RF Superconductivity

an enabling technology for the future

H Edwards

Summary of a decade of dramatic progress

- Status in the 90's
- TESLA superconducting cavity R&D
- other R&D and future applications

prepared with the help of Lutz Lilje, Carlo Pagani, Hasan Padamsee, Charles Reece, Steve Suhring, Claus Rode, Kurt Hubner, with information from many others

and dedicated to Robert Wilson and Bjoern Wiik, two leaders of outstanding talent and vision, for whom it was my great good fortune to work.

RF Superconductivity started early 1960's

P Wilson, Schwettman, Fairbanks-Stanford, electron linac
proposed 20 GeV, 10% Duty Factor, 10 MV/m

Banford & Stafford- Harwell, proton linac

Susini - CERN, lead and Nb surface studies 300MHz,

Montague- CERN separated beam

Stanford- S band cavity studies

20 years later (80's)

Padamsee - Improve thermal conductivity (Increase RRR), titanization 1400C

Cavities ~7MV/m , Cornell (CEBAF), KEK, CERN, Wuppertal

from L Lilje

30 Years after the Beginning
i.e. LINAC 92 Conference
before the start of the TESLA R&D

s.c. cavities in operation were ...

	Nbr. of cav.		MHz	m	MV/m	MV
MACSE	5	5-cell	1500	2.5	6.5	16
S-DALINAC	10	20-cell	3000	10.0	5.9	59
HERA	16	4-cell	500	19.2	3.6	69
HEPL				30.8	3.0	92
TRISTAN	32	5-cell	508	47.2	6.6	310
CEBAF	106	5-cell	1497	53.0	7.6	400
LEP	12	4-cell	352	20.4	3.7	75

and others....

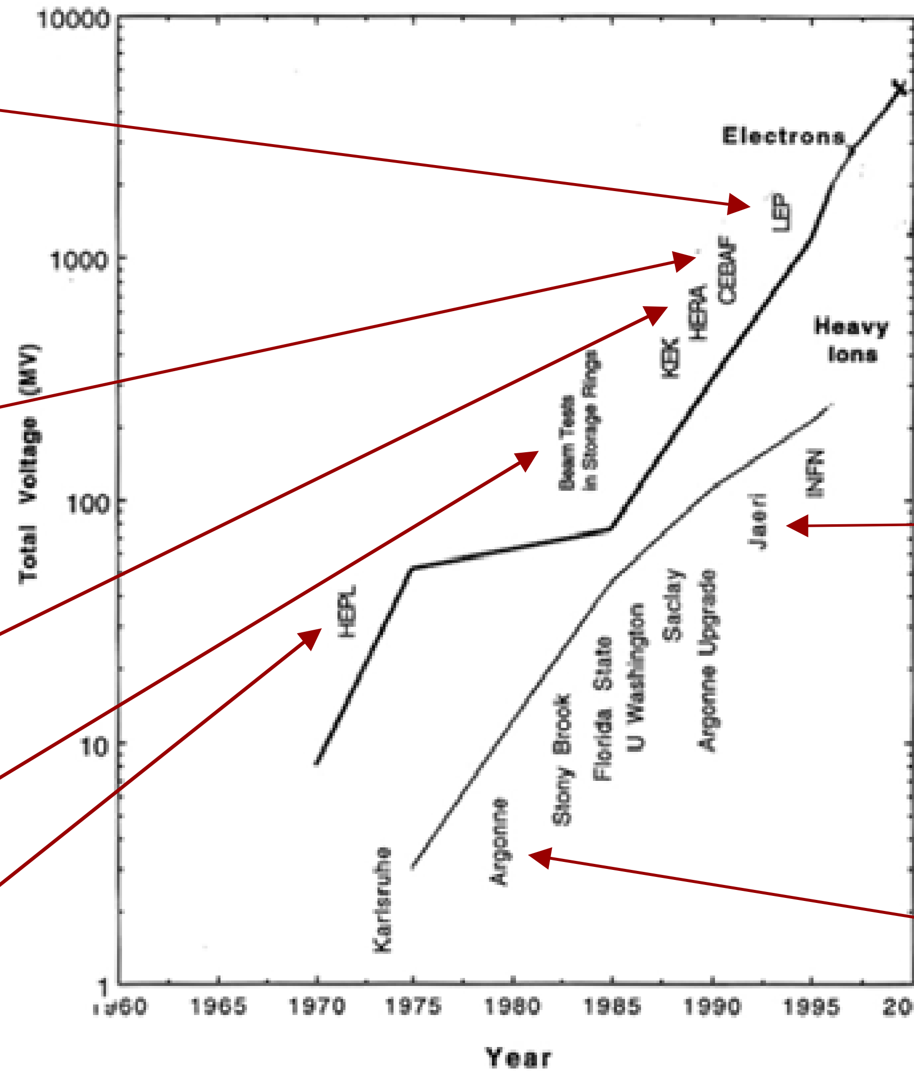
CEBAF with an ogoing rate of 16 Cavities per month

“Livingston Plot” for RF Superconductivity

From Hasan Padamsee

Total >1000 meters

> 5 GV



First a look at two of the projects of the 90's

CEBAF - JLab

LEP - CERN

Both systems are (were) operated above design at a level where trip rates are just tolerable

Evolution of operating energy with time

Superconducting systems very reliable

CEBAF Recirculating Linac

(cavities based on Cornell technology & development)

Jlab- CEBAF, completed 1993, Design 4GeV, 5MV/m
Today 5.8 GeV , 5 pass, 6.9MV/m
active length 169m @6.9MV/m = 1160 MV
338 cavities, 1.5 GHz, 5 cell 1/2m , 42 modules of 8 cavities

Limitation- Design problem with RF window location-
field emission leading to cold window arcing
gradient set by 100 trip/day total, or 1 trip/8hr/cavity,
45 sec recovery

Upgrade underway to 12GeV

LEP

LEP2000-up to 209 GeV CM

288 SRF cavities, 350 GHz, active length 1.7m,

total active length 490m

LEP 7.2 MV/m avg, (Design 6MV/m), 3600 MV

36 klystrons(@1 MW) (8 cavities/klystron)

Operation 1999 margin 16 cavities-2 kly (5.5%)

2000 margin 8 cavities- 1 kly (2.7%) -> ZERO

Trips

Mean Time Before Trip (MTBT) = 14min, recovery 2min

trips due to Field Emission leading to

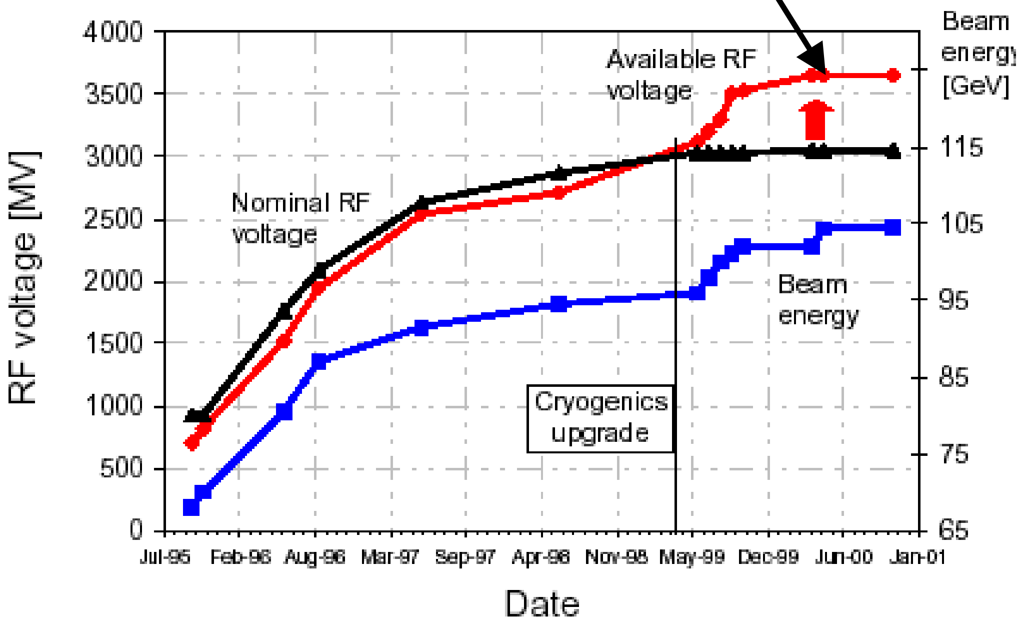
excessive helium usage - helium interlock trips

CERN 350 MHz LEP Cavities

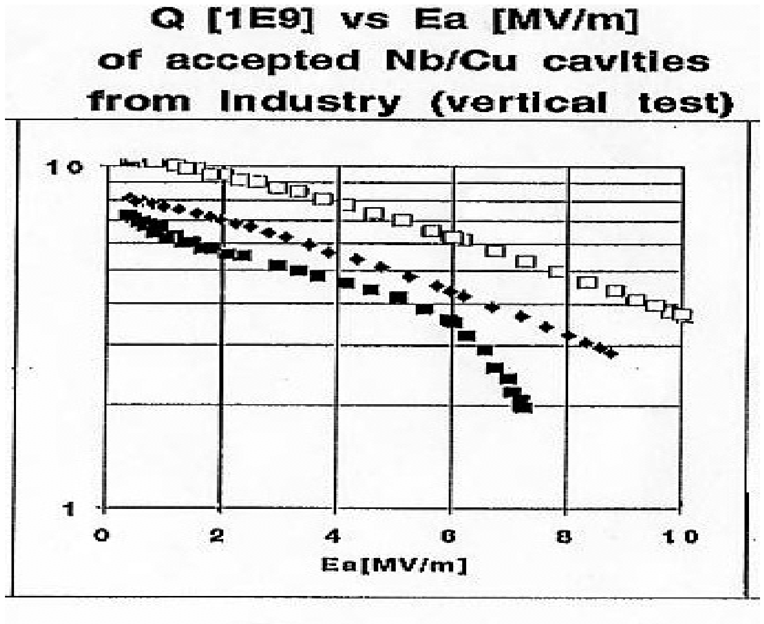
cavities Nb sputtered on Cu

Evolution of beam energy and available RF voltage
Design gradient 6MV/m

Operation above design



Chamonix XI
Assmann



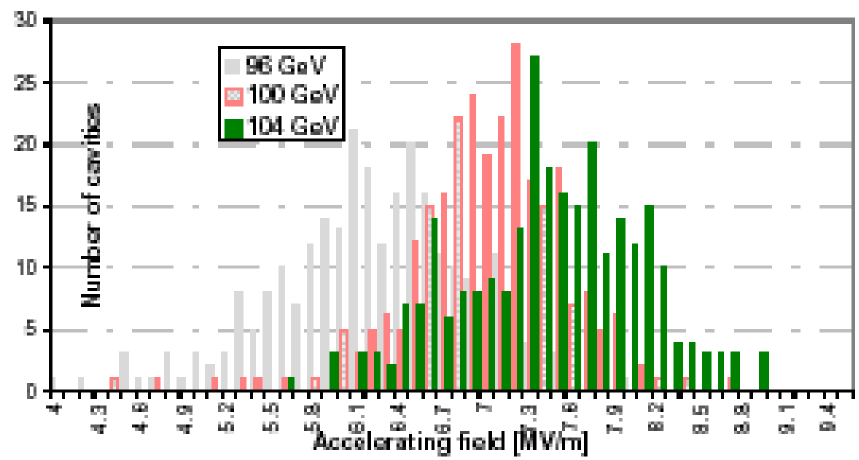


Figure 3.: Histogram of cavity gradient distribution for three different maximum beam energies in 1999 and 2000.

PAC01_MPPH123
Brown, et al

1992 TESLA Linear Collider Concept

Bjoern Wiik organized collaboration to undertake SRF cavity R&D with focus toward its use for linear collider

large aperture, low wake fields, relaxed tolerances,less emittance dilution long pulse trains, fast bunch to bunch feedback, emergency turnoff within fraction of pulse

Potential benefits acknowledged since beginning of LC R&D, but projected costs considered too high.

R&D program to reduce cost factor of 20/MV - Tesla Test Facility (TTF)
Goal -increase gradient (5MV/m) at that time by ~ 5 times (reduce cost per MV)
-reduce cost per unit length over existing installations by ~ 4 times

R&D Goal set 15MV/m at TTF, and a clear path toward 25MV/m for LC
(now for TESLA 800 goal is 35MV/m)

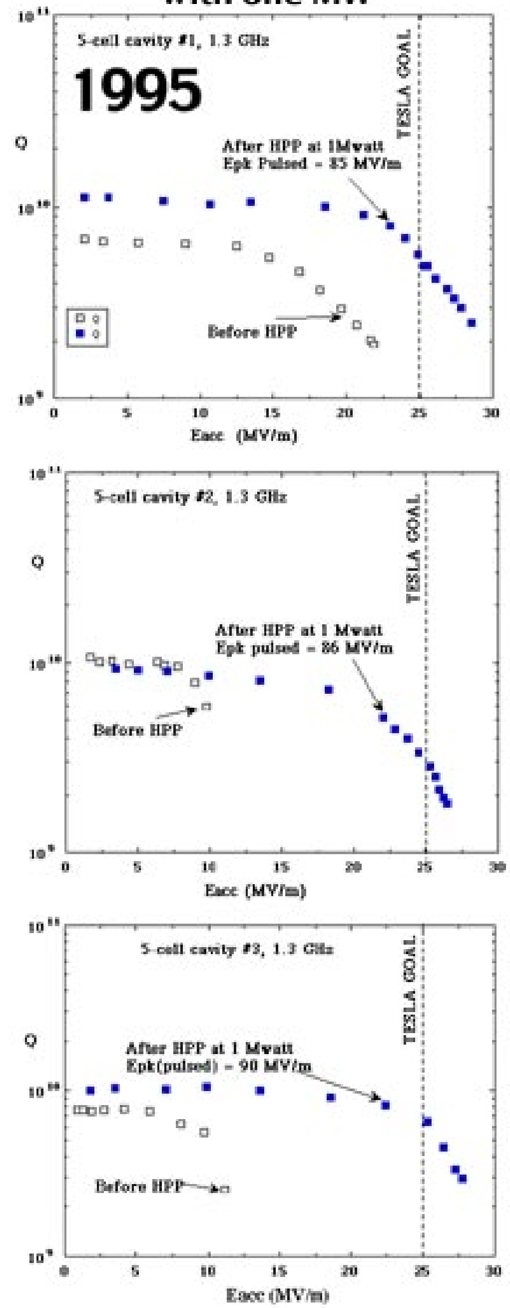
Existence Proof!

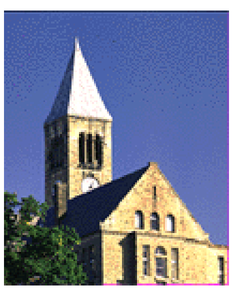
1993-5 at Cornell push to High Gradient
with High Pulse Power Processing
5 cell 1.3 GHz cavities > 25 MV/m

>25MV/m

1
9
9
5

5-cell 1.3 GHz cavities
High Pulse Power Processing
with one MW





CORNELL
UNIVERSITY

Padamsee

TESLA- International collaboration over 40 partners, 12 countries

Cavity improvement efforts

- High RRR Nb (better thermal conductivity)
- Scanned material for defects (eddy current scanner, now squid also)
- care in preparation and E beam welding (good vacuum)
- Titanization High Temp (HT) treatment at 800C/ 1400 C, improve RRR,
  - remove H (Q disease) and O2 (mean free path)
- Chemical etching - Buffered chemical polishing (BCP)
- High Pressure Rinse (HPR)remove particles, eliminate field emission
- Clean room Assembly (class 10, 100)

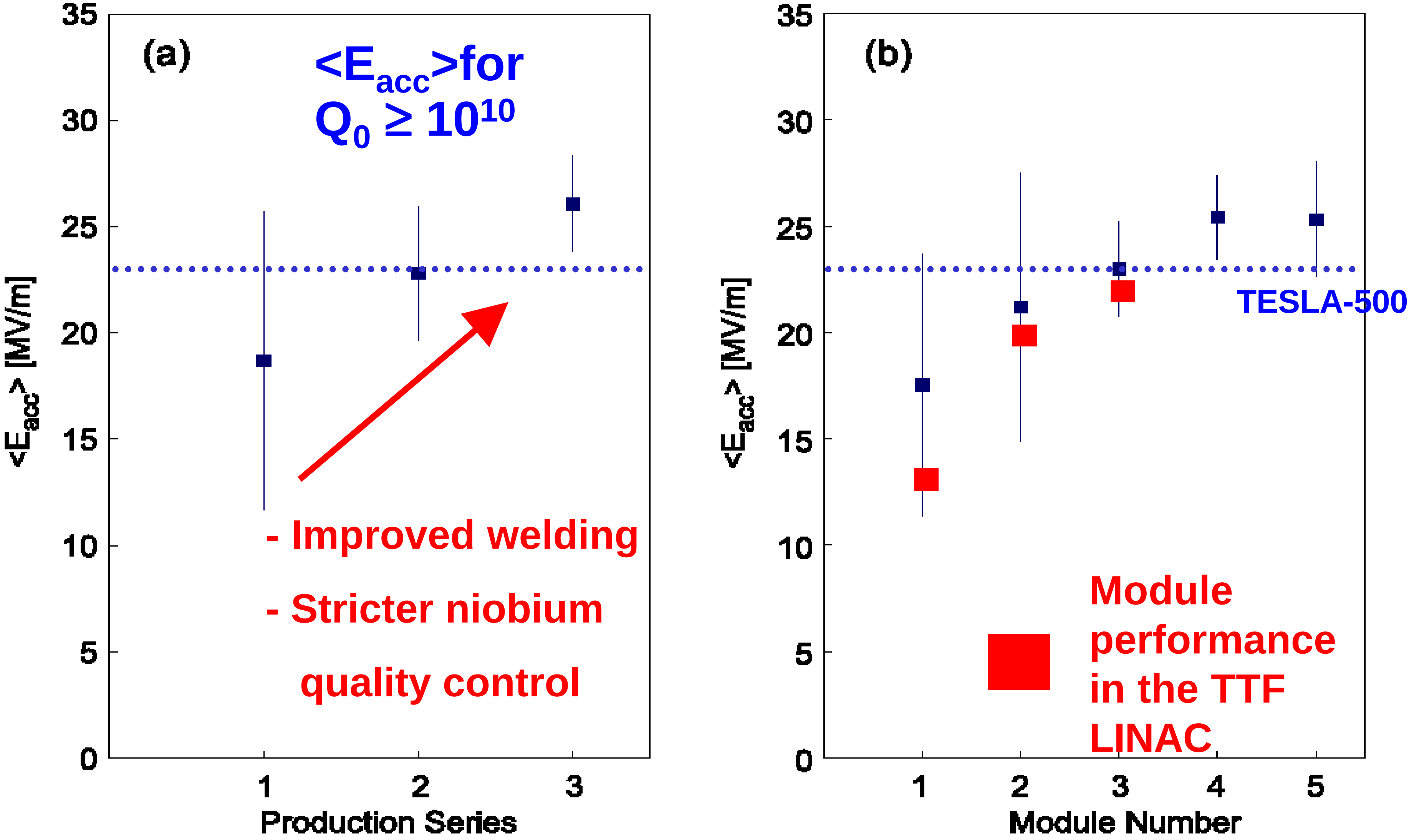
Cavity test steps

- Vertical dewar
- Horizontal test dewar (Chechia)
- Module assemblies (8 cavities/module)
- TTF (TESLA Test Facility) installation and test with beam

Limitations- Quench (Thermal breakdown), Field emission, Multipacting

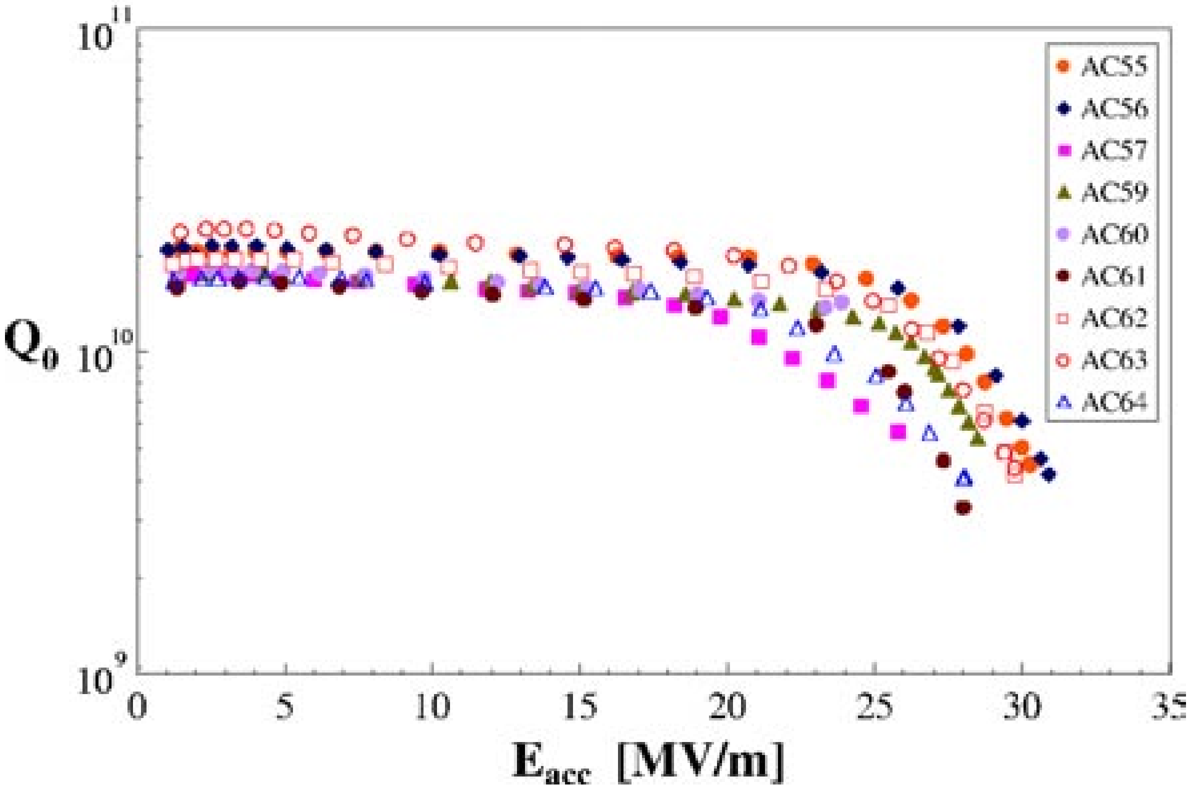
Theoretical Hc limit, inclusions, dust-particles, resistive regions

Results of TESLA cavity productions

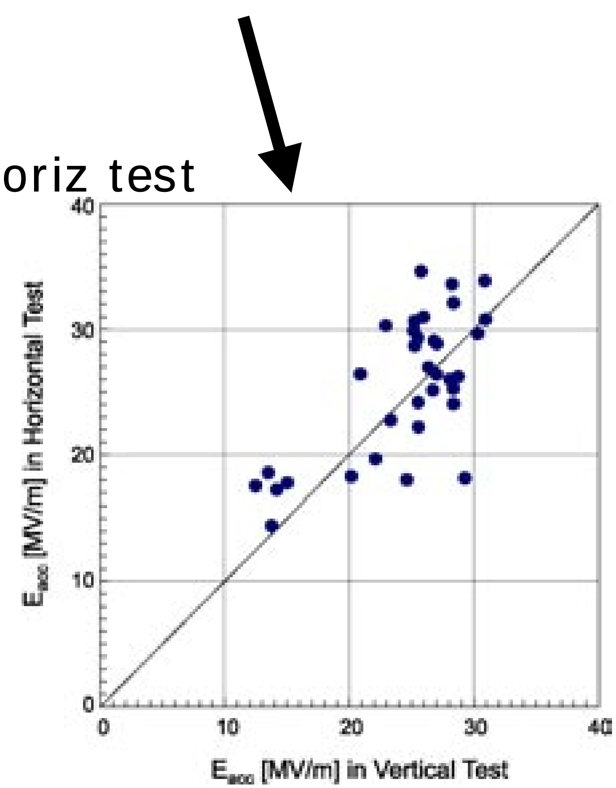


3rd production of TESLA-type nine-cell cavities
BCP preparation

Good correlation between initial Vertical test dewar cw Eacc of" bare" cavity and - Horizontal test dewar results of "dressed cavity" with helium vessel, input coupler, etc. Pulsed 1.3 ms



horiz test



vertical test

But is this the end?

Electropolishing

KEK found good results with electropolishing (EP)

Collaboration KEK, JLab, DESY, CERN, Saclay

(excellent example of international collaboration on SRF)

EP one cell cavities at CERN, EP multicell cavities KEK (Nomura Plating)

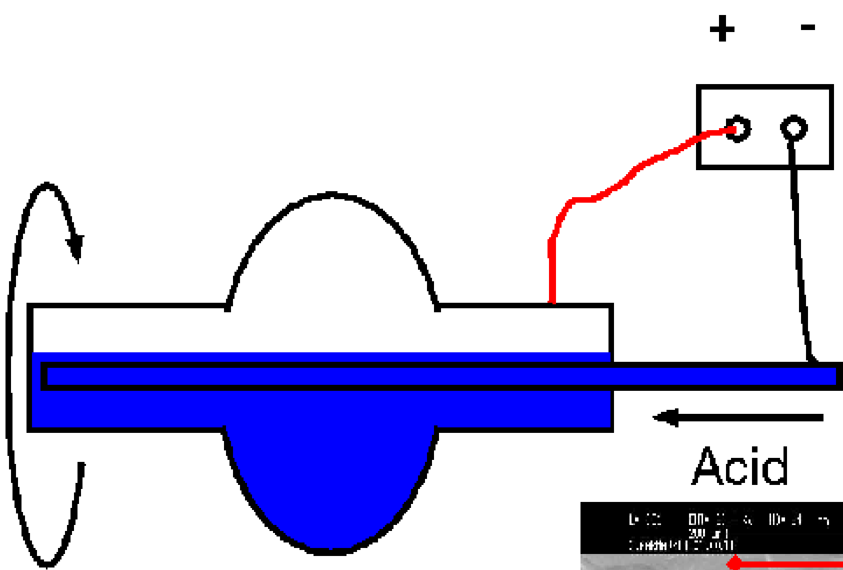
Electropolishing done after initial BCP and HT(heat treatment) 1400 or 800C

cavities are then baked 120 C

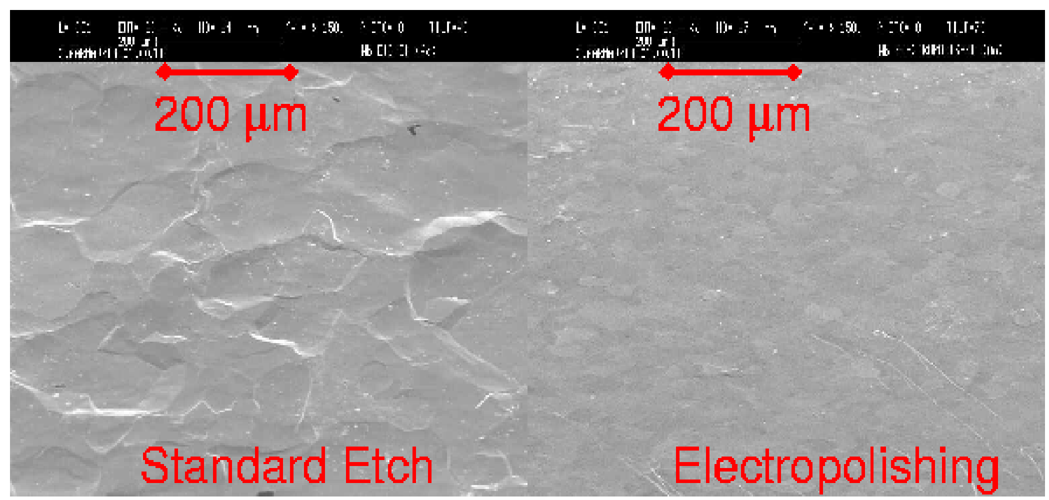
Results from 3rd production

will 35MV/m be achievable ?

Electropolishing of 1-cell cavities (Scheme)



- EP electrolyte
- 90 % H_2SO_4
- 10 % HF
- 30 °C
- 0,5 µm/min removal of material



Smooth Surface BUT probably more!

1 cell cavities

L Lilje

Before bake

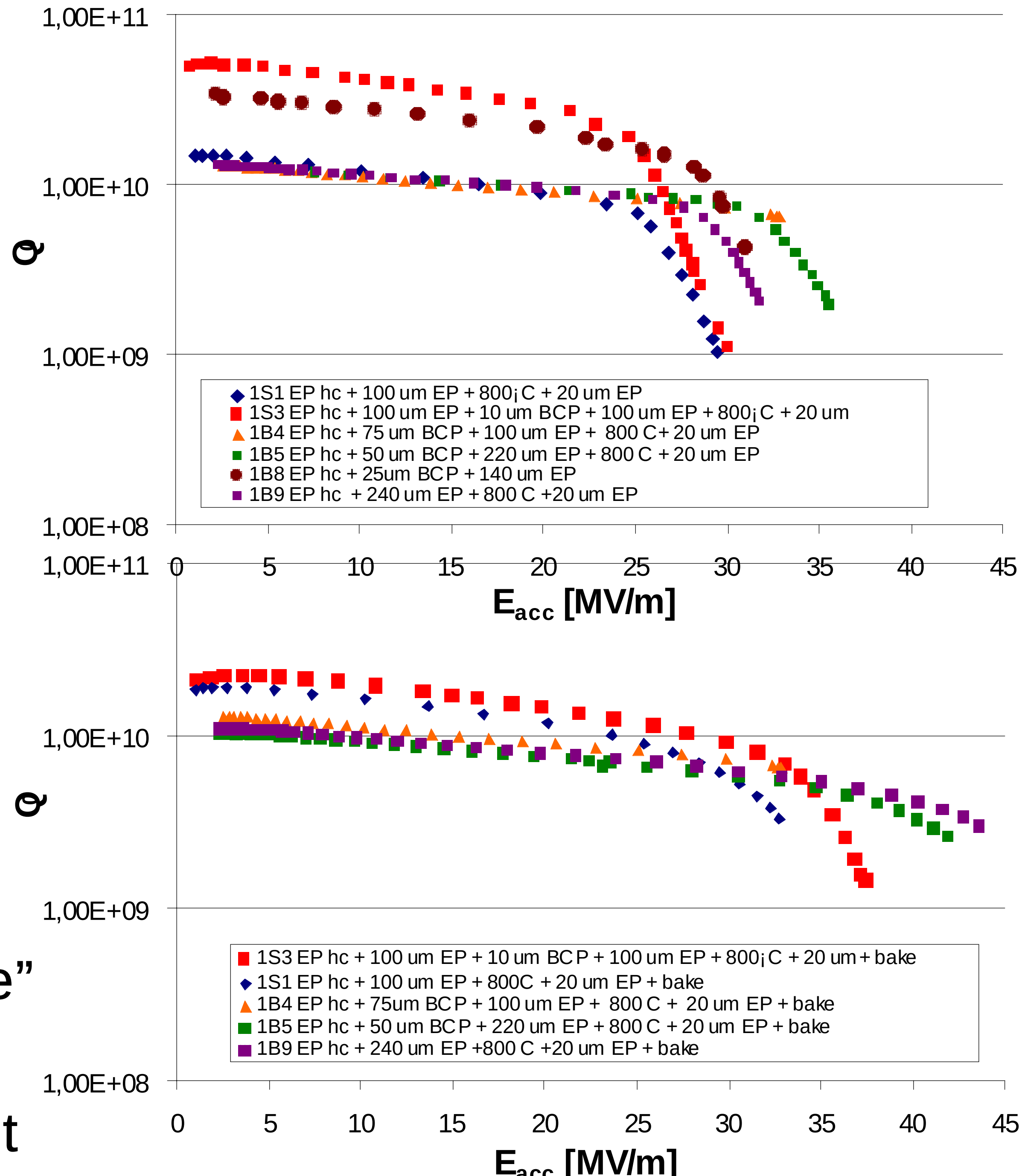
(power limited)

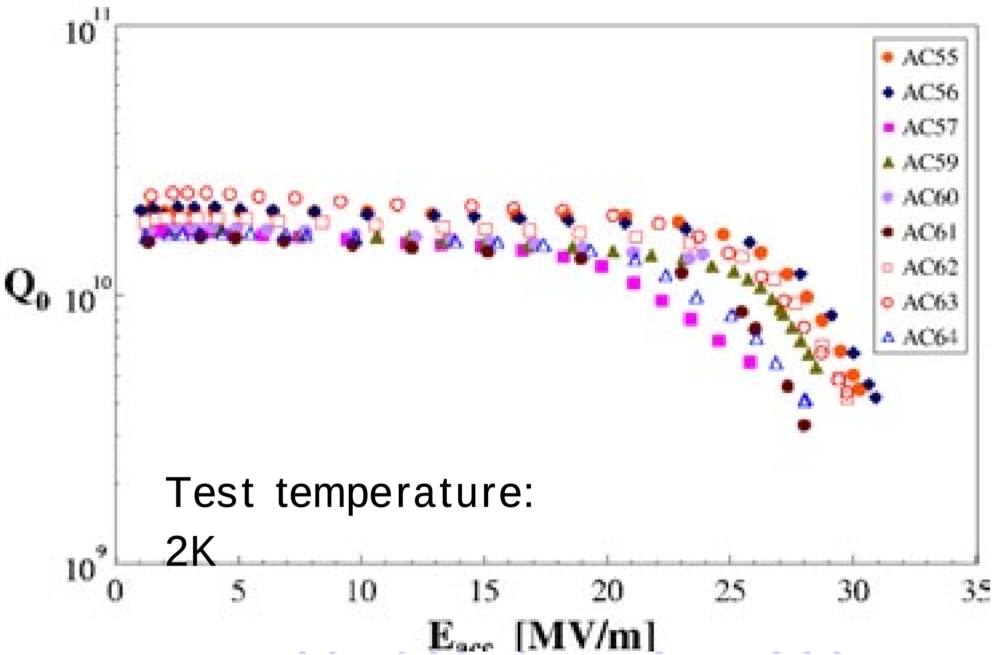
Strong Q slope without field emission

After bake

(thermal breakdown)

Effect of 120C “bake” on EP cavities plus 800C Heat treatment



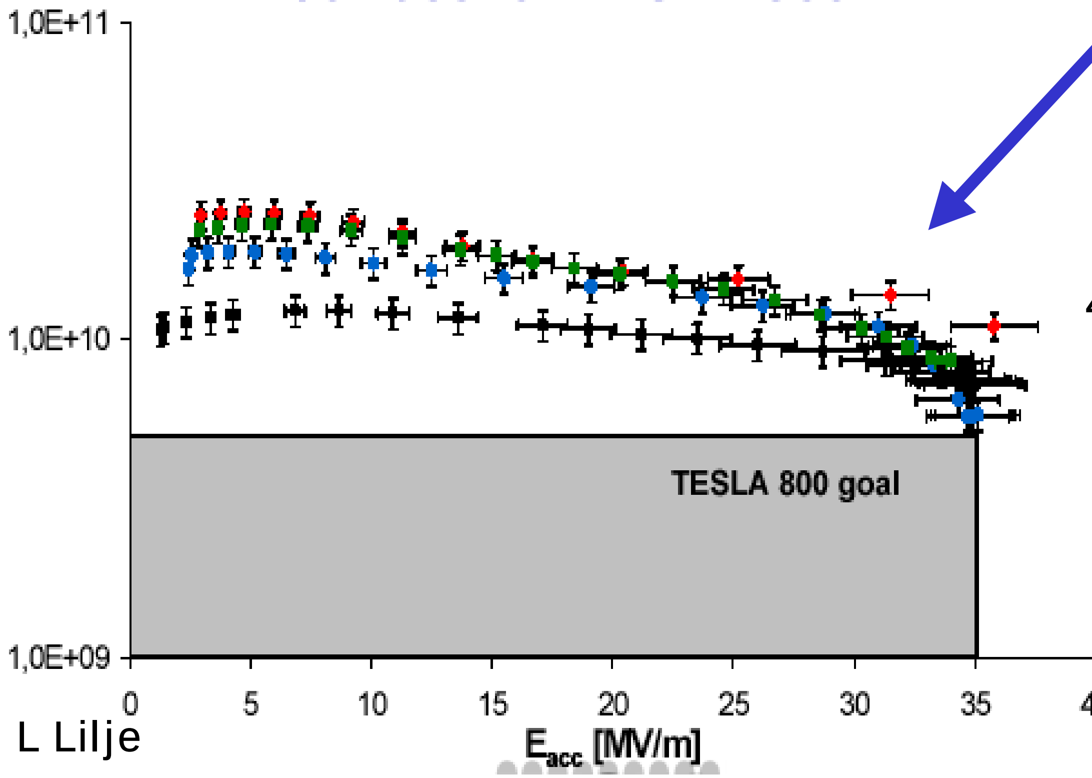


TESLA nine-cell cavities- 3rd Production

BCP chemistry

Some First Results of electropolished (EP) 9 cell cavities

1st EP results



4 cavities @ 34-35 MV/m
out of 9 tested

L Lilje

Recent Activities in other Areas

R&D- Nb sputtered on Cu cavities (like LEP)

Nb - Cu clad

Motivation- cost reduction, less Nb material, important for low frequency cavities, or large projects

Cavity hydroforming without equator welds

New Directions and SRF Applications

HEP- TESLA LC, Neutrino Factory, LHC, KEKB, Cleo, CKM

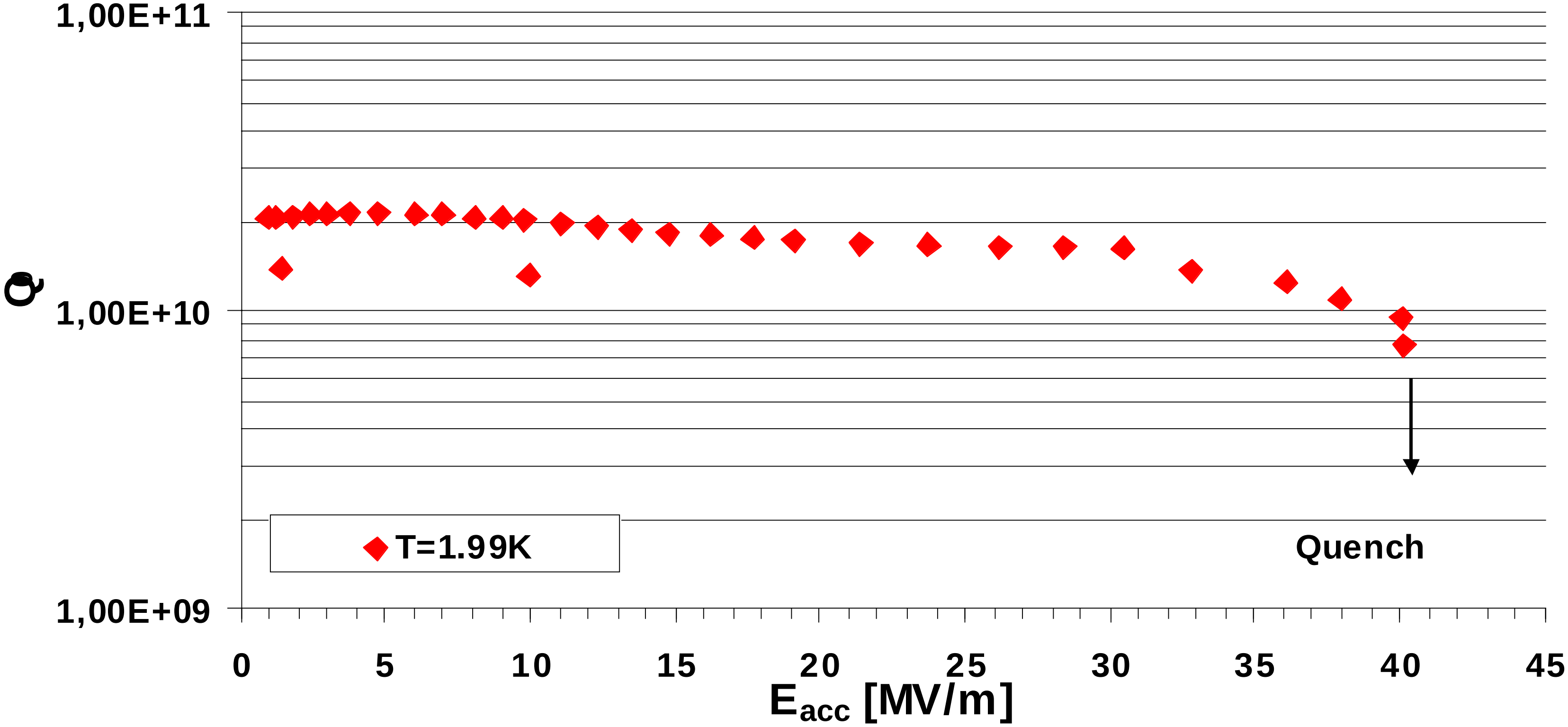
NP- CEBAF Upgrade, RIA

Neutrons-SNS,

Light Sources- TESLA XFEL, FELs, ERLs

Etched Nb/Cu clad cavity hydroformed

- NbCu clad single cell cavity 1NC2 produced at DESY by hydroforming.
- Preparation and HF tests at Jeff. Lab.
- 180 µm BCP, annealing at 800 C, baking at 140 C for 30 hours, HPR.



Kneisel & Singer

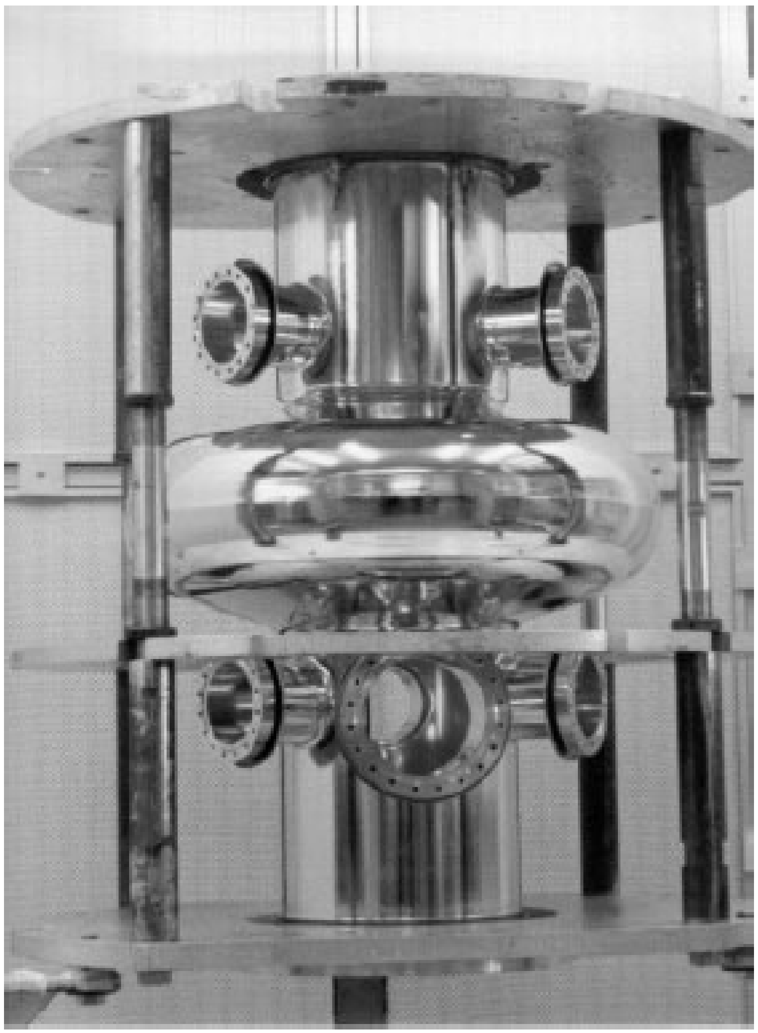
LHC (produced by Accel)

400MHz, single cell, 16cavities

active length, 0.375m

Specifications Eacc 5MV/m, Q 2e9 @4.5K

21 cavities delivered above spec



SRF99_WEP016

Bauer et al

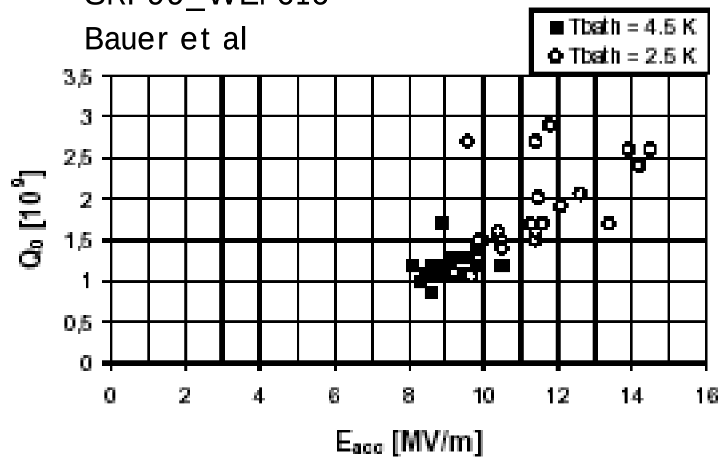


Figure 3: Highest gradients E_{acc} and quality factors Q_0 at the highest gradients achieved at bath temperatures of 4.5 K and 2.5 K in the LHC 400 MHz single cell

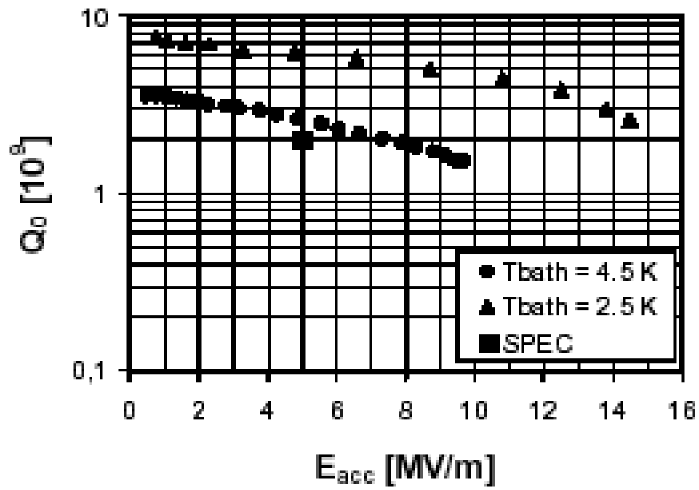
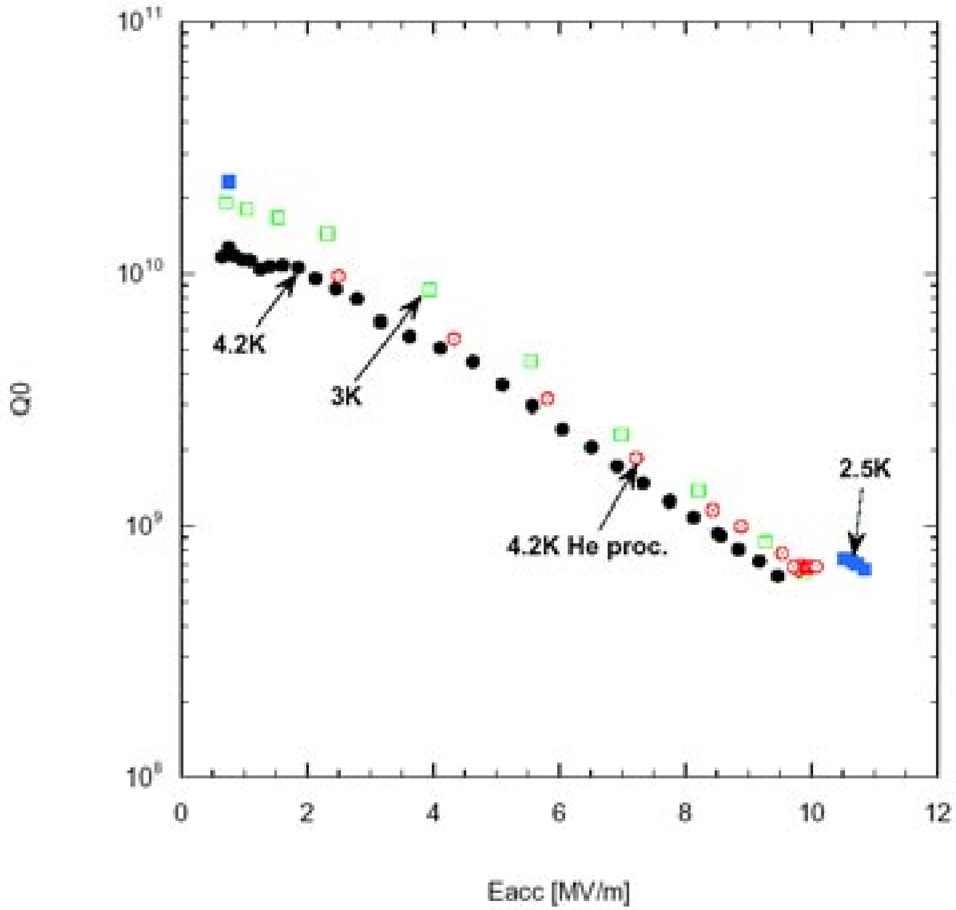


Fig. 4: Performance of cavity A11 at 2.5 K and 4.5 K bath temperature.

200 MHz Cornell CERN Muon Cavity 1st test

Extend SRF to large scale cavities fabrication methods, (need ~600 cells)

Nb sputtered on Cu, Eacc~11MV/m, goal17MV/m



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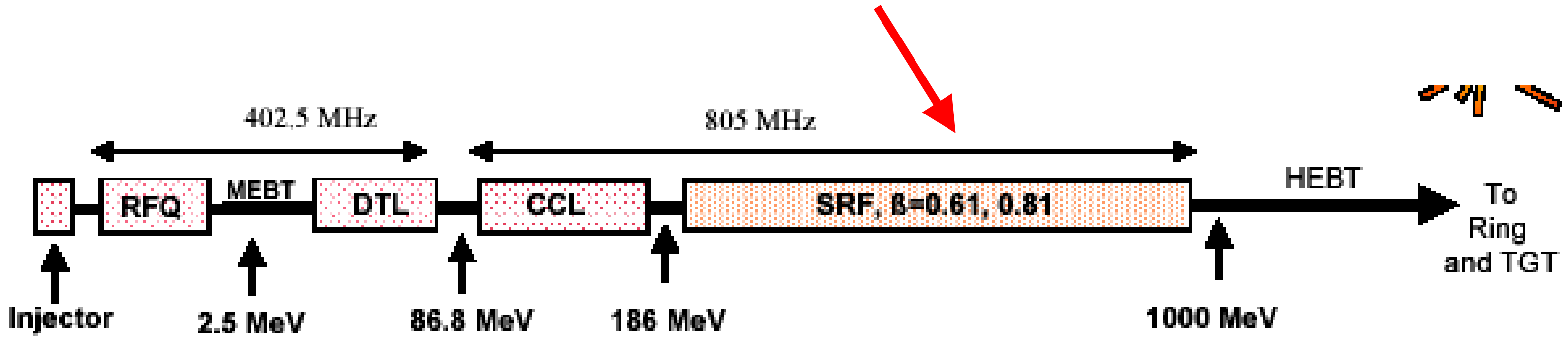
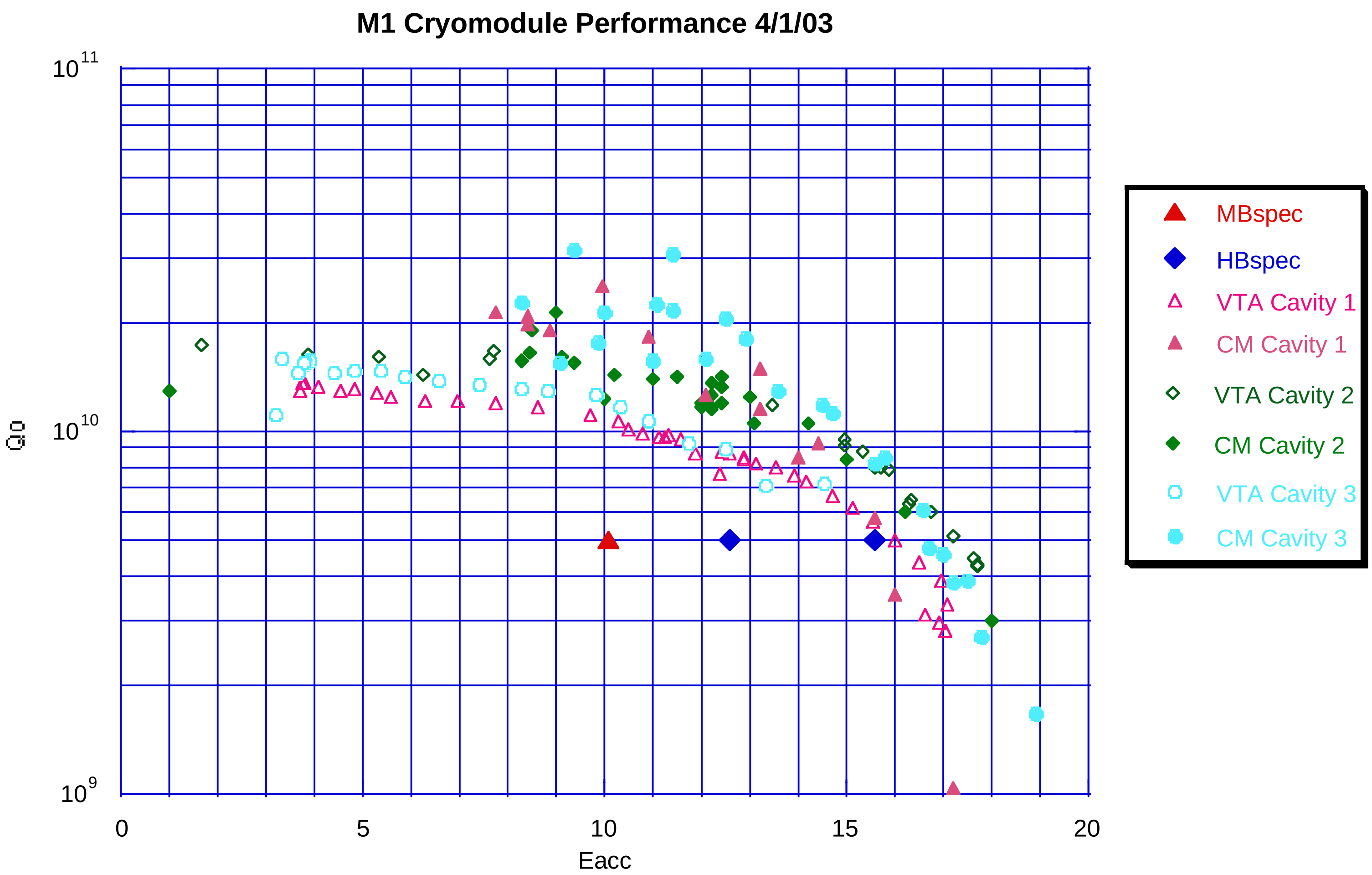
SNS H^- linac SRF 800MHz 186-1000MeV



β= 0.62, 0.81

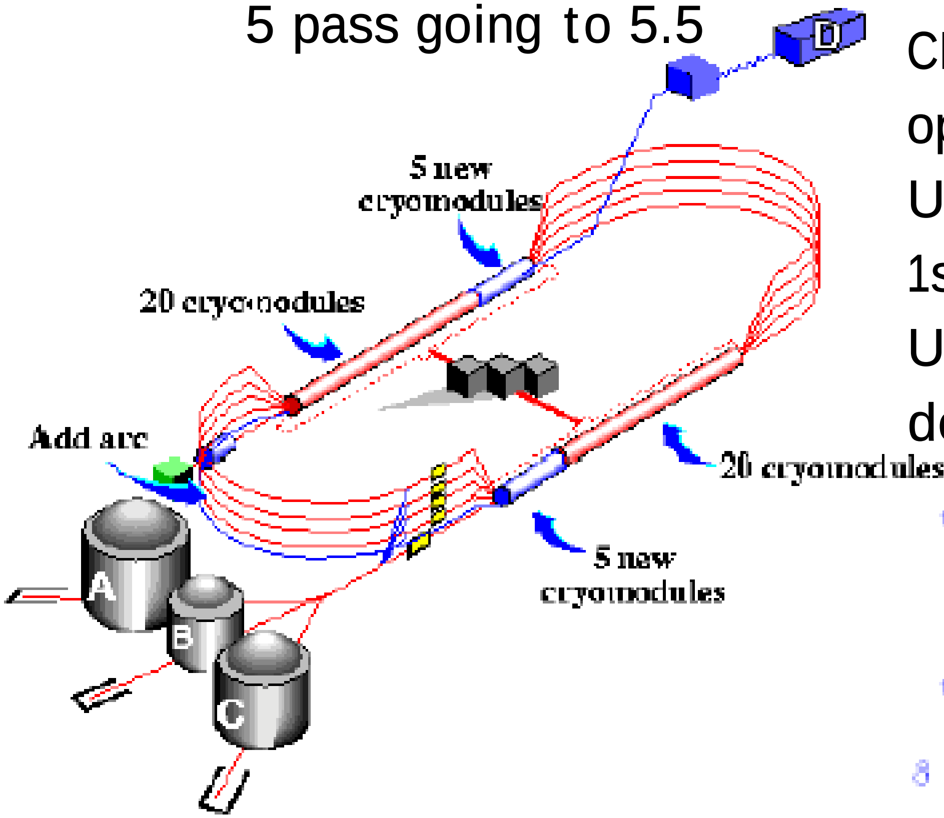
SNS Medium beta cavity tests
first cryomodule tests, 3 cavities



C Rode

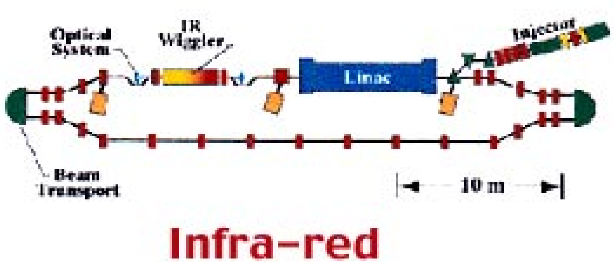
CEBAF 12GeV Upgrade

5 pass going to 5.5



CEBAF designed 4GeV
operates @ 5.7 GeV (6.9MV/m)
Upgrade “70MV modules” 12.6MV/m,
1st 8 cav mod just installed
Upgrade “100MV modules” 19.2MV/m
development underway

TJLab ERL FEL Upgrade 10kW



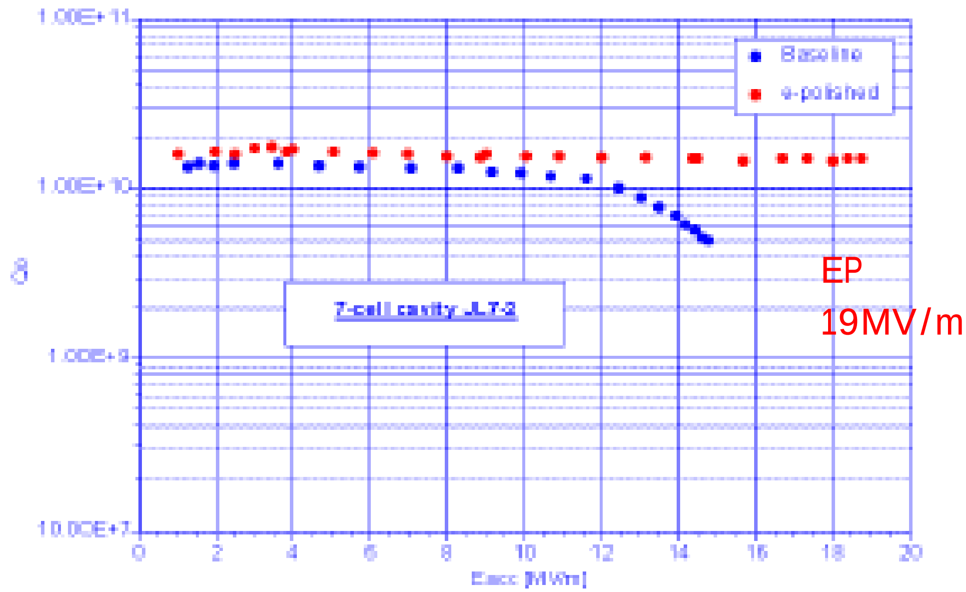


Figure 4 Performance of a cavity that was chemically processed (blue) and electro-polished (red)

RIA low β spoke cavity

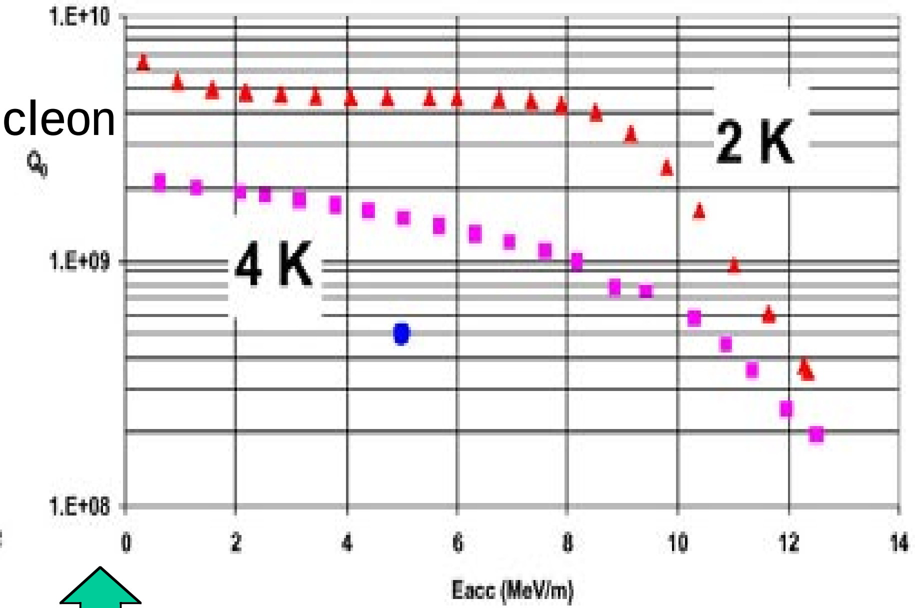
Rare Isotope Accelerator 400MeV/nucleon

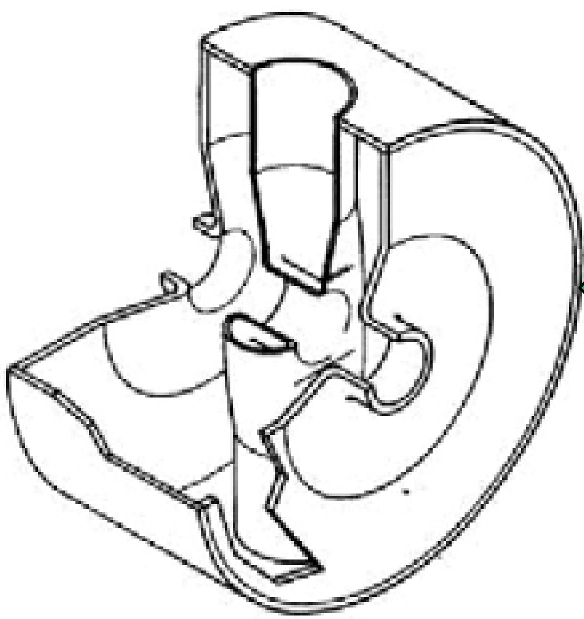
β ~ 0.3- 0.4

LANL/ANL

Consider adopting spoke design as baseline from RFQ to 100 MeV

Use superconducting spoke resonators in place CCDTL.

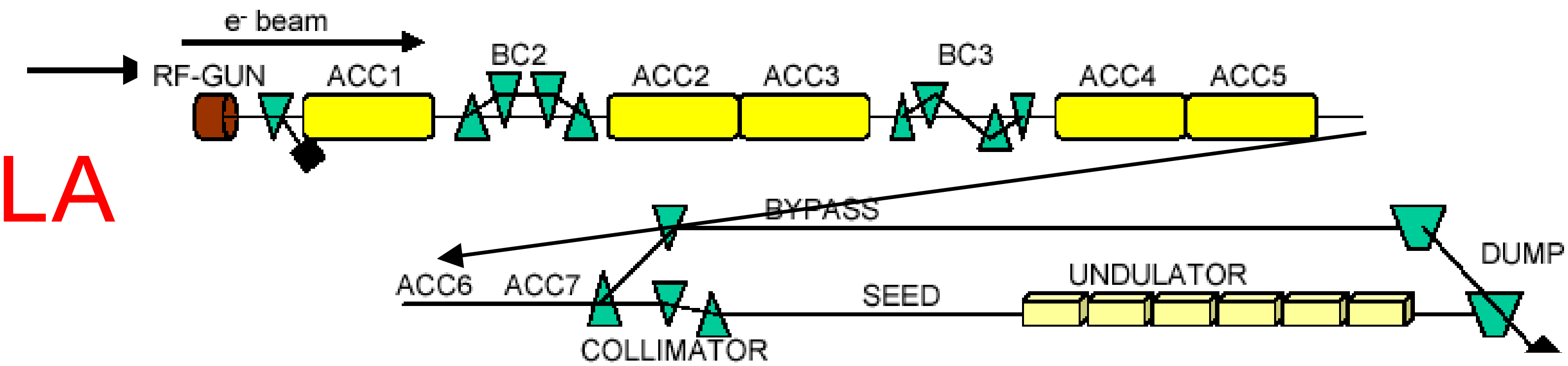




Padamsee

TTF I I

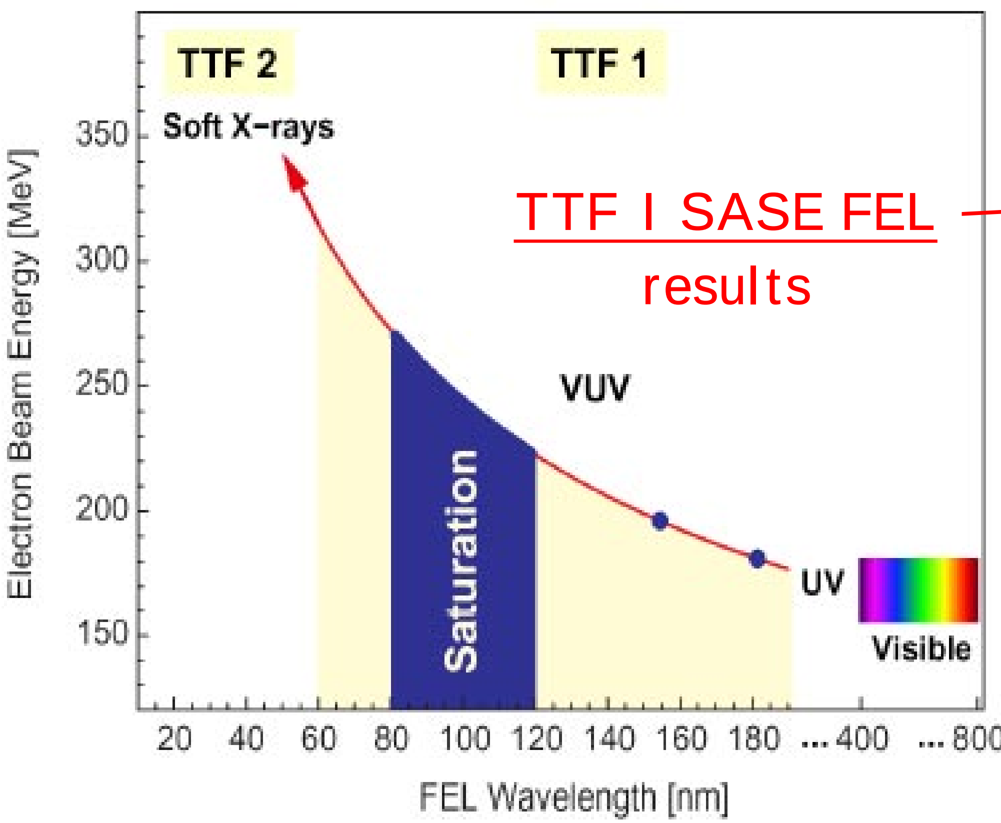
TESLA

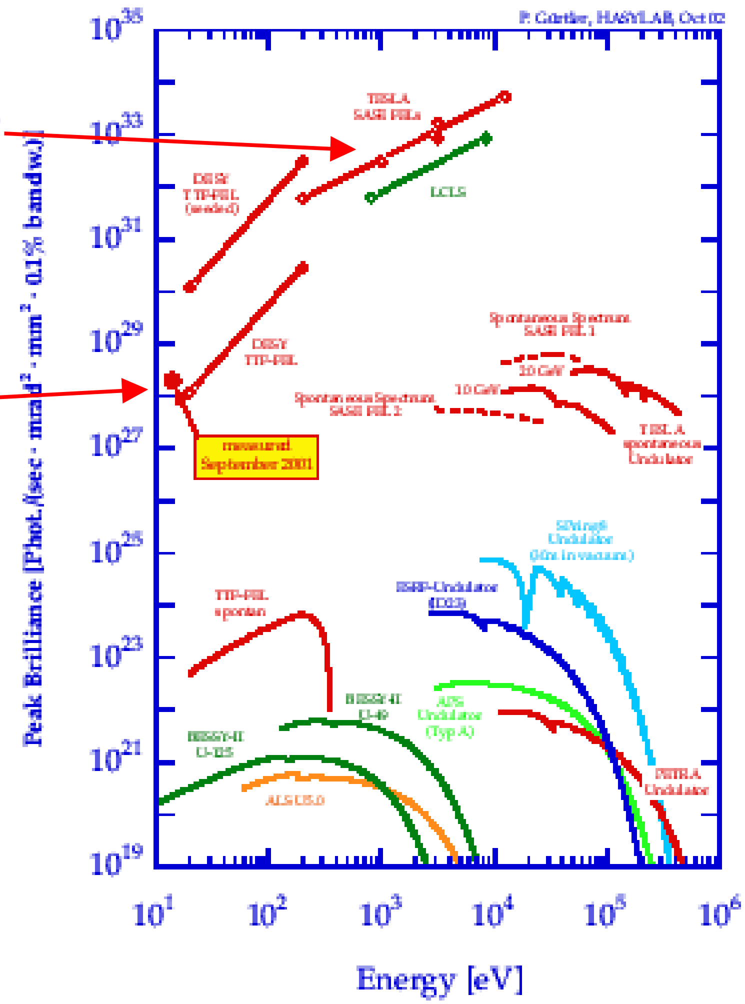


TESLA TTF I I to 6nm

TESLA X FEL to 0.1 nm (10-20GeV)

TTF I SASE FEL results





DOE next 20-year road map reports (scrf technology)

BES-basic energy sciences

SNS - power upgrade to 3MW

"Greenfield" XFEL (beyond LCLS)

ACNS - Acc based Continuous Neutron Source (BNL) 10MW

1.25 GeV sc proton linac

LUX -Linac-based Ultra-fast Xray-(LBL) sc recirculating linac

crosscutting issues- ERLs (Energy recovery linac)

NP-nuclear physics

RIA Rare Isotope Accelerator 400MeV/nucleon

CEBAF 12 GeV Upgrade

HEP-high energy physics

LC Cold or Warm?

CKM "Charged Kaons at Main Injector"

Neutrino Super Beam - Proton Driver (warm or cold BNL or FNAL)

Neutrino Factory

NSF proposals

Cornell ERL

MIT-BATES X-ray laser (4GeV linac)

Conclusions

The TESLA R&D program has been a model of concerted R&D

It has been dramatically successful at pushing the gradient of superconducting cavities to a level required for Linear Collider application

Superconducting RF systems of the 90's have demonstrated remarkable reliability, and operability at limits in excess of design

Superconducting RF has become a major enabling technology for accelerator projects of the future

There is still more work and more to understand