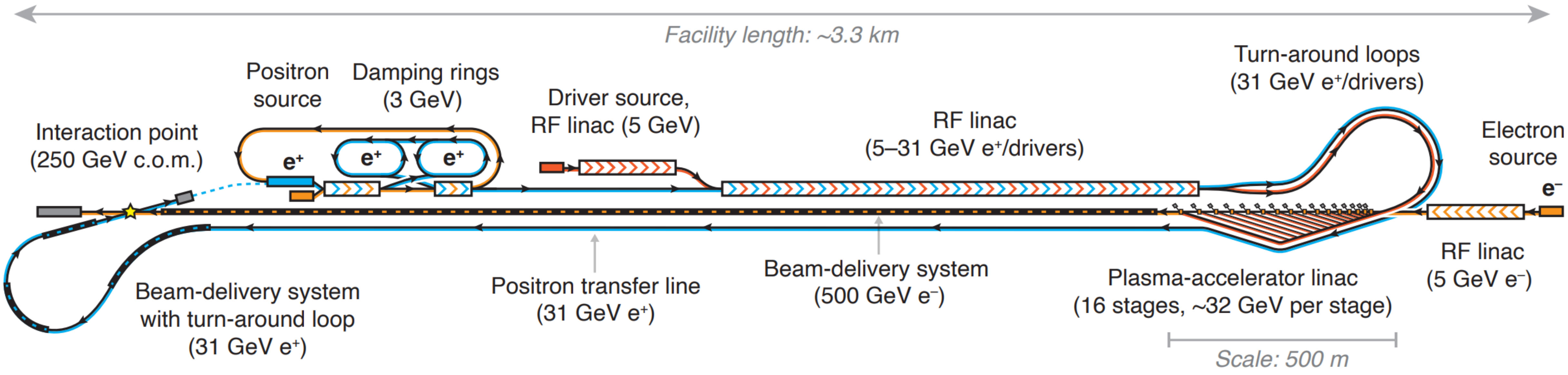
Impressions from the HALHF Workshop



Jonathan Wood, 28th Future Colliders @ DESY Meeting, 12.04.2024

Reporting on HALHF Workshop Oslo, Norway, 04-05.04.2024

HELMHOLTZ

DESY.

Update from the US: Snowmass and P5

Considerations from Snowmass and P5

Mark Hogan, SLAC

Energy Frontiers Committee Priorities

1. Supporting the HL-LHC science program (2025+).
2. Higgs Factory (construction 2030+).
3. Planning for multi-TeV colliders (2035+ - demonstrate readiness for a TeV muon collider, R&D for multi-TeV energy frontier colliders).
4. Cost estimates of new collider $10-50 billion, technology dependent. “Conventional” technologies are among cheapest, with smallest uncertainties. LPWFA could be most expensive.

Mutli-TeV seems to mean ~ 15 TeV.

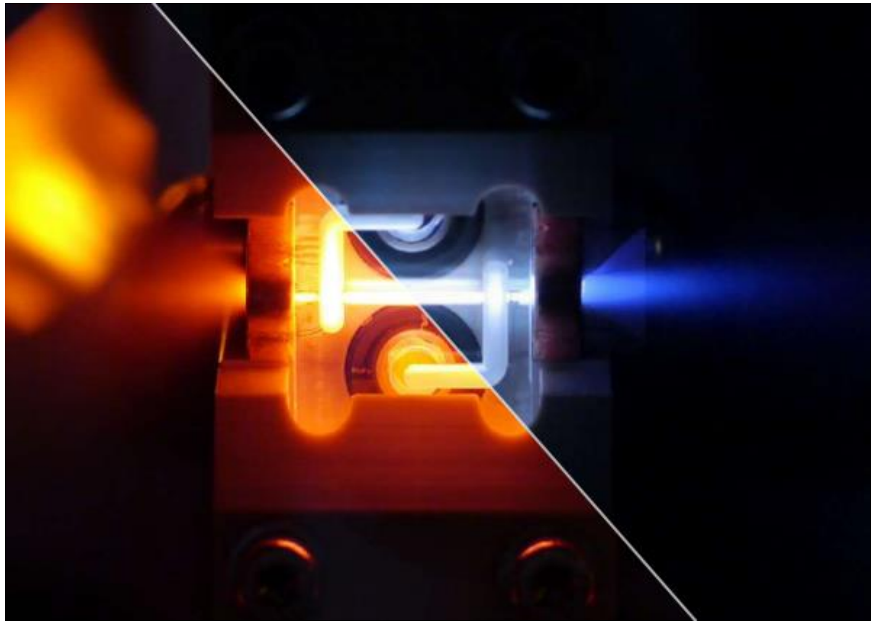
P5 Report Recommendations 2023 (colliders only reported here)

- HL-LHC is high priority.
- Off-shore Higgs factory- US involvement and funding at similar levels to LHC. ILC and FCC-ee designs meet P5 scientific requirements.
- Aggressive R&D program towards 10 TeV pCM collider
- “Progress in advanced wakefield accelerators motivates efforts to develop a self-consistent design to understand feasibility and costs. Each of these research areas will benefit from international engagement to enable timely progress. – HALHF is out in front
- K-Bella mentioned, including about feedbacks for precision operation.
- WarpX used to simulate interaction points

HALHF Overview

Overview of HALHF

Carl Lindstrøm, University of Oslo

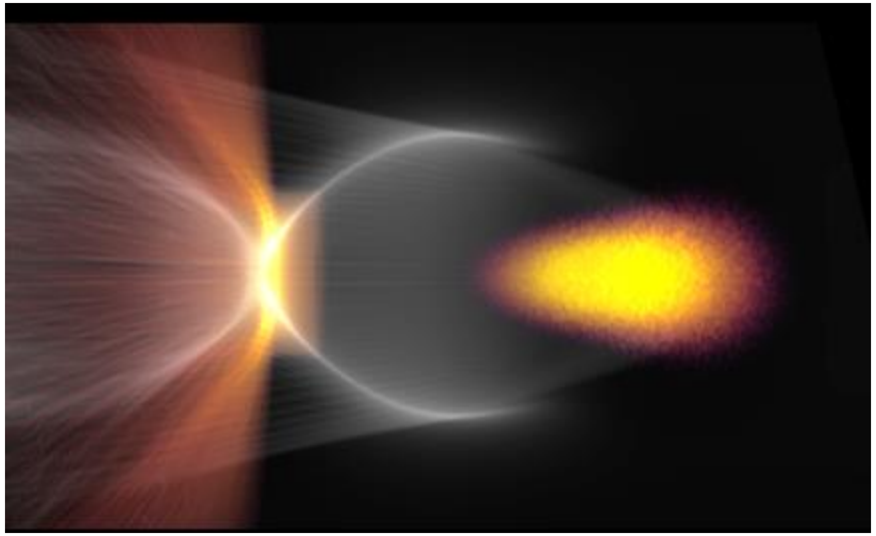


Plasma-wakefield acceleration:

- GV/m gradients, high beam quality, high beam power

Many promising developments in plasma acceleration over the past few years:

- Increased stability (Maier et al. PRX)
- FEL application (Wang et al., Pompili et al. Nature)
- High rep rate (D’Arcy et al. Nature)
- Beam quality preservation (Lindstrøm et al.)
- High energy efficiency, e– driven (Litos et al., Peña et al.)

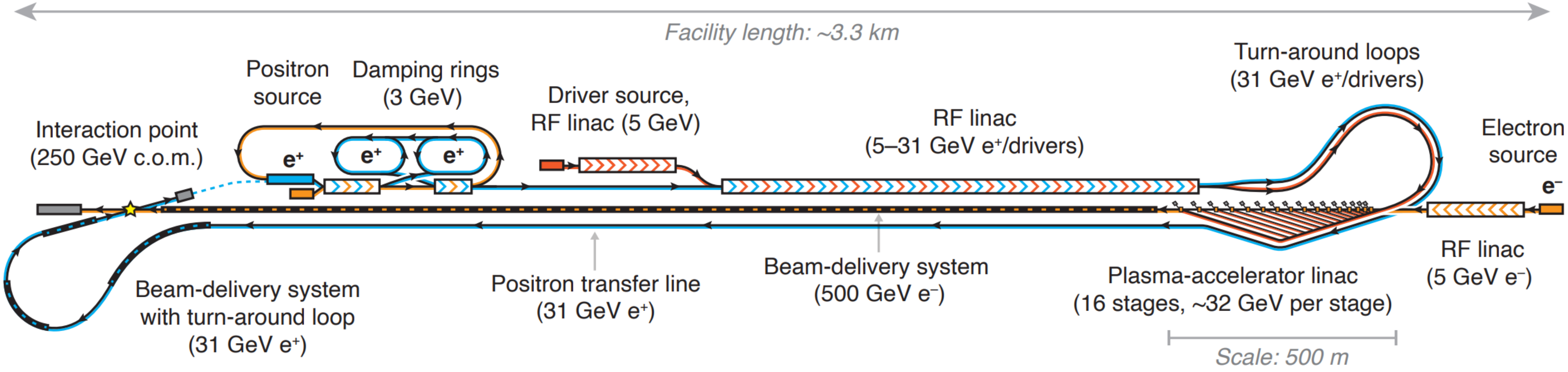


Problem

- No clear route to accelerate large charges of positrons needed for a particle physics experiment

Overview of HALHF

Carl Lindstrøm, University of Oslo



Asymmetric collisions (31 GeV e^+, 500 GeV e^-).

Disadvantage: detectors. Advantage: compact because of e^- acceleration in multi-GV/m plasma stages.

Asymmetric charges (more e^+) fixes power efficiency problem from asymmetry

Foster, D’Arcy & Lindstrøm, New. J. Phys. 25, 093037 (2023)

Overview of HALHF

University of Oslo Team

Parameter	Unit	Value	
Machine parameter			
Center of mass energy	GeV	250	
Plasma density	m^{-3}	$1.1 \cdot 10^{21}$	
Plasma acceleration gradient	$\mathrm{GV\,m}^{-1}$	2.0	
Stage length	m	5.8	
Number of stages		33	
Energy gain per stage	GeV	11.6	
Driver parameter			
Bunch energy	GeV	7.7	
Bunch charge	nC	−8.0	
Bunch length	µm	550	
rms bunch size	µm	103.0	
Beam parameter		e^-	e^+
Collision energy	GeV	375	42
Bunch charge	nC	−1.60	
rms bunch length	µm	28	75
Horizontal rms bunch size	µm	32.1	
Vertical rms bunch size	µm	1.9	
Normalised horizontal emittance	mm mrad	90	
Normalised vertical emittance	mm mrad	0.32	

- Latest parameter set.
- Major change is going to lower plasma density.
  - Can maintain same accelerating gradient by changing acceleration phase.
  - Less susceptible to transverse instabilities.

Latest Cost Model

Carl Lindstrøm, University of Oslo

- Bayesian optimisation model for reducing lifetime machine costs (construction, energy to collect required data, maintenance, people, carbon). https://github.com/carlandreaslindstrom/ColliderCostModel/tree/main
- Currently implemented (analytic only, no simulation):
  - RF linacs (voltage limited by power and BDR, efficiency based on filling time/cooling)
  - Damping rings (radius based on bunch train length, damping time limits rep rate)
  - Plasma linac (lengths and efficiencies, but not yet effect on emittance)
  - PWFA emittance growth due to instabilities (model by Lebedev et al.)
  - Turnarounds, BDS, tunnels, power infrastructure, general overheads, dumps

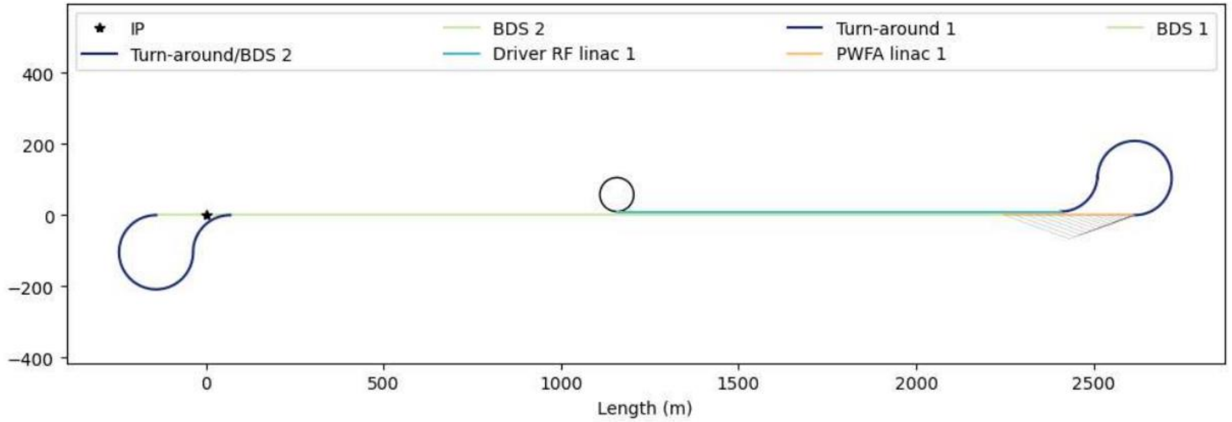
- Most of the construction costs, energy use and operational complexity at HALHF comes from the RF.
- Will use CLIC models for calculating HALHF performace, reducing breakdown rate, reducing cost etc.
- Likely will not change BDS soon. It does not dominate the size of the machine.

Latest Cost Model

Carl Lindstrøm, University of Oslo

Original HALHF design (250 GeV)

2.5/3.9/6.2 BILCU, 3.0 km, 111 MW




```
ELECTRON/POSITRON BUNCH PARAMETERS:
>> Electron final energy = 500.0 GeV
>> Positron final energy = 31.2 GeV
>> Electron charge = 1.60 nC
>> Positron charge = 6.41 nC
>> Electron norm. emittance = 160.0 x 0.56 mm mrad
>> Positron norm. emittance = 10.0 x 0.04 mm mrad
>> Number of bunches in train = 100
>> Bunch separation = 83.5 ns
>> Bunch train rep. rate = 100.0 Hz
>> Average collision rate = 10.0 kHz

PLASMA WAKE PARAMETERS:
>> Accelerating field          = 6.40 GV/m
>> Wake-to-beam efficiency     = 50%
>> Driver depletion efficiency = 75%
>> Longitudinal energy density = 20.5 J/m
>> Energy absorbed per length  = 10.3 J/m
>> Energy remaining per length = 10.3 J/m
>> Peak decelerating field     = 6.40 GV/m
>> Blowout radius              = 2.18 kp^-1
>> Plasma density              = 6.64e+15 cm^-3
>> Plasma skin depth           = 65 µm
>> Normalized field strength   = 0.82
>> Wavebreaking field          = 7.84 GV/m
>> Norm. transverse wakefield  = 0.125

DRIVE BUNCH PARAMETERS:
>> Driver charge       = 4.27 nC
>> Driver energy       = 31.2 GeV
>> Driver bunch length = 43.5 µm rms
>> Driver peak current = 11.8 kA

PLASMA LINAC:
>> Number of stages = 16
>> Stage length = 4.8 m
>> Energy increase per stage = 30.94 GeV
>> Average cooling rate per length in stages = 103 kW/m
>> Matched beta function (initial -> final) = 0.9 -> 9.1 cm
>> Matched beam size (initial -> final) = 12.2x0.7 µm rms ->
>> Total phase advance, µ = 1541 rad
>> Instability parameter, µ*eta_t = 192.7
```

```
DRIVER RF LINAC:
>> Energy per driver train = 213.6 kJ
>> Driver beam power (average) = 21.4 MW
>> Driver linac accelerating gradient = 25.0 MV/m
>> Driver linac peak power per length = 21.7 MW/m
>> Driver bunch separation = 4.9 ns
>> Driver train duration = 8 µs
>> Driver linac length = 1.25 km
>> Number of driver klystrons = 543
>> Driver klystron average power = 133.8 kW
>> Driver linac average power = 72.7 MW
>> Driver linac efficiency = 29.4%
>> Driver linac max field (breakdown limit) = 38 MV/m

DAMPING RINGS:
-- RF POSITRON ARM:
>> Number of rings = 2
>> Damping ring energy = 2.86 GeV
>> Damping ring circumference = 300 m
>> Damping ring char. damping time = 1.0 ms
>> Damping ring total damping time = 6.3 ms
>> Damping ring emitted power = 1.8 MW
```

```
LUMINOSITY:
>> Beam size at IP = 734.6 x 16.0 nm rms
>> Geometric luminosity = 2.7e+33 cm^-2 s^-1
>> Luminosity per power = 2.4e+31 cm^-2 s^-1 MW^-1
>> Time required for collisions (100% uptime) = 10.6 years
>> Integrated energy required = 10.3 TWh

POWER:
>> Driver/e+ RF linac power = 72.7 MW
>> Injector RF linac power  = 0.5 MW
>> Damping ring power       = 20.0 MW
>> Overhead power (25%)     = 18.3 MW
-----------------------------------
>> Collider wallplug power  = 111.5 MW
-----------------------------------

LENGTHS:
>> Driver linac length        = 1.2 km
>> Plasma linac length        = 0.4 km
>> Total turnaround length    = 1.3 km
>> Electron BDS length        = 2.2 km
>> Positron BDS length        = 0.1 km
>> Damping-ring length        = 0.6 km
>> Total tunnel length        = 5.6 km
----------------------------------------
>> Collider length (end-to-end) = 3.0 km
----------------------------------------
```

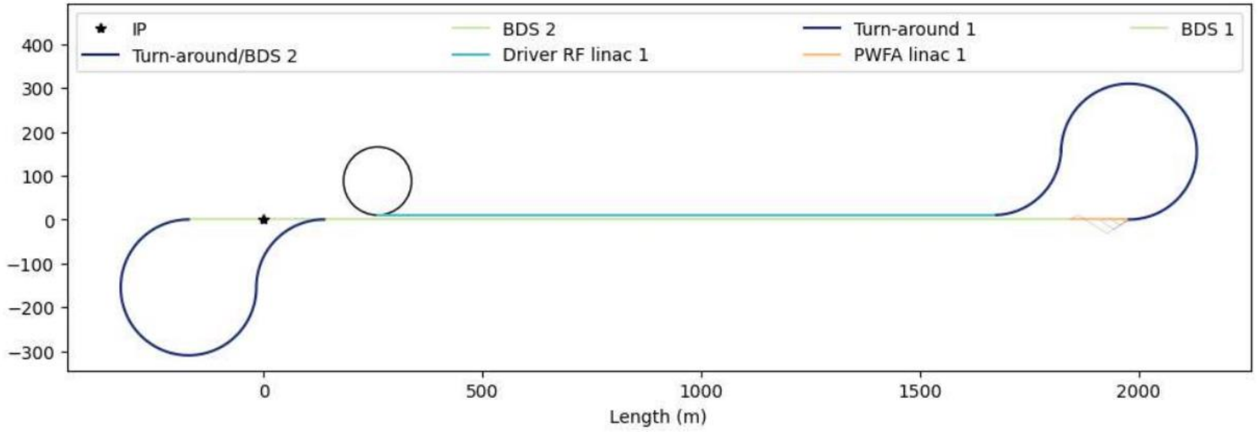
```
COSTS:
>> Particle source cost       = 28 MILCU
>> Damping ring cost          = 180 MILCU
>> Linac cost                 = 1219 MILCU
>> - Driver linacs            = 675 MILCU
>> - Plasma linacs            = 432 MILCU
>> - Injector linacs          = 112 MILCU
>> Power infrastructure cost = 87 MILCU
>> Tunnel cost                = 489 MILCU
>> Beam dump cost             = 98 MILCU
>> Turn-around costs          = 262 MILCU
----------------------------------
>> Total construction cost        = 2.53 BILCU
>> Overhead cost                  = 1.32 BILCU
>> Maintenance cost (for 18 yrs)  = 0.31 BILCU
>> Energy cost (for 0.9/ab)       = 2.07 BILCU
>> Carbon tax (for 267 kton CO2) = 37 MILCU
----------------------------------
>> ITF cost (excl. run costs)     = 3.85 BILCU
>> Full programme cost            = 6.23 BILCU
>> Full programme cost + CO2 tax = 6.27 BILCU
----------------------------------
```

Latest Cost Model

Carl Lindstrøm, University of Oslo

Optimized, original geometry (combined-function RF linac)

2.6/3.9/<u>5.2</u> BILCU, 2.5 km, 148 MW




```
ELECTRON/POSITRON BUNCH PARAMETERS:
>> Electron final energy = 336.5 GeV
>> Positron final energy = 46.4 GeV
>> Electron charge = 1.60 nC
>> Positron charge = 4.81 nC
>> Electron norm. emittance = 72.4 x 0.25 mm mrad
>> Positron norm. emittance = 10.0 x 0.04 mm mrad
>> Number of bunches in train = 163
>> Bunch separation = 110.6 ns
>> Bunch train rep. rate = 79.0 Hz
>> Average collision rate = 12.9 kHz

PLASMA WAKE PARAMETERS:
>> Accelerating field          = 4.91 GV/m
>> Wake-to-beam efficiency     = 30%
>> Driver depletion efficiency = 80%
>> Longitudinal energy density = 26.5 J/m
>> Energy absorbed per length  = 7.9 J/m
>> Energy remaining per length = 18.6 J/m
>> Peak decelerating field     = 3.27 GV/m
>> Blowout radius              = 2.32 kp^-1
>> Plasma density              = 3.37e+15 cm^-3
>> Plasma skin depth           = 92 µm
>> Normalized field strength   = 0.88
>> Wavebreaking field          = 5.58 GV/m
>> Norm. transverse wakefield  = 0.031

DRIVE BUNCH PARAMETERS:
>> Driver charge       = 10.11 nC
>> Driver energy       = 46.4 GeV
>> Driver bunch length = 91.5 µm rms
>> Driver peak current = 13.2 kA

PLASMA LINAC:
>> Number of stages = 5
>> Stage length = 13.5 m
>> Energy increase per stage = 66.29 GeV
>> Average cooling rate per length in stages = 240 kW/m
>> Matched beta function (initial -> final) = 1.3 -> 10.5 cm
>> Matched beam size (initial -> final) = 9.7x0.6 µm rms -> :
>> Total phase advance, µ = 1146 rad
>> Instability parameter, µ*eta_t = 36.0
```

```
DRIVER RF LINAC:
>> Energy per driver train = 382.8 kJ
>> Driver beam power (average) = 30.2 MW
>> Driver linac accelerating gradient = 33.0 MV/m
>> Driver linac peak power per length = 21.7 MW/m
>> Driver bunch separation = 15.4 ns
>> Driver train duration = 15 µs
>> Driver linac length = 1.41 km
>> Number of driver klystrons = 612
>> Driver klystron average power = 165.8 kW
>> Driver linac average power = 101.4 MW
>> Driver linac efficiency = 29.8%
>> Driver linac max field (breakdown limit) = 34 MV/m

DAMPING RINGS:
-- RF POSITRON ARM:
>> Number of rings = 2
>> Damping ring energy = 2.86 GeV
>> Damping ring circumference = 489 m
>> Damping ring char. damping time = 1.6 ms
>> Damping ring total damping time = 10.2 ms
>> Damping ring emitted power = 1.4 MW
```

```
LUMINOSITY:
>> Beam size at IP = 602.6 x 6.9 nm rms
>> Geometric luminosity = 7.3e+33 cm^-2 s^-1
>> Luminosity per power = 5e+31 cm^-2 s^-1 MW^-1
>> Time required for collisions (100% uptime) = 3.9 years
>> Integrated energy required = 5.0 TWh

POWER:
>> Driver/e+ RF linac power = 101.4 MW
>> Injector RF linac power  = 0.6 MW
>> Damping ring power       = 20.0 MW
>> Overhead power (25%)     = 25.5 MW
---------------------------------------
>> Collider wallplug power  = 147.5 MW
---------------------------------------

LENGTHS:
>> Driver linac length       = 1.4 km
>> Plasma linac length       = 0.1 km
>> Total turnaround length   = 1.9 km
>> Electron BDS length       = 1.8 km
>> Positron BDS length       = 0.2 km
>> Damping-ring length       = 1.0 km
>> Total tunnel length       = 6.0 km
-------------------------------------------
>> Collider length (end-to-end) = 2.5 km
-------------------------------------------
```

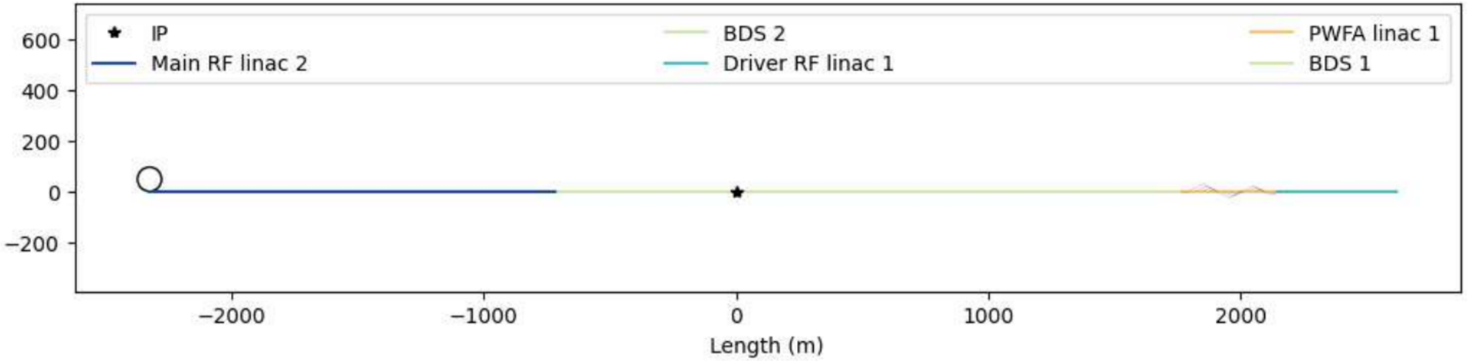
```
COSTS:
>> Particle source cost      = 28 MILCU
>> Damping ring cost         = 293 MILCU
>> Linac cost                = 980 MILCU
>> - Driver linacs           = 760 MILCU
>> - Plasma linacs           = 97 MILCU
>> - Injector linacs         = 123 MILCU
>> Power infrastructure cost = 115 MILCU
>> Tunnel cost               = 521 MILCU
>> Beam dump cost            = 101 MILCU
>> Turn-around costs         = 389 MILCU
-------------------------------------
>> Total construction cost       = 2.58 BILCU
>> Overhead cost                 = 1.34 BILCU
>> Maintenance cost (for 6 yrs)  = 0.12 BILCU
>> Energy cost (for 0.9/ab)      = 1.01 BILCU
>> Carbon tax (for 195 kton CO2) = 27 MILCU
-------------------------------------
>> ITF cost (excl. run costs)    = 3.92 BILCU
>> Full programme cost           = 5.04 BILCU
>> Full programme cost + CO2 tax = 5.07 BILCU
-------------------------------------
```

Latest Cost Model

Carl Lindstrøm, University of Oslo

Preliminary optimum: two linacs, lower asymmetry

2.5/3.9/4.8 BILCU, 4.9 km, 108 MW




```
ELECTRON/POSITRON BUNCH PARAMETERS:
>> Electron final energy = 307.8 GeV
>> Positron final energy = 50.8 GeV
>> Electron charge = 1.60 nC
>> Positron charge = 4.81 nC
>> Electron norm. emittance = 60.6 x 0.21 mm mrad
>> Positron norm. emittance = 10.0 x 0.04 mm mrad
>> Number of bunches in train = 84
>> Bunch separation = 160.0 ns
>> Bunch train rep. rate = 159.2 Hz
>> Average collision rate = 13.4 kHz

PLASMA WAKE PARAMETERS:
>> Accelerating field          = 2.09 GV/m
>> Wake-to-beam efficiency     = 37%
>> Driver depletion efficiency = 80%
>> Longitudinal energy density = 9.0 J/m
>> Energy absorbed per length  = 3.4 J/m
>> Energy remaining per length = 5.6 J/m
>> Peak decelerating field     = 1.40 GV/m
>> Blowout radius              = 1.77 kp^-1
>> Plasma density              = 1.14e+15 cm^-3
>> Plasma skin depth           = 157 µm
>> Normalized field strength   = 0.64
>> Wavebreaking field          = 3.25 GV/m
>> Norm. transverse wakefield  = 0.055

DRIVE BUNCH PARAMETERS:
>> Driver charge        = 8.05 nC
>> Driver energy        = 11.9 GeV
>> Driver bunch length = 157.3 µm rms
>> Driver peak current = 6.1 kA

PLASMA LINAC:
>> Number of stages = 17
>> Stage length = 8.5 m
>> Energy increase per stage = 17.81 GeV
>> Average cooling rate per length in stages = 75 kW/m
>> Matched beta function (initial -> final) = 2.2 -> 17.3 cm
>> Matched beam size (initial -> final) = 11.7x0.7 µm rms ->
>> Total phase advance, µ = 1486 rad
>> Instability parameter, µ*eta_t = 82.5
```

```
DRIVER RF LINAC:
>> Energy per driver train = 136.5 kJ
>> Driver beam power (average) = 21.7 MW
>> Driver linac accelerating gradient = 25.4 MV/m
>> Driver linac peak power per length = 21.7 MW/m
>> Driver bunch separation = 9.4 ns
>> Driver train duration = 13 µs
>> Driver linac length = 0.47 km
>> Number of driver klystrons = 203
>> Driver klystron average power = 303.5 kW
>> Driver linac average power = 61.7 MW
>> Driver linac efficiency = 35.3%
>> Driver linac max field (breakdown limit) = 35 MV/m

MAIN RF LINAC:
>> RF linac accel. gradient = 31.6 MV/m
>> RF linac length = 1.6 km

DAMPING RINGS:
-- RF POSITRON ARM:
>> Number of rings = 2
>> Damping ring energy = 2.86 GeV
>> Damping ring circumference = 300 m
>> Damping ring char. damping time = 1.0 ms
>> Damping ring total damping time = 6.3 ms
>> Damping ring emitted power = 1.2 MW
```

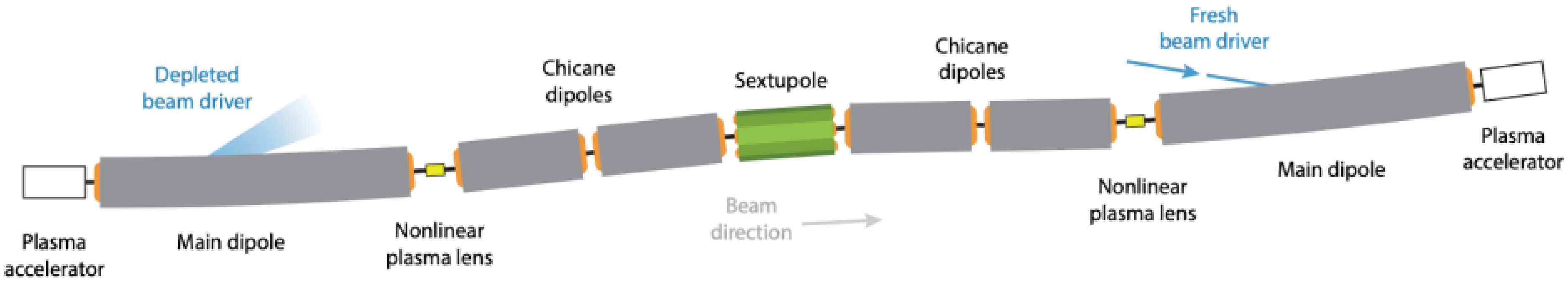
```
LUMINOSITY:
>> Beam size at IP = 576.3 x 7.8 nm rms
>> Geometric luminosity = 7.1e+33 cm^-2 s^-1
>> Luminosity per power = 6.6e+31 cm^-2 s^-1 MW^-1
>> Time required for collisions (100% uptime) = 4.0 years
>> Integrated energy required = 3.8 TWh

POWER:
>> Driver RF linac power     = 61.7 MW
>> Main beam RF linac power  = 8.0 MW
>> Injector RF linac power   = 0.6 MW
>> Damping ring power        = 20.0 MW
>> Overhead power (25%)      = 17.6 MW
------------------------------------
>> Collider wallplug power   = 107.8 MW
------------------------------------

LENGTHS:
>> Driver linac length        = 0.5 km
>> Plasma linac length        = 0.4 km
>> Main RF linac length       = 1.6 km
>> Electron BDS length        = 1.8 km
>> Positron BDS length        = 0.7 km
>> Damping-ring length        = 0.6 km
>> Total tunnel length        = 5.2 km
----------------------------------------
>> Collider length (end-to-end) = 4.9 km
----------------------------------------
```

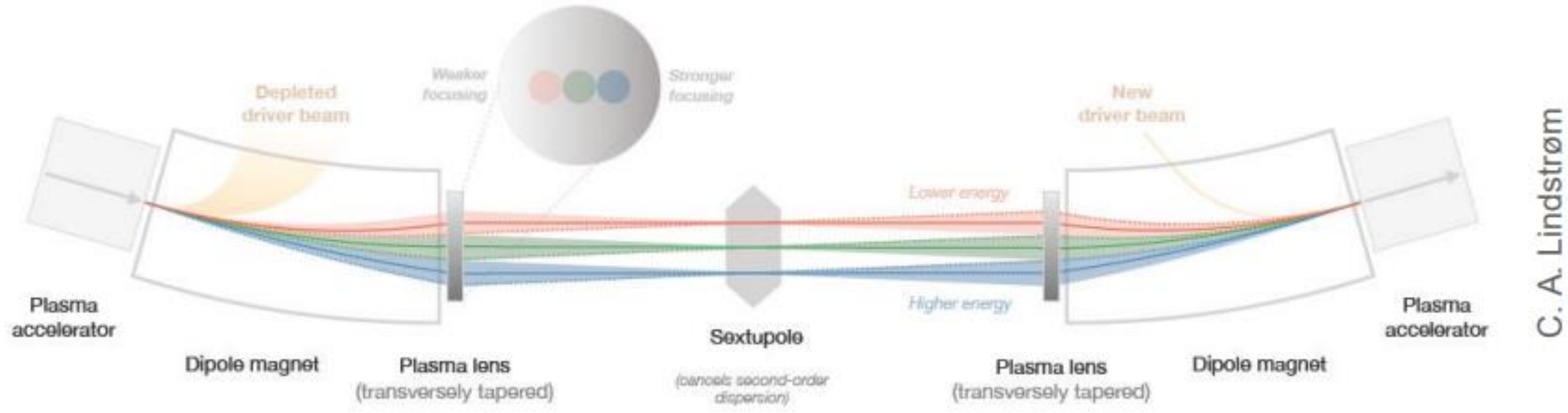
```
COSTS:
>> Particle source cost       = 28 MILCU
>> Damping ring cost          = 180 MILCU
>> Linac cost                 = 1525 MILCU
>> - Driver linacs            = 252 MILCU
>> - Plasma linacs            = 284 MILCU
>> - Main beam linacs         = 868 MILCU
>> - Injector linacs          = 121 MILCU
>> Power infrastructure cost = 87 MILCU
>> Tunnel cost                = 456 MILCU
>> Beam dump cost             = 91 MILCU
-----------------------------------
>> Total construction cost        = 2.54 BILCU
>> Overhead cost                  = 1.32 BILCU
>> Maintenance cost (for 7 yrs)   = 0.12 BILCU
>> Energy cost (for 0.9/ab)       = 0.76 BILCU
>> Carbon tax (for 162 kton CO2) = 23 MILCU
-----------------------------------
>> ITF cost (excl. run costs)     = 3.86 BILCU
>> Full programme cost            = 4.75 BILCU
>> Full programme cost + CO2 tax = 4.77 BILCU
-----------------------------------
```

Plasma Considerations

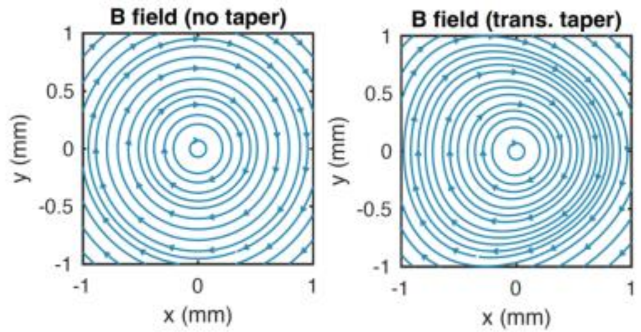
Major Plasma Considerations: Staging

University of Oslo Team





arXiv:2104.14460

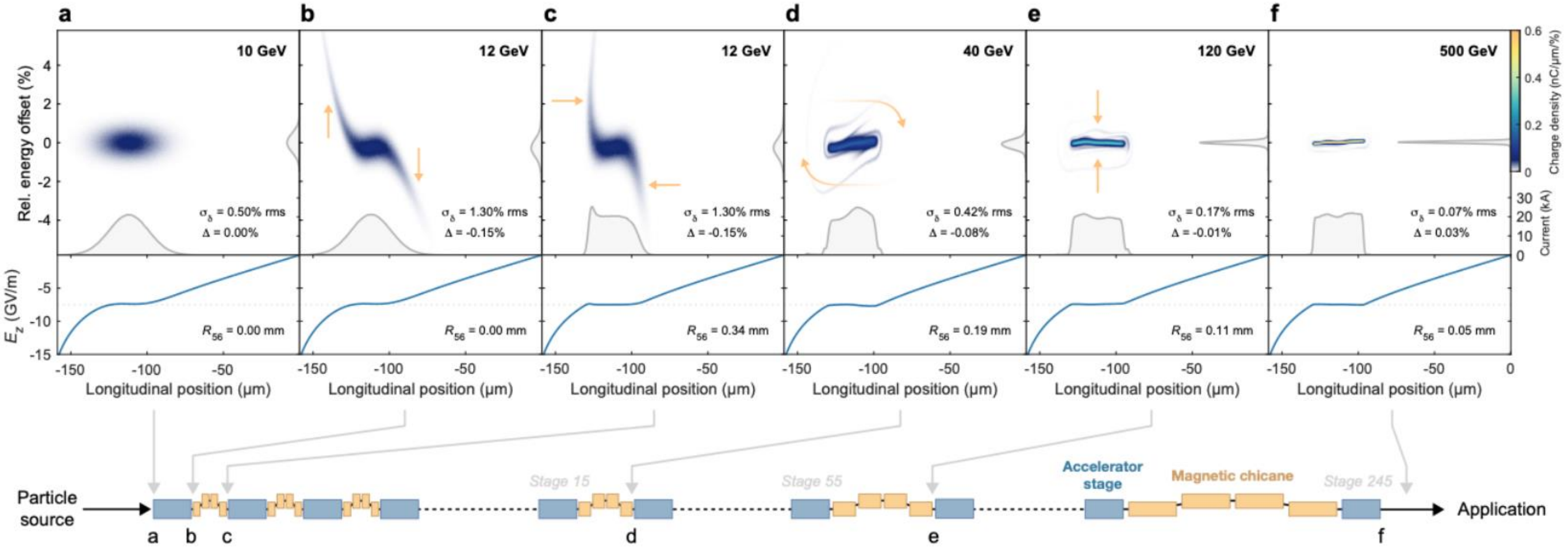


Interstage lattice scheme design:

- Compact
- Corrects chromaticity locally
- Cancels dispersion up to 3rd order
- Preserves emittances
- Non-invasive in/out-coupling of drivers.

Major Plasma Considerations: Staging

University of Oslo Team



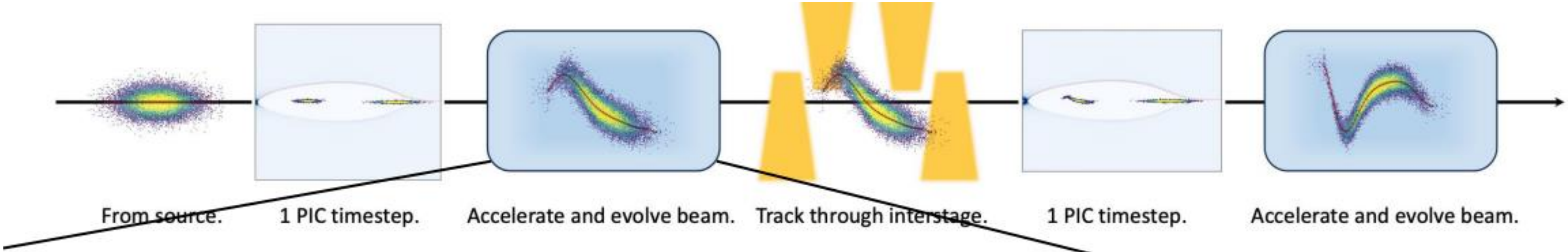
Self-correcting LPS design.

- Apply R_{56} with chicanes.
- High energy particles move forwards, low energy particles move backwards.
- Charge redistributed over many stages to flatten the wakefield.
- The more stages the better!
- Increased timing tolerance (~ 1 fs to ~ 200 fs).
- Must then consider transverse tolerances.

Major Plasma Considerations: Staging & Tolerances

University of Oslo Team

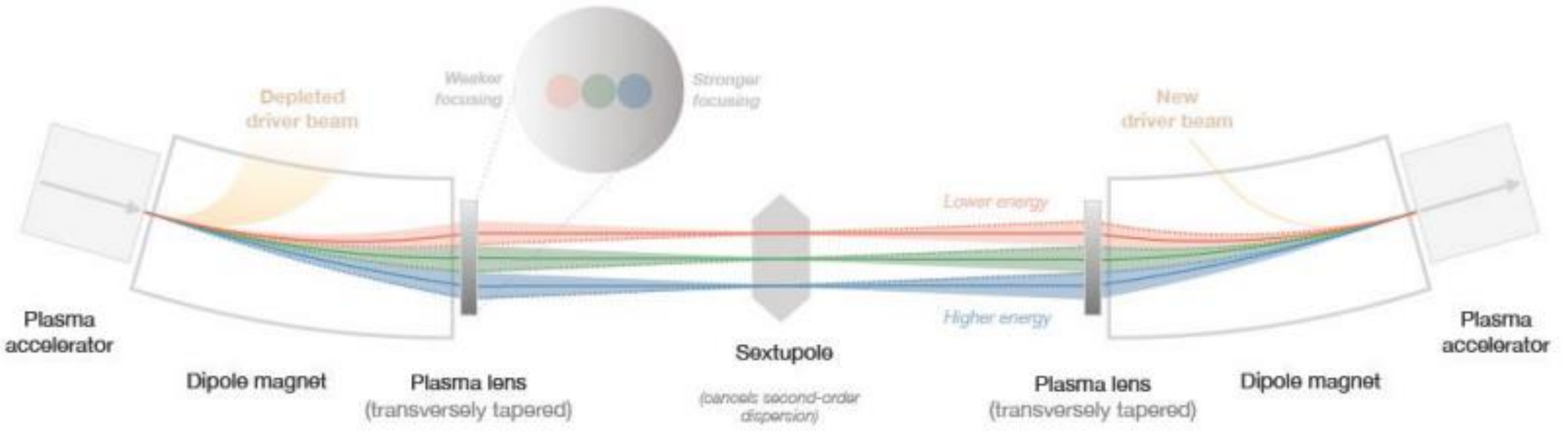
- Building a start-to-end simulation code for the plasma acceleration arm.
- Single PIC timestep, simplified (benchmarked) transverse instability model, radiation reaction from betatron radiation.
- Tracking between plasma stages in ELEGANT, including ISR and CSR.
- For perfect alignment there is an emittance growth of 1.5 x total (all stages) due to radiation and chromatic effects.
- Initial alignment tolerance studies with injection emittance 8 x 0.02 mm-mrad. Ignoring ion motion, alignment tolerance in *y* is only 10-20 nm with current parameter set.
- Thoughts on mitigation schemes to come.



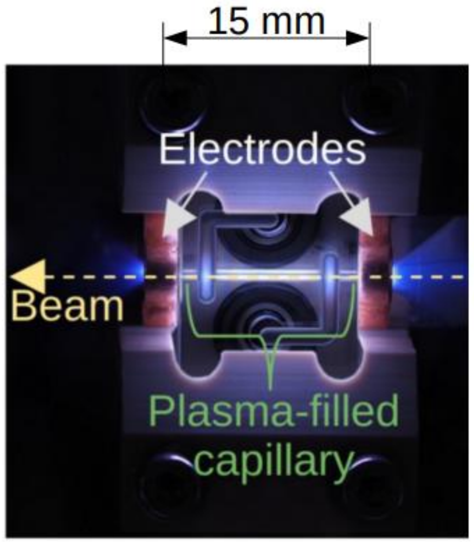
Outline for start-to-end simulation processes using simplified transverse instability model.

Major Plasma Considerations: Staging & Nonlinear Plasma Lens

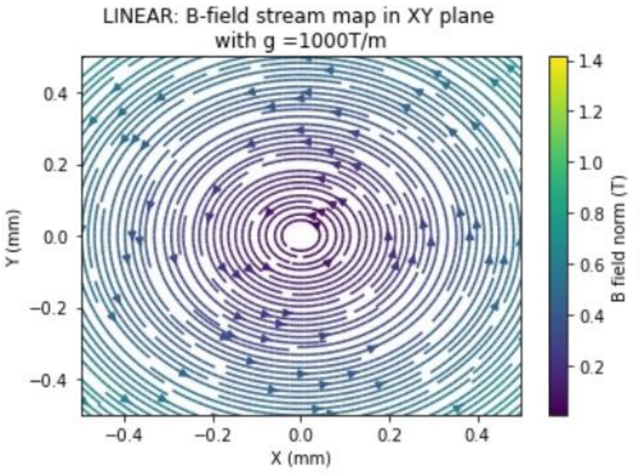
University of Oslo Team

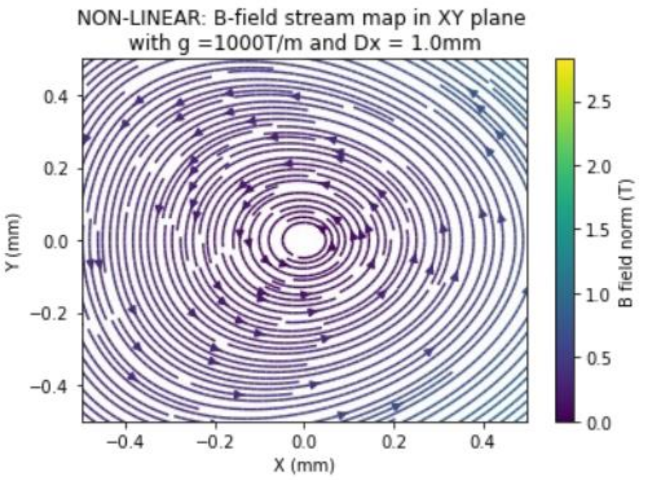


C. A. Lindstrøm



- Achromatic staging scheme requires nonlinear plasma lens- stronger focussing on one side than the other. This does not exist.
- Idea: exploit Hall effect in plasma. External (1D) ***B*** field induces perpendicular internal ***E*** field.
- This modifies the density → conductivity → current → changes B_x, B_y distribution.
- Designing and building this system now, tests planned at CLEAR.

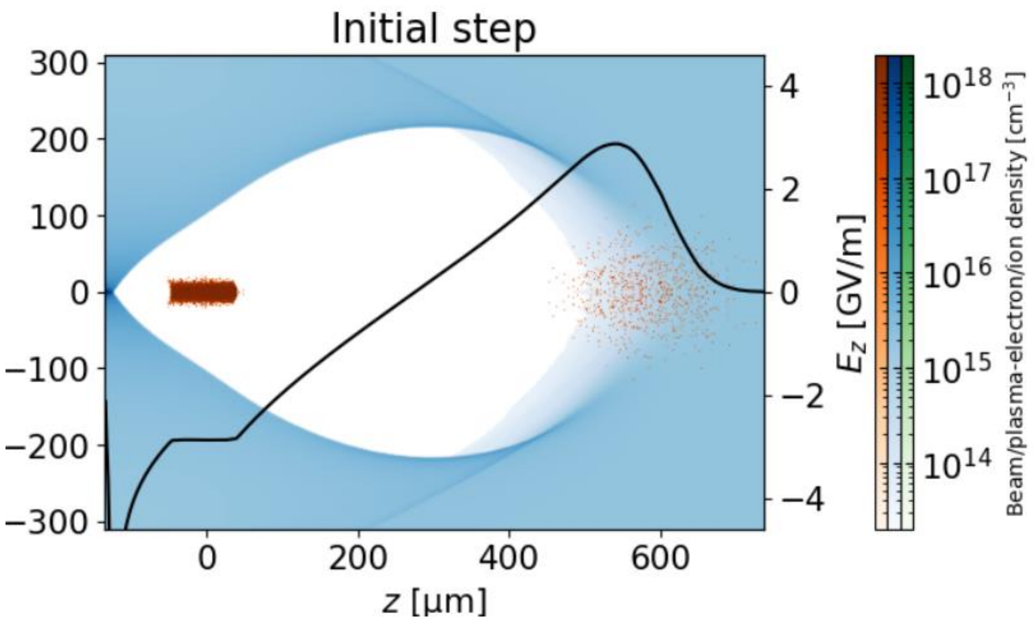




Major Plasma Considerations: Radiation Reaction

University of Oslo Team

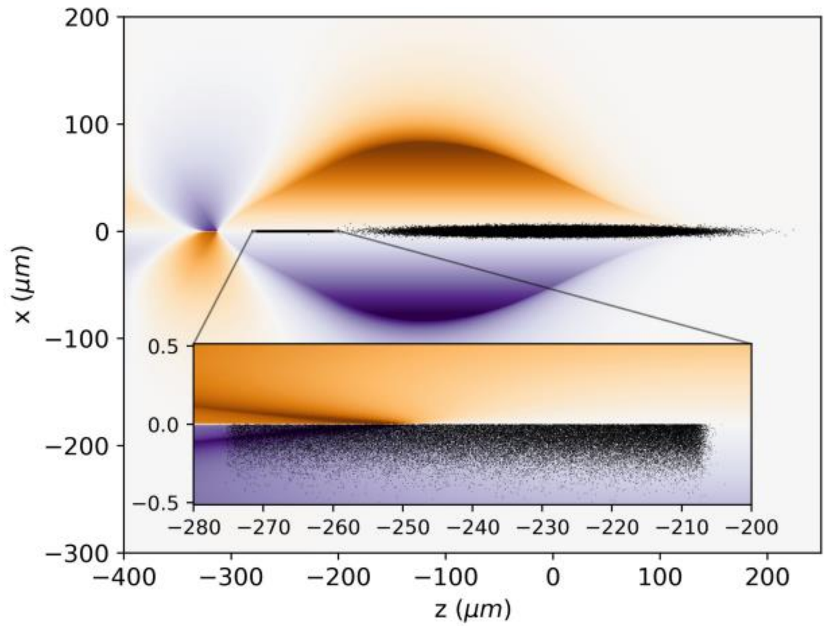
- Finite sized bunches in a plasma accelerate radiate due to their betatron motion: $P \propto (\gamma n_e r)^2$.
- Radiation reaction induces energy spread.
- Assuming perfect alignment, 0 initial energy spread, the energy spread would be 1% at 500 GeV because of radiation reaction at 7x10^{21} m^{-3}.
- Focussing aberrations not discussed.
- Using lower density from new parameter set 2x10^{21} m^{-3} the induced energy spread becomes 0.5%.
- Also studying final energy jitter as a function initial transverse offset. At 500 GeV, 1 μm offset yields only 20 MeV additional energy loss.

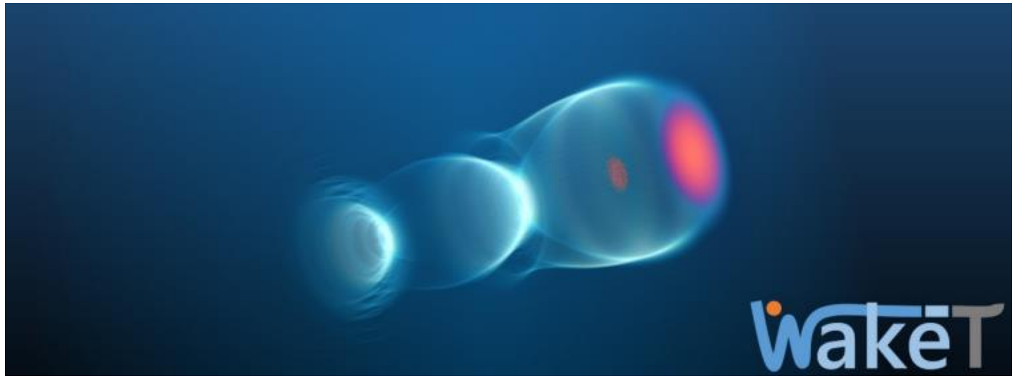


Major Plasma Considerations: Simulations & Flat Beams

Maxence Thévenet, DESY

- DESY-led developments on fast plasma simulation tools.
  - Wake-T: 2D axisymmetric quasistatic code- minutes on a laptop
  - HiPACE++: Full 3D quasistatic code, approx 8 GPU hours per simulation.
- Recent incorporation of spin-tracking for polarisation preservation studies in HiPACE++.
- Mesh refinement developed for HiPACE++ to efficiently simulate low emittance bunches.

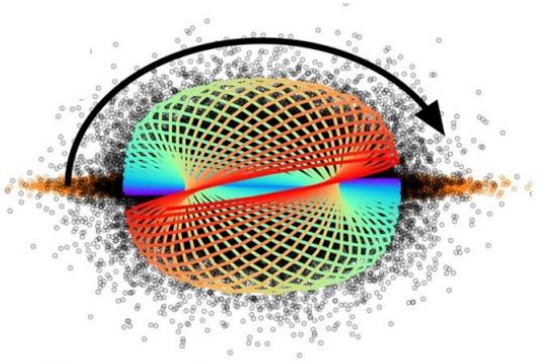




Major Plasma Considerations: Simulations & Flat Beams

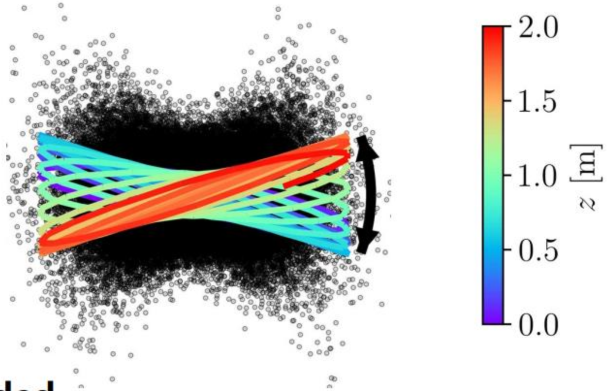
Maxence Thévenet, DESY

- Flat beams not previously studied in plasma accelerators. Recent paper: arXiv:2403.05871.
- Idealised plasma blowout has linear focussing fields- emittance preservation.
- Real plasmas have nonlinear focussing- from ion motion or beam-induced ionisation.
- For axisymmetric nonlinearity, focussing in x_i proportional to x_i and r.
- Radial dependence induces phase space precession, increasing emittance especially in the small emittance direction.
- This effect can be supressed by non-axisymetric nonlinear focussing- how?
- Identified as one of the major problems to be solved for HALHF.



Resonant
- Full-round precession
- Precession frequency may vary

→ Contribute to emittance exchange



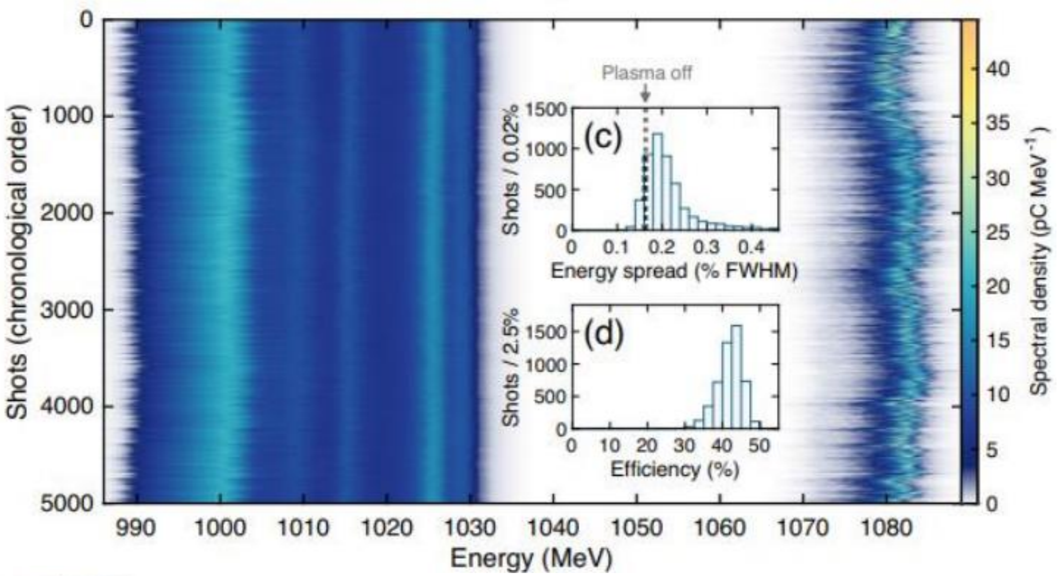
Bounded
- Major axis oscillates, NOT full precession
- Betatron amplitudes in x and y roughly constant

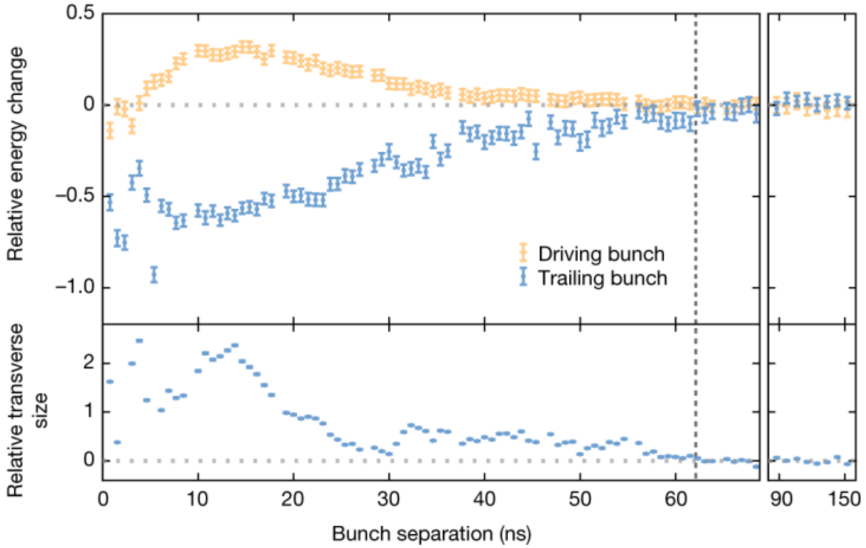
→ Does not contribute to emittance exchange

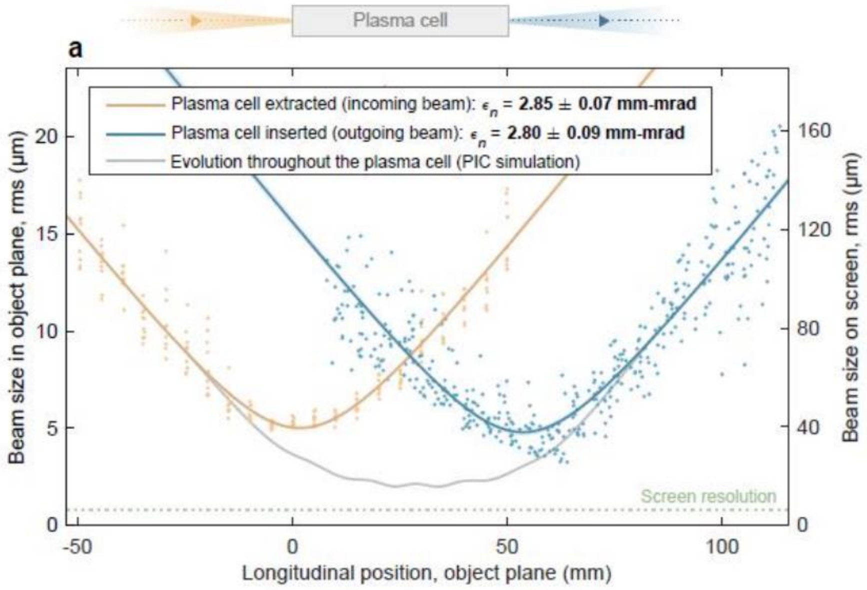
Major Plasma Considerations: Progress at FFWD

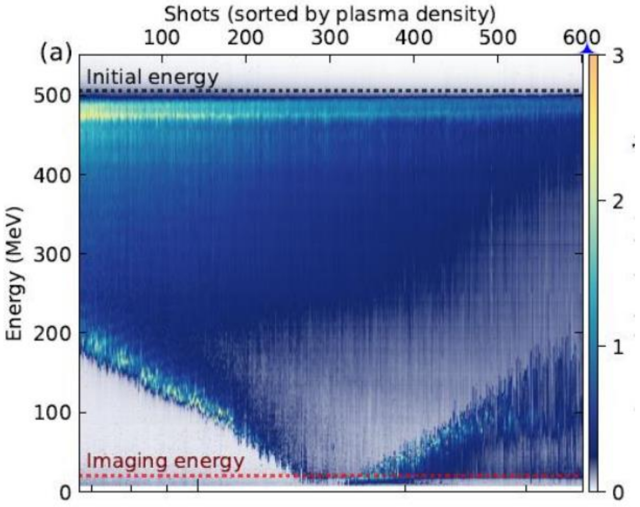
Jonathan Wood, DESY

- Presented recent results on:
  - Charge and per-mille energy spread preservation in PWFA, with optimal beamloading & ~ 40% „instantaneous energy efficiency“ = witness energy gain / driver energy loss.
  - (59 ± 3)% driver to wakefield energy transfer efficiency before reacceleration observed.
  - Emittance preservation (1 axis)
  - Possibility of 10 MHz acceleration (60 ns recovery time)





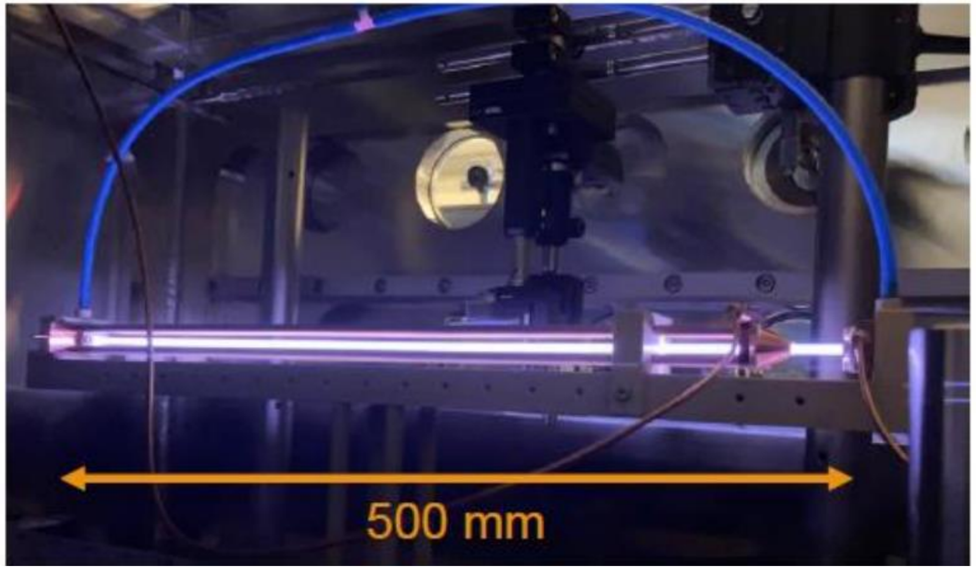


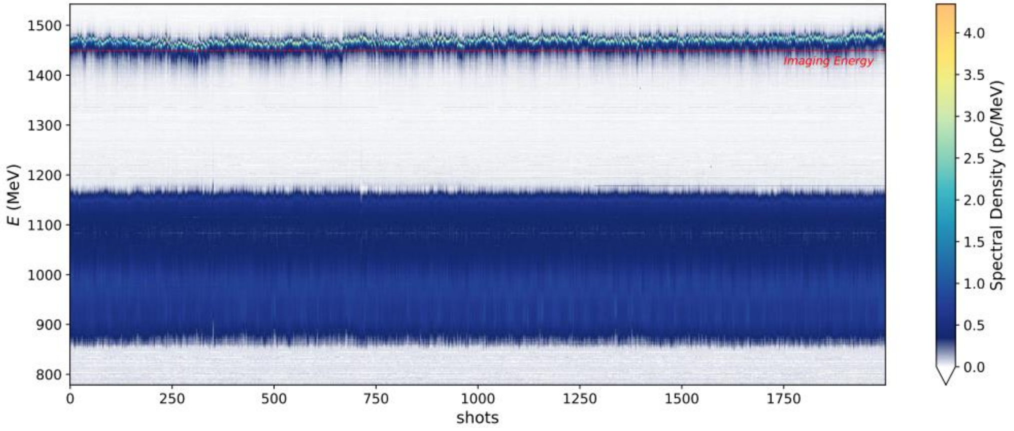


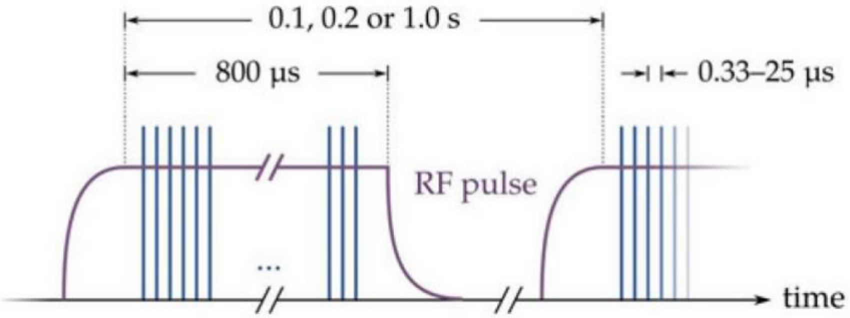
Major Plasma Considerations: Future Plans at FFWD

Jonathan Wood, DESY

- Overall energy efficiency: to what extent can we combine the 60% driver energy depletion with the 40% instantaneous transfer efficiency?
  - Need more acceleration.
  - 500 mm plasma cell developed, first experiment next week, hoping for acceleration from 1.2 → 1.7 GeV.
- Promising initial tests: 250 MeV gain in 195 mm cell in January.
  - 40 pC, charge preserved, 0.5% FWHM energy spread.
- Developing Bayesian optimisation tools & automated controls for future beam quality preservation studies.
- Bunch train acceleration.







Physics and Detectors

Overview on Physics

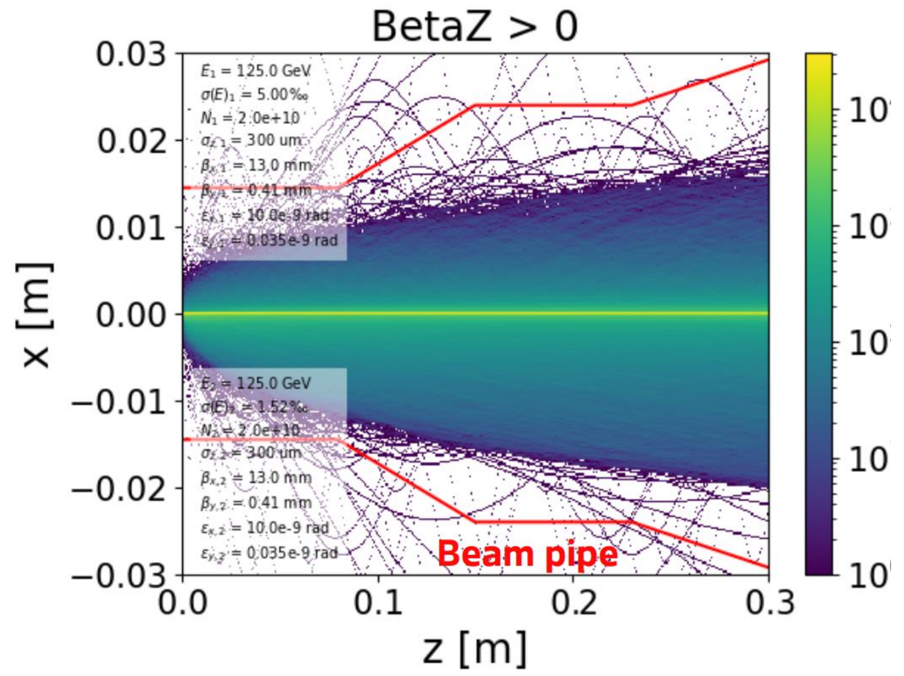
Jenny List, DESY

Energy wishes of Linear Collider Community from discussions with CLIC, C3 and ILC representatives

- Essential energy stages motivated by unique physics measurements
  - ~90 GeV (moderate luminosity): precision EWPO to interpret Higgs measurements
  - ~250 GeV: few MeV Higgs mass needed to interpret H->WW / ZZ branching fractions
  - ~350 GeV: ttbar threshold scan for precision top mass
  - ~550 GeV: top quark electroweak couplings, double Higgs-strahlung
  - ~800…1000 GeV: ttH CP structure, double Higgs production from WW fusion
  - > 1 TeV- exploration of the unknown.
- 250 GeV HALHF gives long-term perspective of “small and cheap” Higgs factory. But other options are more “shovel ready”.
- Motivates thinking about HALHF upgrades, or HALHF-like upgrades of to-be-built future machines.
- Could there be an alternative to FCC-ee?

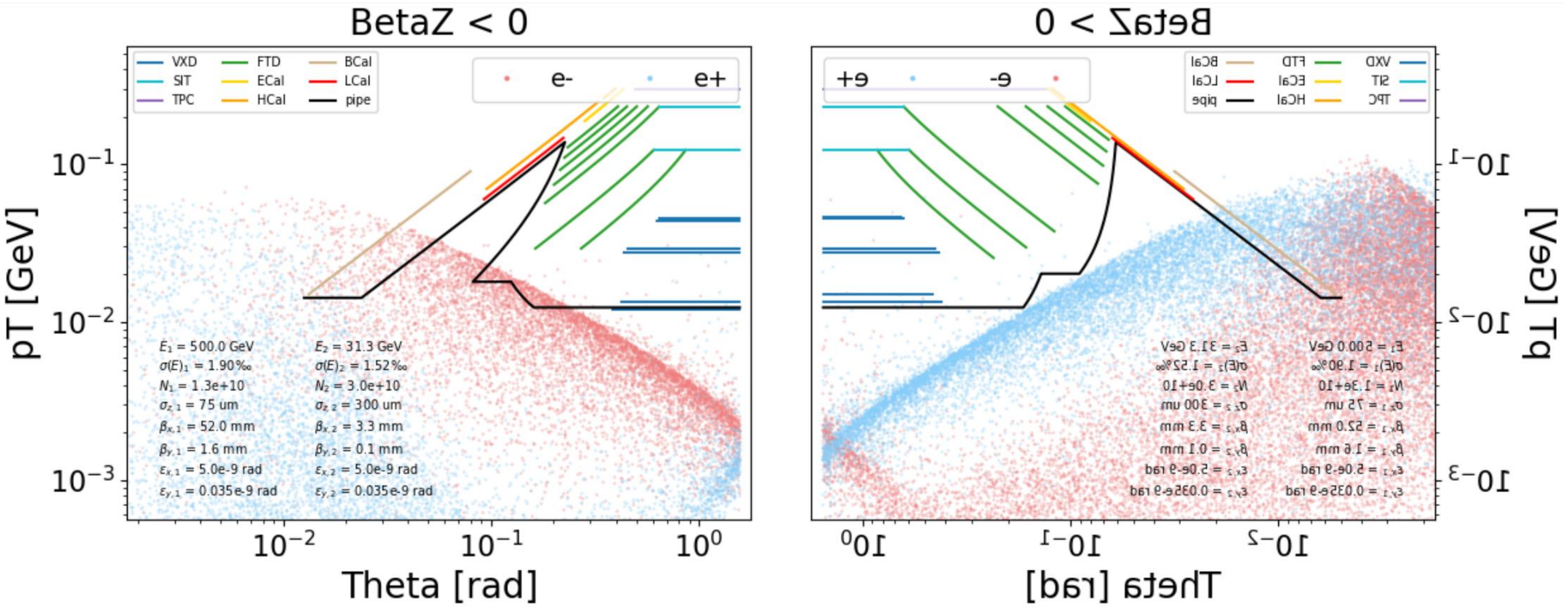
Overview on Detectors

Antoine Laudrain, DESY



- Difficulties of real asymmetric detectors:
  - Particles created on average closer together and in the forward direction → need detectors high spatial resolution & at lower angles.
- Studied beamstrahlung impact on detectors using Guinea-Pig in ILD-type detector for HALHF.
  - Changing energy asymmetry made no difference.
  - Changing charge asymmetry and bunch length asymmetry improved the situation.

- Energy = 500 : 31.3 GeV (e^-:e^+)
- Charge = 1.33 : 3 x 10^{10} particles
- σ_z = 75 : 300 μm
- 5 T detector magnetic field

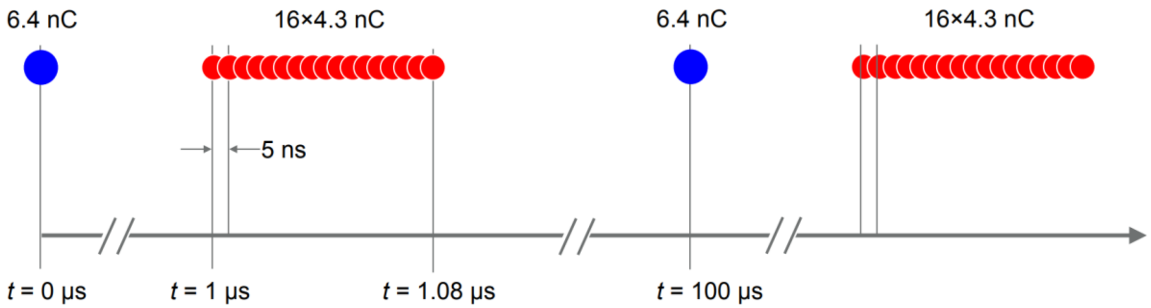


RF

A CW SRF solution for HALHF?

Nick Walker, DESY

- Advantages:
  - Very high $P_{RF} \rightarrow P_{beam}$ efficiency, $Q_0 > 10^{10}$.
- Challenges:
  - HALHF would require huge 2K cryo load. 1W @ 2K = 1kW of AC. HALHF may require 2 x 4kW cryo plants.
  - HALHF uses high charge e^+ & e^- driver bunches (6.4 & 4.3 nC). 752 μA average current for 10 kHz collisions.
  - 15 kW CW per cavity. Needs R&D.
  - Large bunch charge also induces beamloading of the RF. None for e^+, 1.5% for e^-.
  - Can likely compensate with frequency shift.
  - Large e+ charge – how can this be made an captured? CW!



Considerations for a warm RF linac

Benno List, DESY

- High bunch charges pose significant challenges for the linacs: longitudinal wakefields can cause significant energy spread.
  - E.g. drive bunches will have 31 kA current at the PWFAs.
  - Consider 4.3 kA bunches in linac (<2 x CLIC), assume 7.5 x compression later.
- Did not look at transverse wakefields yet, will add to challenges.
- L-band seems most promising, assuming 25 MV/m.
  - Downside: larger cavities and klystrons, more $$$.
  - Upside: permits shorter bunches (150 μm) still with acceptable energy spread.

RF type	Induced energy spread
CLIC	0.35%
S-band (SBLC-like)	0.62%
C3	> 1%
L-band 1.3 GHz	0.49%

Discussion on Design & Changes

Simulation Challenges & Common Parameter Set Discussion

Priority list

1. Solve the flat-beam problem all the way to 500 GeV. (Ion motion vs. beam ionization.)
2. Ramps need to be implemented.
3. Transverse instability and jitters.
4. Beam scattering
5. Polarization
6. Driver distribution scheme
7. Coherent radiation reaction.
8. Long term: Figuring out plasma evolution. MHD–PIC handshake required. *Can the plasma “take” the bunch structure from the proposed RF accelerators?*

Common parameter set for new simulations

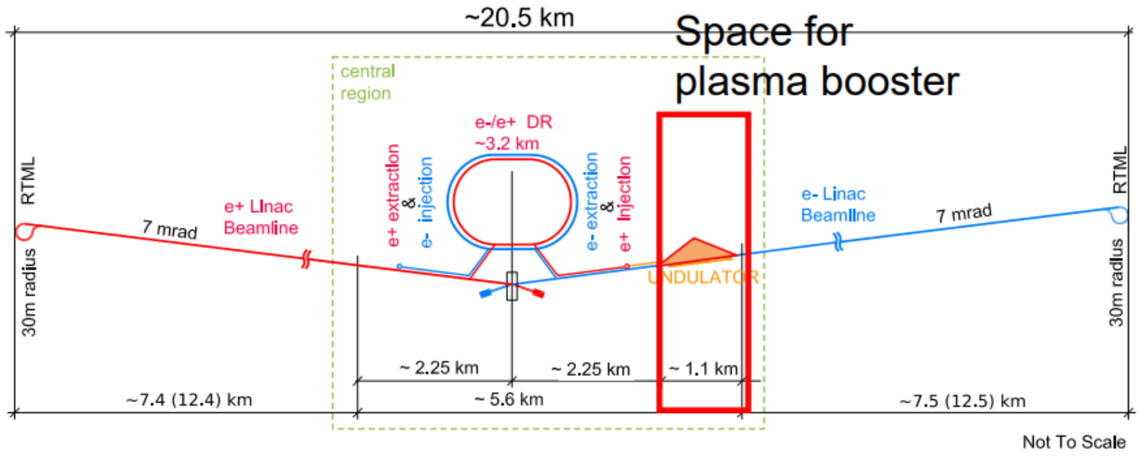
Disclaimer: not the final-final parameter set, but something that takes into account what we know now.

- Plasma density is lower: 1e15/cc.
- Gradient: 2 GV/m.
- Efficiency: ~35% wake-to-beam efficiency, driver depletion efficiency 75–80%
- Electron charge still about 1.6 nC. Driver charge around 8 nC.
- Transfer ratio ~1.5 (somewhat shaped/triangular driver)
- Stage length and number TBC (10-20 still discussed).
- S2e sims in Oslo, individual effects investigated in separate codes (e.g. HiPACE++ @ DESY)

Plasma Upgrade for the ILC

Benno List, DESY

- Assume the ILC has been built. 2 x 125 GeV linacs.
- Upgrade electron arm to 500 GeV with plasma boosters.
- Upgrade Higgs factory to tth/ Zhh factory.
- Electron beam linac provides driver and witness beams.
- Reduce gradient in electron linac and increase number of bunches and bunch to create drivers.
- With gradient reduction by a factor of 4, and 2.7:1 driver:witness bunch charge ratio, require around 6 times more power to accelerate as many witness bunches as original ILC.



Next Steps for HALHF

Richard D’Arcy, University of Oxford

- HALHF progress summary
  - Published concept. ArXiv 02.2023, NJP 08.2023.
  - Kickoff meeting 11.2023.
  - Monthly meetings ongoing – iteratively tackling details. All welcome!
  - Workshop 04.2024 – close to new baseline parameter set.
  - Deadline for input to the ESPP Process 2026 is 31.03.2025. Wish to submit a pre-CDR for HALHF.
  - There will be an ‚expert meeting‘ in 10.2024 in Sicily, with the goal of preparing for this report.

Plenary Discussion Conclusions

- We should keep the original geometry for now (i.e., a combined-function with turn-arounds).
  - Keep improving the Bayesian cost optimiser with more RF details and damping ring details.
  - Make the final decision at a later stage (before the next in-person meeting).
- Maintain focus on the 250 GeV design, and then add an estimate of changes required to achieve 380 and 550 GeV toward the end (but maybe not with as much detail).
- The main task until the next in-person meeting (Erice, Sicily, October 3–8) is to make a credible, self-consistent simulation of the plasma linac.
  - This will mainly be performed in Oslo (using the startto-end framework) with support from DESY.
  - We should add the asymmetric energy upgrade to an ILC-like collider (250 –> 500 GeV c.o.m.) as a separate alternative option.
  - For now just investigate this option on the RF-side (can it actually work?).
  - Should not connect this option too strongly to only ILC (but a general RF collider upgrade of which ILC is an example), in order to avoid political issues.
- A gamma–gamma collider is not a major focus for the HALHF collaboration as of now, but is a useful connection point with the US efforts.

Thanks for listening!