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 ...

<table>
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<th>Nbr. of cav.</th>
<th>MHz</th>
<th>m</th>
<th>MV/m</th>
<th>MV</th>
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<td>3000</td>
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<td>LEP</td>
<td>12</td>
<td>352</td>
<td>20.4</td>
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</table>

and others....
CEBAF with an ongoing 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

Figure 3: Histogram of cavity gradient distribution for three different maximum beam energies in 1999 and 2000.
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 a 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
**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 800°C/ 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

(a) $\langle E_{acc}\rangle$ for $Q_0 \geq 10^{10}$

- Improved welding
- Stricter niobium quality control

(b) Module performance in the TTF LINAC

TESLA-500
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
But is this the end?

**Electropolishing**

KEK found good results with electropolishing (EP)
Collaboration KEK, JLab, DESY, CERN, Saclay
(elegant 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 800°C

cavities are then baked 120°C

Results from 3rd production

will 35MV/m be achievable?
Electropolishing of 1-cell cavities
(Scheme)

- EP electrolyte
- 90% H₂SO₄
- 10% HF
- 30 °C
- 0.5 μm/min removal of material

Smooth Surface BUT probably more!

Standard Etch  Electropolishing
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
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, 16 cavities
active length, 0.375m
Specifications Eacc 5MV/m, Q 2e9 @ 4.5K
21 cavities delivered above spec

Figure 3: Highest gradients $E_{\text{acc}}$ 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.
Extend SRF to large scale cavities fabrication methods, (need ~600 cells)
Nb sputtered on Cu, Eacc~11MV/m, goal17MV/m
SNS H⁻ linac SRF 800MHz 186-1000MeV

$\beta = 0.62, 0.81$
SNS Medium beta cavity tests
first cryomodule tests, 3 cavities

M1 Cryomodule Performance 4/1/03
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 $\beta$ spoke cavity
Rare Isotope Accelerator 400MeV/nucleon
$\beta \sim 0.3 - 0.4$
LANL/ANL

Consider adopting spoke design as baseline from RFQ to 100 MeV

Use superconducting spoke resonators in place CCDTL.

Padamsee
TESLA

TESLA TTF II to 6 nm
TESLA X FEL to 0.1 nm (10-20 GeV)

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