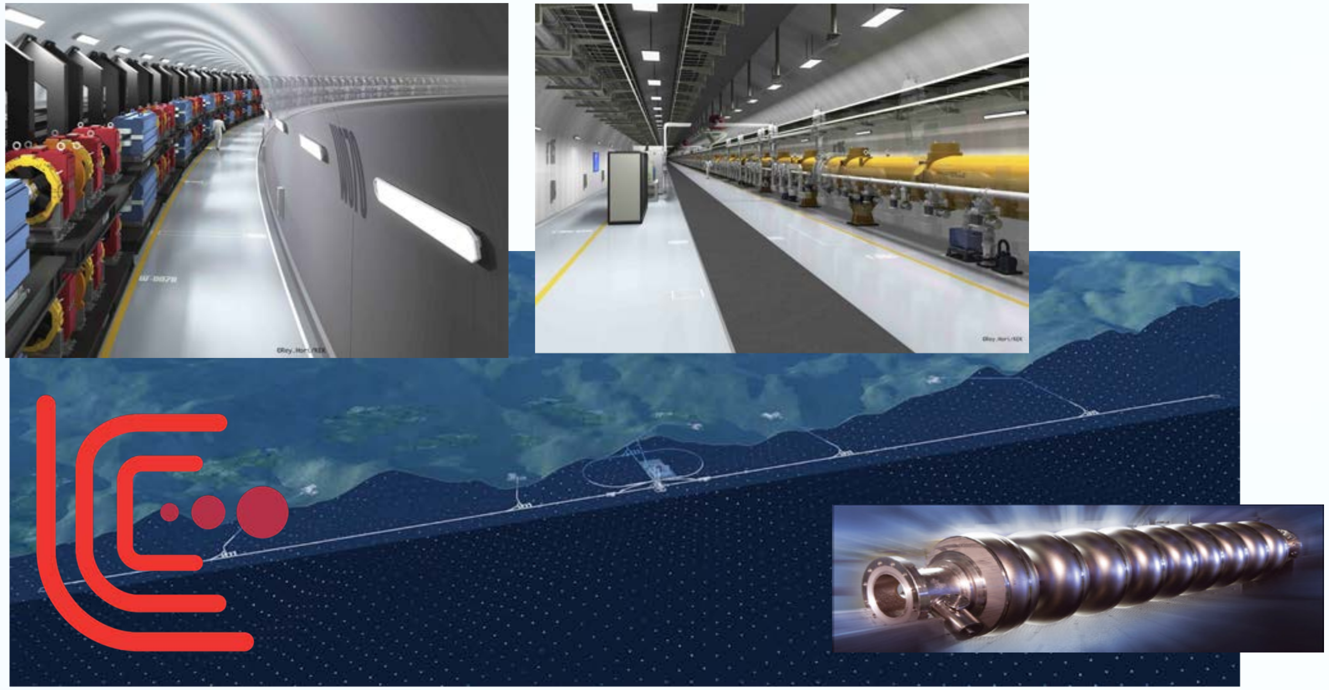
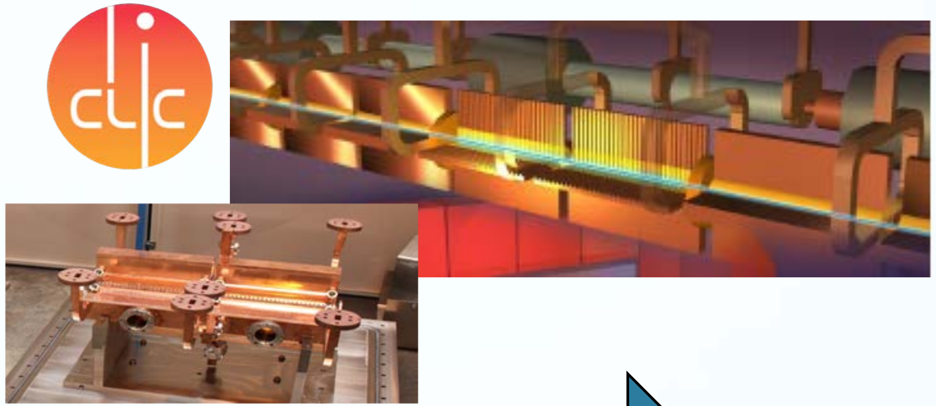




ILC and CLIC

A. Faus-Golfe

Outline

- ILC

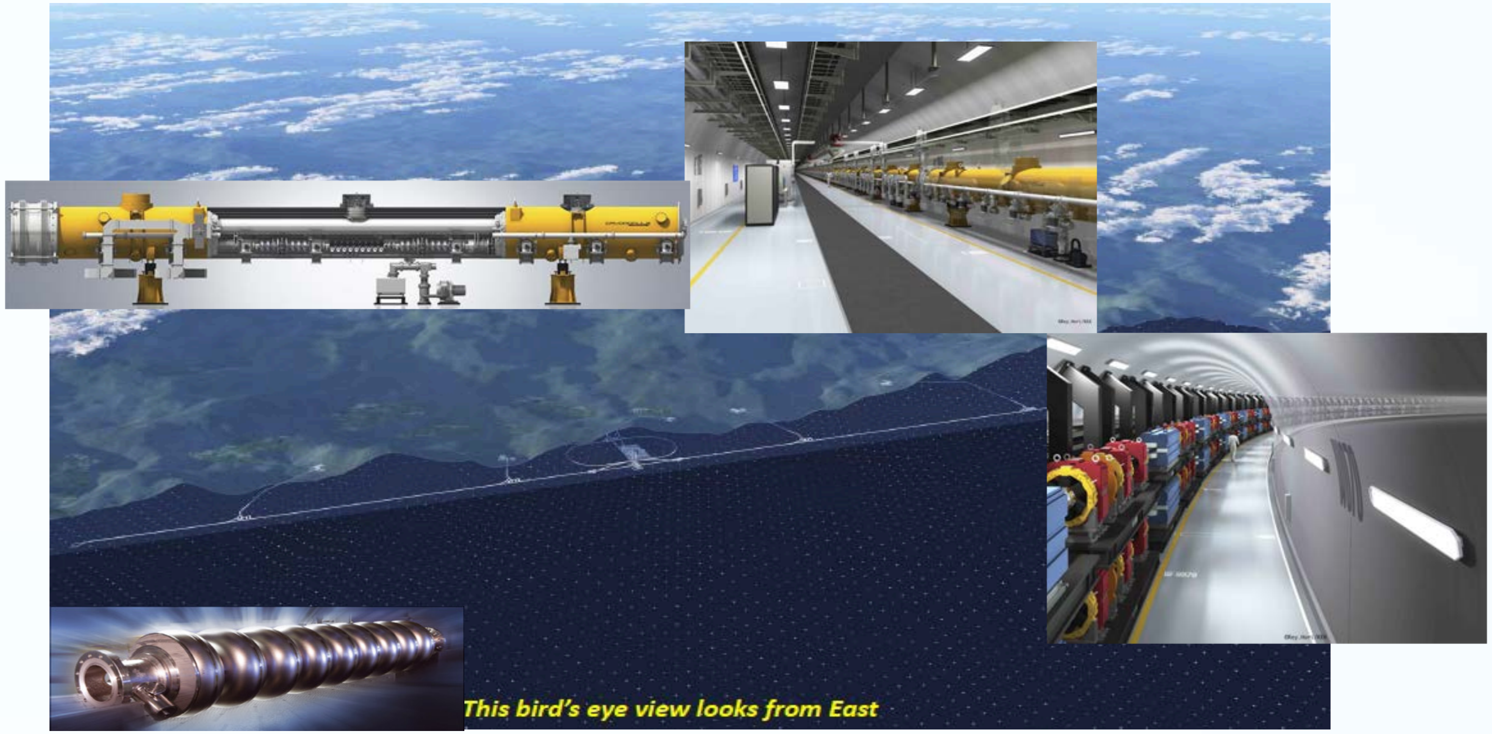
  Technology update

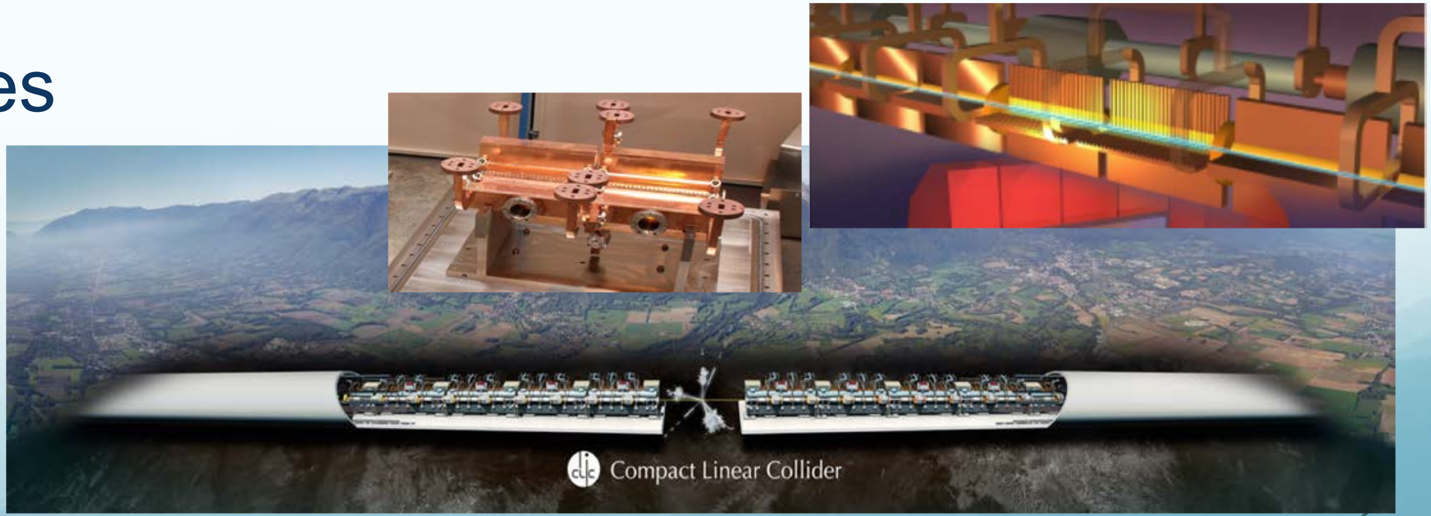
- CLIC

  Technology update

- Summary and perspectives

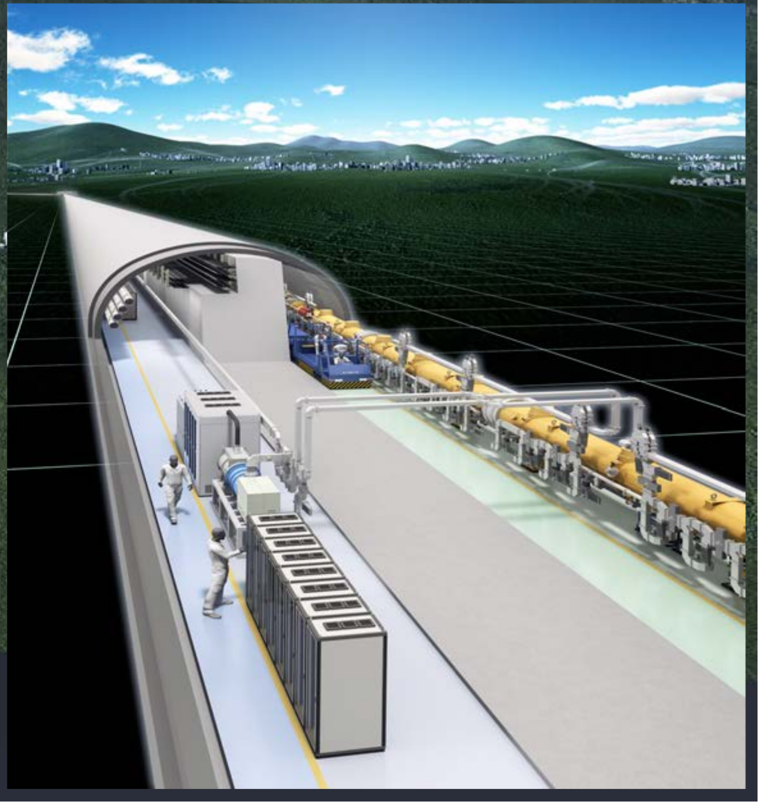
  EPPSU Granada 2019





ILC accelerator: Techology update

http://www.linearcollider.org/



CepC 2019

18-20 November 2019

ILC parameters @ 250GeV and upgrades

The ILC A Global project, EPPSU December 2018

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	2.6 %	0.97 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	129		122	163	300
Site length	L_{site}	km	20.5	20.5	31	31	40

Luminosity upgrade to 10Hz also considered

ILC accelerator progress:

the Z pole @ 250GeV

A study about **the Z-pole (ECM=91.2GeV)** operation of ILC@250, assuming the undulator scheme for positron production has been made:

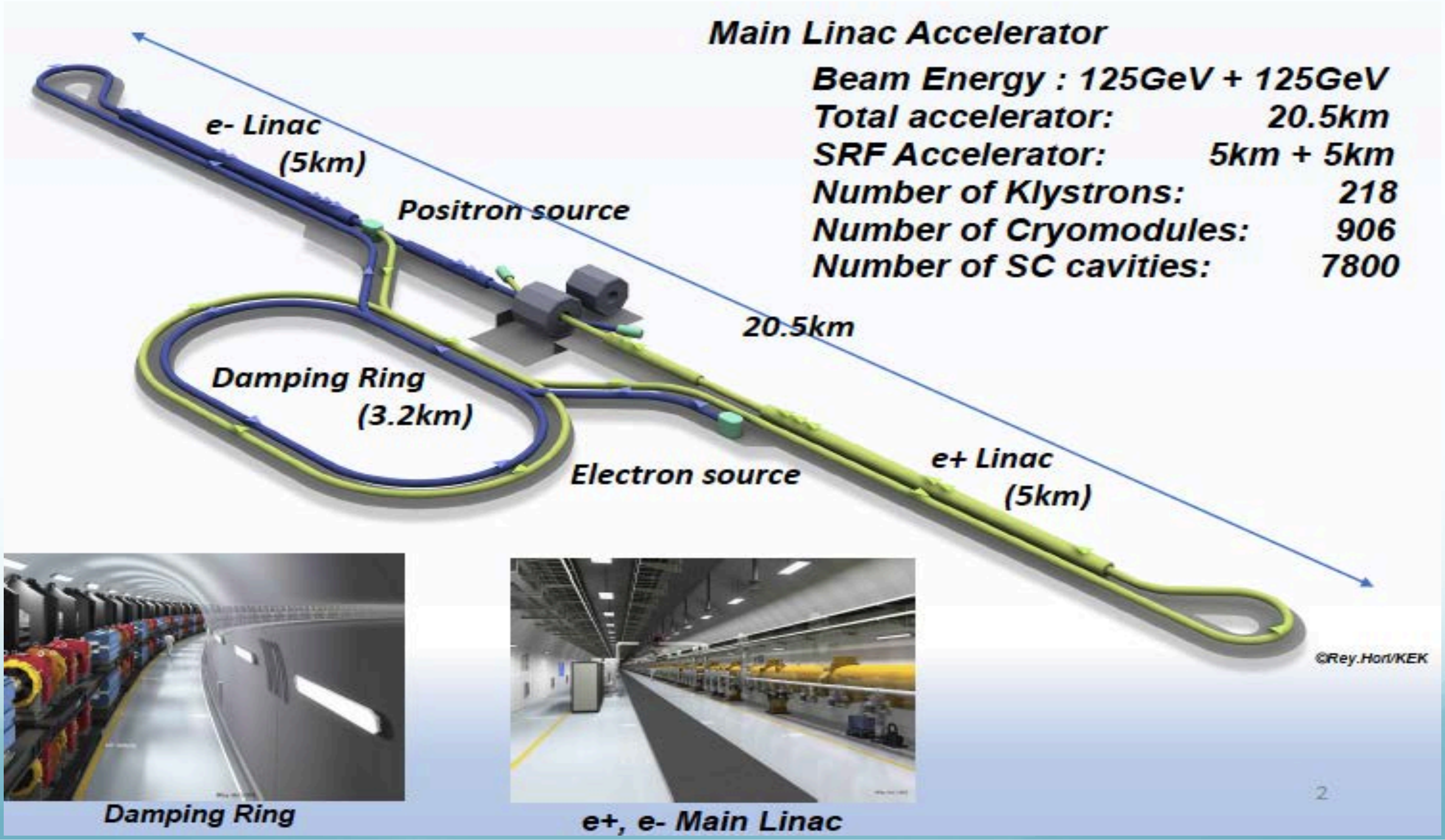
- ILC250 (shorter linac) is worse in total available power up to 3.7+3.7Hz operation, but better in beam dynamics (emittance growth at low gradient)
- The previous luminosity improvement for ILC250 by smaller horizontal emittance brings about significant effects for Z-pole operation
- Expected luminosity is now **L ~ 2.1 x 10^{33}/cm^2/s**
- No particular problem is expected in doubling the luminosity by doubling the number of bunches
- If you want even higher luminosity, the bottle neck is the momentum bandwidth of BDS under the large energy spread of the low energy beam

http://arxiv.org/abs/1908.08212

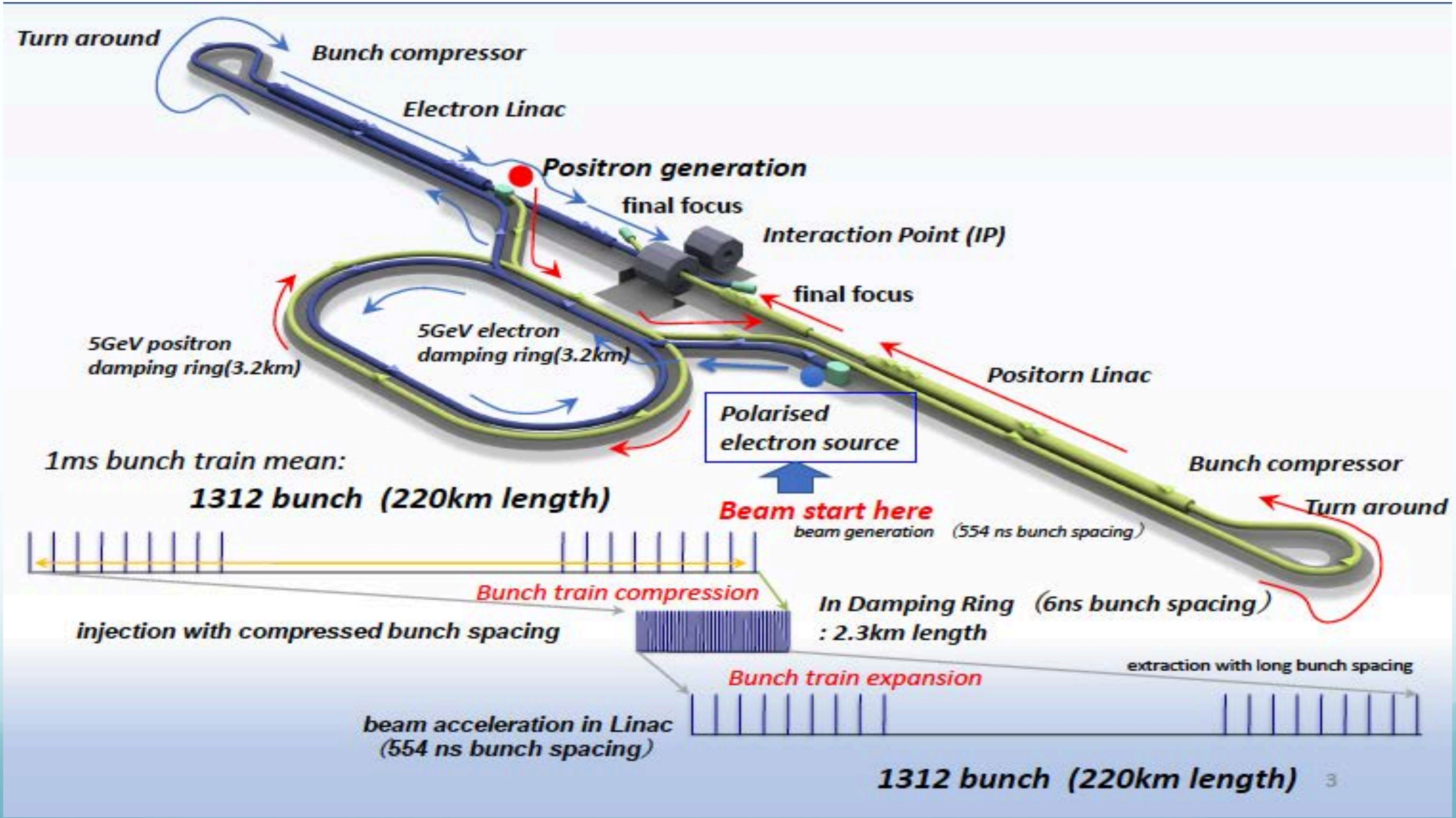
Parameters of Operation at Z-pole

Center-of-Mass Energy	E_{CM}	GeV	91.2	250
Beam Energy	E_{beam}	GeV	45.6	125
Bunch collision rate	f_{col}	Hz	3.7	5
Electron linac rep.rate		Hz	3.7+3.7	5
Pulse interval in electron main linac		ms	135	200
Electron energy for e+ prod.		GeV	125	125
Number of bunches	n_b		1312	1312
Bunch population	N	10^{10}	2	2
Bunch separation	Δt_b	ns	554	554
RMS bunch length	σ_z	mm	0.41	0.30
Electron RMS Beam energy spread at IP	σ_p/p	%	0.30	0.188
Positron RMS Beam energy spread at IP	σ_e/p	%	0.30	0.150
Emittance from DR (x)	$\gamma\varepsilon^{DR}_x$	µm	4	4
Emittance from DR (y)	$\gamma\varepsilon^{DR}_y$	nm	20	20
Emittance at linac exit	$\gamma\varepsilon^{ML}_x$	µm	5	5
Emittance at linac exit	$\gamma\varepsilon^{ML}_y$	nm	35	30
Emittance at IP (x)	$\gamma\varepsilon^*_x$	µm	6.2	5
Emittance at IP (y)	$\gamma\varepsilon^*_y$	nm	48.5	35
Electron polarization	P_-	%	80	80
Positron polarization	P_+	%	30	30
Beta_x at IP	β^*_x	mm	18	13
Beta_y at IP	β^*_y	mm	0.39	0.41
Beam size at IP (x)	σ^*_x	µm	1.12	0.515
Beam size at IP (y)	σ^*_y	nm	14.6	7.66
Disruption Param (x)	Dx		0.41	0.52
Disruption Param (y)	Dy		31.8	35.0
Geometric luminosity	Lgeo	10^{33}	0.95	5.29
Luminosity	L	10^{33}	2.05	13.5
Luminosity at top 1%		%	99.0	74.0
Luminosity emhancement factor	H_D		2.2	2.55
Number of beamstrahlung	n_γ		0.841	1.91
Beamstrahlung energy loss	δ_{BS}	%	0.157	2.62

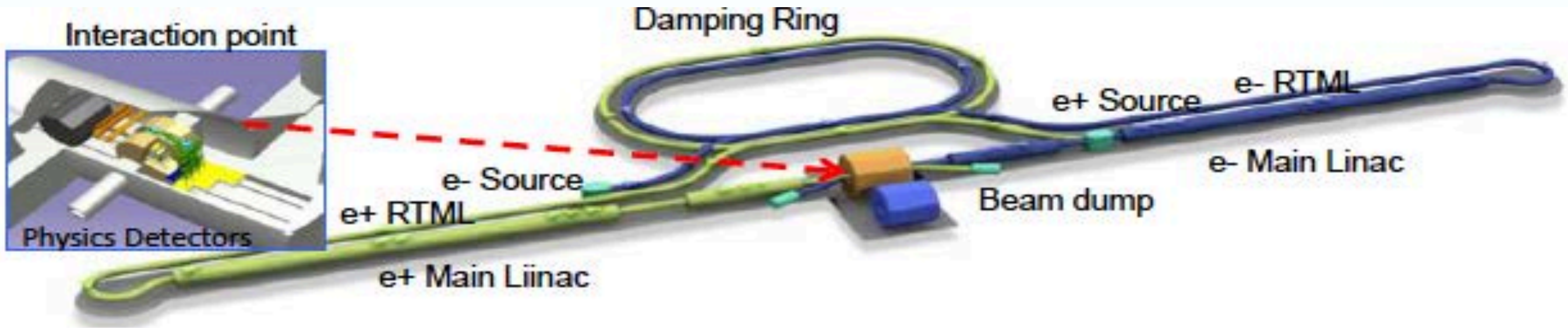
ILC accelerator configuration



ILC beam accelerator sequence



ILC accelerator Technology



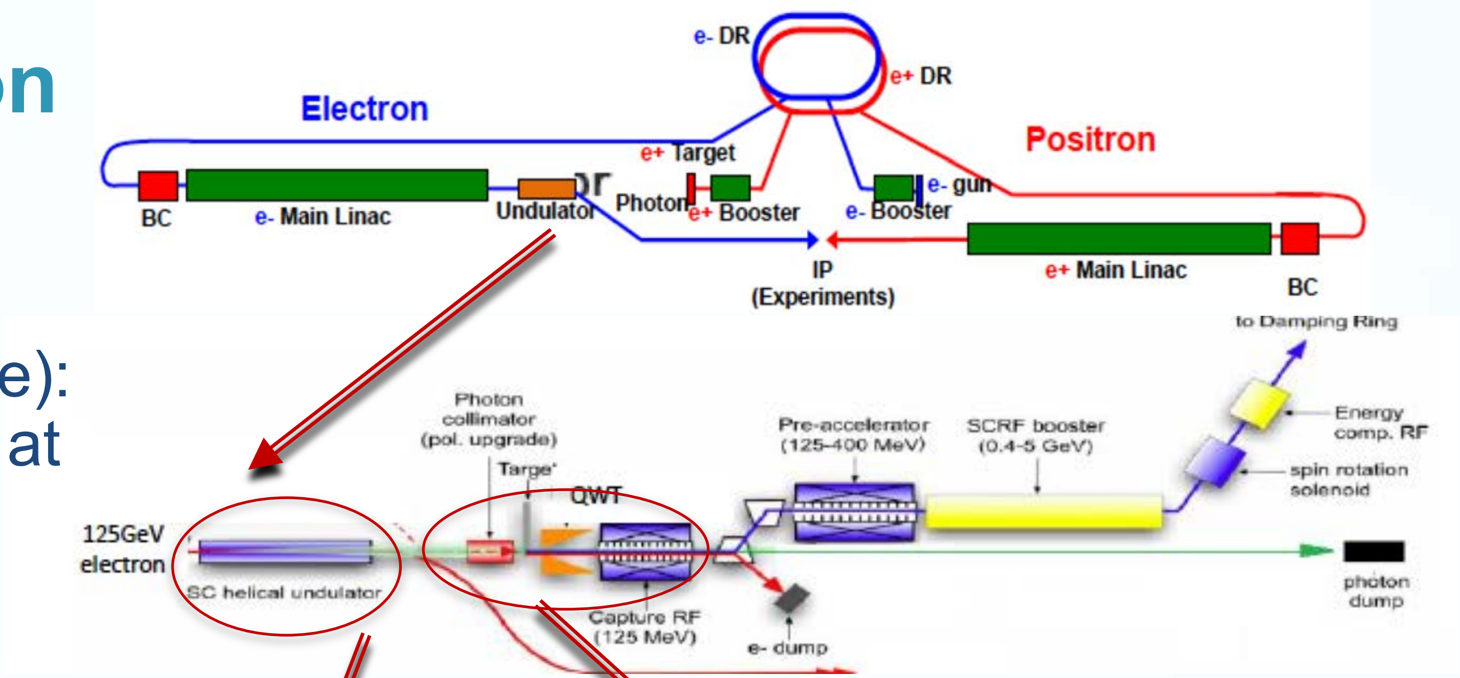
- Creating particles *Sources*
  - polarized elections/positrons
- High quality beams *Damping ring*
  - Low emittance beams
    - Small beam size (small beam spread)
    - Parallel beam (small momentum spread)
- Beam transport *RTML (bunch compressor)*
- Acceleration *Main linac*
  - superconducting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

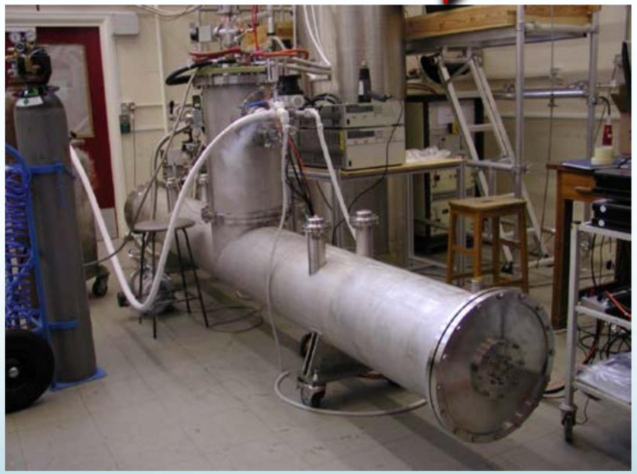
S. Michuzono, LCWS2019

Positron production

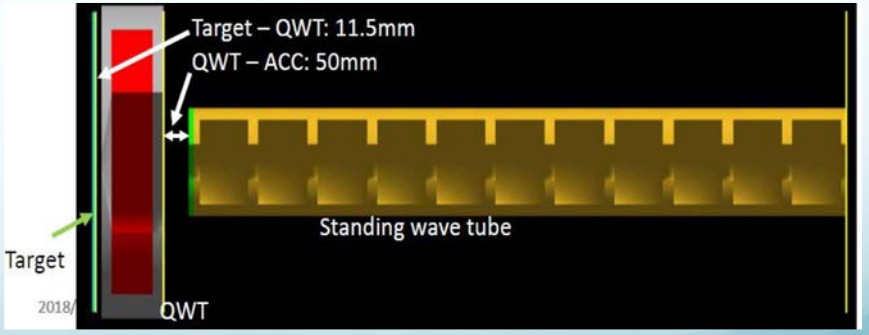
Two concepts considered:

- **SC helical undulators** (baseline): rotating target, polarized, but e$^-$ at 125 GeV are complicated for commissioning/operation.
  Flux concentrator replaced by QWT (long pulse).
  No showstopper seen.
  Detailed engineering specifications for target wheel and experimental tests still to be done



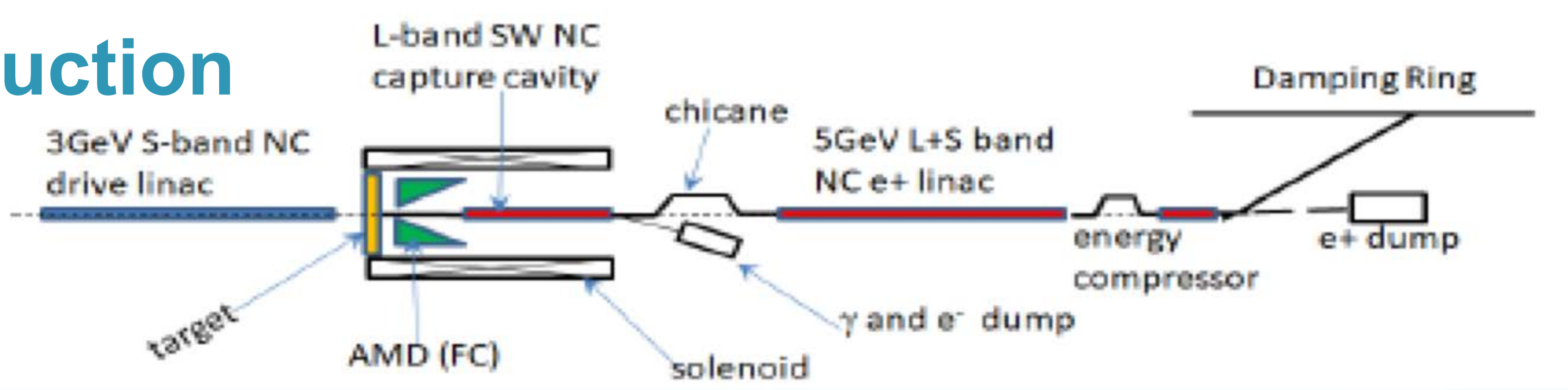


SC undulator prototype developed at RAL

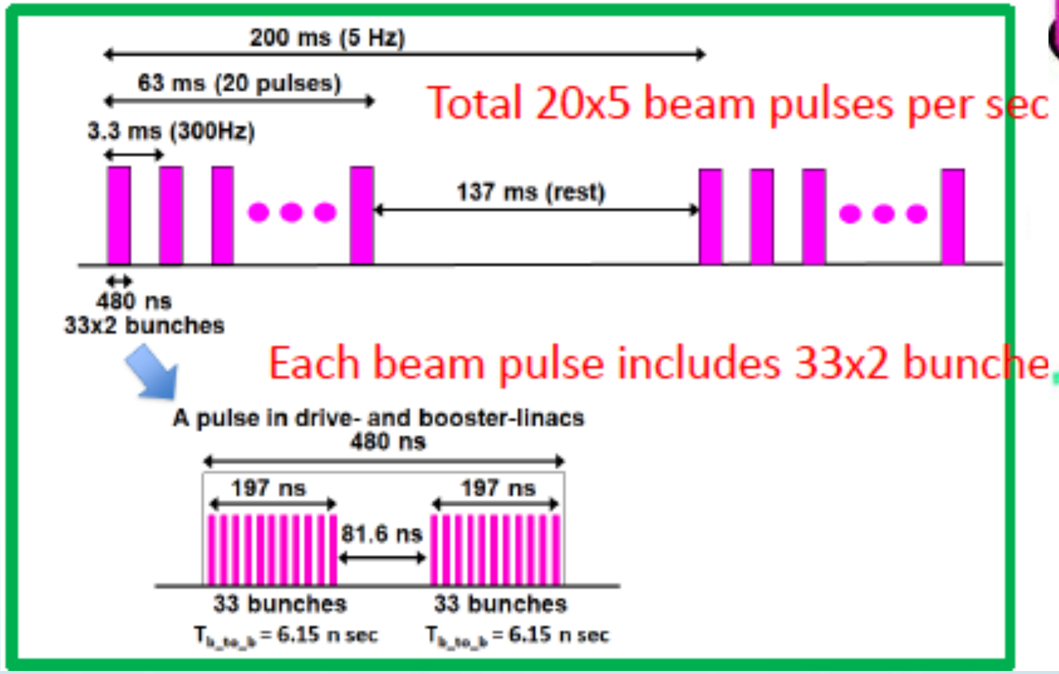


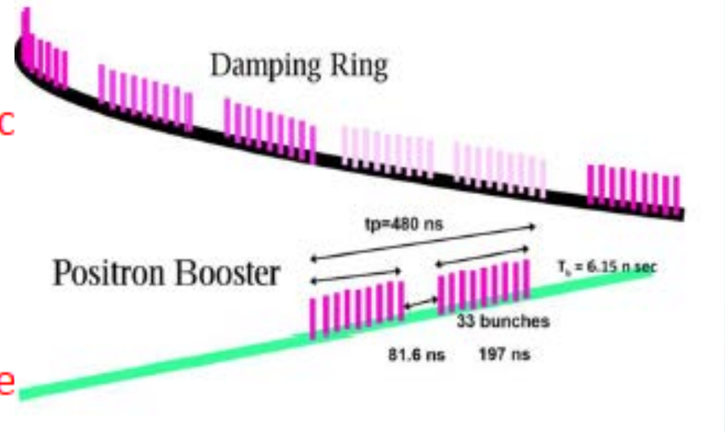
QWT (Quarter Wave Transformer)

Positron production



- **Electron driven source**: dedicated 3 GeV NC S-band TW e⁻ (pair production). High-energy e⁻ are not necessary. e⁻ independent commissioning is possible. However, polarization is not available.





Intensive design/simulation studies on-going at KEK

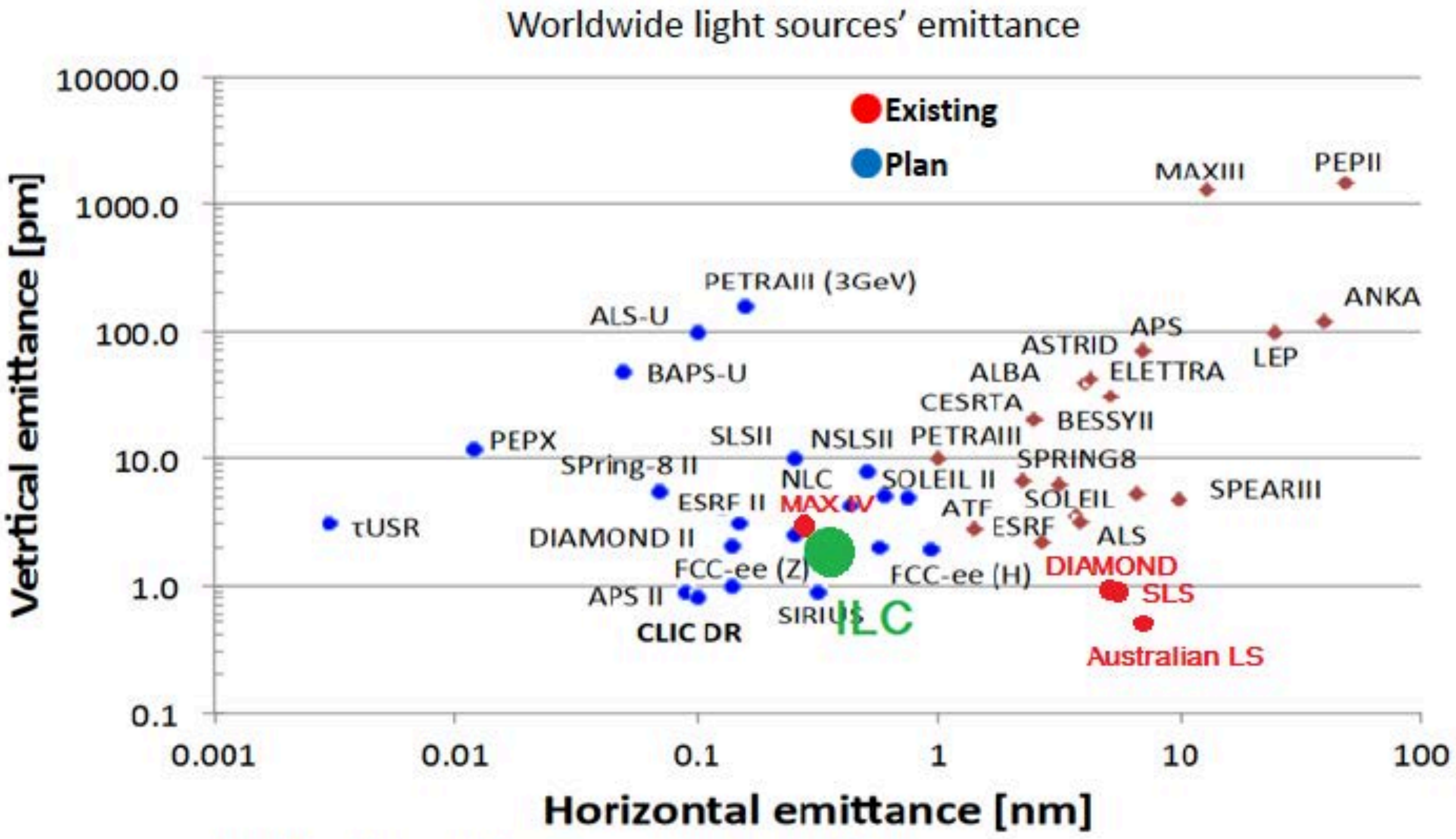
Positron production: demonstrated parameters

Parameter	Requirement	Design	Achieved	Unit	Facility
Bunch Charge	3.2	4.8	8.0	nC	SLAC SLC (E-Driven)
Undulator pitch	11.5	11.5	2.5	mm	SLAC E166
Positron Polarization (optional)	30	30	80	%	SLAC E166
W-Re Target Heat Load (PEDD* for E-Driven)		34	70	J/g	SLAC SLC (E-Driven)
Ti alloy Target Heat Load (PEDD for Undulator)		61	160	J/g	Estimated from physics constant table
Flux Concentrator Peak field (E-Driven)	5.0	5.0	10	T	BINP
QWT peak field (Undulator)	1.0	1.0	2.3	T	KEK

PEDD: peak energy deposition density

S. Michuzono, LCWS2019

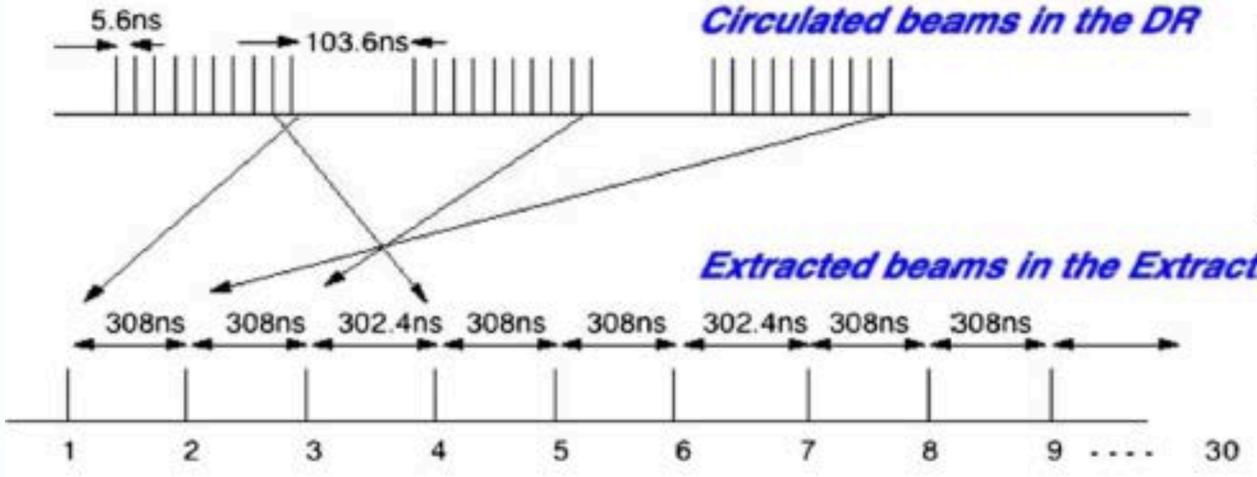
Damping Rings



Horizontal emittance is smaller at MAX IV.
Vertical emittance is smaller at Australian LS, SLS, DIAMOND.

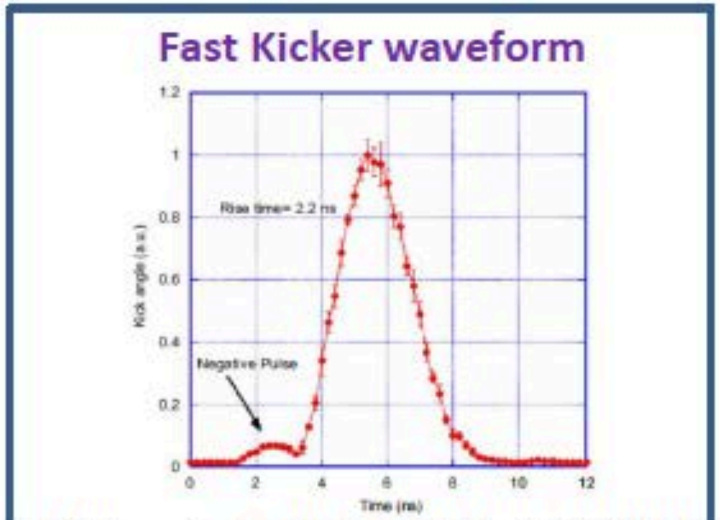
Damping Rings: Fast extraction kicker

Bunch extraction test at ATF

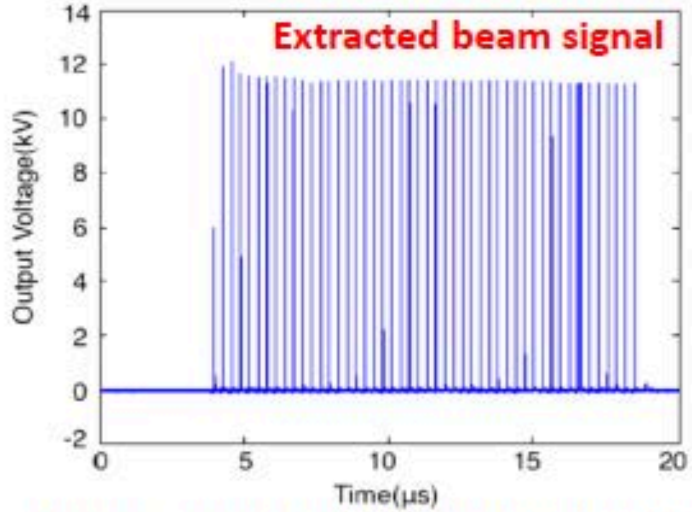


Bunch-space at ATF exp. and ILC

	ATF exp.	ILC
DR	5.60 ns	6.15 ns
extraction	302-308ns	554 ns



T.Naito *et al.*, NIM **A 571** (2007) 599.



T.Naito *et al.*, PR ST-AB **14** (2011) 051002

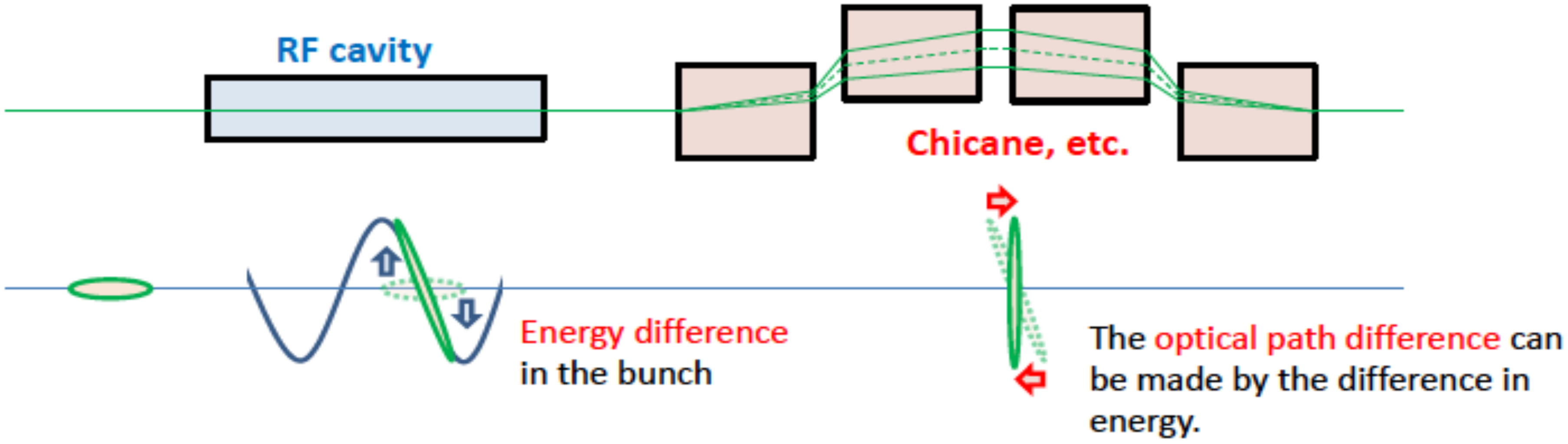
Damping Rings: demonstrated parameters

Parameter	Requirement	Design	Achieved	Facility	Comment
Horizontal Emittance(ε_x)	0.4nm	0.4nm	0.34nm	MAX-IV	Pedro F. Tavares, 2017 Phangs Workshop
Vertical Emittance (ε_y)	2pm	2pm	$<$ 2pm	SLS, Australian LS, Diamond LS	TDR
Normalized Emittance ($\gamma\varepsilon_x/\gamma\varepsilon_y$)	4.0μm/20nm	4.0μm/20nm	4.0μm/15nm	ATF	Y. Honda *et al.*, PRL 92 (2004) 054802.
Fast Ion instability				SuperKEKB	On going
Electron Cloud Instability				SuperKEKB/CesrTA	On going
Kicker Rise Time	< 6.15ns	< 3.07ns	2.2ns	ATF	T. Naito *et al.*, NIM A 571 (2007) 599.
Kicker Voltage	±10kV	±10kV	±10kV	ATF	T. Naito *et al.*, PR ST-AB 14 (2011) 051002.
Kicker Voltage stability	0.07%	0.07%	0.035%	ATF	
Kicker Frequency	1.8MHz	2.7MHz	3.25MHz	ATF	
Fast Kicker extraction test				ATF	

S. Michuzono, LCWS2019

RTML: bunch compressor

S. Michuzono, LCWS2019



"Bunch compressor" compresses the bunch from 6 mm to 0.3 mm before entering the main linac (15GeV).
This final bunch length is one or more orders of magnitude longer than FEL etc., so it is not difficult (eg SACLA; FWHM 3 "µm").

If the phase of the RF cavity is jittered, jitter occurs in the arrival time of the beam at the collision point. Therefore, the phase jitter of the RF cavity of the ILC bunch compressor must be kept within 0.24° (0.15 mm). (but not difficult compared with the XFEL requirements of ~0.01°)

RTML: demonstrated parameters

Parameter	Requirement	Design	Achieved	Facility	Comment
BC phase error	0.24°		0.042°	KEK-STF	M.Omet, Ph.D thesis (2014)
BC amplitude error	0.5%		0.041%	KEK-STF	
Horizontal emittance increase ($\gamma\varepsilon_x$)	1μm	RTML (0.47μm) , BC (0.43μm), ML (0.00μm), total (0.90μm)		In simulation	TDR
Vertical emittance increase ($\gamma\varepsilon_y$)	15 nm	RTML (6.4nm) , ML (4.5nm), total (10.9nm)		In simulation	TDR

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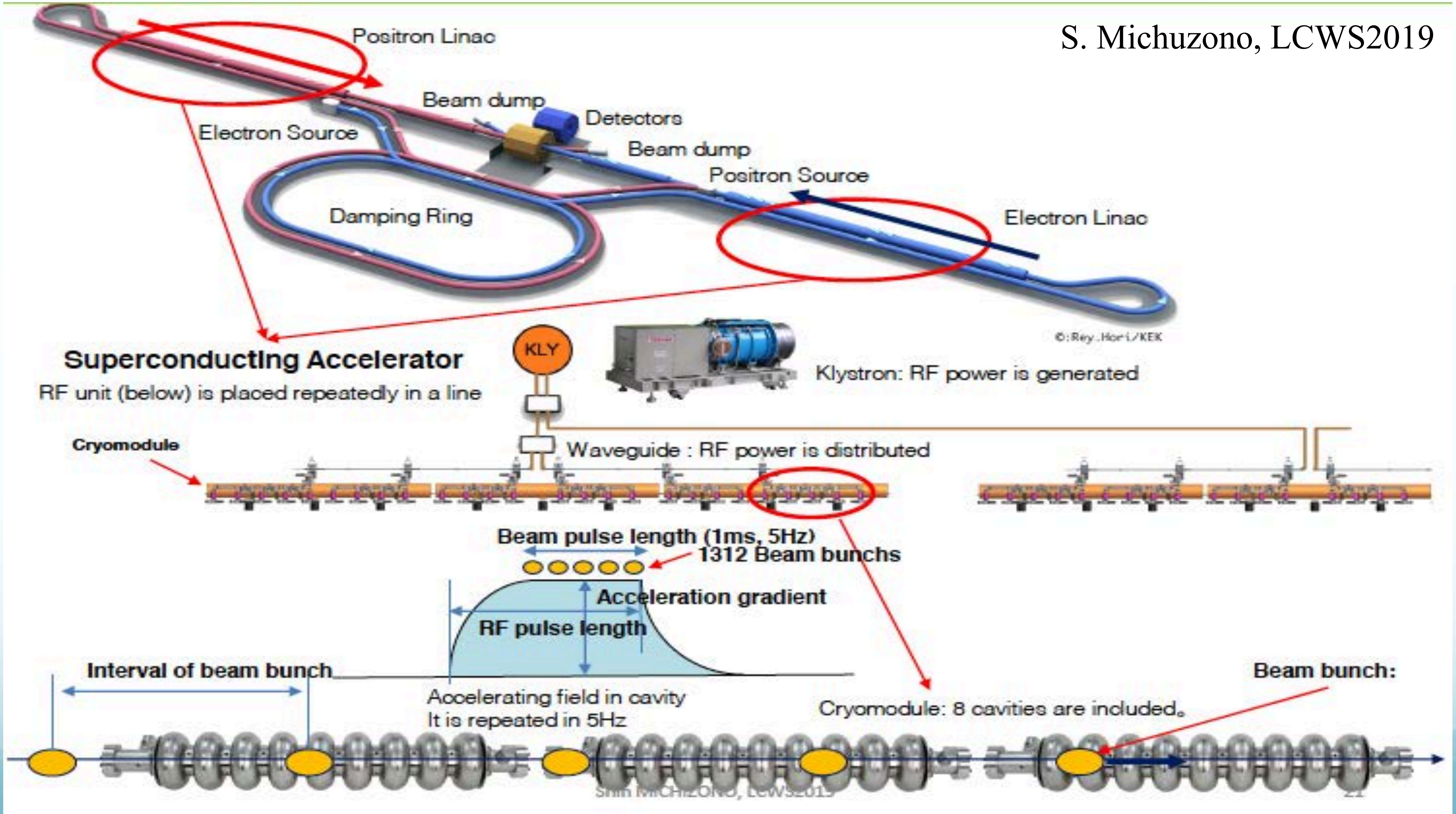
Main linac



S. Michuzono, LCWS2019
Positron Linac
Beam dump
Detectors
Electron Source
Beam dump
Positron Source
Damping Ring
Electron Linac
Superconducting Accelerator
RF unit (below) is placed repeatedly in a line
KLY
Klystron: RF power is generated
Cryomodule
Waveguide : RF power is distributed
Beam pulse length (1ms, 5Hz)
1312 Beam bunchs
Acceleration gradient
RF pulse length
Interval of beam bunch
Accelerating field in cavity
It is repeated in 5Hz
Cryomodule: 8 cavities are included。
Beam bunch:

Main linac

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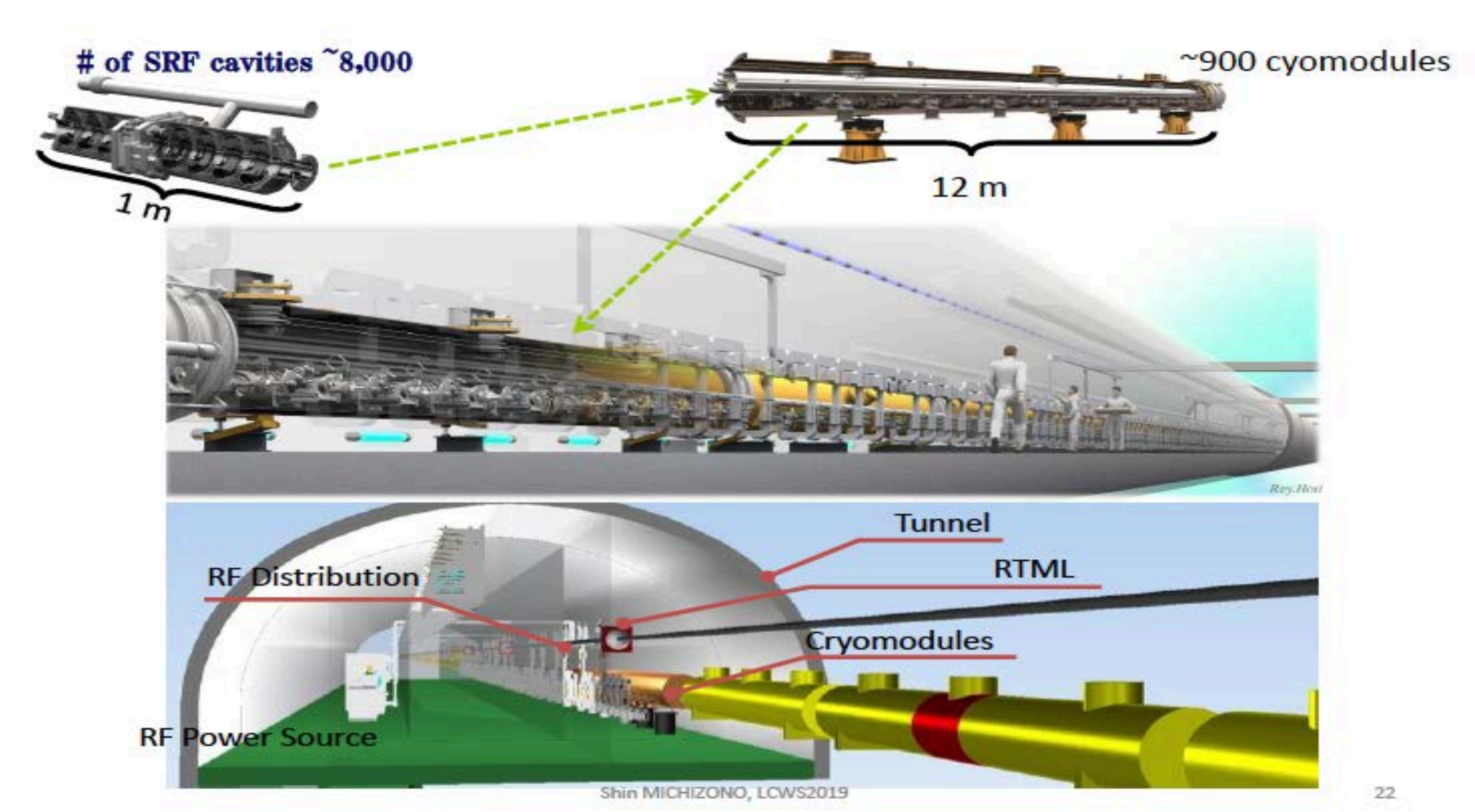


Main Linac: ILC cost reduction R&D US-Japan cost reduction

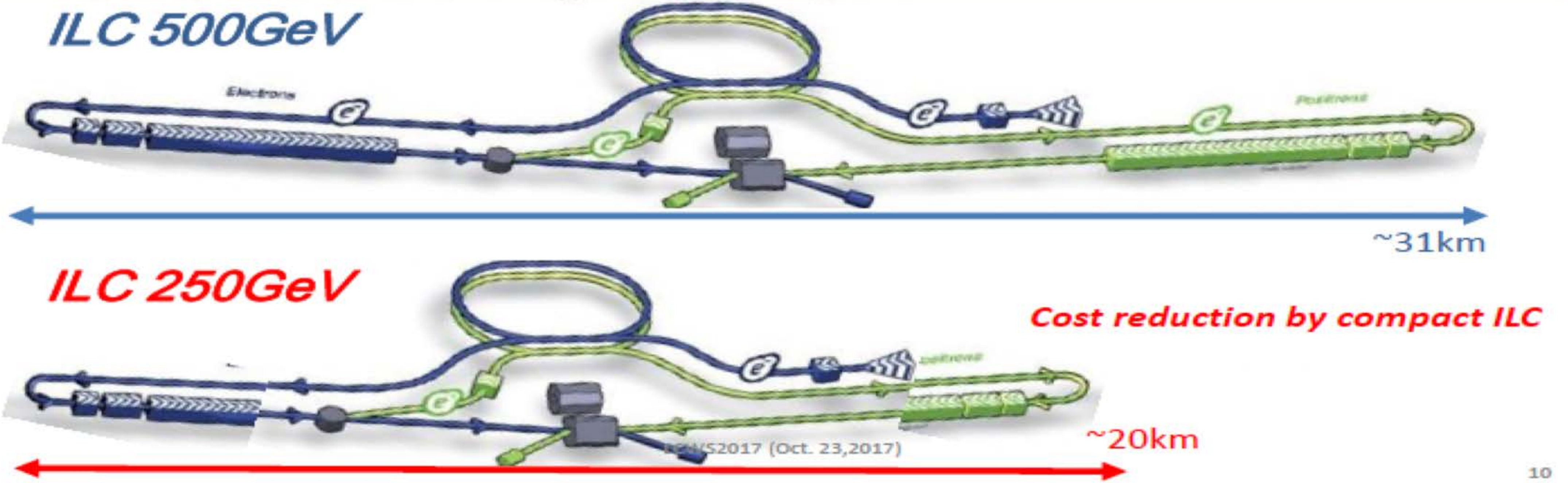
Cost reduction by technological innovation

Innovation of Nb (superconducting) material process: decrease in material cost

Innovative surface processing for high efficiency cavity by FNAL: decrease in number of cavities

Staging

S. Michuzono, LCWS 2018



Main linac: ILC cost reduction R&D US-Japan cost reduction

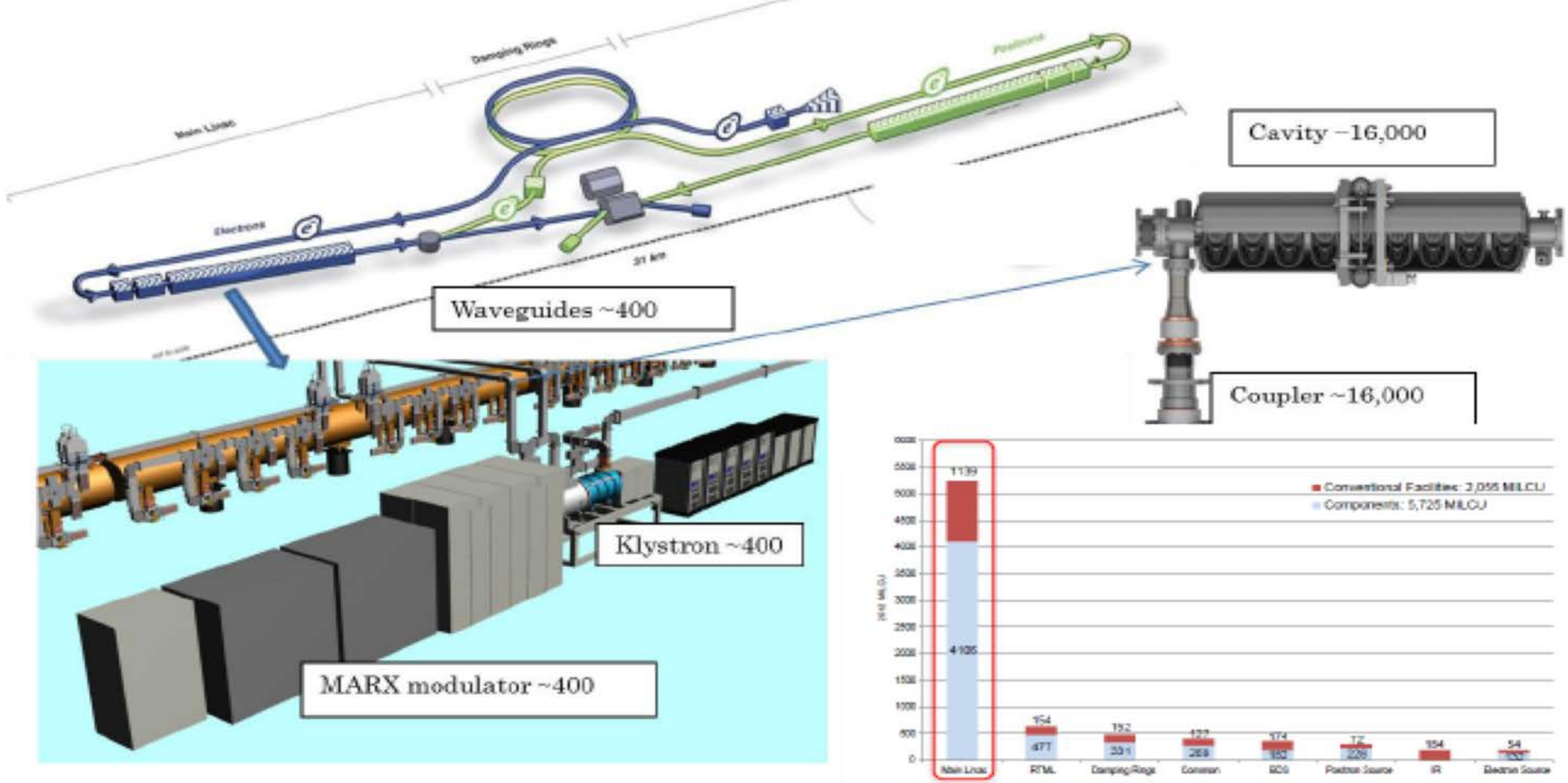


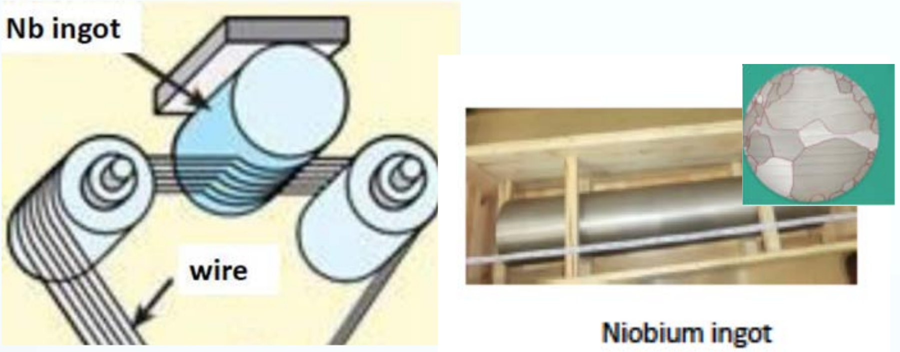
Figure 15.8. Distribution of the ILC value estimate by system and common infrastructure, in ILC Units. The numbers give the TDR estimate for each system in MILCU.

The main fraction of the construction cost is coming from main linac (ML).
Thus we focused our cost reduction R&D into ML (superconducting RF technology)

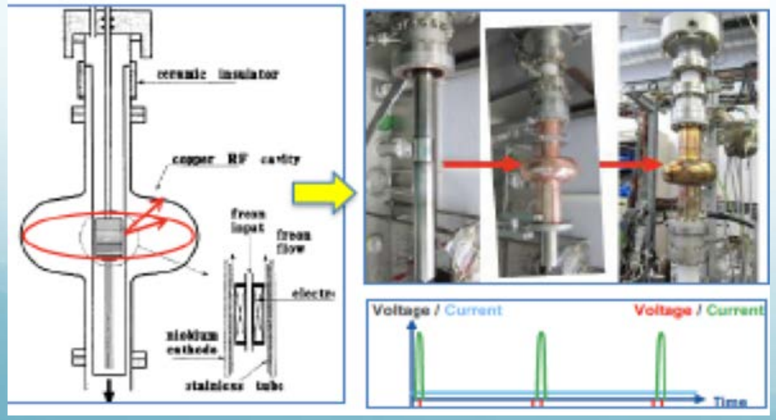
Main Linac: ILC cost reduction R&D US-Japan cost reduction

- **Niobium material preparation**:

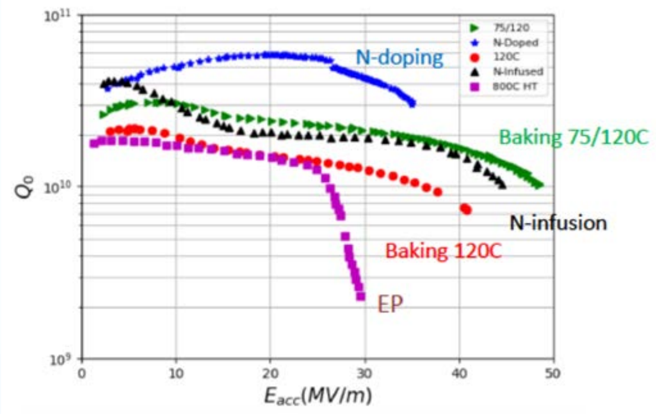
Large grain directly sliced from ingot (cost reduction), **Nb thin-film** coating on Cu based structure (HiPIMS), or Nb_3Sn in Nb or Cu

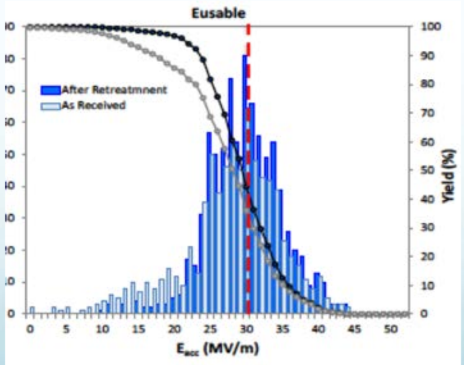


High Power Impulse Magnetron Sputtering (HiPIMS)

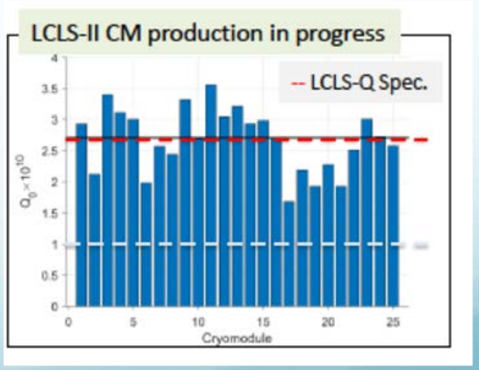


- **SRF cavity fabrication for high-gradient** (N doping well stablished) **and high-Q (**N infusion, low-T baking to be understood)





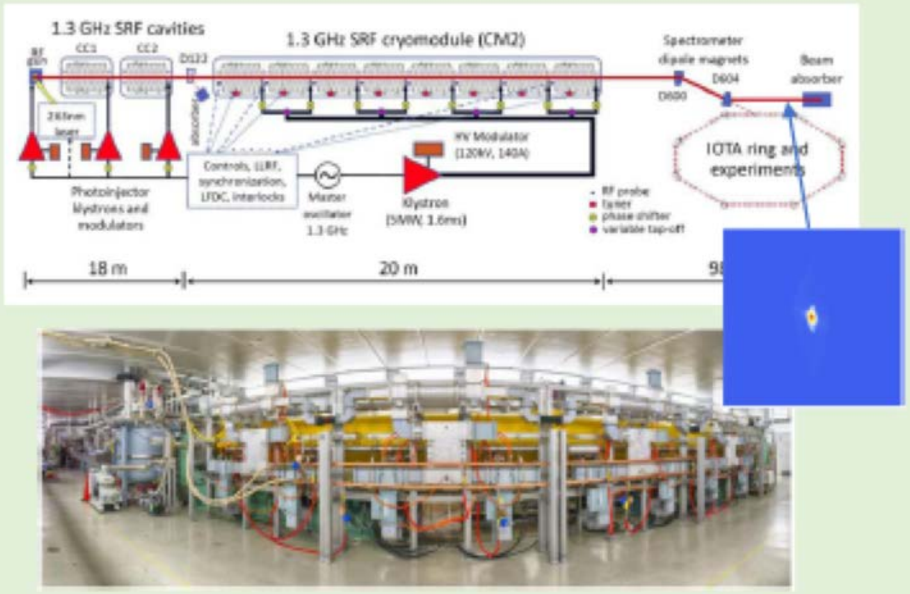
European XFEL: 29 ± 5.1 MV/m



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

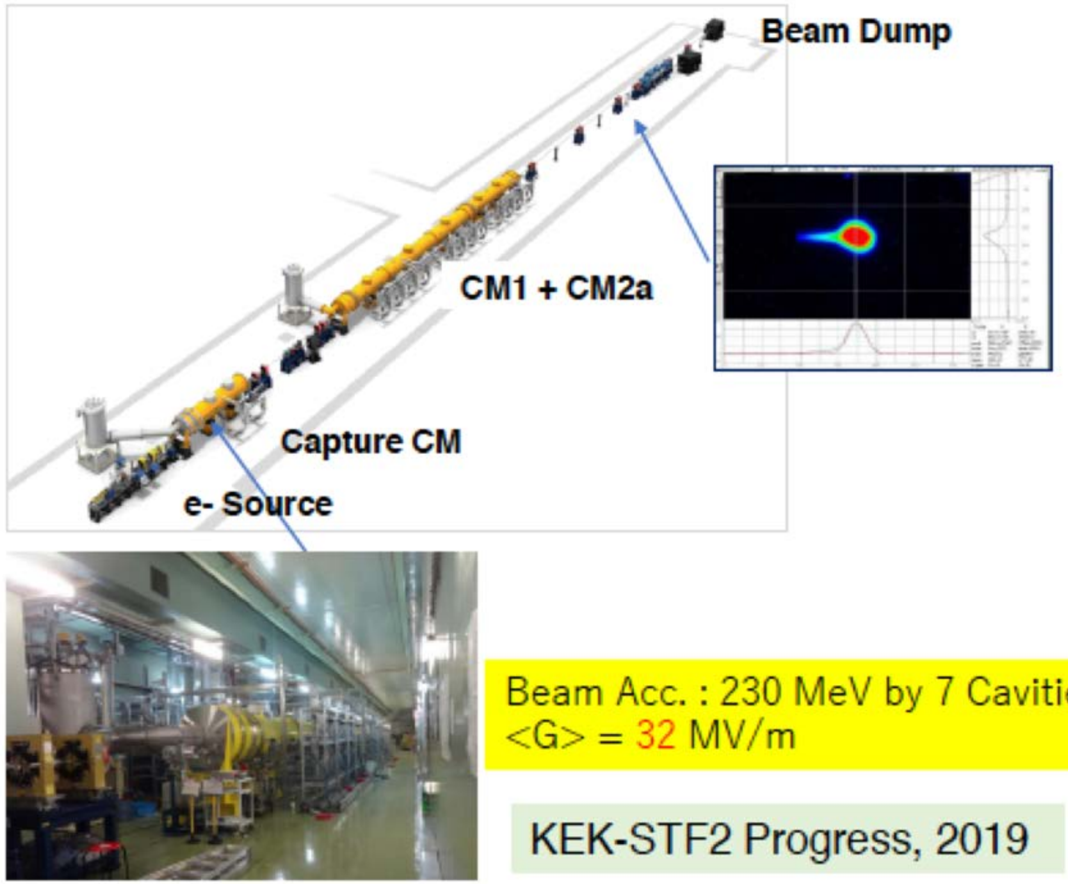
Main Linac: ILC cost reduction R&D US-Japan cost reduction

Fermilab and KEK has achieved ILC gradient goal > 31.5 MV/m with beam



Beam Acc. : 260 MeV by 8 Cavities,
<G> = 32.3 MV/m

Fermilab-FAST Progress, 2017

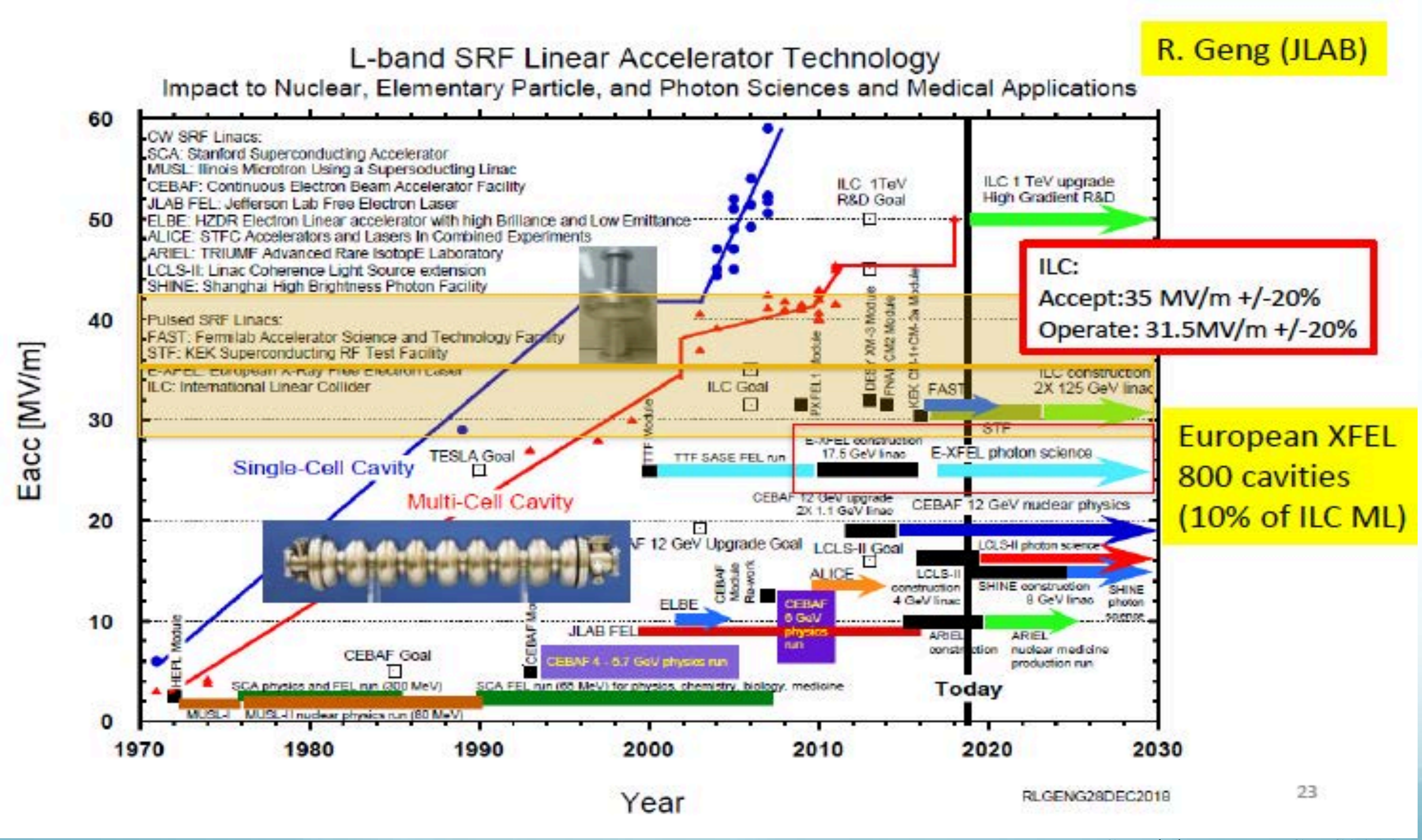


Beam Acc. : 230 MeV by 7 Cavities,
<G> = 32 MV/m

KEK-STF2 Progress, 2019

A. Yamamoto, Granada 2019

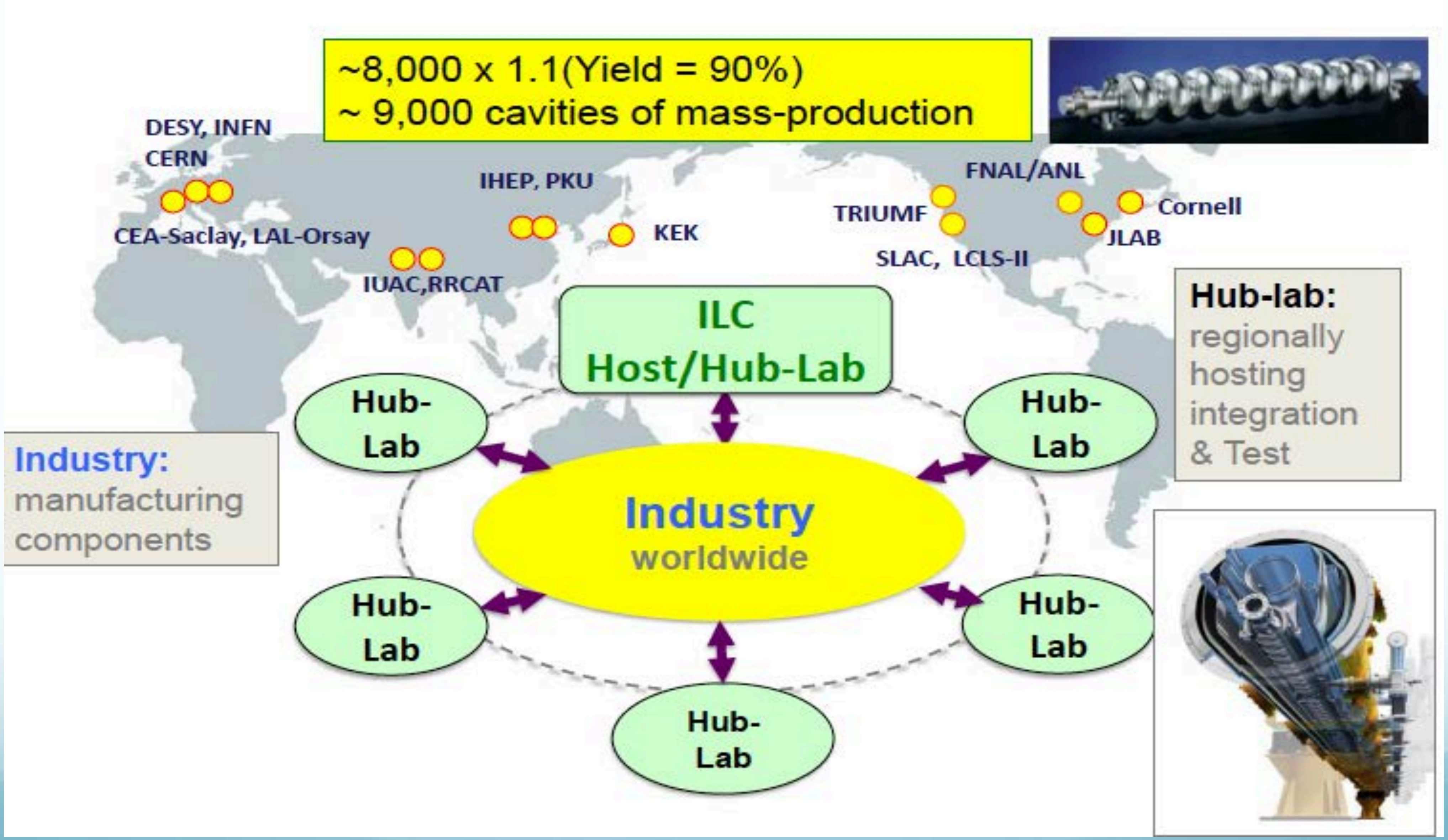
Main linac: SRF mature technology



S. Michuzono, LCWS2019

Main Linac: World wide Labs for RF systems

Main linac: SRF Integrated global model



Main linac: SRF demonstrated parameters

Parameter	Requirement	Achieved	Comment
Acc. Gradient in the cryomodule	31.5 MV/m	32.5MV/m (PXFEL-1, DESY) 31.5MV/m(CM-2, ASTA) 32 MV/m(CM-1&2a,STF)	DESY-Proto-XFEL (ILC-TDR V3, Part-1, p43) FNAL-ASTA (E. Harms, AWLC14 May 2014) STF(KEK news May 22,2019)
Average Q0 in cryomodule	10^{10}	– (PXFEL-1, DESY) 0.9×10^{10}(CM-2, ASTA) 0.7×10^{10}(CM-1&2a,STF)	FNAL-ASTA (E. Harms, AWLC14 May 2014) KEK-STF report (Y. Yamamoto, STF,2016)
Acc. Gradient at vertical test	≧35(±20%) MV/m ≧90%yield	<37 MV/m> ~94%	TDR vol-3 part I, Chapter 2.3
Beam current	5.78mA	6mA (800μs beam pulse length)	DESY-FLASH 9mA-study, TDR vol-3 part I, p.80
Number of bunches	1312	2400 (800μs beam pulse length)	
Bunch charge	3.2nC	3nC (600μs beam pulse length) 2nC (800μs beam pulse length)	
Bunch space	554ns	333ns	
Bunch length	727μs	800μs	
Rf pulse width	1.65ms	>1.65ms	
RF pulse repetition	5Hz	10Hz	DESY XFEL

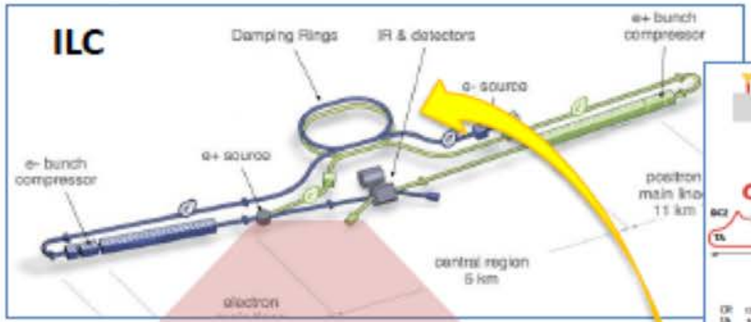
Final Focus: Nanobeam Technology

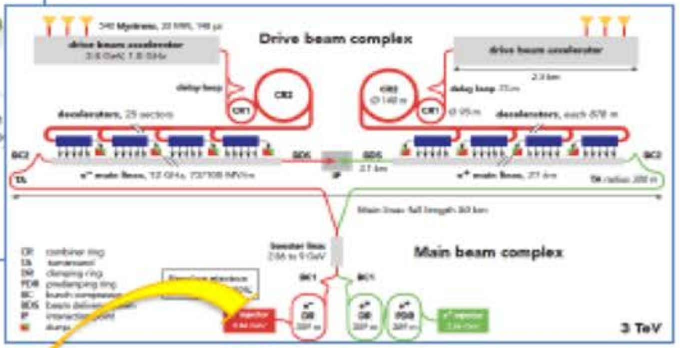
ATF/ATF2: Accelerator Test Facility

Courtesy: N. Terunuma

Develop nano-beam technology for ILC/CLIC

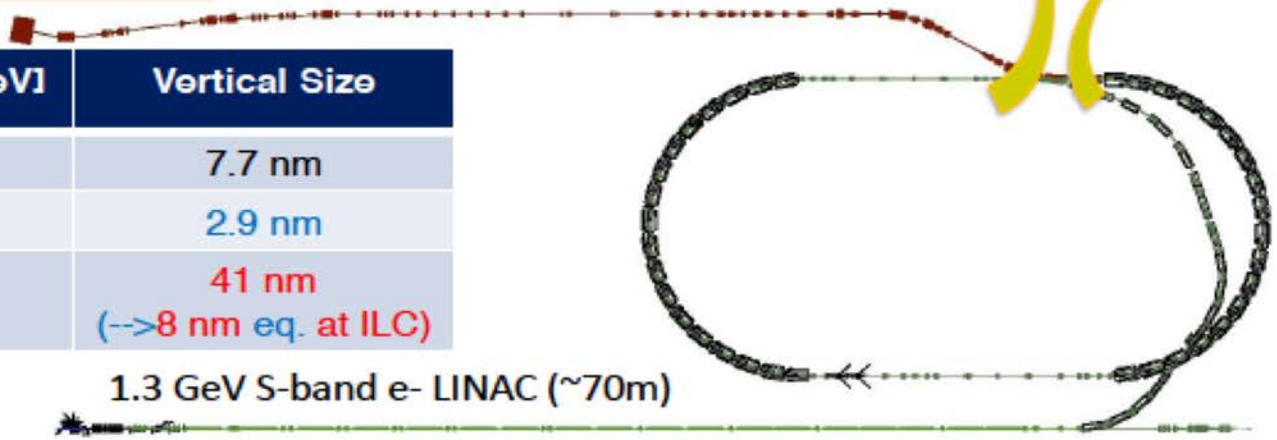
- Goal: Realize small beam-size and theStabilize beam position



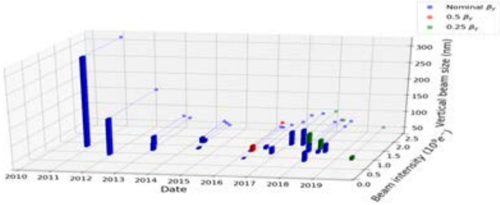


FF: Nano beam-size

	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)



Damping Ring (140m)
Low emittance e- beam



Intensity dependence-wakefiels

A. Yamamoto, 190513bb

8

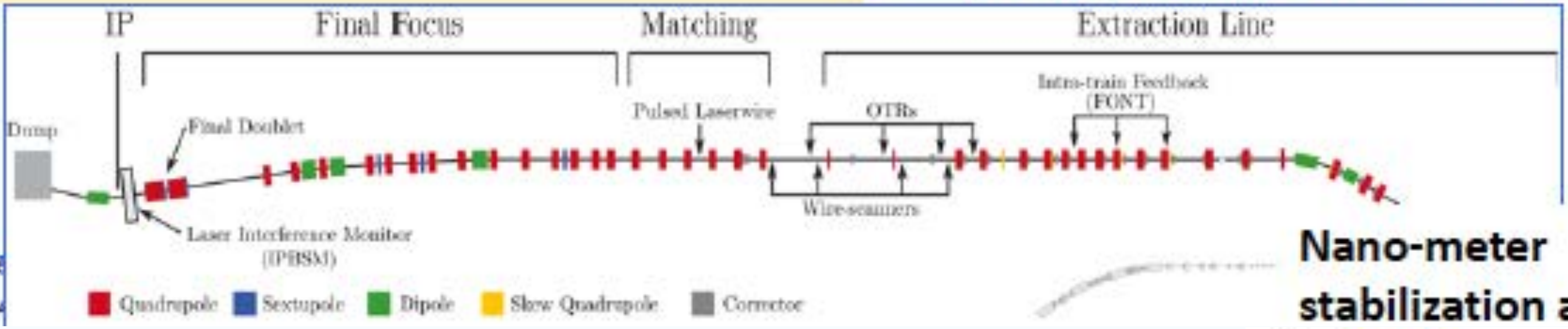
Final Focus: beam size and stability

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

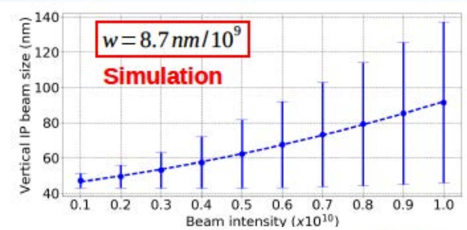
- ATF2 Goal : **37** nm → ILC **7.7** nm (ILC250)
  - Achieved **41 nm** (2016)

Goal 2: Develop a few nm position stabilization for the ILC collision

- **FB latency 133 nsec achieved** (target: < 366 nsec)
- **positon jitter at IP: 106 → 41 nm (2018)** (limited by the BPM resolution)

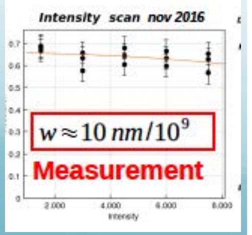


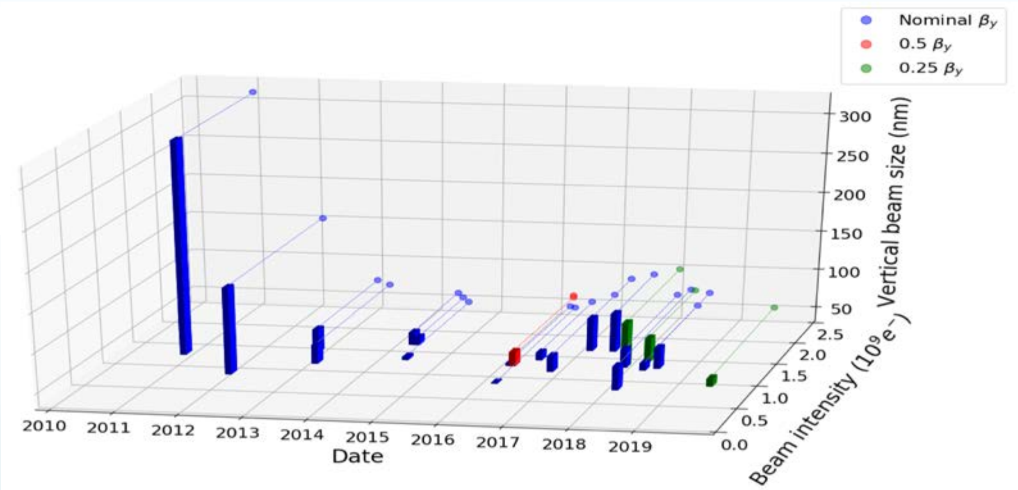
Nano-meter stabilization at IP

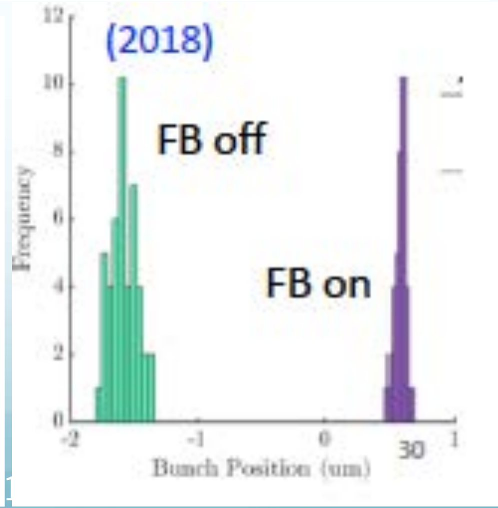


Intensity dependence parameter:

$$w[nm/10^9]=\frac{\sqrt{\sigma_y^2-\sigma_{y,N=0}^2}}{N}$$







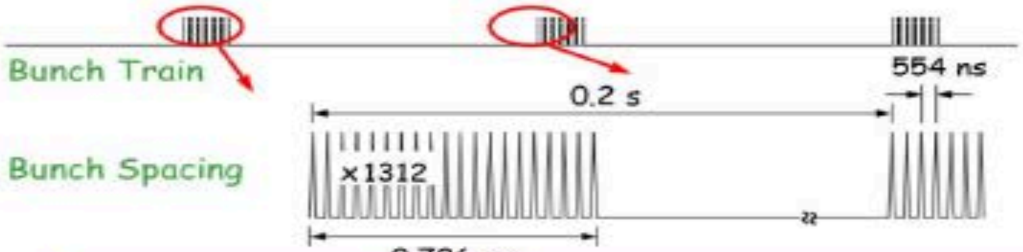
Final Focus: FONT IP feedback

S. Michuzono, LCWS2019

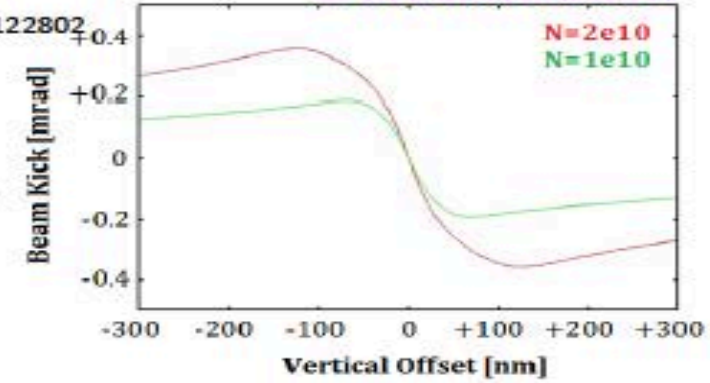
*Feedback On Nanosecond Timescales

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.21.122802

ILC bunch structure

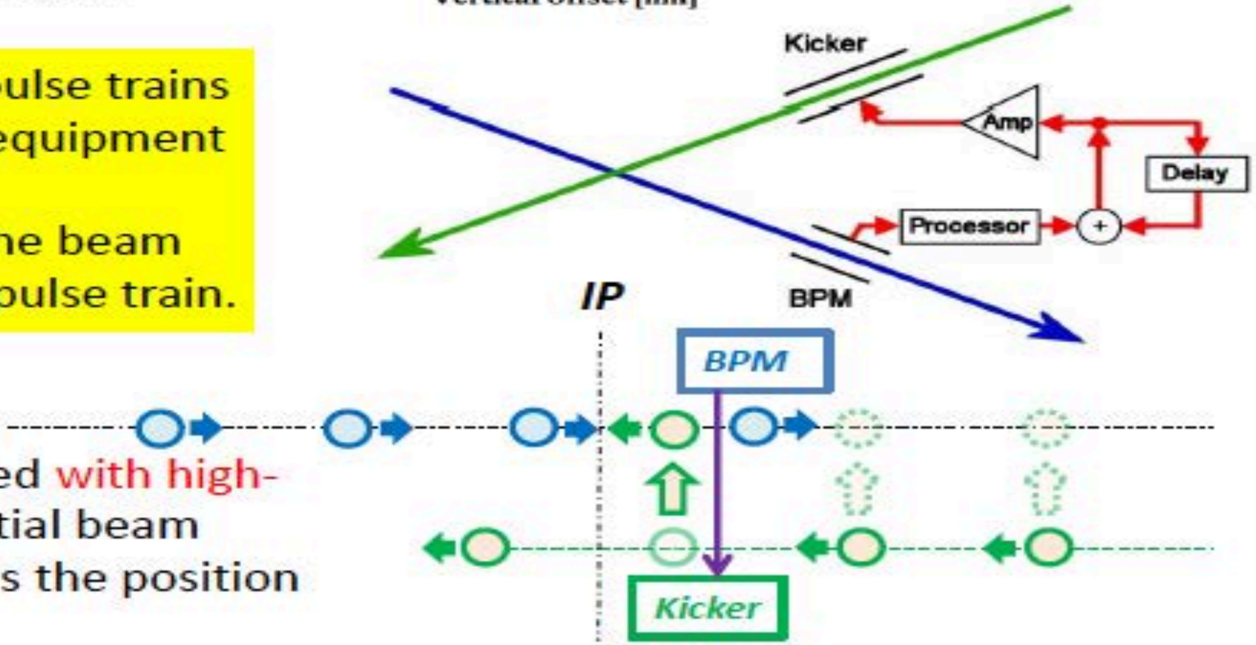


CAIN simulation



Depending on the relative position of the beam, beams are greatly scattered by the beam-beam effect.

The position of the beam between pulse trains shifts due to ground vibrations and equipment noise.
On the other hand, the position of the beam does not change significantly in the pulse train.



Efficient beam collision can be achieved with high-speed feedback that measures the initial beam position of the pulse train and corrects the position of subsequent bunches in the train.

Feedback latency should be less than bunch space.

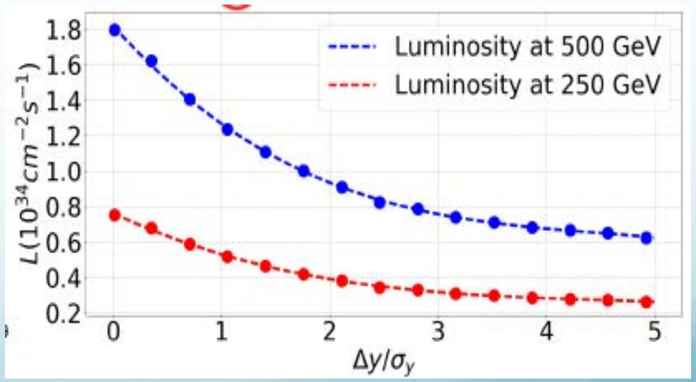
The first bunch does not collide, but the second and subsequent bunches will collide.

Final Focus: Demonstrated ILC parameters

S. Michuzono, LCWS2019

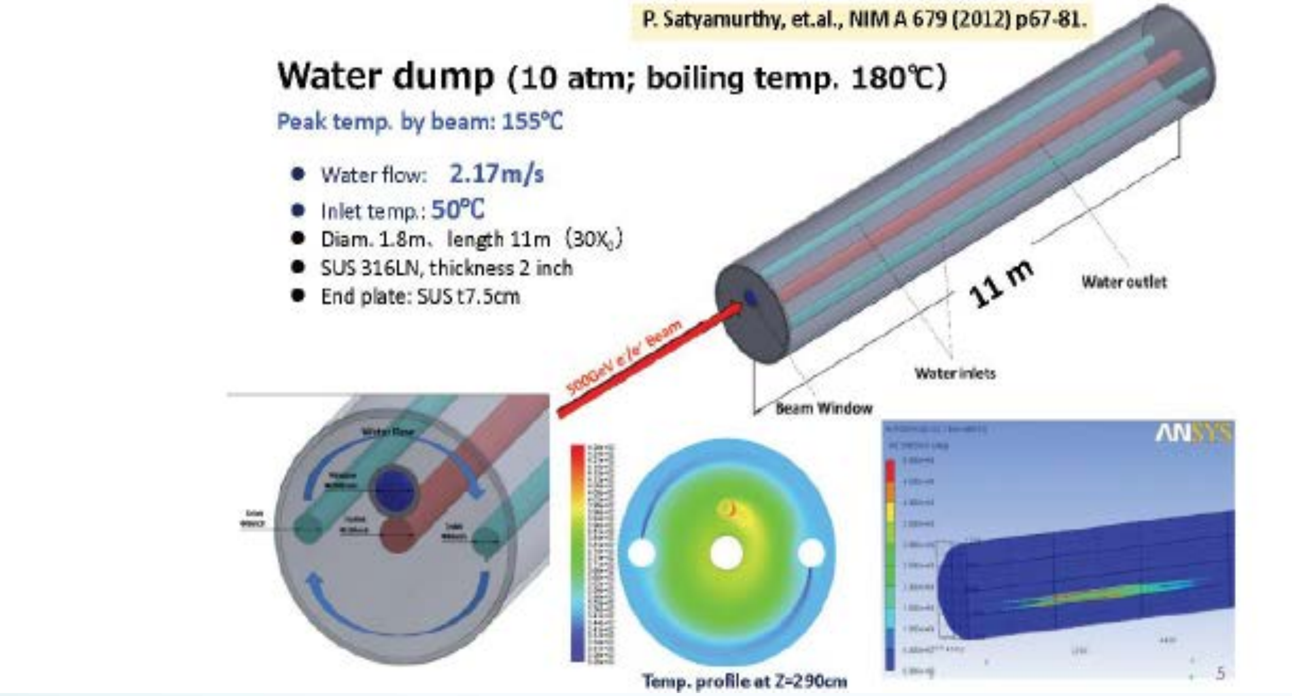
Parameter	Requirement	Design	Achieved	Facility	Comment
ATF2 beam size (σ_y^*)	37 nm (ATF2 design)		41 nm	ATF2	T.Okugi, LINAC2016
ILC beam size	7.7 nm (ILC design)			ATF2	
Feedback position stability	12% of beam size (1nm)	10% of beam size	10% (FB OFF) ⇒ 4% (FB ON)	ATF2	P. Burrows, AWLC2018
Feedback latency	< 554 ns	< 366 ns	133 ns	ATF2	Physics Procedia 37 (2012) 2063. Phys.Rev.Accel.Beams .21.122802

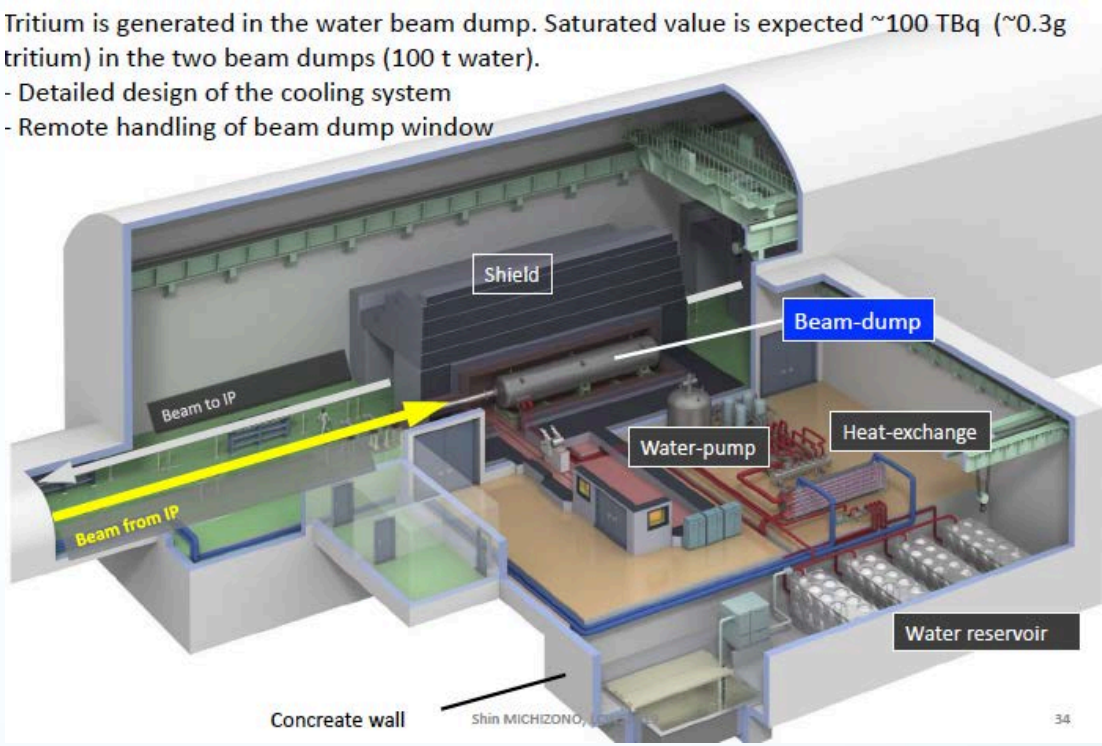
- Same beam-based correction procedure used in ATF2 gives very good results in the ILC BDS
- Short-range wakefields on the IP beam size are negligible in the ILC BDS.
- Long-range wakefields due to resistive walls, in a perfect machine, showed that they induce a significant vertical offset at the IP and thus a luminosity degradation, could be compensated with appropriate IP intra-train feedback.



Beam Dump system

- ILC beam dump is designed for 1TeV collision energy, and ILC250 has enough margin.



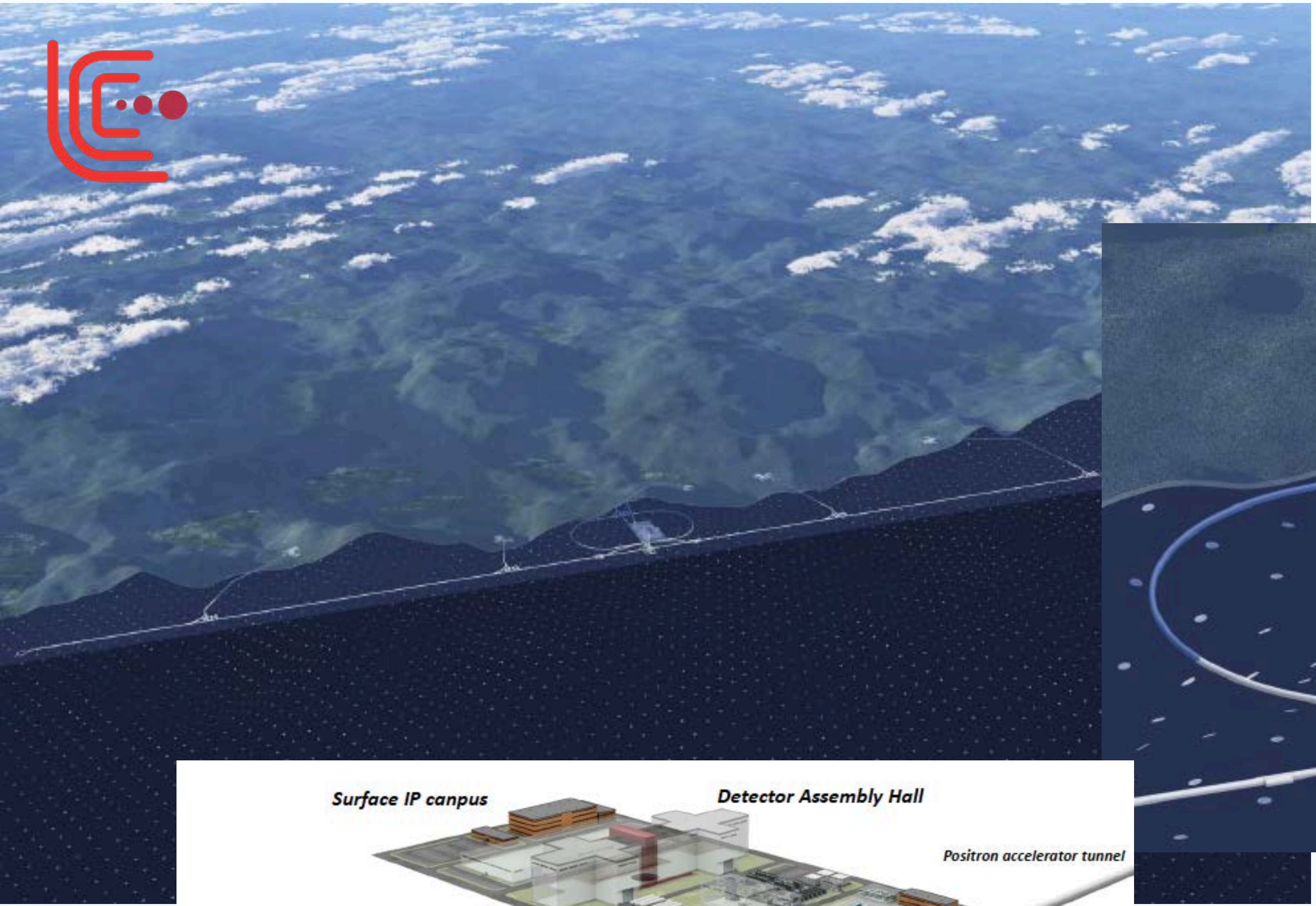


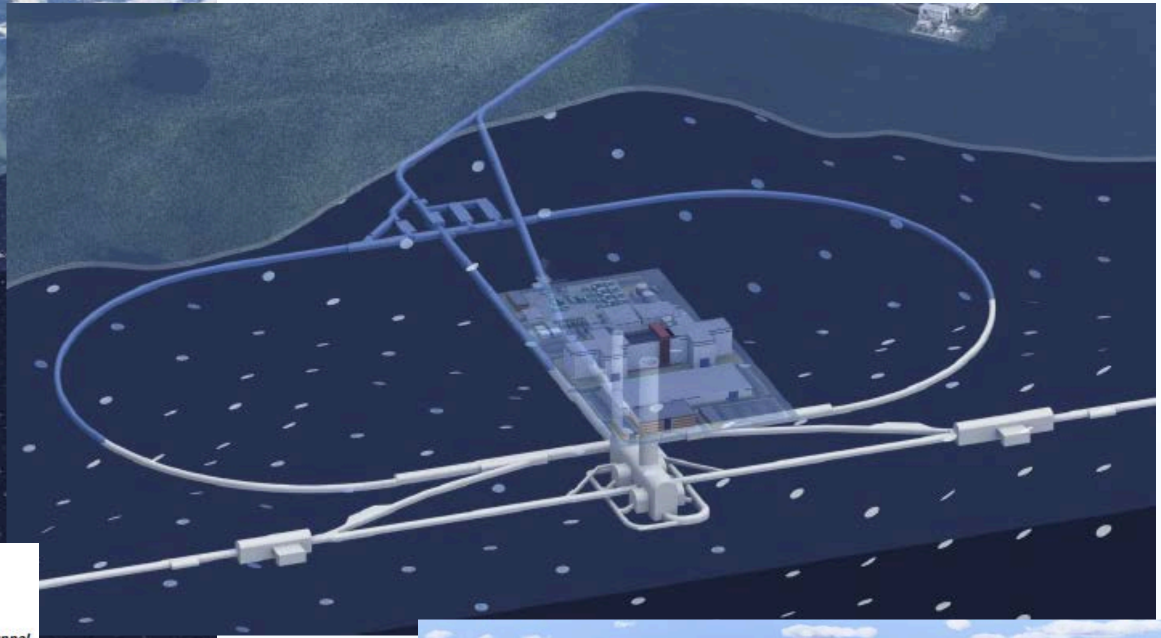
Water beam dump	Req.	Des.	Achieved	unit	Comment
ILC 250GeV	2.6	17	–	MW	Designed for 500GeV beam
SLAC 2mile LINAC	–	2.2	0.75	MW	ILC beam dump prototype
CEBAF	0.9	1.0	0.73	MW	In operation at Jefferson Lab from the 90s to the present. 2 units (2 beam lines). Composite type with aluminum plates arranged in water.

S. Michuzono, LCWS2019

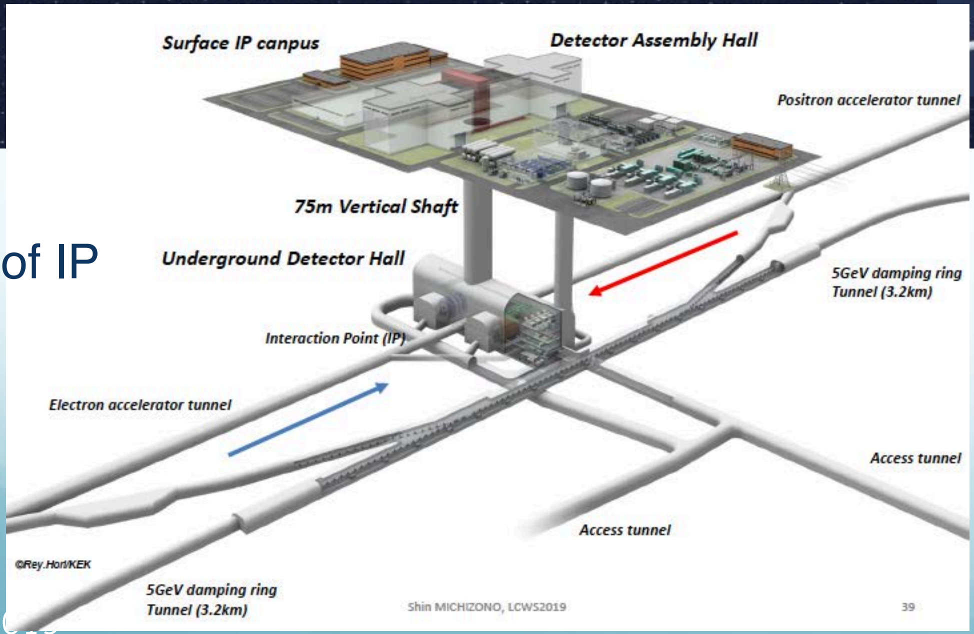
CFS:

N. Terunuma, LCWS2019

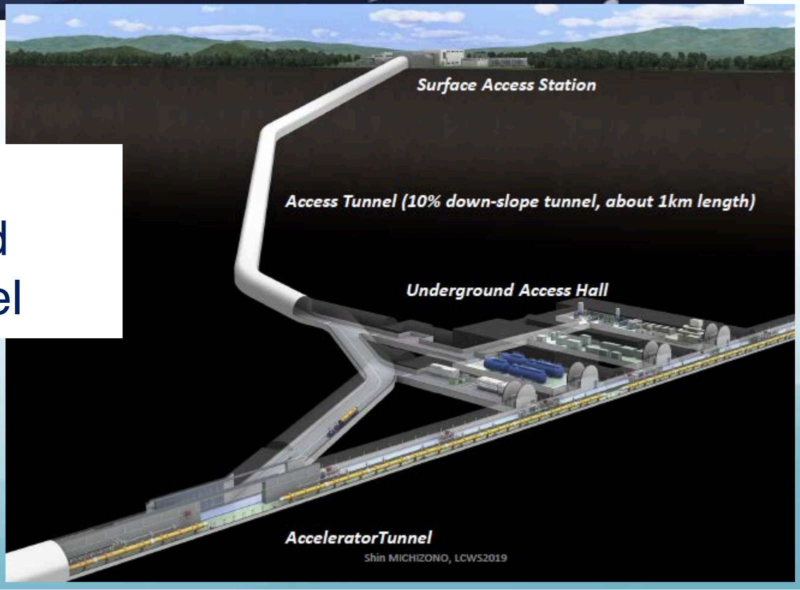




Plan of IP

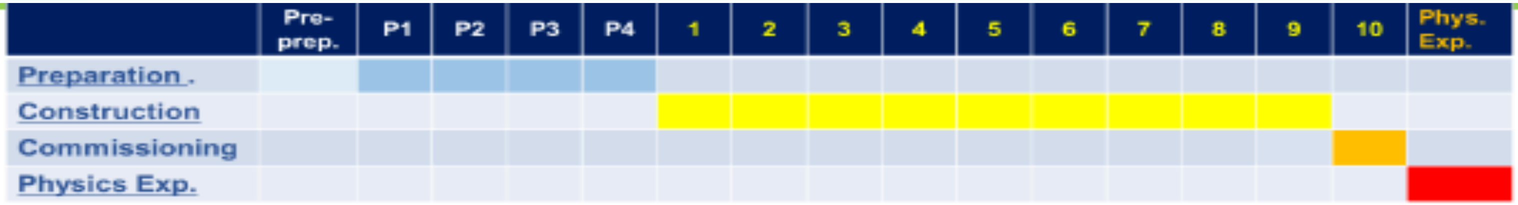


Surface-Underground access tunnel



Acceleration preparation phase R&D

S. Michuzono, LCWS2019



Main tasks to be done during 4-year preparation phase

KEK ILC action plan

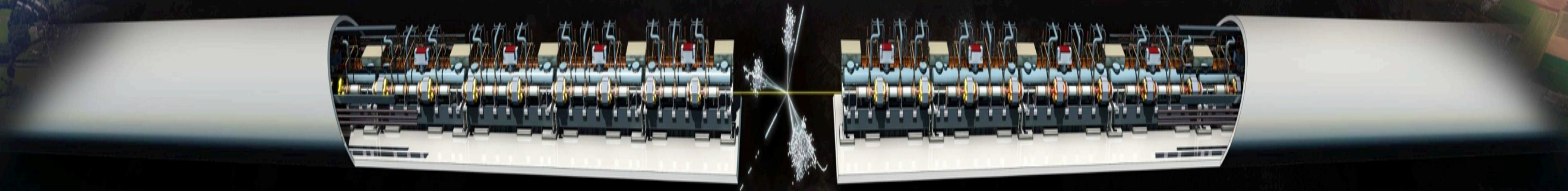
Area	Tasks
Accelerator Design	Design parameter optimization
SCRF	Mass-production and quality control Superconducting material, cavity properties (electric field, resonance characteristics) Hub-lab functioning System performance stabilization (Stabilization of the performance and maintenance, including international transport of CM)
Nanobeam	Minimizing the beam size and demonstrating stability Beam handling (DR, RTML, BDS, BD)*
Accelerator elements - Positron source (e+) - Beam dump	e+: Undulator-driven (polarization) or an electron-driven system (backup), heat balance of the dump, cooling, safety
CFS	Basic Plan by assuming a model site, engineering design, drawings, survey, assessment
common technical support	Safety (radiation, high-pressure gas, etc.) Communication and network
Administration	General affairs, finace n , int. relations, public relations Administrative support for ILC pre-lab

Shin MICHIZONO, LCWS2019 46

European ILC preparation plan

Item/topic	Brief description	CERN	France CEA	Germany DESY	Time line
SCRF	Cavity fabrication including forming and EBW technology,	✓			2017-18
	Cavity surface process: High-Q & –G with N-infusion to be demonstrated with statics, using High-G cavities available (# > 10) and fundamental surface research		✓	✓	2017-18
	Power input-coupler: plug compatible coupler with new ceramic window requiring no-coating	✓			2017-19
	Tuner: Cost-effective tuner w/ lever-arm tuner design	✓	✓		2017-19
	Cavity-string assembly: clean robotic-work for QA/QC.		✓		2017-19
Cryogenics	Design study: optimum layout, emergency/failure mode analysis, He inventory, and cryogenics safety management.	✓			2017-18
HLRF	Klystron: high-efficiency in both RF power and solenoid using HTS	✓			2017- (longer)
CFS	Civil engineering and layout optimization, including Tunnel Optimization Tool (TOT) development, and general safety management.	✓			2017-18
Beam dump	18 MW main beam dump: design study and R&D to seek for an optimum and reliable system including robotic work	✓			2017- (longer)
Positron source	Targetry simulation through undulator driven approach			✓	2017-19
Rad. safety	Radiation safety and control reflected to the tunnel/wall design	✓			2017 – (longer)

CLIC accelerator: status and rebaselining



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

Compact Linear Collider

CLIC Review

CLIC Accelerator Study – Review of objectives for the MTP 2016-2019

March 1st, 2016

Report from the Review Panel

Members: O. Brüning; P. Collier, J.M. Jimenez, R. Losito; R. Saban, R. Schmidt; F. Sonnemann; M. Vretenar (Chair).

Introduction and general remarks

The Panel was very impressed by the enormous amount of work that was presented, by the enthusiasm of the CLIC team and by the wealth of knowledge accumulated by the CLIC study. The CLIC accelerator study has reached a high level of maturity and has been able to establish a large community consisting in about 50 collaborating laboratories and universities, working together on a number of technical challenges

After the publication of the Conceptual Design report in 2012, the CLIC Study is presently in the Development Phase, to prepare a more detailed design and an implementation plan for the next European Strategy Upgrade in 2018-19. This phase is expected to be followed by a Preparation Phase covering the period 2019-25; in case of a positive decision, a construction

Key recommendations

- Optimized, staged design: **380 GeV** (optimised for Higgs + top physics) → 1.5 TeV → 3 TeV
- Optimize **cost** and **power consumption**
- Support efforts to develop **high-efficiency klystrons**
- Develop 380 GeV klystron-only version as alternative to PETS
- Consolidate **high-gradient structure** test results
- Develop plans for 2020-25 (‘preparation phase’)
- Continue and enhance **participation** in **KEK/ATF2 for ultra-low beam sizes**

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

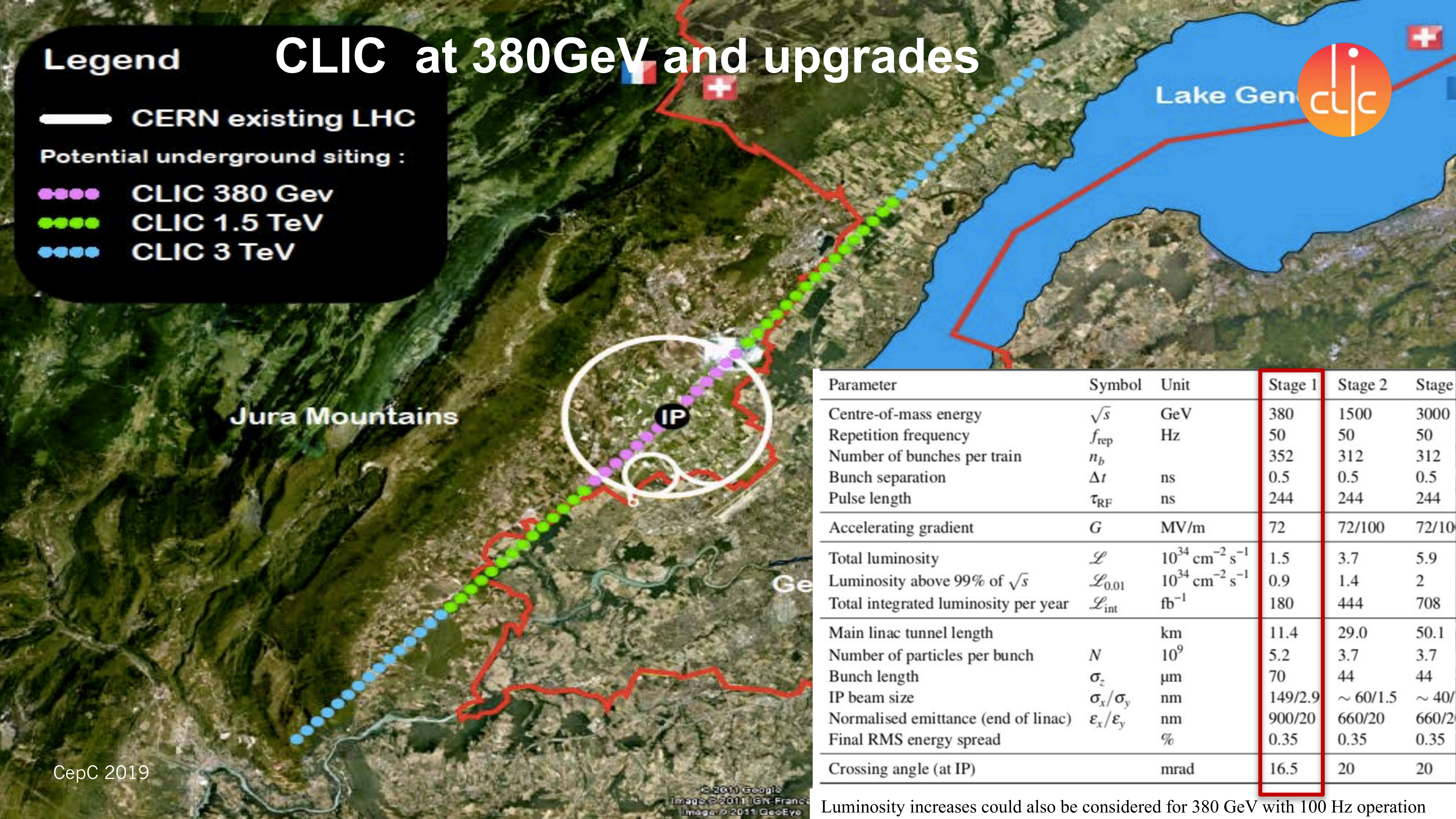
Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

S. Stapnes, CLIC 2019

CLIC at 380GeV and upgrades

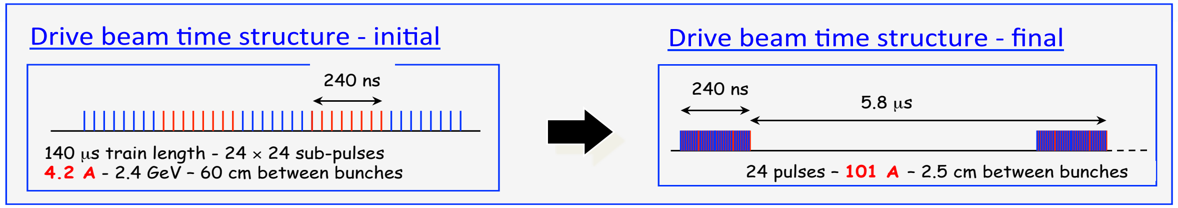


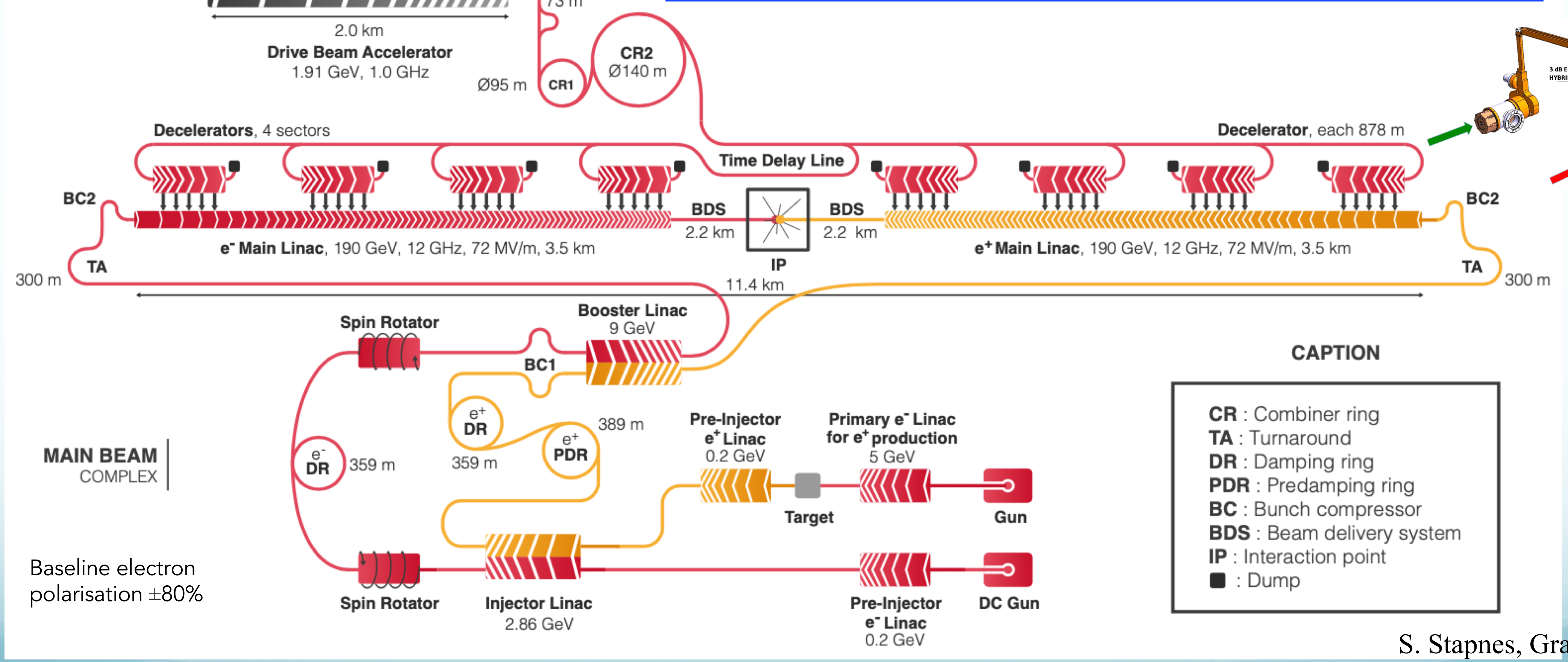
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/10
Total 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	$\mathscr{L}_{int}$	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	~ 60/1.5	~ 40/
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	900/20	660/20	660/2
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

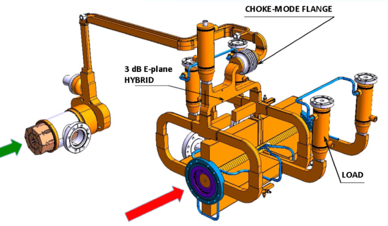
Luminosity increases could also be considered for 380 GeV with 100 Hz operation

CepC 2019

CLIC rebaseline: 380 GeV and power generation





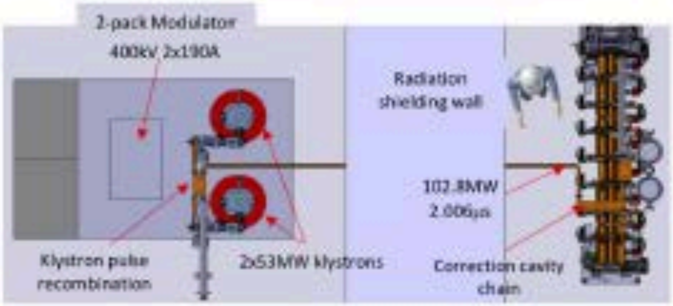


Baseline electron polarisation ±80%

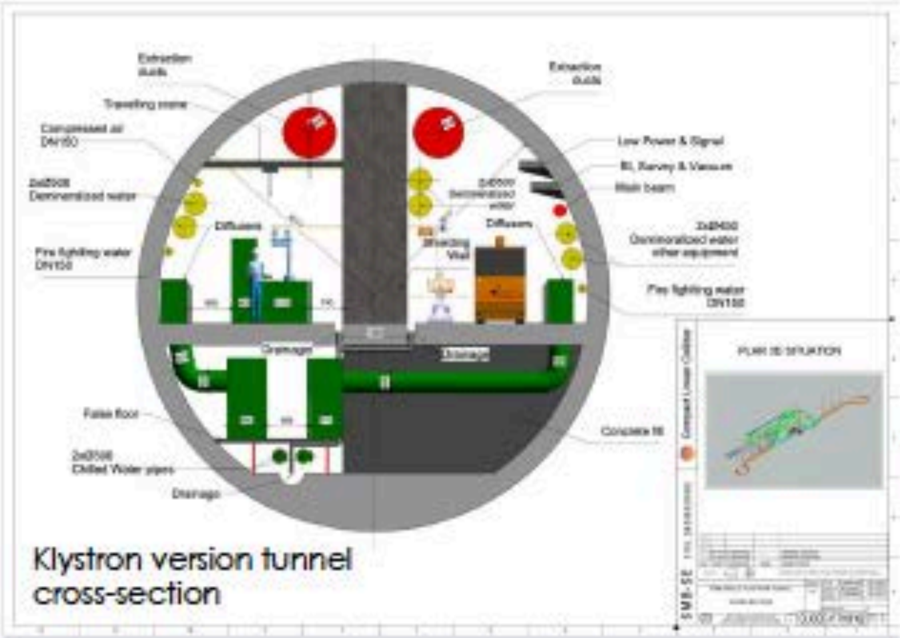
S. Stapnes, Granada 2019

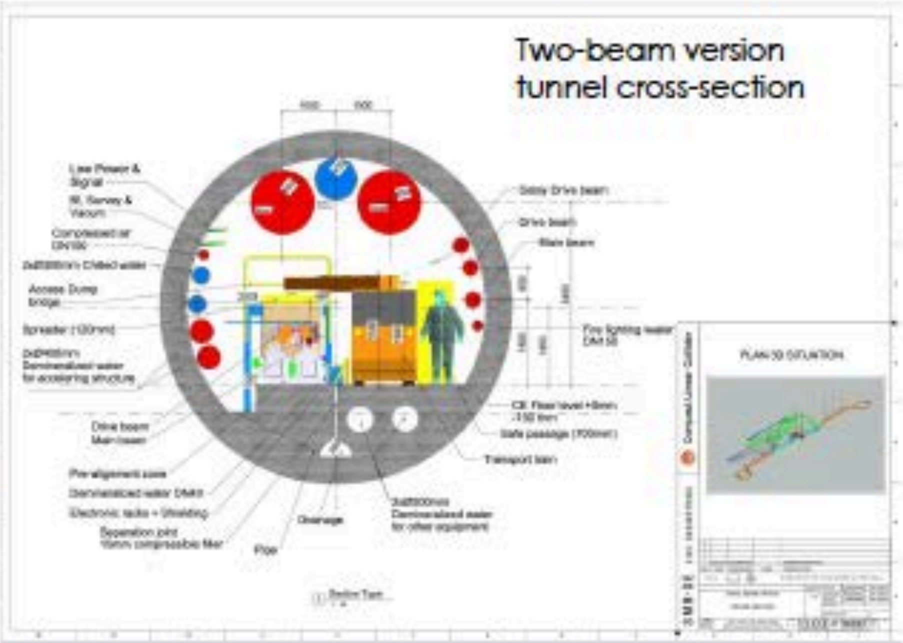
CLIC: Klystron option

R. Corsini LCWS2019

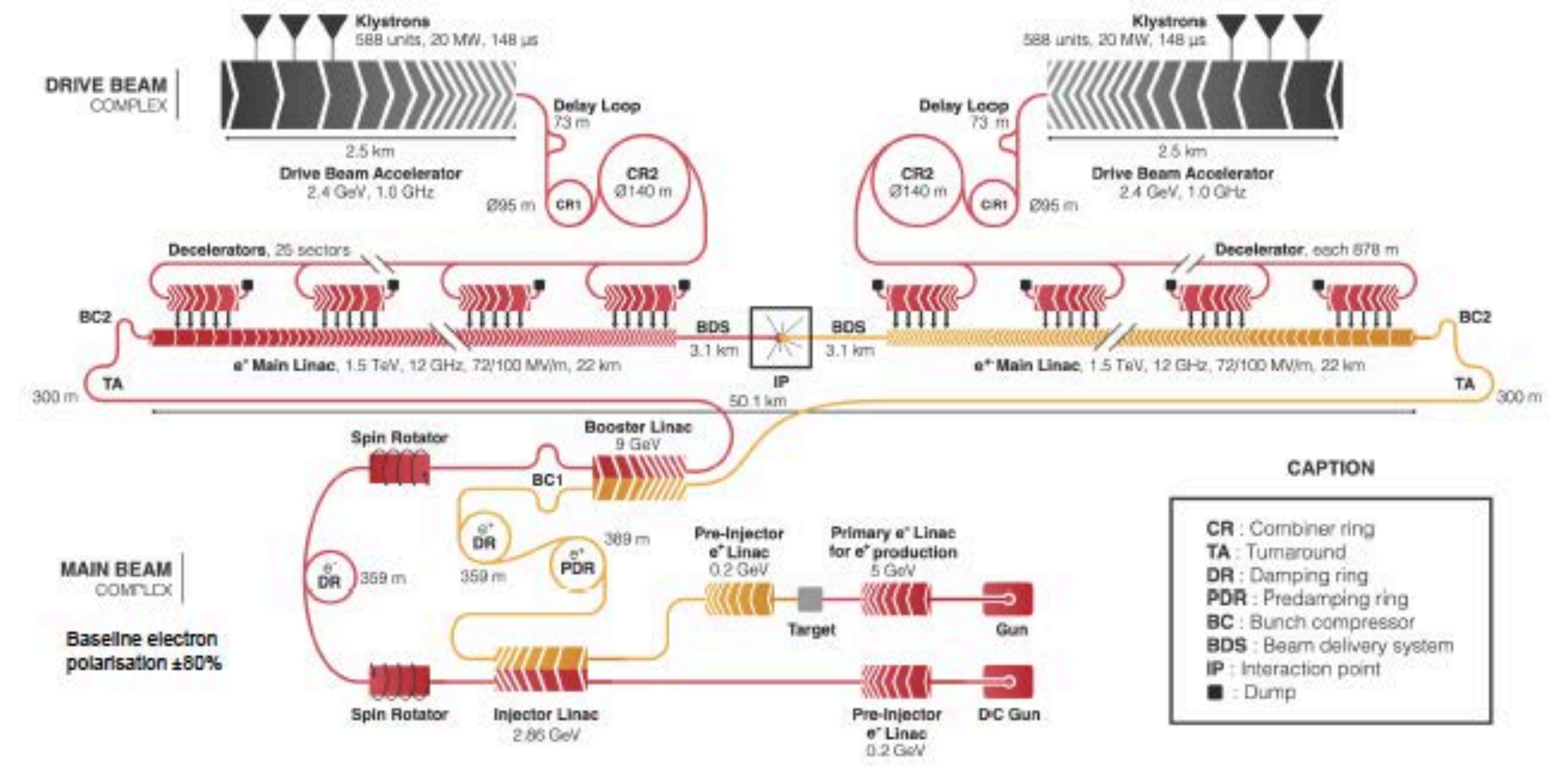


- Klystron-powered version studied and costed for 1st stage (380 GeV c.m.)
- Upgrade to 1 TeV and beyond based in any case on Two-beam scheme (klystron-based sectors re-usable with modifications)



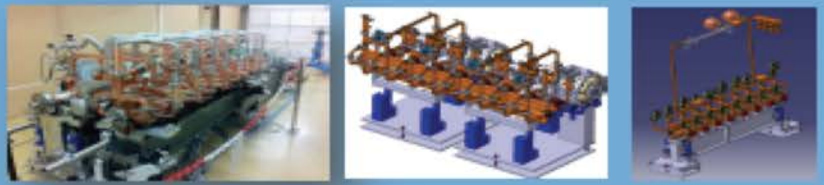
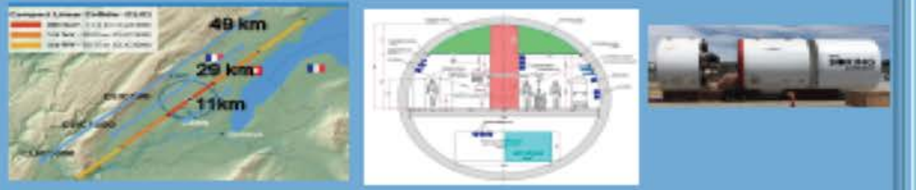


CLIC: 3 TeV and power generation



Technical developments

S. Stapnes, CLIC 2019

Modules (drive-beam, klystron type)		Final modules, from revised designs to industrial modules
Optimized structures		Use existing test-stands for testing, increase manufacturability, brazed, halves, conditioning
Klystrons and Modulators		Efficiency and costs, significant gains possible for efficiency, industrial cost-models and optimisation
Magnets		Permanent magnets, industrial capabilities
Civil engineering, infrastructure		Detailed site layout and CE/ infrastructure designs

Technical developments:

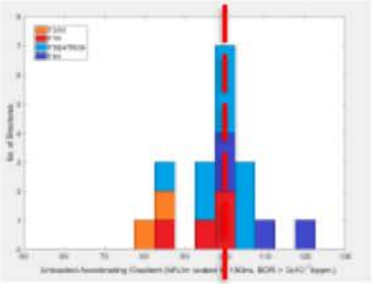
Courtesy: W. Wuensch

Normal Conducting Linac Technology Landscape

Components:

Laboratory with commercial

- Accelerating structures
- pulse compressors
- alignment
- Stabilization, etc.



~ 100 (+/-20) MV/m

Full commercial supply

- X-band klystrons
- solid state modulator,

Systems Facilities:
(100 MeV-range)

- XBoxes at CERN
- (NEXTEF KEK)
- Frascati
- NLCTA SLAC
- Linearizers at Electra, PSI, Shanghai and Daresbury
- Test stand at Tsinghua
- Deflectors at SLAC, Shanghai, PSI and Trieste
- NLCTA
- SmartLight
- FLASH

C-band (6 GHz), low-emittance GeV-range facilities

Operational:

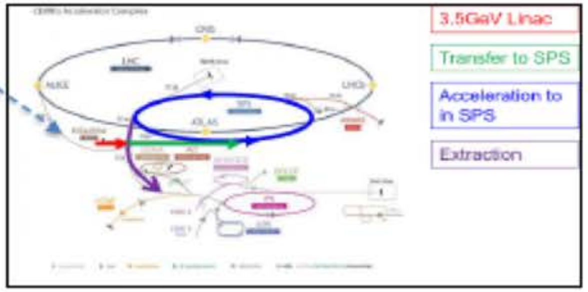
- SACLA
- SwissXFEL (8 GeV)

X-band (12 GHz) GeV-range facilities

Planning:

- Eu-Praxia
- e-SPS
- CompactLight

CLIC



A. Yamamoto, 190513bb

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CLIC DR: extremely low-emittances

Key challenges:

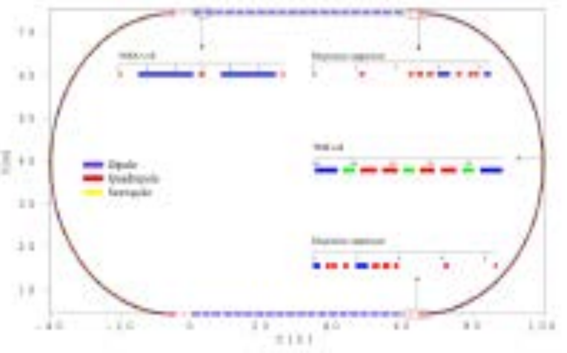
High-current drive beam, bunched at 12 GHz

Power transfer & two-beam acceleration

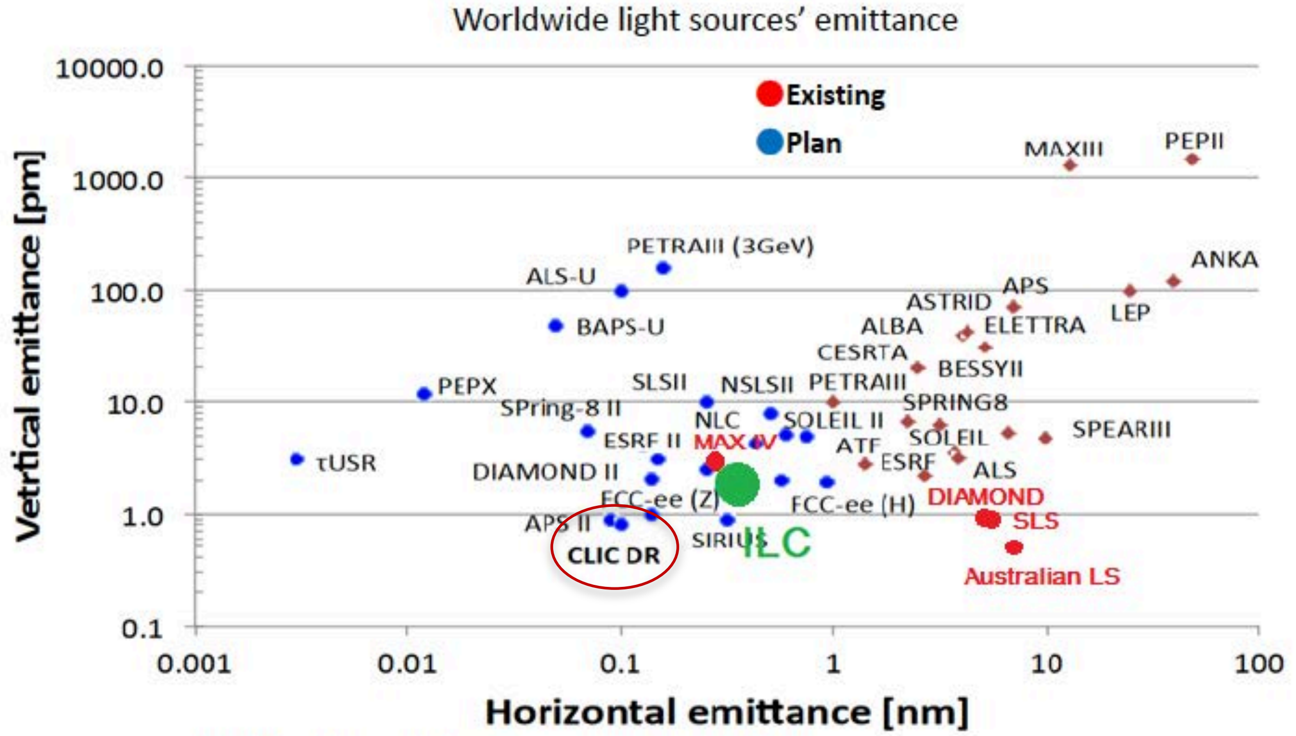
100 MV/m accelerating gradient

Low emittance generation, preservation, collision

CLIC damping ring layout



R. Corsini LCWS2019



Horizontal emittance is smaller at MAX IV.
Vertical emittance is smaller at Australian LS, SLS, DIAMOND.

Table 2.8: Design parameters for the improved design of the CLIC DRs, for the case of $f_{RF} = 2$ GHz and $N_b = 5.7 \times 10^9$. The magnetic field is varying along the dipoles.

Parameters, Symbol [Unit]	Variable dipole
Energy, E [GeV]	2.86
Bunch population, N_b [10^9]	5.7
Circumference, C [m]	259.4
Number of arc cells/wigglers, N_d/N_w	90/40
RF Voltage, V_{RF} [MV]	6.50
RF Stationary phase [°]	63.0
Harmonic number, h	2298
Momentum compaction, α_c [10^{-4}]	1.2
Damping times, (τ_x, τ_y, τ_l) [ms]	(1.15, 1.18, 0.60)
Energy loss/turn, U [MeV]	5.8
Horizontal and vertical tune, (Q_x, Q_y)	(45.81, 13.55)
Horizontal and vertical chromaticity, (ξ_x, ξ_y)	(-109, -51)
Wiggler peak field, B_w [T]	3.5
Wiggler length, L_w [m]	2
Wiggler period, λ_w [cm]	4.9
Normalized horiz. emittance with IBS, $\gamma\epsilon_x$ [nm-rad]	535.9
Normalized horiz. emittance with IBS, $\gamma\epsilon_y$ [nm-rad]	6.5
Longitudinal emittance with IBS, ϵ_l [keVm]	4.8
IBS factors hor./ver./long.	1.22/1.96/1.05

CLIC ML: emittance preservation

R. Corsini LCWS2019

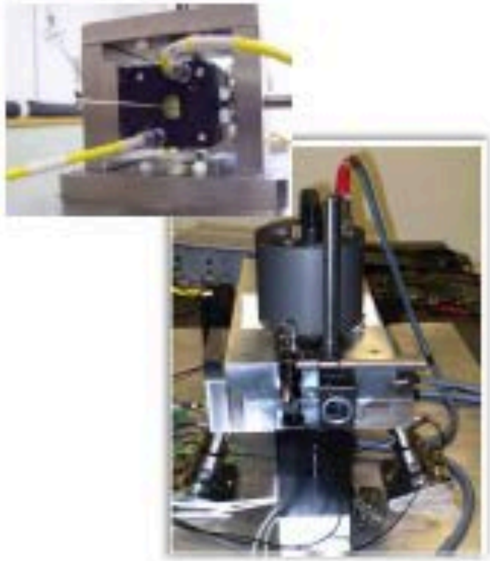
Key challenges:

High-current drive beam, bunched at 12 GHz

Power transfer & two-beam acceleration

100 MV/m accelerating gradient

Low emittance generation, preservation, collision

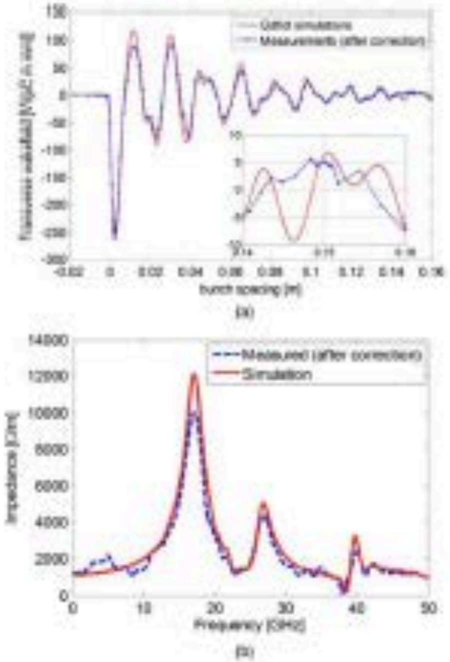


The CLIC strategy:

- Align components (10 µm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Beam based measurements
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks

- Experimental tests in existing accelerators of equipment and algorithms
  (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

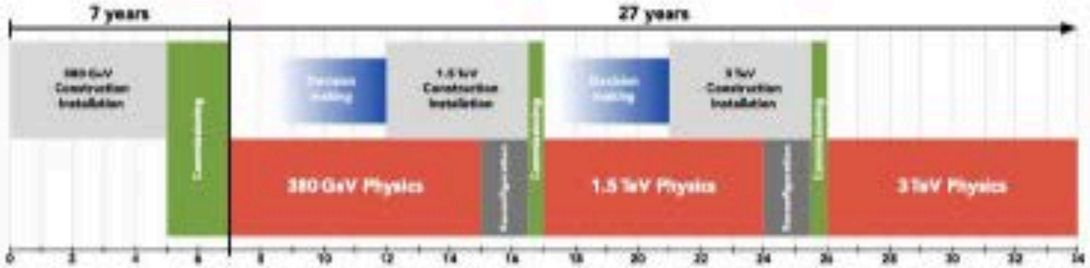
Figure 8.10: Phosphorous beam profile monitor measurements at the end of the FACET linac, before the dispersion correction, after one iteration step, and after three iteration steps. Iteration zero is before the correction.



Wake-field measurements in FACET

(a) Wakefield plots compared with numerical simulations.
(b) Spectrum of measured data versus numerical simulation.

CLIC: next phase



Activities 2020-2025	Purpose
Design and parameters, final optimization and system verifications	Luminosity performance, risk, cost power reduction
Construction of pre-series of modules	Final technical design and industrial capabilities
Accelerator structures optimization and production of modules	Final design, industrial capabilities, conditioning
X-band test facilities inside and outside CERN	Needed for construction, further cost/power reduction
Final parameters and design of magnets, instrumentation, alignment, stability, vacuum systems	Luminosity performance, prepare for construction tenders
Drive beam front end optimization to ~20 MeV and system tests	Drivebeam most critical parts, production preparation
Detailed site design, impact studies, finalise infrastructure specifications	Final CE and infrastructure parameters, permits, tenders

October 2019, Sendai

In Summary

- A **e^+e^- LC** is **ready** for start up ~2035: ILC hosted in Japan and CLIC at CERN, in both cases promoted and set up as international projects

- The main accelerator **technologies** have been **demonstrated** (CLIC need large scale production)
- The cost and implementation time are **similar** to **LHC** (~10B$)
- The physics case is broad and profound, and being further developed
- The detector concept and detector technologies R&D are advanced

Implementing a LC now provides a very attractive, implementable way forward, with a good match between scientific progress and further technology development – not only for LC technologies ..

Summary at a glance

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

***F1* “Technology Readiness” :**

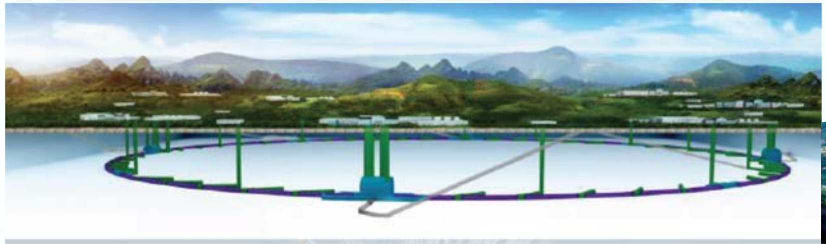
Green	-	TDR
Yellow	-	CDR
Red	-	R&D

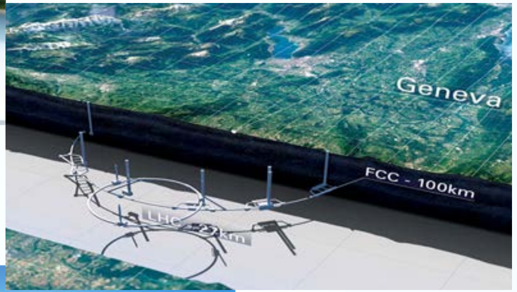
***F2* “Energy Efficiency”**

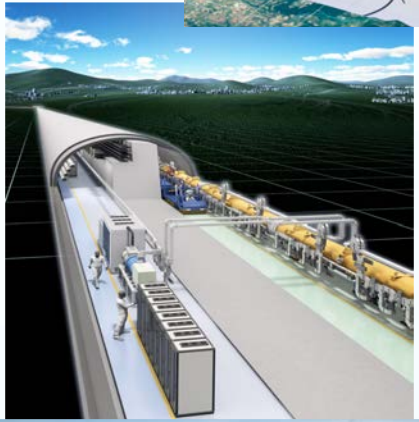
Green	:	100-200 MW
Yellow	:	200-400 MW
Red	:	> 400 MW

***F3* “Cost” :**

Green	:	< LHC
Yellow	:	1-2 x LHC
Red	:	> 2x LHC

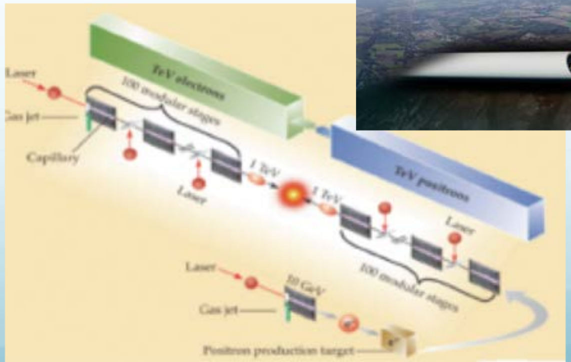


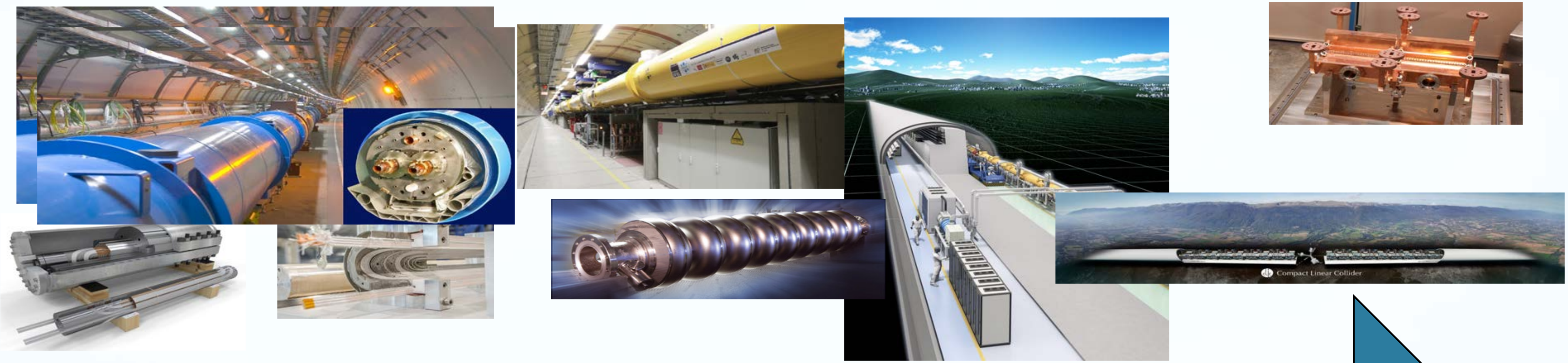




……..But when theorists are more confused, it’s the time for more, not less experiments.

(Nima Arkani-Hamed Cern Courier March 2019)



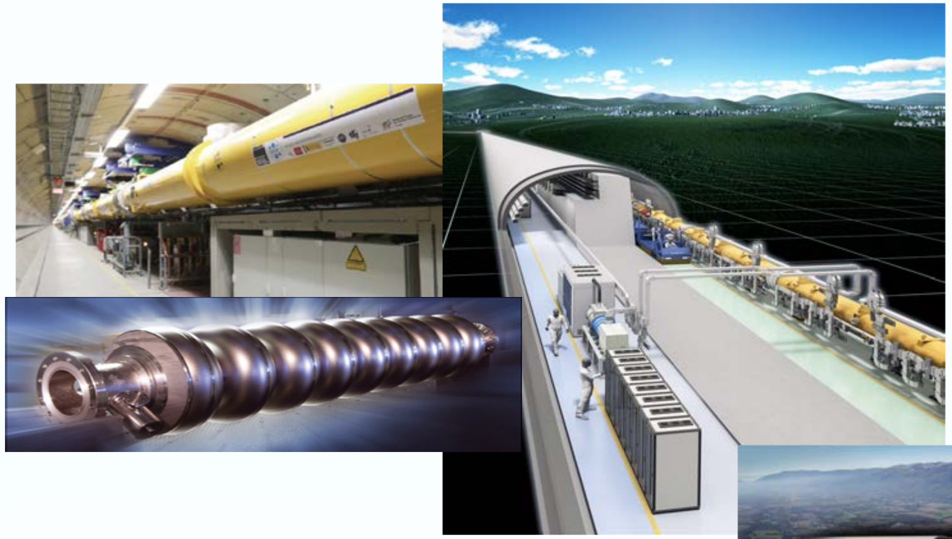


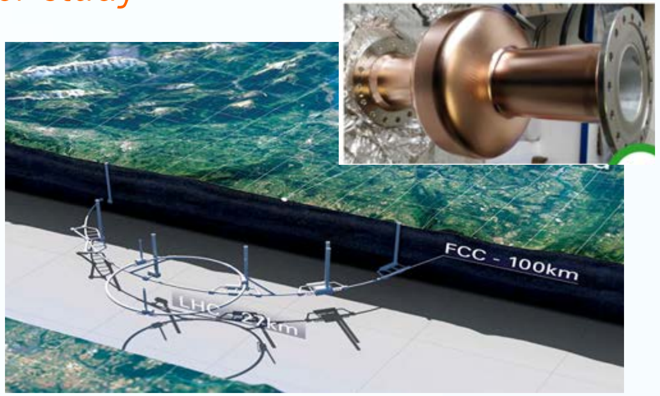
Thanks for your attention

Present and Future Large Accelerator projects

In operation
In construction
Under study

An uncompleted view ...





International Large Scale Projects

EPPSU
FCC/CLIC, ILC ?

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

HL-LHC
11T Nb_3Tn

FAIR

LBNF

CepC.
High current
Z-pole

LHCeC
ERL

PLC

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

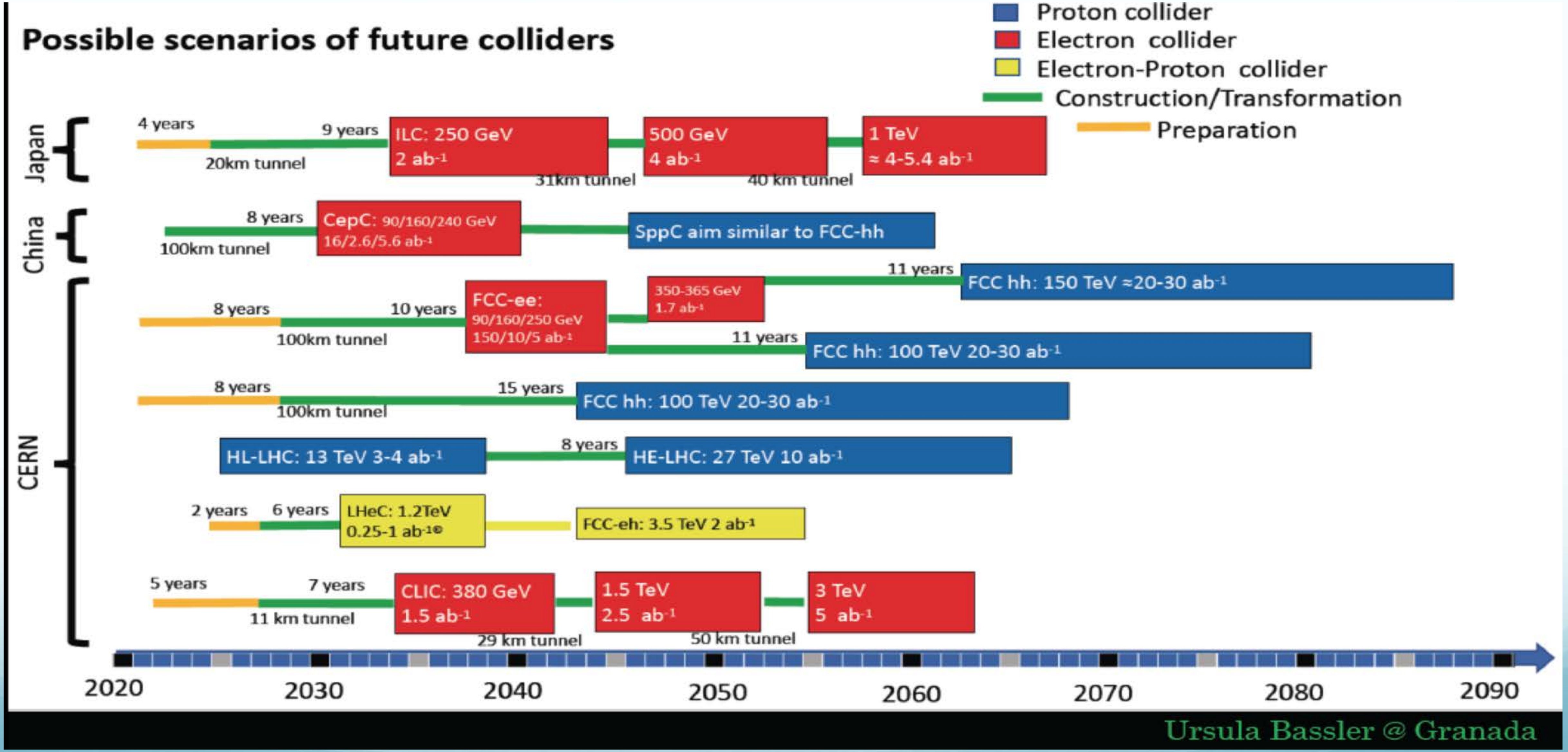
HE-LHC (HL-LHC)
16T Nb_3Tn/NbTn

SppC

FCChh (FCCee)
16T Nb_3Tn/NbTn

$\mu^+\mu^-$

Schedule Implementation



Personal (A. Yamamoto) Technology View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction			Operation		Upgrade
12~14T Nb_3Sn	Short-model R&D		Proto/Pre-series	Construction		Operation	
14~16T Nb_3Sn	Short-model R&D			Prototype/Pre-series		Construction	

Note: **LHC experience**: **NbTi (10 T)** R&D started in 1980's --> **(8.3 T)** Production started in late 1990's, in **~ 15 years**

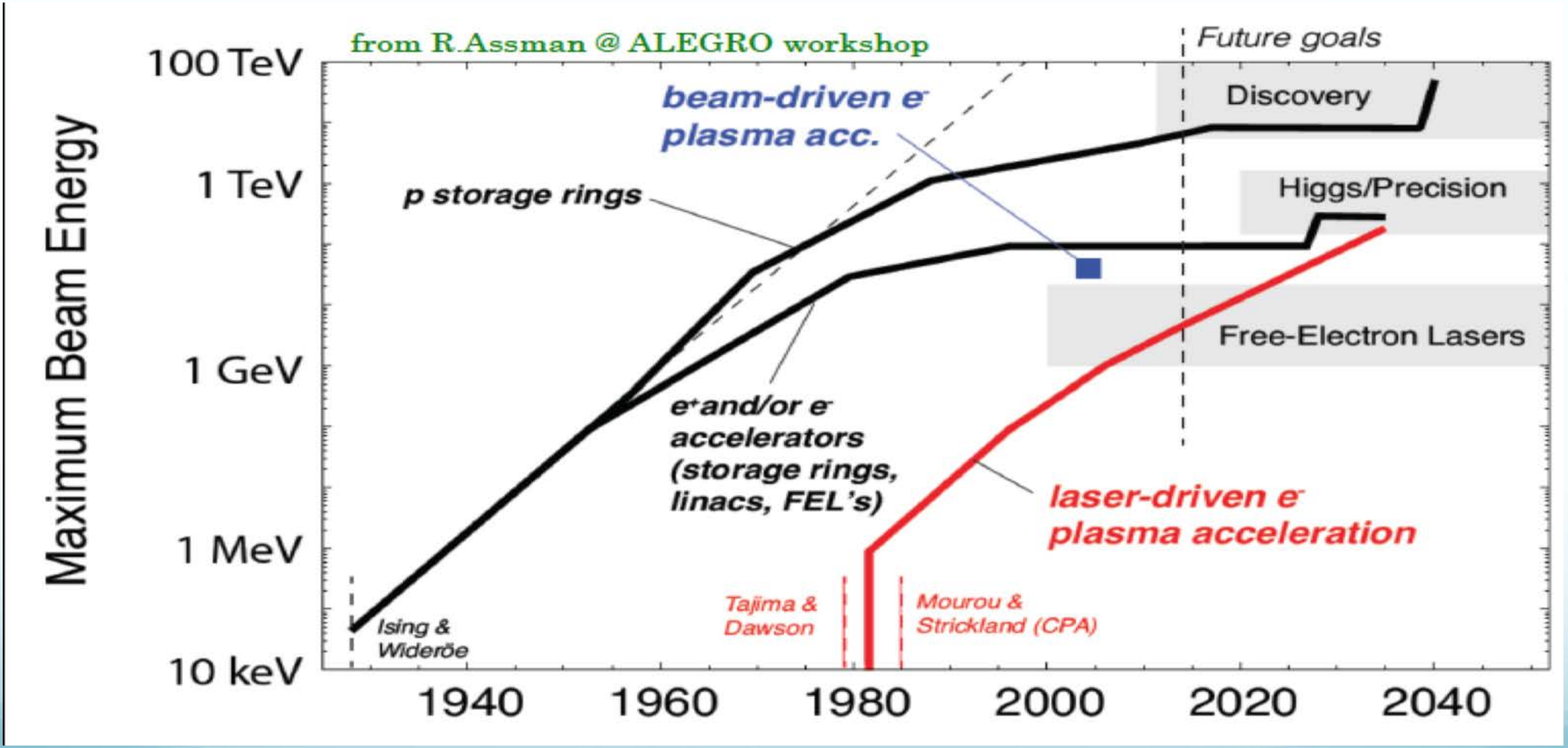
Future Projects Comparisons

D. Schulte, Granada 2019

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Advanced Linear Accelerators

ALEGRO (Advanced LinEar collider study GROup, for a multi-TeV Advanced Linear Collider)
Workshop (March 2018 in Oxford): http://www.physics.ox.ac.uk/confs/alegro2018/index



Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

*Cost estimates are commonly for "**Value**" (material) only.

Large Accelerator Projects Key technologies:

Components			SCRF				NCRF	HLRF	SC Mag.		NC Mag.	Vac.	Optics	Others
Techniques			HG	HQ	CRYO	CRAB		HE-Klys	Nb_3Tn	CRYO				
PROJECTS	FCC	FCC-hh			X	X			X	X		X		
		HE-LHC			X	X			X	X			Coll	Integr.
		FCC-eh/LHeC			X									
		FCC-ee	X	X	X			X			X		IRs	Integr.
	LC	ILC	X	X									IRs	e+
		CLIC					X	X			X		IRs	

ILC Summary

- *Most of the ILC accelerator parameters have been demonstrated at the various facilities.*
- *SRF Technology matured based on the success of European XFEL (10% scale of ILC Main linac).*
- *ILC preparation:*
  - *ILC cost reduction R&Ds are ongoing under US-Japan cooperation and ILC inprovement adopting these results are considered at US.*
  - *KEK issued ILC action plan.*
  - *European ILC preparation plan as "E-JADE" report was summarized.*
- *KEK published "Summary of Recommendations on ILC Project" based on the discussion at the international WG.*
- *The technical preparation plan in response to reports by ILC Advisory Panel organized by MEXT and the Science Council of Japan is presented.*
- *The plan identifies technical tasks to be carried out through international collaboration.*

CLIC Summary

- CLIC is now a mature project, ready to move towards the next phase
- There is an consistent way forward with an initial stage at 380 GeV, keeping the options open for future upgrades and/or other options
- The cost and implementation time for CLIC 380 are similar to LHC
- Key technical challenges have been solved, now further optimizing cost, power and performance

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

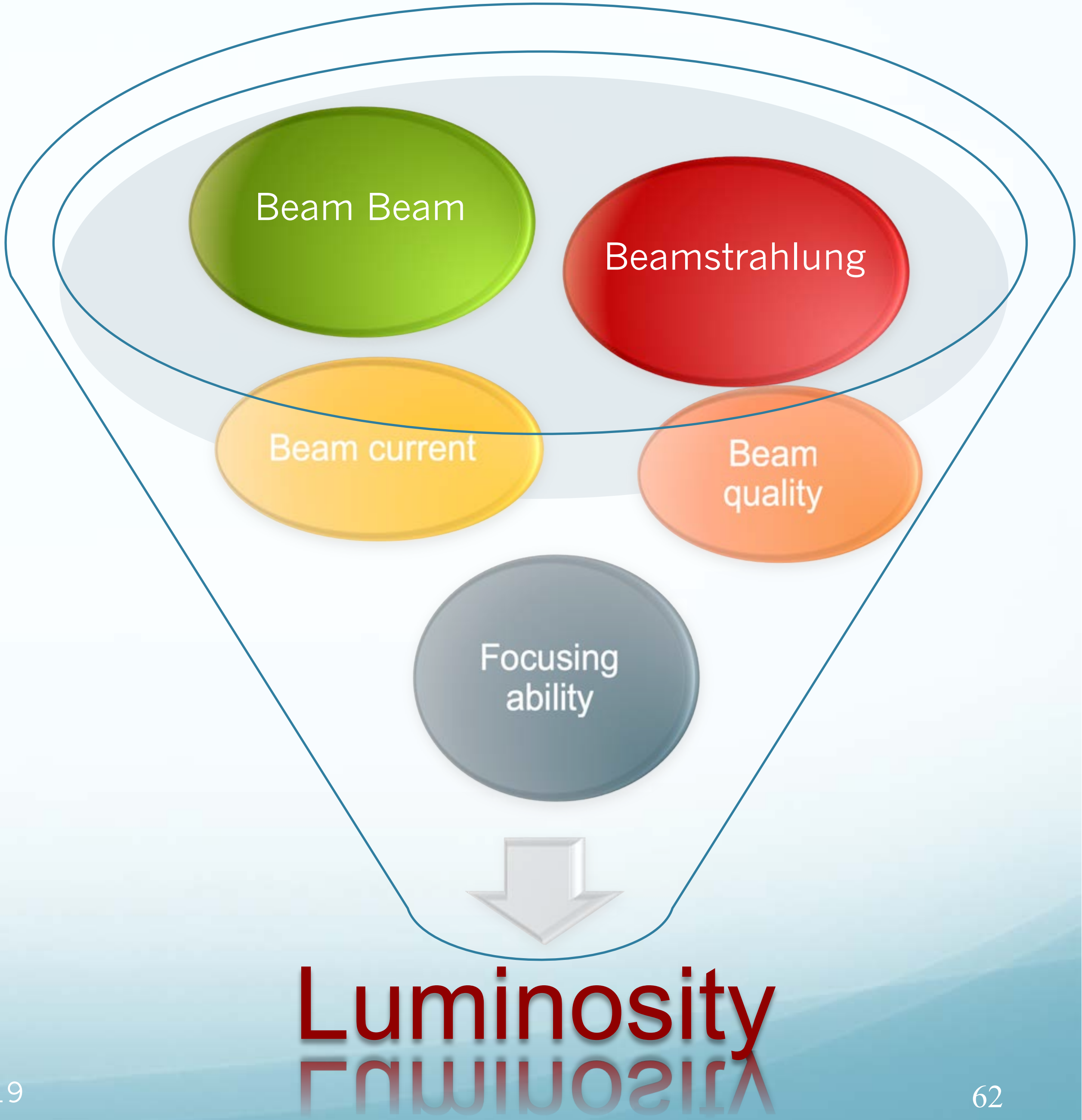
$$\langle \Delta\gamma \rangle = \frac{4}{9}\sqrt{\frac{\pi}{3}} N^2 \frac{r_e^3}{\sigma_x^2 \sigma_z} \gamma^2$$

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

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



Luminosity recipe: the "dreamt" Luminosity

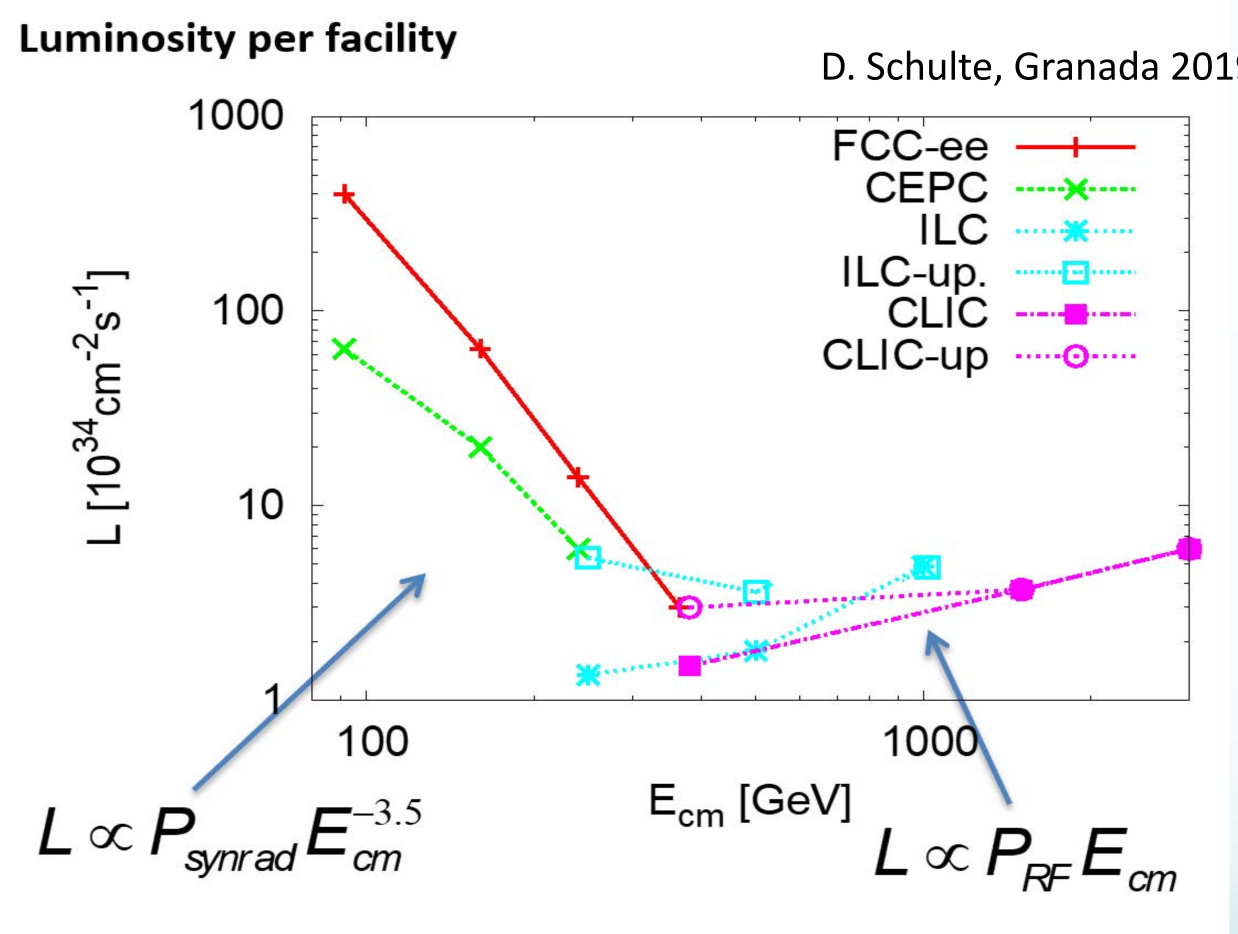
Energy dependence:

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
Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung

Boosted Luminosity

Benno List, Daniel Schulte, Dmitry Shatilov, Cheng Hui Yu, Vladimir Litvinenko, Thomas Roser