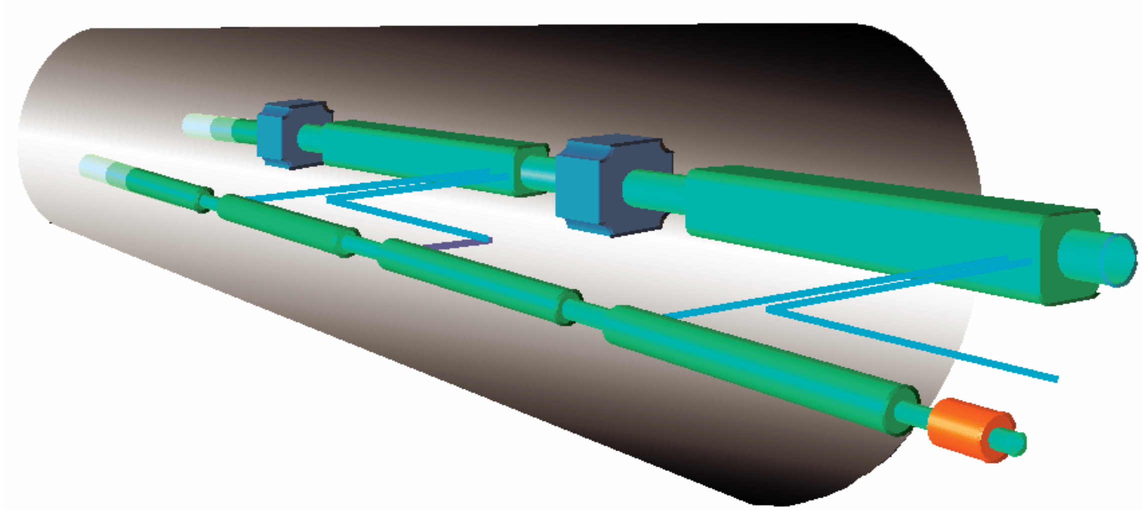
Drive Beam Generation & decelerator sectors



The studies on CLIC accelerating structures point in the direction of shorter structures, with shorter fill-time and RF pulse length (about a factor 2).

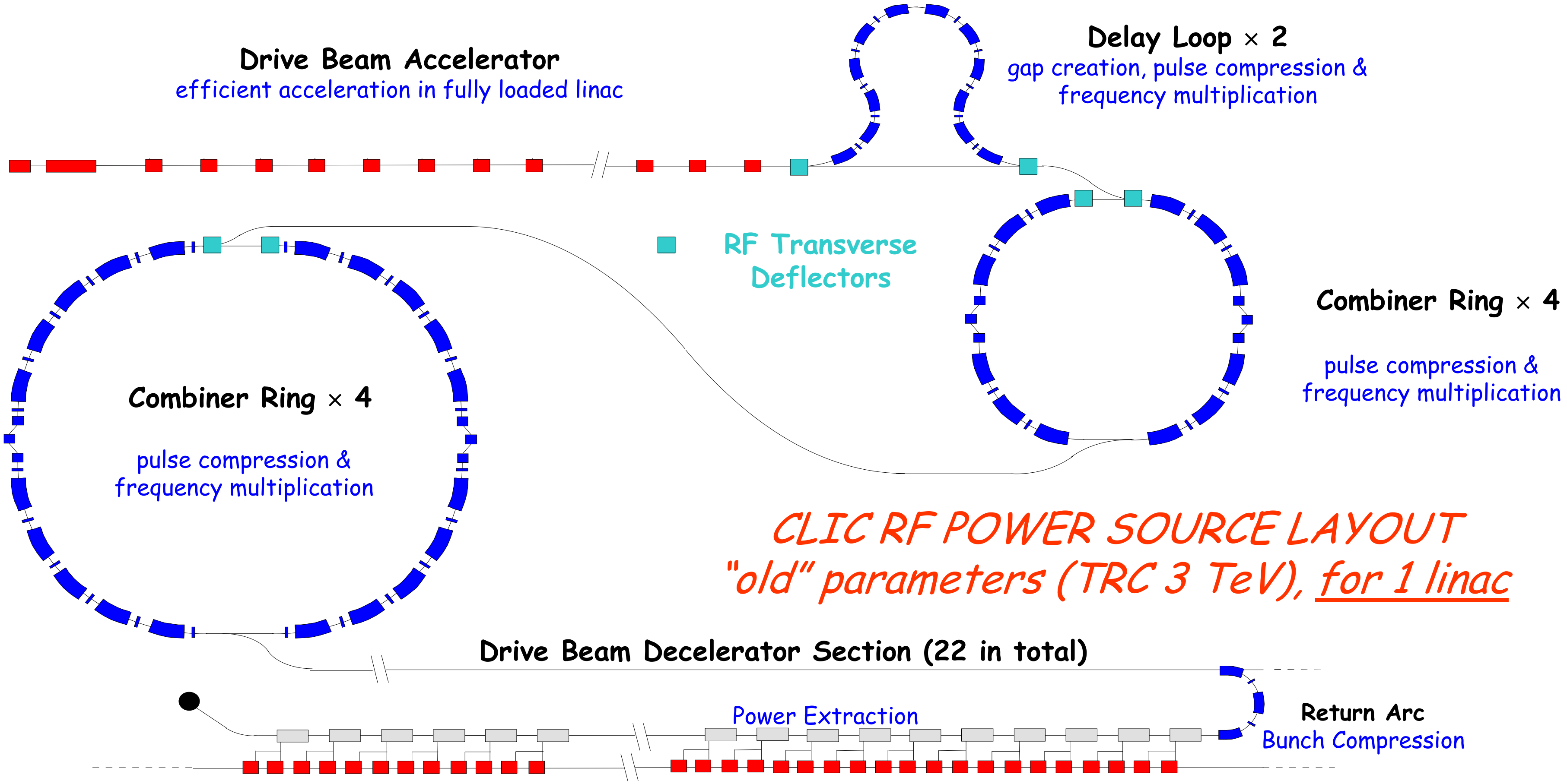
These structures can provide RF-to-beam efficiencies equal or better than the "old" structures and require about the same power per meter.

What are the consequences on the drive beam generation complex ?

In particular these quantities are linked to the RF pulse length:

- delay loop and combiner rings dimensions
- number of decelerator sectors
- drive beam energy and current

CLIC RF POWER SOURCE LAYOUT
“old” parameters (TRC 3 TeV), for 1 linac



Drive Beam Accelerator
efficient acceleration in fully loaded linac

Delay Loop × 2
gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 4
pulse compression & frequency multiplication

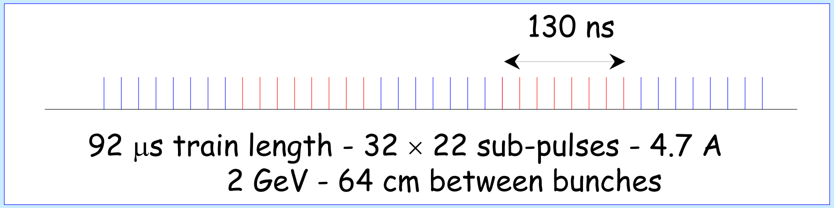
Combiner Ring × 4
pulse compression & frequency multiplication

Drive Beam Decelerator Section (22 in total)

Power Extraction

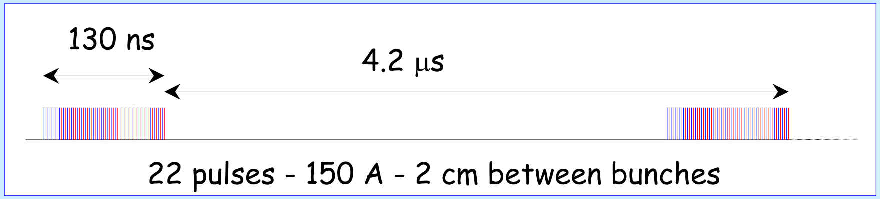
Return Arc
Bunch Compression

Drive beam time structure - initial



92 µs train length - 32 × 22 sub-pulses - 4.7 A
2 GeV - 64 cm between bunches

Drive beam time structure - final



22 pulses - 150 A - 2 cm between bunches

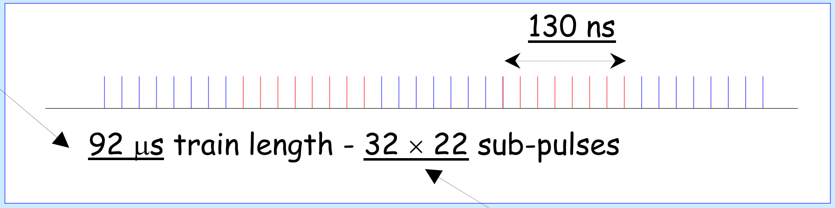
Drive beam initial pulse length and RF pulse length

c • 92 μs = 27.5 km

The initial pulse length is fixed by the length of the main linac (final energy, accelerating gradient, main linac fill-factor)

The length of the sub-pulses is equal to the length of the 30 GHz RF pulse

Initial pulse structure



The combination factor and the number of decelerator sections link the RF pulse length to the initial pulse length

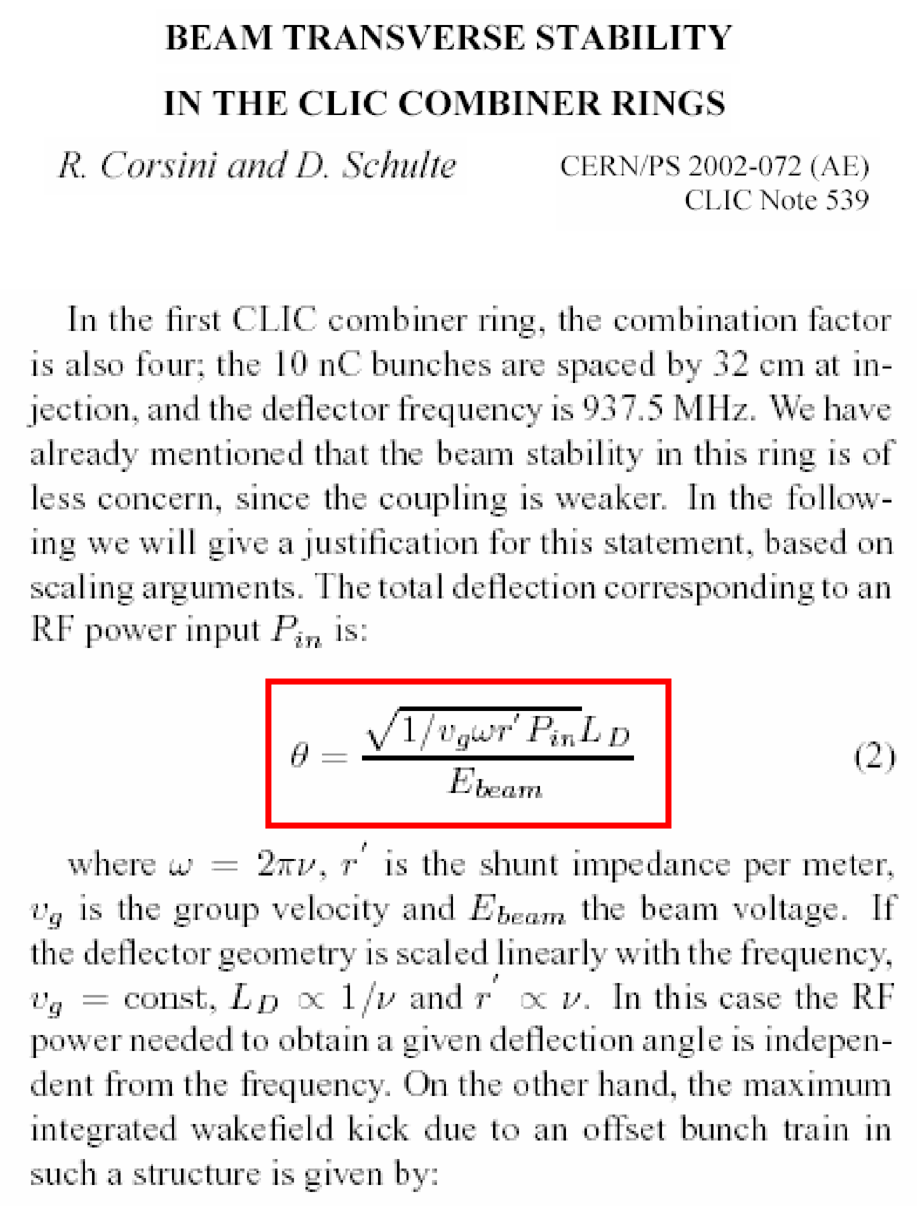
Combination factor

130 ns × 32 × 22 = 92 μs

Number of sectors

- If the 30 GHz RF pulse length is shortened, the “obvious” consequence is an increase in the number of drive beam decelerator sections
- With a straightforward scaling, the length of the delay loop and the rings decrease

Drive beam stability in RF deflectors scaling with frequency



BEAM TRANSVERSE STABILITY IN THE CLIC COMBINER RINGS

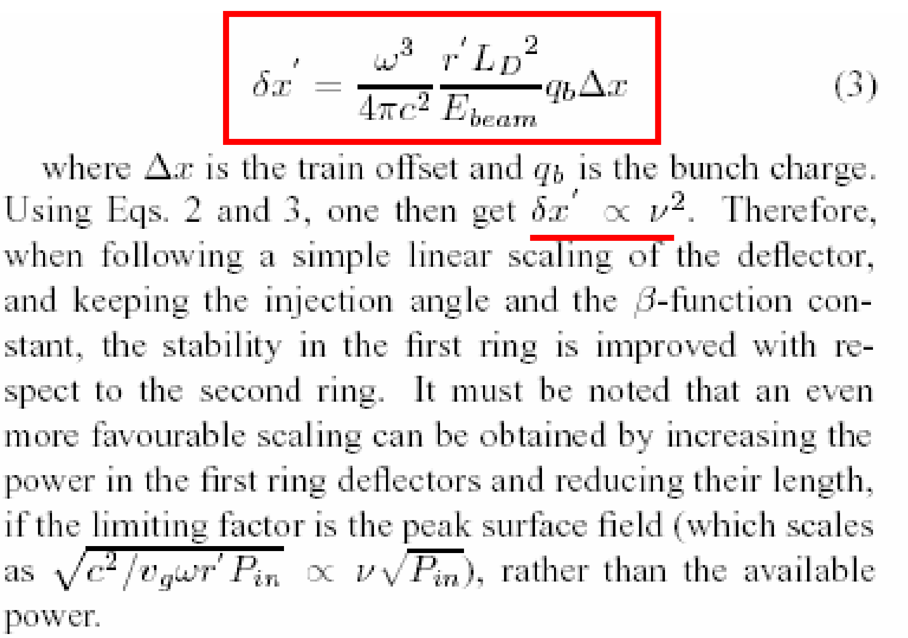
R. Corsini and D. Schulte

CERN/PS 2002-072 (AE)
CLIC Note 539

In the first CLIC combiner ring, the combination factor is also four; the 10 nC bunches are spaced by 32 cm at injection, and the deflector frequency is 937.5 MHz. We have already mentioned that the beam stability in this ring is of less concern, since the coupling is weaker. In the following we will give a justification for this statement, based on scaling arguments. The total deflection corresponding to an RF power input P_{in} is:

$$\boxed{\theta = \frac{\sqrt{1/v_g \omega r' P_{in}}\, L_D}{E_{beam}}} \qquad (2)$$

where $\omega = 2\pi\nu$, r' is the shunt impedance per meter, v_g is the group velocity and E_{beam} the beam voltage. If the deflector geometry is scaled linearly with the frequency, v_g = const, $L_D \propto 1/\nu$ and $r' \propto \nu$. In this case the RF power needed to obtain a given deflection angle is independent from the frequency. On the other hand, the maximum integrated wakefield kick due to an offset bunch train in such a structure is given by:



$$\boxed{\delta x' = \frac{\omega^3}{4\pi c^2} \frac{r' {L_D}^2}{E_{beam}} q_b \Delta x} \qquad (3)$$

where Δx is the train offset and q_b is the bunch charge. Using Eqs. 2 and 3, one then get $\delta x' \propto \nu^2$. Therefore, when following a simple linear scaling of the deflector, and keeping the injection angle and the β-function constant, the stability in the first ring is improved with respect to the second ring. It must be noted that an even more favourable scaling can be obtained by increasing the power in the first ring deflectors and reducing their length, if the limiting factor is the peak surface field (which scales as $\sqrt{c^2/v_g \omega r' P_{in}} \propto \nu\sqrt{P_{in}}$), rather than the available power.

OLD parameters
(TRC, 3 TeV)

CM Energy (TeV)		3.3
Average Gradient (MeV/m)		120
Linac Length (Km)		27.46
Repetition Frequency (Hz)		100
Pulse Length (nsec)		102
Number of bunches		154
Charge per bunch (10^9)		4
HE Beam Total Energy (KJ)		151
Number of Drive Beams		22
Rf Pulse Total Energy (KJ)		622
Drive Beam Pulse Length (nsec)		130
Frequency Multiplication		32
Deceleration Section Length (m)		624
Delay Loop Length (m)		39
1st Combiner Length (m)		78
2nd Combiner Length (m)		312
Drive beam Pulse (Microsec)		92
Total Drive beam Energy (KJ)		839
Drive Beam Energy (GeV)		1.99
Drive Beam Current (A)		4.6
Drive Beam Bunch Charge (nC)		9.8
Frequency of DBA (MHz)		937
Length of DBA (m)		515
Structure Length (m)		4.67
Power per Structure (MW)		85
Number of 50 MW Klystrons		221
Total RF Efficiency (%)		40
Wall to beam Efficiency (%)		9.7

Example: reduce the pulse length by a factor 2

CM Energy (TeV)		3.3
Average Gradient (MeV/m)		120
Linac Length (Km)		27.46
Repetition Frequency (Hz)		100
Pulse Length (nsec)		51
Number of bunches		77
Charge per bunch (10^9)		4
HE Beam Total Energy (KJ)		75
Number of Drive Beams	More sectors	44
Rf Pulse Total Energy (KJ)		311
Drive Beam Pulse Length (nsec)		65
Frequency Multiplication		32
Deceleration Section Length (m)		311
Delay Loop Length (m)		19
1st Combiner Length (m)	Small rings	39
2nd Combiner Length (m)		155
Drive beam Pulse (Microsec)		92
Total Drive beam Energy (KJ)	Low initial energy	417
Drive Beam Energy (GeV)		0.99
Drive Beam Current (A)		4.6
Drive Beam Bunch Charge (nC)		9.8
Frequency of DBA (MHz)		937
Length of DBA (m)		256
Structure Length (m)		4.67
Power per Structure (MW)		85
Number of 50 MW Klystrons		110
Total RF Efficiency (%)		40
Wall to beam Efficiency (%)		9.7

Pros & Cons

- Number of pulses/decelerator sections: more turn-arounds (cost), less energy per pulse (effect of losses)
- Small delay loop: the CTF3 delay loop is folded up due to space constraints, in CLIC it will be constituted by two lines ⇒ no problem
- Small rings: for the first combiner ring there is a problem ⇒ 78 m is already short
- Other potential limitation: short “hole” for fast extraction kicker in the 1st combiner ring
- Low initial energy: ring impedance and CSR cause an energy spread whose absolute value does not depend on energy ⇒ relative energy spread doubles

N.B.: The drive beam energy can be increased if the PETS impedance and the current are decreased, but the scaling of beam stability in the decelerator is unfavorable

The “old” parameters (10 nC/bunch, 2 GeV, beam current from 4.6 A to 150 A) seem a good compromise between transverse stability in the decelerator and collective effects (wakes and CSR) in the DB generation complex

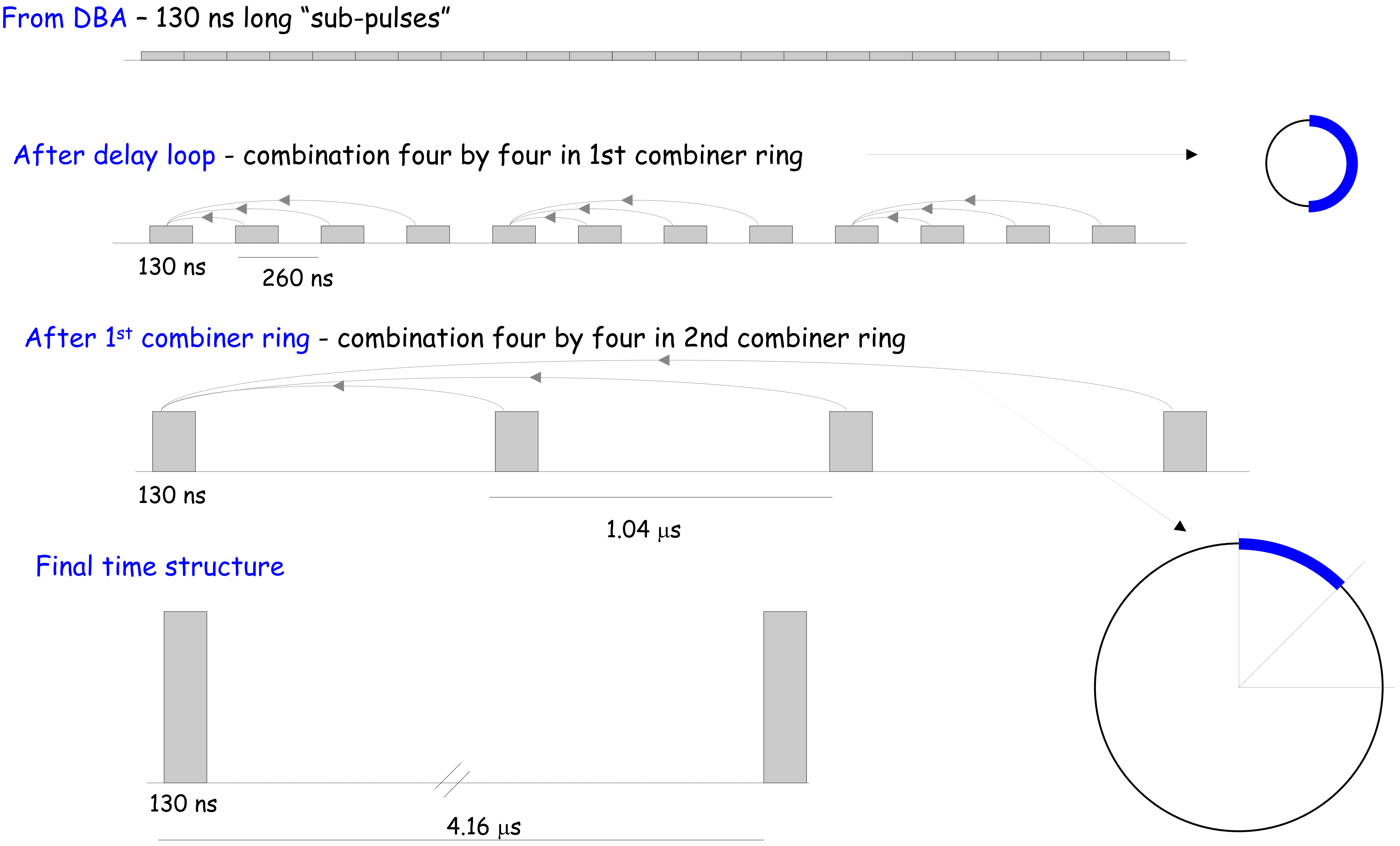
Is there a way to stay in the same parameter space with short RF pulses ?

single DB generation complex

Daniel proposed time ago to combine the DB generation for both e+ and e- linacs, in order to improve the DB stability in the decelerator. This can be done as follows :

- Use a single accelerator with double length ⇒ double beam energy
- Same initial pulse length
- Same DL and CRs lengths
- Switch subsequent pulses to power the e+ and e- main linacs
- The distance between pulses in each decelerator is now doubled
- Half the number of decelerator sectors

"Standard" scheme



From DBA – 130 ns long "sub-pulses"

After delay loop - combination four by four in 1st combiner ring

130 ns

260 ns

After 1st combiner ring - combination four by four in 2nd combiner ring

130 ns

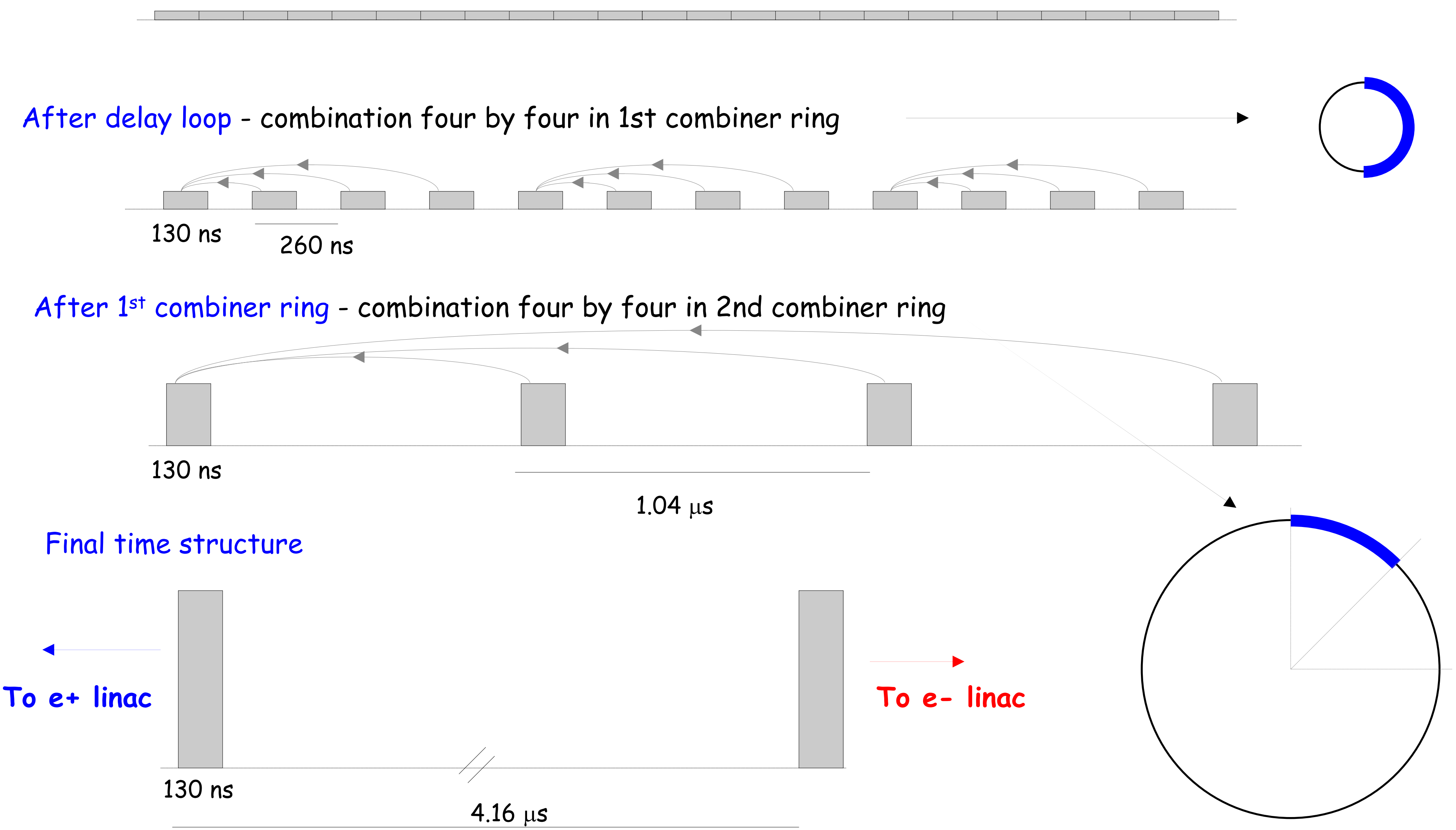
1.04 μs

Final time structure

130 ns

4.16 μs

"Single DB generation complex" scheme



From DBA – 130 ns long "sub-pulses"

After delay loop - combination four by four in 1st combiner ring

130 ns

260 ns

After 1^{st} combiner ring - combination four by four in 2nd combiner ring

130 ns

1.04 μs

Final time structure

To e+ linac

To e- linac

130 ns

4.16 μs

"Double pulse" scheme

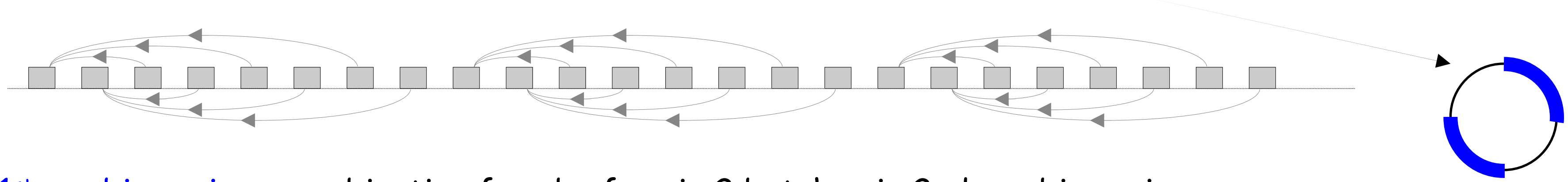
In the case of a short RF pulse, it is possible to use a single drive beam generation complex to feed both linacs, in a different way:

- Use a "short" delay loop (e.g., 21 m for 70 ns)
- Use "long" combiner rings (e.g., 84 m and 334 m for 70 ns)
- In each ring, two pulses will circulate (and be combined) at the same time
- The combined pulse couples can be split and sent to the e+ and e- main linacs
- The number of decelerator sections is "small" (e.g., 21)
- The drive beam energy is "high" (e.g., 2.4 GeV)

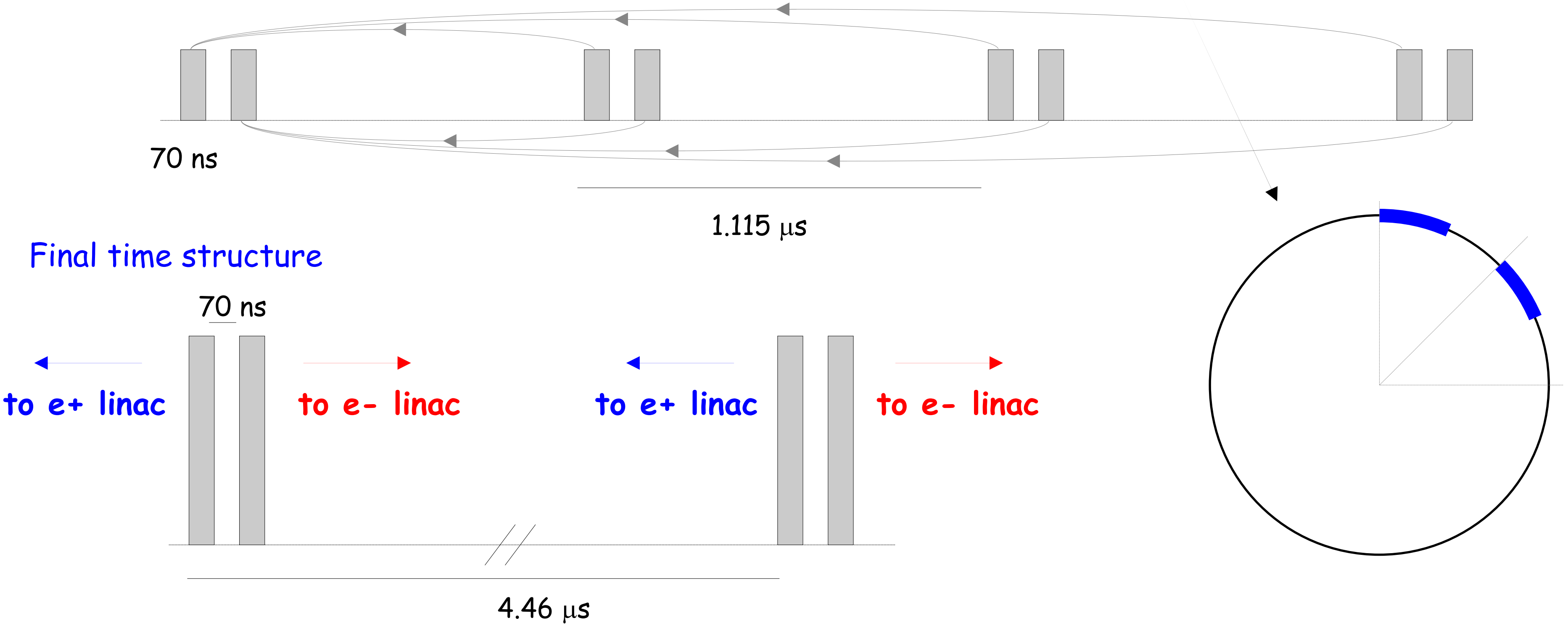
"Double pulse" scheme

From DBA - 70 ns long "sub-pulses"

After delay loop - combination four by four in 2 batches in 1st combiner ring

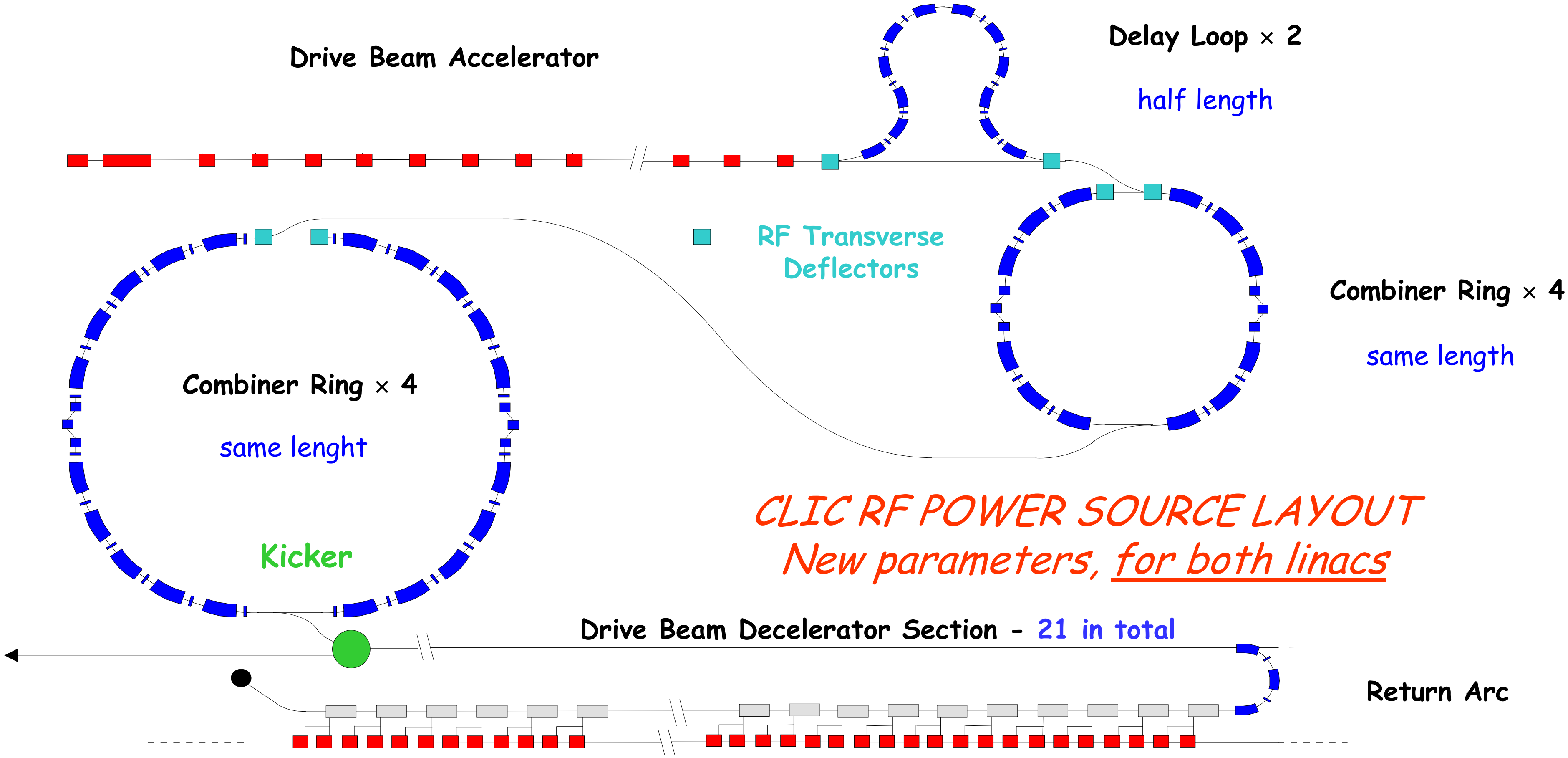


After 1st combiner ring - combination four by four in 2 batches in 2nd combiner ring

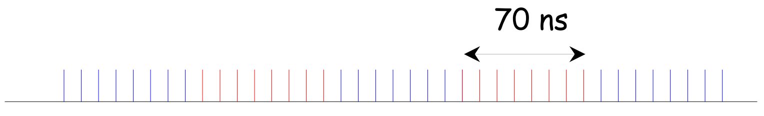


Final time structure

CLIC RF POWER SOURCE LAYOUT
New parameters, <u>for both linacs</u>

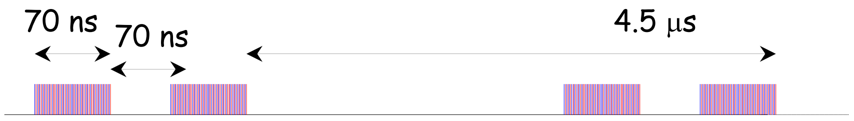


<u>Drive beam time structure - initial</u>



94 µs train length - 32 × 21 × 2 sub-pulses - 5.7 A
2.4 GeV - 64 cm between bunches

<u>Drive beam time structure - final</u>



2 x 21 pulses - 180 A - 2 cm between bunches

NEW parameters

Parameter Table for 3 TeV Case		
CM Energy (TeV)		3.0
Average Gradient (MeV/m)		117
Linac Length (Km)		28.09
Repetition Frequency (Hz)		150
Pulse Length (nsec)		58
Number of bunches		220
Charge per bunch (10^9)		2.56
HE Beam Total Energy (KJ)		135
Number of Drive Beams		21
Rf Pulse Total Energy (KJ)		465
Drive Beam Pulse Length (nsec)		70
Frequency Multiplication		32
Deceleration Section Length (m)		669
Delay Loop Length (m)		21
1st Combiner Length (m)		84
2nd Combiner Length (m)		334
Drive beam Pulse (Microsec)		94
Total Drive beam Energy (KJ)		628
Drive Beam Energy (GeV)		2.37
Drive Beam Current (A)		5.7
Drive Beam Current (A)		181
Drive Beam Bunch Charge (nC)		12.1
Frequency of DBA (MHz)		937
Length of DBA (m)		641
Structure Length (m)		3.64
Power per Structure (MW)		78
Number of 40 MW Klystrons		352
Total RF Efficiency (%)		40
Wall to beam Efficiency (%)		11.6
Total AC power (MW)		347

Single DB generation complex: rings issues

Several issues were studied to check the limitations of beam energy in the combiner rings:

- Increased field in magnets

- Synchrotron radiation:
    - Energy loss
    - Power loss in vacuum chamber
    - Energy spread & emittance increase

- Coherent synchrotron radiation
    - Beneficial effect

- Deflectors
    - Higher power for given angle
    - Constant power from real emittance damping

Fields in magnets

Ring 1

	1.2 GeV	2.4 GeV
Dipole length	1.4 m	
Bending radius	3.6 m	
Dipole field	1.1 T	2.2 T
Quad length	0.3 m	
Max quad gradient	14 T/m	28 T/m
Sext length	0.3 m	
Max sext gradient	26 T/m^2	52 T/m^2

Ring 2

	1.2 GeV	2.4 GeV
Dipole length	1.4 m	
Bending radius	17.8 m	
Dipole field	0.22 T	0.44 T
Quad length	0.3 m	
Max quad gradient	14 T/m	28 T/m
Sext length	0.3 m	
Max sext gradient	120 T/m^2	240 T/m^2

NB: Using the design of the yellow report on CLIC RF Power Source

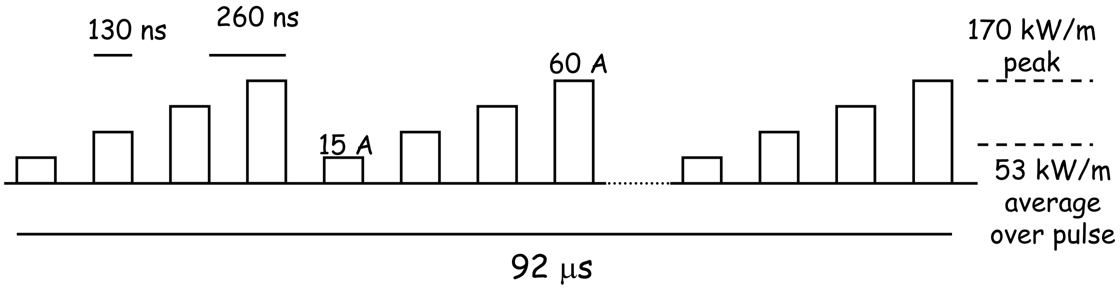
Power loss from SR

$$\boxed{\delta P\big|_{SR,turn} = -C_\gamma \frac{E^4}{\rho}}$$

$$C_\gamma = 8.85\,10^{-32} \quad \left[\mathrm{m/eV^3}\right]$$

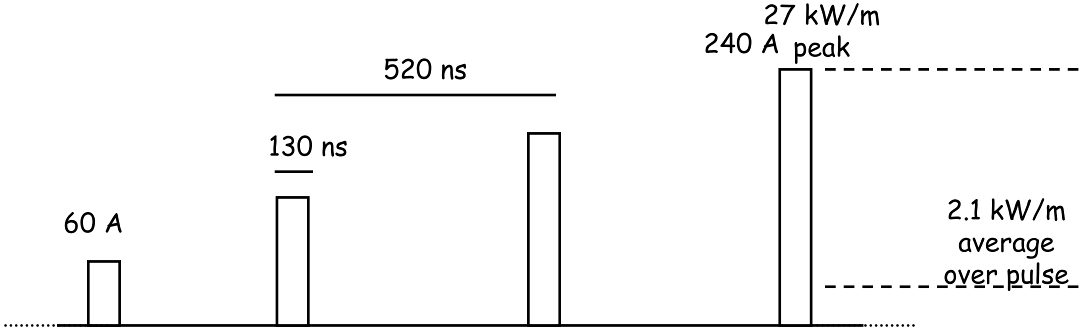
1st Ring - E = 1.2 GeV

4.9 kW, 480 W/m total average



2nd Ring - E = 1.2 GeV

0.98 kW, 19 W/m total average

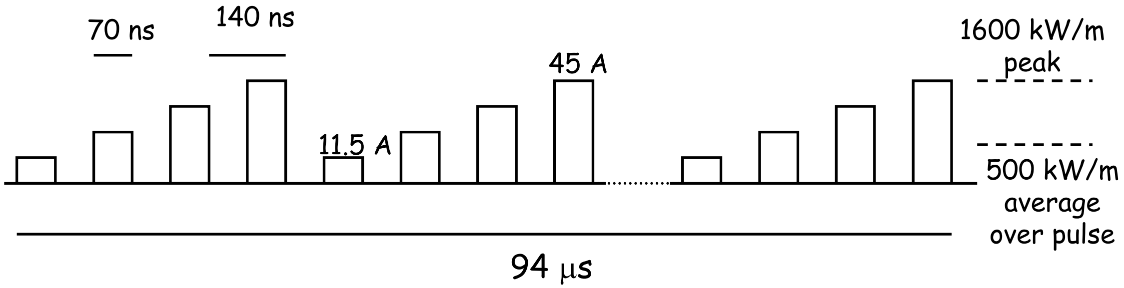


Power loss from SR

$$\boxed{\delta P\Big|_{SR,turn} = -C_\gamma \frac{E^4}{\rho}} \qquad C_\gamma = 8.85\,10^{-32} \quad \left[\mathrm{m/eV^3}\right]$$

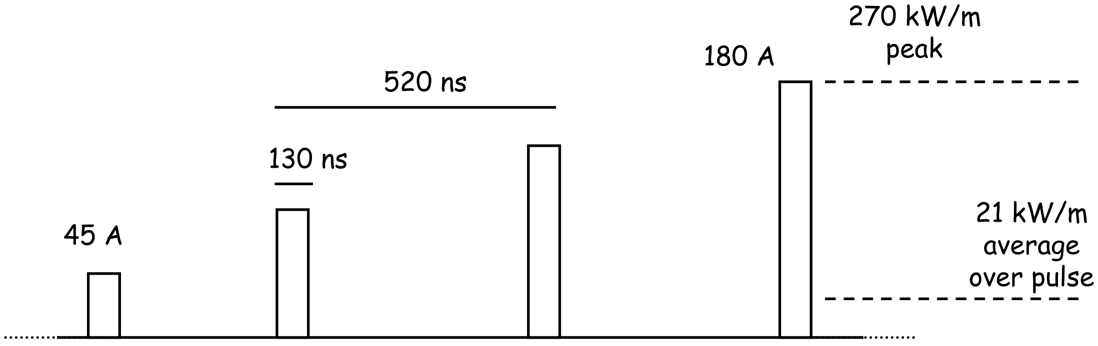
1st Ring - E = 2.4 GeV - 150 Hz

80 kW, 7 kW/m total average



2nd Ring - E = 2.4 GeV - 150 Hz

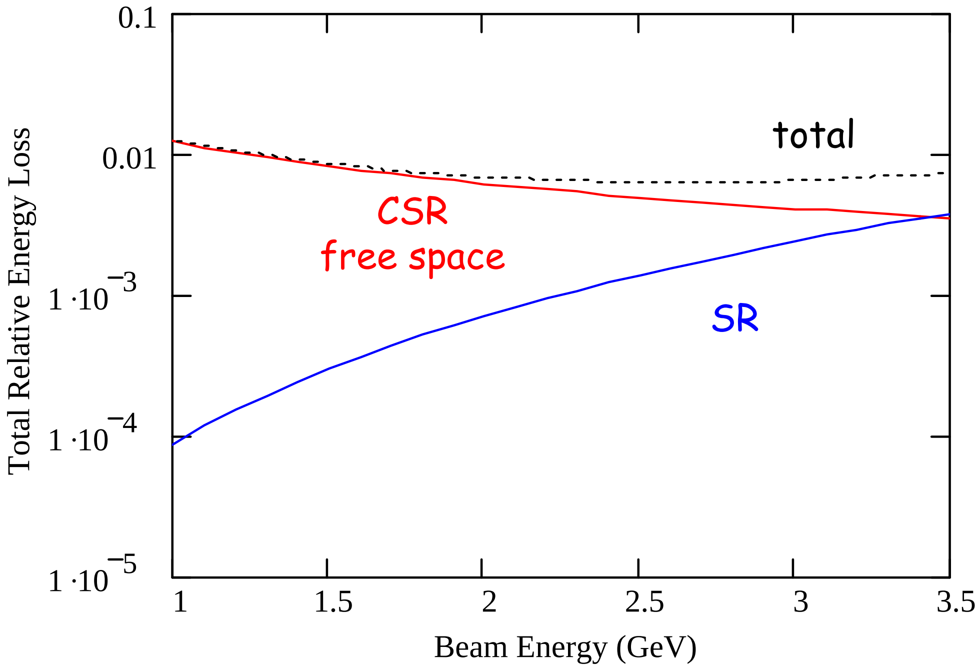
16 kW, 290 W/m total average

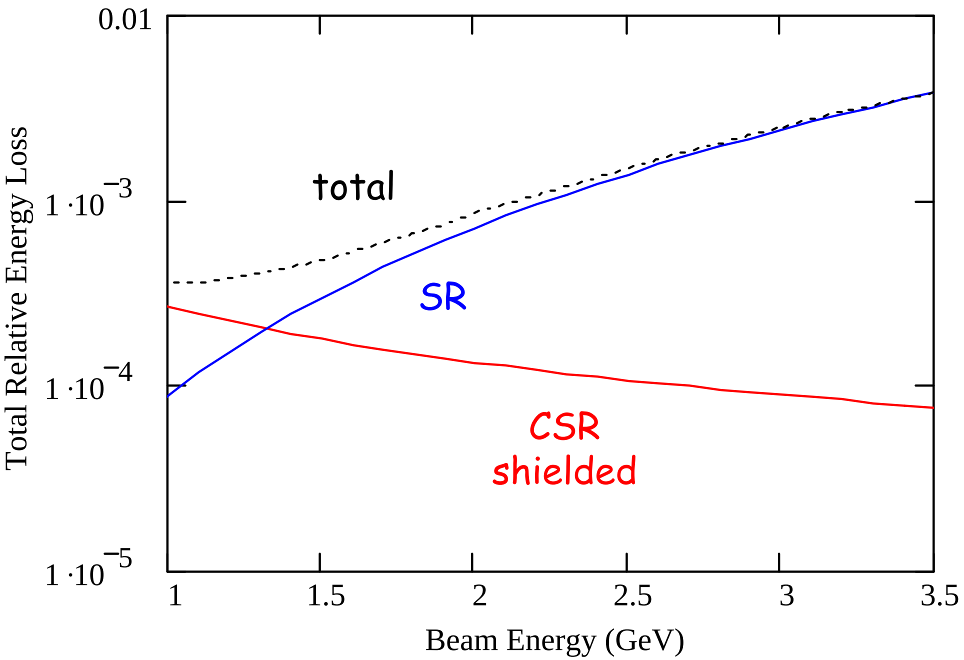


Energy loss from SR and CSR

σ = 2 mm, Qb = 12 nC

Both rings - ρ = 3.6 m - 18 m

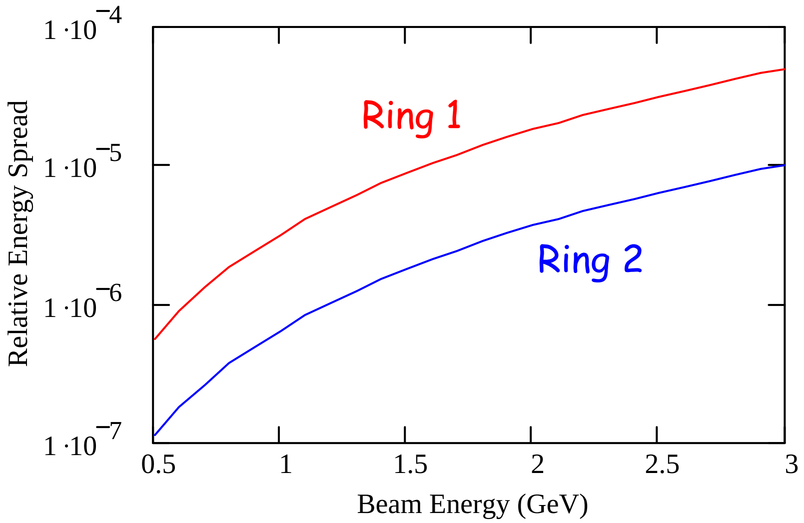




An increase of the energy to 2.4 GeV is indeed possible

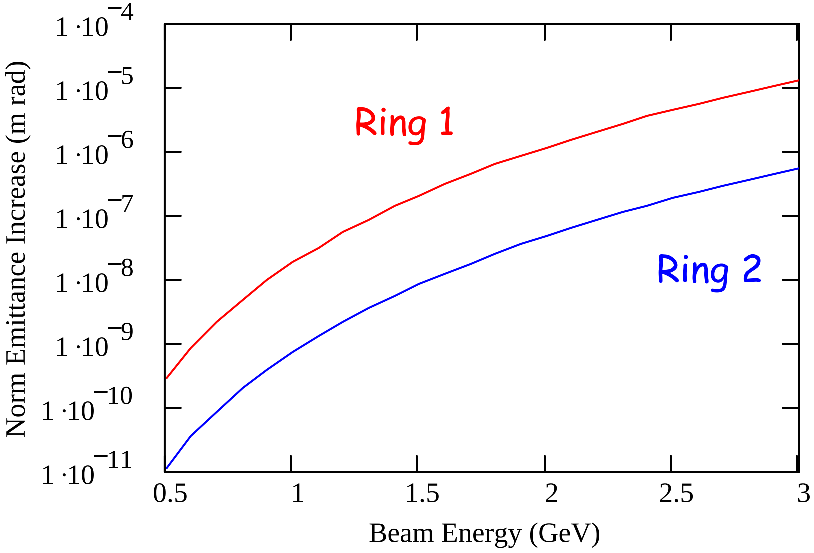
Energy spread and emittance increase from SR

$$\sigma E = 3.438\,10^{-8} \frac{\gamma^{7/2}}{\rho} \quad [\mathrm{eV\ m}]$$

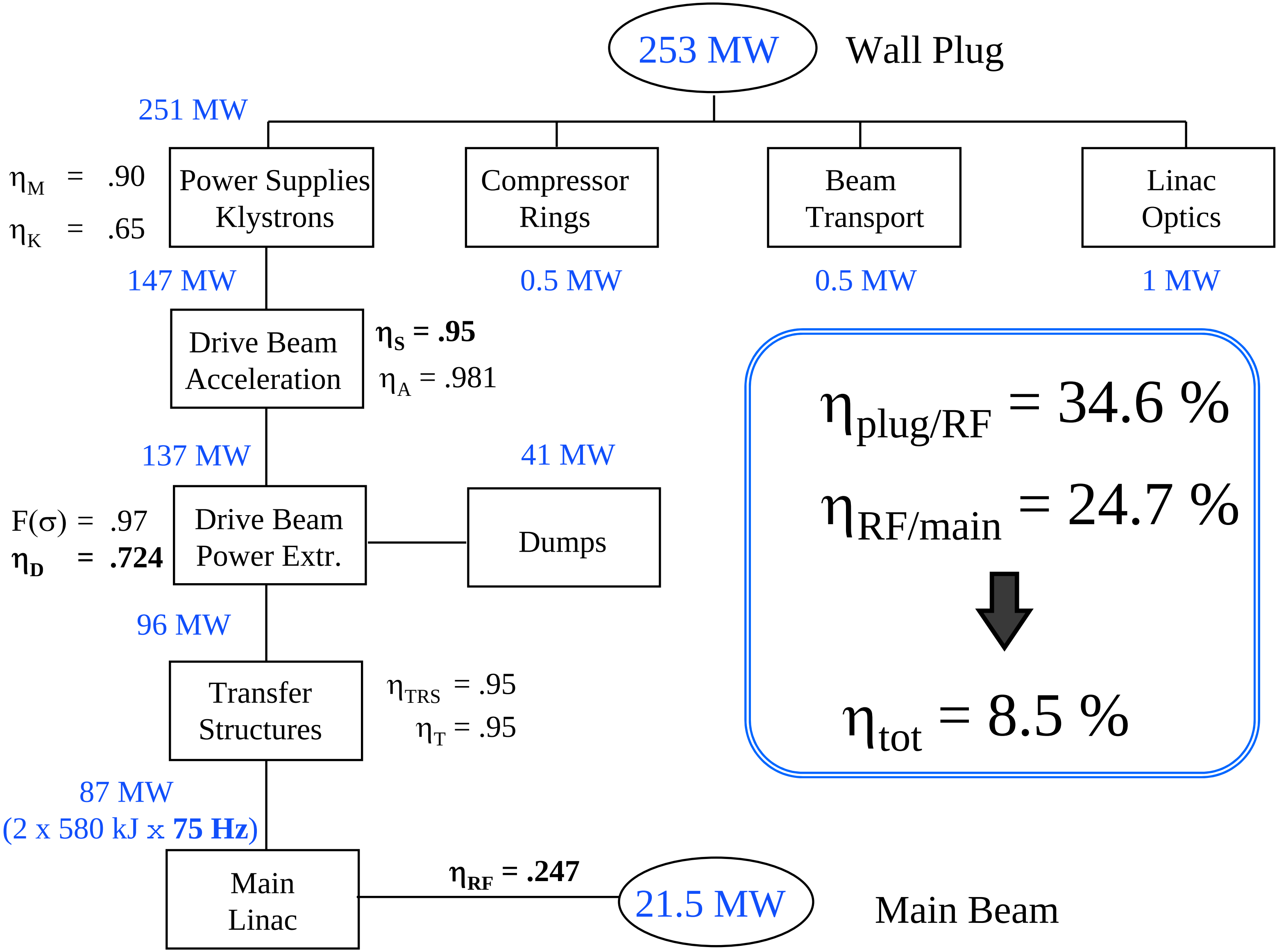


NB: Nominal emittance $\varepsilon_{N,rms}$ = 1 10^{-4} m rad

$$\Delta\varepsilon = 1.32\,\pi\,10^{-27} \frac{\gamma 6}{\rho^2} \langle H \rangle \quad [\mathrm{m^2\ rad}] \qquad \langle H \rangle \approx 1$$



Yellow report - CLIC RF Power Source (1999)



253 MW Wall Plug

251 MW

$\eta_M = .90$

$\eta_K = .65$

Power Supplies Klystrons

147 MW

Compressor Rings

0.5 MW

Beam Transport

0.5 MW

Linac Optics

1 MW

Drive Beam Acceleration

$\eta_S = \mathbf{.95}$

$\eta_A = .981$

137 MW

41 MW

$F(\sigma) = .97$

$\eta_D = \mathbf{.724}$

Drive Beam Power Extr.

Dumps

96 MW

Transfer Structures

$\eta_{TRS} = .95$

$\eta_T = .95$

87 MW

(2 x 580 kJ x **75 Hz**)

Main Linac

$\eta_{RF} = \mathbf{.247}$

21.5 MW Main Beam

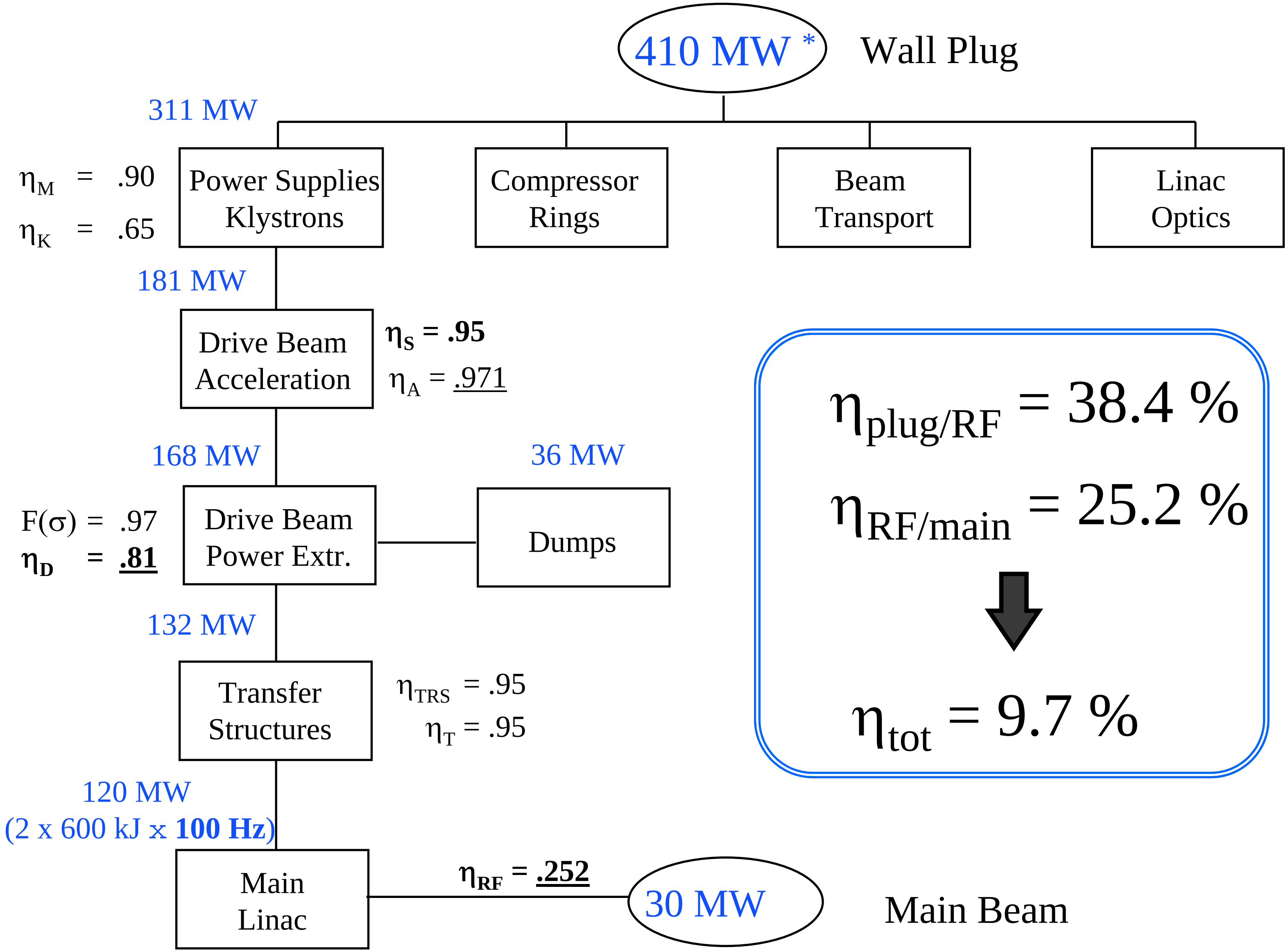
$$\eta_{plug/RF} = 34.6\ \%$$

$$\eta_{RF/main} = 24.7\ \%$$

$$\Downarrow$$

$$\eta_{tot} = 8.5\ \%$$

TRC Parameters (3 TeV)



410 MW * Wall Plug

311 MW

η_M = .90

η_K = .65

Power Supplies Klystrons

Compressor Rings

Beam Transport

Linac Optics

181 MW

Drive Beam Acceleration

η_S = **.95**

η_A = <u>.971</u>

168 MW

36 MW

F(σ) = .97

η_D = **<u>.81</u>**

Drive Beam Power Extr.

Dumps

132 MW

Transfer Structures

η_{TRS} = .95

η_T = .95

120 MW

(2 x 600 kJ x **100 Hz**)

Main Linac

η_{RF} = **<u>.252</u>**

30 MW Main Beam

$\eta_{plug/RF}$ = 38.4 %

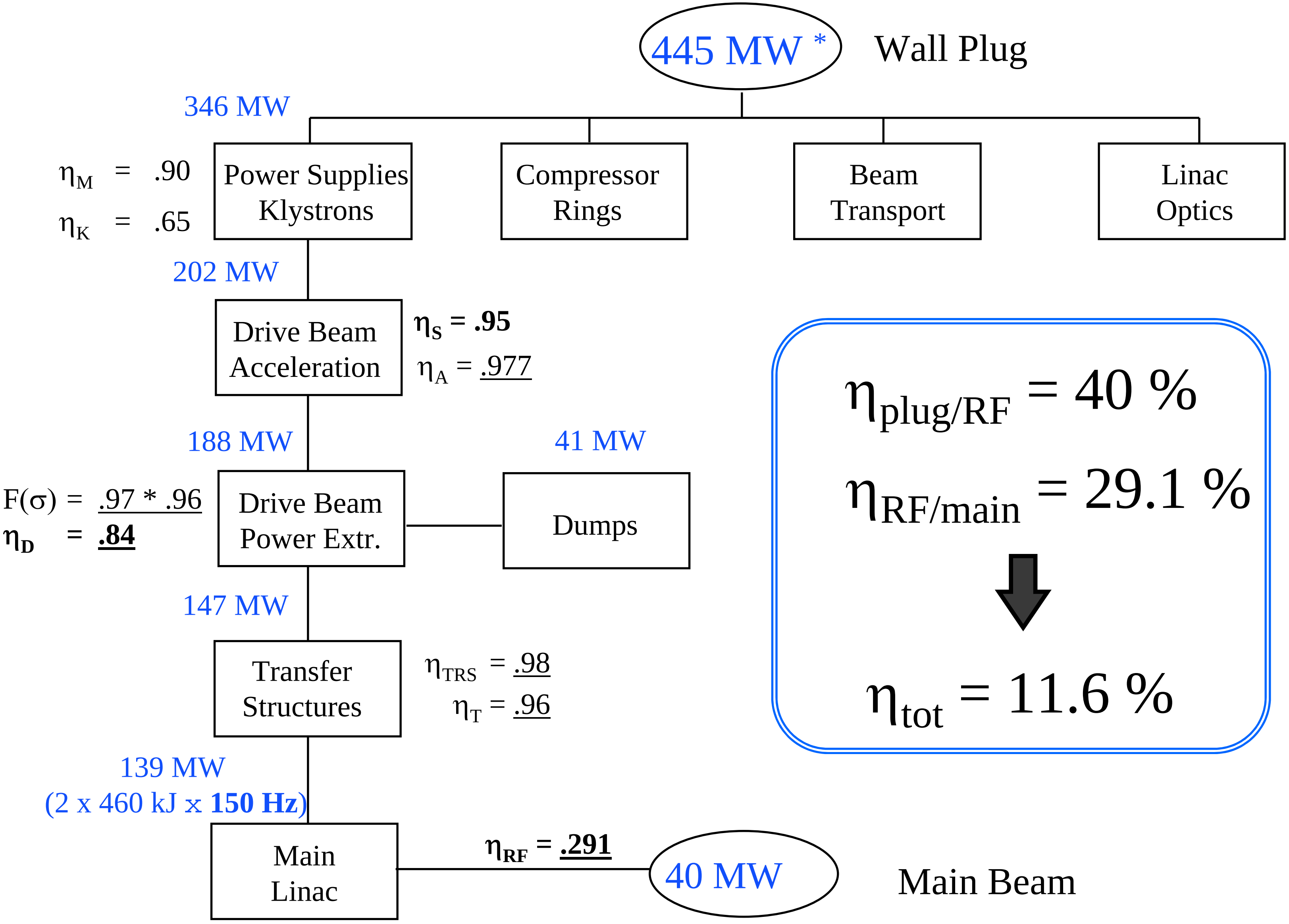
$\eta_{RF/main}$ = 25.2 %

⬇

η_{tot} = 9.7 %

* See Hans

New Parameters (3 TeV)



445 MW * Wall Plug

346 MW

η_M = .90

η_K = .65

Power Supplies Klystrons

Compressor Rings

Beam Transport

Linac Optics

202 MW

Drive Beam Acceleration

η_S = **.95**

η_A = .977

188 MW

41 MW

F(σ) = .97 * .96

η_D = **.84**

Drive Beam Power Extr.

Dumps

147 MW

Transfer Structures

η_{TRS} = .98

η_T = .96

139 MW

(2 x 460 kJ x **150 Hz**)

Main Linac

η_{RF} = **.291**

40 MW Main Beam

$\eta_{plug/RF}$ = 40 %

$\eta_{RF/main}$ = 29.1 %

η_{tot} = 11.6 %

* See Hans