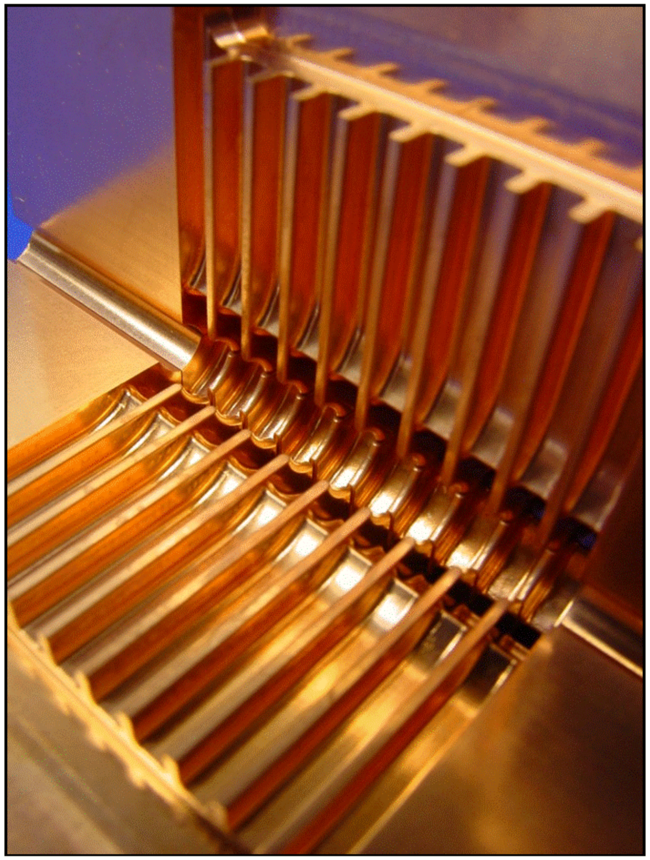
Technological challenges of CLIC

Motivations, general description, test facilities

R. Corsini



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

TECHNOLOGICAL CHALLENGES OF CLIC

12 June	Motivation, general description, test facilities	R. Corsini
13 June	RF power generation and high gradient issues	S. Döbert
14 June	Materials for accelerating structures	G. Arnau-Izquierdo
15 June	Components alignment and stability	H. Mainaud, S. Redaelli
16 June	Beam diagnostics equipment	T. Lefevre

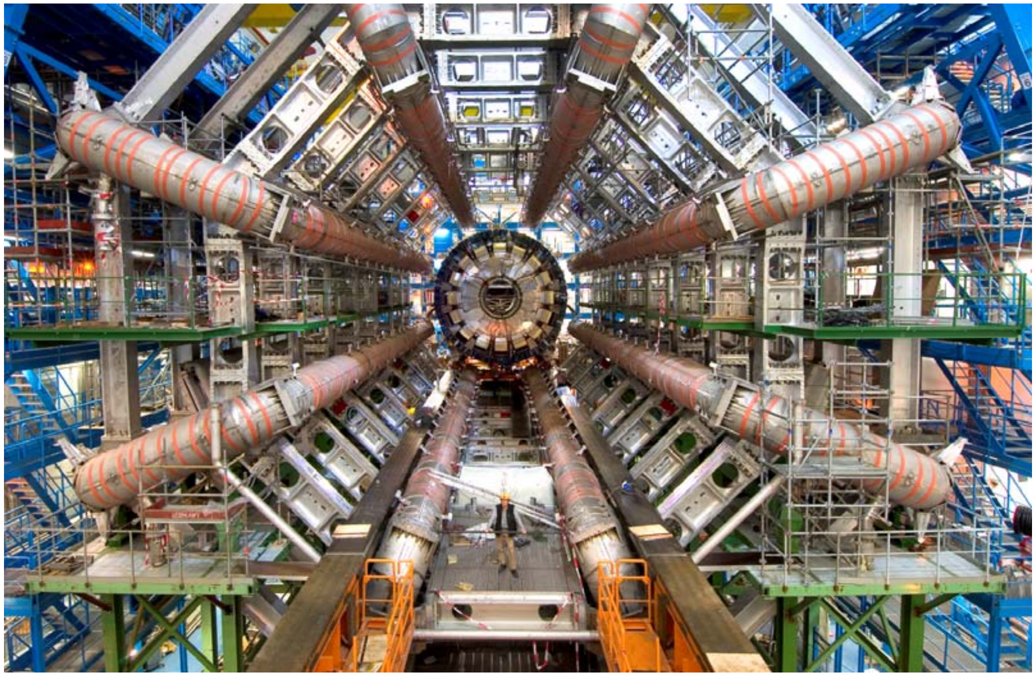
TALK OUTLINE

- Linear colliders: physics and technology
- The CLIC Multi-TeV Linear Collider scheme
- Main challenges
- What has been achieved so far
- What remains to be done

Will focus on CTF 3 – the test facility addressing the key issues

- Particle accelerators have a long, successful history as indispensable tools in the quest to understand Nature at smaller and smaller scales

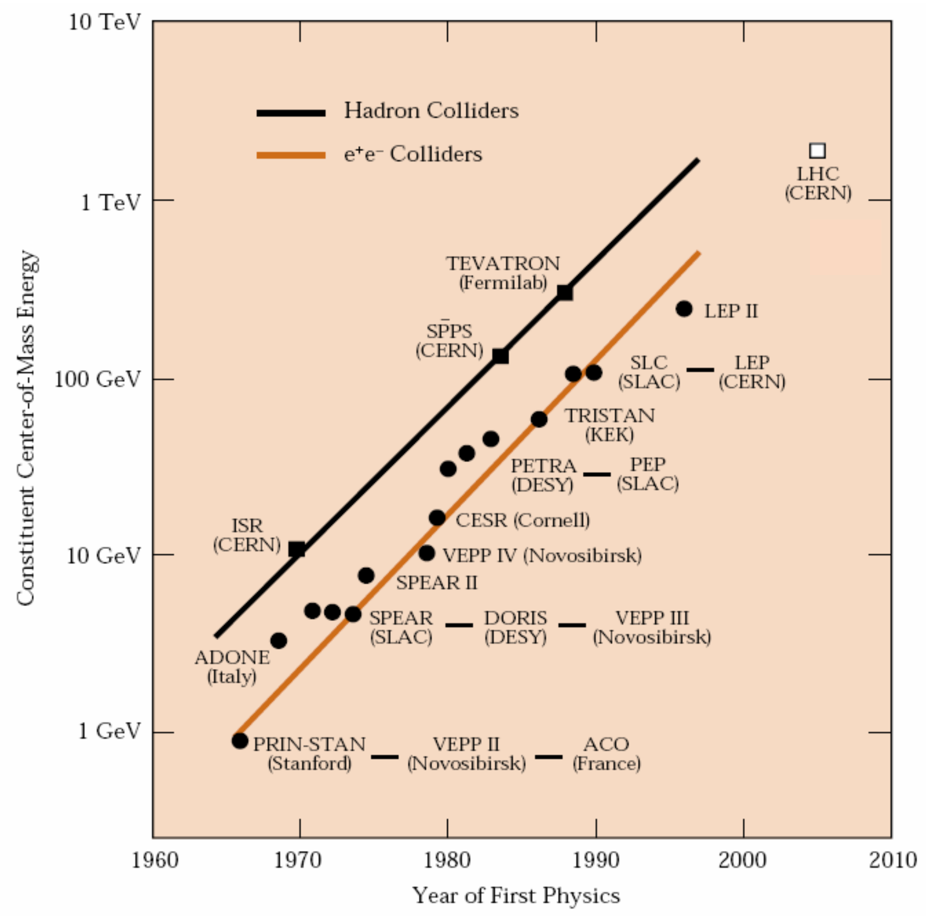
View of the ATLAS cavern with its 8 barrel toroids installed and fixed



Ernest Lawrence's first successful cyclotron, built in 1930. It was 13 cm in diameter and accelerated protons to 80 keV

- Particle accelerators have a long, successful history as indispensable tools in the quest to understand Nature at smaller and smaller scales
- Since the 70s, most new revelations in particle physics have come from colliders - machines using two accelerated beams in collision

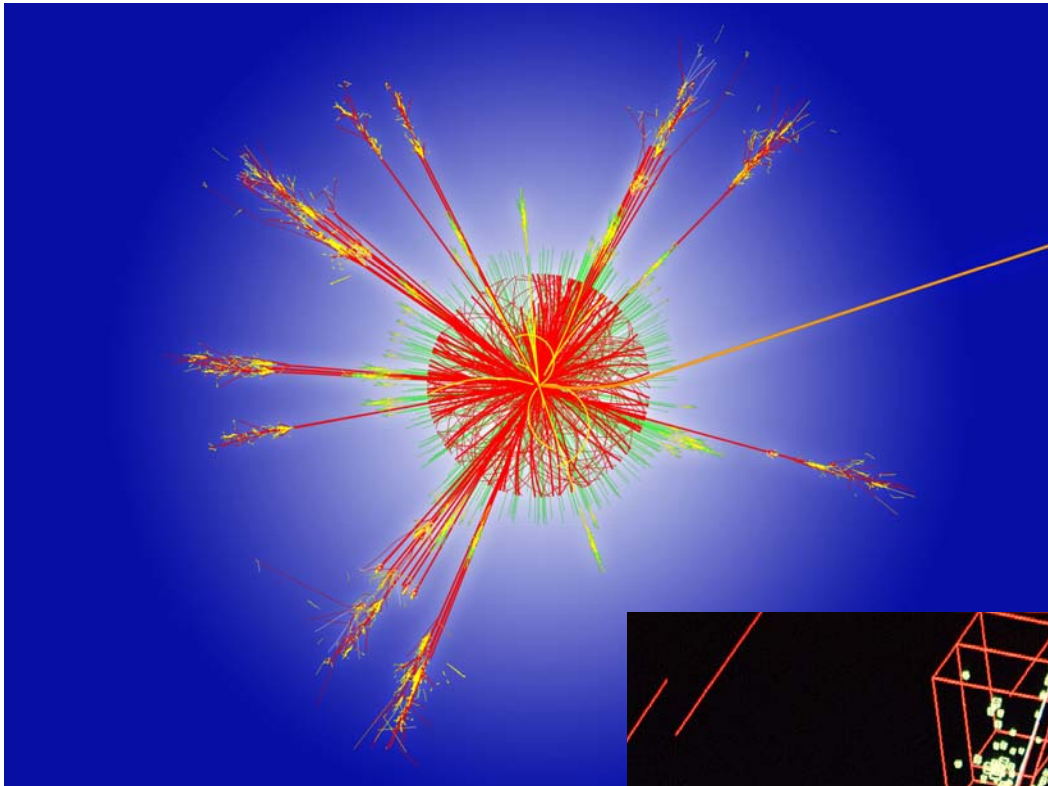
"Livingstone" plot (adapted from W. Panofsky)



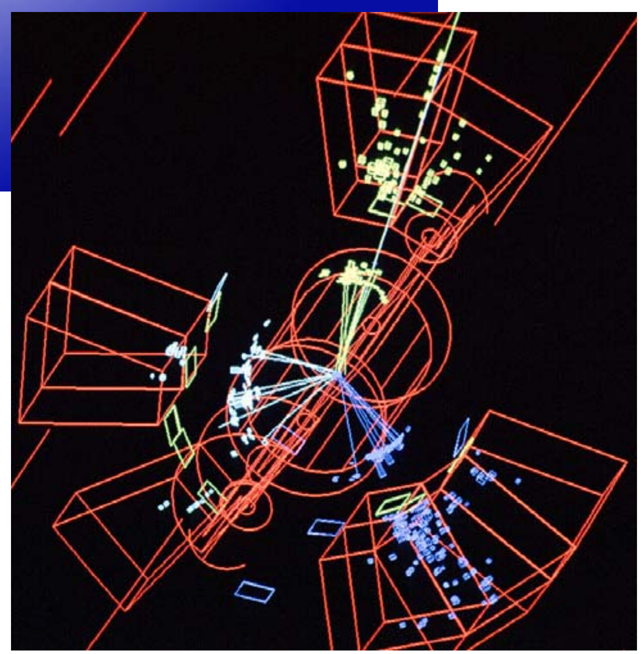
- Energy (<u>exponentially !</u>) increasing with time

  ⇒ a factor 10 increase every 8 years !

- Hadron Colliders at the energy frontier
- Lepton Colliders for precision physics
- LHC coming online from 2007
- Consensus to build a lepton linear collider with Ecm > 500 GeV to complement LHC physics



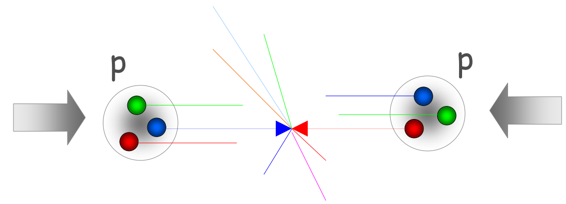
Simulated event of the collision of two protons in the ATLAS Experiment viewed along the beam pipe.



A 3-jet event probably originating from the decay of a Z0 into a quark and an antiquark together with a gluon as seen in the L3 detector

Hadron Colliders (p, ions):

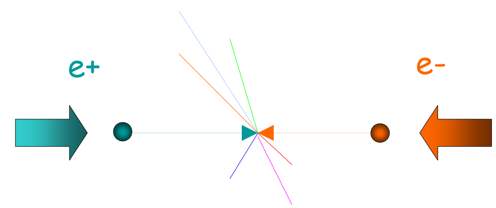
- Protons are composite objects



- Only part of proton energy available
- Can only use pt conservation
- Huge QCD background

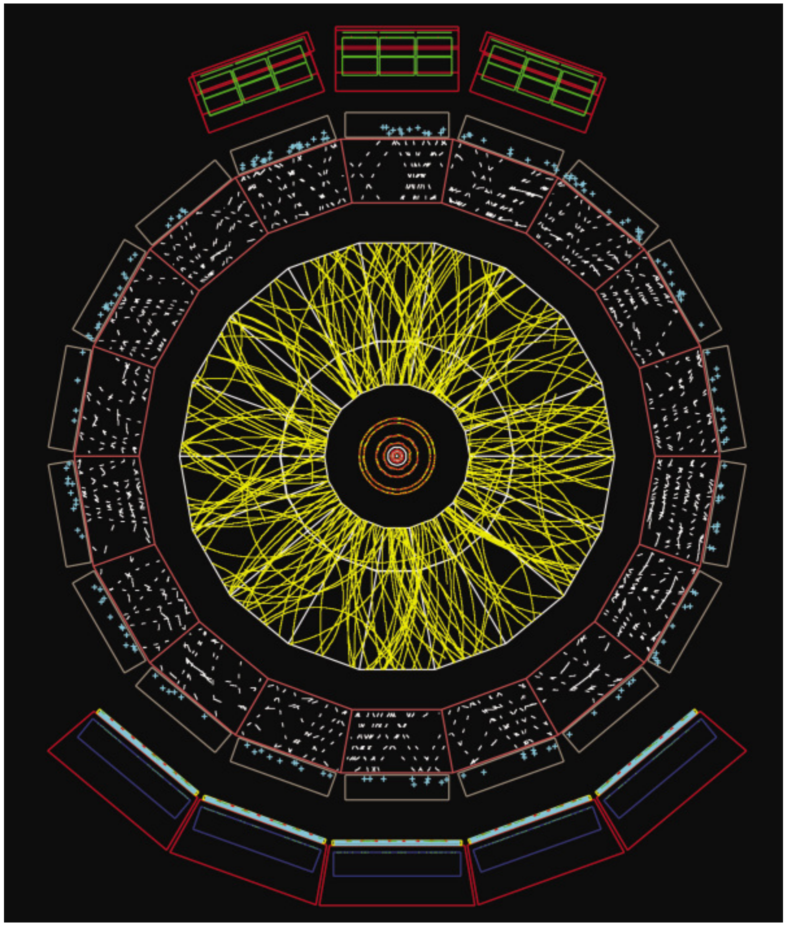
Lepton Colliders:

- Leptons are elementary particles



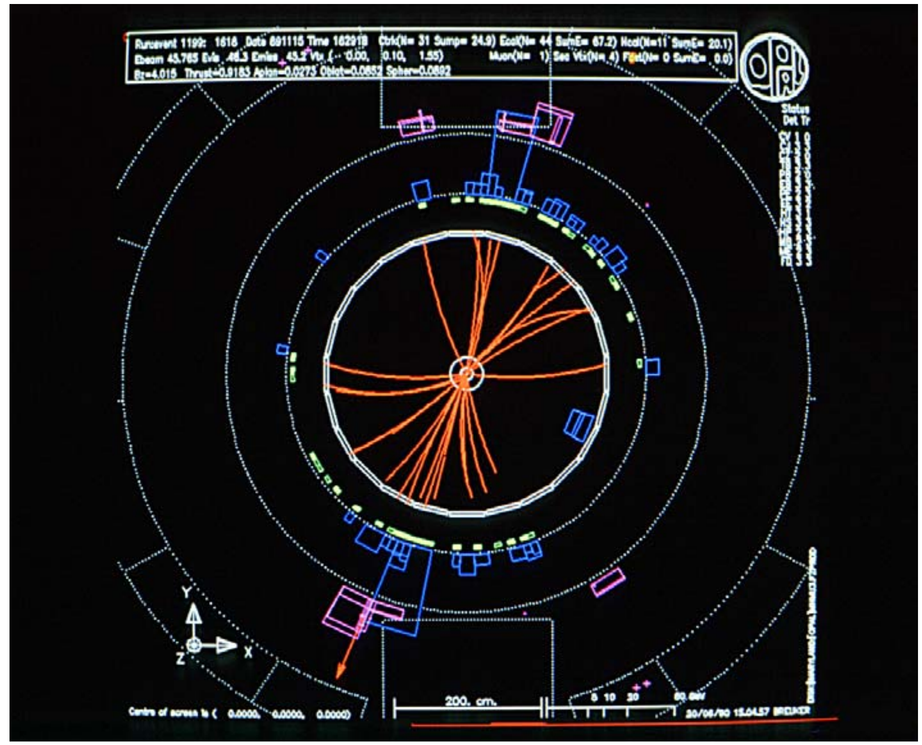
- Well defined initial state
- Momentum conservation eases decay product analysis
- Beam polarization

Hadron collision



Simulation of a lead-lead
collision in the ALICE detector

Lepton collision

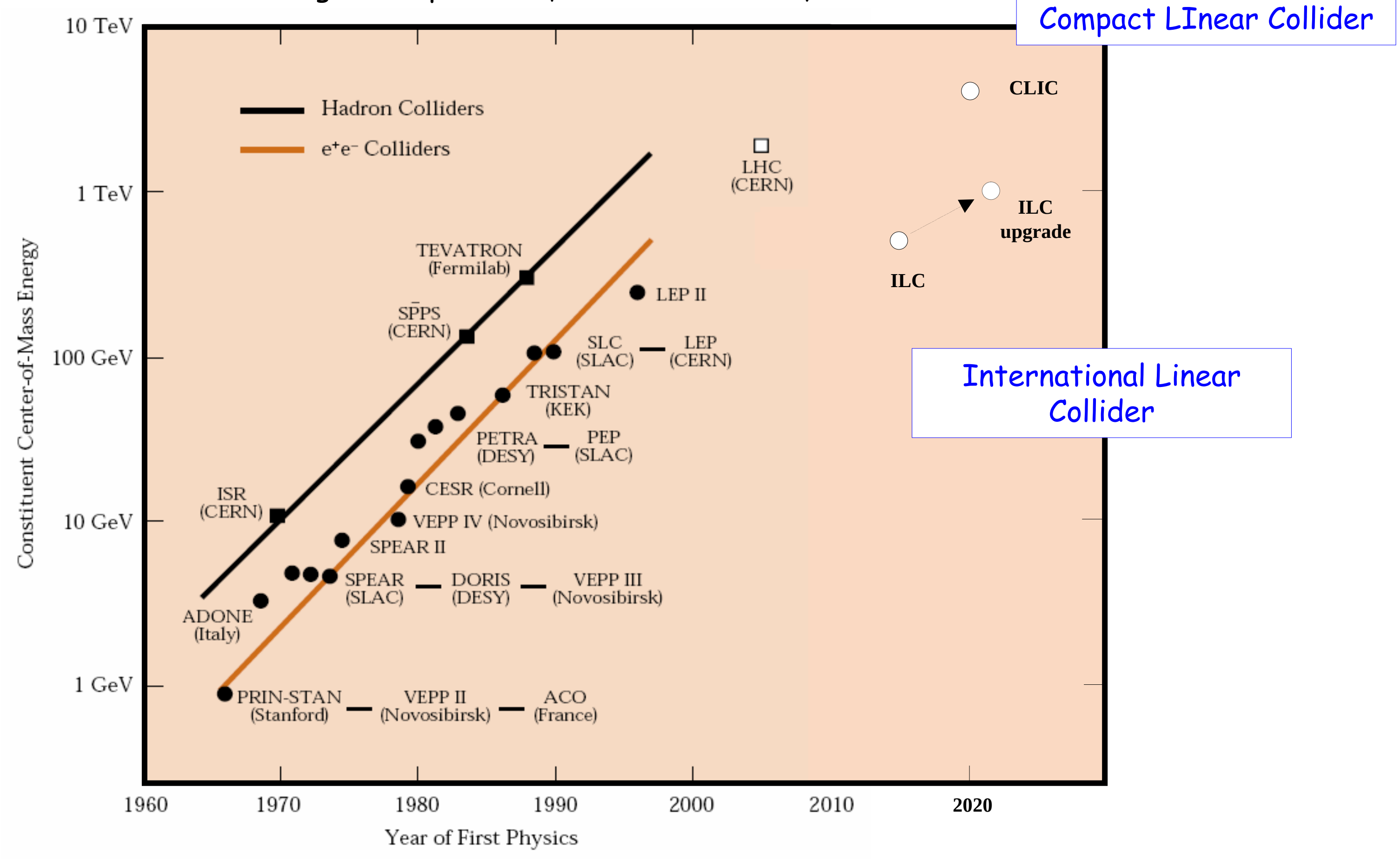


Display from OPAL showing the decay of a Z into two
jets of particles, originating from a quark-antiquark pair

Some (recent) history

- 2001: ICFA recommendation of a world-wide collaboration to construct a high luminosity e+/e-Linear Collider with an energy range up to at least 400 GeV/c
- 2003: ILC-Technical Review Committee to assess the technical status of the various designs of Linear Colliders
- 2004: International Technology Recommendation Panel down-selecting the super-conducting technology for an International Linear Collider (ILC) Linear Collider in the TeV energy range
- 2004: CERN council support for R&D addressing the feasibility of the CLIC technology to possibly extend Linear Colliders into the Multi-TeV energy range.

"Livingstone" plot (adapted from W. Panofsky)



Physics motivations

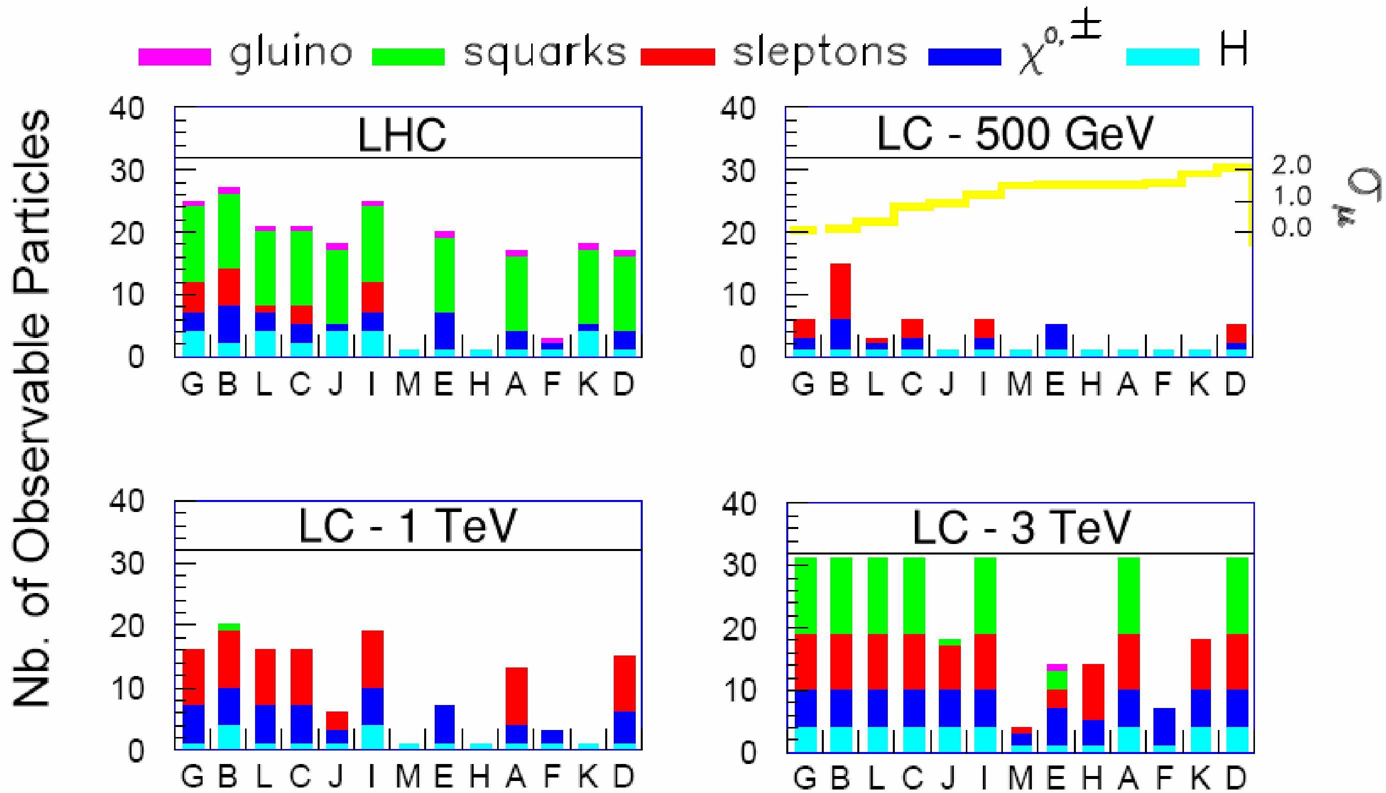
See for instance "Physics at the CLIC Multi-TeV Linear Collider: report of the CLIC Physics Working Group", CERN report 2004-5

- Higgs physics
  - Tevatron/LHC should discover Higgs (or something else)
  - LC explore its properties in detail
- Supersymmetry
  - LC will complement the LHC particle spectrum
- New physics
  - Extra spatial dimensions
  - New strong interactions
  - . . .

$\Rightarrow$ a lot of new territory to discover beyond the standard model

Example: supersymmetry

Different sparticle species observable in a number of benchmark supersymmetric scenarios at different colliders.



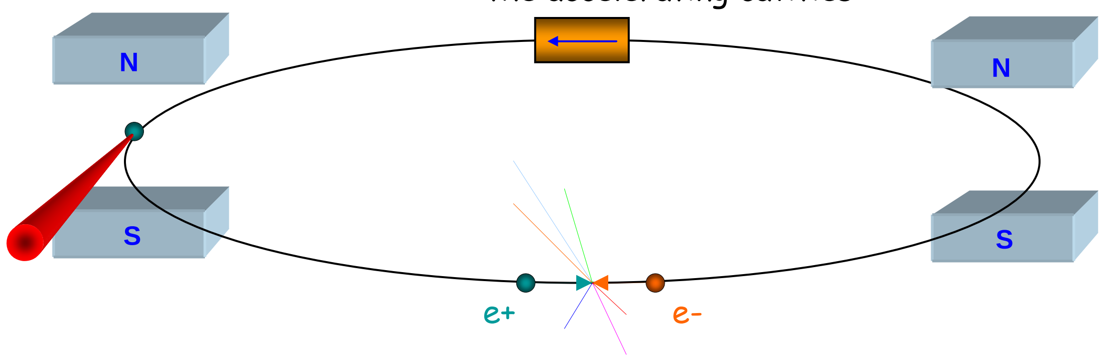
adapted from "Physics at the CLIC Multi-TeV Linear Collider: report of the CLIC Physics Working Group", CERN report 2004-5

Lower-energy linear e+e– colliders largely complement the LHC by discovering or measuring better the lighter electroweakly-interacting sparticles.

Detailed measurements of the squarks would, in many cases, be possible only at CLIC.

Why a linear collider ?

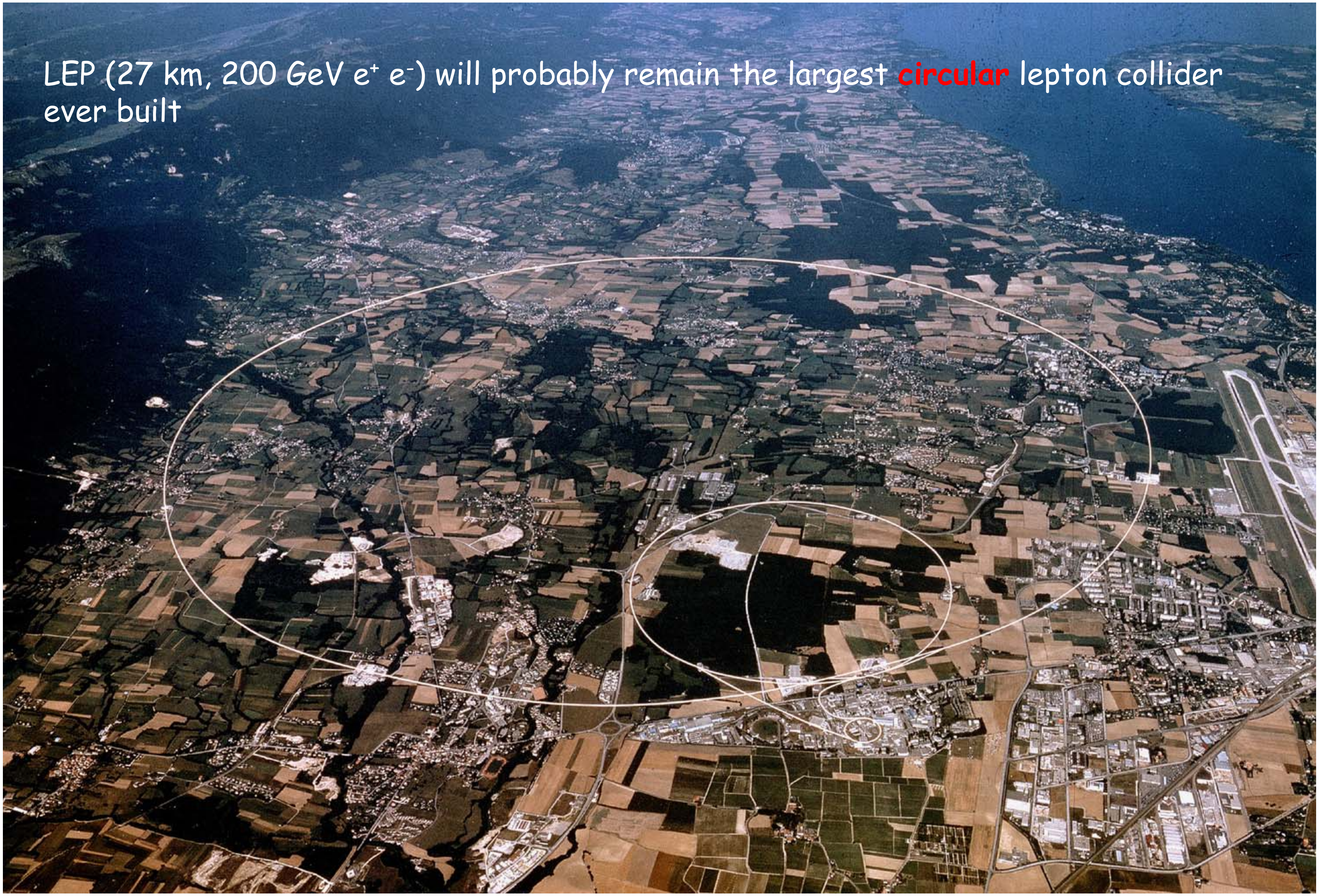
Circular colliders use magnets to bend particle trajectories
Their advantage is that they re-use many times



However, charged particles emit synchrotron radiation in a magnetic field

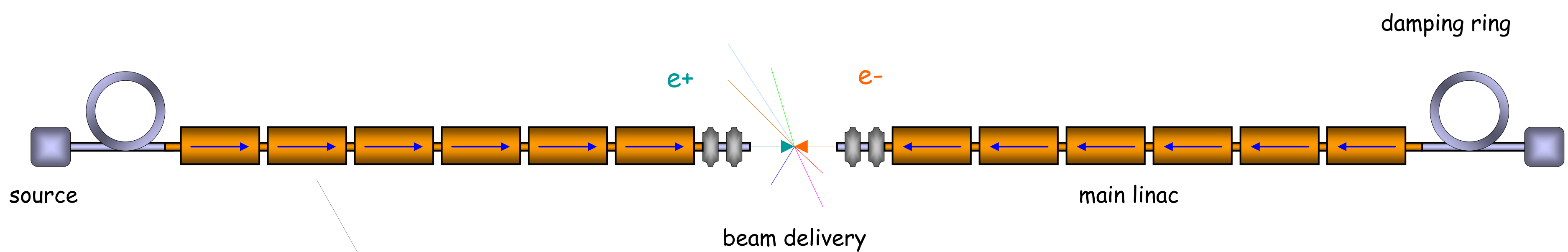
$$P = \frac{2}{3} \frac{r_e}{\left(m_o c^2\right)^3} \frac{E^4}{\rho^2} \quad \Rightarrow \quad \Delta E_{turn} = \frac{4}{3} \pi \frac{r_e}{\left(m_o c^2\right)^3} \frac{E^4}{\rho}$$

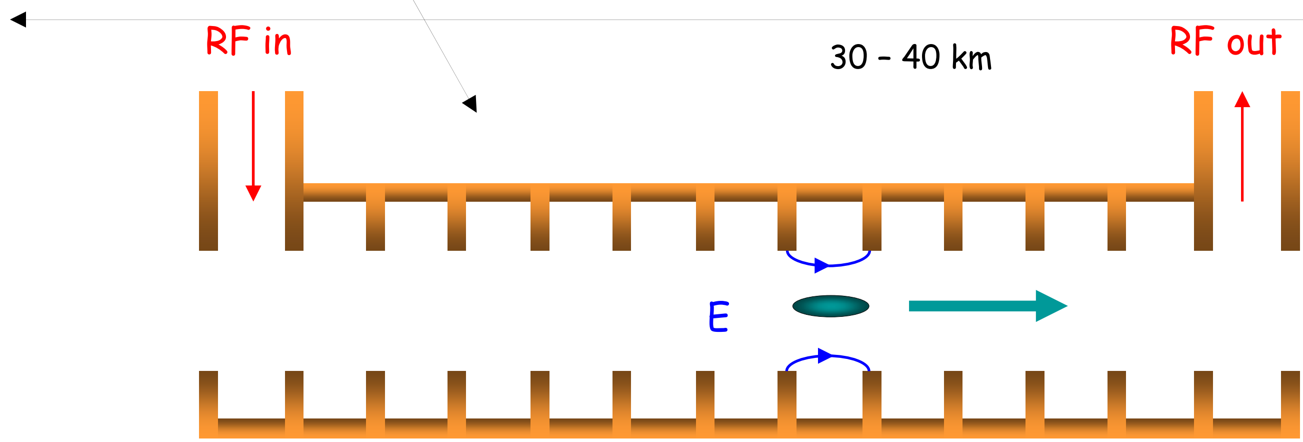
Much less important for heavy particles, like protons


LEP (27 km, 200 GeV $e^+ e^-$) will probably remain the largest **circular** lepton collider ever built

A linear collider uses the accelerating cavities only once:

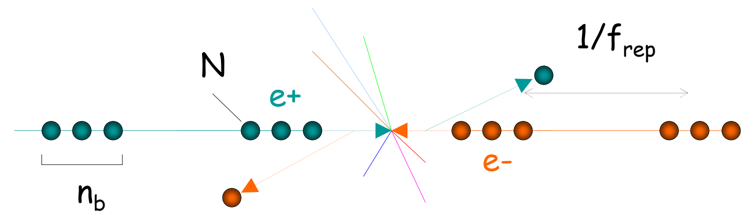
- Lots of them !
- Need a high accelerating gradient to reach the wanted energy in a "reasonable" length (total cost, cultural limit)





A linear collider uses the beam pulses only once:

- Beams are dumped after collision
- Need to accelerate lots of particle
- Need very small beam sizes



Number of interactions ⇒ Luminosity

(interaction rate per second per unit cross section)

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^* \sigma_y^*} \times H_D$$

Scaling in a linear collider:

$$L \propto \frac{\eta_{beam}^{AC} P_{AC}}{\varepsilon_y^{1/2}} \frac{\delta_{BS}^{1/2}}{E_{cm}}$$

wall-plug to beam efficiency

wall-plug power

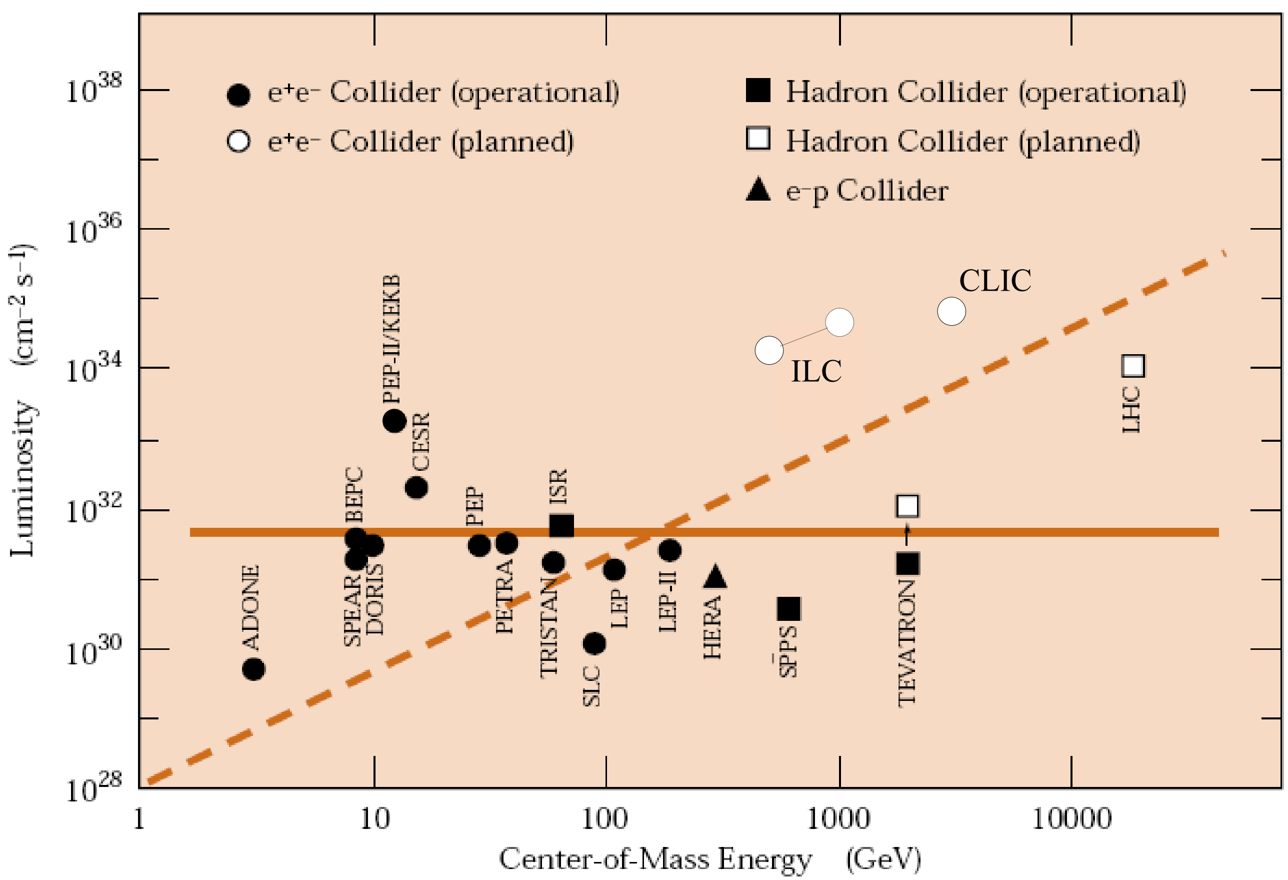
energy loss by beamstrahlung

vertical emittance (phase-space area of the beam)

center-of-mass energy

Particle physicists ask to increase Luminosity with energy…

Luminosity plot (adapted from W. Panofsky)



What matters in a linear collider ?

Energy reach

$$E_{cm} = 2\,F_{fill}\,L_{linac}\,G_{RF}$$

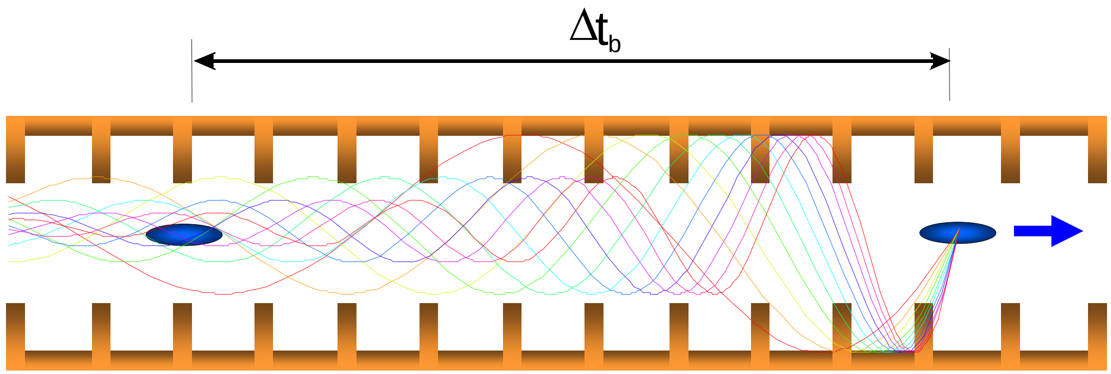
- High gradient

Luminosity

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D \propto \frac{\eta_{beam}^{AC}\,P_{AC}}{\varepsilon_y^{1/2}}\,\frac{\delta_{BS}^{1/2}}{E_{cm}}$$

- Acceleration efficiency
- Generation of small emittance — damping rings
- Conservation of small emittance — wake-fields, alignment, stability
- Extremely small beam spot at Interaction Point — beam delivery system, stability

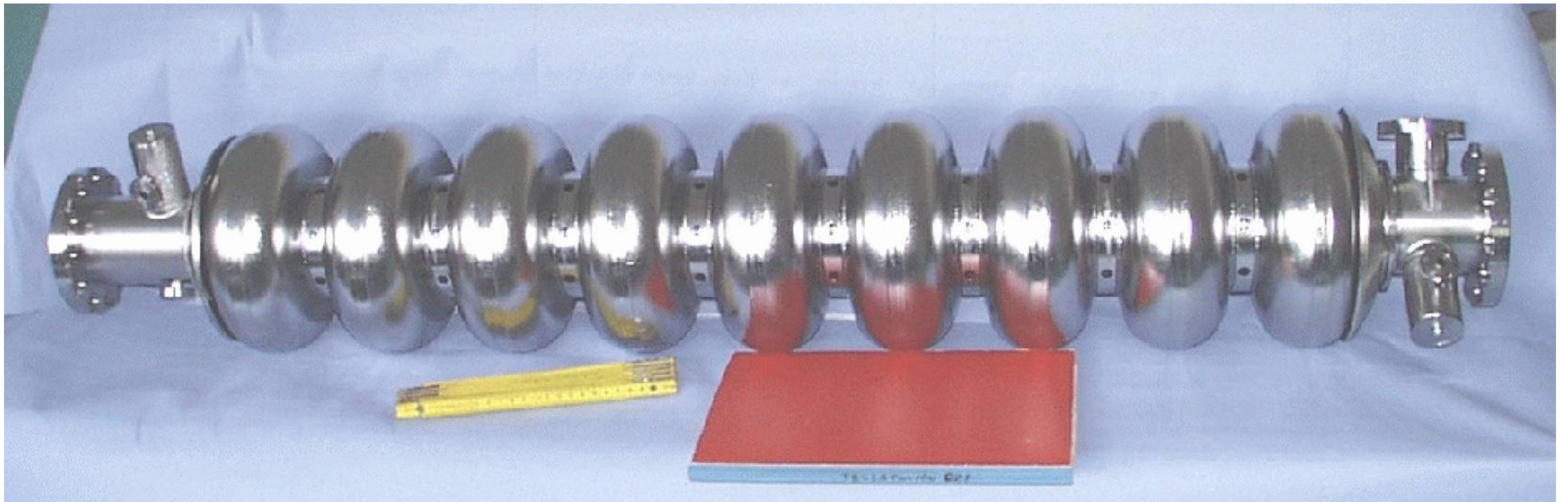
Wake-fields



- Bunches traveling in accelerating structures induce fields which perturbs later bunches
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Later bunches are kicked transversely

beam break-up ⇒ Emittance growth !!!

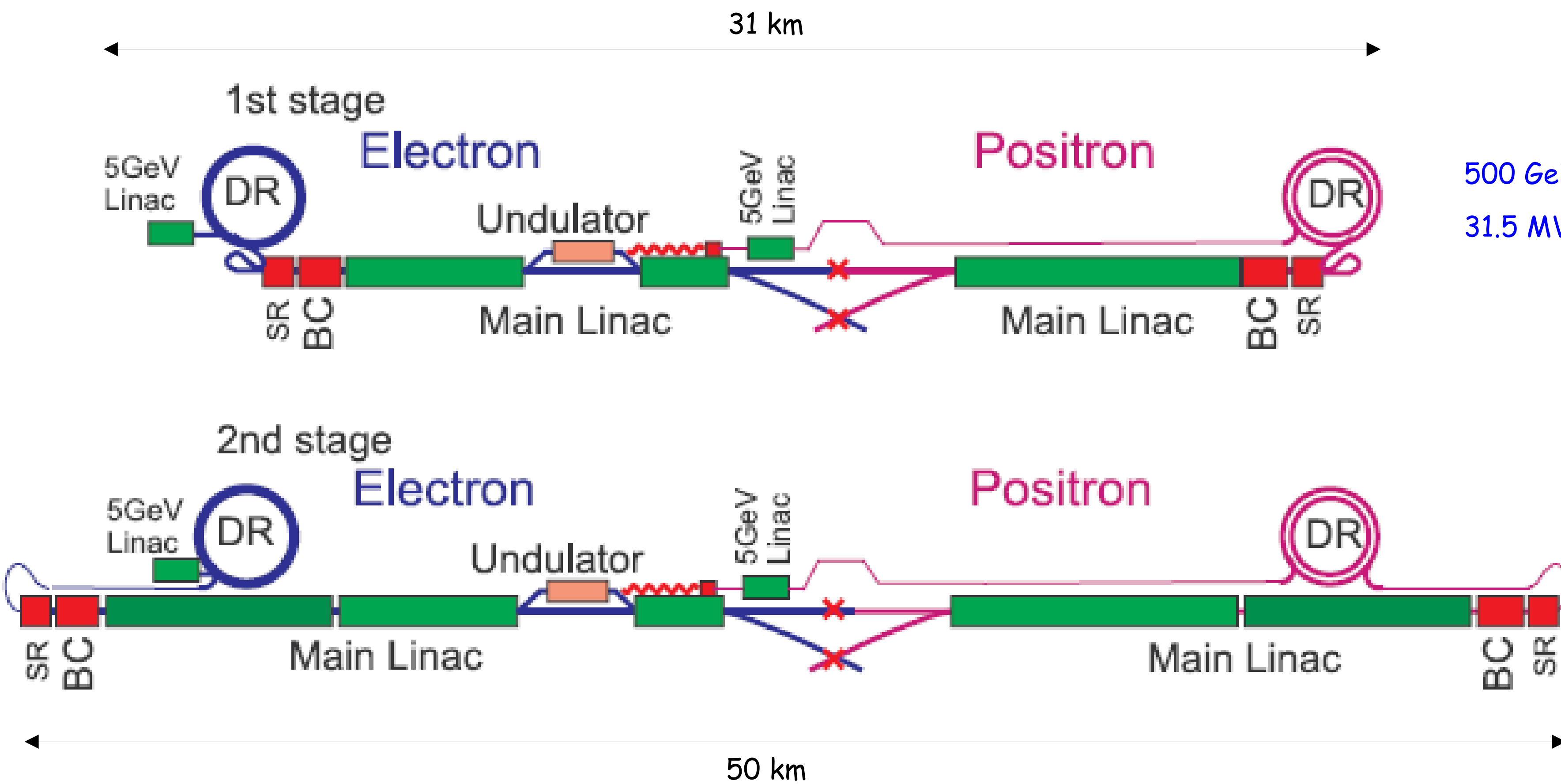
In 2004, the International Technology Recommendation Panel (ITRP), set up by ICFA, compared normal and super-conducting technologies for a 500 GeV Linear collider (upgradable to 1 TeV) and recommended to use the "cold" option.


9-cell 1.3GHz Niobium Cavity – TESLA technology

- Superconducting cavities ⇒ very high efficiency
- Low frequency ⇒ large apertures ⇒ low wake-fields
- Long bunch trains ⇒ intra-pulse feed-back to improve stability

Drawback ⇒ Highest gradient for superconducting technology limited to about 40 MV/m

ILC Baseline Configuration for 500 GeV machine with expandability to 1 TeV



500 GeV

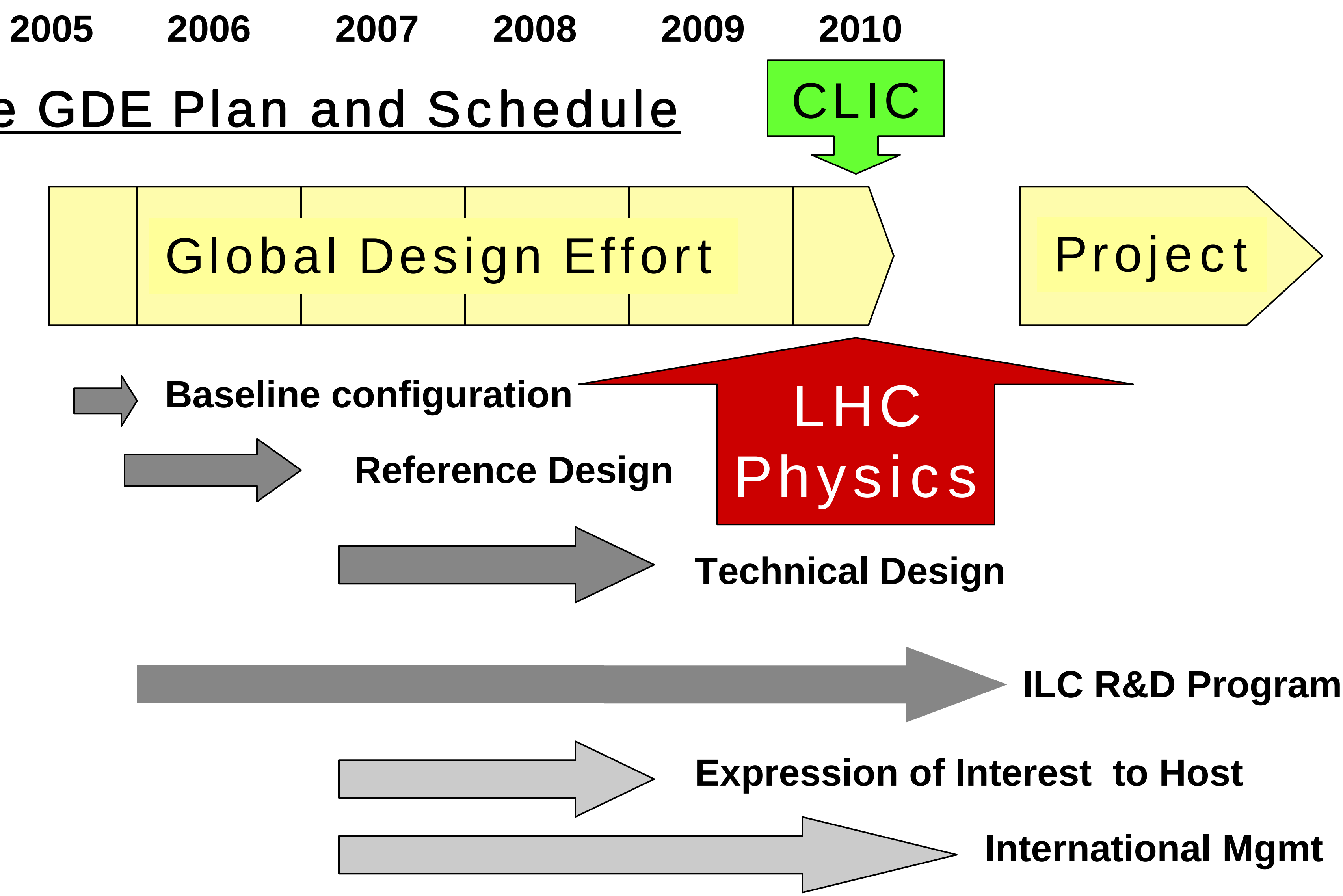
31.5 MV/m

1 TeV

36.5 MV/m

From B. Barish, ILC Global Design Effort director

The GDE Plan and Schedule



CLIC aim: Develop technology for e^-/e^+ collider with E_{CM}= 1 -5 TeV

Present mandate: Demonstrate all key feasibility issues by 2010

Physics motivation: *"Physics at the CLIC Multi-TeV Linear Collider: report of the CLIC Physics Working Group"*, CERN report 2004-5

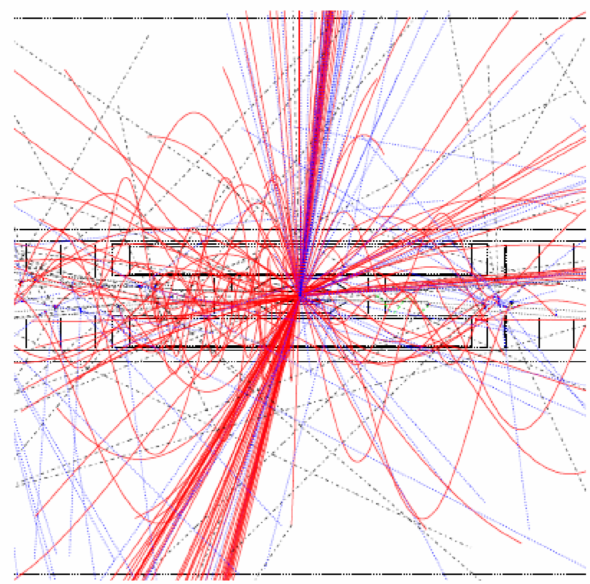
The LHC will provide unique physics at the energy frontier in the TeV energy range, for many years after its commissioning.

However, scenarios for physics in the TeV range generally have aspects that the LHC is unable to test. Electron–positron linear colliders can complement the LHC by producing directly new weakly-interacting particles and making possible precision studies.

These are the core motivations for a linear collider with centre-of-mass energy in the TeV range.

However, a complete understanding of physics in the TeV range may require a multi-TeV linear e^+e^- collider, for which the only available candidate is CLIC.

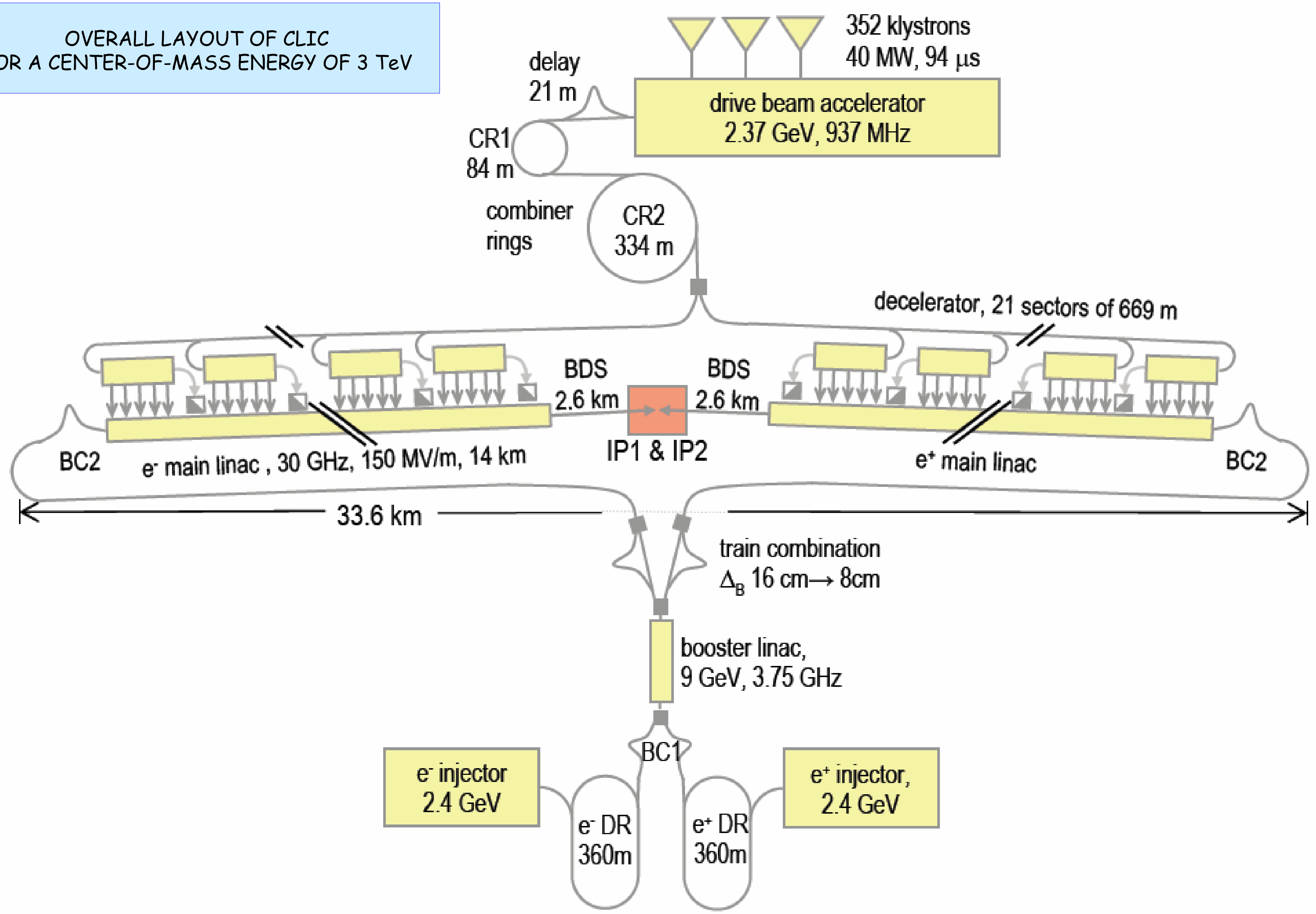
Charged-Higgs analysis. Display of a $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$ event at $\sqrt{s}$ = 3 TeV. The accelerator-induced backgrounds are not overlaid.



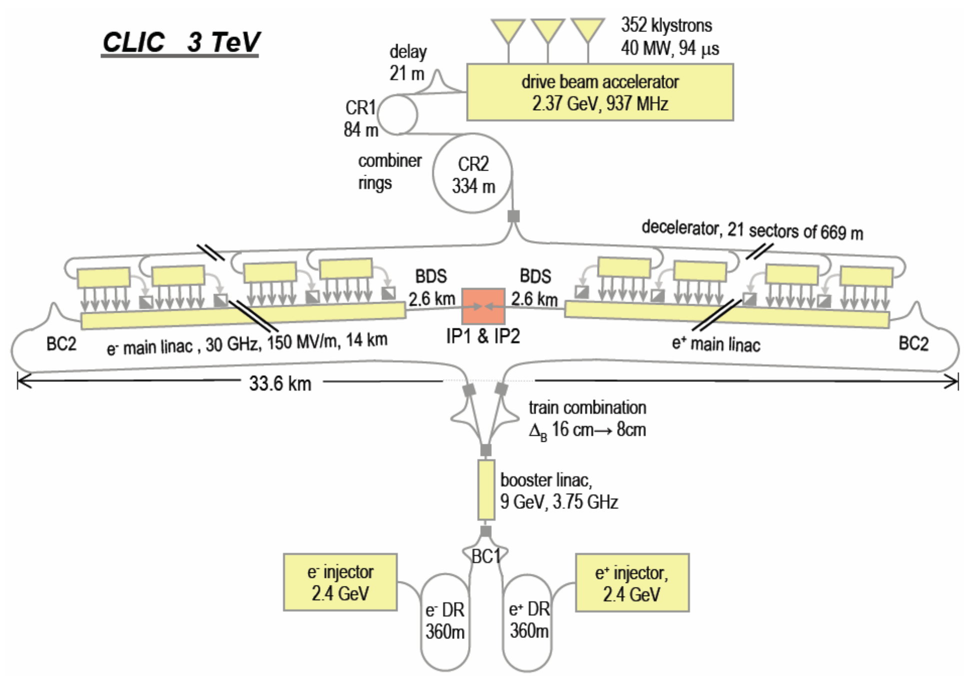
WORLD WIDE CLIC COLLABORATION

Ankara University (Turkey):	CTF3 beam studies & operation
Berlin Tech. University (Germany):	Structure simulations GdfidL
BINP (Russia):	CTF3 magnets development & construction
CERN:	Study coordination, structures devel., CTF3 construction/commissioning
CIEMAT (Spain):	CTF3 septa and kickers, correctors, power extraction structures
DAPNIA/Saclay (France):	CTF3 probe beam injector
Finnish Industry (Finland):	Sponsorship of mechanical engineer
INFN / LNF (Italy):	CTF3 delay loop, transfer lines & RF deflectors, ring vacuum chambers
JINR & IAP (Russia):	Surface heating tests of 30 GHz structures
KEK (Japan):	Low emittance beams in ATF
LAL/Orsay (France):	Electron guns and pre-buncher cavities for CTF3
LAPP/ESIA (France):	Stabilization studies, CTF3 beam position monitors
LLBL/LBL (USA):	Laser-wire studies
North-West. Univ. Illinois (USA):	Beam loss studies & CTF3 equipment
RAL (England):	Lasers for CTF3 and CLIC photo-injectors
SLAC (USA):	High Gradient Structure testing, structure design, CTF3 injector design
Uppsala University (Sweden):	Beam monitoring systems for CTF3

OVERALL LAYOUT OF CLIC
FOR A CENTER-OF-MASS ENERGY OF 3 TeV



Basic features of CLIC



OVERALL LAYOUT OF CLIC
FOR A CENTER-OF-MASS ENERGY OF 3 TeV

- High acceleration gradient (150 MV/m)

- "Compact" collider - overall length < 40 km
- Normal conducting accelerating structures
- High RF frequency (30 GHz)

- Two-Beam Acceleration Scheme

- Capable to reach high frequency
- Cost-effective & efficient (~ 10% overall)
- Simple tunnel, no active elements

- Central injector complex

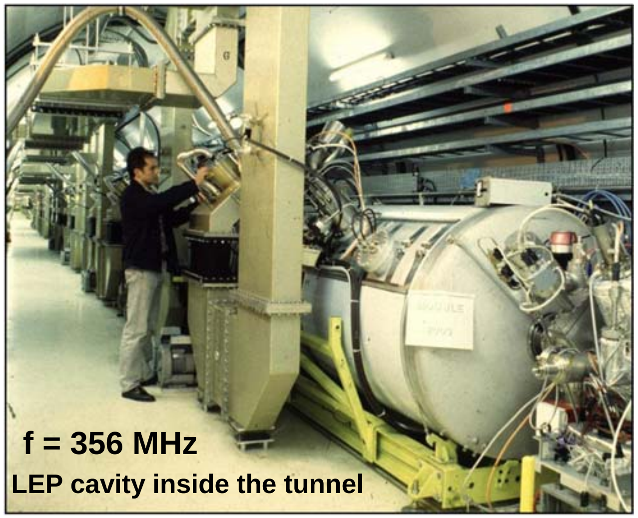
- "Modular" design, can be built in stages

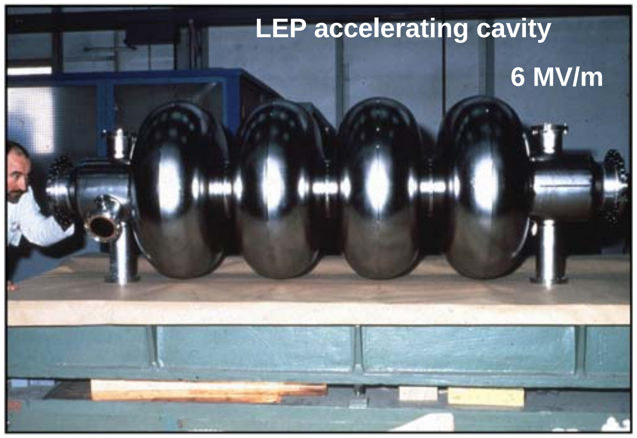
Why high frequency ?

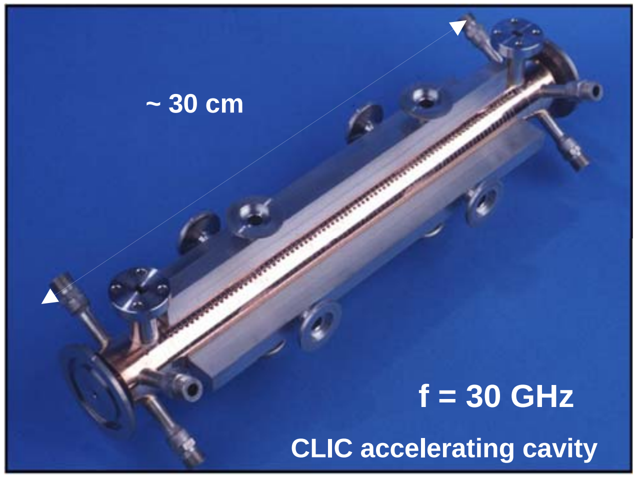
Cavity dimensions scale inversely with frequency

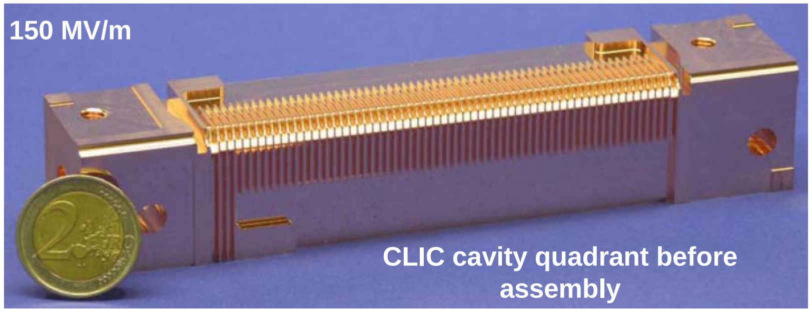
$\Rightarrow$ Volume $\propto 1 / f^3$

Need much less RF pulse energy for a given accelerating gradient







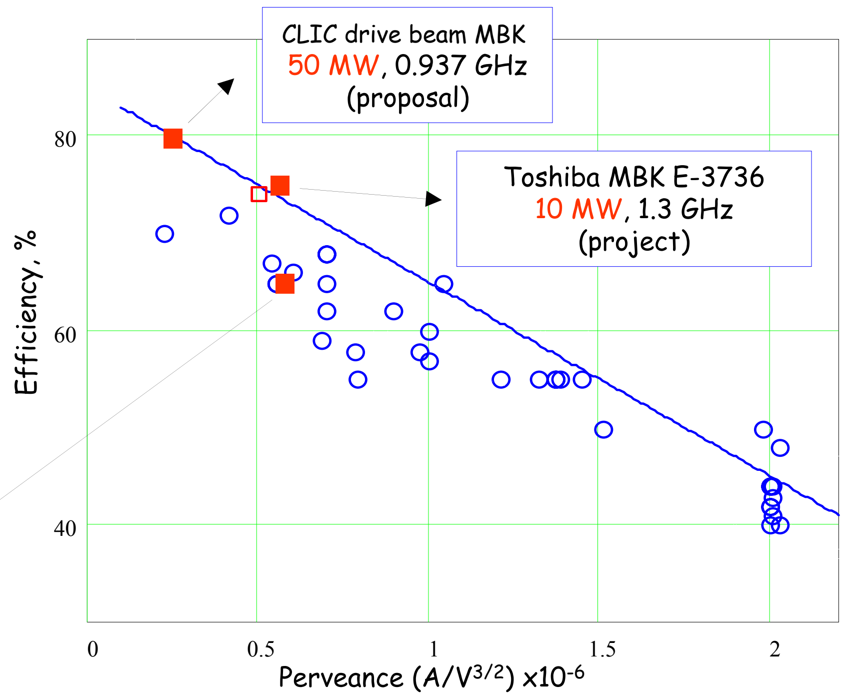


Why two-beam acceleration ?

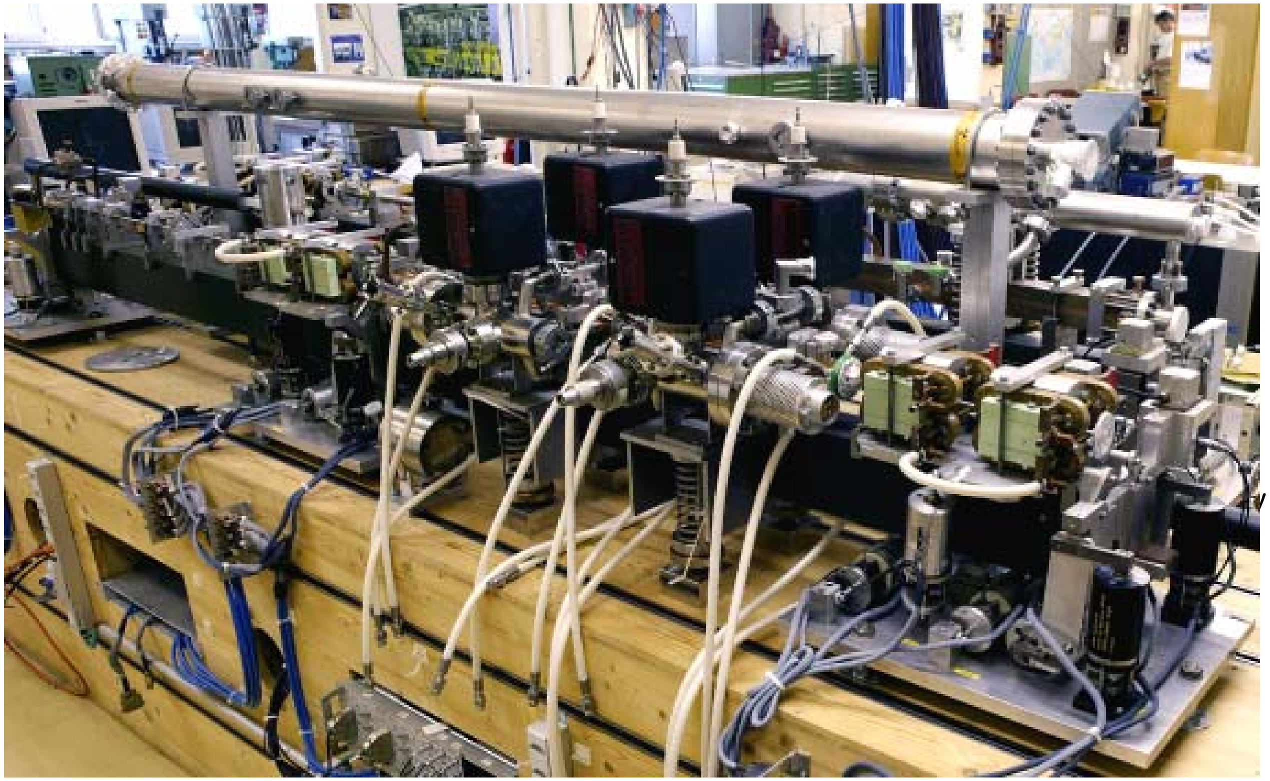
- Standard RF power sources (klystrons) are limited to low frequencies, especially for high-power and large efficiencies
- A 30 GHz klystron would never provide the power and efficiencies needed for CLIC

$\Rightarrow$ Need something different

Thales MBK TH1801
10 MW, 1.3 GHz
(measured)



State-of-the-art klystron efficiencies vs. perveance

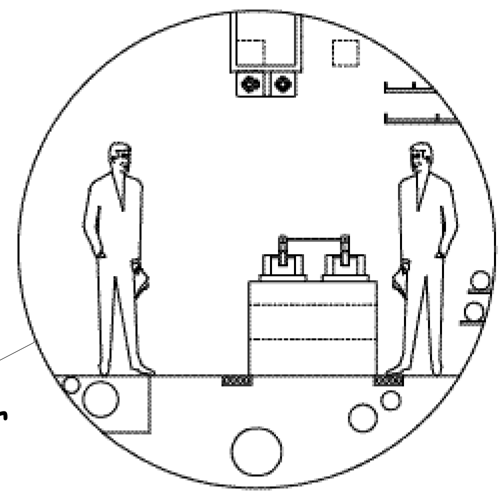


CLIC MODULE

(12000 modules at 3 TeV)

CLIC Two-Beam scheme

CLIC TUNNEL CROSS-SECTION



3.8 m diameter

CLIC Main parameters at 3 TeV

Center of mass energy	E_{cm}	3000	GeV
Main Linac RF Frequency	f_{RF}	30	GHz
Luminosity	L	6.5	10^{34} cm^{-2} s^{-1}
Luminosity (in 1% of energy)	$L_{99\%}$	3.3	10^{34} cm^{-2} s^{-1}
Linac repetition rate	f_{rep}	150	Hz
No. of particles / bunch	N_b	2.56	10^9
No. of bunches / pulse	k_b	220	
Bunch separation	Δt_b	0.267 (8 periods)	ns
Bunch train length	τ_{train}	58.4	ns
Beam power / beam	P_b	20.4	MW
Unloaded / loaded gradient	$G_{unl/l}$	172 / 150	MV/m
Overall two linac length	l_{linac}	28	km
Total beam delivery length	l_{BD}	2 x 2.6	km
Proposed site length	l_{tot}	33.2	km
Total site AC power	P_{tot}	418	MW
Wall plug (RF) to main beam power efficiency	η_{tot}	12.5	%

The CLIC Challenges

COMMON TO MULTI-TEV LINEAR COLLIDERS

- Accelerating gradient
- Generation and preservation of ultra-low emittance beams
- Beam Delivery & IP issues
- Alignment & stability

SPECIFIC TO THE CLIC TECHNOLOGY

- 30 GHz components
- Efficient RF power production by Two Beam Acceleration

⇒ addressed in the CLIC Test Facility CTF3

The CLIC Technology-related key issues as pointed out by ILC-TRC 2003

Covered by CTF3

R1: Feasibility

- R1.2: Validation of drive beam generation scheme with fully loaded linac operation
- R1.1: Test of damped accelerating structure at design gradient and pulse length
- R1.3: Design and test of damped ON/OFF power extraction structure

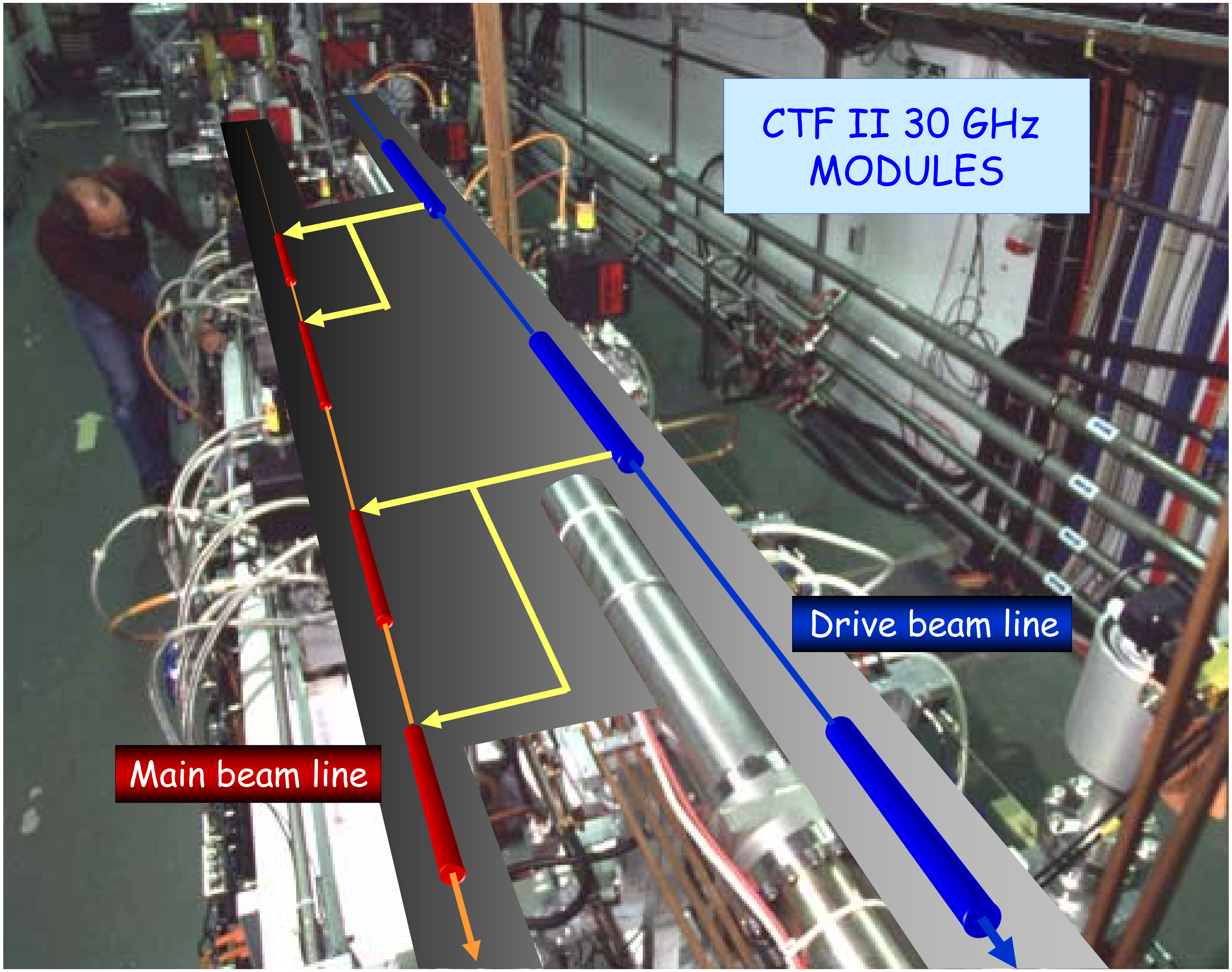
R2: Design finalization

- R2.1: Developments of structures with hard-breaking materials (W, Mo…)
- R2.2: Validation of stability and losses of DB decelerator; Design of machine protection system
- R2.3: Test of relevant linac sub-unit with beam
- R2.4: Validation of drive beam 40 MW, 937 MHz Multi-Beam Klystron with long RF pulse *
- R2.5: Effects of coherent synchrotron radiation in bunch compressors
- R2.6: Design of an extraction line for 3 TeV c.m.

Covered by EUROTeV

* *Feasibility study done – need development by industry.*
N.B.: Drive beam acc. structure parameters can be adapted to other klystron power levels

CLIC TEST FACILITY CTF II

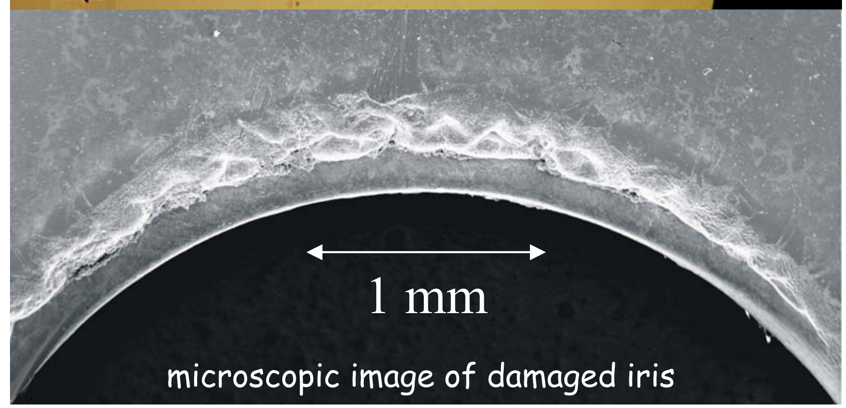


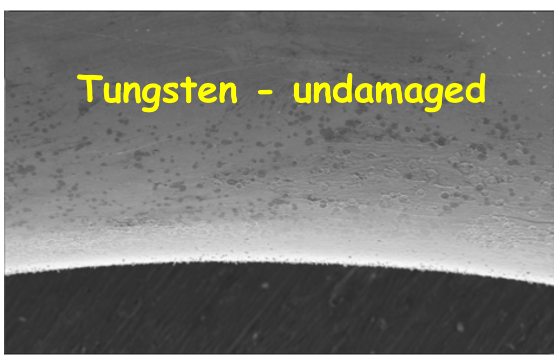
Gradient limitations

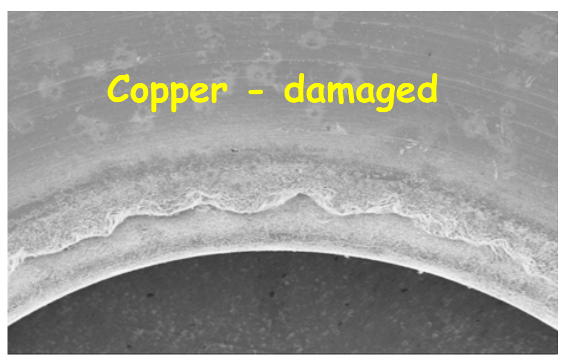
13 June RF power generation and high gradient issues S. Döbert

- The main limitation to gradient in normal conducting structures is due to break-downs (sparks) at the surface, for very high electric fields
- At surface fields of about 300-400 MV/m the surface can be damaged (tests in CTF II and elsewhere)

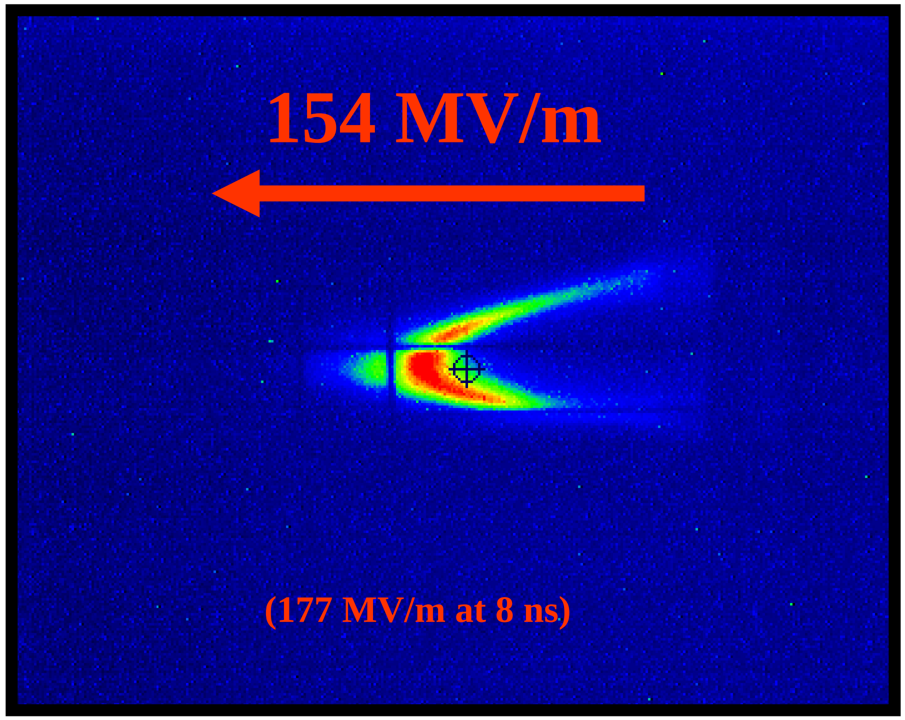
- Modify the RF design to obtain lower surface-field to accelerating-field ratio (Es/Ea ~ 2)
- Investigating new materials that are resistant to arcing - tungsten looked promising

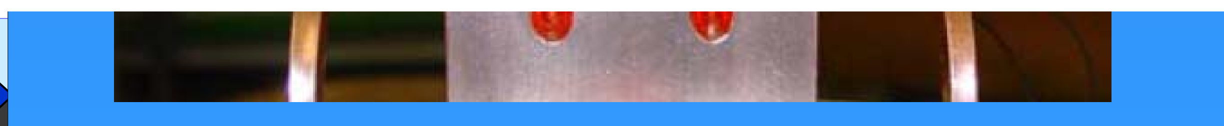






Irises after high-gradient testing to about the same field level





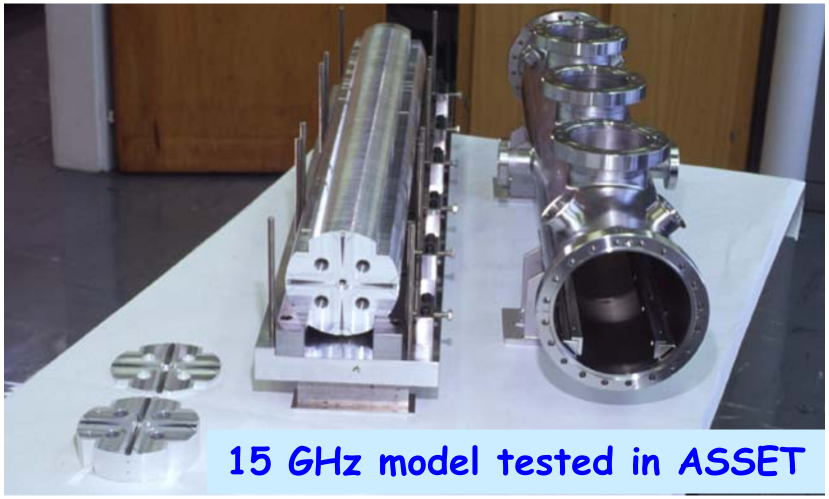
y exceeded
amage

190 MV/m accelerating gradient in first cell - tested with beam ! (but only 16 ns pulse length)

How to control transverse wake-fields

- short-range wakes ⇐ BNS damping
- long-range wakes ⇐ damping and detuning

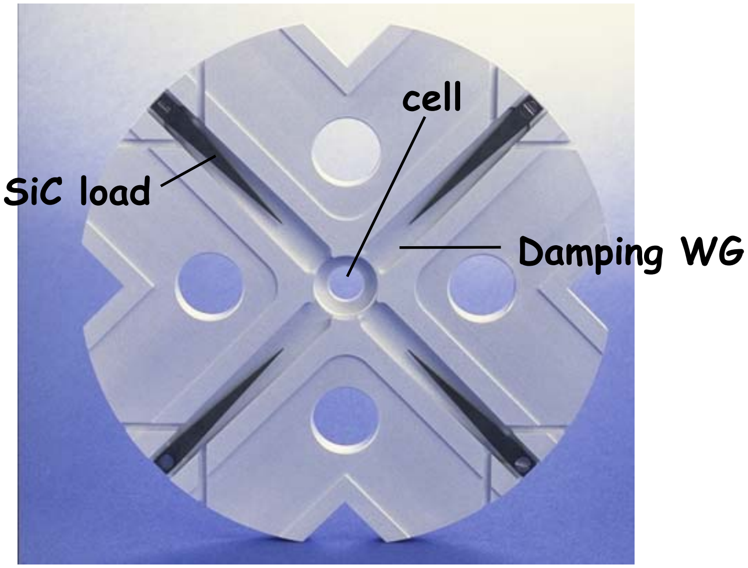
+ beam-based trajectory correction, ε bump

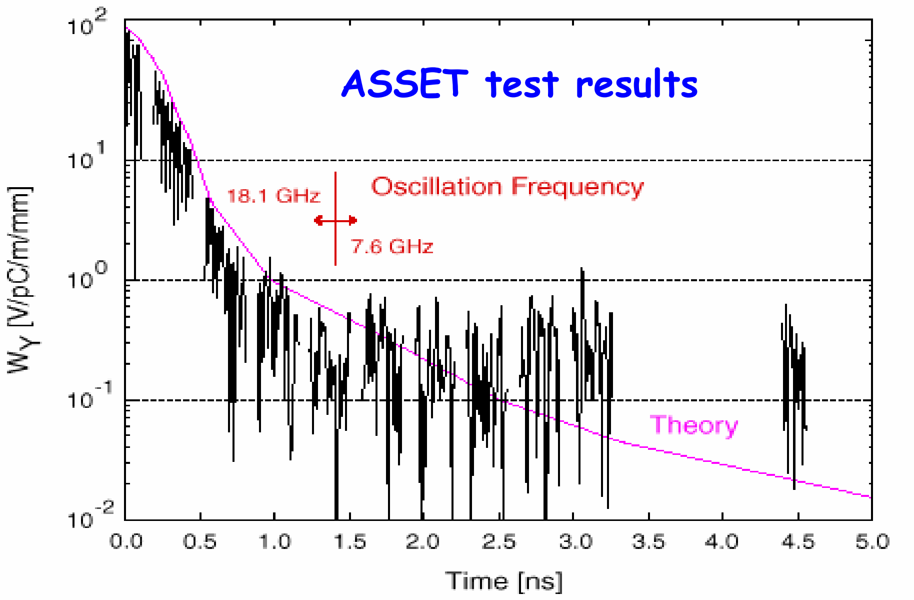


damped structures

Each cell is damped by 4 radial WGs terminated by discrete SiC RF loads.

Excellent agreement obtained between theory and experiment – believe we can solve damping problem





Accelerating Structure Development

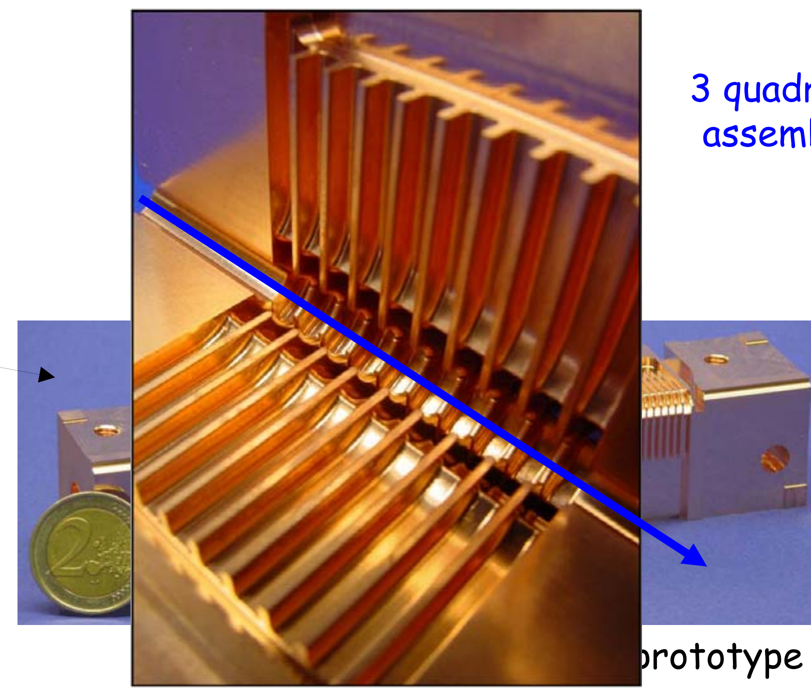
14 June Materials for accelerating structures G. Arnau-Izquierdo

Potential problem: fatigue limit of copper due to cyclic RF pulsed heating →
- Structure design optimization, shorter RF pulse

CTF2 & CTF3 experience →
- New materials, bi-metallic structure assembly, new construction concepts (HDS)

GOAL:

final structure design tested in CTF3 in 2008

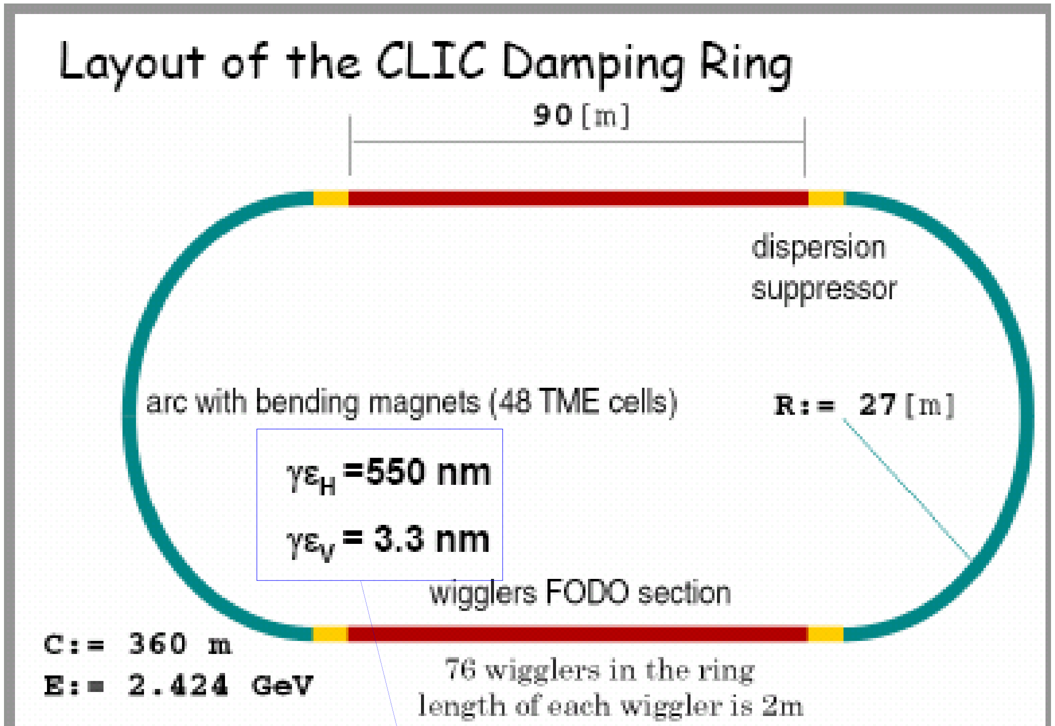


3 quadrants assembled

rototype

Generation of ultra-low emittance beams

Damping rings use synchrotron radiation to reduce to beam phase-space area



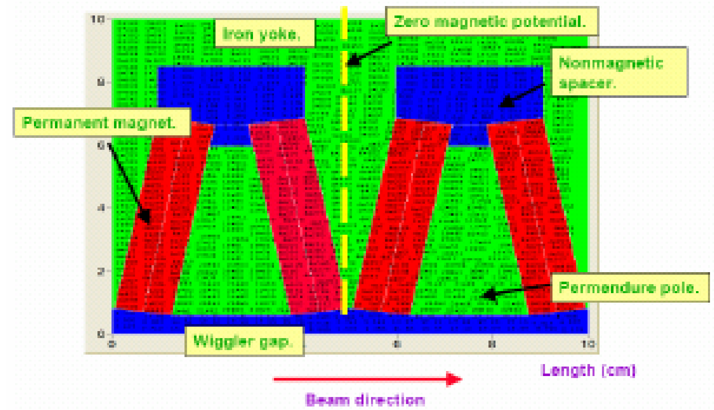
State-of-the-art (ATF -KEK Japan):

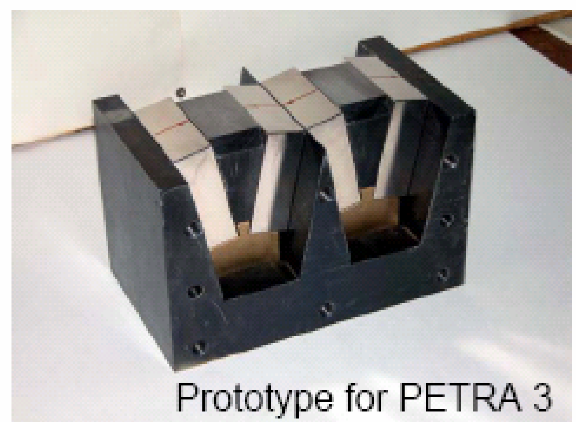
$\gamma\,\varepsilon_H =$ 2800 nm

$\gamma\,\varepsilon_V =$ 10 nm

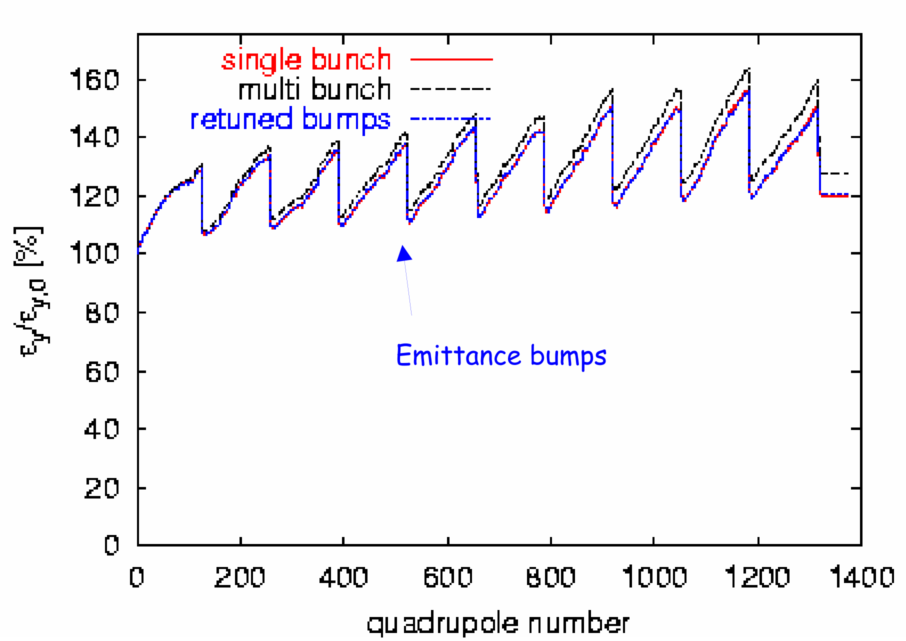
CLIC damping wiggler parameters	
Period:	10 cm
Gap:	12 mm
Pole width:	50 mm
Length:	2 m
Field amplitude:	1.7 T
Field quality @ ±1 cm:	10^{-3}
Total length:	160 m

CLIC damping wiggler configuration





Emittance preservation



beam simulations predict ~ 20%

- In parameter list ⇒ budgeted for 100% blow-up – some margin at least on paper
- Rely to precise beam diagnostics (position and beam profile)

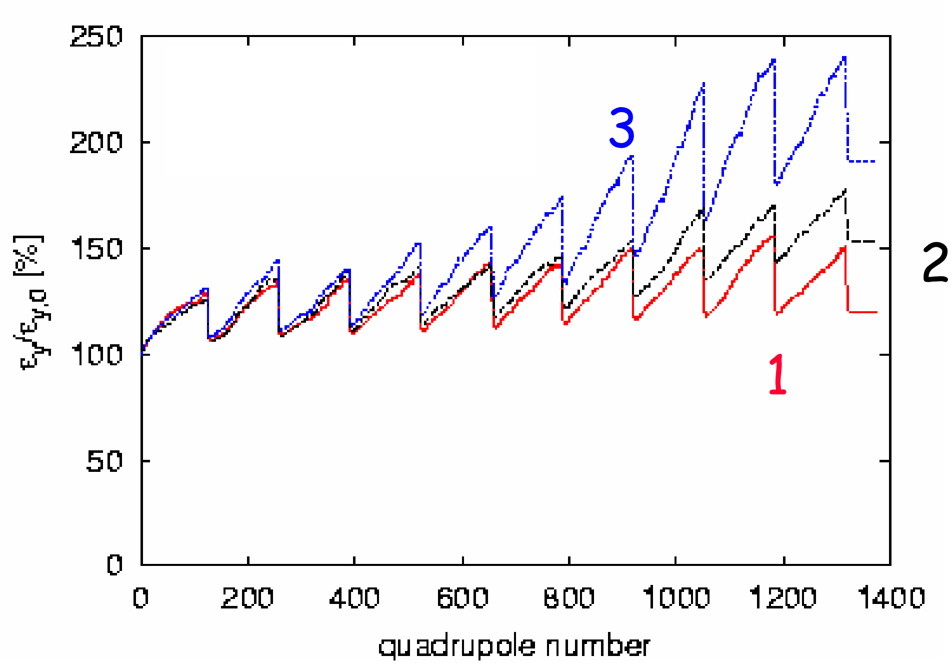
16 June Beam diagnostics equipment T. Lefevre

ALIGNMENT STRATEGY

15 June
Components alignment and stability
H. Mainaud, S. Redaelli

- Pre-align cavities and BPMs in linac to 10 microns
- Use ballistic method to align BPMs with greater precision
- Correct beam position by moving quads (“few-to-few” correction)
- Re-align structures to new beam position by moving girders.
- Use 10 emittance bumps (as in SLC) to locally reduce blow-up (measure emittance, move a few RF structures and a few quadrupoles).

Sensitivity to beam jitter & ground motion



Emittance deteriorate with time unless we apply beam correction schemes and readjust our initial settings

1) **Initial condition** at start of run after beam alignment

2) After about **one day** (10^5 s) of running and continuous one-to-one correction in feedback mode

3) After about **10 days** (10^6 s) of running with continuous one-to-one correction and readjustment of emittance bumps

Operational procedure

- Emittance bumps readjusted every day
- BPMs realigned by "ballistic method" every week

CLIC

Stability studies

15 June Components alignment and stability H. Mainaud, S. Redaelli

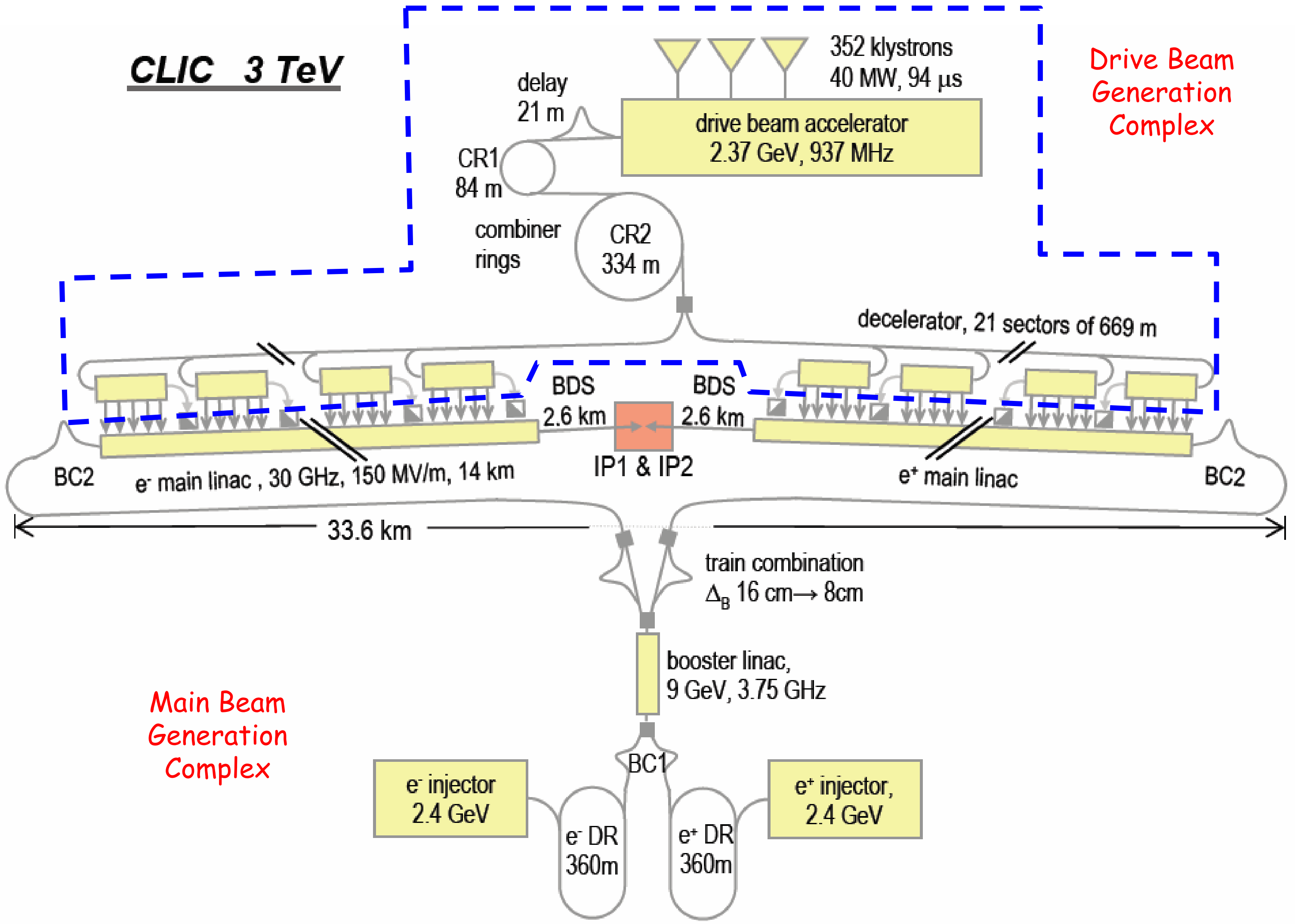
Vertical spot size at IP is ~ 1 nm *(size of water molecule)*

Stability requirements (> 4 Hz) for a 2% loss in luminosity

Magnet	Ix	Iy
Linac (2600 quads)	14 nm	1.3 nm
Final Focus (2 quads)	4 nm	0.2 nm

Need active damping of vibrations

The CLIC 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*

350 Klystrons

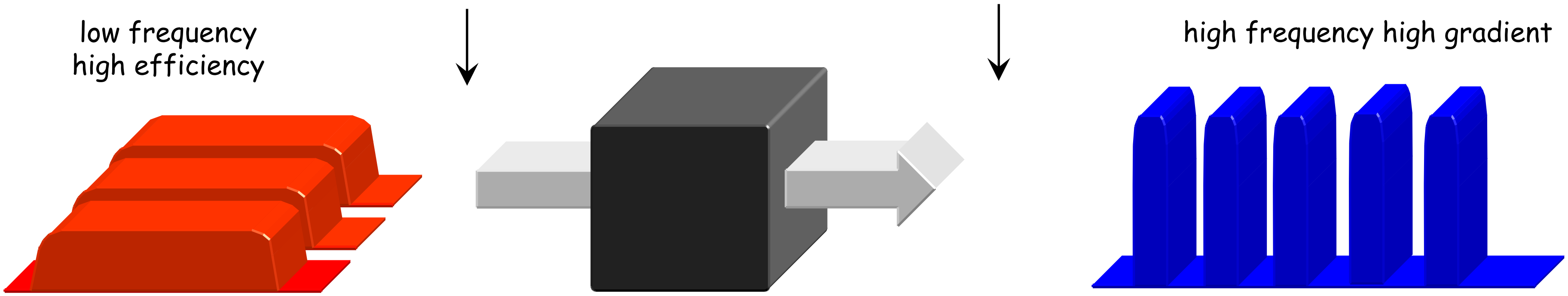
low frequency
high efficiency

Power stored in electron beam

Power extracted from beam in resonant structures

48000 Accelerating Structures

high frequency high gradient



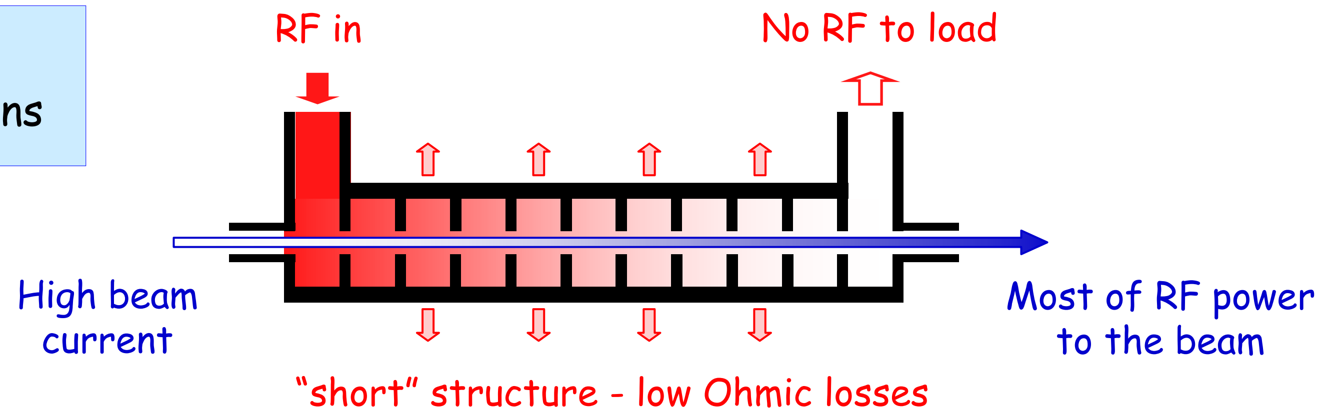
Long RF Pulses
P_0 , ν_0 , τ_0

Electron beam manipulation

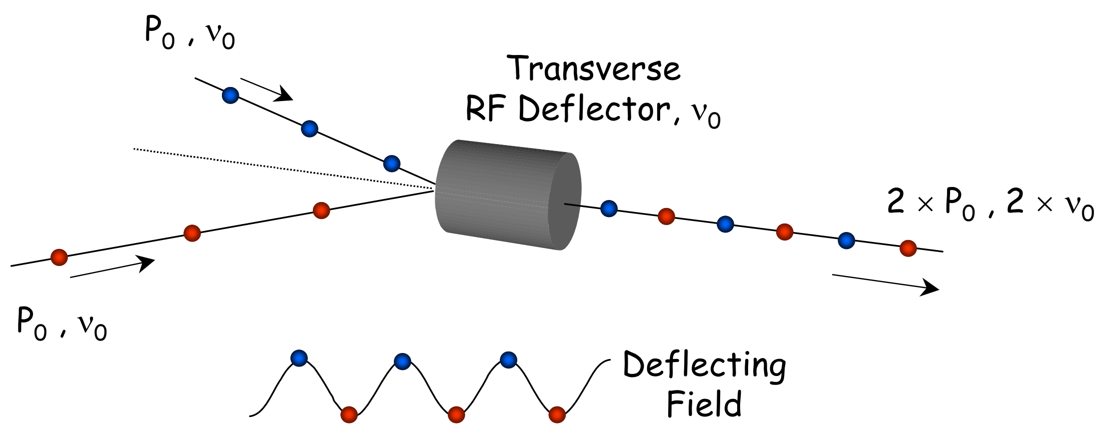
Short RF Pulses
$P_A = P_0 \times N_1$
$\tau_A = \tau_0 / N_2$
$\nu_A = \nu_0 \times N_3$

RF Power Source "building blocks"

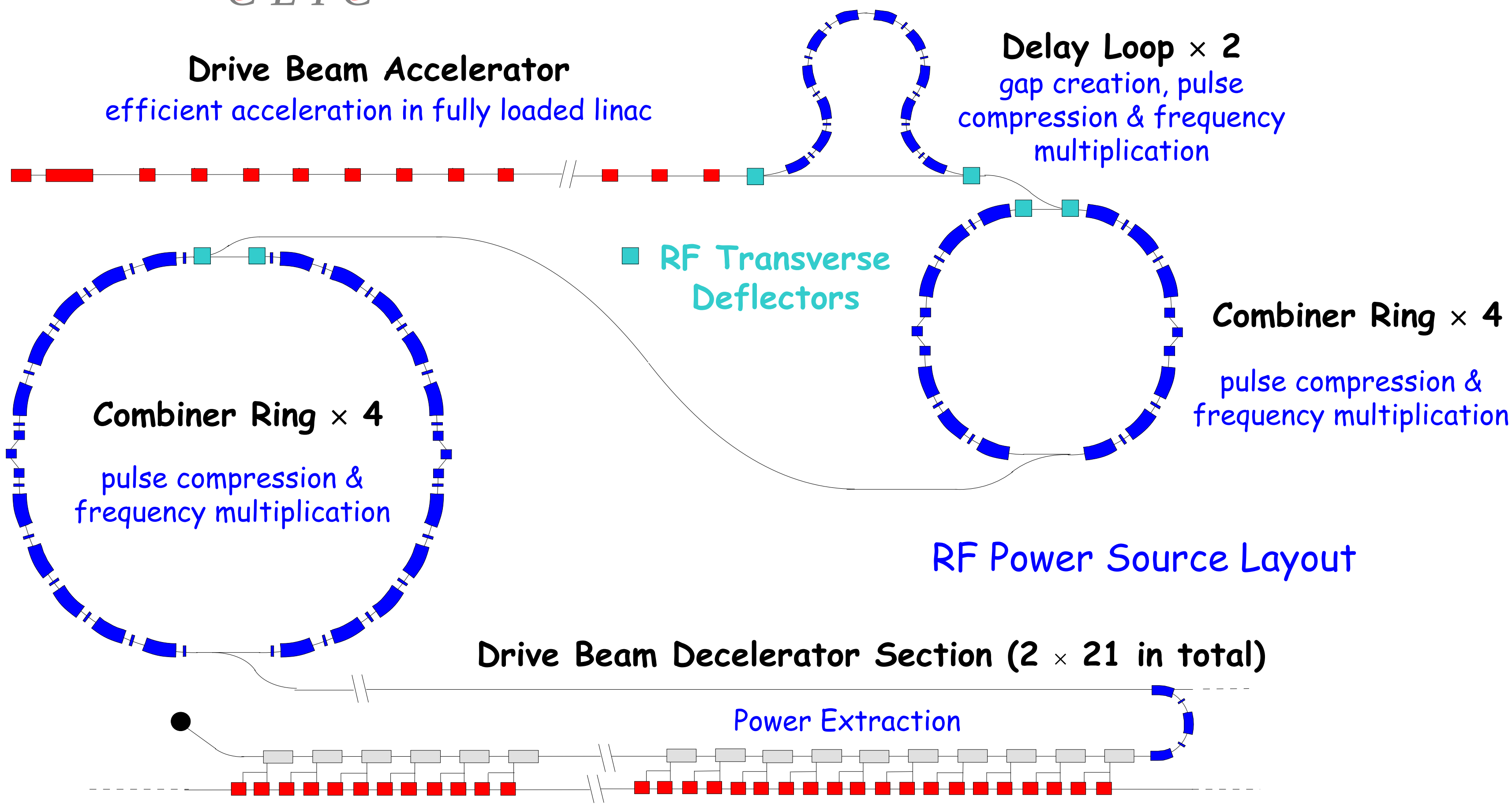
Full beam-loading acceleration in TW sections



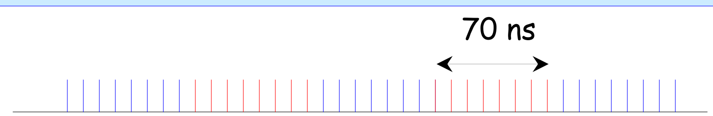
Beam combination/separation by transverse RF deflectors



RF Power Source Layout

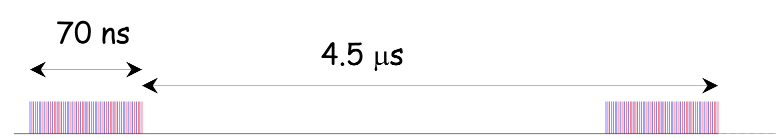


Drive beam time structure - initial



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

Drive beam time structure - final

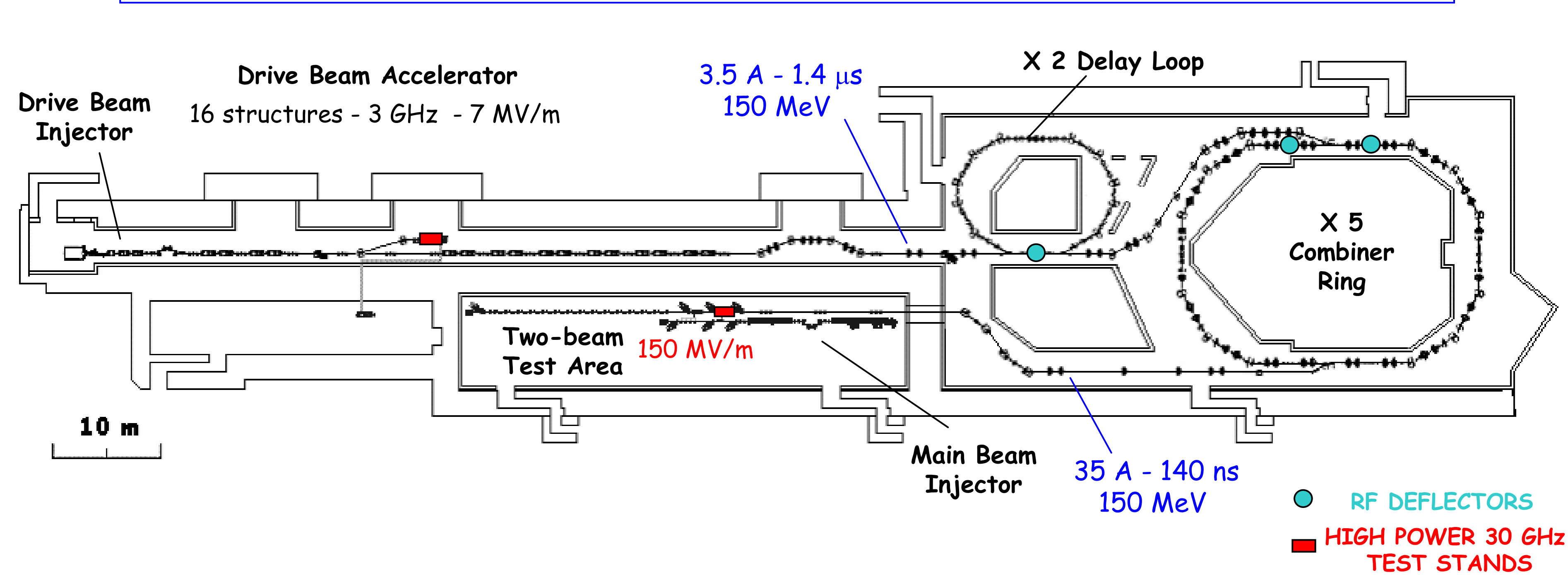


2 × 21 pulses – 180 A - 2 cm between bunches

CTF3 motivations and goals

CTF3 COLLABORATION

Ankara University , (Turkey)
BINP, Russia
CIEMAT, (Spain)
CERN, Geneva (Switzerland)
DAPNIA, Saclay (France)
HIP, Helsinki (Finland)
IAP, (Russia)
INFN , Frascati (Italy)
LAL , Orsay (France)
LAPP, Annecy (France)
Northwestern University, (USA)
RAL, (England)
SLAC , San Francisco (USA)
Svedberg Lab. (Sweden)
Uppsala University , (Sweden)



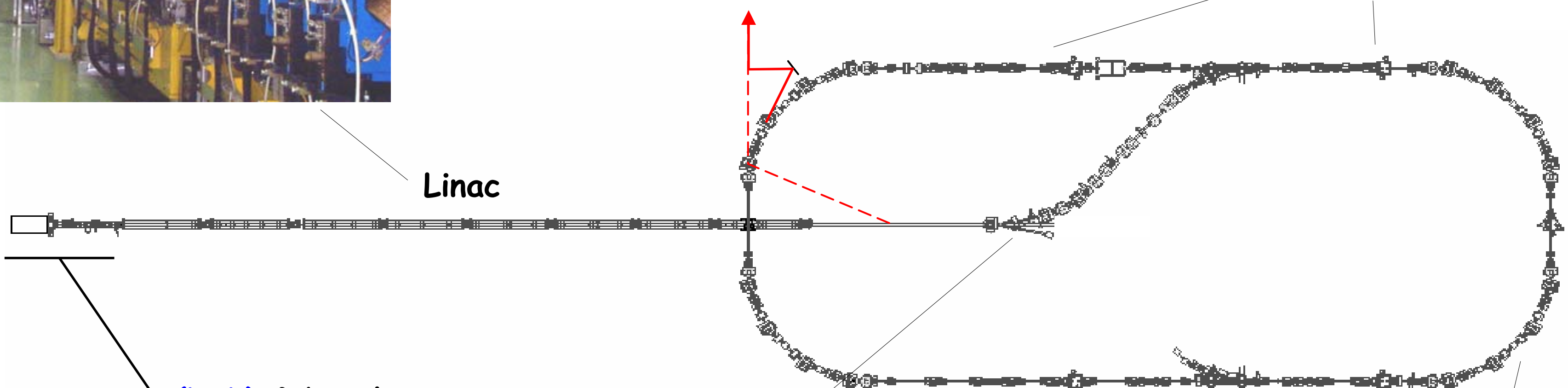
CTF3 Preliminary Phase (2001-2002)

Modified LEP pre-injector complex

RF deflectors (INFN-LNF)

streak camera measurement

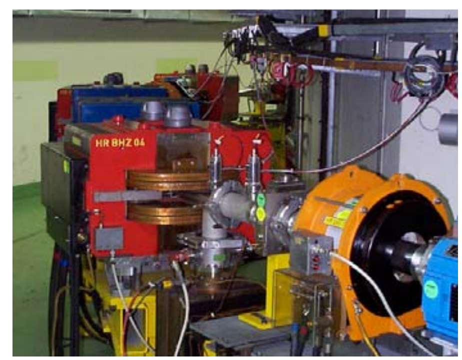
Linac



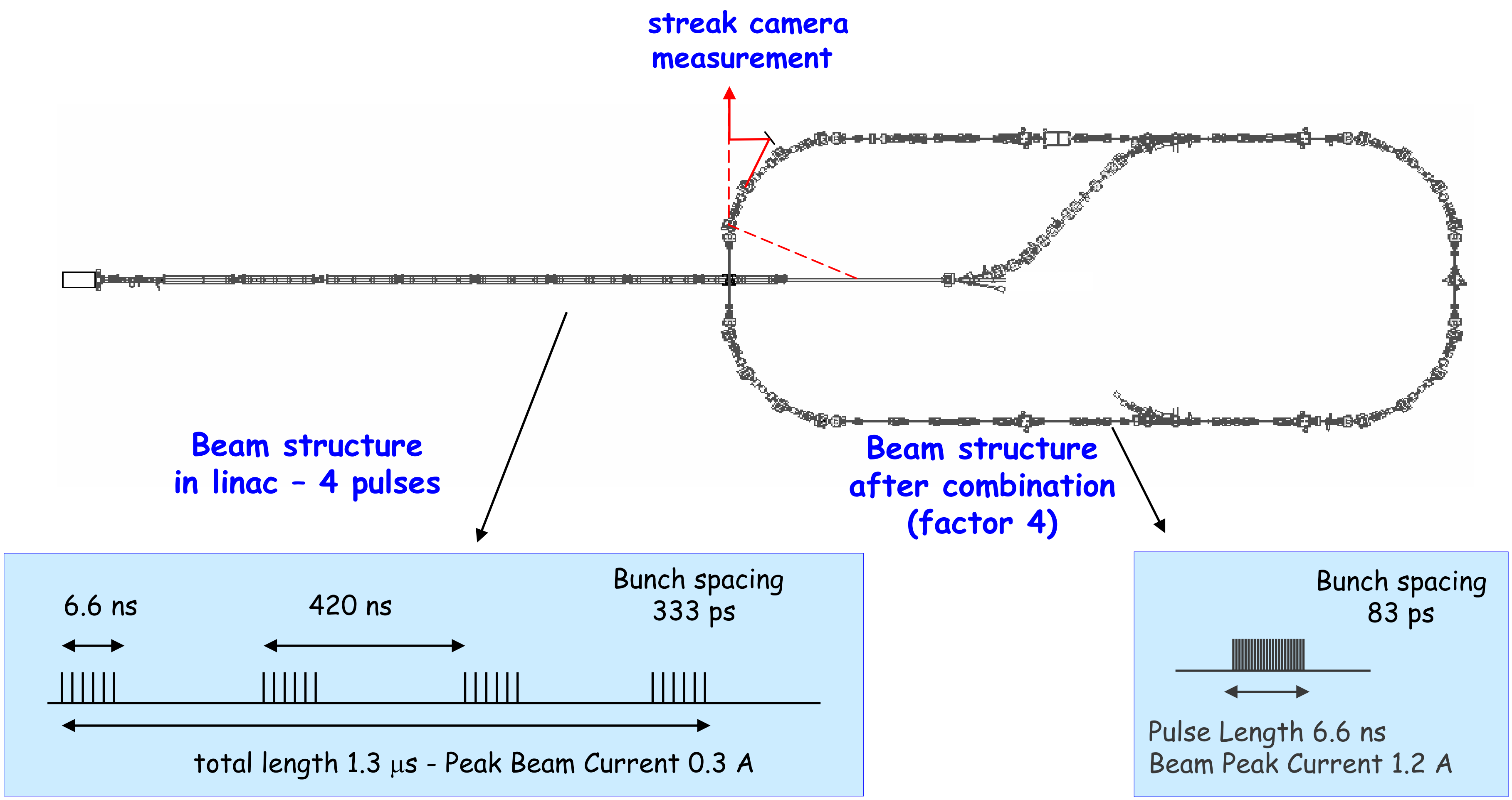
gun (LAL) & bunching system

isochronous injection line

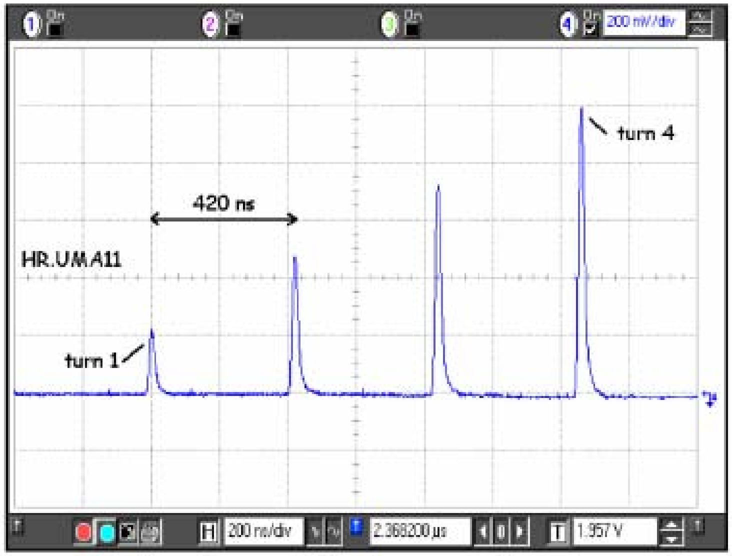
isochronous arcs



CTF3 Preliminary Phase
(2001-2002)



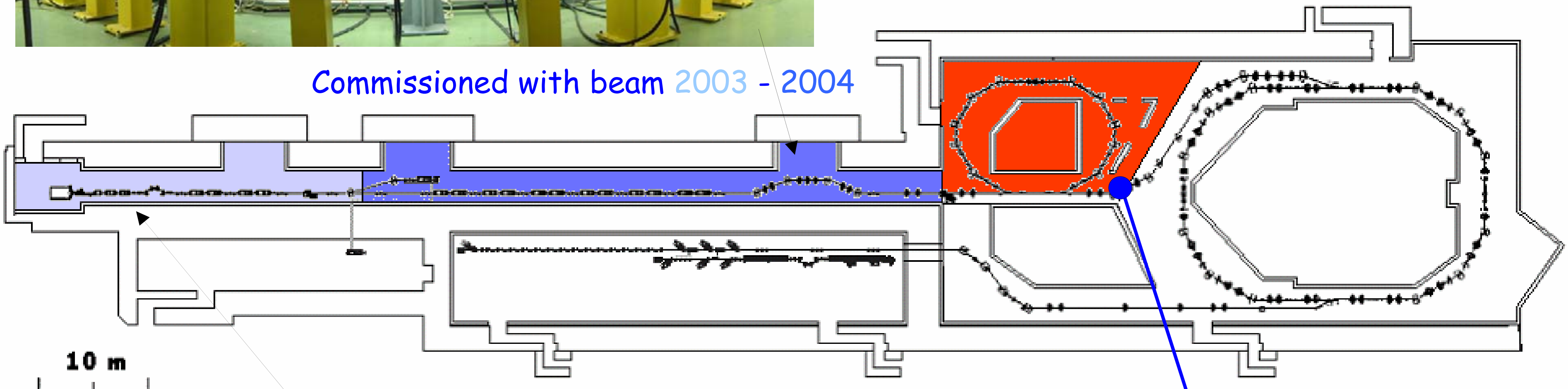
Preliminary Phase results
Bunch combination (factor 4)



Beam current circulating in the ring measured during combination with a beam current monitor

CTF3 Status

Installed 2005 (INFN/LNF)
Commissioning started end 2005

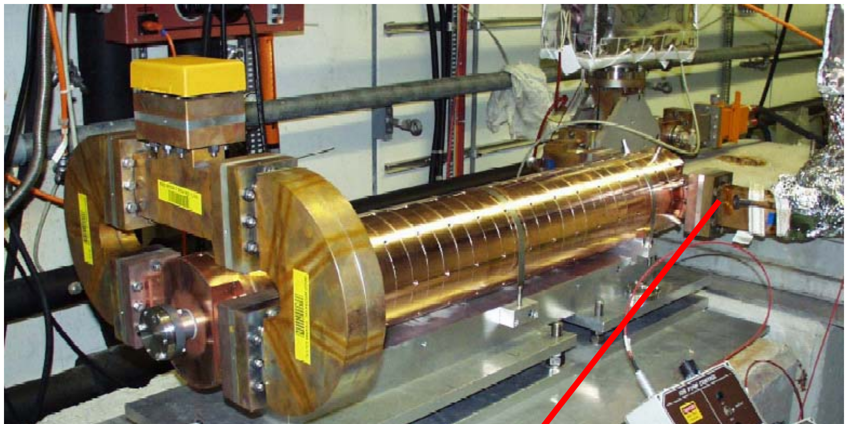


Main beam parameters

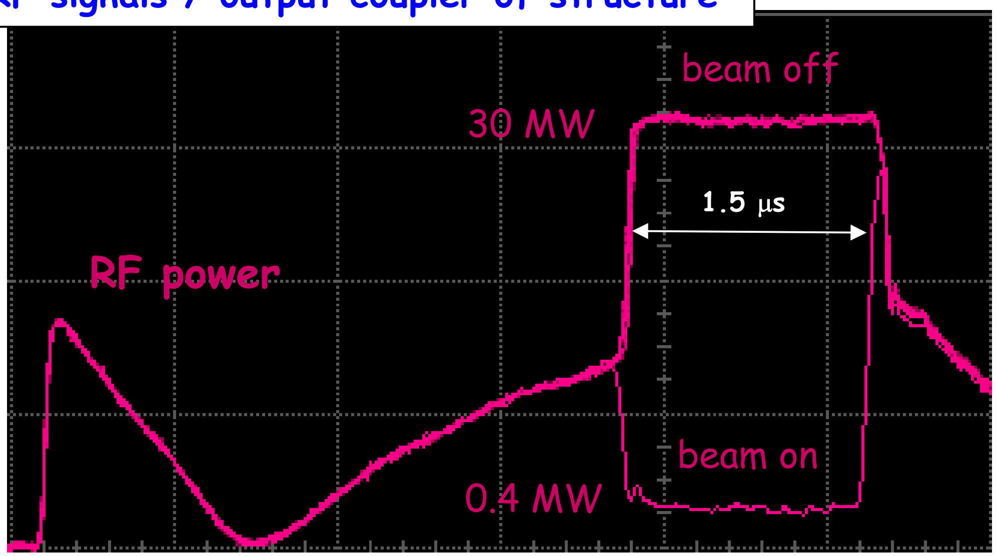
	Nominal	Achieved
I	3.5 A	5 A
τ_p	1.5 μs	1.5 μs
E	150 MeV	100 MeV
$\varepsilon_{n,rms}$	100 π mm mrad	100 π mm mrad *
$\tau_{b,rms}$	5 ps	4 ps *

* for 3.5 A, 1.5 μs beam

First "full beam loading" operation in CTF3

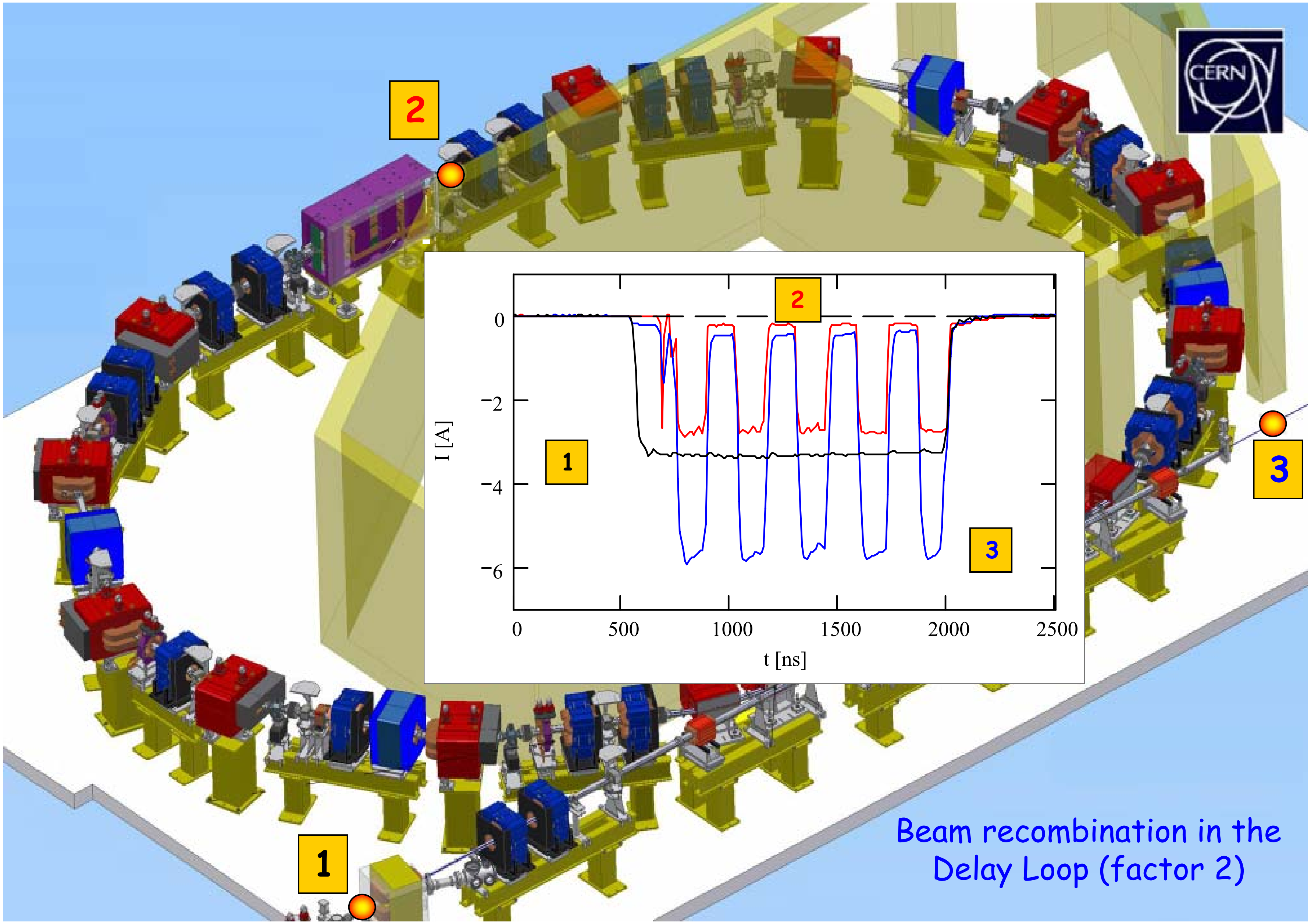


RF signals / output coupler of structure

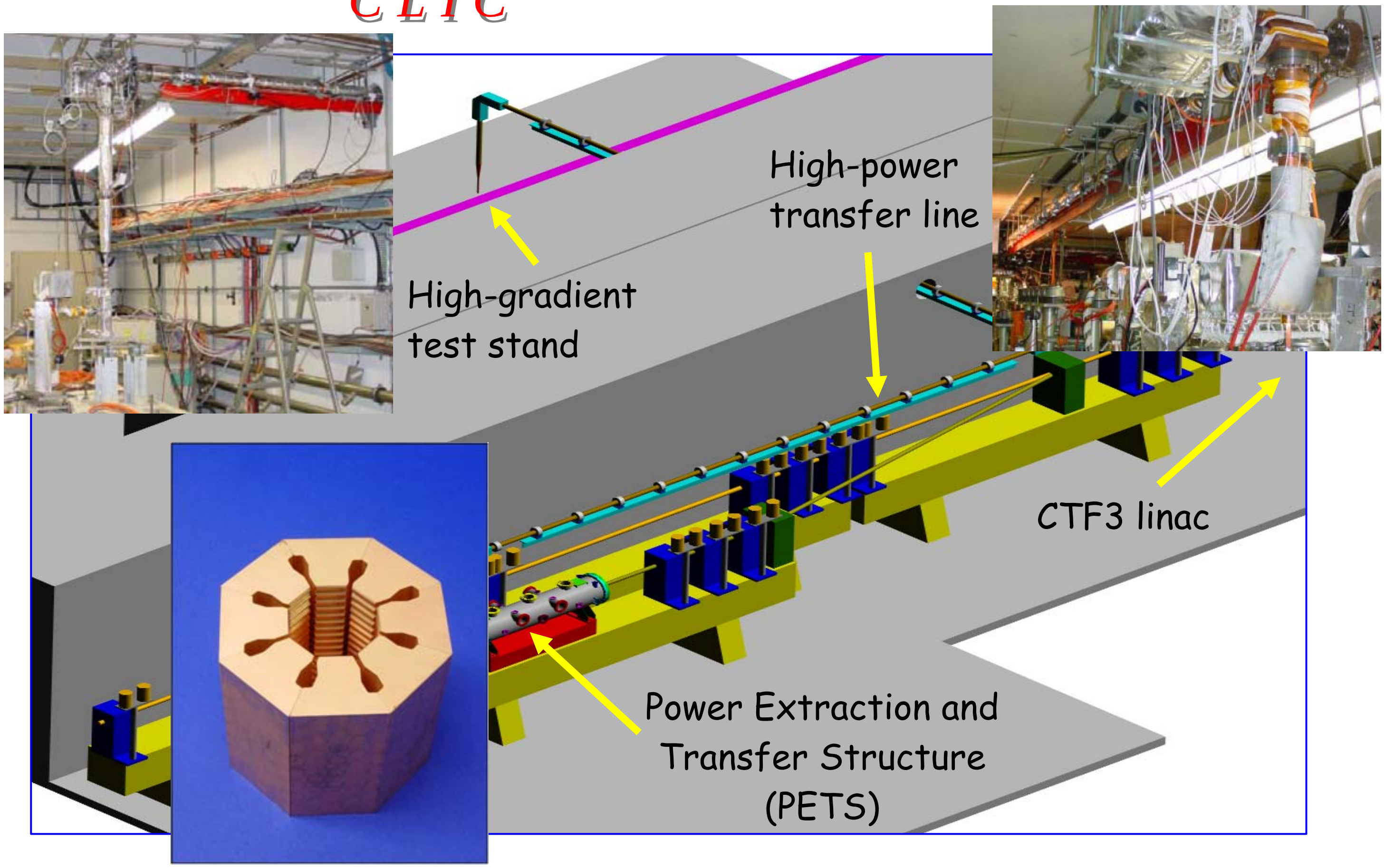


Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning

Beam current	4 A
Beam pulse lenght	1.5 μs
Power input/structure	35 MW
Ohmic losses (beam on)	1.6 MW
RF power to load (beam on)	0.4 MW
RF-to-beam efficiency	~ 94%



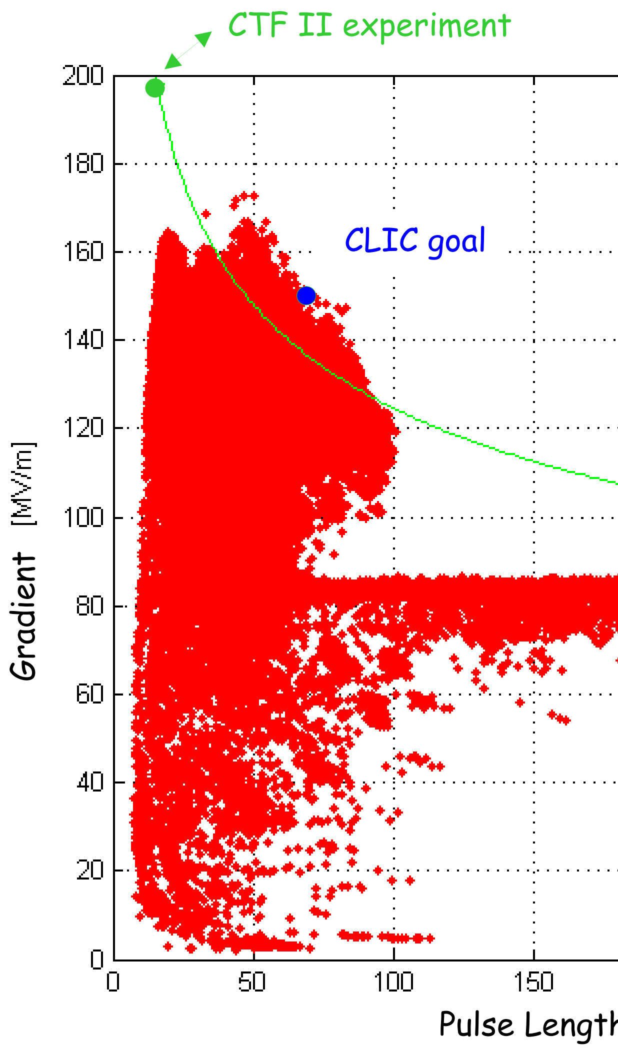
Beam recombination in the Delay Loop (factor 2)



30 GHz power production in CTF3

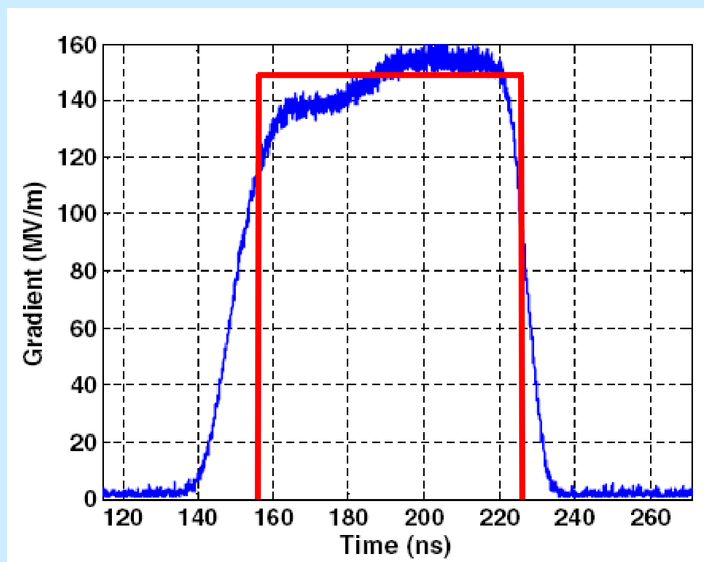
- Produced power up to about 100 MW - structure tests started in 2005

Accelerating structure tests in CTF3 (Mo iris)



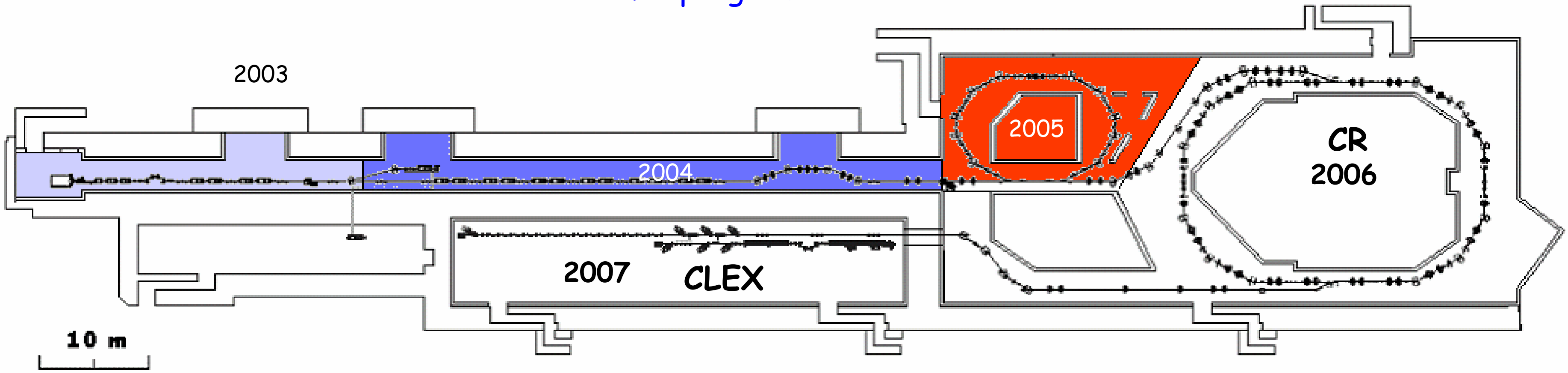
Reached nominal CLIC values :

150 MV/m 70 ns



...some damage

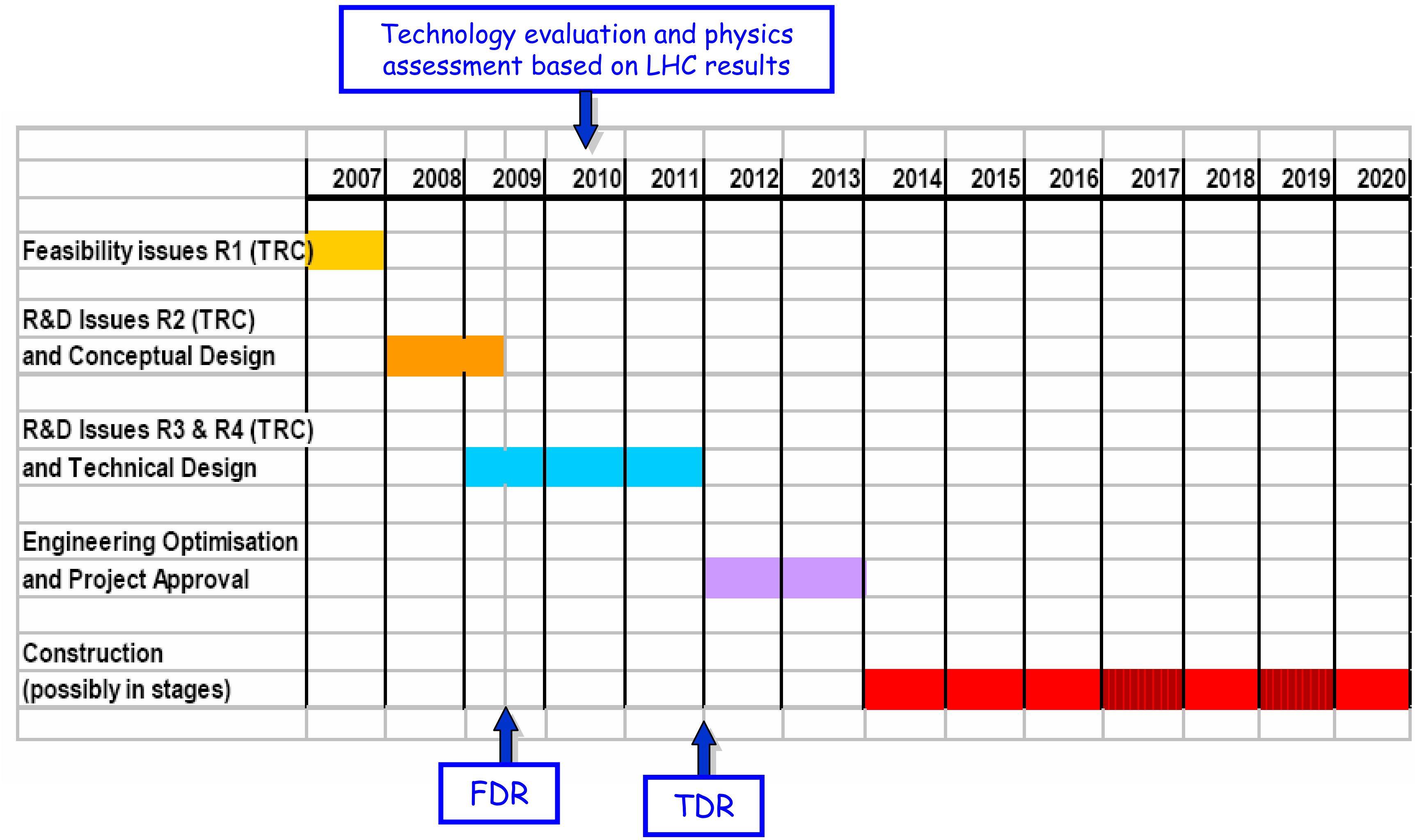
CTF3 scientific program



SCHEDULE WITH EXTRA RESOURCES	2004	2005	2006	2007	2008	2009
Drive Beam Accelerator	■					
30 GHz power test stand in Drive Beam accelerator	■	■				
30 GHz power testing (4 months per year)		■	■	■	■	■
R1.1 feasibility test of CLIC structure				■ (magenta)		
Delay Loop	■	■				
Combiner Ring	■	■	■			
R1.2 feasibility test of Drive beam generation				■ (magenta)		
CLIC Experimental Area (CLEX)		■	■			
R1.3 feasibility test PETS				■ (magenta)		
Probe Beam			■	■		
R2.2 feasibility test representativeCLIC linac section					■ (magenta)	
Test beam line		■	■	■	■	
R2.1 Beam stability bench mark tests					■ (magenta)	■ (magenta)

TENTATIVE LONG-TERM CLIC SCENARIO

(success oriented)

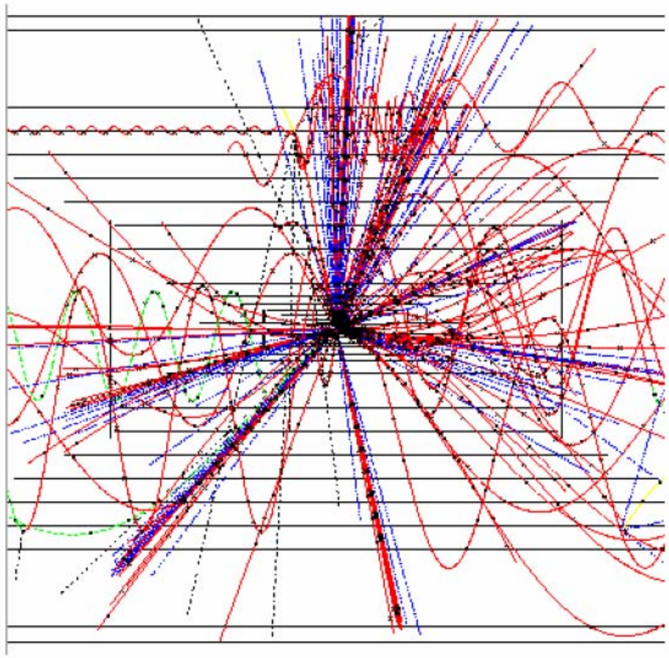


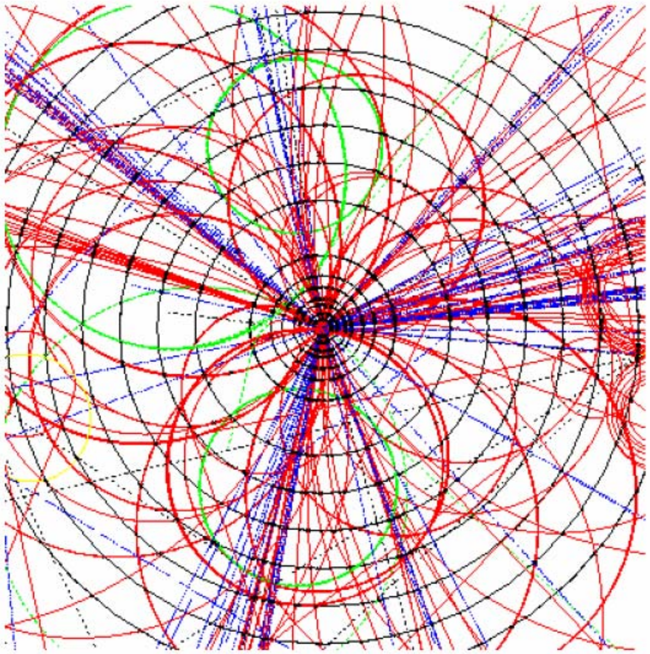
CONCLUSIONS

- CLIC is the only possible scheme to extend the Linear Collider energy into the Multi-TeV range
- CLIC technology is not mature yet, requires challenging R&D
- Very promising results were already obtained in CTF II and in the first stages of CTF3
- Remaining key issues clearly identified (ILC-TRC)
- Technology independent key issues studied within EuroTeV and in close collaboration with ILC
- CLIC-related key issues addressed in CTF3 by 2010

Aim to provide the High Energy Physics community with the feasibility of CLIC technology for Linear Collider in due time, when physics needs will be fully determined following LHC results

Safety net to the SC technology in case sub-TeV energy range is not considered attractive enough for physics





…experiments at CLIC will be able to exploit fully its high centre-of-mass energy for tests of the Standard Model as well as unique probes of ideas for new physics beyond the Standard Model.

CLIC will take physics at the energy frontier to a new scale and level of accuracy.