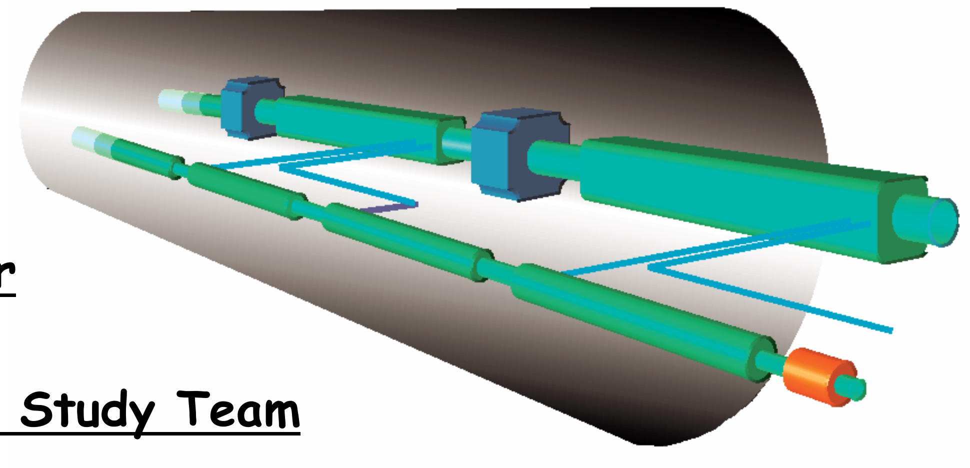
THE COMPACT LINEAR COLLIDER (CLIC) STUDY



J.P.Delahaye for

The Compact LInear Collider Study Team

The CLIC study is a site independent feasibility study aiming at the development of a realistic technology at an affordable cost for an e± Linear Collider in the post-LHC era for Physics in the multi-TeV center of mass colliding beam energy range.

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

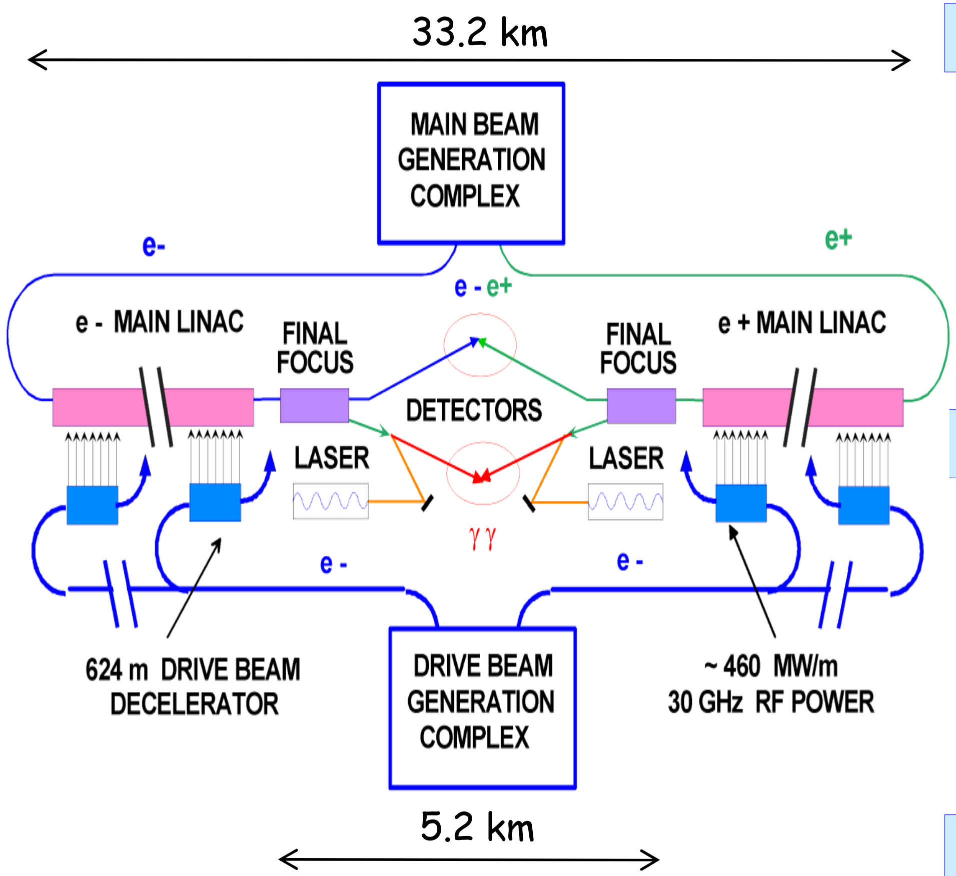
Outline

- The CLIC scheme
- Main challenges
- What has been achieved so far
- What remains to be demonstrated
- CTF3, the facility to address the key issues
- Plans and schedule
- Conclusion

World wide CLIC collaboration

- BERLIN Technical University (Germany) : Structure simulations GdfidL
- Finnish Industry (Finland) : Sponsorship of a mechanical engineer
- INFN / LNF (Italy): CTF3 delay loop, transfer lines & RF deflectors
- JINR & IAP (Russia): Surface heating tests of 30 GHz structures
- KEK (Japan): Low emittance beams in ATF
- LAL (France) : Electron guns and pre-buncher cavities for CTF3
- LAPP/ESIA (France) : Stabilization studies
- LLBL/LBL (USA) : Laser-wire studies
- North Western University (Illinois) : Beam loss studies & CTF3 equipment
- RAL (England) : Lasers for CTF3 and CLIC photo-injectors
- SLAC (USA) : High Gradient Structure testing, structure design, CTF3 drive beam injector design
- UPPSALA University (Sweden) : Beam monitoring systems for CTF3

Basic features of the CLIC scheme



Overall layout for a center of mass energy of 3 TeV/c

- High acceleration gradient (150 MV/m)

- "Compact" collider-overall length≈33 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)

- Two-Beam Acceleration Scheme

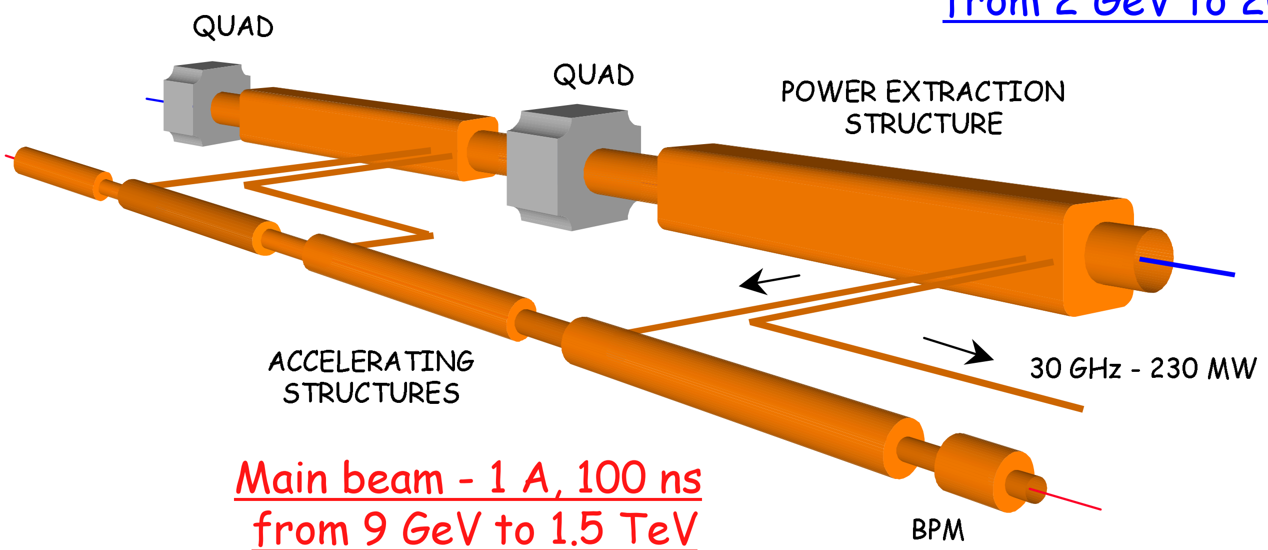
  - RF power generation at high frequency
  - Cost-effective & efficient (~ 10% overall)
  - Simple tunnel, no active elements

- Central injector complex

  - "modular" design, can be built in stages
  - Easily expendable in energy

CLIC Two-Beam scheme

Drive beam - 150 A, 130 ns
from 2 GeV to 200 MeV

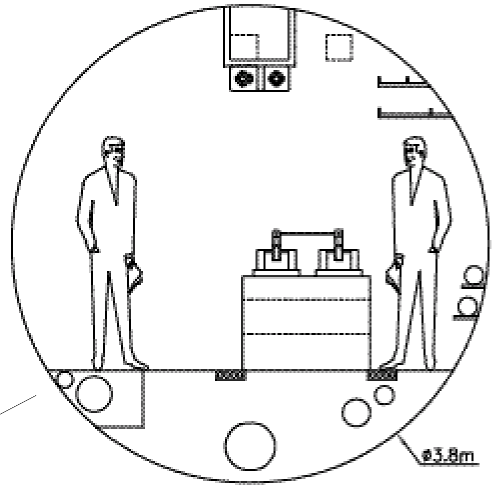


Main beam - 1 A, 100 ns
from 9 GeV to 1.5 TeV

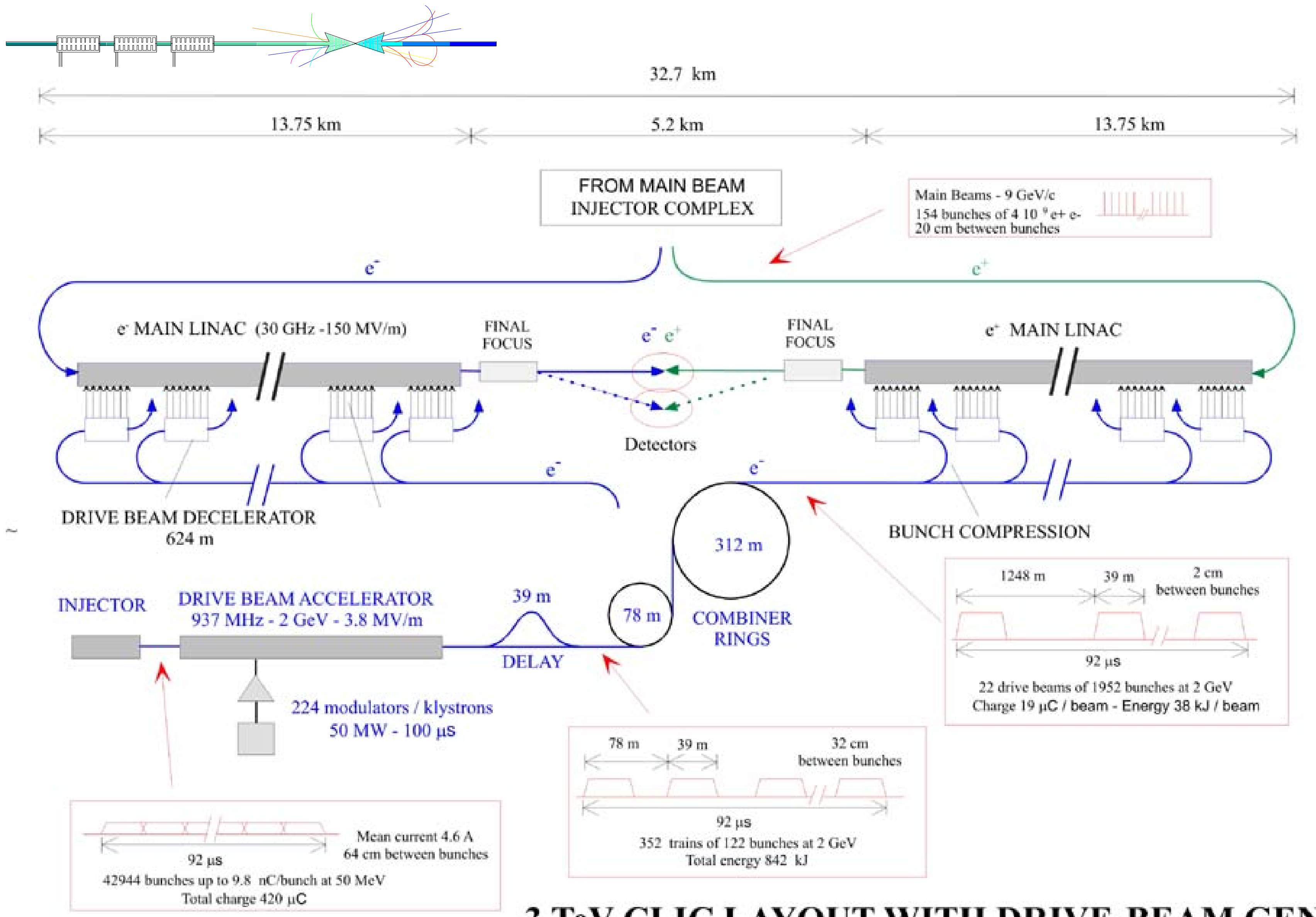
CLIC MODULE

(6000 modules at 3 TeV)

CLIC TUNNEL
CROSS-SECTION



3.8 m diameter

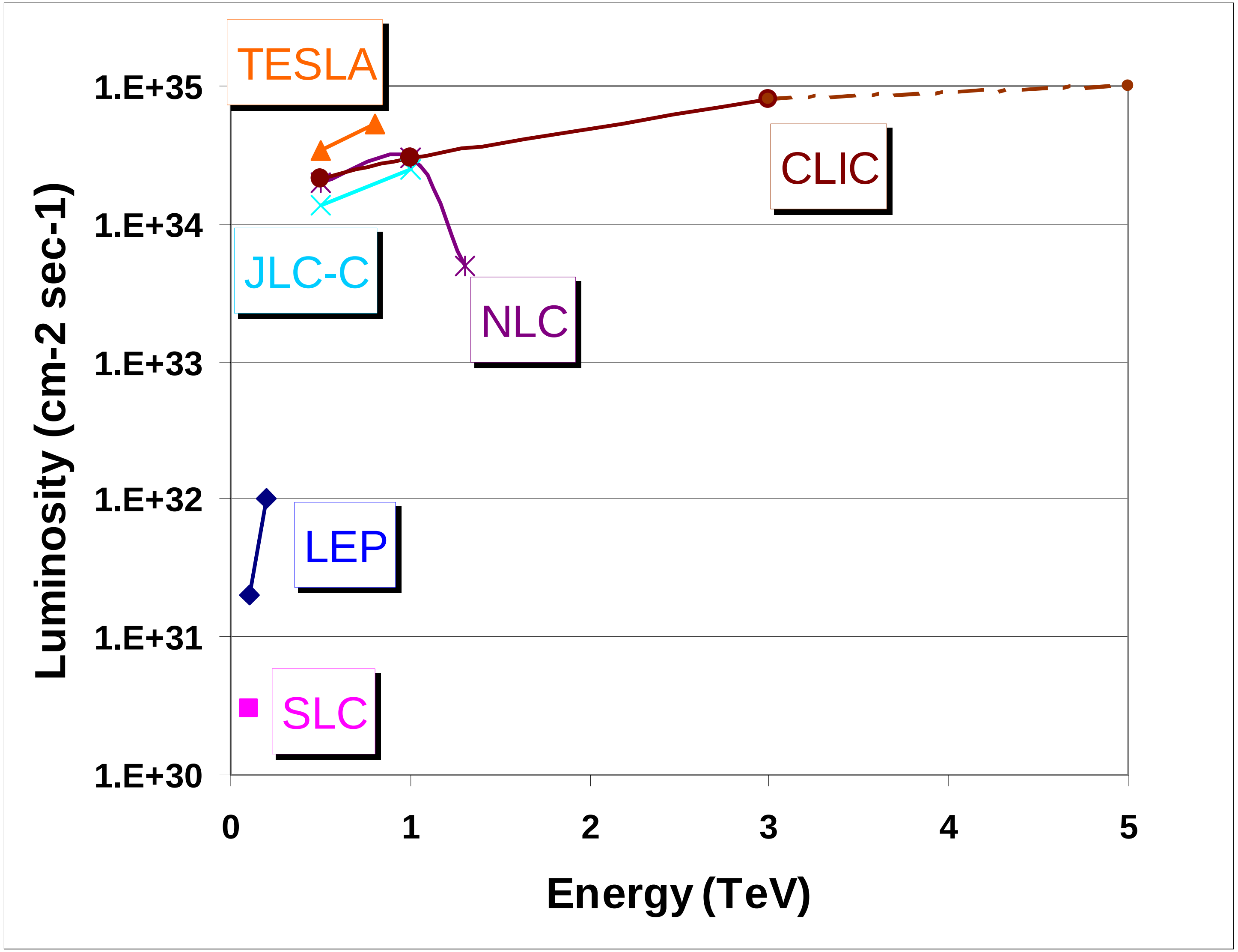


3 TeV CLIC LAYOUT WITH DRIVE-BEAM GENERATION

The CLIC main parameters

Center of mass Energy (TeV)	0.5 TeV	3 TeV
Luminosity (10^{34} $cm^{-1}s^{-1}$)	2.1	8.0
Mean energy loss (%)	4.4	21
Photons / electron	0.75	1.5
Coherent pairs per X	700	6.8 10^8
Rep. Rate (Hz)	200	100
10^9 $e^{\pm}$ / bunch	4	4
Bunches / pulse	154	154
Bunch spacing (cm)	20	20
H/V ε_n (10^{-8} rad.m)	200/1	68/1
Beam size (H/V) (nm)	202/1.2	60/0.7
Bunch length (μm)	35	35
Accelerating gradient (MV/m)	150	150
Overall length (km)	7.7	33.2
Power / section (MW)	230	230
RF to beam efficciency (%)	23.1	23.1
AC to beam efficiency (%)	9.3	9.3
Total AC power for RF (MW)	105	319
Total site AC power (MW)	175	410

Performances of Lepton Colliders



The CLIC main challenges

COMMON TO MULTI-TEV LINEAR COLLIDERS

- Accelerating gradient *
- Generation and preservation of ultra-low emittance beams
- Beam Delivery & IP issues:
  - **nanometer size beams**
  - **Sub-nanometer component stabilisation** *
- Physics with colliding beams in high beamstrahlung regime

SPECIFIC TO THE CLIC TECHNOLOGY

- 30 GHz components with manageable wakefields*
- Efficient RF power production by Two Beam Acceleration *
- Operability at high power (beam losses) and linac environment* (RF switch)

* ⇒ addressed in Test Facilities

Luminosity Scaling

energy loss by beamstrahlung

wall-plug to beam efficiency

wall-plug power

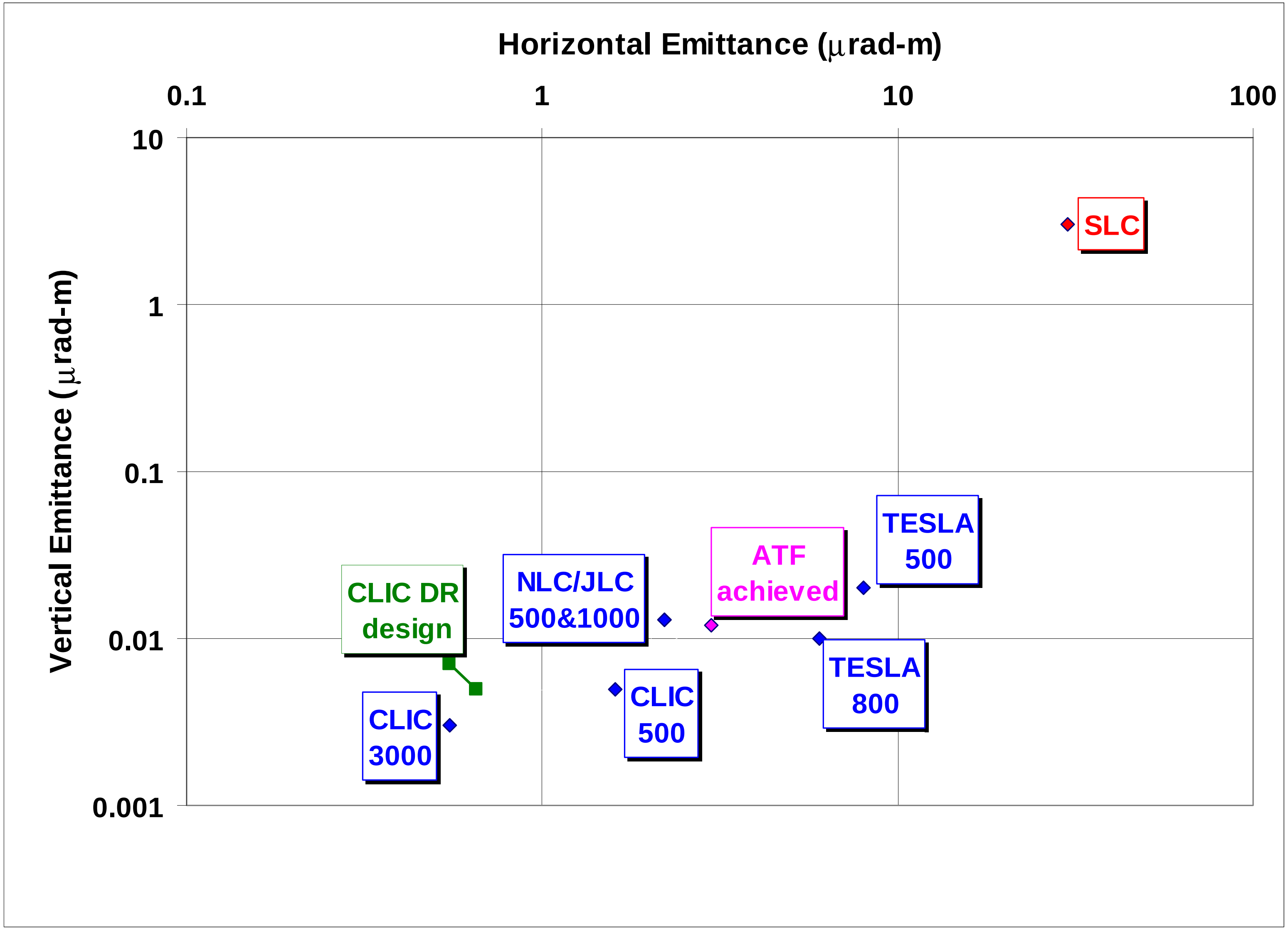
$$L = \frac{k_b\, N_b^2\; f_{rep}}{4\pi U_{cm}\, \sigma_x^{\,*}\, \sigma_y^{\,*}} \propto \frac{\delta_B^{1/2} \times \eta_{beam}^{AC} \times P_{AC}}{U_{cm}\; \varepsilon_{ny}^{*\;1/2}}$$

center-of-mass energy

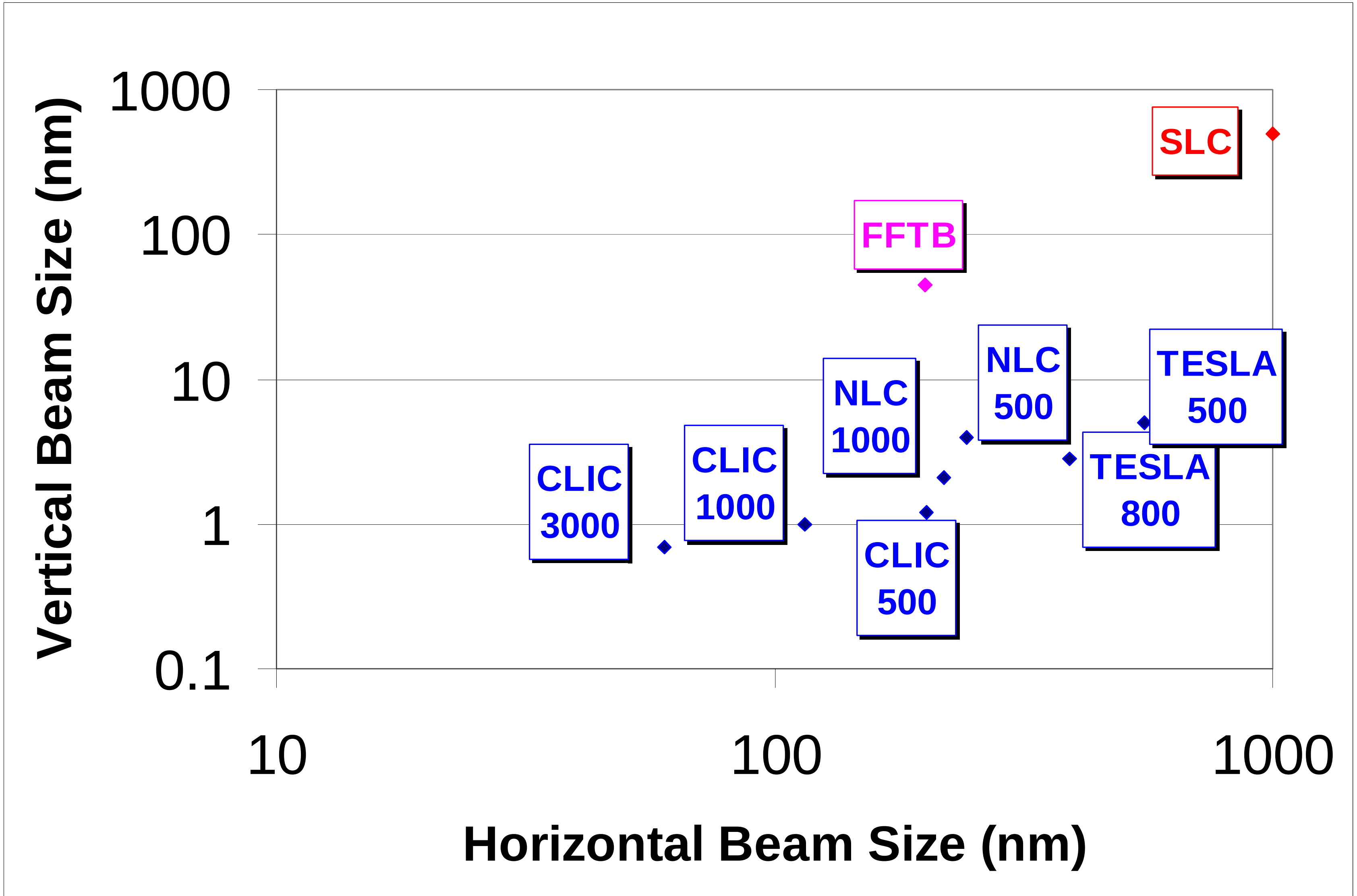
Vertical emittance

- **Vertical beam emittance** at I.P. as small as possible
- **Wall-plug to beam efficiency** as high as possible
- **Beamstrahlung energy spread** increasing with c.m. colliding energies

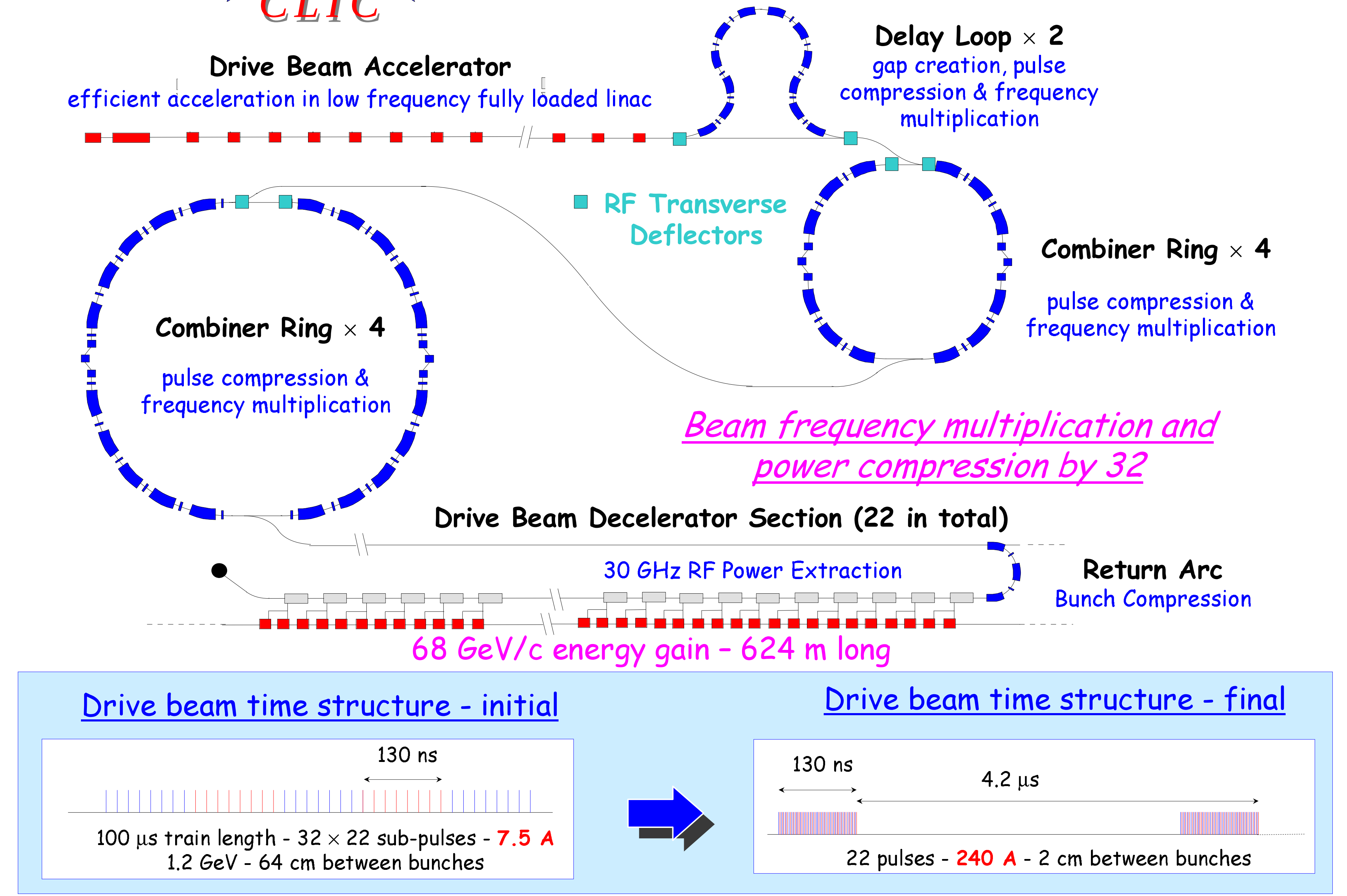
Beam emittances at Damping Rings



Beam sizes at Collisions



The CLIC RF Power Source



What does the RF power Source do?

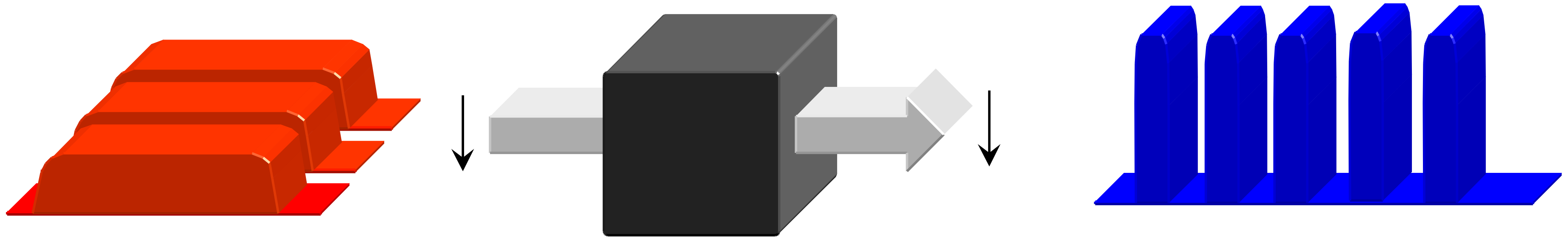
The CLIC RF power source can be described as a "black box", combining *very long RF pulses*, and transforming them in *many short pulses*, with *higher power* and with *higher frequency*

200 Klystrons
Low frequency
High efficiency

Power stored in electron beam

Power extracted from beam in resonant structures

43000
Accelerating Structures
High Frequency - High field

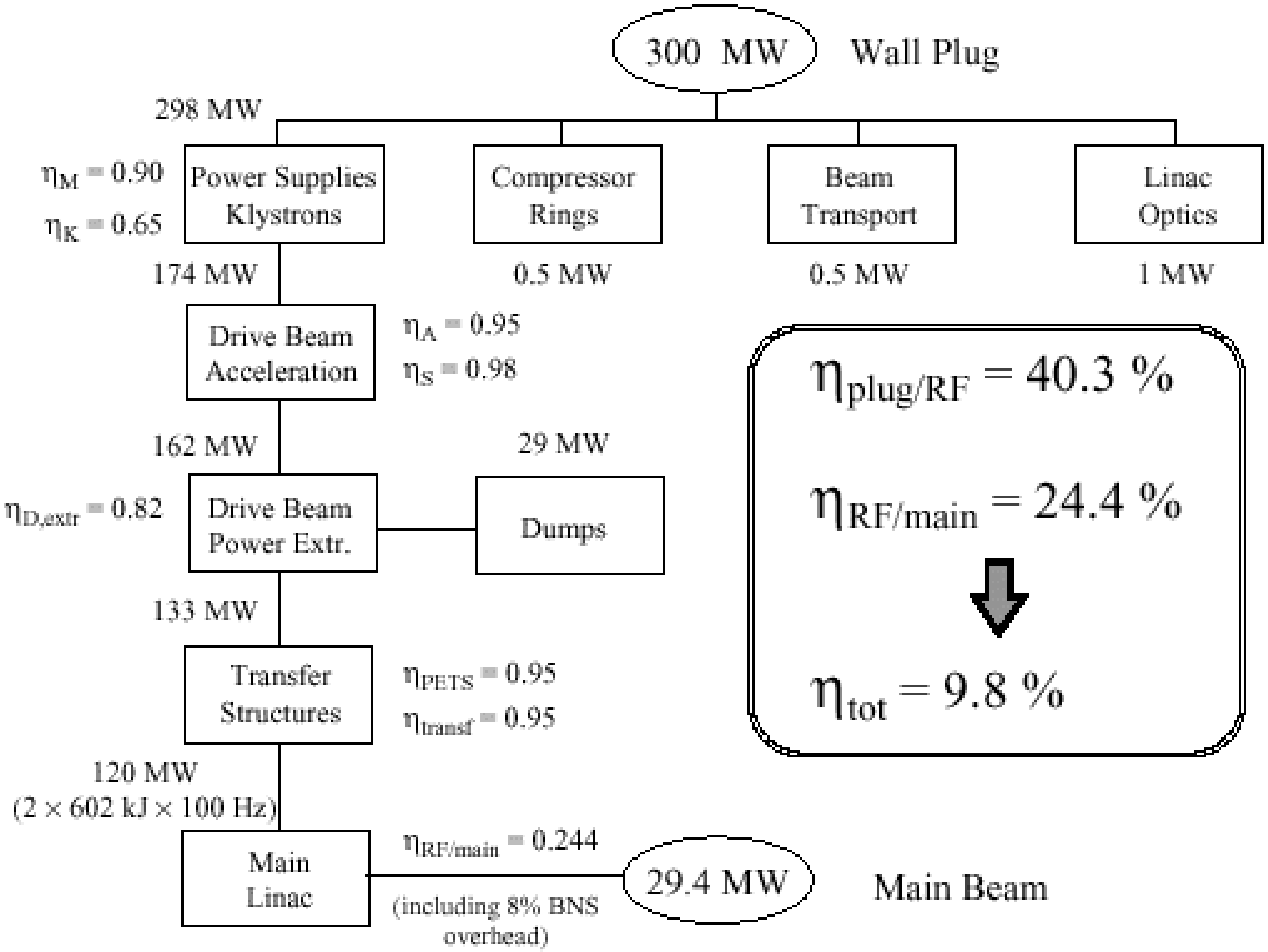


Long RF Pulses
P_0 , ν_0 , τ_0

Electron beam manipulation
Power compression
Frequency multiplication

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

Power flow from the grid to the beam



Improving the efficiency

CLIC

Wall Plug & 30 GHz RF power in CLIC

Wall plug: 300 MW

1 GHz Klystron: 65%
&
Modulator: 90%

30 GHz: 120 MW

New klystron development

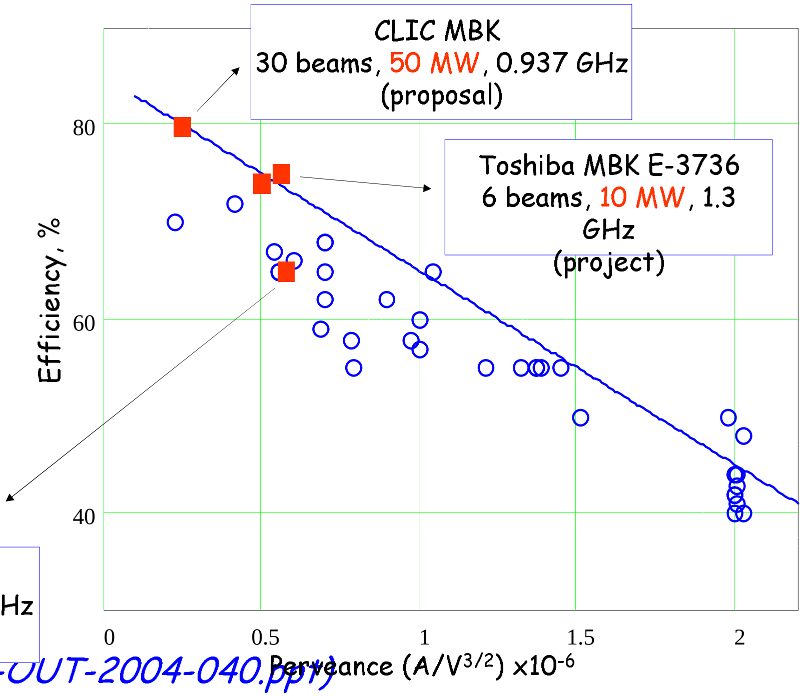
Wall plug: 230 MW

1 GHz Klystron: 80%
&
Modulator: 95%

30 GHz: 120 MW

drive beam acceleration, manipulation & 30 GHZ RF power extraction

Thales MBK TH1801
6 beams, 10 MW, 1.3 GHz
(measured)



Why Multi Beam?

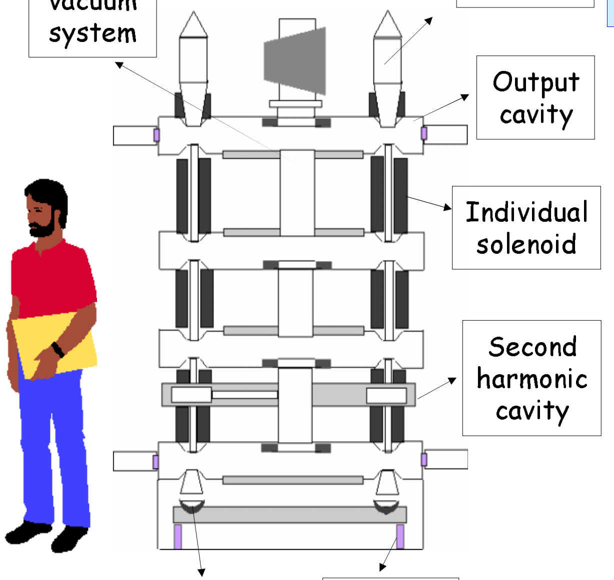
- Low perveance ($A/V^{3/2}$) favor klystron efficiency.
- Multi Beam devices keep single beam perveance small to provide high efficiencies for high RF power output (tens of MW).

State-of-the-art klystron efficiencies vs. perveance for
single beam ○
multi-beam ■

A novel idea of super-efficient Multi-Beam Klystron (80%)

CLIC

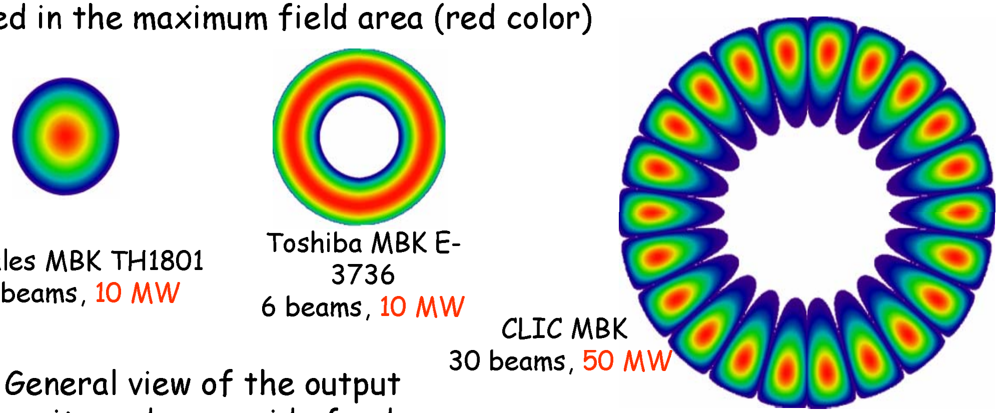
General layout of CLIC MBK
0.937 GHz, 50 MW



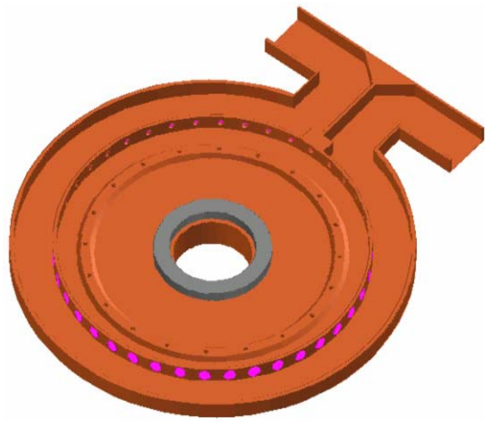
In order to host a large number of beams in a MB Klystron, it is necessary to use RF cavities operating at a mode with higher 1) radial or 2) azimuthal order.

The second case was chosen for the CLIC MBK, which allows higher impedance seen by single beam.

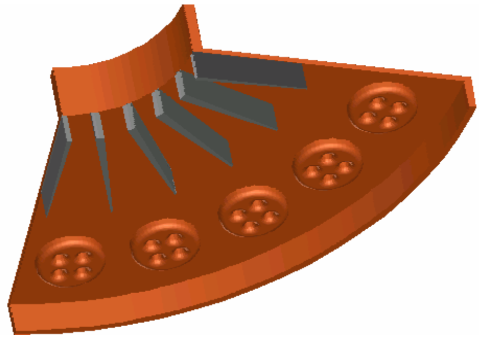
Electric field plots for different MBK's RF cavities. The beams are located in the maximum field area (red color)



General view of the output cavity and waveguide feeder



Damping of the HOM with array of many thin SiC wedges



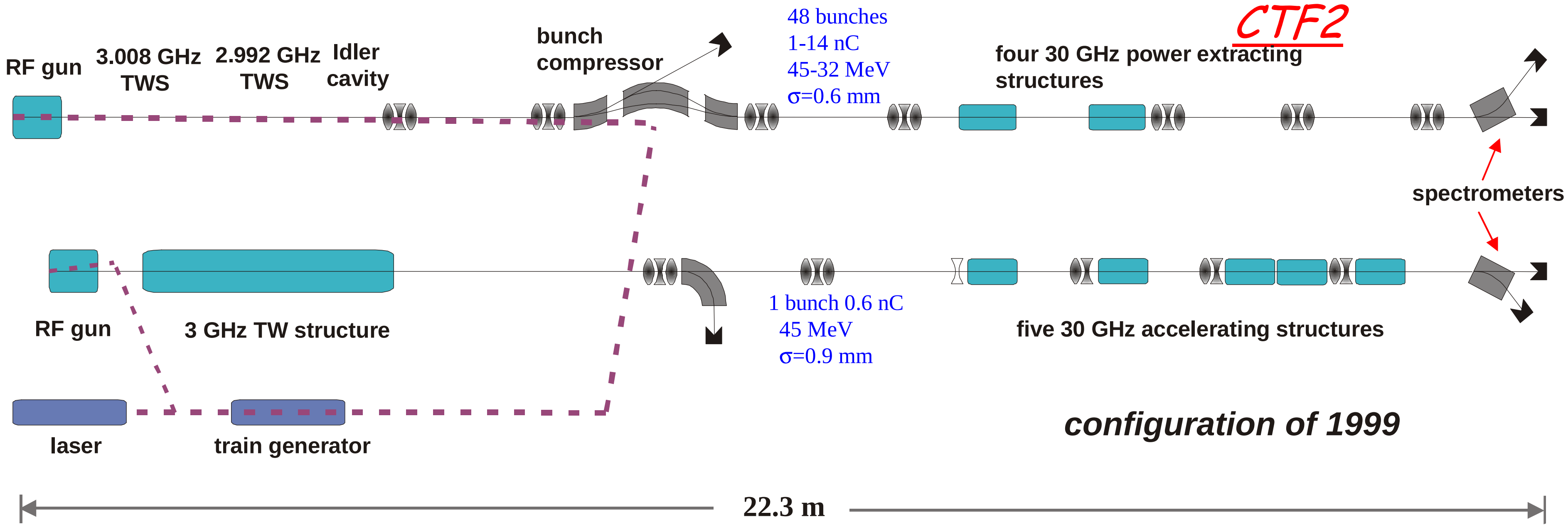
The CLIC MBK uses a series of mini-windows instead of a single ceramic window, thus reducing local RF power flow and ensuring reliability.

CLIC Test Facility (CTF2) 1996-2002

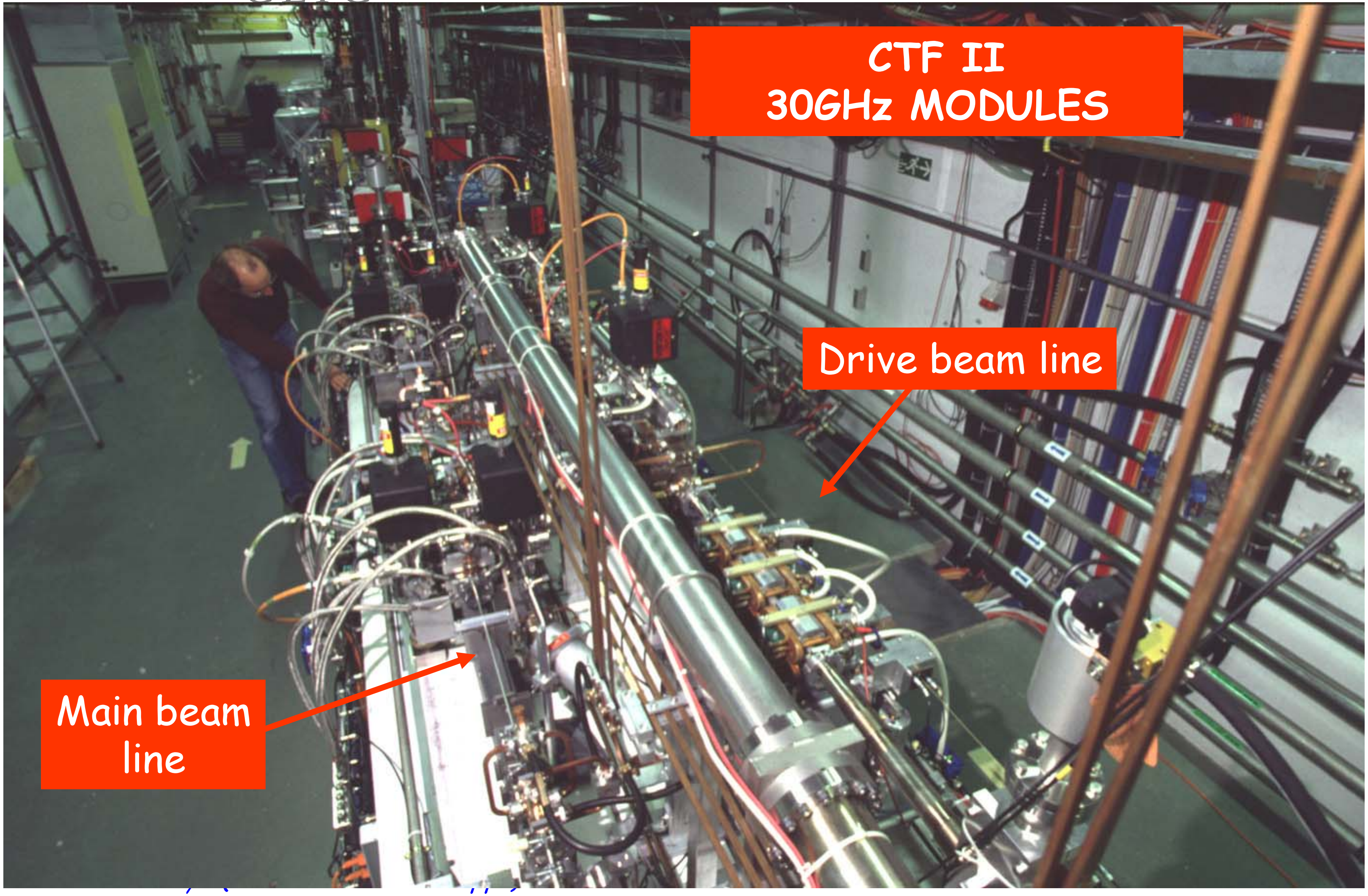
CTF2 goals :

- to demonstrate feasibility of CLIC two-beam acceleration scheme
- to study generation of short, intense e-bunches using laser-illuminated PCs in RF guns
- to demonstrate operability of μ-precision active-alignment system in accelerator environment
- to provide a test bed to develop and test accelerator diagnostic equipment
- to provide high power 30 GHz RF power source for high gradient testing ~90 MW 16 ns pulses

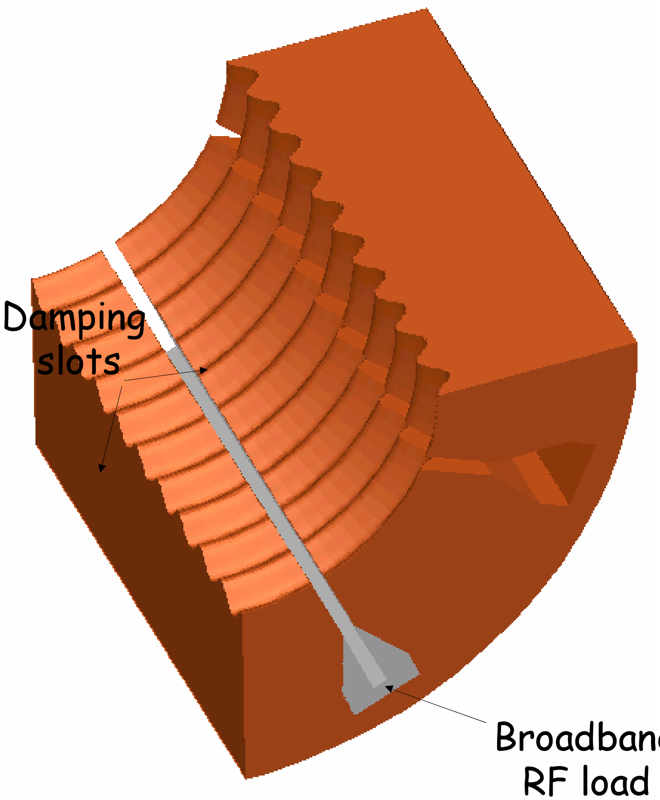
All-but-one of 30 GHz two-beam modules removed in 2000 to create a high-gradient test stand.



Two Beams set-up in CTF2



Power ExTraction Structure (PETS)



Quarter geometry of C-PETS

- Circularly-symmetric
- Large aperture (25 mm)
- Very shallow sinus-type corrugations
- Eight 1 mm-wide damping slots

Table 1. Parameters of the C-PETS.

Beam chamber diameter, mm	25
Synch. mode frequency, GHz	29.9855
Synch. mode β_g	0.85 c
Synch. mode R'/Q, Ω/m	244
Synch. mode Q-factor	12000
Peak transverse wakefield V/pC/m/mm	0.83
Transverse mode Q-factor (damped)	< 50

80 cm length of this structure produces about **560 MW** of 30 GHz RF power ⇒ enough to drive two CLIC accelerating structures

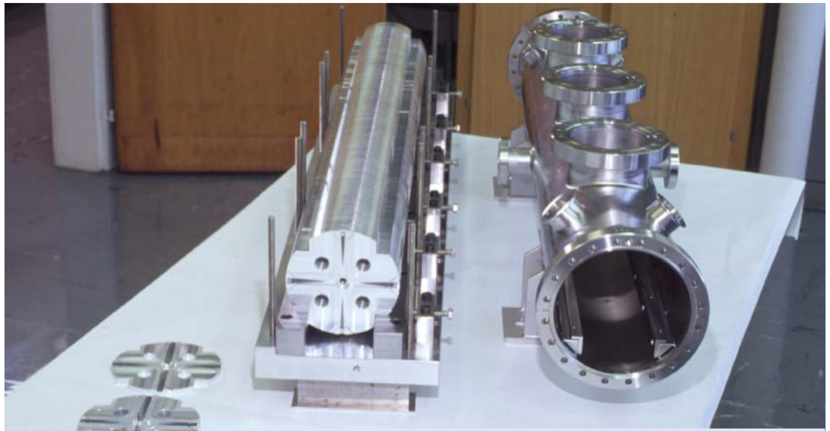
Accelerating structure developments

CONTROL OF TRANSVERSE WAKEFIELDS

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

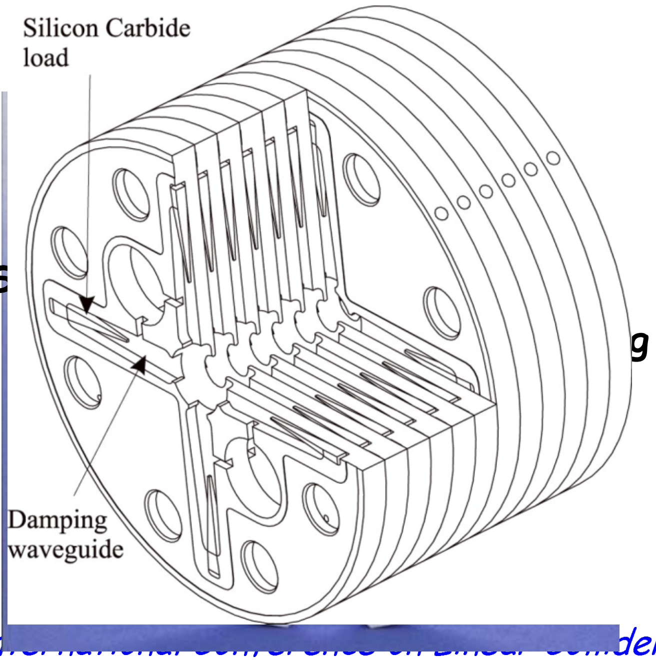
+ beam-based trajectory correction, ε bump

For wake suppression - work still focused on here. Each cell is damped by 4 radial WGs terminated by waveguide-damped structures of type shown discrete SiC RF loads.



15 GHz model tested in ASSET

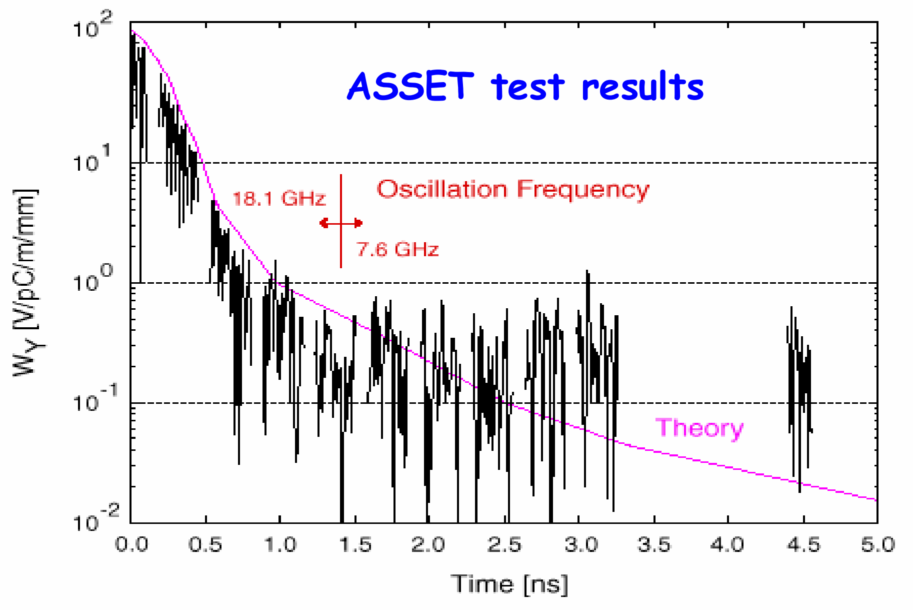
Excellent agreement obtained between theory and experiment – believe we can solve damping problem



g WG

J.

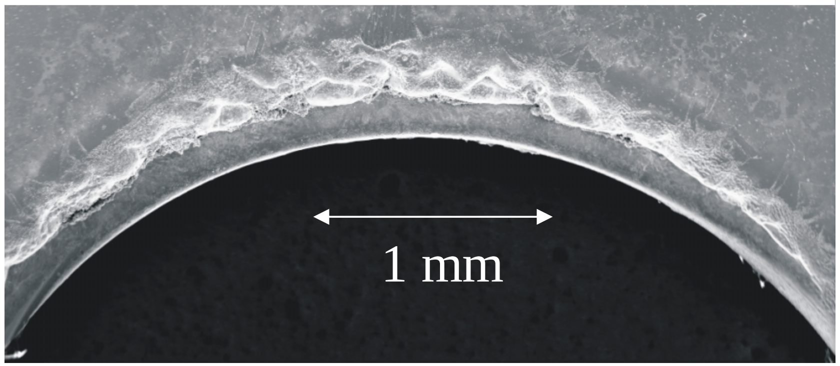
In... ders (LCWS0



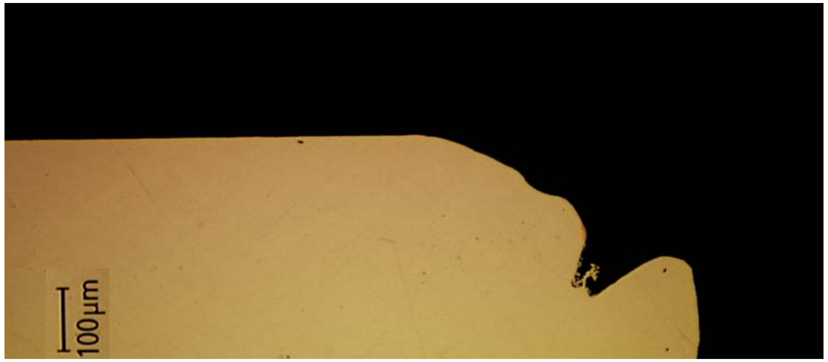
Structure breakdown and damages

High-power tests of copper accelerating structures indicates that for RF pulses **>10 ns**, the maximum surface field that can be obtained with copper is always around **300-400 MV/m.**

At these field levels structures with large apertures (or rather with large a/λ ratios) seem to suffer **severe surface damage.**



Microscopic image of damaged iris

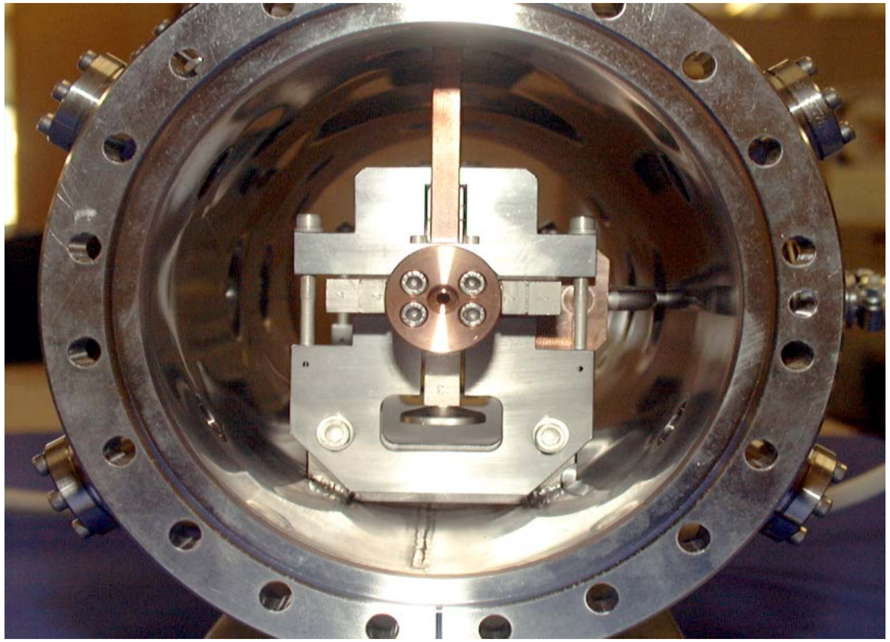


Damaged iris – longitudinal cut

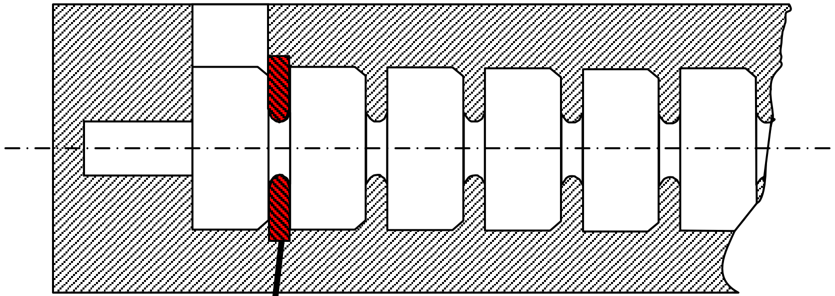
The CLIC study group is adopting a two-pronged approach to solving the breakdown problem

- **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** looks promising

Tests of tungsten iris in CTF2

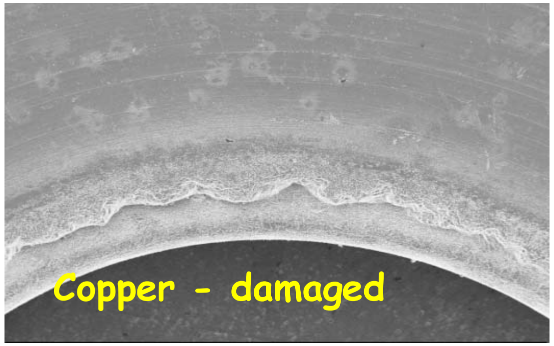


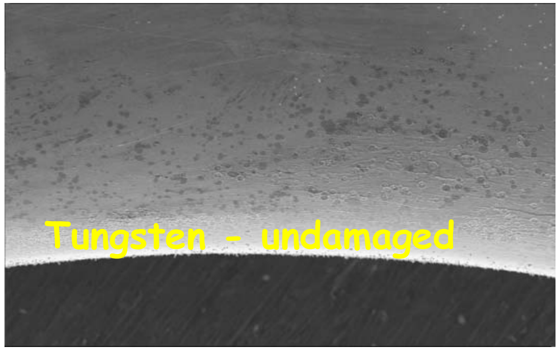
Test structure in external vacuum can, with clamped coupler cell



Copper iris replaced by Tungsten iris

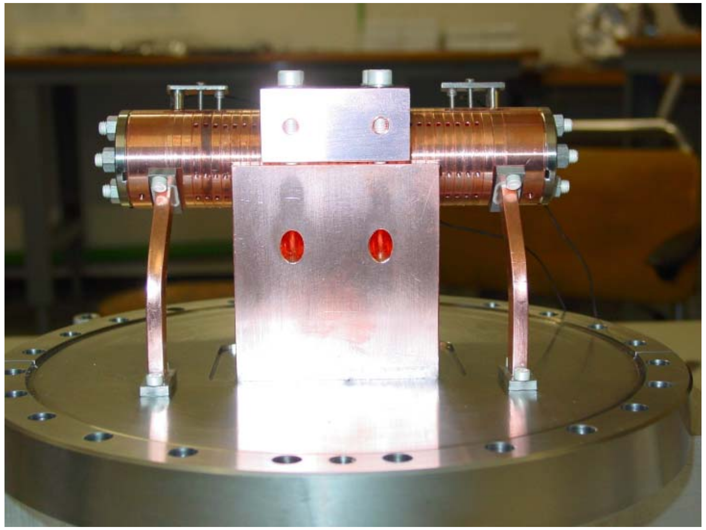
Irises after high-gradient testing to about the same field level



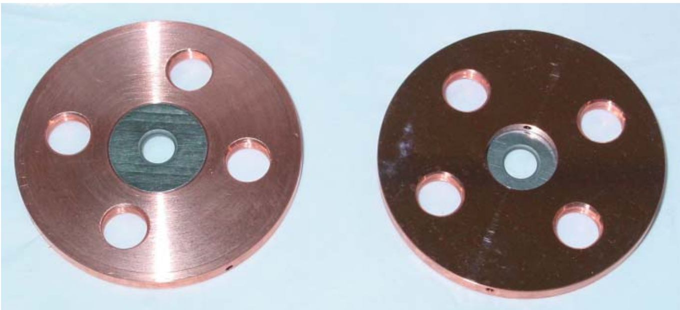


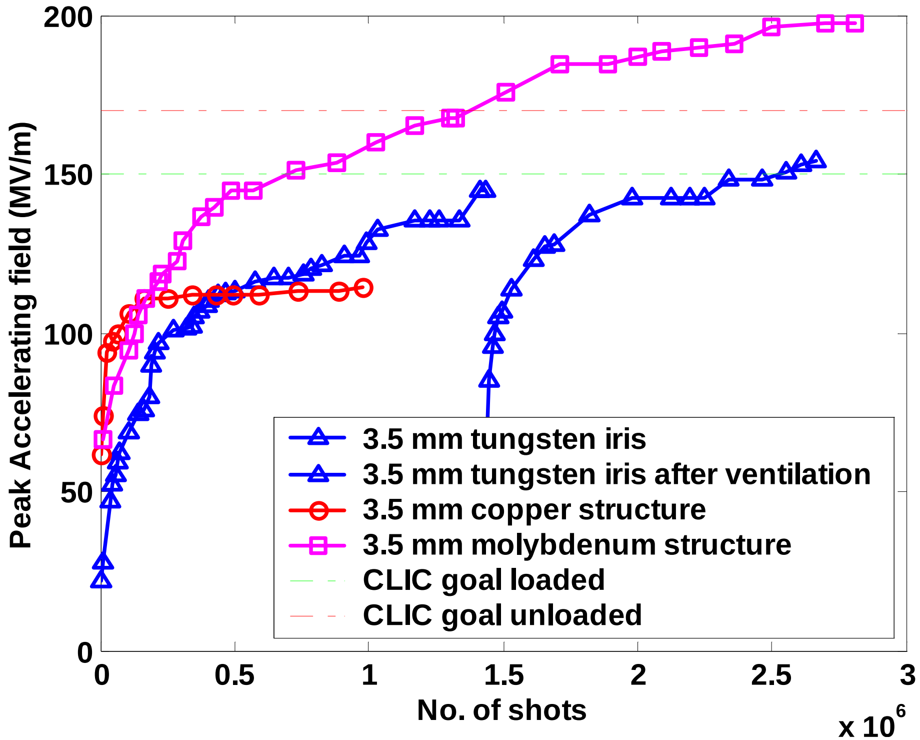
Achieved accelerating fields in CTF2

High gradient tests of new structures with molybdenum irises reached 190 MV/m peak accelerating gradient without any damage well above the nominal CLIC accelerating field of 150 MV/m but with RF pulse length of 16 ns only (nominal 100 ns)



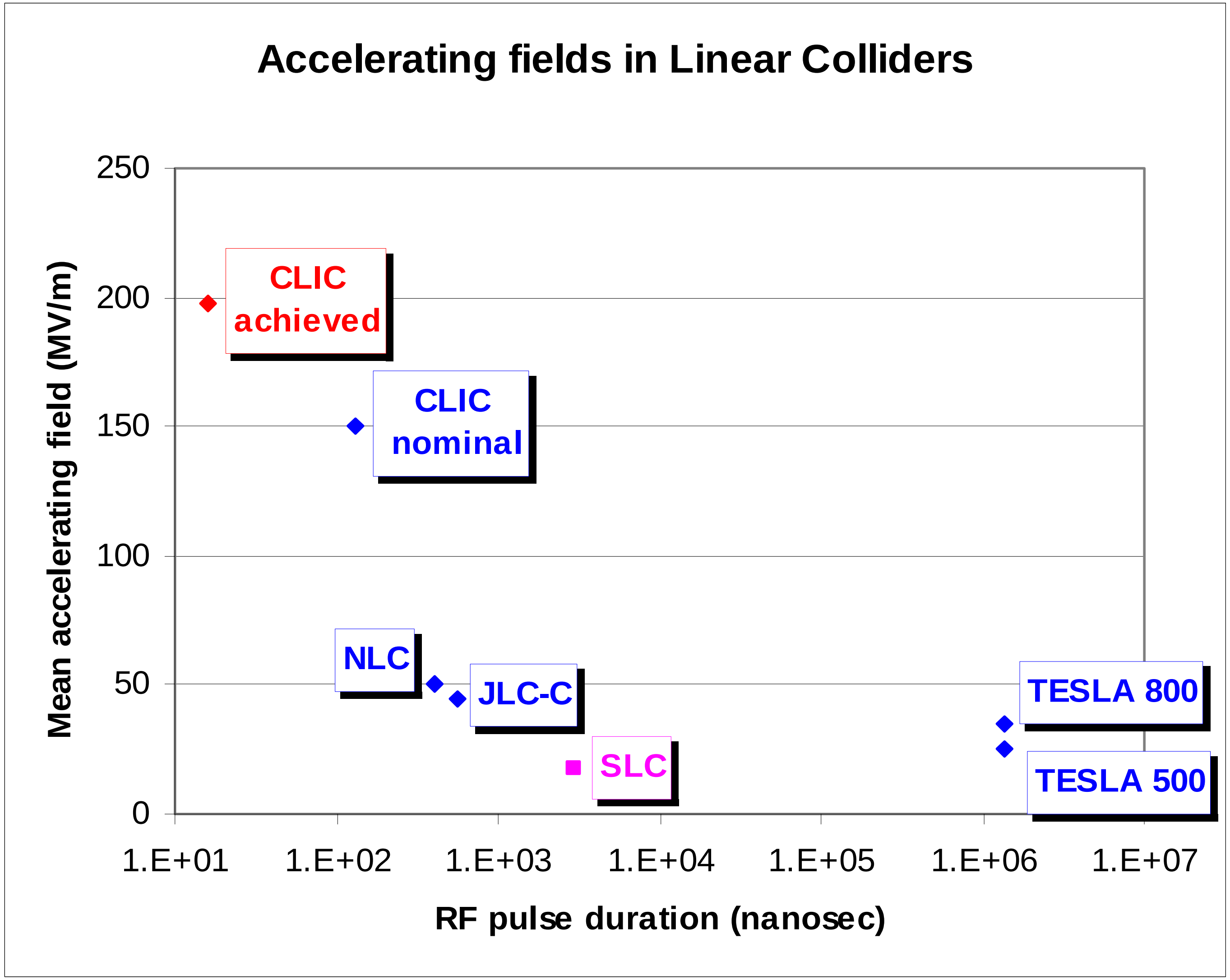
30 cell clamped tungsten-iris structure





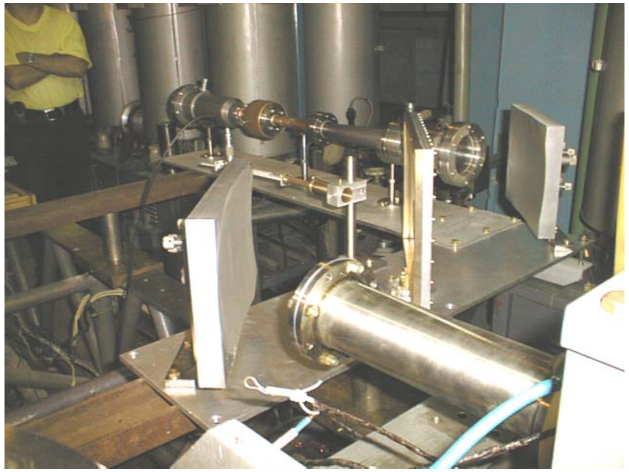
A world record !!!

Accelerating fields in Linear Colliders

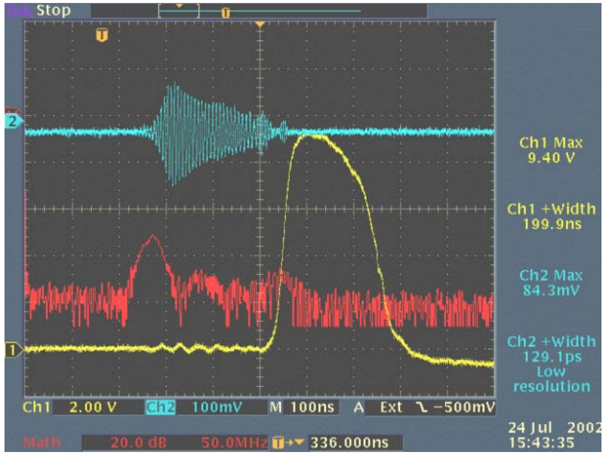


RF pulse heating experiment

The fatigue limit of cooper surface due to cyclic pulsed heating is being tested with an experimental setup based on 30 GHz FEM in Dubna, JINR.
RF accessories designed and manufactured in Nizny Novgorod, IAP.



General views of the experimental setup



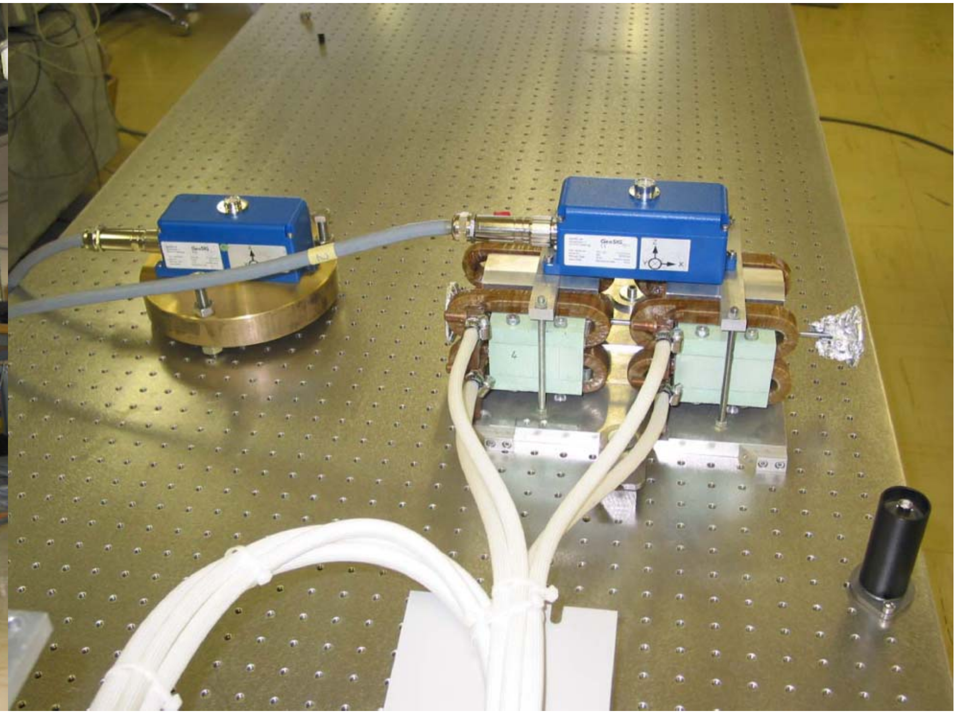
30 GHz, 25 MW, 200 ns RF pulse

Test H_{012} cavity

Nanometer stabilisation

Latest stabilization technology applied to the accelerator field

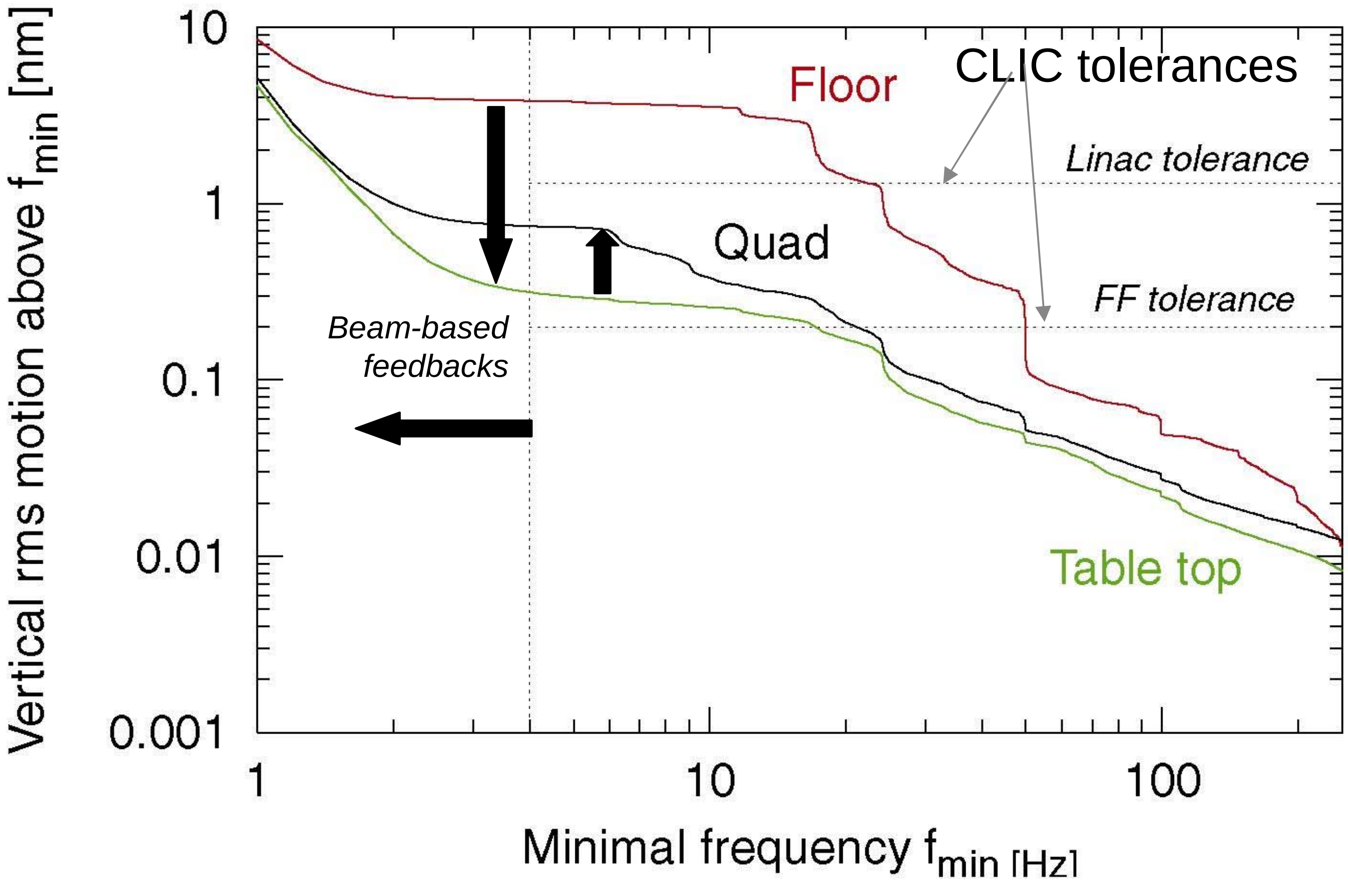
The most stable place on earth!!!



Stabilizing quadrupoles to the **0.5 nm** level!

(up to 10 times better than supporting ground, above 4 Hz)

Achieved stability performances



On magnet top:

without cooling water.

HORIZONTAL:
(0.4 ± 0.1) nm

VERTICAL:
(0.9 ± 0.1) nm
(0.3 nm on table top)

LONGITUDINAL:
(3.2 ± 0.4) nm

Big step towards believing that nanobeams can be made colliding on sites with CERN-like stability

Review of the various Linear Colliders studies requested by ICFA (February 2001)

ILC-TRC Report (2003)

- **Status of various studies (TESLA, JLC-C/X, NLC, CLIC)**
- **Ranking of R&D topics still to be made for each study**
  - ✓ **R1: R&D needed for feasibility demonstration**
  - ✓ **R2: R&D needed to finalize design choices**
  - ✓ **R3: R&D needed before starting production**
  - ✓ **R4: R&D desirable for technical/cost optimisation**

Key issues common to all Linear Colliders studies

independently of the chosen technology

R1: Feasibility: None

R2: Design finalisation (11)

- **Generation of ultra low emittances in Damping-ring (4)**
  - Electron cloud effects (also ATF, LHC)
  - Fast ion instability
  - Stability to < 10^{-3} of extraction kickers
  - Emittance correction
- **Low-emittance measurement and transport (3)**
  - Static tuning, including dynamic effects
  - Beam instrumentation (intra-train L monitors, laser-wire profile monitors)
  - On-girder sources of vibration
- **Reliability (2)**
  - Evaluation of the reliability of critical subsystems, acceptable failure rate
  - Beam based tuning procedures to align magnets and structures, in presence of beam and components errors
- **Multi-TeV operation (2)**
  - Effects of coherent synchrotron radiation in bunch compressors
  - Design of an extraction line of the beam delivery system with large momentum spread

CLIC technology-related key issues

R1: Feasibility

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

R2: Design finalisation

- ✓R2.1: Validation of stability and losses of drive beam decelerator; Design of machine protection system
- ✓R2.2: Test of relevant linac sub-unit with beam
- ✓R2.3: Validation of Multi-Beam Klystron with long RF pulse

This list covers all of the CLIC-specific TRC Ranking 1 and 2 items except the two below which are valid for any multi-TeV Collider:

- Effects of coherent synchrotron radiation in CLIC bunch compressors (TRC R2)
- Design of an extraction line for 3 TeV c.m. (TRC R2)

Strategy

- **Key issues common to all Linear Collider studies independently of the chosen technology:**
  - **Collaboration with other Linear Collider studies and with European Laboratories in the frame of a "Design Study" proposed for funding by EU Framework Programme (FP6)**

- **Key issues specific to CLIC technology:**
  - **Focus of the CLIC study**
  - **All R1 (feasibility) and R2 (design finalisation) key issues addressed in new test facility: CTF3**

    except the Multi-Beam Klystron (MBK) which does not require R&D but development by industry (feasibility study already done)

Coordinated Accelerator Research in Europe (CARE)

•CARE submitted by European Steering Group for Accelerator R&D (ESGARD: Chairman R.Aleksan/Saclay) to the EU 6th Framework Programme.

• Requested 29 M€ - Granted 15.2 M€

3 Network activities - 4 Joint research activities

N2: Coordination of studies and technical R&D for electron linear accelerators and colliders (ELAN) - EU:0.67M€ /1.6M€
Coordinator: F. Richard (CNRS-IN2P3-Orsay)
Deputy: D.Schulte (CERN)

JRA3: Charge production with photo-injector(PHIN) - EU:3.54M€ /5.88M€
Coordinator: A. Ghigo (INFN-LNF)
Deputy: L. Rinolfi (CERN)

CLIC

The Photo-Injector
a performing e⁻ source for CTF3

CERN

Photocathodes

+

Timing

RF power

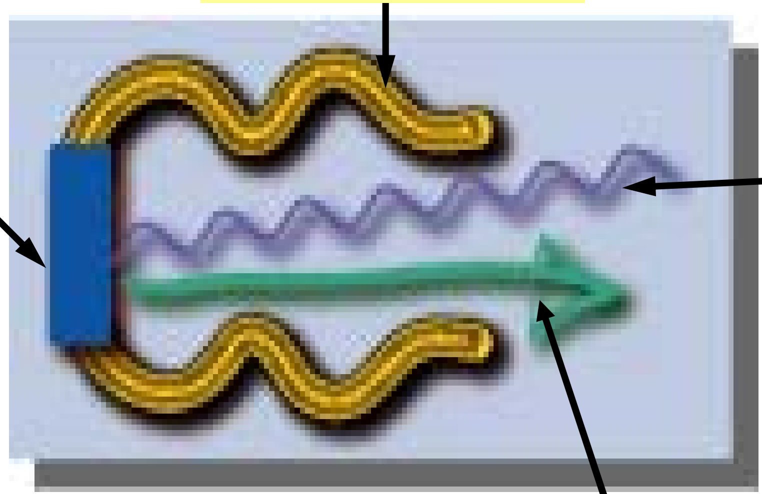
Laser beam transport

Installation

Monitoring …

LAL (F)

3 GHz RF gun



RAL (GB)

High power Laser

2332 e^- pulses distant from 667 ps ; σ = 4 ps ; Q_{pulse} = 2.33 nC

2004 - 2006 : construction and installation of the photo-injector included in the European program CARE (FP6)

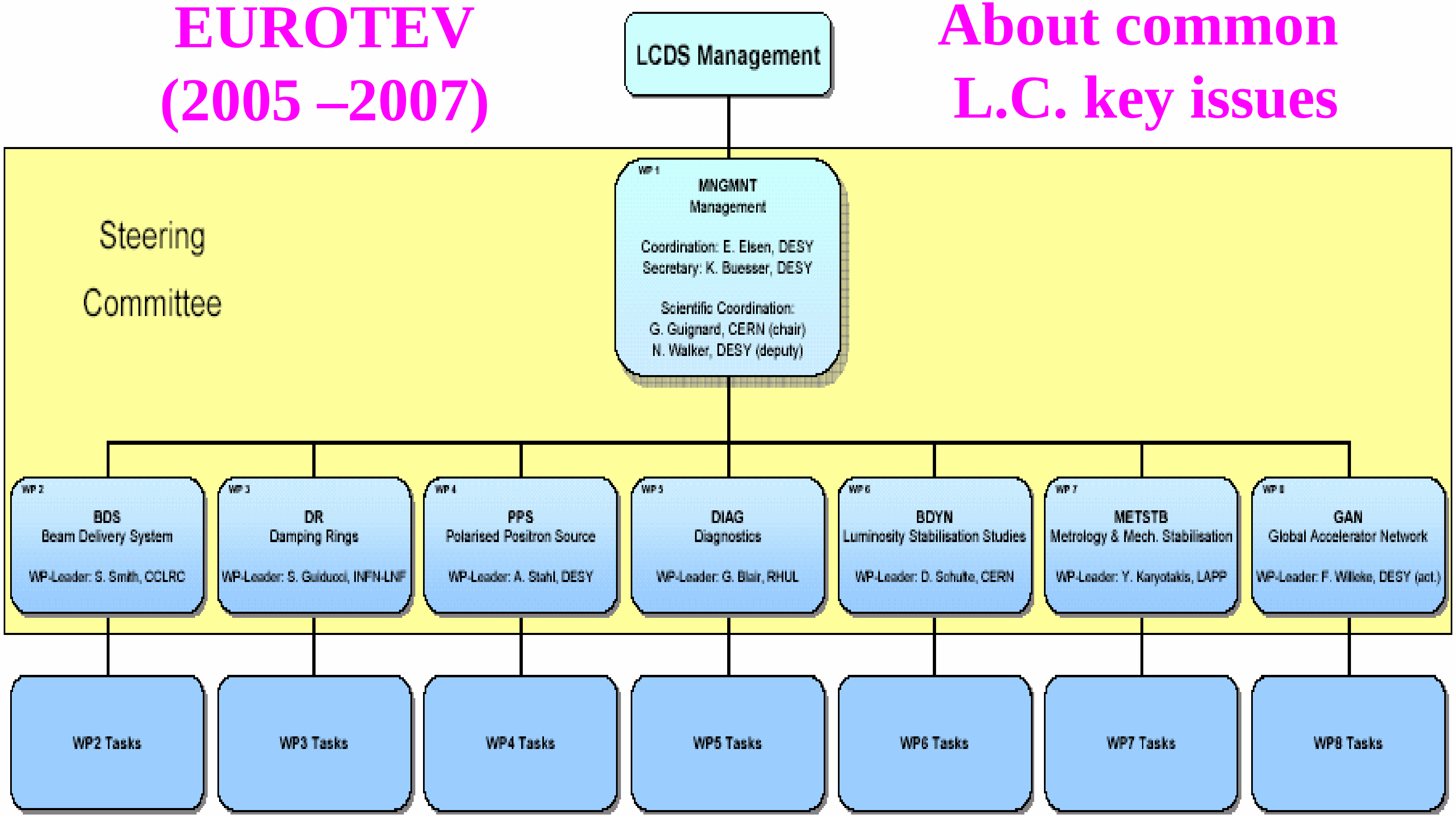
E.U. funding: 90 % of the request ≈ 2 MCHF

Proposal for EU supported Linear Colliders Design Study

CLIC

EUROTEV (2005 –2007)

About common L.C. key issues

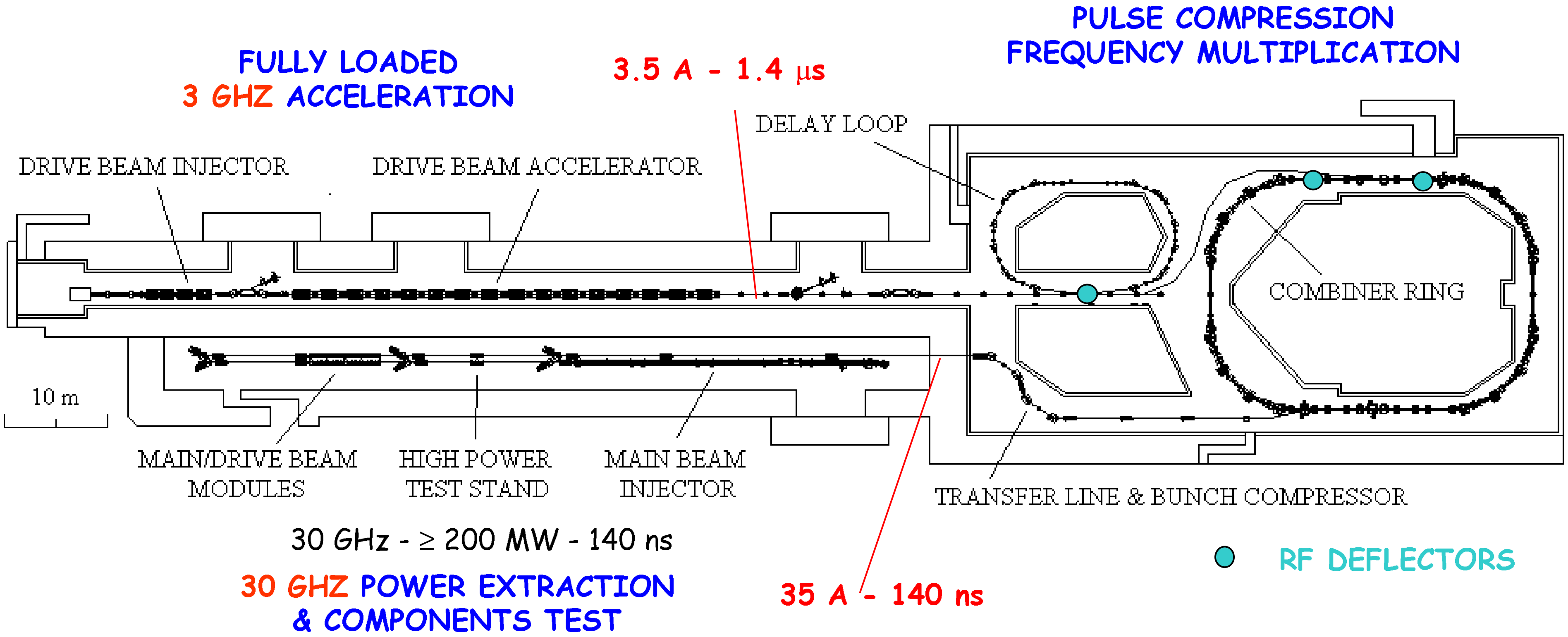


27 collaborating institutes

Institute	WP1: MNGMNT	WP2: BDS	WP3: DR	WP4: PPS	WP5: DIAG	WP6: ILPS	WP7: METSTB	WP8: GANMVL
CCLRC	X	C	X	X			X	
CEA		X						
CERN	C	X	X		X	C		
DESY	C		X	C	X	X	X	C
ELETTRA								X
FHG								X
GSI								X
INFN-LNF	X		C					X
INFN-Mi								X
INFN-Ro2								X
IPPP				X				
LAL					X	X		
LAPP	X						C	
PSI						X		
QMUL		X				X		
RHUL	X				C	X		
TEMF,TUD		X						
UBER				X				
UCAM					X			
UCL					X			
ULANC		X						
ULIV				X				
UMA		X				X		
UMH								X
UNIUD								X
UOXF.DL					X		X	
UU					X	X		

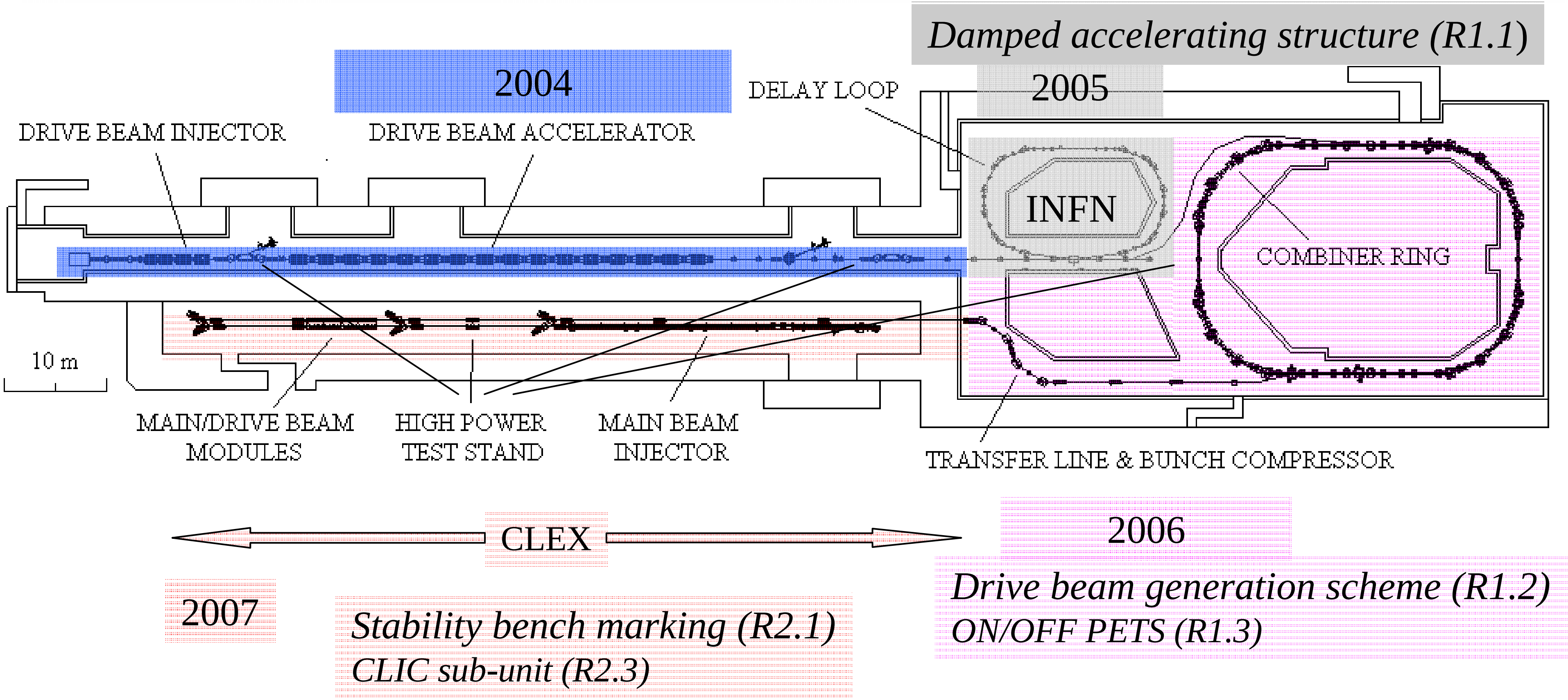
All R1 and R2 CLIC key issues addressed in CLIC Test Facility (CTF3)

Test of Drive Beam Generation, Acceleration & RF Multiplication by a factor 10
Two Beam RF power generation & component tests with nominal fields & pulse length



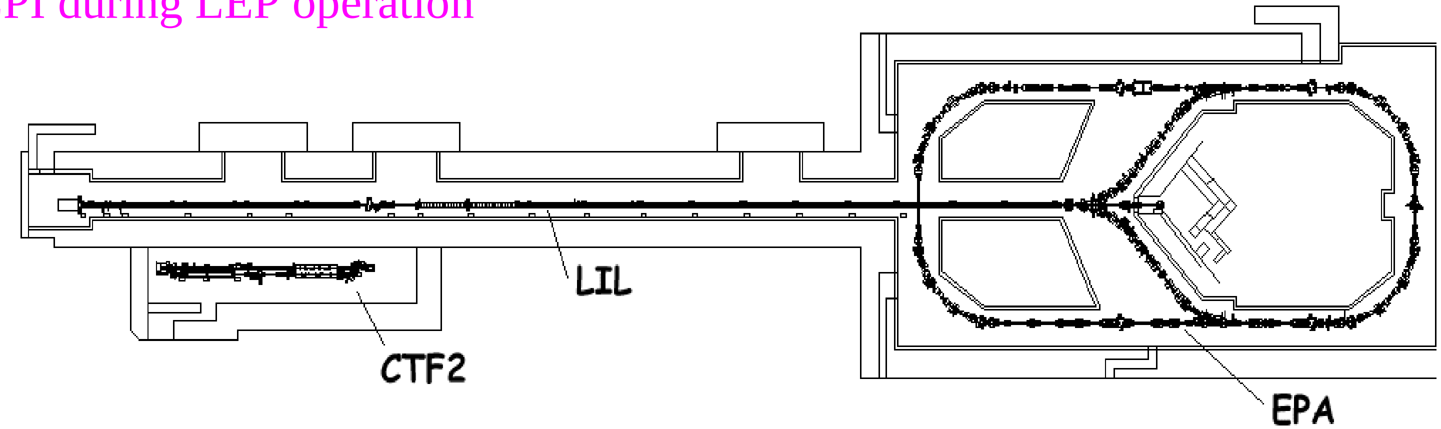
CLIC Test Facility: CTF3

Collaboration CERN –INFN –LAL –NWU –RAL –SLAC -Uppsala

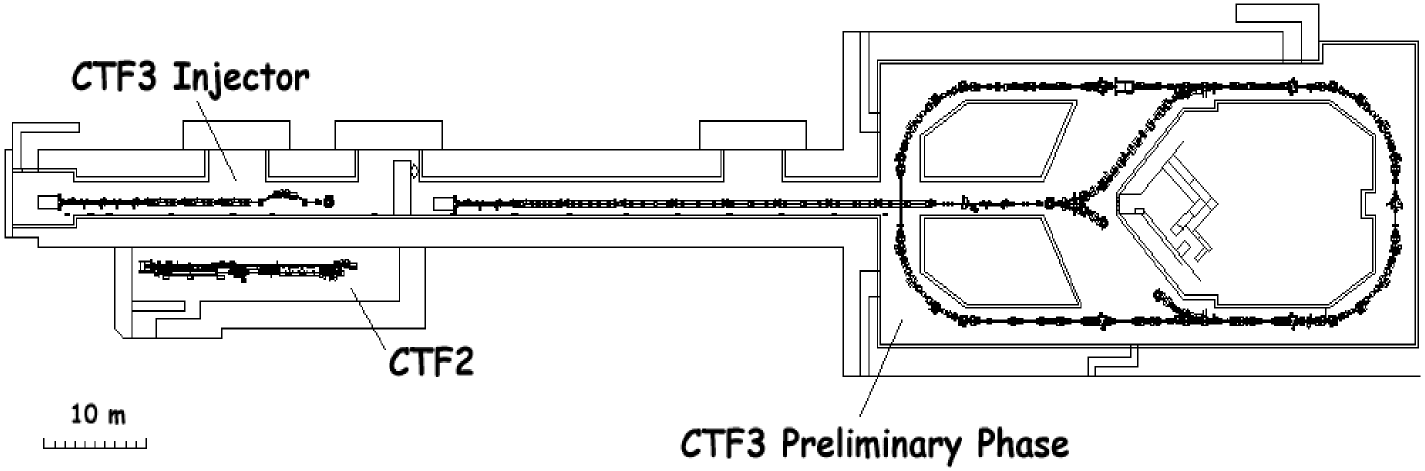


Preliminary phase with LEP Pre-Injector (LPI)

LPI during LEP operation



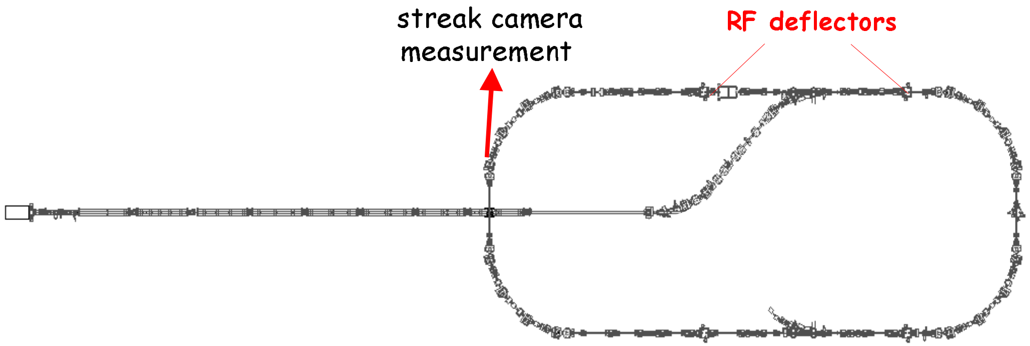
LPI in 2003

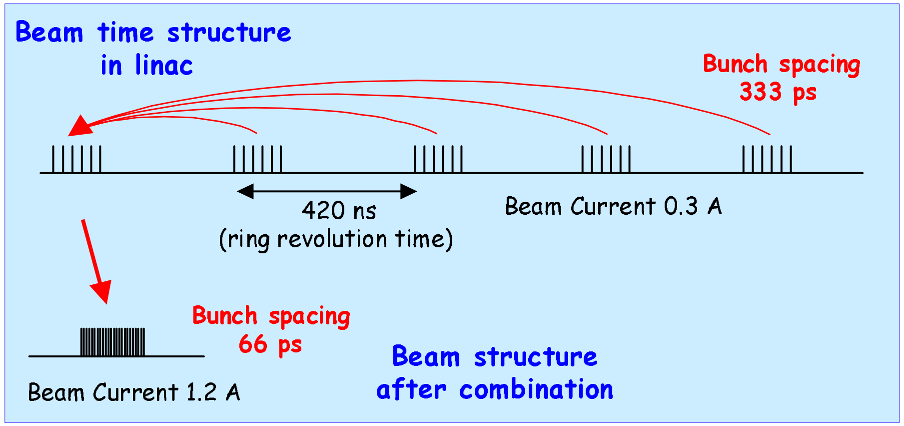


Beam power and frequency multiplication

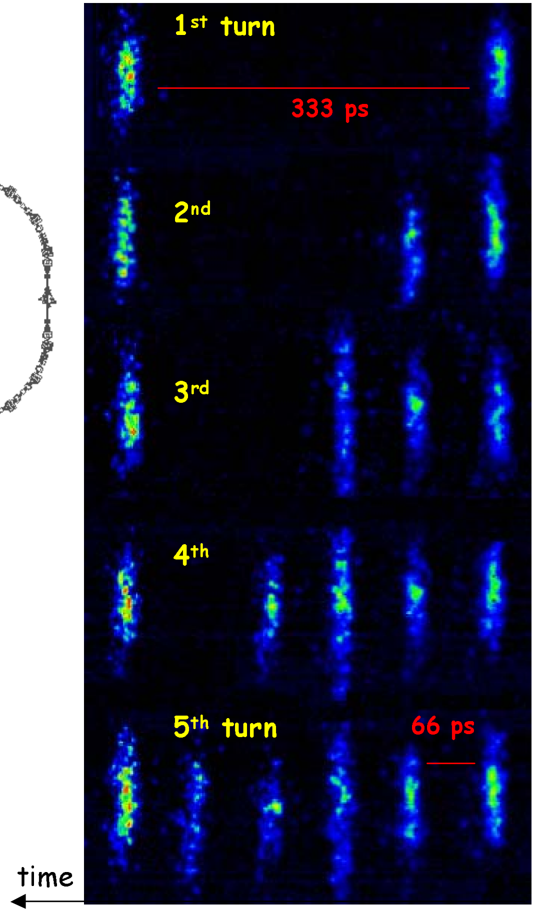
CTF3 - PRELIMINARY PHASE

low-charge demonstration of electron pulse combination and bunch frequency multiplication by up to factor 5

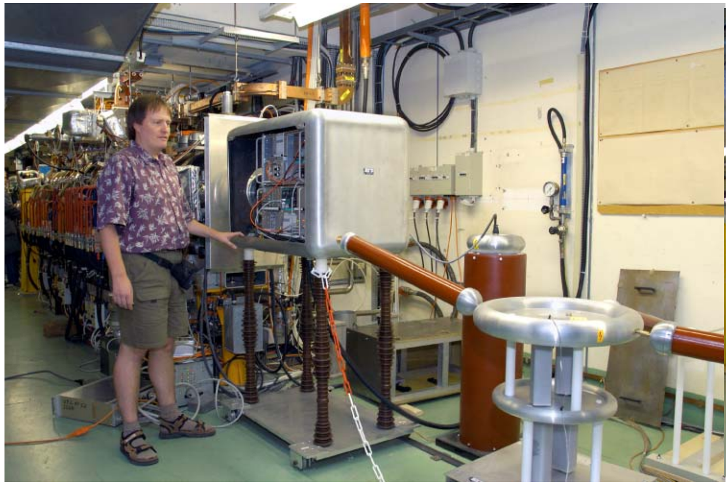




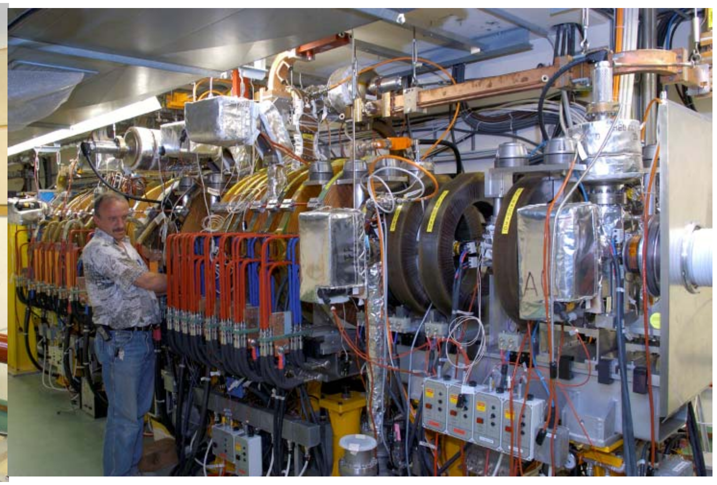
Streak camera image of
beam time structure evolution



CTF3 Injector installation



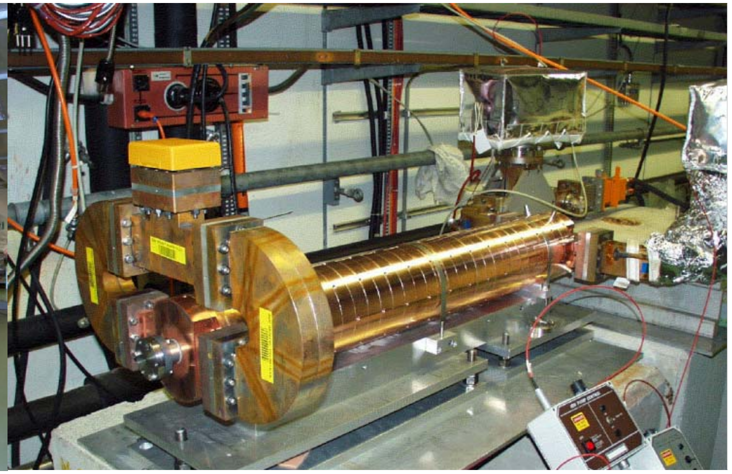
7A Thermionic Gun (LAL-SLAC)



Bunchers(LAL)&Solenoids(SLACstudy)

Novel RF power compression with Barrel Open Cavity (BOC)

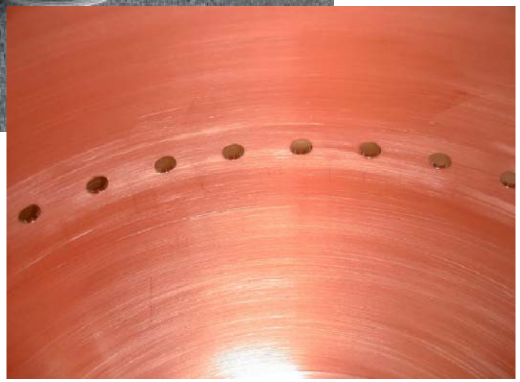
Bunch length adjustment with magnetic chicane

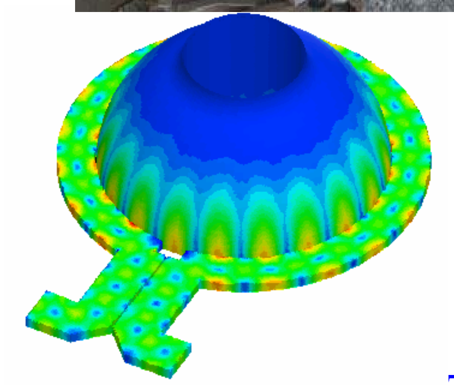


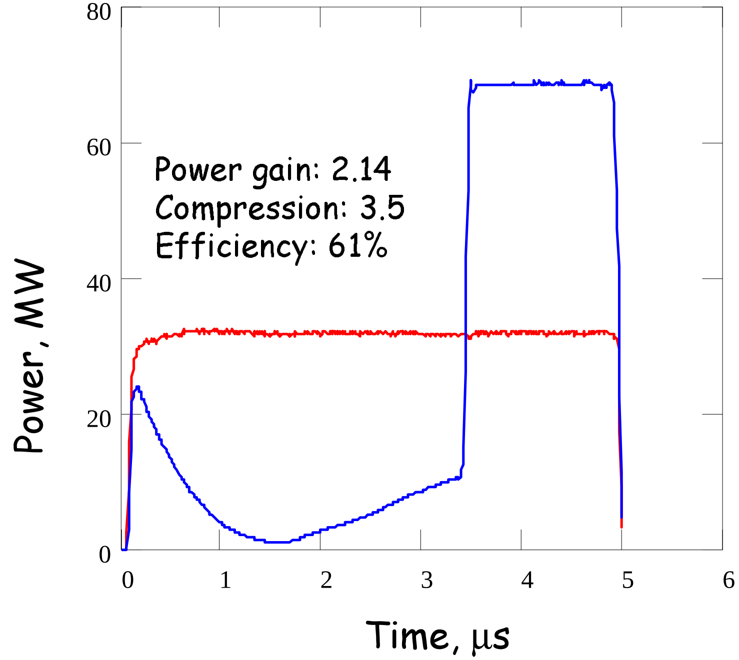
Accelerating structure with full beam loading

Novel method of RF pulse compression with flat pulse

3 GHz Barrel Open cavity RF pulse Compressor







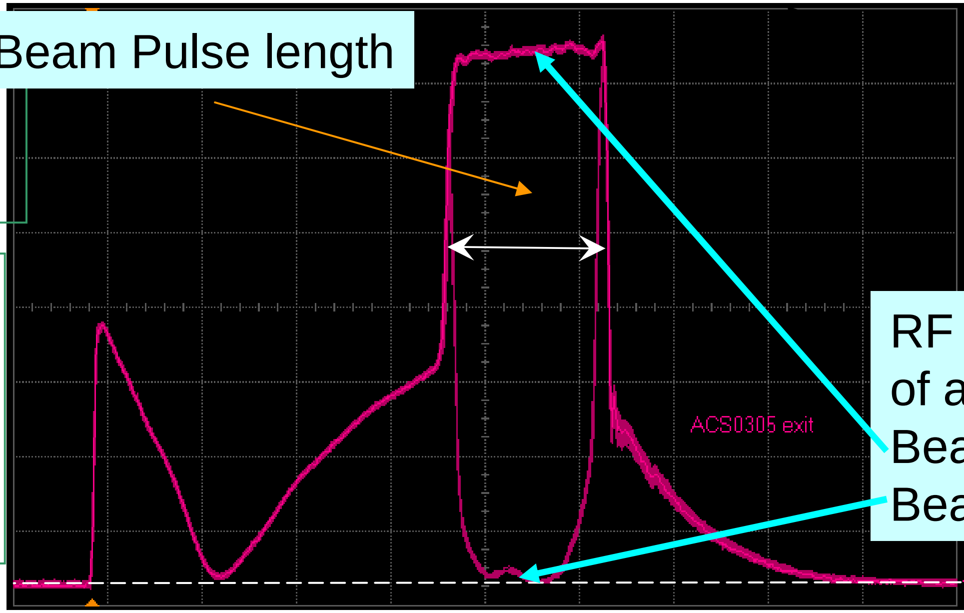
Rotating "whispering gallery" mode ($E_{1,1,10}$). HFSS RF simulations. High power tests demonstrated full validity of the method.

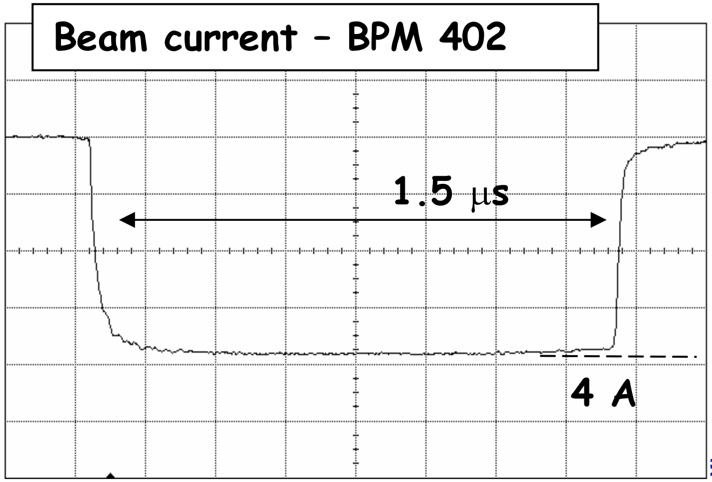
CTF3 injector
Achieved performances in 2003

A world premiere

Demonstration of full beam loading

94% RF to Beam transfer efficency (better than Superconducting Cavities!)

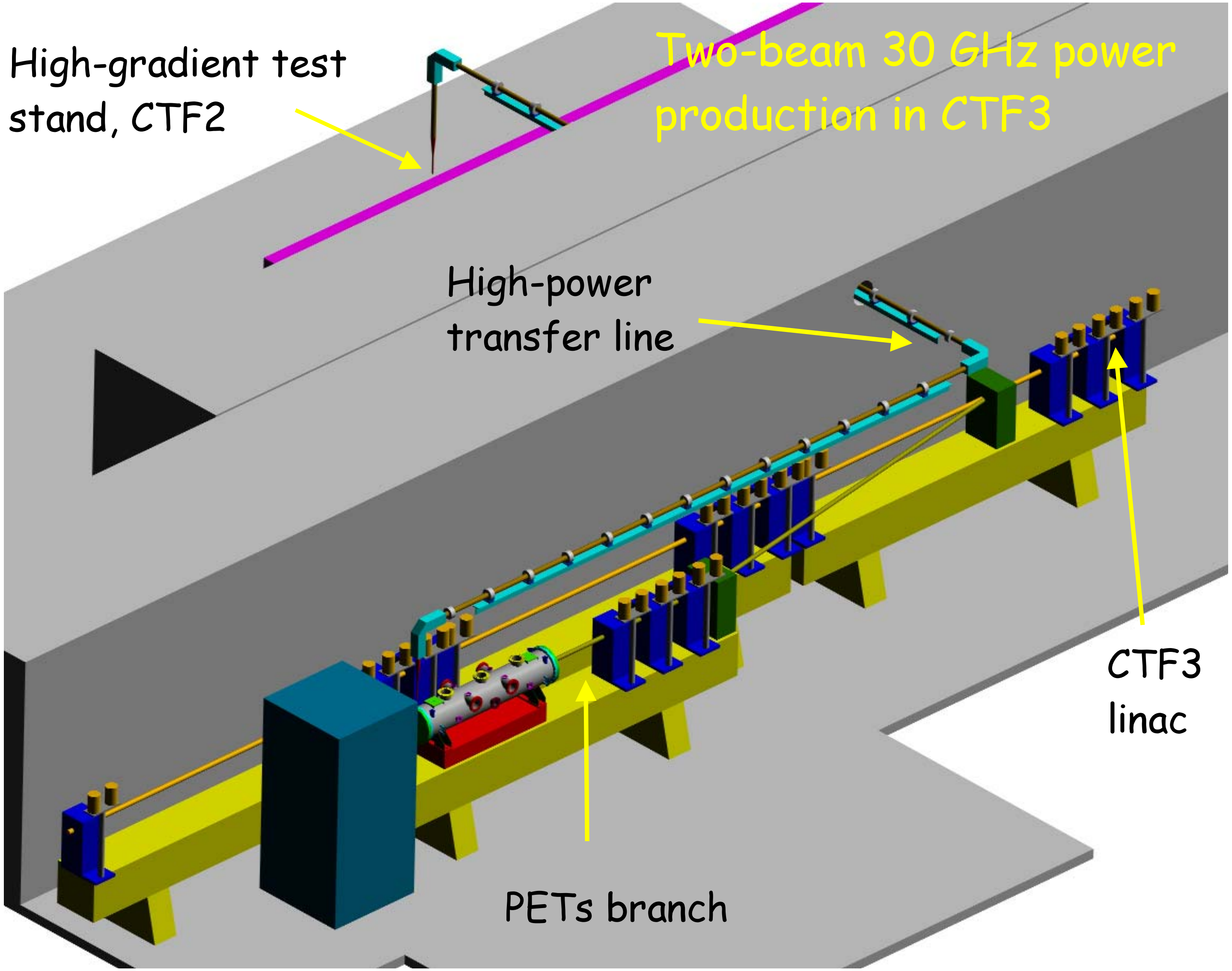




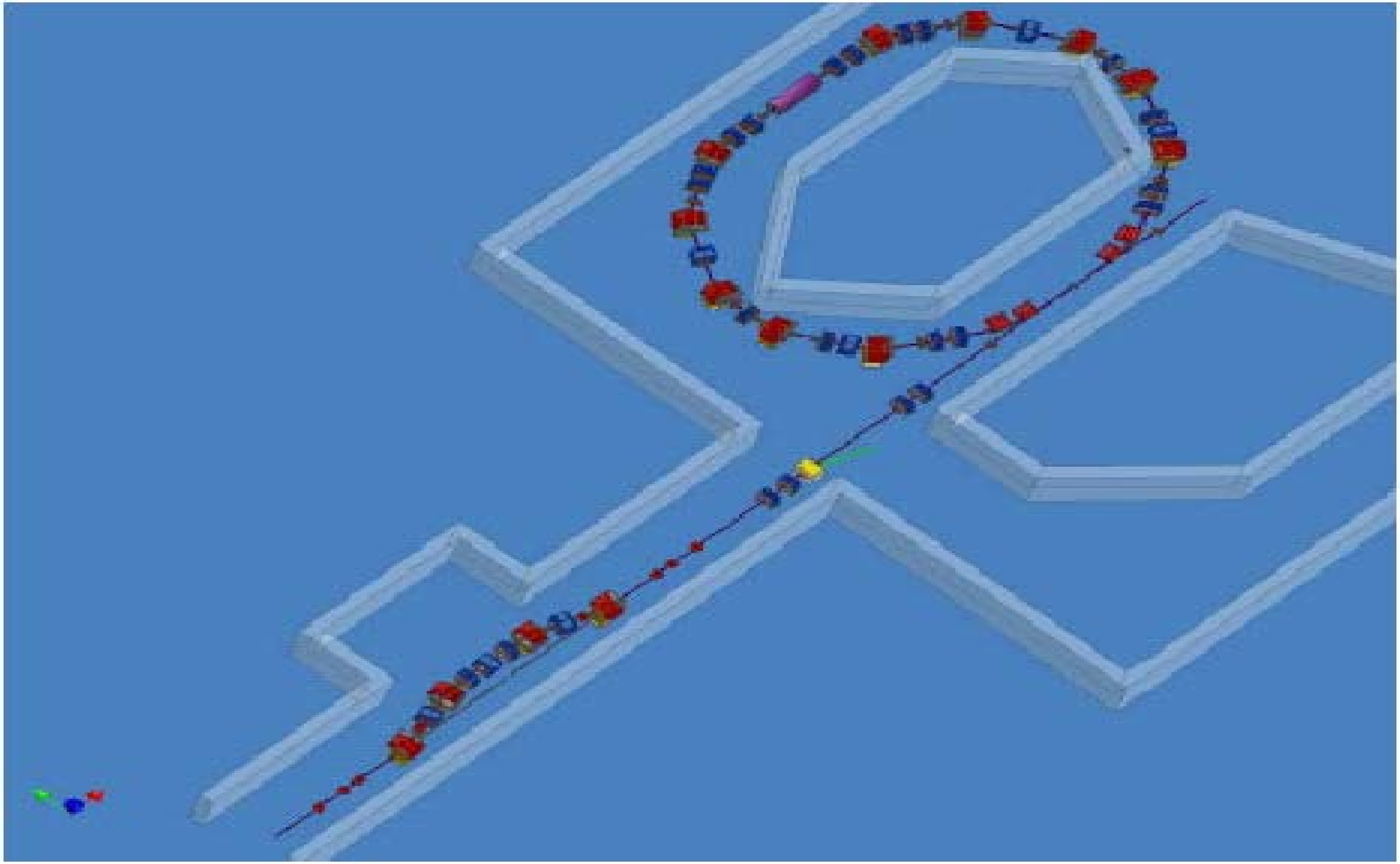
Nominal Beam parameters reached

Beam current	4 A
Beam pulse length	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%
Phase variation along pulse	±4°

Two beam test stand

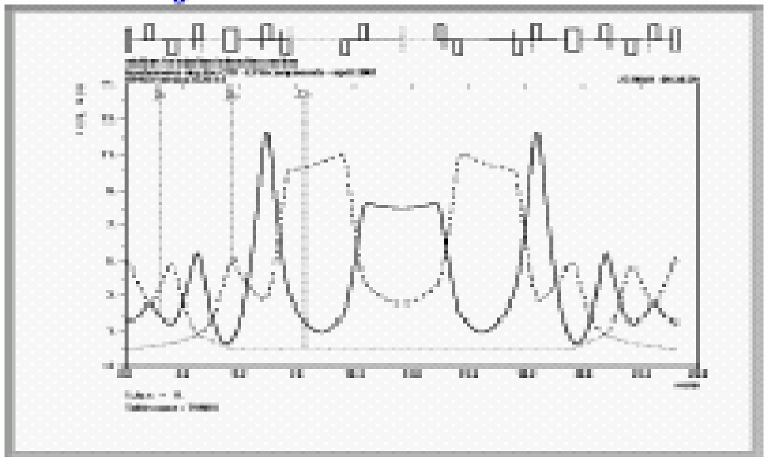


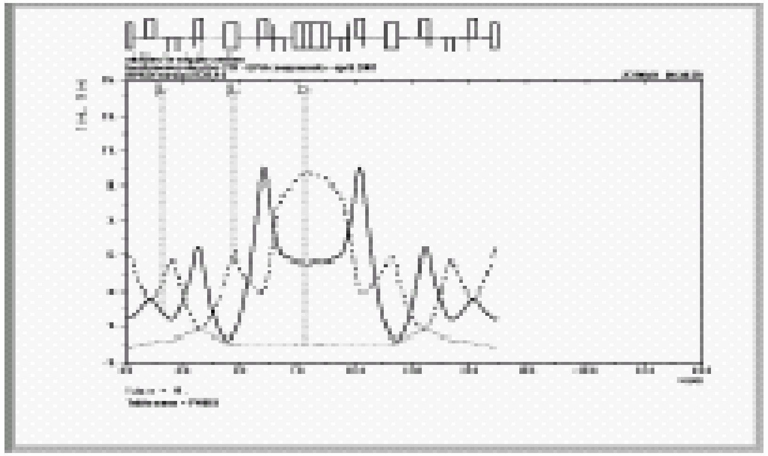
Bunch Compressor and Delay Loop (design, construction, resources by INFN-LNF)



Combiner Ring design (INFN-LNF)

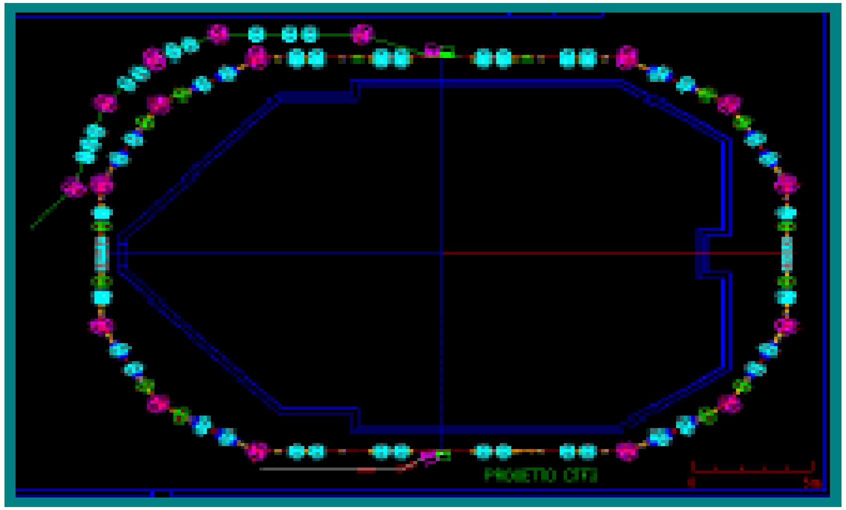
Injection/extraction sections





Wiggler sections

Isochronicity in CR



Isochronicity and achromaticity in each arc of the ring

π phase advance between rf deflectors

Optimum phase advance for minimum beam loading in rf deflectors

M&P resources

Some important elements of the CTF3 are presently unfunded due to the focusing of the CERN budget on the cost to completion of the LHC:

- The combiner ring (estimated cost 5.7 MCHF & 14 m-y)
- The experimental area, CLEX, including high-gradient test stands and test beam lines (8.5 MCHF & 38 m-y)
- A linac-driven high gradient test stand (2 MCHF & 6m-y)
- Structure technology developments (0.5 MCHF & 12 m-y)
- CTF3 exploitation (0.5 MCHF & 25 m-y)

- Total: 17.2 MCHF & 95 m-y over 6 years (2004-2009)

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				■		
Delay Loop	■	■				
Combiner Ring	■	■	■			
R1.2 feasibility test of Drive beam generation				■		
CLIC Experimental Area (CLEX)		■	■			
R1.3 feasibility test PETS				■		
Probe Beam			■	■		
R2.2 feasibility test representativeCLIC linac section					■	
Test beam line		■	■	■	■	
R2.1 Beam stability bench mark tests					■	■

CLIC key issues

- **CLIC technology-related key issues in CTF3**
  - ✓**Feasibility issues: 2007**

    Assuming extra resources (8.2 MCHF and 45 M-y) are available early enough (3 MCHF to be committed in 2004), the installations needed can be completed by 2006 and the tests with beam by 2007

  - ✓**Design finalisation issues: 2009**

    Assuming additional extra resources (9 MCHF and 50 M-y) are available, the installations needed can be completed by 2008 and the tests with beam by 2009

- **Key-issues common to Linear Collider: 2008**

  Assuming approval of Design study by EU within the 6th EU Framework Programme (FP6), studies in collaboration with European Institutes can be completed by 2008.

Plea for collaboration

- Institutes are invited to contribute to this programme by:
  - ✓ taking full responsibility for part, complete of one or several work-packages
  - ✓ providing voluntary contributions "a la carte" in cash, in kind and/or in man-power

- Multilateral collaboration network of volunteer institutes (from which CERN is one of them) participating jointly to the technical coordination and management of the project.

Collaboration meeting to be held at CERN on 19/05/04

CONCLUSION

- CLIC only possible scheme to extend Linear Collider energy range into the Multi-TeV range.
- CLIC technology requires challenging R&D
- Very promising performances already demonstrated in CTF2
- Remaining key issues clearly identified (ILC-TRC)
- Key-issues independent of the technology studied by 2008 in a wide collaboration of European Institutes (Design Study submitted to EU FP6 funding)
- CLIC-related key-issues addressed in CTF3 (feasibility by 2007 and design finalisation by 2009) if extra resources can be found

CONCLUSION

- All Institutes invited to join a **multilateral collaboration network** (from which CERN is one of them) by **taking full responsibility of work packages, providing corresponding resources** and participating jointly to the technical coordination & management of the project.

- Provide the High Energy Physics community with the information about the **feasibility of CLIC technology for Linear Collider in due time** when Physics needs will be fully determined following LHC results.