Fermilab Response – November 11, 2015

August 31, 2015

"Survey and Analysis of the Technical Feasibility of the International Linear Collider (ILC) Project and Technical Challenges Posed by Construction of the ILC Accelerator"

Questionnaire for Commissioned Survey of Research Institutes and Companies

[Questionnaire Sheet]

Nomura Research Institute, Ltd.

[Request for participation in survey]

[How to complete this questionnaire sheet]

1. All participants in this survey have been sent the same comprehensive questionnaire sheet. Please answer questions that you feel apply to you given your institute's activities (e.g., technology development/integration, performance testing) or the products that your company is involved in manufacturing.

2. If you select more than one category of "technology or product" in response to Q1, please answer Q2-Q4 regarding each technology or product you have selected.

3. Please refer to the attached sample when filling in this questionnaire sheet. The sample covers "superconducting acceleration cavities." Please therefore substitute the technology or product you will be responding about.

4. This questionnaire sheet and the following interview survey will be conducted in the following two stages. We thank you in advance and look forward to your kind cooperation at each stage.
   (1) Stage 1 (pre-visit questionnaire survey)
   This questionnaire sheet is being sent out ahead of the interview survey. Please complete and return it as an e-mail attachment before the visit as indicated below.
   • Return by: October 29, 2015
   • Return to: (Mr.) Daisuke YAJIMA, Nomura Research Institute
   E-mail: d-yajima@nri.co.jp
   (2) Stage 2 (interview visits)
   We will visit each institute and company according to a prearranged schedule. During these visits, our interview team will ask additional or more in-depth questions based on the responses given in this questionnaire sheet.

5. If you have any questions about this questionnaire sheet or the interview survey, please do not hesitate to contact:
   (Mr.) Daisuke YAJIMA, Senior Consultant

E-mail: d-yajima@nri.co.jp

(Mr.) Michio KITAMURA, Deputy General Manager
E-mail: m-kitamura@nri.co.jp

Social System Consulting Department
Nomura Research Institute, Ltd.

[Information about yourself]

Please provide the following information about yourself.

Item	Your response
a. Your name	Hasan Padamsee
b. Your position	Former Chief Technology Officer, Head of Technical Division Retired July 2015
c. Your contact e-mail address	Hsp3@cornell.edu

[The technologies or products you will be responding about]

Q1: Please indicate what technology or product (machinery/equipment/parts) you will be responding about by selecting from the following options and entering the corresponding number in the box provided below.

No.	Technology/product category
A	Superconducting acceleration cavity technologies
A-1	Superconducting technology
A-1-1	Superconducting acceleration cavities
A-1-2	Cryomodules (elements, assemblies)
A-1-3	Superconducting magnets
A-2	Cryogenic/cooling technologies
A-2-1	Cryomodule cooling
A-2-2	Cryogenics/Refrigerators
A-2-3	Refrigerant feed, circulation, and storage
A-3	Vacuum technology
A-4	Manufacturing technologies
A-4-1	Precision machining equipment
A-4-3	Electropolishing equipment
A-5	Inspection and tuning equipment
A-5-1	Superconducting cavity surface inspection devices
A-5-2	Superconducting acceleration cavity tuning machines
A-7	Superconducting acceleration cavity system testing
A-8	Superconducting accelerator/beam acceleration testing

B	Radio frequency technologies
B-1	High-power RF technology
B-1-1	Modulators
B-1-2	Klystrons
B-1-3	Couplers
B-1-4	Waveguides
B-1-5	Circulators
B-1-6	Dummy loads
B-1-7	Vacuum viewing ports
B-1-8	Other waveguide elements
B-2	Low-voltage RF control technologies
C	Beam technologies
C-1	Polarized electron source technology
C-1-1	RF electron gun
C-1-2	Polarization measuring technology
C-2-2	Gamma ray generators
C-3	Beam measuring technology
C-3-1	Beam position monitors
C-3-2	Beam profile monitors
C-3-3	Interferometers
C-3-4	Signal reading systems
C-4	Beam transportation, orbit, and focusing technologies
C-4-1	Dipole magnets
C-4-2	Quadrupole magnets
C-4-3	Multipole magnets
C-4-4	High-speed kickers
C-4-5	Electromagnet power sources and power source controllers
C-4-6	Beam monitoring/feedback technologies
C-5	Beam dumping technologies
C-5-1	Beam dumping systems
C-5-2	Tuning/emergency beam dumping systems
C-5-3	Beam sweepers
C-5-4	Window material
C-6	Other (not shown above)
D	Civil engineering technologies
D-1	Tunnel technologies
D-1-1	Tunnel frames, bulkheads, and earthquake proofing
D-1-2	Tunnel temperature and humidity control

D-1-3	Tunnel waterproofing and drainage
D-1-4	Tunnel disaster prevention and safety
D-2	Large-scale precision installation technology
D-2-1	Laser trackers
D-2-2	Alignment scopes
D-3	Utility supply technologies
D-3-1	Electricity supply
D-3-2	Helium feed
D-4	Other (not shown above)
E	Information processing and software technologies
E-1	Bulk data transmission technologies
E-2	Software technologies
F	Other (not shown above)

<Field for your response to Q1> *Please enter only one of the above in the box below.

No.	Name of technology or product (machinery/equipment/parts)
A-1	Superconducting technology

*Please answer the following questions (Q2-Q4) regarding the technology or product (machinery/equipment/parts) that you have answered above.

*If you are willing to provide answers regarding more than one technology/product category (i.e., if you would like to enter more than one number from the list of options above), please copy and paste the questions below and complete separate answers for each technology/product category.

Q2: The questions in this section are about the current state of ILC technologies or products (machinery/equipment/parts) and issues faced.

Q2-1: Please describe the state of verification testing, current attainment of performance required by the ILC (target performance indicated in the TDR), future outlook, and technical obstacles to attain required performance at your institute/company regarding the technology or product selected in response to Q1.

*Please answer regarding the technology or product (machinery/equipment/parts) selected in response to Q1.

Question	Your response

a. State of verification testing of performance of technology/product	*Summary* A-1. Superconducting technology Fermilab has comprehensive capabilities that enable accelerator science and technology R&D, SRF science and technology R&D for future accelerators, as well as for several SRF-based projects and national programs. Our test capabilities have allowed records to be exceeded in high Q R&D, ILC high gradients in cryomodules, and the first beam (at 20 MeV) through the FAST injector and the SRF capture cavity cryomodule. FNAL was a key player in the GDE SRF R&D, helping to establish the gradient yield performance needed for ILC. FNAL processed and tested about 20 ILC 9-cell cavities, to qualify ILC cavities. FNAL is a partner in LCLS-II and will deliver 17 CW ILC-style cryomodules to SLAC, with a gradient spec of 16 MV/m for CW operation at high Q. FNAL will also deliver two 3.9 GHz CM for bunch manipulation. FNAL completed two ILC like CM for the GDE phase. The second CM exceeded ILC spec of 31.5 MV/m. The CM was populated by cavities prepared and qualified by JLAB. The cavities were manufactured by a US vendor, AES.
b. Current state and future outlook regarding attainment of performance required by the ILC	*Summary* FNAL installed the complete suite of infrastructure necessary for ILC cavity inspection, tumbling, electropolishing and vertical testing. FNAL has demonstrated that ILC performance of cavities can be maintained in cryomodules by exceeding ILC spec. All the cavities in the FNAL CM2, which meets the ILC cryomodule specification, were initially processed and qualified at JLab to above ILC specifications. FNAL has pioneered two spectacular breakthroughs on the high-Q frontier allow Q values to more than double the expected value at 2K at medium gradients up to 20 MV/m.

c. Main technical obstacles to attaining performance required by the ILC	*Summary* One of the main obstacles is the "medium field Q-slope" which can decrease the Q to below ILC spec thereby reducing the "usable gradient" even if the maximum gradient falls within ILC spec. For example more than 50% of XFEL cavity show this type of limit. Fermilab R&D has demonstrated that with the addition of one more step in the final treatment of cavities, called HF rinsing, it is possible to raise the overall Q vs E curve to overcome this limitation and significantly raise the usable gradient yield. Field emission is another obstacle (limiting about 20% of XFEL cavities). This can be reduced by increasing the fraction of cavities that go through the 2nd cycle of high pressure rinsing. FE can also be reduced by high power rf conditioning which is regularly used during commissioning of cavities.
d. Reference data/articles on a.-c. above (if available)	

Q2-2: Please describe the features of the technology developed at your institute/company of the technology selected in response to Q1.

[Features of technology]

Question	Your response
The features of the technology developed at your institute/company (E.g., State of technologies owned, their features, processing capacity)	*Summary* FNAL has three Vertical Cavity Test stands to accomplish cavity testing rates (to >150 test cycles/year). Two dewars could hold up to 4 cavities at once. One test stand has advanced diagnostics such as T-map, second sound, fast thermometry, and fluxgate magnetometers at temperatures down to 1.4K. Regrigeration capacity at test area is 300 L/hr. with increases planned. If funds are available the goal is to double the present cryo capacity to 600 L/hr within two years. FNAL has three Horizontal Test Stand for testing fully dressed cavities

	at high power. Our Cryomodule Assembly Facility (CAF) is capable of assembly of one cryomodule per month in production including the cavity string assembly in Class 10 clean room. FNAL has one production horizontal EP machine for 9-cell cavities located at Argonne National lab. The horizontal EP machine has demonstrated multiple cycles per week. The ANL/FNAL cavity processing system can electro-polish bare cavities and He-vessel dressed cavities. FNAL has two production HPR machines, each of which can do one 9-cell process per day. Cavity Processing Lab (CPL) located at FNAL includes EP, tumbling, furnace treatments including nitrogen doping, and RF tuning lab for projects and SRF R&D. Advanced Analytical instruments including SEM/EBSD/EDX, LCSM optical profilometry, DC magnetometry, AC susceptibility, resistivity, and thermal transport measurements in PPMS, Instron® machines, metallurgical polishing equipment, and sample chemical preparation lab Engineering Computing facilities including a suite of software tools for advanced engineering modeling FNAL has one cryomodule test area in the accelerator test facility (FAST) with a throughput capacity of 1 CM/month. There is building space to install additional CMs. At the FAST Facility (Fermilab Accelerator Science and Technology Facility), the FAST photo-injector was completed and commissioned with 20 MeV beam accelerated through an SRF Cryomodule (CC2); Cryomodule-2 (CM2) was operated for 6 months. CMTS1 test cave was constructed and it's cryogenic distribution system have been procured. *Reference data/articles* (Please attach if available, or provide a reference, URL, or other source.)

Q3: The questions in this section are about the obstacles to and feasibility of mass production of products (machinery/equipment/parts) for the ILC.

Q3-1: Please describe the obstacles and feasibility of mass production at your institute/company of the product selected in response to Q1.

[Obstacles to mass production of product]

*Please answer regarding the technology or product (machinery/equipment/parts) selected in response to Q1.

Question	Your response
Obstacles to mass production of product	*Summary* Competition with other HEP projects depending on their priority relative to ILC, e.g PIP-II and PIP-III. *Reference data/articles* (If available, please attach or provide a reference, URL, or other source.)

[Feasibility of mass production of product]

*Please answer regarding the technology or product (machinery/equipment/parts) selected in response to Q1.

Question	Your response
a. Selection of mass production methods (e.g., line automation, upgrading/upsizing of facilities, workforce shift arrangements)	*Summary* Promising cost reduction avenues should be explored as early as possible. These include hydroforming and spinning of 3-cells or 9-cells. Explosion bonded Nb-Cu should be explored to reduce Nb cost and Nb required. Proof of principle for high performance cavities (single cells and some multicell) has already been demonstrated. Cost benefit and Q-beneift of ingot Nb (sheets direcly sliced from the ingot) should be pursued. But funding for these explorations needs to be available. DESY has demonstrated very high performance in a CM with ingot Nb technology (~45 MV/m)
b. Technical feasibility and timing of availability of mass production methods	*Summary* FNAL will be ready and capable of supporting ILC production needs after completion of the LCLS-II and PIP-II project (2023?). Strategic investments to increase throughput should be planned and started ahead of time.
c. Financial feasibility of mass production methods (e.g., cost performance)	*Summary* Some cost reduction in large-scale production may be expected through learning curves, automation, bulk procurements etc. To achieve bigger cost reductions alternative methods, materials and processes should be explored. The opportunity to do this is now. Once the project construction is launched there will be no time for significant changes.
d. Reference data/articles on a.-c. above (if available)	*Please attach or provide a reference, URL, or other source.*

Q4: <u>The questions in this section are about the obstacles to reduce the cost of products (machinery/equipment/parts) for the ILC and ways around these obstacles.</u>

Q4-1: Are there any possible substitutes (in terms of greater compactness or cost performance) for the technology or product (machinery/equipment/parts) selected in response to Q1 at your institute or company?

Yes (substitutable technology/products available now or in the future)

1) ILC cavity shape may be redesigned for better performance
2) ILC cavity fabrication might be simplified
3) Nb-Cu composite and ingot Nb can be pursued to lower material cost

Q4-2: If you answered yes to Q4-1 above, please provide the following information regarding the current state of development of technologies for them and issues that need to be addressed.

- Developer of the technology
- Content and level of technology development
- State of testing and verification
- Obstacles to practical application
- Time required until practical application becomes possible
- Financial expenditure required until practical application becomes possible (approximate)

[Current state of development of substitutable technology/products and issues to address]

Question	Your response
a. Developer of technology (own institute / own company / other institute / other company)	*Summary* 1) Low-Loss shape and Re-entrant shape single cell cavities have demonstrated gradients above 50 MV/m. SLAC low-surface-field (LSF) cavity could also provide improvement. 2) Seamless cavity fabrication R&D via hydroforming is ongoing at KEK, USA (via SBIR), and was happening at DESY (halted during XFEL production). Seamless cavities via spinning is continuing at INFN – Legnaro. Could be much cheaper and avoid e-beam welds in high magnetic field region.

b. Content/level of technology development	*Summary* 1) Several low-loss cavities (“Ichiro”) single cell have been made and tested and have exceeded 50 MV/m. Multicell cavities need to be demonstrated with field emission as the limiting factor. SLAC LSF cavity has been modeled and single-cell cavities built and tested, but not yet built or tested in 9-cell form. 2) 3-cell seamless cavities have been made with encouraging results at DESY/JLab. KEK has demonstrated good forming control. US vendor is just starting trials. A 3-cell fully spun cavity (at INFN) has been tested at FNAL to reach 34 MV/m at Q of 10^10. 5) Successful demonstrations on 9-cell cavities of bipolar and HF-free EP recipes has been demonstrated by a company in collaboration with FNAL.
c. State of testing and verification of technology	*Summary* 1) LSF 1-cell cavity has achieved 41 MV/m (theoretical limit is >50 MV/m) accelconf.web.cern.ch/AccelConf/IPAC2015/papers/wepwi013.pdf. Ichiro (LL) cavity shape achieved and 42 MV/m in 9-cell cavity (SRF 2011 (RF Superconductivity), Chicago, IL (United States), 25-29 Jul 2011. Saito, K.; Furuta, F.; Konomi, T.; Eremeev, G. V.; Geng, R. L.). 2) DESY/JLab 3-cell seamless cavity achieved 35 MV/m. 3) JLab waveguide couplers deliver up to 13 kW average power. Peak power capability has never been tested. JLab FEL prototype window was tested to 65 kW average power. CESR 500 MHz cavity waveguide window delivered ~0.5 MW average power. NLC waveguide windows delivered 10 MW peak power in short pulse, low duty factor. Nobody is working on waveguide couplers for ILC specs. 4) High RRR ingot cavities at DESY (built by RI) achieved 45 MV/m in a CM. 5) 1-cell cavities processed with HF-free recipe have achieved ~30 MV/m. 6) 9-cell cavity has been treated with HF-free recipe to reach ? 35 MV/m

d. Obstacles to practical application	*Summary* One obstacle to change is the success of the incumbent design/process. People are reluctant to change anything and it is very hard to gather statistics to compete with the standard process. Another factor is the drop in global R&D support since the end of the GDE phase. In the USA the funding has dropped essentially to zero. What Generic SRF R&D is happening is based on individual lab funding or other project needs.
e. Time required until practical application (approximate)	*Summary* 1). Further development of low cost approaches needs funding and/or a project willing to put such cavities in a cryomodule. It could be adopted quickly without other changes to the CM. 2) Seamless cavity R&D is active in KEK and on a small scale in the USA. DESY is inactive on this during XFEL production. Seamless dumbbell tests were done at MHI. First cavity results could be achieved within 1 year. Turning it into a production process could take 2-5 years depending on the level of investment. It could be adopted quickly without other changes to the CM. 4) High RRR ingot cavities have been proven and are ready to use now. This could be adopted without other changes to the CM. Relaxed material spec (increased Ta, decreased RRR) should be tested in a statistically significant number of cavities. 5) HF-free EP and vertical EP are being demonstrated in the lab now., but a statistically significant sample of cavities needs to be done if well-funded.
f. Expenditure required until practical application (approximate)	*Summary* All of the above activities are funding limited. A strong program in any one is of the order of $1 – 2 M/year in one lab or multi $M in multiple labs. Great progress was made during the GDE phase. If those budgets were restored globally many of these tasks could make significant progress in time to benefit ILC.

g. Reference data/articles on a.-f. (if available)	*Please attach or provide a reference, URL, or other source.*

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No.	Name of technology or product (machinery/equipment/parts)
C-4-1	Dipole magnets
C-4-2	Quadrupole magnets
C-4-3	Multipole magnets
C-4-4	High-speed kickers
C-4-5	Electromagnet power sources and power source controllers

Fermilab maintains its position as a world leader in superconducting magnet R&D, with the capability moving into production of challenging magnets.

The Magnet Test Facilities at FNAL covers the operation and maintenance of world class facilities related to construction and testing magnets. This includes basic measurement systems, fabrication of test magnets, the infrastructure for inspection of incoming components.

Accelerator Test Facilities maintains multiple test stands for measuring both superconducting and room temperature magnets. For room temperature magnets, existing equipment supports coil winding, grit blasting, vacuum impregnation, epoxy curing, core lamination stacking, ferrite brick magnetization, and a multitude of in-process inspections. For superconducting magnets, existing equipment supports strand and cable testing, cable making, coil winding, coil reacting, coil collaring, and magnet assembly. We plan to extend that capability to allow programming of cable paths, in addition to the current manual operation.

The High Field Magnet (HFM) Program at Fermilab is developing advanced superconducting (SC) magnets, materials and baseline technologies for present and future particle accelerators. During the past decade the program focused on the 10-15 T Nb_3Sn accelerator magnets. In the longer term, the program will thrust the development of accelerator magnets beyond the limits of Nb_3Sn technology with fields of 20-25 T based on LTS (Nb_3Sn) and HTS (Bi-2212 or YBCO) coils. The development of the 11 T Nb_3Sn dipole for LHC upgrades, performed since FY11 in collaboration with CERN, has been finished.