

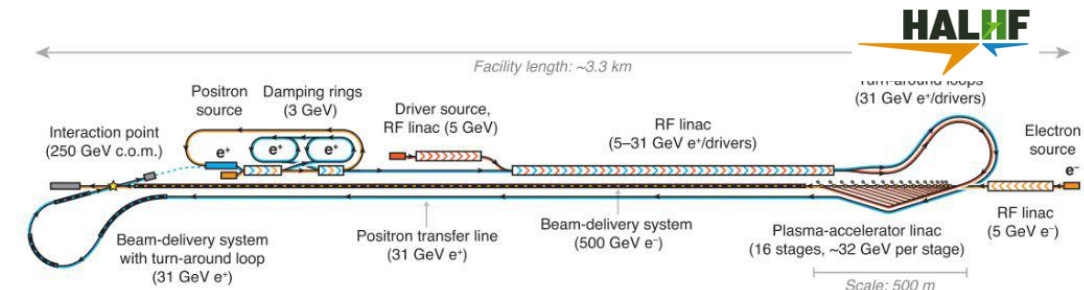
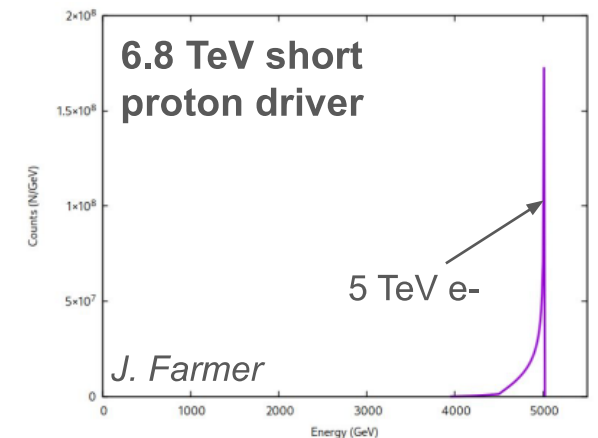
PWFA Linac (D. Storey, A. Knetsch, L. Verra)

- **Status of Working Group:**

- Kick off meeting in January with Beam Drivers and Sources working groups. Further discussions with the simulation working group
- Set up series of ~monthly meetings to discuss progress (~50 people on the mailing list)

- **Discussion: PWFA Linac and Drivers**

- Protons and electron drivers, which direction to pursue? *Talks by J. Farmer, F. Willeke*
 - **Action item** → Document potential parameters, pros/cons, costs
- Discussion of tolerances between drive and witness
 - **Action item** → Simulate tolerances in the last stage to determine requirements on beam driver (jitter, pointing, quality, etc)
- **Action item** → Global optimization of parameters - will the drive power dominate the design in this energy regime?
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Discussion: PWFA Staging

- Discussion on how to move forward:
 - Demonstrator of 2 stages + interstage coupling (where? how?)

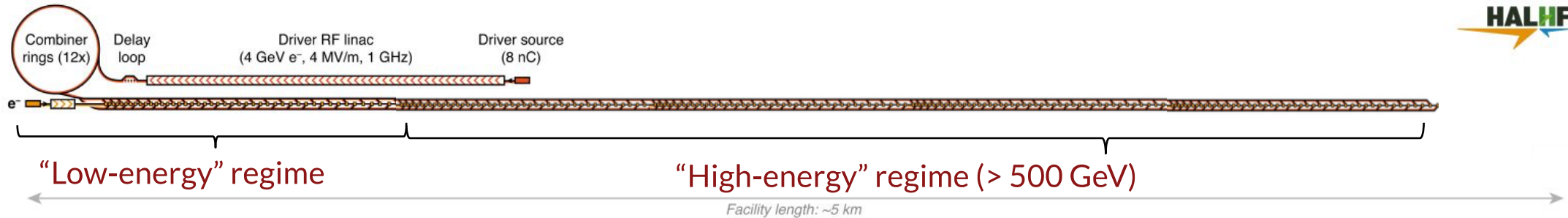
Action Item: determine if possible in any existing facility and define goals (BTF@Frascati? FACET? EuPRAXIA? PEP ring?)
 - Simulation studies of interstage device including SR effect

Action Item: understand target parameters and tolerances (e.g. alignment)
Action Item: understand how proposed schemes scale at TeV level

Action Item: define whether there is a maximum value of achievable energy (e.g. when the energy loss due to SR becomes $>$ energy gain, or effective gradient $<$ target)
- General discussion: need a group of people with ownership of the study (simulations and/or experiment)

Action Item: make a list of people who are determined to ACTIVELY work on the project (as a fraction of their day job)

Discussion: Simulations at very high energies



Are we equipped to model the largest part of the PWFA LINAC ?

- Do we have a complete understanding of physics relevant in high-energy stages ?
- Can full PIC codes describe all relevant physics of high-energy plasma stages ?
- Simulating 100s of stages can become computationally expensive.
What is the best strategy to accelerate these simulations ?
- Can we scale current staging concepts into the high-energy regime ? Are quadrupoles too weak, do ramps become too expensive ?

Driver Beam Species

Protons: pros



Single stage

- higher average gradient
- inject once at relatively low energy
- adiabatic self-matching

Potential to reuse existing infrastructure

Better than linear scaling with driver energy

Moderately nonlinear wakefields allow for positron acceleration, but still not a solution for high quality beams.

Protons: cons



Needs short proton driver at high rep-rate

Protons are heavy

- acceleration limited by longitudinal dispersion

Protons are positively charged

- lower transformer ratio
- needs tailored emittance

No staging means limited opportunities for correction

- external focussing
- stability becomes very important

Fast Proton Acceleration

GOAL: Proton (and e^+ , e^-) bunch frequency limited by Beam Power **100 MW**

- **Linear accelerator 500 GeV:**
 - no, would be cheaper to build Linear Collider
- **Recirculating LINAC GeV:**
 - Either too expensive or too many circulations
- **Rapid Cycling Synchrotron:**
 - hard to get high bunch repetition rate pre-accelerator chain will limit bunch rate even more
- **Non-scaling FFAG:**
 - relatively few turns N , voltage requirement too large $eU = E / N$, too expensive
- **Scaling FFAG:**
 - Very complex beyond state-of-the-art superconducting magnets

F. Willeke,
ALEGRO2025

Proton-driven challenges

- Fast cycling synchrotrons: fast ramping magnets up to 2-3 T
 - And injection time
 - Cannot reach 14 kHz
- Fixed field gradient accelerator
 - No ramping
 - Beyond state-of-the-art superconducting magnets
- Compression to $\sigma_z \sim \lambda_{pe}$
- Non-linear regime is unfavored for positive charge drivers
 - Need a self-matching process to preserve emittance of the witness bunch
- Single long plasma for Higgs factory
 - Need higher energy and even longer plasma for TeV scale (km-scale)
 - Need a dedicated proton beam facility

→ Need experimental demonstration of driver beam feasibility

Parameter		Value	unit
Beam Energy	E	125	GeV
Number of particles per bunch	N	2×10^{10}	
e^- bunch length	$\sigma_{e^-,z}$	105	μm
e^+ bunch length	$\sigma_{e^+,z}$	75	μm
Horizontal β -function at IP	β_x^*	13	mm
Vertical β -function at IP	β_y^*	0.41	mm
Norm. horizontal e^- emittance	$\gamma\varepsilon_{e^-,x}$	100	nm
Norm. vertical e^- emittance	$\gamma\varepsilon_{e^-,y}$	100	nm
Norm. horizontal e^+ emittance	$\gamma\varepsilon_{e^+,x}$	400	nm
Norm. vertical e^+ emittance	$\gamma\varepsilon_{e^+,y}$	400	nm
Bunch frequency	f	7.2	kHz
Centre-of-mass energy	E_{cm}	250	GeV
Geometric luminosity	$\mathcal{L}_{\text{geom}}$	1	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Simulated luminosity	$\mathcal{L}$	9.3	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Luminosity in the top 1%	$\mathcal{L}_{1\%}$	0.34	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

TABLE I. Luminosity parameters for a Higgs factory based on proton-driven plasma wakefield acceleration.

Caldwell et al., [arXiv:2503.21669](https://arxiv.org/abs/2503.21669) (2025)

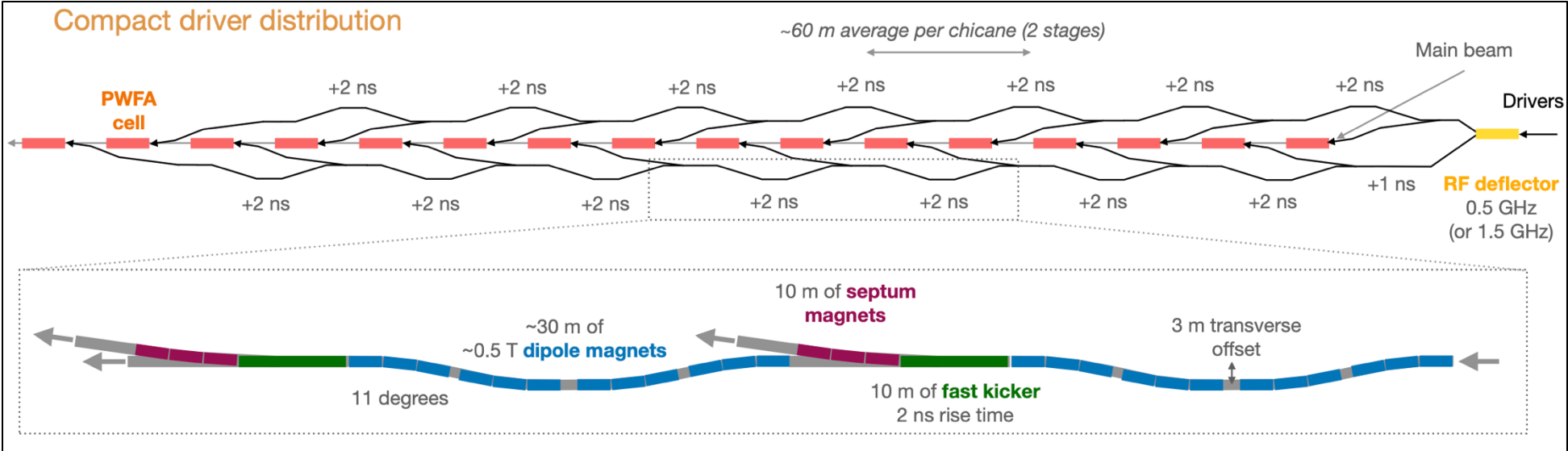
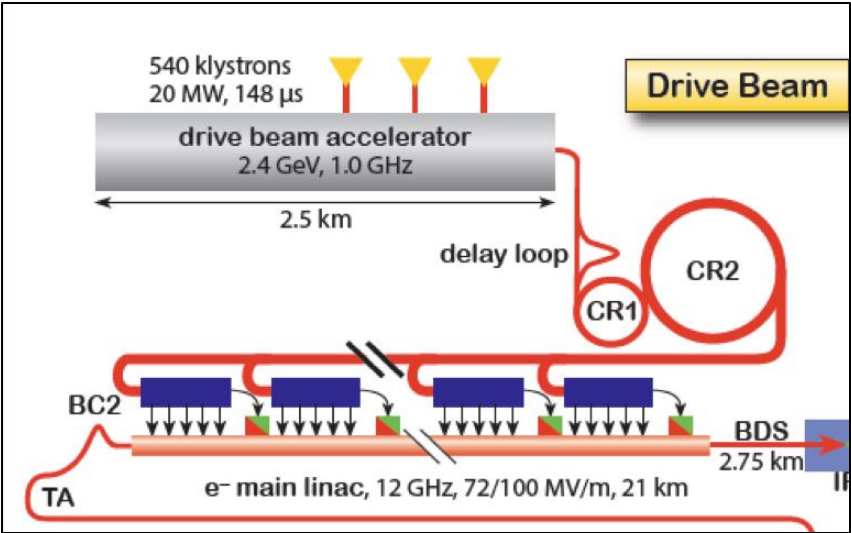
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Electrons:

- Benefit from e+e- LC R&D
- “Cheap” high-charge beams at high rep-rate
- Limited energy gain in each plasma
→ Staging
- Driver distribution:
RF kickers/deflectors?
- Witness beam extraction and injection
- $W_{eff} < W_{plasma}$



Machine parameters	Unit	Value (250 GeV)		Value (380 GeV)		Value (550 GeV)	
Centre-of-mass energy	GeV	250		380		550	
Centre-of-mass boost		1.67		1.67		1.67	
Bunches per train		160		160		160	
Train repetition rate	Hz	100		100		100	
Average collision rate	kHz	16		16		16	
Luminosity	cm ^{−2} s ^{−1}	1.2 × 10 ³⁴		1.7 × 10 ³⁴		2.5 × 10 ³⁴	
Luminosity fraction in top 1%		63%		53%		46%	
Quantum parameter (Υ)		0.9		1.6		2.8	
Estimated total power usage	MW	106		154		218	
Total site length	km	4.9		6.5		8.4	
Colliding-beam parameters							
		e [−]	e ⁺	e [−]	e ⁺	e [−]	e ⁺
Beam energy	GeV	375	41.7	570	63.3	825	91.7
Bunch population	10 ¹⁰	1	3	1	3	1	3
Bunch length in linacs (rms)	μm	40	150	40	150	40	150
Bunch length at IP (rms)	μm		150		150		150
Energy spread (rms)	%	0.15		0.15		0.15	
Horizontal emittance (norm.)	mm mrad	90	10	90	10	90	10
Vertical emittance (norm.)	mm mrad	0.32	0.035	0.32	0.035	0.32	0.035
IP horizontal beta function	mm		3.3		3.3		3.3
IP vertical beta function	mm		0.1		0.1		0.1
IP horizontal beam size (rms)	nm		636		519		429
IP vertical beam size (rms)	nm		6.6		5.2		4.4
Average beam power delivered	MW	9.6	3.2	14.6	4.9	21.1	7.0
Bunch separation	ns		16		16		16
Average beam current	μA	26	77	26	77	26	77
Positron cool-copper RF linac parameters (S-band)							
Average cavity gradient	MV/m	40		40		40	
Average gradient	MV/m	36		36		36	
Wall-plug-to-beam efficiency	%	11		11		11	
RF power	MW	11.7		17.8		25.8	
Cooling power	MW	17.9		27.3		39.5	
Total power	MW	29.6		45.1		65.3	
Klystron peak power	MW	67		67		67	
Number of klystrons		321		452		678	
RF frequency	GHz	3		3		3	
Operating Temperature	K	77		77		77	
Length (after damping ring, starting at 3 GeV)	km	1.1		1.7		2.5	
Driver linac RF parameters (L-band)							
Average cavity gradient	MV/m	4		4		4	
Average gradient	MV/m	3		3		3	
Wall-plug-to-beam efficiency	%	55		55		55	
RF power usage	MW	42.9		66.0		96.4	
Klystron peak power	MW	21		21		21	
Number of klystrons		409		630		919	
RF frequency	GHz	1		1		1	
Length	km	1.3		1.9		2.8	
Combiner ring parameters							
Delay loop length	m	1.5		1.5		1.5	
CR1 diameter	m	244		244		244	
CR2 diameter	m	244		244		244	
PWFA linac and drive-beam parameters							
Number of stages		48		48		48	
Plasma density	cm ^{−3}	6 × 10 ¹⁴		6 × 10 ¹⁴		6 × 10 ¹⁴	
In-plasma accel. gradient	GV/m	1		1		1	
Av. gradient (incl. optics)	GV/m	0.33		0.38		0.43	
Transformer ratio		2		2		2	
Length per stage	m	7.8		11.8		17.1	
Energy gain per stage	GeV	7.8		11.8		17.1	
Initial injection energy	GeV	3		3		3	
Driver energy	GeV	4		5.9		8.6	
Driver bunch population	10 ¹⁰	5.0		5.0		5.0	
Driver bunch length (rms)	μm	253		253		253	
Driver average beam power	MW	23.8		36.2		52.6	
Driver bunch separation	ns	4		4		4	
Driver-to-wake efficiency	%	80		80		80	
Wake-to-beam efficiency	%	50		50		50	
Driver-to-beam efficiency	%	40		40		40	
Wallplug-to-beam efficiency	%	22		22		22	
Cooling req. per stage length	kW/m	38.4		38.4		38.4	
Length	km	1.1		1.5		1.9	

Table 1: HALHF parameters for the updated baseline designs at 250 GeV, 380 GeV and 550 GeV CoM energies.

Benefit from current facilities/experiments, HALHF design study.

Biggest unknown remains staging and driver beams handling

<i>Machine parameters</i>	<i>Unit</i>	<i>Value (250 GeV)</i>		<i>Value (380 GeV)</i>		<i>Value (550 GeV)</i>	
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Homework for us:

➔ Produce a similar table for 10TeV and iterate with other WG’s

Looking ahead

- Volunteers are welcome for taking one of the tasks and for presenting at meetings
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