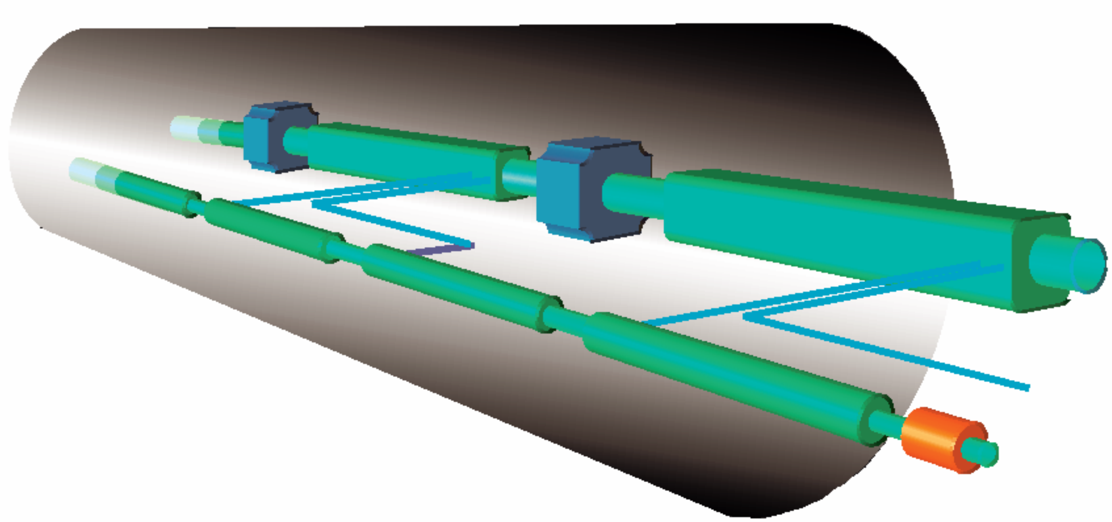
Drive Beam Generation and Main Beam RF Pulse-length, Possibilities and Limitations



Motivations

The latest studies on CLIC accelerating structures (taking into account limitations in accelerating gradient, RF power flow and pulsed surface heating) point in the direction of shorter structures, with shorter fill-time and shorter RF pulse length (about a factor 2 !).

Note that the main beam parameters (bunch charge and bunch spacing) are also adapted to the structure taking into account beam dynamics constraints and optimizing for luminosity and efficiency. These structures can provide RF-to-beam efficiencies equal or better than the "old" structures and require about the same power per meter.

Question:

What are the consequences on the drive beam generation complex ?

In particular, the delay loop and combiner rings dimensions, the number of decelerator sectors, and also the drive beam energy and current are linked to the RF pulse length.

What are the limitations, and how flexible is the drive beam generation complex ?

Accelerating structure optimization - limits

Given parameters of the first and last cells and N, N_b, N_{cycles}

$E_{surf}^{max}, \Delta T^{max}, P_{in}, t_p$ are calculated for each structure

- rf breakdown limits for Mo

$$E_{surf}^{max} < 420 \times 0.9 = 378 \, MV/m$$

and

$$P_{in} < \sqrt{150 ns / t_p} \cdot 100 \, MW$$

- pulsed surface heating limits for CuZr alloy

$$\Delta T^{max} < 70 \times 0.8 = 56 \, K$$

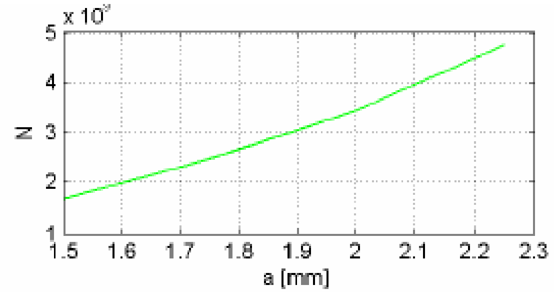
72932 (59%) structures satisfy these conditions

(Alexej Grudiev, CLIC meeting 3 oct.)

Beam dynamics constraints

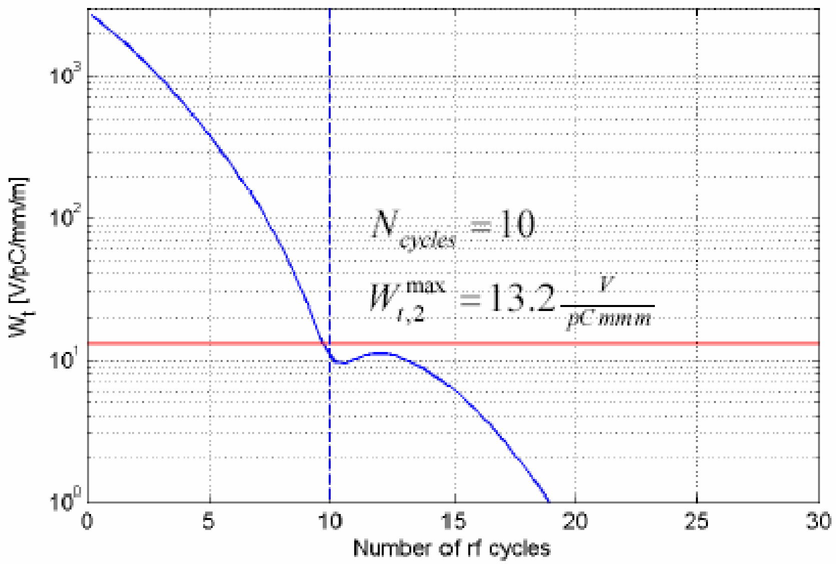
For each structure:

- N is constrained by short-range wakefields



- N_{cycles} is limited by long-range wakefields

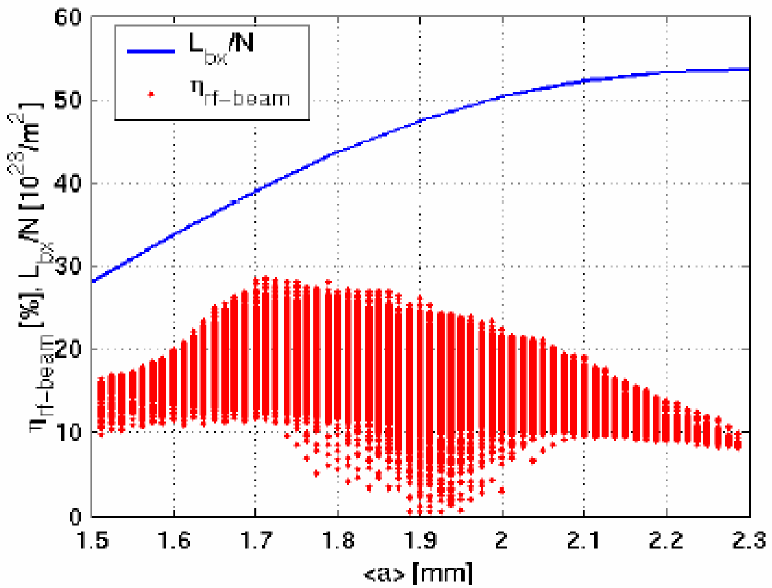
$$N \times W_{t,2}^{\max} = 4 \cdot 10^9 \times 10 \frac{V}{pC\,mm\,m}$$



(Alexej Grudiev, CLIC meeting 3 oct.)

"Best structure"

$$\max\left\{\frac{\int L\,dt}{\int P\,dt}\right\} \sim \max\left\{\frac{L_{bx}}{N}\cdot\eta_{rf\rightarrow beam}\right\}$$



$a = 2.125 \div 1.675,\ d = 0.8 \div 0.75\,mm,\quad N_{cells} = 93,\quad l = 28.5\,cm$

$N = 3.04\times 10^9$

$N_{cycles} = 10$

$N_b = 108$

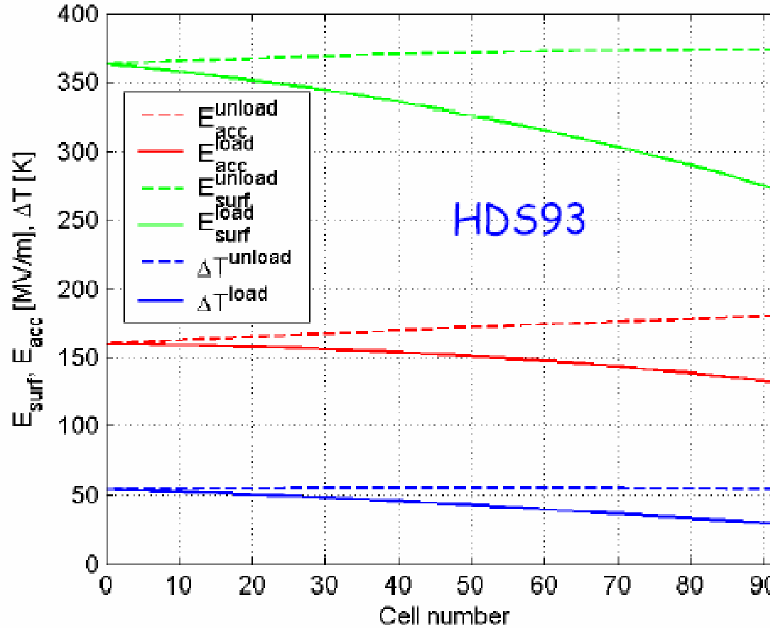
$t_p = 48.4\,ns$

$E_{surf}^{max} = 374\ MV/m$

$\Delta T^{max} = 54.7\,K$

$\eta_{rf\rightarrow beam} = 26\%$

$P_{in} = 176\,MW$

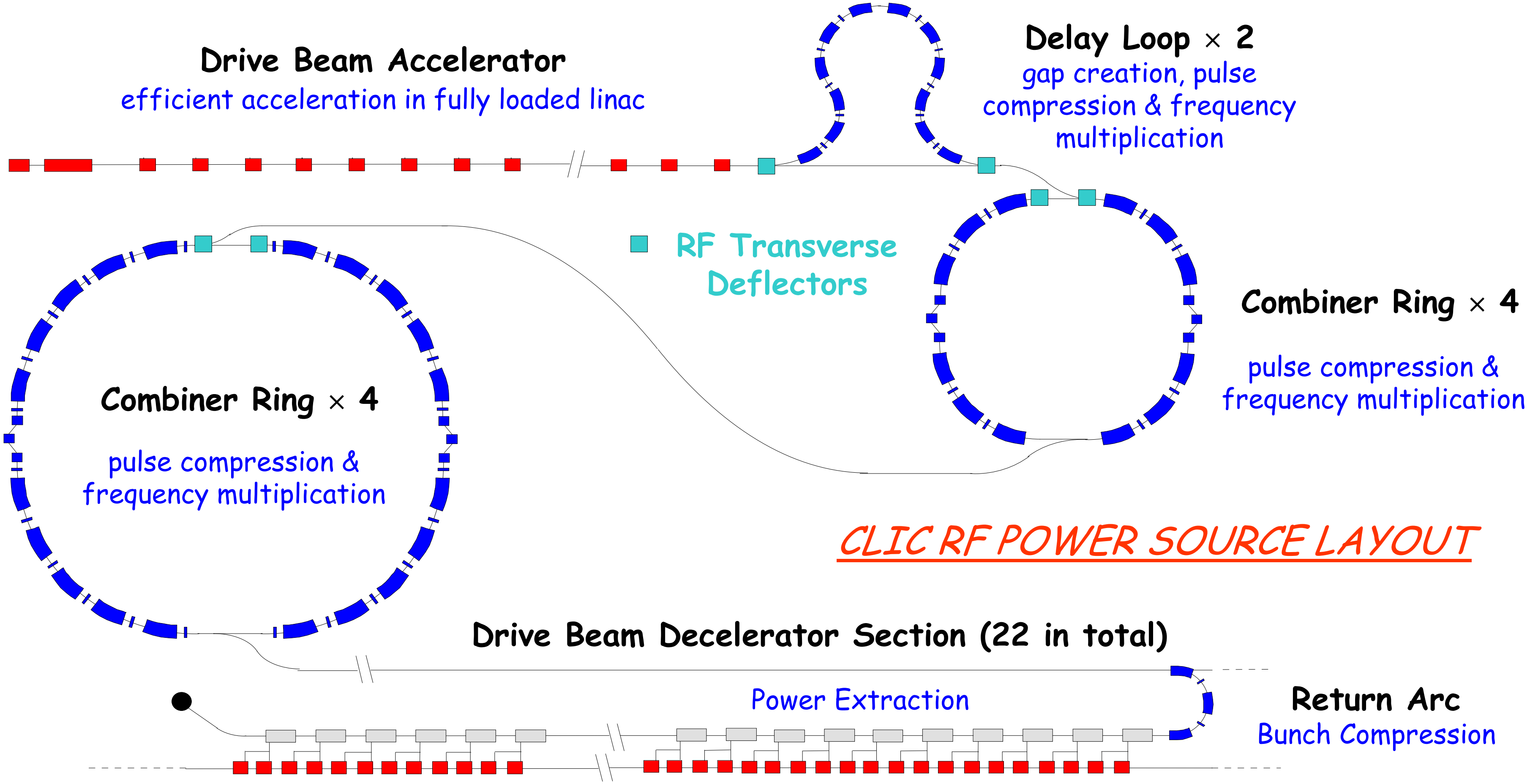


(Alexej Grudiev, CLIC meeting 3 oct.)

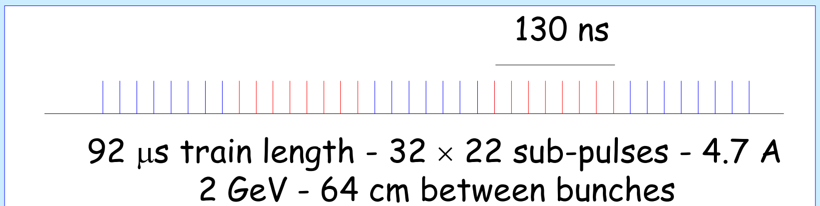
Present parameters

(TRC, 3 TeV)

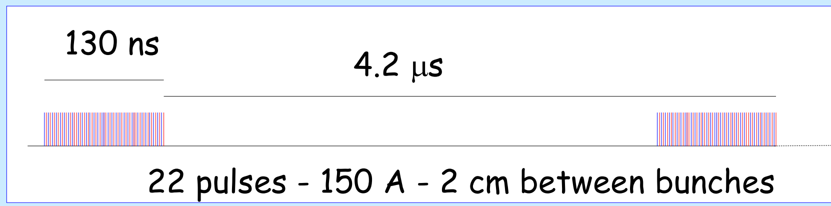
Parameter Table for 3 TeV Case	4wg - 2 on 1	
CM Energy (TeV)		3.3
Average Gradient (MeV/m)		120
Linac Length (Km)		27.46
Repetition Frequency (Hz)		100
Pulse Length (nsec)		102
Number of bunches		154
Charge per bunch (10^9)		4
HE Beam Total Energy (KJ)		151
Number of Drive Beams		22
Rf Pulse Total Energy (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



Drive beam time structure - initial



Drive beam time structure - final



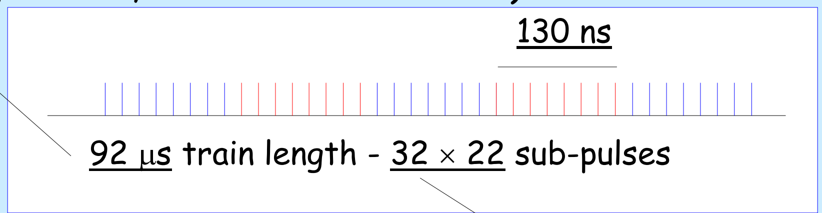
Drive beam initial pulse length and RF pulse length

$c \cdot 92\ \mu s = 27.5\ km$

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

$$130\ ns \times 32 \times 22 = 92\ \mu s$$

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

BEAM TRANSVERSE STABILITY

IN THE CLIC COMBINER RINGS

R. Corsini and D. Schulte

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

Drive beam stability in RF deflectors scaling with frequency

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:

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

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:

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

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.

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)		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

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	417
Drive Beam Energy (GeV)		0.99
Drive Beam Current (A)	energy	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

  The drive beam energy can be increased if the PETS impedance and the current are decreased, but the scaling of beam stability is unfavorable (and SR power loss – see later)

  The "present" 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

A trick of the trade: single DB generation complex

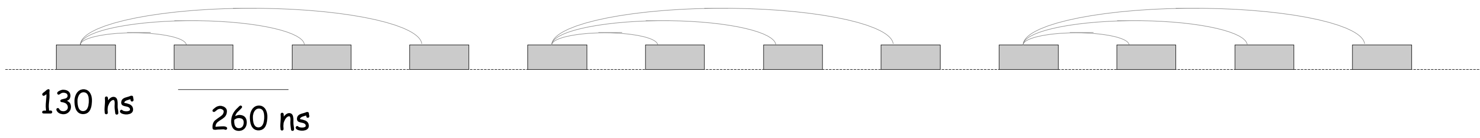
Daniel proposed time ago to combine the DB generation for both e+ and e- linacs, in order to improve the DB stability in the decelerator. This can be done as follows :

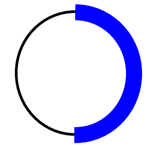
- Use a single accelerator with double length $\Rightarrow$ double beam energy
- Same initial pulse length
- Same DL and CRs lengths
- Switch subsequent pulses to power the e+ and e- main linacs
- The distance between pulses in each decelerator is now doubled
- Half the number of decelerator sectors

"Standard" scheme

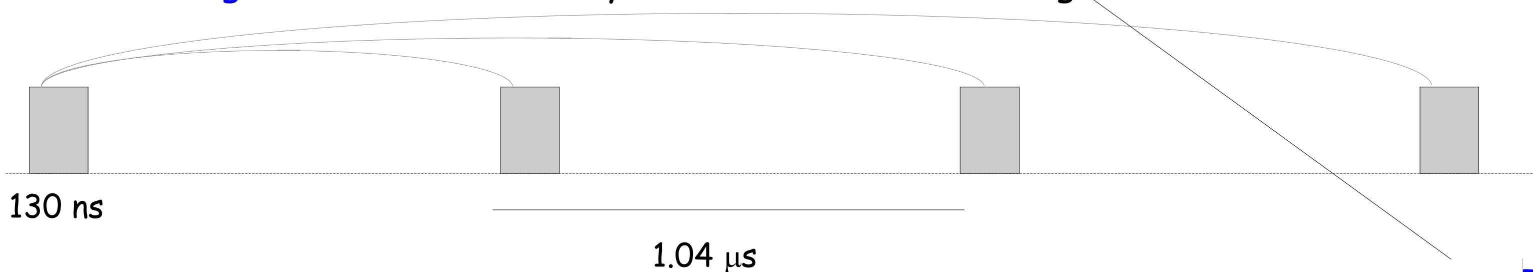
From DBA – 130 ns long "sub-pulses"

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

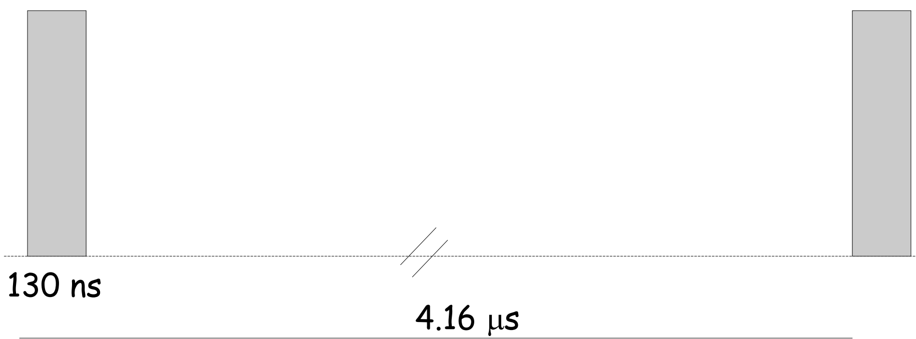


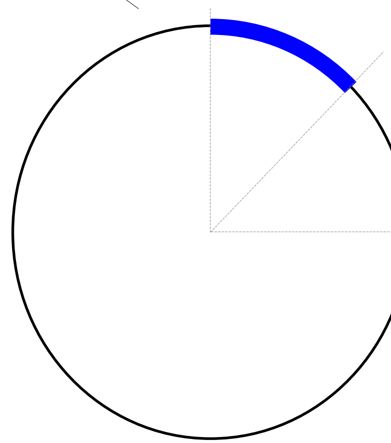


After 1st combiner ring - combination four by four in 2nd combiner ring



Final time structure

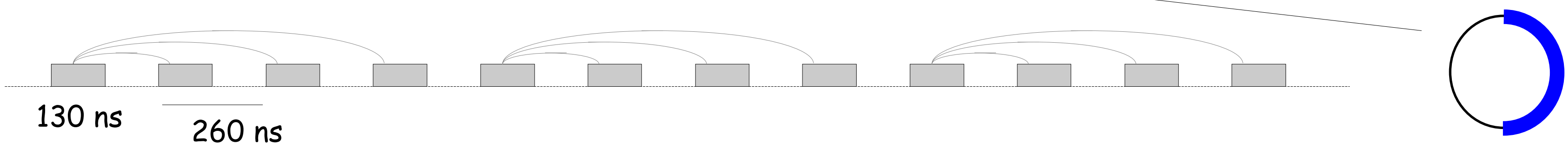




"Single DB generation complex" scheme

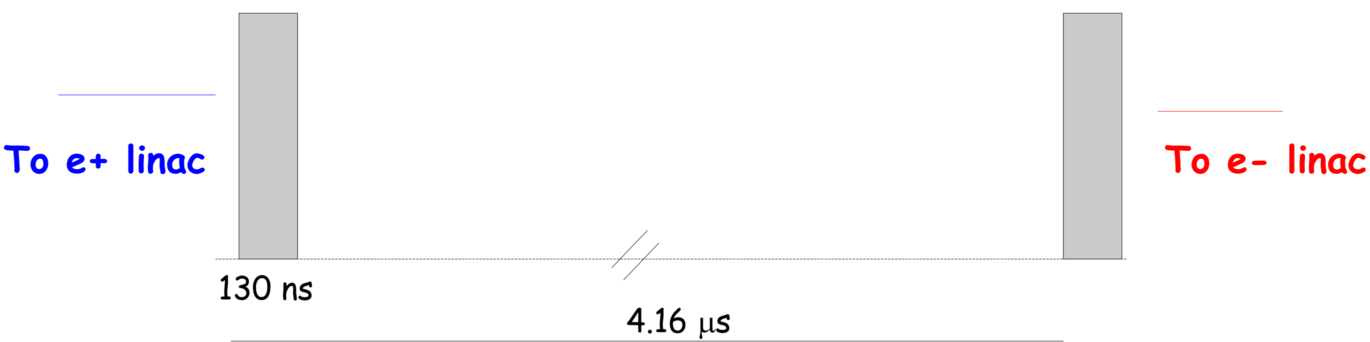
From DBA – 130 ns long "sub-pulses"

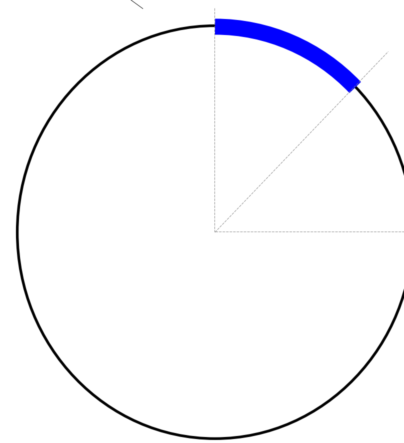
After delay loop - combination four by four in 1st combiner ring



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

Final time structure





Single DB generation complex: rings issues

Several issues were studied at the time 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: Parameters as in Yellow Report - ring lengths to be scaled from 86 m and 344 m to 78 m and 312 m

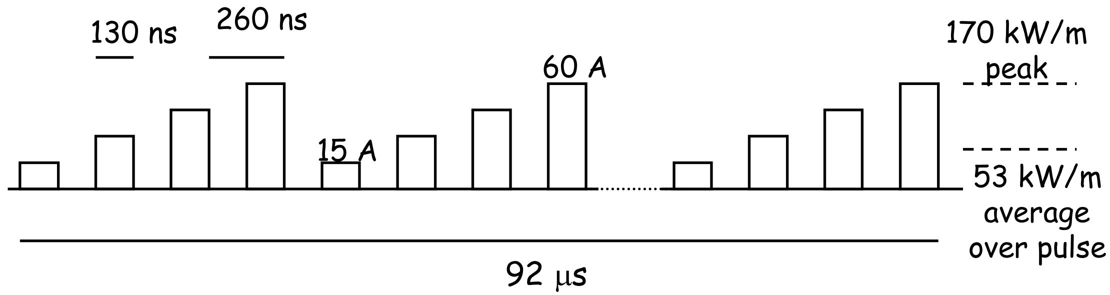
Power loss from SR

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

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

1st Ring - E = 1.2 GeV

4.9 kW, 480 W/m total average

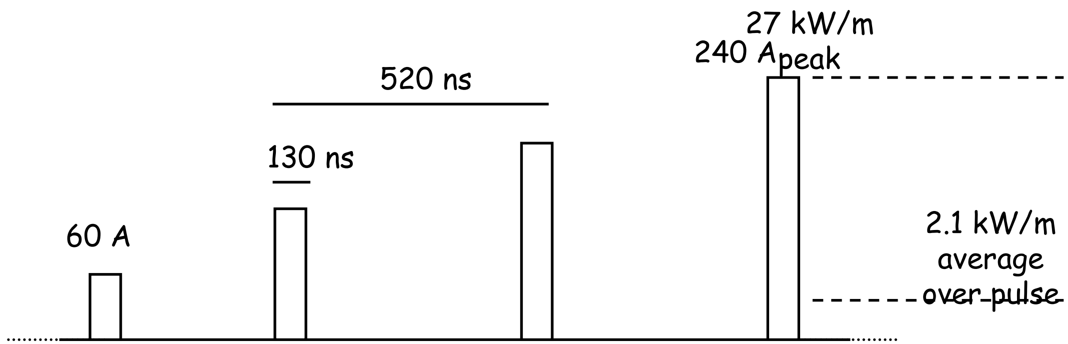


E =2.4 GeV - 16 times more losses

7700 W/m total average (2700 kW/m peak, 840 kW/m average over pulse)

2nd Ring - E = 1.2 GeV

0.98 kW, 19 W/m total average

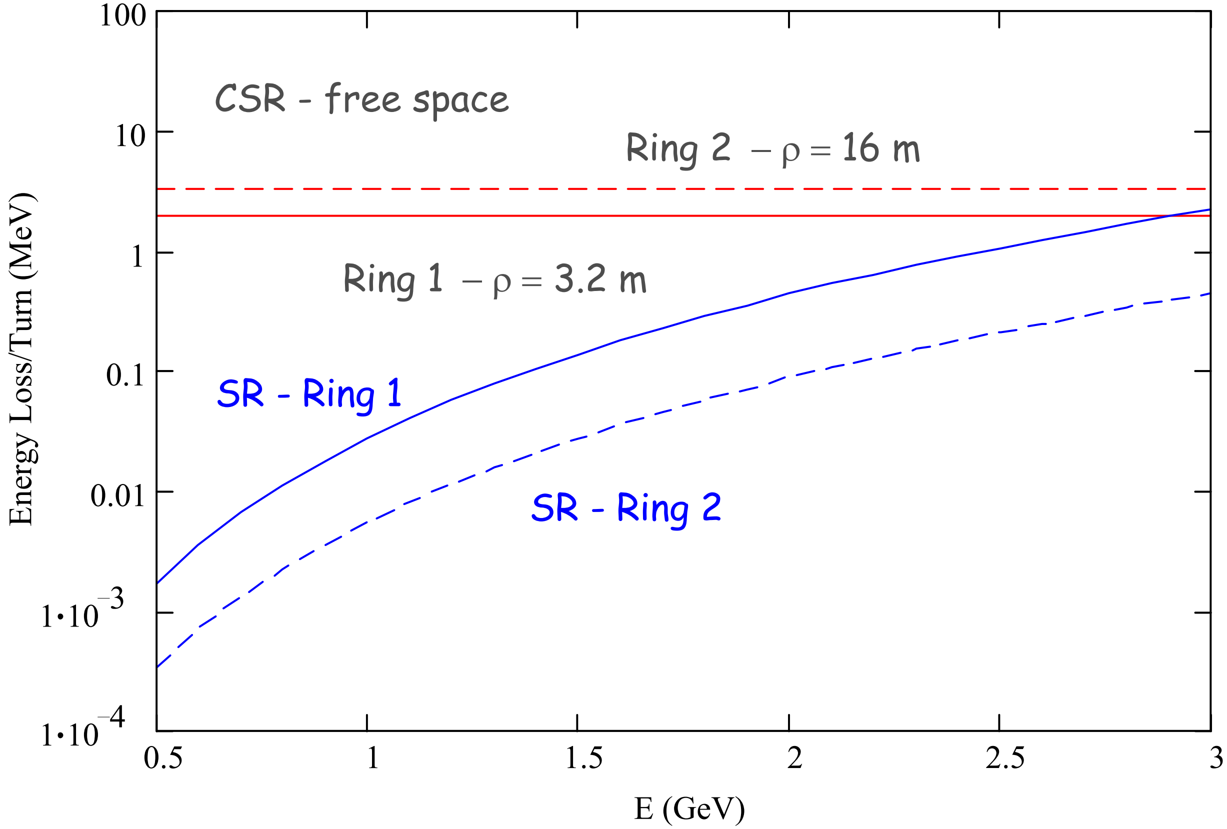


E =2.4 GeV - 16 times more losses

304 W/m total average (430 kW/m peak, 34 kW/m average over pulse)

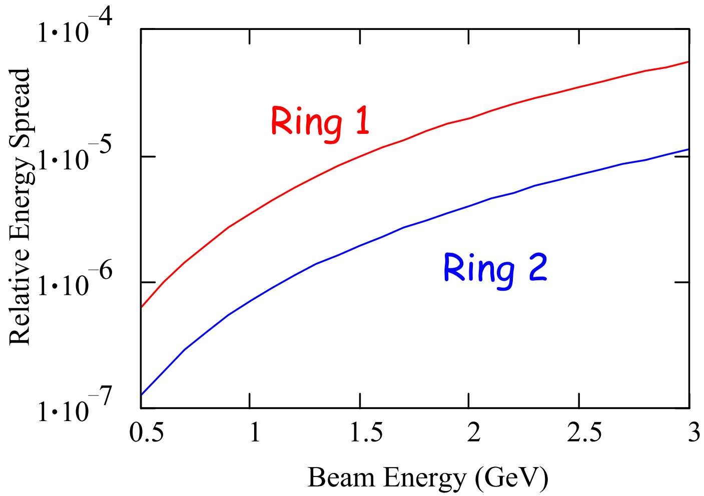
Energy loss from SR and CSR

σ = 2 mm, Qb = 16 nC



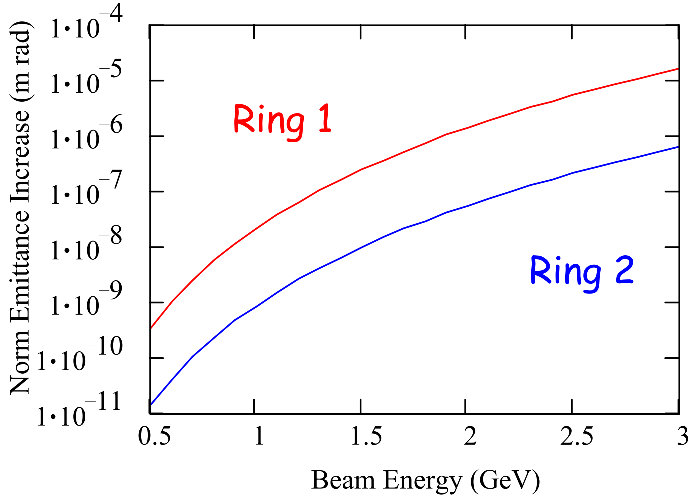
Energy spread and emittance increase from SR

$$\sigma E = 3.43810^{-8} \frac{\gamma^{7/2}}{\rho} \quad [\mathrm{eV\,m}]$$



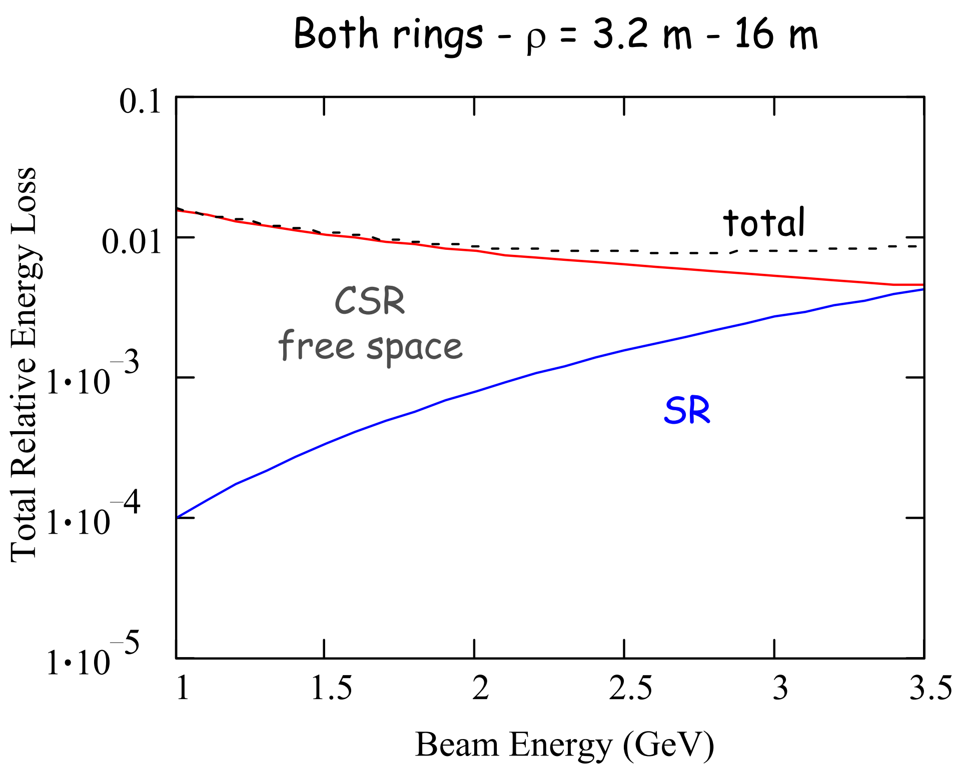
NB: Nominal emittance $\varepsilon_{N,rms}$ = 1 10^{-4} m rad

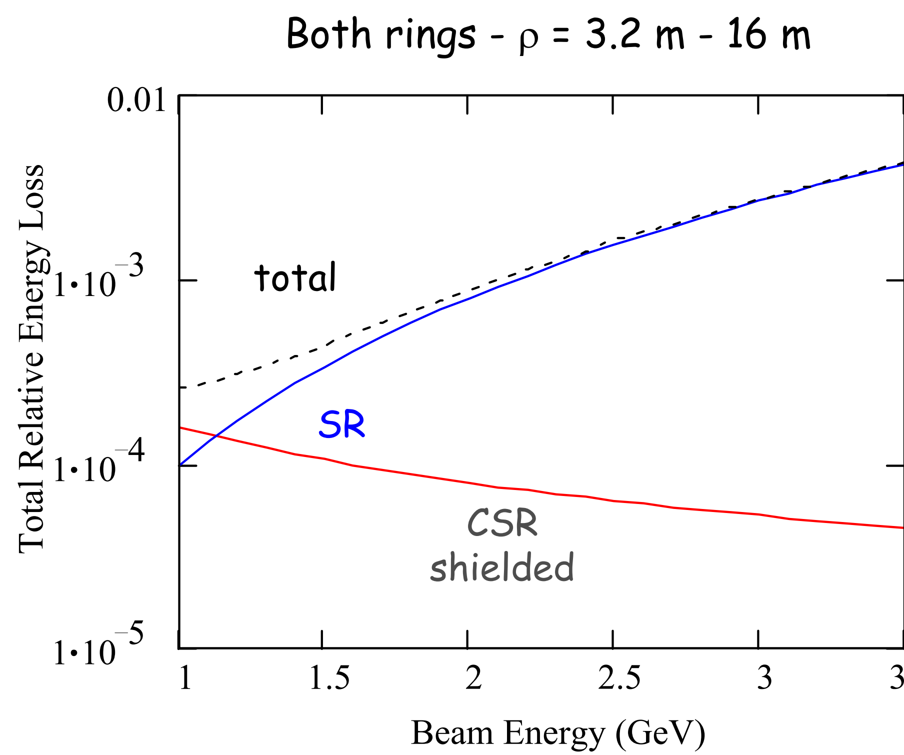
$$\Delta\varepsilon = 1.32\,\pi\,10^{-27} \frac{\gamma 6}{\rho^2} \langle H \rangle \quad [\mathrm{m^2\,rad}] \qquad \langle H \rangle$$



Energy loss from SR and CSR

σ = 2 mm, Qb = 16 nC





It was concluded at the time that a doubling of the energy to 2.4 GeV was indeed possible

"Double pulse" scheme

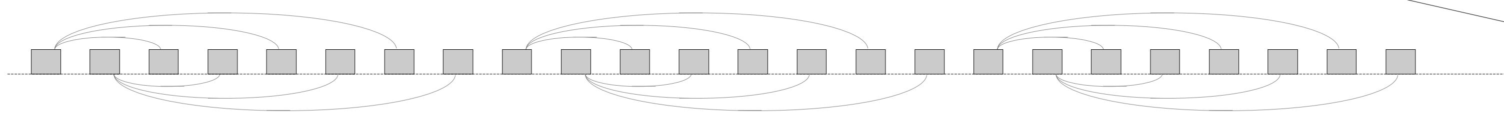
In the case of a short RF pulse, it is possible to use a single drive beam generation complex to feed both linacs, in a different way:

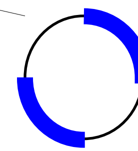
- Use a "short" delay loop (e.g., 19 m for 65 ns)
- Use "long" combiner rings (e.g., 78 m and 312 m for 65 ns)
- In each ring, two pulses will circulate (and be combined) at the same time
- The combined pulse couples can be split and sent to the e+ and e- main linacs
- The number of decelerator sections is "small" (e.g., 22)
- The drive beam energy is "high" (e.g., 2 GeV)

"Double pulse" scheme

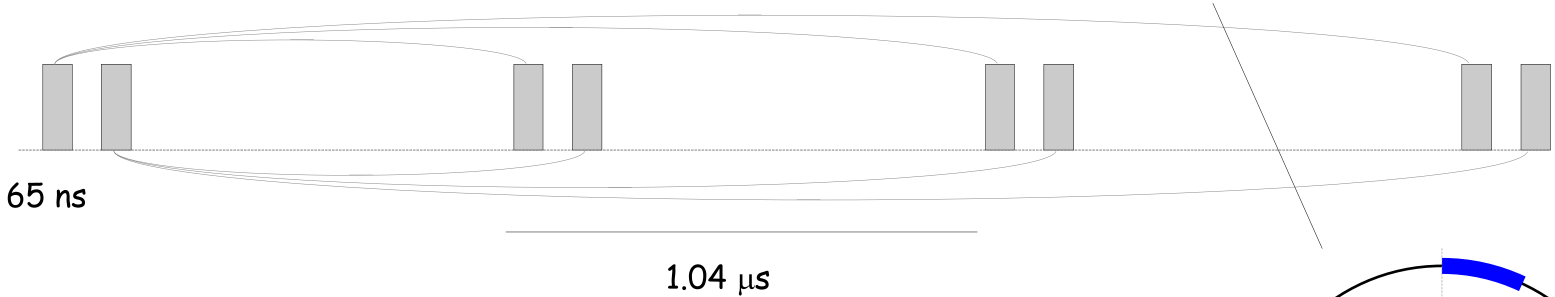
From DBA - 65 ns long "sub-pulses"

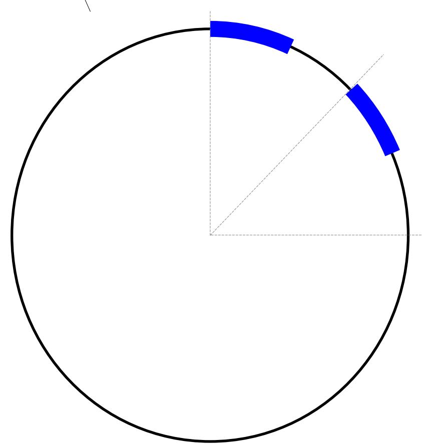
After delay loop - combination four by four in 2 batches in 1st combiner ring



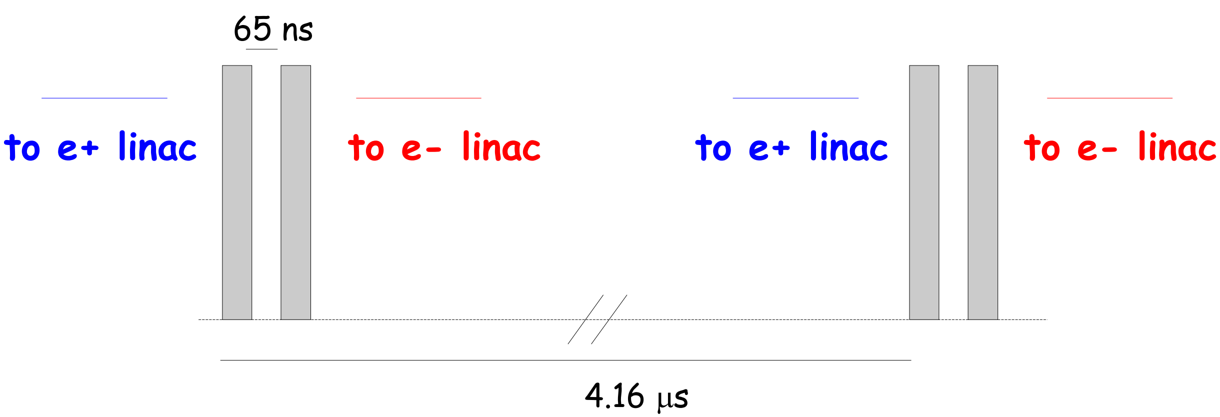


After 1st combiner ring - combination four by four in 2 batches in 2nd combiner ring





Final time structure



An exercise: TWS - This Week Structure

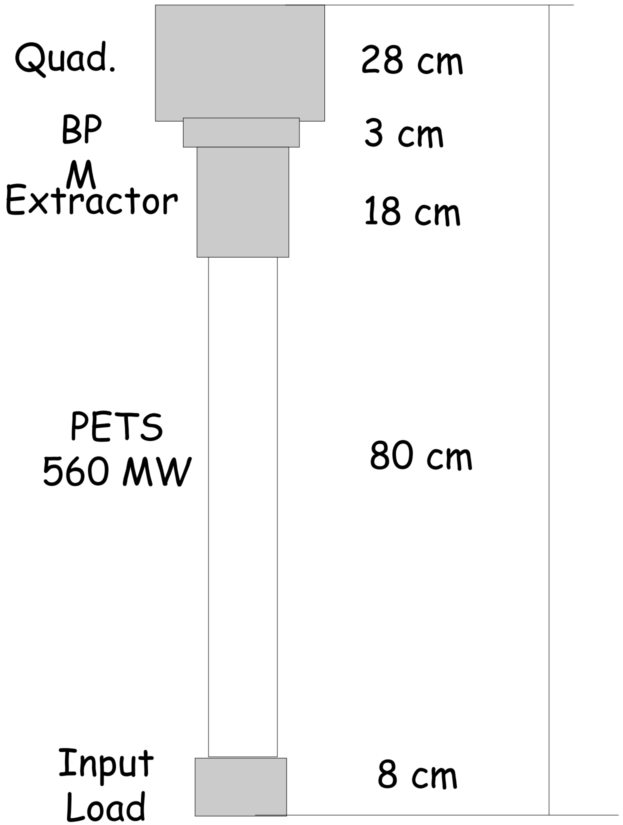
<a> [mm]	L/N* η	Nb	Qb [10^9]	Tp [ns]	η [%]	Pin [MW]	Ncells
1.7125	11.0	171	2.33	65.0	28.5	128	81
1.7875	12.2			55.1		146	85
1.8625	12.4	134	2.88	56.7	26.8	162	87
1.9	12.4	108	3.04	48.4	26	176	93
1.9875	10.5			33.8		210	107

(Alexej Grudiev)

(Igor Syratchev)

Case N1 (based current design)

$I=I_0 L$ total=137 cm



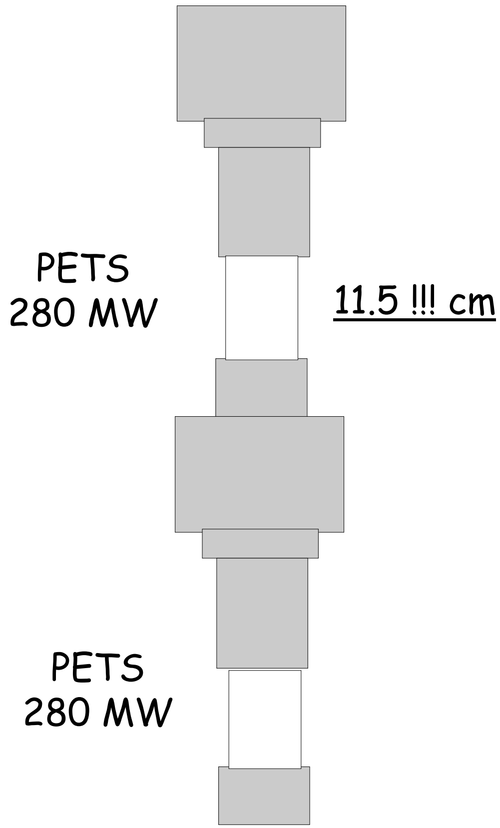
Inactive length ~41%

1.37 m

Fits to 4, 90 cells acc. structures

Case N2_1: 2 half power PETS Cons. Quads.

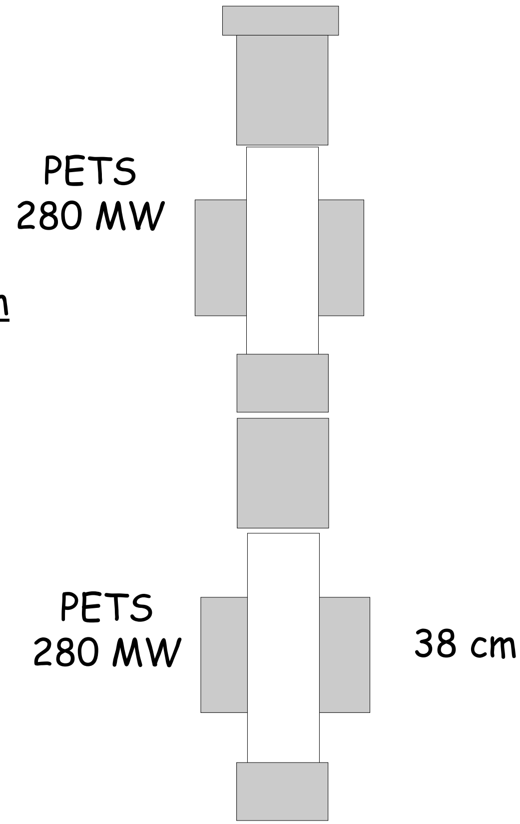
$I \sim I_0 \times 5$



Inactive length 83%!!!

Case N2_1: 2 half power PETS R. Around Quads.

$I \sim I_0 \times 2^{0.5}$



Inactive length 40%

Drive Beam Complex parameters for TWS

case N1
1 PETS for 4 accelerating structures

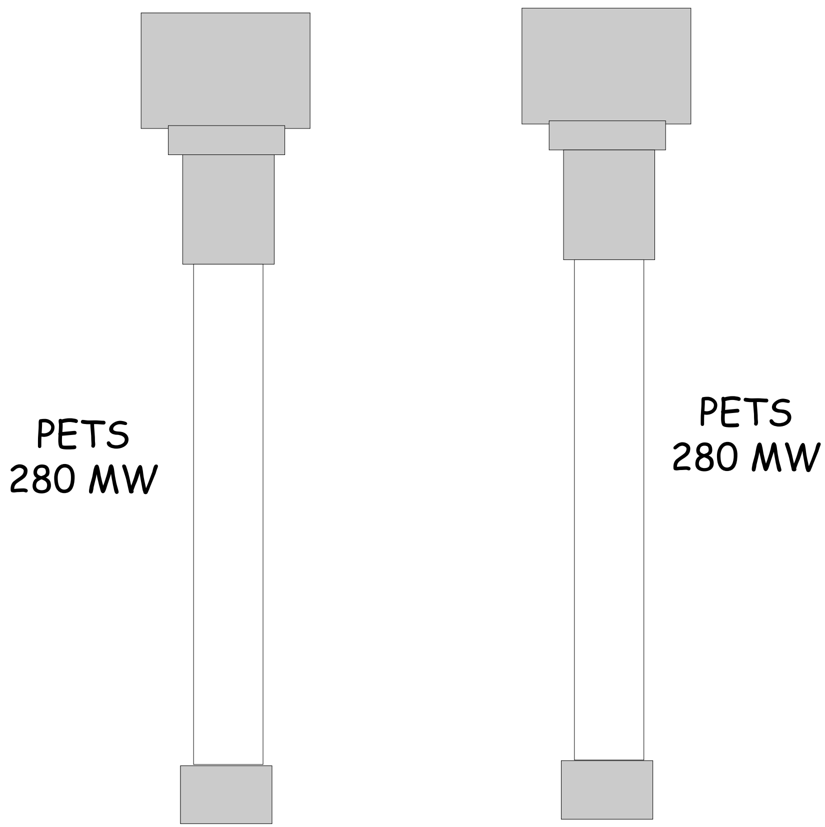
"Double pulse" scheme

Parameter Table for 3 TeV Case		
CM Energy (TeV)		3.2
Average Gradient (MeV/m)		117
Linac Length (Km)		27.46
Repetition Frequency (Hz)		100
Pulse Length (nsec)		44
Number of bunches		134
Charge per bunch (10^9)		2.88
HE Beam Total Energy (KJ)		92
Number of Drive Beams		24
Rf Pulse Total Energy (KJ)		367
Drive Beam Pulse Length (nsec)		60
Frequency Multiplication		32
Deceleration Section Length (m)		572
Delay Loop Length (m)		18
1st Combiner Length (m)		72
2nd Combiner Length (m)		286
Drive beam Pulse (Microsec)		92
Total Drive beam Energy (KJ)		496
Drive Beam Energy (GeV)		1.98
Drive Beam Current (A)		5.5
Drive Beam Bunch Charge (nC)		11.6
Frequency of DBA (MHz)		937
Length of DBA (m)		472
Structure Length (m)		4.28
Power per Structure (MW)		101
Number of 50 MW Klystrons		220
Total RF Efficiency (%)		40
Wall to beam Efficiency (%)		10.1

Case N3 doubled decelerators
$I \sim I_0/2^{0.5}$

(Igor Syratchev)

L total=137 cm



Drive Beam Complex parameters for TWS

case N3
1 PETS for 2 accelerating structures
double decelerator

"Double pulse" scheme

Parameter Table for 3 TeV Case		
CM Energy (TeV)		3.2
Average Gradient (MeV/m)		117
Linac Length (Km)		27.46
Repetition Frequency (Hz)		100
Pulse Length (nsec)		44
Number of bunches		134
Charge per bunch (10^9)		2.88
HE Beam Total Energy (KJ)		92
Number of Drive Beams		24
Rf Pulse Total Energy (KJ)		367
Drive Beam Pulse Length (nsec)		60
Frequency Multiplication		32
Deceleration Section Length (m)		572
Delay Loop Length (m)		18
1st Combiner Length (m)		72
2nd Combiner Length (m)		286
Drive beam Pulse (Microsec)		92
Total Drive beam Energy (KJ)		248
Drive Beam Energy (GeV)		1.40
Drive Beam Current (A)		3.9
Drive Beam Bunch Charge (nC)		8.2
Frequency of DBA (MHz)		937
Length of DBA (m)		334
Structure Length (m)		6.06
Power per Structure (MW)		102
Number of 50 MW Klystrons		110
Total RF Efficiency (%)		79
Wall to beam Efficiency (%)		10.0