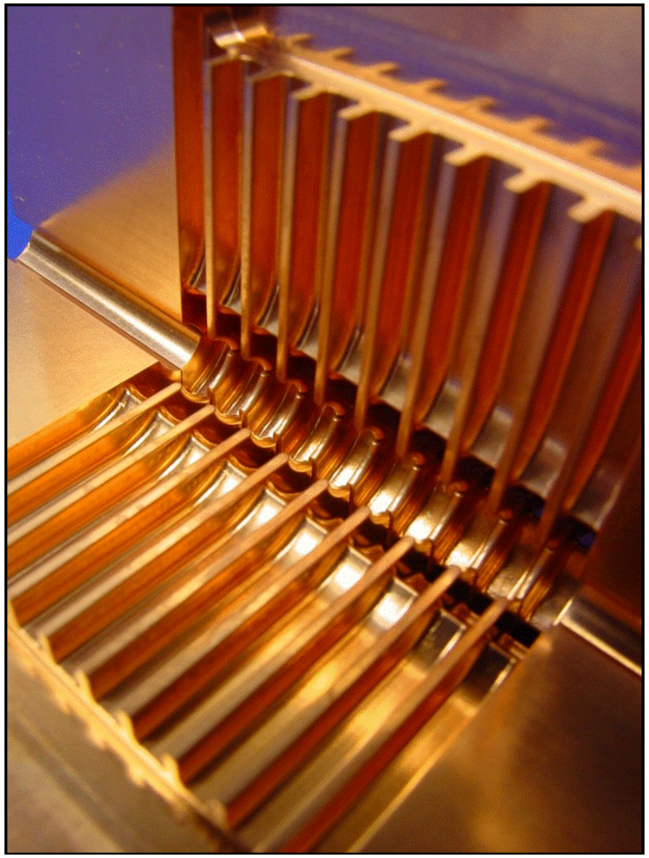
Linear Colliders

(high-energy e+/e- colliders)

Frank Tecker – CERN

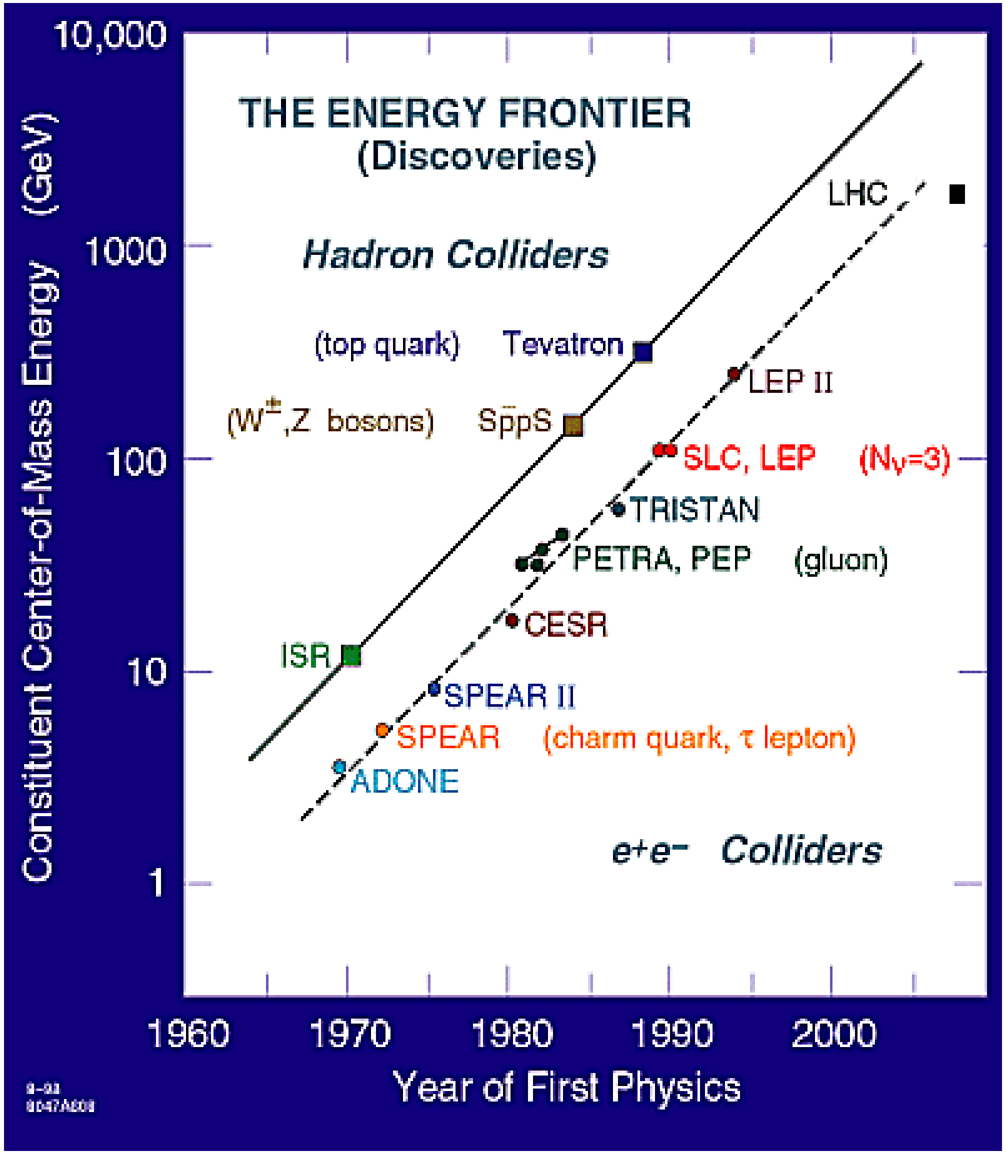
- Physics motivation
- Generic Linear Collider Layout
- ILC (International Linear Collider)
- CLIC (Compact Linear Collider)
- CTF3 (CLIC Test Facility)
- Conclusion



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)

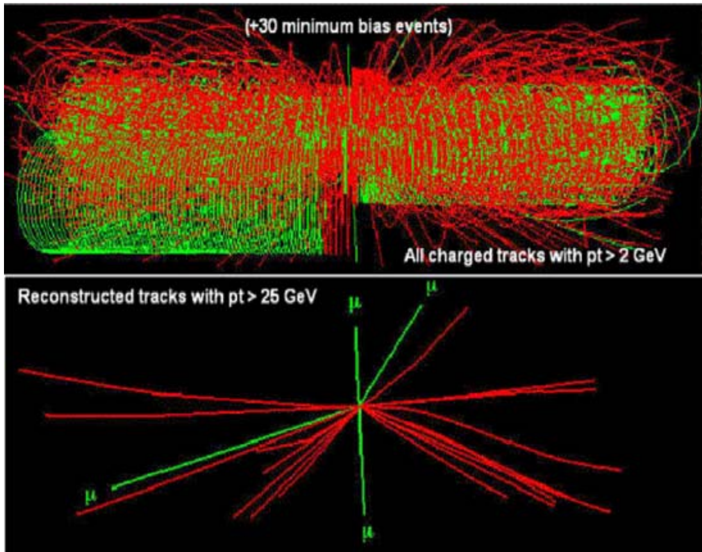
Path to higher energy

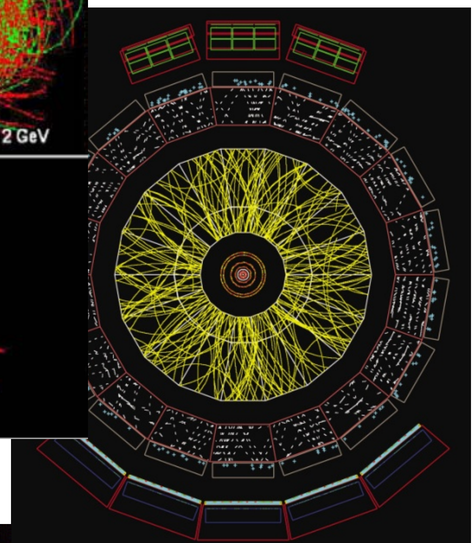


- History: Storage Rings
  - Energy constantly increasing with time
  - Hadron Collider at the energy frontier
  - Lepton Collider for precision physics
- LHC coming online very soon
- Consensus to build Lin. Collider with $E_{cm} > 500$ GeV to complement LHC physics
  (*European strategy for particle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

Lepton vs. Hadron Collisions

LHC: H → ZZ → 4μ

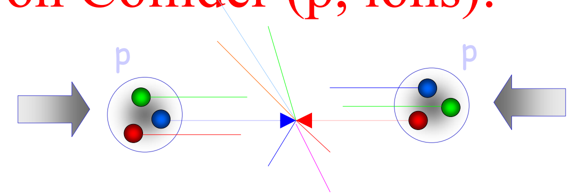




ALICE:
Ion event

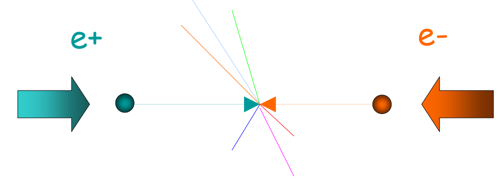
LEP event:
$Z^0 \rightarrow$ 3 jets

- Hadron Collider (p, ions):



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

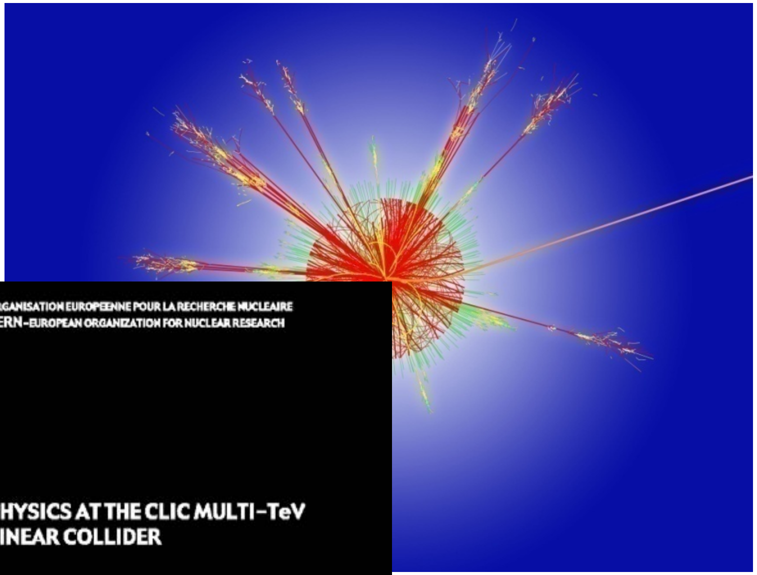
- Lepton Collider:

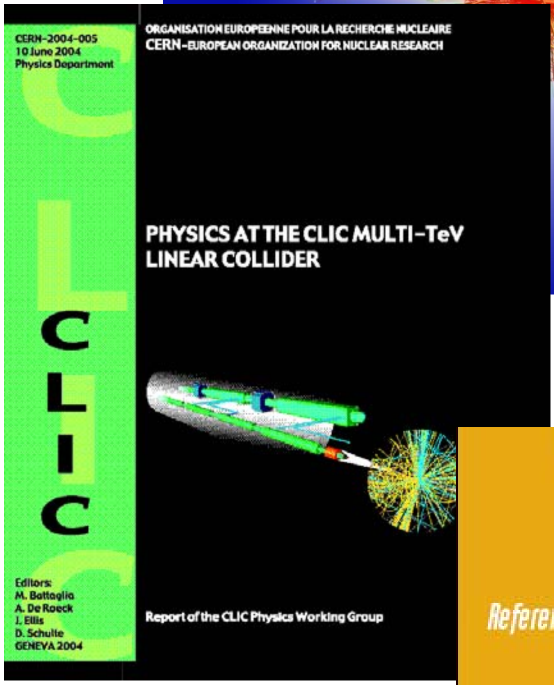


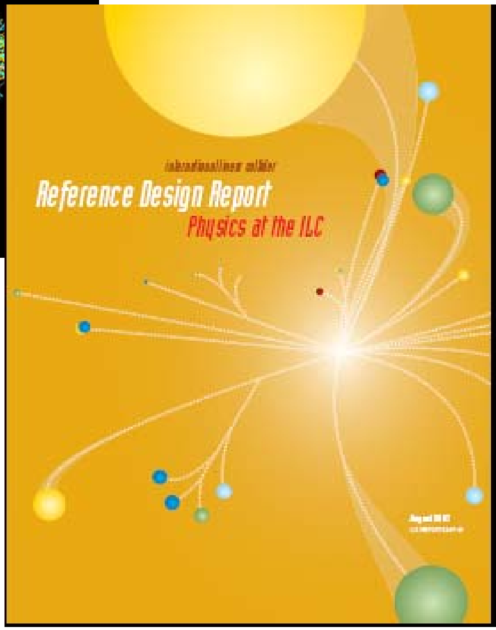
  - Elementary particles
  - Well defined initial state
  - Beam polarization
  - produces particles democratically
  - Momentum conservation eases decay product analysis

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







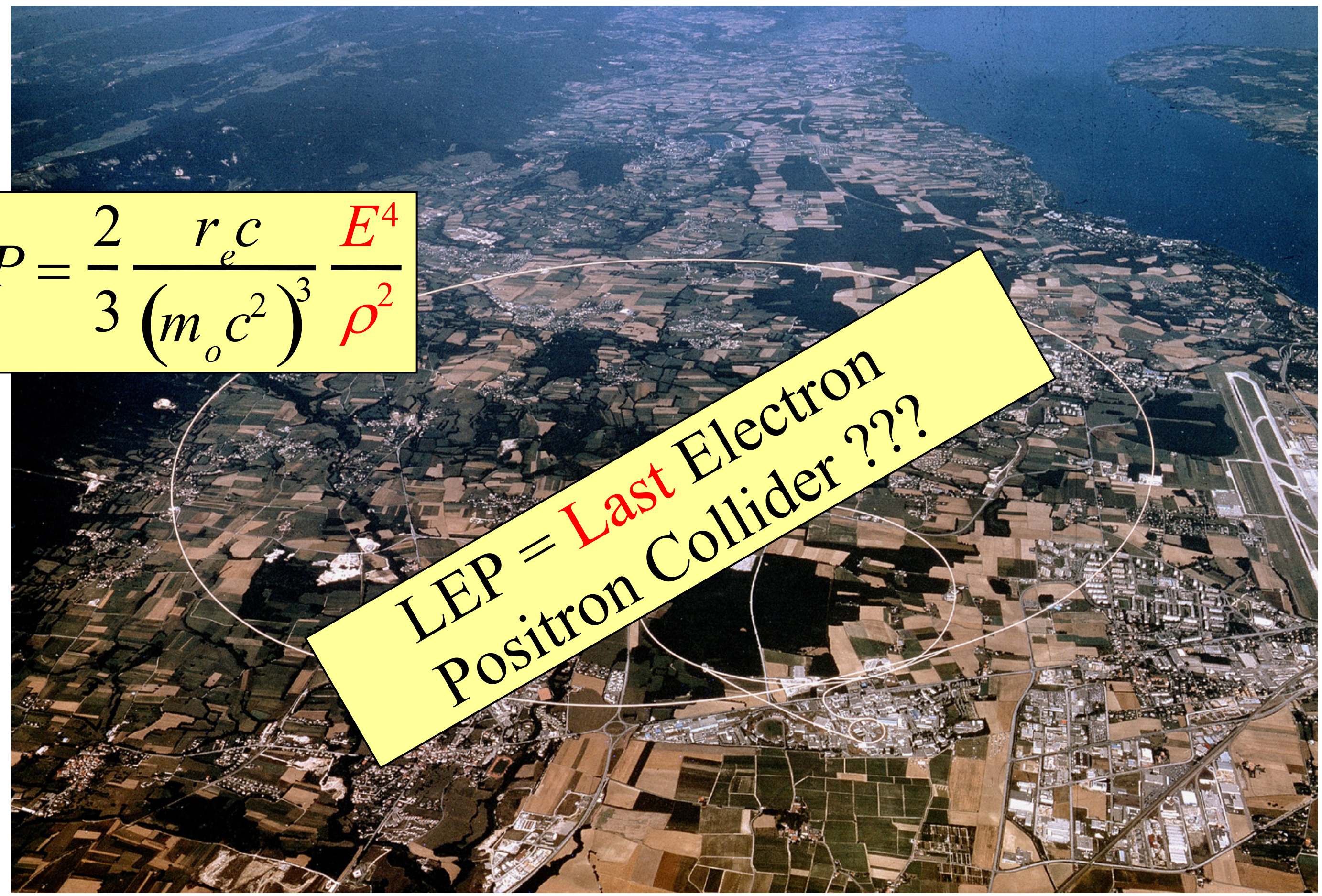
- "Physics at the CLIC Multi-TeV Linear Collider" CERN-2004-005
- "ILC Reference Design Report – Vol.2 – Physics at the ILC" www.linearcollider.org/rdr

The LEP collider

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

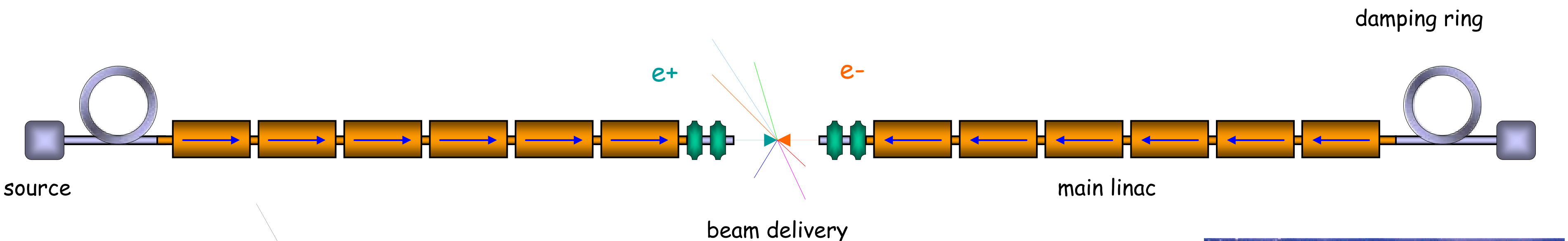
- Problem for any ring: Synchrotron radiation
- Emitted power: scales with E^4 !! and $1/m_0^3$ (much less for heavy particles)
- This energy loss must be replaced by the RF system !!
- particles lost 3% of their energy each turn!

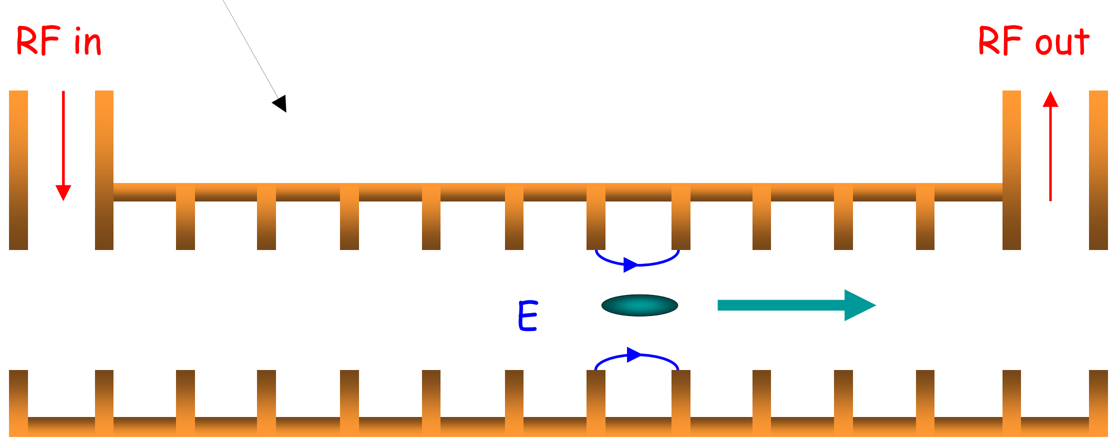
$$P = \frac{2}{3} \frac{r_e c}{\left(m_o c^2\right)^3} \frac{E^4}{\rho^2}$$

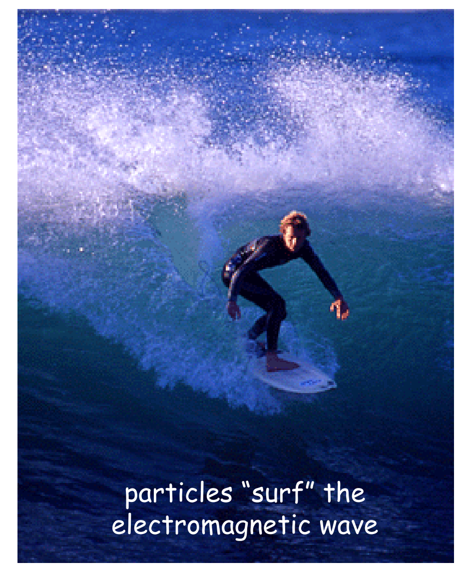


The next lepton collider

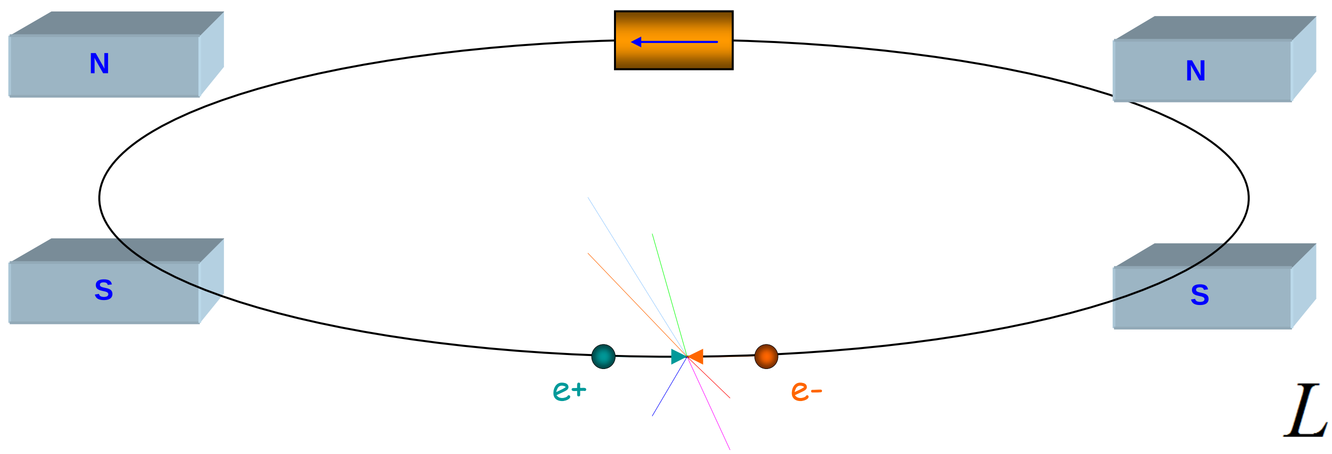
- Solution: LINEAR COLLIDER
- avoid synchrotron radiation
- no bending magnets, huge amount of cavities and RF







Linear Collider vs. Ring



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

- **Storage rings:**
  - accelerate + collide every turn
  - 're-use' RF + 're-use' particles
- $\Rightarrow$ efficient

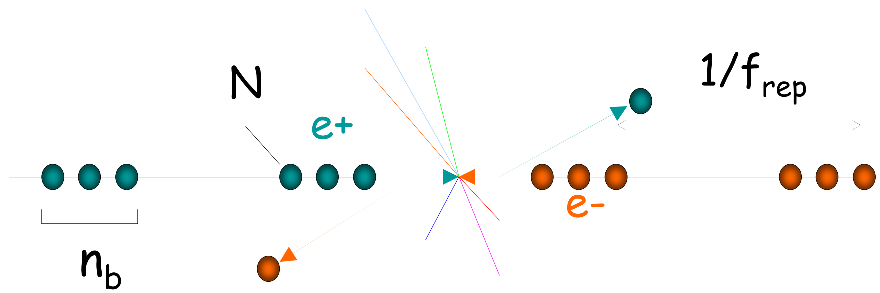
- **Linear Collider:**
  - one-pass acceleration + collision $\Rightarrow$ need
  - high gradient
  - small beam size σ and emittance

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

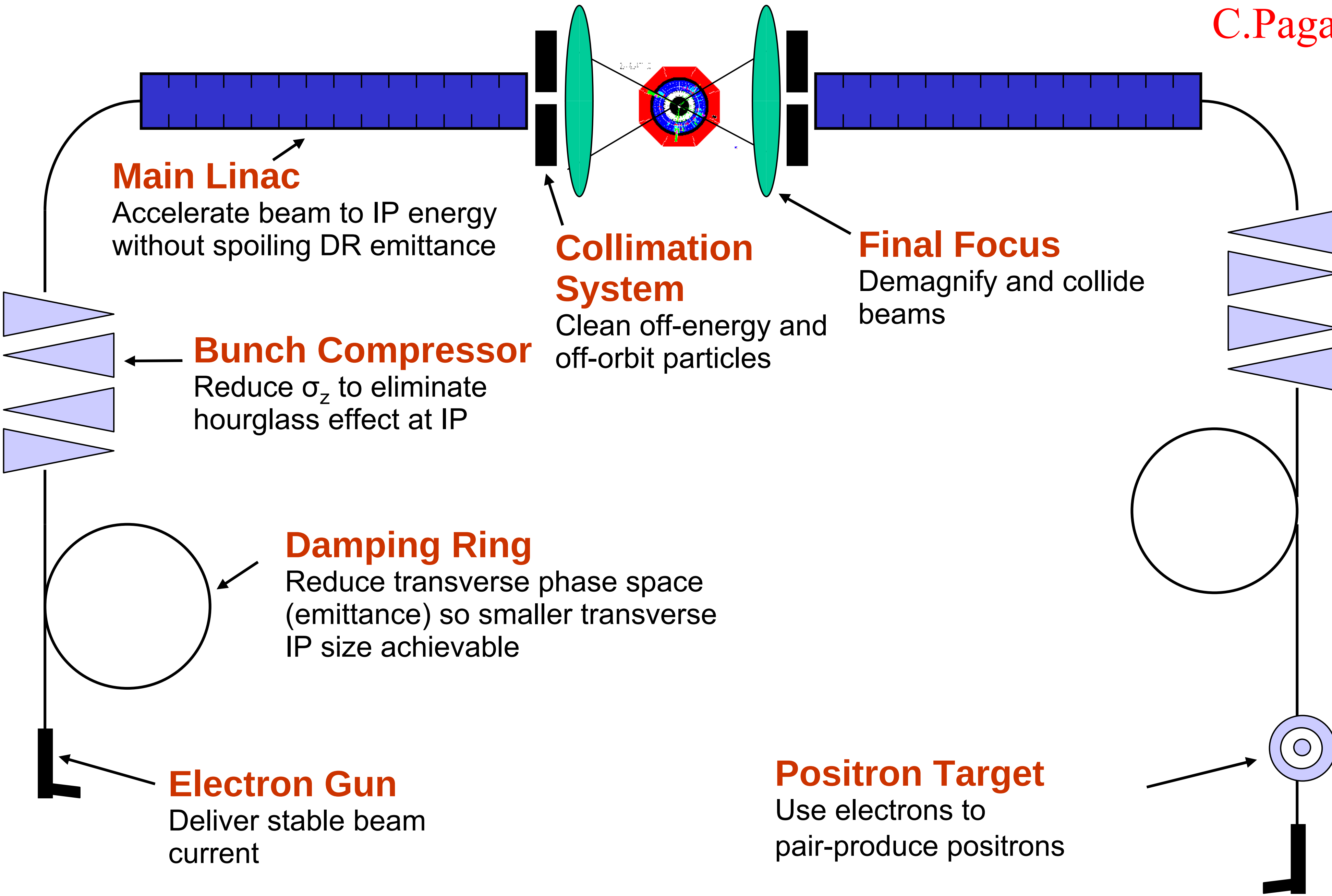


$\sigma_{x,y}$ = transverse beam size

- 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



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

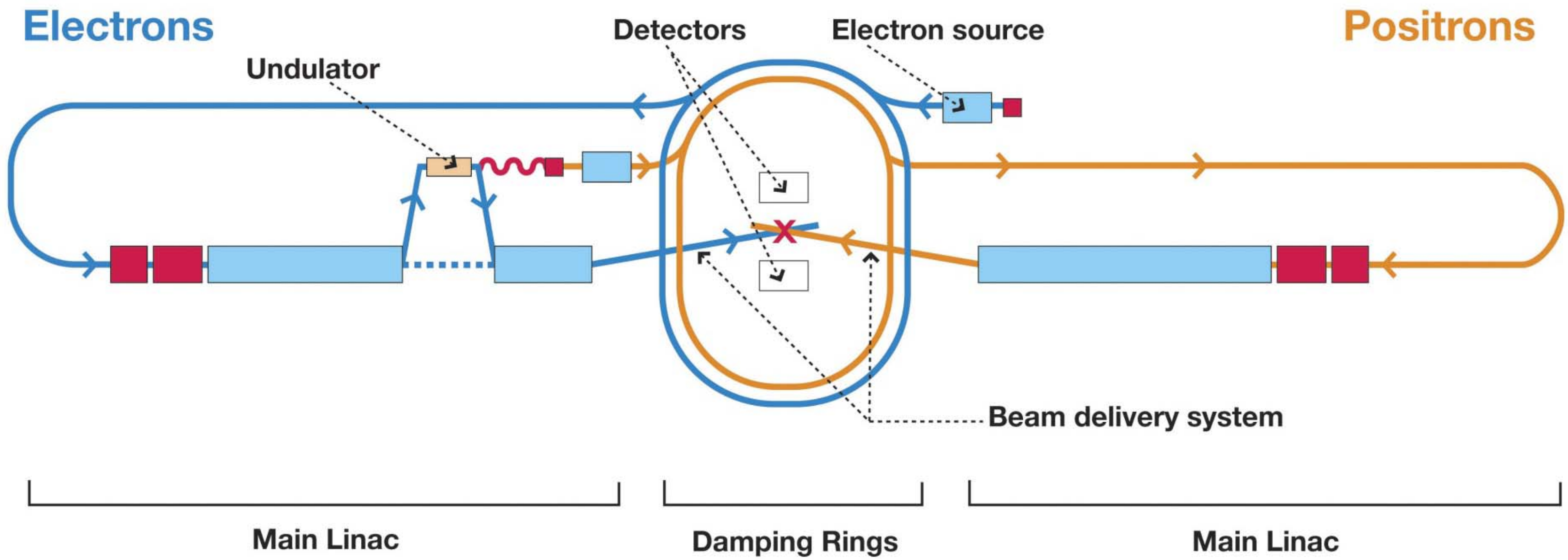
A 10% prototype!

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	130
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

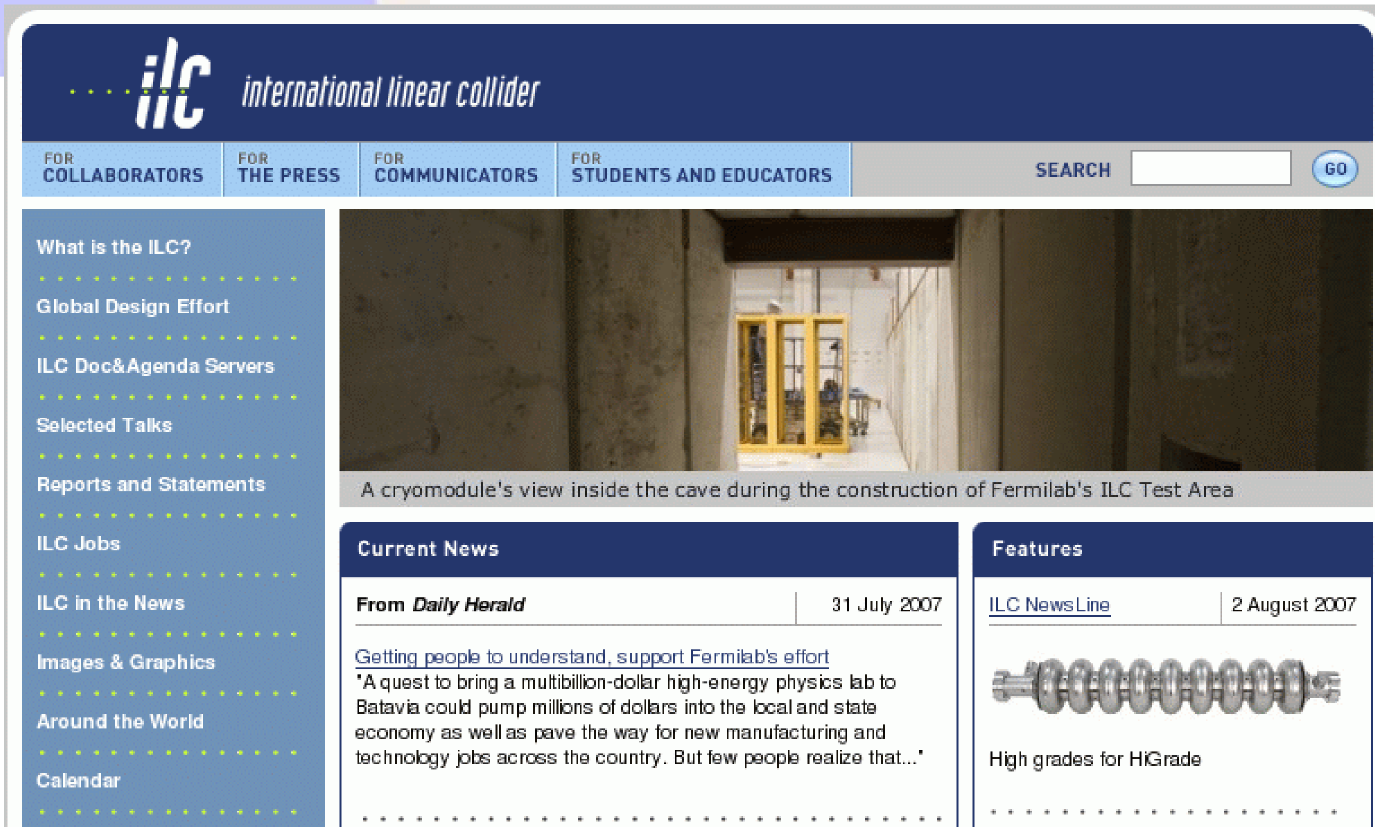
DRAFT

INTERNATIONAL LINEAR COLLIDER

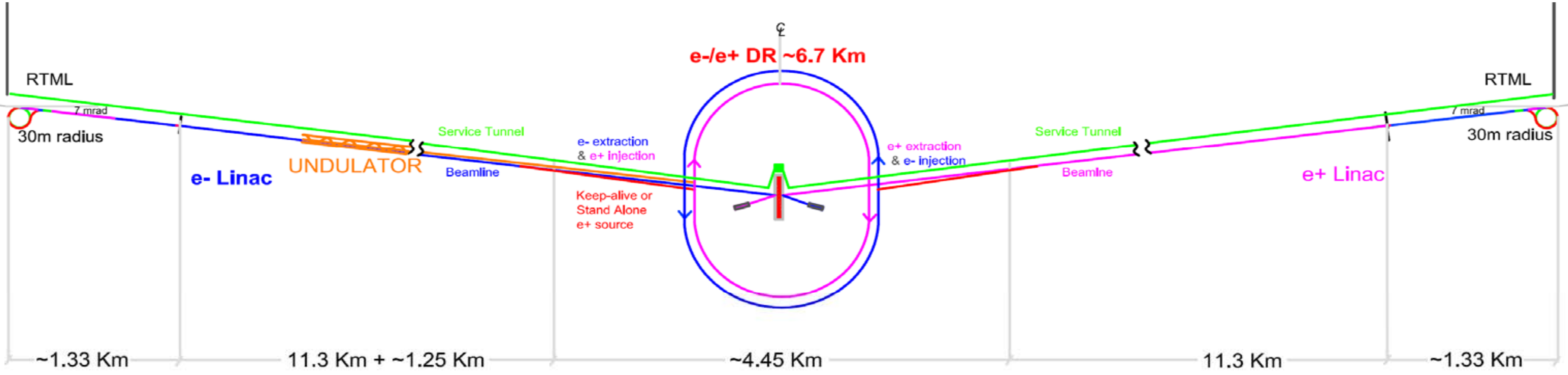
REFERENCE DESIGN REPORT

2007

APRIL, 2007

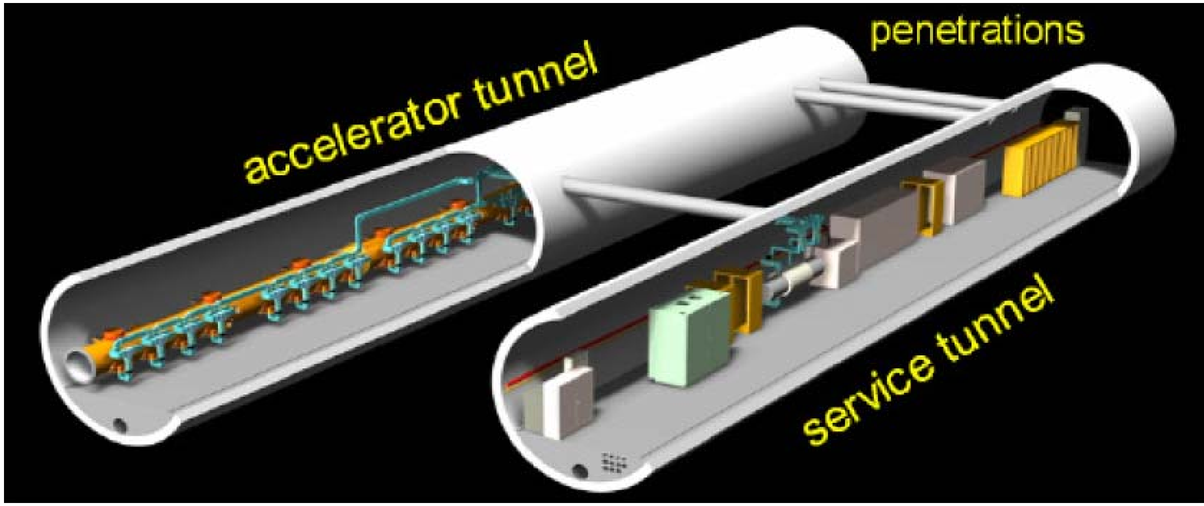


ILC Schematic



Schematic Layout of the 500 GeV Machine

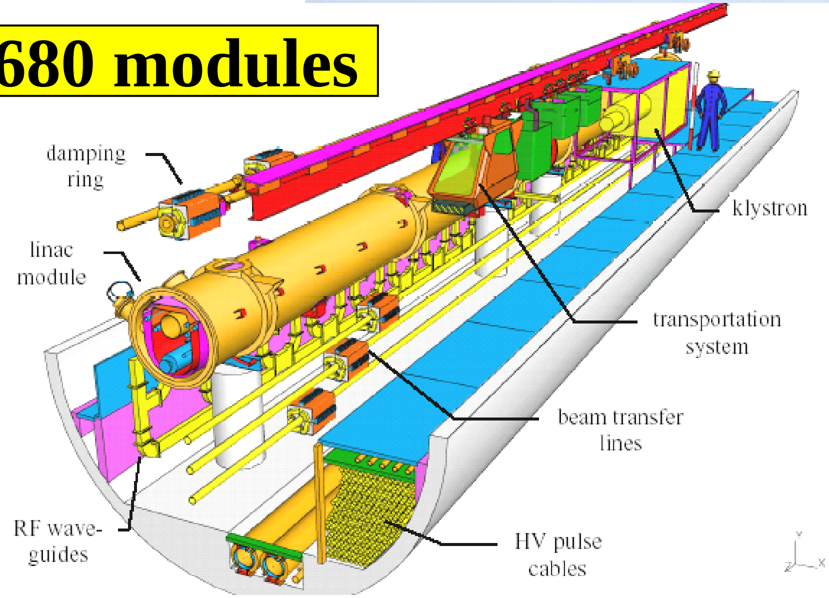
- Two 250 Gev linacs arranged to produce nearly head on e+e- collisions
  - Single IR with 14 mrad crossing angle
- Centralized injector
  - Circular 6.7 km damping rings
  - Undulator-based positron source
- Dual tunnel configuration for safety and availability

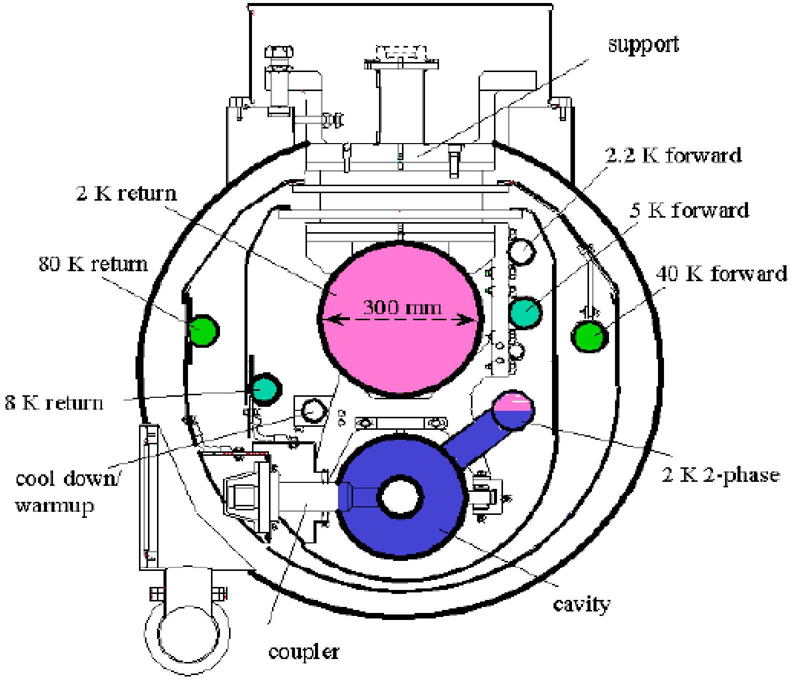


The core technology for the ILC is 1.3GHz superconducting RF cavity intensely developed in the TESLA collaboration, and recommended for the ILC by the ITRP on 2004 August.
The cavities are installed in a long cryostat cooled at 2K, and operated at gradient 31.5MV/m.

14560 cavities

1680 modules

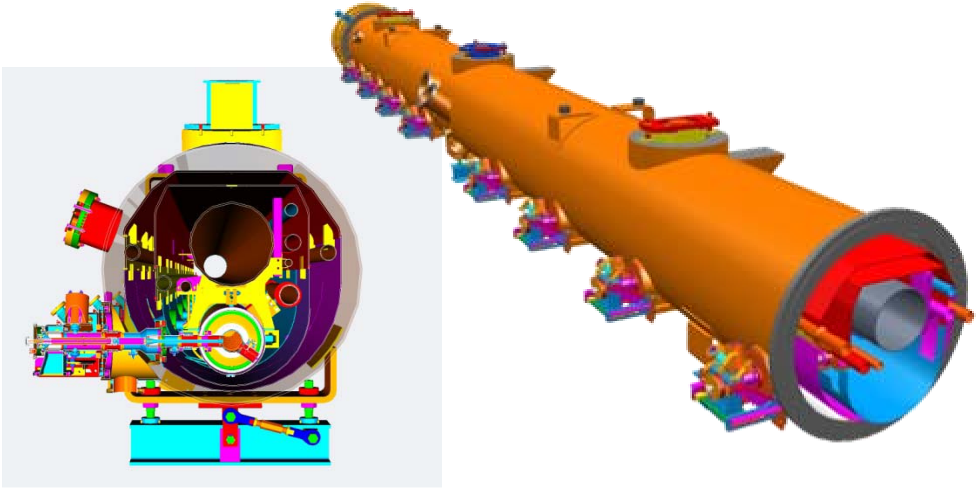




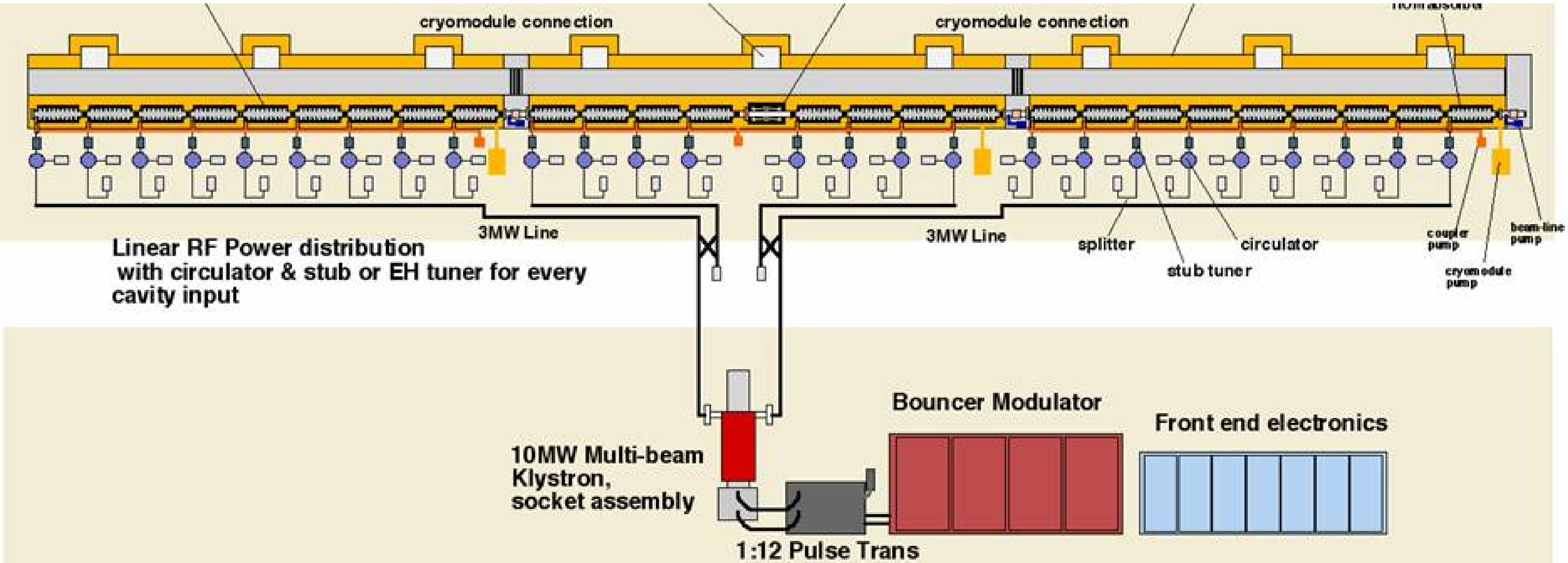
ILC Main Linac RF Unit

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**

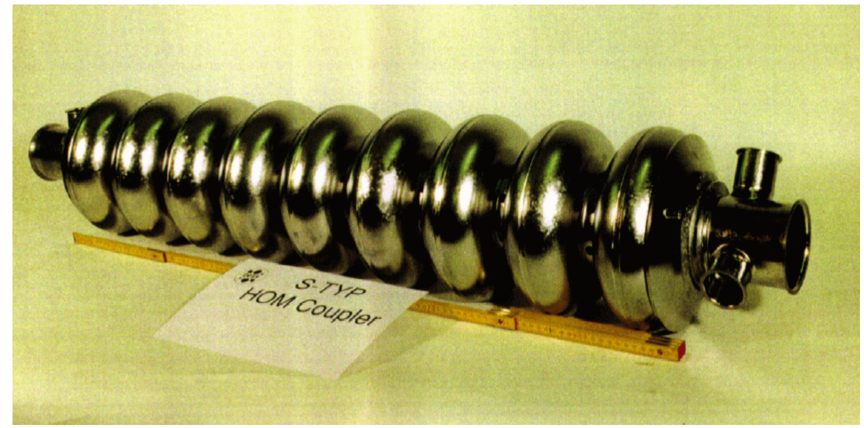


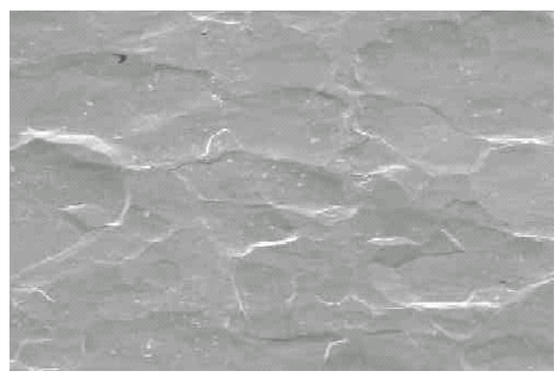
Total of 1680 cryomodules and 14 560 SC RF cavities



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





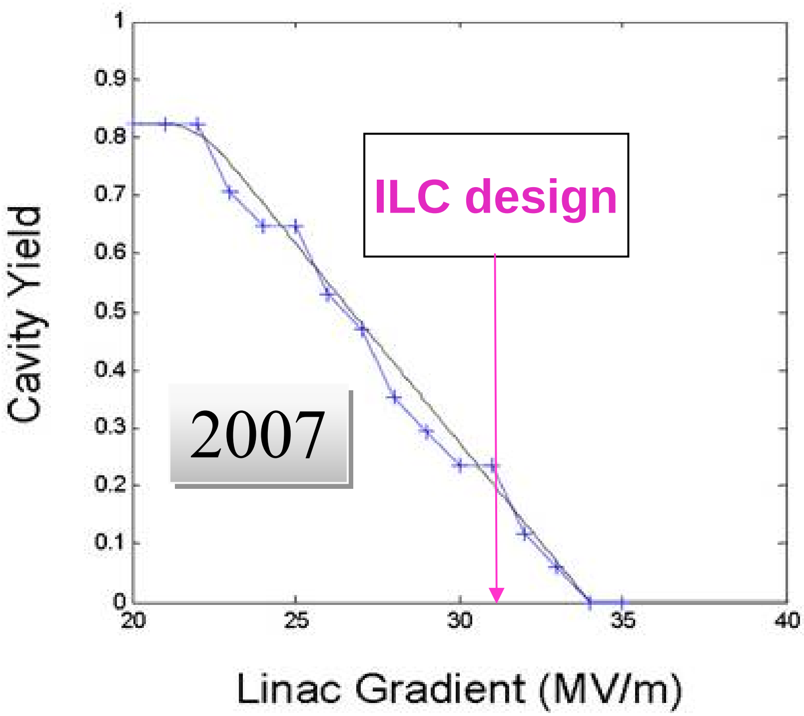
Chemical polish

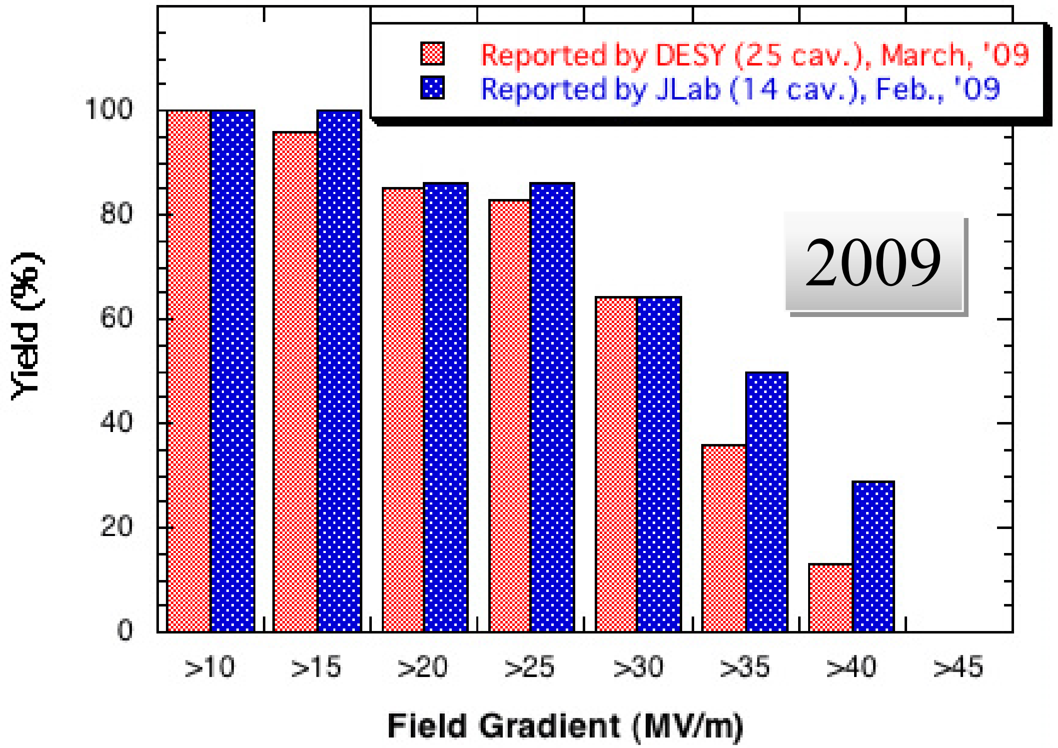
⇒

Electropolishing

Achieved accelerating gradients

- 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

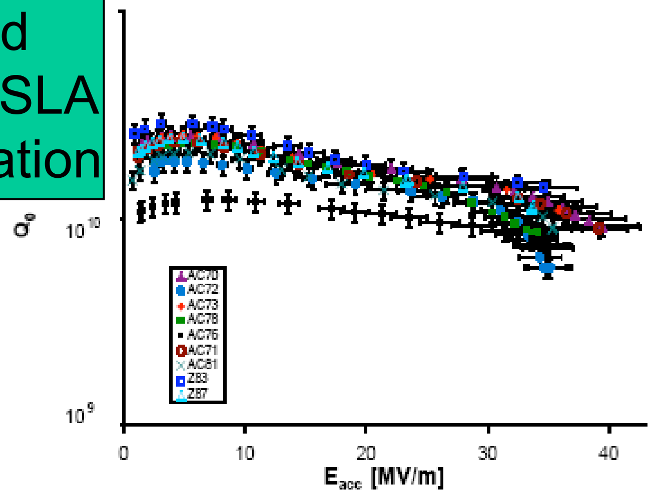




R&D of SCRF cavities

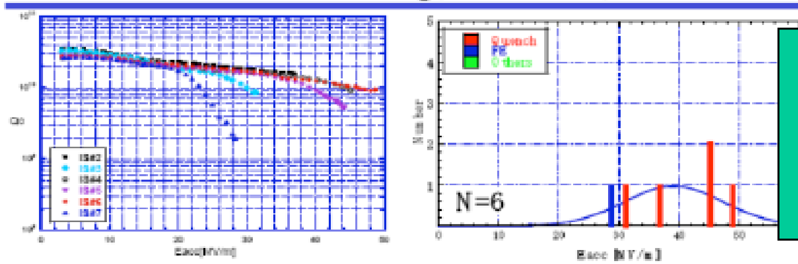
TESLA Nine-Cells: (Proof-of-Principle)
Best tests of 9 best Cavities (Vertical Test Results)

Derived From TESLA Collaboration



(A) CBP+CP+Anneal+EP(80μm) +HPR+Baking(120C*48hrs)

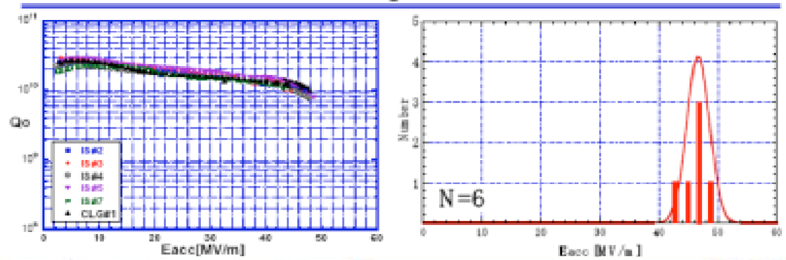
K. Saito et al.



New preparation techniques

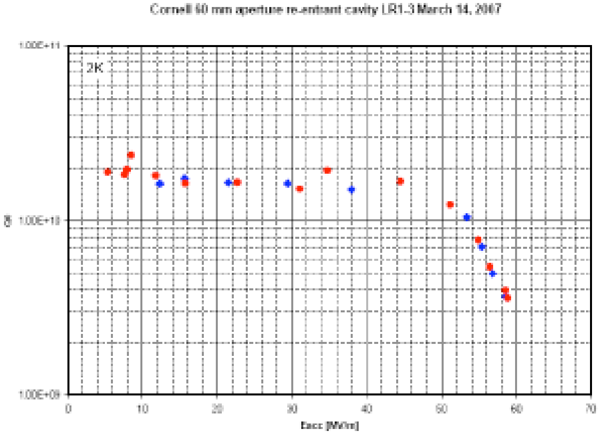
(D) +EP(20μm)+EP(3μm, fresh, closed) +HPR+Baking (120C*48hrs)

K. Saito et al.

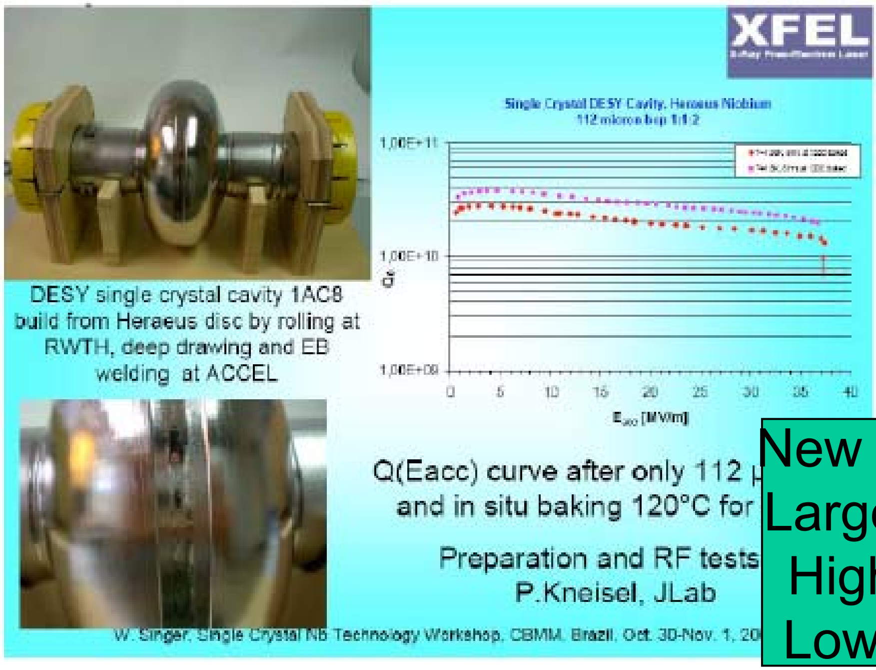


60mm-Aperture Re-Entrant Cavity, 58 MV/m!

KEK/Cornell Collaboration



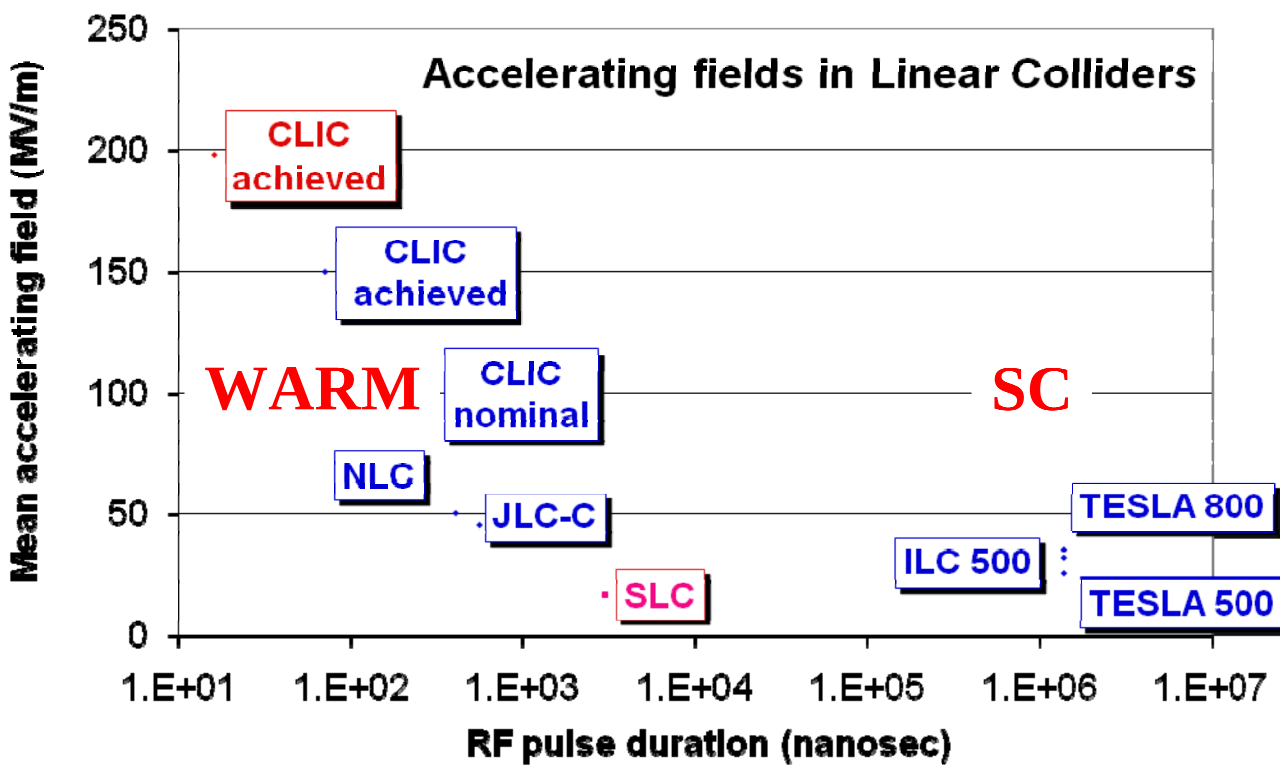
New cavity shapes



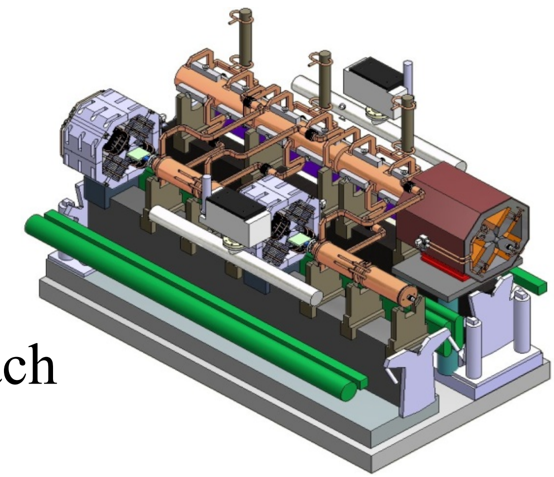
New material
Large grains
Higher perf
Lower cost

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 (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 $\Rightarrow E_{cm} = 0.5 – 3$ 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 2010 (possibly TDR by 2016)

World-wide CLIC&CTF3 Collaboration

33 Institutes involving 21 funding agencies and 18 countries

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

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

JINR (Russia)
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Oslo University (Norway)

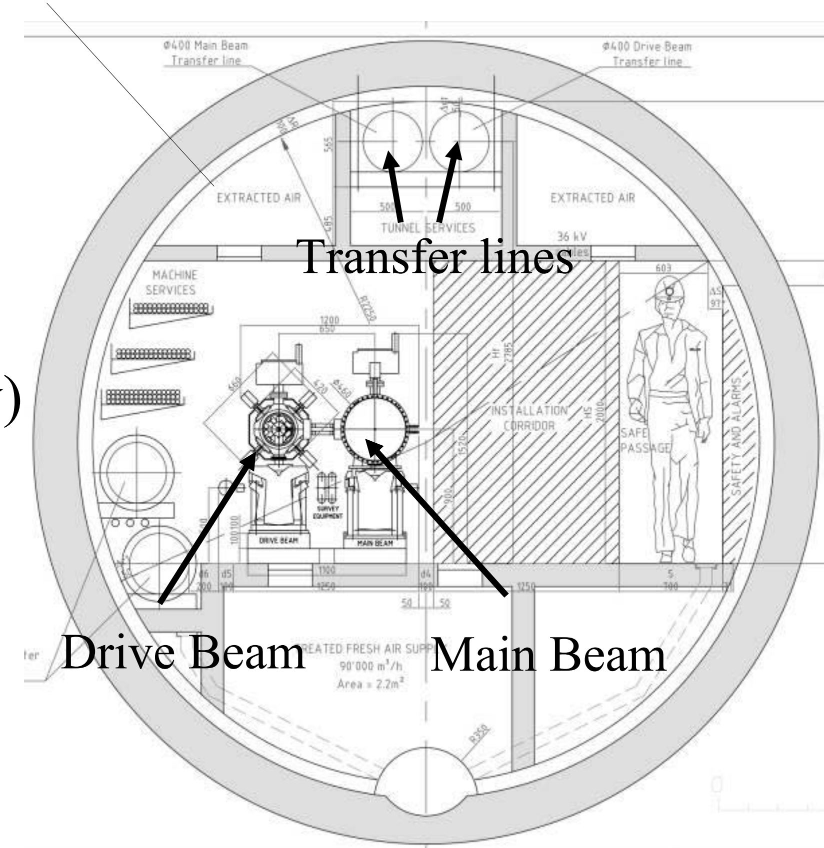
Patras University (Greece)
Polytech. University of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Thrace University (Greece)
Uppsala University (Sweden)

CLIC – basic features

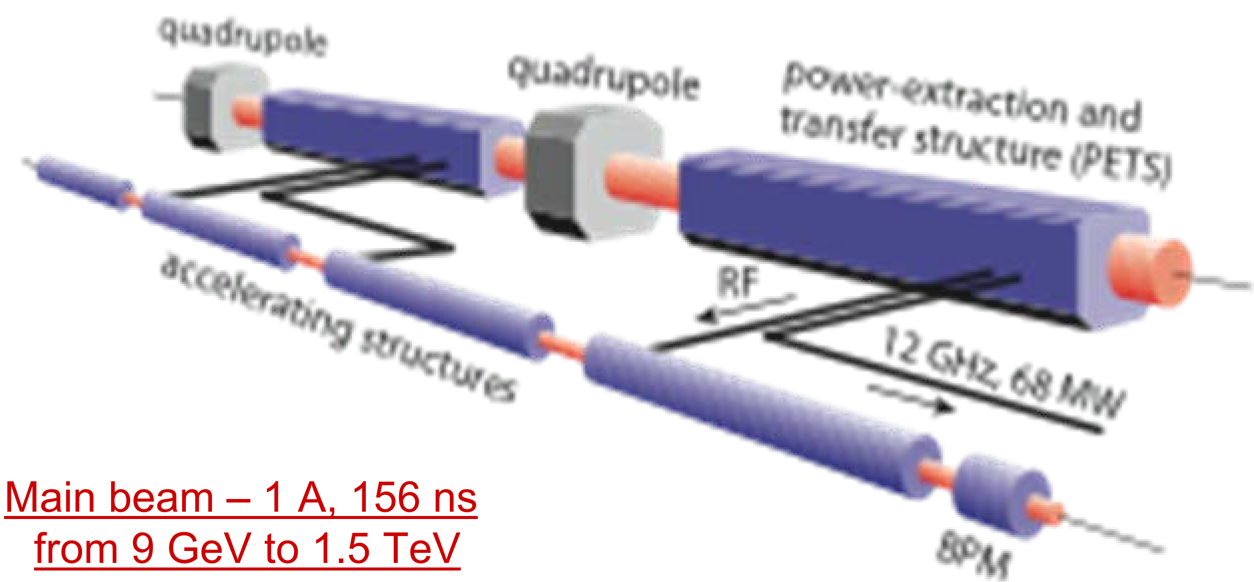
- High acceleration gradient
  - "Compact" collider – total length < 50 km
  - Normal conducting acceleration structures
  - High acceleration frequency (12 GHz)
- Two-Beam Acceleration Scheme
  - High charge Drive Beam (low energy)
  - Low charge Main Beam (high collision energy)
  - ⇒ Simple tunnel,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

CLIC TUNNEL CROSS-SECTION

4.5 m diameter



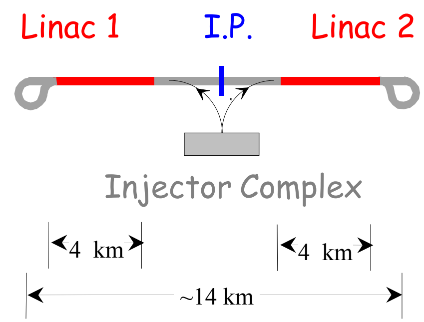
Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV



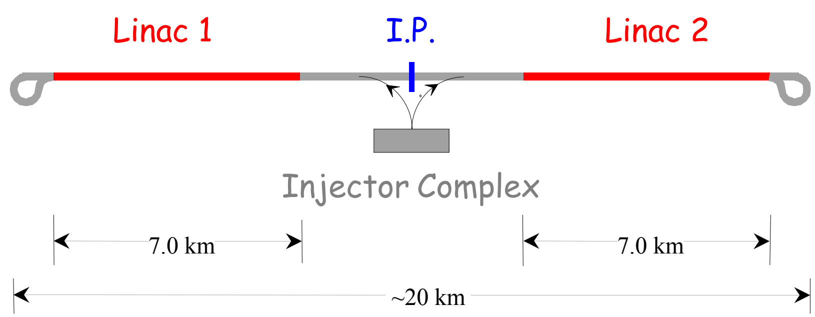
Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

CLIC Layout at various energies

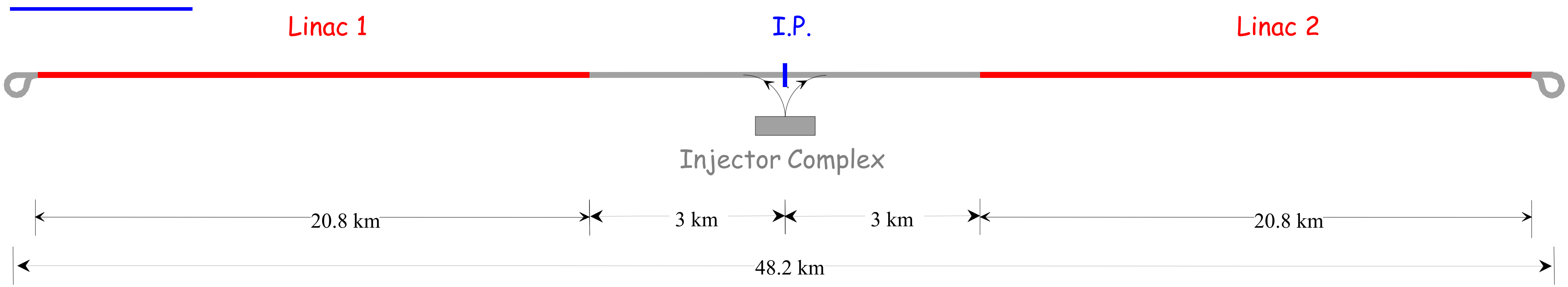
0.5 TeV Stage



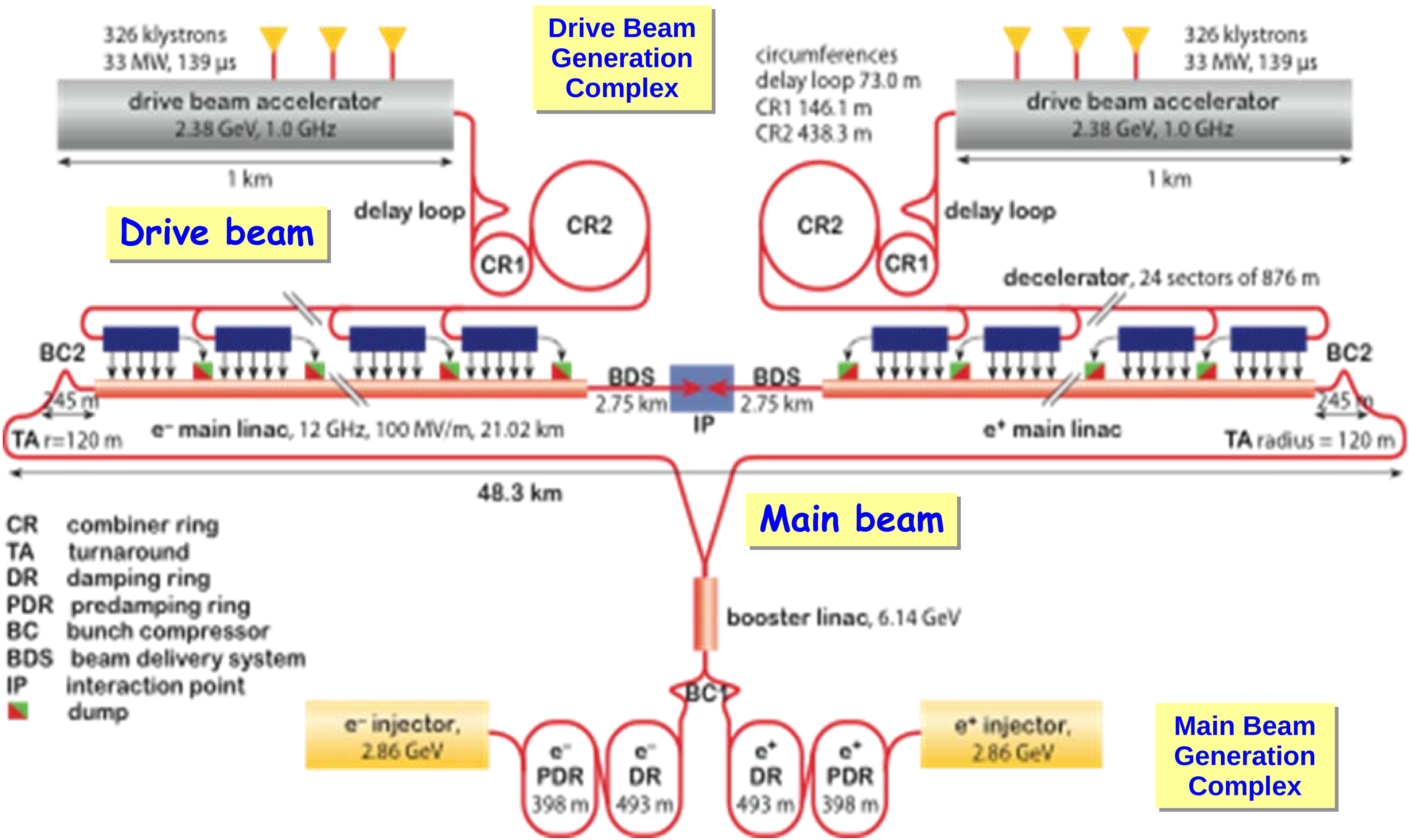
1 TeV Stage



3 TeV Stage



CLIC – overall layout – 3 TeV

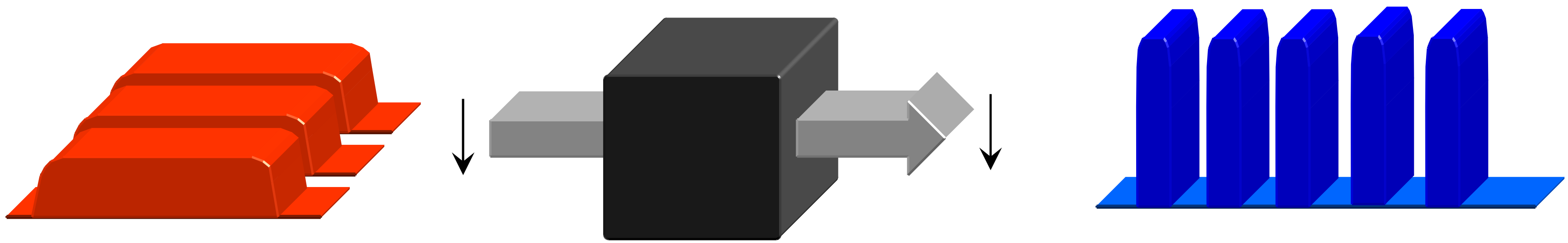


CLIC main parameters

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

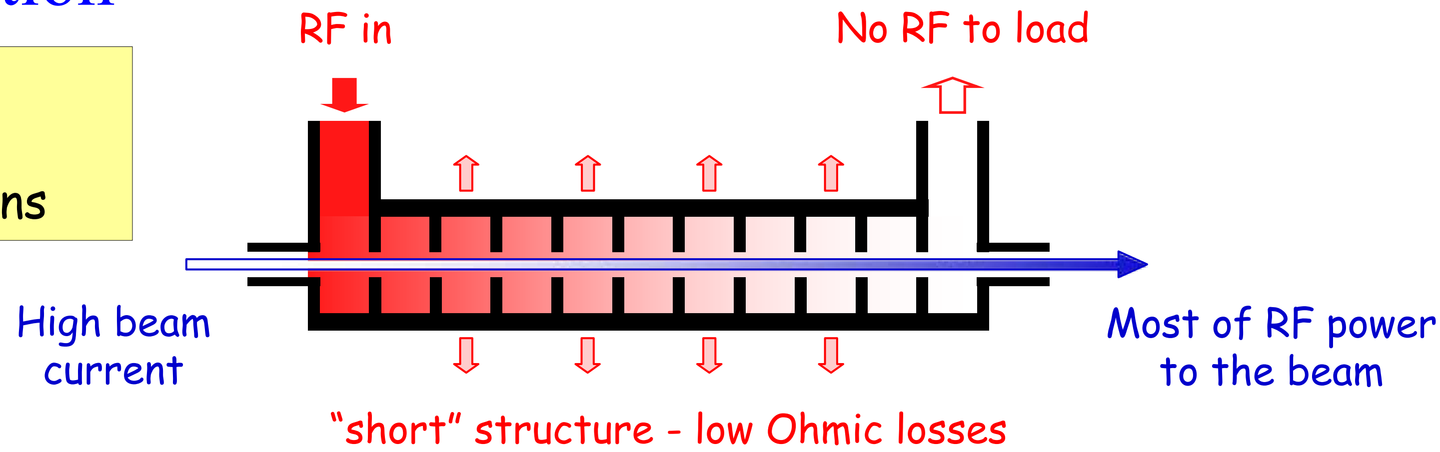
- Very high gradients possible with NC accelerating structures at high RF frequencies (30 GHz → 12 GHz) and short RF pulses (~100 ns)
- Extract required high RF power from an intense e- "drive beam"
- Generate efficiently long beam pulse and compress it (in power + frequency)



Drive beam generation basics

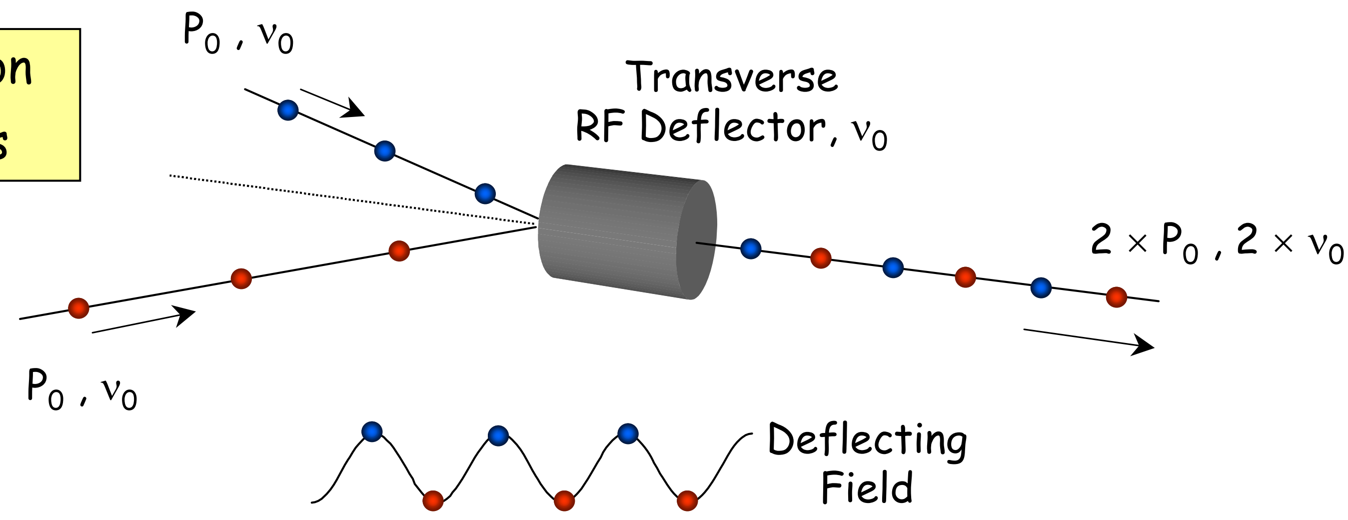
- Efficient acceleration

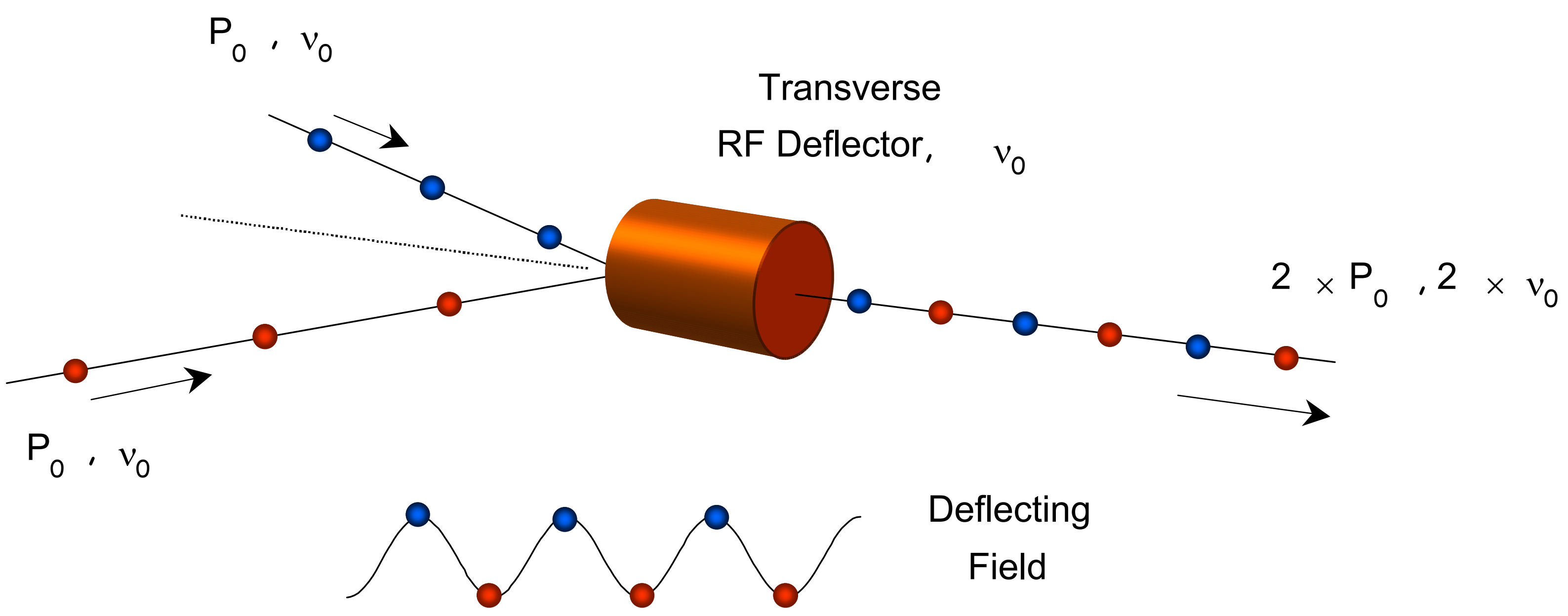
Full beam-loading acceleration in traveling wave sections



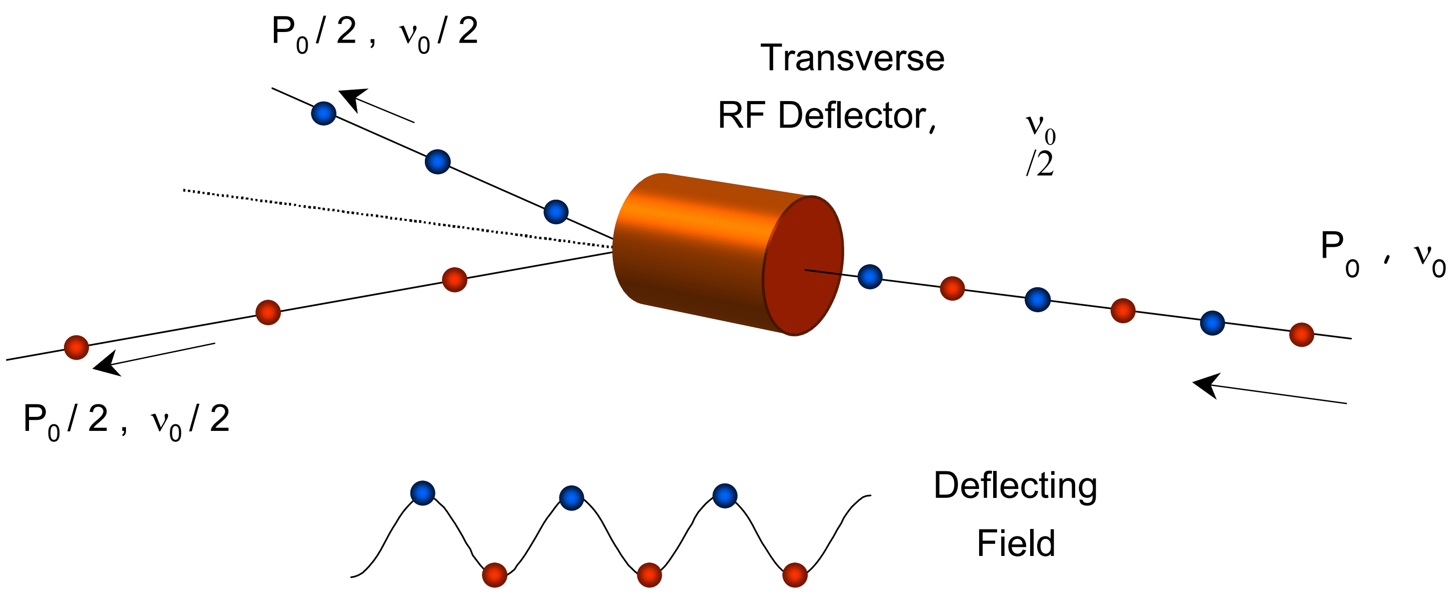
- Frequency multiplication

Beam combination/separation by transverse RF deflectors



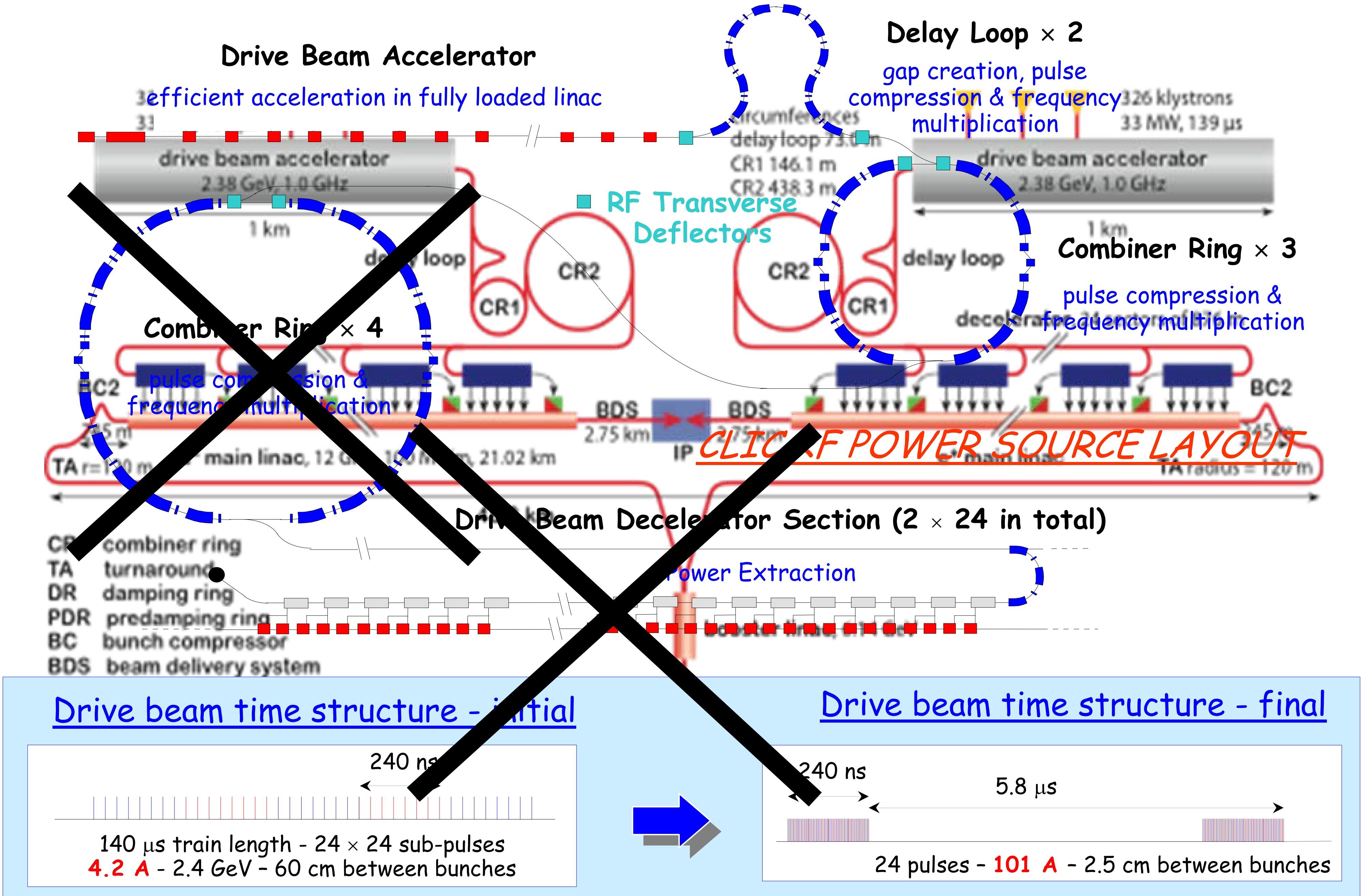


P0 , ν0
Transverse
RF Deflector, ν0
2 × P0 , 2 × ν0
P0 , ν0
Deflecting
Field



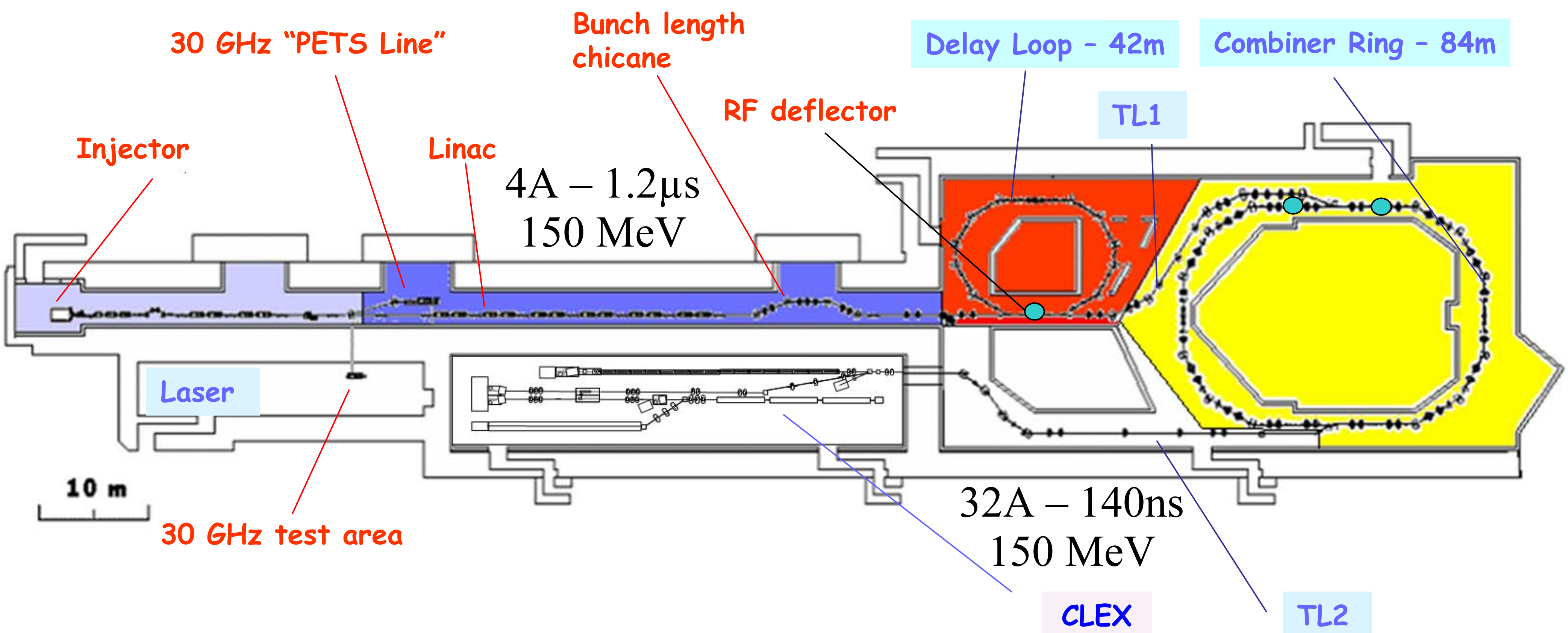
$P_0 / 2$, $\nu_0 / 2$
Transverse
RF Deflector, ν_0 /2
P_0 , ν_0
$P_0 / 2$, $\nu_0 / 2$
Deflecting
Field

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)

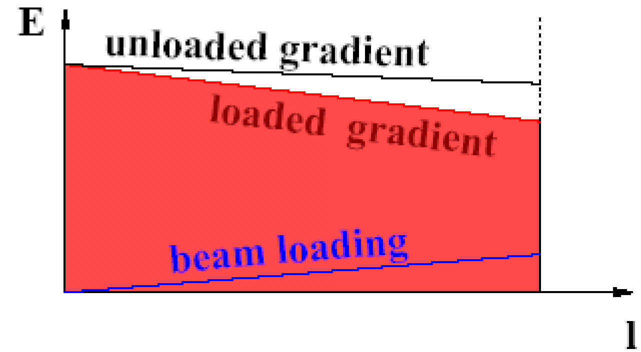


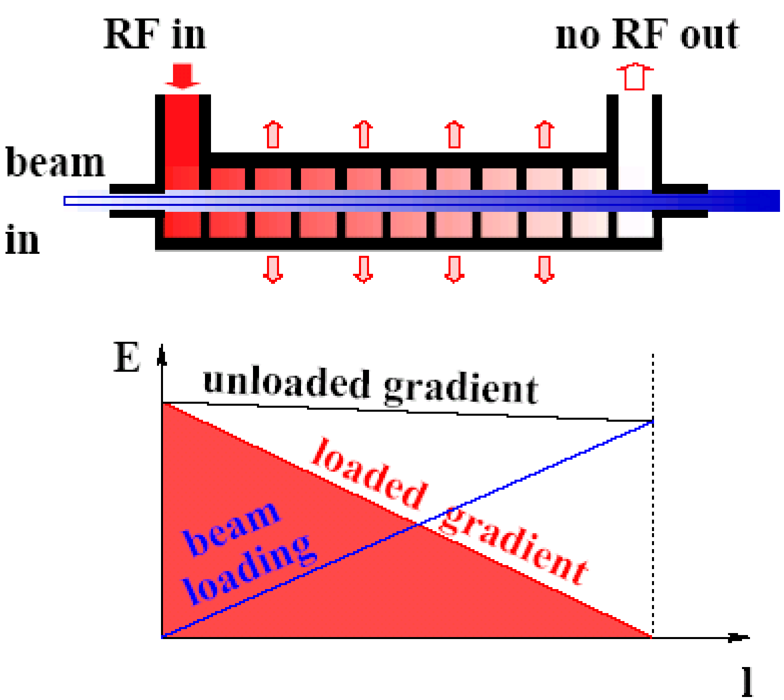
Fully loaded operation

- efficient power transfer from RF to the beam needed

"Standard" situation:

- small beam loading
- power at structure exit lost in load

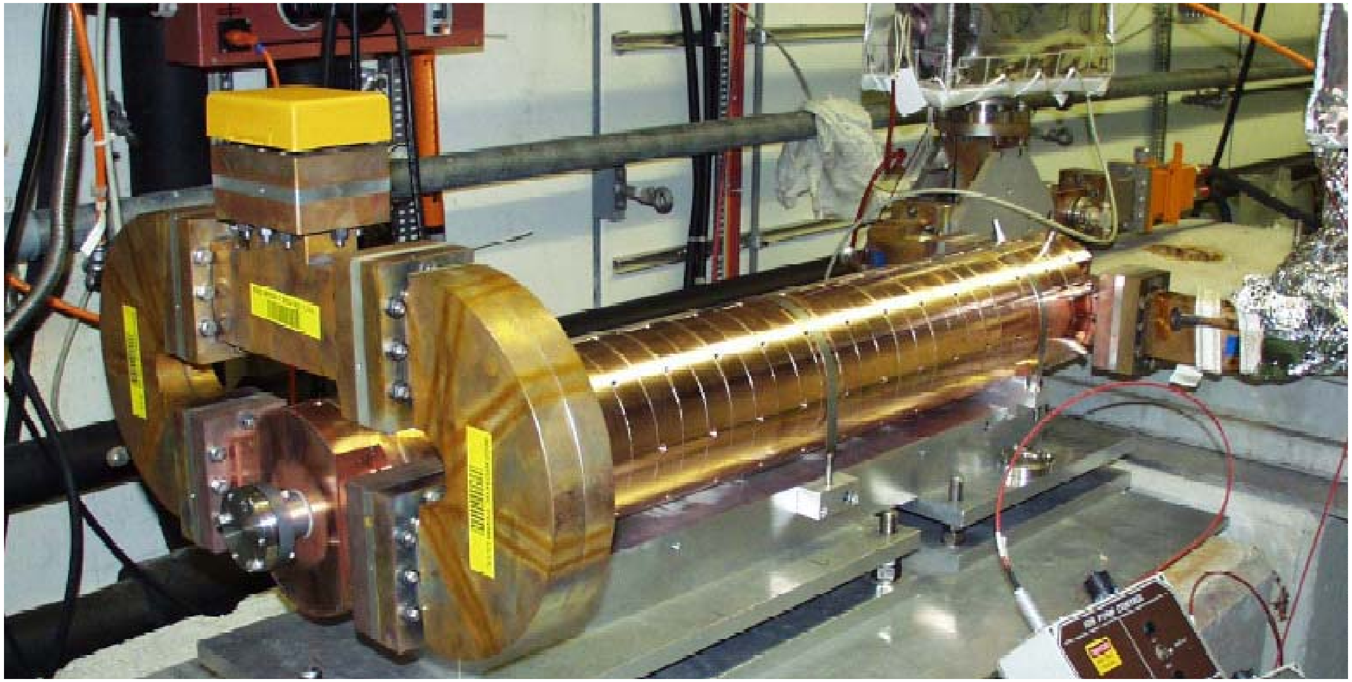




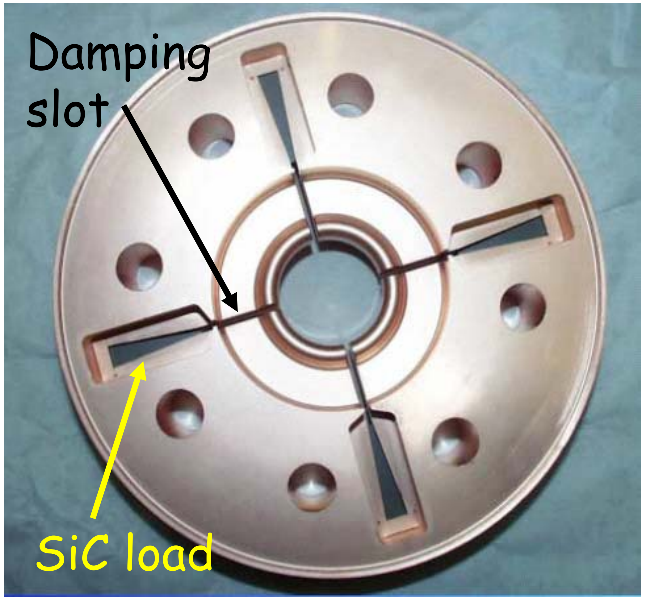
"Efficient" situation:

- high beam current
- high beam loading
- no power flows into load
- $V_{ACC} \approx 1/2\ V_{unloaded}$

CTF3 linac acceleration structures



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

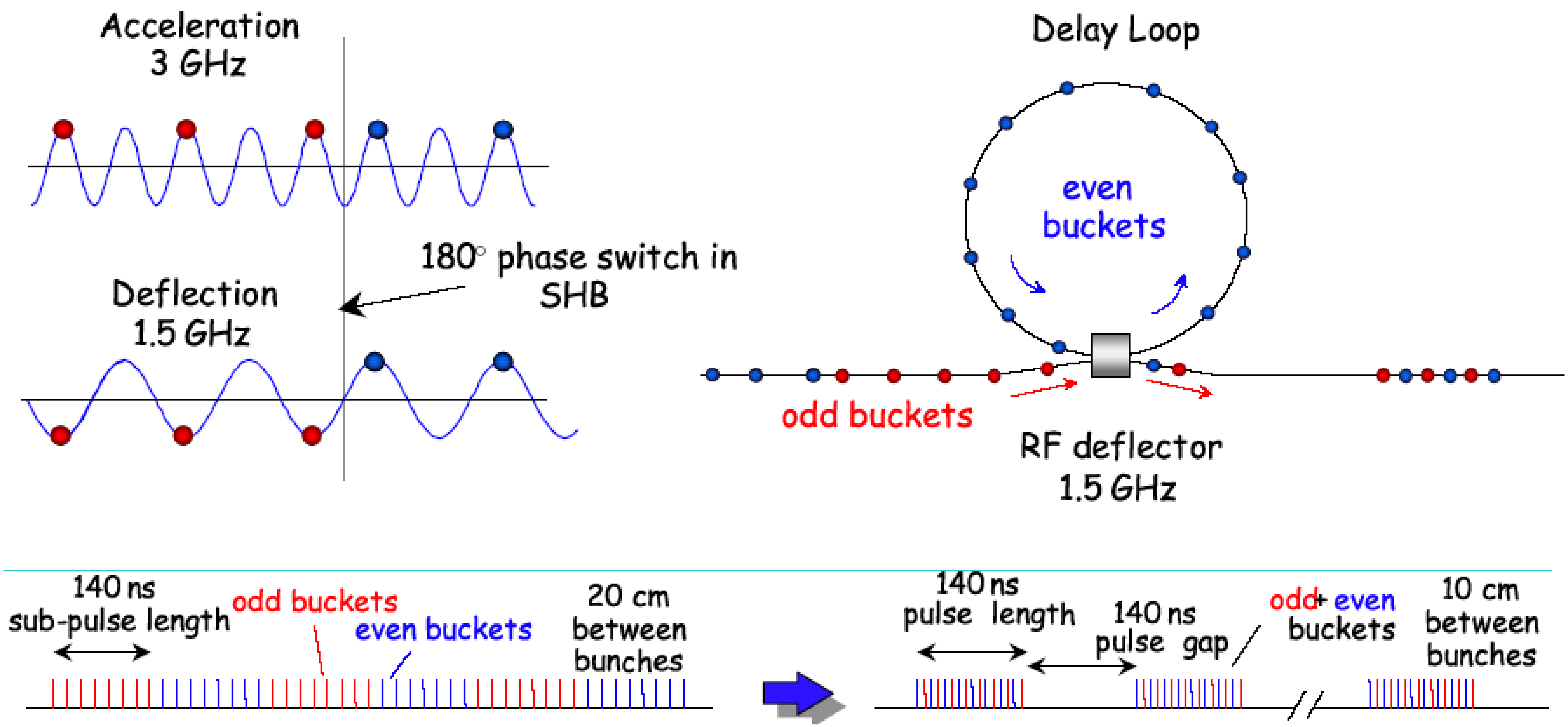


- 3 GHz $2\pi/3$ traveling wave structure
- constant aperture
- slotted-iris damping + detuning with nose cones
- up to 4 A 1.4 μs beam pulse stably accelerated

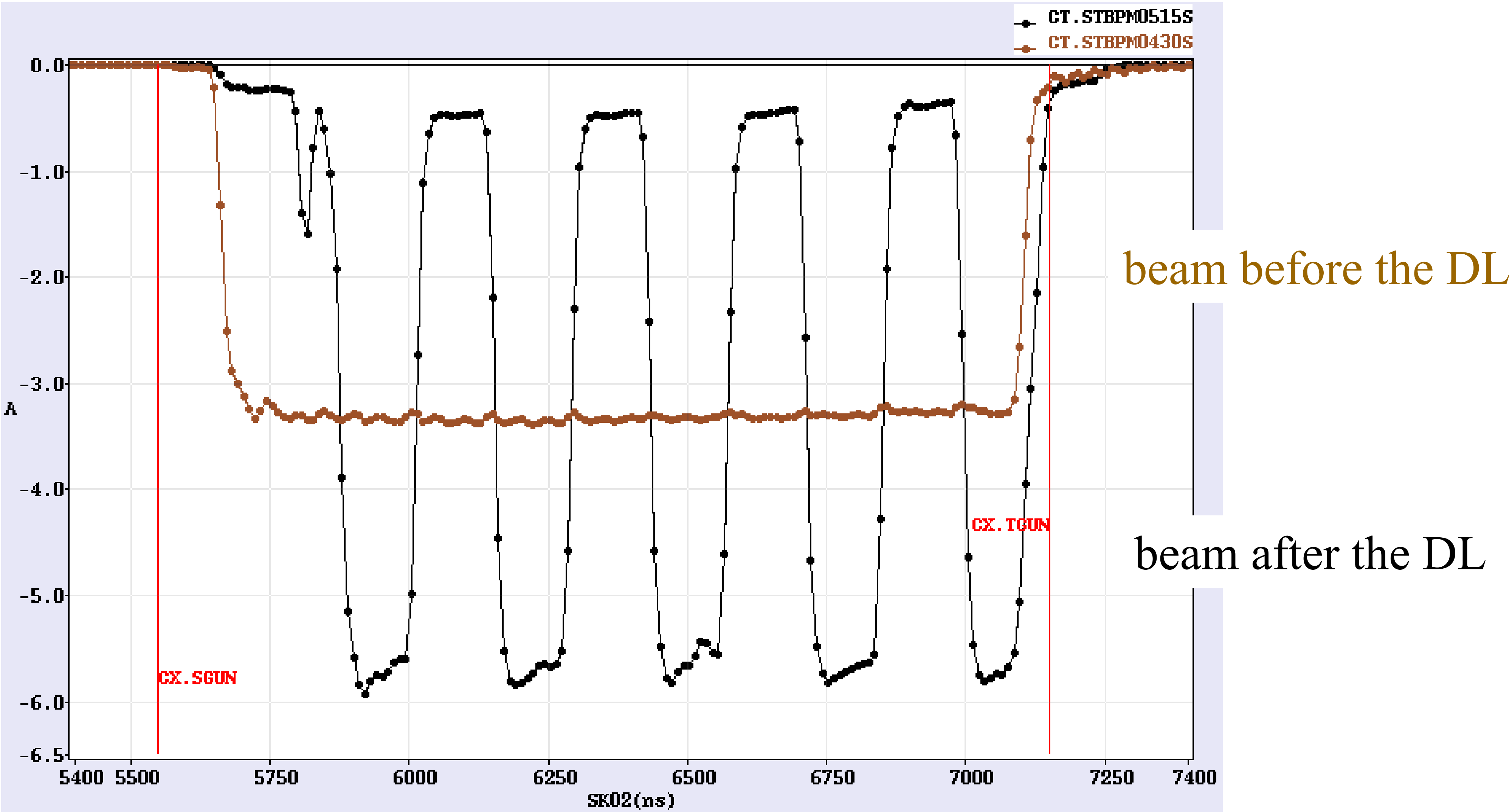
- Measured RF-to-beam efficiency 95.3%
- Theory 96% (~ 4 % ohmic losses)

Delay Loop Principle

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



CTF3 Delay Loop

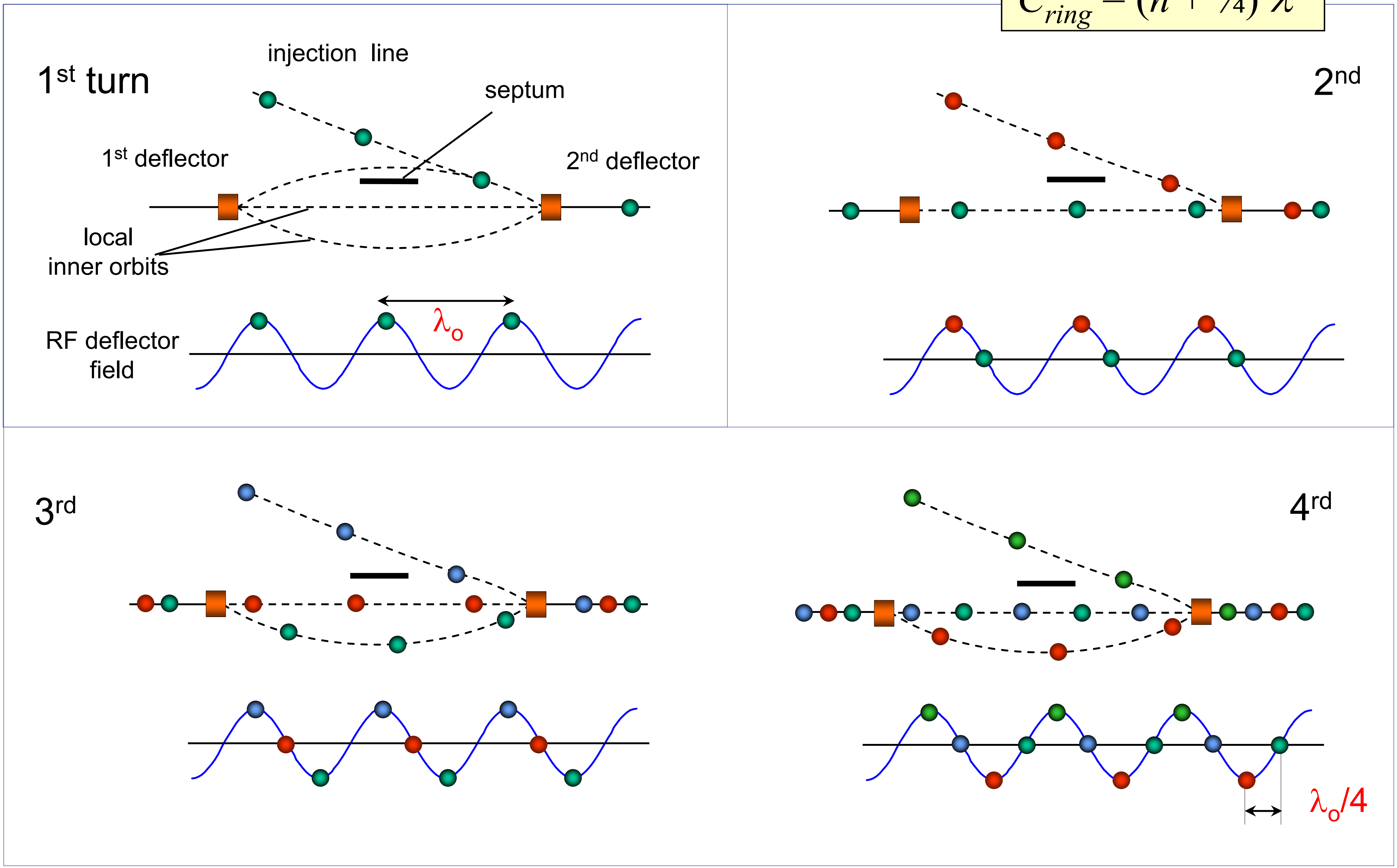


- 3.3 A after chicane => < 6 A after combination (satellites)

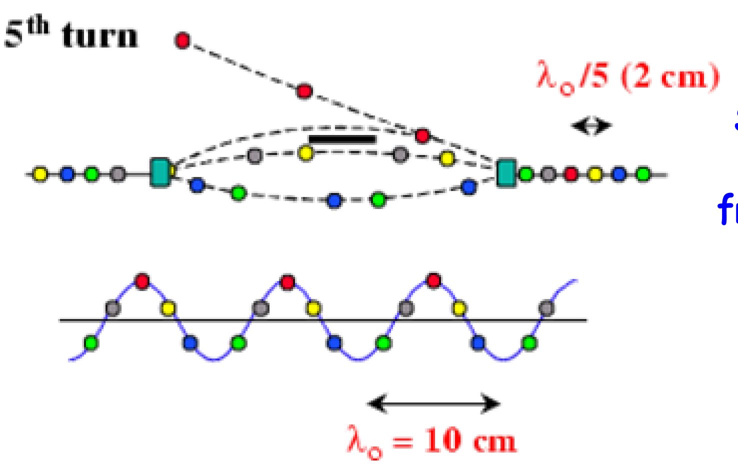
demonstrated in CTF3

- combination factors up to 5 reachable in a ring

$$C_{ring} = (n + ¼)\ \lambda$$

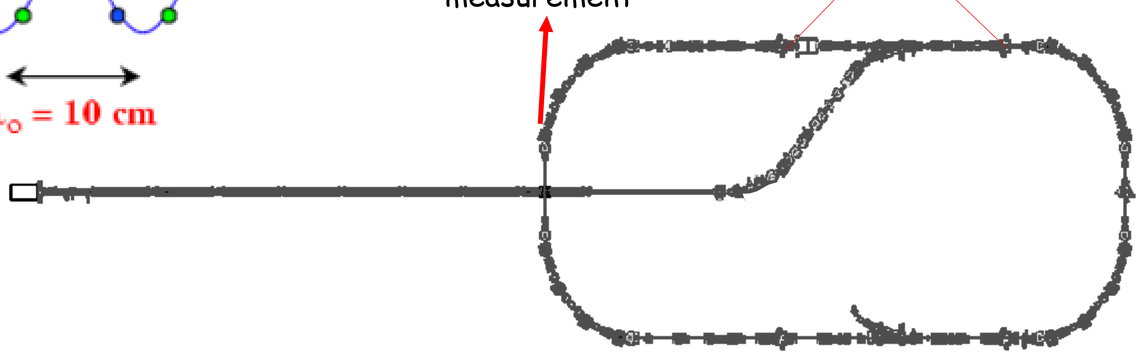


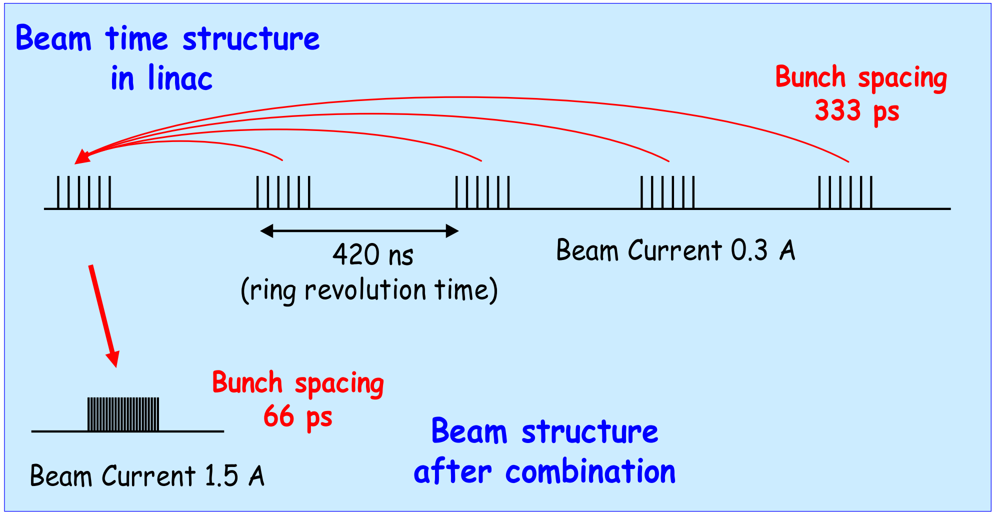
Combination factor 5



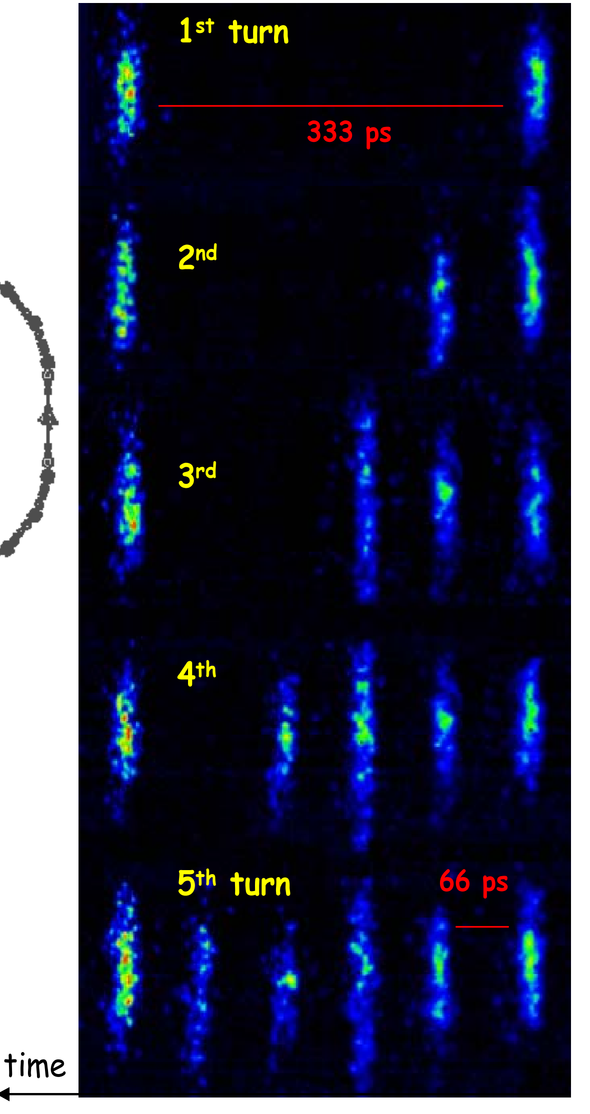
CTF3 - PRELIMINARY PHASE
2001/2002

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



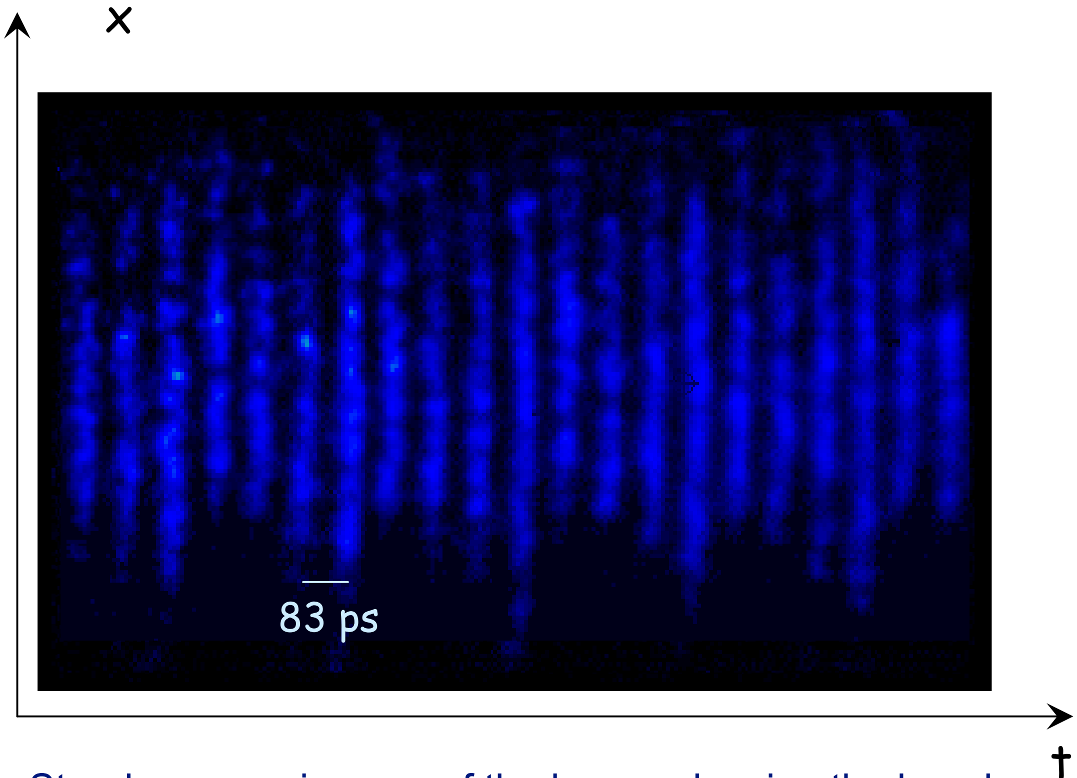


Streak camera image of beam time structure evolution



RF injection in combiner ring

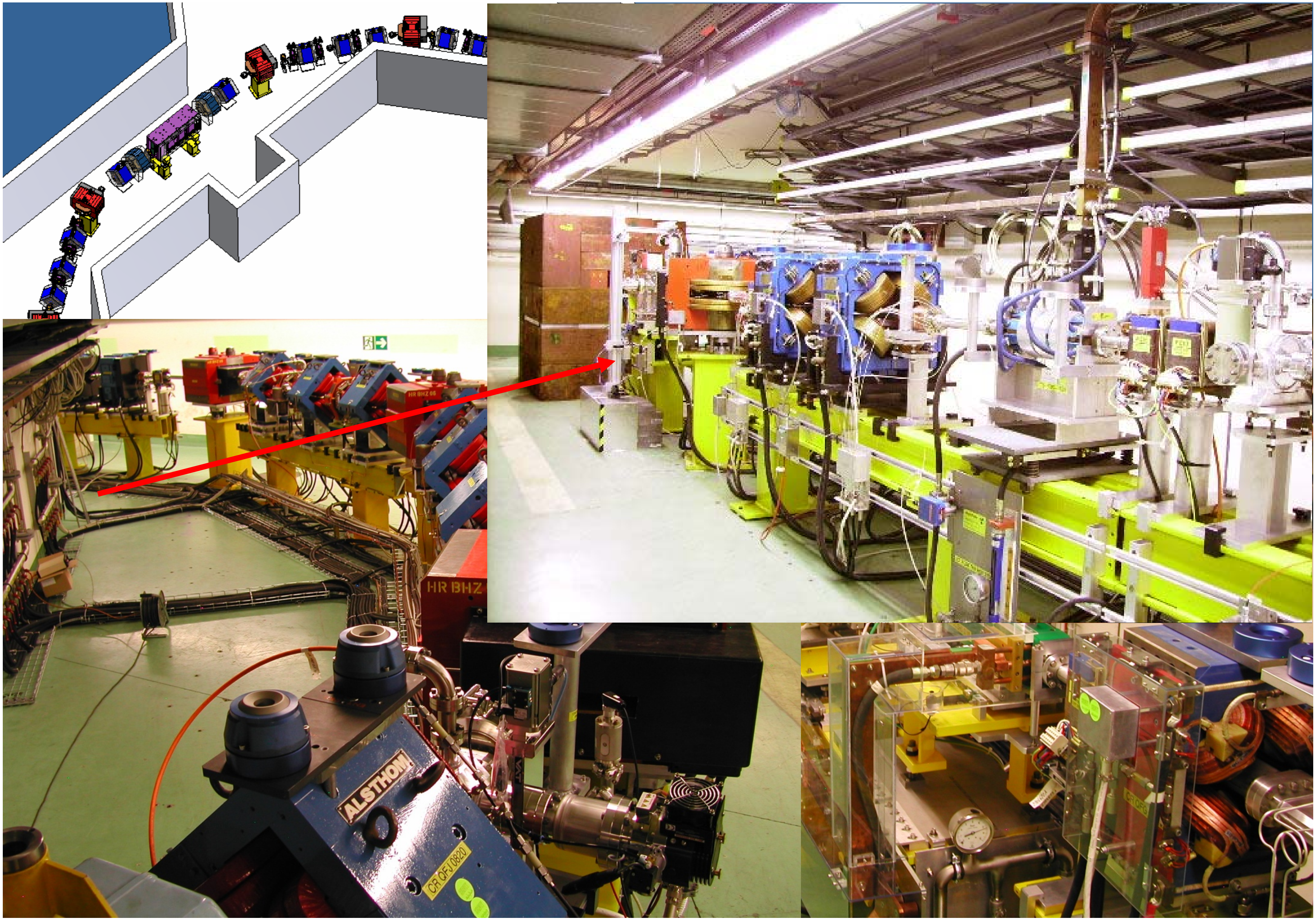
Combination factor 4



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

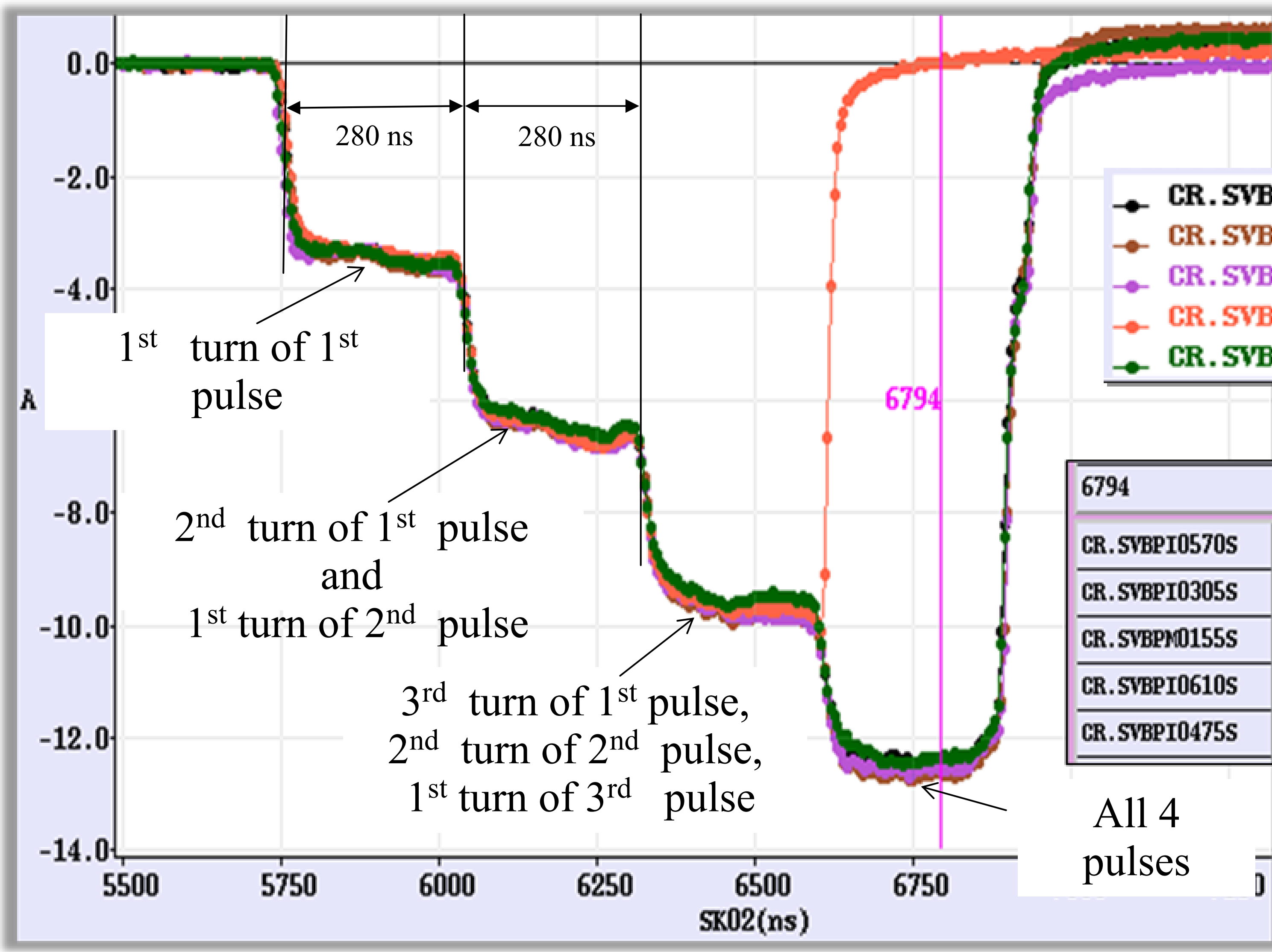
A first ring combination test was performed in 2002, *at low current and short pulse*, in the CERN Electron-Positron Accumulator (EPA), properly modified

CTF3 combiner ring

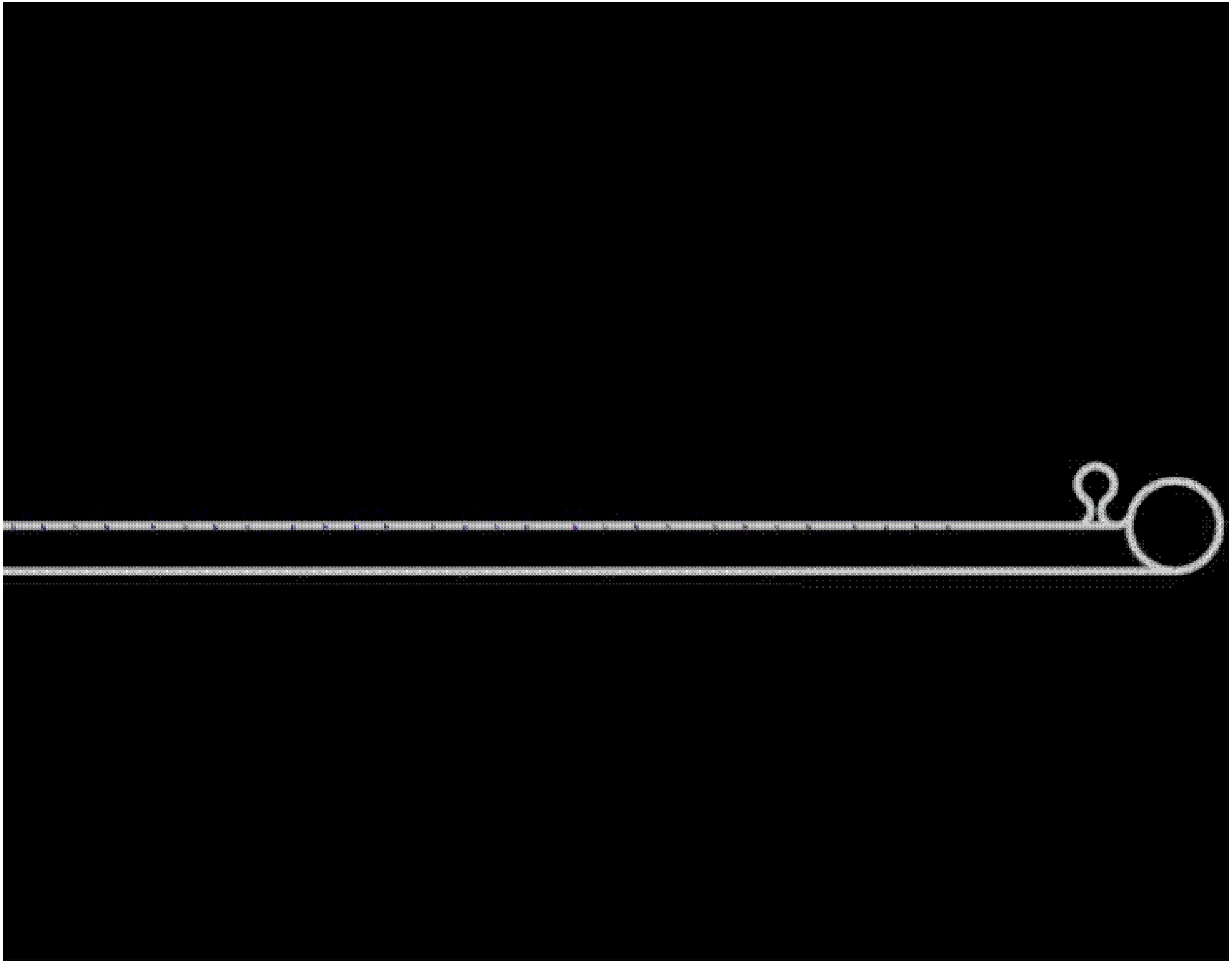


Combiner ring - latest status

- factor 4 combination achieved with 13 A, 280 ns,



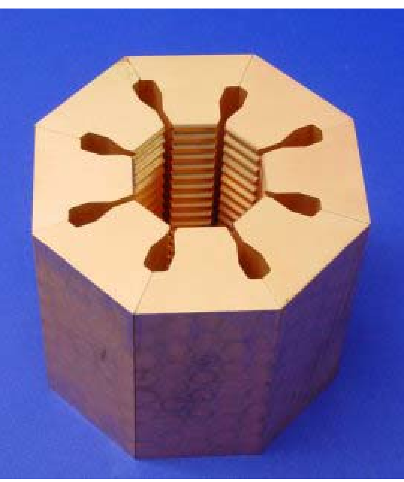
6794	
CR.SVBPI0570S	-12.38300
CR.SVBPI0305S	-12.63820
CR.SVBPM0155S	-12.54400
CR.SVBPI0610S	0.02320
CR.SVBPI0475S	-12.37720

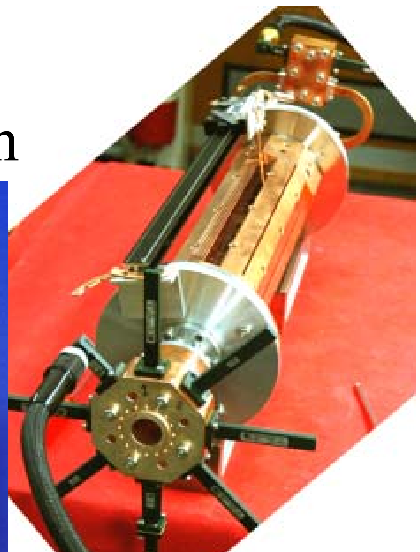


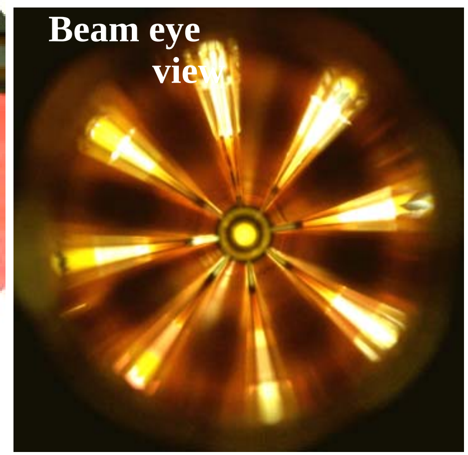
Alexandra Andersson

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

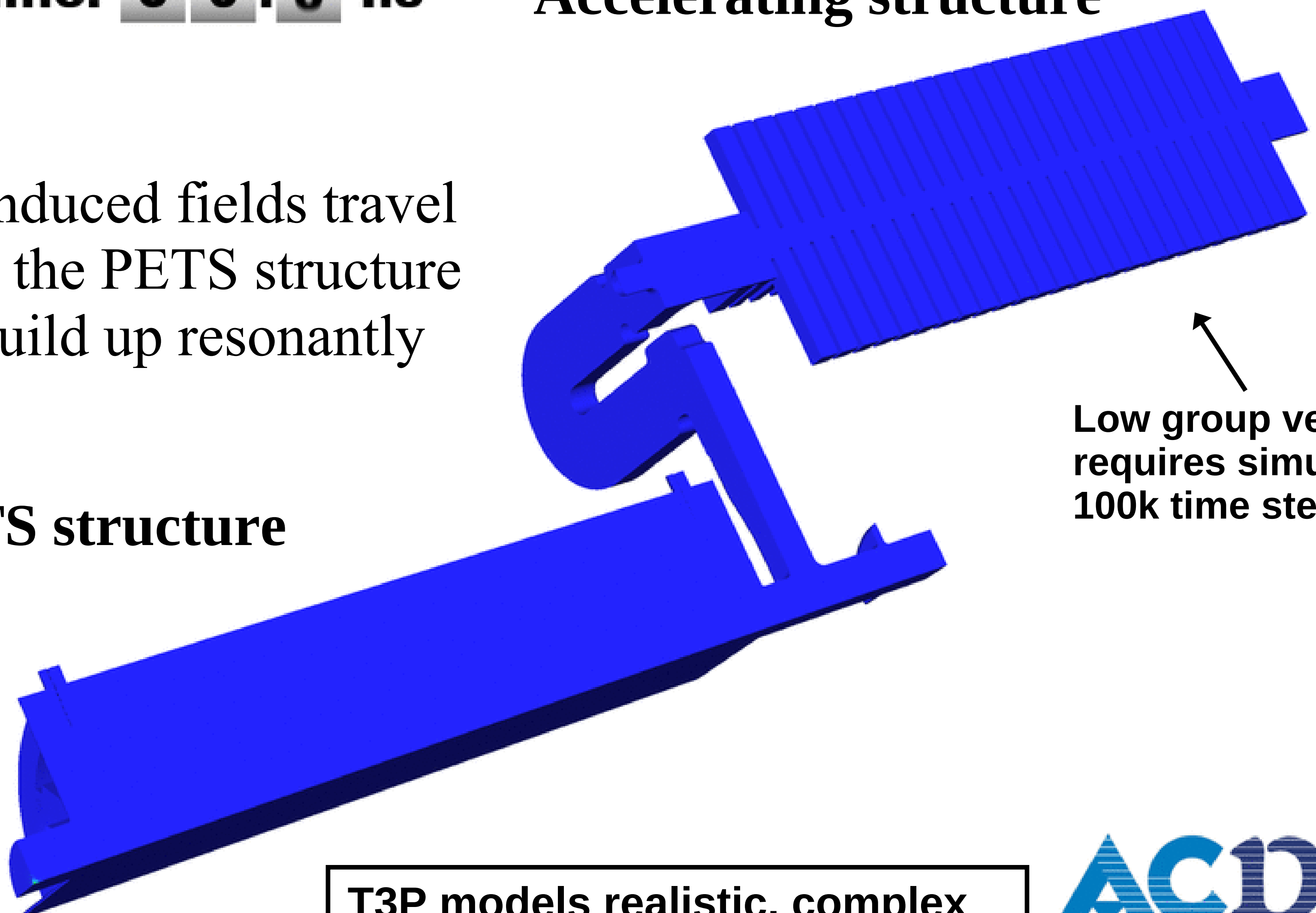
$$P = I^2 L^2 F_b^2 \omega_0 \frac{R/Q}{V_g 4}$$

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

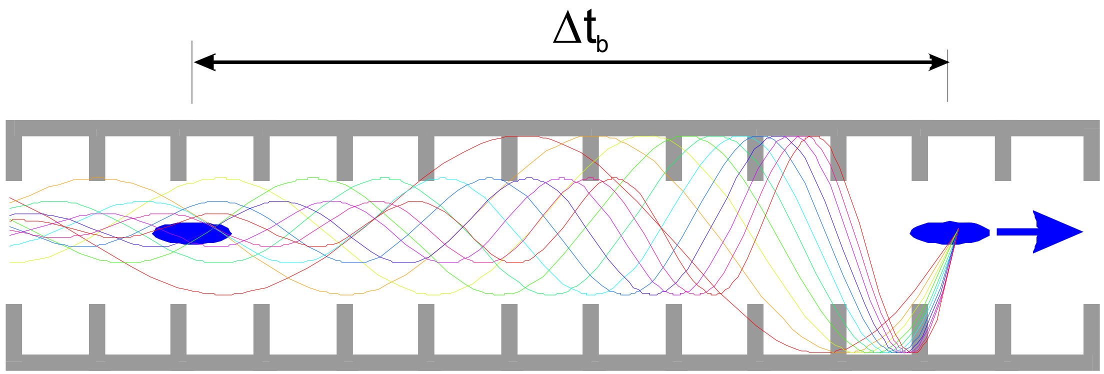
- The induced fields travel along the PETS structure and build up resonantly



T3P models realistic, complex accelerator structures with unprecedented accuracy

Arno Candel, SLAC

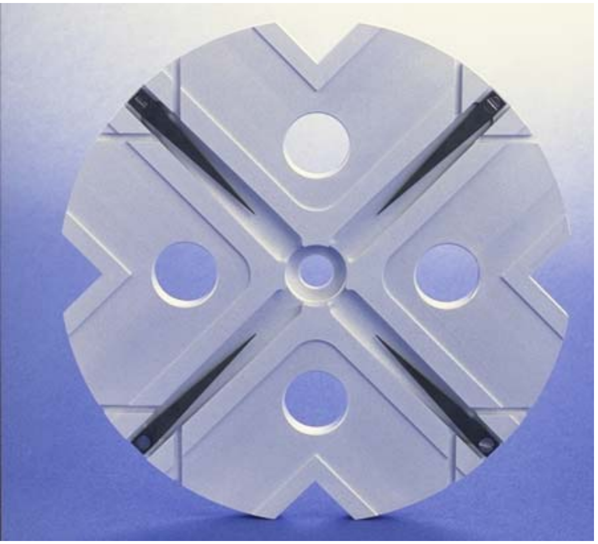
RF structures: transverse wakefields

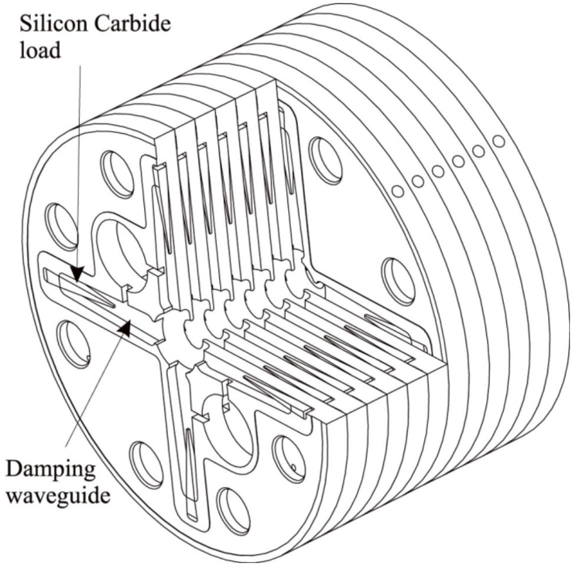


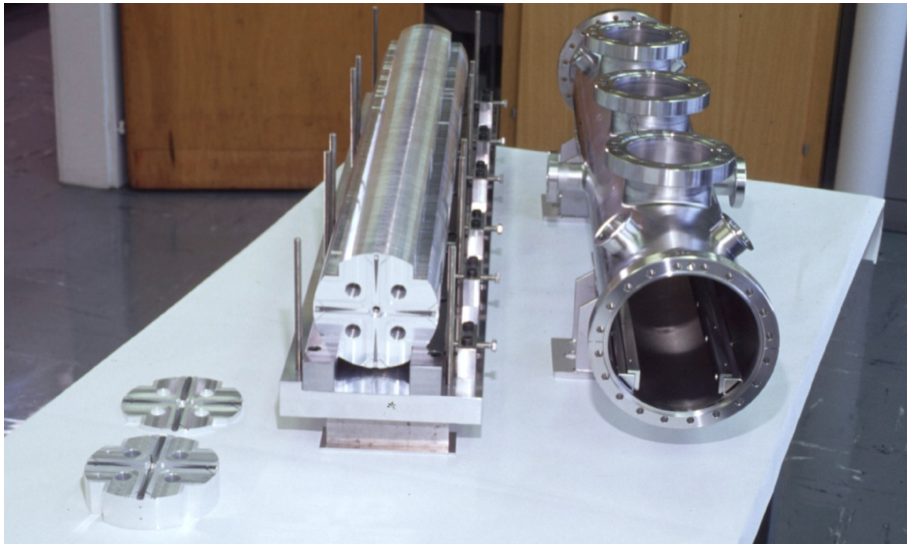
- Bunches induce wakefields in the accelerating cavities
- Later bunches are perturbed by the Higher Order Modes (HOM)
- Can lead to emittance growth and instabilities!!!

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

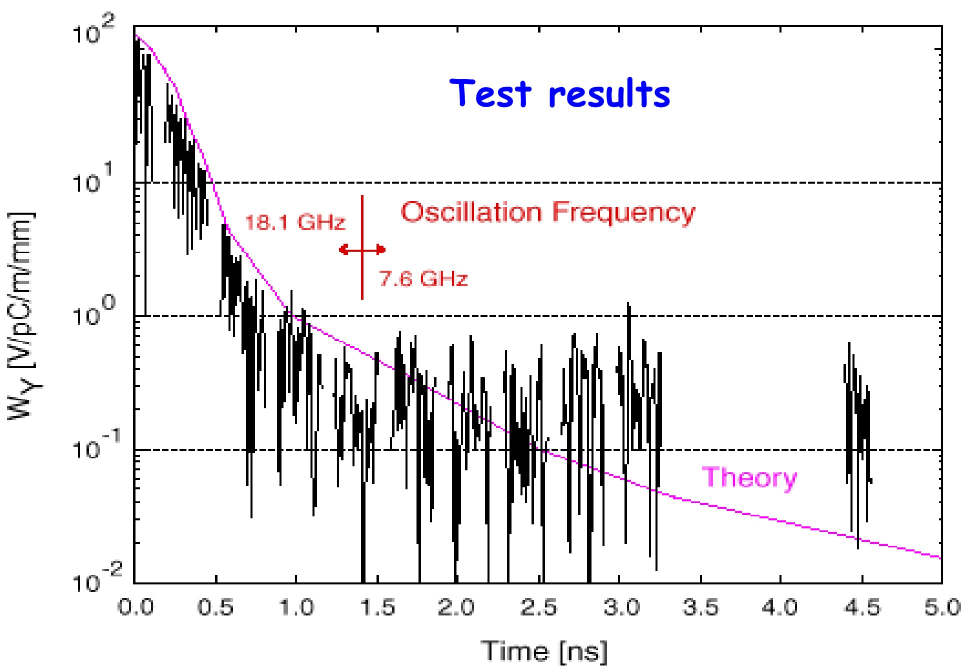
Accelerating structure developments





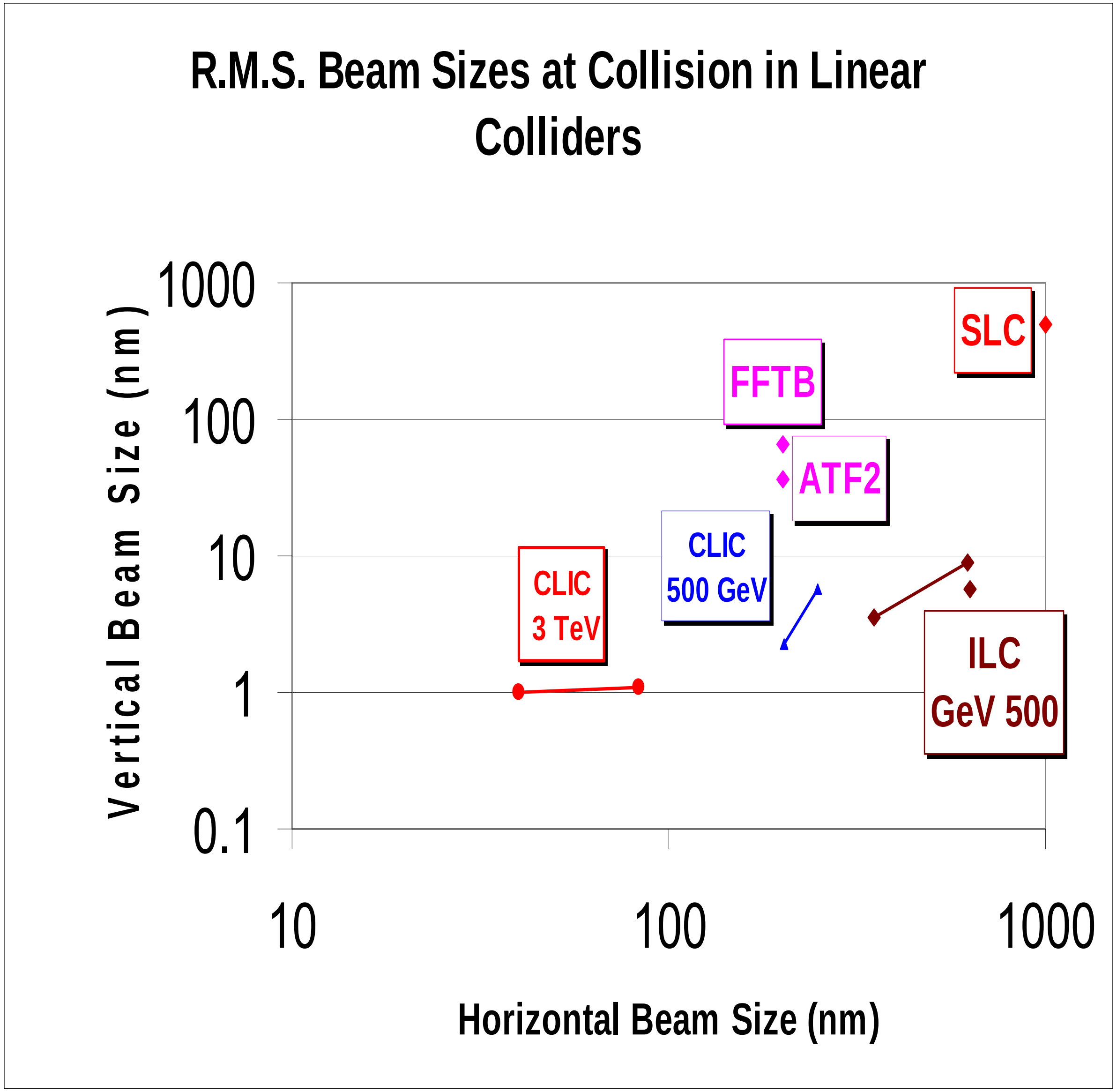


- Structures built from discs
- Slight detuning between cells makes HOMs decohere quickly
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- HOM enter WG
- Long-range wakefields efficiently damped



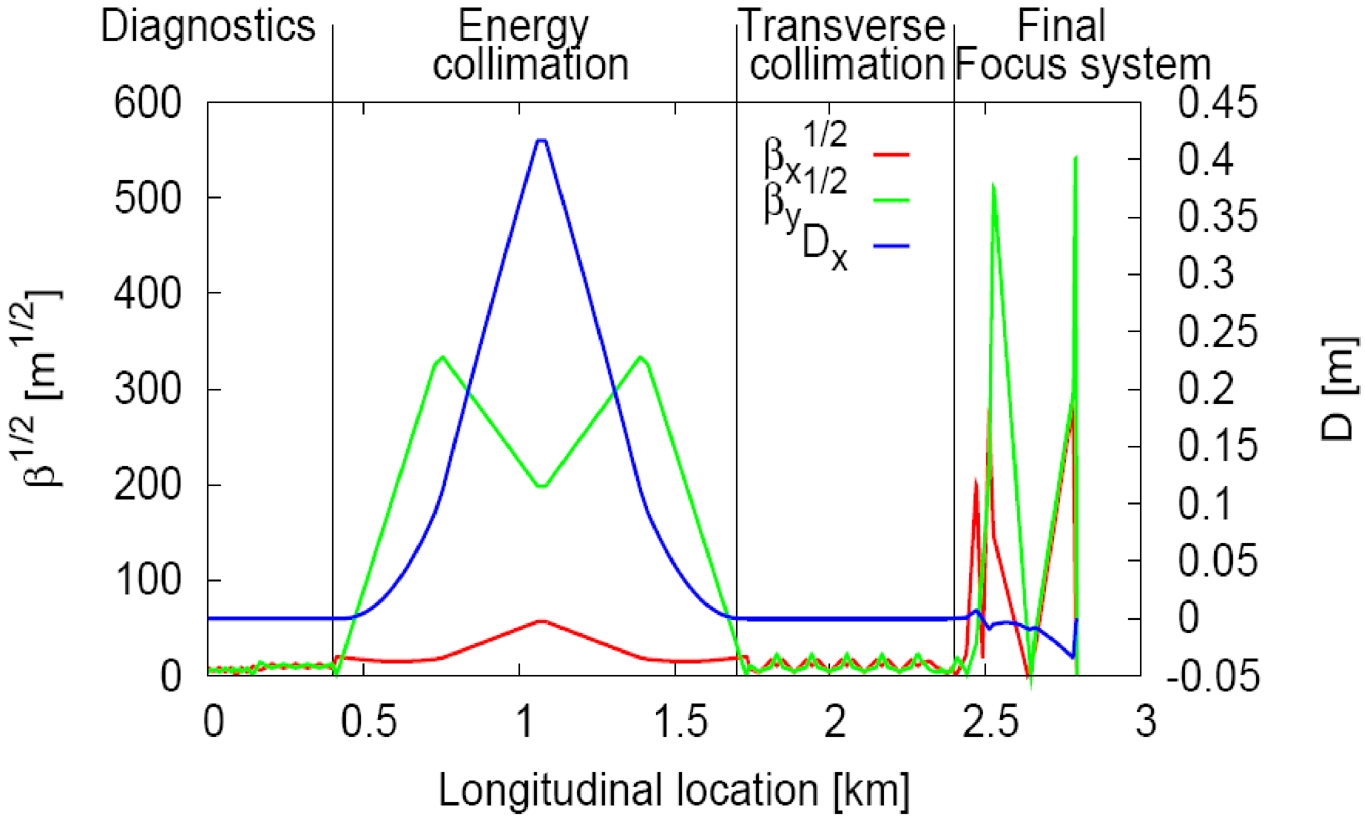
Crucial for luminosity: Emittance

- 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



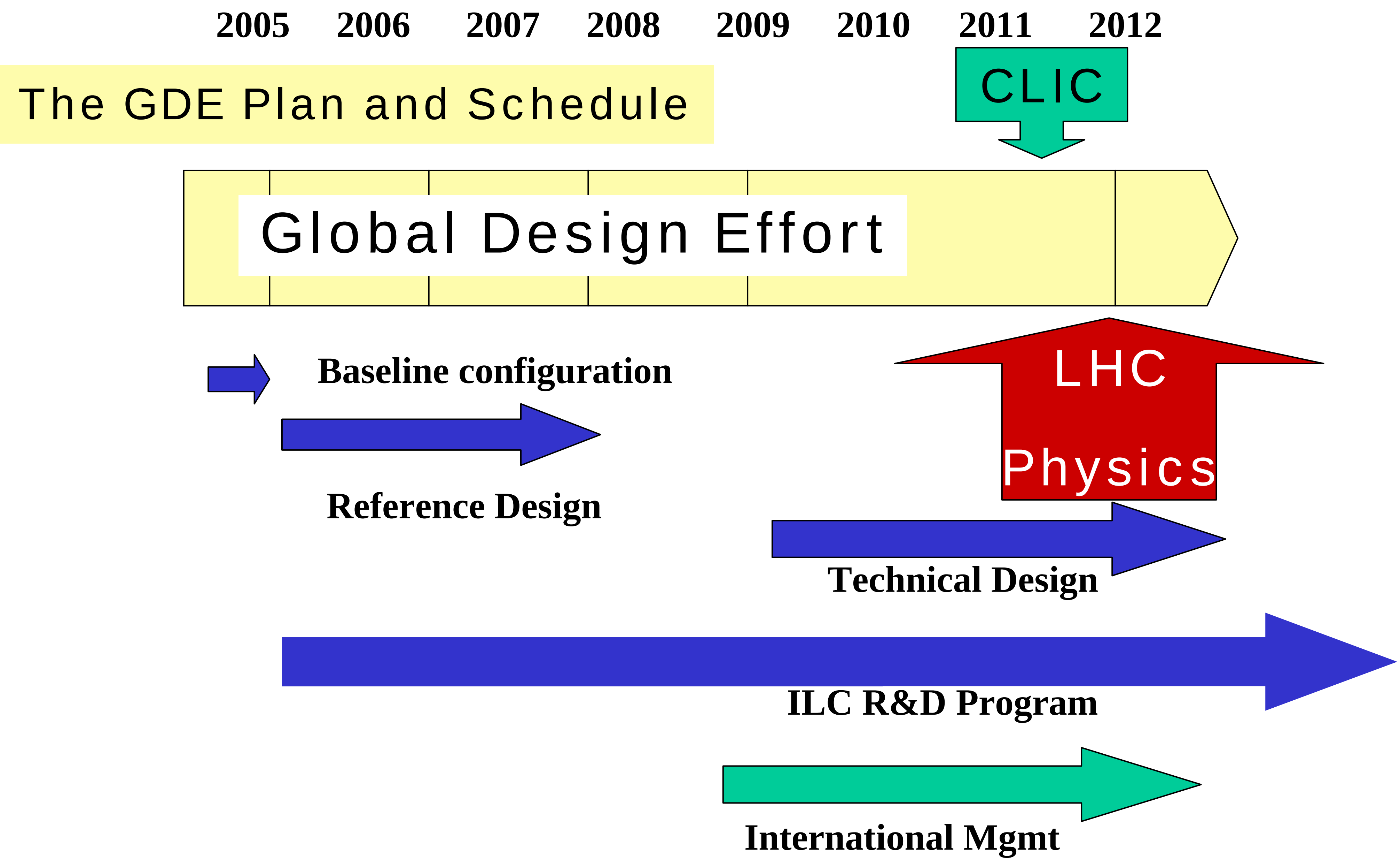
Beam Delivery System

- 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



CLIC and ILC timeline

From B. Barish, ILC Global Design Effort director



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 2010

- Possible decision from 2010-12 based on LHC results
- Looking forward to a successful LHC operation

Documentation

- ILC information http://www.linearcollider.org
- General documentation about the CLIC study: http://cern.ch/CLIC-Study/
- CLIC scheme description: http://preprints.cern.ch/yellowrep/2000/2000-008/p1.pdf
- Recent 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 Workshop 2008 (most actual information) http://cern.ch/CLIC08
- EDMS http://edms.cern.ch/nav/CERN-0000060014
- CLIC ACE (advisory committee meeting) http://indico.cern.ch/conferenceDisplay.py?confId=58072
- 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