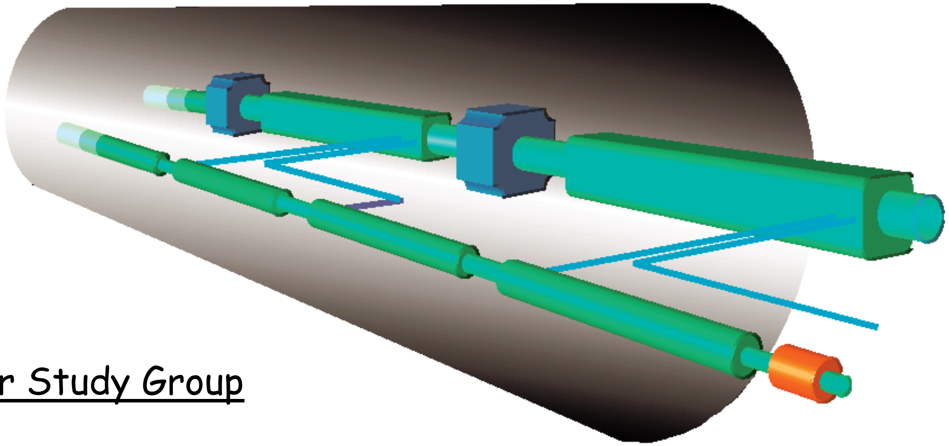
CLIC: Technology, Test Facilities and Future



R. Corsini for

The Compact Linear Collider Study Group

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

The CLIC study is a feasibility study with the aim to propose a technically viable multi-TeV e± Linear Collider for the post-LHC era, covering a range of centre-of-mass energies from ~ 0.5 - 5 TeV

CLIC: Technology, Test Facilities and Future

TALK OUTLINE

- The CLIC scheme – brief introduction
- Main challenges
- What has been achieved so far
- What remains to be done
- CTF 3 – the facility which addresses the main key issues

WORLD WIDE CLIC COLLABORATION

Berlin Tech. 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-West. Univ. Illinois (USA):	Beam loss studies & CTF3 equipment
RAL (England):	Lasers for CTF3 and CLIC photo-injectors
SLAC (USA):	High Gradient Structure testing, structure design, CTF3 drive beam injector design
Uppsala University (Sweden):	Beam monitoring systems for CTF3

LUMINOSITY SCALING IN A LINEAR COLLIDER

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

energy loss by beamstrahlung (δ_B)

wall-plug to beam efficiency (η_{beam}^{AC})

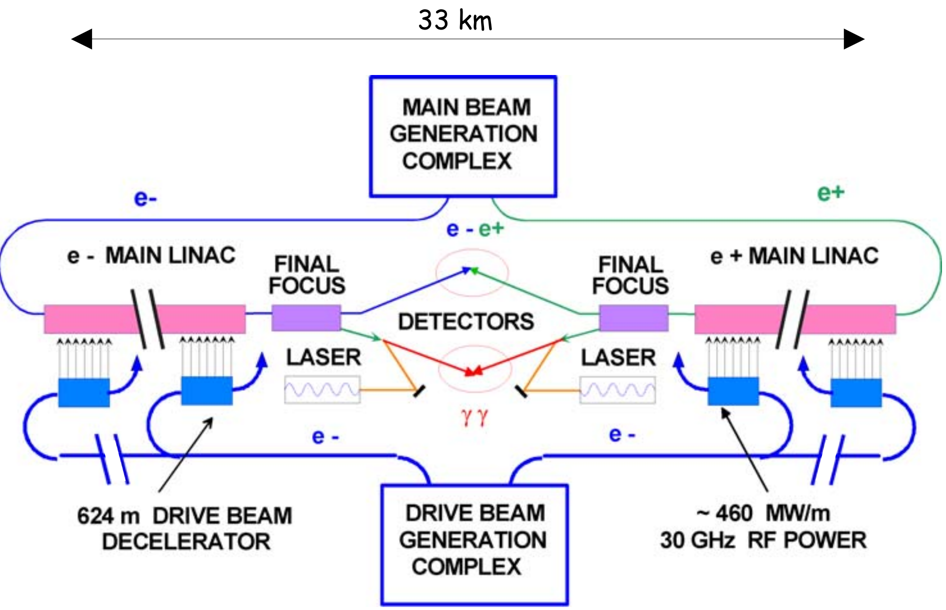
wall-plug power (P_{AC})

center-of-mass energy (U_{cm})

Vertical emittance (ε_{ny}^*)

- **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

BASIC FEATURES OF CLIC



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

- High acceleration gradient (150 MV/m)

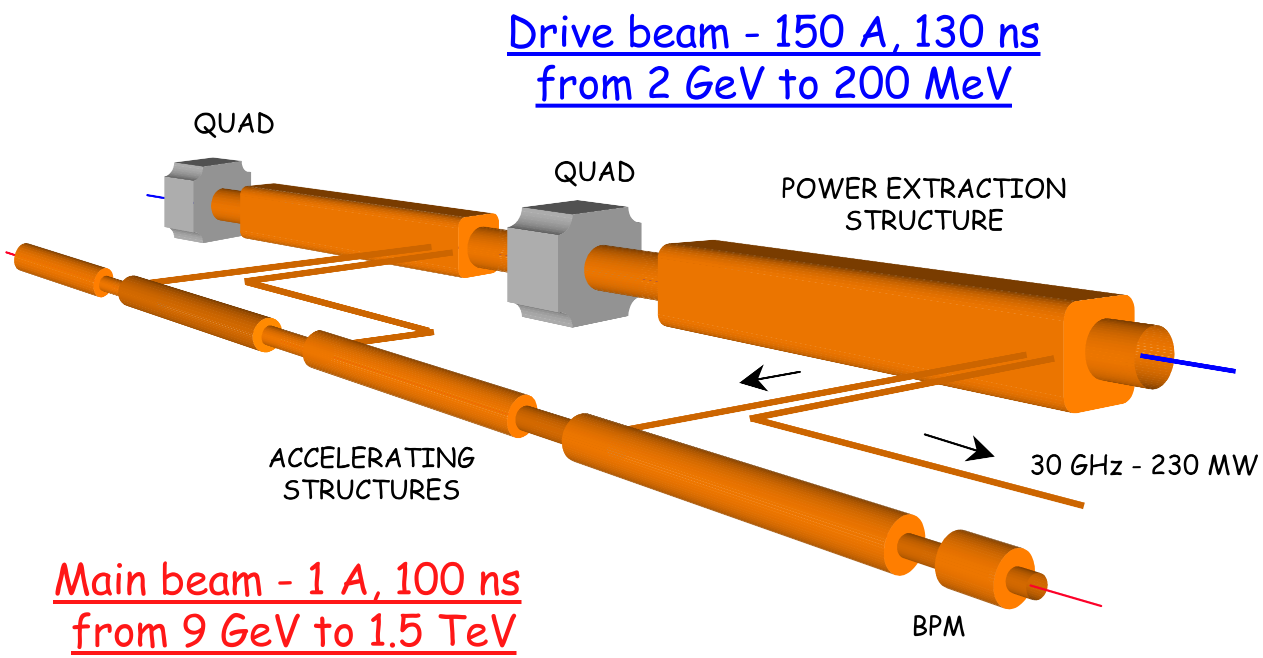
  - "Compact" collider - overall length < 40 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)

- Two-Beam Acceleration Scheme

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

- Central injector complex

  - "Modular" design, can be built in stages

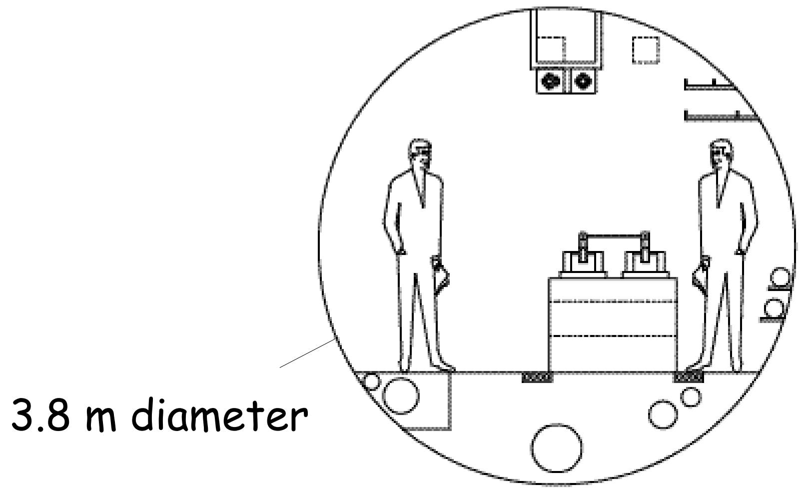


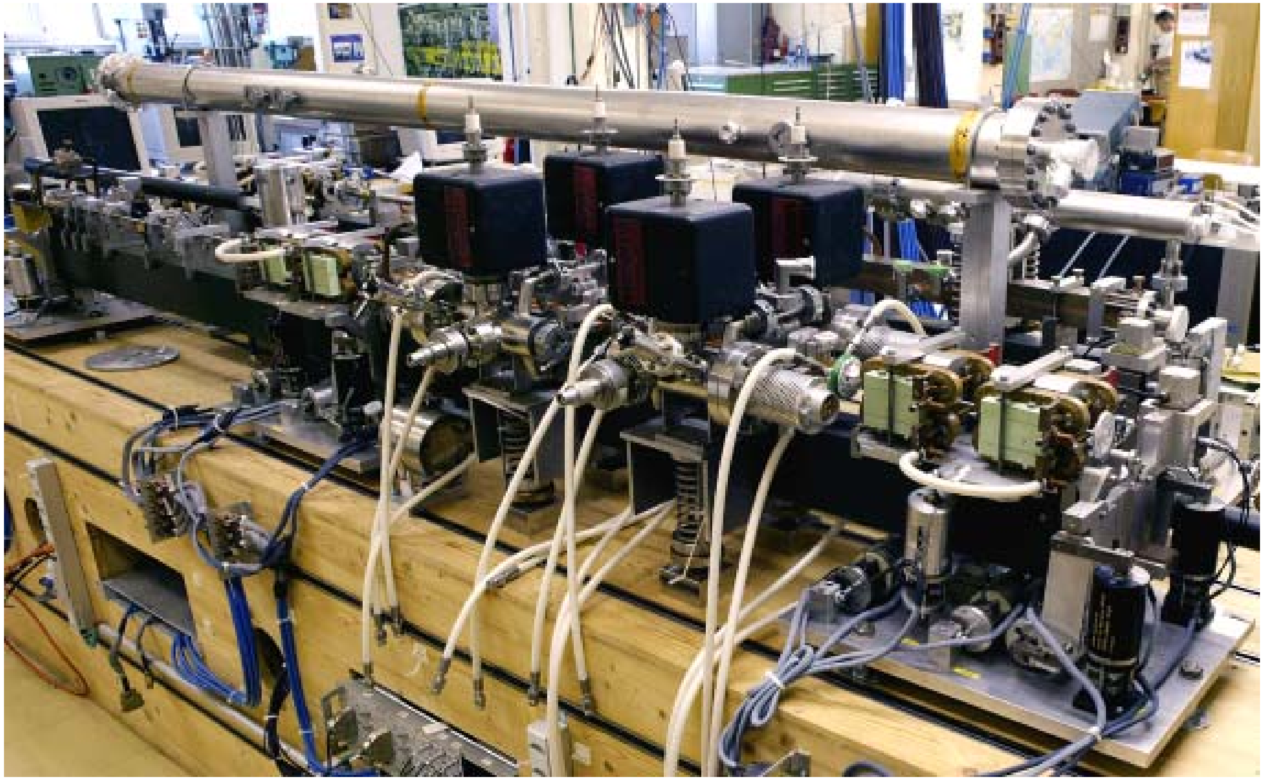
CLIC MODULE

(6000 modules at 3 TeV)

CLIC TWO-BEAM SCHEME

CLIC TUNNEL CROSS-SECTION

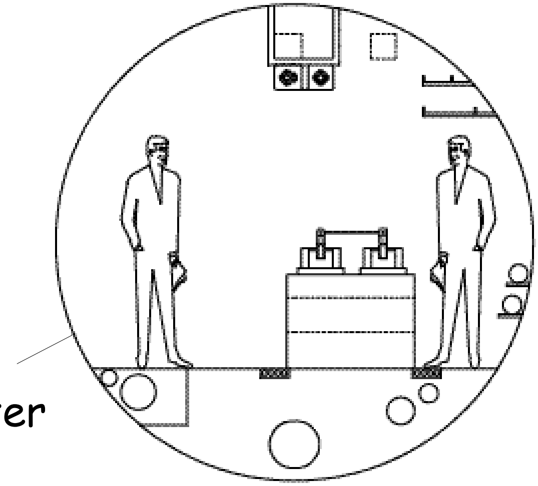




CLIC MODULE

(6000 modules at 3 TeV)

CLIC TUNNEL CROSS-SECTION



3.8 m diameter

CLIC TWO-BEAM SCHEME

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	100	4.4 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

THE CLIC CHALLENGES

COMMON TO MULTI-TEV LINEAR COLLIDERS

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

SPECIFIC TO THE CLIC TECHNOLOGY

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

⇒ addressed in CTF2 and CTF3

INTERNATIONAL LINEAR COLLIDER TECHNICAL REVIEW COMMITTE

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**

INTERNATIONAL LINEAR COLLIDER TECHNICAL REVIEW COMMITTE

TRC Ranking	Affecting	Common to all studies	TESLA	NLC/JLC	CLIC			
					Technology (TRC)	High energy (TRC)	Additional to TRC	Common to all studies but more difficult CLIC parameters
R1 Feasibility	Energy	0	1	2	2	0		
	Luminosity	0	0	0	0	0		
	Reliability	0	0	0	1	0		
R2 Design optimisation	Energy	4	2	2	4	0		
	Luminosity	3	3	0	1	1	2	3
	Reliability	2	1	0	0	0		
R3 Production optimisation	Energy	4	6	7	?1	?1		
	Luminosity	17	8	6	?3	?1		
	Reliability	5	3	2	?1	?0		
R4 Technical/cost optimisation	Energy	3	2	4	?0	?0		
	Luminosity	4	3	1	?0	?0		
	Reliability	0	0	0	?0	?0		

INTERNATIONAL LINEAR COLLIDER TECHNICAL REVIEW COMMITTE

CLIC TECHNOLOGY-RELATED KEY ISSUES, ACCORDING TO 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

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

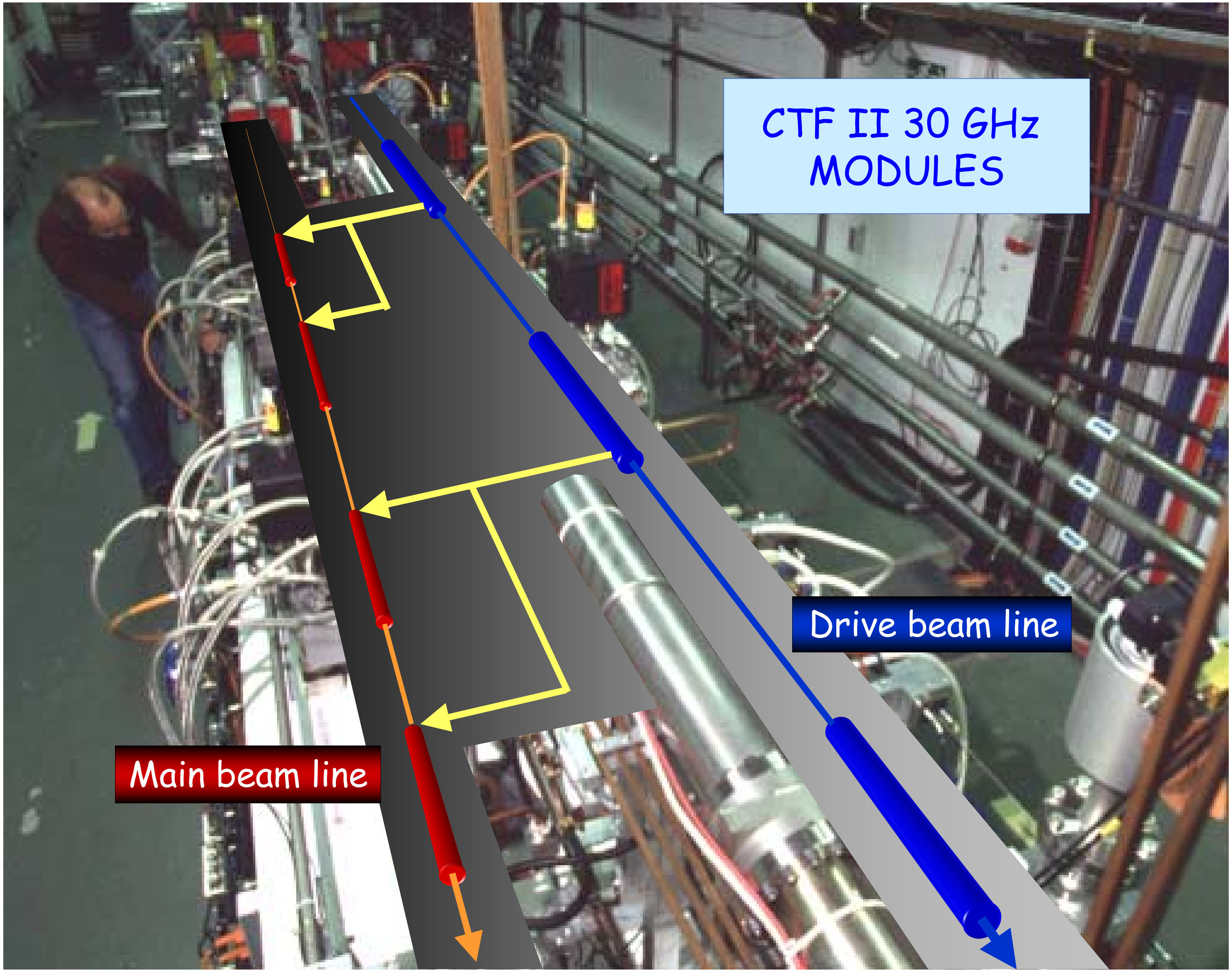
    except the Multi-Beam Klystron (MBK) which does not require R&D but development by industry (feasibility study already done)

CLIC TEST FACILITY (CTF II)

1996 -2002

CTF II goals :

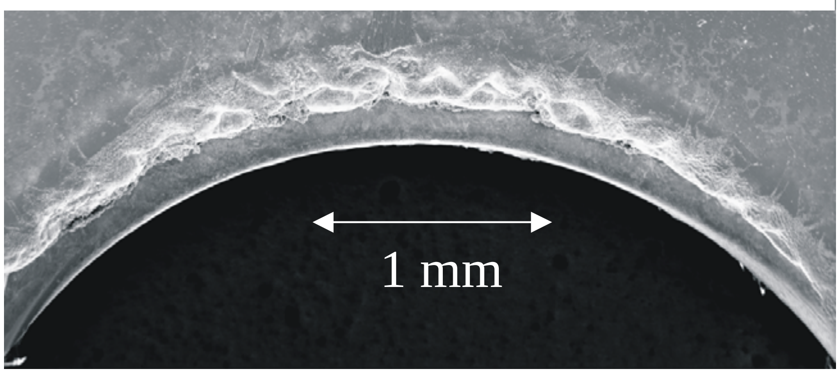
- Demonstrate feasibility of a two-beam acceleration scheme
- Study generation of short, intense e-bunches using photocathode RF guns
- Demonstrate operability of μ-precision active-alignment system in accelerator environment
- Provide a test bed to develop and test accelerator diagnostic equipment
- Provide high power 30 GHz RF source for high gradient testing (90 MW, 16 ns pulses)


CTF II 30 GHz MODULES
Drive beam line
Main beam line

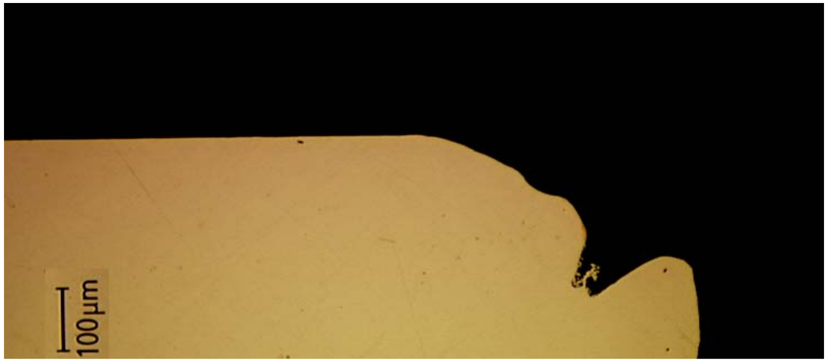
BREAKDOWN AND DAMAGE OF STRUCTURES

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

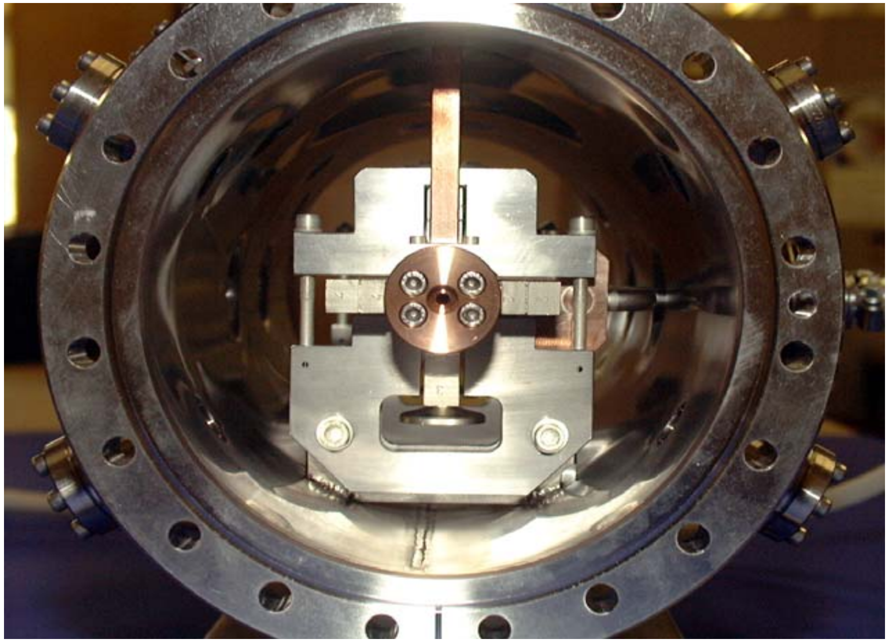


Damaged iris – longitudinal cut

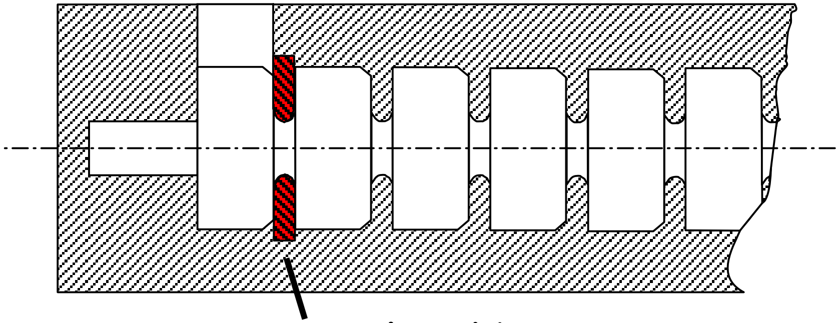
The CLIC study group adopted a two-pronged approach to solving the breakdown problem :

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

FIRST TEST OF TUNGSTEN IRIS IN CTF II

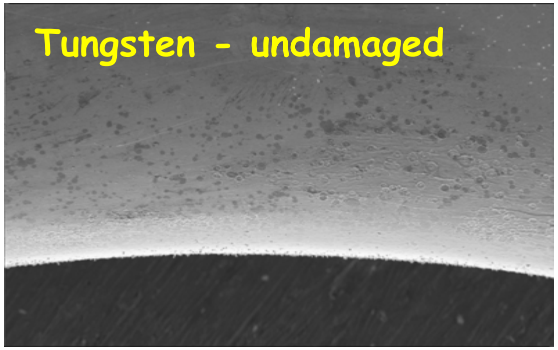


Test structure in external vacuum can, with clamped coupler cell

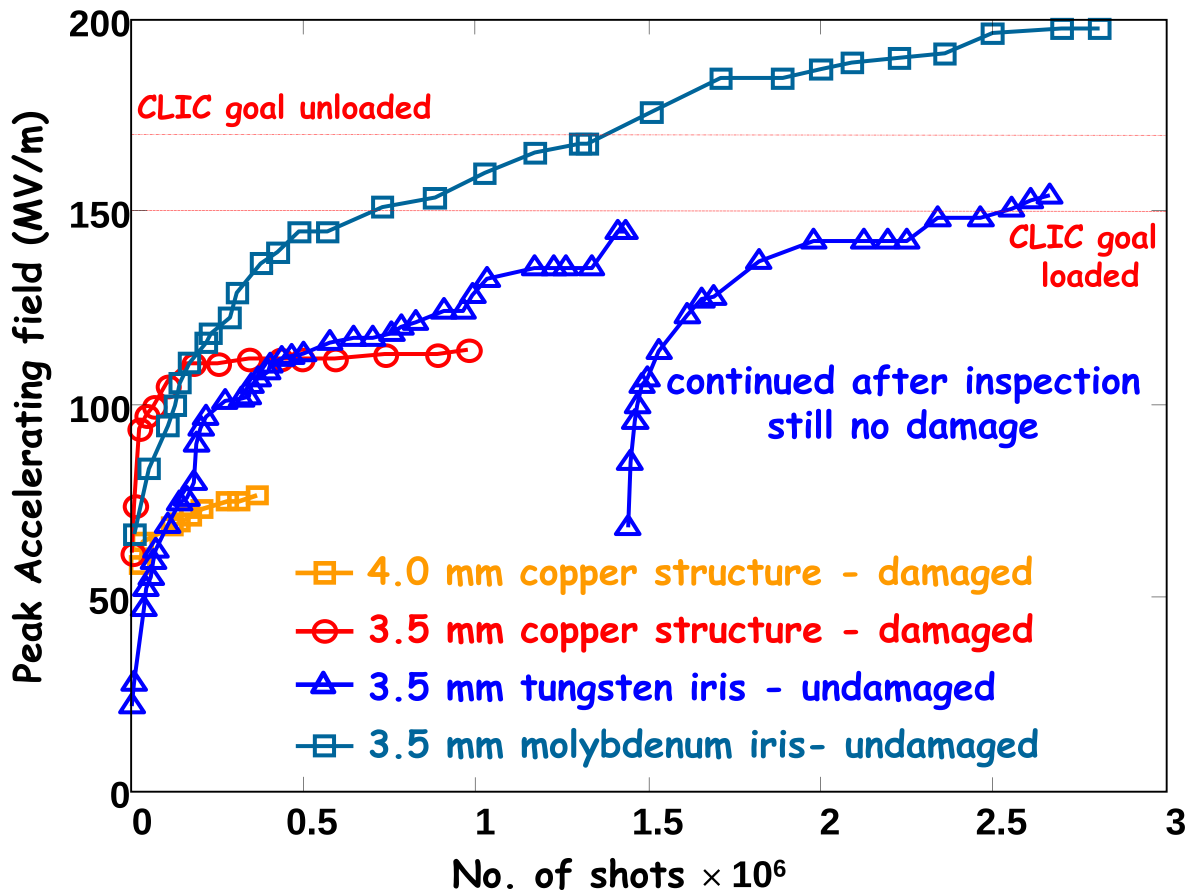


Copper iris replaced by Tungsten iris

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



HIGH-GRADIENT TESTS in CTF II

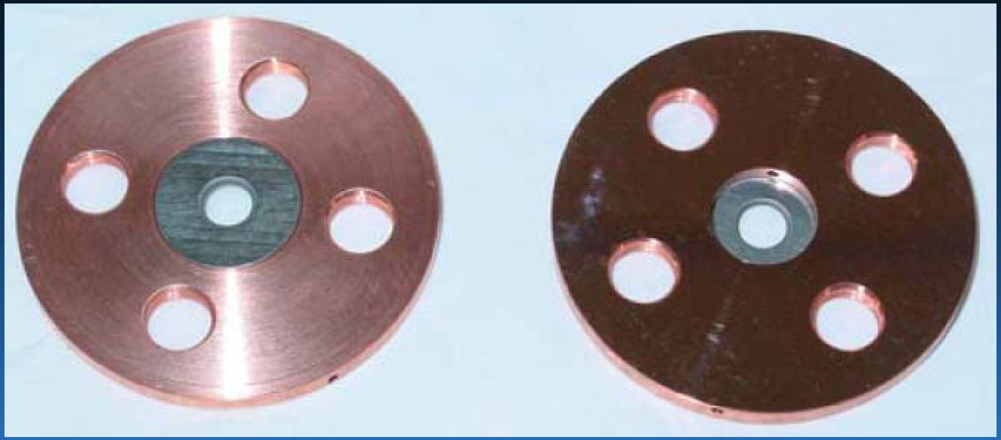


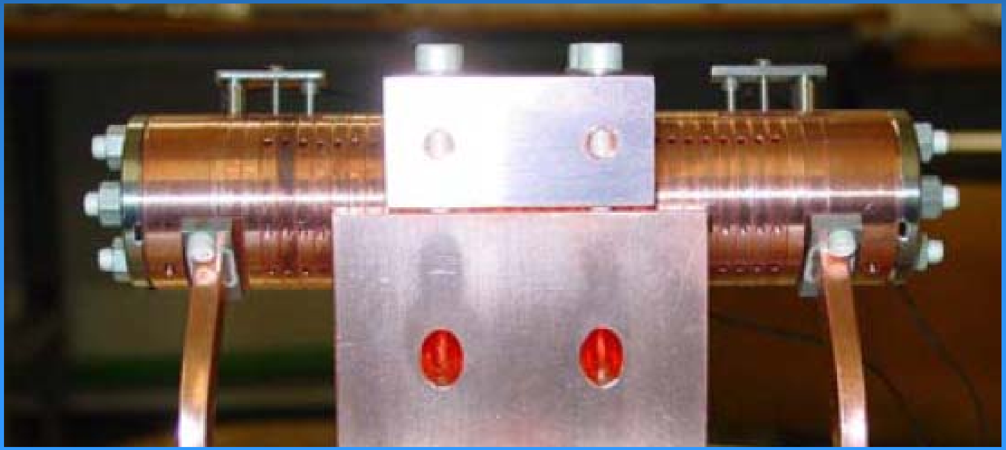
A 30-cell structure with Mo irises and low E_S/E_A largely exceeded the CLIC accelerating field requirements without any damage

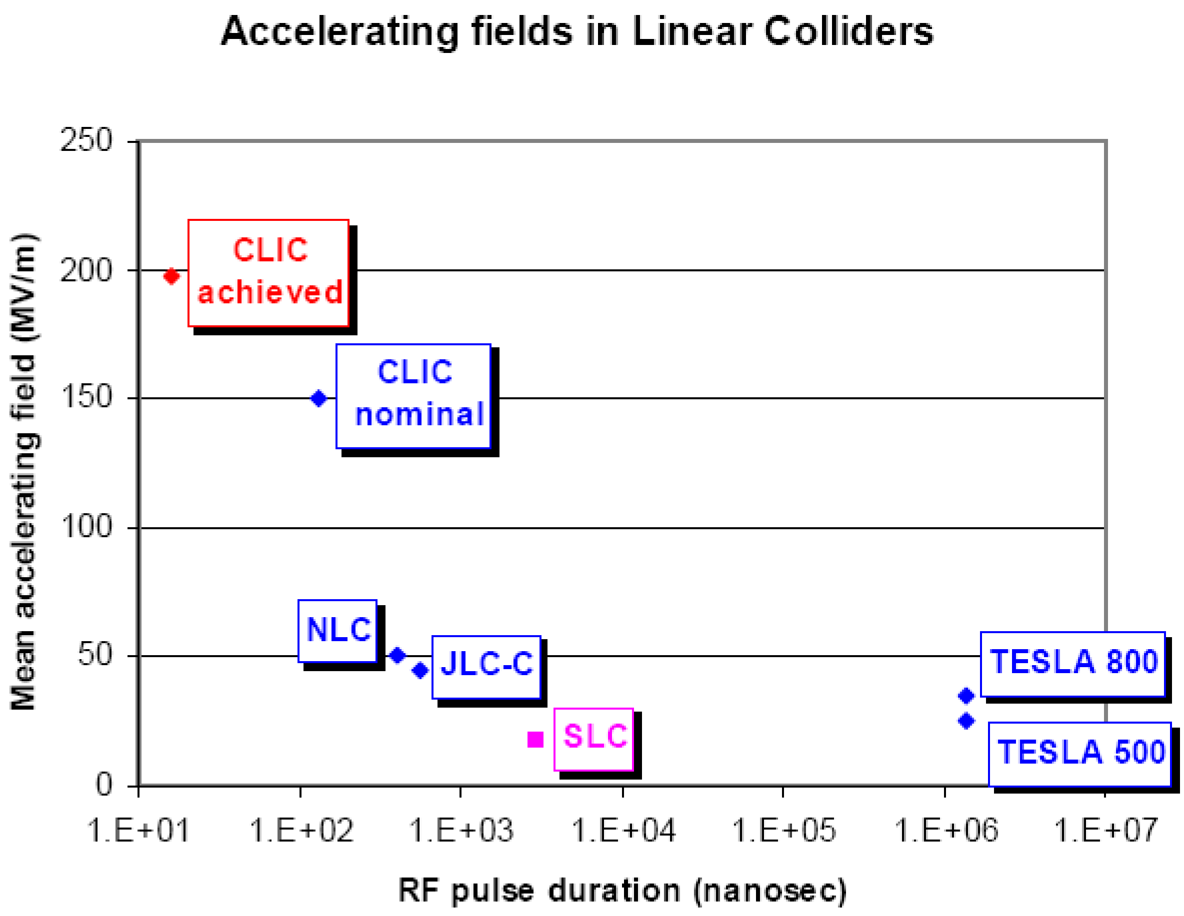
190 MV/m accelerating gradient in first cell - tested with beam ! (but only 16 ns pulse length)

HIGH-GRADIENT TESTS in CTF II

30-cell clamped tungsten-iris structure



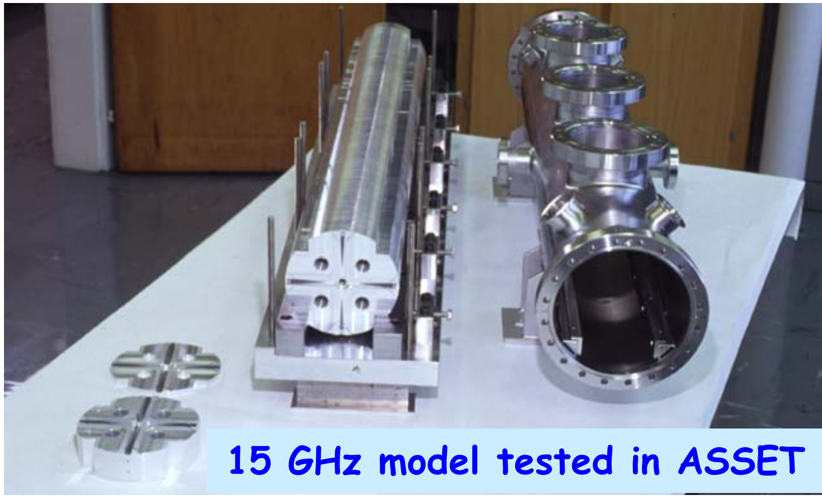



Accelerating fields in Linear Colliders
Mean accelerating field (MV/m)
250
200
150
100
50
0
CLIC achieved
CLIC nominal
NLC
JLC-C
SLC
TESLA 800
TESLA 500
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
RF pulse duration (nanosec)

CONTROL OF TRANSVERSE WAKEFIELDS

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

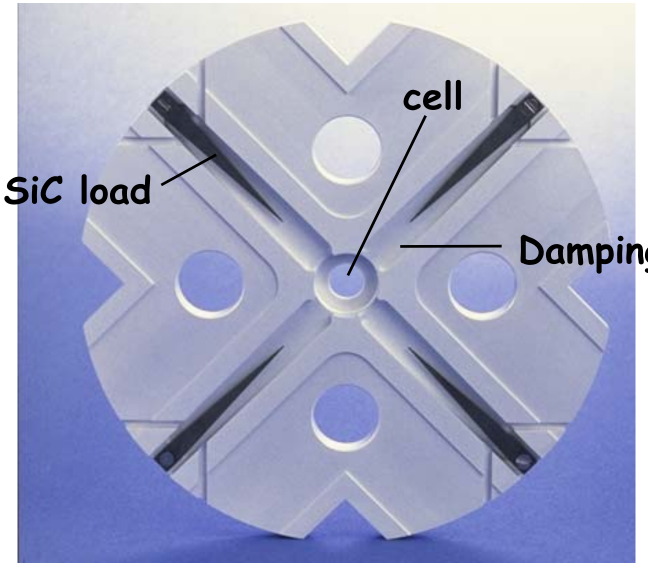
+ beam-based trajectory correction, ε bump

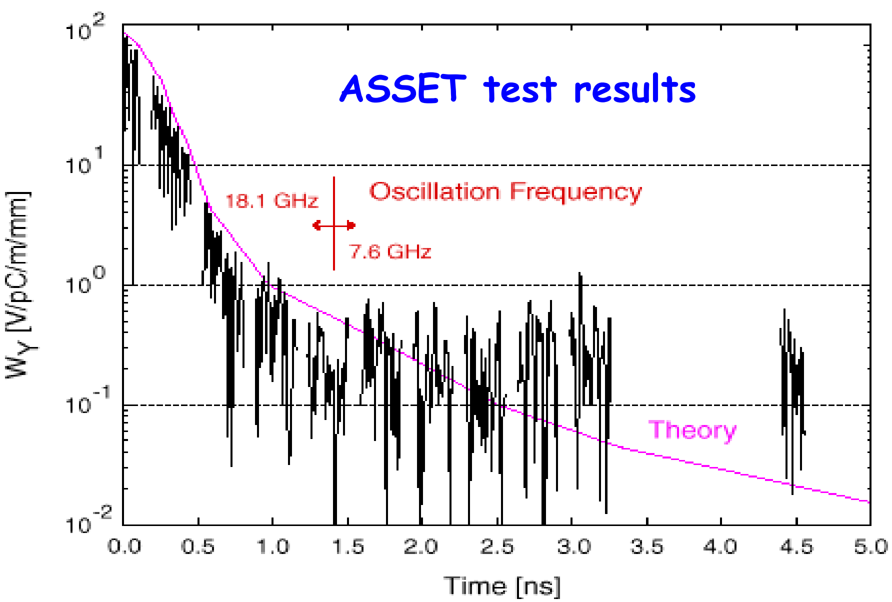


15 GHz model tested in ASSET

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

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



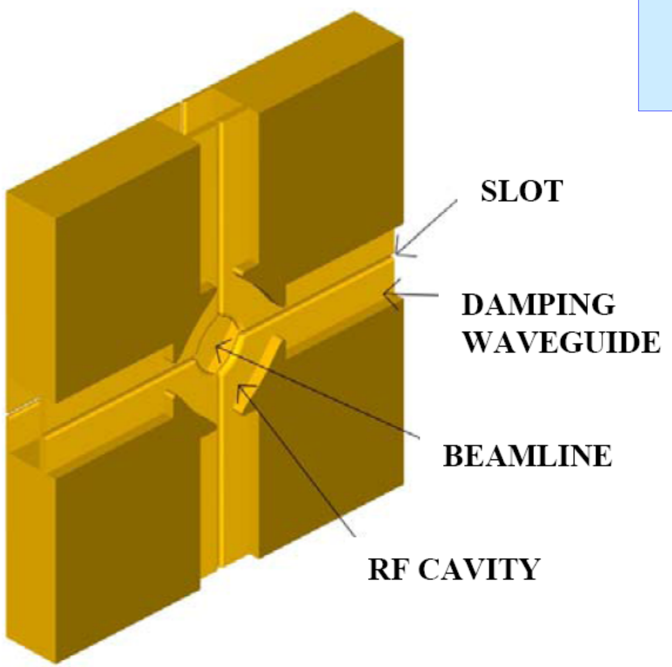


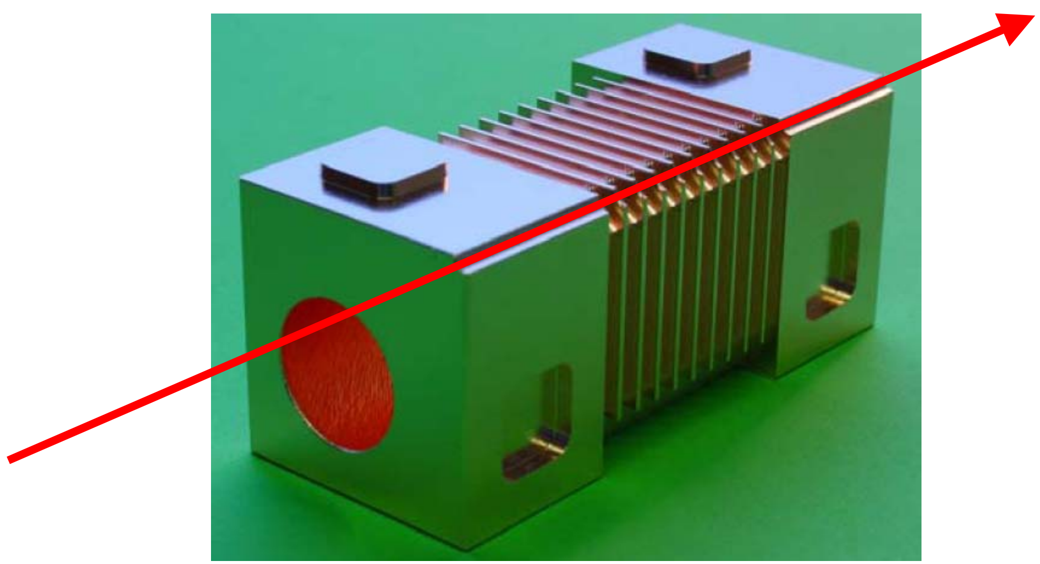
NEXT STEPS IN ACCELERATING STRUCTURE DEVELOPMENT

Potential problem:
fatigue limit of copper due to cyclic RF pulsed heating

- New structure design optimization (short RF pulse, frequency ?)
- New materials, construction concepts, bi-metallic structure assembly

GOAL: final structure design tested in CTF3 in 2008



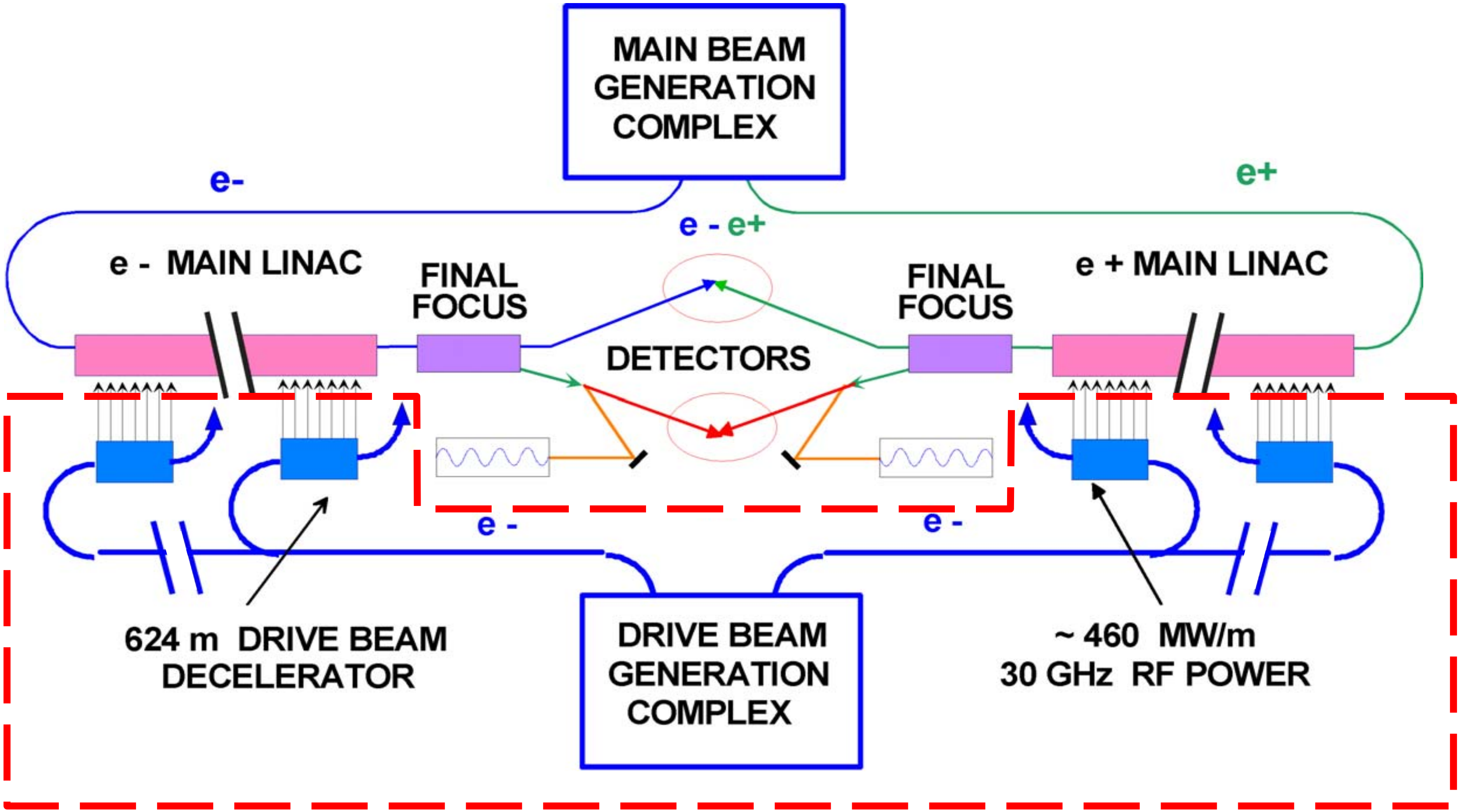


New structure design will determine parameter change

CLIC MAIN PARAMETERS

Parameter	Symbol	Present	New	Unit
Overall Parameters				
Center of mass energy	E_{cm}	3000	3000	GeV
Main Linac RF Frequency	f_{RF}	30	30	GHz
Luminosity	L	8	6.2	10^{34} cm^{-2} s^{-1}
Luminosity (in 1% of energy)	$L_{99\%}$	3.3	3.3	10^{34} cm^{-2} s^{-1}
Linac repetition rate	f_{rep}	100	300	Hz
No. of particles / bunch	N_b	4.2	2.36	10^9
No. of bunches / pulse	k_b	154	157	
Bunch separation	Dt_b	0.67	0.267 (8 periods)	ns
Bunch train length	t_{train}	101	41.7	ns
Beam power / beam	P_b	14.8	26.6	MW
Unloaded / loaded gradient	$G_{unl/l}$	172 / 150	175 / 150	MV/m
Overall two linac length	l_{linac}	28	~28	km
Total beam delivery length	l_{BD}	2 x 2.6	2 x 2.6	km
Proposed site length	l_{tot}	33.2	~33.2	km
Total site AC power	P_{tot}	410	540	MW
Wall plug to main beam power efficiency	h_{tot}	9.3	12.9	%

THE CLIC RF POWER SOURCE



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

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*

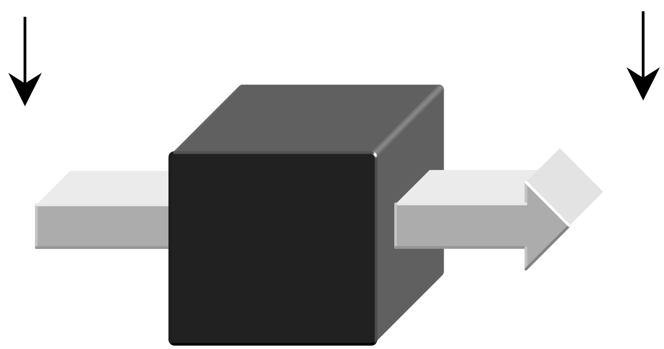
450 Klystrons

low frequency
high efficiency

Long RF Pulses
P_0 , ν_0 , τ_0

Power stored in electron beam

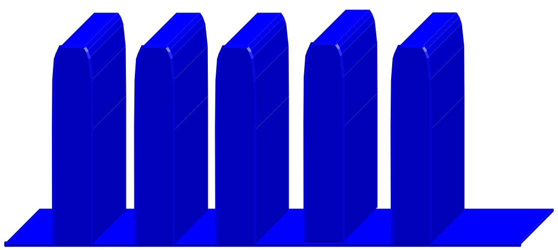
Power extracted from beam in resonant structures



Electron beam manipulation

43000 Accelerating Structures

high frequency high gradient



Short RF Pulses

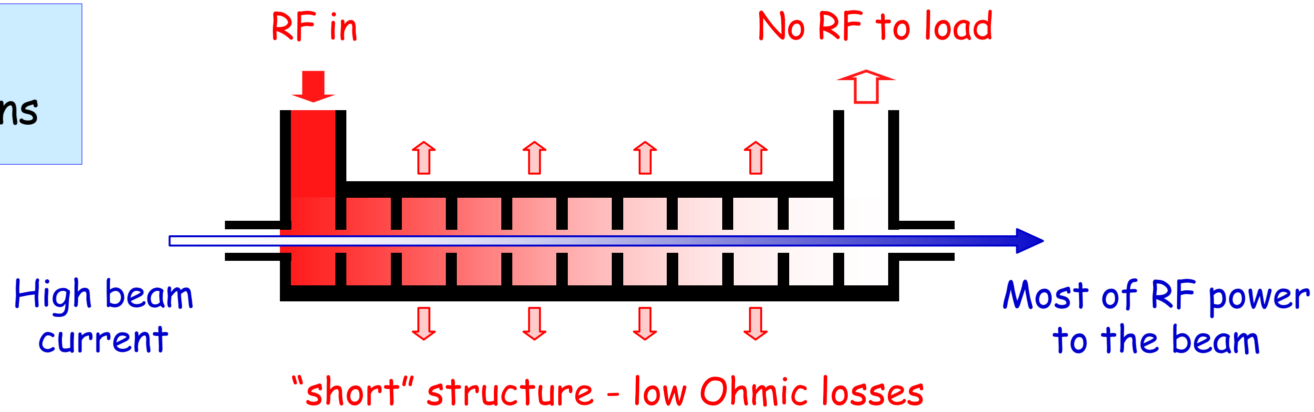
$P_A = P_0 \times N_1$

$\tau_A = \tau_0 / N_2$

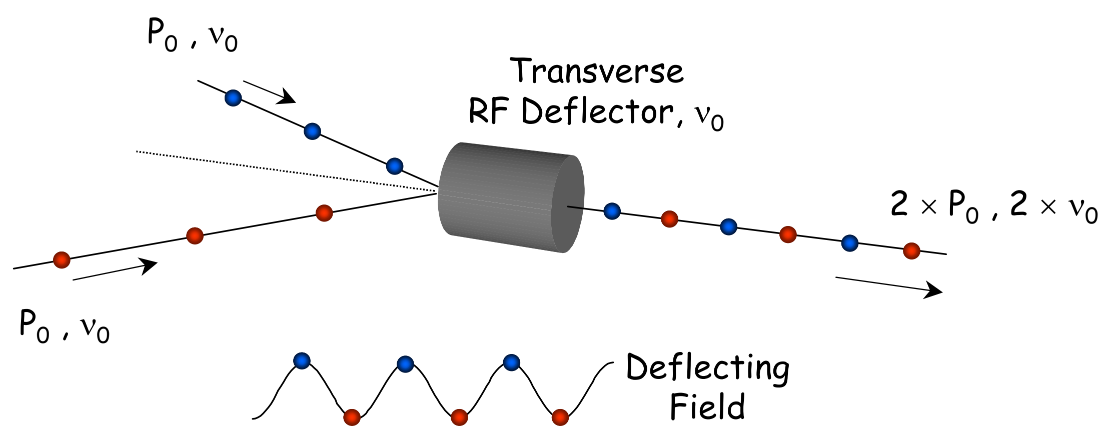
$\nu_A = \nu_0 \times N_3$

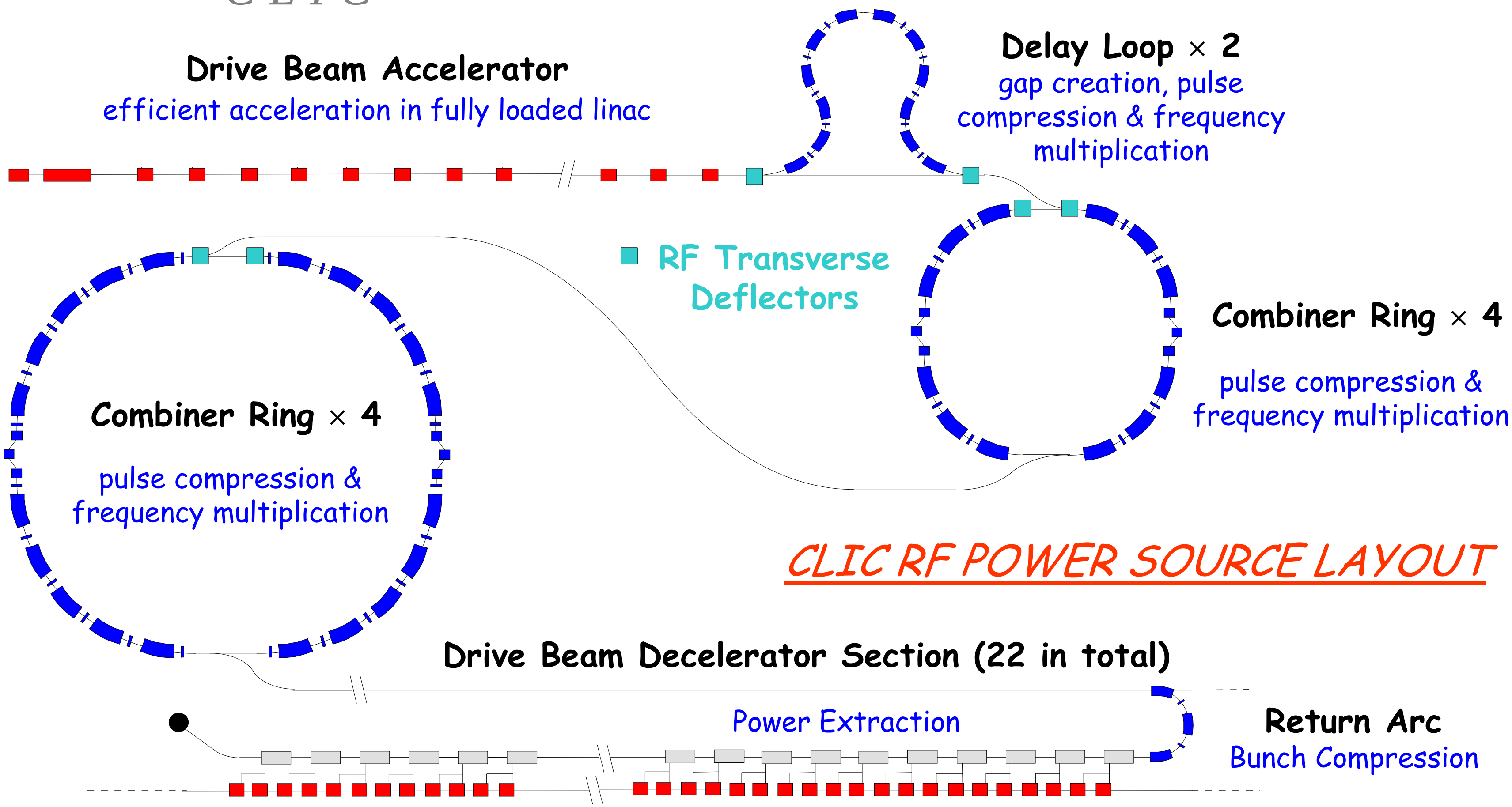
RF POWER SOURCE "BUILDING BLOCKS"

Full beam-loading acceleration in TW sections

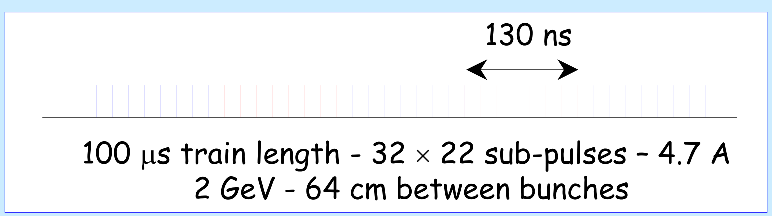


Beam combination/separation by transverse RF deflectors

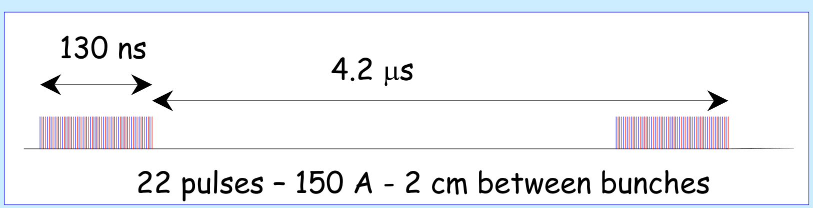




Drive beam time structure - initial



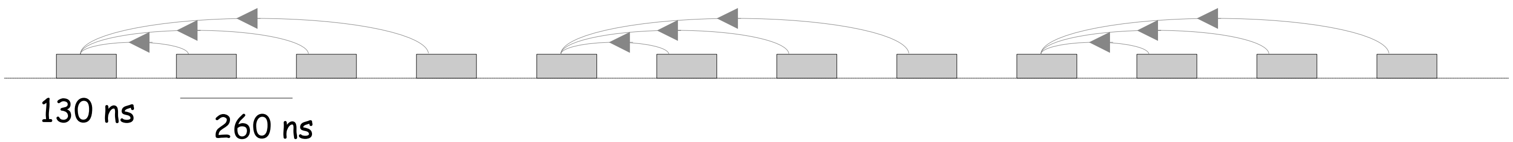
Drive beam time structure - final



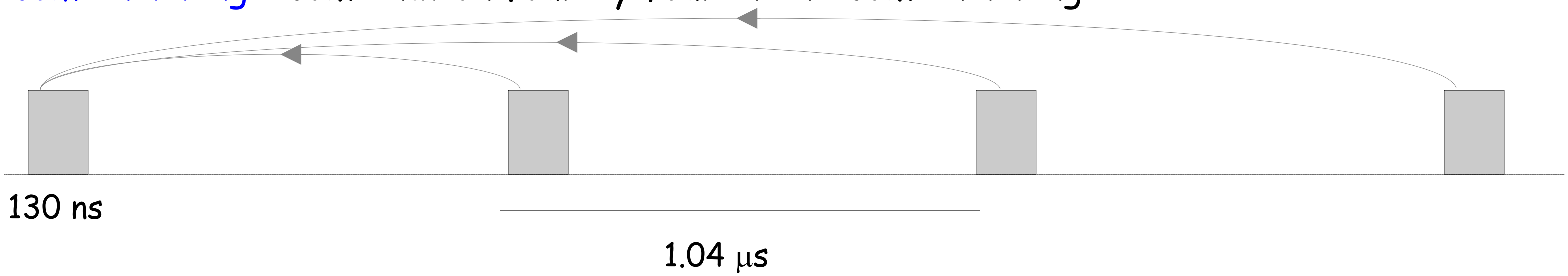
DRIVE BEAM TIME STRUCTURE EVOLUTION

From DBA – 130 ns long "sub-pulses"

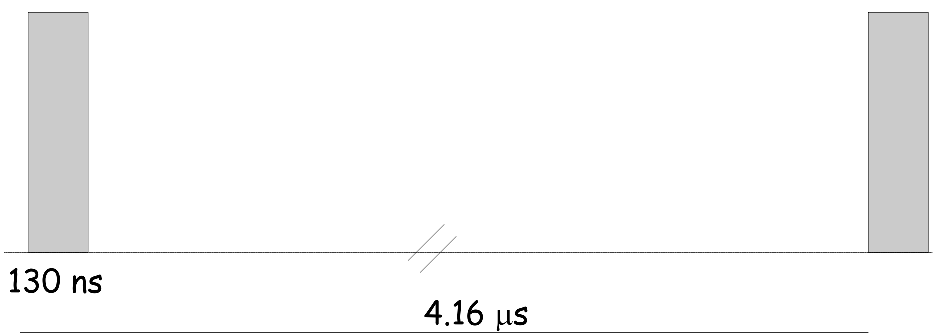
After delay loop - combination four by four in 1st combiner ring



After 1st combiner ring - combination four by four in 2nd combiner ring



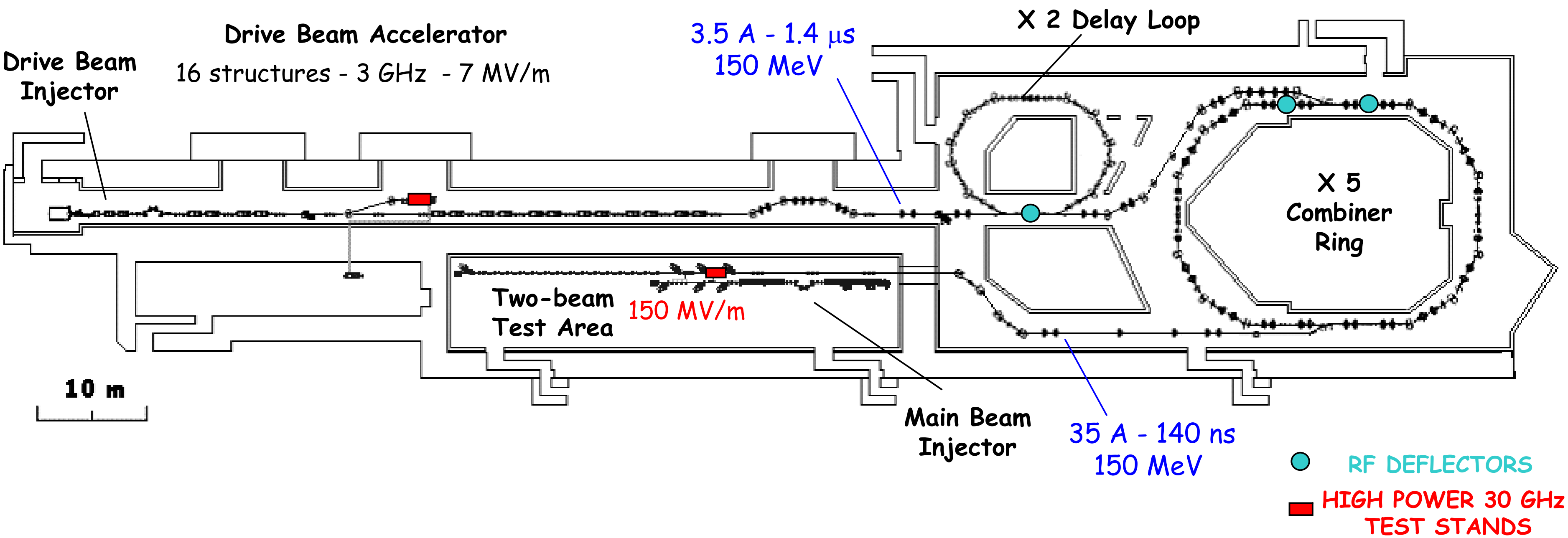
Final time structure – 22 pulses



Each pulse sent to one decelerator section

CTF3 MOTIVATIONS AND GOALS

- Build a small-scale version of the CLIC RF power source, in order to demonstrate:
  - full beam loading accelerator operation
  - electron beam pulse compression and frequency multiplication using RF deflectors
- Provide the 30 GHz RF power to test the CLIC accelerating structures and components at the nominal gradient and pulse length (150 MV/m for 130 ns) .



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- CTF3 is built in the area of the former LEP pre-injector complex (LPI). It will make maximum use of the existing equipment (3 GHz RF power plant, magnets…)
- CTF3 is being built in stages. The final phase is foreseen to start in 2005
- The first phase, CTF3 Preliminary, has given the expected results and has been dismantled
- The project is based in the AB Department of CERN, with collaboration with other Divisions and external institutes (INFN-Frascati, SLAC, LAL/Orsay, Uppsala University, RAL)

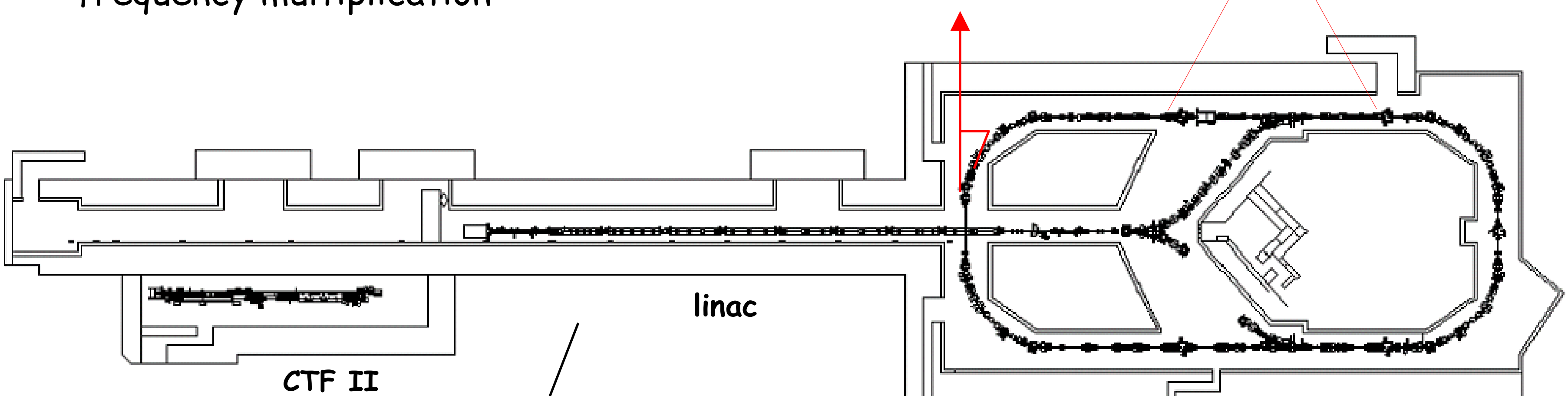
CTF3 COLLABORATION

CERN, Geneva (Switzerland)	Northwestern University, (USA)
INFN , Frascati (Italy)	SLAC , San Francisco (USA)
LAL , Orsay (France)	Uppsala University , (Sweden)

PRELIMINARY PHASE

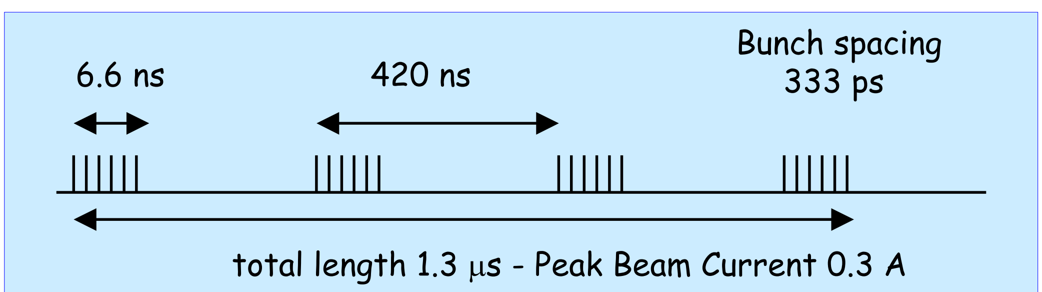
Bunch charge	0.1 nC
Beam energy	350 MeV
$\gamma\varepsilon_{x,y}$	25 π mm mrad
σ_t	< 7 ps
σ_E	~ 0.5 %

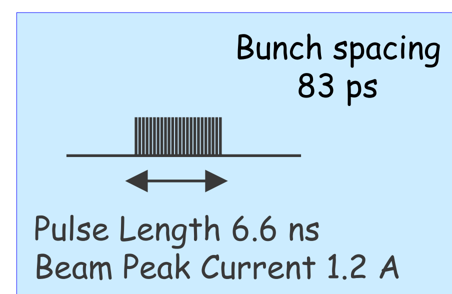
low-charge demonstration of the electron pulse compression and frequency multiplication



Beam structure in linac – 4 pulses

Beam structure after combination (factor 4)





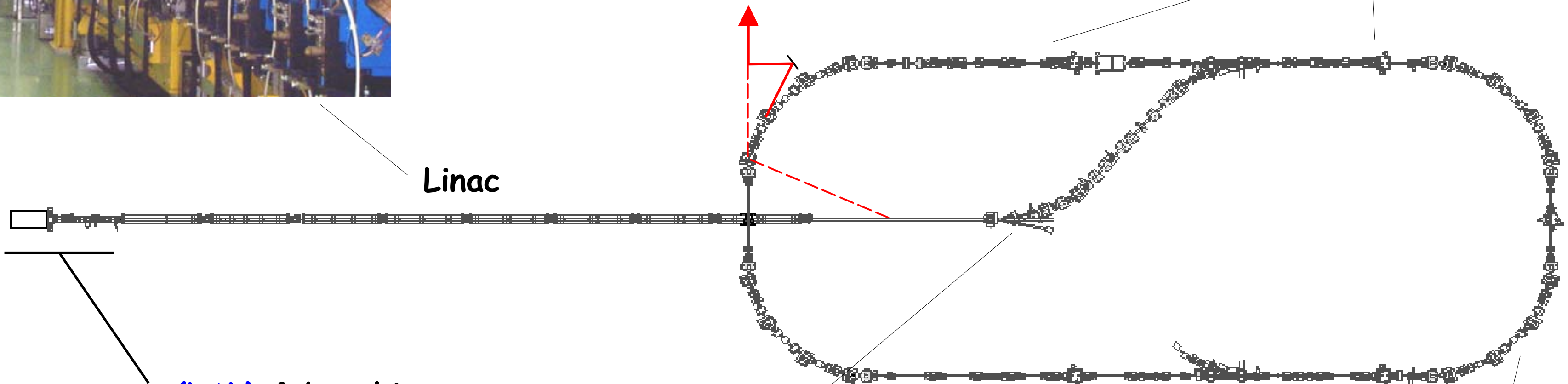
Modifications to the LEP pre-injector complex

CTF3 PRELIMINARY PHASE

(2001-2002)

RF deflectors (INFN-LNF)

streak camera measurement

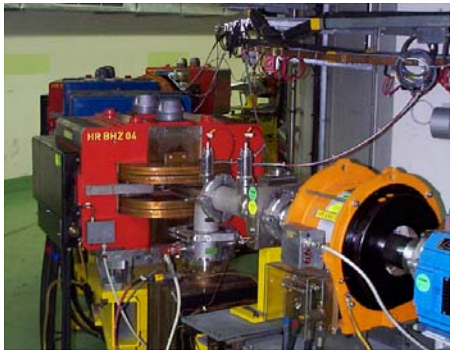


Linac

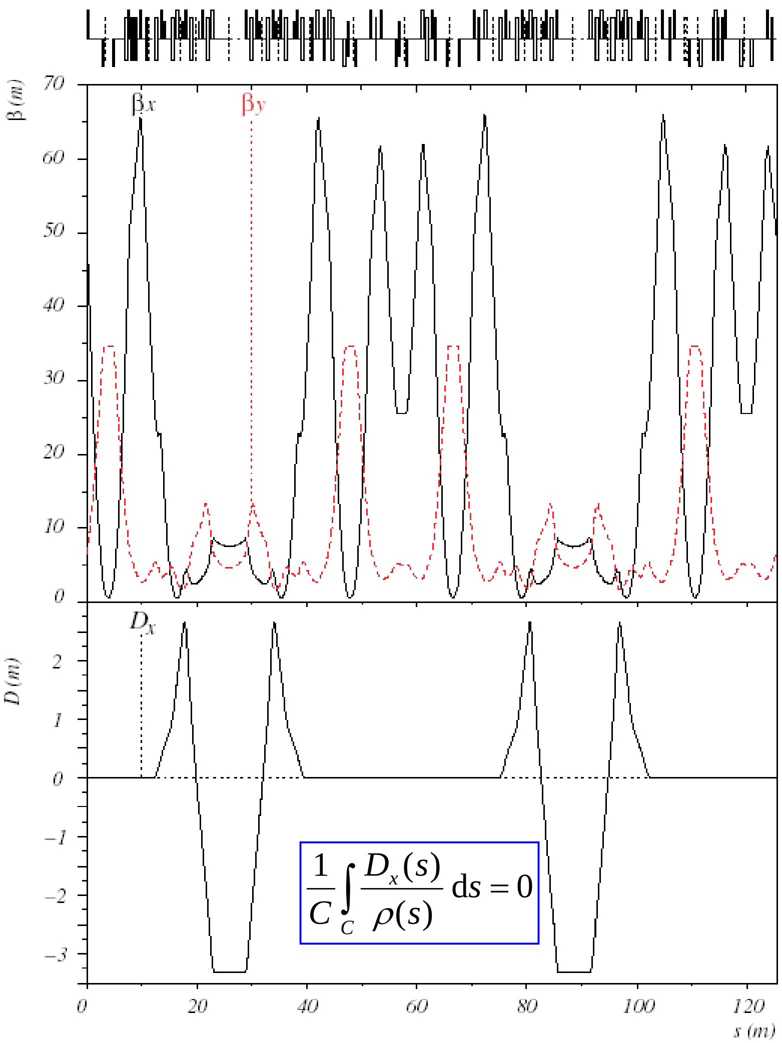
gun (LAL) & bunching system

isochronous injection line

isochronous arcs



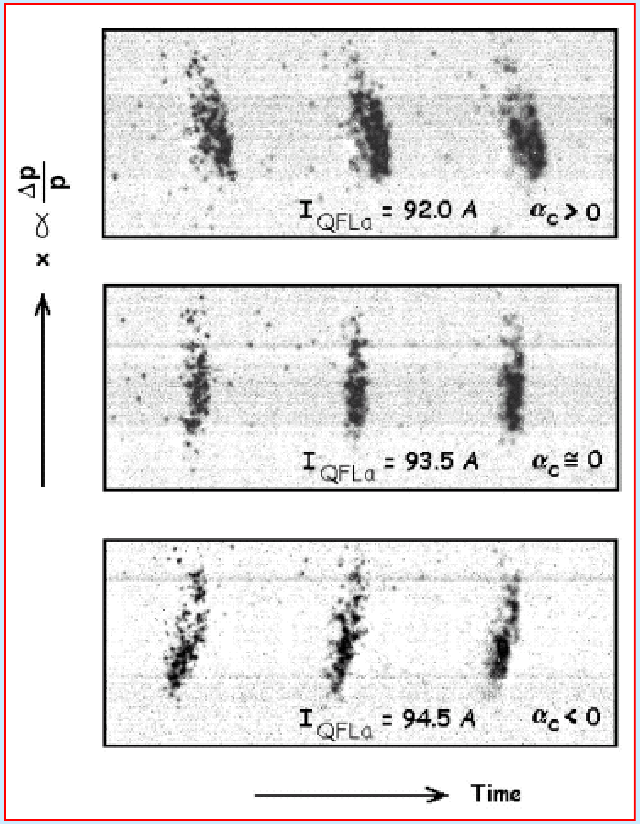
ISOCHRONICITY



$$\frac{1}{C}\int_C \frac{D_x(s)}{\rho(s)}\,ds = 0$$

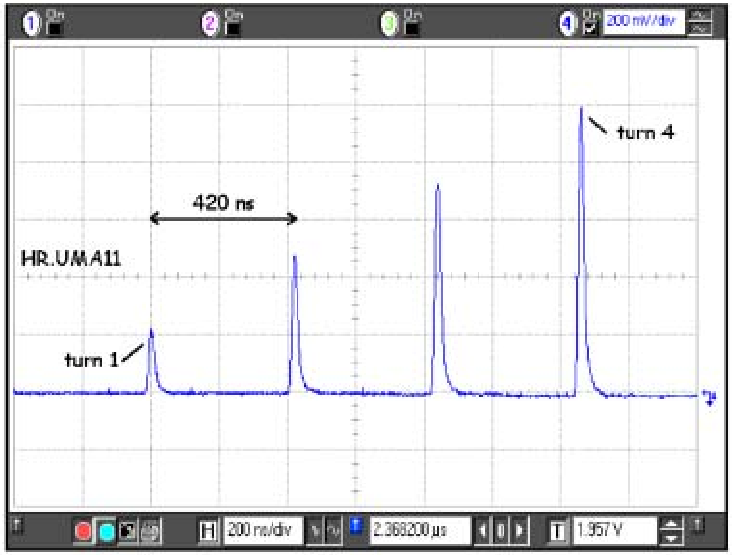
Design optics of the isochronous ring

Transition from **positive to negative** momentum compaction α_c seen on streak camera images for different settings of one quad family.

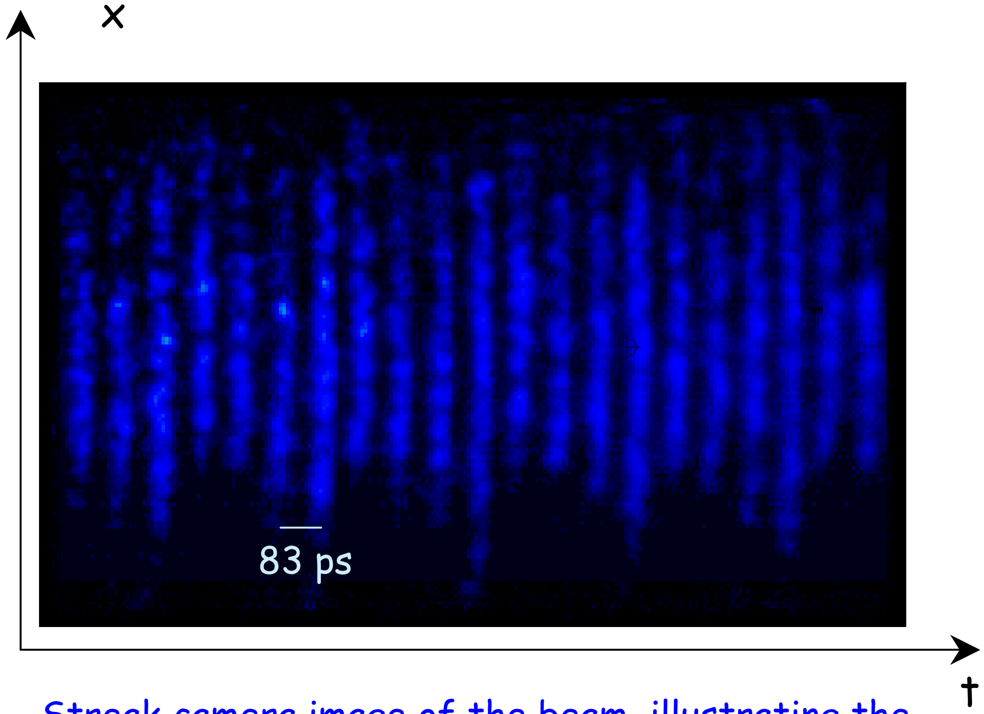


Images taken during the tenth turn at a location with nonzero dispersion. The horizontal position x is dependent on momentum, so the time-momentum correlation becomes apparent.

PRELIMINARY PHASE RESULTS
BUNCH COMBINATION (FACTOR 4)



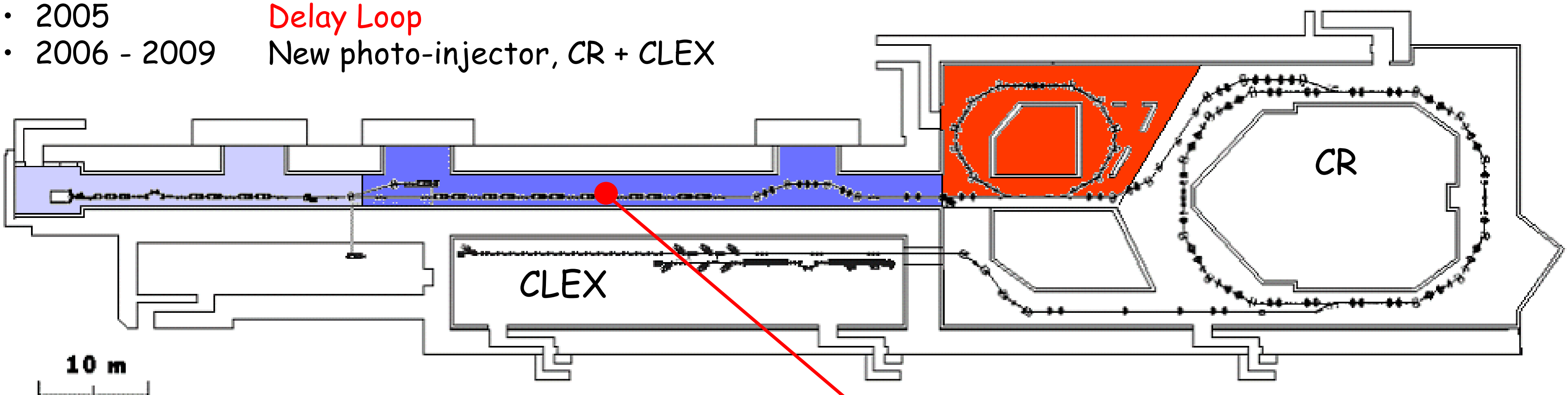
Beam current circulating in the ring measured during combination with a beam current monitor



Streak camera image of the beam, illustrating the bunch combination process

CTF3 EVOLUTION

- 2003 Injector + part of linac
- 2004 Linac + 30 GHz test stand
- 2005 Delay Loop
- 2006 - 2009 New photo-injector, CR + CLEX

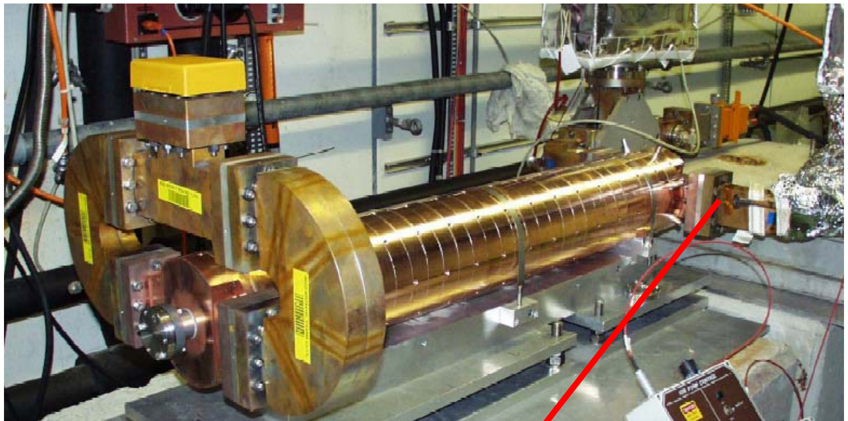


Main beam parameters

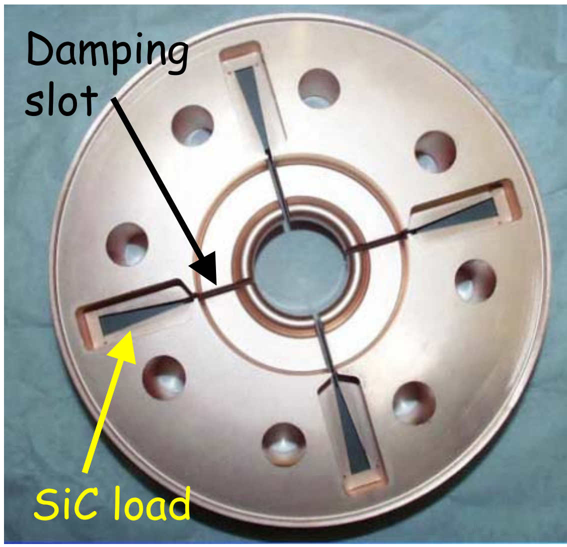
	Nominal	Achieved
I	3.5 A	5 A
τ_p	1.5 μs	1.5 μs
E	35 MeV	35 MeV
$\varepsilon_{n,rms}$	100 π mm mrad	~ 110 π mm mrad *
$\tau_{b,rms}$	5 ps	~ 4 ps *

* for 3.5 A, 1.5 μs beam

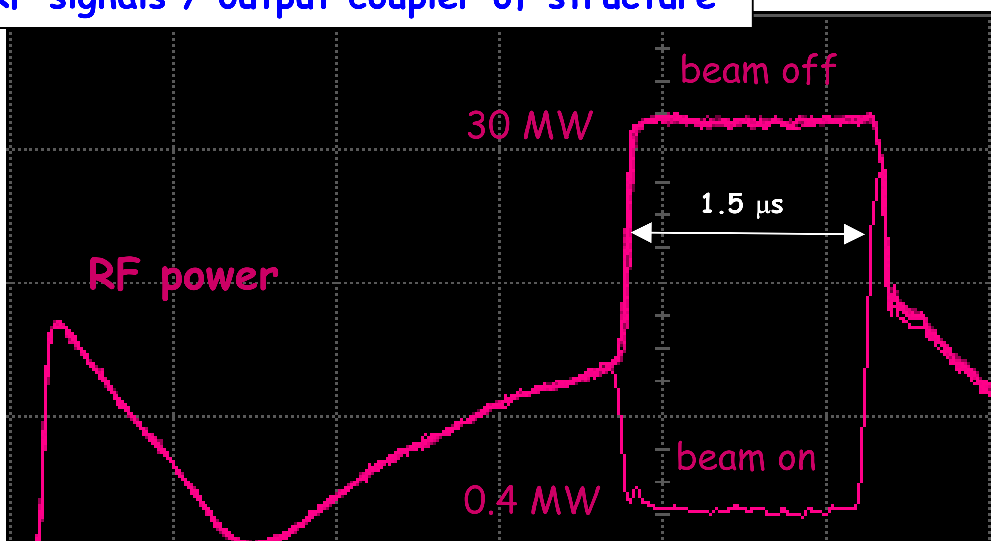
FIRST "FULL" BEAM LOADING OPERATION IN CTF3



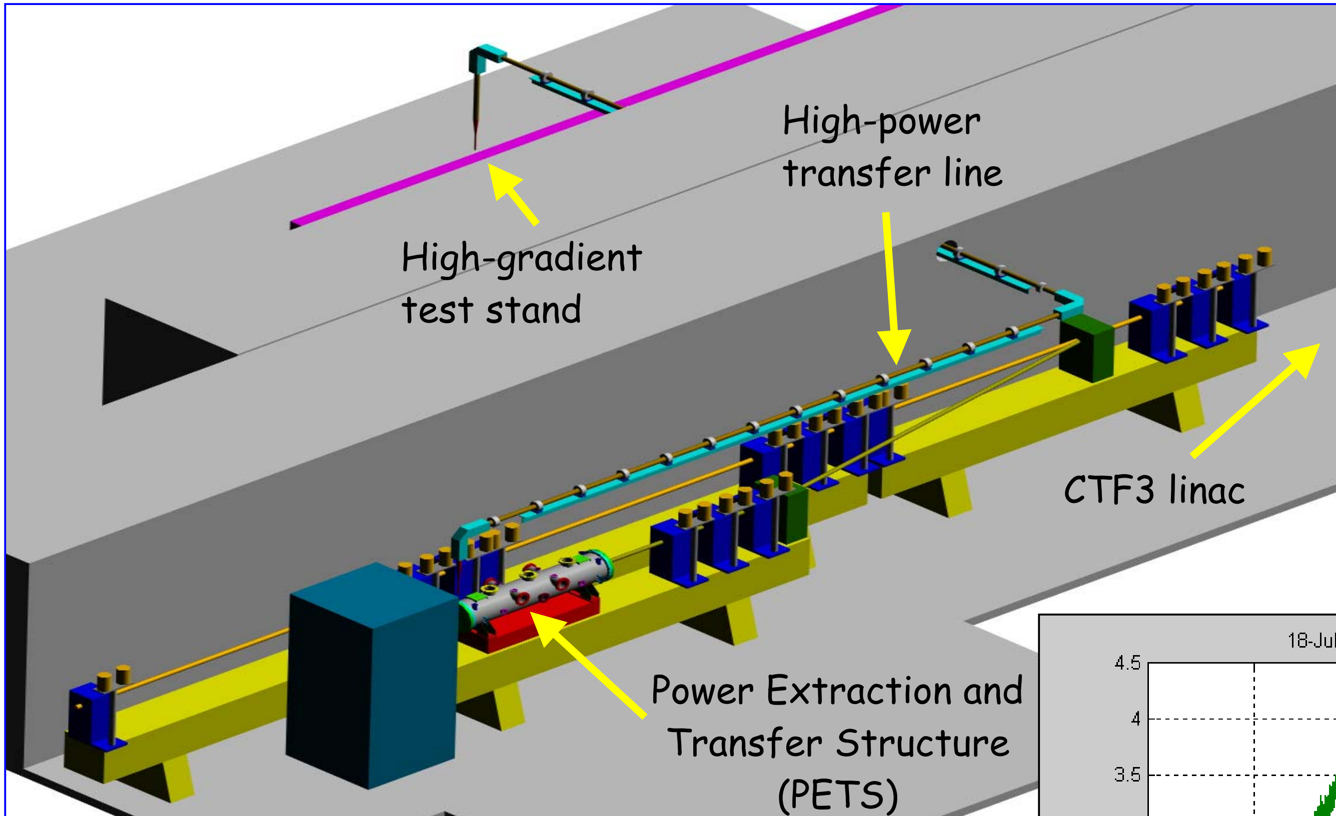
Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning



RF signals / output coupler of structure

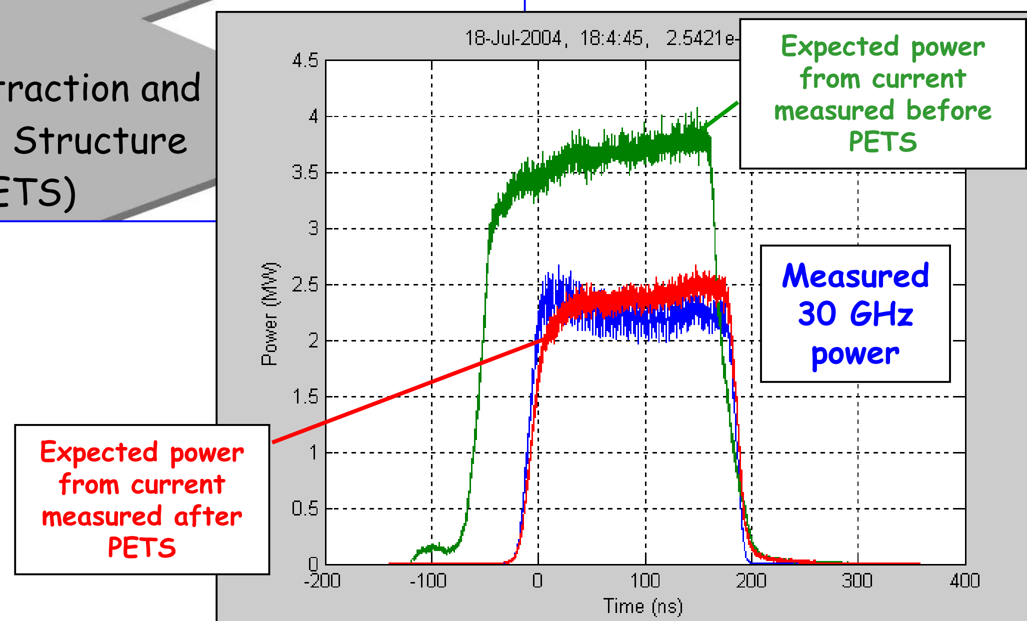


Beam current	4 A
Beam pulse lenght	1.5 µs
Power input/structure	35 MW
Ohmic losses (beam on)	1.6 MW
RF power to load (beam on)	0.4 MW
RF-to-beam efficiency	~ 94%



Two-beam 30 GHz power production in CTF3 June 2004

- "short" PETS installed in first 2004 run
- "long" PETS is in now, expect ~ 12 times more power
- Will start again accelerating structure tests in 2005



CTF3 MAIN RESULTS UP TO NOW

Preliminary phase (2001-2002)

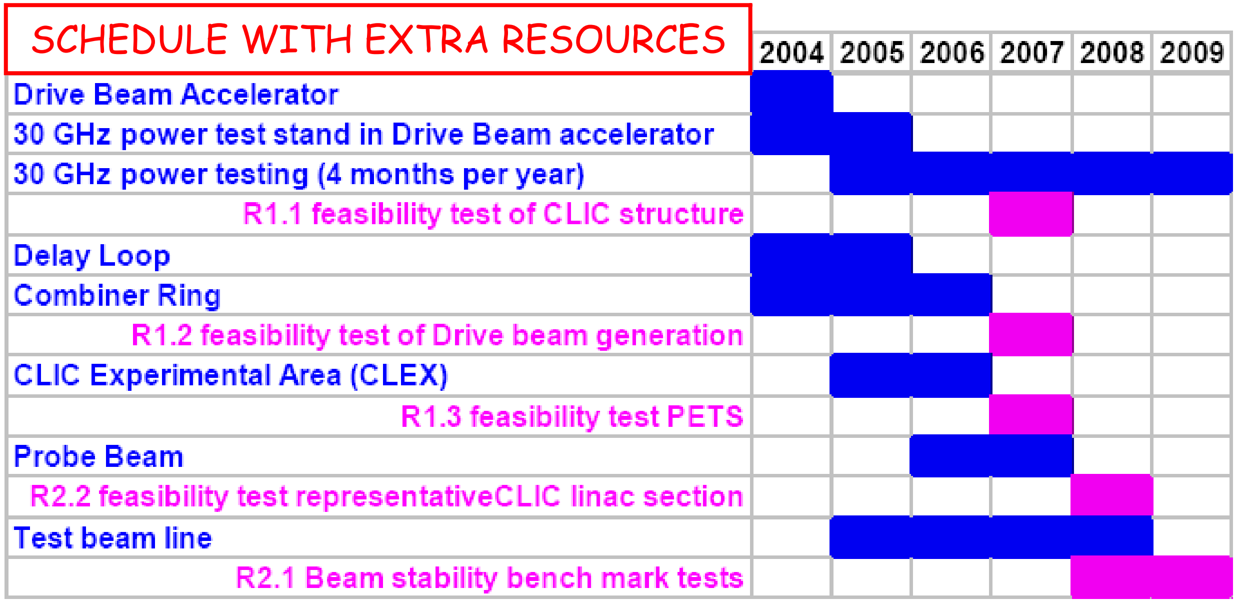
Low current demonstration of bunch frequency multiplication using RF deflectors

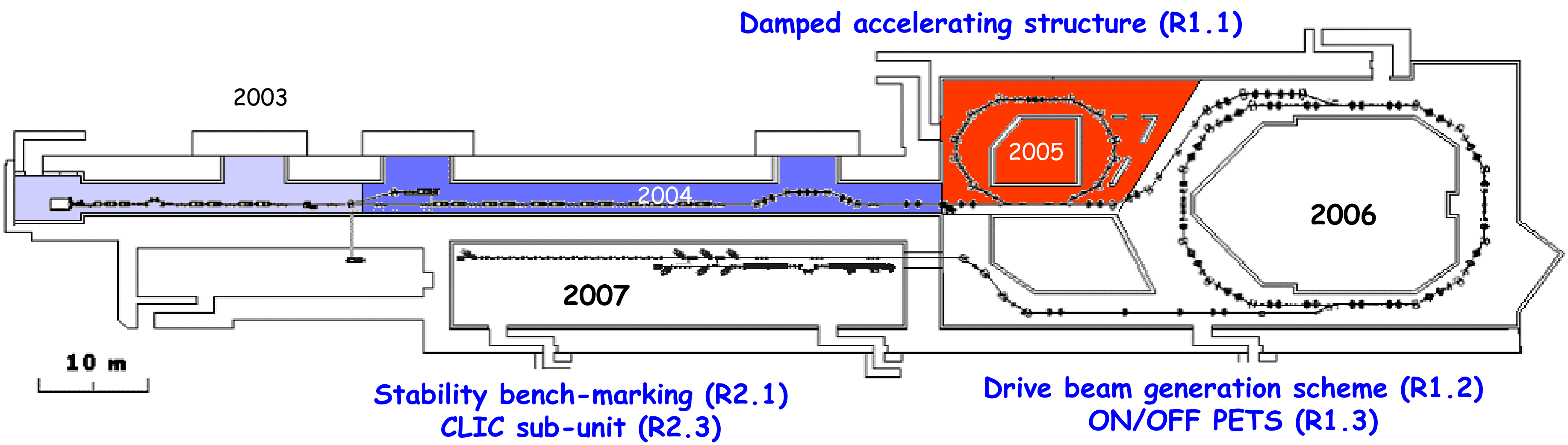
CTF3 injector and linac commissioning (2003-2004)

Nominal parameters achieved in injector and first part of linac

Stable operation in full beam loading condition

First production of 30 GHz RF power beyond CLIC nominal pulse length





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					■	■

TENTATIVE LONG-TERM CLIC SCENARIO
(success oriented)