International Linear Collider (ILC) 
Superconducting Radio Frequency (SRF) Acceleration 
and 
ILC High Gradient SRF Cavity R&D at JLab 

Rong-Li Geng 
Jefferson Lab 

JLab Graduate Student Lunch Seminar, September 21, 2011
THE MYSTERIOUS UNIVERSE
Exploring Our World With Particle Accelerators
The Nature of Matter

Could there be more quarks? Or something smaller?

Structure within the Atom

Quark
Size $< 10^{-19}$ m

Nucleus
Size $\approx 10^{-14}$ m

Atom
Size $\approx 10^{-10}$ m

Electron
Size $< 10^{-18}$ m

Neutron and Proton
Size $\approx 10^{-15}$ m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Atoms as we know them today
The fundamental questions

- What is the nature of the universe and what is it made of?
- What are matter, energy, space and time?
- How did we get here and where are we going?
Today’s biggest question

What’s beyond the Standard Model?

1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

from the Quantum Universe
Addressing the Questions

• Neutrinos
  – Particle physics and astrophysics using a weakly interacting probe

• Particle Astrophysics/Cosmology
  – Dark Matter; Cosmic Microwave, etc

• High Energy pp Colliders
  – Opening up a new energy frontier (~ 1 TeV scale)

• High Energy $e^+e^-$ Colliders
  – Precision Physics at the new energy frontier
Megascience project --- LHC

3 isolated leptons
+ 2 b-jets
+ 4 jets
+ $E_{\text{miss}}$
Exploring the Terascale

the tools

• The LHC
  – It will lead the way and has large reach
  – Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  – Broadband initial state

• The ILC
  – A second view with high precision
  – Electron-positron collisions with fixed energies, adjustable between 0.1 and 1.0 TeV
  – Well defined initial state

• Together, these are our tools for the terascale
Why a TeV Scale $e^+e^-$ Accelerator?

- Two parallel developments over the past few years (the science & the technology)
  - The precision information from LEP and other data have pointed to a low mass Higgs; Understanding electroweak symmetry breaking, whether supersymmetry or an alternative, will require precision measurements.
  - There are strong arguments for the complementarity between a ~0.5-1.0 TeV ILC and the LHC science.
Possible TeV Scale Lepton Colliders

**ILC**

- **ILC** < 1 TeV
- Technically possible
- ~ 2019

**CLIC**

- **CLIC** < 3 TeV
- Feasibility?
- ILC + 5-10 yrs

**Muon Collider**

- Much R&D Needed
- Neutrino Factory R&D +
- bunch merging
- much more cooling
- etc

Rongli Geng
The ILC

- Two linear accelerators, with tiny intense beams of electrons and positrons colliding head-on-head
- Total length ~ 30 km long (comparable scale to LHC)
- COM energy = 500 GeV, upgradeable to 1 TeV
LHC --- Deep Underground

Tunnel is 27 km long
50-150m below ground
ILC --- Deep Underground

Main Research Center

Particle Detector

~30 km long tunnel

Two tunnels
- accelerator units
- other for services - RF power
## Comparison: ILC and LHC

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Particle</td>
<td>Electron \times Positron</td>
<td>Proton \times Proton</td>
</tr>
<tr>
<td>CMS Energy</td>
<td>0.5 – 1 TeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td>Luminosity Goal</td>
<td>$2 \times 10^{34} \text{ /cm}^2/\text{sec}$</td>
<td>$1 \times 10^{34} \text{ /cm}^2/\text{sec}$</td>
</tr>
<tr>
<td>Accelerator Type</td>
<td>Linear</td>
<td>Circular Storage Rings</td>
</tr>
<tr>
<td>Technology</td>
<td>Supercond. RF</td>
<td>Supercond. Magnet</td>
</tr>
</tbody>
</table>
LHC --- Superconducting Magnet

The 15-m long LHC cryodipole
**Linear Collider Conceptual Scheme**

- **Electron Gun**: Deliver stable beam current.
- **Damping Ring**: Reduce transverse phase space (emittance) so smaller transverse IP size achievable.
- **Bunch Compressor**: Reduce $\sigma_z$ to eliminate hourglass effect at IP.
- **Main Linac**: Accelerate beam to IP energy without spoiling DR emittance.
- **Final Focus**: Demagnify and collide beams.
- **Positron Target**: Use electrons to pair-produce positrons.
• **Electron source**
  
  To produce electrons, light from a titanium-sapphire laser hit a target and knock out electrons. The laser emits 2-ns "flashes," each creating billions of electrons. An electric field "sucks" each bunch of particles into a 250-meter-long linear accelerator that speeds up the particles to 5 GeV.

• **Positron source**
  
  To produce positron, electron beam go through an undulator. Then, photons, produced in an undulator, hit a titanium alloy target to generate positrons. A 5-GeV accelerator shoots the positrons to the first of two positron damping rings.

• **Damping Ring for electron beam**
  
  In the 6-kilometer-long damping ring, the electron bunches traverse a wiggler leading to a more uniform, compact spatial distribution of particles. Each bunch spends roughly 0.2 sec in the ring, making about 10,000 turns before being kicked out. Exiting the damping ring, the bunches are about 6 mm long and thinner than a human hair.
• **Damping Ring for positron beam**

To minimize the "electron cloud effects," positron bunches are injected alternately into either one of two identical positron damping rings with 6-kilometer circumference.

• **Main Linac**

Two main linear accelerators, one for electrons and one for positrons, accelerate bunches of particles up to 250 GeV with 8000 superconducting cavities nestled within cryomodules. The modules use liquid helium to cool the cavities to -2°C. Two 12-km-long tunnel segments, about 100 meters below ground, house the two accelerators. An adjacent tunnel provides space for support instrumentation, allowing for the maintenance of equipment while the accelerator is running. Superconducting RF system accelerate electrons and positrons up to 250 GeV.

• **Beam Delivery System**

Traveling toward each other, electron and positron bunches collide at 500 GeV. The baseline configuration of the ILC provides for two collision points, offering space for two detectors.
# RDR Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Center-of-mass energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$\sim 2 \times 10^{34}$ 1/cm$^2$s</td>
</tr>
<tr>
<td>Beam Current</td>
<td>9.0 mA</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Average accelerating gradient</td>
<td>31.5 MV/m</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>0.95 ms</td>
</tr>
<tr>
<td>Total Site Length</td>
<td>31 km</td>
</tr>
<tr>
<td>Total AC Power Consumption</td>
<td>$\sim 230$ MW</td>
</tr>
</tbody>
</table>
ILC Reference Cryomodule

- Developed by INFN for TTF-TESLA
- 3rd generation of improvements
- Many years of successful operation
- Baseline for XFEL and ILC
- Reference for others (Project X, etc)
Superconducting RF Linac Technology

cavity

cryomodule
coupler

SCRF Linac Technology
tuner

LLRF

RF

HOMs
Milestones that led to accelerators based on SRF

Superconductivity

1908: Heike Kamerlingh Onnes (Holland)
Liquefied Helium for the first time.

1911: Heike Kamerlingh Onnes
Discovered Superconductivity.

1928-34: Walther Meissner (Germany)
Discovered Superconductivity of Ta, V, Ti and Nb.

RF Acceleration

1924: Gustaf Ising (Sweden)
The First Publication on RF Acceleration
Arkiv för Matematik, Astronomi och Fysik.

1928: Rolf Wideröe (Norway, Germany)
Built the first RF Accelerator,
Arch. für Elektrotechnik 21, vol.18.

1947: Luis Alvarez (USA)
Built first DTL (32 MeV protons).

1947: W. Hansen (USA)
Built first 6 MeV e-accelerator, Mark I
(TW- structure).
1961: W. Fairbank (Stanford Univ.)
Presented the first proposal for a superconducting accelerator for electrons
A. Banford and G. Stafford (Rutherford Appleton Lab.)
Presented the first proposal for a superconducting accelerator for protons

1964: W. Fairbank, A. Schwettman, P. Wilson (Stanford Univ.)
First acceleration of electrons with sc lead cavity

1970: J. Turneaure (Stanford Univ.)
$E_{\text{peak}} = 70 \text{ MV/m and Q} \sim 10^{10}$ in 8.5 GHz cavity!

Developed and Constructed the Superconducting Accelerator SCA

Since then, many sc accelerators were built and we are constructing and making plans for many new facilities.
Superconductivity – Zero DC Resistance

Heike Kammerlingh-Onnes, 1911, discovery of SC in mercury
Superconductivity – Meissner Effect

Magnetic field is expelled from a superconductor

Complete magnetic shielding by circulating surface supercurrents
Energy Gap and Two-Fluid Model

- Two fluid model
  - SC electrons
    - Cooper pairs
    - Below $T_{c}$, Cooper pairs are formed with an energy gap $2\Delta$
  - Normal electrons
- DC case
  - Cooper pairs short out field
  - Normal electrons not accelerated
  - SC is Lossless even at $T > 0$ K

Energy Gap

At $T > 0$K, some "normal" electrons not yet condensed into pairs

$\text{n}_{\text{normal}} \propto \exp \left( -\frac{\Delta}{k_{B}T} \right)$
Losses in Superconductor

• Now look at the RF case
• Cooper pairs have inertia
  – They can not follow the AC field instantly
    • Thus do not shield AC field perfectly
    • A residual field remains
    • The normal electrons are accelerated
      – Thus dissipate power

• Scaling of RF surface resistance
  – The faster the field oscillates the less perfect the shielding
    • RF surface resistance increases with frequency
  – The more normal electrons, the lossier the material
    • RF surface resistance decreases with temperature below Tc
Figure of Merit

Surface current ($\propto H$) results in power dissipation proportional to the surface resistance ($R_s$)

$$\frac{dP_c}{ds} = \frac{1}{2} R_s |H|^2$$

Total power dissipation in cavity wall

$$P_c = \frac{1}{2} \int_{S} R_s |H|^2 \, ds$$

Stored energy in cavity

$$U = \frac{1}{2} \mu_0 \int_{V} |H|^2 \, dv$$

Cavity quality factor

$$Q_0 = \frac{\omega_0 U}{P_c} = \frac{\omega_0 \mu_0}{R_s} \int_{S} |H|^2 \, dv$$

= $10^4$ for n.c.

= $10^{10}$ for s.c.

Measure of how lossy the cavity material is
Features of SRF Cavity

• Low power dissipation
  – allows high gradient in CW or long-pulsed operation
    • Less number of cells
      – Less disruption to beam
    • Shorter linac and tunnel length
      – Cost saving
  – allows cavity design with large beam tube
    • Many benefits (next slide)
Features of SRF Cavity

Large beam tube & Fewer cells

- Reduces the interaction of the beam with the cavity (scales as size³) →
- The beam quality is better preserved (important for, e.g., FELs).
- HOMs are removed easily → better beam stability → more current accelerated (important for, e.g., B-factories)
- Reduce the amount of beam scraping → less activation in, e.g., proton machines (important for, e.g., SNS, Neutrino factory)

Large aperture of SRF cavity relaxes wakefields
Type-I and Type-II Superconductor

- Two types of superconductors defined by Ginsburg-Landau

$$\kappa = \frac{\lambda(T)}{\xi(T)}$$

- $\kappa < 1/\sqrt{2}$ and $\kappa > 1/\sqrt{2}$
DC and RF Critical Field of Superconductor

Superheating field due to surface barrier to vertex penetration
### SCRF Technology Required

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>$500$ GeV</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Beam Rep. rate</td>
<td>$5$ Hz</td>
</tr>
<tr>
<td>Pulse time duration</td>
<td>$1$ ms</td>
</tr>
<tr>
<td>Average beam current</td>
<td>$9$ mA (in pulse)</td>
</tr>
<tr>
<td><strong>Av. field gradient</strong></td>
<td><strong>31.5 MV/m</strong></td>
</tr>
<tr>
<td># 9-cell cavity</td>
<td><strong>14,560</strong></td>
</tr>
<tr>
<td># cryomodule</td>
<td><strong>1,680</strong></td>
</tr>
<tr>
<td># RF units</td>
<td><strong>560</strong></td>
</tr>
</tbody>
</table>
Gradient a Major Cost Driver for ILC

H. Padamsee, 1\textsuperscript{st} ILC workshop, 2004
### Global Plan for ILC Gradient R&D

<table>
<thead>
<tr>
<th>Year</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>TDP-1</td>
<td>TDP-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity Gradient in v. test to reach 35 MV/m</td>
<td>→ Yield 50%</td>
<td>→ Yield 90%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity-string to reach 31.5 MV/m, with one-cryomodule</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Test with beam acceleration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preparation for Industrialization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**New baseline gradient:**
Vertical acceptance: 35 MV/m average, allowing ±20% spread (28-42 MV/m)
Operational: 31.5 MV/m average, allowing ±20% spread (25-38 MV/m)
Baseline ILC Nb Cavity Proc. Procedure

- Cavity manufacture (EBW) using RRR 300 Nb
- Initial light chemistry 5-30 μm (BCP)
- Heavy chemistry 80-150 μm (EP)
- Post-EP cleaning
- Vacuum furnace heat treatment 750-800 °C
- Light chemistry 20-50 μm (EP)
- Post-EP cleaning (ER/USC+HOM coupler brushing)
- Initial HPR
- Clean room assembly
- Final HPR
- Pump down
- 120 °Cx48hr bake-out
16 cavities processed and tested at JLab since July 1, 2008
Fabrication: 10 by ACCEL/RI, 6 by AES

9 out of 16 exceed ILC vertical test spec after 1st-pass proc.
13 out of 16 exceeded ILC vertical test spec up to 2nd-pass proc.

A11: 2nd pass (+USC+HPR), RF power limit
A12: 2nd pass (+EP+120Cx48hr), quench limit
A13: 1st pass, FE limit
A14: 1st pass, RF power limit
A15: 1st pass (limited by one defect in cell #3), quench limit
A16: 2nd pass (+EP + 120Cx48hr), quench limit
R118: 2nd pass (+EP + 120Cx48hr), RF power limit
R119: 2nd pass (+HPR), quench limit
R127: 1st pass, Note: 1.8 K data shown, quench limit
R128: 2nd pass (+HPR), quench limit
* Note: A12 and R119 already qualified by 1st-pass proc
* Note: R127 1st pass at 2K 41 MV/m, cable limit

AES5: 1st pass (limited by one defect in cell #3), quench limit
AES6: 2nd pass (+800Cx2hr+EP+120Cx48hr), quench limit
AES7: 1st pass, administrative limit
AES8: 1st pass, administrative limit
AES9: 2nd pass (+EP+120Cx48hr), quench limit
AES10: 1st pass, quench limit
* Note: AES6 quench limited 14 MV/m by same defect area in cell #5 in 1st pass processing and testing
A15 gradient limit at 19 MV/m: T-mapping found a hot spot correlated to quench.
Long distance microscope identified a defect near the hot spot.
Fine grain EP
twin defects causing quench 17 MV/m. Cavity by a new vendor
Local Heating near Quench-Causing Defect
Examples with Observable Defect

Deep pit at boundary of under-bead of equator EBW

Twin defects 300-500μm dia. 8mm from equator EBW seam

Potential Max. Gradient for MHI#8 @9/Jul/2009

Max. Gradient Reached in Each Cell (Pi-mode Equivalent) AES6 1st-Pass Processing and Testing, 30apr09
Main Issue: quench limit ~ 20 MV/m due to local geometrical defect (near equator EBW sub-mm dia.).

Gradient Scatter (up to 2nd-pass proc.)

16 9-cell cavities (10 built by ACCEL/RI and 6 by AES) processed and tested at JLab since July 2008.

Each of the 3 failed cavities is limited by one defect in one cell.

Hpk 160-180 mT
AES6 reached 36 MV/m at Q0 1E10
“Mirror finish” CBP at FNAL, then USC, HT, EP, bake, test at JLab

![Graph showing AES6 Performance](image)
Today July 15, 2011 at ILC ART Director Visit of JLab

Yield at 35 MV/m achieved at
Average gradient 39 MV/m

16 recent data from cavities built by ACCEL/RI and AES

16 9-cell cavities (10 built by ACCEL/RI and 6 by AES) processed and tested at JLab since July 2008

AESS After Mechanical Polishing at Cornell
ACC15 after Mechanical Polishing at FNAL
AES6 after CBP at FNAL

JLAB + FNAL

100% yield at ≥31 MV/m

Jefferson Lab Fermilab

Average gradient 39 MV/m
Understanding FE Behaviors w/ Samples

Surface studies of Nb samples EP’ed together w/ 9-cell cavities

- Scan Nb surface with biased tip – DC field upto 140 MV/m
- Field emission sites and I-V curve registered
- Sample transferred to SEM chamber under vacuum
- Nature of field emitter determined

JLab Scanning Field Emission SEM

Dominant field emitters on as EP’ed Nb surface
Understanding FE Behaviors w/ Samples

Bacteria growth after extended Contact with DI water

KEK Sponge cleaning Collaboration with JLab US-Japan Cooperation Fund

Before

After
Understanding FE Behaviors w/ Real Cavities
Observation of Baking Induced Field Emission in EP’ed Cavity
First Example of Reducing/Eliminating Field Emission by Re-cleaning

More details of multiple processing and testing results can be found in JLab report at ILC SCRF meeting, April 21-25, 2008, FNAL

Rongli Geng
Graduate Student Lunch Seminar, 9/21/2011

USC=ultrasonic cleaning
HPR=high pressure water rinse
More Examples of Reducing/Eliminating Field Emission by Re-cleaning

Another example is A6: last S0 test at JLab 37 MV/m, limited by field emission. After shelf storage over a year, A6 re-cleaning (USC + HPR) and shipped under vacuum, RF test at FNAL saw an improved Q(Eacc) over the last test at JLab.
Gradient Yield of 10 ILC Cavities Built by One Vendor Processed and Tested at JLab since July 2008

Yield [%]

10 ILC 9-cell cavities built by ACCEL/RI: A11, A12, A13, A14, A15, A16, RI18, RI19, RI27, RI28

Eacc [MV/m]
Gradient
State-of-the-art
then and now

2004 DESY EP 9-cell cavities
Gradient distribution in cells from pass-band measurements (~ 8 cavities)

2010
average 38.1 MV/m

Comparison of EP to Standard Etch
(Results from the KEK-DESY Collaboration)

- EP offers systematically higher gradient than standard etch (single cell results from mode analysis of multi-cells)

2004
35 MV/m

2010
38 MV/m
Achieved Peak Surface Magnetic Field in L-band SRF Niobium Cavities
(Circle: Single-Cell Cavity; Triangle: Multi-Cell Cavity)

- DESY AC155, AC158
  - Hpk 1910-1950 Oe
  - New 9-cell record
- CESR Z93, AC146 & JLab RI27
  - Hpk 1810 - 1830 Oe
  - 9-cell record
- Cornell LR1-3
  - Hpk 2065 Oe
  - Single-cell record
- DESY Z93
- ILC 500 GeV
- ILC 1 TeV
- Project X
- XFEL
- FRIB QWR, HWR
- CEBAF 4 GeV
- CEBAF 12 GeV
- 650 Oe
- > 95% confidence

Best elliptical
Best QWR, spoke
Best HWR

Rongli Geng
Graduate Student Lunch Seminar,
9/21/2011
Achieved Peak Surface Electric Field in L-band SRF Niobium Cavities
(Circle: Single-Cell Cavity; Triangle: Multi-Cell Cavity)

- Cornell LR1-3
  - Epk 125 MV/m
  - single-cell record

- KEK ICHIRO7
  - Epk 95 MV/m
  - 9-cell record

- ILC 1 TeV

- ILC 500 GeV

- Best QWR, HWR

- FRIB QWR, HWR

- CEBAF 4 GeV

- CEBAF 12 GeV

- XFEL

- RLGENG21Jan2011
CEBAF upgrade, under construction now, will double its energy to 12 GeV. The present 6 GeV machine has 42 old cryomodules. The additional 6 GeV is achieved by adding only 10 new modules with high gradient cavities.
SRF Cavity Gradient R&D Impacts & Benefits

Cryomodule cavity 24.3 MV/m
640 cavities needed
DESY qualified many cavities up to 35-43 MV/m

As a result of DESY’s TTF experience and FLASH operation, European XFEL, under construction now, will reach 14 GeV with 640 high gradient cavities.

Photo courtesy Hans Weise of DESY
Steady progress in SRF cavity gradient makes SRF an enabling technology. SRF based electron linacs (CW & pulsed) have track record of successful operations.
Conclusion

• High gradient SRF cavity R&D at JLab a success
  • Defended ILC design gradient choice
  • Built a technical base of high gradient expertise at JLab
  • Provided direct benefit to CEBAF upgrade project
    • Final surface processing of upgrade cavities
  • Validated the first US industrial vendor for high performance SRF cavity fabrication

• Our understanding of gradient limiting mechanisms including quench limit and field emission is much improved by instrumented cavity testing and cryogenic temperatures.
• The program provided a unique opportunity for JLab SRF workers, scientists, technicians and students, to advance SRF science and technology.