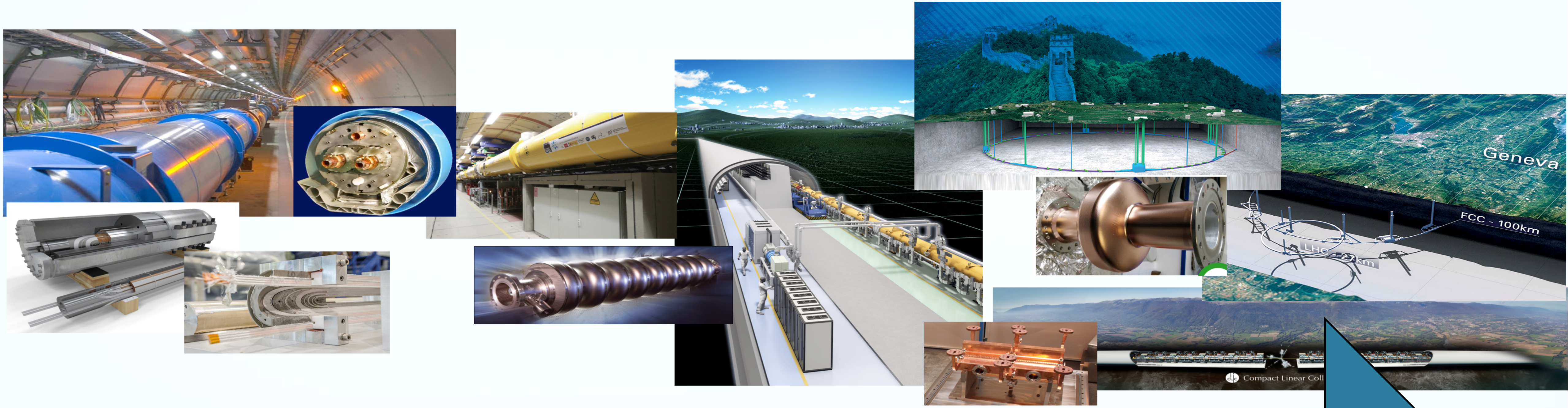
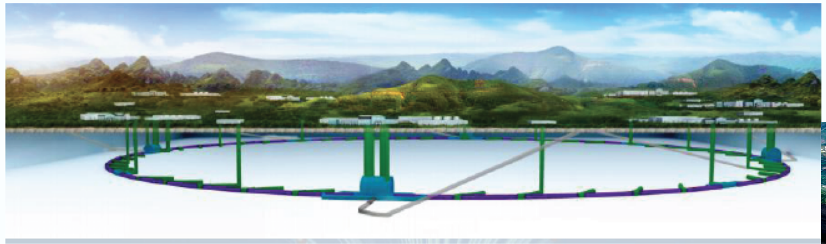
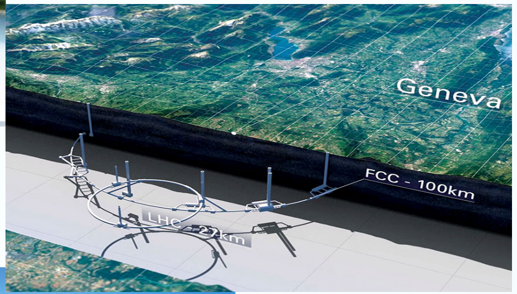
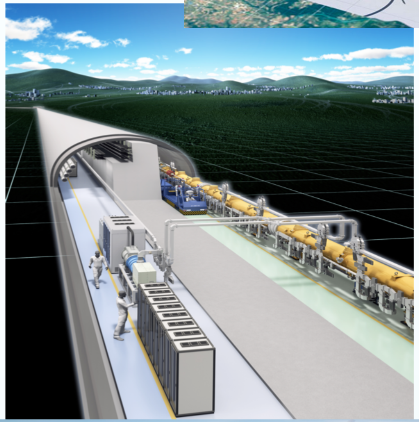


Reality and Dreams in Future $e^+ e^-$ Colliders

A. Faus-Golfe

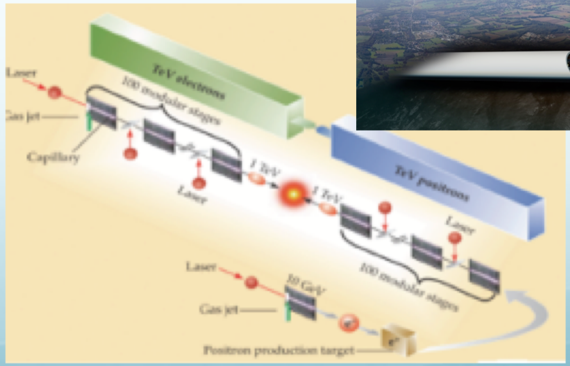






…….But when theorists are more confused, it’s the time for more, not less experiments.

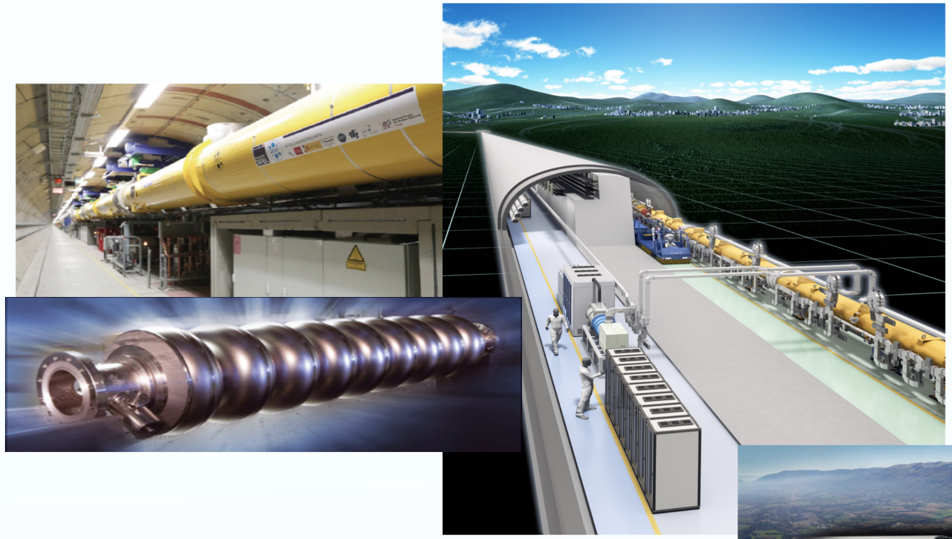
(Nima Arkani-Hamed Cern Courier March 2019)

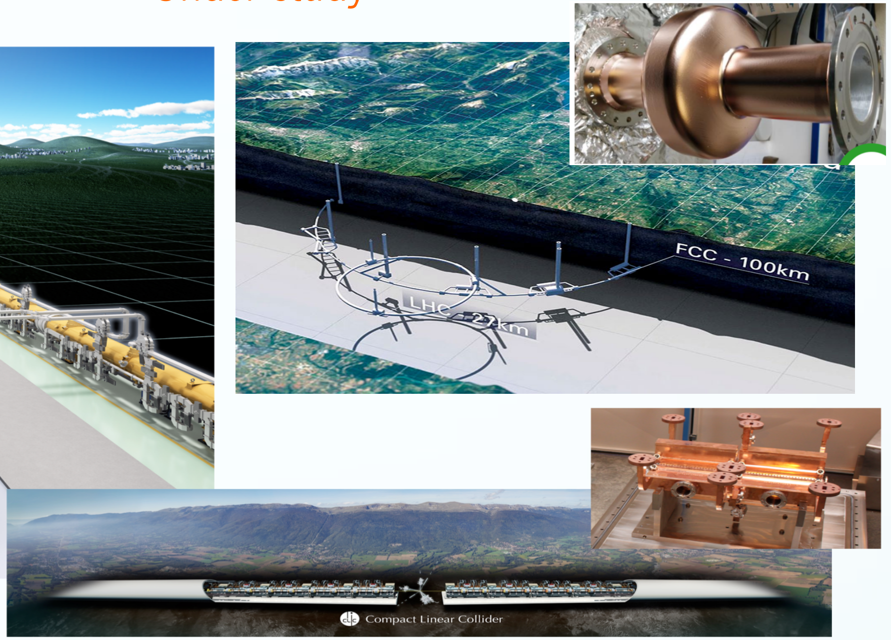


Present and Future Large Accelerator projects

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_3Sn

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

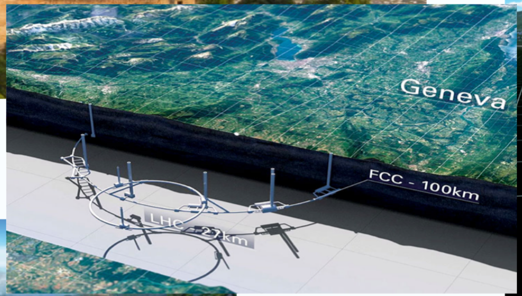
FCChh (FCCee)
16T Nb_3Tn/NbTn

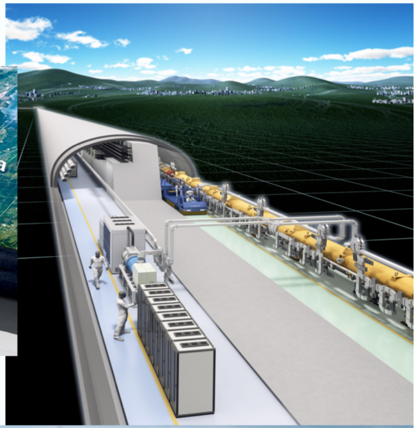
$\mu^+\mu^-$

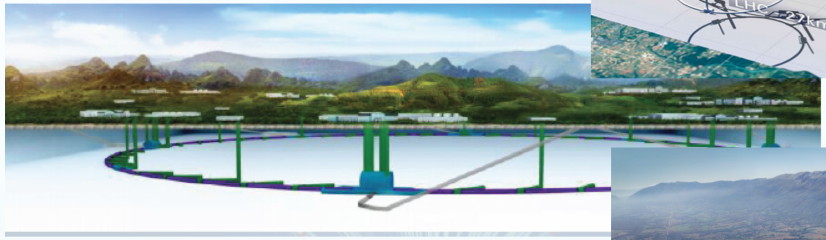
Outline

- Summaries from EPPSU Granada

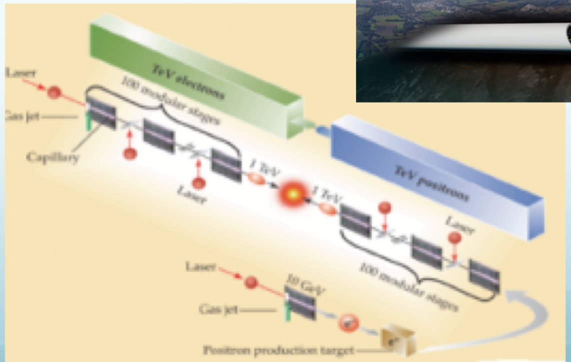
- Focusing in “real” e^+e^- colliders
  - LC projects: ILC, CLIC
  - CC projects: FCC-ee, CepC







- Some “dreamt” e^+e^- colliders
  - Boosting the performances
  - Advanced Linear Colliders e^+e^-



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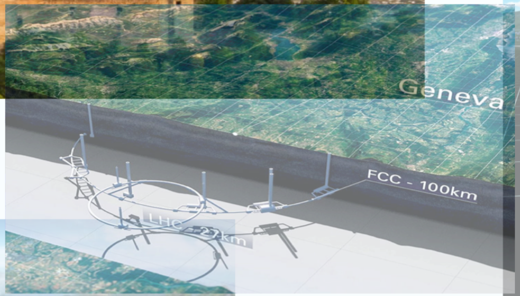

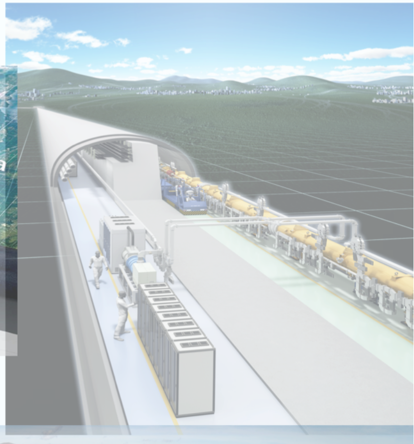

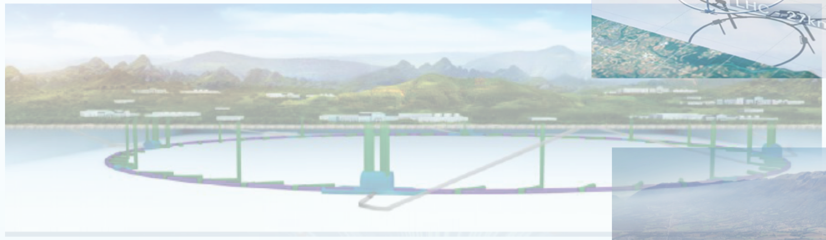

- Some "dreamt" e^+e^- colliders
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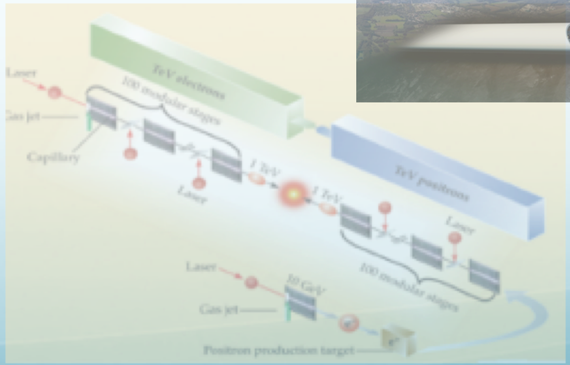
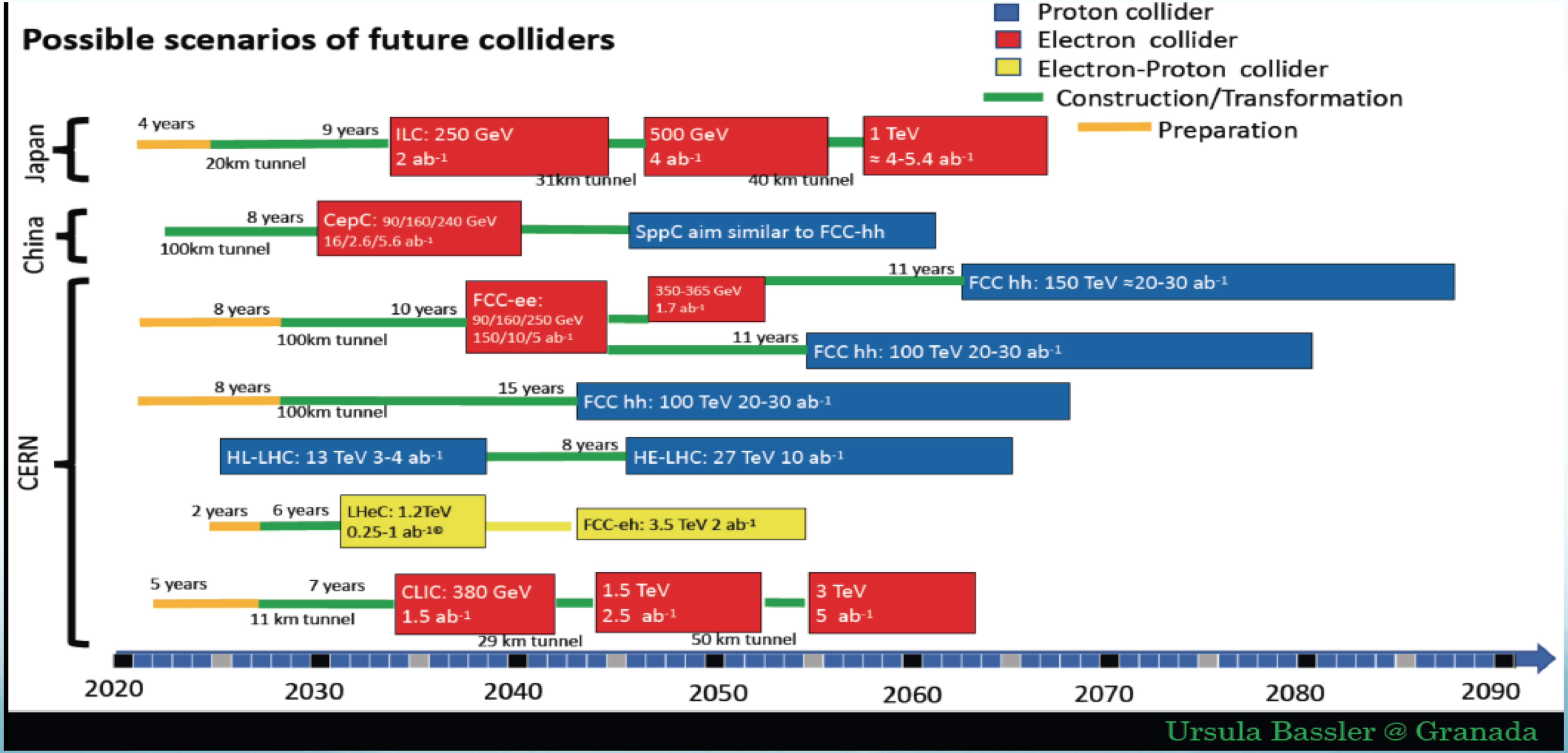


Schedule Implementation



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**

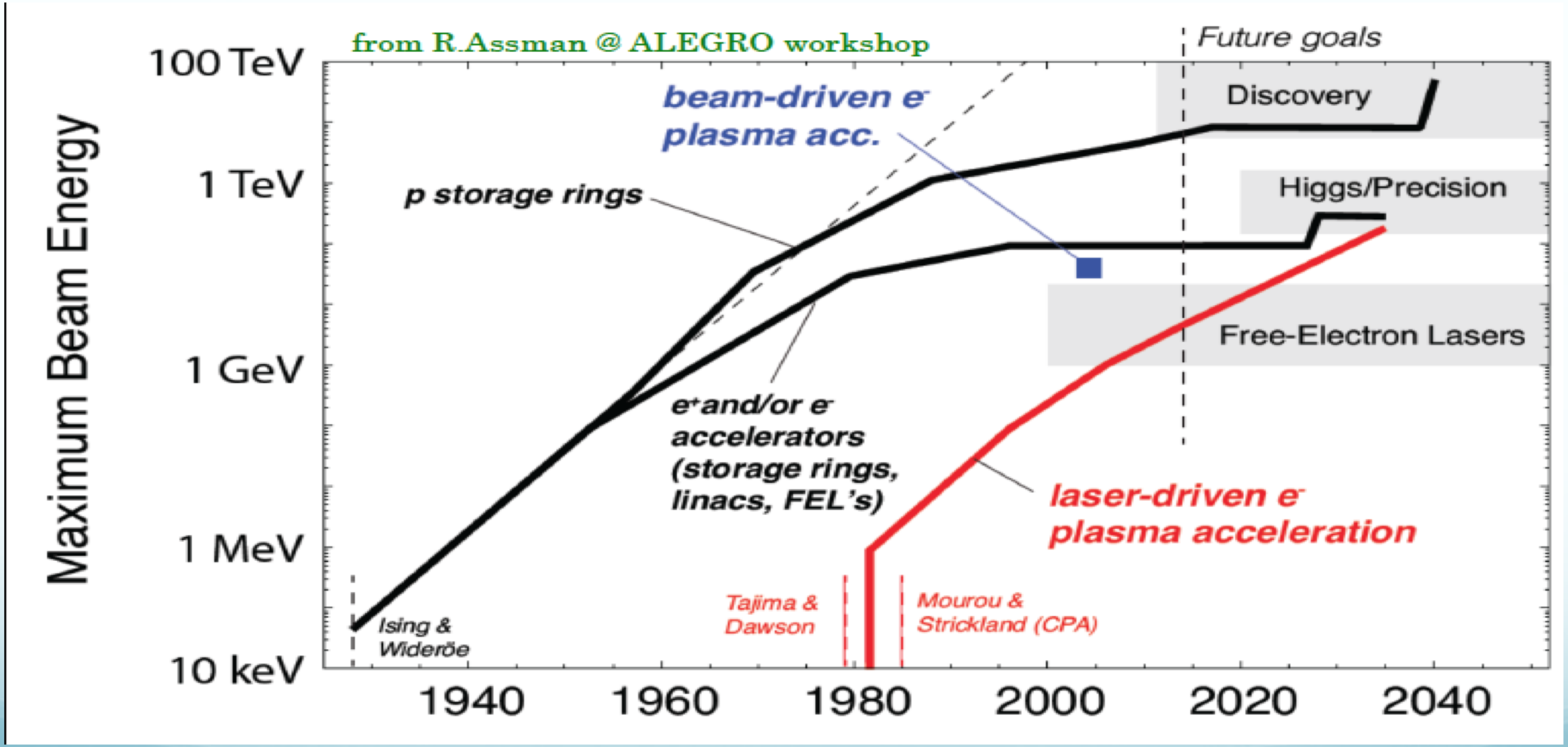
Future Projects Comparisons

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



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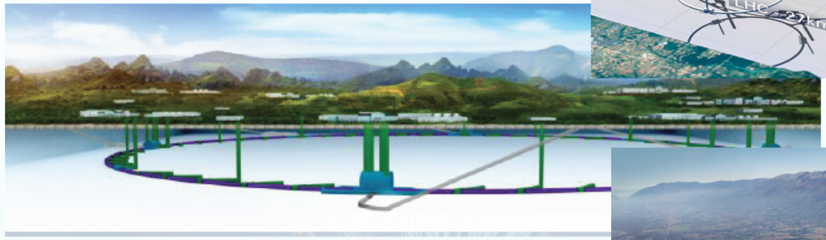

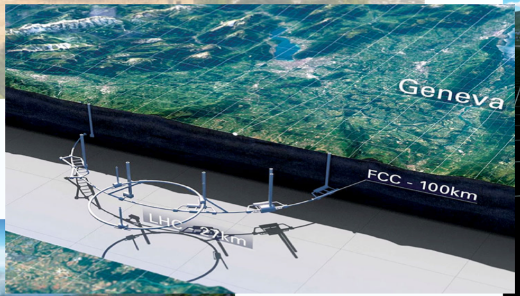

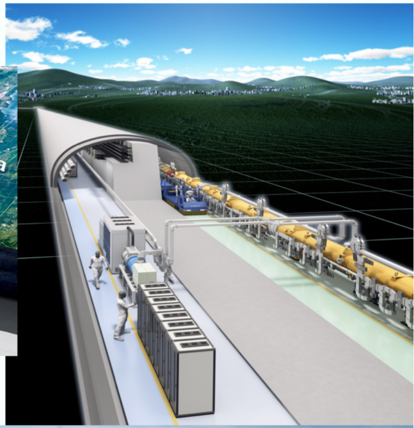

- Some “dreamt” e^+e^- colliders
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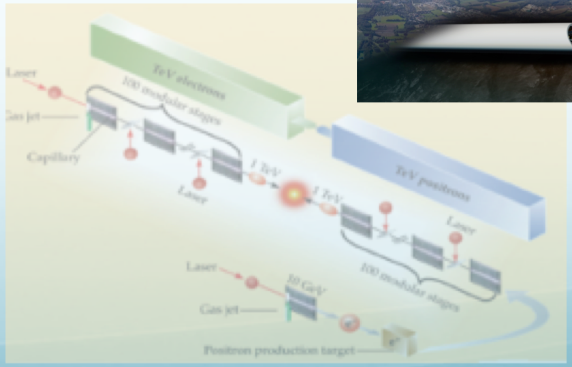
  - Advanced Linear Colliders e^+e^-



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

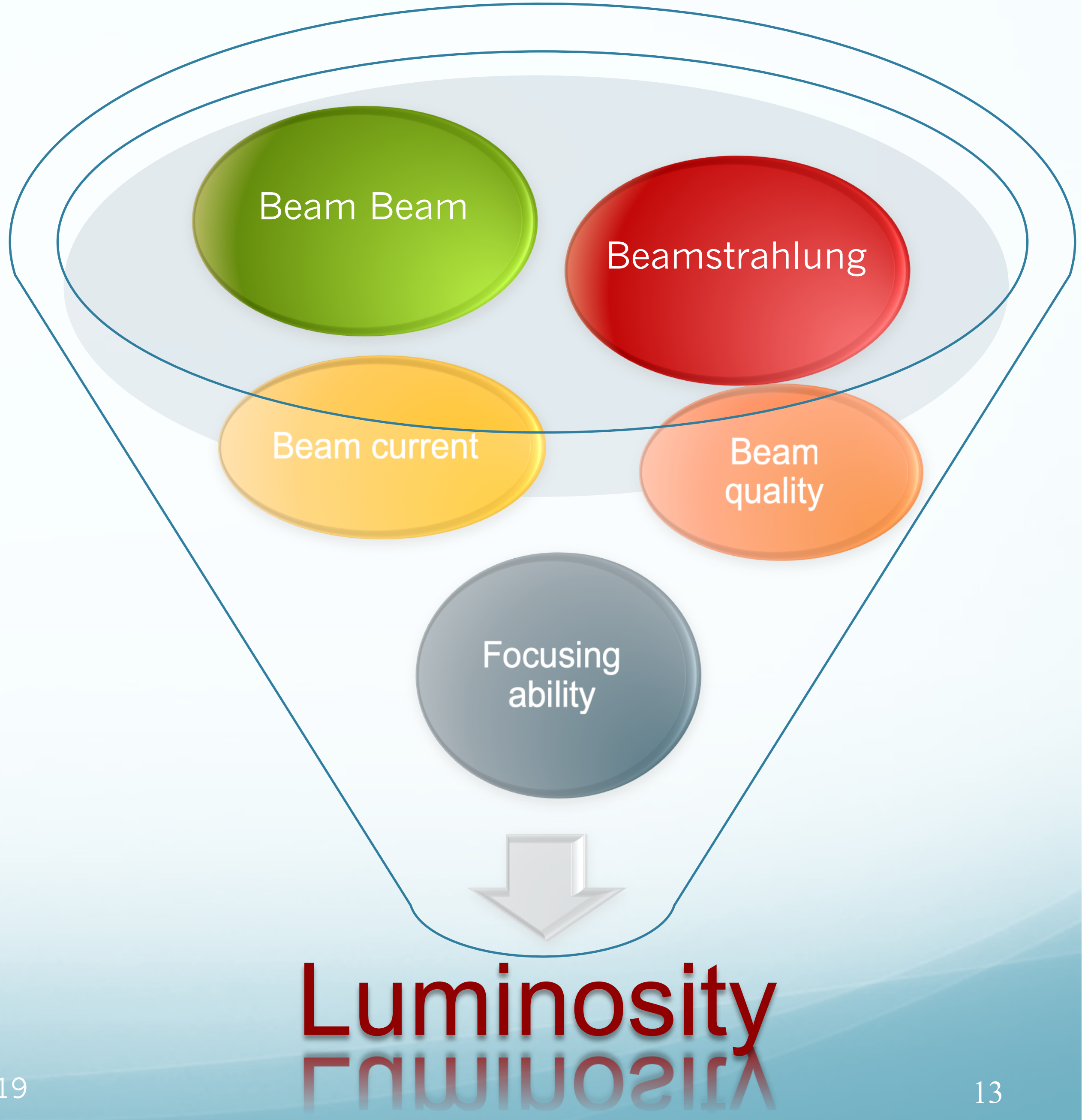
$$\langle \Delta\gamma \rangle = \frac{4}{9}\sqrt{\frac{\pi}{3}} N^2 \frac{r_e^3}{\sigma_x^2 \sigma_z} \gamma^2$$

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

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

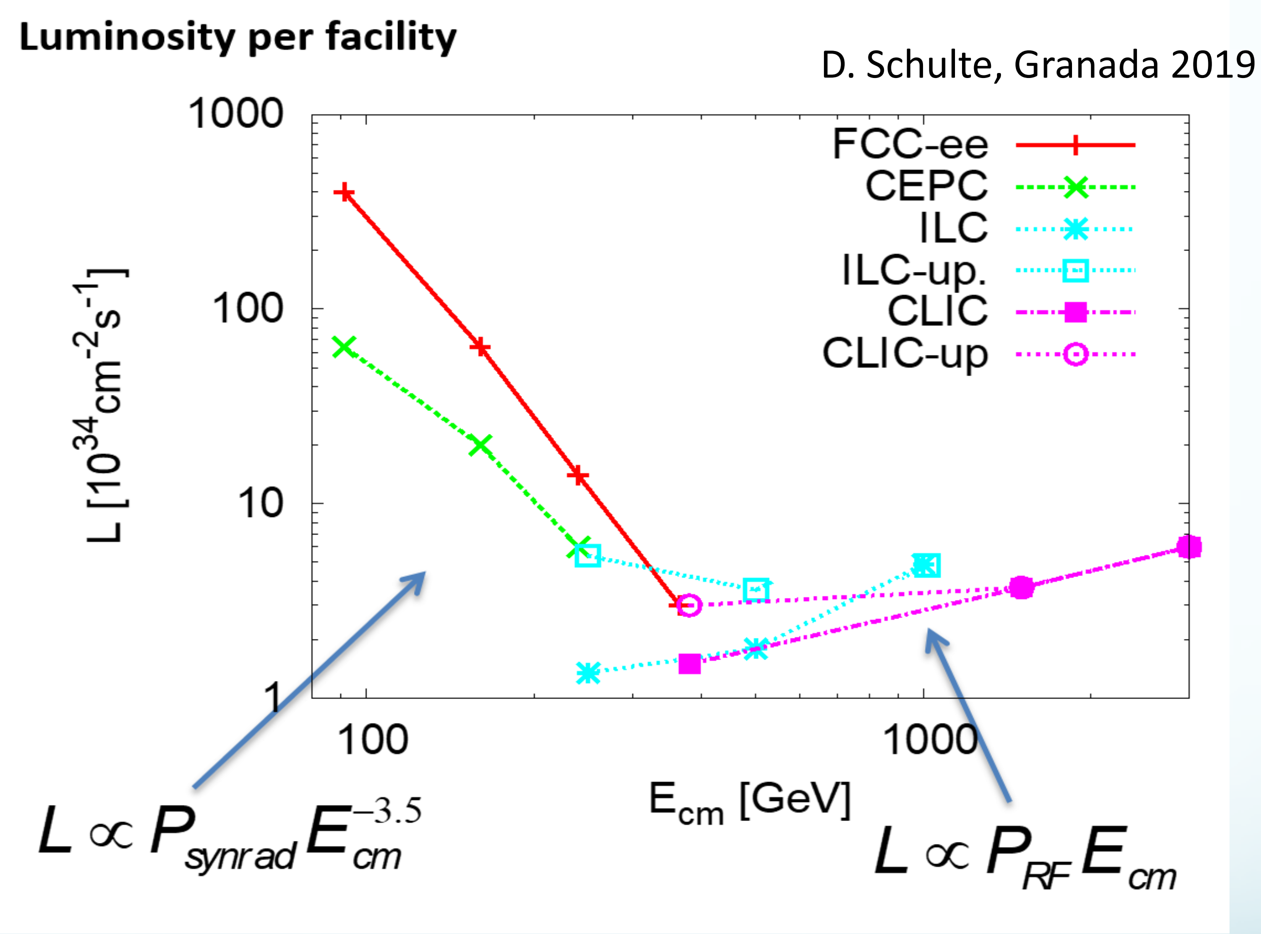
Energy dependence:

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



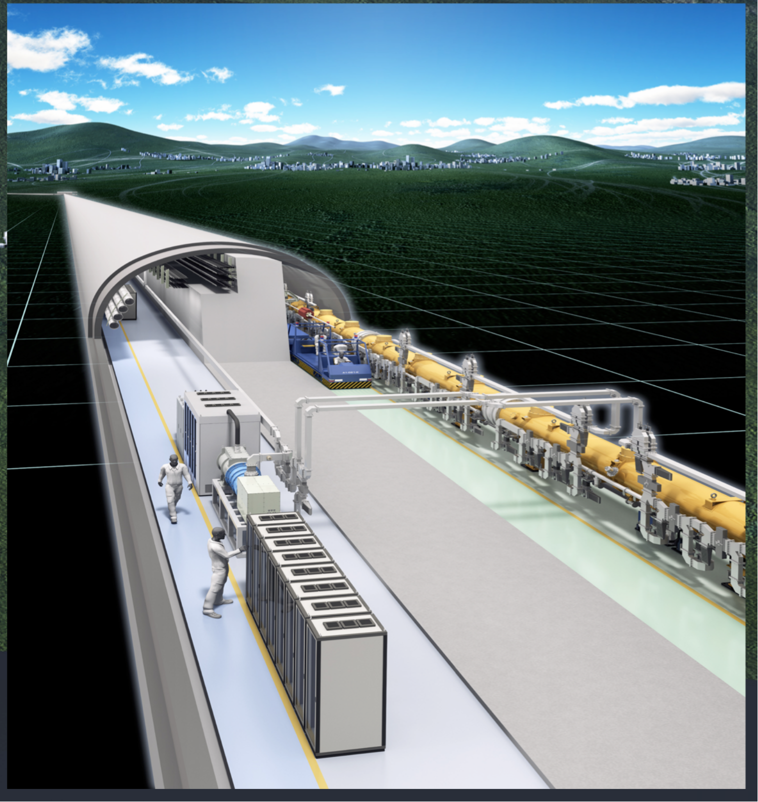
Note: The typical higgs factory energies are close to the cross over in luminosity
Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung

ILC accelerator: status and optimizitation

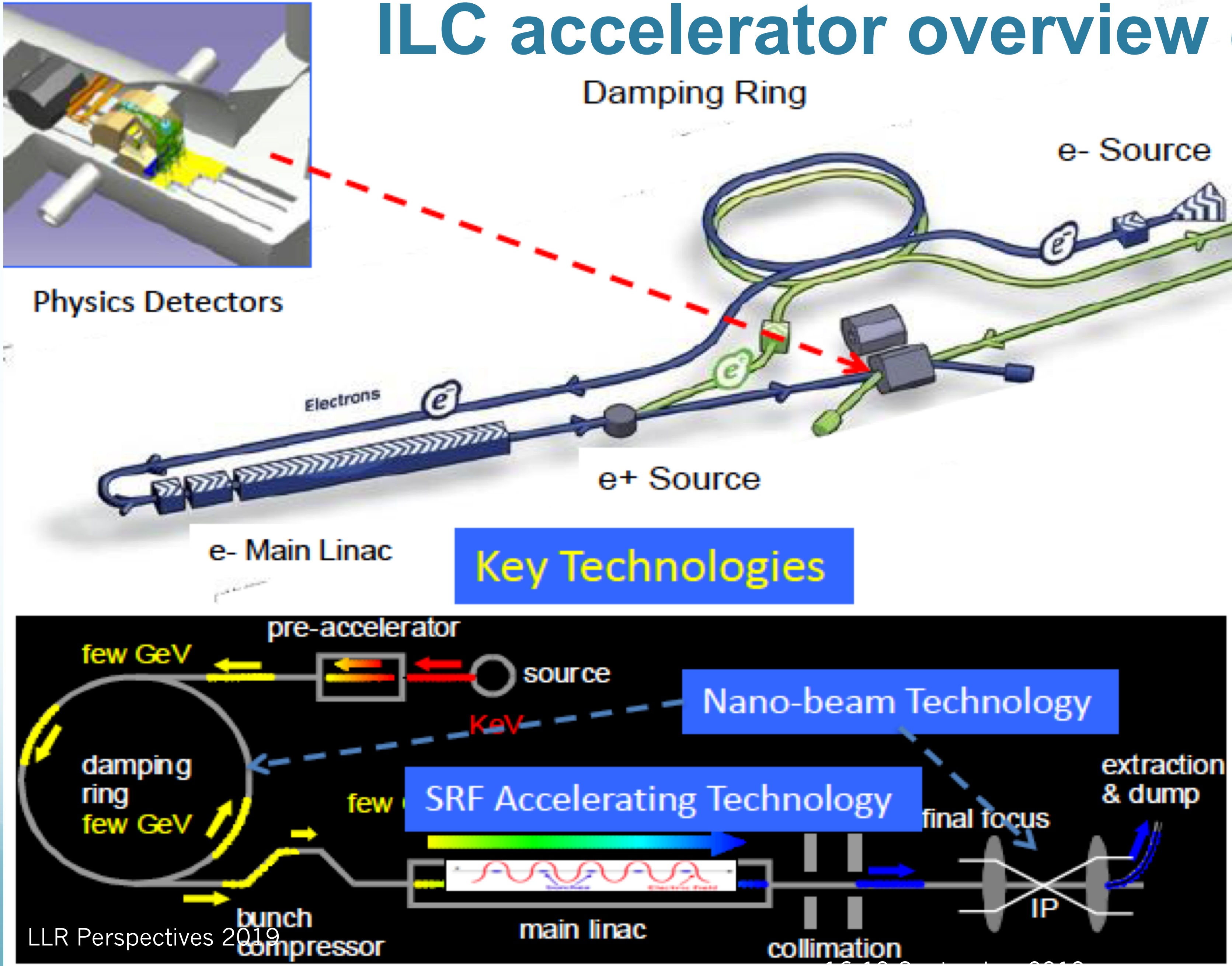
http://www.linearcollider.org/

LLR Perspectives 2019

16-19 September 2019



ILC accelerator overview (TDR 2013)



Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 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	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m Q_0 = 1x10^{10}

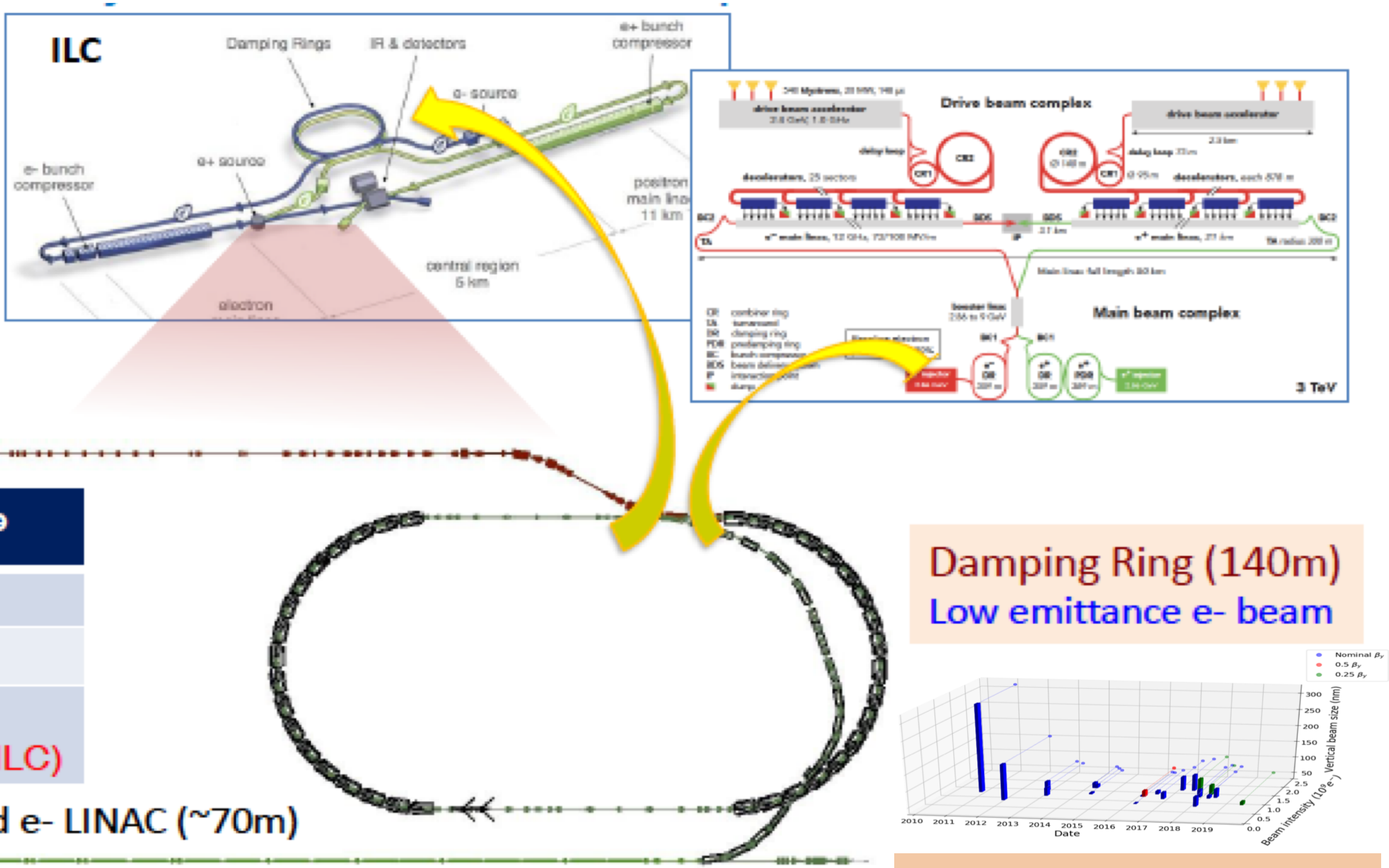
Nanobeam Technology

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)

1.3 GeV S-band e- LINAC (~70m)

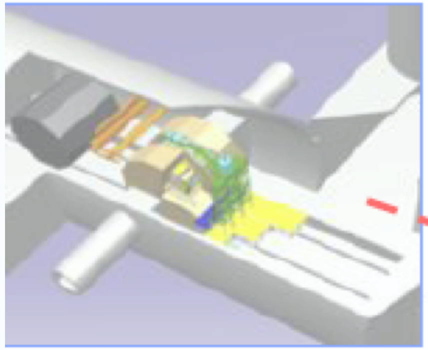
Damping Ring (140m)
Low emittance e- beam

Intensity dependence-wakefiels

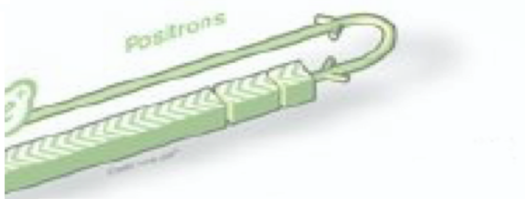
A. Yamamoto, 190513bb

8

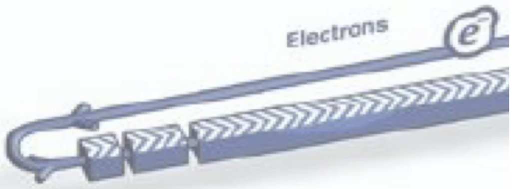
The “staging” process



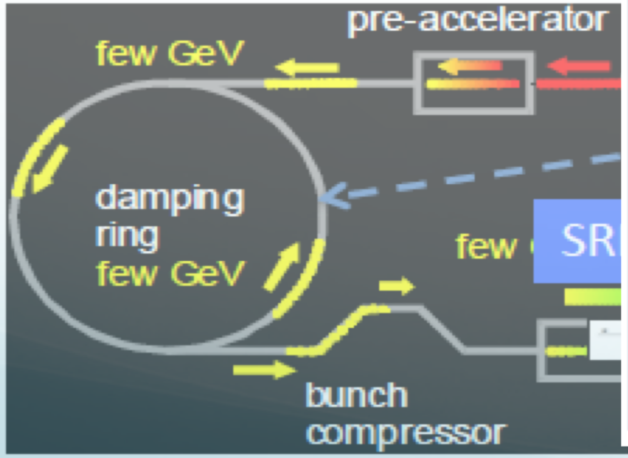
Physics Detectors



e+ Main Liinac



e- Main Linac



LCC-ILC (Shin MICHIZONO)

Technical & change management board (TCMB)

Ad-hoc WG1
Positron (Kaoru YOKOYA)

Ad-hoc WG2
CFS for staging (Hitoshi HAYANO)

CFS Conventional Facilities and Siting

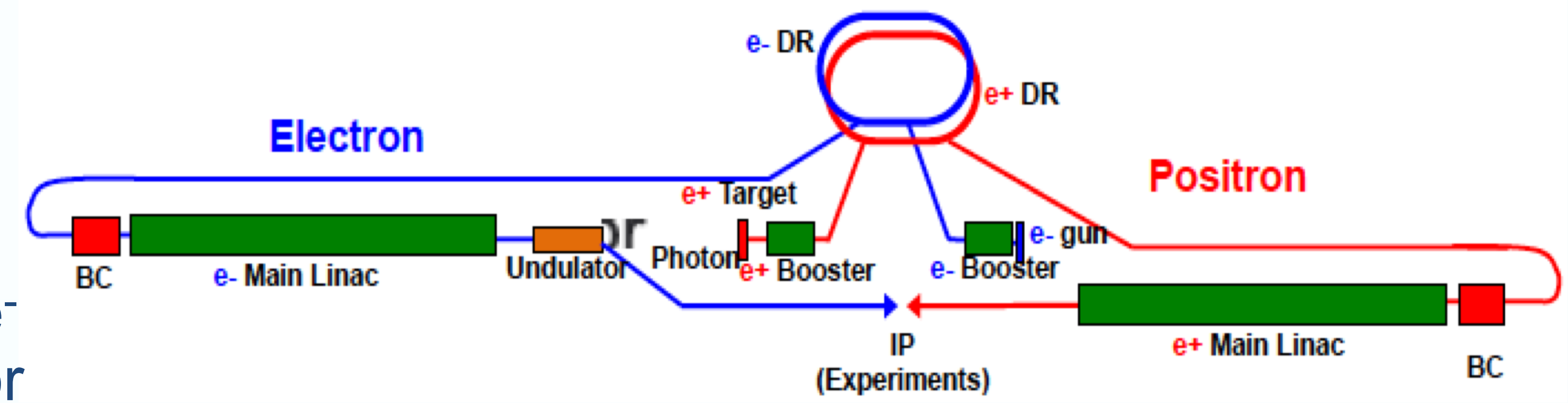
Ad-hoc WG3
Resource Optimization (Akira YAMAMOTO)

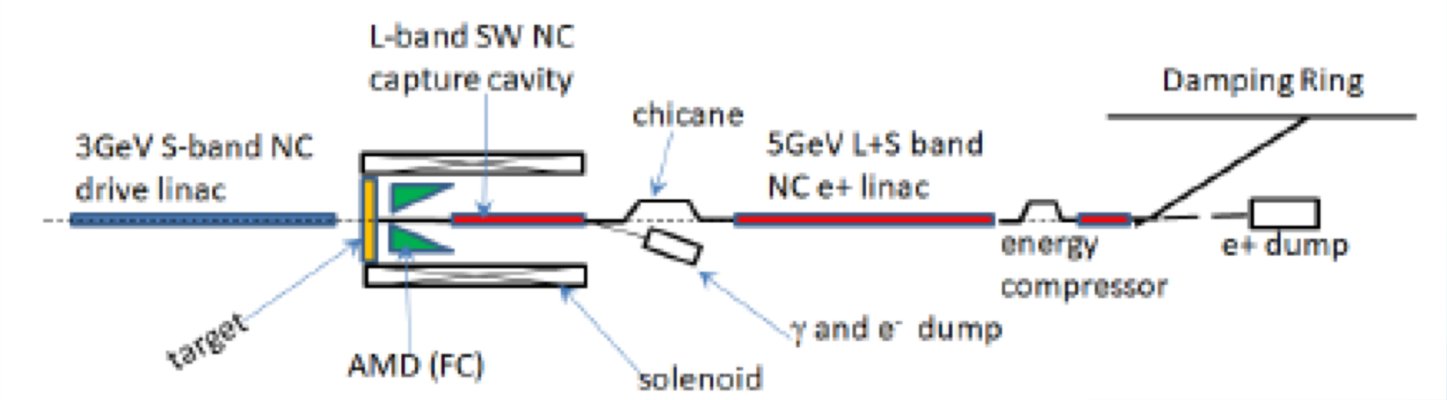
	Parameters
ergy	500 GeV
	31 km
sity	1.8 x10^{34} cm^{-2}s^{-1}
on	5 Hz
ulse Period	0.73 ms
urrent	5.8 mA (in pulse)
ze (y) at FF	5.9 nm
ity G.	31.5 MV/m Q_0 = 1x10 ^{10}

Positron production

Two concepts considered:

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

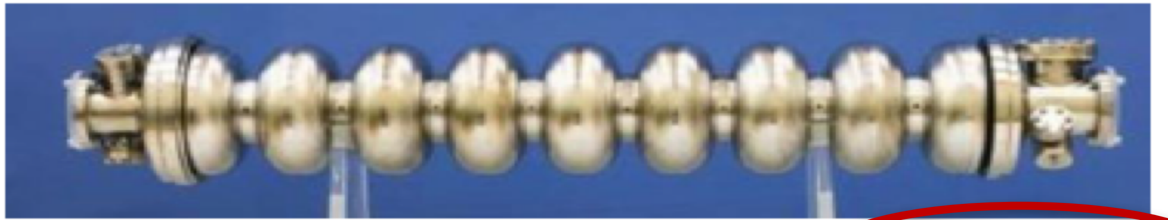




- **Electron driven source**: dedicated 3 GeV S-band e⁻ (pair production), no polarized

A decision will be made before the detailed engineering design

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



Cost reduction by technological innovation

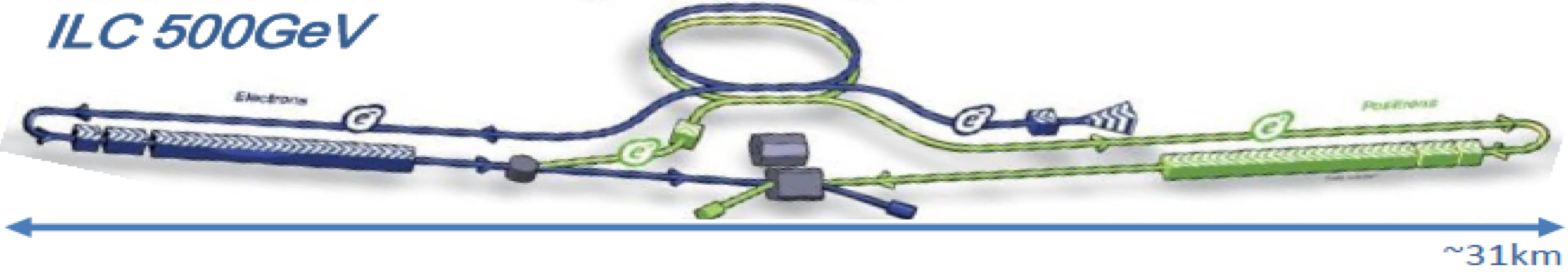
Innovation of Nb (superconducting) material process: decrease in material cost

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

Staging

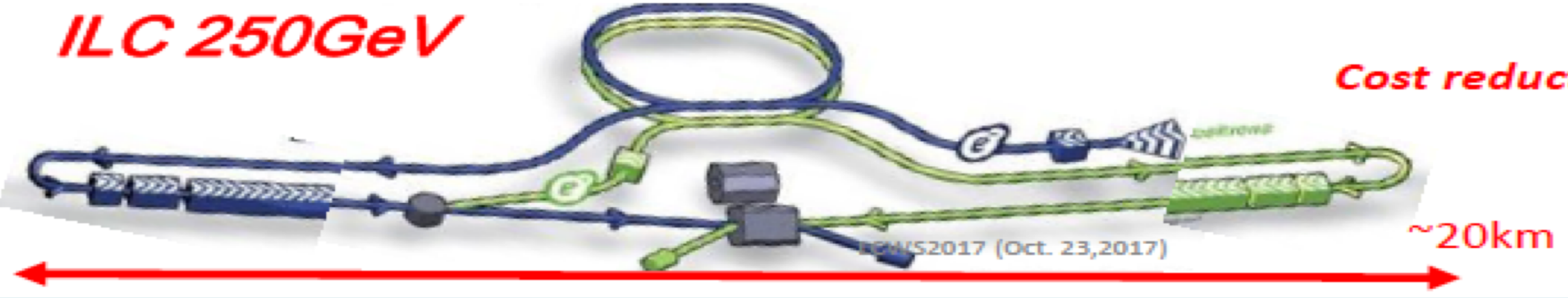
S. Michuzono, LCWS 2018

ILC 500GeV



ILC 250GeV

Cost reduction by compact ILC



ILC cost reduction R&D

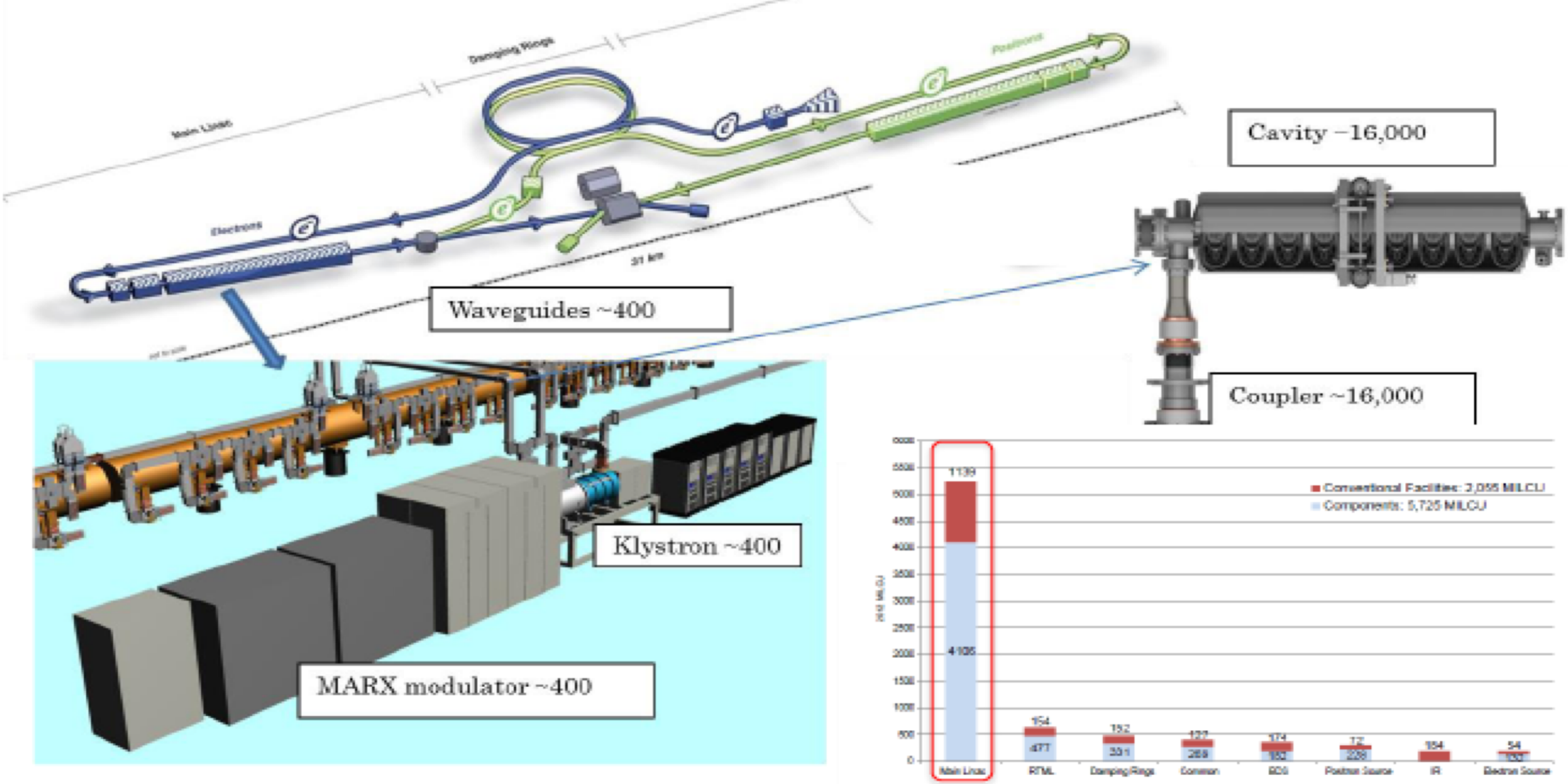


Figure 15.8. Distribution of the ILC value estimate by system and common infrastructure, in ILC Units. The numbers give the TDR estimate for each system in MILCU.

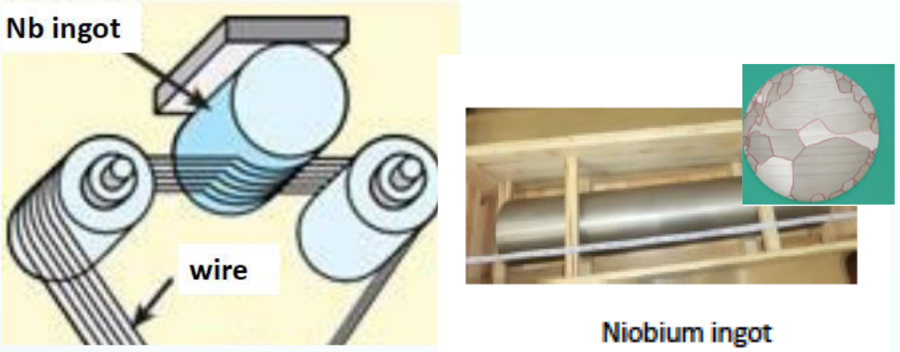
The main fraction of the construction cost is coming from main linac (ML).
Thus we focused our cost reduction R&D into ML (superconducting RF technology)

S. Michuzono, LCWS 2018

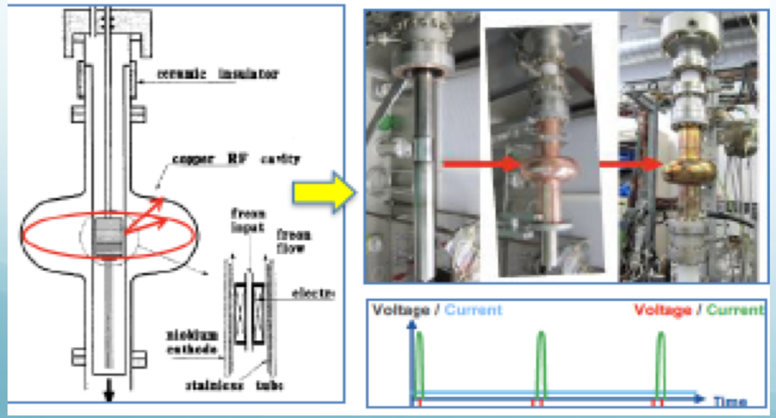
ILC cost reduction R&D: US-Japan cost reduction

- **Niobium material preparation**:

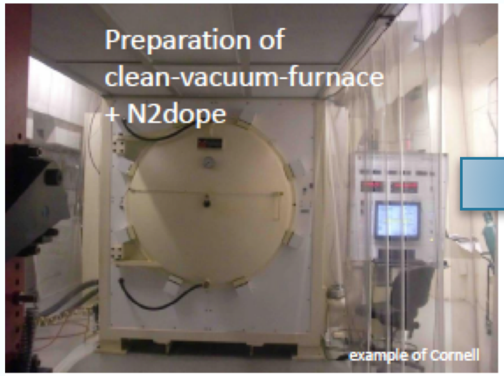
Large grain directly sliced from ingot (cost reduction), **Nb thin-film** coating on Cu based structure (HiPIMS), or Nb_3Sn in Nb or Cu

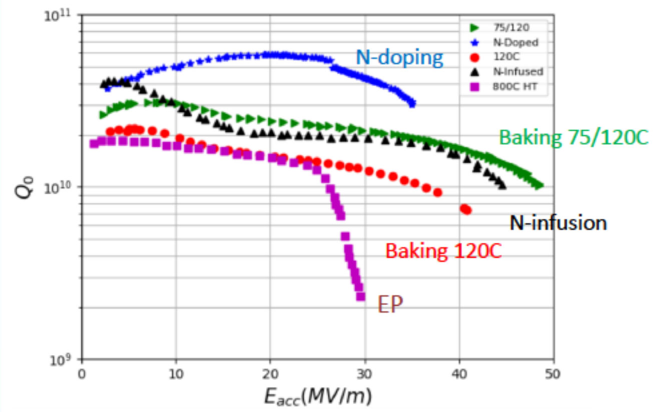


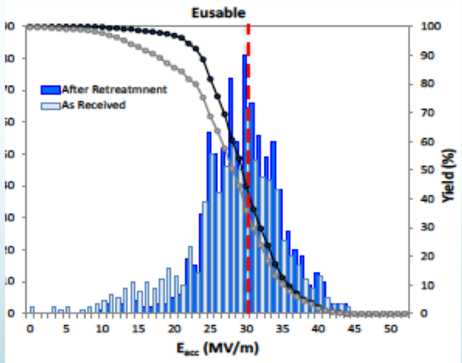
High Power Impulse Magnetron Sputtering (HiPIMS)



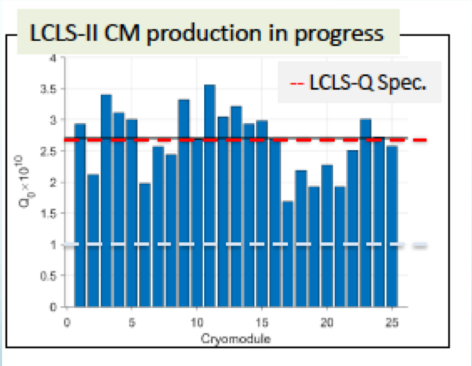
- **SRF cavity fabrication for high-gradient** (N doping well stablished) **and high-Q (**N infusion, low-T baking to be understood)







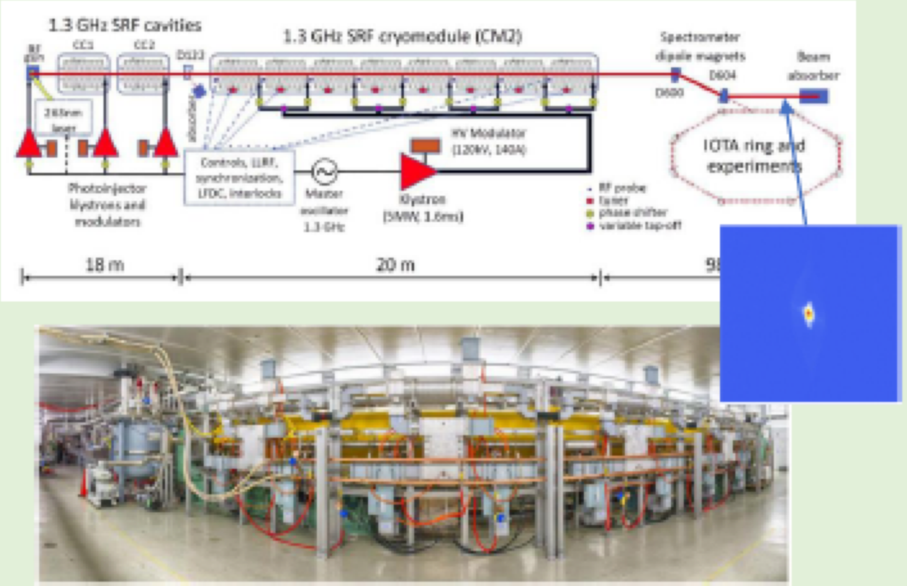
European XFEL: 29 ± 5.1 MV/m



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

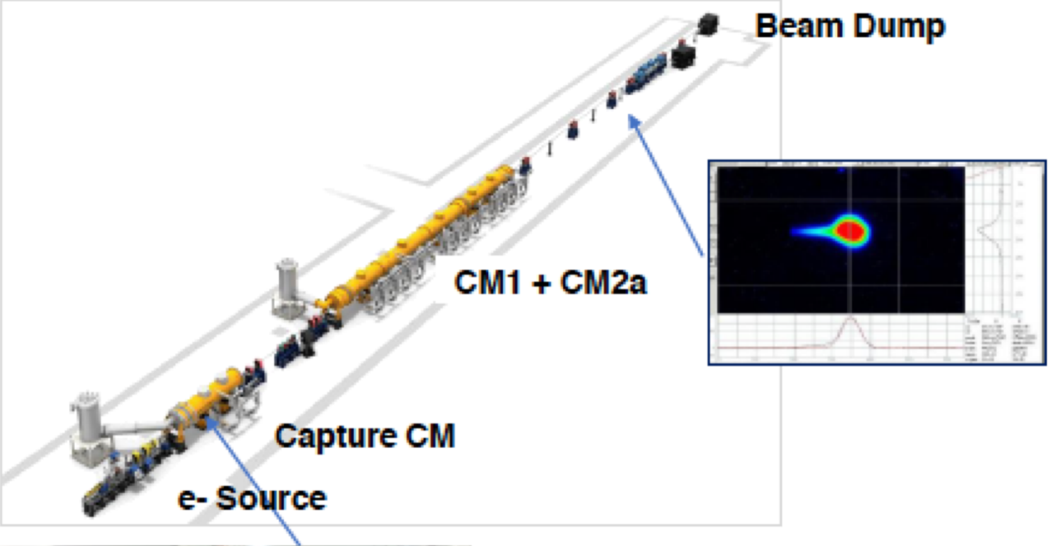
ILC cost reduction R&D: US-Japan cost reduction

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

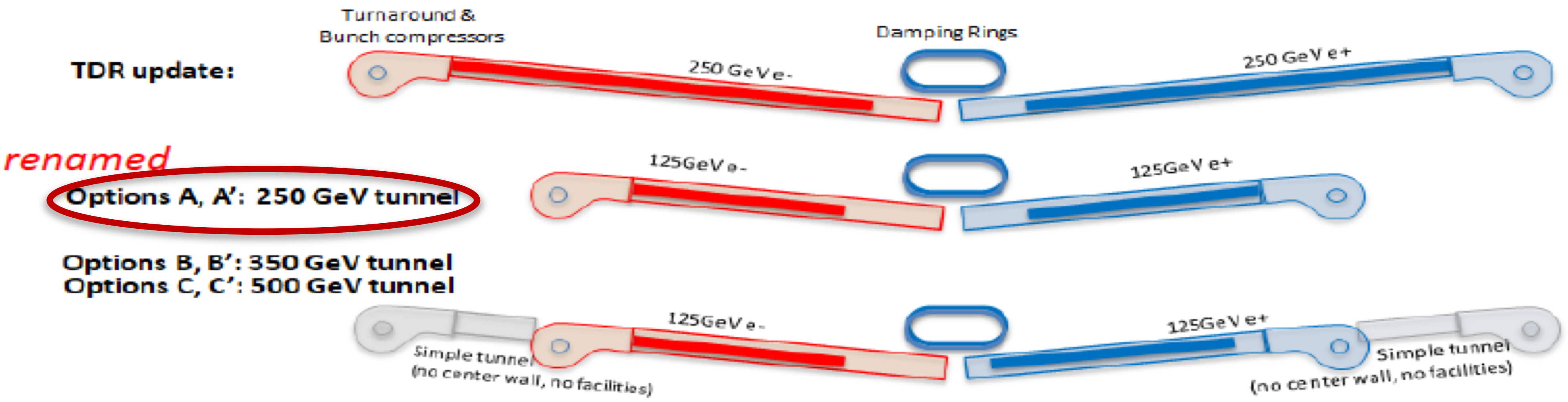


Beam Acc. : 230 MeV by 7 Cavities,
<G> = 32 MV/m

KEK-STF2 Progress, 2019

A. Yamamoto, Granada 2019

Staging: Options for ILC 250GeV



Options	Gradient [MV/m]	E_{CM} [GeV]	Total E_{CM} Margin	n	Space margin	Reserved tunnel	Total tunnel
TDR update	31.5	500	2%	10	1,473 m	0 m	33.5 km
Option A		250	6%	6	583 m	0 m	20.5 km
Option B				6&8		3,238 m	27 km
Option C				6&10		6,477 m	33.5 km
Option A'	35			6	1,049 m	0 m	20.5 km
Option B'				6&8		3,238 m	27 km
Option C'				6&10		6,477 m	33.5 km

S. Michuzono, LCWS 2018

Staging: Options for ILC 250GeV

	TDR-500	Option A (250 GeV)	Option A' (+R&D)
Electricity (Power)	167 /25* MW	129 MW/15* MW	~ 120/12* MW (TBC)
Labor (FTE)	850 FTE	~640 FTE	~640 FTE
Average Fraction	1	0.77	< 0.75

* For cryogenics to be standing-by
Further power for other standing by to be investigated

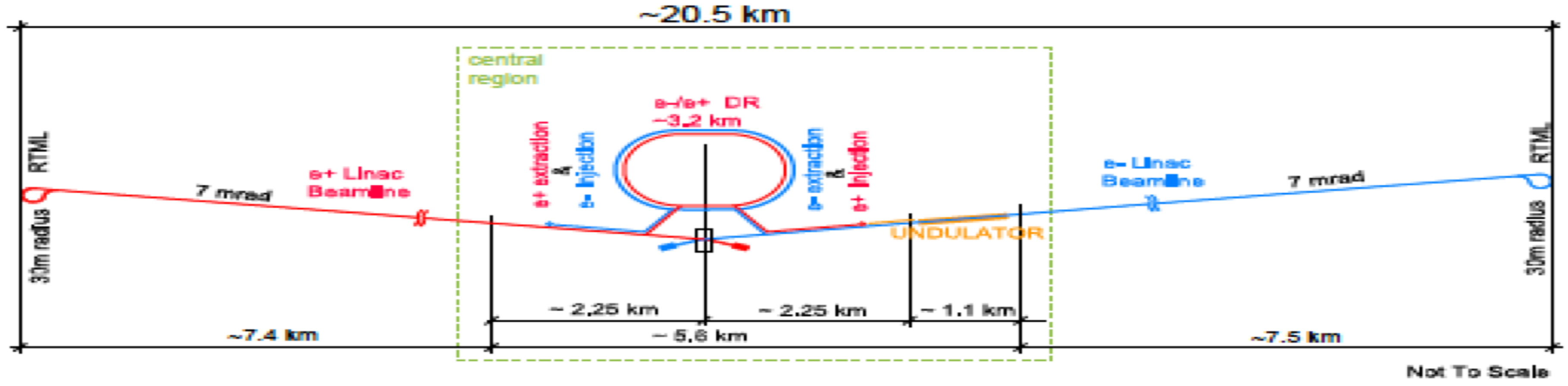
S. Michuzono, LCWS 2018

World wide Labs for RF systems

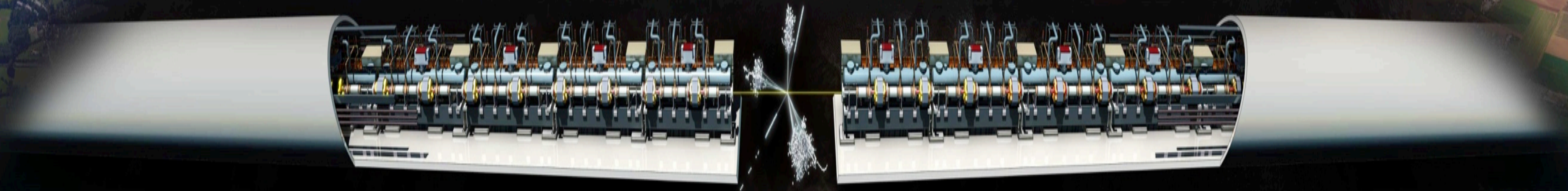
ILC at 250GeV and upgrades

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



CLIC accelerator: status and rebaselining



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

Compact Linear Collider

CLIC Review

Key recommendations

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

- 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**

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

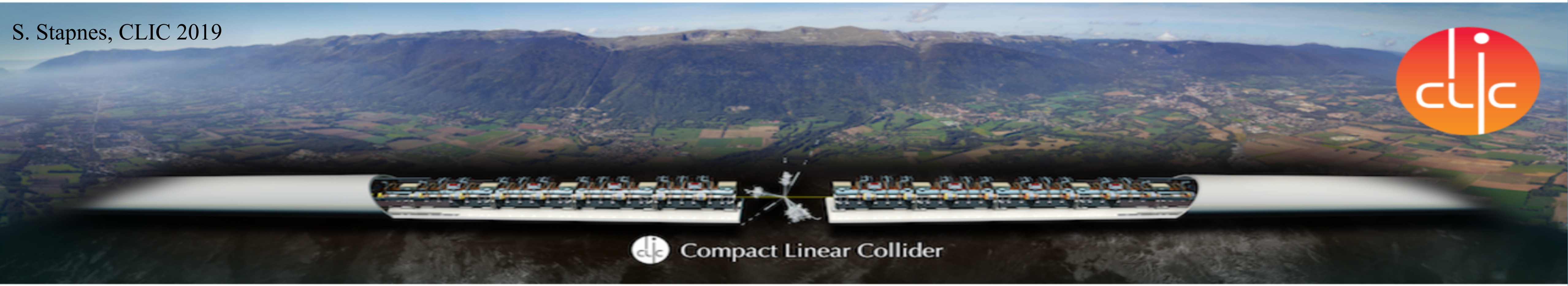
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

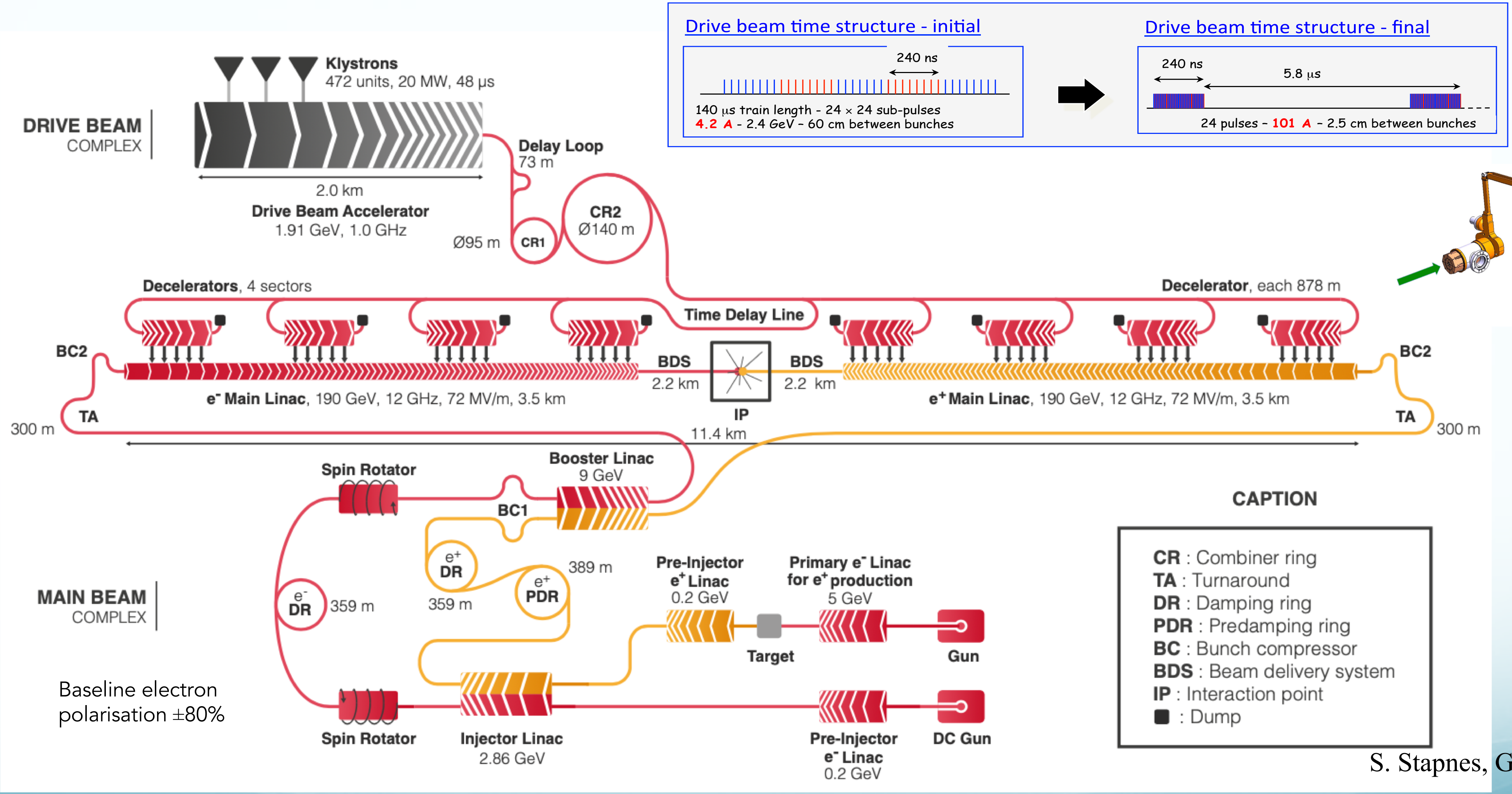
Ready for construction; start of excavations

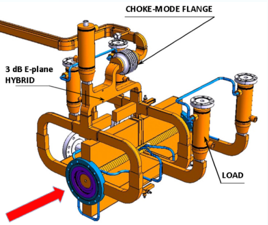
2035 First Beams

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



CLIC rebaseline: 380 GeV and power generation



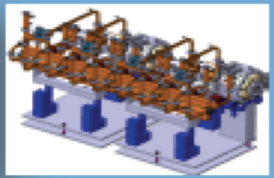
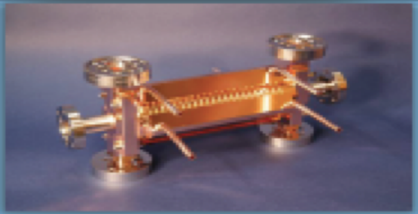
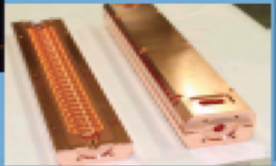
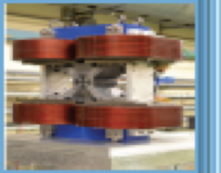


Baseline electron polarisation ±80%

S. Stapnes, Granada 2019

Technical developments

S. Stapnes, CLIC 2019

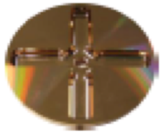
Modules (drive-beam, klystron type)	  	Final modules, from revised designs to industrial modules
Optimized structures	  	Use existing test-stands for testing, increase manufacturability, brazed, halves, conditioning
Klystrons and Modulators	  	Efficiency and costs, significant gains possible for efficiency,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

Technical developments:

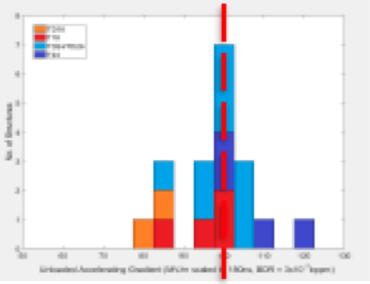
Courtesy: W. Wuensch

Normal Conducting Linac Technology Landscape

Components:

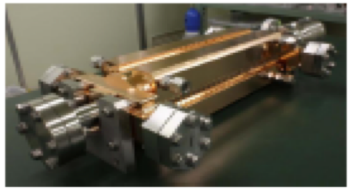


Laboratory with commercial
- Accelerating structures
- pulse compressors
- alignment
- Stabilization, etc.



~ 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

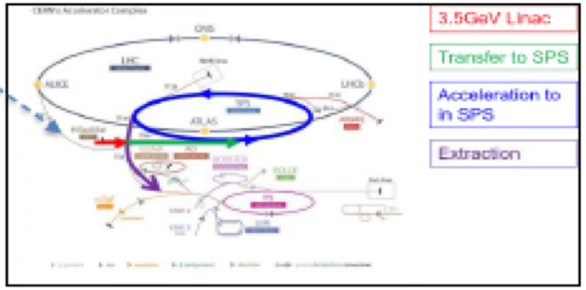
C-band (6 GHz), low-emittance GeV-range facilities

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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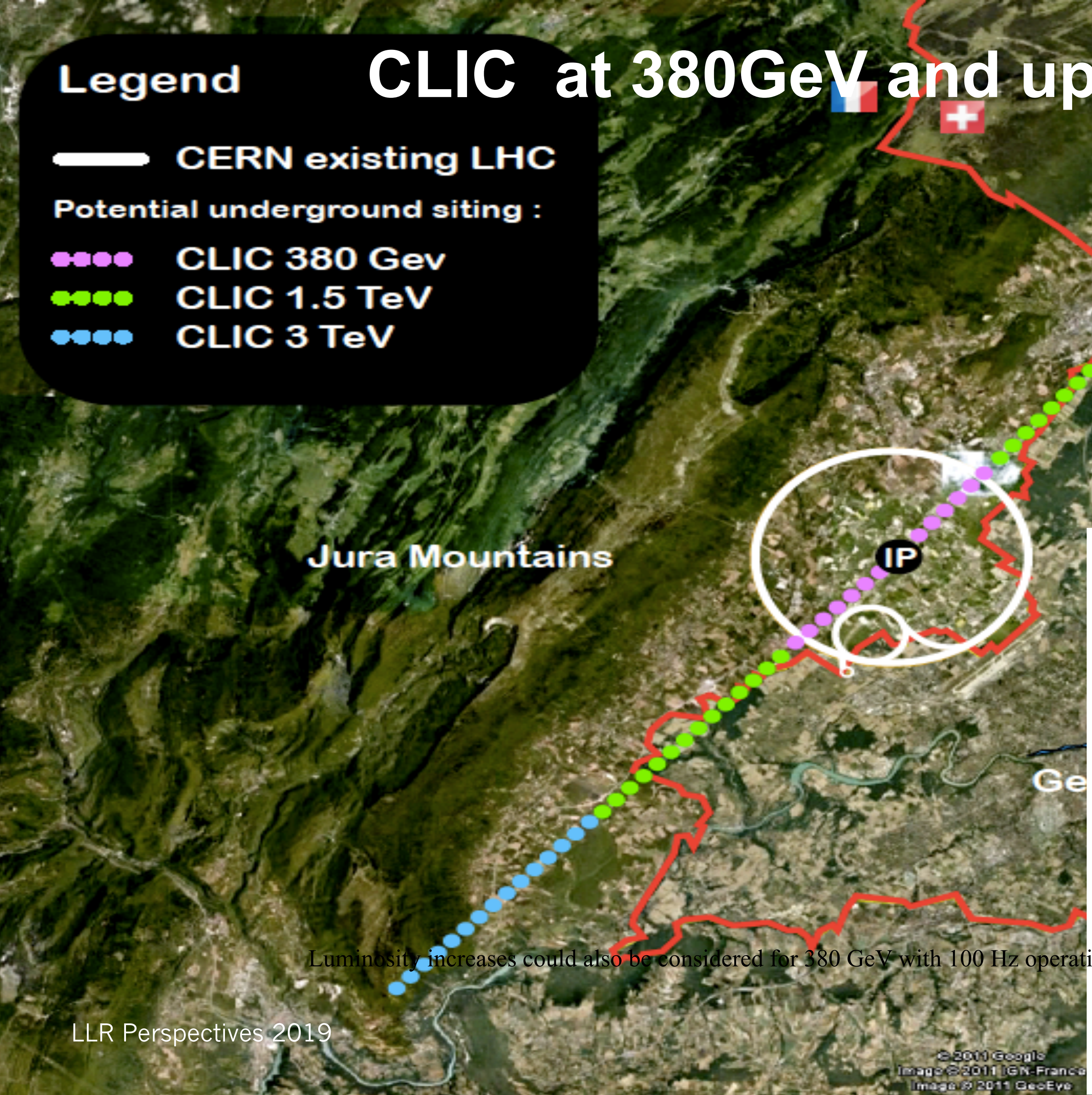
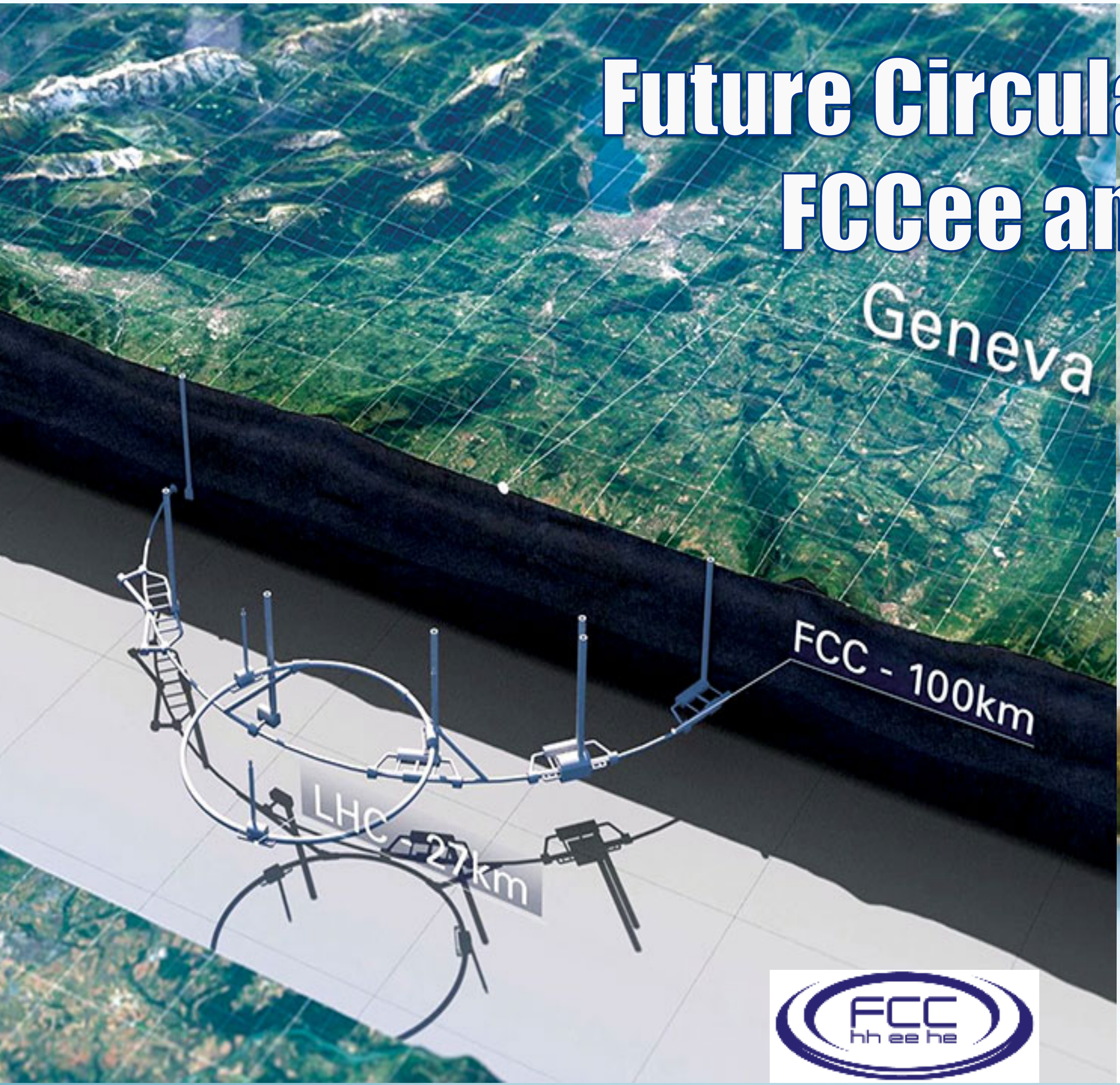
CLIC at 380GeV and upgrades



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	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/
Normalised emittance (end of linac)	ϵ_x/ϵ_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

Future Circular Colliders: FCCee and CepC



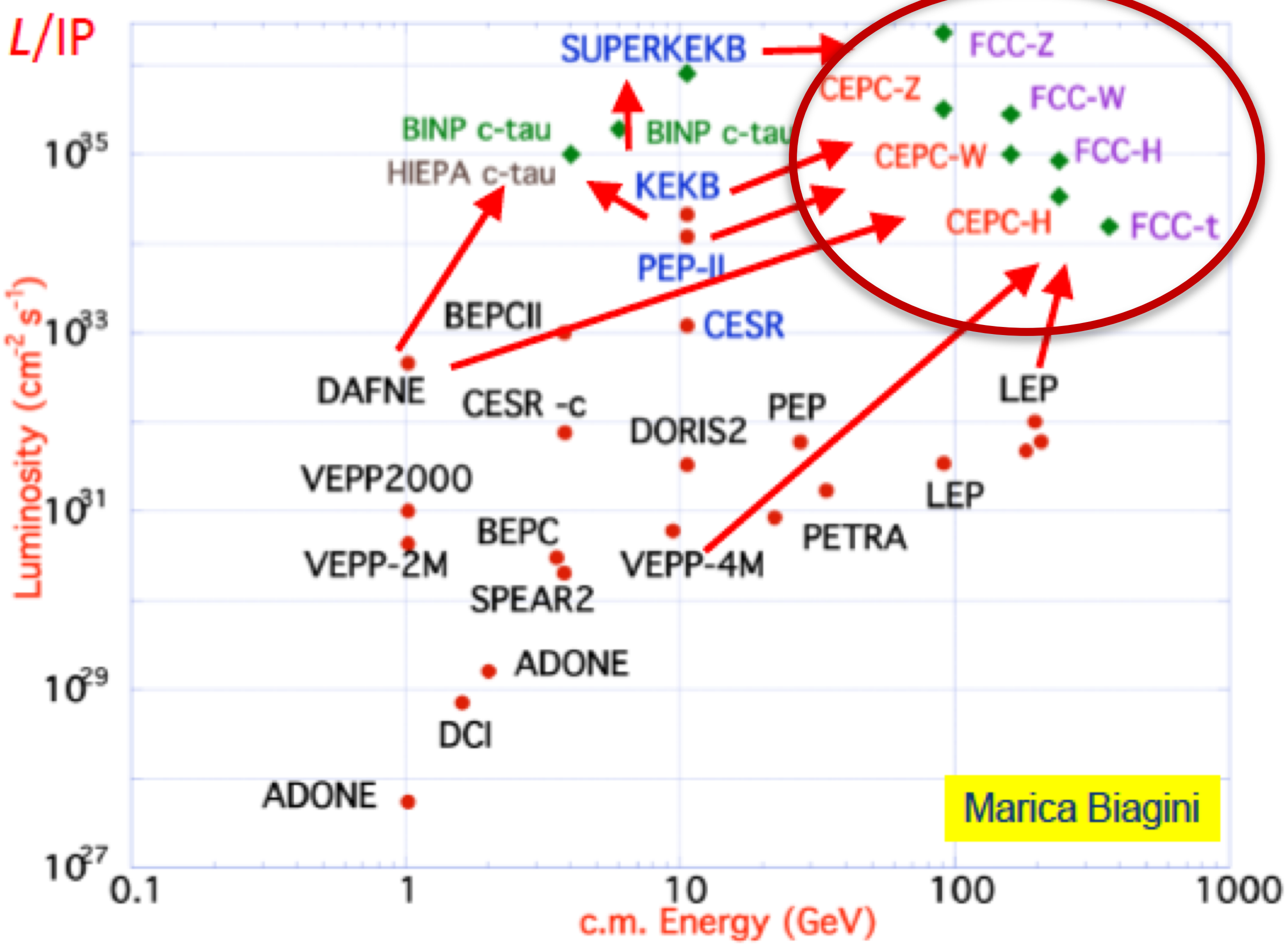
Key parameters for CC e+e-

M. Benedikt, Granada 2019

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

Many similar parameters and strong synergies for design

CC based on proven techniques from past colliders and light sources



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

DAFNE: crab waist, double ring

Super B-factories, S-KEKB: low β_y^*

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: *e*$^+$ source

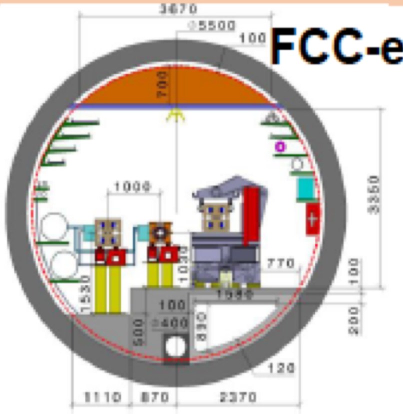
HERA, LEP, RHIC: spin gymnastics

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

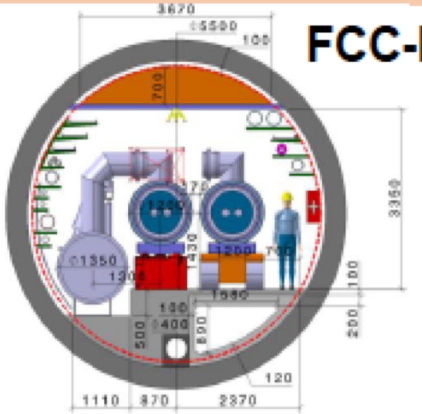
FCCee and CepC: parallel path

double ring e^+e^- colliders as Z, W, H and t factory at $E_{c.o.m.}$ of 90 - 365 GeV; As Higgs factory: design luminosities 17 (6) x 10^{34} $cm^{-2}s^{-1}$ (2 IPs) ; β_y^*= 1.0 (1.5) mm; crab waist collision scheme; beam lifetime >12 minutes; top-up injection, e^+ rate ~ $1x10^{11}$ /s ; CDRs complete

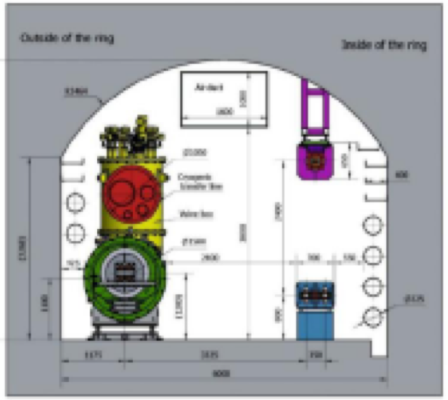
- **FCC-ee and CEPC are part of integrated proposals and each followed by a hadron collider with common footprint.**
- **Circumference** ~100 km
- **Presently 2 IPs,** alternatives with 3 / 4 IPs under study
- **Synchrotron radiation power 50 (30) MW/beam** at all beam energies, cf. LEP2 with 11 MW/beam; SR power/length ~factor 10 below light sources
- **Top-up injection** scheme requires **booster synchrotron in collider tunnel**



FCC-ee



FCC-hh

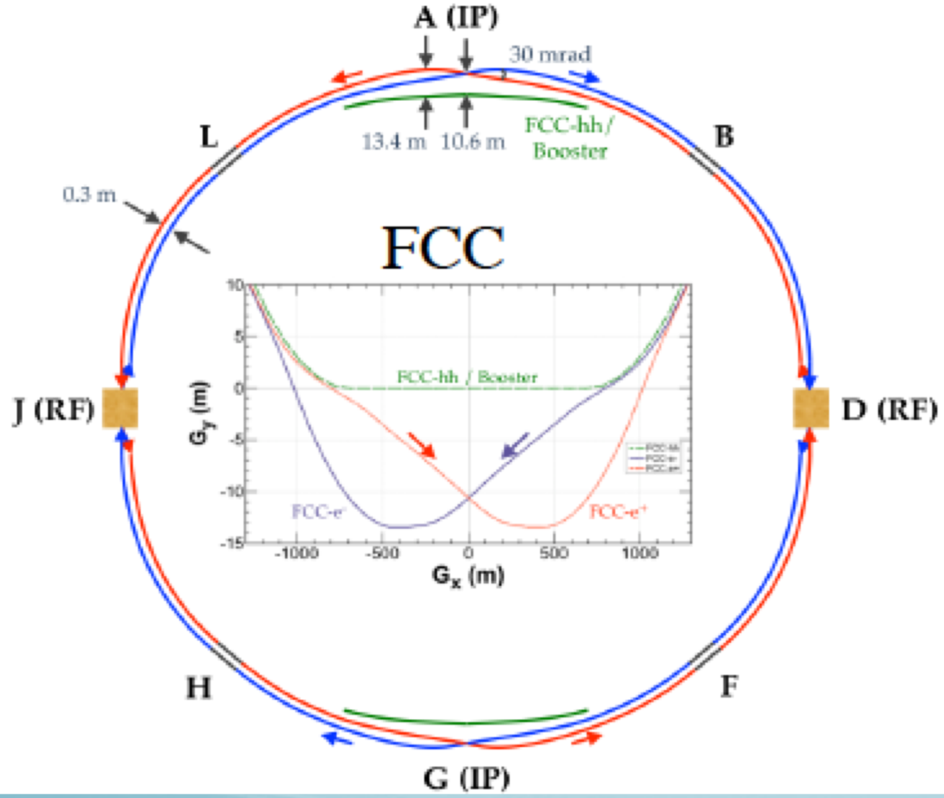


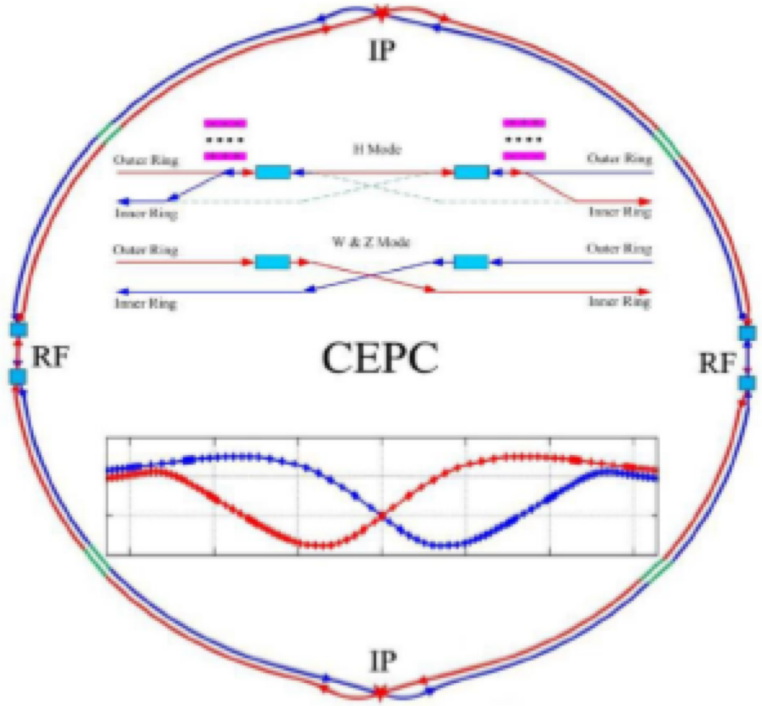
CEPC SppC

values in brackets refer to CEPC

FCCee and CepC: similar design solutions

- **Double ring** colliders with full-energy **top-up booster** ring,
- **CEPC evolved** from initial 54 km - single-ring design, practically **to the FCC-ee 100 km design**.
- **2 IPs, 2 RF straights**, tapering of arc magnet strengths to match local energy
- **Asymmetric IR** layout to limit SR of incoming beams towards detectors and generate large crossing angle
- Common use of RF systems for both beams at highest energy working point (ttbar/ZH for FCC-ee/CEPC)

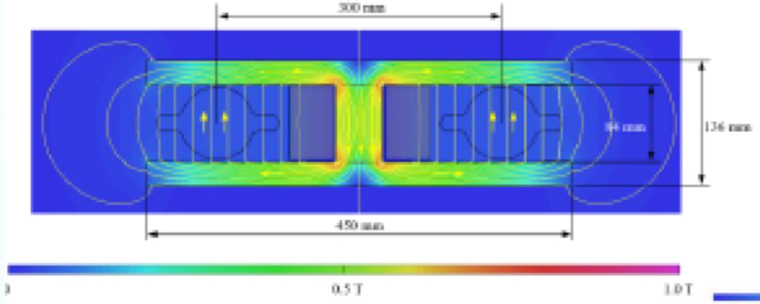


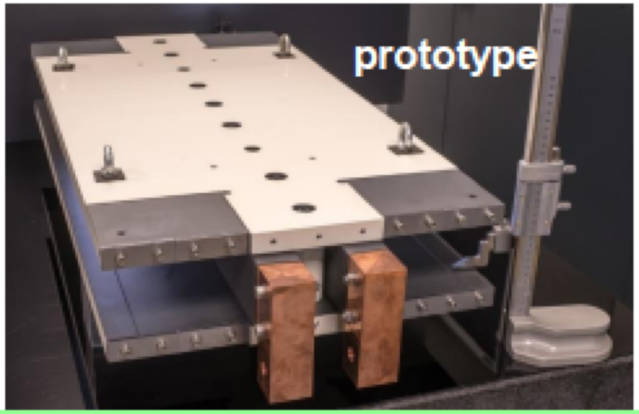


FCCee and CepC: similar low-power magnets

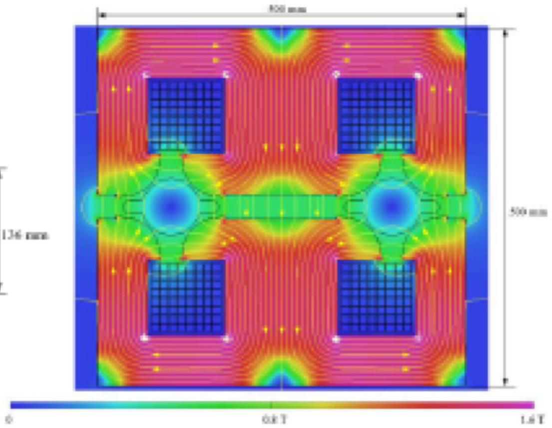
FCC-ee

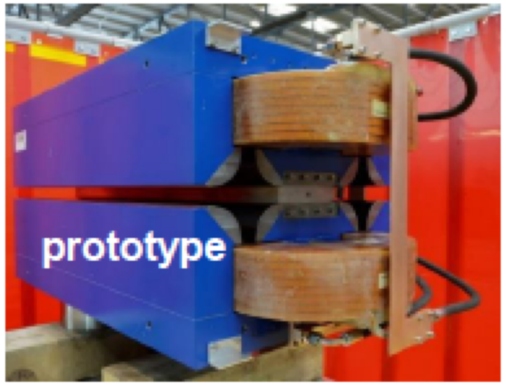
Twin-dipole design with 2× power saving 16 MW at 175 GeV



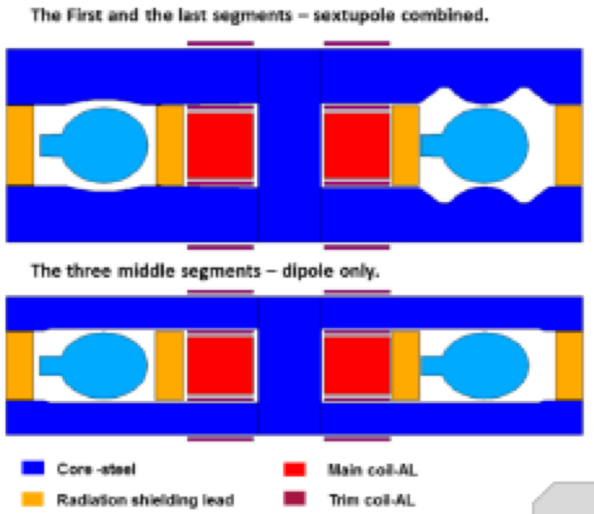


Twin F/D arc quad with 2× power saving 25 MW at 175 GeV



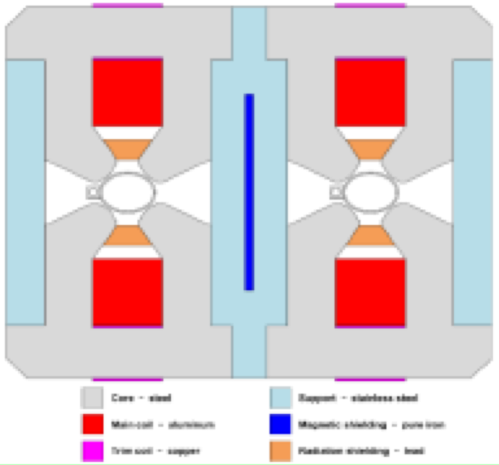


CEPC



Twin arc magnet combined function dipole with sextupole component

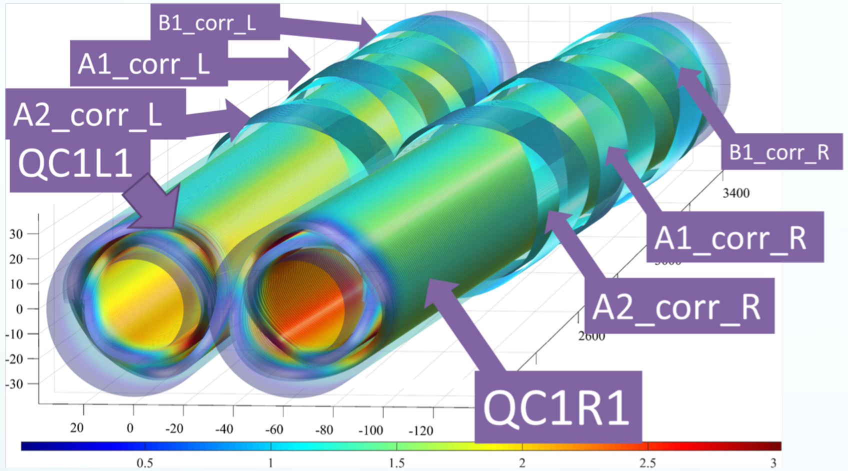
Twin F/D arc quad with 2× power saving



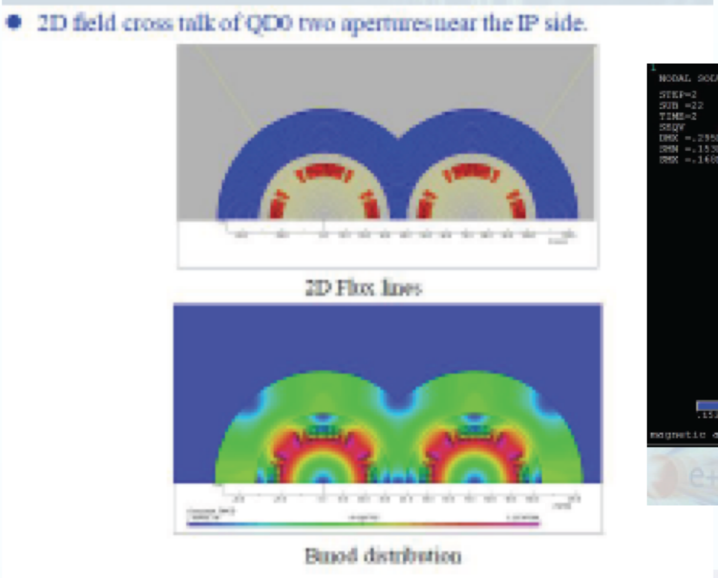
power reduction by factor 2 w.r.t. single-aperture magnets

FCCee and CepC: similar advances in FF-SC magnets

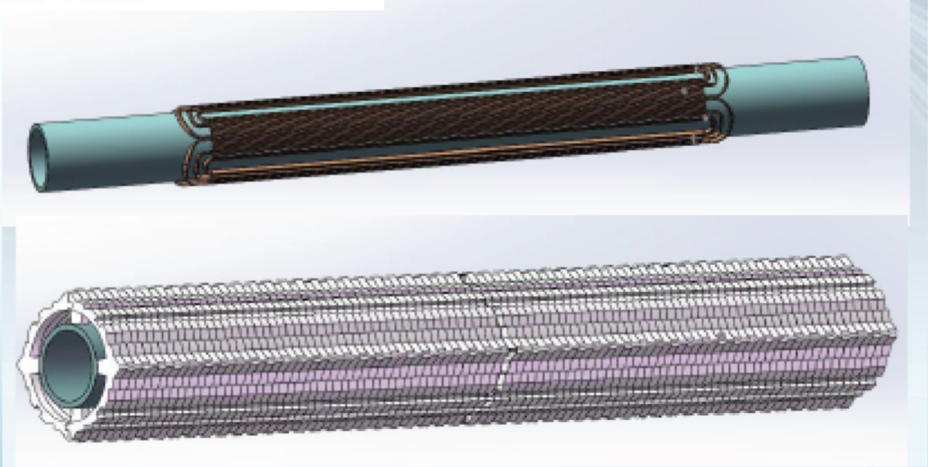
FCCee



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



SC QD coils



CepC

FCCee and CepC: RF systems

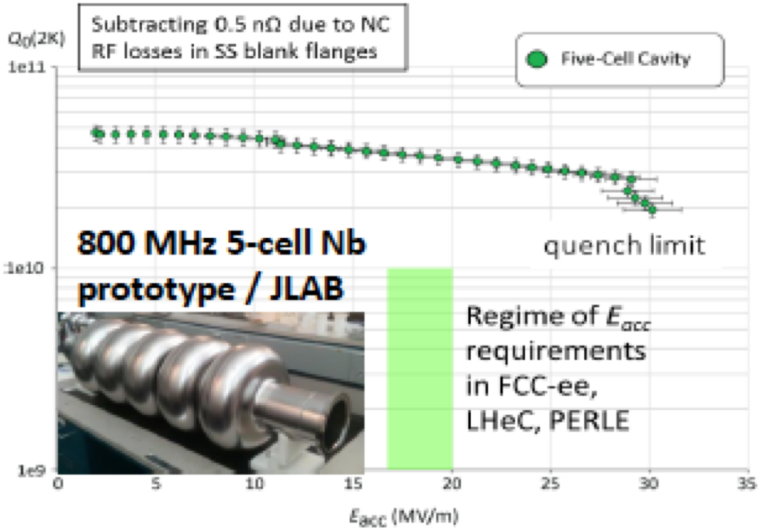
	f_{RF} [MHz]	#cavities	#cell/cavity	$V_{RF,tot}$ [MV]	acc. gradient [MV/m]	technology
SuperKEKB	509	30 (ARES) 8 (SCC)	1 1	15 12	2 6	warm Cu bulk Nb
charm-tau	500	1 / ring	1	2x1	6	bulk Nb
FCC-ee-H	400	136 / ring	4	2000	10	Nb/Cu
FCC-ee-t (addt'l)	800	372	5	6930	19.8	bulk Nb
CEPC	650	240	2	2200	19.7	bulk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

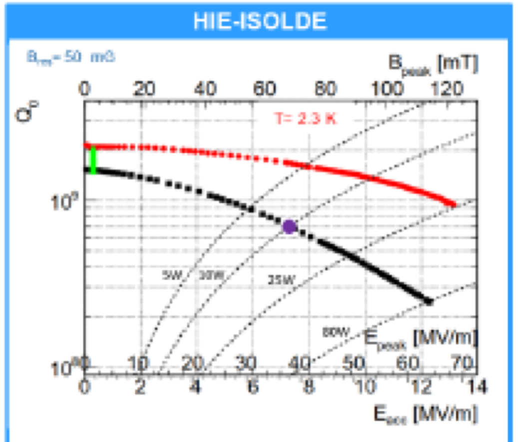
- all systems between 400 and 800 MHz, various technologies,
- preference for SC cavities,
- FCC-ee RF system optimized for each working point, CEPC features single system

FCCee : RF R&D activities

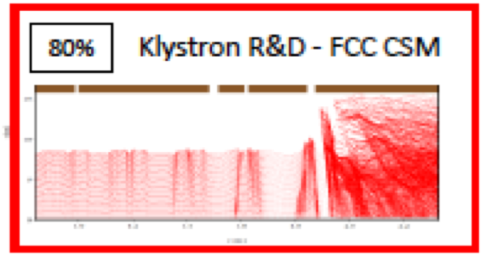
Several R&D lines aim at improving performance and efficiency and reducing cost:

- Improved Nb/Cu coating/sputtering (e.g. ECR fibre growth, HiPIMS)
- New cavity fabrication techniques (e.g. EHF, improved polishing, seamless…)
- Coating of A15 superconductors (e.g. Nb_3Sn)
- Bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP
- High efficiency klystrons (e.g. COM, BAC, CSM) – synergy with HL-LHC and CLIC
- MW-class fundamental power couplers for 400 MHz





Highest field ever reached by a Nb/Cu cavity

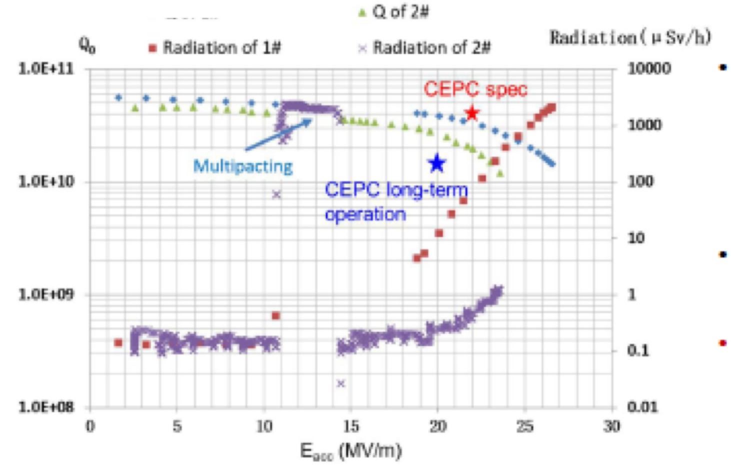


CepC: RF R&D activities

- 650 MHz 2-cell cavity (BCP without N doping) reached 3.2 10^{10} at 22 MV/m
- N doping and Electro Polishing (EP) on 650 MHz cavity under investigation
- EP under commissioning
- High-Efficiency 650 MHz Klystron development
- First 650MHz manufacturer and Infrastructure preparation in progress

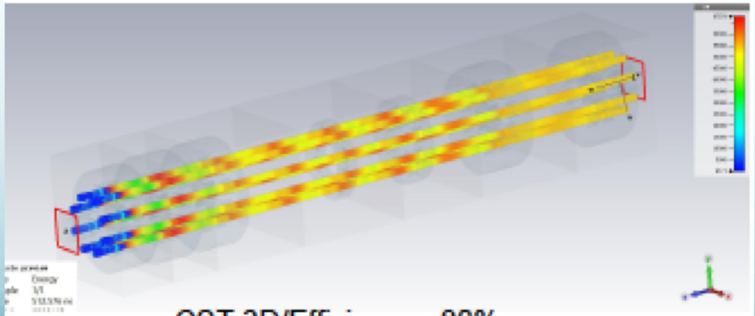

CEPC 650 MHz 2-cell cavity by HERT


Klystron output window

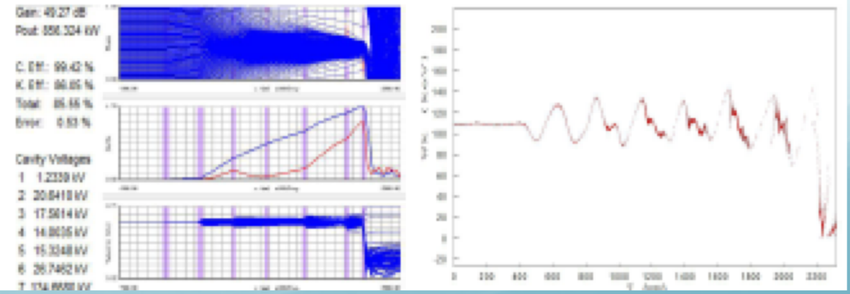



Cavities components

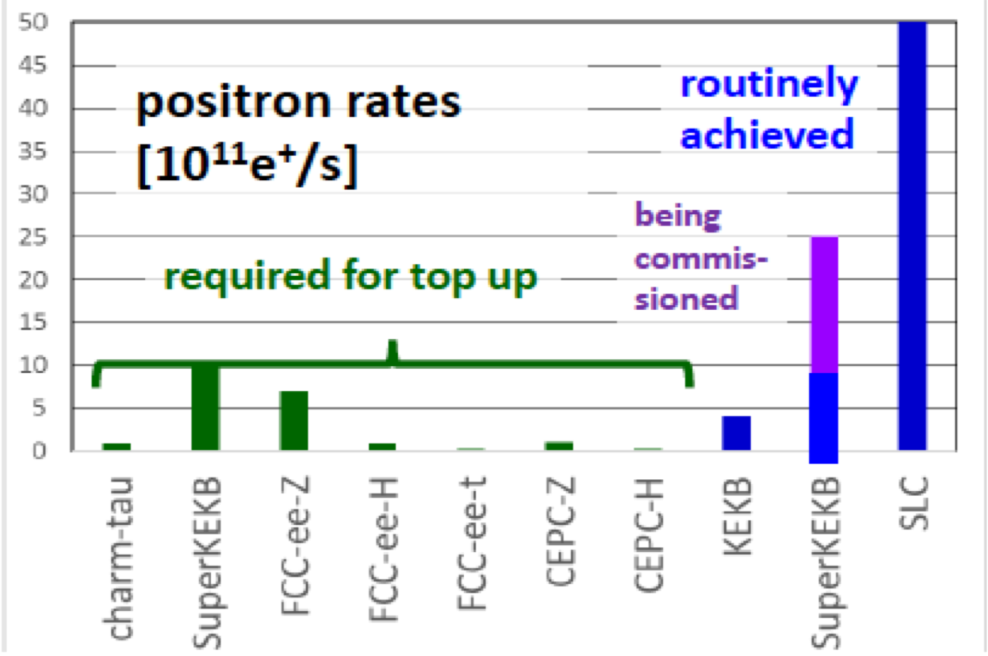
Multi-beam klystron@8 beams

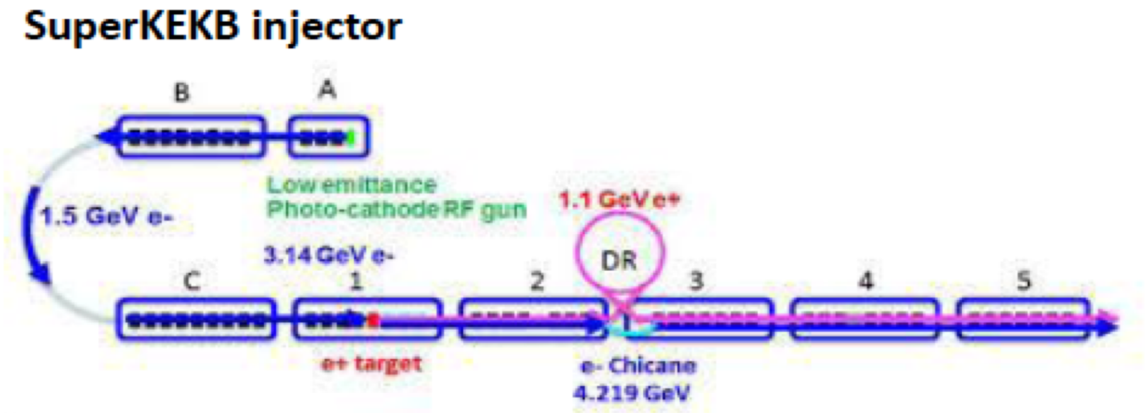

CST-3D/Efficiency ~80%

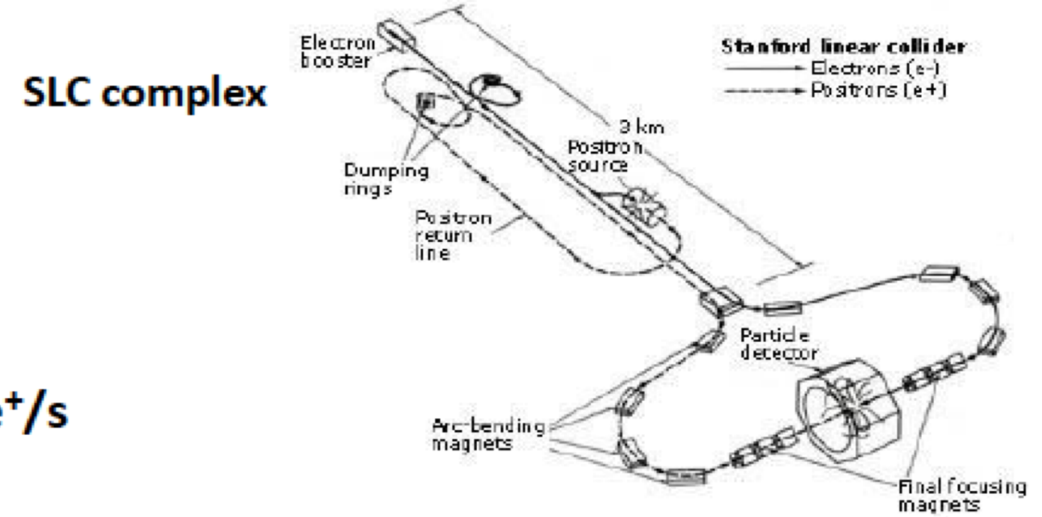
Single beam klystron@110kV/9.1A



FCCee and CepC: R&D on positron production







Routinely achieved positron rates:

SLC, 1 bunch/pulse, 65 nC , 120 Hz, **5×10^{12} e⁺/s**

KEKB, 2 bunches/pulse 2x0.6 nC, 50 Hz, **4×10^{11} e⁺/s**

Under commissioning:

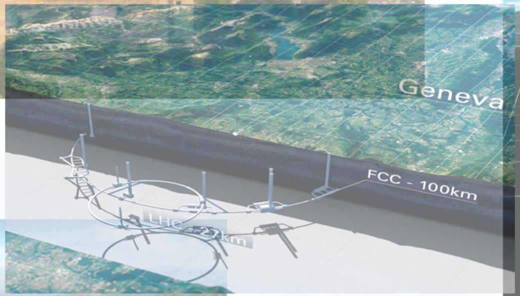
SuperKEKB, 2 bunches/pulse 2x4 nC, 50 Hz, **2.5×10^{12} e⁺/s,** ~1.0×10^{12} e⁺/s already achieved

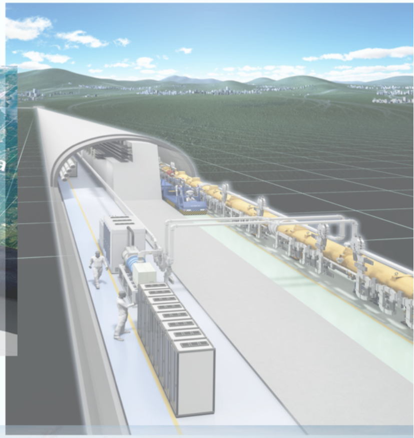
Increasing the efficiency of the production is under investigation

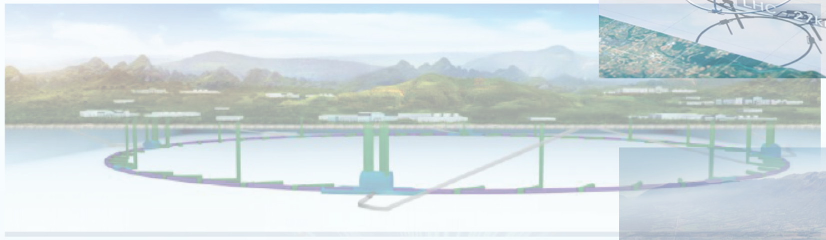
Outline

- Summaries from EPPSU Granada

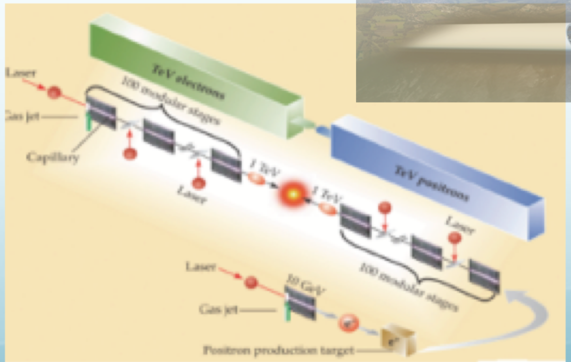
- Focusing in “real” e^+e^- colliders
  - LC projects: ILC, CLIC
  - CC projects: FCC-ee, CepC







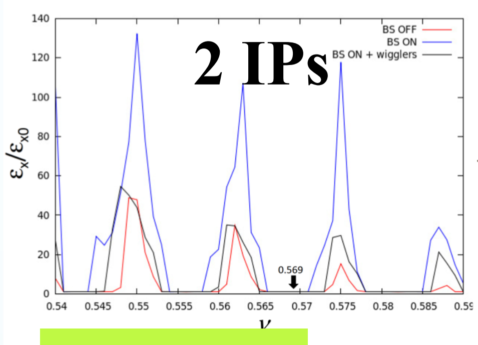
- Some “dreamt” e^+e^- colliders
  - Boosting the performances
  - Advanced Linear Colliders e^+e^-

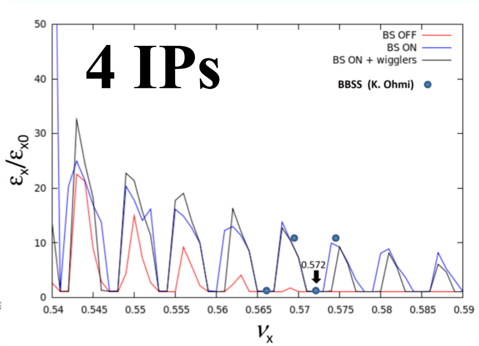


Boosting the performances

- ➢ **FCCee with increased interactions points**

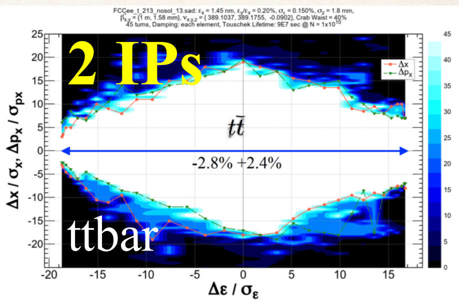
ε_x blow up due to coherent instability vs Q_x

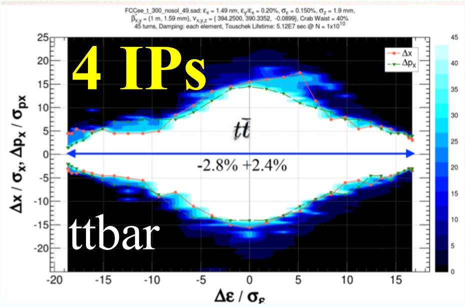




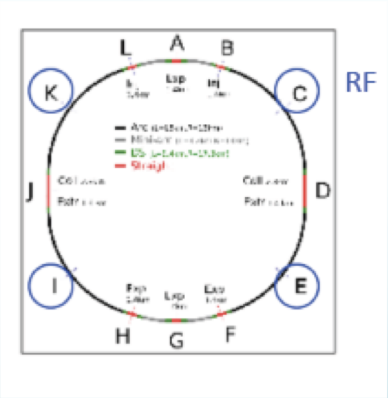
D. Shatilov

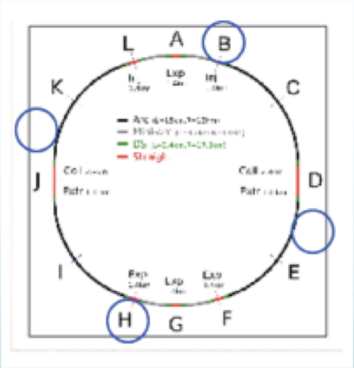
off-mom. dynamic aperture

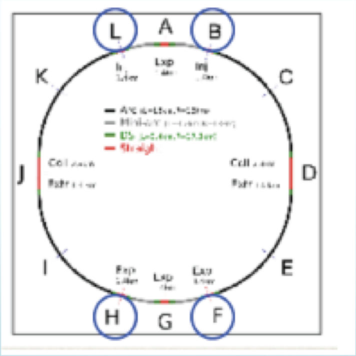




K. Oide







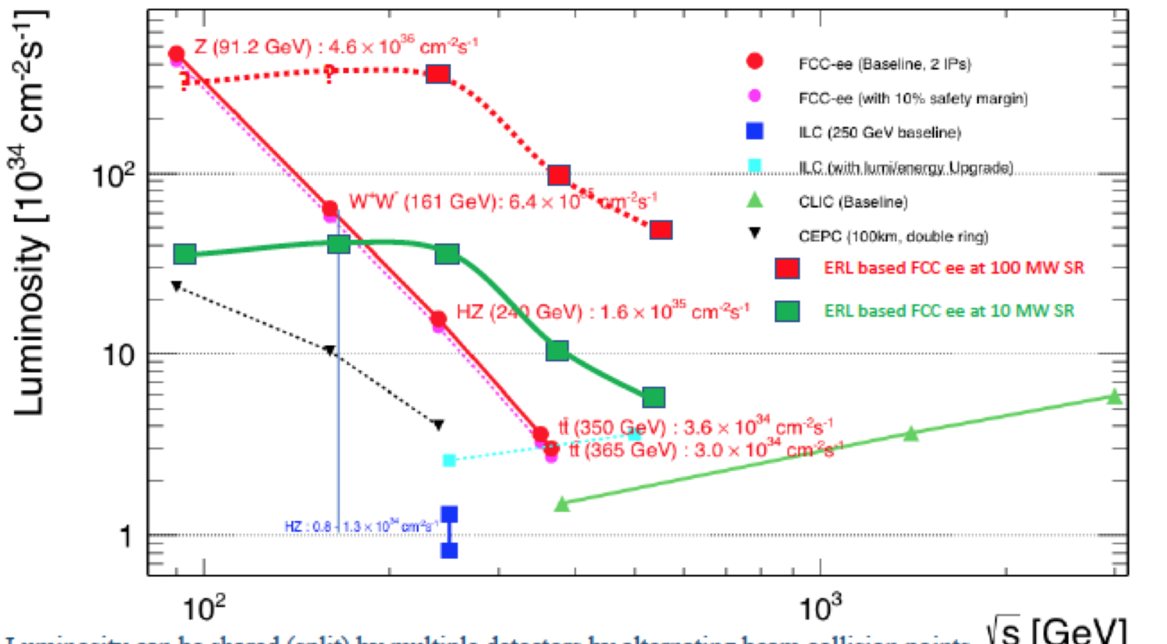
4 IP will have a huge impact on the layout, FCC-hh design, many components such as RF, injection, beam abort, polarimeter, etc.

Boosting the performances

- ERL based FCC-ee upgrade for higher luminosity & energy

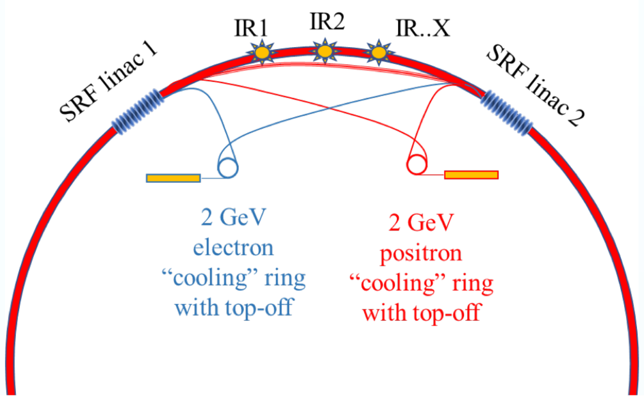
V. Litvinenko,
T. Roser
M. Chamizo

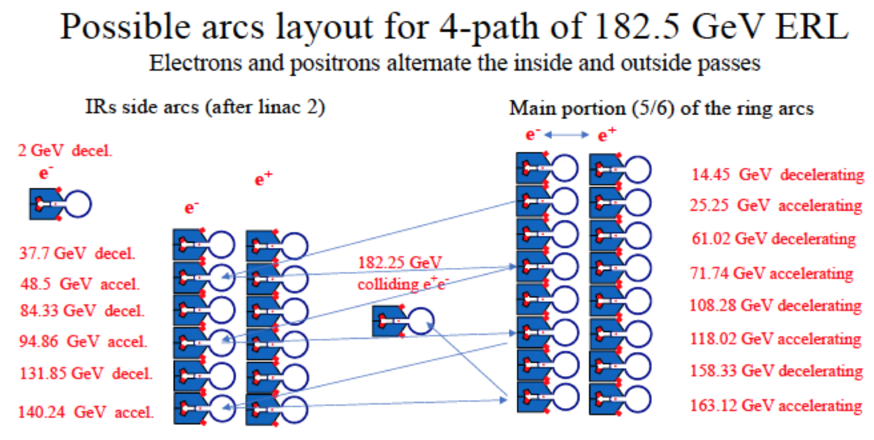
Luminosity scales linear with SR power – would see other limitations – but 100 MW SR power is not what we are proposing.



Luminosity can be shared (split) by multiple detectors by alternating beam collision points.
Potential of increasing total luminosity requires detailed simulations

FCCee

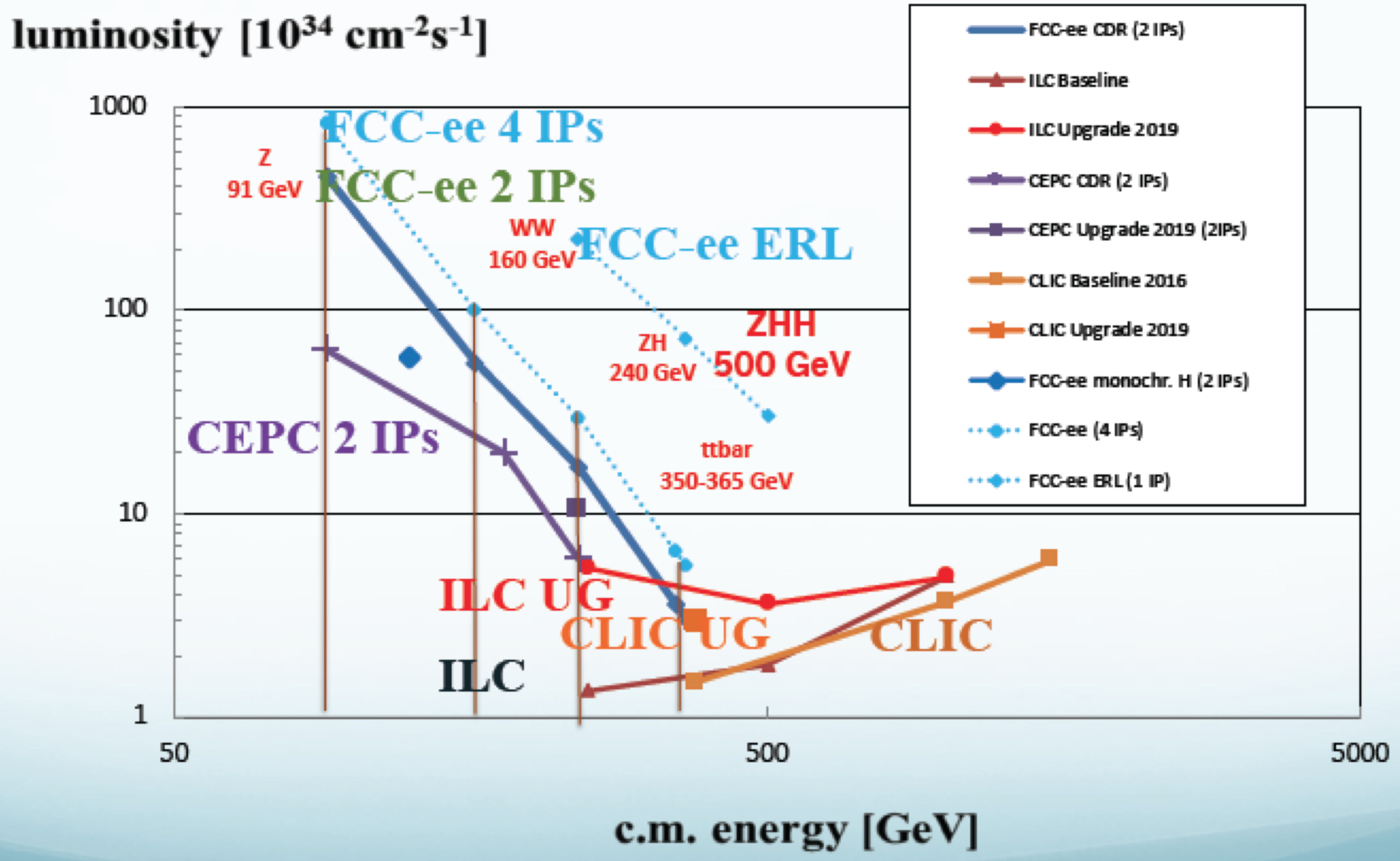




arXiv:1909.04437 (cross-list from physics.acc-ph) [pdf] Future High Energy Circular e+e- Collider using Energy-Recovery Linacs Vladimir N Litvinenko, Thomas Roser, Maria Chamizo Llatas

Boosted Luminosity

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

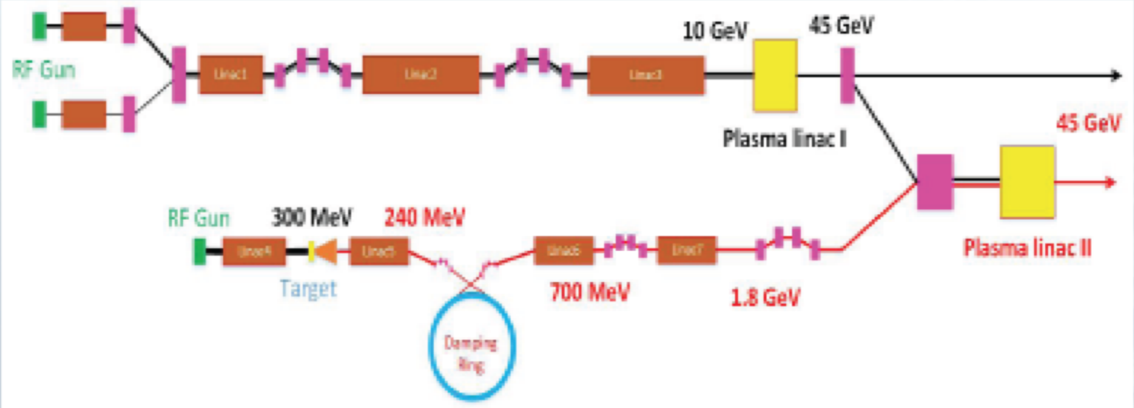


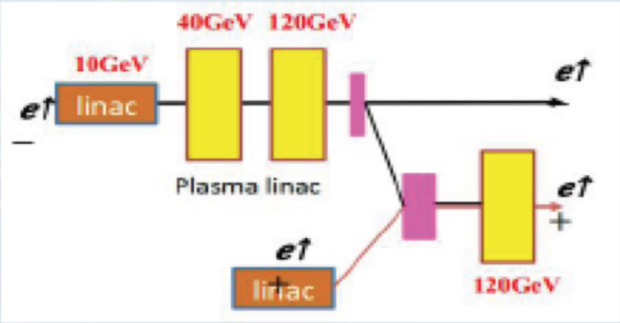
Boosting the performances

- **CEPC Injector Alternative:** Plasma Accelerator up to 45GeV single stage)~120GeV (cascade)

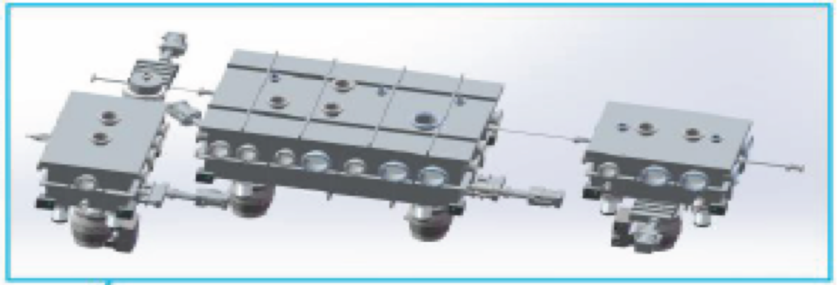
W. Lu

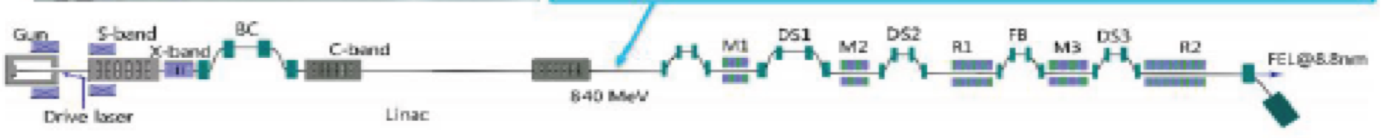
A dedicated budget of 8Million has been alocated by IHEP





Electron (SXFEL-TF)	
Energy	840MeV
Energy spread(rms)	≤0.1%
Norm. Emittance(rms)	≤1.5mmmrad
Length(FWHM)	≤1ps
Charge	0.5nC
Repetition rate	10Hz





- **Electron plasma acceleration will be tested in Shanghai's Soft XFEL Facility**
- **Positron plasma acceleration scheme will be tested at FACET-II at SLAC**

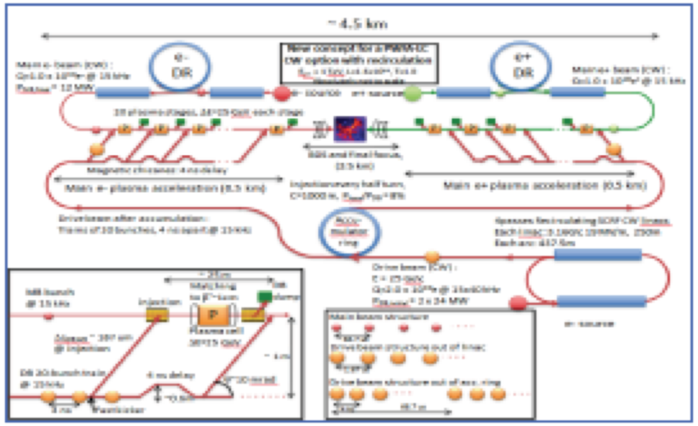
Advance Linear Collider e^+e^-: HEP Energies in PWA

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

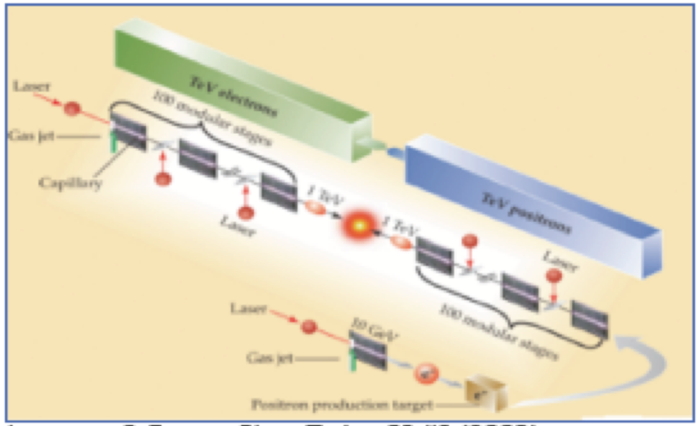
Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

- **Electron/laser driven PWA:** need several stages
  - effective gradient reduced because of long sections between accelerating elements….



E. Adli et. al.,arXiv:1308.1145 (2013)



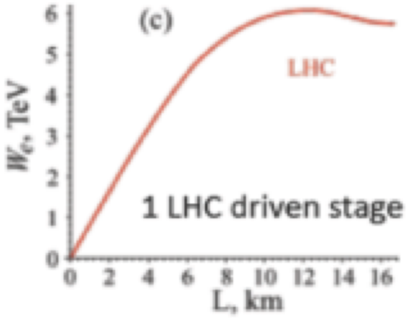
Leemans & Esarey, Phys. Today 63 #3 (2009)

➔ Challenges: staging, matching, tolerances, driver technologies, efficiencies

- **Proton driven PWA:** large energy content in proton bunches ➔ allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

➔ Challenges: long plasma sources , efficiency

Dephasing:
SPS: ~70 m
LHC: ~few km
FCC: ~ ∞



A. Caldwell and K. V. Lotov, Phys. Plasmas 18, 103101 (2011)

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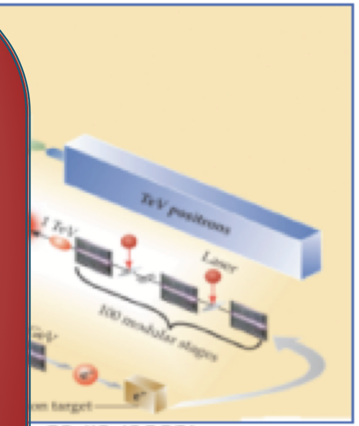


63 #3 (2009)

- **Electron/la**
  - effecti
    betwe

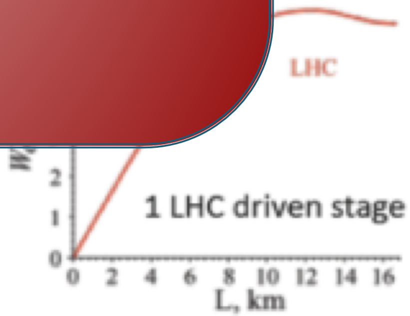
➔ Challe

Achieved Individually
And
Not simultaneously

- **Proton driv**
  - A single

➔ Challenges: long plasma sources , efficiency

SPS: ~70 m
LHC: ~few km
FCC: ~ ∞



A. Caldwell and K. V. Lotov, Phys. Plasmas 18, 103101 (2011)

Advanced Linear Colliders e^+e^-: HEP Energies in PWA

ALEGRO proposal aims at design of plasma collider -- the Advanced Linear International Collider (ALIC).

ALEGRO

Advanced LinEar collider study GROup

- Construct dedicated facilities **over the next five to ten years** that can reliably deliver high-quality, multi-GeV electron beams from a small number of stages.

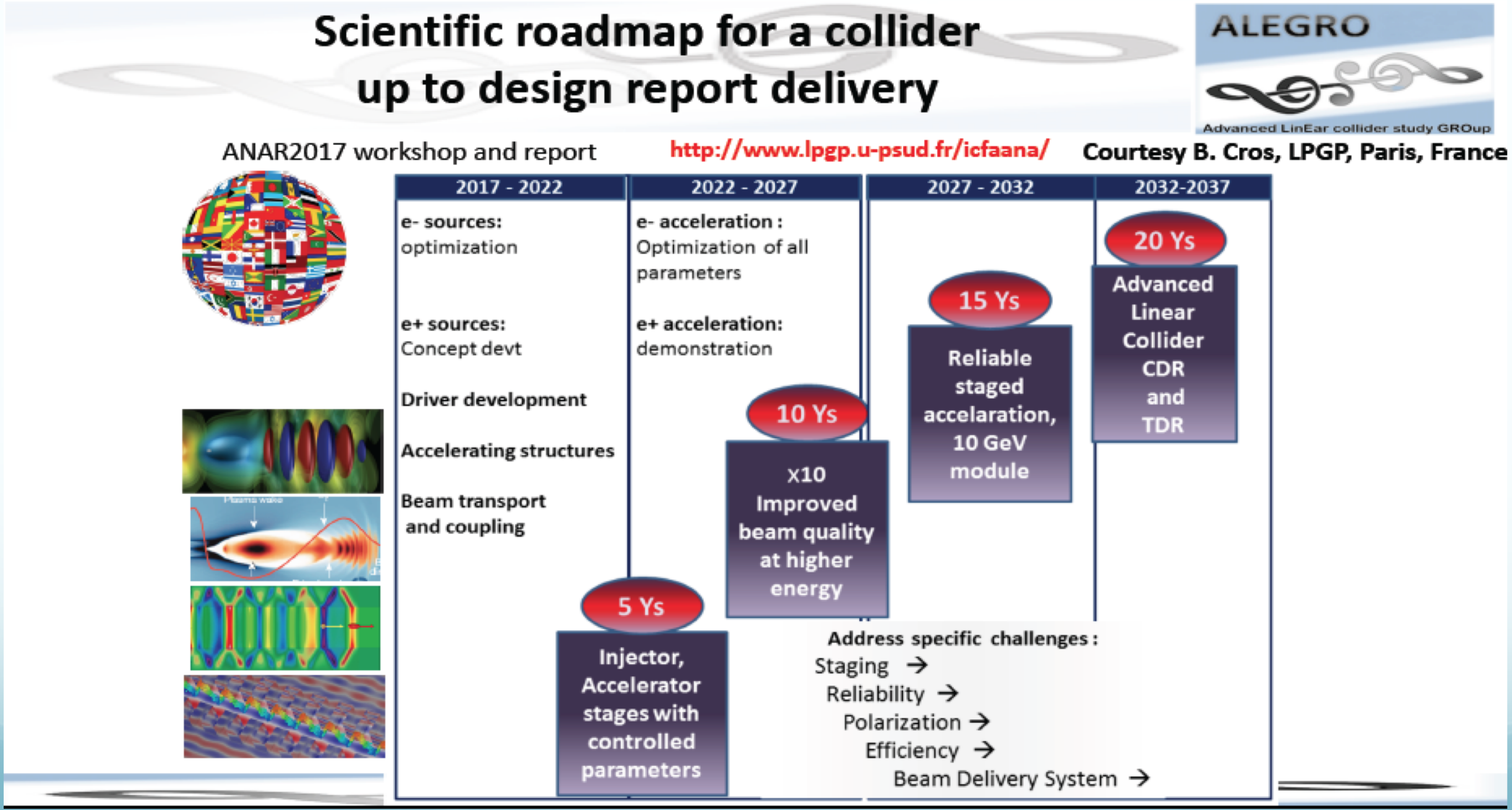
Key topics: front end of ALIC, consisting of an injector plus accelerator module:

- External injection
- Bunch quality, efficiency, stability and reproducibility
- Plasma sources
- Operation at high repetition rate
- High-quality electron (e^-) and positron (e^+) bunches
- Independently shaped drive- and main-beam
- Multi-stage challenges with high-energy beams

Courtesy B. Cros, LPGP, Paris, France

We need a European study for a plasma based collider with start-to-end simulations

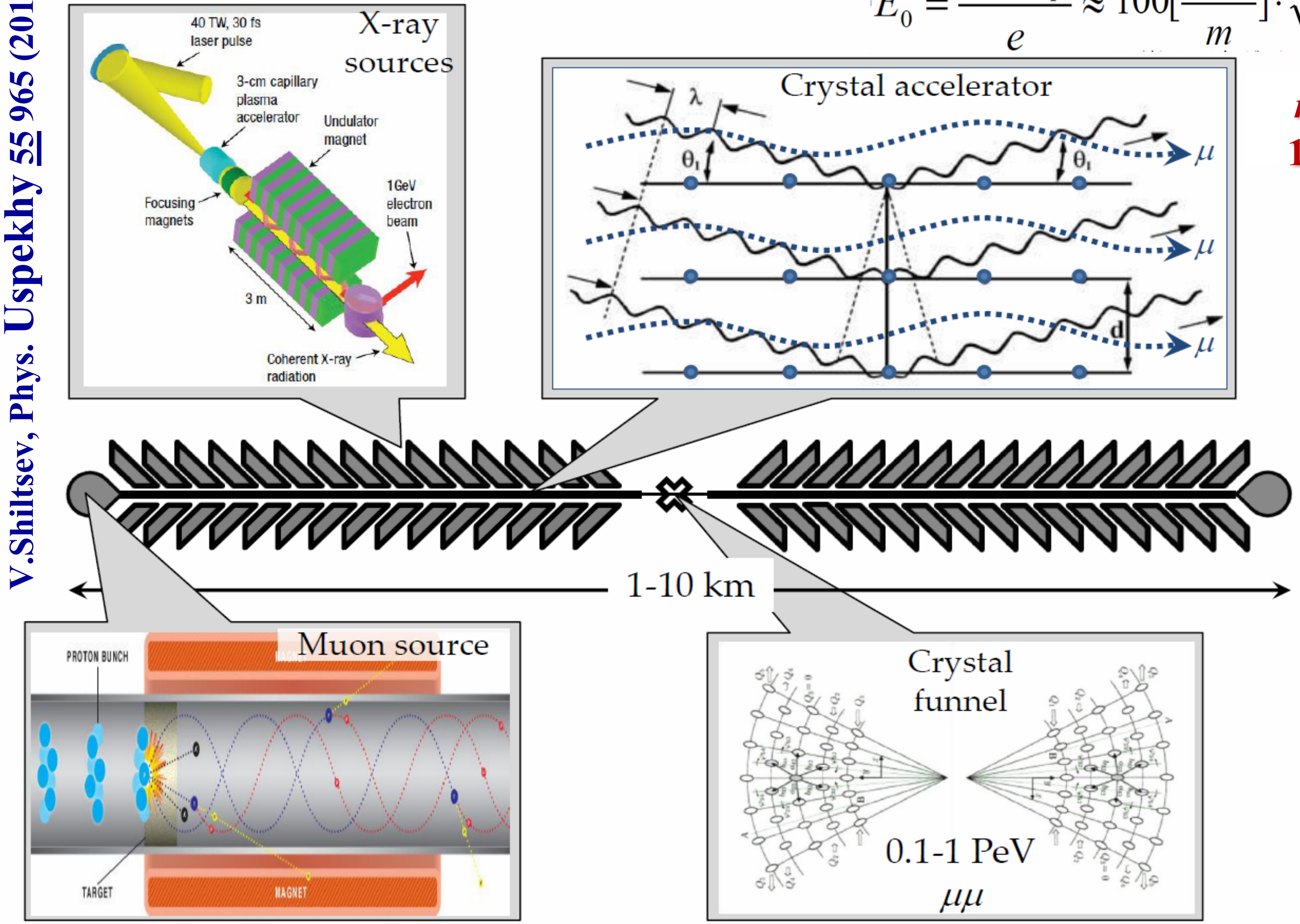
Advance Linear Collider e^+e^-: HEP Energies in PWA



"Dream" Collider = Muons + Acceleration in Crystals + Continuous Focusing (Channeling)

V.Shiltsev, Phys. Uspekhy 55 965 (2012)

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$



***n*~10^{22} cm^{-3}, 10 TeV/m →**

1 PeV =

1000 TeV

n_μ ~1000

n_B ~100

f_{rep} ~10^6

L ~$10^{30\text{-}32}$

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" :**

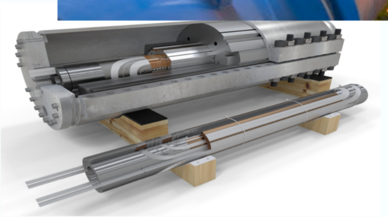
- Green - TDR
- Yellow - CDR
- Red - R&D

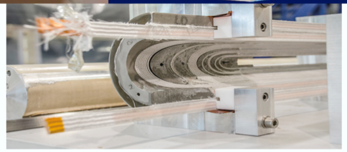
***F2* "Energy Efficiency"**

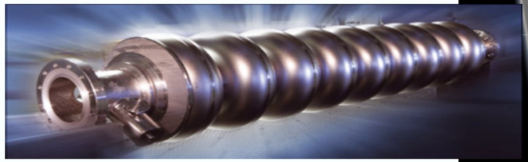
- Green : 100-200 MW
- Yellow : 200-400 MW
- Red : > 400 MW

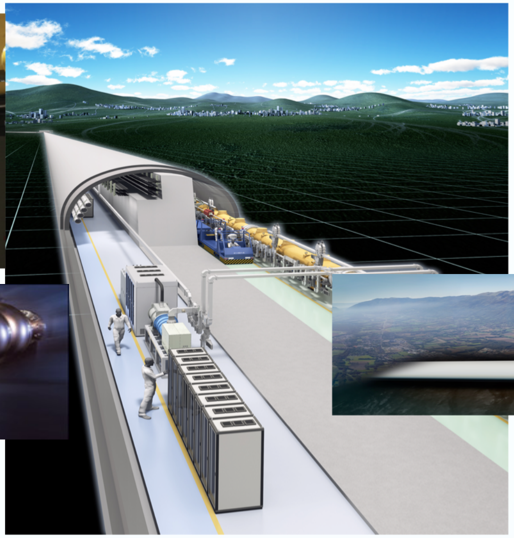
***F3* "Cost" :**

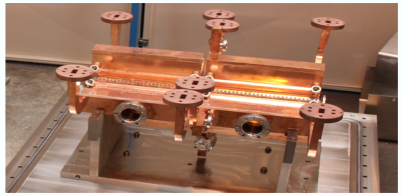
- Green : < LHC
- Yellow : 1-2 x LHC
- Red : > 2x LHC











Thanks for your attention

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 ..

- **e^+e^- CCs** are combining concepts and techniques developed, implemented and demonstrated by past and present circular colliders.
- All key **technologies** and concepts are **available**
- **Efficient RF power** generation and efficient **SRF structures** are being **investigated**
- Optimized **engineering design** for **cost efficient construction, availability, maintainabil**ity is also **ongoing**

Building on the successful model of LEP & LHC at CERN, integrated proposals for future HEP Infrastructures, FCC ee, hh, he and CEPC/SppC, based on ~100 km tunnels, **starting with highest luminosity EW factory** to be **followed** by **highest energy hadron collid**er at later stage, are very powerful and attractive **long-term options** for HEP.

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

A. Yamamoto, 190513b

*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	