Future Colliders

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To start

- I am sorry for full of my personal prejudice in this talk!

In 2006

- The first European strategy for particle physics was adopted in June 2006: Colliders at the moment were:

– HERA @ DESY	ep	DE
– DAFNE @ LNF	e^+e^-	I
– LHC @ CERN under construction	pp	CH
– CESR-C @ Cornell	e^+e^-	US
– Tevatron @ FNAL	pp	US
– RICH @ BNL	$(p,d,Cu,Au,U)^2$	US
– PEP II @ SLAC	e^+e^-	US
– KEKB @ KEK	e^+e^-	JP
– BEPC-II @ IHEP under construction	e^+e^-	CN
– VEPP4M @ BINP	e^+e^-	RU
– VEPP2000 @ BINP under construction	e^+e^-	RU

Then…

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Some have been stopped…

And now

- The last European strategy for particle physics was adopted in May 2013: Existing colliders were:
  - DAFNE @ LNF — e^+e^- — I
  - LHC @ CERN — pp — CH
  - RICH @ BNL — $(p,d,Cu,Au,U)^2$ — US
  - SuperKEKB @ KEK under construction — e^+e^- — JP
  - BEPC-II @ IHEP — e^+e^- — CN
  - VEPP4M @ BINP — e^+e^- — RU
  - VEPP2000 @ BINP — e^+e^- — RU

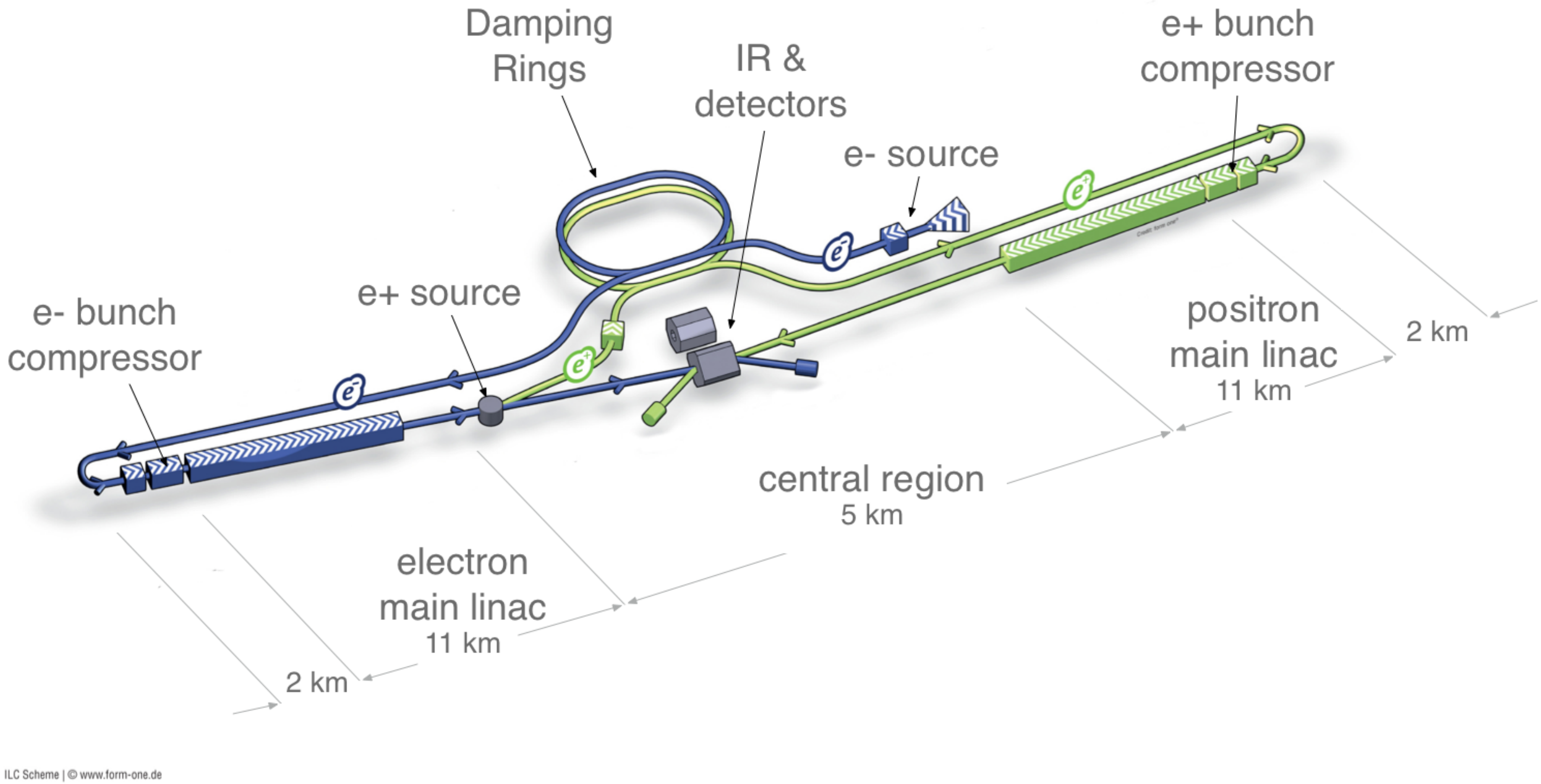
Five closed down and **only one has been approved**…

But many ideas are around

- e^+e^- Linear Collider
  - ILC: superconductive cavities, up to 500 GeV-1 TeV, $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
    ready to start construction project
  - CLIC: double beam acceleration, up to ~3 TeV, $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
    still many R&D required to be ready for construction

ILC

- TDR Generic design for 500 GeV, ~10^{34}cm^{-2}s^{-1}: ~30km

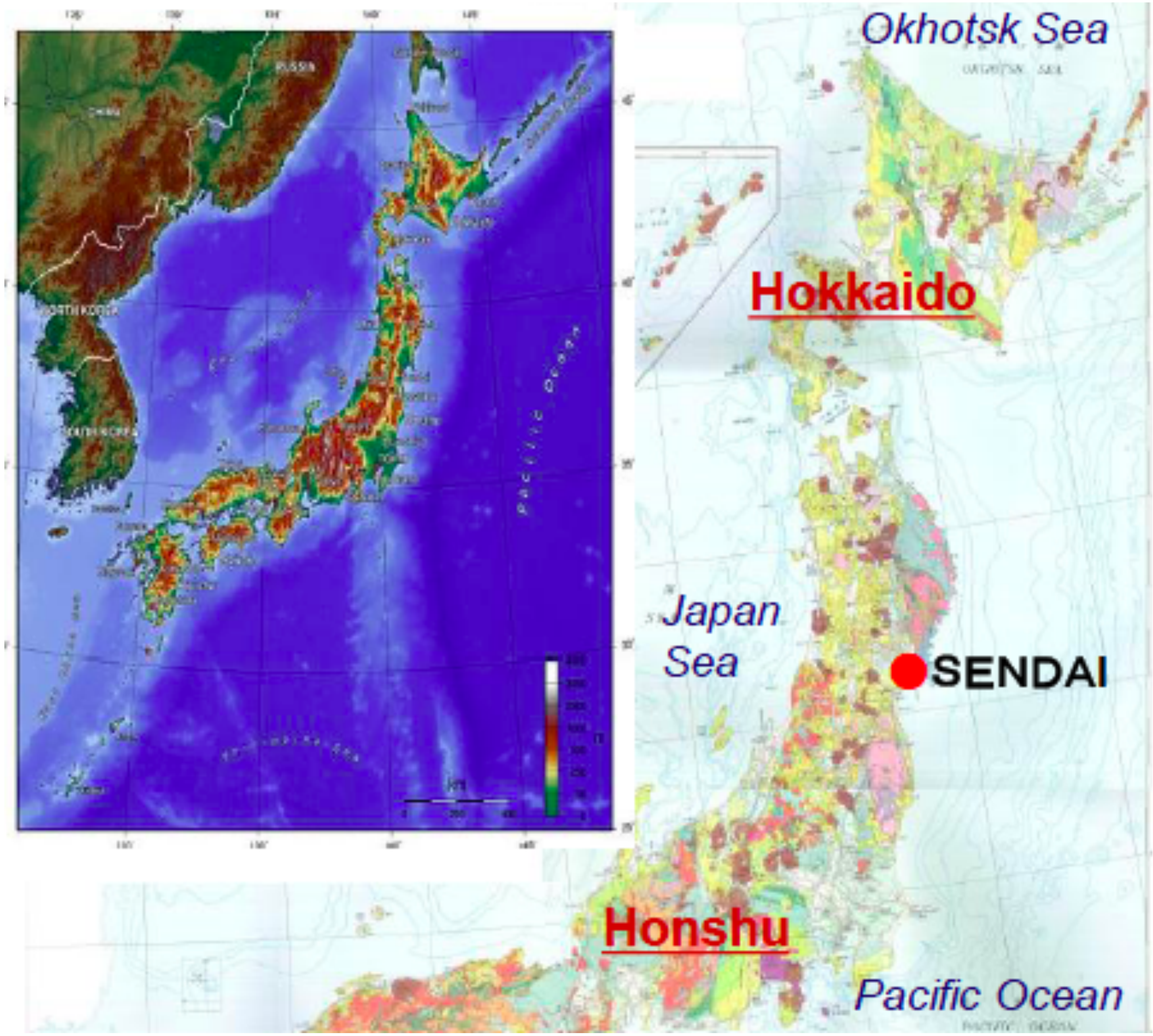


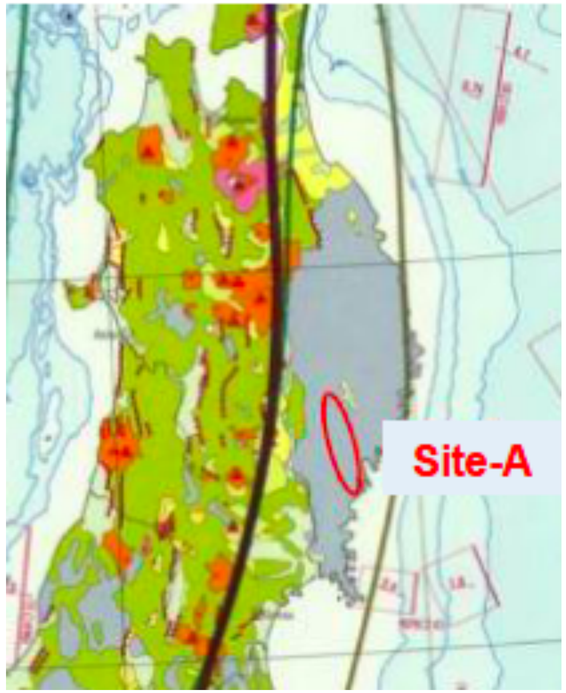
ILC

- Long worldwide effort
  e.g. ECFA study group since early 2000
- Technology is mature, many R&D works have been done including the industrialisation, with "module 0", i.e. European XFEL @ Hamburg
- Cover wide energy range: can be boosted to ~1 TeV
- Still require a rather long tunnel (30km for 500 GeV)
- Some complication to accommodate multiple detectors (push-pull)

ILC Japanese site candidate

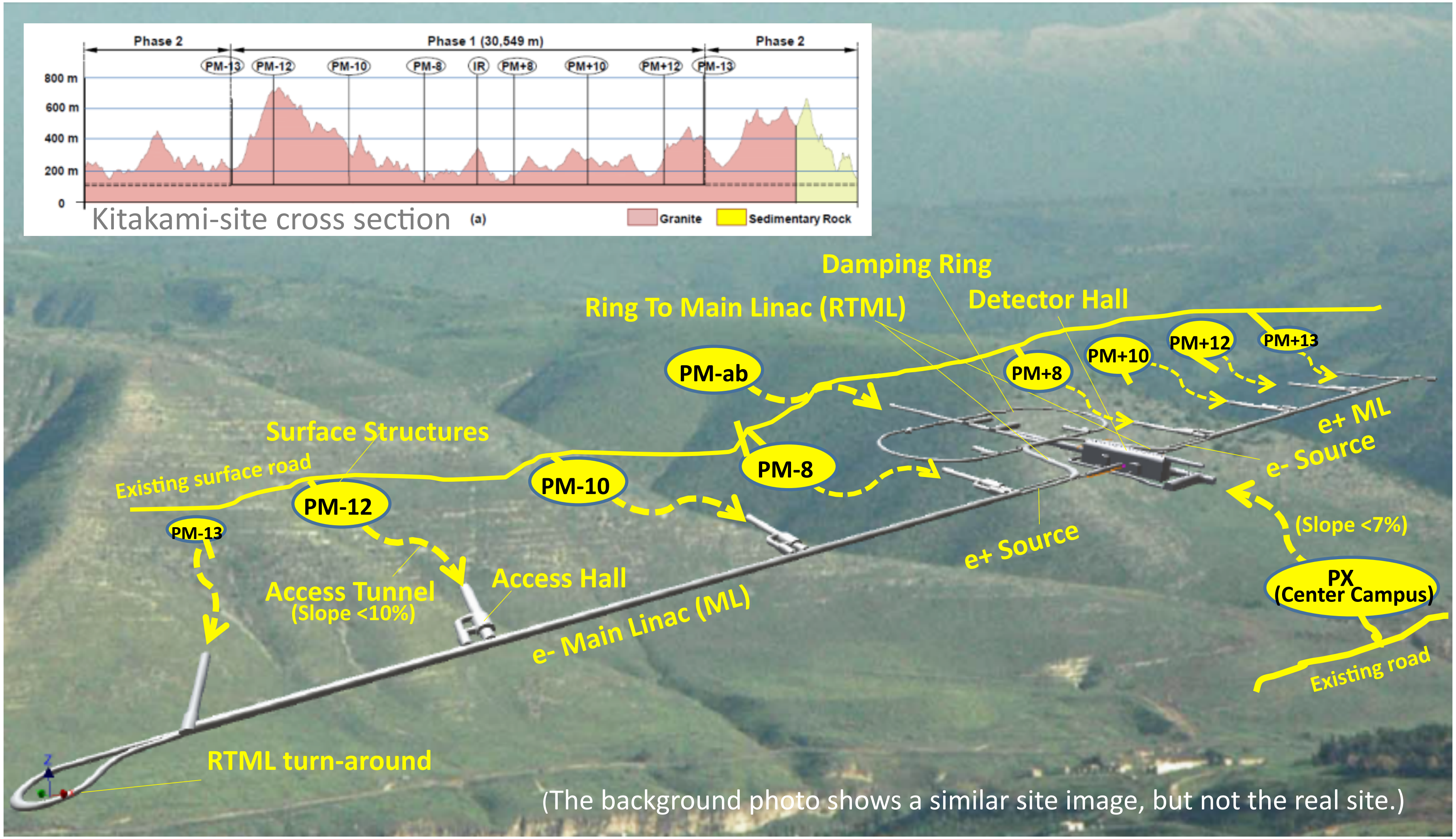
- Kitakami site selected by the Japanese scientists





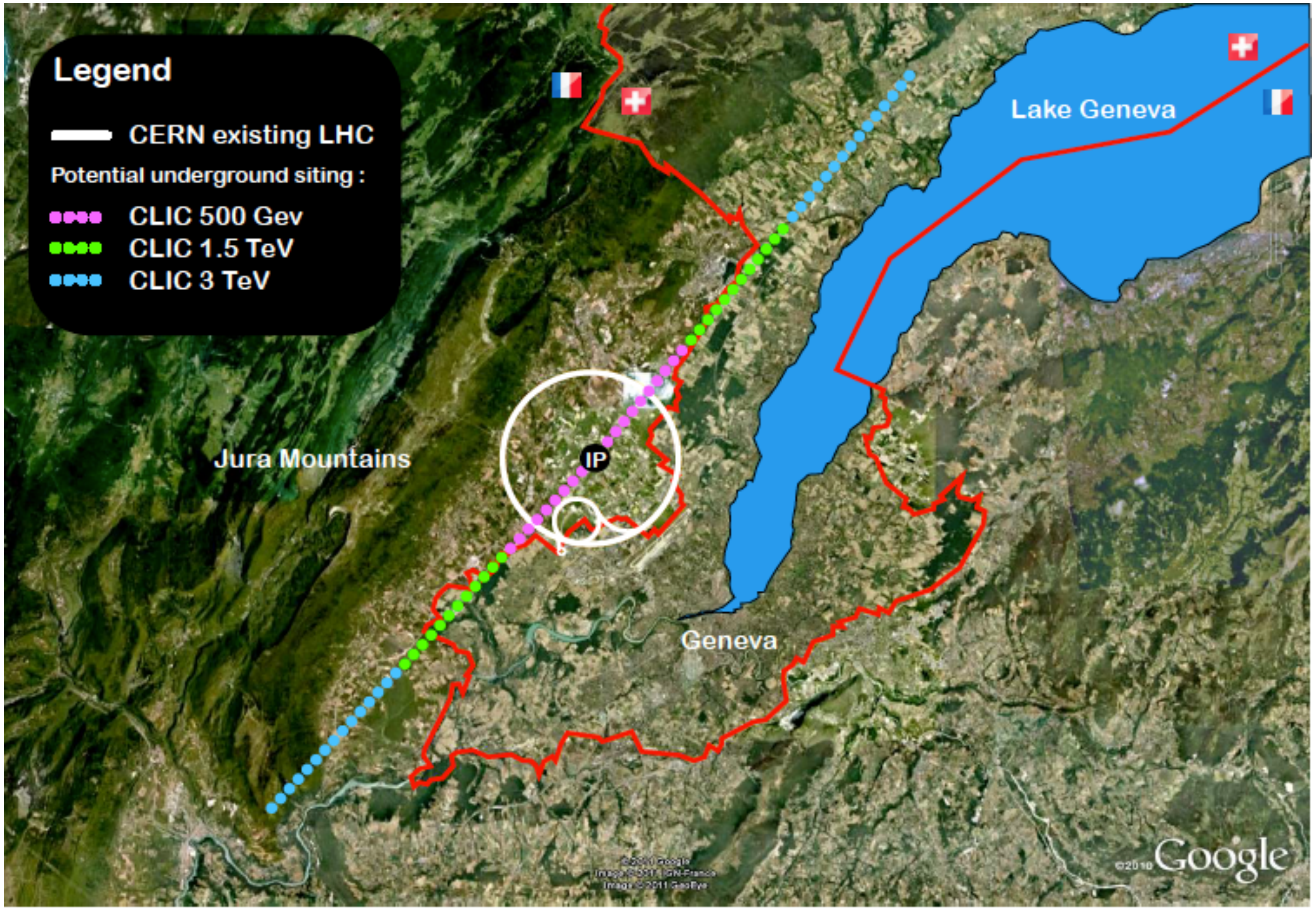
ILC

- The design being adjusted for the Japanese Kitakami site



CLIC

- R&D effort started at CERN quite sometime ago, aiming at a higher acceleration gradient with two beam technology, go beyond 1 TeV, up to ~3 TeV

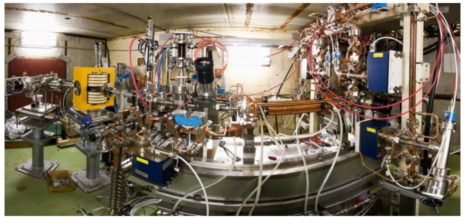


CLIC

- Many R&D effort by an international collaboration, a la HEP experiment

Previous:
Scaled 11.4 GHz
tests at SLAC and KEK.

NEXTEF at KEK

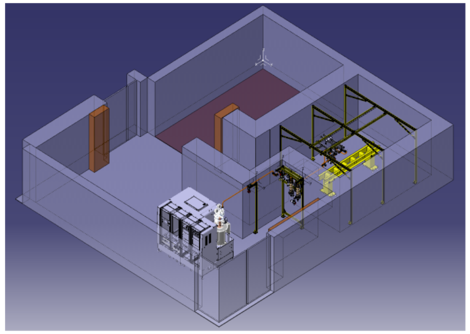


ASTA at SLAC

XBOX1 at CERN with SLAC klystron

100 MW can be provided in pulses of 250 ns, 50 Hz.
Can power two CLIC accelerating structures.

XBOX2 at CERN, industrial klystron
ready next … then XBOX3



Planned capacity : power six CLIC accelerating structures

Important goal: greatly increased X-band rf test capability, at 12 GHz, at CERN

- Still more R&D needed to reach the TDR level. Collaboration with ILC.

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- e^+e^- Circular Collider
  - LEP 3: with the existing LEP/LHC tunnel, up to 240 GeV
  - TLEP: new 80 to 100km tunnel, up to 350 GeV → see FCC later
  - Other similar ideas are IHEP Circular Higgs factory, SuperTRISTAN with ~50km new tunnel

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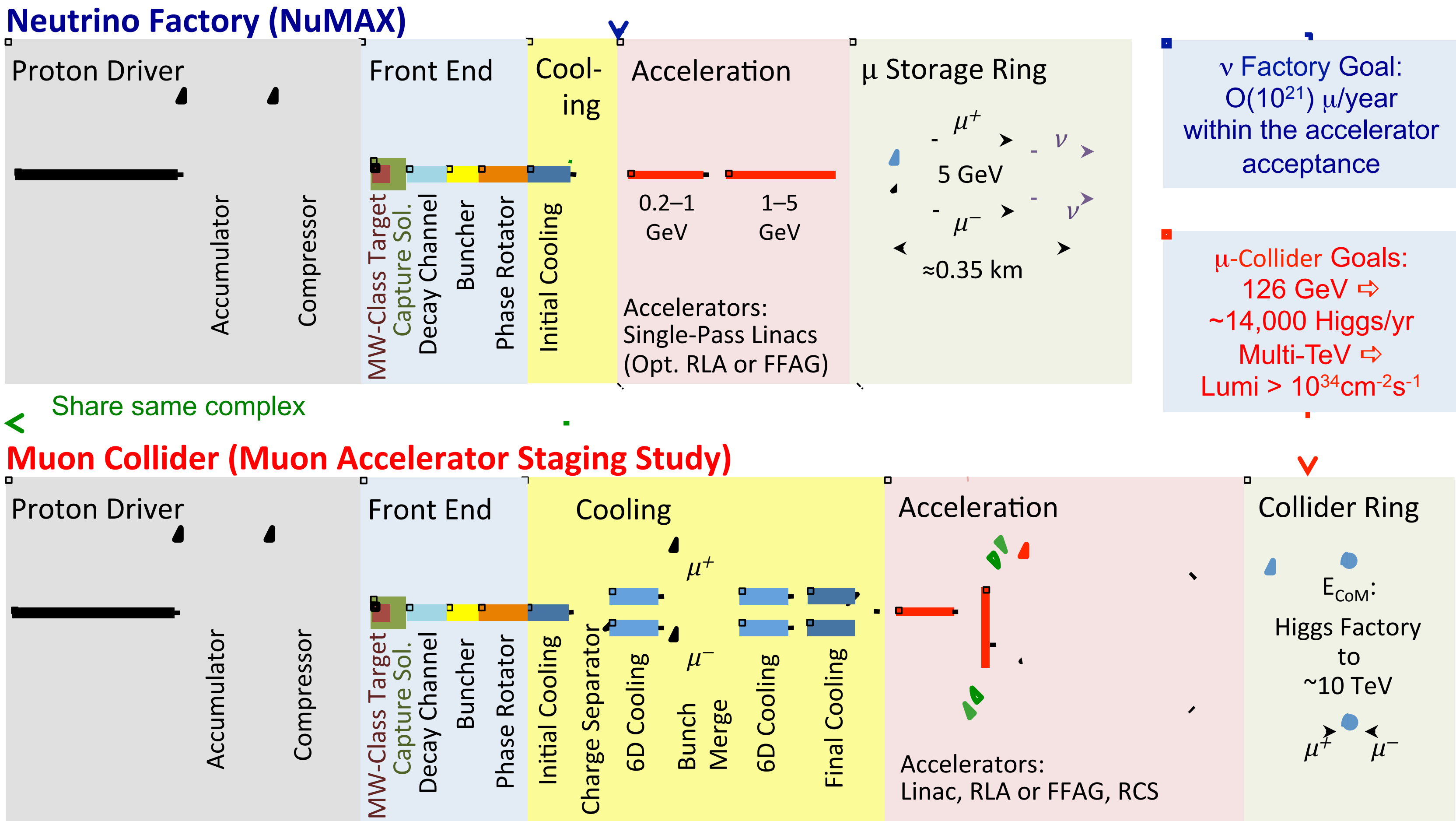
- $\mu^+\mu^-$ Circular Collider

  up to ~10TeV similar size as Tevatron, synergy with neutrino factory

  many R&D needed even for a conceptual design

Muon collider

- Some R&D, such as target and cooling, are in progress by international collaborations in view of a neutrino factory.

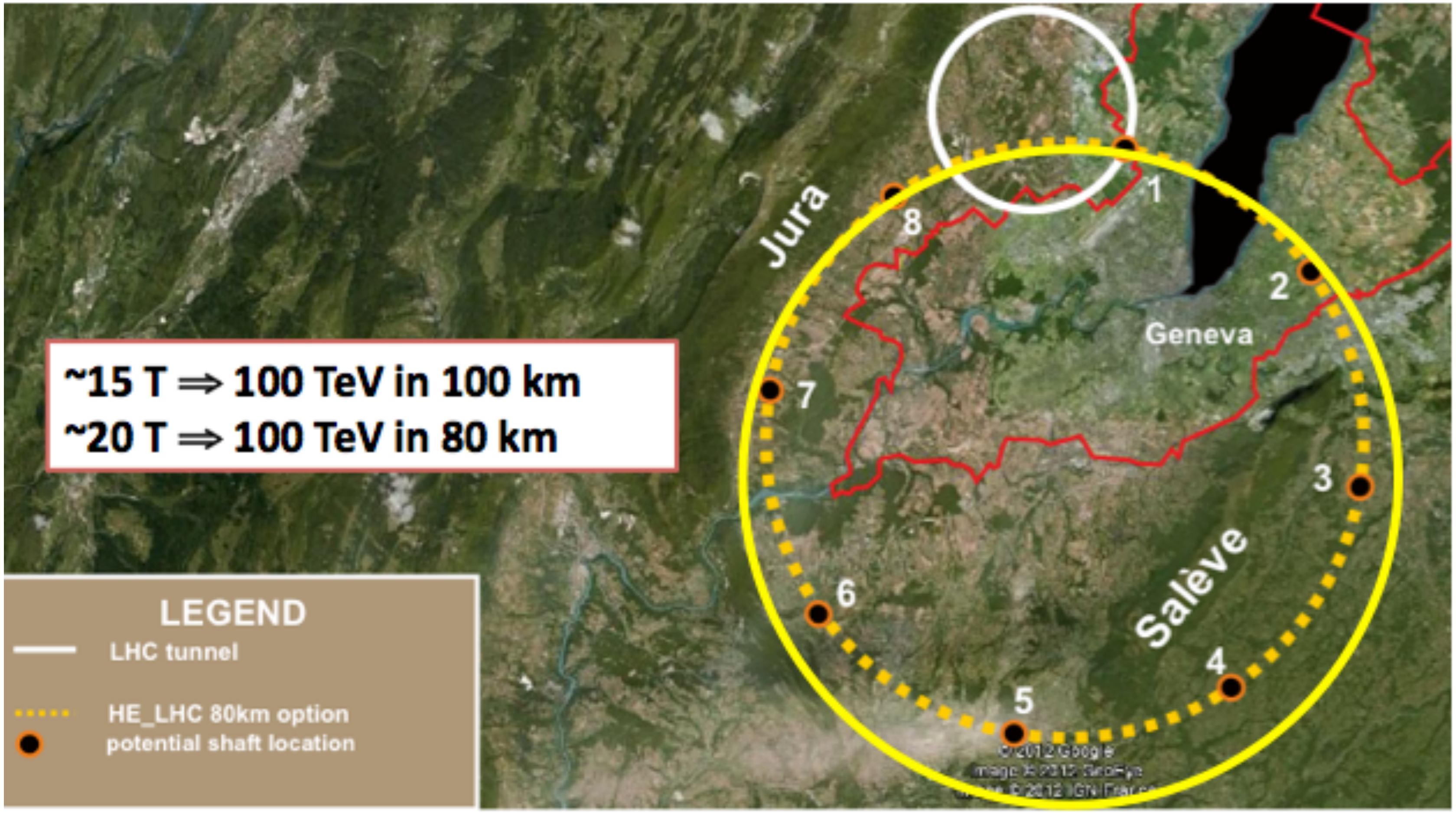


But many ideas are around

- pp Circular Collider
  - HL-LHC: luminosity upgrade of the exiting LHC, $5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$
    ESPP highest priority, natural upgrade step for LHC
  - HE-LHC: in the LHC tunnel, up to 33 TeV
    20T dipole required for 33 TeV
  - VHE-LHC: with 80 to 100km tunnel, up to 100 TeV
    same tunnel with TLEP, 15T dipole for 100 km → FCC
- ep(ion) Collider
  - LHeC: p(ion) of LHC against e from a 60 GeV linac
  - eRICH: p(ion) of RICH against e from a 5-30 GeV linac
  - ep option for VHE-LHC → FCC

Future Circular Collider

- Study effort initiated by CERN, based on 80~100 km tunnel, with a primary goal for 100 TeV pp collider. The tunnel could accommodate 350 GeV e^+e^-, and ep colliders.



Future Circular Collider

- Kick-off workshop organised by CERN will be in Geneva, 12-15 February 2014, to gather worldwide interest and establish global working groups to study technical aspects and physics potential. Any of the performance numbers are not much beyond the back of envelope calculations.

Main parameters for FHC *(VHE-LHC)*

PRELIMINARY

- **Energy** **100 TeV c.m.**
- **Dipole field** **~ 15 T (design limit) [20 T option]**
- **Circumference** **~ 100 km**
- #IPs 2 main (tune shift) + 2
- Beam-beam tune shift 0.01 (total)
- **Bunch spacing** **25 ns [5 ns option]**
- Bunch population (25 ns) $1\text{x}10^{11}$ p
- #bunches 10500
- **Stored beam energy** **8.2 GJ/beam**
- Emittance normalised $2.15\text{x}10^{-6}$m, normalised
- **Luminosity** **$5\text{x}10^{34}$ cm^{-2}s^{-1}**
- β* 1.1 m [2 m conservative option]
- **Synchroton radiation arc** **26 W/m/aperture (filling fact. 78% in arc)**
- **Longit. emit damping time** **0.5 h**

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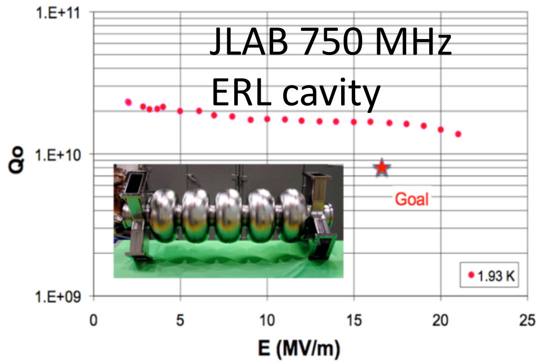
Parameter	TLEP-Z	TLEP-WW	TLEP-H	TLEP-$t\bar{t}_{bar}$
E (GeV)	45	80	120	175
I (mA)	1400	150	30	7
$\beta^*_{x/y}$ (mm)	500 / 1	200 / 1	500 / 1	1000 / 1
ε_x (nm)	30	3	2	4
ε_y (pm)	60	17	15	2
L (10^{32} cm^{-2}s^{-1})	5800	1600	500	120

Future Circular Collider

- Kick-off workshop is a good occasion to establish the R&D programme inline with the ESPP.

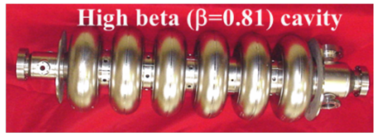
d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

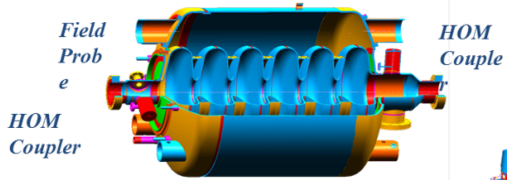
Program	Goals	Main partners	Status	
US-base program	High field Nb_3Sn dipoles as technology demonstrators	DOE (BNL, FNAL, LBNL)	D20 reached 13.5 T (50 mm) in 1997, HD1 reached 16 T (0 mm) in 2004. LD1 shell and conductor procured	
EuCARD FReSCa2	13 T (100 mm) Nb_3Sn dipole	EuCARD collaboration (CEA, CERN)	SMC reached 13.5 T (0 mm) in 2013, RMC in construction, FReSCa2 structure procured and tested at CERN, coils in fabrication at CEA	
US-LARP	140 T/m (150 mm) Nb_3Sn quadrupoles for the LHC IR upgrade	DOE US-LARP (BNL, FNAL, LBNL), CERN	Short HQ models (120 mm), long LQ prototype (90 mm) tested, QXF (150 mm) models in production (US-LARP and CERN)	
11 T	11 T (60 mm) Nb_3Sn dipoles for the LHC DS collimators	FNAL, CERN	2 short models tested, 1 mirror in test at FNAL, first model in production at CERN	

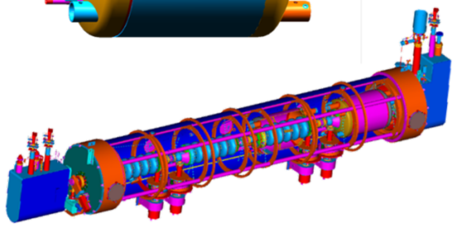


ORNL-SNS

β=0.81 Specifications:
E_a=15.8 MV/m, Q_o> 5E9 at 2.1 K







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- γγ Collider as a Higgs factory (inverse of H→γγ)
  - 80 GeV e^- linacs is sufficient, i.e. no e^+ needed
  - laser part requires many R&D

Issues for making-up our mind

- Scientific requirements
- Technological maturity
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- Scientific requirements
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- They all change with time
- Unfortunately, the last three issues cannot be ignored

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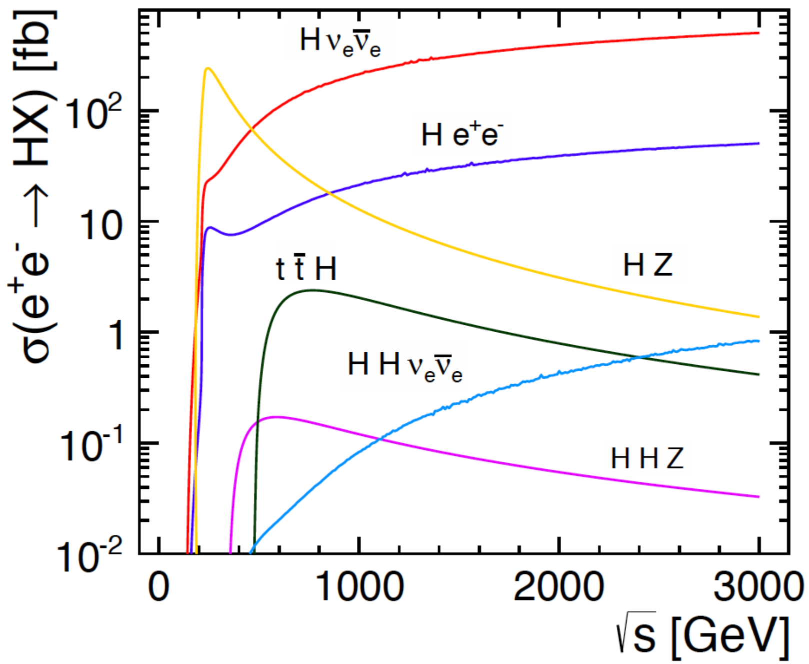
  examples are…
  - at ~250 GeV: with $e^+e^- \to HZ$, clean studies of H decays by tagging Z
    i.e. can access to decays into cc, invisible, …
  - at ~500 GeV: with $e^+e^- \to Htt$, coupling to tt
  - for H self-coupling, >1 TeV needed



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- But, clear sign of new physics from neither the direct search nor the precision measurements (electroweak and flavour).
  ⇒ No reliable ideas on the energy scale of new physics.
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- Coming LHC 14 TeV data will be essential to see whether
  - weakly coupling new particles can be accessed by a 500 TeV e^+e^- collider
  - strongly (and possibly weakly coupling?) new particles can be accessed by a TeV e^+e^- collider

i.e. is the energy scale for new physics ~TeV?

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  ⇒ No reliable ideas on the energy scale of new physics.
  How can we argue the energy of new colliders?
  ⇒What are the possible consequences of 14 TeV data?

Case for the e^+e^- colliders

- e^+e^- Higgs factory has already a clear physics goal
  - LC strategy: exploiting the full energy range up to 500 GeV
  - CC strategy: exploiting the high integrated luminosity at 250 GeV (with an extension to pp machine)

  and tt physics

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- 14 TeV LHC data needed to see whether there is a strong motivation for a TeV e^+e^- collider
  - if no new physics, justification for a TeV e^+e^- collider will be difficult
  - depending on the mass, there could be a case for the both colliders

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My naïve question to theoreticians: $H \rightarrow ff$ and $H \rightarrow WW(ZZ)$ are tree processes. How sensitive such tree processes to new physics, compared to a loop process such as $H \rightarrow \gamma\gamma$?

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  - All pp colliders considered will explore the mass spectrum of particle associated to new physics.
- If new physics were not found by 14 TeV LHC data:
  - For VHE-LHC, energy scale for new physics could be ~10 TeV
  - For lower energy pp colliders, pushing the SM precision measurements further may result in deviations

⇒ really difficult case for a large investment …

Other colliders

- Muon Collider
  - s-channel Higgs production, very precise coupling measurement to μ)
  - very precise Higgs mass and width measurements
  - exploring 10 TeV energy scale

- γγ Collider
  - s-channel Higgs production, via loop diagram

- LHeC (or VHE-LHeC)
  - primary physics goal is the QCD studies: has its own physics merit but not necessarily addressing the frontier physics

Other issues

- Given the long time scale needed for constructing a large collider, we need to set up a clear plan.
- Muon collider and $\gamma\gamma$ collider needs substantial R&D to show the feasibility
- All the options are not cheap if not VERY expensive. ~5 billion CHF to >10 billion CHF, global planning and funding needed? (except LHeC?)
- LHC has to be exploited for the next >15 years and Europe will be too busy with the LHC upgrade for starting a new large project in Europe soon
- Japanese HEP community is promoting to host the ILC supported by some politicians; i.e. possible injection of new money outside of the normal science budget. Waiting for a clear sign from the Japanese government.

European Strategy Says

- Exploitation of the LHC till ~2030 the highest priority
- Accelerator R&D and design studies for high energy frontier machines as the post LHC project in Europe to be chosen by the 14 TeV LHC data
- Participate in ILC if Japanese government moves forward with the project

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What do **you** think about the future high energy frontier facility? (in particular at the next strategy update)