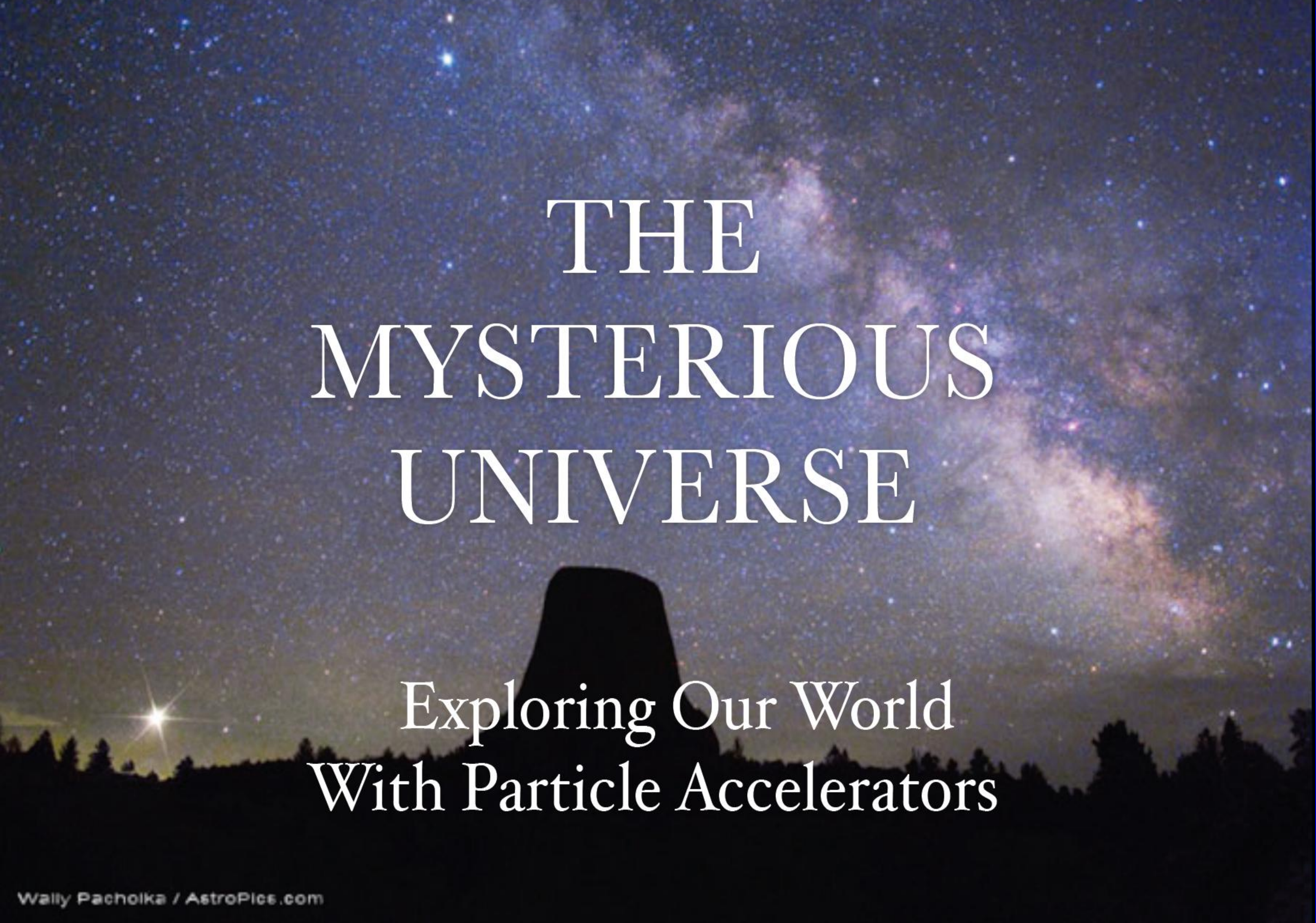
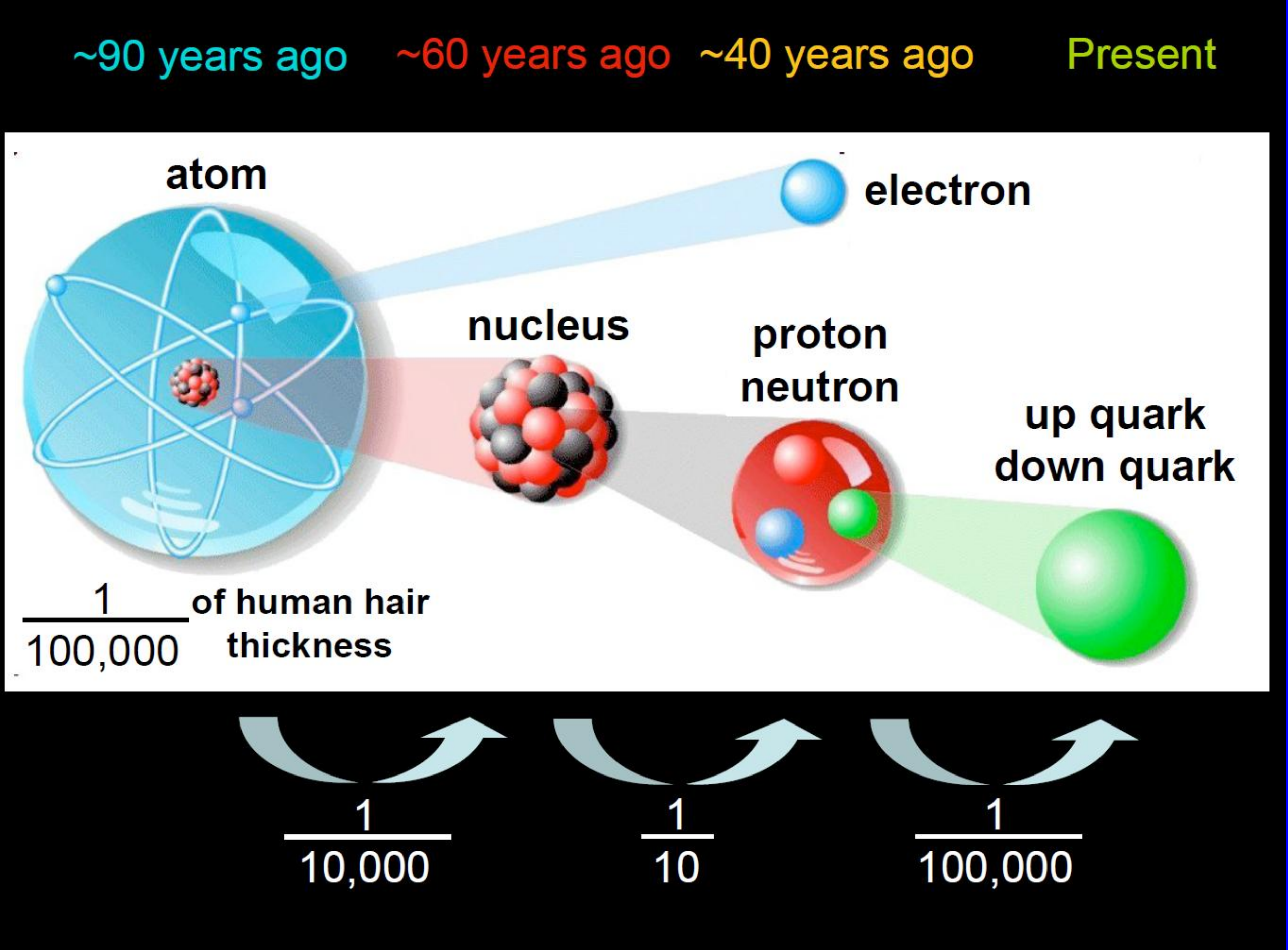
International Linear Collider (ILC) Superconducting Radio Frequency (SRF) Acceleration and ILC High Gradient SRF Cavity R&D at JLab

Rong-Li Geng

Jefferson Lab

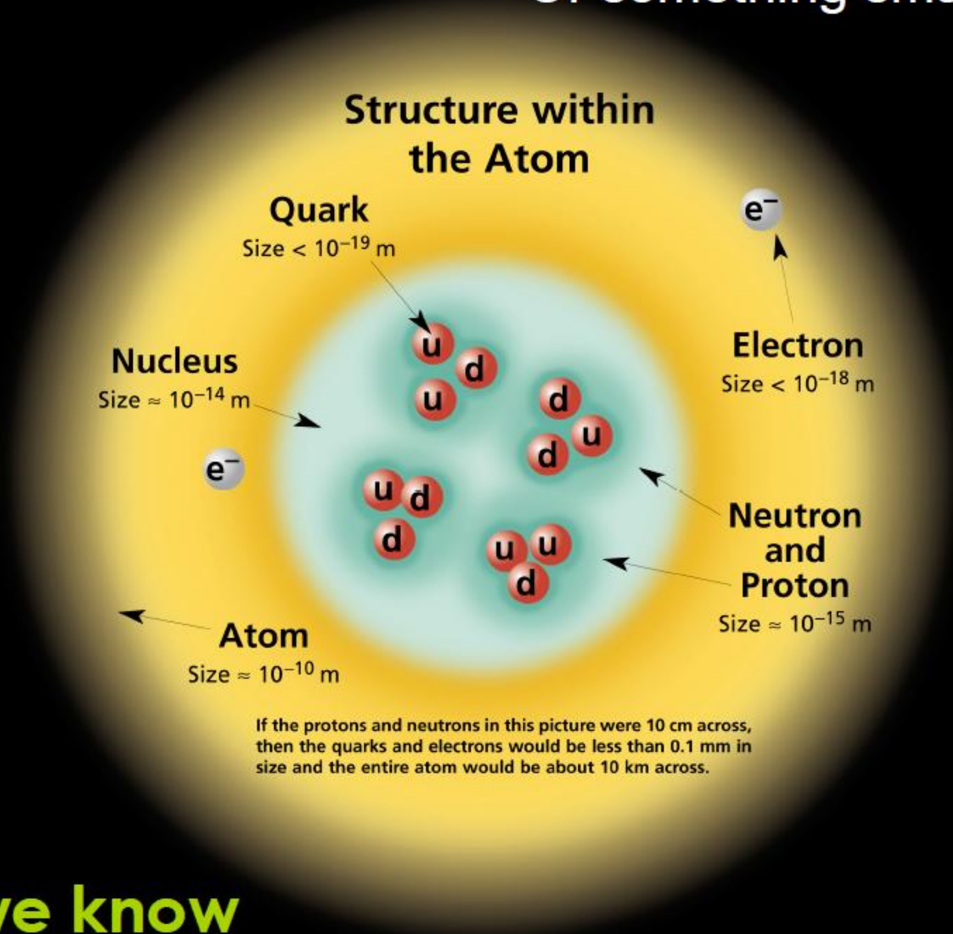
JLab Graduate Student Lunch Seminar, September 21, 2011


THE
MYSTERIOUS
UNIVERSE
Exploring Our World
With Particle Accelerators
Wally Pacholka / AstroPics.com


~90 years ago
~60 years ago
~40 years ago
Present
atom
electron
nucleus
proton
neutron
up quark
down quark
1/100,000 of human hair thickness
1/10,000
1/10
1/100,000

The Nature of Matter

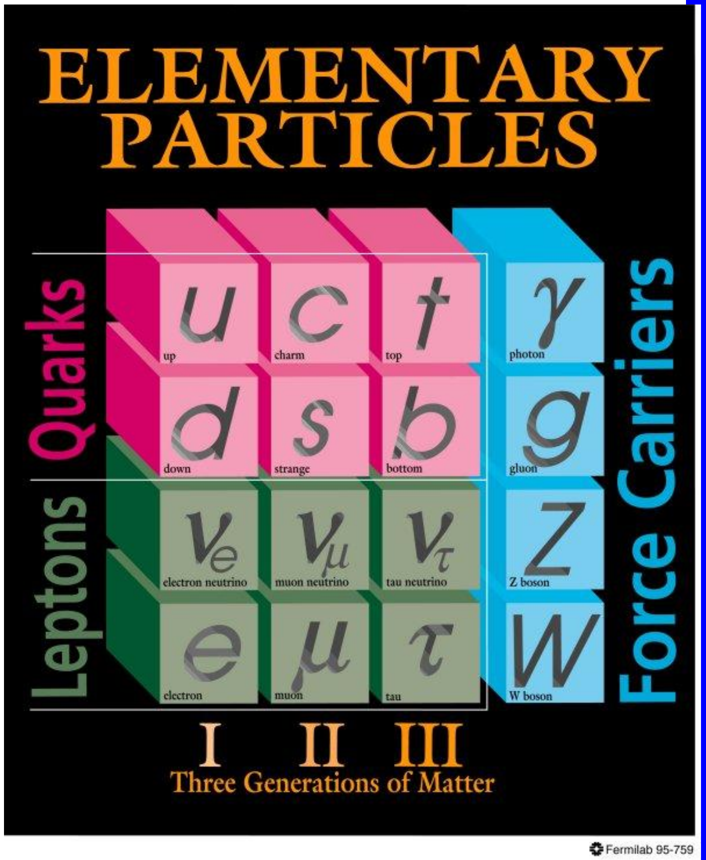
Could there be more quarks?
Or something smaller?



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?**

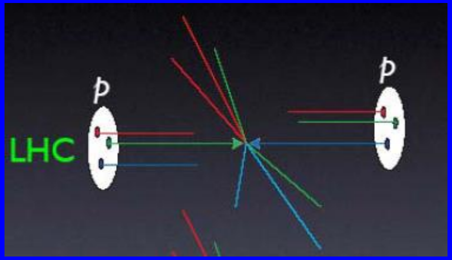
from the Quantum Universe

Addressing the Questions

- Neutrinos
  - Particle physics and astrophysics using a weakly interacting probe

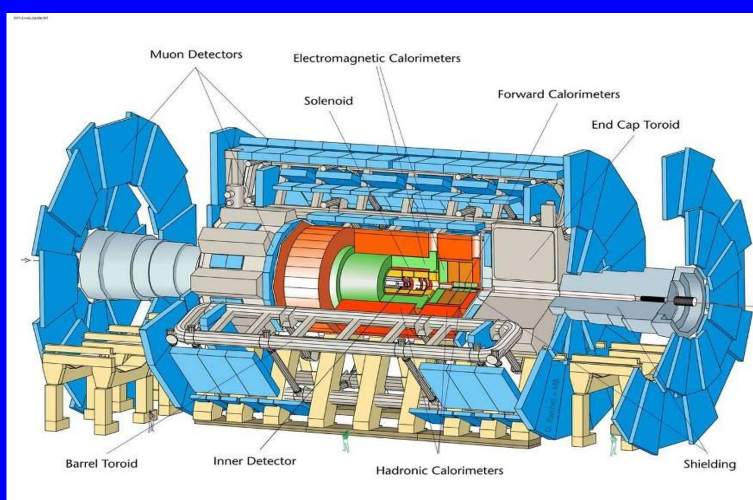
- Particle Astrophysics/Cosmology
  - Dark Matter; Cosmic Microwave, etc

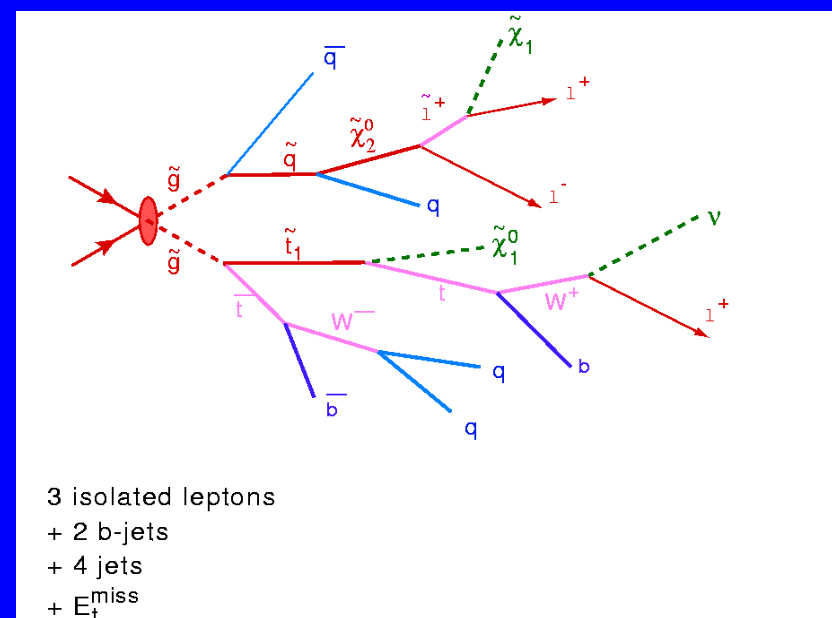
- High Energy pp Colliders
  - Opening up a new energy frontier (~ 1 TeV scale)



- High Energy e^+e^- Colliders
  - Precision Physics at the new energy frontier

Megascience project --- LHC





Exploring the Terascale

the tools

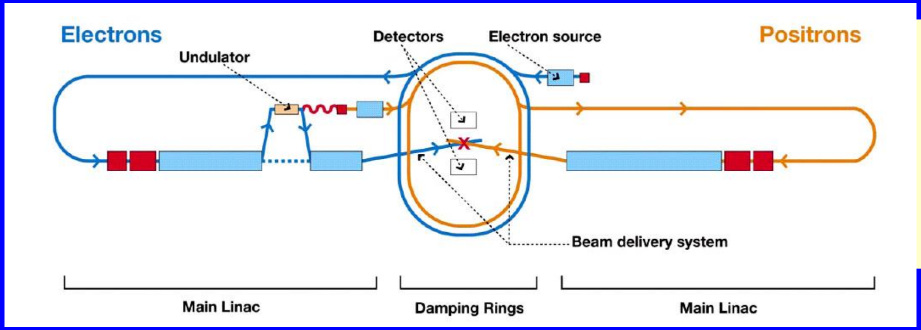
- The LHC
  - It will lead the way and has large reach
  - Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  - Broadband initial state
- The ILC
  - A second view with high precision
  - Electron-positron collisions with fixed energies, adjustable between 0.1 and 1.0 TeV
  - Well defined 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

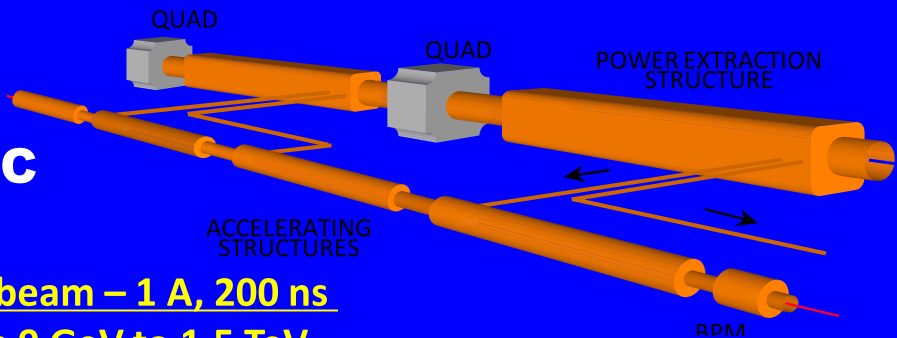
ILC



ILC < 1 TeV
Technically possible
~ 2019

Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV

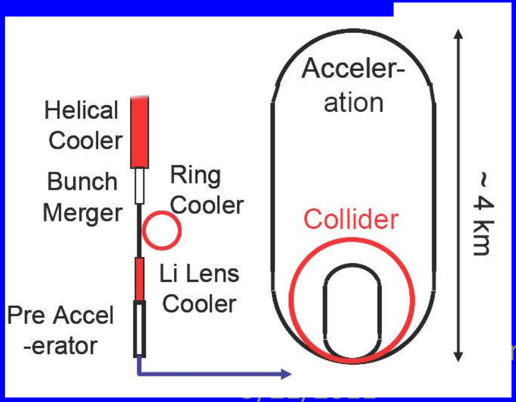
CLIC



Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

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

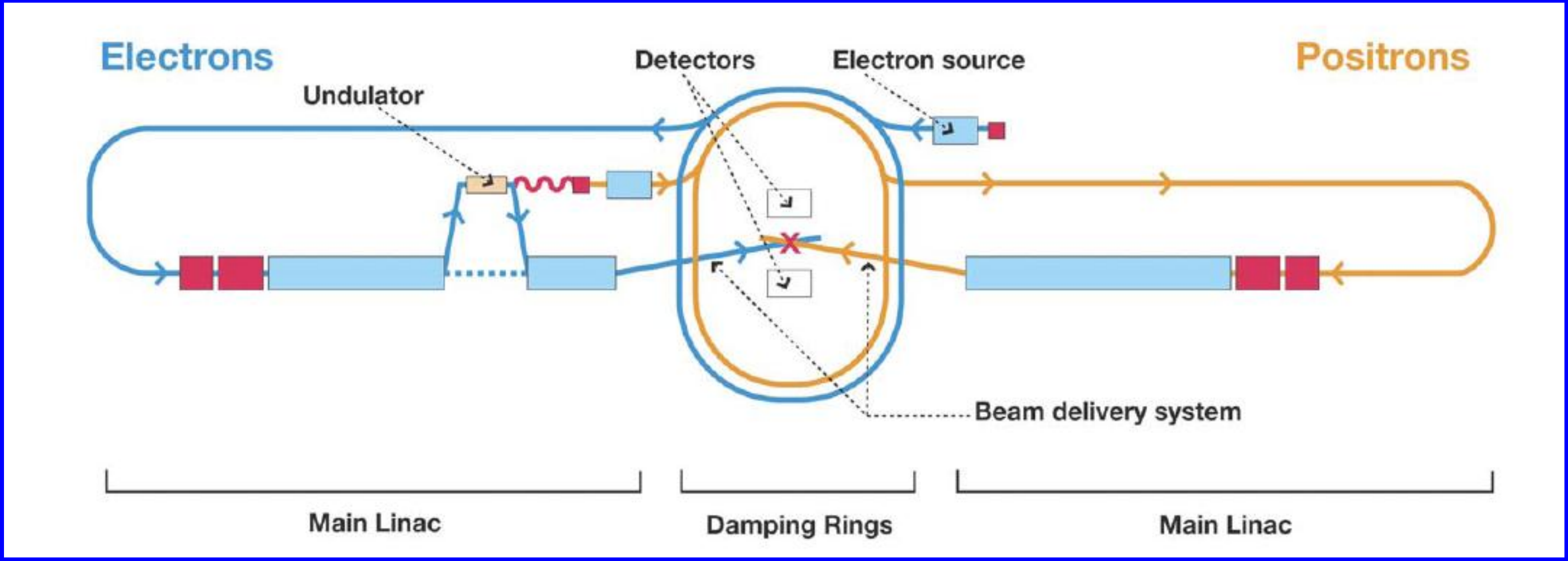
Muon Collider



Muon Collider
< 4 TeV
FEASIBILITY??
ILC + 15 yrs?

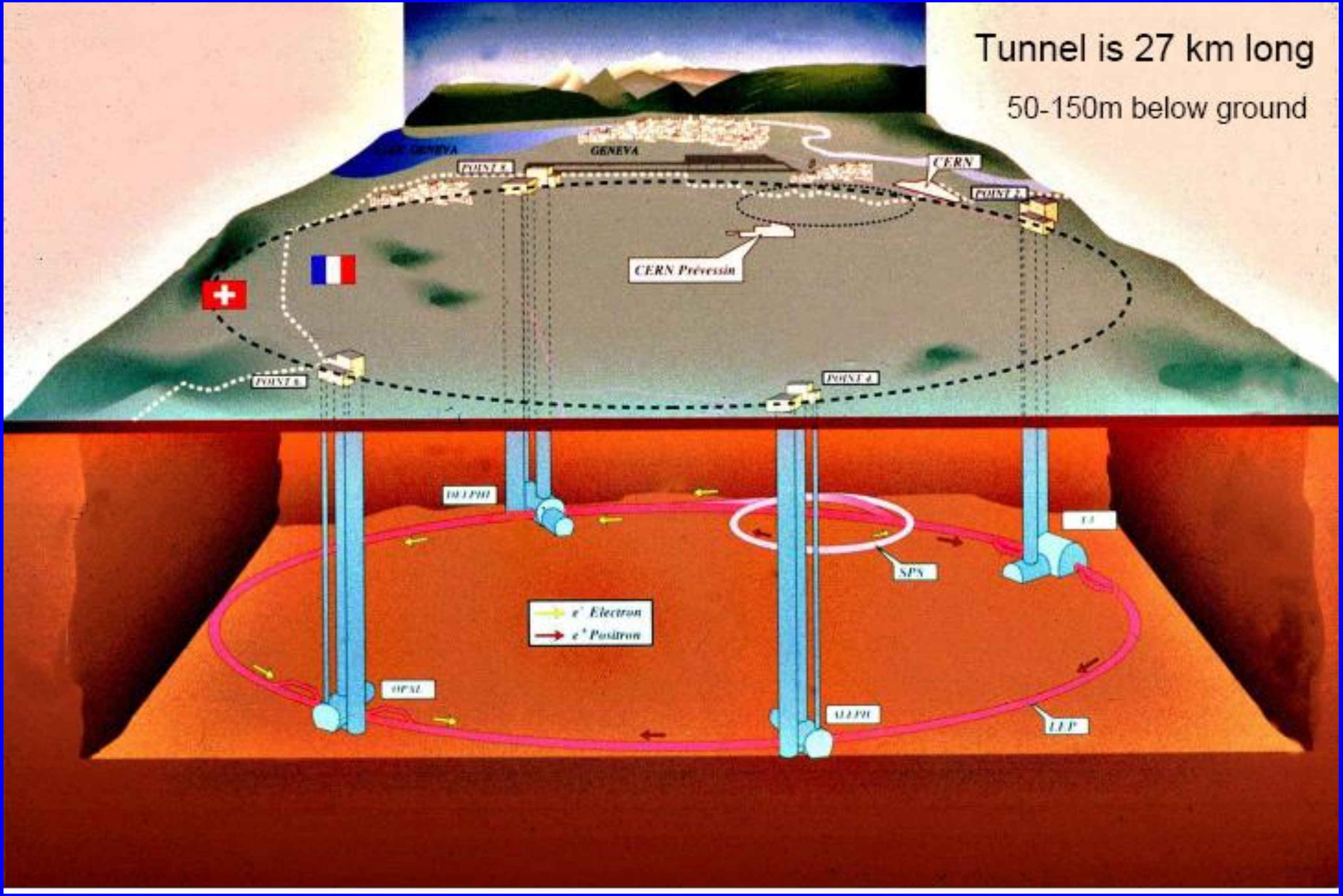
Much R&D Needed
- Neutrino Factory R&D +
- bunch merging
- much more cooling
- etc

The ILC

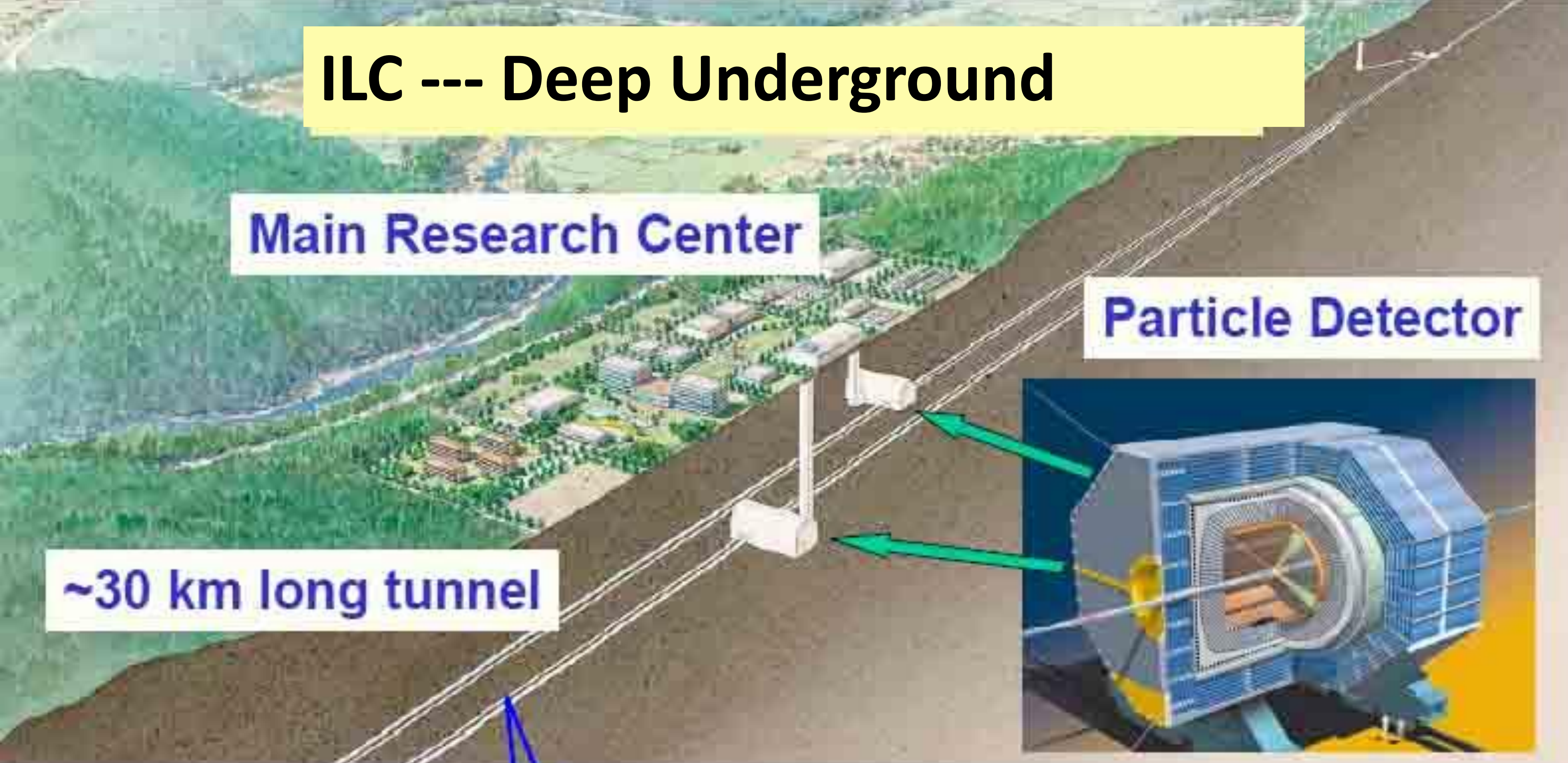


- **Two linear accelerators, with tiny intense beams of electrons and positrons colliding head-on-head**
- **Total length ~ 30 km long (comparable scale to LHC)**
- **COM energy = 500 GeV, upgradeable to 1 TeV**

LHC --- Deep Underground



ILC --- Deep Underground



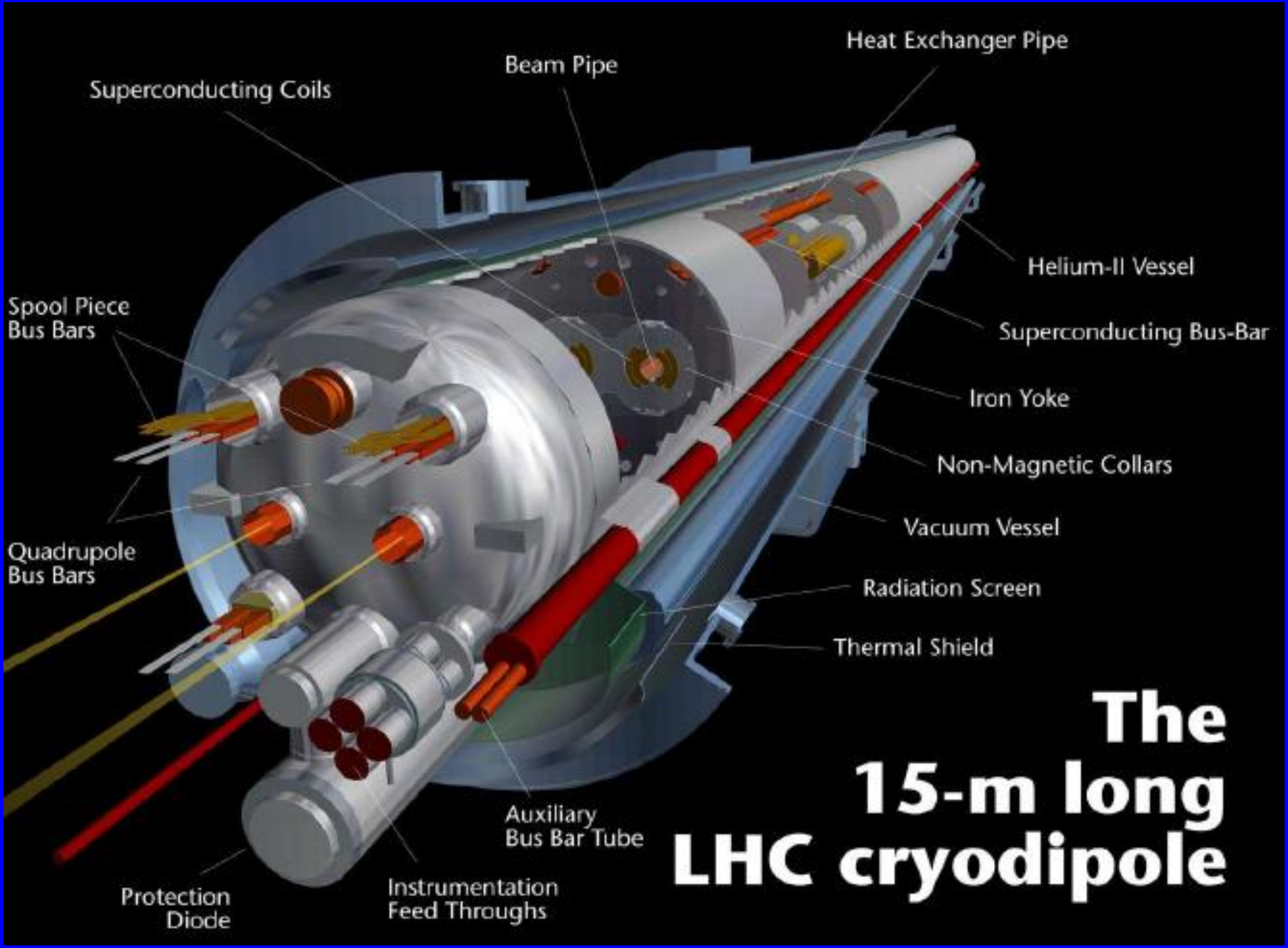
Two tunnels

- accelerator units
- other for services - RF power

Comparison: ILC and LHC

	ILC	LHC
Beam Particle :	Electron x Positron	Proton x Proton
CMS Energy :	0.5 – 1 TeV	14 TeV
Luminosity Goal :	2 x 10^{34} /cm^2/sec	1 x10^{34} /cm^2/sec
Accelerator Type :	Linear	Circular Storage Rings
Technology :	Supercond. RF	Supercond. Magnet

LHC --- Superconducting Magnet



ILC - Superconducting RF Cryomodule

Linear Collider Conceptual Scheme

ILC Subsystems

- **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 particlesup to 250 GeV with 8000 superconducting cavities nestled within cryomodules. The modules use liquid helium to cool the cavities to - 2°K. 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**

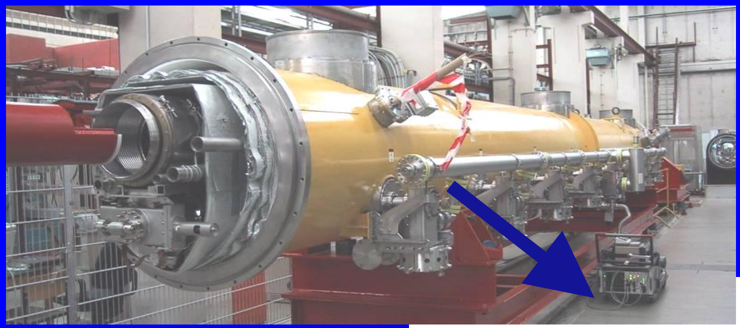
  Traveling toward each other, electron and positron bunches collide at 500 GeV. The baseline configuration of the ILC provides for two collision points, offering space for two detectors.

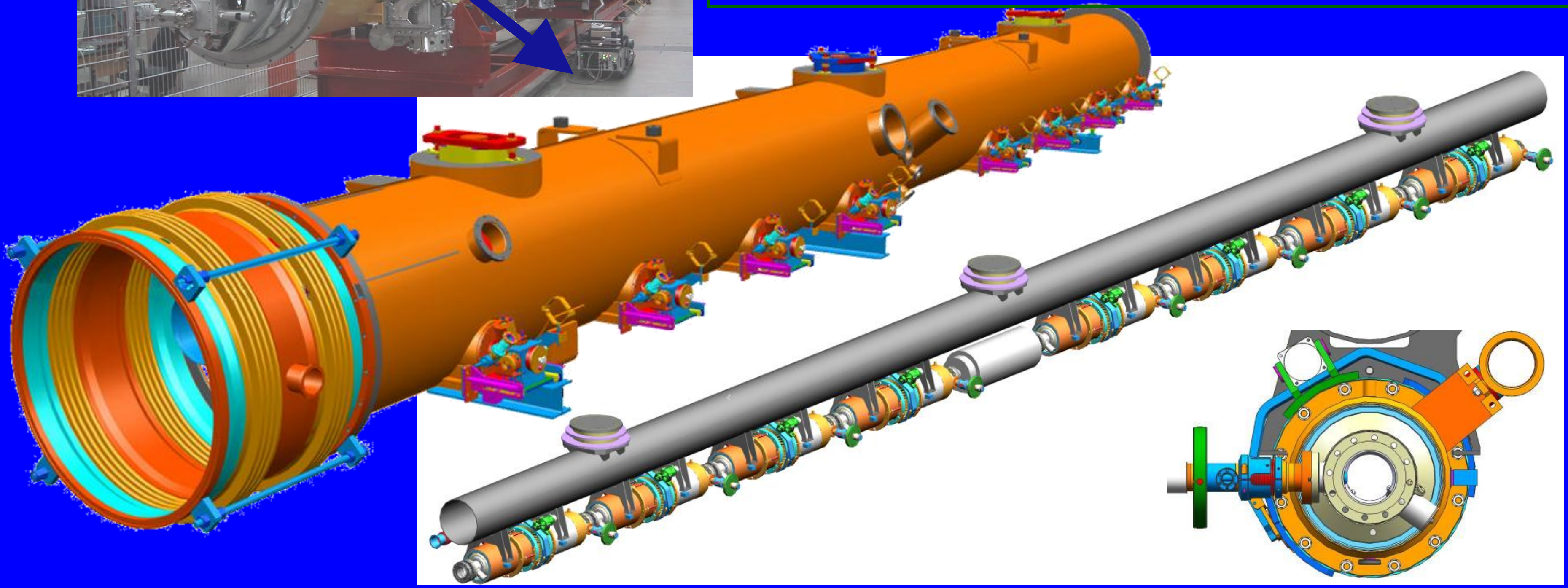
RDR Design Parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	~$2x10^{34}$	$1/cm^2s$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

ILC Reference Cryomodule

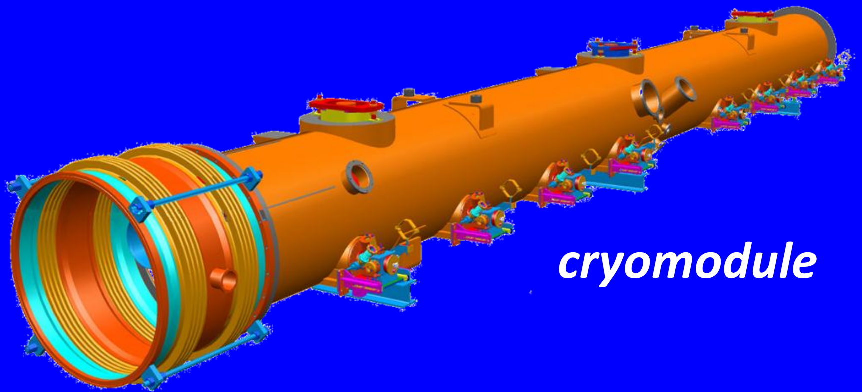
- Developed by INFN for TTF-TESLA
- **3rd generation of improvements**
- **Many years of successful operation**
- **Baseline for XFEL and ILC**
- **Reference for others (Project X, etc)**





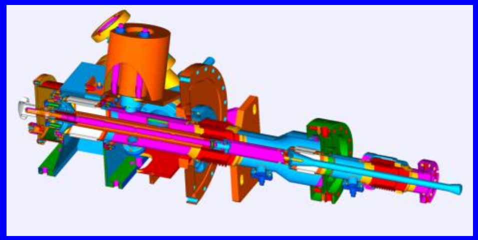
Superconducting RF Linac Technology

cavity

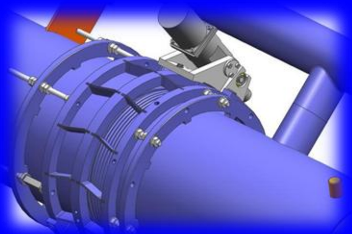


cryomodule

SCRF Linac Technology

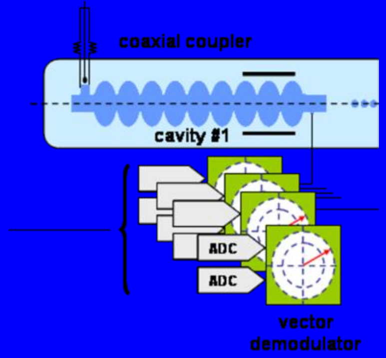


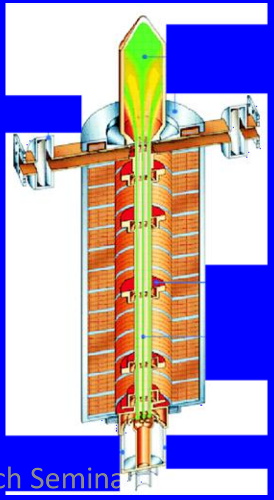
coupler



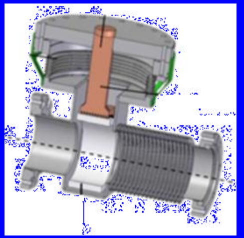
tuner

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).

<u>1961:</u> 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

<u>1964:</u> W. Fairbank, A. Schwettman, P. Wilson (Stanford Univ.)

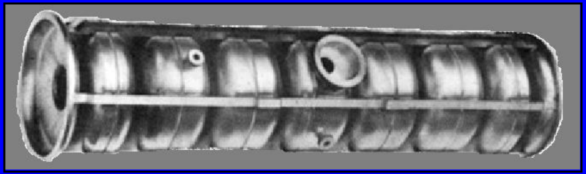
First acceleration of electrons with sc lead cavity

<u>1970:</u> J. Turneaure (Stanford Univ.)

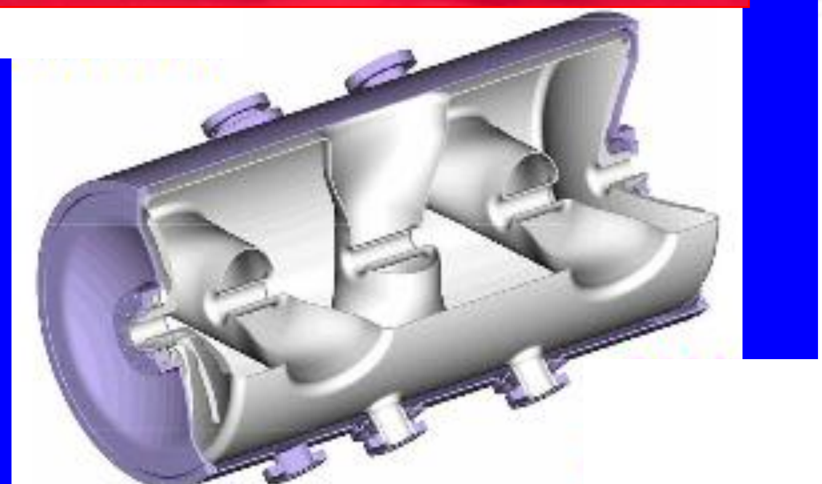
E_{peak} =70 MV/m and Q~10^{10} in 8.5 GHz cavity !

<u>1968-1981:</u> M. McAshan, A. Schwettman, T. Smith, J. Turneaure, P. Wilson (Stanford Univ.)

Developed and Constructed the Superconducting Accelerator SCA

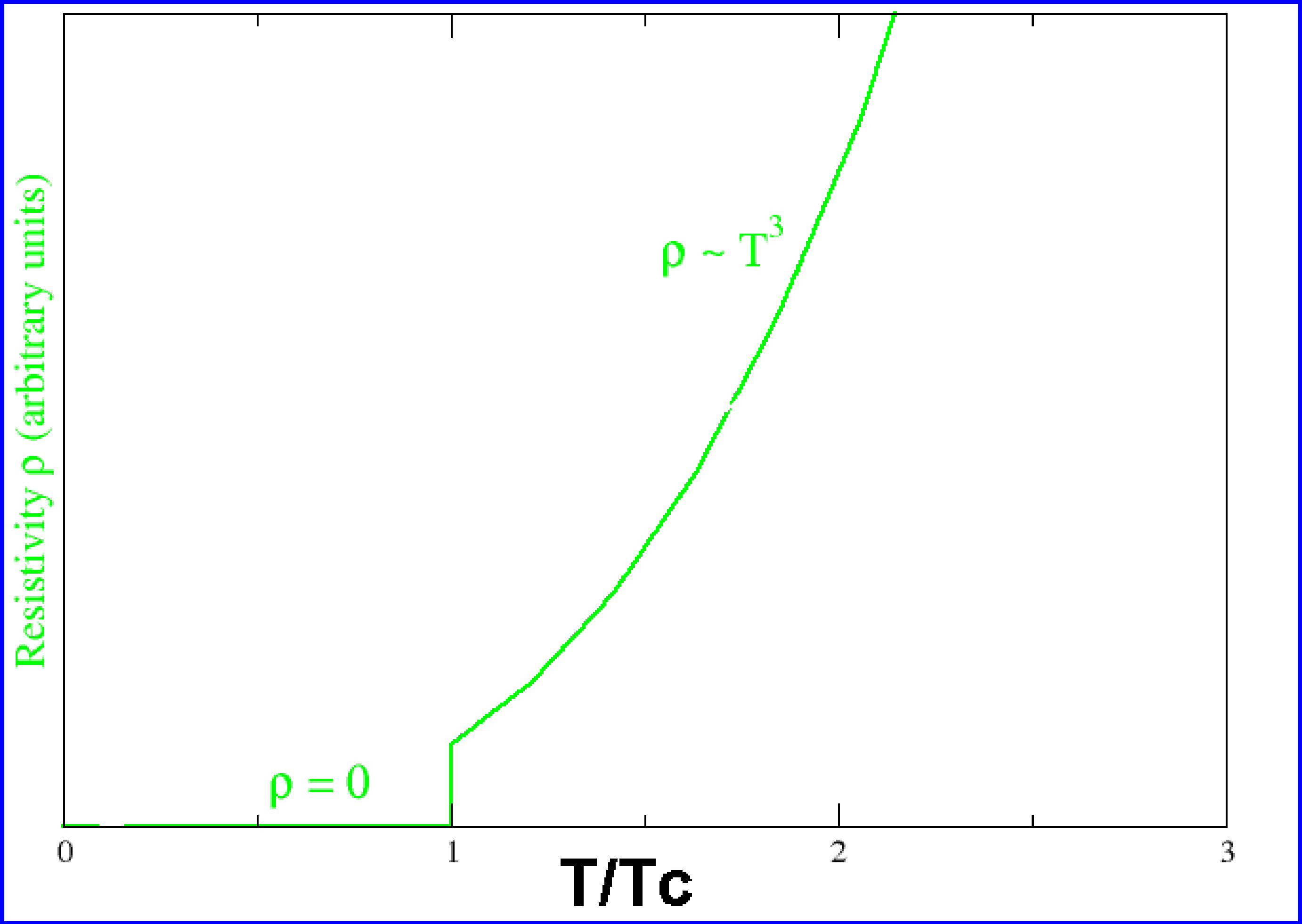


Since then, many sc accelerators were built and we are constructing and making plans for many new facilities.



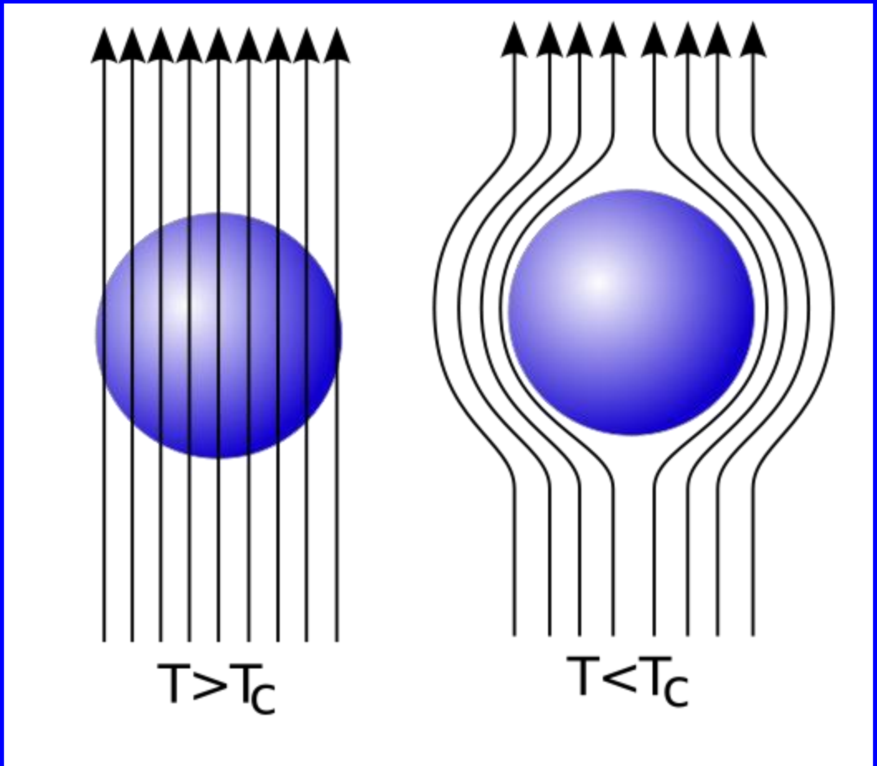
Superconductivity – Zero DC Resistance

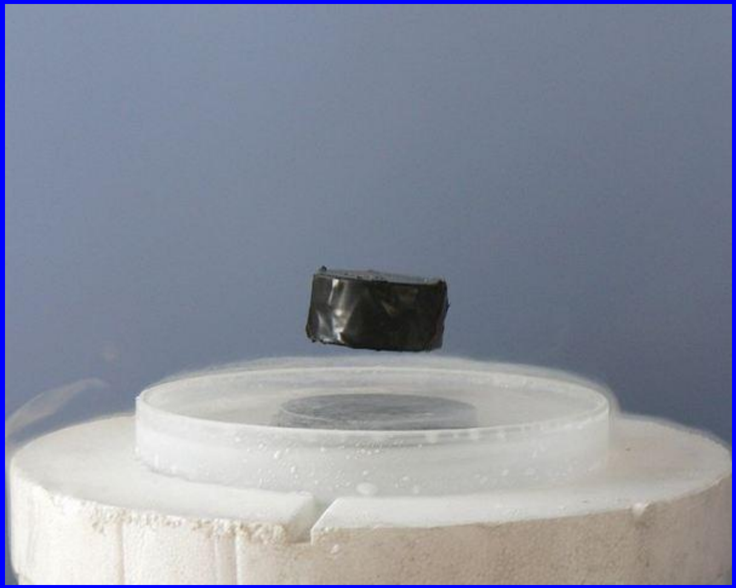
Heike Kammerlingh-Onnes, 1911, discovery of SC in mercury



Superconductivity – Meissner Effect

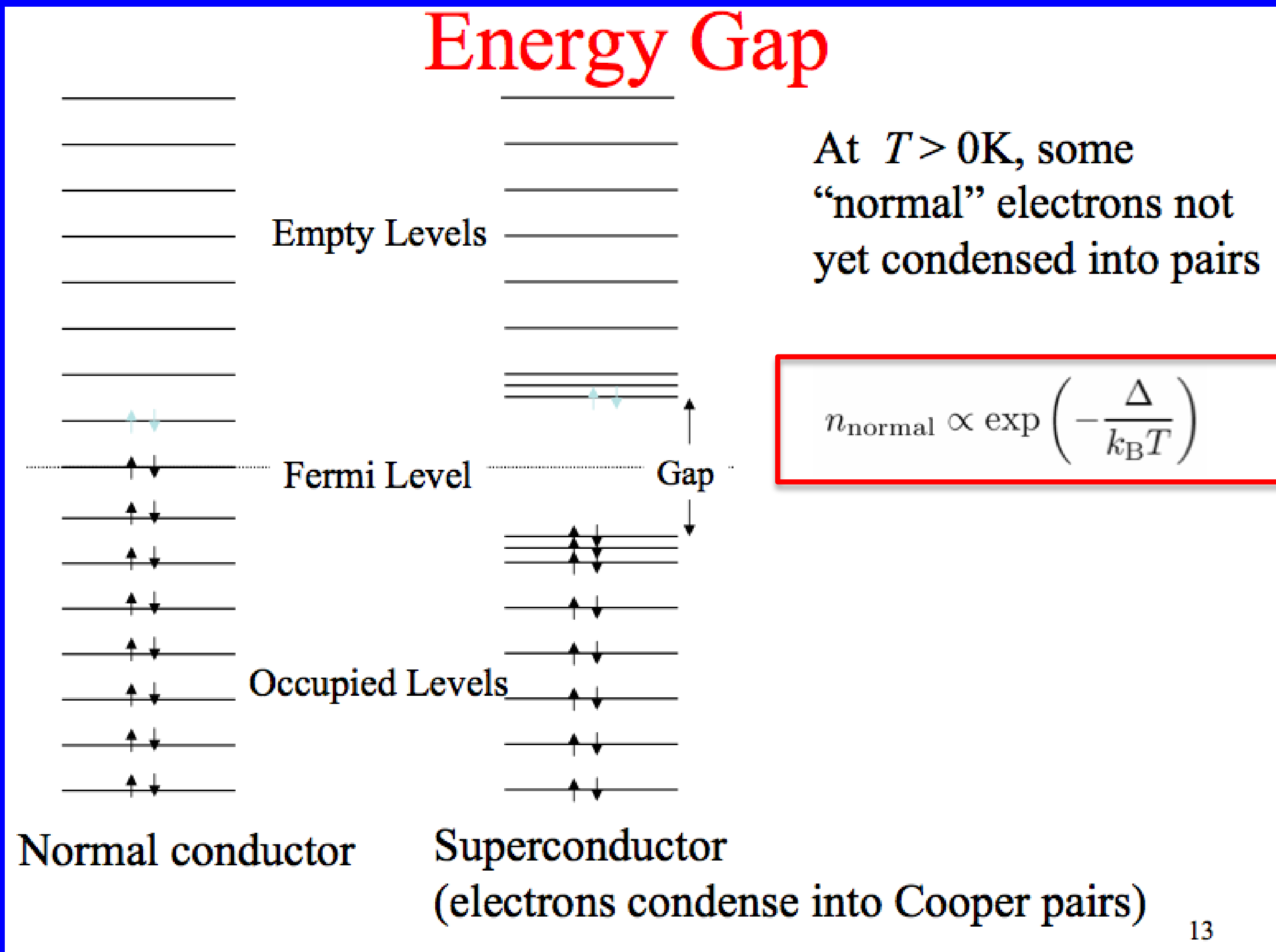
Magnetic field is expelled from a superconductor





Complete magnetic shielding by circulating surface supercurrents

Energy Gap and Two-Fluid Model



- Two fluid model
  - SC electrons
    - Cooper pairs
    - Below Tc, Cooper pairs are formed with an energy gap 2Δ
  - Normal electrons
- DC case
  - Cooper pairs short out field
  - Normal electrons not accelerated
  - SC is Lossless even at T > 0 K

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 deceases with temperature below Tc

Figure of Merit

Surface current (∝ H) results in power dissipation proportional to the surface resistance (R_s)

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

Total power dissipation in cavity wall $$P_c = \frac{1}{2} \int_S R_s |\mathbf{H}|^2 \,\mathrm{d}s$$

Stored energy in cavity $$U = \frac{1}{2} \mu_0 \int_V |\mathbf{H}|^2 \,\mathrm{d}v$$

Cavity quality factor $$Q_0 = \frac{\omega_0 U}{P_c} = \frac{\omega_0 \mu_0}{R_s} \frac{\int_V |\mathbf{H}|^2 \,\mathrm{d}v}{\int_S |\mathbf{H}|^2 \,\mathrm{d}v}$$

= 10^4 for n.c.
= 10^{10} for s.c.

Measure of how lossy the cavity material is

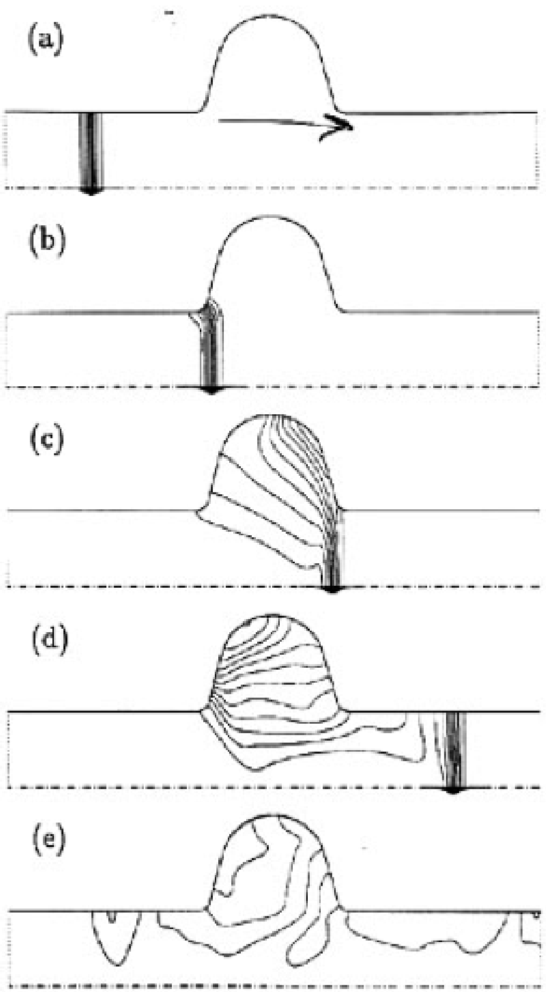
Features of SRF Cavity

- 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 size^3) →
- 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)

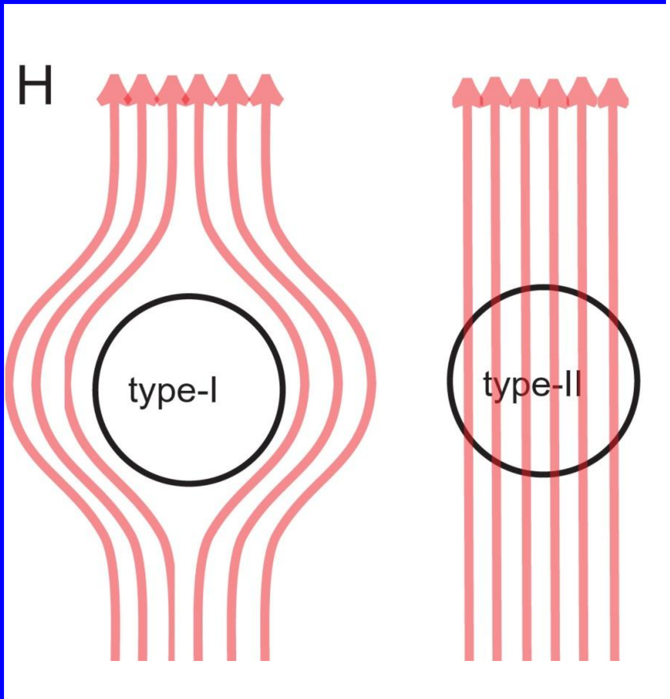


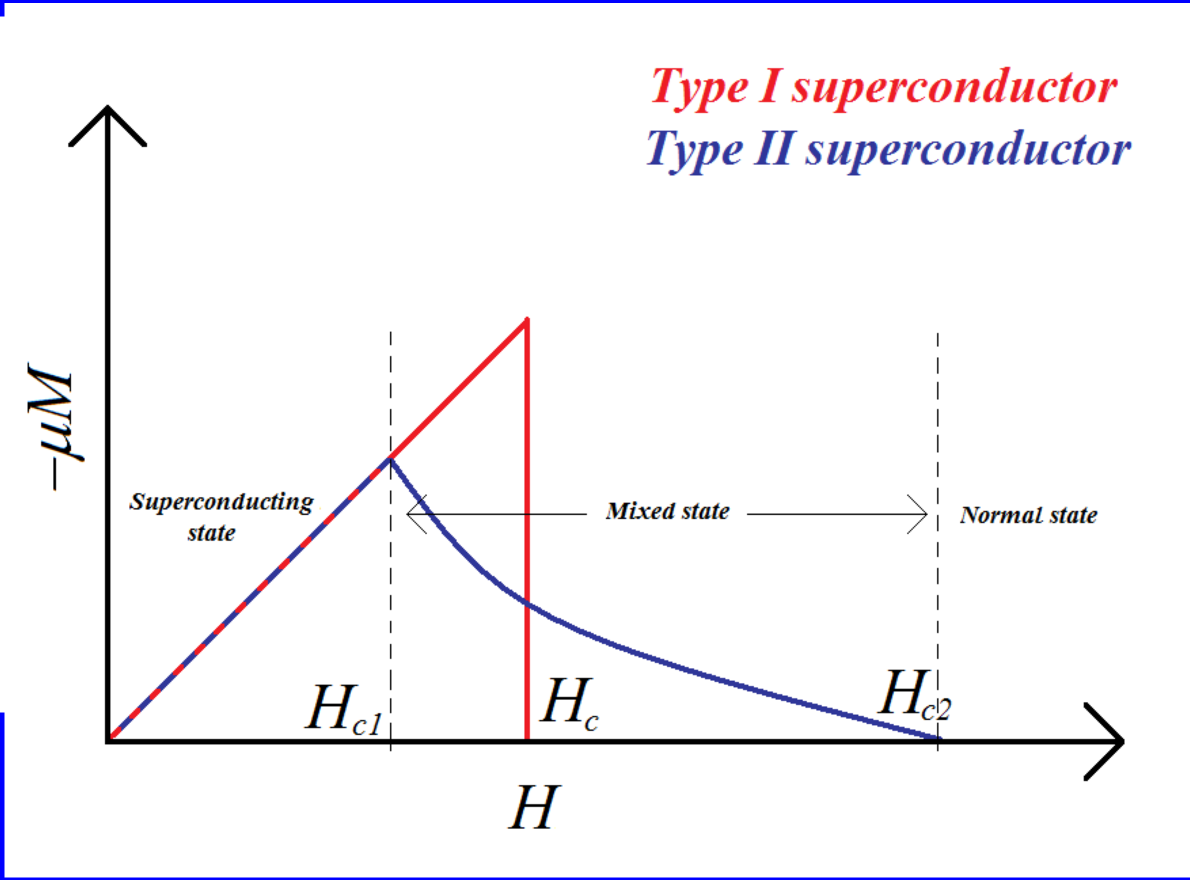
Large aperture of SRF cavity relaxes wakefields

Type-I and Type-II Superconductor

- Two types of superconductors defined by Ginsburg-Landau

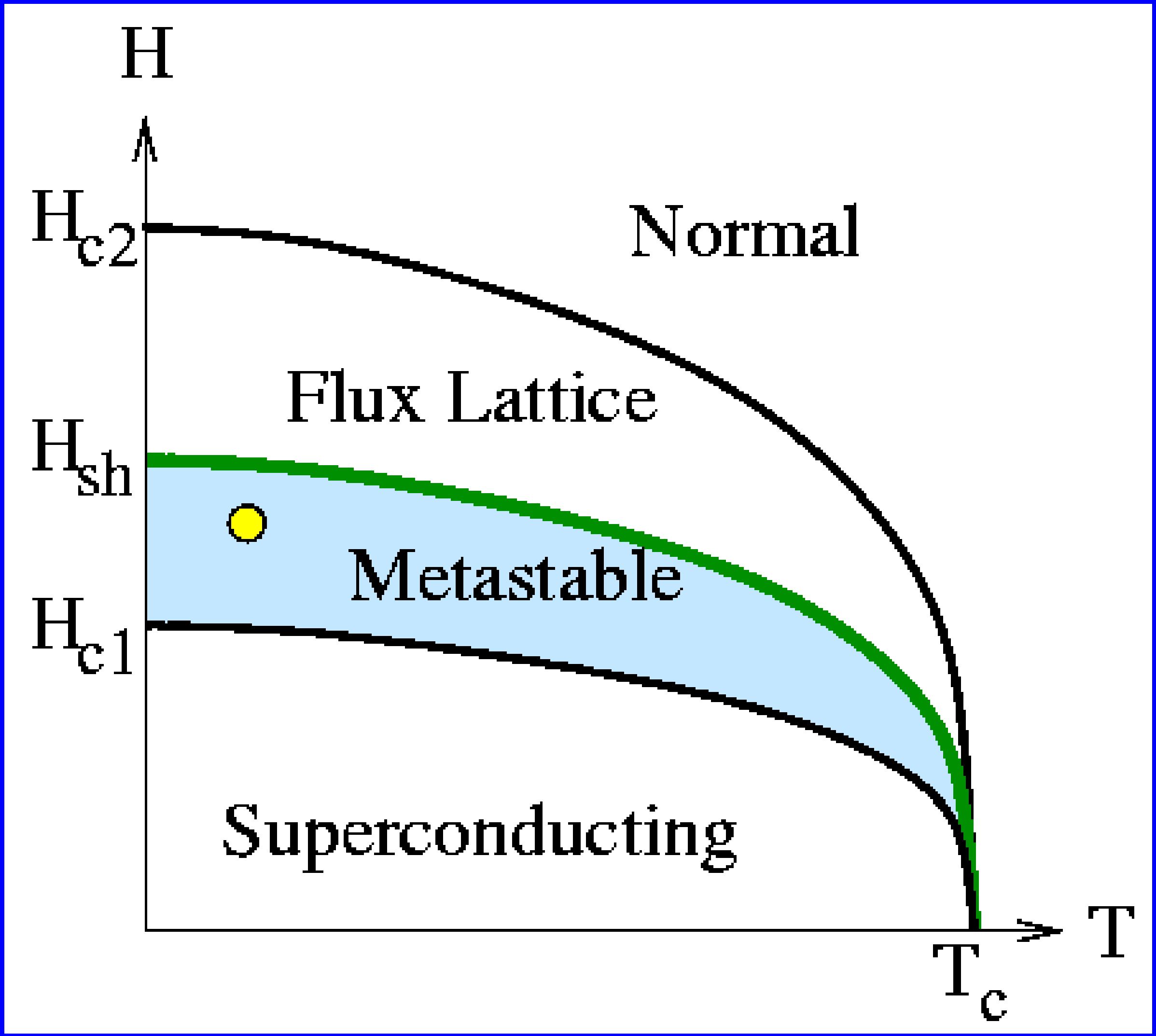
$$\kappa = \lambda(T) / \xi(T)$$





- $\kappa<1/\sqrt{2}$ and $\kappa>1/\sqrt{2}$

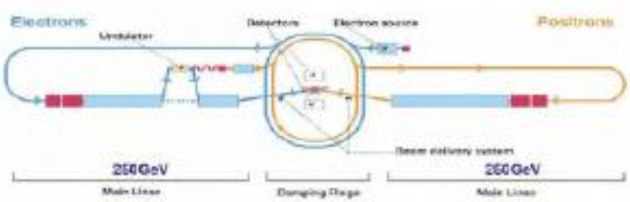
DC and RF Critical Field of Superconductor

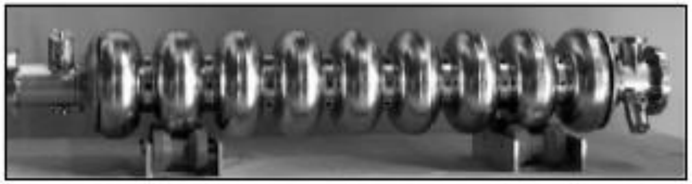


Superheating field due to surface barrier to vertex penetration

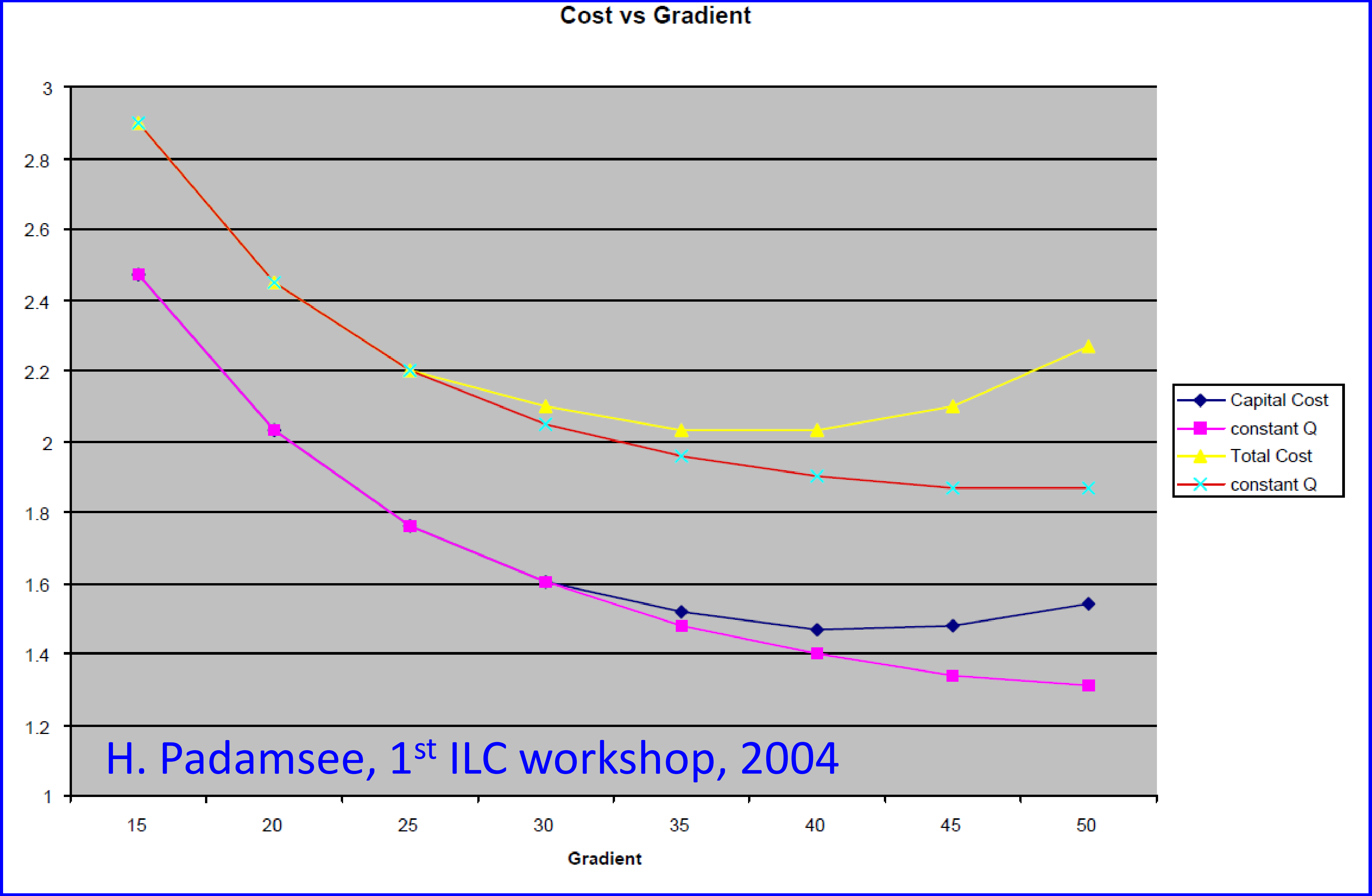
SCRF Technology Required

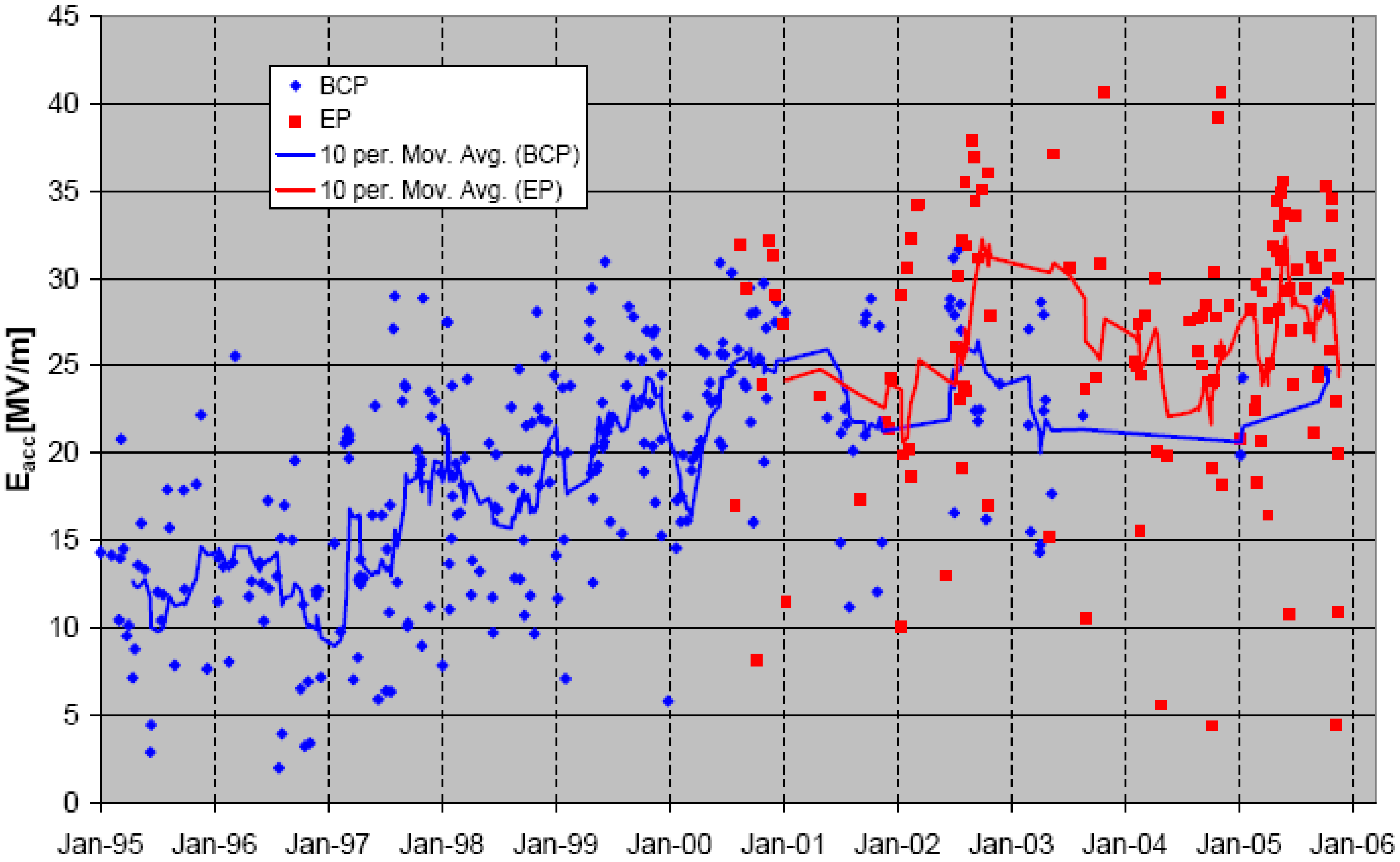
Parameter	Value
C.M. Energy	500 GeV
Peak luminosity	$2x10^{34}$ $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse time duration	1 ms
Average beam current	9 mA (in pulse)
Av. field gradient	**31.5 MV/m**
# 9-cell cavity	**14,560**
# cryomodule	**1,680**
# RF units	**560**





Gradient a Major Cost Driver for ILC





Lutz Lilje DESY -MPY-

28.07.2006

Global Plan for ILC Gradient R&D

Year	07	2008	2009	2010	2011	2012
Phase	TDP-1			TDP-2		
Cavity Gradient in v. test to reach 35 MV/m	→ Yield 50%			→ Yield 90%		
Cavity-string to reach 31.5 MV/m, with one-cryomodule		Global effort for string assembly and test (DESY, FNAL, INFN, KEK)				
System Test with beam acceleration		FLASH (DESY) , NML (FNAL) STF2 (KEK, test start in 2013)				
Preparation for Industrialization			Production Technology R&D			

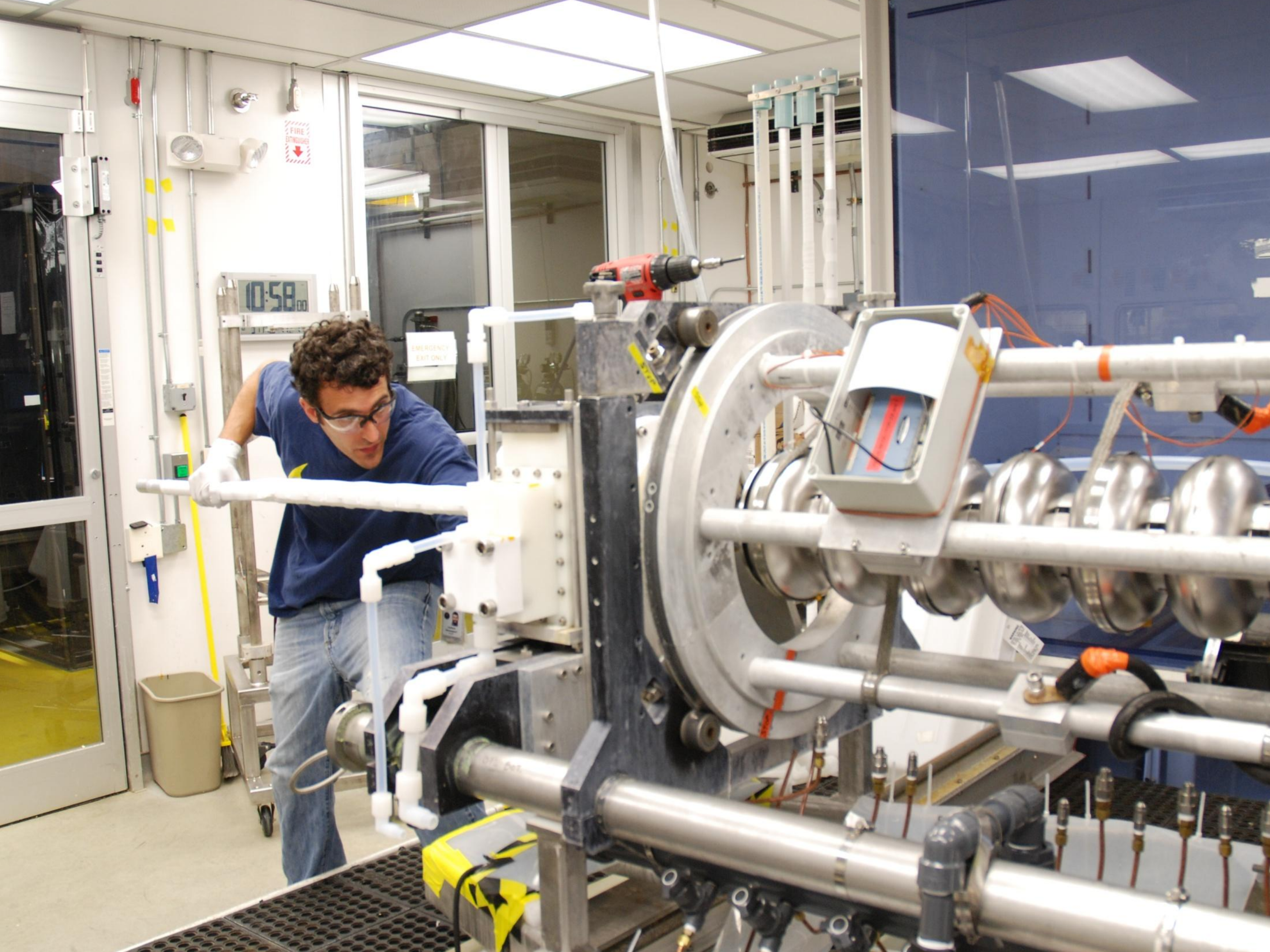
New baseline gradient:

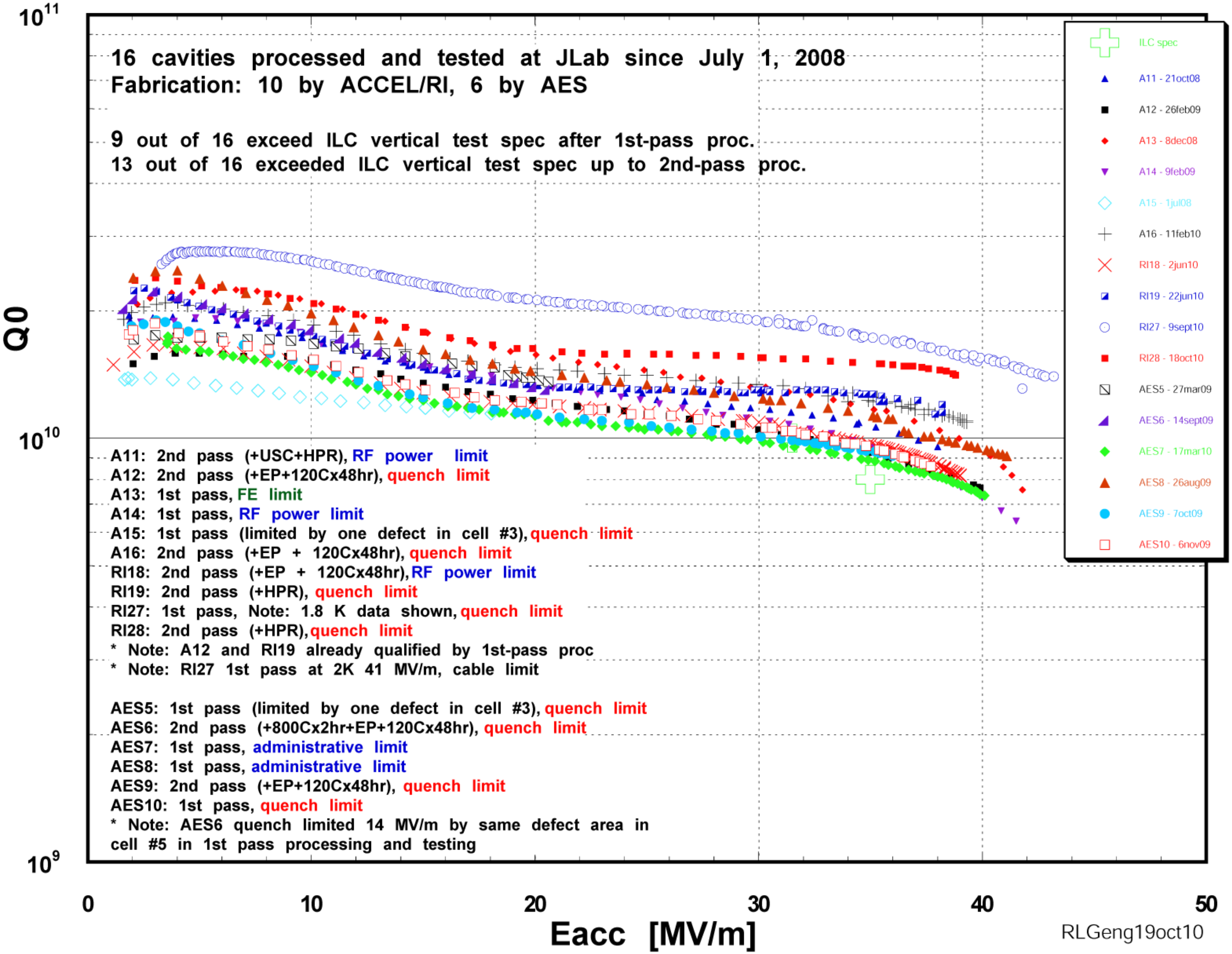
Vertical acceptance: 35 MV/m average, allowing ±20% spread (28-42 MV/m)

Operational: 31.5 MV/m average, allowing ±20% spread (25-38 MV/m)

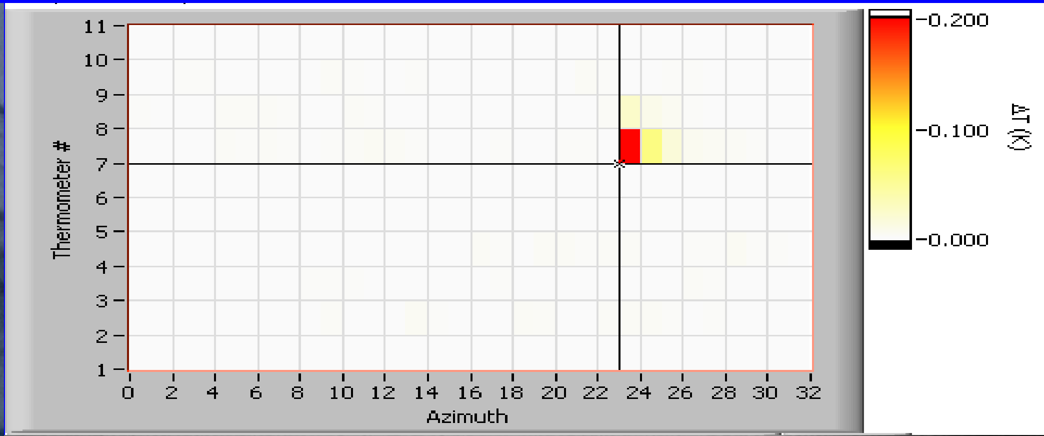
Baseline ILC Nb Cavity Proc. Procedure

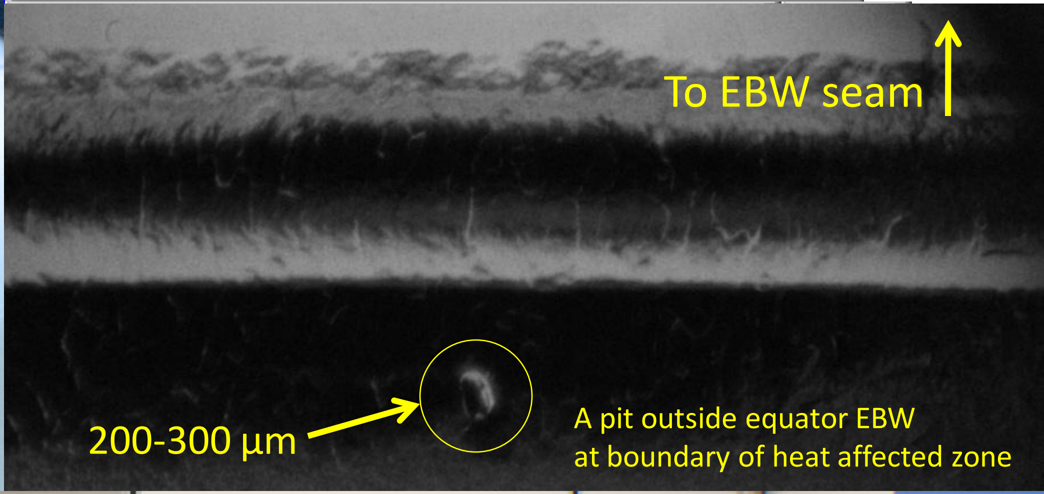
- Cavity manufacture (EBW) using RRR 300 Nb
- Initial light chemistry 5-30 μm (BCP)
- Heavy chemistry 80-150 μm (EP)
- Post-EP cleaning
- Vacuum furnace heat treatment 750-800 °C
- Light chemistry 20-50 μm (EP)
- Post-EP cleaning (ER/USC+HOM coupler brushing)
- Initial HPR
- Clean room assembly
- Final HPR
- Pump down
- 120°Cx48hr bake-out


FIRE EXTINGUISHER
10:58
EMERGENCY EXIT ONLY


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
RI18: 2nd pass (+EP + 120Cx48hr), RF power limit
RI19: 2nd pass (+HPR), quench limit
RI27: 1st pass, Note: 1.8 K data shown, quench limit
RI28: 2nd pass (+HPR), quench limit
* Note: A12 and RI19 already qualified by 1st-pass proc
* Note: RI27 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
ILC spec
A11 - 21oct08
A12 - 26feb09
A13 - 8dec08
A14 - 9feb09
A15 - 1jul08
A16 - 11feb10
RI18 - 2jun10
RI19 - 22jun10
RI27 - 9sept10
RI28 - 18oct10
AES5 - 27mar09
AES6 - 14sept09
AES7 - 17mar10
AES8 - 26aug09
AES9 - 7oct09
AES10 - 6nov09
Q0
10^11
10^10
10^9
0
10
20
30
40
50
Eacc [MV/m]
RLGeng19oct10

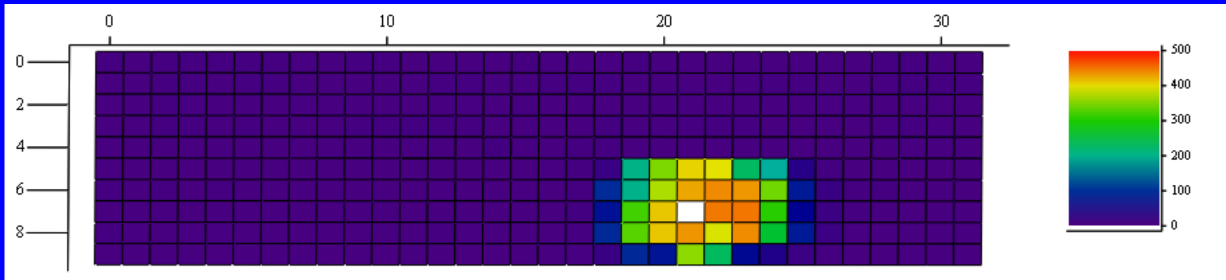
A15 gradient limit at 19 MV/m: T-mapping found a hot spot correlated to quench
Long distance microscope identified a defect near hot spot

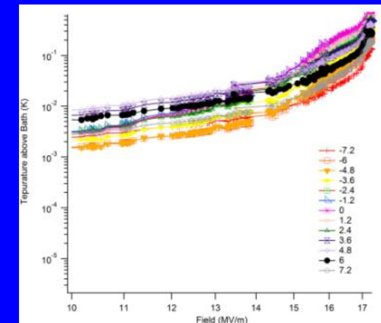


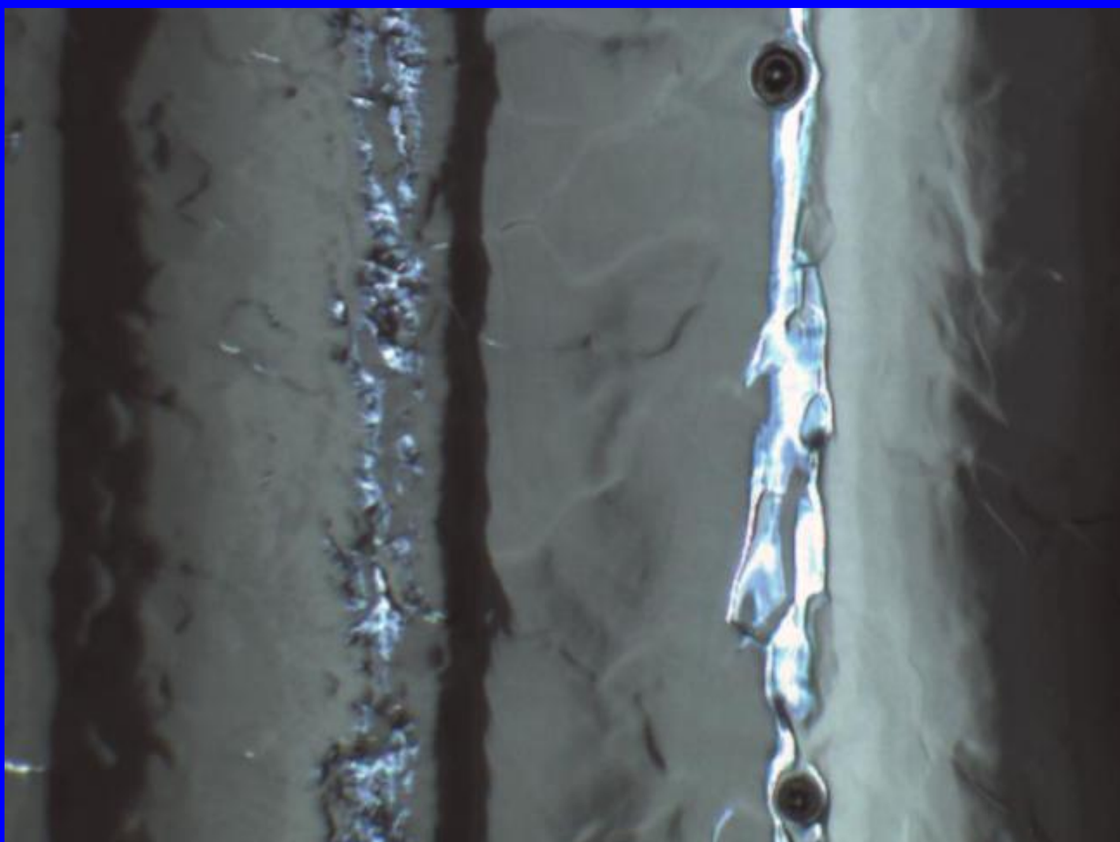


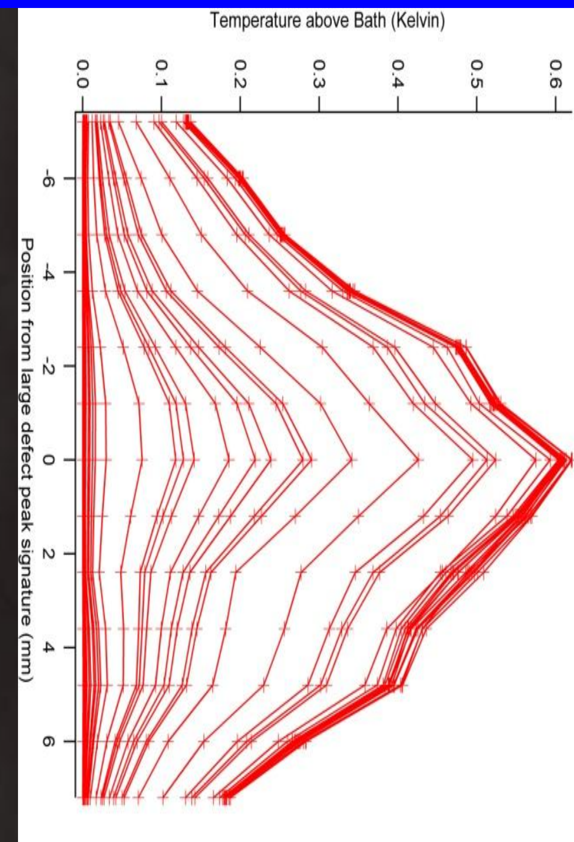
Fine grain EP

twin defects causing quench 17 MV/m. Cavity by a new vendor

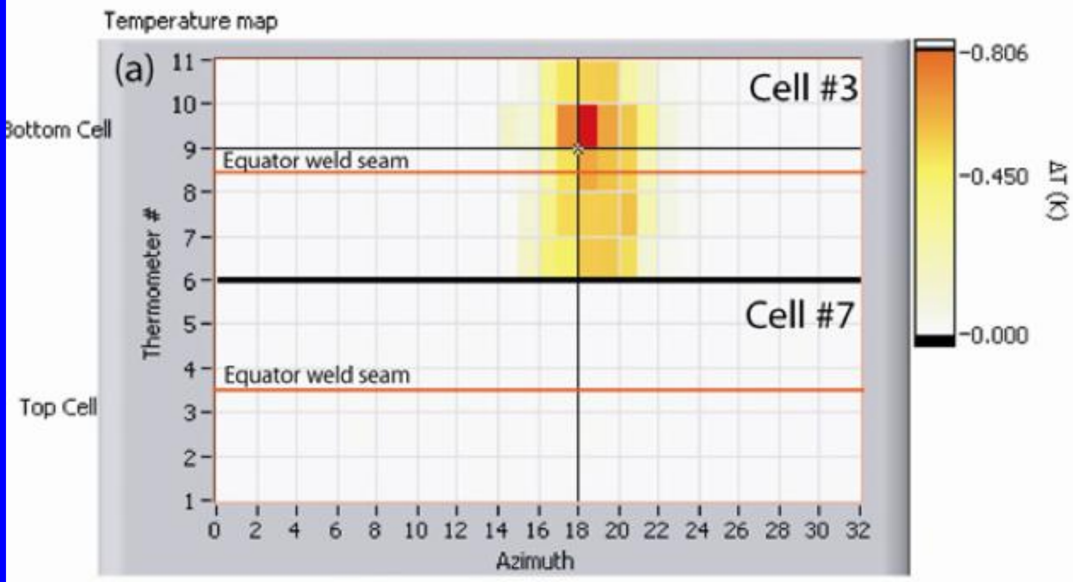


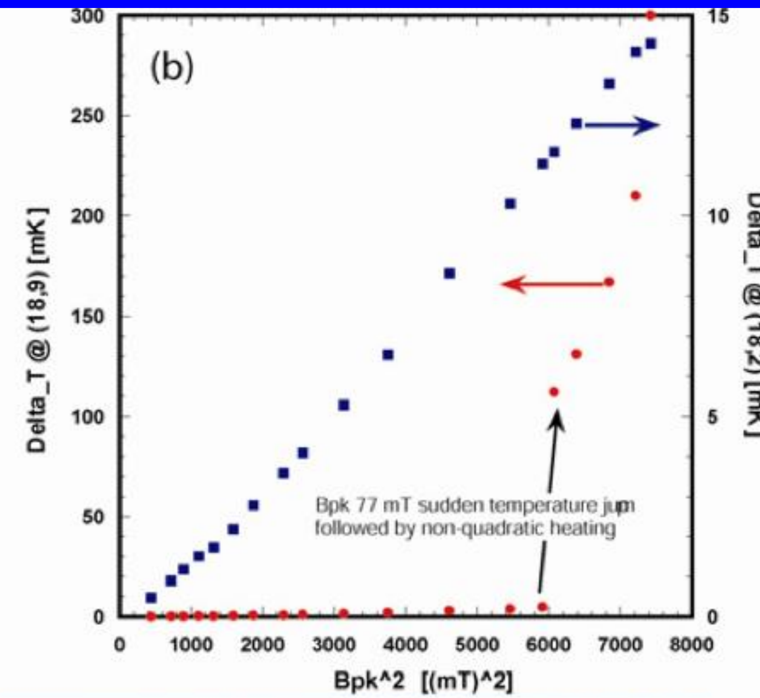






Local Heating near Quench-Causing Defect

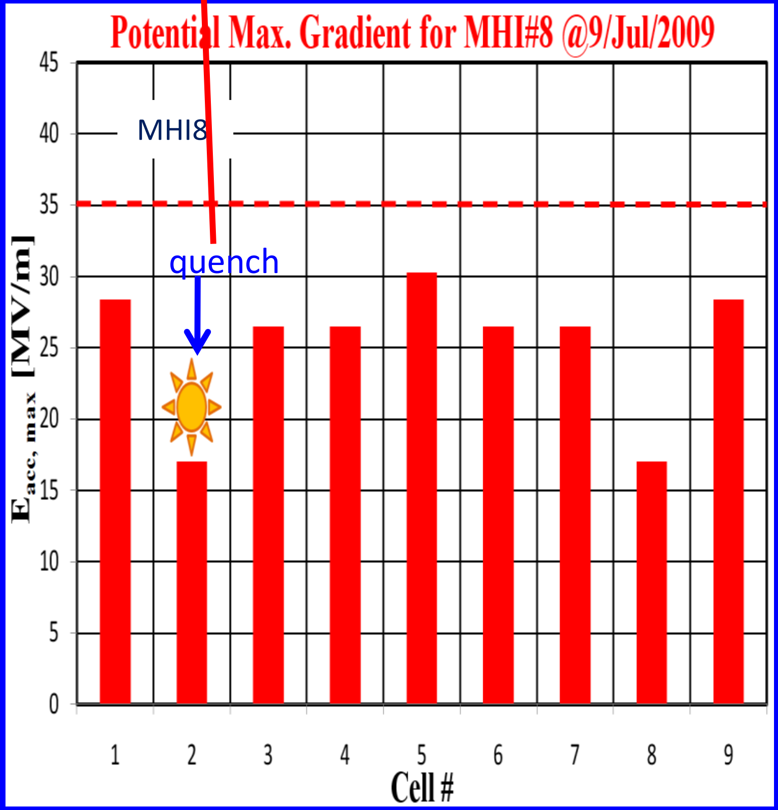


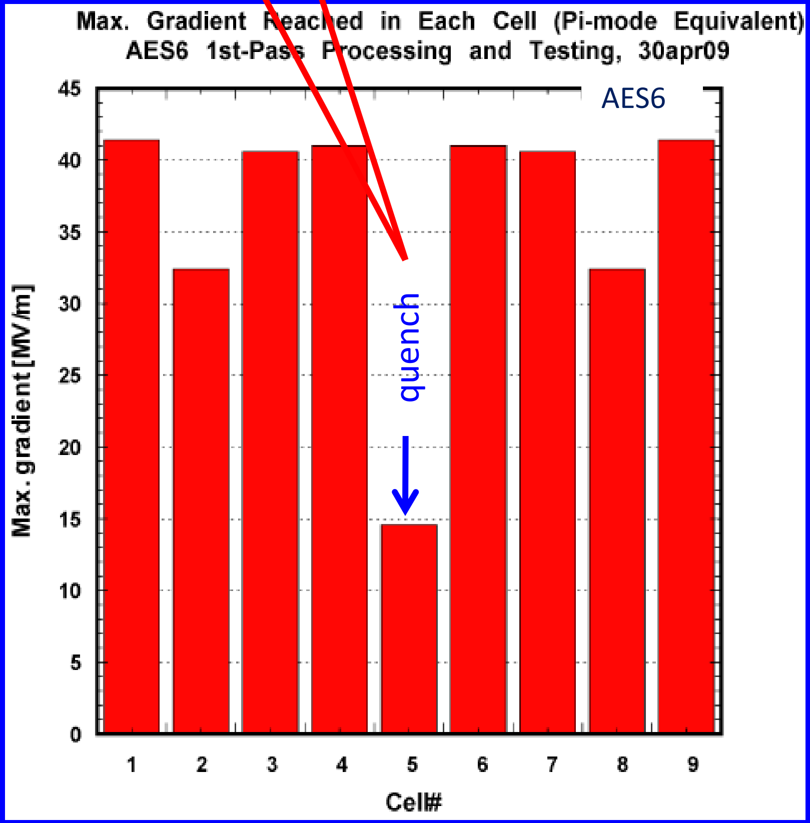


Examples with Observable Defect

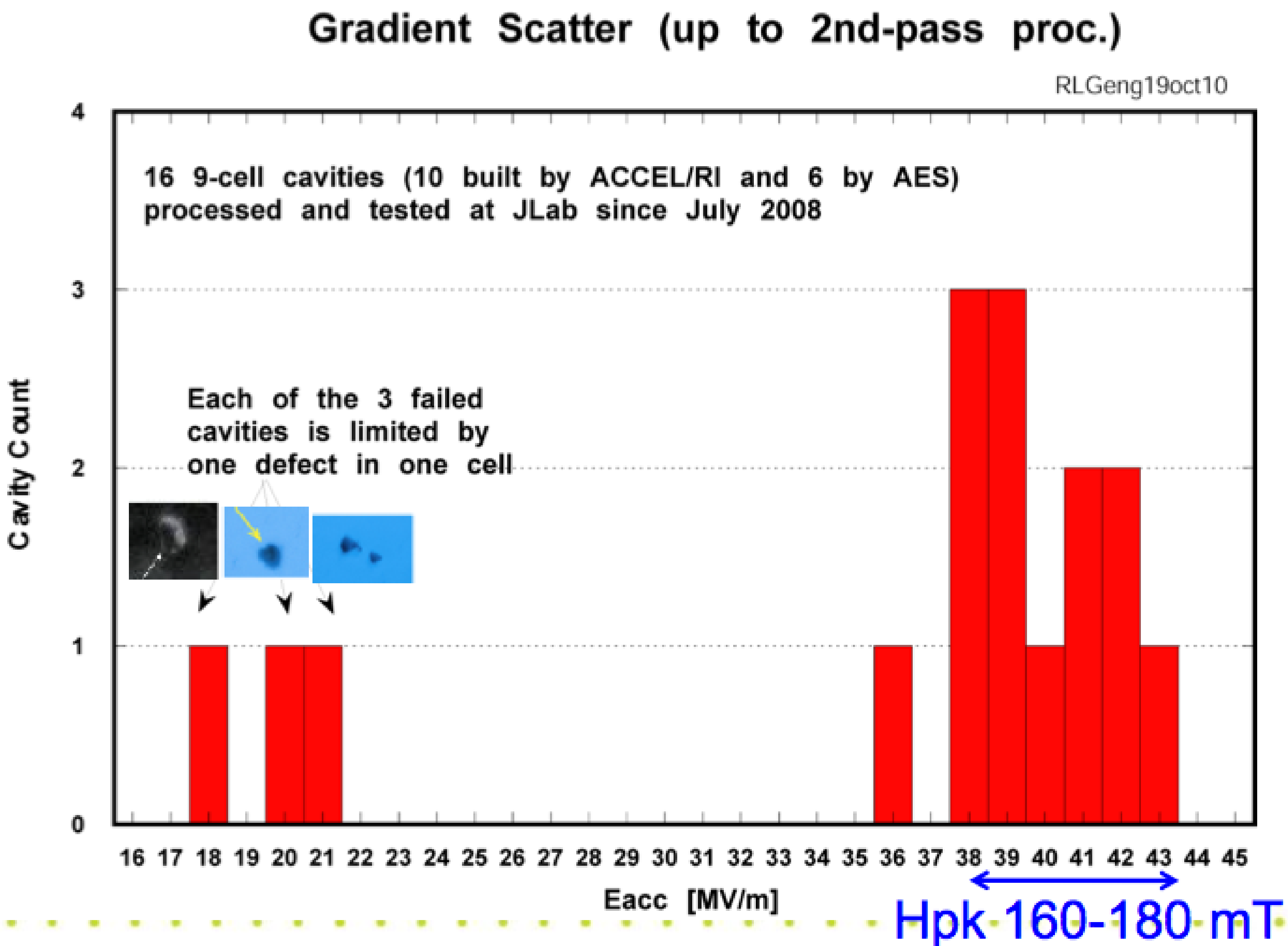
Deep pit at boundary of under-bead of equator EBW

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



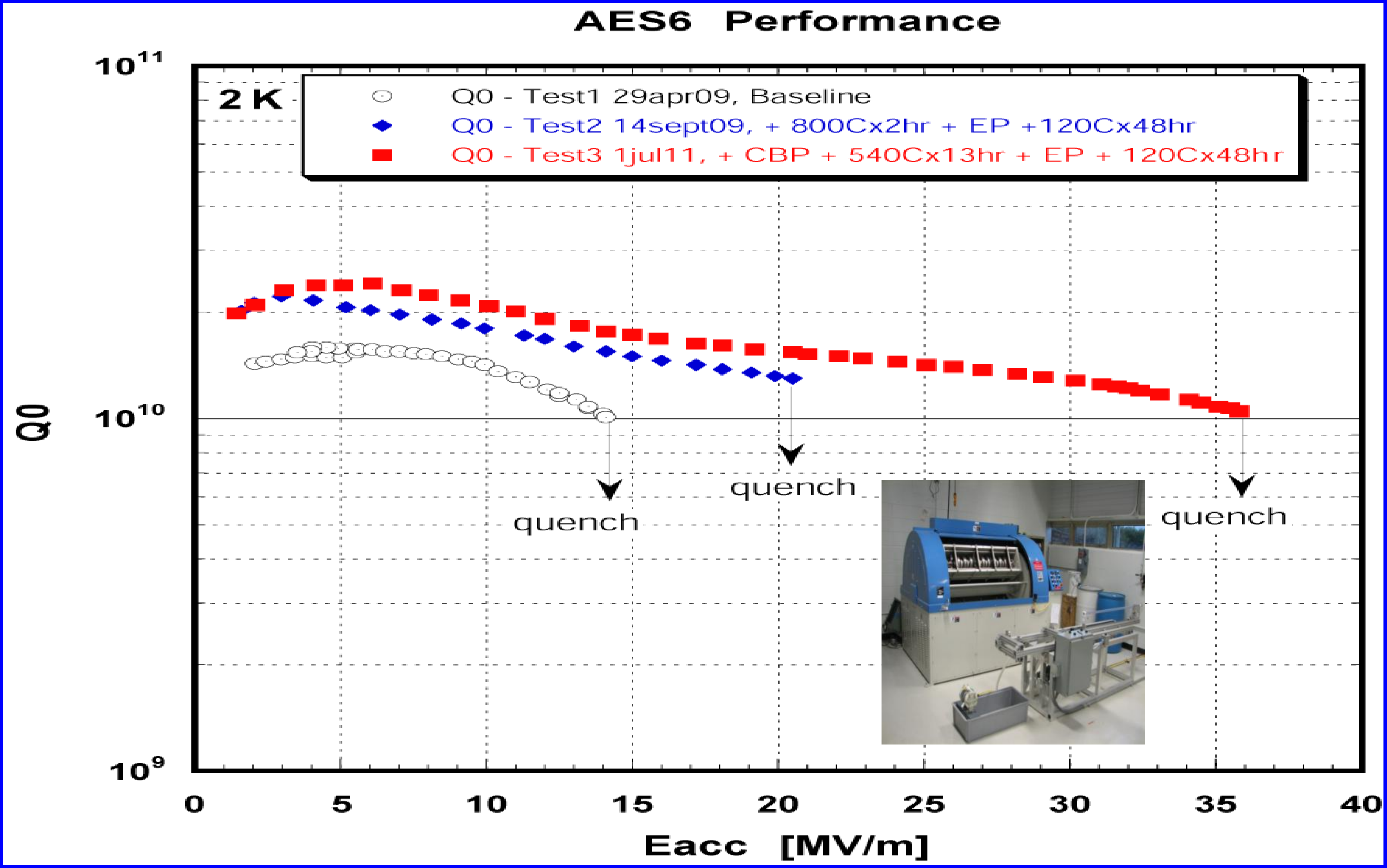


Main Issue: quench limit ~ 20 MV/m due to local geometrical defect (near equator EBW sub-mm dia.)

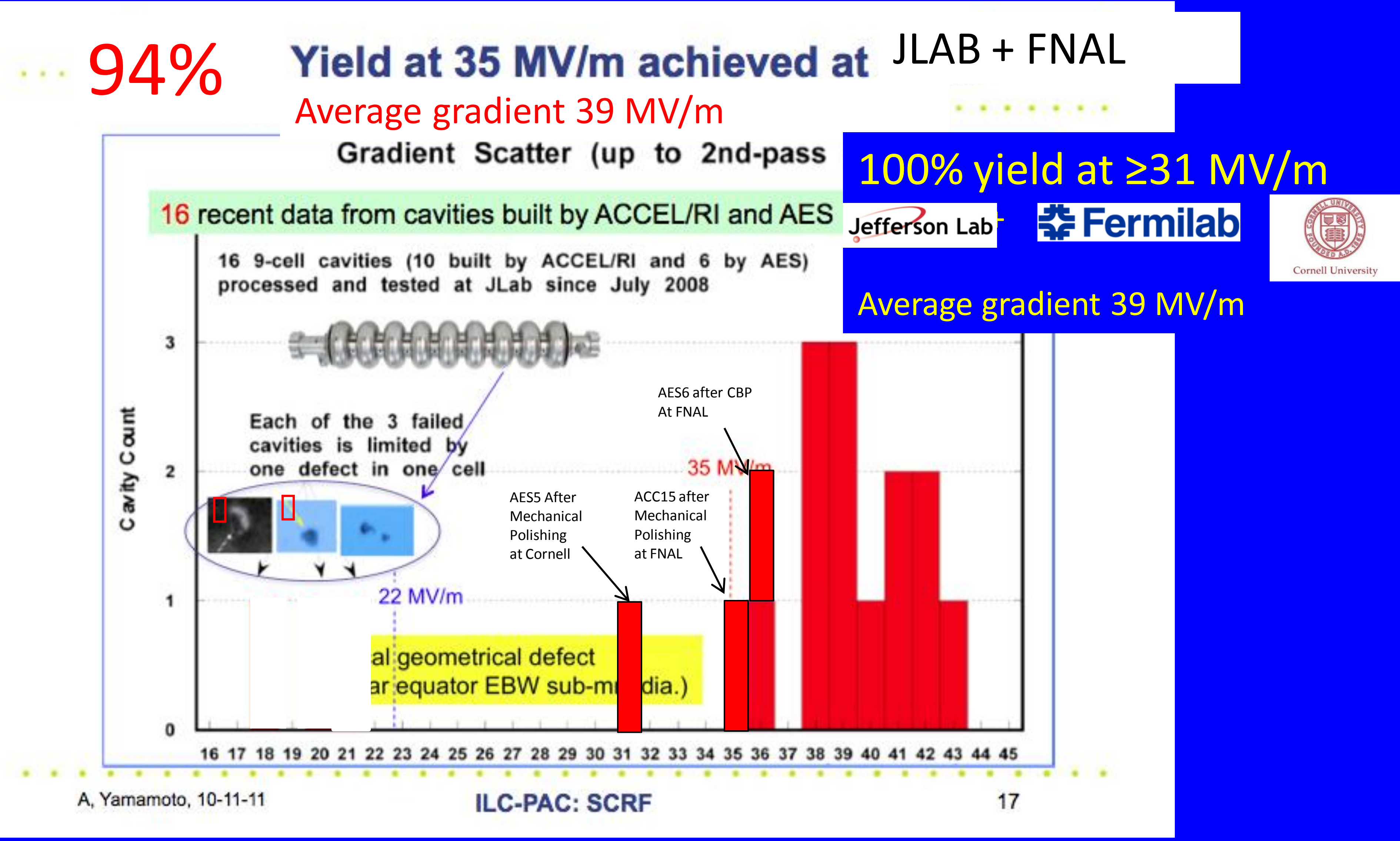


AES6 reached 36 MV/m at Q0 1E10

“Mirror finish” CBP at FNAL, then USC, HT, EP, bake, test at JLab



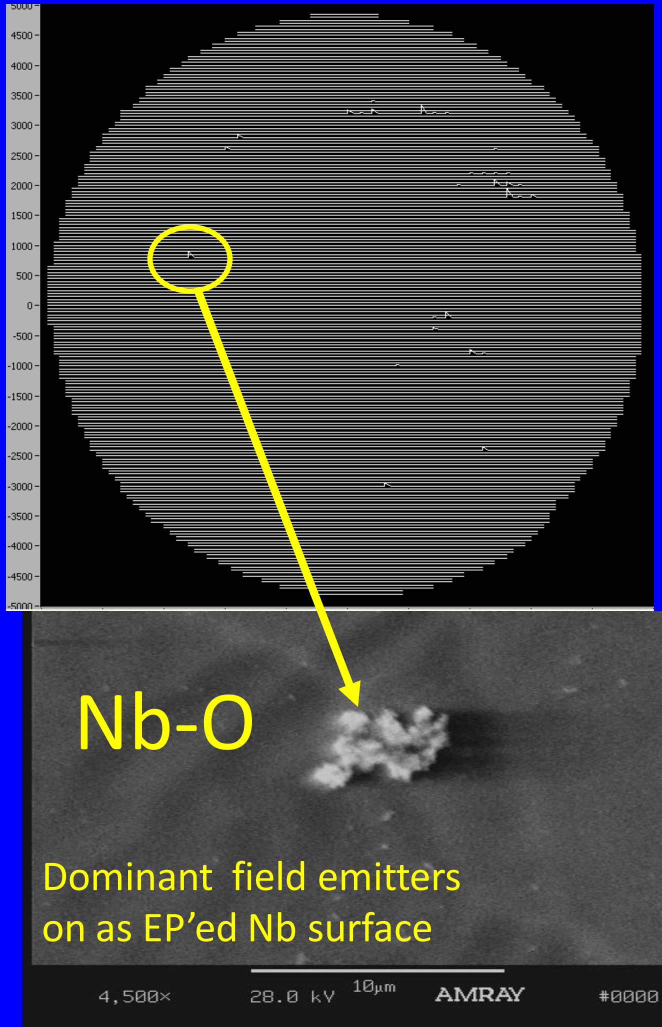
Today July 15, 2011 at ILC ART Director Visit of JLab



Understanding FE Behaviors w/ Samples

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

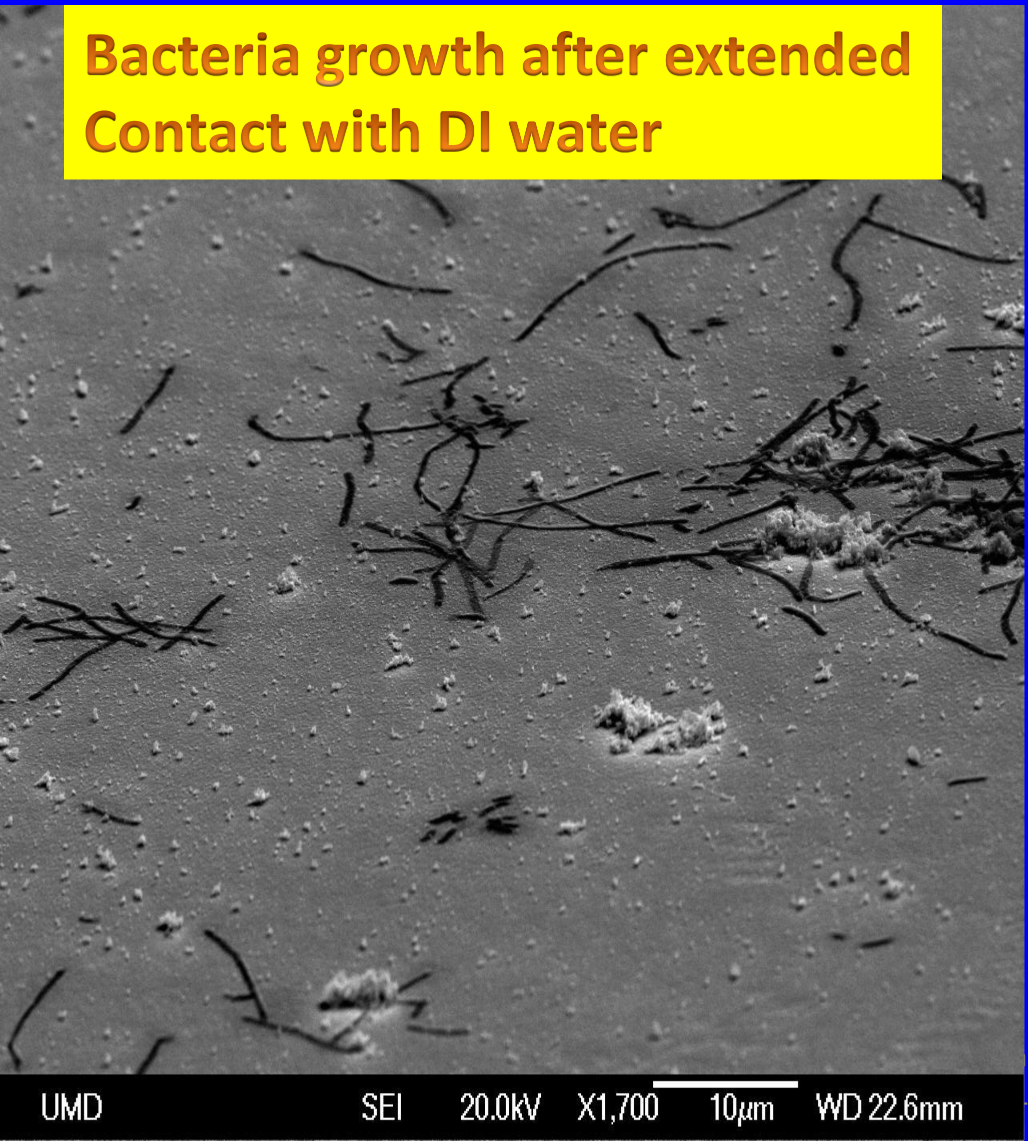
JLab Scanning Field Emission SEM



- 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

Understanding FE Behaviors w/ Samples

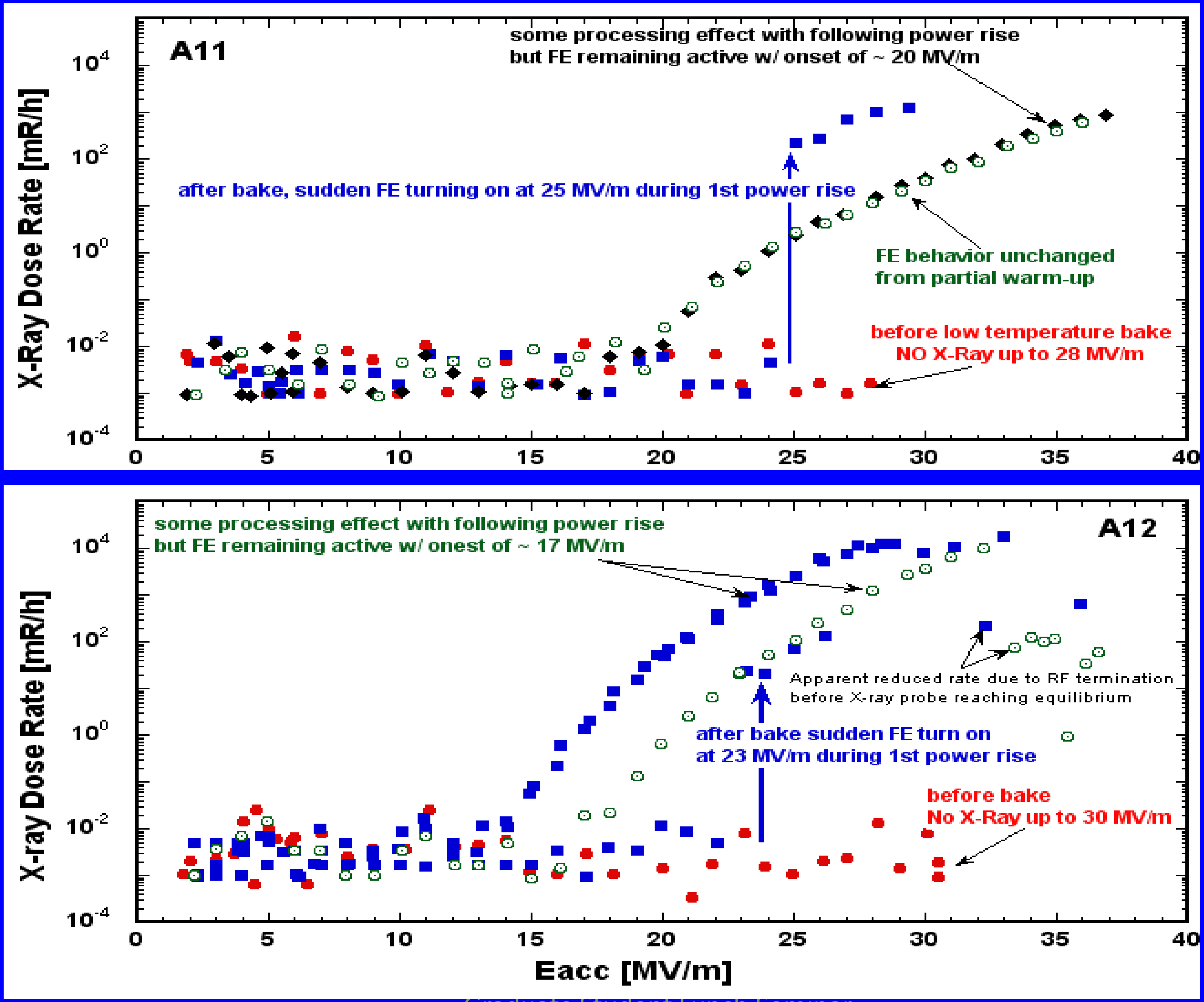
Bacteria growth after extended Contact with DI water



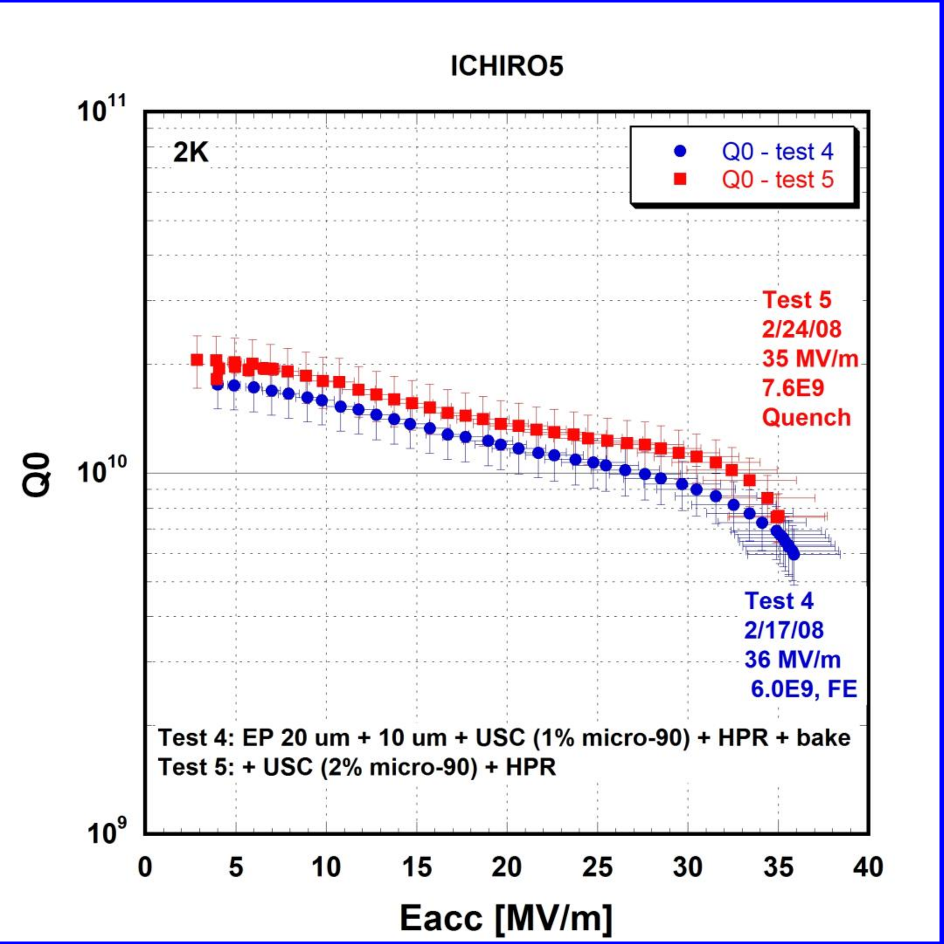
KEK Sponge cleaning
Collaboration with JLab
US-Japan Cooperation Fund

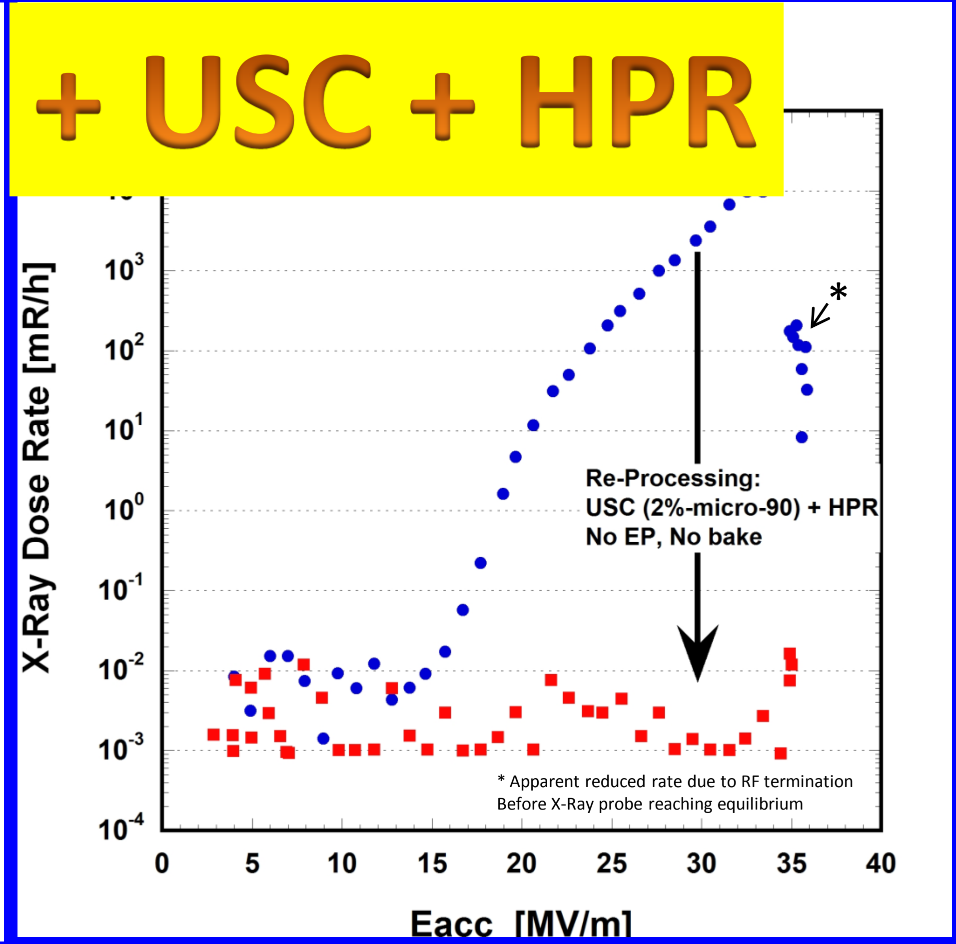
Understanding FE Behaviors w/ Real Cavities

Observation of Baking Induced Field Emission in EP'ed Cavity



First Example of Reducing/Eliminating Field Emission by Re-cleaning

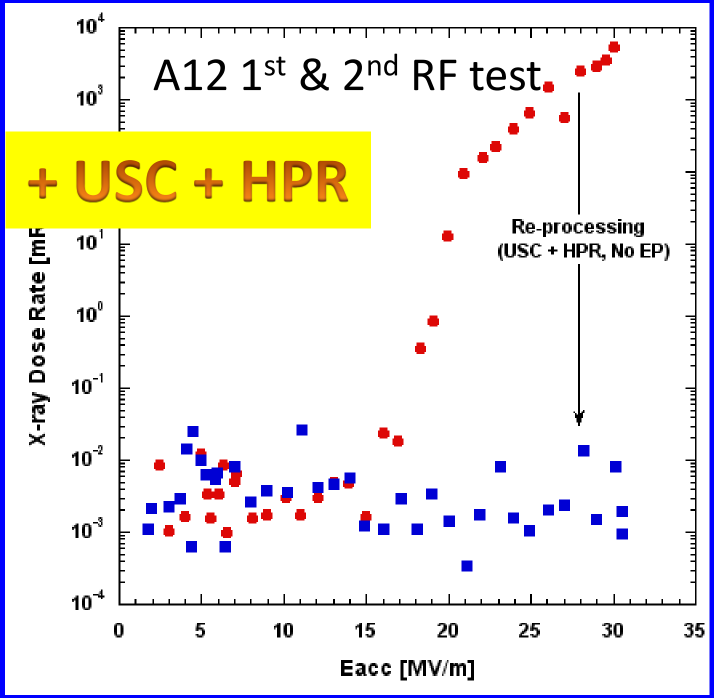


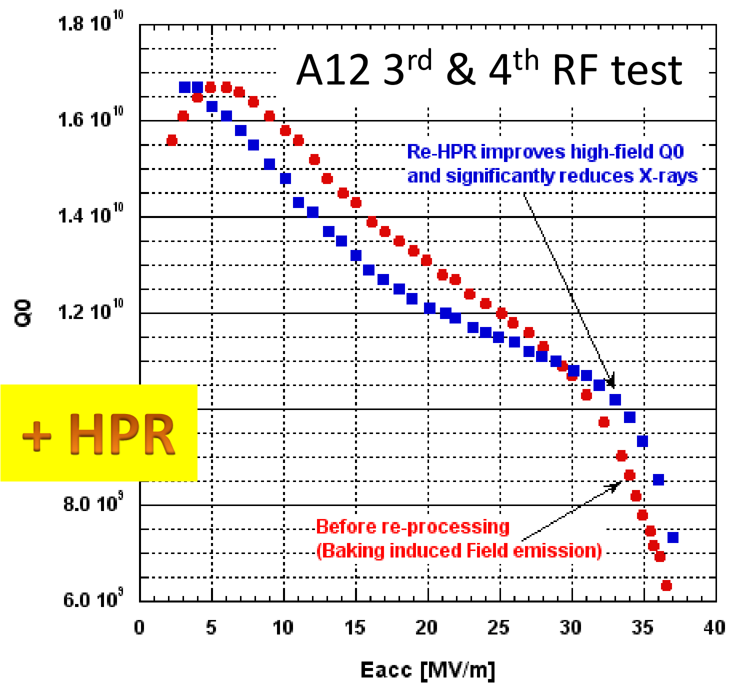


More details of multiple processing and testing results can be found in JLab report at ILC SCRF meeting, April 21-25, 2008, FNAL

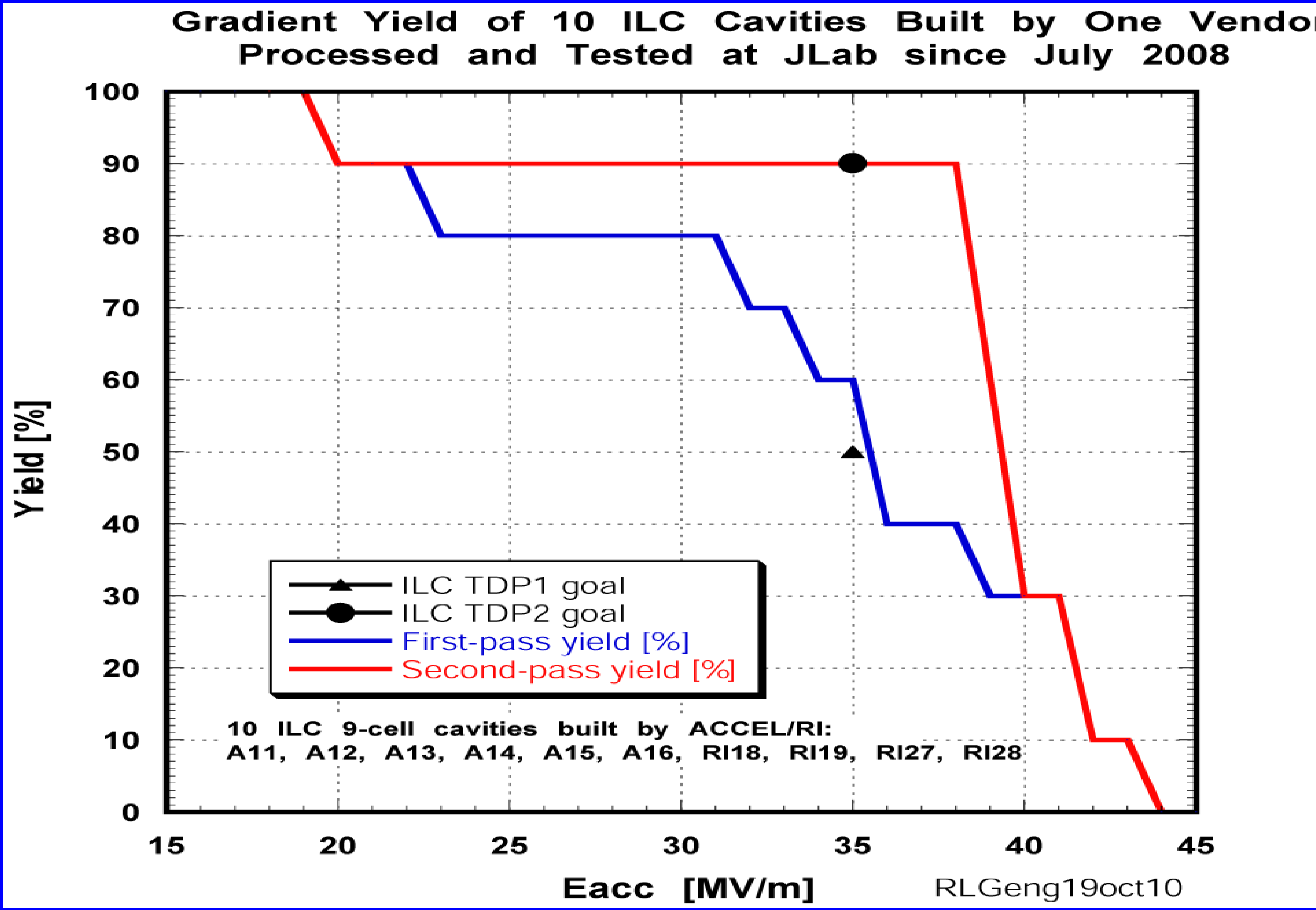
USC=ultrasonic cleaning
HPR=high pressure water rinse

More Examples of Reducing/Eliminating Field Emission by Re-cleaning

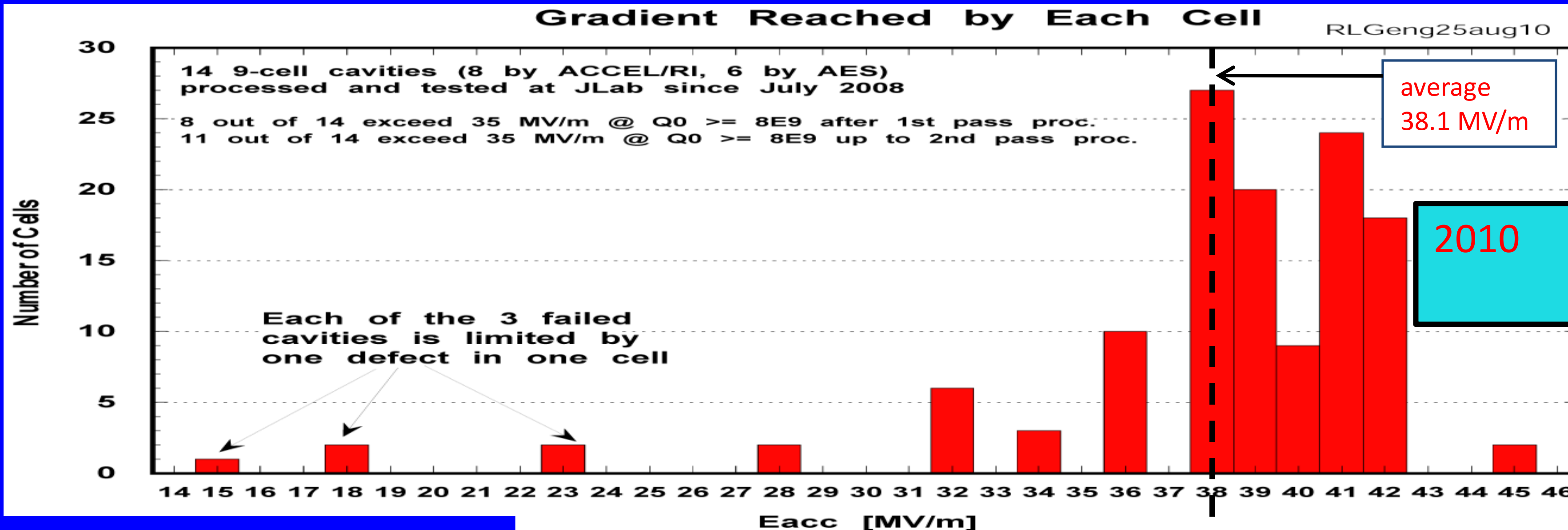




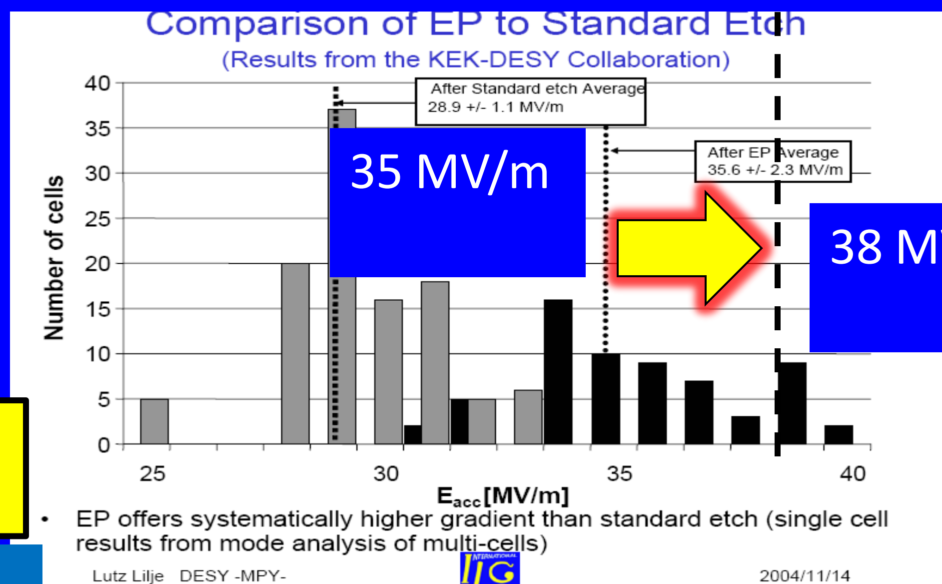
Another example is A6: last S0 test at JLab 37 MV/m, limited by field emission.
After shelf storage over a year, A6 re-cleaning (USC + HPR) and shipped under vacuum, RF test at FNAL saw an improved Q(Eacc) over the last test at JLab.


Gradient Yield of 10 ILC Cavities Built by One Vendor
Processed and Tested at JLab since July 2008
Yield [%]
100
90
80
70
60
50
40
30
20
10
0
15
20
25
30
35
40
45
Eacc [MV/m]
RLGeng19oct10
ILC TDP1 goal
ILC TDP2 goal
First-pass yield [%]
Second-pass yield [%]
10 ILC 9-cell cavities built by ACCEL/RI:
A11, A12, A13, A14, A15, A16, RI18, RI19, RI27, RI28

Gradient State-of-the-art then and now



2010

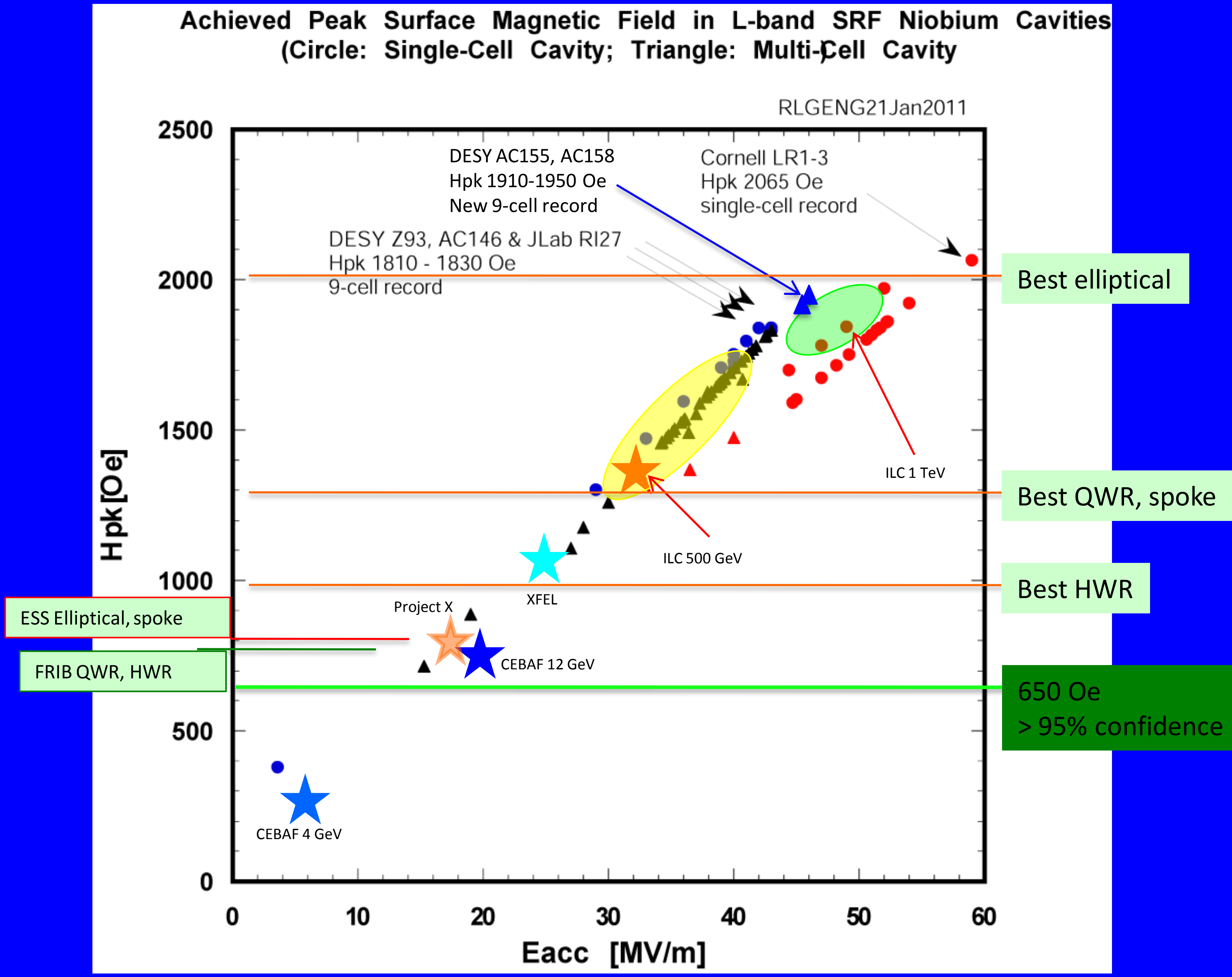


35 MV/m

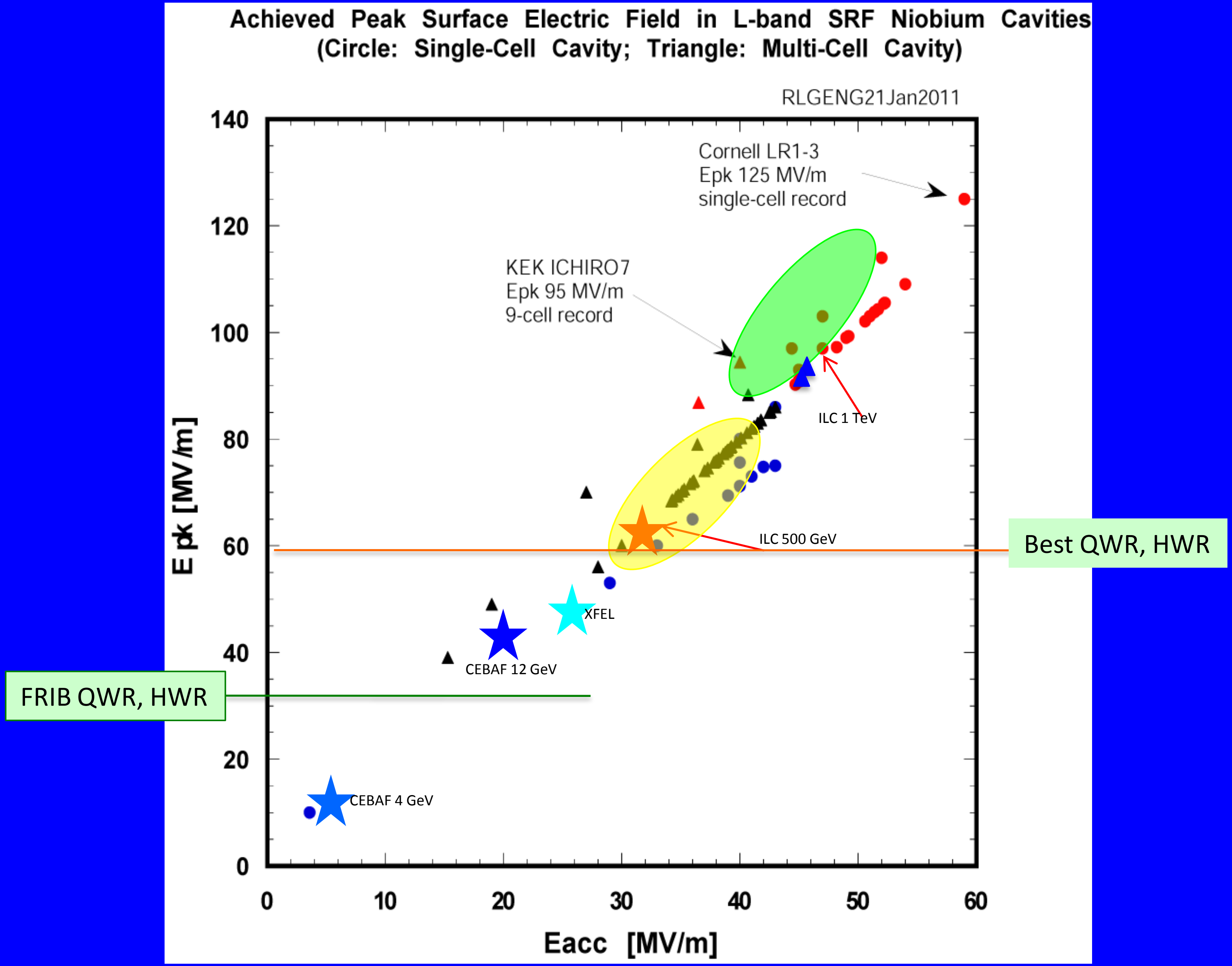
38 MV/m

2004

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



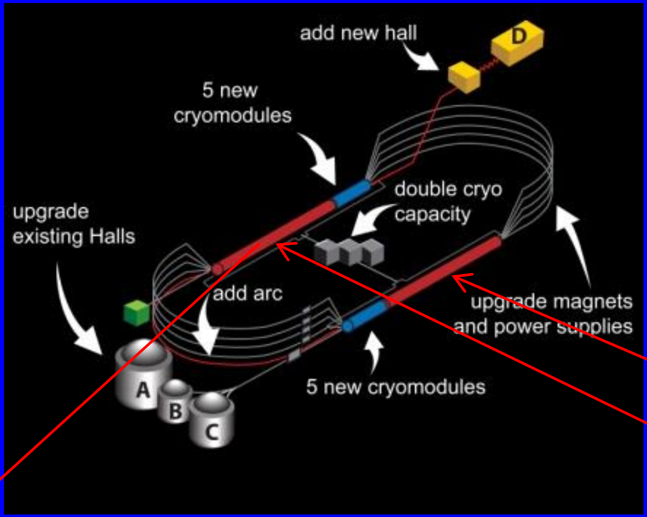
Achieved Peak Surface Magnetic Field in L-band SRF Niobium Cavities
(Circle: Single-Cell Cavity; Triangle: Multi-Cell Cavity
RLGENG21Jan2011
DESY AC155, AC158
Hpk 1910-1950 Oe
New 9-cell record
Cornell LR1-3
Hpk 2065 Oe
single-cell record
DESY Z93, AC146 & JLab RI27
Hpk 1810 - 1830 Oe
9-cell record
Best elliptical
ILC 1 TeV
Best QWR, spoke
ILC 500 GeV
XFEL
Best HWR
ESS Elliptical, spoke
Project X
CEBAF 12 GeV
FRIB QWR, HWR
650 Oe
> 95% confidence
CEBAF 4 GeV
Hpk [Oe]
Eacc [MV/m]
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60

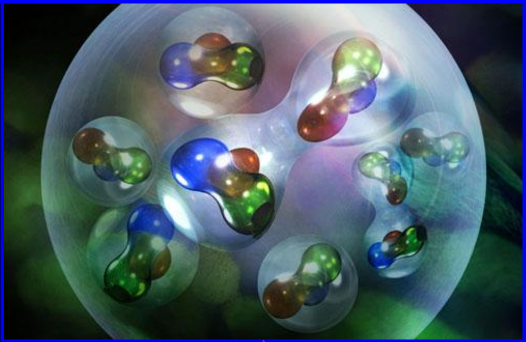

Achieved Peak Surface Electric Field in L-band SRF Niobium Cavities
(Circle: Single-Cell Cavity; Triangle: Multi-Cell Cavity)
RLGENG21Jan2011
Cornell LR1-3
Epk 125 MV/m
single-cell record
KEK ICHIRO7
Epk 95 MV/m
9-cell record
ILC 1 TeV
ILC 500 GeV
Best QWR, HWR
XFEL
CEBAF 12 GeV
FRIB QWR, HWR
CEBAF 4 GeV
E pk [MV/m]
Eacc [MV/m]
0
20
40
60
80
100
120
140
0
10
20
30
40
50
60

SRF Cavity Gradient R&D Impacts & Benefits

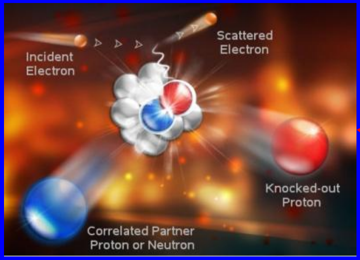
1991 (BCP)
Cryomodule cavity 5 MV/m
320 cavities installed in linacs

2011 (BCP+HTA+EP+HPR+LTB)
Cryomodule cavity 19.2 MV/m
80 cavities needed, many qualified to >25 MV/m, some up to 35-43 MV/m



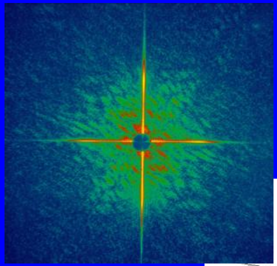


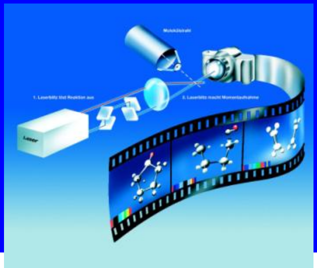
CW SRF Linac

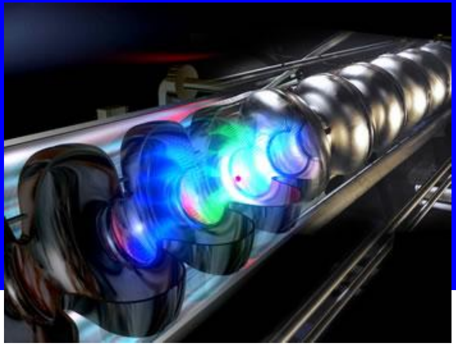


CEBAF upgrade, under construction now, will double its energy to 12 GeV. The present 6 GeV machine has 42 old cryomodules. The additional 6 GeV is achieved by adding only 10 new modules with high gradient cavities.

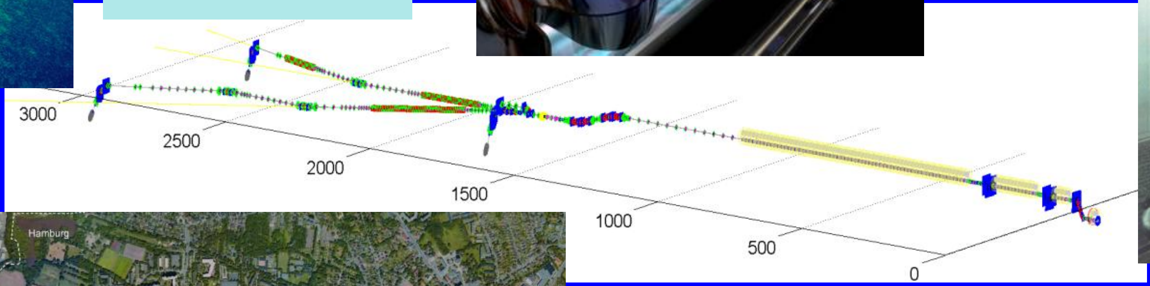
SRF Cavity Gradient R&D Impacts & Benefits







2011 (EP+HTA+EP/BCP+HPR+LTB)
Cryomodule cavity 24.3 MV/m
640 cavities needed
DESY qualified many cavities up to 35-43 MV/m



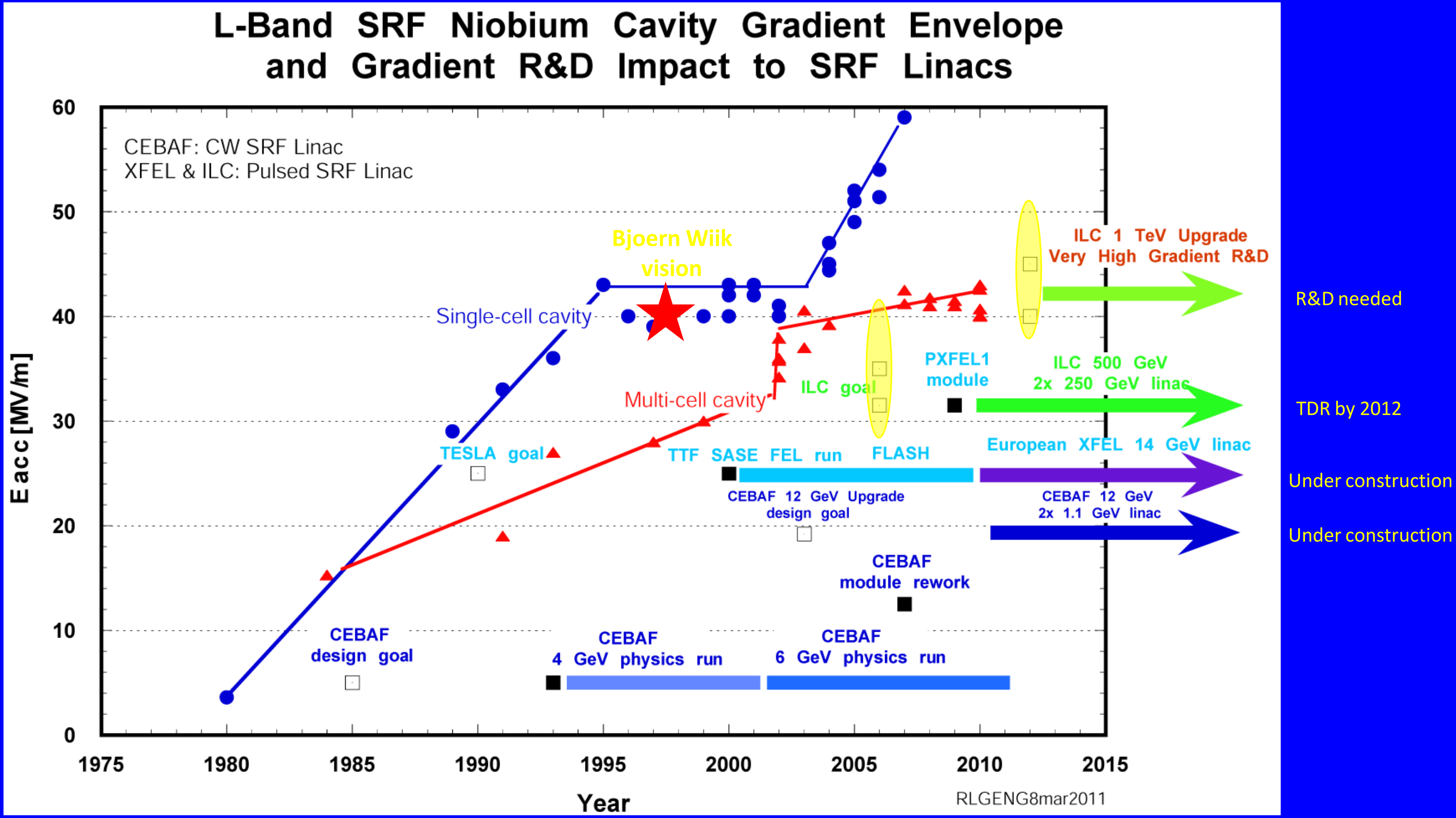
Pulsed SRF Linac

80 cryomodules needed

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

SRF Cavity Gradient Progress



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 he 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.