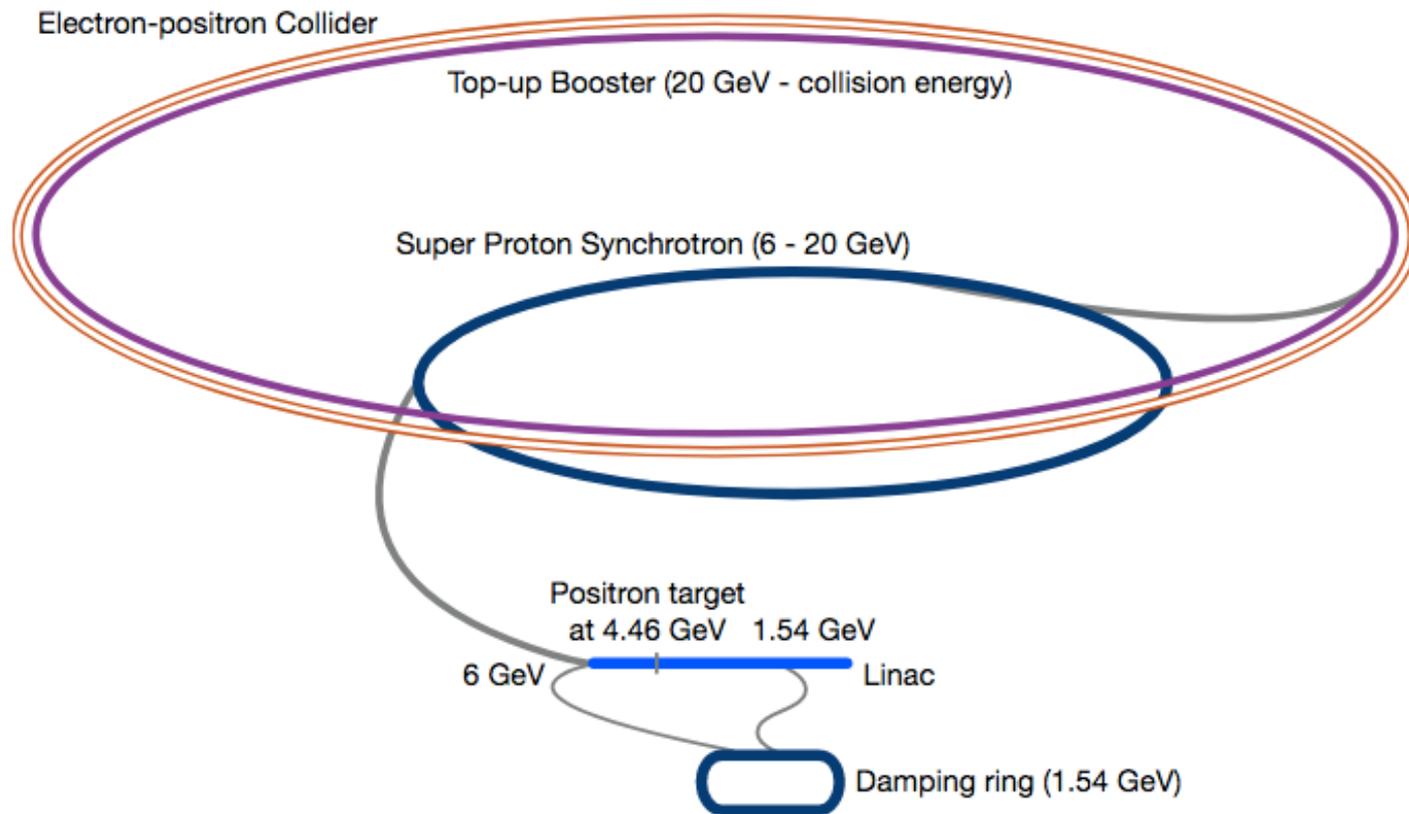# Alternatives

D. Schulte

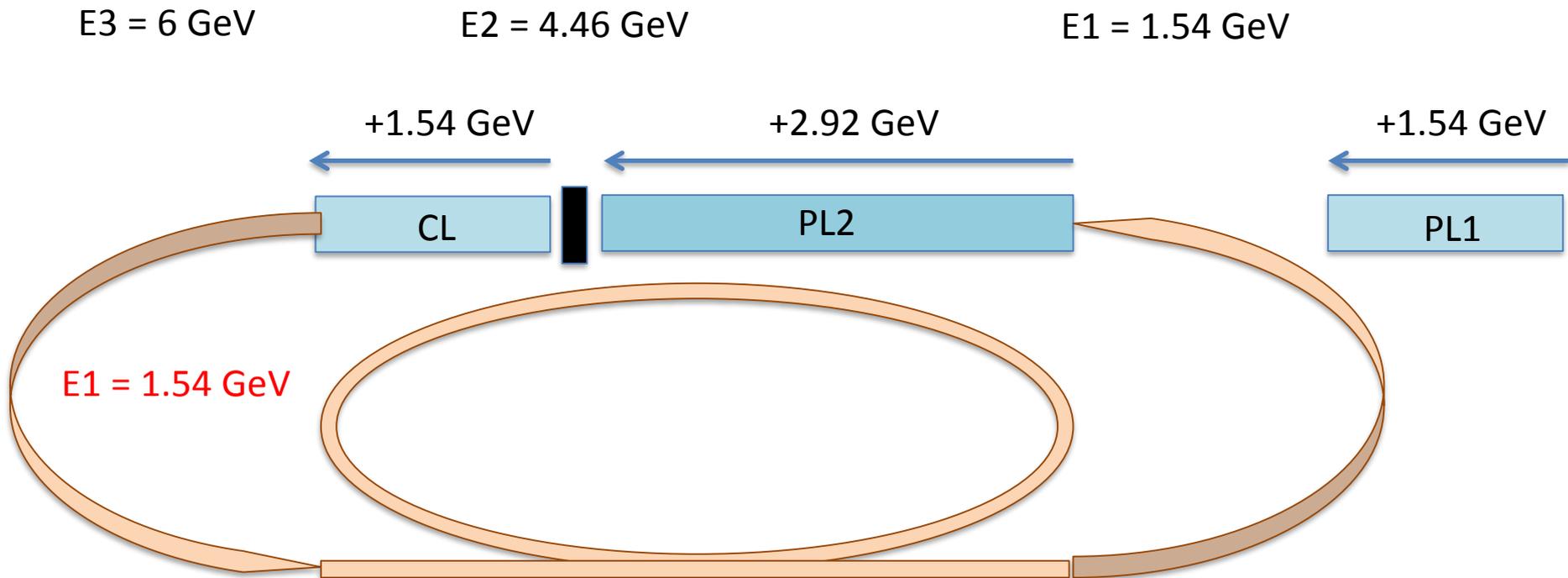# Injector Complex Layout in CDR

The same complex is used for electrons and positron

The current baseline has important changes compared to the CDR to consolidate the design
⇒   See today's presentations

Simplified Current Concept

- Rational
  - Chose damping ring energy (E1 = 1.54 GeV)
  - Chose injection energy into pre-booster (E3 = 6 GeV)
  - Then define energy at target (E2 = E3 − E1 = 4.46 GeV)

E3 = 6 GeV   E2 = 4.46 GeV   E1 = 1.54 GeV

+1.54 GeV   +2.92 GeV   +1.54 GeV

CL   PL2   PL1

E1 = 1.54 GeV

CDR Specifications

Parameter [unit]	Z		W		H		$t\bar{t}$	
Beam energy [GeV]	45.6		80		120		182.5	
Type of filling	Initial	Top-up	Initial	Top-up	Initial	Top-up	Initial	Top-up
Linac bunches/pulse	2				1			
Linac repetition rate [Hz]	200			100				
Linac RF frequency [GHz]	2.8							
Bunch population [10^{10}]	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
No. of linac injections	1040		1000		328		48	
PBR minimum bunch spacing [ns]	10		10		70		477.5	
No. of PBR cycles	8			1				
No. of PBR bunches	16640		2000		328		48	
PBR cycle time [s]	6.3		11.1		3.7		0.9	
PBR duty factor	0.84		0.56		0.30		0.08	
No. of BR/collider bunches	2080		2000		328		48	
No. of BR cycles	10	1	10	1	10	1	20	1
Filling time (both species) [sec]	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

Current [10^{11} s^{-1}]	69	28	8.9	0.6

Max current [10^{11} s^{-1}]	85	38	19	14

In CLIC each main linac 915 x 10^{11} s^{-1} (50 Hz)

New Parameters

	Z	WW	ZH	tt
Collider energy [GeV]	45.6	80	120	182.5
Collider & BR bunches / ring	16640	2000	328	48
Collider particles / bunch [10^{10}]	17	15	18	23
Injector particles / bunch [10^{10}]	$\leqq 3.0$ *			
Bootstrap particles / bunch [10^{10}]	1.7	0.9	1.1	1.3
# of BR ramps (to 1/2 stored current)	3	3	3	4
# of BR ramps (bootstrap)	5	7	8	8
BR ramp time (up + down) [s]	0.6	1.5	2.5	4.1
# of PBR cycles	14			7
PBR ramp time (up + flat top + down) [s]	0.5			
PBR bunches / ring	1190	143	24	7
Linac pulses	595	71	12	4
Linac repetition frequency [Hz]	200			
PBR injection time [s]	3.0	0.36	0.06	0.02
Collider filling time from scratch [s]	396.8	135.4	113.7	92.9
Collider filling time for top-up [s]	49.6	13.5	10.3	7.7
Collider interval between top-ups (2 IP) [s]	< 400	< 212	< 44	< 44

Alternatives

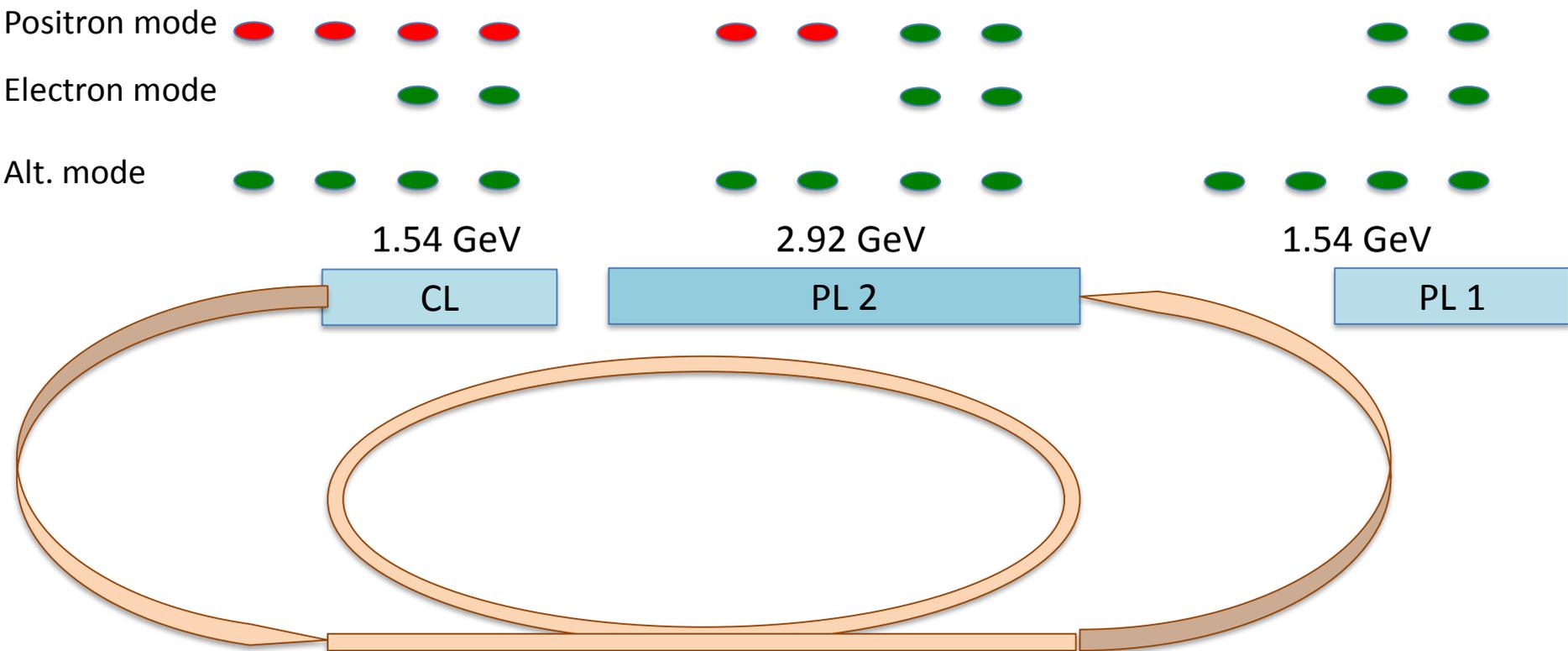A number of alternatives can be considered for the injector complex

- To make complex more robust
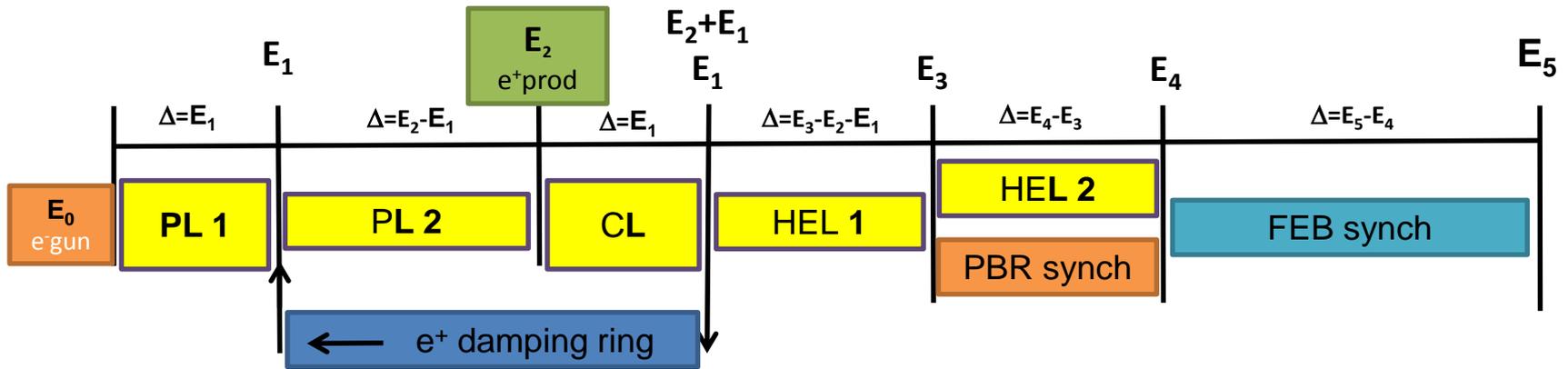
- Reduce cost

Some example options are:

- Inject directly into booster

- Consider using bunch trains

- Consider doubling the number of bunches for electrons

- …

Example: Electron Filling

- For electrons, can reach beam emittances with gun
  - Hence just pass through the linacs
- Need power for more bunches in PL 2 and CL
  - RF must be dimensioned for 2-3 times the electron pulse charge
$\Rightarrow$ Electron filling time could be (much) shorter than positron filling time
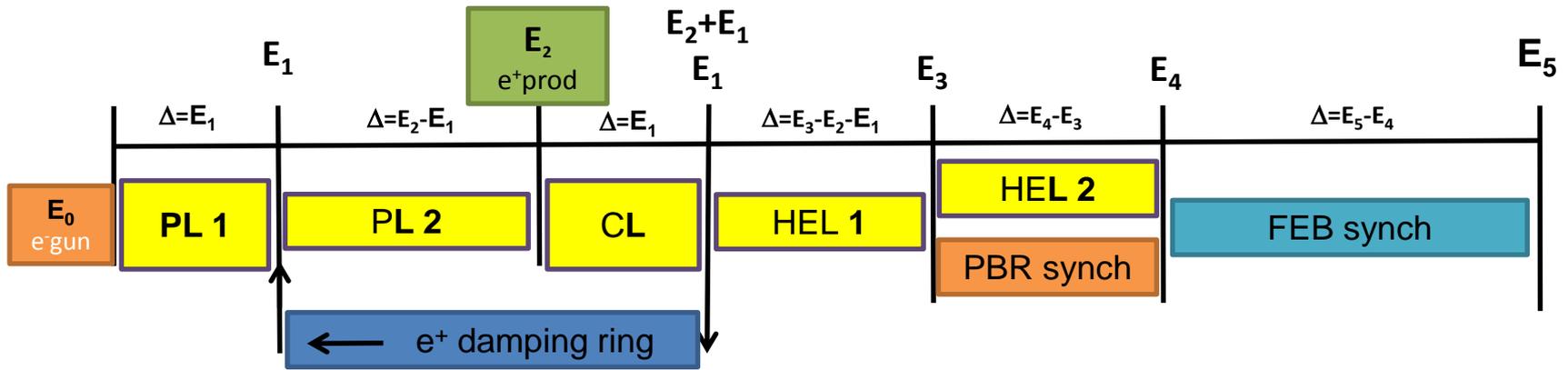 - Provided we upgrade PL 1
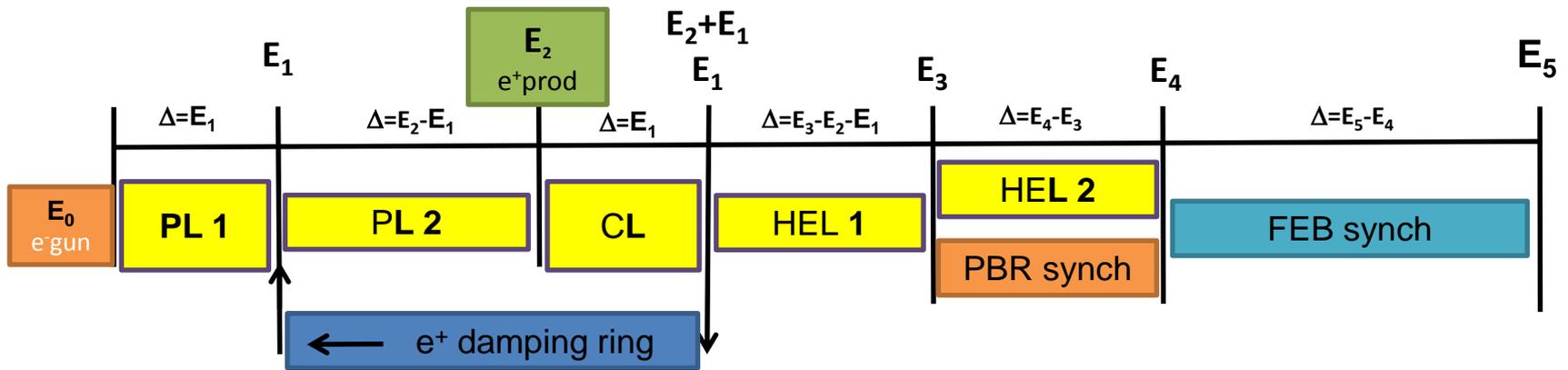
Generic Layout

- Break into functional pieces

- Leave parameters flexible
  - Baseline choice right now is to have no HEL1
  - HEL2 is considered as alternative

- Other configurations can be envisaged
  - But would lead to far today

RF Design

- In current baseline all RF is S-band
  - Except for HEL2, which is C-band
- But need actual RF design of each linac
  - RF structures, pulse compressors etc.

- Each linac has its own requirements
  - Emittances
    - CL needs to transport large emittance beam from target
    - PL2 only sees small emittance beams
  - Currents
    - PL2 has a higher current during positron production
      - Electron and positron beam
    - Similar for CL
      - Positron beam from target and positron beam toward collider
  - Might want to consider RF frequency choices

Energy Choices

- What are the best choices of the different energies?
  - Need to understand each system well enough to be able to properly perform the trade-off
    - E.g. what is the best RF frequency and gradient in each system?
    - E.g. E_4 depends on the final booster and on the high-energy linac
  - Efficiency of positron production depends on E_2
  - With the baseline scheme currents in different linacs are different
- Note other configurations could also be considered, e.g. to have a CL dedicated to the positrons after production only

Top-up Flexibility

- Do we need to control the charge of the circulating collider bunches?
  - I would guess, yes.
  - Non-colliding bunches need to be treated differently
  - Bunches might lose particles at different rates
  - Different schemes could be envisaged
    - Control of top-up bunch charge, e.g. at gun level
    - Sparing given bunches from top-up for one round
    - Both will produce additional constraints

- How flexible do we need to be with the filling pattern?

- How do we transfer?
  - All bunches in one go?
  - Otherwise, how do we deal with the current small difference in booster and collider circumference?

Bunch Trains

Accelerating bunch trains allow to increase the RF-to-beam efficiency
• typically requires increase of RF energy per pulse
• but one accelerate much more charge per pulse
• This allows a faster filling of the pre-booster or booster

Likely can reduce 50 ns spacing in linacs
• certainly by damping the structures but maybe even without

Could aim for 15 to 20 ns bunch spacing to produce (pre-) booster patter right away
• Number of bunches per pulse depends on RF frequency and trade-off with pulse compressor
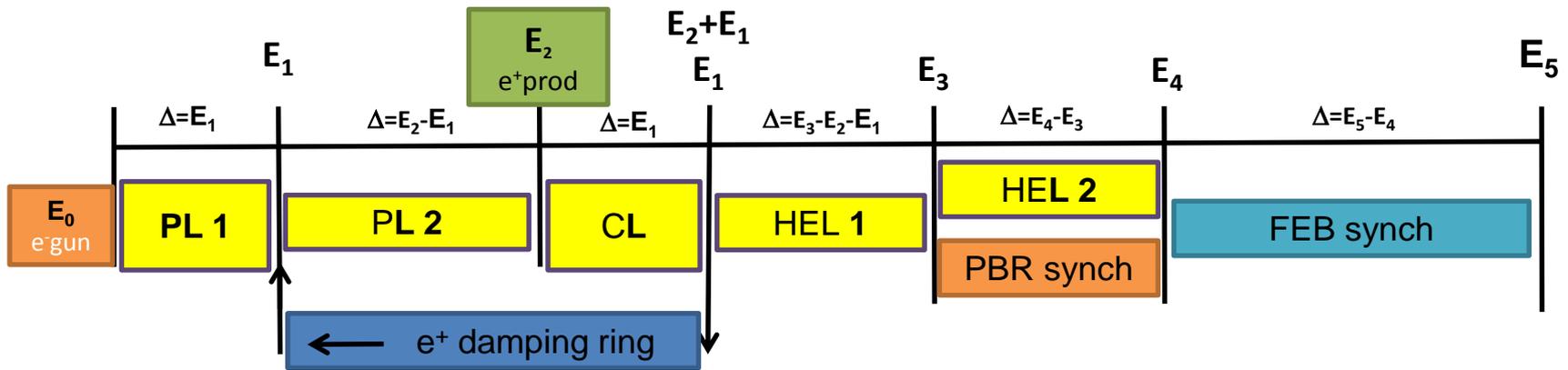• Typically can expect O(10) bunches per pulse

Can also use bunch trains to reduce the charge per bunch
• roughly the same charge per pulse (slight increase required)
• this allows smaller aperture structures (higher frequency or smaller a/lambda), which can be more efficient and can reach higher gradients
• could consider more bunches in booster than in collider and do more than one round of top-up

How to Move Forward?

- Develop an optimized injector layout (linacs, rings, energies, etc.)

  - Matching the performance requirements of FCC-ee at all working points

  - ~40 to ~200 GeV injection energy into collider in top-up mode.

  - Provision of some flexibility for filling patterns (e.g. lifetime of individual bunches)

  - Fast-filling will be most critical requirement for current

  - Most stringent requirements in patterns/intensity/flux at Z (45 GeV).

- Form a collaboration for this purpose

FCC-ee Injector Workpackages

WP0: Electron Gun and injector

WP1: Production Linac (PL1 to E1, PL2 to E2)
- PL1: 2 electron bunches or 2 production bunches acceleration to E1
- PL2: 2 electron bunches or 2 production bunches & 2 positron bunches (energy gain E2-E1)

WP2: Positron production (E2)
- Target design, - capture optimisation
- Energy choice (E2), production bunch intensity versus production energy, etc.

WP3: Positron Capture Linac (CL, E1)
- Pre acceleration of 2 positron bunches (before DR) and acceleration (after DR) of 2 e+ bunches (energy gain E1 per passage)
- Acceleration of 2 electron bunches (energy gain E1)

WP4: Damping Ring (E1)
- Choice of E1
- Impedance, space charge, e+ emittances, etc.

WP5: High Energy Linacs (HEL1+2, acceleration from (E1+E2) to E3 or E4)
- Choice of end energy kept flexible at the moment,
- Optimisation with Full Energy Booster (FEB) or Pre-Booster Ring (PBR) design at later stage

WP6: Pre-Booster Ring (PBR)
- Either SPS or new ring
- Impact of injection energy E3
- Full ring design

WP7: Full-Energy Booster (FEB)
- Impact of injection energy E4
- Full ring design

WP8: Beam transfer system design
- Transfer line design (from High Energy Linac onwards)
- Injection and extraction concepts, linked to ring designs
- HW concepts

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FCC-ee Injector Collaboration

- Proposed starting point is **consolidation and analysis of present baseline scheme** that matches exactly the bunch number and fill pattern requirements that came out of the collider luminosity optimization.

- Should be good starting point for investigations of alternative designs and future optimization.

- Current design provides **1 or 2 bunches per RF pulse** for the collider, assembled in trains either in a pre-booster or full-energy booster, with a **maximum charge of 2E10 particles per bunch**.

- Additional e- bunches (production bunches) are used to produce the e+ bunches of identical intensity. Presently the bunch pair distance is 60 ns.

- The baseline design assumes S-band linac structures throughout.

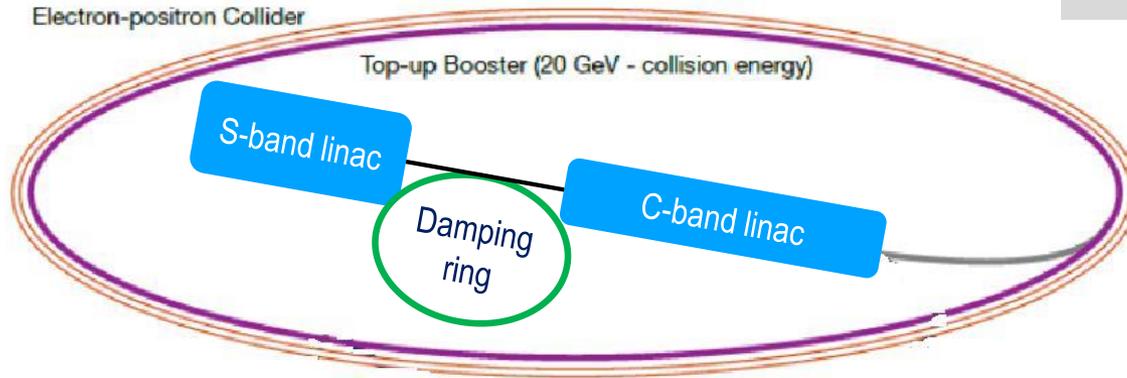# Next Steps

- Assumption that general understanding is met with potential partners.

- Development of brief descriptions of activities for each work package for first phase, i.e. review and optimisation of baseline: PBR vs HE linac (E3 and/or E4), e+ production energy, etc.

- Design goals, key parameters, interfaces, time lines

- Resources estimates.

- Further common discussion of programme

First Proposals Already Appeared

FCC-ee injector, second look at Linac

H. Braun
Yesterday

	S-band Linac	C-band Linac Opt. 2	C-band Linac Opt. 3
Energy gain	2 GeV	18 GeV	44 GeV
Final energy	n.a.	20 GeV	46 GeV
Length	0.12 km	0.7 km	1.7 km
Gradient	20 MV/m	30 MV/m	30 MV/m
Number RF stations	17	75	184
Cost incl. building	50 MCHF	230 MCHF	550 MCHF

O. Brüning

Recirculating linac from LHeC/FCC-eh

Reserve

Positron Filling

- Linac after the target should have large aperture for capture efficiency

- In CLIC can tolerate production of 18×10^{11} positrons per pulse

- Could consider splitting charge in several bunches with short spacing

- Reasoning for 60 ns spacing in CDR not clear
  - CDR refers to longitudinal wakes
  - Referred paper mentions transverse wakes
  - No damping used in accelerator, so no fundamental limit

1.54 GeV   2.92 GeV   1.54 GeV
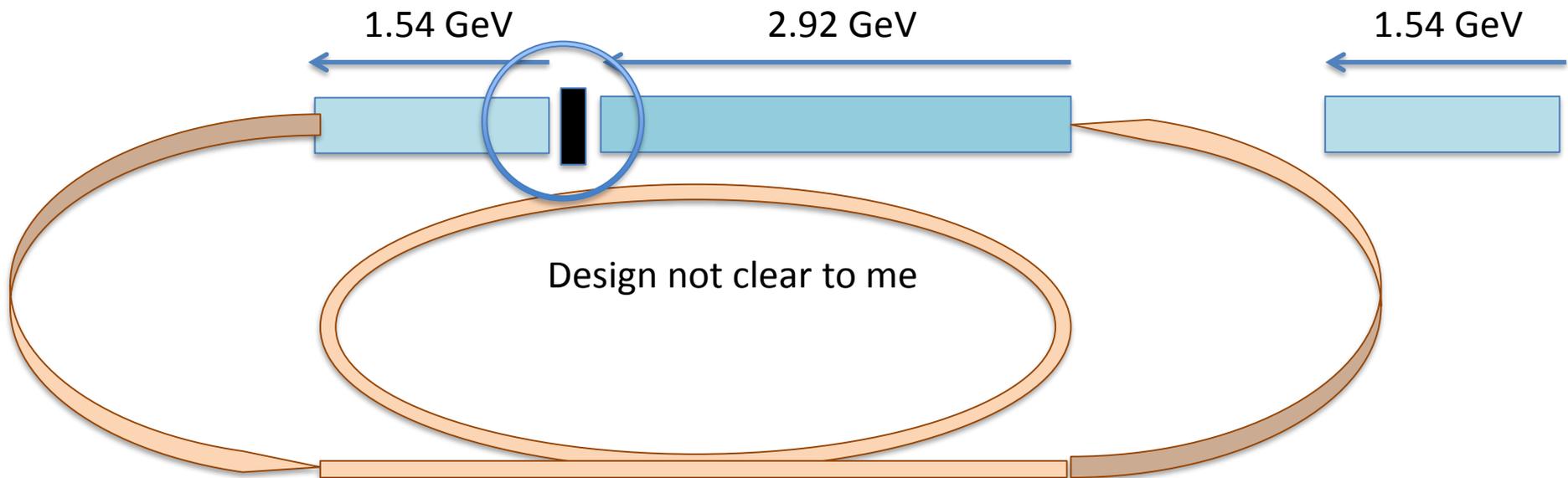
Positron Filling

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1.54 GeV   2.92 GeV   1.54 GeV

Design not clear to me

Impact on Specifications

Parameter [unit]	Z		W		H		t$\bar{\text{t}}$	
Beam energy [GeV]	45.6		80		120		182.5	
Type of filling	Initial	Top-up	Initial	Top-up	Initial	Top-up	Initial	Top-up
Linac bunches/pulse	2				1			
Linac repetition rate [Hz]	200		100					
Linac RF frequency [GHz]	2.8							
Bunch population [10^{10}]	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
No. of linac injections	1040		1000		328		48	
PBR minimum bunch spacing [ns]	10		10		70		477.5	
No. of PBR cycles	8		1					
No. of PBR bunches	16640		2000		328		48	
PBR cycle time [s]	6.3		11.1		3.7		0.9	
PBR duty factor	0.84		0.56		0.30		0.08	
No. of BR/collider bunches	2080		2000		328		48	
No. of BR cycles	10	1	10	1	10	1	20	1
Filling time (both species) [sec]	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

Could be reduced to 1.6-1.7

Could be reduced to 200-216

Could be reduced to 1.41-1.52

Could be reduced to 780-830

Impact on Specifications

Parameter [unit]	Z		W					
Beam energy [GeV]	45.6		80					
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Filling time (both species) [sec]	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

Reduced RF in damping ring and linacs
Or decreased apertures for higher gradient and lower cost
Smaller top-up fluctuations

Could be reduced to 1.6-1.7

Could be reduced to 200-216

Could be reduced to 1.41-1.52

Could be reduced to 780-830

More on Bunch Trains

To increase in bunch number per pulse allows to
- Further reduce the bunch charge
    - Can help for accelerating structure design, smaller apertures, higher gradient, higher efficiency, less wakefield effects, …
- Increase the charge per pulse
    - This requires slightly more RF but might increase the efficiency
    - Would allow to lower the repetition rate
    - Have to pay attention to charge in the damping ring to not require excessive RF
    - E.g. doubling the number of bunches allows to half repetition rate but does not require twice the peak power

Can reduce the charge for H and t as well by considering to use more bunches in the booster than in the collider
- Ramp up and stay for a short moment at top energy for beam transfer in stages
- Could also accelerate a few bunches per pulse in this scenario to limit time for injection

Booster Linac

Proposal in CDR

Parameter	Value
Length	858 m
Injection-extraction energy	1.54 GeV-20 GeV
Injected emittance (h/v)	1.9/0.4 nm
Average extracted emit. (h/v)	4.0/0.3 nm
Transmission for 3.2 nC	92%

Charge seems high for C-band linac
8% losses seems very high, should aim for close to 0%
Why this large emittance growth in linac?

$\Rightarrow$ Try to reduce charge per bunch
$\Rightarrow$ But use more bunches

$\Rightarrow$ This allows to use smaller aperture and hence higher gradient
$\Rightarrow$ Could also enable higher frequency

Low Charge Considerations

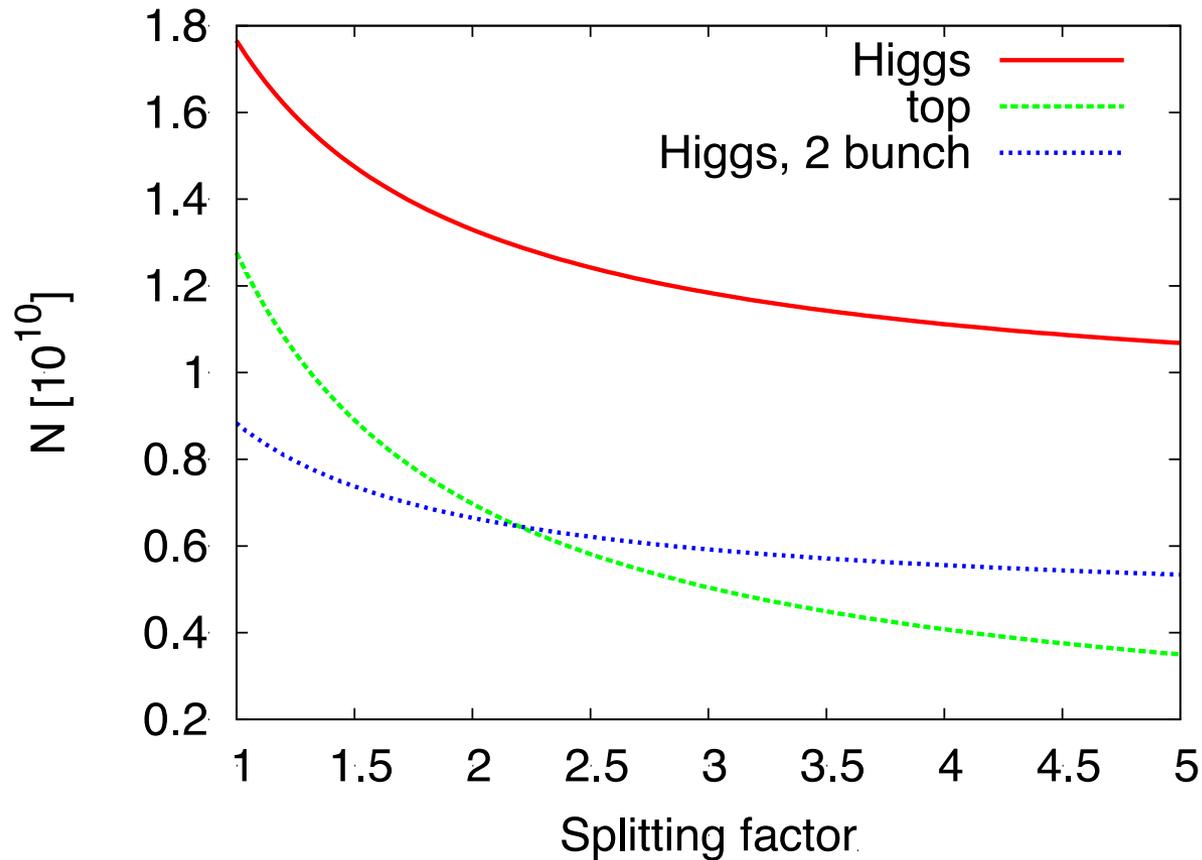| Parameter [unit]	Z		W		H		$t\bar{t}$	
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Filling time (both species) [sec]	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

Required filling pattern in CDR not clear to me
- Some study will be required

Conservatively assume equal spacing
But circumferences are different so could in principle use different patters

Low Charge Considerations

For top and Higgs can reduce bunch charge if we use more bunches
For Higgs accelerating two bunches per pulse would be useful
Need to delay one by O(1000 ns) could be done in 50 turns of the booster

Lower Charge Consideration

Lower charge for Z and WW more difficult, since many bunches are already used

Pessimistic assumption for Z: Accelerate bunches with 19.6 ns spacing
This allows 10 bunches in X-band train
Assume 100 Hz
Can fill booster ring in 16.64 s
With ramp need 18 s
$\Rightarrow$ Can have about three booster ramps instead of one
$\Rightarrow$ Can reduce bunch charge by factor 3 to about 0.7×10^{10}

$\Rightarrow$ Similar at WW

Linac Studies

- Why not European S-band? (2.855 vs. 3 GHz)
- Linac hardware in simulations are not quite clear
    - Aperture of first S-band structures is 20 mm radius and they have the same 25 MV/m gradient as the later ones with 10 mm radius?
    - Arrangement of BPMs not clear, seem to use accelerating structures for this
- Bunch spacing in linac is set to 60 ns due to long-range longitudinal wakefields
    - In SLC long-range transverse effects were observed for 60 ns (this is the referred paper)
    - Damping of structures should avoid such effects
- Extra drifts in 20 GeV linac to reduce impact of BPM misalignments seems not clear
    - I suspect that the BPMs in front of the quadrupoles are missing
- Transmission loss of 8% from 6 to 20 GeV seems a lot
    - Should expect only small tail losses
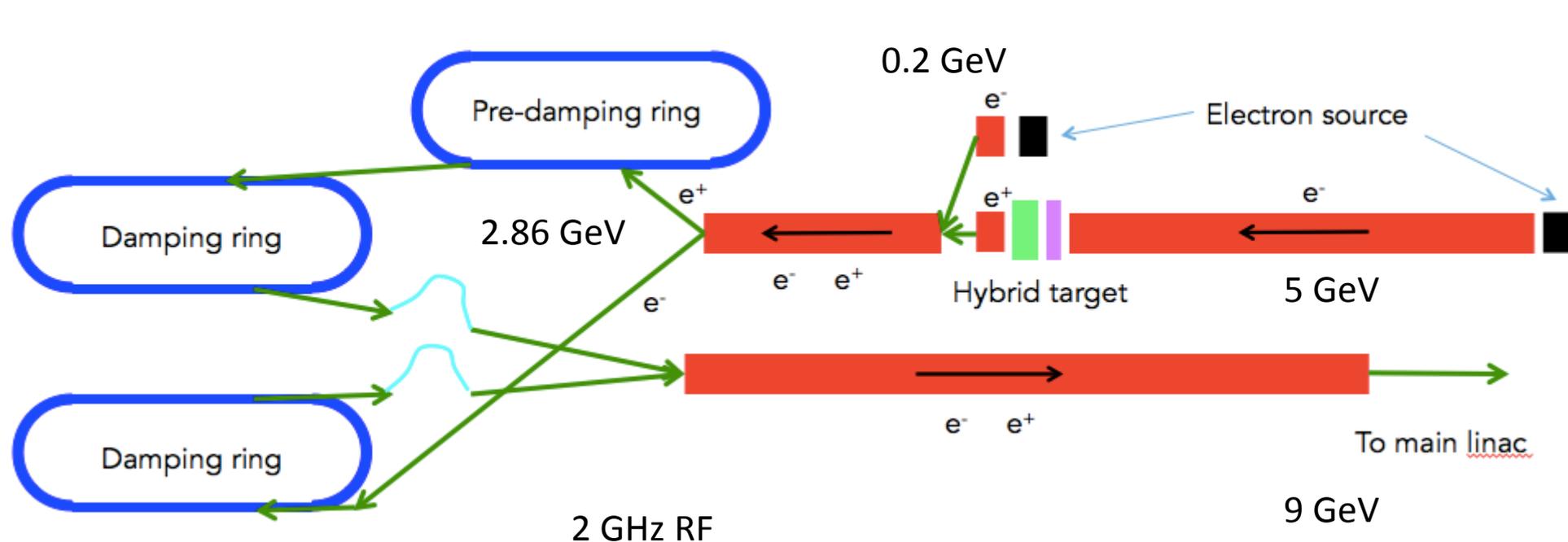   - Large losses make operation hard

Linac Studies

- Trains
- In CDR, bunch spacing in linac is set to 60 ns due to long-range longitudinal wakefields
  - Now 50 ns is assumed
  - In SLC long-range transverse effects were observed for 60 ns (this is the referred paper)
  - Damping of structures should avoid such effects
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  - Large losses make operation hard

Conclusion

- Too early to conclude

- But should consider some points
  - More electron bunches in the current baseline scenario
  - Review of RF frequencies and apertures
    - Will depend on other choices
  - Powering scheme
    - Not clear to me right now, would need to be understood
  - Are bunch trains useful?
    - Detailed look required
  - Would a reduced bunch charge help for a linac to 20 GeV?
  - Clarify the questions concerning the linac design
  - Check if higher positron capture efficiency is possible

- More points will come up

CLIC Positron Production

- Assumed positron yield is about 0.5 at 4.5 GeV
- Positron yield of about 1 in CLIC for 5 GeV electrons
- Should try to understand the difference in capture efficiency
- Important implication for the linacs

Some Questions

- Damping ring final horizontal emittance 3.2 μm
- High charge electron pulse and positron pulse in same linac?
- Normalised emittance at 1.54 GeV is > 15 μm
  - Should be no problem to provide better for electron source
- Bunch spacing in linac is set to 60 ns due to long-range longitudinal wakefields
  - In SLC long-range transverse effects were observed for 60 ns
  - Damping the structures should avoid such effects
- Extra drifts in 20 GeV linac to reduce impact of BPM misalignments seems not clear
- Transmission loss of 8% from 6 to 20 GeV seems a lot
  - Should expect only small tail losses
  - Large losses make operation hard
- Positron yield of about 1 in CLIC for 5 GeV electrons
- Emittance extracted at 1.54 GeV is much larger than injected at 1.54 GeV

Bunch Trains

Accelerating bunch trains allow to increase the RF-to-beam efficiency
- typically requires increase of RF energy per pulse
- but one accelerate much more charge per pulse
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Increase in bunch number per pulse beyond two allows to
- Reduce the bunch charge
    - Can help for accelerating structure design, smaller apertures, higher gradient, higher efficiency, less wakefield effects, …
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