Applications of LC technology

Andrea Latina (CERN)

LCWS2019, Sendai, Japan

Contents

- Purpose: discuss applications of LC technology
    - SC: ILC RF technology
    - NC: CLIC X-band high-radient RF technology
- Presentations:
    1. H. Sakai: **Industrial Applications of “Compact ERL”**
    2. G. D’Auria (W. Wuensch): **The CompactLight Design Study**
    3. W. Wuensch: **Applications of X-band and high-gradient technology**
    4. V. Telnov: **Gamma-Gamma collider based on European XFEL as a precursor of PLC at the ILC**
    5. M. Checchin: **R&D of high-coherence superconducting quantum systems**
    6. Y. Iwashita: **Superconducting Accelerator for Compact Neutron Source**
- Discussion

Industrial application of "Compact ERL (cERL)"

Contents

Hiroshi Sakai (On behalf of cERL development team)

Center for Applied Superconducting Accelerators (CASA), Accelerator Division

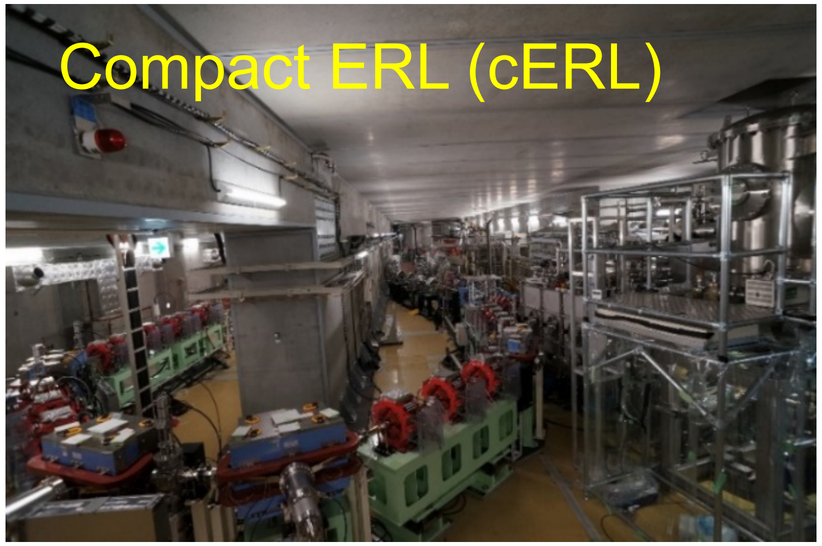
High Energy Accelerator Research Organization (KEK)

Center for Applied Superconducting Accelerators (CASA)
was newly organized in 2019 in Accelerator Division of KEK.
Its aim is to promote the industrial application by using Superconducting accelerator technologies.
https://www.kek.jp/casa/ja/

CASA Center for Applied Superconducting Accelerator 応用超伝導加速器センター

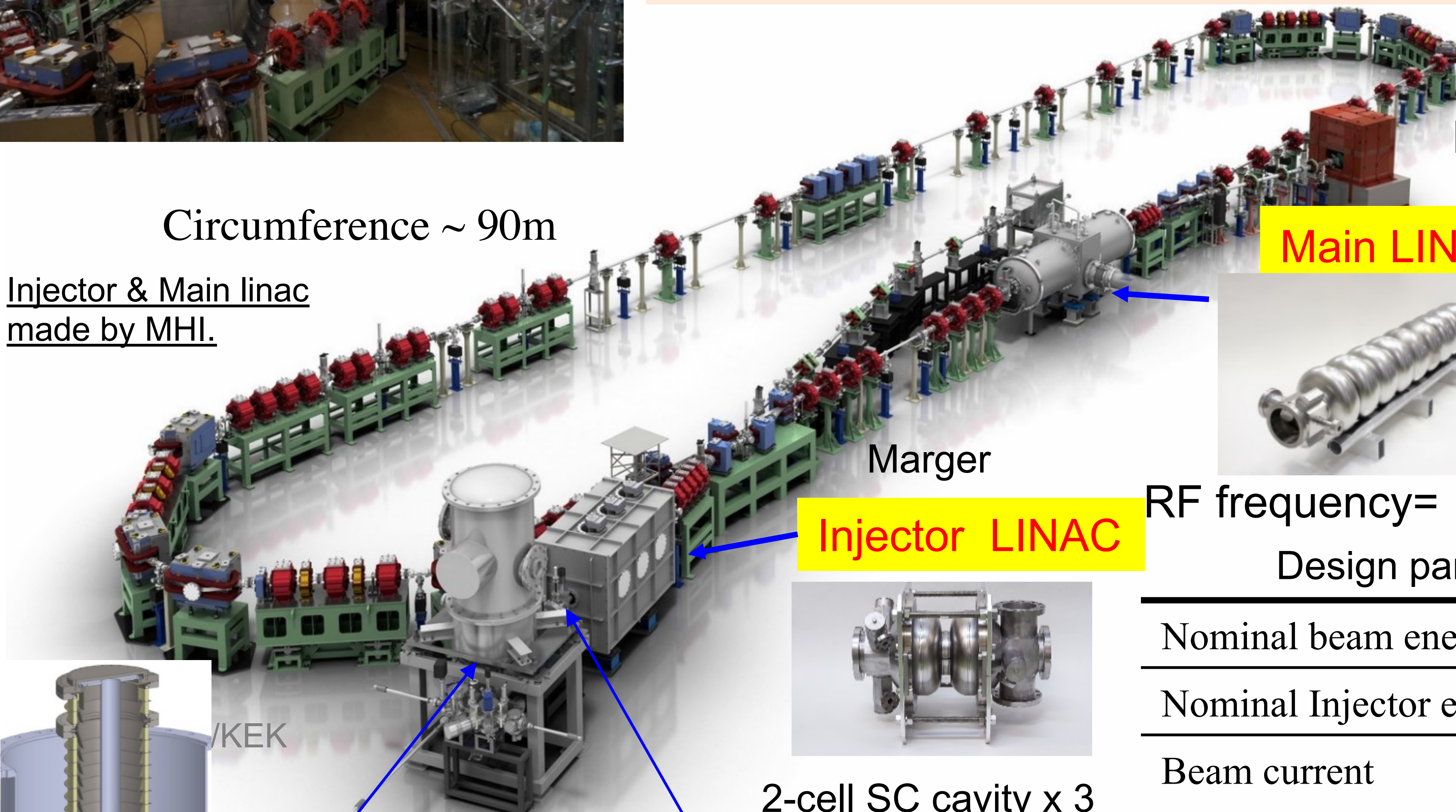
(15min.) *LCWS2019 @Sendai (2019.Oct.29)* (14 pages)

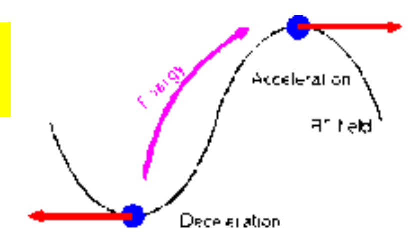
A Compact ERL (cERL) at KEK (H. Sakai)



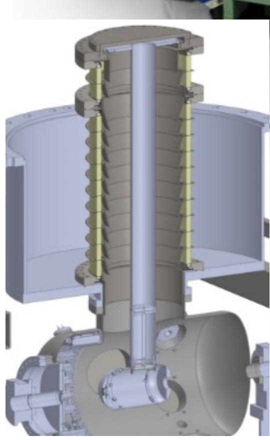
Compact ERL (**cERL**) has been constructed in 2013 at KEK to demonstrate energy recovery with low-emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL with SRF cavities.

2019: cERL was re-organized under the (CASA) in KEK to promote the industrial application by using cERL.





9-cell SC cavity x 2



2-cell SC cavity x 3

RF frequency= 1.3 GHz

17.5 MeV & 19MeV

Design parameters of the cERL

Nominal beam energy	35 MeV → 20MeV
Nominal Injector energy	5 MeV →2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

DC gun & SRF linac are based on linear collider technologies → **cERL is a real LC application.**

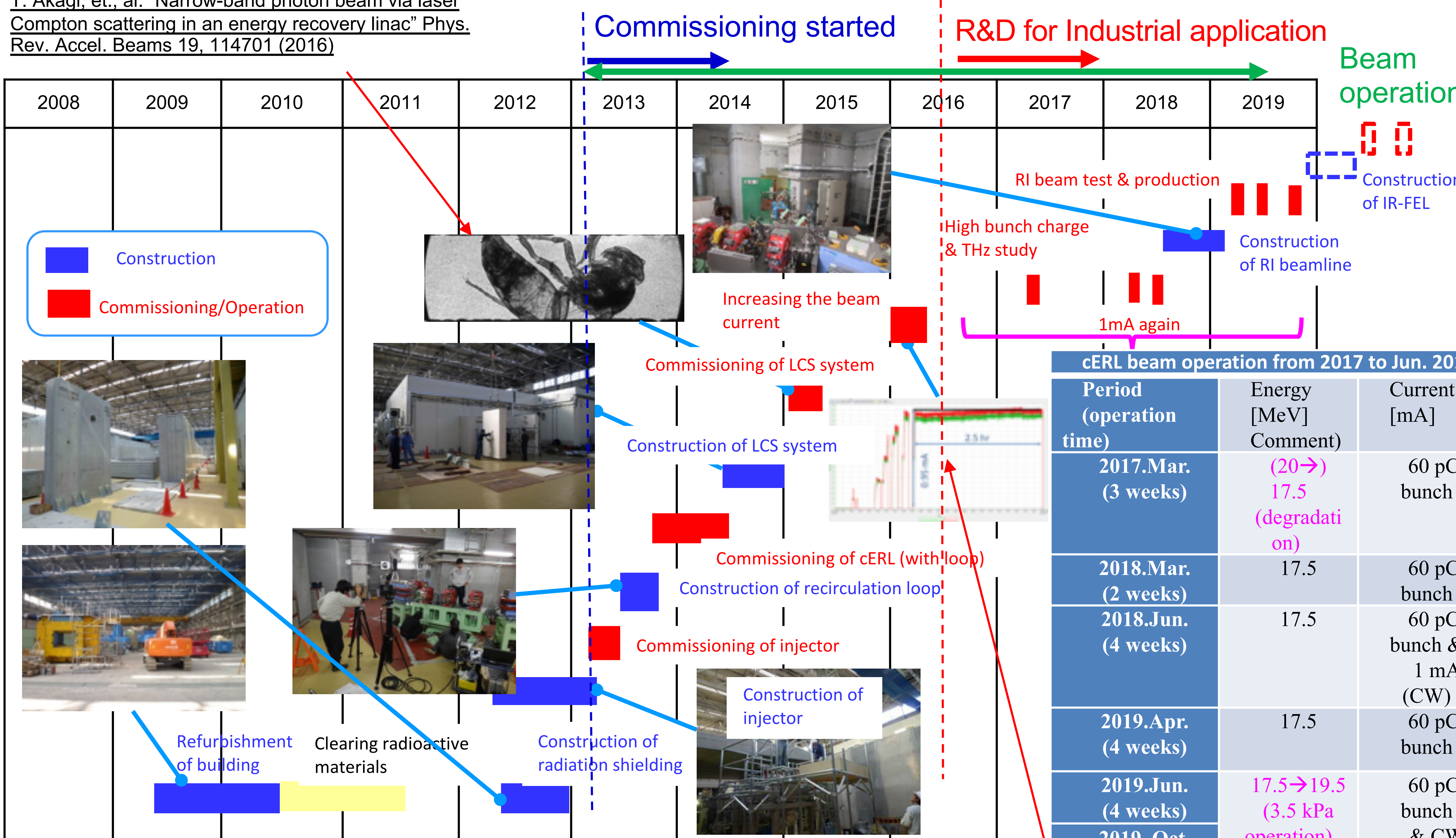
Construction and Commissioning of cERL

(H. Sakai)

(Published) M. Akemoto *et al.*, "Construction and commissioning of the compact energy-recovery linac at KEK" Nucl. Instrum. Method A 877 p.197-219 (2018).

Laser Compton scattering experiment in ERL

T. Akagi, et., al. "Narrow-band photon beam via laser Compton scattering in an energy recovery linac" Phys. Rev. Accel. Beams 19, 114701 (2016)



cERL beam operation from 2017 to Jun. 2019

Period (operation time)	Energy [MeV] Comment)	Current [mA]
2017.Mar. (3 weeks)	(20→) 17.5 (degradation)	60 pC/ bunch
2018.Mar. (2 weeks)	17.5	60 pC/ bunch
2018.Jun. (4 weeks)	17.5	60 pC/ bunch & 1 mA (CW)
2019.Apr. (4 weeks)	17.5	60 pC/ bunch
2019.Jun. (4 weeks)	17.5→19.5 (3.5 kPa operation)	60 pC/ bunch & CW beam (<10μA)
2019. Oct. (4 weeks)		

Construction started in 2009 and commissioning start in 2013.

Now we continue beam operation in 2019 → 2020

1mA ERL achieved

(B) Applications by using cERL (H. Sakai)

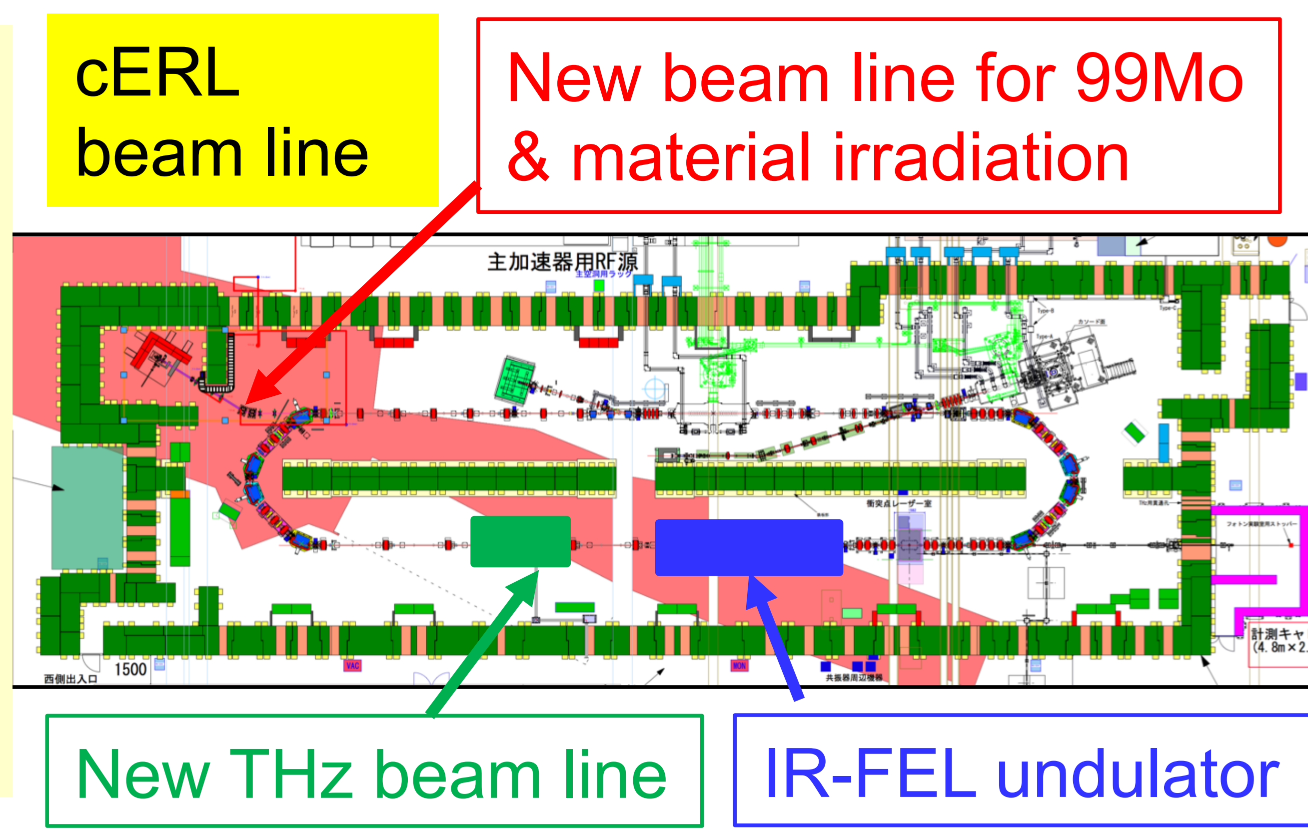
- Super conducting accelerator with ERL scheme gives us high current linac-based electron beam (~10mA) with high quality of the electron beam such as small emittance, Short pulses.
- The unique performance gives us several important industrial applications as follows.
  - High resolution X-ray imaging device for medical use
  - Nuclear security system (gamma-ray by LCS)
  - (1) RI manufacturing facility for nuclear medical examination
  - (2) EUV-FEL for Future Lithography for industrial application
  - (3) Intense THz light generation

Already achieved these application by using Laser Compton Scattering (LCS) Exp.

Next targets in a few year

<u>Plan of cERL beam operation (2018~2020)</u>

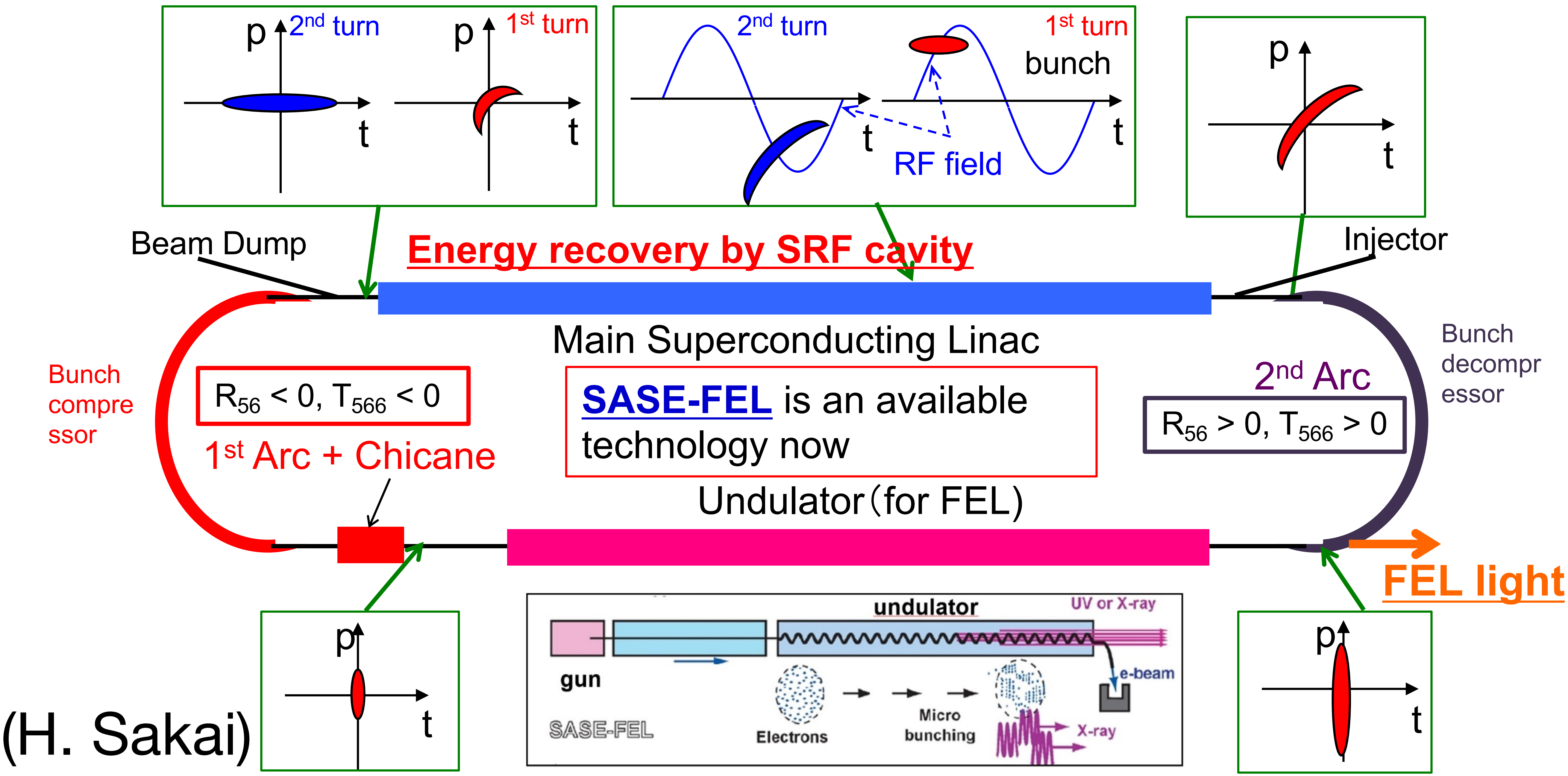
- New beam line for 99Mo RI production & material irradiation in cERL. (from 2019)
- We will produce FEL with this high current beam in the IR-FEL regime. (<u>POC of EUV-FEL plan</u>) Including high charge beam operation (~60pC).
- < 200fs bunch operation with THz generation (RCDR experiment)



Design Concept for high repetition high current EUV-FEL

EUV Source (ERL)

- Target : 10kW power @ 13.5 nm, (800 MeV, 10mA)
- Use available technology (based on SASE-FEL) without too much development
- Make ERL scheme by cERL designs, technologies and operational experiences



Energy recovery is needed for accelerating more than 10 mA to reduce beam dump and save RF power.
This operational experience with high current is studied in Compact ERL (cERL) at KEK

A Compact ERL (cERL) at KEK Summary (H. Sakai)

- Show our status of cERL at KEK . High current beam operation of 1mA was achieved at cERL. → plan to increase 10 mA.
- cERL now move to use for the industrial application by using SCRF technology. ^{99}Mo beam line was built for RI production with CW intense beam with 10uA and successfully produce ^{99}Mo under the contract business with the company.
- Conceptual design study for EUV-ERL-FEL based on SASE scheme was carried out to open the era of more higher light source of EUV-lithography, 10 kW class high power EUV light source is NOT just a dream from the experience of cERL in KEK with 10mA beam.
- In order to demonstrate ERL-SASE-FEL scheme, IR-FEL production started in cERL. 100 W IR-FEL with SASE scheme will be produced by constructing 2 x 3 m undulators in cERL beam line in 2020 based on the budget of NEDO project in Japan.
- Diffraction radiation by Resonant cavity can give high intense THz with ERL CW beam with about 100 fs bunch.

Funded by the
European Union

Compact

CompactLight, a X-band based FEL facility

Gerardo D'Auria, Elettra – Sincrotrone Trieste,
on behalf of the CompactLight Collaboration (XLS)

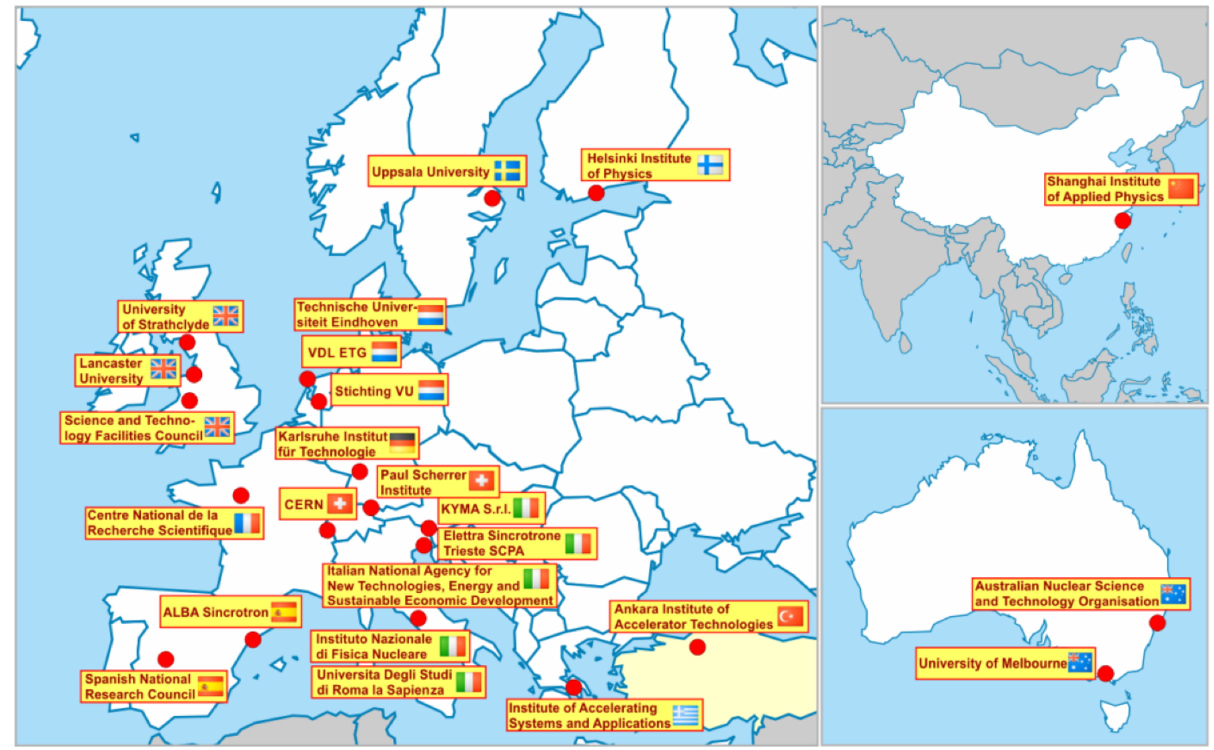
Funded by the
European Union

The CompactLight Design Study

Compact

CompactLight (XLS) is an initiative among several International Laboratories aimed at promoting the construction of the next generation FEL based photon sources with innovative accelerator technologies

	Organisation Name	Country
1	Elettra – Sincrotrone Trieste S.C.p.A.	Italy
2	CERN - European Organization for Nuclear Research	Intern.
3	Science and Tech. Facility Council – Daresbury Lab.	UK
4	Shanghai Institute of Applied Physics	China
5	Institute of Accelerating Systems and Applications	Greece
6	Uppsala Universitet	Sweden
7	Melbourne University	Australia
8	Australian Nuclear Science and Tecnology Org.	Australia
9	Ankara Univ. Institute of Accel. Techn.	Turkey
10	Lancaster Univ.	UK
11	VDL Enabling Technology Group Eindhoven	NL
12	Technische Universiteit Eindhoven	NL
13	Istituto Nazionale di Fisica Nucleare	Italy
14	Kyma S.r.l.	Italy
15	Rome Univ. "La Sapienza"	Italy
16	ENEA	Italy
17	ALBA Lab. de Luz Sincrotron	Spain
18	CNRS Centre Nat. de la Rech. Scient.	France
19	Karlsruher Instritut für Technologie	Germany
20	Paul Scherrer Institute	CH
21	CSIC Valencia Univ.	Spain
22	Helsinki Univ. Institute of Physics	Finland
23	ARCLN Amsterdam	NL
24	Strathclyde Univ.	UK



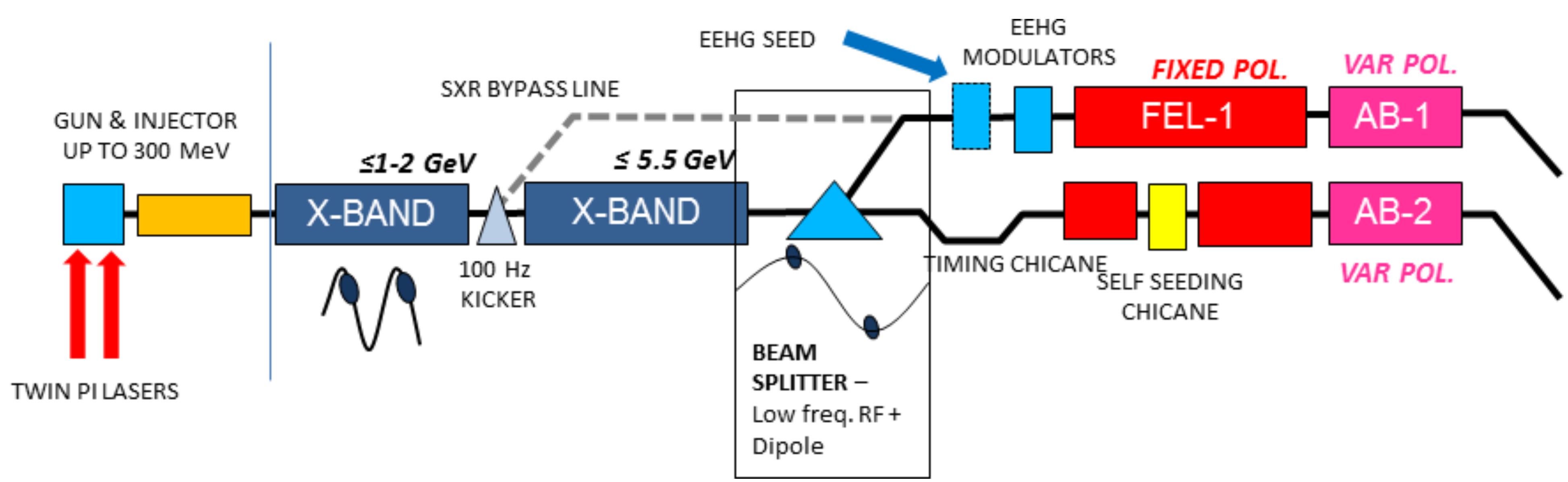
http://CompactLight.eu

- **CompactLight is an EU Design Study (RIA)**
- **Starting date 01-01-2018**
- **Duration 36 months**
- **Total cost of the project 3.5 M€**
- **EU contribution: 3 M€**
- **24 participating organisations within 13 countries including CERN + 5 associated partners.**
- **7 Work Packages**

CompactLight Objectives (G. D' Auria)

Based on FEL Scientific Requirements, collected from the Scientific Community, we plan to design a Hard X-ray facility using the very latest concepts for:

- High brightness electron photoinjectors
- Very high gradient accelerating structures (X-band)
- Novel short period undulators



Operating modes:

1. FEL-1/FEL-2 independent double pulses to one experiment HXR 100Hz
2. FEL-1/FEL-2 independent single pulses to two experiments HXR 100Hz
3. FEL-1/FEL-2 independent double pulses to one experiment SXR 1kHz
4. FEL-1/FEL-2 independent single pulses to two experiments SXR 1kHz
5. FEL-1 SASE/SEEDED SXR 100Hz + FEL-2 SASE/SELF SEEDED HXR 100Hz

Funded by the European Union

Accelerating gradients

Compact

European XFEL (Germany)	24 MV/m	Superconducting L-band
Swiss FEL (Switzerland)	28 MV/m	Normal-conducting C-band
SACLA (Japan)	35 MV/m	Normal-conducting C-band

Examples of Linac gradients for most recent X-ray FELs

Parameter	Value
Length L	0.75m
Phase advance per cell φ	120°
First iris aperture a1/λ	0.15
Last iris aperture a2/λ	0.1
First iris thickness d1	0.9mm
Last iris thickness d2	1.7mm
Fill time τ	150ns
Operational gradient G	65MV/m
Input power Pin	41.8MW

Preliminary parameters of an optimized RF structure (X-band)

Preliminary parameters of the X-band RF unit, compared with the C-band SwissFEL technology.

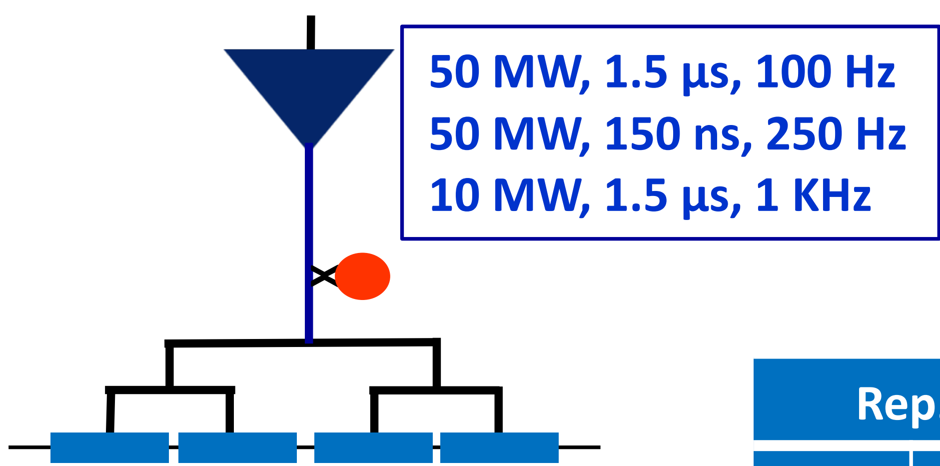
	unit	XLS X-band	SwissFEL C-band
Structures per RF unit		10	4
Klystrons per RF unit		2	1
Structure length	m	0.75	1.98
Allowed gradient	MV/m	80+	
Operating gradient	MV/m	65	27.5
Energy gain per RF unit	MV	488	203
Klystron nominal power	MW	50	50
Power in operation	MW	45	40
Klystron pulse length	μs	1.5	3
RF energy/pulse/GeV	J	277	591

Funded by the
European Union

Accelerating structure

Compact

RF system parameter and layouts done for 100 Hz baseline, 100/250 Hz dual mode and 100/1000 Hz dual klystron



	Rep. rate [Hz]		
	100	250	1000
Average gradient <G> [MV/m]	65	32	30.4
Max klystron available out. power [MW]	50	50	10
Req. klystron power per module [MW]	39	42.5	8.5
RF pulse length [µs]	1.5	0.15	1.5
SLED	ON	OFF	ON
Av. diss. power per structure [kW]	1	0.31	2.2
Peak input power per structure [MW]	68	10.6	14.8
Av. Input power per structure [MW]	44	10.6	9.6
Module energy gain [MeV]	234	115	109

Parameter	Value
Frequency [GHz]	11.9942
Phase advance per cell [rad]	$2\pi/3$
Shunt impedance R [MΩ/m]	90-131
Effective shunt Imp. R_s [MΩ/m]	387
Group velocity v_g [%]	4.7-1.0
P_{out}/P_{in}	0.215
Filling time [ns]	144
Number of cells per structure	108
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23000
# structures per module N_m	4
Module active length L_{mod} [m]	3.6
Average iris radius <a>	3.5
Iris radius input-output [mm]	4.3-2.7
Structure length L_s [m]	0.9

D. Alesini

Applications of X-band and high-gradient technology

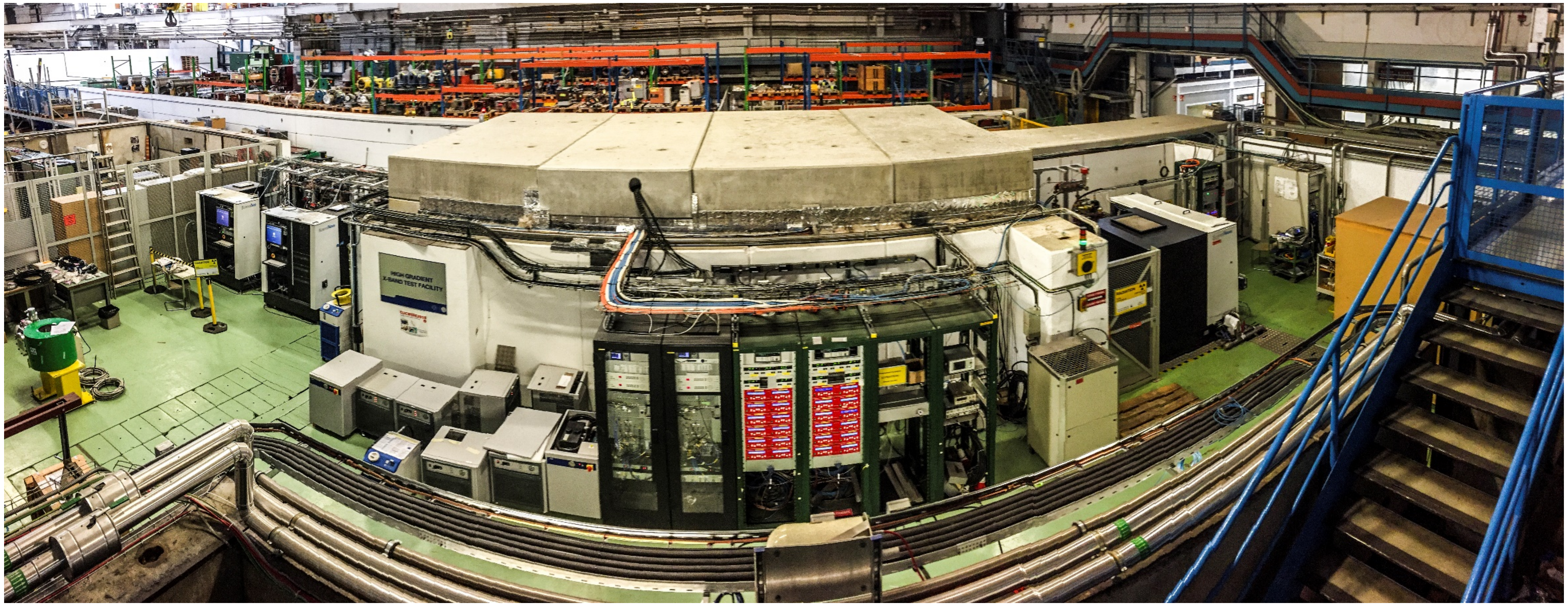
W. Wuensch (CERN)

Introduction

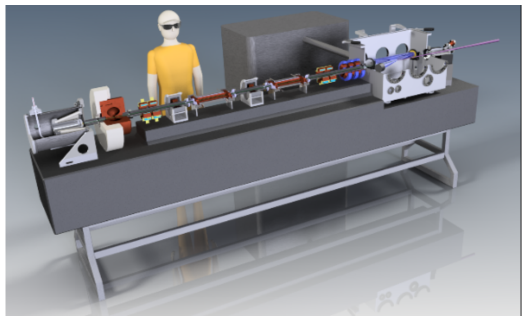
An important aspect of the CLIC R&D strategy is to assist and promote application of high-gradient, X-band and advanced normal conducting technology.

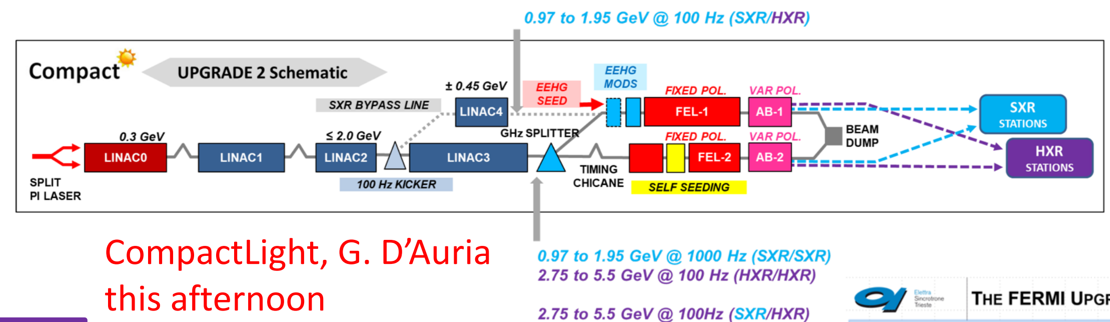
The objective is to add to direct resources with those in other projects and broaden the technical base.

I will now present a selection of examples of projects CLIC actively collaborates with.

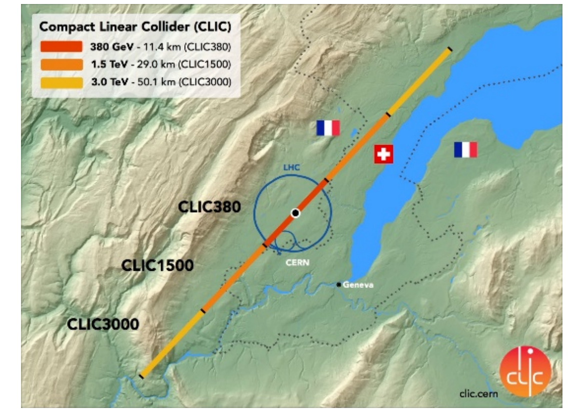


X-band and high-gradient applications overview (W. Wuensch)





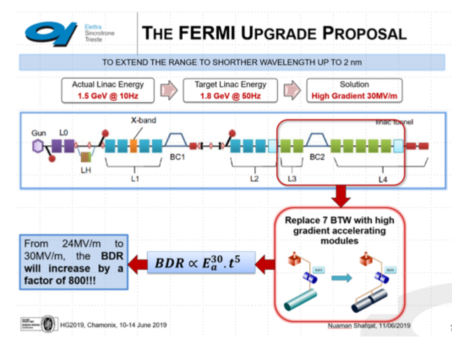
CompactLight, G. D'Auria this afternoon

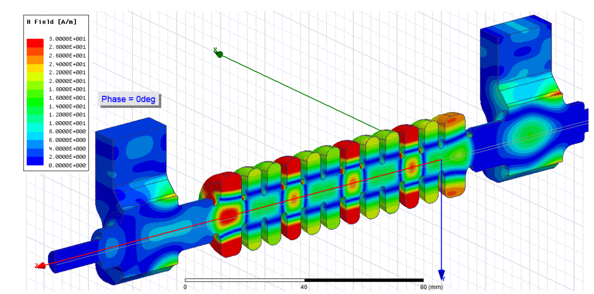


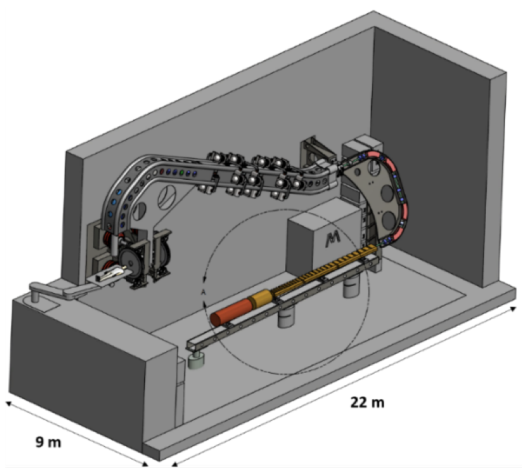
Linear collider

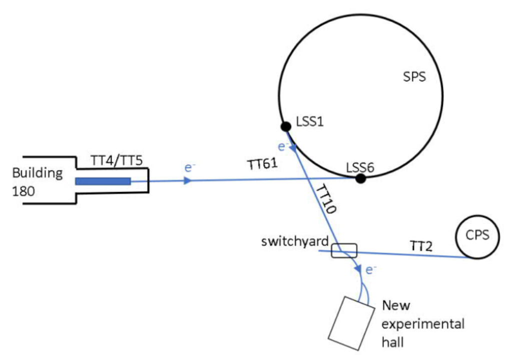
Inverse Compton Scattering Source

XFEL



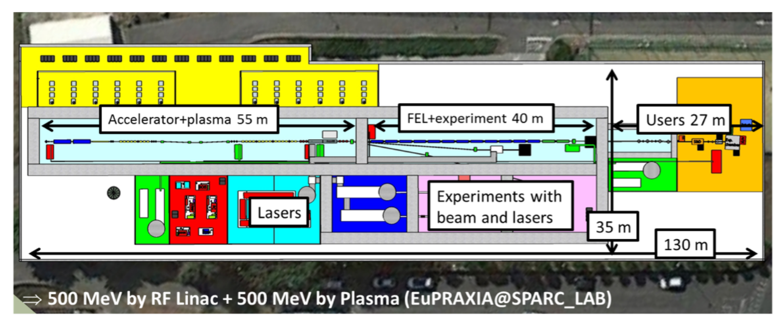




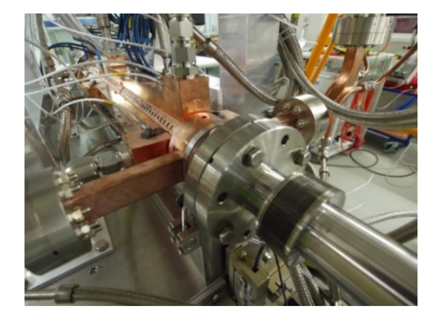


eSPS, S. Stapnes this afternoon

Medical applications



⇒ 1 GeV by high gradient RF Linac only (EuSPARC)



GeV-range research linacs

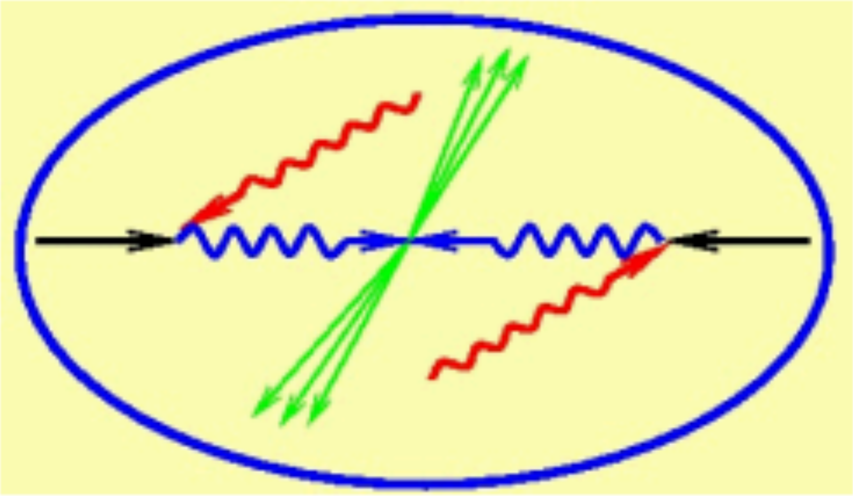
Beam manipulation

X-band linearizers and deflectors

Trieste	Linearizer for Fermi	50 MW	Operational
PSI	Linearizer for SwissFEL	50 MW	Operational
	Deflector for SwissFEL	50 MW	Procurement
DESY	Deflector for FLASHforward	6 MW	Operational
	Deflector for FLASH2	“	Installation
	Deflector for Sinbad	10 MW	Procurement
SINAP	Linearizer for soft X-ray FEL	6 MW	Operational
	Deflectors for soft X-ray FEL	2x50 MW	Procurement
Daresbury	Linearizer	6 MW	Procurement
SLAC	LCWS linearizer	50 MW	Operational
	LCWS deflector	50 MW	Operational
Dalian	Linearizer for DCLS	50 MW	Design

X-band linacs

SLAC	NLCTA+XTA	2x50 MW, 11 GHz	Operational
Eindhoven	Compact Compton source - 25 MeV	6 MW	Procurement
CERN	CLEAR – 50 MeV (from Xbox-1)	50 MW	Installation
Tsinghua	Thompson source upgrade + 50 MeV	50 MW	Procurement
	200 MeV Thompson source	2x50 MW	Proposal
Frascati	XFEL, injector to plasma - 1 GeV	8x50 MW	CDR submitted
Daresbury	Xara – 1 GeV	6x50 MW	Design study
Collaboration	CompactLight – 5.5 GeV	30x50 MW	Design study
CERN	eSPS – 3.5 GeV	24x50 MW	Letter of intent submitted
Groningen	1.4 GEV XFEL Accelerator - 1.4 GeV		NL roadmap
CERN	CLIC – 380 GeV	5800x50 MW	European Strategy Update



$\gamma\gamma$ collider on the energy W<12 GeV based on European XFEL as a precursor of PLC at ILC

Valery Telnov

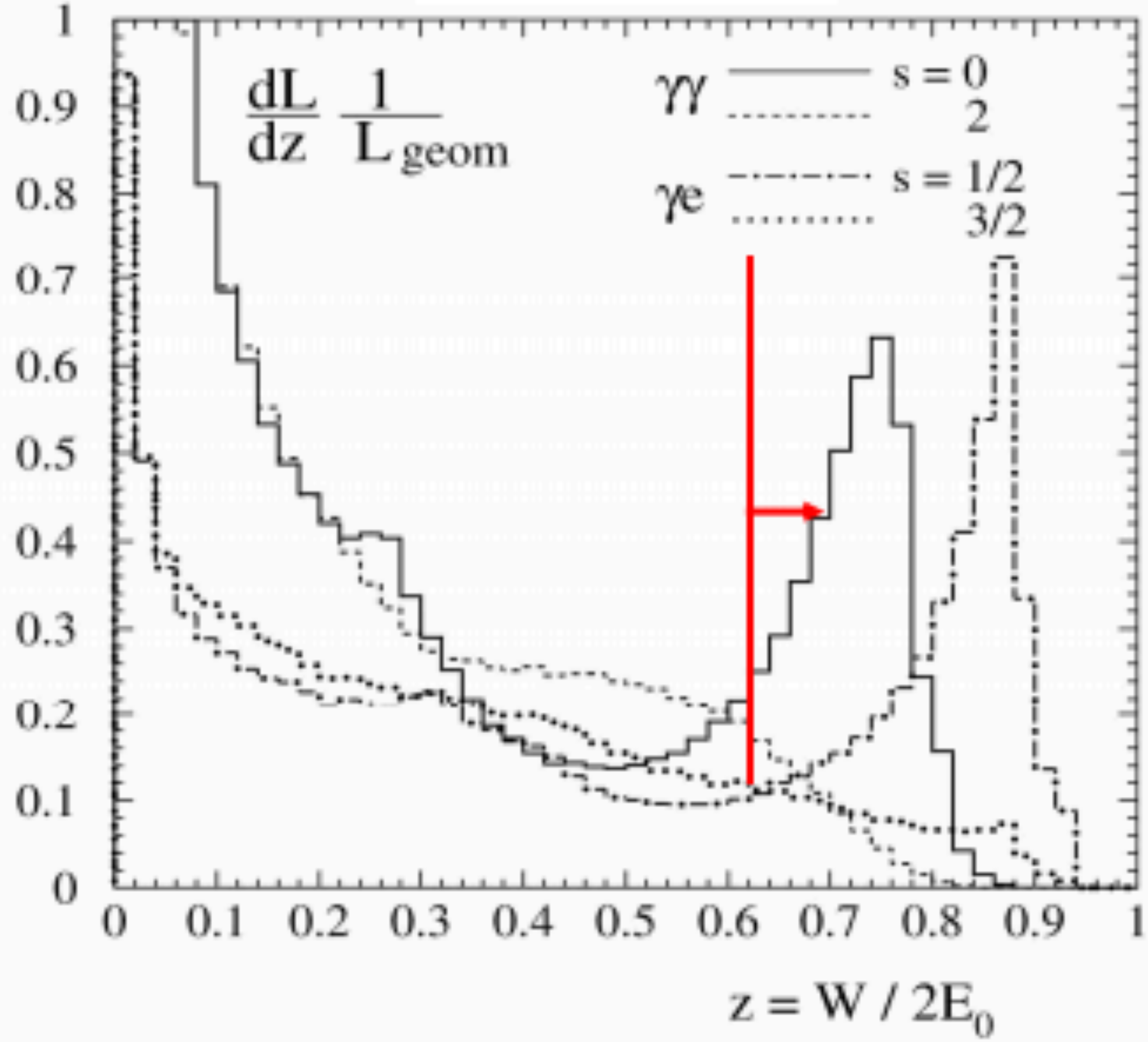
Budker INP and Novosibirsk State Univ.

LCWS-2019, 29.10.2019, Sendai, Japan

Typical $\gamma\gamma$, γe luminosity spectra

simulation with account all important effect at CP and IP regions:
multiple Compton scattering in CP, beamstrahlung, coherent pair creation, beam repulsion e.t.c.

ILC(500)

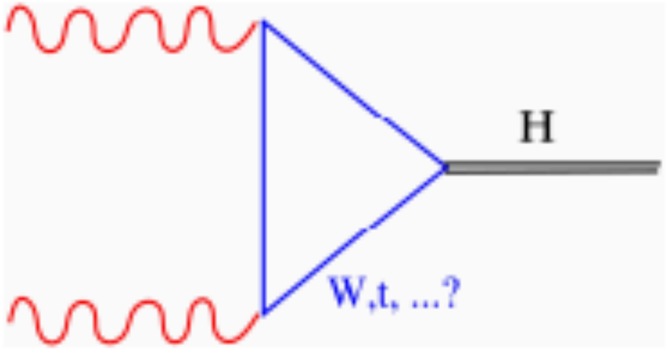


Luminosity spectra and their polarization properties can be measured using QED processes

$L_{\gamma\gamma}(z>0.8z_m) \sim 0.1\ L_{e-e-}(\text{geom})$

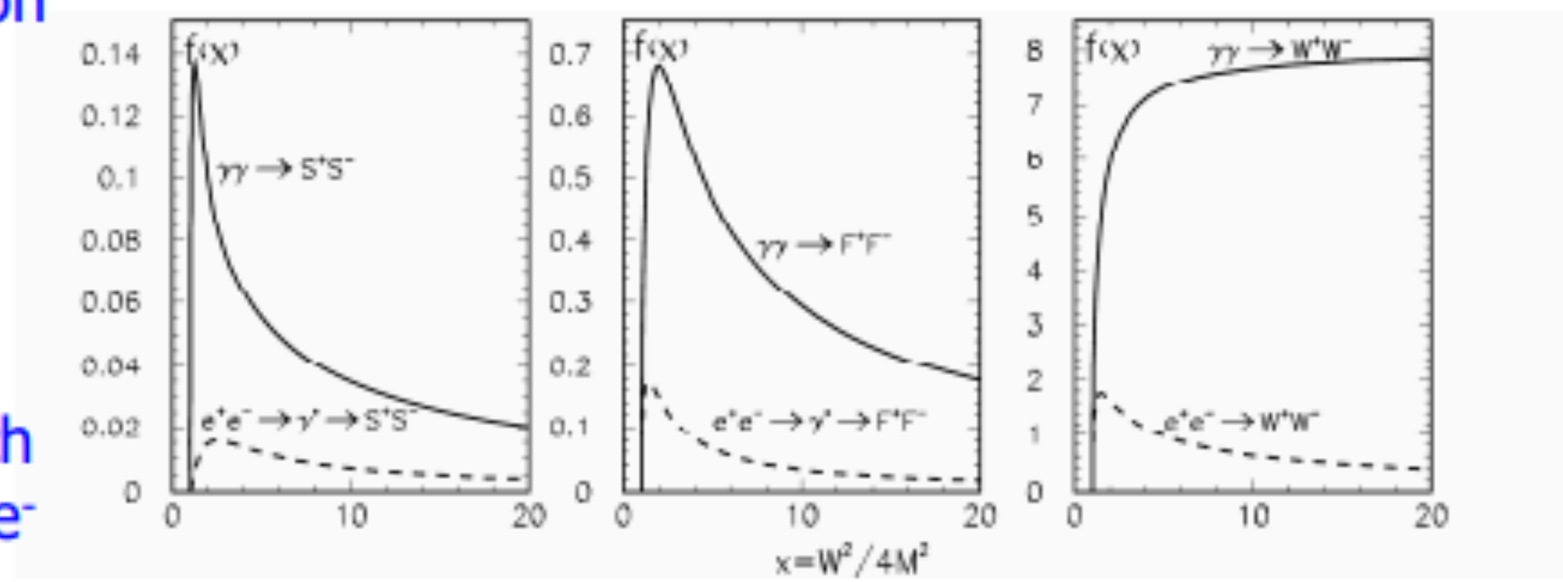
$\gamma\gamma$ physics at high energy linear colliders

resonance Higgs production

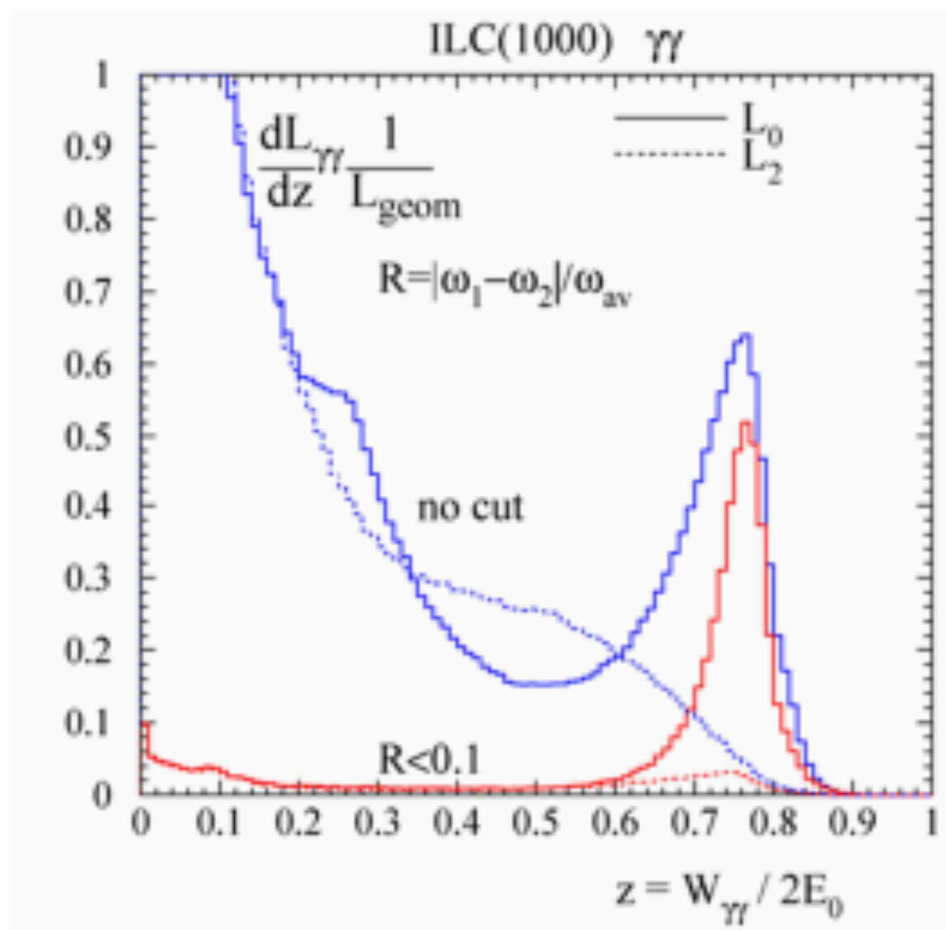


$\Gamma_{\gamma\gamma}(H)$ can be measured much better (~8 times) than in e^+e^-

Any charge pairs production



Unfortunately only H(125) is found at the LHC, but surprises are not excluded.



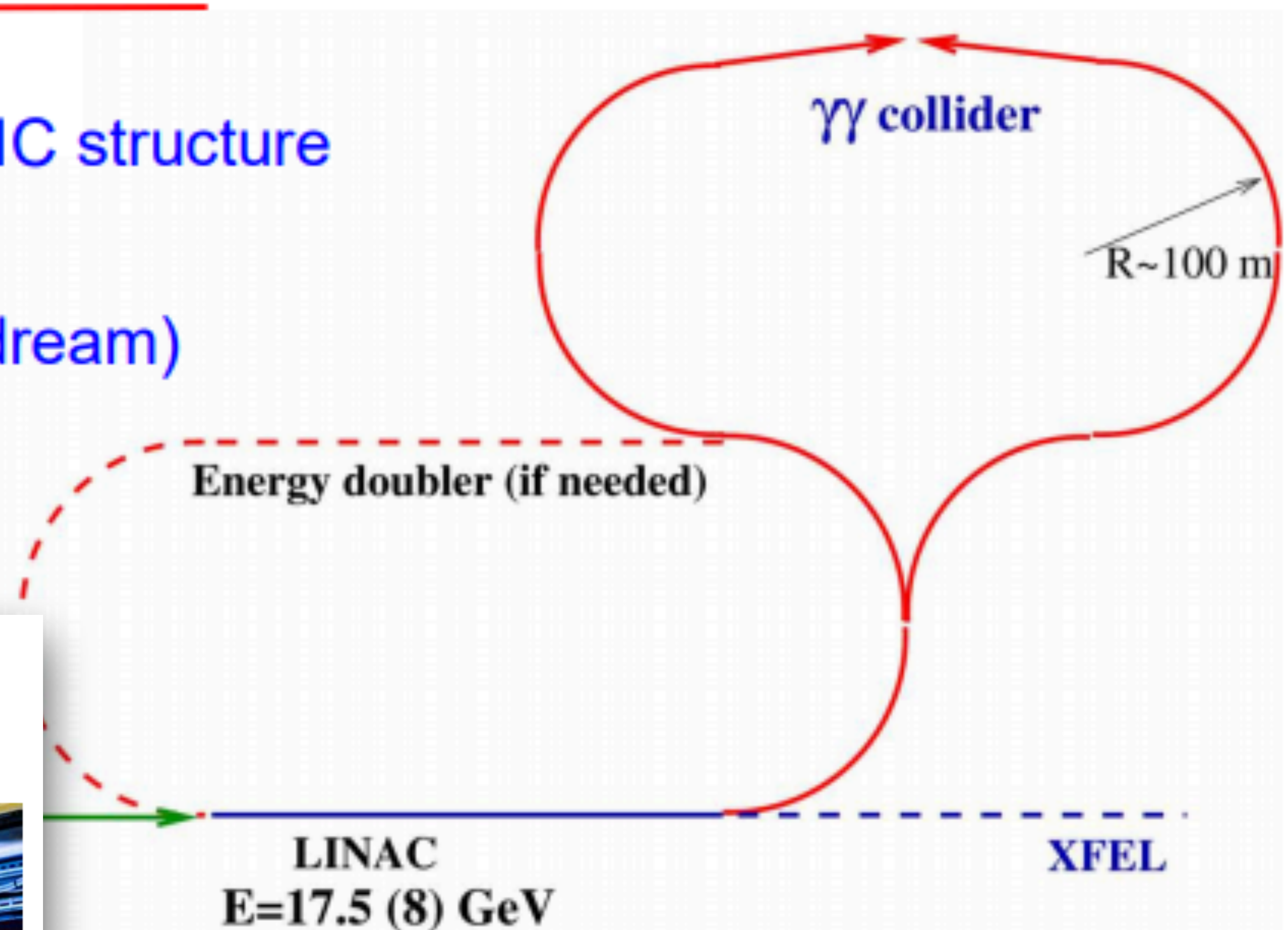
$\gamma\gamma$, γe luminosity spectra at the ILC(1000) (for λ=2 μm)

Such collider would be best for study of the (fake) diphoton peak seen at the LHC at 750 GeV.

Scheme of the collider

There are several possible electron "drivers" for c-b-$\gamma\gamma$-collider:

1) SC European 17.5 GeV XFEL (used beams?)
2) Warm cavity linac (CLIC structure with klystrons)
3) Plasma accelerator (dream)



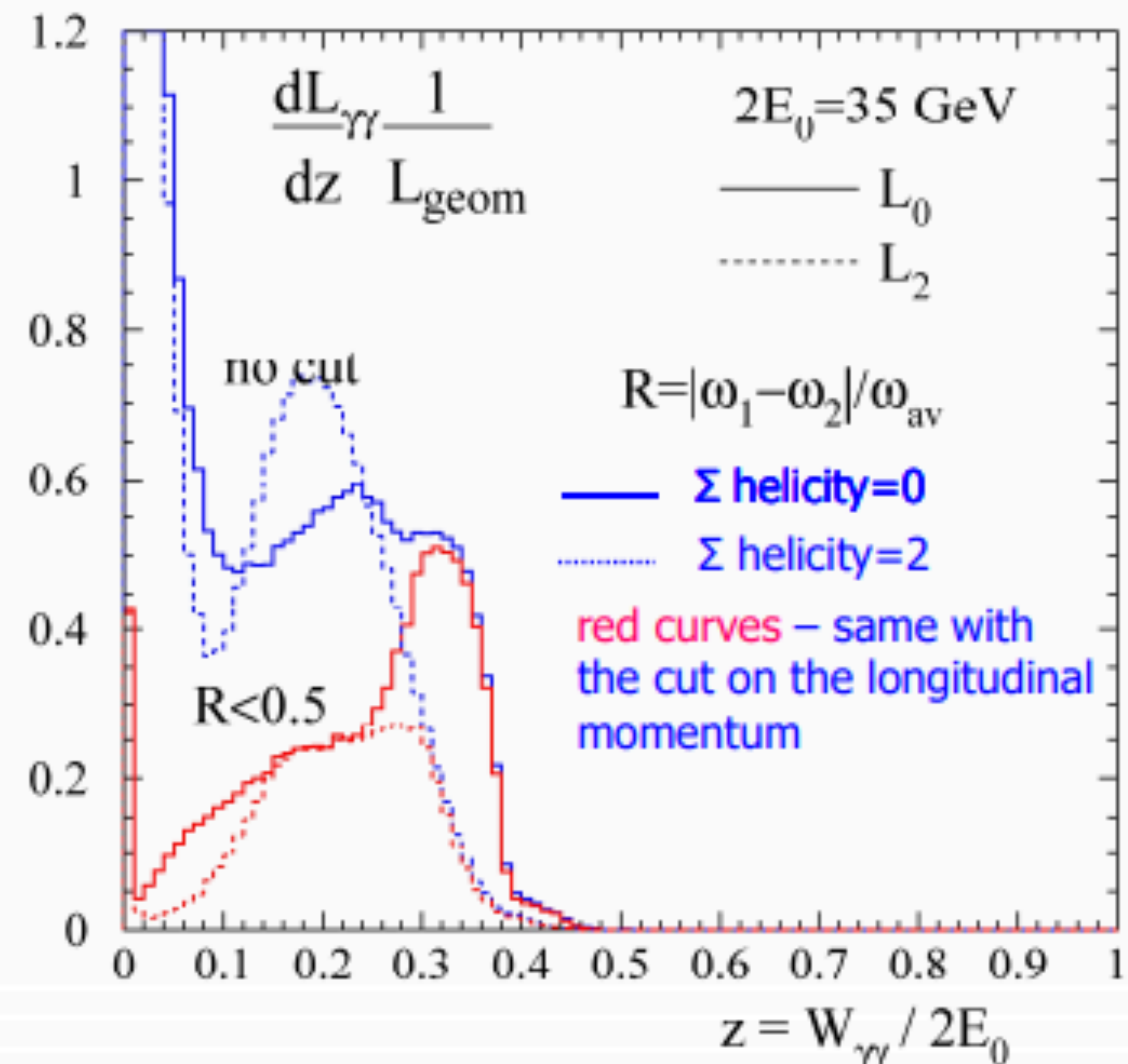
(Linac not in scale)

Main (most expensive) part of the photon collider is already in operation since 2017

Parameters of photon collider for bb-energy region (W<12 GeV)

E_0, GeV	17.5 (23)
$N/10^{10}$	0.62
f, kHz	15
σ_z, μm	70
$\varepsilon_{nx}/\varepsilon_{ny}$, mm mrad	1.4/1.4
β_x/β_y, μm	70/70
σ_x/σ_y, nm	53/53
laser λ, μm (x≈0.65)	0.5 (1)
laser flash energy, J	3 (ξ^2=0.05)
f#, τ, ps	27, 2
crossing angle, mrad	~30
b, (CP-IP dist.), mm	1.8
L_{ee}, 10^{33}	1.6
$L_{\gamma\gamma}(z>0.5z_m)$, 10^{33}	0.21
$W_{\gamma\gamma}$(peak), GeV	12

Unpolarized electrons, P_c=-1



In Table the XFEL emittance is assumed. With promised plasma gun the luminosity can be larger ~10 times.

Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

R&D of High-coherence Superconducting Quantum Systems

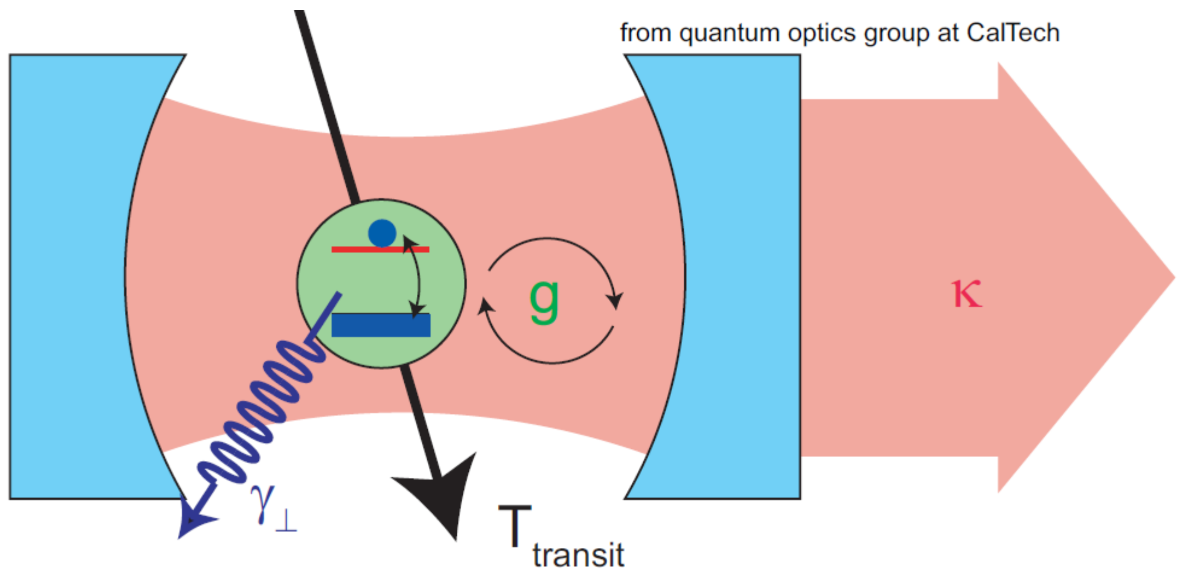
Mattia Checchin

LCWS 2019, Sendai, Japan

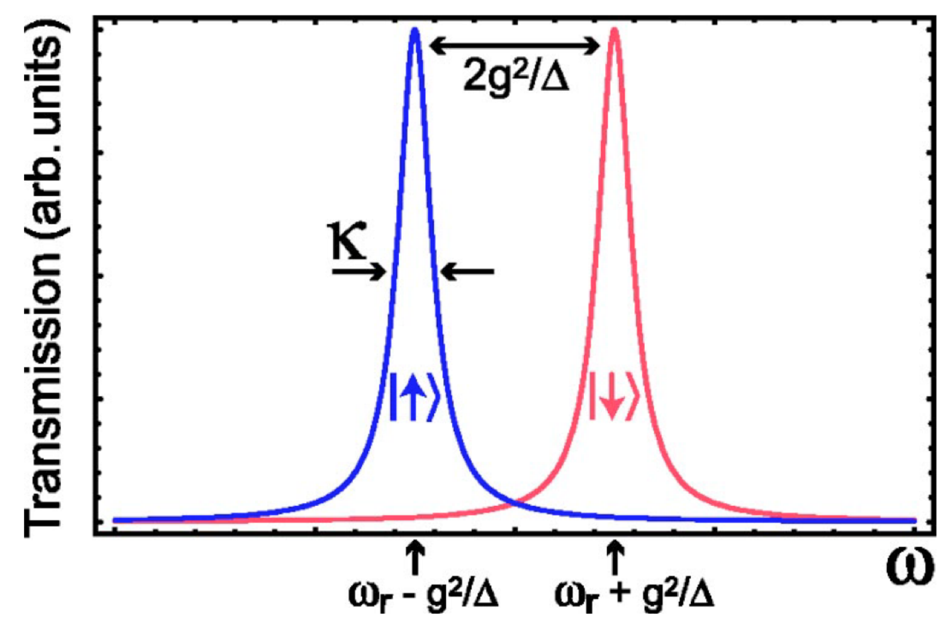
29 November 2019

Cavity Quantum Electrodynamics (QED)

- Qubit read-out based on frequency shift of coupled resonator



A. Blais et al., PRA 69, 062320 (2004)



$$\mathcal{H} = \underbrace{\hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)}_{\text{cavity}} + \underbrace{\frac{\hbar\omega_{eg}}{2}\sigma^z}_{\text{qubit/atom}} + \underbrace{\hbar g\left(a^\dagger\sigma^- + \sigma^+ a\right)}_{\text{interaction term}} + \mathcal{H}_\kappa + \mathcal{H}_\gamma$$

Serge Haroche and David Wineland Nobel Prize 2012

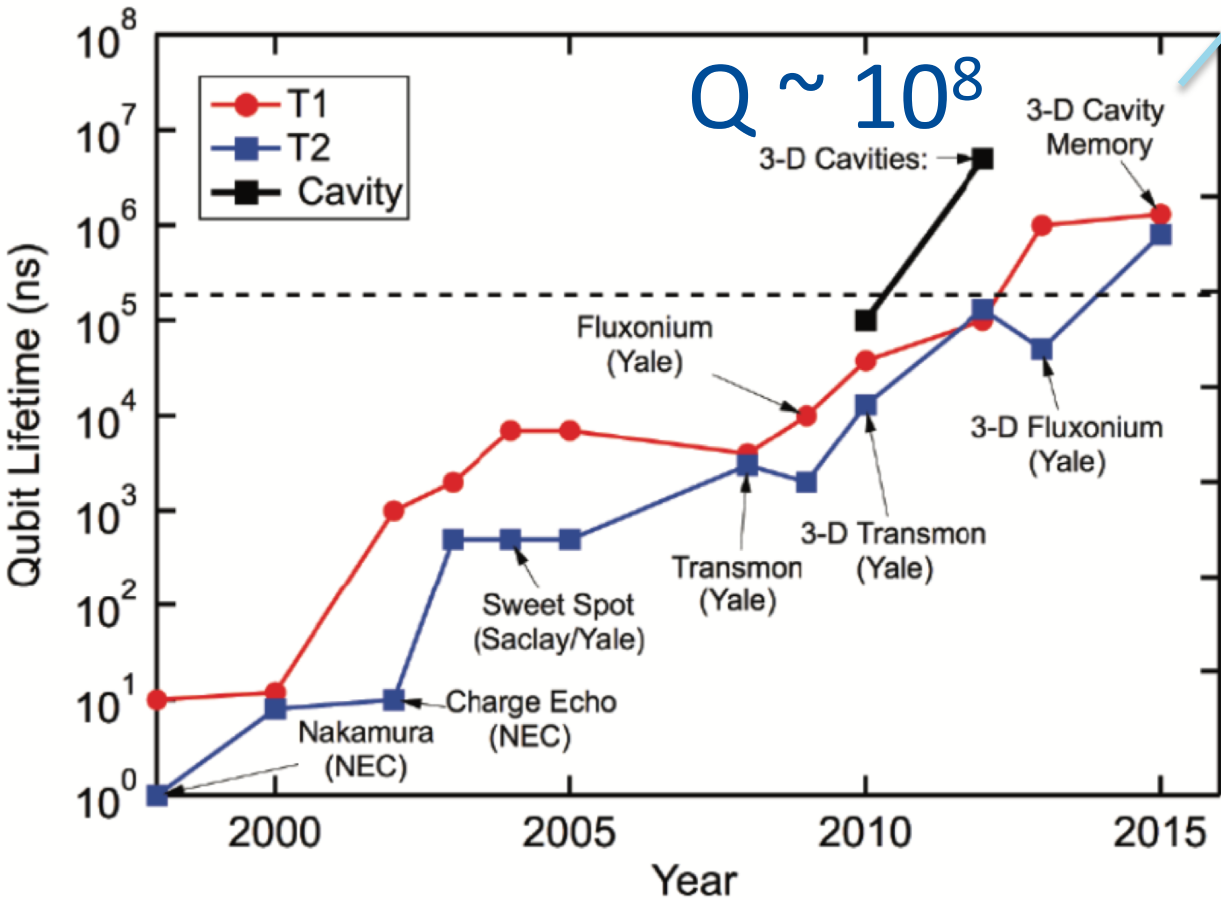
Qubit decoherence

- Decoherence = tendency of a quantum system to loose information
- We can beat decoherence by developing:
  - Better qubits
    - Protect qubit against sources of noise (flux and charge)
    - Minimize spurious two-level systems
  - Better resonators
    - Increasing Q-factor
    - Minimize TLS
    - **We can take advantage of High-Q SRF technology!**

High Q SRF 3D cavities for improved coherence

$Q > 10^{11}$ ~10 <u>seconds</u> of coherence

~10 msec photon lifetime/coherence is a record

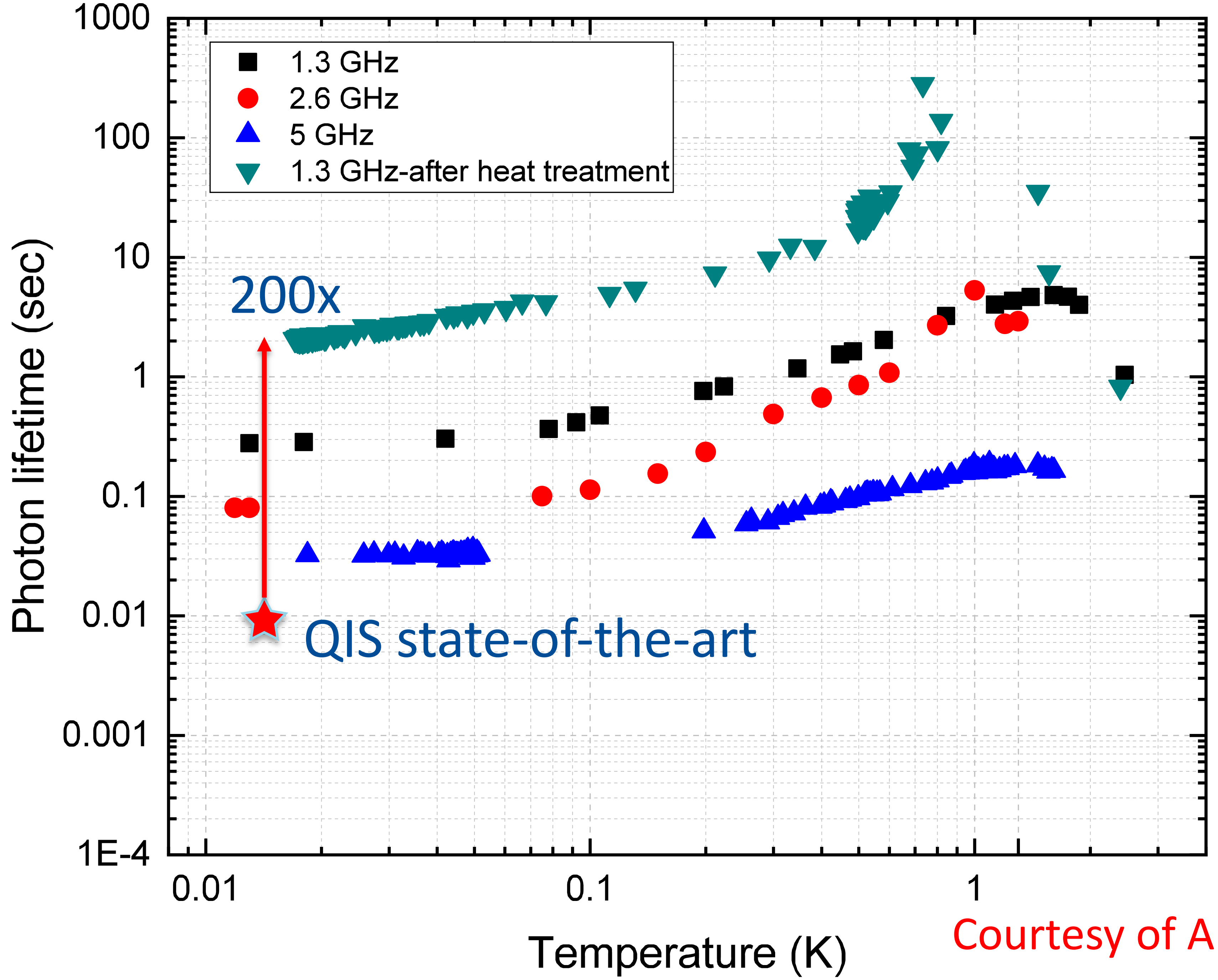


1-cell Fermilab cavities of various frequencies

M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)

Courtesy of A. Romanenko

Record high photon lifetimes achieved



Courtesy of A. Romanenko

A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

ACCELERATOR LABORATORY
ADVANCED RESEARCH CENTER FOR BEAM SCIENCE
INSTITUTE FOR CHEMICAL RESEARCH
KYOTO UNIVERSITY

Superconducting Accelerator Neutron Source — ScANS —

Y. Iwashita, Kyoto University

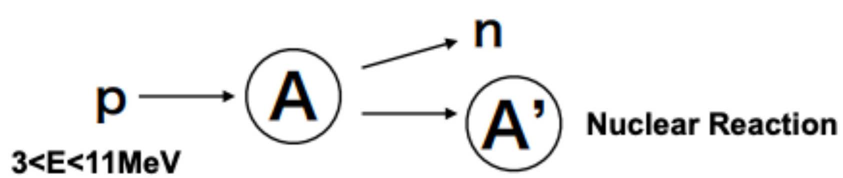
Compact Neutron Sources

Needs to extract **n** from nuclei by electrons or protons:

1) MeV γ from electrons interact with nuclei at giant resonance.

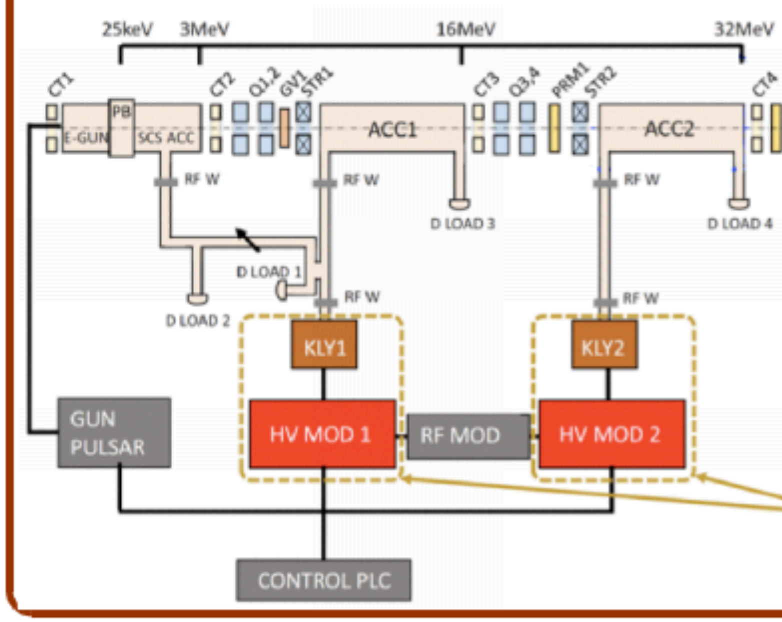
Note: No precise energy control needed!

2) Photodisintegration of Beryllium 9
$^{9}Be + \gamma \rightarrow n + {}^{8}Be$ (Sn = 1.665 MeV)



Typical Compact Neutron Sources

We pick up e-Linac. Specification is following:
30 MeV x 250 mA pk = 7.5MW, 0.1 ~ 4μs, 1~100 pps
x 100 μA ave.= 3 kW. **Average is much less!**



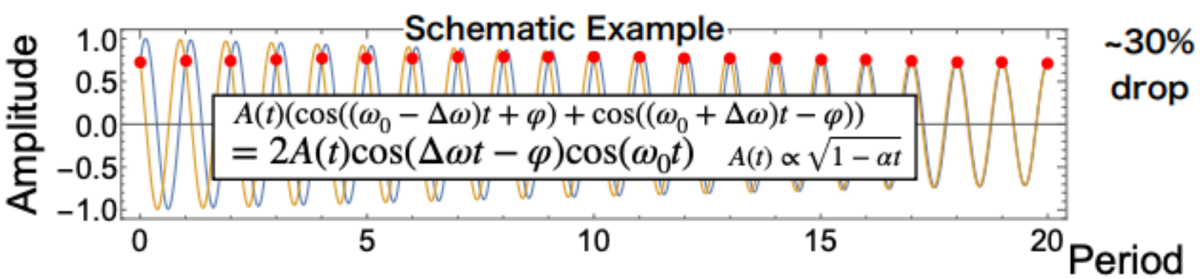
Can generate cold ~ fast neutrons ~10^{12} n/s.

This system uses **7.5MW** klystron x 2.

RF power source costs half of linac.

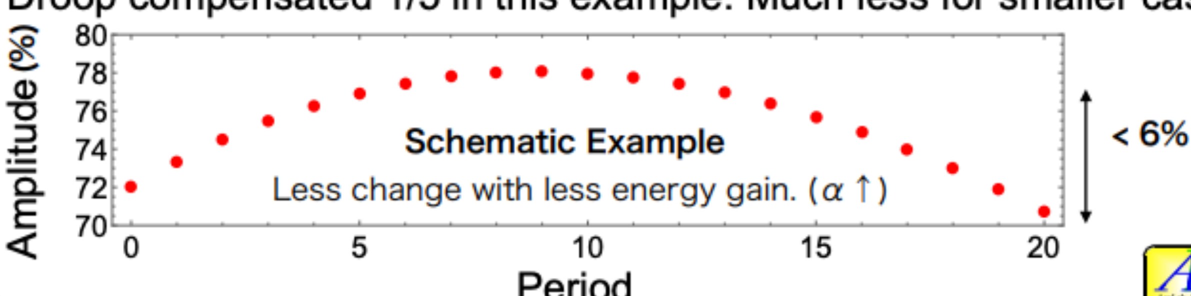
Two cavity phasing

The two 25 MV/m x1m cavities can be adjusted to achieve 30 MeV acceleration by phasing with slightly different frequencies.



~30% drop

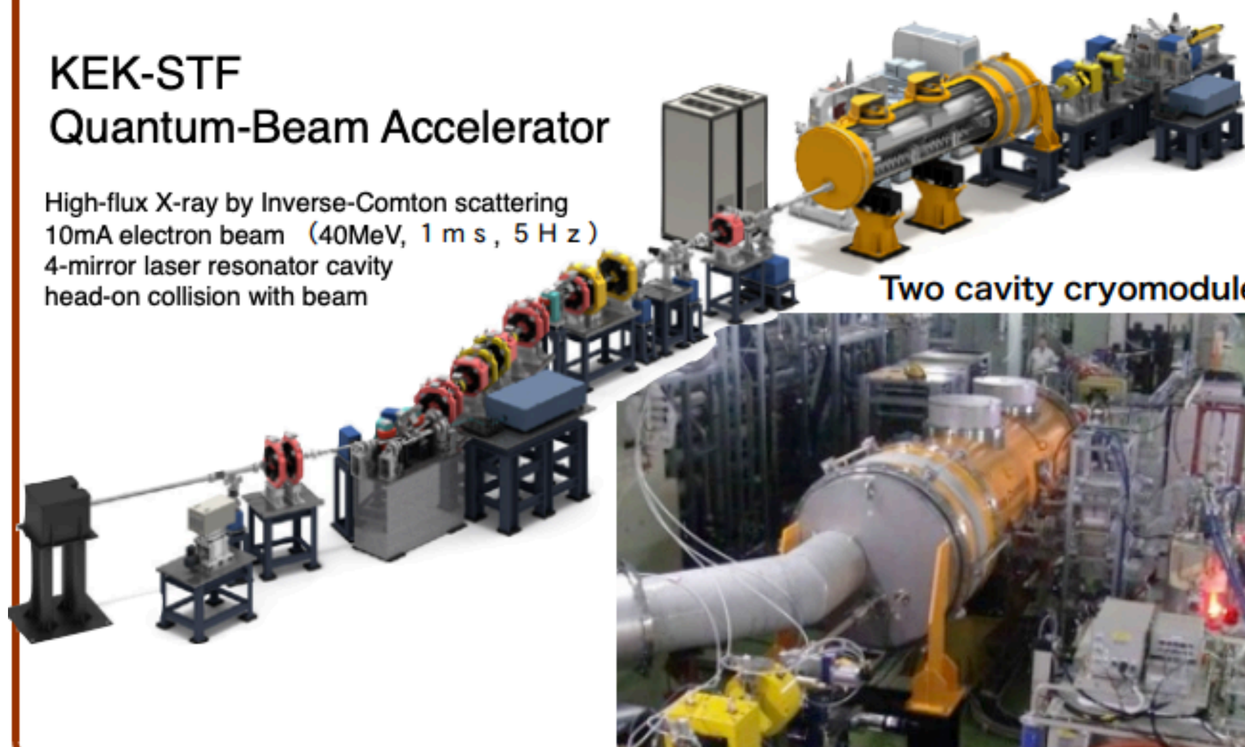
Droop compensated 1/5 in this example. Much less for smaller case.



STF@KEK

KEK-STF
Quantum-Beam Accelerator

High-flux X-ray by Inverse-Comton scattering
10mA electron beam (40MeV, 1 m s, 5 H z)
4-mirror laser resonator cavity
head-on collision with beam



Discussion

- “ERL: SC RF is best for high-current ERL. ILC is rather “high-gradient” SC RF technology. Perhaps lower gradients are more desirable for ERL”

- “γγ-collider: One should consider the parasitic use of 5 GeV beam or 15 GeV beam at 10 Hz for various uses, e.g. LCLS or EuroXFEL. Yet, parasitic operation doesn’t normally encounter the favor of light-source folks nor nuclear physics folks”

- "Envisage other uses of ILC beam is not easy, as they need to be formulated about 15 ahead of time. Better to focus on the applications of the technology instead”