# CLIC Main Beam Injector Complex review

L. Rinolfi

with many contributions from CLIC collaborators

# Preliminary overview

The CLIC Main Beams Injector Complex has 3 studies corresponding to 3 configurations:

## 1) Base Line configuration:

The study is based on 3 TeV (c.m.) with unpolarized $e^+$ source and with very tiny emittances for the Damping Rings.

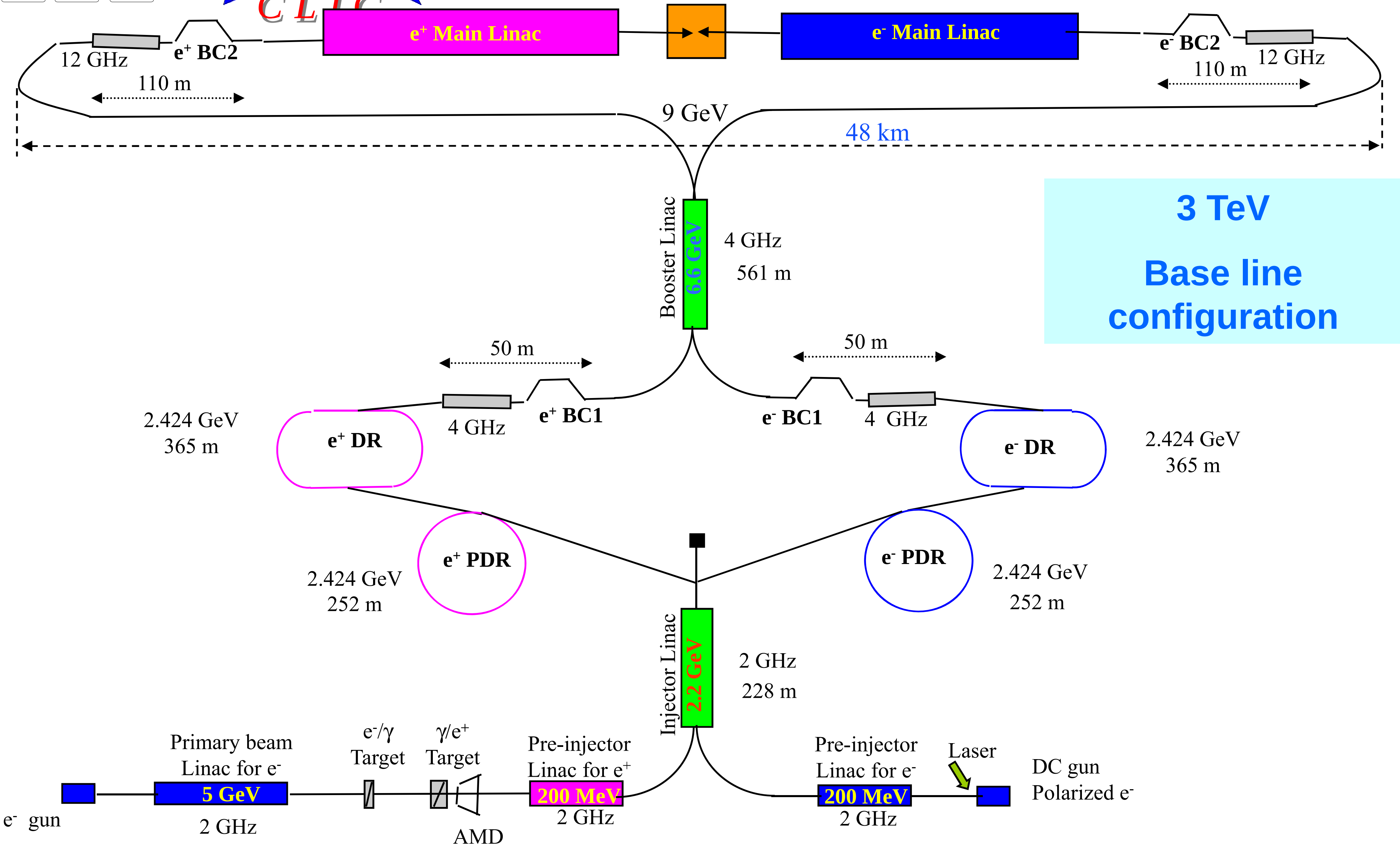
## 2) Compton configuration:

The study is based on 3 TeV (c.m.) with polarized $e^+$ source. The undulator option is an alternative.

## 3) Low energy configuration:

The study is based on 500 GeV (c.m.) but with a double charge per bunch:
=> impacts on the $e^-$ / $e^+$ sources and Damping Rings.

# The CLIC Injector complex in 2008



# CLIC Main beam parameters

## At the entrance of the Main Linac for e⁻ and e⁺

| | | NLC (1 TeV) | CLIC 2008 (0.5 TeV) | CLIC 2008 (3 TeV) | ILC (0.5 TeV) |
|---|---|---|---|---|---|
| $E$ | GeV | 8 | 9 | 9 | 15 |
| $N$ | $10^9$ | 7.5 | 7 | 3.72 - 4 | 20 |
| $n_b$ | - | 190 | 312 | 312 | 2625 |
| $\Delta t_b$ | ns | 1.4 | 0.5 (6 RF periods) | 0.5 (6 RF periods) | 369 |
| $t_{pulse}$ | ns | 266 | 156 | 156 | 968925 |
| $\varepsilon_{x,y}$ | nm, nm | 3300, 30 | 2620, 10 | 600, 10 | 8400, 24 |
| $\sigma_z$ | µm | 90-140 | 72 | 43 - 45 | 300 |
| $\sigma_E$ | % | 0.68 (3.2 % FW) | 2 | 1.5 - 2 | 1.5 |
| $f_{rep}$ | Hz | 120 | 50 | 50 | 5 |
| $P$ | kW | 219 | 180 | 90 | 630 |

# CLIC $e^-$ Beam Source Parameters

| Parameter | Symbol | CLIC |
|---|---|---|
| Number Electrons per microbunch | $N_e$ | $6 \times 10^9$ |
| Number of microbunches | $n_b$ | 312 |
| Width of microbunch | $t_b$ | ~ 100 ps |
| Time between microbunches | $\Delta t_b$ | 500.2 ps |
| Microbunch rep rate | $f_b$ | 1999 MHz |
| Width of macropulse | $T_B$ | 156 ns |
| Macropulse repetition rate | $f_{rep}$ | 50 Hz |
| Charge per micropulse | $C_b$ | 0.96 nC |
| Charge per macropulse | $C_B$ | 300 nC |
| Average current from gun ($C_B$ x $f_{rep}$) | $I_{ave}$ | 15 uA |
| Average current macropulse ($C_B$ / $T_B$) | $I_B$ | 1.9 A |
| Duty Factor w/in macropulse (100ps/500ps) | DF | 0.2 |
| Peak current of micropulse ($I_B$ / DF) | $I_{peak}$ | 9.6 A |

If spot radius = 1 cm

=> challenge for an cathode/anode optics with uniform focusing properties

=> Current density
$J = 3\ A/cm^2$

For 500 GeV option

=> I peak ≈ 20 A
=> Current density
$J \approx 6\ A/cm^2$

# ILC and CLIC $e^-$ sources

M. Poelker / JLAB F. Zhou / SLAC

| Parameters | ILC | CLIC |
|---|---|---|
| Electrons/microbunch | ~3E10 | 6E9 |
| Number of microbunches | 2625 | 312 |
| **Width of Microbunch** | **1 ns** | **~100 ps** |
| **Time between microbunches** | **~360 ns** | **500.2 ps** |
| **Width of Macropulse** | **1 ms** | **156 ns** |
| Macropulse repetition rate | 5 Hz | 50 Hz |
| **Charge per macropulse** | **~12600 nC** | **300 nC** |
| Average current from gun | 63 μA | 15 μA |
| Peak current of microbunch | 4.8 A | 9.6 A |
| **Current density (1 cm radius)** | **1.5 A/cm$^2$** | **3 A/cm$^2$** |
| **Polarization** | **>80%** | **>80%** |

# Summary



- SLAC has an unique diagnostic to characterize polarized photo-cathodes.

- Recent systematic measurements for one InAlGaAs/AlGaAs sample

- 0.3% QE

- QE lifetime measured is 120-150 hrs.

- 84% of polarization

- Surface charge limit is observed, current intensity with 0.06 A/cm$^2$ @ 7x10$^{18}$/cm$^3$ of doping in surface.

- First observation of polarization dependence on surface charge limit.

- Need optimize parameters of InAlGaAs/AlGaAs to meet cathode critical requirements for linear collider sources.

# CLIC polarized e$^-$ source challenges

## From JLAB and SLAC experience:

- Photocathode material (Strained GaAs…) => Polarization > 80 %
- Photo-cathodes preparation techniques => High QE
- High voltage and high field gradient => No field emission
- Ultrahigh vacuum requirements => range of $10^{-11}$ Torr

## CLIC challenges:

- High bunch charge and high peak current => Space charge and surface charge limits
- Pre-Injector design
- Drive laser
- For 500 GeV option, the gun could be a critical issue if the charge is doubled

**Collaborations are on going with JLAB and SLAC**

# Transport efficiency for $e^+$ beam

| | # of bunches per pulse | # of positrons per bunch | # of positrons per pulse | Total charge (nC) | Current (A) |
|---|---|---|---|---|---|
| Exit of BC2 = Entrance of Main Linac ( 9 GeV) | 312 | $4 \times 10^9$ | $1.24 \times 10^{12}$ | 200 | 1.3 |
| At exit Pre- Damping ring (2.424 GeV) | 312 | $4.4 \times 10^9$ | $1.37 \times 10^{12}$ | 220 | 1.4 |
| At exit Injector Linac (2.424 GeV) | 312 | $6.4 \times 10^9$ | $2 \times 10^{12}$ | 319 | 2 |
| At exit Pre- Injector Linac (200 MeV) | 312 | $6.7 \times 10^9$ | $2.1 \times 10^{12}$ | 334 | 2.1 |

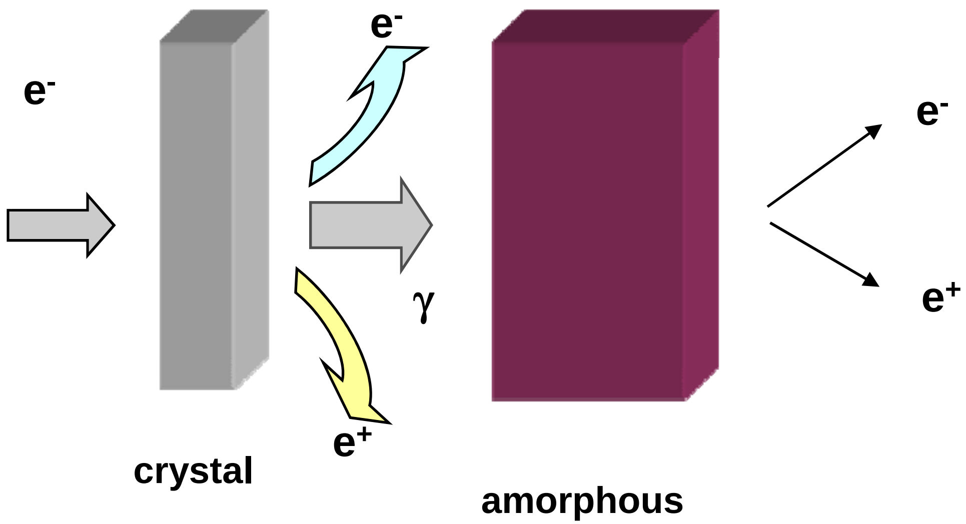
Assuming ~ 90 % efficiency between the PDR and the Main Linac

Assuming ~ 70 % capture efficiency in the PDR

Assuming ~ 95 % efficiency between the Pre-Injector and the Injector Linac

# Unpolarized $e^+$ source by channelling

A $e^-$ beam impinges on the crystal:
- energy of 5 GeV
- beam size of 2.5 mm




- A crystal e+ source :
- - a 1.4 mm thick W crystal oriented along <111> axis
- - a 10 mm thick W amorphous disk

- Charged particles are swept off after the crystal:only γ (> 2MeV) impinge on the amorphous target.

Yield: 0.92 $e^+$ / $e^-$

@ 200 MeV

- The distance between the 2 targets is 2 meters.

R. Chehab / IPNL-Lyon, A. Variola, A. Vivoli / LAL, V.M.Strakhovenko / BINP - Novosibirsk

# $e^+$ by channeling from hybrid targets

| Parameter | Unit | CLIC |
|---|---|---|
| **Primary $e^-$ Beam** | | |
| Energy | GeV | 5 |
| N $e^-$ /bunch | $10^9$ | 7.5 |
| N bunches / pulse | - | 312 |
| N $e^-$ / pulse | $10^{12}$ | 2.34 |
| Pulse length | ns | 156 |
| Repetition frequency | Hz | 50 |
| Beam power | kW | 94 |
| Linac frequency | GHz | 2 |
| Beam radius (rms) | mm | 2.5 |
| Bunch length (rms) | mm | 0.3 |

| Parameter | Unit | | |
|---|---|---|---|
| **Target** | | Crystal | Amorph. |
| Material | | W | W |
| Length | mm | 1.4 | 10 |
| Beam power deposited | kW | 0.2 | 7.5 |
| Deposited P / Beam Power | % | 0.2 | 8 |
| Energy lost per volume | $10^9$ GeV/mm$^3$ | 0.8 | 1.9 |
| Peak energy deposition density (PEDD) | J/g | 6.8 | 15.5 |

**Experimental limit found at SLAC: PEDD = 35 J/g => We have a factor 2 as safety margin**

**At 500 GeV, if charge is doubled => Double target stations ??**

# Parameters for $e^+$ capture section

| | | R. Chehab (*) | A. Vivoli (**) |
|---|---|---|---|
| AMD[1] Magnetic Field | T | 7 - 0.5 | 6 - 0.5 |
| AMD Length | m | 0.21 | 0.5 |
| Pre-accelerator Length | m | | 43 |
| Solenoid Magnetic Field | T | 0.5 | 0.5 |
| Cavities Frequency | GHz | 1.5 | 1.3 |
| Peak Electric Field intensity | MV/m | 25 | 18 |

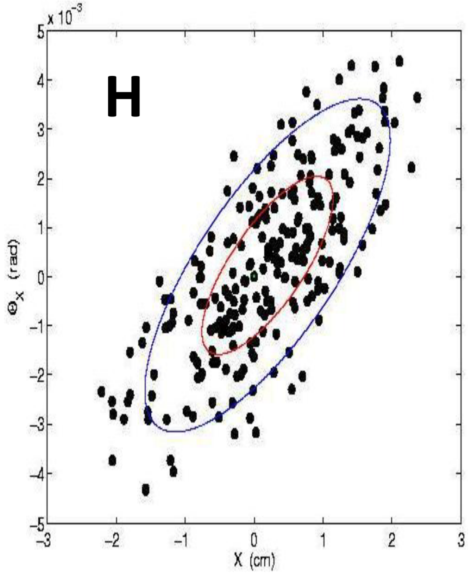
(*) CLIC previous parameters (CLIC Note 465)

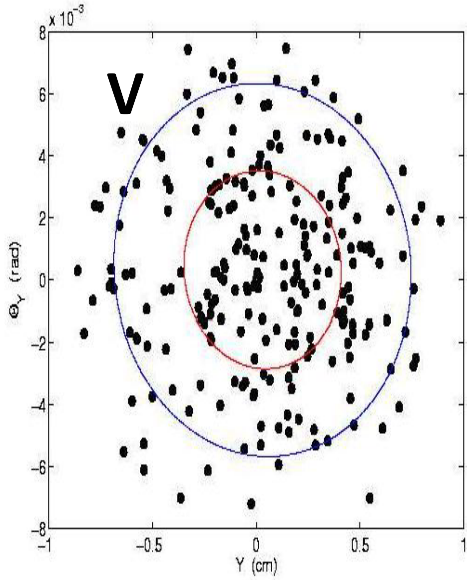
(**) New AMD with ILC frequency and gradient. Simulations will be revisited with CLIC frequency (at 2 GHz) and CLIC gradient (15 MV/m).

1) AMD = Adiabatic Matching Device : it is composed of a flux concentrator and long solenoids along the linac accelerating sections

# Simulations $e^+$ source based on channelling

- **TRANSVERSE EMITTANCES AT END OF CLIC PRE-INJECTOR ($\sigma^- = 2.5$ mm)**



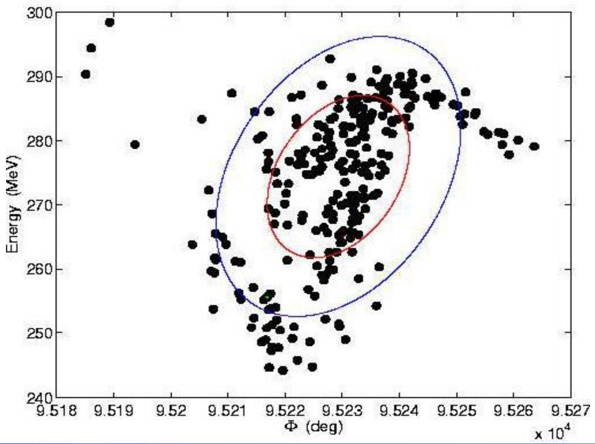




**Blue: 80 %**
**Red: rms**

$\varepsilon_x = \varepsilon_y$ = **17$\pi$ mm.mrad**

$\gamma\varepsilon_x = \gamma\varepsilon_y$ = **6650 $\pi$ mm.mrad**

- **LONGITUDINAL EMITTANCE AT END OF CLIC PRE-INJECTOR @ 200 MeV**




**Blue: 80 %**

**Red: rms**

$\varepsilon_z$ **= 13.6 cm.MeV = 136000 eV.m**

**R. Chehab, A. Variola, A. Vivoli, V.M.Strakhovenko**

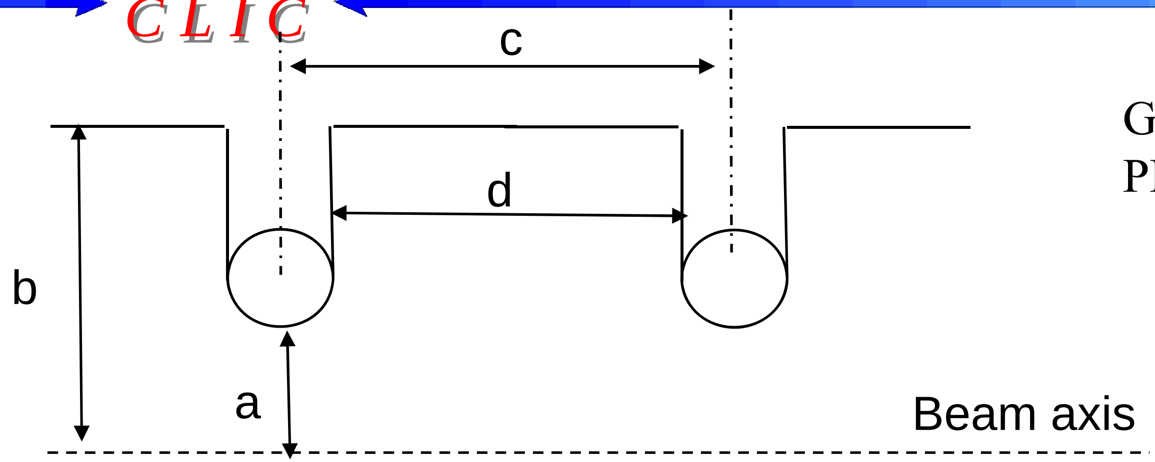
# Pre-Injector Linac for $e^+$

| Parameter | Unit | CLIC Note 465 (T. Kamitani, L.R.) | CLIC 2008 (A. Vivoli) |
|---|---|---|---|
| Energy (E) | GeV | 0.2 | 0.2 |
| No. of particles/bunch (N) | $10^9$ | 6.7 (*) | 6.7 (*) |
| Bunch length (rms) ($\sigma_z$) | mm | 5 | 11 |
| Energy Spread (rms) ($\sigma_E$) | % | 3.5 | 6 |
| Longitudinal emittance | eV.m | 35000 | 136000 |
| Horizontal emittance ($\gamma\varepsilon_x$) | mm. mrad | 9200 | 6650 |
| Vertical emittance ($\gamma\varepsilon_y$) | mm. mrad | 9200 | 6650 |

(*) Assuming 95 % of transmission efficiency in the Injector Linac and 70% of capture efficiency in the PDR

=> N ($e^+$) = 6.4 x $10^9$ => Q $\cong$ 1 nC

# Scaling from NLC (S-band) structures




Geometry needed for
PLACET simulations

| | Units | 2 GHz | 2.856 GHz | 4 GHz |
|---|---|---|---|---|
| a | mm | 22 | 15.4 | 11 |
| b | mm | 64.3 | 45 | 32 |
| c | mm | 50 | 35 | 25 |
| d | mm | 42.8 | 30 | 21 |
| G (unloaded) | MV/m | 17 | 25 | 36 |
| G (loaded) 1.3 A | MV/m | 15 | 22 | 30 |
| L | m | 4 | 4 | 3 |
| | | CLIC Injector | NLC structure | CLIC Booster |

# Injector Linac output parameters

Pre-Damping ring input

rms values

| Parameter | Unit | **$e^-$** | **$e^+$** |
|---|---|---|---|
| Energy (E) | GeV | 2.424 | 2.424 |
| No. of particles/bunch (N) | $10^9$ | 4.4 | 6.4 |
| Bunch length (rms) ($\sigma_z$) | mm | 1 | 5 |
| Energy Spread (rms) ($\sigma_E$) | % | 0.1 | 2.7 (*) |
| Horizontal emittance ($\gamma\varepsilon_x$) | mm. mrad | 100 | 9300 |
| Vertical emittance ($\gamma\varepsilon_y$) | mm. mrad | 100 | 9300 |

(*) Simulations have been performed with a bunch compressor at the entrance of the Injector Linac which brings the bunch length from 5 mm down to 2mm:

=> The rms energy spread, at 2.4 GeV, is just below 1% (see CLIC Note 737)

# CLIC Pre-Damping Ring for the Base line

F. Antoniou / CERN

| PARAMETER | PDR |
|---|---|
| Eenergy [GeV] | 2.424 |
| Circumference [m] | 252 |
| Number of particles / bunch [$10^9$] | 4.4 |
| Number of trains | 1 |
| FWHH momentum spread [%] accepted at injection | 3 % (~ 1.3 % rms) (*) |
| Hor. /ver. / lon./ damping times [ms] | 2.5 / 2.5 / 1.2 (**) |
| Repetition rate [ms] | 20 |
| RF frequency [GHz] | 2 |

(*) The rms momentum spread at injection could be reduced (~ 1%) by implementing either a bunch compressor at the entrance of the injector Linac (see previous slide) or an harmonic cavity which smooth the longitudinal distribution.

(**) With 6 damping times the injected normalized emittances are reduced from:

$\gamma\varepsilon$ = 9300 mm.mrad down to $\gamma\varepsilon$ = 18 mm.mrad

# CLIC Pre-Damping Ring for $e^+$ stacking

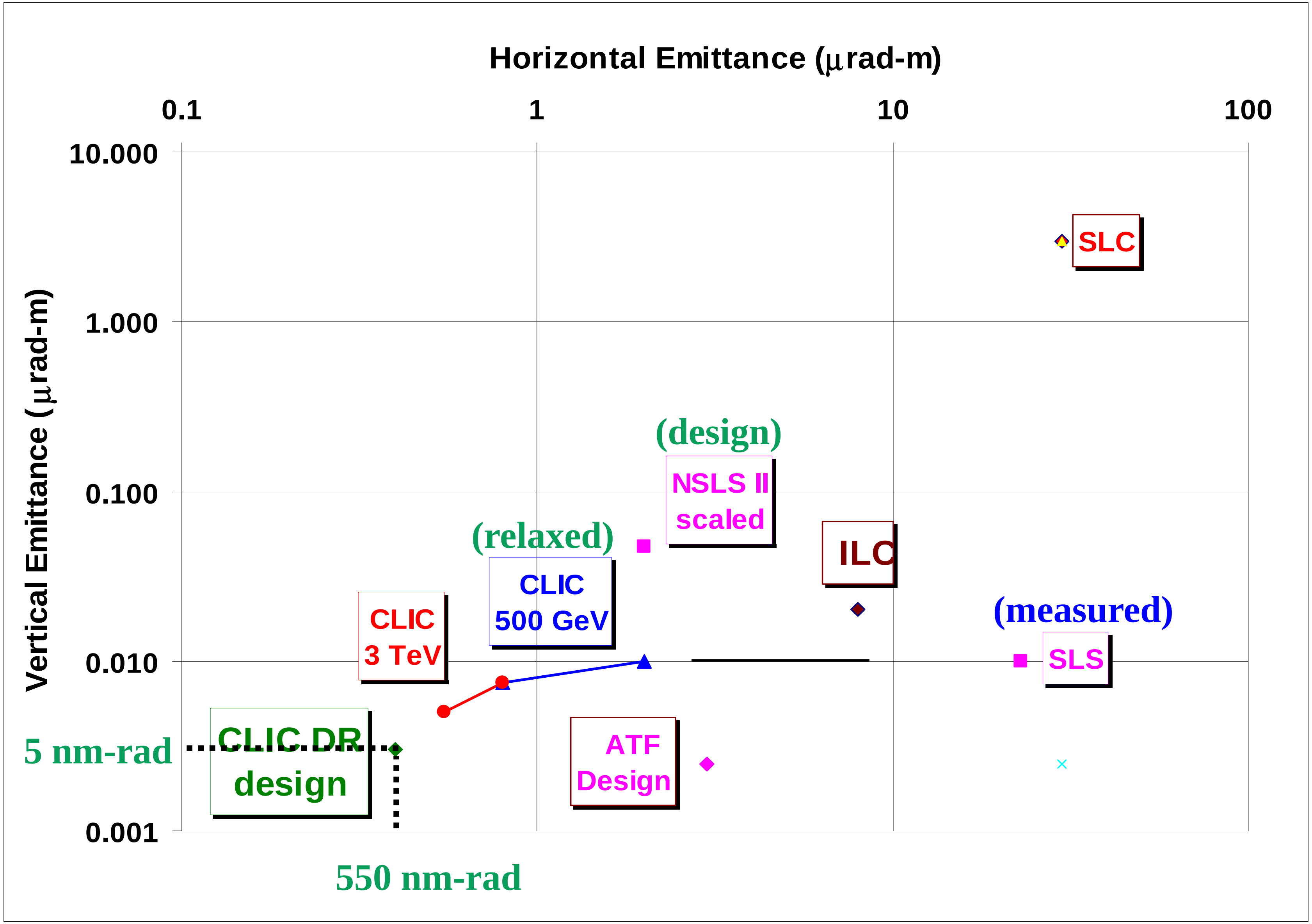
| PARAMETER | PDR Present design | PDR Larger ring |
|---|---|---|
| Eenergy [GeV] | 2.424 | 2.424 |
| Ring circumference [m] | 252 | ≈ 500 |
| Number of particles / bunch [$10^9$] | 4.4 | 4.4 |
| Number of trains | 3 | 1 |
| rms momentum spread [%] accepted at injection | 1.3 | 1.3 |
| Hor./ver./ lon./ damping times [ms] | 2.5 / 2.5 / 1.2 | ≈ 1 / 1 / 0.5 |
| Repetition rate [ms] | 20 | 20 |
| RF frequency [GHz] | 2 | 2 |

The present layout needs to do stacking with 3 trains into the PDR.

However if the circumference is doubled, and superconducting wigglers implemented, may be $\tau_{x,y} \approx 1$ ms (which could to allow ≈ 10 damping times) and then have roughly 10 ms for the $e^+$ stacking.

# Beam emittances at Damping Rings

J.P. Delahaye / CERN



# CLIC Damping Rings emittances

Y. Papaphilippou / CERN

| PARAMETER | NLC | CLIC requested | (obtained by design) |
|---|---|---|---|
| Energy (GeV) | 1.98 | 2.424 | |
| Bunch population ($10^9$) | 7.5 | 4.1 | |
| Bunch spacing [ns] | 1.4 | 0.5 | |
| Number of bunches / train | 192 | 312 | |
| Number of trains | 3 | 1 | |
| Repetition rate [Hz] | 120 | 50 | |
| Extracted hor. normalized emittance [nm] | 2370 | <550 | (382) |
| Extracted ver. normalized emittance [nm] | <30 | <5 | (4) |
| Extracted long. normalized emittance [eV m] | 10890 | <5000 | (4990) |

For 500 GeV option, the nominal requested rms normalized emittances are:

$$\gamma\varepsilon_x = 2400 \text{ nm-rad} \quad \text{and} \quad \gamma\varepsilon_y = 10 \text{ nm-rad}$$

CLIC

# Collective effects issues

## 1) Pre-Damping Rings and Damping Rings

- Space Charge

  => important emittance growth

- Single bunch instability thresholds
- Resistive wall coupled bunch instabilities
- Electron cloud (Positron rings)

  => constraints on the wigglers

  => special vacuum chamber coating

- Fast Beam Ion Instability (Electron rings)

  => vacuum < 1 nTorr

- Intra Beam Scattering (IBS)

  => crucial effects on emittances

## 2) Transfer Lines

- Fast Beam Ion Instabilities

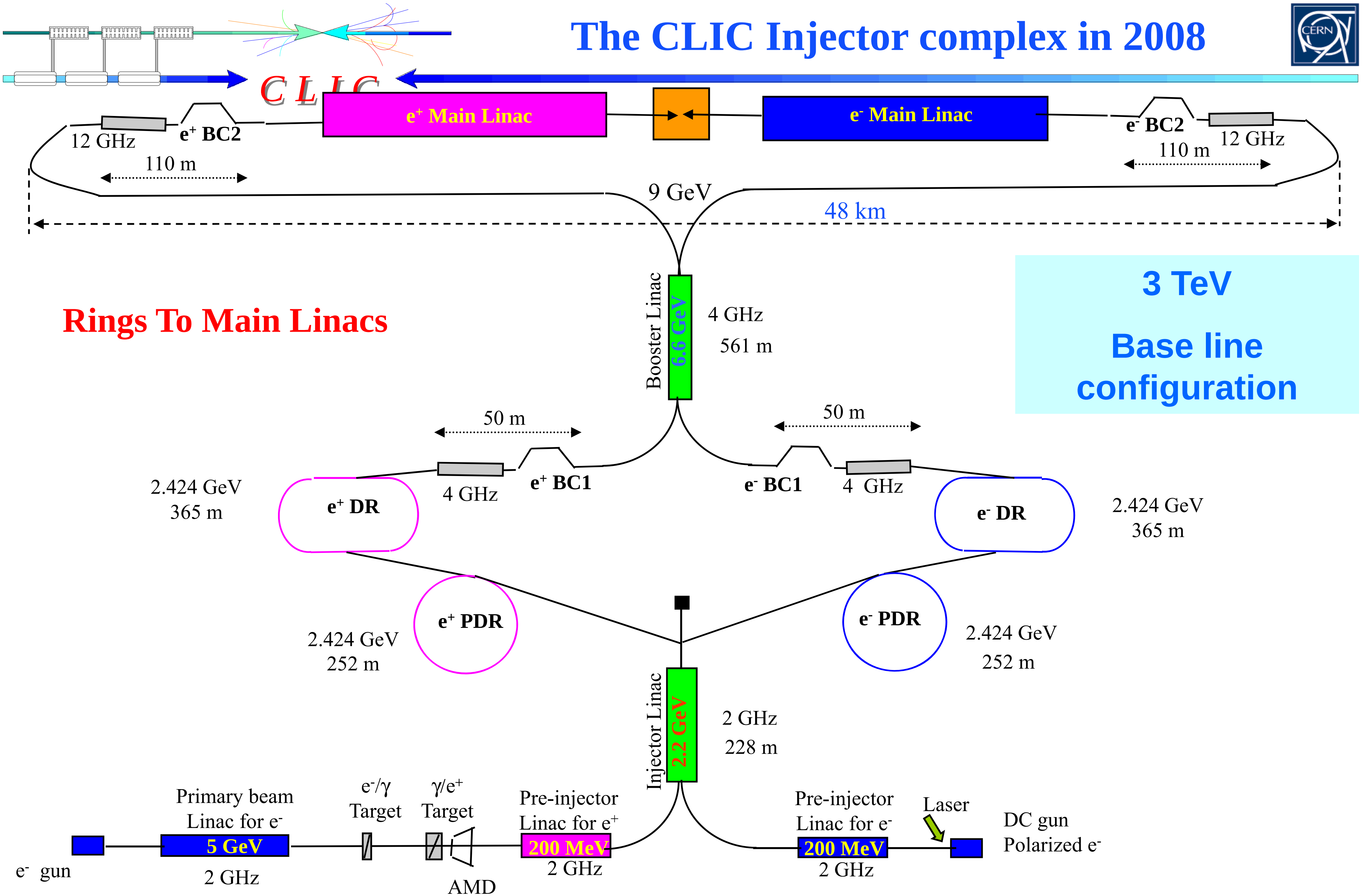
  => vacuum 0.1 nTorr

- CSR in Bunch Compressors
- ISR in turn around loop

See talks:

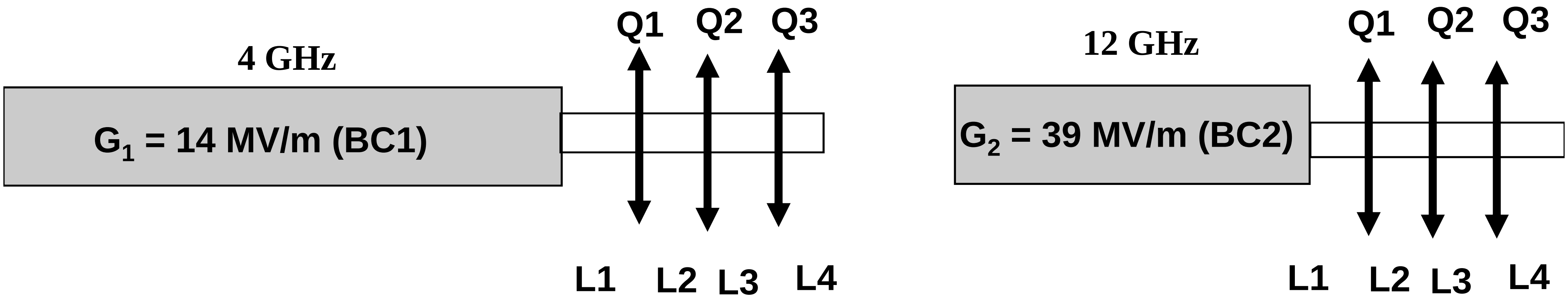
**M. Martini / CERN**
**G. Rumolo / CERN**
**F. Stulle / CERN**
**M. Taborelli / CERN**

# The CLIC Injector complex in 2008



# BC1 and BC2 for the energy-time correlation

| Triplet for BC1 | |
|---|---|
| *Number of Accelerating sections (L= 4 m)* | 4 |
| *Number of quadrupoles between accelerating sections (Quad length = 36 cm)* | 4 x 3 = 12 |



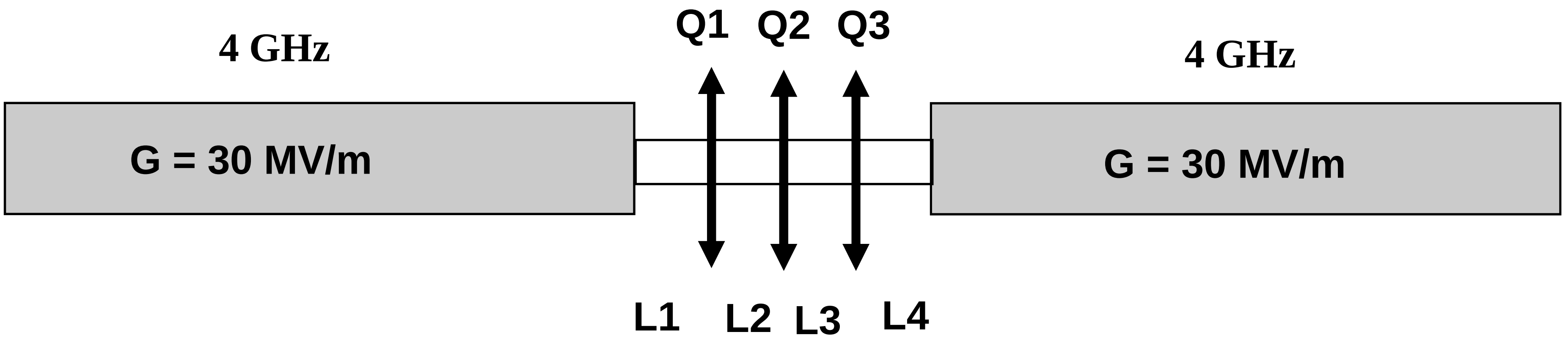

| Triplet for BC2 | |
|---|---|
| *Number of Accelerating sections (L= 1 m)* | 64 |
| *Number of quadrupoles between accelerating sections (Quad length = 36 cm)* | 64 x 4 = 256 |

# The two stages of the Bunch Compressor

| Parameter | DR | BC1 | | BC2 | |
|---|---|---|---|---|---|
| | Out | In | Out | In | Out |
| Energy (GeV) | 2.424 | 2.424 | 2.424 | 9 | 9 |
| No. of $e^+$ /bunch ($10^9$) | 4.1 | 4.1 | 4.1 | 3.9 | 3.9 |
| Bunch length (rms) (mm) | 1.5 | 1.5 | 0.175 | 0.175 | 0.044 |
| Energy Spread (rms) (%) | 0.137 | 0.137 | 1.17 | 0.316 | 1.26 |
| Longitud. emitt. (eV.m) | < 5000 | < 5000 | < 5000 | < 5000 | < 5000 |
| BC factor | - | 8.6 | | 4 | |
| RF frequency | - | 4 GHz | | 12 GHz | |
| Gradient (Loaded) | - | 14 MV/m | | 39 MV/m | |
| Structure length | | 4 m | | 1 m | |
| RF voltage | - | 224 MV (4 ACS) | | 2480 MV (64 ACS) | |
| Length of linac | - | 16 m | | 64 m | |
| Length of chicane | - | 30 m | | 40 m | |
| Total length | - | ~ 50 m | | ~ 110 m | |

# CLIC Booster Linac optics parameters

| **Triplet** | |
|---|---|
| *Number of Accelerating sections (L= 3 m)* | 75 |
| *Number of quadrupoless between accelerating sections (Quad length = 36 cm)* | 75 x 3 = 225 |




$Q1 = Q3 = 0.19\ m^{-2}$

$Q2 = 0.37\ m^{-2}$

L1 = L2 = L3 = L4 = 0.60 m

# Booster Linac output parameters

Beginning of the long transfer line

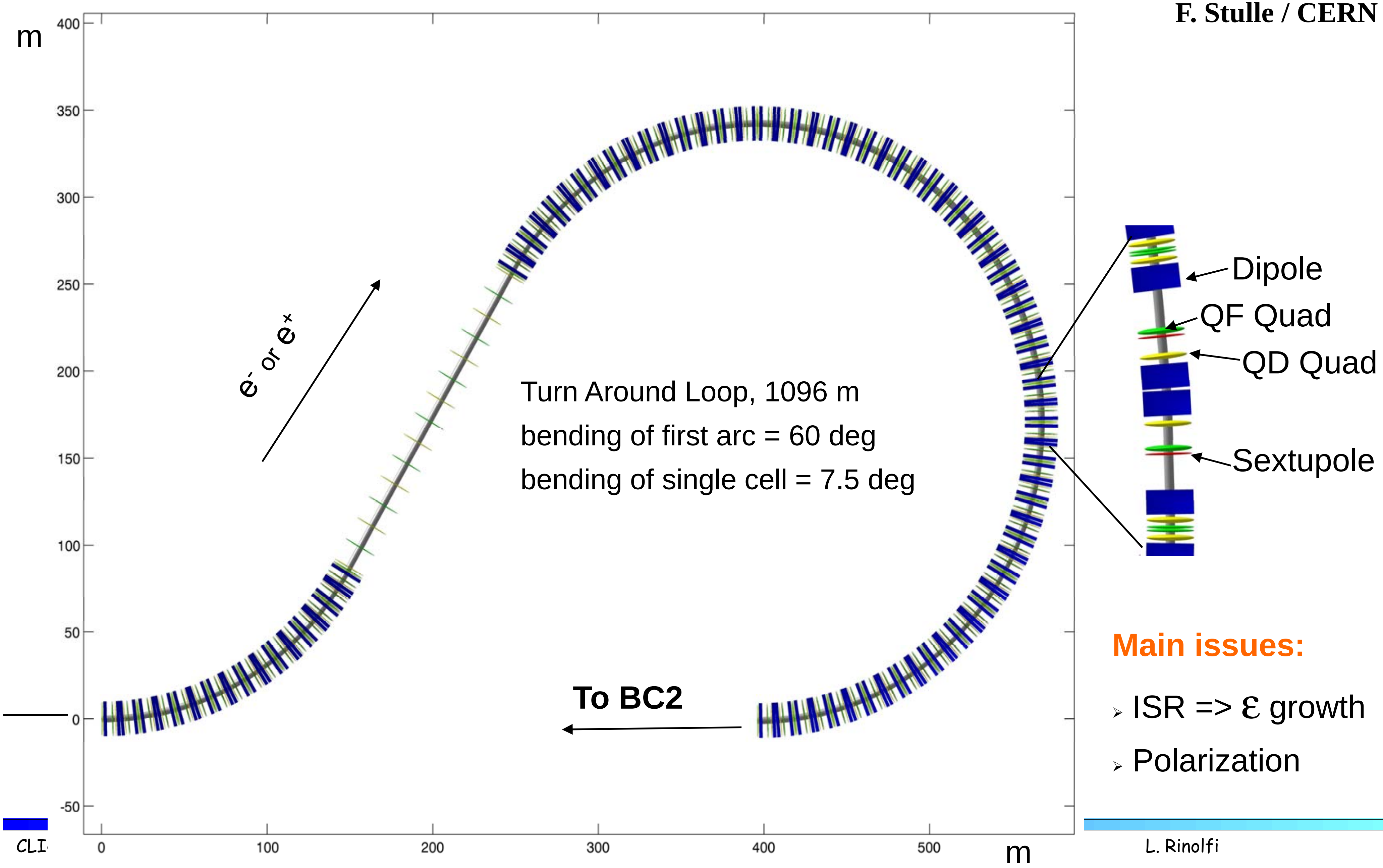
rms values

| Parameter | Unit | e $^-$ / e $^+$ |
|---|---|---|
| Energy (E) | GeV | 9 |
| No. of particles/bunch (N) | $10^9$ | 4 |
| Bunch length (rms) ($\sigma_z$) | mm | 0.173 |
| Energy Spread (rms) ($\sigma_E$) | % | 0.32 |
| Horizontal emittance ($\gamma\varepsilon_x$) | nm. rad | 380 |
| Vertical emittance ($\gamma\varepsilon_y$) | nm. rad | 4.1 |

If charge is doubled (for 500 GeV) => Wakefield effects should be investigated carefully

# Turn Around Loop

F. Stulle / CERN




## Main issues:

- ISR => ε growth
- Polarization

# Ring To Main Linac (RTML)

| Emittances requested @ DR output | Unit | **$e^-$ / $e^+$** | **Emittance budget $\Delta\varepsilon$ (nm.rad)** |
|---|---|---|---|
| Horiz. emittance ($\gamma\varepsilon_x$) | nm. rad | 550 | $\Delta\varepsilon = 50$<br>no design solution today |
| Verti. emittance ($\gamma\varepsilon_y$) | nm. rad | 5 | $\Delta\varepsilon = 5$<br>under evaluation |
| Emittances obtained @ DR output | | | |
| Horizontal emittance ($\gamma\varepsilon_x$) | nm. rad | 382 | $\Delta\varepsilon = 218$<br>design solution exists today |
| Vertical emittance ($\gamma\varepsilon_y$) | nm. rad | 4 | $\Delta\varepsilon = 6$<br>under evaluation |

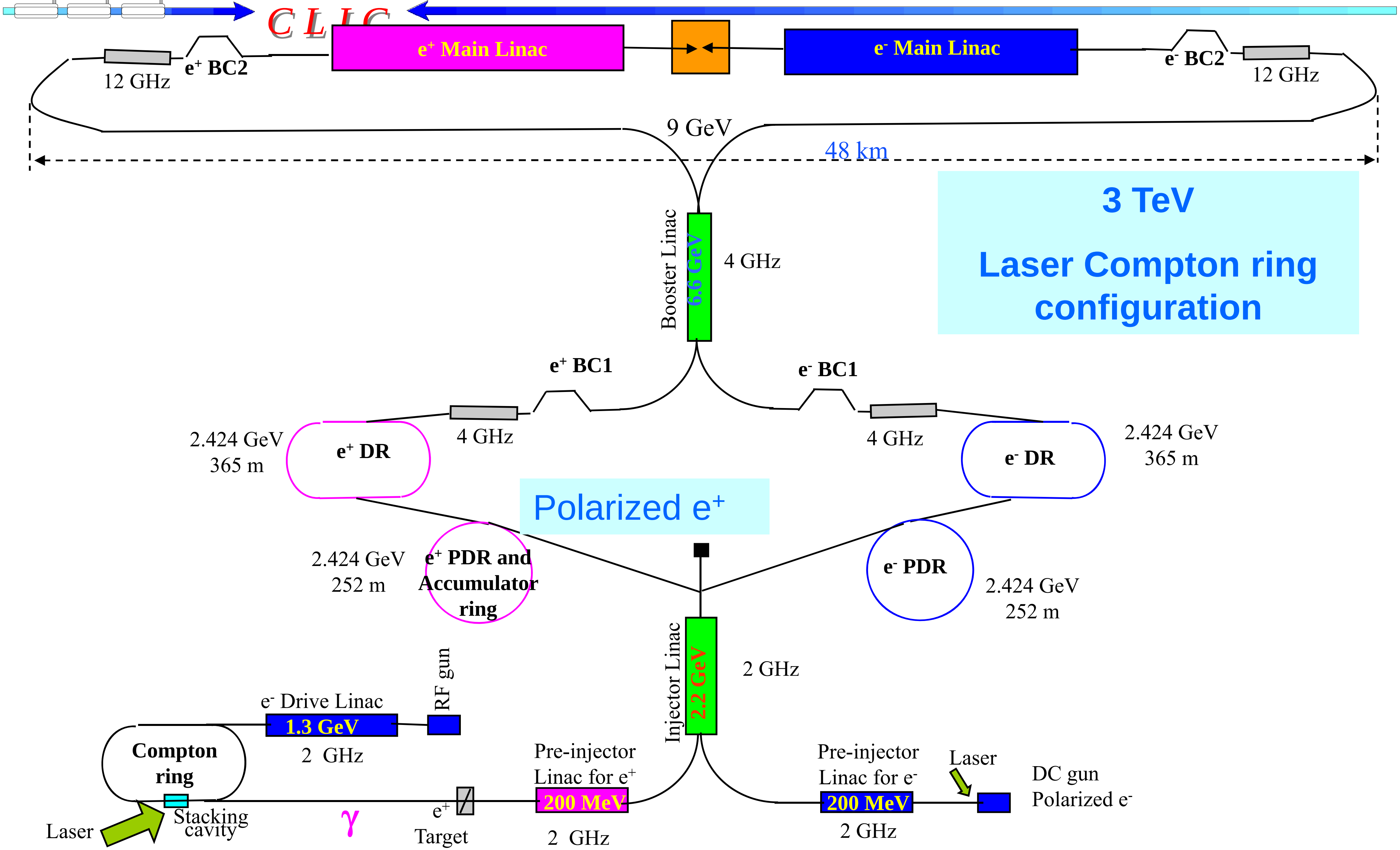
# Compton polarized positron source

- Compton schemes are very attractive for the polarized positron sources. For CLIC they present many advantages

BUT:

- ➢ Need of strong R&D on lasers and optical cavities
- ➢ Careful optimization of the interaction point
- ➢ Design of the Compton ring

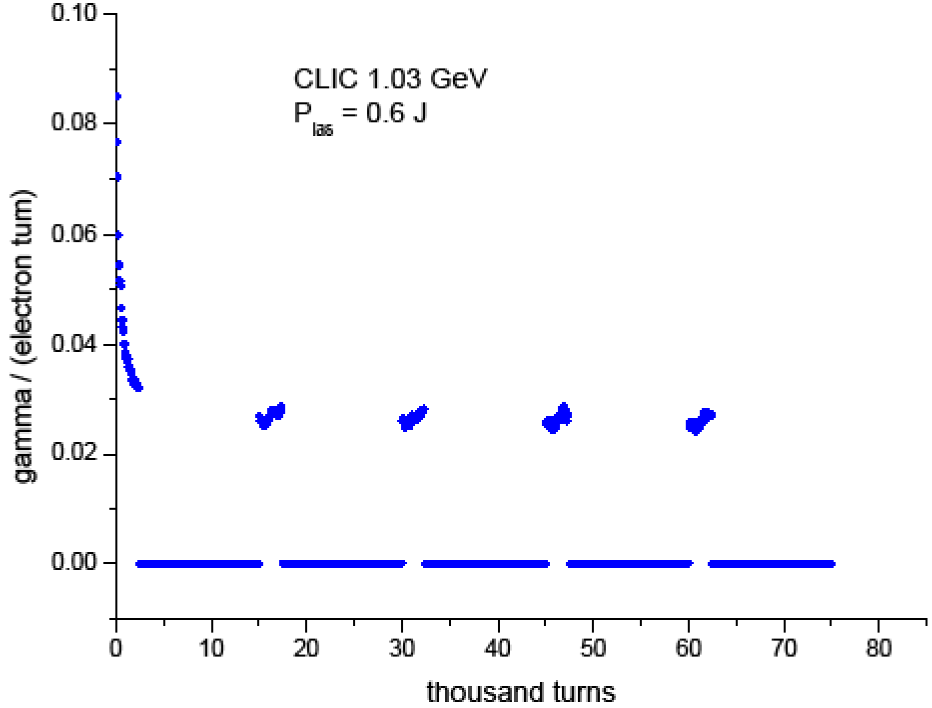
# The CLIC Injector complex (Compton ring)

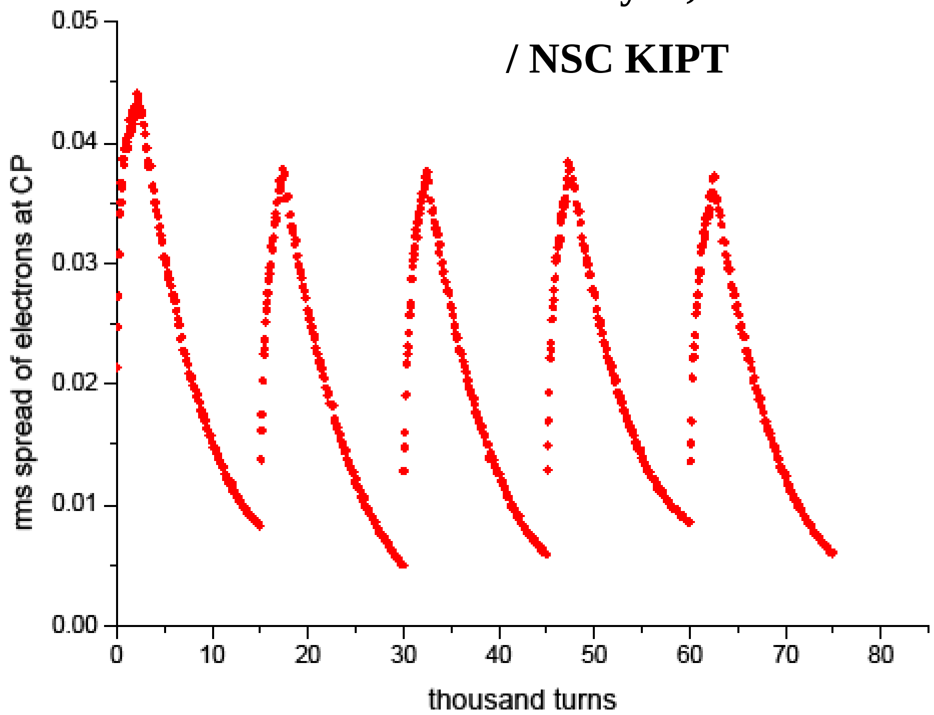


# Compton ring design

E. Bulyak, P.Gladkikh

/ NSC KIPT




Number of e- = 312 x 6.2 x $10^{10}$ = 1.93 x$10^{13}$ in the ring

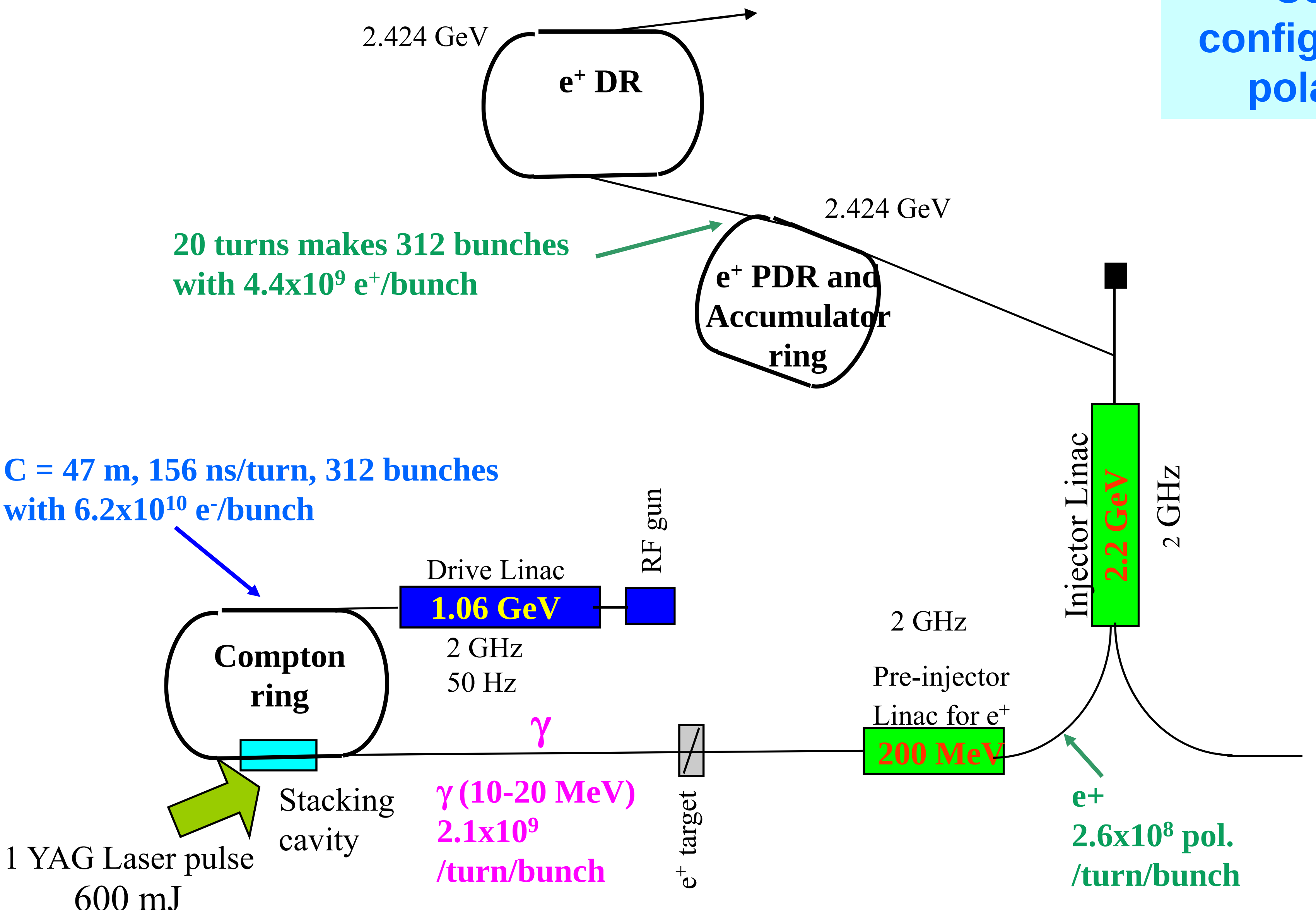
1 cycle = 15 000 turns = > T = 156 ns x 15 000 = 2.3 ms

Laser on during 2500 turns

Photon yield = 85 photons / e-

# CLIC Compton scheme

**Compton configuration for polarized e+**



# CLIC Compton scheme challenges

Current in the Compton ring ( ≈ 20 A)

Design of the Compton ring (with a double chicane)

Energy of laser

Optical stacking cavity

Design of the interaction point

Repetition rate of Pre-Injector Linac and Injector Linac

Injection efficiency into the PDR

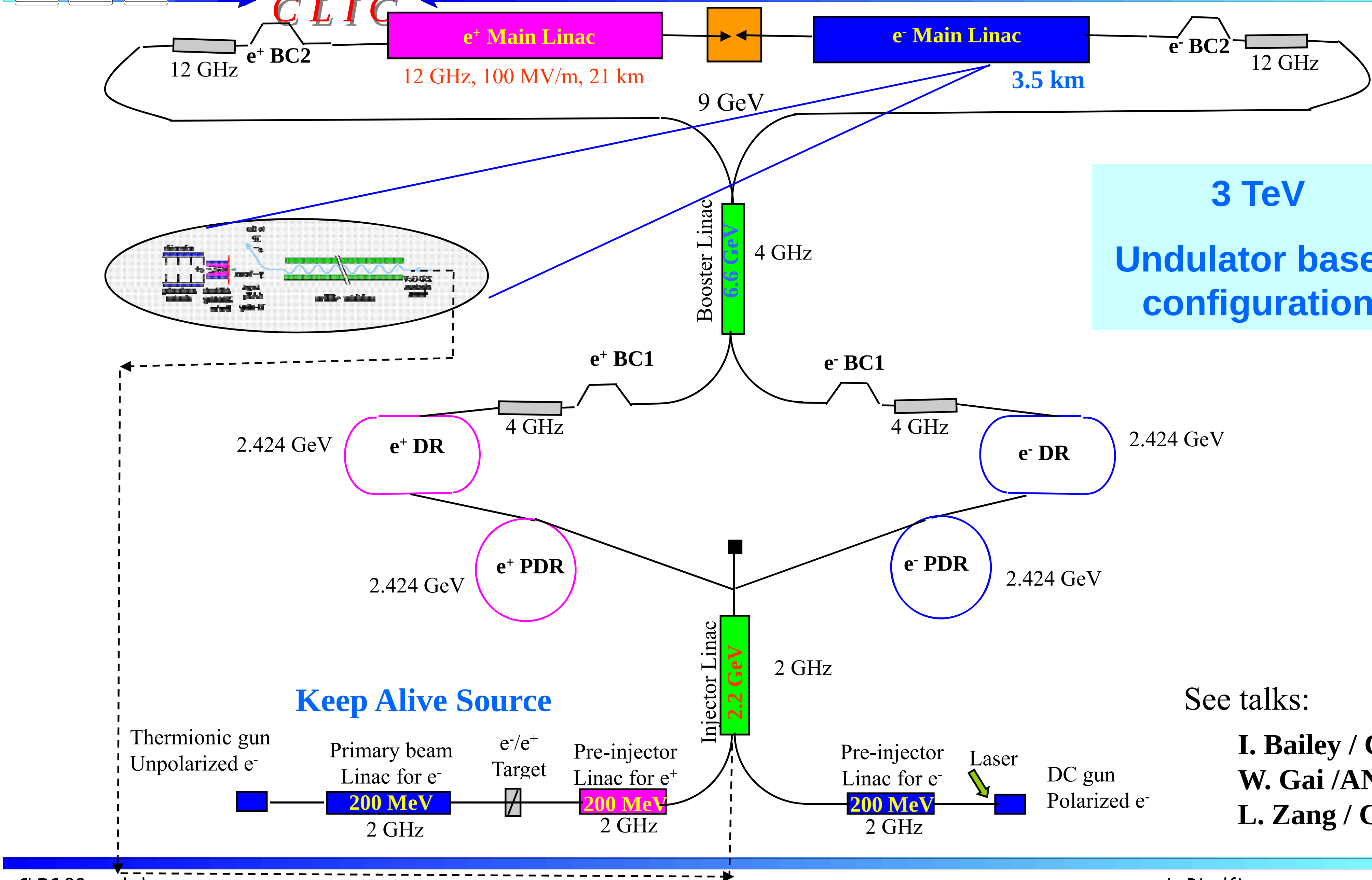
PDR parameters (momentum compaction, RF voltage, damping times, dynamic acceptance,…)

Stacking efficiency

See talks:

**F. Antoniou / CERN**
**A.Variola / LAL**
**F. Zimmermann / CERN**

# The CLIC Injector complex (Undulator)




## 3 TeV

## Undulator based configuration

See talks:

**I. Bailey / CI**
**W. Gai /ANL**
**L. Zang / CI**

# Studies &challenges for CLIC Injector Complex

1) Polarized electron source

2) Pre-Injector design for electron

3) Unpolarized $e^+$ source based on channeling with hybrid targets

4) Capture and acceleration of $e^+$ at 200 MeV

5) Design of the Injector Linac (review)

6) $e^+$ beam parameters at the entrance of the PDR

7) Optimize the PDR characteristics (damping time, energy acceptance,…)

8) Damping Ring design (review)

9) IBS effects on beam performance

10) Design of superconducting wigglers

11) Collective effects (CSR, ISR, FBII, wake fields,…) and misalignments effects

12) Design of the Booster Linac (review the 9 GeV choice ?)

13) Design the short and long transfer lines optics

# Studies &challenges for CLIC Injector Complex

14) Design the Compton ring for polarized $e^+$
15) Design the optical cavity and the laser system
16) Performance of the polarized $e^+$ source based on Compton ring
17) Impact of low $e^+$ charge on the Pre-Injector and Injector Linacs (repetition rate)
18) Stacking process into the PDR
19) Alternative option based on undulator scheme
20) Polarization studies (measurements, spin rotators, depolarization effects,…)
21) Beam diagnostics (resolution, accuracy, precision,…)
22) Power consumption
23) Civil engineering
24) Cost estimate
25) …

# CERN students and fellows

## for the CLIC Injectors complex

F. Antoniou: Pre Damping Ring studies

F. Stulle: RTML (Ring to Main Linac) studies

A. Vivoli: IBS (Intra Beam Scattering) for DR and $e^+$ generation studies

# External collaborations

## for the CLIC Injectors complex

| | |
|---|---|
| 1) DC gun for polarized electron: | JLAB (USA), SLAC (USA) |
| 2) Injector and Booster Linacs optics: | Uppsala University (Sweden), FNAL (USA) |
| 3) Unpolarized $e^+$ from channeling: | IPNL (France), LAL (France), Ankara University (Turkey) |
| 4) Polarized $e^+$ from Compton ring: | LAL, NSC KIPT (Kharkov Ukraine), KEK (Japan) |
| 5) Polarized $e^+$ from Undulator: | Cockcroft Institute (UK), ANL (USA), SLAC (USA) |
| 6) Wiggler for Damping Rings: | BINP (Russia), ANKA (Germany) |
| 7) Beam dynamics studies for DR: | BINP (Russia), Cockcroft Institute (UK), LNF (Italy), PSI (CH) |

# Conclusion

1) Many progress since the last CLIC 08 workshop.

2) For the Base Line configuration, a preliminary design exit for the Injector Complex which fulfill the requirements at the Main Linac input for 3 TeV.

3) Nevertheless a lot of work remains to be done to optimize the beam performance and evaluate the effects of the various sources of degradation for the beam parameters.

4) Damping Rings design for  tiny emittances remains big a challenge.

5) The 500 GeV option (double charge) has a serious impact on the Complex.

6) Polarized $e^+$ source still require a lot of studies and R&D .

7) International collaborations have been developed.

8) Two new ILC/CLIC working groups: "$e^+$ sources" and "Damping Rings"

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