Participation of U.S. Labs in the ITN

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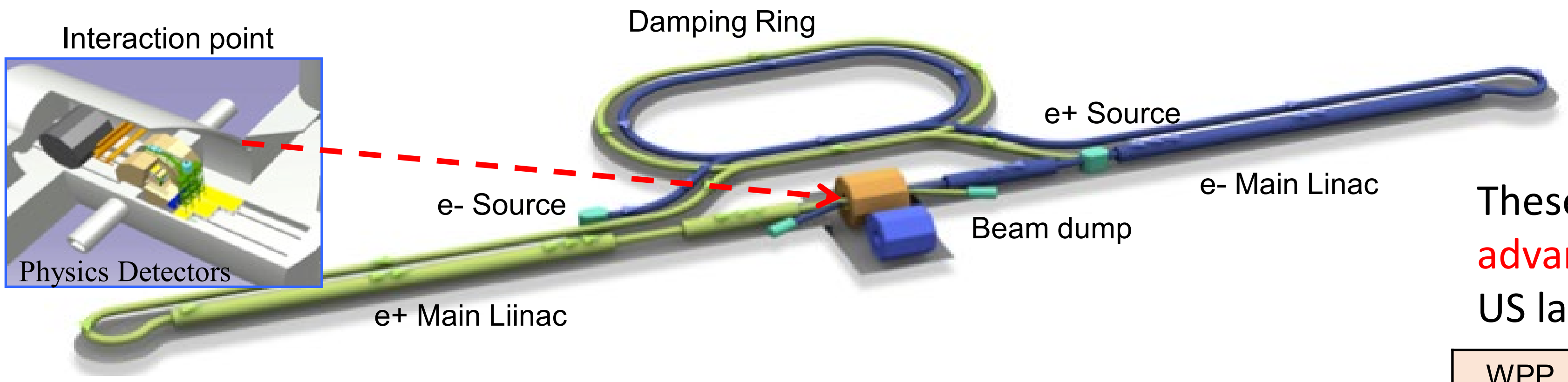
IDT Americas Liaison

These slides were prepared by Sergey Belomestnykh

for the P5 SLAC Town Hall on May 3, 2023,

with some minor modifications by me.

WP-Primes at ILC Technology Network



These WPs can be applied to various advanced accelerators.
US labs welcome to join!

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

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

Introduction

U.S. coordination group prepared this input to P5 on potential U.S. contributions to ILC.

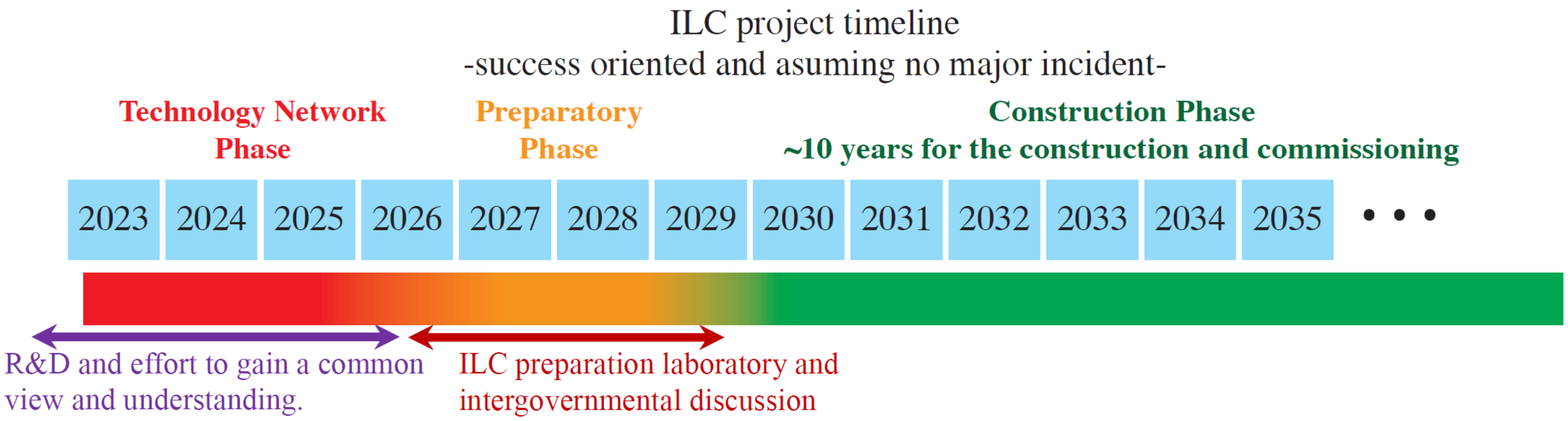
Members of the group are S. Belomestnykh (Fermilab), S. Gessner (SLAC), D. Rubin (Cornell), G. White (SLAC), with contributions from many others.

- The U.S. accelerator community has a long history of involvement in ILC:
  - Made major contributions in developing many ILC accelerator technologies, including Superconducting RF (SRF), and to the ILC Global Design Effort (GDE) and Technical Design Report (TDR)
  - Continued to actively participate in accelerator studies at Accelerator Test Facility (ATF) at KEK and in the IDT accelerator working group (WG2)
- U.S. accelerator expertise is required for the realization of the ILC, and substantial deliverables to ILC accelerator construction (~1/3) are needed for this global project.
- With a recommendation from P5 and DOE approval, we hope that support will be extended to the ITN phase and beyond.
  - This presentation focuses on the pre-construction activities (ITN + Pre-lab)
  - ITN activities lead to preparatory phase activities and construction responsibilities.
- Note: ITN plan is to fully cover all ITN work packages before considering additional tasks.

Potential U.S. contributions to ILC

The U.S. community is interested in partnering on the following areas:

1. Main Linac (ML) and SRF, including crab cavities
2. Polarized electron source
3. Polarized and electron-driven positron source options
4. Damping rings
5. Beam delivery system
6. Simulations, software management and global systems



U.S. participation in ITN: WP-prime 1

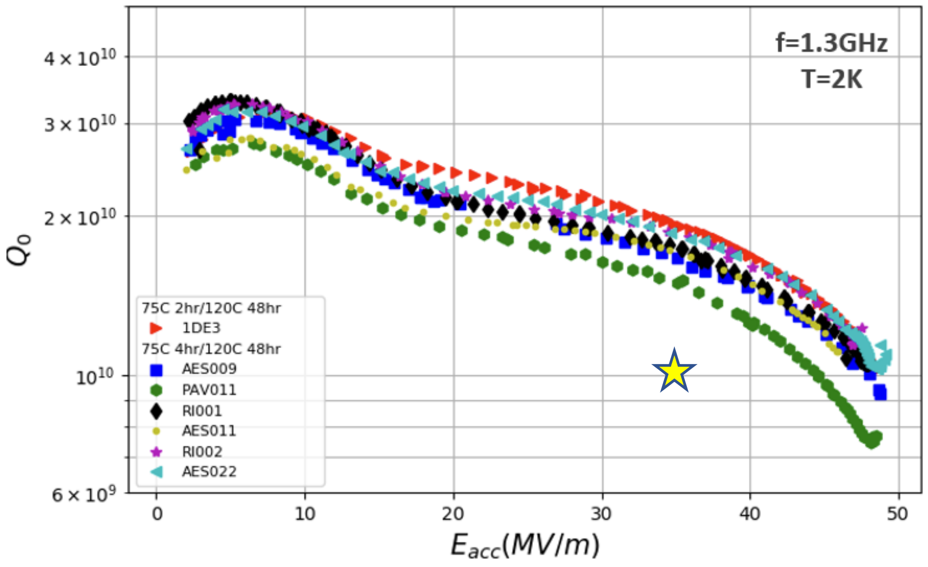
SRF cavity production readiness

a) Optimize the production process based on recent advances in cavity surface treatment (first on single-cell cavities, then on 9-cell cavities) – confirm via cavity exchange between regions

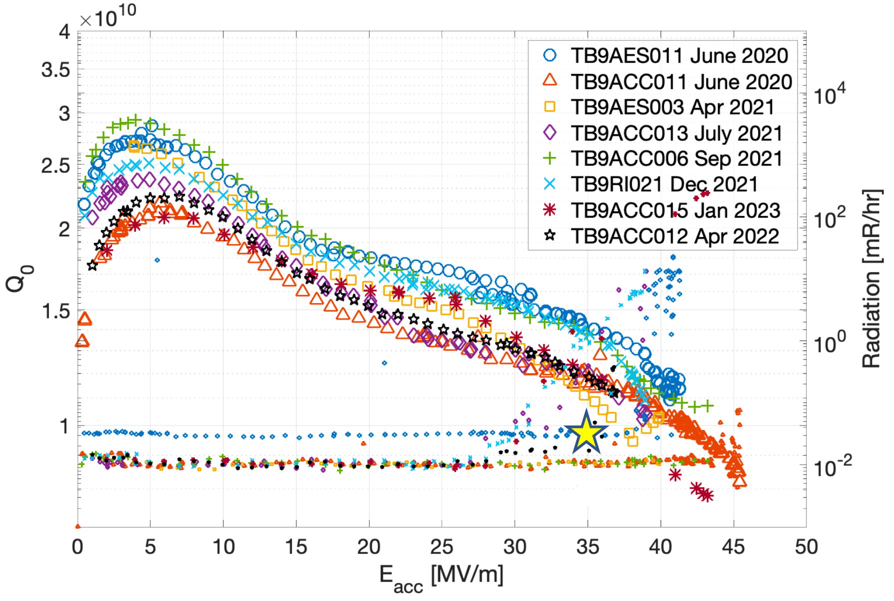
b) Establish the cavity design compliant with the Japanese High Pressure Gas Safety (HPGS) regulation in close collaboration with KEK

c) Transfer the cavity treatment to industry, order a set of cavities (2 batches for Americas during ITN, 4 cavities per batch), confirm performance yield. Continue with larger statistics through the **Preparatory Phase**

2-step low-temperature baking (single-cell cavities)



Grassellino et al. https://arxiv.org/abs/1806.09824



U.S. participation in ITN: WP-prime 2

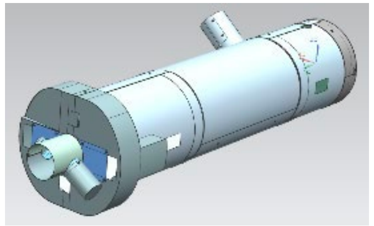
Cryomodule (CM) design

a) Finalize the common CM design incorporating lessons learned from recent SRF projects (European XFEL, LCLS-II) and test facilities' operation (STF at KEK, FAST at Fermilab). Goals: improve performance, lower cost. Some potential changes: compact LCLS-II style frequency tuner, split conduction-cooled SC magnet, better magnetic shielding of cavities for high Q-factor preservation)

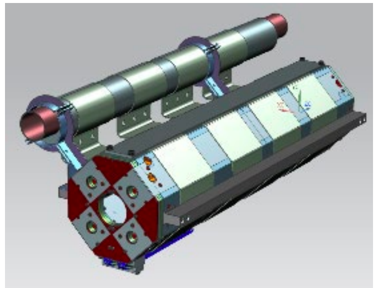
b) Confirm that the CM design is compliant with the Japanese HPGS – close collaboration with KEK, learn from AST-IFMIF experience

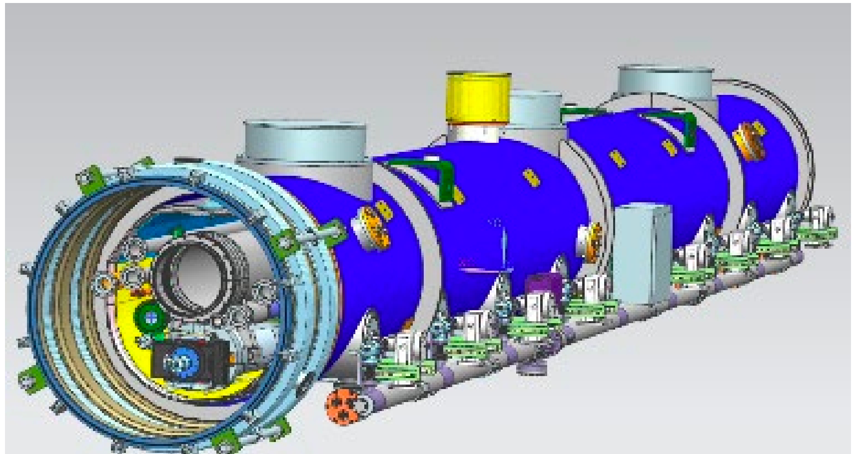
c) Engineering design and transport study during the **Preparatory Phase**

Cavity magnetic shield



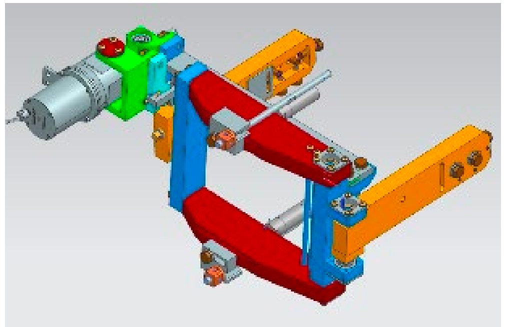
SC magnet package





ILC cryomodule

Compact frequency tuner



U.S. participation in ITN: WP-prime 3

SRF Crab Cavity (CC) development

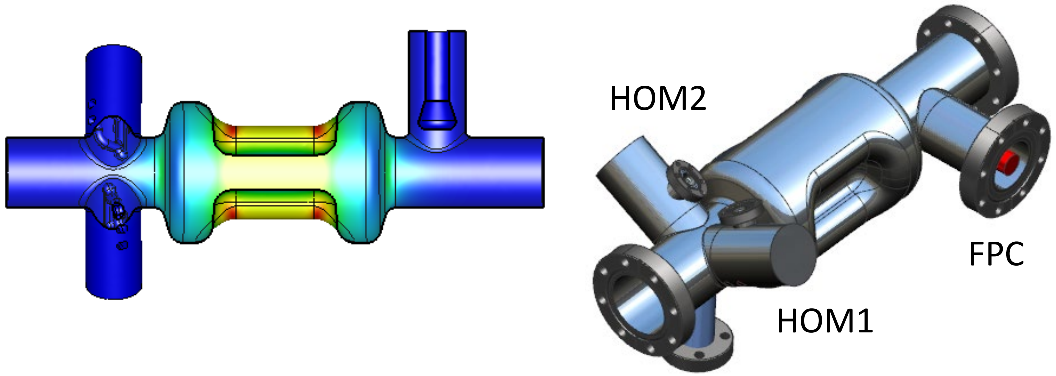
a) HL-LHC R&D and prototyping demonstrated viability of compact crab cavity designs. ILC team has initiated efforts on re-optimization of the CC design. 5 designs were under initial consideration.

b) After the recent first down-selection review, 2 designs were selected to proceed to the next stage. Both designs are from U.S. teams: RF Dipole cavity (ODU/JLAB) and QMiR cavity (FNAL)

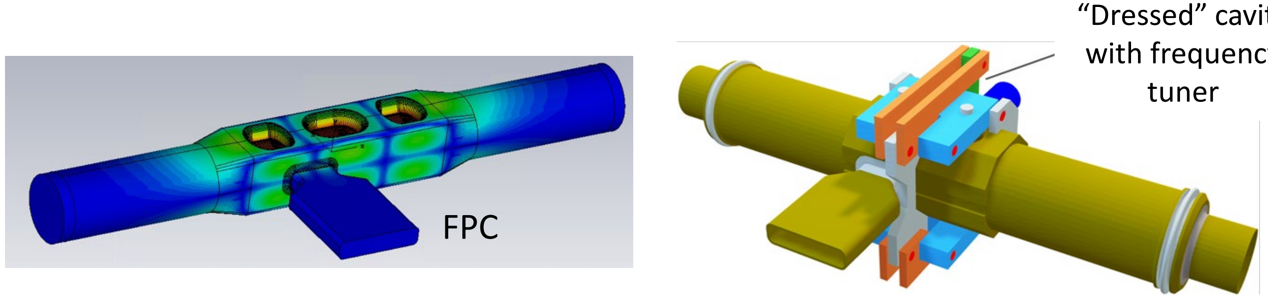
c) Next stage: development and testing of a prototype cavity of each design (KEK will provide Nb material); demonstration of synchronized operation with the two prototypes (possibly in UK); selection of the final cavity design

d) Engineering design of the cryomodule for the selected CC design during **Preparatory Phase**

RF Dipole 1.3 GHz crab cavity (ODU/JLAB)

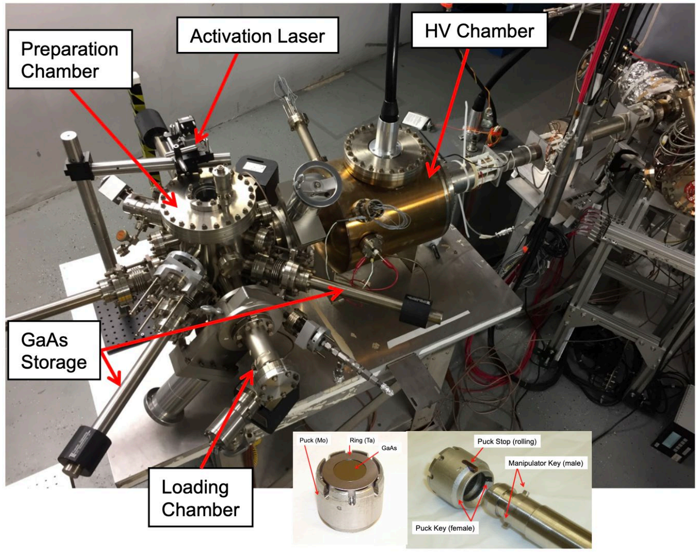


QMiR 2.6 GHz crab cavity (FNAL)

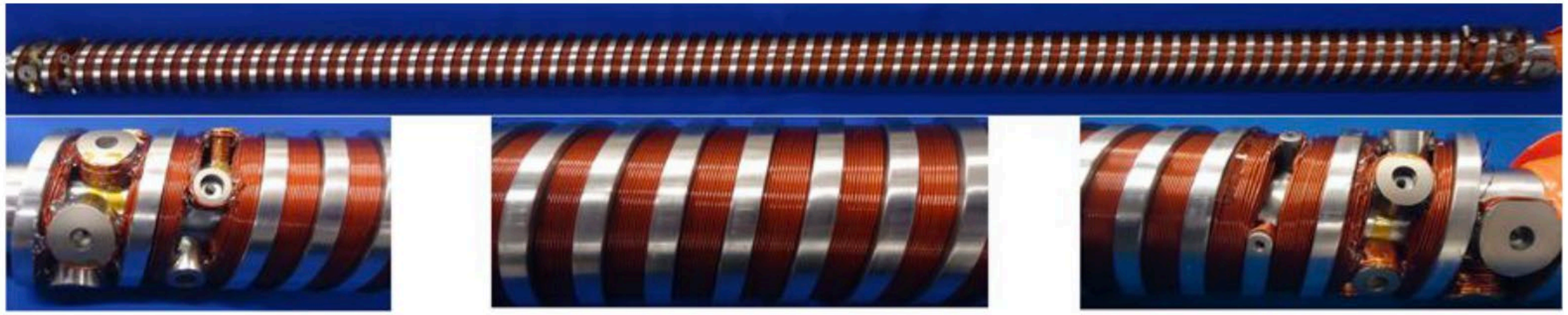


Polarized e^- and e^+ sources, WP-prime 4-10

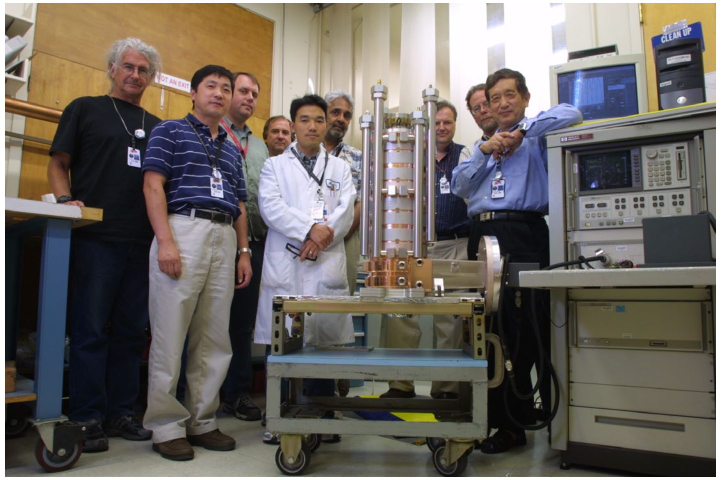
1. **Polarized electron source design**
   - JLab played leading role in planning remaining development, there is a new US-Japan collaboration
2. **Polarized positron source (baseline)**
   - Target, capture, and acceleration for positron source (was prototyped during GDE phase by U.S. labs)
   - Developing undulator technology for positron source – synergy with light sources, where helical undulators are now used
3. **e^- driven positron source (backup)**
   - Investigation of shortening electron linac using C^3 technology



Polarized electron source at JLab,
P. Adderley et al., Phys. Rev. Acc. Beams (2010)



Superconducting helical undulator at Argonne, M. Kasa et al. Phys. Rev. Acc. Beams (2020)



L-Band capture section at SLAC
F. Wang et al., PAC09 (2009)

Damping rings (DRs), WP-prime 12&14

The damping ring described in the TDR satisfies the basic requirements. However, developments in magnet technology, high current positron storage rings (SuperKEKB), low emittance light sources, fast kickers, and optimization of the collider parameters, in the decade since, suggest some refinement and reevaluation of the ring design and instrumentation. The U.S. community has significant expertise in design and operation of storage rings.

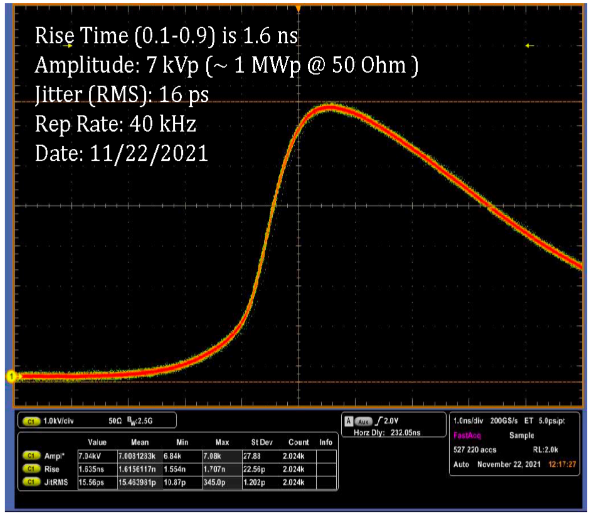
The U.S. community is interested in partnering on the following DR areas:

1. **DR system design**
   a) Revisit lattice design. Consider combined function/hybrid magnets. Modify injection and extraction straights for consistency with anticipated kicker properties. – **ITN Phase**
   b) Magnet design: normal magnets and SC damping wigglers. Because of the very high synchrotron radiation in the wiggler straight, and the required electron cloud mitigation, design of the vacuum chambers in that region should be integrated with the engineering design of the magnets. – **Preparatory Phase**
   c) Magnet design: permanent magnets. Design of permanent magnets (a possible alternative to electromagnetics) can begin when the lattice design is finalized – **Preparatory Phase**

Damping rings (cont'd.)

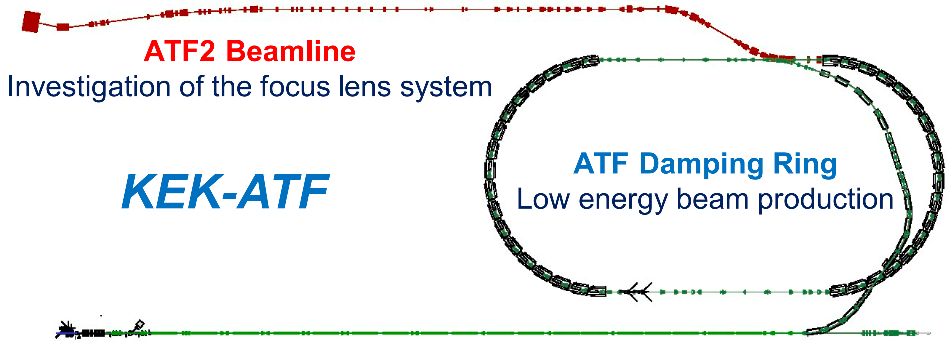
2. **Collective effects** (electron cloud, ion trapping and fast ion instabilities) – **ITN Phase**
    a) Once the design of the lattice is finalized, the thresholds should be reevaluated.
    b) Fast ion instability feedback should be developed (simulations and scaling from SuperKEKB HER) and possibly tested with beam (if not done already at SuperKEKB)
3. **DR injection/extraction kickers**: System design, prototyping, and stability test – **ITN / Preparatory Phase**
4. Other opportunities for **Preparatory Phase / Construction**: vacuum chamber, SRF system, instrumentation, SC wigglers, magnets

Demonstration of ns rise time,
MW power pulse at SLAC

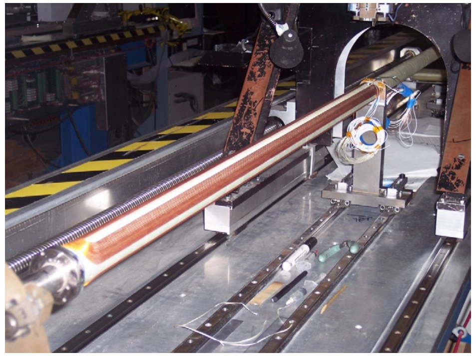


Beam delivery system (BDS), WP-prime 15&16

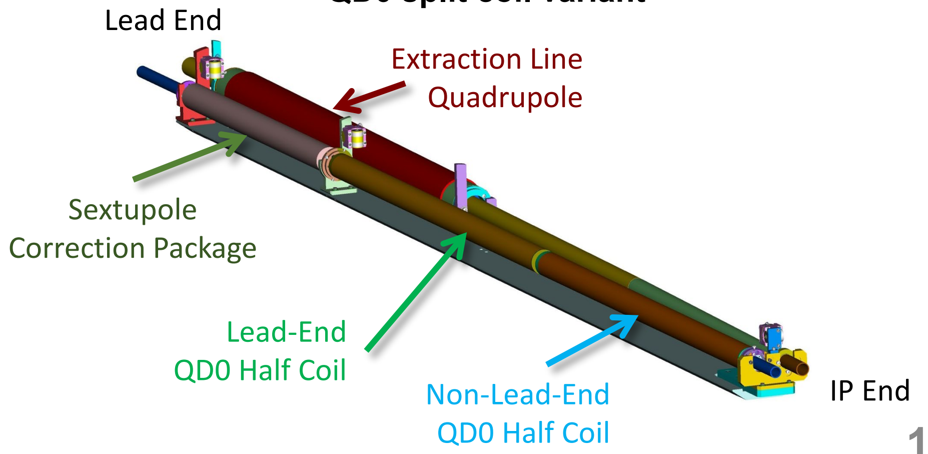
1. **BDS design**
   a) Participation in the ATF3 studies, e.g., wakefield and magnetic multi-pole characterization and mitigation
   b) Machine Learning applications to Final Focus System (e.g., Bayesian optimized luminosity tuning) – possible to also demo @ ATF3? (Strong accelerator-focused ML group at SLAC)
   c) Fast-kicker hardware for emergency abort dumps (synergy with DR)
   d) MDI work
2. **Final doublet (FD) design optimization**
   a) Direct-wind technology for SC FD magnet complex assembly (BNL-specific)
   b) Strong need for full-scale prototype and vibration tests at 2 K, need to complete efforts started many years ago – this is arguably priority #1 for outstanding BDS R&D – large consequences if fail to meet vibration tolerances in terms of re-design work for BDS/MDI



QD0 split coil winding



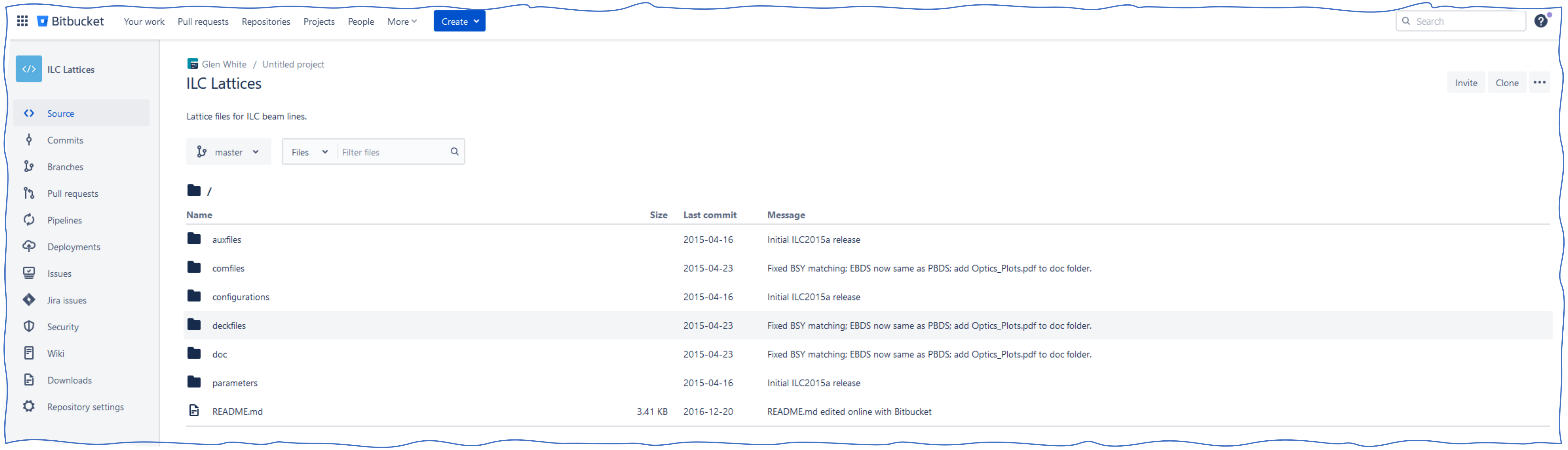
QD0 split coil variant



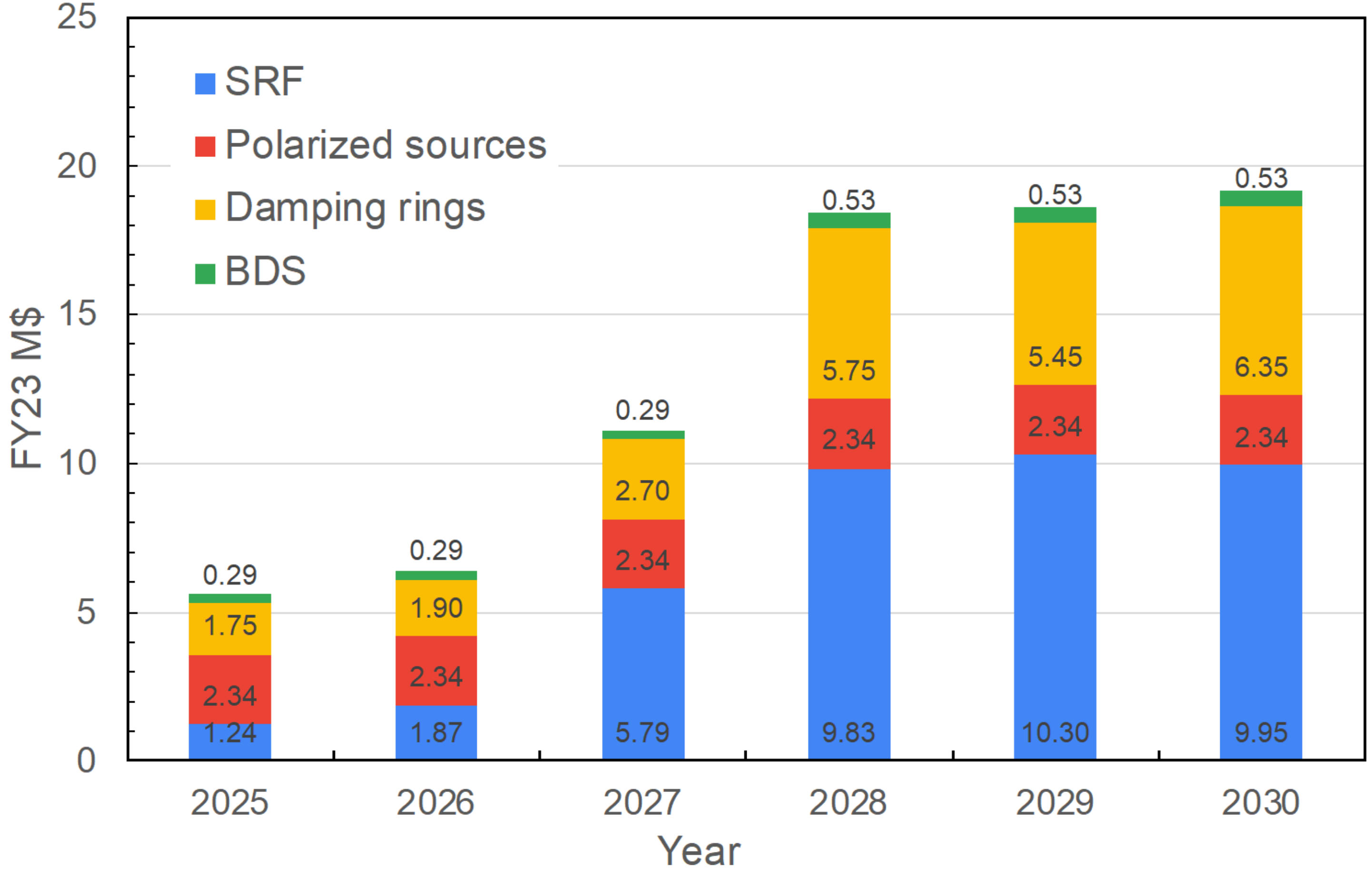
Simulations, software management and global systems

The U.S. ILC community is also interested in

1. Integration & management of all optics decks, enforcement of change control, software repository management, etc.
2. Start-to-end tracking simulation framework



Possible U.S. budget through ITN and Preparatory Phases



- Budget based on U.S. estimate of costs of U.S. activities,
  using IDT costs as a reference.

- Total ~ 80M$ for ITN and Preparatory phases
- Including FTEs increasing from 13.7 in 2025 to 50.6 in 2030

U.S. accelerator expertise relevant to ILC

	ANL	BNL	Cornell	FNAL	JLAB	LBNL	ODU	SLAC	
Main Linac SRF			✗	✗	✗			✗	
Crab cavities				✗	✗		✗		
Polarized *e-* source		✗	✗		✗			✗	
Undulators for polarized *e+* source	✗					✗		✗	
DR system design & subsystems (SRF, vacuum chamber, magnets, instrumentation …)	✗	✗	✗	✗	✗	✗		✗	
Beam optics, collective effects …	✗	✗	✗	✗	✗	✗		✗	
Fast kickers				✗				✗	
BDS design		✗		✗	✗			✗	
Final doublet		✗		✗		✗			

Outlook

DOE HEP is awaiting P5 strategic plan & HEPAP approval. (Dec. 7-8)

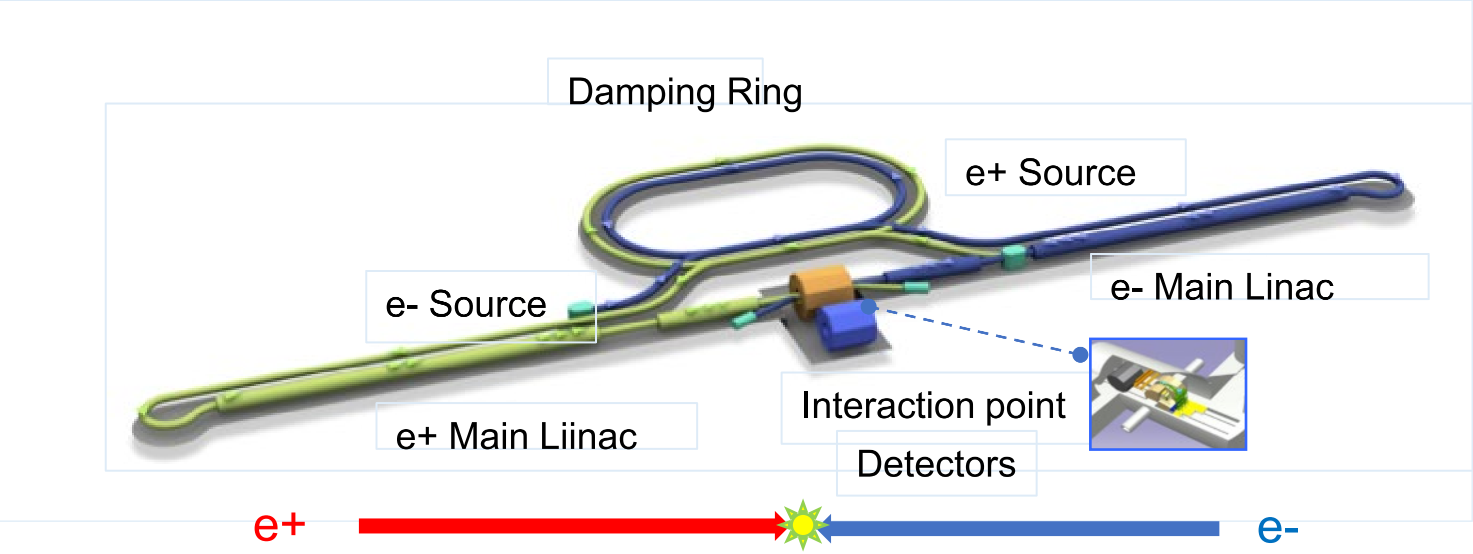
- What will P5 recommend concerning future colliders, and a future Higgs factory in particular?
- What will P5 recommend concerning R&D, for accelerators & detectors?
- How will HEP want to see proposals?
  - No guidance on this subject yet.
  - Siegrist/Patwa plan was for a coordinated proposal across all labs.

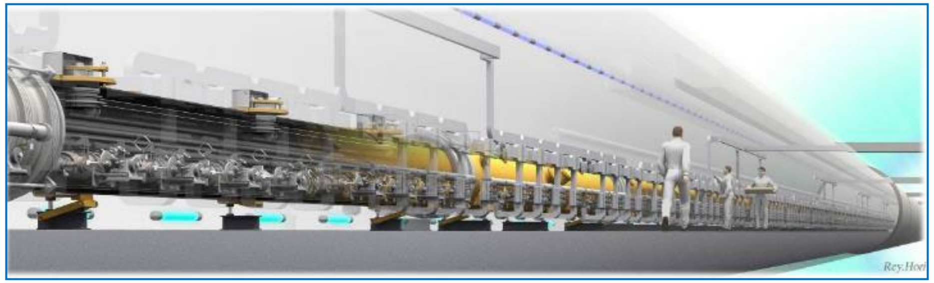
Comments:

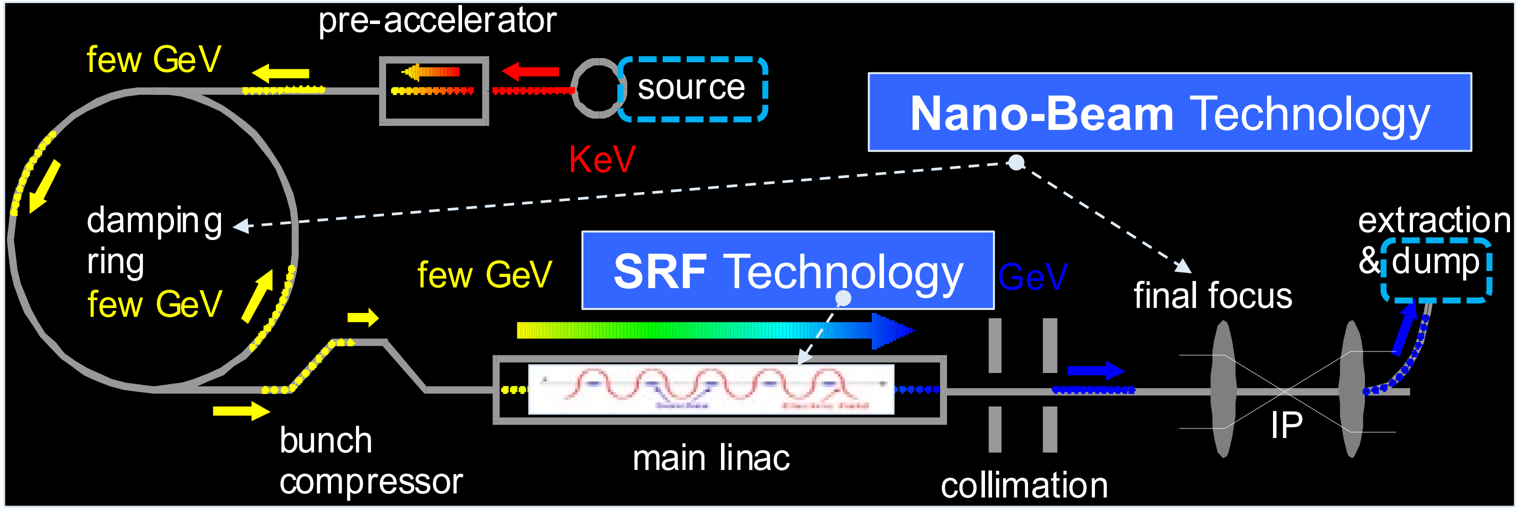
- How long will HEP need to work out its implementation plan?
- Little wiggle room in FY24 budget (if there is an FY24 budget).
- I have received positive feedback concerning HEP appreciating the need to support early engagement in future projects. At the same time, I have heard concerns about difficulty ramping up investment with current budget commitments to projects.

BACKUP

ILC and the Accelerator Technology



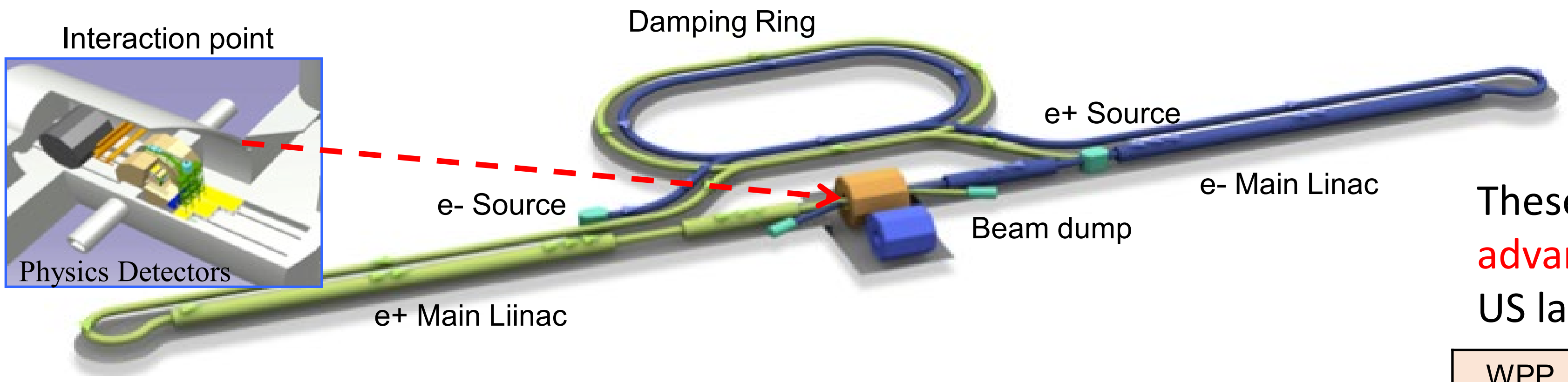




Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF	**7.7** nm
SRF Field gradient	< 31.5 > MV/m (+/-20%) Q_0 = 1x10^{10}
#SRF 9-cell cavities (CM)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

TDR was published in 2013.

WP-Primes at ILC Technology Network



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- Go to ***Beam dumps***

SRF: WPP 1–3
e-, e+ Sources: WPP 4–11
Nano-Beam: WPP 12–17

WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
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WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

WP-prime 1: SRF Cavity

(Scoping the Industrial-Production Readiness)

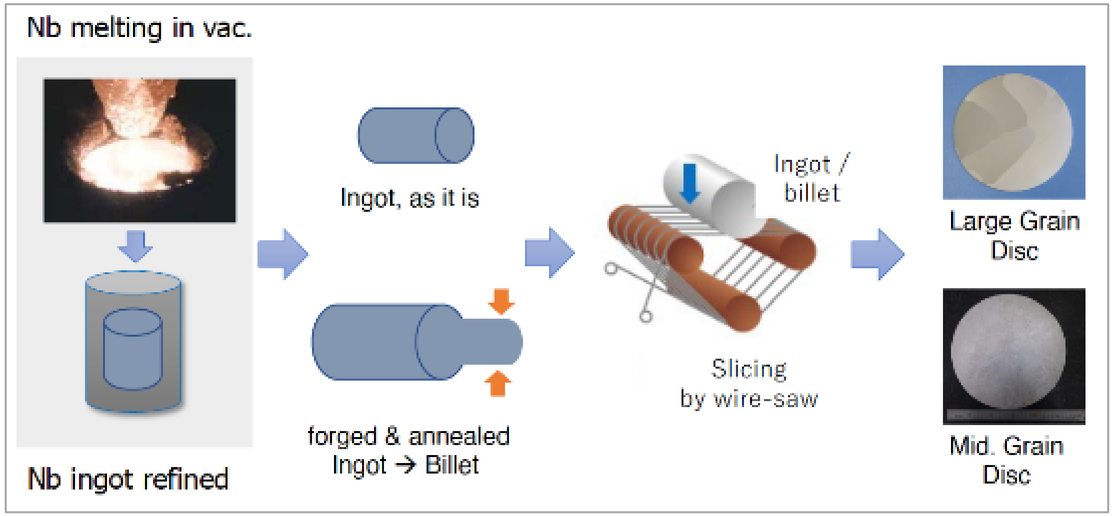
Referring European XFEL and LCLS-II experiences

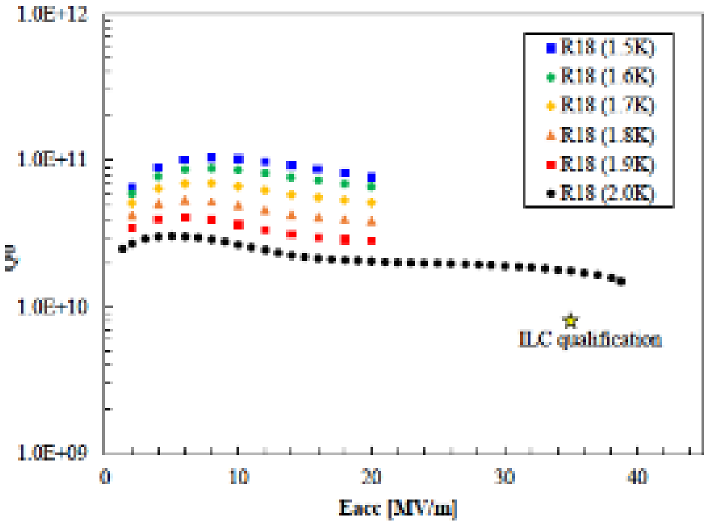
- Research with single-cell cavities to establish the best production process including:
  - Advanced Nb sheet production method
  - Advanced surface treatment recipe
- Globally common design with compatible High Pressure Gas Safety (HPGS) regulation
- 24 nine-cell cavities are to be developed for industrial-production readiness
  - 8 cavities (4 / batch) in each region
  - Production process encouraged to be optimized in each region
  - Cavity performance expected: E_{acc} = <35 MV/m> (+/− 20%), $Q_0 = 1.0 \times 10^{10}$, Yield = ≥90%
- RF performance/success yield to be examined (including 2nd pass and further)
  - 3rd pass to be examined if effective

	# of cavities to be produced		
	Americas	Europe	JP/Asia
single-cell	2	2	2 (+4)
nine-cell	8	8	8 (+ 4)

Material/Sub-component → QA of Material/Sub-C → Cavity Production → Surface Process → Vertical Test = Cavity RF Test

Production process

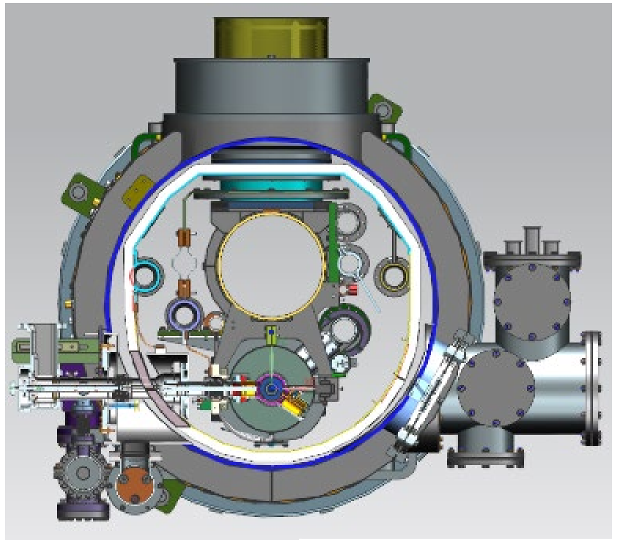


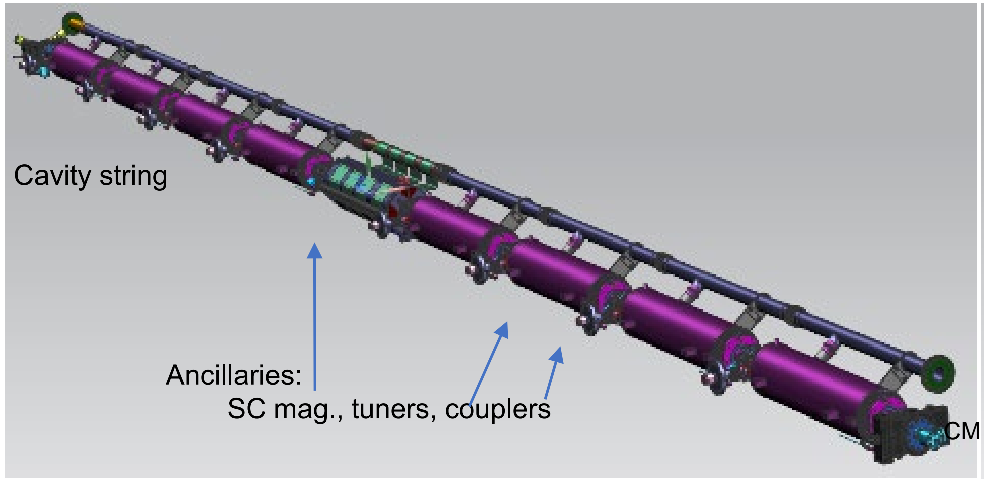


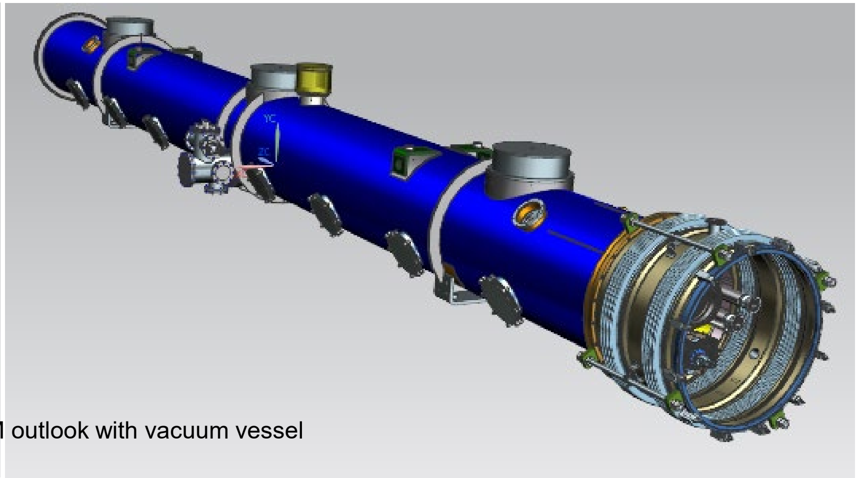
WP-prime 2: Cryomodule (CM) Design
(Scoping the CM Global Transfer and Performance Assurance)

Referring European XFEL and LCLS-II experiences

- Unify cryomodule (CM) design with ancillaries, based on globally common engineering design, drawings & data-base
- 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.		

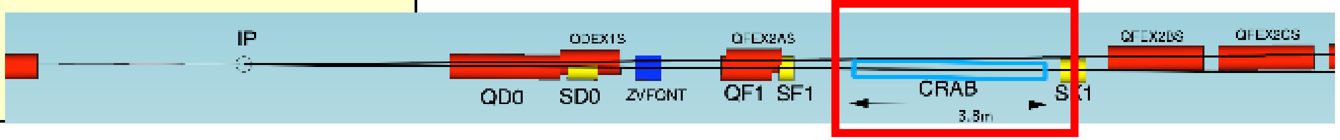
WP-prime 3: Crab Cavity Development

- Pre-down-selection review hosted by KEK chose two primary candidates on Apr/2023
  - RFD (1st), QMiR (2nd), Elliptical (3rd)
- Development and evaluation of two prototype cavities
  - KEK will provide for necessary Nb material to produce them
- RF property simulation to optimize cavity design
- Demonstration of synchronized operation with two prototypes
- Down-selection to choose final cavity design
- Cryomodule design based on final cavity design

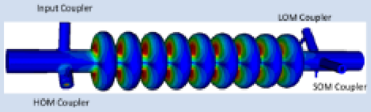
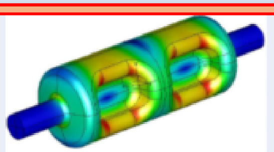
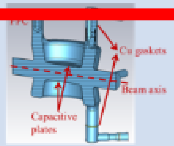
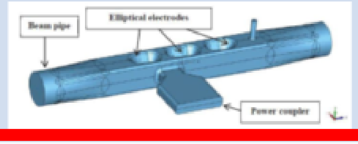
→ Both two candidates are from US!

two beamline distance

14.049m x 0.014rad = **197mm**



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)

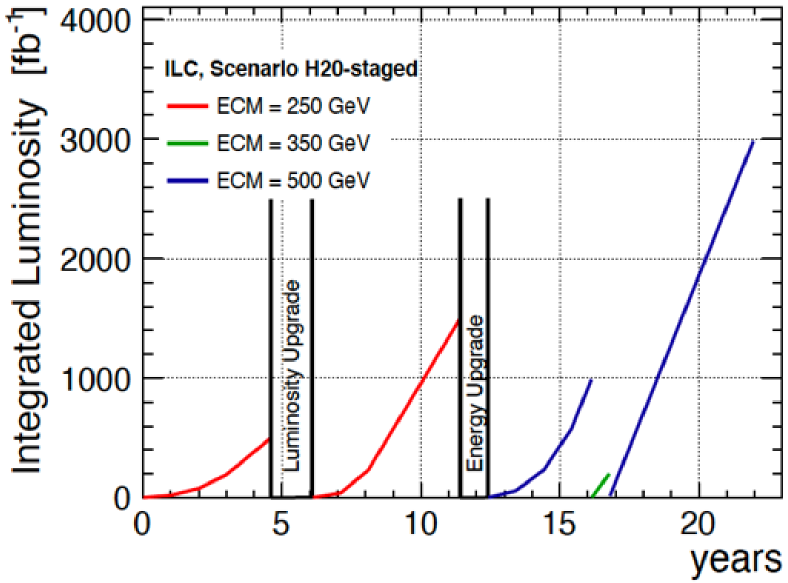
Elliptical/Racetrack (3.9 GHz)	Lanc. Univ.	
RF Dipole (RFD)	ODU	
Double Quarter Wave (DQW)	CERN	
Wide Open Waveguide (WOW)	BNL	
Quasi-waveguide MultIcell Resonator (QMIR)	FNAL	

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

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

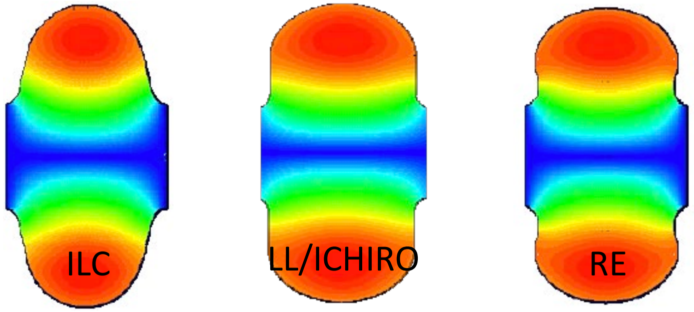
Energy upgrades:
- 500GeV (**31.5 MV/m Q_0=1** x 10^{10})
  - 1TeV (**45 MV/m Q_0=2** x 10^{10}, 300 MW)
  - more SCRF, tunnel extension



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

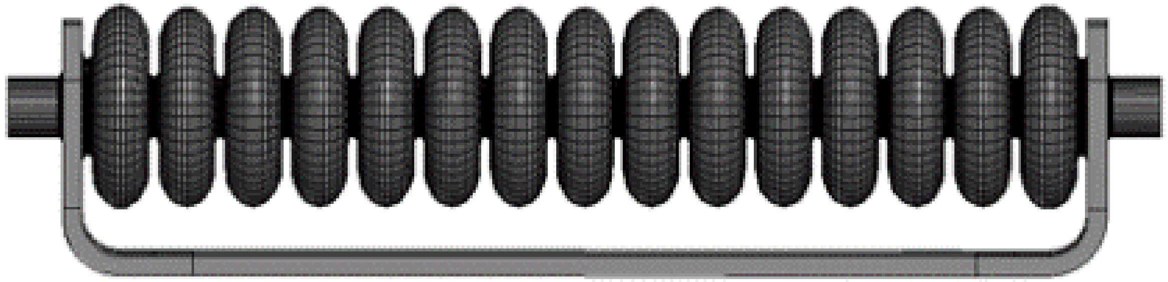
SRF technology for ILC-250 and beyond present limits

- The baseline Main Linac SRF technology was developed in 1990s-2000s and described in the TDR.
- It is a mature technology, already used in such machines as European XFEL and LCLS-II / LCLS-II-HE. The U.S. community is one of the leaders that brought the technology to where it is today.
- However, ongoing generic SRF R&D efforts (not part of the ILC ITN and Preparatory Phase, but funded by GARD, US-Japan and other programs) promise to bring SRF to a new level with potential applications to the ILC energy upgrades as well as other future accelerators.
    1. Advanced shape standing wave SRF cavities – Low Loss (LL), ICHIRO, Reentrant (RE) – increase peak quench magnetic field by 10-20%, potentially bringing accelerating gradient limit to $\lesssim 60$ MV/m



SRF technology R&D

2. Traveling wave (TW) SRF offers better cryogenic efficiency and higher accelerating gradient up to ~ 70 MV/m – possible application: ILC energy upgrade, HELEN collider, Accelerator Complex Evolution at Fermilab



3. Advanced SRF materials – Nb_3Sn cavities can potentially reach ~ 90 MV/m