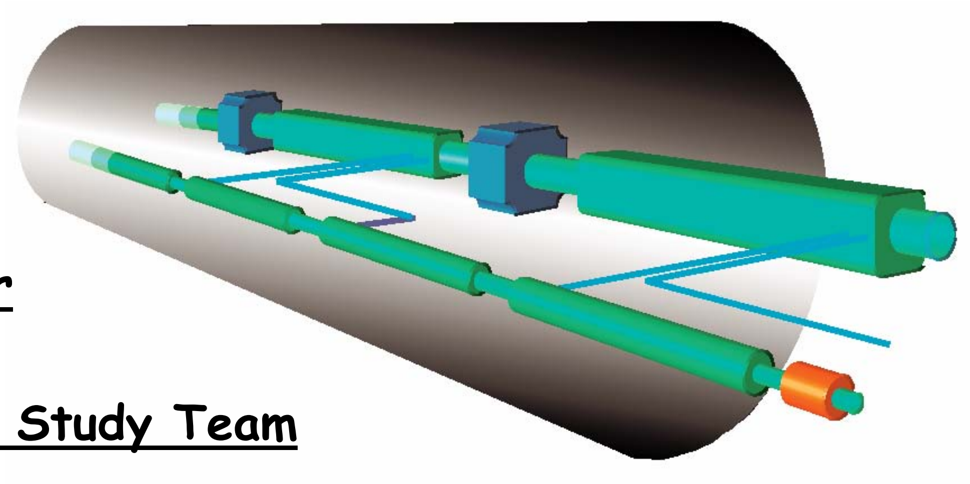
THE COMPACT LINEAR COLLIDER (CLIC) STUDY



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/

CERN 2000-008, CERN 2003-007, CERN 2004-005

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
- Possible facilities at low energy
- Conclusion

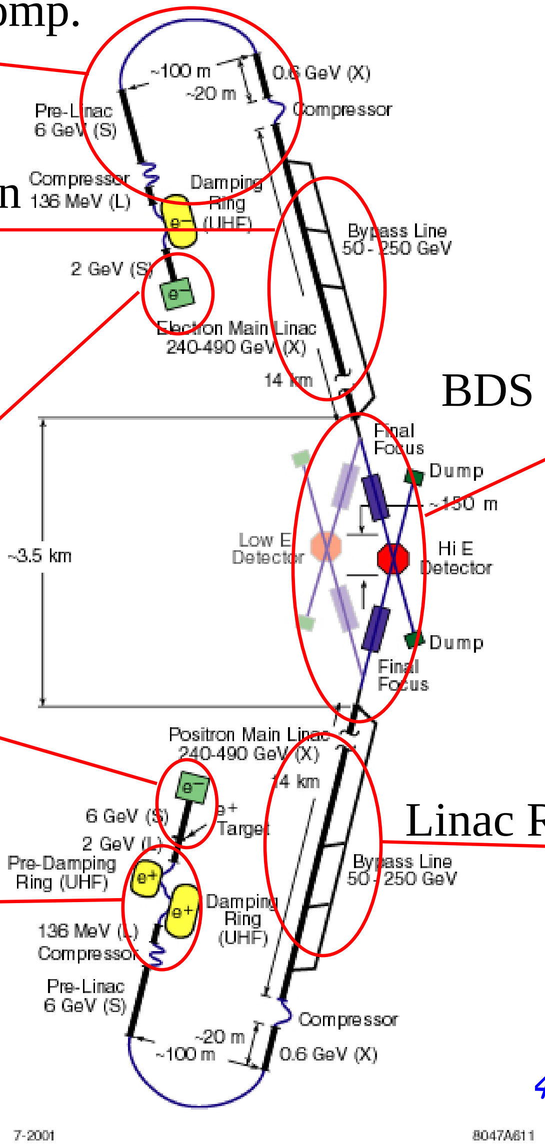
CLIC

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

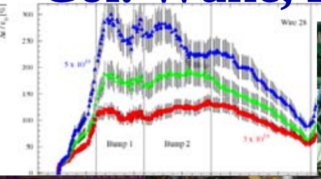
Generic Linear Collider
(systems prototyped & validated in Test Facilities)

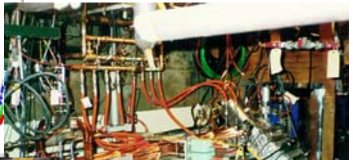
(Courtesy of T.Markiewitz for the NLC)

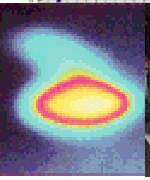


SLC and FEL's — Bunch Comp.

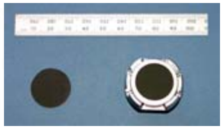
SLC, FFTB, ASSET, Col. Wake, E-158 — ε preservation



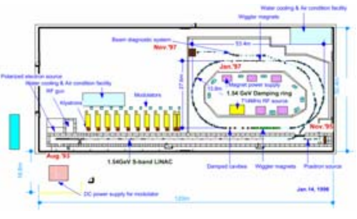




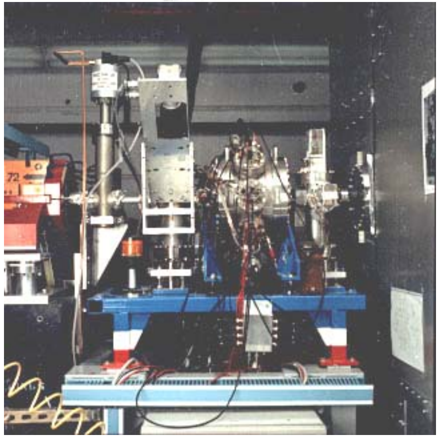
SLC, E158, Nagoya Univ. — e+ / e- sources



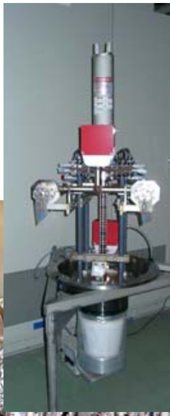
ATF, 3rd gen. SRS, SLC — DR's

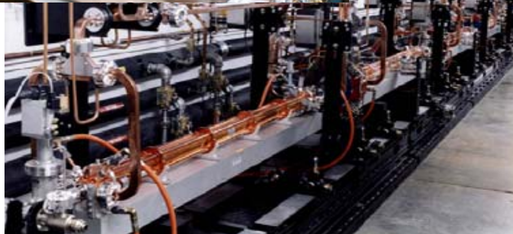


SLC and FFTB — BDS & IR

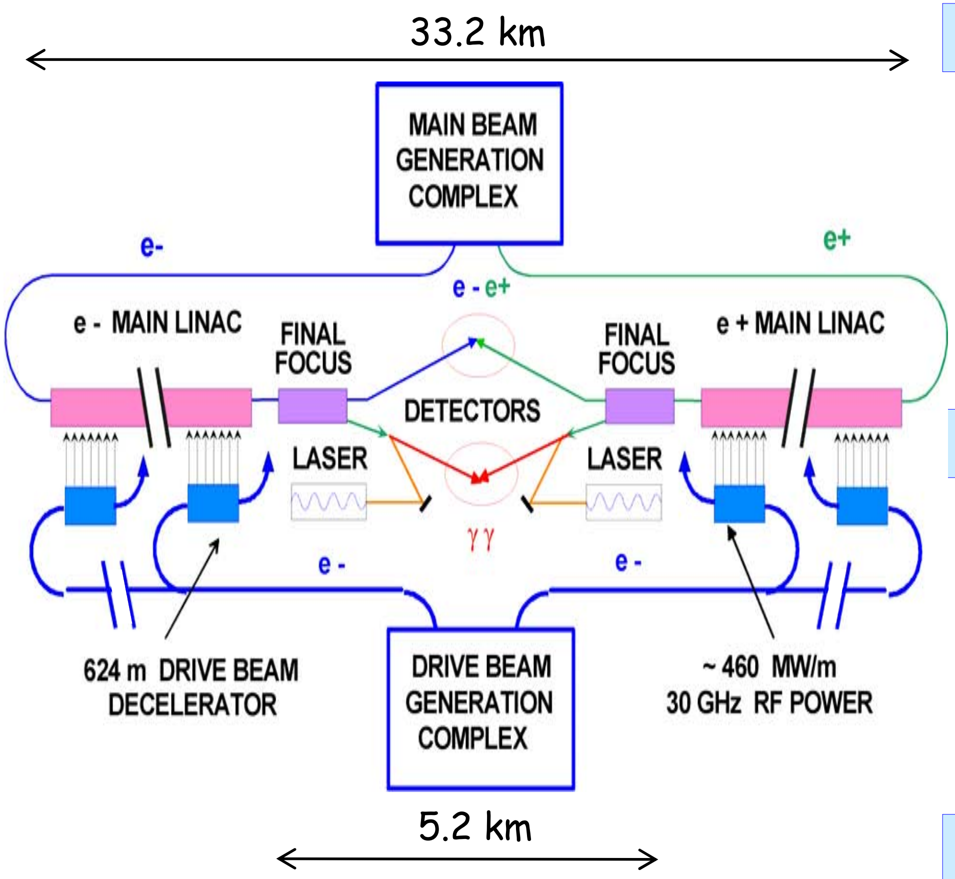


KEK and SLAC X-band RF — Linac RF





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

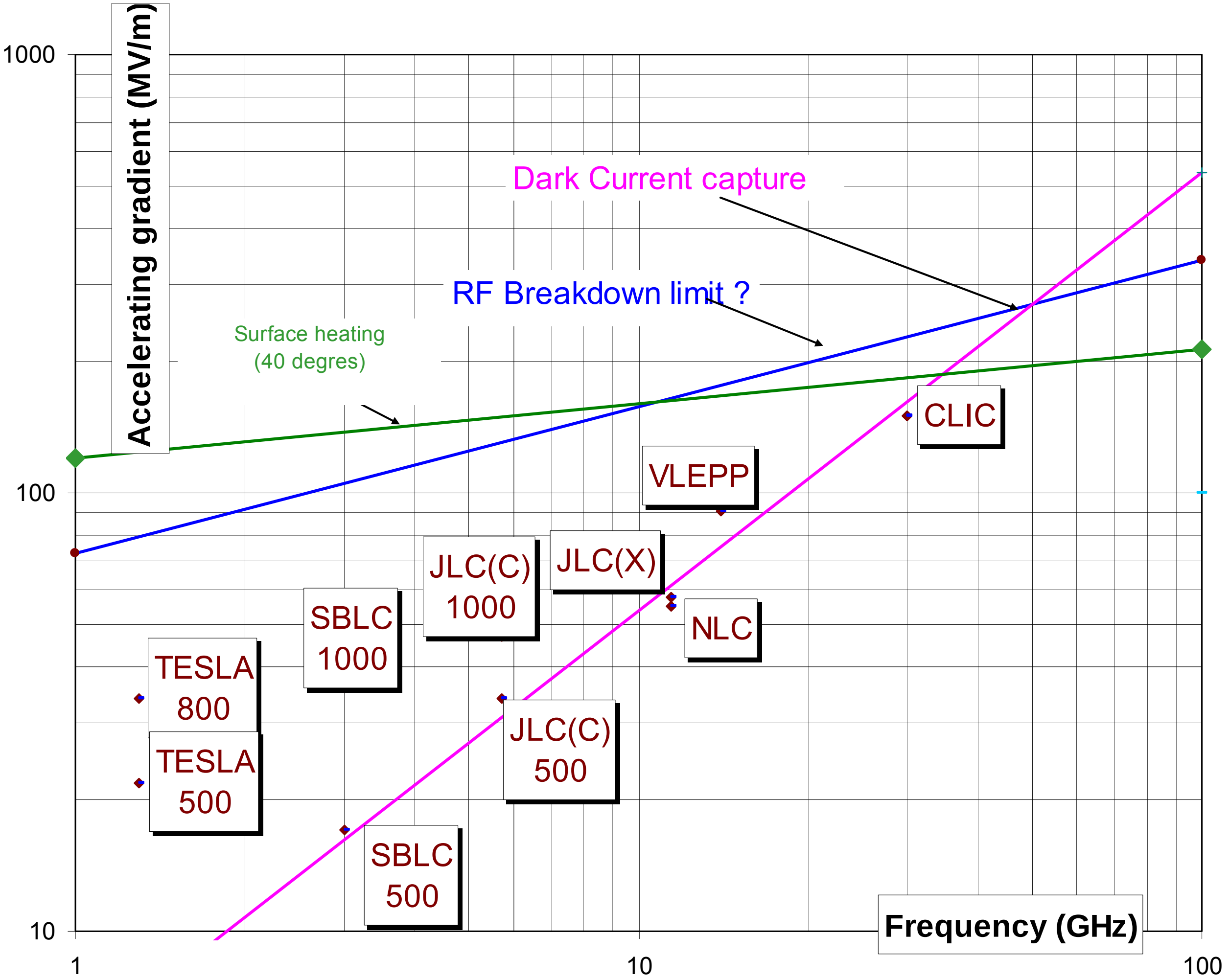
  - RF power generation at high frequency
  - Cost-effective & efficient (~ 10% overall)
  - Simple tunnel, no active elements

- Central injector complex

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

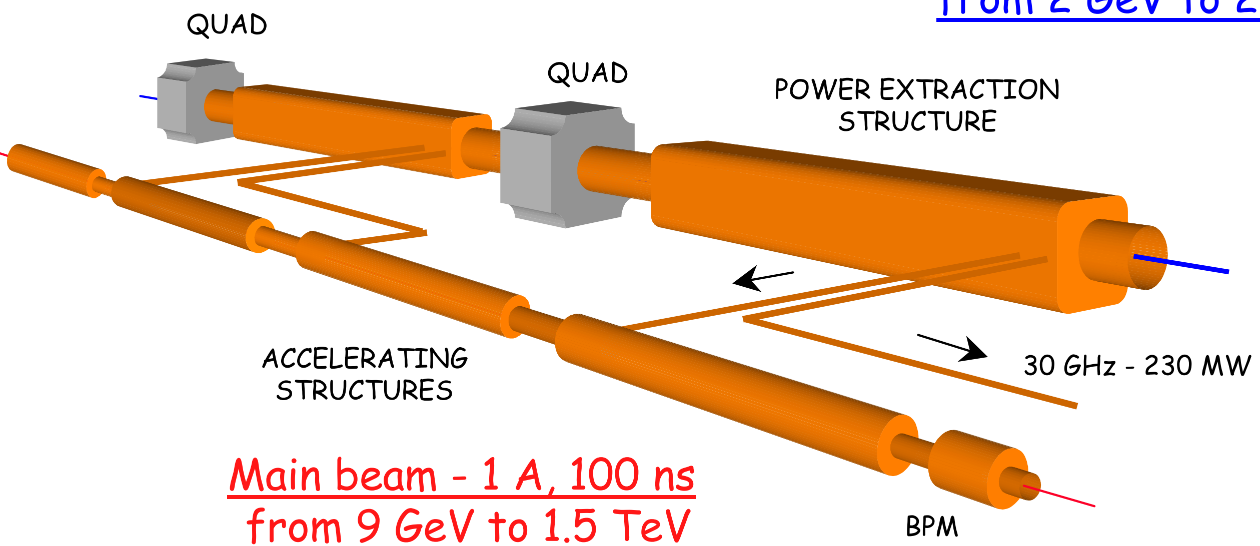
Accelerating Gradients

Loaded accelerating gradients in the TLC designs



CLIC Two-Beam scheme

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

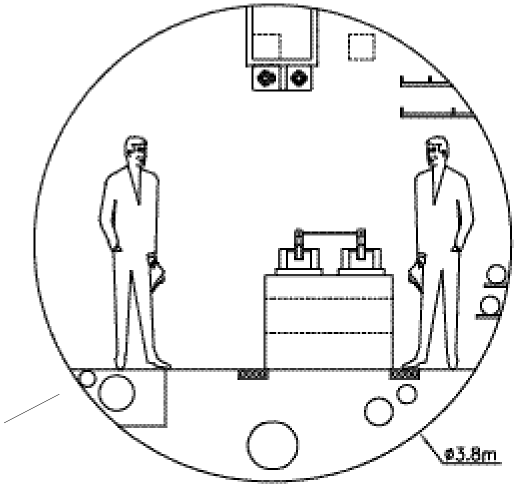


Main beam - 1 A, 100 ns
from 9 GeV to 1.5 TeV

CLIC MODULE

(6000 modules/linac at 3 TeV)

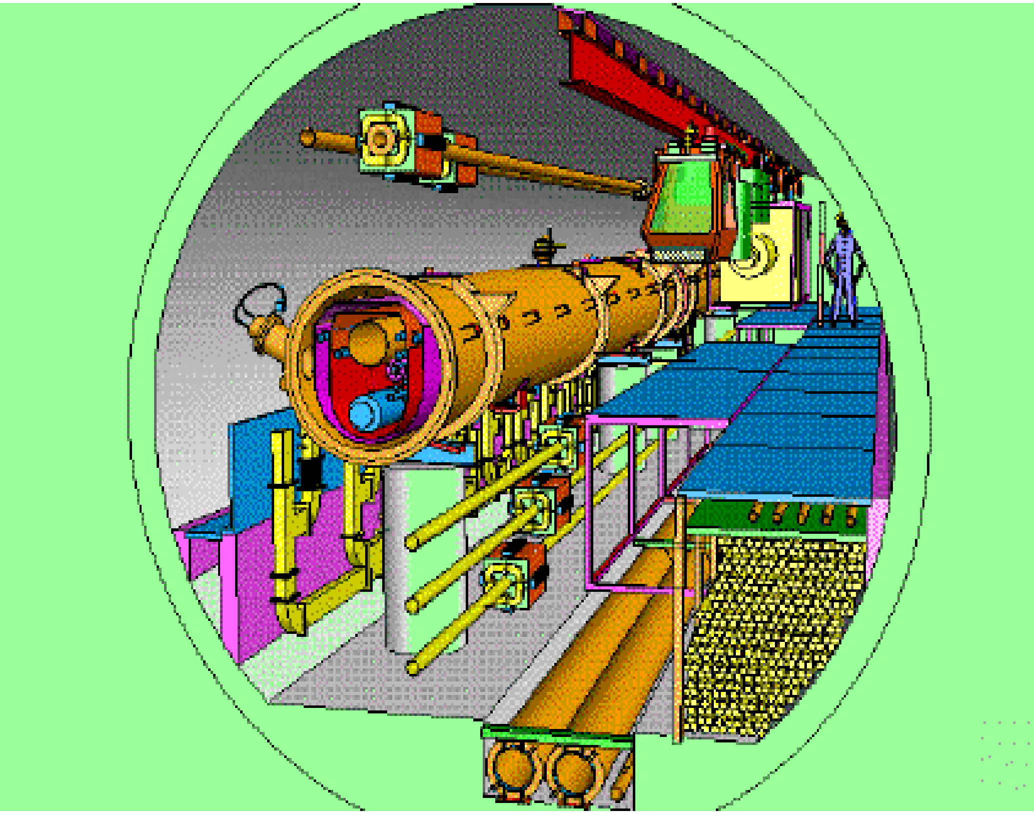
CLIC TUNNEL CROSS-SECTION

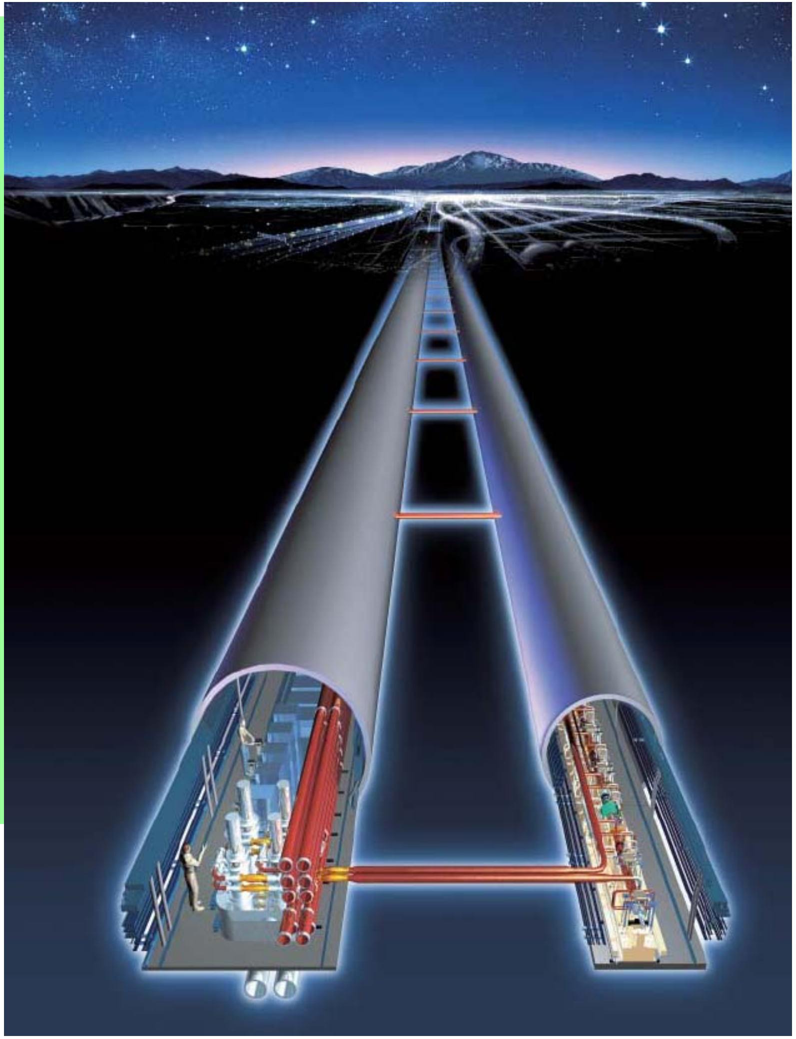


3.8 m diameter

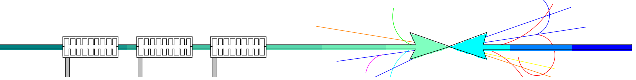
TESLA & NLC TUNNELS

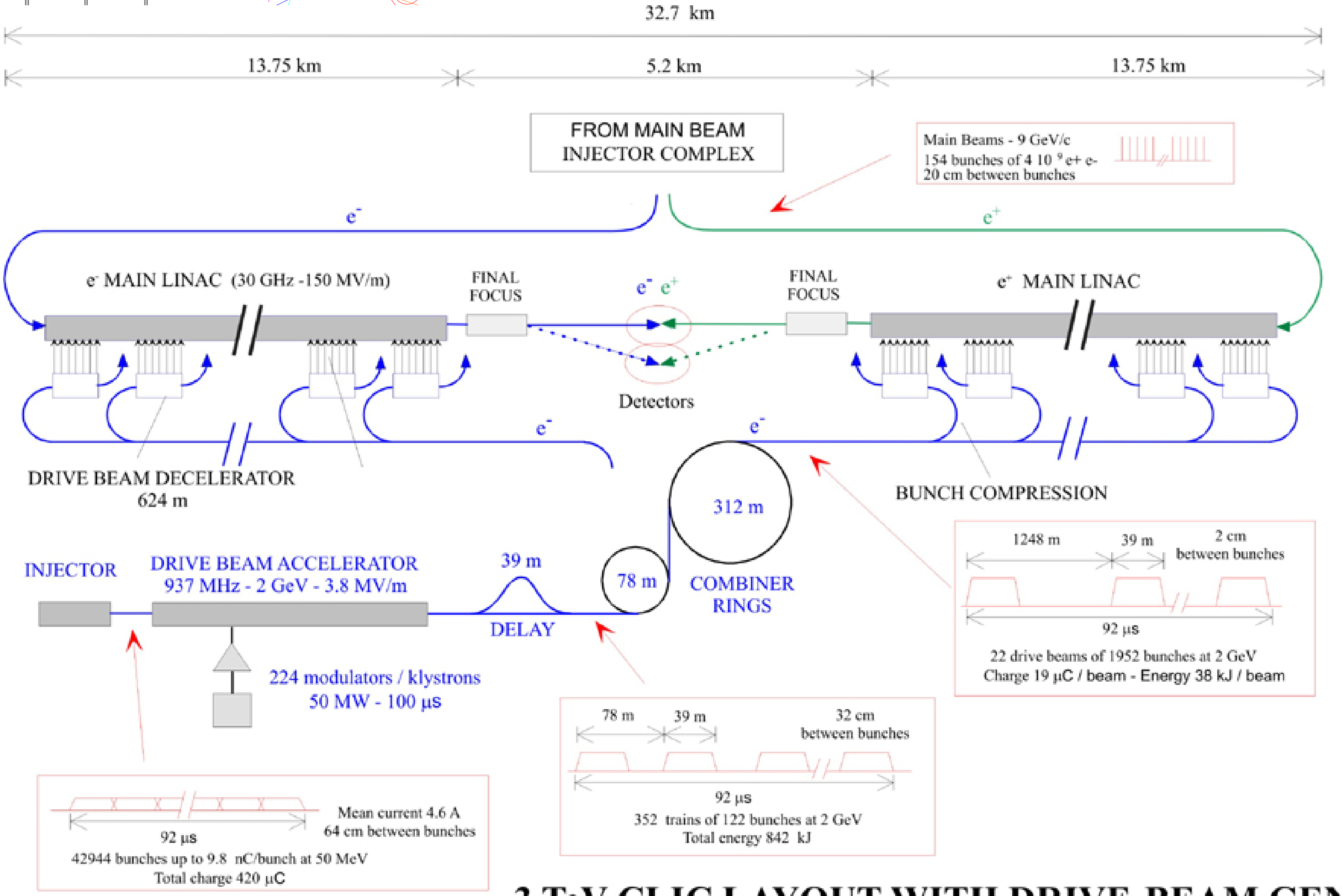
NLC TUNNEL
CROSS-SECTION





TESLA TUNNEL
CROSS-SECTION





32.7 km

13.75 km

5.2 km

13.75 km

FROM MAIN BEAM
INJECTOR COMPLEX

Main Beams - 9 GeV/c
154 bunches of 4 10^9 e+ e-
20 cm between bunches

e^-

e^+

e^- MAIN LINAC (30 GHz -150 MV/m)

FINAL
FOCUS

e^- e^+

FINAL
FOCUS

e^+ MAIN LINAC

Detectors

e^-

e^-

DRIVE BEAM DECELERATOR
624 m

BUNCH COMPRESSION

312 m

INJECTOR

DRIVE BEAM ACCELERATOR
937 MHz - 2 GeV - 3.8 MV/m

39 m

DELAY

78 m

COMBINER
RINGS

224 modulators / klystrons
50 MW - 100 µs

1248 m
39 m
2 cm
between bunches
92 µs
22 drive beams of 1952 bunches at 2 GeV
Charge 19 µC / beam - Energy 38 kJ / beam

78 m
39 m
32 cm
between bunches
92 µs
352 trains of 122 bunches at 2 GeV
Total energy 842 kJ

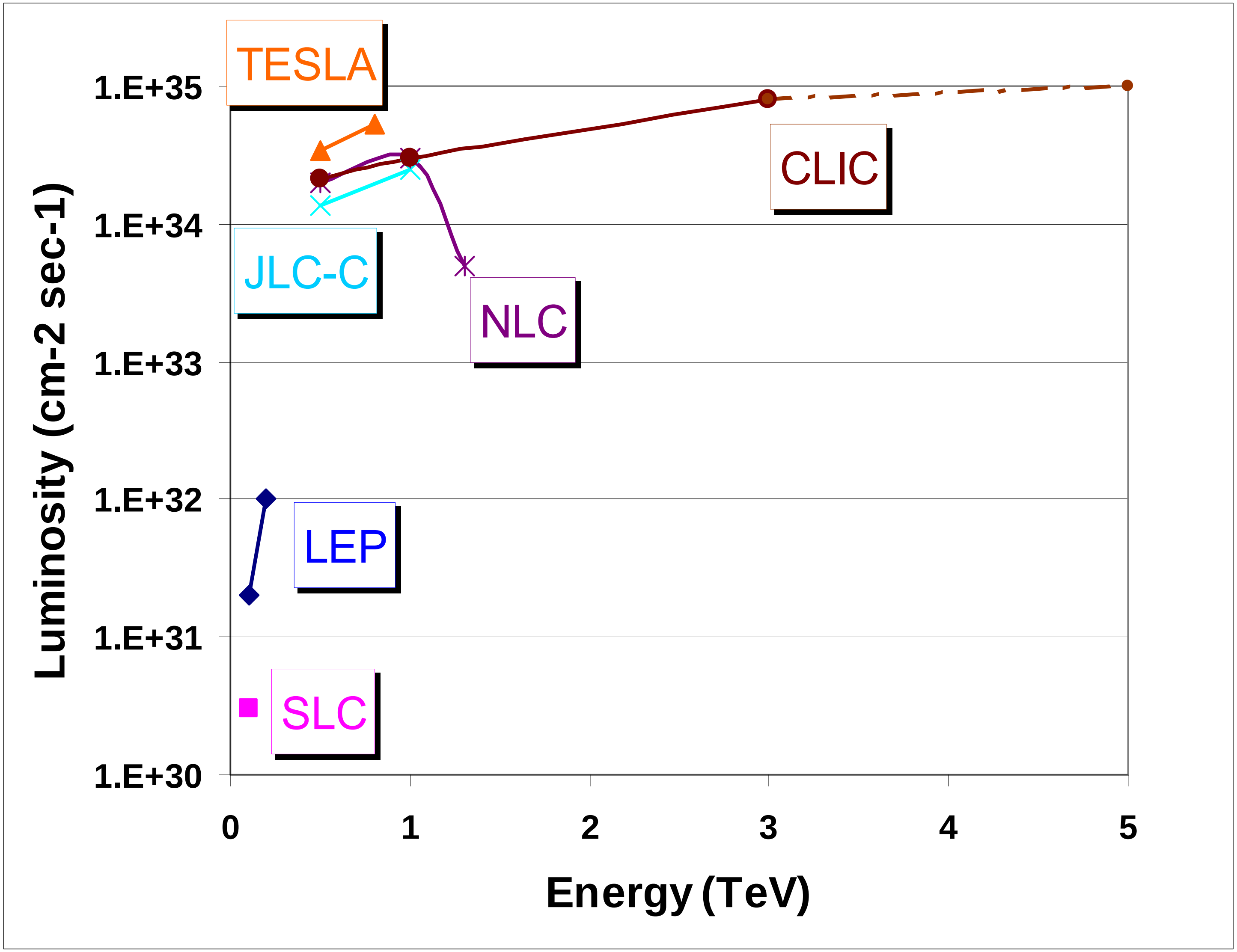
92 µs
Mean current 4.6 A
64 cm between bunches
42944 bunches up to 9.8 nC/bunch at 50 MeV
Total charge 420 µC

3 TeV CLIC LAYOUT WITH DRIVE-BEAM GENERATION

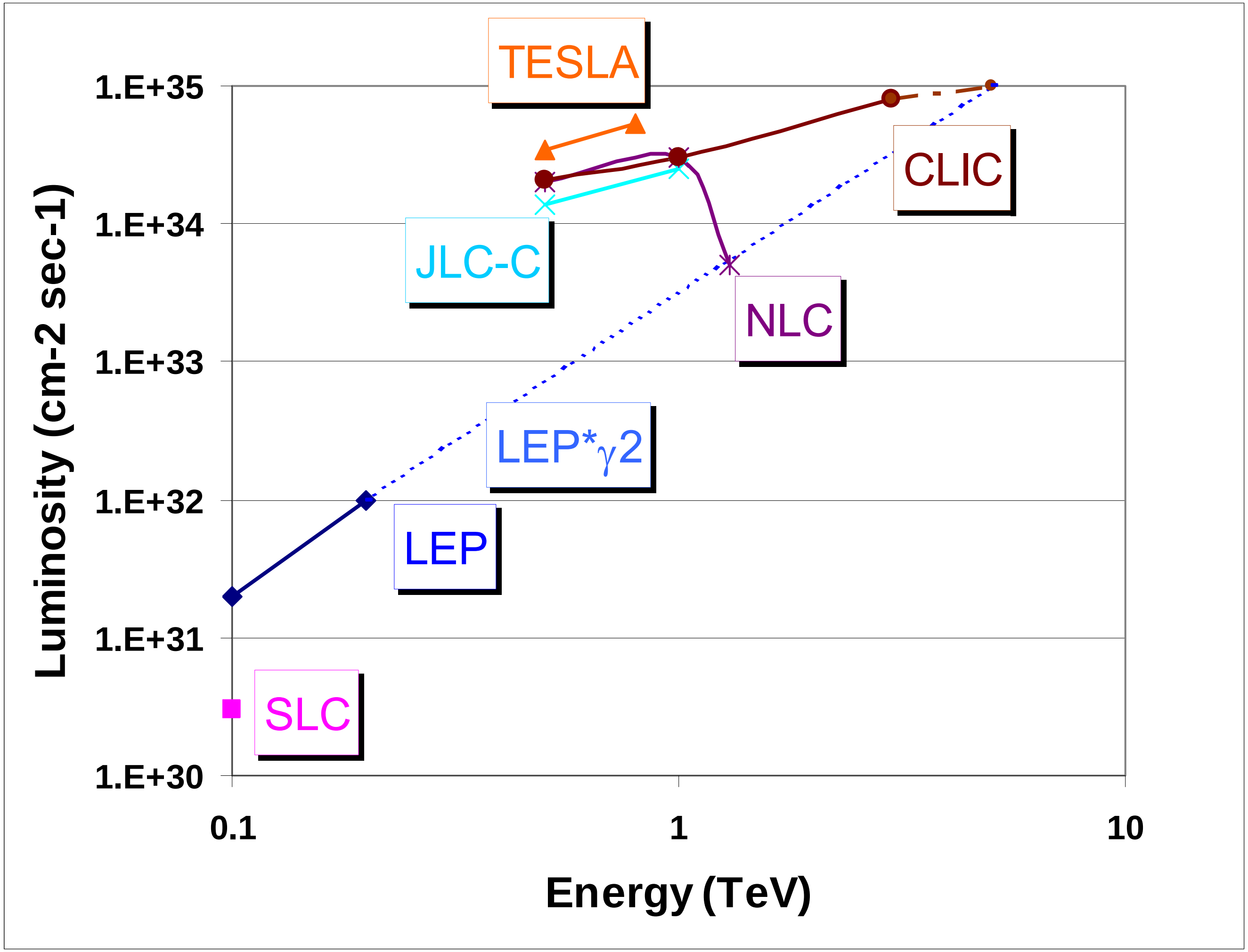
The CLIC main parameters

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

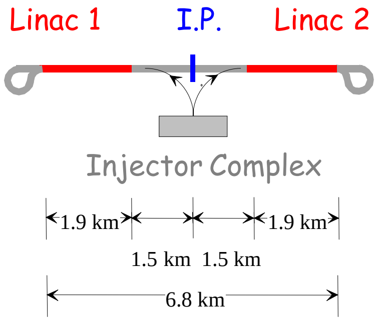


Performances of Lepton Colliders

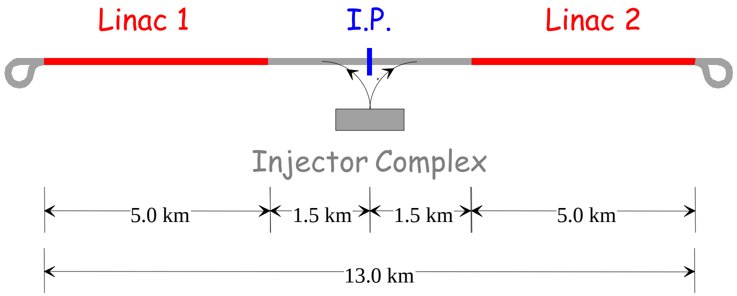


CLIC Layout at various energies

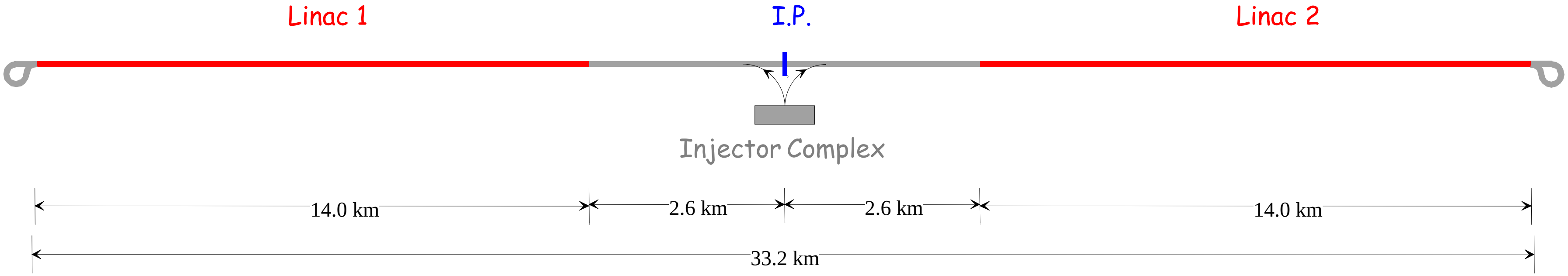
0.42 TeV Stage



1 TeV Stage



3 TeV Stage



Luminosity Scaling

Scaling laws for e+/e- Linear Colliders

(J.P.Delahaye et al: NIM A421-1999-p 369-405)

energy loss
by beamstrahlung

wall-plug to beam
efficiency

wall-plug
power

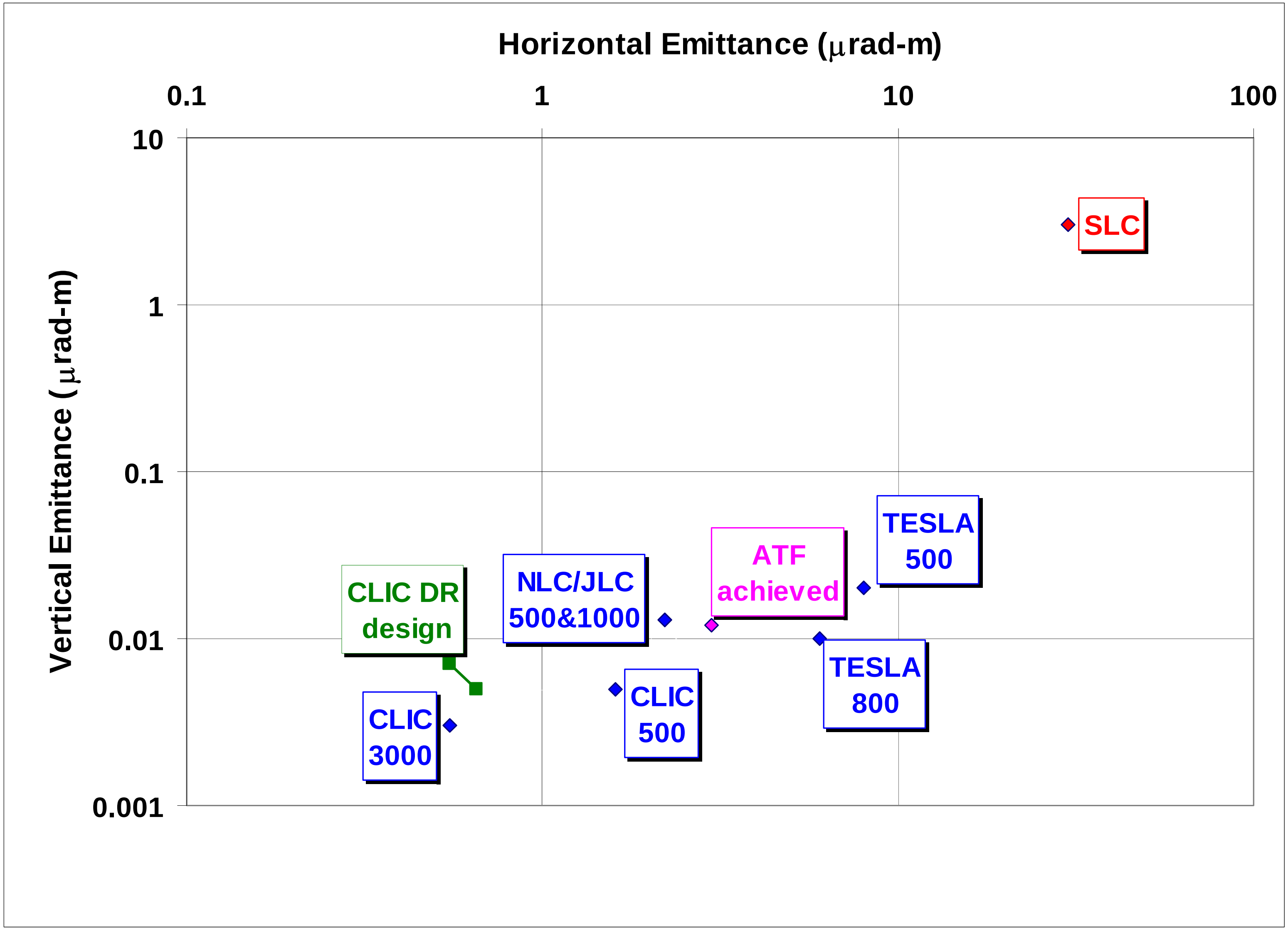
$$L = \frac{k_b N_b^2 f_{rep}}{4\pi U_{cm} \sigma_x^* \sigma_y^*} \propto \frac{\delta_B^{1/2} \times \eta_{beam}^{AC} \times P_{AC}}{U_{cm} \, \varepsilon_{ny}^{*\,1/2}}$$

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

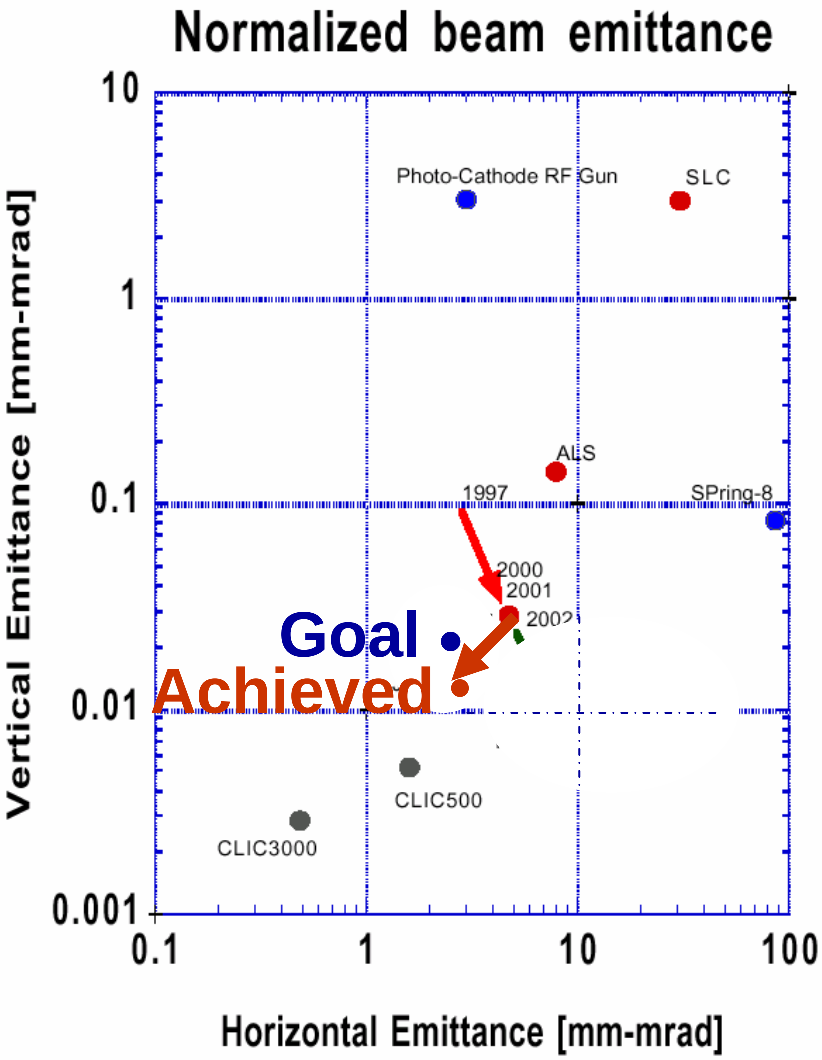
Beam emittances at Damping Rings



Ultra low beam emittances achieved at ATF Damping Ring (KEK)

SLAC and KEK physicists survey ring

"Laser Wire"



Beam Emittance Preservation

(NIM A421-1999-p 369-405)

Beam emittance growth due to wakefields induced by RF cavities misalignment Δy_{RF}

$$(\Delta \varepsilon_{ny})_{RF} \propto N_b^2 \sigma_z^2 (a/\lambda)^{-7} \omega^8 G_a^{-1} \langle \beta_0 \rangle L_s \langle \Delta y_{RF}^2 \rangle$$

First impression : ω^8 ‼ ⇒ High frequencies excluded !

BUT: N, σ_z, (a/λ), G_a, β_o, L_s, Δy also functions of ω

From analysis of LC designs over broad frequency range:

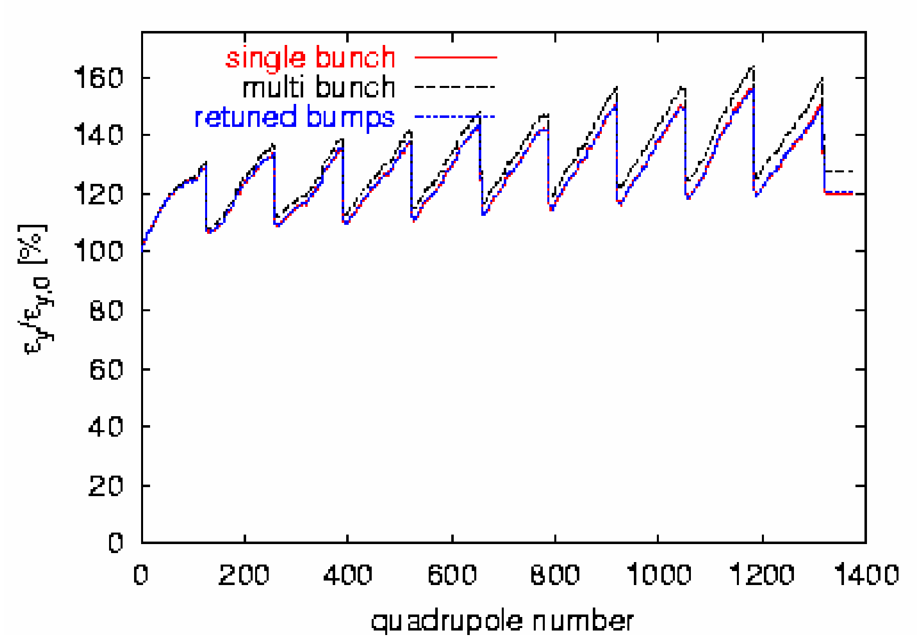
- Length of accelerating structures: $L_S \propto \omega^{-1} G_a^{1/3}$
- Iris and vacuum chamber dimension: $a \propto \omega^{-4/5}$
- Focusing optics: $\beta_0 \propto \omega^{-2/5}$
- Alignment tolerances $\langle \Delta y_{RF} \rangle \propto \omega^{-3/4}$
- Bunch length: $\sigma_Z \propto \omega^{-2/3} G_a^{-1/3}$

By choosing a scaling $N_b \propto \omega^{-6/5} G_a^{2/3}$

$$\boxed{\Delta\varepsilon \propto \omega^0 \propto \text{const}}$$

Effect of wakefields and beam emittance preservation are frequency independent
CLIC scheme not better or worse than low frequency linear collider designs

EMITTANCE BLOW-UP IN THE LINAC

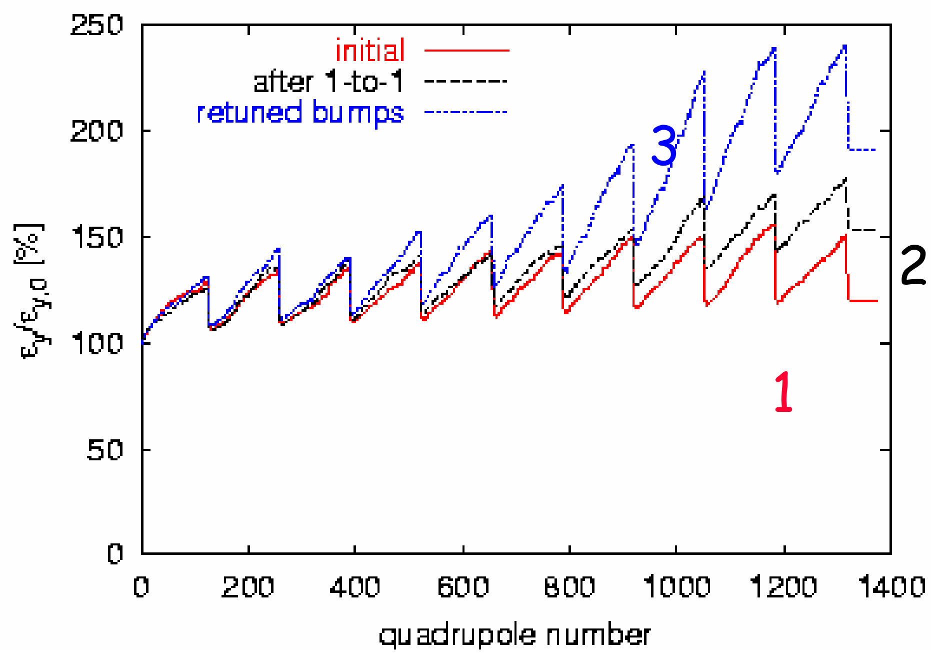


- beam simulations however predict only ~ 20%.
- Design ⇒ budget of 100% blow-up.

Beam-based ALIGNMENT STRATEGY

- 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 (uses a few RF structures and a few quadrupoles).

SENSITIVITY TO BEAM JITTER & GROUND MOTION



Emittance deteriorates with time

Continuous beam-based re-alignment

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

Required and achieved magnet stability

CLIC

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

Need active damping of vibrations

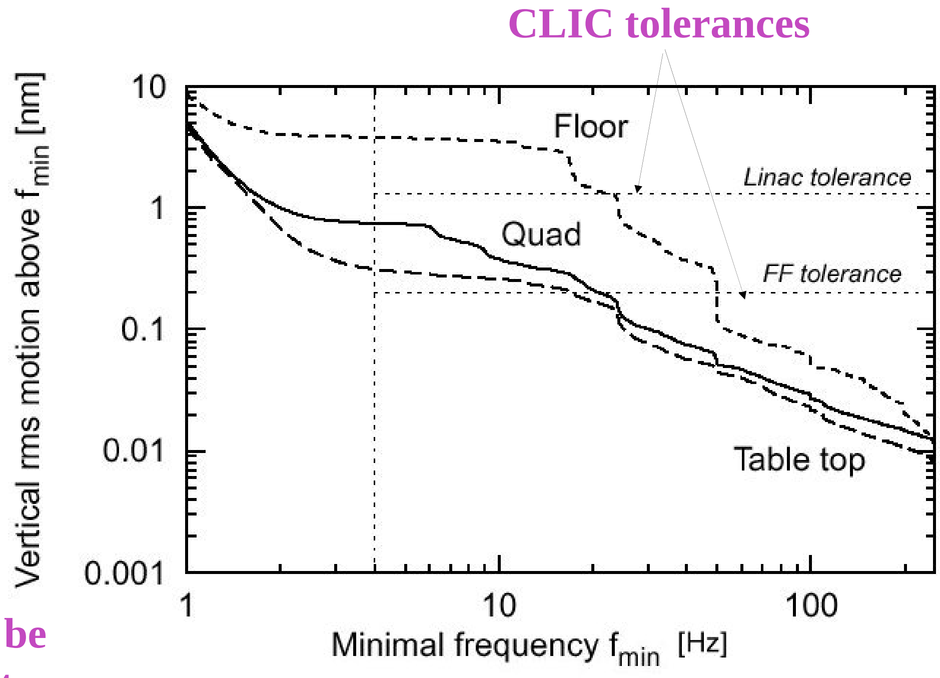
Magnet	Ix	Iy
Linac (2600 quads)	14 nm	1.3 nm
Final Focus (2quads)	4 nm	0.2 nm

Achieved stability on CERN vibration test stand

Test made in noisy environment, active damping reduced vibrations by a factor about 20, to rms residual amplitudes of:

Vert. 0.9 ± 0.1 nm
1.3 ± 0.2 nm with cooling water

Horiz. 0.4 ± 0.1 nm

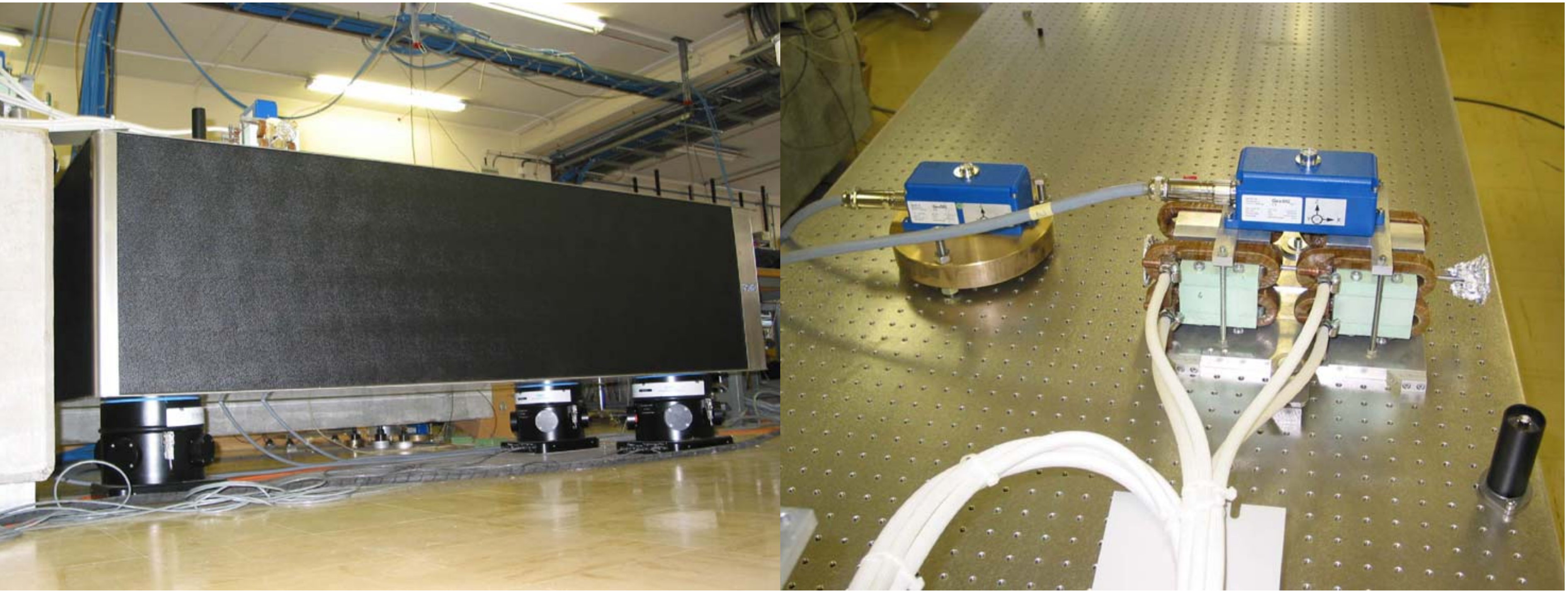


Big step towards believing that nanobeams can be made colliding on sites with CERN-like stability

Nanometer stabilisation

Latest stabilization technology applied to the accelerator field

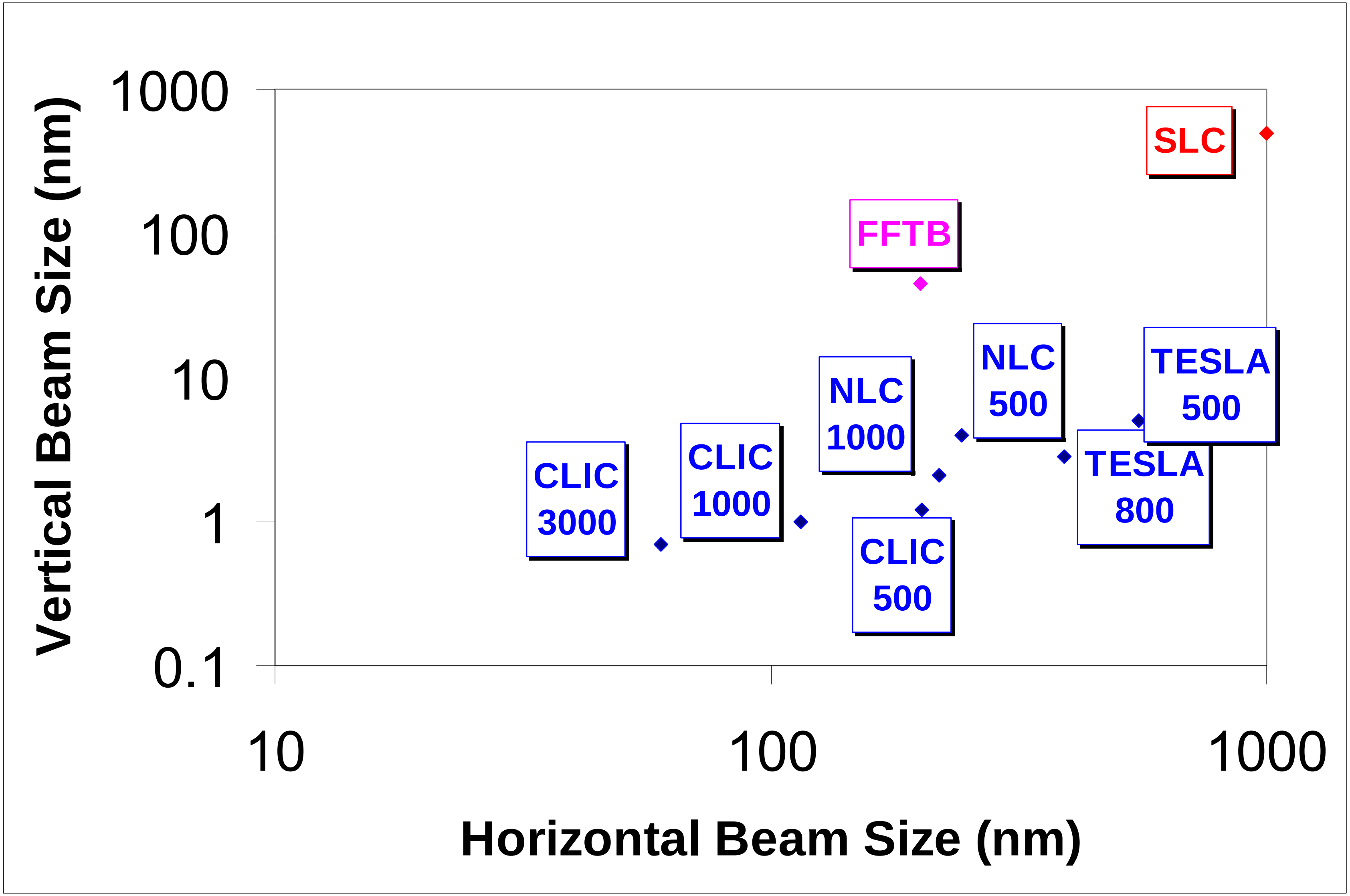
The most stable place on earth!!!



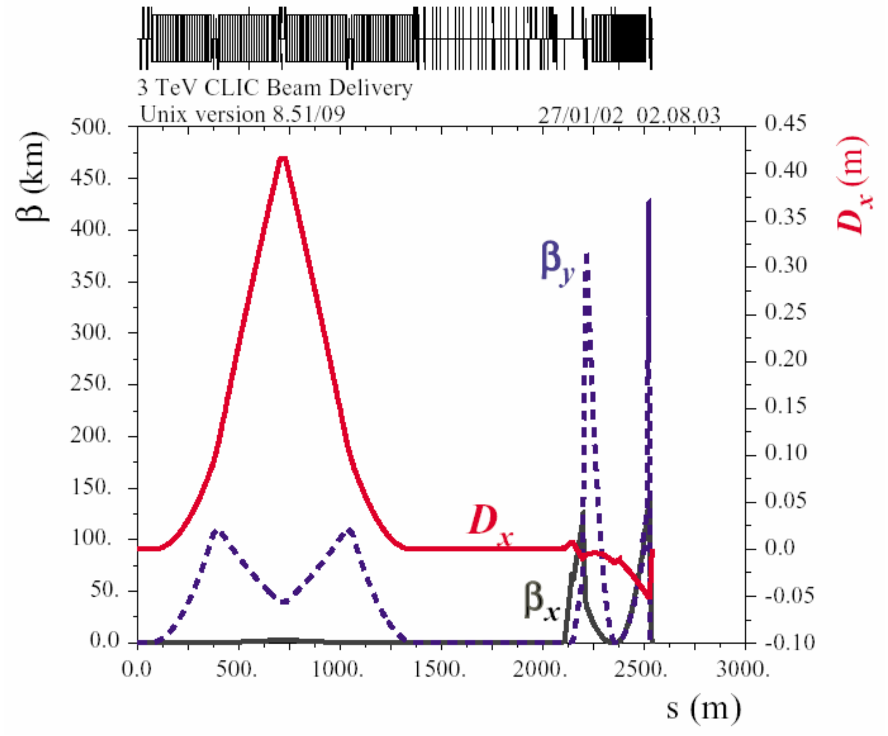
Stabilizing quadrupoles to the **0.5 nm** level!

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

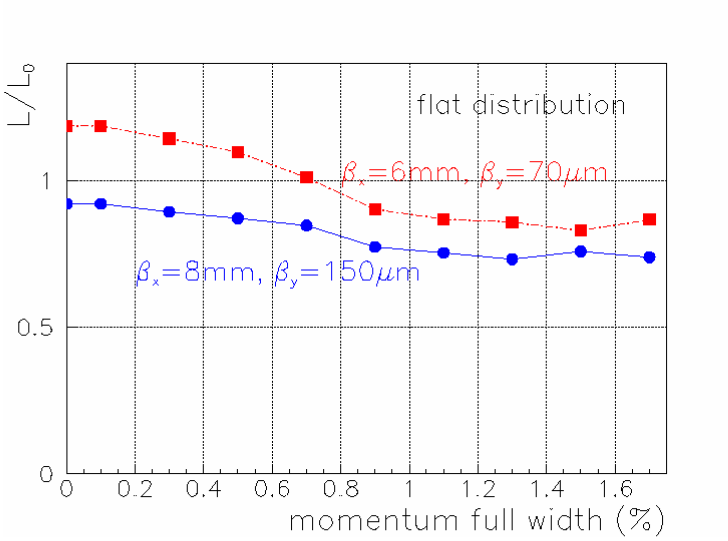
Beam sizes at Collisions



BEAM DELIVERY SYSTEM



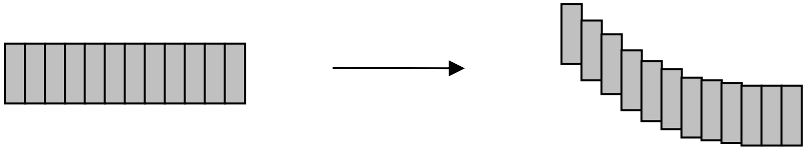
Present design based on scaling of the NLC BDS



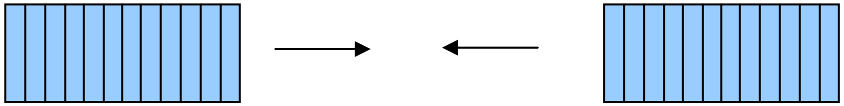
Length reduced to about 2.5 km per side	
Final Focus	~ 0.5 km
Energy Collimation (± 1.5%)	~ 1.4 km
Betatron Collimation (± 10 σ_x and ± 80 σ_y)	~ 0.6 km

LUMINOSITY LOSS –"BANANA" EFFECT

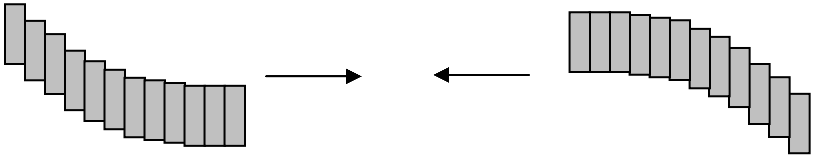
Beam-beam simulations have shown that there are significant differences between the luminosities calculated using projected end-of-linac emittances instead of using the real bunch profiles



Usual technique : determine end-of-linac SB blow-up



then use projected emittance to calculate luminosity



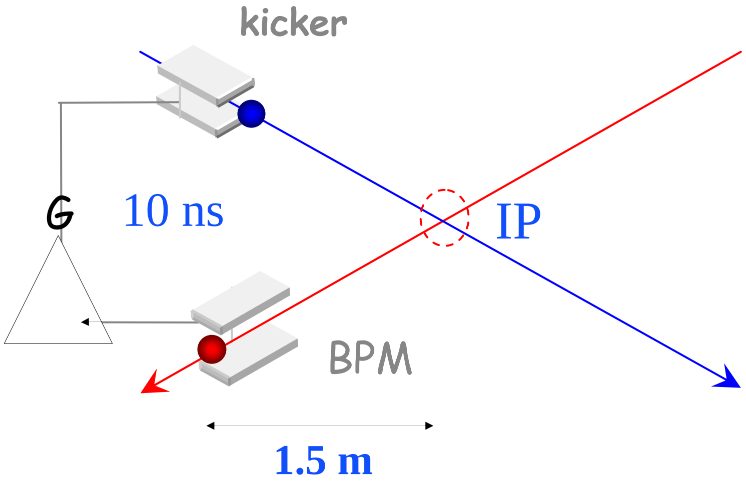
should use real bunch profiles

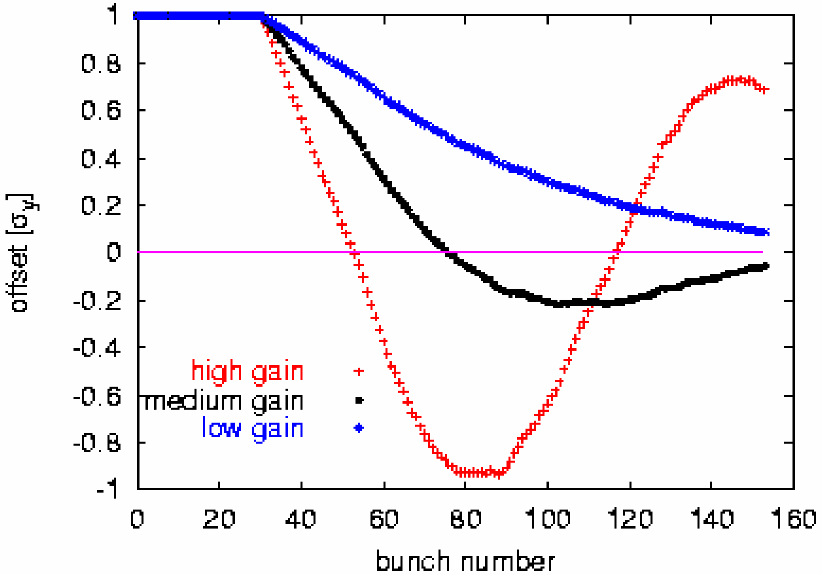
16% reduction in luminosity
for case with 20% $\Delta\varepsilon$ in linac

INTRA-PULSE FEEDBACK

Not so easy in CLIC (short pulse length ~ 100 ns)

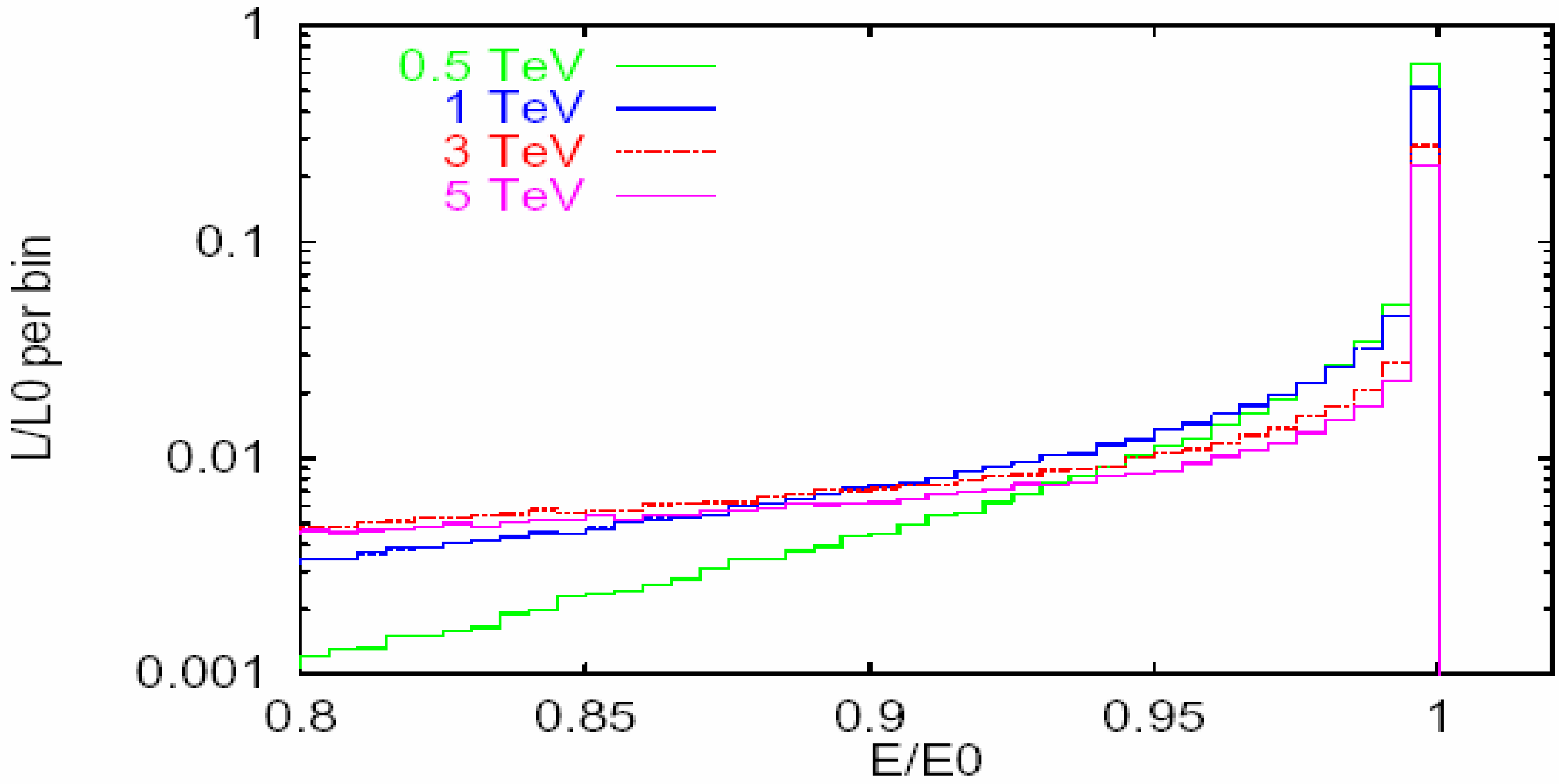
- When beams collide with vertical off-set – receive strong kick from beam/beam interaction.
- Position of this deflected **outgoing** beam is measured at short distance from IP
- Compensating signal is sent to a kicker on the same side of the IP to correct the **incoming** beam
- Results in response time of ~ **20 ns**





With a BPM resolution of 10 μm simulations show that the luminosity loss for small vertical off-sets can be reduced by factor 3.

Luminosity Spectrum



Energy (TeV)	0.5	1	3	5
L in 1% E_{cm}	71%	56%	30%	25%
L in 5% E_{cm}	87%	71%	42%	34%

Momentum spread after collision increases with colliding beam energy. Substantial luminosity from particles within small momentum spread.

CLIC PHYSICS STUDY GROUP

From April 2000 - in response to a growing interest in the physics potential of a multi-TeV e+e- collider - a CLIC Physics Study Group has been set-up in order to:

1) Identify and investigate key processes that can help to optimize the machine design:

   luminosity spectrum,
   accelerator induced background,
   beam-beam background

2) Explore the physics program for CLIC and define a concept of the detector

3) Make a comparative assessment of the CLIC physics potential

http://clicphysics.web.cern.ch/CLICphysics/

Report summarizing the physics potentials of a facility operating at a centre-of-mass energy from 1 to 5 TeV with luminosities in the order of 10^{35} cm^{-1} sec^{-2}.
"Physics at the CLIC Multi-TeV Linear Collider": CERN-2004-005

The CLIC main challenges

COMMON TO MULTI-TEV LINEAR COLLIDERS

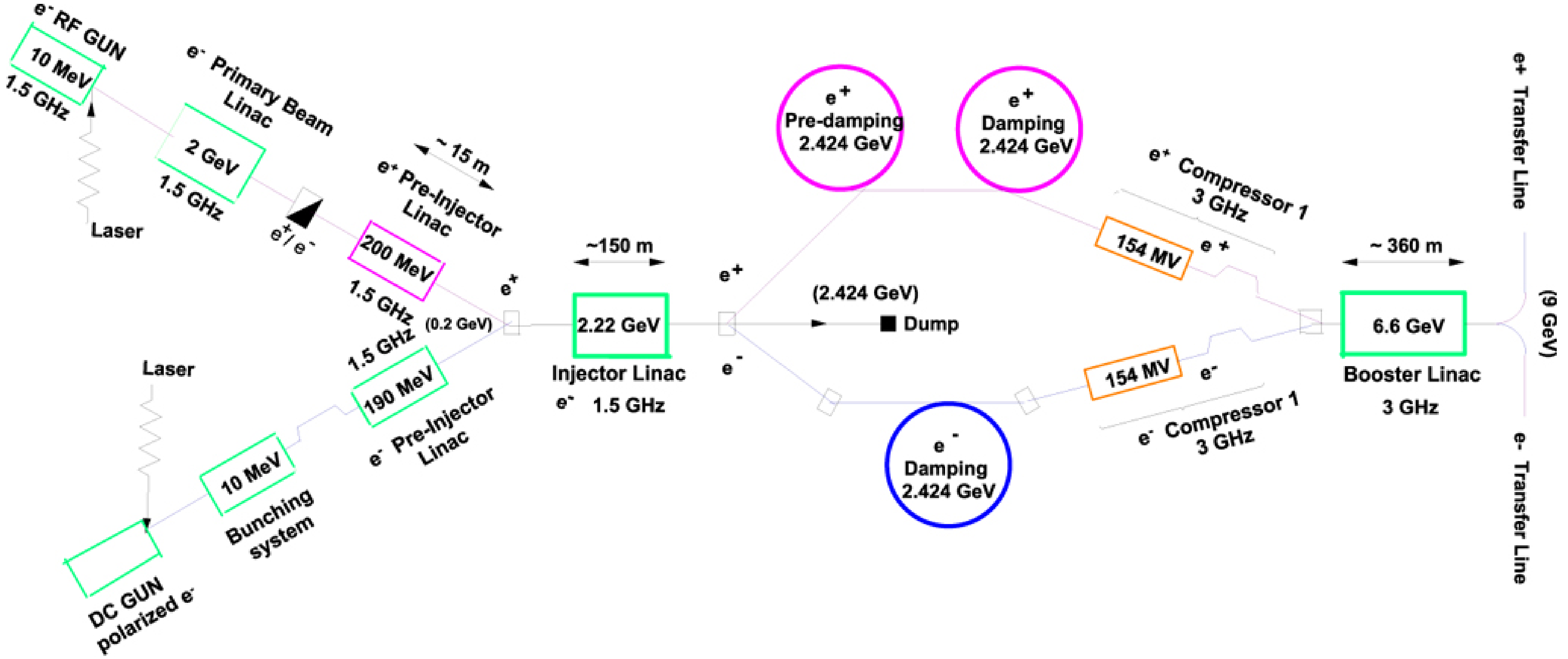
- Accelerating gradient *
- Generation and preservation of ultra-low emittance beams
- Beam Delivery & IP issues:
    - **nanometer size beams**
    - **Sub-nanometer component stabilisation** *
- Physics with colliding beams in high beamstrahlung regime

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

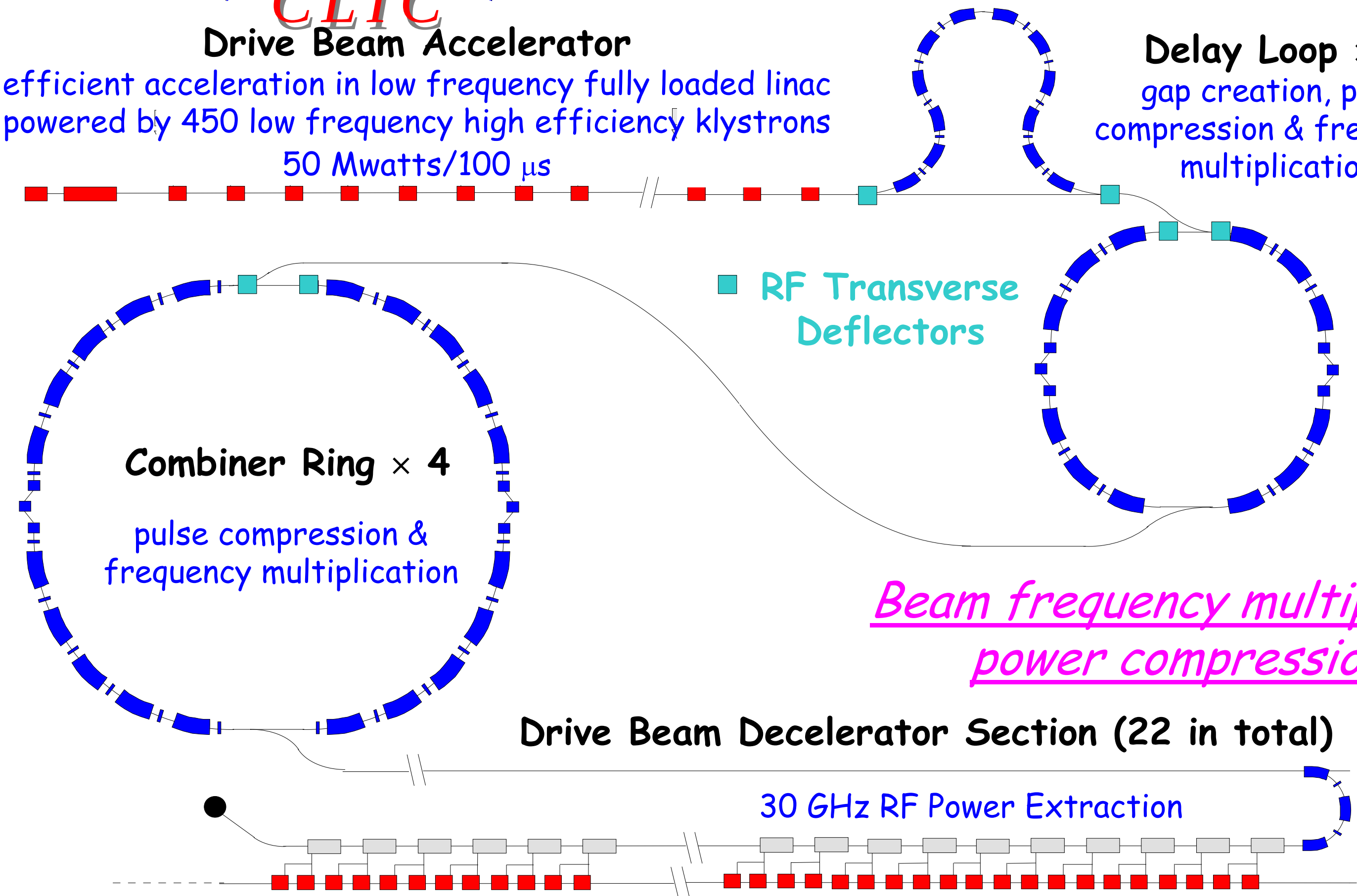
The CLIC Injector complex



CLIC INJECTOR COMPLEX FOR THE e$^+$ and e$^-$ MAIN BEAMS

Polarized or unpolarized electrons / unpolarized positrons

The CLIC RF Power Source



Drive Beam Accelerator

efficient acceleration in low frequency fully loaded linac
powered by 450 low frequency high efficiency klystrons
50 Mwatts/100 µs

Delay Loop × 2

gap creation, pulse compression & frequency multiplication

🟦 RF Transverse Deflectors

Combiner Ring × 4

pulse compression & frequency multiplication

Combiner Ring × 4

pulse compression & frequency multiplication

Beam frequency multiplication and power compression by 32

Drive Beam Decelerator Section (22 in total)

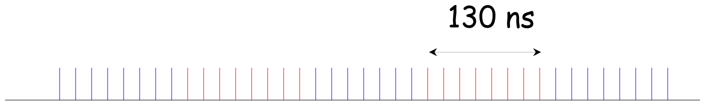
30 GHz RF Power Extraction

Return Arc

Bunch Compression

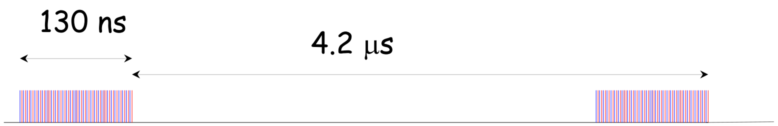
68 GeV/c energy gain – 624 m long

Drive beam time structure - initial



100 µs train length - 32 × 22 sub-pulses – **4.6 A**
2 GeV - 64 cm between bunches

Drive beam time structure - final



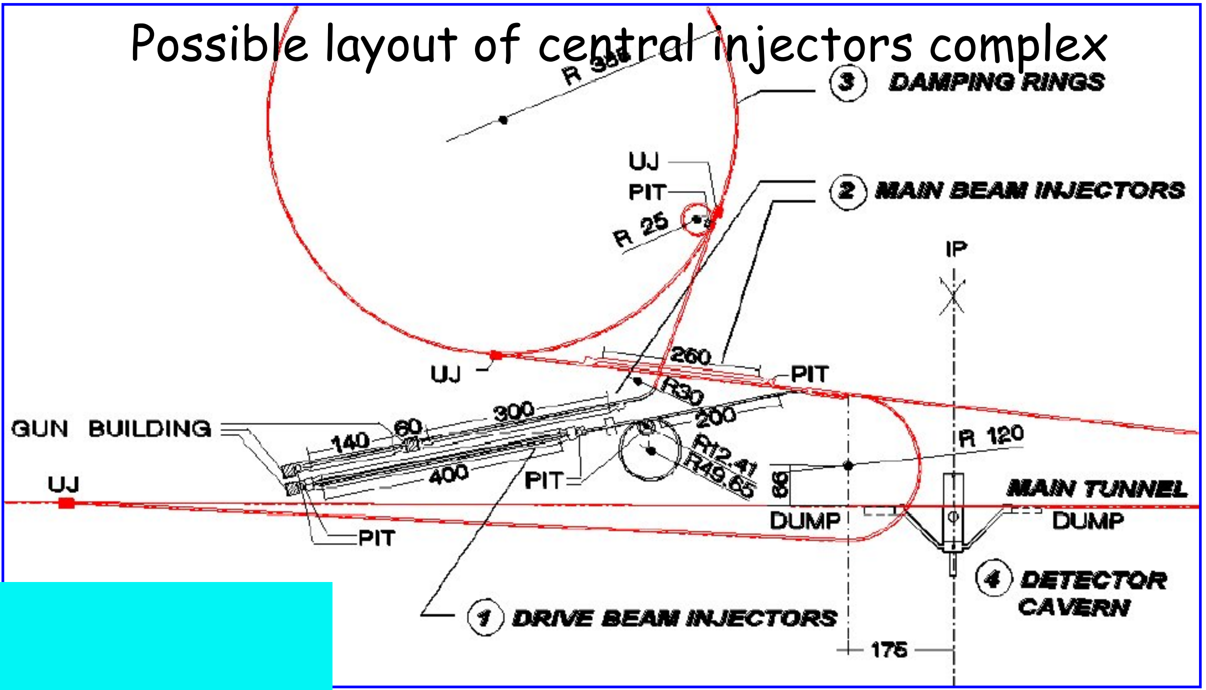
22 pulses - **147 A** - 2 cm between bunches

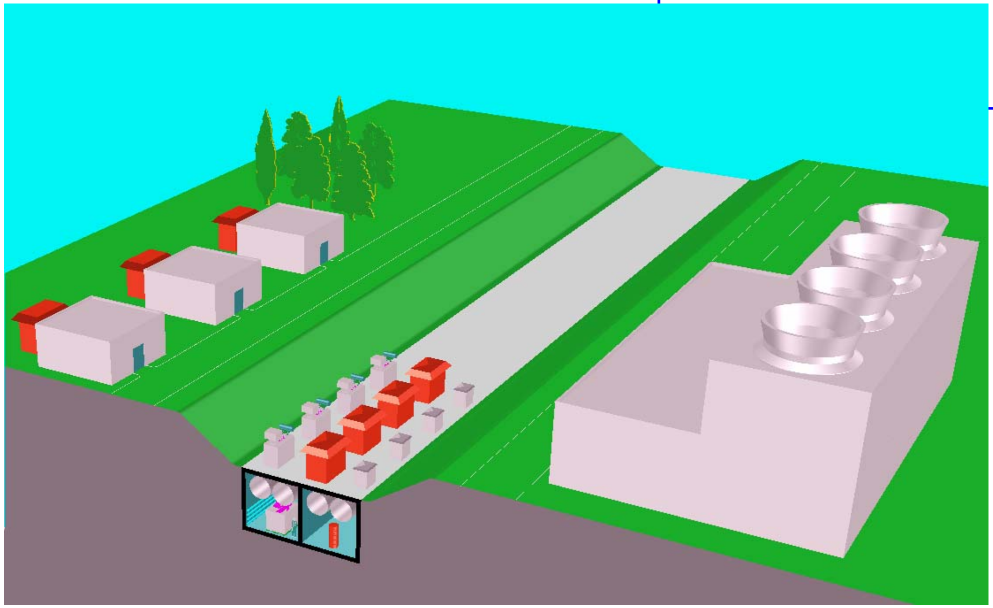
CIVIL ENGINEERING

Layouts for

- Central Area with Injectors
- Tunnels for 937 MHz klystrons
- Main tunnel - Shafts
- Detector cavern

Possible layout of central injectors complex

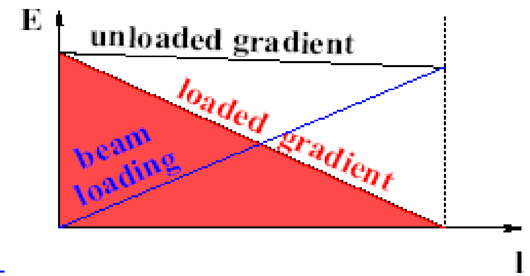




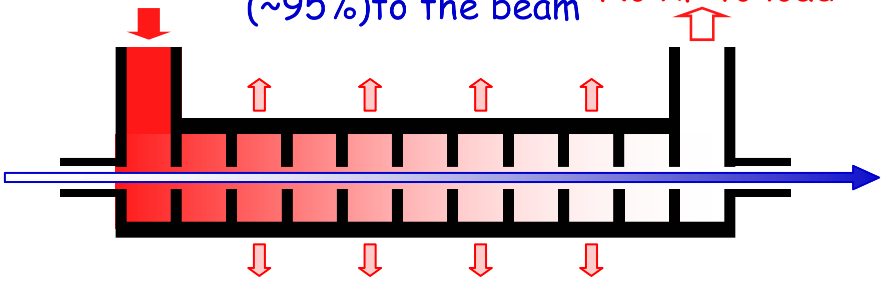
Sketch of Drive Beam Accelerator Powering & Cooling

RF Power Source building blocks

Full beam-loading acceleration of high intensity beams in TW sections



High beam current



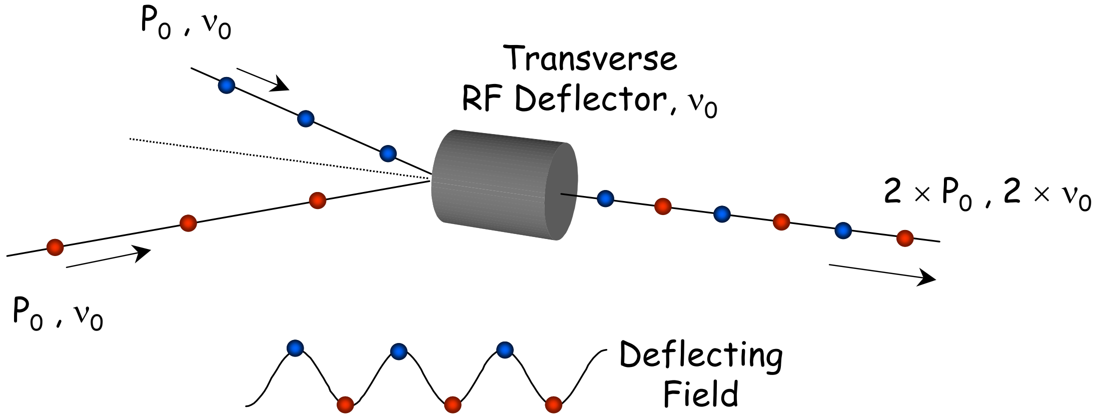
RF in

Most of RF power (~95%)to the beam

No RF to load

“short” structure - low Ohmic losses

Beam combination/separation by transverse RF deflectors



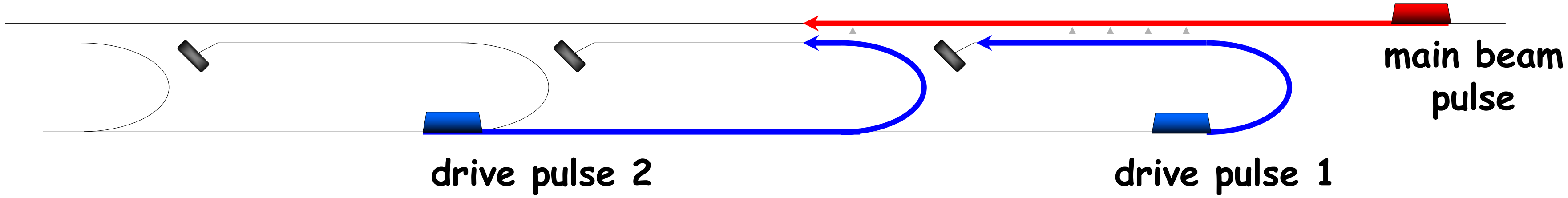
P_0 , ν_0

Transverse RF Deflector, ν_0

$2 \times P_0$, $2 \times \nu_0$

P_0 , ν_0

Deflecting Field

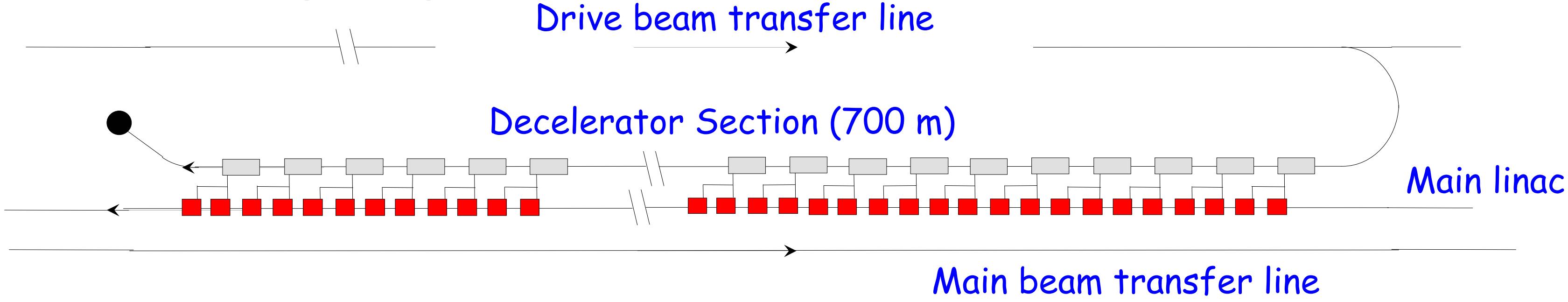


main beam pulse

drive pulse 2

drive pulse 1

The Drive Beam Decelerator

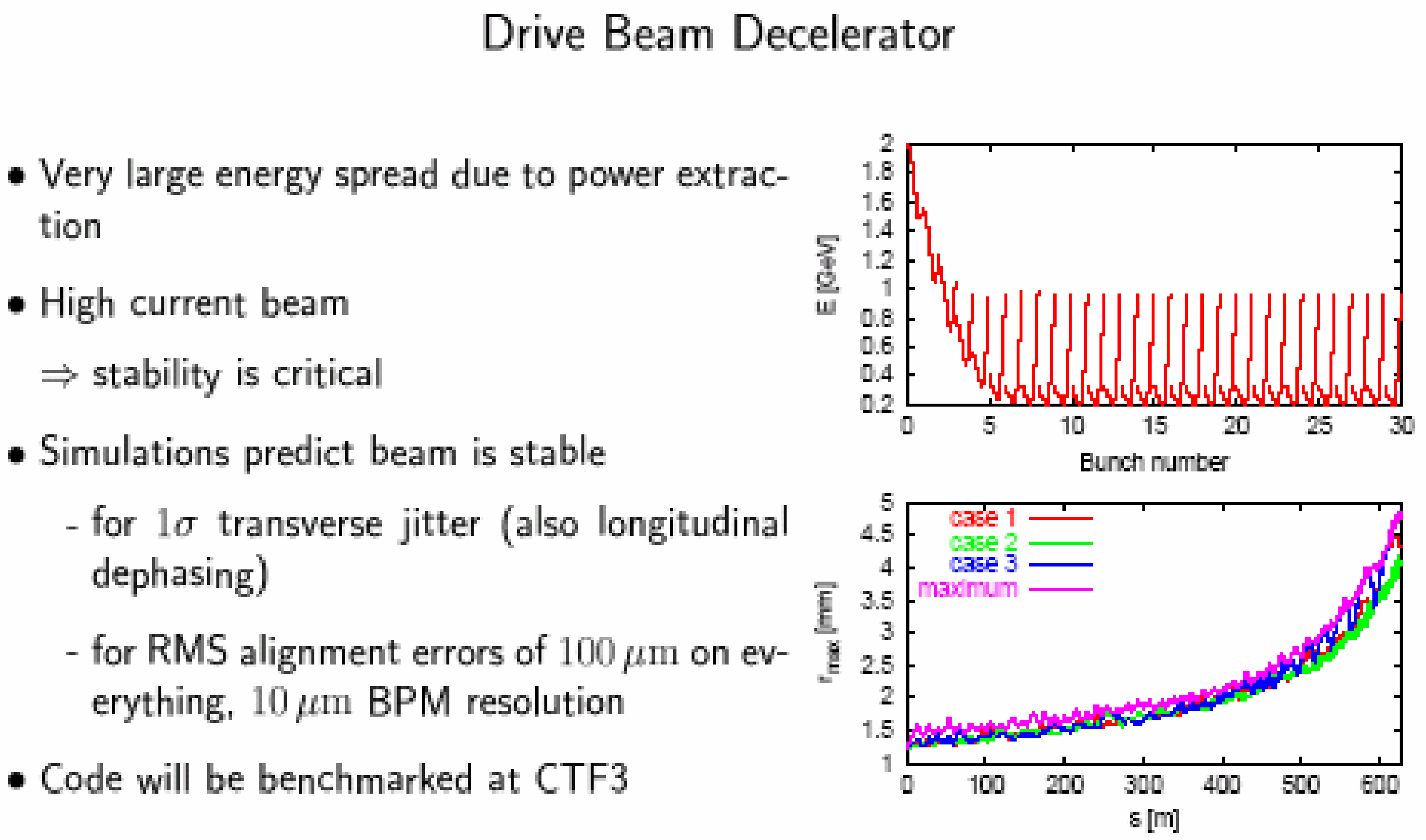


Drive beam transfer line

Decelerator Section (700 m)

Main linac

Main beam transfer line

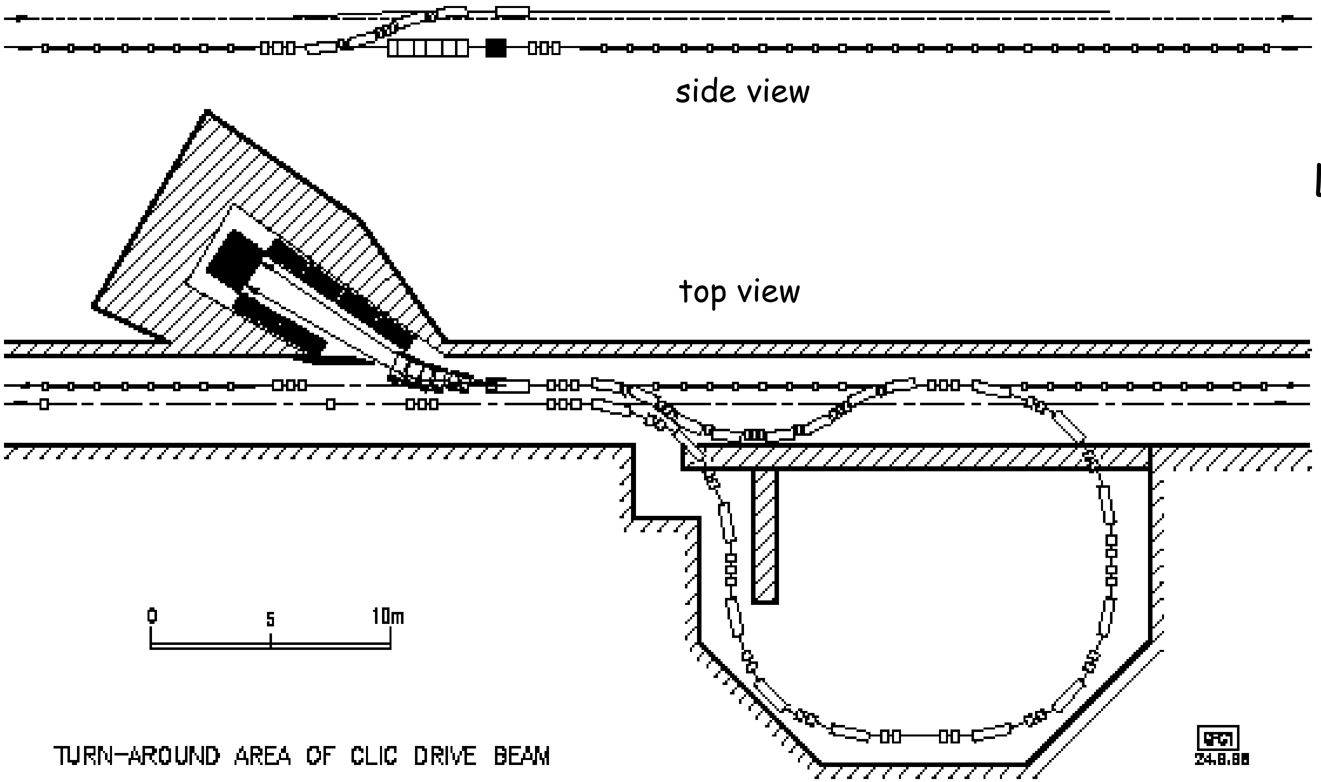


Drive Beam Decelerator

- Very large energy spread due to power extraction
- High current beam

  ⇒ stability is critical
- Simulations predict beam is stable
  - for 1σ transverse jitter (also longitudinal dephasing)
  - for RMS alignment errors of $100\ \mu m$ on everything, $10\ \mu m$ BPM resolution
- Code will be benchmarked at CTF3

Drive Beam Turnaround & Dump



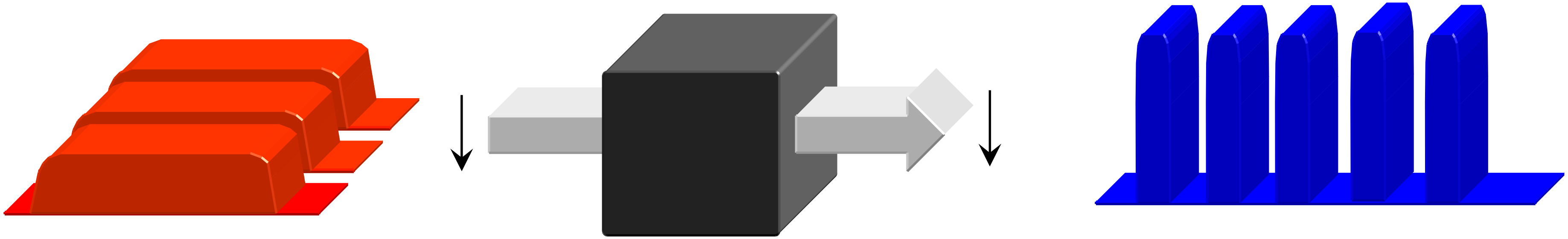
Layout of the turnaround area, including the spent beam dump (top left)

MAIN ISSUES

- <u>Bunch Compression</u>
- Tolerable CSR effects
- Path-length tuning for phase adjustments
- Vertical and horizontal beam translation

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

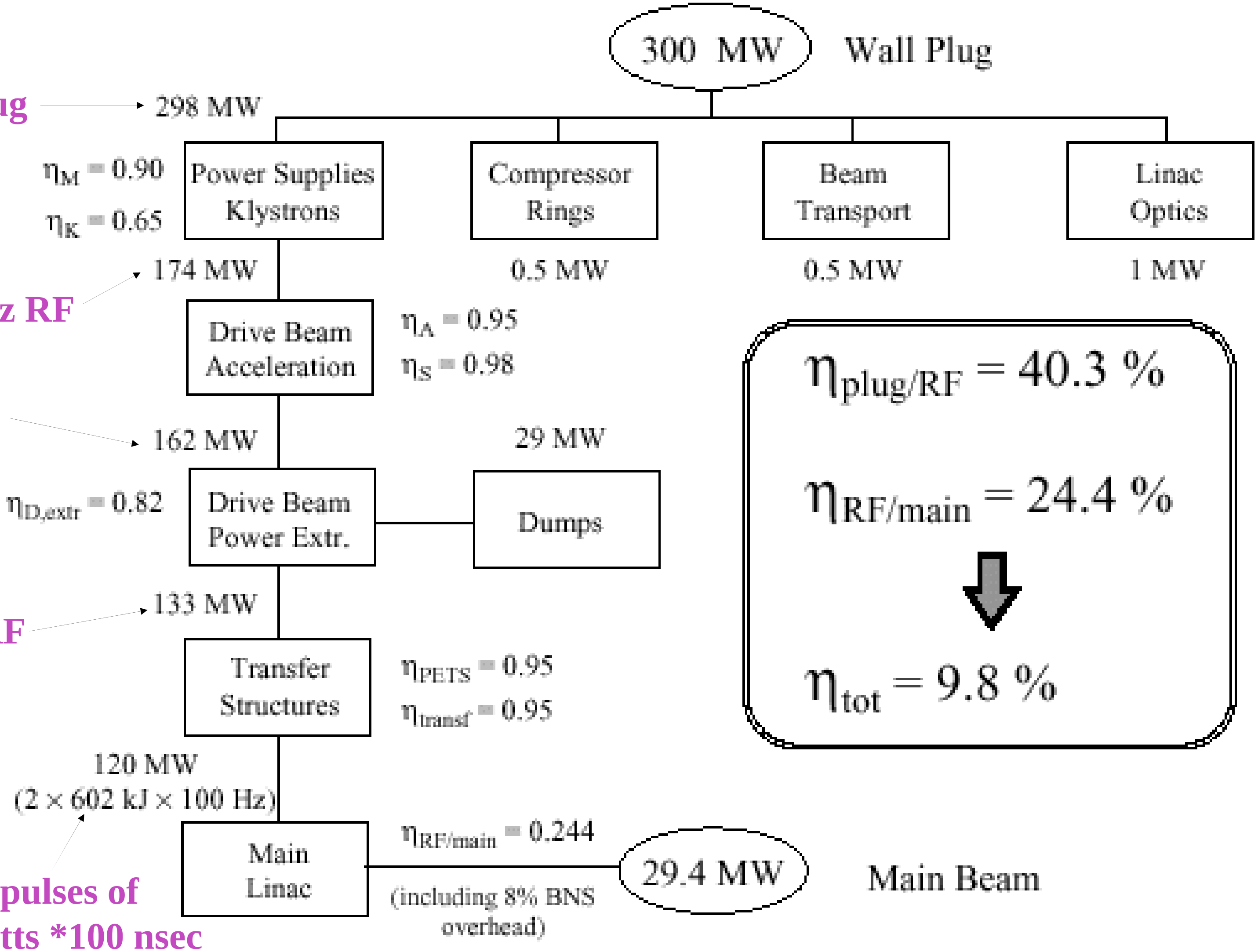
43000
Accelerating Structures
High Frequency – High field

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



$\eta_{plug/RF} = 40.3\ \%$

$\eta_{RF/main} = 24.4\ \%$

⇩

$\eta_{tot} = 9.8\ \%$

Wall Plug

937 MHz RF

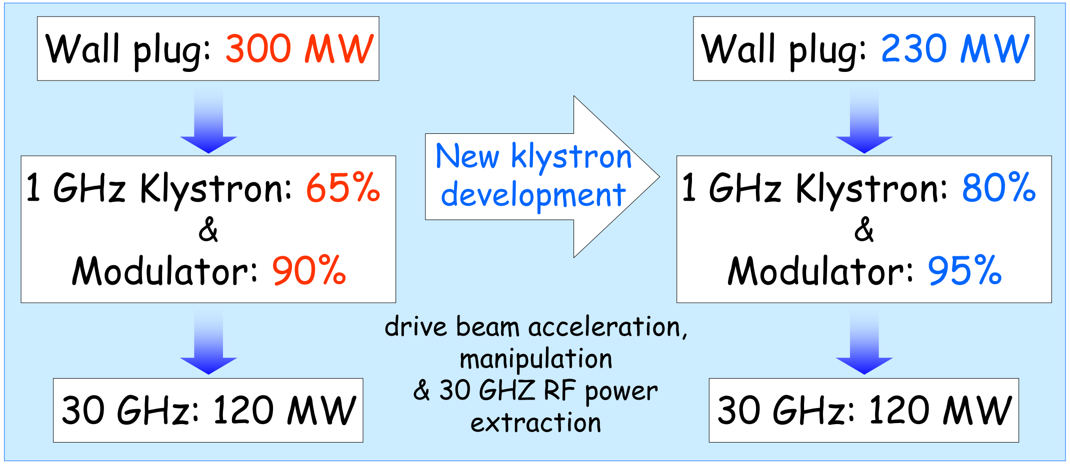
Beam

30 GHz RF

24000 pulses of 250 MWatts *100 nsec

Improving the efficiency

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

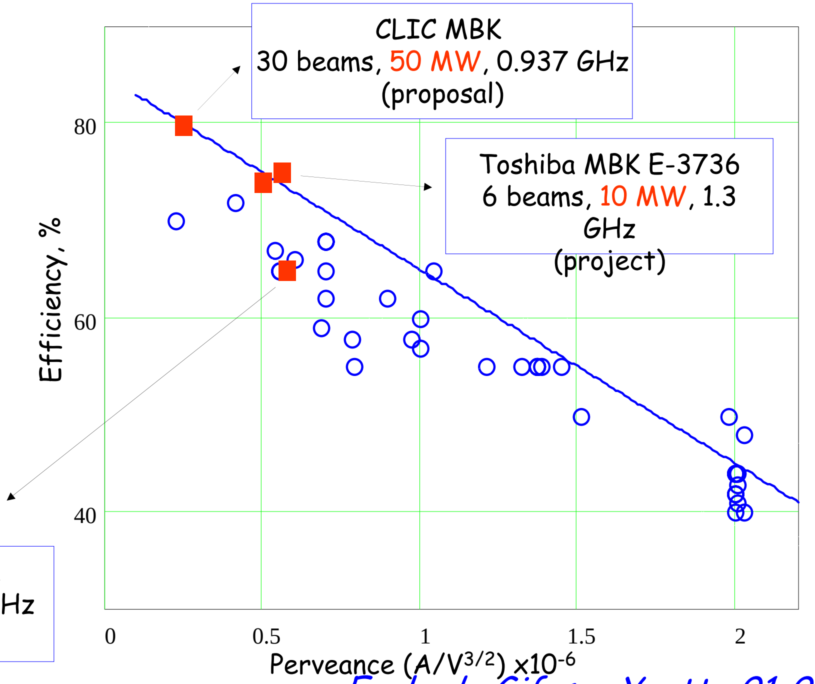
Wall plug: 230 MW

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)



CLIC MBK
30 beams, 50 MW, 0.937 GHz
(proposal)

Toshiba MBK E-3736
6 beams, 10 MW, 1.3 GHz
(project)

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

Why Multi Beam?

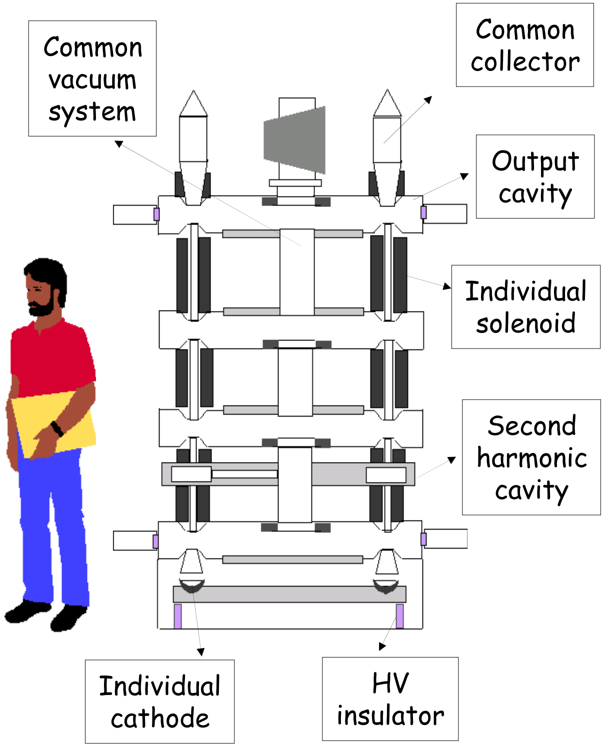
- Low perveance (A/$V^{3/2}$) favor klystron efficiency.
- Multi Beam devices keep single beam perveance small to provide high efficiencies for high RF power output (tens of MW).

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

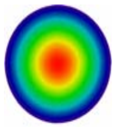
In order to host a large number of beams in a MB Klystron, it is necessary to use RF cavities operating at a mode with higher 1) radial or 2) azimuthal order.

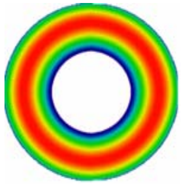
The second case was chosen for the CLIC MBK, which allows higher impedance seen by single beam.

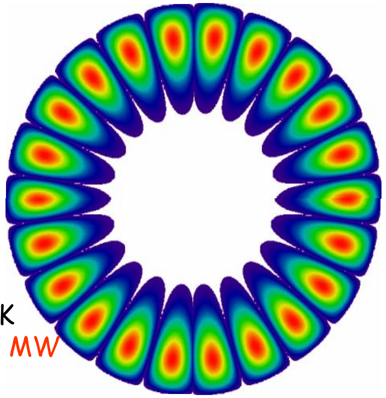
General layout of CLIC MBK 0.937 GHz, 50 MW



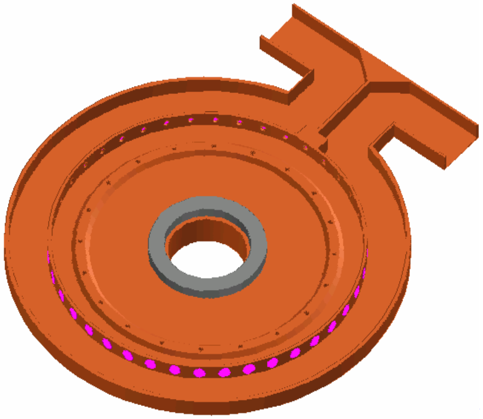
Electric field plots for different MBK's RF cavities. The beams are located in the maximum field area (red color)


Thales MBK TH1801
6 beams, 10 MW


Toshiba MBK E-3736
6 beams, 10 MW

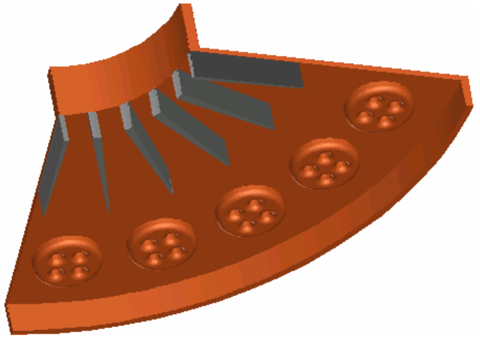

CLIC MBK
30 beams, 50 MW

General view of the output cavity and waveguide feeder



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

Damping of the HOM with array of many thin SiC wedges

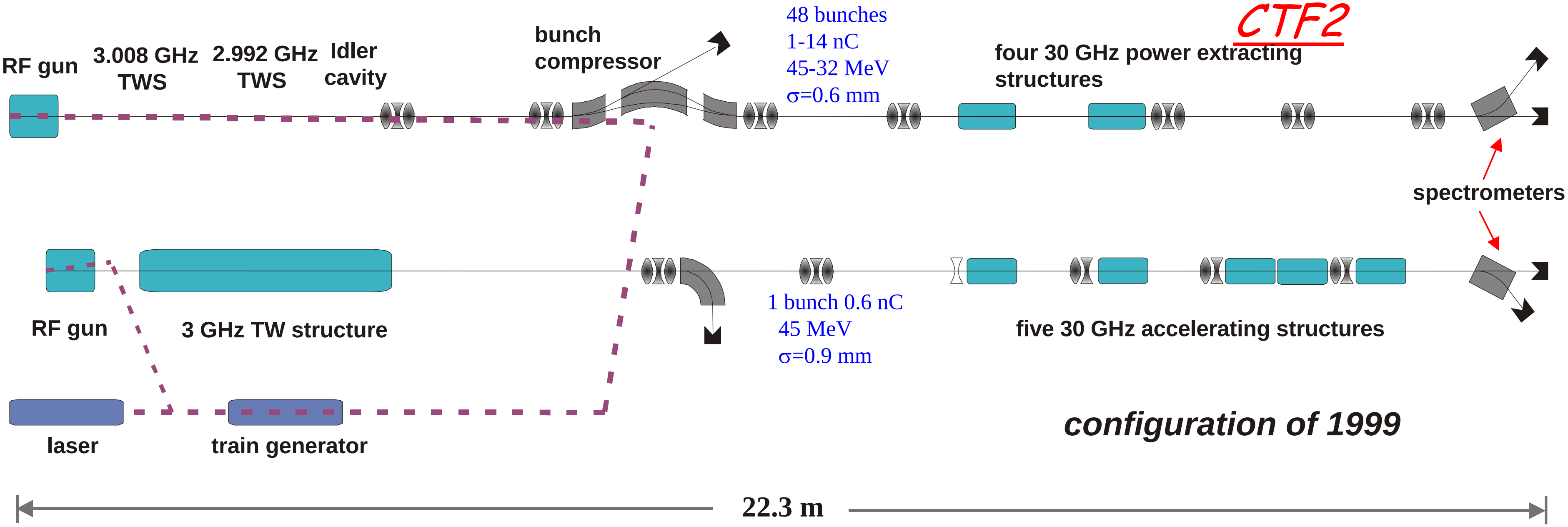


CLIC Test Facility (CTF2) 1996-2002

CTF2 goals :

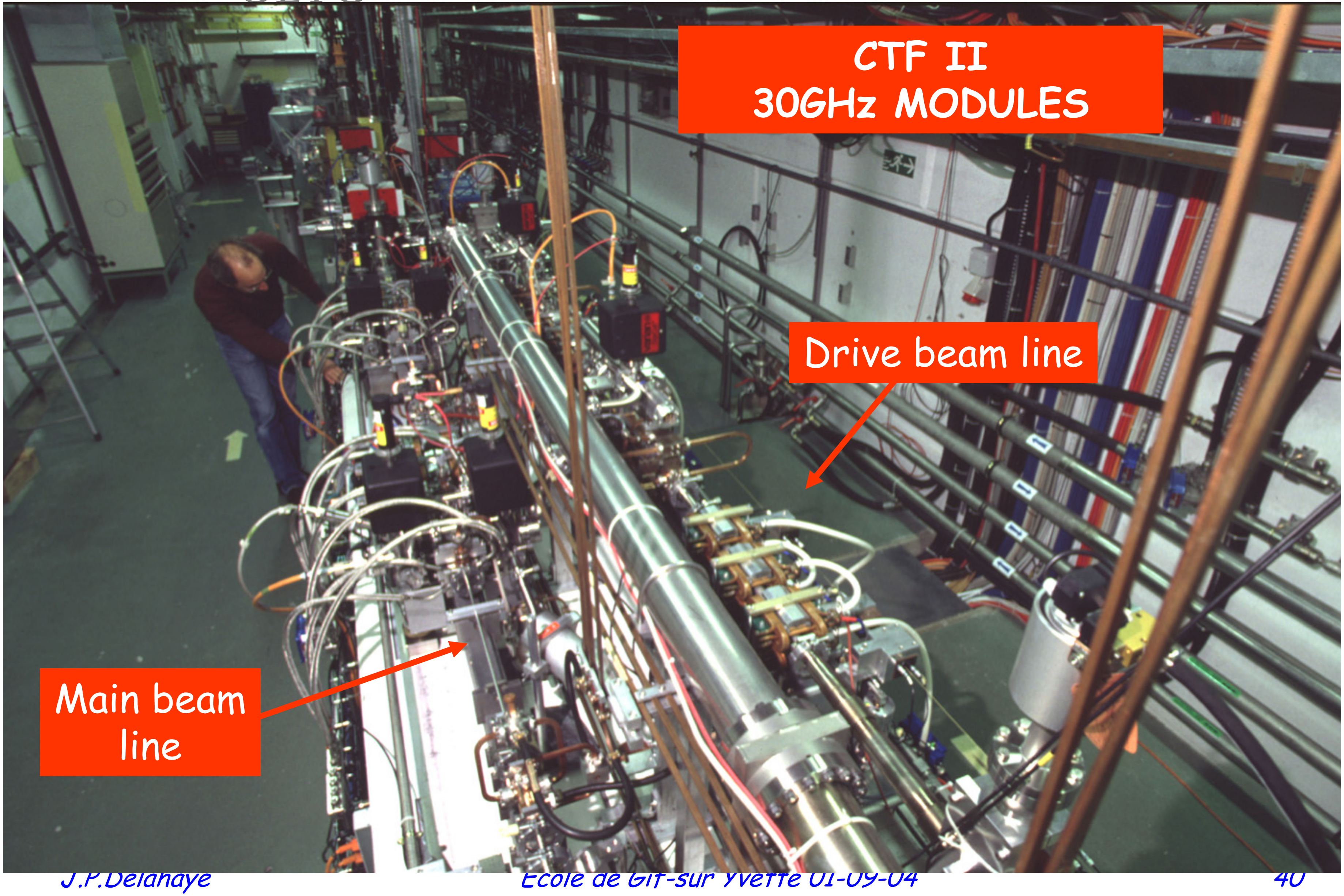
- to demonstrate feasibility of CLIC two-beam acceleration scheme
- to study generation of short, intense e-bunches using laser-illuminated PCs in RF guns
- to demonstrate operability of μ-precision active-alignment system in accelerator environment
- to provide a test bed to develop and test accelerator 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.



configuration of 1999

Two Beams set-up in CTF2

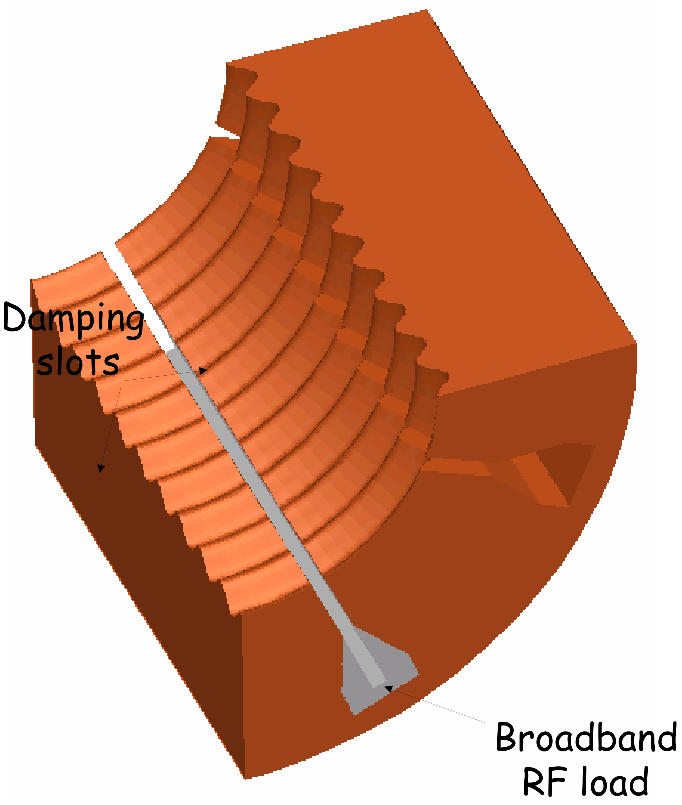


CTF II
30GHz MODULES

Drive beam line

Main beam line

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

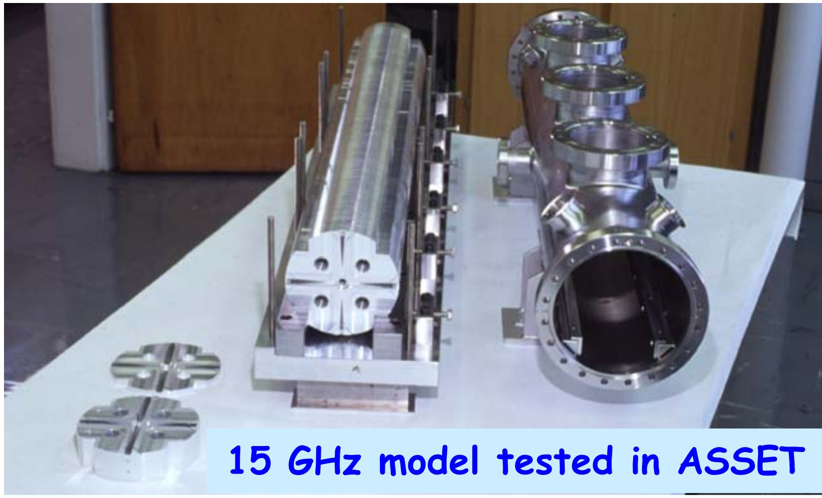
Accelerating structure developments

CLIC

CONTROL OF TRANSVERSE WAKEFIELDS

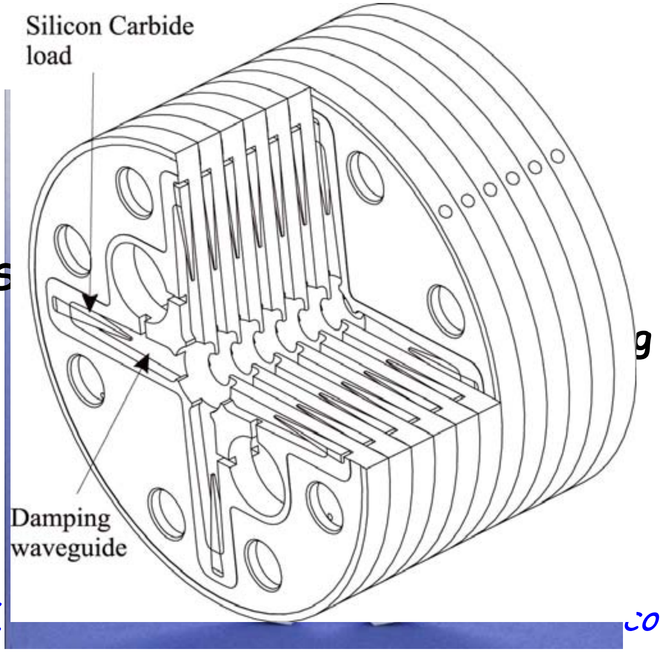
- short-range wakes ⇐ BNS damping
- long-range wakes ⇐ damping and detuning

+ beam-based trajectory correction, ε bump


15 GHz model tested in ASSET

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.

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

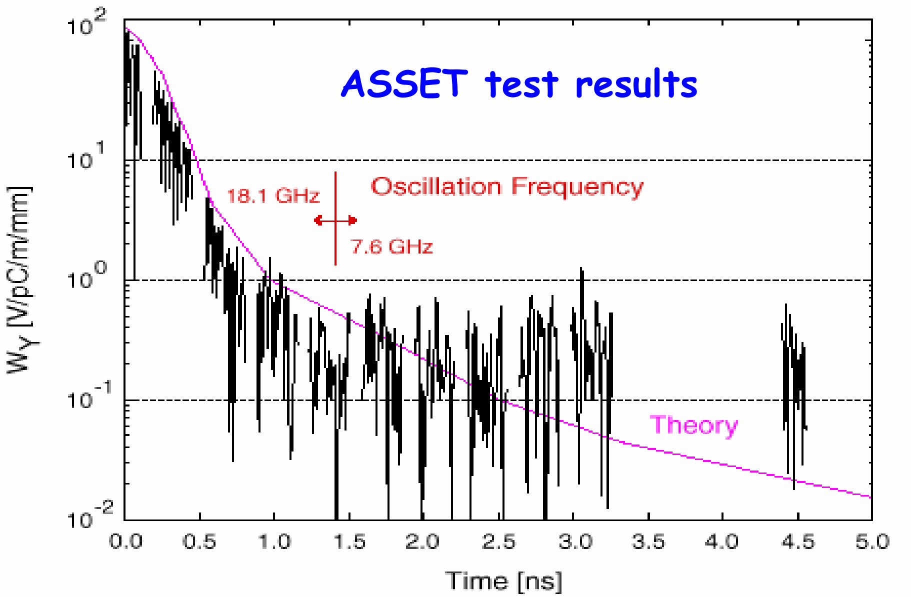


S

g WG

J.

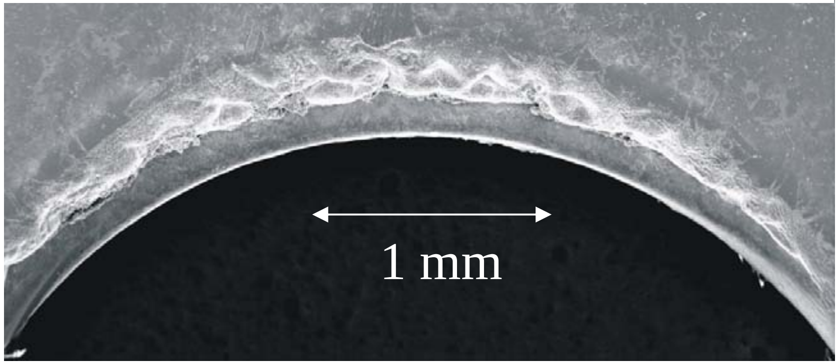
cole de Gif-su



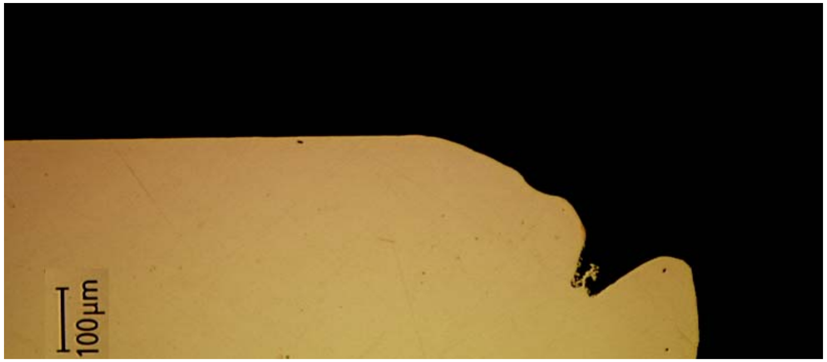
Structure breakdown and damages

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

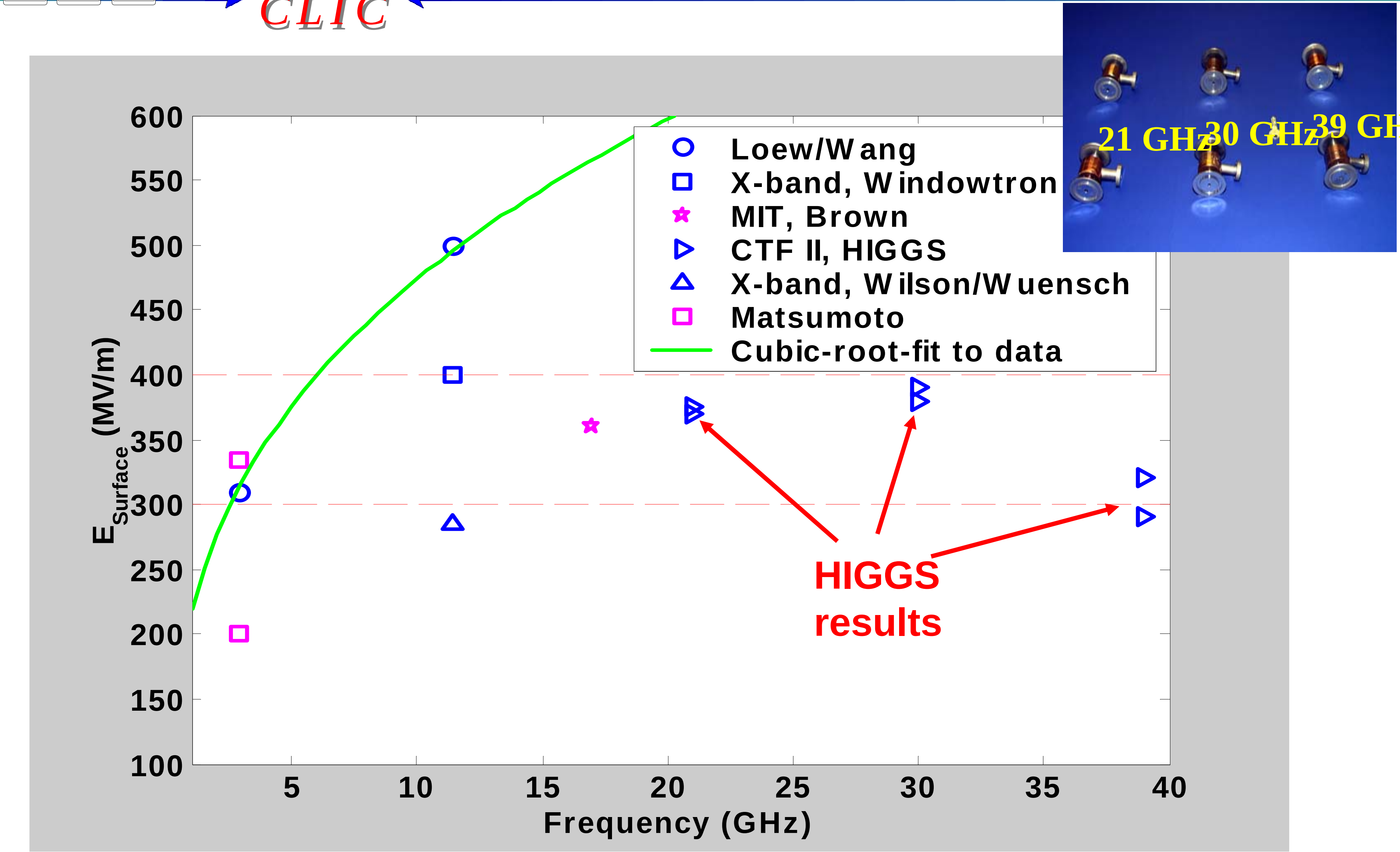


Damaged iris – longitudinal cut

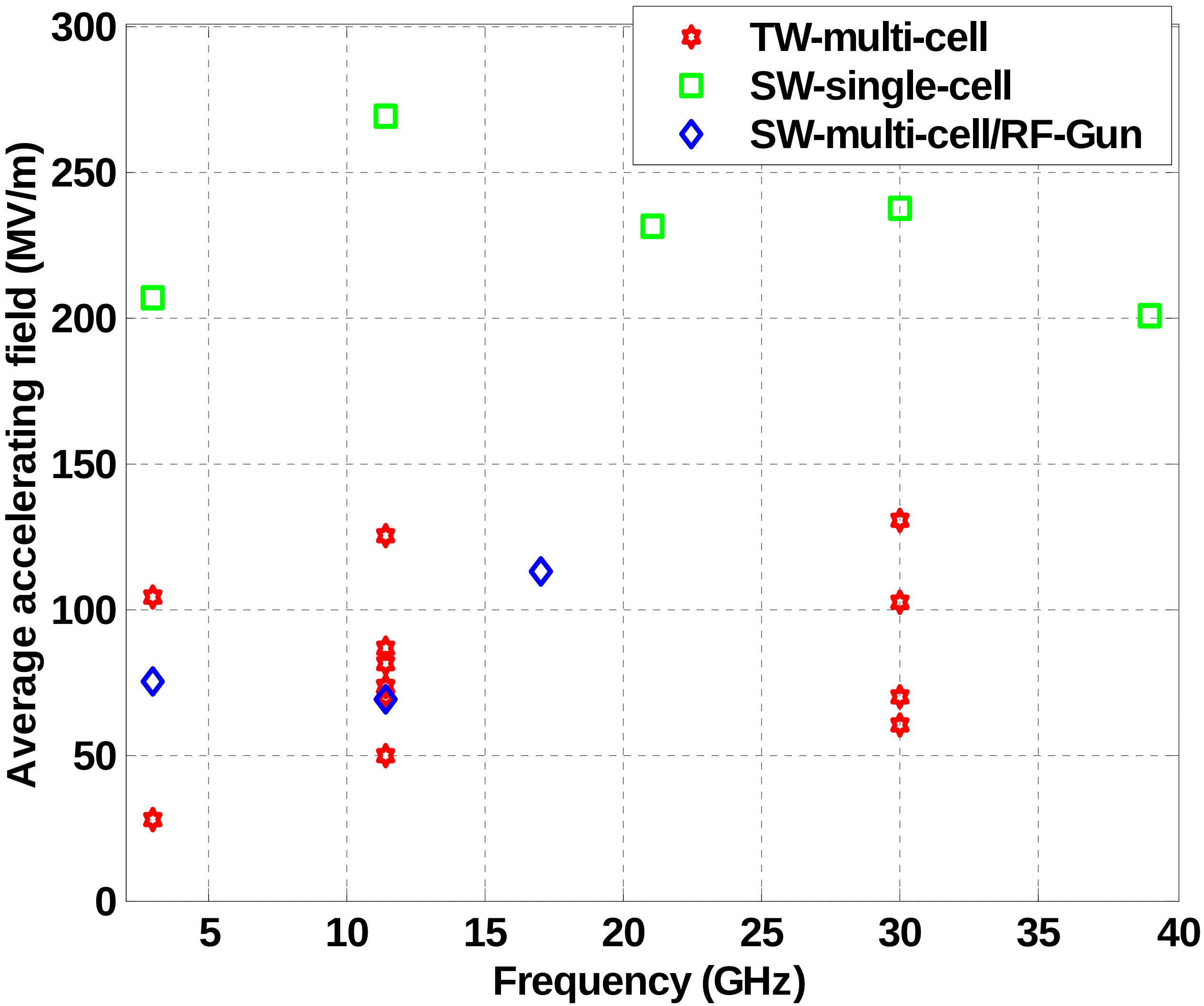
The CLIC study group is adopting a two-pronged approach to solving the breakdown problem

- **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

Field limits on copper surfaces



Accelerating field performances



Data from:

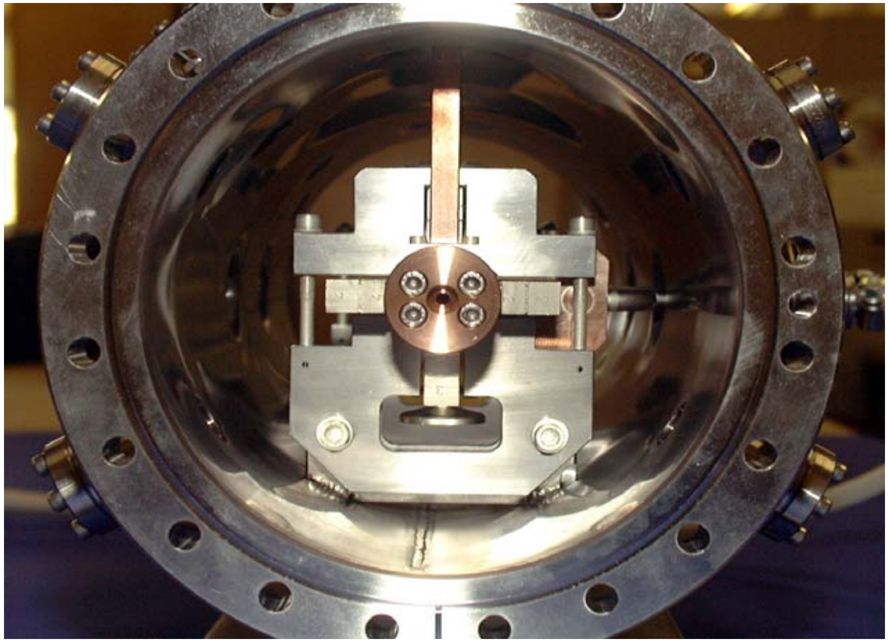
KEK

SLAC

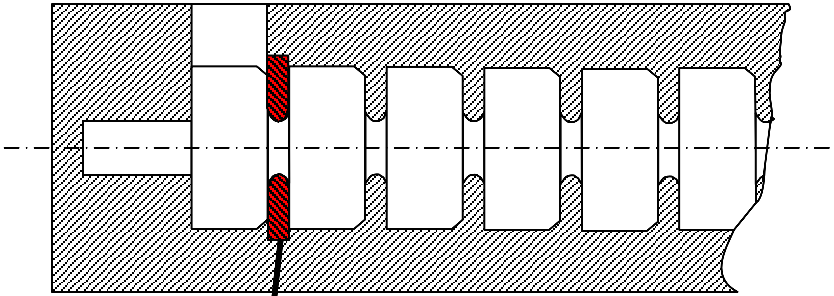
MIT

CERN

Tests of tungsten iris in CTF2

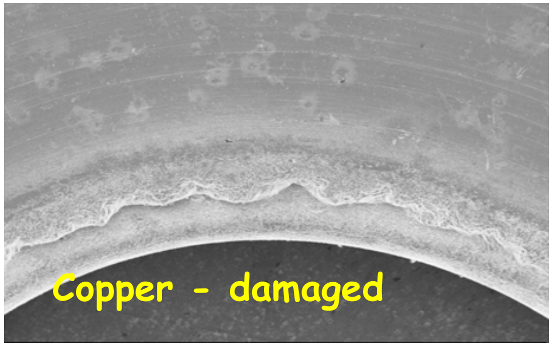


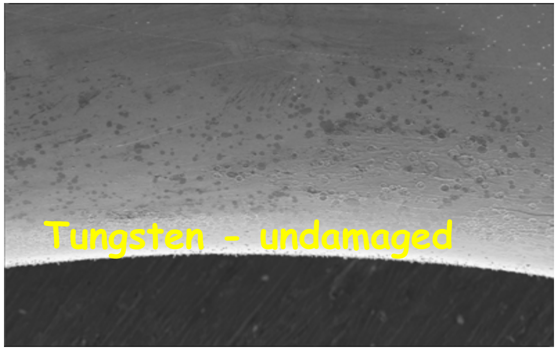
Test structure in external vacuum can, with clamped coupler cell



Copper iris replaced by **Tungsten** iris

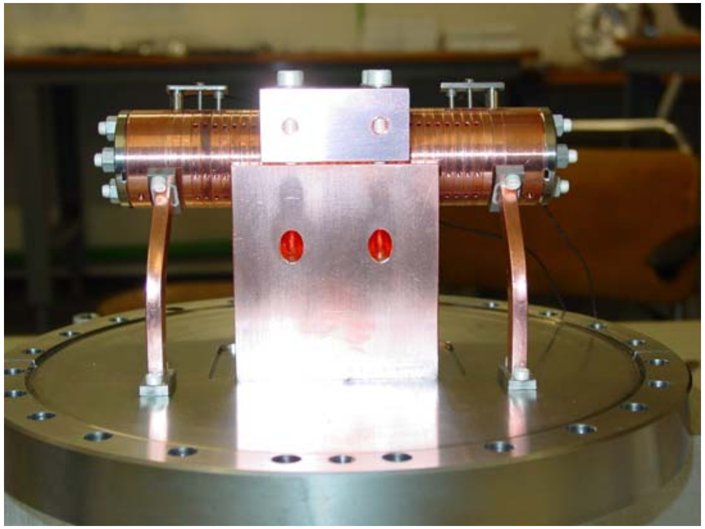
Irises after high-gradient testing to about the same field level



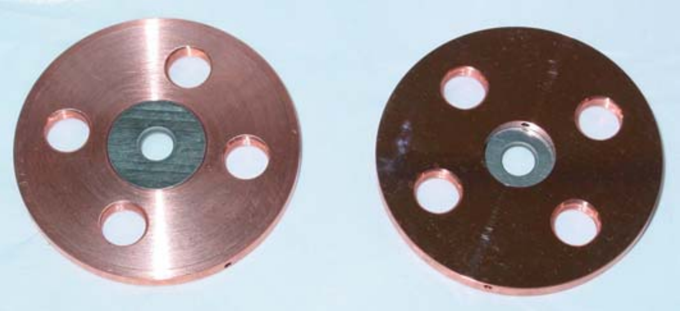


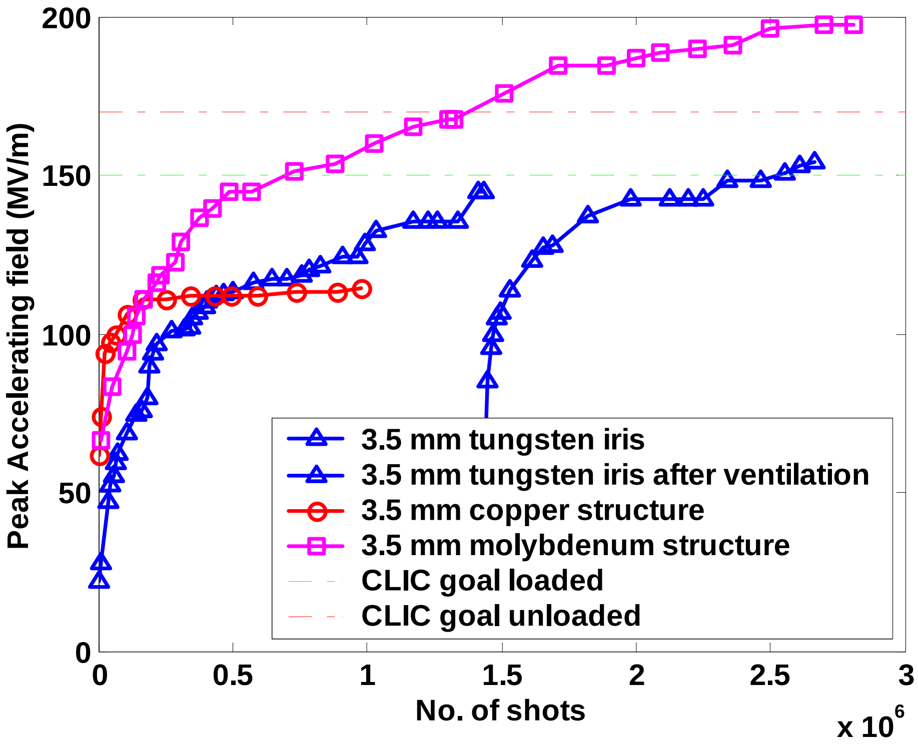
Achieved accelerating fields in CTF2

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)



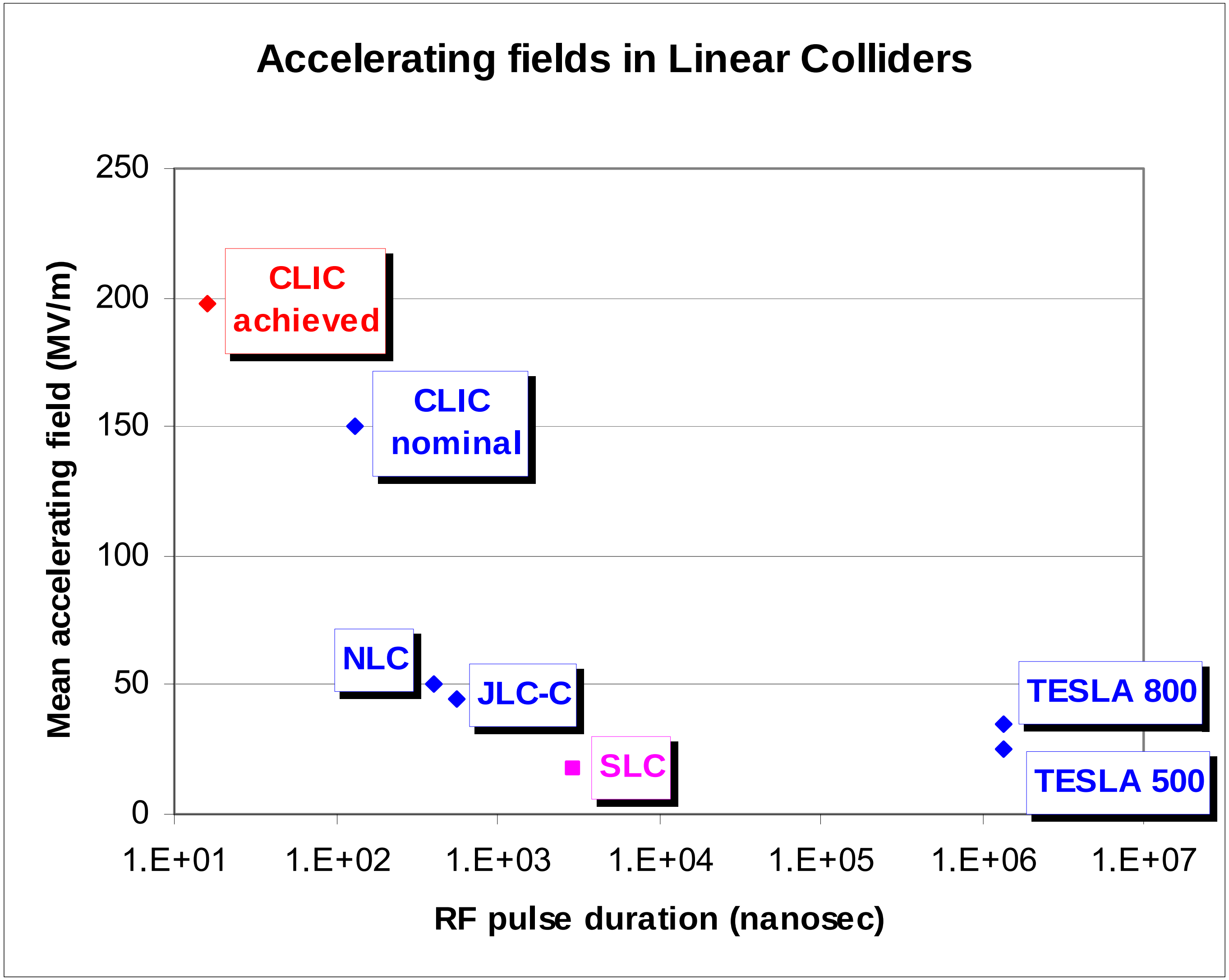
30 cell clamped tungsten-iris structure





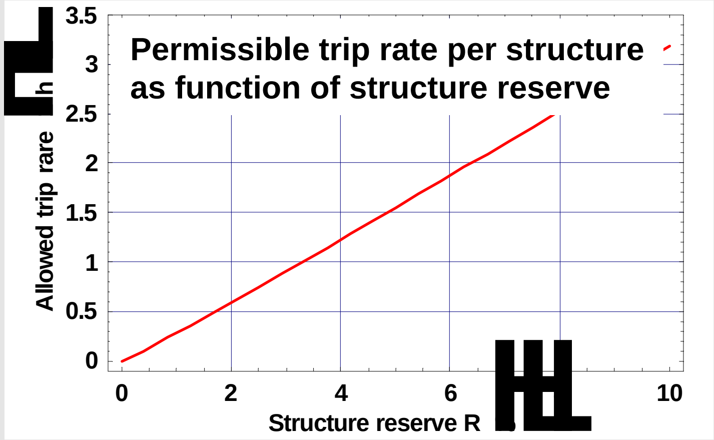
A world record !!!

Accelerating fields in Linear Colliders

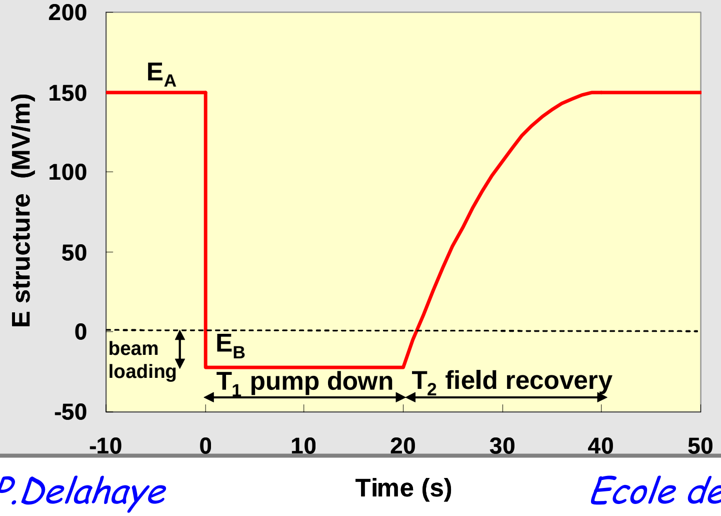


Acceptable Trip Rate of CLIC accelerating structures

Limits imposed by energy management



assuming this trip recovery scenario:



Limits imposed by effect of RF break-down on beam

- Effect on beam of RF break-down in a structure not well known

  Can be measured in CTF3 with probe beam (available 2007).

- Vertical kick of $\Delta P_Y \approx 20$keV/c is sufficient to take beam out of collision.

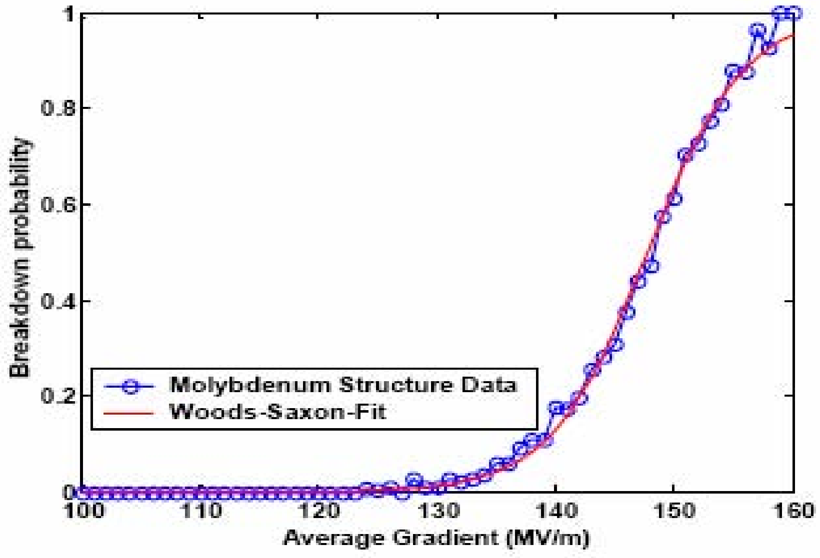
- Assuming, in the worst case, that every beam pulse having suffered from one single structure breakdown does not contribute to the integrated luminosity::

For <1% luminosity loss:

Trip rate per structure < *0.05 h^{-1}*

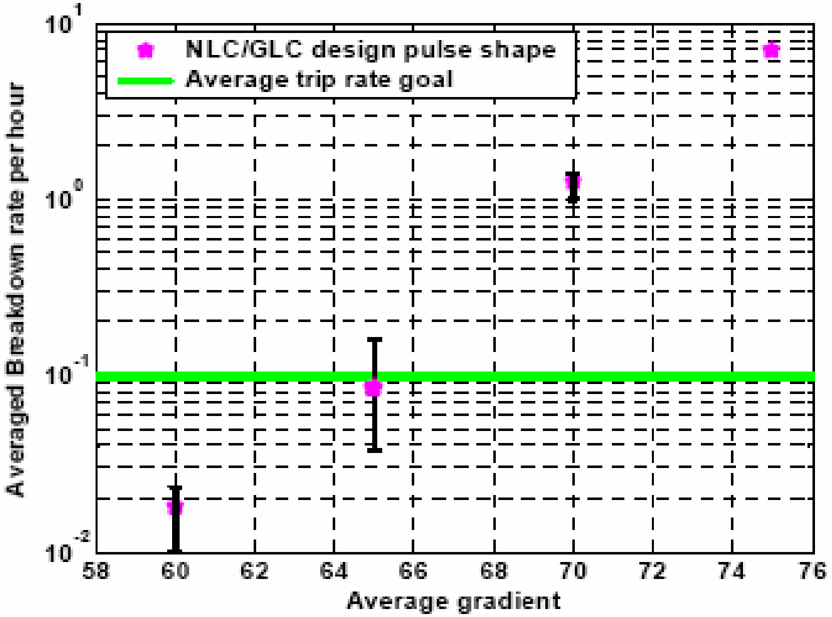
1 over 10^{7} RF pulses at 100 Hz repetition rate

RF Breakdown rates in structures



Breakdown rates during RF conditioning of a CLIC structure equipped with Mo iris

No reliable breakdown rates available for CLIC structures after RF conditioning

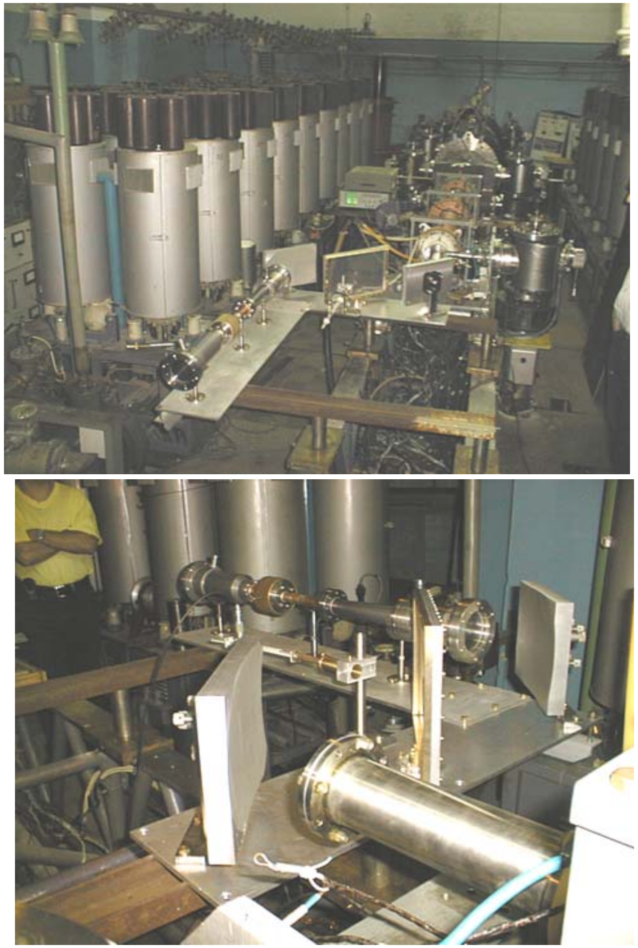


Factor 10 reduction of breakdown rate of NLC structure by 5.5 MeV reduction in accelerating field (SLAC-PUB-10463 May 2004)

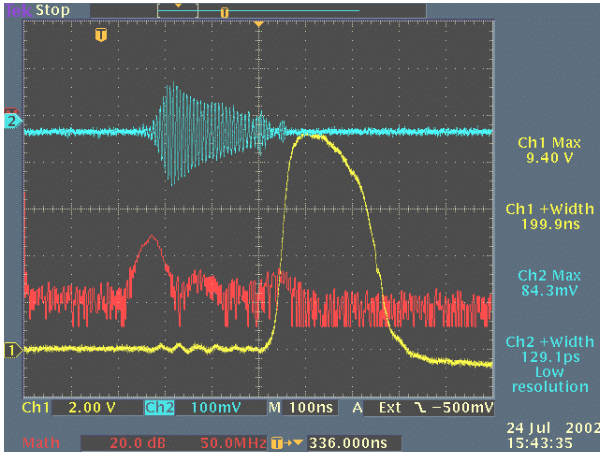
40 MeV/m reduction in field for a 10^7 reduction in RF breakdown

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

International Technical Review Committee

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 (9)

- **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**

More difficult in CLIC because of larger wakefields, smaller beam emittances and smaller beam sizes at IP

CLIC technology-related key issues as pointed out by ILC-TRC

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: Developments of structures with hard-breaking materials (W, Mo…)

✓R2.2: Validation of stability and losses of drive beam decelerator;
Design of machine protection system

✓R2.3: Test of relevant linac sub-unit with beam

✓R2.4: Validation of 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.

Valid for any Multi-TeV Linear Collider independently of the technology

CLIC

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)

The Photo-Injector
a performing e^- source for CTF3

CERN

Photocathodes

+

Timing

RF power

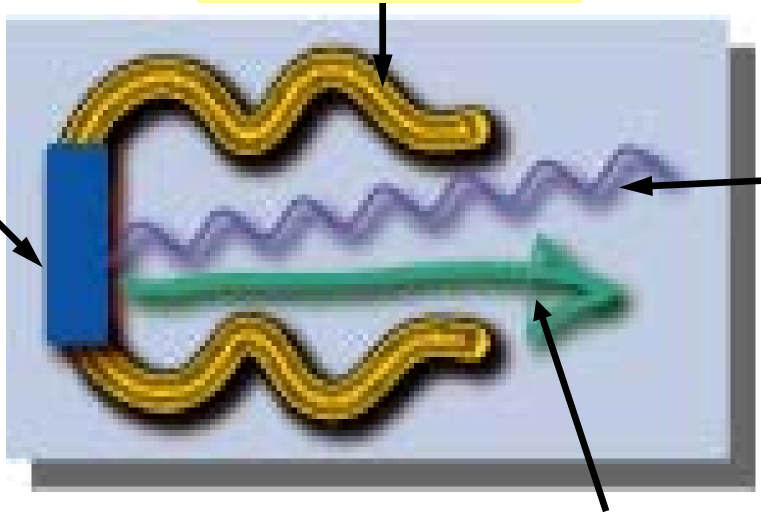
Laser beam transport

Installation

Monitoring …

LAL (F)

3 GHz RF gun



RAL (GB)

High power

Laser

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

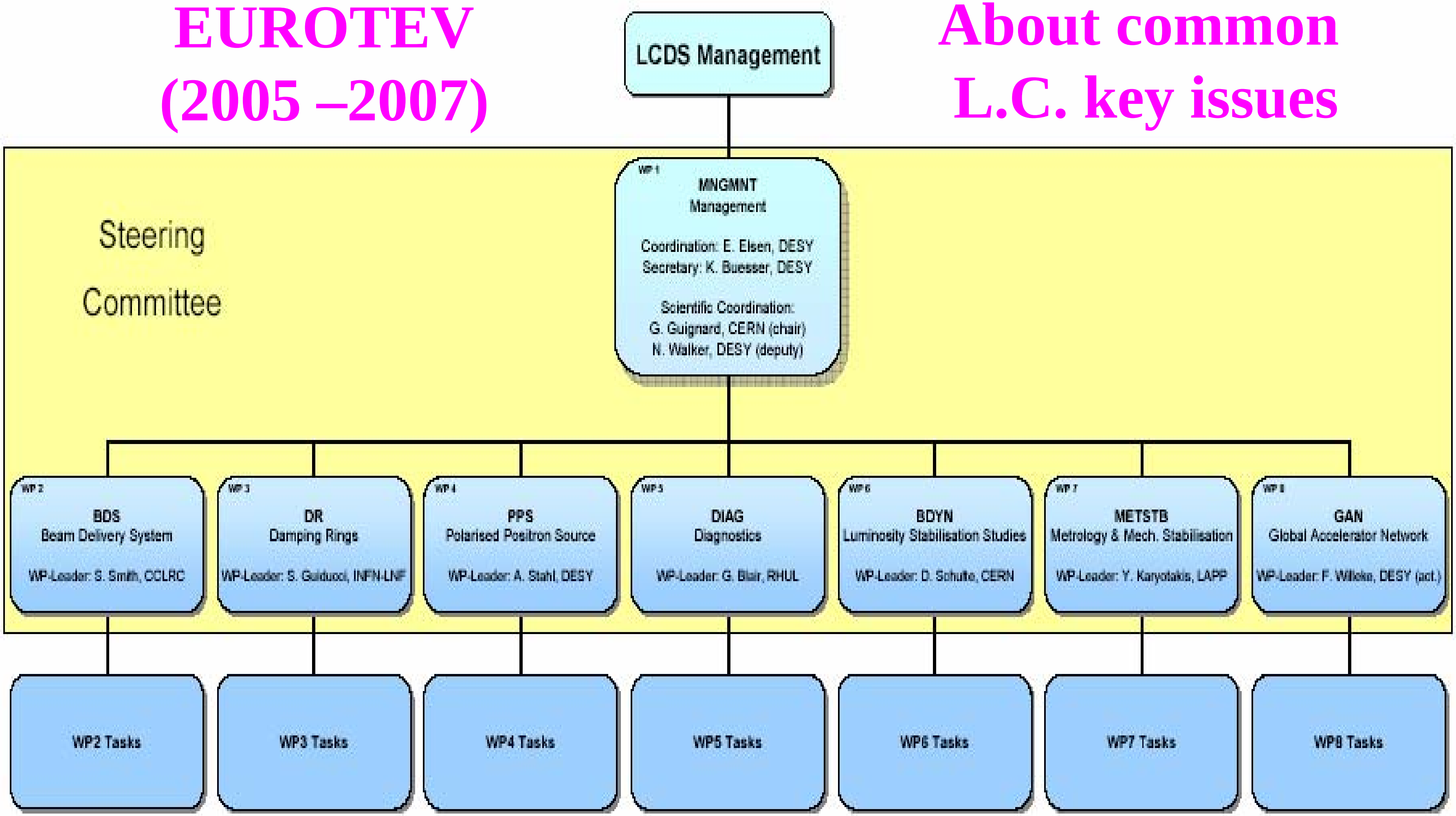
2004 - 2006 : construction and installation of the photo-injector included in the European program CARE (FP6)

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

EU supported (9MEuros) Linear Colliders Design Study

EUROTEV (2005 –2007)

About common L.C. key issues



LCDS Management

Steering Committee

WP 1
MNGMNT
Management

Coordination: E. Elsen, DESY
Secretary: K. Buesser, DESY

Scientific Coordination:
G. Guignard, CERN (chair)
N. Walker, DESY (deputy)

WP 2
BDS
Beam Delivery System
WP-Leader: S. Smith, CCLRC

WP 3
DR
Damping Rings
WP-Leader: S. Guiducci, INFN-LNF

WP 4
PPS
Polarised Positron Source
WP-Leader: A. Stahl, DESY

WP 5
DIAG
Diagnostics
WP-Leader: G. Blair, RHUL

WP 6
BDYN
Luminosity Stabilisation Studies
WP-Leader: D. Schulte, CERN

WP 7
METSTB
Metrology & Mech. Stabilisation
WP-Leader: Y. Karyotakis, LAPP

WP 8
GAN
Global Accelerator Network
WP-Leader: F. Willeke, DESY (act.)

WP2 Tasks

WP3 Tasks

WP4 Tasks

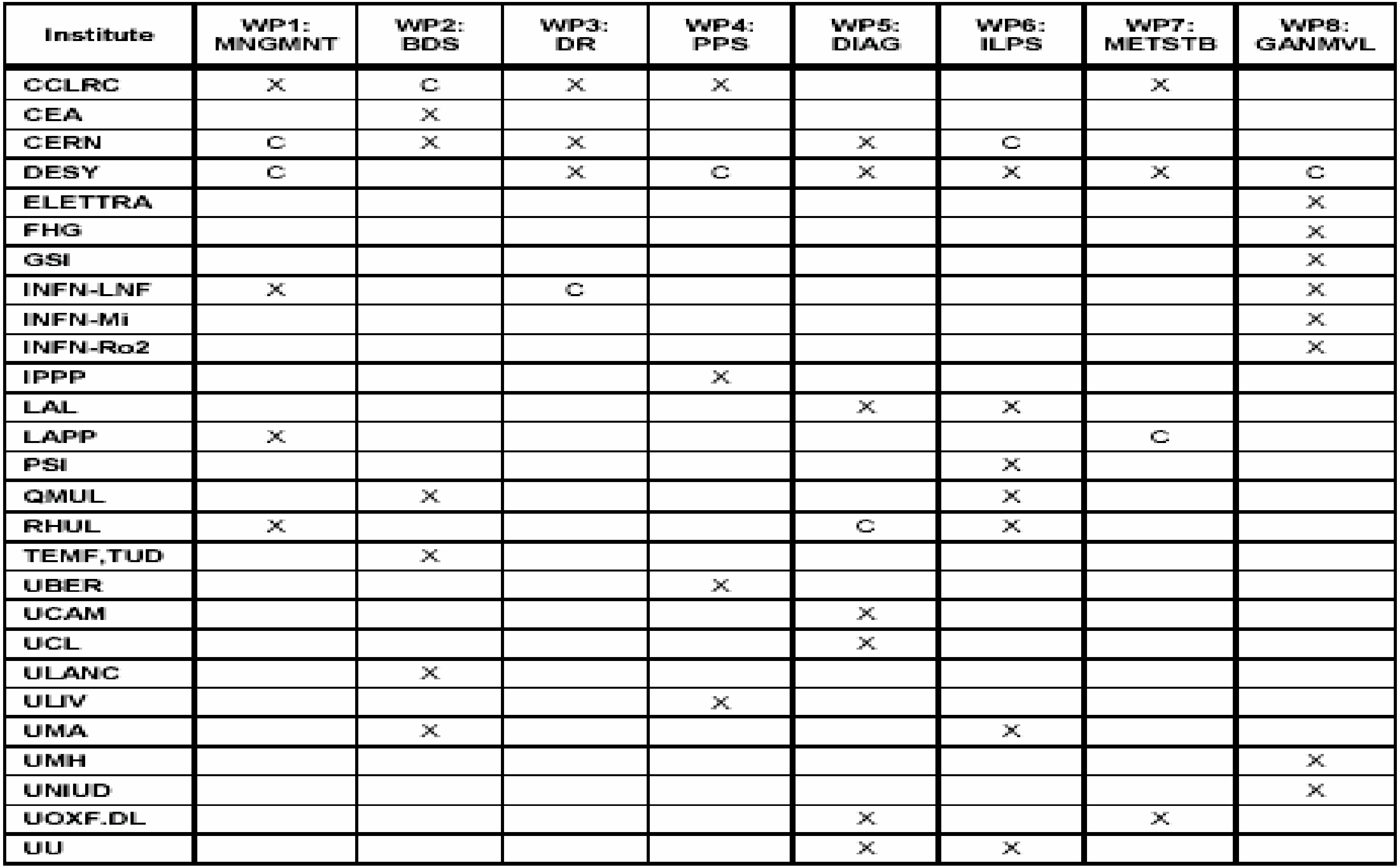
WP5 Tasks

WP6 Tasks

WP7 Tasks

WP8 Tasks

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		

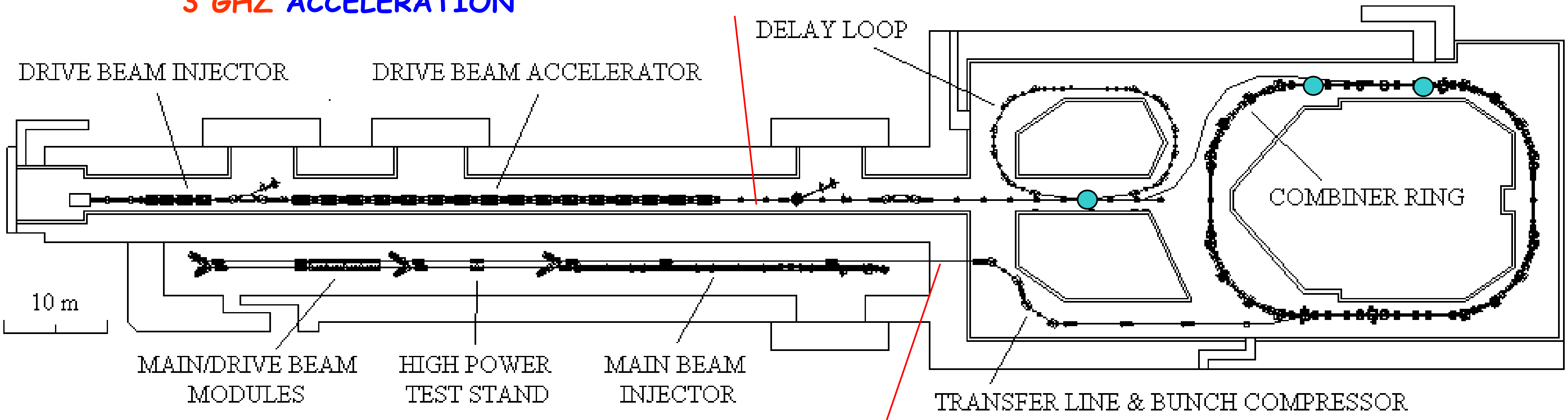
All R1 and R2 CLIC key issues addressed in CLIC Test Facility (CTF3)

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

FULLY LOADED
3 GHZ ACCELERATION

3.5 A - 1.4 µs

PULSE COMPRESSION
FREQUENCY MULTIPLICATION



30 GHz - ≥ 200 MW - 140 ns

30 GHZ POWER EXTRACTION
& COMPONENTS TEST

35 A - 140 ns

● RF DEFLECTORS

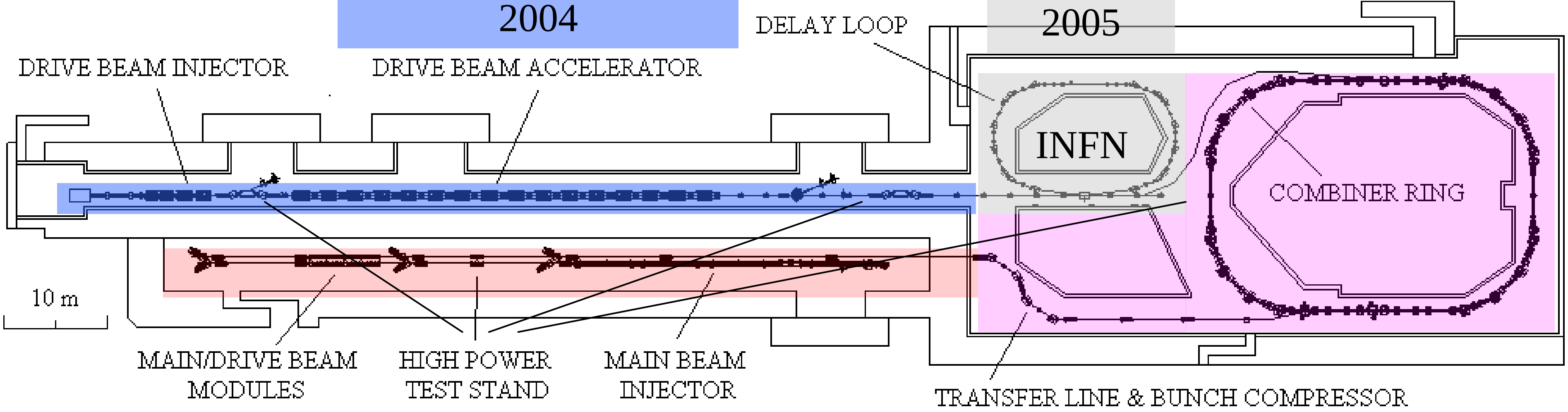
CLIC Test Facility: CTF3

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

Damped accelerating structure (R1.1)

2004

2005



CLEX

2006

Drive beam generation scheme (R1.2)
ON/OFF PETS (R1.3)

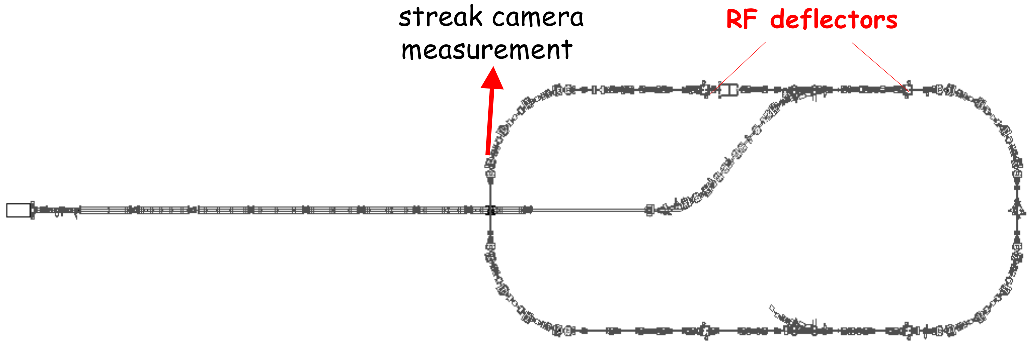
2007

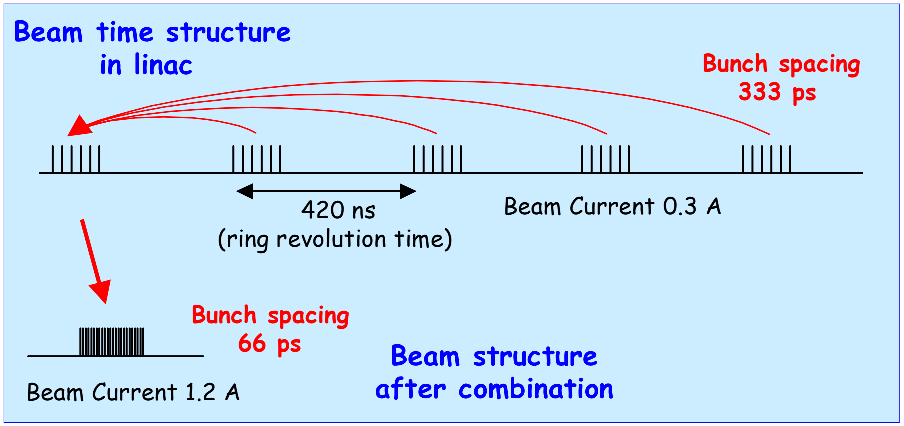
Stability bench marking (R2.1)
CLIC sub-unit (R2.3)

Beam power and frequency multiplication

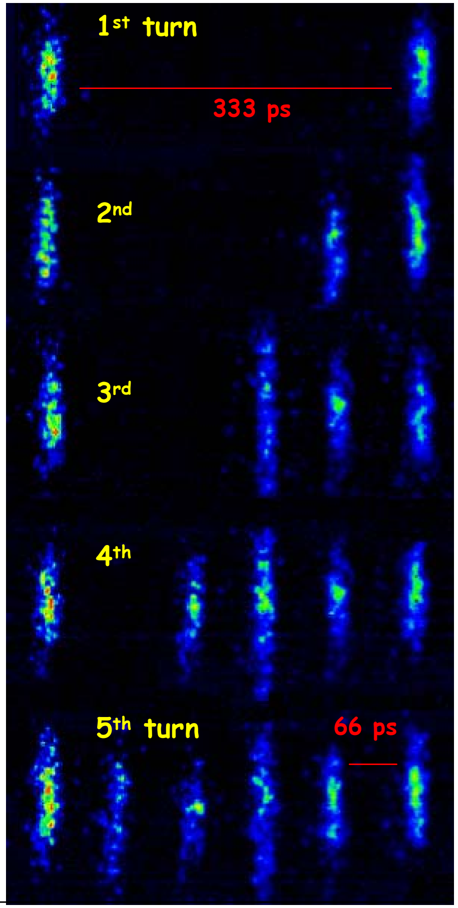
CTF3 - PRELIMINARY PHASE

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



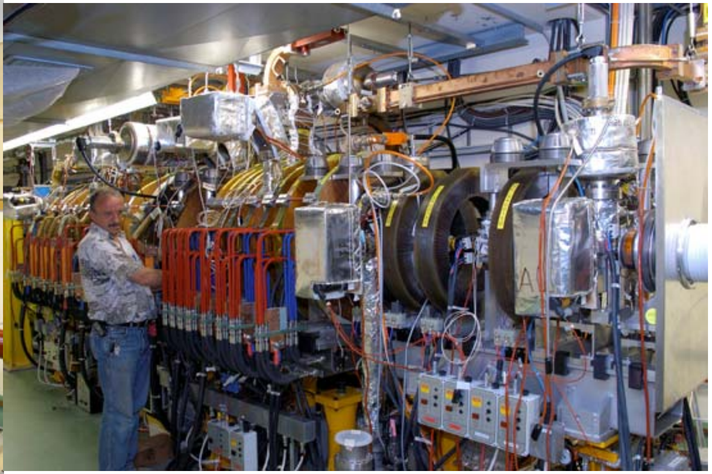


Streak camera image of beam time structure evolution



CTF3 Injector installation

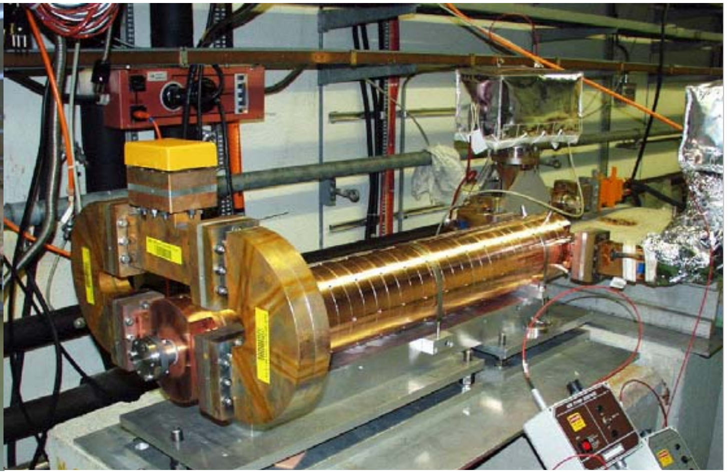
7A Thermionic Gun (LAL-SLAC)



Bunchers(LAL)&Solenoids(SLACstudy)

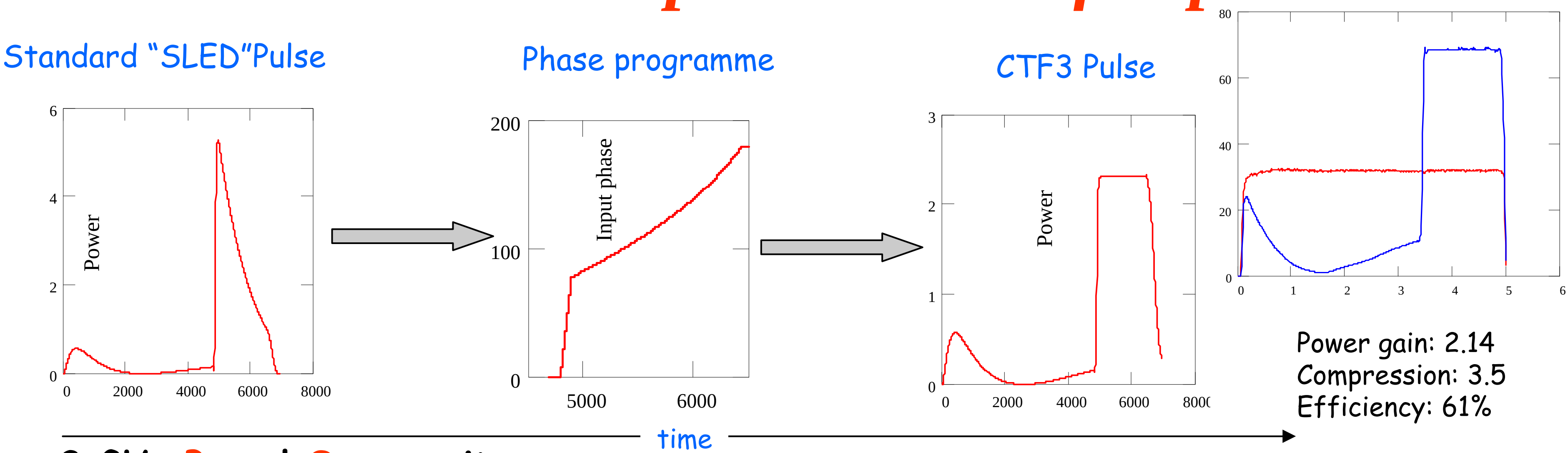
Novel RF power compression with Barrel Open Cavity (BOC)

Bunch length adjustment with magnetic chicane



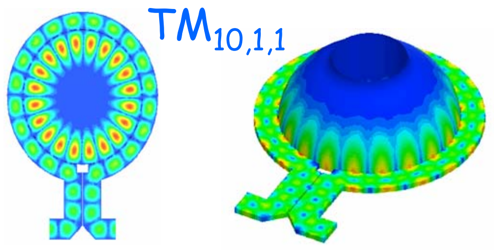
Accelerating structure with full beam loading

Novel method of RF pulse compression with flat pulse

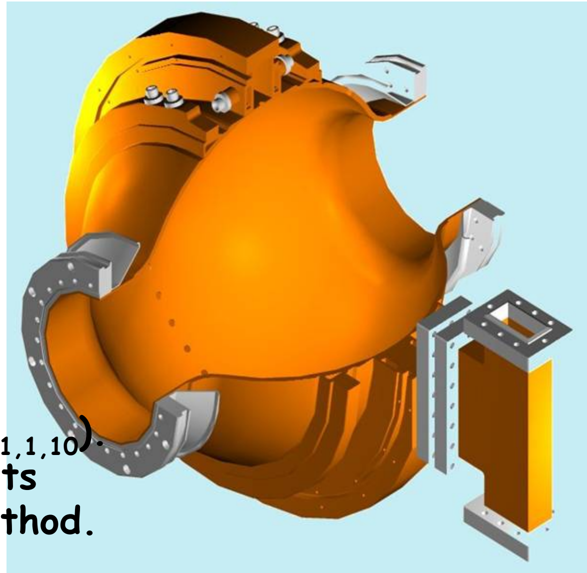


Power gain: 2.14
Compression: 3.5
Efficiency: 61%

3 GHz **B**arrel **O**pen cavity RF pulse **C**ompressor



Electric Field Magnetic Field



Prototype power tested, installed
5 more being manufactured

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

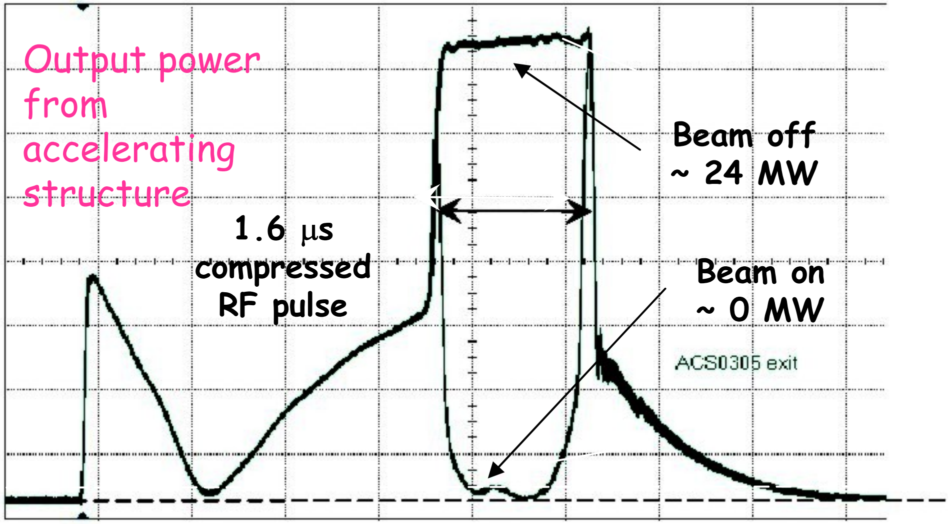
Injector commissioning 2003

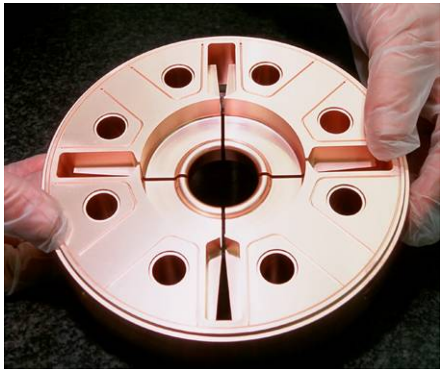
Nominal Beam parameters reached

	Nominal	Achieved
I	3.5 A	4.5 A
τ_p	1.5 μs	1.5 μs
E	20 MeV	20 MeV
$\varepsilon_{n,rms}$	100 π mm mrad	60-90 π mm mrad
$\tau_{bunch,rms}$	5 ps	< 6.5 ps

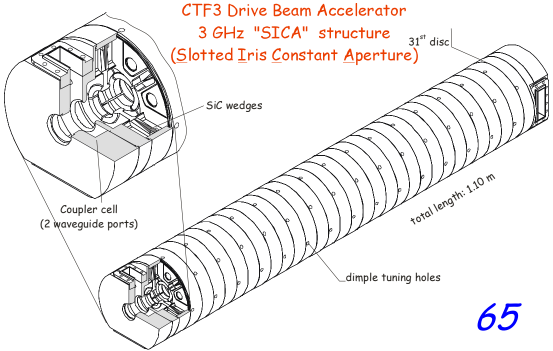
Full Beam Loading demonstrated:
>95 % efficiency ! More than with Superconducting systems (when including cryogenics)!
Beam stable !

First demonstration of full beam loading



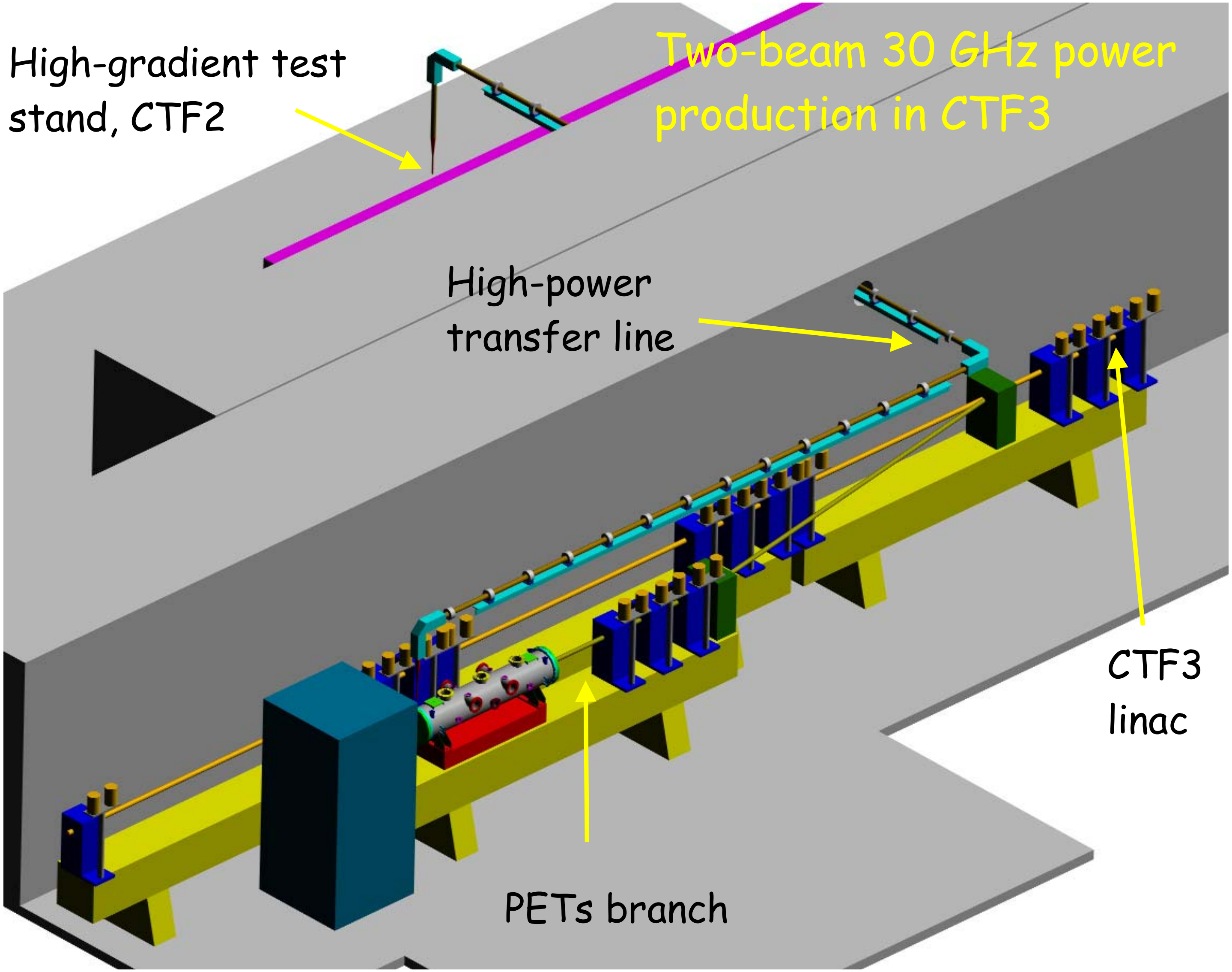


Damped DBA structure



R. Corsini – 18/08/2003

Two beam test stand



High-gradient test stand, CTF2

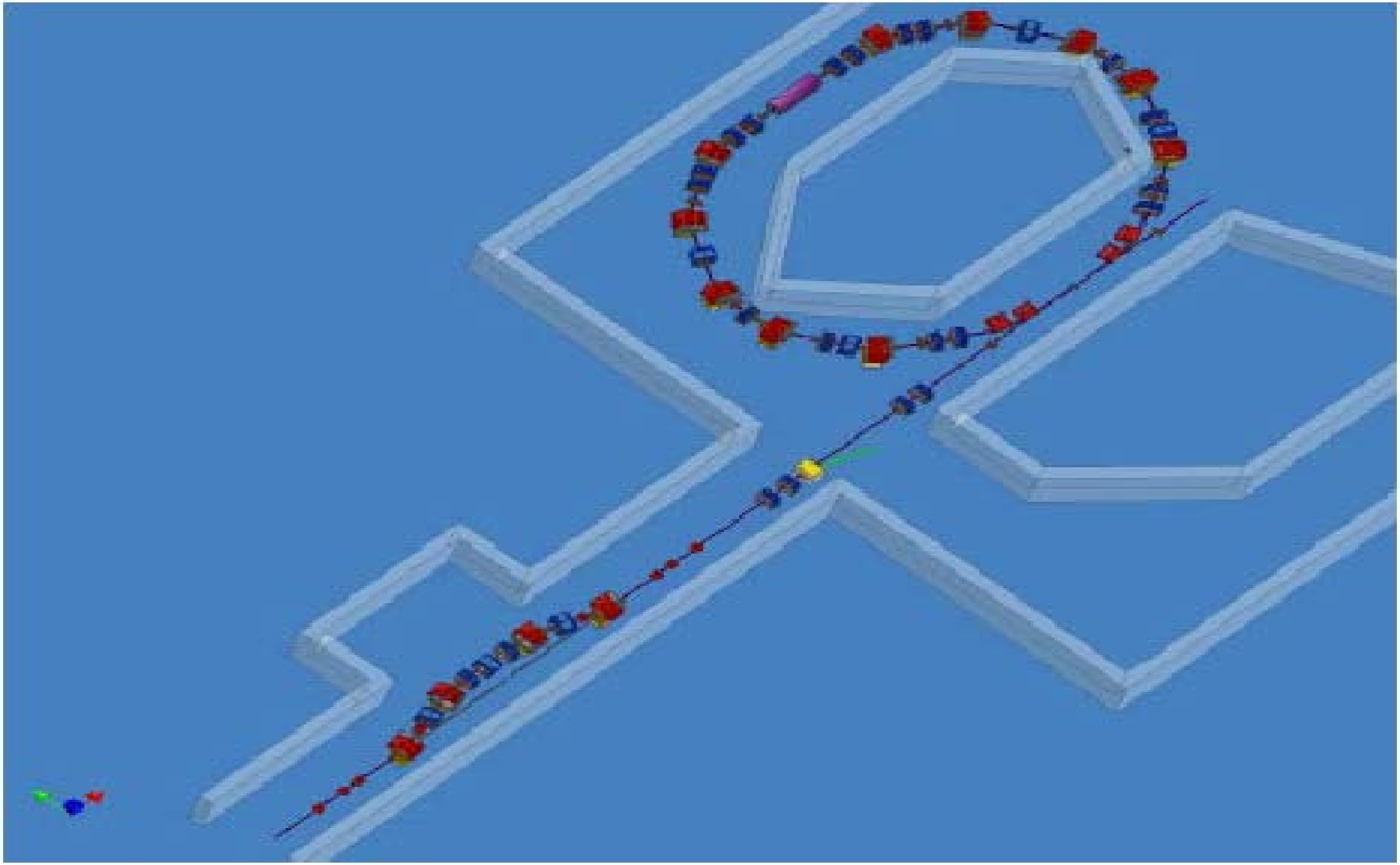
Two-beam 30 GHz power production in CTF3

High-power transfer line

CTF3 linac

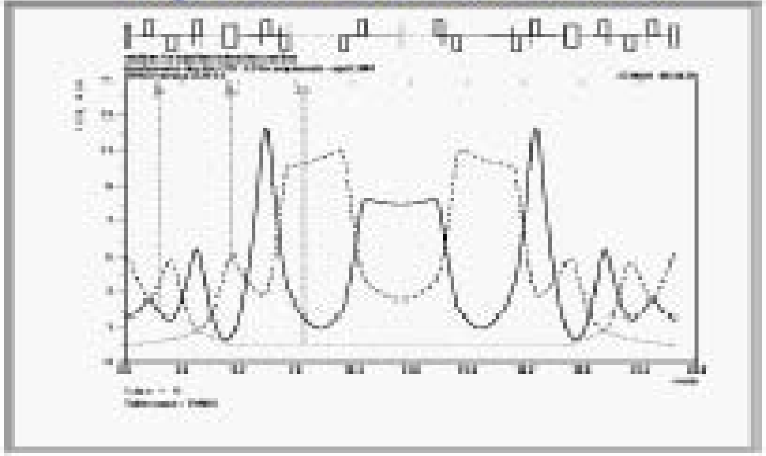
PETs branch

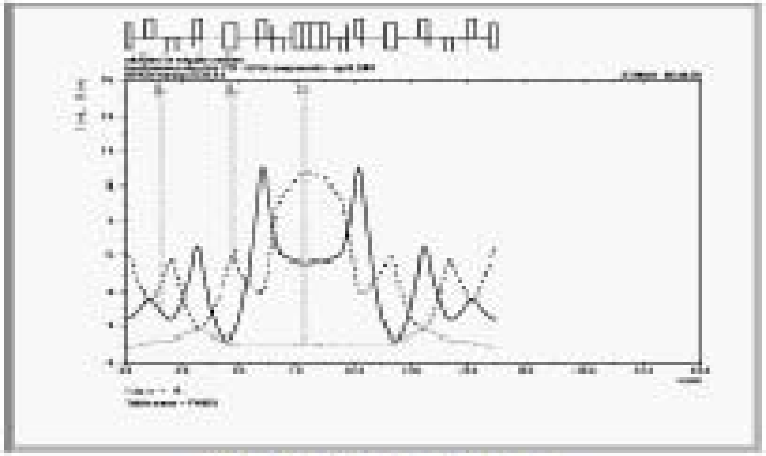
Bunch Compressor and Delay Loop (design, construction, resources by INFN-LNF)



Combiner Ring design (INFN-LNF)

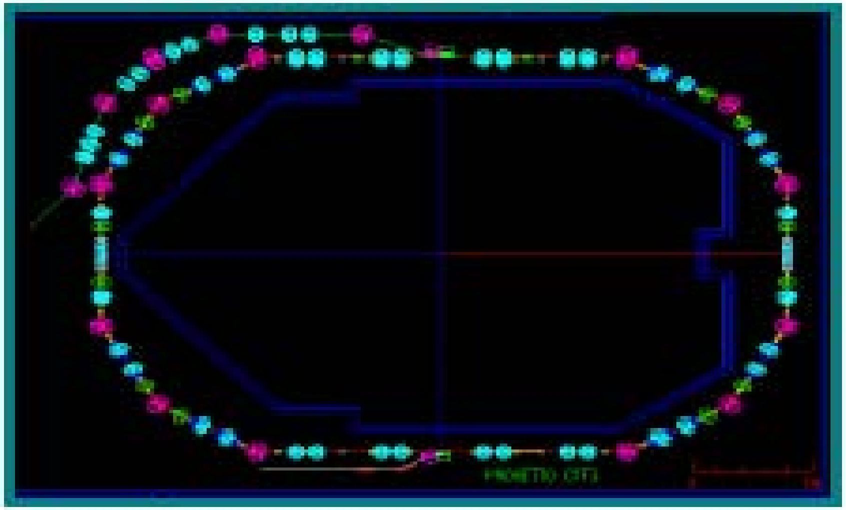
Injection/extraction sections





Wiggler sections

Isochronicity in CR

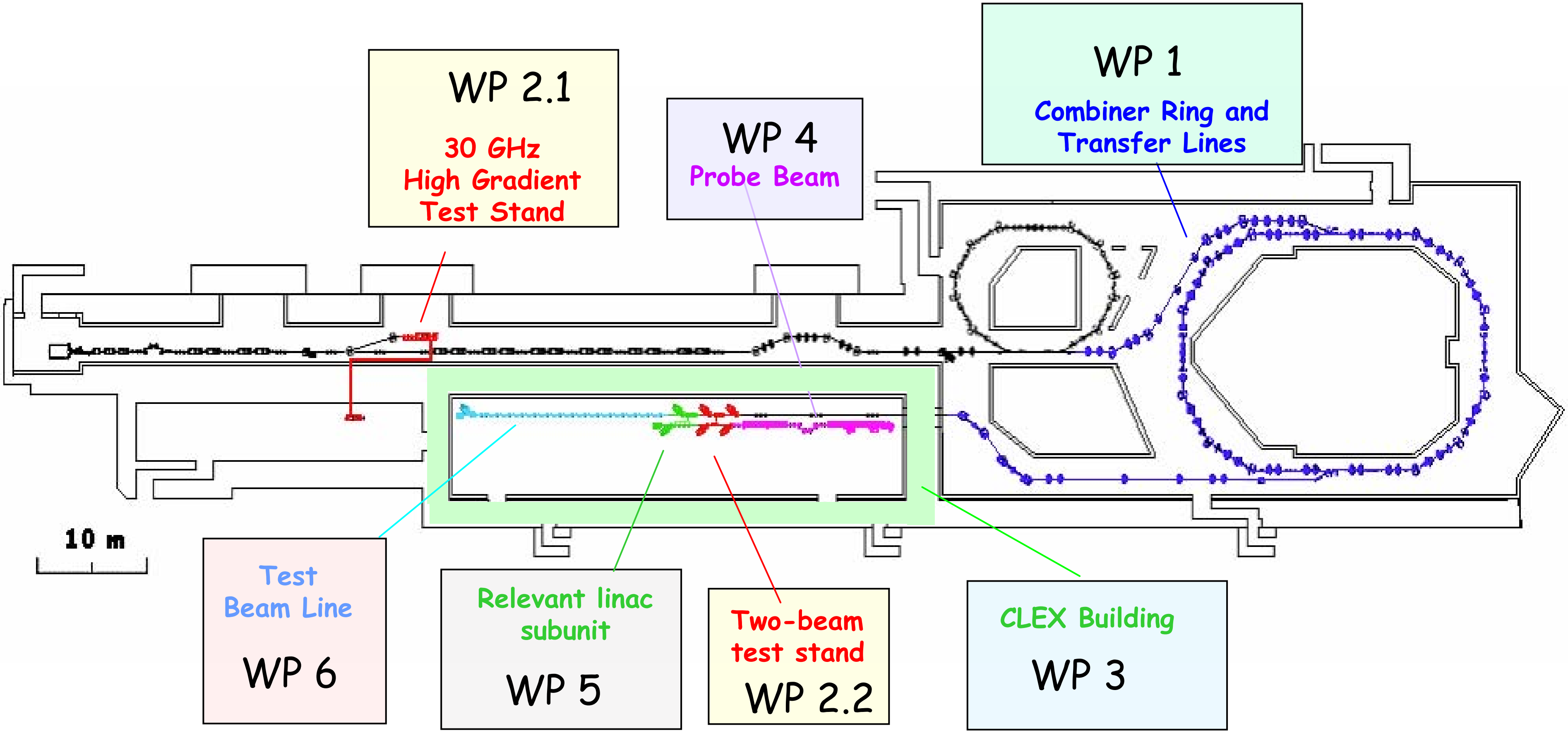


Isochronicity and achromaticity in each arc of the ring

π phase advance between rf deflectors

Optimum phase advance for minimum beam loading in rf deflectors

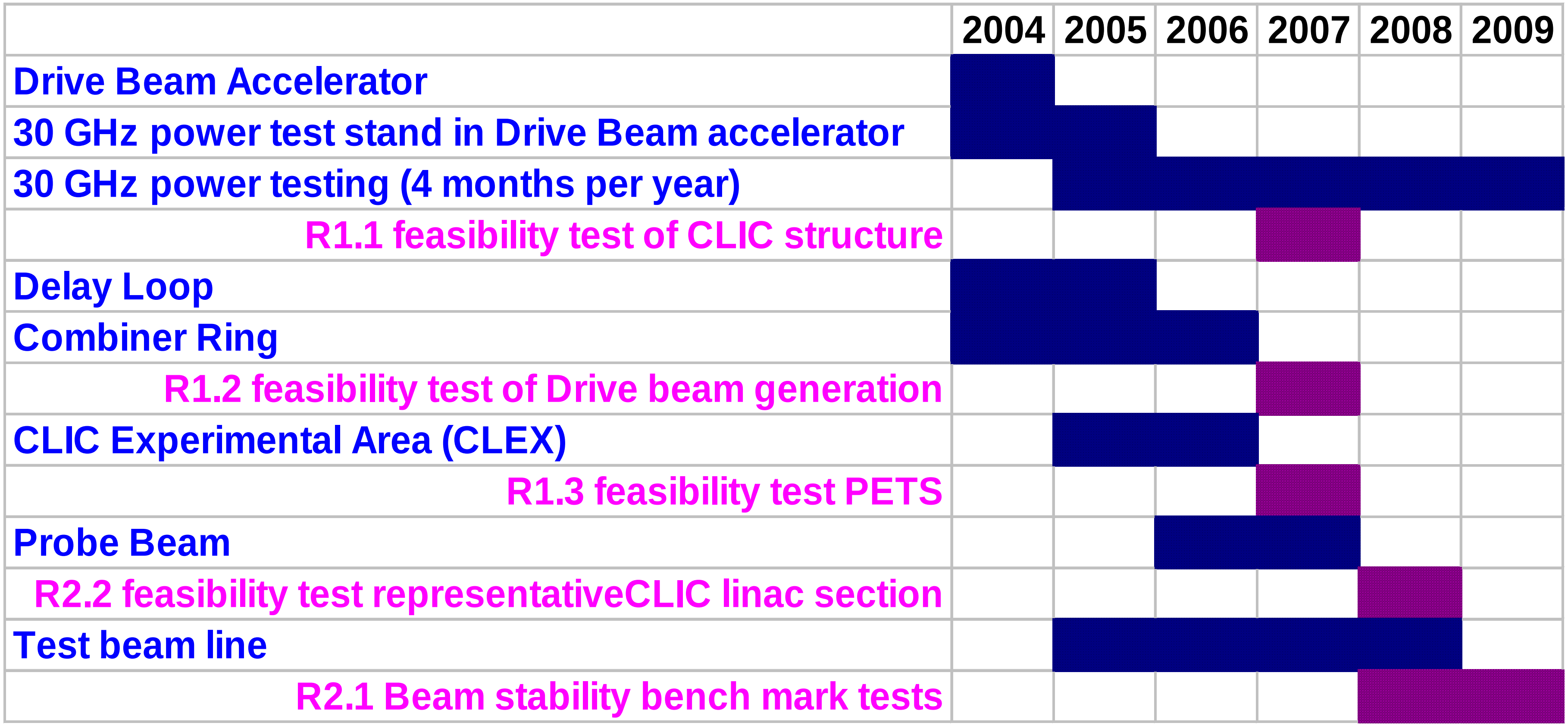
Work packages



Extended collaboration

- **Laboratories and Institutions 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.**
- **Expression of Interest from 12 Institutes at CLIC Collaboration Meeting (19/05/04)**
- **MoU to be signed before end of the year**

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**

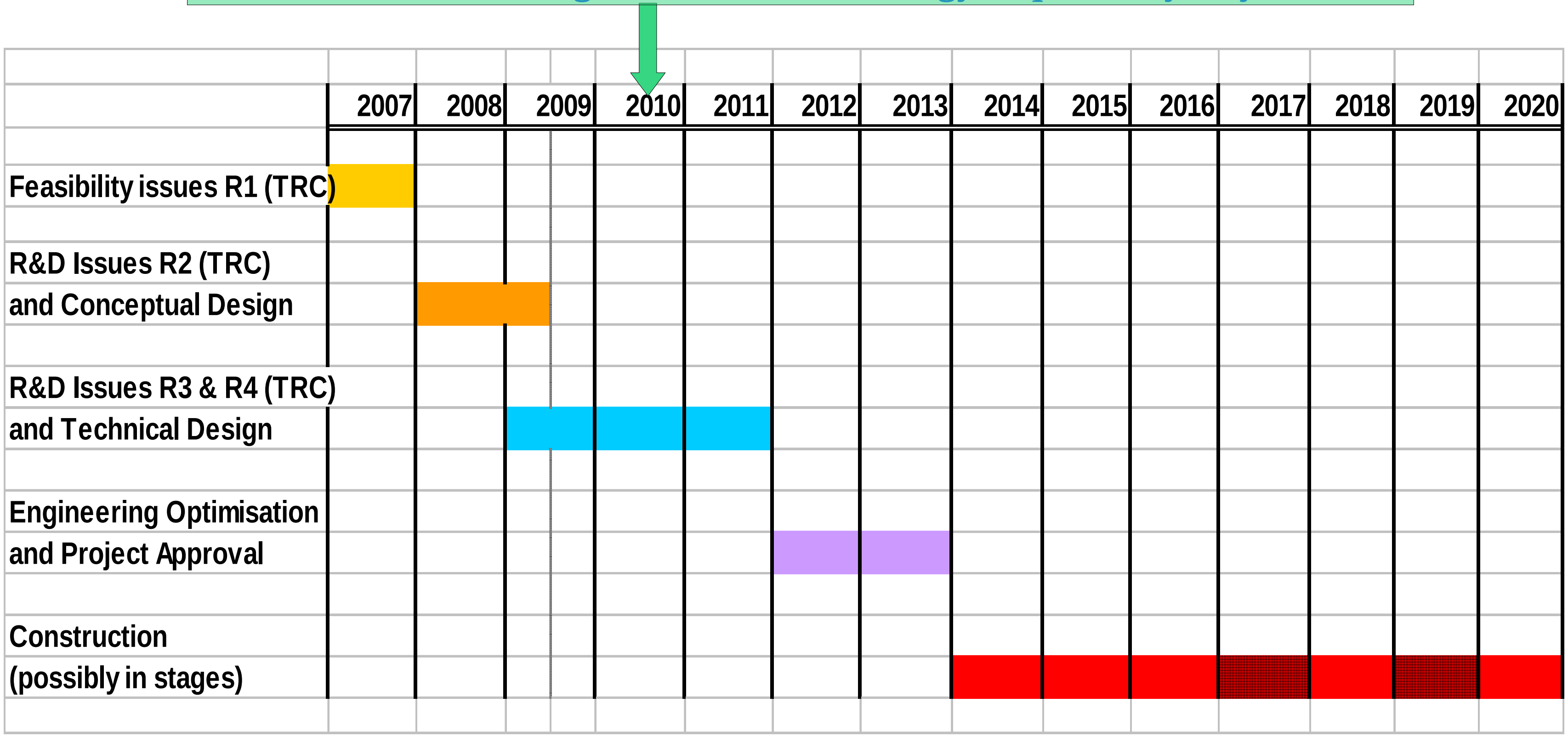
  Assuming additional extra resources (9 MCHF and 50 M-y) are available, the installations needed can be completed by 2008 and the tests with beam by 2009

- **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.

Tentative long-term CLIC scenario
Shortest and technically limited schedule

Technology evaluation and Physics assessment based on LHC results for a possible decision on Linear Collider funding with staged construction starting with the lowest energy required by Physics

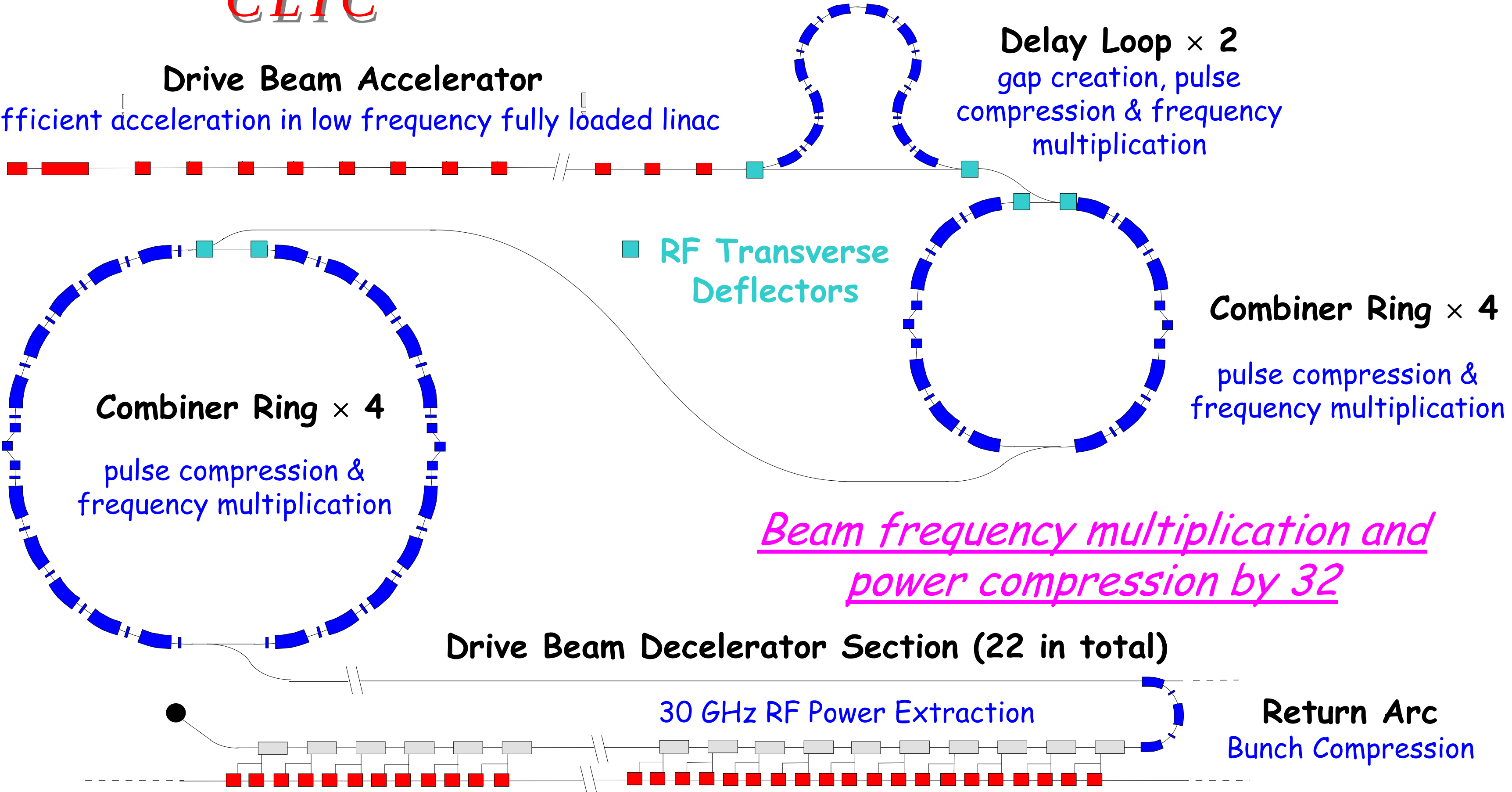


	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Feasibility issues R1 (TRC)	🟨													
R&D Issues R2 (TRC) and Conceptual Design		🟧	🟧											
R&D Issues R3 & R4 (TRC) and Technical Design			🟦	🟦	🟦									
Engineering Optimisation and Project Approval						🟪	🟪							
Construction (possibly in stages)								🟥	🟥	🟥	▦	🟥	▦	🟥

Staged approach

Possible low energy Physics facilities which could be built with CLIC technology on the way towards a Linear Collider

A single CLIC section: 68 GeV



Drive Beam Accelerator
efficient acceleration in low frequency fully loaded linac

Delay Loop × 2
gap creation, pulse compression & frequency multiplication

🟦 RF Transverse Deflectors

Combiner Ring × 4
pulse compression & frequency multiplication

Combiner Ring × 4
pulse compression & frequency multiplication

Beam frequency multiplication and power compression by 32

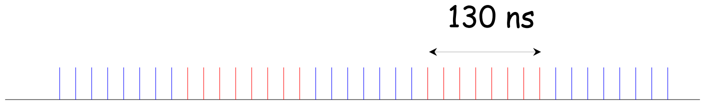
Drive Beam Decelerator Section (22 in total)

30 GHz RF Power Extraction

Return Arc
Bunch Compression

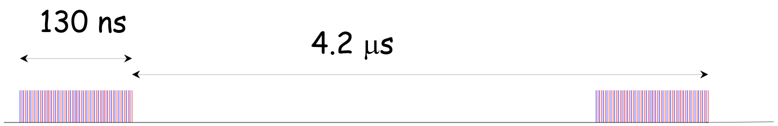
68 GeV/c energy gain – 624 m long

Drive beam time structure - initial

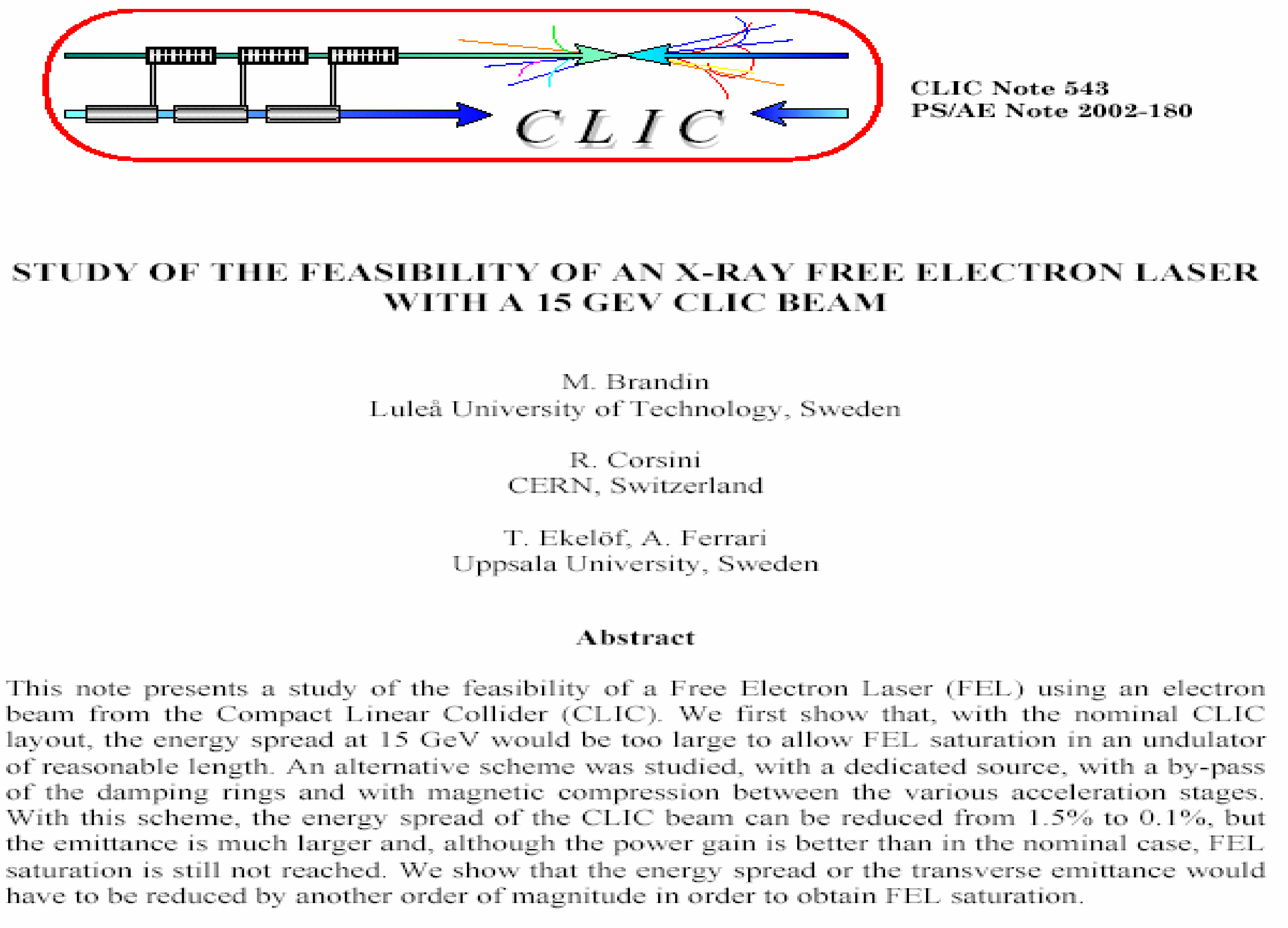


100 µs train length - 32 × 22 sub-pulses – **4.8 A**
1.2 GeV - 64 cm between bunches

Drive beam time structure - final



22 pulses - **150 A** - 2 cm between bunches



CLIC Note 543
PS/AE Note 2002-180

STUDY OF THE FEASIBILITY OF AN X-RAY FREE ELECTRON LASER WITH A 15 GEV CLIC BEAM

M. Brandin
Luleå University of Technology, Sweden

R. Corsini
CERN, Switzerland

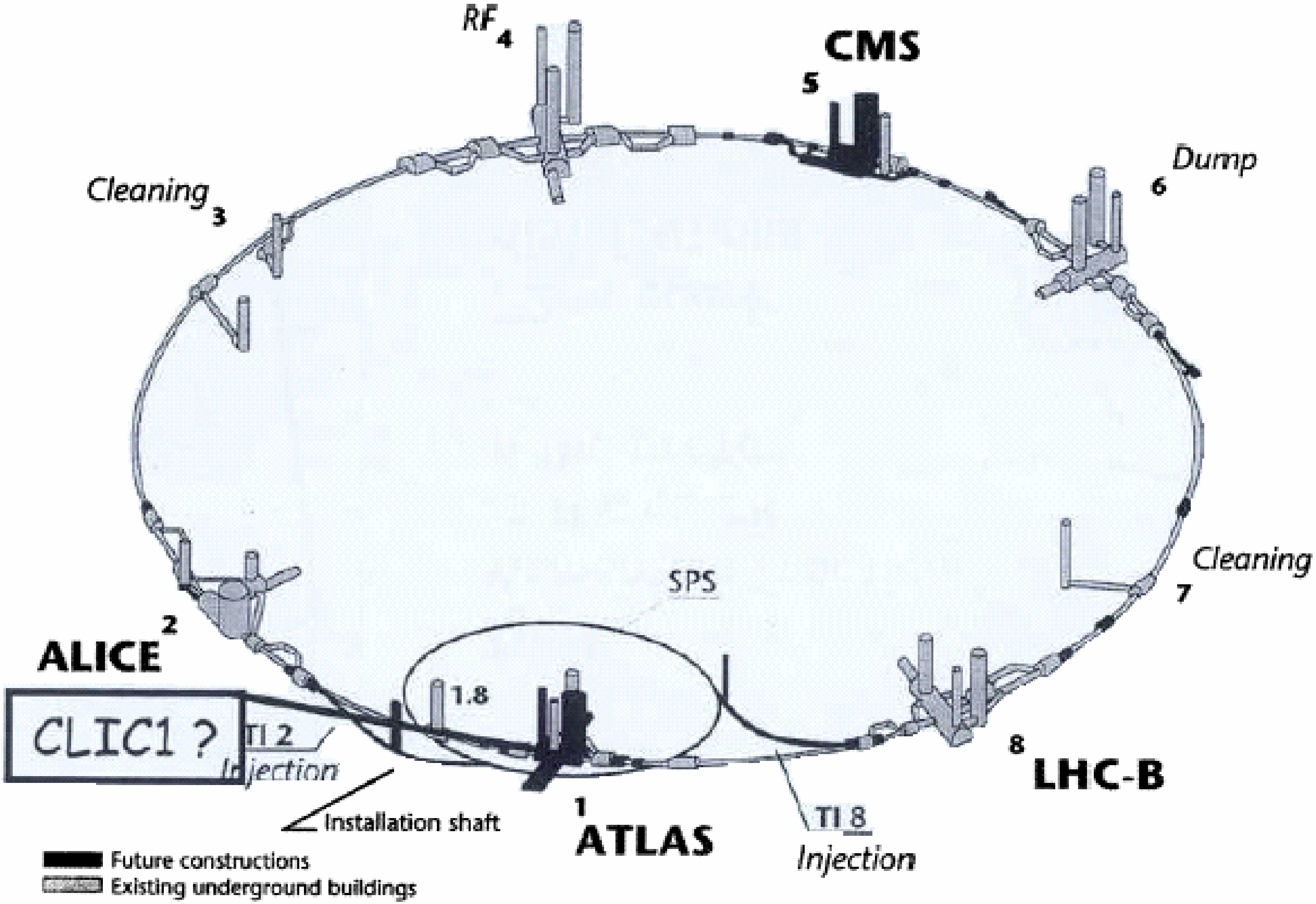
T. Ekelöf, A. Ferrari
Uppsala University, Sweden

Abstract

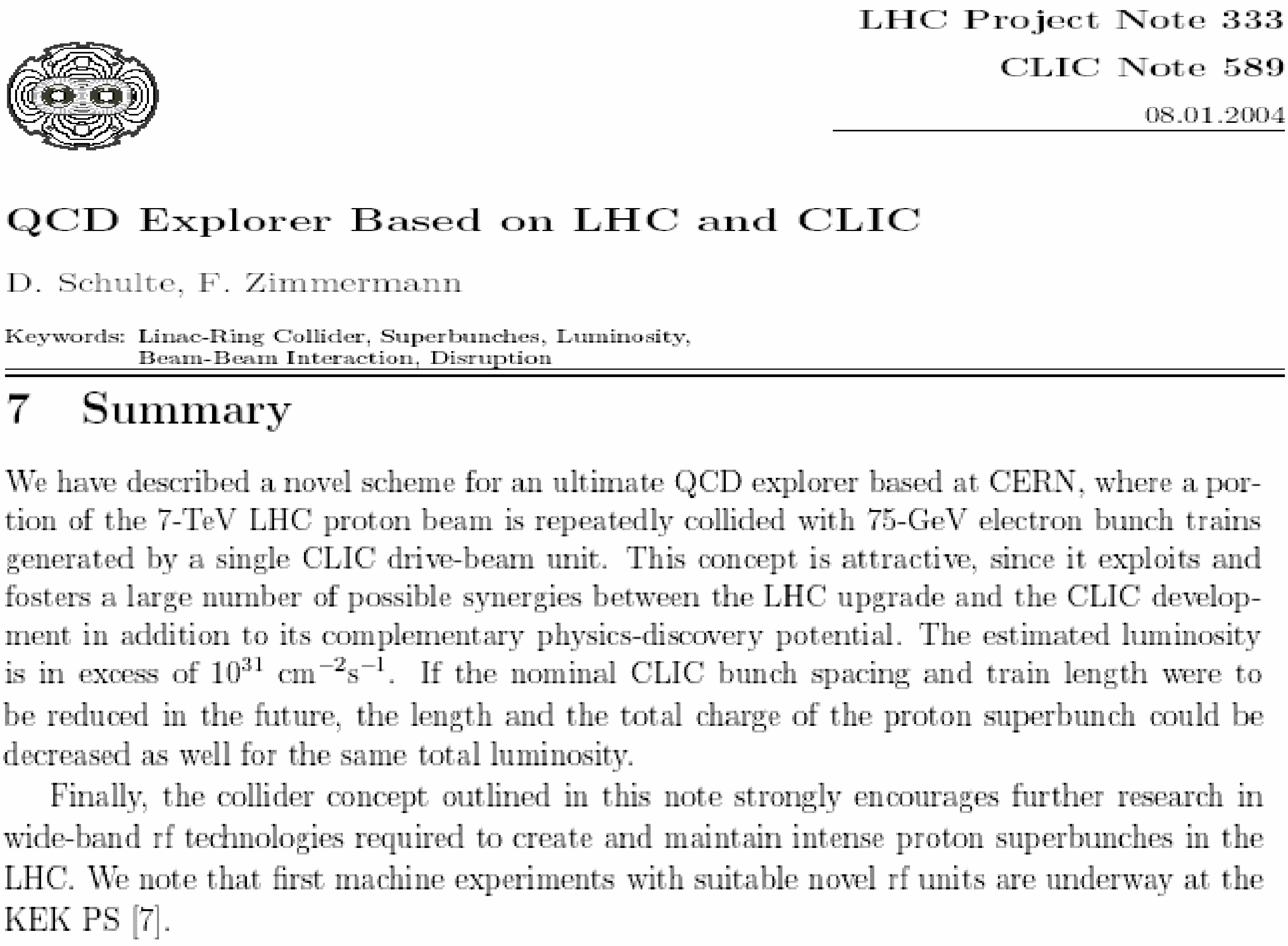
This note presents a study of the feasibility of a Free Electron Laser (FEL) using an electron beam from the Compact Linear Collider (CLIC). We first show that, with the nominal CLIC layout, the energy spread at 15 GeV would be too large to allow FEL saturation in an undulator of reasonable length. An alternative scheme was studied, with a dedicated source, with a by-pass of the damping rings and with magnetic compression between the various acceleration stages. With this scheme, the energy spread of the CLIC beam can be reduced from 1.5% to 0.1%, but the emittance is much larger and, although the power gain is better than in the nominal case, FEL saturation is still not reached. We show that the energy spread or the transverse emittance would have to be reduced by another order of magnitude in order to obtain FEL saturation.

LHC-CLIC1

(A de Roeck, D.Schulte, F.Zimmermann)



CERN AC - HF267 - 04.07.1997



LHC Project Note 333

CLIC Note 589

08.01.2004

QCD Explorer Based on LHC and CLIC

D. Schulte, F. Zimmermann

Keywords: Linac-Ring Collider, Superbunches, Luminosity,
Beam-Beam Interaction, Disruption

7 Summary

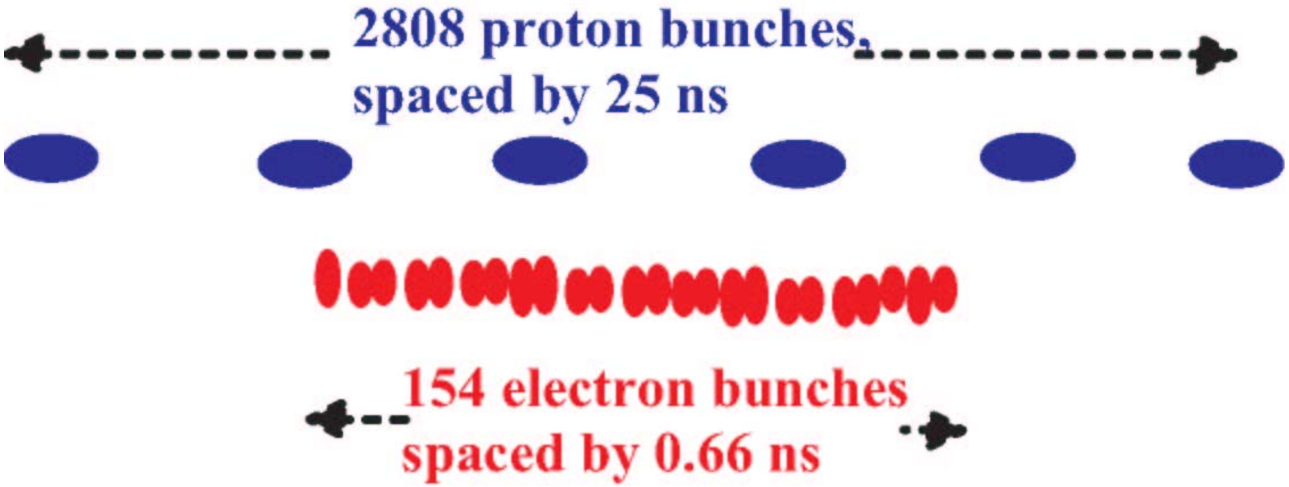
We have described a novel scheme for an ultimate QCD explorer based at CERN, where a portion of the 7-TeV LHC proton beam is repeatedly collided with 75-GeV electron bunch trains generated by a single CLIC drive-beam unit. This concept is attractive, since it exploits and fosters a large number of possible synergies between the LHC upgrade and the CLIC development in addition to its complementary physics-discovery potential. The estimated luminosity is in excess of 10^{31} cm^{-2}s^{-1}. If the nominal CLIC bunch spacing and train length were to be reduced in the future, the length and the total charge of the proton superbunch could be decreased as well for the same total luminosity.

Finally, the collider concept outlined in this note strongly encourages further research in wide-band rf technologies required to create and maintain intense proton superbunches in the LHC. We note that first machine experiments with suitable novel rf units are underway at the KEK PS [7].

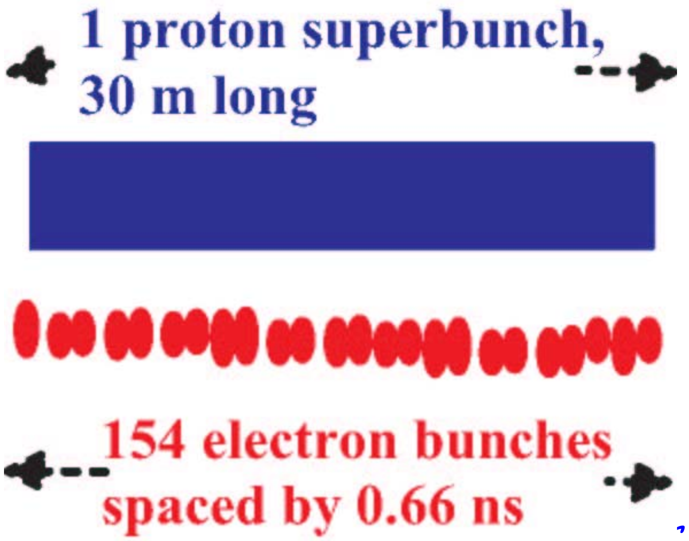
QCD Explorer based on LHC and CLIC-1

- **highest energy of electron (70 GeV) / proton (7 TeV) linac-ring collider**
- **extends reach of HERA by 2 orders of magnitude**
- **optimum luminosity L>10^{31} cm^{-2} s^{-1} is achieved with proton superbunch (LHC upgrade)**
- **one single CLIC accelerating section (624 m)**
- **Simplified injector as only electron needed (no positron) and with relaxed parameters (larger emittances)**
- **Half of RF power source injector complex (one linac)**
- **The simplest CLIC complex ideal to validate the scheme with full parameters but not at the optimum location for a logical extension in the future**

Luminosity maximized by concentrating LHC protons over length of CLIC electron pulse

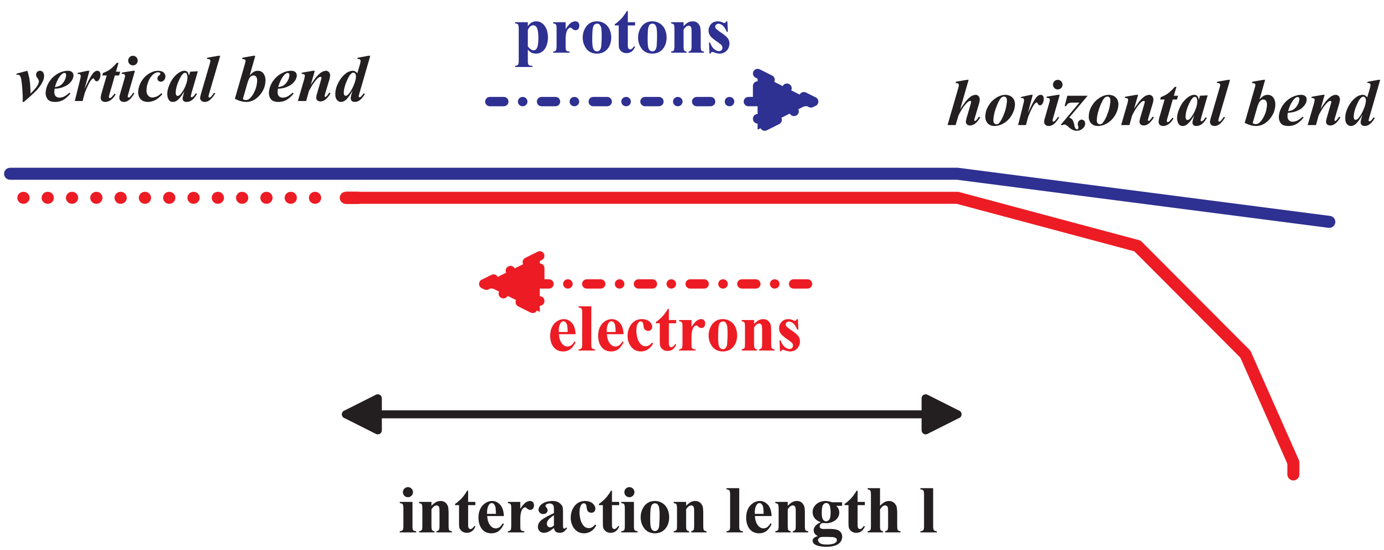


filling patterns with nominal LHC proton beam

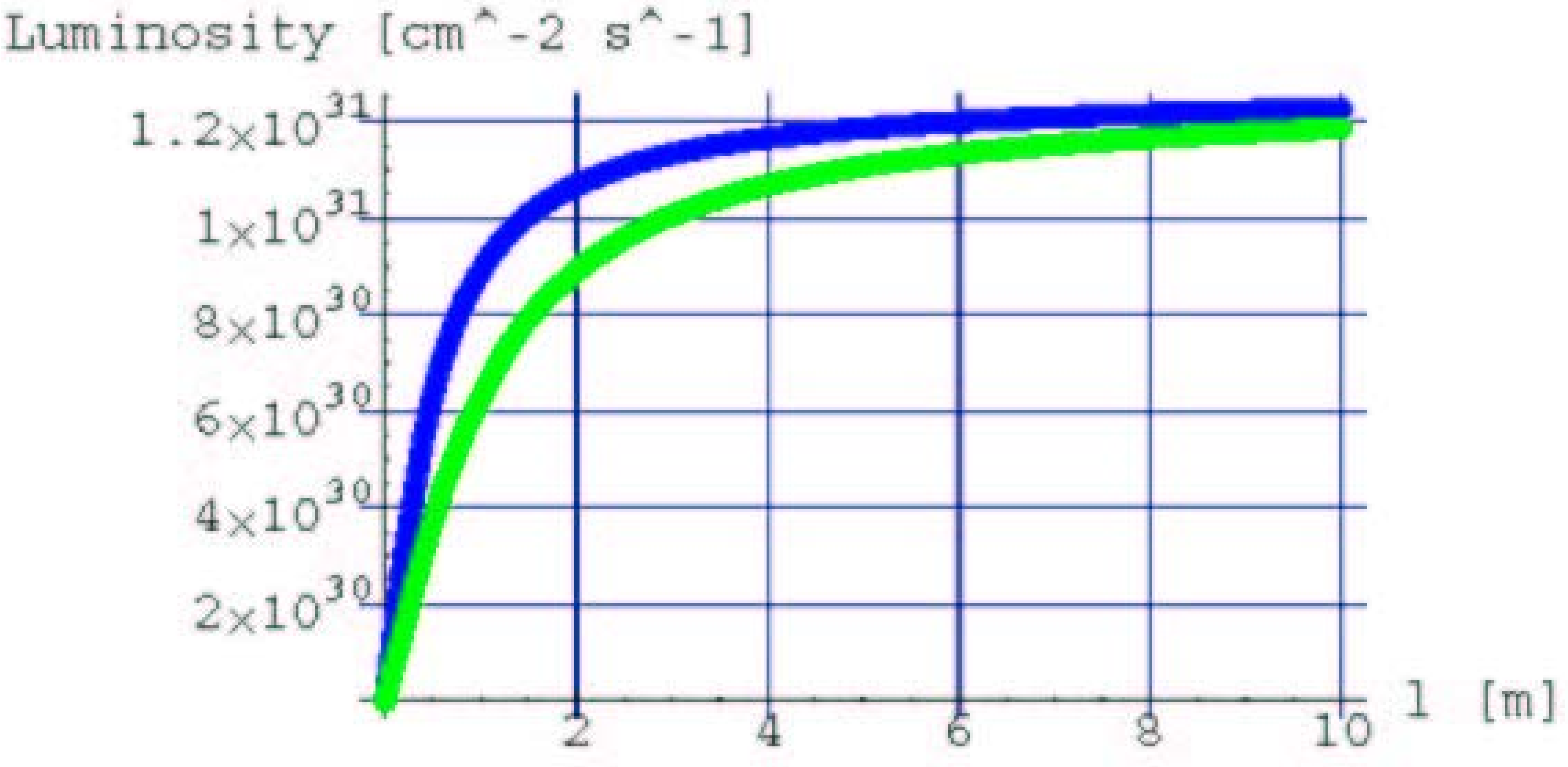


filling patterns with LHC proton superbunch

Schematic IR layout



vertical and horizontal dipoles combine and separate the two beams

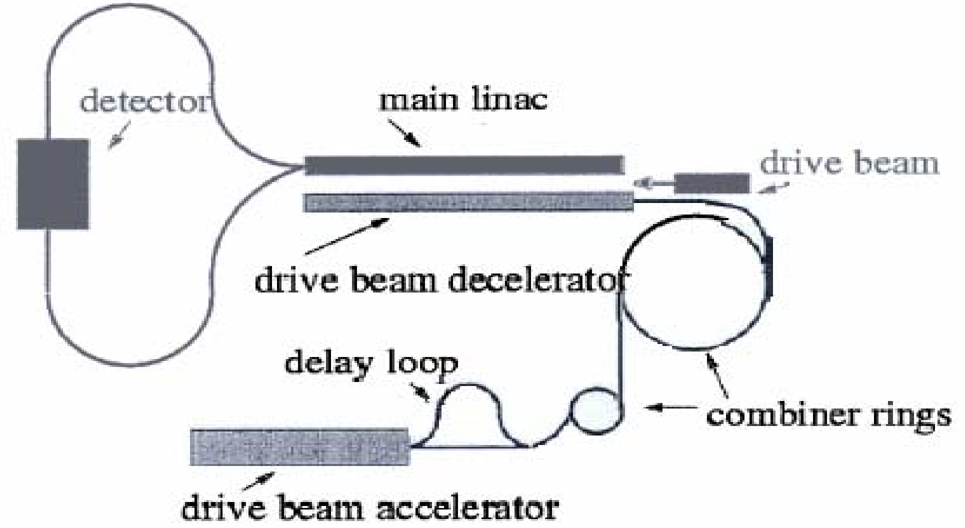


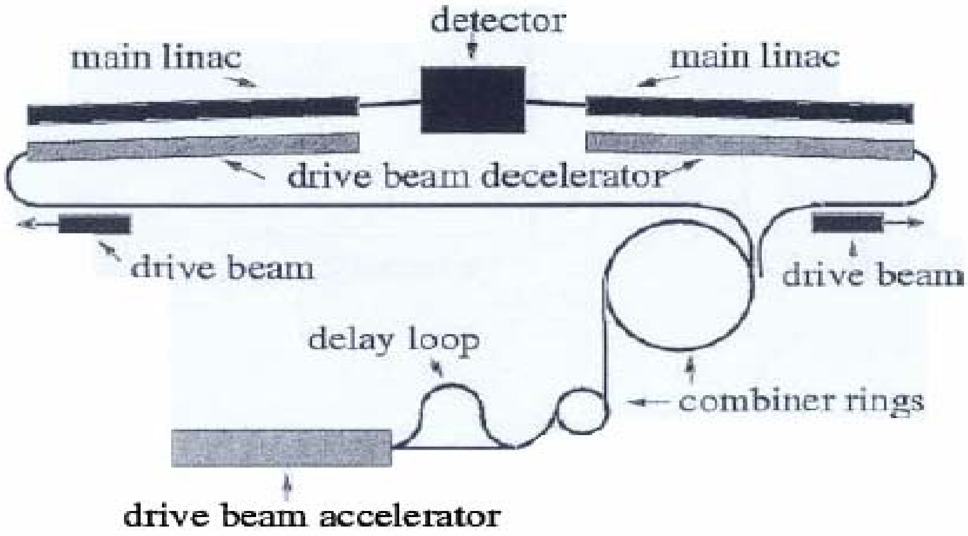
Luminosity of CLIC-LHC QCD Explorer vs. length of interaction region for β*=0.25 m and β*=0.5 m.

QCDE main parameters

	electrons	protons
energy	75 GeV	7 TeV
bunch population	4×10^{9}	6.5×10^{13}
Rms bunch length	35 μm	9 m
#bunches	154	1
effective pulse density	2×10^{10} m^{-1}	2×10^{12} m^{-1}
IP beta function	0.25 m	0.25 m
IP spot size	11 μm	11 μm
Interaction length	2 m	
Normalized emittance	73 μm	3.75 μm
Collision frequency	100 Hz	
luminosity	1.1×10^{31} cm^{-2} s^{-1}	
beam-beam tune shift	N/A	0.004

Z factory with 1*1 CLIC section





Possible layouts

1 module + arc

2 modules

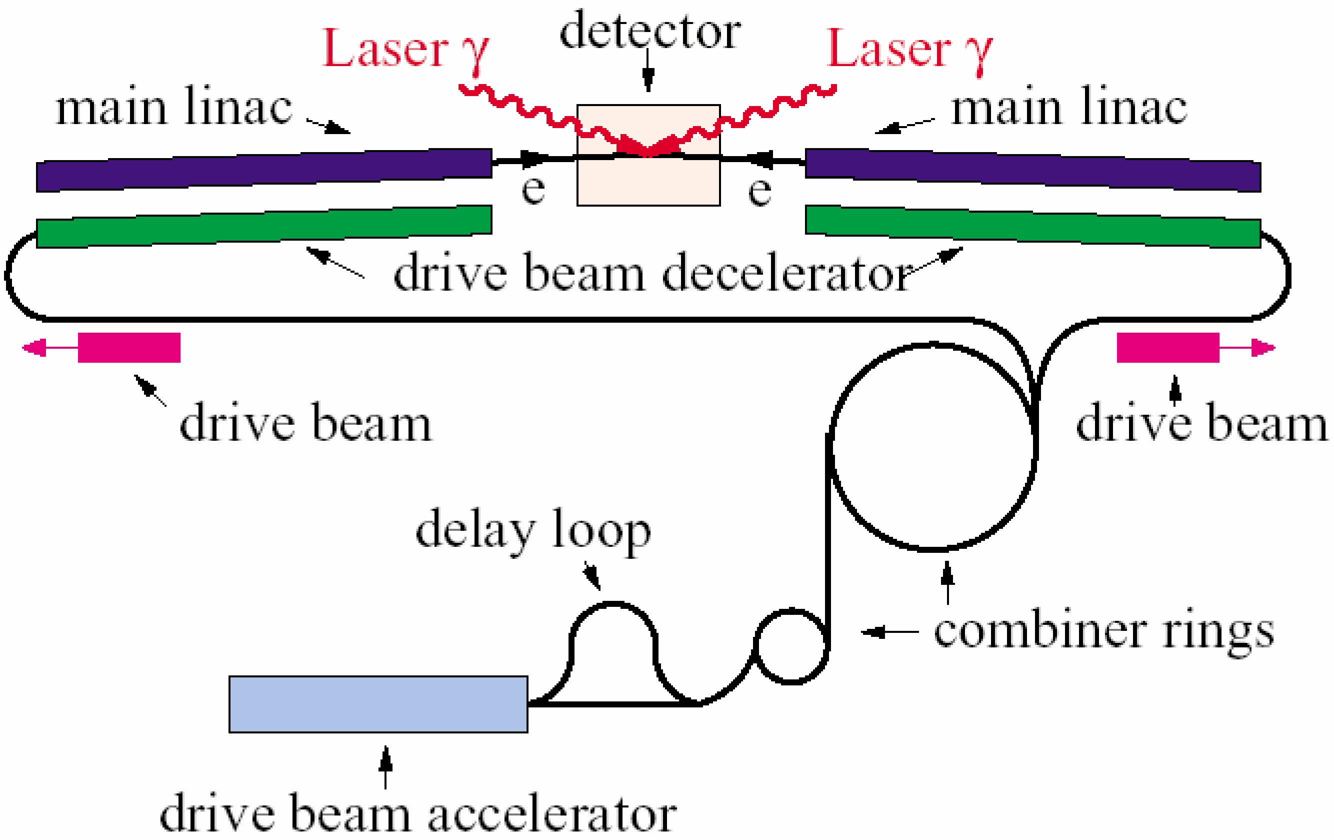
Latter is presently preferred

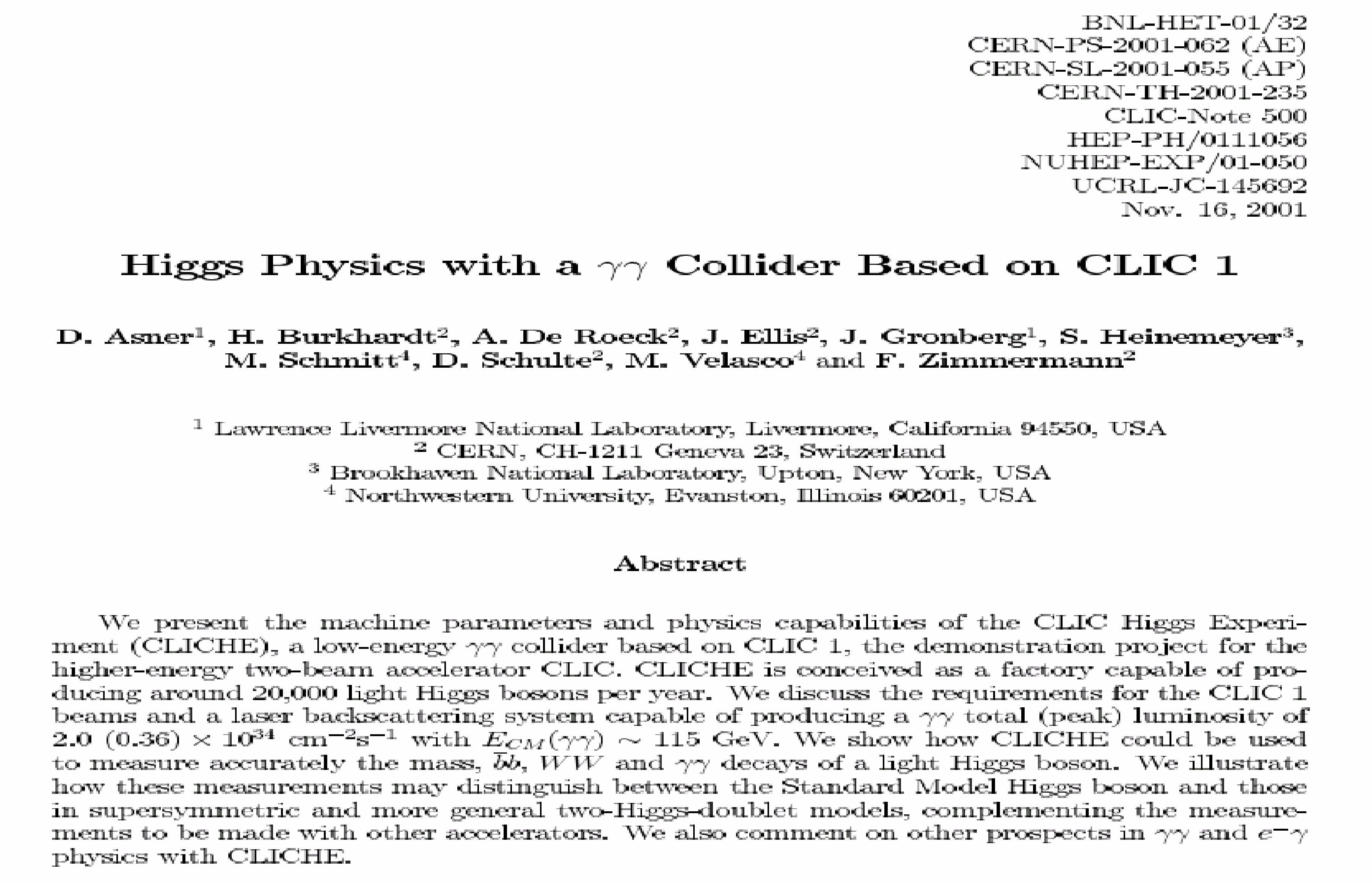
12

Z to W factories

- Electron to positron collisions at 90 GeV (Z) up to 160 GeV (W) with two linacs made each by one CLIC section with an overall length of about 2 km
  - 9 GeV fom injector and 68 GeV by linac at nominal gradient
  - 36 GeV by linac for Z at reduced gradient of 80 MV/m
  - 71 GeV by linac for W at increased gradient of 157 MV/m (possibly two CLIC sections and an overall length of 3.5 km)
- Luminosity (L1%) of 8 10^{33} cm^{-2} s^{-1} at Z and 1.3 10^{34} cm^{-2} s^{-1} at W if accelerating structures can be powered at 200 Hz repetition rate (to be demonstrated)
- Complete injector complex of electrons and positrons required with possible polarisation of electrons but not of positrons
- Half of power source injector complex powering alternatively both linacs

CLIC HIGGS Experiment (CLICHÉ)





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Higgs Physics with a $\gamma\gamma$ Collider Based on CLIC 1

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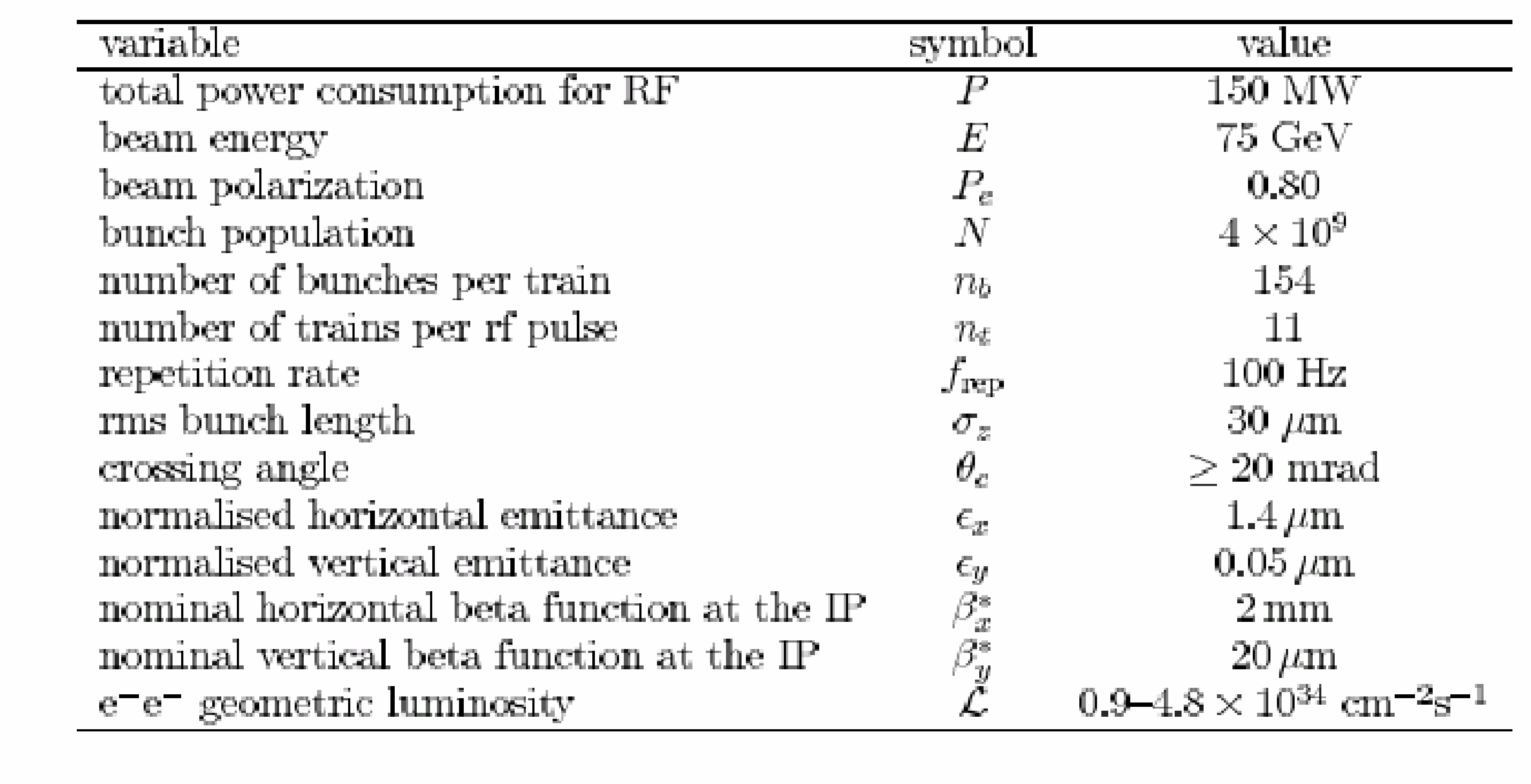
Abstract

We present the machine parameters and physics capabilities of the CLIC Higgs Experiment (CLICHE), a low-energy $\gamma\gamma$ collider based on CLIC 1, the demonstration project for the higher-energy two-beam accelerator CLIC. CLICHE is conceived as a factory capable of producing around 20,000 light Higgs bosons per year. We discuss the requirements for the CLIC 1 beams and a laser backscattering system capable of producing a $\gamma\gamma$ total (peak) luminosity of 2.0 (0.36) $\times 10^{34}$ cm^{-2}s^{-1} with $E_{CM}(\gamma\gamma) \sim 115$ GeV. We show how CLICHE could be used to measure accurately the mass, $\bar{b}b$, WW and $\gamma\gamma$ decays of a light Higgs boson. We illustrate how these measurements may distinguish between the Standard Model Higgs boson and those in supersymmetric and more general two-Higgs-doublet models, complementing the measurements to be made with other accelerators. We also comment on other prospects in $\gamma\gamma$ and $e^-\gamma$ physics with CLICHE.

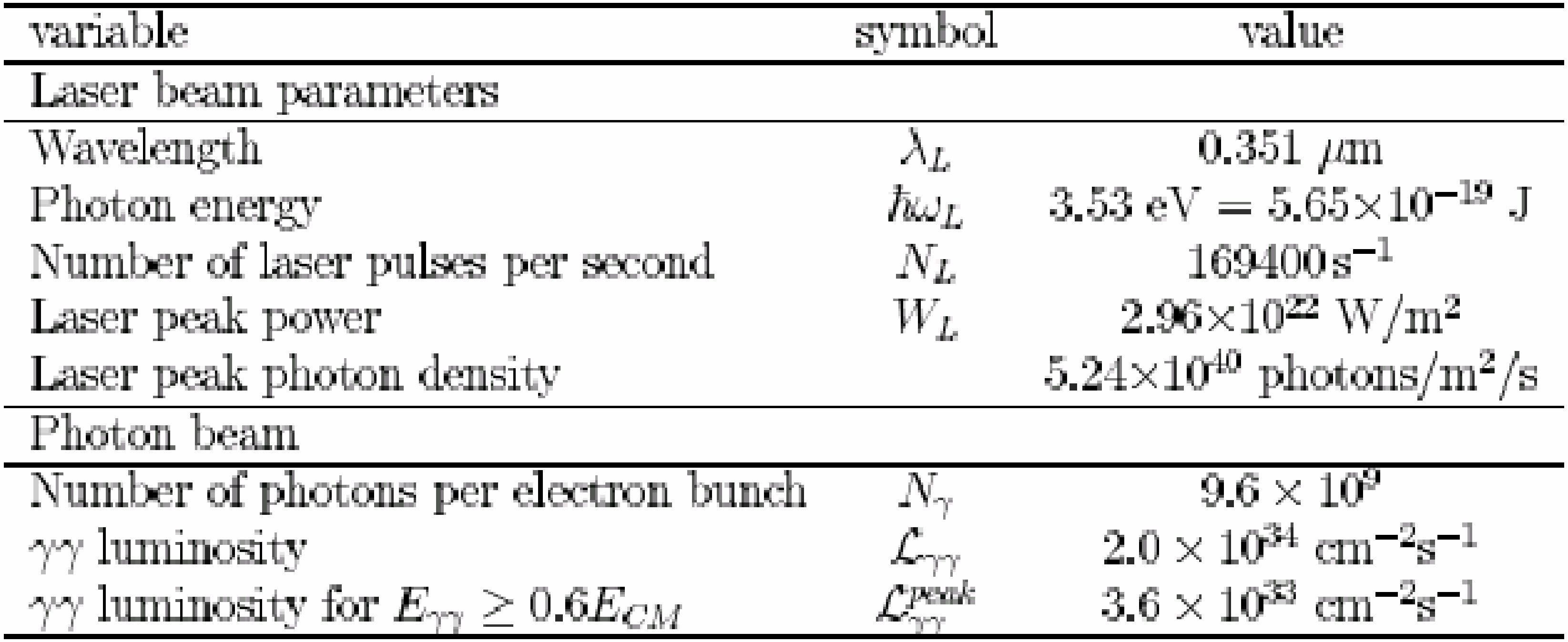
Tentative CLICHÉ parameters



variable	symbol	value
total power consumption for RF	P	150 MW
beam energy	E	75 GeV
beam polarization	P_e	0.80
bunch population	N	4×10^9
number of bunches per train	n_b	154
number of trains per rf pulse	n_t	11
repetition rate	$f_{\rm rep}$	100 Hz
rms bunch length	σ_z	30 μm
crossing angle	θ_c	$\geq$ 20 mrad
normalised horizontal emittance	ϵ_x	1.4 μm
normalised vertical emittance	ϵ_y	0.05 μm
nominal horizontal beta function at the IP	β_x^*	2 mm
nominal vertical beta function at the IP	β_y^*	20 μm
e^-e^- geometric luminosity	$\mathcal{L}$	0.9–4.8×10^{34} cm^{-2}s^{-1}

- E-/E- geometric luminosity of 9 10^{33} cm^{-2} s^{-1} envisageable if accelerating structures shown to be able to handle 200 Hz repetition rate

Challenging Laser parameters

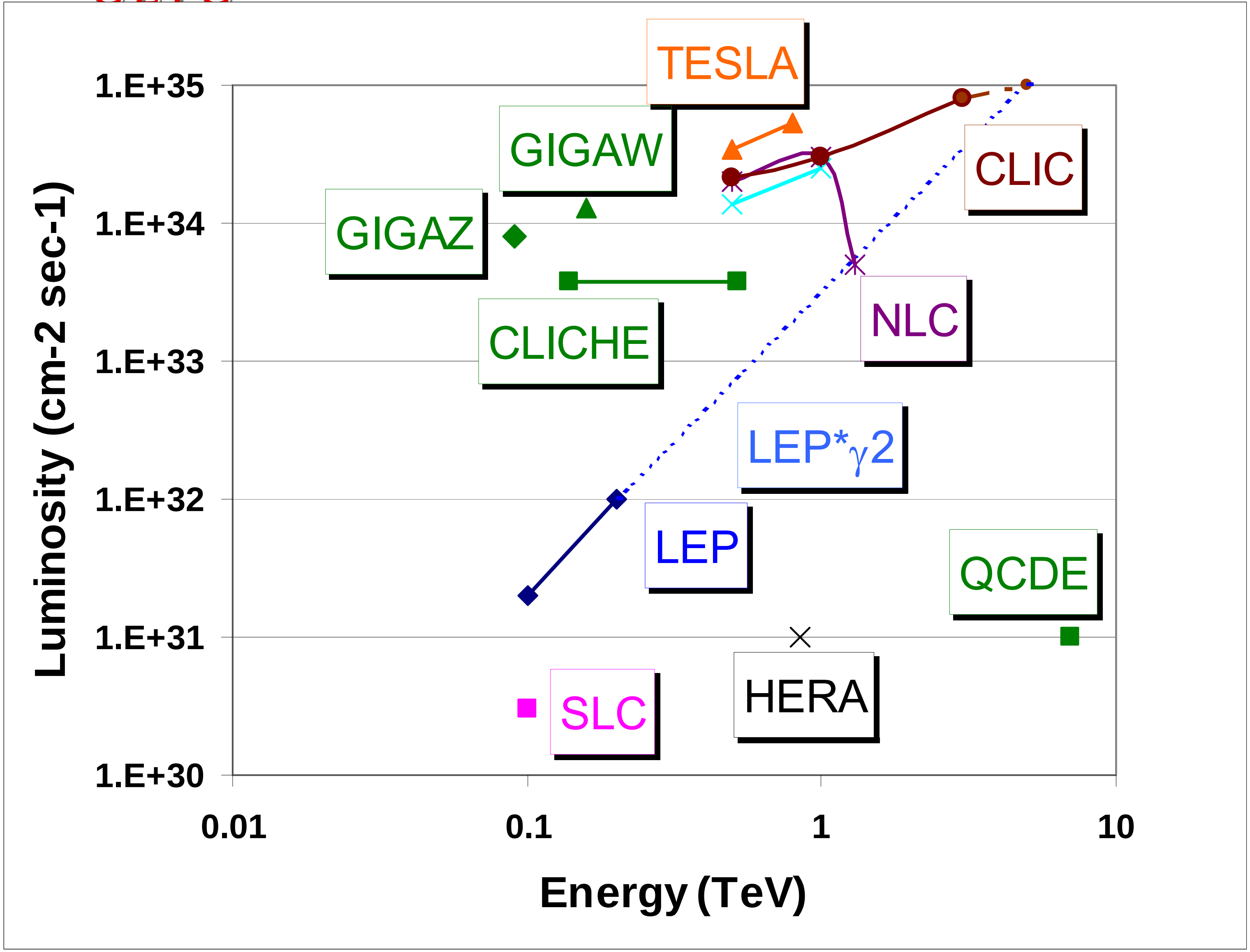


variable	symbol	value
Laser beam parameters		
Wavelength	λ_L	0.351 μm
Photon energy	$\hbar\omega_L$	3.53 eV = 5.65×10^{-19} J
Number of laser pulses per second	N_L	169400 s^{-1}
Laser peak power	W_L	2.96×10^{22} W/m^2
Laser peak photon density		5.24×10^{40} photons/m^2/s
Photon beam		
Number of photons per electron bunch	N_γ	9.6×10^{9}
$\gamma\gamma$ luminosity	$\mathcal{L}_{\gamma\gamma}$	2.0×10^{34} cm^{-2}s^{-1}
$\gamma\gamma$ luminosity for $E_{\gamma\gamma}\geq 0.6E_{CM}$	$\mathcal{L}^{peak}_{\gamma\gamma}$	3.6×10^{33} cm^{-2}s^{-1}

Parameters above assume unrealistic 11*100 e- beam repetition rate and 154*1100=169400 laser pulses /sec

$\gamma\gamma$ luminosity of 3.8 10^{33} cm^{-2} s^{-1} (6.8 10^{32} cm^{-2} s^{-1} for E $\gamma\gamma$ > 0.6 Ecm) envisageable if accelerating structures shown to be able to handle 200 Hz repetition rate and laser with 30000 pulse/sec developed

Summary


TESLA
GIGAW
GIGAZ
CLIC
CLICHE
NLC
LEP*γ2
LEP
QCDE
SLC
HERA
1.E+35
1.E+34
1.E+33
1.E+32
1.E+31
1.E+30
Luminosity (cm-2 sec-1)
0.01
0.1
1
10
Energy (TeV)

CONCLUSION

- CLIC only possible scheme to extend Linear Collider energy into the Multi-TeV range
- CLIC technology not mature yet, requires challenging R&D
- A development:
  - ✓complementary to Super-Conducting technology recently down-selected by ITRP for a TeV Linear Collider
  - ✓necessary in order to extend energy range of LC in the future
- Very promising performances already demonstrated in CTF2
- Remaining key issues clearly identified (ILC-TRC)
- L.C. 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

- Provides 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
- Safety net to the Super-Conducting technology in case sub-TeV energy range is not considered attractive enough for Physics
- Possible construction in stages starting with low energy applications
- A lot still to be done before the CLIC technology can be made operational;
- Novel Ideas and Challenging work in world-wide collaborations needed
- YOU ARE ALL WELCOME to participate and make the CLIC scheme and technology a realistic tool in the best interest of Physics

References

- Scaling laws for e+/e- Linear Colliders: NIM A421 (1999) p 369-405
- A 3 TeV e+/e- Linear Collider based on CLIC technology: CERN 2000-008
- CTF3 Design Report: CERN/PS 2002-008
- CLIC contribution to the Technical Review Committee on a 500 GeV e+/e- Linear Collider: CERN 2003-007
- Physics at the CLIC Multi-TeV Linear Collider: CERN 2004-005