Progress of Linear Colliders: ILC/CLIC

Junping Tian (U. Tokyo)

Many thanks to Shinichiro Michizono & Steinar Stapnes for accelerator inputs

Talk is largely based on a combined talk given at ECFA HF Workshop 2022 by F. Simon & JT

2023 CEPC Workshop, October 23-27 @ Nanjing U.

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Driving force of future e+e-

Perspective of Energy

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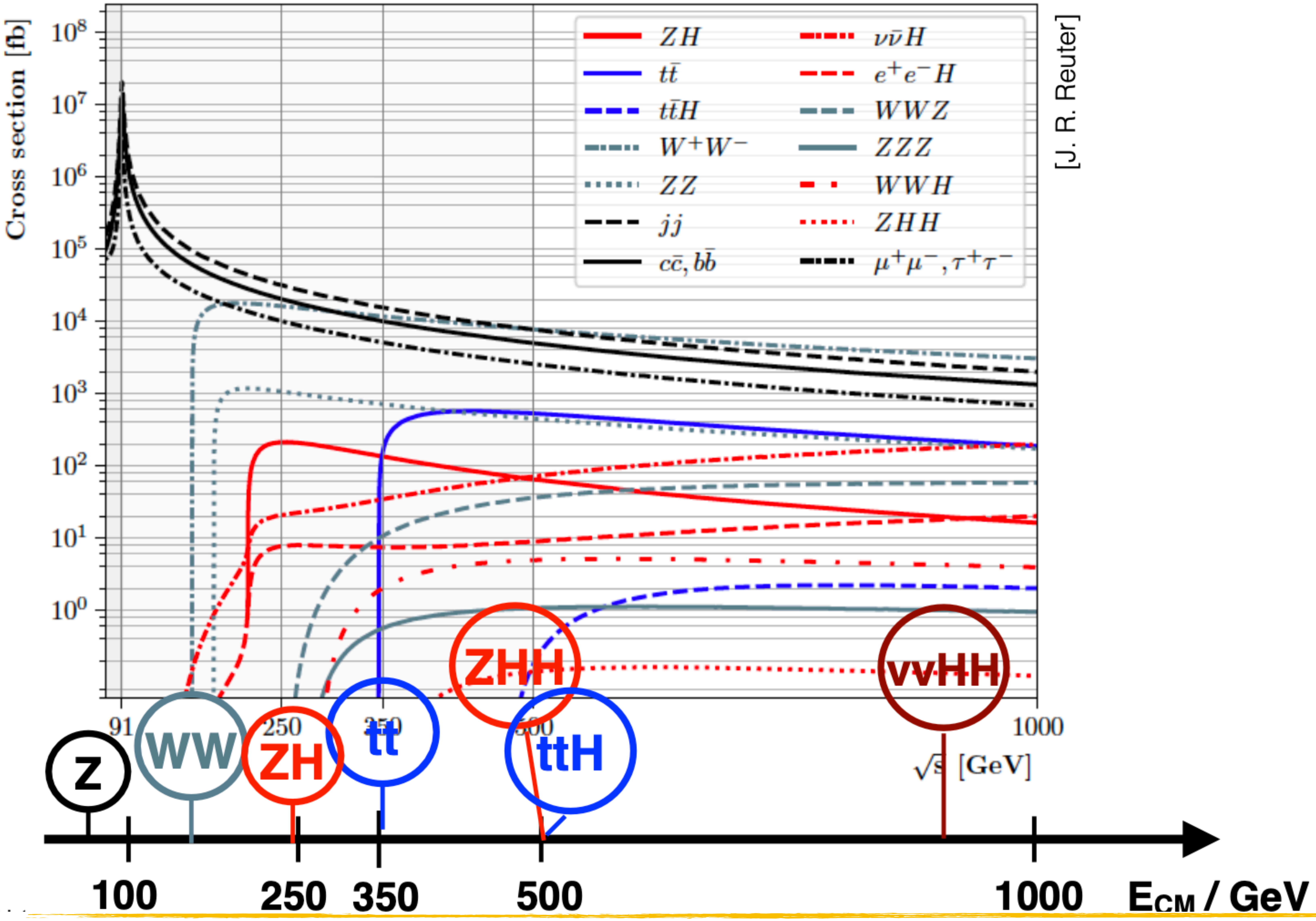
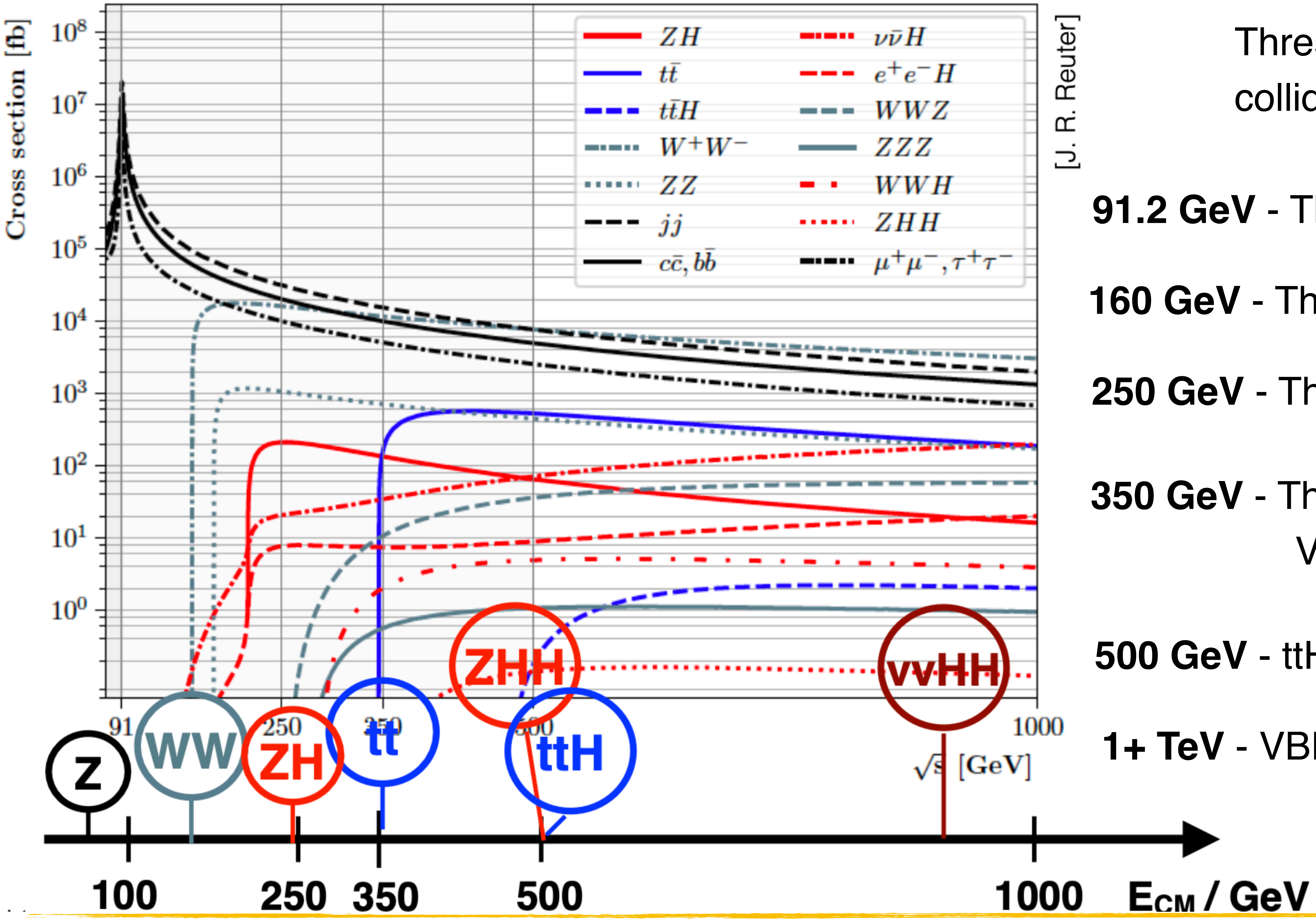


Driving force of future e+e-

Perspective of Energy



Thresholds and cross sections set collider energy targets:

91.2 GeV - The Z pole

160 GeV - The WW threshold

250 GeV - The ZH maximum

350 GeV - The top threshold,
VBF Higgs production

500 GeV - ttH, ZHH

1+ TeV - VBF double Higgs

Driving force of future e+e-

Perspective of Energy

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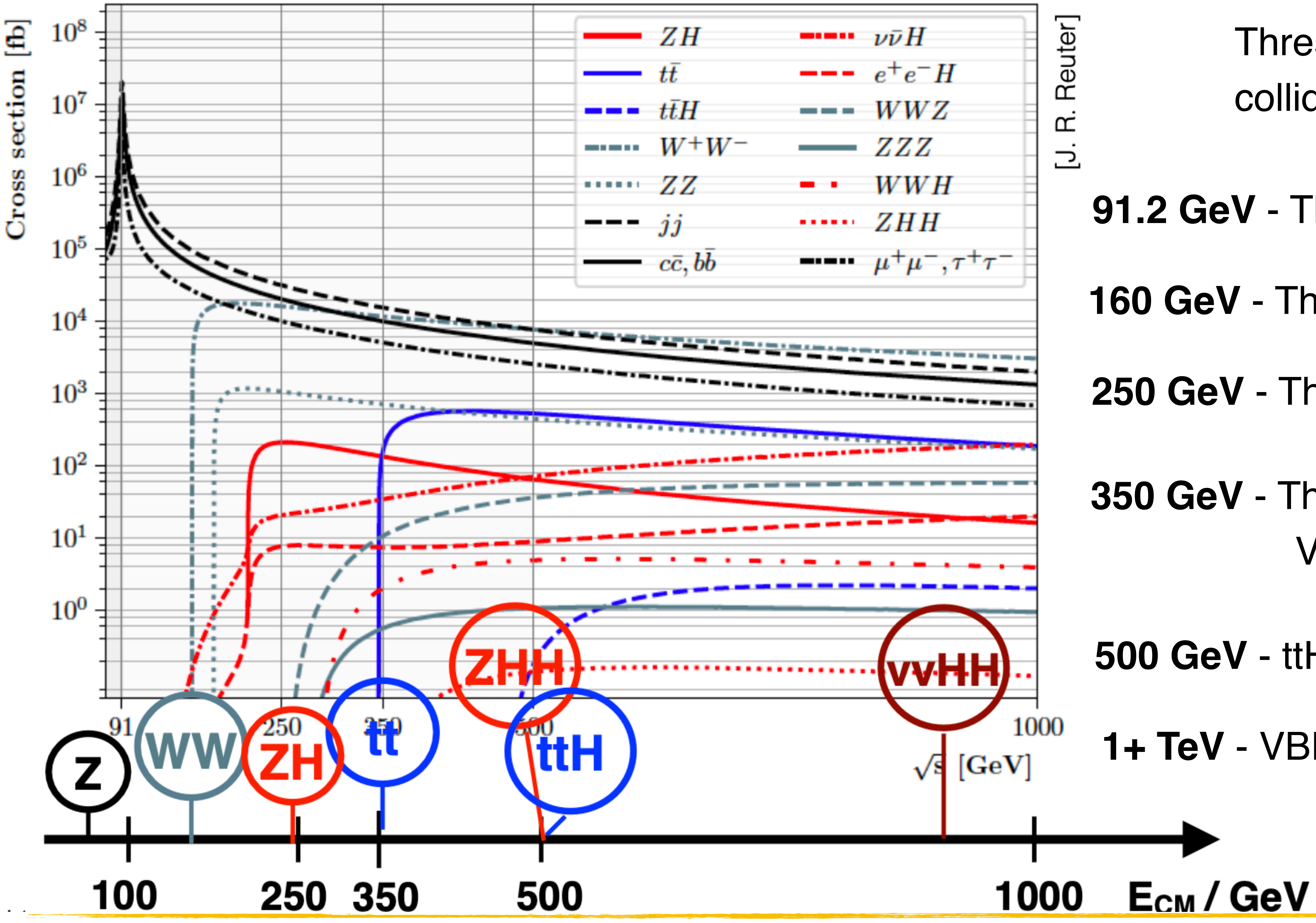

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Precision electroweak, Flavour, QCD, …

Higgs properties & couplings

Top properties, Top as probe

Direct top Yukawa
Higgs selfcoupling

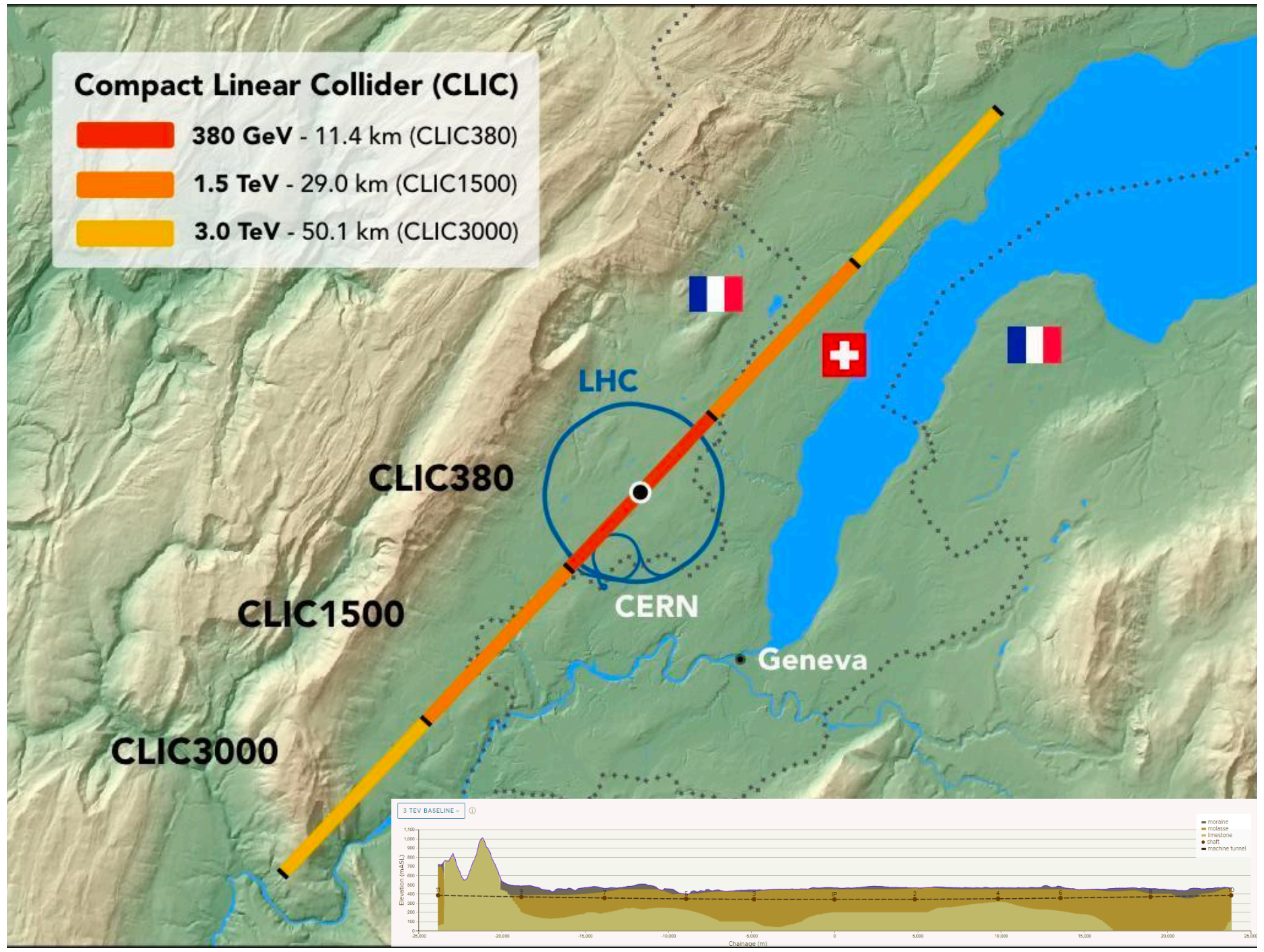
Search at the energy frontier

Linear Colliders

ILC & CLIC specs

- Energy extendability to TeV scale lies in the heart of linear colliders: ILC focuses on √s from 250 GeV to 1 TeV; CLIC 380 GeV to 3 TeV; keeping options to run at Z-pole (“GigaZ”)
- Complementary approaches: “Warm” & “Cold” accelerating technologies; 72MeV/m @ CLIC380; 31.5MeV/m @ ILC250
- Polarized beams: both offering 80% for electron; 30% for positron in ILC default design

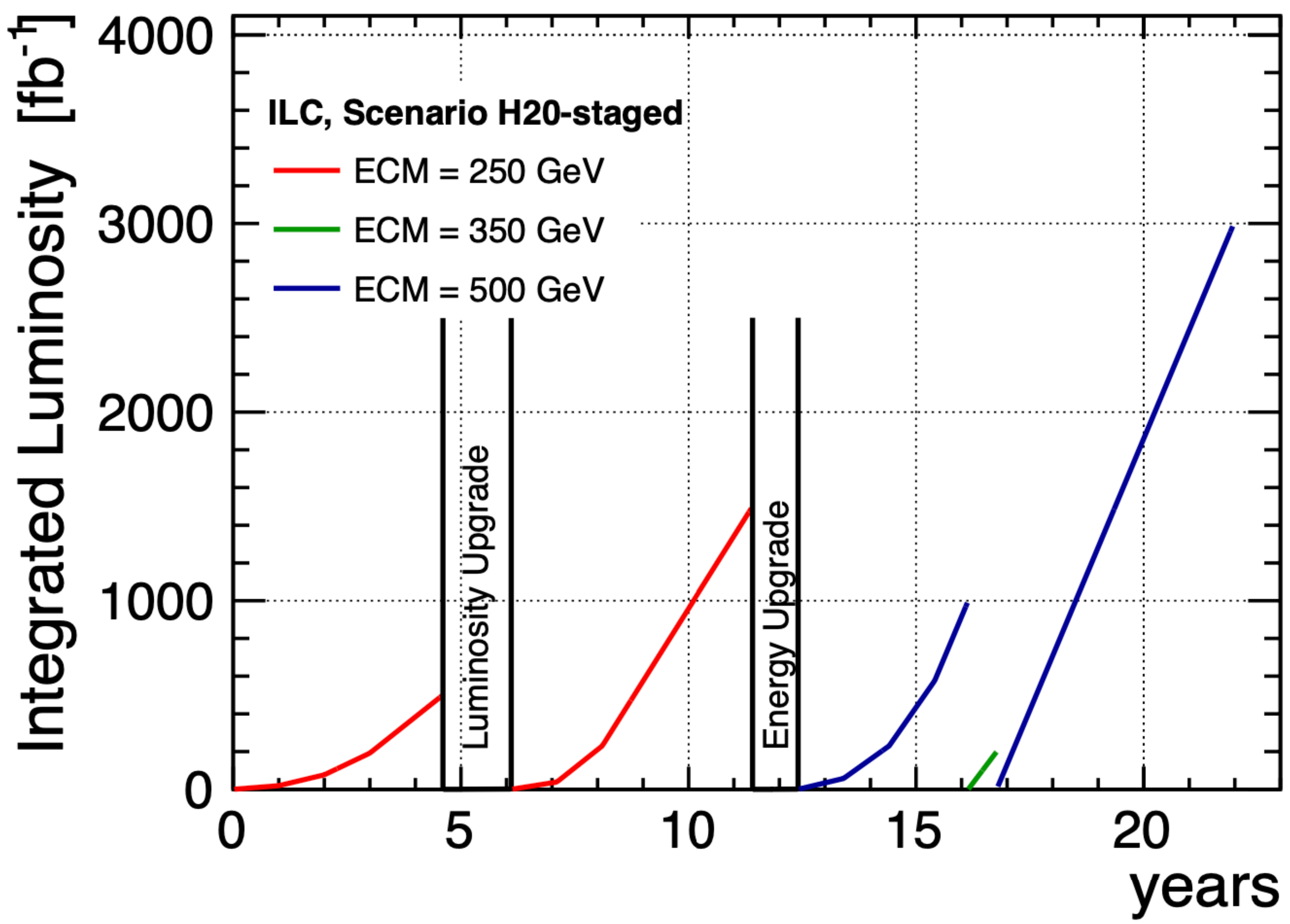
ILC250 ~ 20km



Linear Colliders

running scenarios for benchmark studies

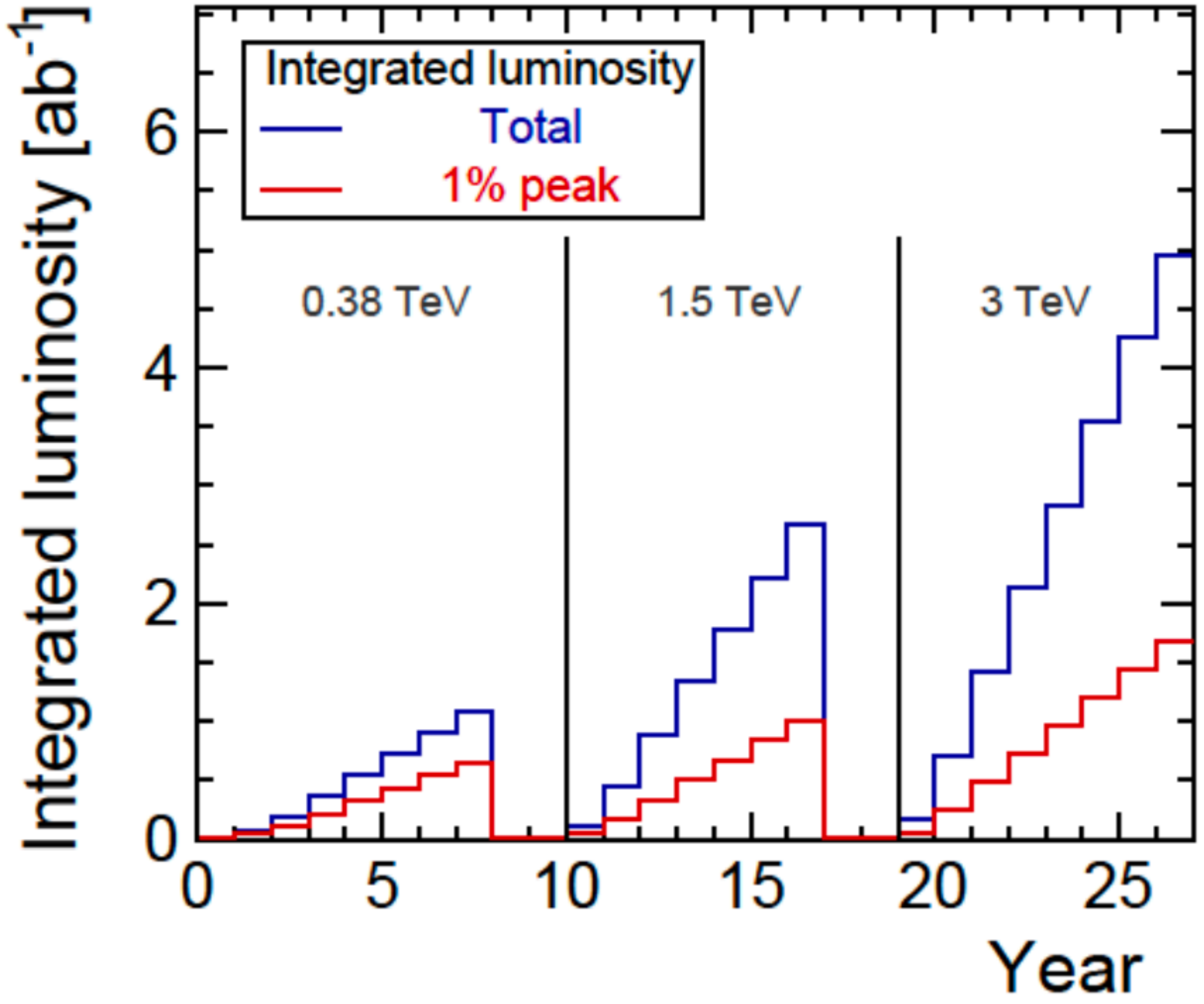
ILC



	91 GeV	250 GeV	350 GeV	500 GeV	1000 GeV
$\int \mathcal{L}$ (ab^{-1})	0.1	2	0.2	4	8
duration (yr)	1.5	11	0.75	9	10
beam polarization (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(LL, LR, RL, RR) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)
δ_{ISR} (%)	10.8	11.7	12.0	12.4	13.0
δ_{BS} (%)	0.16	2.6	1.9	4.5	10.5

[arXiv:2203.07622]

CLIC



	380 GeV	1.5 TeV	3 TeV
∫L (ab^{-1})	1	2.5	5
P(e-,e+;%)	80/0	80/0	80/0
(LR,RL)	(50,50)	(80,20)	(80,20)

[arXiv:2203.07622]

ILC Accelerator Status

from mature to ready

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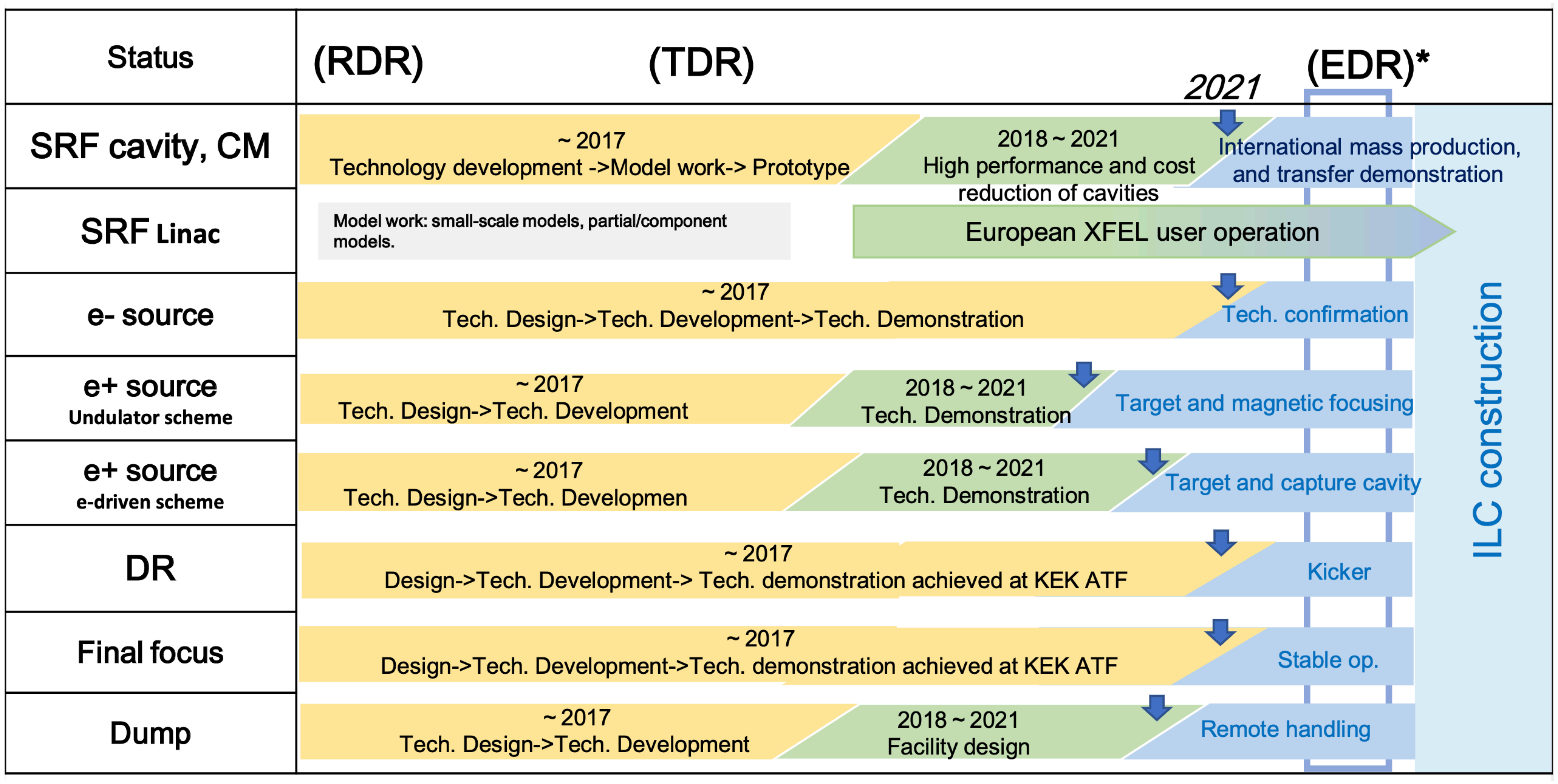
- TDR published in 2013; progress steadily towards to final technology choice and engineering design; optimization to lower cost
- Key technology

  SRF accelerating
  Nano-beam

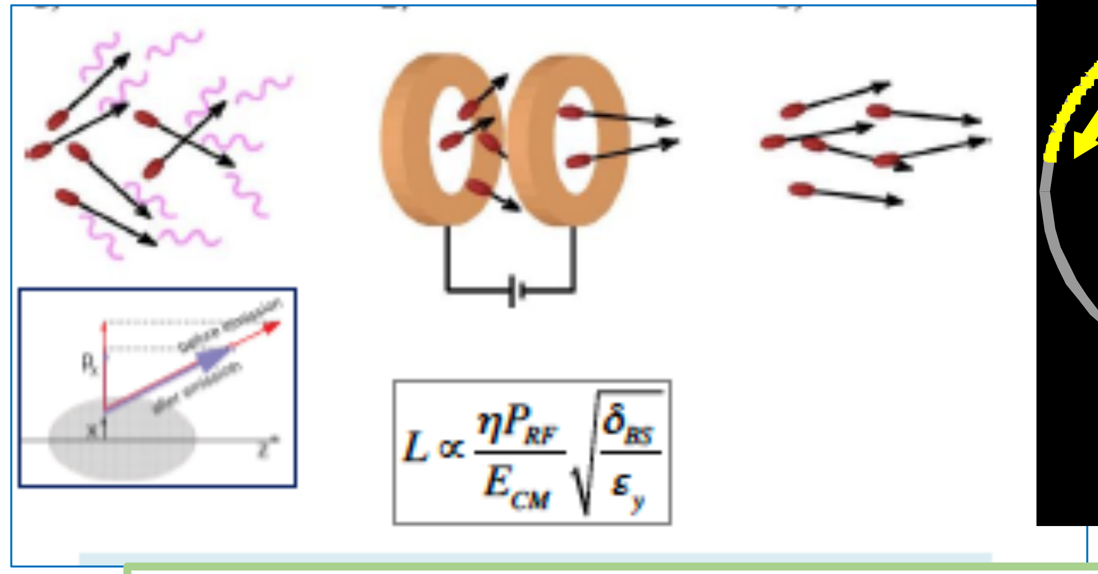
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}

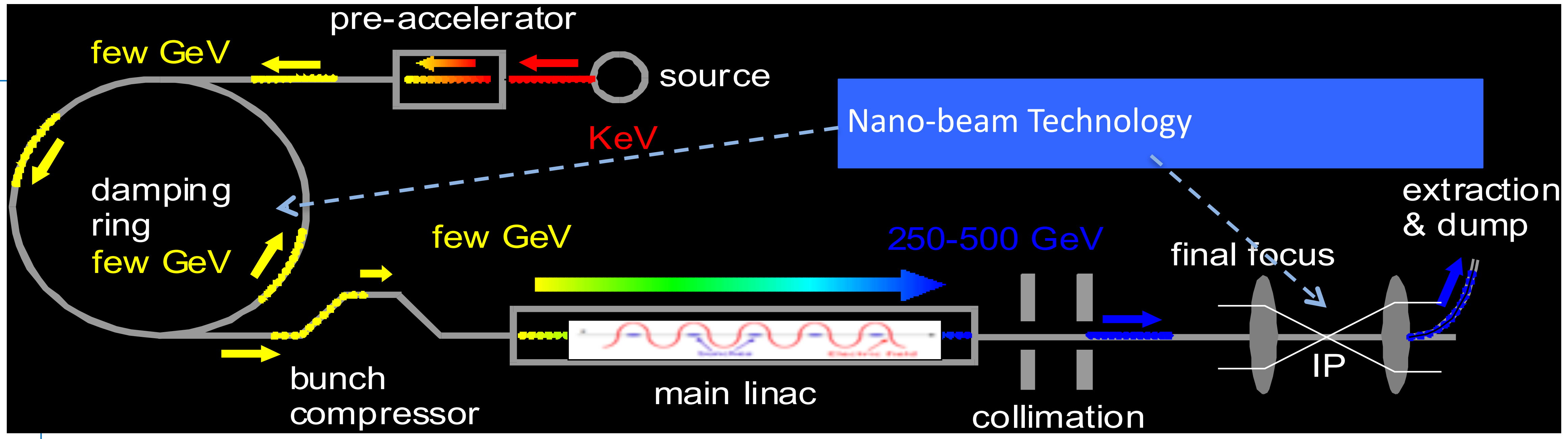


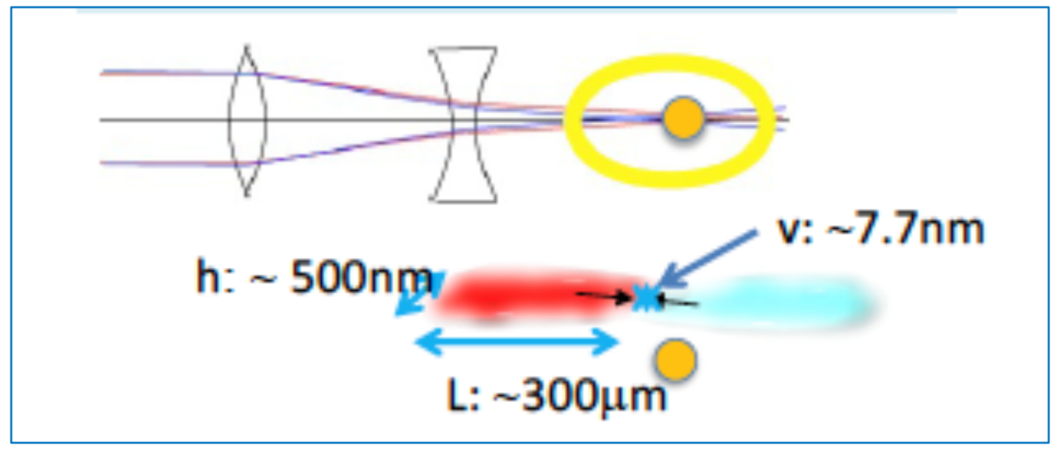
[S.Michizono @ ILCX2021]

Progress in Nano-beam Technology

Damping ring & Final focus





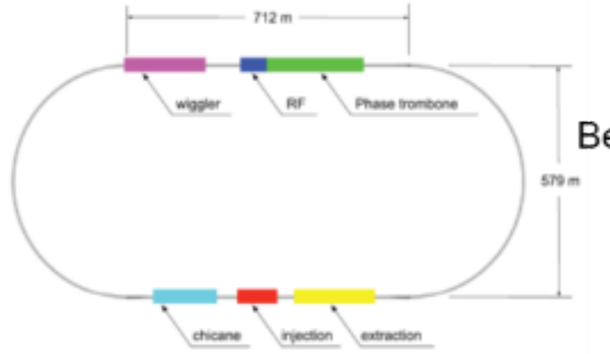


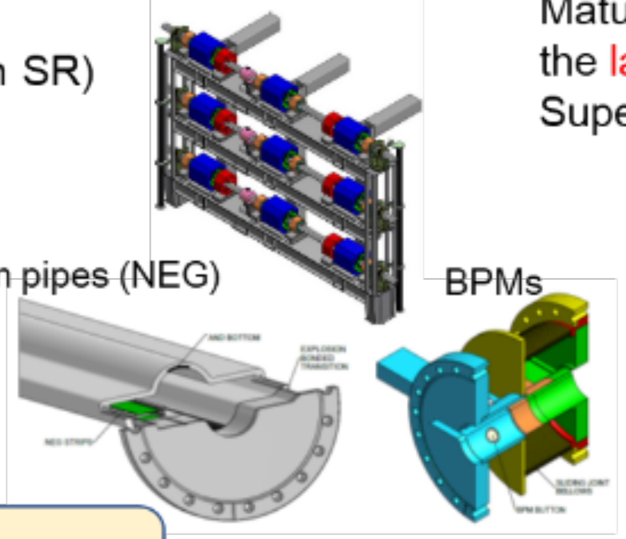
Progress in DR

~2017	2018~

DR — Eng. design

Design based on experience with circular accelerators (4th generation SR) around the world

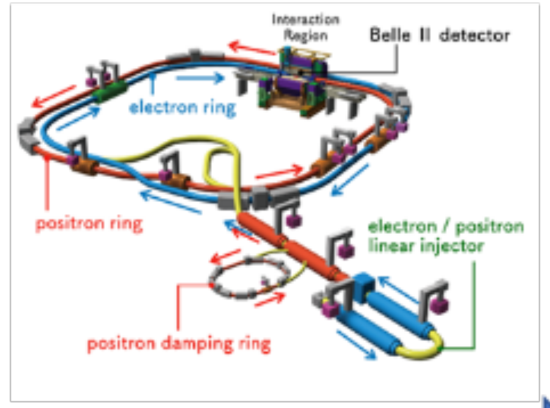




Beam pipes (NEG)

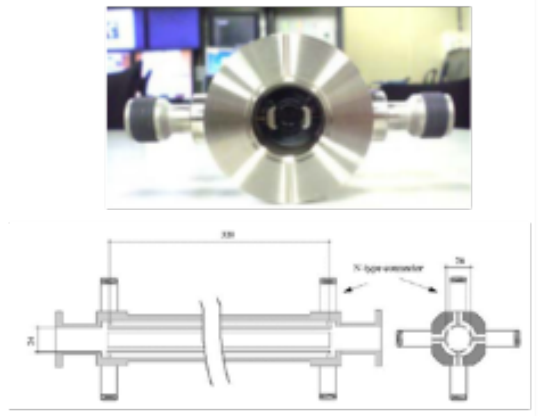
BPMs

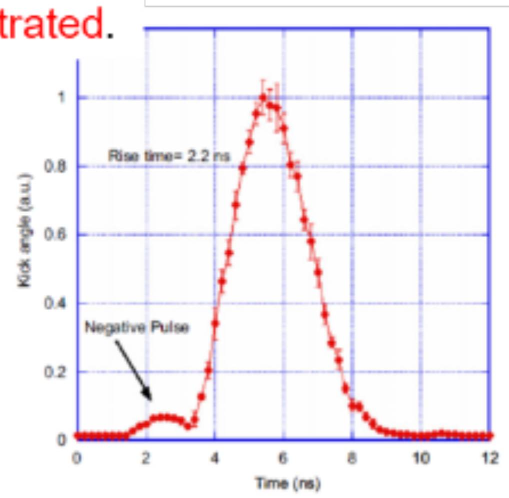
Maturing technology for beams in the latest ring accelerators such as SuperKEKB



Inj./Ext. — Eng. Design / Equipment verification

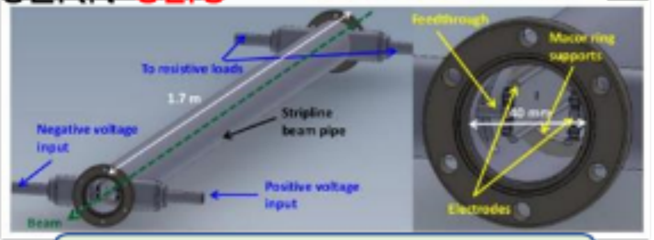
Beam extraction demonstrated.





LBNL

CERN-CLIC

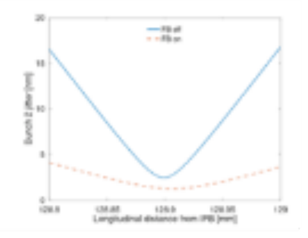


Fast kicker technology

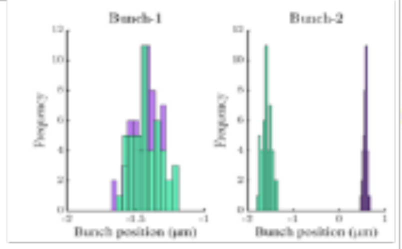
Progress in Final Focus

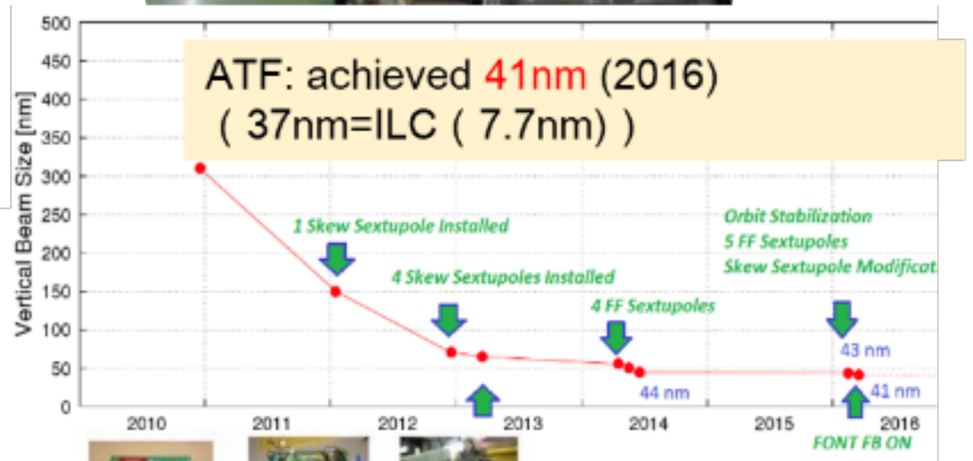
~2017	2018~

Tech. design completed
Spec. almost achieved

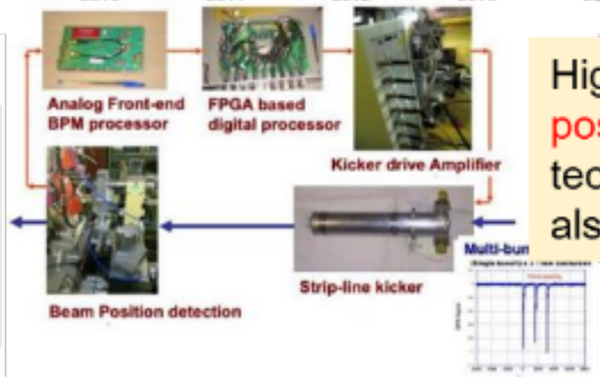


Distribution of bunch positions measured at IPB, with two-BPM FB off (green) and on (purple)





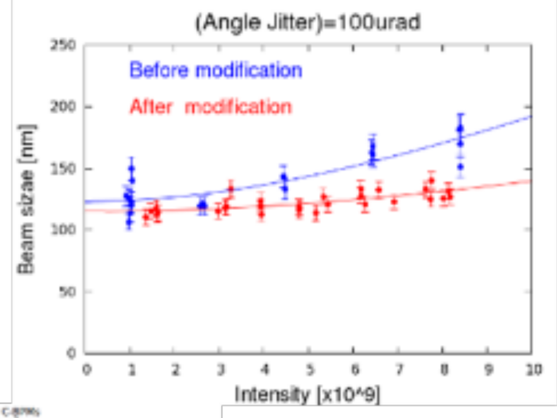
ATF: achieved 41nm (2016)
(37nm=ILC (7.7nm))

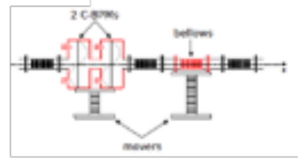


High-speed beam position control technology was also demonstrated.

FONT feedback system

Wakefield effects





ATF2 wakefield knobs system be-tween BPM QD10BFF and QD10AFF

Wakefield effect was evaluated at ATF.
-confirm no serious problem at ILC
-demonstrate a technique to reduce the wakefield effect

ATF International Review (Committee)*
-The committee highly evaluated the achievements of ATF so far.
-The committee pointed out the importance of continuing research to contribute to the detailed design of the ILC final convergence.

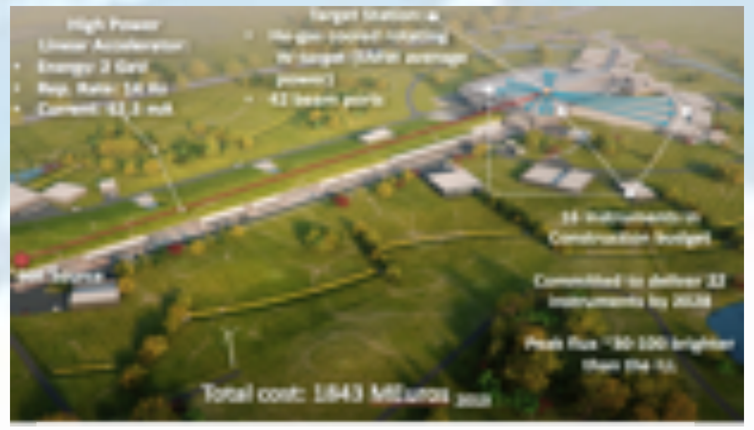
*https://agenda.linearcollider.org/event/8626/

Progress in SRF Technology

~1.3 GHz worldwide SRF accelerators

European XFEL
(in operation, 2017~)

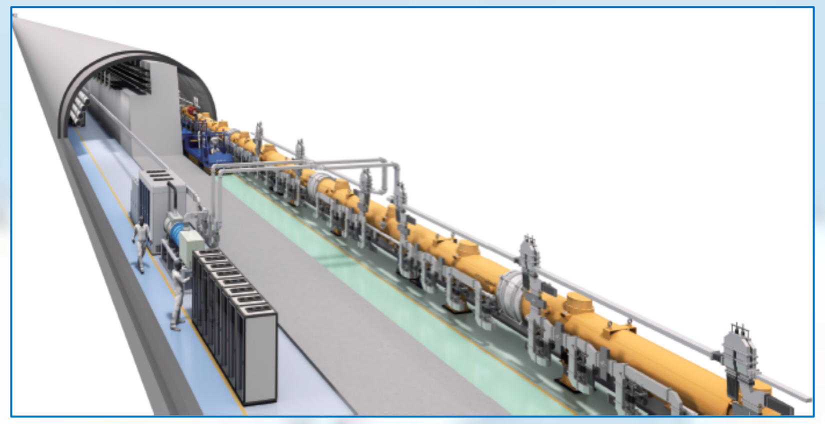
800 cavities
100 CMs
17.5 GeV (Pulsed)



ESS (0.8 GHz)
(under construction)

SHINE
(under construction)

~600 cavities
75 CMs
8 GeV (CW)



ILC (planned)

8,000 9-cell cavities
900 CMs
2 x 125 GeV (Pulsed)

LCLS-II -HE
(in commissioning)

-280+200 cavities
-35+25 CMs
- 4 +4 GeV (CW)

JLab-CEBAF(1.5 GHz)
(in operation)
40 CMs
6~12 GeV(CW)

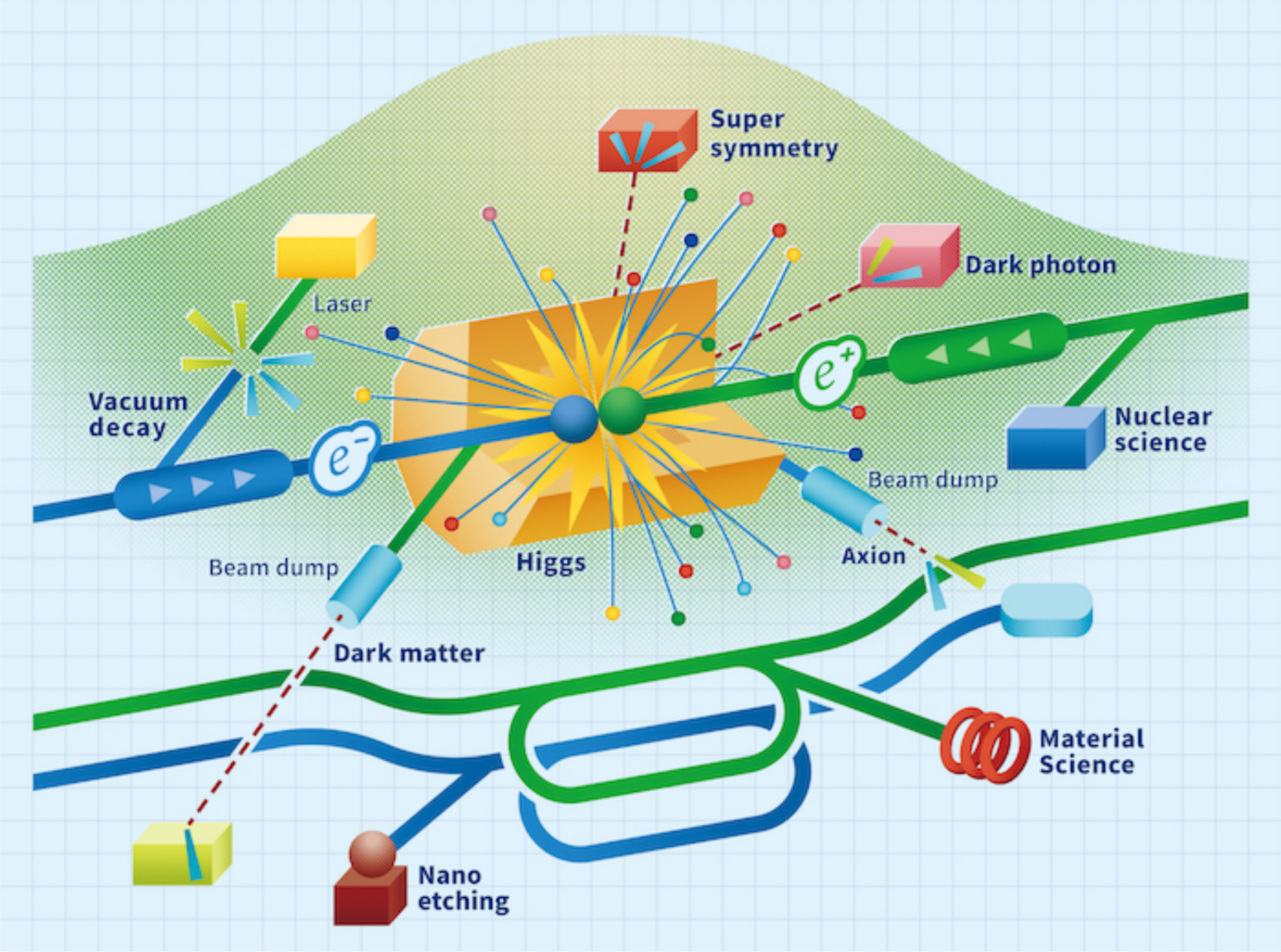
> 2,000 SRF cavities being realized!

ILC Facility News

Make more out of the beams

- Turn the beam dump into fixed-target experiment: 4×10^{21}/y electrons on target
- Dedicated detectors away from IP
- Accommodate strong QED experiment: Schwinger E-field (e+e- pair production from vacuum)
- Beam extraction for Nuclear or Material Science
- Under active discussion

[ILCX2021 workshop]



CLIC Accelerator Status

2021-2025

CLIC is working towards a Project Readiness Report 2025/26 as a step toward a TDR – for next ESPP

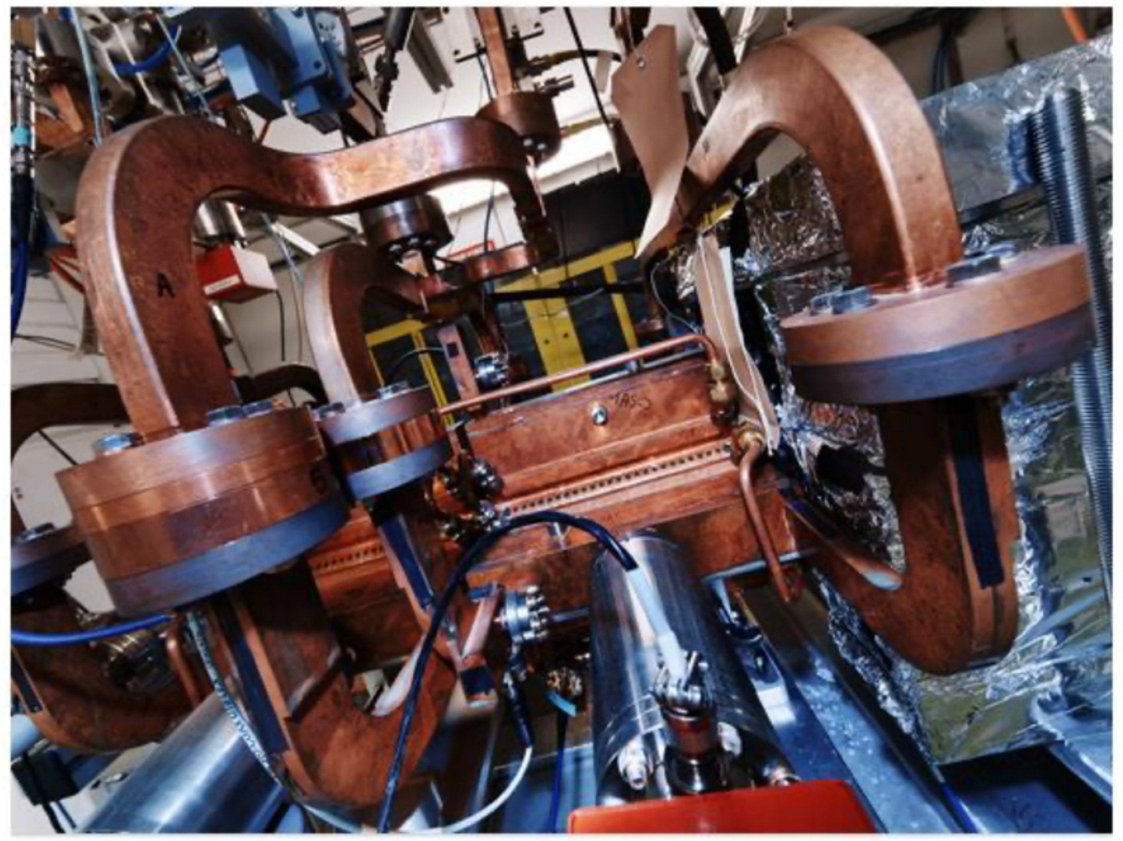
Focusing on:

- X-band technology readiness for the 380 GeV CLIC initial phase — more and more driven by use in small compact accelerators where immediate industrial readiness is needed
- Optimizing the luminosity at 380 GeV
- Improving power efficiency for both initial phase & high energies

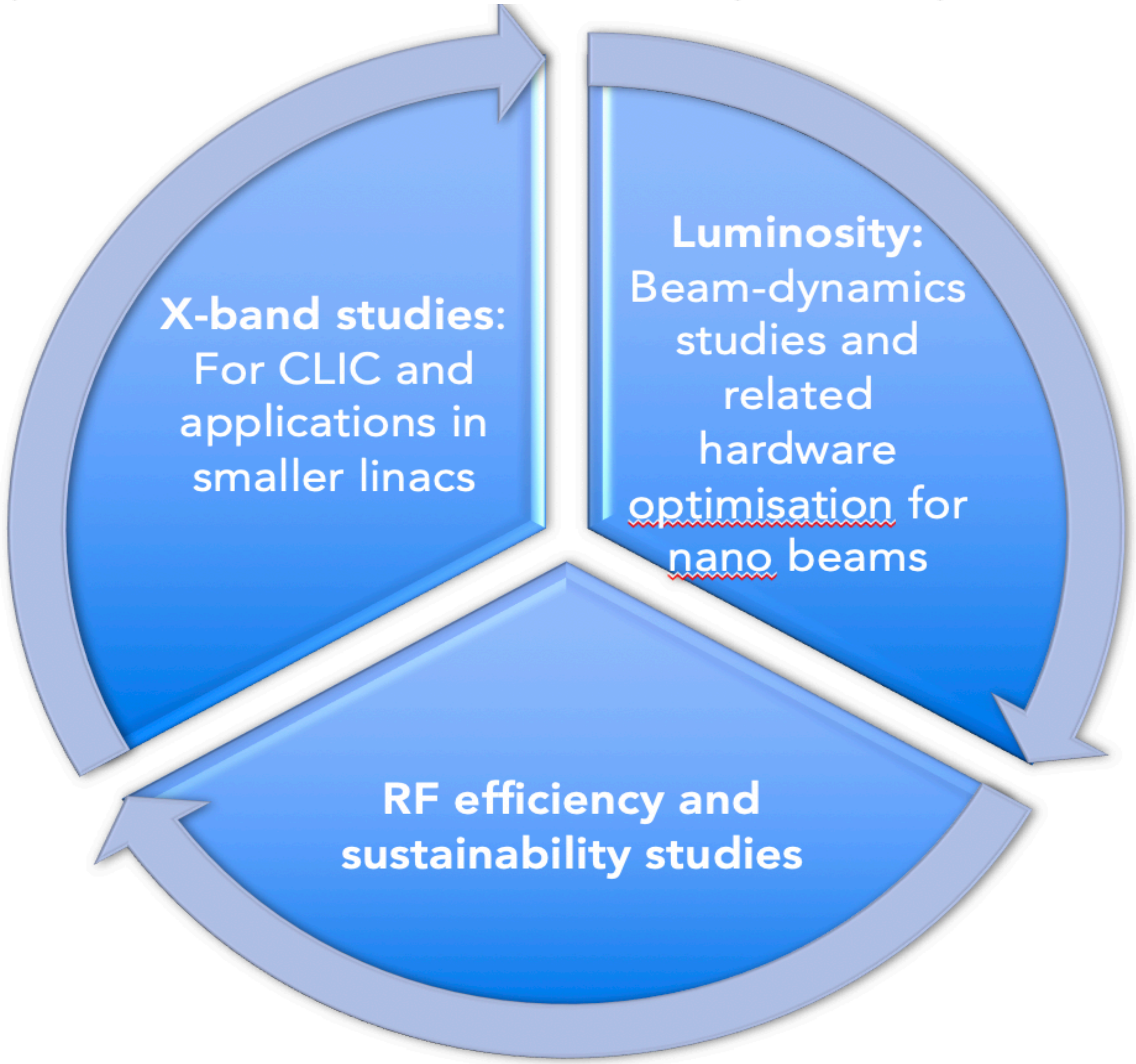
CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

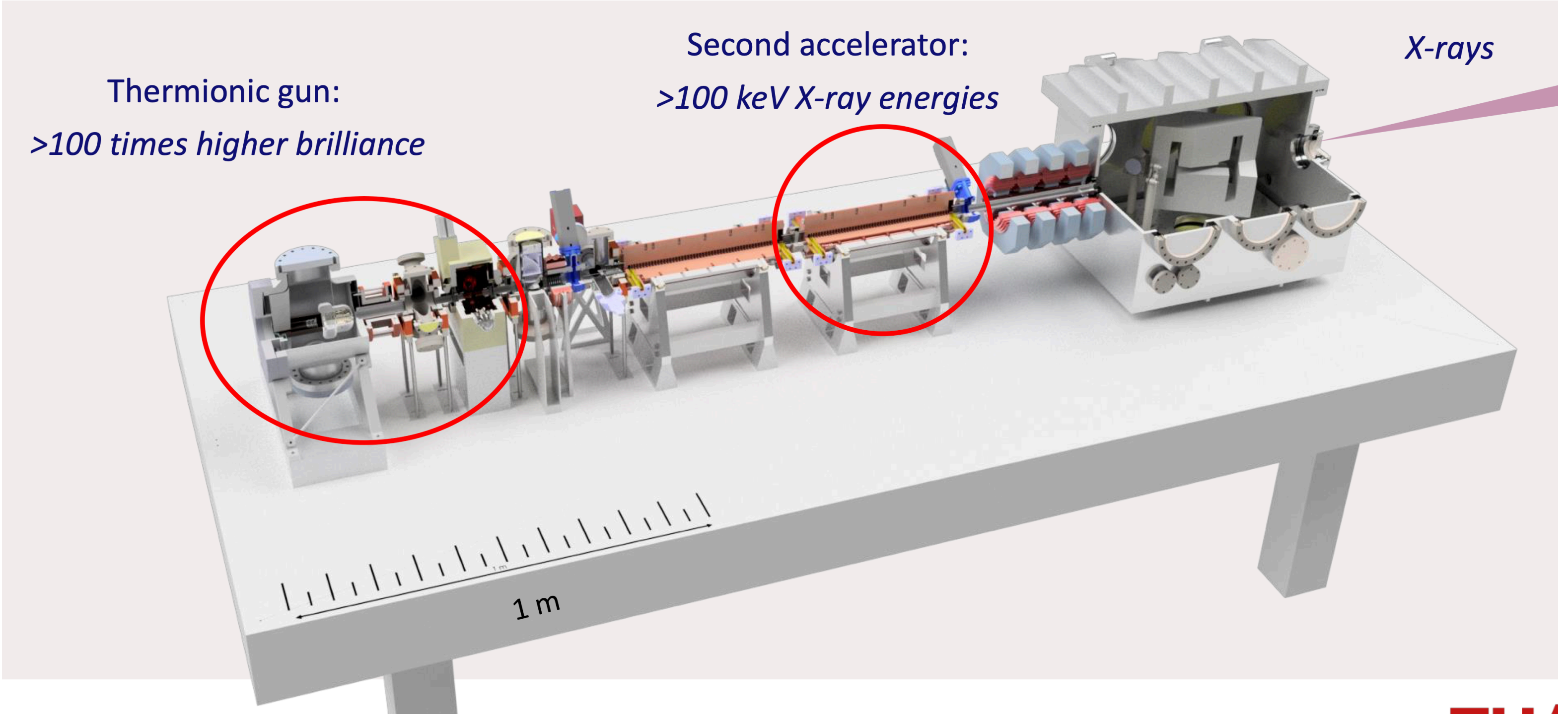
CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020



Close-up of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)





CLIC Accelerator Status

Extensive prototyping over the last ~5-10 years

The CLIC accelerator studies are mature:

Optimised design for cost and power

Many tests in CTF3, FELs, lightsources and test-stands

Technical developments of “all” key elements

ILC Project News

towards realization

- MEXT (represents Japanese government) didn't approve the original Pre-Lab proposal [newsline]
- Not entirely negative: pointed out what directions to move forward ["hosting is not the problem", S.Asai]
- Support to carry out time-critical R&D that was in the Pre-Lab proposal
- A really encouraging sign from this April: a fact of 2 increase on KEK funding for ILC R&D by MEXT
- ILC Technology Network (ITN) is launched: memorandum between KEK & CERN signed
- Promotion under leadership by International Development Team (IDT), KEK and ILC-Japan

What is the goal in spring 2023? [T.Nakada @ Snowmass 2022]

- The International Network for the ILC related technology development is ready to start or even has started.
- The International Expert Panel makes a significant advancement in the discussion for Step 1

Step 1 **Developing a path for a global project adoptable for the ILC:**

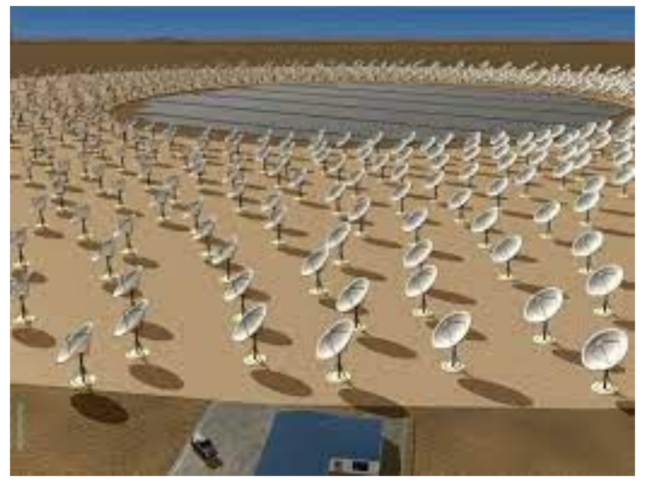
Step 2 **Developing the ILC decision roadmap by adopting this path**

ILC Promotion

Paradigm shift: from “international” to “global”

Global project: Starts and evolves as a collaborative project of partner countries who make collective decisions on all aspects of the project, such as the scheme for cost and responsibility sharing, project organisation, and host and site location. The ownership is shared among the partners.

ILC



SKA

ITER

[S. Asai]

International project: Initiated as a project of a laboratory with a limited international participation, a total of O(10~20%) of the accelerator, like HERA (started as a DESY project) and LHC (started as a CERN project). This fraction may become larger but the ultimate ownership remains with the initiator.

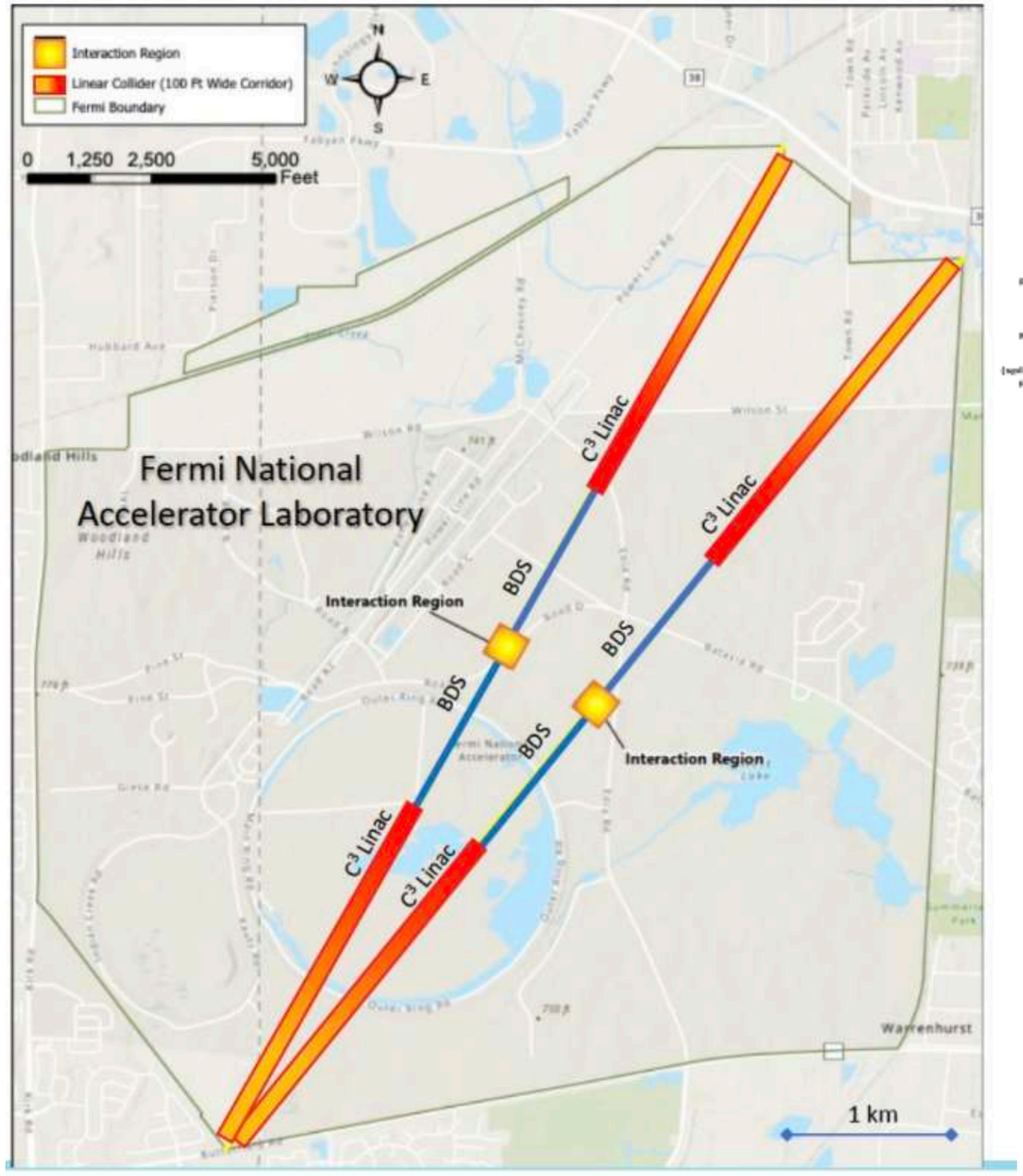
Our usual approach

- If ILC is not moving forward as expected…
- New linear collider proposals sited in US as discussed in Snowmass 2022

C3 Workshop 2022

[V.Sheltsev @ Snowmass 2022]

arxiv:2203.08211 arxiv:2110.15800

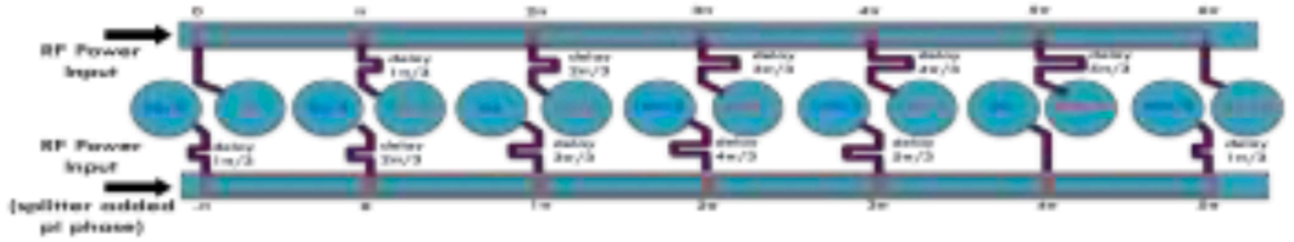


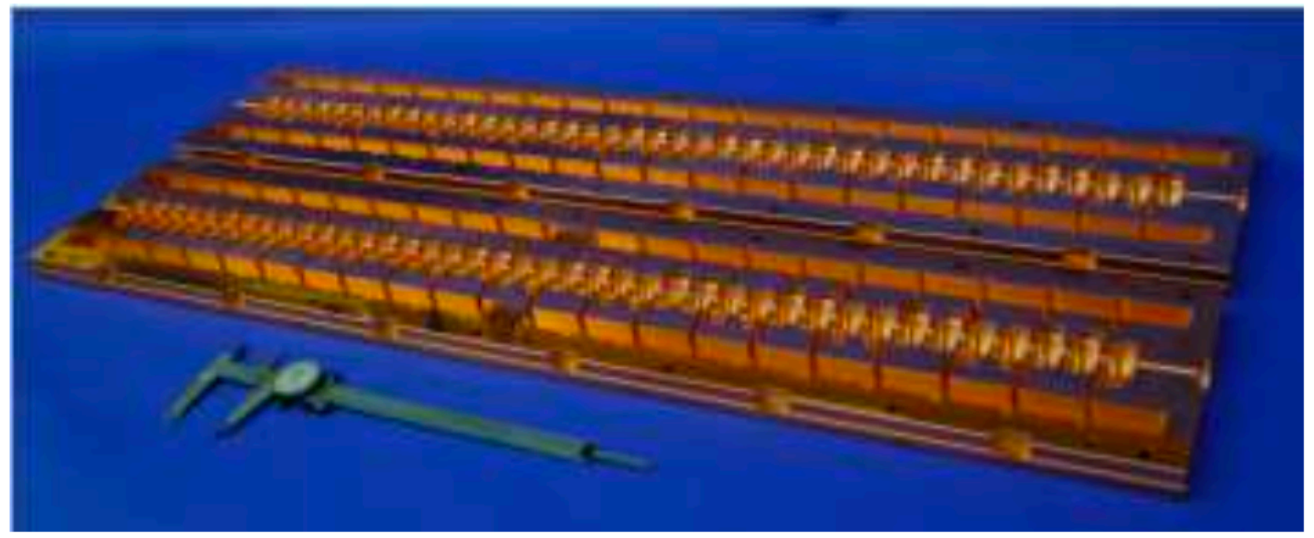
Must fit ~7 km including BDS

Required gradients of **at least 70MV/m**

Compact → lower cost (wrt ILC/CLIC)

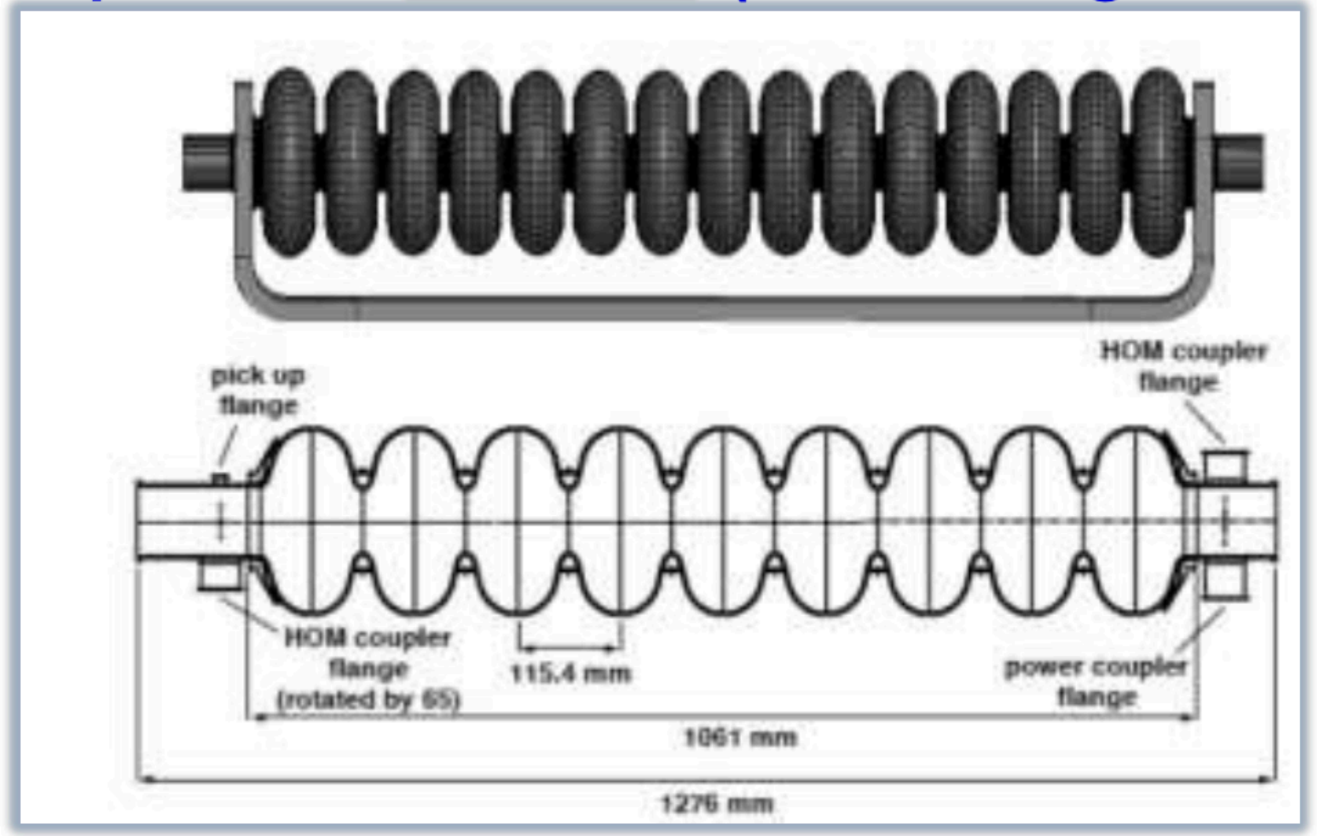
Option 1: Cool Copper Collider (C^3)





5.7GHz
77K

Option 2: *HELEN* (Travelling Wave ILC)



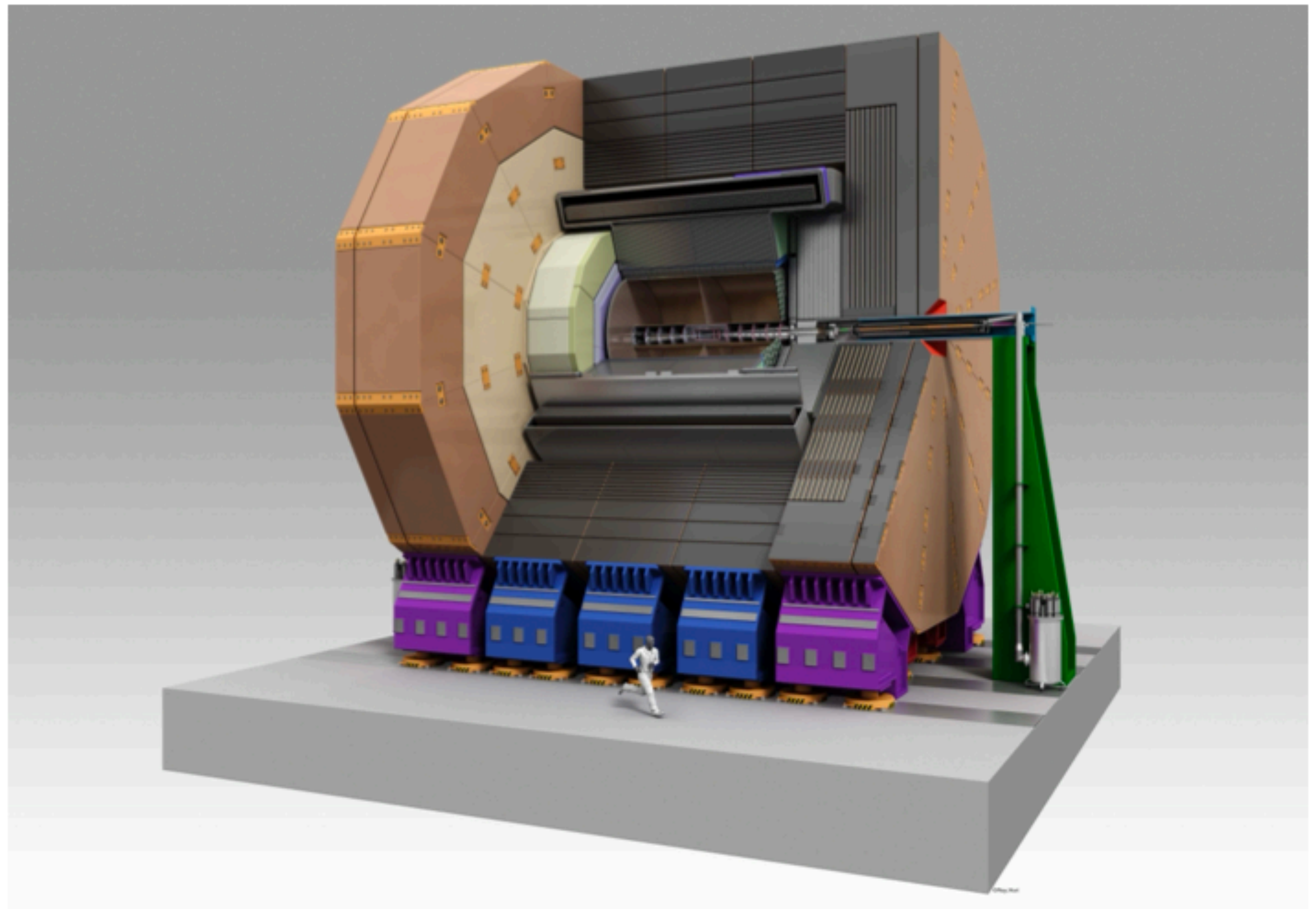
1.3GHz
2 K

Detector for Linear Colliders

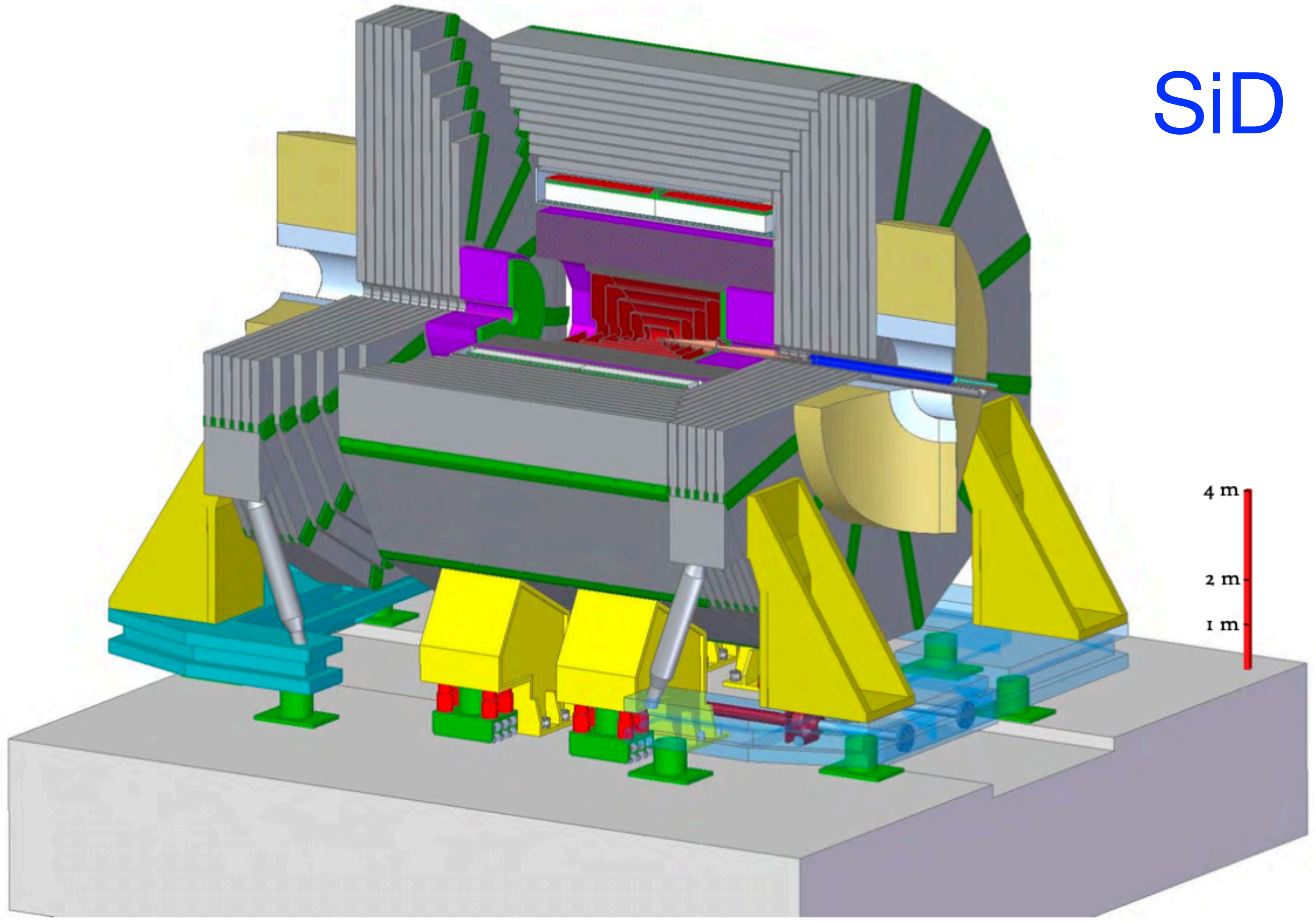
lineup

- Only one IP at linear colliders; two detector concepts proposed for ILC with "push-pull" scheme
- ILD and SiD concepts are very mature: Detailed Baseline Design (DBD) completed a decade ago; continuous prototyping and demonstrating by beam test; very close collaboration with CALICE, LCTPC, FCAL
- Current status are summarized in ILD interim design report and Updating the SiD concept
- [ILD2022] towards a strategy for ILD not only at ILC but also at other e+e-

ILD



SiD

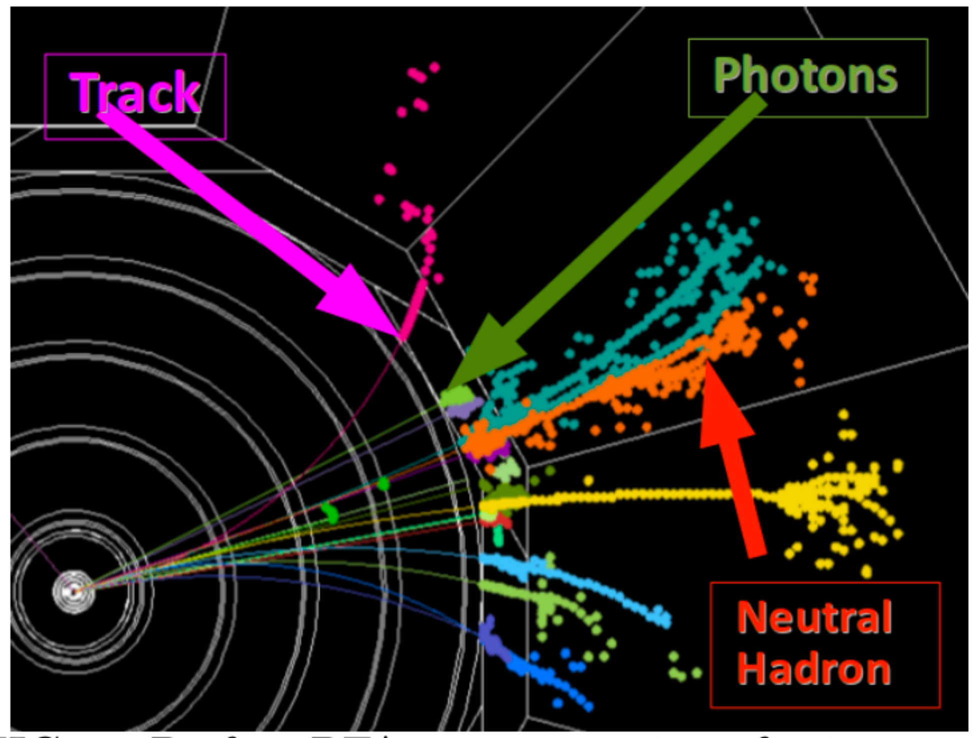


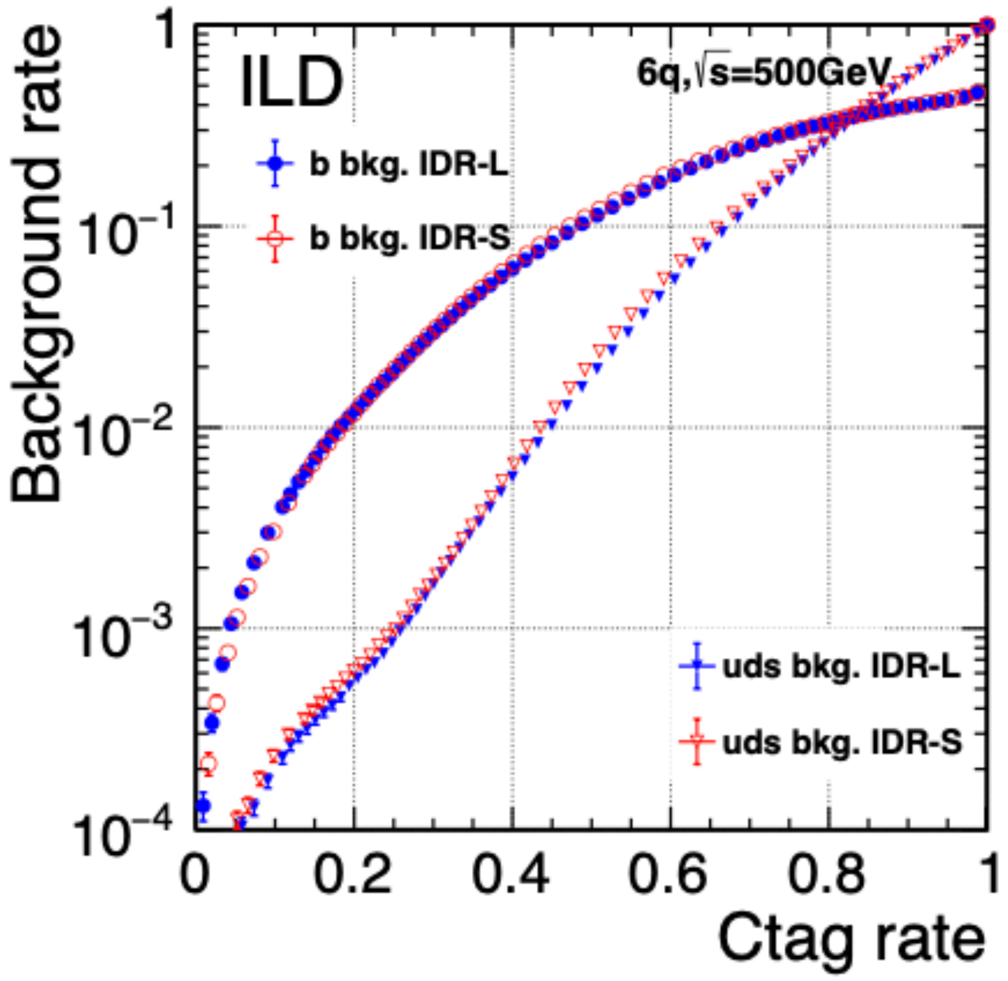
similar performance; major difference in tracking volume, TPC vs Full Silicon;

Detector Concepts

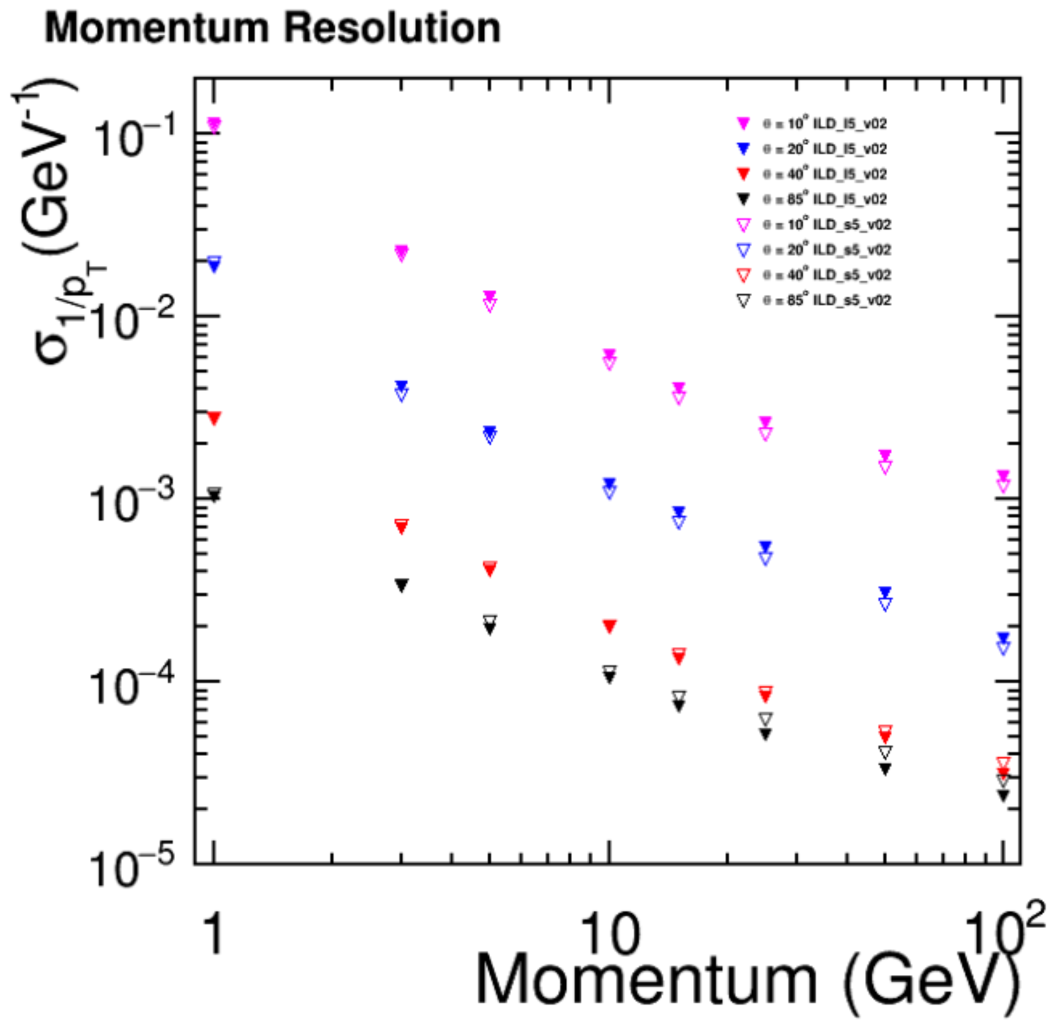
meet the requirements

- Key criteria: Particle Flow Algorithm (PFA), allowing a complete event reconstruction
- High granular calorimeters in both electromagnetic and hadronic sections
- Very low material budget in the vertexing and tracking volumes

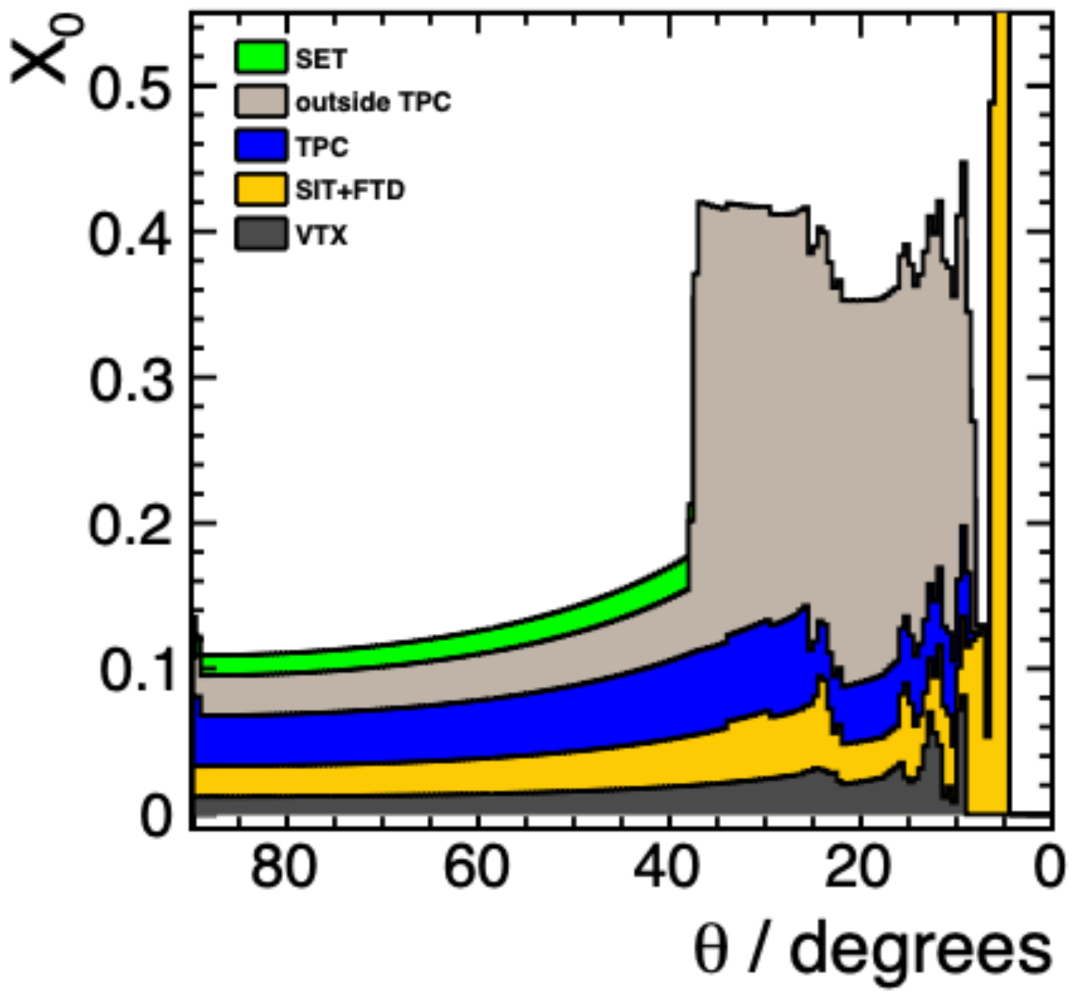




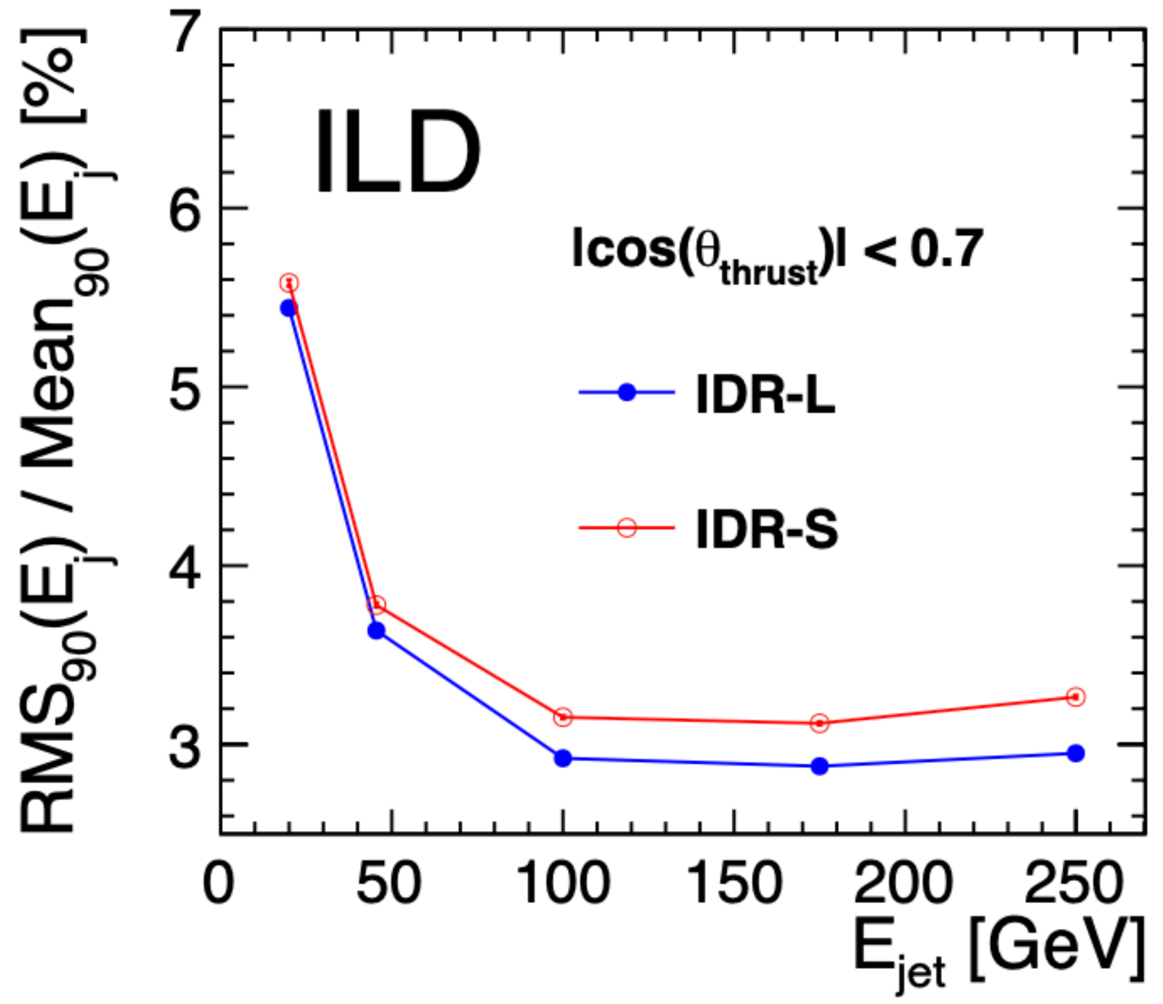
charm tagging



momentum resolution



material budget



jet energy resolution

[see details in many talks / posters in this workshop]

Simulation Tools for Linear Colliders

ecosystem

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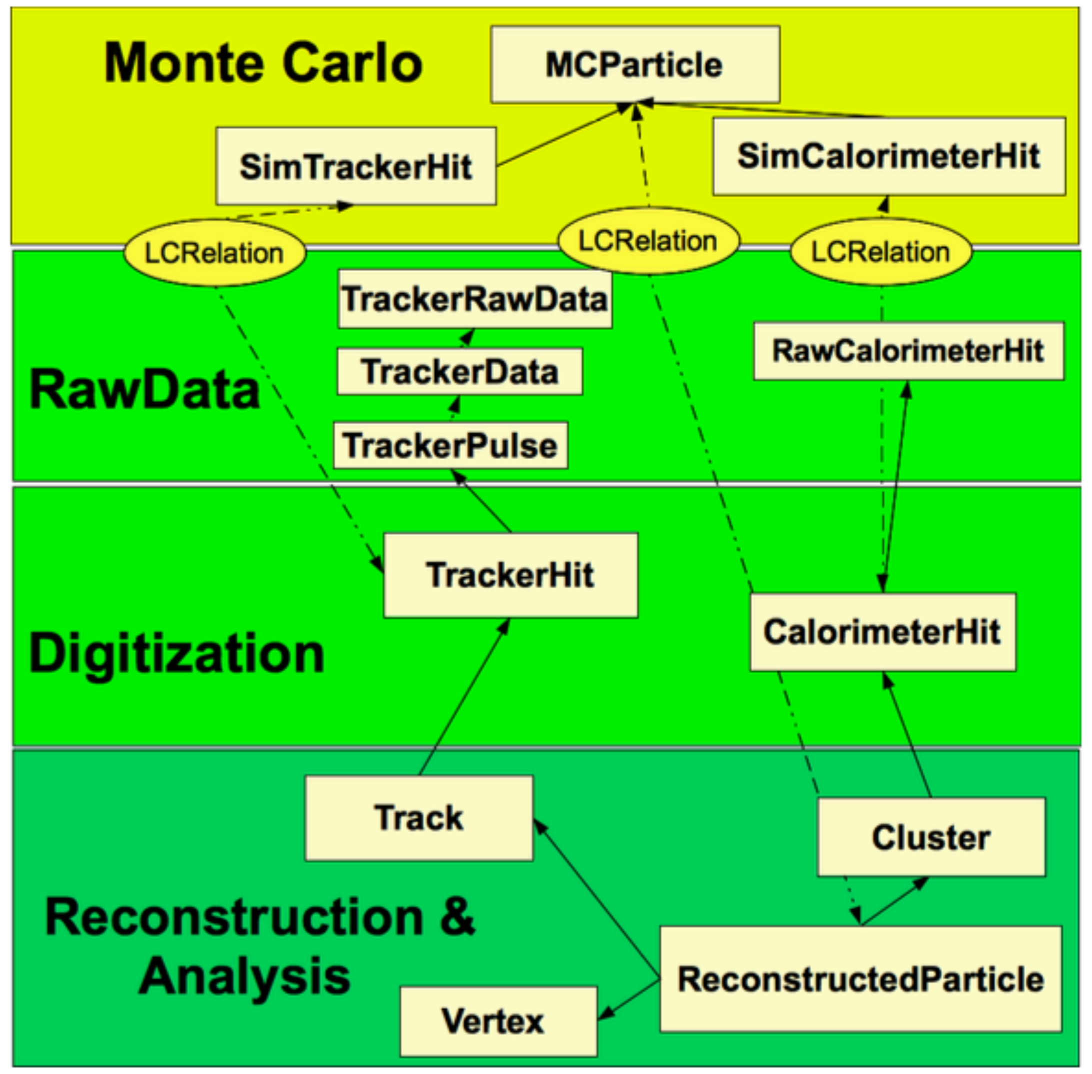
- Linear colliders community has been leading the development of software tools for full detector simulation studies over a decade
- Given the very demanding performance required on detectors, it is very important to take into account all details in the detectors that may sensitively affect our projections of physics performance.
- *iLCSoft* is the common linear collider ecosystem that integrates core tools includes
  - LCIO, the common event data model
  - DD4HEP, detector description toolkit, including interface to GEANT4 [predecessor, Mokka]
  - Marlin, C++ application framework, highly modularized to accommodate various event reconstruction tools: MarlinTrk for tracking; PandoraSDK for particle flow; LCFI+ for vertex finder and flavor tagging; and many more high level reconstruction algorithms like FastJet for jet-clustering

now integrated in key4HEP framework

Simulation Tools for Linear Colliders

analysis flow

- Main event generator: Whizard, including full SM background contribution for a given process; Pythia, for parton shower and hadronization; Beam-beam interaction by Guinea-Pig; ISR and FSR all implemented
- In addition to the main full detector simulation tools, fast simulation tools SGV and DELPHES cards are also used; there is also a lightweight access to the full simulation data through miniDST events without being formal members of ILD/SiD
- MC production is done mostly on Grid using iLCDirac; significant experience gained on computing resources via a series of production campaigns over a decade



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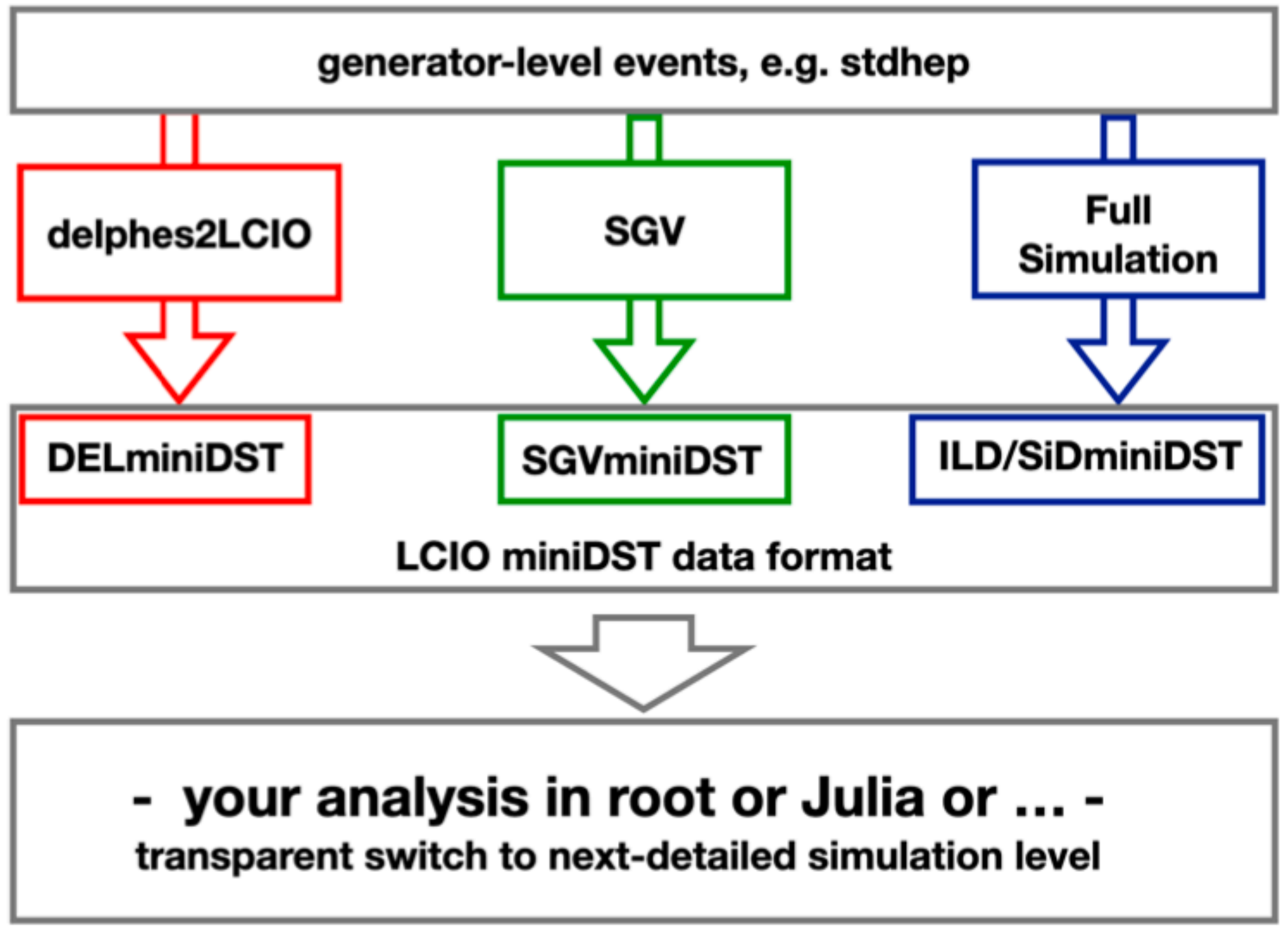

(b)

Physics Analysis for ILC

cornerstone for making the physics case

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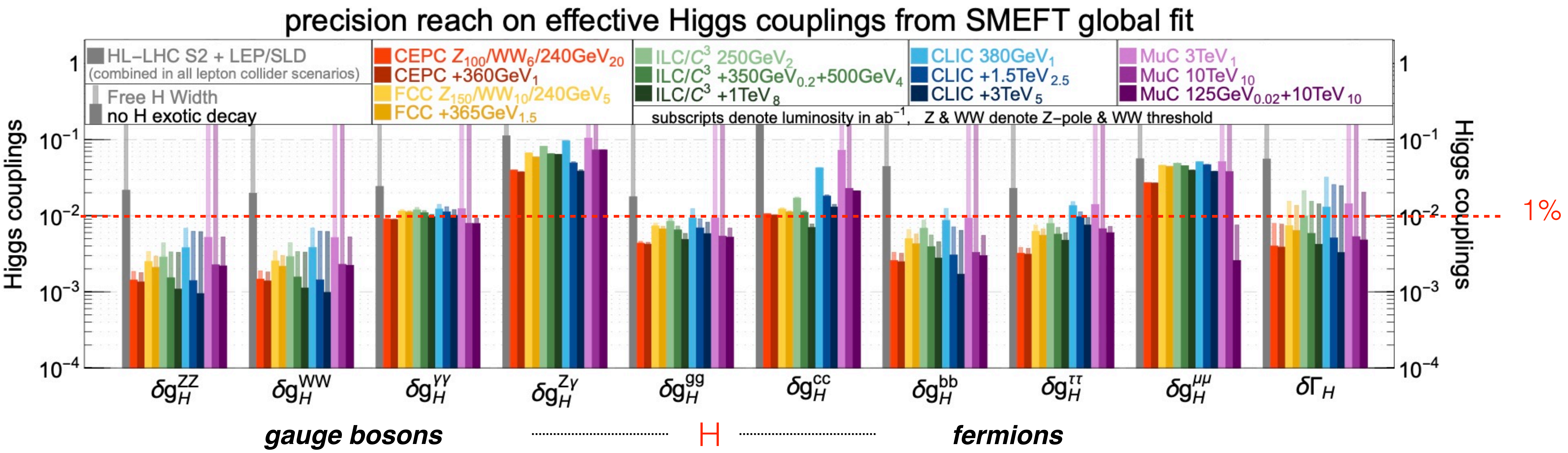
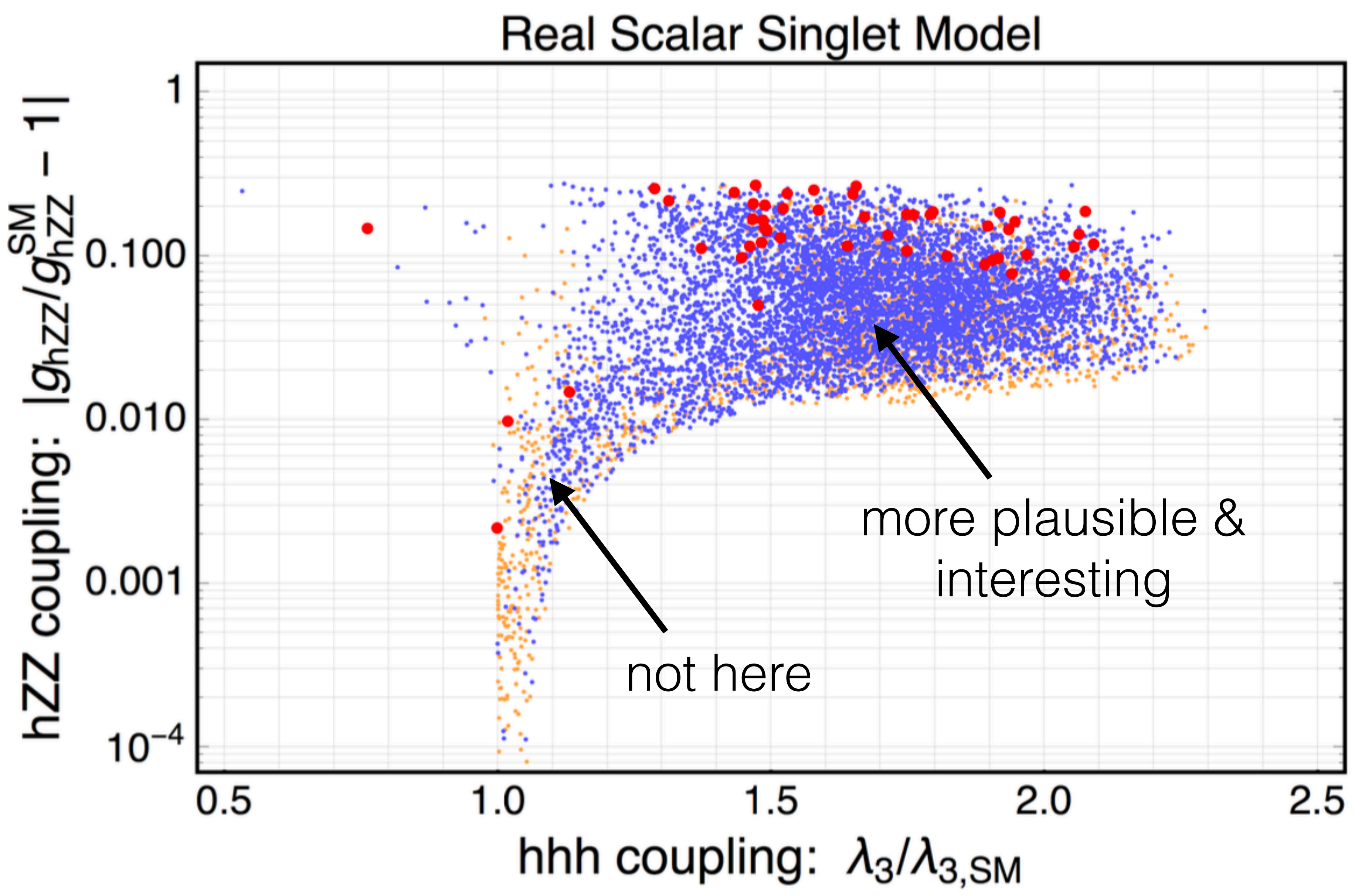
- thanks to the advanced simulation tools, numerous physics analyses on Higgs/EW, top/heavy flavor, and New Particle searches, have been carried out to shape the physics case for ILC/CLIC.



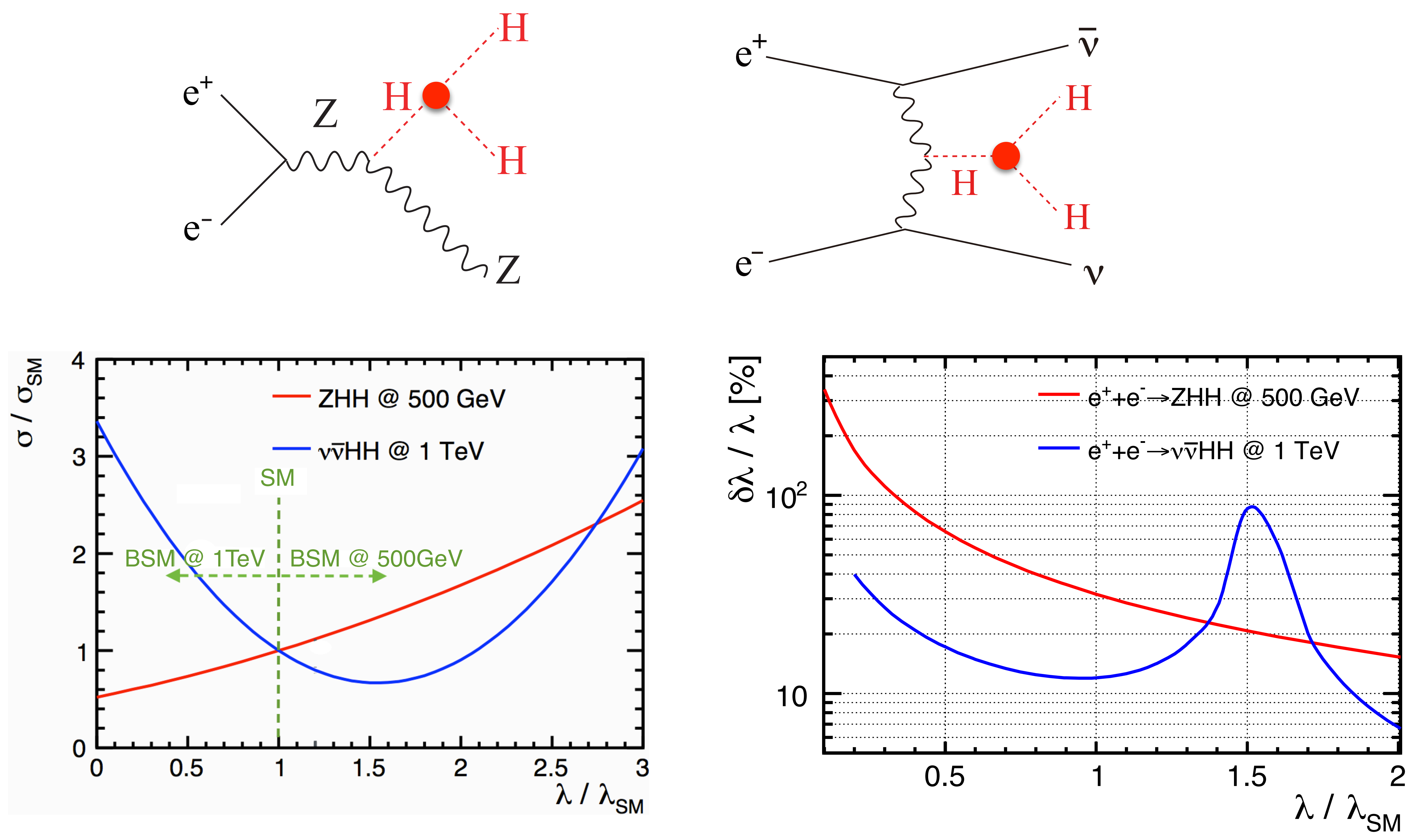
Physics Analysis for ILC

unique role of 500 e+e-

hZZ vs. hhh in EW Baryogenesis



[Huang, Long, Wang, '16]



- $\lambda_{HHH} \neq \lambda_{SM}$ has profound effect on di-Higgs processes
- complementarity between ZHH & ννHH (& LHC): different interference
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be *discovered* (~13%) using ZHH at 500 GeV e+e-

Summary

- Linear colliders are competitive “Higgs Factories” with mature technologies
- ILC is entering a new phase with the realization of ILC Technology Network
  - promotion paradigm shift from “International” to “Global”
- CLIC is preparing a project readiness report for next ESP

Summary

- Linear colliders are competitive "Higgs Factories" with mature technologies
- ILC is entering a new phase with the realization of ILC Technology Network
  - promotion paradigm shift from "International" to "Global"
- CLIC is preparing a project readiness report for next ESP

All recent strategy processes agree that the physics case for a detailed exploration of the Higgs and electroweak sectors is compelling - this requires a

e^+e^- Higgs-Top-Electroweak Factory

We should work together to make (at least) one such facility a reality.

Extras

IDT Scope for ILC Realization

-success oriented and asuming no major incident-

Technology Network Phase				Preparatory Phase			Construction Phase ~10 years for the construction and commissioning						
2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	• • •

R&D and effort to gain a common view and understanding.

ILC preparation laboratory and intergovernmental discussion

2021 May

Technical Preparation and Work Packages (WPs) during ILC Pre-lab

Work Packages (**WPs**) for ILC Pre-Lab

2022 June

Time-critical WPs for the ILC construction

WP-Primes for Time Critical

http://doi.org/10.5281/zenodo.4742018

https://agenda.linearcollider.org/event/10075/contributions/52733/attachments/38998/61522/Time-Critical_WPsV8e.pdf

ILC Technology Network (ITN)

-- global collaboration program---

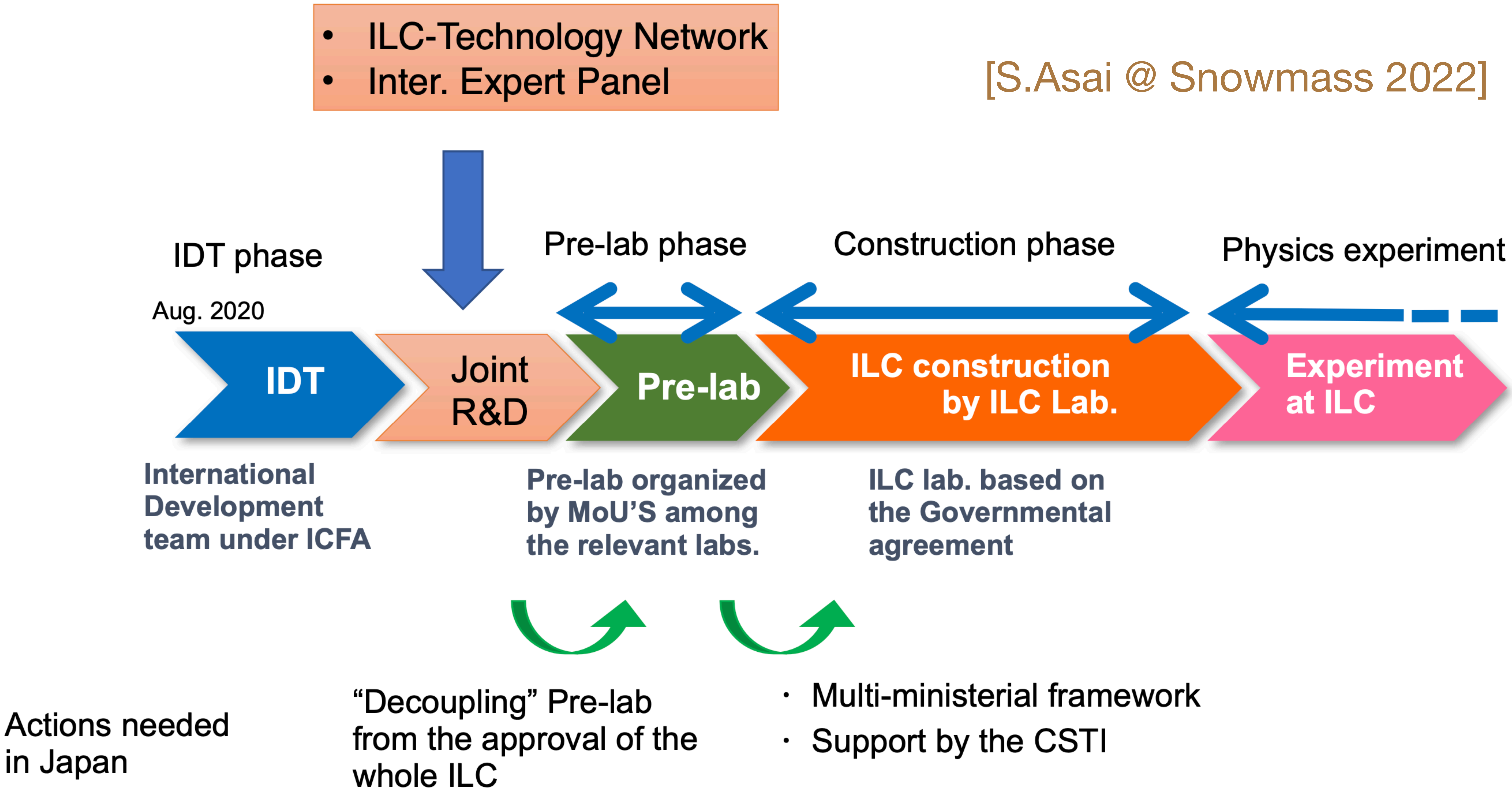
- **Acc. R&Ds** focusing on
  - SRF
  - e- & e+ Sources
  - Nano-beam

Synergy with other colliders

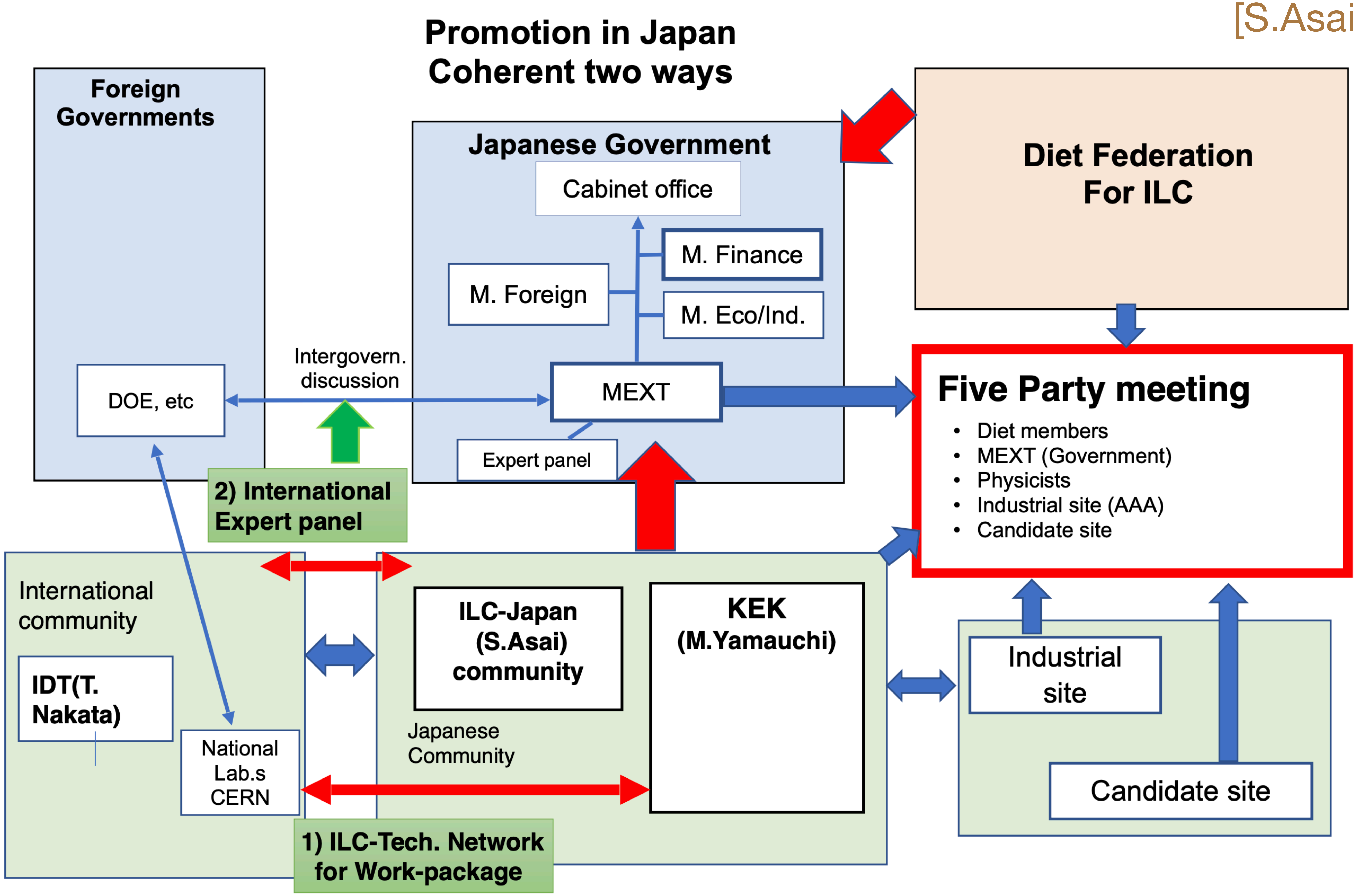
KEK obtained a budget for these R&Ds and started the activity from this April.

ILC Project News

current plan



[S.Asai @ Snowmass 2022]



CLIC Accelerator Status

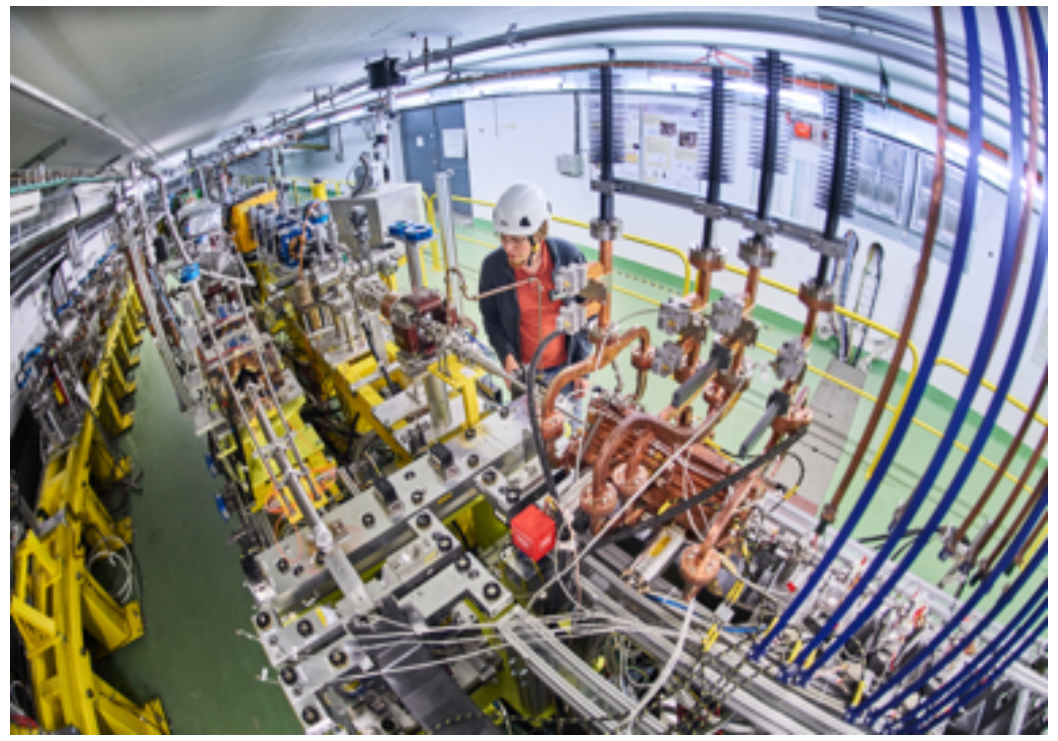
2021-2025

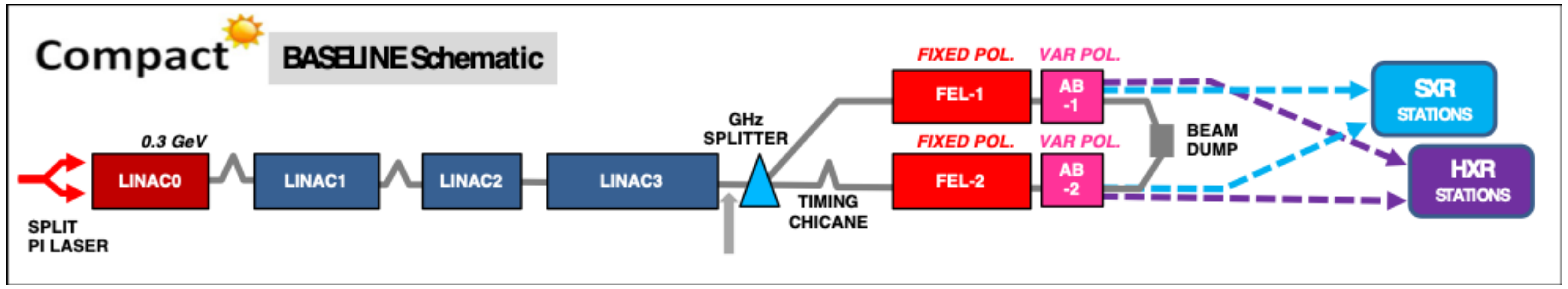
X-band technology:

- Design and manufacturing of X-band structures and components
- Study structures breakdown limits and optimization, operation and conditioning
- Baseline verification and explore new ideas
- Assembly and industry qualification
- Structures for applications, FELs, medical, etc

Technical and experimental studies, design and parameters:

- Module studies
- Beamdynamics and parameters: Nanobeams (focus on beam-delivery), pushing multi TeV region (parameters and beam structure vs energy efficiency)
- Tests in CLEAR (wakefields, instrumentation) and other facilities (e.g. ATF2)
- High efficiency klystrons
- Injector studies suitable for X-band linacs (coll. with Frascati)



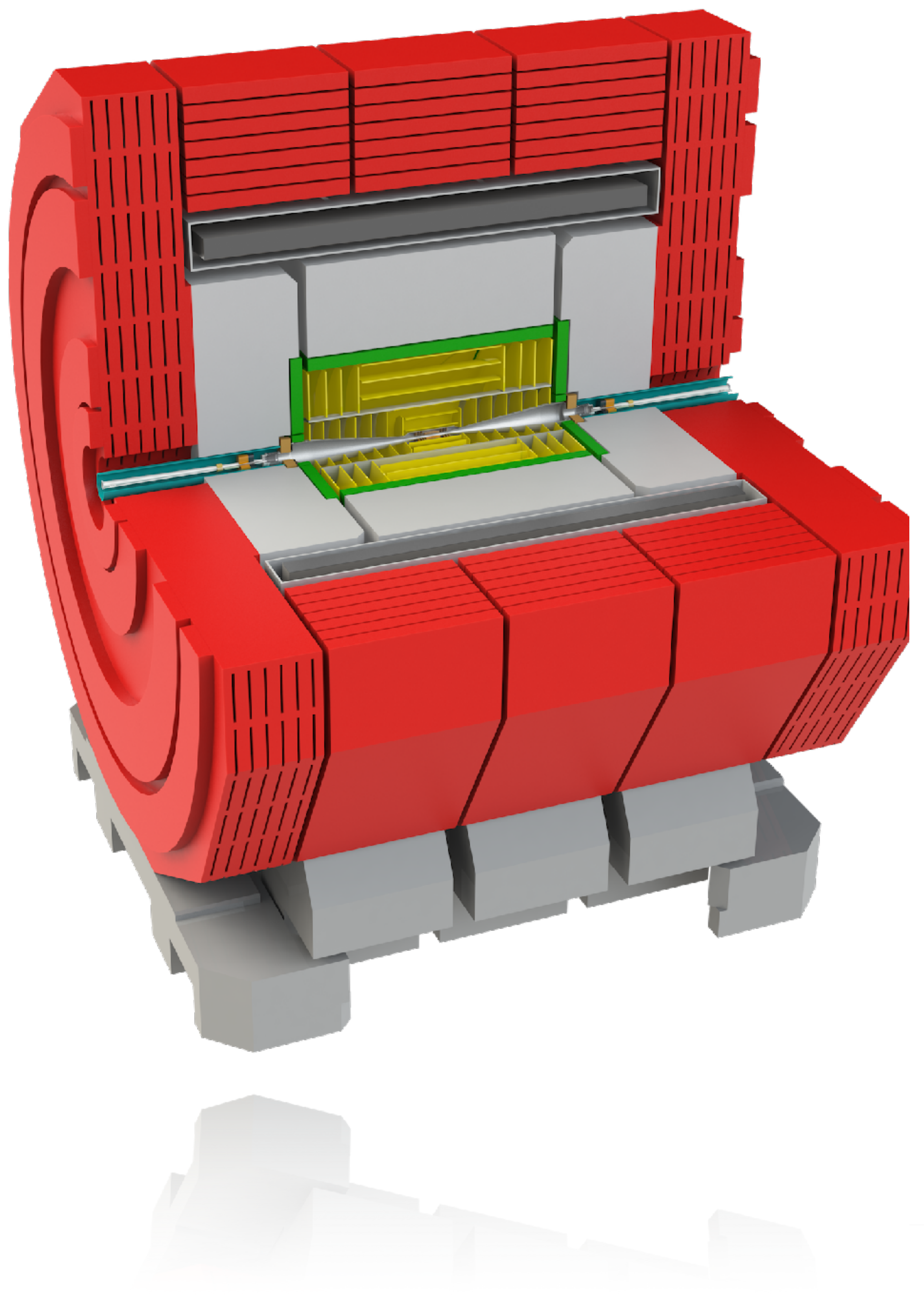


Application of X-band technology (examples):

- A compact FEL (CompactLight: EU Design Study 2018-21)
- Compact Medical linacs (proton and electrons)
- Inverse Compton Scattering Source (SmartLight)
- Linearizers and deflectors in FELs (PSI, DESY, more)
- 1 GeV X-band linac at LNF Frascati

CLIC Detector

status and plan



Calorimeter R&D => within CALICE and FCAL

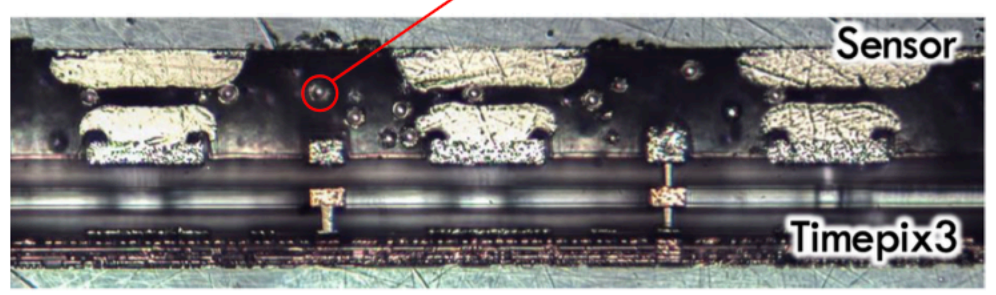
Silicon vertex/tracker R&D:

- Working Group within CLICdp and strong collaboration with DESY + AIDAinnova
- Now integrated in the CERN EP detector R&D programme

A few examples:

Hybrid assemblies:

◆ Development of bump bonding process for CLICpix2 hybrid assemblies with 25 μm pitch
https://cds.cern.ch/record/2766510



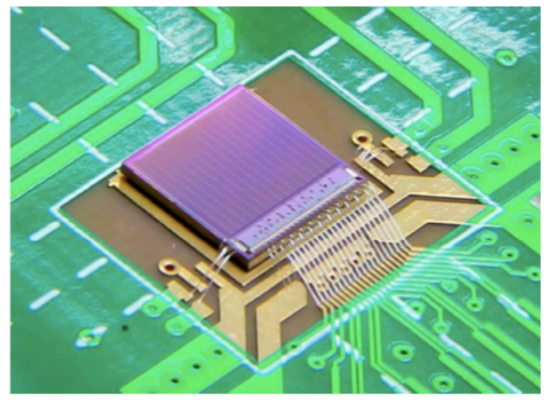
◆ Successful sensor+ASIC bonding using Anisotropic Conductive Film (ACF), e.g. with CLICpix2, Timepix3 ASICs.
ACF now also used for module integration with monolithic sensors.
https://agenda.linearcollider.org/event/9211/contributions/49469/

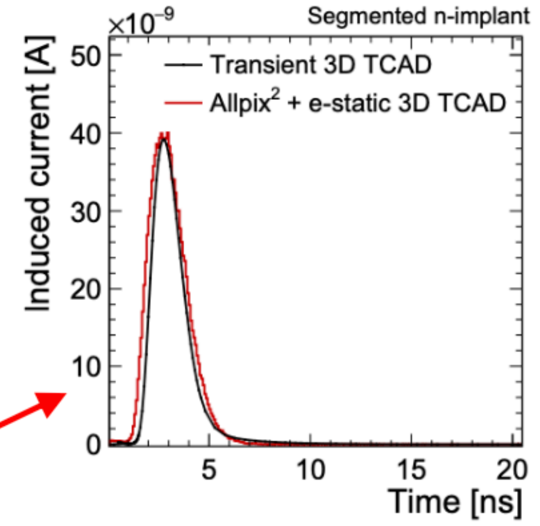
Monolithic sensors:

◆ Exploring sub-nanosecond pixel ... CT FASTPIX demonstrator in 180 nm monolithic CMOS
https://clicdp.web.cern.ch/content/wg-vertex-and-tracking-detector-technology
https://agenda.linearcollider.org/event/9211/contributions/49445/

◆ Ongoing qualification of modified 65 nm CMOS imaging process for further improved performance

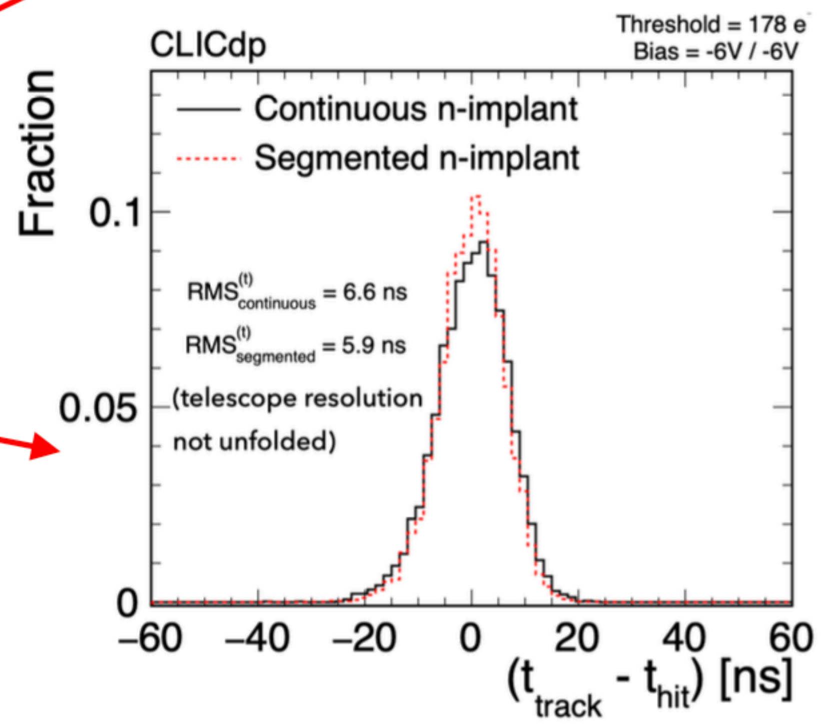
CLICTD monolithic tracking sensor:





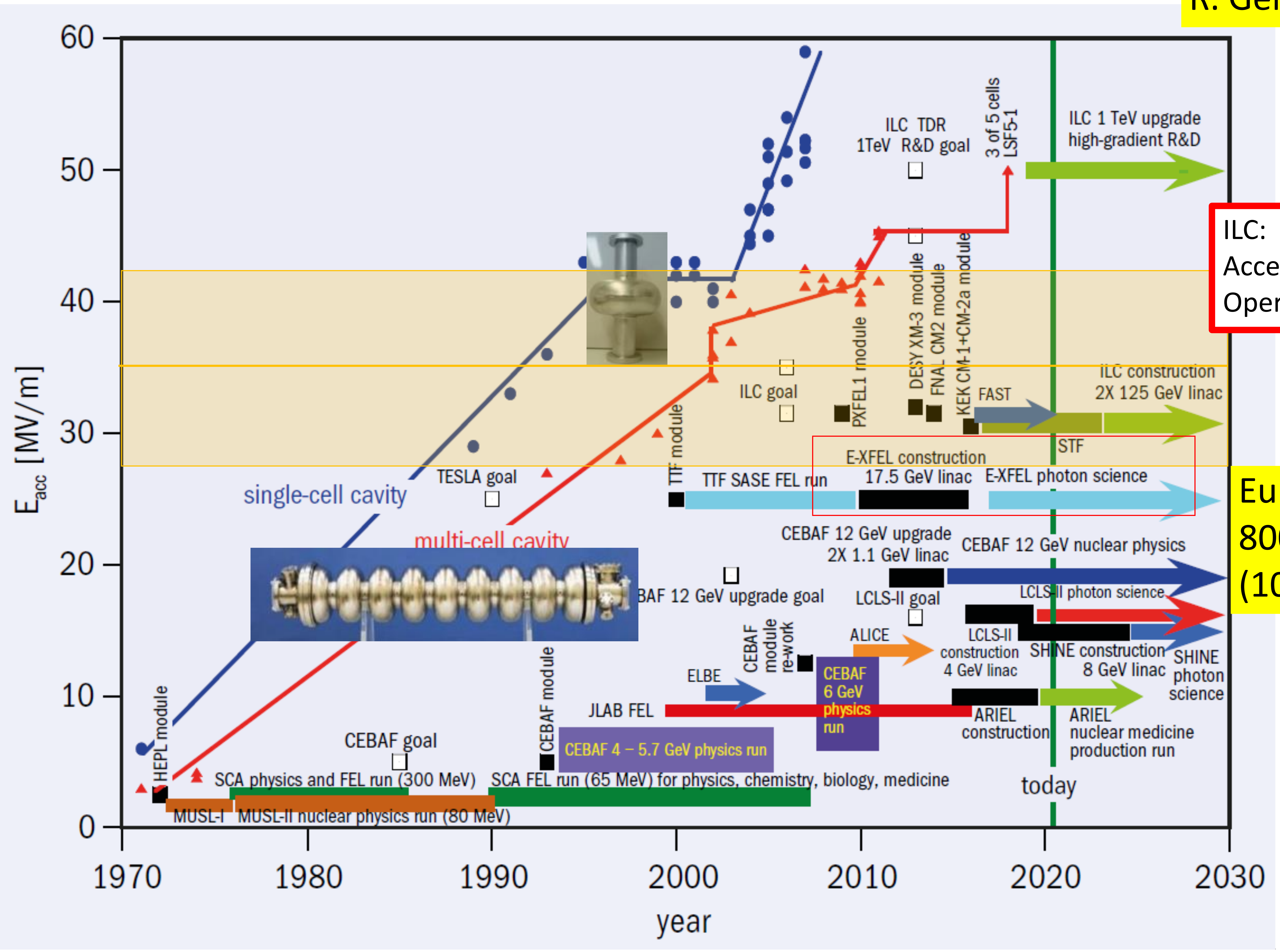
Detailed simulations, Allpix^2 transient Monte Carlo combined with electrostatic 3D TCAD.

Beam tests at DESY, e.g. 5.8 ns CLICTD time resolution achieved
https://agenda.linearcollider.org/event/9211/contributions/49443/



Matured SRF technologies

R. Geng (JLAB)



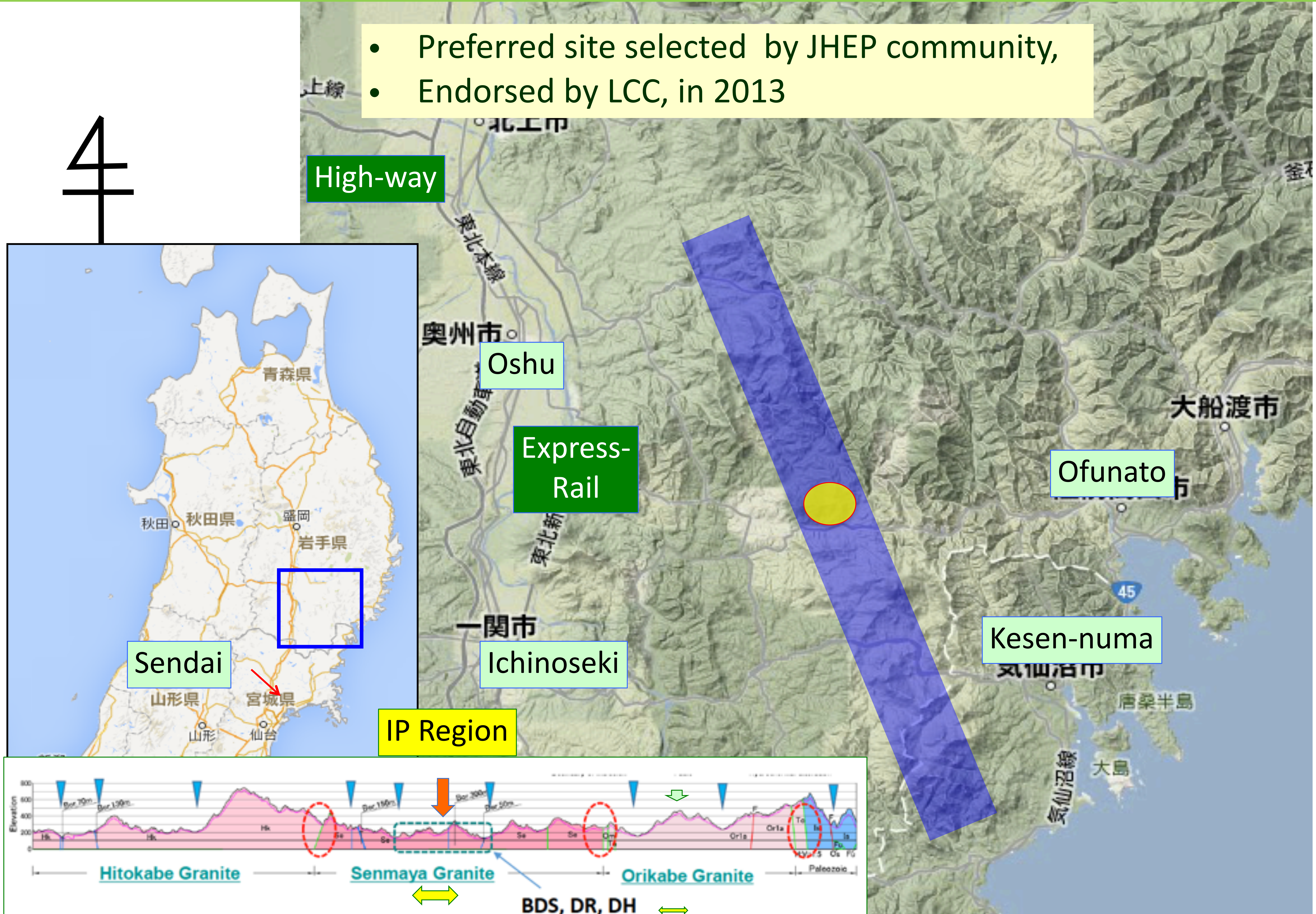
ILC:
Accept:35 MV/m +/-20%
Operate: 31.5MV/m +/-20%

European XFEL
800 cavities
(10% of ILC ML)

Civil Engineering

ILC Site Candidate Location in Japan: Kitakami

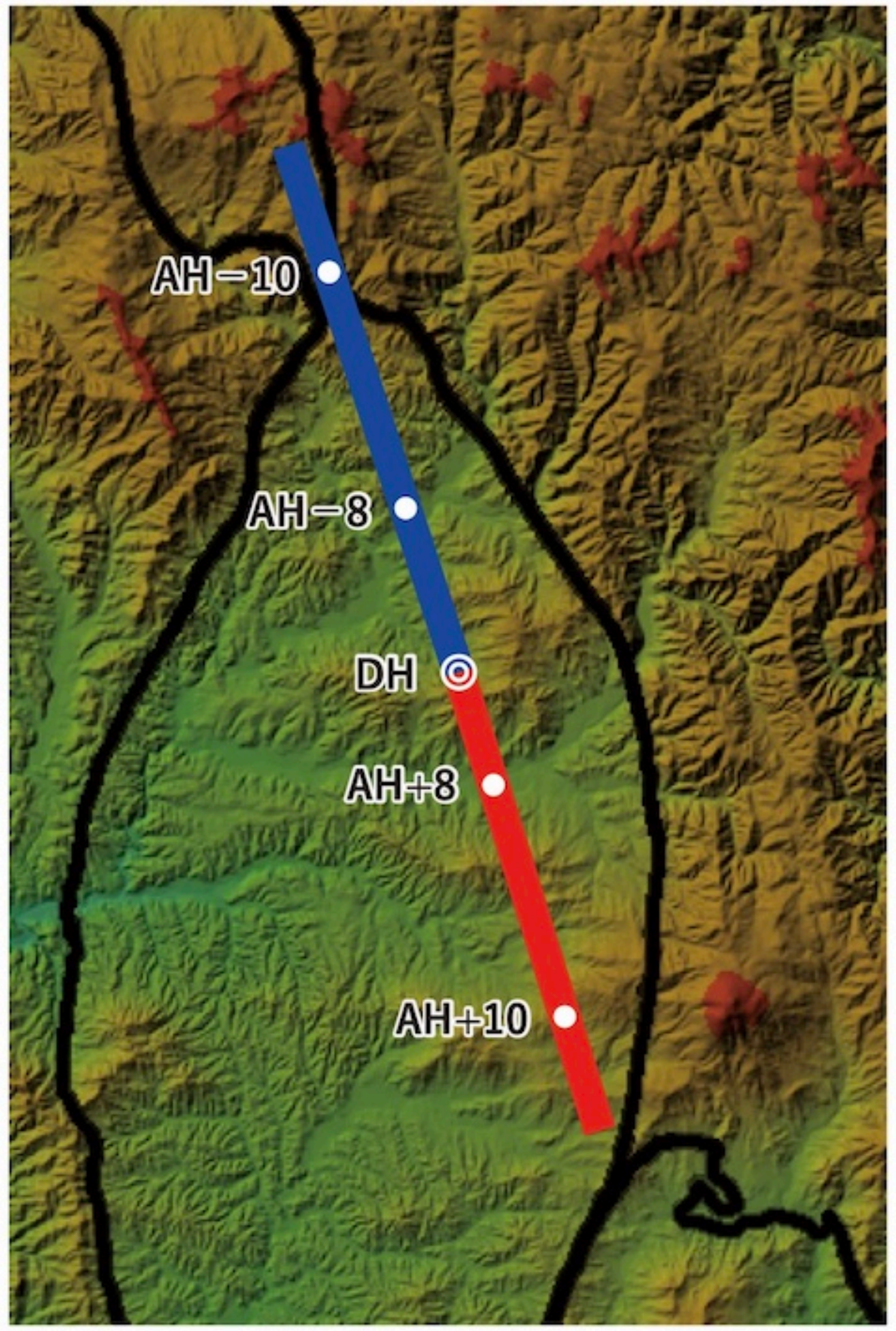
- Preferred site selected by JHEP community,
- Endorsed by LCC, in 2013

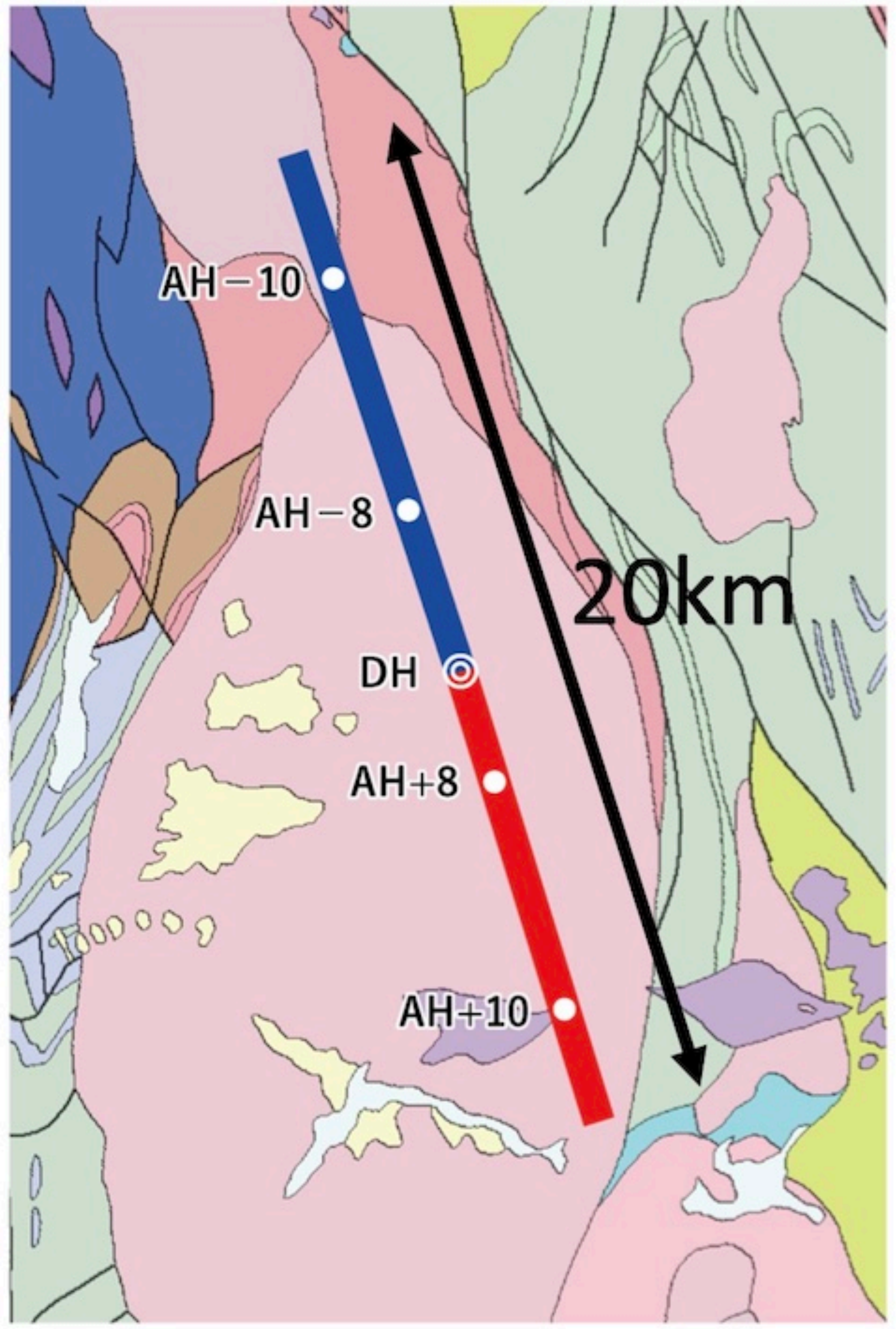


Topography and geology assumed in civil engineering design of ILC

- Rock mass is generally uniform over a long distance of 50 km
- Solid rock zone is less susceptible to ground vibration
- No "known faults" crosses the site, which is expected to be active faults

granite zone

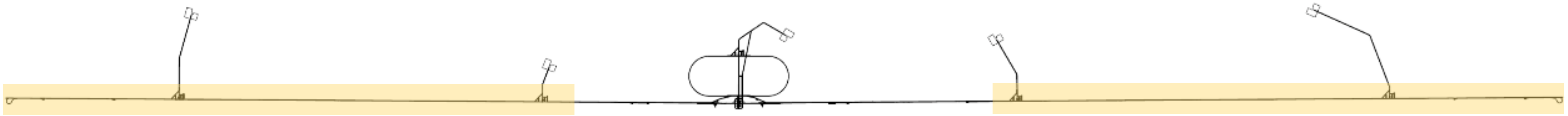




Tohoku ILC Civil Engineering Plan
https://tipdc.org/assets/uploads/2021/03/Tohoku_ILC_CEP.pdf

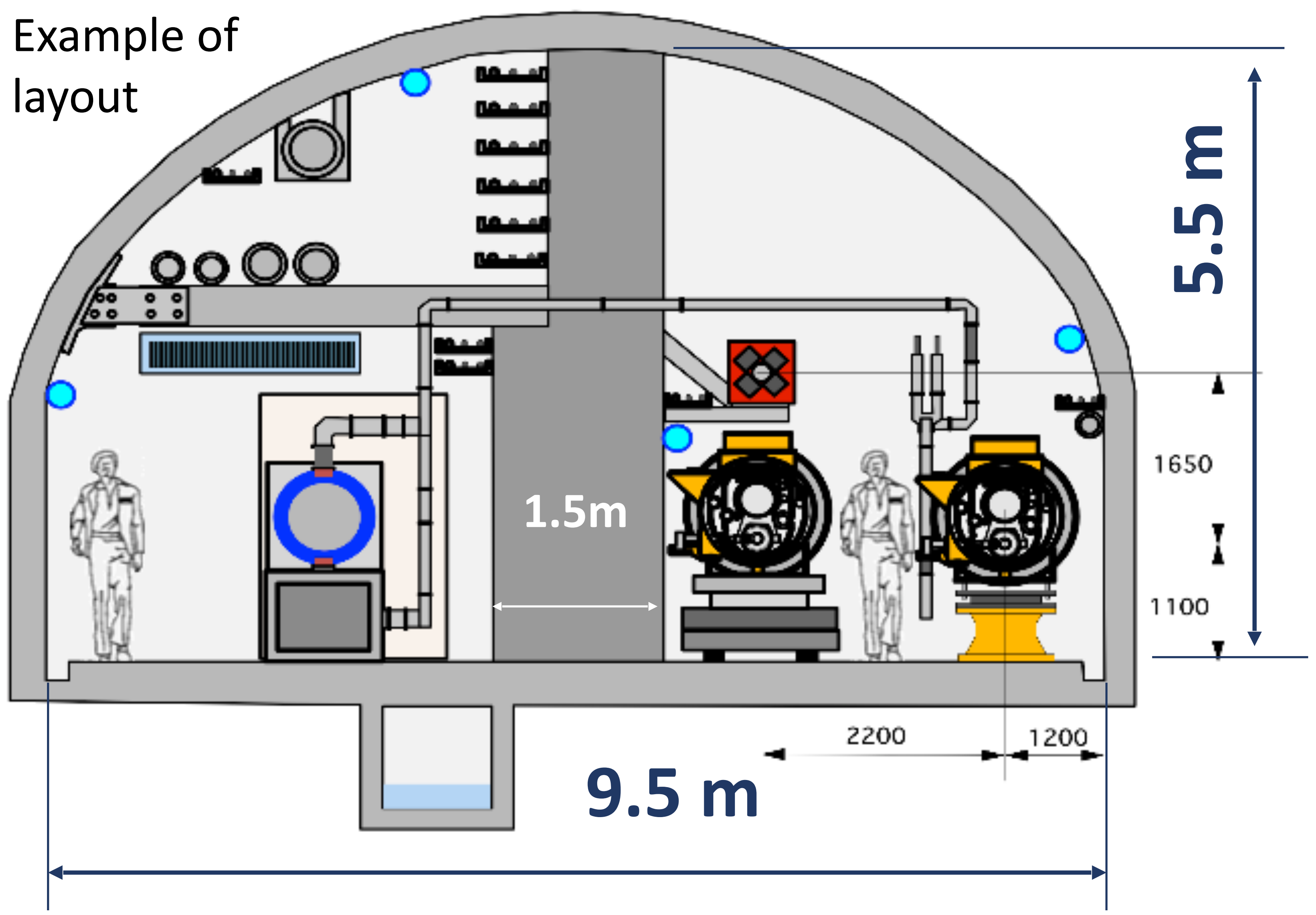
- Seismic survey (total 30 km), electromagnetic survey (13 km), and borehole survey (7 boreholes) were carried out.
- In the area of the accelerator tunnel, hard and uncracked granite is considered to be widely distributed.

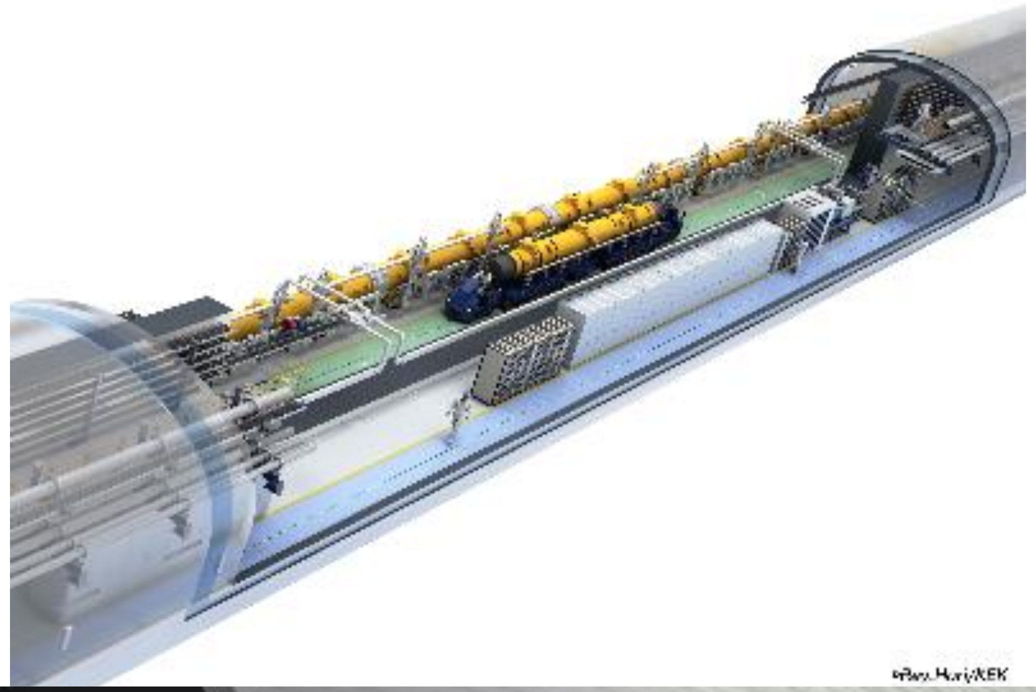
Main Linac (ML) tunnel

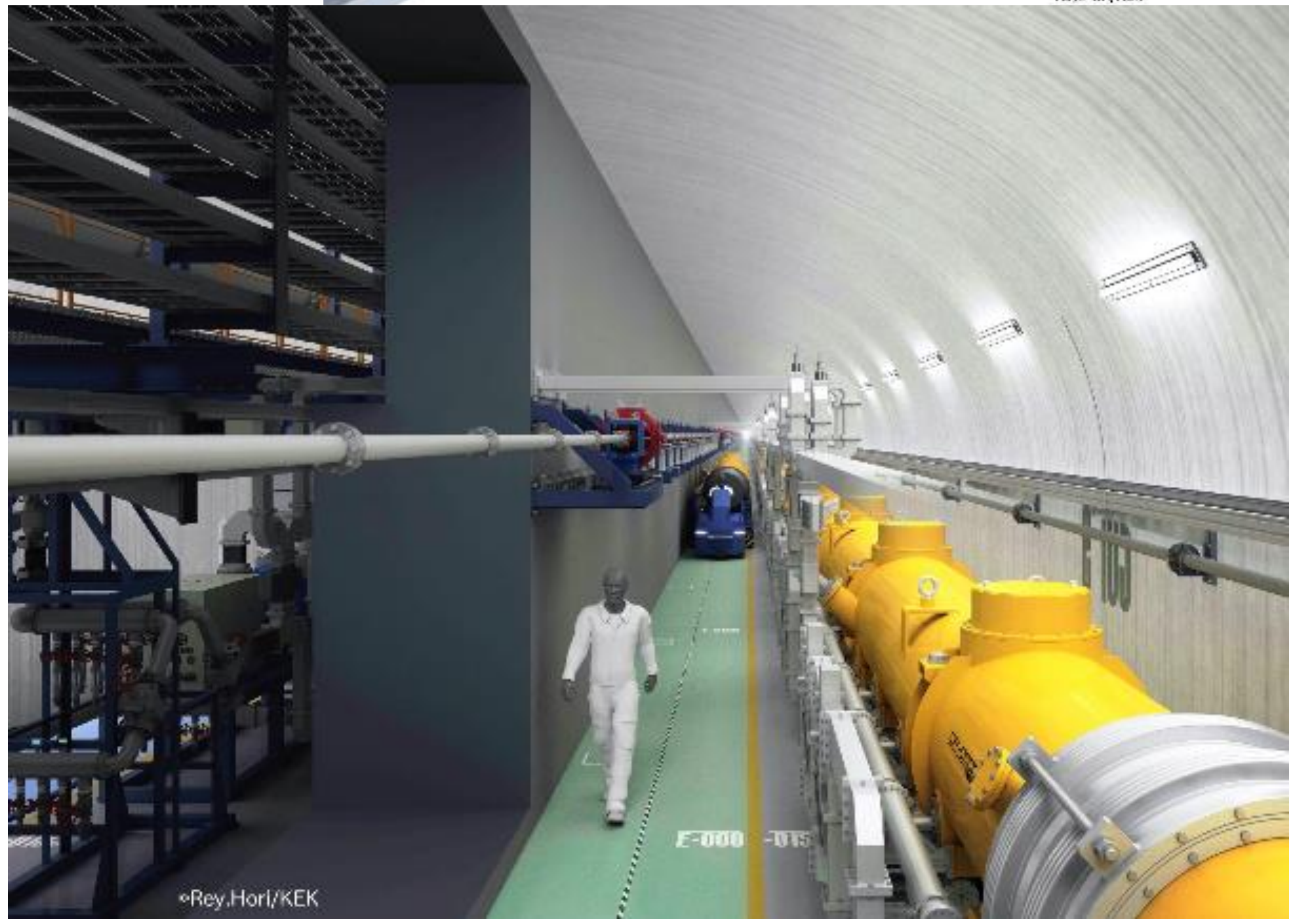


- 15 km in (e+e-) total
- follow the geoid in vertical
- **Kamaboko 9.5m X 5.5m**
- **1.5m central radiation shield**
- Further optimization will be done.

- **66 kV distribution cables**
- **Cooling water pipes**
- Fan Coil Units
- Low power and signal cables
- **RF klystrons and modulators**
- **Electric Power Stations**



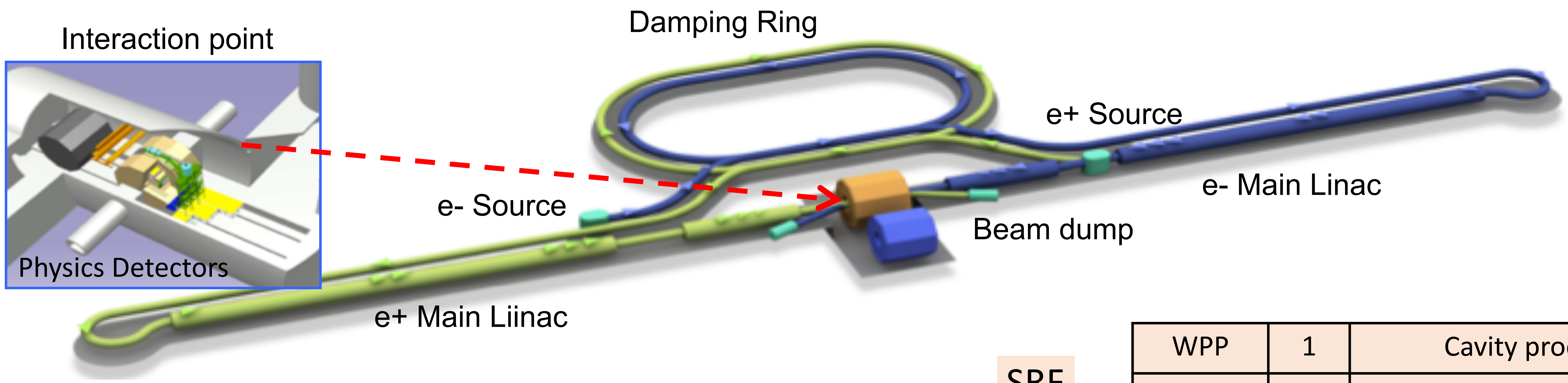




- **ML Cryomodules**
- **RTML**
- Low power and signal cables

Technology network phase

WP-Primes at ILC Technology Network



- Creating particles — ***Sources***
  - polarized elections / positrons
- High quality beams — ***Damping ring***
  - Low emittance beams
    - Small beam size (small beam spread)
    - Parallel beam (small momentum spread)
- Acceleration — ***Main linac***
  - superconducting radio frequency (SRF)
- Getting them collided — ***Final focus***
  - nano-meter beams
- Go to ***Beam dumps***

SRF

e-, e+ Sources

Nano-Beam

WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

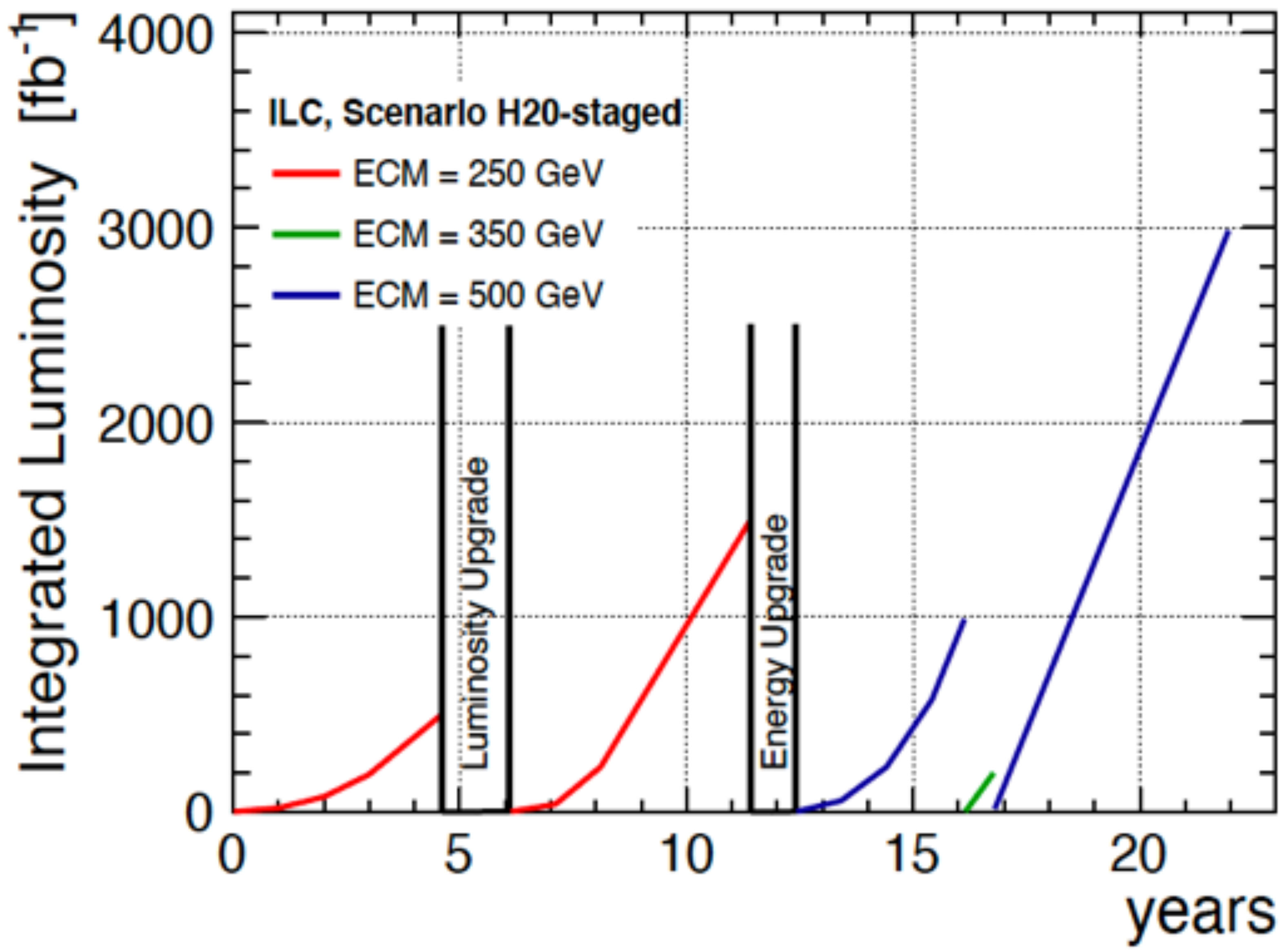
Future upgrade

ILC Baseline and the Upgrades

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Accelerating gradient	G	MV/m	31.5	31.5	31.5	31.5	31.5	45
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ_z^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ_x^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power *	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

- AC plug-power may be further reduced (10 ~ 20 %), if the RF (Klystron) and SRF/ Cryogenics (Q-value) Efficiency may be improved.

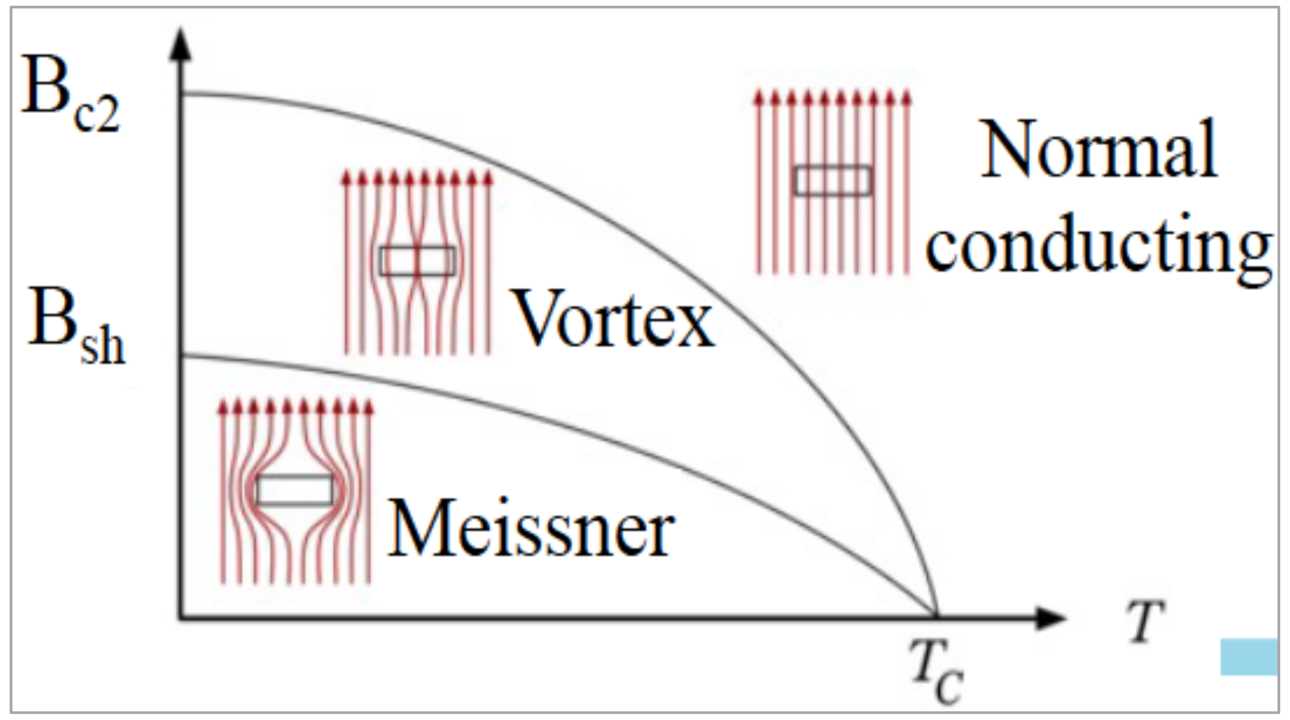
Energy upgrades:
- 500GeV (31.5 MV/m Q_0=1 x 10^{10})
  - 1TeV (45 MV/m Q_0=2 x 10^{10}, 300 MW)
  - more SCRF, tunnel extension



Further energy upgrades can be realized by
- Nb_3Sn cavity (>80MV/m)
- Nb Traveling Wave (TW) structures (>70MV/m)

Nb_3Sn cavity for the future upgrade

Courtesy, S. Posen

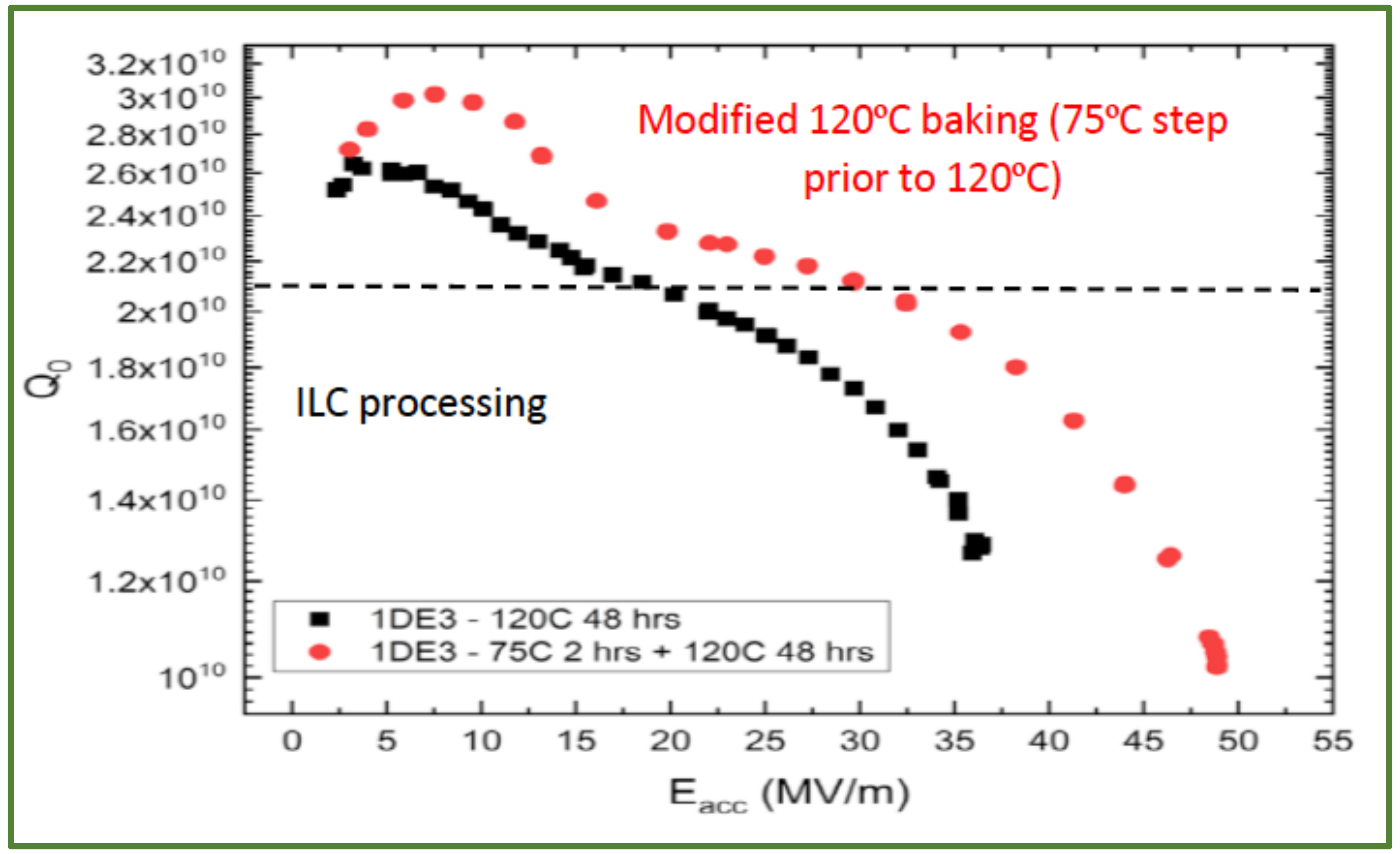


SRF cavity

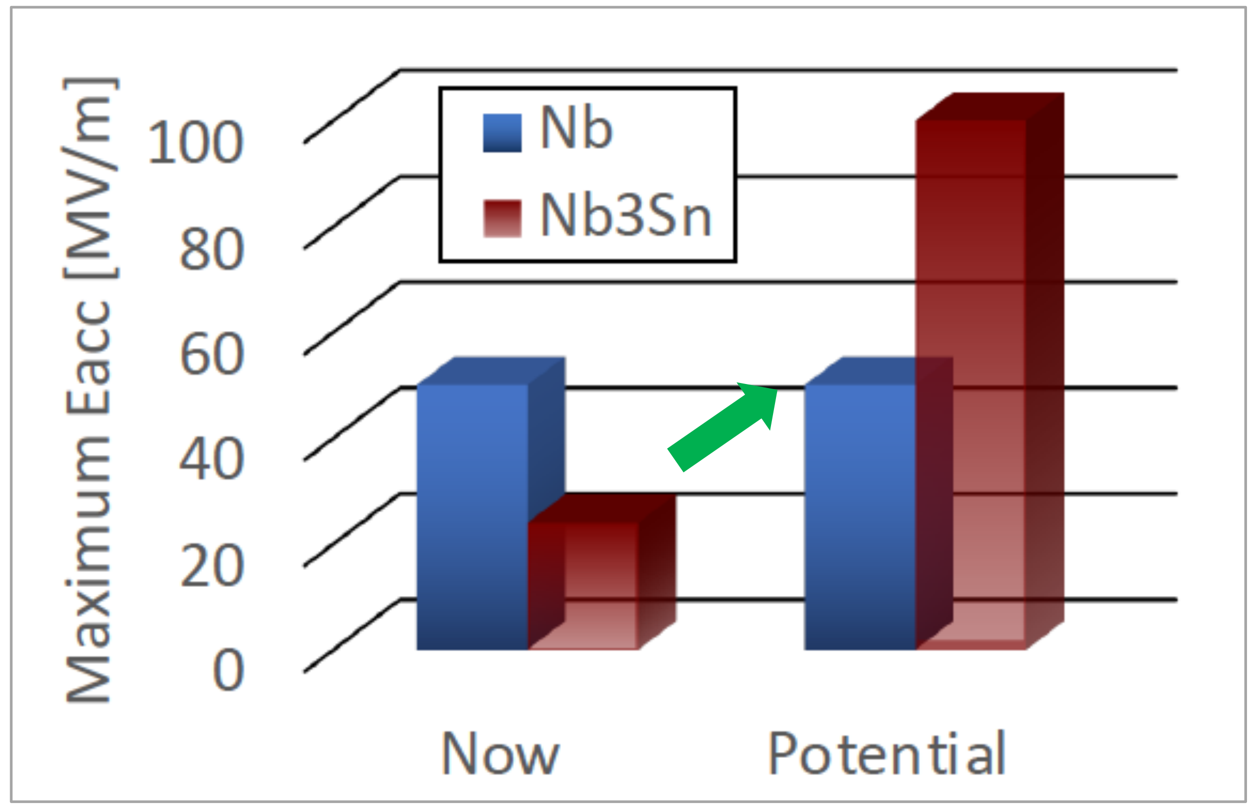
- B_{sh} = practical limit for SRF
  - $Bs_{sh\text{-}Nb}$: 210 mT
  - $Bs_{sh\text{-}Nb3Sn}$: 430mT

x2

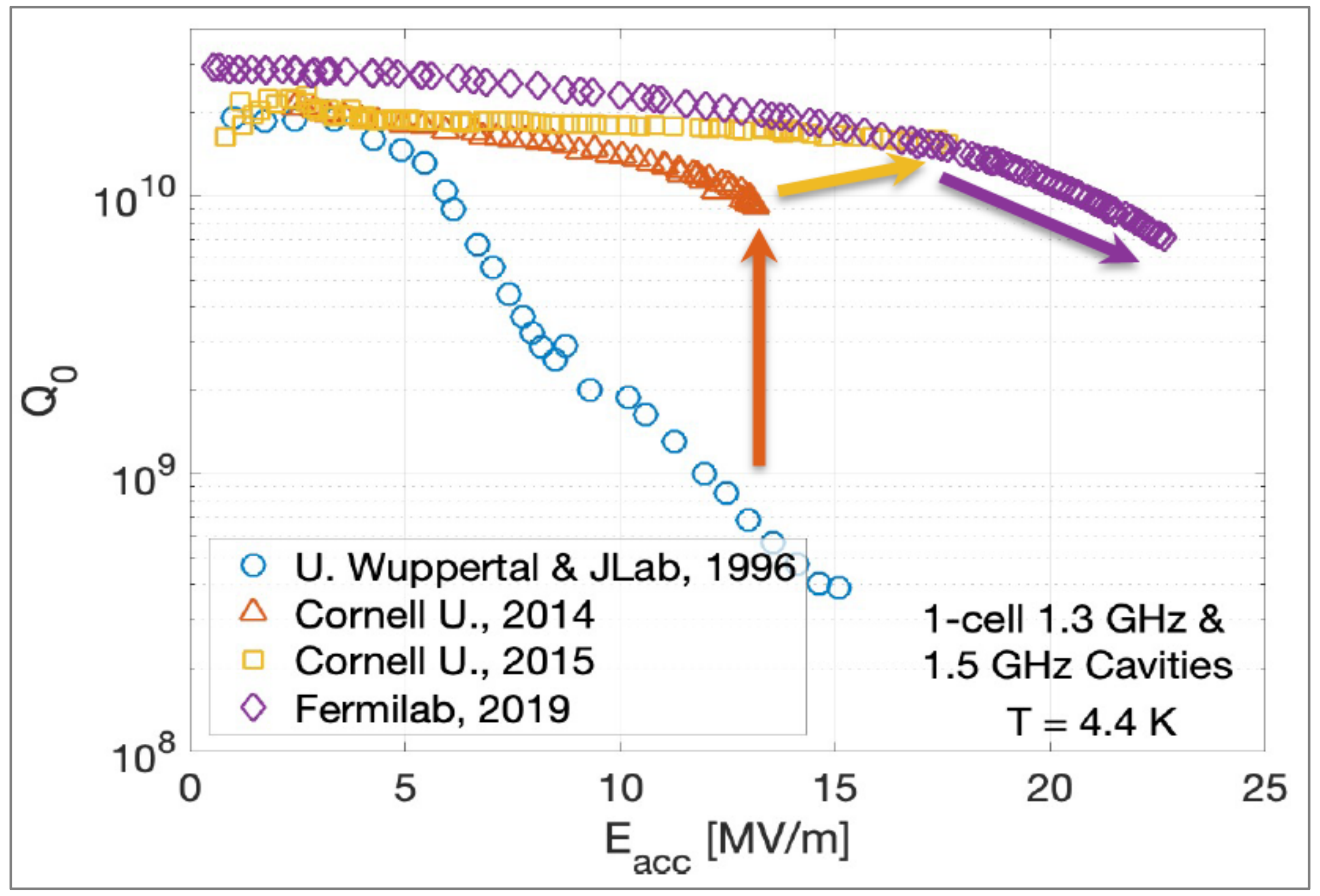
>80 MV/m in future



Progress at Fermilab: Nb, 75/120 bake
A. Grassellino et al., arXiv: 1806/09824



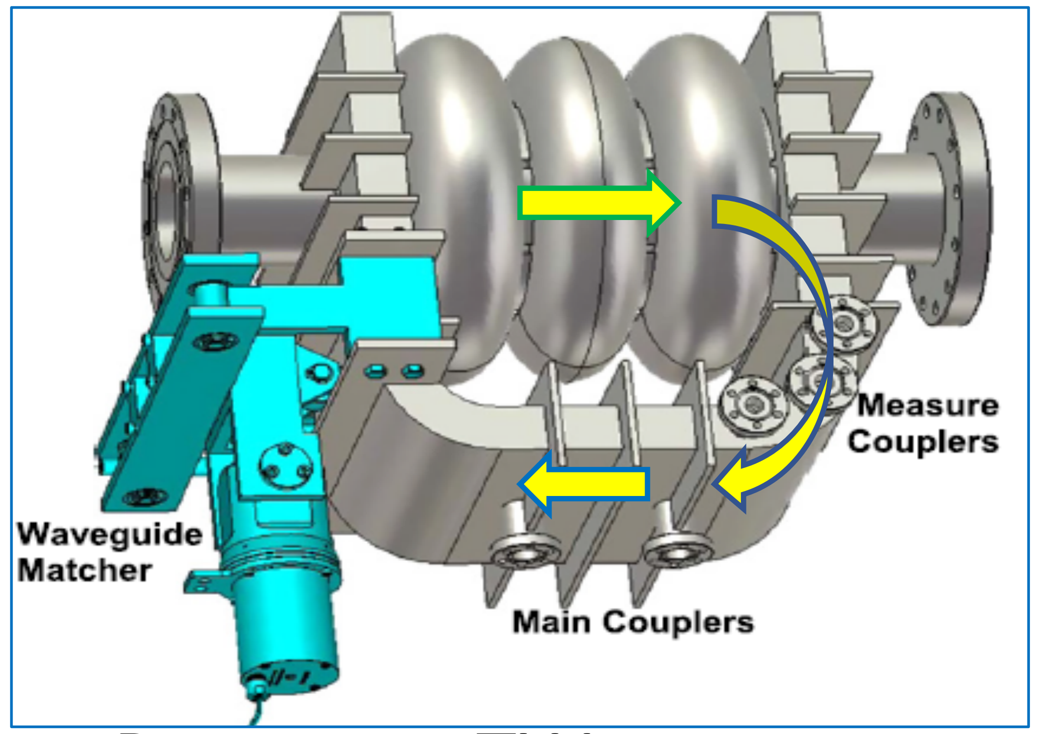
Nb_3Sn progress at Fermilab.
S. Posen et al., SUST, 34, 02507 (2021)



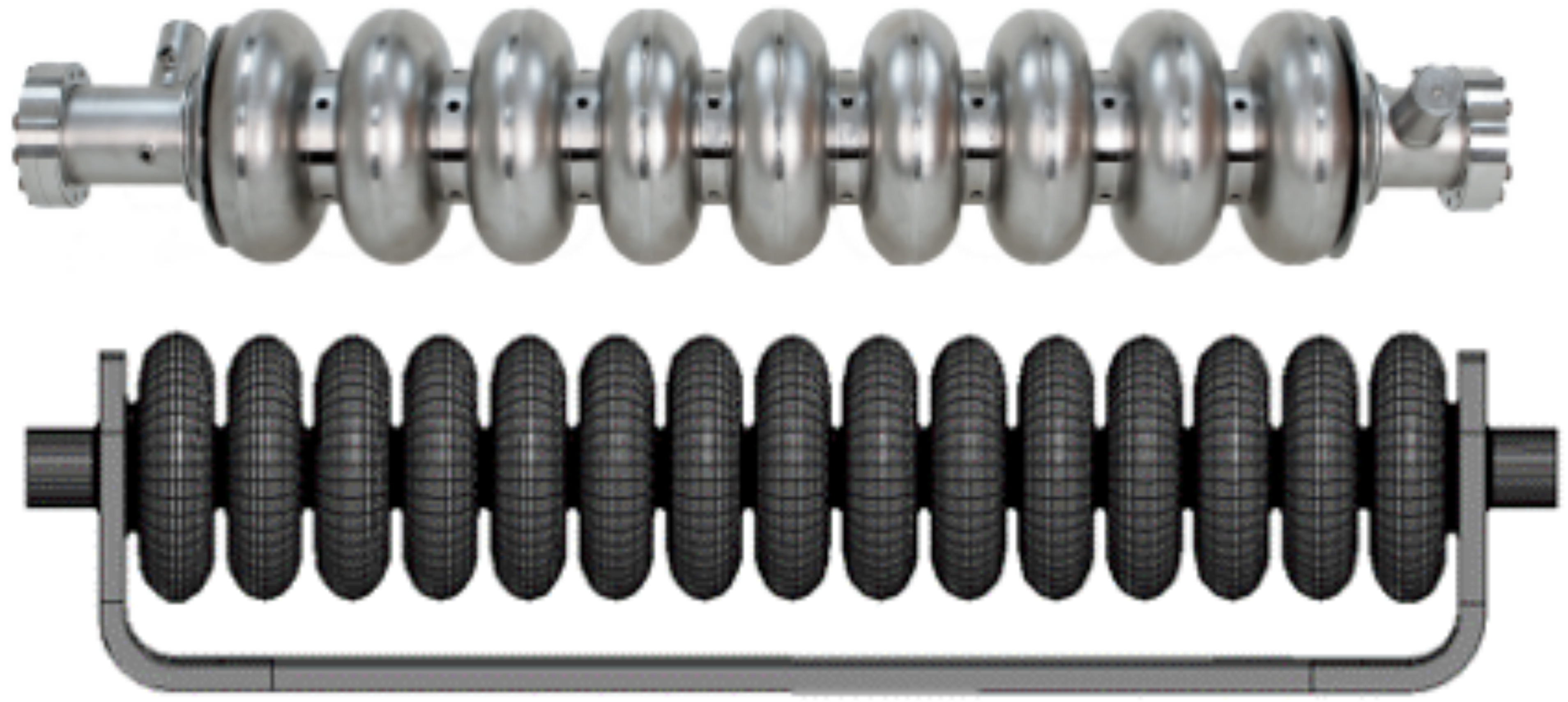
Nb_3Sn Potential in high-G future

A new concept for SRF proposed for ILC-3TeV and Helen: Traveling Wave (TW) SRF cavity, compared with Standing Wave

Courtesy: H. Padamsee et al., for ILC-3TeV
S. Belomestnykh et al., for HELEN



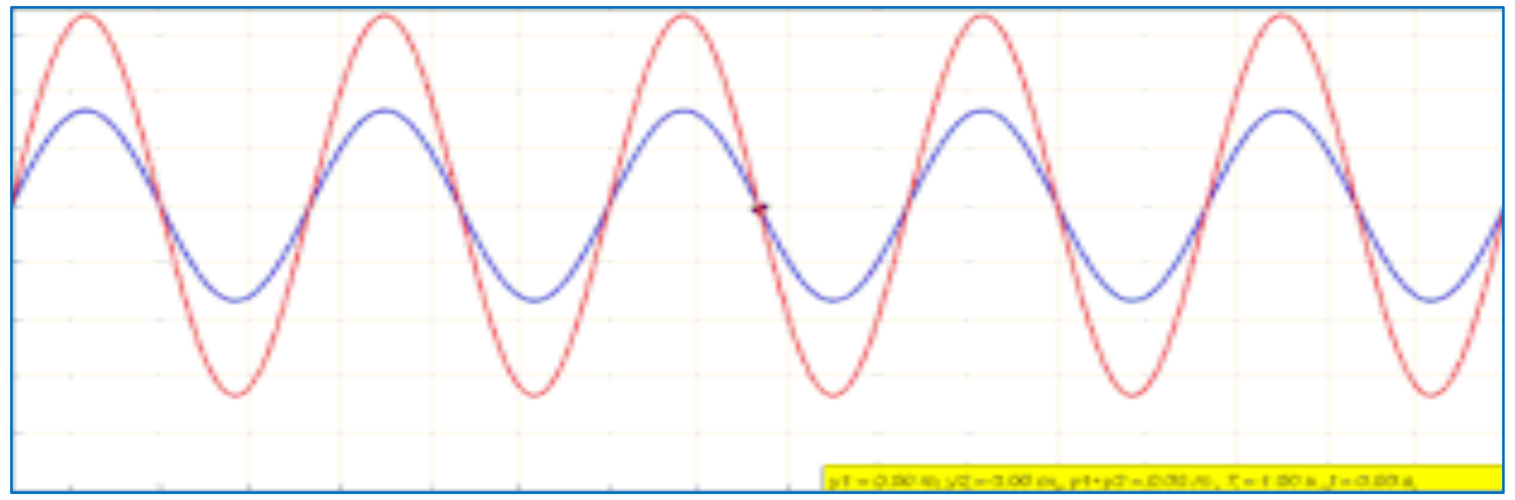
Prototype TW structure under test



SW: TESLA cavity (ILC baseline)

TW: proposed for ILC-3TeV, Helen

>70 MV/m operation



← Red standing wave – High Peak Fields,

← Green (acc.) and Blue (Return) Waves are Travelling Waves Lower peak fields,

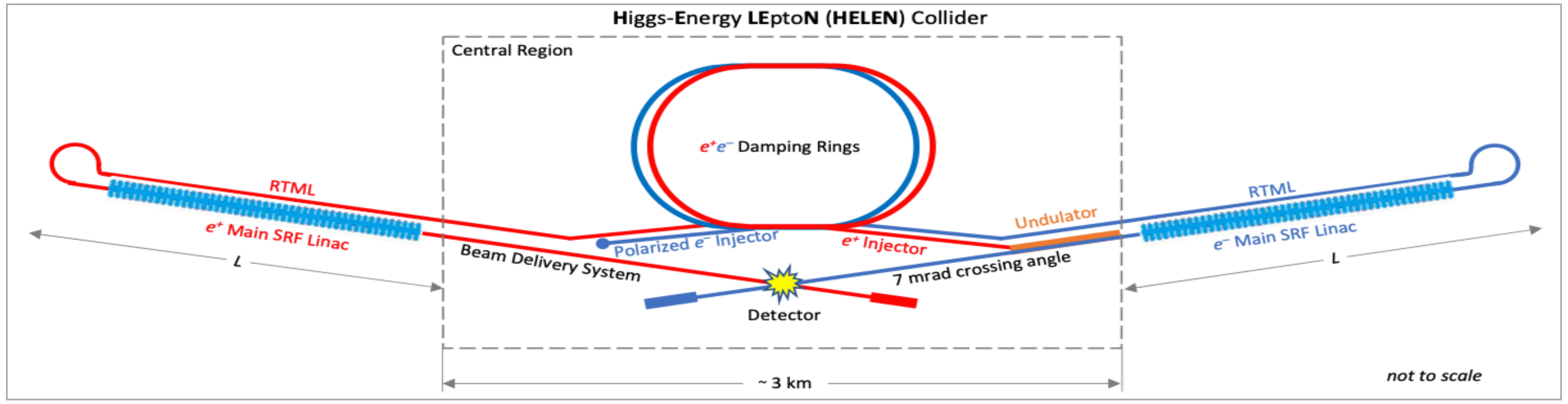
← **Guide blue** wave in a return wave-guide to avoid SW peak fields

– attached to both ends

HELEN: A LINEAR COLLIDER BASED ON ADVANCED SRF TECHNOLOGY*

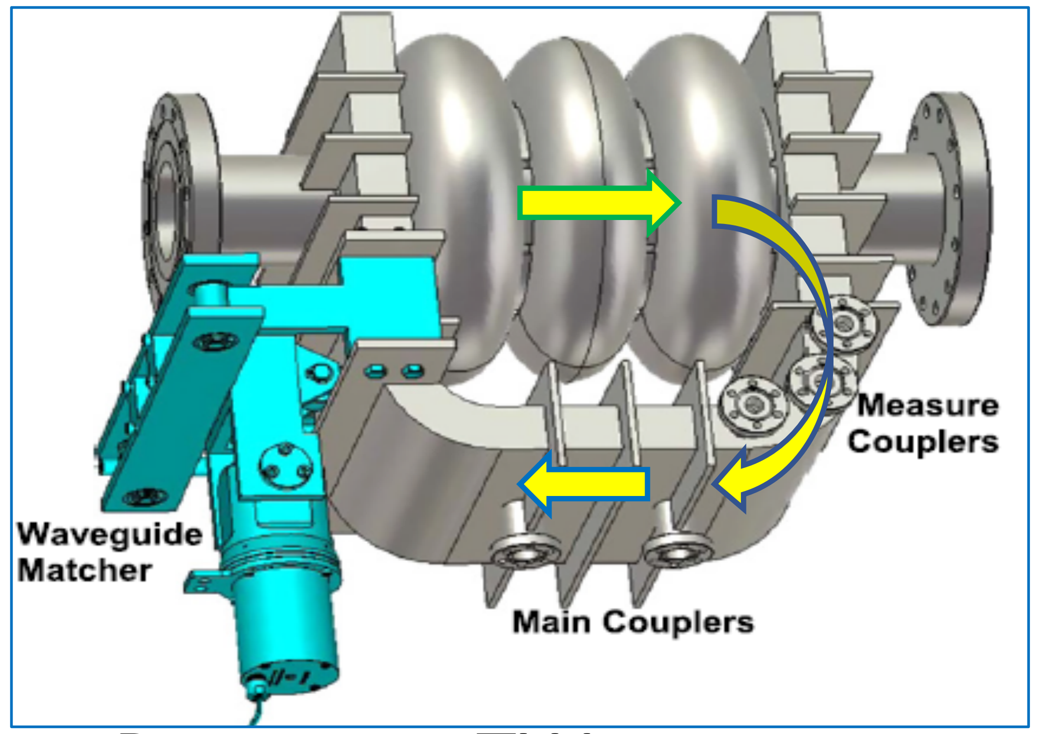
S. Belomestnykh†,1, P. C. Bhat, M. Checchin‡, A. Grassellino, M. Martinello‡, S. Nagaitsev[2], H. Padamsee[3], S. Posen, A. Romanenko, V. Shiltsev, A. Valishev, V. Yakovlev
Fermi National Accelerator Laboratory, Batavia, IL, USA
[1]also at Stony Brook University, Stony Brook, NY, USA
[2]also at University of Chicago, Chicago, IL, USA
[3]also at Cornell University, Ithaca, NY, USA

https://doi.org/10.48550/arXiv.2209.01074



A new concept for SRF proposed for ILC-3TeV and Helen: Traveling Wave (TW) SRF cavity, compared with Standing Wave

Courtesy: H. Padamsee et al., for ILC-3TeV
S. Belomestnykh et al., for HELEN



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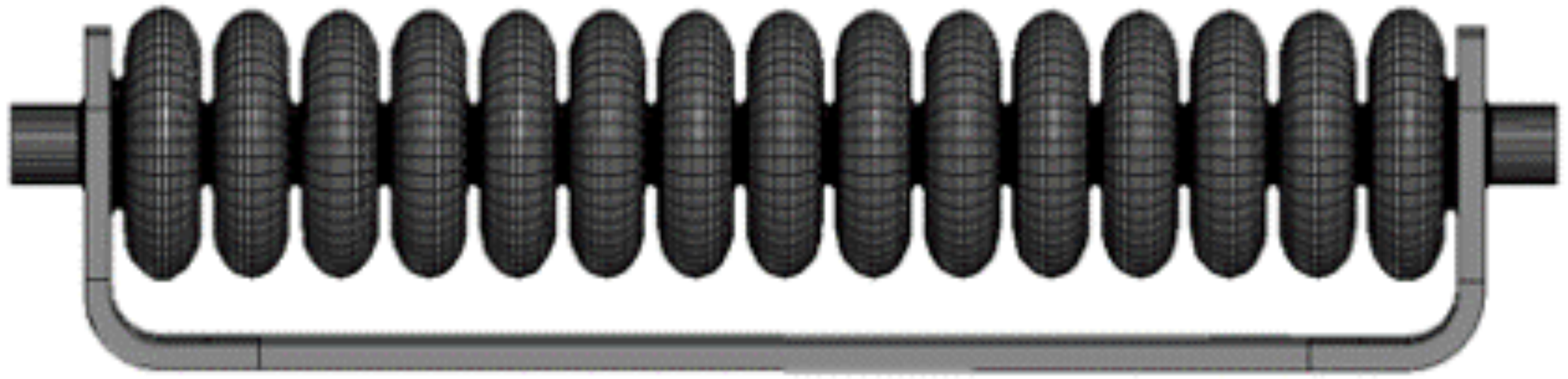

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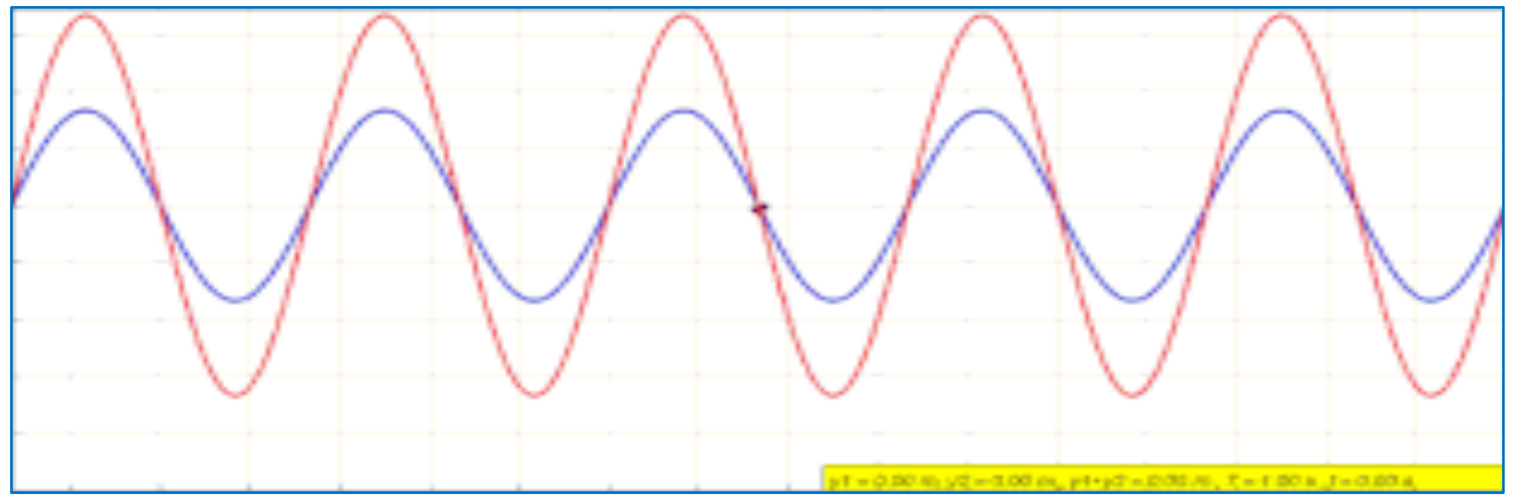

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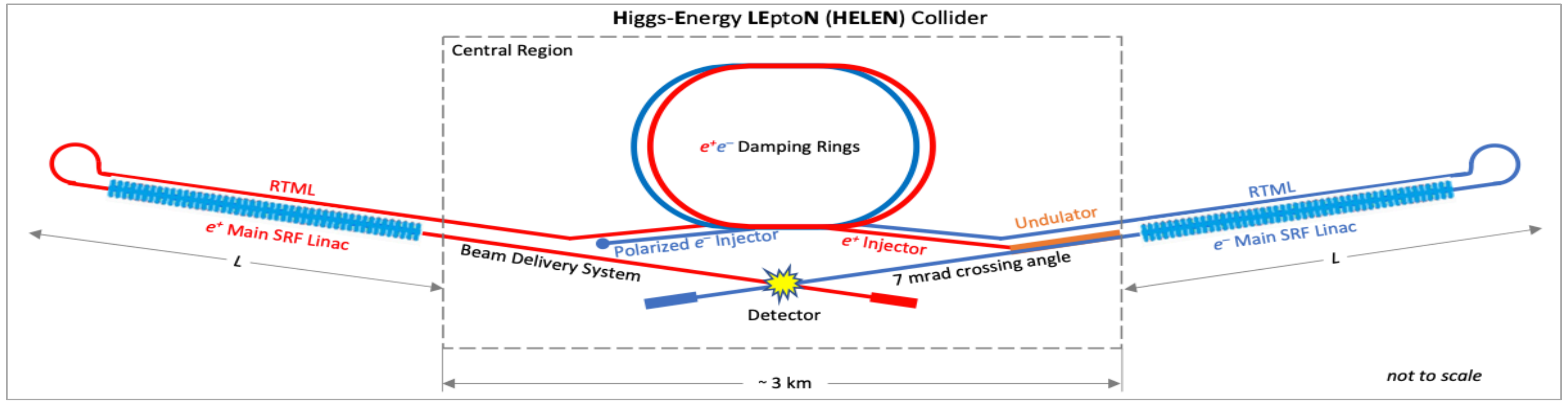
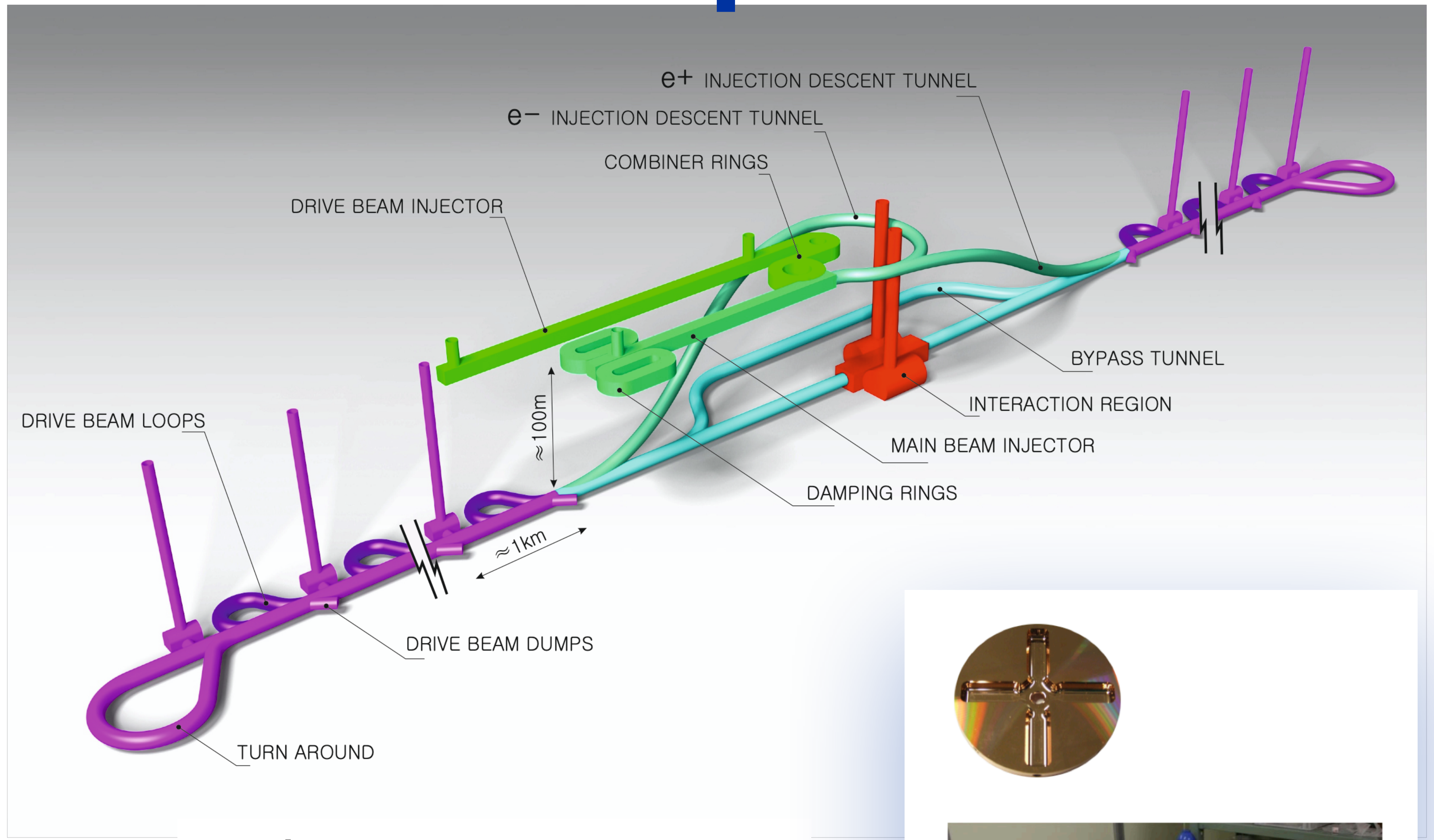
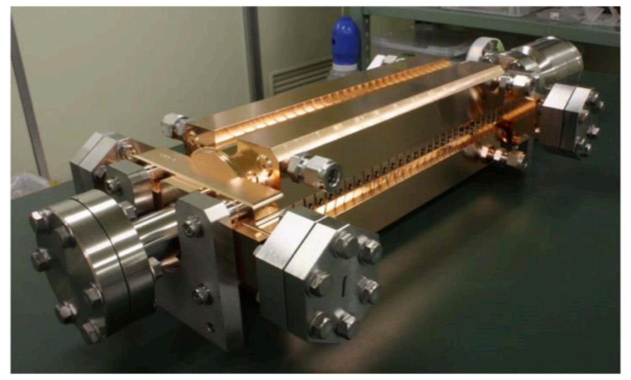


The Compact Linear Collider (CLIC)





Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

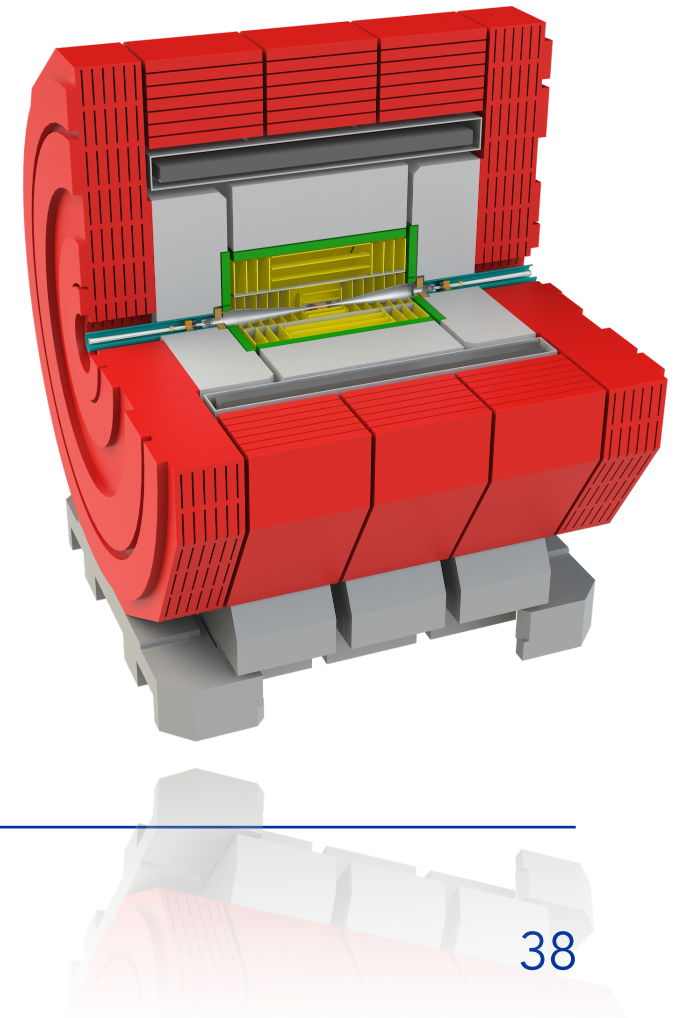
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

The CLIC accelerator studies are mature:

- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of “all” key elements

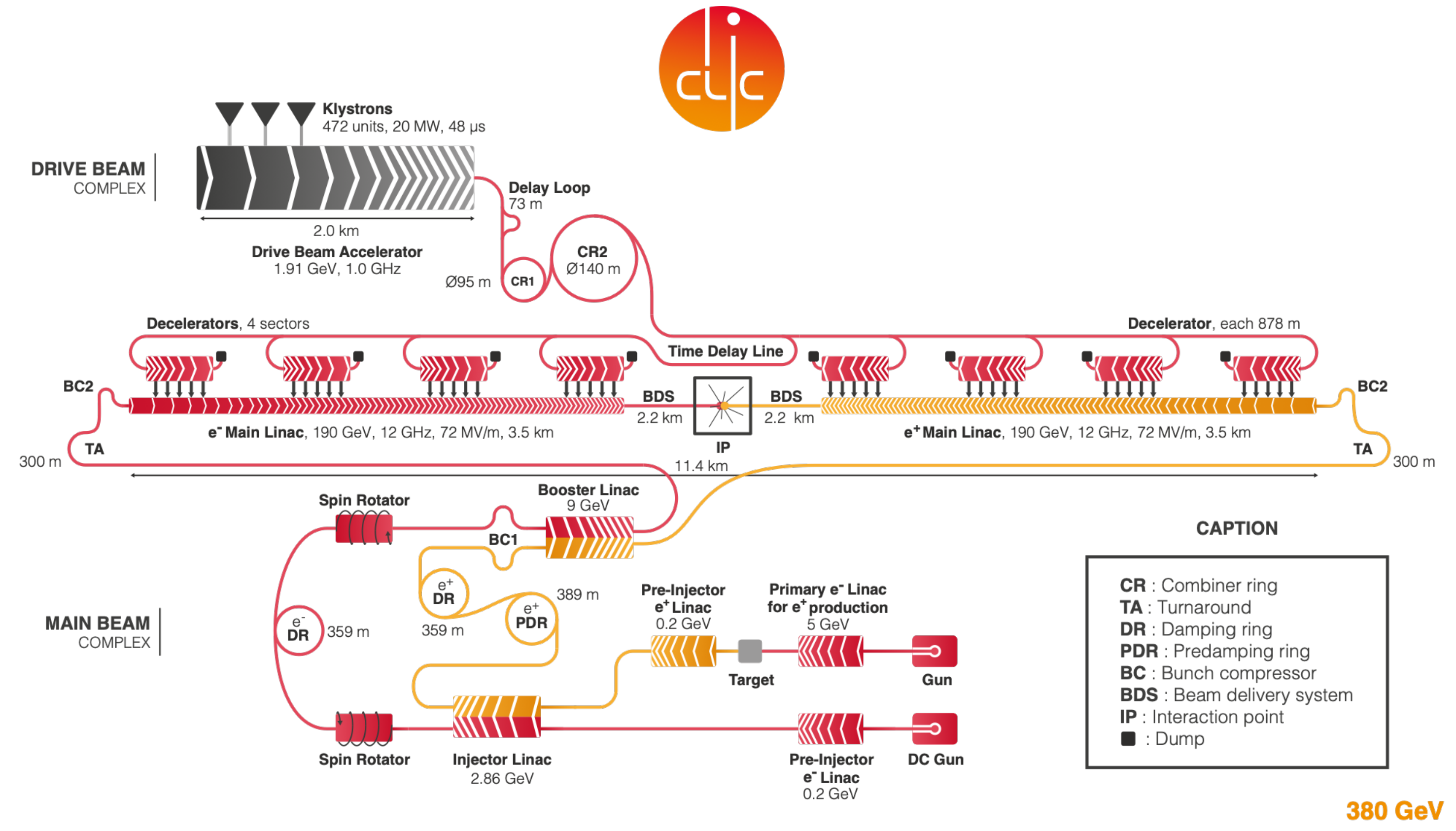
Recent summary document: LINK (Snowmass)

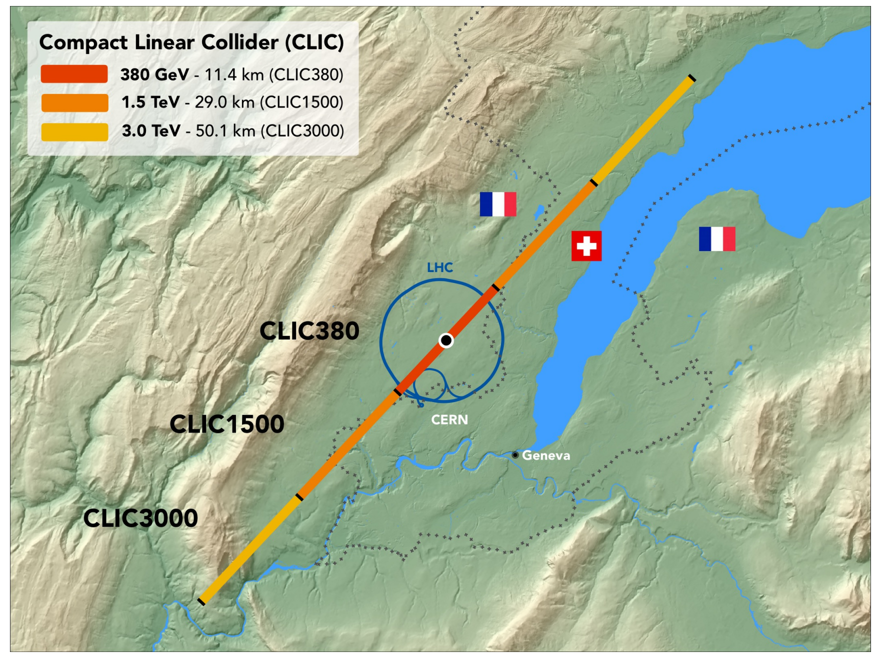
Comprehensive Physics and Detector studies

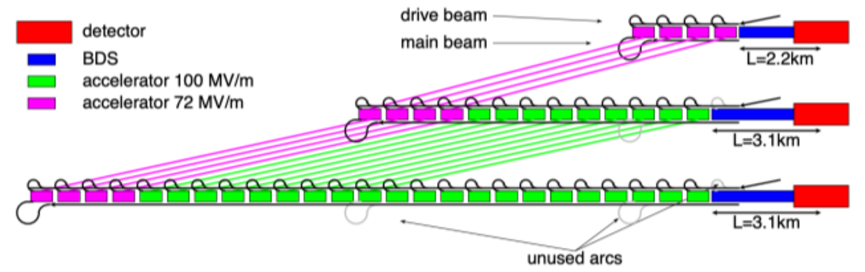


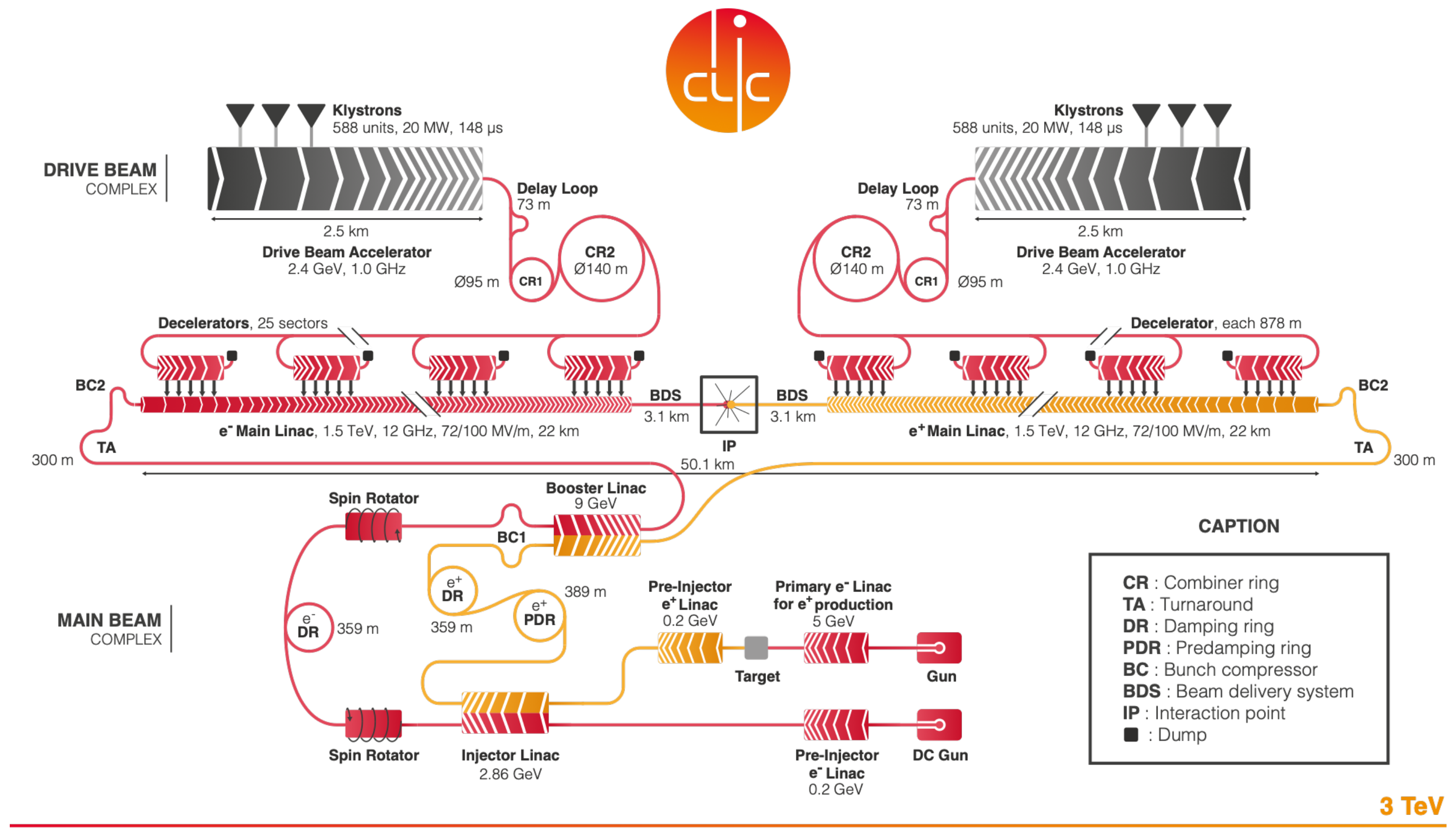
CLIC energy upgrades – parameter overview

CLIC can easily be extended into the multi-TeV region (3 TeV studied in detail)









CLIC – Scheme of the Compact Linear Collider (CLIC)

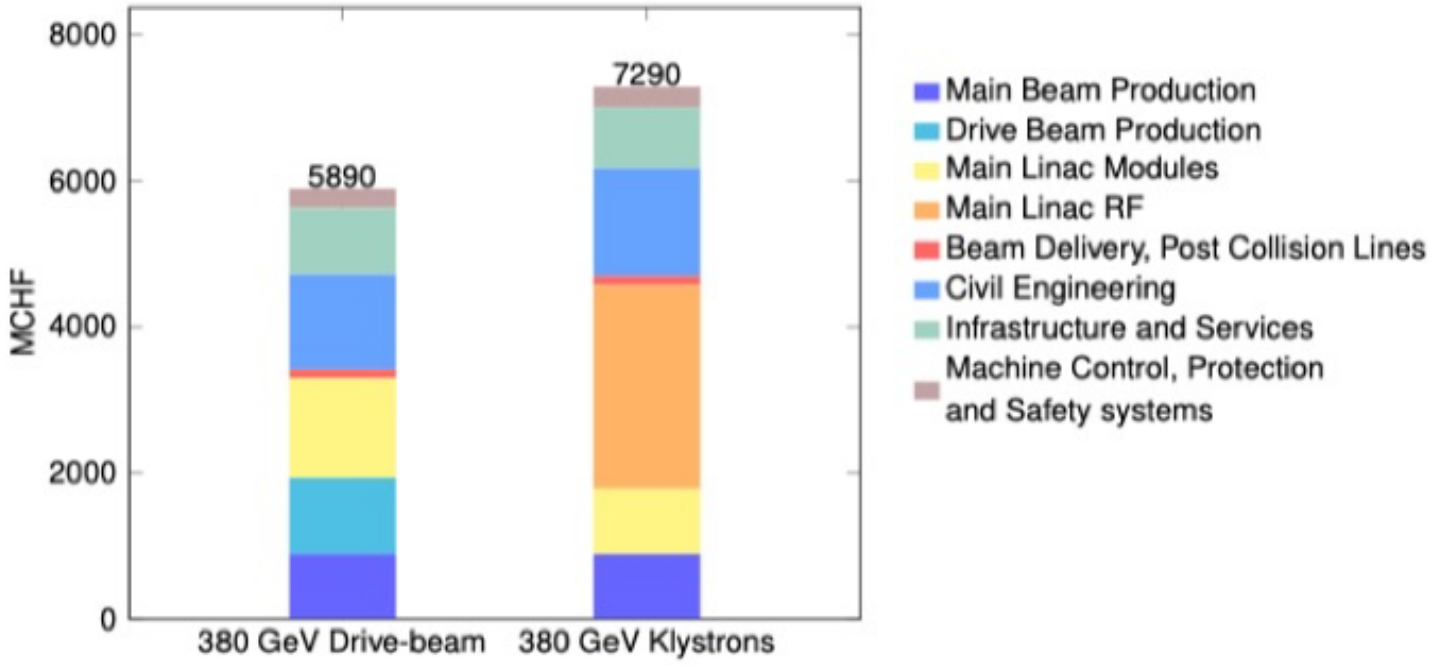
Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV

Table 1.1: Key parameters of the CLIC energy stages.

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

Cost - I

Machine has been re-costed bottom-up in 2017-18
- Methods and costings validated at review on 7 November 2018 – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated



Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.

Cost - II

Other cost estimates:

Construction:
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

Operation:
- 116 MCHF (see assumptions in box below)
- Energy costs

- 1% for accelerator hardware parts (e.g. modules).
- 3% for the RF systems, taking the limited lifetime of these parts into account.
- 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.

CLIC Project Readiness 2025-26

Goals for the studies by ~2025-26, key improvements:

- Luminosity numbers, covering beam-dynamics, nanobeam, and positrons - at all energies. Performance risk reduction, system level studies
  - Substantial progress already documented in Snowmass report and associated references, remains a focus for beamdynamics, nanobeam related technical developments and positron production studies

- Energy/power: 380 GeV well underway, 3 TeV to be done, L-band klystron efficiency
  - In Snowmass report for 380 GeV

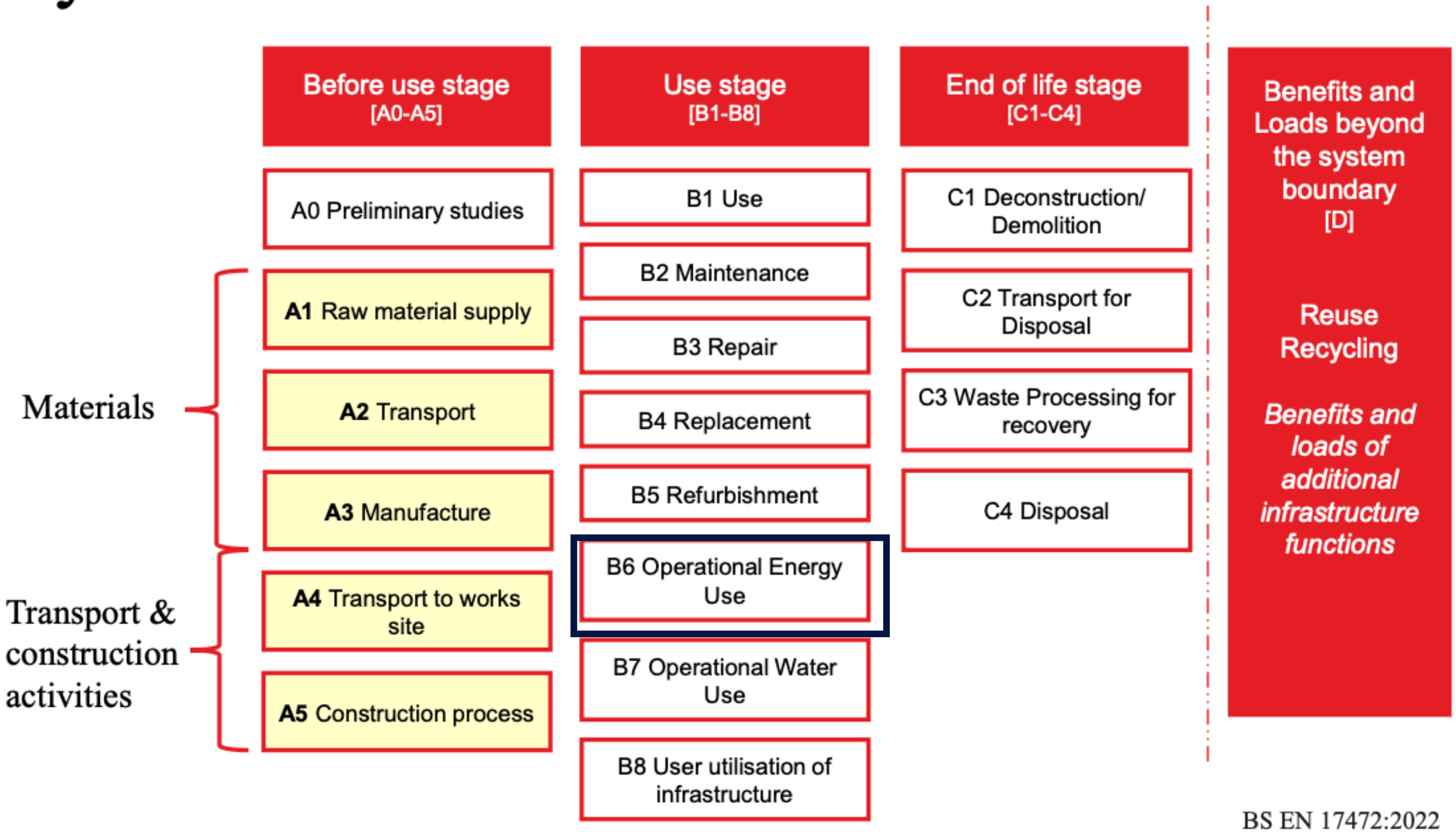
- Sustainability issues, more work on running/energy models and carbon footprint
  - Life Cycle Assessment, Initial studied in Project Implementation Plan (PiP) 2018, just referred to briefly in Snowmass report

- X-band progress – for CLIC, smaller machines, industry availability, including RF network
  - Addressed by establishing improved baseline, CompactLight Design Study (FEL linac) very important and many smaller setup. No complete documentation in PiP 2018 or Snowmass report 2022.

- R&D for higher energies, gradient, power, prospects beyond 3 TeV
  - Links also to power, nanobeam and beamdynamics

- Cost update, only discuss changes wrt Project Implementation Plan in 2018

System boundaries



BS EN 17472:2022

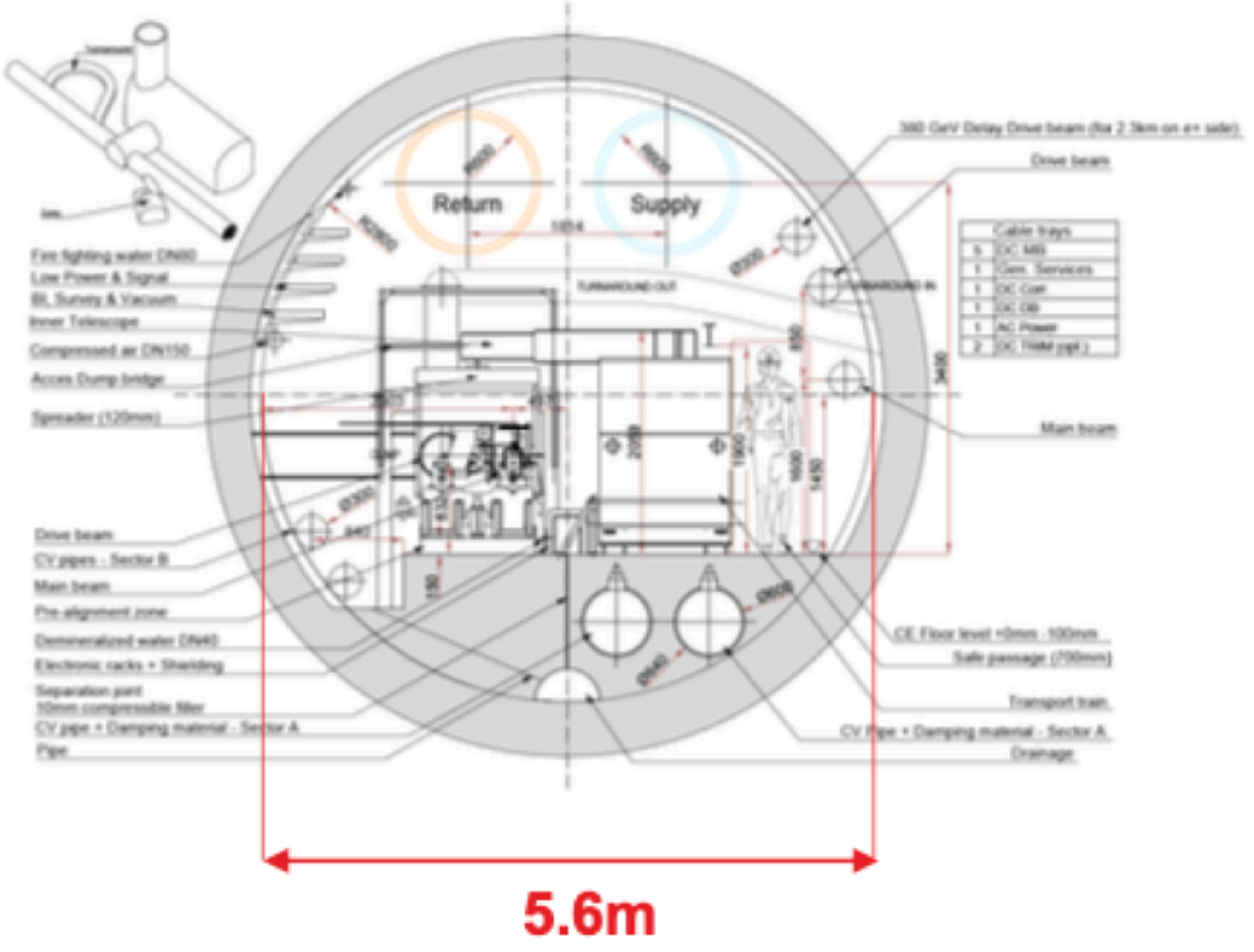
Only B6 normally discussed related to operation, now discuss A1-A5 for the CE
Missing A1-A5 for accelerator, some surface installations, all maintenance and upgrades, all EoL activities

ARUP

Linear Collider Options

1. CLIC Drive Beam

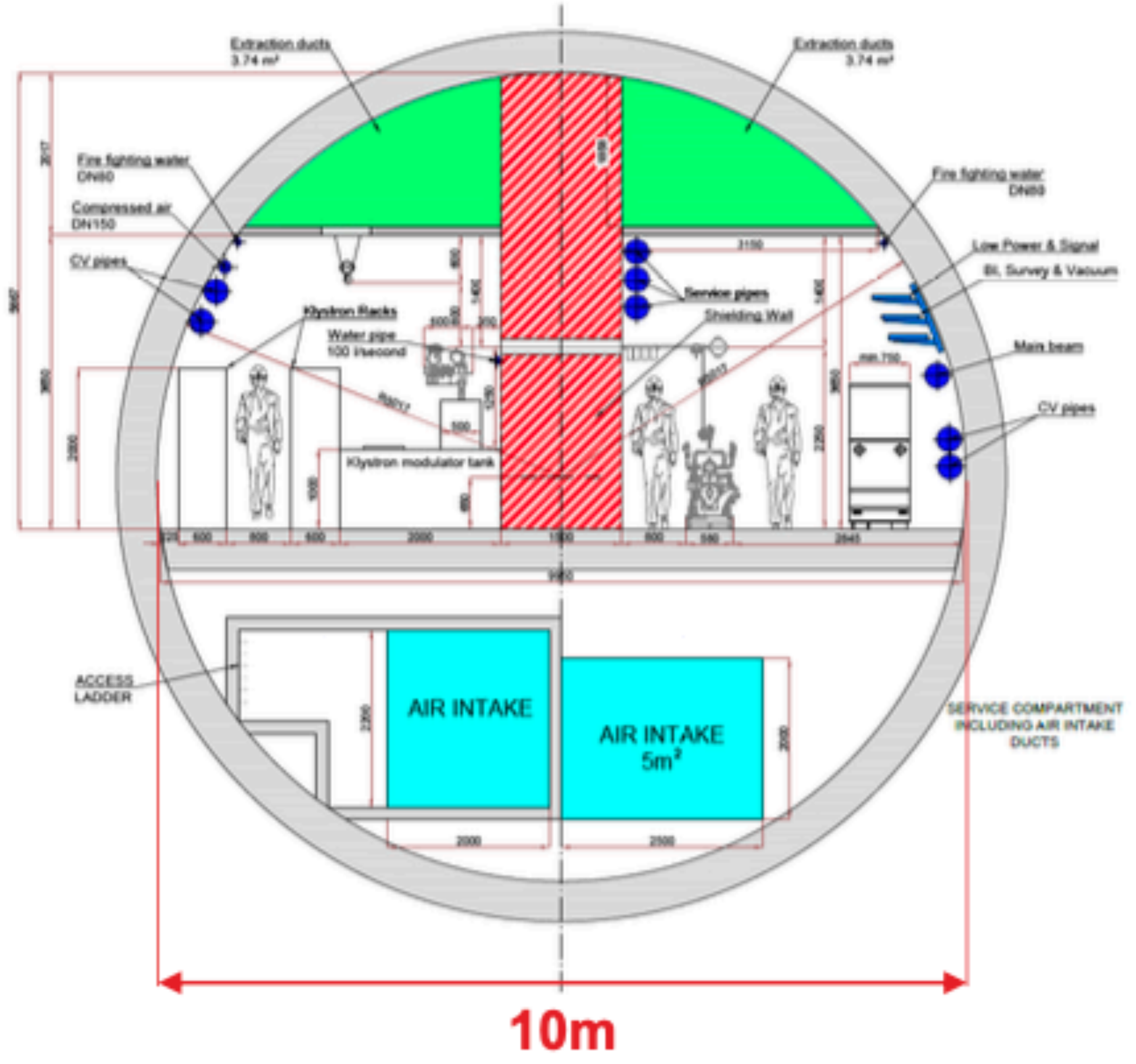
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)



Reference: CLIC Drive Beam tunnel cross section, 2018

2. CLIC Klystron

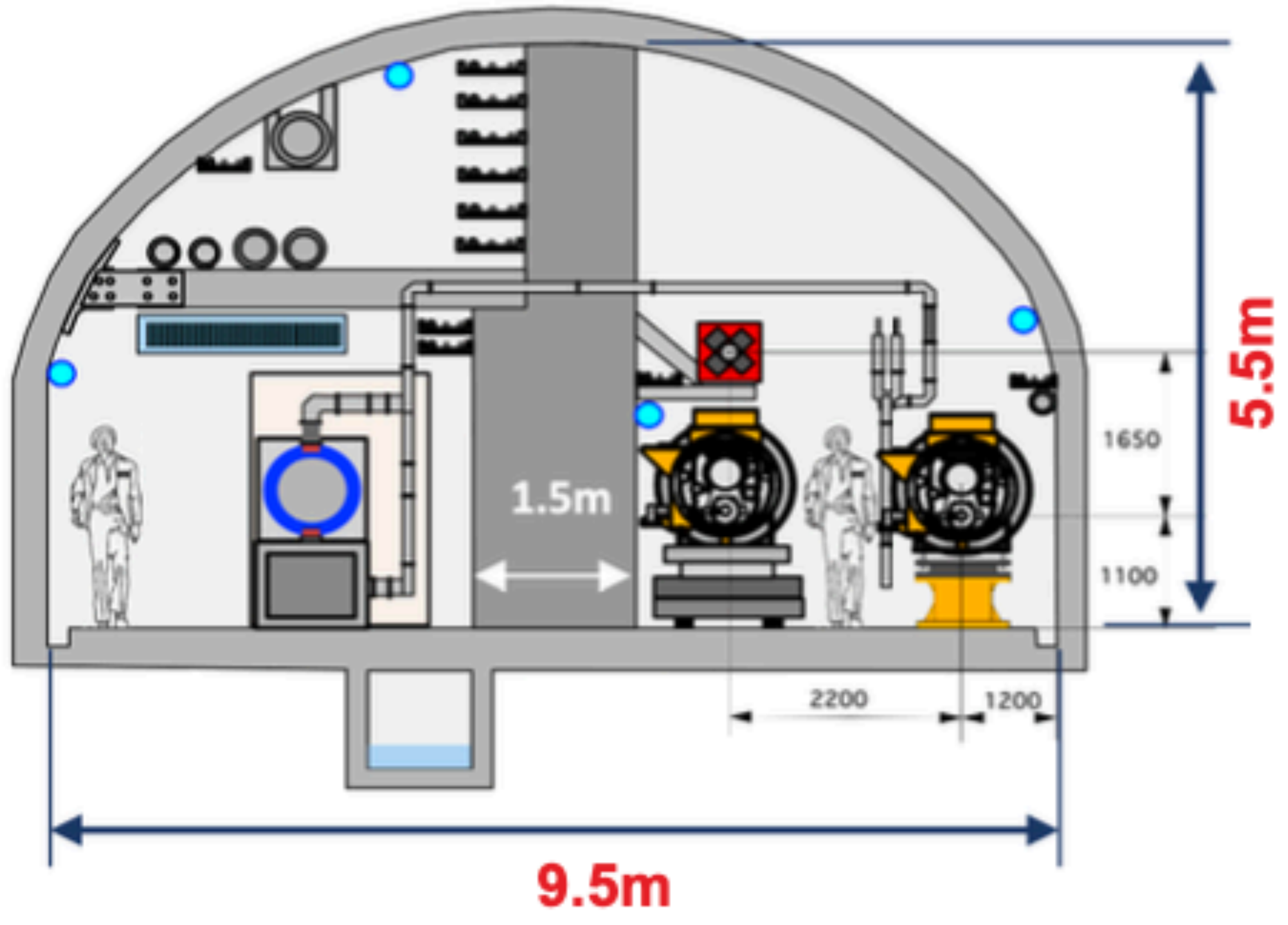
10m internal dia. Geneva.
(380GeV)



Reference: CLIC Klystron tunnel cross section, 2018

3. ILC

Arched 9.5m span. Japan.
(250GeV)



Reference: Tohoku ILC Civil Engineering Plan, 2020

LCA wrap up

100% of projects due to be completed in 2030 or after are net zero carbon in operation

with at least 40% less embodied carbon compared to current practice

2030 Breakthroughs UNFCCC

ARUP

UN Breakthrough Outcomes for 2030

A1-A5: Tunnel construction (ILC and CLIC DB dimensions) is around 6kton/km
- Add shafts, caverns , access tunnels, DR, etc + from 30 to 60%
- Add transports, power used in construction, etc + 25%

= > ILC (20km) around 270 kton, CLIC (11 km) around 125 kton

Possible savings (but at a cost to be defined) of ~40%
Adding accelerator components and injectors more consistently (possibly 50% increase – very early days)

Operation (in ~2050)
Nuclear 5g/kWh and re-newables (sun/wind/hydro) 20g/kWh – suitable for Europe, what is suitable as goal for Japan ?
Can be higher with poor energy mix, can be lower with good contracting (good mix)
Assume 50/50 mix => 1 TWh is 12.5 kton

France in summer months are at ~40 g/kWh, a factor three better towards 2050 within reach ?

In Japan this is harder, contracting on low carbon energy an important tool
A green field site offers more flexibility for compensation (as in the green ILC approach)

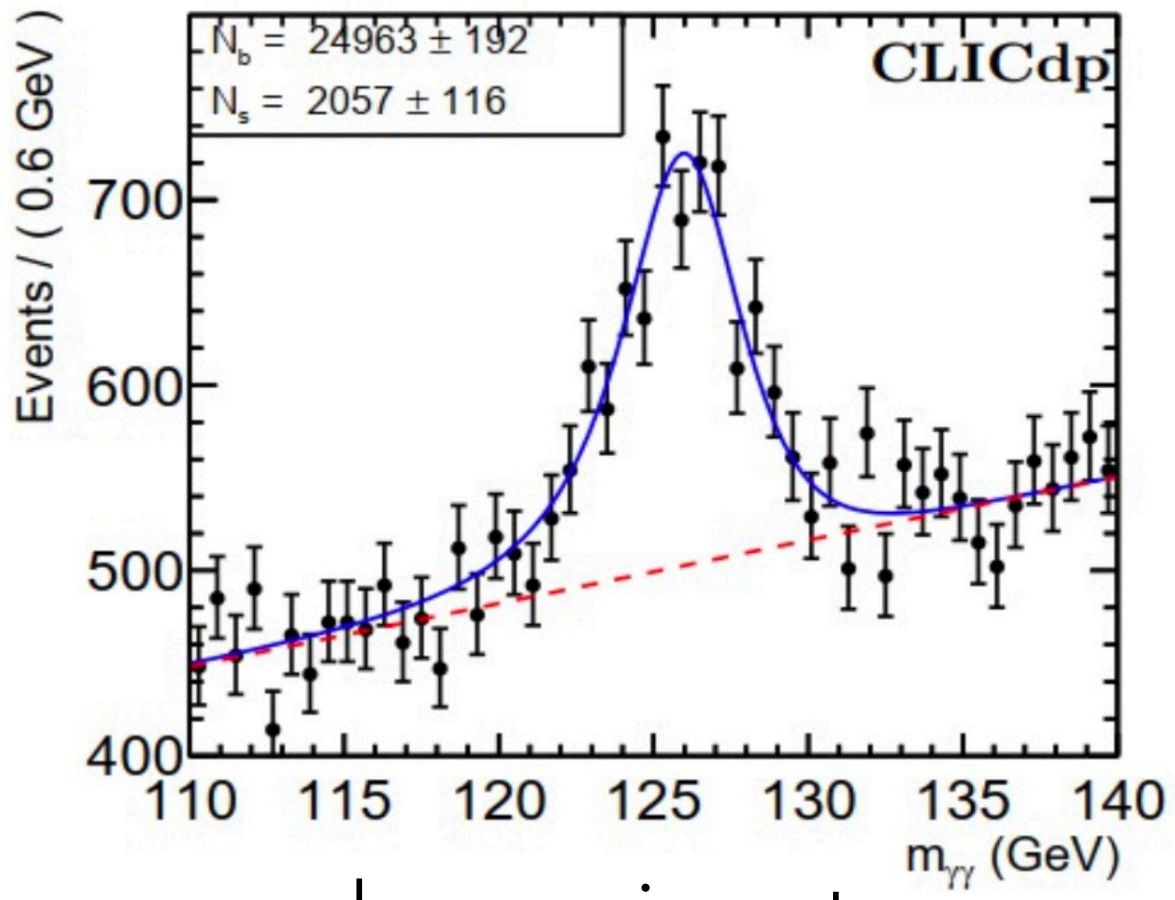
-> Energy use estimated for LCs 0.6-0.8 TWh annually, i.e. around 10 kton CO2
-> Power nevertheless has huge cost impact, and secondary effects on CO2 (more material)

Physics Analysis at CLIC

ongoing activities

- **Recent publications:**

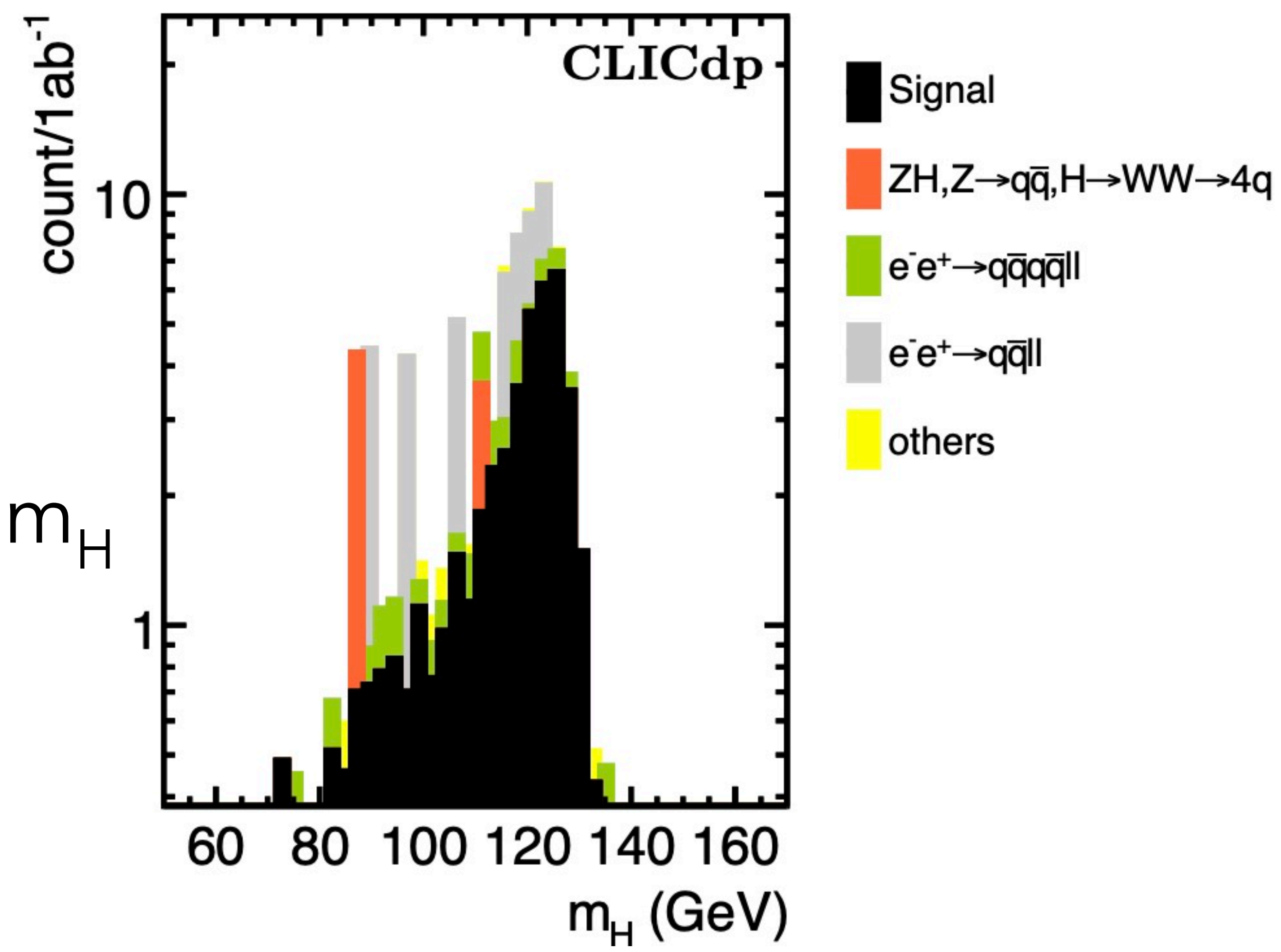
Br(H->γγ) at 3TeV
Full simulation study to confirm extrapolation from 1.4TeV
Phys. Rev. D **105**, 092009 (2022)
-> see poster from G. Kacarevic

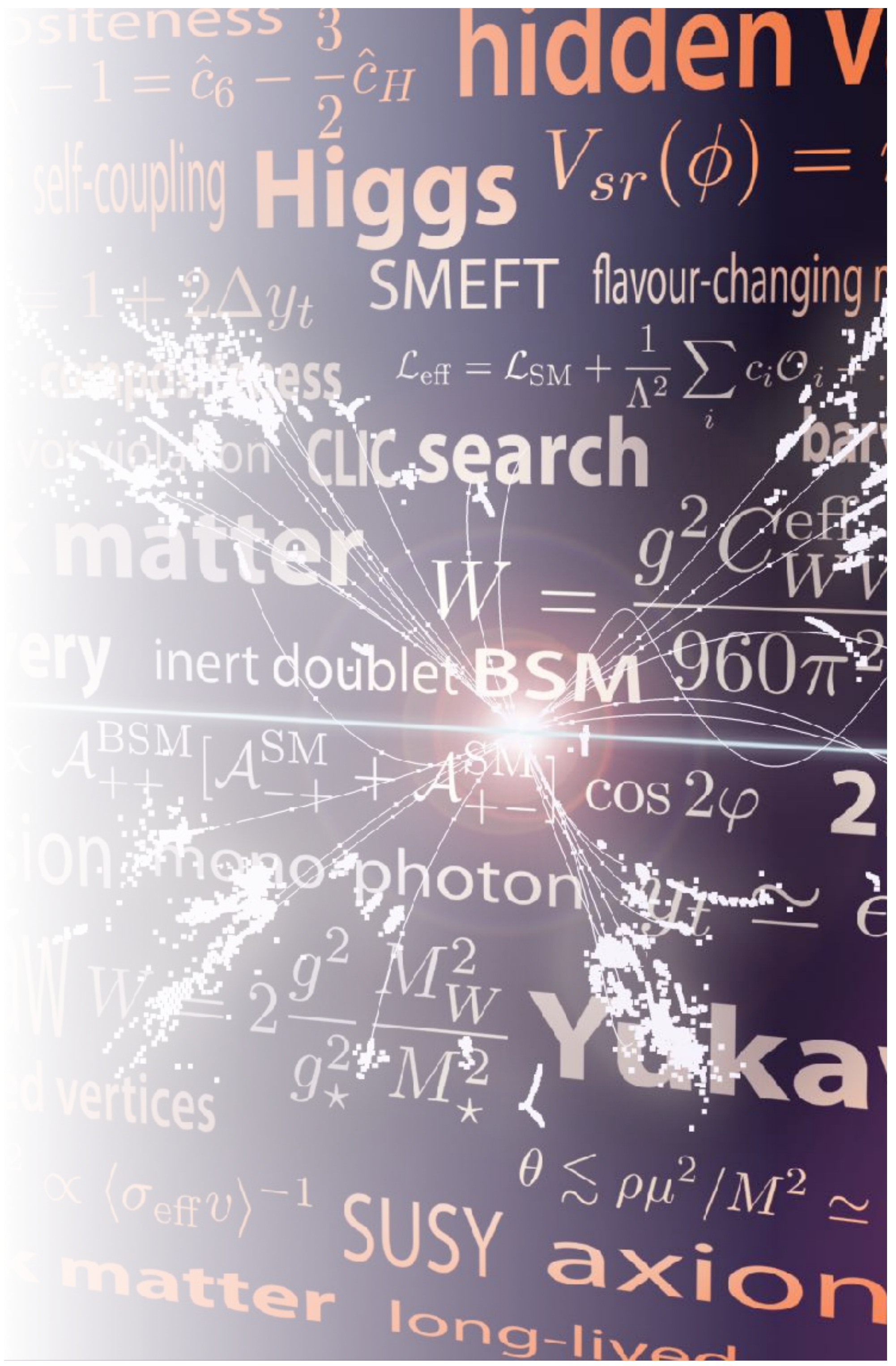


pseudoexperiment

Br(H->ZZ) at 350GeV and 3TeV
Full simulation using semileptonic final states
Phys. Rev. D **105**, 092008 (2022)
-> see talk from N. Vukasinovic

reconstructed m_H after full MVA selection





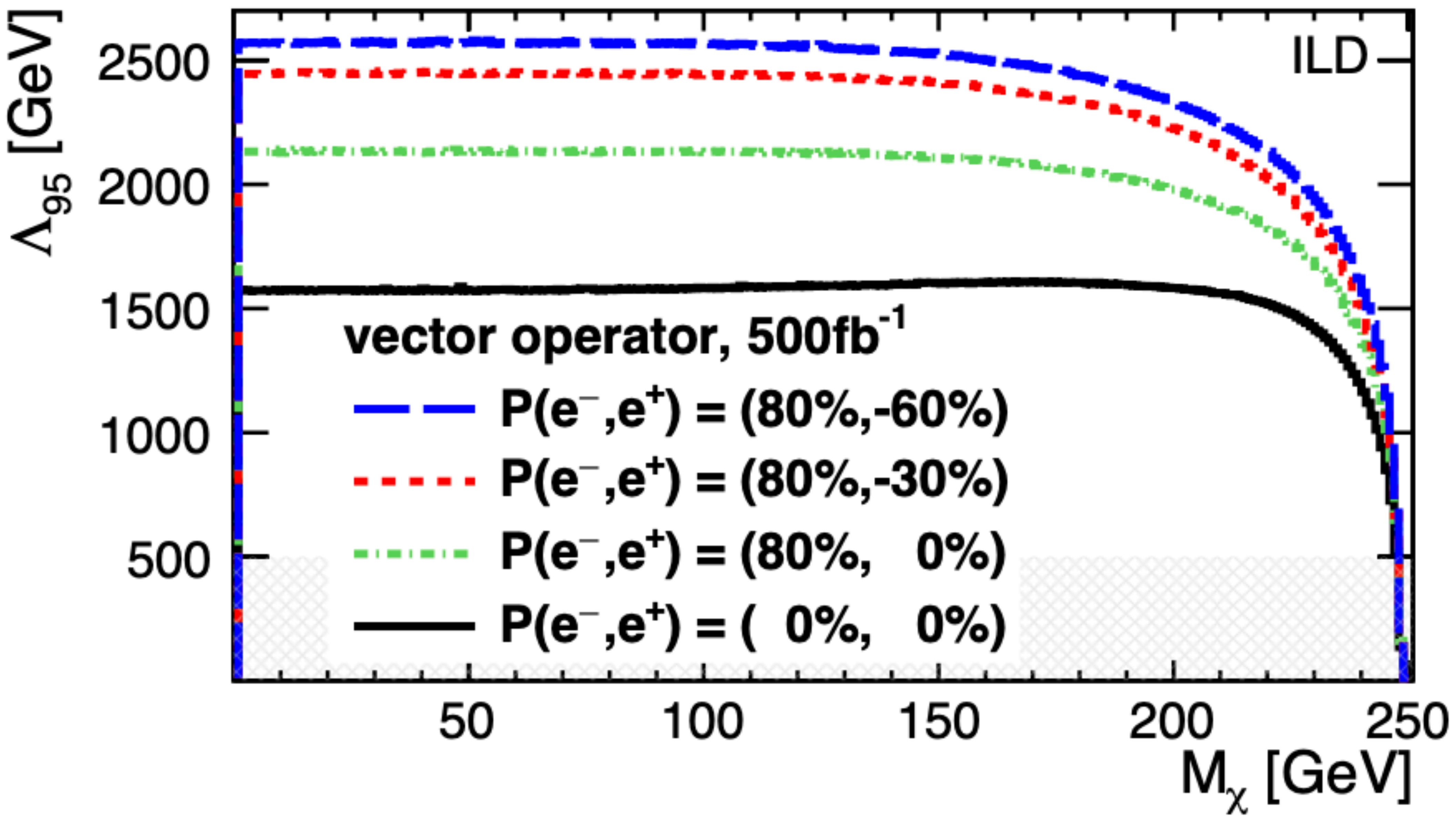
- **Ongoing studies:**

Searches for exotic long-lived particles at CLIC using displaced vertices
CP Violation studies in H->ZZ at 1.4TeV
Lepton flavour-violating Higgs decays

Physics Analysis on Role of Beam Polarizations

cornerstone for making the physics case

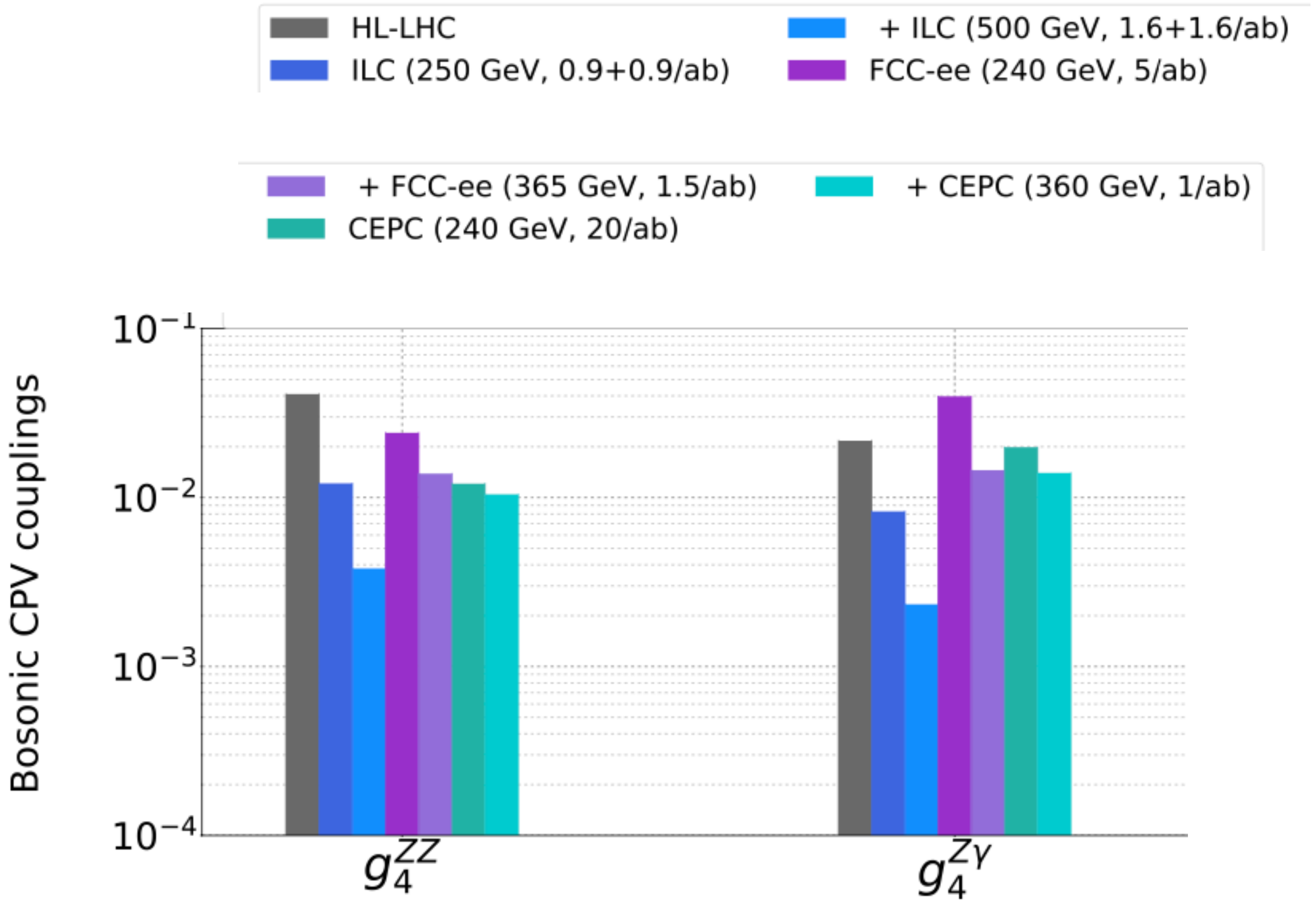
- constantly being explored what advantages polarized beams would bring in physics analysis



WIMP search

[M. Habermehl, PhD Thesis]

M. Habermehl,



CP-violating HZZ and HZγ couplings

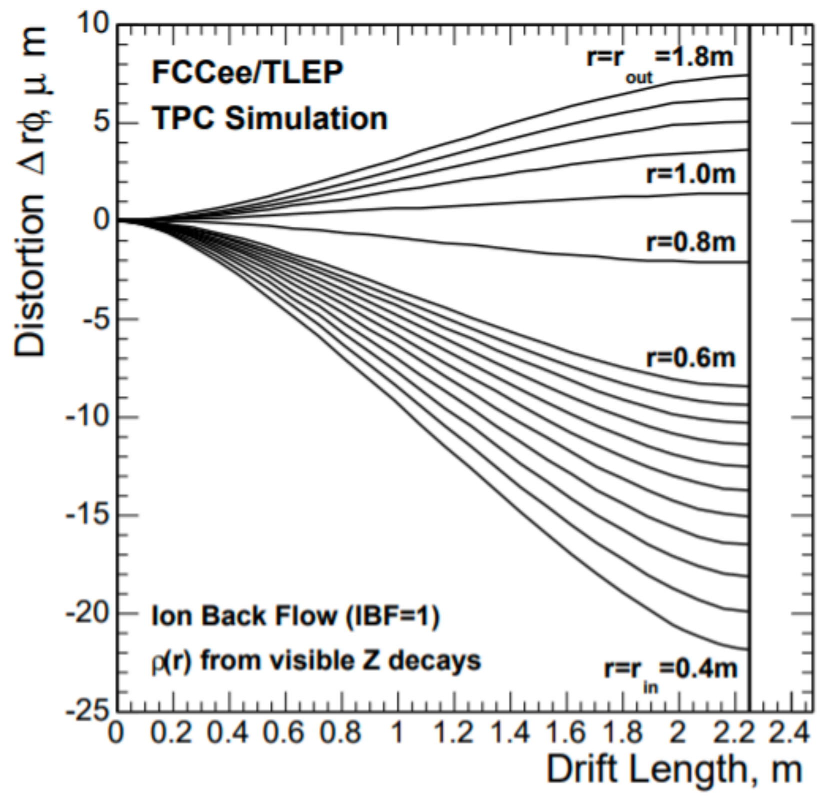
[➟talk by V.Miralles]

ILD strategy (open to all e+e-)

[T. Behnke @ ILD2022]

Feedback from TPC

- Need to really understand the relevant parameters
  - Impact of space charge
  - Occupancies
- Operating a TPC above the Z does not seem to be a problem independent of the technology
- Pixel TPC seems an interesting option also for Z running and might work



$D^0 \to \pi^+ K^-$ reconstruction with Z-pole samples

	ϵ (%)	p (%)
$\lvert mass - mass_{D0} \rvert < 0.01\,\mathrm{GeV/c^2}$	90.39 ± 0.24	2.16 ± 0.07
IMP $> 0.02\,\mathrm{mm}^2$	79.12 ± 0.21	5.04 ± 0.11
vertex fitted $\chi^2 < 5.15$	72.62 ± 0.23	15.36 ± 0.18
dis of vertex to IP > 0.305 mm	69.24 ± 0.24	28.41 ± 0.23
PID	68.19 ± 0.24	89.05 ± 0.16

Detector Concepts

driving factors

- "Clean" environment at e+e- allows the design of detectors with very ambitious performance: event rate, event complexity, radiation level, all much lower comparing to that at hadron colliders
- Performance requirement driven by physics program from Z-pole to TeV

detector performance		physics performance
Impact Parameter resolution	$5\ \mu\mathrm{m} \oplus \frac{10\ \mu\mathrm{m\ GeV}/c}{p\ \sin^{3/2}\theta}$	flavor tagging, e.g. hadronic Higgs BR meas. for bb/cc/gg
Momentum resolution	$\Delta(1/p) = 2\times10^{-5}\ (\mathrm{GeV/c})^{-1}$	leptonic recoil mass meas.
Jet Energy Resolution	ΔE/E = 3-4%	hadronic decays of W/Z
Triggerless readout		
Power pulsing		

(asymptotic resolution)

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