Drive Beam Complex and Power Generation including CLIC Module

or rather

An introduction to the CLIC RF power source

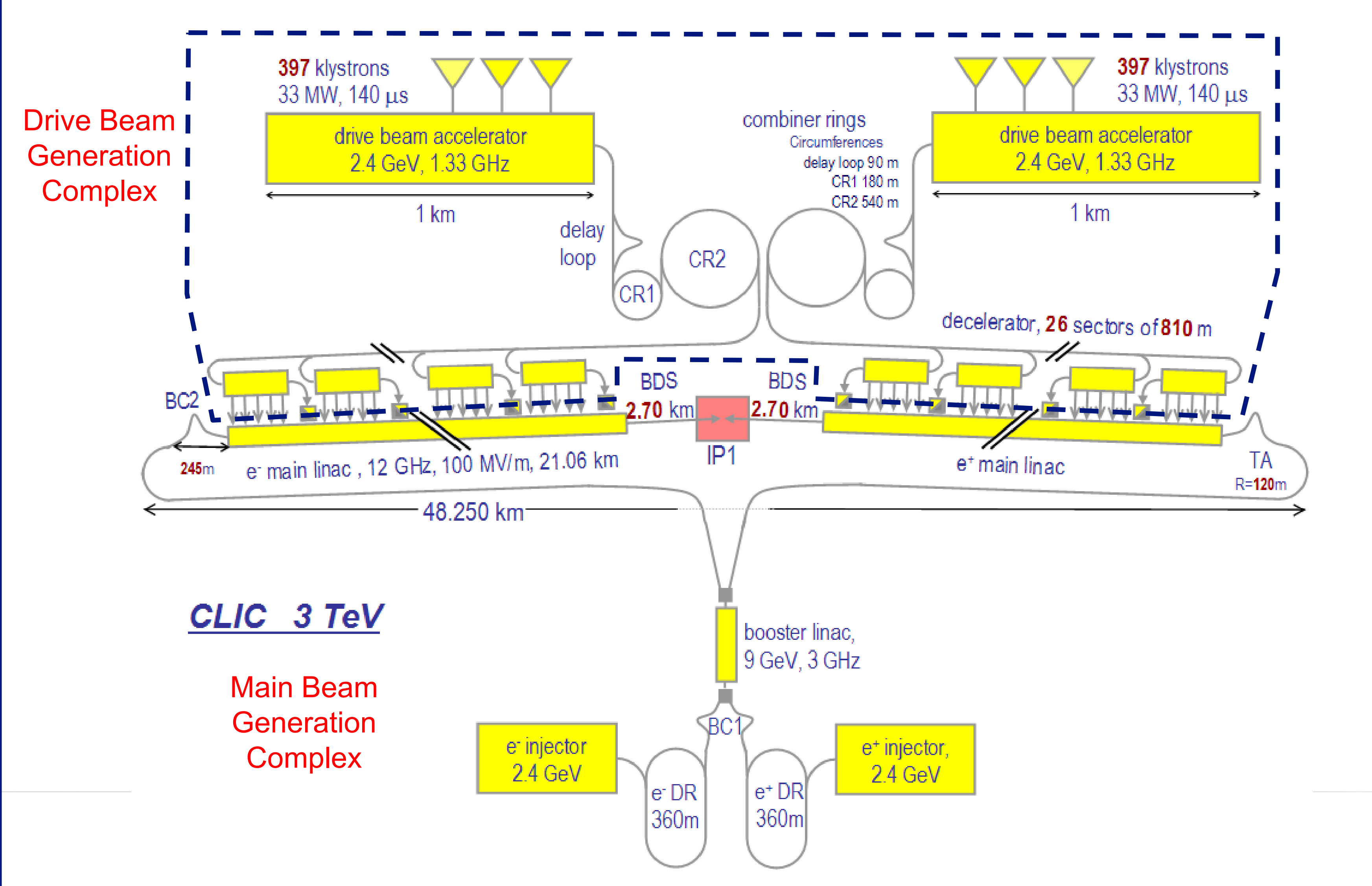
Aim of the talk:

- How the drive beam generation works – basics !

Will also try to cover:

- Some (non exhaustive) issues
- Why not klystrons ?
- Power consumption

The CLIC RF power source

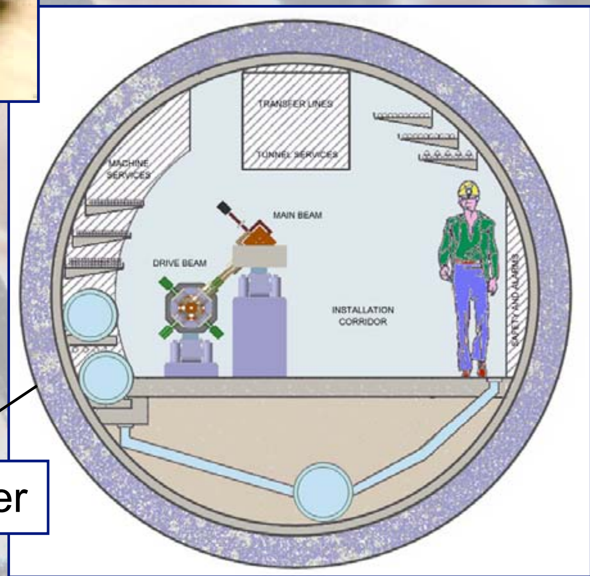


Drive Beam Complex and Power Generation including CLIC Module

CLIC MODULE

(20700 modules at 3 TeV)

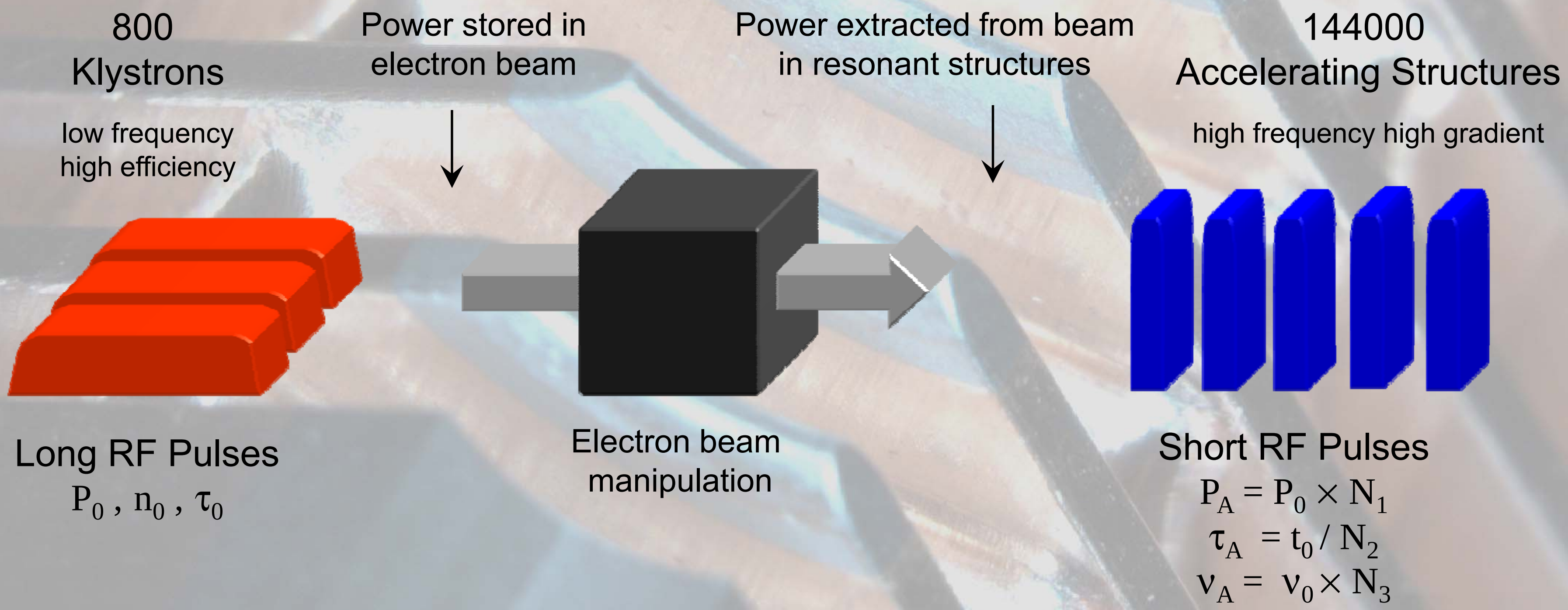
CLIC TUNNEL CROSS-SECTION



4.5 m diameter

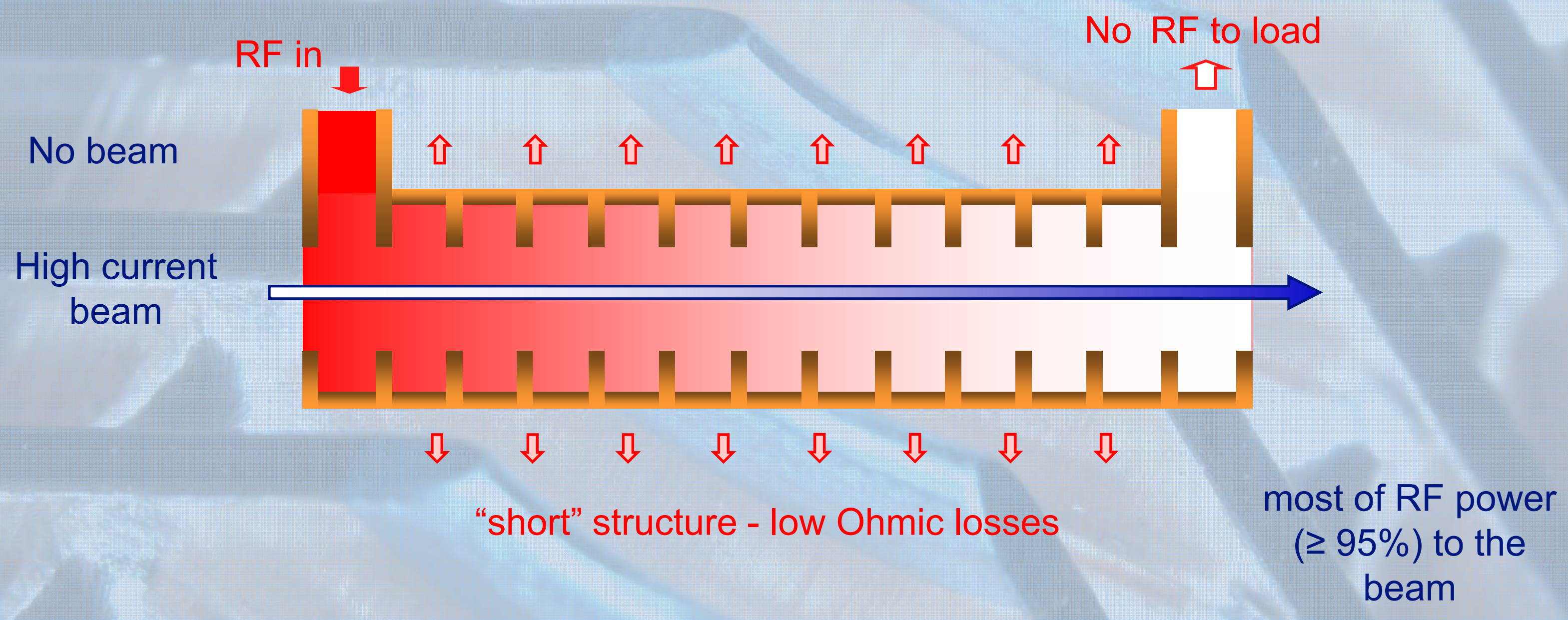
What does the RF Power Source do ?

The CLIC RF power source can be described as a “black box”, combining *very long RF pulses*, and transforming them in *many short pulses*, with *higher power* and with *higher frequency*

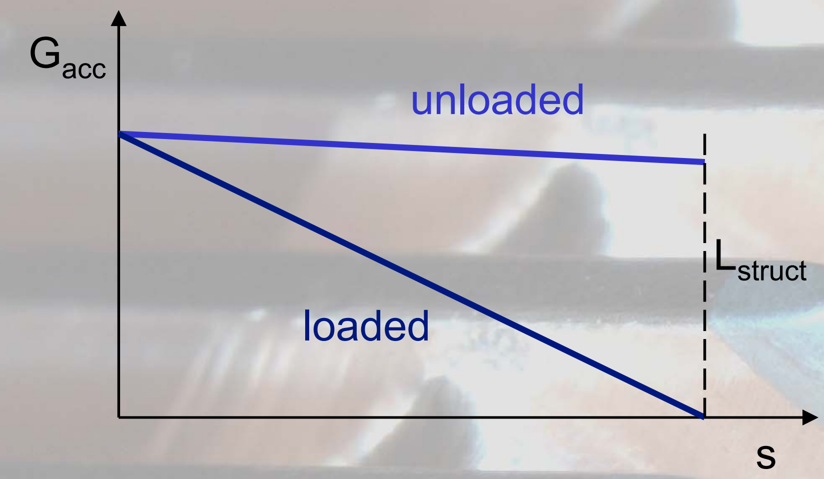


RF Power Source "building blocks"

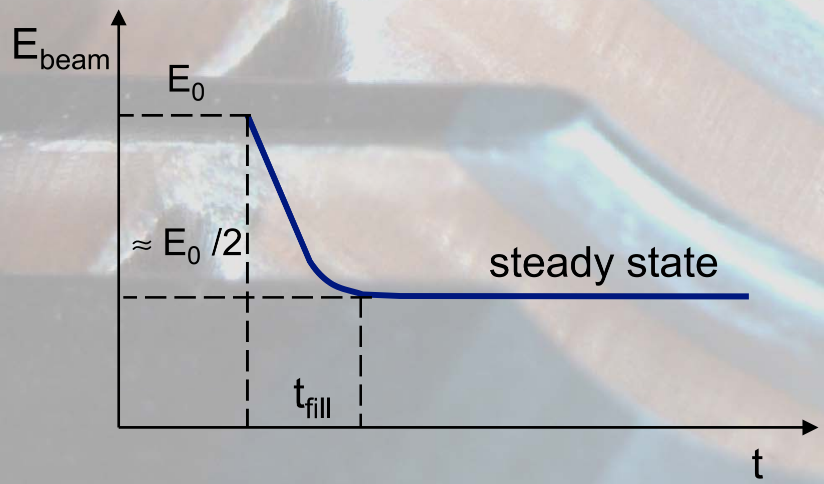
Full beam-loading acceleration in TW sections



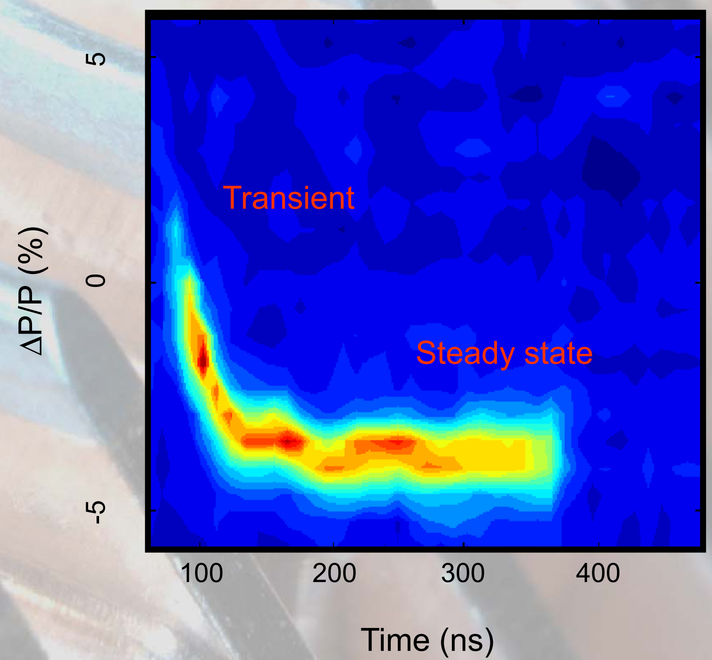
RF Power Source "building blocks"



Full beam-loading acceleration in TW sections



Time resolved beam energy spectrum measurement in CTF3

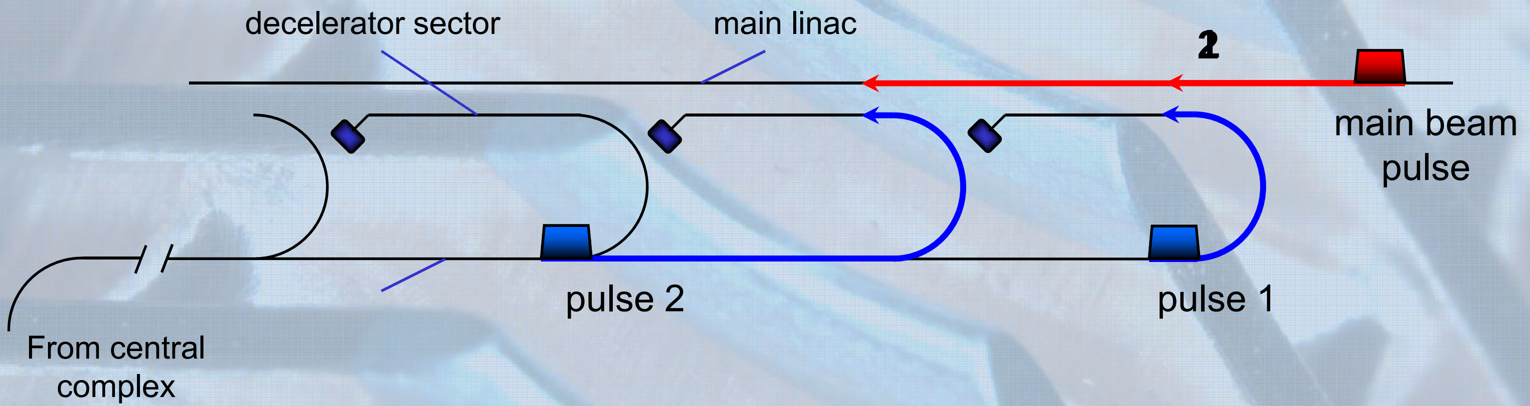


RF Power Source "building blocks"

Counter propagation from central complex

Instead of using a single drive beam pulse for the whole main linac, several (N_S = 26) short ones are used.

Each one feed a 800 m long sector of TBA.



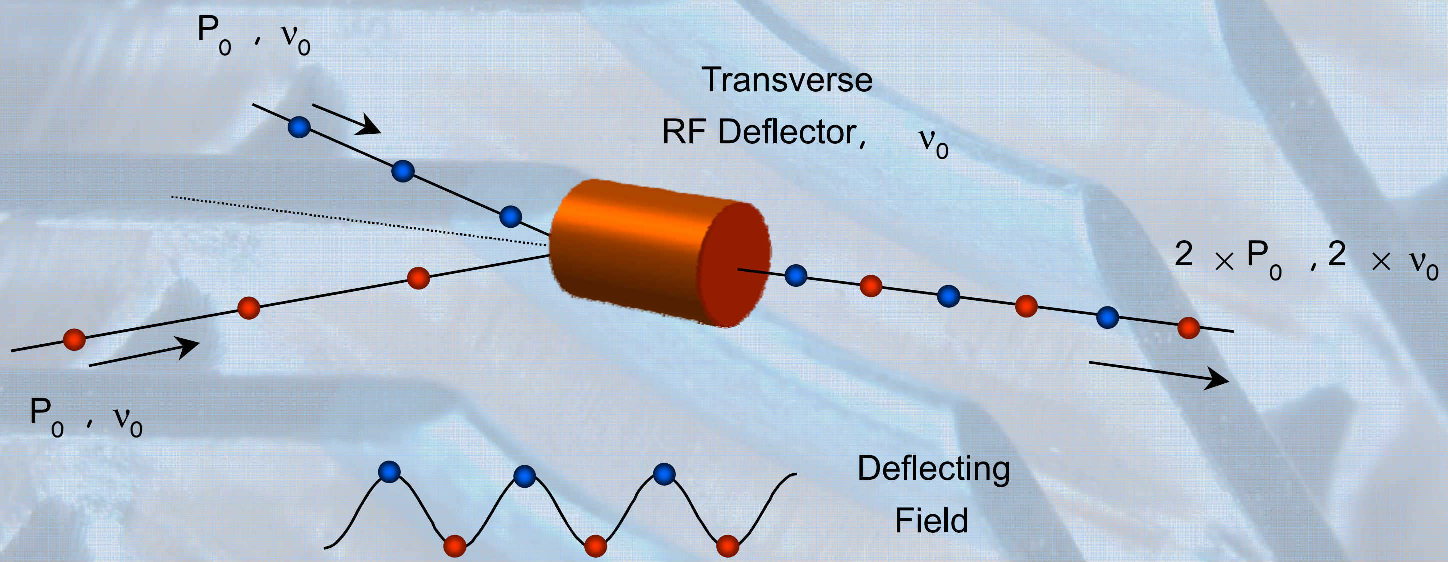
(DLDS-like system)

Counter-flow distribution allows to power different sectors of the main linac with different time bins of a single long electron pulse.

The distance between pulses is 2 L_S = 2 L_{main}/N_S. The initial drive beam pulse length is equal to 2 L_{main}= 140 µs/c.

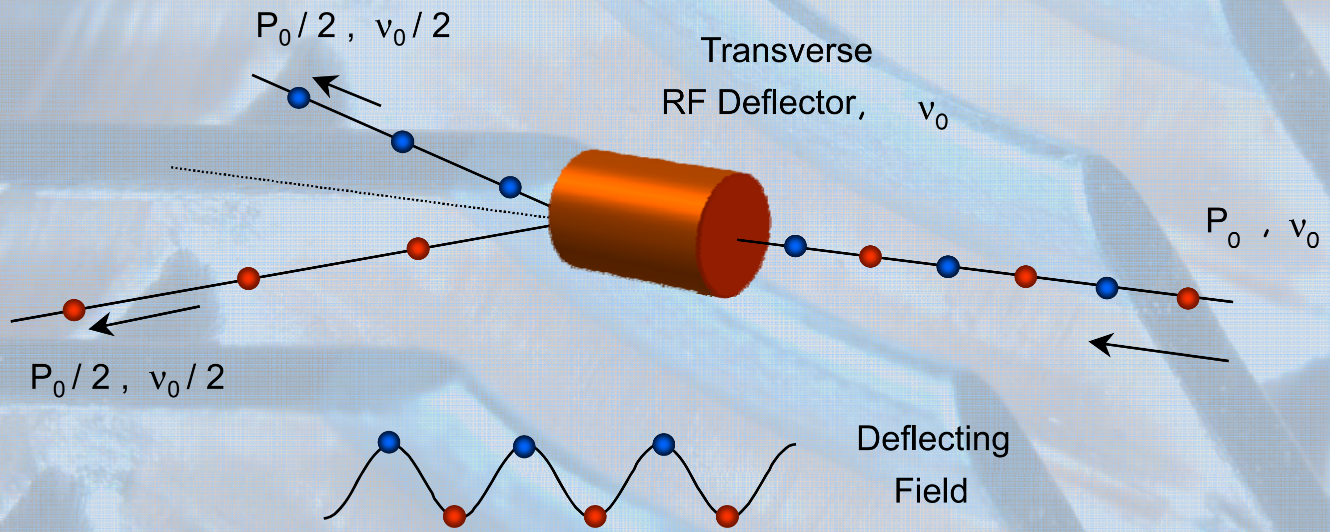
RF Power Source "building blocks"

Beam combination/separation by transverse RF deflectors

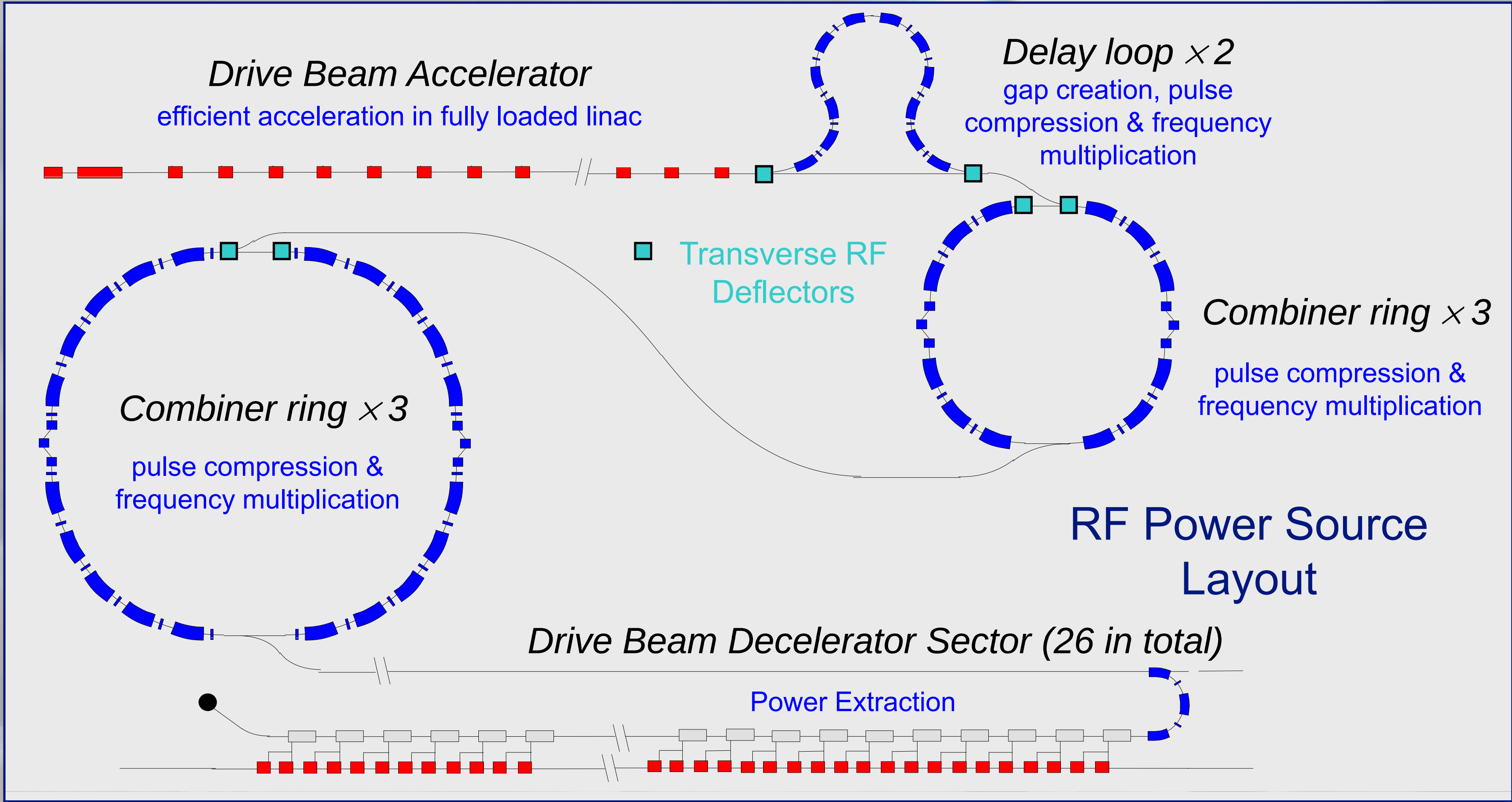


RF Power Source “building blocks”

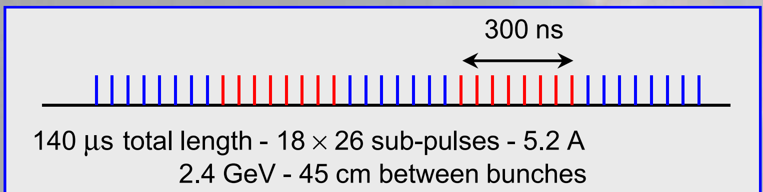
Beam combination/separation by transverse RF deflectors



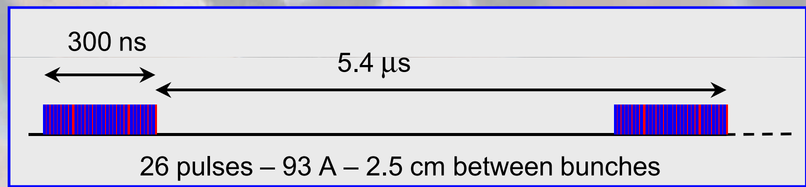
Drive Beam Complex and Power Generation including CLIC Module



Drive beam time structure - initial



Drive beam time structure - final

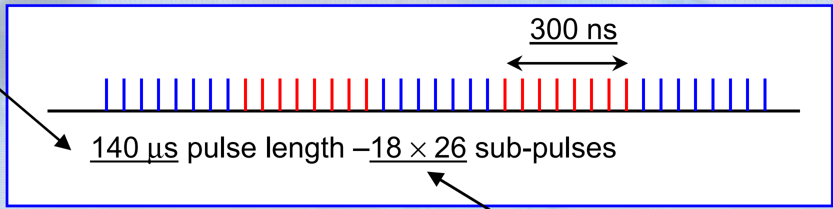


Drive beam initial pulse length and RF pulse length

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 12 GHz RF pulse

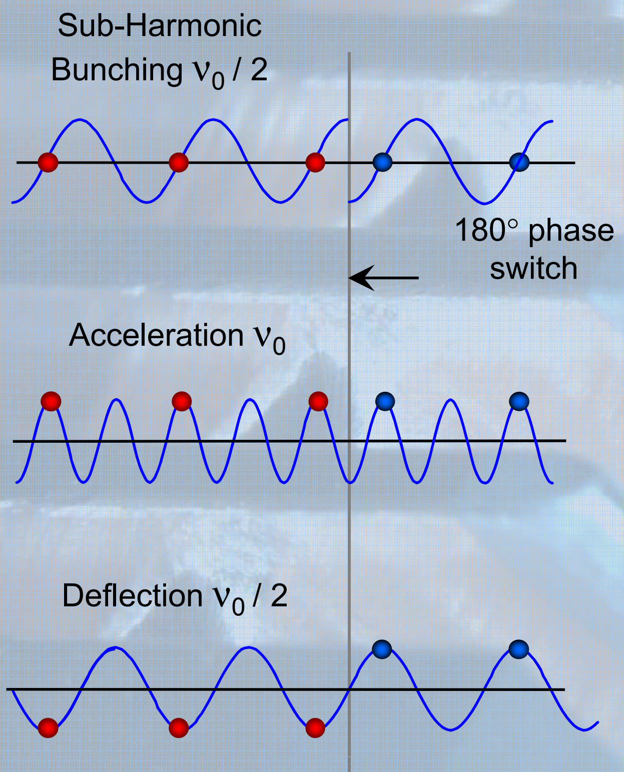
Initial pulse structure



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

Phase coding

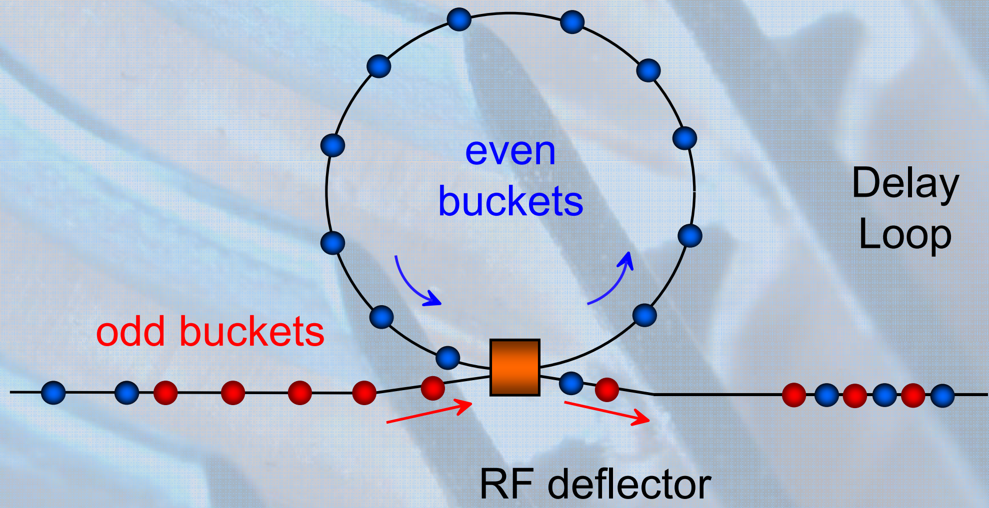
How to "code" the sub-pulses



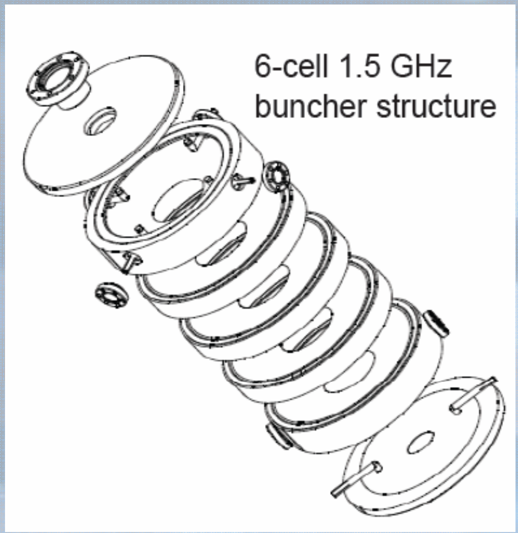
Gap creation & first multiplication × 2

$$L_{delay} = n\,\lambda_0 = c\,T_{sub\text{-}pulse}$$

Combination scheme

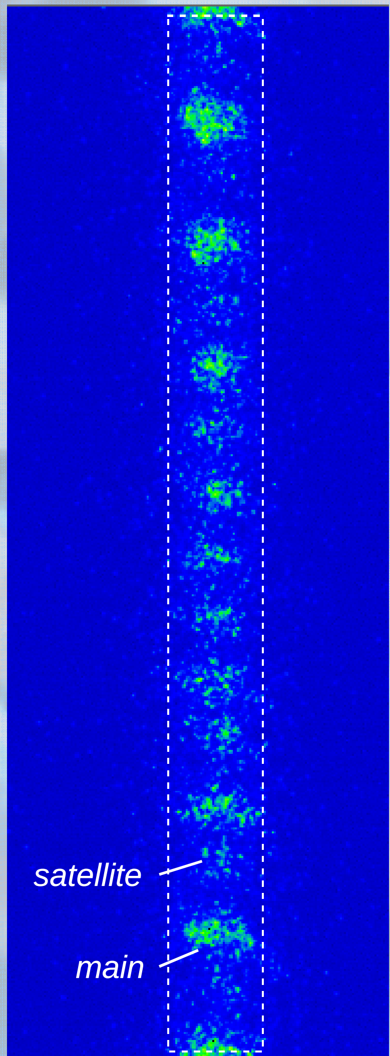


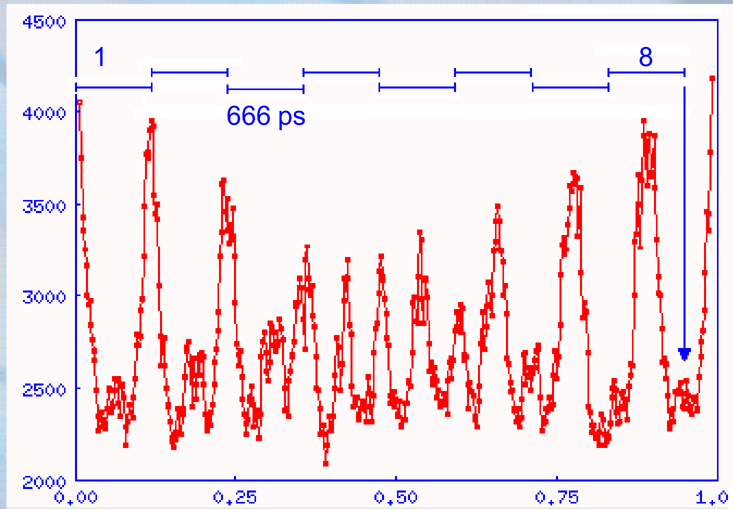
Fast phase switch from SHB system (CTF3)



3 TW Sub-harmonic bunchers, each fed by a wide-band TWT

Streak camera – 500 ps/mm



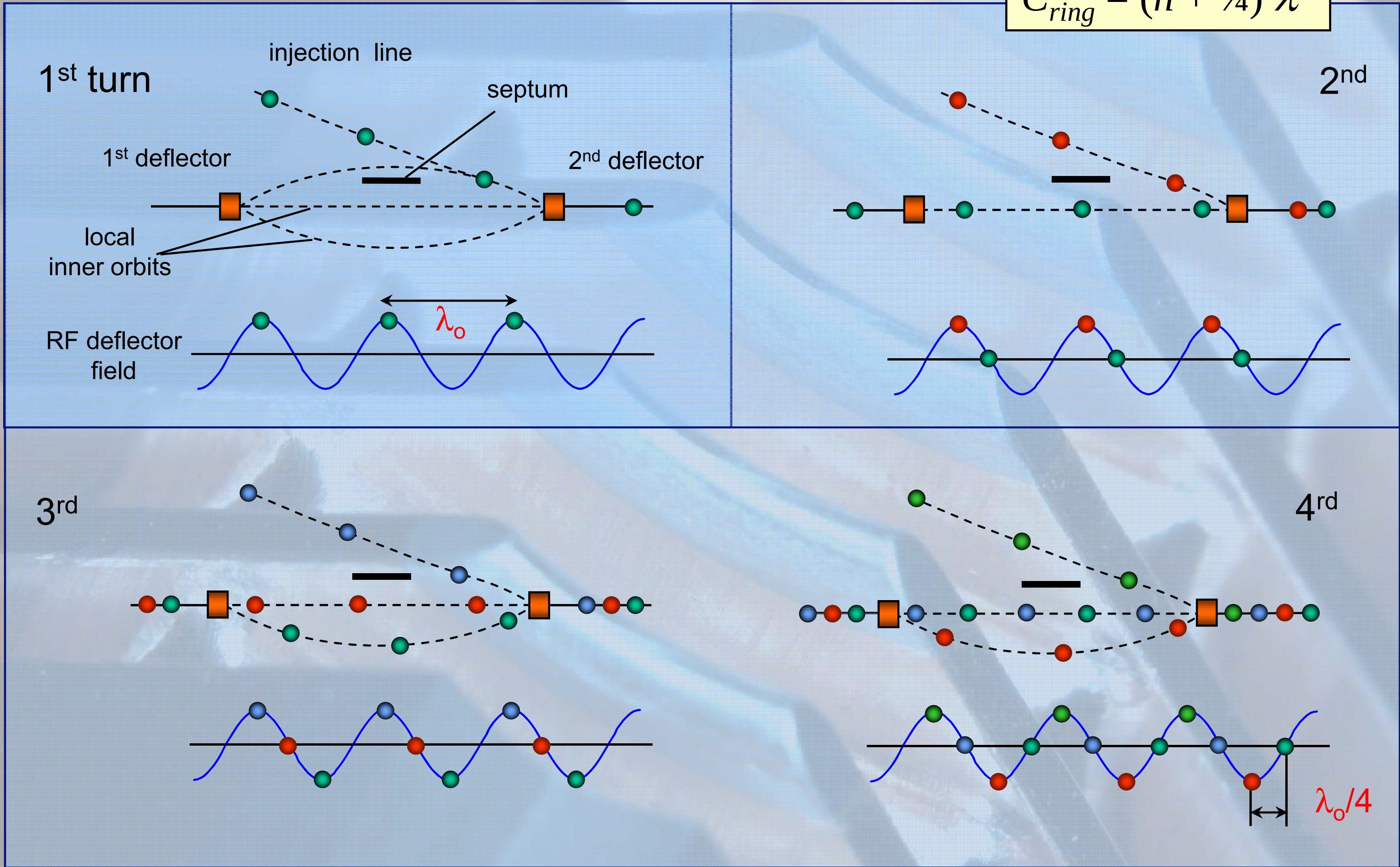


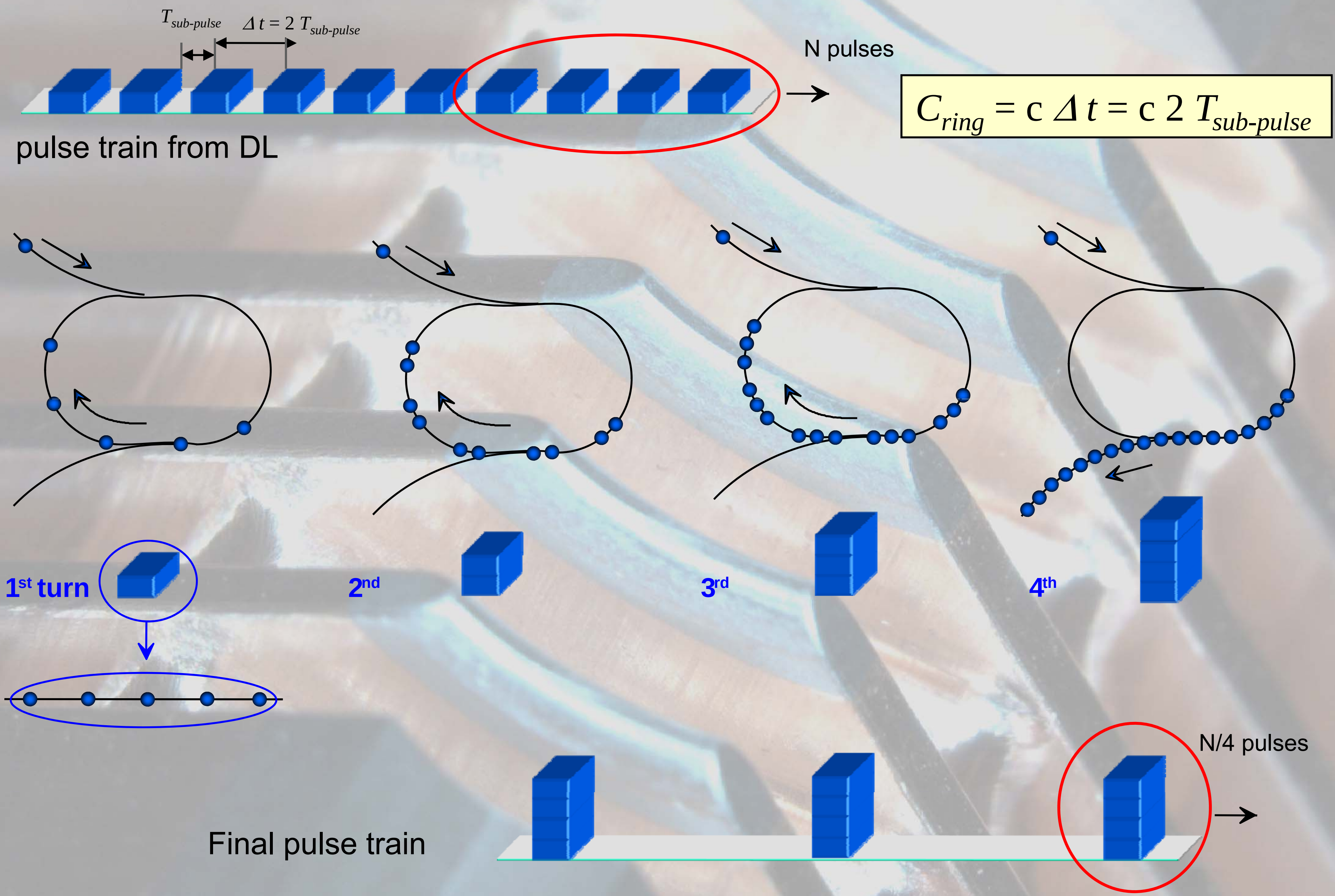
8.5 · 666 ps = 5.7 ns

… or use a laser + photo-injector

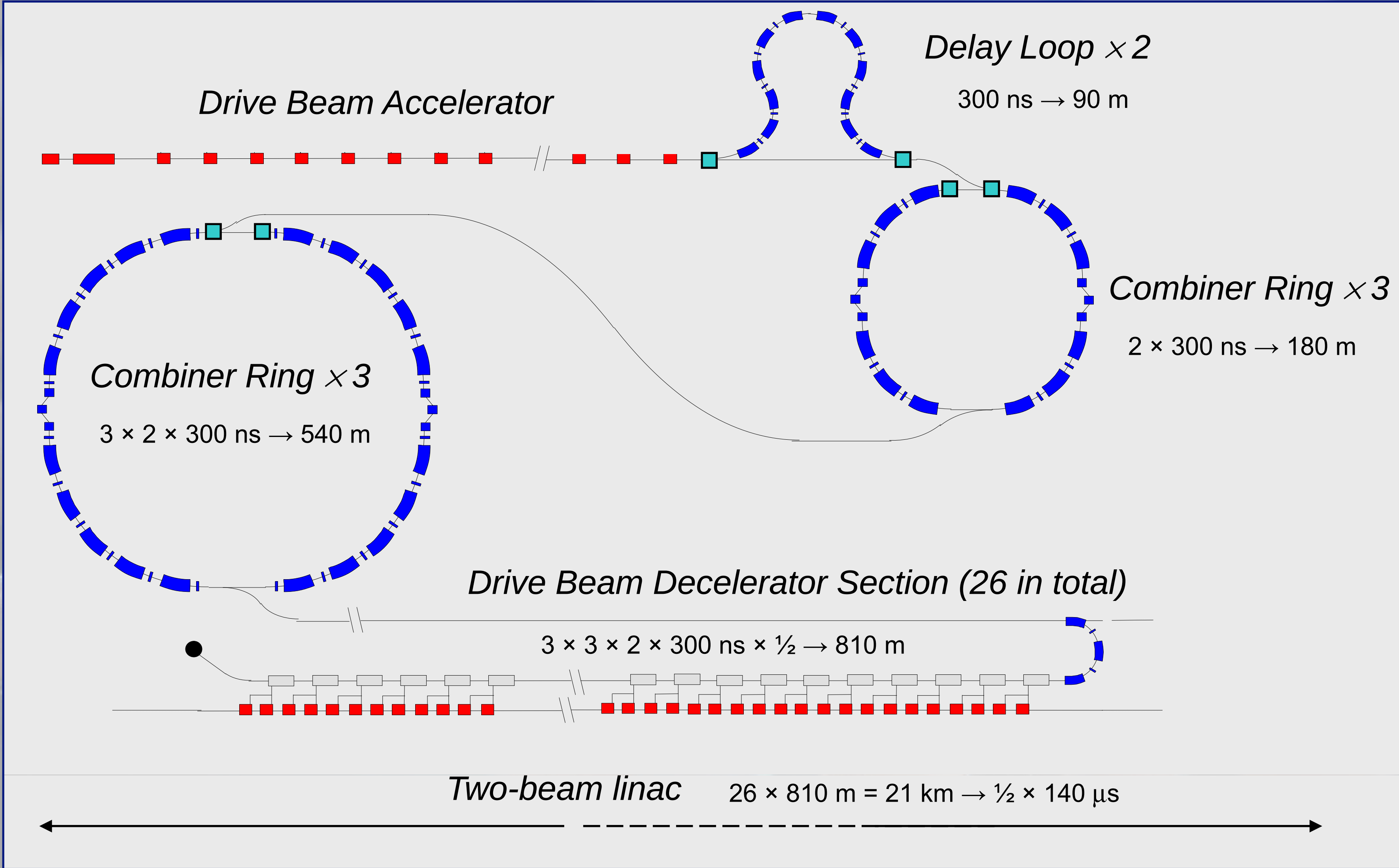
RF injection in combiner ring (factor 4 for simplicity)

$C_{ring} = (n + ¼)\,\lambda$




$T_{sub\text{-}pulse}$
$\Delta t = 2\ T_{sub\text{-}pulse}$
N pulses
pulse train from DL
$C_{ring} = c\ \Delta t = c\ 2\ T_{sub\text{-}pulse}$
1st turn
2nd
3rd
4th
N/4 pulses
Final pulse train

Space & time are linked in the RF power source...



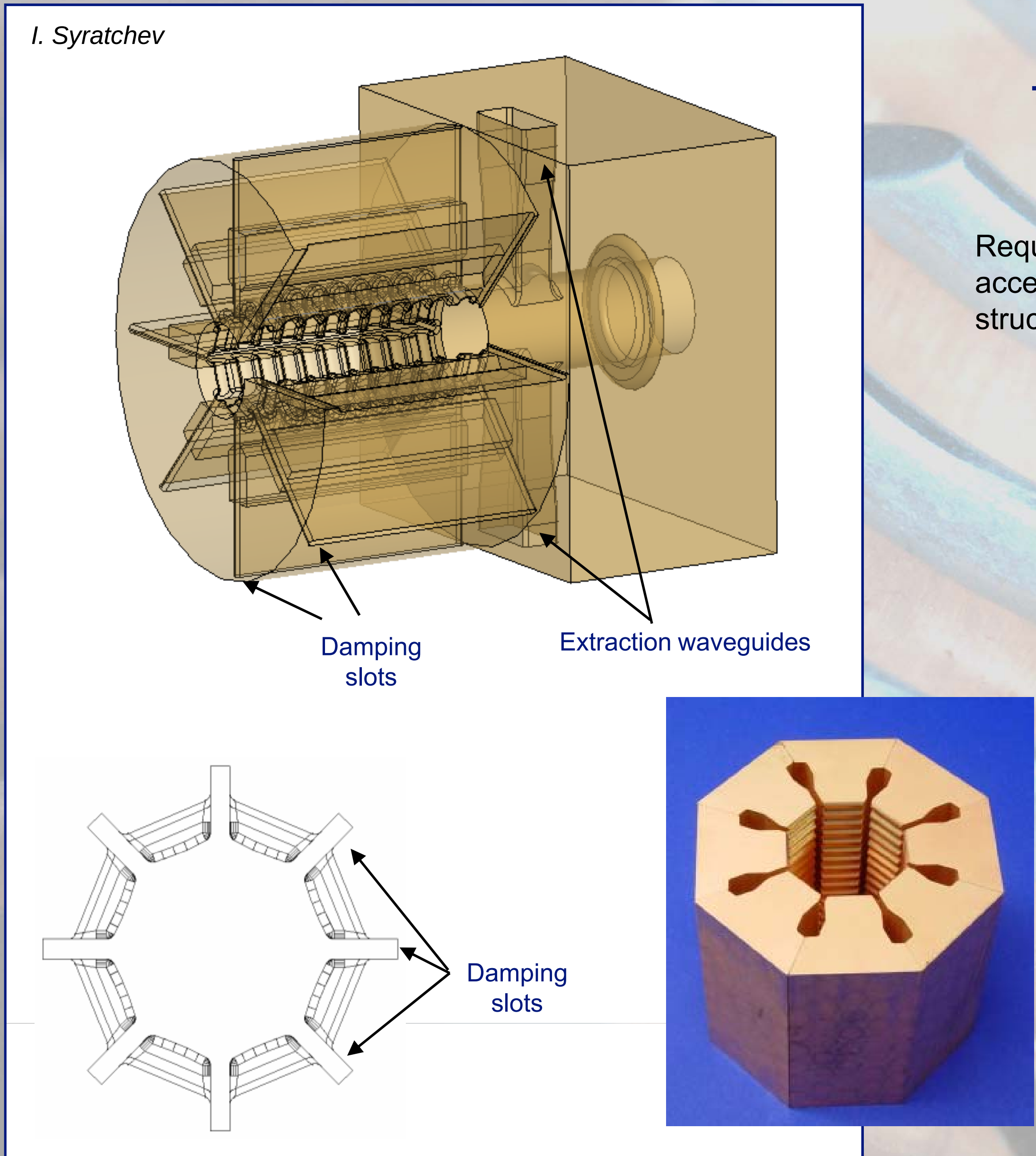
CLIC RF power source main parameters

Drive beam current initial	5.2 A
Drive beam current final	93 A
DB bunch charge	7.8 nC
Drive beam energy	2.4 GeV (⇒ 240 MeV)
DB acceleration frequency	1.33 GHz
DB bunch frequency initial	0.67 GHz
DB bunch frequency final	12 GHz
DB pulse length initial	140 μs
DB pulse length final	300 ns
Combination factor	2 × 3 × 3 = 18
Number of sectors/linac	26
Sector length	810 m
Length delay loop/line	90 m
Length combiner ring 1	180 m
Length combiner ring 2	540 m

?

2

2 × 3 × 3 = 18



CLIC Power Extraction & Transfer Structure (PETS)

Required by accelerating structure(s)

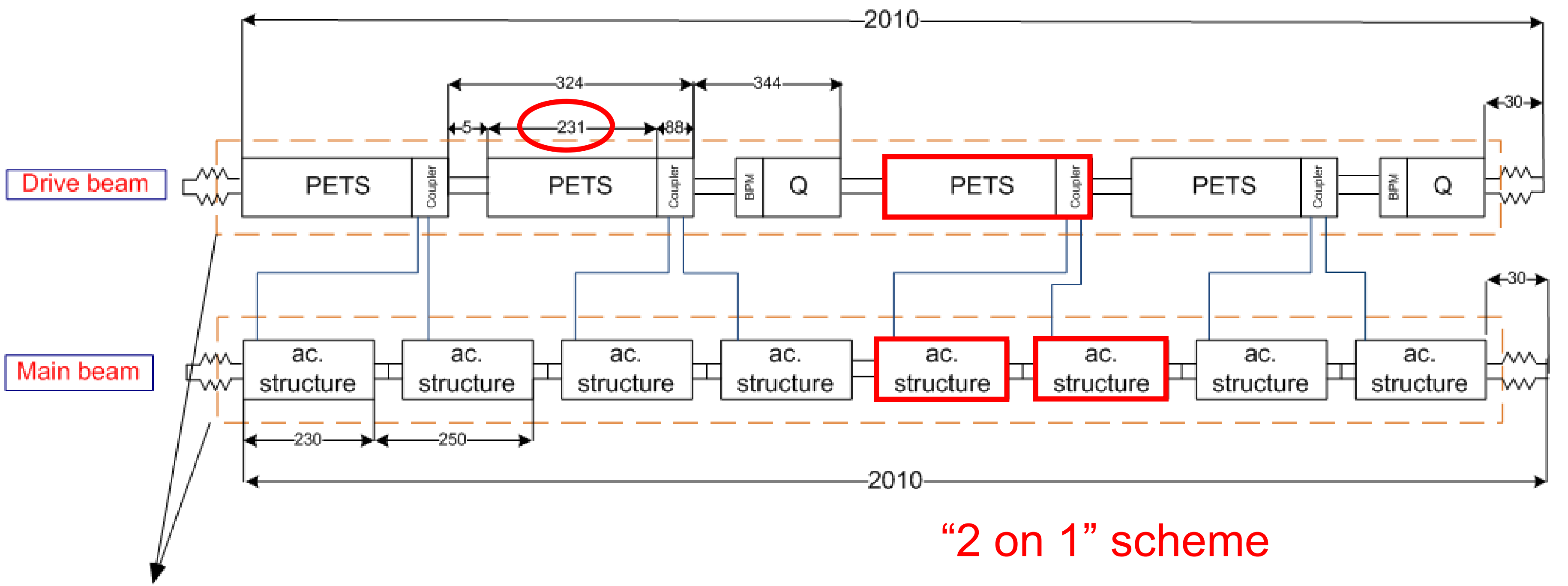
~ 1 for efficiency

PETS "power factor" ~ aperture

$$P = I^2 F_b^{\,2} \omega_0 \frac{R/Q}{4 v_g} L^2$$

"free" parameters

PETS to accelerating structure ratio



Schematic layout of the CLIC module

G. Riddone

N.B.:

1 on 1	exceed P/C limit of PETS (too many Wuensches…)
3 on 1, 2 on 1	PETS too short (high current and/or small aperture)

Drive beam current & energy trade-off

Since the power per sector is fixed by the accelerating structure, the product $I_{beam} E_{beam}$ is constant

For:	*is good to have*
Transverse beam stability in decelerator	high current, large aperture, long PETS
Drive beam combination in rings	small current, high energy (but below about 2.5 GeV)

Drive beam energy limits in rings

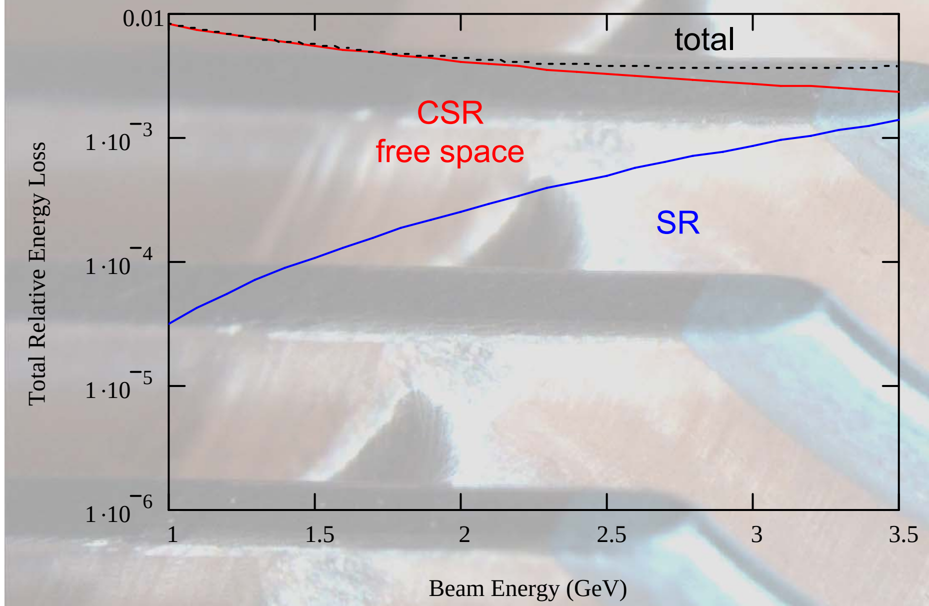
Several issues can put an upper limit to the beam energy in the combiner rings:

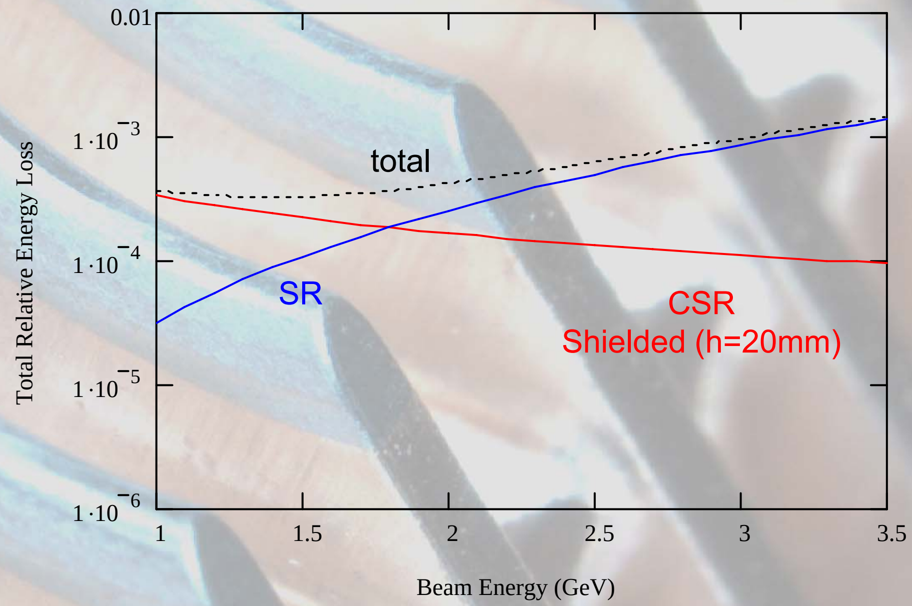
- Too high field in magnets — not an issue (long rings – long RF pulse length)
- Synchrotron radiation:
  - Energy loss — not limiting
  - Power loss in vacuum chamber — potential limit
  - Energy spread & emittance increase — negligible
- Coherent synchrotron radiation
  - Beneficial effect
- Deflectors
  - Higher power for given angle
  - Constant power from damping of real emittance → neutral

Energy loss from SR and CSR

σ_Z = 2 mm, Qb = 7.7 nC

Both rings - ρ = 10 m - 27 m





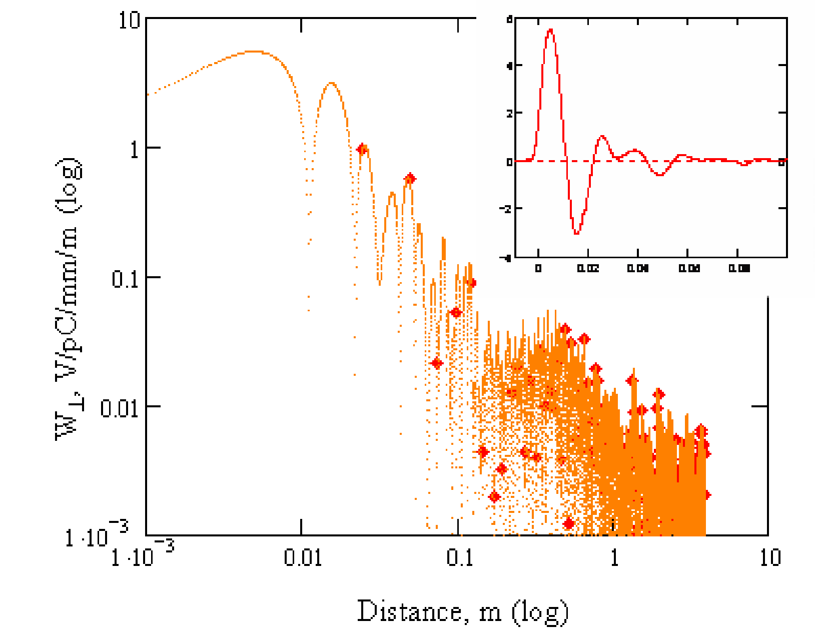
NB: I have kept the same σ_Z in the rings as the old parameter set – now we need only a factor 2 in final compression

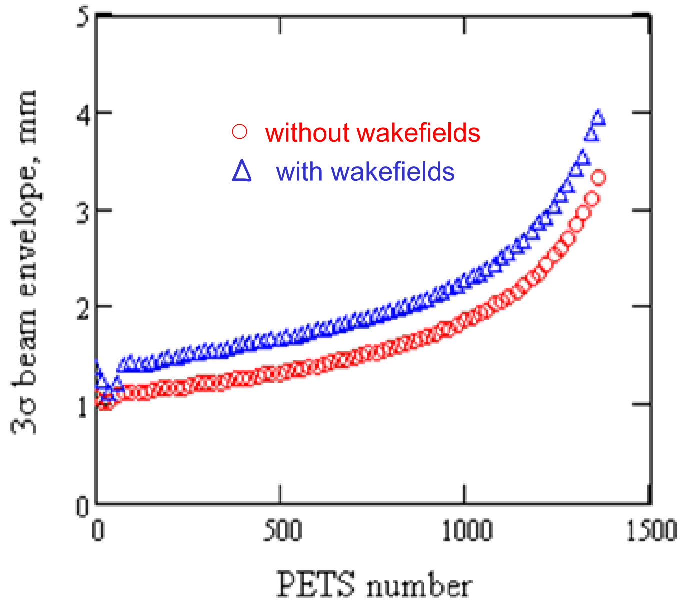
⇒ can accept more longitudinal phase space distortion
⇒ will be less sensitive to energy variation for drive beam phase stability

PETS parameters

Aperture, mm	23
Phase advance/cell, degrees	90
R/Q, Ohm	2290
Group velocity, V_g/c	0.453
Q-factor	7200
Active length, m	0.231 (37 cells)
RF pulse length, ns	300
RF power, MW	138

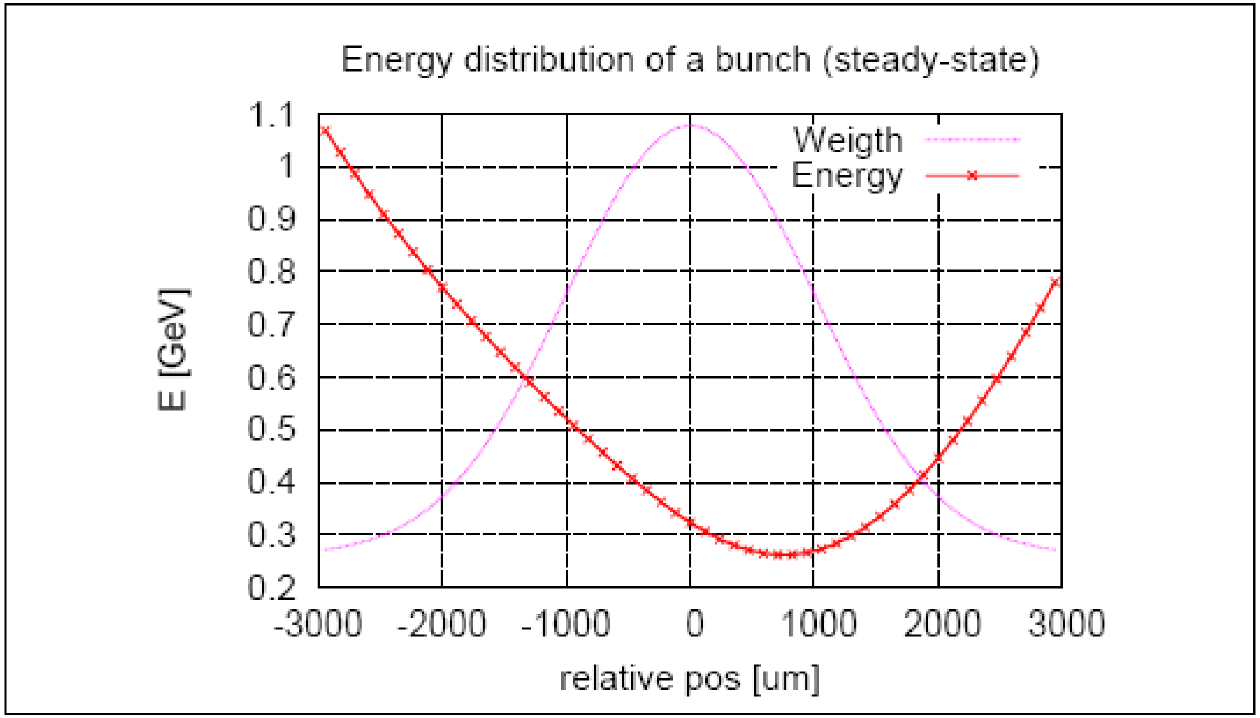
PETS wake-fields





PLACET was used to analyze the beam dynamic along the decelerator with strong deceleration and wake-fields.
The results indicate that the calculated suppression of the transverse wake-fields is strong enough to guarantee beam transport without losses

More transverse stability in the decelerator sectors



CLIC 12 GHz, $\eta_{dist} = 97.3\%$ $(l_{PETS,CLIC} = 0.3 l_{PETS,TBL})$

Another ring issue – transverse stability in the RF deflectors

D. Schulte – R. Corsini

old parameters

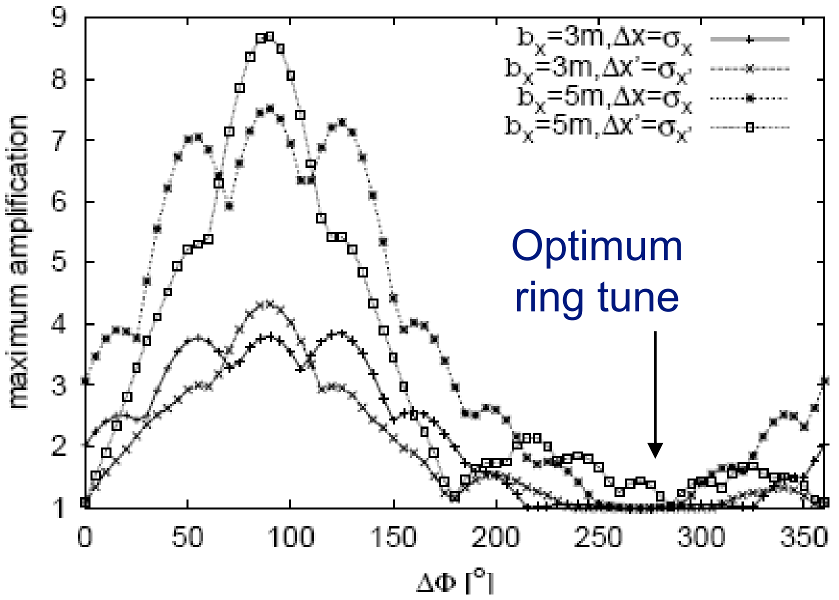
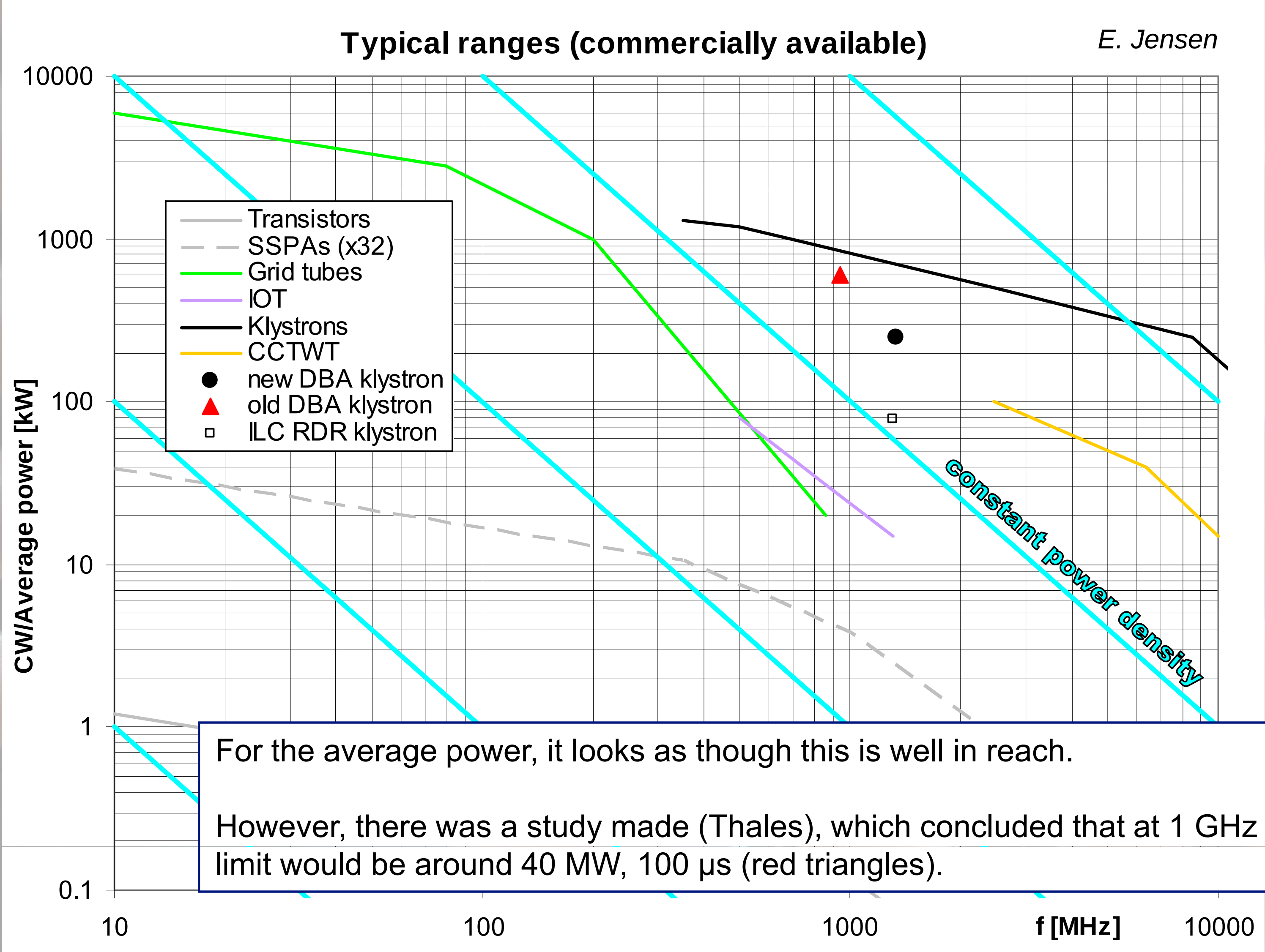


Figure 2: Amplification of an initial error as a function of the betatron phase advance in the ring, for $\beta_x = 3$ m and $\beta_x = 5$ m

Old & new parameters

	2005 - CLIC Note 627	June 2007
Drive beam current initial	5.7 A	5.2 A
Drive beam current final	181 A	93 A
DB bunch charge	12.1 nC	7.8 nC
Drive beam energy	2.4 GeV ($\Rightarrow$ 240 MeV)	2.4 GeV ($\Rightarrow$ 240 MeV)
DB acceleration frequency	0.937 GHz	1.33 GHz
DB bunch frequency initial	0.46 GHz	0.67 GHz
DB bunch frequency final	15 GHz	12 GHz
DB pulse length initial	94 μs	140 μs
DB pulse length final	70 ns	300 ns
Combination factor	$2 \times 4 \times 4 = 32$	$2 \times 3 \times 3 = 18$
Number of sectors/linac	21	26
Sector length	670 m	810 m
Length delay loop/line	21 m	90 m
Length combiner ring 1	84 m	180 m
Length combiner ring 2	334 m	540 m
Rms bunch length final	400 μm	1 mm
Power per PETS	640 MW	140 MW

The drive beam accelerator klystrons



For the average power, it looks as though this is well in reach.

However, there was a study made (Thales), which concluded that at 1 GHz the limit would be around 40 MW, 100 μs (red triangles).

The drive beam accelerator

E. Jensen

Freqency 1.3327 GHz Beam current 5.2778 A

Further assumptions:

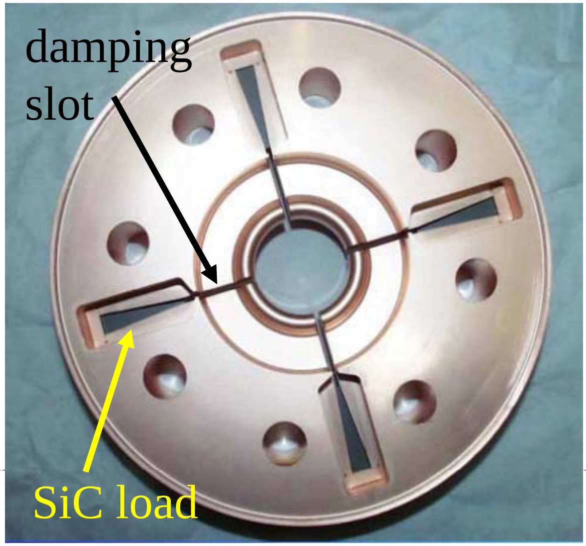
Structures scaled from known data for a variation of group velocity from 5.15 %c to 2.32 %c.

r/Q varies from 1.4 to 1.46 kOhm/m.

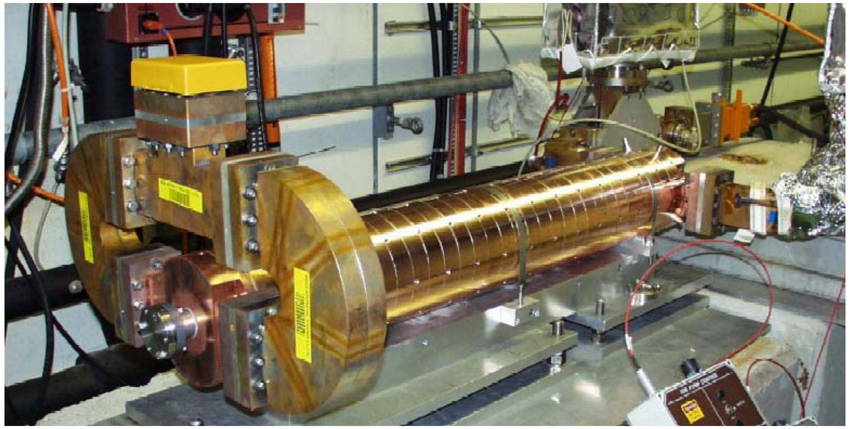
Q varies from 20800 to 16400.

Following table calculates the power necessary for full beam loading

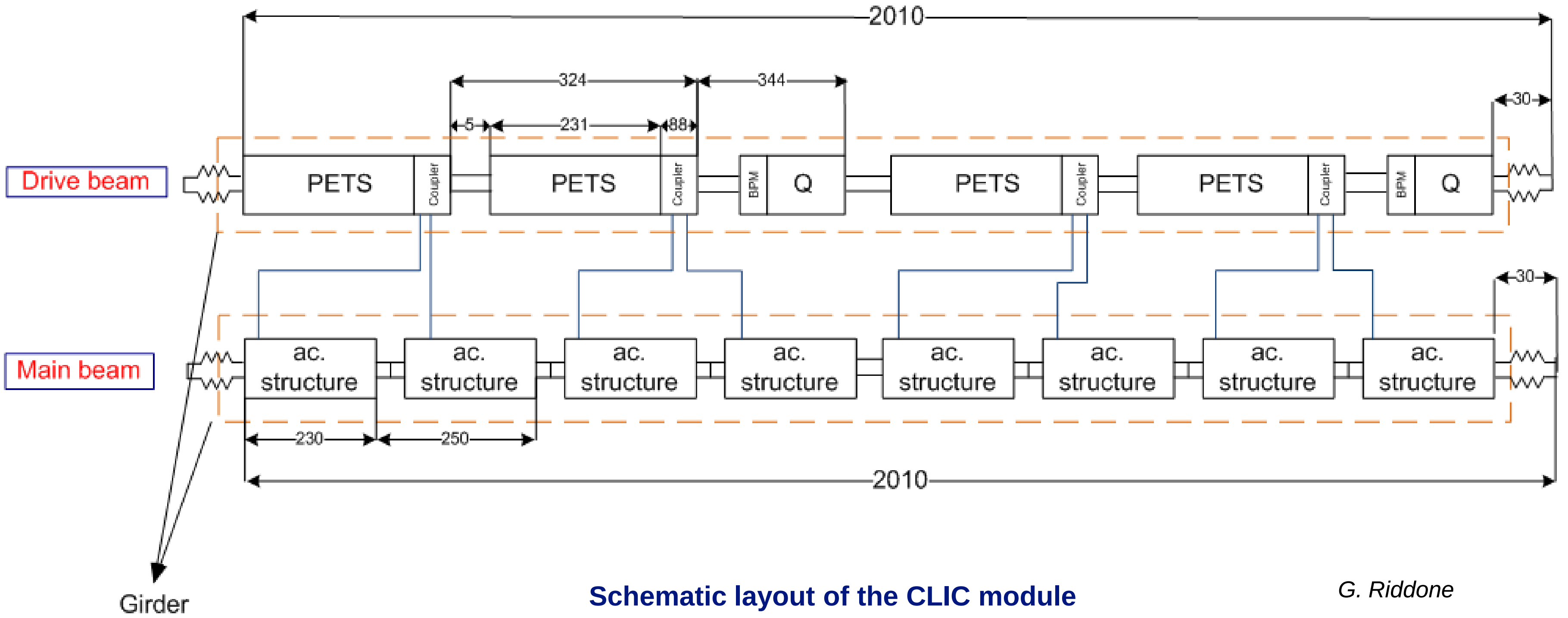
Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning



CTF3 !



The CLIC module



Schematic layout of the CLIC module

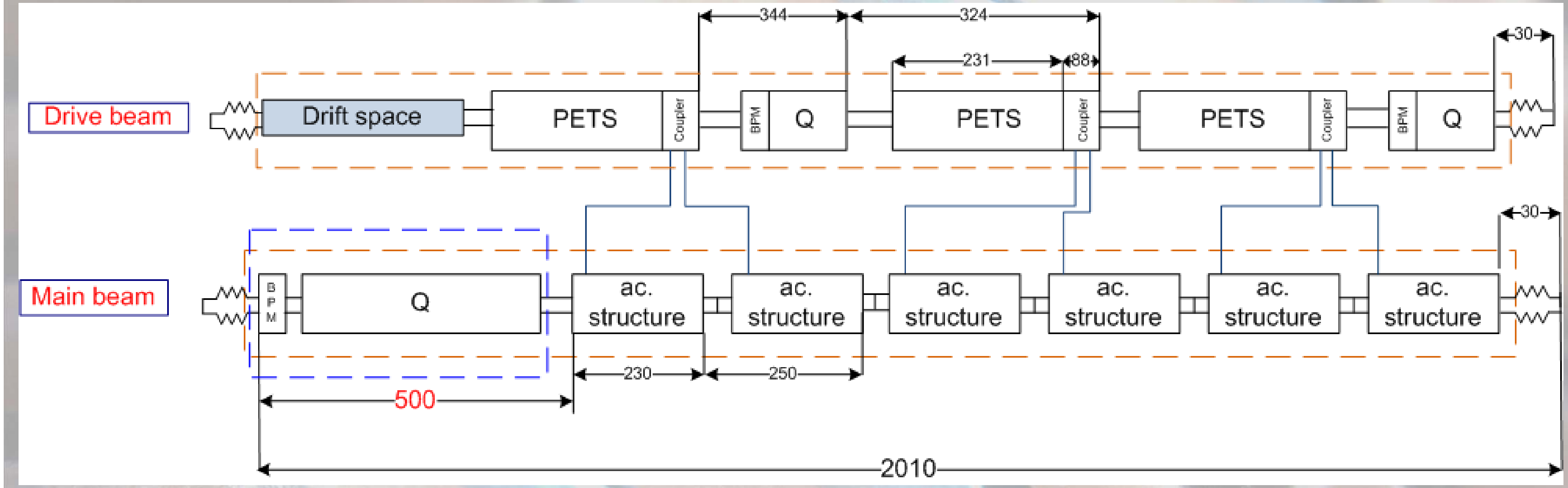
G. Riddone

Module working group:

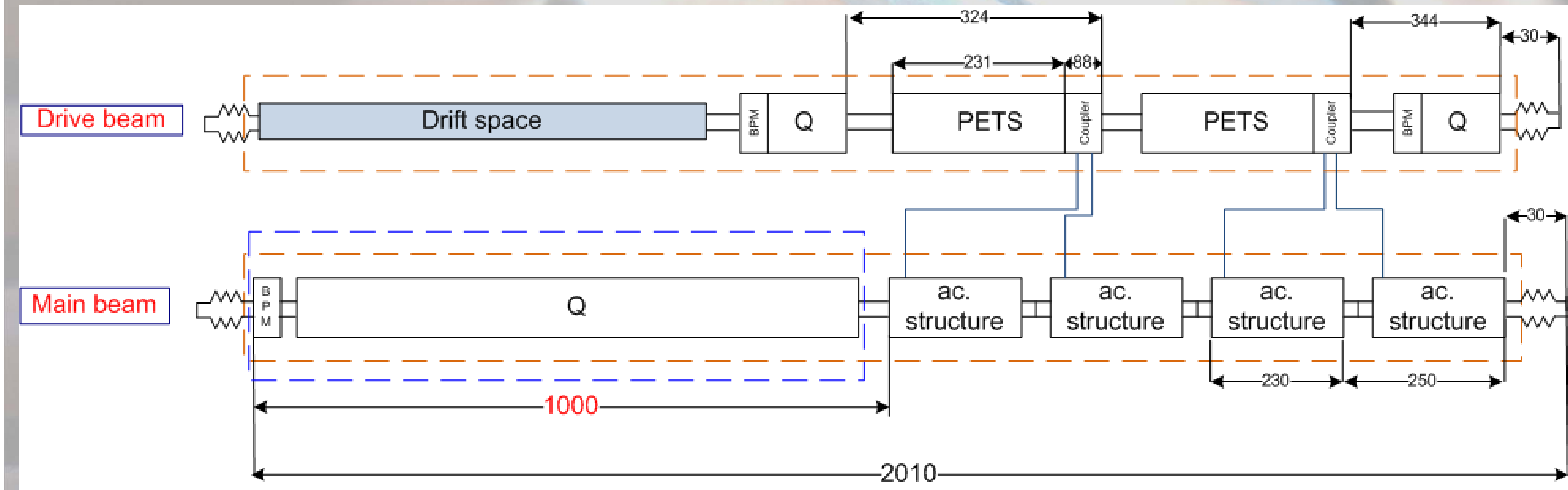
general layout, system integration, space hindrance, number of components and their position, alignment/supporting system, cooling system, vacuum system, tunnel integration

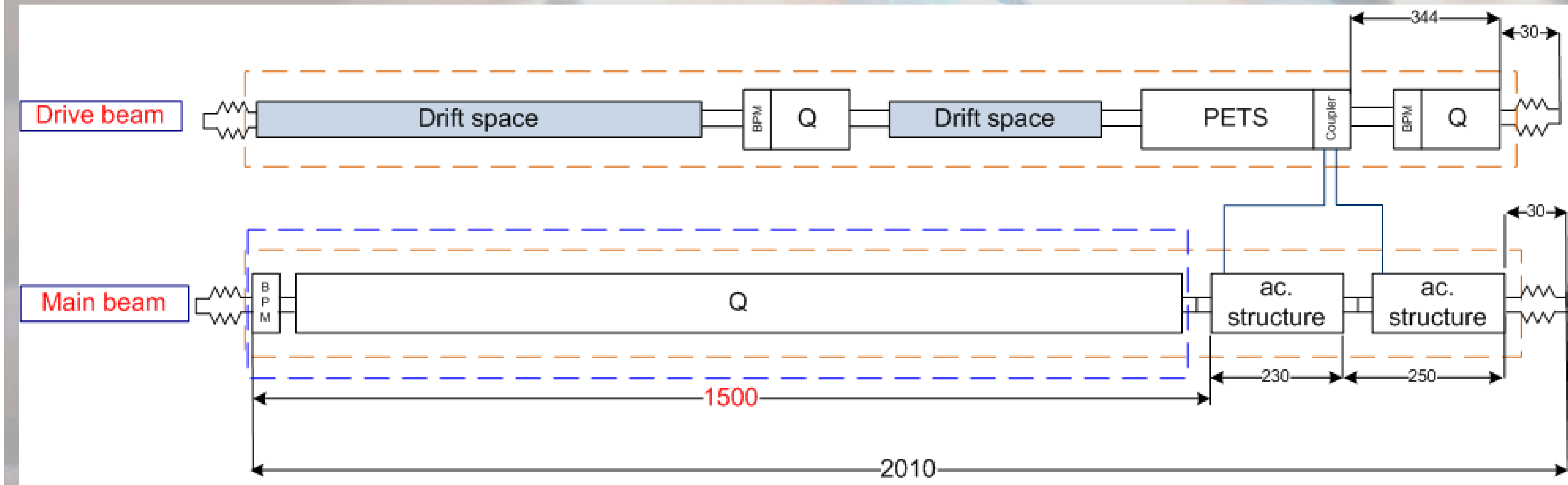
Identify critical points - Cost estimate

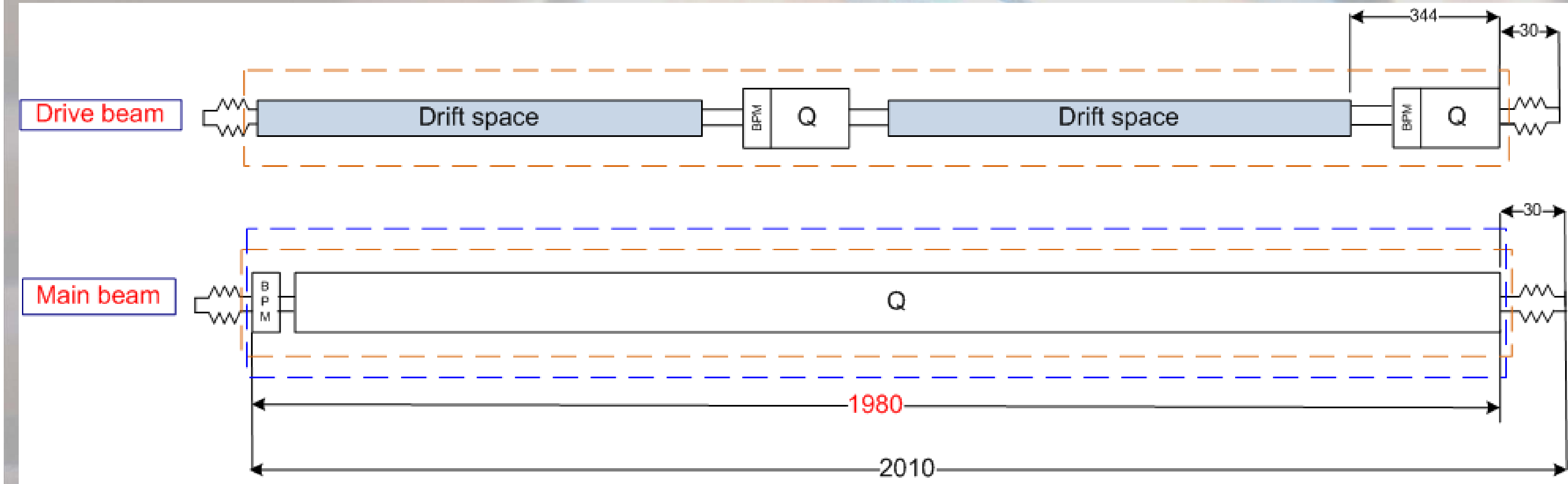
Drive Beam Complex and Power Generation including CLIC Module



Drive Beam Complex and Power Generation including CLIC Module

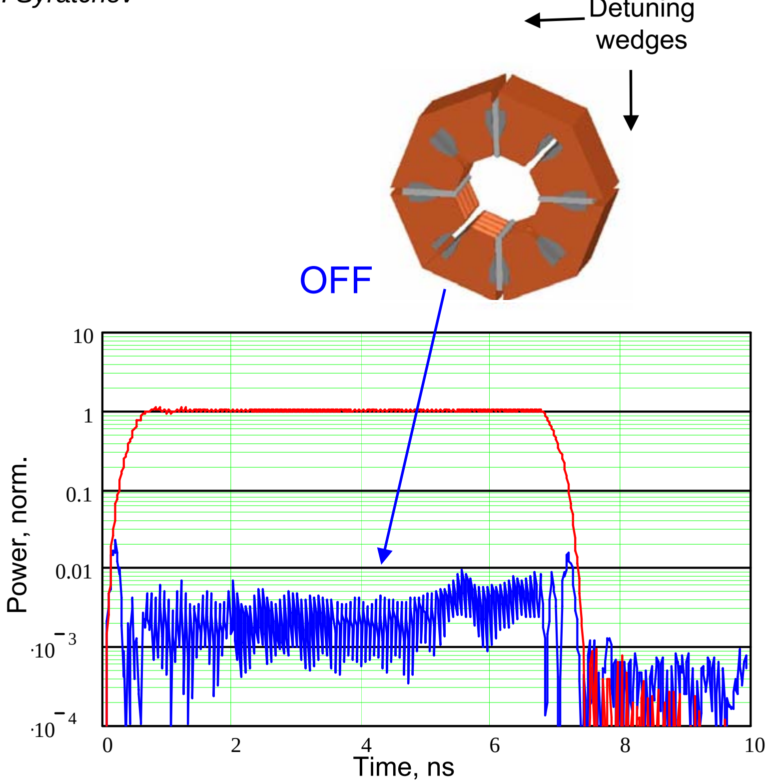



344
30
Drive beam
Drift space
BPM
Q
Drift space
PETS
Coupler
BPM
Q
30
Main beam
B P M
Q
ac. structure
ac. structure
230
250
1500
2010


344
30
Drive beam
Drift space
BPM
Q
Drift space
BPM
Q
30
Main beam
B P M
Q
1980
2010

How to switch the PETS on & off

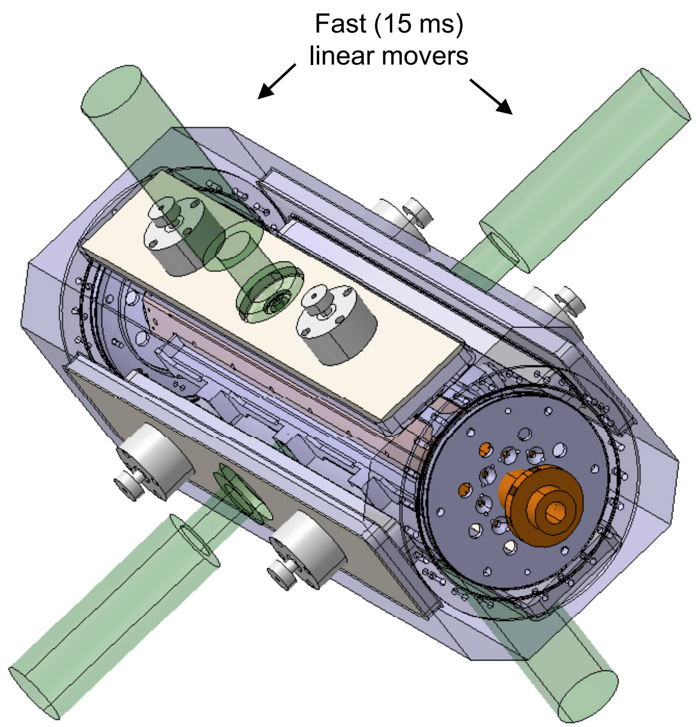
I. Syratchev



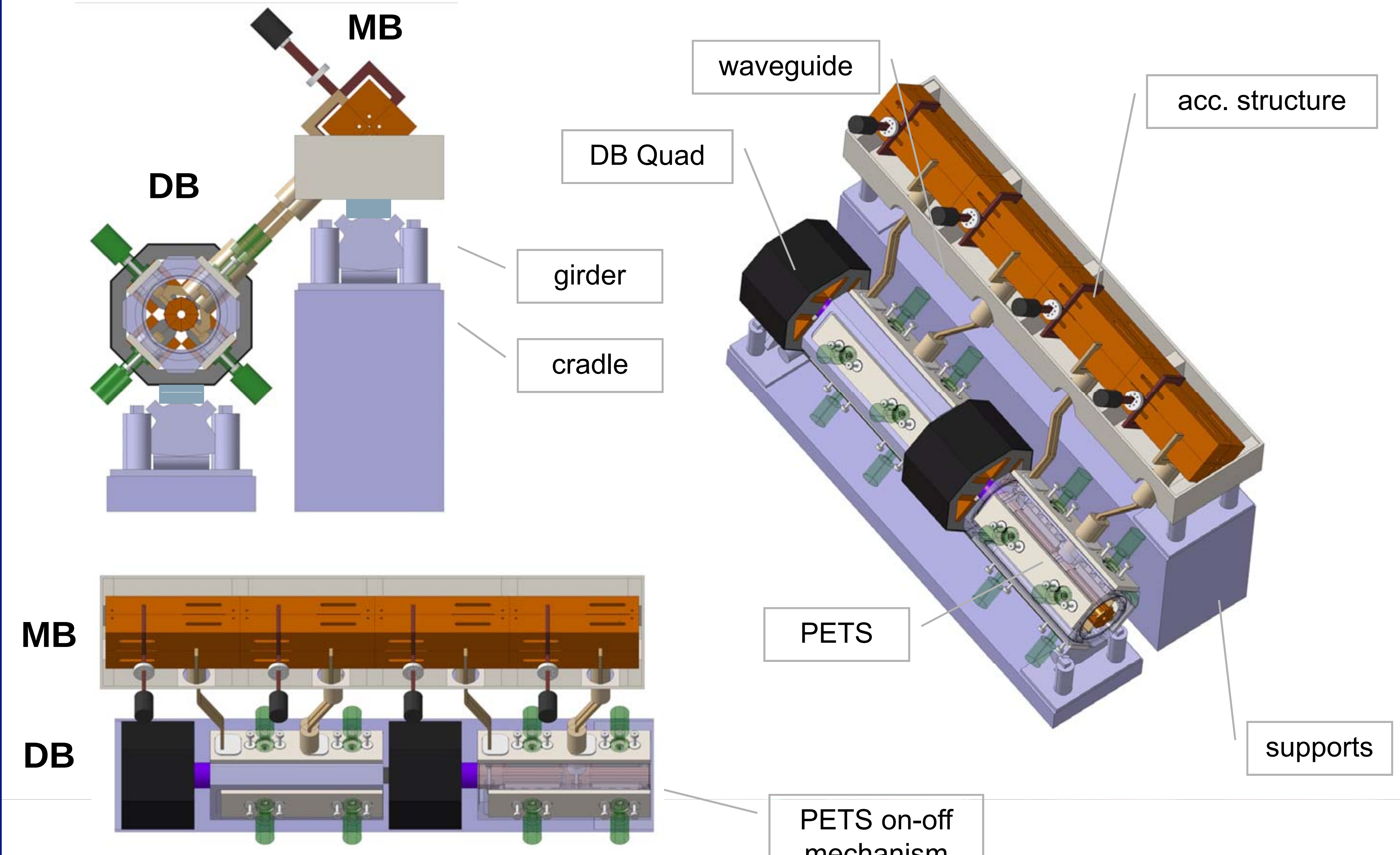
PETS output pulse envelopes

Reconstructed from GDFIDL data

"The Petsonov"

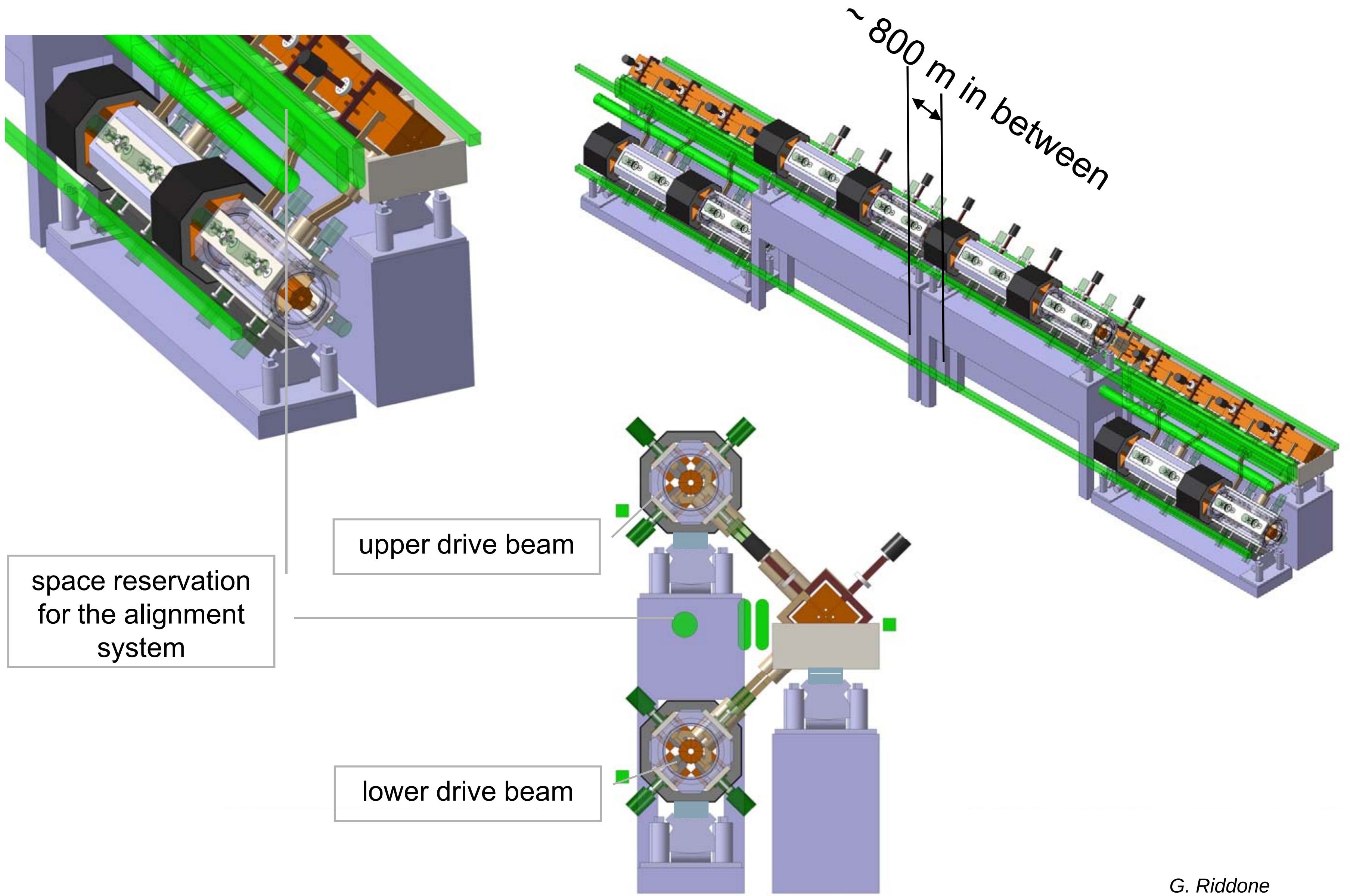


(PETS ON/OFF mechanism)


MB
DB
waveguide
acc. structure
DB Quad
girder
cradle
PETS
MB
DB
supports
PETS on-off mechanism

G. Riddone

Drive Beam Complex and Power Generation including CLIC Module



G. Riddone

ILC Power requirements – from ILC RDR 2007

The power requirements are dominated by the RF system (modulators) located in the Service Tunnel along the length of the Main Linac. Table 4.3-1 gives an overview of the estimated *nominal*[1] power consumption for 500 GeV center-of-mass operations, broken down by system area and load types. The cost estimate is based on a total nominal power requirement of 216.3 MW. The additional required power for a potential upgrade to 1 TeV centre-of-mass is not included in the current power load tabulation.

TABLE 4.3-1
Estimated Nominal Power Loads (MW) for 500 GeV Centre-of-Mass Operation

Area System	RF Power	Conventional Power				Emer Power	Total (by area)
		Conv	NC Magnets	Water Systems	Cryo		
Sources e^-	1.05	1.19	0.73	1.27	0.46	0.06	4.76
Sources e^+	4.11	7.32	8.90	1.27	0.46	0.21	22.27
DR	14.0	1.71	7.92	0.66	1.76	0.23	26.29
RTML	7.14	3.78	4.74	1.34	0.0	0.15	17.14
Main Linac	75.72	13.54	0.78	9.86	33.0	0.4	134.21
BDS	0.0	1.11	2.57	3.51	0.33	0.20	7.72
Dumps	0.0	3.83	0.0	0.0	0.0	0.12	3.95
Totals (by system)	102.0	32.5	25.6	17.9	36.9	1.4	216.3

Comparison with klystron-based power source

CLIC with klystrons vs. CLIC with drive beam

H. Braun

Present CLIC X - band structure parameters are

$L_{eff} = 0.229\text{m}, P_{in} = 69\ \text{MW}, Tpulse = 297\ \text{ns}, G_{loaded} = 100\ \text{MV/m}$

CLIC with $E_{cms} = 3$ TeV needs a total loaded RF voltage of $V_{RF} = 3.3$ TV (with 10% overhead for BNS etc.). The total number of accelerating structures is therefore

$$N_{Acc} = \frac{V_{RF}}{G_{loaded} L_{eff}} = 144106$$

And the instantentenous 12 GHZ RF power for both linacs is

$$P_{Inst} = N_{Acc} P_{In} = \frac{V_{RF} P_{In}}{G_{loaded} L_{eff}} = 9.94\ \text{TW}$$

A NLC RF unit consisting of 2 klystrons (75 MW each and 1.6 μs pulselength) provide with SLED II compression 475 MW during 400 ns. For the shorter RF pulse of CLIC we assume for the sake of simplicity that the peak power can be raised by the ratio of pulse length

$$P_{RFunit} = 475\ \text{MW} \frac{400\ \text{ns}}{297\ \text{ns}} = 640\ \text{MW}$$

Therefore the number of NLC RF units required to feed CLIC is

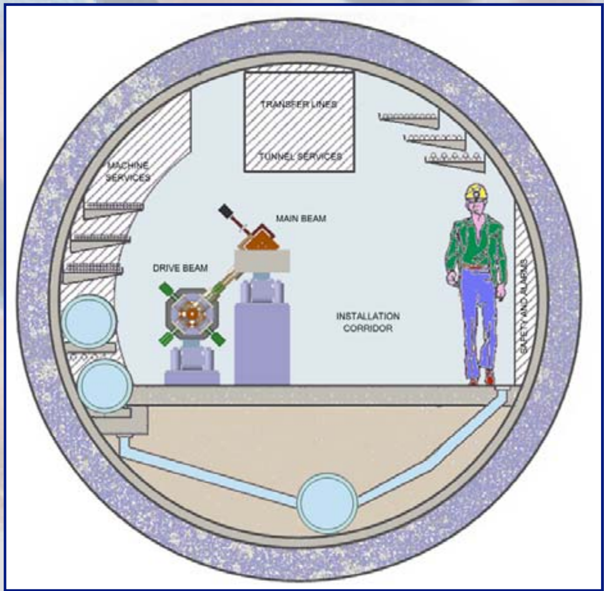
$$N_{RFunit} = \frac{P_{Inst}}{P_{RFunit}} = \frac{V_{RF} P_{In}}{G_{loaded} L_{eff} P_{RFunit}} = 15538$$

~ 30000 klystrons for MK based CLIC

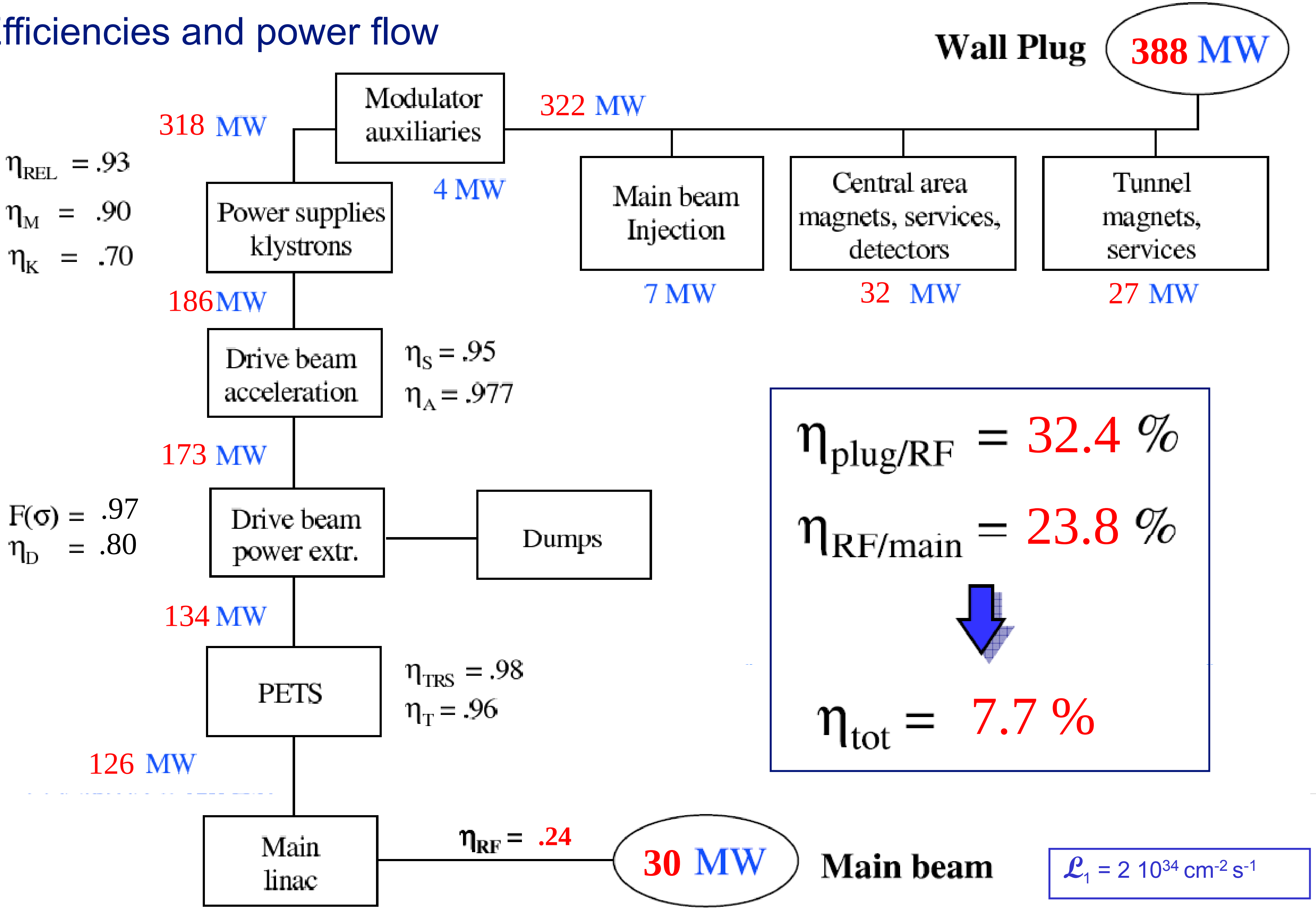
~ 800 klystrons for TBA based CLIC

Advantages of Two Beam Acceleration:

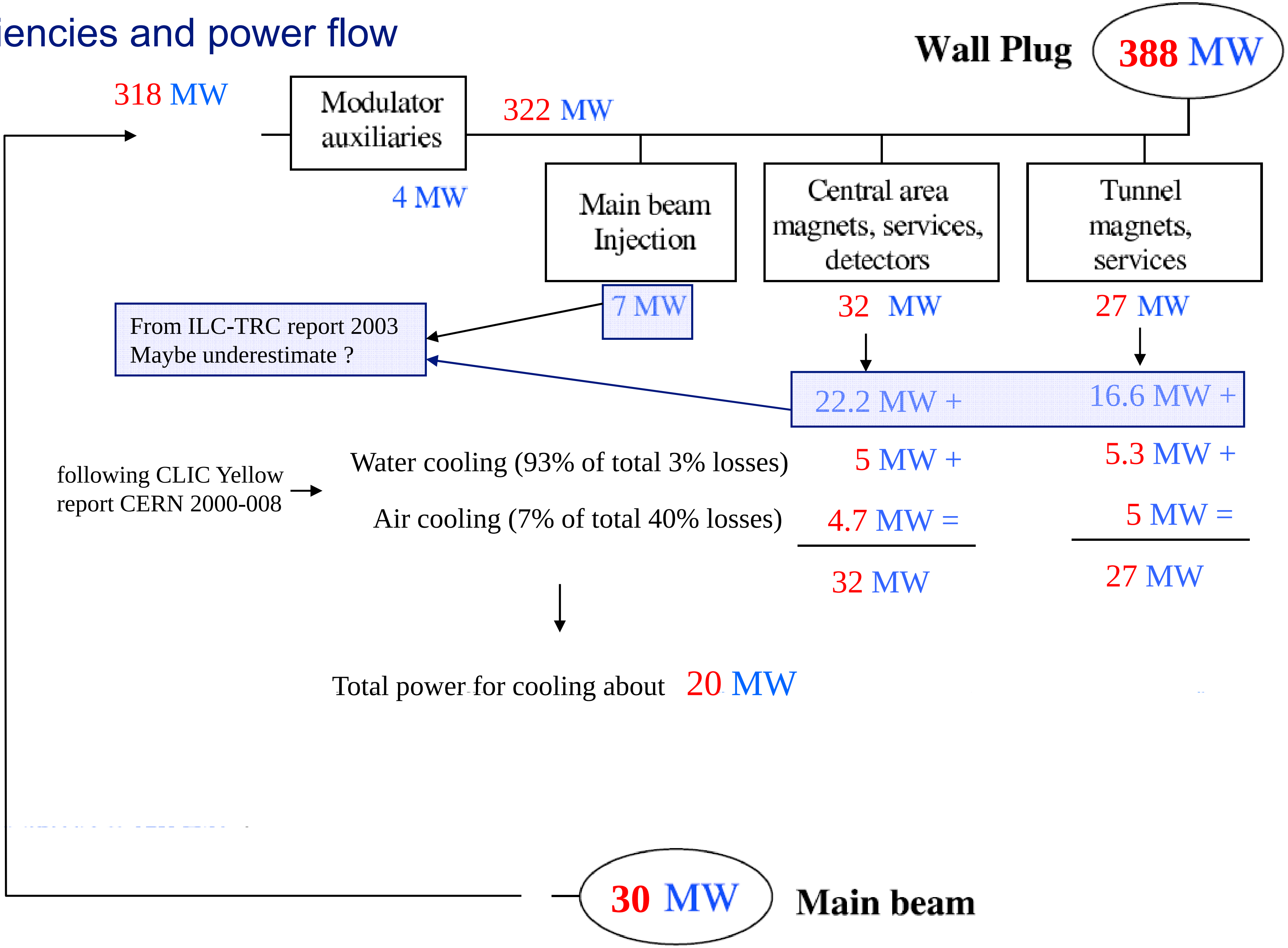
- Much smaller No of klystrons
  - Operability
  - Cost
- All klystrons in central area
  - Easy access – operability again
  - Single tunnel vs 2 tunnels (or larger one)
  - Less cooling needed in tunnel
  - Easier upgrade



Efficiencies and power flow



Efficiencies and power flow

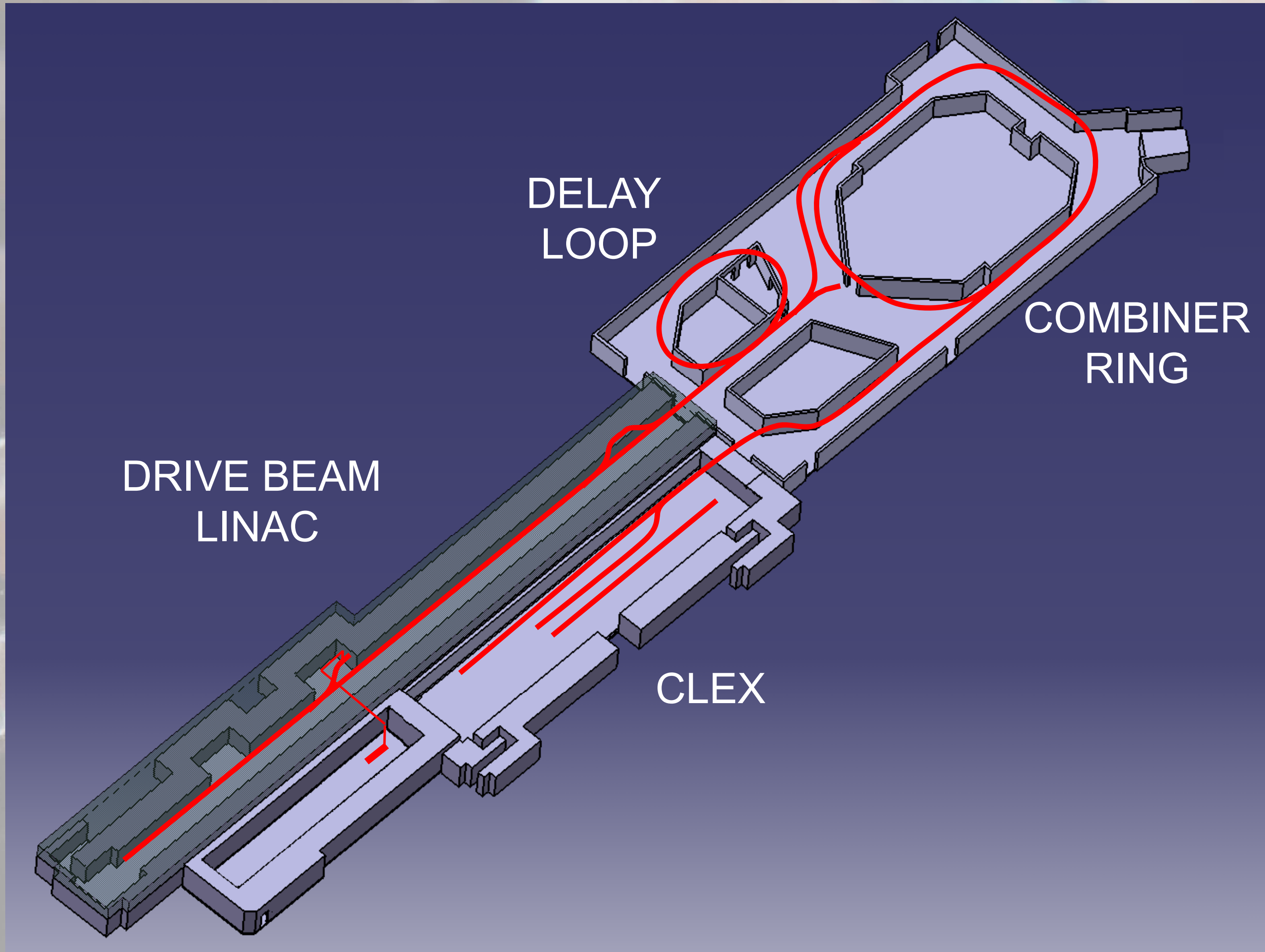


Rough comparison ILC – CLIC @ 500 GeV cm

	ILC *	CLIC **
Pulse current	9 mA	0.96 A
Pulse length	970 μs	207 ns
Rep rate	5 Hz	100 Hz
Main beam power P_{main} (2 beams)	21 MW	9.9 MW
Wall plug power P_{tot}	230 - 216 MW	158 MW
Full luminosity L_{tot}	2 10^{34} cm^{-2} s^{-1}	2 10^{34} cm^{-2} s^{-1}
L_{tot} /P_{main}	9.5 10^{26} cm^{-2} s^{-1} W^{-1}	20 10^{26} cm^{-2} s^{-1} W^{-1}
P_{main}/P_{tot}	9.5 – 9.7 %	6.3 %
L_{tot} /P_{tot}	0.92 10^{26} cm^{-2} s^{-1} W^{-1}	1.27 10^{26} cm^{-2} s^{-1} W^{-1}

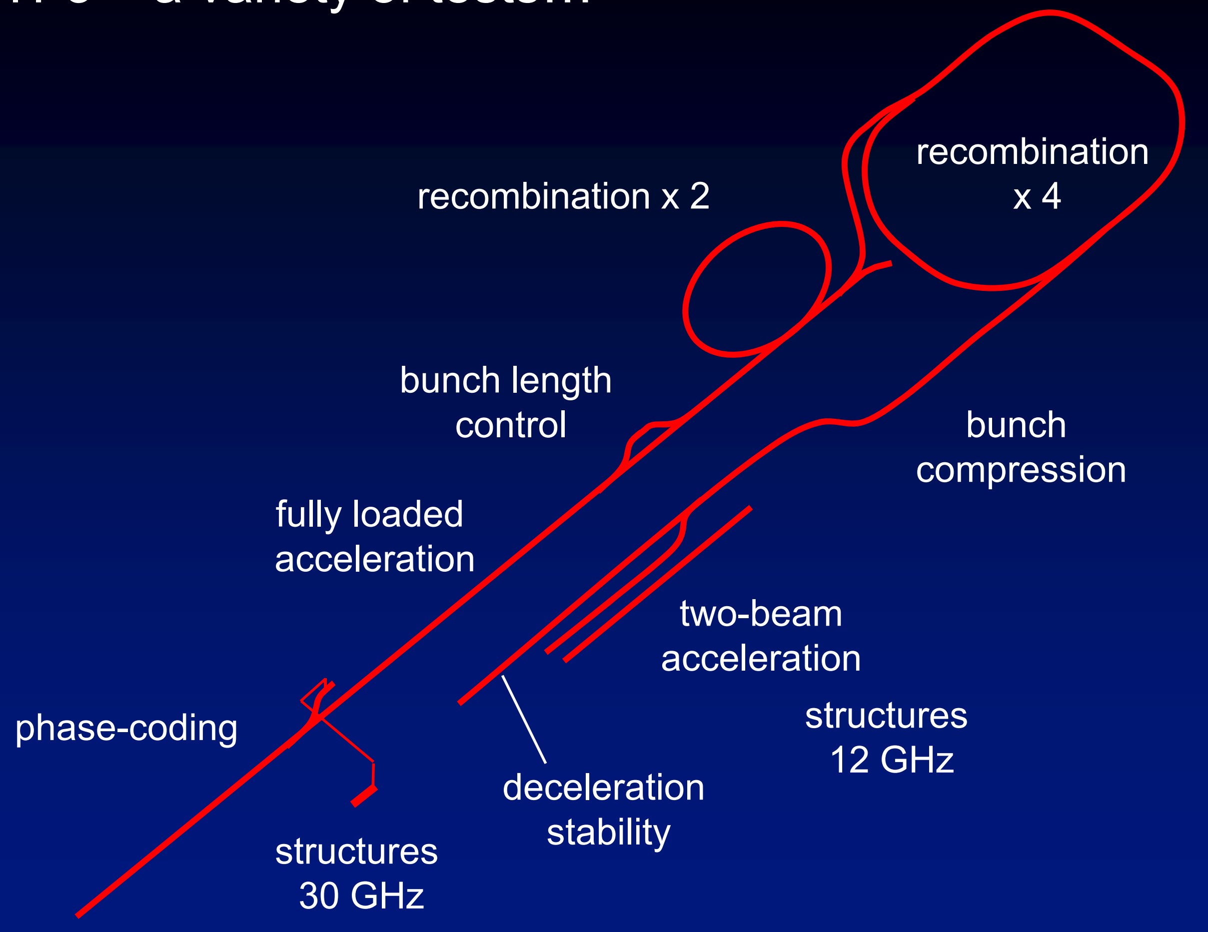
* International Linear Collider Reference Design Report 2007
** assumptions for CLIC, from D. Schulte – CLIC Parameter Meeting 29 May 07

CTF3 – a model of the CLIC RF Power Source



CTF3 – a model of the CLIC RF Power Source

CTF3 – a variety of tests…



CTF3 – a model of the CLIC RF Power Source

…some of which pretty much advanced