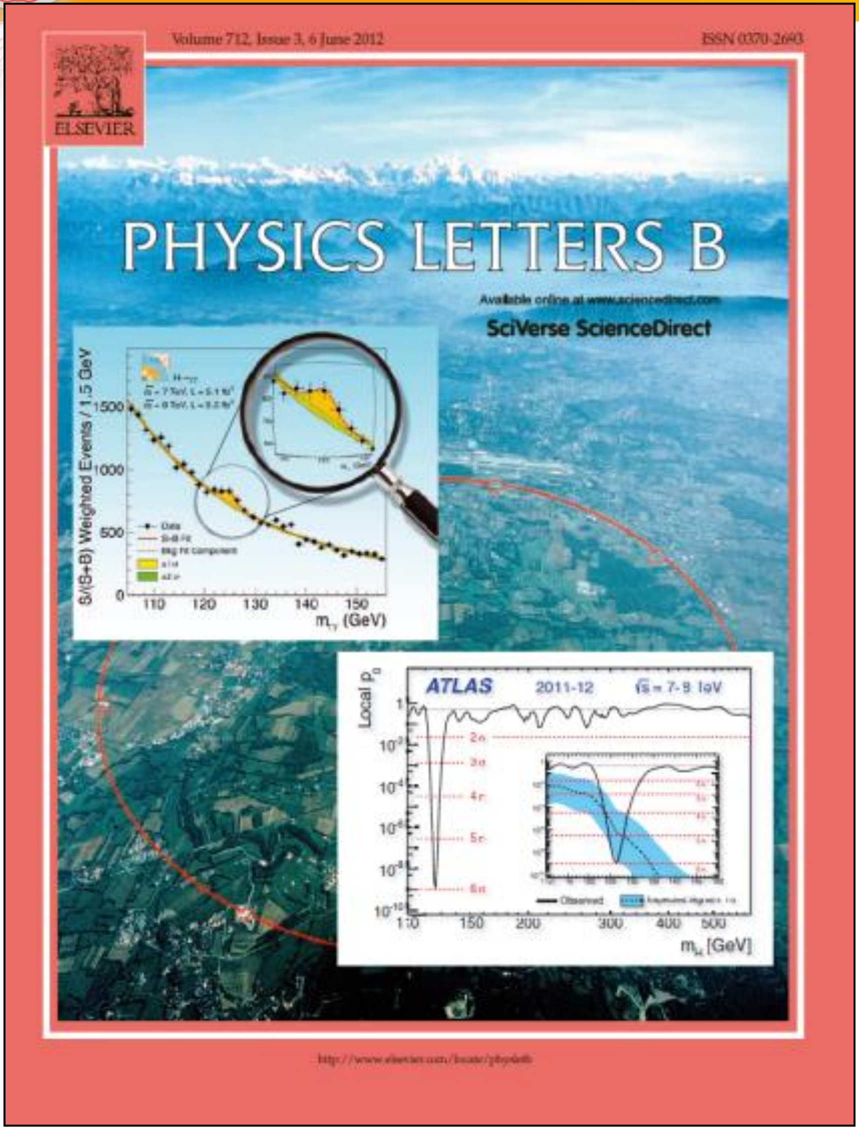
Beyond the LHC

Lyn Evans – CERN/*Linear Collider Collaboration*

IWMNP Bormio 28th January 2015

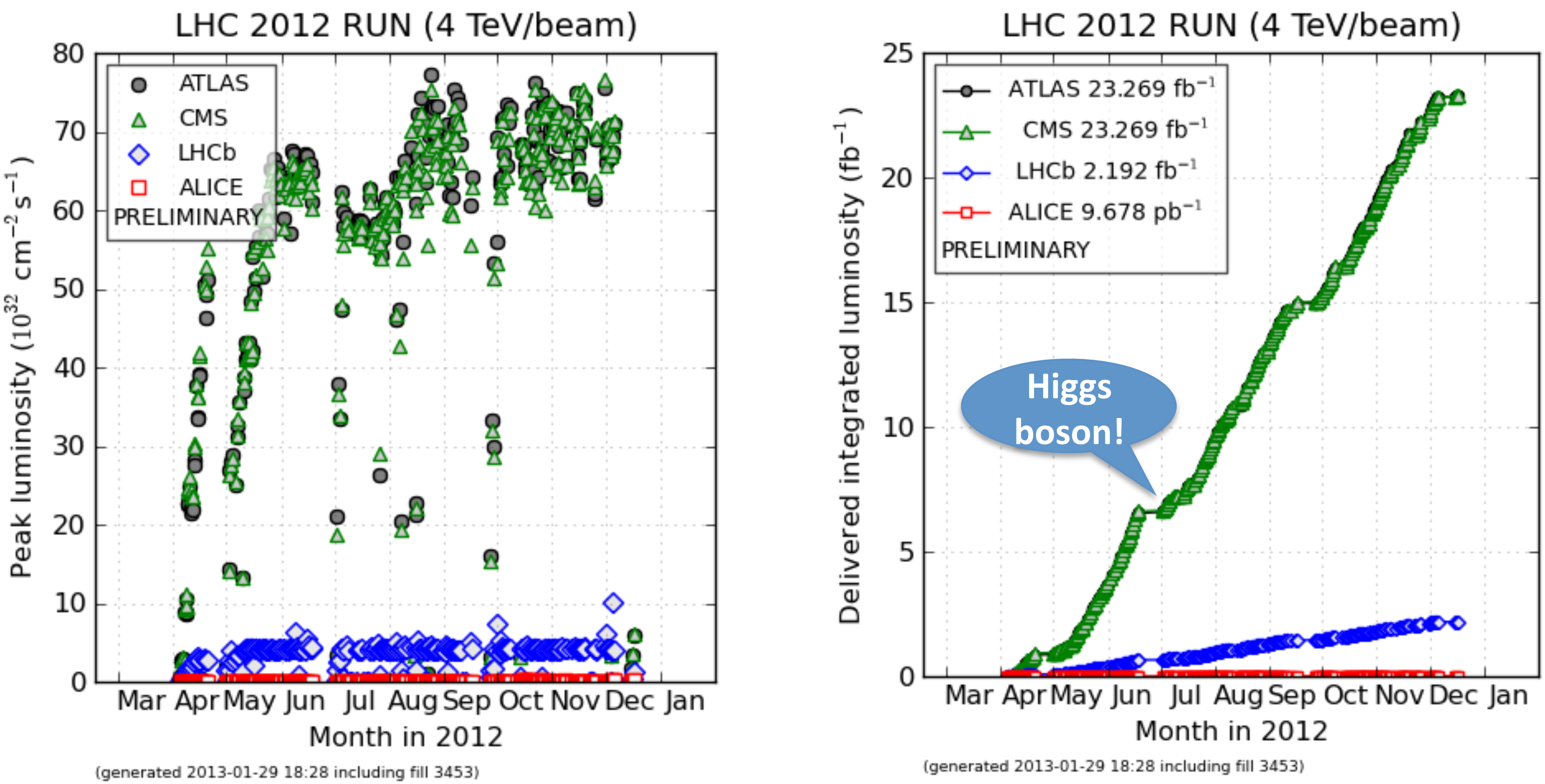
The highlight of a remarkable year 2012



Main parameters of LHC (p-p)

Circumference	26.7	km
Beam energy at collision	7	TeV
Beam energy at injection	0.45	TeV
Dipole field at 7 TeV	8.33	T
Luminosity	10^{34}	$cm^{-2}.s^{-1}$
Beam current	0.56	A
Protons per bunch	1.1×10^{11}	
Number of bunches	2808	
Nominal bunch spacing	24.95	ns
Normalized emittance	3.75	μm
Total crossing angle	300	μrad
Energy loss per turn	6.7	keV
Critical synchrotron energy	44.1	eV
Radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Stored energy in magnets	11	GJ
Operating temperature	1.9	K

The LHC lumi harvest in 2012



The next steps?

- Full exploitation of the LHC and its upgrades
- High luminosity LHC
- High energy LHC?
- FCC hadrons
- FCC-ee
- International Linear Collider (ILC)
- Compact Linear Collider (CLIC)

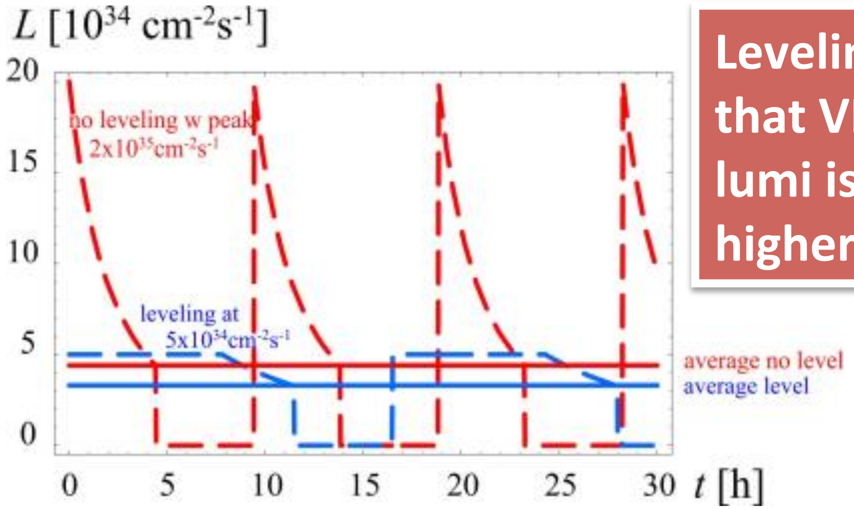
Goal of High Luminosity LHC (HL-LHC) as fixed in November 2010

EU collaboration with JP and USA :FP7 – **HiLumi LHC Design Study**

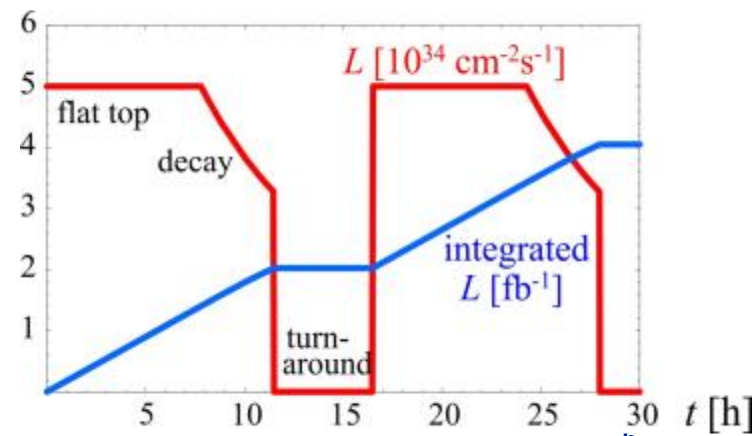
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of **5×10^{34} cm^{-2}s^{-1} with levelling,** allowing:

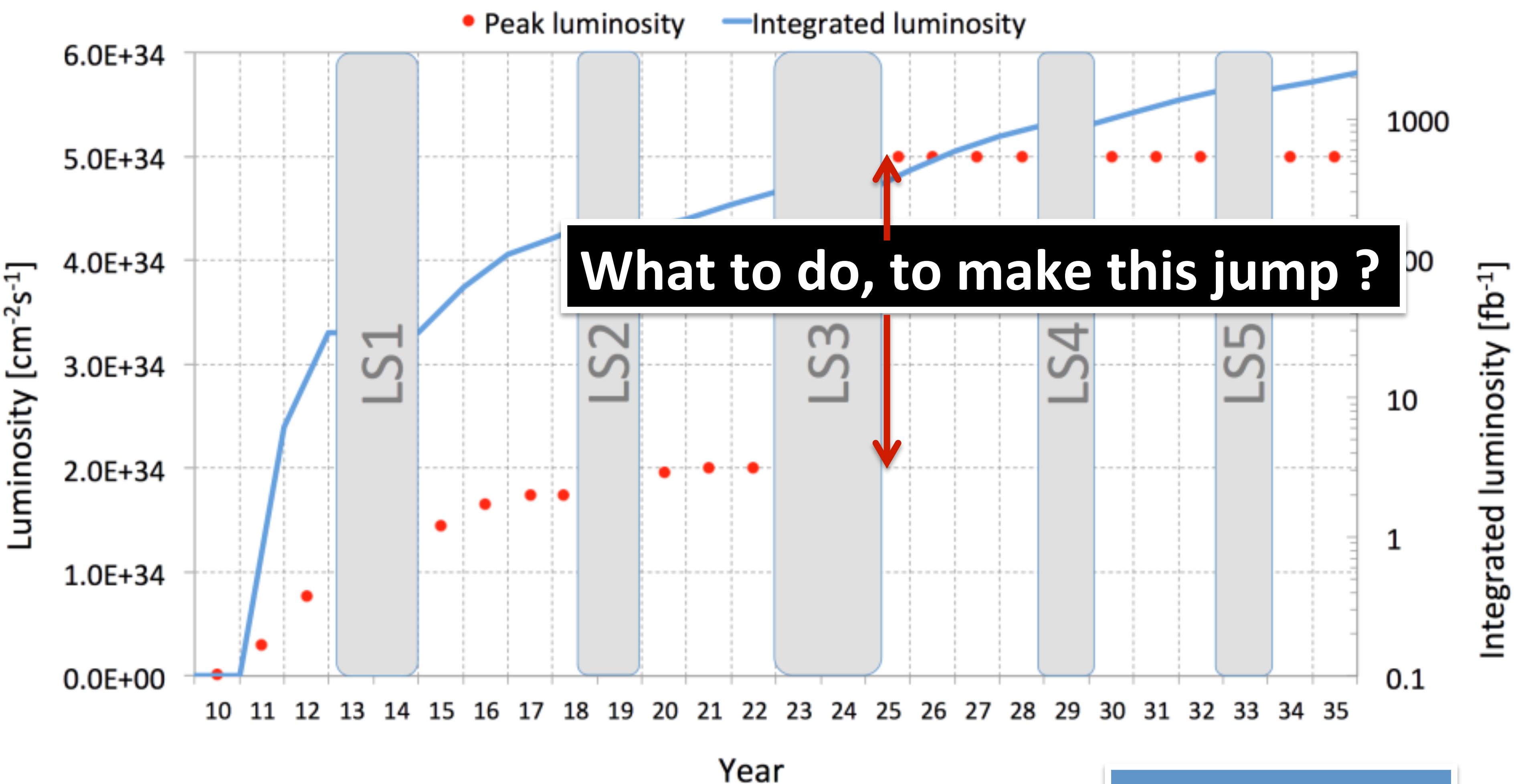
An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **3000 fb^{-1}** twelve years after the upgrade.



Leveling means that VIRTUAL lumi is mich higher!



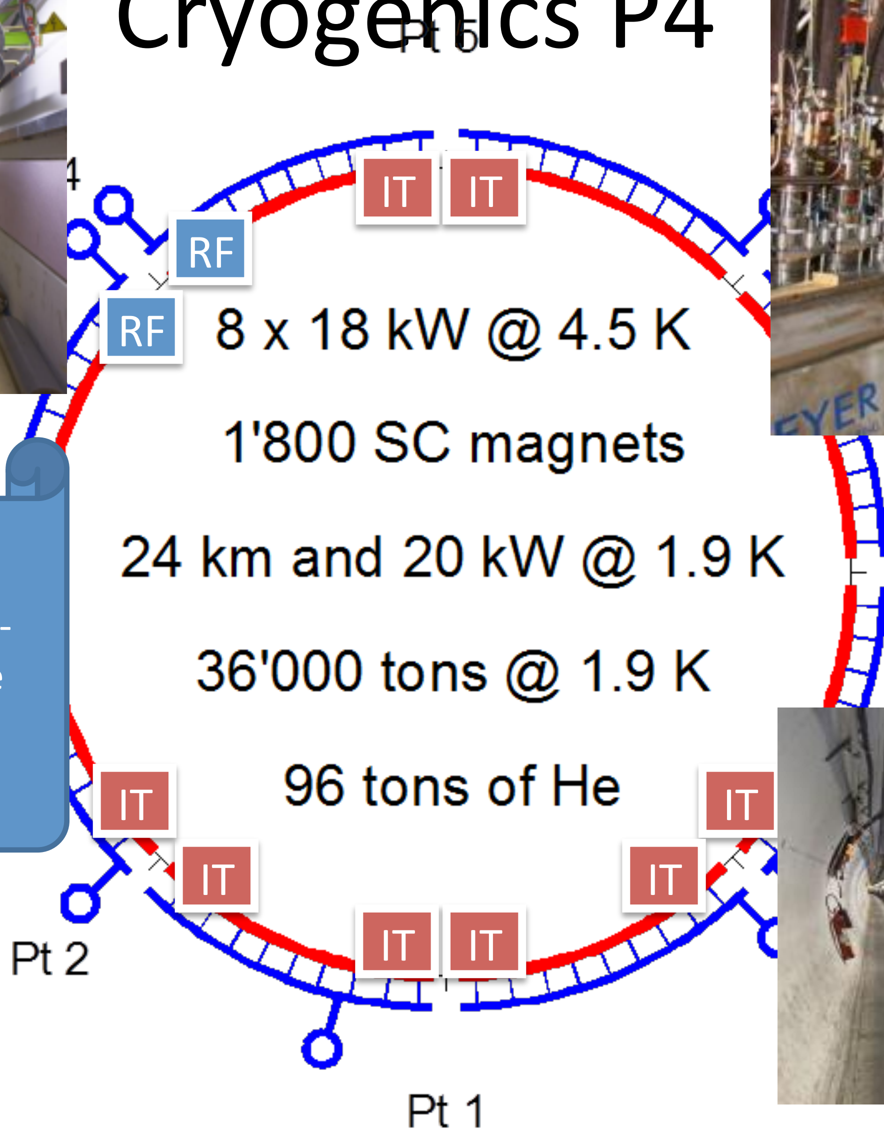
This goal would be reached by



M. Lamont, CERN

Technical bottlenecks

Cryogenics P4



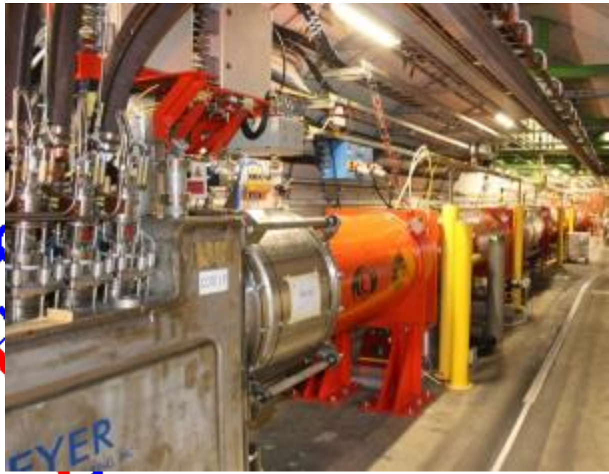
8 x 18 kW @ 4.5 K

1'800 SC magnets

24 km and 20 kW @ 1.9 K

36'000 tons @ 1.9 K

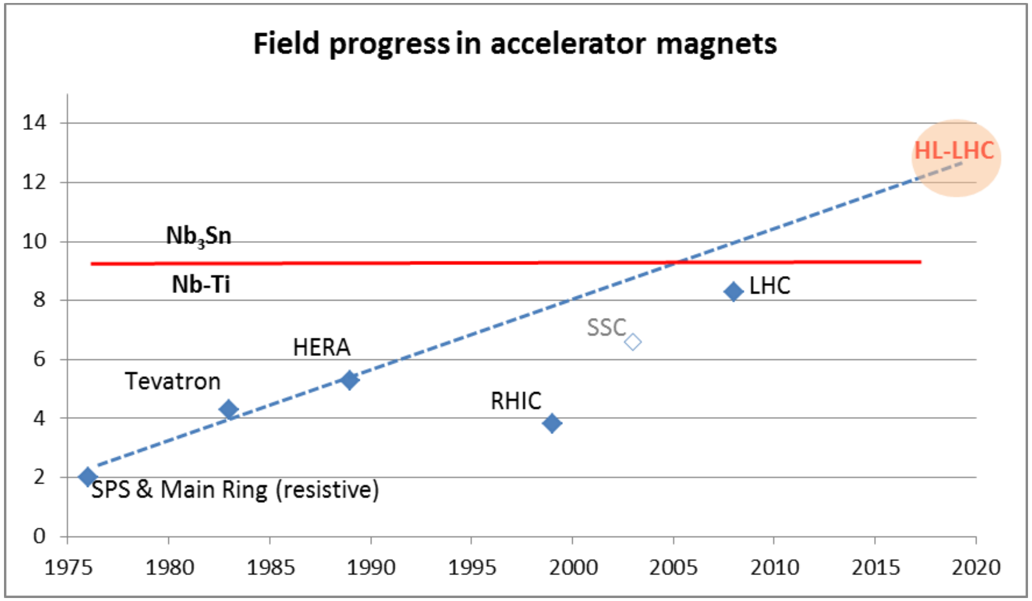
96 tons of He



Never good to couple RF with Magnets !
Reduction of availabe cryo-power and coupling of the RF wiht the Arc (thermal cycle requires > 2 months and many tests)

Magnet the progress

- LHC dipoles features 8.3 T in 56 mm (designed for 9.3 peak field)
- LHC IT Quads features 205 T/m in 70 mm with 8 T peak field
- HL-LHC
  - 11 T dipole (designed for 12.3 T peak field, 60 mm)
  - New IT Quads features 140 T/m in 150 mm > 12 T operational field, designed for 13.5 T).



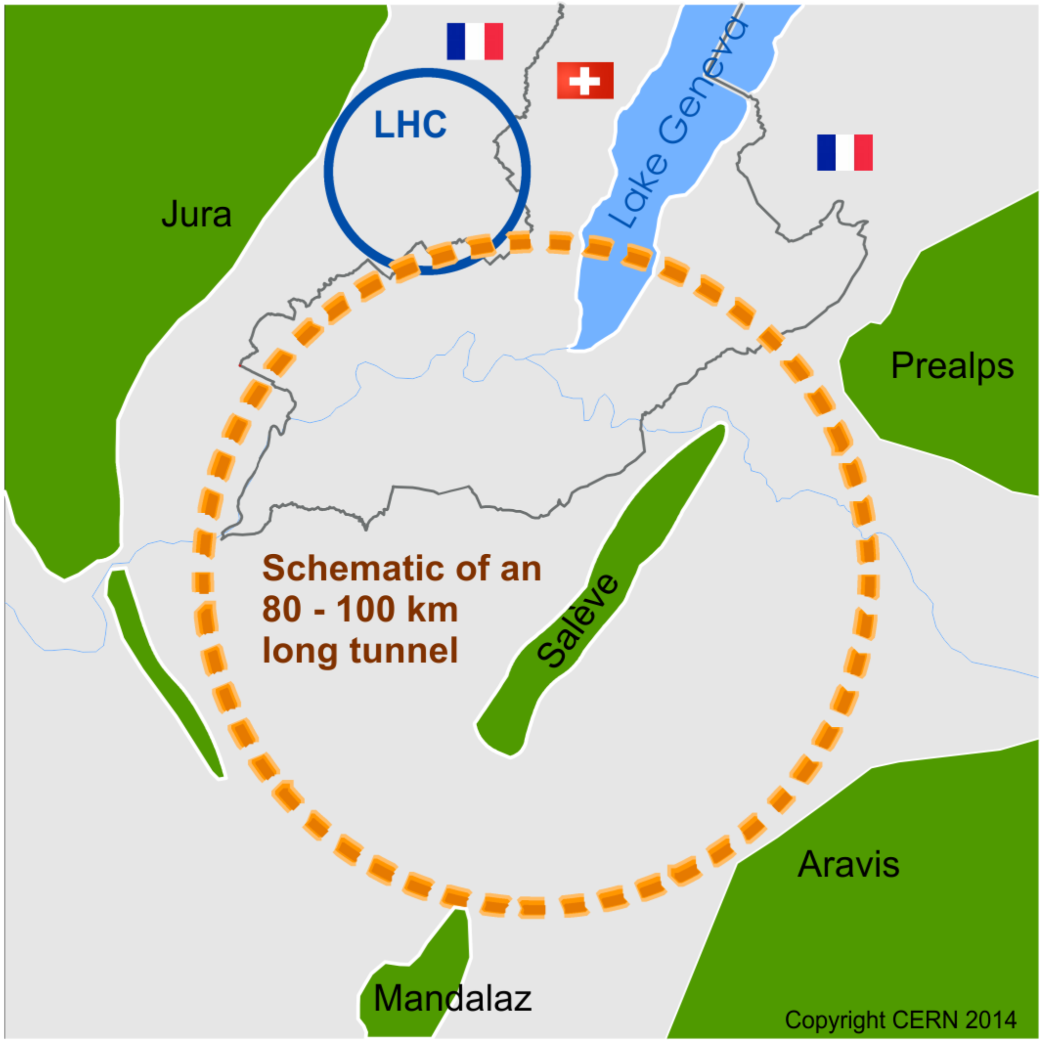
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

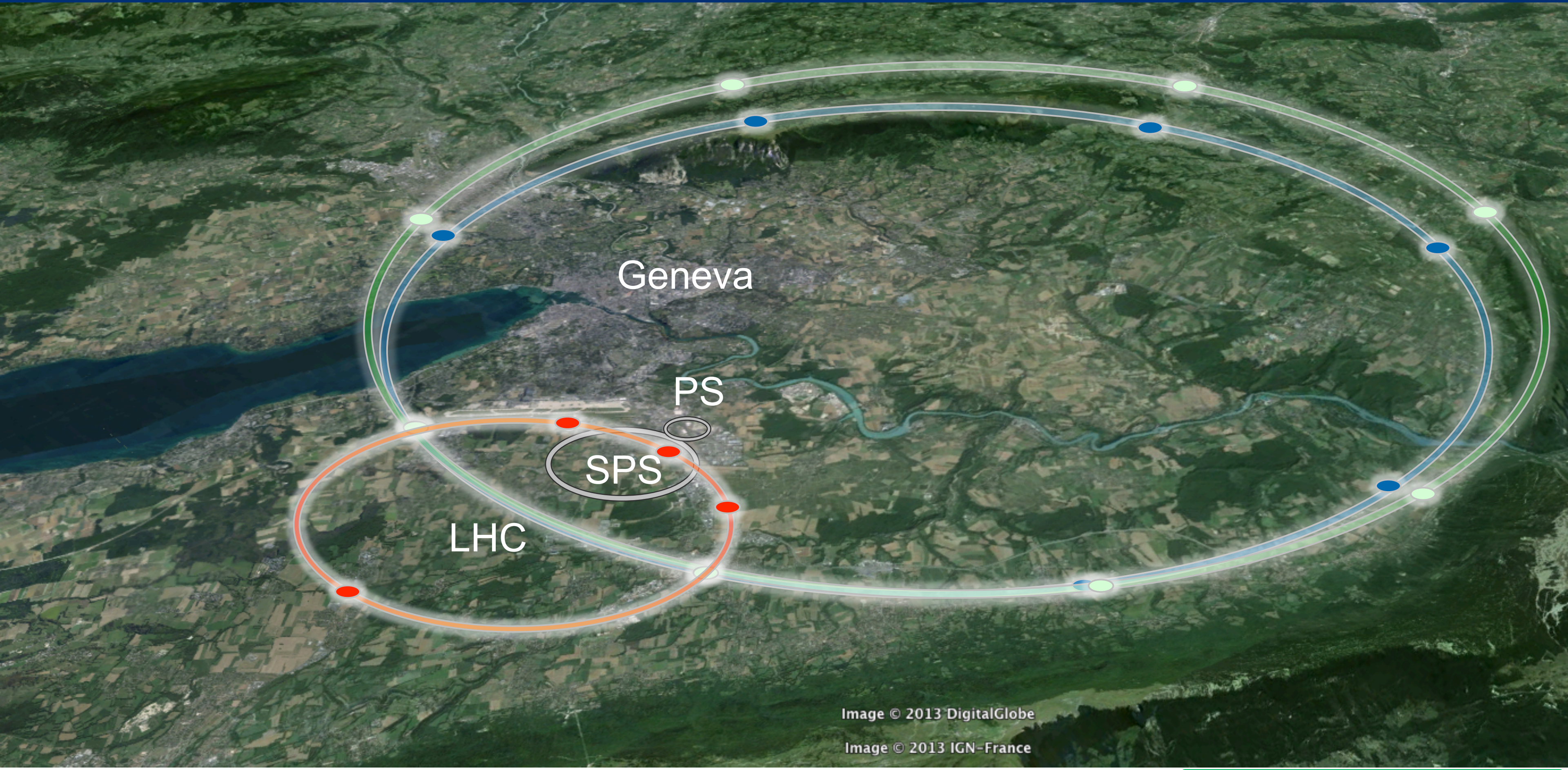
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **80-100 km infrastructure** in Geneva area
- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**



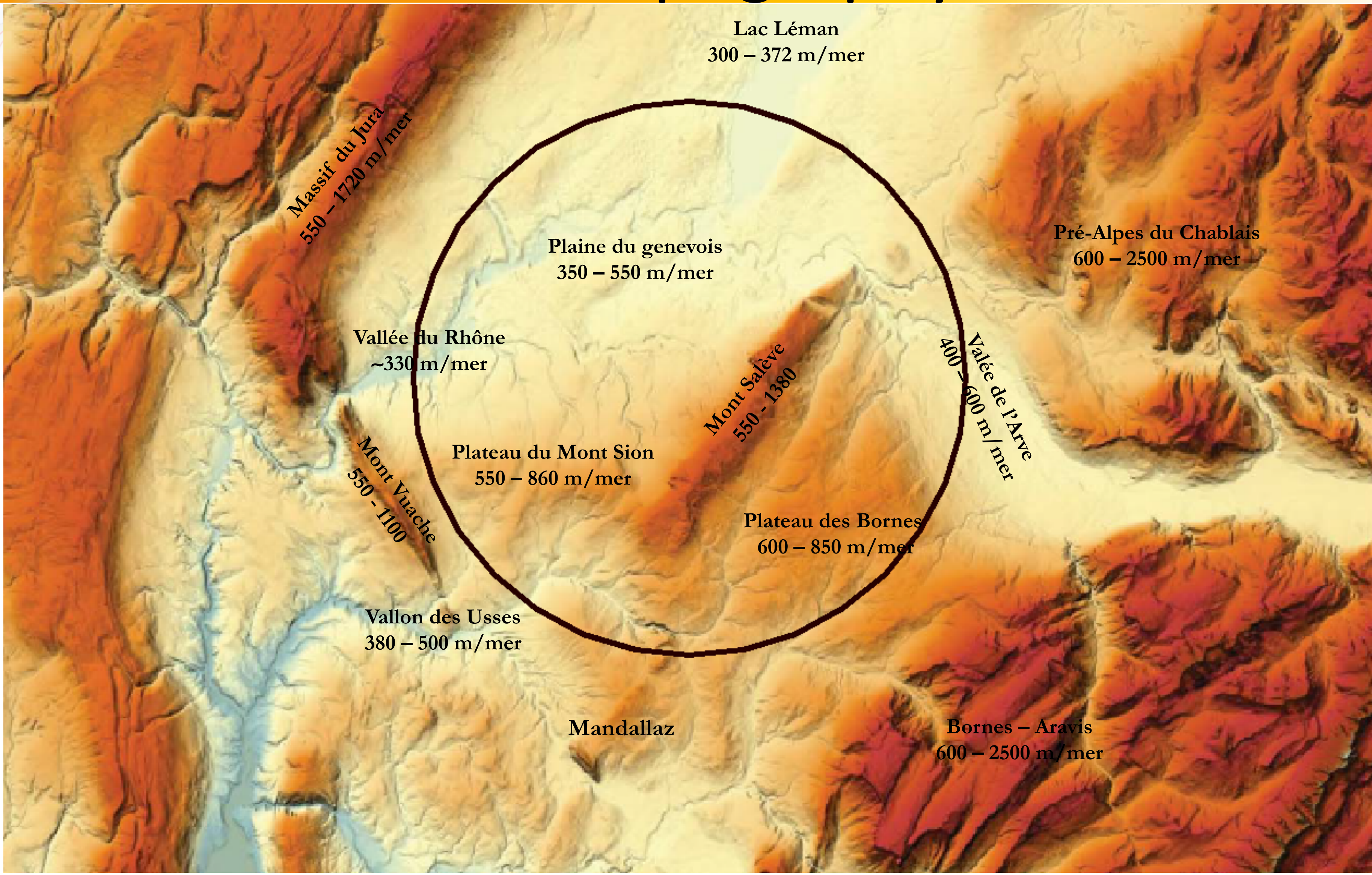
FCC-hh: 100 TeV *pp* collider



LHC	"HE-LHC"	FCC-hh (alternative)	FCC-hh (baseline)
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	33 TeV (c.m.)	100 TeV (c.m.)	100 TeV (c.m.)

L. Bottura
B. Strauss

FCC topography



J. Osborne

FCC-hh opens three physics windows

➥ Access to new particles in the few TeV to 30 TeV mass range, beyond LHC reach

➥ Immense/much-increased rates for phenomena in the sub-TeV mass range → increased precision w.r.t. LHC and possibly ILC

➥ Access to very rare processes in the sub-TeV mass range → search for stealth phenomena, invisible at the LHC

M. Mangano

FCC-hh key parameters

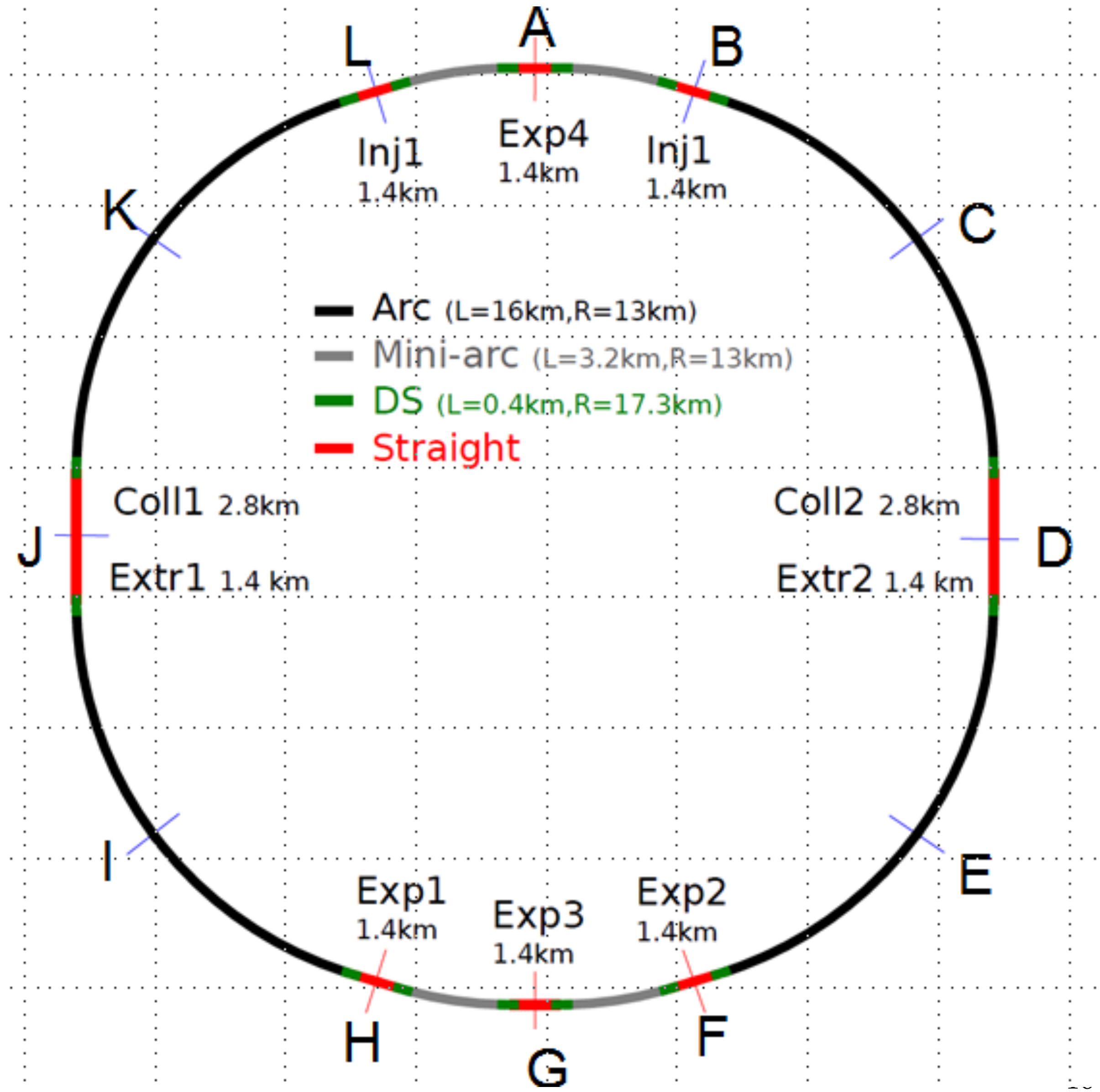
parameter	FCC-hh	LHC
energy	**100 TeV c.m.**	14 TeV c.m.
dipole field	**16 T**	8.33 T
# IP	2 main, +2	4
normalized emittance	2.2 μm	3.75 μm
luminosity/IP_{main}	**5 x 10^{34}** $cm^{-2}s^{-1}$	1 x 10^{34} $cm^{-2}s^{-1}$
energy/beam	**8.4 GJ**	0.39 GJ
synchr. rad.	**28.4 W/m/apert.**	0.17 W/m/apert.
bunch spacing	25 ns (5 ns)	25 ns

Preliminary, subject to evolution (several luminosity scenarios)

parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	26.7		100 (83)
luminosity [10^{34} $cm^{-2}s^{-1}$]	1	5	5 [→20?]
bunch spacing [ns]	25		25 {5}
events / bunch crossing	**19**	**135**	**170 {34}**
bunch population [10^{11}]	1.15	2.2	1 {0.2}
norm. transverse emitt. [μm]	3.75	2.5	2.2 {0.44}
IP beta-function [m]	0.55	0.15	1.1
IP beam size [μm]	16.7	7.1	6.8 {3}
synchrotron rad. [W/m/aperture]	0.17	0.33	28 (44)
critical energy [keV]	0.044		4.3 (5.5)
total syn.rad. power [MW]	**0.0072**	**0.0146**	**4.8 (5.8)**
longitudinal damping time [h]	**12.9**		**0.54 (0.32)**

FCC tunnel configuration

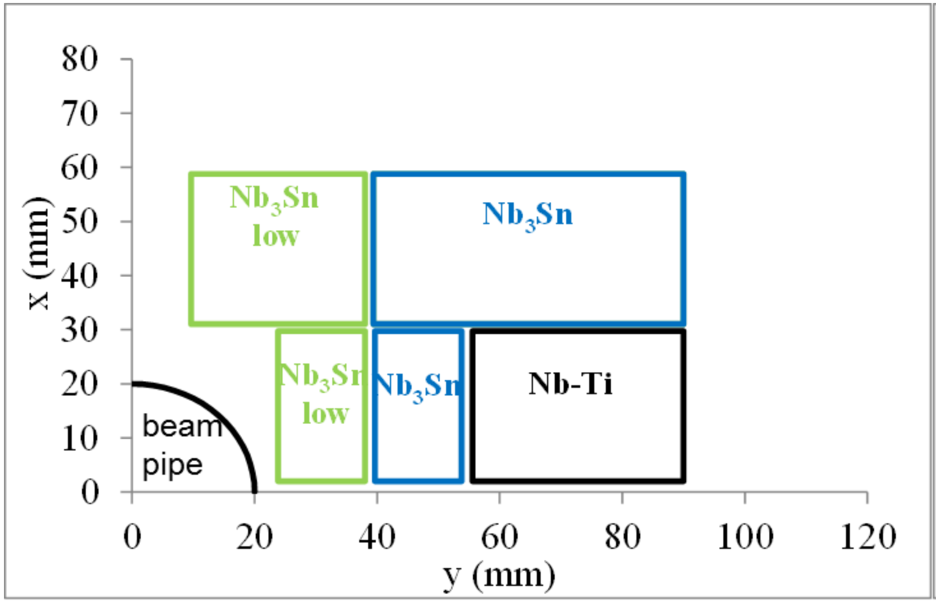
- FCC circumference is a multiple of LHC :
  - 80 km
  - 87 km
  - 93 km
  - 100 km



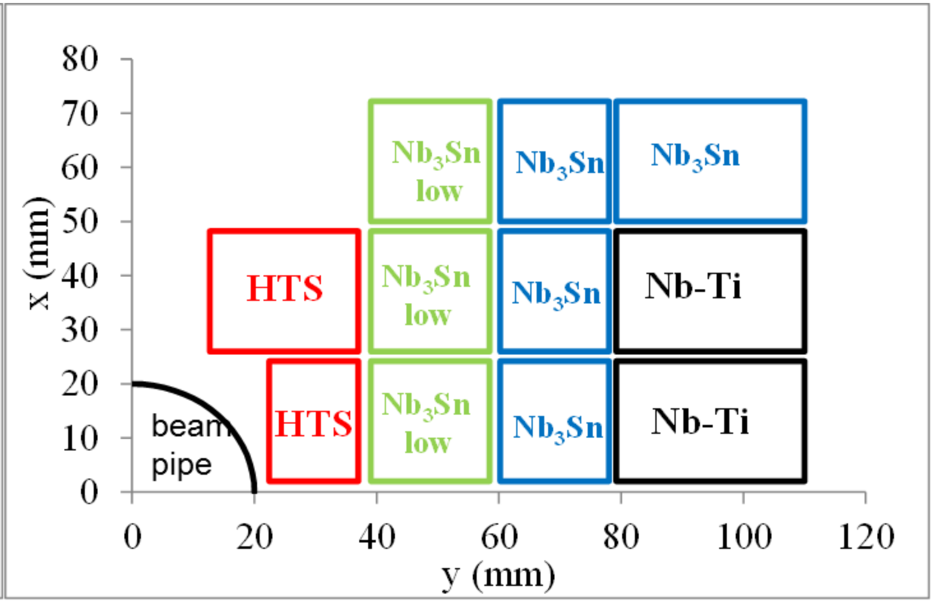
Ph. Lebrun

cost-optimized high-field dipole magnets

15-16 T: *Nb-Ti* & *Nb_3Sn*



20 T: *Nb-Ti* & *Nb_3Sn* & *HTS*



only a quarter is shown

"hybrid magnets"

example block-coil layout

L. Rossi, E. Todesco, P. McInty

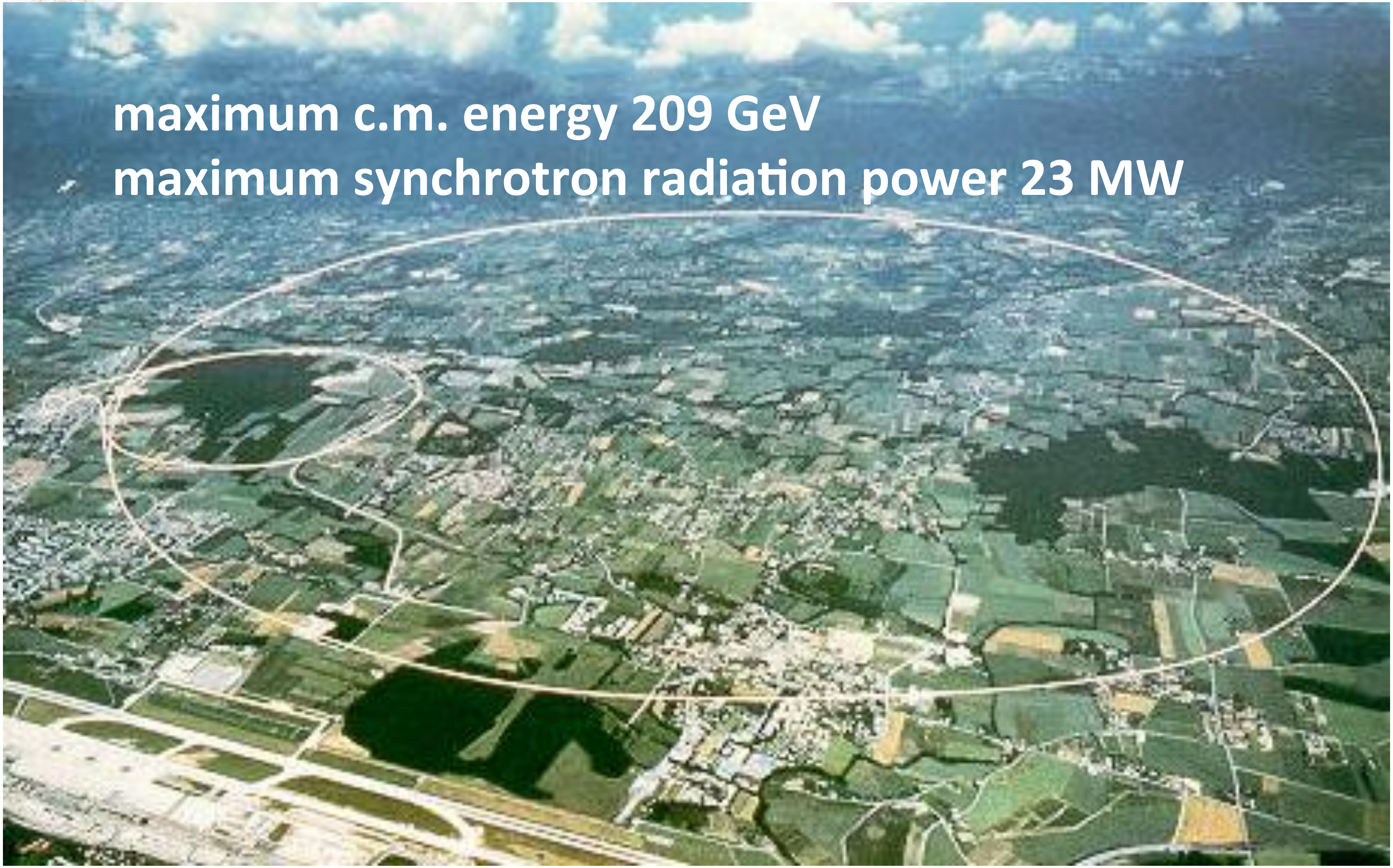
machine protection

energy per proton beam

LHC: 0.4 GJ → *FCC-hh*: 8 GJ (20x more !)

- kinetic energy of Airbus A380 at 720 km/h
- can melt 12 tons of copper, or drill a 300-m long hole

LEP – highest energy e^+e^- collider so far



physics requirements for *FCC-ee*

- highest possible luminosity for a wide physics program ranging from the Z pole to the $t\bar{t}$ production threshold
  - *beam energy range from 45 GeV to 175 GeV*
- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold,*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): $t\bar{t}$ threshold*
- some polarization up to ≥80 GeV for beam energy calibration
- optimized for operation at 120 GeV?!

FCC-ee key parameters

parameter	FCC-ee	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	**98 – 16700**	4
beam current	**6.6 – 1450 mA**	3 mA
hor. emittance	**~2 nm**	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_y$	**0.1%**	1%
vert. IP beta function β_y^*	**1 mm**	50 mm
luminosity/IP	**1.8-28** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
energy loss/turn	0.03-7.55 GeV	3.34 GeV
synchr. power	**100 MW**	23 MW
RF voltage	2.5 – **11 GV**	3.5 GV

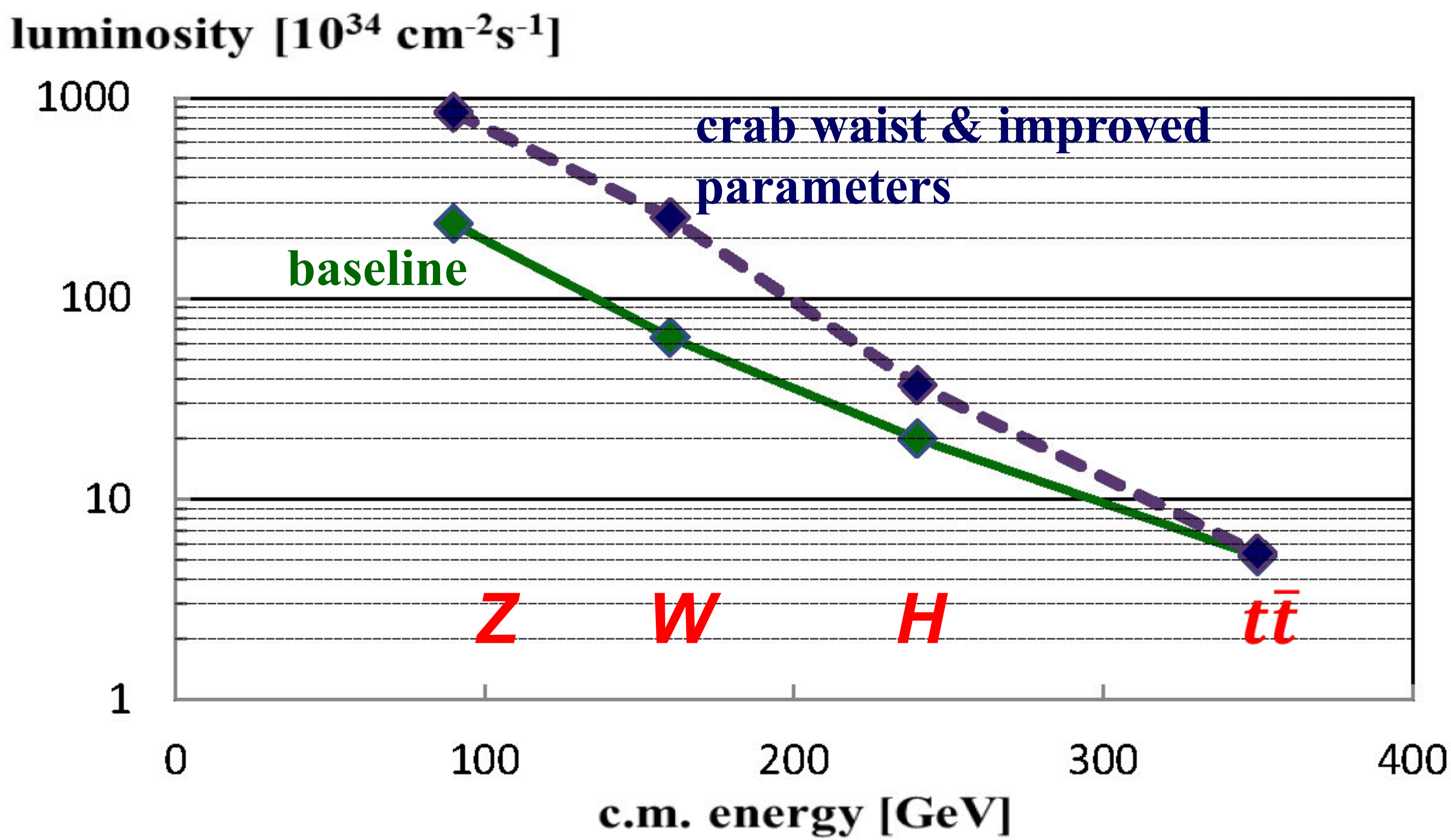
Preliminary, subject to evolution (staging scenarios)

parameter	LEP2	FCC-ee					CepC
		Z	Z (c.w.)	W	H	t	H
E_{beam} [GeV]	104	45	45	80	120	175	120
circumference [km]	26.7	100	100	100	100	100	54
current [mA]	3.0	1450	1431	152	30	6.6	16.6
$P_{SR,tot}$ [MW]	22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
no. bunches	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4	3.7
ε_x [nm]	22	29	0.14	3.3	0.94	2	6.8
ε_y [pm]	250	60	1	1	2	2	20
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0	0.8
β^*_y [mm]	50	1	1	1	1	1	1.2
σ^*_y [nm]	3500	250	32	130	44	45	160
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16	2.3
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49	2.7
hourglass factor F_{hg}	0.99	0.64	0.94	[illegible]	[illegible]	[illegible]	0.61
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7	1.8
τ_{beam} [min]	300	287	39	72	30	23	40

the large number of bunches at *Z*, *W* & *H* requires 2 rings

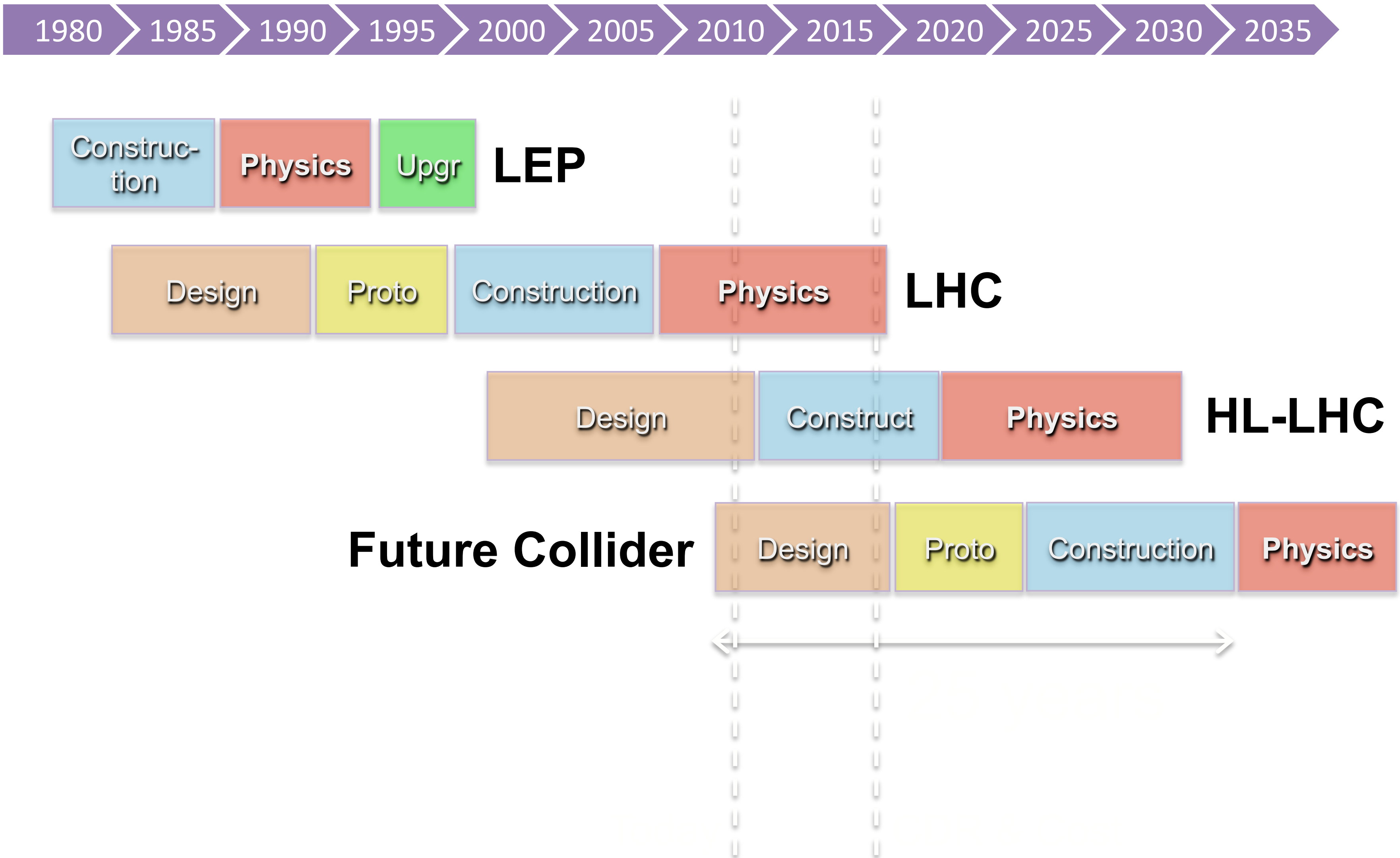
short lifetimes due to high luminosity
→ continuous injection (top-up)

FCC-ee luminosity vs energy



M. Benedikt, A. Blondel, A. Bogomyagkov, E. Levichev, D. Shatilov, J. Wenninger, F. Zimmermann,…

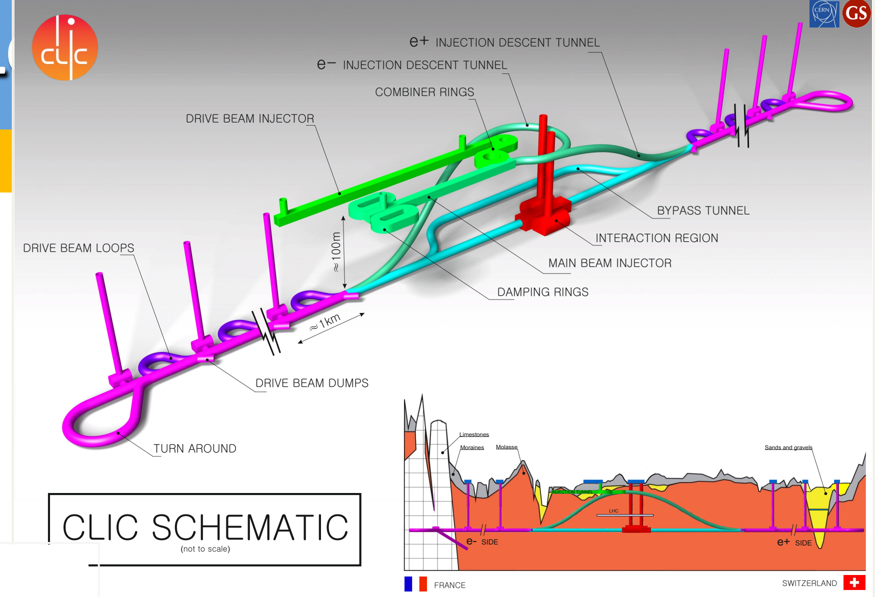
HEP time scale

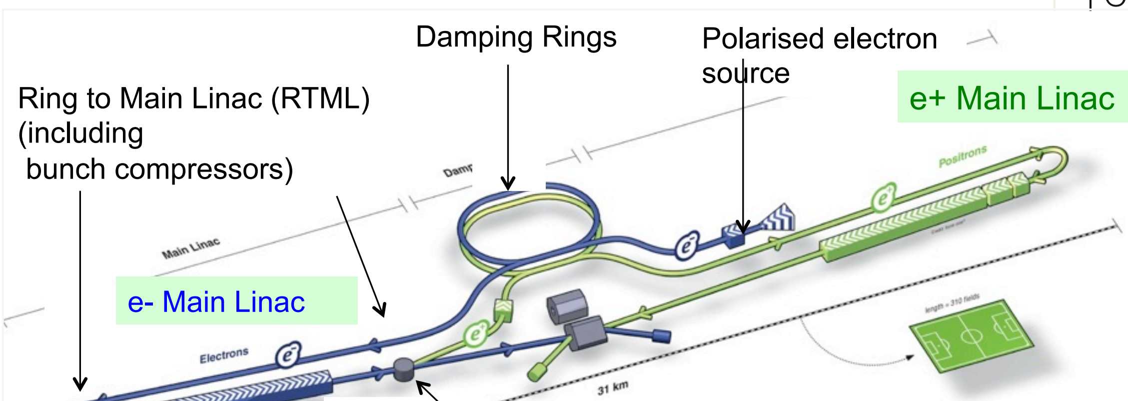


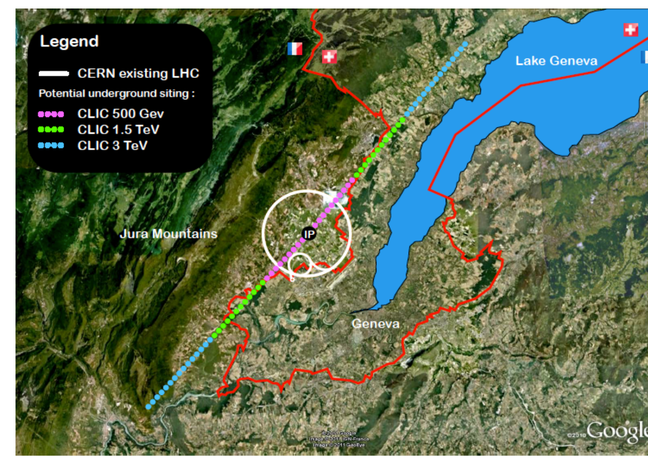
Linear Colliders (IL

Outline:

- ILC and CLIC – project overview
- Physics consideration
- Brief status and plans
- Realization of the projects
- Summary







Steinar Stapnes, CERN
LCC collaboration

Key points

The ILC and CLIC accelerator studies are organised under the heading of LCC with goals:

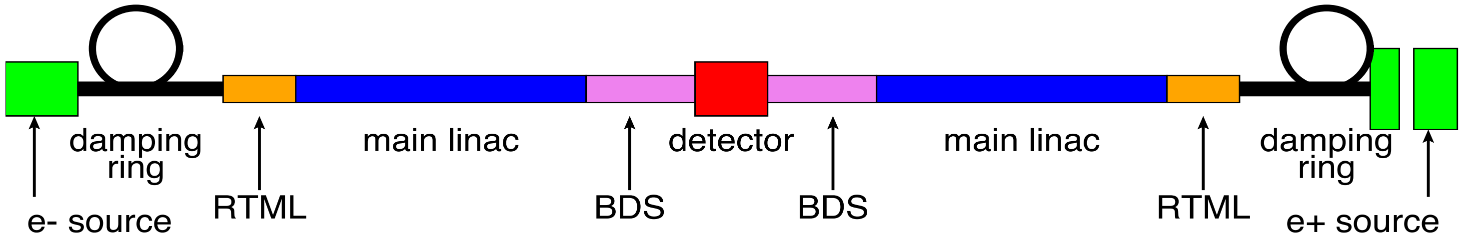
- Strongly support the Japanese initiative to construct a linear collider as a staged project in Japan
- Prepare CLIC machine and detectors as an option for a future high-energy linear collider at CERN
- Further improve collaboration between CLIC and ILC machine experts
- Beyond the significant progress on the basic RF studies, increased and successful effort on system-studies of various types (FACET, ATF, etc)
- Many common challenges with 3rd generation light sources and FELs, the latter providing very important industrial/lab production experiences

Comprehensive physics studies – and in parallel technical detector R&D and concept studies – demonstrate the realism and unique impact of LC e+e- measurements and searches at energy scales from 250 to 3 TeV

The on-going process in Japan for ILC is nevertheless (by some margin) the most central activity right now

Linear Colliders

Generic LC:



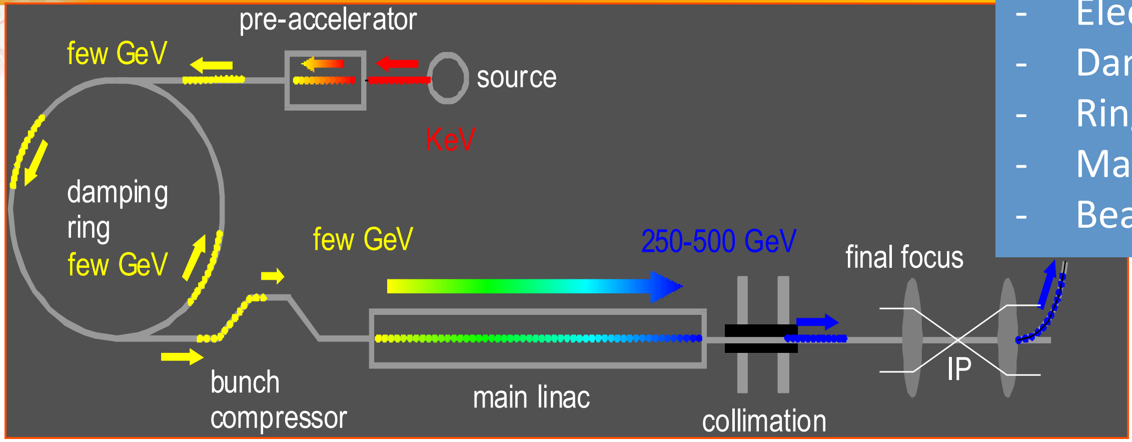
Key features: scalable to high energies, expandable (also with novel technologies later), very linked to light-sources (low emittance rings and FEL linacs)

Challenges: Gradients, luminosity (nano beams), power efficiency

Strategies:

- Japan-KEK: Consider hosting ILC
- European Strategy: High energy frontier beyond LHC: CLIC technology an option to be pursued, ILC in Japan a welcome initiative - shorter timescale, follow up Higgs discovery
- Snowmass -> P5: High-lights physics potential of ILC and US participation (within 2025 Horizon)
- Many other countries have their own strategies with LC activities central

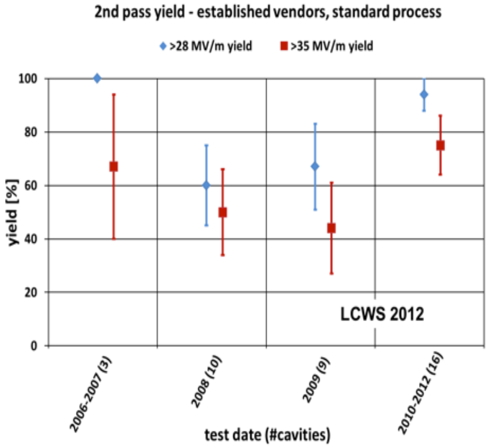
The ILC Accelerator Concept



- Electron and Positron Sources (e-, e+)
- Damping Ring (DR)
- Ring to ML beam transport (RTML)
- Main Linac (ML) : SCRF Technology
- Beam Delivery System (BDS)

1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	436

Production yield: 94 % at > 35+/-20%
Average gradient: 37.1 MV/m
> R&D goal of 35 MV/m reached (2012)



ILC parameters (TDR)

Table 2.1. Summary table of the 200–500 GeV baseline parameters for the ILC. The reported luminosity numbers are results of simulation [12]

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	µm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	µm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

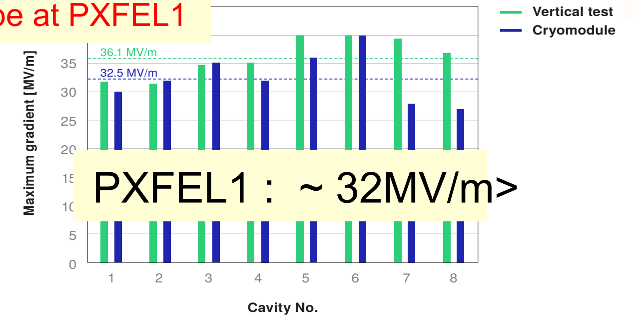
Upgradeable to 1 GeV – parameter sets also available

Cryomodule System Tests

DESY: FLASH

- 1.25 GeV linac (TESLA-Like tech.)
- ILC-like bunch trains:
- 600 ms, **9 mA** beam (2009); ← Demonstrated
  800 ms 4.5 mA (2012)
- RF-cryomodule string with beam → PXFEL1 operational at FLASH

XFEL Prototype at PXFEL1

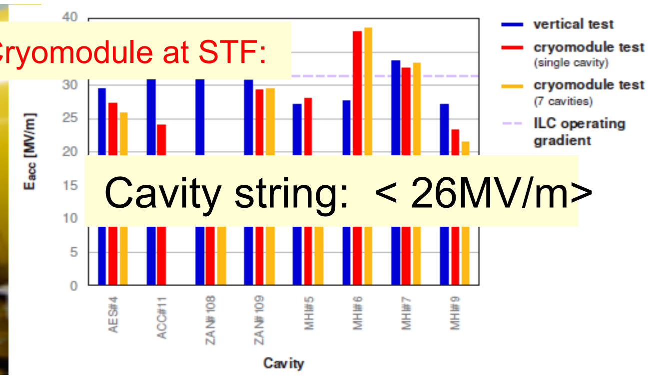


PXFEL1 : ~ 32MV/m>

KEK: STF/STF2

- S1-Global: completed (2010)
- Quantum Beam Accelerator (Inverse Llaser Compton): 6.7 mA, **1 ms** ← Demonstrated
- CM1 test with beam (2014 ~2015)
- STF-COI: Facility to demonstrate CM assembly/test in near future

S1 Global Cryomodule at STF:



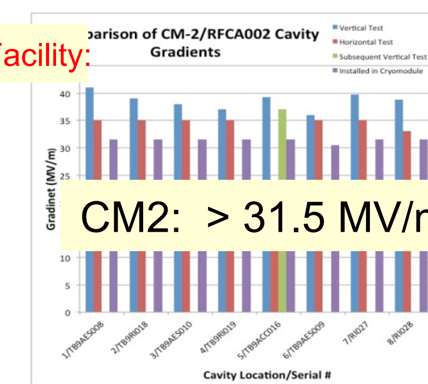
Cavity string: < 26MV/m>

FNAL: ASTA

(Advanced Superconducting Test Accelerator)

- CM1 test complete
- CM2 operation (2013)
- CM2 with beam (soon)

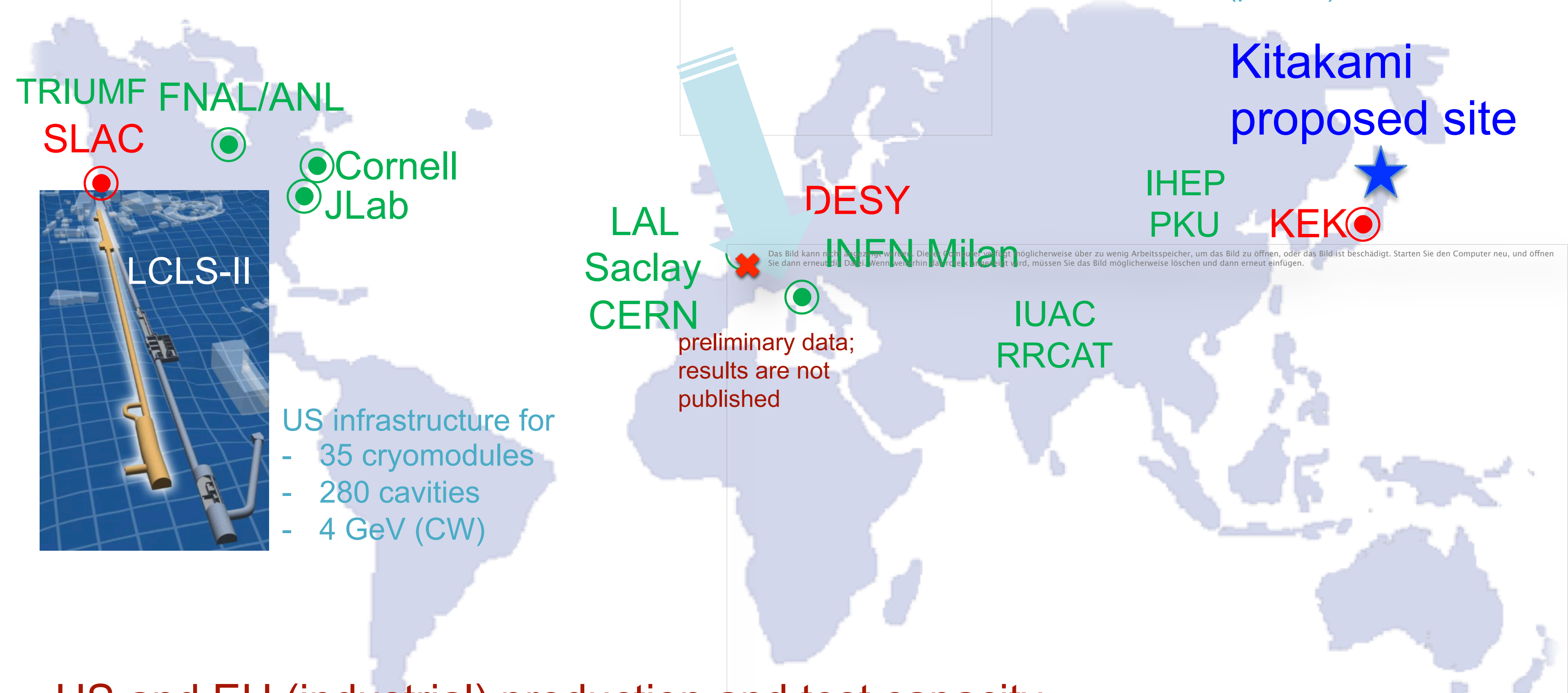
CM2 at NML Facility:



CM2: > 31.5 MV/m>

FEL and advanced linacs with SCRF modules

Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV (pulsed)



US infrastructure for
- 35 cryomodules
- 280 cavities
- 4 GeV (CW)

US and EU (industrial) production and test capacity. Perfectly placed for start of ILC construction end of this decade.

ILC post TDR team: towards site specific design

Category	Work-base	Specific subject	Global Collaboration w/
Positron Source		Positron source	PosiPol Collaboration
Nano Beam	ATF	37 nm beam 2 nm stability	ATF collaboration
SCRF Cavity Integration	STF	Power Input Coupler Tuner He-Vessel	CERN-DESY-KEK CEA-Fermi/SLAC-KEK DESY-KEK
CM integration	STF, ILC	Conduction-cooled SC Quadrupole	Fermilab-KEK
Cryogenics	ILC	Cryog. Underground He inventry High p. Gas Safety	CERN-Fermilab-KEK (WS at CERN, 18 June)
CFS	ILC	CFS design prep.	CERN-Fermilab-KEK
Radiation Safety	ILC	ML radiation shield	SLAC-DESY-CERN-KEK

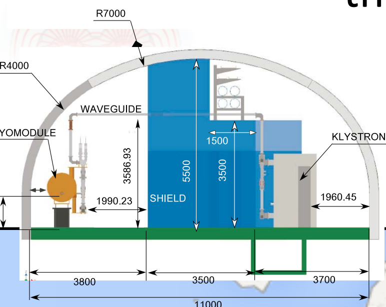
	N. Walker and H. Hayano		*KEK LC Project Office Head: A. Yamamoto		
		KEK-Leader* Deputy	Sub-Group	Global Leader Deputy/Contact P.	KEK-Leader* Deputy
Integr.	K. Yokoya(KEK)	K. Yokoya	SRF	H. Hayano (KEK) C. Ginsburg (Fermi), E. Montesinos (CERN)	H. Hayano Y. Yamamoto
Sources (e-, e+)	W. Gai (ANL) M. Kuriki (Hiroshima U.)	J. Urakawa T. Omori	RF Power & Cntl	S. Michizono (KEK) TBD (AMs , EU)	Michizono T. Matsumoto
Damping Ring	D. Rubin (Cornell) N. Terunuma (KEK)	N. Terunuma	Cryogenics (incl. HP gas issues)	H. Nakai: KEK T. Peterson (Fermi), D. Delikaris (CERN)	H. Nakai Cryog. Center
RTML	S. Kuroda (KEK) A. Latina (CERN)	S. Kuroda	CFS	A. Enomoto (KEK) V. Kuchler (Fermi), J. Osborne (CERN),	A. Enomoto M. Miyahara
Main Linac (incl. B. Compr. & B. Dynamics)	N. Solyak (Fermi) K. Kubo (KEK)	K. Kubo	Radiation Safety	T. Sanami (KEK) TBD (AMs, EU)	T. Sanami T. Sanuki
BDS	G. White (SLAC), R. Tomas (Cern) T. Okugi (KEK)	T. Okugi	Electrical Support (Power Supply etc.)	TBD	TBD
MDI	K. Buesser (DESY) T. Tauchi (KEK)	T. Tauchi	Mechanical S. (Vac. & others)	TBD	TBD
			Domestic Program, Hub Lab. Facilities	TBD	H. Hayano T. Saeki

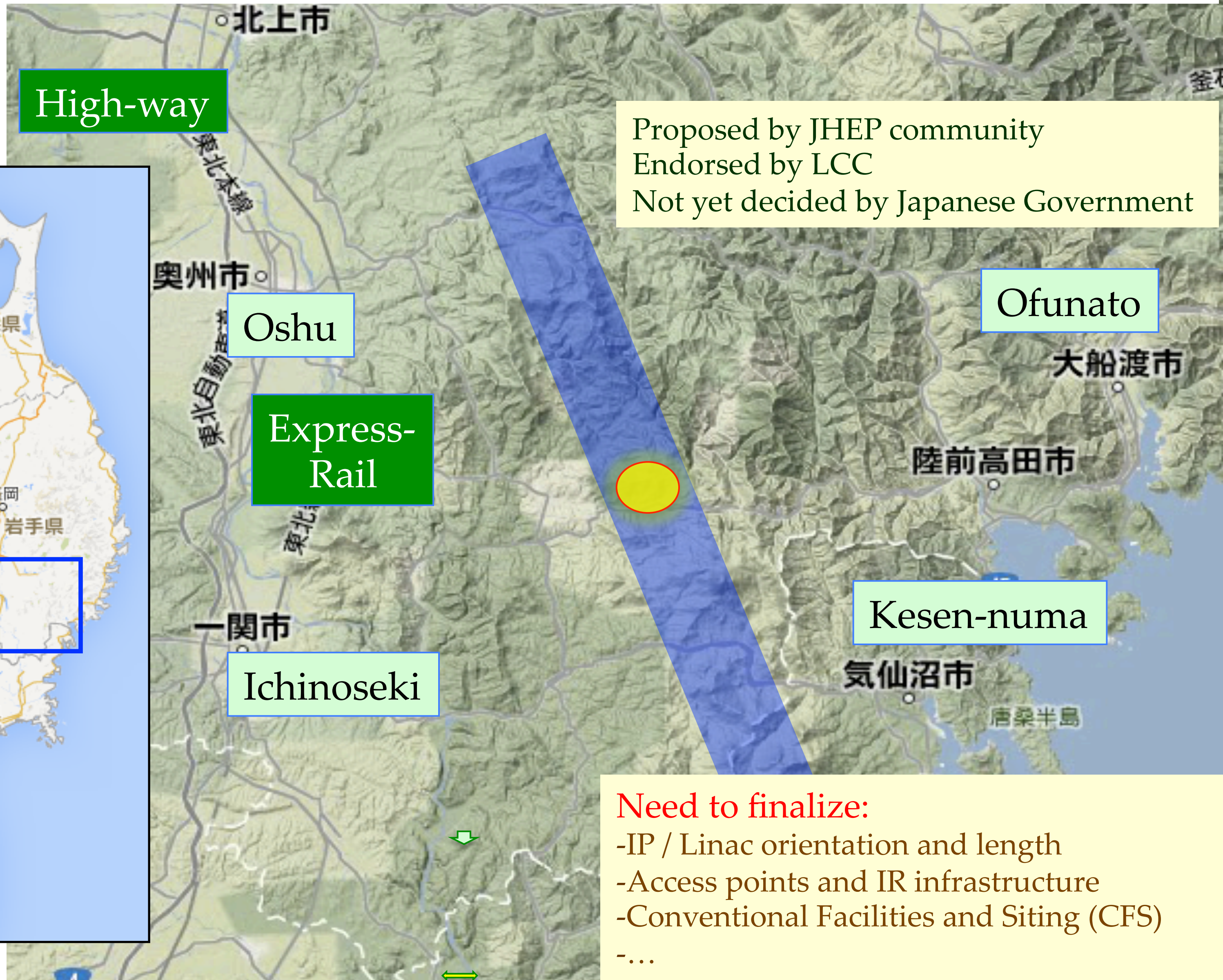
ILC Project Overview

Years	TDR baseline Scenario
1 - 2	Pre-preparation for 2yrs (for technical effort continuity)
3 - 6	Preparation (4 yrs)
7 - 15	Construction (9 yrs)
(12 -)	(start installation)
(13 -)	(start preparation for Operation)
16 -	Beam Commissioning start
17 –	Operation at 250 ~ 500 GeV (550 GeV)
TBD	Toward 500 GeV HL upgrade
TBD	Toward 1 TeV upgrade

Site specific studies

Establish a site-specific Civil Engineering Design - map the (site independent) TDR baseline onto the preferred site - assuming "Kitakami" as a primary candidate

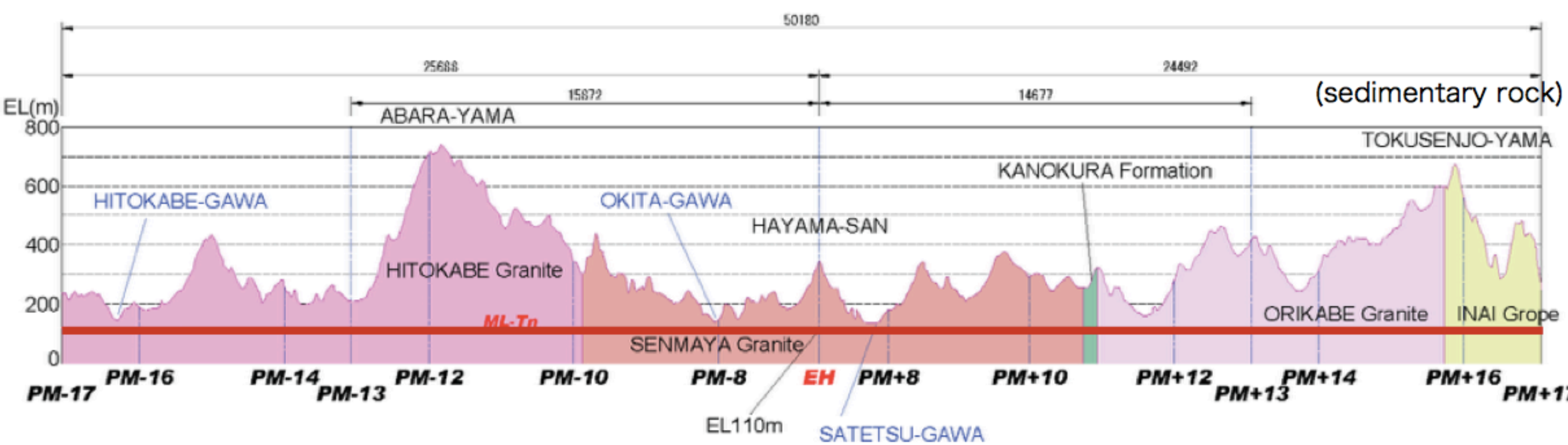




Proposed by JHEP community
Endorsed by LCC
Not yet decided by Japanese Government

Need to finalize:
- -IP / Linac orientation and length
- -Access points and IR infrastructure
- -Conventional Facilities and Siting (CFS)
- -…

ILC preferred site - Kitakami



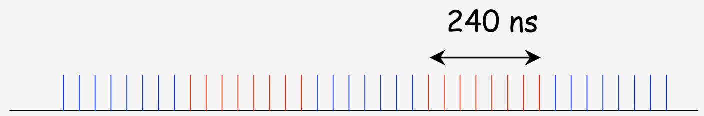
30km

al

CLIC Layout at 3 TeV

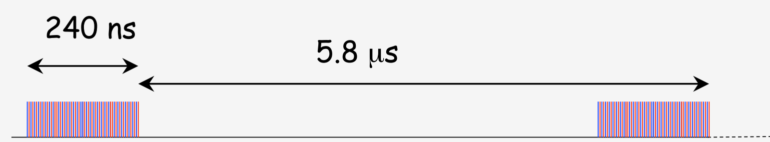
Drive Beam Generation

Drive beam time structure - initial

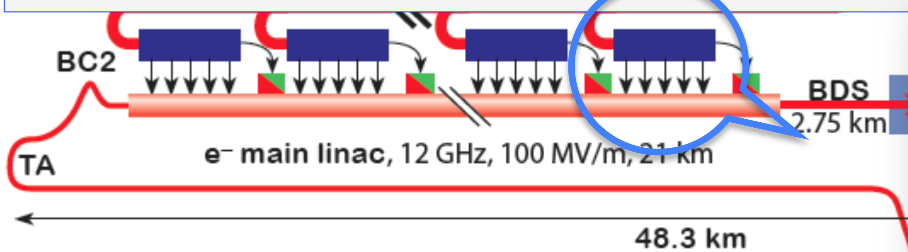


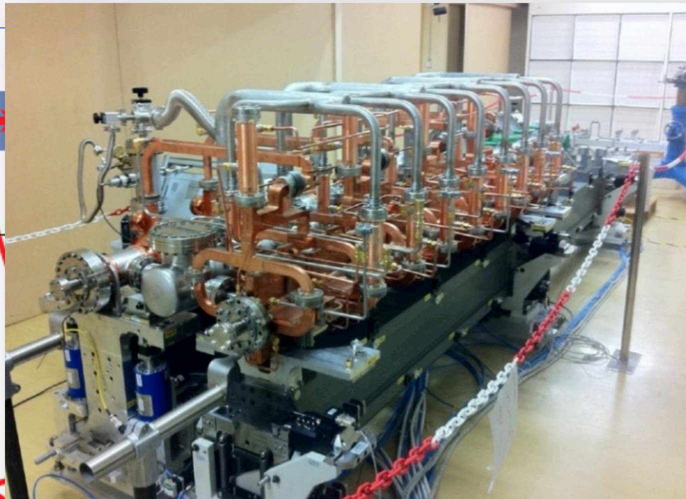
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

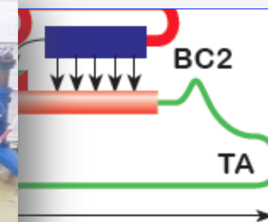
Drive beam time structure - final



24 pulses – 101 A – 2.5 cm between bunches



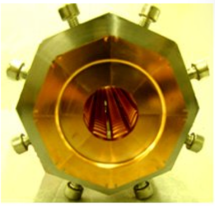


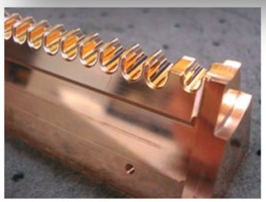


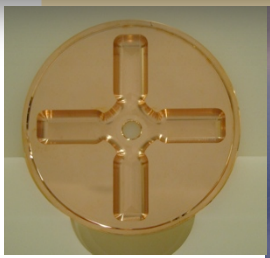
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump

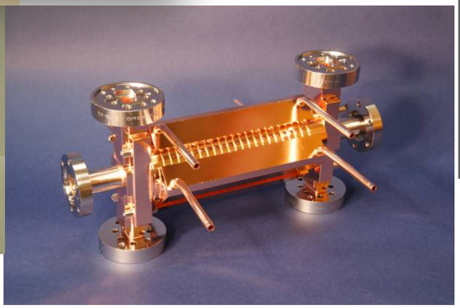
e⁻ injector, 2.86 GeV

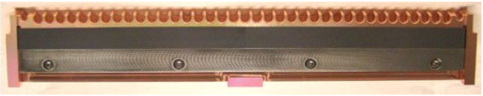
Main Beam Generation Complex



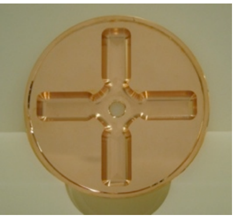


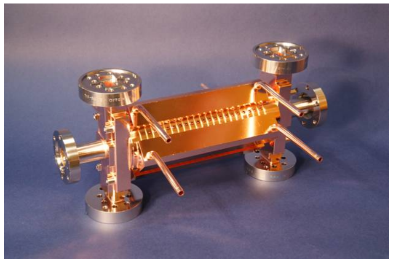






Possible CLIC stages studied in the CDR





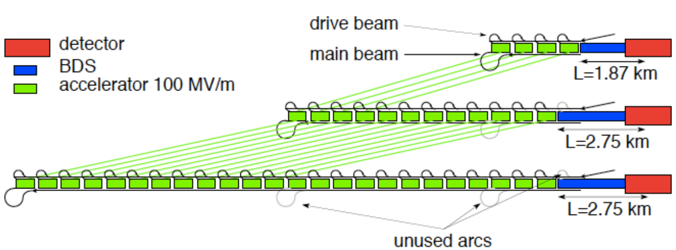


Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.

Key features:

- High gradient (energy/length)
- Small beams (luminosity)
- Repetition rates and bunch spacing (experimental conditions)

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

Table 2: Parameters for the CLIC energy stages of scenario B.

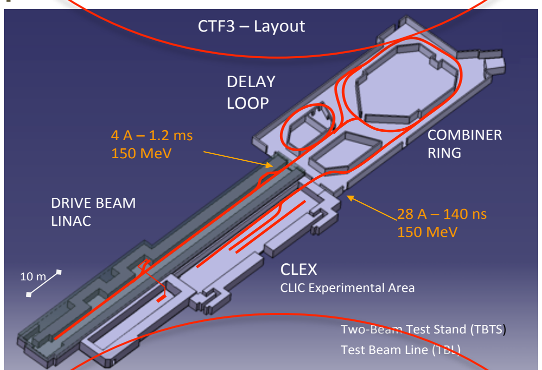
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	~~37~~
Estimated power consumption	P_{wall}	MW	235	364	589

New institutes are joining:
In 2014 SINAP Shanghai and IPM Tehran

Detector collaboration operative with 23 institutes

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



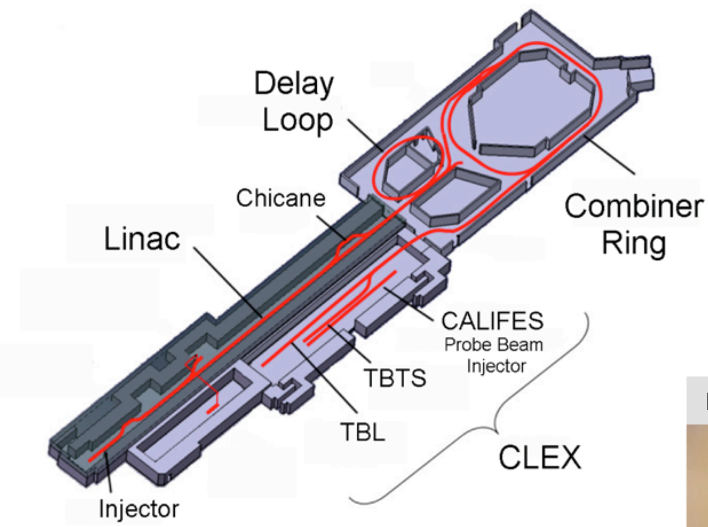
2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

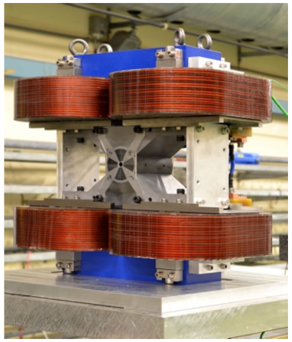
- Common work with ILC related to several acc. systems as part of the LC coll., also related to initial stage physics and detector developments
- Common physics benchmarking with FCC pp and common detect. challenges (ex: timing, granularity), as well as project implementation studies (costs, power, infrastructures …)

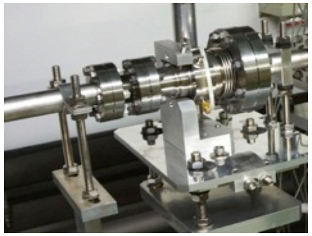
Main activities

Experimental verification
- Drive Beam and two beam scheme (CTF3)
- Low emittance ring tests – low emittances
- System Tests: ATF – final focus, FACET and FELs – beam based alignment and emittance preservation in linacs (see later)

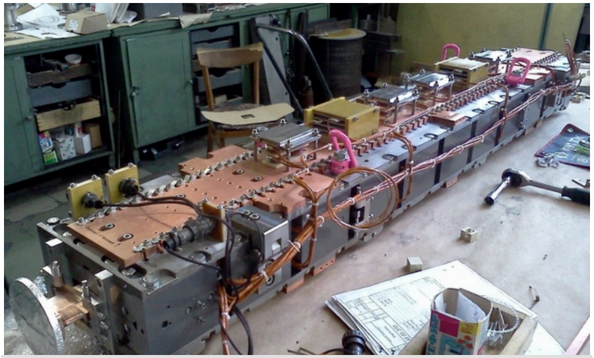


Technical Developments
- Key components for systemtests, machine performance, cost or power reduction





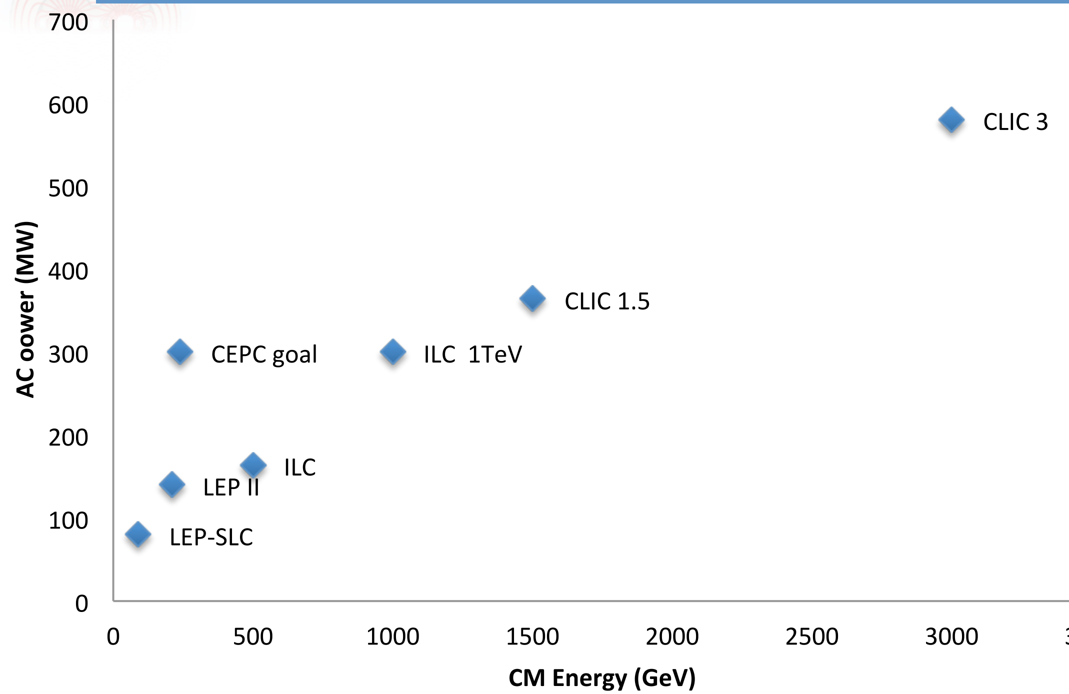
Module into CTF



QD0, nm-stabilization, BPM, NbTi wiggler

e+/e- Colliders: P vs E

P_AC versus E_CM



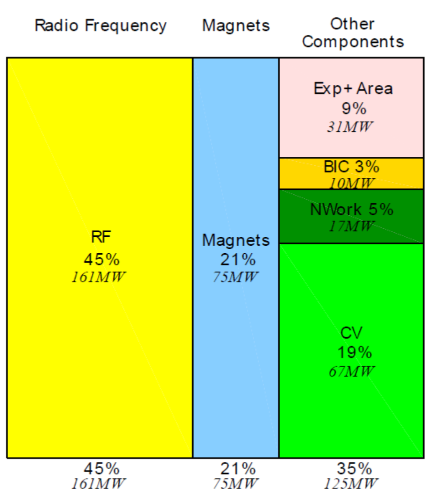
Power reductiions are being looked at (ILC more optmised than CLIC):

- •Design and parameters – optimise power
- •Look at key components – magnets
- •Klystron and modulator efficiences
- •Optimisation
- •Recover energy

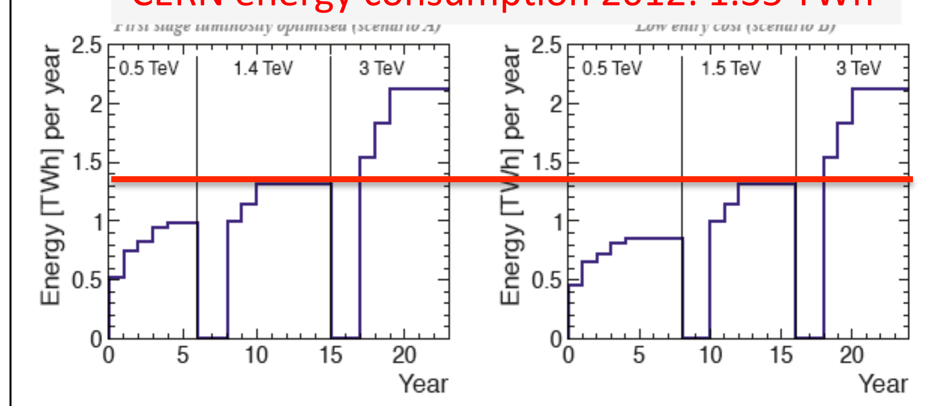
Consider where the power is dissipated (distributed or central)

Look at daily and yearly fluctuation – can one run in "low general demand" periods

Understand and minimize the energy (consider also standby, MD, down periods, running scenarios



CERN energy consumption 2012: 1.35 TWh



Thanks

- Slides/figures/advice from Lucio Rossi, Michael Benedict, Frank Zimmerman and Steiner Stapnes.