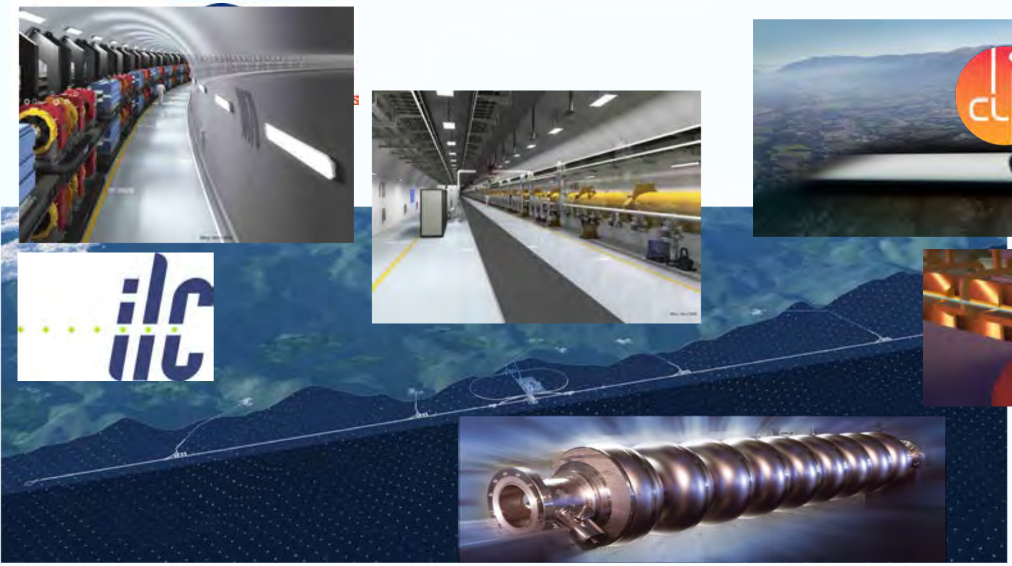
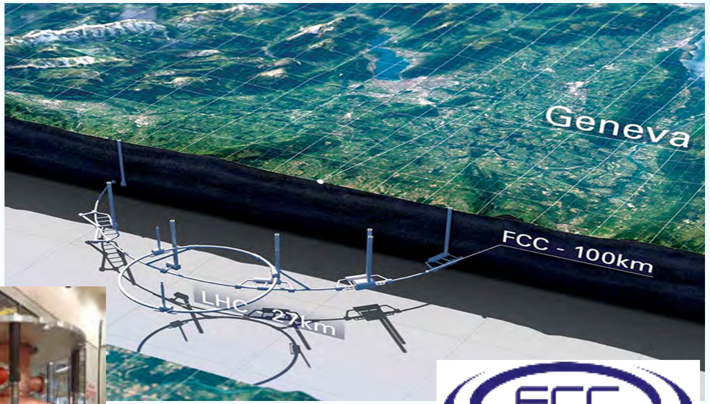




Towards a e^+e^- collider: Higgs factories

A. Faus-Golfe

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
CNRS IN2P3 Les deux infinis

INFIERI

The e⁺e⁻ Higgs factories

Note: H. Abramowizc ESG January 2020.

European Strategy

2020 Strategy Statements

Guide through the statements

2 statements on Major developments from the 2013 Strategy
a) Maintain focus on successful completion of HL-LHC upgrade
b) Mai...
US ...

3 state...
a) Pres...
com...
b) Str...
c) Acknowledge the global nature of PP research

2 statements on High-priority future initiatives
a) Higgs factory as the highest-priority next collider and investigation of the technical and financial feasibility of a future hadron collider at CERN
b) Vigorous R&D on innovative accelerator technologies – through roadmap

Letters for itemizing the statements are introduced for identification, do not imply prioritization

4 statements on Other essential scientific activities
a) Support for high-impact, financially viable
...oadmap
...ucture

...elds
b) Astroparticle – cooperation with APPEC

3 statements on Organisational issues
a) Framework for projects in and out of Europe
b) Strengthen relations with European Commissi...
c) Play active role in supporting Open Scienc...

4 statements on Environmental and societ... impact
a) Mitigate environmental impact of p... icle physics
b) Invest in next generation of rese... ers
c) Support knowledge and technol... transfer
d) Spread cultural heritage: pu... engagement, education and communicat...

e+e- Higgs factory is highest priority in HEP

➢ **Technology View on Relative Timelines**

Timeline	~5	~10	~15	~20	~25	~30	~35
Lepton Colliders – Linear and Circular:							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF–LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collier – Circular :							
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series		Construction		
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
9~12T Nb_3Sn	Model/Proto/Pre-series	Construction		Operation			Upgrade
6~8T NbTi	Proto/Pre-series	Construction		Operation		Upgrade	

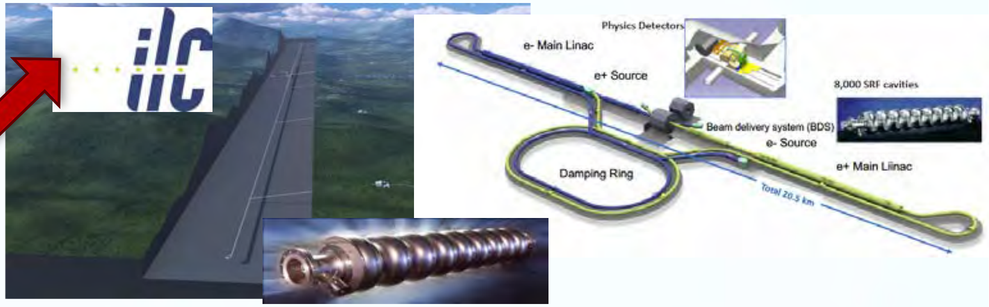
Note: LHC experience: NbTi, 10 T R&D started in 1980's and 8.3 T Production started in late 1990's, after ~ 15 years

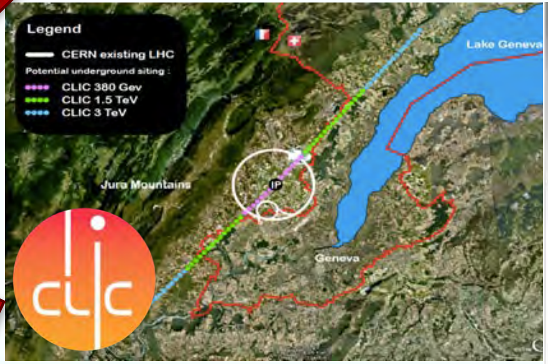
A. Yamamoto, 190513/updated 190628

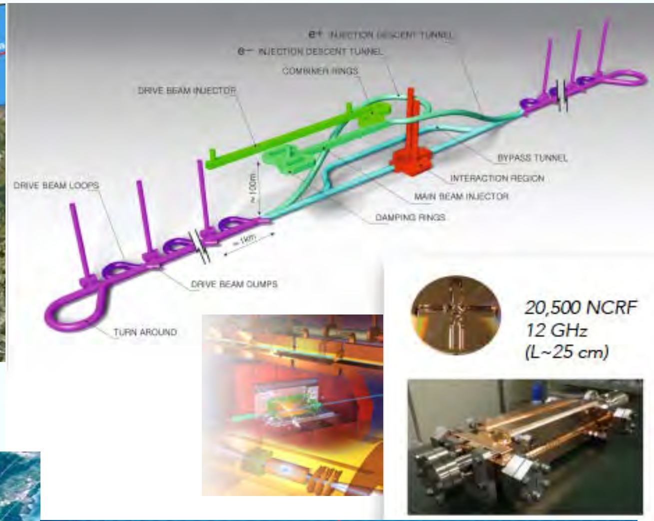
➢ **Higgs Factories**

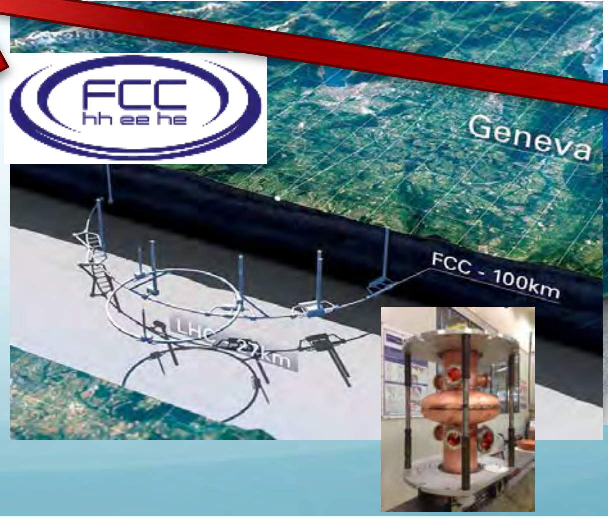
Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear 250 GeV			
ee Rings 240GeV/tt			
μμ Collider 125 GeV			*
ALIC 125 GeV		?	?

F1 "Technology Readiness": Green - TDR; Yellow - CDR; Red - R&D
F2 "Energy Efficiency": Green : 100-200 MW; Yellow : 200-400 MW; Red : > 400 MW
F3 "Cost": Green : < LHC; Yellow : 1-2 x LHC; Red : > 2x LHC









The e^+e^- Higgs factories

Note: H. Abramowizc ESG January 2020.

European Strategy

2020 Strategy Statements

Guide through the statements

2 statements on Major developments from the 2013 Strategy
a) Maintain focus on successful completion of HL-LHC upgrade
b) Maintain support for long-baseline ν experiments in Japan and US and the Neutrino Platform

3 statements on General considerations for the 2020 update
a) Preserve the leading role of CERN for success of European PP community
b) Strengthen the European PP ecosystem of research centres
c) Acknowledge the global nature of PP research

2 statements on High-priority future initiatives
a) Higgs factory as the highest-priority next collider and investigation of the technical and financial feasibility of a future hadron collider at CERN
b) Vigorous R&D on innovative accelerator technologies -

4 statements on Other essential scientific activities
a) Support for high-impact, financially viable, experimental initiatives world-wide
b) Acknowledge the essential role of theory
c) Support for instrumentation R&D – through roadmap
d) Support for computing and software infrastructure

2 statements on Synergies with neighbouring fields
a) Nuclear physics – cooperation with NuPECC
b) Astroparticle – cooperation with APPEC

3 statements on Organisational issues
a) Framework for projects in and out of Europe
b) Strengthen relations with European Commissi
c) Play active role in supporting Open Scienc

4 statements on Environmental and socie ... mpact
a) Mitigate environmental impact of p... cle physics
...ers
transfer
...ngagement,

Higgs factory technology is ready

...ies

		...ower-Eff.	Cost
			*
		?	?

Nb_3Sn	Short-model R&D	Prototype/re-series	Construction		
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series	Construction	Operation	
9~12T Nb_3Sn	Model/Proto/P re-series	Construction	Operation	Upgrade	
6~8T NbTi	Proto/ Pre-series	Construction	Operation	Upgrade	

Note: LHC experience: NbTi, 10 T R&D started in 1980's and 8.3 T Production started in late 1990's, after ~ 15 years

pp collider 125 GeV
ALIC 125 GeV

F1 "Technology Readiness": Green - TDR, Yellow - CDR, Red - R&D
F2 "Energy Efficiency": Green: 100-200 MW, Yellow: 200-400 MW, Red: > 400 MW
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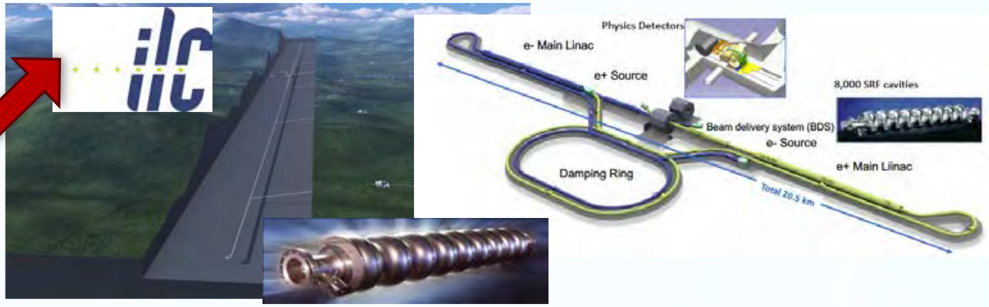
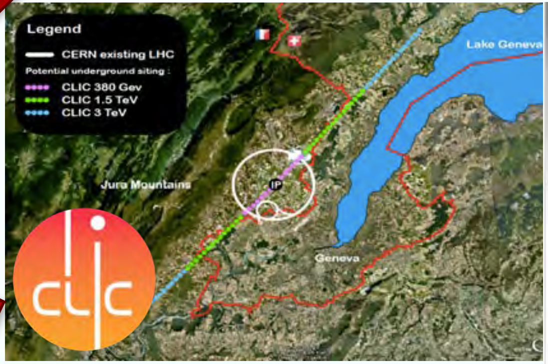
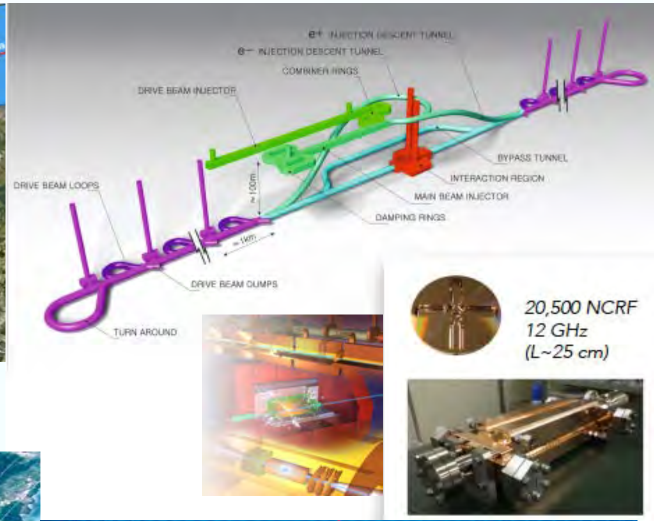
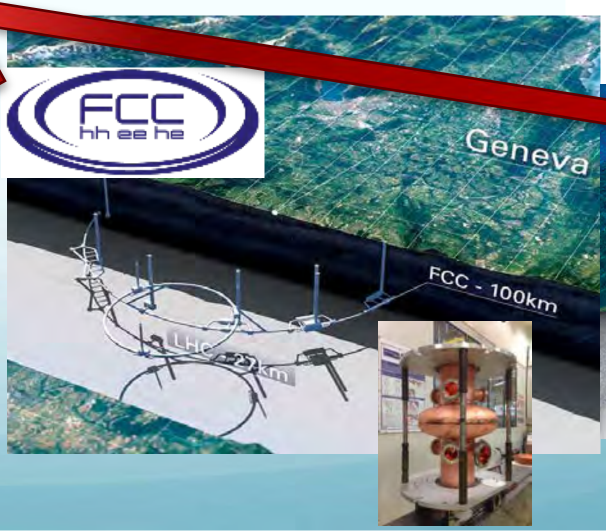


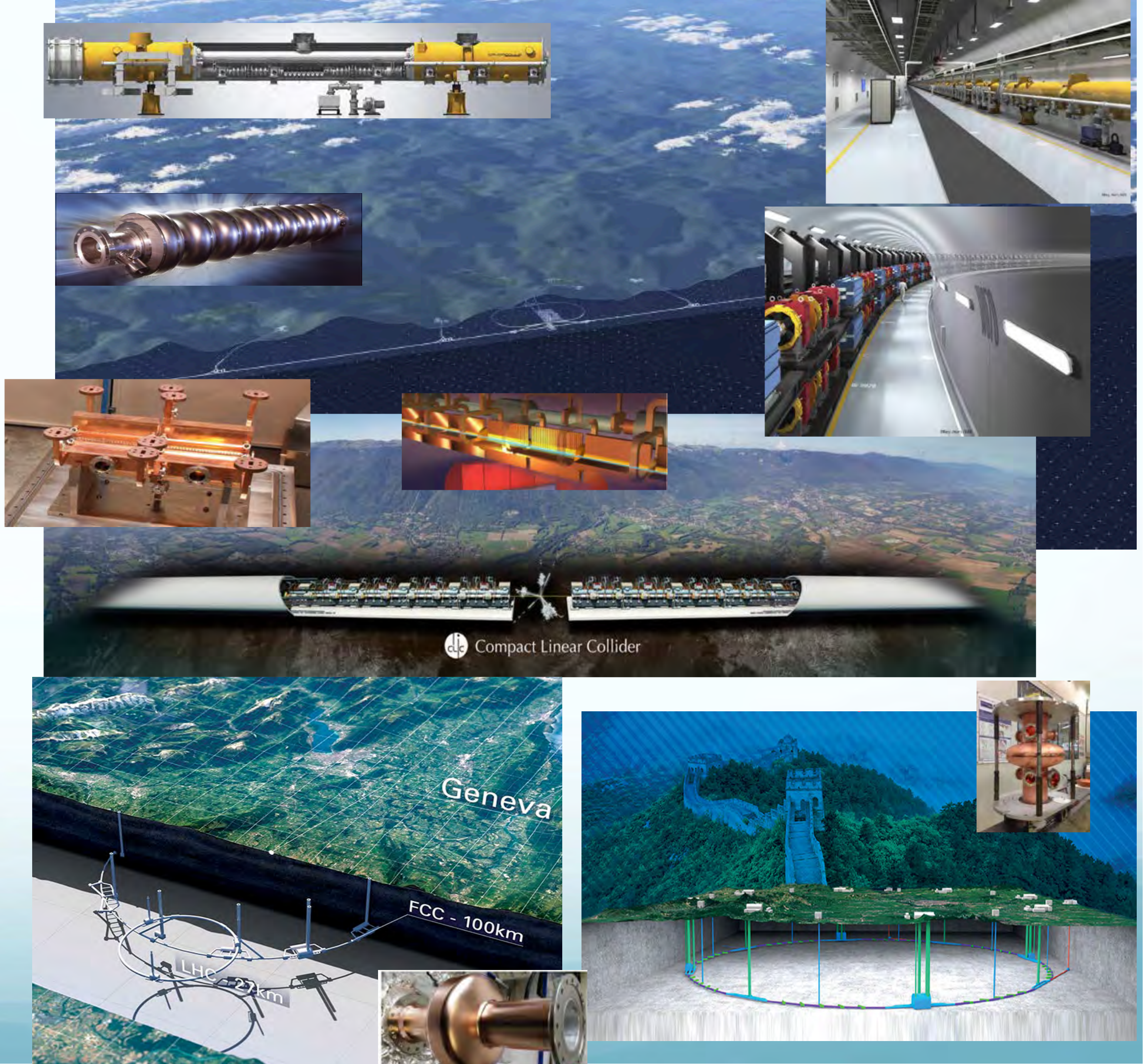




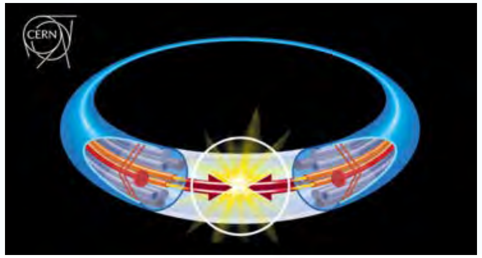


Outline

- ➢ Luminosity issues
- ➢ The e^+e^- Linear colliders
  - ILC-IDT: Technology update
  - CLIC: Technology update
- ➢ The e^+e- Circular colliders
  - FCCee: Technology update
  - CepC: Technology update (J. Gao's talk)
- ➢ Summary and Perspectives



Luminosity recipe: linear vs circular



$$L = f_c \frac{N_{e-} N_{e+}}{4\pi \sqrt{\beta_x^* \varepsilon_x} \sqrt{\beta_y^* \varepsilon_y}} = \frac{I_{e-} I_{e+}}{4\pi \sqrt{\beta_x^* \varepsilon_x} \sqrt{\beta_y^* \varepsilon_y} \cdot f_c \cdot e^2}$$

$$P_{SR} = V_{SRe-} I_{e-} + V_{SRe+} I_{e+}$$

The way to reduce SR power is to reduce beam currents in both electron and positron beam. To keep luminosity high, one would need to reduce one, two or all in

$$\sqrt{\beta_x^* \beta_y^*} \cdot \sqrt{\varepsilon_x \varepsilon_y} \cdot f_c$$

Luminosity recipe: linear vs circular

- In **storage rings** additional limitations appear: **beam-beam tune shift** and IP chromaticity (small β_y^*) which favors **high beam currents**, **large emittance** and **high collision frequencies**

$$\xi_{x,y} = \frac{N\, r_0 \beta^*_{x,y}}{2\pi\gamma\, \sigma_{x,y}\,(\sigma_x + \sigma_y)} < 0.1 - 0.5$$

- In **linear** the relevant number is the **disruption parameter**

$$D_{x,y} = \frac{N_e}{\gamma_e} \frac{2r_e}{(\sigma_x + \sigma_y)\sigma_{x,y}} \sigma_z$$

- At **high-energies** the most dangerous effect **is beamstrahlung**: SR in strong EM field of opposing beam during collision. It can cause significant amount of energy loss, induce large energy spread and loss of the particles. Using very **flat beams** is the main way of mitigating this effect

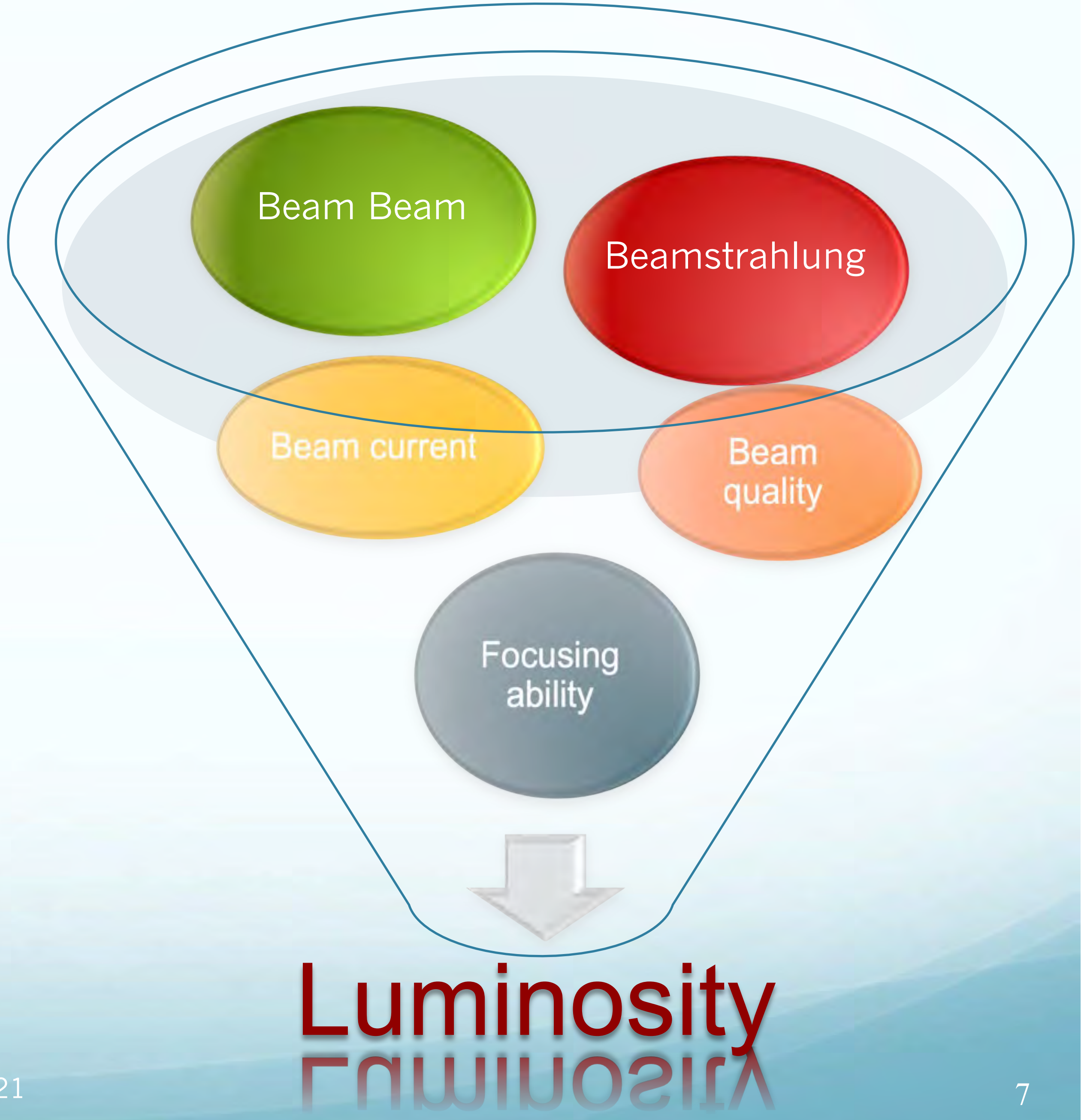
$$\langle \Delta\gamma \rangle = \frac{4}{9}\sqrt{\frac{\pi}{3}} N^2 \frac{r_e^3}{\sigma_x^2 \sigma_z} \gamma^2$$

$$for\ \sigma_x >> \sigma_y$$

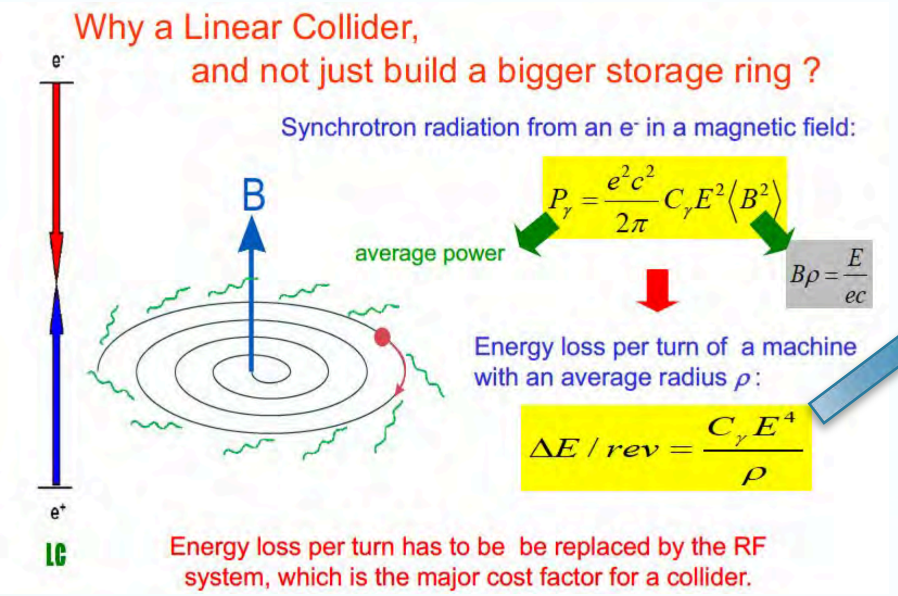
Luminosity recipe

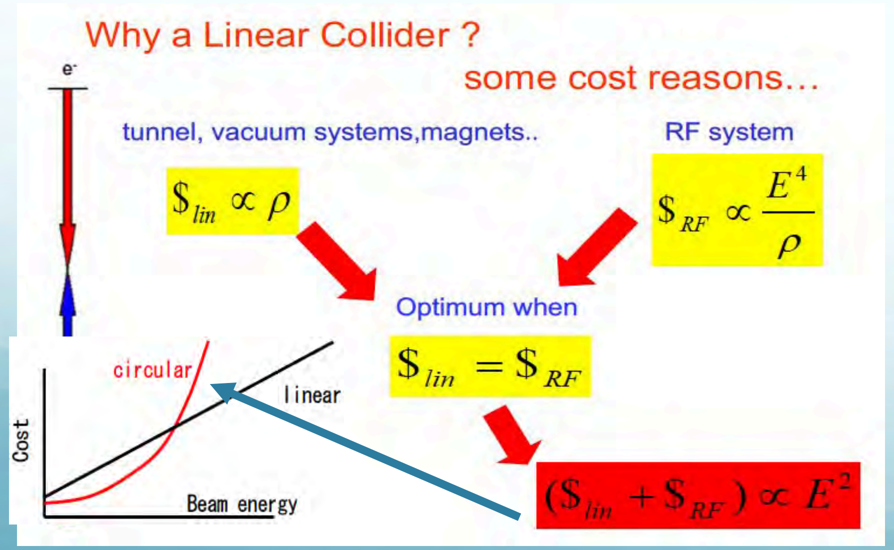
Luminosity cannot be fully demonstrated before project implementation:

- ➢ Luminosity is a feature of the facility not the individual technologies
- ➢ Relying in experience, theory and simulations
- ➢ Foresee margins



Other linear vs circular....





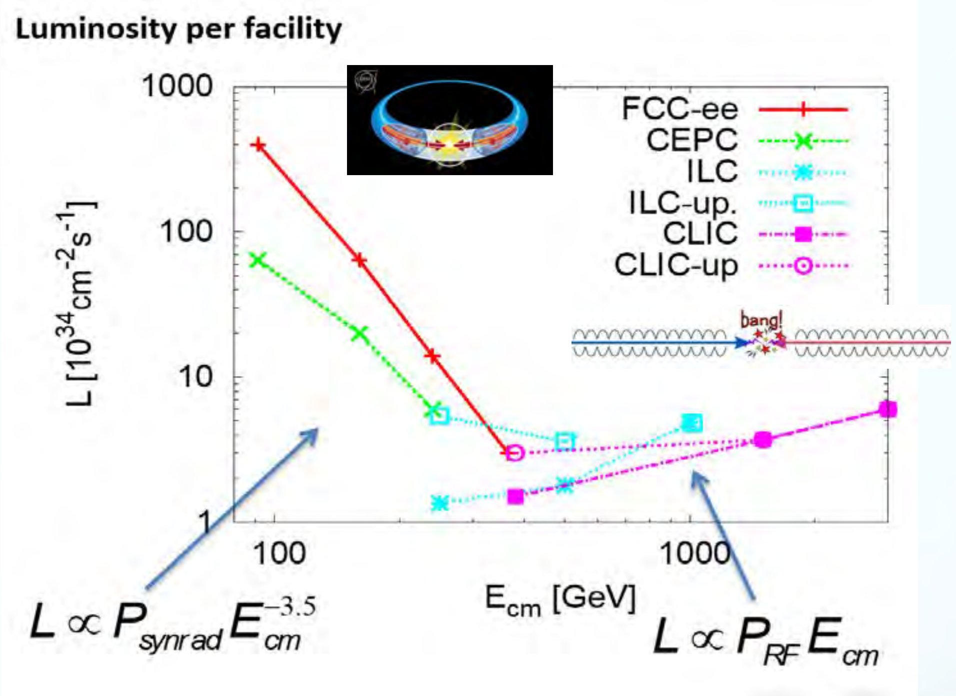
- **Energy dependence:**

At **low energies circular** colliders surpass

- Reduction at high energy due to SR

At **high energies linear** colliders excel

- Luminosity per beam power roughly constant



Note: The typical Higgs factory energies are close to the cross over in luminosity

- **Others LCs advantages:**

- LCs have **polarized beams** (80% e^-, ILC also 30% e^+), the spin of the e^+e^- beam can be maintained during the acceleration and collision. This can help significantly improve measurement precision.

- **Upgradeability**: LCs can extend its collision energy by longer tunnel/ higher gradient

Outline

- ➤ Luminosity issues
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  - ILC-IDT: Technology update
  - CLIC: Technology update
- ➤ The e^+e- Circular colliders
  - FCCee: Technology update
  - CepC: Technology update (J. Gao's talk)
- ➤ Summary and Perspectives

LCs Accelerator Challenges and Key Technologies

Construction cost
$ ~ L

Energy

$$E_{CM} = L \cdot g$$

Luminosity

$$\mathcal{L} = \frac{\eta P_{AC}}{E_{CM}} \cdot \frac{N_e}{4\pi \sigma_x^* \sigma_y^*} H_D$$

Operation cost
$ ~ P_{AC}

High Gradient g

High Efficiency η

Main Linac Technology

Losses in cavity walls

$$\frac{P_{wall}}{L} \propto \frac{g^2 R_s}{\omega}$$

Low resistivity

Small duty cycle:
Pulsed operation

High frequency &
Ultra-short pulses

ILC SCRF

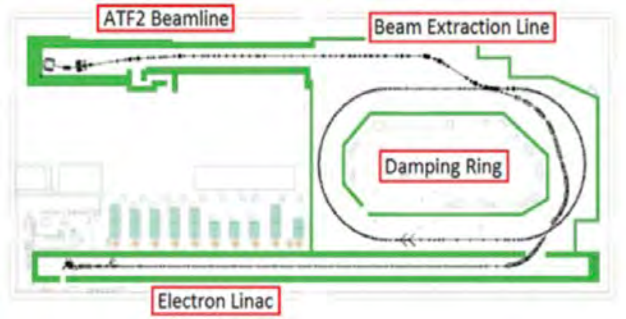
CLIC
2 beam acceleration

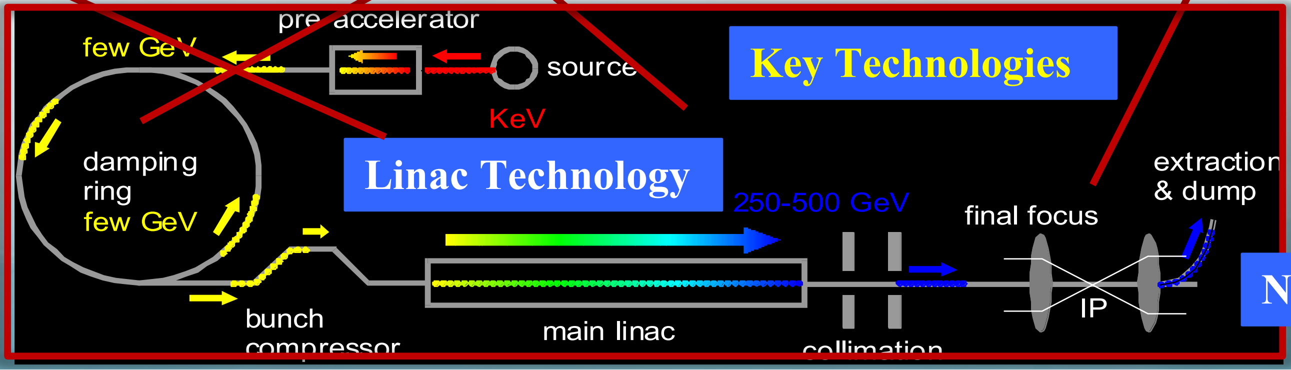
Small Beamspot $\sigma^*_x \sigma^*_y$

$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

Nanobeam Technology

- Damping ring (ε)
- Final focus (β^*)

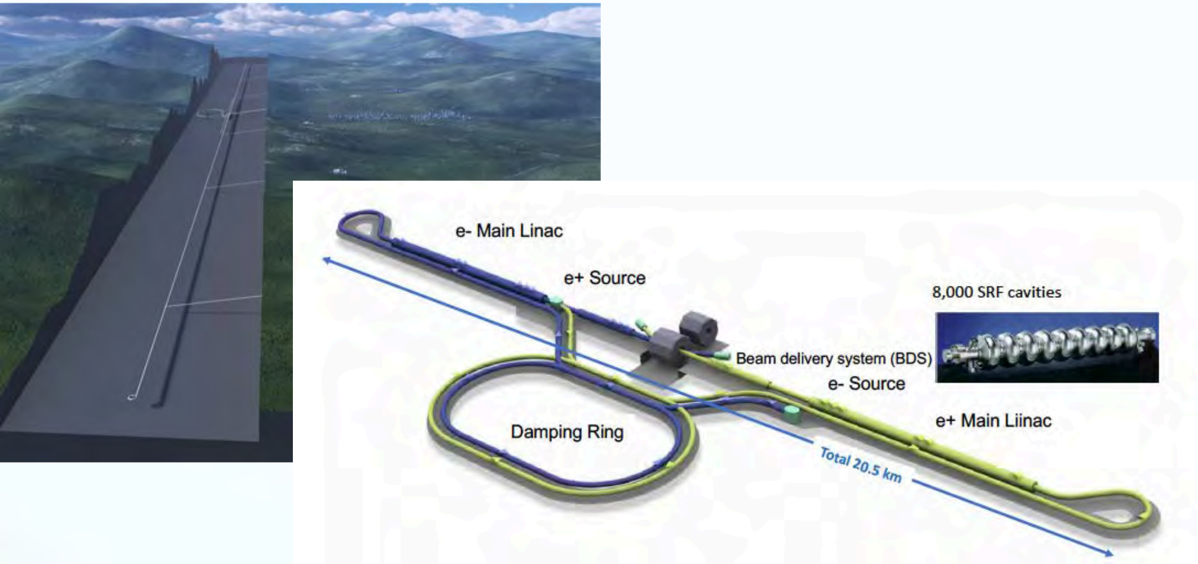


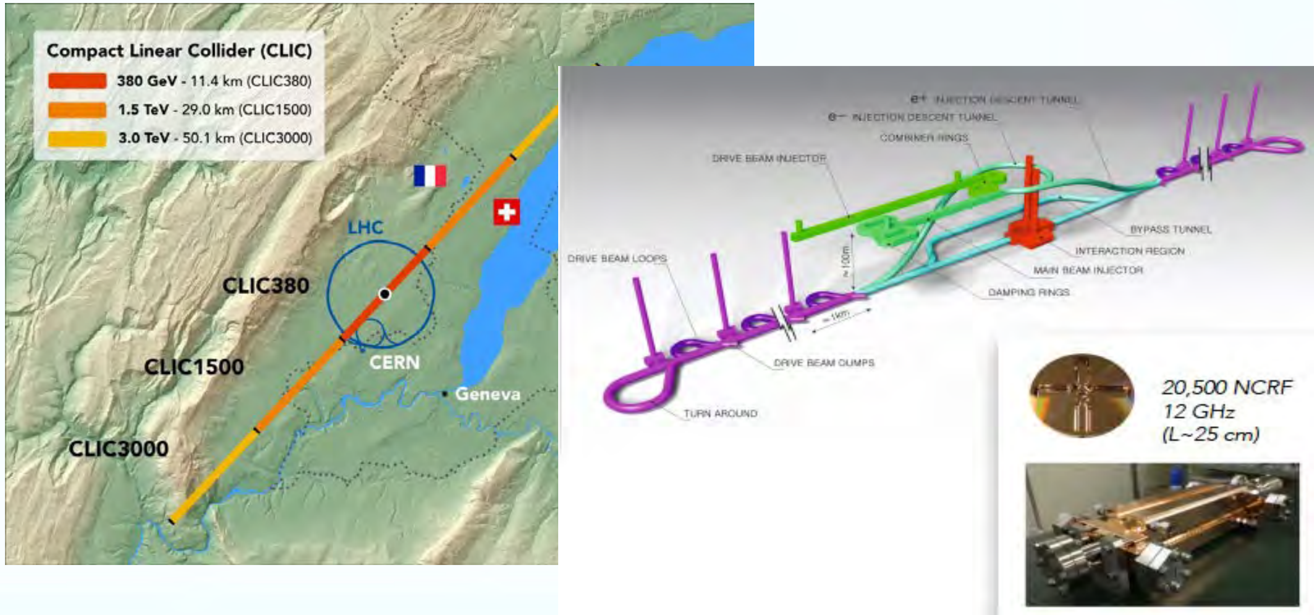


Nanobeam Technology

ILC and CLIC in a nutshell

Two e+e- linear collider designs, starting as a Higgs factory





International Linear Collider ILC

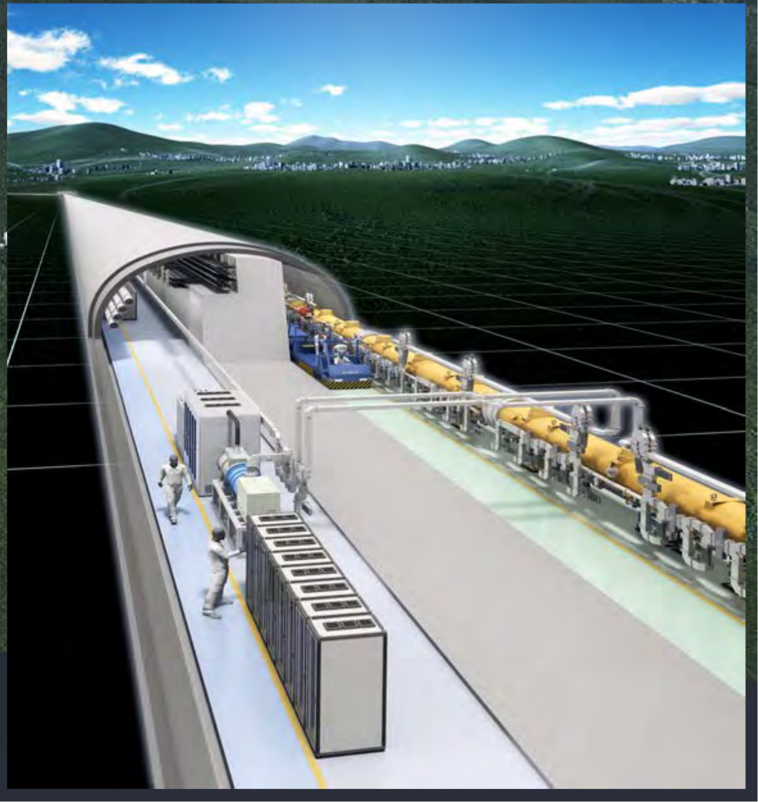
- Superconducting Cavities, 1.3GHz, 31.5MV/m
- Klystrons
- 250GeV CME, upgradeable to 500, 1000GeV
- L = 1.35×10^{34} $cm^{-2}s^{-1}$ (at initial 250GeV)
- 20km length, in Tohoku / Japan
- Polarisation 80%(e-), 30%(e+)

Compact Linear Collider CLIC

- NC Copper Cavities, 12.0GHz, 72 - 100MV/m
- Two-beam acceleration
- 380GeV CME, upgradeable to 1500, 3000GeV
- L = 1.50×10^{34} $cm^{-2}s^{-1}$ (at initial 380GeV)
- 11.4km long, at CERN / France & Switzerland
- Polarisation 80% (e-)

ILC accelerator: Techology update

http://www.linearcollider.org/



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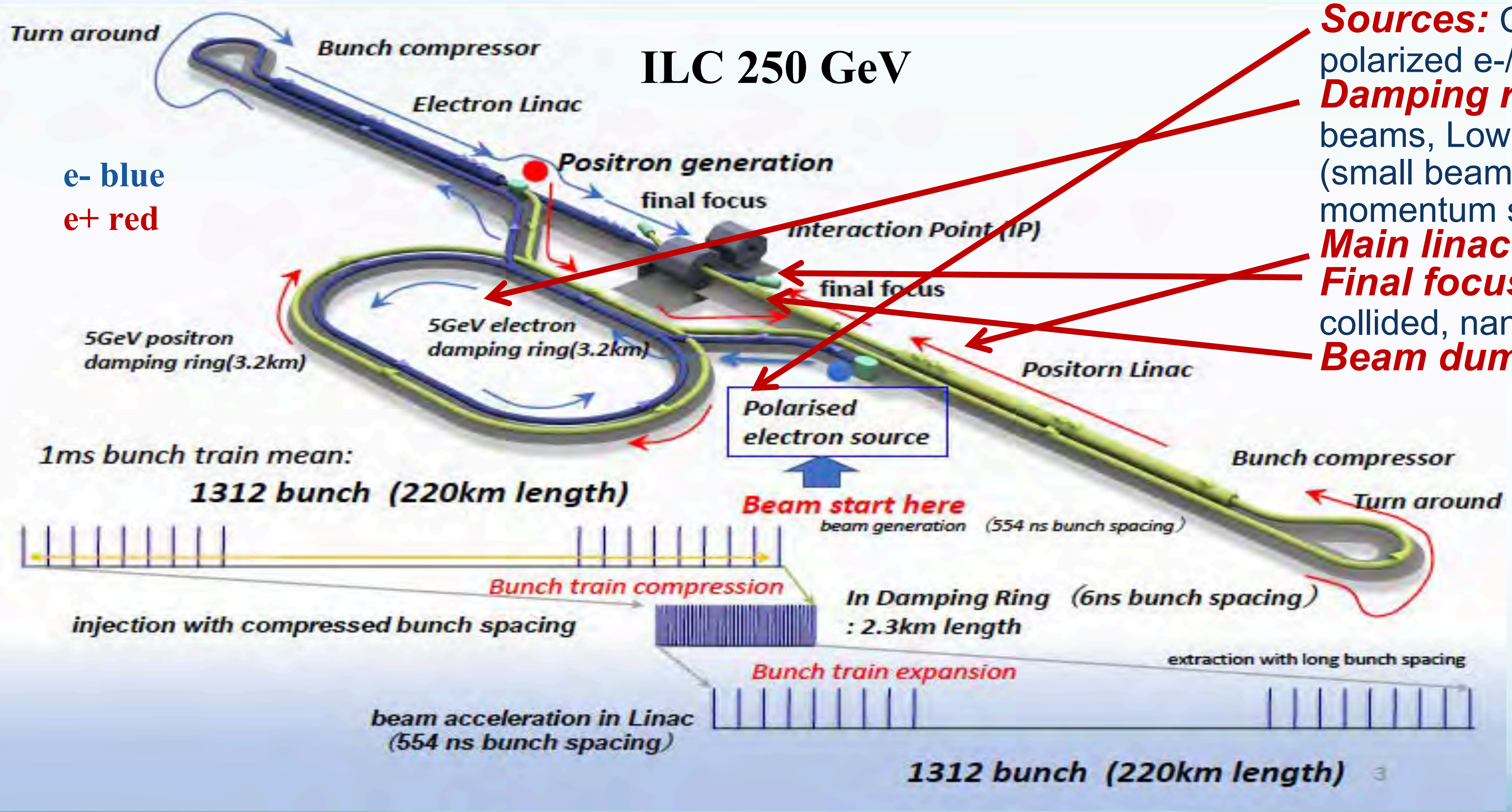
ILC accelerator sequence and main area systems



Sources: Creating particles and polarized e-/e+
Damping rings: High quality beams, Low emittance beams (small beam spread /small momentum spread)
Main linac Acceleration SRF
Final focus Getting them collided, nano-meter beams
Beam dumps

ILC updated parameters and upgrades

The ILC can be upgraded to higher energy and luminosity

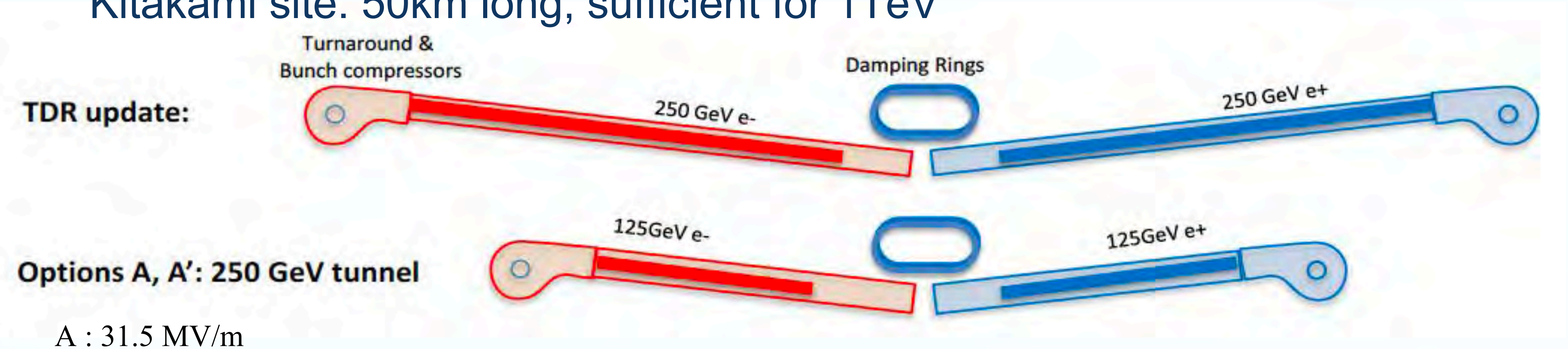
			Z-Pole [4]		Higgs [2,5]			500GeV [1*]		TeV [1*]
			Baseline	Lum. Up	Baseline	Lum. Up	L Up.10Hz	Baseline	Lum. Up	case B
Center-of-Mass Energy	E_{CM}	GeV	91.2	91.2	250	250	250	500	500	1000
Beam Energy	E_{beam}	GeV	45.6	45.6	125	125	125	250	250	500
Collision rate	f_{col}	Hz	3.7	3.7	5	5	10	5	5	4
Pluse interval in electron main linac		ms	135	135	200	200	100	200	200	200
Number of bunches	n_b		1312	2625	1312	2625	2625	1312	2625	2450
Bunch population	N	10^{10}	2	2	2	2	2	2	2	1.737
Bunch separation	Δt_b	ns	554	554	554	366	366	554	366	366
Beam current		mA	5.79	5.79	5.79	8.75	8.75	5.79	8.75	7.60
Average beam power at IP (2 beams)	P_B	MW	1.42	2.84	5.26	10.5	21.0	10.5	21.0	27.3
RMS bunch length at ML & IP	σ_z	mm	0.41	0.41	0.30	0.30	0.30	0.30	0.30	0.225
Emittance at IP (x)	$\gamma\varepsilon^*_x$	µm	6.2	6.2	5.0	5.0	5.0	10.0	10.0	10.0
Emittance at IP (y)	$\gamma\varepsilon^*_y$	nm	48.5	48.5	35.0	35.0	35.0	35.0	35.0	30.0
Beam size at IP (x)	σ^*_x	µm	1.118	1.118	0.515	0.515	0.515	0.474	0.474	0.335
Beam size at IP (y)	σ^*_y	nm	14.56	14.56	7.66	7.66	7.66	5.86	5.86	2.66
Luminosity	L	$10^{34}/cm^2/s$	0.205	0.410	1.35	2.70	5.40	1.79	3.60	5.11
Luminosity enhancement factor	H_D		2.16	2.16	2.55	2.55	2.55	2.38	2.39	1.93
Luminosity at top 1%	$L_{0.01}/L$	%	99.0	99.0	74	74	74	58	58	45
Number of beamstrahlung photons	n_γ		0.841	0.841	1.91	1.91	1.91	1.82	1.82	2.05
Beamstrahlung energy loss	δ_{BS}	%	0.157	0.157	2.62	2.62	2.62	4.5	4.5	10.5
AC power [6]	Psite	MW			111	138	198	173	215	300
Site length	Lsite	km	20.5	20.5	20.5	20.5	20.5	31	31	40

Energy

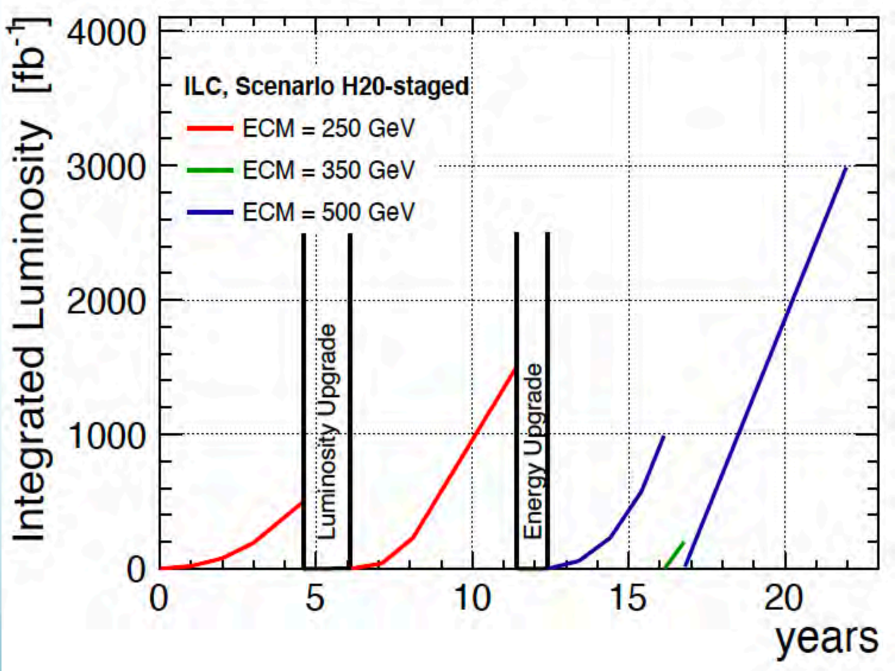
Lumi.

ILC updated parameters and upgrades

➢Possible **energy upgrades**: 500GeV, 1TeV need tunnel extension
Kitakami site: 50km long, sufficient for 1TeV



A : 31.5 MV/m
A': 35 MV/m



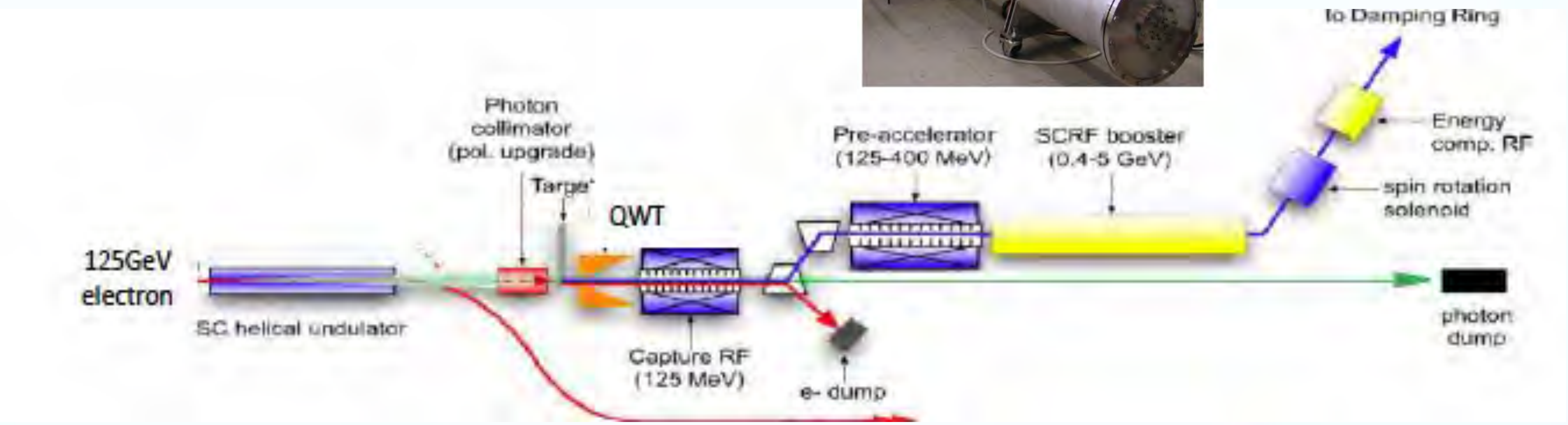
➢ **Luminosity upgrades**:
- More RF: factor 2 (1.35 -> 2.7x10^{34})
- Run = 500GeV machine at 250GeV, 10Hz: factor 2 (2.7x10^{34} -> 5.4x10^{34})
- Improves power efficiency

Sources: Positron production

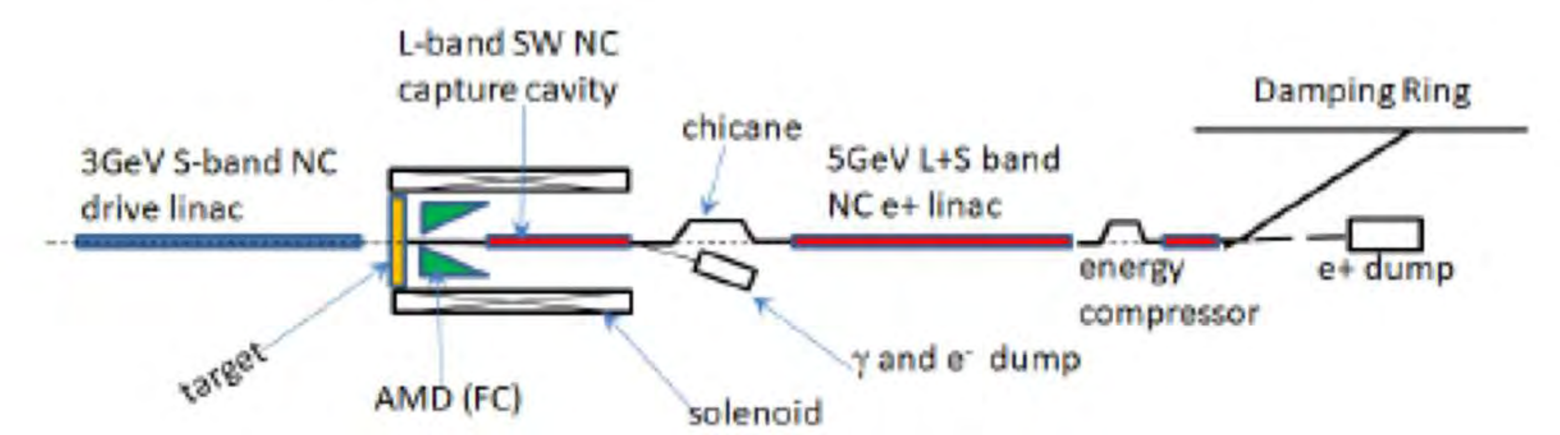
Two undulators in one cryomodule were tested at Daresbury. Both achieved nominal magnetic fields.

Two concepts considered:

- **SC helical undulators:** baseline, polarized, but e^- at 125 GeV complicated for commissioning/operation



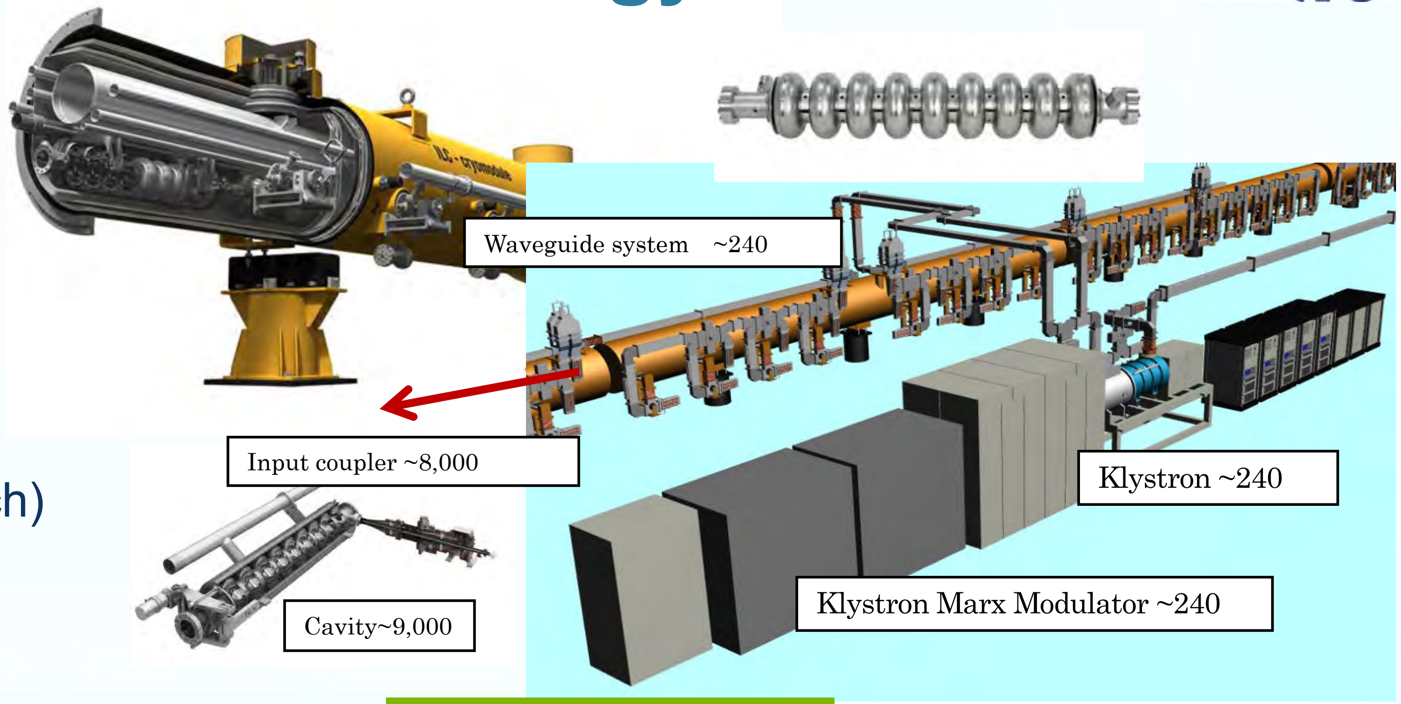
- **e^- driven source**: dedicated 3 GeV NC S-band TW e^- (pair production), not polarized, special tunnel infrastructure



R&D is ongoing in the framework of the ILC-IDT WG2

ILC Main Linac: SRF Technology

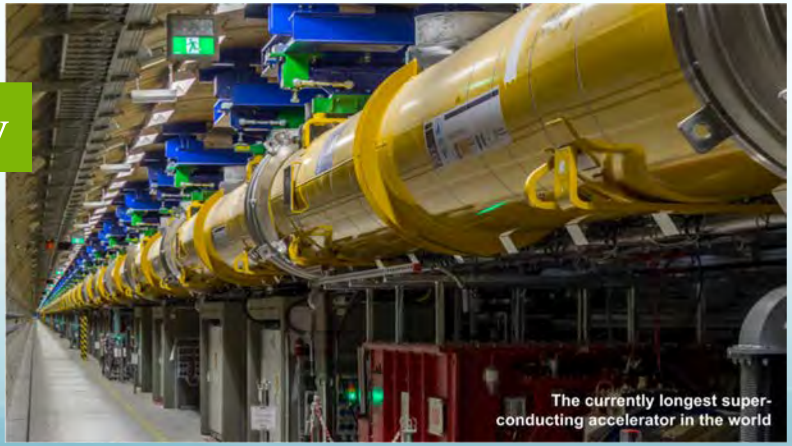
- ~8000 SC 9-cell **cavities**:
  1.3 GHz, 1.038m long, 31.5MV/m
- 9 cavities per 12m long **cryomodule**
- 10MW pulsed **klystron** per 4½ modules
- 2K operating **temperature**:
  4-6 cryo plants 19kW@4.5K
- **Pulsed operation**, 5Hz x 0.73ms (1312 bunch)



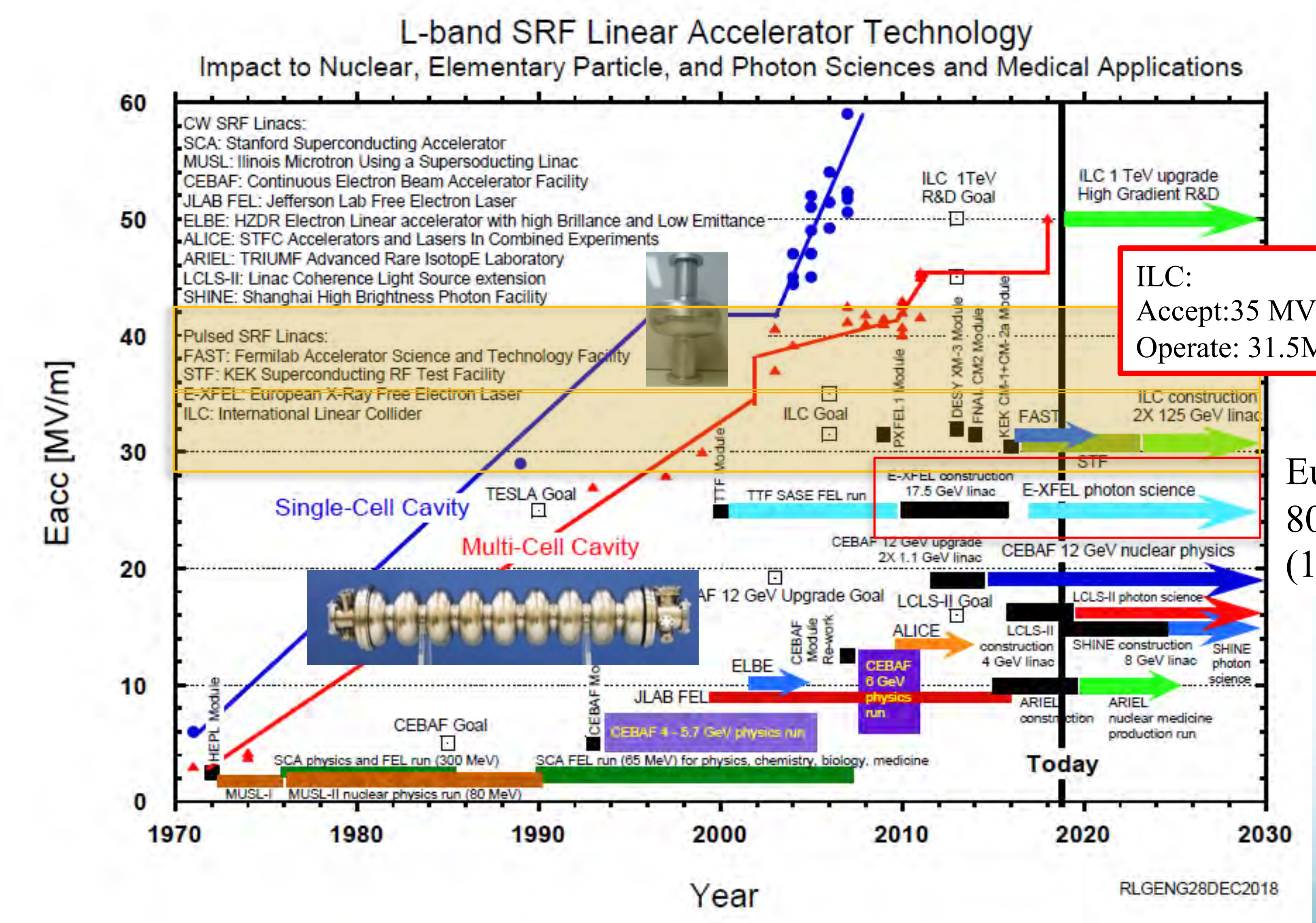
- European XFEL in operation
  100 cryomodules, 800 cavities
- LCLS-II, SHINE: Under construction / planned

ILC: artistic view

E-XFEL: Reality



Matured SRF technologies

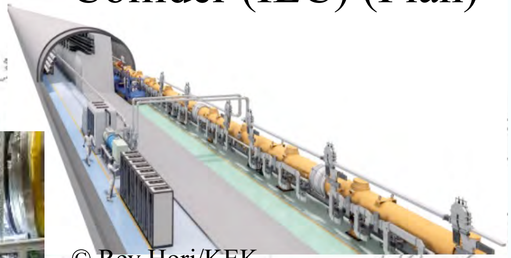


ILC:
Accept:35 MV/m +/-20%
Operate: 31.5MV/m +/-20%

European XFEL
800 cavities
(10% of ILC ML)

Worldwide large scale SRF accelerators

International Linear Collider (ILC) (Plan)



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Euro-XFEL
Operation started from 2017
-100 cyromodules
-800 cavities
-17.5 GeV (Pulsed)

DESY
LAL/Saclay
INFN

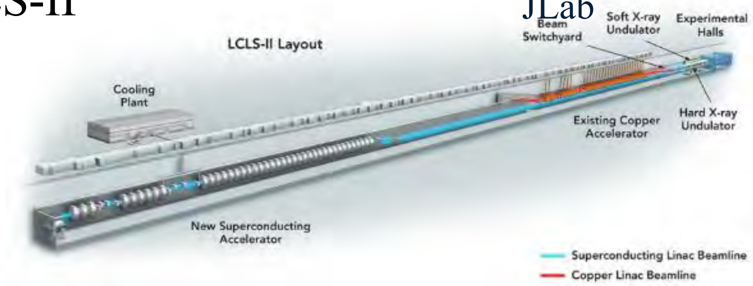
LCLS-II + HE (under construction)
35 + 20 cyromodules
-280 + 160 cavities
- 4 + 4 GeV (CW)

SLAC
FNAL
Cornell
JLab

ILC
-900 cyromodules
-8,000 cavities
-250 GeV (Pulsed)

KEK
SINAP

LCLS-II



SHINE (under construction)
-75 cyromodules
-~600 cavities
- 8 GeV (CW)

1.3GHz 9 cell cavity

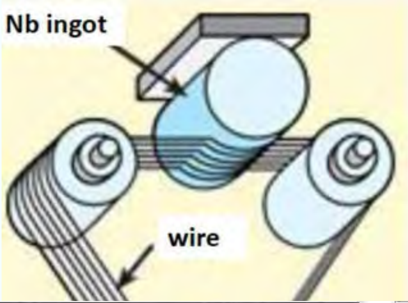
ILC Main Linac: Technology challenge

R&D to reduce cost fabrication and to push performance limits

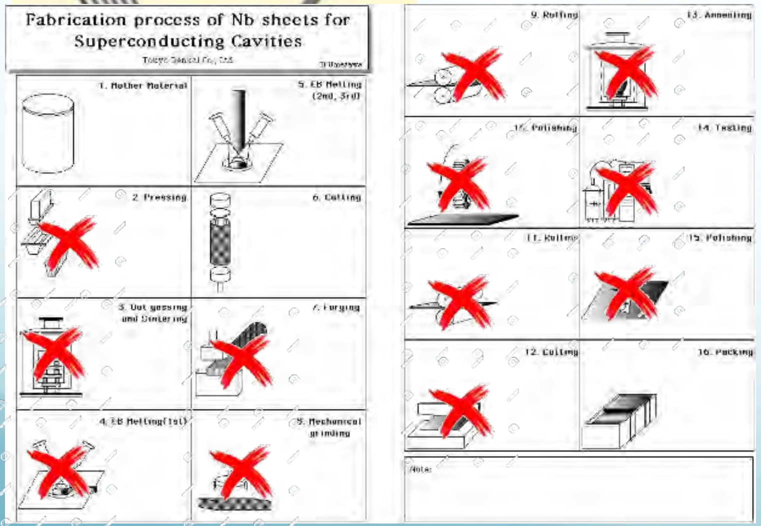
- **Niobium material/sheet preparation**:

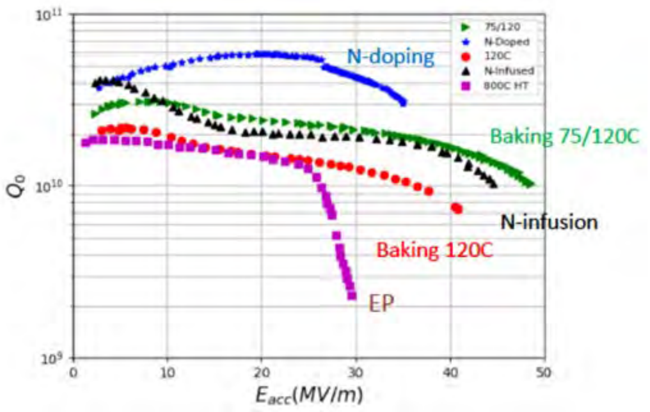
Large grain directly sliced from ingot (cost reduction), **Nb thin-film** coating on Cu based structure (HiPIMS), or Nb_3Sn in Nb or Cu

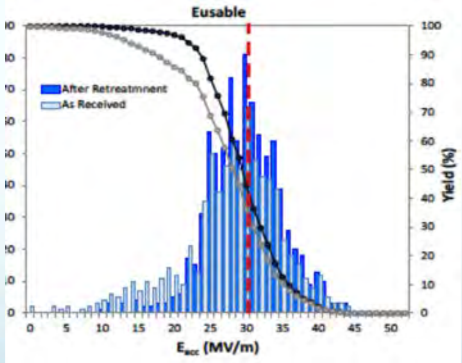
- **SRF cavity fabrication for high-gradient** (N doping well stablished), **high-Q (**N infusion, low-T baking) and **high-yield**.



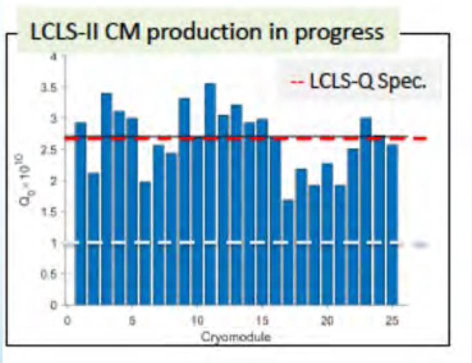
Niobium ingot







European XFEL: 29 ± 5.1 MV/m

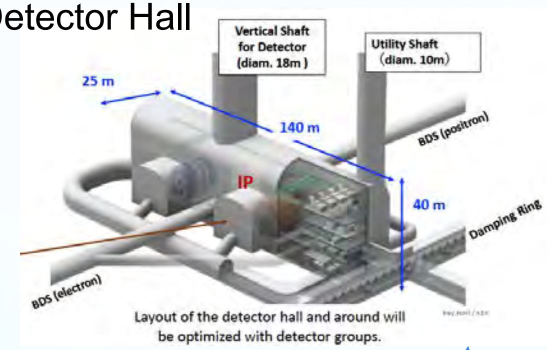


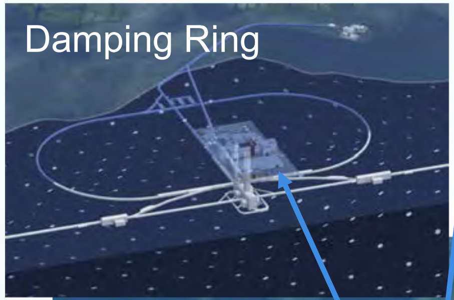
LCLS-II: 18-21 MV/m
Q>2.7 10^{10}

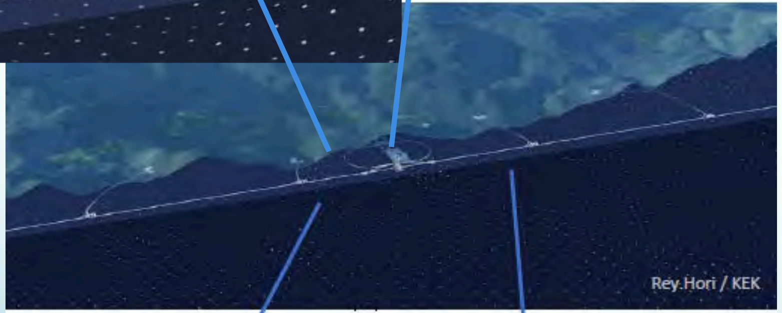
Mass production still a challenge , R&D in the framework of the ULC-IDT WG2

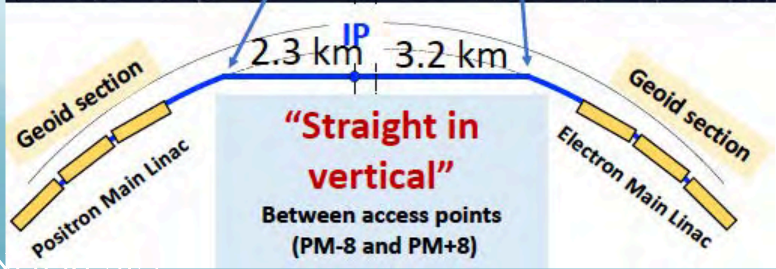
ILC Site Selection and Civil Engineering

Detector Hall





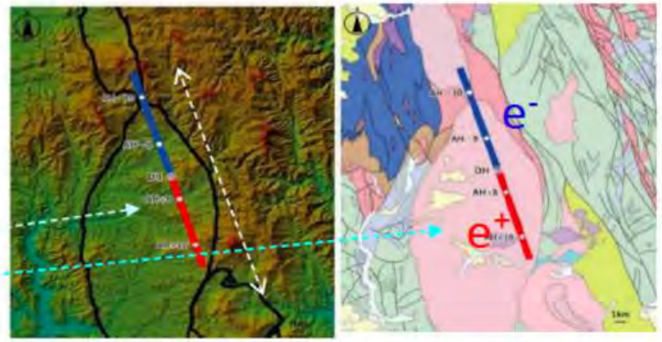




Kitakami mountains

① ILC Location

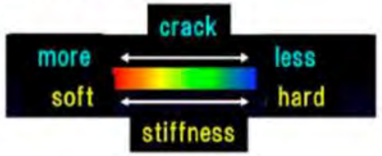
ILC accelerator area : inside the granite rock bodies
→ inside black curves (left)
→ in the pink color (right)
→ possible up to 50 km

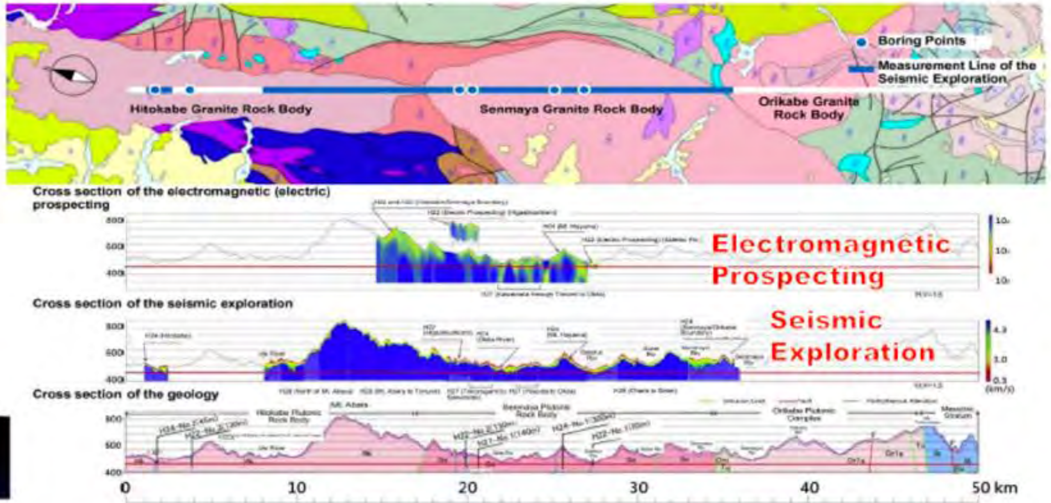


→ On-going jobs : Optimal accelerator placement, considering surface environment, land-use and land-acquisition

② Geological Surveys

- Electric Prospecting (crack)
- Seismic Exploration (stiffness)
- Boring Survey
- Borehole Camera
- Measurement of Initial Stress of the Ground





→ no issues from previous surveys

→ requiring : additional surveys around access tunnel head and access tunnel inside for detailed designing

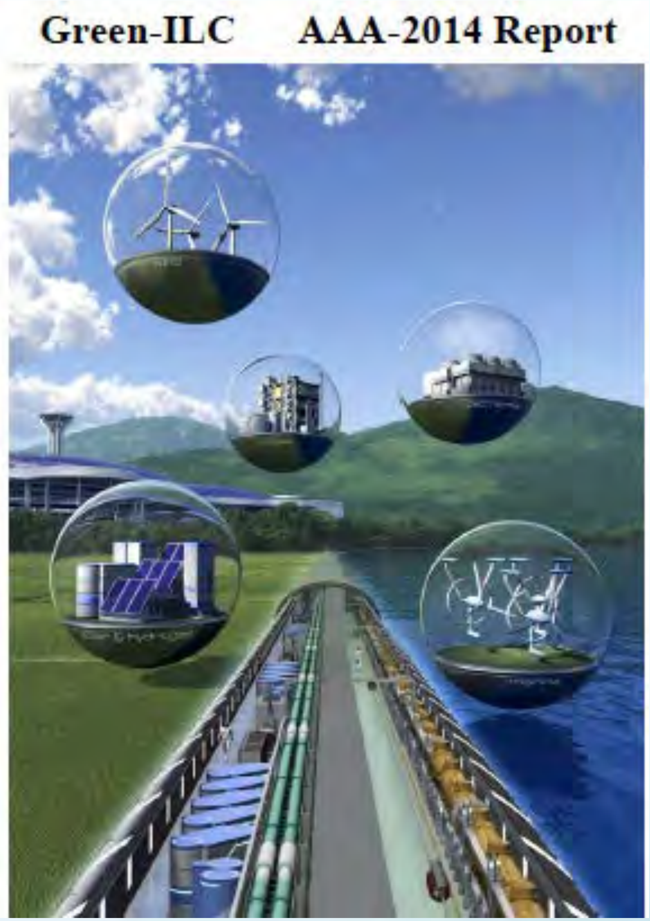
“Green ILC” and Carbon neutrality

Although SRF has been adopted, the AC power consumption for ML part is <50%, what is a total of 110 MW

- **“Green ILC”**: Past efforts include increasing the efficiency of accelerators (SC, klystron) https://green-ilc.in2p3.fr/documents/

- **Carbon neutrality**: Common challenge for all future HEP accelerators. The use of SC will contribute to carbon neutrality in the future.

Work is ongoing to study these issues

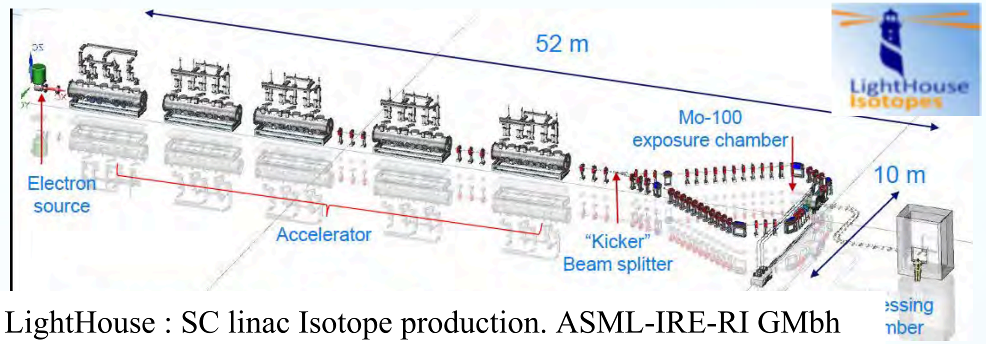


Extending the Physics potentiality of ILC and applications of ILC technology

- Experiments using the **main dump**
- Experiments using **Extracted beam**
- **Far detector**

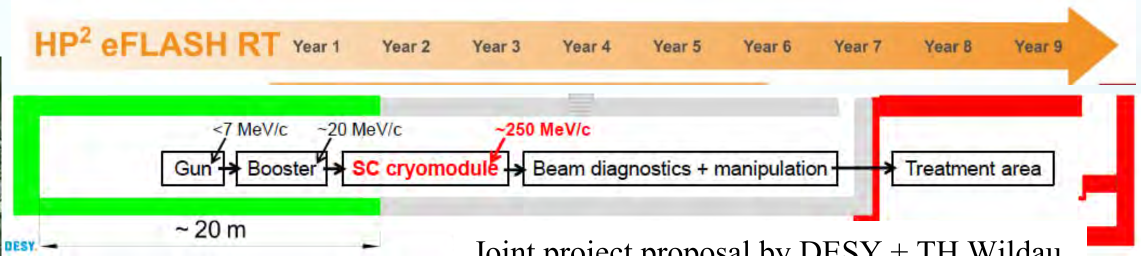
- ILC technology for different applications
  - XFEL accelerators: EuXFEL, LCLSII, SHINE
  - Medical linacs
  - Industrial linacs
  - etc

1.3GHz 9 cell cavity

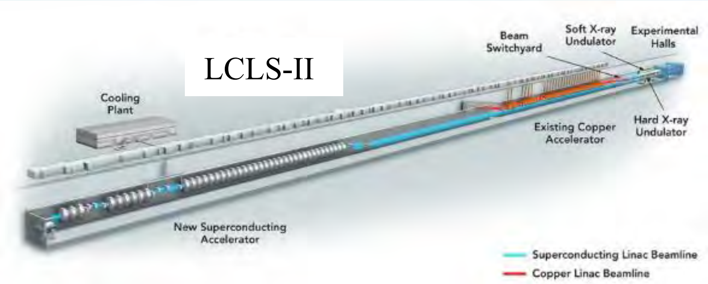


LightHouse : SC linac Isotope production. ASML-IRE-RI GMbh

SCRF compact for water treatment

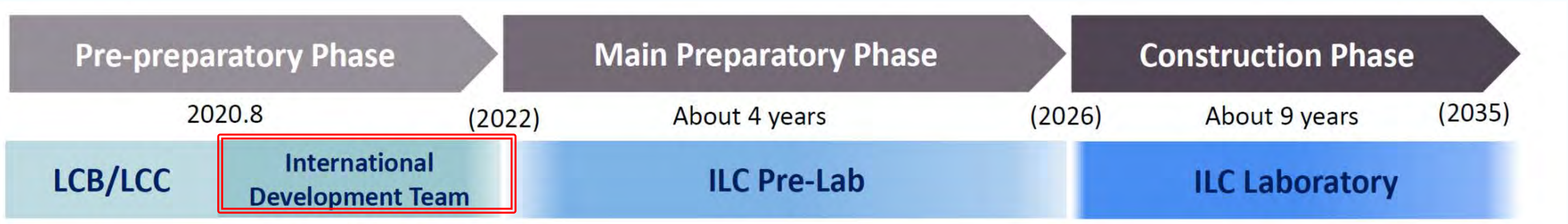


Joint project proposal by DESY + TH Wildau



SHINE under construction

International Development Team (IDT)



IDT: to prepare for smooth transition to the ILC Pre-lab

- Prepare a proposal for the organization and governance of the ILC Pre-Lab
- Prepare the work and deliverables of the ILC Pre-laboratory and workout a scenario for contributions with national and regional partners

ILC Timeline

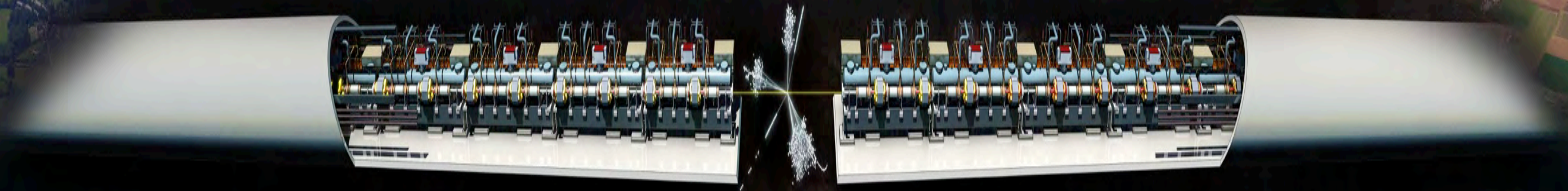
- **International Development Team** (IDT) prepares **Pre-Lab**
- 4 year Pre-Lab (hosted by KEK, Japan) phase for **R&D**, **Engineering Design Report**, Construction preparation
- **ILC Laboratory** (international): 10 year construction phase

2022 2026

	IDT	ILC Pre-Lab				ILC Lab.										
	PP	P1	P2	P3	P4	1	2	3	4	5	6	7	8	9	10	Phys. Exp.
Preparation CE/Utility, Survey, Design Acc. Industrialization prep.																
Construction																
Civil Eng.																
Building, Utilities																
Acc. Systems																
Installation																
Commissioning																
Physics Exp.																

Following a four-year ILC Pre-Lab phase, ILC construction will continue for about ten years.

CLIC accelerator: Technology update

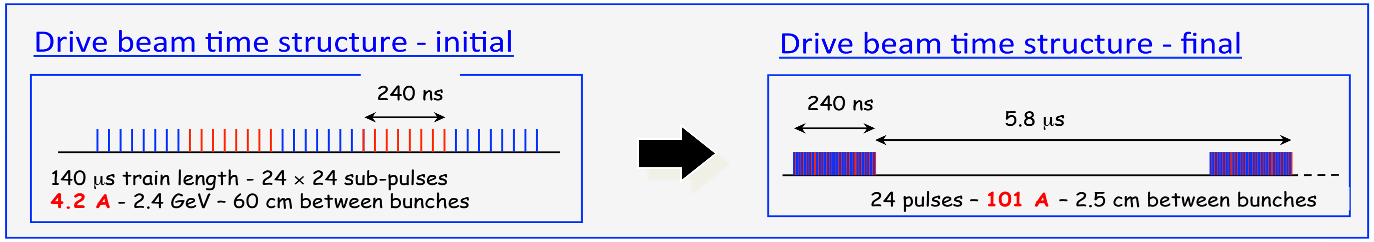


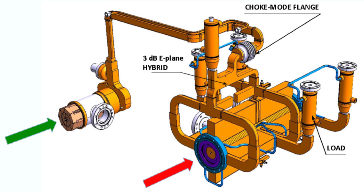
http://clic-study.web.cern.ch/

Compact Linear Collider

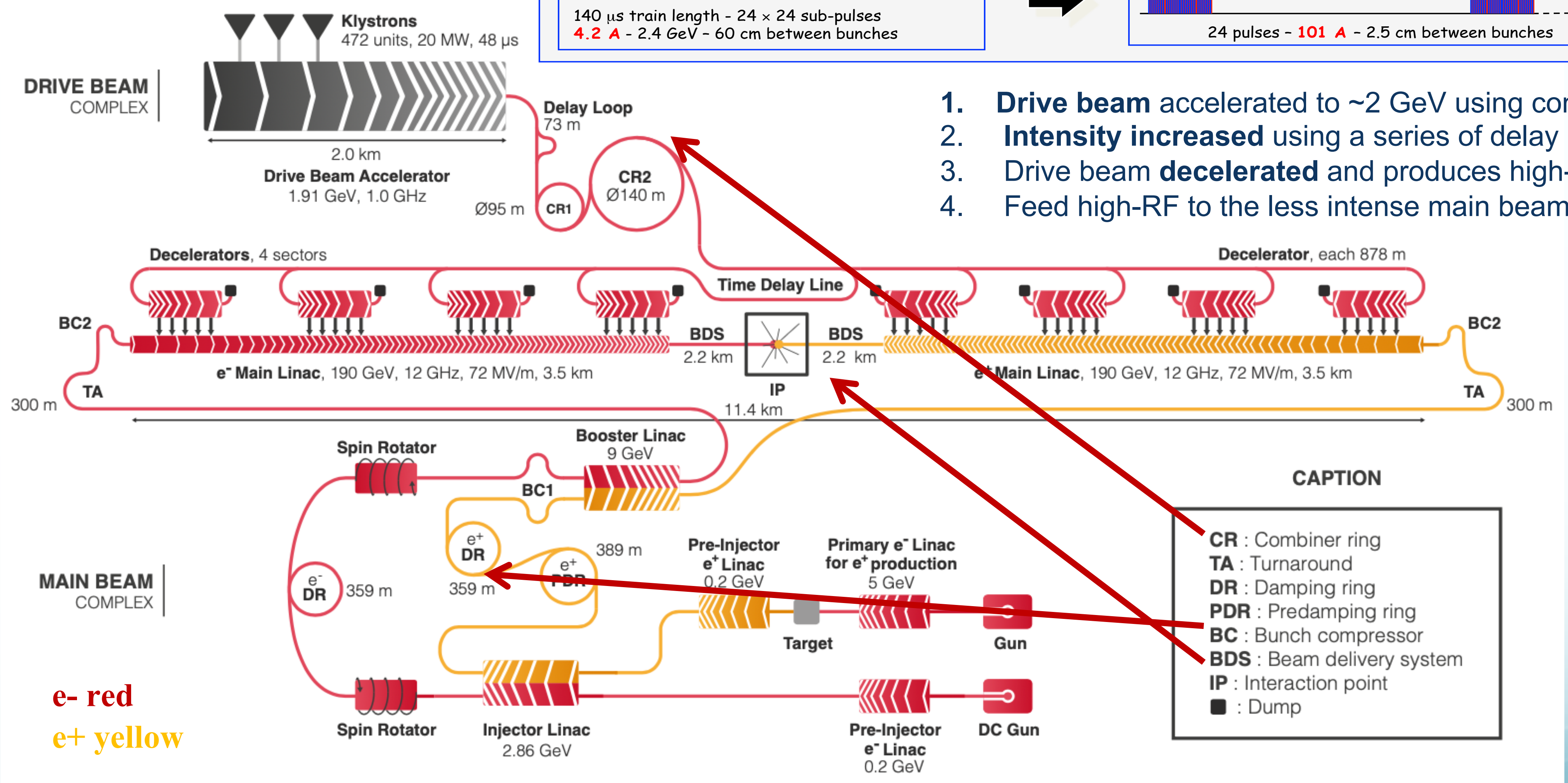
CLIC accelerator sequence and main area systems

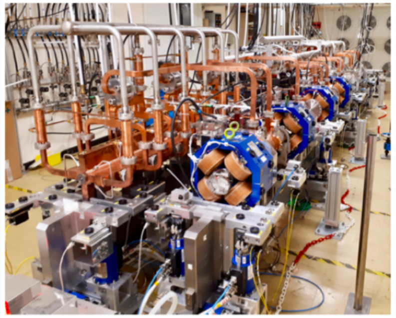
CLIC 380 GeV

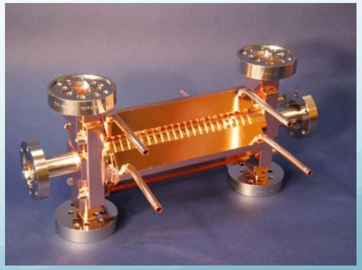




1. **Drive beam** accelerated to ~2 GeV using conventional klystrons
2. **Intensity increased** using a series of delay loops and combiner rings
3. Drive beam **decelerated** and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides





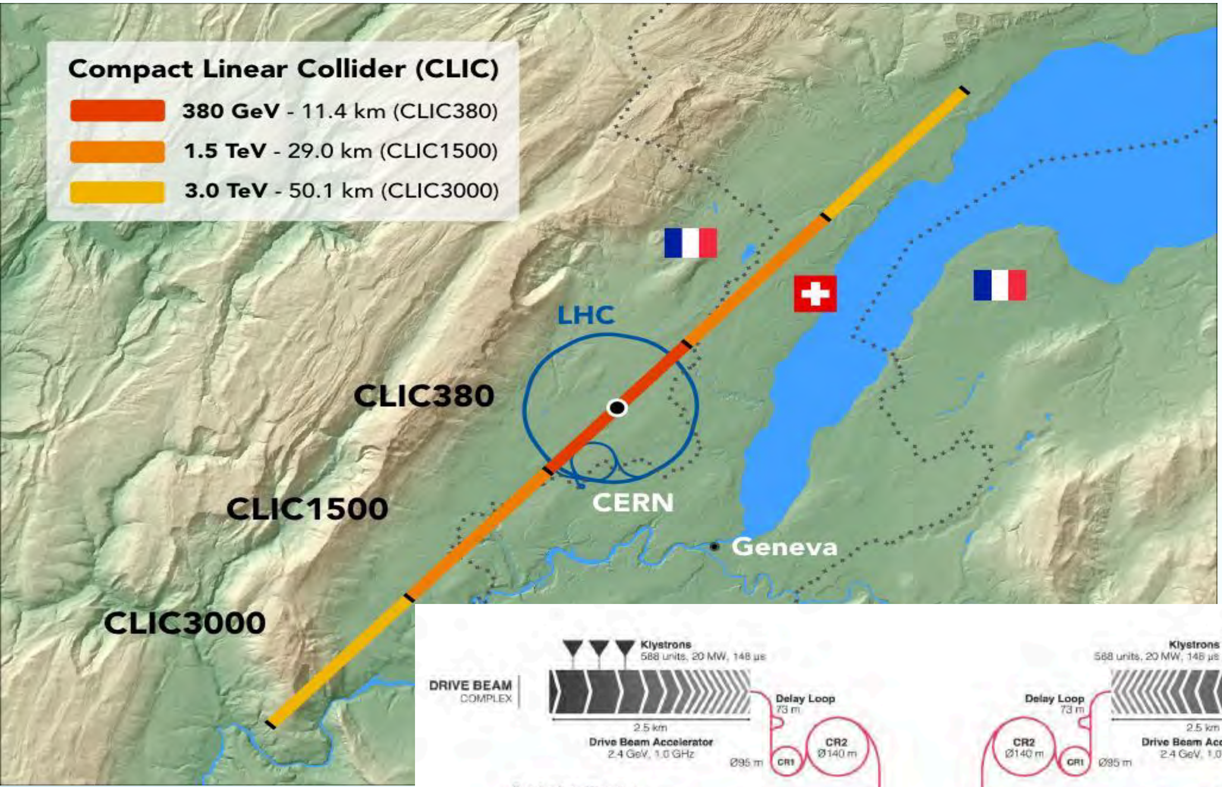


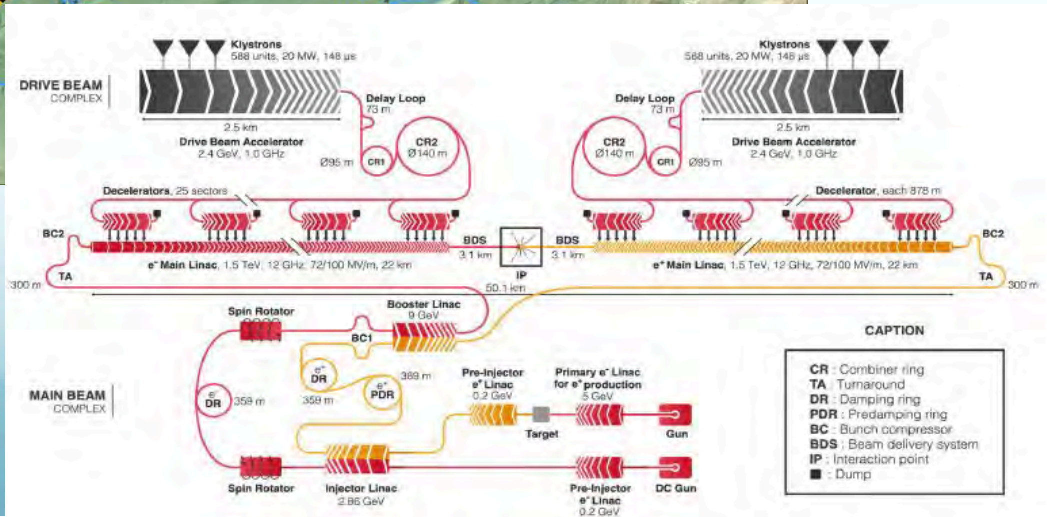
CLIC updated parameters and stages

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2} s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2} s^{-1}	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

CLIC updated parameters and upgrades

➢ Possible **energy upgrades**: 1.5 and 3TeV need tunnel extension, CERN site: 50km long, sufficient for 3 TeV

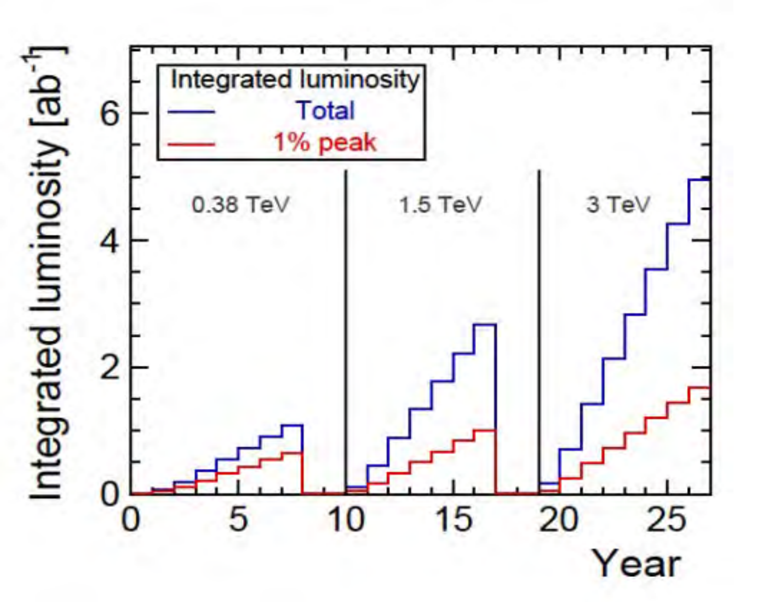




CLIC 3 TeV

➢ **Luminosity upgrades**: Baseline polarisation scenario adopted: electron beam (–80%, +80%) polarised in ratio (50:50) at √s=380GeV; (80:20) at √s=1.5 and 3TeV. Doubling frequency (50 Hz ->100 Hz, but double the luminosity, with power +50 MW and cost ~5% increases.

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

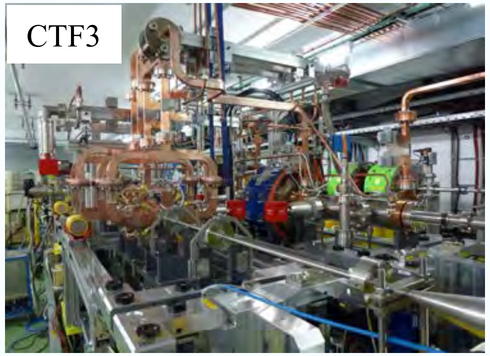


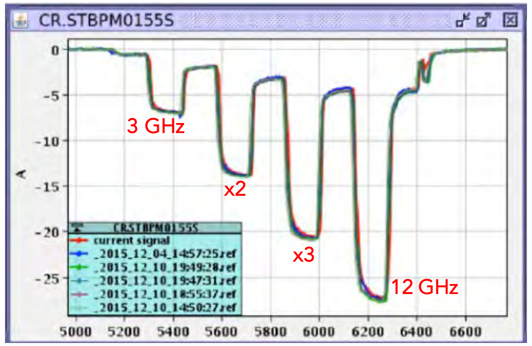
CLIC Main Linac: NCRF Technology

- ML **NC RF X band copper cavities** (20,500 structures)
- **Drive-beam based machine** (PET structures), two beams acceleration demonstrated, CTF3 (CLIC Test Facility at CERN) program addressed all drive-beam production issues.
- **Klystron-powered** option also studied (high-efficiency)
- **High-current drive** beam bunched at 12 GHz
- Achieved **100 MV/m gradient** in main-beam cavities

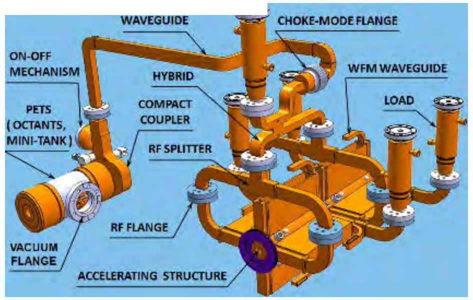
- X-band technology developed and verified with prototyping, test-stands, and use in smaller systems
- Two C-band XFELS (SACLA and SwissFEL – the latter particularly relevant) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs

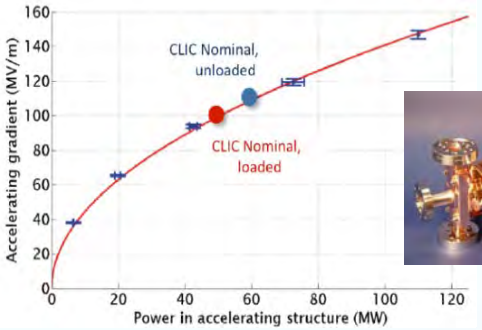
CTF3





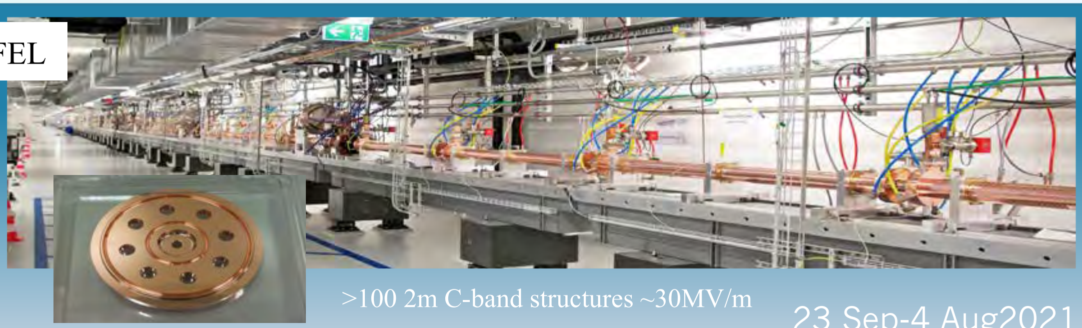
Main linac RF unit





Xboxes test stand

SwissFEL



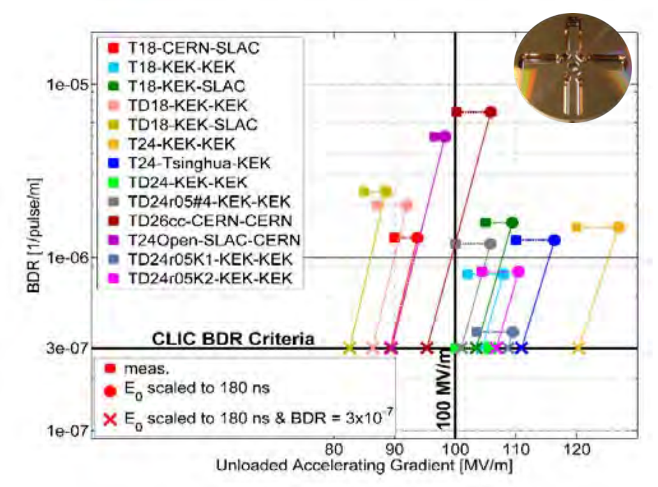
>100 2m C-band structures ~30MV/m

Details in PIP, DOI: http://dx.doi.org/10.23731/CYRM-2018-004

CLIC Main Linac: Technology challenge

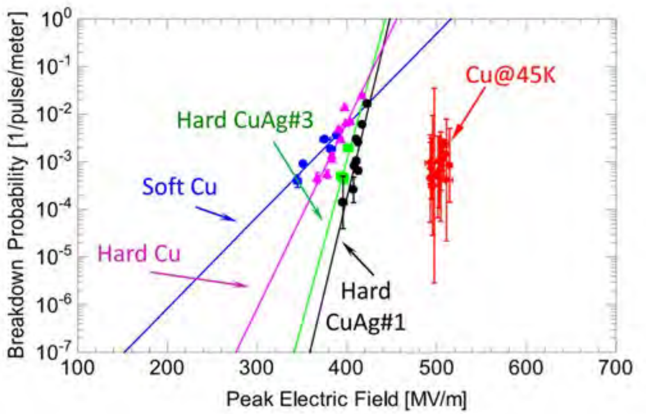
R&D to reduce cost fabrication and to push performance limits

- **Fundamental process for high-fields and material dynamics:** Understanding the limits by: Field emission, Vacuum arcing (breakdown) and Fatigue due to pulsed surface heating.



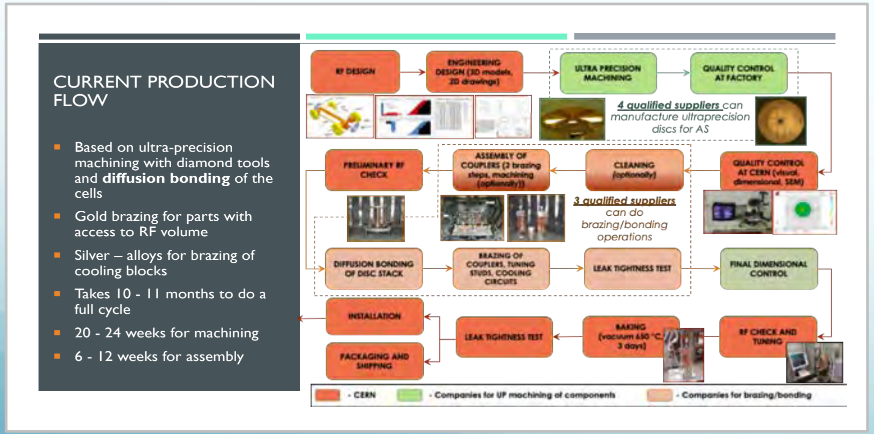
XBox-3

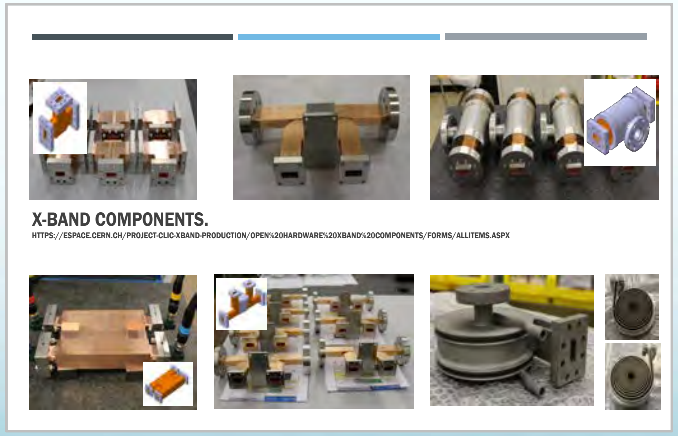
XBox-2



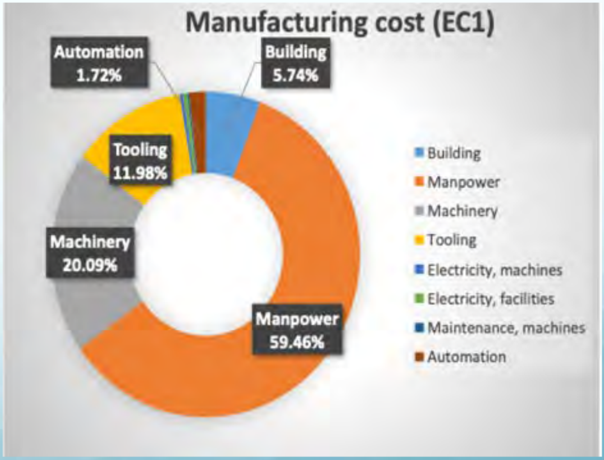
Cryo-cooled copper cavity, SLAC

- **X band RF structures fabrication:** Processes, Developments (rectangular disks, brazing, halves), Fabrication capacity and Components for systems.





Industrial questionnaire: Based on the companies feedback, the preparation phase to the mass production could take five years. Capacity clearly available.

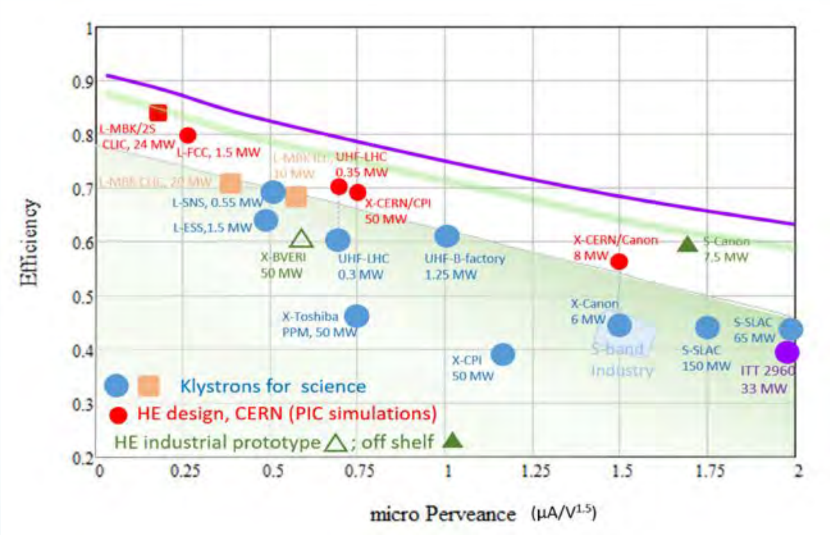


Industrialization and mass production still a challenge

CLIC Main Linac: Technology challenge

R&D for high-efficiency klystrons

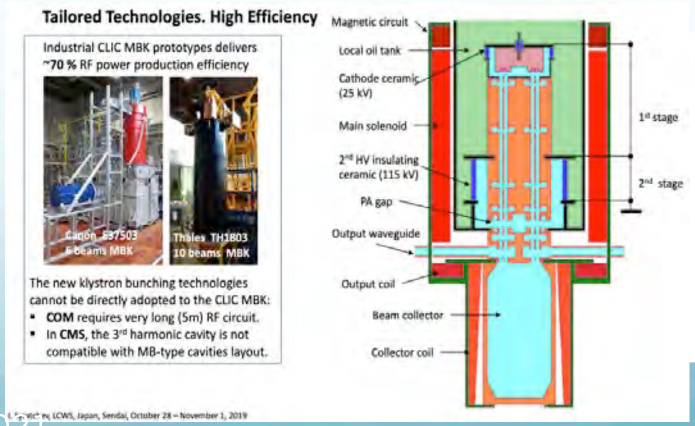
- The CERN **high-efficiency klystron** program develops klystrons for numerous accelerators including LHC, CLIC, FCC-ee and ILC.
- For **CLIC**, this includes the L-band and X-band sources

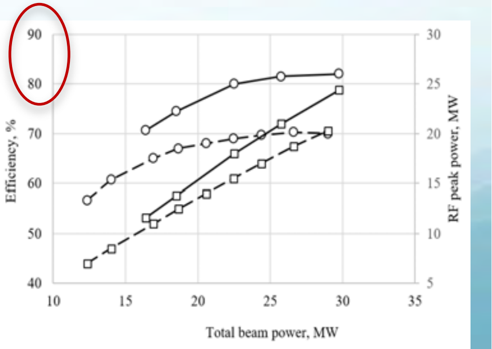


High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).

50 MW	VKX-8311A	[illegible] (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / KlyC
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35/0.6
RF circuit length, m	**0.32**	**0.32**

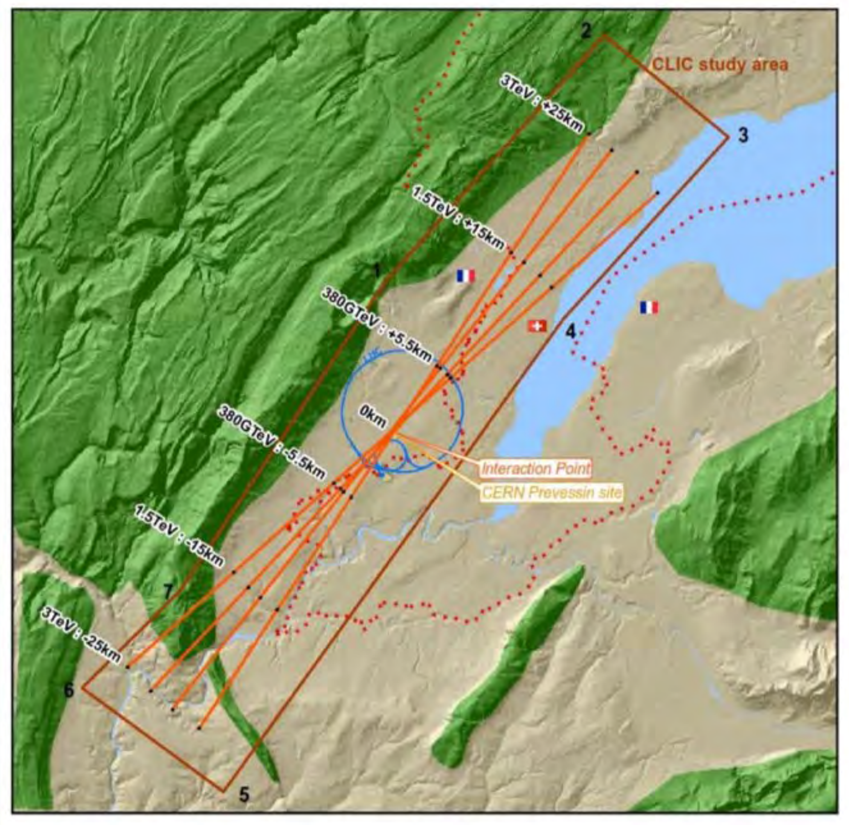
8-10 MW	E37113 at factory	[illegible] (CERN/Canon)
Voltage, kV	154	154
Current, A	93	90
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	58
Efficiency, %	42	57/ FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	**0.127**	**0.127**





Drivebeam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs total beam power.
https://ieeexplore.ieee.org/document/9115885

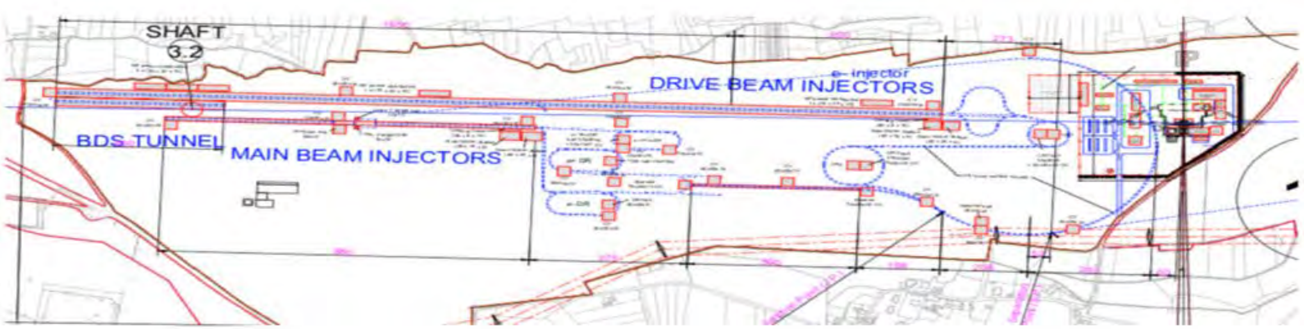
CLIC Site Selection and Civil Engineering

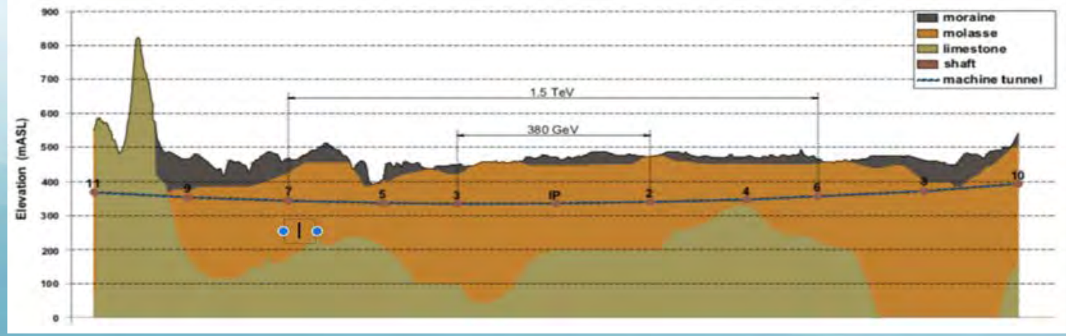


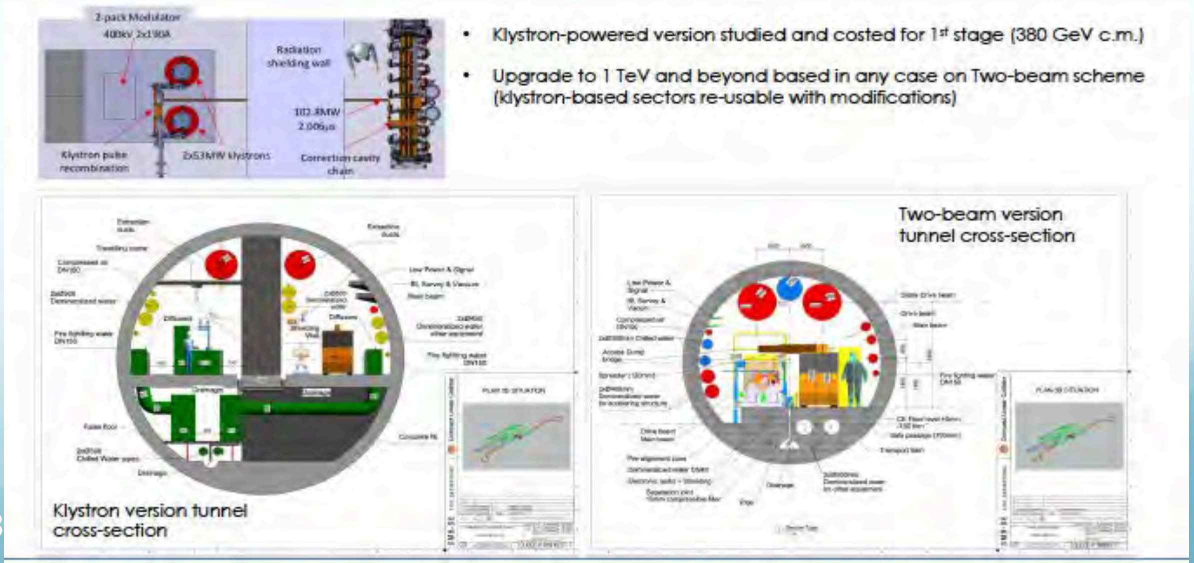
Important effort within:

- Civil engineering
- Electrical systems
- Cooling and ventilation
- Transport, logistics and installation
- Safety, access and radiation protection systems

Crucial for cost/power/schedule

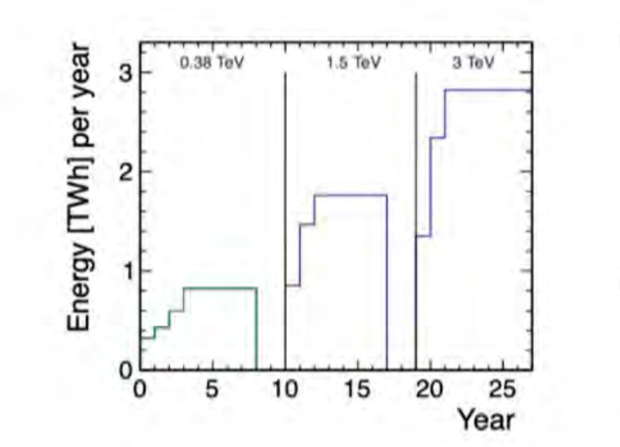




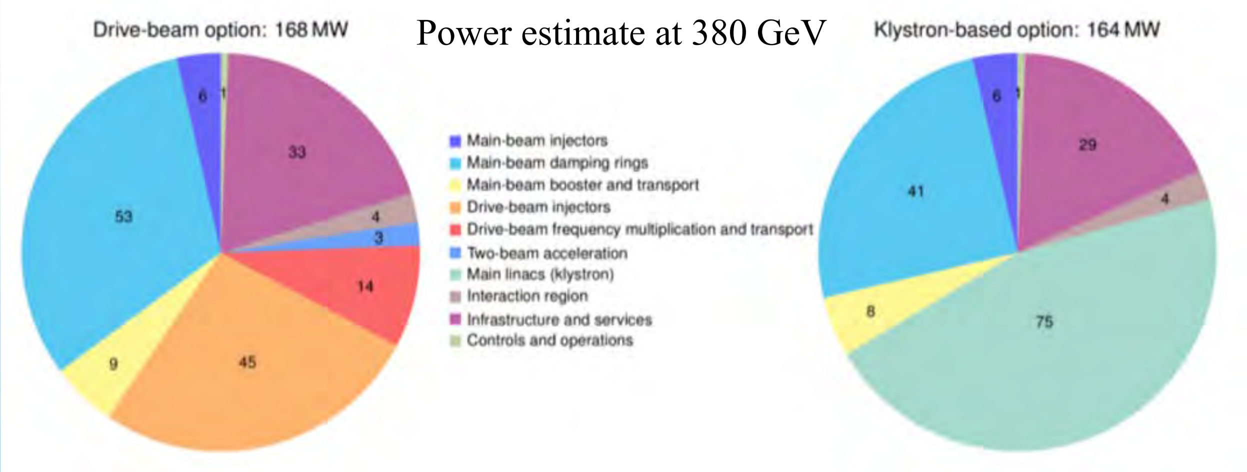


“Green CLIC” and Carbon neutrality

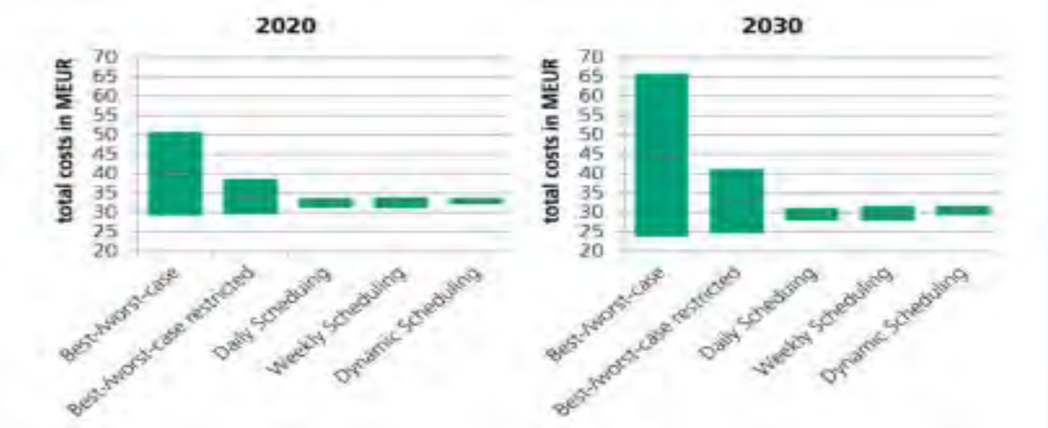
Collision Energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17



- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimisation, etc
- Further savings possible, main target damping ring RF and improved L-band klystrons for drivebeam



- Energy studies:
  - Running when energy is cheap

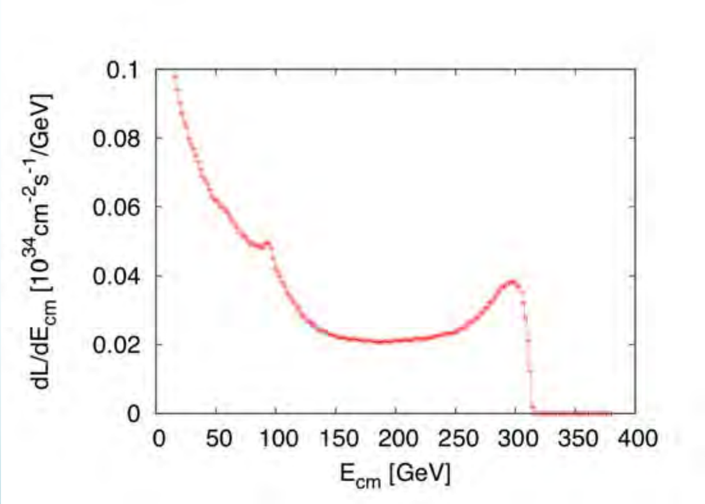


Relative energy cost by no scheduling, avoiding the wintermonths (restricted), daily, weekly and dynamic scheduling. Central values of the ranges shown should be considered best estimates. The absolute cost scale will depend on price, contracts and detailed assumption about running times, but the relative cost differences indicate that significant cost-reductions could be achieved by optimizing the running schedule of CLIC to avoid high-energy cost periods (Fraunhofer)

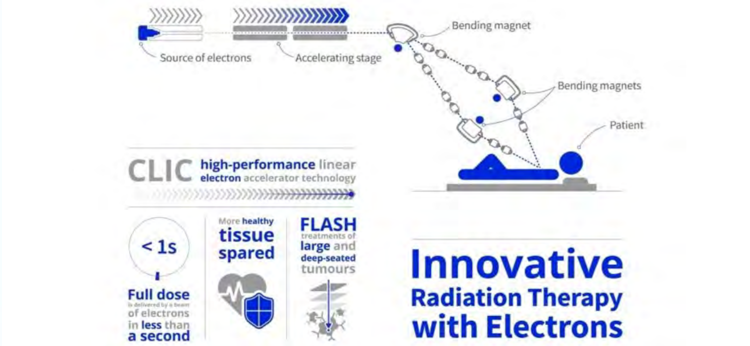
- Renewable energy (carbon footprint)
- Recovering energy

Extending the Physics potentiality of CLIC and applications of CLIC technology

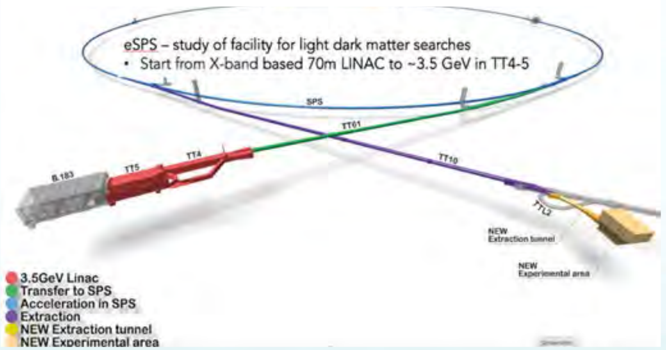
- Further work on luminosity performance, possible improvements and margins, operation at the Z-pole and gamma-gamma are ongoing.



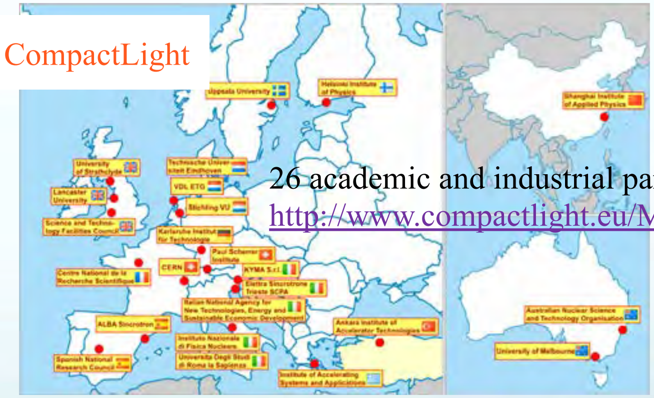
- CLIC technology for different applications
  - EU co-funded FEL design study
  - 1 GeV linac at INFN-LNF
  - Medical linacs
  - ICS
  - etc



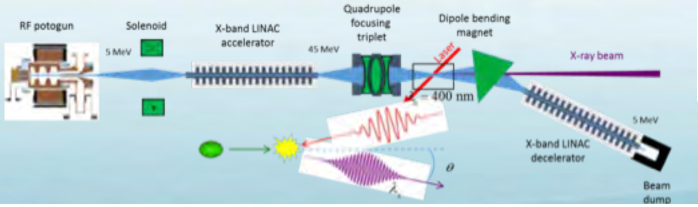
CERN: eSPS study (3.5 GeV X-band linac)



CompactLight



26 academic and industrial partners:
http://www.compactlight.eu/Main/HomePage



Eindhoven University SMART*LIGHT Compton Source

INFN Frascati advanced acceleration facility
EuPRAXIA@SPARC_LAB

CLIC Timeline

Project Readiness Report as a step toward a TDR – for next ESPP

Assuming ESPP in 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

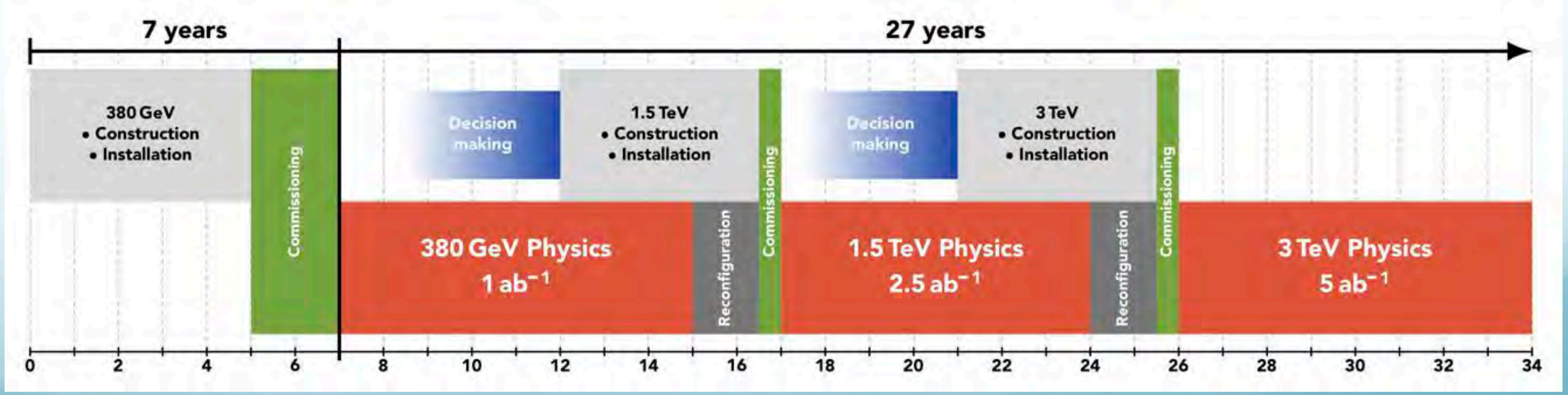
➢ Focusing on:

- **The X-band technology** readiness for the 380 GeV CLIC initial phase
- **Optimizing the luminosity** at 380 GeV
- **Improving the power efficiency** for both the initial phase and at high energies

➢ More details:

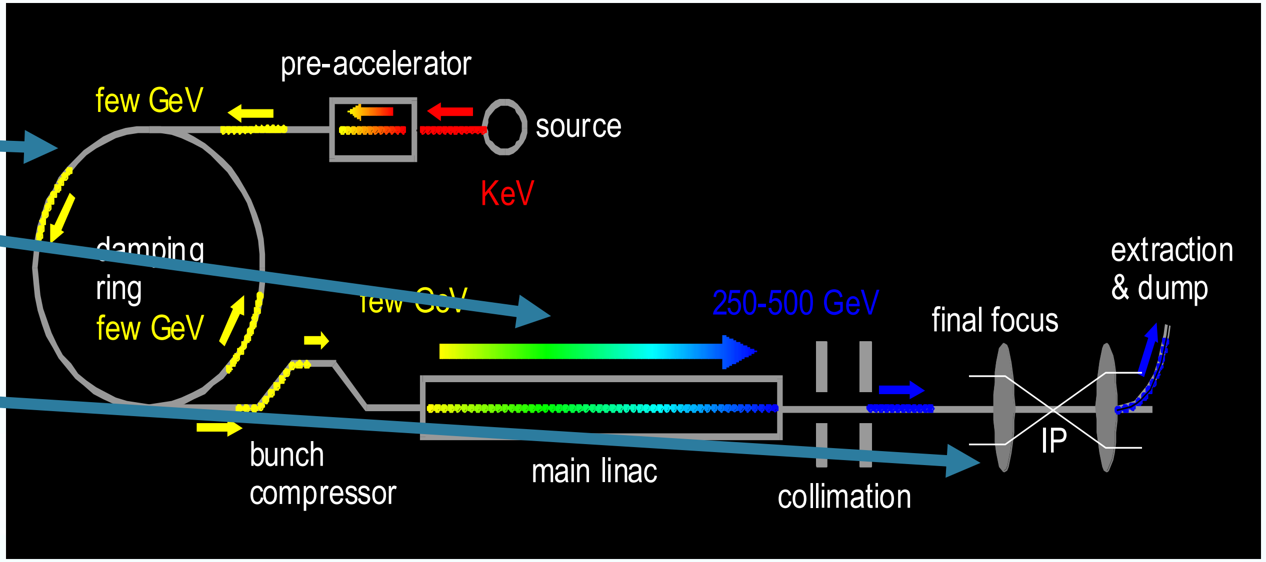
- **X-band studies**: Structure manufacturability and optimized conditioning, interfaces to all connecting systems for large scale production, designs for and support of use in applications from the 1 GeV linac at LNF to medical linacs
- **Luminosity:** beamdynamics studies and related hardware optimisation for nano beams from damping rings to final focus (mechanical and thermal stability, alignment, instrumentation, vacuum systems, stray field control, magnet stability, etc)
- **Improving** damping ring and drive beam RF **efficiency,** study parameter changes to reduce power at multi-TeV energies maintaining high luminosities

➢ **Technology Driven Schedule** with a preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)



Nanobeam Systems: what is needed to get nanobeam sizes?

- **Small emittances**
  - from Damping Ring (DR)
  - emittance preservation in linac (wakefields, spurious dispersion)
- **Final Focus System**
  - providing focalization
  - minimizing aberrations and SR effects

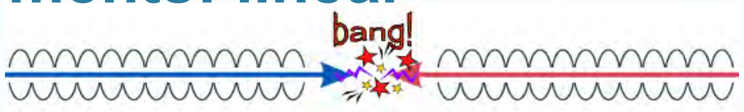


Generic LC (at least one half of it)

- **Tuning recipe**
  - scanning orthogonal tuning knobs
  - beam-beam deflection scans or luminosity dither feedback
- **Stability**
  - pulse-to-pulse orbit stability (DR instability, wakefileds, kicker)
  - pulse-to-pulse beam size / emittance stability

Nanobeams past and recent achievements: linear

*1998
**1997
*** 2016



	Units	SLC		FFTB		ATF2		ILC	CLIC
		design	achieved*	design	achieved**	design	standard***		
E_{cm}	[GeV]	50	50	50	46	1.3	1.3	250	380
$\mathcal{L}$	[10^{34} cm^{-2} s^{-1}]	0.0006	0.00014					1.35	1.5
f_{rep}	[Hz]	180	120			3.12	3.12	5	50
n_b	1					1 - 20	1	1312	352
N_e	[10^{10}]	7.2	3.7	1.2		1.0	0.1	2.0	0.52
σ_b	[μm]	1000	1000	500	500	7000	7000	300	70
$\gamma\epsilon_x$	[nm]	42000	54000	32000	30000	5000	5000	5000	950
$\gamma\epsilon_y$	[nm]	42000	10000	3000	1000	30	30	35	30
σ_x^*	[nm]	1650	1840	1000	1700	9000		516	149
σ_y^*	[nm]	1650	980	60	70	37	41	7.7	2.9
β_x^*	[mm]	5	2.8	0.1	10	4	40	13	8
β_y^*	[mm]	5	1.5	3.0	0.1	0.1	0.1	0.41	0.1

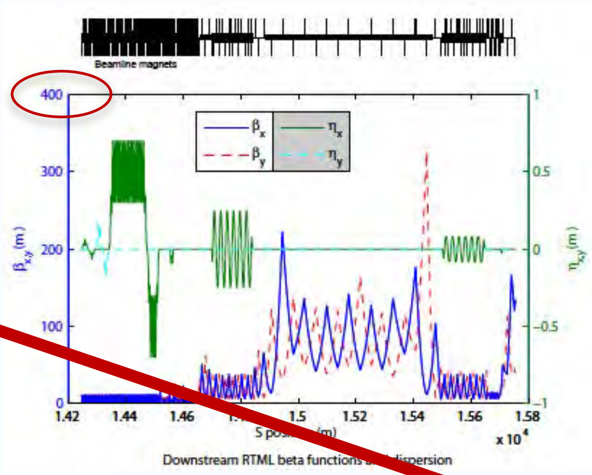
Nanobeam Systems: FFS designs

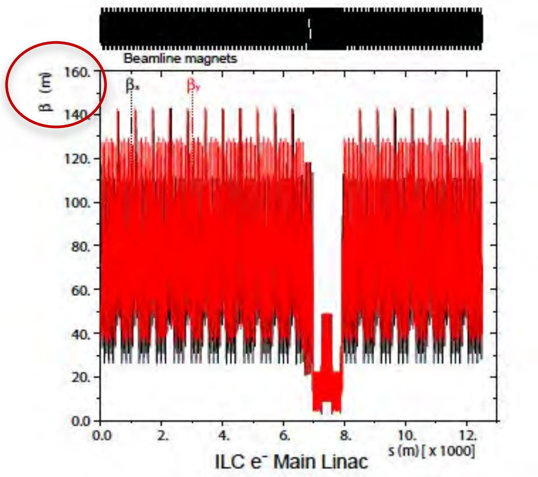
FFS is among the most challenging sections of a LCs

- **Chromaticity correction** is the **main problem**
  - **Interleaved** sextupoles (SLC)
  - **Non-interleaved** sextupoles (FFTB)
  - **Local chromaticity correction** (ATF2)

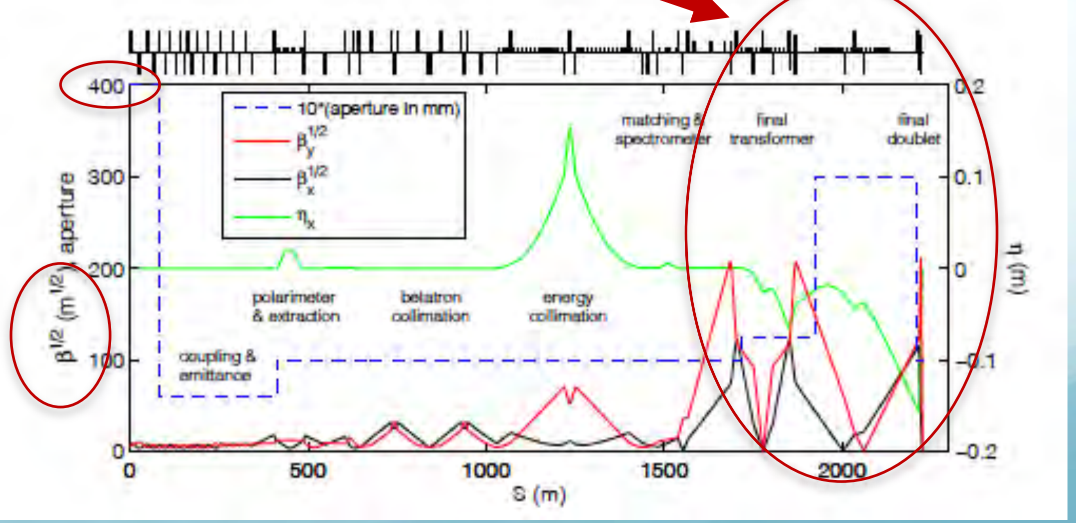
- **Very-large** β and the presence of **nonlinear elements** make it **extremely sensitive** to any kind of **imperfections.**

ILC optics



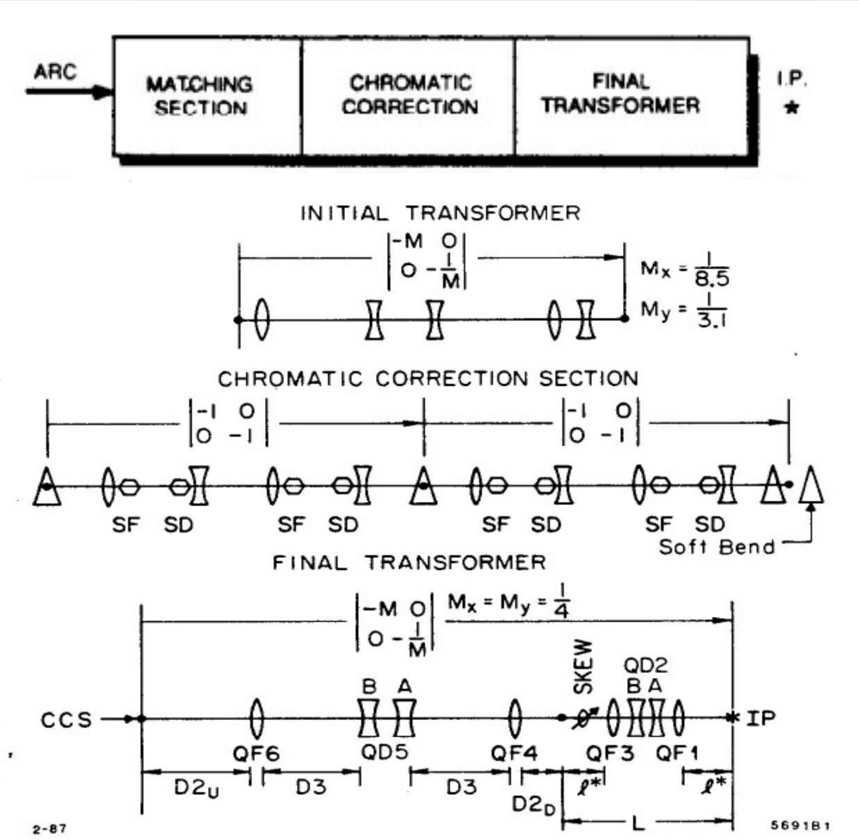


Beam Delivery System



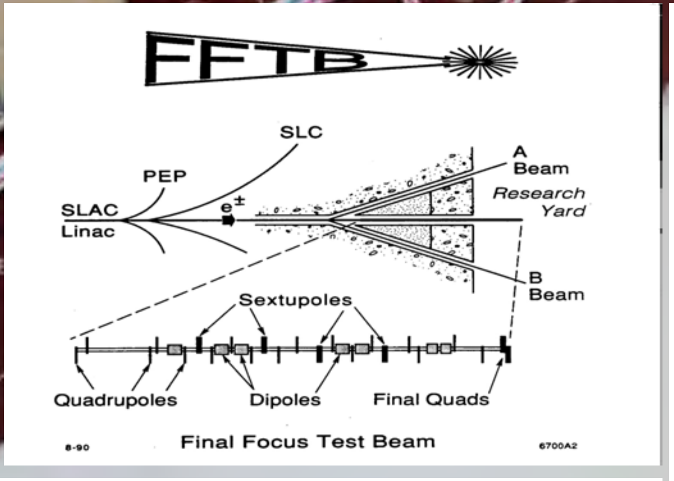
Nanobeam Systems: FFS designs

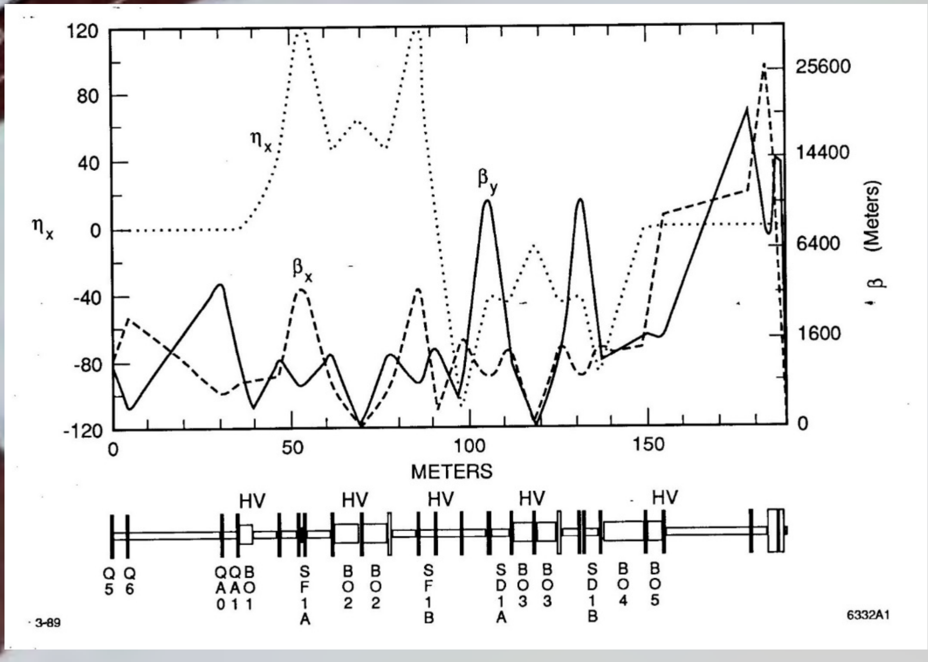
- **SLC type** (interleaved sextupoles)



SLC final focus, J. Murray, K. Brown T. Fieguth, PAC1987

- **FFTB type** (modular, non-interleaved sextuples)





Non-interleaved modular final focus for the **FFTB**, K. Oide, IEEE PAC 1989

ATF2 the ILC-CLIC FFS testbench

ATF/ATF2: Accelerator Test Facility

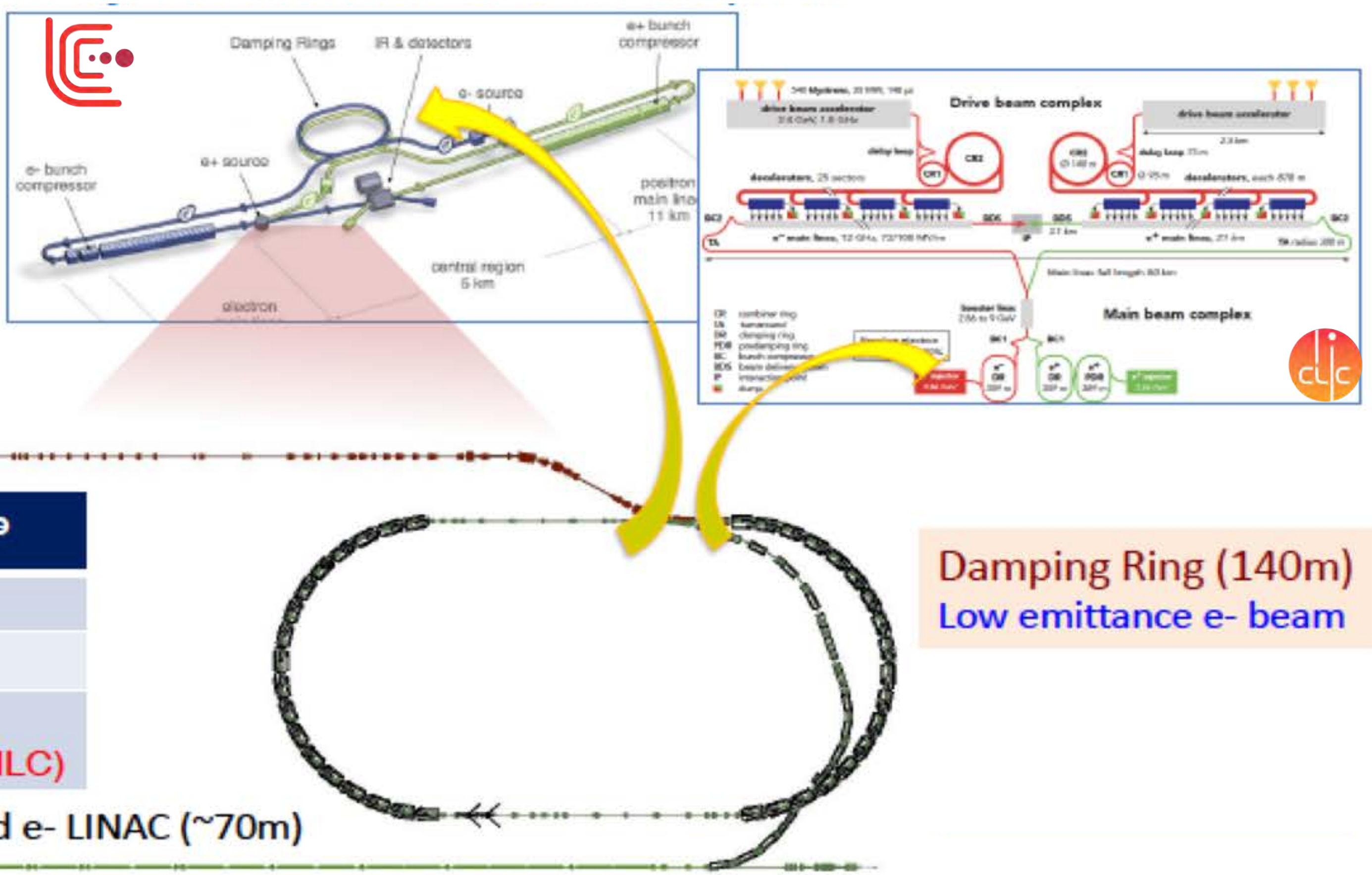
Courtesy: N. Terunuma

Develop nano-beam technology for ILC/CLIC

- Goal: Realize small beam-size and theStabilize beam position

FF: Nano beam-size

	B Energy [GeV]	Vertical Size
ILC-250	125	7.7 nm
CLIC-380	190	2.9 nm
ATF2 (achieved)	1.3	41 nm (-->8 nm eq. at ILC)



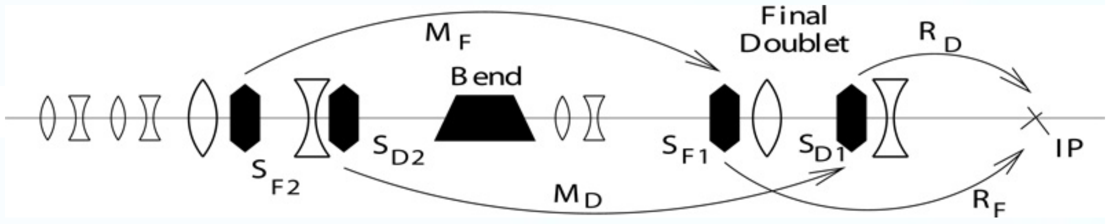
A. Yamamoto, 190513bb

8

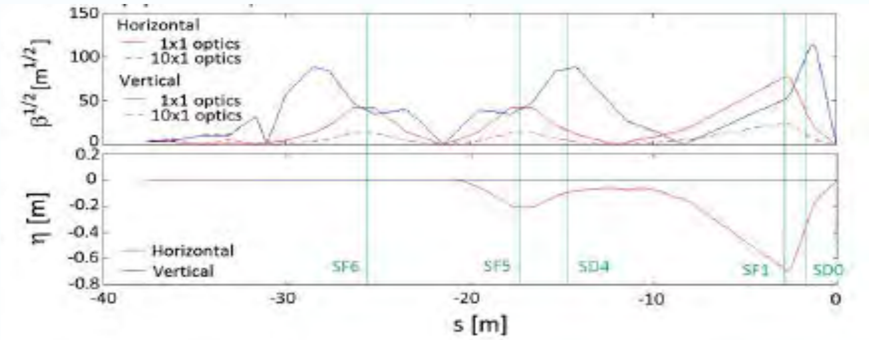
Nanobeam Systems: FFS designs

➢ **Compact ILC/CLIC/ATF2** local chromatic correction

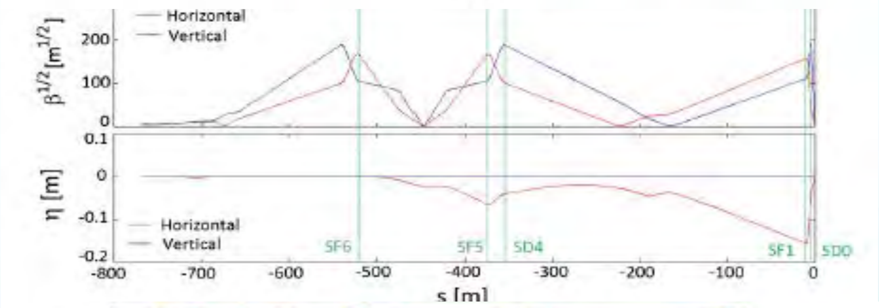
	Units	ATF2	ILC	CLIC
E_{cm}	[GeV]	1.3	250	380
$\mathcal{L}$	[10^{34} cm^{-2} s^{-1}]		1.35	1.5
f_{rep}	[Hz]	3.12	5	50
$n_{bunches}$	1	1 - 20	1312	352
N_e	[10^{10}]	1.0	2.0	0.52
σ_b	[µm]	7000	300	70
Δt_b	[ns]	154	554	0.5
$\gamma\epsilon_x / \gamma\epsilon_y$	[nm]	5000 / 30	5000 / 35	950 / 30
σ_x^* / σ_y^*	[nm]	9000 / 37	516 / 7.7	149 / 2.9
$IP_{Stabilization}$	σ_y^*	< 0.05	< 0.2	< 0.08
L^*	[m]	1	4.1	6
β_x^* / β_y^*	[mm]	40 / 0.1	13 / 0.41	8 / 0.1



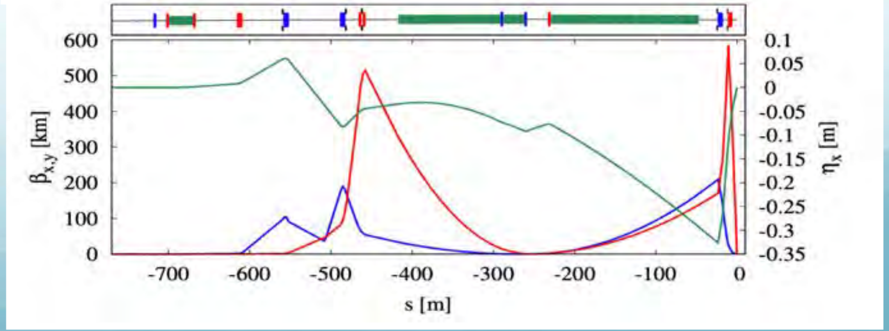
FFS optics



ATF2



ILC



CLIC

Compact final focus (ATF-2/ILC/CLIC), P. Raimondi, A. Seryi, Phys. Rev. Lett. 86, 3779 (2001)

Nanobeam Systems: FFS designs

FFS is among the most challenging sections of a LCs

- **Very-large β** and the presence of **nonlinear elements** make it **extremely sensitive** to **imperfections as:**
  - **Wakefields** introduce energy spread, bunch head-to-tail distortions, and amplify transverse deflections...
  - **Magnets misalignment** introduce dispersion, beta-beating, orbit deflections, transverse coupling, …
  - **Beam jitter** unavoidably cause betatron oscillations that propagate all the way to the IP, etc.

- **Similar Chromaticities** ($L^*/\beta^*_{x,y}$)**: 25 / 10000** (ATF2) , **315 / 10000** (ILC), **750 / 60000** (CLIC) and similar **tolerances** for **FD multipole field errors** (ATF2 and ILC) PRAB 17, 023501 (2014)

- In **ILC and CLIC**, the **much shorter bunch length** and the **much larger beam energy** make the situation **"simpler"**

- **ATF2** tackles its critical task with **two major disadvantages** w.r.t. its "bigger brothers":
  - **Bunch length** is much longer: 7000 vs 300 (ILC) / 70 (CLIC) µm, **23 / 100 times larger**
  - **Beam energy** is significantly lower: 1.3 vs 125 (ILC) / 190 (CLIC) GeV, **100 / 150 times smaller**

- **Measurement** of the **nanobeam sizes involves a** complex device: Shintake monitor (IPBSM)

Na… …ns of a linear collider

- Very-large β and … xtremely sensitive to **imperfections as** …
  - **Wakefields** … y transverse deflections...
  - **Magnets mis** … ansverse coupling, …
  - **Beam jitter** … o the IP, etc.
- **Similar Chromati** … **750 / 60000** (CLIC) and similar **tolerances** … B 17, 023501 (2014)
- In **ILC and CLIC** … **ger beam energy** make the situation **"sim** …
- **ATF2** tackles its … bigger brothers":
  - **Bunch len** … 100 times larger
  - **Beam ener** … , 100 / 150 times smaller
- **Measurement** of the … onitor (IPBSM)

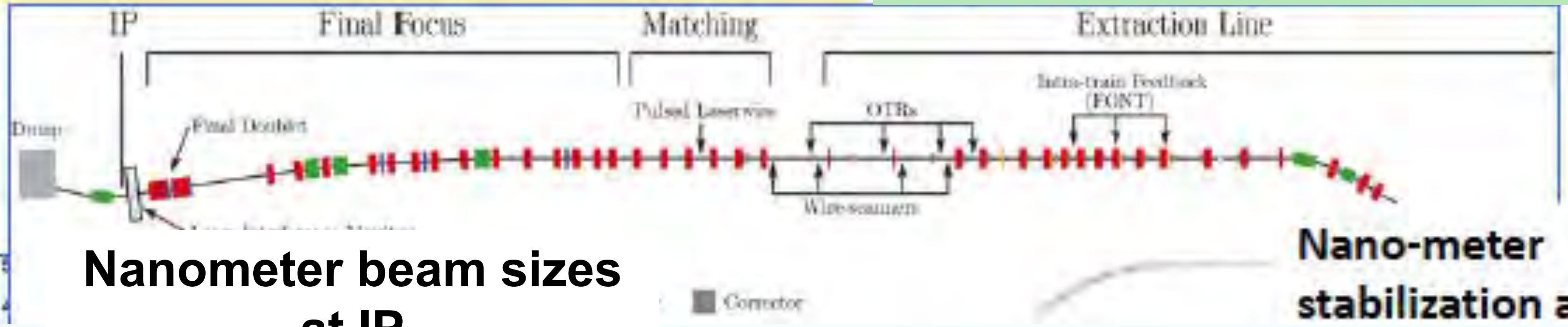
Nanobeam Systems: Experimental results

Goal 1: Establish the ILC final focus method with same optics and comparable beamline tolerances

- ATF2 Goal : **37** nm → ILC **7.7** nm (ILC250)
  - Achieved **41 nm** (2016)

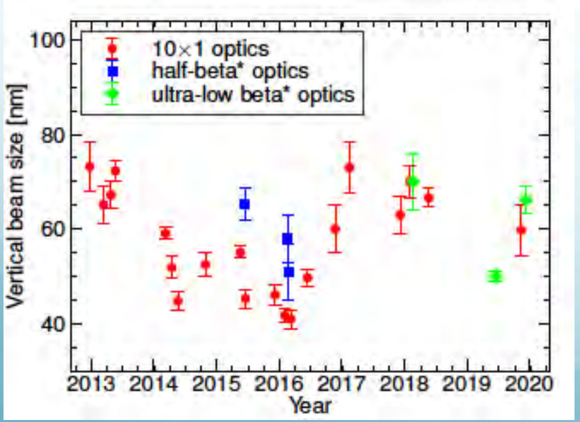
Goal 2: 2 nm beam stabilization at ATF2 IP, (much harder than nm stabilization in collision at ILC).

- **FB latency 133 nsec achieved** (target < 366 nsec)
- **Position jitter at ATF2 IP: 41 nm (2018)** (direct stabilization limited by IPBPMs resolution 20 nm). Upstream FB shows capability for 2nm stabilization. **Demonstrated ILC IPFB system.**

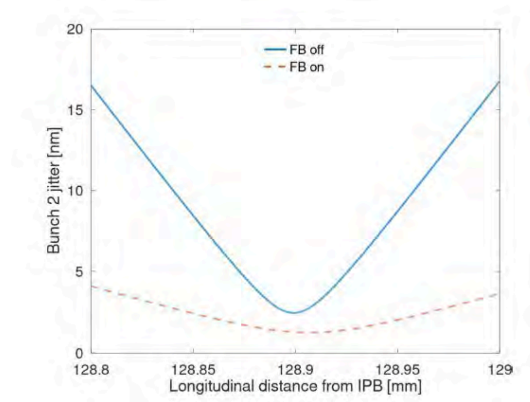


Nanometer beam sizes at IP

Nano-meter stabilization at IP

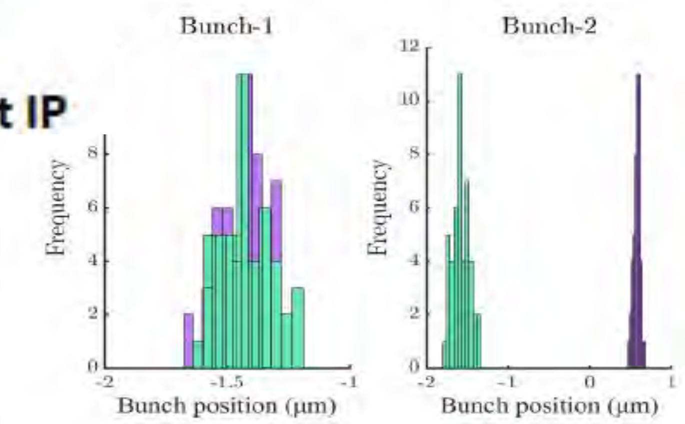


Small beam sizes were obtained with beam intensities of 0.5-1.5 10^9 e^- /bunch (10^{10} design value) and reduced aberration optics ($10\beta_x^* \times \beta_y^*$)



Predicted vertical position jitter with FB on-off

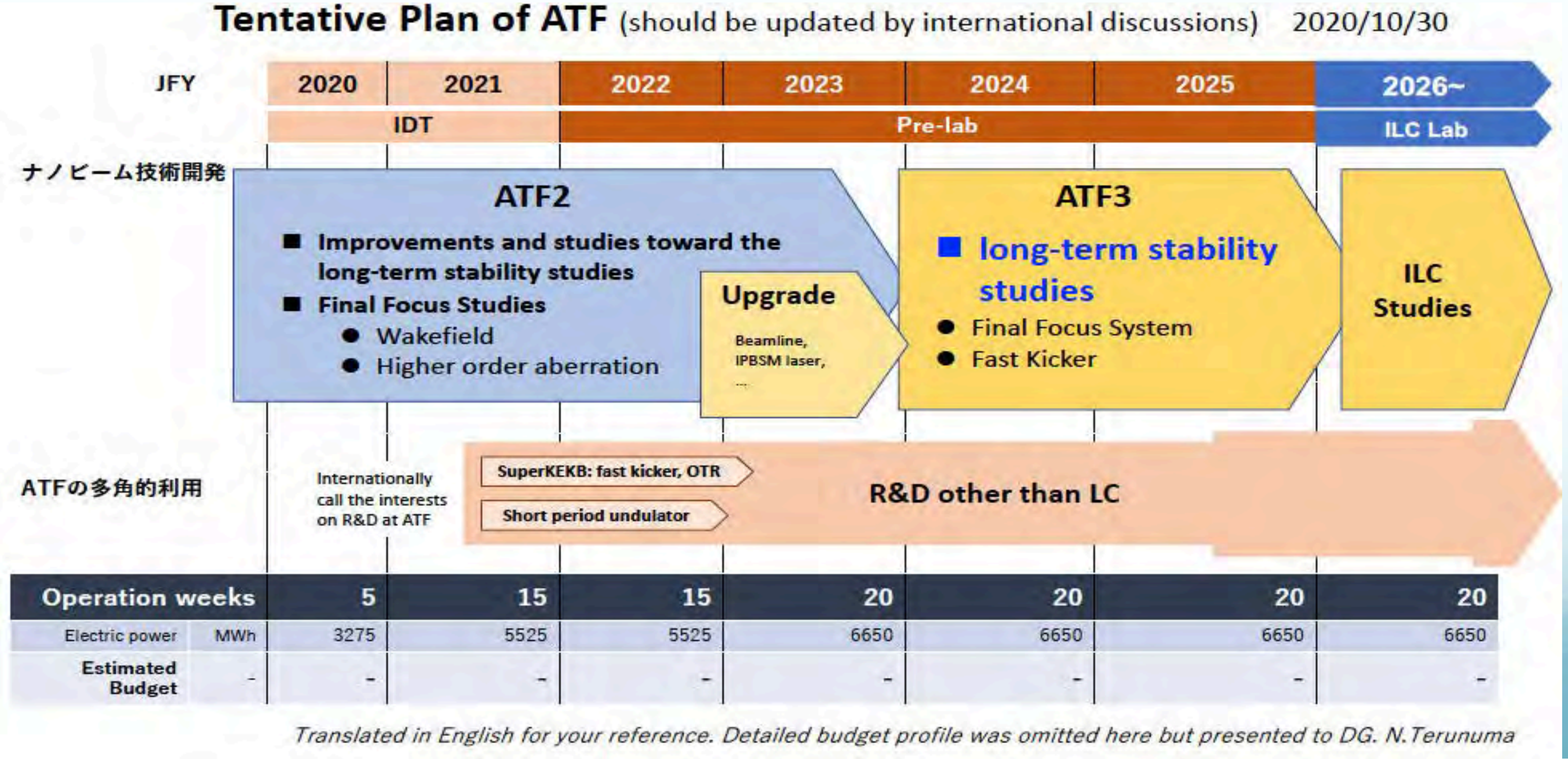
Distribution of bunch positions measured at IPB, with two-BPM FB off (green) and on (purple)



Future studies: ILC FFS - ATF3

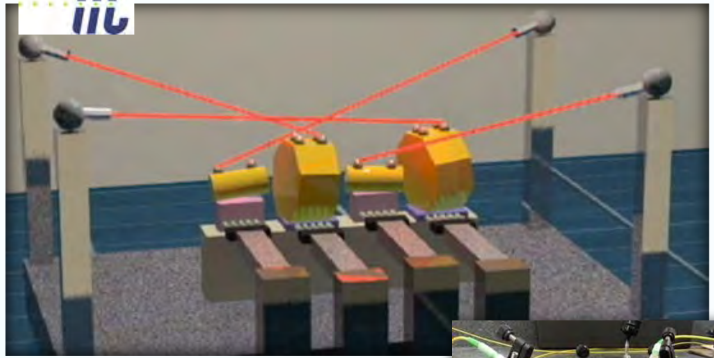
Based on the achievements of the ATF2 no showstopper for ILC has been found, **ATF3** plan is to pursue the necessary R&D to **maximize** the **luminosity potential of ILC**. In particular the assessment of the **ILC FFS system design** from the point of view of the beam dynamics aspects and the technological/hardware choices and the **long-term stability operation issues.**

ILC-IDT WG2 Technical proposal

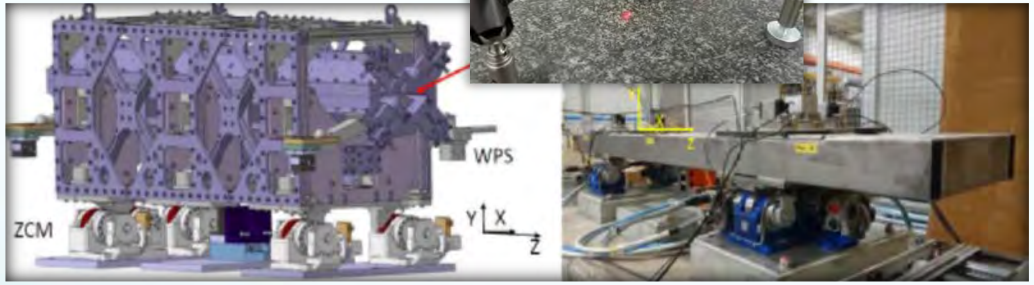


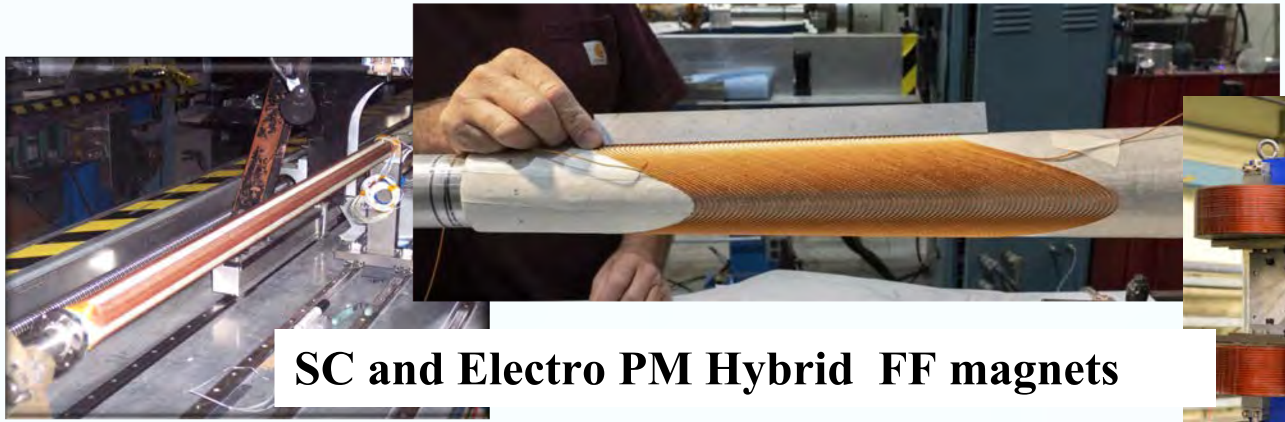
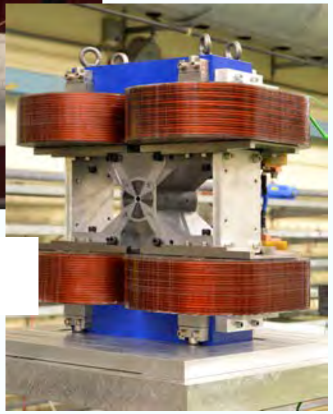
Nanobeam Technologies: devices and monitoring

Nanobeam Technologies (1-3 February 2021) **https://indico.cern.ch/event/980103/**



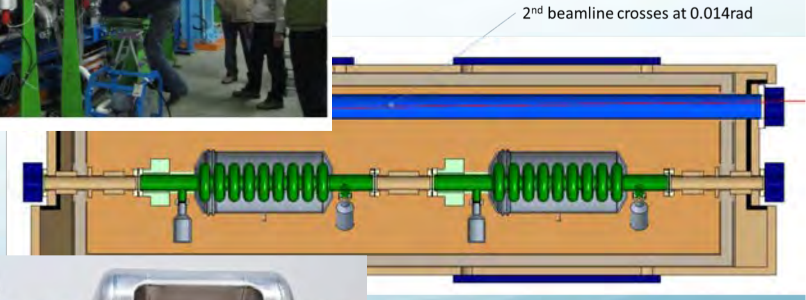

Alignment and Positioning



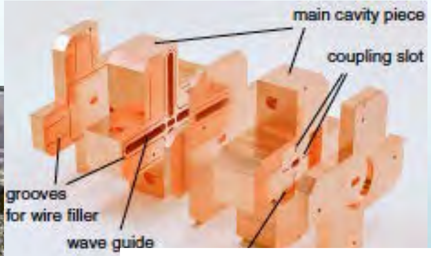



SC and Electro PM Hybrid FF magnets

Crab cavities



Nano BSM

Nano BPMs

Outline

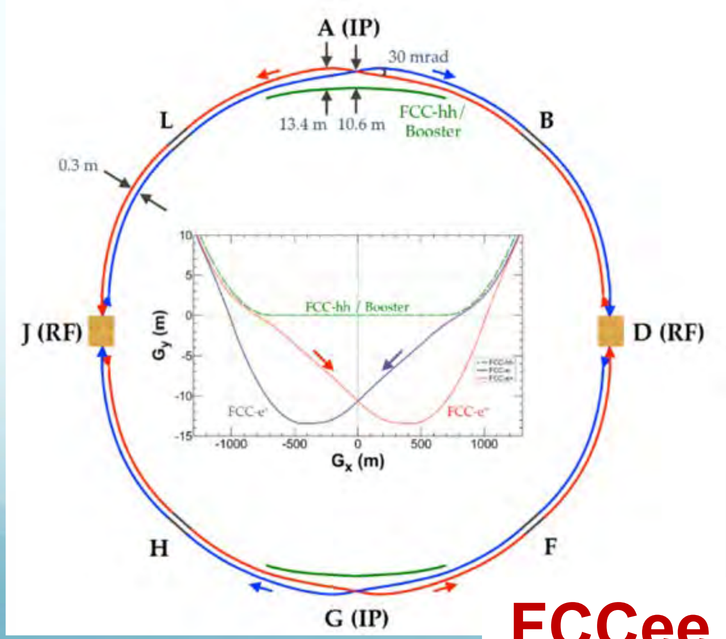
- Luminosity issues
- The e⁺e⁻ Linear colliders
  - ILC-IDT: Technology update
  - CLIC: Technology update
- The e⁺e- Circular colliders
  - FCCee: Technology update
  - CepC: Technology update (J. Gao's talk)
- Summary and Perspectives

The FCC integrated program

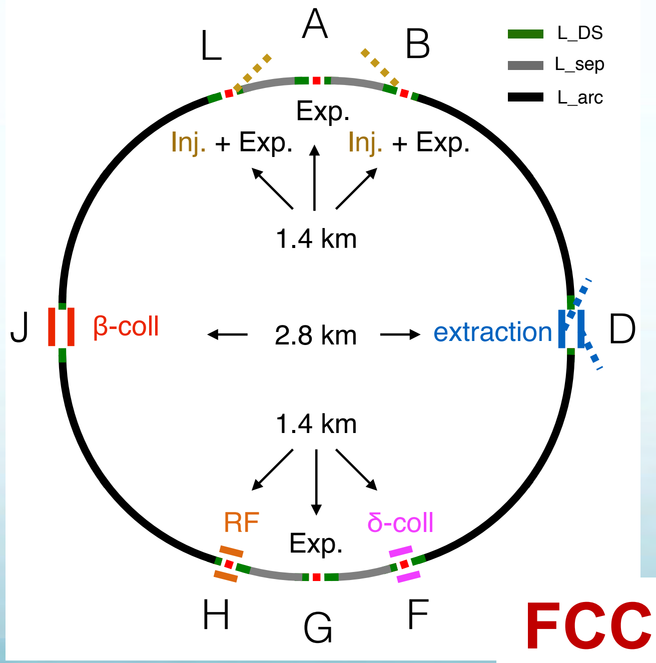
Inspired by successful LEP – LHC programs at CERN

FCC is a comprehensive long-term program maximizing physics opportunities

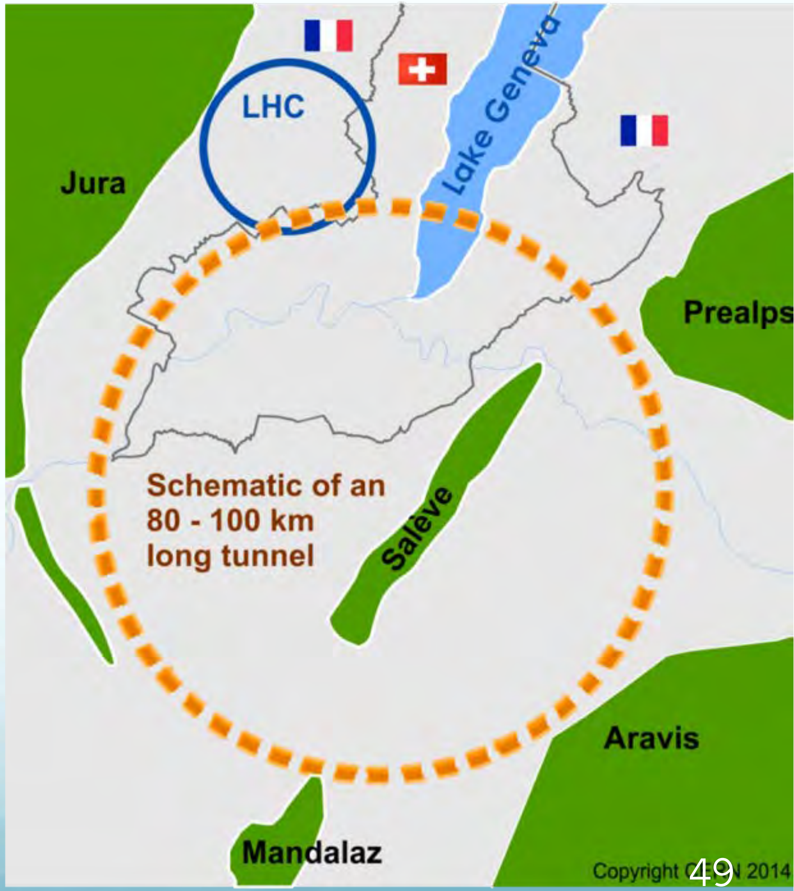
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures
- building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC



FCCee

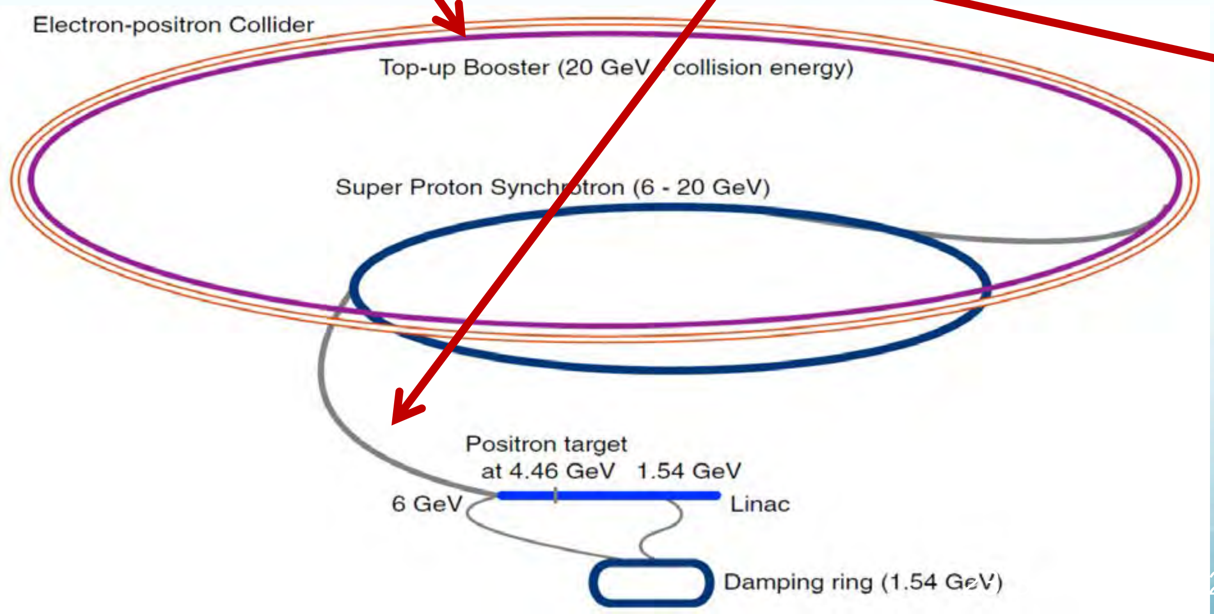


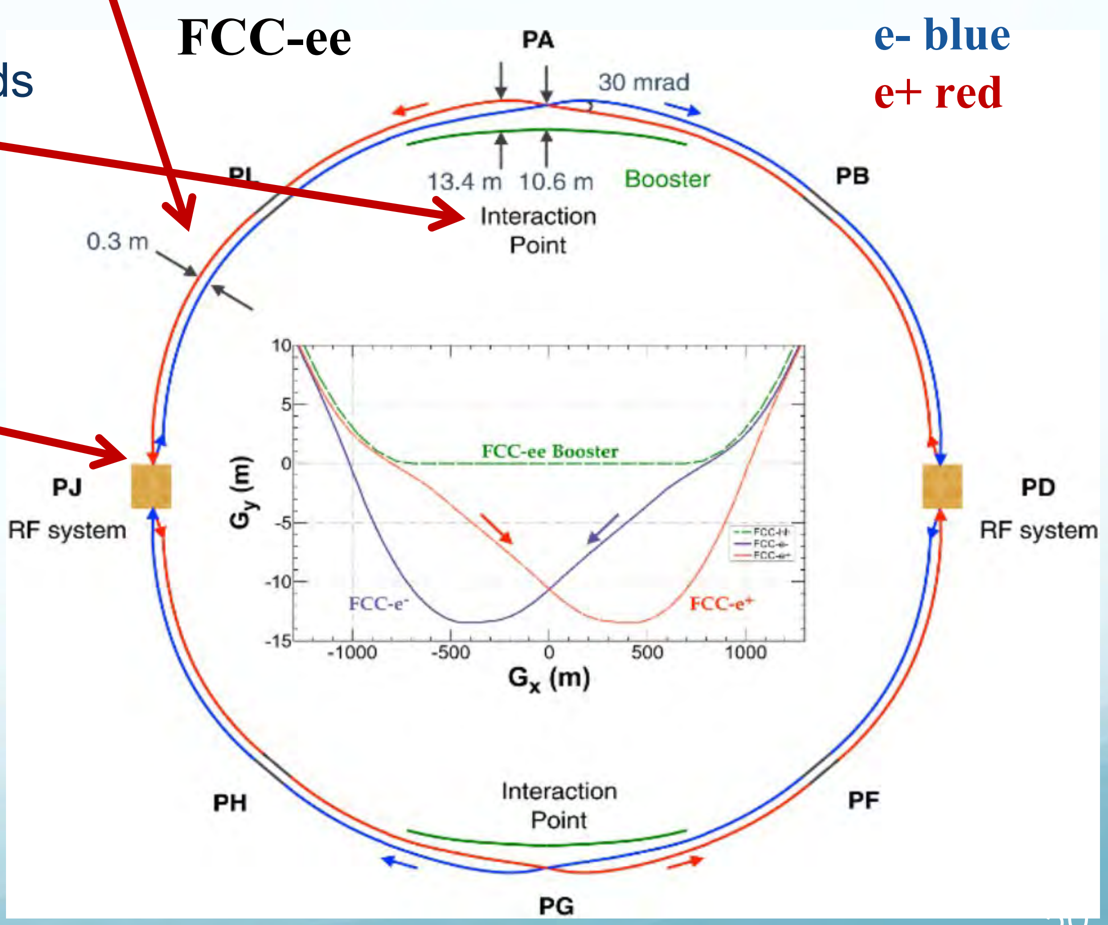
FCChh



FCCee accelerator sequence and main area systems

- **Double ring** e+e- circular collider with ~100 km circumference
- **Rapid cycling booster** required for **top-up injection**
- **Baseline 2 IPs (4 IPs alternative),** tapering of arc magnet strengths to match local energy
- **Asymmetric IR** layout to limit SR of incoming beams towards detectors and generate large crossing angle
- **2 RF straights** with **common** use of **RF** systems for both beams at highest energy working point

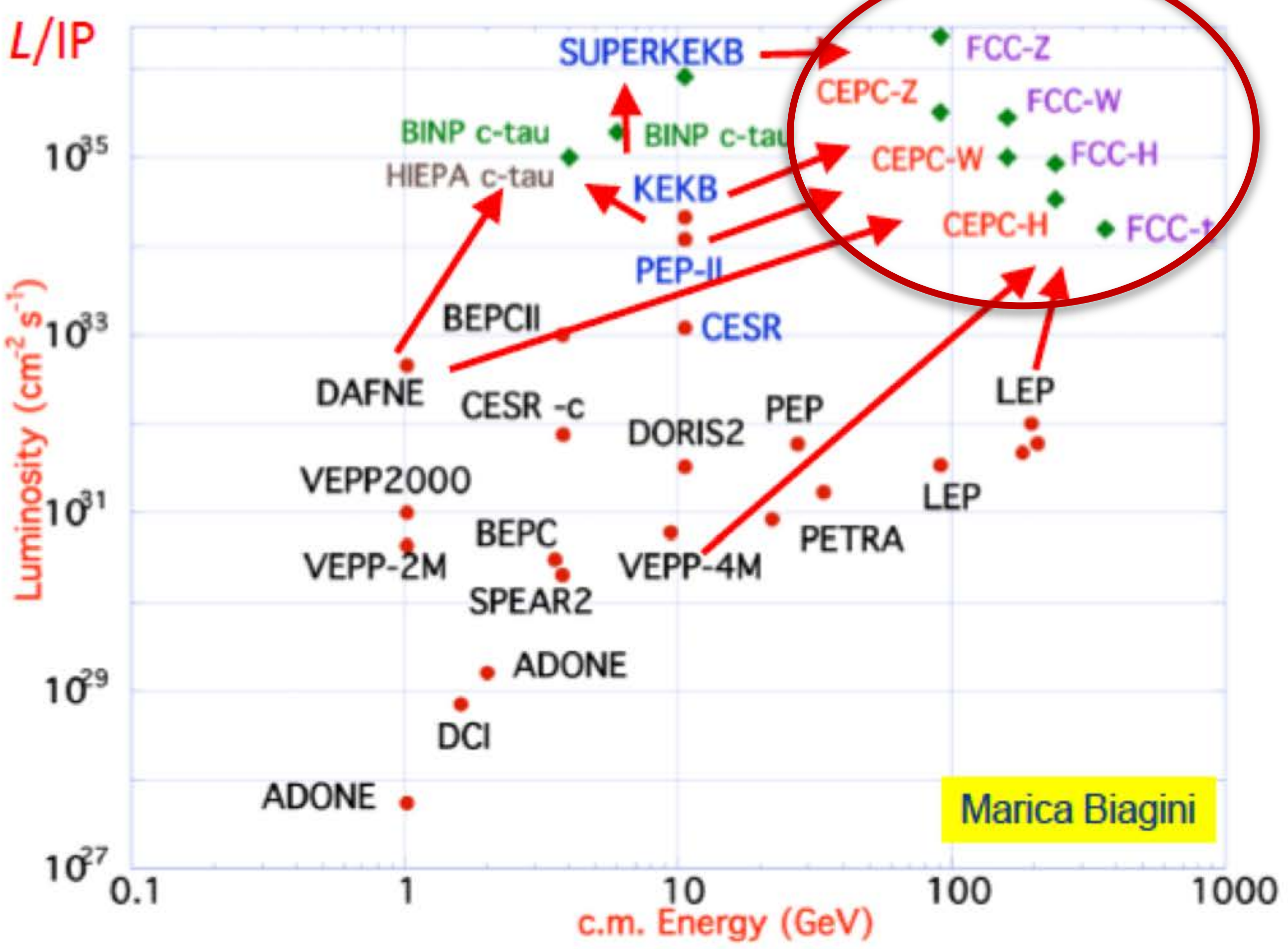




FCCee updated parameters and operation modes

Parameter	Z	WW	ZH	$t\bar{t}$	LEP2
energy/beam [GeV]	**45.6**	**80**	**120**	**182.5**	105
bunches/beam	16640	2000	328	48	4
beam current [mA]	1390	147	29	5.4	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**230**	**28**	**8.5**	**1.6**	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.2	3.34
synchrotron power [MW]			**100**		22
RF voltage [GV]	0.1	0.75	2.0	4.0 + 6.9	3.5
rms bunch length (SR,+BS) [mm]	3.5, 12	3.0, 6.0	3.2, 5.3	2.0, 2.5	12, 12
rms emittance $e_{x,y}$ [nm, pm]	0.27, 1	0.84, 1.7	0.63, 1.3	1.5, 2.9	22, 250
longit. damping time [turns]	1273	236	70	20	31
vert. IP beta function b_y* [mm]	0.8	1.0	1.0	1.6	50
beam lifetime, rad. Bb + BS [min]	68	59	12	12	434

FCCee is based on proven techniques from past colliders and light sources



B-factories: KEKB & PEP-II:
- double-ring lepton colliders,
- high beam currents,
- top-up injection

DAFNE: crab waist, double ring

Super B-factories, S-KEKB: low β_y^*

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

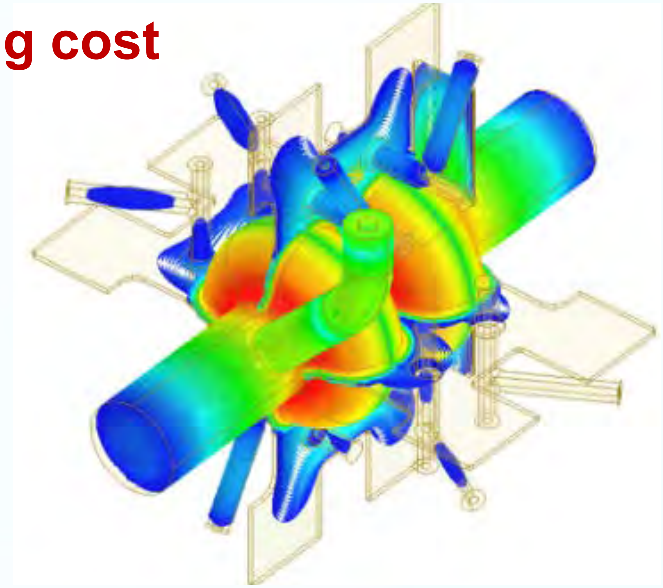
KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

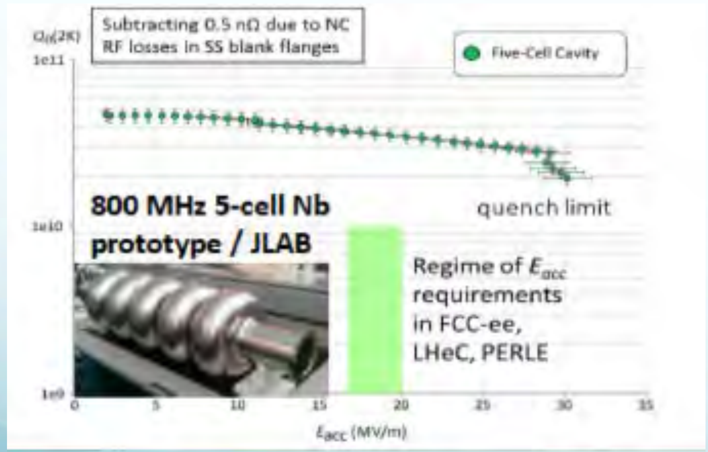
combining successful ingredients of several recent colliders → highest luminosities & energies

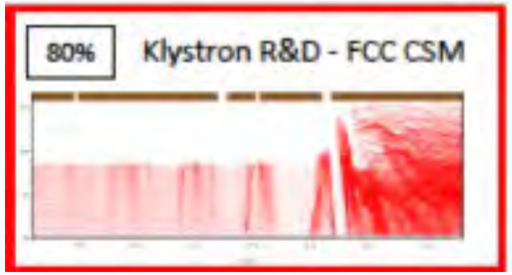
FCCee: Technology challenge

RF R&D to improve performance and efficiency and reducing cost



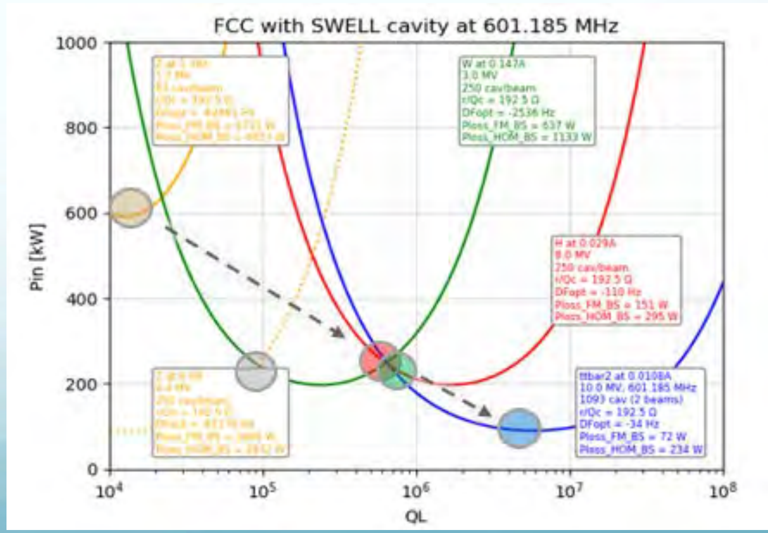
- **Improved Nb/Cu coating/sputtering** (e.g. ECR fibre growth, HiPIMS)
- Coating of A15 (e.g. Nb3Sn)
- **Bulk Nb cavity R&D** at FNAL, JLAB, Cornell, KEK and CepC/IHEP
- **New cavity fabrication techniques** (e.g. Improved polishing, seamless, SWELL cavities)
- The CERN **high-efficiency klystron** program develops klystrons for numerous accelerators including LHC, CLIC, FCC-ee and ILC.
- **MW-class fundamental power couplers** for 400 MHz





400 MHz SRF cryomodule, + prototype multi-cell cavities for FCC ZH operation

SWELL cavity: one for all energies

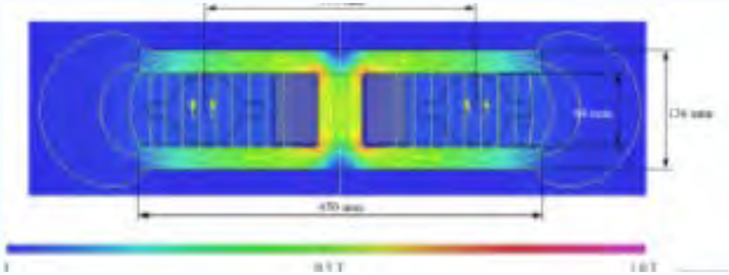


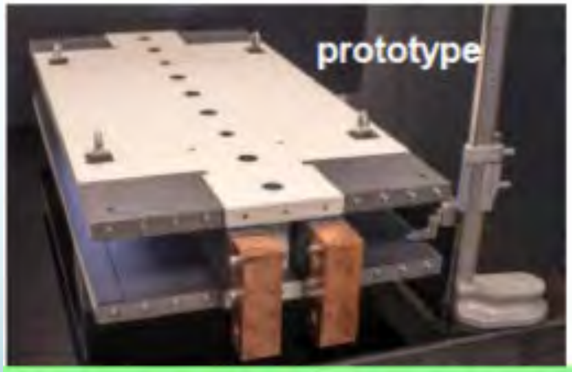
recent topical FCC review April-June '21

FCCee: Technology challenge

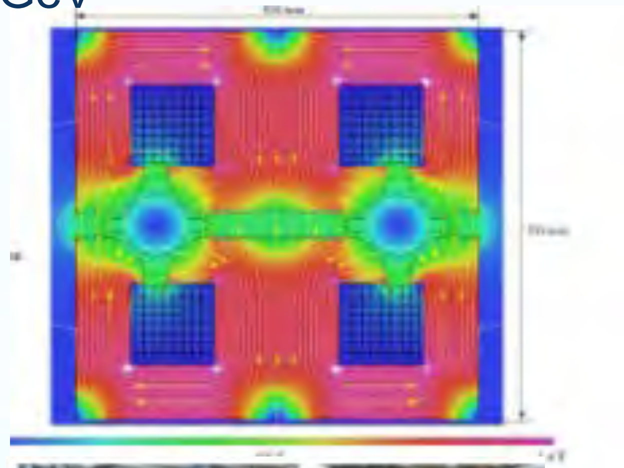
Magnet R&D for low power

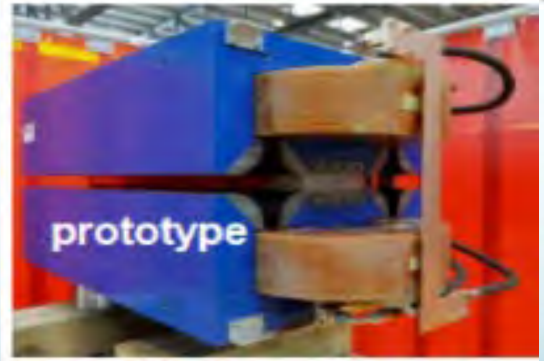
- **Twin-dipole** design with 2xpower saving 16 MW at 175 GeV



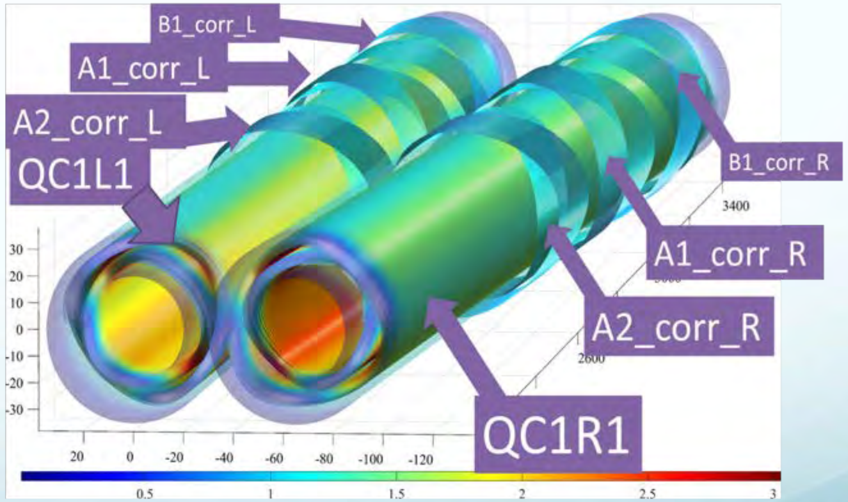


- **Twin F/D quad** design with 2xpower saving 25 MW at 175 GeV





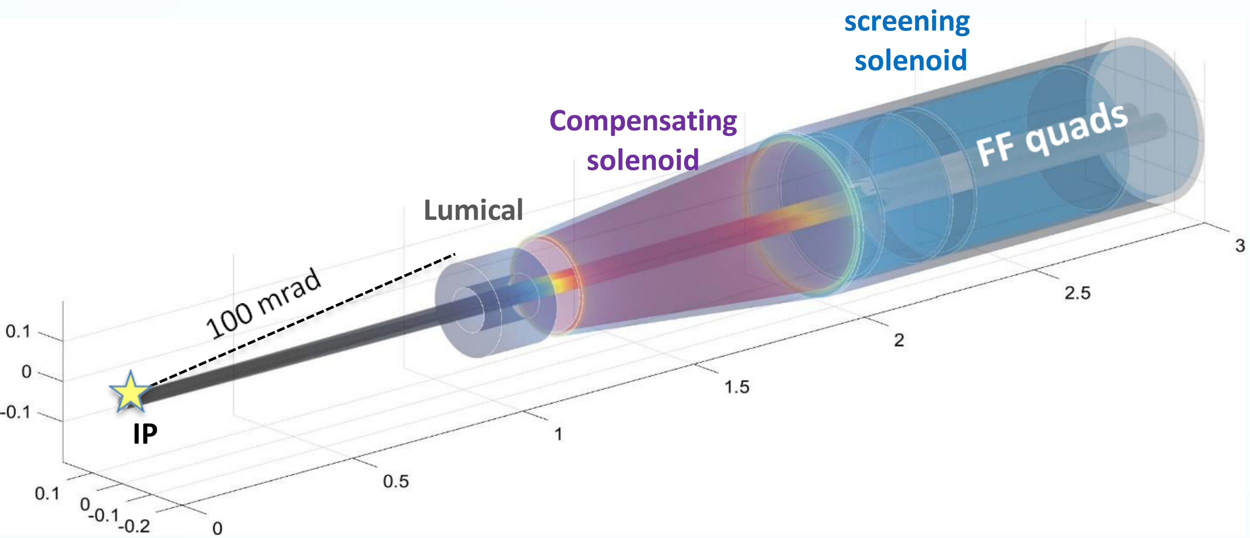
- **Final quadrupole pair** near **IP**; canted-cosine-theta concept; with orbit corrector & skew quadrupole; to be built with Nb-Ti or HTS wires



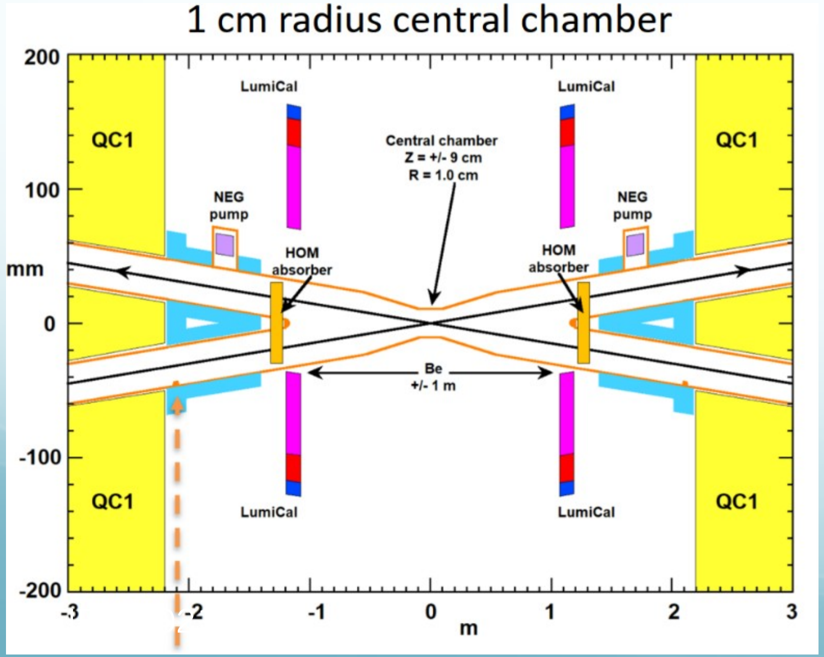
Power reduction by 2 w.r.t. single aperture magnets

FCCee: Technology challenge

R&D in Machine Detector Interface

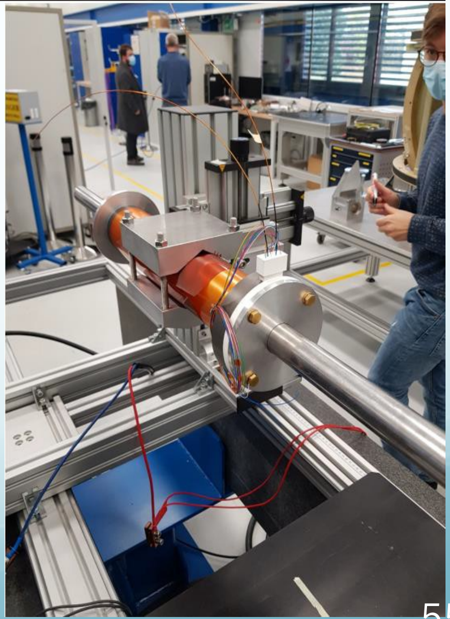


- **challenging integration:** 2 T detector solenoid, luminosity monitor (Bhabha scattering), compensation and shielding solenoids



- **Narrow central chamber** with 1 cm radius, also avoids trapped modes

- **Q1 prototype:** canted cosine theta with fringe field correction, using LHC SC cable

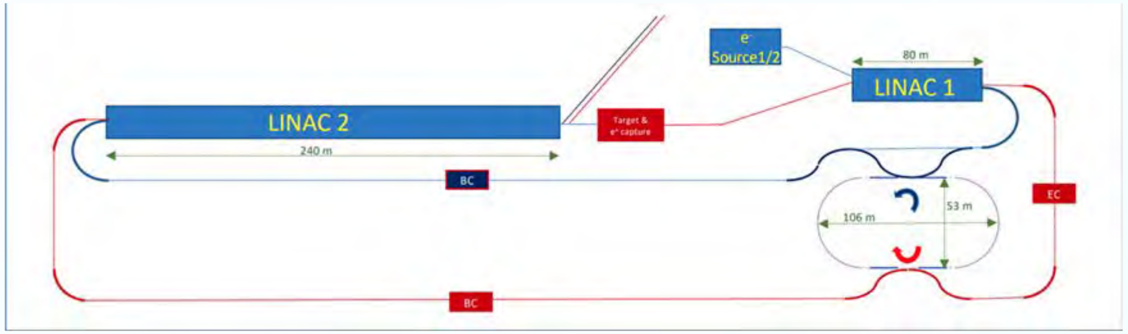


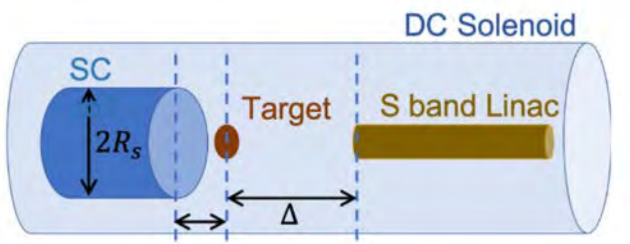
field measurement at warm

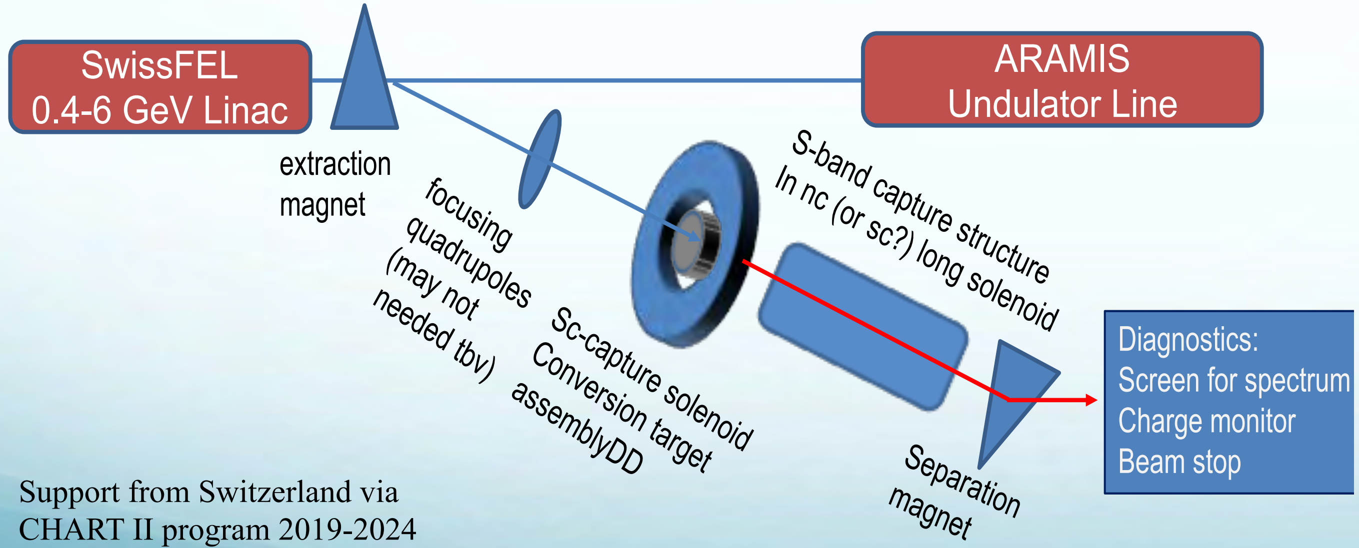
FCCee: Technology challenge

R&D for optimized FCCee injector to improve performance and efficiency

- FCC-ee injector **new design**, conservative approach SuperKEKB based, optimized layout
- **High-yield positron source** target with DC SC solenoid or flux concentrator
- **Positron capture linac** large aperture S-band linac
- **Beam test** of e^+ source and capture linac at SwissFEL – yield measurement





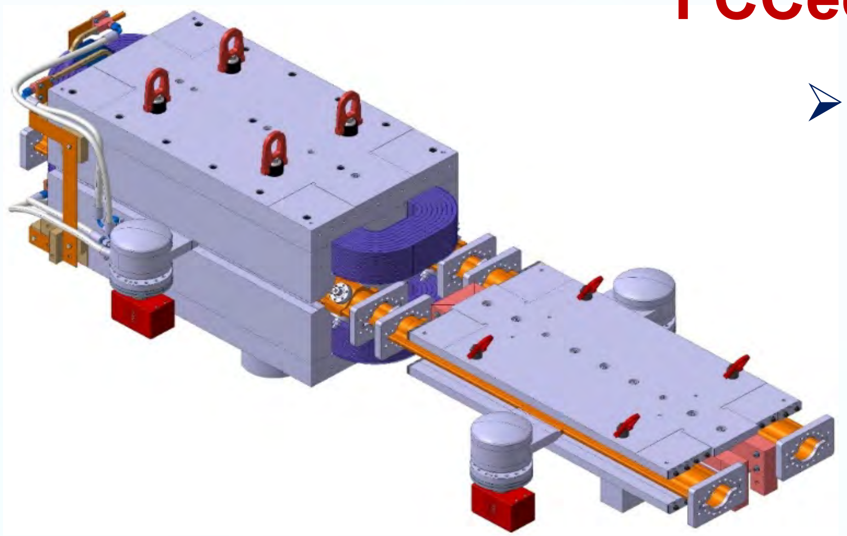


Support from Switzerland via CHART II program 2019-2024 for FCC-ee injector

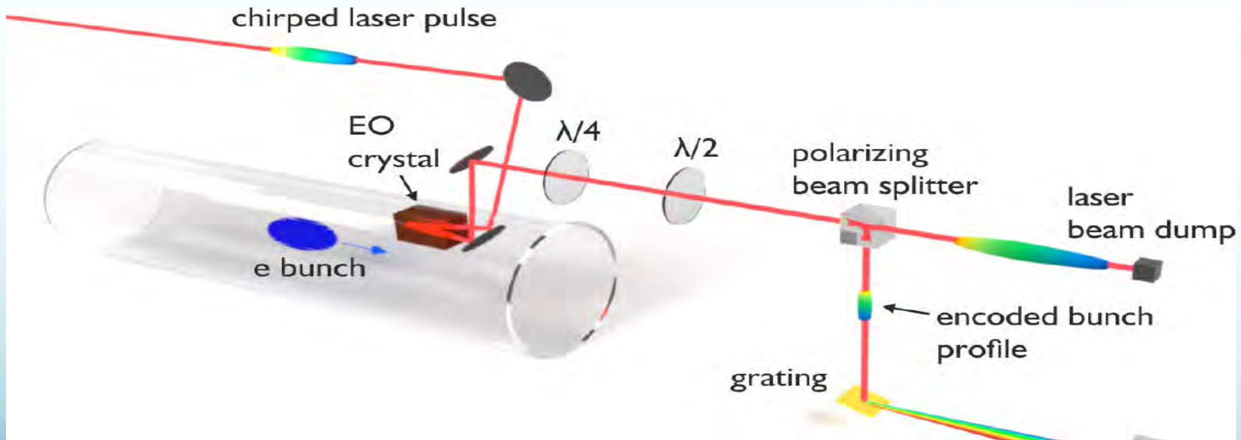
recent topical FCC review April-June '21

FCCee: Technology challenge

FCCee R&D: prototypes by 2025



- **FCCee complete arc half-cell mock up** including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.



bunch electric field at the crystal changes the laser pulse polarization

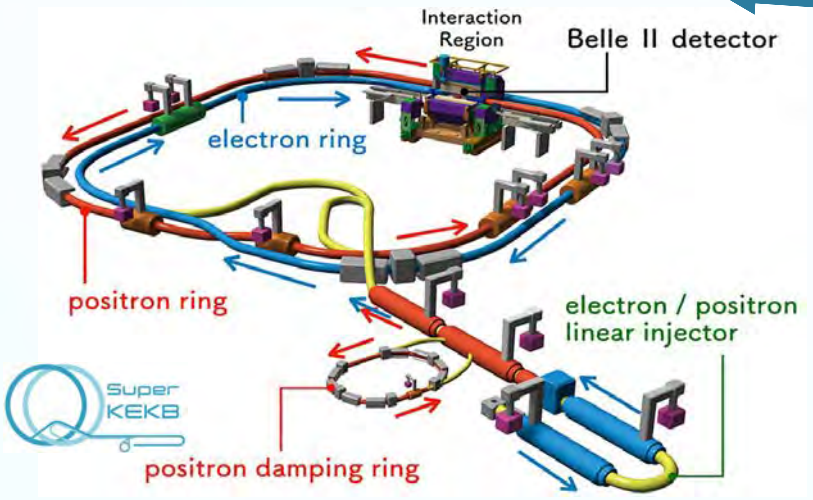
- **Key beam diagnostics elements**
  - bunch-by-bunch turn-by-turn **longitudinal charge density profiles** based on electro-optical spectral decoding (beam tests at KIT/KARA) ;
  - **ultra-low emittance measurement** (X-ray interferometer tests at SuperKEKB, ALBA)
  - **beam-loss monitors** (IJCLab/KEK) ;
  - **beamstrahlung monitor** (KEK);
  - **polarimeter** ; **luminometer**

Nanobeams past and recent achievements: circular

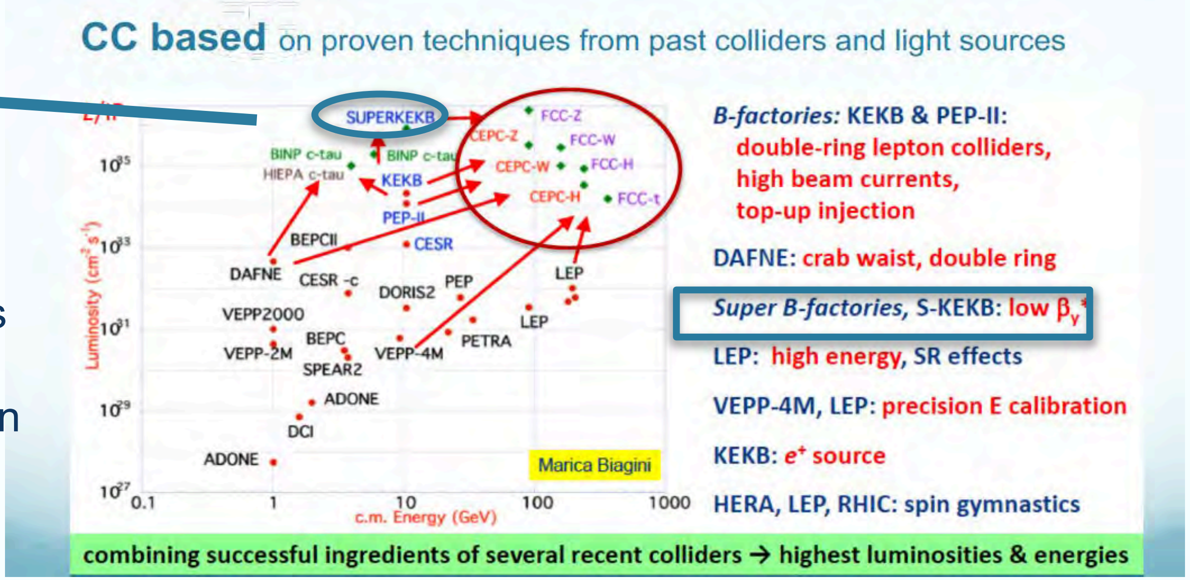
	Units	SuperKEKB				FCCee (Z)	CepC (Z)
		design		Achieved *			
E_{cm}	[GeV]	4 (LER)	7 (HER)	4 (LER)	4.6 (HER)	45	45.5
$\mathcal{L}/IP$	[10^{34} cm^{-2} s^{-1}]	80		3.12		230	101.1
I	[mA]	3600	2600	790	687	1390	841
n_b	1	2500		1174		16640	10870
N_e	[10^{10}]					17	16.1
σ_b	[µm]	6000		6000		3500	9600
$\gamma\epsilon_x$	[nm]	25049	63013	31702	63013	23777	46301
$\gamma\epsilon_y$	[nm]					88	142.5
σ_x^*	[nm]	10100	10700	17900	16600	6300	8800
σ_y^*	[nm]	48	62	229	229	28	40
β_x^*	[mm]	32	25	80	60	150	150
β_y^*	[mm]	0.27	0.3	1.0	1.0	0.8	1.0

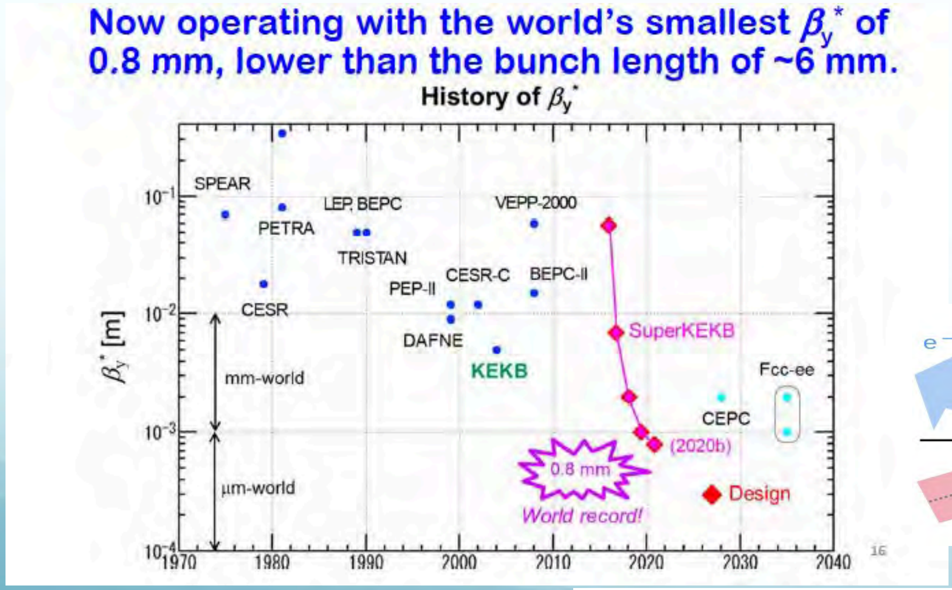
* June 2021

Past and recent achievements: circular

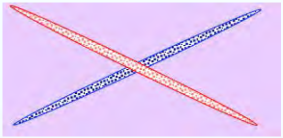


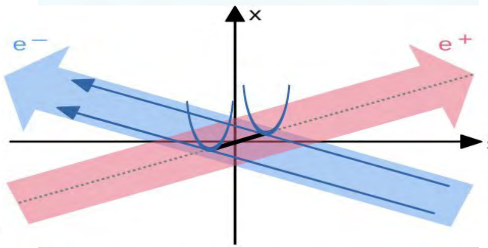
SuperKEKB is demonstrating FCCee key concepts: $b_y^* = 0.8$ mm achieved in both rings using the FCCee-style “virtual” crab-waist collision scheme

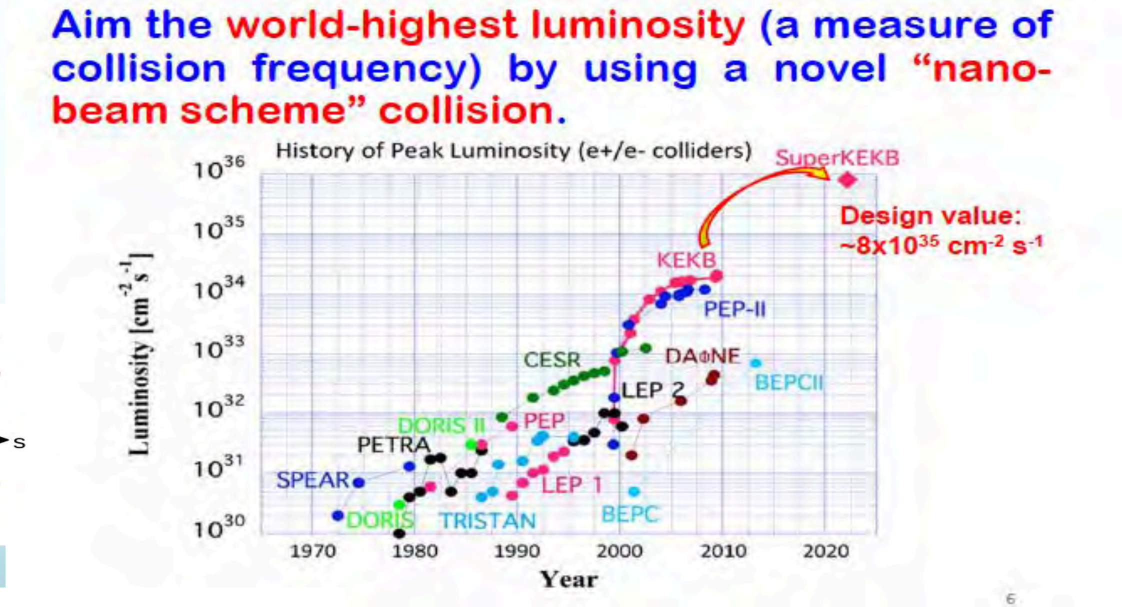




“pencil beams”



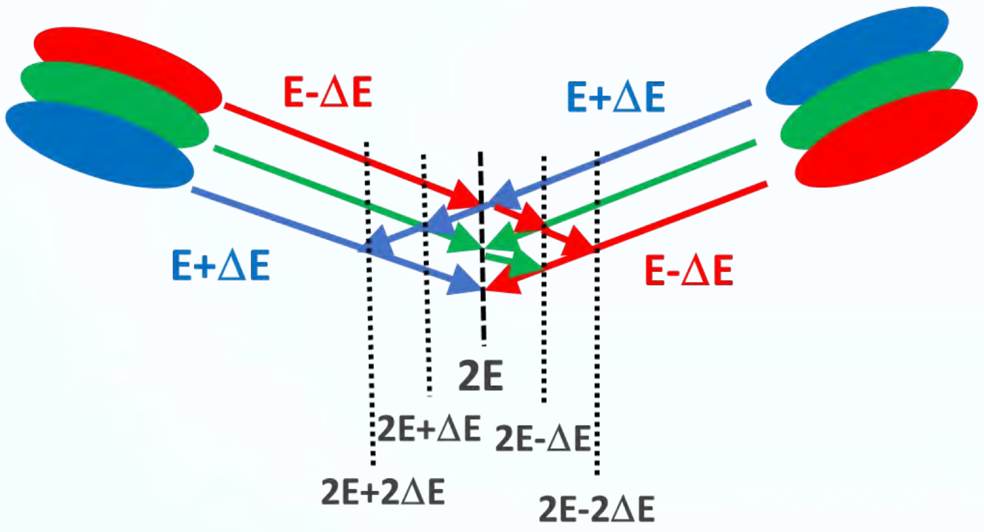




Understanding SuperKEKB essential for FCC-ee!

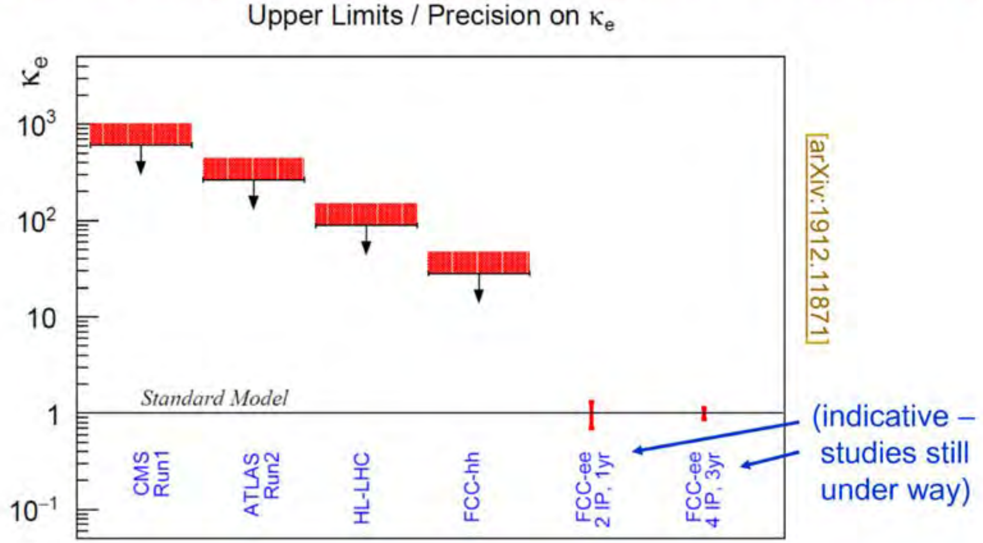
FCCee: Technology challenge

FCC-ee monochromatization option

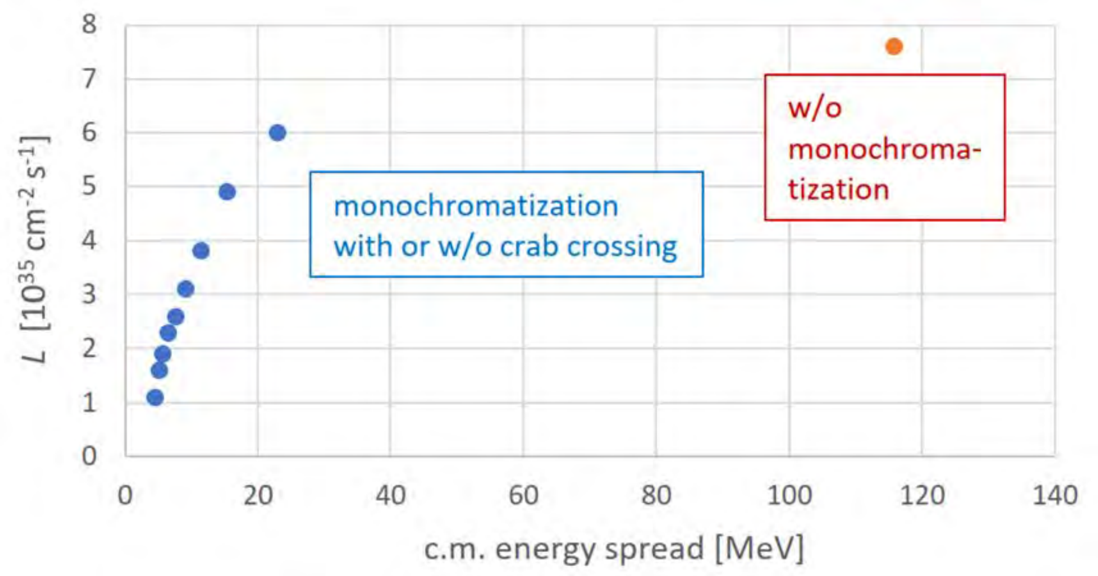


- Measure the **electron Yukawa coupling in a dedicated run at ~125 GeV collision energy**, reducing the centre-of-mass (CM) energy spread by means of **monochromatization**

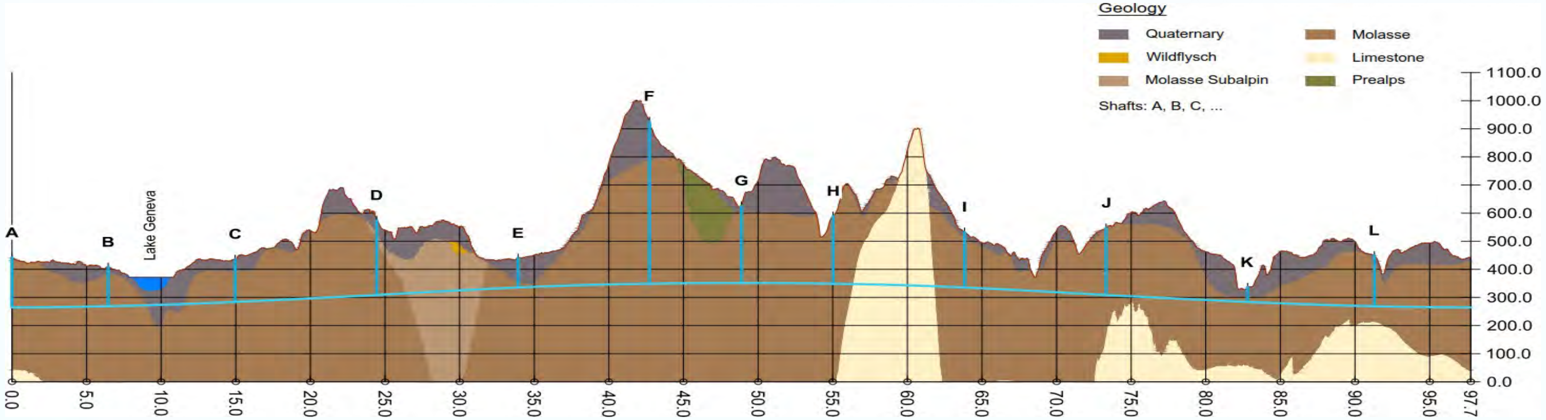
Studies still underway – likely require several years to reach SM value at 3σ. However, can do vastly better than any other machine. Also, motivation for 4 IPs !



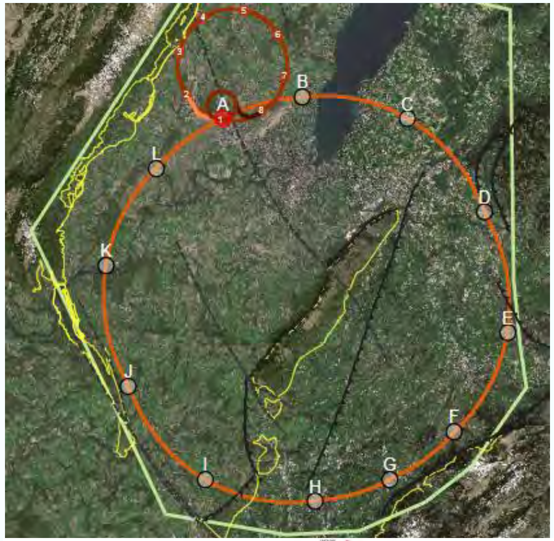
Final remark: operation at E_{CM}=125 GeV is also valuable for accumulating radiative returns to the Z and improving sensitivity to the number of neutrino families.



FCCee Site Selection and Civil Engineering

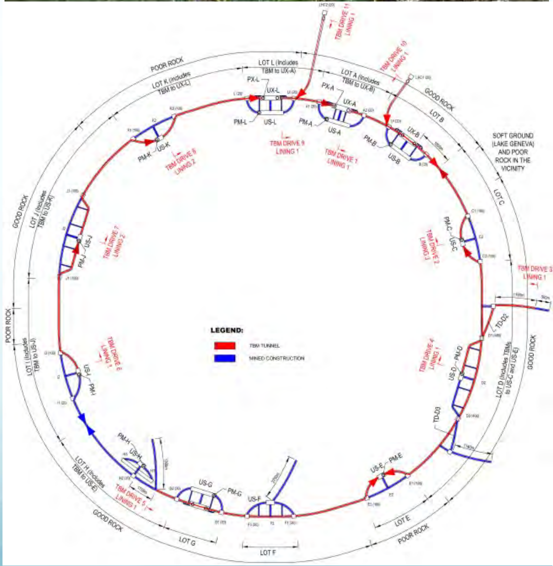


- 90 – 100 km circumference
- 12 surface sites with few ha area each



➢ **Present baseline position was established considering:** Molasse rock preferred for tunnelling, avoid limestone with karstic structures, low risk and fast construction

SECTOR	RISK	FINAL RISK INDEX							Std. Dev.*
		17-0.8	19-0.3	21-0.3	31-0.4	35-0.6	37-0.3	38-0.1	
LAKE	Quaternary soft ground, water bearing	47	28	54	29	65	79	40	20
ARVE	Quaternary soft ground, water bearing	12	4	9	6	6	4	5	3
MANDALLAZ	Limestone, water bearing karsts	96	96	96	96	96	96	96	0
USSES	Quaternary soft ground, water bearing	7	7	5	3	1	2	2	2
VUACHE	Limestone, water bearing karsts	24	442	240	12	50	12	12	16
RHONE	Quaternary soft ground, water bearing	18	5	8	11	8	11	12	4
JURA	Limestone, water bearing karsts	100	672	864	100	100	100	100	0
	TOTAL	304	1254	1276	257	326	303	267	29



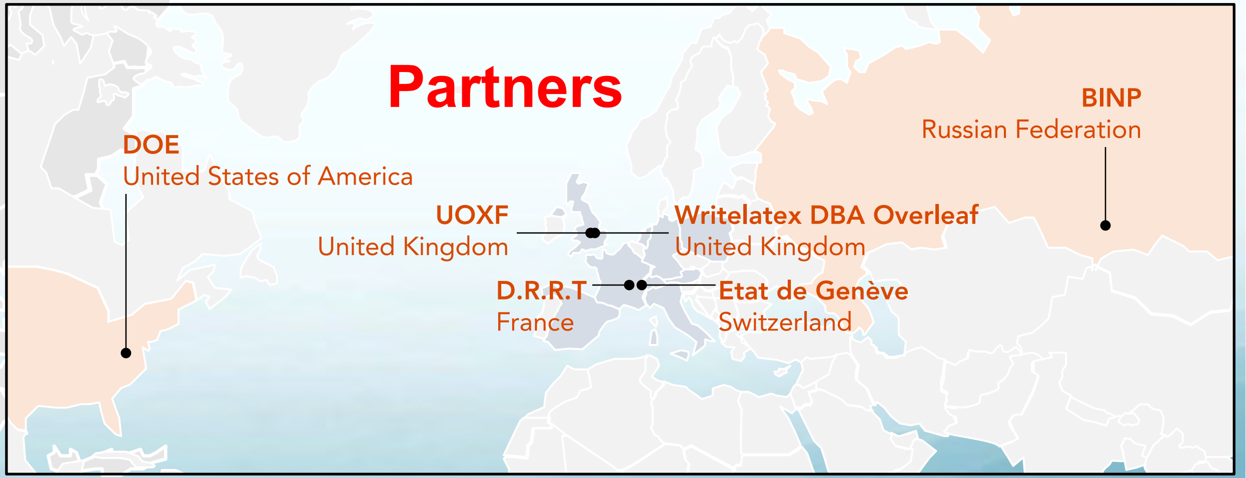
Placement minimizing the risk, define leave open later choice between 2 and 4 IPs, reduced number of surface sites

H2020 DS FCC Innovation Study 2020-24

Beneficiaries

Topic	INFRADEV-01-2019-2020
Grant Agreement	FCCIS 951754
Duration	48 months
From-to	2 Nov 2020 – 1 Nov 2024
Project cost	7 435 865 €
EU contribution	2 999 850 €
Beneficiaries	16
Partners	6

Partners



FCCIS Work Packages

- **WP1: study management**

- **WP2: collider design**

Deliver a **performance optimised machine design**, integrated with the territorial requirements and constraints, considering cost, long-term sustainability, operational efficiency and design-for- socio-economic impact generation.

- **WP3: integrate Europe**

Develop a feasible **project scenario compatible with local – territorial constraints** while guaranteeing the required physic performance.

- **WP4: impact & sustainability**

Develop the **financial roadmap of the infrastructure project**, including the analysis of socio-economic impacts.

- **WP5: leverage & engage**

Engage stakeholders in the preparation of a new research infrastructure. Communicate the project rationale, objectives and progress. Create lasting impact by building theoretical and experimental physics communities, creating awareness of the technical feasibility and financial sustainability, forging a project preparation plan with the host states (France, Switzerland).

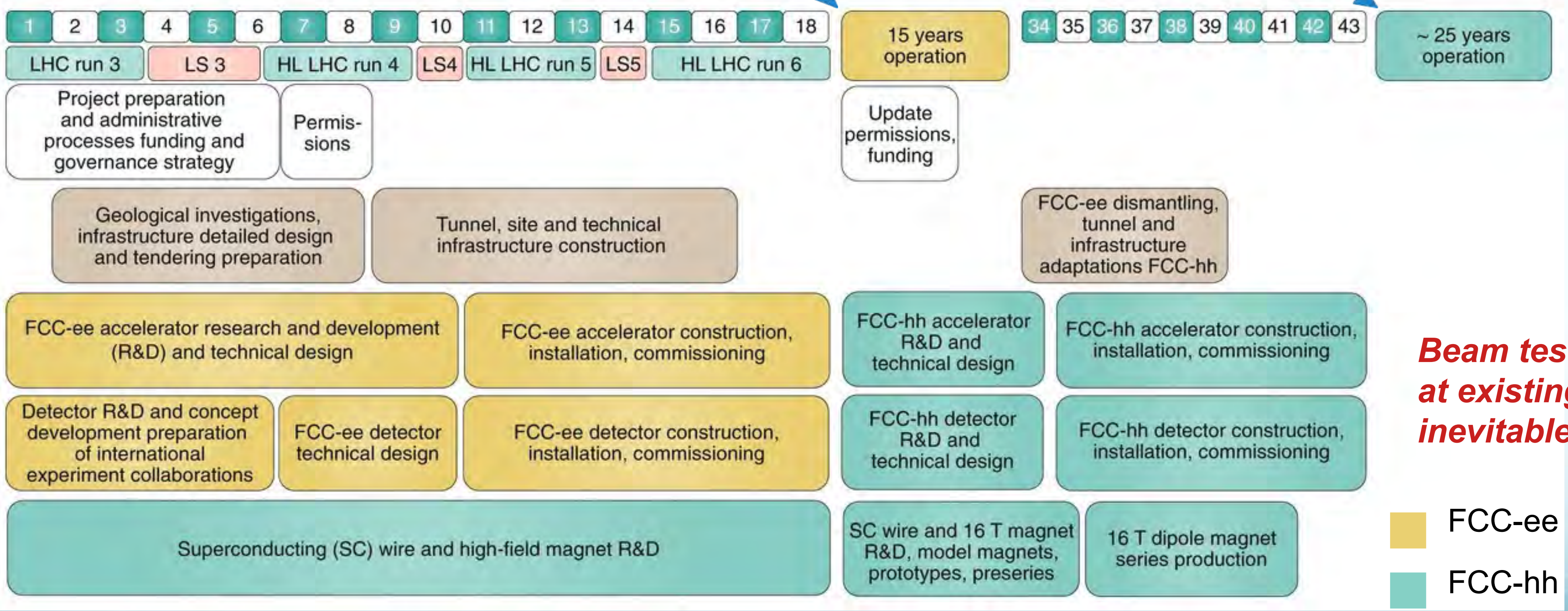
FCC Integrated Timeline

- **Lepton collider** (FCCee) followed by **hadron collider** (FCChh)

FCCee commissioning around 2040

FCChh commissioning around 2065

Starts at 2021



Beam tests for FCC-ee at existing facilities inevitable

Conclusions

- **two circular Higgs and electroweak factories** are being developed, FCC-ee and CEPC; both promise highly efficient performance over large energy range from *Z* pole to top pair threshold
- independent design efforts led to **similar layouts & parameters**; further improvements possible (e.g. monochr. s-channel *H* production, 4 IPs,…)
- **synergetic R&D efforts** are ongoing, prototyping of key components,…
- either machine would **prepare the ground for a subsequent hadron collider**, FCC-hh or SPPC, plus several other options, and would enable an exciting **frontier physics programme spanning over a century**
- FCC has entered **feasibility study phase**, results of which will inform the **next update of European Strategy** for Particle Physics ~2026/27

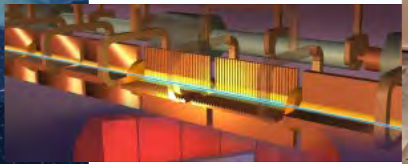
Medium Term Plan

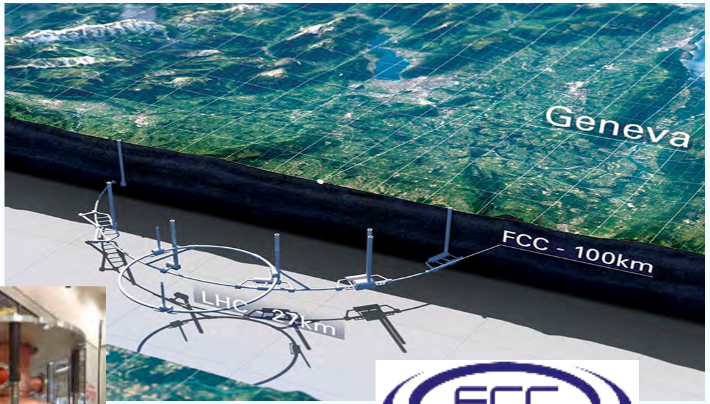
EPPSU ⟷ EPPSU

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037

- A **LC Higgs factory** is **ready** for start up ~2035: **ILC** hosted in Japan and **CLIC** at CERN, are **mature designs** in both cases promoted and set up as international projects
  - Main accelerator **technologies** have been **demonstrated** (mass production still a challenge)
  - Cost and implementation time are **similar** to **LHC** (~10B$)
  - Physics case is broad and profound, and being further developed
  - Detector concept and detector technologies R&D are well advanced

- **Circular Higgs and electroweak factories** are being developed, FCC-ee and CEPC; both promise highly efficient performance over large energy range from *Z* pole to top pair threshold.
  - Independent design efforts led to **similar layouts & parameters**; further improvements possible
  - **Synergetic R&D efforts** are ongoing, prototyping of key components,…
  - Either machine would **prepare the ground for a subsequent hadron collider**, FCC-hh or SPPC,
  - FCC **feasibility study phase**, results of which will inform the **next update of EPPS**





Thanks for your attention

Special thanks to

Shin Michuzono, Steinar Stapnes, Benno List and Frank Zimmermann, Katsunobu Oide and Yoshihiro.funakoshi

Present and Future Large Accelerator projects

In operation
In construction
Under study

An uncompleted view …

International Large Scale Projects

EPPSU (2019) — EPPSU (2026)

2018 | 2020 | 2022 | 2024 | 2026 | 2028 | 2030 | 2032 | 2034 | 2036 | 2038 | 2040 | 2042 | 2044 | 2046 | 2048 | 2050 | 2052 | 2054 | 2056

LHC
ATF2
Super KEKB
XFEL
…

ESS
SC linac

ATF3

HL-LHC
11T Nb_3Tn

FAIR

LBNF

CepC.
High current
Z-pole

LHeC
ERL

EIC

ILC
1.3GHz SC
nano-beam/stabilization

CLIC
12 GHz
nano-beam/stabilization

FCCee
High current
Z-pole

FCChh
16T Nb_3Tn/NbTn

FCCeh
ERL

HE-LHC (HL-LHC)
16T Nb_3Tn/NbTn

SppC

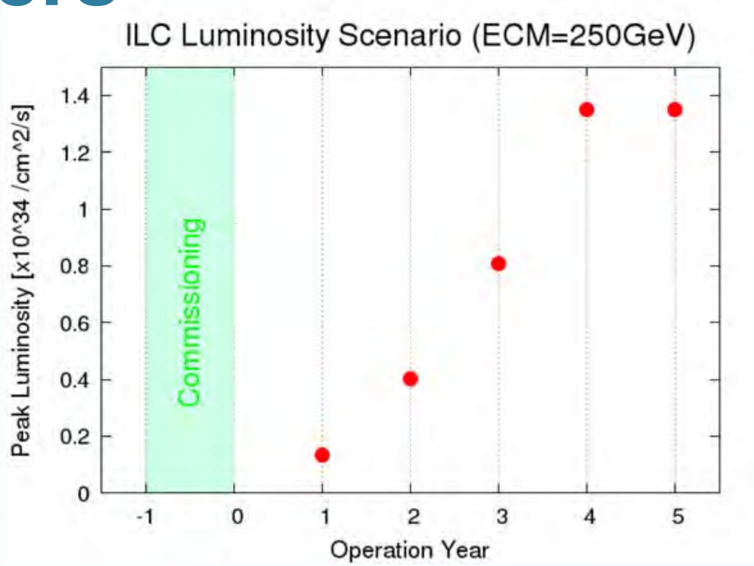
FCChh (FCCee)
16T Nb_3Tn/NbTn

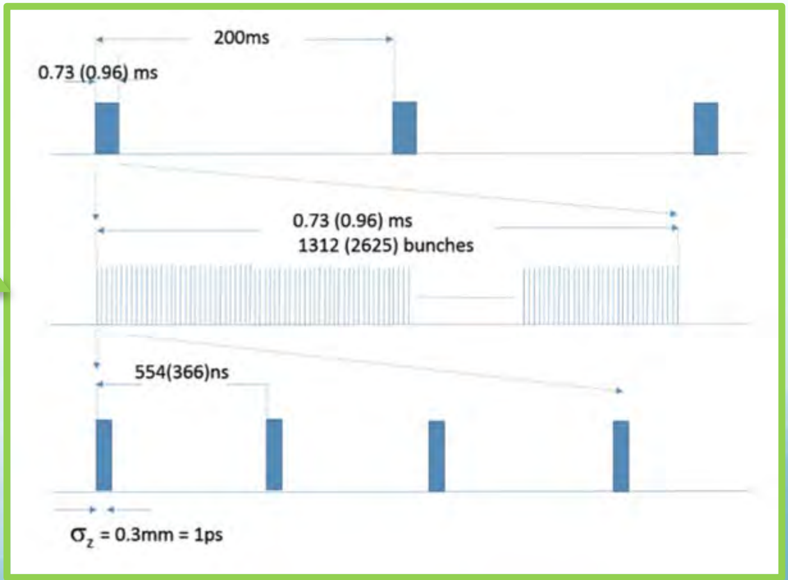
$\mu^+\mu^-$

ILC 250 GeV baseline parameters

ILC Parameters	Units	ILC250
Beam Energy	GeV	125 (e^-) and 125 (e^+)
Peak Luminosity (10^{34})	cm^{-2} s^{-1}	1.35
Int. Luminosity	ab^{-1}/yr	0.24*
Beam dE/E at IP		0.188% (e^-), 0.150% (e^+)
x/y Beam sizes at IP	nm	515 / 7.66
Rms bunch length /	cm	0.03 (σ_z)
beta*	mm	bx*=13mm, by*=0.41mm
Crossing angle	mrad	14
Rep./Rev. frequency	Hz	5
Bunch spacing	ns	554
# of bunches		1,312
Length/Circumference	km	20.5
Facility site power	MW	111
Cost (value) range	$B US	~5 (tunnel and accelerator)
Timescale till operations	years	(~1) + 4(prep.) + 9(construction)

** 5,000-hour operation at peak luminosity*





Accelerator activities at ILC Pre-lab phase

Technical preparations & SRF R&D for cost reduction [shared across regions]

- SRF performance R&D, quality testing of a large number of cavities (~100), fabrication and sh… n North America and Europe (for validating shipping)
- Positron source final design and verification
- Nanobeams (ATF3 and related): Interaction region: beam focus, control; and Damping ring: fast kicker, feedback
- Beam dump: system design, beam window, cooling water circulation
- Other technical developments considered performance critical

Technical preparation

Final technical design and documentation [central office in Japan with a support from other labs]

- Engineering design and documentation, WBS
- Cost confirmation/estimates, tender and purchase preparation, transport planning, mass-production planning and QA plans, schedule follow up and construction schedule preparation
- Site planning including environmental studies, CE, safety and infrastructure (see below for details)
- Review office
- Resource follow up and planning (including human resources)

Engineering Design Report (EDR)

Preparation and planning of deliverables [distributed across regions coordinated by the central office]

- Prototyping and qualification in local industries and laboratories, from SRF production lines to individual W…
- Local infrastructure development including preparation for the construction phase (including Hub.Lab)
- Financial follow up, planning and strategies for these activities

Planning and preparation of Hub lab.

Civil engineering, local infrastructure and site [mainly by the Japanese institutions]

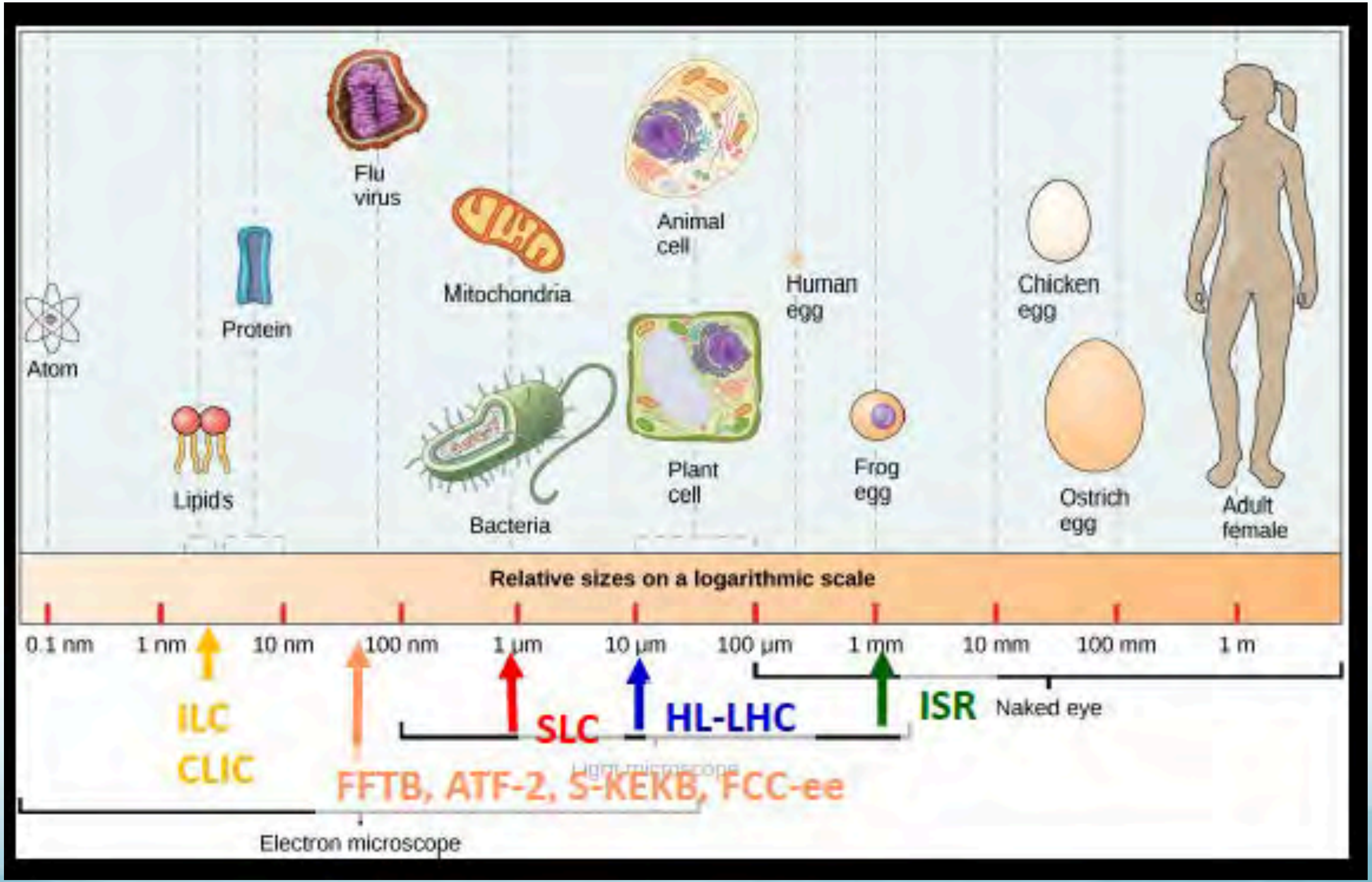
- Engineering design including cost confirmation/estimate
- Environmental impact assessment and land access
- Specification update of the underground areas including the experimental hall
- Specification update for the surface building for technical scientific and administrative needs

Civil engineering

Positron production performances in colliders

Parameters \ Colliders		SLC	LEP	SuperKEKB	CLIC	ILC	CEPC	FCC-ee baseline
e^- beam energy @ target [GeV]		33	0.2	3.5	5/5[3]	126.5	4	4.46
e^-/bunch[10^{10}]		3-5	0.5-30	6.25	0.52/0.44	2	6.25	4.2 (or 6.25)[4]
Bunch/pulse		1	1	2	352/312	1312	1	2
Repetition rate [Hz]		120	100	50	50/50	5	100	200
Target Scheme	γ production way for pair creation	bremsstrahlung	bremsstrahlung	bremsstrahlung	Oriented Crystal (channeling)	helical undulator	bremsstrahlung	bremsstrahlung \ Oriented Crystal
	Target material	W74-Re26	W74-Re26	W	radiator (W) + converter (W74-Re26)	Ti	W	W74-Re26 \ radiator (W) + converter (W74-Re26)
Target mobility		moving	fixed	fixed	fixed	moving	fixed	moving
Capture system		AMD[1]	QWT[2]	AMD	AMD	AMD	AMD	AMD
Capture linac frequency [GHz]		2.856	2.999	2.856	1.999	1.3	2.860	1.999/2.856
DR energy [GeV]		1.15	0.5	1.1	2.86	5	1.1	1.54
e^+ yield @ injector exit		1.1	0.003	0.4	1	1.5	≥ 0.3	≥ 0.7

Where are we?



Atom
Lipids
Protein
Flu virus
Mitochondria
Bacteria
Animal cell
Plant cell
Human egg
Frog egg
Chicken egg
Ostrich egg
Adult female
Relative sizes on a logarithmic scale
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
10 mm
100 mm
1 m
ILC
CLIC
FFTB, ATF-2, S-KEKB, FCC-ee
SLC
HL-LHC
ISR
Naked eye
Electron microscope

Key parameters for CC e+e-

M. Benedikt, Granada 2019

Collider (all double rings)	Beam energy [GeV]	Peak luminosity (per IP) [10^{34} cm^{-2}s^{-1}]	β_y^* [mm]	beam current [mA]	Collision scheme	Beam lifetime [min]	e^+ top-up rate [10^{11}/s]
SuperKEKB	4 (e^+), 7 (e^-)	80	0.3	3600 (e^+), 2600 (e^-)	Nano-beam	<5	10
BINP c-t	1-3	5-20	0.5	2200	Crab waist	<10	1
HIEPA c-t	1.5-3.5	~10	0.6	2000	Crab waist	<10	1
FCC-ee (Z)	45.6	230	0.8	1500	Crab waist	68	7
FCC-ee (H)	120	8.5	1.0	29	Crab waist	12	1
FCC-ee (t)	182.5	1.6	1.6	5	Crab waist	12	0.2
CEPC (Z)	45.5	32	1.0	460	Crab waist	150	1.1
CEPC (H)	120	3	1.5	17	Crab waist	26	0.2

Many similar parameters and strong synergies for design

FCCee and CepC: RF systems

	f_{RF} [MHz]	#cavities	#cell/cavity	$V_{RF,tot}$ [MV]	acc. gradient [MV/m]	technology
SuperKEKB	509	30 (ARES) 8 (SCC)	1 1	15 12	2 6	warm Cu bulk Nb
charm-tau	500	1 / ring	1	2x1	6	bulk Nb
FCC-ee-H	400	136 / ring	4	2000	10	Nb/Cu
FCC-ee-t (addt'l)	800	372	5	6930	19.8	bulk Nb
CEPC	650	240	2	2200	19.7	bulk Nb

- all systems between 400 and 800 MHz, various technologies,
- preference for SC cavities,
- FCC-ee RF system optimized for each working point, CEPC features single system

Machine parameters of SuperKEKB in June 2021

	LER	HER	Units
Beam energy [-60MeV from Υ(4S) resonance], E_b	4.000-0.023	7.007-0.040	GeV
Luminosity	3.12 x 10^{34}		$cm^{-2}s^{-1}$
Revolution freq. f_{rev}	99.39		kHz
Date & Time	June 22nd 2021, 18:30		
Injector rep. rate	12.5 (2bunch/inj.)	25 (1bunch/inj.)	Hz
Beam current, I_b	790.3	686.6	mA
Half crossing angle	41.5		mrad
# of bunches, N_b	1174		
β_x^*	80	60	mm
β_y^*	1	1	mm
σ_x^*	24	22	µm
σ_y^*	0.26	0.23	µm
Bunch length, σ_z	5.9	6.2	mm
Vertical beam-beam parameter, ξ_y	0.0529	0.0264	