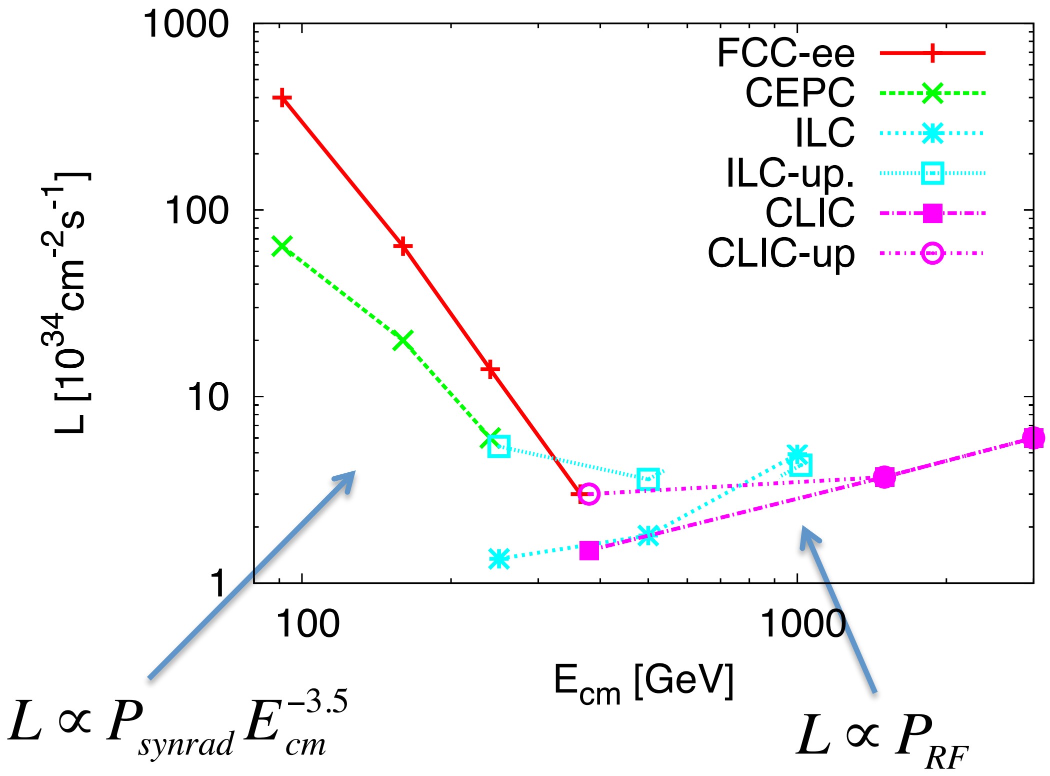
HEP Lepton Collider Parameters

D. Schulte

Proposed Lepton Colliders (ESU-PP)

Luminosity per facility



Only projects with CDR

Maximum proposed energy: CLIC 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy
But is it affordable?

Mentioned with no CDR:

- plasma-based colliders
- muon collider

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Luminosity goal from the muon collider study
CLIC @ 10 TeV: Luminosity has large impact on physics potential (Ph. Roloff)

CLIC

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Charge per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

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IP beam size	[illegible]	[illegible]	[illegible]	[illegible]	1
Normalised emittance (end of linac)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Normalised emittance	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Estimated power consumption	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Matches the goal $1.8\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$ of

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s}_\mu}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

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Main luminosity drivers

Beam-beam Effect

Bunches are squeezed strongly to maximise luminosity

↓

Electron magnetic fields are very strong

↓

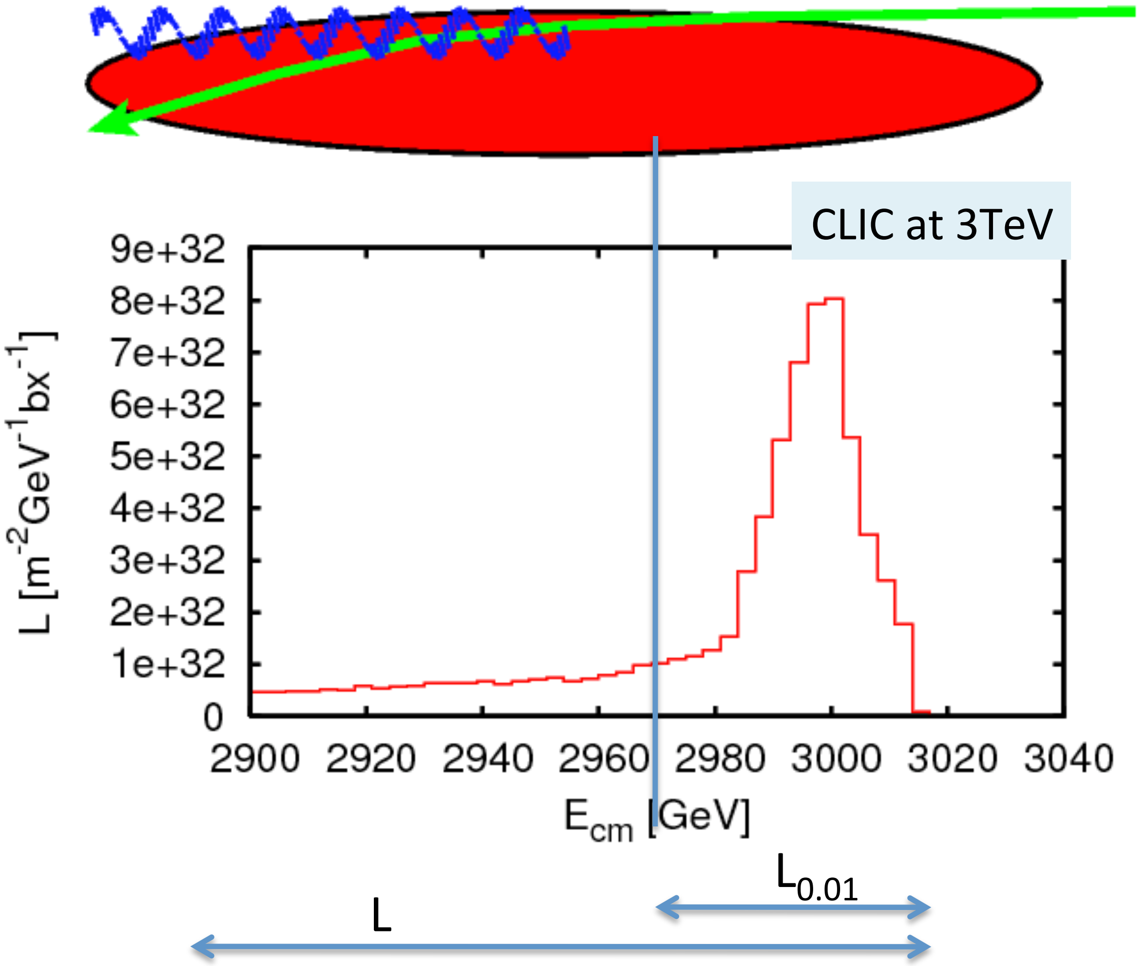
Beam particles travel on curved trajectories

↓

They emit photons (O(1)) (beamstrahlung)

↓

They collide with less than nominal energy



$L_{0.01}$ is luminosity with E_{cm}> 0.99 $E_{cm,0}$

Request from physics
$L_{0.01}/L > 0.6$ below 500GeV
$L_{0.01}/L > 0.3$ at 3TeV

Beamstrahlung Optimisation

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

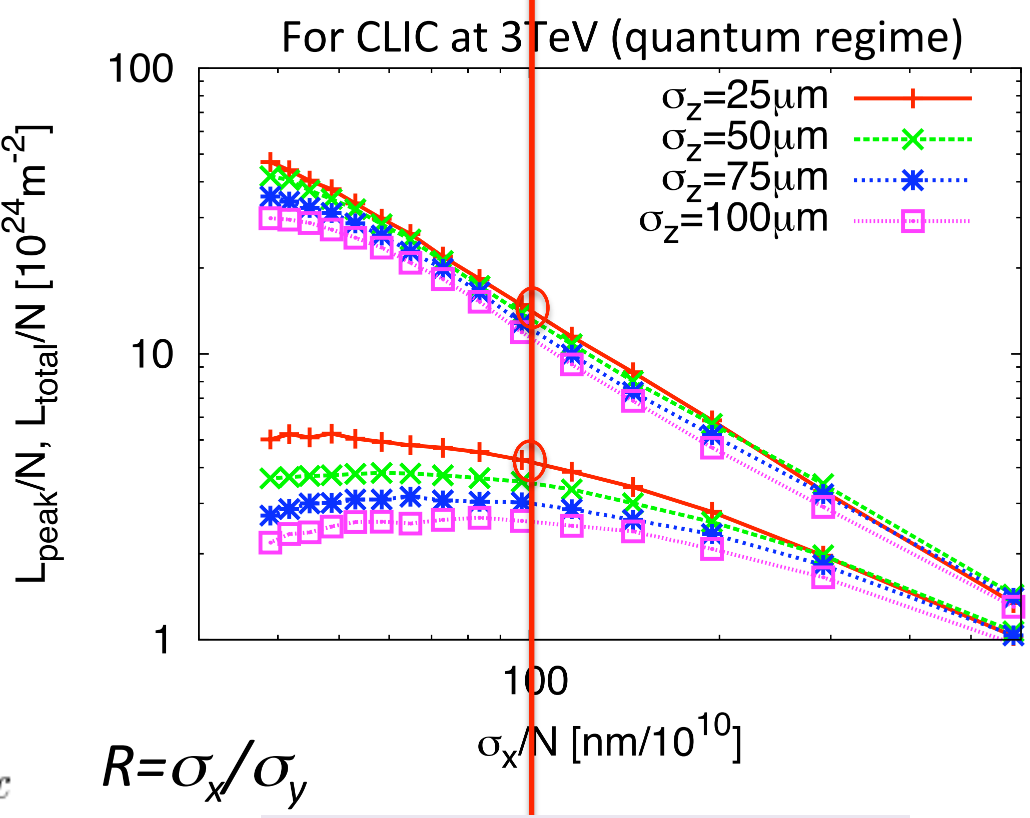
+

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \; I_{beam}$$

↓

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$

$R=\sigma_x/\sigma_y$



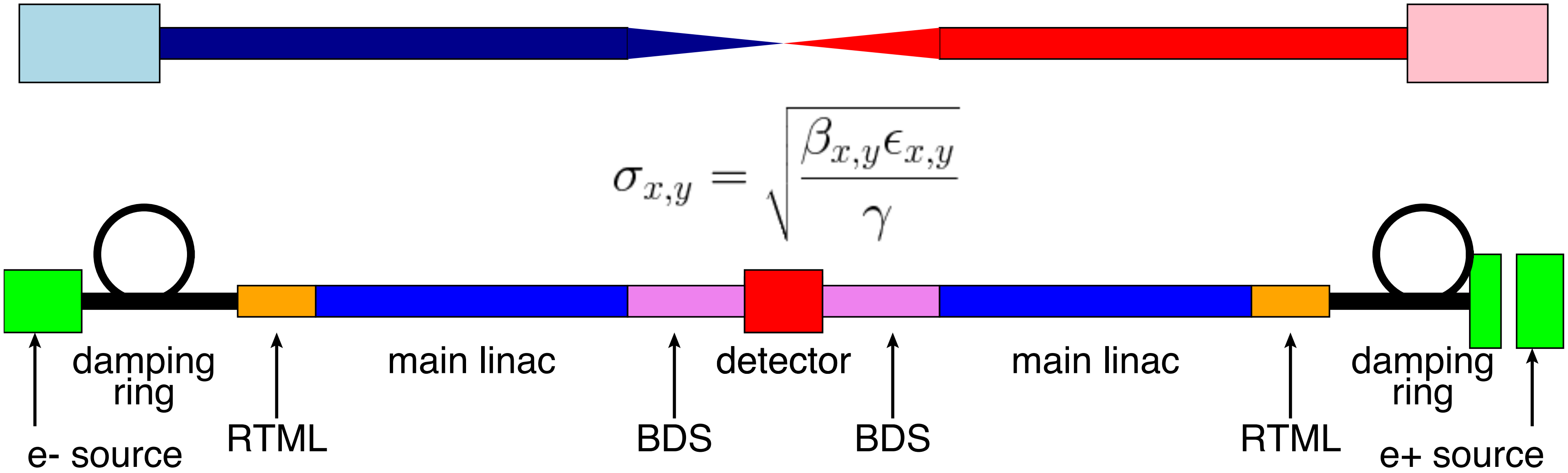
CLIC parameter choice $n_\gamma \approx 2$

$$\sqrt{\beta_x \epsilon_x} \propto N$$

$$\sqrt{\beta_x \epsilon_x} \propto N\sqrt{\sigma_z}$$

Optimum horizontal beam size scales with charge
Must not be smaller
First formula for classical regime
Second formula is for quantum regime

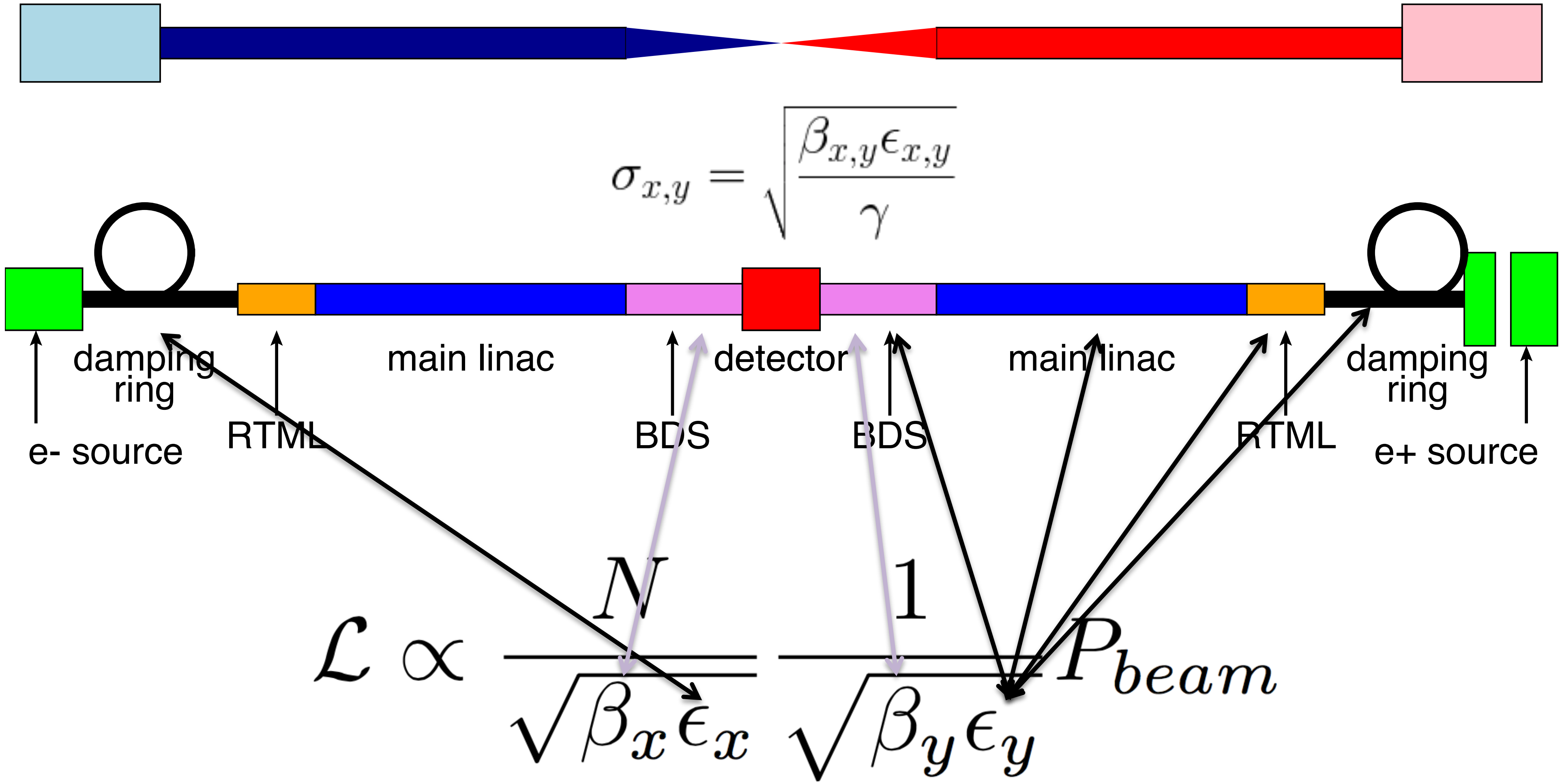
Generic Linear Collider



$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

Generic Linear Collider



Systematic Parameter Determination

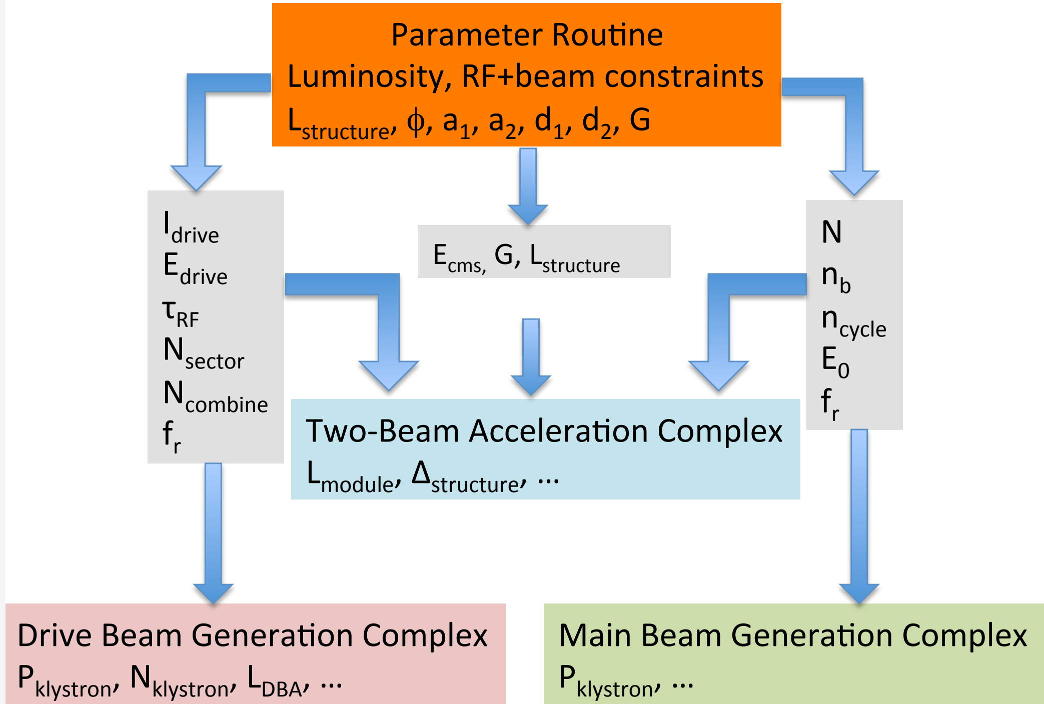
Determined **minimum emittances** and **minimum betafunctions**

Push damping rings as far as possible and budget increase in linac

Push final focus system as far as possible

Determined minimum spot size at interaction point

For each accelerating structure maximise beam current to maximise efficiency



Increase bunch charge and adjust bunch length to remain within 0.35% energy spread at BDS until beam becomes unstable due to transverse wakefields

At IP increase horizontal beam size if required by beamstrahlung

Tried 1.7 billion cases

$\Rightarrow$ Optimum solution is at the limit both of the **minimum beam size** and the **beamstrahlung**

CLIC Luminosity and Imperfections

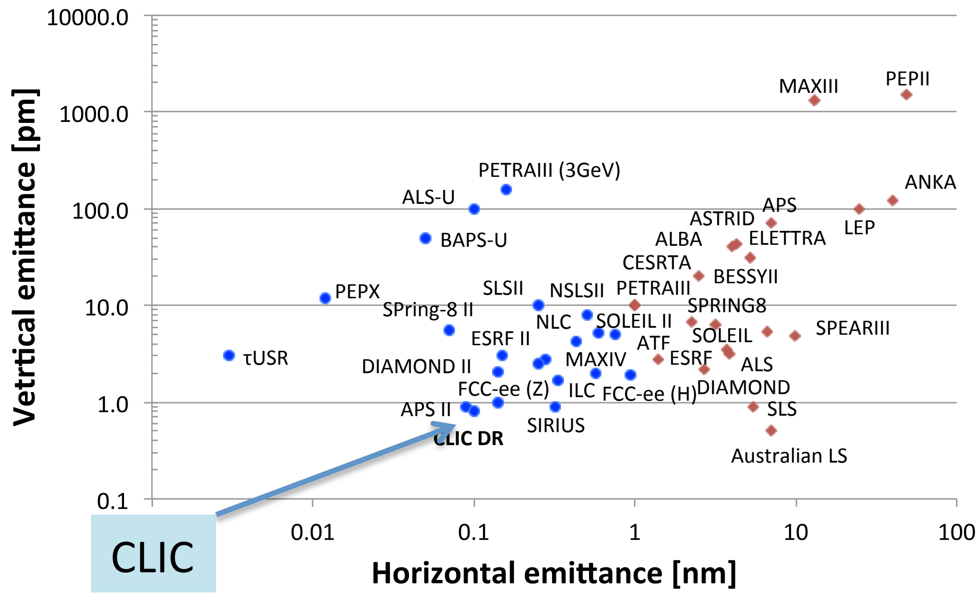
Horizontal emittance mainly driven by design of damping ring, important zero current value and some increase with charge

Vertical emittance is driven by imperfections in all systems

Indicative table for contributions

With no imperfections: more than twice the luminosity

Note: In plasma, **very tight tolerances for driver jitter**, PWFA at E_{cm} = 10 TeV:
position O(0.35 nm)
angle O(0.1 nradian)



	$\Delta \varepsilon_y$ [nm]		
	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	5	+0	+0
End of RTML	1	+2	+2
End of main linac	0	+5	+5
Interaction point	0	+5	+5
sum	6	+12	+12

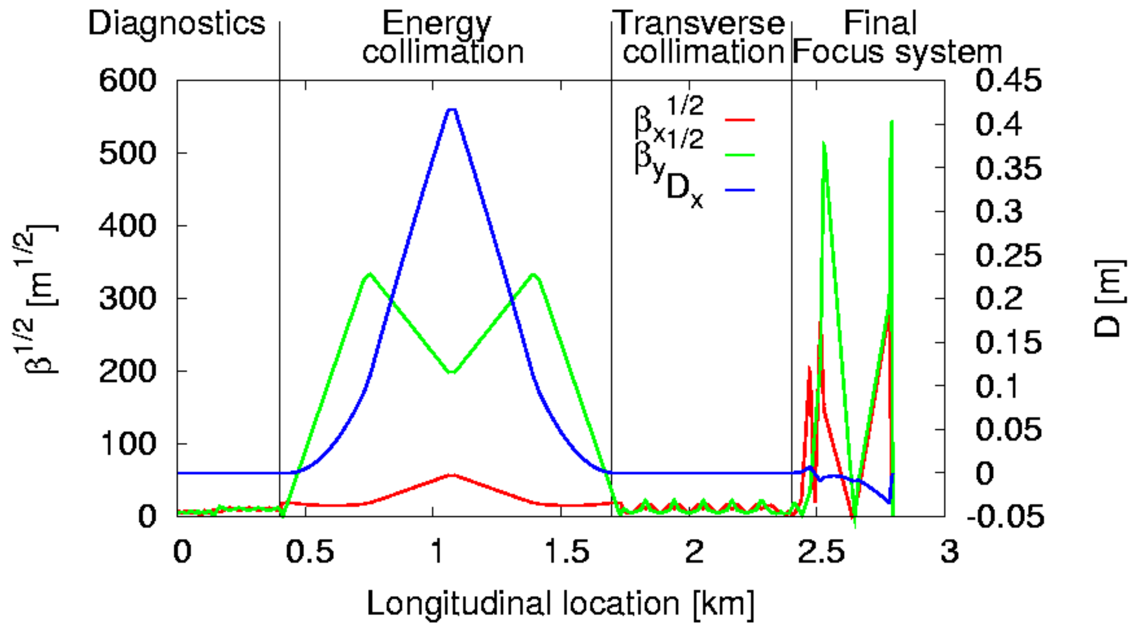
Energy Spread and Focusing

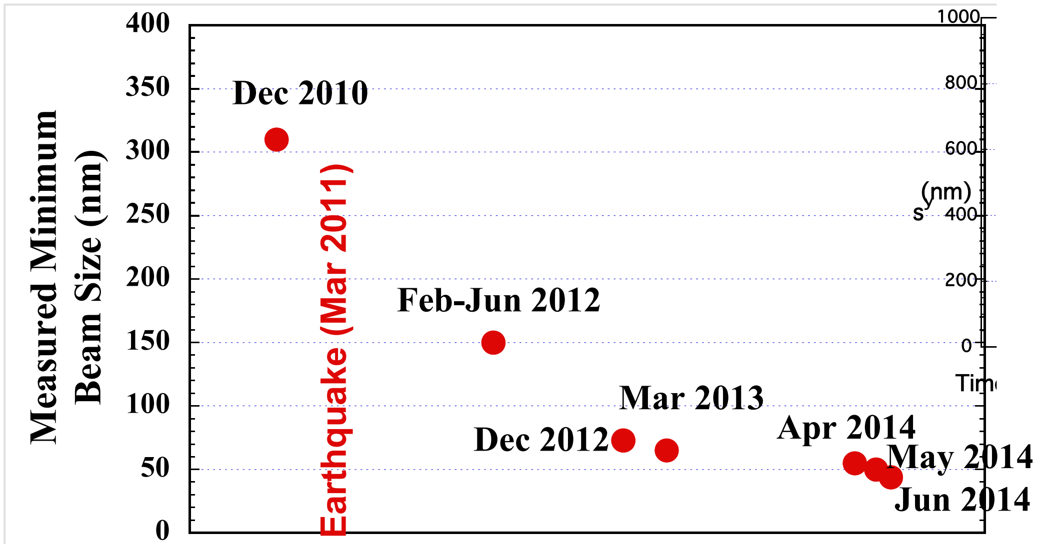
Typically achieve collision betafunctions of O(8 mm x 0.1 mm)

Slightly smaller values do exist but typically we see nonlinear effects at higher energy
⇒ this becomes worse with energy
⇒ "effective betafunction" is limited

Also have limited energy bandwidth
⇒ In CLIC 0.35% RMS spread
⇒ This is an important limitation for CLIC efficiency

Important testing effort at ATF2 shows the difficulty of reaching the focusing of current linear collider parameters
=> very hard to push beyond





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Parameter Scaling

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

For constant technology

- bunch charge and length constant
  - they are driven by the main linac technology
- emittances constant
  - they are driven by the beam source
  - preservation of the emittance becomes harder with energy
- betafunctions constant
  - they reflect your ability to design the focusing system
  - focusing becomes harder with energy due to synchrotron radiation

CLIC at 14 TeV:

about 200 MW beam power to reach L = 40 x 10^{34}cm^{-2}s$^{\wedge-1}$

about 600 MW beam power to reach $L_{0.01}$ = 40 x 10^{34}cm^{-2}s$^{\wedge-1}$

Total power consumption is 10-20 x larger

Parameter Examples

Parameter	Unit	"CLIC"	"CLIC"
E_{cm}	TeV	14	14
L	10^{35} $cm^{-2}s^{-1}$	13	0.65
$L_{0.01}$	10^{35} $cm^{-2}s^{-1}$	4	0.2
Coh.		0.5	0.5
Trid.		0.014	0.014
N	10^9	3.73	3.73
f_r	kHz	220	11
P_{beam}	MW	562	28
σ_z	µm	44	44
β_x / β_y	mm	16 / 0.04	16 / 0.04
ε_x / ε_y	nm	660 / 30	
σ_x / σ_y	nm	28 / 0.3	28 / 0.3

Inofficial parameter list

Full luminosity and constant beam power option

f_r values are not ideal

L/P_{beam} is indeed constant but only with a small trick

Had to increase horizontal betafunction because of beamstrahlung

Assume aggressive vertical betafunction, **requires important improvement in focusing**

Do not forget: harder at higher energy

How to Obtain More Luminosity?

Push beam power

Assume the same bunch charge (it is likely similar)

Hard to beat CLIC efficiency (optimistic PWFA from past Snowmass promised factor 2, but seems rather less), hard to increase total power consumption

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

$$\sqrt{\beta_x \epsilon_x} \propto N \sqrt{\sigma_z}$$

Beamstrahlung limit is improved by shorter bunch in plasma, but need novel ideas to reduce betafunction or emittance

CLIC pushed for many years

Need novel ideas to reduce betafunction or emittance

Linear colliders tried for years

A most critical field that requires inventions

Positron Current Impact

Small charge in positron beam $N_+ = \alpha N_-$
⇒ for same spot size luminosity scales as **$L \approx \alpha L_0$**

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

Beam reduces radiation of electron beam
⇒ more collisions at full energy

$$n_\gamma \propto \left(\frac{\sqrt{\sigma_z} N}{\sqrt{\epsilon_x \beta_x} + \sqrt{\epsilon_y \beta_y}} \right)^{2/3}$$

$N_+ = 0.1 N_-$
Almost no radiation from electrons
⇒ Can about double radiation for positrons
⇒ Can reduce horizontal beamsize by sqrt(1/8)
 ⇒ provided we can achieve this
⇒ Only loose about factor 4 in luminosity

$N_+ < 0.1 N_-$
lose about linearly with $L \approx 2.5\ \alpha\ L_0$

$N_+ = 0.3 N_-$
lose about factor 2

Need to maintain reasonable positron current
Need to push horizontal beam size even further

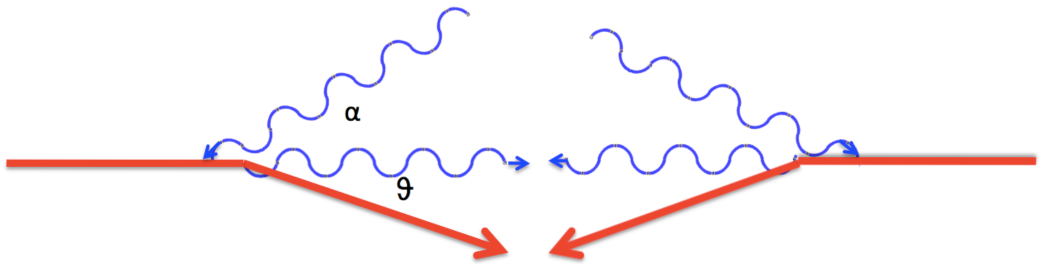
Note: Background is not forward-backward symmetric

Gamma-gamma Collider Concept

Based on $e^- e^-$ collider

Collide electron beam with laser beam before the IP

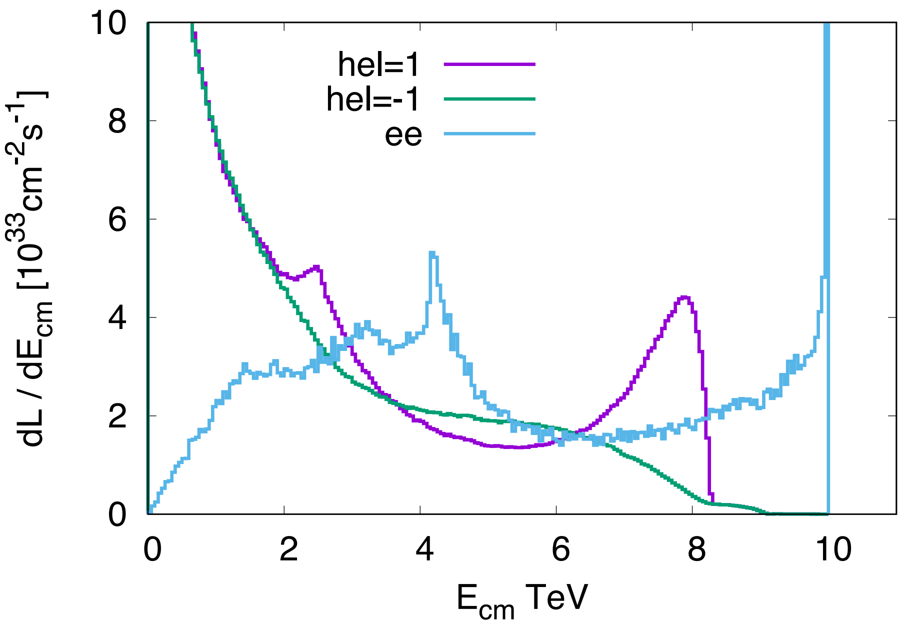
Still focus beam to minimal spot size



Backscattered photons form a spectrum

Practical maximum energy is 83% of electron energy

Typically gamma-gamma luminosity above 60% of the nominal centre-of-mass energy is O(0.1) of electron-positron luminosity for same beam parameters

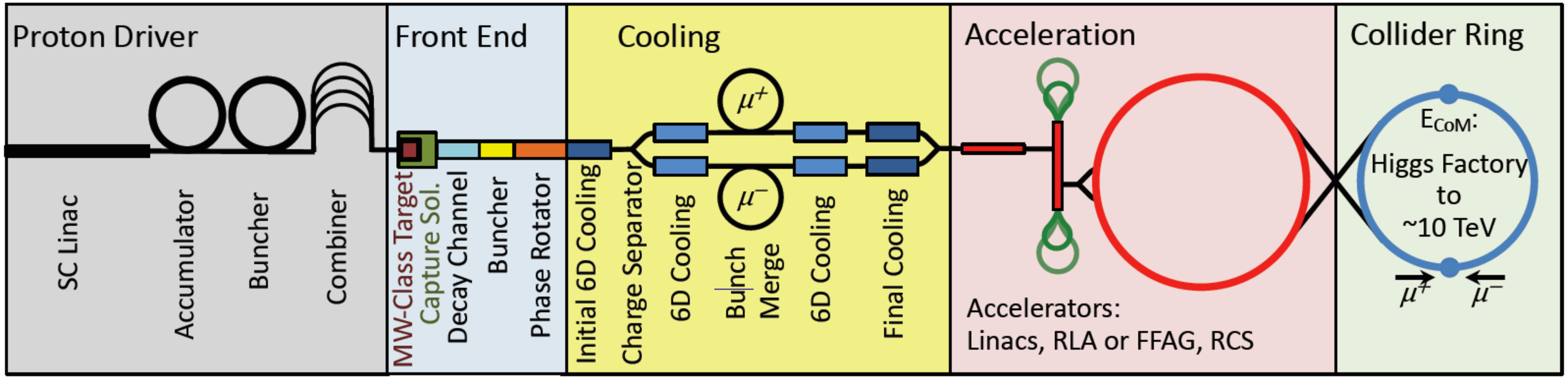


Luminosity for arbitrary 10 TeV example based on CLIC parameters

total	$1.2\ L_{geom}$	$= 0.8\ L$
above 60%	$0.15\ L_{geom}$	$= 0.1\ L$

Proton-driven Muon Collider Concept

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Collision

Potentially, plasma could be useful for acceleration (but high bunch charge, potential alternative LEMMA scheme with much smaller charge, much larger emittances are OK)
Other options should be explored
Plasma expertise could help for cooling studies (gas-filled cavities)

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Conclusion

- Plasma-based technology is potentially interesting to reduce the cost of linear collider main linacs
- But require preservation of excellent beam quality is much harder than in CLIC
  - challenging because of the strong focusing, which is required for beam stability

- Extension beyond 3 TeV will require novel solutions to reach high luminosity
  - much reduced emittance compared to CLIC
  - or much better focusing
- This requires to move beyond where linear colliders have been able to go
  - ⇒ Have to search for novel solutions
  - ⇒ Synergy with linear colliders
- Luminosity is very important

- Positron acceleration is important, lower current is impacting luminosity
  - I do not think that hollow plasma allows stable positrons beams

- Gamma-gamma collider have large energy spread and luminosity is reduced by about one order of magnitude
  - even smaller beams would be required