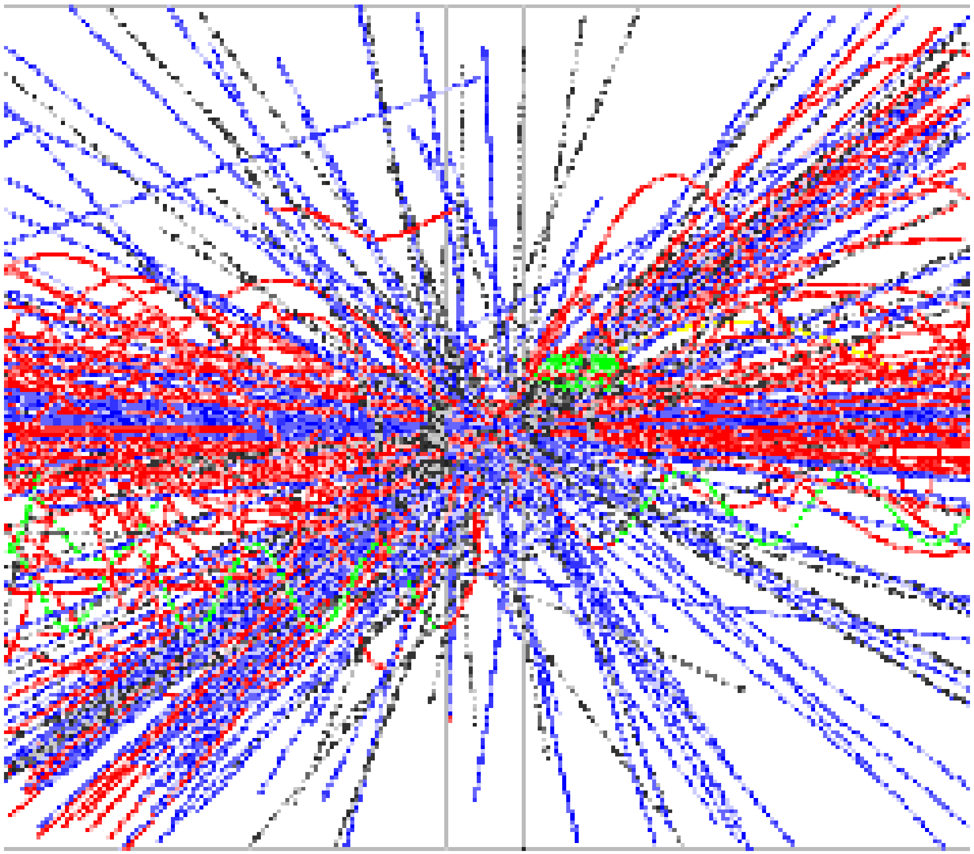
Possible future $e^+ e^-$ linear colliders

with special emphasis on CLIC

Louis Rinolfi

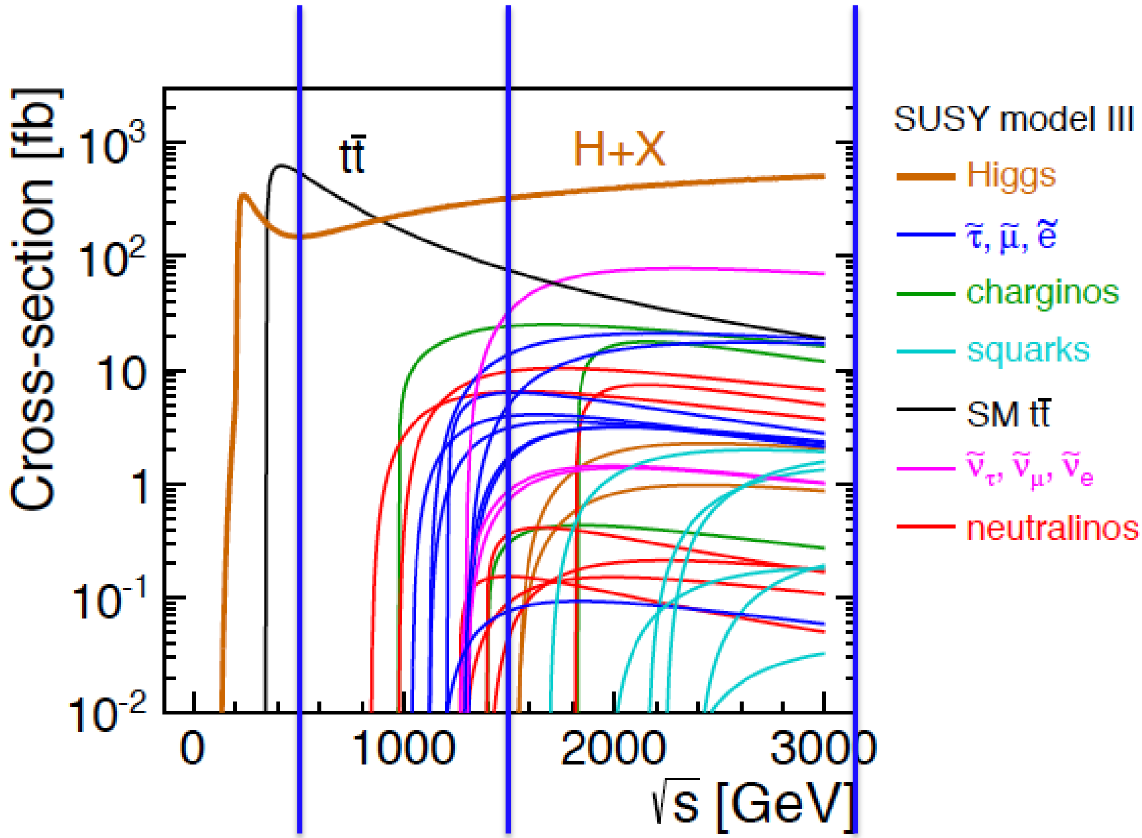
The Physics in the multi-TeV energy range



S. Stapnes / CERN

LHC complementarity at the energy frontier:

•How do we build the optimal machine given a physics scenario (partly seen at LHC ?)



Stage 1: ~500 (350) GeV => Higgs and top physics
Stage 2: ~1.5 TeV => ttH, ννHH + New Physics (lower mass scale)
Stage 3: ~3 TeV => New Physics (higher mass scale)

General Physics context

LHC discovery:

LHC announced on 4th July 2012 the discovery of a possible Higgs boson at 126 GeV

LHC expectation:

LHC continues to investigate what physics is behind this discovery and at what energy scale should considered: Do we need multi-TeV energy ?
Future LHC results would establish the scientific case for a Linear Collider

ILC expectation:

ILC nominal energy study is 0.5 TeV.
However the present design is done in order to run up to 1 TeV

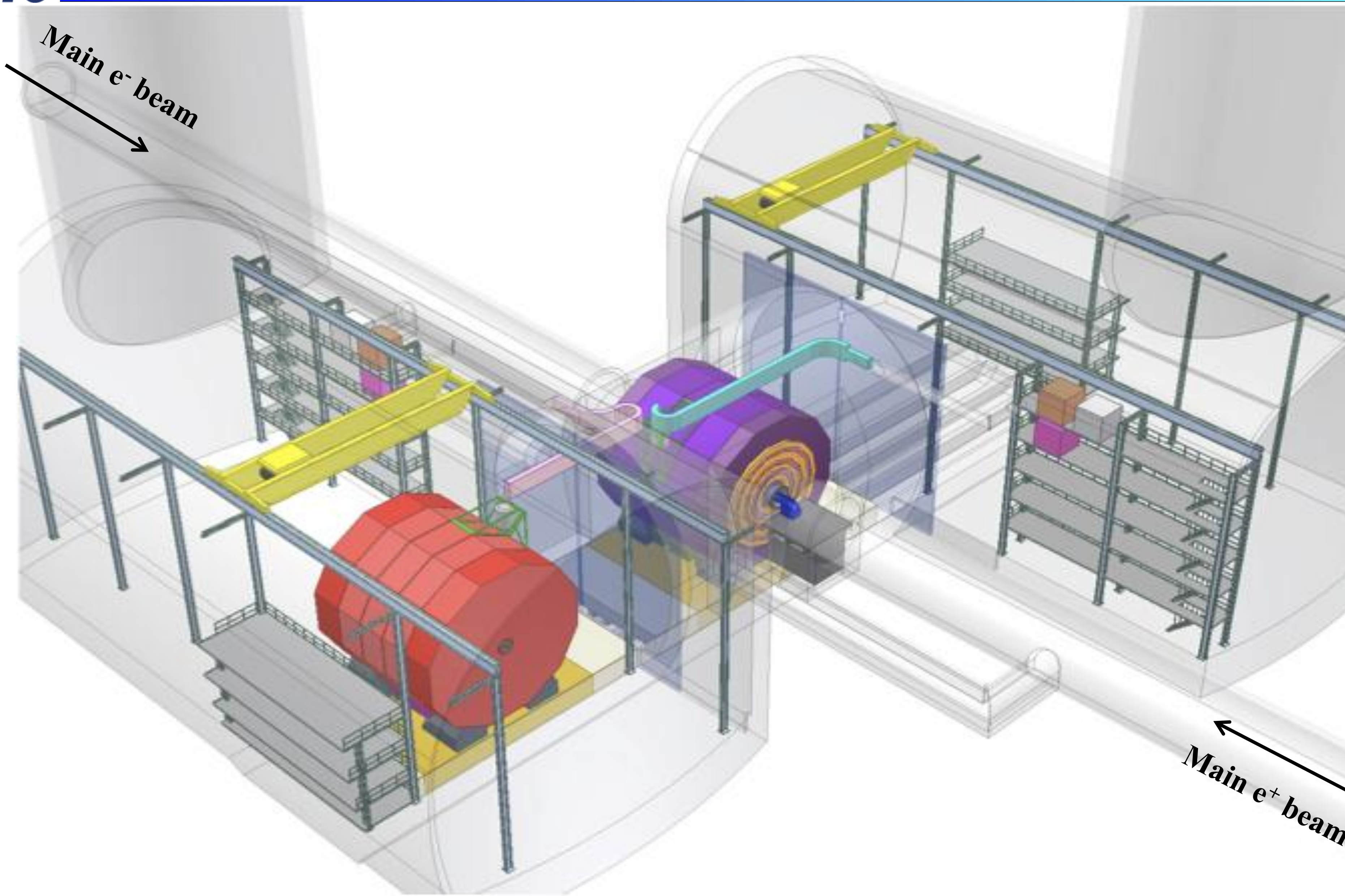
CLIC expectation:

CLIC nominal energy study is 3 TeV.
However the present design is done in order to run over a wide energy range: 0.5 to 3 TeV (studies have been performed up to 5 TeV).

K. Peach / JAI

5 good arguments for 2 detectors:

1. Sociological argument
   - Too many physicists for 1 detector
2. Moral argument
   - Two detectors keep us honest
3. Risk argument
   - If one breaks, we have another
4. Systematic error argument
   - 2 detectors with different systematic errors when combined give much reduced systematic error
5. Statistics argument
   - low statistics regions of phase space need 2 detectors to separate signal from noise


Main e$^-$ beam
Main e$^+$ beam

A very brief CLIC history

1985: **CLIC = CERN Linear Collider**

CLIC Note 1: "Some implications for future accelerators" by J.D. Lawson => first CLIC Note

1995: **CLIC = Compact Linear Collider**

=> 6 Linear colliders studies (TESLA, SBLC, JLC, NLC, VLEPP, CLIC)

2004: International Technology Recommendation Panel selects the Superconducting RF technology (TESLA based) versus room temperature technology (JLC/NLC based)

=> ILC at 1.3 GHz for the TeV scale and CLIC study at 30 GHz continues for the multi-TeV scale

2006: CERN Council Strategy group (Lisbon July 2006) => "… a coordinated programme should be intensified to develop the CLIC technology … for future accelerators…."

2007: **Major parameters changes:** 30 GHz => **12 GHz** and 150 MV/m => **100 MV/m**

2008: **Successful test of a CLIC structure @ 12GHz** (designed @cern, built @kek, RF tested @slac)

2012 : July: Announce observation at LHC of particle consistent with long-sought Higgs boson
CERN Council Strategy group for Particle Physics (Krakow September 2012)

Publication of CLIC - CDR (Conceptual Design Report)

28 years !!!

CLIC R&D prospects

Present R&D proceeds with the following requirements :

- *Energy center of mass* E_{CM} **= 0.5 - 3 TeV**, and beyond
- *Luminosity L* > few **10^{34} cm^{-2} s^{-1}** with acceptable background and energy spread
- Design should be compatible with a maximum l*ength* ~ **50 km**
- Total power consumption < **300 MW**
- Affordable (CHF, €, $, £,……)

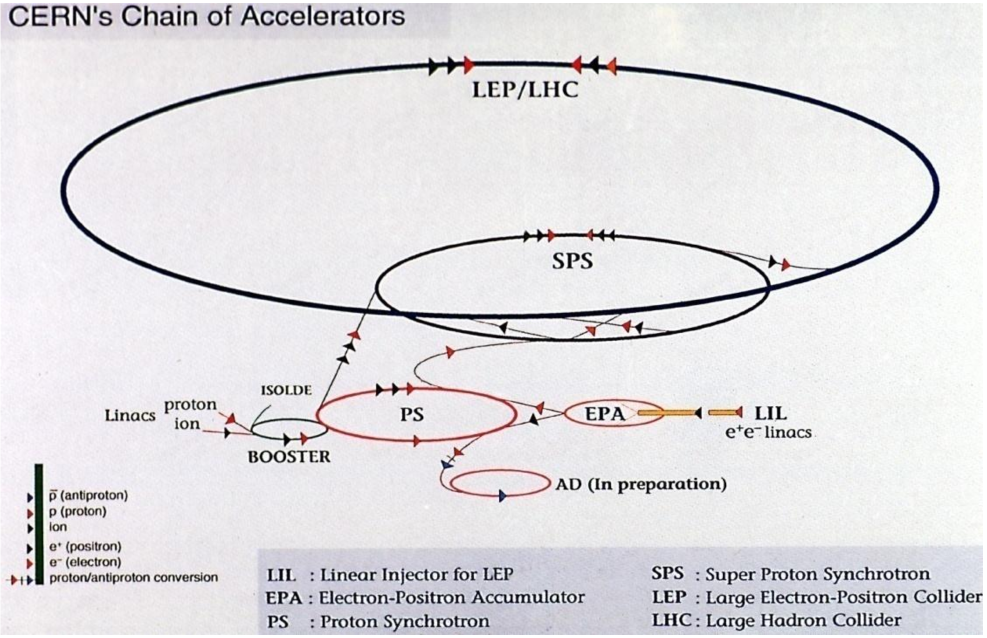
Present goal:

Demonstrate all key feasibility issues and make a realistic cost estimate

Some figures for LEP

LEP = Large Electron Positron collider

- Circumference : 27 km



- Power consumption (1998):

LPI (LIL + EPA) @ 0.5 GeV:	1 MW
PS @ 3.5 GeV:	12 MW
SPS @ 450 GEV :	52 MW
LEP @ 100 GeV :	120 MW
4 Detectors:	52 MW (Aleph, Delphi, L3, Opal)
TOTAL :	237MW

- Cost: ~ 3 BCHF

The International Collaboration

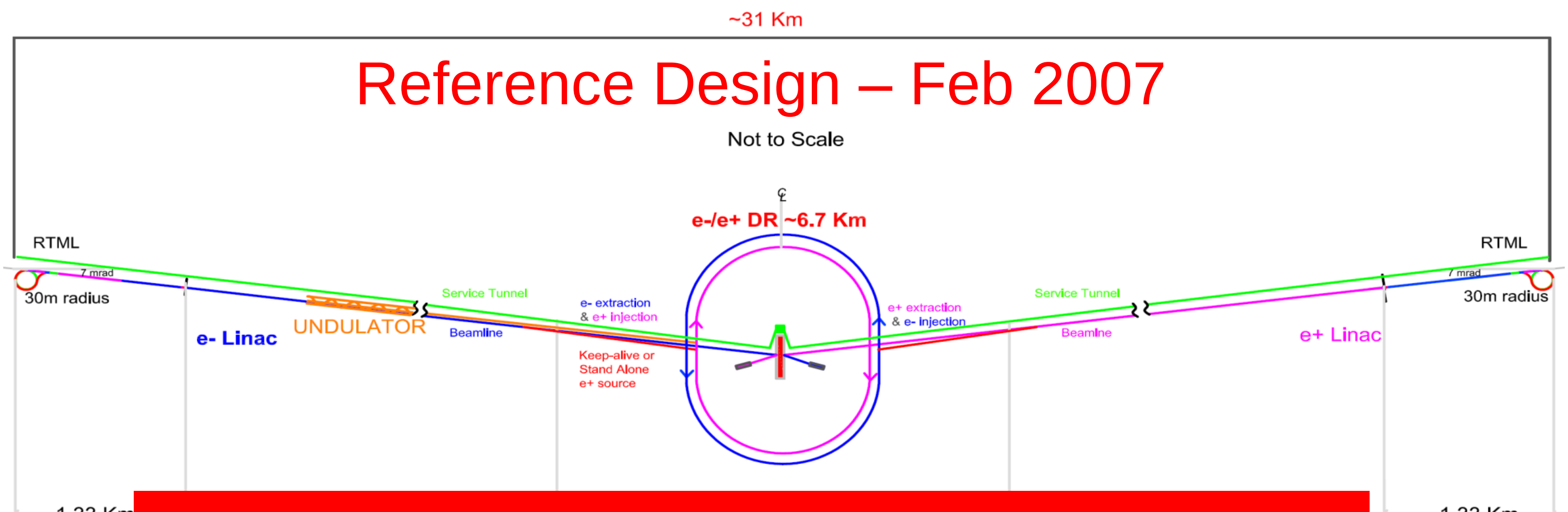
http://clic-meeting.web.cern.ch/clic-meeting/CTF3_Coordination_Mtg/Table_MoU.htm

Current CLIC Collaboration

ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETH Zurich (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)
Joint Institute for Power and Nuclear Research SOSNY /Minsk (Belarus)
John Adams Institute/RHUL (UK)
JINR
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. Univ. of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Sincrotrone Trieste/ELETTRA (Italy)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
University of Vigo (Spain)
Uppsala University (Sweden)
UCSC SCIPP (USA)

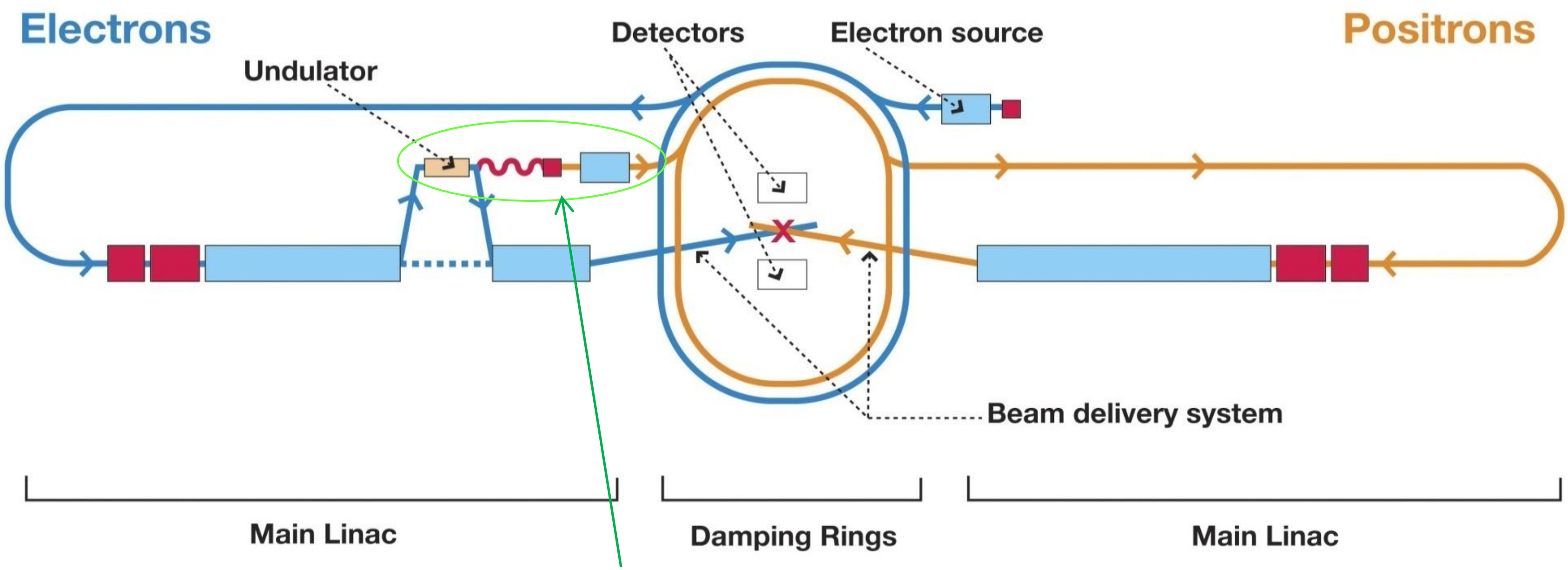
International Linear Collider (ILC)

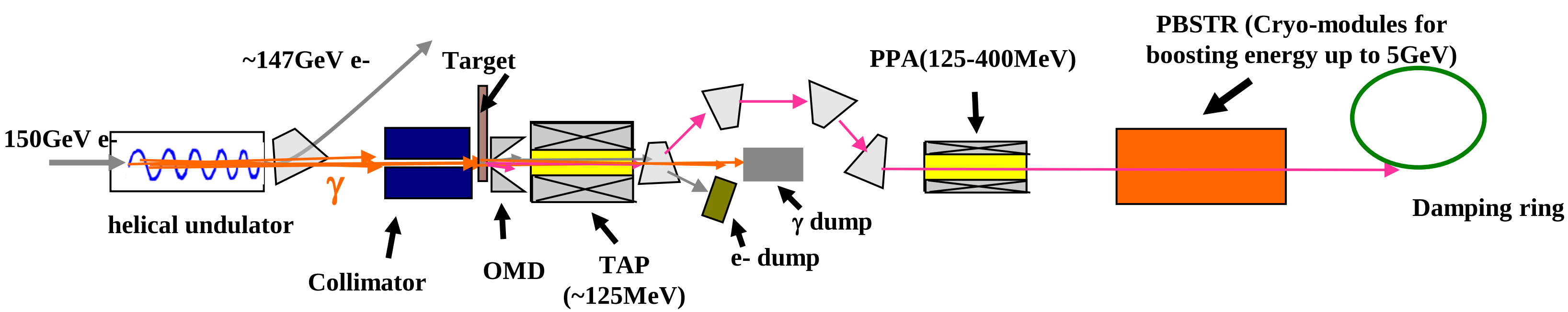
- 11km SC linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
  - Circular damping rings for electrons and positrons
  - Undulator-based positron source
- Single IR with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability



Documented in Reference Design Report

ILC RDR baseline schematic



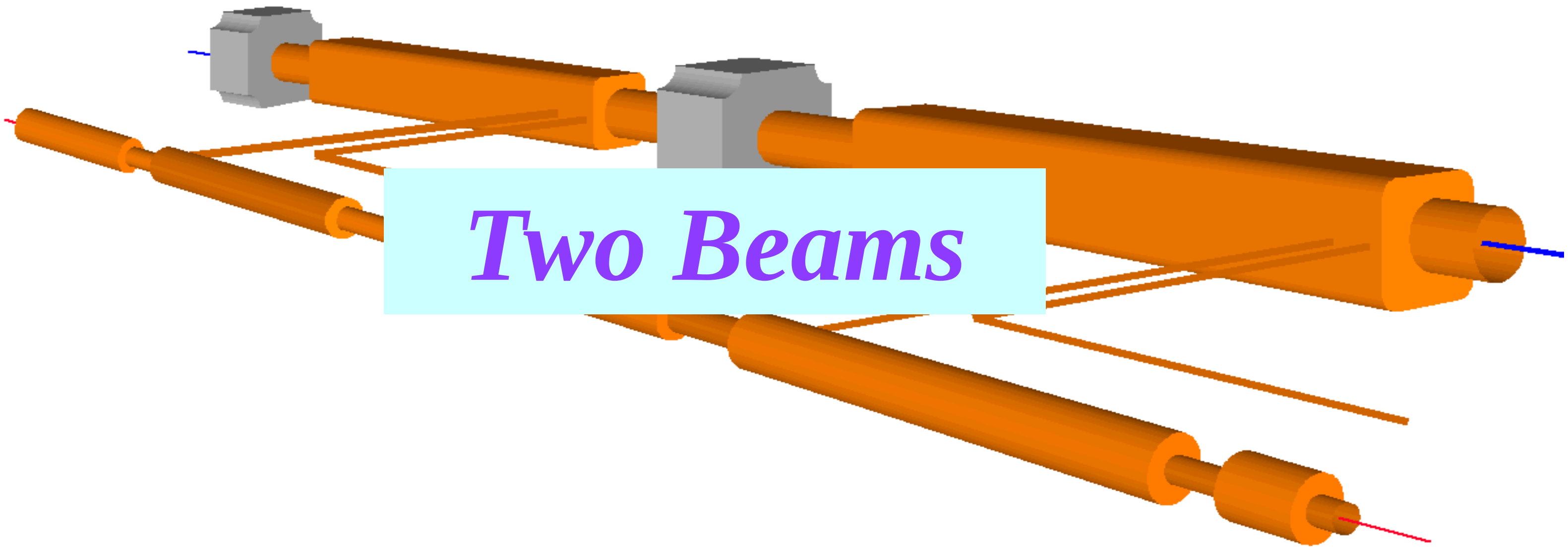


ILC/CLIC Collaboration Working Groups

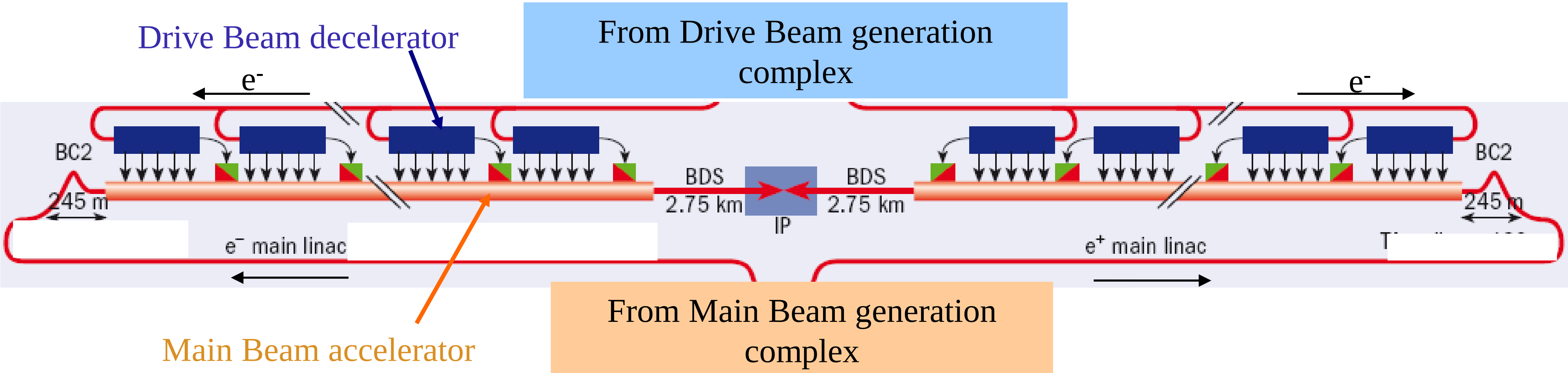
Physics & Detectors
Beam Delivery System (BDS) & Machine Detector Interface (MDI)
Civil Engineering & Conventional Facilities
Positron Generation
Damping Rings
Beam Dynamics
Cost & Schedule
General Issues

9 common working groups

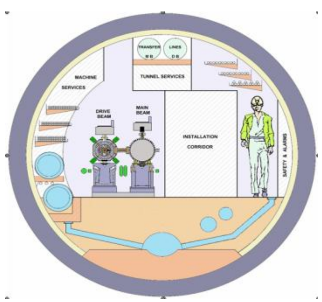
The Two Beams Concept



The basic layout for a Two-Beam scheme



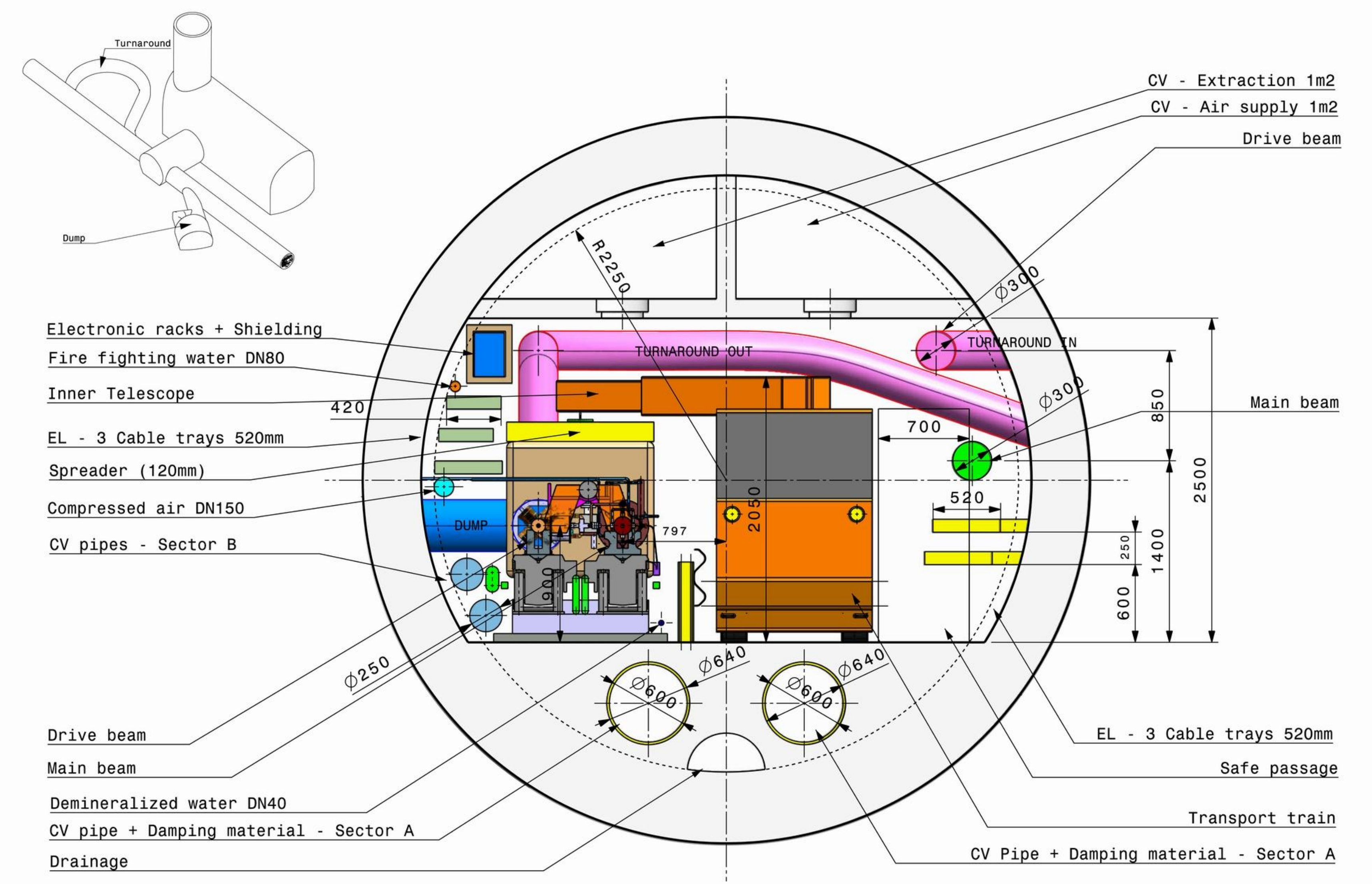
- ➢ **High acceleration gradient and high frequency**
- "Compact" collider
- Normal conducting accelerating structures



➢ Two-Beam Acceleration Scheme

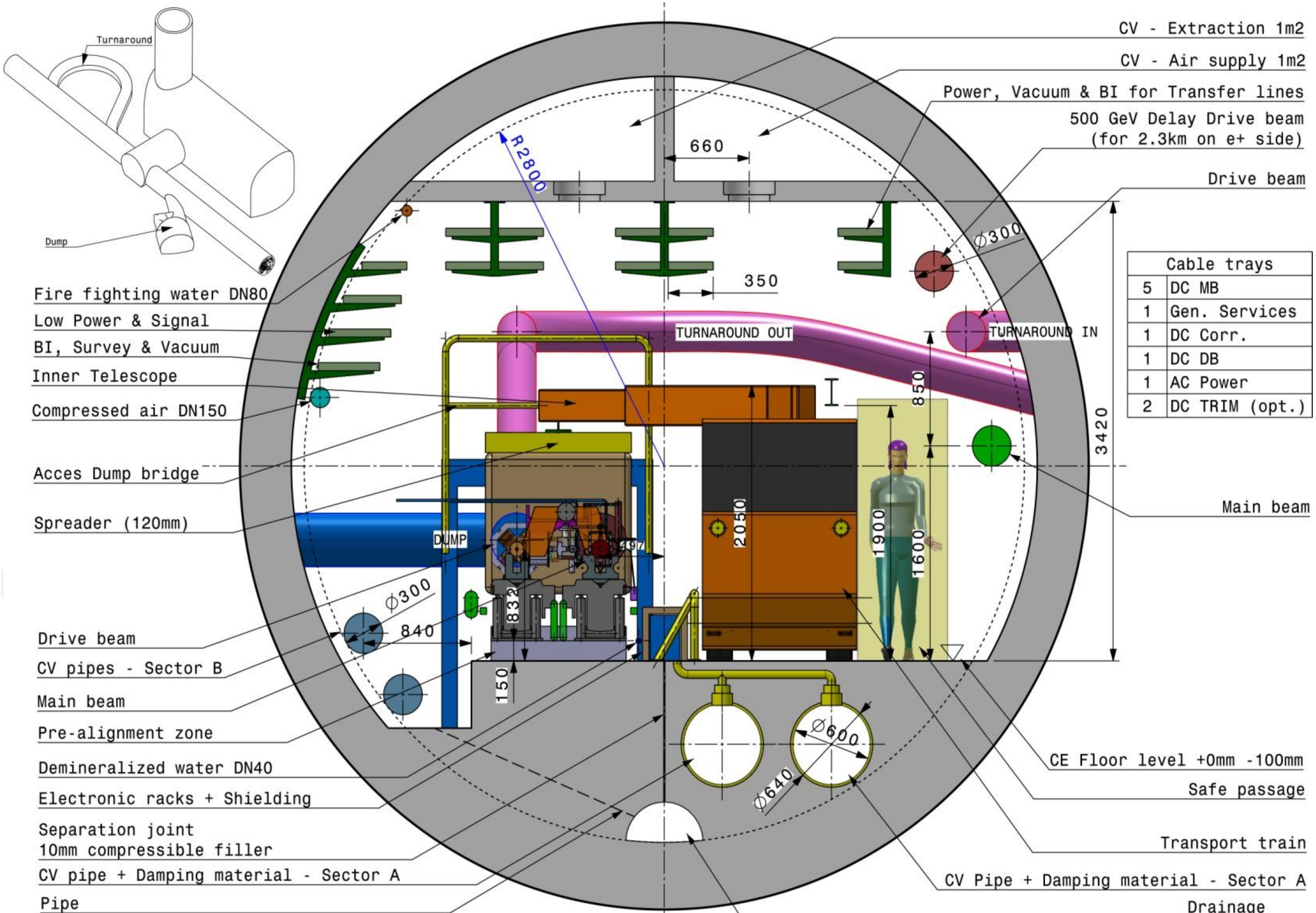
- Simple tunnel, no active elements
- Modular, easy energy upgrade in stages

The CLIC tunnel in October 2009 (ϕ = 4.5 m)



CLIC - Typical Cross Section - Diameter 4500mm - Junction with Turnaround - 1:25
Draft - J.Osborne / A.Kosmicki -October 12th 2009

The CLIC tunnel in February 2011 (ϕ = 5.6 m)

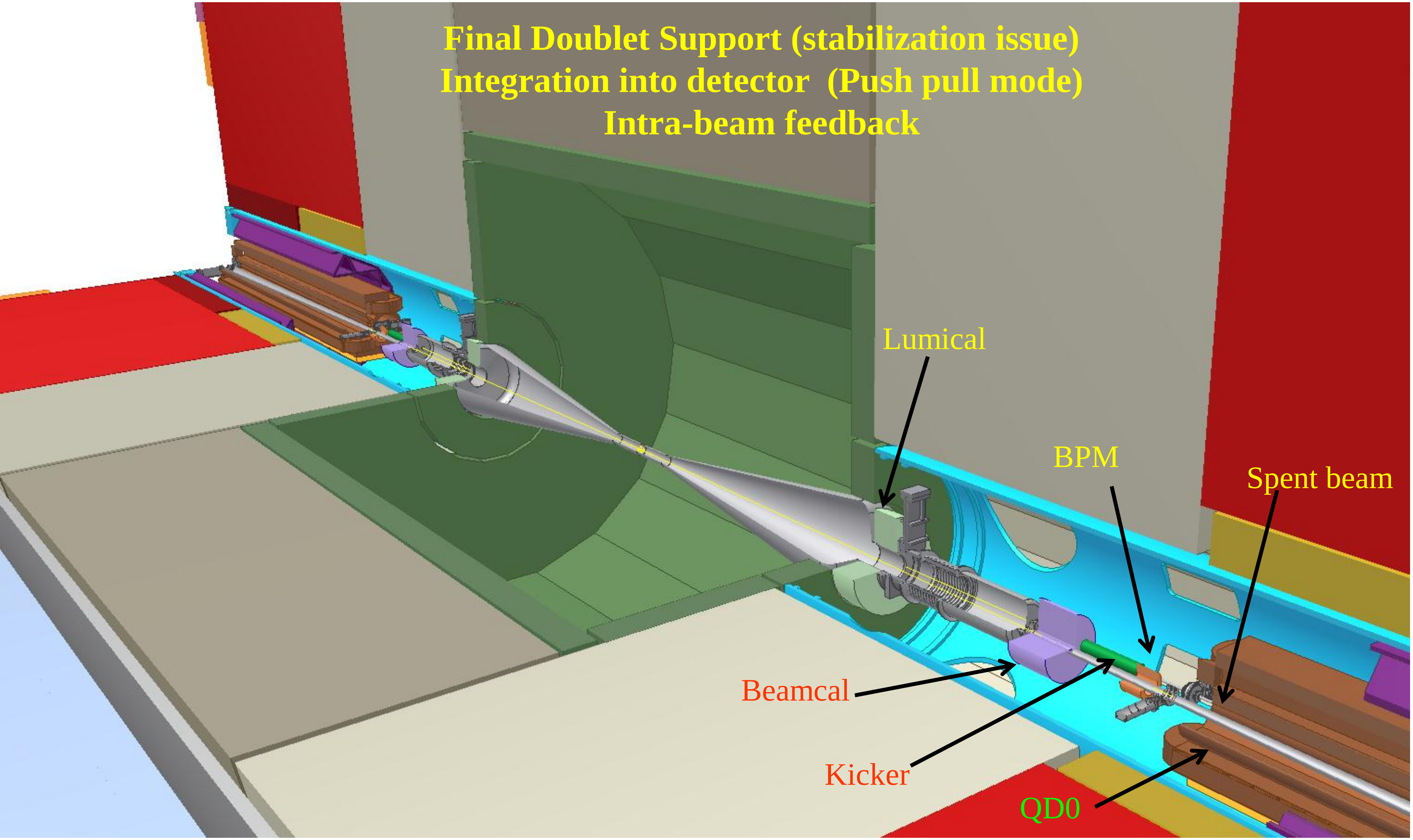


Cable trays	
5	DC MB
1	Gen. Services
1	DC Corr.
1	DC DB
1	AC Power
2	DC TRIM (opt.)

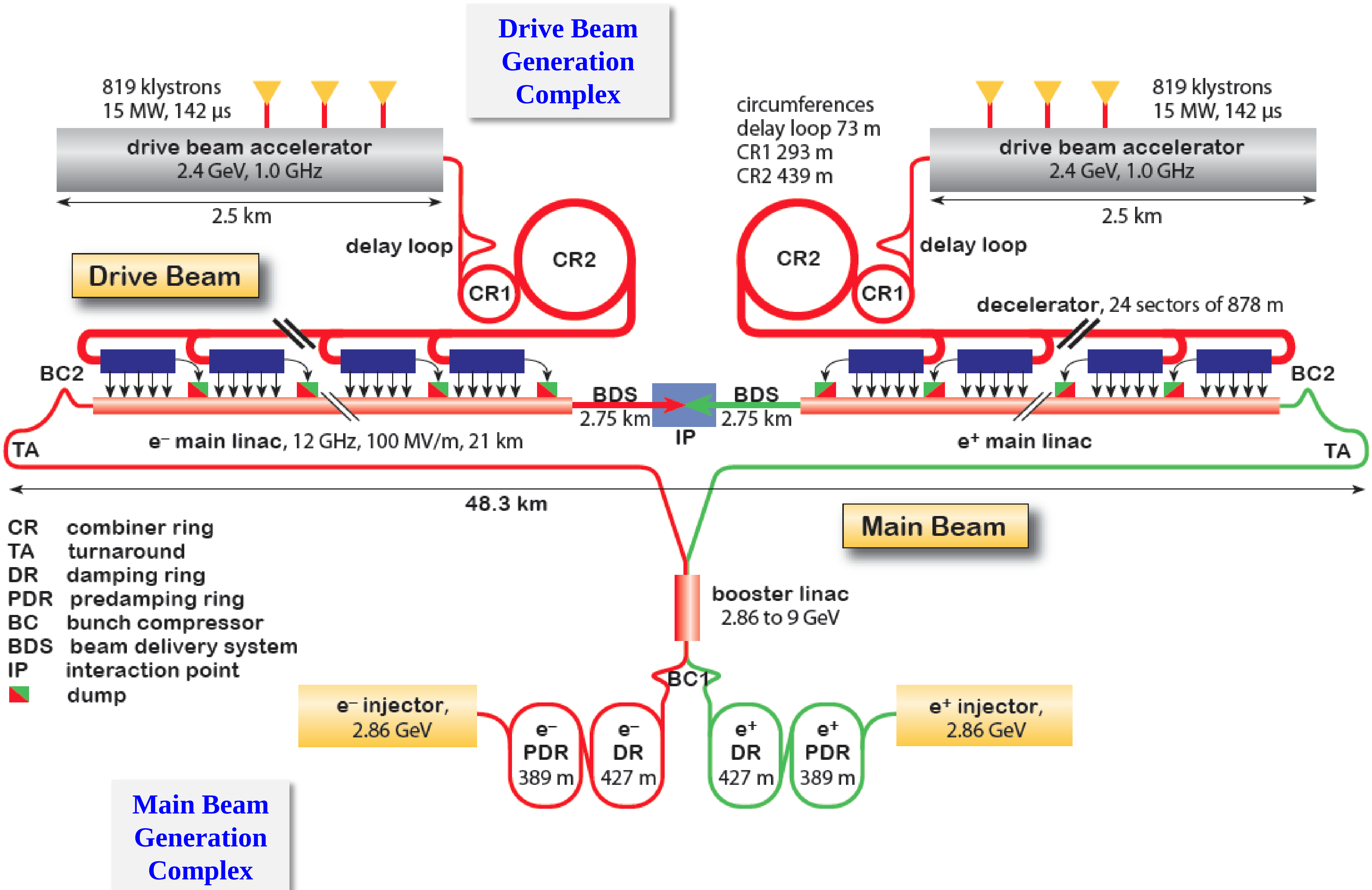
CLIC - Typical Cross Section - Diameter 5600mm - Junction with Turnaround - 1:25

Machine Detector Interface (MDI)

A. Hervé / ETH Zurich



CLIC Layout at 3 TeV

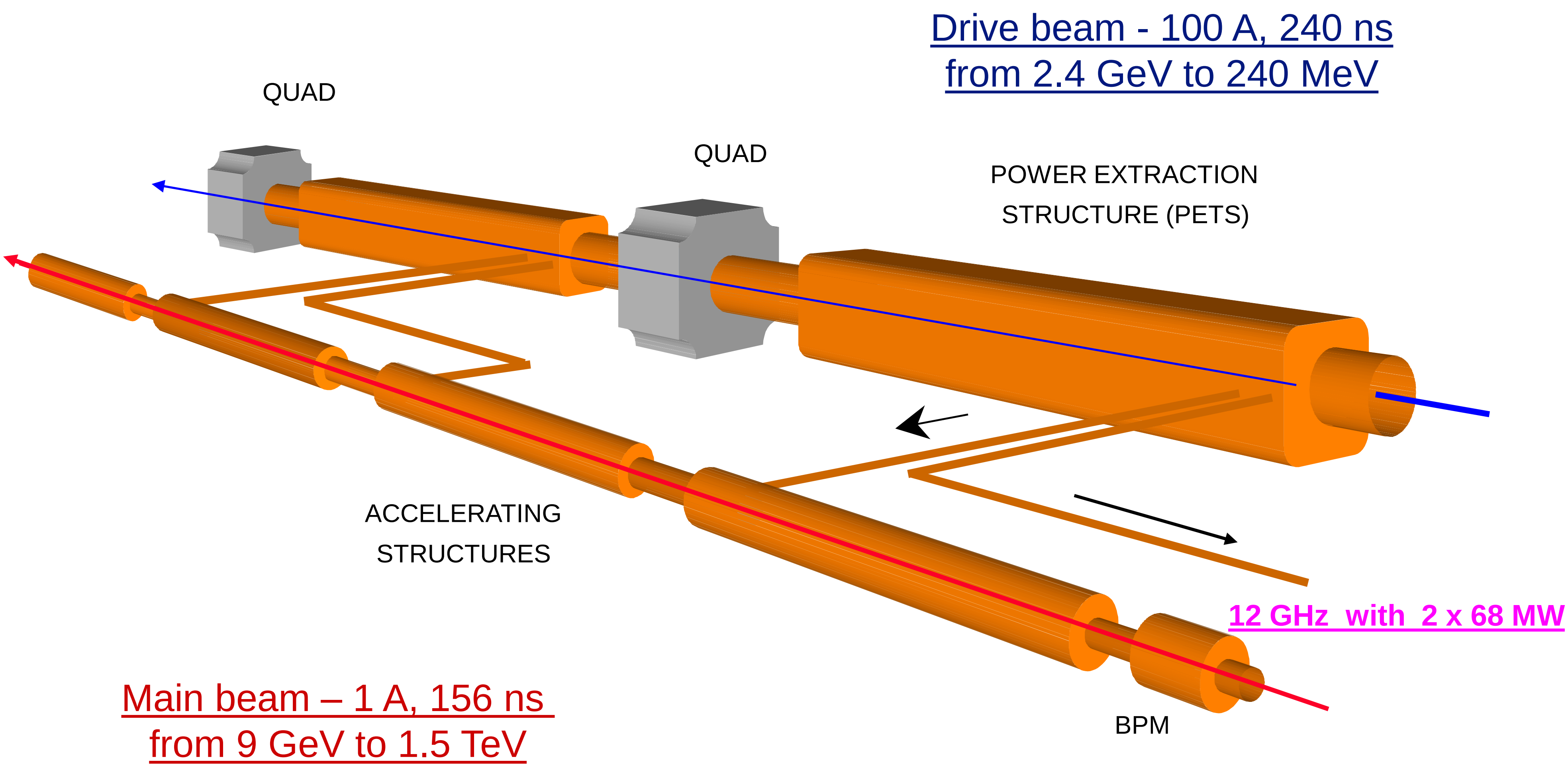


CLIC nominal parameters at I.P.

Table 1: Parameters for the CLIC energy stages of scenario A.

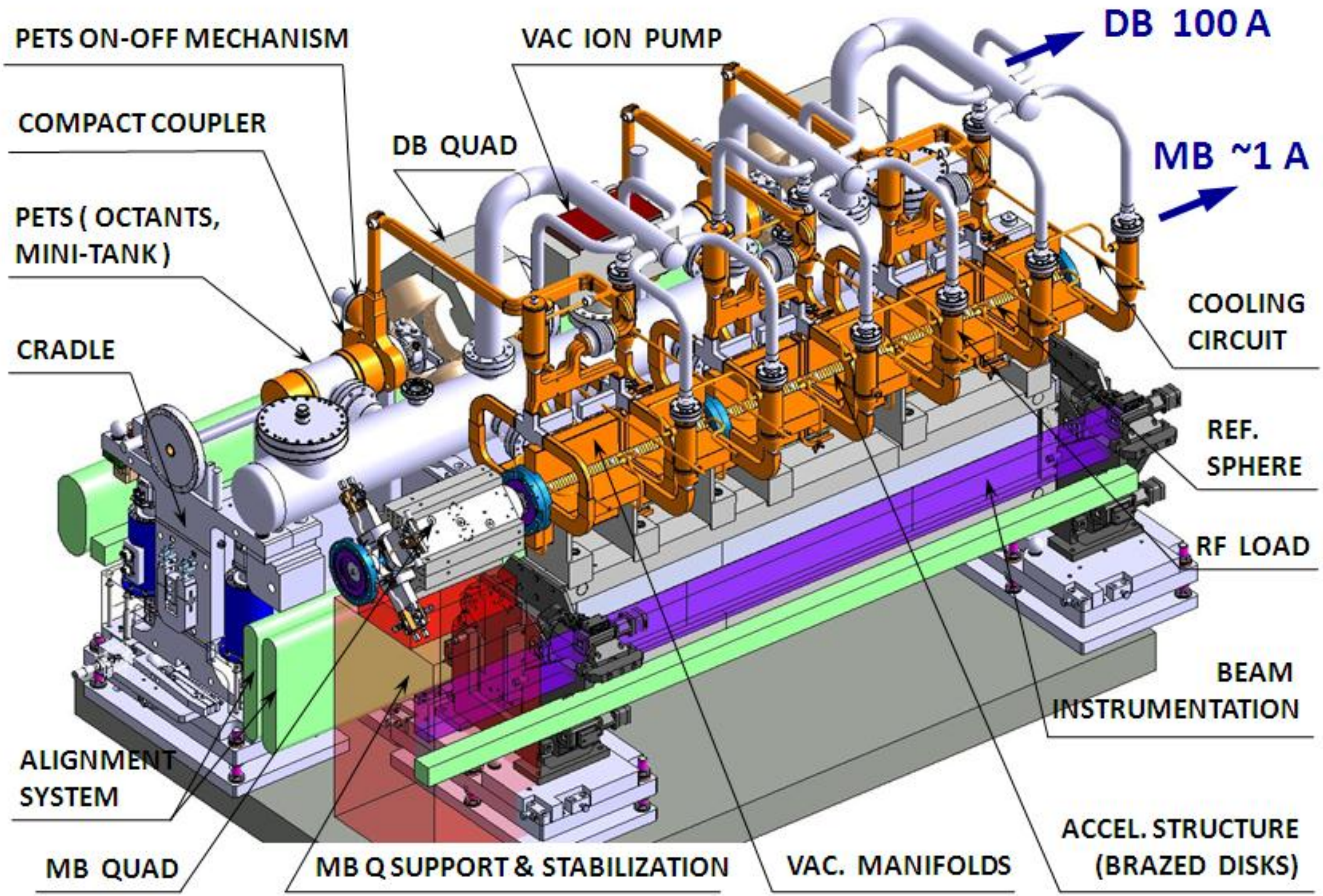
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	µm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	2350/20	660/20	660/20
Normalised emittance (IP)	$\varepsilon_x/\varepsilon_y$	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

CLIC Two-Beam module

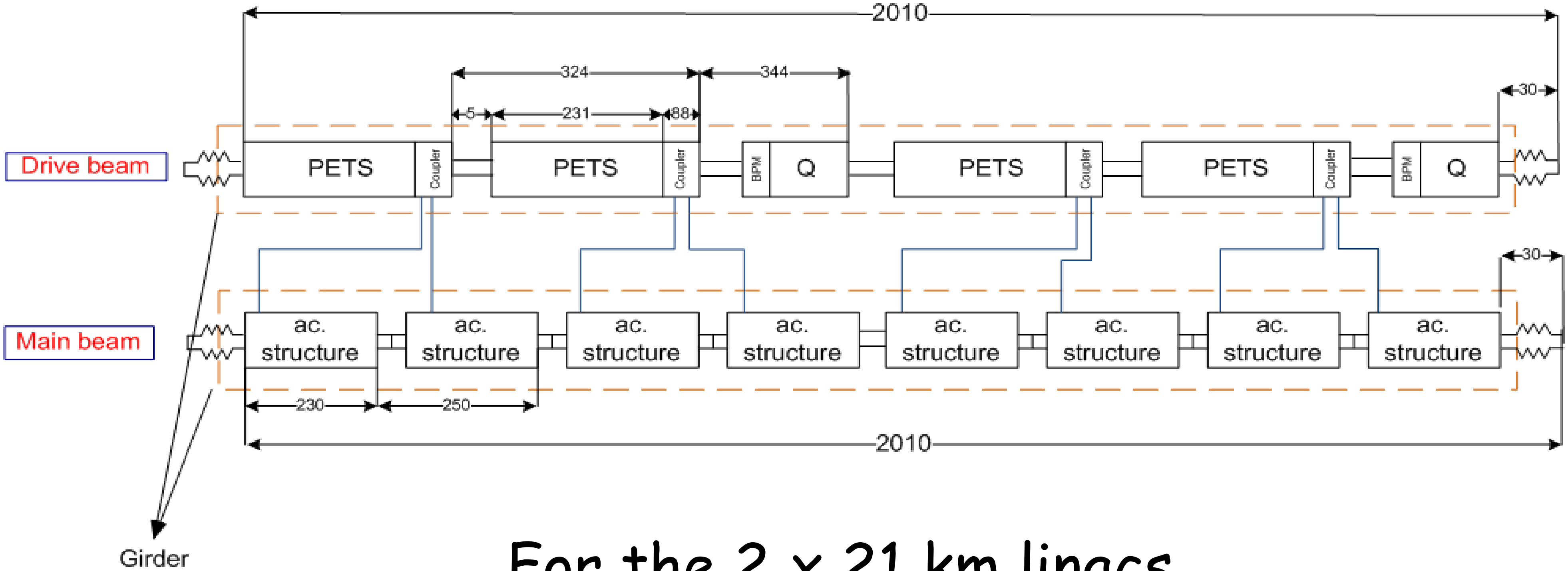


CLIC Two-Beam Module

A. Samoshkin



CLIC Two-Beam Module



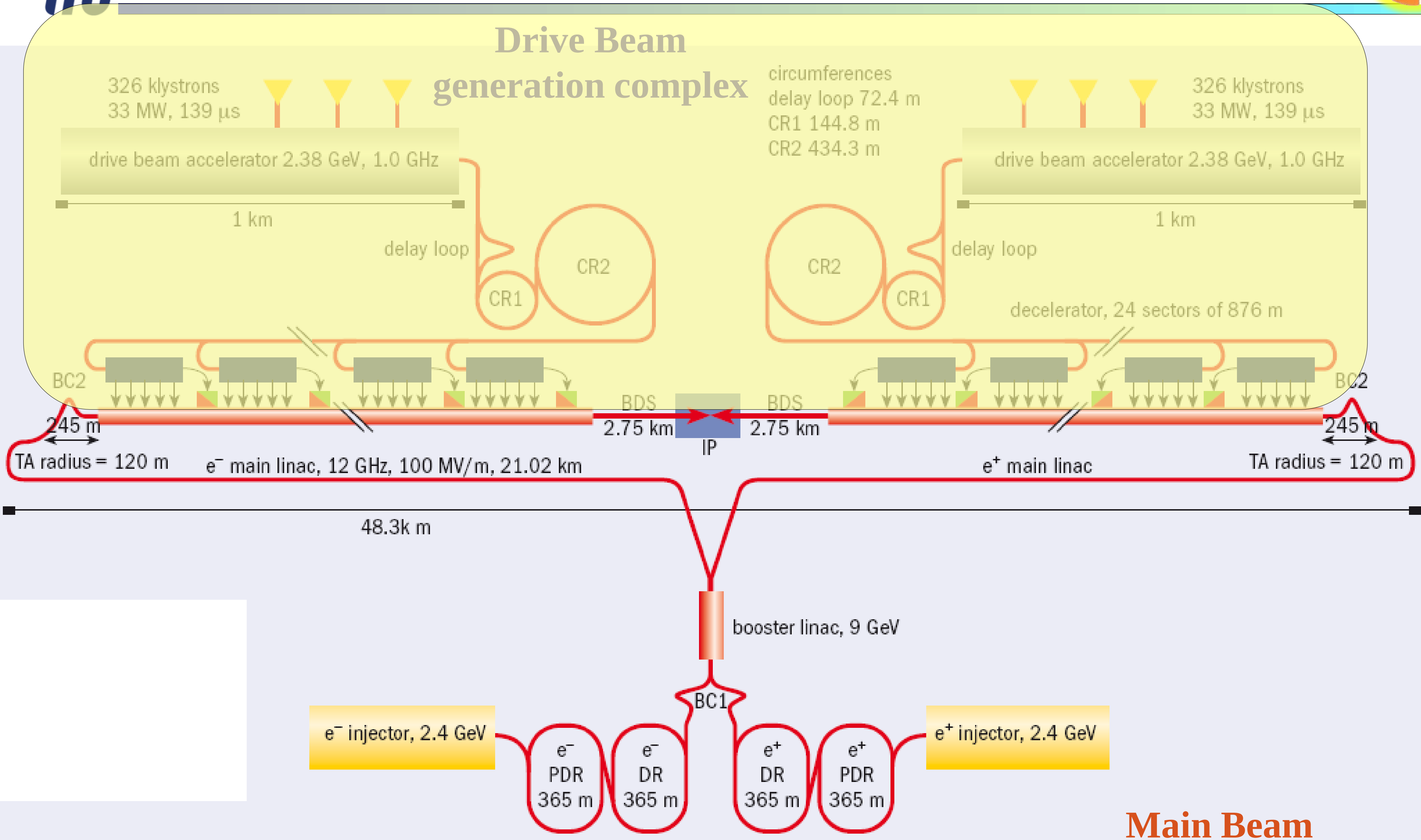
For the 2 x 21 km linacs

20 924 CLIC modules of 2.010 m each

71 406 Power Extraction and Transfer Structures (PETS) for the Drive Beams

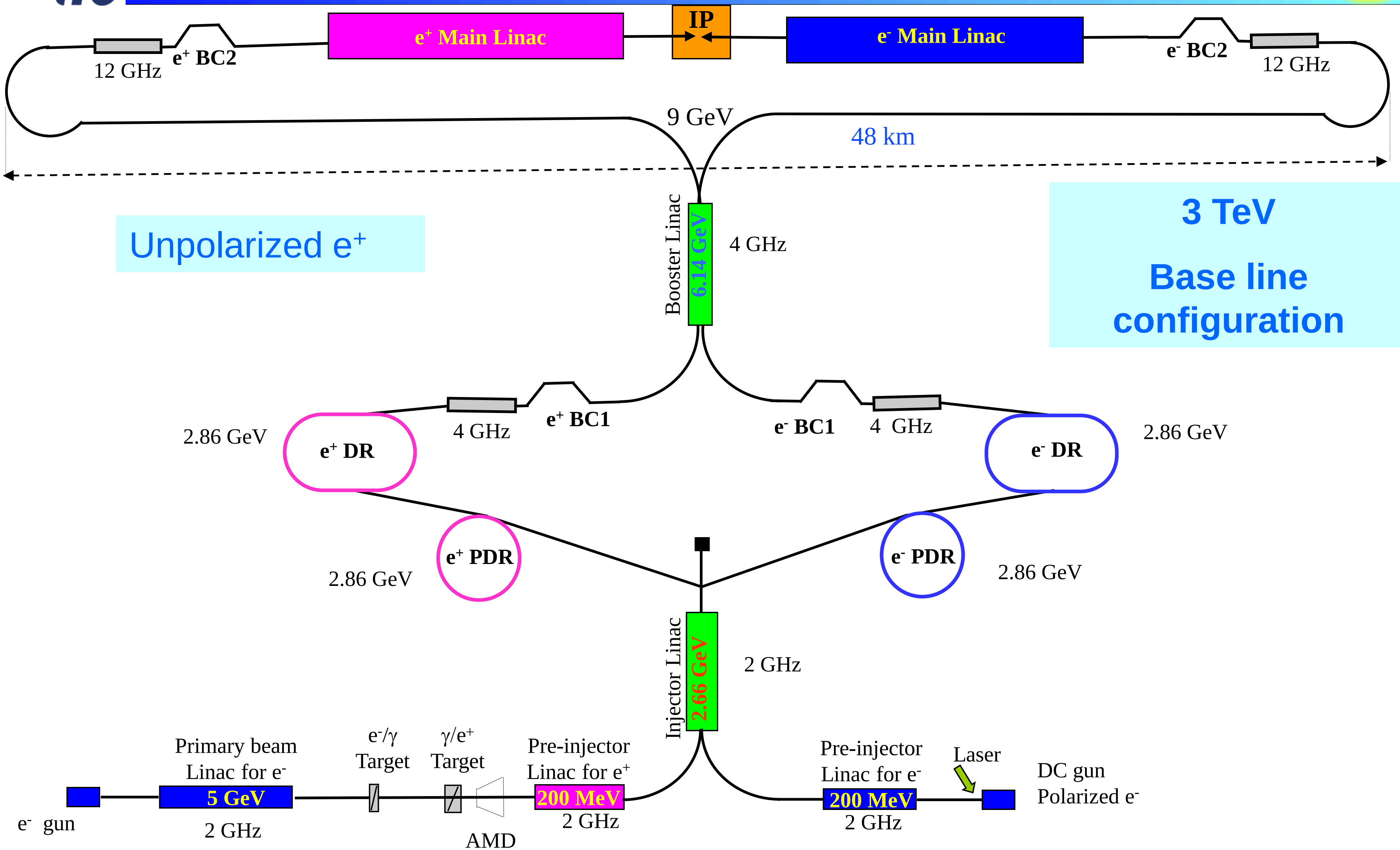
142 812 CLIC Accelerating Structures (CAS) for the Main Beams

CLIC Main Beam Injector complex



Main Beam generation complex

CLIC Main Beam Injector Complex



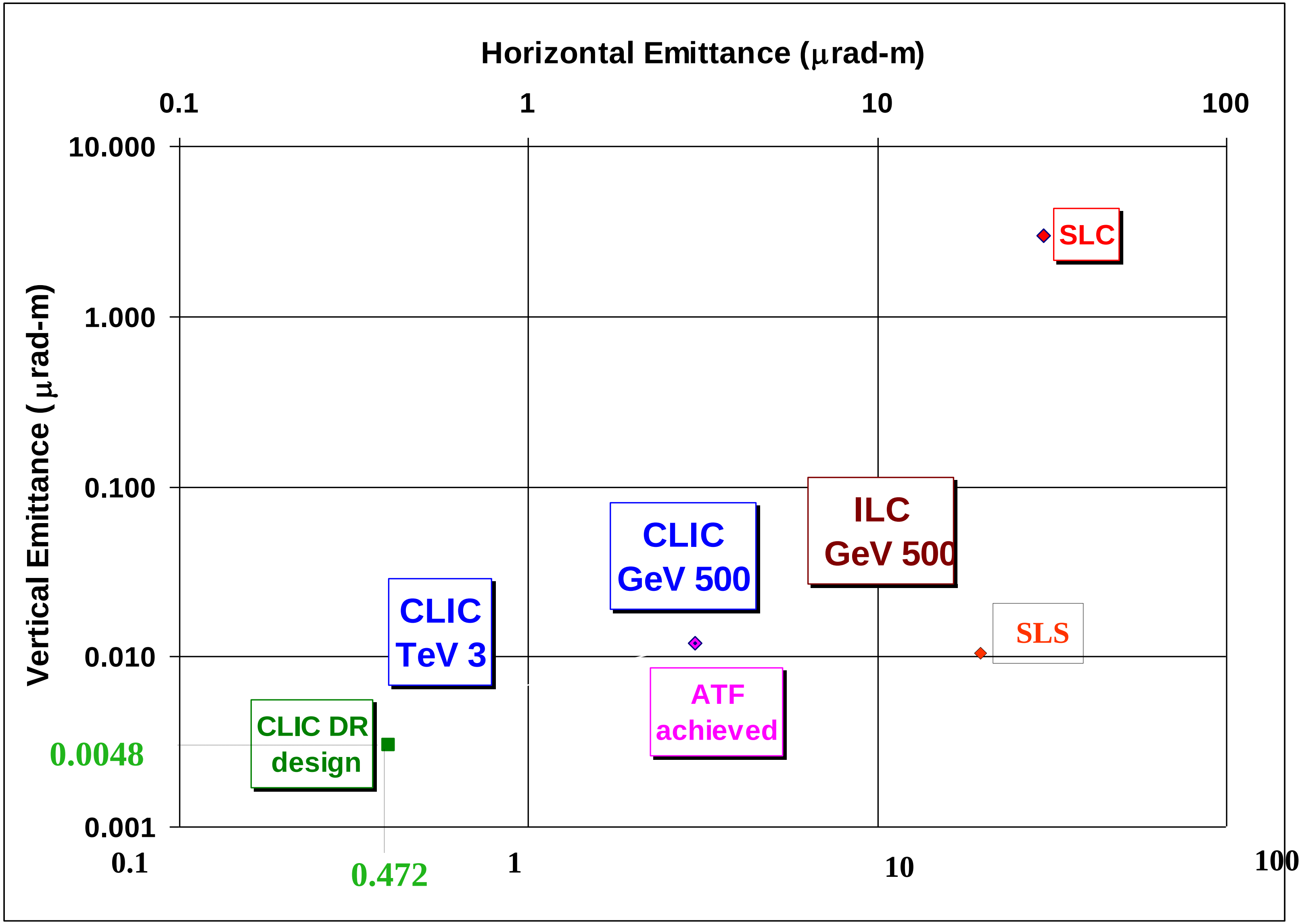
Flux of e^+

	SLC	CLIC (3 TeV)	CLIC (0.5 TeV)	ILC (RDR)	LHeC (pulsed)	LHeC ERL
Energy	1.19 GeV	2.86 GeV	2.86 GeV	5 GeV	140 GeV	60 GeV
e^+/ bunch (at IP)	40×10^9	3.7×10^9	7.4×10^9	20×10^9	1.6×10^9	2×10^9
e^+/ bunch (aft. capture)	50×10^9	7×10^9	14×10^9	30×10^9	1.8×10^9	2.2×10^9
Bunches / macropulse	1	312	354	2625	100 000	NA
Rep. Rate (Hz)	120	50	50	5	10	CW
Bunches / s	120	15600	17700	13125	10^6	20×10^6
e^+ / second $\times 10^{14}$	**0.06**	**1.1**	**2.5**	**3.9**	**18**	**440**

x 20 x 70 x 7000

The challenge of the small beam emittances

Normalized rms emittances at the Damping Ring extraction

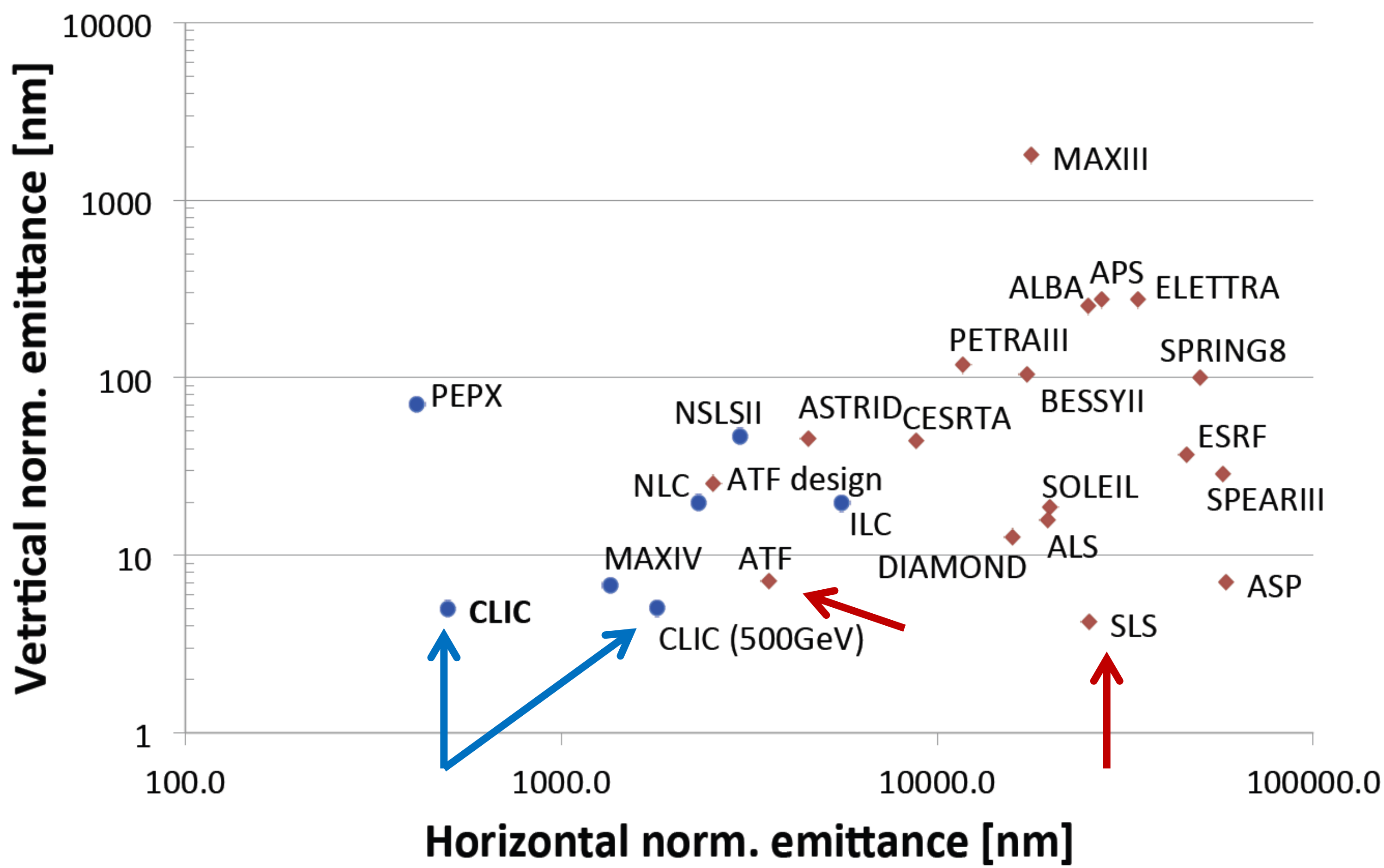


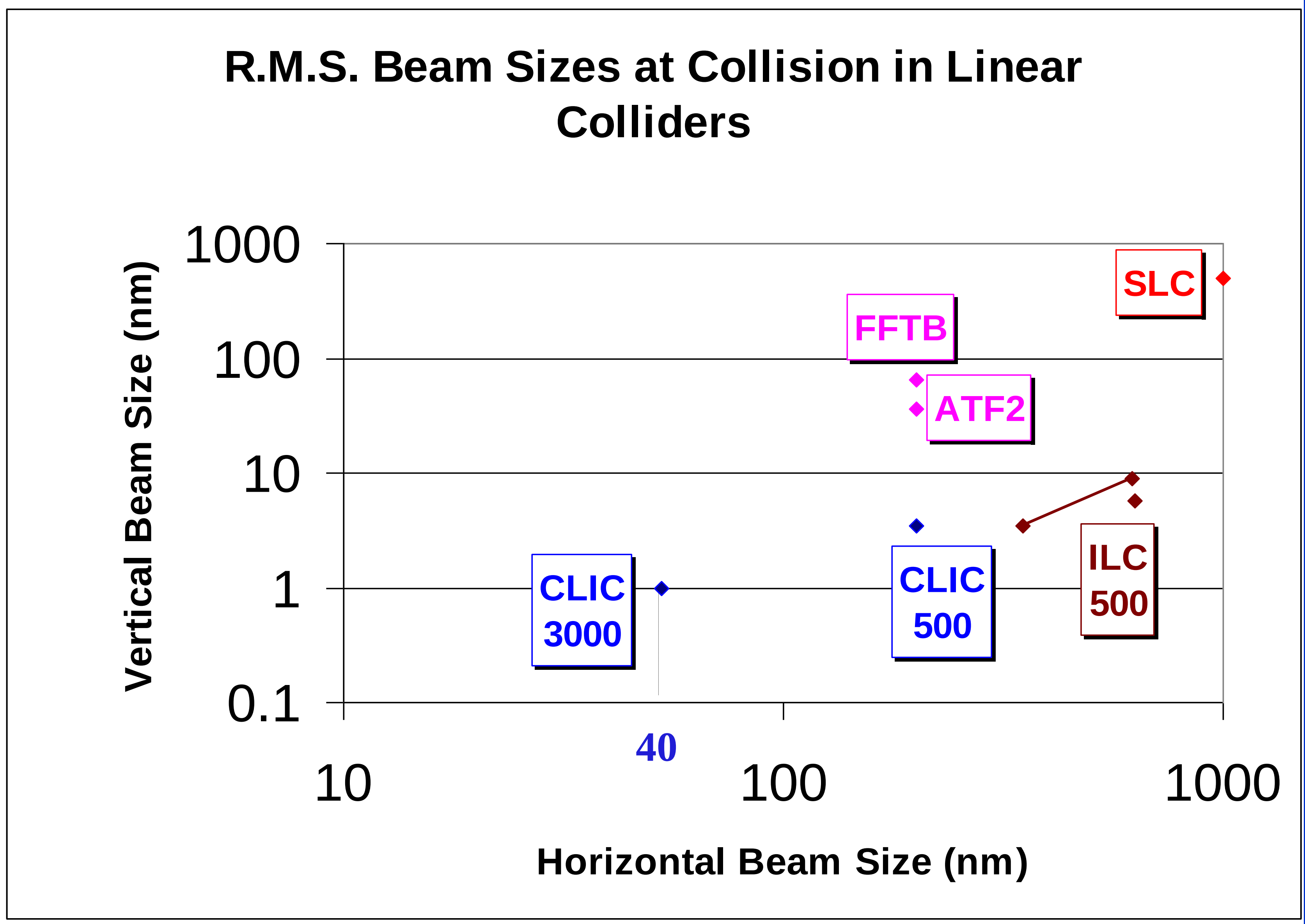
Emittances generation

Many design issues:

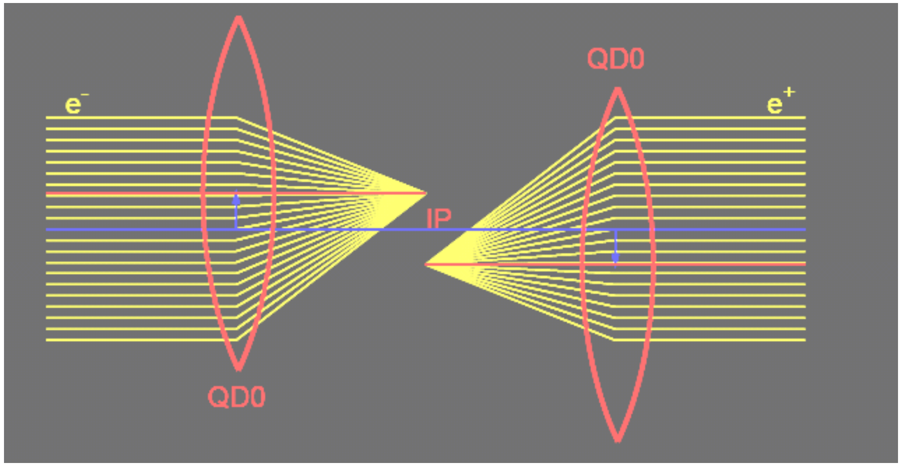
- lattice design
- dynamic aperture
- tolerances
- intra-beam scattering
- space charge
- wigglers
- RF system
- vacuum
- electron cloud
- kickers

Red = achieved Blue = planned




R.M.S. Beam Sizes at Collision in Linear Colliders
1000
100
10
1
0.1
Vertical Beam Size (nm)
SLC
FFTB
ATF2
CLIC 3000
CLIC 500
ILC 500
40
10
100
1000
Horizontal Beam Size (nm)

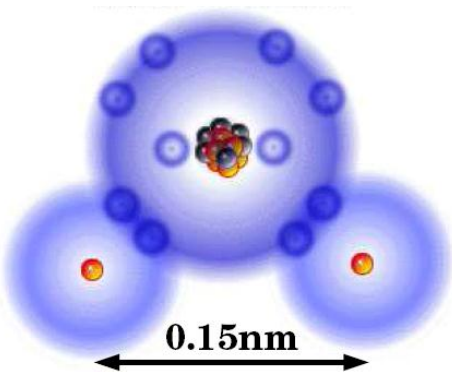
Vertical spot size at IP is 1 nm



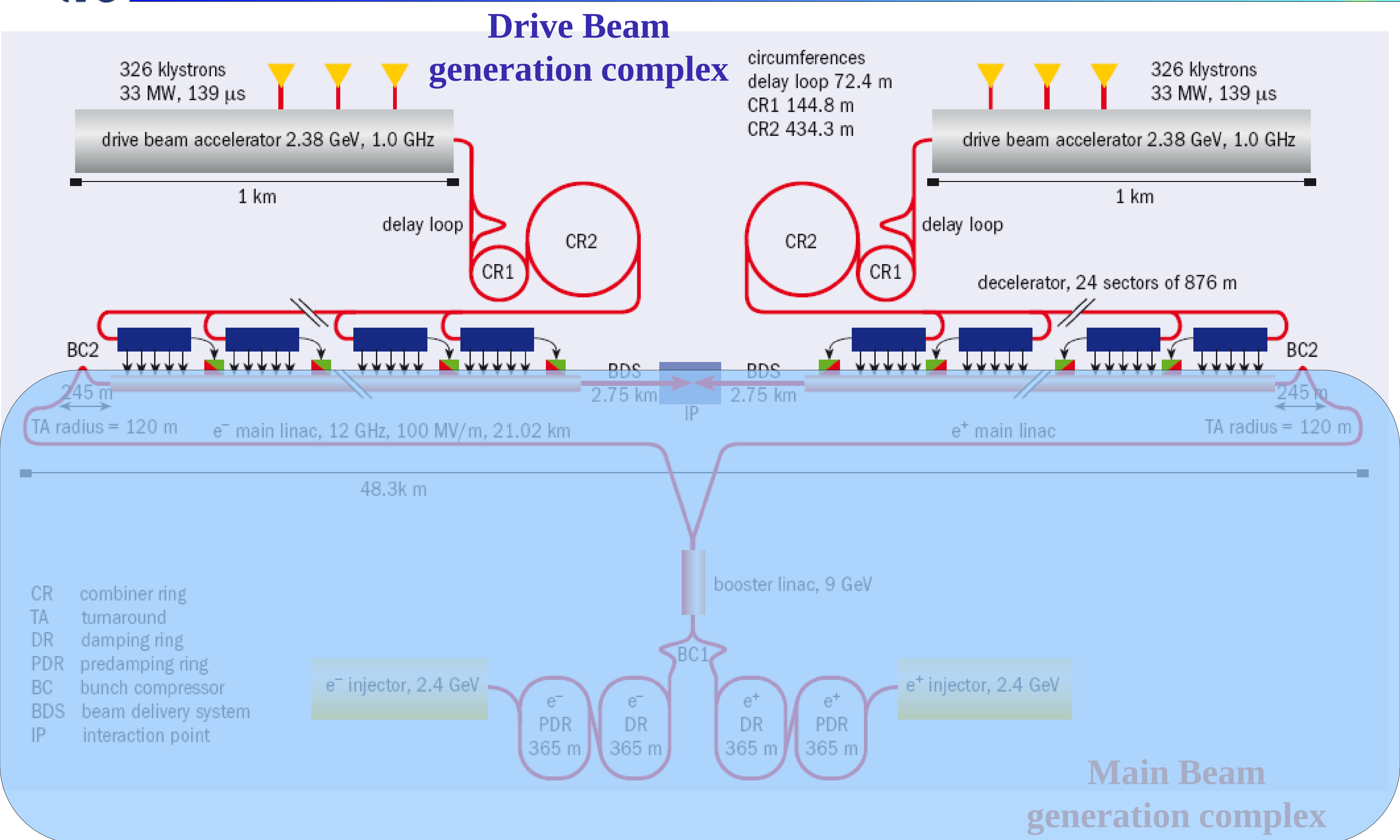
Stability requirements (> 4 Hz) for a 2% loss in luminosity

Magnet	Horizontal jitter	Vertical jitter
Linac (2600 quads)	14 nm	1.3 nm
Final Focus (2 quads) QD0	4 nm	0.15 nm

H_2O molecule



CLIC Drive Beam complex



What does the RF power source do ?

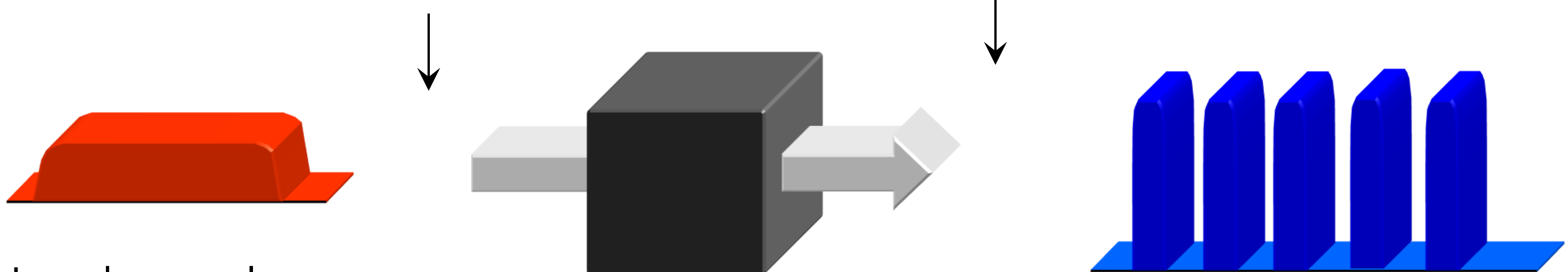
The CLIC RF power source can be described as a “black box”, combining *very long beam pulses*, and transforming them in *many short pulses*, with *higher intensity* and with *higher frequency*

Accelerator Linac

Power stored in electron beam

Power extracted from beam in resonant structures

Decelerator Linac



Long beam pulses

I_0, Δt_0, f_0

Electron beam manipulation

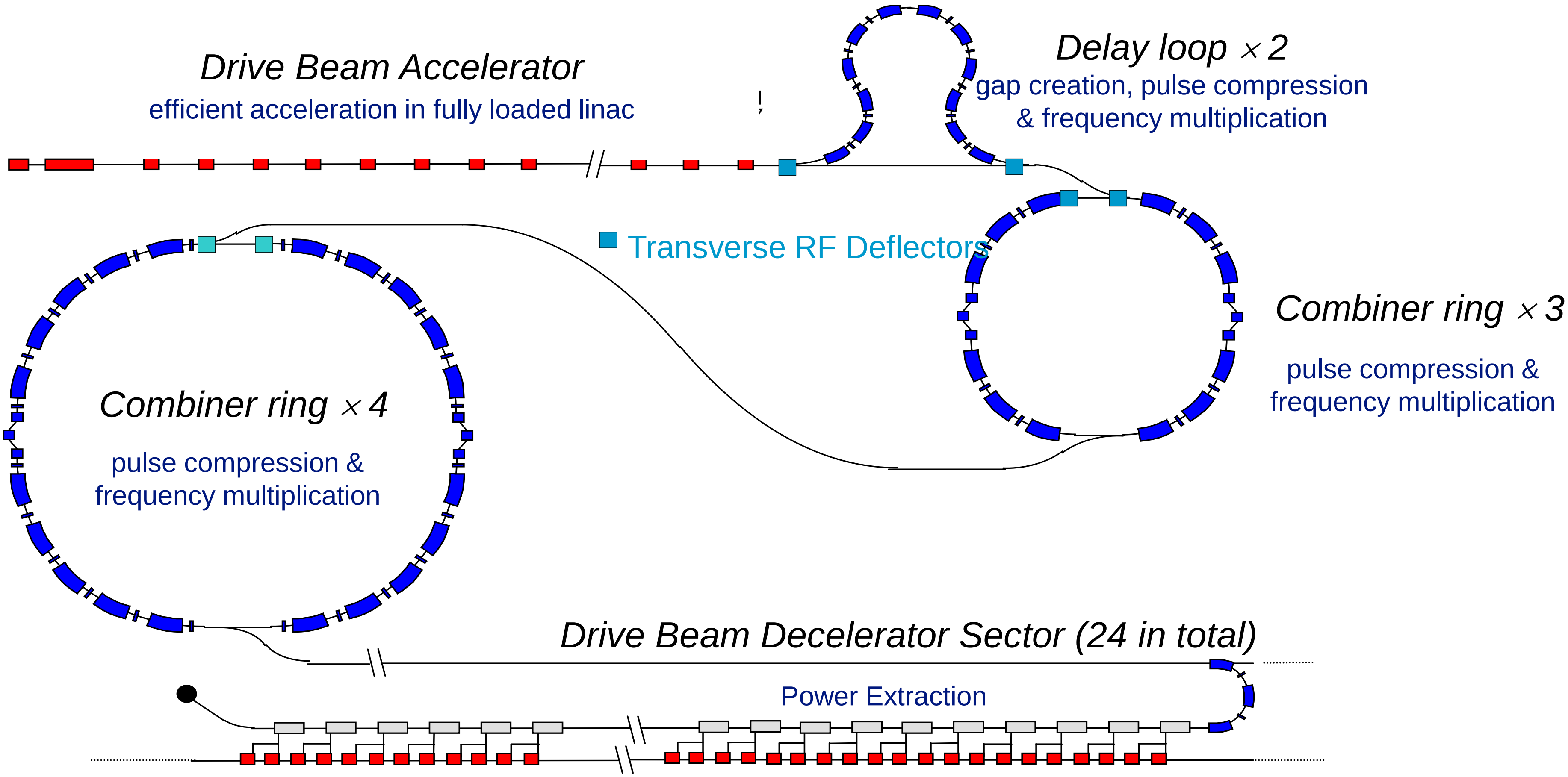
Short beam pulses

$I_1 = I_0 \text{ x } N$

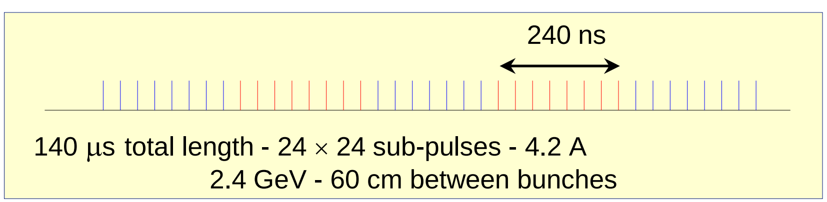
$\Delta t_1 = \Delta t_0 / N$

$f_1 = f_0 \text{ x } N$

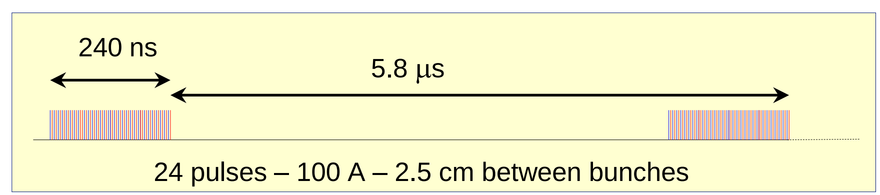
The Drive Beam generation



Drive beam time structure - initial



Drive beam time structure - final



The CLIC Test Facilities

1988-1995: CTF = CLIC Test Facility 1

First Test Facility with a single beam making demonstration of acceleration with high gradient based on 30 GHz RF power

1995-2002: CTF 2 = CLIC Test Facility 2

Second Test Facility for demonstration of the two beams acceleration concept

High gradient tests in single cells 30 GHz cavities

2001-2003: CTF 3 = CLIC Test Facility 3 (Preliminary phase)

Third Test Facility for demonstration of the RF frequency multiplication by a factor 4

2003-2013: CTF 3 = CLIC Test Facility 3

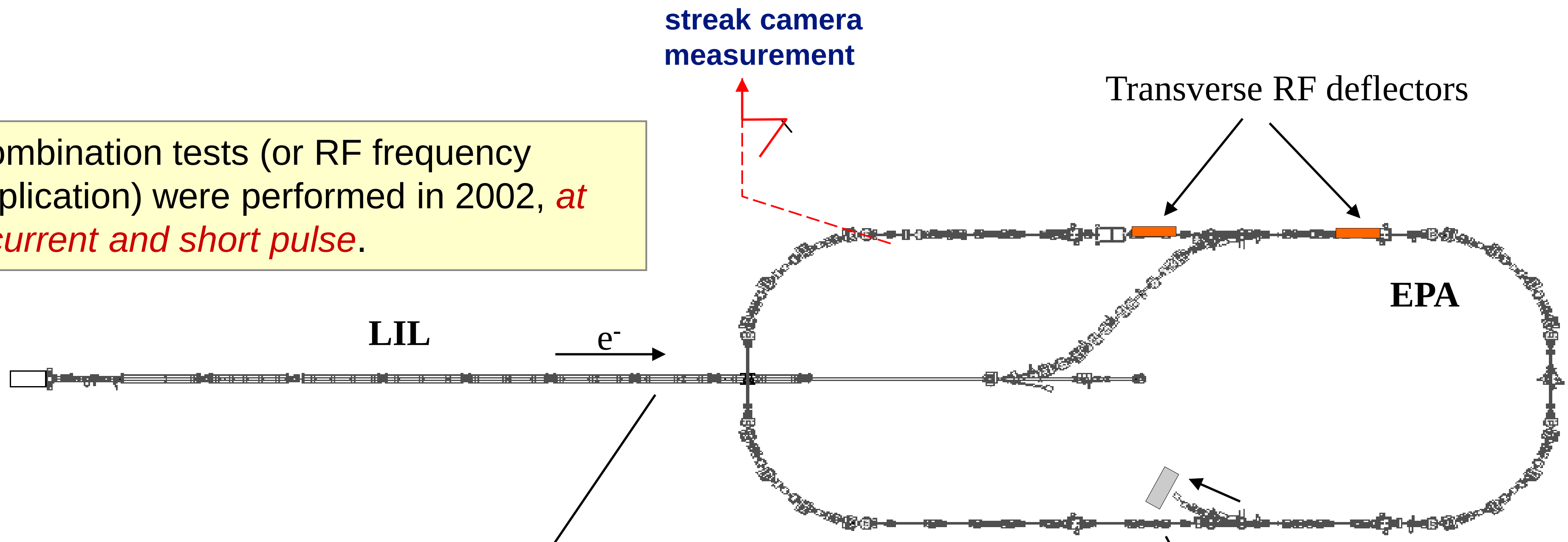
Demonstration of the fully loaded linac and all CLIC technology-related key issues initially listed in the ILC-TRC 2003 report and reviewed by the CLIC Advisory Committee

Recombination of electron beam pulses

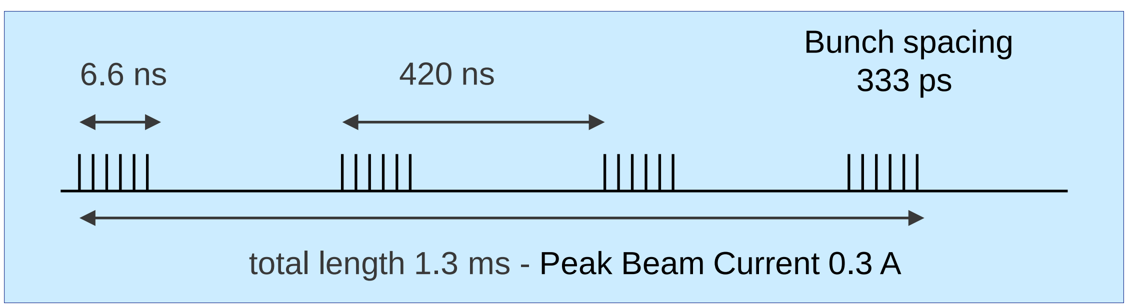
LIL = LEP Injector Linac

EPA = Electron Positron Accumulator

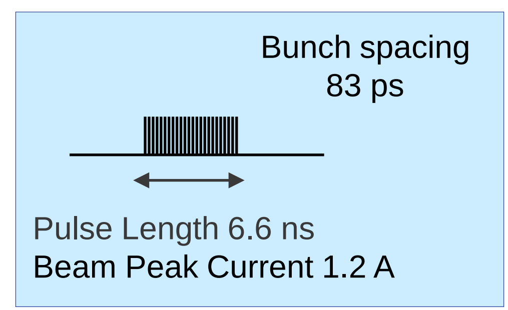
Recombination tests (or RF frequency multiplication) were performed in 2002, *at low current and short pulse*.



Beam structure in linac – 4 pulses

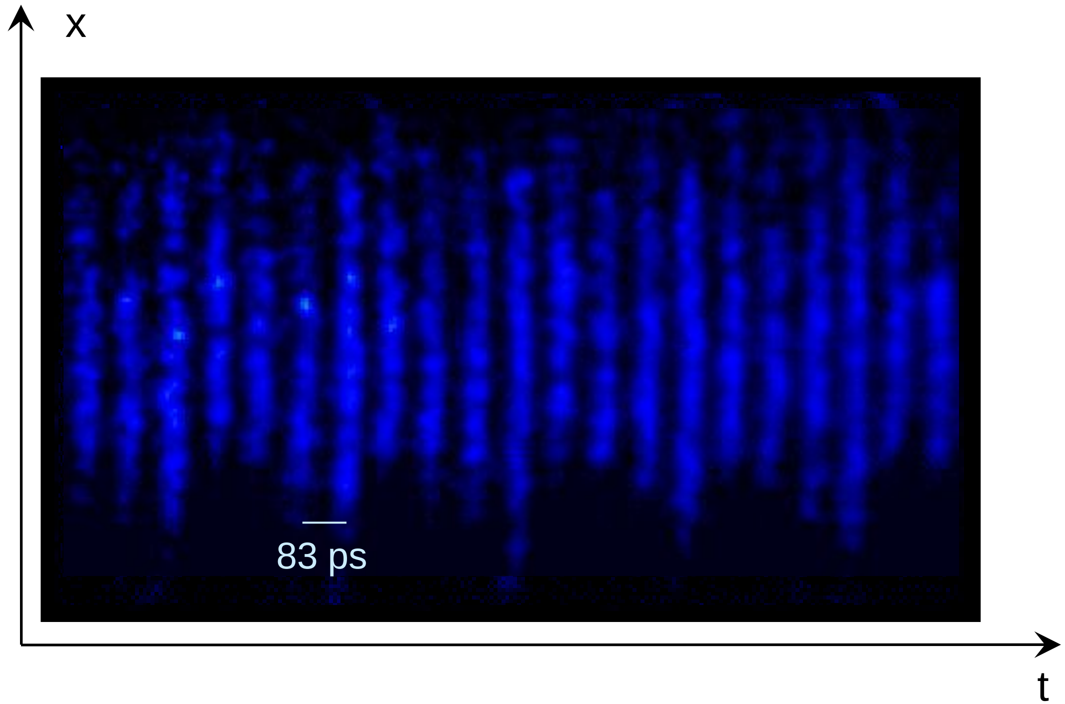


Beam structure after combination (factor 4)



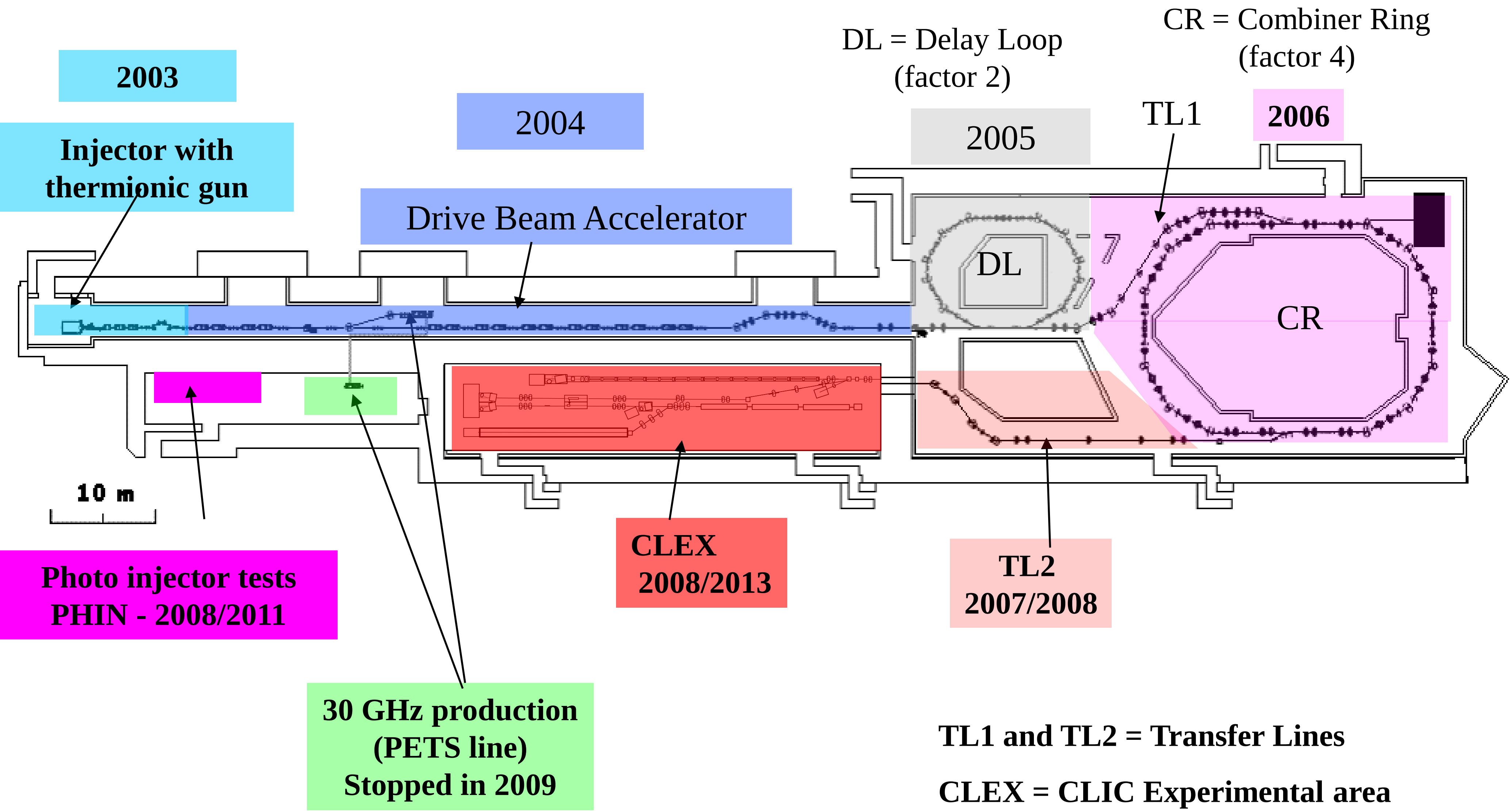
Streak camera images

Recorded during the CTF 3 Preliminary phase



4^{th} turn

Showing the bunch combination process or RF frequency multiplication by a factor 4



TL1 and TL2 = Transfer Lines

CLEX = CLIC Experimental area

CLIC - CTF3 infrastructures

CTF2 hall

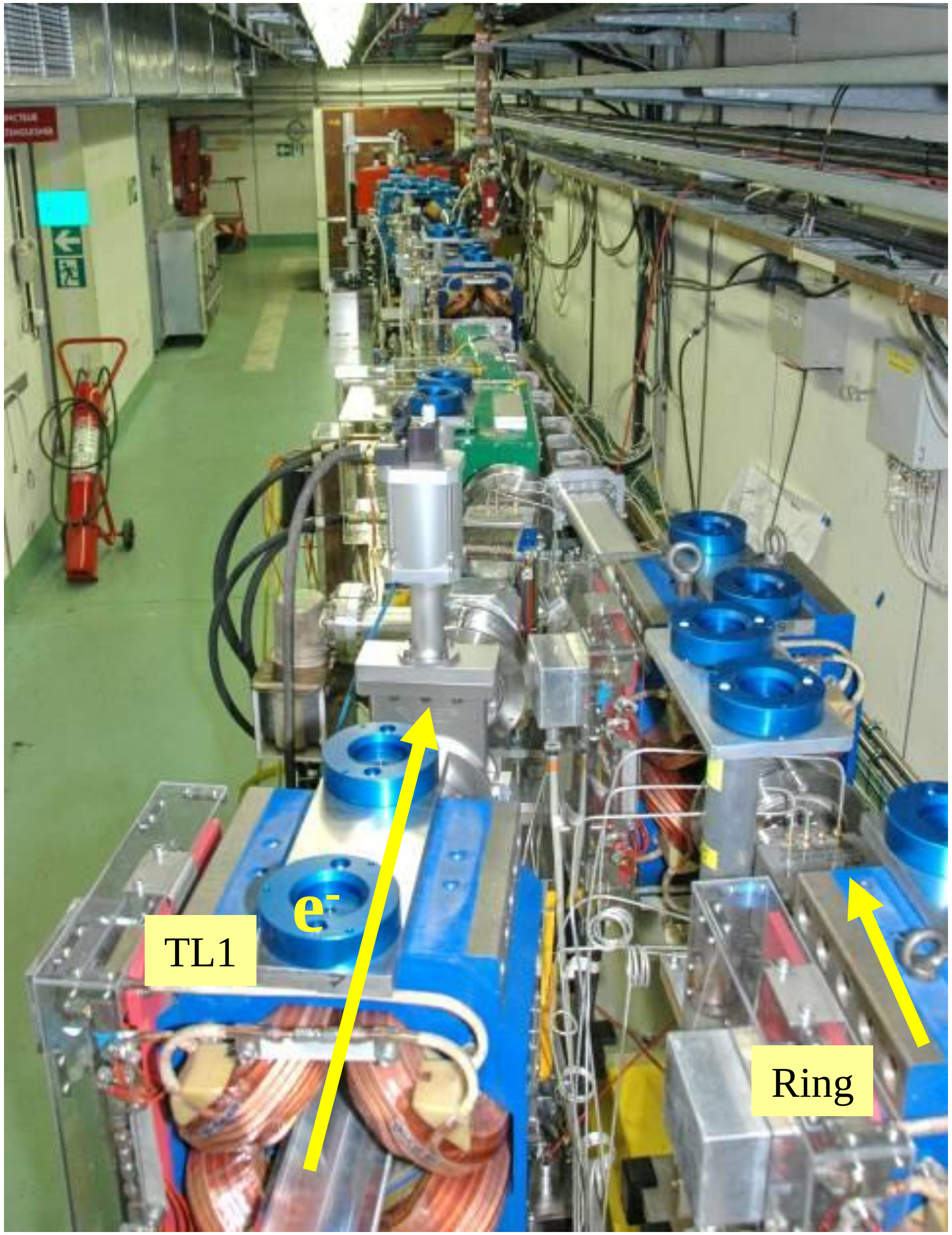
including Photoinjector PHIN

CLEX hall

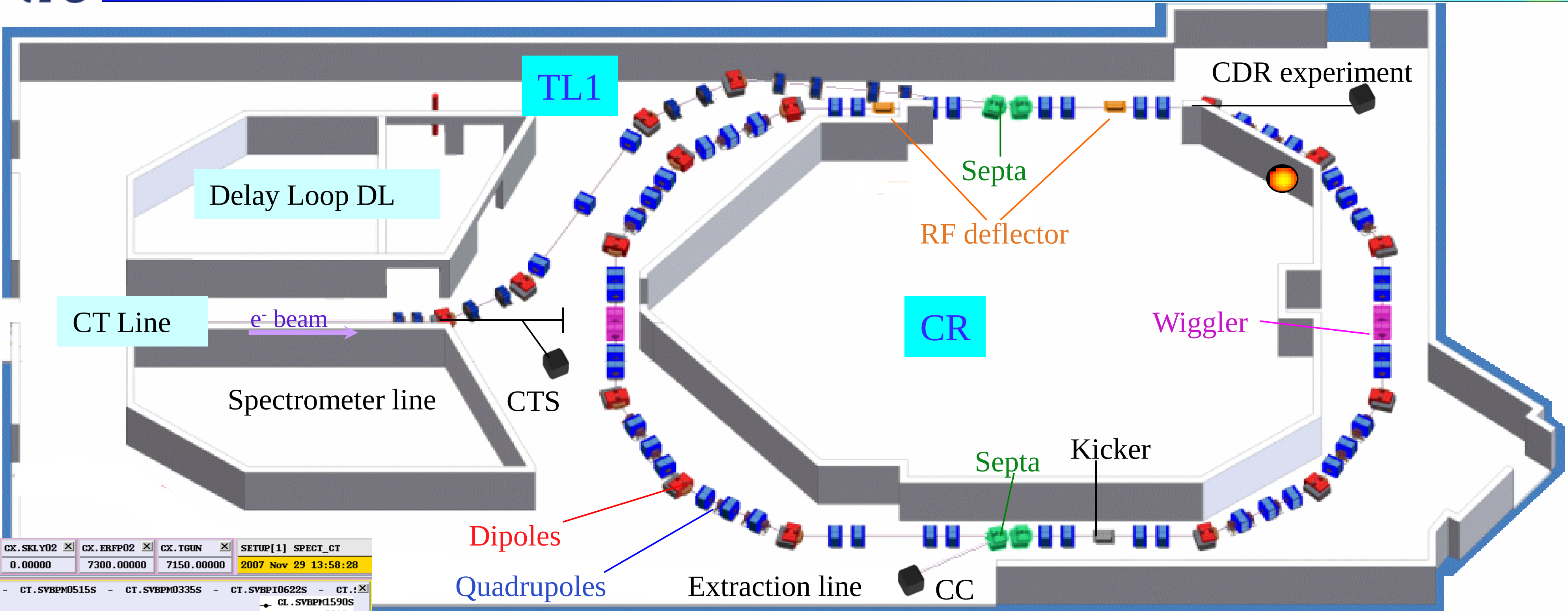
CTF3 Injector Linac

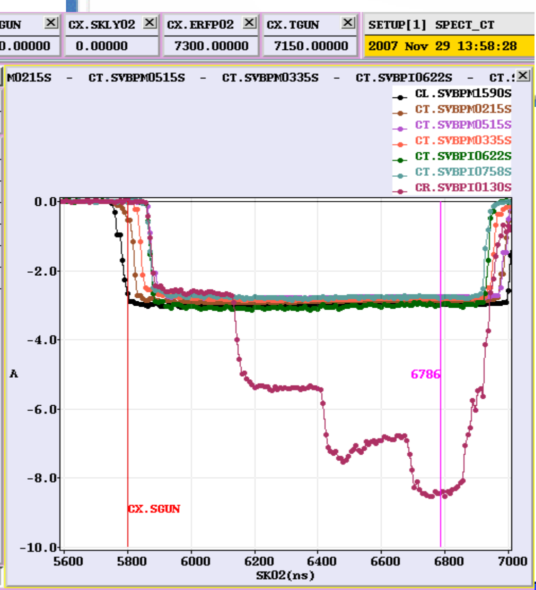
Delay Loop Injection area

Injection region in the Combiner Ring



Combiner Ring

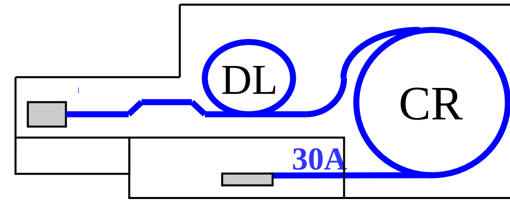


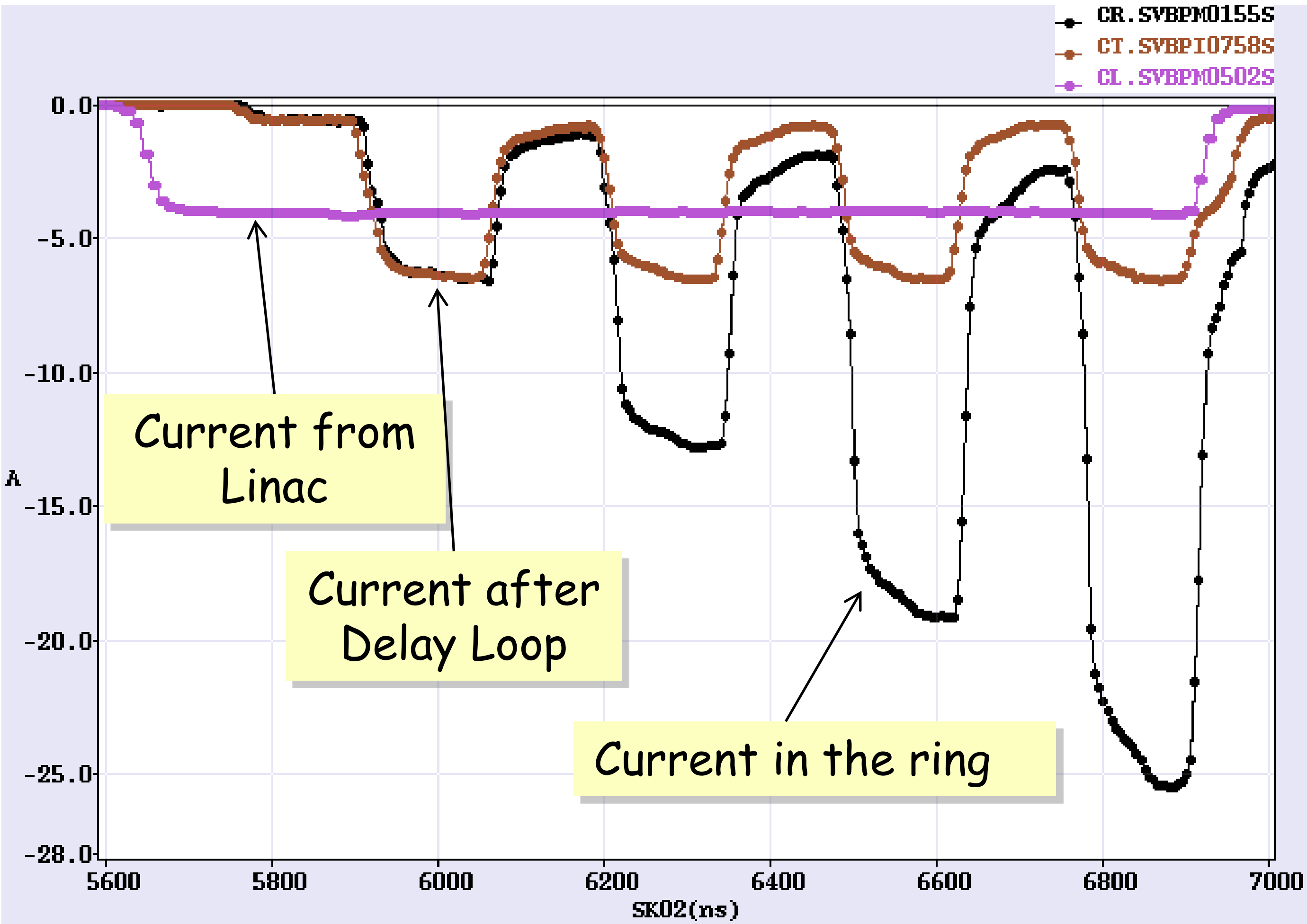


First combination with a factor 4
(November `07)

Beam recombination in both rings

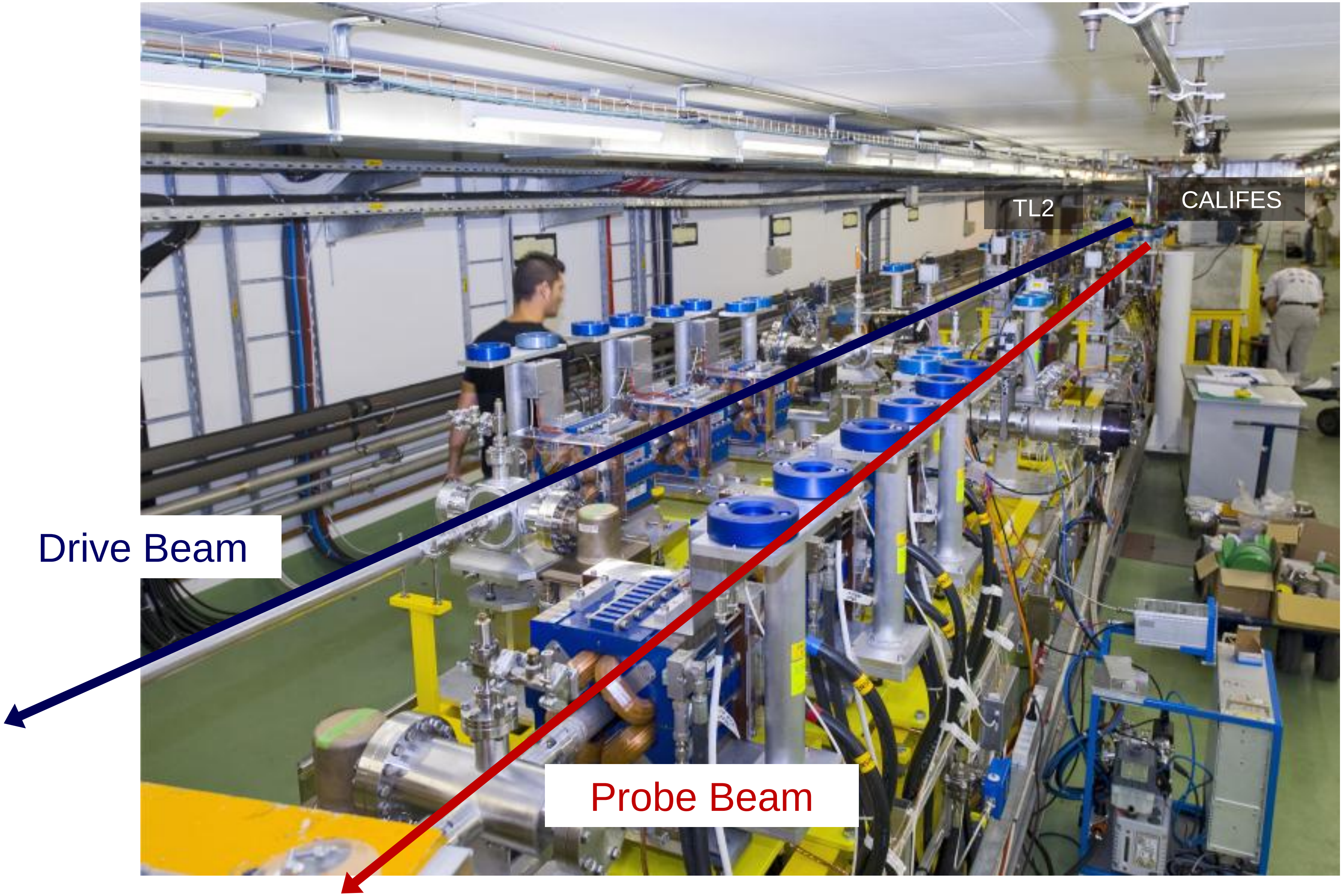
- factor 8 combination achieved with 26 A, 140 ns (Delay Loop + Combiner Ring))





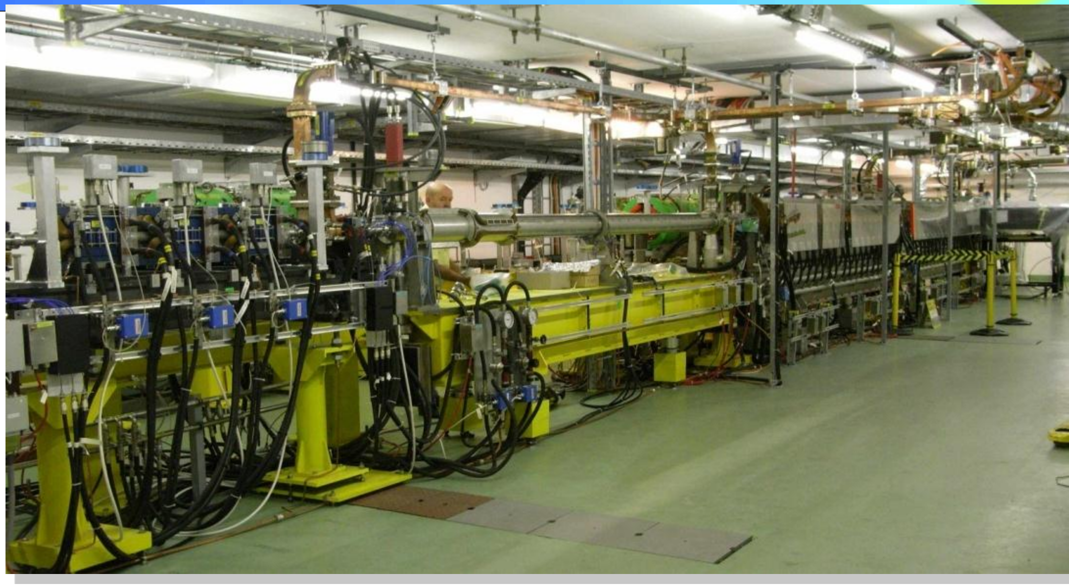
Transfer line TL2 from Combiner Ring to CLEX

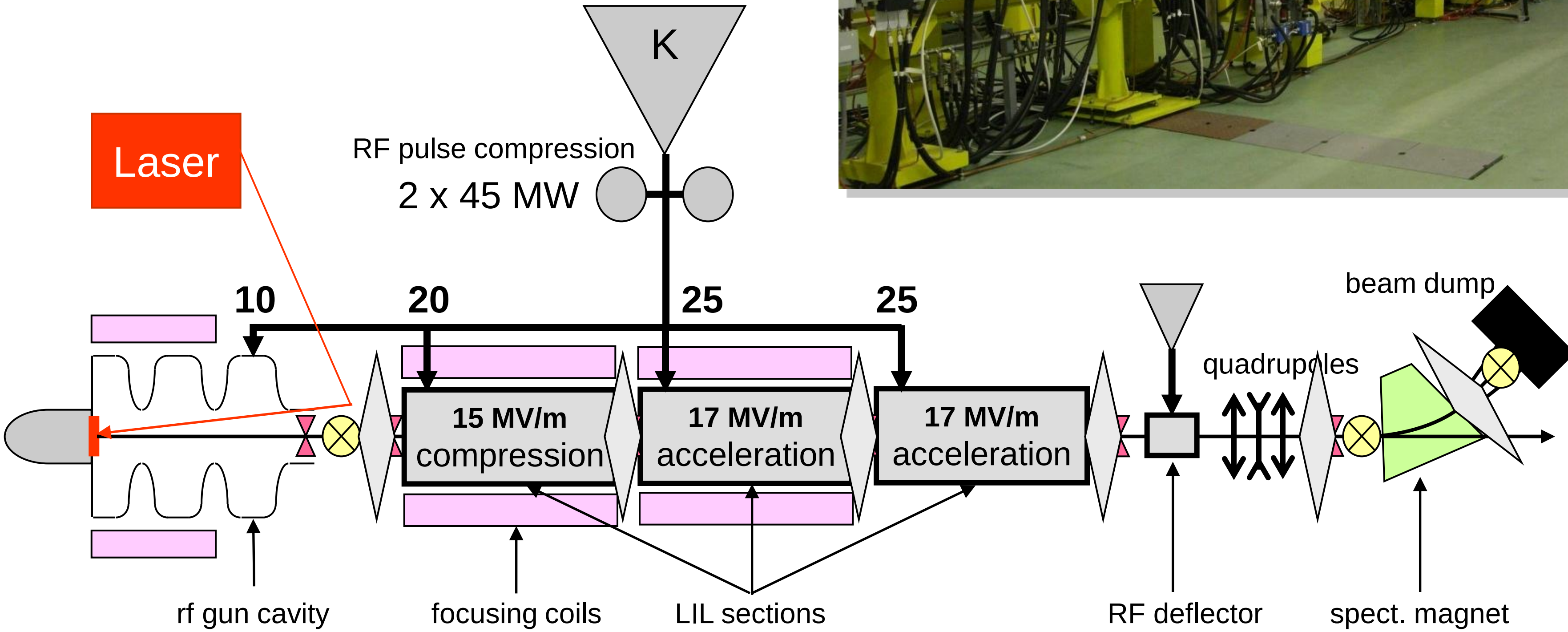
Two Beams in CLEX



Probe Beam CALIFES

180 MeV
bunch charge 0.6 nC
number of bunches 1 or 32 or 226





C A L I F E S = Concept d'Accélérateur Linéaire pour Faisceau d'Electrons Sonde

IRFU (DAPNIA), CEA, Saclay, France

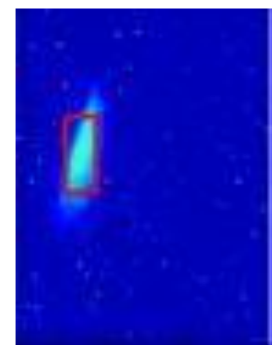
Problem with RF deflecting cavity CALIFES ?

15th May 09: The conditioning of the deflecting RF cavity experiences too high reflected power (-13 dB). After many investigations, we suspected an obstacle in the long waveguide line (~80 m) from the klystron MKS14 to the deflecting cavity.

Reflectometric method allows to spot this waveguide.

Object found inside the RF wave guide. It was a device used in the brazing oven

Cavity OFF
σ_y = 0.24 mm



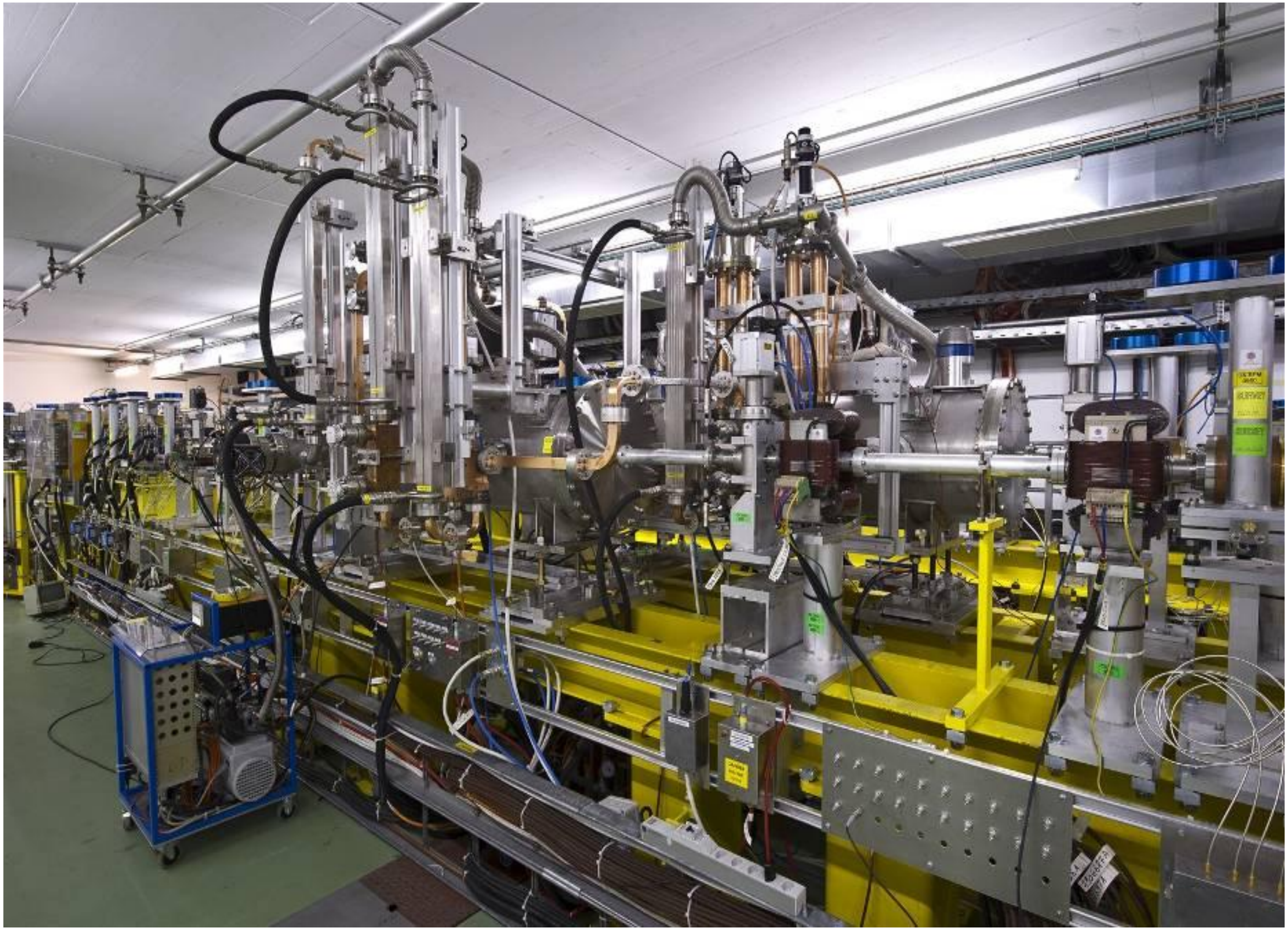
Cavity ON
σ_y = 1.47 mm

$\Rightarrow$ Electron bunch length σ_t = 1.42 ps

with a laser pulse σ_t = 7 ps

PETS tank on Drive Beam line into CLEX

PETS = Power Extraction and Transfer Structure

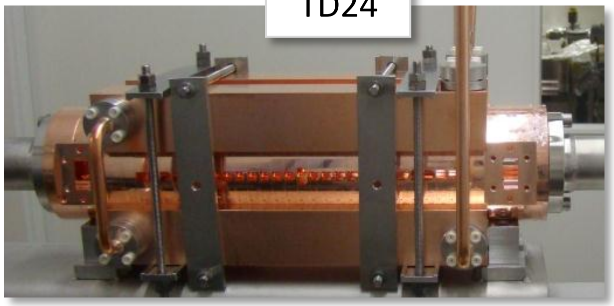


Two-Beam Acceleration achieved gradient

Two-Beam Acceleration demonstration in TBTS

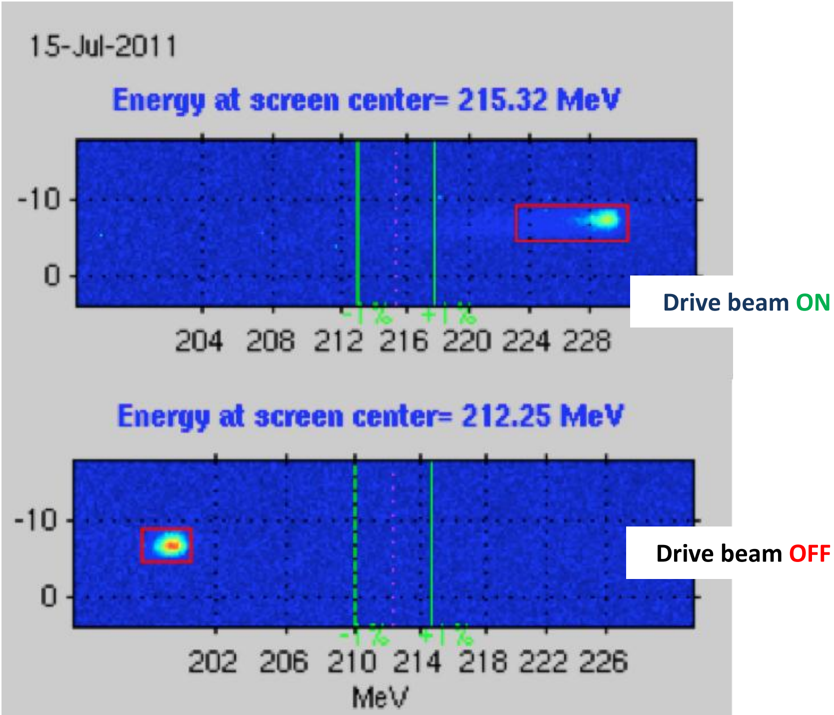
Up to 145 MV/m measured gradient

TD24



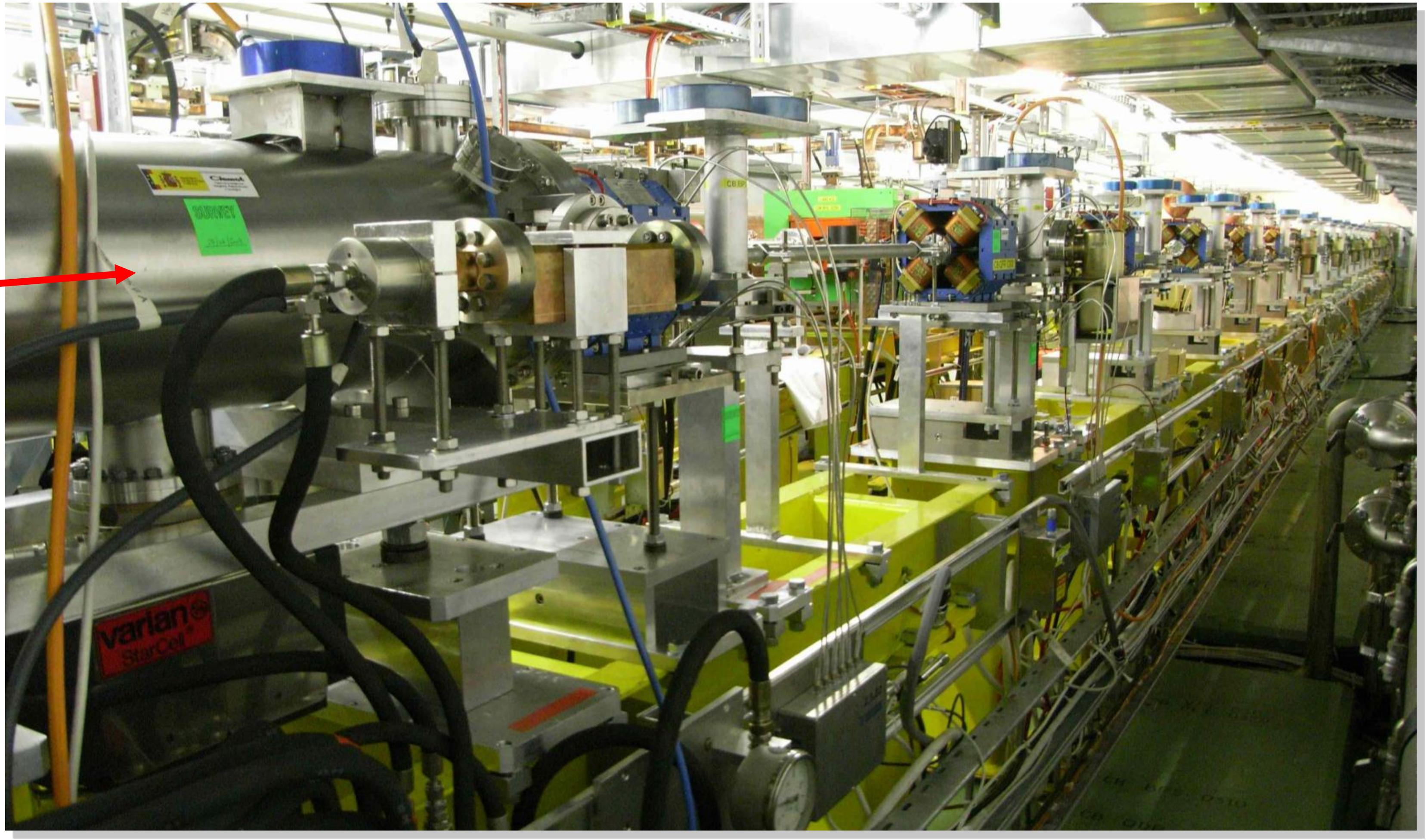
Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of **145 MV/m**



Test Beam Line (TBL) into CLEX hall

e^-



- Beam up to 10 A through PETS ==> 20 MW max produced at a pulse length of 280 ns

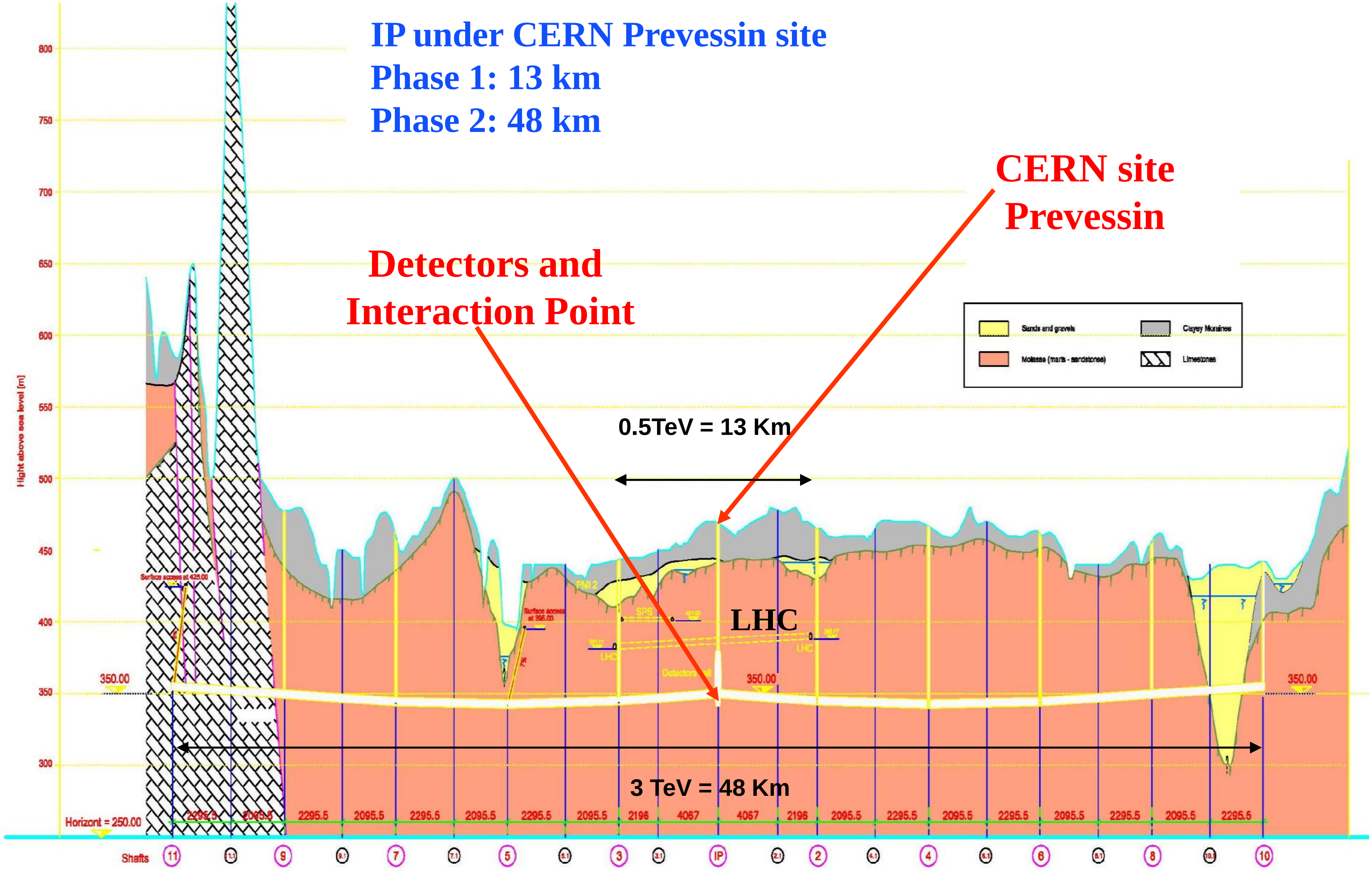
JUAS 2013 students into CLEX hall

From CTF3 to CLIC

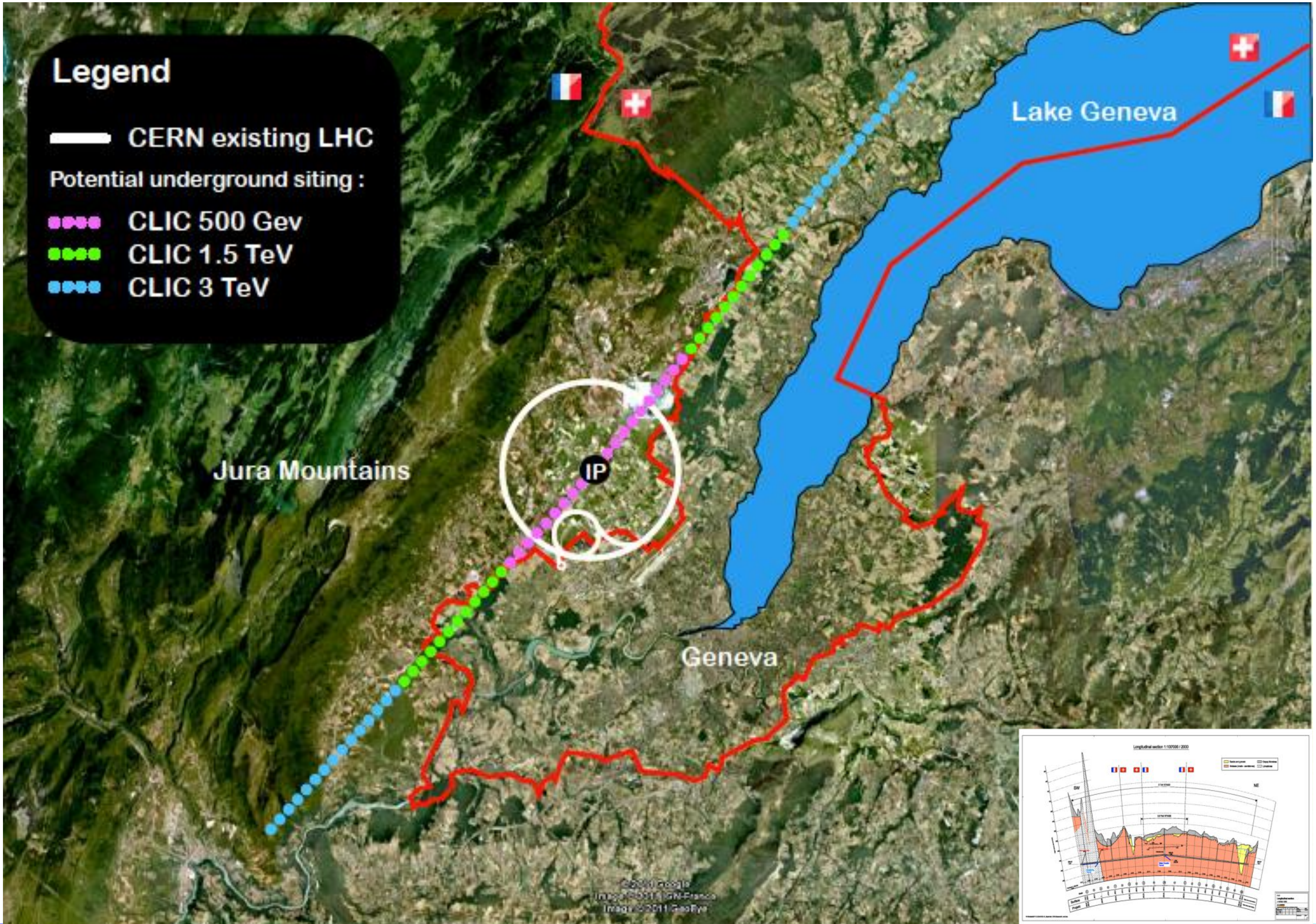
		CTF3	CLIC
Energy	GeV	0.15	2.4
Current	A	32	100
Normalized (geom) emittance	mm mrad	100 (0.3)	100 (0.02)
Pulse length	ns	140	240
train length in linac	μs	1.2	140
RF Frequency	GHz	3	1
Compression factor		2 x 4	2 x 3 x 4

Longitudinal section on CERN site

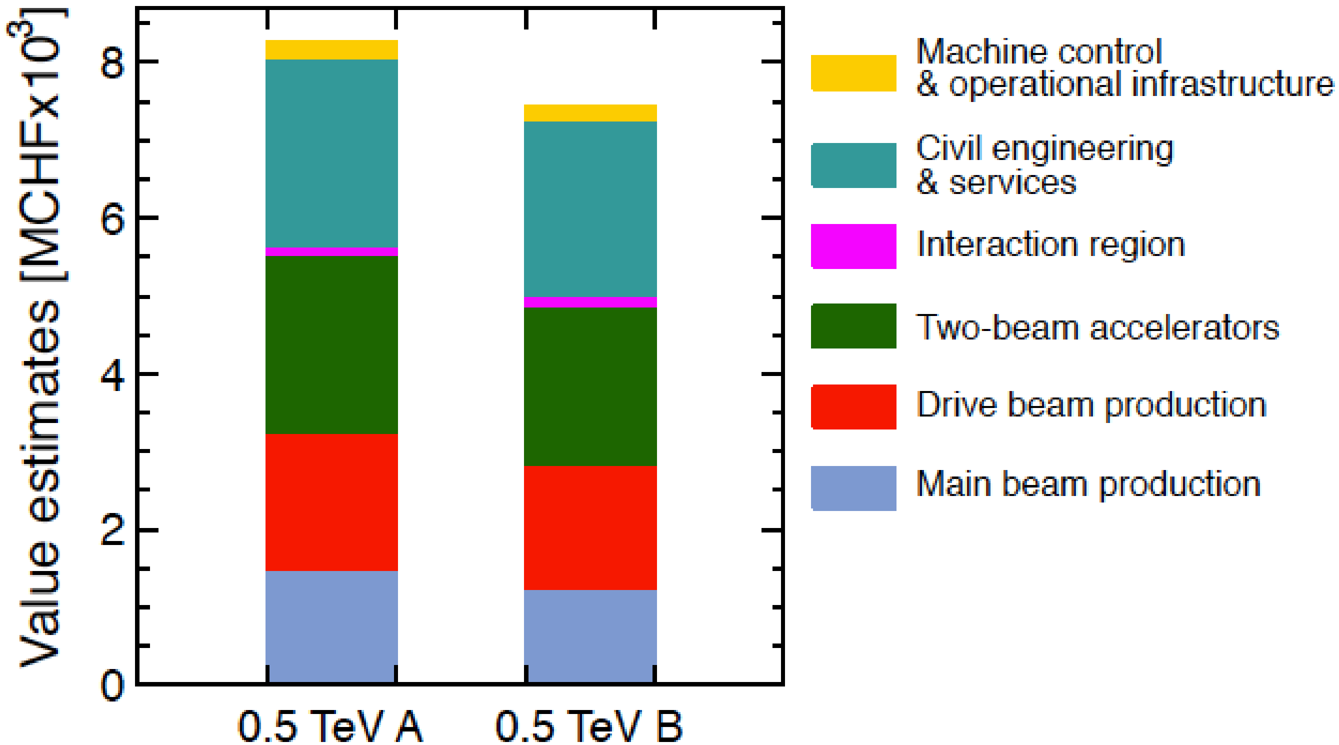
IP under CERN Prevessin site
Phase 1: 13 km
Phase 2: 48 km



CLIC near CERN



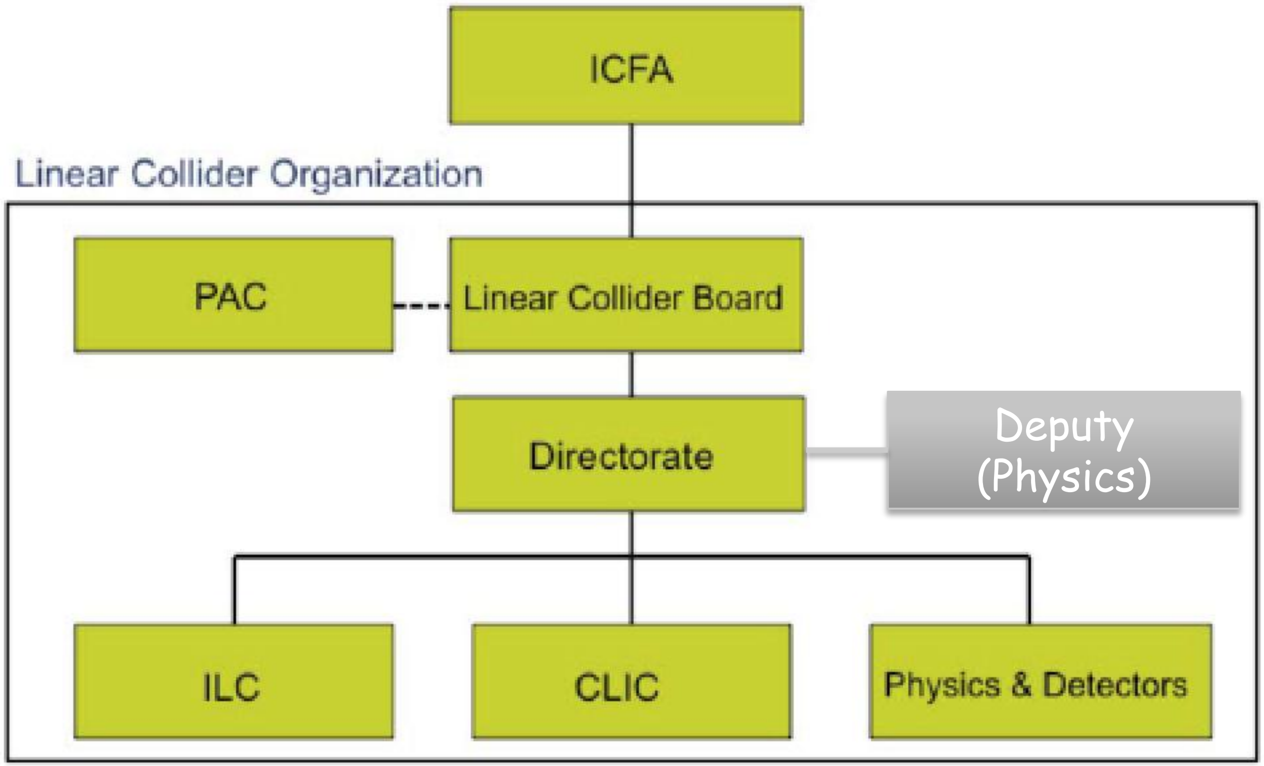
S. Stapnes / CERN



First to second stage: 4 MCHF/GeV (i.e. initial costs are very significant)

Uncertainties 20-25%
However – first stage not optimised (work for next phase), parameters largely defined for 3 TeV final stage

Linear Collider organization



Future Linear Collider objectives

- Strongly support the Japanese initiative to construct a linear collider as a staged project in Japan
- Prepare CLIC machine and detectors as an option for a future high-energy linear collider at CERN
- Further improve collaboration between CLIC and ILC machine experts
- Move towards a "more normal" structure of collaboration in the detector community to prepare for the construction of two high-performance detectors

Lyn Evans 22-Oct-12
LCWS12 - Arlington, TX

Final remark at CLIC09 workshop

B. Barish / GDE

- The central frontier of particle physics is and will continue to be the energy frontier!
- The LHC will open a new era at that frontier and its discoveries will motivate the next machine --- a lepton collider.
- That machine could be the ILC or CLIC (or maybe a muon collider). Science must dictate the choice of machines, informed by the realities of technical performance, readiness, risk and cost for each option.
- It is our jobs (ILC and CLIC design teams) to make sure our R&D and design work will enable the best informed decision for our field.

Conclusion

Although very promising results have been achieved with the various tests facilities, CLIC and ILC machines are not yet ready to be built

Novel ideas are necessary in order to tackle the challenging R&D

The world-wide collaboration is certainly a major asset

Your participation is warmly welcome to the CLIC and ILC studies

Acknowledgements

B. Barish, S. Bettoni, N. Chritin, R. Corsini, W. Farabolini, R. Heuer, J. Osborne, Y. Papaphilippou, K. Peach, R. Ruber, A. Samoshkin, S. Stapnes