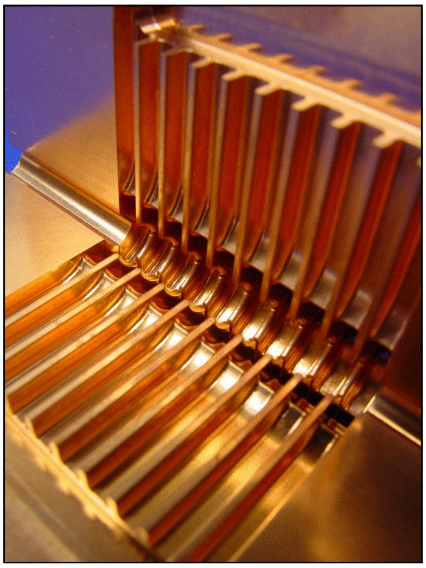
Linear Colliders

(high-energy e+/e- colliders)



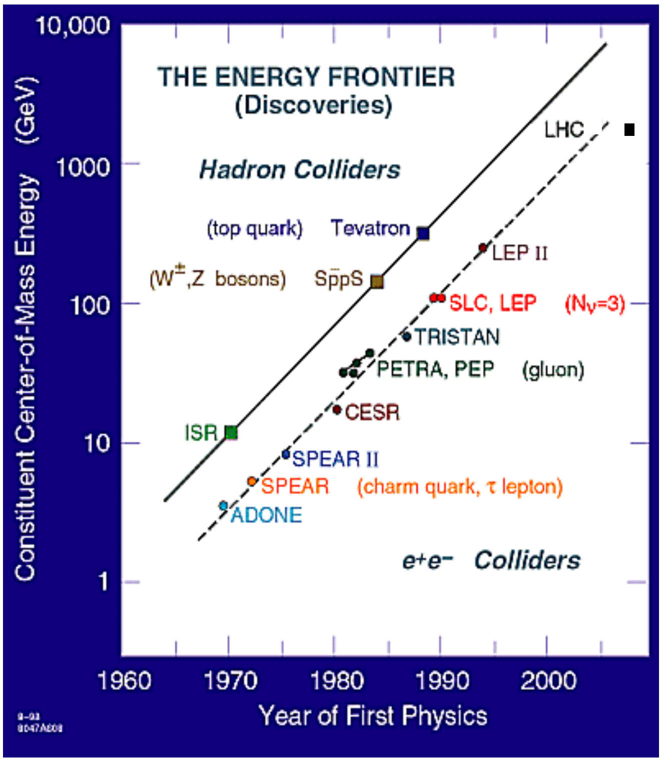
Frank Tecker – CERN

- Physics motivation
- Generic Linear Collider Layout
- ILC (International Linear Collider)
- CLIC (Compact Linear Collider)
- CTF3 (CLIC Test Facility)
- Conclusion

Preface

- Complex topic --- but: DON'T PANIC!
- Approach:
  - Explain the fundamental layout of a linear collider and the specific designs based on SuperConducting (SC) and normal conducting (NC) technology
  - I will not go much into technical details
  - Try to avoid formulae as much as possible
- Goal: You understand
  - Basic principles
  - Some driving forces and limitations in linear collider design
  - The basic building blocks of CLIC
- Ask questions at any time! Any comment is useful! (e-mail: tecker@cern.ch)

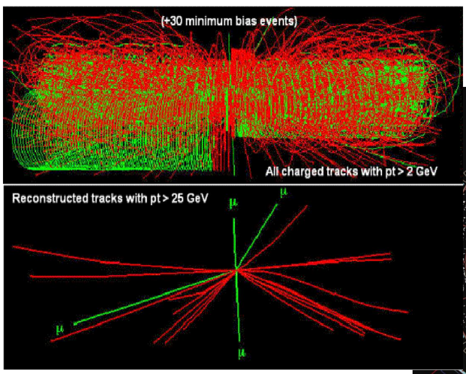
Path to higher energy

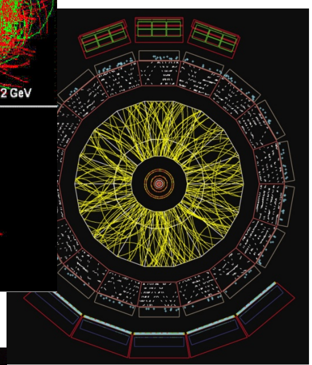


- History: Storage Rings
  - Energy constantly increasing with time
  - Hadron Collider at the energy frontier
  - Lepton Collider for precision physics
- LHC physics results soon
- Consensus to build Lin. Collider with E_{cm} > 500 GeV to complement LHC physics
  (*European strategy for particle physics* by CERN Council)

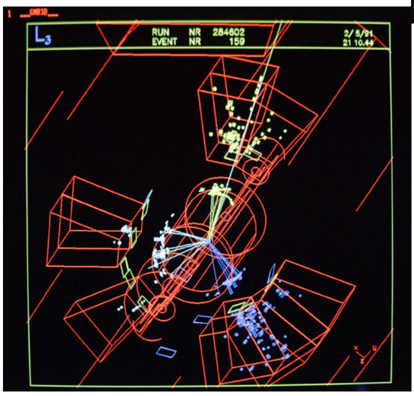
Lepton vs. Hadron Collisions

LHC: H → ZZ → 4μ



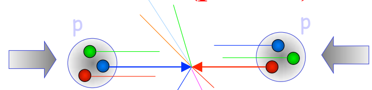


ALICE:
Ion event

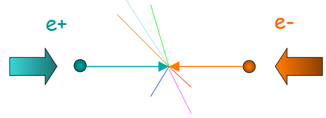


LEP event:
$Z^0 \rightarrow$ 3 jets

- Hadron Collider (p, ions):



  - Composite nature of protons
  - Can only use p_t conservation
  - Huge QCD background
- Lepton Collider:



  - Elementary particles
  - Well defined initial state
  - Beam polarization
  - produces particles democratically
  - Momentum conservation eases decay product analysis

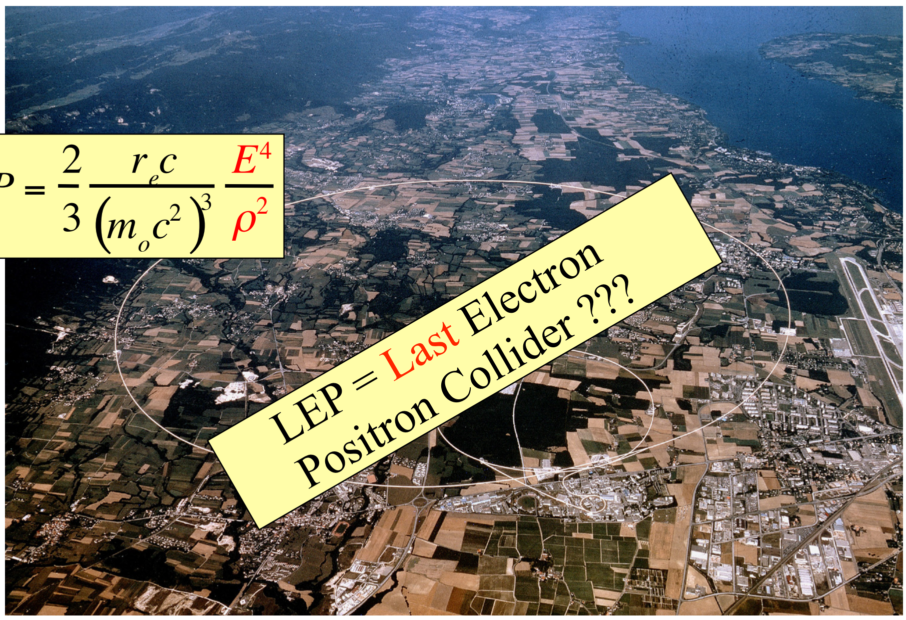
TeV e+e- physics

- Higgs physics
  - Tevatron/LHC should discover Higgs (or something else)
  - LC explore its properties in detail
- Supersymmetry
  - LC will complement the LHC particle spectrum
- Extra spatial dimensions
- New strong interactions
- . . .
  => a lot of new territory to discover beyond the standard model
- "Physics at the CLIC Multi-TeV Linear Collider"
  CERN-2004-005
- "ILC Reference Design Report – Vol.2 – Physics at the ILC"
  www.linearcollider.org/rdr

The LEP collider

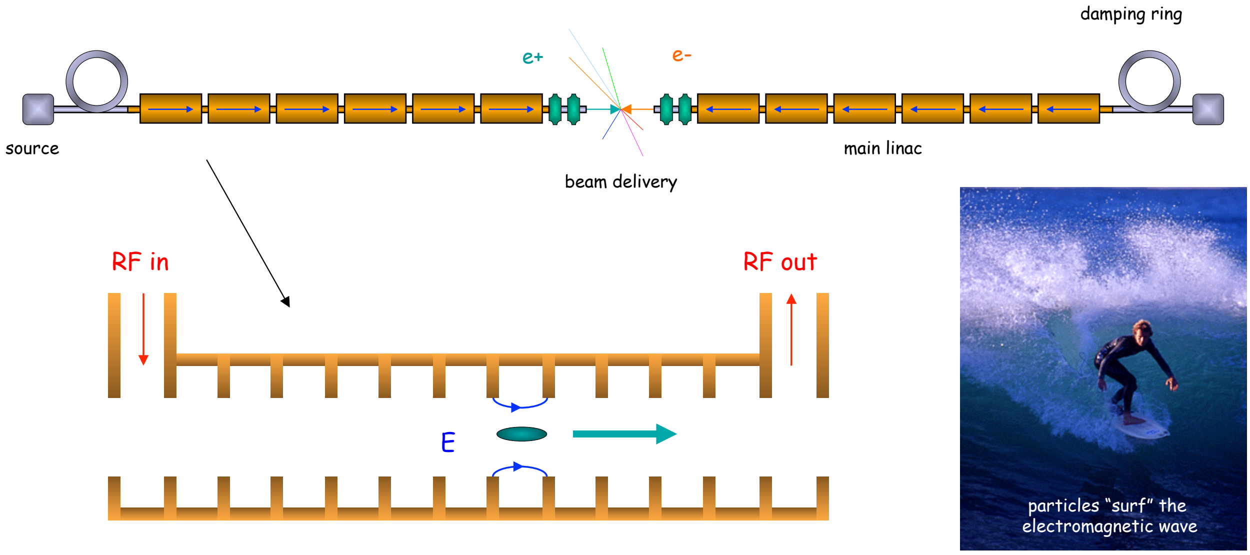
- LEP (Large Electron Positron collider) was installed in LHC tunnel
- e+ e- circular collider (27 km) with E_{cm}=200 GeV
- Problem for any ring: Synchrotron radiation
- Emitted power: scales with E^4 !! and $1/m_0^3$ (much less for heavy particles)
- This energy loss must be replaced by the RF system !!
- particles lost 3% of their energy each turn!

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

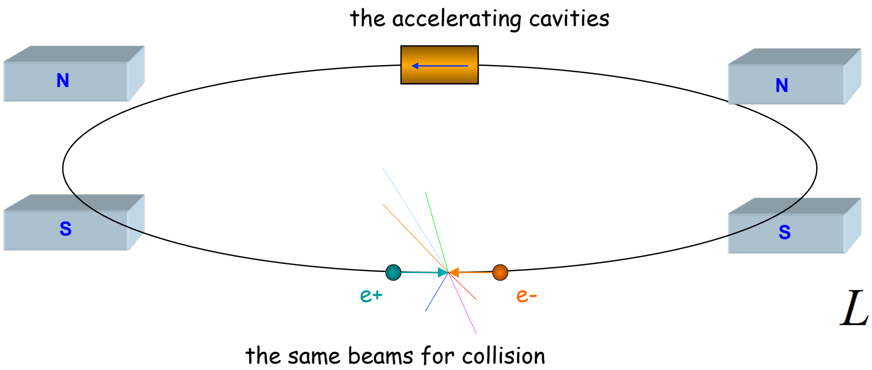


The next lepton collider

- Solution: LINEAR COLLIDER
- avoid synchrotron radiation
- no bending magnets, huge amount of cavities and RF



Linear Collider vs. Ring



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

Storage rings:

- accelerate + collide every turn
- 're-use' RF + 're-use' particles
- => efficient

Linear Collider:

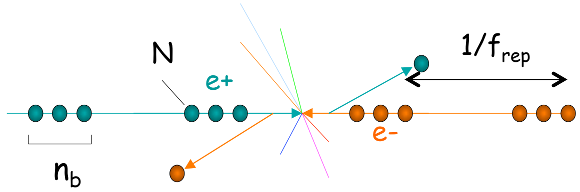
- one-pass acceleration + collision => need
  - high gradient
  - small beam size σ and emittance

to reach high luminosity L (event rate)

What matters in a linear collider ?

Energy reach $E_{cm} = 2\,F_{fill}\,L_{linac}\,G_{RF}$ → High gradient

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

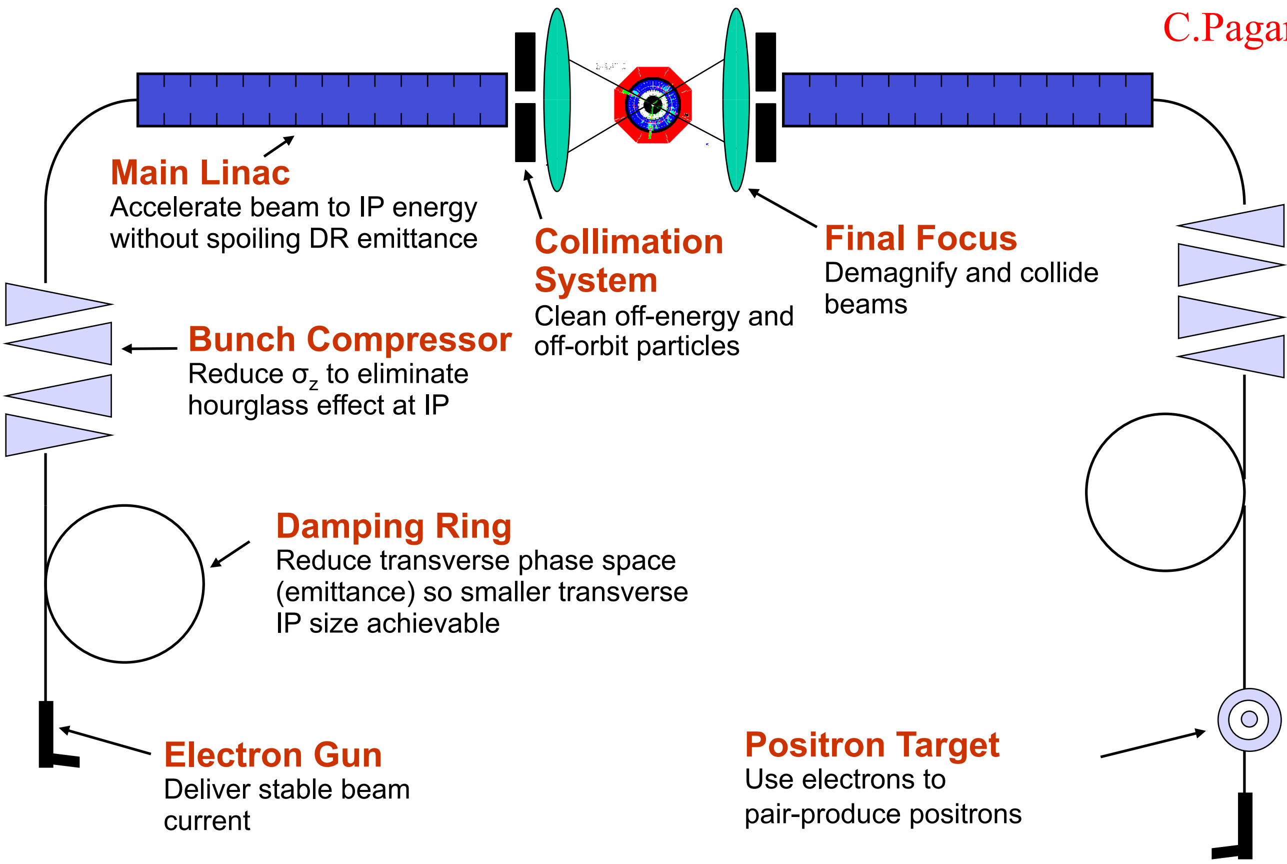


$\sigma_{x,y}$ = transverse beam size

- Acceleration efficiency η
- Generation and preservation of small emittance ε — damping rings, alignment, stability, wake-fields
- Extremely small beam spot at collision point — beam delivery system, stability

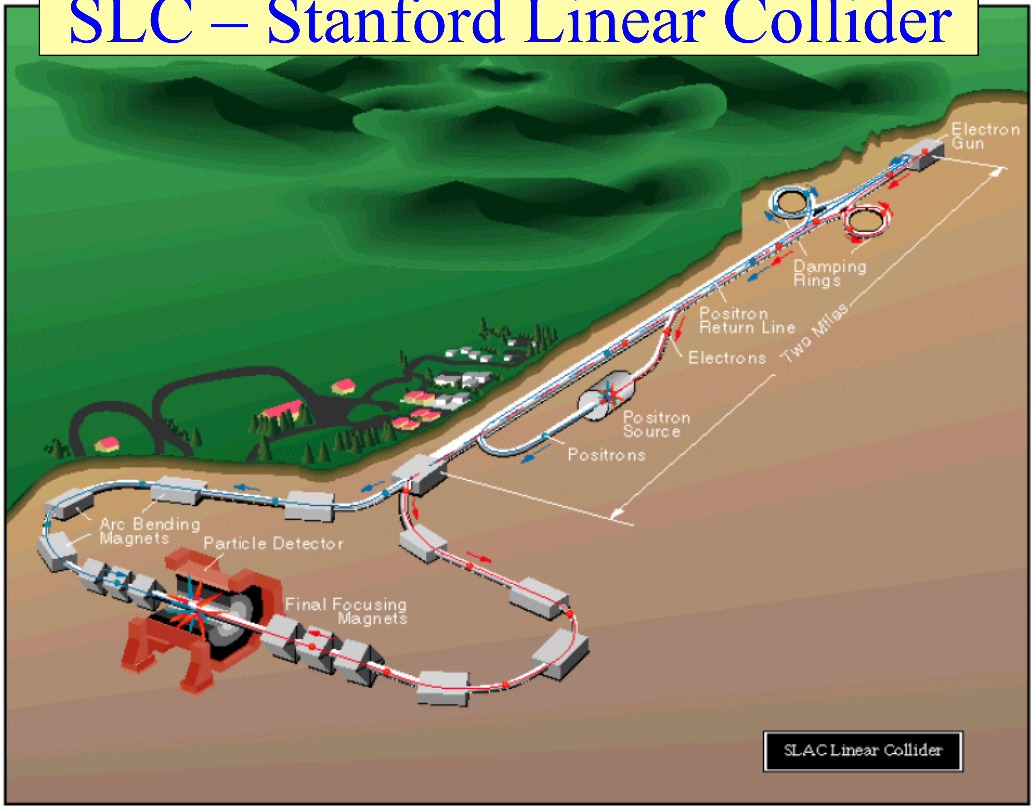
Generic Linear Collider

C.Pagani



First Linear Collider: SLC

SLC – Stanford Linear Collider



Built to study the Z^0 and demonstrate linear collider feasibility

Energy = 92 GeV
Luminosity = 2e30

Has all the features of a 2nd gen. LC except both e+ and e- used the same linac

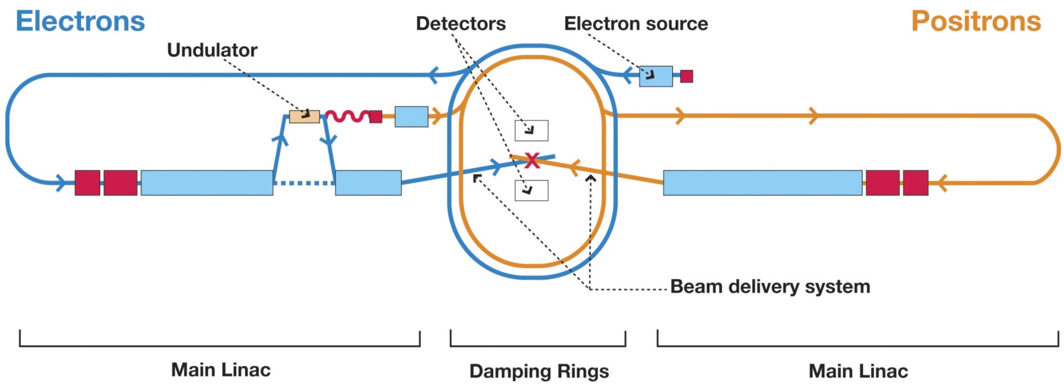
A 10% prototype!

T.Raubenheimer

Linear Collider projects

- ILC (International Linear Collider)
  - Technology decision Aug 2004
  - Superconducting RF technology
  - 1.3 GHz RF frequency
  - ~31 MV/m accelerating gradient
  - 500 GeV centre-of-mass energy
  - upgrade to 1 TeV possible
- CLIC (Compact Linear Collider)
  - normalconducting technology
  - multi-TeV energy range (nom. 3 TeV)

~35 km total length



Parameter comparison

	SLC	TESLA	ILC	J/NLC	CLIC
Technology	NC	Supercond.	Supercond.	NC	NC
Gradient [MeV/m]	20	25	31.5	50	100
CMS Energy E [GeV]	92	500-800	500-1000	500-1000	500-3000
RF frequency f [GHz]	2.8	1.3	1.3	11.4	12.0
Luminosity L [10^{33} cm^{-2}s^{-1}]	0.003	34	20	20	21
Beam power P_{beam} [MW]	0.035	11.3	10.8	6.9	5
Grid power P_{AC} [MW]		140	230	195	240
Bunch length σ_z^* [mm]	~1	0.3	0.3	0.11	0.03
Vert. emittance $\gamma\varepsilon_y$ [10^{-8}m]	300	3	4	4	2.5
Vert. beta function β_y^* [mm]	~1.5	0.4	0.4	0.11	0.1
Vert. beam size σ_y^* [nm]	650	5	5.7	3	2.3

Parameters (except SLC) at 500 GeV

ILC Global Design Effort

- ~700 contributors from 84 institutes in the RDR
- Web site: www.linearcollider.org


ILC-REPORT-2007-01
AAI-PUB-2007-002
CHEP A07-001 (CHEP/KNU)
CLNS 07/1991
Cockcroft-07-04
DESY 07-046
FERMILAB-TM-2382-AD-CD-DO-E-FESS-TD
JAI-2007-001
JINR Dubna-E9-2007-39
JLAB-R-2007-01
KEK Report 2007-1
LNF-07/9(NT)
SLAC-R-857

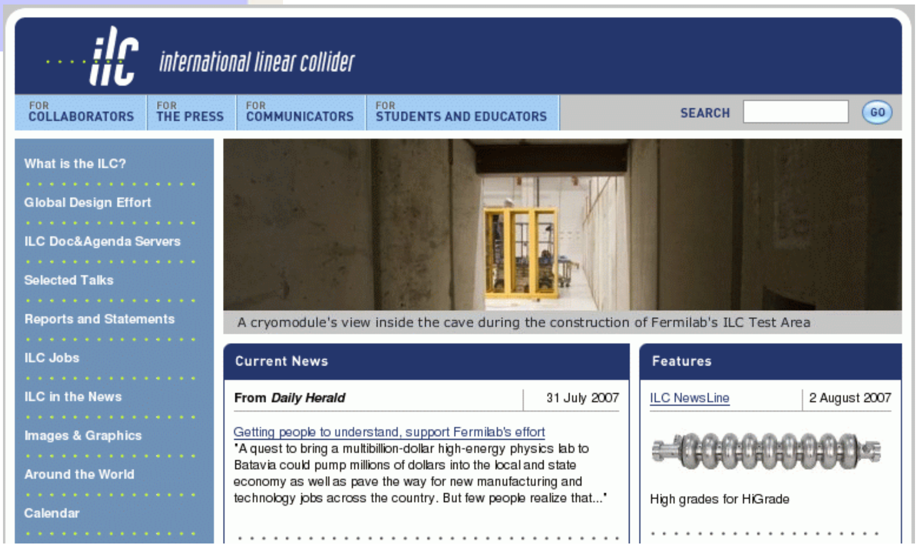
DRAFT

INTERNATIONAL LINEAR COLLIDER

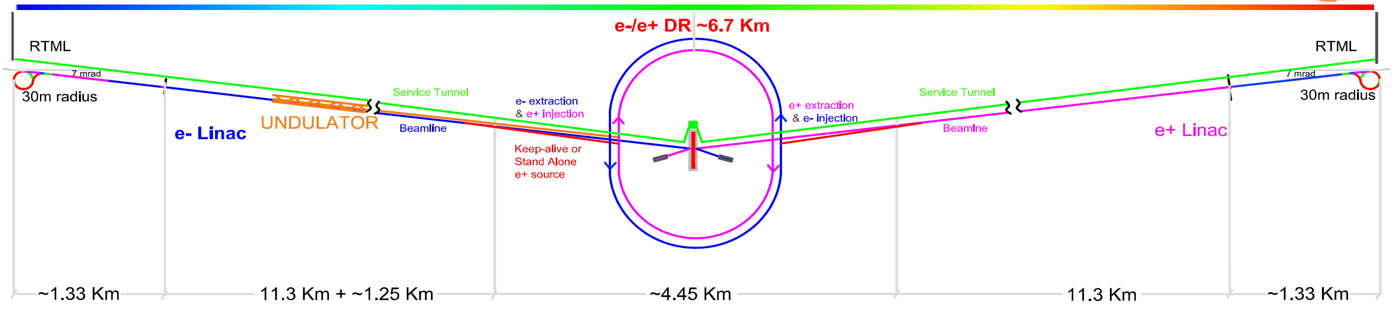
REFERENCE DESIGN REPORT

2007

APRIL, 2007

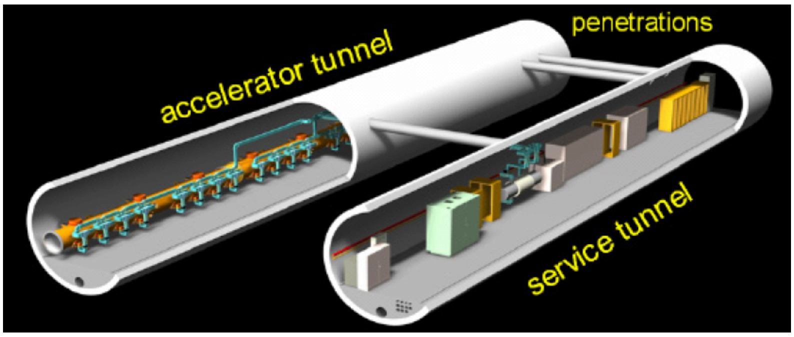


ILC Schematic



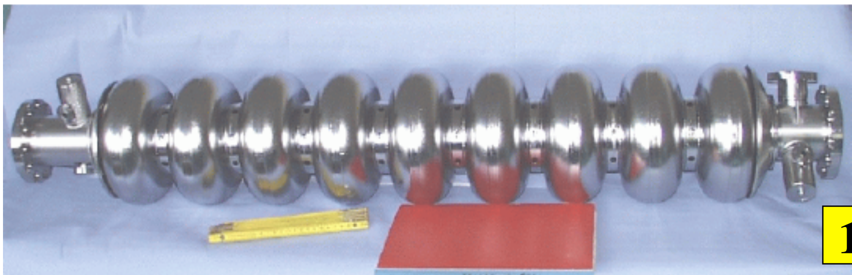
Schematic Layout of the 500 GeV Machine

- Two 250 Gev linacs arranged to produce nearly head on e+e- collisions
  - Single IR with 14 mrad crossing angle
- Centralized injector
  - Circular 6.5/3.2 km damping rings
  - Undulator-based positron source
- Dual tunnel configuration for safety and availability (single tunnel recently)



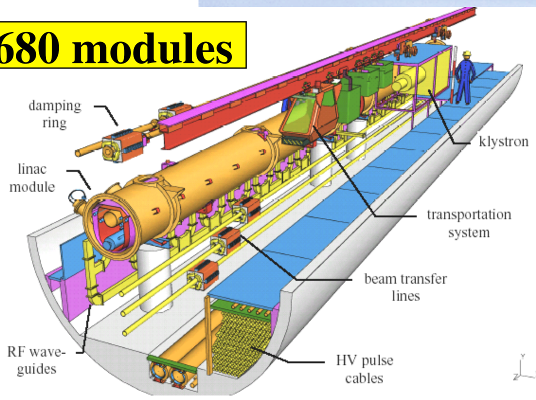
ILC Super-conducting technology

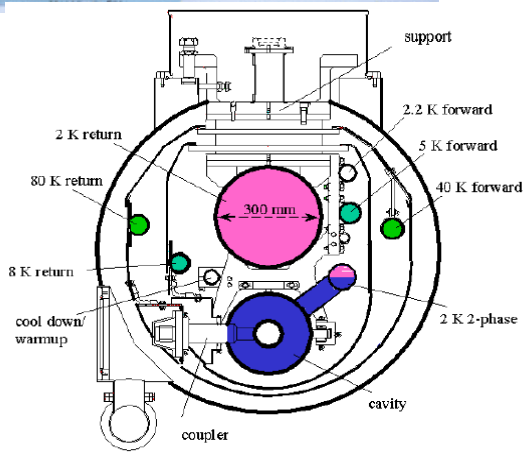
The core technology for the ILC is 1.3GHz superconducting RF cavity intensely developed in the TESLA collaboration, and recommended for the ILC by the ITRP on 2004 August.
The cavities are installed in a long cryostat cooled at 2K, and operated at gradient 31.5MV/m.



14560 cavities

1680 modules

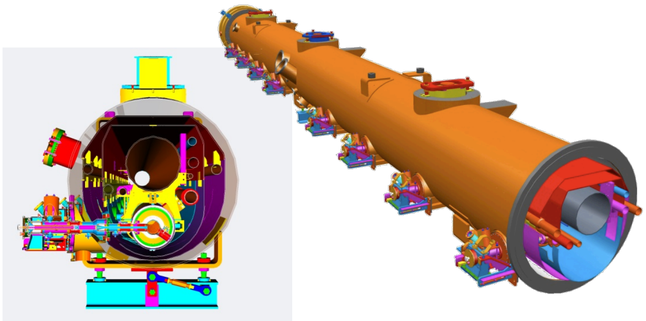




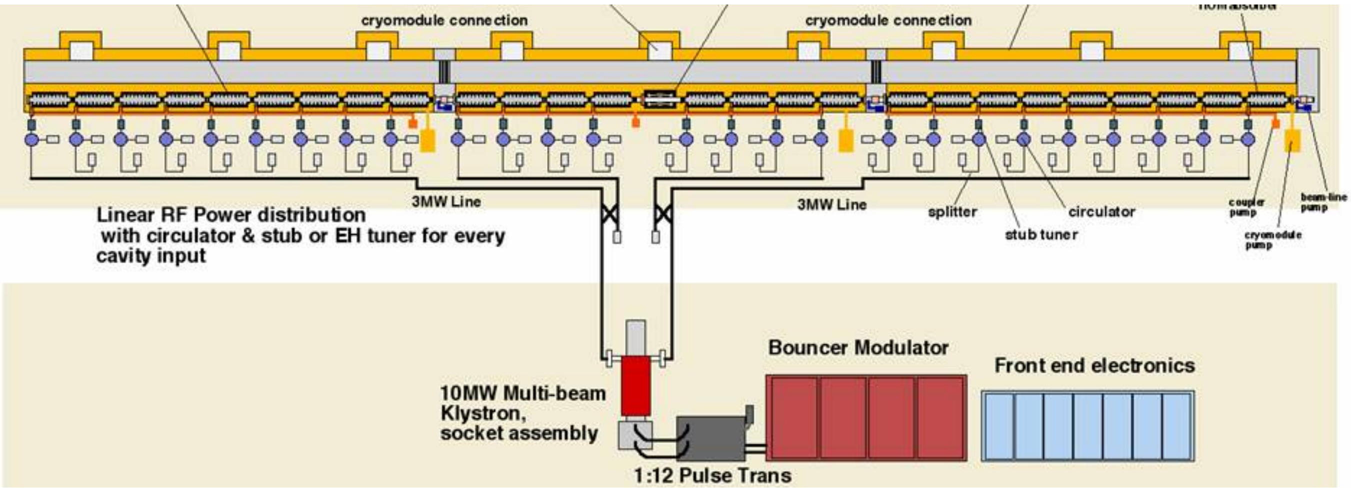
ILC Main Linac RF Unit

560 RF units each one composed of:

- **1 Bouncer type modulator**
- **1 Multibeam klystron (10 MW, 1.6 ms)**
- **3 Cryostats (9+8+9 = 26 cavities)**
- **1 Quadrupole at the center**

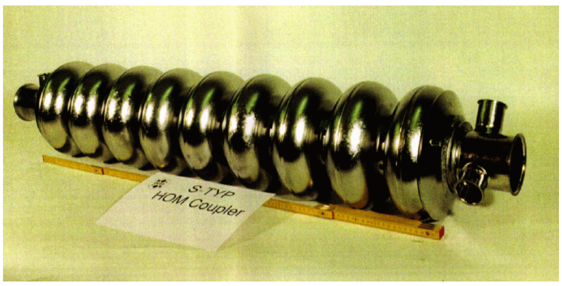


Total of 1680 cryomodules and 14 560 SC RF cavities



SC Technology

- In the past, SC gradient typically 5 MV/m and expensive cryogenic equipment
- TESLA development: new material specs, new cleaning and fabrication techniques, new processing techniques
- Significant cost reduction
- Gradient substantially increased
- Electropolishing technique has reached ~35 MV/m in 9-cell cavities
- Still requires essential work
- 31.5 MV/m ILC baseline



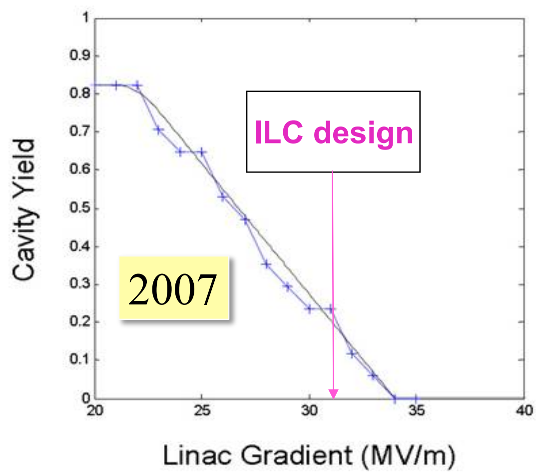
Chemical polish

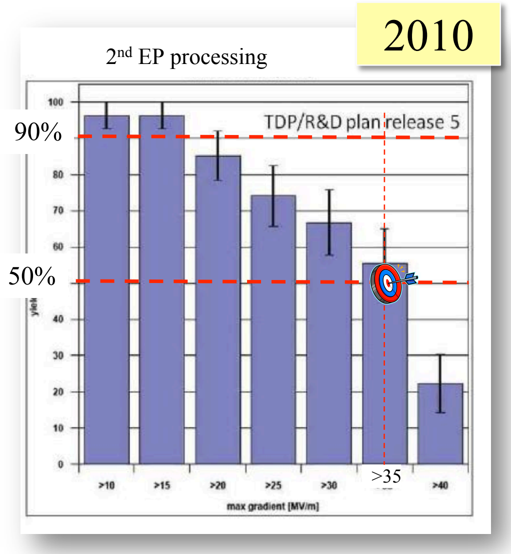
=>

Electropolishing

Achieved SC accelerating gradients

- Recent progress by R&D program to systematically understand and set procedures for the production process
- reached goal for a 50% yield at 35 MV/m by the end of 2010
- 90% yield foreseen later



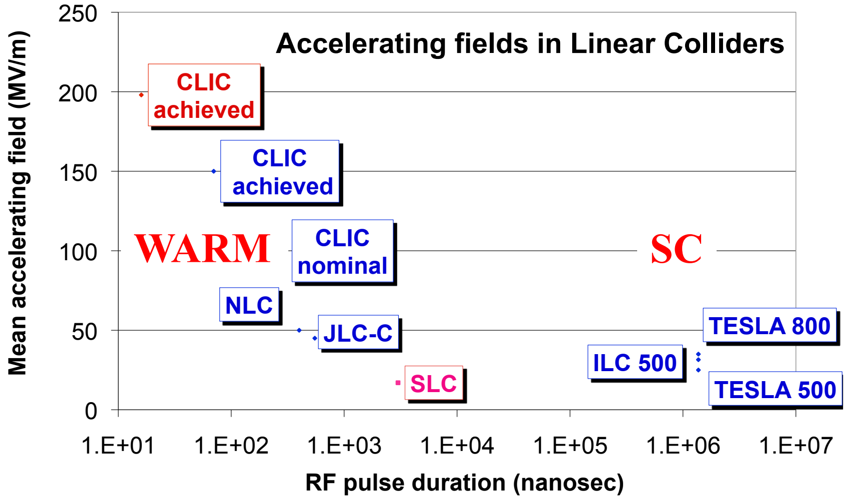


Nick Walker

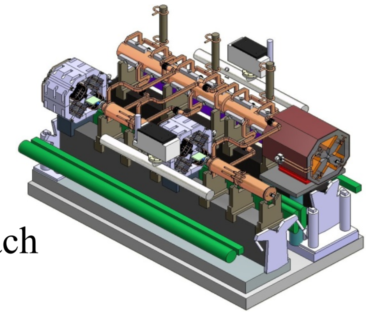
Accelerating gradient

- Superconducting cavities:
  fundamentally limited in gradient by critical magnetic field
  => become normal conducting above
- Normal conducting cavities:
  limited in pulse length + gradient by
  - "Pulsed surface heating" => can lead to fatigue
  - RF breakdowns (sparks, field collapses => no acceleration, deflection of beam)

- Normal conducting cavities:
  higher gradient with shorter RF pulse length
- Superconducting cavities:
  lower gradient with long RF pulse



Multi-TeV: the CLIC Study



- Develop technology for linear e+/e- collider with the requirements:
  - E_{cm} should cover range from ILC to LHC maximum reach and beyond => E_{cm} = 0.5 – 3 TeV
  - Luminosity > few 10^{34} cm^{-2} with acceptable background and energy spread
    - E_{cm} and L to be reviewed once LHC results are available
  - Design compatible with maximum length ~ 50 km
  - Affordable
  - Total power consumption < 500 MW
- Present goal: Demonstrate all key feasibility issues and document in a CDR by 2011

World-wide CLIC&CTF3 Collaboration

ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETHZurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)

Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)

John Adams Institute/RHUL (UK)
JINR (Russia)
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NIKHEF/Amsterdam (Netherland)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)

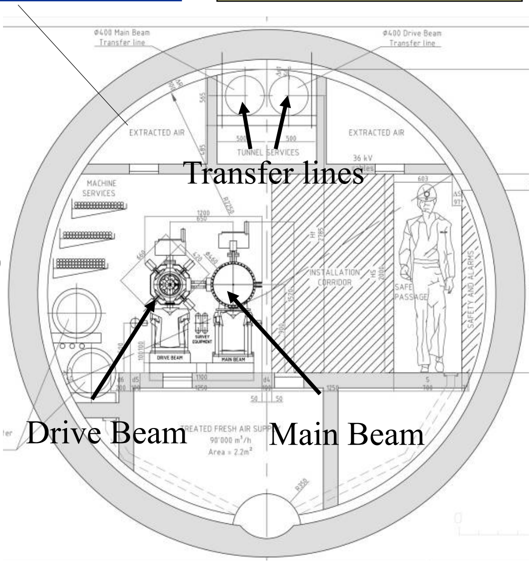
Polytech. University of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
Uppsala University (Sweden)
UCSC SCIPP (USA)

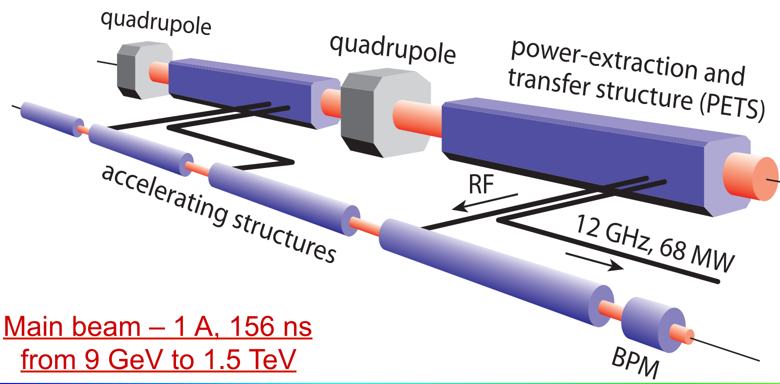
CLIC – basic features

- High acceleration gradient
  - "Compact" collider – total length < 50 km
  - Normal conducting acceleration structures
  - High acceleration frequency (12 GHz)
- Two-Beam Acceleration Scheme
  - High charge Drive Beam (low energy)
  - Low charge Main Beam (high collision energy)
  - => Simple tunnel, no active elements
  - => Modular, easy energy upgrade in stages

CLIC TUNNEL CROSS-SECTION

4.5 m diameter



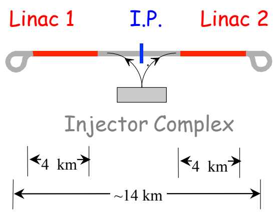


Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

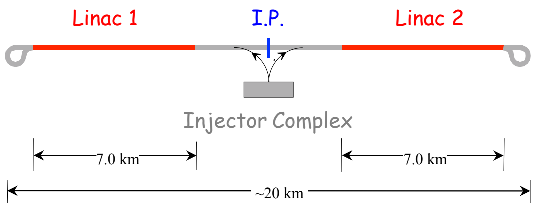
Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

CLIC Layout at various energies

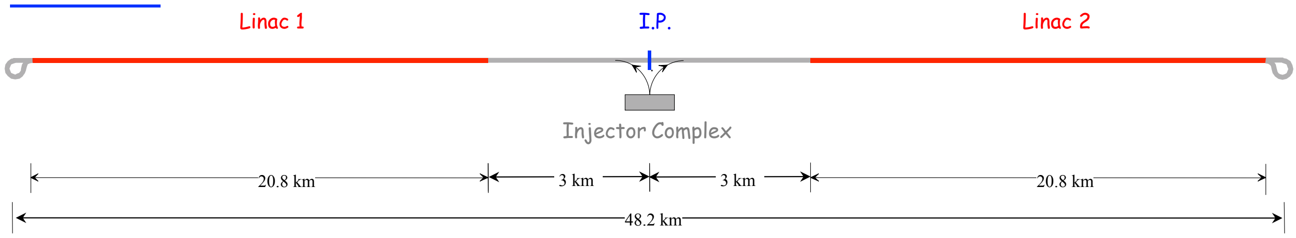
0.5 TeV Stage



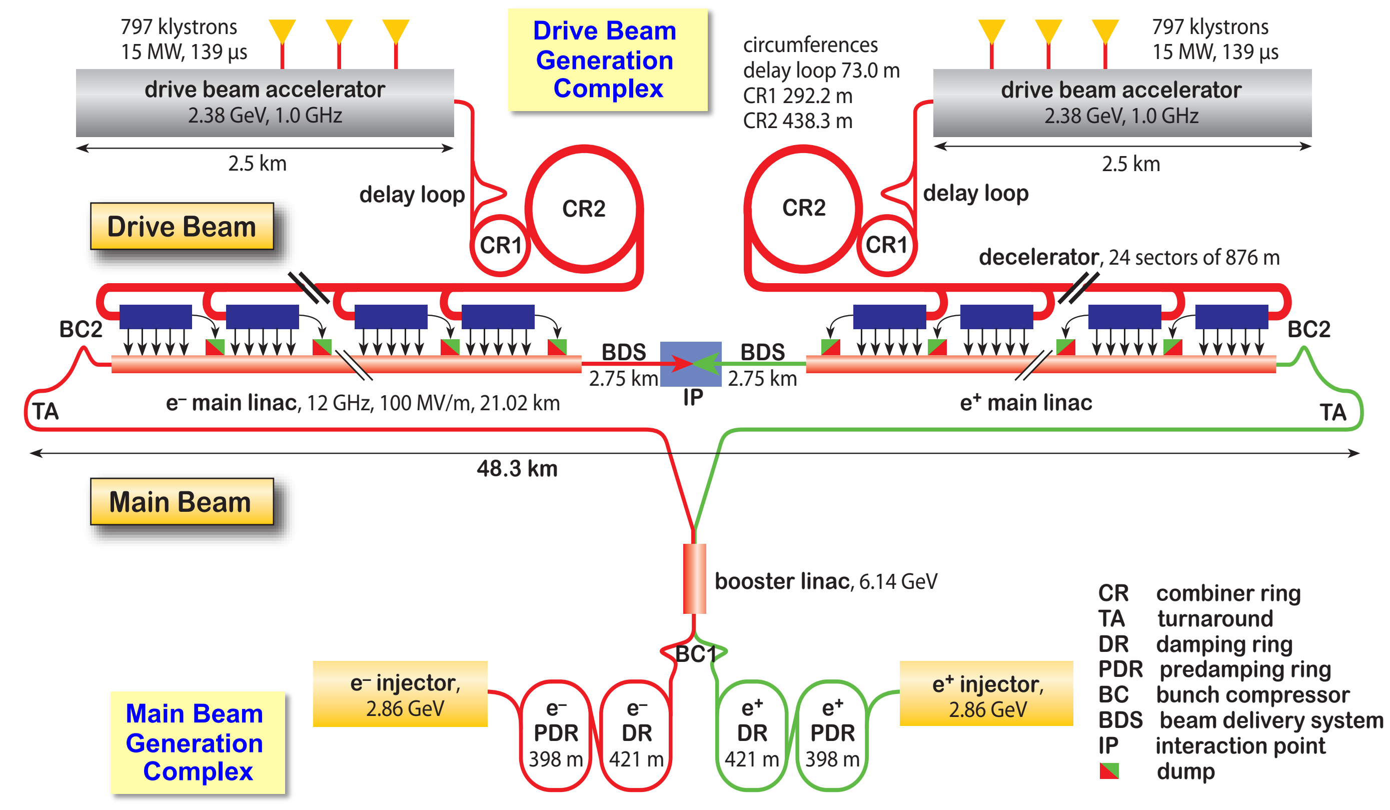
1 TeV Stage



3 TeV Stage



CLIC – overall layout 3 TeV

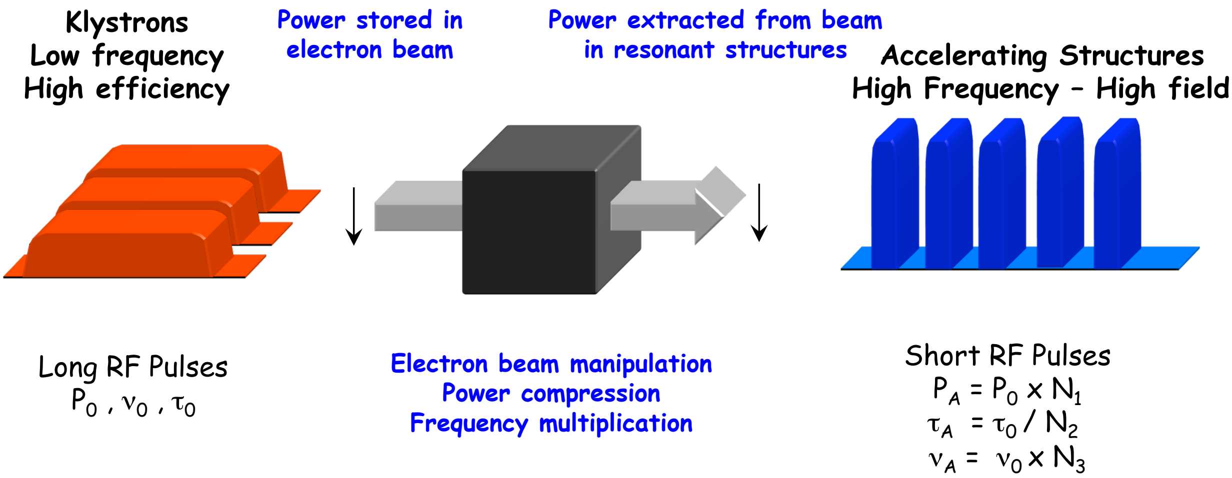


CLIC main parameters

Center-of-mass energy	3 TeV
Peak Luminosity	$6 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	42 km
Bunch charge	$3.7 \cdot 10^{9}$
Beam pulse length	156 ns
Average current in pulse	1 A
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size before pinch	45 / ~1 nm
Total site length	48.3 km
Total power consumption	415 MW

CLIC drive beam scheme

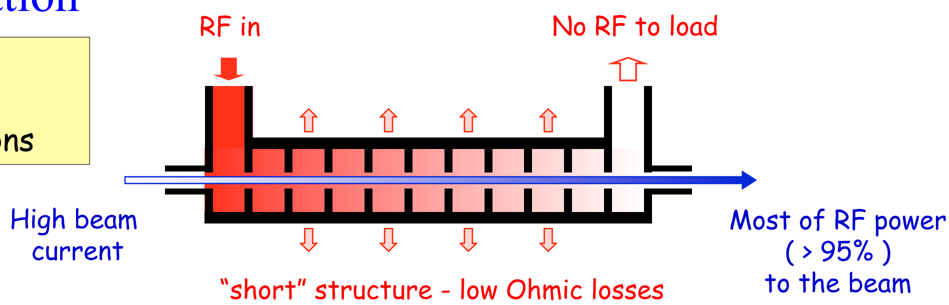
- Very high gradients possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz) and short RF pulses (~100 ns)
- Extract required high RF power from an intense e- “drive beam”
- Generate efficiently long beam pulse and compress it (in power + frequency)



Drive beam generation basics

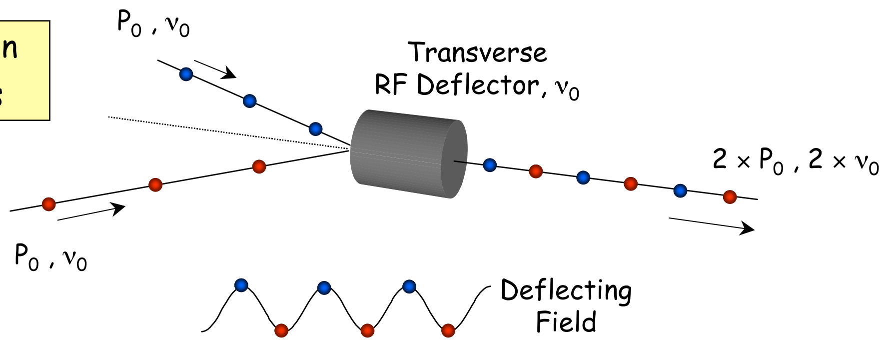
- Efficient acceleration

Full beam-loading acceleration in traveling wave sections

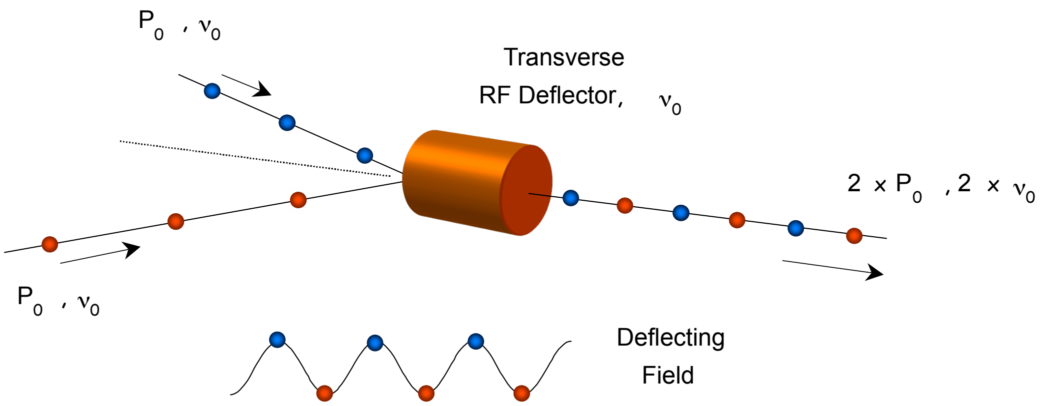


- Frequency multiplication

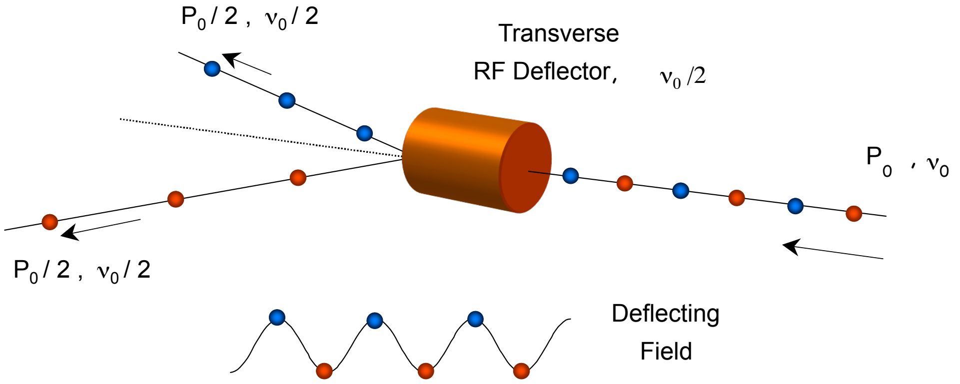
Beam combination/separation by transverse RF deflectors



Beam combination by RF deflectors

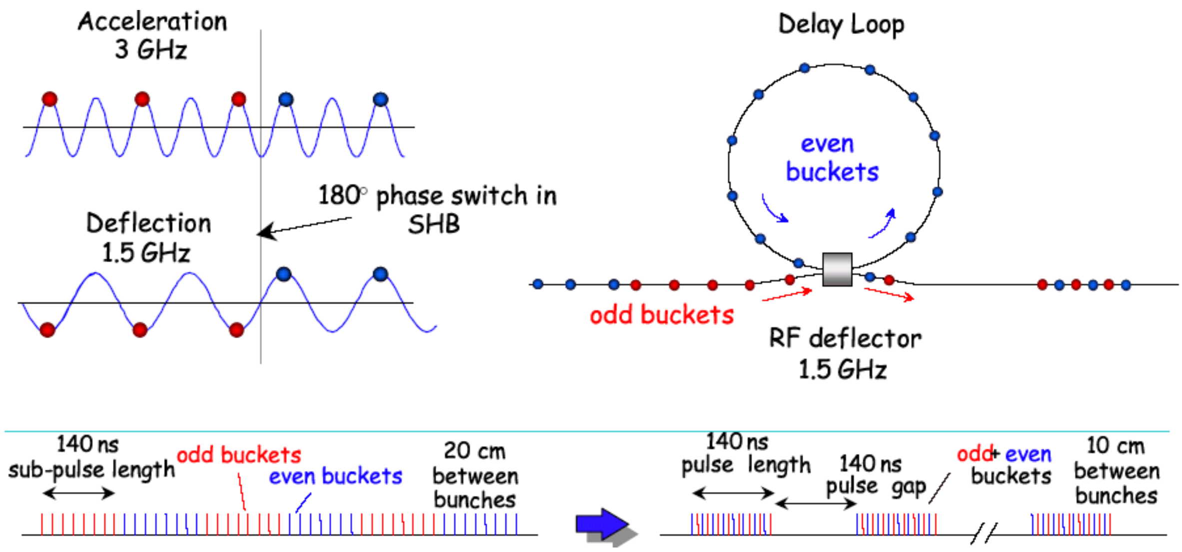


Beam separation by RF deflectors



Delay Loop Principle

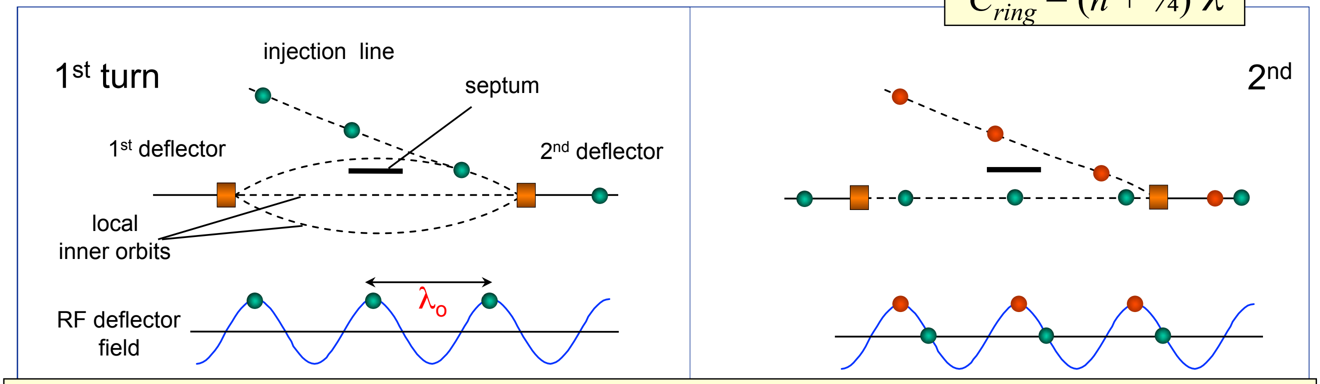
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches



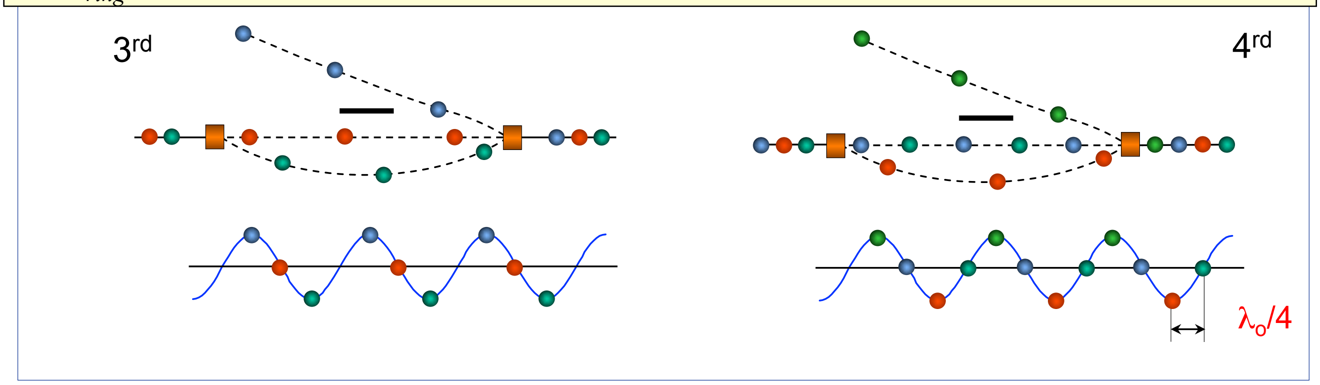
RF injection in combiner ring (factor 4)

- combination factors up to 5 reachable in a ring

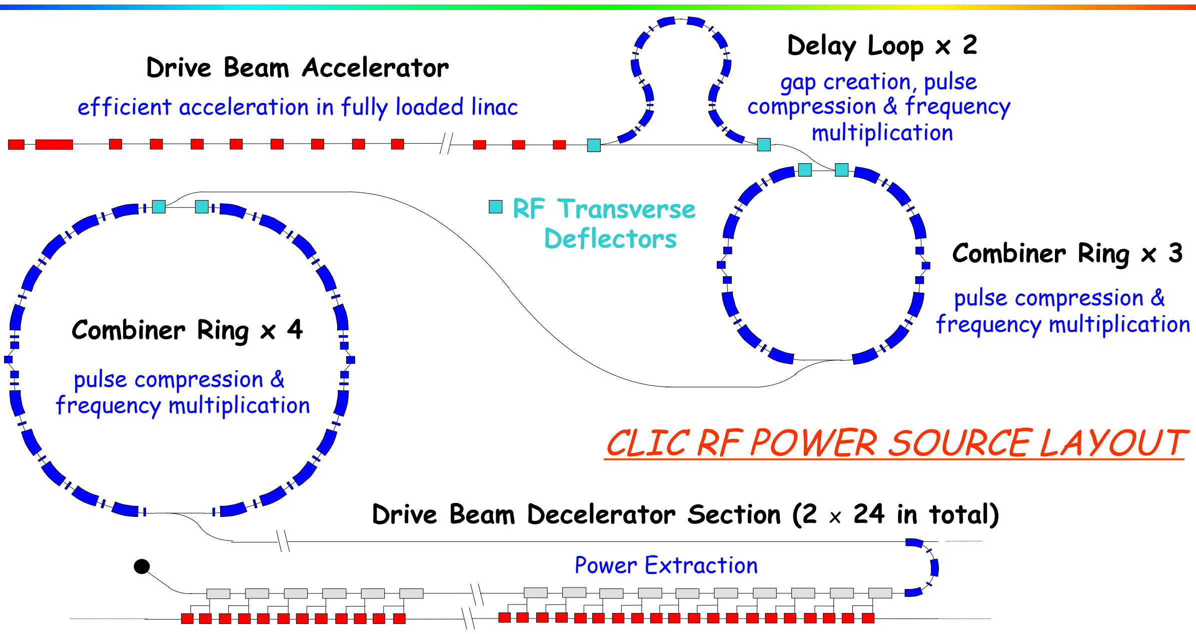
$C_{ring} = (n + ¼)\ \lambda$

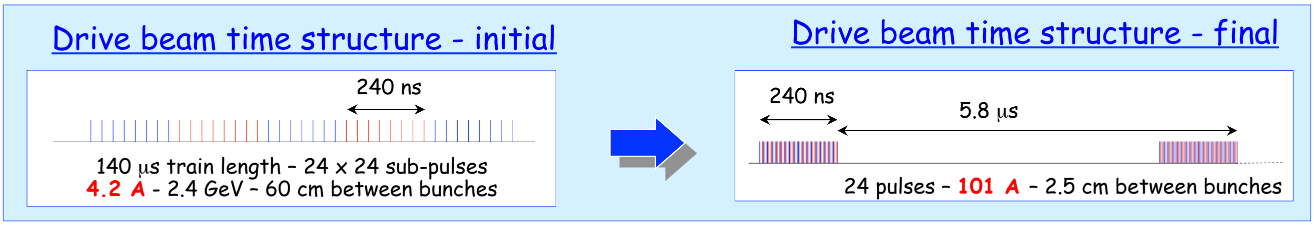


C_{ring} has to correspond to the distance of pulses from the previous combination stage!



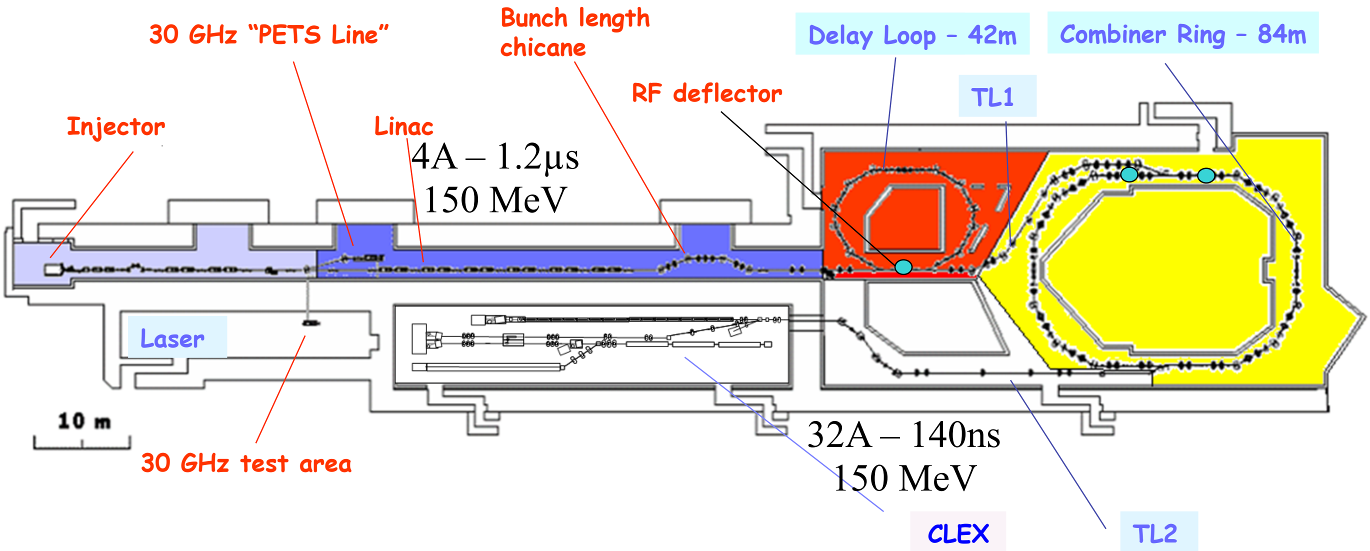
CLIC Drive Beam generation



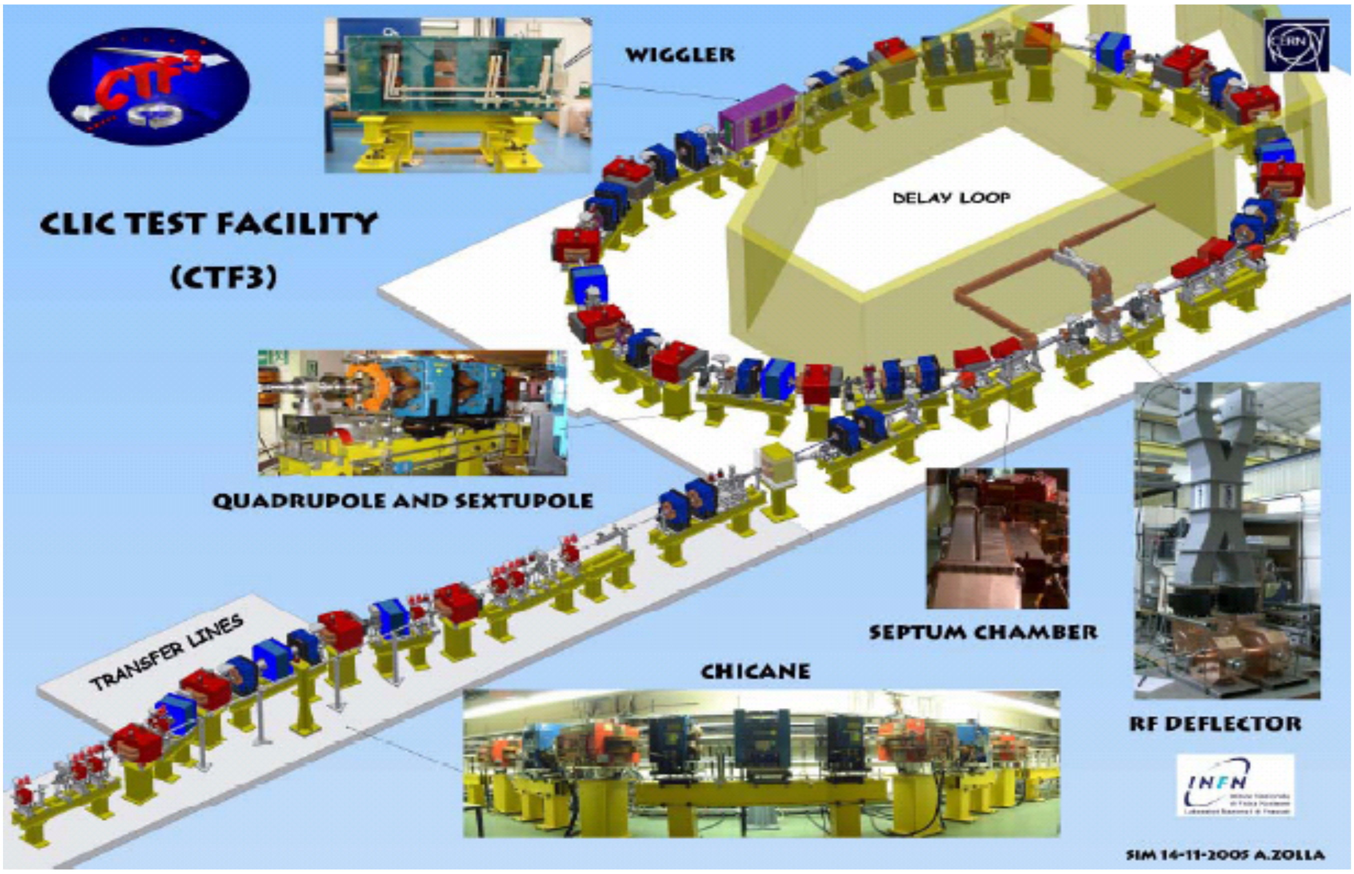


CTF 3

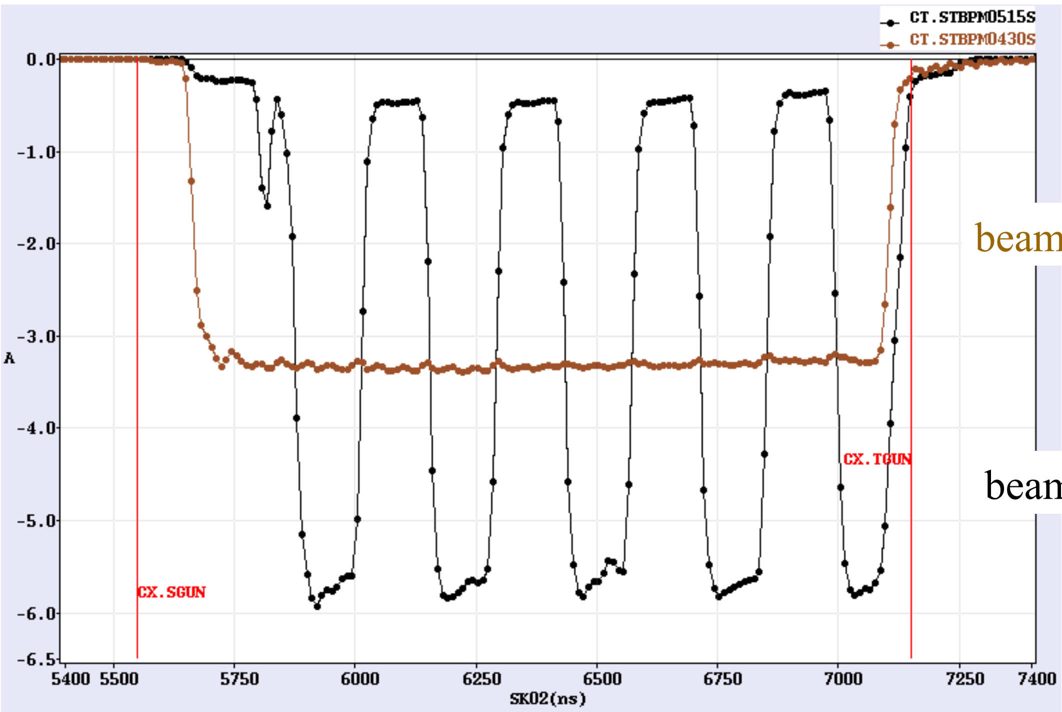
- demonstrate Drive Beam generation
  (fully loaded acceleration, bunch frequency multiplication 8x)
- Test CLIC accelerating structures
- Test power production structures (PETS)



CTF3 Delay Loop



Delay Loop – full recombination



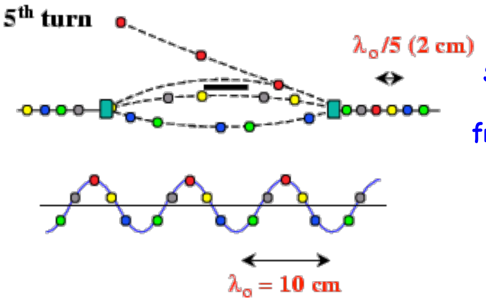
beam before the DL

beam after the DL

- 3.3 A after chicane => < 6 A after combination (satellites) demonstrated in CTF3

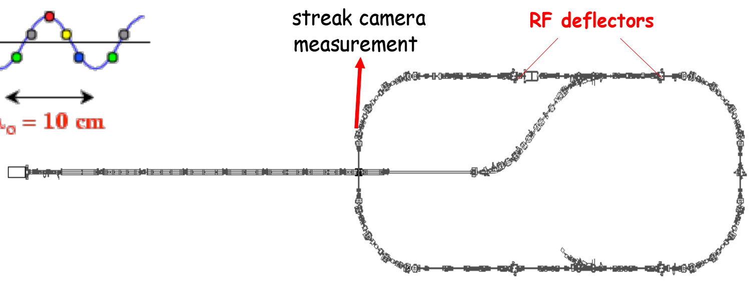
Demonstration of frequency multiplication

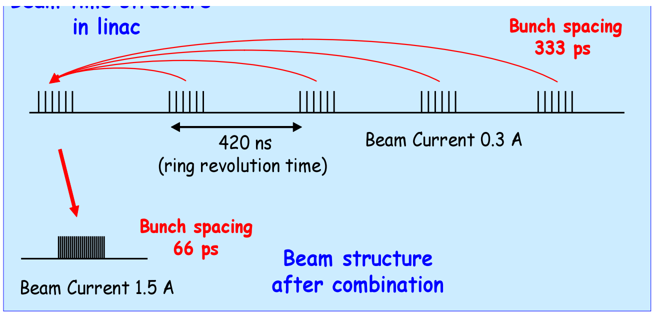
Combination factor 5



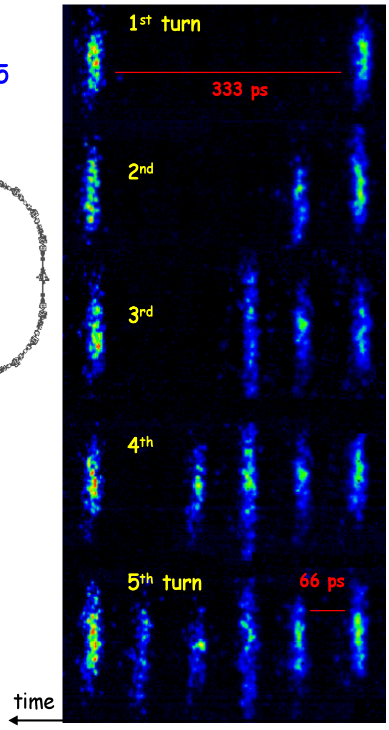
CTF3 - PRELIMINARY PHASE 2001/2002

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





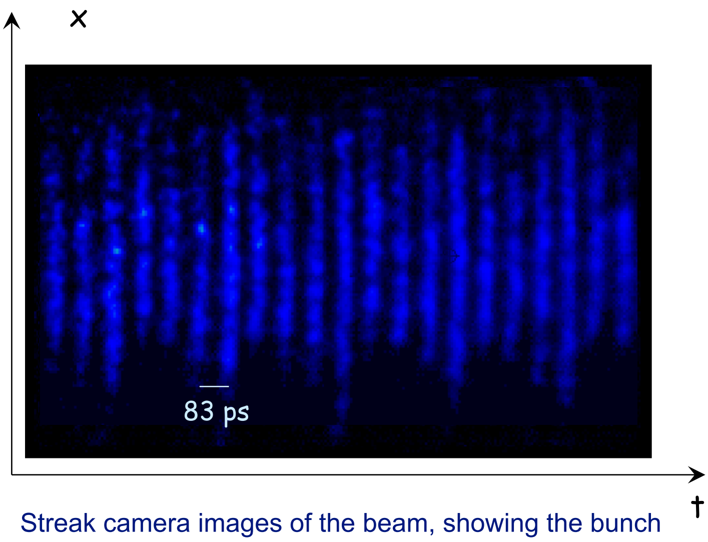
Streak camera image of beam time structure evolution



CTF3 preliminary phase (2001-2002)

RF injection in combiner ring

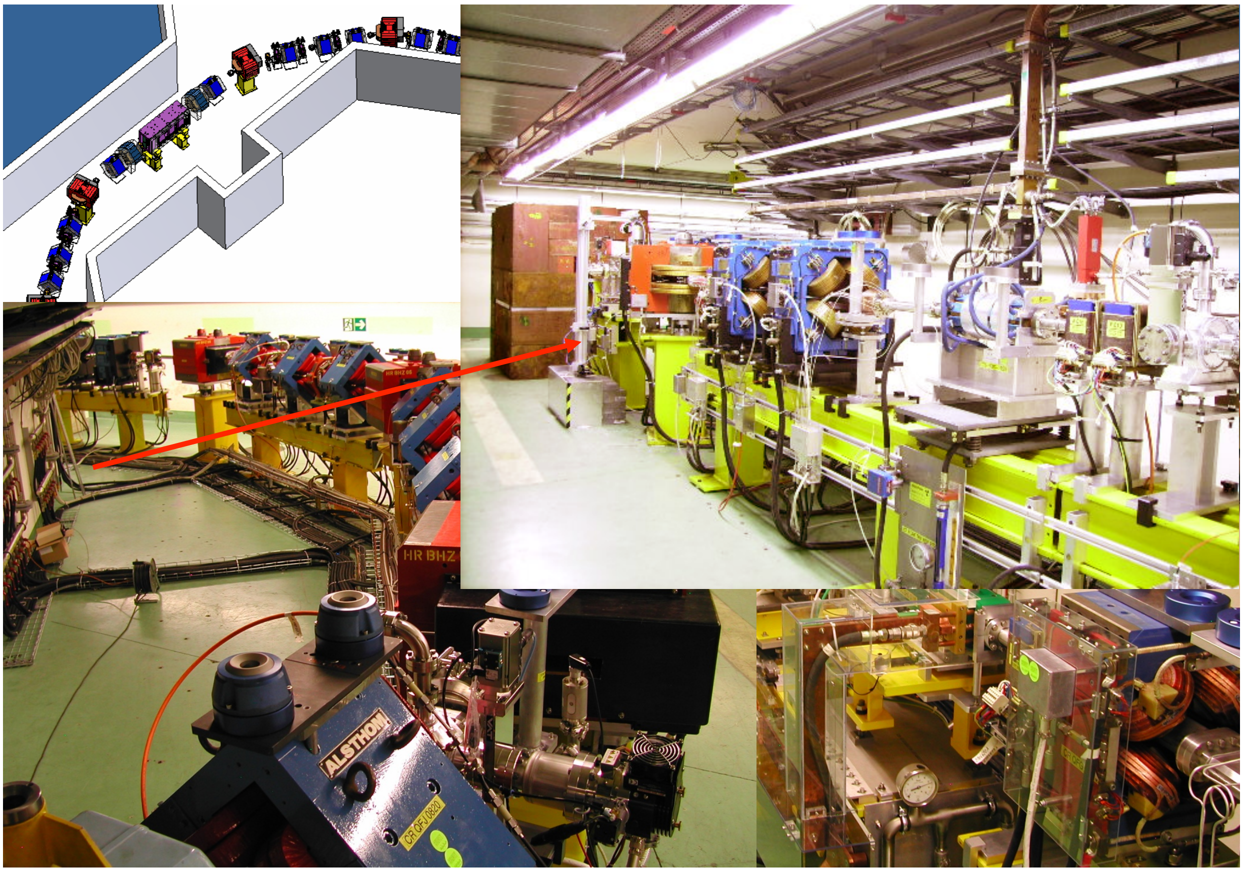
Combination factor 4



Streak camera images of the beam, showing the bunch combination process

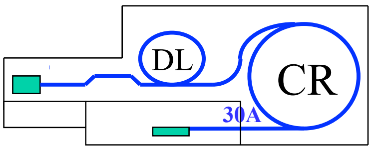
A first ring combination test was performed in 2002, *at low current and short pulse*, in the CERN Electron-Positron Accumulator (EPA), properly modified

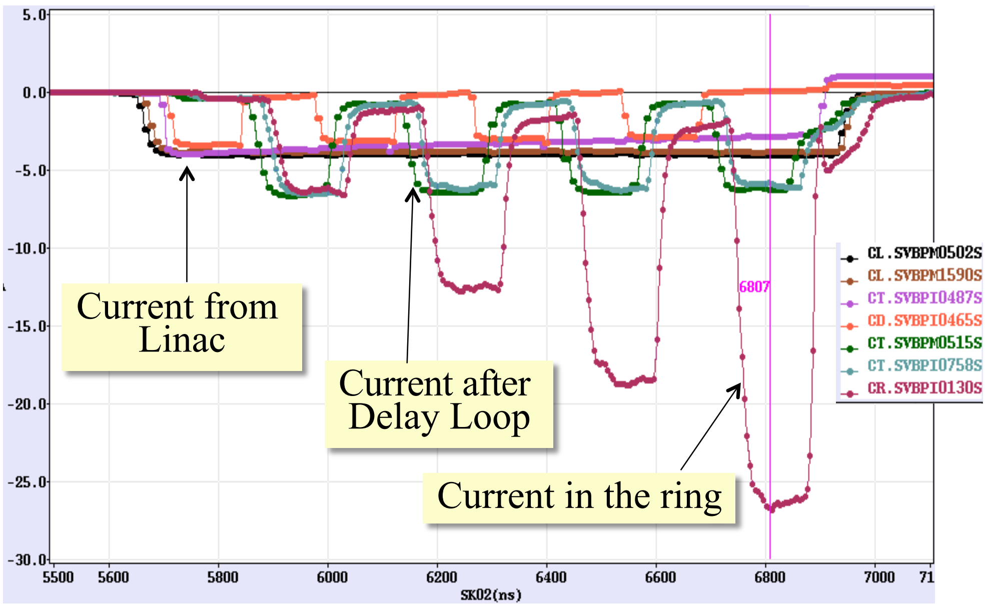
CTF3 combiner ring



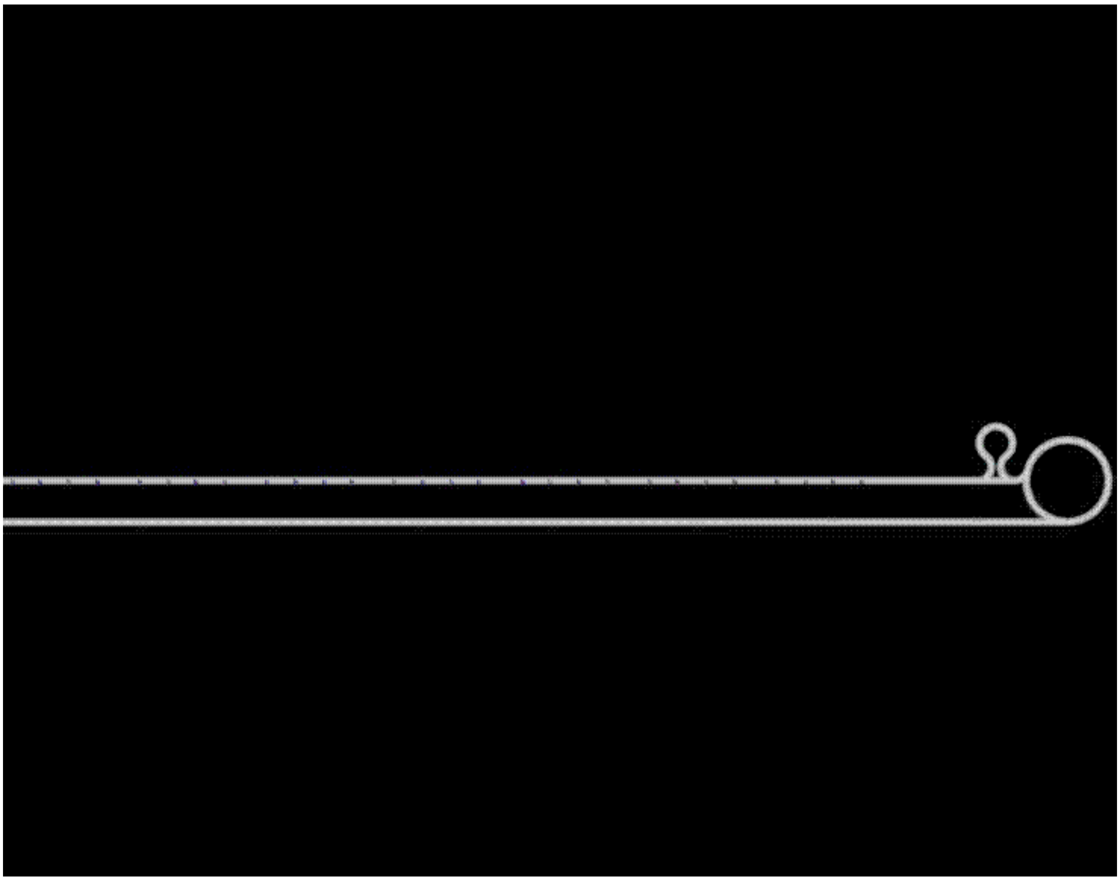
Factor 8 combination (DL+CR)

- combined operation of Delay Loop and Combiner Ring (factor 8 combination)
- ~26 A combination reached, nominal 140 ns pulse length
- => **Full drive beam generation achieved** (in 2009)





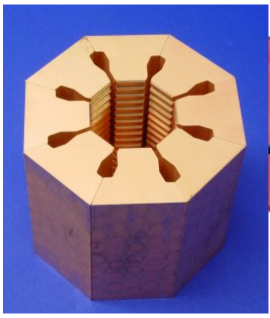
Lemmings Drive Beam

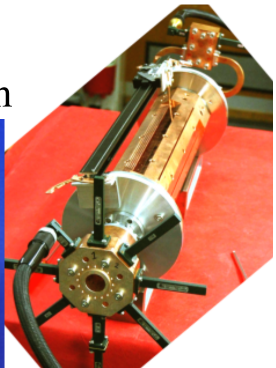


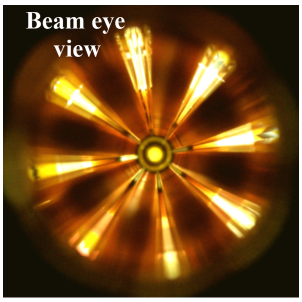
Alexandra Andersson

Power extraction structure PETS

- must extract efficiently >100 MW power from high current drive beam
- passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power
- periodically corrugated structure with low impedance (big a/λ)
- ON/OFF mechanism







The power produced by the bunched (ω_0) beam in a constant impedance structure:

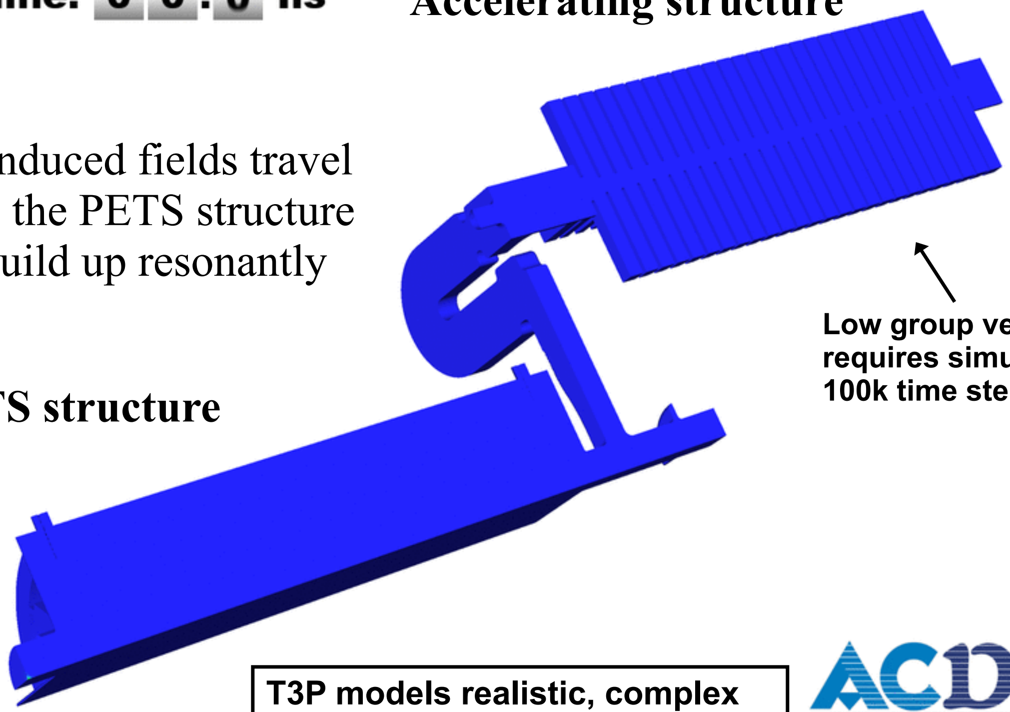
Design input parameters → PETS design

$$P = I^2 L^2 F_b^{\,2} \omega_0 \frac{R/Q}{V_g 4}$$

P - RF power, determined by the accelerating structure needs and the module layout.
I - Drive beam current
L - Active length of the PETS
F_b - single bunch form factor (≈ 1)

Simulation of RF Power Transfer

time: 0 0.0 ns



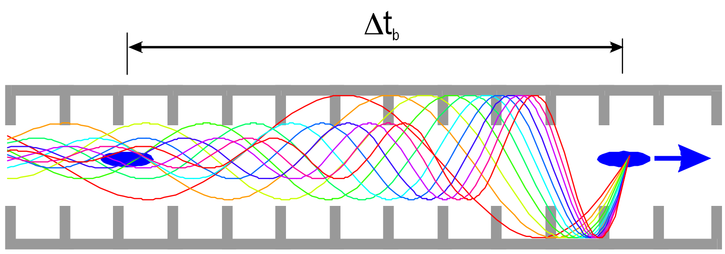
- The induced fields travel along the PETS structure and build up resonantly

T3P models realistic, complex accelerator structures with unprecedented accuracy

ACD ADVANCED COMPUTATIONS

Arno Candel, SLAC

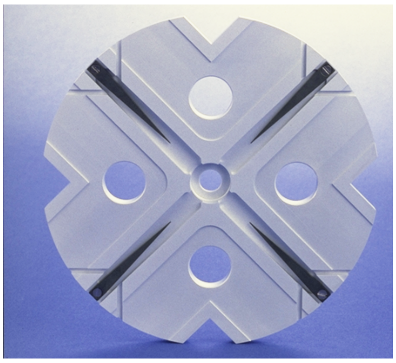
RF structures: transverse wakefields

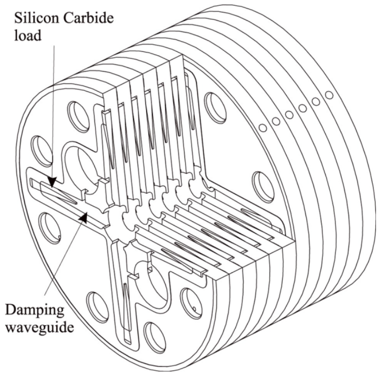


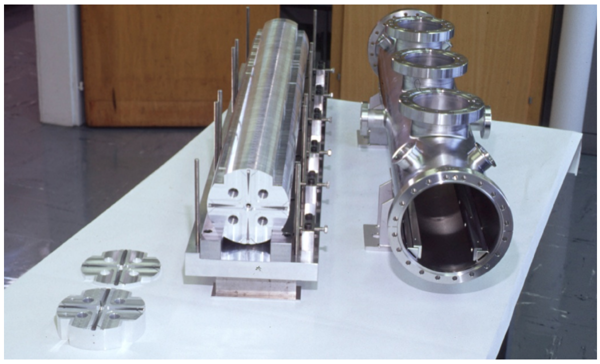
- Bunches induce wakefields in the accelerating cavities
- Later bunches are perturbed by the Higher Order Modes (HOM)
- Can lead to emittance growth and instabilities!!!

- Effect depends on a/λ (a iris aperture) and structure design details
- transverse wakefields roughly scale as $W_\perp \sim f^3$
- less important for lower frequency:
  Super-Conducting (SW) cavities suffer less from wakefields
- Long-range wakefields minimised by structure design

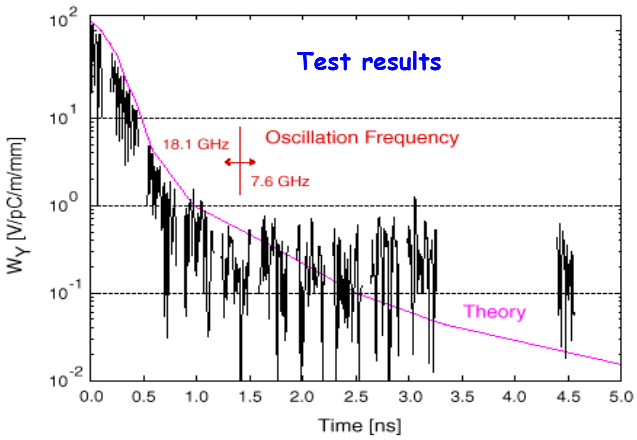
Accelerating structure developments





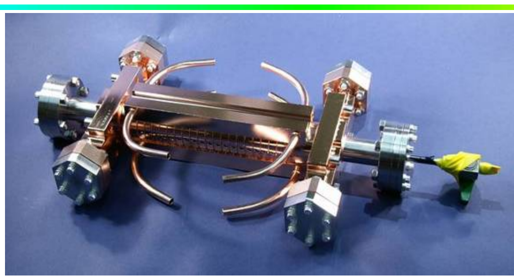


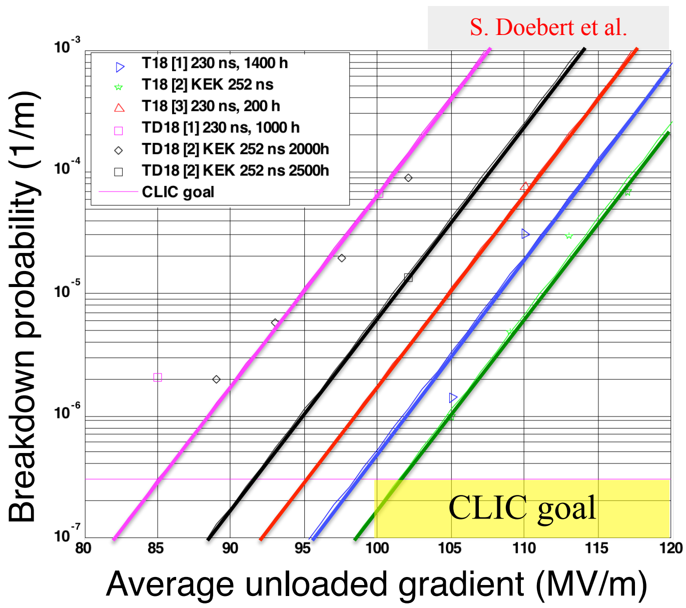
- Structures built from discs
- Slight detuning between cells makes HOMs decohere quickly
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- HOM enter WG
- Long-range wakefields efficiently damped



Accelerating Structure Results

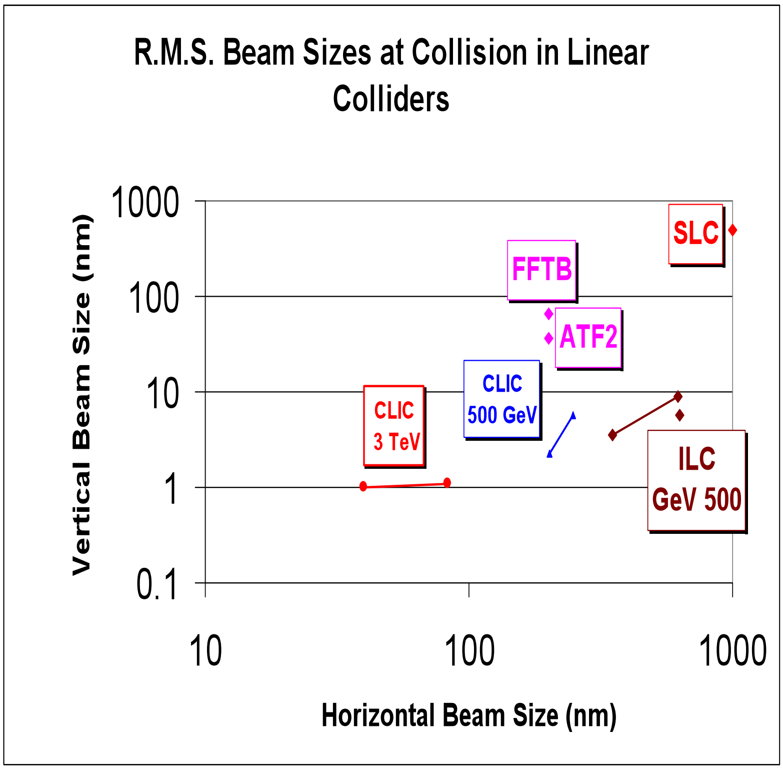
- RF breakdowns can occur => no acceleration and deflection
- Goal: 3 10^{-7}/m breakdowns at 100 MV/m loaded at 230 ns
- structures tested at SLAC and KEK
- => exceeded 100 MV/m at nominal CLIC breakdown rate
- Damped structure reaches an extrapolated 85MV/m
- CLIC prototypes with improved design (TD24) are being tested
- expect similar or slightly better performances





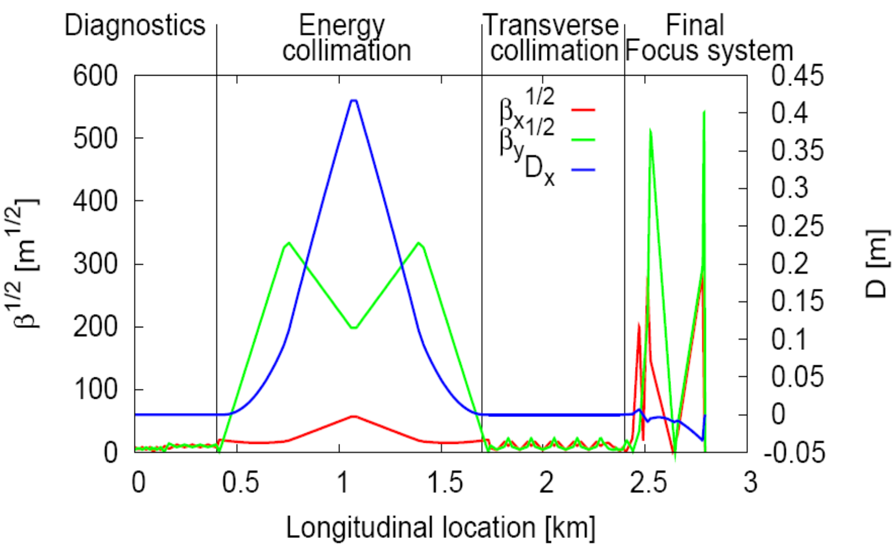
Crucial for luminosity: Emittance

- CLIC aims at smaller beam size than other designs
- Implications:
  - Generate small emittance in the Damping Rings
  - Transport the beam to the IP without significant blow-up
  - Wakefield control
  - Very good alignment
  - Precise intrumentation
  - Beam based corrections and feed-backs



Beam Delivery System

- reduce the beam size to a few x a few tens of nanometers
- many common issues for ILC and CLIC
- diagnostics, emittance measurement, energy measurement, …
- collimation, crab cavities, beam-beam feedback, beam extraction, beam dump



CONCLUSION

- World-wide Consensus for a Lepton Linear Collider as the next HEP facility to complement LHC at the energy frontier

- Presently two Linear Collider Projects:
  - International Linear Collider based on Super-Conducting RF technology with extensive R&D in world-wide collaboration:
    - First phase at 500 GeV beam collision energy, upgrade to 1 TeV
    - in Technical Design phase
  - CLIC technology only possible scheme to extend collider beam energy into Multi-TeV energy range
    - Very promising results but not mature yet, requires challenging R&D
    - CLIC-related key issues addressed in CTF3 by 2011

- Possible decision from 2012 based on LHC results
- Looking forward to get interesting LHC results

Documentation about ILC/CLIC

- Int. Linear Collider Workshop 2010 (most actual information) https://espace.cern.ch/LC2010
- General documentation about the ILC: http://linearcollider.org
- General documentation about the CLIC study: http://CLIC-study.org
- CLIC scheme description: http://preprints.cern.ch/yellowrep/2000/2000-008/p1.pdf
- CERN Bulletin article: http://cdsweb.cern.ch/journal/article?issue=28/2009&name=CERNBulletin&category=News%20Articles&number=1&ln=en
- CLIC Physics http://clicphysics.web.cern.ch/CLICphysics/
- CLIC Test Facility: CTF3 http://ctf3.home.cern.ch/ctf3/CTFindex.htm
- CLIC technological challenges (CERN Academic Training) http://indico.cern.ch/conferenceDisplay.py?confId=a057972
- CLIC ACE (advisory committee meeting) http://indico.cern.ch/conferenceDisplay.py?confId=115921
- CLIC meeting (parameter table) http://cern.ch/clic-meeting
- CLIC parameter note http://cern.ch/tecker/par2007.pdf
- CLIC notes http://cdsweb.cern.ch/collection/CLIC%20Notes