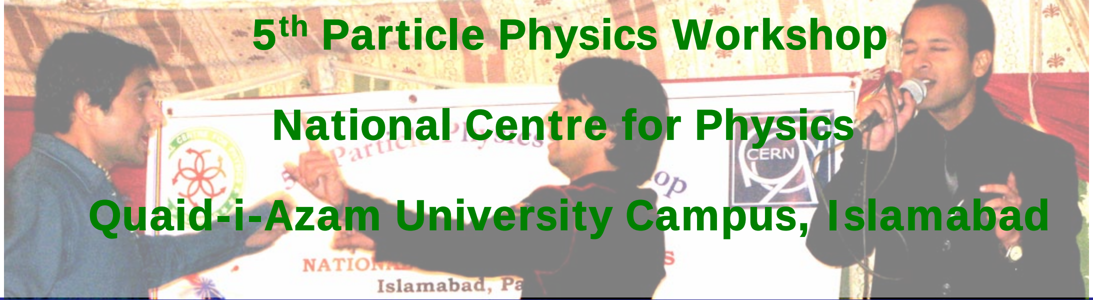


5th Particle Physics Workshop

National Centre for Physics

Quaid-i-Azam University Campus, Islamabad

PARTICLE BEAMS,
TOOLS FOR MODERN SCIENCE AND MEDICINE

Hans-H. Braun, CERN

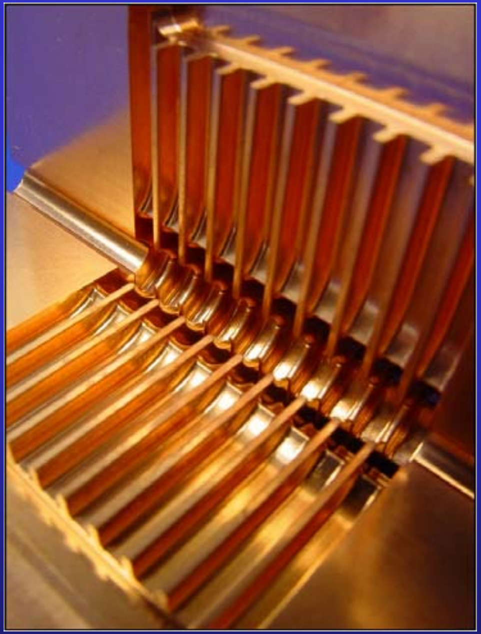
3rd Lecture

Introduction to Linear e^+/e^- Colliders and CLIC
the Next Generation of Tools for Particle Physics

o Linear Colliders - Motivation and Concept

o Technical Challenges for Linear Colliders

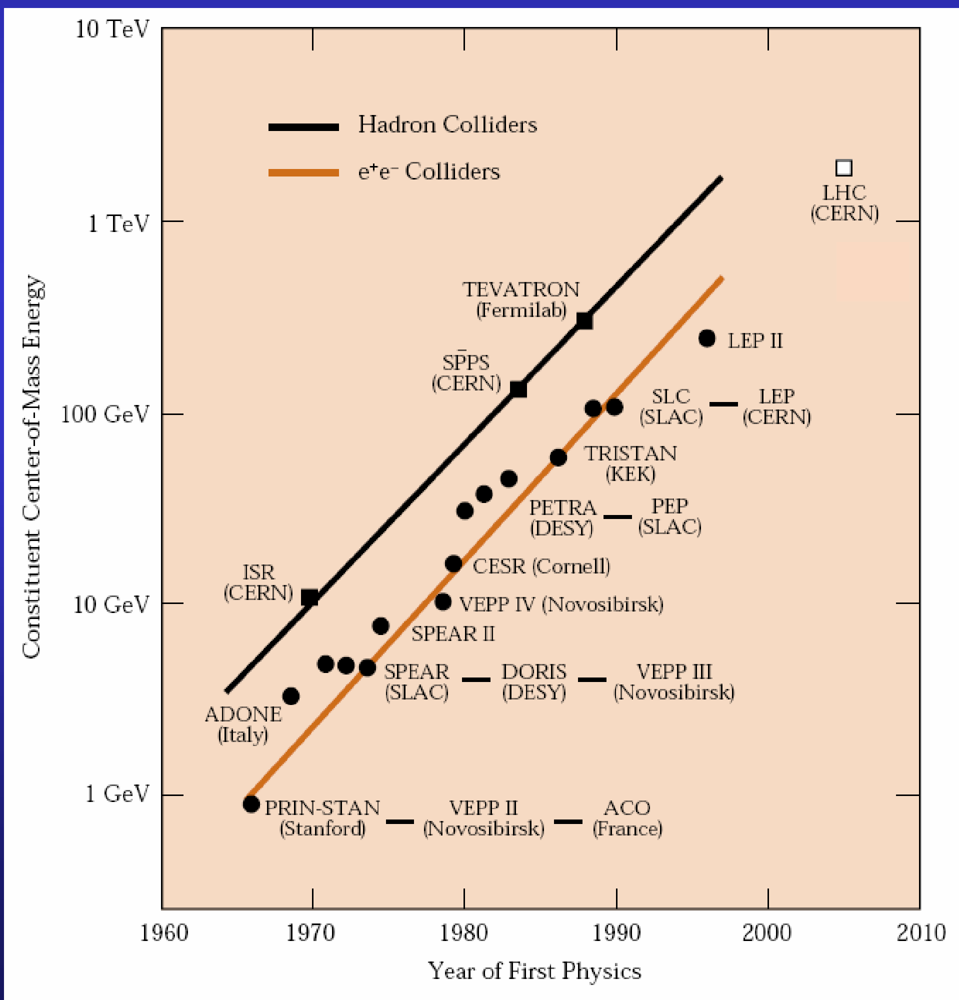
o CLIC



Collider History

Since the 60s, most new revelations in particle physics have come from colliders

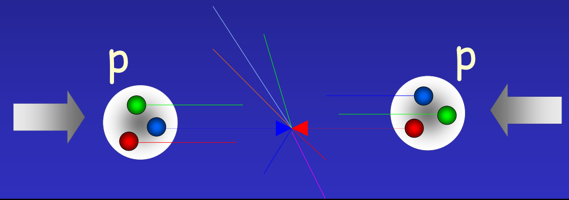
"Livingstone" plot (adapted from W. Panofsky)



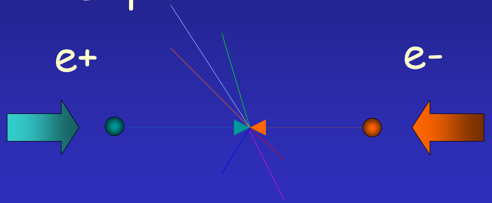
- Energy (<u>exponentially !</u>) increasing with time
  - ⇒ a factor 10 increase every 8 years !
- Hadron Colliders at the energy frontier
- Lepton Colliders for precision physics, catching up in energy ~10y later
- LHC coming online from 2007
- Consensus to build a lepton linear collider with E_{cm} > 500 GeV to complement LHC physics

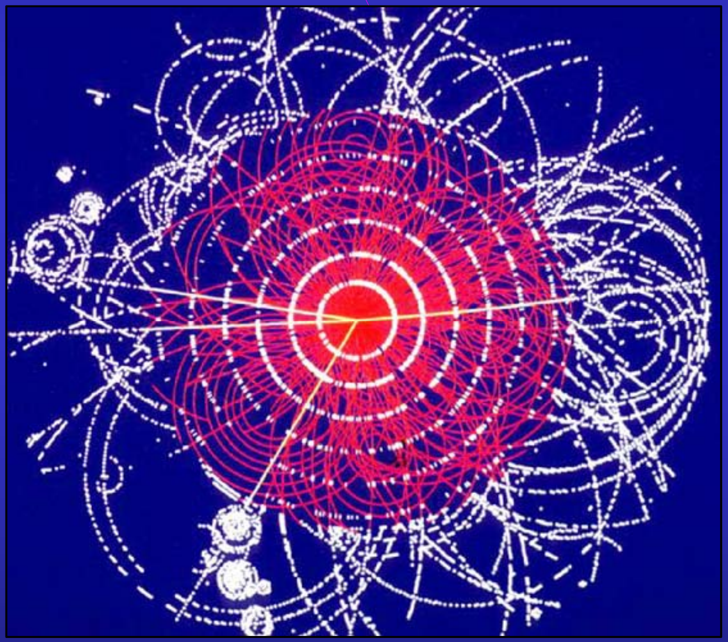
Hadrons vs Leptons, typical event pattern for the Higgs particle

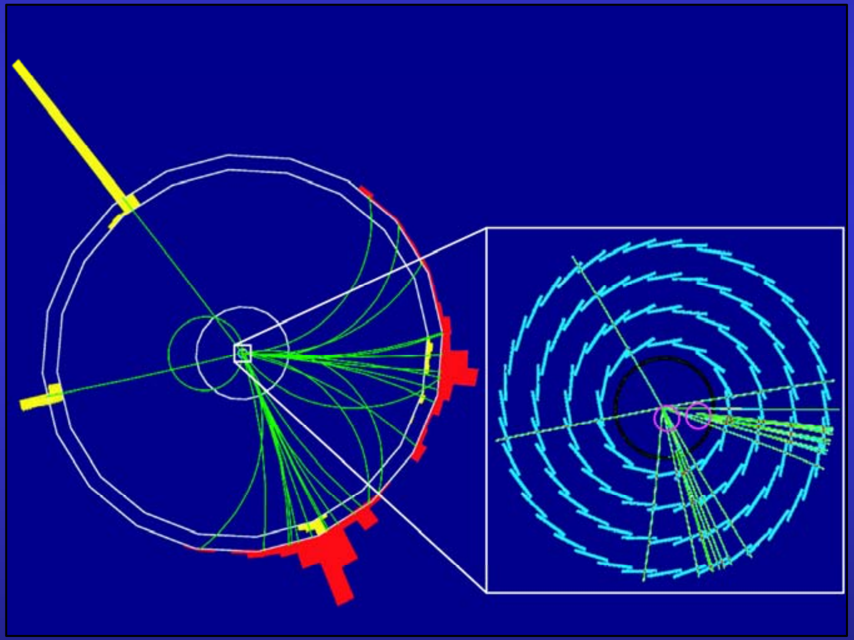
Hadron collision



Lepton collision





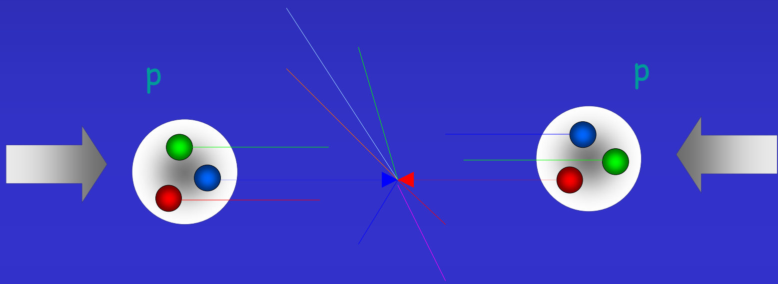


Simulation of HIGGS production $e^+ e^- \to Z H$

$Z \to e^+ e^-$, $H \to b \bar{b}$

Hadron Colliders

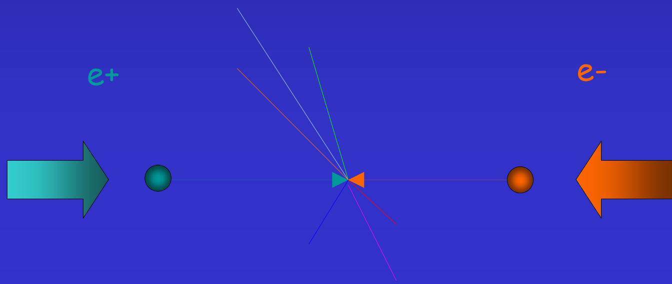
- Protons are composite objects



- Only fraction (≈1/6) of total proton energy available for collision of constituents
- Can only use p_t conservation
- Huge QCD background

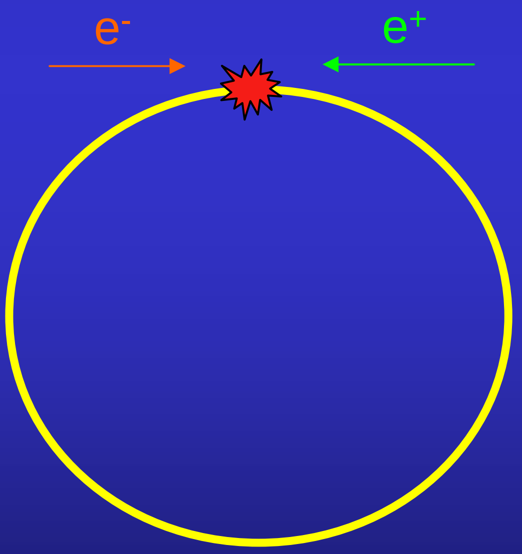
Lepton Colliders

- Leptons are elementary particles

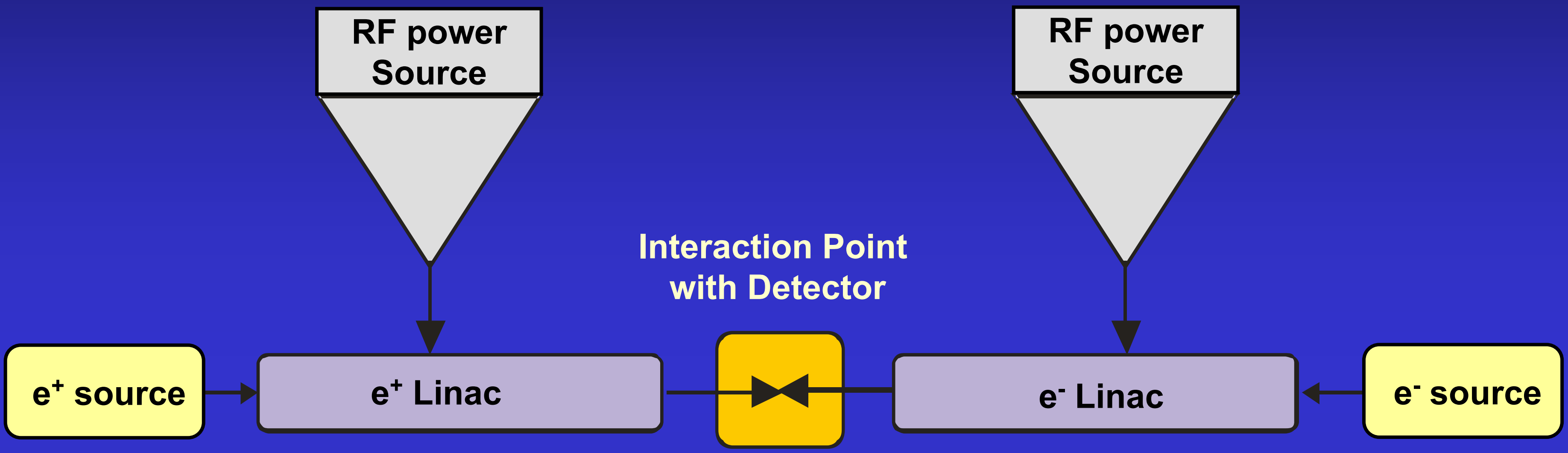


- Well defined initial state
- Momentum conservation eases decay product analysis
- With beam polarization full knowledge of initial state

Linear vs circular e^+/e^- collider



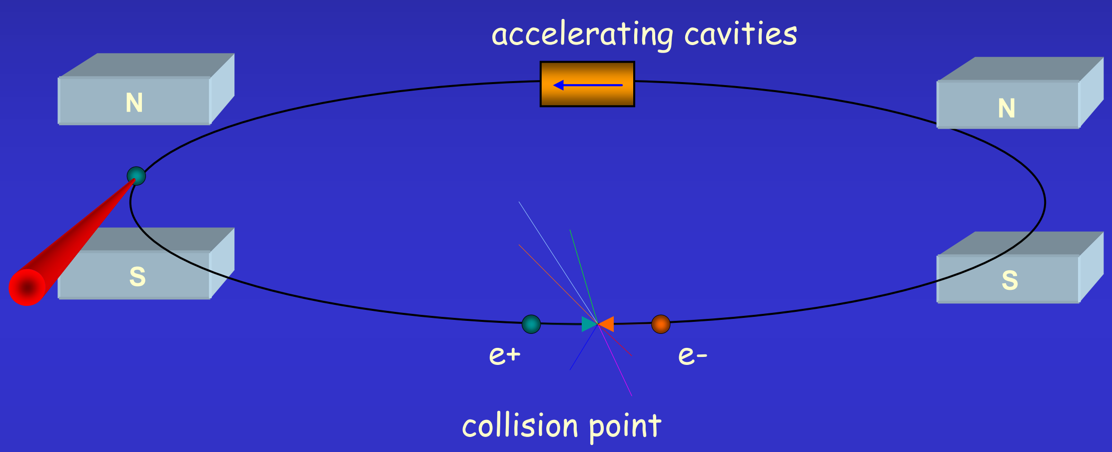
What is a Linear Collider



- No big bending magnets
- But a lot of RF acceleration
- High Accelerating Gradient to minimize size and cost
- Exceptional beam quality needed (colliding nm-size beams)

Why a Linear Collider

Circular colliders re-use acceleration and beams



Charged particles emit synchrotron radiation in a magnetic field

$$P = \frac{2}{3} \frac{r_e}{\left(m_o c^2\right)^3} \frac{E^4}{\rho^2}$$

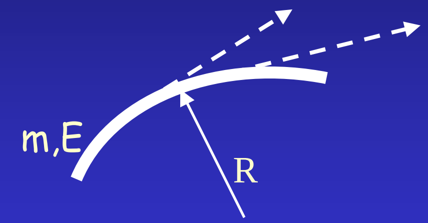
$$\Delta E_{turn} = \frac{4}{3} \pi \frac{r_e}{\left(m_o c^2\right)^3} \frac{E^4}{\rho}$$

Much less important for heavy particles, like protons

Cost of Lepton Colliders

Synchrotron radiation

– $\Delta E \sim (E^4/m^4 R)$

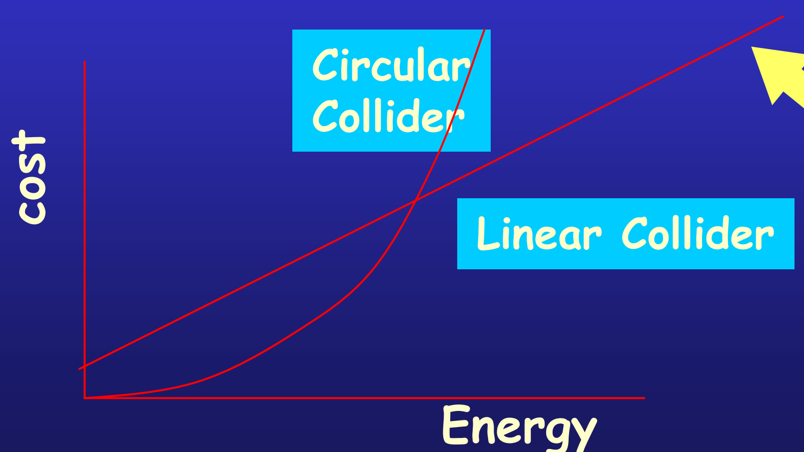


Therefore

– Cost (circular) $\sim a R + b \Delta E \sim a R + b (E^4/m^4 R)$

Optimization $R \sim E^2 \Rightarrow \text{Cost} \sim c E^2$

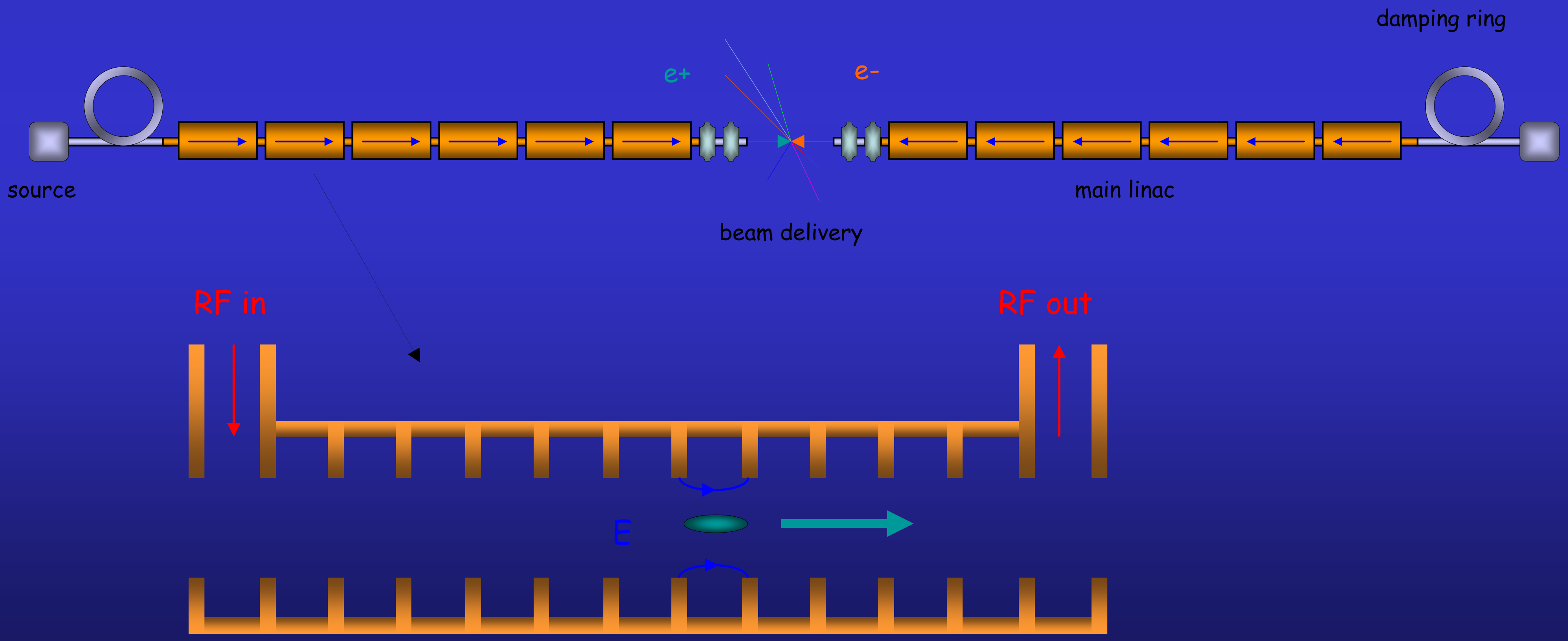
– Cost (linear) $\sim a' L$, where $L \sim E$



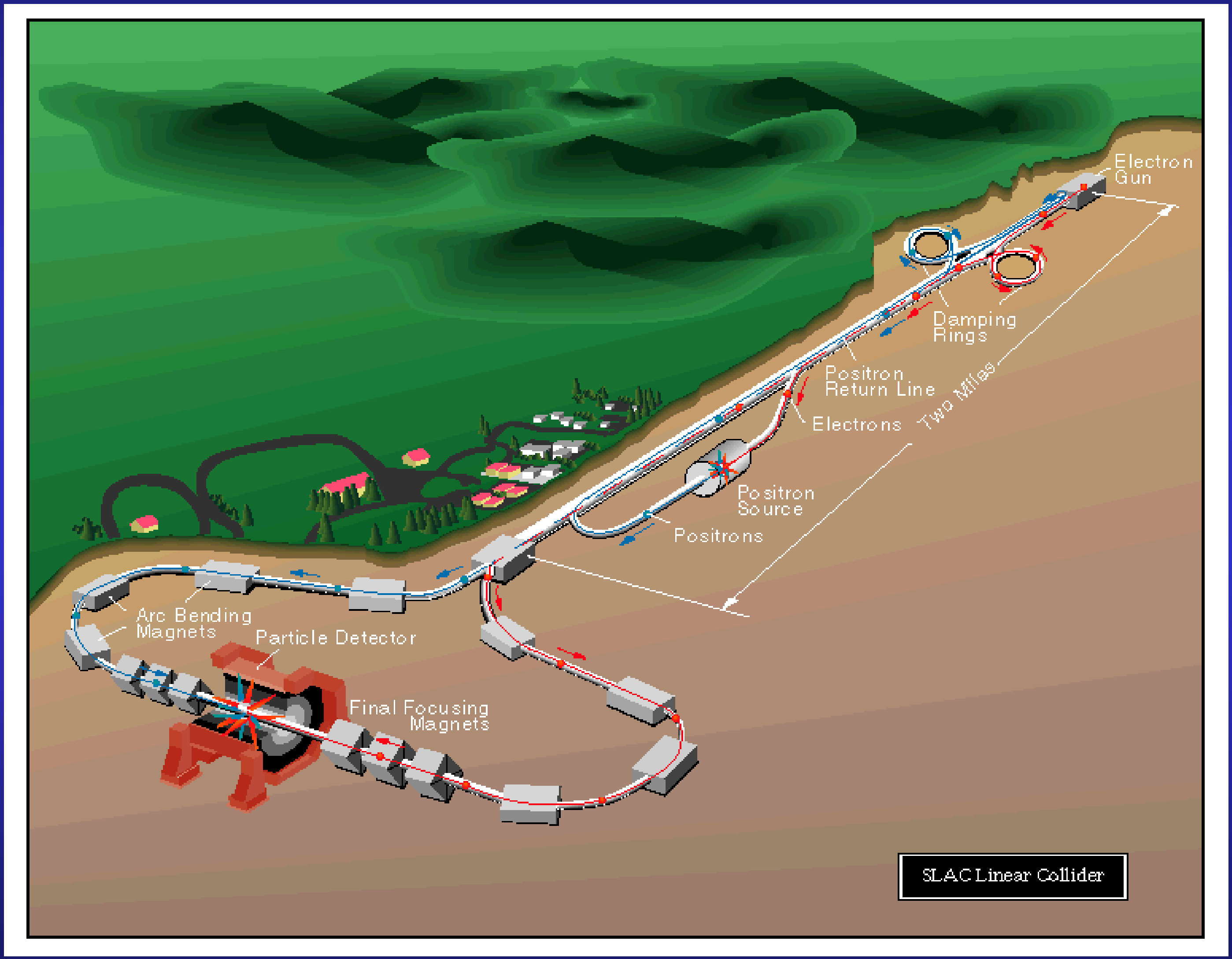
At high energy, linear collider is more cost effective

A linear collider uses the accelerating cavities only once:

- Lots of them !
- Need a **high accelerating gradient** to reach the wanted energy in a "reasonable" length (total cost, cultural limit)



SLC: The 1st Linear Collider



Built to study the Z_0 and demonstrate linear collider feasibility

Energy = 92 GeV

Luminosity = 3e30

E=20 MV/m

Had all the features of a 2^{nd} gen. LC except both e^+ and e^- shared the same linac

Challenges for Linear Collider

Center of mass Energy

$$E_{CMS} = \text{Length} \cdot \text{Accelerating field}$$

Rate of physics event

$$\dot{N}_{Event} = \text{cross section} \cdot \text{Luminosity}$$

Decreases $\sim 1/E_{CMS}^2$

for many key processes

Accelerator property

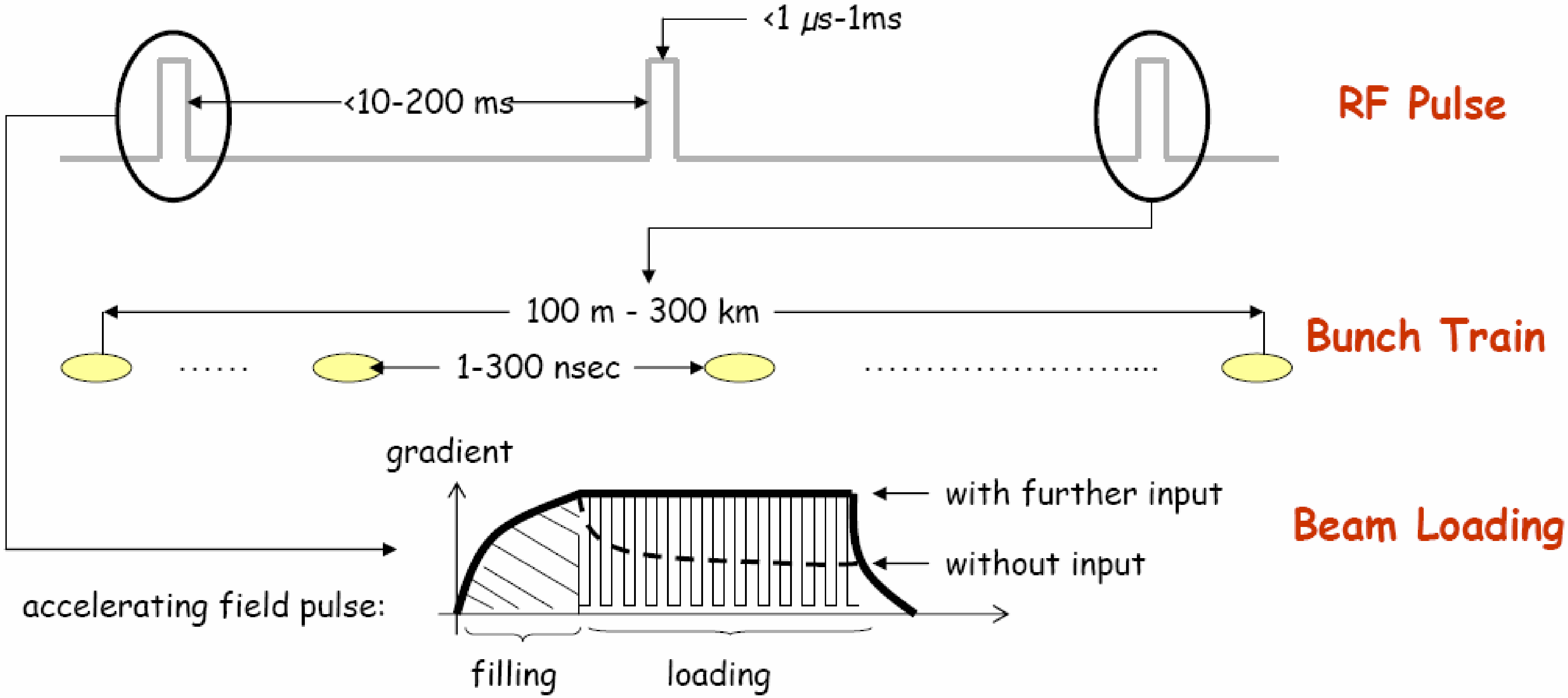
$$L = \frac{n_b N^2 f_{rep}}{4\pi \, \sigma_X \sigma_Y} H_D$$

where:

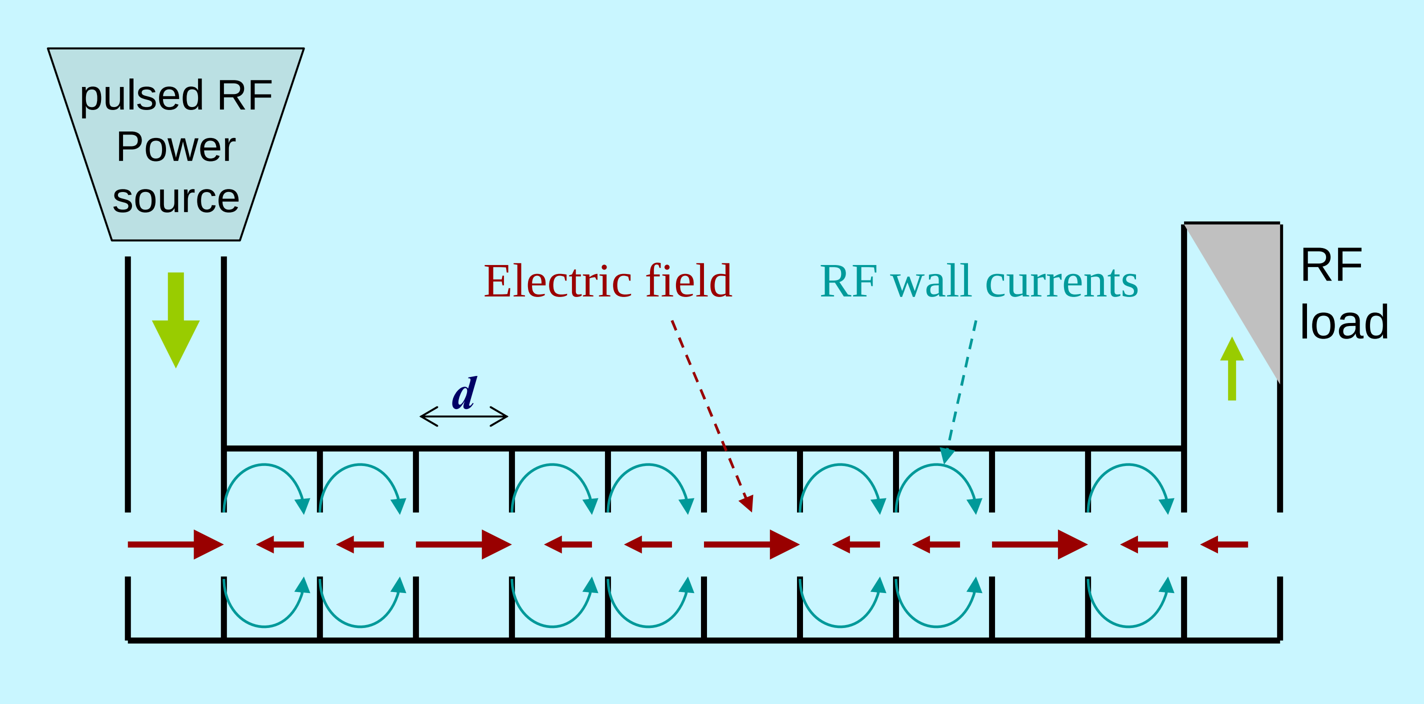
- n_b = bunches / train
- N = particles per bunch
- f_{rep} = repetition frequency
- $\sigma_{X/Y}$ = beam horiz./vert. beam size at IP
- H_D = beam-beam enhancement factor

LCs are pulsed machines

- duty factors are small
- pulse peak powers can be very large



Traveling wave structure, the building block of normal conducting electron linacs

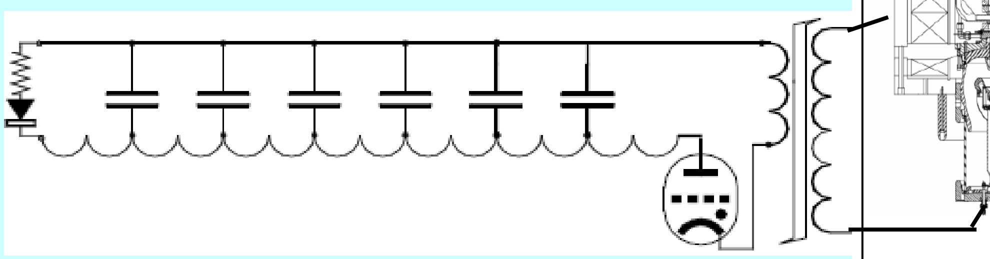


see Walter's talk

Klystrons, the RF power amplifier for linear accelerators

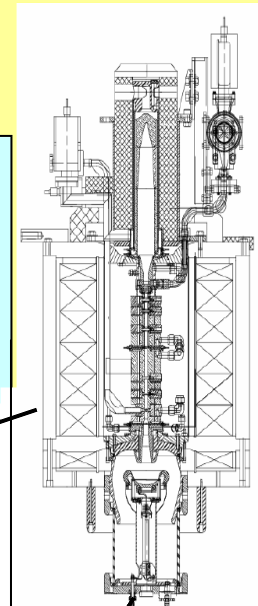
Modulator

Energy storage in capacitors
charged up to 20-50 kV (between pulses)



High voltage
switching and
voltage transformer
rise time > 300 ns

Klystron



U 150 -500 kV
I 100 -500 A
f 0.2 -20 GHz

P_{ave} < 1.5 MW
P_{peak} < 150 MW

efficiency 40-70%

$\Rightarrow$ ***for power efficiency operation pulse length t_{PULSE} > 1 µs favorable***

RF wall currents heat up cavity wall during pulse

Acceleration Field $E_{ACC} \sim \sqrt{P_{RF}}$

Temperature rise $\Delta T \sim P_{RF}\sqrt{t_{PULSE}}$

for given allowable $\Delta T \Rightarrow E_{ACC} \sim \frac{1}{\sqrt[4]{t_{PULSE}}}$

To get accelerating fields of ≈ 100 MV/m pulse length is limited to ≈100ns

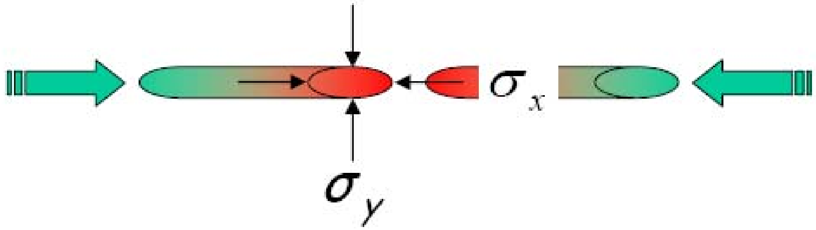
For high accelerating fields there is a mismatch

between klystron requirement $t_{PULSE} > 1\mu s$

and RF structure requirement $t_{PULSE} < 100ns$

How to get High Luminosity ?

$$L \propto \frac{N_e^2}{\sigma_x \sigma_y}$$



$$L \propto n_b \times f_{rep}$$

L = Luminosity

N_e = # of electron per bunch

$\sigma_{x,y}$ = beam sizes at IP

IP = interaction point

$$L \propto \frac{P_b}{E_{c.m.}} \times \frac{N_e}{\sigma_x \sigma_y}$$

n_b = # of bunches per pulse

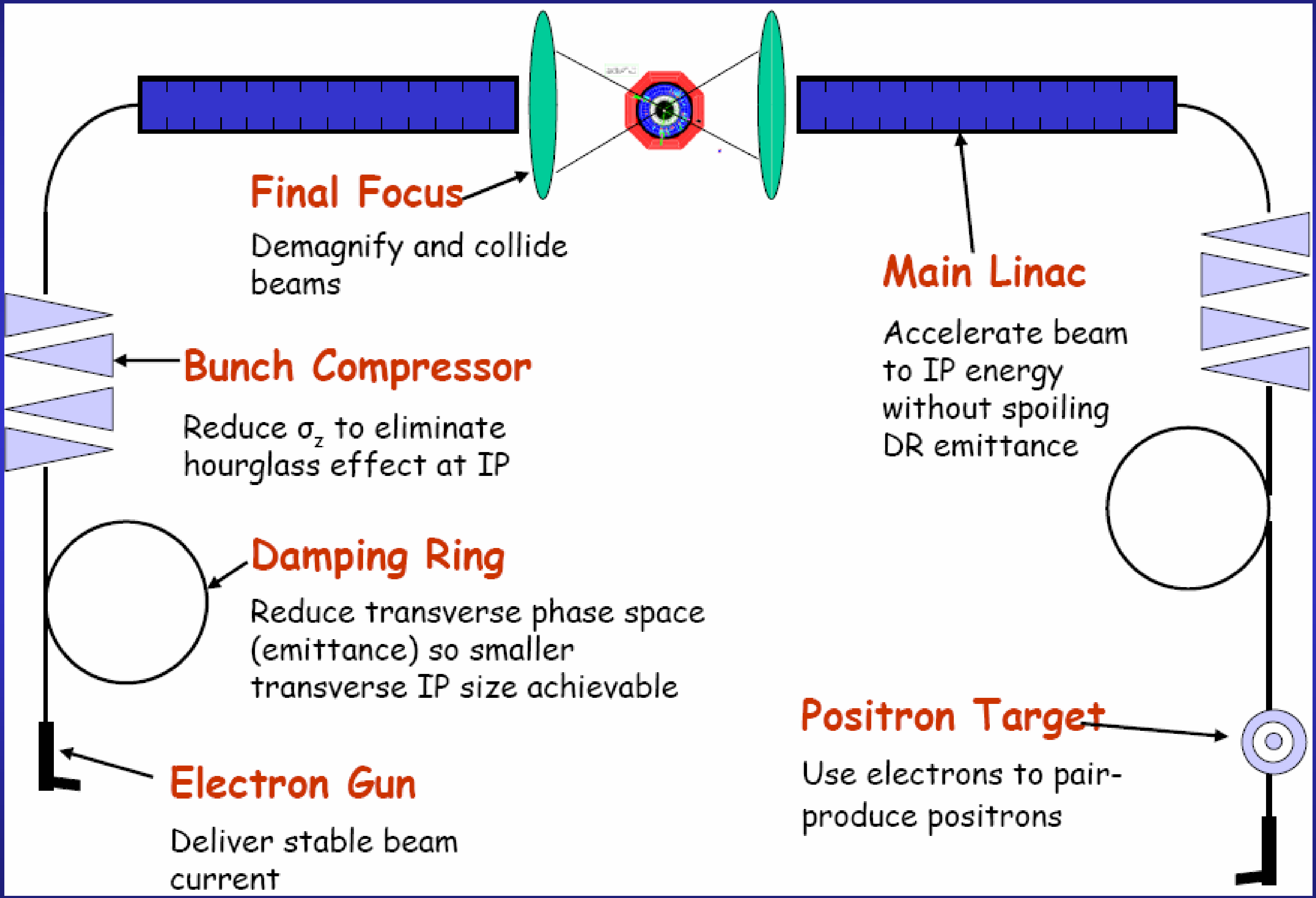
f_{rep} = pulse repetition rate

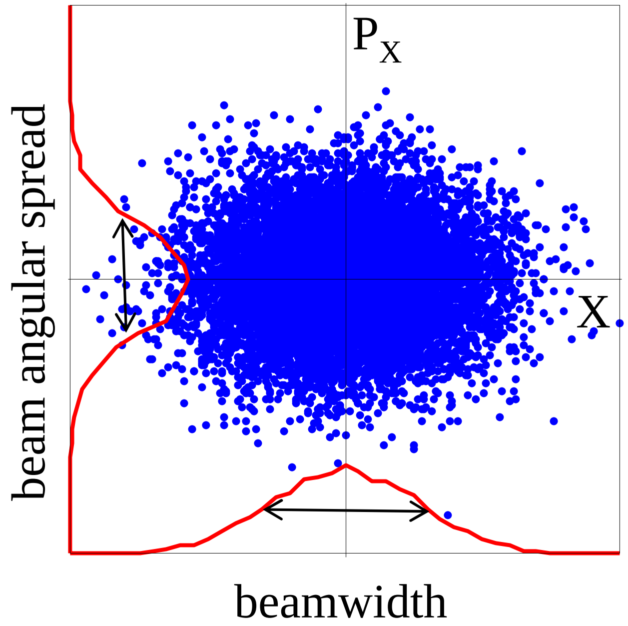
P_b = beam power

$E_{c.m.}$ = center of mass energy

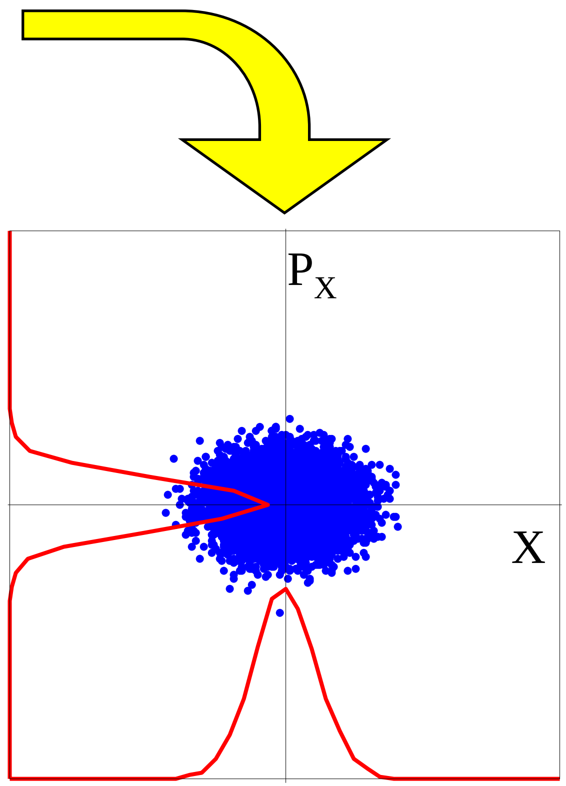
Parameters to play with

- ↓ Reduce **beam emittance** $(\varepsilon_x \cdot \varepsilon_y)$ for smaller beam size $(\sigma_x \cdot \sigma_y)$
- ↑ Increase bunch population (N_e)
- ↑ Increase beam power $(P_b \propto N_e \times n_b \times f_{rep})$
- ↑ Increase **beam to-plug power efficiency** for cost

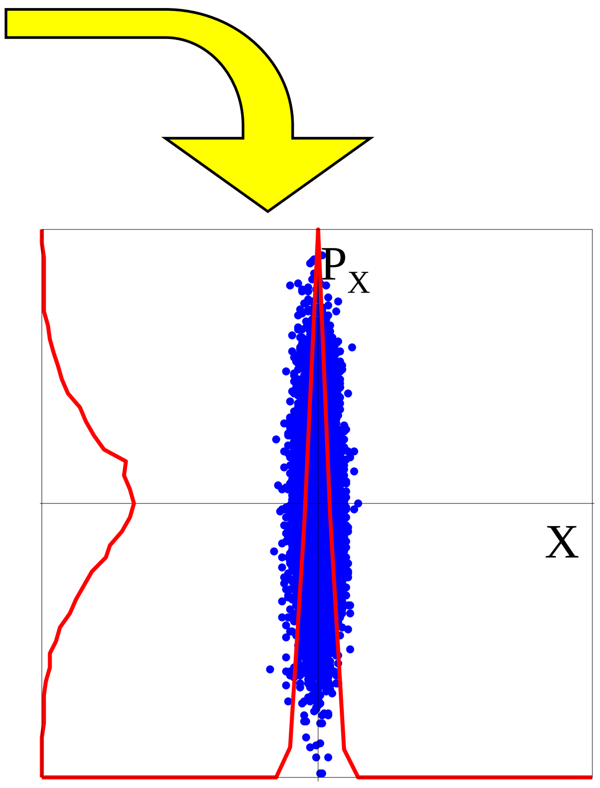

Final Focus
Demagnify and collide beams
Main Linac
Accelerate beam to IP energy without spoiling DR emittance
Bunch Compressor
Reduce σ_z to eliminate hourglass effect at IP
Damping Ring
Reduce transverse phase space (emittance) so smaller transverse IP size achievable
Positron Target
Use electrons to pair-produce positrons
Electron Gun
Deliver stable beam current



reduction of beam **emittance** with **damping ring**



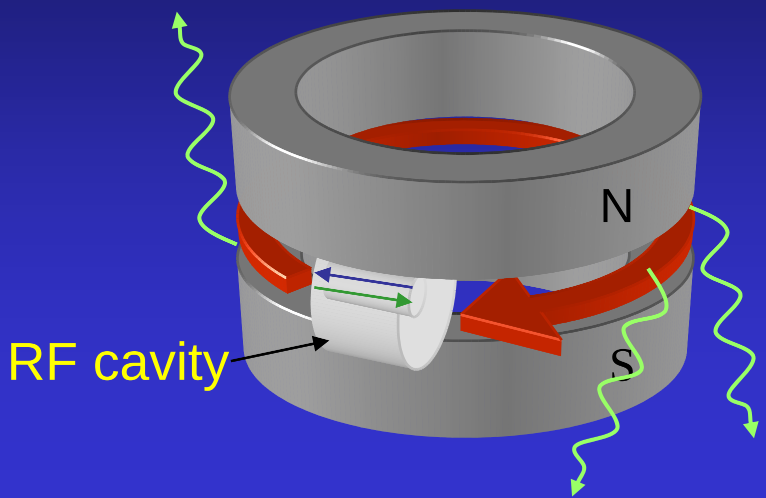
focusing of beam to small size with **final focus system**



Emittance = beam width x beam angular spread

Conserved quantity for linear focusing elements
(i.e. quadrupoles)

Damping Rings, reduction of emittance with radiation damping



δp replaced by RF such that $\Delta p_z = \delta p$.

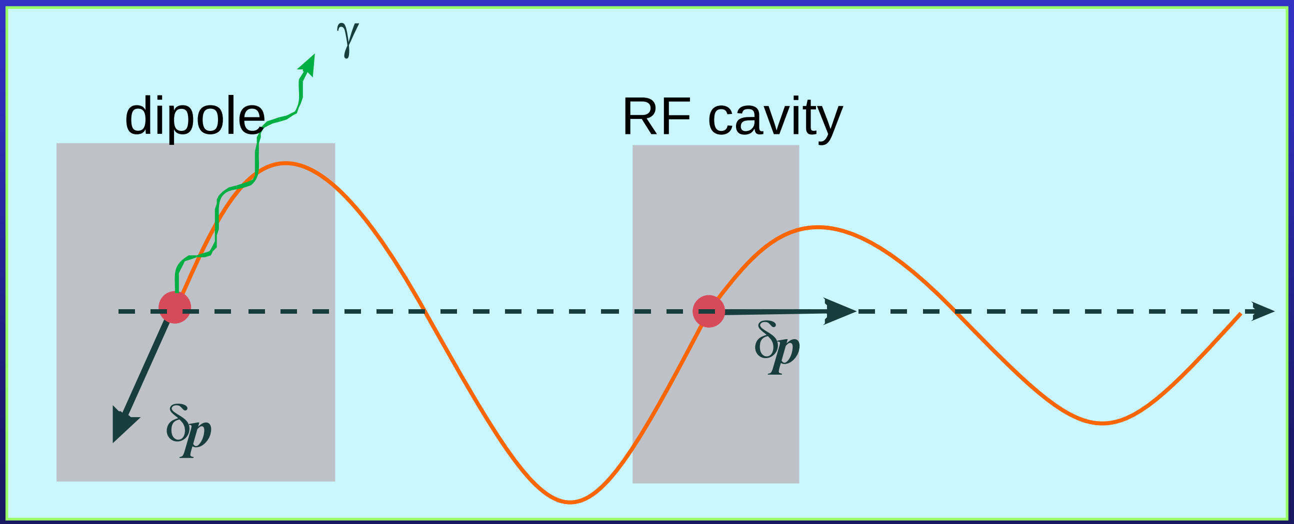
since

$$y' = dy/ds = p_y/p_z,$$

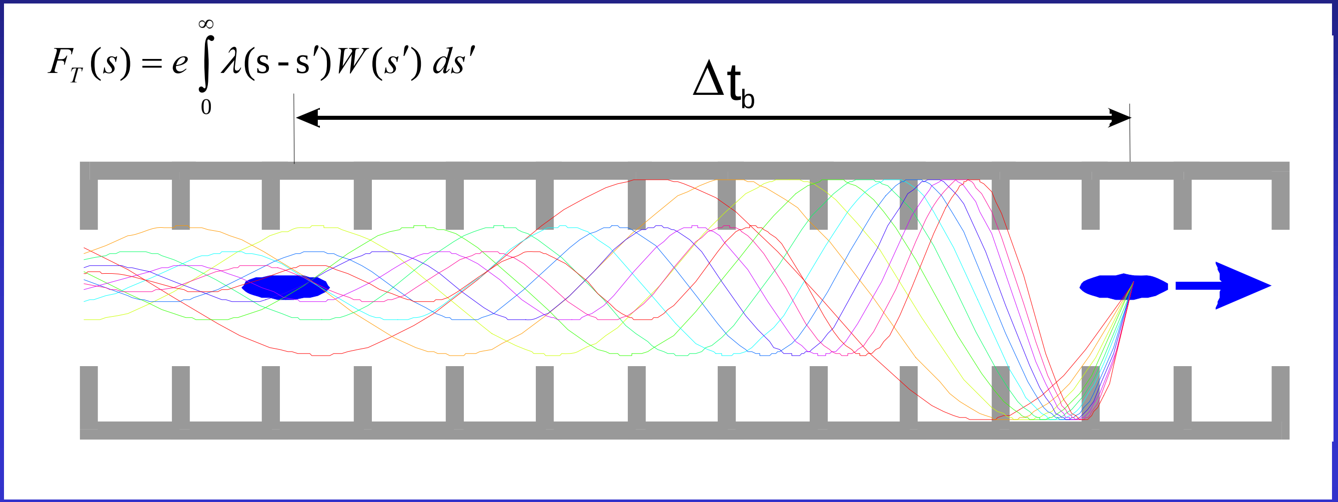
we have a reduction in amplitude:

$$\delta y' = -\delta p\, y'$$

But photon emission is a quantized, statistical fluctuation of photon number sets ***lower limit for emittance***



Emittance preservation during acceleration in main linac
Main problem: **Transverse Wakes Fields**



Bunch current generates transverse deflecting modes when bunches are not on cavity axis.
Later bunches are kicked transversely

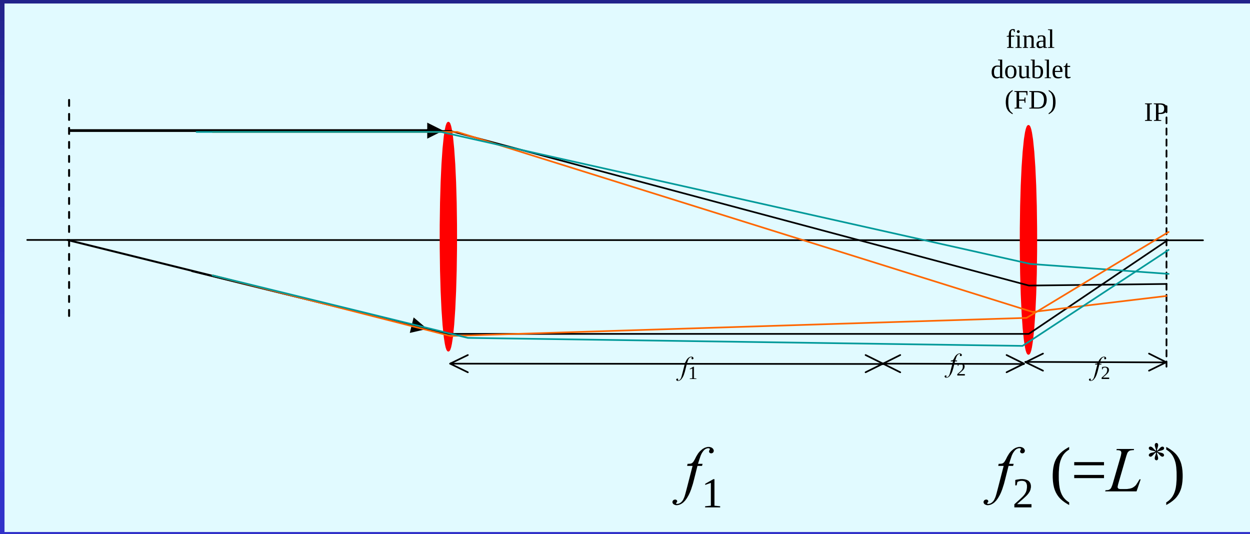
Countermeasures

- Detuning of dipole frequencies from cell to cell
- Damping of dipole modes with HOM couplers
- Strong focusing
- Tight alignment and orbit control
- Feedbacks
- Increase of bunch spacing
- Limit bunch charge

Final focus system to minimize beam size at IP

Essential part of final focus is final telescope. It “demagnify” the incoming beam ellipse to a smaller size.

A minimal number of quadrupole magnets, to construct a telescope with arbitrary demagnification factors, is four.

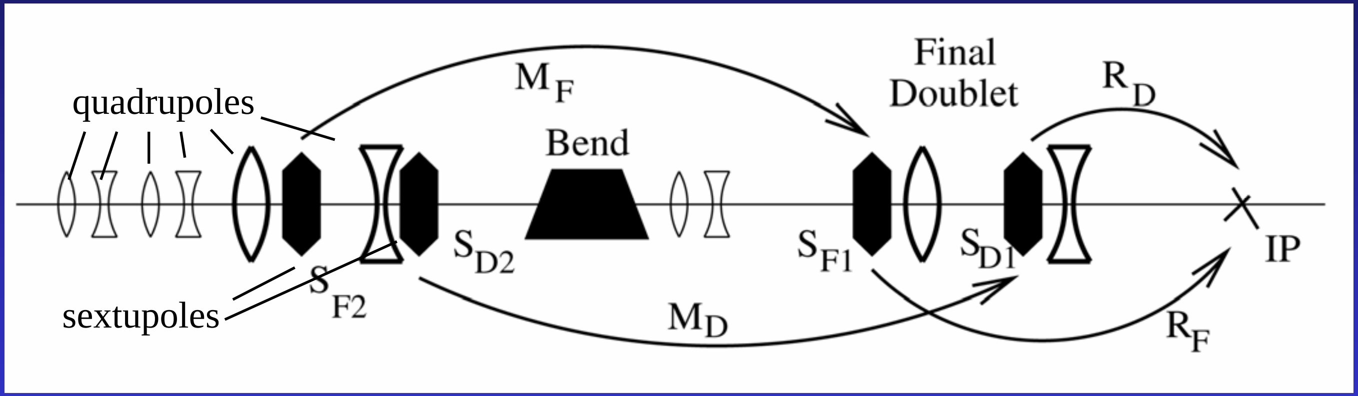


However, energy spread of beam

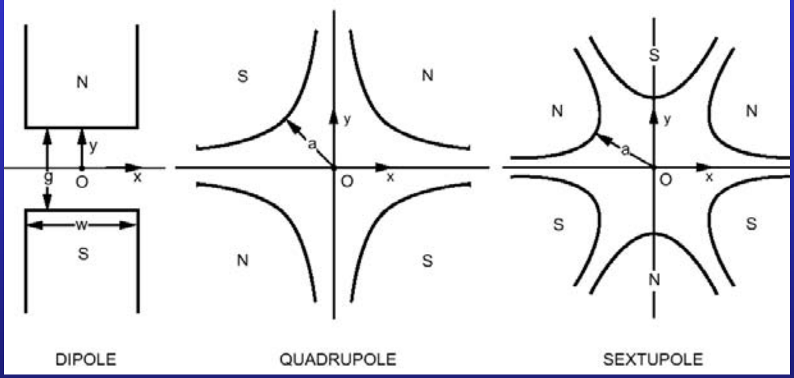
Leads to chromatic errors, which limit minimum beamsize at IP

Telescope optics to demagnify beam by factor $m = f_1/f_2 = f1/L^*$

Final focus with local chromatic correction



- Chromaticity is cancelled <u>locally</u> by two sextupoles interleaved with final quadrupole doublet, a bend upstream generates dispersion across final quadrupoles
- Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend



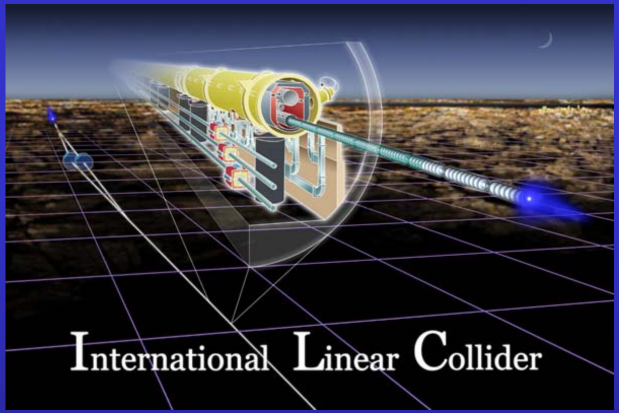
Just bend the trajectory

Focus in one plane, defocus in another:
$x' = x' + G\,x$
$y' = y' - G\,y$

Second order effect:
$x' = x' + S\,(x^2-y^2)$
$y' = y' - S\,2xy$

Solutions to pulse mismatch

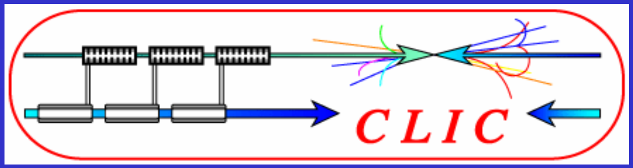
Use superconducting RF cavities at cryogenic temperatures



RF pulse compression

NLC project discontinued

CLIC two beam scheme



The International Linear Collider (ILC)

It is a project designed to smash together electrons and positrons at the center of mass energy of 0.5 TeV initially and 1 TeV later.

The ILC Global Design Effort team, established in 2005, has been making its accelerator design. Recently, it worked out the baseline configuration for the 30-km-long 500 GeV collider. (from Fumihiko Takasaki / KEK)

But theoretical limit: $E_{ACC} \leq 50$ MV/m because magnetic surface fields exceed B_{CRIT} of superconductivity

$\Rightarrow \quad E_{CMS} \leq 1$ TeV

CLIC aim:

develop technology for e^-/e^+ collider with E_{CMS}= 1 - 5 TeV

Physics motivation:

"Physics at the CLIC Multi-TeV Linear Collider :

report of the CLIC Physics Working Group," CERN report 2004-5

Present mandate:

Demonstrate all key feasibility issues by 2010

BASIC FEATURES OF CLIC

- High acceleration gradient (>100 MV/m)

  - "Compact" collider - overall length < 35 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)

- Two-Beam Acceleration Scheme

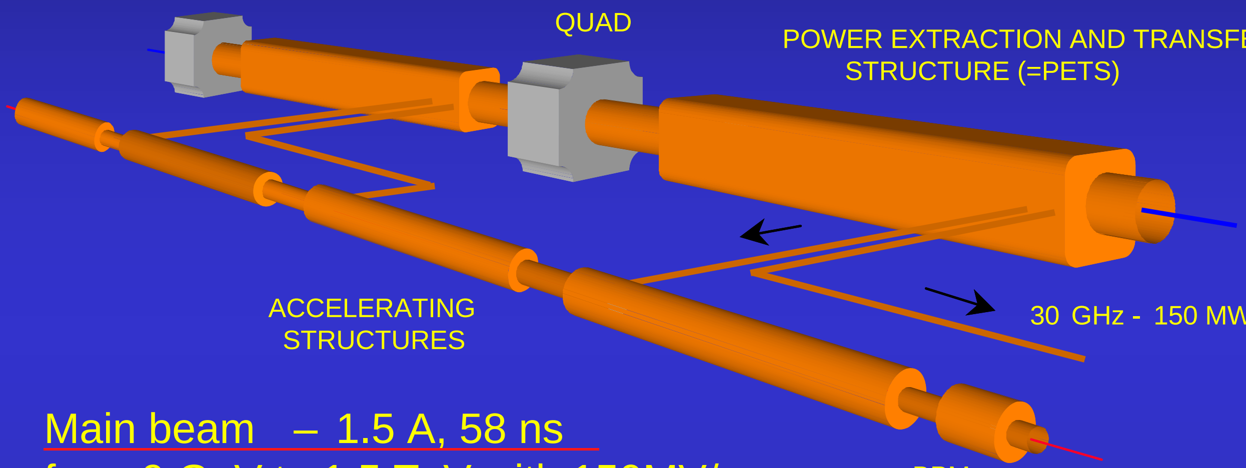
  - Capable to reach high frequency
  - Cost-effective & efficient
  - Simple tunnel, no active elements

- Central injector complex

  - "Modular" design, can be built in stages

CLIC TWO-BEAM SCHEME

Drive beam - 180 A, 70 ns
from 2.4 GeV to 240 MeV with -9MV/m

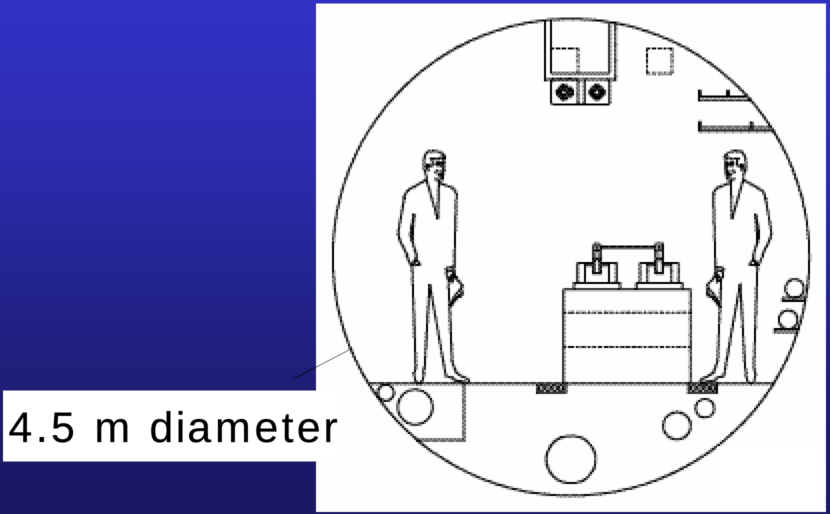


Main beam – 1.5 A, 58 ns
from 9 GeV to 1.5 TeV with 150MV/m

CLIC MODULE

(6000 modules at 3 TeV)

CLIC TUNNEL CROSS-SECTION



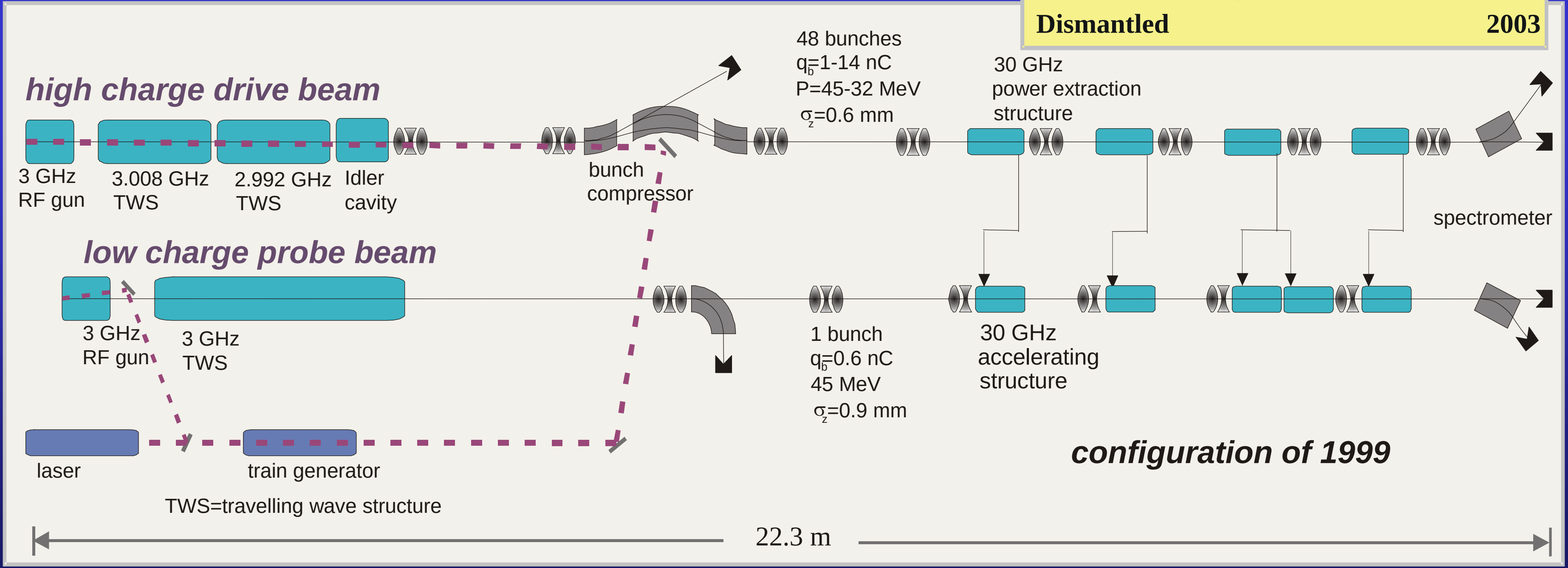
CTF II, a two beam accelerator to demonstrate CLIC linac technology

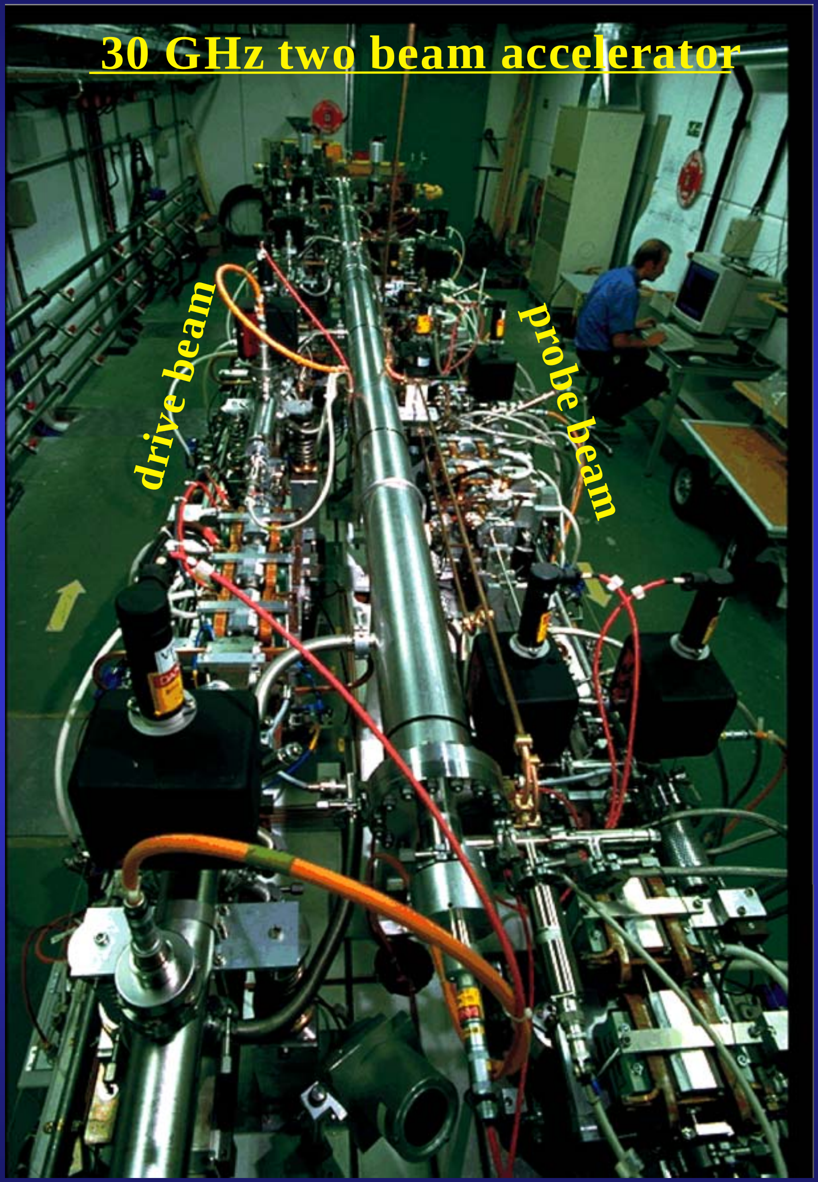
Goals of CTF II

- design and construct a fully engineered representative CLIC style test section
- develop and test drive beam generation and transport
- demonstrate two beam acceleration scheme at 30 GHz with a string of RF structures
- test active alignment system in an accelerator environment

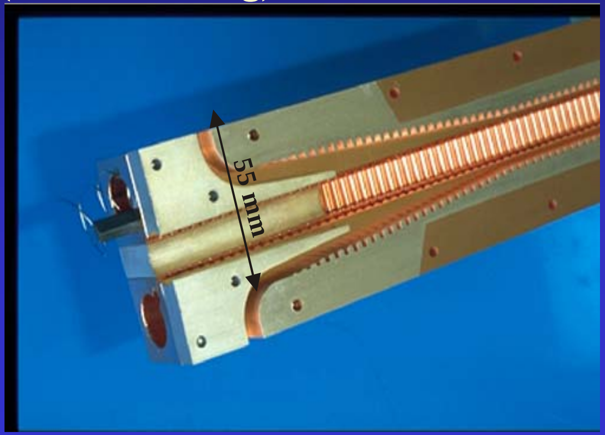
CTF II milestones

design completed	1995
start of construction	1996
operation with 2 CLIC modules	1998
operation with 4 CLIC modules	1999
conversion into high power test stand	2000
Dismantled	2003



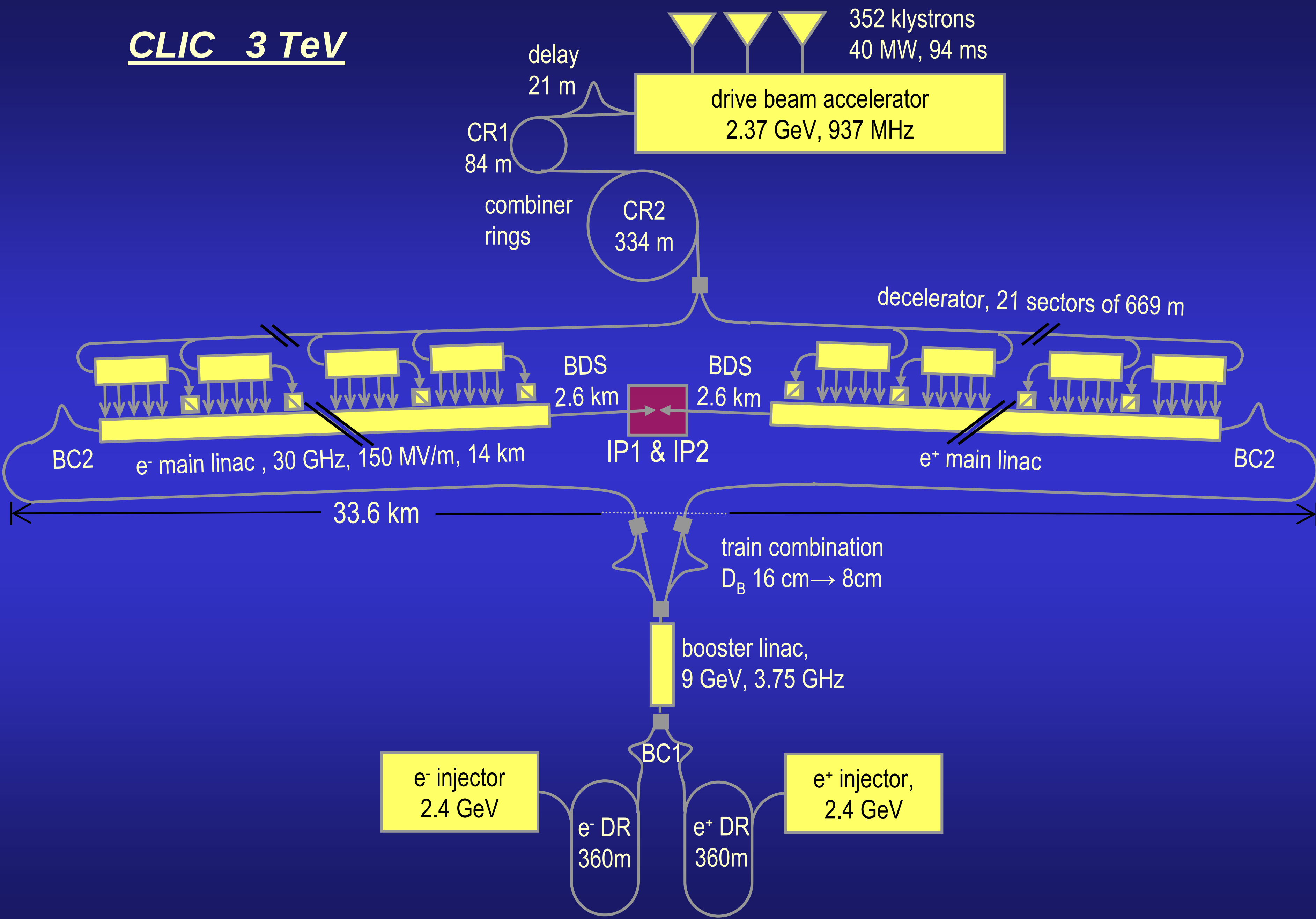


30 GHz power extraction structure for CTF II drive beam (before brazing)

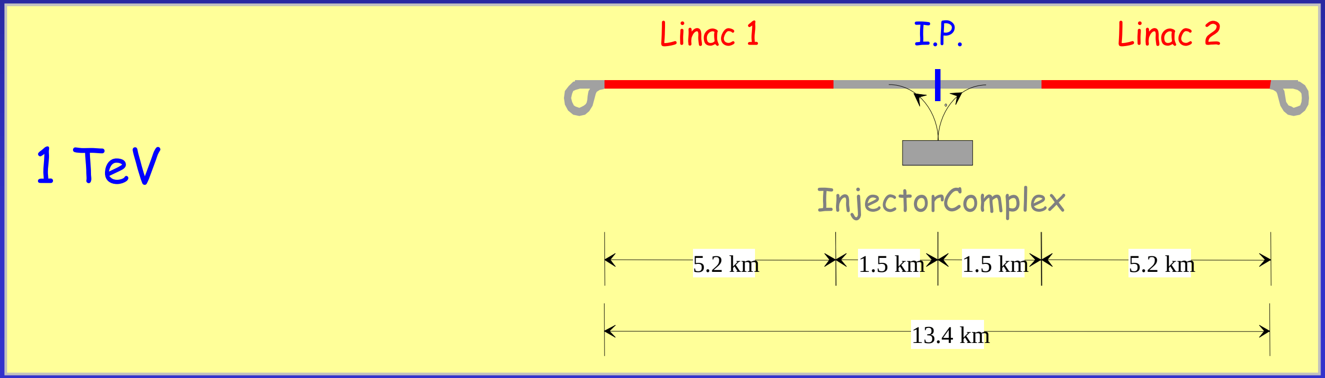


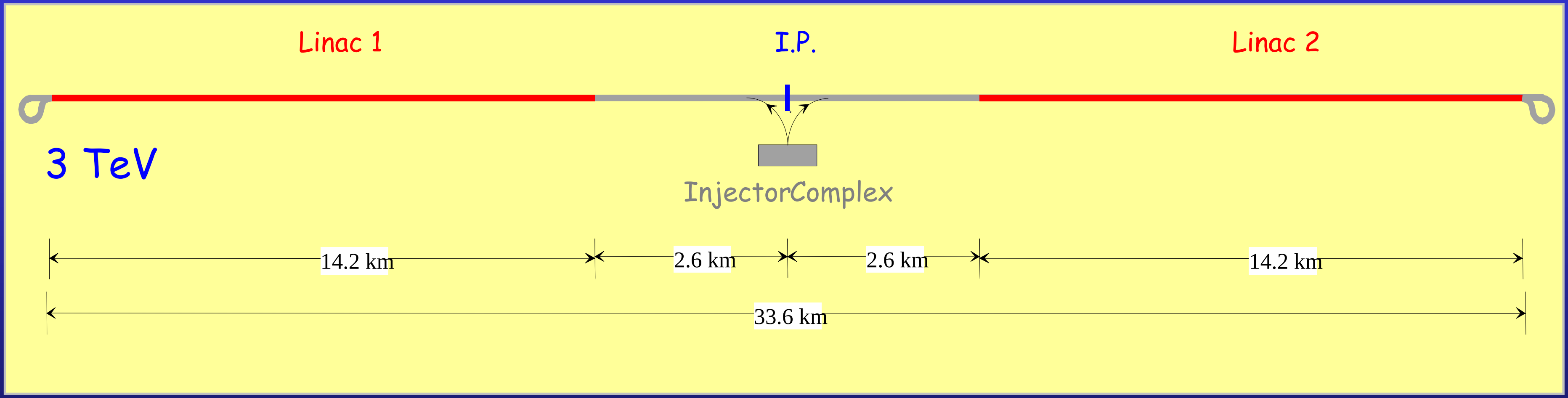
30 GHz accelerating structure of CTF II main beam

CLIC 3 TeV


352 klystrons
40 MW, 94 ms
delay
21 m
drive beam accelerator
2.37 GeV, 937 MHz
CR1
84 m
combiner
rings
CR2
334 m
decelerator, 21 sectors of 669 m
BDS
2.6 km
BDS
2.6 km
IP1 & IP2
BC2
e- main linac , 30 GHz, 150 MV/m, 14 km
e+ main linac
BC2
33.6 km
train combination
D_B 16 cm→ 8cm
booster linac,
9 GeV, 3.75 GHz
BC1
e- injector
2.4 GeV
e- DR
360m
e+ DR
360m
e+ injector,
2.4 GeV

Phased construction of CLIC





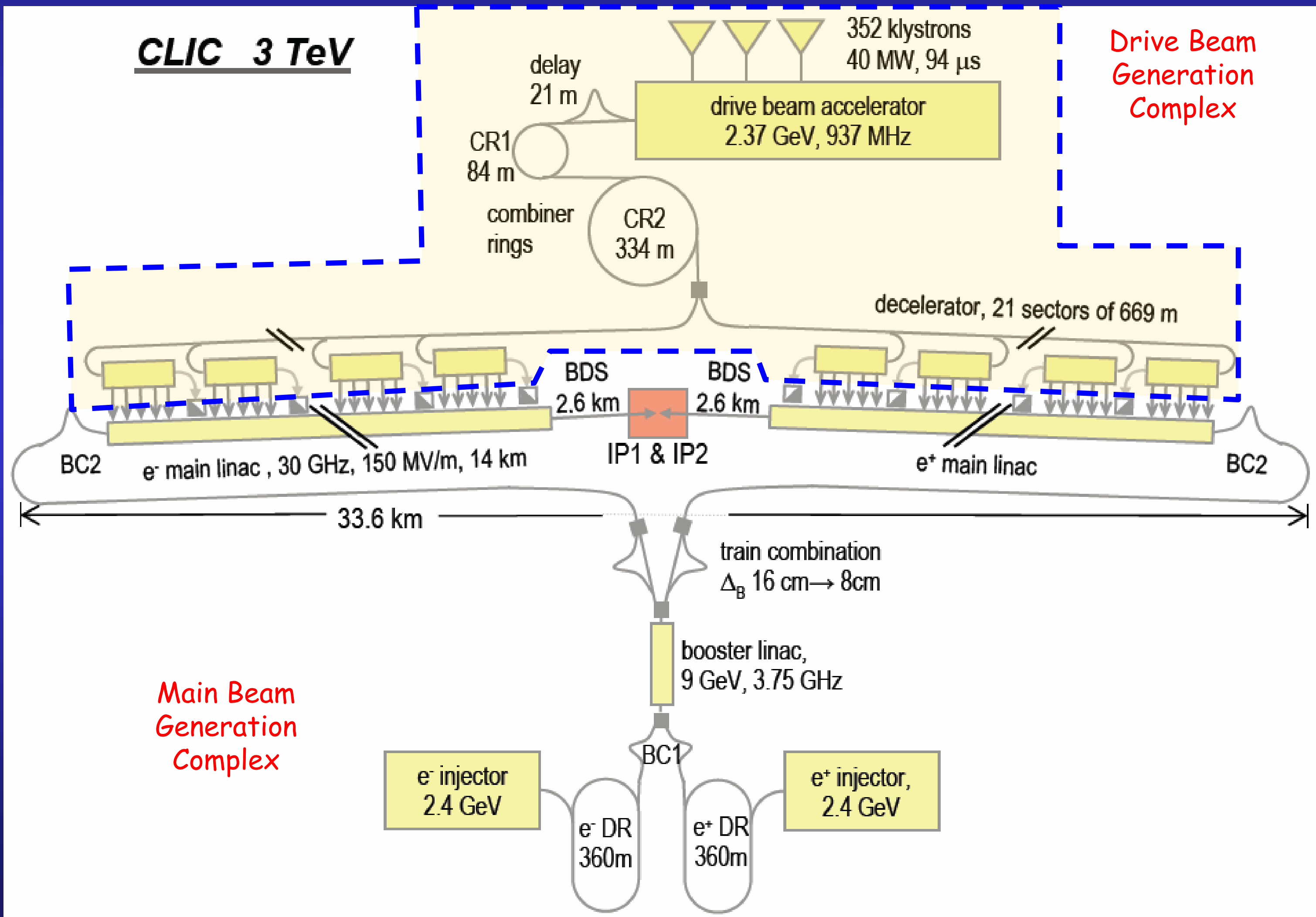
CLIC Parameter “who drives who” map*

CLIC parameters

Center of mass energy	GeV	3000
Main Linac RF Frequency	GHz	30
Unloaded / loaded gradient	MV/m	172 / 150
Linac repetition rate	Hz	150
No. of particles / bunch	10^9	2.56
No. of bunches / pulse	1	220
Bunch separation	ns	0.267
$\gamma \varepsilon_x$	nm	660
$\gamma \varepsilon_y$	nm	10
σ_x^*	nm	60
σ_y^*	nm	0.7
Bunch train length	ns	58.4
Total length	km	33.6
AC to beam efficiency	%	12.5
Total site AC power	MW	418
Luminosity	10^{34} cm^{-2} s^{-1}	6.5
Luminosity (in 1% of energy)	10^{34} cm^{-2} s^{-1}	3.3
Beamstrahlung mom. spread	%	16
GeV per klystron	GeV	8.5

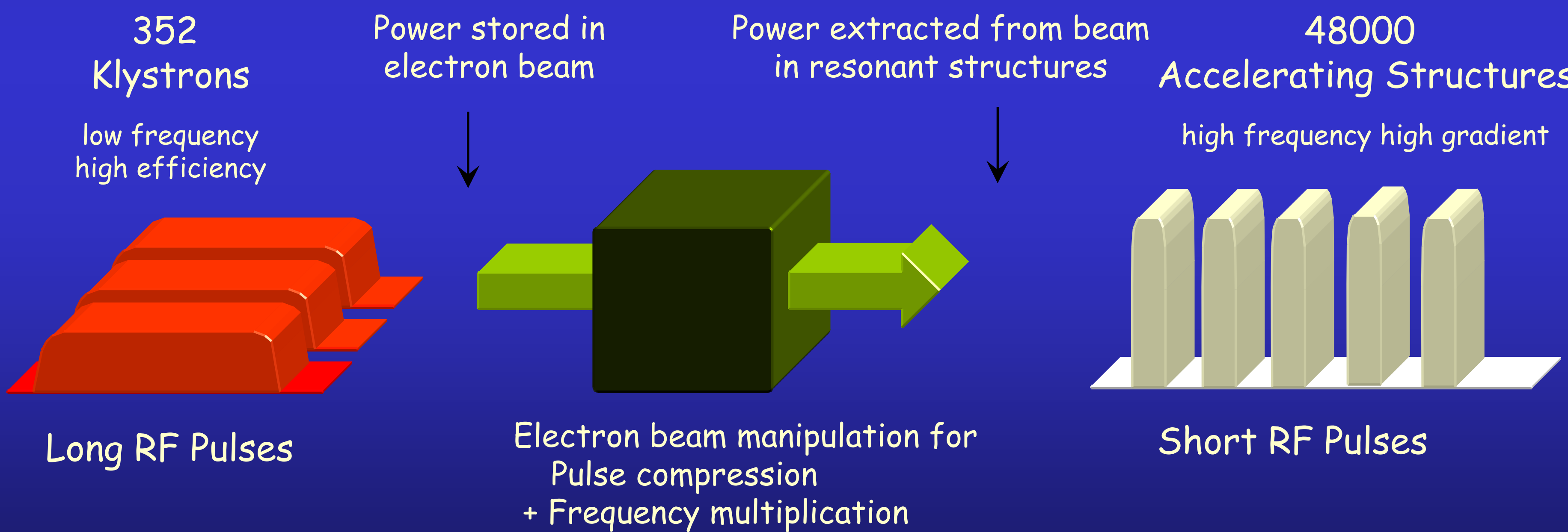
Recent structure test result
$\Rightarrow$ feasibility ?
$\Downarrow$
will probably go down

The CLIC 30 GHz RF Power Source



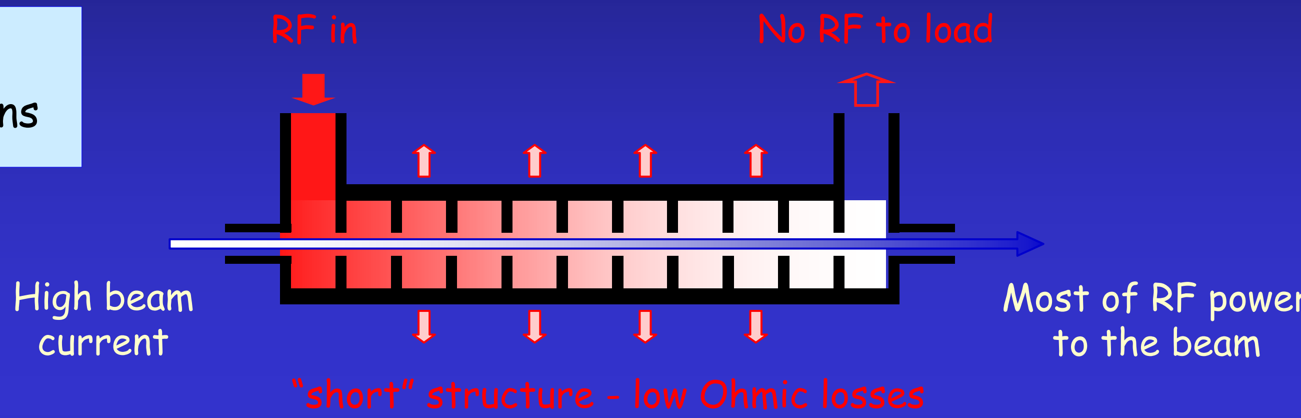
WHAT DOES THE RF POWER SOURCE DO ?

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*

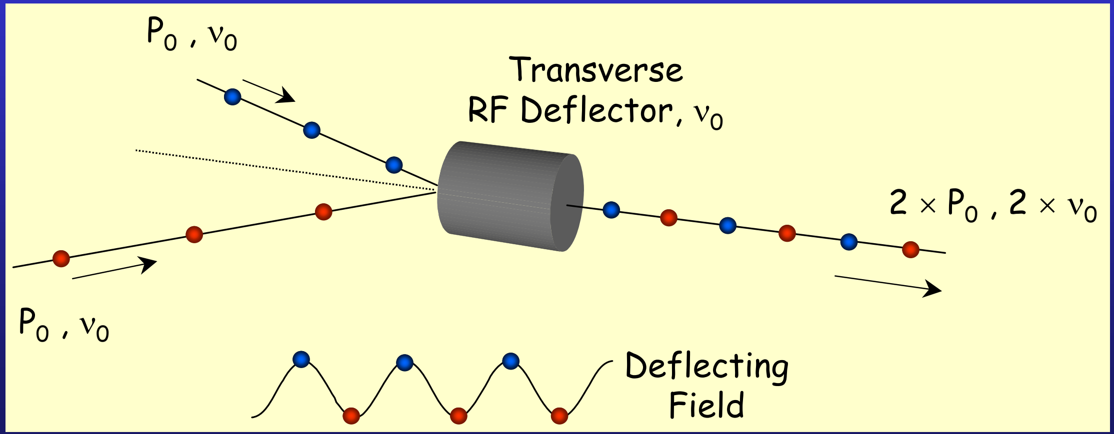


RF POWER SOURCE "BUILDING BLOCKS"

Full beam-loading acceleration in TW sections

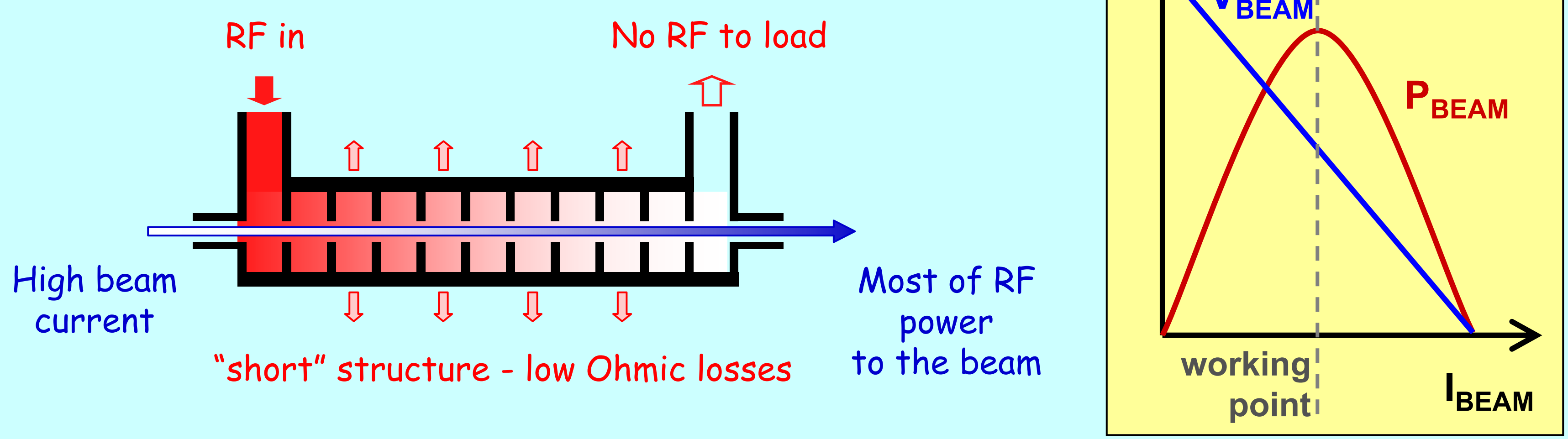


Beam combination/separation by transverse RF deflectors



Very efficient acceleration of drive beam, i.e. a ratio of beam power to input RF power of **>93%.** This is achieved with the so called fully beam loaded operation.

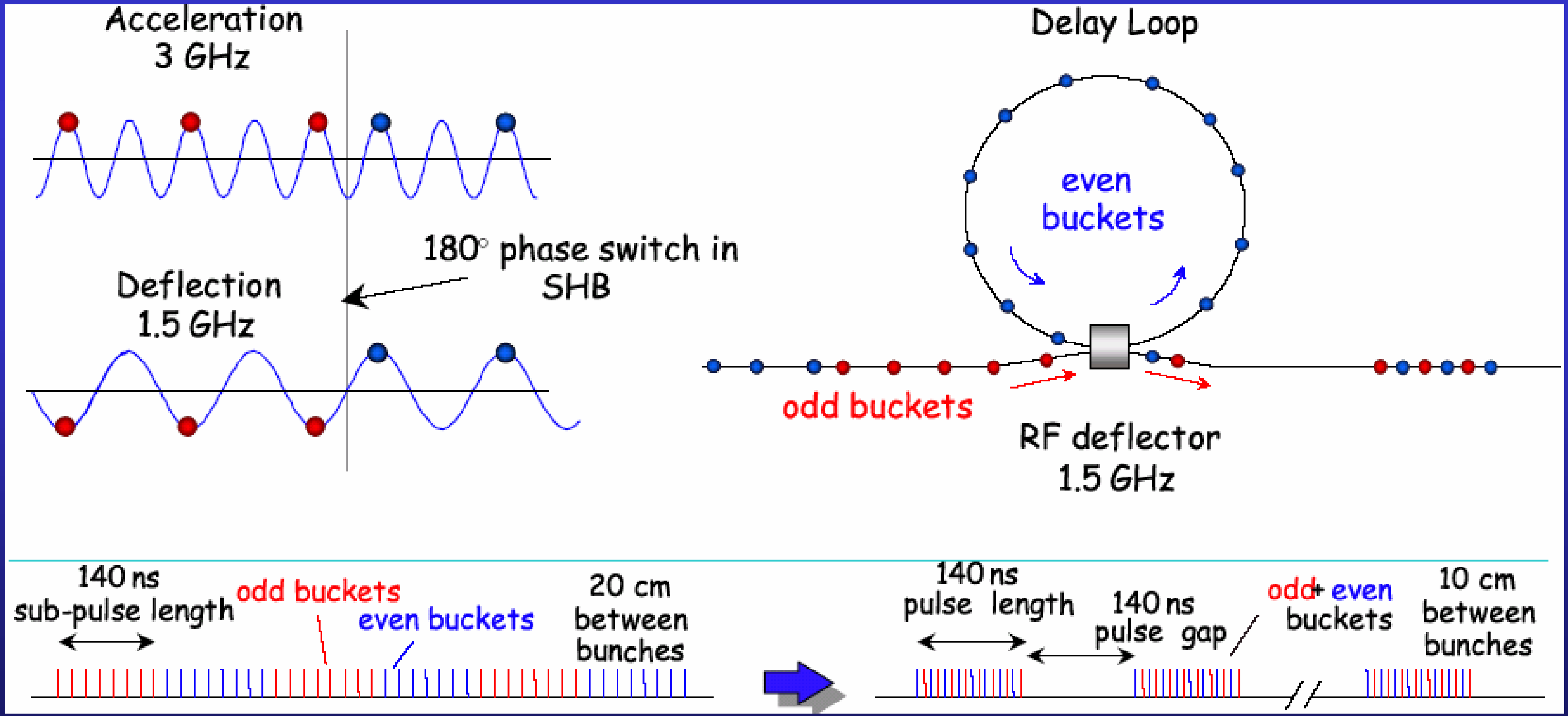
Full beam-loading acceleration in RF accelerator sections



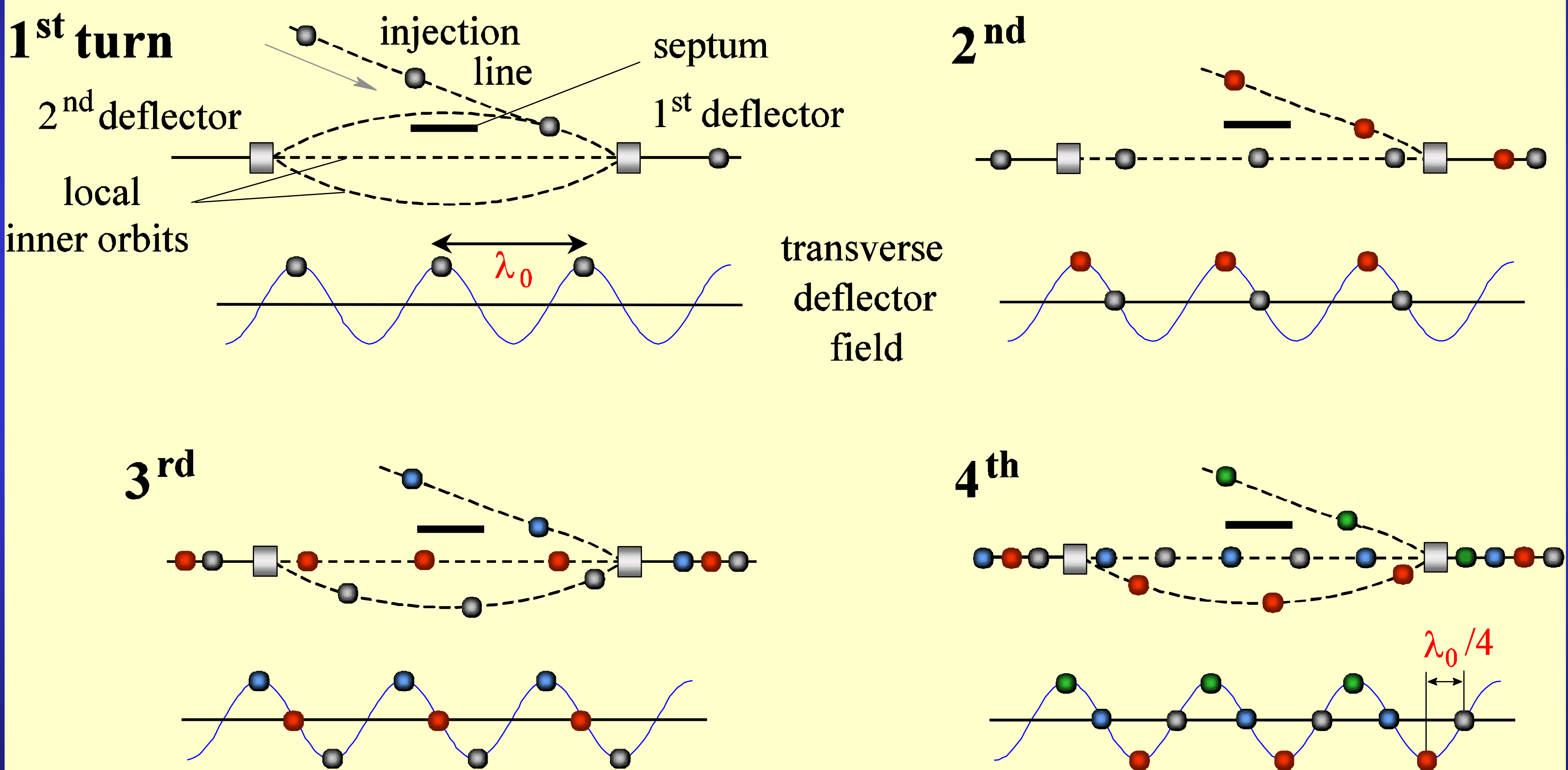
Similar to the load of a power supply, which has to have a resistance matched to the internal resistance of the power supply for best efficiency.

Delay Loop Principle

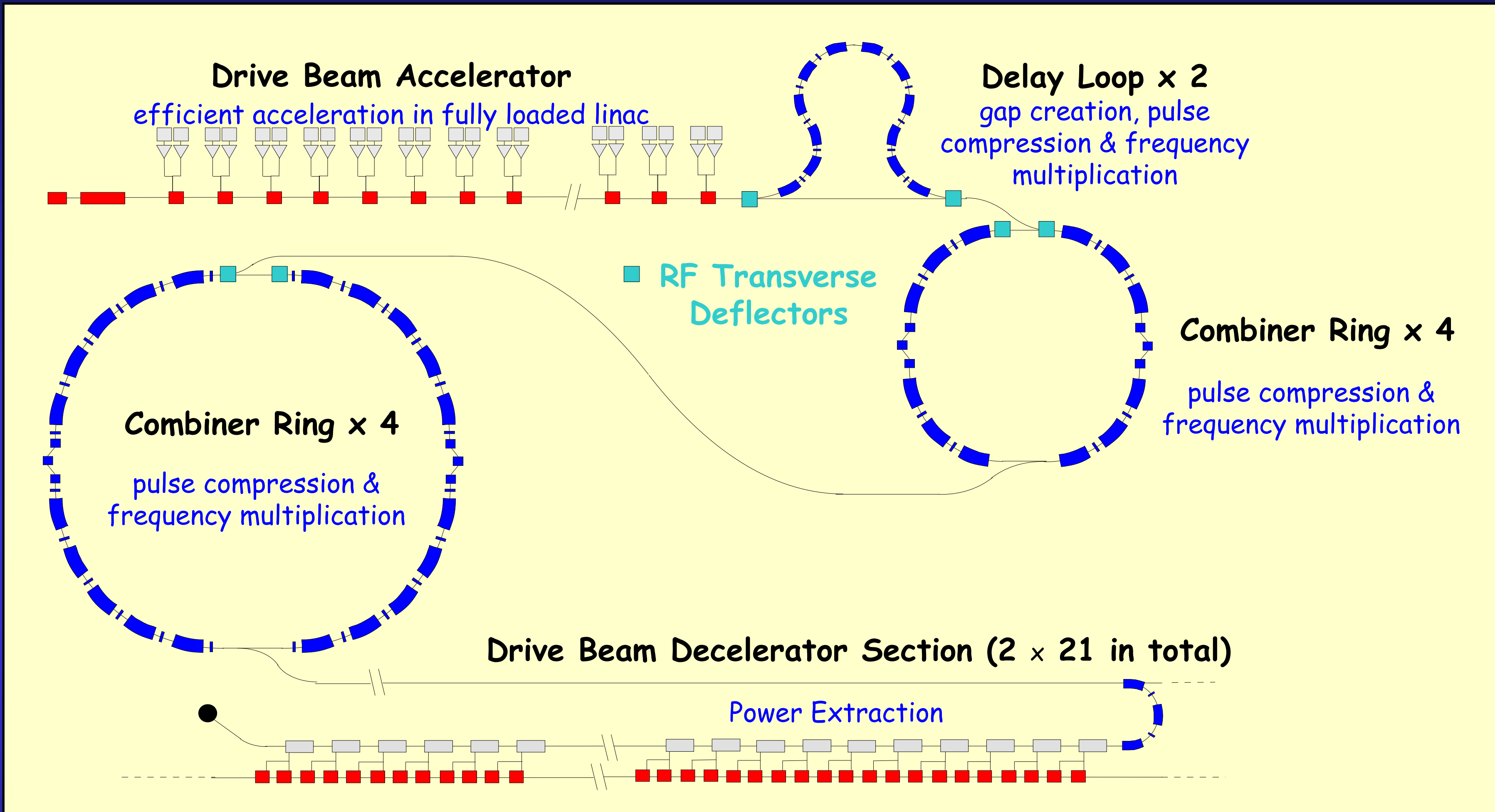
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches



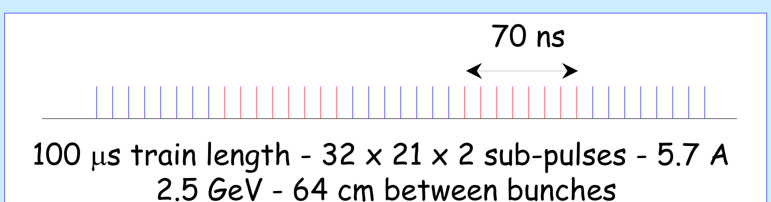
- Higher combination factors reachable in a ring



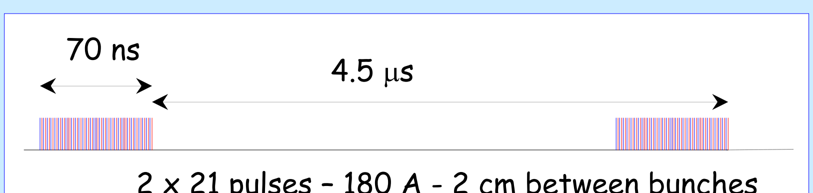
CLIC RF power source layout



Drive beam time structure - initial



Drive beam time structure - final



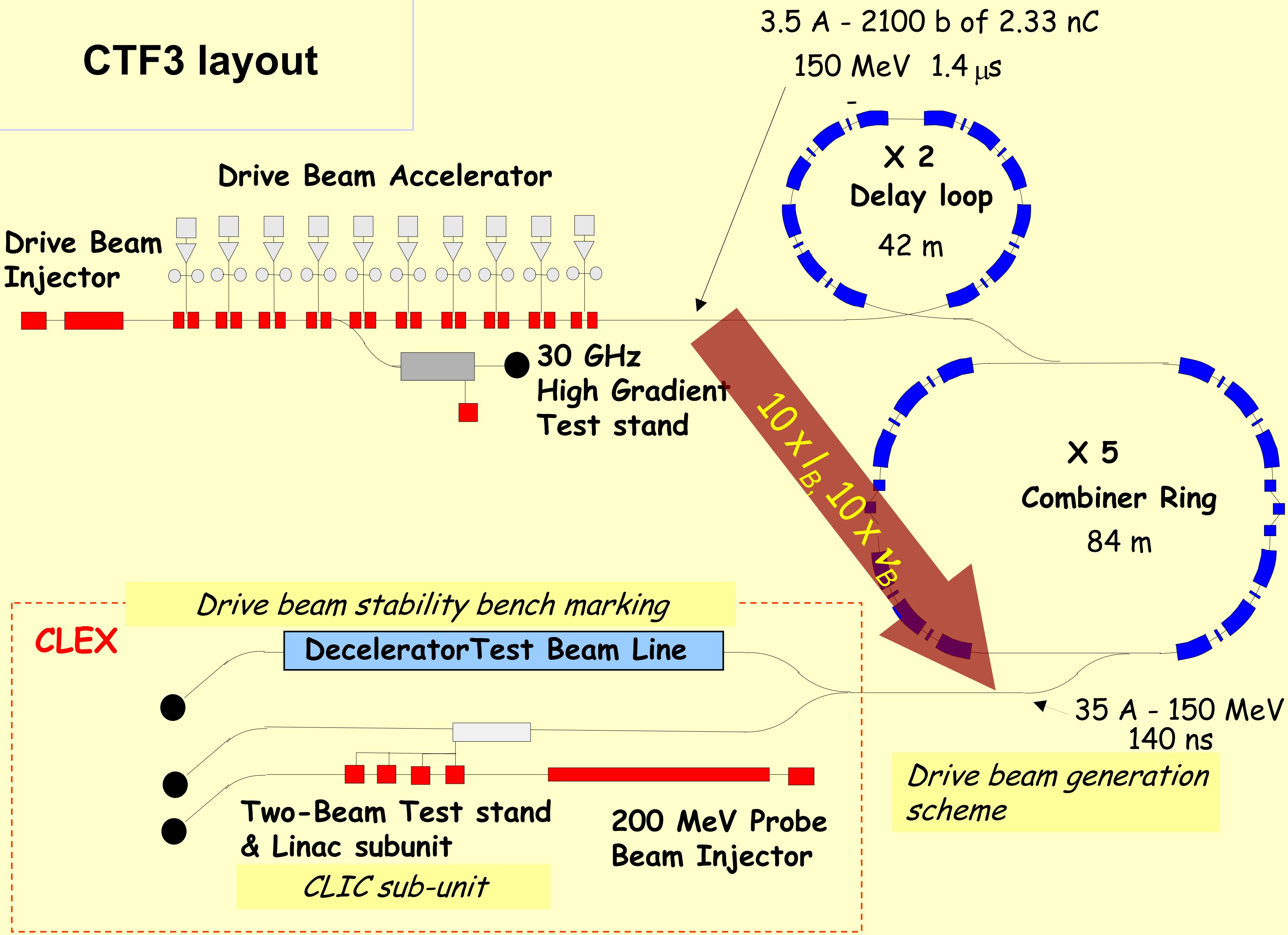
Motivation and Goals of CTF3 collaboration

- Build a small-scale version of the CLIC RF power source, in order to demonstrate:
  - full beam loading accelerator operation
  - electron beam pulse compression and frequency multiplication using RF deflectors

- Provide the 30 GHz RF power to test the CLIC accelerating structures and components at and beyond the nominal gradient and pulse length (150 MV/m for 70 ns) . ⇒ ***Walter's talk***

- ***Tool to demonstrate until 2010 CLIC feasibility issues identified by ILC-TRC in 2003***

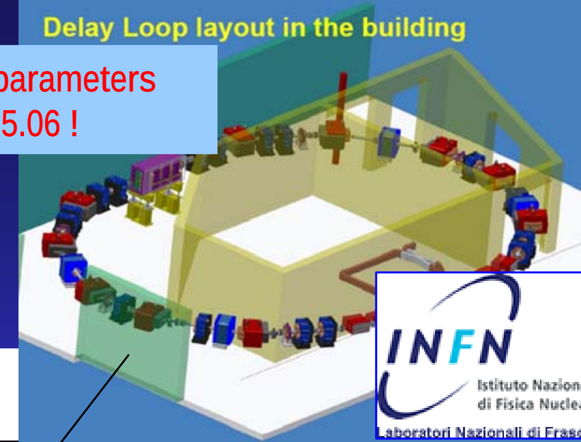
CTF3 layout

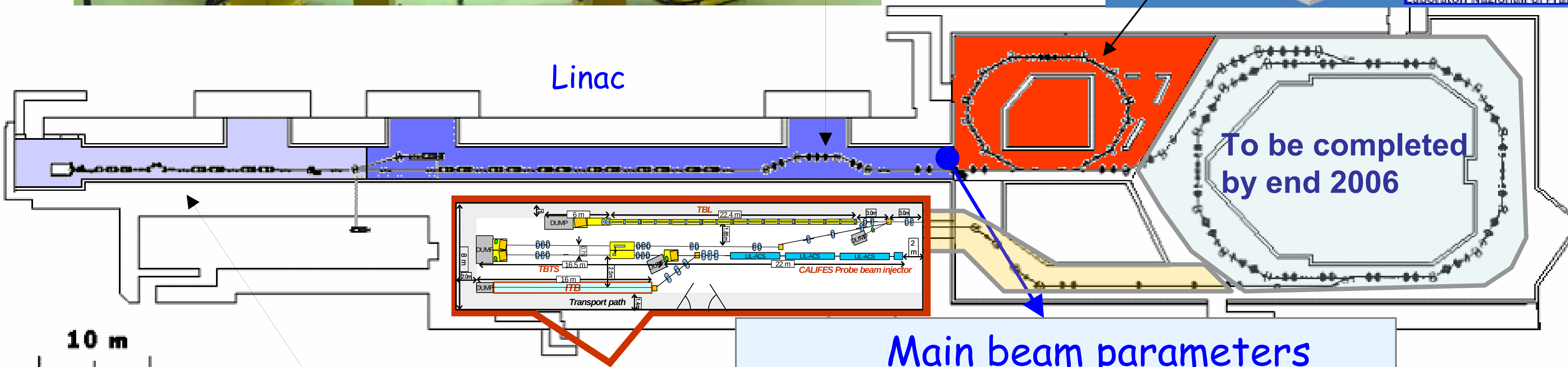


3.5 A - 2100 b of 2.33 nC
150 MeV 1.4 μs
X 2
Delay loop
42 m
Drive Beam Accelerator
Drive Beam Injector
30 GHz High Gradient Test stand
10 x I_B, 10 x ν_B
X 5
Combiner Ring
84 m
Drive beam stability bench marking
CLEX
DeceleratorTest Beam Line
35 A - 150 MeV
140 ns
Drive beam generation scheme
Two-Beam Test stand & Linac subunit
200 MeV Probe Beam Injector
CLIC sub-unit

CTF3 Status

Nominal beam parameters achieved on 11.5.06 !





INJECTOR (SLAC & LAL & CERN)

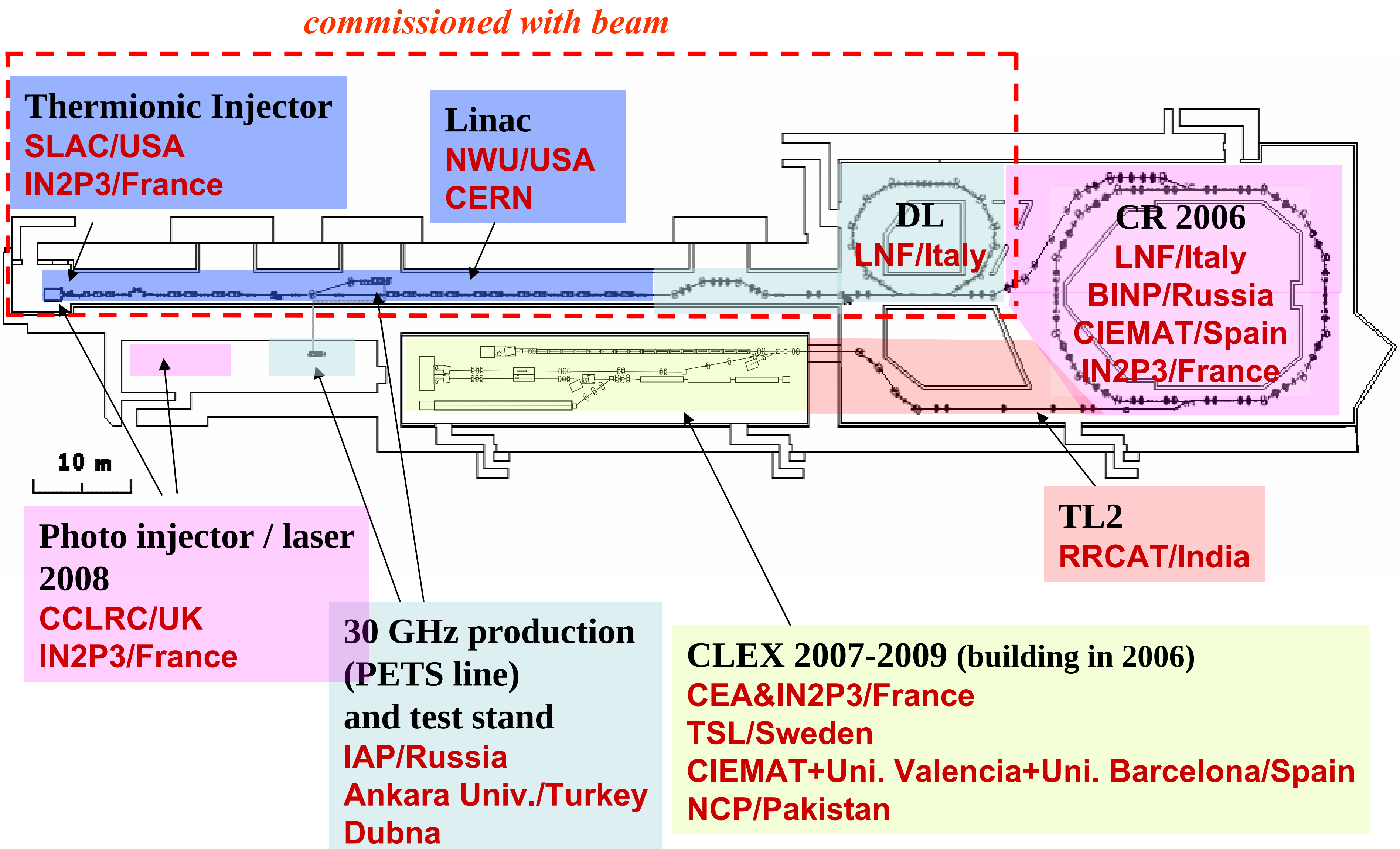
Main beam parameters

	Nominal	Achieved
I	3.5 A	5 A
T_P	1.5 ms	1.5 ms
E	150 MeV	100 MeV
ε_n	100 π mm mrad	150 π mm mrad *
σ_t	5 ps	4 ps *

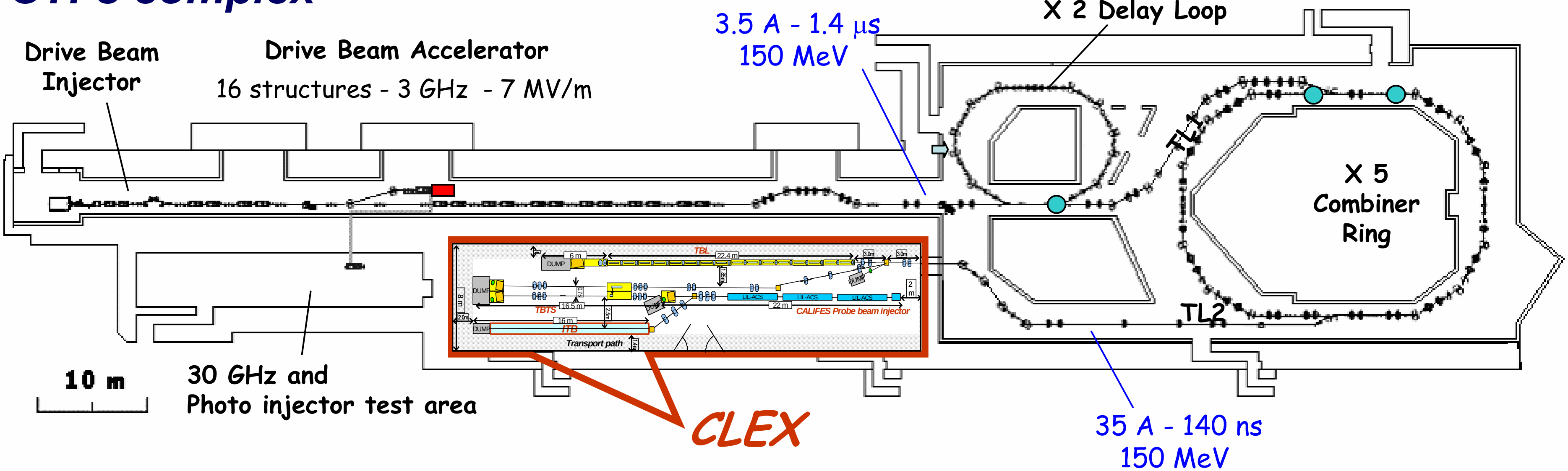
RF-to-beam efficiency ~ 94%*

* for 3.5 A, 1.5 μs beam

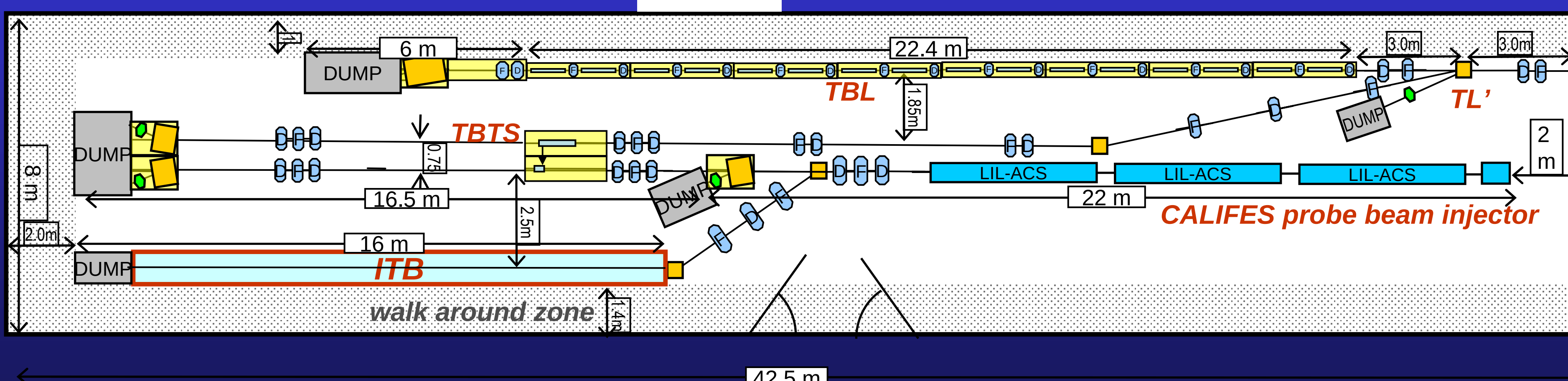
CTF3 build by a collaboration like a particle physics experiment



CTF3 complex



CLEX



CONCLUSIONS

– An electron/positron collider in LHC energy range has to be a linear collider

– Presently two schemes under consideration, ILC and CLIC

– CLIC is presently the only scheme to extend the Linear Collider energy into the Multi-TeV range

– CLIC technology is less mature than ILC technology, both still requires challenging R&D before construction can start

– Very promising results were already obtained in CTF II and in the first stages of CTF3

– Remaining key issues identified by ILC-TRC

– CLIC-related key issues addressed in CTF3 aiming for a feasibility proof by 2010

Linear Collider, some Links & Literature

R.B. Palmer, “Prospects for High Energy $e^+ e^-$ Linear Colliders,” Annu. Rev. Nucl. Part. Sci. vol. 40, p. 529, 1990

G. Loew (editor), ILC-TRC committee reports 1995, 2003. Includes descriptions of the various projects.
http://www.slac.stanford.edu/xorg/ilc-trc/2002/index.html

2006 Accelerator school on Linear Collider
http://cocoa.kek.jp/ilcschool/lecture.html

2006 CERN academic training lectures on CLIC
http://agenda.cern.ch/fullAgenda.php?ida=a057972

CLIC home page
http://clic-study.web.cern.ch/CLIC-Study

ILC home page
http://www.linearcollider.org