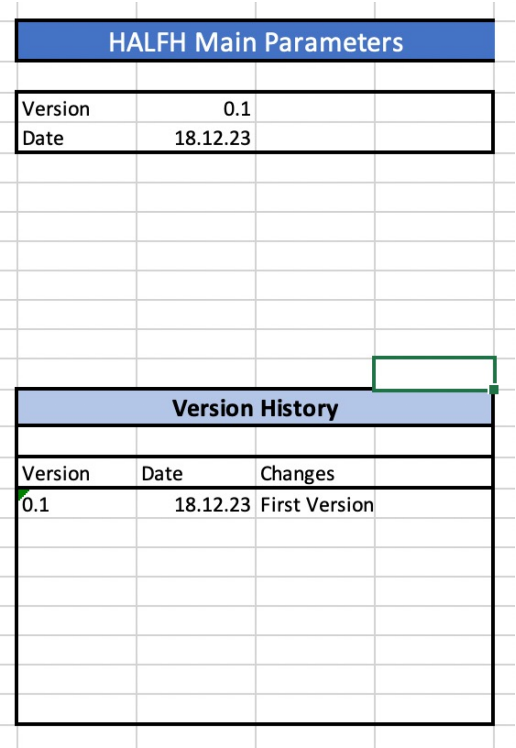
Parameters and Drive Linac.

Parameters as a specification of HALHF subsystems, in particular the drive beam

Benno List
HALHF accelerator meeting 18.12.23

Introduction

- Parameter Table summarizes most important design parameters of HALHF
- Starting point: Parameters as given in the paper, or as deduced from paper
- Future will see evolution / alternative configurations
- Start from Top-Level parameters, then propagate down to subsystems:
  - Design choices at top level become requirements for the subsystem level
- -> Requires a definition of subsystems

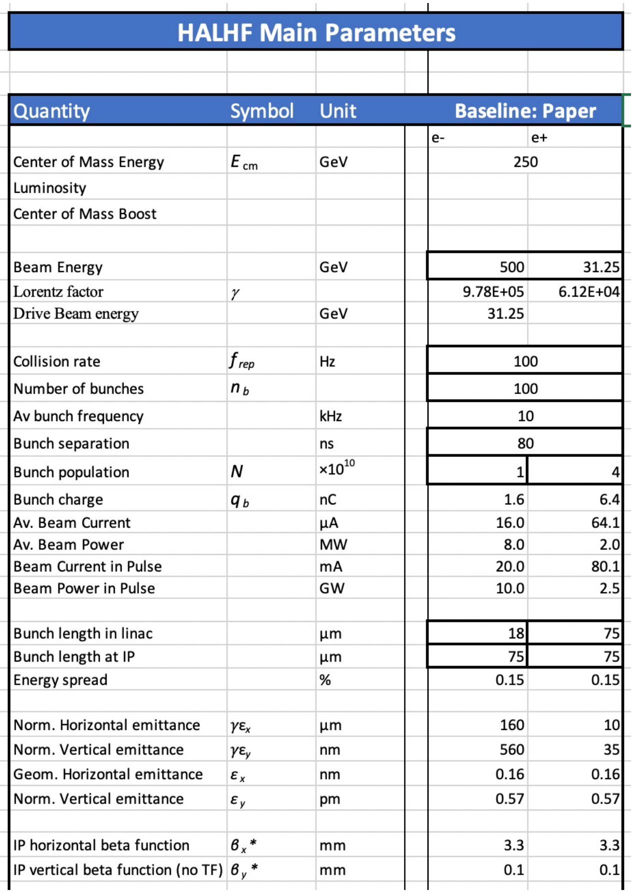


HALFH Main Parameters

Version	0.1
Date	18.12.23

Version History

Version	Date	Changes
0.1	18.12.23	First Version



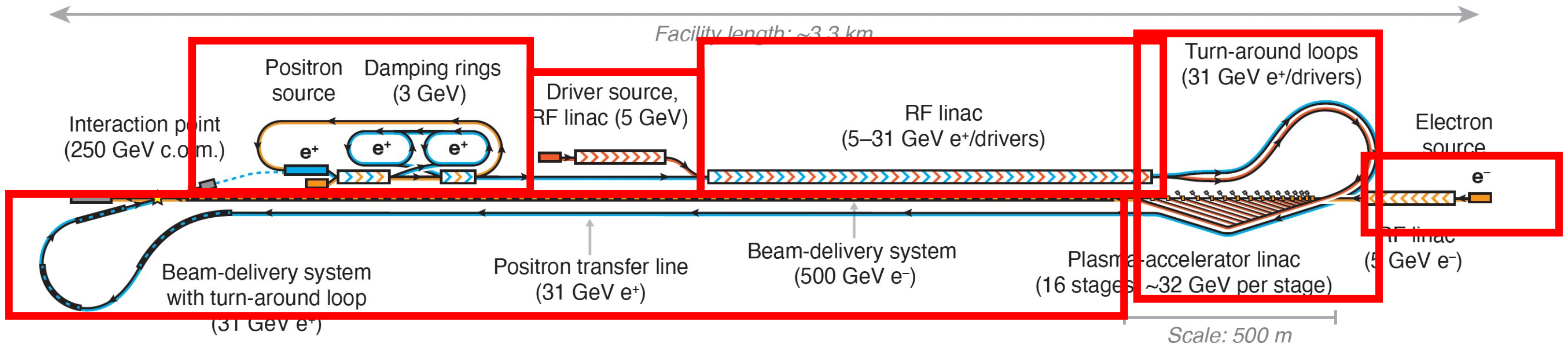
HALHF Main Parameters

Quantity	Symbol	Unit	Baseline: Paper	
			e-	e+
Center of Mass Energy	E_{cm}	GeV	250	
Luminosity				
Center of Mass Boost				
Beam Energy		GeV	500	31.25
Lorentz factor	γ		9.78E+05	6.12E+04
Drive Beam energy		GeV	31.25	
Collision rate	f_{rep}	Hz	100	
Number of bunches	n_b		100	
Av bunch frequency		kHz	10	
Bunch separation		ns	80	
Bunch population	N	$\times 10^{10}$	1	4
Bunch charge	q_b	nC	1.6	6.4
Av. Beam Current		µA	16.0	64.1
Av. Beam Power		MW	8.0	2.0
Beam Current in Pulse		mA	20.0	80.1
Beam Power in Pulse		GW	10.0	2.5
Bunch length in linac		µm	18	75
Bunch length at IP		µm	75	75
Energy spread		%	0.15	0.15
Norm. Horizontal emittance	$\gamma\varepsilon_x$	µm	160	10
Norm. Vertical emittance	$\gamma\varepsilon_y$	nm	560	35
Geom. Horizontal emittance	ε_x	nm	0.16	0.16
Norm. Vertical emittance	ε_y	pm	0.57	0.57
IP horizontal beta function	$\beta_x{}^*$	mm	3.3	3.3
IP vertical beta function (no TF)	$\beta_y{}^*$	mm	0.1	0.1

Subsystem Definition

A first attempt to define subsystems (i.e. a PBS)

- HALHF Accelerator Compex
  - Drive Beam Injector Facility
  - Positron Injector Facility
  - Drive Beam Linac Facility
  - Electron Injector Facility
  - Plasma Main Accelerator
  - Positron Transport
  - Beam Delivery System



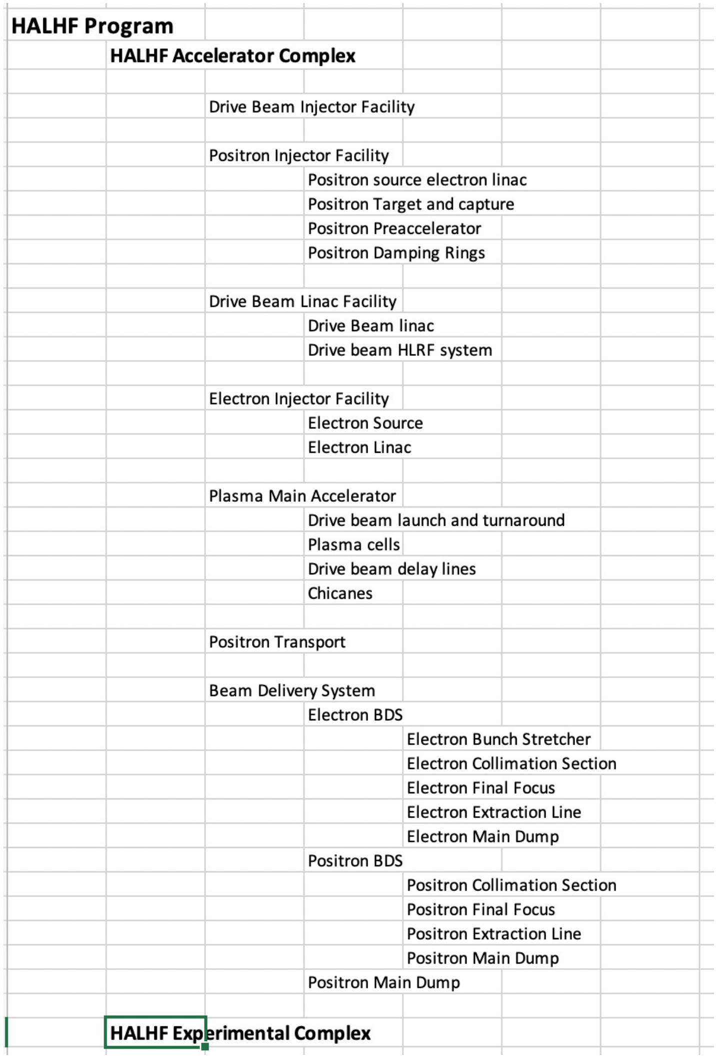
Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

Discussion points (for later?):

- Damping rings: part of positron injector or separate?
- Turn around / beam preparation for plasma: part of drive beam linac or plasma main accelerator?
- Dumps, Electron "recycler" for positron source: Part of BDS?

Subsystem Definition: Next level

- Defining the next PBS level(s) clarifies where subsystem boundaries are and which parameters are needed

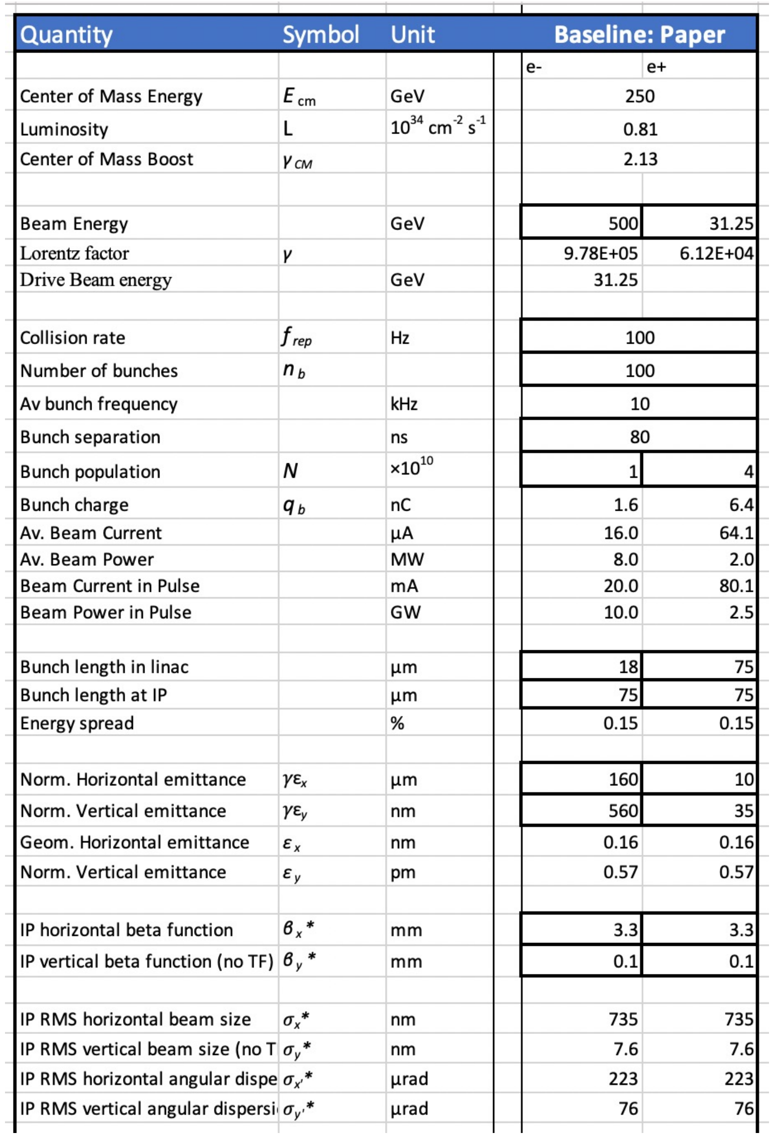


- **HALHF Program**
  - **HALHF Accelerator Complex**
    - Drive Beam Injector Facility
    - Positron Injector Facility
      - Positron source electron linac
      - Positron Target and capture
      - Positron Preaccelerator
      - Positron Damping Rings
    - Drive Beam Linac Facility
      - Drive Beam linac
      - Drive beam HLRF system
    - Electron Injector Facility
      - Electron Source
      - Electron Linac
    - Plasma Main Accelerator
      - Drive beam launch and turnaround
      - Plasma cells
      - Drive beam delay lines
      - Chicanes
    - Positron Transport
    - Beam Delivery System
      - Electron BDS
        - Electron Bunch Stretcher
        - Electron Collimation Section
        - Electron Final Focus
        - Electron Extraction Line
        - Electron Main Dump
      - Positron BDS
        - Positron Collimation Section
        - Positron Final Focus
        - Positron Extraction Line
        - Positron Main Dump
      - Positron Main Dump
  - **HALHF Experimental Complex**

Parameter Table

Main Parameter section

- Main design choices:
    - Beam energies
      -> CM energy, boost
    - Collision rate and bunch intensity -> beam current, power
    - Emittance and beta fkt at IP -> luminosity



Quantity	Symbol	Unit	Baseline: Paper	
			e-	e+
Center of Mass Energy	E_{cm}	GeV	250	
Luminosity	L	10^{34} cm^{-2} s^{-1}	0.81	
Center of Mass Boost	γ_{CM}		2.13	
Beam Energy		GeV	500	31.25
Lorentz factor	γ		9.78E+05	6.12E+04
Drive Beam energy		GeV	31.25	
Collision rate	f_{rep}	Hz	100	
Number of bunches	n_b		100	
Av bunch frequency		kHz	10	
Bunch separation		ns	80	
Bunch population	N	$\times 10^{10}$	1	4
Bunch charge	q_b	nC	1.6	6.4
Av. Beam Current		μA	16.0	64.1
Av. Beam Power		MW	8.0	2.0
Beam Current in Pulse		mA	20.0	80.1
Beam Power in Pulse		GW	10.0	2.5
Bunch length in linac		μm	18	75
Bunch length at IP		μm	75	75
Energy spread		%	0.15	0.15
Norm. Horizontal emittance	$\gamma\varepsilon_x$	μm	160	10
Norm. Vertical emittance	$\gamma\varepsilon_y$	nm	560	35
Geom. Horizontal emittance	ε_x	nm	0.16	0.16
Norm. Vertical emittance	ε_y	pm	0.57	0.57
IP horizontal beta function	β_x*	mm	3.3	3.3
IP vertical beta function (no TF)	β_y*	mm	0.1	0.1
IP RMS horizontal beam size	σ_x*	nm	735	735
IP RMS vertical beam size (no T	σ_y*	nm	7.6	7.6
IP RMS horizontal angular dispe	$\sigma_{x'}$*	μrad	223	223
IP RMS vertical angular dispersi	$\sigma_{y'}$*	μrad	76	76

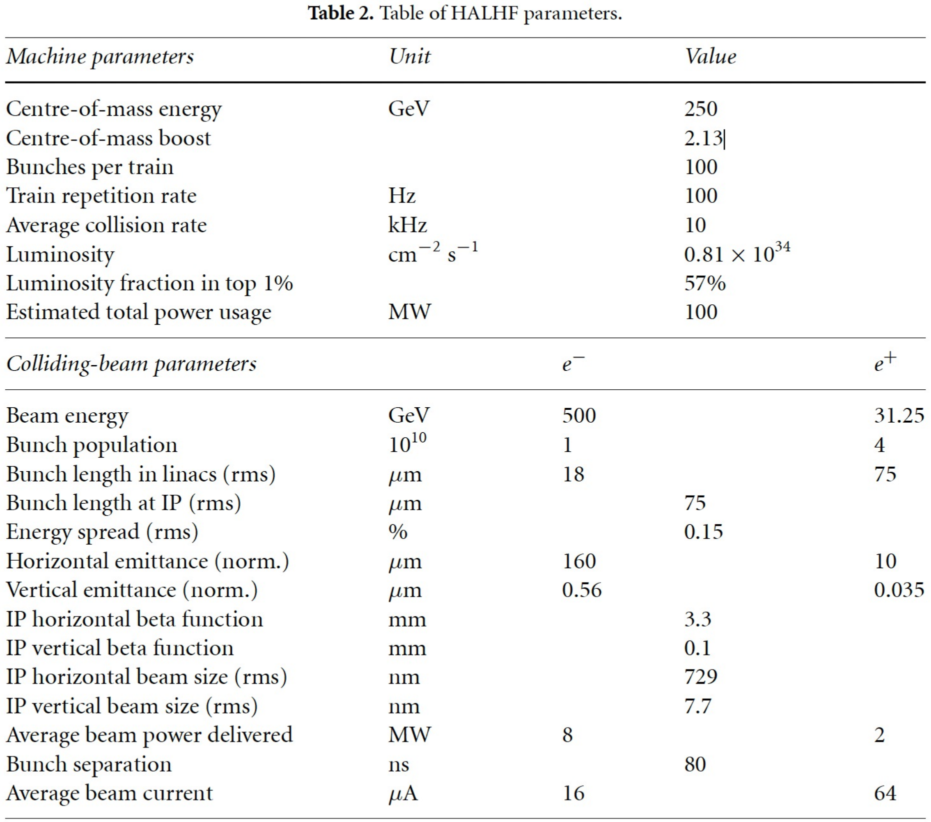
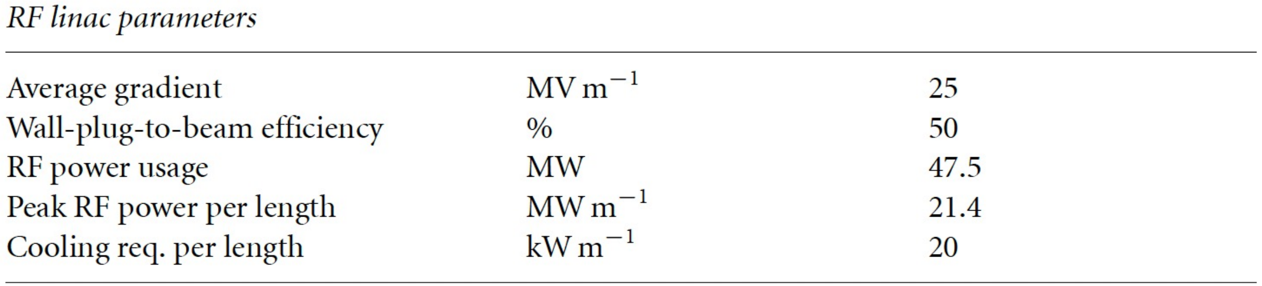


Table 2. Table of HALHF parameters.

Machine parameters	*Unit*		*Value*	
Centre-of-mass energy	GeV		250	
Centre-of-mass boost			2.13	
Bunches per train			100	
Train repetition rate	Hz		100	
Average collision rate	kHz		10	
Luminosity	cm^{-2} s^{-1}		0.81×10^{34}	
Luminosity fraction in top 1%			57%	
Estimated total power usage	MW		100	
Colliding-beam parameters		e^-		e^+
Beam energy	GeV	500		31.25
Bunch population	10^{10}	1		4
Bunch length in linacs (rms)	μm	18		75
Bunch length at IP (rms)	μm		75	
Energy spread (rms)	%		0.15	
Horizontal emittance (norm.)	μm	160		10
Vertical emittance (norm.)	μm	0.56		0.035
IP horizontal beta function	mm		3.3	
IP vertical beta function	mm		0.1	
IP horizontal beam size (rms)	nm		729	
IP vertical beam size (rms)	nm		7.7	
Average beam power delivered	MW	8		2
Bunch separation	ns		80	
Average beam current	μA	16		64

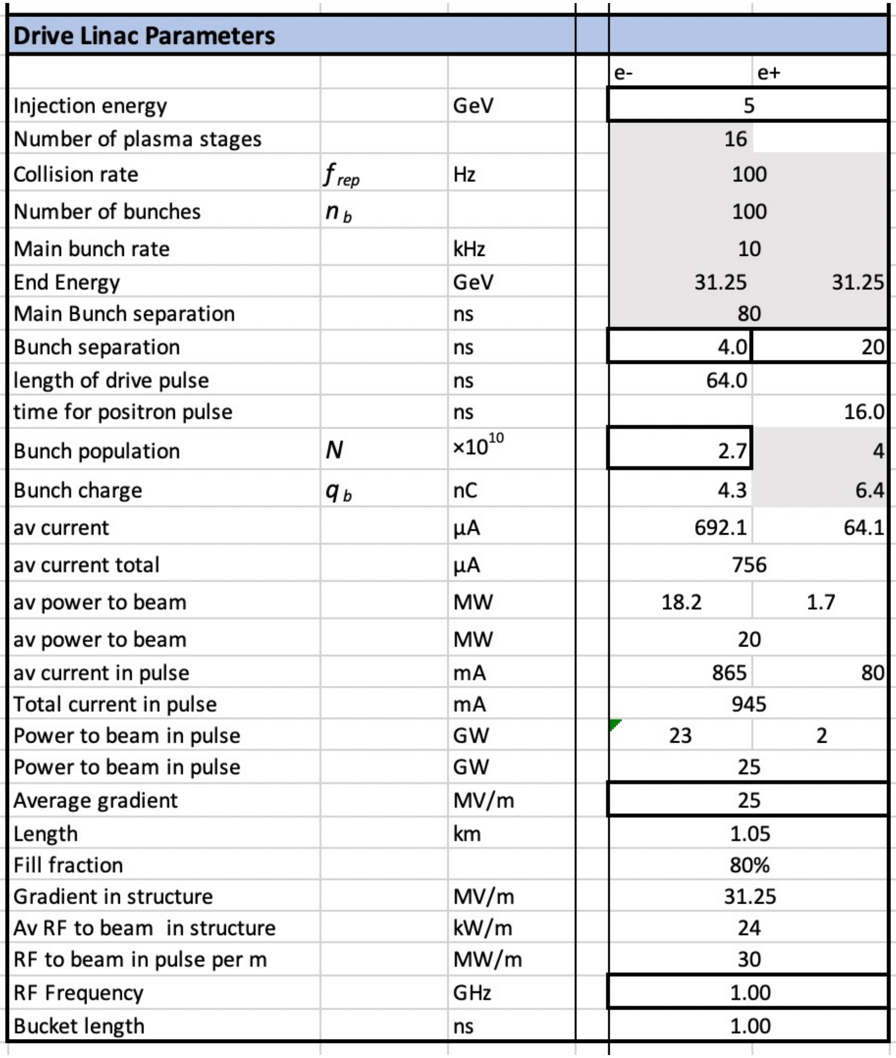
Drive Linac Parameters

- Main Design Parameters
  - Injection energy (transition from DB and positron sources to drive linac)
  - Number of drive bunches per positron bunch (plasma stages)
  - Bunch separation (must be consistent with overall main bunch separation!)
    Note: within main bunch separation (80ns), number of DB bunches + positron bunch must fit; try to keep beam loading even
  - Drive beam bunch population (from plasma accelerator)
  - Average gradient -> length



RF linac parameters

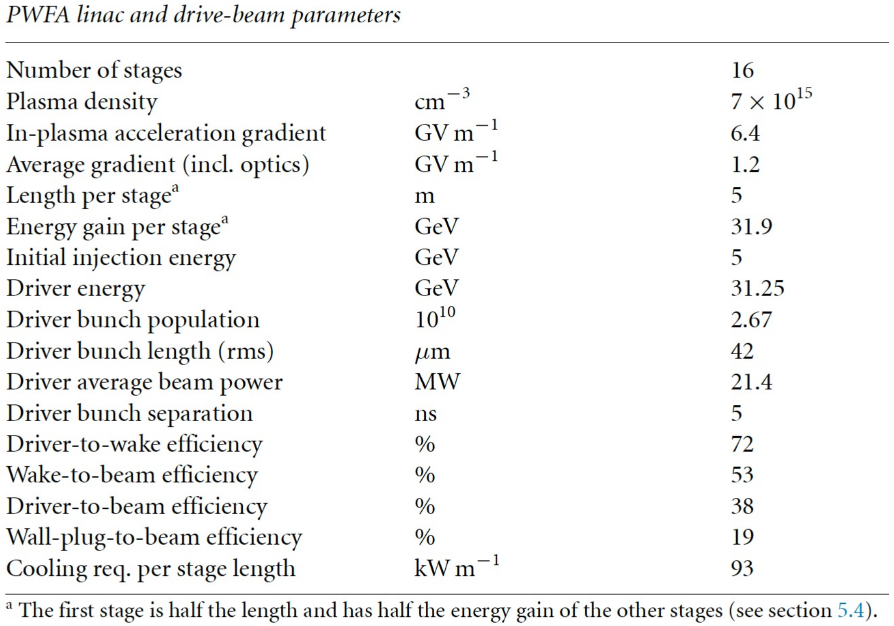
Average gradient	MV m^{-1}	25
Wall-plug-to-beam efficiency	%	50
RF power usage	MW	47.5
Peak RF power per length	MW m^{-1}	21.4
Cooling req. per length	kW m^{-1}	20



Drive Linac Parameters				
			e-	e+
Injection energy		GeV	5	
Number of plasma stages			16	
Collision rate	f_{rep}	Hz	100	
Number of bunches	n_b		100	
Main bunch rate		kHz	10	
End Energy		GeV	31.25	31.25
Main Bunch separation		ns	80	
Bunch separation		ns	4.0	20
length of drive pulse		ns	64.0	
time for positron pulse		ns		16.0
Bunch population	N	$\times 10^{10}$	2.7	4
Bunch charge	q_b	nC	4.3	6.4
av current		µA	692.1	64.1
av current total		µA	756	
av power to beam		MW	18.2	1.7
av power to beam		MW	20	
av current in pulse		mA	865	80
Total current in pulse		mA	945	
Power to beam in pulse		GW	23	2
Power to beam in pulse		GW	25	
Average gradient		MV/m	25	
Length		km	1.05	
Fill fraction			80%	
Gradient in structure		MV/m	31.25	
Av RF to beam in structure		kW/m	24	
RF to beam in pulse per m		MW/m	30	
RF Frequency		GHz	1.00	
Bucket length		ns	1.00	

Plasma Parameters

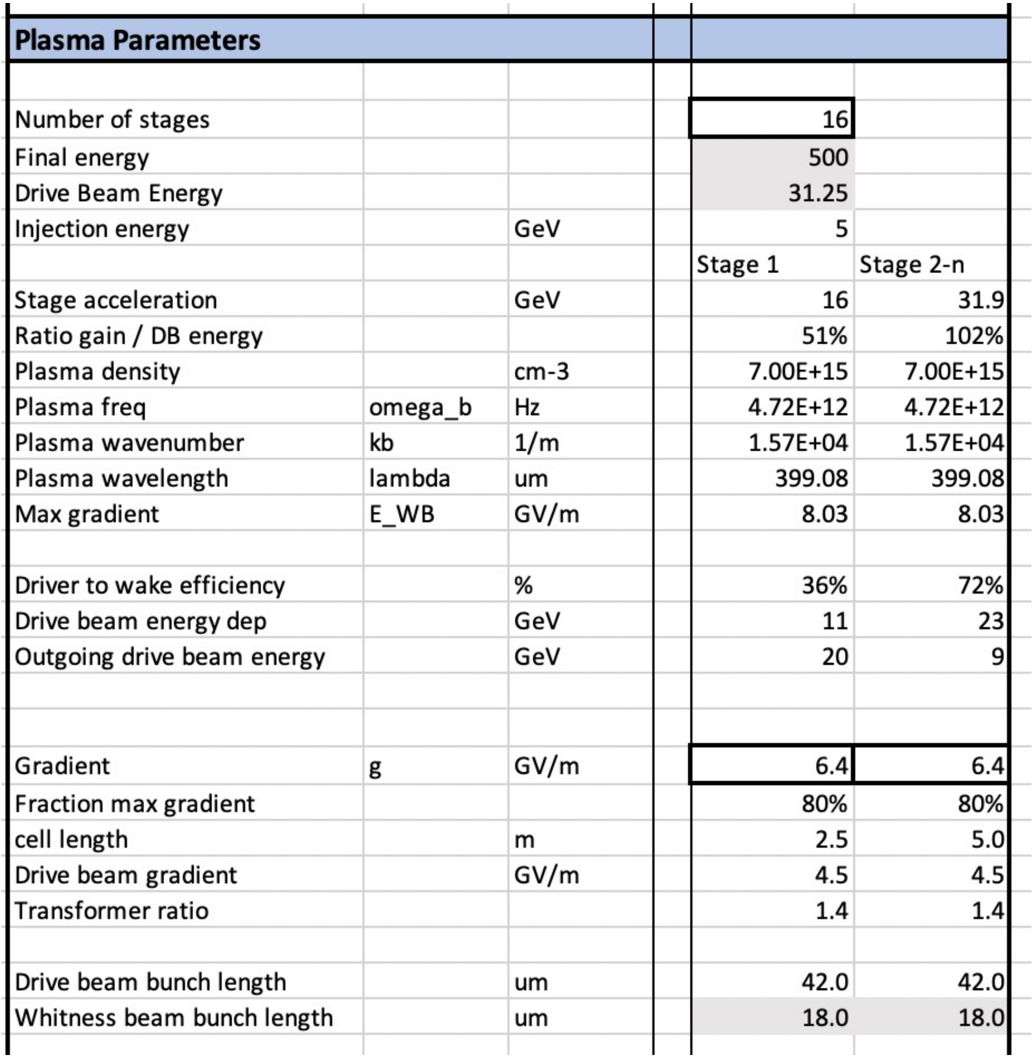
- Main Design Parameters:
  - Number of stages
  - Plasma density
    -> gradient, spacing driver/witness beam, bunch length, transverse size
  - Transformer ratio / bunch charge ratio driver/witness beam



PWFA linac and drive-beam parameters

Number of stages		16
Plasma density	cm^{-3}	7×10^{15}
In-plasma acceleration gradient	$\mathrm{GV\,m}^{-1}$	6.4
Average gradient (incl. optics)	$\mathrm{GV\,m}^{-1}$	1.2
Length per stage[a]	m	5
Energy gain per stage[a]	GeV	31.9
Initial injection energy	GeV	5
Driver energy	GeV	31.25
Driver bunch population	10^{10}	2.67
Driver bunch length (rms)	μm	42
Driver average beam power	MW	21.4
Driver bunch separation	ns	5
Driver-to-wake efficiency	%	72
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	38
Wall-plug-to-beam efficiency	%	19
Cooling req. per stage length	$\mathrm{kW\,m}^{-1}$	93

[a] The first stage is half the length and has half the energy gain of the other stages (see section 5.4).



Plasma Parameters				
Number of stages			16	
Final energy			500	
Drive Beam Energy			31.25	
Injection energy		GeV	5	
			Stage 1	Stage 2-n
Stage acceleration		GeV	16	31.9
Ratio gain / DB energy			51%	102%
Plasma density		cm-3	7.00E+15	7.00E+15
Plasma freq	omega_b	Hz	4.72E+12	4.72E+12
Plasma wavenumber	kb	1/m	1.57E+04	1.57E+04
Plasma wavelength	lambda	um	399.08	399.08
Max gradient	E_WB	GV/m	8.03	8.03
Driver to wake efficiency		%	36%	72%
Drive beam energy dep		GeV	11	23
Outgoing drive beam energy		GeV	20	9
Gradient	g	GV/m	6.4	6.4
Fraction max gradient			80%	80%
cell length		m	2.5	5.0
Drive beam gradient		GV/m	4.5	4.5
Transformer ratio			1.4	1.4
Drive beam bunch length		um	42.0	42.0
Whitness beam bunch length		um	18.0	18.0

Plasma Parameters: Interplay with Drive Linac

- Assumptions:
  - Drive beam linac accelerates also positrons
  - Positrons **RF phase** same or similar to drive beam RF phase (note: could be different, e.g. to level beam loading) -> *make this a parameter*
  - -> drive beam energy same as positron energy (?)
- Number of plasma stages (16) / Transformer ratio (1)
  -> number of drive beam pulses per main bunch (16)
  -> bunch charge of drive beam bunch (2.7E10)
- Choices:
  - Drive beam RF frequency (1GHz? -> see slide)
  - Bunch spacing in drive linac (5ns)
    -> **drives layout / size of delay lines**
  - Bunch spacing to positron bunch (6ns = 4ns*4/2.7?)
- Results
  - Bunch separation of main beam ("80ns")
    -> needs a bit of adjustment
  - Drive beam current, pulse length (**800mA, 8us**)
- More plasma stages: lower transformer ratio, lower drive beam charge, more drive beam bunches
  -> optimize for overall efficiency
- Required drive bunch length:
  - Not too different from positron bunch length
  - Compatible with drive beam linac parameters / technology

Drive Beam Linac: Requirements from Plasma Acceleration

- **What are the requirements on drive beam from the plasma accelerator**?
  - Bunch length: 42um
    -> might require bunch compressor?
  - Normalised emittance? 100um OK?
  - Energy spread? Energy chirp?
  - Current profile?
  - Beam stability / jitter?

- Requirements on positron beam / bunches:
  - Bunch length: 75um
  - Emittance: 10um(!)
  - Energy spread: 0.15%

Plasma Parameters: Interplay with BDS

- Plasma density
  -> Plasma wavenumber
  -> transverse and longitudinal beam size
- For ne=7E15/cm3, bunch length 18um
- At IP: Bunch length 75um
  -> **requires bunch lengthening by factor 4**
- Different (lower) plasma density
  -> longer cells (-> lower power density)
  -> larger bunches, relaxed transverse tolerances, less bunch lengthening required
- -> but larger energy spread at IP -> chromaticity?

- Bunch lengthening by energy compressor:
  - Chicane with sizeable R56
  - Dechirper (Plasma???)

Remark: Shift between positrons and drive beam

- Shift between positrons and drive beam necessitated by layout of beamlines
- Enormous variation of beam loading in drive linac
  -> negative impact on RF, efficiency, etc
  -> Can this be avoided by different beamline layout? (delay loop for drive beam)?
- 2nd observation: positron bunches have larger bunch intensity (4E10 vs 2.7E10) than drive bunches
  -> levelize beam loading by larger gap (10ns vs 5ns)?

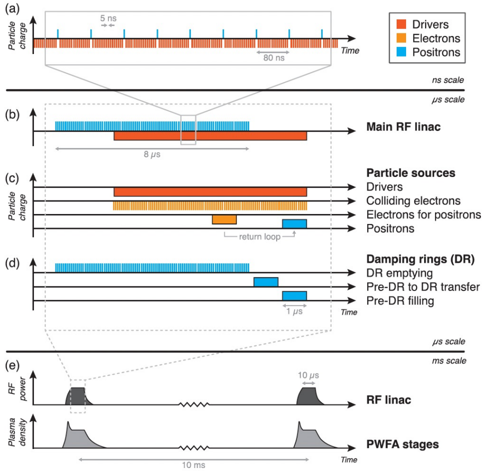
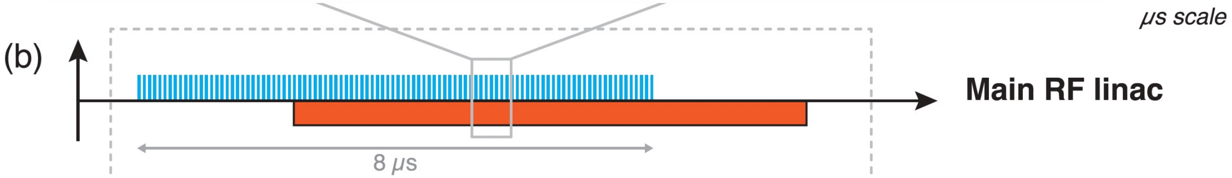


Figure 3. Bunch-train pattern, showing (a) the shortest relevant time structure (ns-scale) of the driver trains, interspersed with positron bunches, during acceleration in the the main RF linac, which (b) continues for the duration of a burst (μs scale). The positron train must be shifted somewhat forward in time since it will traverse an additional turn-around loop. (c) Drivers, colliding electrons, and electron bunches delivered to the positron source are created at appropriate times. (d) The produced positrons are extracted from the damping ring at the appropriate separation, after which the pre-damping ring transfers its bunches to the damping ring, followed by the pre-damping ring being refilled. (e) The RF linac and PWFA stages operate with a ~10 μs flattop at a repetition rate of 100 Hz (ms scale).



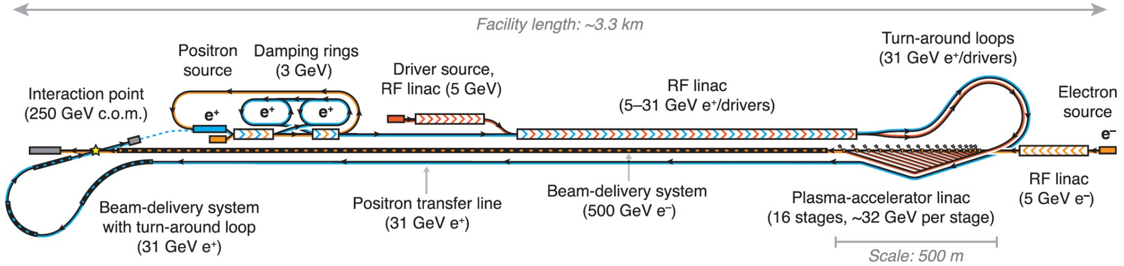
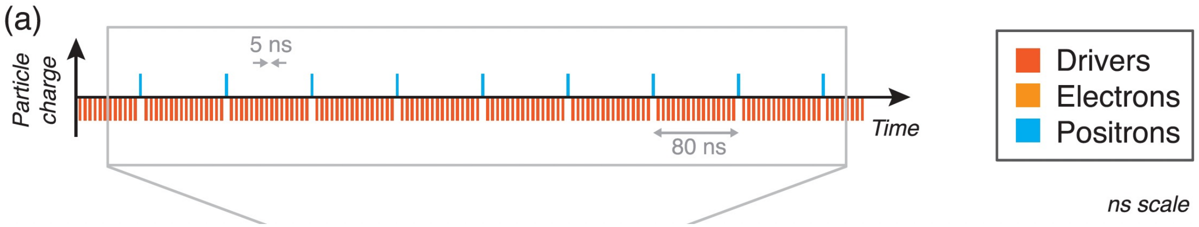


Figure 1. Schematic layout of the hybrid asymmetric linear Higgs factory. Particle sources provide electrons (orange), positrons



Drive Beam Accelerator: Basic Observations

- Assuming Input energy 5GeV, output 31.25GeV, 16x2.7E10 drive bunches, 4E10 main e+ bunch, 10kHz average bunch rate (100Hz x 100):
  20 MW RF to beam (in pulse: 25GW)
- Drive beam linac delivers 84% of the total beam power (rest in 5GeV linacs) – power does not depend on bunch pattern, frequency, … it is just the overall beam power
- This is a lot. Requires e.g. 500 x 50MW klystrons, modulators, couplers etc
- Length / gradient is not only limited by achievable gradient, but by amount of power that can be handled per meter
- Drive beam linac should not dominate site length -> push for high gradient (25MV/m-ish)

Drive Beam Linac: Consider CLIC Design

- CLIC Drive Beam Linac:
  Travelling wave, fully loaded, 93% RF to beam!
- Requires careful matching of cavity geometry (iris, number of cells), bunch charge / beam current, gradient -> very little flexibility

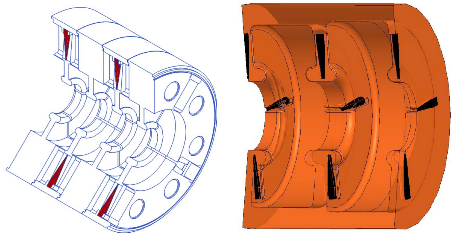


Fig. 5.50: Conceptual view of two SICA structures; left: The 3 GHz CTF3 structure; right: The baseline structure for the CLIC Drive Beam Accelerator at 1 GHz.

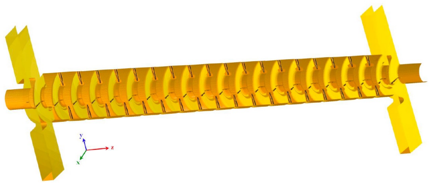


Fig. 5.51: Baseline SICA structure for the CLIC Drive Beam accelerator consisting of 21 cells (19 accelerating cells and a coupling cell at each end). The total length is 2.4 m.

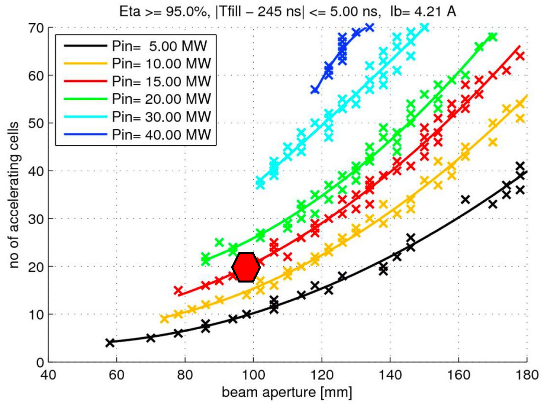


Fig. 5.52: Structure optimisation: For several input powers (colour coded) and beam pipe apertures (diameter), the number of accelerating cells and the group velocity in each cell can be chosen such that the RF-to-beam efficiency is above 95% while the fill time is 245±5 ns. The CLIC DBA baseline structure has a beam pipe aperture of 98 mm and is made of 19 accelerating cells.

CLIC TDR, CERN-2012-007

Drive Beam Parameters CLIC and HALHF

Parameter	CLIC	HALHF
Beam current (A)	4.2	0.86
Bunch charge (nC)	8	4.3
Bunch spacing (ns)	0.5	5
RF pulse length (us)	140	8-10
RF to beam efficiency (%)	95	?
Klystron power (MW)	20	?
Frequency (GHz)	1	1 ; 2 ; ?
Gradient (MV/m)	1.5	25
Drive Power/m (MW)	7.8	21.4
Total voltage (GV)	2.37	31

Detailed RF-structure parameters missing to evaluate

S.Doebert, CERN, SY-RF

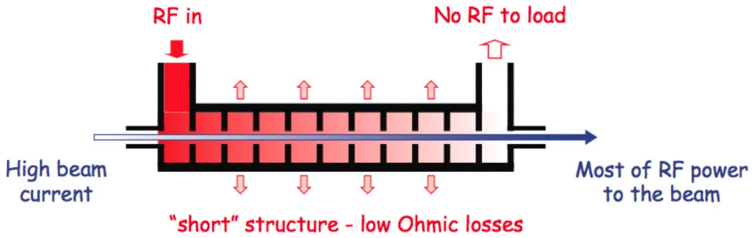


Fig. 2.9: Acceleration of a beam in a travelling wave structure. Under full beam loading operation no RF power is leaving the structure

CLIC Drive Beam: Structures

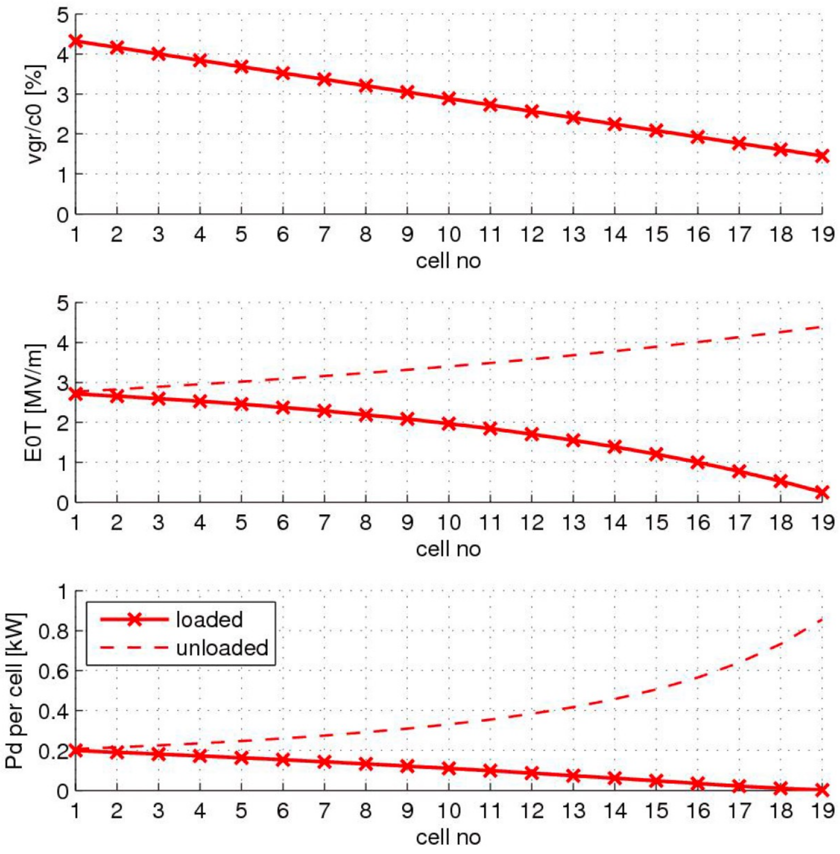


Fig. 5.53: Electromagnetic properties of the CLIC DBA structure for the 19 accelerating cells. Top: group velocity profile in reference to the speed of light; middle: the accelerating gradient for the loaded (solid line, beam current 4.2 A) and the unloaded (dash line) case; bottom: average dissipated power in each cell for the loaded and unloaded case for an RF duty cycle of 7.5‰.

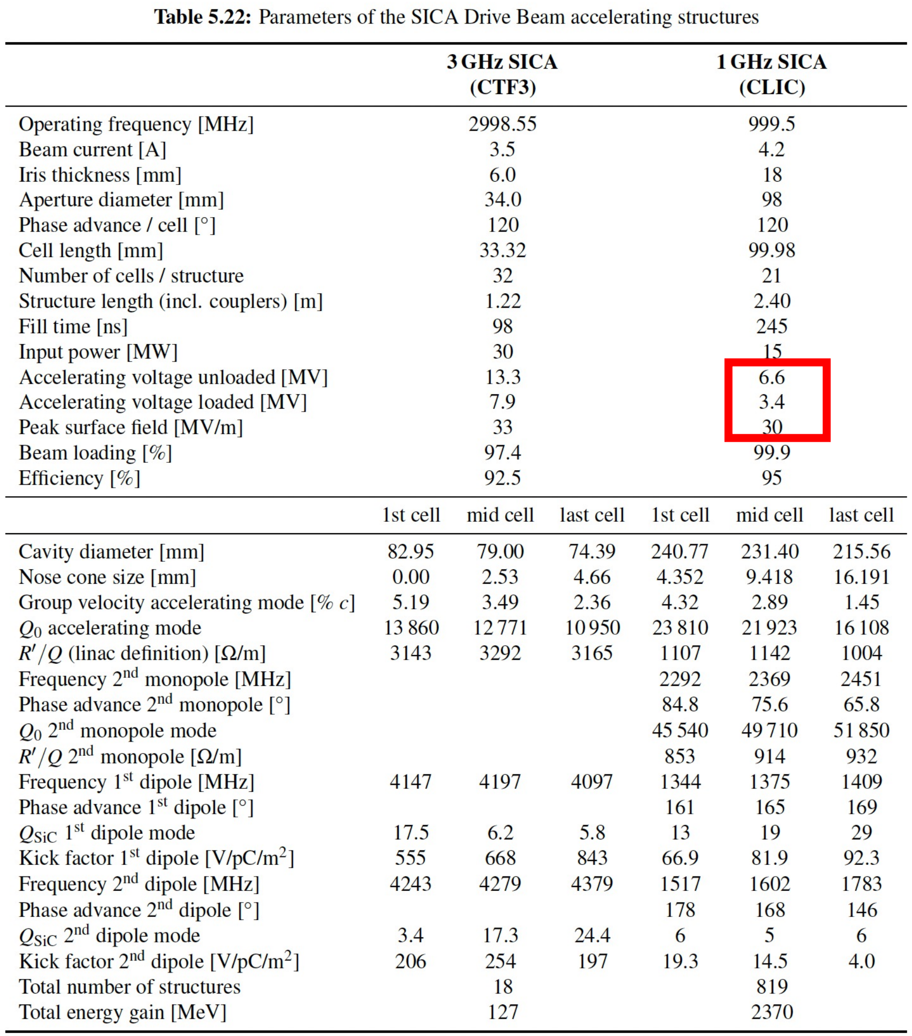


Table 5.22: Parameters of the SICA Drive Beam accelerating structures

	3 GHz SICA (CTF3)			1 GHz SICA (CLIC)		
Operating frequency [MHz]		2998.55			999.5	
Beam current [A]		3.5			4.2	
Iris thickness [mm]		6.0			18	
Aperture diameter [mm]		34.0			98	
Phase advance / cell [°]		120			120	
Cell length [mm]		33.32			99.98	
Number of cells / structure		32			21	
Structure length (incl. couplers) [m]		1.22			2.40	
Fill time [ns]		98			245	
Input power [MW]		30			15	
Accelerating voltage unloaded [MV]		13.3			6.6	
Accelerating voltage loaded [MV]		7.9			3.4	
Peak surface field [MV/m]		33			30	
Beam loading [%]		97.4			99.9	
Efficiency [%]		92.5			95	
	1st cell	mid cell	last cell	1st cell	mid cell	last cell
Cavity diameter [mm]	82.95	79.00	74.39	240.77	231.40	215.56
Nose cone size [mm]	0.00	2.53	4.66	4.352	9.418	16.191
Group velocity accelerating mode [% c]	5.19	3.49	2.36	4.32	2.89	1.45
Q_0 accelerating mode	13 860	12 771	10 950	23 810	21 923	16 108
R'/Q (linac definition) [Ω/m]	3143	3292	3165	1107	1142	1004
Frequency 2nd monopole [MHz]				2292	2369	2451
Phase advance 2nd monopole [°]				84.8	75.6	65.8
Q_0 2nd monopole mode				45 540	49 710	51 850
R'/Q 2nd monopole [Ω/m]				853	914	932
Frequency 1st dipole [MHz]	4147	4197	4097	1344	1375	1409
Phase advance 1st dipole [°]				161	165	169
Q_{SiC} 1st dipole mode	17.5	6.2	5.8	13	19	29
Kick factor 1st dipole [V/pC/m^2]	555	668	843	66.9	81.9	92.3
Frequency 2nd dipole [MHz]	4243	4279	4379	1517	1602	1783
Phase advance 2nd dipole [°]				178	168	146
Q_{SiC} 2nd dipole mode	3.4	17.3	24.4	6	5	6
Kick factor 2nd dipole [V/pC/m^2]	206	254	197	19.3	14.5	4.0
Total number of structures		18			819	
Total energy gain [MeV]		127			2370	

30MV/m
surface field
for 1.7MV/m
mean acc. Gradient

-> go to higher freq?
2GHz?

CLIC TDR, CERN-2012-007

CLIC Drive Beam Linac Parameters

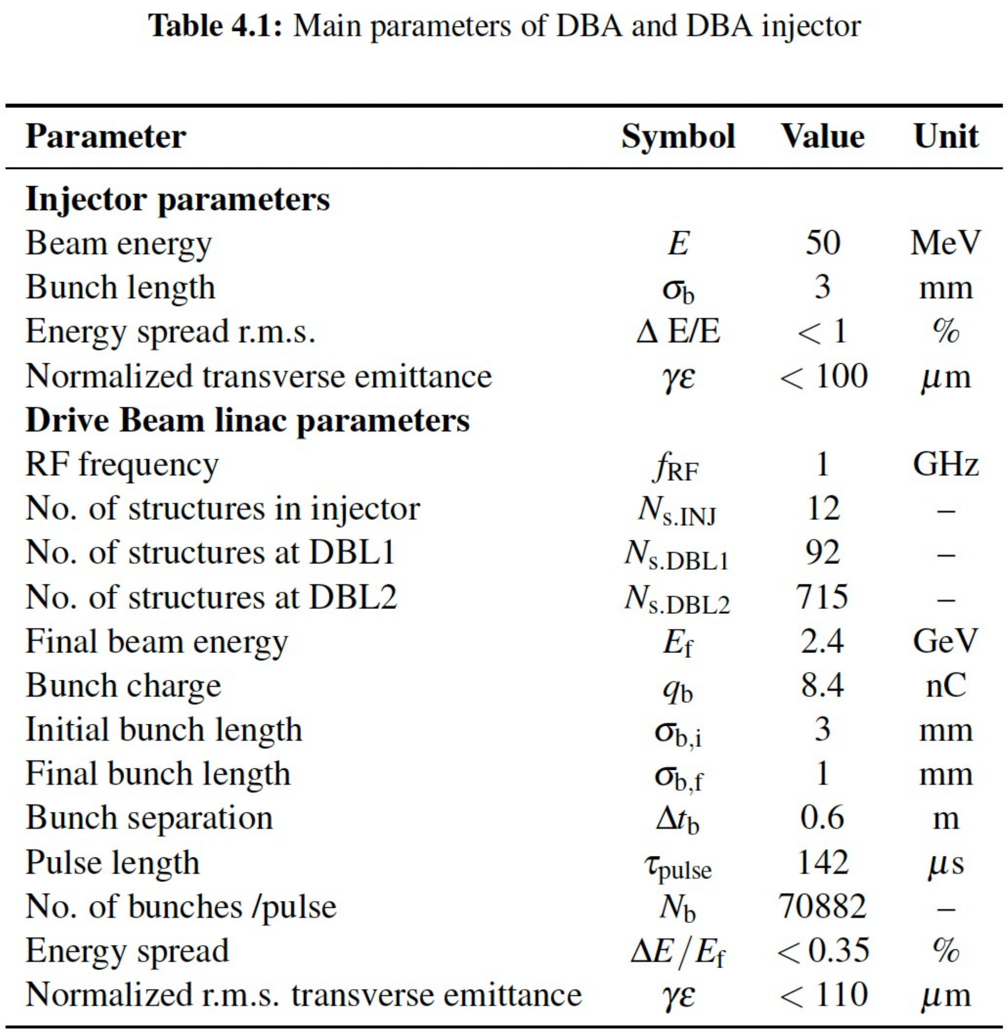


Table 4.1: Main parameters of DBA and DBA injector

Parameter	**Symbol**	**Value**	**Unit**
Injector parameters			
Beam energy	E	50	MeV
Bunch length	σ_b	3	mm
Energy spread r.m.s.	Δ E/E	< 1	%
Normalized transverse emittance	$\gamma\varepsilon$	< 100	μm
Drive Beam linac parameters			
RF frequency	f_{RF}	1	GHz
No. of structures in injector	$N_{s.INJ}$	12	–
No. of structures at DBL1	$N_{s.DBL1}$	92	–
No. of structures at DBL2	$N_{s.DBL2}$	715	–
Final beam energy	E_f	2.4	GeV
Bunch charge	q_b	8.4	nC
Initial bunch length	$\sigma_{b,i}$	3	mm
Final bunch length	$\sigma_{b,f}$	1	mm
Bunch separation	Δt_b	0.6	m
Pulse length	τ_{pulse}	142	μs
No. of bunches /pulse	N_b	70882	–
Energy spread	$\Delta E/E_f$	< 0.35	%
Normalized r.m.s. transverse emittance	$\gamma\varepsilon$	< 110	μm

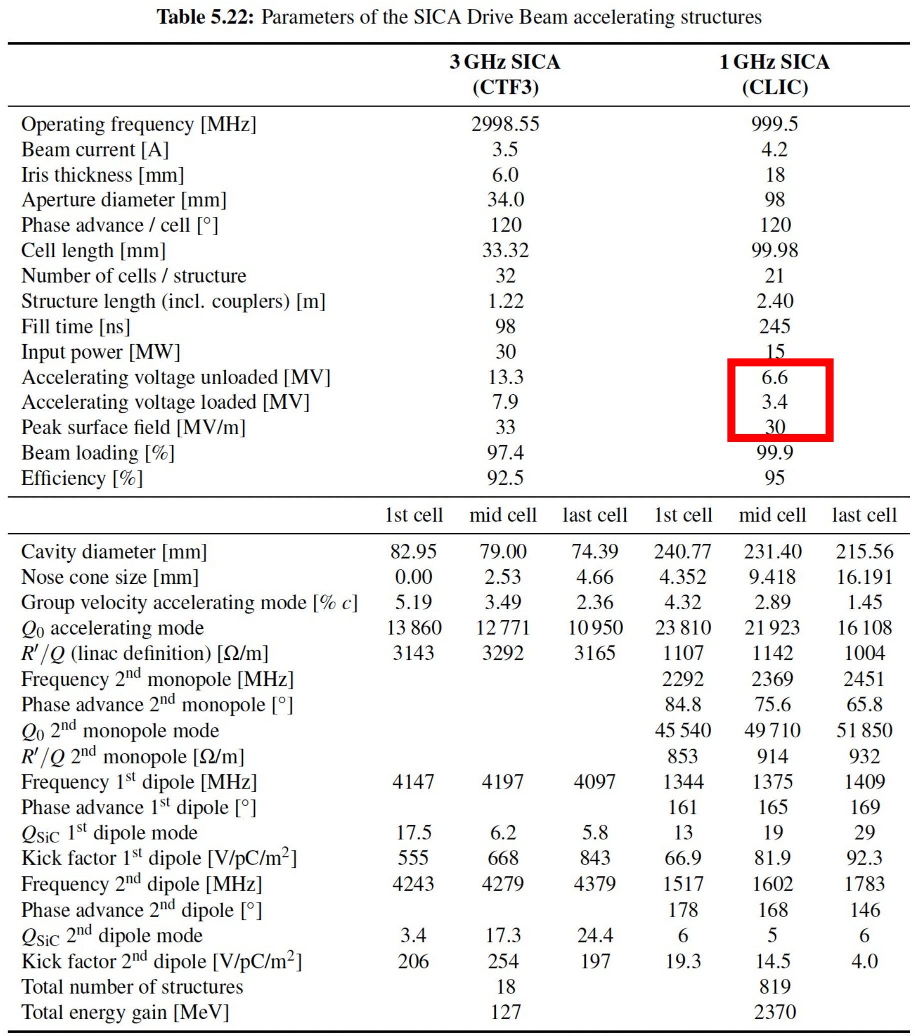


Table 5.22: Parameters of the SICA Drive Beam accelerating structures

	3 GHz SICA (CTF3)	1 GHz SICA (CLIC)
Operating frequency [MHz]	2998.55	999.5
Beam current [A]	3.5	4.2
Iris thickness [mm]	6.0	18
Aperture diameter [mm]	34.0	98
Phase advance / cell [°]	120	120
Cell length [mm]	33.32	99.98
Number of cells / structure	32	21
Structure length (incl. couplers) [m]	1.22	2.40
Fill time [ns]	98	245
Input power [MW]	30	15
Accelerating voltage unloaded [MV]	13.3	6.6
Accelerating voltage loaded [MV]	7.9	3.4
Peak surface field [MV/m]	33	30
Beam loading [%]	97.4	99.9
Efficiency [%]	92.5	95

	1st cell	mid cell	last cell	1st cell	mid cell	last cell
Cavity diameter [mm]	82.95	79.00	74.39	240.77	231.40	215.56
Nose cone size [mm]	0.00	2.53	4.66	4.352	9.418	16.191
Group velocity accelerating mode [% c]	5.19	3.49	2.36	4.32	2.89	1.45
Q_0 accelerating mode	13 860	12 771	10 950	23 810	21 923	16 108
R'/Q (linac definition) [Ω/m]	3143	3292	3165	1107	1142	1004
Frequency 2nd monopole [MHz]				2292	2369	2451
Phase advance 2nd monopole [°]				84.8	75.6	65.8
Q_0 2nd monopole mode				45 540	49 710	51 850
R'/Q 2nd monopole [Ω/m]				853	914	932
Frequency 1st dipole [MHz]	4147	4197	4097	1344	1375	1409
Phase advance 1st dipole [°]				161	165	169
Q_{SiC} 1st dipole mode	17.5	6.2	5.8	13	19	29
Kick factor 1st dipole [V/pC/m^2]	555	668	843	66.9	81.9	92.3
Frequency 2nd dipole [MHz]	4243	4279	4379	1517	1602	1783
Phase advance 2nd dipole [°]				178	168	146
Q_{SiC} 2nd dipole mode	3.4	17.3	24.4	6	5	6
Kick factor 2nd dipole [V/pC/m^2]	206	254	197	19.3	14.5	4.0
Total number of structures		18			819	
Total energy gain [MeV]		127			2370	

30MV/m
surface field
for 1.7MV/m
mean acc. Gradient

-> go to higher freq?
2GHz?

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Superconducting drive linac?

The average power is the challenge (not the gradient)

Edited version
Reflecting discussion

- TESLA type couplers handle order of kW of average power; one coupler per cavity (1.04m)
  -> limits power to ~~~2kW/m~~ 5kW/m
  -> ~~10km~~ 4km for a 20MW SC linac
- Conclusion:
  a 10km SC linac can deliver a 250-300GeV beam for physics, or possibly the drive beam for a 500GeV plasma driven beam
- A SC drive linac would require a ~~completely~~ different coupler ~~development~~ which exists, e.g. EIC
- Different time structure (longer bunch distances, lower current) for SC linac – completely new game
- Generically, drive linac has very high current
  -> ideal for NC linac (ratio of power to beam vs cavity wall losses favourable)

Summary / Conclusions

- Parameter Excel document has been set up
  -> distribution? Start with DESY synch & share?
- Definition of PBS / system boundaries needs to continue
- Look at interplay between subsystem design choices, in particular between plasma and conventional accelerator

Kontakt

Deutsches Elektronen-Synchrotron DESY

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