Key R&D Issues in SCRF and FNAL Collaboration

Marc Ross

Superconducting RF

- **Luminosity requires beam power;**
  - **Superconducting RF is the *most effective* way to create high power beams**
- **Proven design:**
  - **1.3 GHz sheet metal cavities**
  - **ILC - Each cavity delivers 285 KW to 9mA beam**
  - **ILC - fill time 38% total pulse**
  - **ILC - linac efficiency (RF to beam): 50%**
    - **Fill time, distribution and feedback overhead**
- **Large irises → minimal emittance growth with achievable tolerances**
  - **If we can achieve tighter assembly/tuning tolerances, can improve efficiency**

Adopt TESLA cavity design

- Capitalize on momentum of the DESY-centered development
  - 1992 to present
  - Copy, Develop, Extend, Deploy →full system Test
    - Unprecedented scale → ILC >16000 cavities
- US labs / universities:
  - Will appropriate and perfect 'large scale' preparation technology
    - ('RD – scale' systems to date)
  - Are suited for this task:
    - Substantial expertise – distributed –
    - JLab, Cornell, ANL, MSU, LANL, FNAL, SLAC… (Cavities, Cryo, RF)

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SRF Infrastructure Plan: Goals

- **To perfect U.S. fabrication & processing of SCRF cavities and modules and to demonstrate performance with a full range of testing (including beam performance)**
  - ***Copy* TESLA-style design / processing / assembly techniques**
  - **Establish *process controls* to reliably achieve high gradient cavity operation and cryomodule performance**
  - **Test cavities and cryomodules at the component level and in a *systems test* to demonstrate yield, reproducibility and beam performance**
- **To facilitate commercial production of SCRF components and modules**
  - **Provide training and facilities to allow *industrial participation* and input to the process**
  - **(Similar to SC cable and magnet technology transfer)**
- **To participate in SCRF Research and Development**
  - **Our attempt to *aggressively support* the world's SCRF RD community**
- **All of this work will be carried out in collaboration with US/international partners**

Setting the Scale

- **For ILC: produce 4 to 6 cryomodules in the next 4 years**
  - **~ 50 cavities used;**
  - **additional needed for development and testing**
- **The number of cavities needed and the scope of work required to establish a reliable, cost-able process determine the scale of the US infrastructure**
- **International (ILC/GDE) coordination:**
  - **S0 'tight loop':**
    - **Process and re-process the inside surface of a limited number of cavities, repeatedly, testing each time… (~100 procedures/year for several years)**
    - **Answers due 08, 09 → guidance for a final gradient recommendation**
  - **S1 cryomodule demo:**
    - **31.5 MV/m OPERATING cryomodule**
  - **S2 'string test':**
    - **Put it all together**
    - **Various critical tasks**

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This talk:

1. What are the key R&D issues faced by the U.S. accelerator community in the area of SCRF?

4. Does the laboratory make effective use of collaboration and existing SCRF assets at other laboratories and universities?

- **Outline specific 'RD' tasks (~8)**
  - **Based on technical risk v/v state of the art**
  - **Based on ILC Linac cost-drivers**
- **How does our proposal connect to each?**
- **How national SCRF RD 'fabric' connects to each?**
  - **i.e. what is role of collaboration**

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Specific tasks - technical

- (Key challenges that will still be with us 09..)
- Electron beam welding (EBW) of formed Nb sheet
- High volume etching of finished assemblies
- Surface smoothness and particulates
- Practical gradient → radiation, Q, dissipation (multipactor)
- Assembly, including power couplers and Higher Order Mode couplers
- HOM
- Process and Testing Diagnostics
- Full power system tests – static, dynamic (w&w/o beam)

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Specific Tasks – Cost

Cryomodule costs	fraction	sum
Cavity Fabrication	36%	36%
Power Couplers	10%	46%
Helium Vessel Fabrication	8%	54%
Magnetic Package (Quad)	7%	61%
Tuners	7%	68%
Assembly, Testing, Transport	5%	72%

(Next 7 items – to 1% level (22%)– Vacuum vessel,shields, interconnect, processing, dressing, pipes, supports, instrumentation)

The cryomodule / cavities in it are a cost driver for the ILC linac.

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Cavity Fabrication: EBW

- (Almost) all Nb cavity welds done in HiVac conditions with EBW
- Identified as critical path for ILC Linac construction
  - KEK – based evaluation: 2003
- a single cavity requires dozens of welds
- e.g. 800 machines produced by Mitsubishi Electric Company to date → mostly small
- typical cost 3 M$, 80% used for automotive precision welding (from KEK study)

- EBW supports RD → flexibility
- RD needed to reduce EBW costs/perfect operation
- JLAB EBW machine at 2 shifts now…

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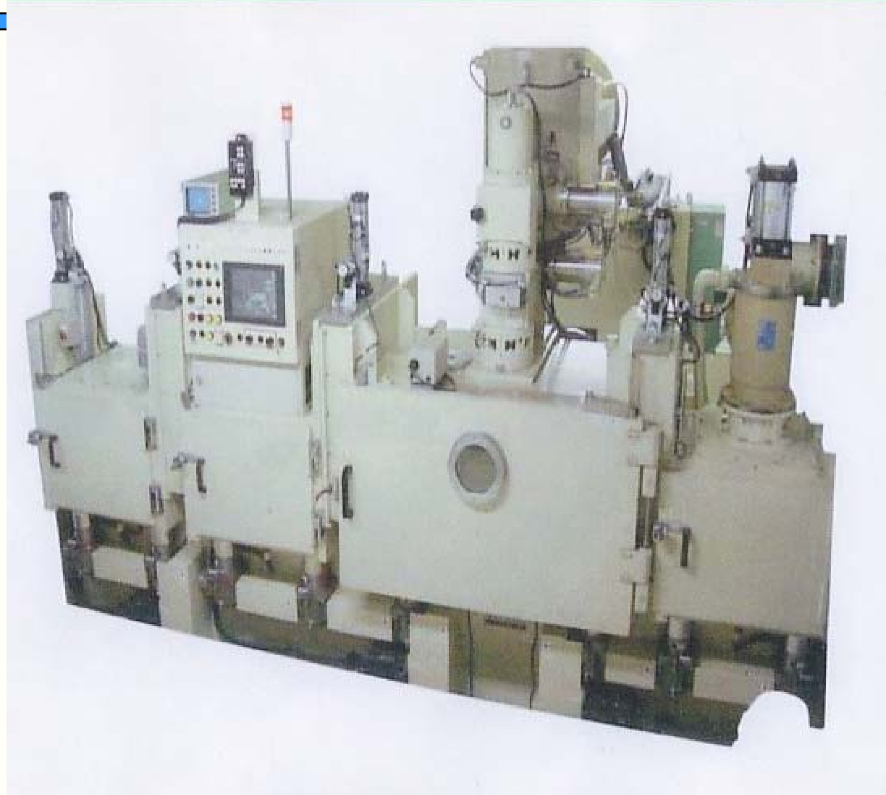
Electron Beam Welding (2)

- 7x time reduction (v/v RD) using multi-chamber-type high-speed machine with load-lock. ← TESLA TDR
- EBW for automotive components has multi-chambers with gate valve separation. PRIUS NiMH →
- Most comprehensive: KEK-TESLA TDR eval. (2004)
  - Needed capital investment (MEC):
    - 6 dedicated for the 9-cell cavities (60M$ for specialized machines),
    - 12 dedicated small machines for stiffening rings (24M$ for specialized machines).
    - Additional machines for HOM couplers and beam pipes, using 'standard' welders



三菱電子ビーム加工機

FNAL EBW: Buy one 'properly configured machine'

(M. Foley)

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High Volume Electro-Etching

DESY Process parameters: HF / H2SO4 (10/90)

Process data	fixed in middle of 2005	
Voltage	17 V	
Acid refill volume	9- 10 l / min (flow)	→ **200 liters total**
Average temperature		
Cavity inlet	24 C	
Cavity outlet	29 C	→ **'active' cooling required**
Average current	240 A	→ **4kW power dissipation**
N2 overlay	30 l/min	
Acid usage up to	12-14 gr Niobium per liter acid	→ **2.5 kG acid load**
Main EP		
Duration	2*180 Min	
Removal	nominal 144 µm	→**(cavity wall thickness ~ 2.5 mm)**
Fine EP		
Duration	1*120 min	
Removal	nominal 48 µm	
Cooling	regulation to flat Current curve	

Reproducible performance: EP ?

Is max cavity gradient 'scatter' due to EP process?

- Process parameters:
  - non-reproducibility,non-uniformity of material removal
- Set-up:acid level, cathode bag, cathode shielding, current leads, T-control
- "Q-disease": unpredictable, material?
- Reproducibility in acid composition (DESY)
- Draining and rinsing:
  - overheating? for multi-cell cavities

- Is scatter caused by
  - "environmental" problems?
  - Malfunction of system
  - Problems during rinsing and/or assembly
  - Vacuum problems
  - Problems during testing
  - Human errors
- (Peter Kneisel - JLAB)

List (and prioritize)

- Re-visit residual contamination of EP surfaces: XPS,SIMS? FE
- Investigate different rinsing methods:
  - hot water (Henkel), H_2O_2 + US, anodizing, oxipolishing,..
  - on samples, single cells: either several or reference cavity of known performance
- Removal of sulfur from mixture:
  - filtering?, solvents,…
- Implement “on line” monitoring of HF concentration and polarization curves, purity (gas chromatography)
- Shaping of cathode:
  - more uniform material removal, more uniform polarization curves over whole surface, lower voltage to achieve required current density, more uniform T-distribution?
- Does it make sense to explore other acid mixtures? Or should one concentrate on making present process “fool proof”?

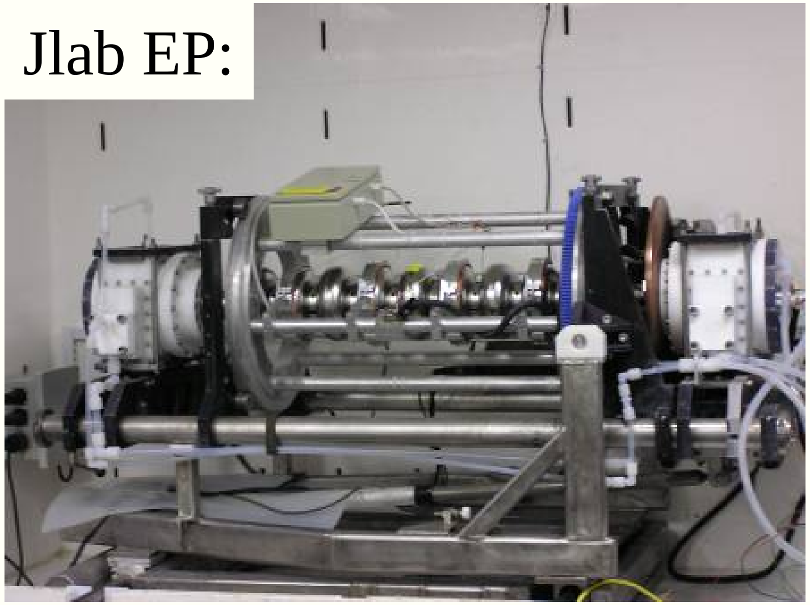
Identify resources:

EP4

- **Surface studies:**
  - Saclay, Univ. Wuppertal, Jlab/Fnal, INFN Genoa,Cornell?
- **Rinsing studies:**
  - KEK, DESY,Jlab/Fnal,Cornell,Saclay,ANL,MSU?
- **Electrode shaping:**
  - INFN Legnaro, DESY/Henkel,KEK,Jlab, Cornell,ANL/Fnal
- **Implementation of "on-line" monitoring:**
  - DESY,KEK/Nomura Plating, Jlab/Fnal, Henkel, ANL?

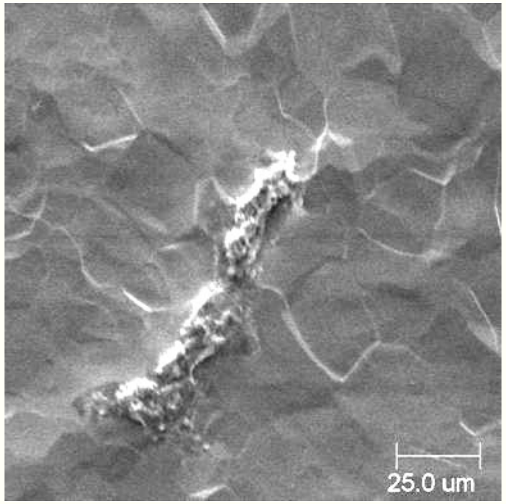
(slides adapted from Peter Kneisel, TTC 09.06)

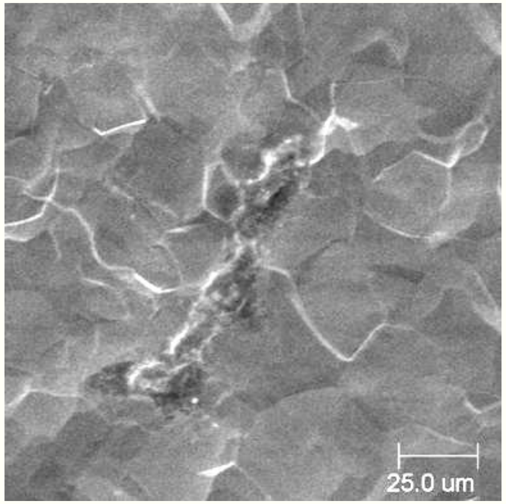
Jlab EP:



FNAL EP: H. Carter / C. Antoine

Surface smoothness / particulates



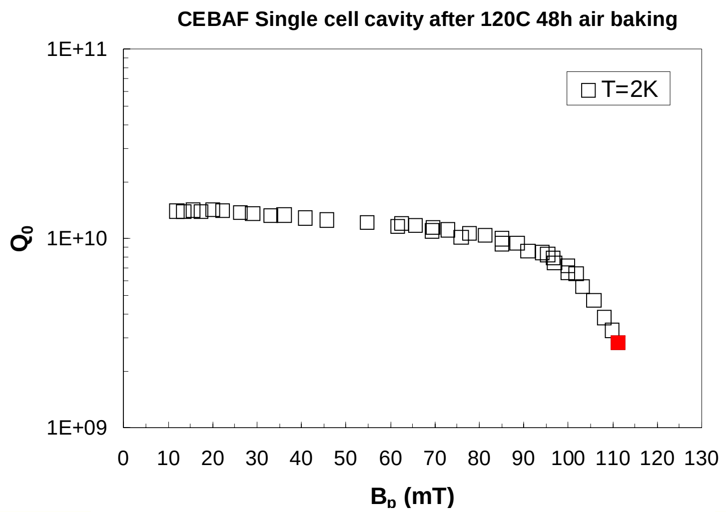


- **Residual 70 um particulate – sulfur – in single cell test at Cornell**
  - **Before and after high pressure rinse**
- **New method needed to clean post-polished surface**
- **Sulfur residue from H_2SO_4 decomposition → EP process**
  - **Acid preparation/degradation?**

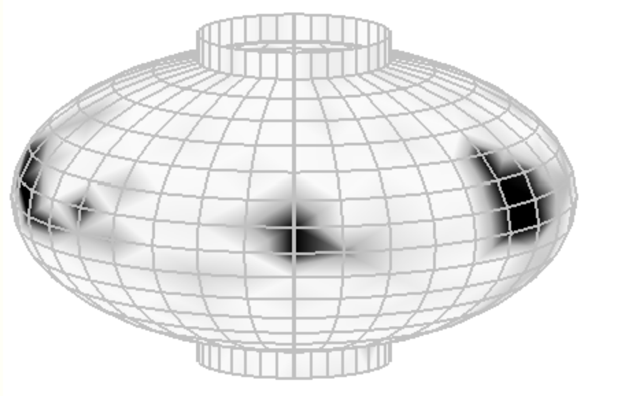
Advance Material R&D

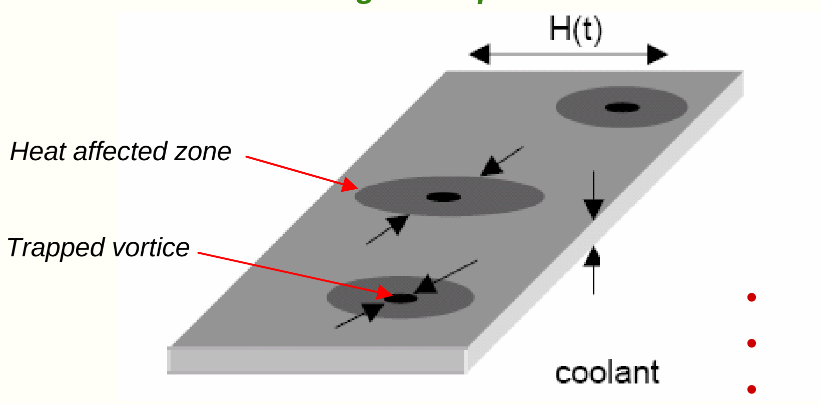
Superconductivity limits

The theoretical limits for RF superconductivity aren't well known



- ***What causes the high field losses/ hot spots ?***
  - *Morphology ?*
  - *Grain boundaries*
  - *Surface contamination (O)*
- ***Recommendations***
  - *Basic R&D on superconductivity*
    - *e.g. Hot Spot Model – A. Gurevich (Coll'n w FSU)*





- *Effect of trapped vortices*
- *Heat source ~ can be very small (nm to mm)*
- *Thermally affected zone: ~ 5 mm and growing with B!*

FNAL Materials RD: C. Antoine

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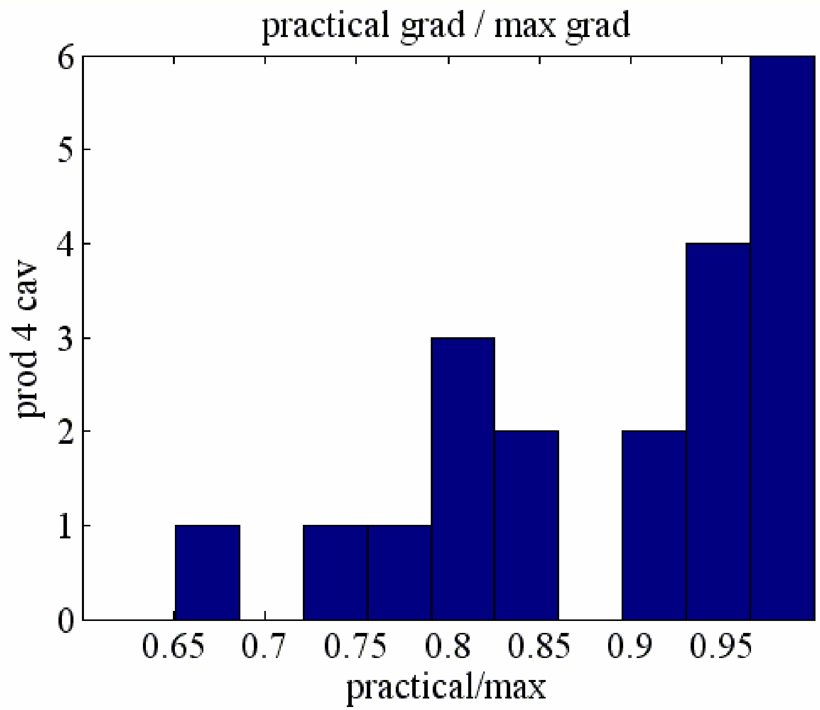
‘Practical’ (usable) gradient

- **Feedback from vertical test: 3 criteria**
  - **Achievable field (quench)**
  - **Q and dQ/dE 1W/cavity in pulsed operation (5e9@25) – (cryogenic load)**
  - **Radiation (x-ray)**
- **Vertical test provides the first indication**
- **How to interpret the vertical test result:**
  - **What is the ‘real yield’?**
- **Practical gradient degraded from max achievable**
  - **VTS analysis key to understanding above limitations**

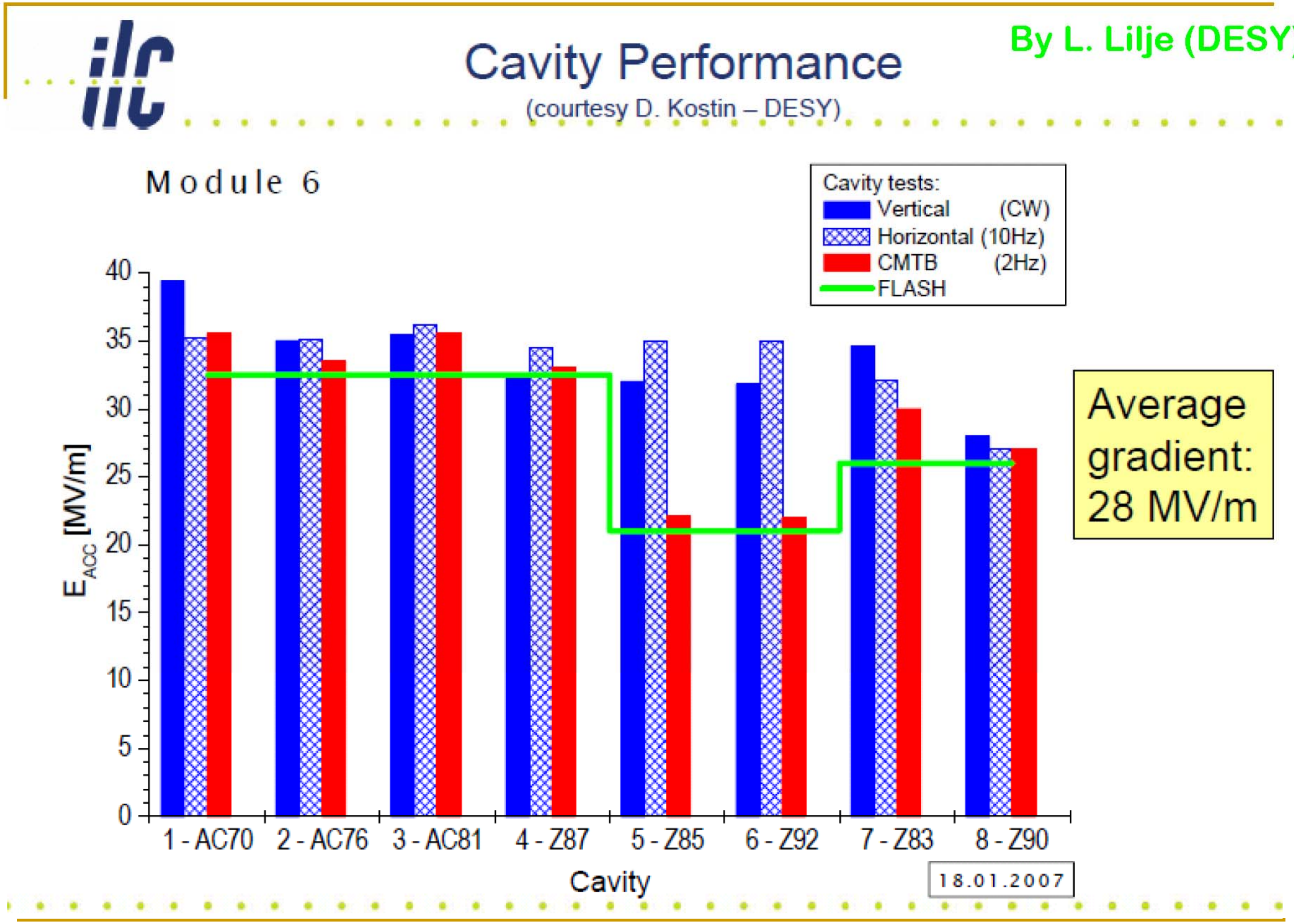
DESY Data: 22 cavities – 2006
Predicted usable gradient based on vertical test results:



FNAL Vertical Test: C. Ginsburg

Assembly - Does performance further degrade due to handling?

Typical assembly variation is *better*; esp. Horizontal to CM



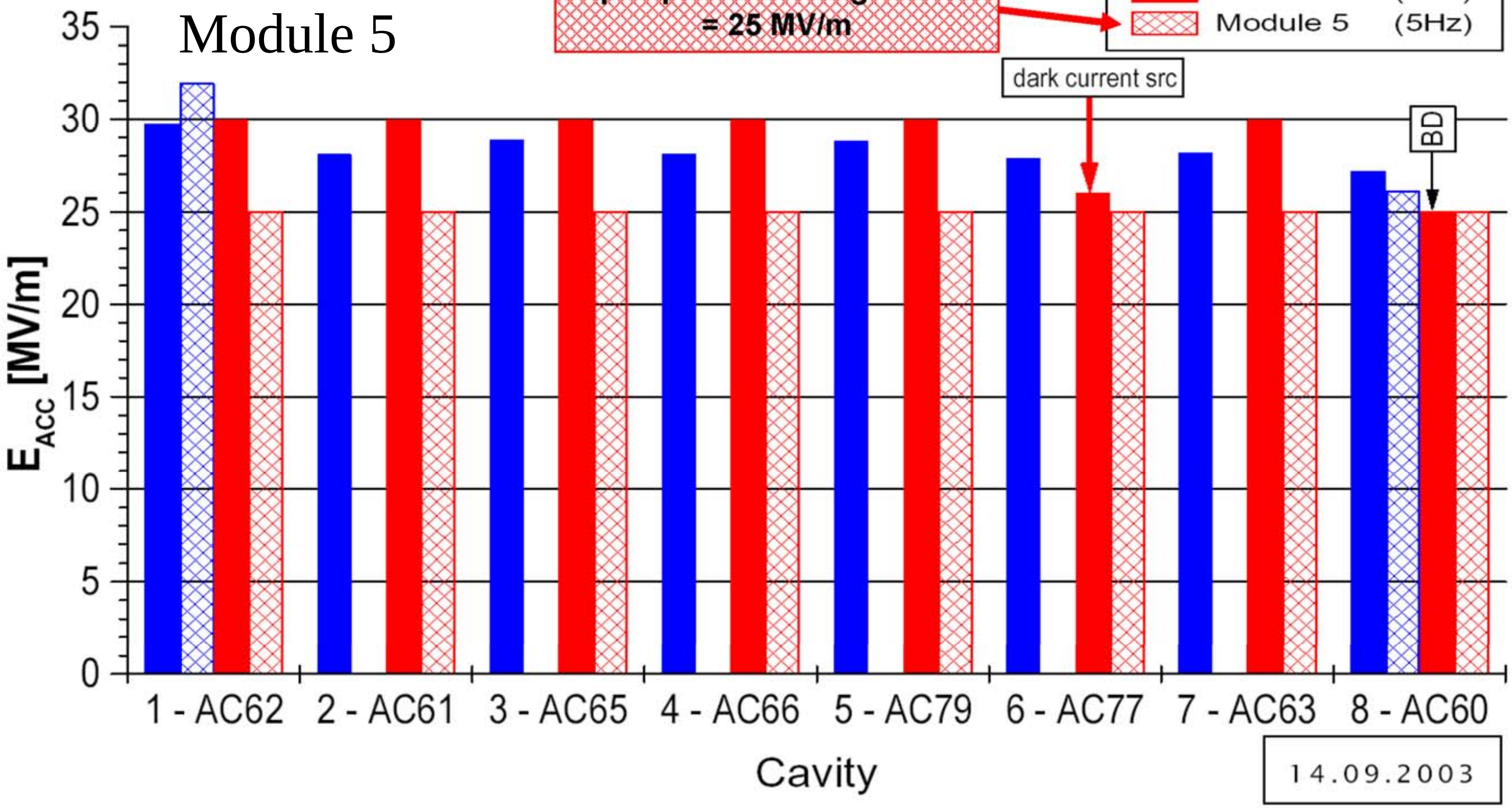
Performance of FLASH Accelerator Modul From H. Weise/ D. Kostin

A State-of-the-art module

- cryogenic type III
- latest coupler generation
- Etched (BCP) cavities

In single cavity measurements 6 out of 8 cavities reach 30 MV/m!

Equal power feeding <Eacc> = 25 MV/m



Cavity String Assembly

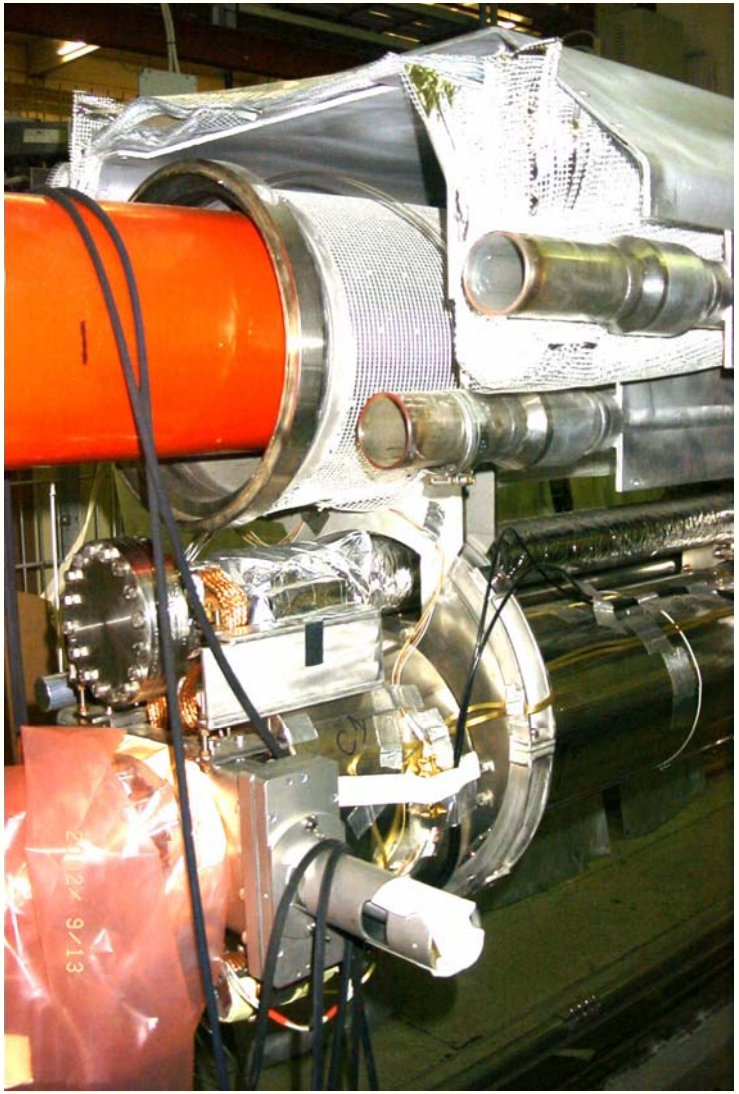
The assembly of an 8 cavity string

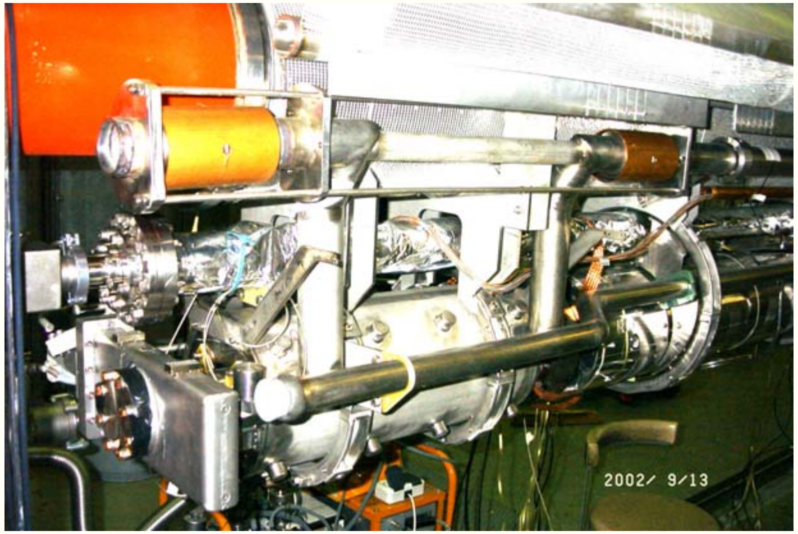
- **is a standard procedure at DESY**
- **was done by technicians from the TESLA Technology Collaboration**
- **was the basis for two industrial studies.**

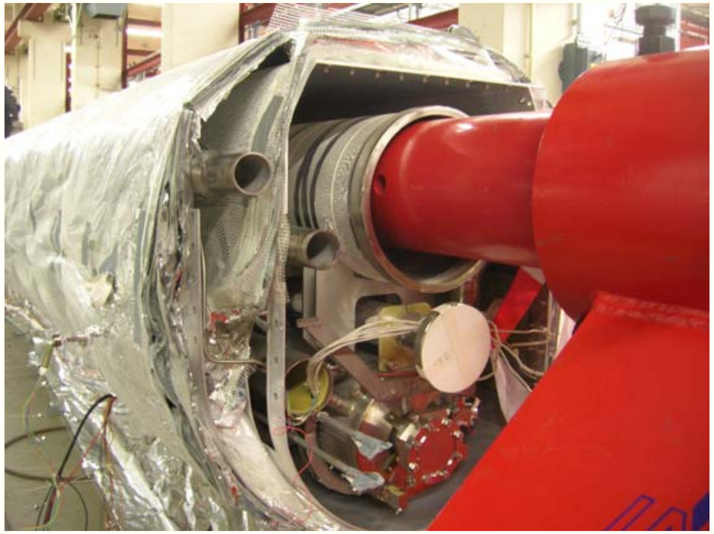
The transfer of this well known and complete procedure to industry has started.

DESY will provide sub-components for the first string / module built in industry; this allows for an early training.

Cryomodule assembly: 1200+ parts







FNAL CM Assembly: T. Arkan

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HOM

- **Single most serious problem with SNS cryogenic accelerator cavities**
  - **Also implicated as most critical failure in 3 separate 2006 RD programs**
    - **2 cavity developments at KEK**
    - **Fermilab / DESY 3.9 GHz cavity**
- **Typical failure:**
  - **Modelling of multi-pactor thermal breakdown**
  - **Failure to clean closely spaced components**
  - **Failure to adequately cool coaxial feedthrough**
  - **Coupling strength to fundamental**
  - **Construction / fabrication**
- **For new cavity designs, clean HOM extraction must be demonstrated with beam**
  - **System test issue #1**

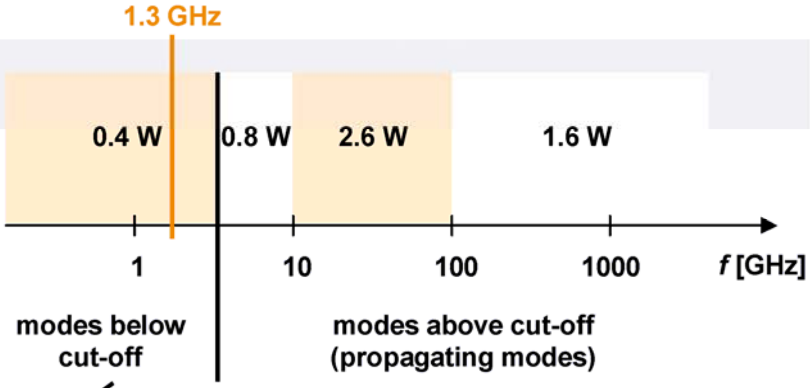
FNAL HOM: H. Edwards

Damping of Higher Order Modes (HOMs)

The spectrum of the electron bunch (σ_z = 25 µm) reaches high frequencies up to 5 THz.

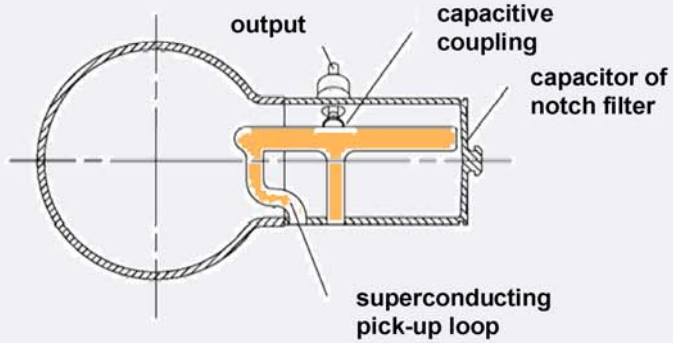
The standard accelerator module has an integrated loss factor of 135 V/pC.

The total power deposited by the nominal beam is 5.4 W per module.

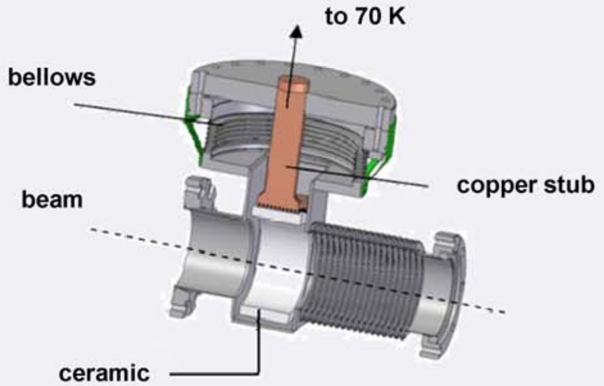


The design of the HOM coupler and the beam pipe absorber take into account a possible XFEL upgrade (more bunches / CW mode).

The HOM coupler was tested in CW mode. The absorber is specified for 100 W.



HOM coupler



beam pipe absorber

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Diagnostics

- **Best opportunity/ unique opportunity for Fermilab particle physics community to contribute**
  - **Labs with fully operational 9 cell cavity vertical test stands don't have resources or time for this challenge (JLab, DESY, KEK, Cornell)**
  - **Radiation, thermal, data acquisition/control and RF control**
- **Goal:**
  - **Identify and track field emitters through 9 cell / 1 cell cavity process (VTS, HTS, CM assy/test, final install)**
  - **Cleanly separate failure modes:**
    - **Quench due to 'flaws'**
    - **Field emission & field emission induced quench**
    - **Multi-pactor and related thermal breakdown**
    - **Q- reduction**
- **Dynamics changes through process**
  - **CW, high power, high peak power**

FNAL Vertical Test: C. Ginsburg

Full power tests; System tests

- **Purpose of system test - ILC evaluation:**

Test:	Comment	Risk
Component testing for reliability		high – specialized tests also required
Full intensity beam energy stabilization	will be done at DESY	medium – controls
'Dirty vent' / fast protection		
Fault recognition – controls	developed at DESY	high
quench/coupler breakdown rates		high
dark I		
gradient spread		
long term testing		high
trapped HOM		medium
Stability energy / phase		high
x-ray		
thermal cycling		
heat loads		
vibration control - incl quad		
test bed for dev ancillary		high
demonstration of effective international management		high

- **Critical Goal for FNAL infrastructure: System test**

FNAL System Test 'NML': S. Nagaitsev

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RD Challenges Summary (1):

- **EBW is a platform for development: prototype Nb sheet structures / cavities**
  - **Buy an EBW, to be used for prototyping and understanding weld performance and geometry**
- **Chemistry remains single most serious limit**
  - **Develop systems at JLab and ANL, stair-step to next generation here**
- **Residue implicated, not properly removed by rinse(s)**
  - **Rinsing program underway at KEK, starting at JLab (TTC)**
- **Final acceptance testing will be done at lab**
  - **All project ‘scenarios’ have VTS defined as a ‘Lab function’**

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RD Challenges Summary (2):

- CM assembly tooling still quite primitive
  - DESY staff have not had time to work things forward
  - Their industrial transfer is starting, we are observers
- HOM coupler remains weak link in the design
  - Sort of a surprise. FNAL group active throughout the development process
- Diagnostics require substantial development effort
  - Technical
- System test is primary demonstration
  - NML is the US system test
  - World system test in many ways
    - KEK / STF will not have high power beams
    - DESY / TTF does not have flexibility for long term high power tests

Collaboration – Summary

- International partners: cavity technology transfer
  - From DESY
  - From KEK
  - NML 'joint venture'
- US partners, SRF labs: long term (multi-year) relationship
  - Strong staff exchange and infrastructure development
  - Jefferson Lab
  - Argonne
- US partners, universities: fundamental RD
  - Cornell, MSU, LANL, FSU, Universities
  - Various, ranging from materials physics to tooling development and data analysis
- High Level: How does this work? →

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TESLA Technology Collaboration

- The mission of the collaboration is
  - to advance SCRF technology research and development and related accelerator aspects across the broad diversity of scientific applications, and
  - to keep open and provide a bridge for communication and sharing of ideas, developments, and testing across projects
- Interwoven in S0 plan
  - Parallel single cell rinsing studies
    - (defined in TTC EP study 1.2005)
- Interaction with TTC
  - TTC is the resident 'pool' of SRF expertise
    - Thanks to DESY for the formation of this group through the TESLA effort (~10+ years)
    - Ideal group for RD, review and analysis
  - Requested TTC perform single cell work
    - September 2006
  - Affirmation of interest.

FNAL – DESY

- **Management and technical connections:**
- **Excellent ~15 year history, based largely on efforts of Helen Edwards**
  - **TTF Beam Time Allocation Committee member**
  - **Fermilab-built hardware is basic component of TTF**
  - **Ongoing TTF studies: HOM, LLRF, beam dynamics…**
- **Steady exchange of testing and infrastructure development staff**
  - **XFEL Project has (informally) offered management role ←→ mutual benefit**
  - **Participation offer leads to expectation of steady collaboration through XFEL construction**

FNAL – KEK

- **Technical connections:**
  - Strong staff exchange through KEK – ATF (instrumentation and control) 15 years (MCR)
    - three-way collaboration with DESY on HOMs
  - Parallel development of infrastructure – competition and collaboration (KEK is ahead)
  - Orthogonal development: new shapes at KEK; design work at Fermilab
- **Starting inter-lab SCRF projects**
  - Cavity pre-tuning machine (DESY also)
  - Cavity exchange (part of GDE ‘S0’) to start in 2 months (personnel accompaniment)

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FNAL – JLAB

- **JLAB is lead US lab for 07 'ILC –S0' cavity processing demonstration**
  - **Recent results extremely encouraging: 40MV/m & 30 MV/m in JLAB –processed cavities**
  - **JLAB has produced more niobium cavities than any other lab now holds (close to) the world's performance record.**
  - **We have participated in this work – through:**
- **FNAL staff on long-term assignment (~2 FTE 07)**
- **Joint team development of JLAB infrastructure (tooling, diagnostics, procedures)**
- **Long term (~5 year) commitment to work through process technology**

FNAL – ANL

- **Formal linkage between lab directorates**
- **A heavily shared 'local' resource**
  - **ANL 20+ years of expertise, including electro polishing**
- **Now:**
  - **Chemistry rooms at ANL 'co-fab project'**
    - **Electro-polish and chemical etching**
  - **To be fully operational in mid-late 2007**
  - **Development of spoke resonators (HINS)**
- **Soon:**
  - **Active participation in cavity processing and testing on day to day basis**

Why is THIS the right strategy?

- **What is the relationship between infrastructure development on site and collaboration with US Labs?**
  - **Our infrastructure will be based on what we learn through collaboration now established**
- **How do the facilities in this plan accomplish goals?**
  - **Each process component (we know of) is included; each step is to be extended**
- **What are the priorities?**
  - **Support the GDE – determined priorities (TTC); focus on equipment needed to answer toughest questions: Chemistry, system test, diagnostics**

Why is THIS the right strategy? (2)

- How do we complement facilities at SLAC, JLab, Cornell, MSU, and ANL? What are the costs/benefits of each of these relationships? How would we like them to grow?
  - We will learn from these facilities, through staff exchange, usage and feedback, and then develop each.
  - The equipment left behind in this process enriches each partner
- What is the impact of the infrastructure on each of the (known) projects – including non-wholly-owned – like ANL/JLab projects, XFEL
  - Diverse projects facilitate understanding
  - Projects with added momentum (i.e. XFEL) will benefit from accessible, flexible, test area.
  - We benefit from their 'volume' and management lessons learned

Fermilab and SCRF

- US must demonstrate competence in this field in order to host ILC
- Such competence is also a requirement for related machines
  - FEL, ERL, proton…
- In a very basic way, Fermilab and collaborating US labs must compete
  - (i.e. in order to be a viable ILC host)
  - 'Doing' is the best way to learn, and this project contains required components