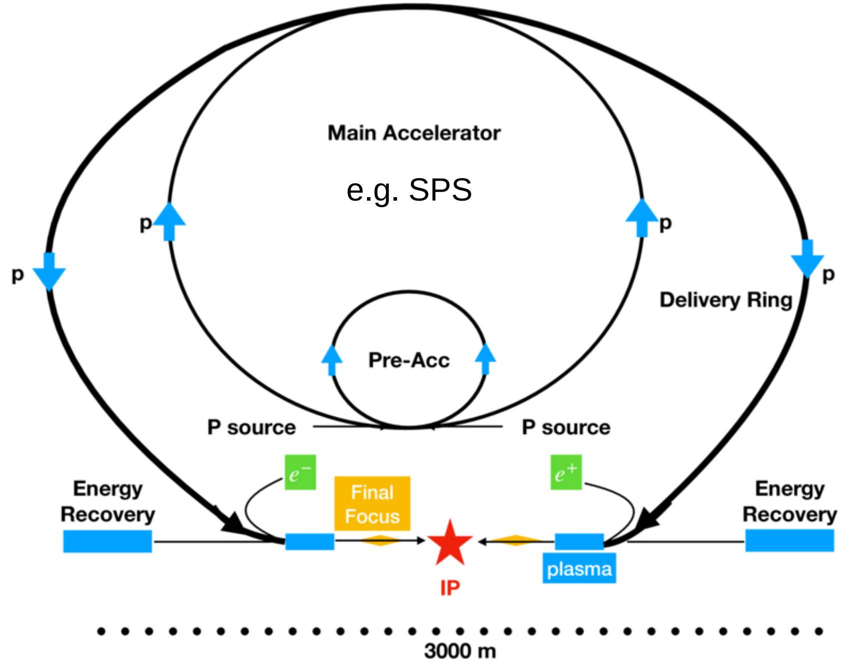
Re-use existing infrastructure (lower cost, reduced carbon footprint): proton drive bunches from fast cycling synchrotron or FFAG for competitive luminosity, plasma stages are comparatively short O(100s metres).

Short proton driver (first schemes now being developed) with plasma density gradient prevents dephasing, allows acceleration to very high energy <u>in a single plasma stage</u>.



Farmer *et al.*, NJP (2024)

Better-than-linear scaling:
400 GeV driver gives
125 GeV witness.
1.0 TeV driver gives
500 GeV witness.



Key challenges:
Short (sub-mm) driver, high (kHz) rep rate, positron acceleration in plasma.
(not necessary for e−p/e−A collider or asymmetric schemes).

10 TeV Wakefield Collider Summary

We are motivated to uncover a path to the **energy frontier** starting from a Linear Collider Facility.

- We envisage an LC Higgs factory to be the first step towards a 10 TeV Linear Collider

The goals for the **10 TeV pCM Wakefield Accelerator Collider Design Study** have been set by the 2023 P5 Report:

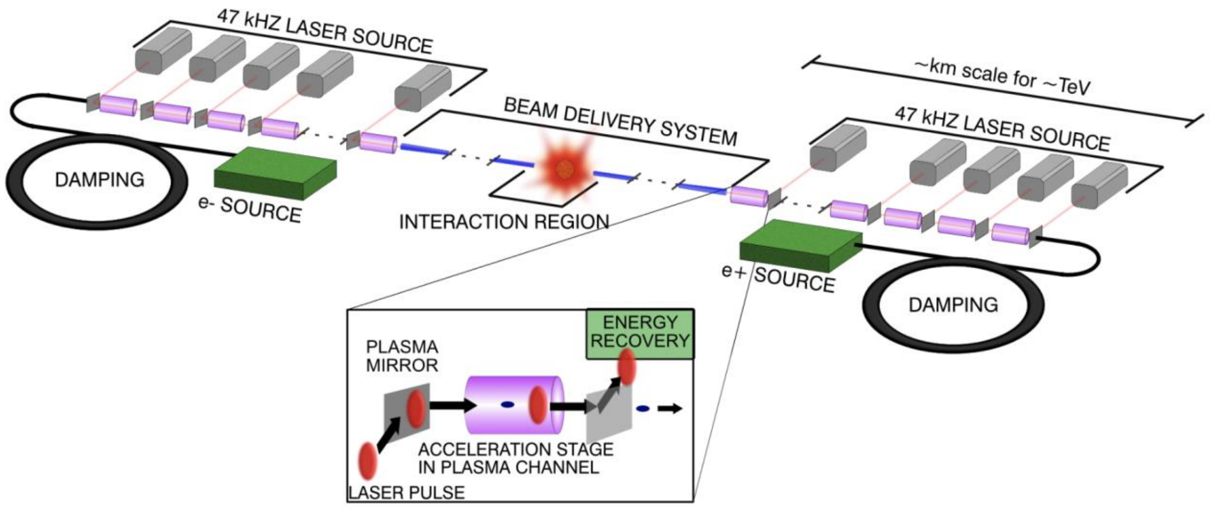
> ". . . delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout."

Working group conveners from the US and Europe are organizing the study, with the first meetings starting this week. We will deliver an overview of the study as input to ESPP, and the final design report will be delivered in 2028.

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.

10 TeV Wakefield Collider Summary

Advertisement

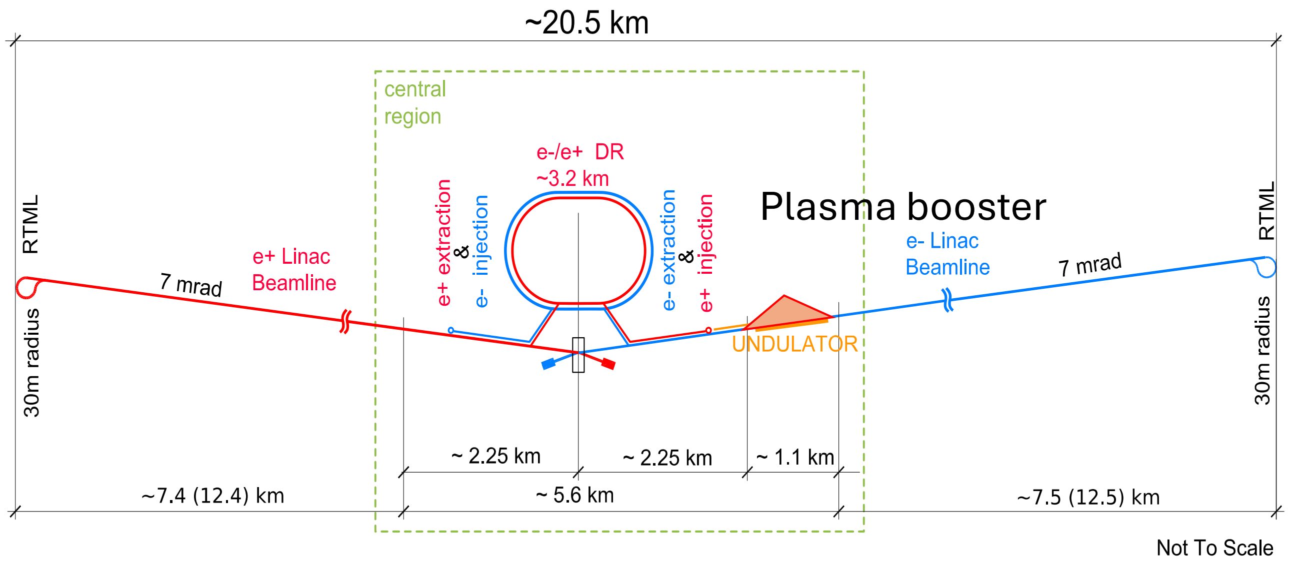
- The design study kicks off in earnest this week!

- Link to interest form:
  - https://forms.gle/X8zRv75C8zbTs7Uu5

- We will deliver dedicated input to ESPP describing the goals, organization, and timeline for the study:
  - https://www.overleaf.com/read/jbztkjnpjmpp#8f96cb

HALHF Technology as Energy Booster

- Assume: 250 GeV ILC has been built,
  -> 2x125GeV linacs available
- Goal: upgrade electron arm to 500GeV with plasma
  -> 125x500GeV -> 500GeV COM
  -> Boost ~ 1.25 – negligible except for lumi. counter
  -> 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)

HALHF Technology as Energy Booster

- Rep-rate: 10Hz (2xILC baseline, OK with DR)
- Time between colliding bunches: 1.6us (3 x ILC)
- In drive beam linac: mini-trains: 16 drive bunches + witness bunch in ~80ns, then gap
  -> pulse length: 1.1ms
- Average current in pulse: 46mA
  -> 5x ILC at ¼ gradient
  -> cavity fill time: 32us – very short
- Power 1.5 cryomodules (13 cavities) with one klystron -> **9.8MW** matched power per klystron
- Requires 3x more klystrons than in baseline configuration (baseline: 2 klystrons for 9 cryomodules) -> fits RF cell structure
  -> next slide

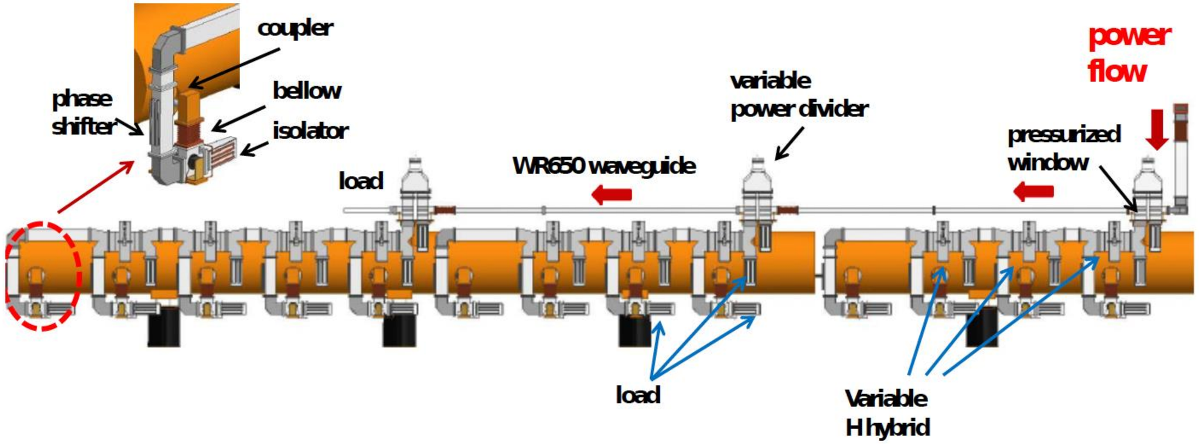
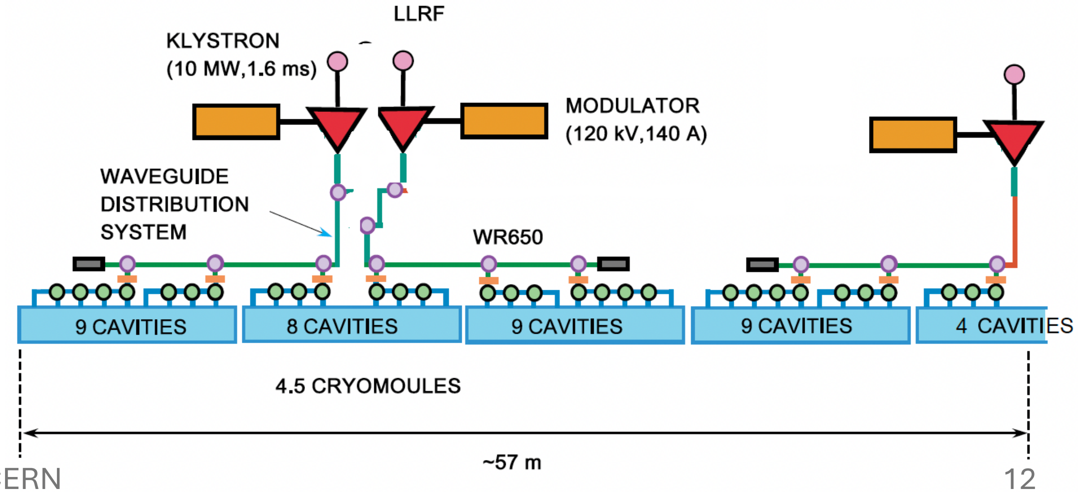


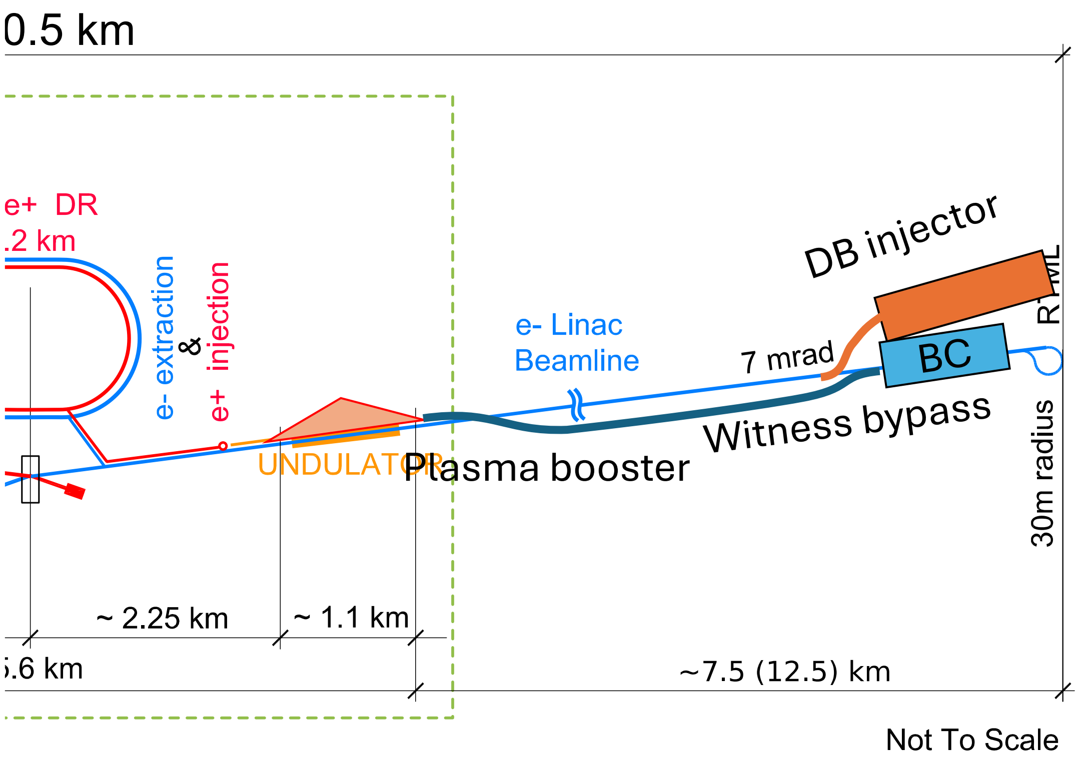
Figure 3.33. CAD model of a 13-cavity local power-distribution system (LPDS)

TDR, Vol 3.II



HALHF Technology as Energy Booster

- There are complications:
- A "HALHF" type plasma booster for ILC 250 could boost the CoM energy to ~550 GeV
  -> enough to reach tth threshold
- Overall beam intensity would be half compared to ILC250 or full ILC500
  -> half of luminosity or less
- Compared to full ILC500 further luminosity reduction from larger emittance / asymmetric beams -> needs to be studied
- BDS of ILC designed for 500GeV beams
  -> should work
- Bunch Compressors are an issue
  -> bunch length for plasma input critical



Alternative - remove entire ILC e^- arm & replace with HALHF e^- arm. Mixture of SCRF & warm technology problematic. CLIC is much more compatible with such PWFA upgrades than ILC.

Summary

1. Much activity towards stand-alone PWFA solutions for pp, from Higgs factory -> 10 TeV.

2. HALHF new baseline to be approved next week – longer, more expensive but more realistic.

3. Several PWFA upgrades to existing LC possible.

4. Stand-alone HALHF paper for EPPSU drafted; will be integrated with LCVision paper.