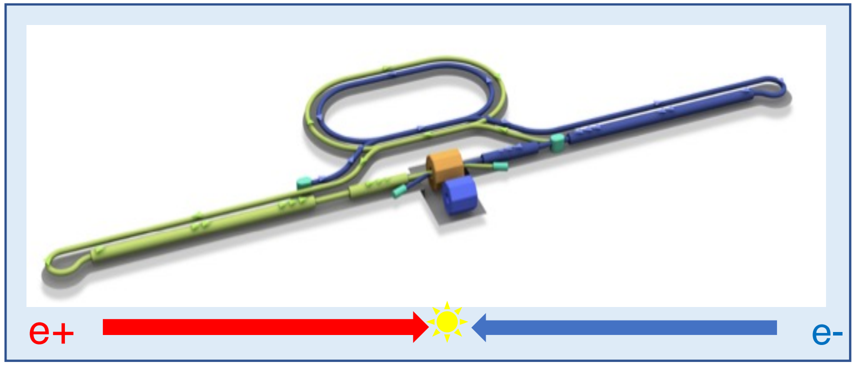


Draft-230214

ILC Progress

Shin-ichiro Michizono and Akira Yamamoto

(ILC-IDT and KEK)

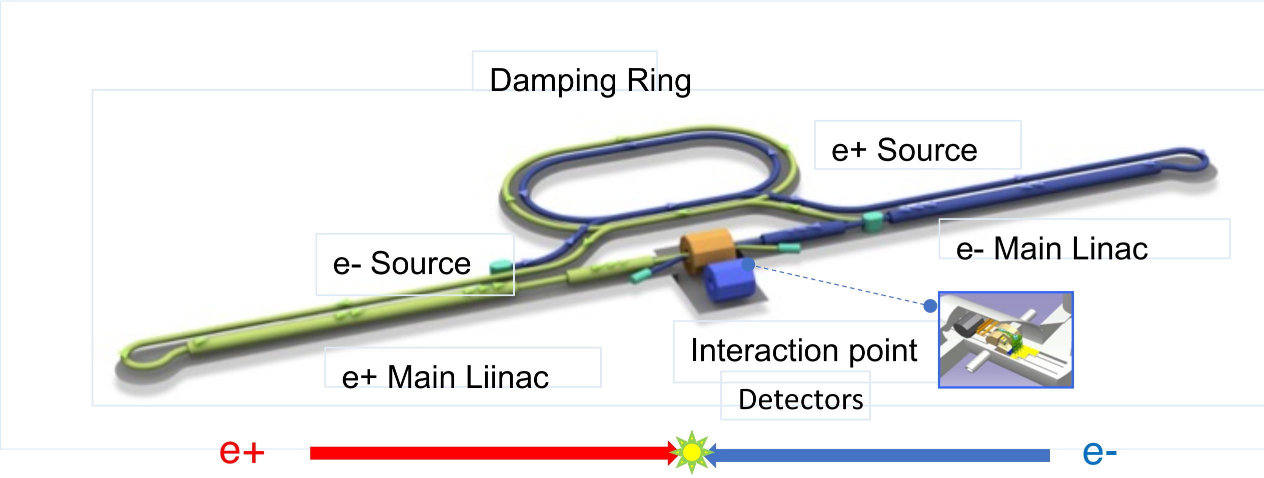
To be presented at HKUST IAS HEP Conference*, Feb. 15, 2023

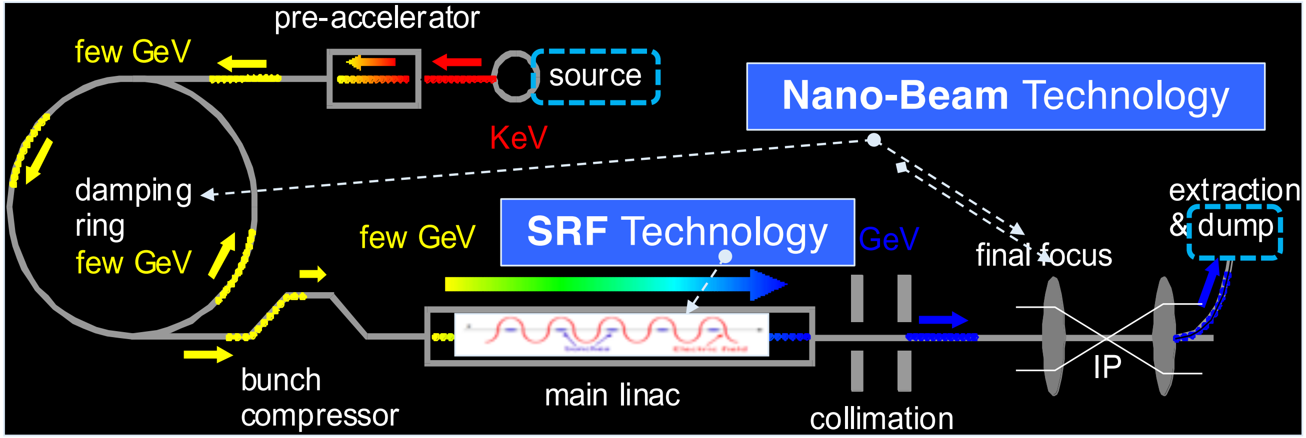
* https://ias.hkust.edu.hk/events/high-energy-physics-2023

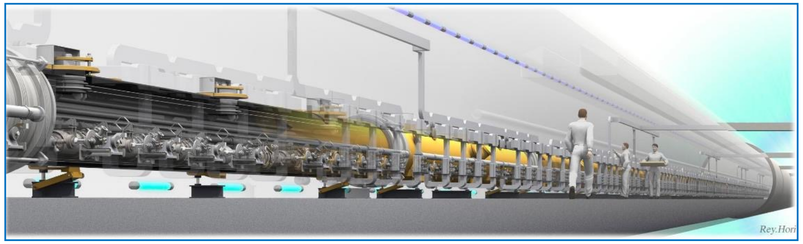
Outline

- Introduction:
  - Progress in Accelerator Technology
- **ILC T**echnical **N**etwork (**ITN**) for Global Acc. R&D Programs
- Future Prospect in Technology Advances
- Summary

ILC and the Accelerator Technology

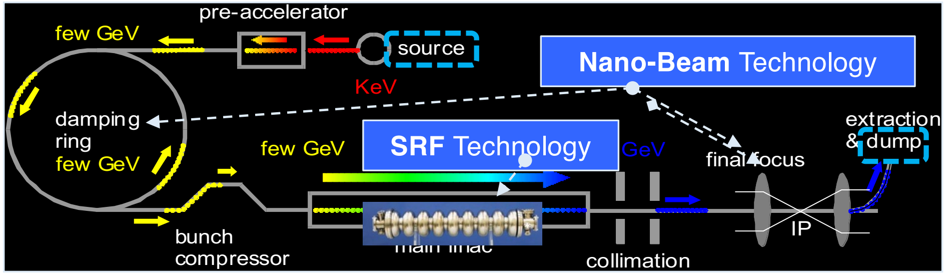






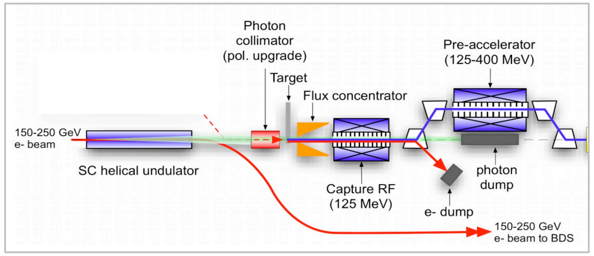
Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF	**7.7** nm
SRF Field gradient	< 31.5 > MV/m (+/-20%) Q_0 = $1x10^{10}$
#SRF 9-cell cavities (CM)	~ 8,000 (~ 900)
AC-plug Power	111 / 138 MW

ILC Area systems

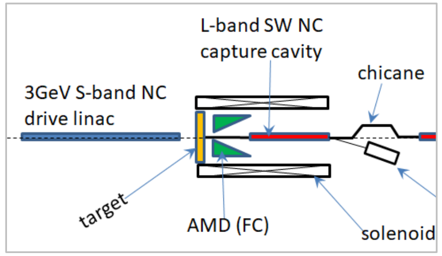


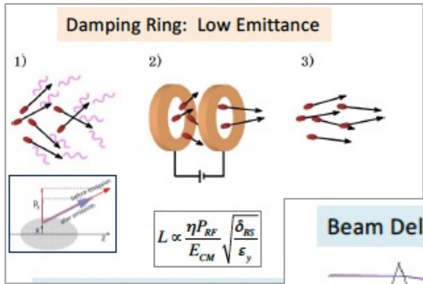
- Creating particles → *Sources*
  - polarized elections / positrons
- High quality beams → *Damping ring*
  - Low emittance beams
    - Small beam size (small beam spread)
    - Parallel beam (small momentum spread)
- Acceleration → *Main linac*
  - superconducting radio frequency (SRF)
- Getting them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

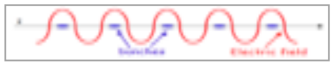
Undulator driven **e+** source

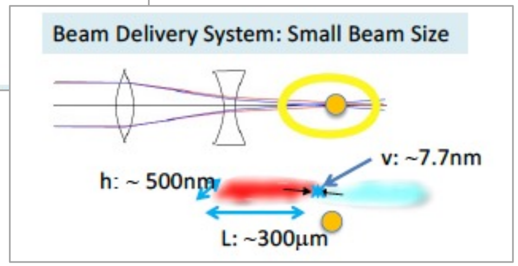


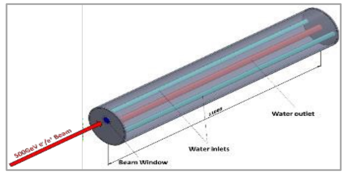
e-driven **e+** source











ILC Baseline and the Upgrades

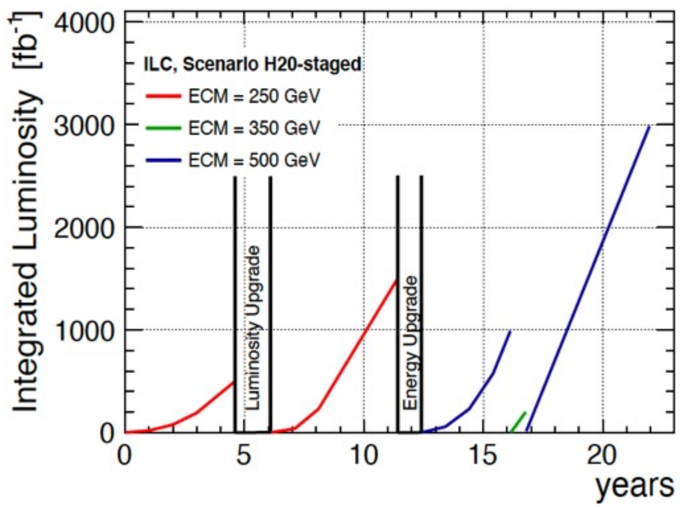
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)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

- * **AC** plug-**power** may be further **reduced** (10 ~ 20 %), if the RF **(Klystron)** and SRF/Cryogenics (Q-value) **Efficiency** may be **improved,** and
- the **peak power reduction** will become **critical important**, as a primary requirement.

2023/2/15

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

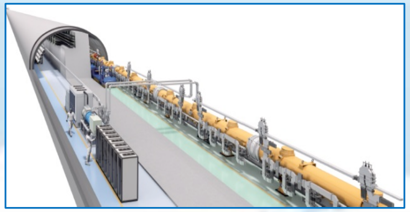
Energy upgrades:
- 500GeV (**31.5 MV/m Q_0=1** x 10^{10})
  - 1TeV (**45 MV/m Q_0=2** x 10^{10}, 300 MW)
  - more SCRF, tunnel extension
  - Site: 50km long, sufficient for 1TeV



Courtesy: S. Michizono

~ 1.3 GHz SRF Accelerators, worldwide

ESS (0.8 GHz)
(under construction)



ILC (planned)

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

LCLS-II -HE
(in commissioning)

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

European XFEL
(in operation, 2017~)

800 cavities
100 CMs
17.5 GeV (Pulsed)

SHINE
(under construction)

~600 cavities
75 CMs
8 GeV (CW)

JLab-CEBAF(1.5 GHz)
(in operation)

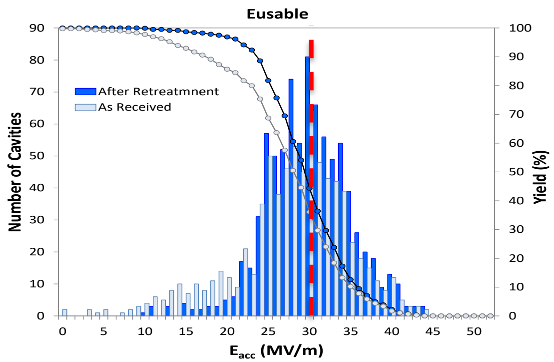
40 CMs
6~12 GeV(CW)

> 2,000 1.3 GHz SRF cavities being realized, in these decades !

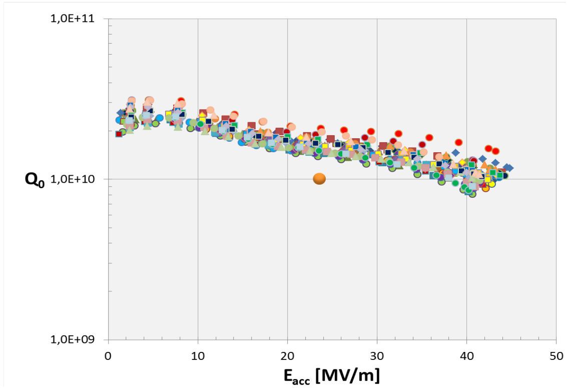
European XFEL, SRF Linac Completed and 5-year Operation

Progress:
- 2013: Construction started
- 2017: E-XFEL beam start
- 2018: 17.5 GeV achieved

1.3 GHz / 23.6 MV/m
800+4 SRF acc. Cavities
100+3 Cryo-Modules (CM)



<E-usable> : 29.8 MV/m
(RI): 31 MV/m w/ 2° process
33 MV/m w/ 3° process

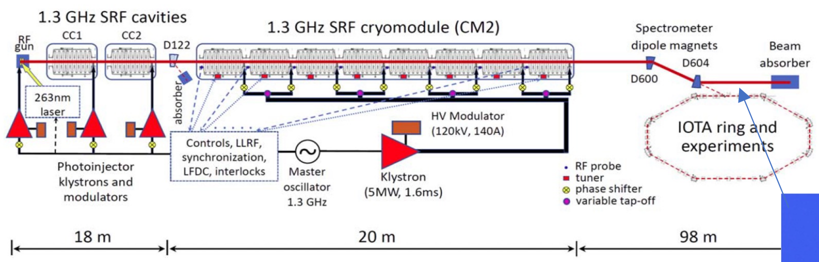


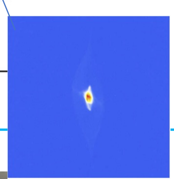
>10 % (47/420, RI) cavities exceeding 40 MV/m

Courtesy: V. Shiltsev, Y. Yamamoto

Fermilab, KEK achieving ILC Gradient Goal ≥ 32 MV/m with beam

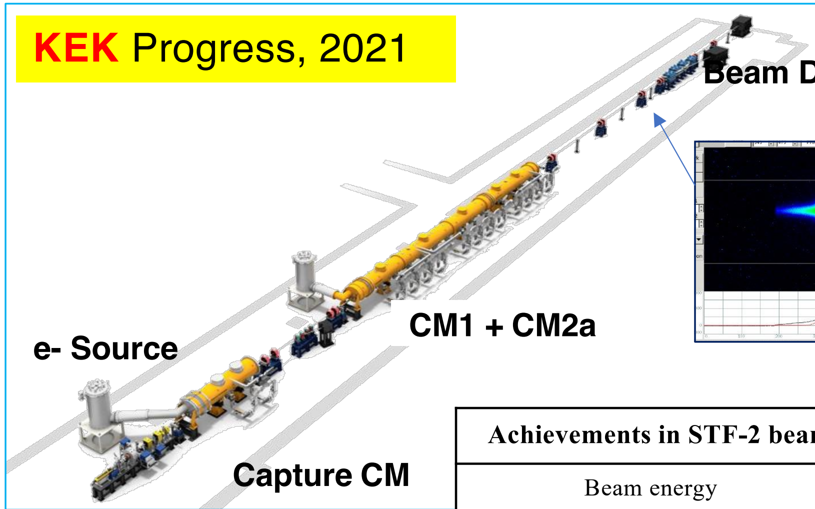
Fermilab-FAST Progress, 2017

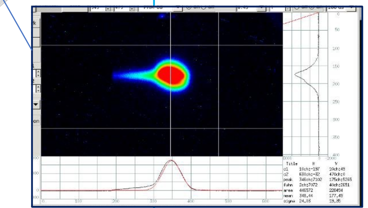




Beam Acc. : 260 MeV by 8 Cavities,
<G> = 32.3 MV/m

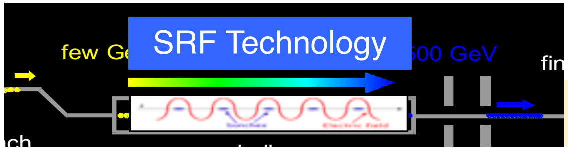
KEK Progress, 2021





Achievements in STF-2 beam commissioning	
Beam energy	280 MeV
Beam power	75 W
Beam current	275 nA
Charge	55 nC/pulse
# of bunches	1000 / pulse
Average gradient estimated from beam energy	33.1 MV/m
Average gradient measured by power meter	33.8 MV/m

<G> = 33.1 MV/m (averaging for 7 cavities)



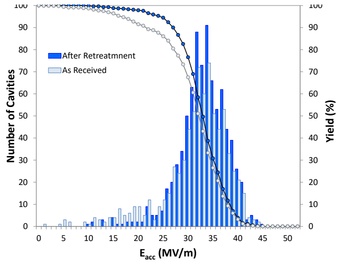
Progress Summary in SRF

～2018	2018～2021	2022～

Cavity

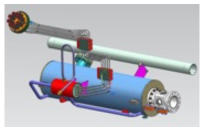
Yield evaluation of cavities based on TDR

Eu-XFEL: 33MV/m achieved at 82%.
(ILC specification: 35MV/m at 90%)



Cryomodule

Eng. design



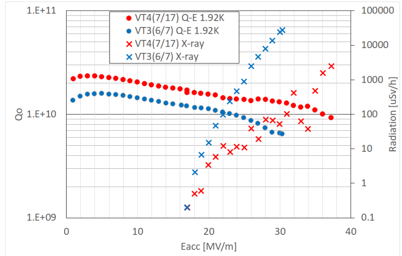
Euro-XFEL Operation (Europe)
~800 cavities/
~100 Modules

LCLS-II Construction (USA)
~280 cavities/
~35 Modules

Realized through international cooperation and procurement

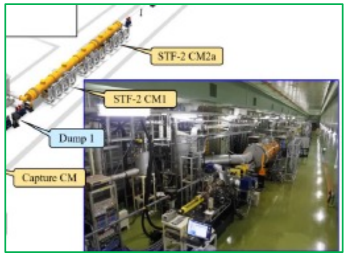
High performance and cost reduction

High performance with new surface treatment, etc.



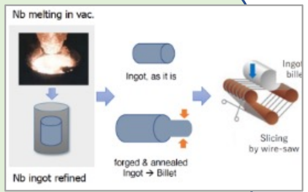
N-infusion cavity Installation to the STF-2 (KEK)

Module assembly



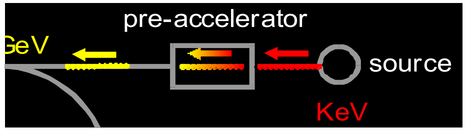
Accelerator performance verification at KEK-STF2

Development of clean environment construction and assembly automation to maintain cavity performance

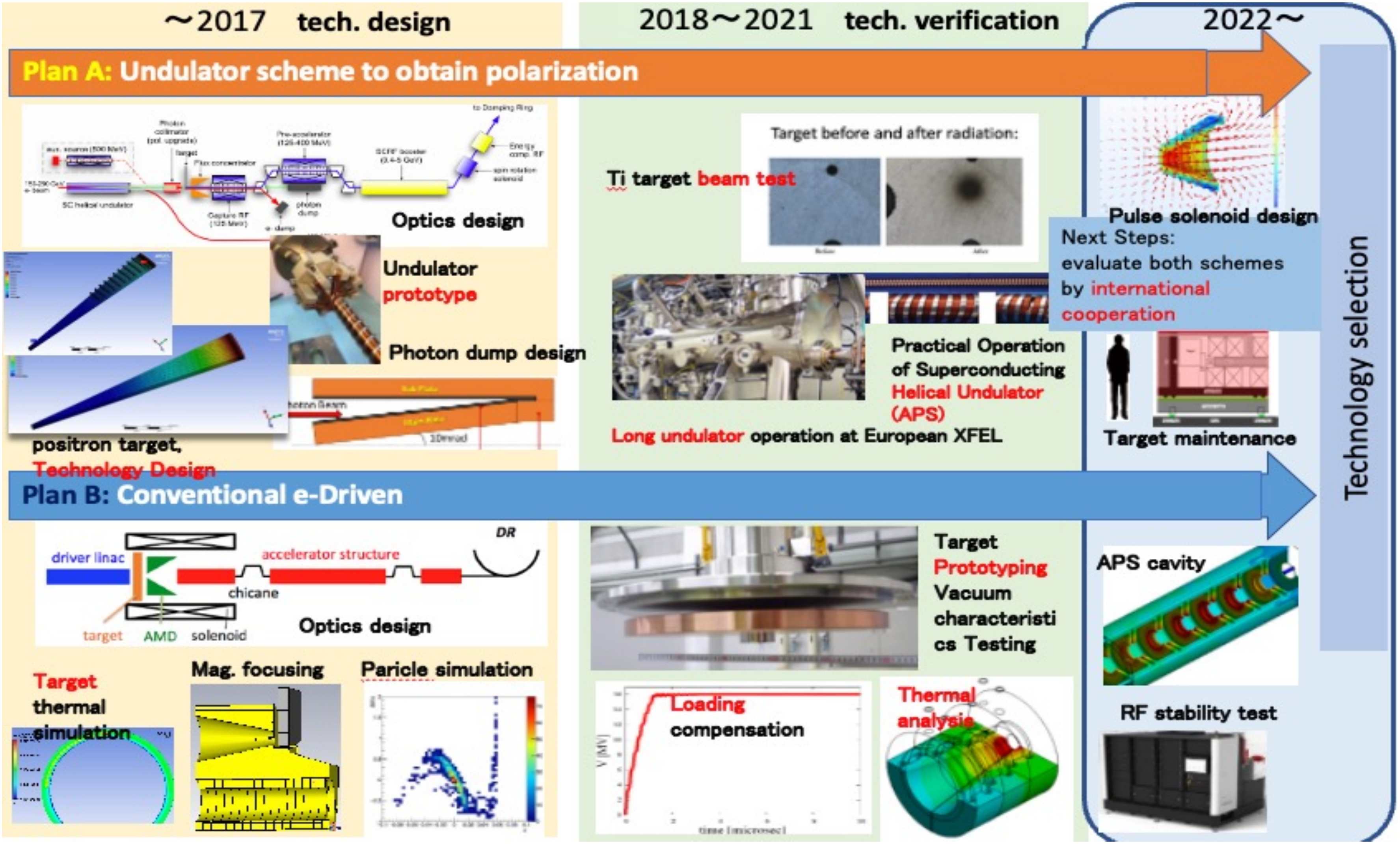


Cavity manufacturing, performance demonstration (Yield demonstration in three areas)

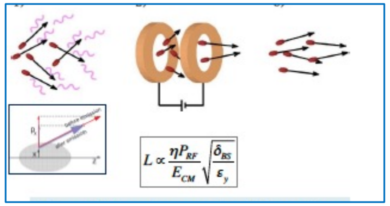
Update of cryomodule engineering design assembly, and performance

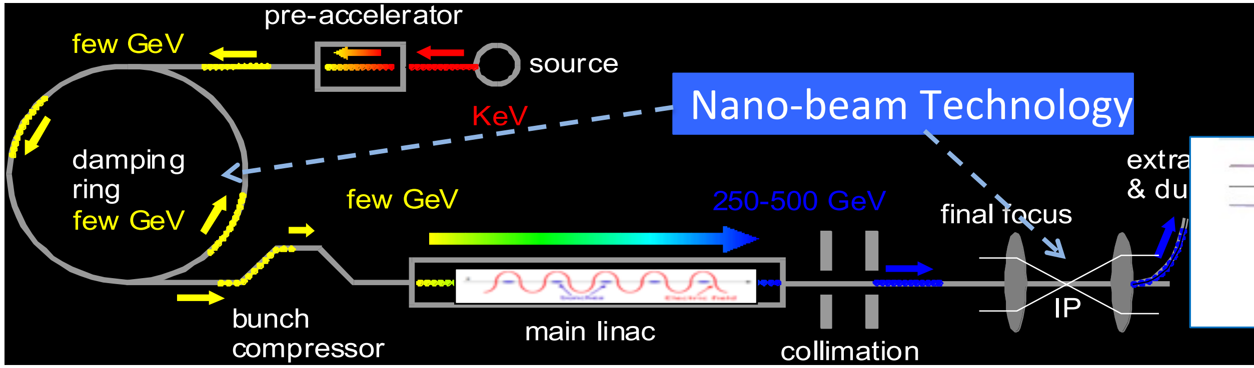


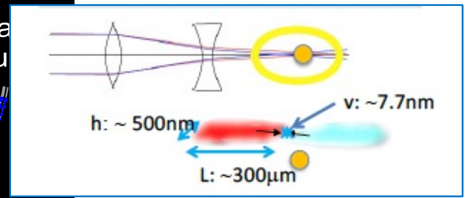
Progress in positron source

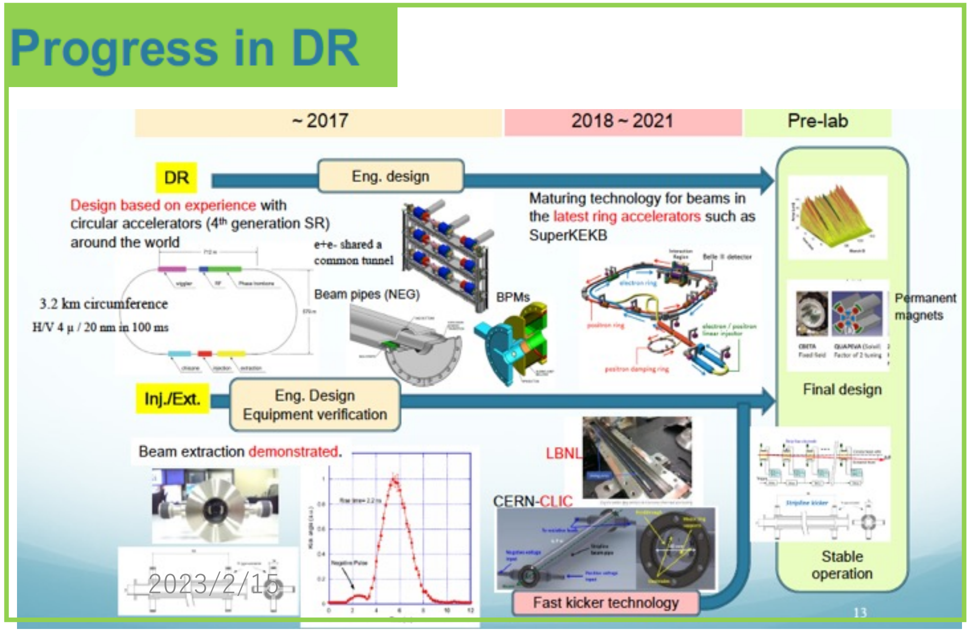


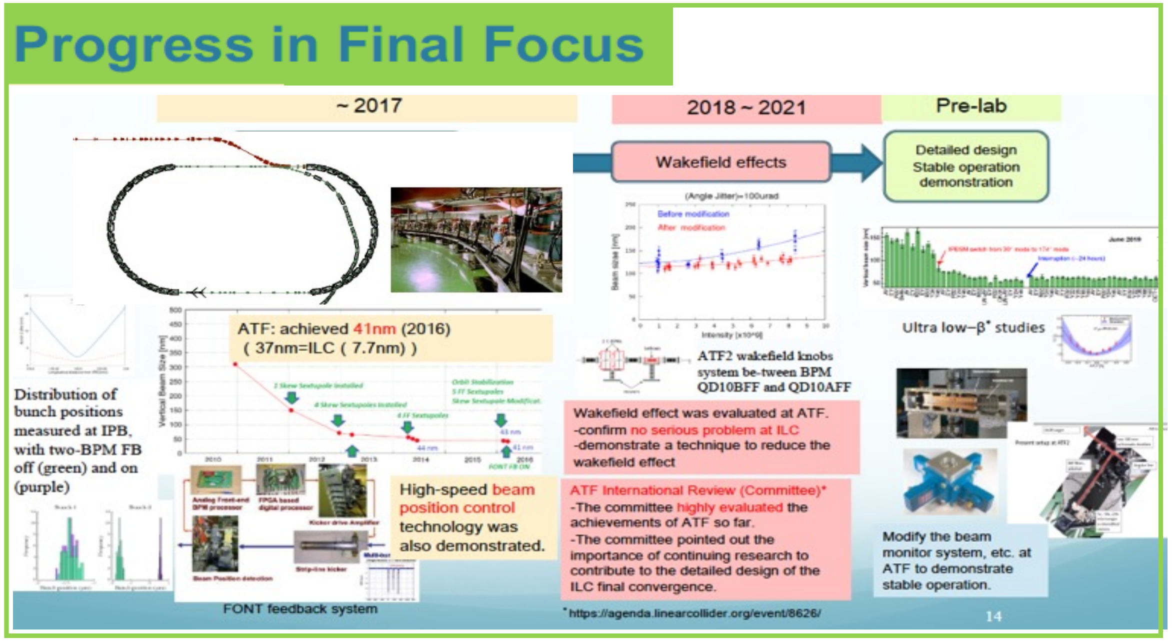
Progress in Nano-beam Technology











Summary of ILC Technology Readiness Level

Reached in 2021

Since CDR/**RDR** in 2007 and **TDR** in 2013, the technical development has progressed toward ILC construction.

Status	(RDR) (TDR)	2021	(EDR)*	
SRF cavity, CM	~2017 Technology development ->Model work-> Prototype	2018~2021 High performance and cost reduction of cavities	International mass production, and transfer demonstration	ILC construction
SRF Linac	**Model work: small-scale models, partial/component models.**	European XFEL user operation		
e- source	~2017 Tech. Design->Tech. Development->Tech. Demonstration		Tech. confirmation	
e+ source **Undulator scheme**	~2017 Tech. Design->Tech. Development	2018~2021 Tech. Demonstration	Target and magnetic focusing	
e+ source **e-driven scheme**	~2017 Tech. Design->Tech. Developmen	2018~2021 Tech. Demonstration	Target and capture cavity	
DR	~2017 Design->Tech. Development-> Tech. demonstration achieved at KEK ATF		Kicker	
Final focus	~2017 Design->Tech. Development->Tech. demonstration achieved at KEK ATF		Stable op.	
Dump	~2017 Tech. Design->Tech. Development			

***EDR:**
Detailed Engineering Design Report required to start construction.

: ~2017
: 2018~2021
: Pre-lab (expected)

Outline

- Introduction:
  - Progress in Accelerator Technology
- **ILC T**echnical **N**etwork (**ITN**) for Global Acc. R&D Programs
- Future Prospect in Technology Advances
- Summary

History of ILC Collaboration

international development team

2004 ‘06 ’07 ’08 ‘09 ‘10 ‘11 ‘12 ‘13 ‘14 ‘15 ‘16 ‘17 ‘18 ‘19 ‘20 ‘21 ’22 ‘23

RDR | ILC-GDE | TDR | LCC

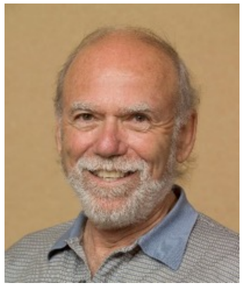
Technology selection

ILC technical design

TDR:
49 countries
392 institutions
>2400 researchers

*I*nternational *D*evelopment *T*eam

Tatsuya Nakada (EPFL)
IDT chair



Barry Barish
GDE director
(the Nobel Prize winnerin 2017)

Lyn Evans
LCC director
(former LHC project manager)

LHC

European XFEL

LCLS-II

ICFA

ILC International Development Team

Executive Board

Americas Liaison	Andrew Lankford (UC Irvine)
Working Group 2 Chair	Shinichiro Michizono (KEK)
Working Group 3 Chair	Jenny List (DESY)
Executive Board Chair and Working Group 1 Chair	Tatsuya Nakada (EPFL)
KEK Liaison	Yasuhiro Okada (KEK)
Europe Liaison	Steinar Stapnes (CERN)
Asia-Pacific Liaison	Geoffrey Taylor (U. Melbourne)

Working Group 1
Pre-Lab Setup

Working Group 2
Accelerator

Working Group 3
Physics & Detectors

ILC supported by ICFA

April 2022:

ICFA re-stated support for ILC and extended IDT mandate:

- **IDT,** oversighted by ICFA, has identified:
  - **Time-critical Work Packages** (**WP-prime's**), and is exploring collaboration among KEK and international partners, with **ILC Techical Network** (**ITN**), with new funding expected in Japan, **JFY2023 ~** (starting April 2023) , enabling Japanese contribution to encourage other region's efforts,
  - **Preparing** the phase for **ILC-Prelab** & **E**ngineering **D**esign **R**eport (**EDR**) for the ILC **construction,**

    and
- **ICFA** continues to encourage:
  - inter-governmental discussions between Japan and potential partner nations toward an **ILC** realization.

https://icfa.hep.net/wp-content/uploads/ICFA_Statement_April2022_Final.pdf

Courtesy: T. Nakada, in 2022

The IDT Mandates and Activities

- Organising ILC Technology Network,
- Making further advances in the development of ILC related technologies in view of providing more solid **bases for the ILC engineering design** and opportunities for other accelerator **applications.**
- The work programme derived from the work packages in the ILC Pre-lab proposal by selecting technically **most critical items (WP-primes)** and those that require long time to develop, based on **collaboration** agreements between **KEK** and interested **laboratories worldwide**.
- The execution of the work will be managed by each collaborations.
- The **IDT** will provide the **overall coordination** work including;
  1. Technical description of the work programme
  2. Definition of deliverables and required resources
  3. Distribution of the deliverables and defining the timeline
  4. Help drafting of MoU and research agreements
  5. Follow up and monitoring of the **overall project**
- Anticipated start in **April 2023**, i.e. the start of the Japanese Fiscal Year 2023 for a period of around two to four years depending on the work.

IDT Scope for ILC Realization

Aug. 2020

IDT → IDT → Pre-lab → ILC construction by ILC Lab. → Experiment at ILC

International **D**evelopment **T**eam, under ICFA

Pre-lab organized by MoU's Among the relevant labs.

ILC lab. based on Governmental Agreement

2021 May

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

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

2022 June

Time-critical WPs for the ILC construction

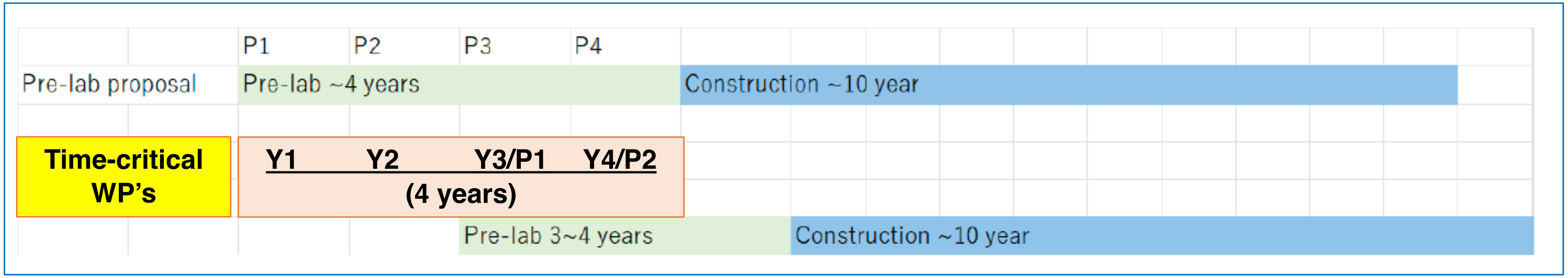
WP-Primes for Time Criticals

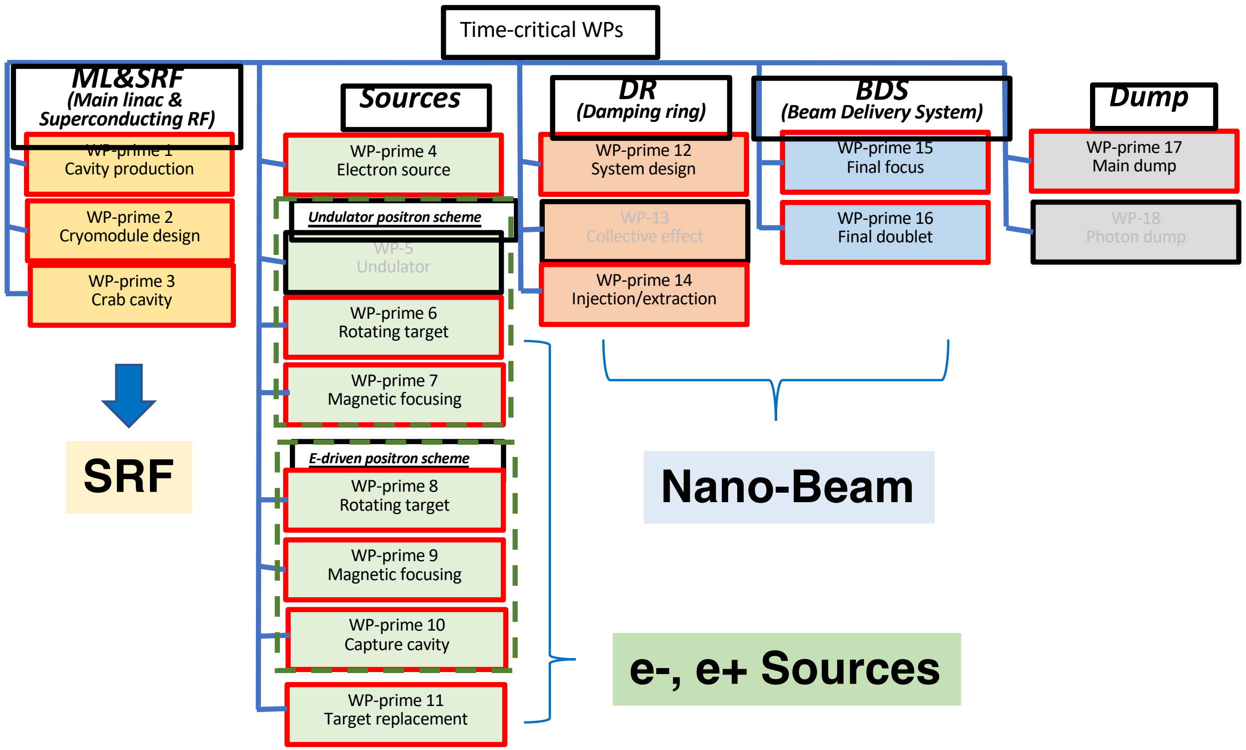
- **ILC Technical Network (INT)**
  - **Acc. R&Ds** to prepare fo EDR, focusing on
    - SRF
    - e- & e+ Sources
    - Nano-beam
    - Beam Dump

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

https://agenda.linearcollider.org/event/9735/c ontributions/50816/attachments/38190/5996 8/Time-Critical_WPsV8b.pdf

WP-Primes at ILC Technology Network



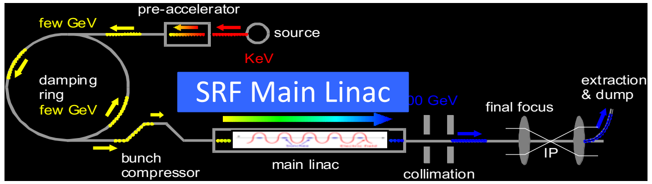


WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	5	
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	System design
WPP	13	
WPP	14	Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

SRF (WPP 1–3)

e-, e+ Sources (WPP 5–11)

Nano-Beam (WPP 12–16)

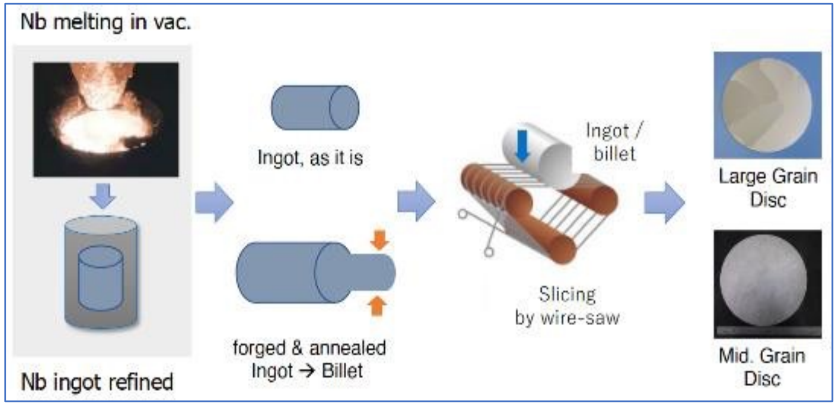


WP-prime 1: SRF Cavity

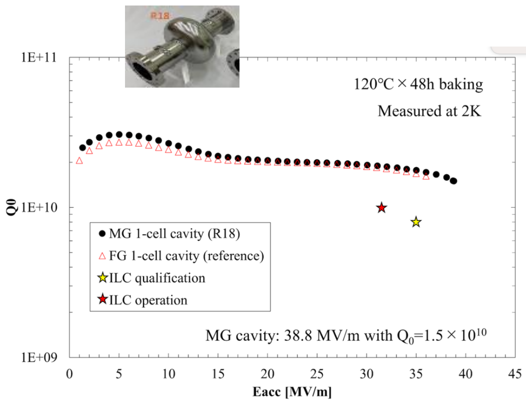
Aiming at Production Readiness with Cost effective production

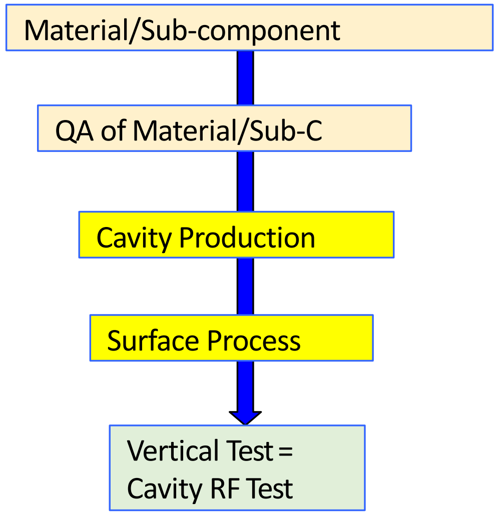
- ◆Research with single-cell cavities to establish the best production process including:
  - ◆Advanced Nb sheet/disk cost effective production method → MG
  - ◆Advanced surface treatment recipe
- ◆Globally common design with compatible High Pressure Gas Safety (HPGS) regulation
- ◆24 nine-cell cavities are to be developed for industrial-production readiness
  - ◆8 cavities (4 / batch) in each region → 4 with **FG** and 4 with MG
  - ◆Production process encouraged to be optimized in each region
- ◆RF performance/success yield to be examined (including 2nd pass and further)
  - ◆3rd pass to be examined if effective

	# cavities to be produced		
	Americas	Europe	JP/Asia
single-cell	2	2	2
nine-cell	8	8	8+a



Medium **G**rain (**MG**) Nb Disk
A cost-effective production

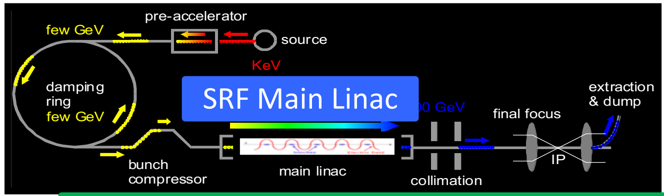


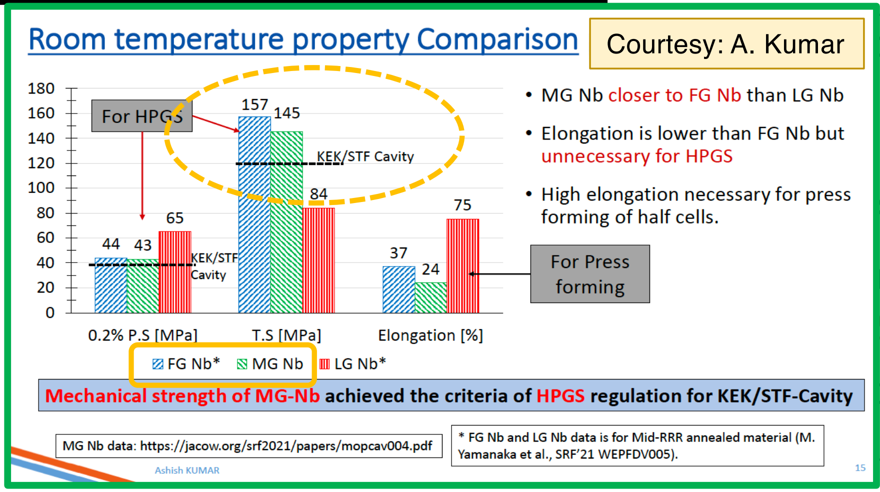


Production process

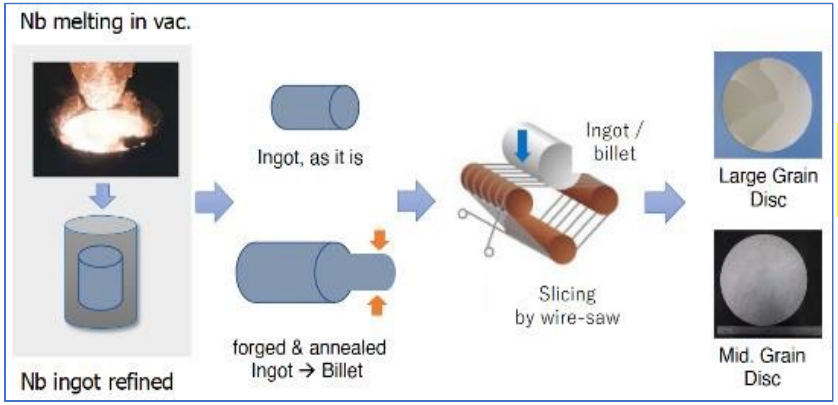
WP-prime 1: SRF Cavity

Aiming at Production Readiness with Cost effective production

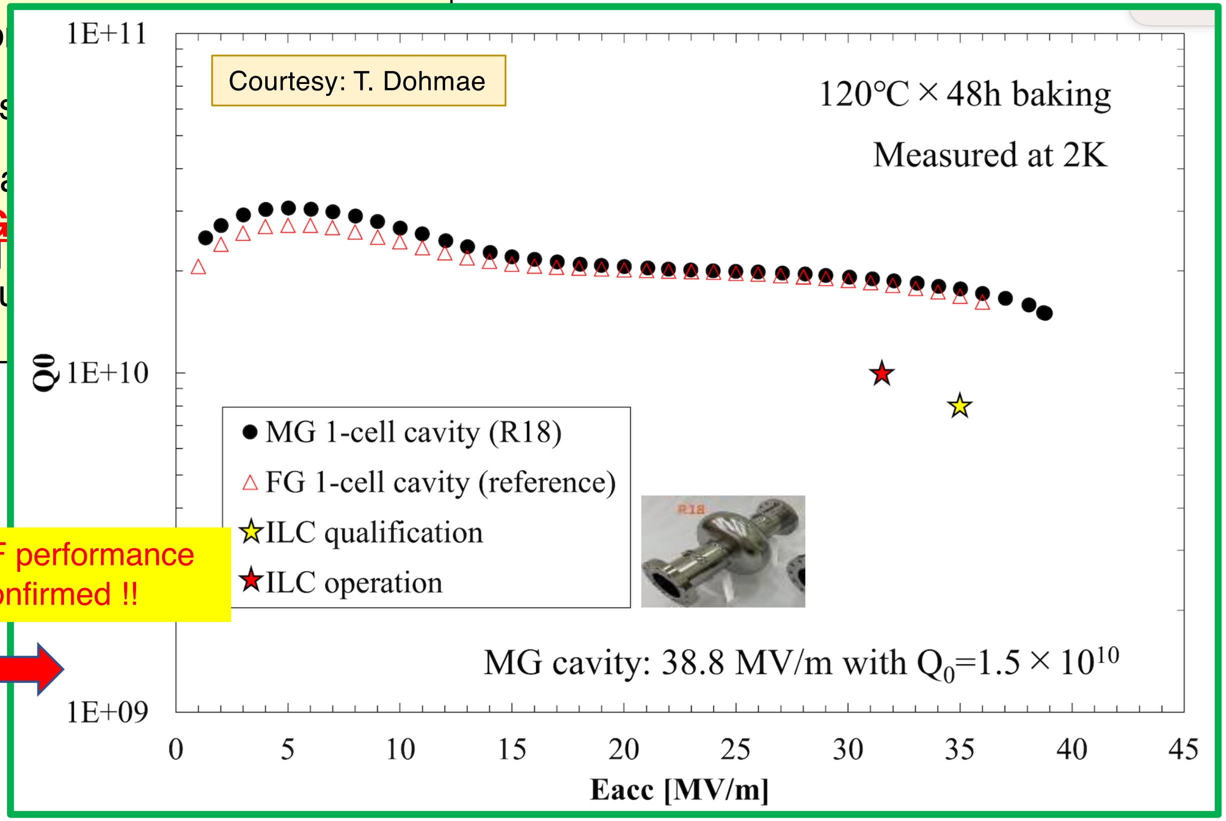




est production process



Medium Grain (MG) Nb Disk
A cost-effective production



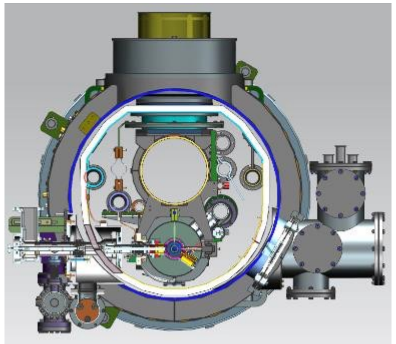
RF performance Confirmed !!

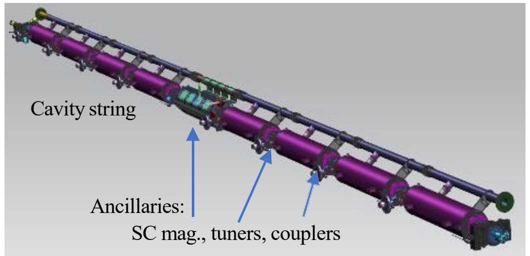
Production process

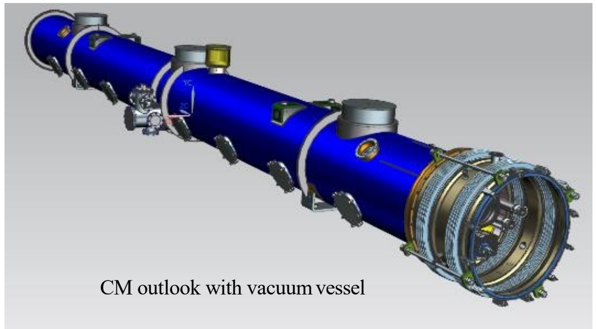
WP-prime 2: Cryomodule (CM) Design

Referring progress in particular LCLS-II experiences

- Unify cryomodule (CM) design with ancillaries, based on globally common engineering design, drawings. and
- Establish globally compatible safety design base to be approved/authorized by HPGS regulations individually in each region, most likely referring ASME guidelines to be compatible with Japanese regulations.







Region Regulation	Americas ASME	Europe Eu-EN, TUV	Japan/Asia JP-HPGS Act
CM tech. design base	LCLS-II	Euro-XFEL	KEK-STF, AST-IFMIF
ILC CM design	Common CM design globally compatible to HPGS regulation in all regions, and most likely ASME guidelines to be compatible with Japanese regulations.		

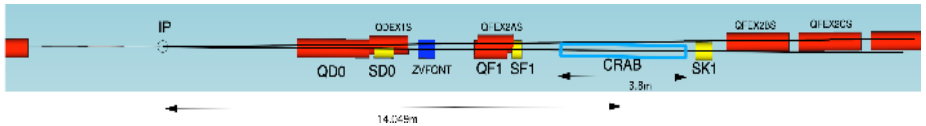
An **International CM,** KEK contributed, to be demonstrated with **cavities globally contributed !!**

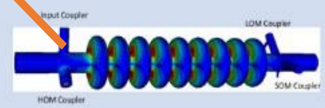
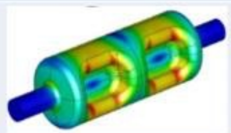
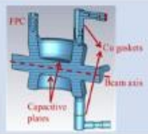
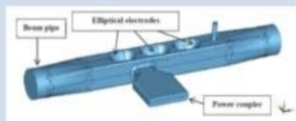
WP-prime 3: Crab Cavity Development with Two-Design Down-selection and Prototypes

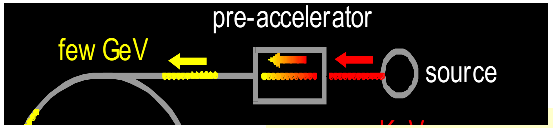
- RF property simulation to optimize cavity design
- Pre-down-selection to choose two primary candidates
- Development and evaluation of **two prototype** cavities
- Demonstration of synchronized operation with prototypes
- Down-selection to choose final cavity design
- Cryomodule design based on final cavity design

Item	Recent specification (after TDR)
Beam energy	125 GeV (e^-)
Crossing angle	**14 mrad**
Installation site	14 m from IP
RF repetition rate	5 Hz
Bunch train length	727 μsec
Bunch spacing	554 nsec
Operational temperature	2.0 K (?)
Cavity frequency	1.3/3.9 GHz
Total kick voltage	1.845/0.615 MV
Relative RF phase jitter	0.023/0.069 deg rms (49 fs rms)

two beamline distance 14.049m x 0.014rad = **197mm**



Elliptical/Racetrack (3.9 GHz)	Lanc. Univ.	
RF Dipole (RFD)	ODU	
Double Quarter Wave (DQW)	CERN	
Wide Open Waveguide (WOW)	BNL	
Quasi-waveguide MultIcell Resonator (QMIR)	FNAL	



WP-prime 4: Electron Gun

- The electron gun consists of
  - High-voltage photo gun
  - Drive laser system
  - GaAs/GaAsP Photocathode
- High-voltage gun is the most urgent item
  - The gun voltage in TDR is 200 kV. A higher voltage desirable.
  - Meaningful technical progresses since TDR would be reflected in a new design
  - New GaAs gun based on lessons learned from 350 kV CsKSb magnetized dc photogun

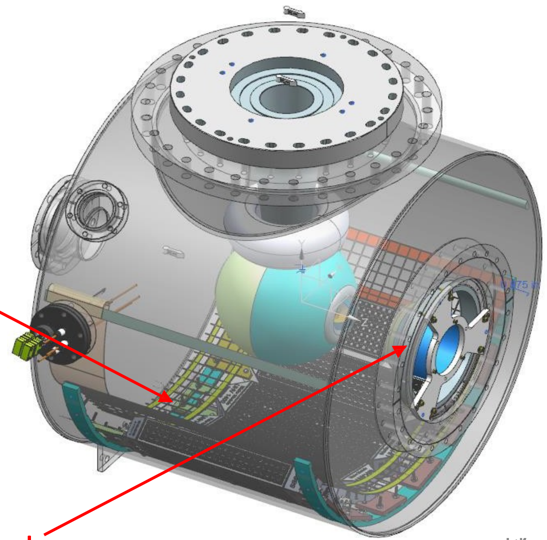
350 kV alumina insulator

Triple-junction shield

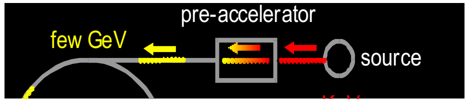
NEG pumps

Cathode electrode

Photocathode

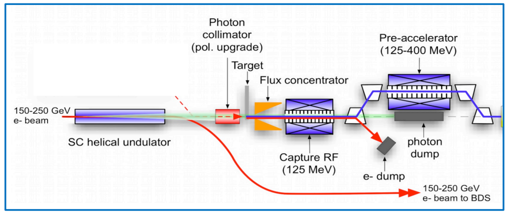


Biased and Tilted Anode



WP-p-6: Undulator-driven e+ Source:

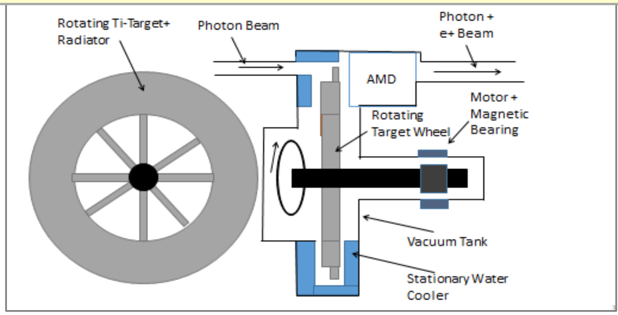
Rotating Target , WP-p-7: Focusing System

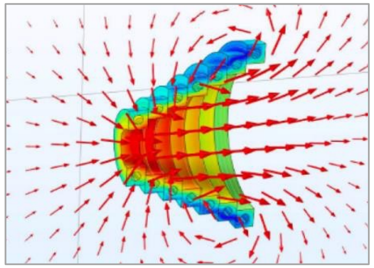


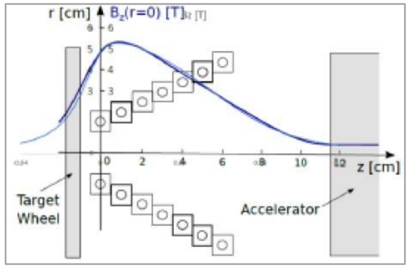
Undulator positron source

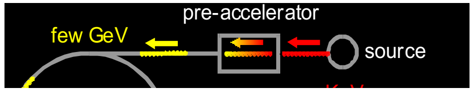
- Target specification
  - Titanium alloy, 7mm thick (0.2 X_0), diameter 1m
  - Rotating at 2000 rpm (100 m/s) in vacuum
  - Photon power ~60 kW, deposited power ~2 kW
  - Radiation cooling, Magnetic bearings
- R&D to be done as WP-prime
  - Design finalization, partial laboratory test, mock-up design (in the first 2 years)
  - Magnetic bearings: performance, specification, test

- The critical item for the undulator scheme is the magnetic focusing system right after the target
- Possible candidates are: (a) Pulsed solenoid, (b) Plasma lens
- The strongest candidate is (a) pulsed solenoid.
- R&D items to be done as WP-prime
  - Detailed simulations for (a) (already on-going)
  - Principal design for a prototype pulsed solenoid
  - Field measurements with 1kA (pulsed and DC) and with 50kA both in a single pulse mode and finally in a 5ms pulsed mode
  - Prototype of (b) plasma lens (funded study on-going)

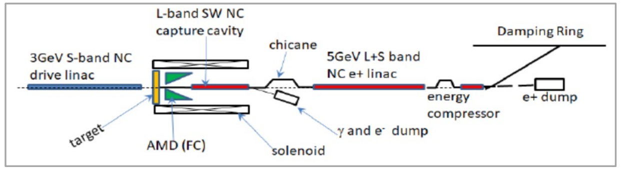








WP-Prime 8~11:
Electron(e-) driven positron source (1/3)

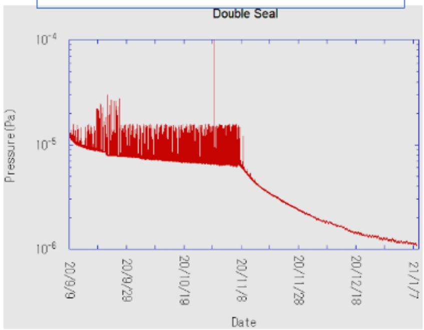


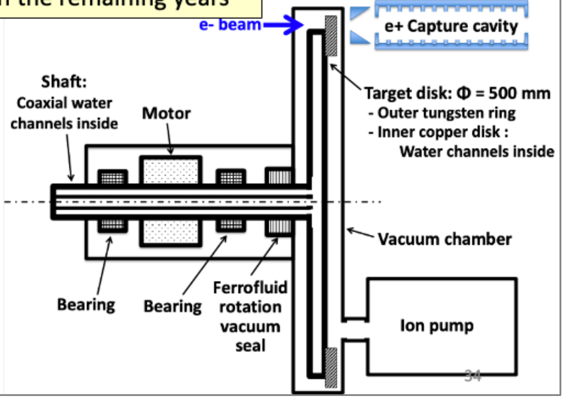
WP-prime 8: Rotating Target for e-Driven Scheme

Similar to C3 positron source

- Target specification
  - W or W-Re, 16 mm (5 X_0) thick, diameter 50cm
  - Rotating at 5 m/s in vacuum
  - Water cooled.
  - Vacuum seal by ferromagnetic seal
- R&D items to be done in 2 years
  - Target stress calculation with FEM
  - Vacuum seal
  - Target module design
- Target module prototyping can be done in the remaining years

Vacuum test with double seal



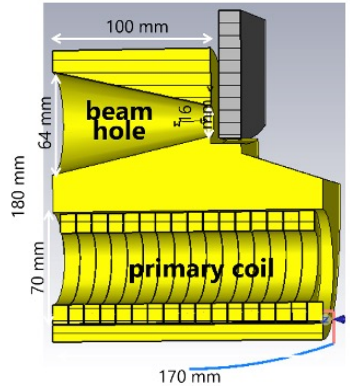


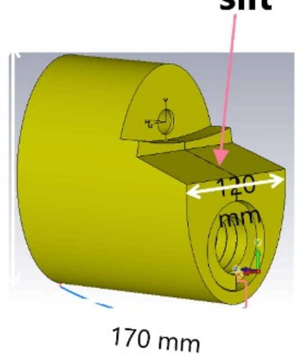
WP-prime 9: Focusing System for e-Driven Scheme

Similar to C3 positron source

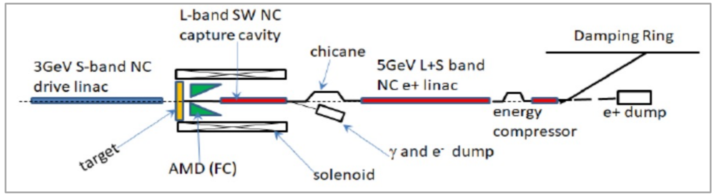
- Flux Concentrator (FC) is chosen as the focusing device after the target
- The specification parameters such as max field, electric current and the dynamic force are satisfied in existing target, but the pulse energy and the heat load are higher.
- A prototype necessary after detailed design study
- R&D items as WP-prime
  - Flux concentrator conductor design (in first 2 years)
  - Conductor prototyping (in the remaining years)

Parameter	ILC FC	Unit
Max. B field	5	T
Max. surf. current	25	KA
Dynamic force	125	kA.T
Pulse energy	140	J
Average Power	13.7	kW





WP-Prime 8~11:
e- driven positron source (2/3)

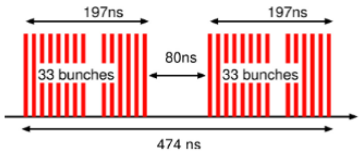


WP-prime 10: Capture Cavity and Linac for e-Driven Scheme

- The positrons after the magnetic focusing system are accelerated to 5GeV through various linacs (Standing wave, travelling wave, S-band, L-band) and injected into the damping ring.

Similar to C3 positron source

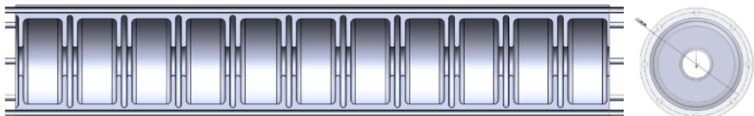
- Technically the most critical element is the L-band, standing-wave structure right after the target and FC.
  - High beamloading (up to ~1A)
  - Special bunch pattern →
  - Changing beam current (mixed electron-positron, capture process in RF buckets)



- The technologies of the power unit is known well but it is needed for the test.

- R&D items as WPP-10 for the first 2 years
  - APS (Alternating Periodic Structure) cavity design and cold model
  - Beam-loading compensation and tuning method
  - L-band klystron design
  - Power unit prototype design
  - solenoid design
- Prototyping of these components in later years

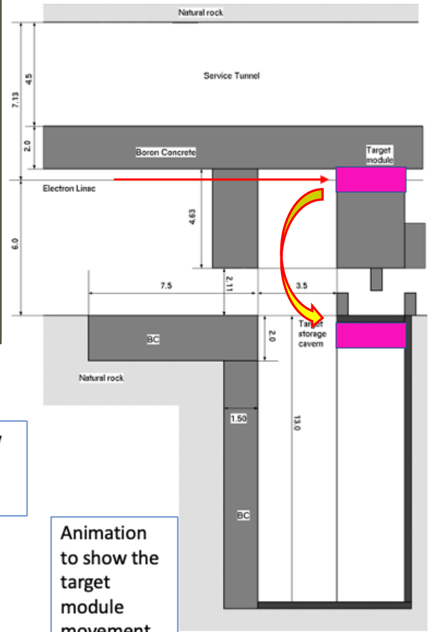
APS cavity →

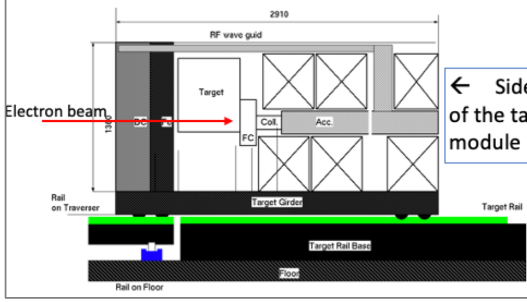


WP-prime 11:Target replacement

- Special attention is needed due to the high radiation of the target area. This is a common issue for E-Driven and Undulator positron source.
- Careful design of shielding is required.
- The components near the target (target, flux concentrator, first cavity with solenoid) require replacement in every few years. The work must be done by remotely.
- The works to be done as WP-prime
  - Conceptual design
  - Fabricate Mockup
  - Prototyping of critical components

Floor layout of the target section.





← Side view of the target module

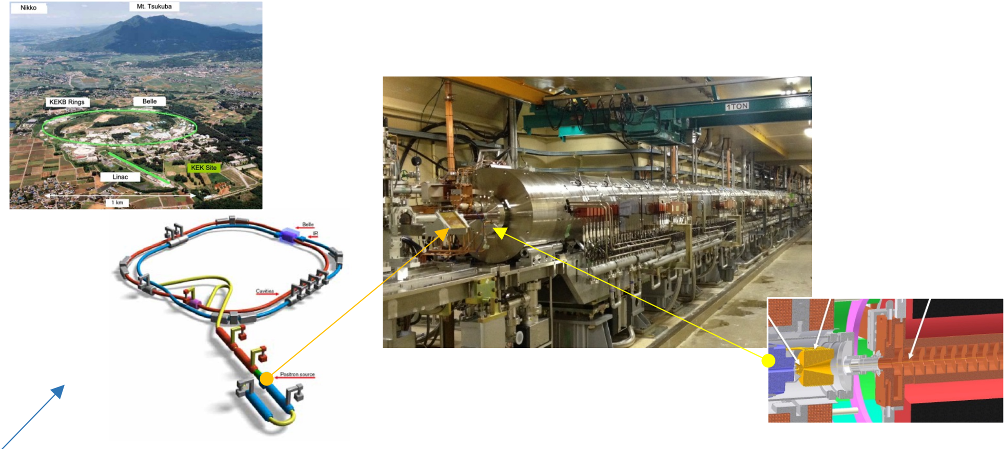
Animation to show the target module movement

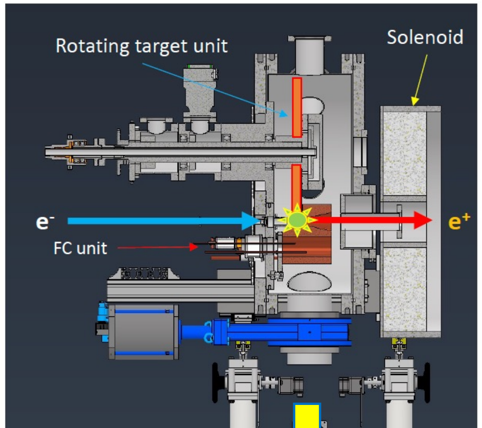
WP-Prime 8~11:
e-driven e+ source (3/3)

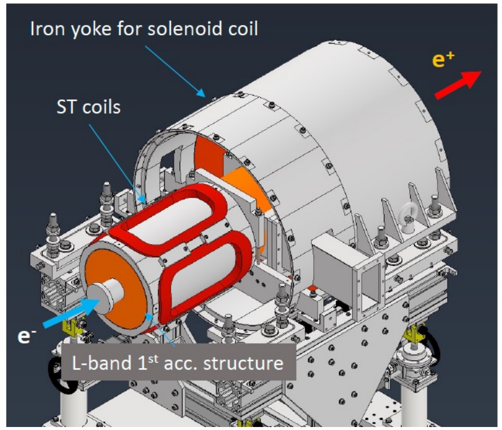
An effort to be enhanced in the WP-Prime 8-11, ITN phase :

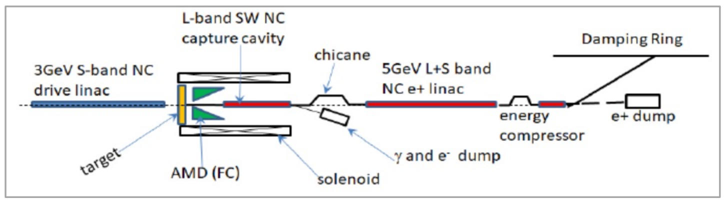
- A prototype development, based on experiences at Super-KEKB e+ source

- Engineering design toward ILC:
  - 3D-CAD model and engineering drawings for manufacturing, based on simulation and experiments

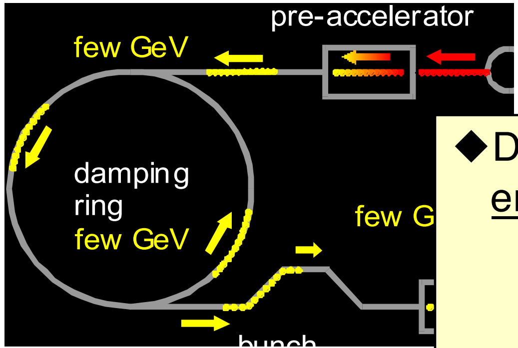


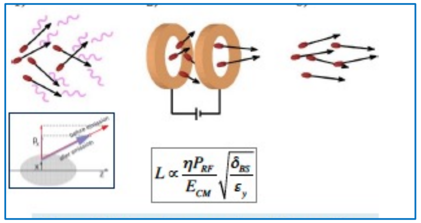






WP-prime 12: DR System Design





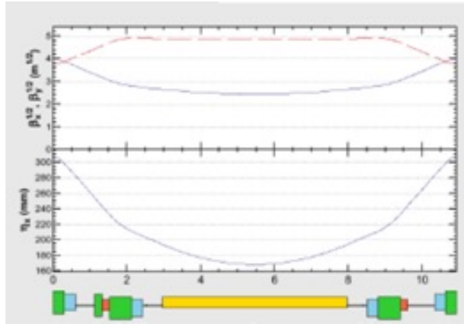
◆Damping Ring (DR) design required to satisfy the low emittance and the large dynamic aperture simultaneously:

- DR design will be **further improved** by incorporating findings of the latest light source design.

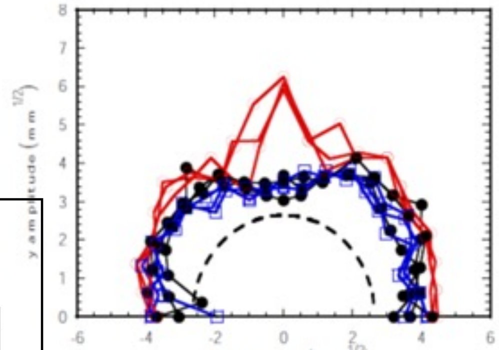
◆ Increasing the dynamic aperture is also important:

- By quantitatively evaluating effects of fringe field to the dynamic aperture of magnets in ILC DR, the method for evaluating the fringe field to the dynamic aperture in accelerator design will be established.

◆The system design of ILC DR will be further optimized.

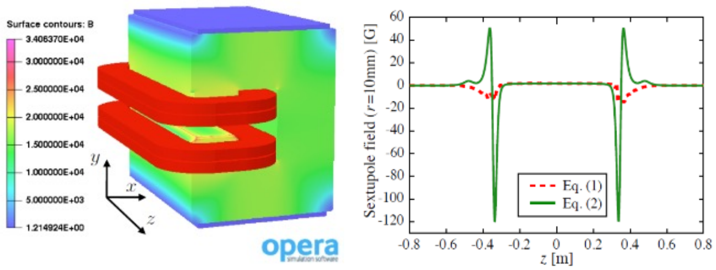


Damping ring optics

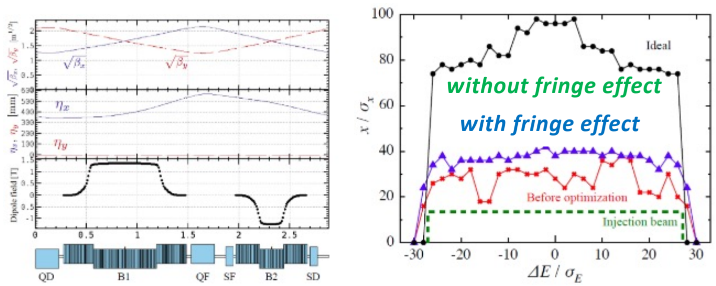


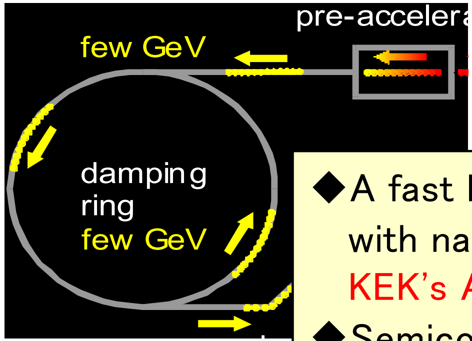
Dynamic aperture for ILC DR (hard edge)

Modeling of the fringe field for SuperKEKB DR



Dynamic aperture evaluation with fringe effect (SuperKEKB DR)



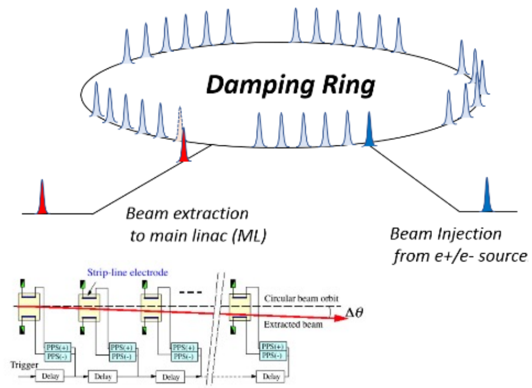


WP-prime 14: System design of ILC DR injection/extraction kickers

Courtesy:
ATF collaboration

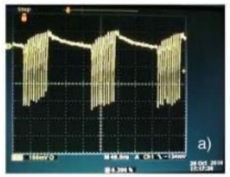
- ◆A fast kicker system using a semiconductor pulse power supply with nanosecond response was confirmed as proof of principle at KEK's ATF about 10 years ago.
- ◆Semiconductor technology has been evolving, and it is now possible to advance nanosecond response beam injection/excitation systems using the recent semiconductor technology.
- ◆The technical evaluation of the fast kicker power supply using the recent semiconductor technologies.
- ◆The evaluation of fast pulsed power supply technology will contribute not only to the fast kicker system but also to the performance and reliability of nanosecond–scale beam control technology and its application to a wide range of accelerator systems.

ILC fast injection/extraction system

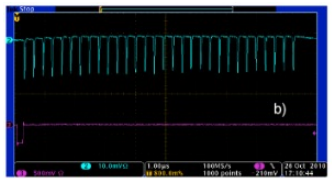


Beam extraction test at KEK ATF

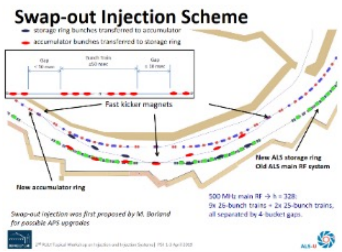
Stored beam in DR

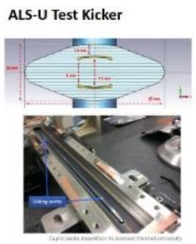


Extracted beam from DR

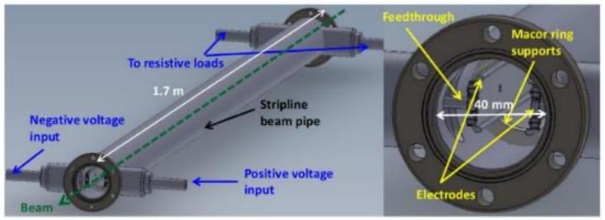


Swap-out injection system planned at LBNL



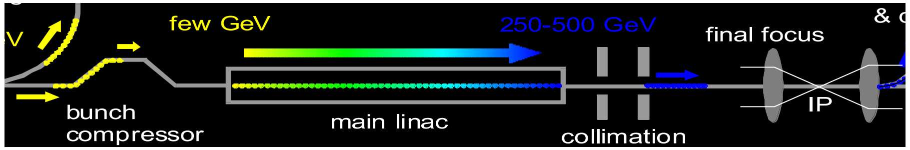


Beam injection/extraction system for CLIC damping ring

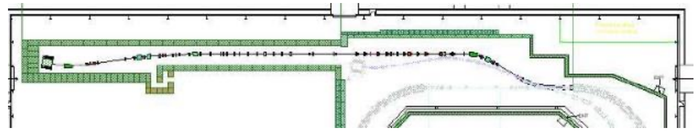


WP-prime 15: System design of ILC FF System

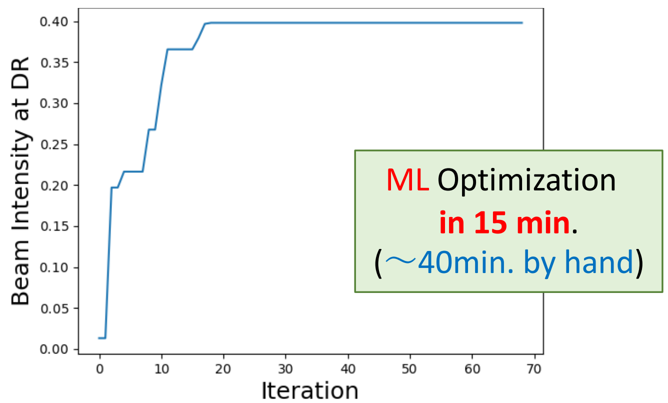
Courtesy:
ATF collaboration



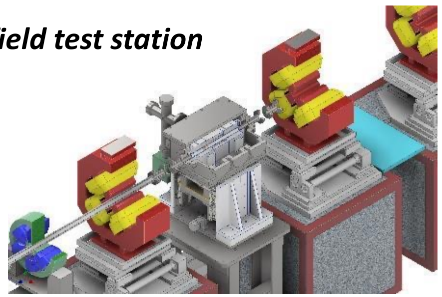
ATF2 beamline



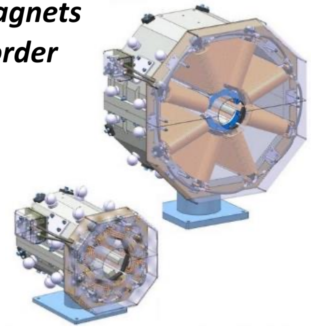
- ◆ATF2 beamline is the only existing test accelerator, around the world, for advanced study of the final focus system (FFS) of linear colliders, as a common subject with CLIC.
- ◆The following 3 research topics are important topics to be pursued at the ATF.
  - ◆ Wake-field mitigation
  - ◆ correction of higher-order aberration
  - ◆ training for ILC beam tuning
- ◆The technical research at ATF2 should be extended by the ATF international collaboration, or its extension (ATF3 under discussion, and welcome new collaborators).



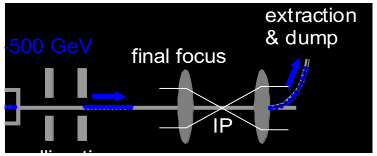
Wakefield test station



Octupole magnets for higher-order aberration



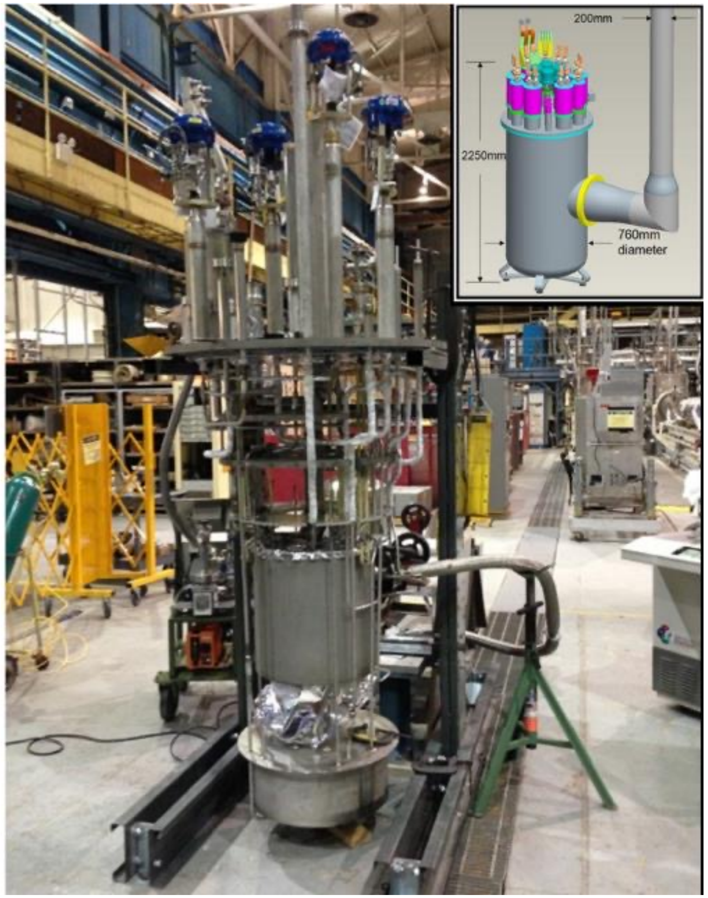
Maximum search algorithms applied to beam tuning (→Machine Learning (ML))



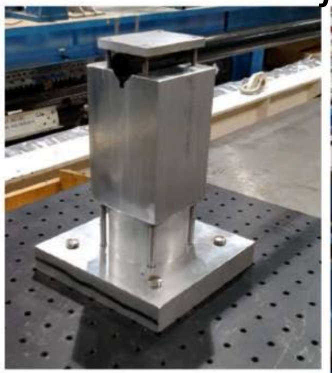
WP-prime 16: Final doublet design optimization

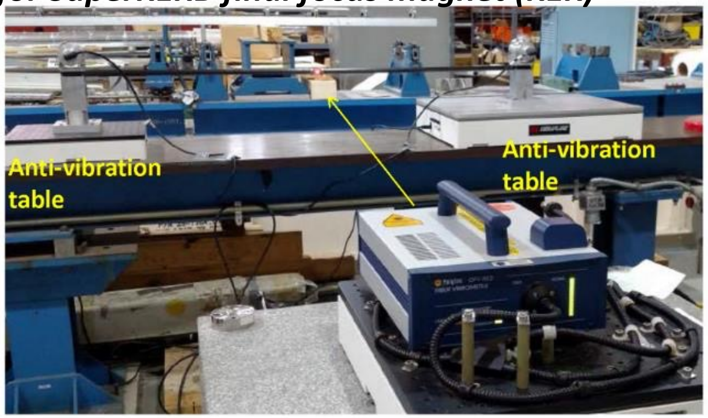
- ◆Cooling of the superconducting ILC final focus magnets will be performed using 2K superfluid helium to realize superconducting magnets with high oscillation stability.
- ◆Quantitative evaluation of the vibration generated by the 2K cooling system located on the side of the final focus magnets has not been completed.
- ◆We will measure and evaluate the vibration generated by the 2K cooling system by using the prototype.

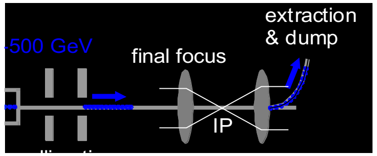
Prototype of ILC service cryostat
(2K cooling system ; BNL)



Vibration measurement system
for SuperKEKB final focus magnet (KEK)





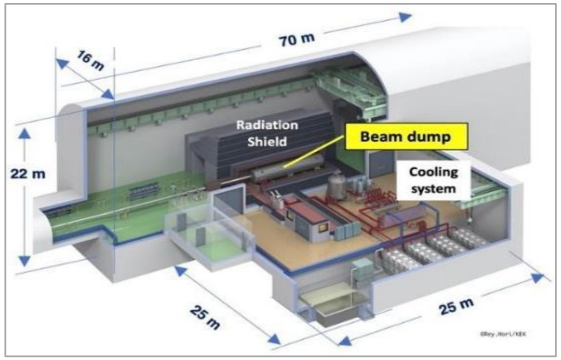


WP-prime 17: Beam Dump

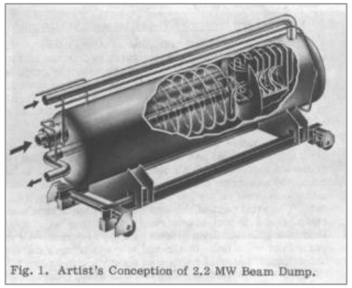
◆ Finalize the engineering design of the main beam dump system

- Vortex water flow in the dump vessel
- Cooling water circulation and heat exchange
- Remote exchange of the beam window
- Countermeasure for failures / safety system

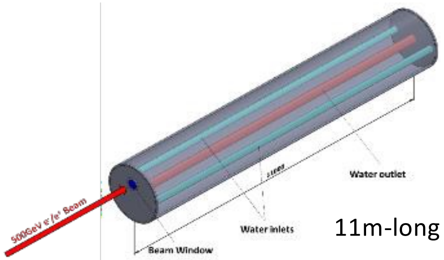
JLAB has long experience in operating the water dump.



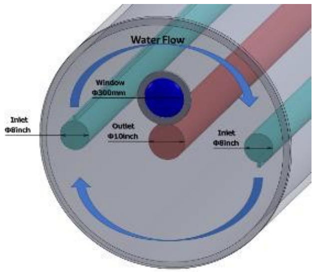
Imaginary view of the main dump section



SLAC 2.2MW water dump (precedent) as a reference

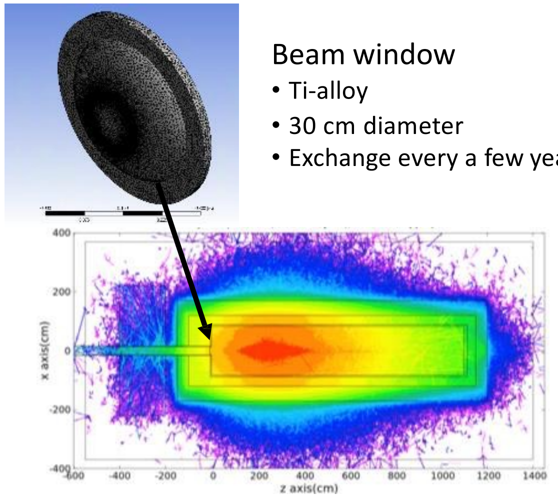


11m-long x 2m(diameter) water



Vortex water flow

- **17 MW** at 500 GeV beam
- 1 MPa to prevent boiling



Beam window

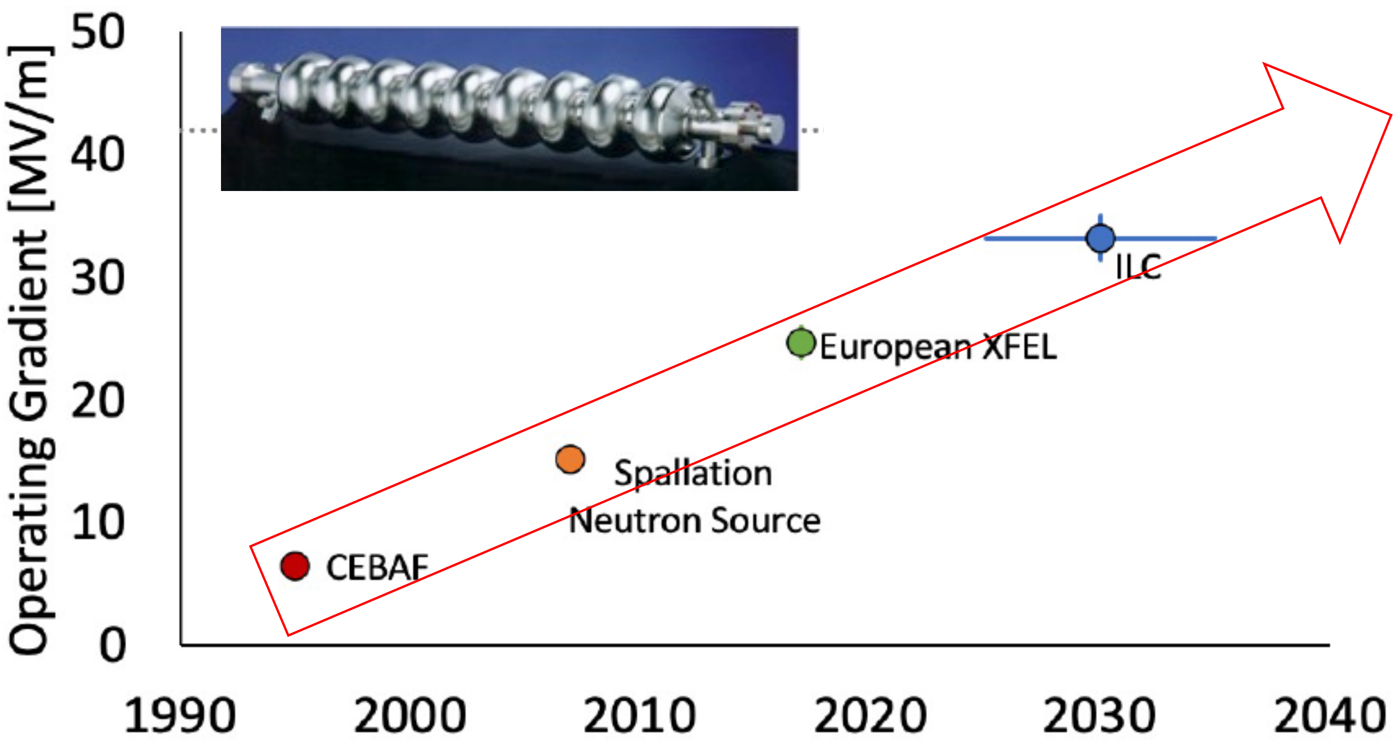
- Ti-alloy
- 30 cm diameter
- Exchange every a few years

Remote exchange of the beam window
under high radiation dose

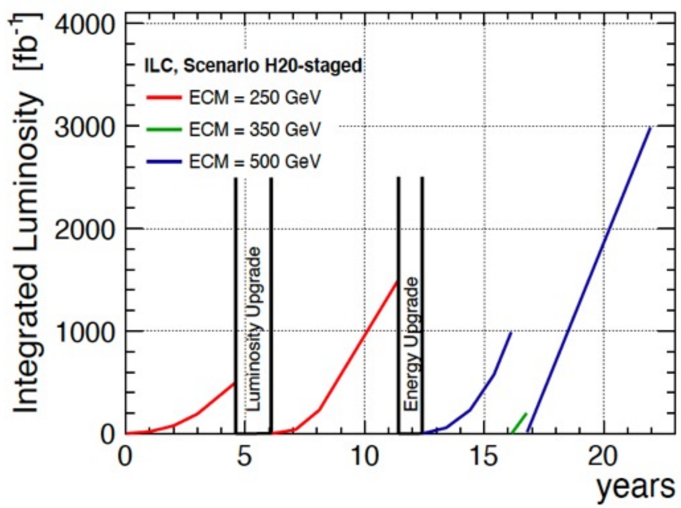
Outline

- Introduction:
  - Progress in Accelerator Technology
- **ILC T**echnical **N**etwork (**ITN**) for Global Acc. R&D Programs
- Future Prospect in Technology Advances

SRF Higher Performance toward Energy Upgrade

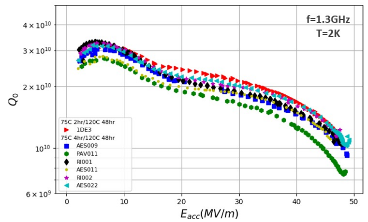


Energy upgrades:
- 500GeV (31.5 MV/m Q_0=1 x 10^{10})
  - 1TeV (45 MV/m Q_0=2 x 10^{10}, 300 MW)
  - more SCRF, tunnel extension
  - Site: 50km long, sufficient for 1TeV

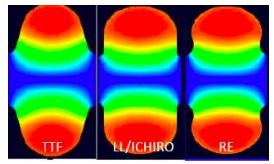


Beyond Present Limits of SRF

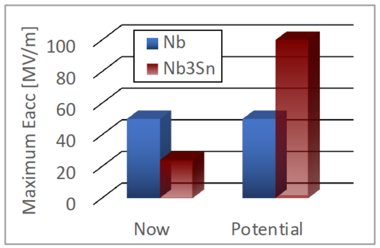
- **Nb-based Standing Wave** (SW) TESLA type structure is
  - limited to a gradient of **~ 50 MV/m** by B_{sh} ~ 200 – 210 mT.



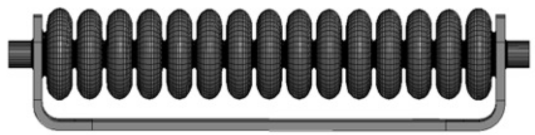
- **Advanced shape** cavities will be limited by **~ 60 MV/m**
  - Re-entrant, Low-Loss, Ichiro, Low Surface Field
  - Aiming at lower *Hpk/Eacc* (10-20%), but raise *Epk/Eacc* (15-20%)



- Advances material such as **Nb_3Sn**-based
  - Nb_3Sn, expecting Gradient limit up to **~ 80 MV/m**, at Bsh ~ 430 mT



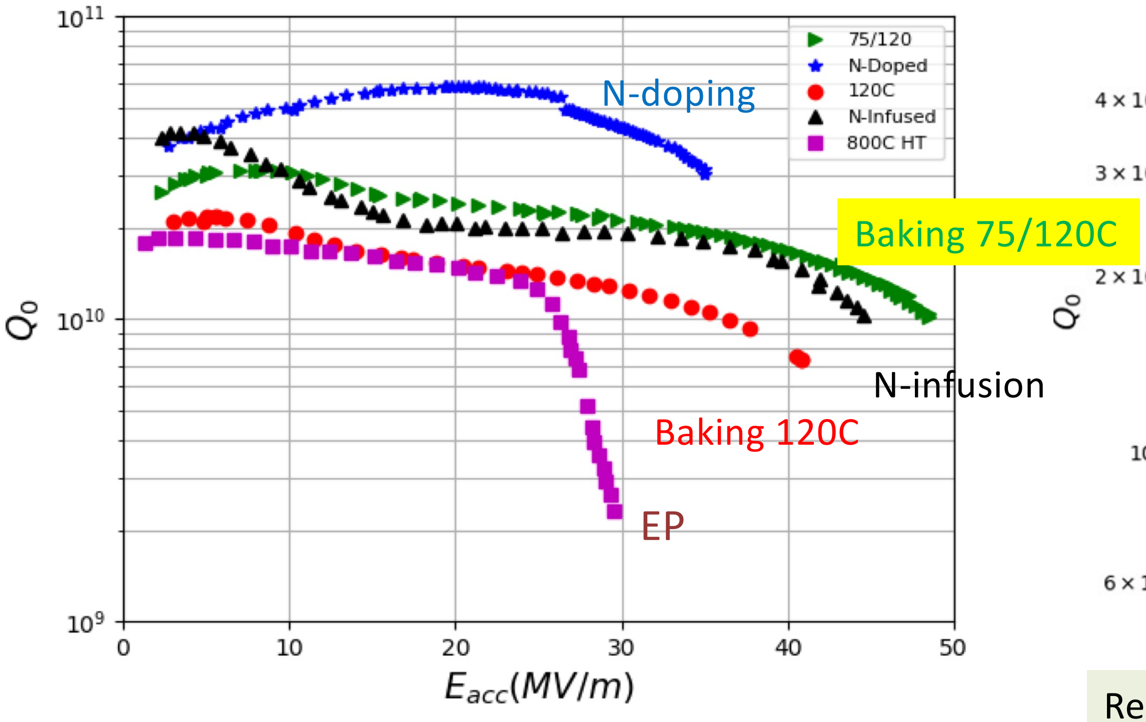
- Explore the option of **Nb-based Traveling Wave** (TW) structures
  - Expecting Effective Gradient to be **~ 70 MV/m** or higher

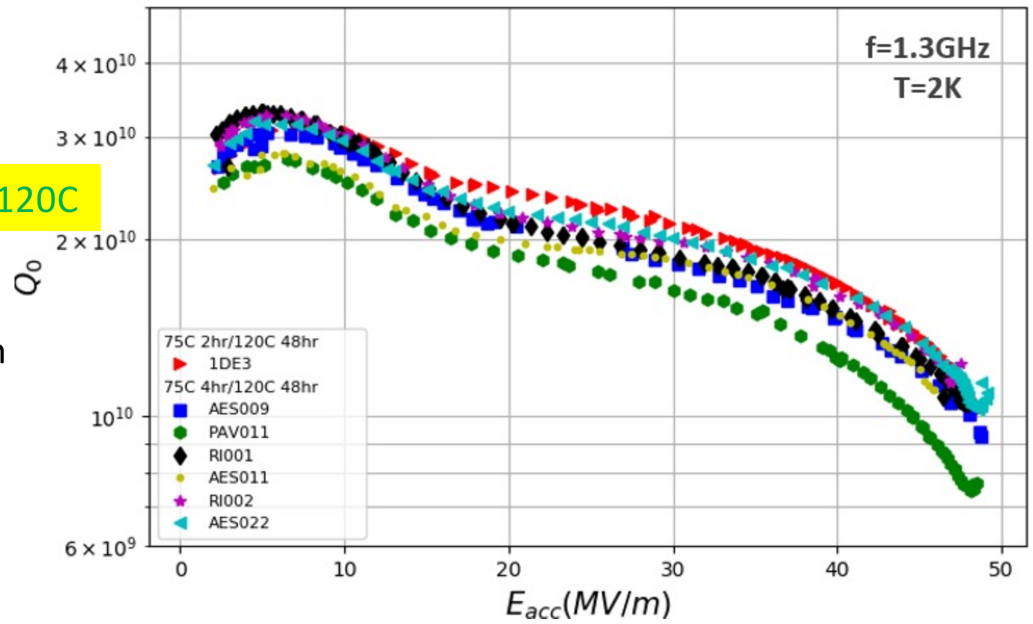


"**ILC:** The International Linear Collider -- Report to Snowmass 2021", Aryshev *et al.*, arXiv:2203.07622 (15 March, 2022)

Advances in SRF Technology
High-Q and High-G (1.3 GHz, 2K)

Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019





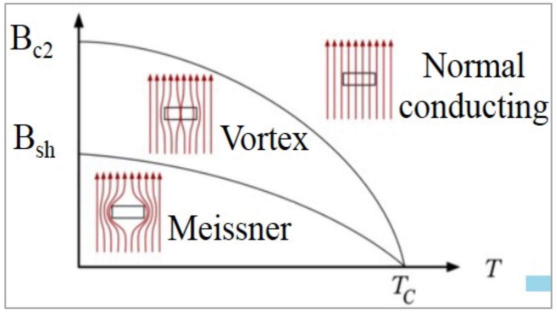
Repeated on second cavity TE1AES009 (fine grain, AES, WC)

https://arxiv.org/abs/1806.09824

- Performance at **Fermilab** confirmed by **Cornell**, **DESY**, and **JLab.**

Recent Progress and Future Prospect in SRF Technology

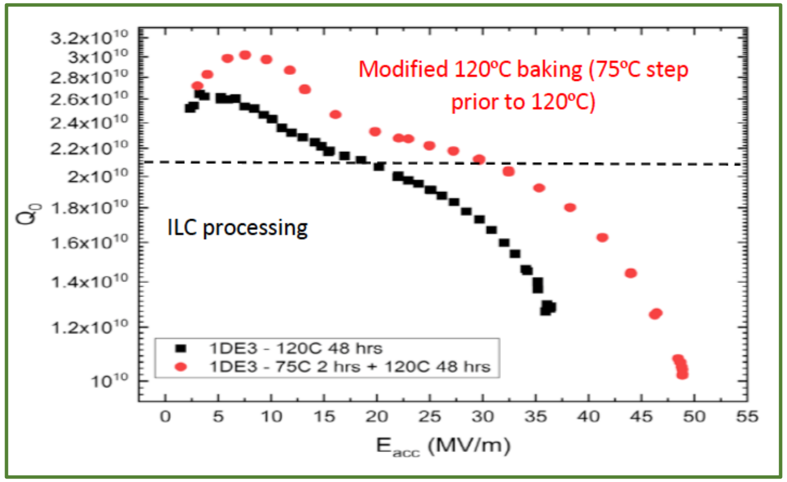
Courtesy, S. Posen



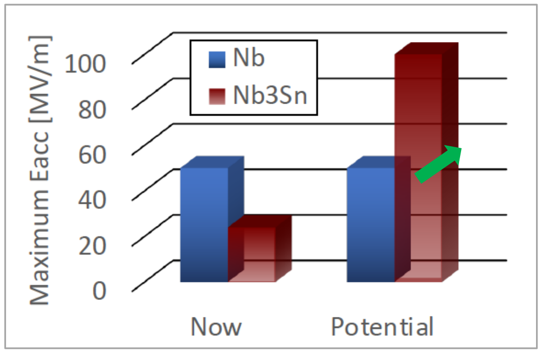
SRF cavity

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

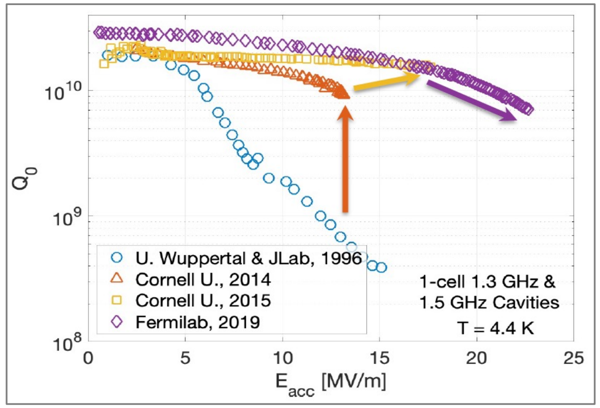
x2



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



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

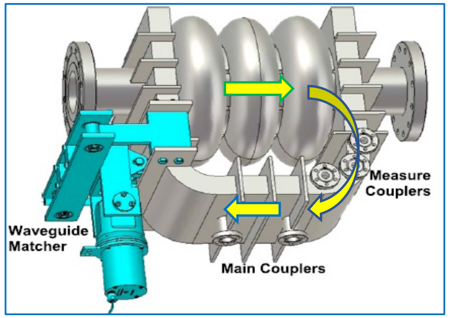


Nb_3Sn Potential in high-G future

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

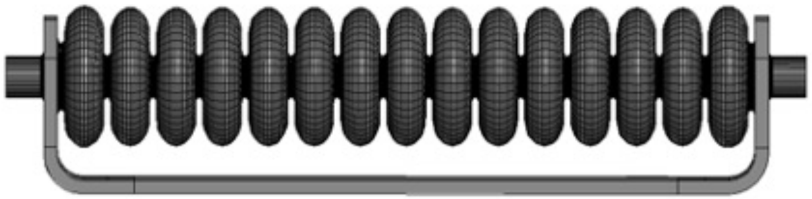
A new concept for SRF proposed for ILC-3TeV and Helen: Traveling Wave (TW) SRF cavity, compared with Standing Wave

arXiv: 2208/-6-3-v1, arXiv:2209.01074v1

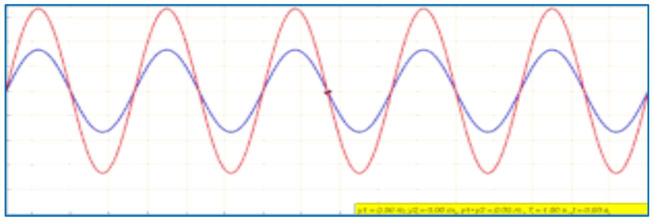


Prototype TW structure under test

SW: TESLA cavity (ILC baseline)



TW: proposed for ILC-3TeV, Helen



← Red standing wave – High Peak Fields,

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

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

– attached to both ends

Courtesy: S. Belomestnykh

Traveling Wave Cavity Technology

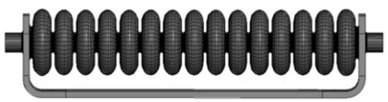
development anticipated
in cooperation with HELEN R&D program at Fermilab

Table 1: Tentative Baseline Parameters of HELEN

Parameter	Value
Center of mass energy	250 GeV
Collider length	7.5 km
Peak luminosity	1.35×10^{34} cm^{-2}s^{-1}
Repetition rate	5 Hz
Bunch spacing	554 ns
Particles per bunch	2×10^{10}
Bunches per pulse	1312
Pulse duration	727 μs
Pulse beam current	5.8 mA
Bunch length, rms	0.3 mm
Crossing angle	14 mrad
Crossing scheme	crab crossing
RF frequency	1300 MHz
Accelerating gradient	70 MV/m
Real estate gradient	55.6 MV/m
Total site power	110 MW

HELEN: A LINEAR COLLIDER BASED ON ADVANCED SRF TECHNOLOGY*

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



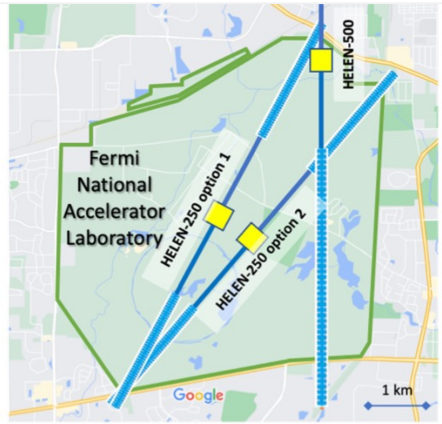
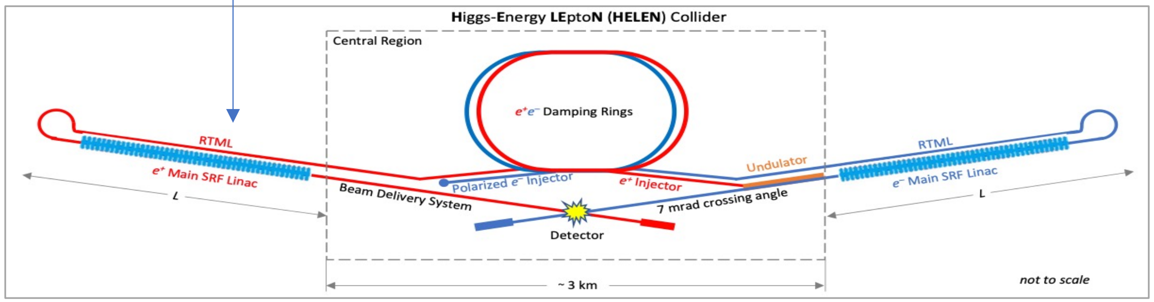


Figure 3: Options for HELEN collider at Fermilab.



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

Report of the Snomass'21 Collider Implementation Task Force

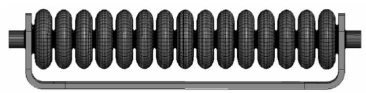
Thomas Roser et al.,

arXiv: 2208.06030v1, [11 Aug. 2022]

(- based on standing wave SRF cavity

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

Table 1: Main parameters of the submitted Higgs factory proposals. The cost range is for the single listed energy. The superscripts next to the name of the proposal in the first column indicate (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis; (2) Energy calibration possible to 100 keV accuracy for M_Z and 300 keV for M_W; (3) Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes



(- based on traveling wave SRF cavity

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
High Energy ILC	3 (1-3)	6.1	5-10	19-24	18-30	~400
High Energy CLIC	3 (1.5-3)	5.9	3-5	19-24	18-30	~550
High Energy CCC	3 (1-3)	6.0	3-5	19-24	12-18	~700
High Energy ReLiC	3 (1-3)	47 (94)	5-10	>25	30-50	~780
Muon Collider	3 (1.5-14)	2.3 (4.6)	>10	19-24	7-12	~230
LWFA - LC (Laser-driven)	3 (1-15)	10	>10	>25	12-80	~340
PWFA - LC (Beam-driven)	3 (1-15)	10	>10	19-24	12-30	~230
Structure WFA - LC (Beam-driven)	3 (1-15)	10	5-10	>25	12-30	~170

Table 2: Main parameters of the lepton collider proposals with CM energy higher than 1 TeV. Total peak luminosity for multiple IPs is given in parenthesis. The cost range is for the single listed energy. Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes.

"**ILC:** The International Linear Collider -- Report to Snowmass 2021", Aryshev *et al.*, arXiv:2203.07622 (15 March, 2022)

A. "**HELEN:** A Linear Coolider Based on Advanced SRF Technology", S.Belomestnykh *et al.,* arXiv:2209.01074v1, [2 Sept. 2022]

Prospects for SRF Technology Advances

- **SRF technology** has been well **matured** for the realization of the ILC, including industrial participation, based on the very successful **Euro-XFEL** completion constructed and stable operation since 2017, and with **LCLS-II** being in commissioning.
- SRF technology **advances with high-G and -Q** highly **expected** for future upgrades:
  - **Nb-bulk, SW:** **~ 50 MV/m,** for ~ 1-TeV upgrade ,
  - **Nb3Sn, SW:** **> 50 MV/m,** for > 1-TeV upgrade, and
  - **Nb-bulk, TW:** **~ 70 MV/m,** for further upgrade to reach beyond (up to ~ 3 TeV).
- **Note: Q-Value** improvement will become also critically important.

Outline

- Introduction:
  - Progress in Accelerator Technology
- **ILC T**echnical **N**etwork (**ITN**) for Global Acc. R&D Programs
- Future Prospect in Technology Advances
- Summary

Summary

- The ILC key technologies of “**SRF**”, and “**Nano-beam**”
  - **Matured** to be ready for an e+e- Higgs Factory based on the **Linear Collider** technology.

- ILC International Development Teams (IDT) is identifying and proposing:
  - Time-critical Work Package primes (WP-prime’s), to explore collaboration of KEK & int’l partners,
  - **ILC Technical Network** (ITN), to be **funded** in Japan/KEK, JFY2023 ~ (**April 2023 ~**) ,
    - for enabling Japan to encourage other international partner’s efforts, and
  - to prepare the phase for ILC-Prelab & **Engineering Design Repor**t (EDR) for the ILC construction,

- For the future:
  - ILC accelerator can be upgraded **up to 1 TeV** with continuous effort for the **existing** SRF technology, and **beyond** with new approaches expected with **Nb_3Sn**, and **TW technology** with maximizing the **worldwide synergy** for various R&D efforts for Higgs Factories and other wide applications.

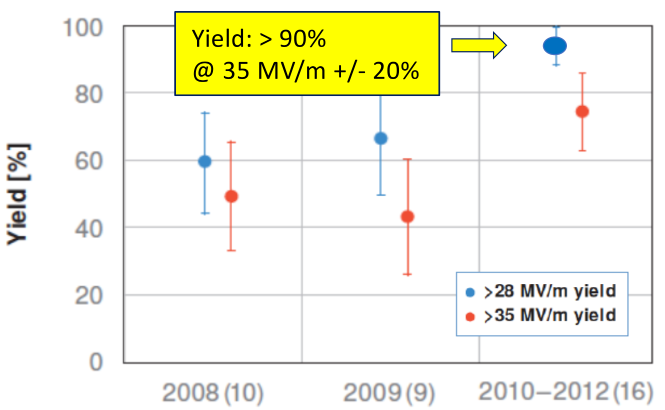
Courtesy: R. Geng,

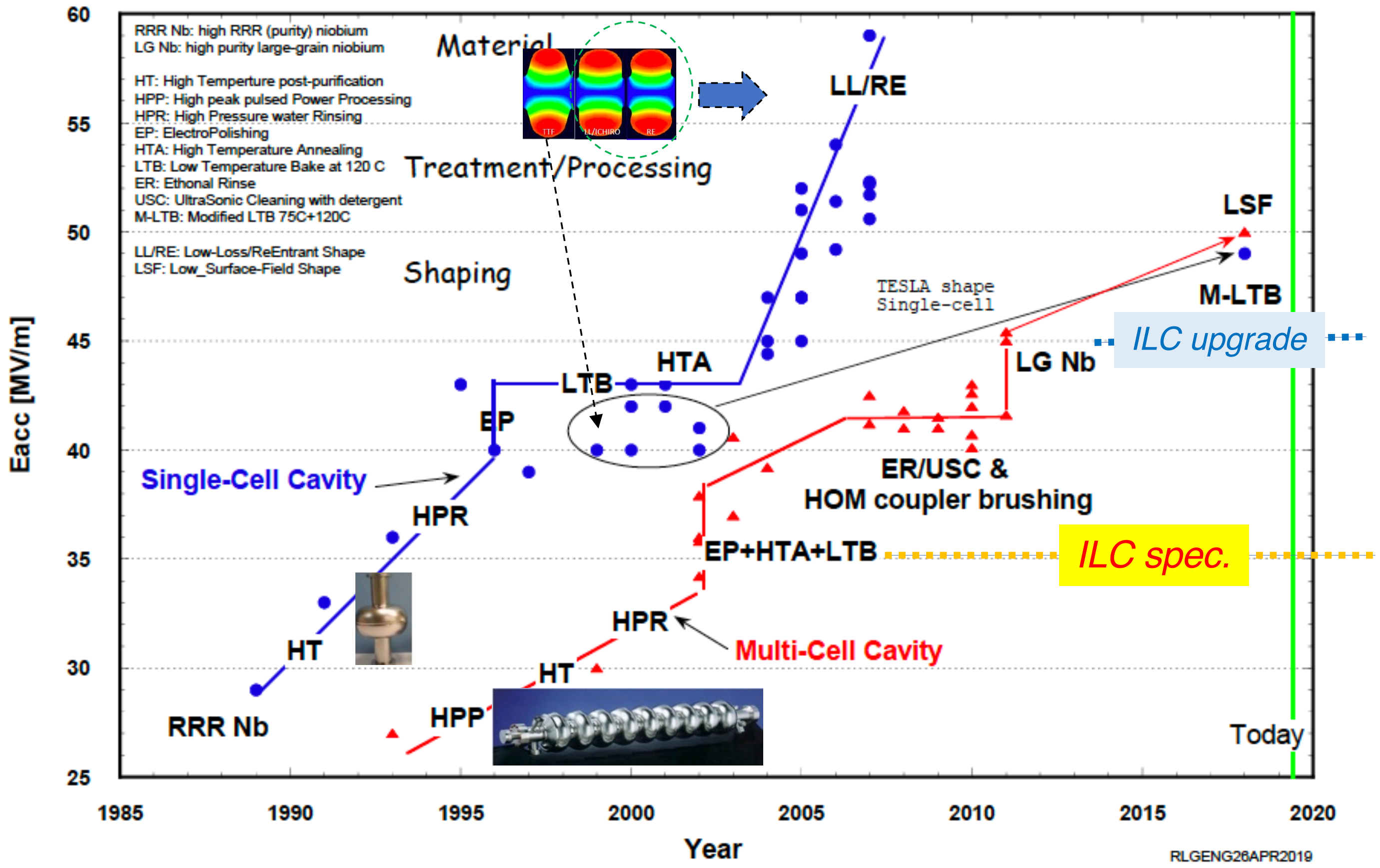
Advances in L-band (~ 1GHz) SRF Cavity Gradient

Gradient | Surface | Material

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

Thermal conductance | Surface, Shape





Advantages of TW Structures

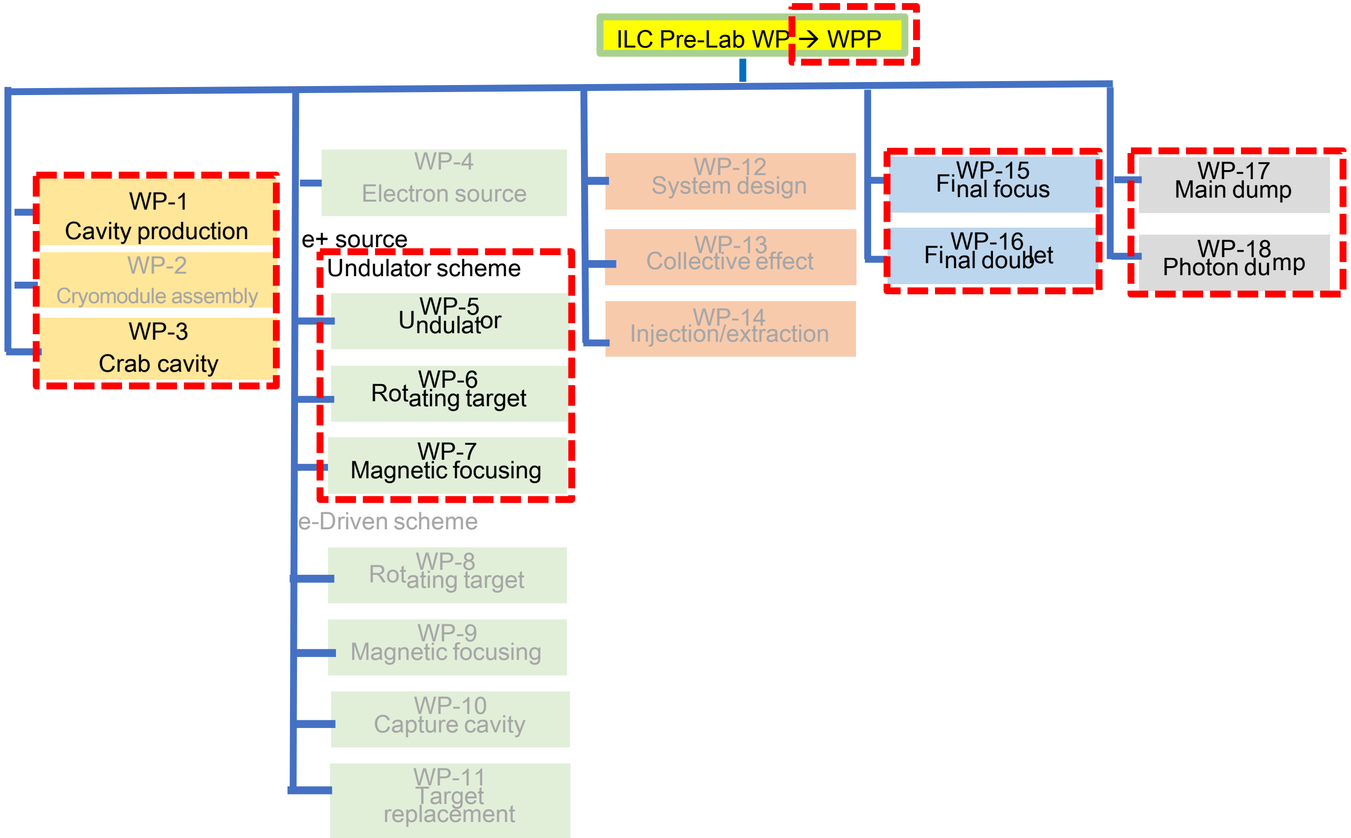
- **Travelling wave (green) structures lower BOTH *Hpk/Eacc* and *Epk/Eacc***
  - Because RF power returns (blue) not through the accelerating structure (to form a standing wave (red) with harmful peaks)
  - But power returns through a separate return Nb waveguide
- + Travelling wave structures offer 2X higher *R/Q*
  - lowers Cryo power and RF power and lower AC power
- **By choosing the Low-Loss cell shape + reduced aperture (see below) it is possible to lower *Hpk/Eacc* by 48% over the TESLA structure!**
- **Opening the door to *Eacc* > 70 MV/m !!**
  - *Hpk* = 200 mT, *Epk* = 120 MV/m
- Lower aperture is allowed because bunch charge for 3 TeV will about 3 X less to get acceptable IP background…
- **Putting SRF on the Road to ILC – 3 TeV with Nb**
  - With Capital cost comparable to CLIC 3 TeV and AC power much less than CLIC 3 TeV
  - Without struggling with exotic new superconductors (sorry!)

Long-term scope in
Snowmass, ILC White-Paper

Travelling Wave SRF cavity anticipated for ILC Energy-Upgrade beyond 1 TeV

	units	ILC 1 TeV TDR	ILC 2 TeV path 1a	ILC 2 TeV path 1b	ILC 3 TeV path 2a	ILC 3 TeV path 2b
Energy	TeV	1	2	2	3	3
Luminosity	10^{34}	4.9	7.9	7.9	6.1	6.1
AC Power	MW	< 300	345	315	400	525
Cap. Cost	B ILCU	+ 5.5	+6.0	+4.9	+11.8	+11.0
(total)		13.3	19.3	18.2	25.1	24.3
Gradient	MV/m	45	55	70	70	80
(new linac)						

Path 2a: 3 TeV Upgrade from 1 TeV with 70 MV/m (w/ Nb and **Travelling Wave (TW)**)


ILC Pre-Lab WP → WPP
WP-1
Cavity production
WP-2
Cryomodule assembly
WP-3
Crab cavity
WP-4
Electron source
e+ source
Undulator scheme
WP-5
Undulator
WP-6
Rotating target
WP-7
Magnetic focusing
e-Driven scheme
WP-8
Rotating target
WP-9
Magnetic focusing
WP-10
Capture cavity
WP-11
Target replacement
WP-12
System design
WP-13
Collective effect
WP-14
Injection/extraction
WP-15
Final focus
WP-16
Final doublet
WP-17
Main dump
WP-18
Photon dump