**JOINT ISTC-CERN-JINR SUMMER SCHOOL ON HIGH ENERGY PHYSICS AND ACCELERATOR PHYSICS**

# Frontier High Energy Accelerators

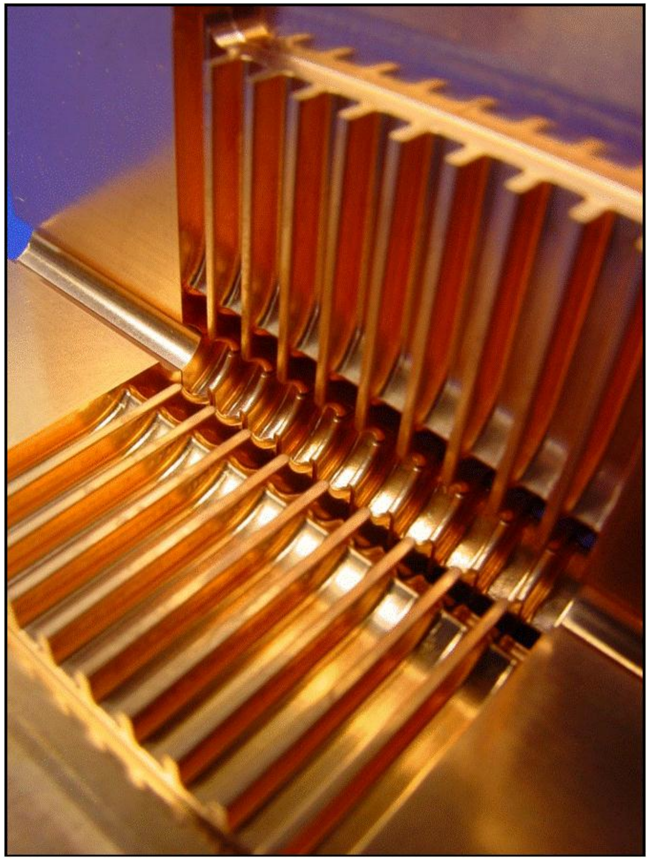
*Hermann Schmickler -CERN*

*Wednesday, 28th September 2011*

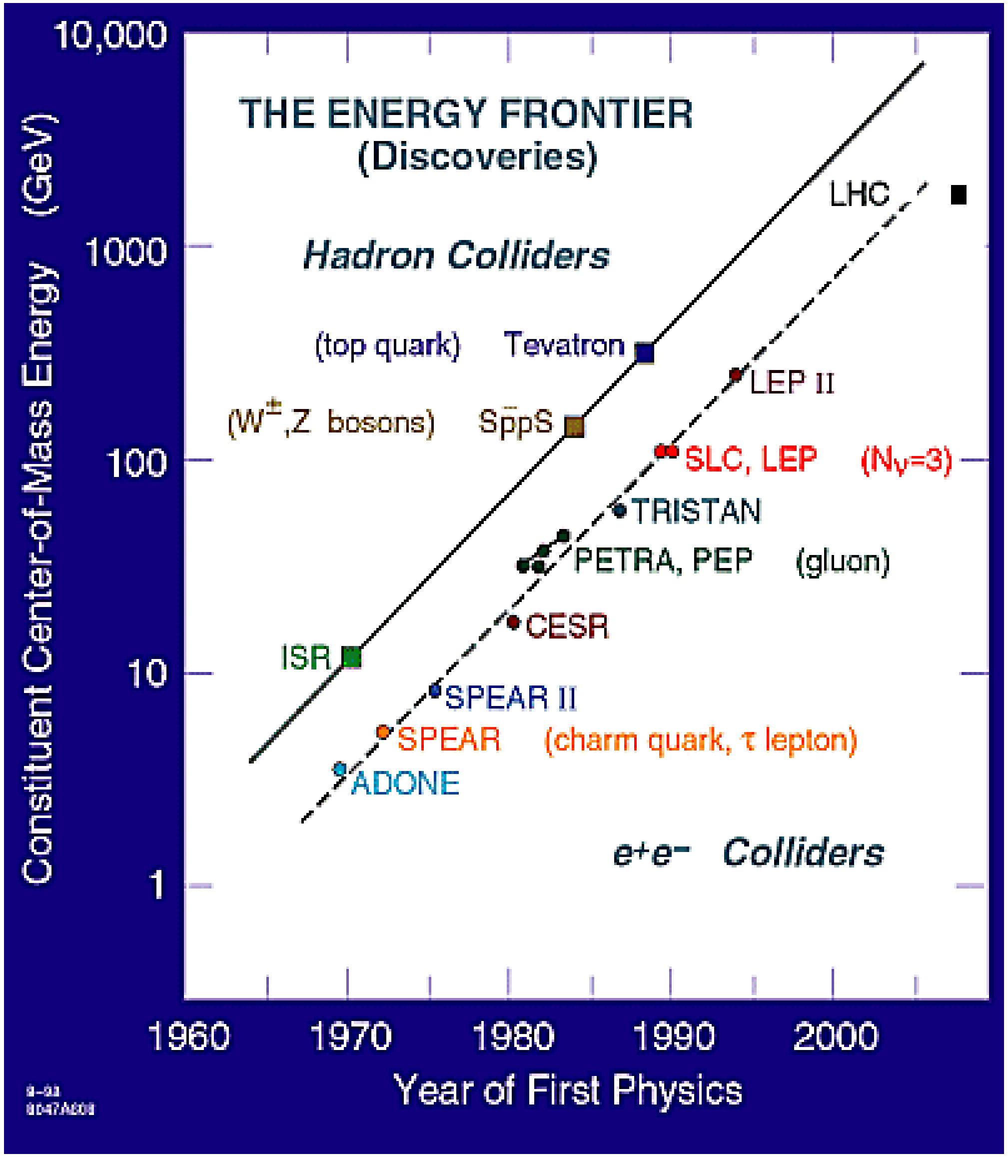
*CLIC- ILC*

# Future Linear Colliders

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



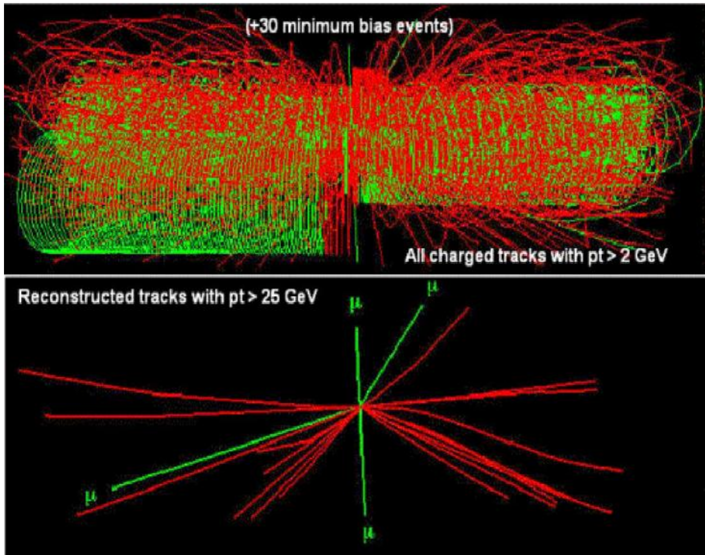
# Path to higher energy

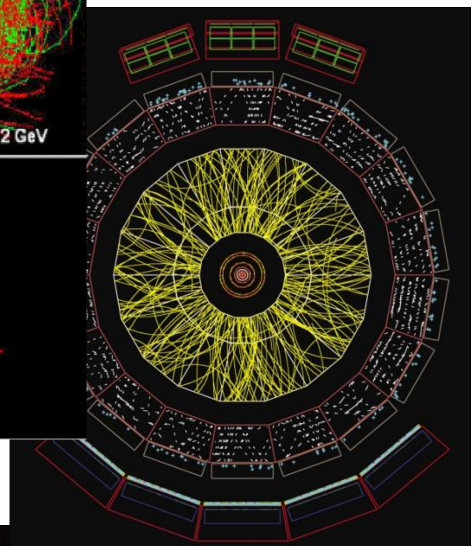



- History:
  - Energy constantly increasing with time
  - Hadron Collider at the energy frontier
  - Lepton Collider for precision physics
- LHC online now
- Consensus to build Lin. Collider with $E_{cm}$ > 500 GeV to complement LHC physics (*European strategy for particle physics* by CERN Council)

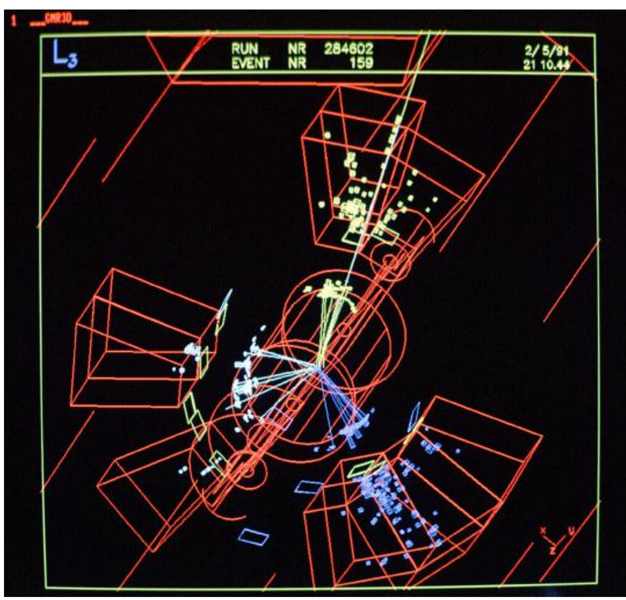
# Lepton vs. Hadron Collisions

LHC: H $\rightarrow$ ZZ $\rightarrow$ 4μ



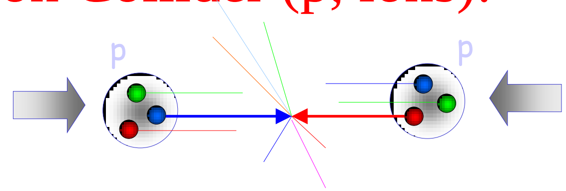



ALICE:
Ion event



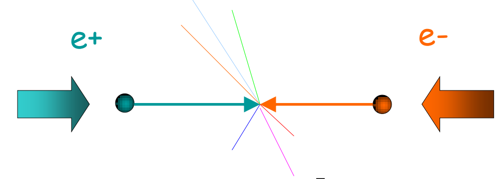

LEP event:
$Z^0 \rightarrow$ 3 jets

- Hadron Collider (p, ions):




  - Composite nature of protons
  - Can only use $p_t$ conservation
  - Huge QCD background

- Lepton Collider:



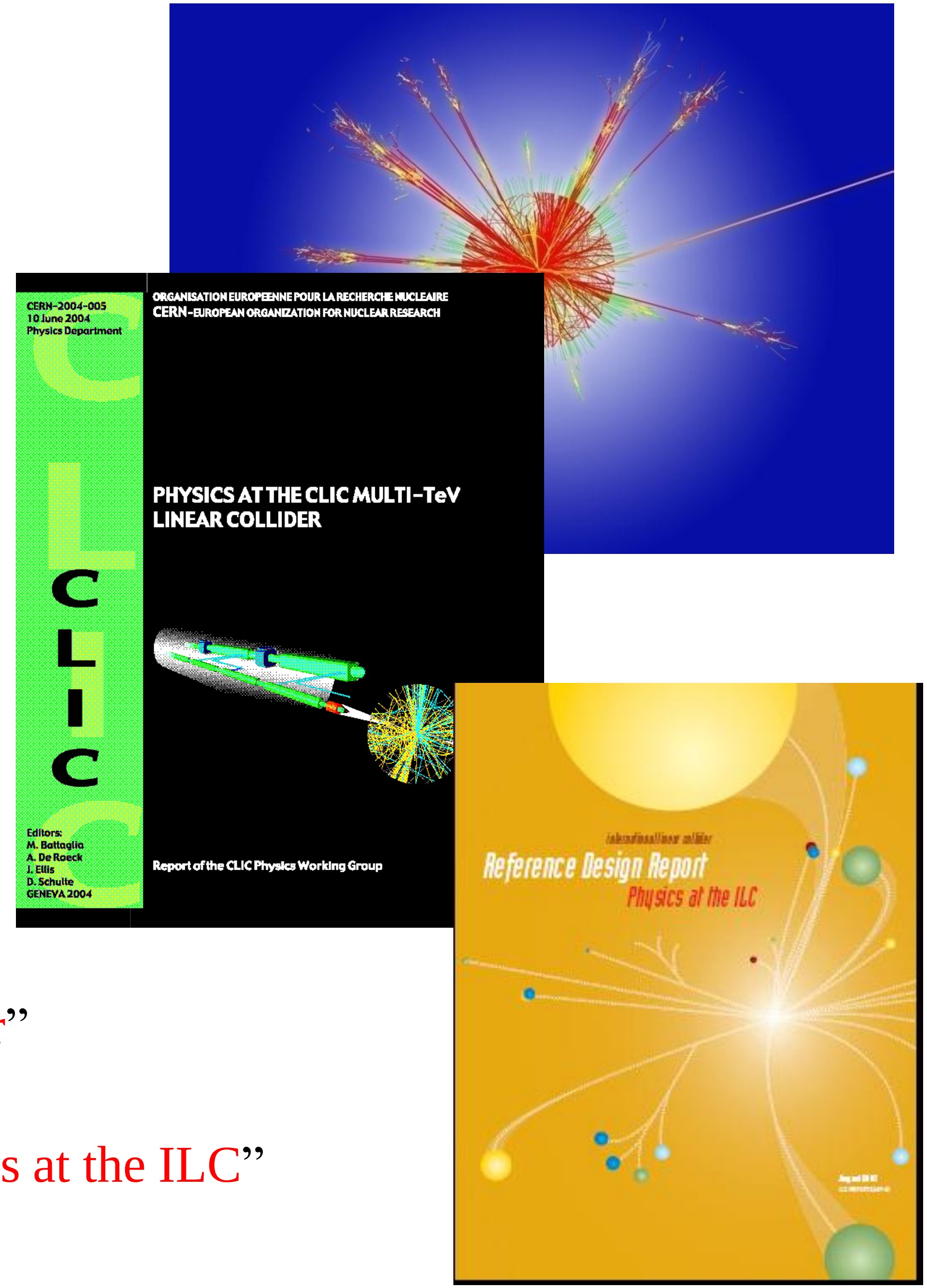

  - Elementary particles
  - Well defined initial state
  - Beam polarization
  - produces particles democratically
  - Momentum conservation eases decay product analysis

# 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

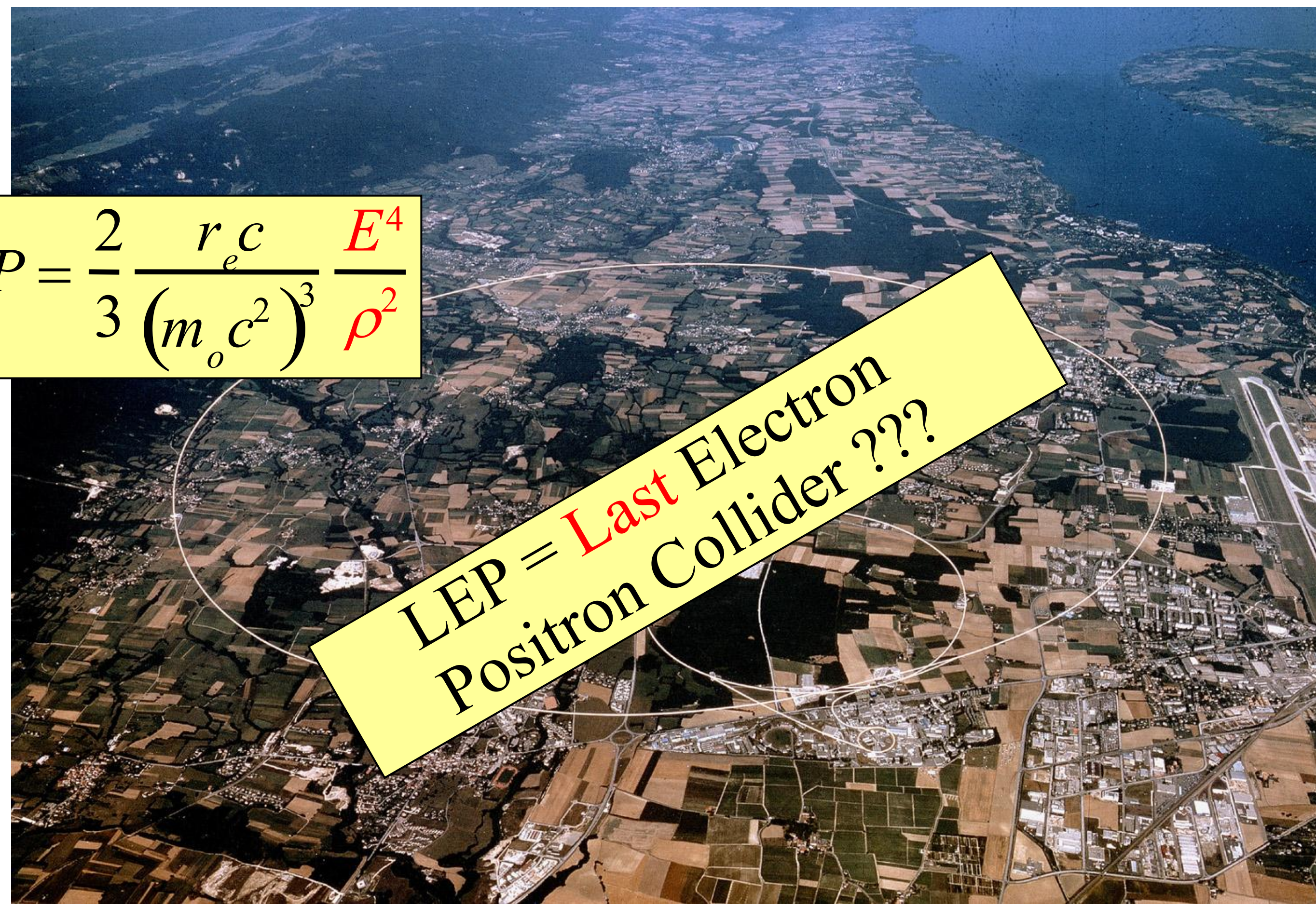


# The LEP collider

- LEP (Large Electron Positron collider) was installed in LHC tunnel
- e+ e- circular collider (27 km) with $E_{cm}$=200 GeV

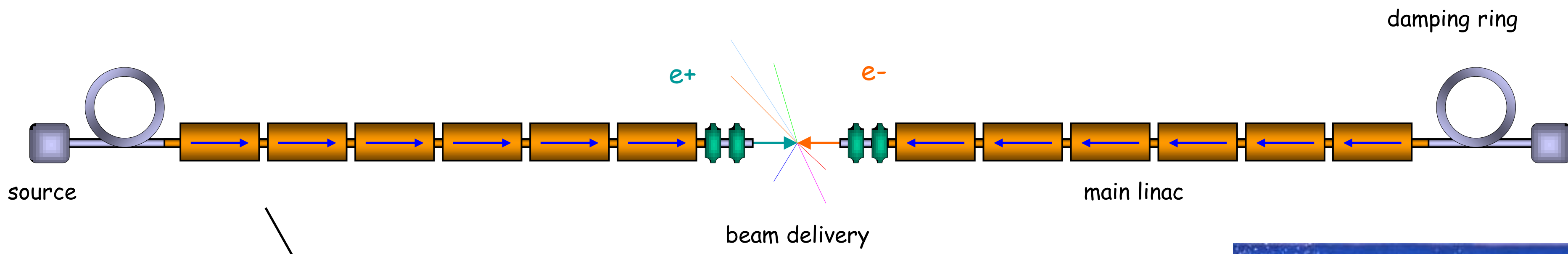
- Problem for any ring: Synchrotron radiation
- Emitted power: scales with $E^4$ !! and $1/m_0^3$ (much less for heavy particles)
- This energy loss must be replaced by the RF system !!
- particles lost 3% of their energy each turn!

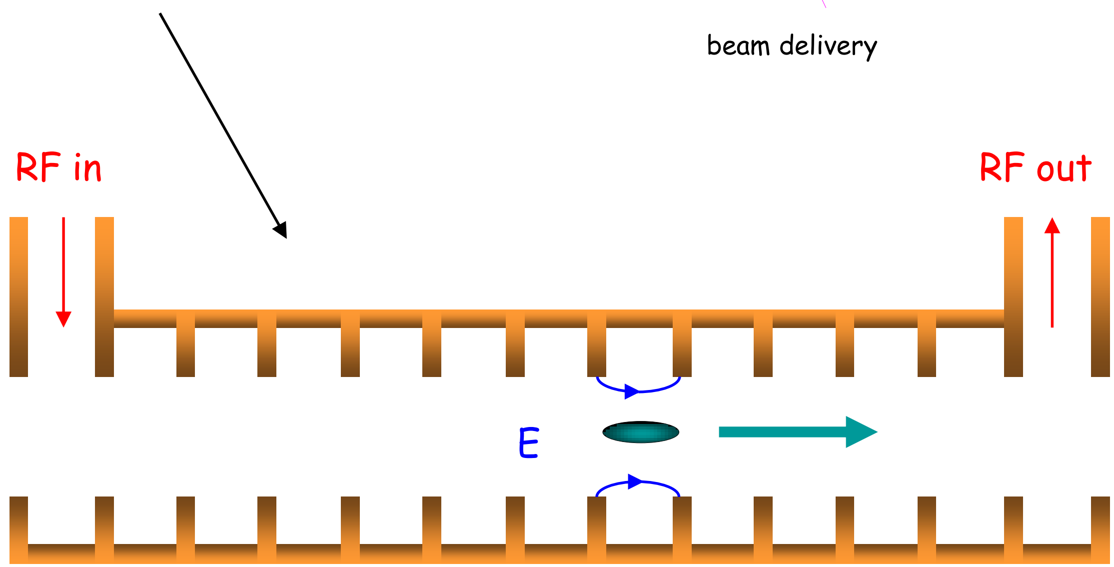
$$P = \frac{2}{3} \frac{r_e c}{\left(m_o c^2\right)^3} \frac{E^4}{\rho^2}$$



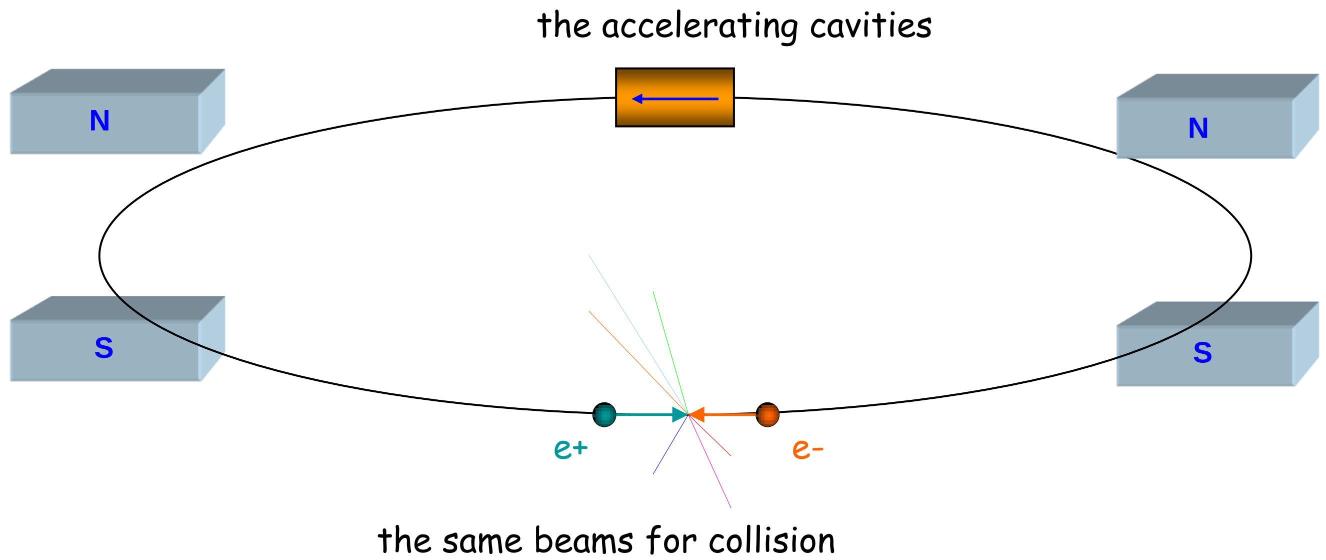
# The next lepton collider

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




# Linear Collider vs. Ring




- **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

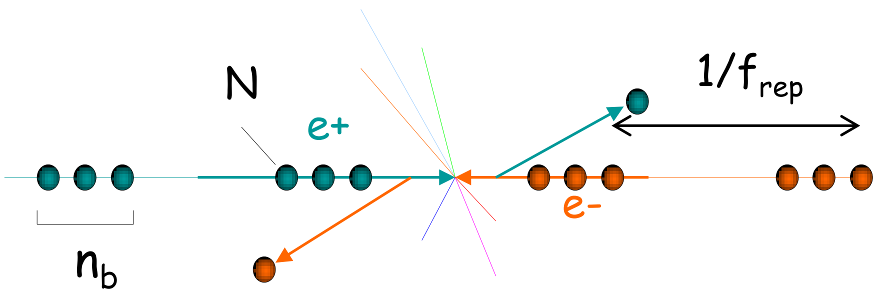
  to reach high event rate (Luminosity)

# What matters in a linear collider ?

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

- High gradient

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

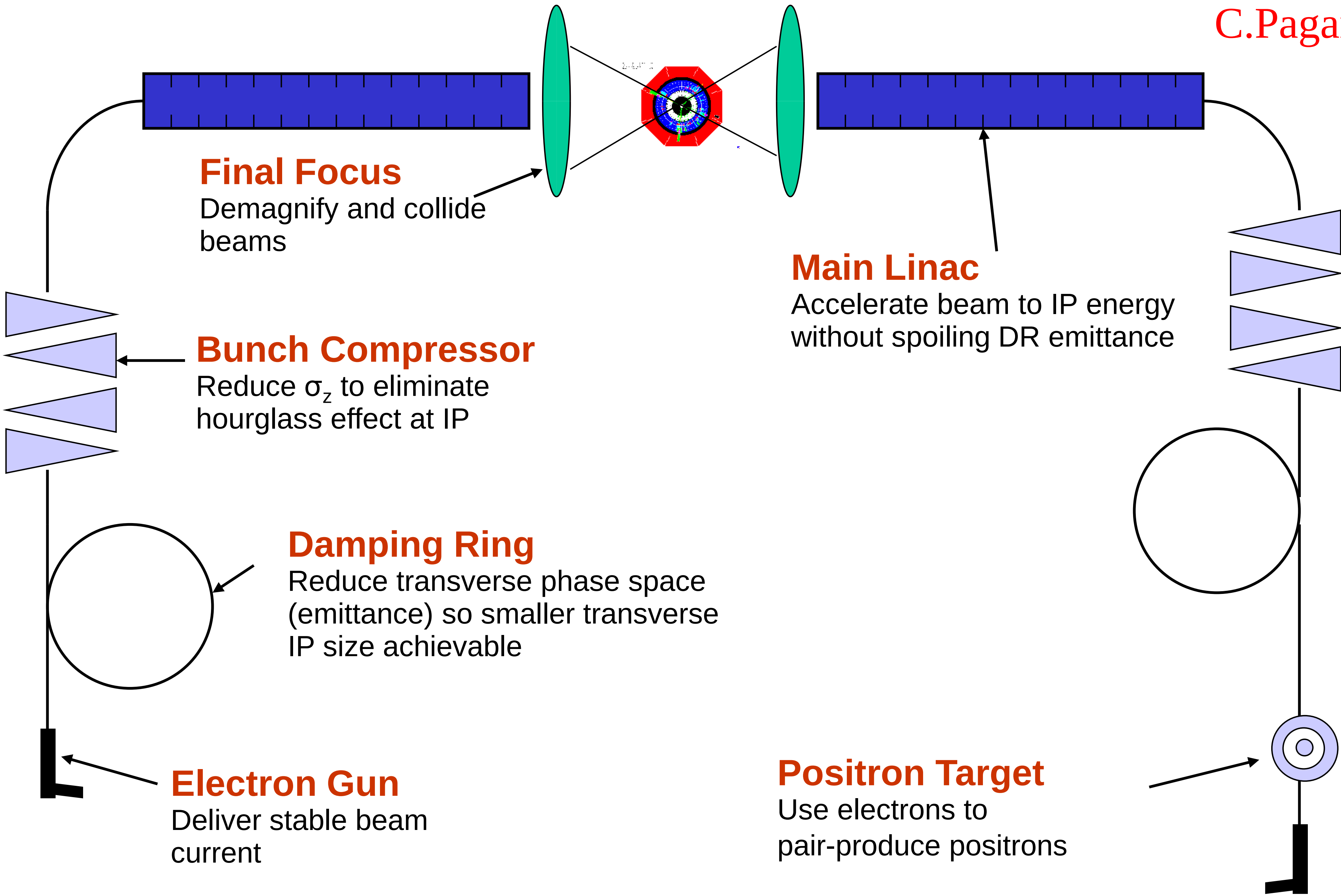



$\sigma_{x,y}$ = transverse beam size

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

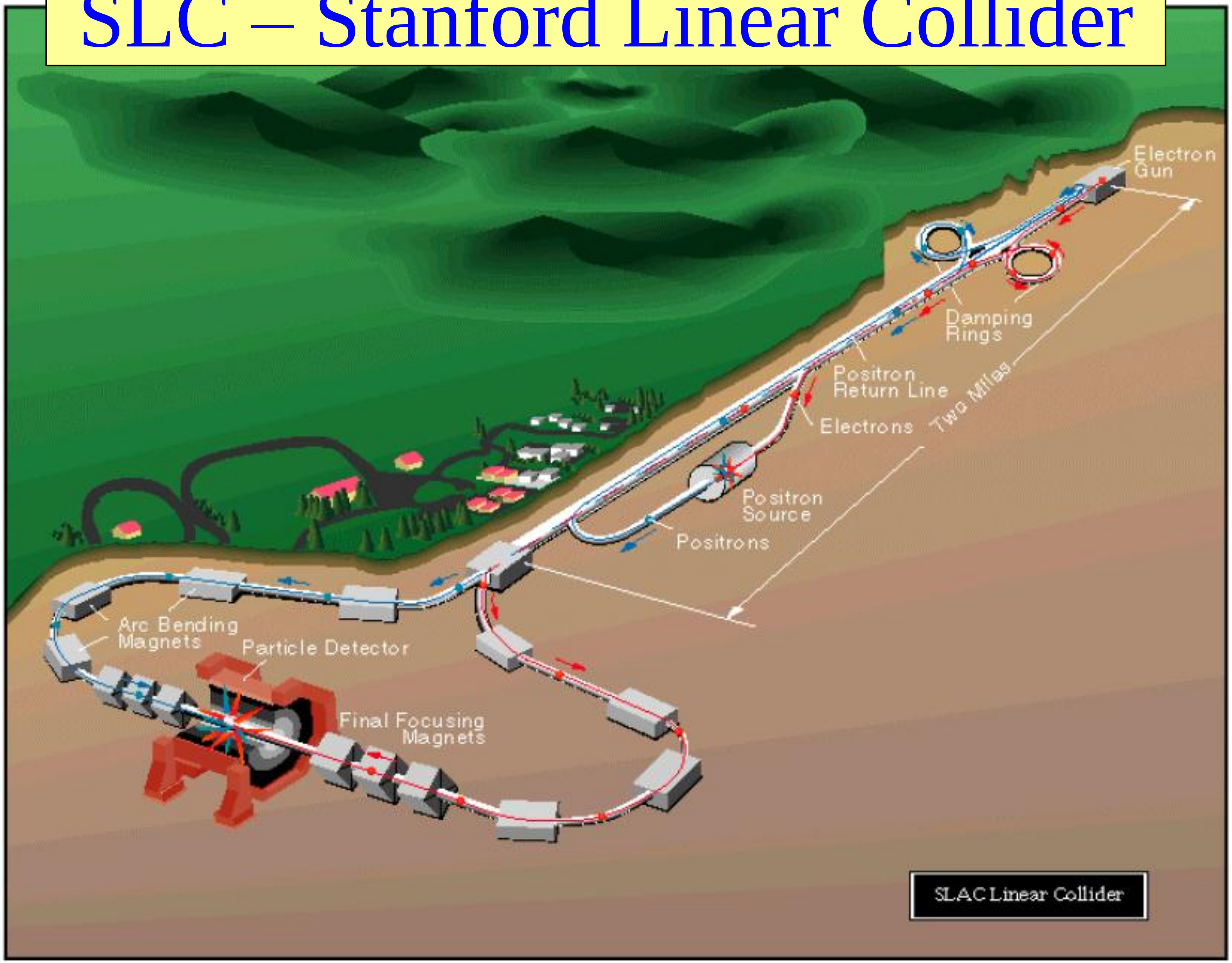
# Generic Linear Collider

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

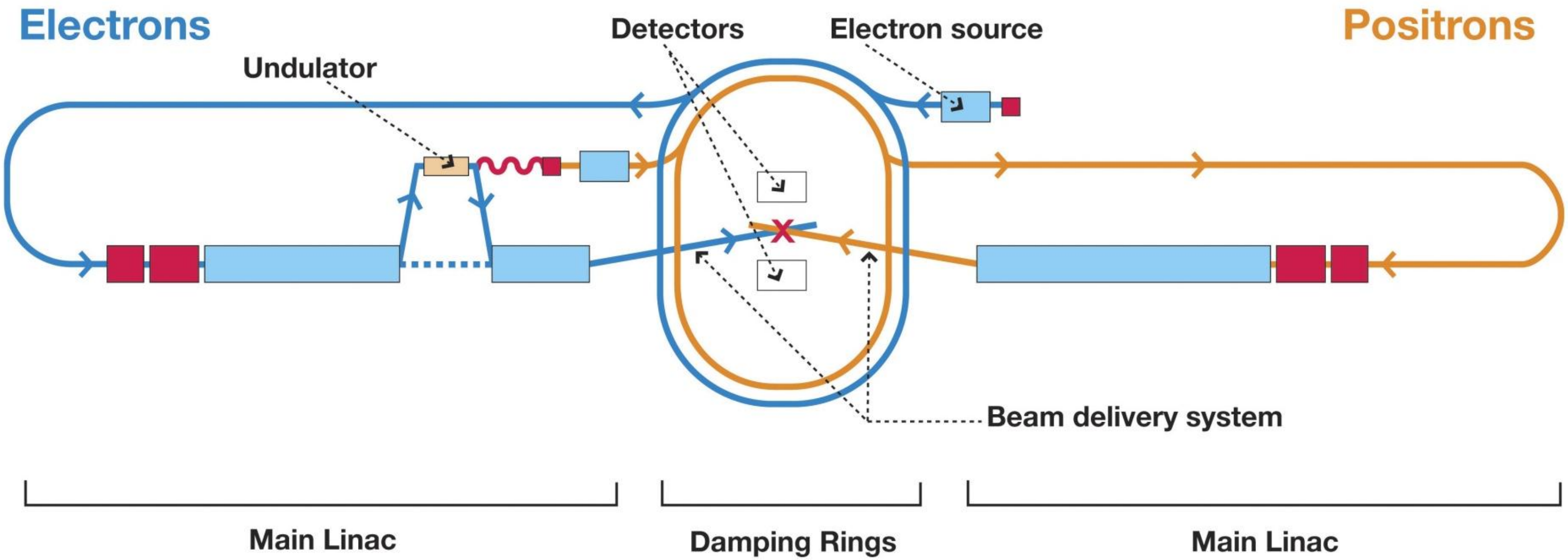
A 10% prototype!

T.Raubenheimer

# Linear Collider projects

- ILC (International Linear Collider)
  - Technology decision Aug 2004
  - Superconducting technology
  - 1.3 GHz RF frequency
  - 31.5 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 | 130 |
| **Bunch length $\sigma_z^*$ [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 $\beta_y^*$ [mm]** | ~1.5 | 0.4 | 0.4 | 0.11 | 0.1 |
| **Vert. beam size $\sigma_y^*$ [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

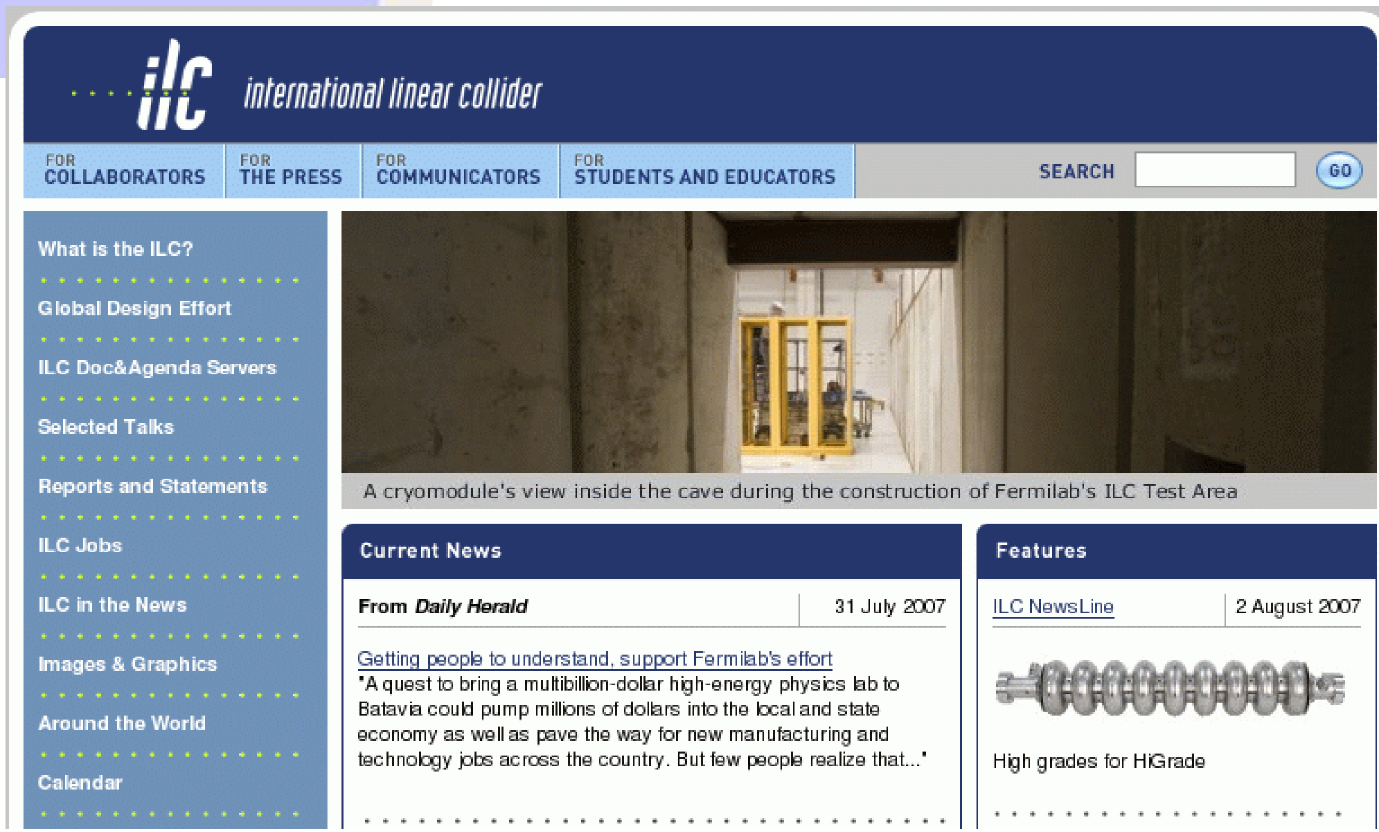
DRAFT

INTERNATIONAL LINEAR COLLIDER

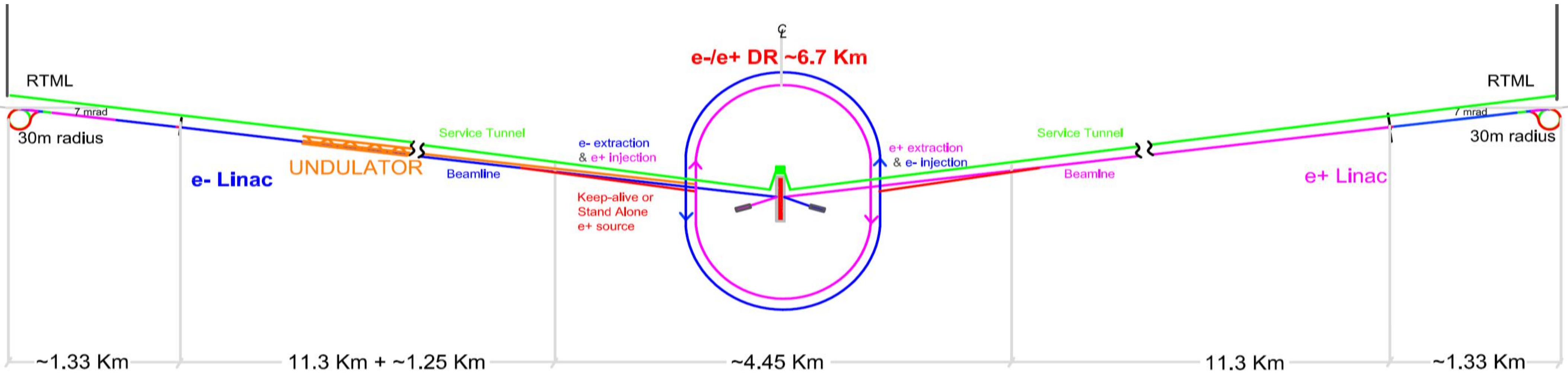
REFERENCE DESIGN REPORT

2007

APRIL, 2007

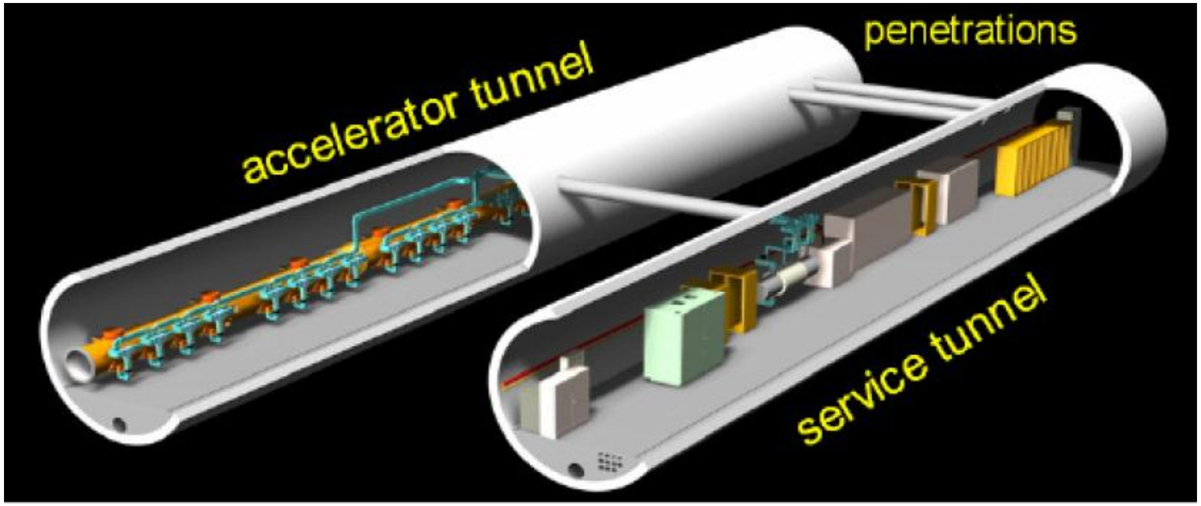


# ILC Schematic




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 6.7 km damping rings (3.2 km studied)
  - Undulator-based positron source
- Dual tunnel configuration for safety and availability (now 1-tunnel option studied)

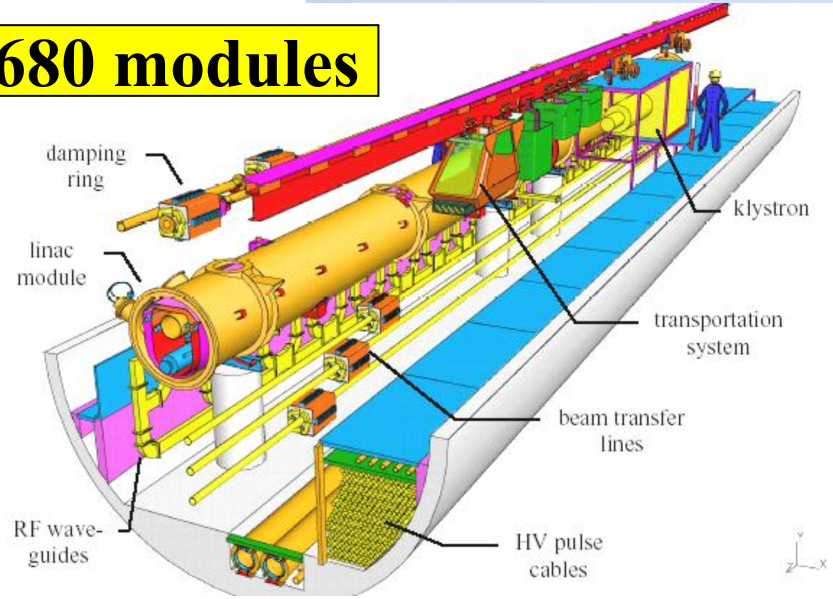


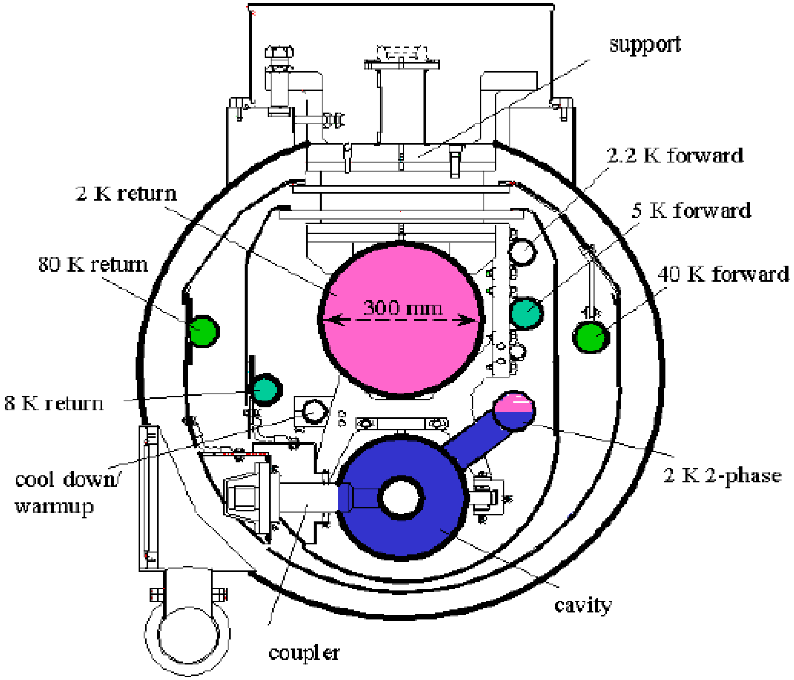
# ILC Super-conducting technology

**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**

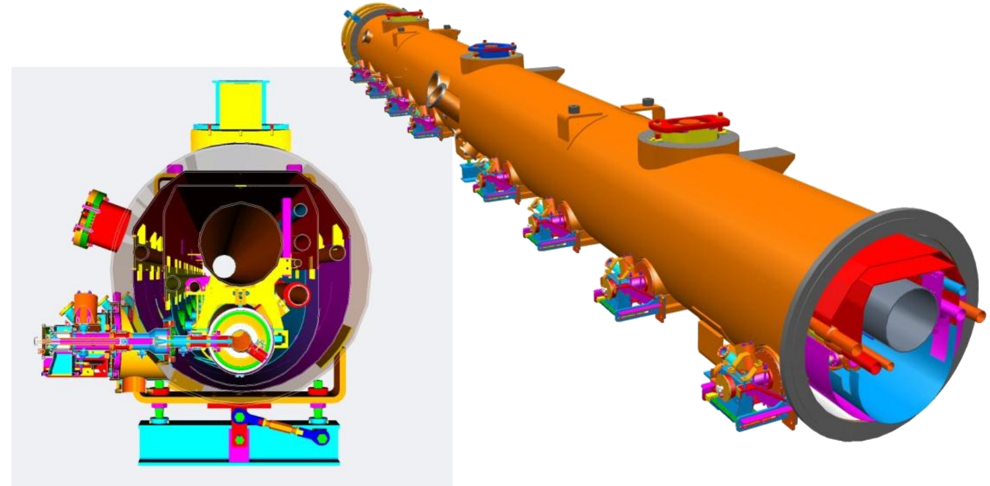


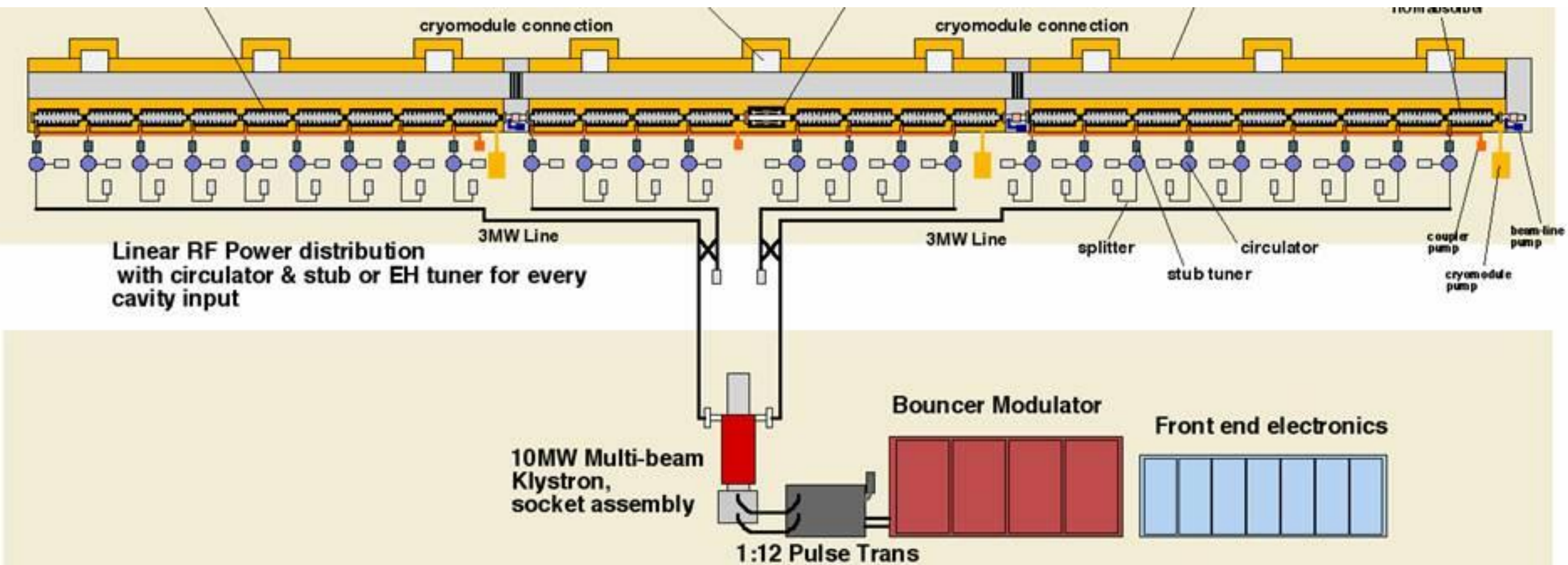
# ILC Main Linac RF Unit

**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**

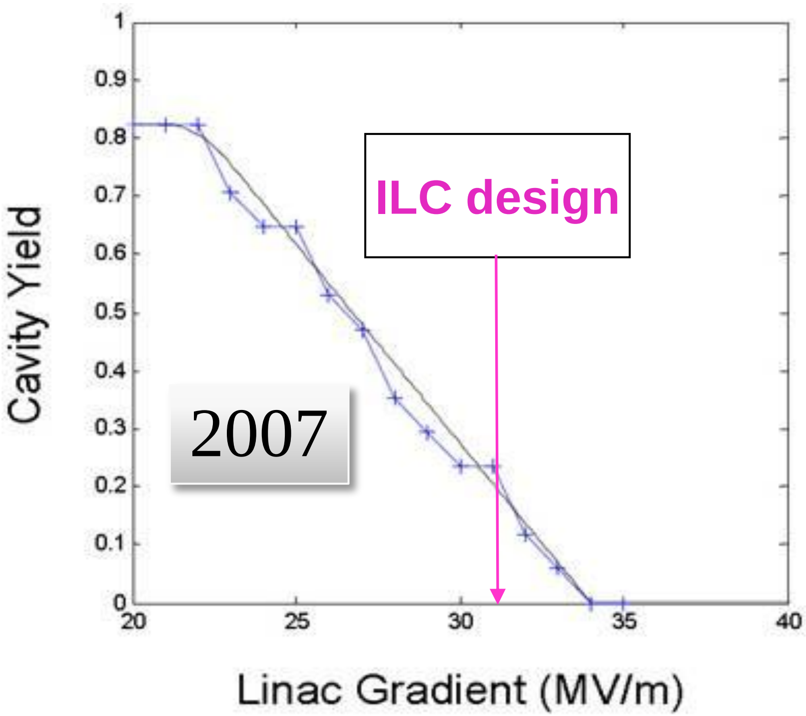


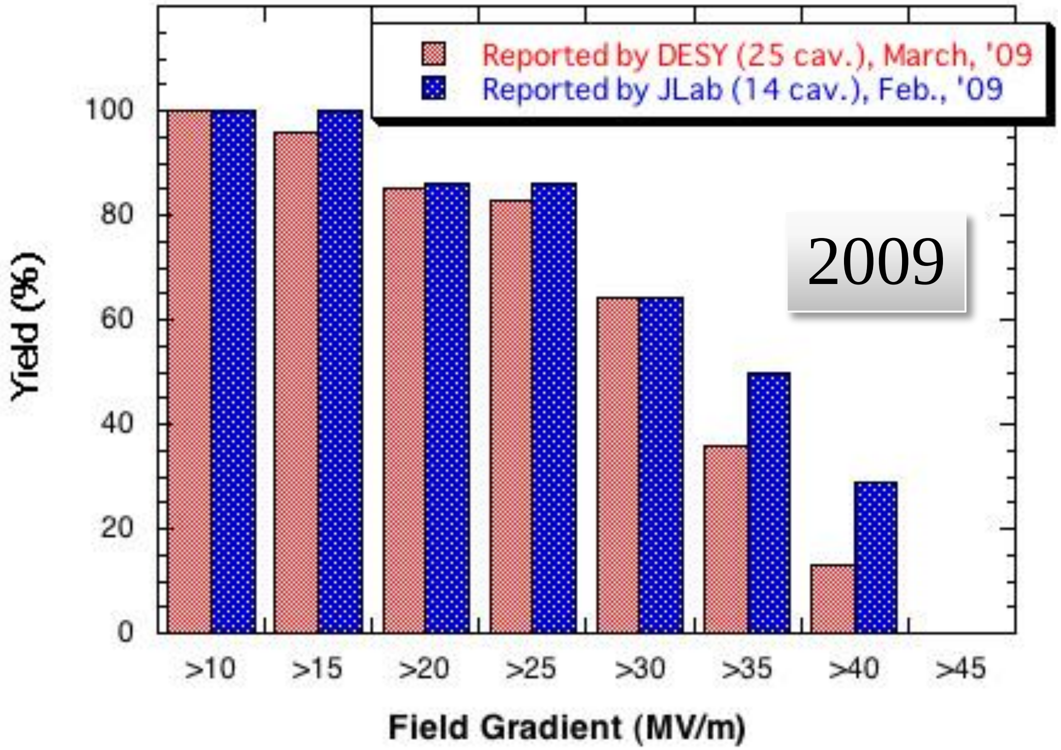
**Total of 1680 cryomodules and 14 560 SC RF cavities**



# Achieved accelerating gradients

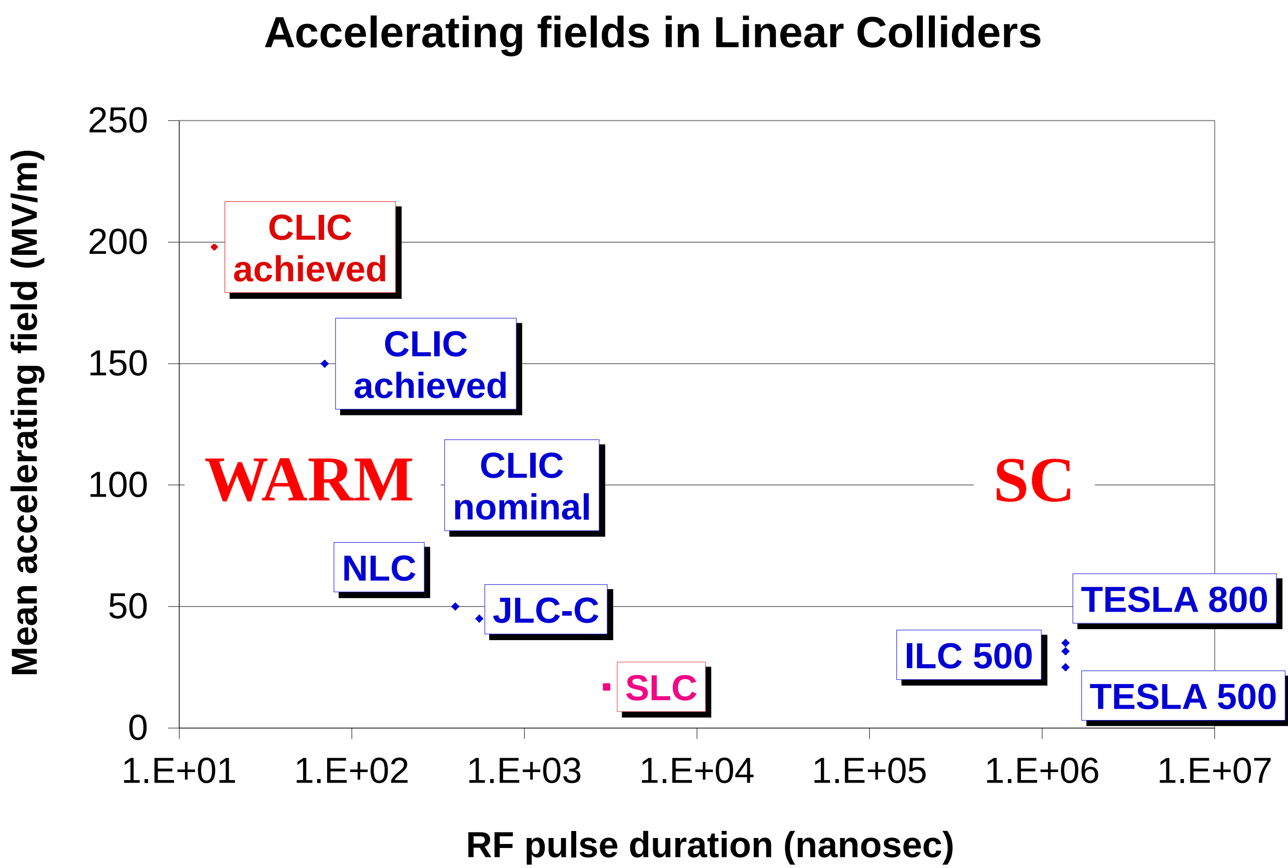
- 31.5 MV/m ILC baseline
- Recent progress by R&D programme to systematically understand and set procedures for the production process
- goal to reach a 50% yield at 35 MV/m by the end of 2010
- already approaching that goal, 90% yield foreseen later



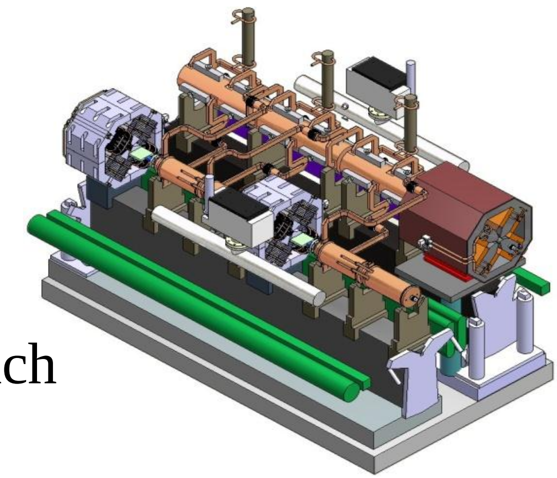



# Accelerating gradient

- Superconducting cavities fundamentally limited in gradient by critical magnetic field => become normal conducting above
- Normal conducting cavities are limited in pulse length by "Pulsed surface heating" => can lead to fatigue
- 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 (possibly TDR by 2016)

# CLIC scheme

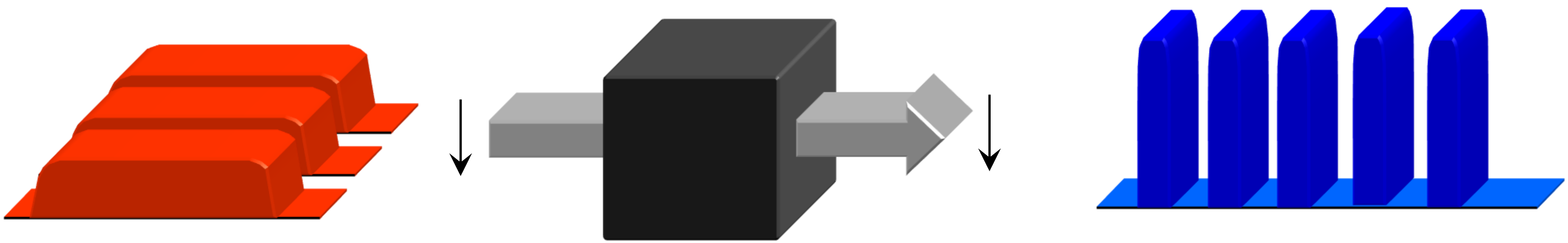
- Very high gradients possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz) and short RF pulses (~100 ns)
- Extract required high RF power from an intense e- “drive beam”
- Generate efficiently long beam pulse and compress it (in power + frequency)

Klystrons
Low frequency
High efficiency

Power stored in
electron beam

Power extracted from beam
in resonant structures

Accelerating Structures
High Frequency – High field



Long RF Pulses
$P_0$ , $\nu_0$ , $\tau_0$

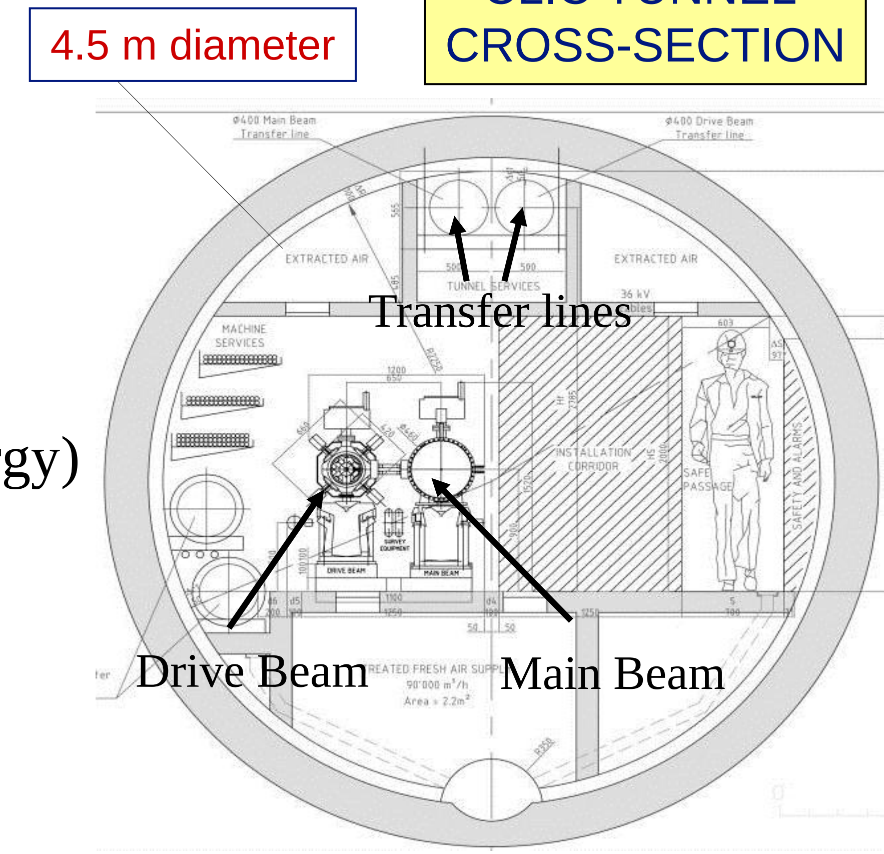
Electron beam manipulation
Power compression
Frequency multiplication

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

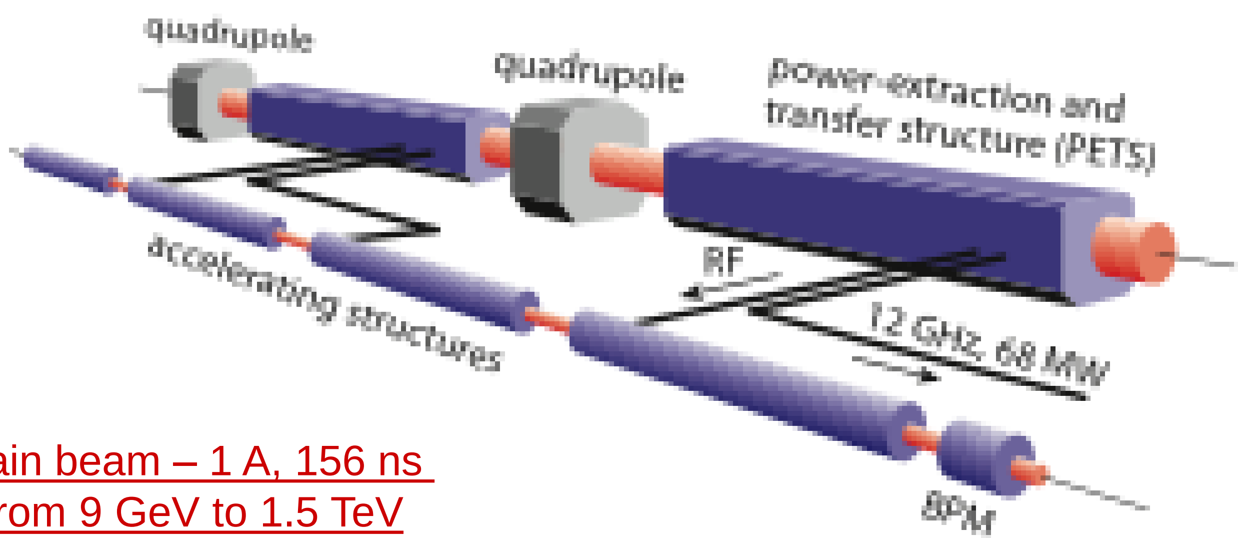
# CLIC – basic features

- 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

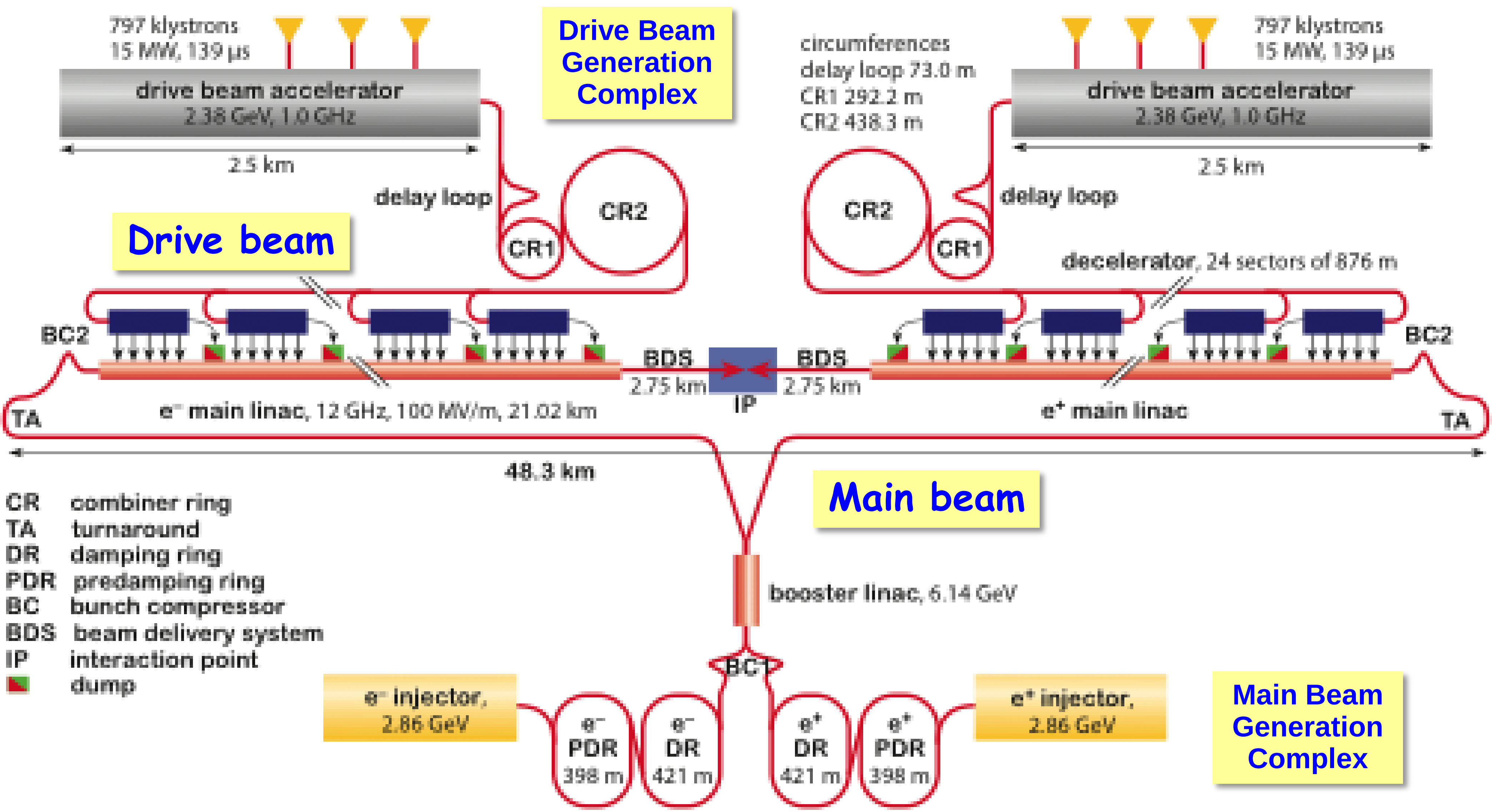



Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV




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

# CLIC – overall layout

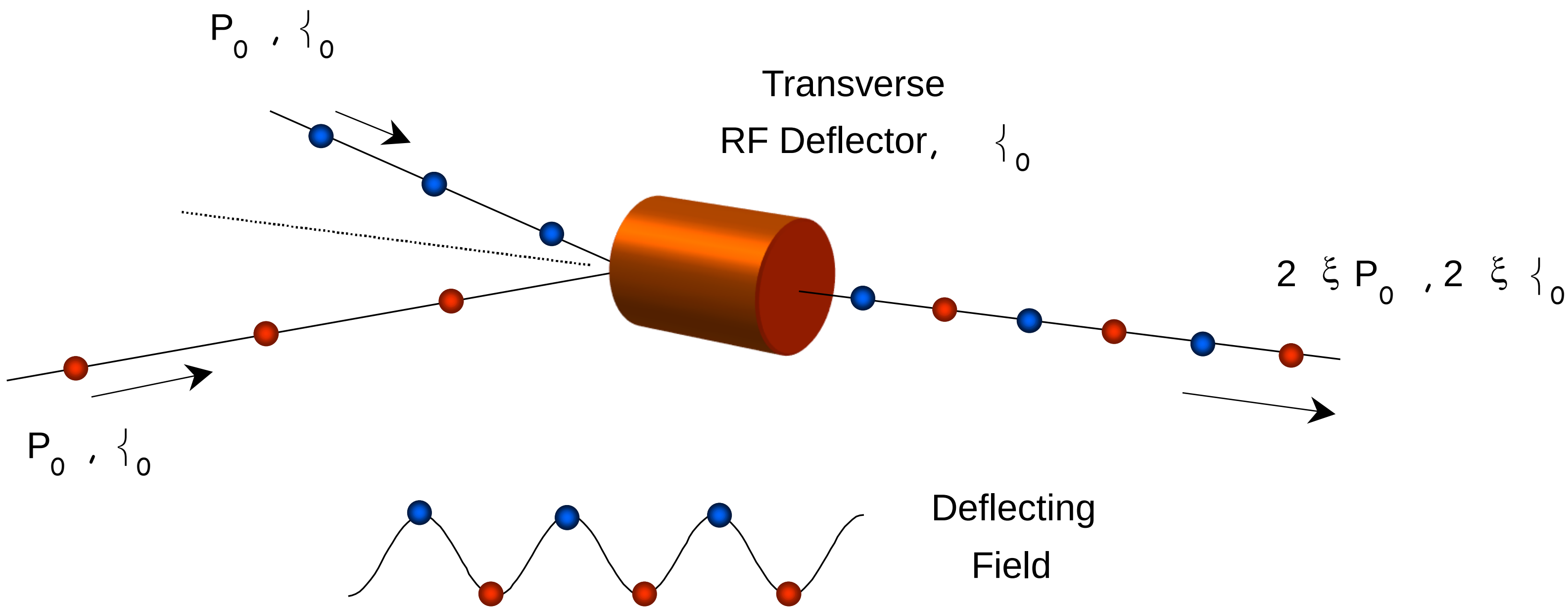


# CLIC main parameters

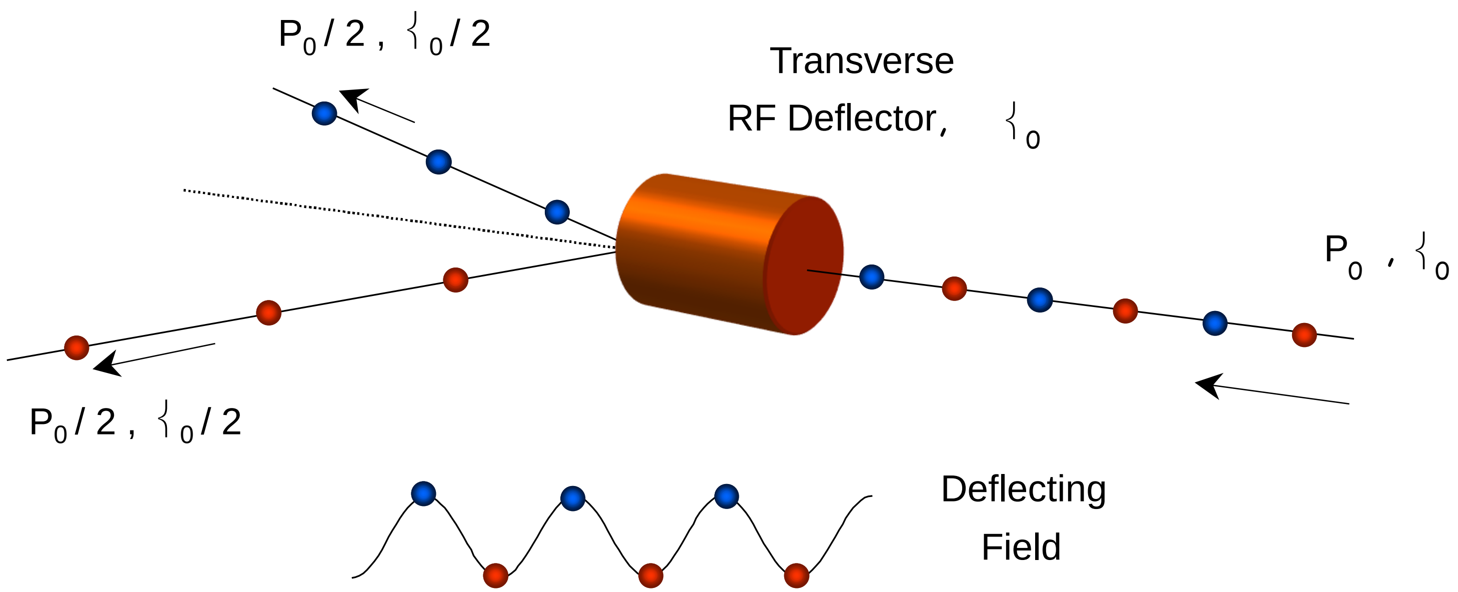
| | |
|---|---|
| Center-of-mass energy | 3 TeV |
| Peak Luminosity | $6\cdot10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Peak luminosity (in 1% of energy) | $2\cdot10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Repetition rate | 50 Hz |
| Loaded accelerating gradient | 100 MV/m |
| Main linac RF frequency | 12 GHz |
| Overall two-linac length | 41.7 km |
| Bunch charge | $3.7\cdot10^{9}$ |
| 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 | 48.4 km |
| Total power consumption | 400 MW |

Provisional values

# Beam combination by RF deflectors

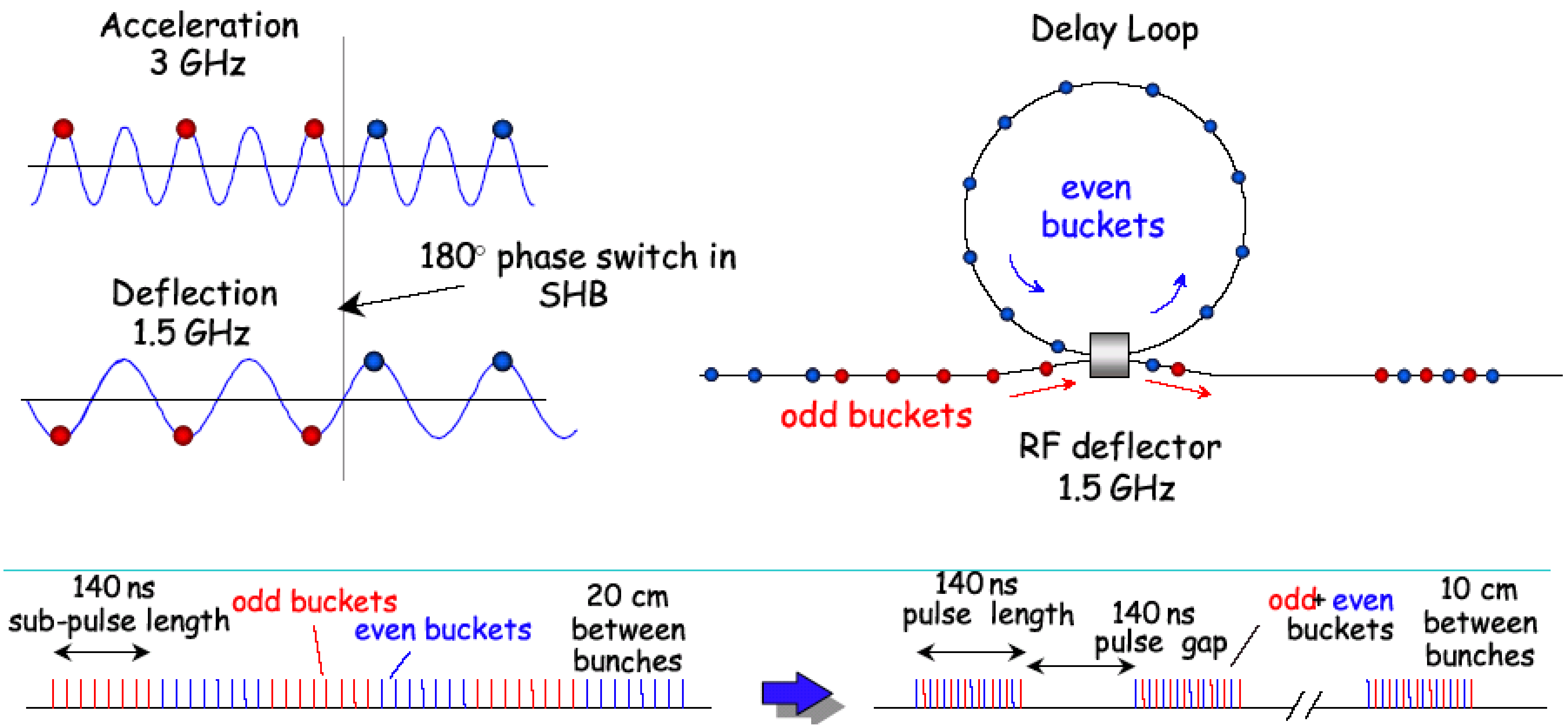


# Beam separation by RF deflectors



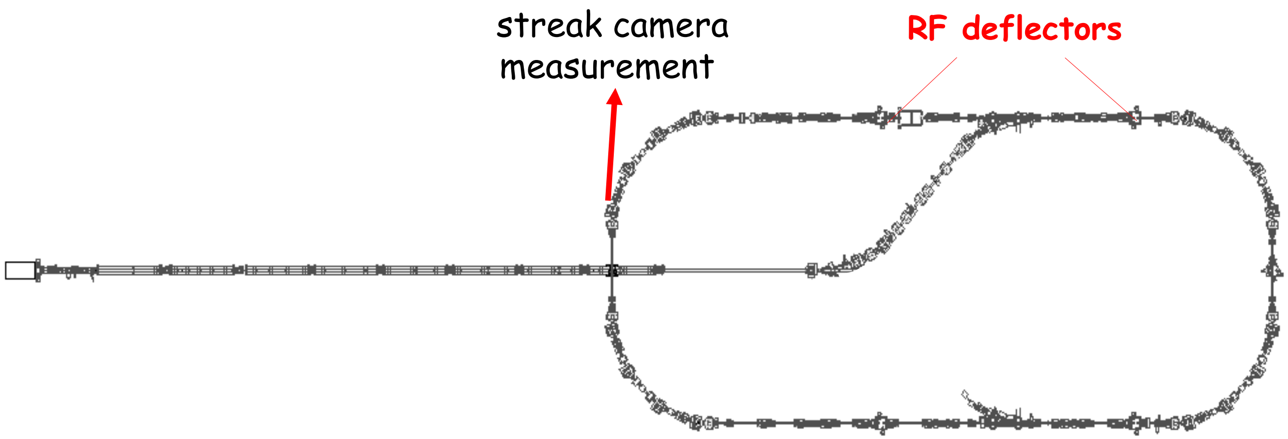
# Delay Loop Principle

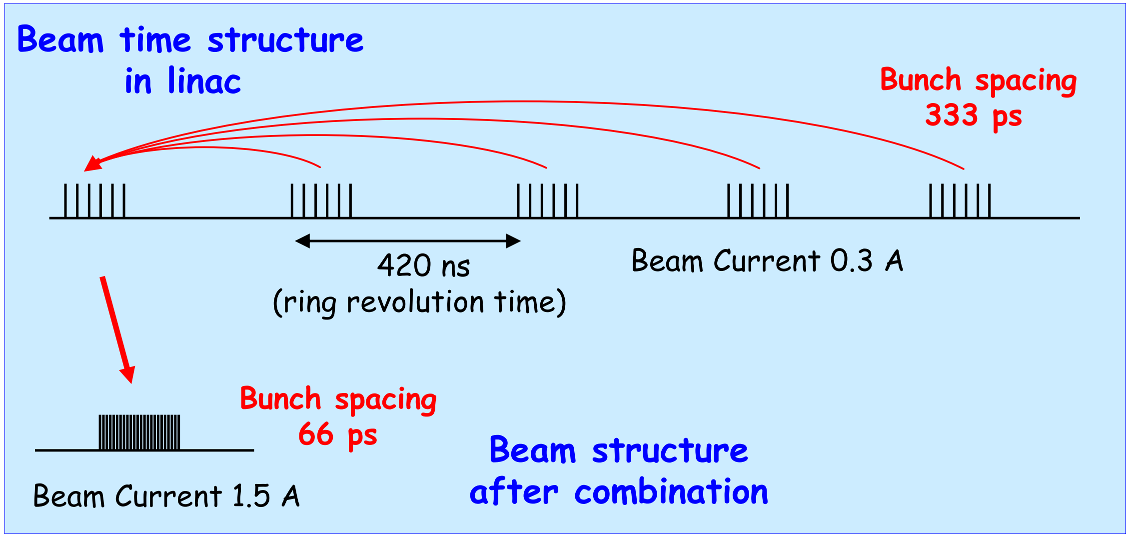
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches



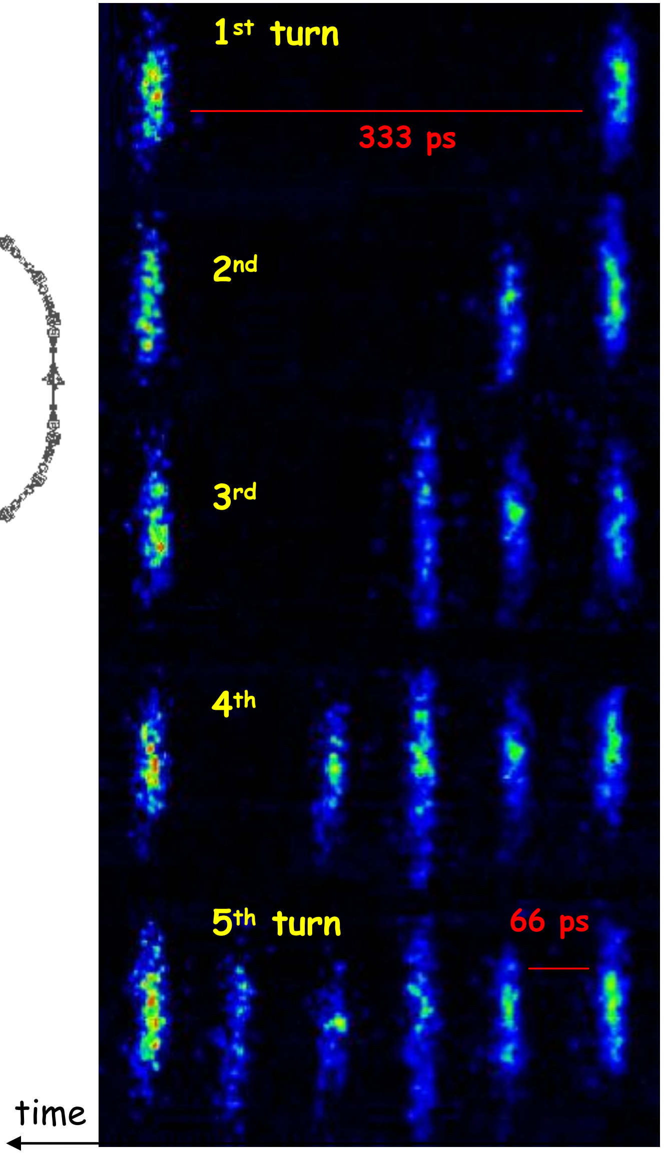
## CTF3 - PRELIMINARY PHASE 2001/2002

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



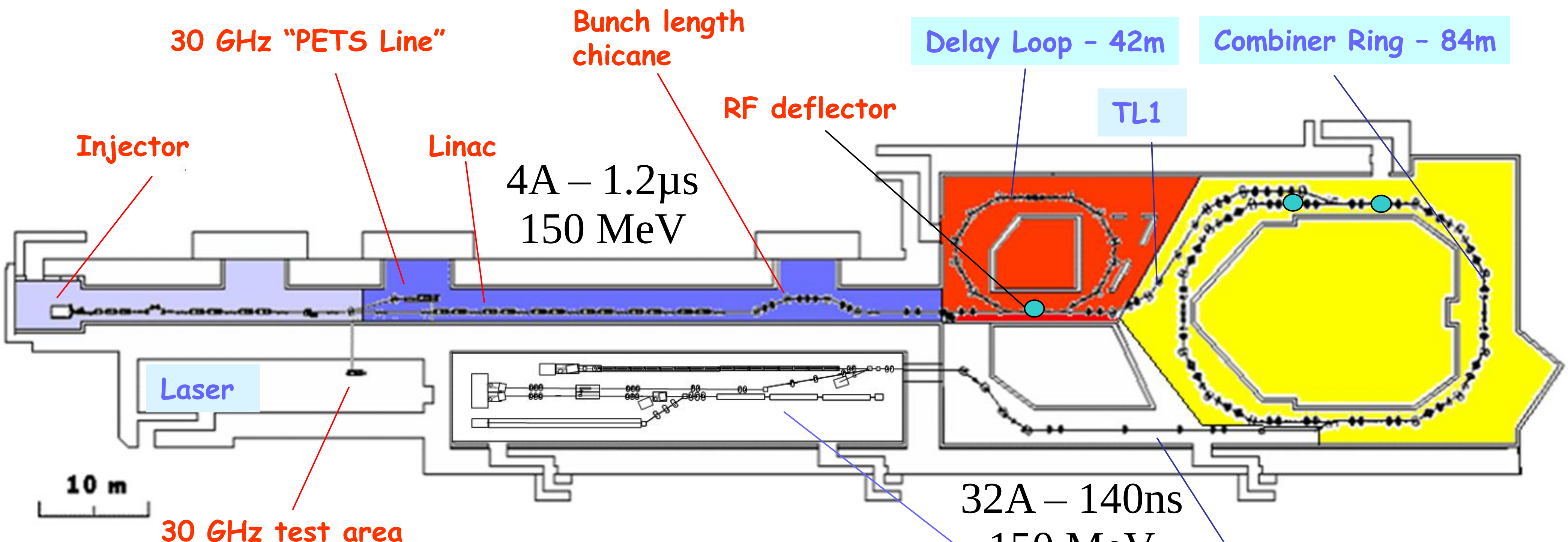




Streak camera image of
beam time structure evolution



# CTF 3

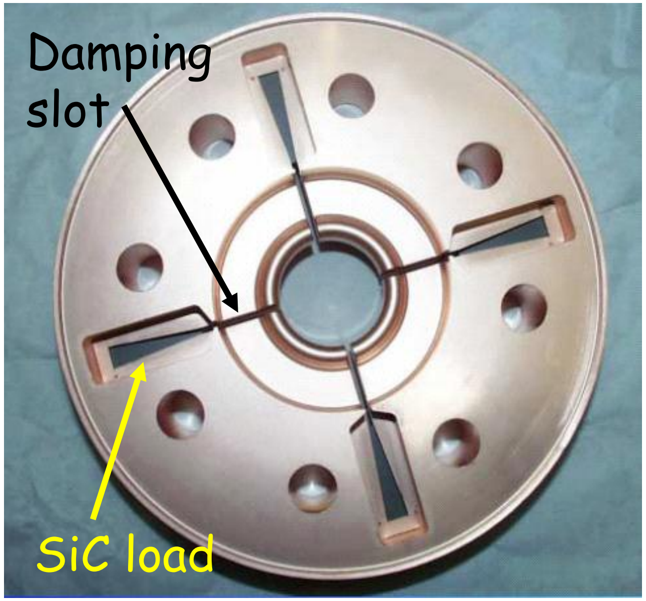
- demonstrate Drive Beam generation (fully loaded acceleration, bunch frequency multiplication 8x)
- Test CLIC accelerating structures
- Test power production structures (PETS)




- 2003 Injector + part of linac
- 2004 Linac + 30 GHz test stand
- 2005 Delay Loop
- 2006/07 TL1 + Combiner Ring
- 2008/09 New photo-injector, TL2 + CLEX

# CTF3 linac acceleration structures

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

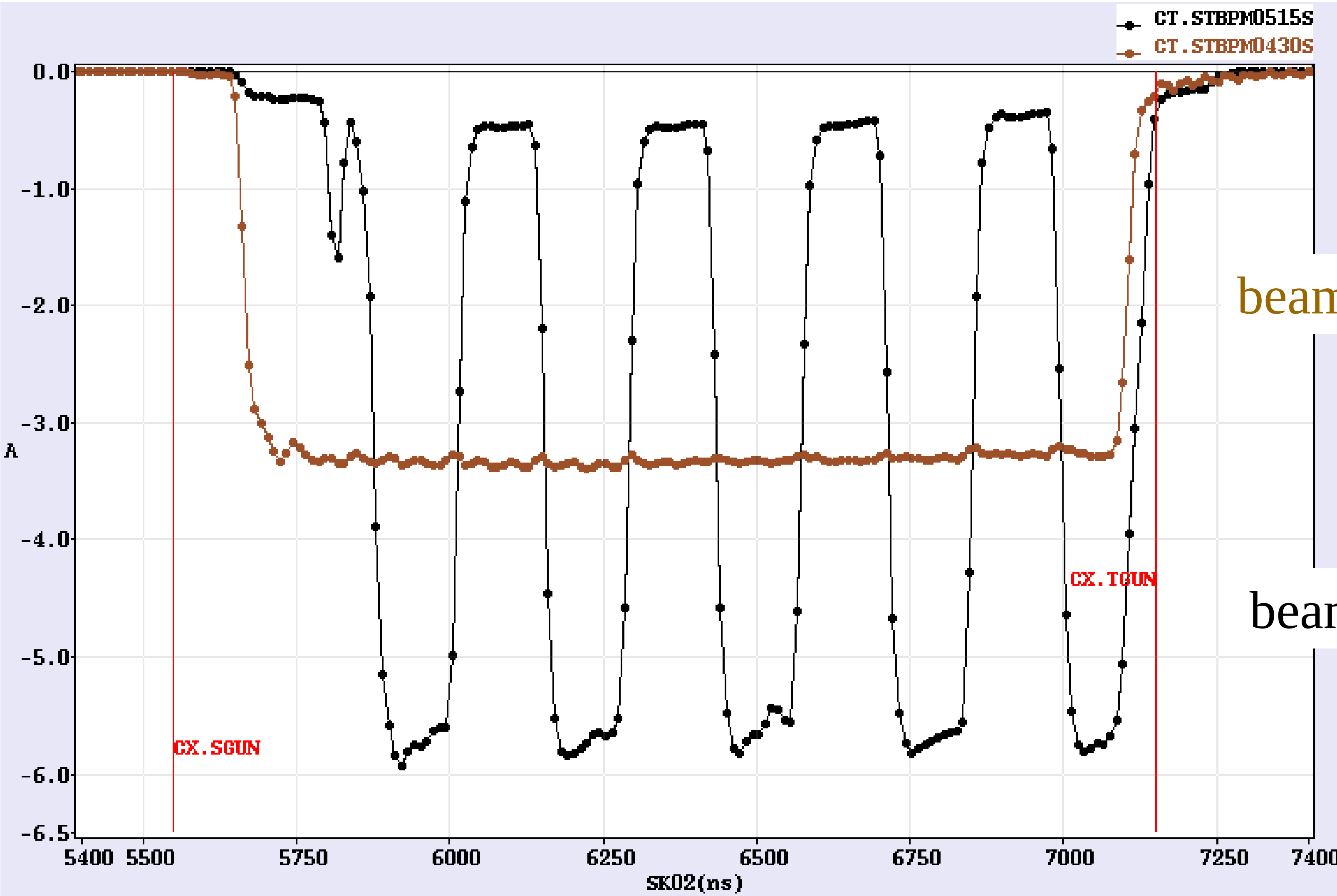



- 3 GHz $2\pi/3$ traveling wave structure
- constant aperture
- slotted-iris damping + detuning with nose cones
- up to 4 A 1.4 μs beam pulse stably accelerated

- Measured RF-to-beam efficiency 95.3%
- Theory 96% (~ 4 % ohmic losses)

# CTF3 Delay Loop

# Delay Loop – full recombination

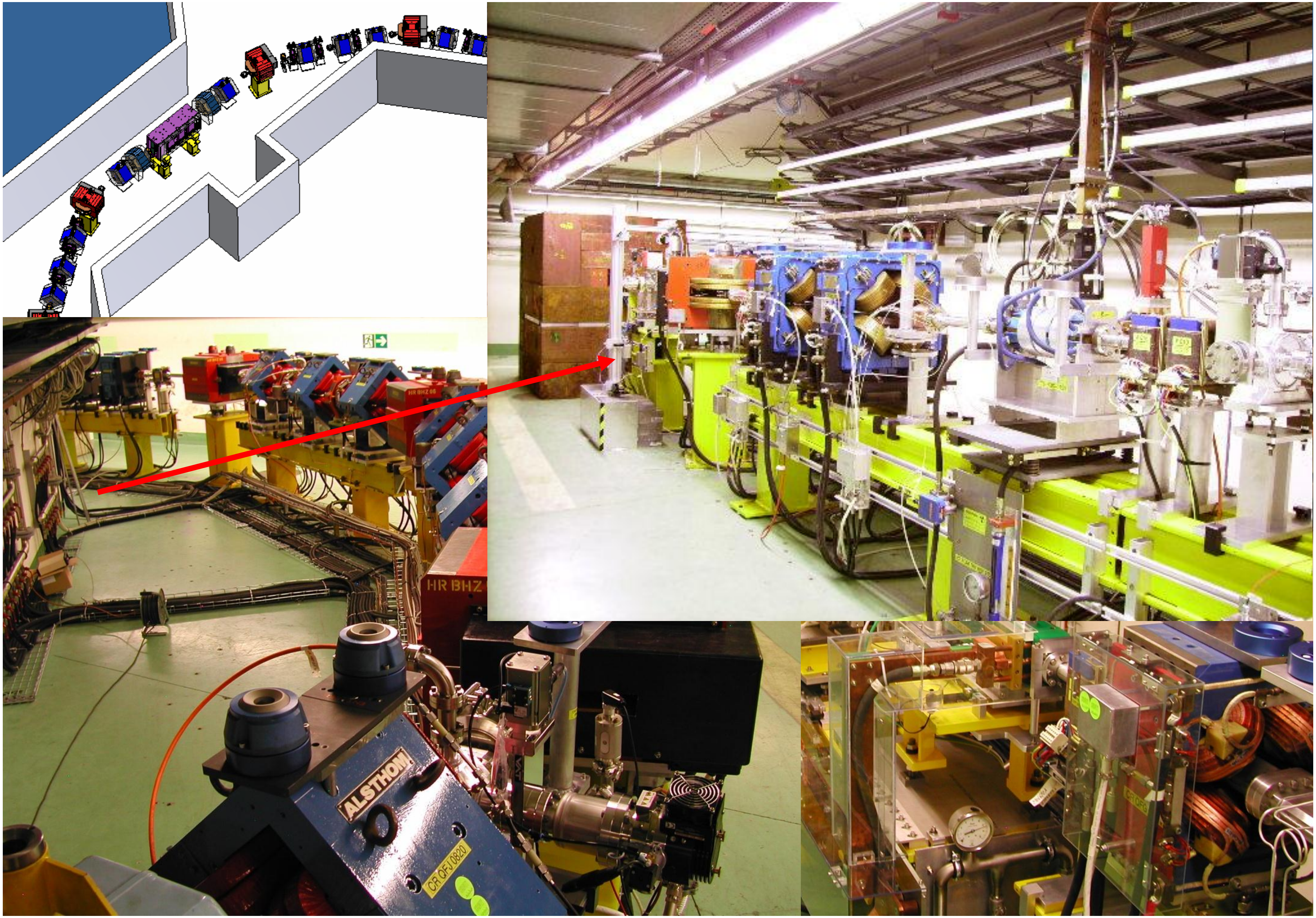



beam before the DL

beam after the DL

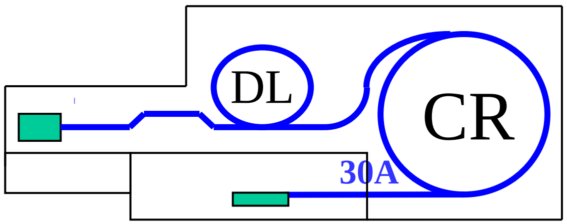
- 3.3 A after chicane => < 6 A after combination (satellites)

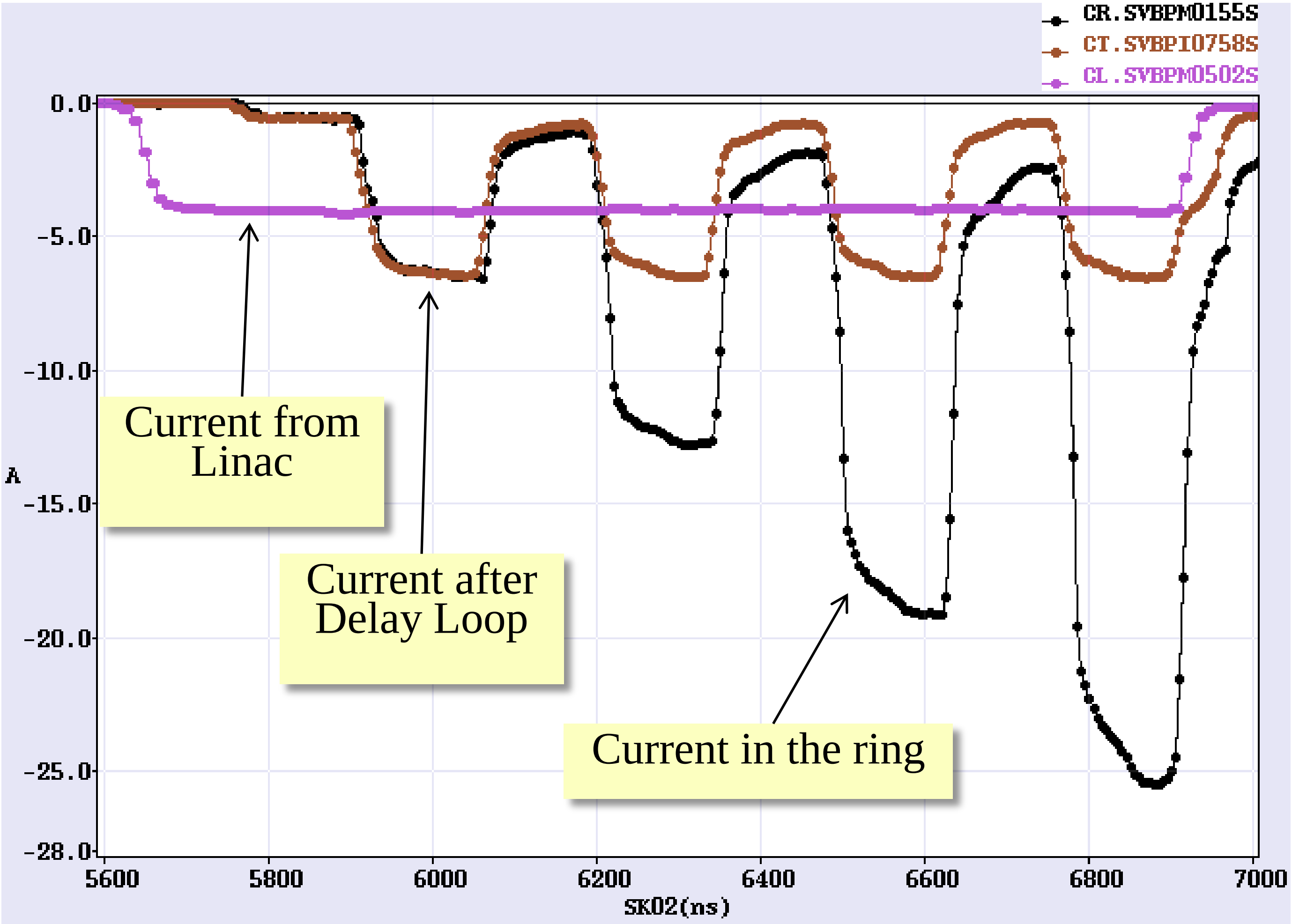
# CTF3 combiner ring



# Drive beam generation achieved

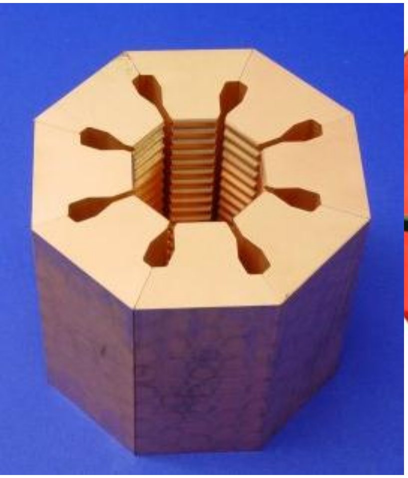
- combined operation of Delay Loop and Combiner Ring (factor 8 combination)
- ~26 A combination reached, nominal 140 ns pulse length
- => **Full drive beam generation**, main goal of 2009, **achieved**

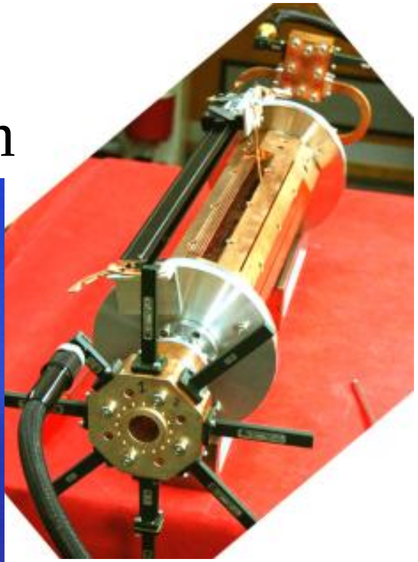


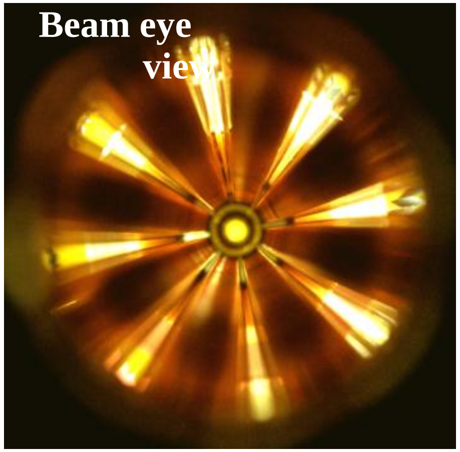



# Power extraction structure PETS

- 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







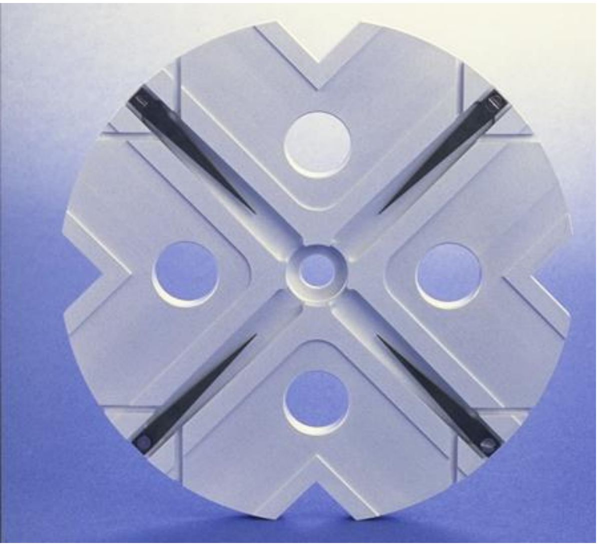

The power produced by the bunched ($\rceil_0$) beam in a constant impedance structure:

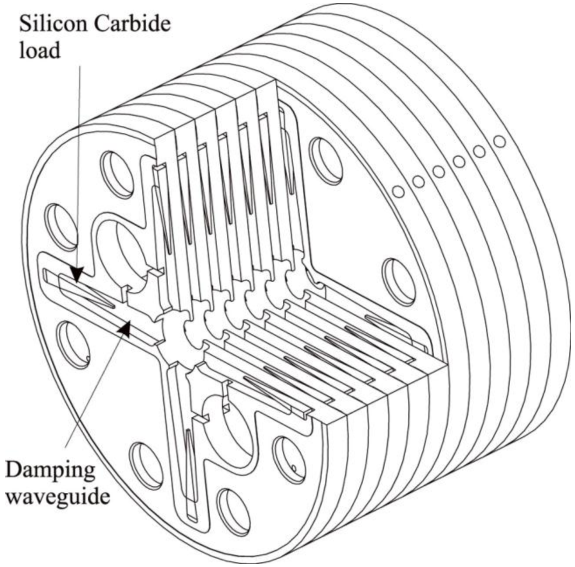
Design input parameters — PETS design

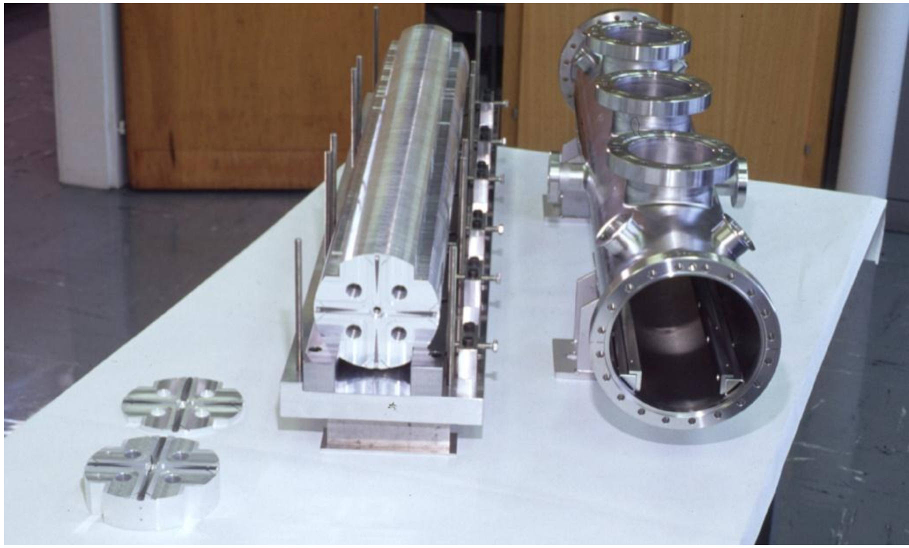
$$P = I^2 L^2 F_b^2 \omega_0 \frac{R/Q}{V_g 4}$$

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)

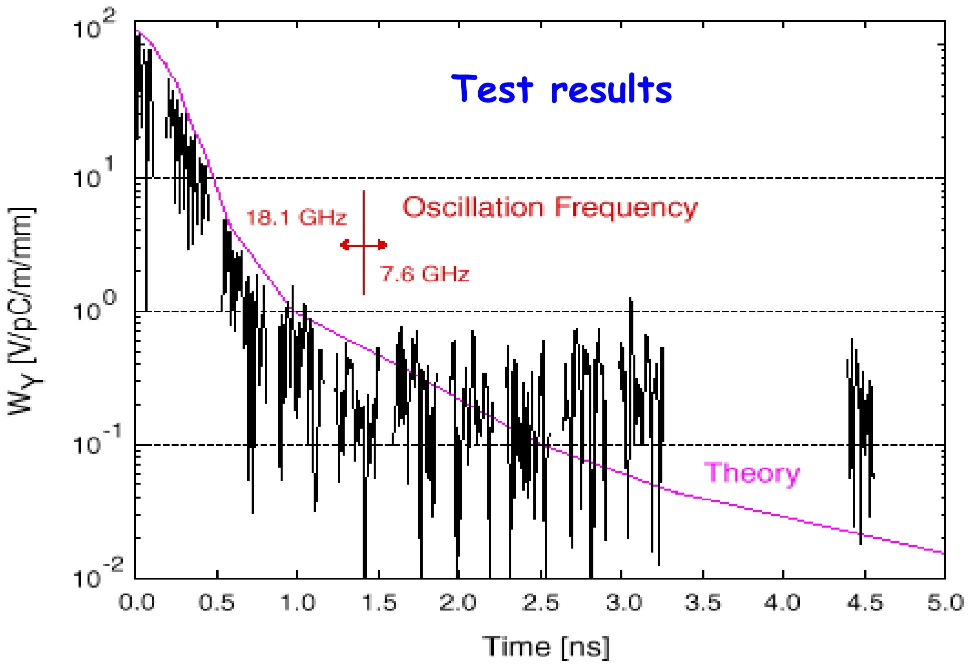
# Accelerating structure developments





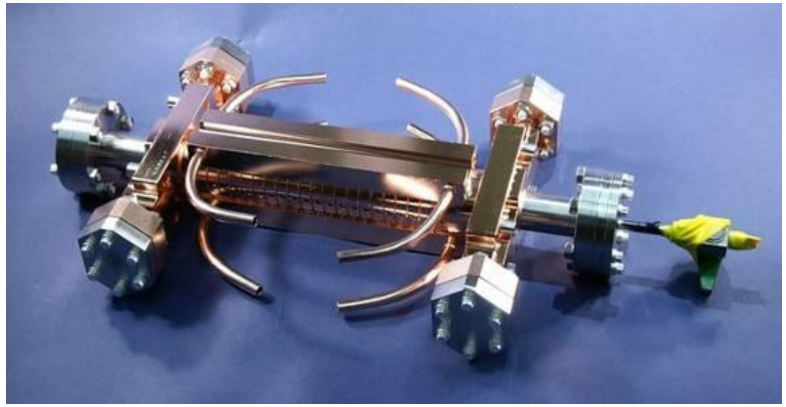



- Structures built from discs
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- HOM enter WG
- Long-range wakefields
  efficiently damped
- HOM frequencies detuned in cells

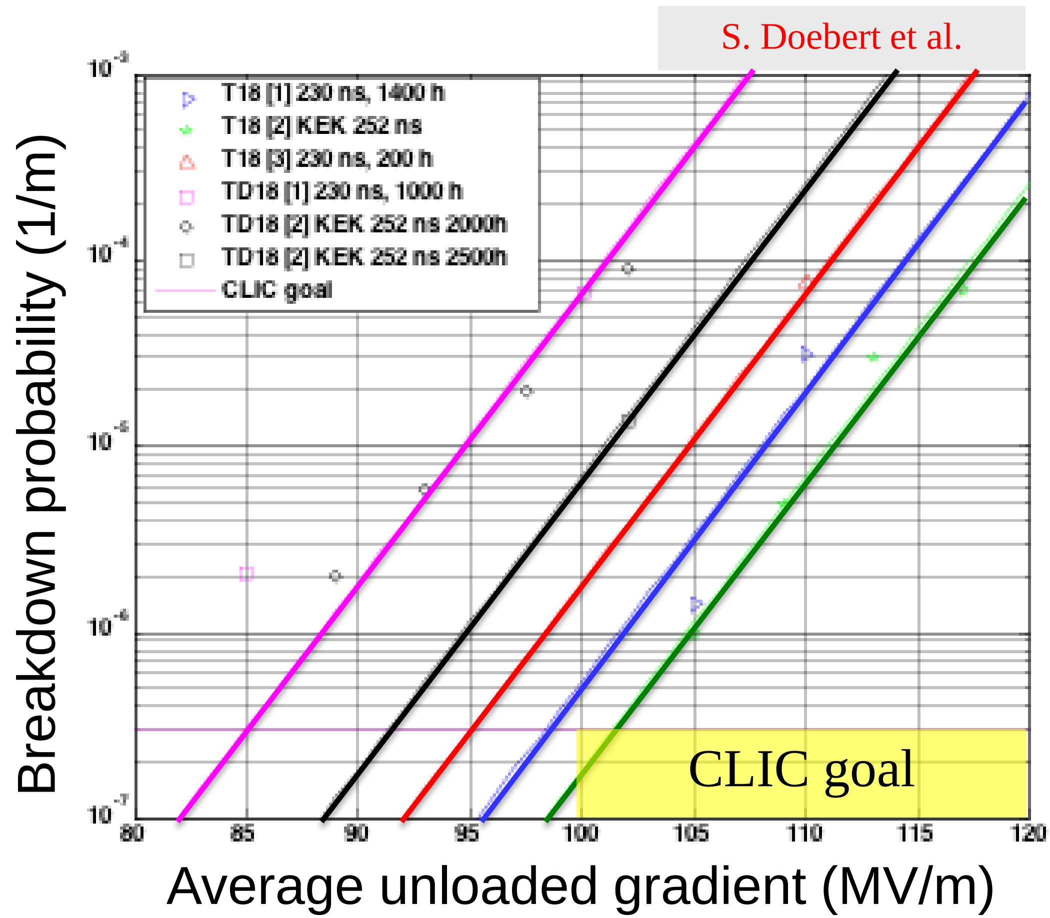


# Accelerating Structure Results

- RF breakdowns can occur => no acceleration and deflection
- Goal: 3 $10^{-7}$/m breakdowns at 100 MV/m loaded at 230 ns



- T18 and TD18 built and tested at SLAC and KEK
- T18 reached 95-105 MV/m
- Damped TD18 reaches an extrapolated 85MV/m
- Second TD18 under test at KEK
- CLIC prototypes with improved design (TD24) will be tested this year
- expect similar or slightly better performances



# 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 (TDR end 2012)
  - 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
    - Conceptual Design Report will be presented mid 2011 to Council

- Possible decision based on LHC results
- Looking forward to more results from a successful LHC operation