Report on SRF 2003
- A Personal Selection-

P. Kneisel
11. Workshop on RF Superconductivity

- Location: Travemuende, Germany
- Time: September 8 – 12, ’03
- Participation: 212
- Institutions: 60, 17 from Industry
- Jlab Part.: 15
- # of papers/posters: 146
- Jlab Invited Talks: 9
- Jlab Contributions: 17

Oct. 10, ‘03
Topics

• Review of RF Superconductivity and sc materials
  Basics, material properties of Nb, fundamental limits, alternative materials

• Progress in performance of SRF cavities
  limitations by FE, MP, quenches, surface preparation, diagnostics…

• Technical issues
  couplers, tuners, microphonics, Lorentz force detuning, fabrication techniques.

• Operational aspects
  energy recovery, rf control, cryo-systems for CW, failure modes…

• Posters on laboratory activities

• Future developments
  proposals for new sc accelerators

Oct. 10, ‘03
Organization of Program

- Invited talks on current subjects
- Review talks
- Tutorials
- Working Groups
  - “Q – drop”, critical rf field
  - Medium beta cavities
  - Couplers, tuners
  - High gradient CW modules/ cryogenics
Outline

• Cavity Performance Issues
  Latest results, limiting fields, Q-drop, surface studies,
• Cavity Fabrication: seamless
• High Intensity Proton Sources
• Energy Recovery Linacs/FEL’s
• Superconducting Photo-Injectors
Cavity Performance Issues

- **High Gradients in Multi-cell Cavities** (L. Lilje, DESY)
- **Theoretical Critical Field for RF Application** (K. Saito, KEK)
- **Q – Slope at High Gradients** (B. Visentin, CEA Saclay)
- **Magnetic Susceptibility Measurements** as a tool to characterize Niobium for RF Cavities (S. Casalbuoni, DESY)
- **Study of Material Parameters in SC Cavities** (G. Ciovati, Jlab)
- **Performance of Seamless Cavities** (W. Singer, DESY)
Elliptical multi-cell cavities (L. Lilje)

- Since this discovery the SRF community concentrated on this shape for $\beta=1$ applications and is pursuing many different projects
  - high current storage rings
  - TESLA linear collider
  - synchrotron light sources
  - XFEL Driver Linacs
  - CW Linacs
- More recently, this cavity shape is becoming more attractive also for $0.47<\beta<1$
  - Protons (SNS, KEK/Jaeri, XADS/Eurisol, APT/AAA, Trasco)
  - Ions (RIA/MSU)
Preparation of niobium surfaces

• Typically 100-200 µm of damage layer are removed to obtain high gradients
  – etching is still the most commonly used method
  – electropolishing – due to the impressive results at KEK on single-cells – becomes more and more popular (for good reasons – see below)

• One major limitation of cavities is still field emission:
  – High pressure rinsing with ultrapure water is a necessity
  – Dust-free assembly with quality control is needed
Projects/Prototypes

• Beta < 1 Cavities
  • SNS (805 MHz, 6 cells, 0.61, 0.81, $E_{\text{peak}} = 27.5 - 35$ MV/m))
  • KEK/JAERI:J-Parc (600 MHz, 5-cells, 0.604, $E_{\text{peak}} = 40$ MV/m; 972 MHz, 9-cells, 0.725, $E_{\text{peak}} = 30$ MV/m)
  • Eurosol/XADS: 700 MHz, 5-cell, 0.65, $E_{\text{acc}} = 16$ MV/m)
  • RIA (805 MHz, 6 cells, 0.47, $E_{\text{peak}} >\sim 40$ MV/m)
TESLA:
Etched cavities

- All cavities from the last production
- AC67: test with He leak
- AC63: With EP

3rd Production - BCP Cavities

Oct. 10, '03
Nine-cell Cavities for TESLA-800

Oct. 10, '03

Oct. 10, '03
Results of Vertical Test (last Production):

- 6 out of 9 nine-cell cavities with $E_{\text{acc}} \geq 30\text{MV/m}$
- One cavity with 800°C only achieved 35 MV/m
- 2 cavities show early and strong field emission despite high pressure rinsing
- Preliminary: From T-maps done so far indicate that the quenches are not located at the equator
Overview on the high power test of an EP nine-cell

- Objectives of endurance test of the cavity
  - operate at maximum gradient for long time at 5 Hz, 500us fill, 800 us flat-top
  - demonstrate active detuning compensation using piezos
- Coupler and cavity processing went smoothly: 130 + 38 hours
  - heating of the coupler (standard in CHECHIA)
- Cavity has shown multipacting
  - resonant electron emission results in an avalanche
  - Xray emission at power levels corresponding to 20 MV/m disappeared after processing for a few hours (see below)
  - barrier is soft:
    • when the cavity is kept below some 100 K no new processing necessary
    • after warmup very short processing is needed (some minutes)
- Cavity performance measurements
  - 35 MV/m at 7*10⁹ stable, comparable to continuous wave test
  - max. gradient >36 MV/m
  - field emission observable only above 35 MV/m

Oct. 10, ‘03
High Power Test of an Electropolished nine-cell cavity

AC73 - Vertical and Horizontal Test Results

Oct. 10, ‘03
Single Cell Performances: \( E_{\text{acc}} \sim 40 \text{ MV/m} \)

KEK results for electropolished niobium cavities

K. Saito et al. KEK 1998/1999

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Critical Field for RF Application (K. Saito, KEK)

Experimental CW

Experimental, pulsed

Saturation around 40 MV/m (KEK)

RF critical measurement (Cornell)

Oct. 10, '03
Critical Field for RF Application (K. Saito, KEK)

Theoretical
There exists a solution (metastable) in the GL equation, which keeps the Meissner state up to a field $H_{sh} > H_{c1}$ (type-II) or $H_c$ (type-I). The field is called as superheating field.

Oct. 10, ‘03
Critical Field for RF Application (K. Saito, KEK)

Energy balance between nucleation of vortices and magnetic energy surrounding nc cores leads to (vortex line nucleation model)

\[ H_{SH} = \sqrt{2} / \kappa(T) * H_C \]

\[ \kappa = \frac{\lambda}{\xi} \]

**Nb:** \( \kappa (0) = 1.6 \quad H_{SH} \sim 180 \text{ mT}, E_{acc} \sim 40 \text{ MV/m} \)

**Nb_3Sn:** \( \kappa (0) = 7.4 \quad H_{SH} \sim 110 \text{ mT} \)

\[ f = f_{core} + f_{mag} = -\pi \xi^2 \frac{H_C^2}{8\pi} + \pi \lambda^2 \frac{H_C^2}{8\pi} \leq 0 \]
Q vs Eacc

Typical Q vs Eacc without “in-situ” baking for a “good” cavity

Oct. 10, ‘03
Excitation curves of bulk Nb cavities show 3 different “anomalous behaviors” in absence of field emission:
quality factor \Rightarrow strong degradation

- $E_{acc} > 20 \text{ MV/m}$ TTF cavities ($B_p > 85 \text{ mT}$)
- field emission not involved (no $e^-$, no X-rays)
- T map: global heating ($B_p$ max)
- limitation by RF power supply or quench
- seemingly a typical feature of BCP cavities

"European Headache" superiority of EP without Q-slope

K. Saito et al.
SRF '97
(Abano Terme)

(L. Lilje et al. - SRF '99 - Santa Fe)

(E. Kako et al. - SRF '99 - Santa Fe)
“Q – Slope” (B. Visentin, CEA Saclay)

- Q-slope is influenced by “in-situ” baking: diffusion of oxygen into Nb
- Change of material parameters and oxide-interface composition

\[ R_{BCS} = \frac{A\left(T, \frac{\varepsilon}{T}, \ell\right)}{T} e^{-\frac{\Delta F}{kT}} \]

\( R_{BCS} \downarrow (\text{baking time}) \Rightarrow \text{saturation} \)

**Graph:**
- Diffusion process (300 nm)
- \( R_{BCS} @ T = 4.2 \, K \)
- \( T_{\text{bake}} = 145^\circ C \)

**Figure:**
- ARXPS by A. Daccà INFN
- Change of the structure oxide after baking
  - \( \text{Nb}_2\text{O}_5 \downarrow \) and \( \text{NbO} - \text{NbO}_{0.2} \uparrow \)

( P. Kneisel - SRF '99 - Santa Fe )
“Q – slope”

Several models have been proposed to explain the Q-drop

- Field enhancement at grain boundaries (K. Knobloch et al)
- Interface tunnel exchange in Nb/oxide interface (J. Halbritter)
- Thermal feedback: $T$-dependence of $R_{BCS}$ (E. Haebel)
- Magnetic field dependence of energy gap (K. Saito)
- Granular Superconductivity: Grain boundary contribution to $R_{BCS}$ (B. Bonin, H. Safa)

- None of the models can explain all observed features of the Q-slope at high fields
- The “race” is on to explore the physics with surface studies and special experiments

Oct. 10, ‘03
Q – slope (G. Ciovati et al)

"H enhancement at grain bound." ⇔ "Interface Tunnel Exchange"

- Single cell cavity (BCP - EP - w/o Baking) excited in modes $\text{TM}_{010}$ or $\text{TM}_{011} : H_S$
- Two cell cavity $\text{TM}_{010}$ (0-π mode) : scan the surface (E, H)
- $Q_0$ (B_peak) - (BCP - EP - w/o Baking)
- Preliminary results:

(G. Ciovati et al. - PAC ’2003 - Portland)

Oct. 10, ‘03
Q – slope (G. Ciovati et al)
Results: Effect of Baking (G. Ciovati)

- T=1.37K
- T=2.2K
- T=2K
- T=2K, 120C 48hr bake
- T=1.37K, 120C 48hr bake
- T=2.2K, 120C 48hr bake

Oct. 10, ‘03
Superconductivity above $H_{c2}$ as a probe for Niobium RF-cavity surfaces

S. Casalbuoni, L. von Sawilski, J. Kötzler

Institute of Applied Physics and Microstructure Research Center
University of Hamburg

10.09.03 SRF2003

Oct. 10, ‘03
- Volume characterization
- Surface characterization: $\chi(H, H_{AC}, \omega, T) \Rightarrow H_{C3}$
  $\cdot M(H) \Rightarrow J_C$

- Conclusions
Surface Superconductivity (S. Casalbuoni)

Nucleation of surface superconductivity: $H_{C3}$

![Graph showing $\chi''$ vs $H$ and $\chi'$ vs $H$ for different samples.](image)

**Temperature variation of $H_{C3}$**

- BCP
- BCPbaked
- EP
- EPbaked
+ 100μm BCP

<table>
<thead>
<tr>
<th>$H_{C3}/H_{C2}$</th>
<th>BCP</th>
<th>BCPbaked</th>
<th>EP</th>
<th>EPbaked</th>
<th>BCPbaked + 10μm BCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{C3}/H_{C2}$</td>
<td>1.86(3)</td>
<td>2.16(3)</td>
<td>2.10(3)</td>
<td>2.57(2)</td>
<td>1.86(3)</td>
</tr>
</tbody>
</table>

$H_{C3}$ is increased by baking for EP and BCP
$H_{C3}$ is increased by EP
EP+baking gives the larger $H_{C3}$

Oct. 10, ‘03
Conventional cavity fabrication (TESLA shape)

Deep drawing a niobium disk into a half cell

Electron beam welding of a cavity. Iris welds (inside), equator welds (outside)

Well developed procedure
Seamless Cavities

Why seamless cavities?

• EBW can cause RRR degradation in weld and heat affected zone: highest H – field region
• Grain growth can lead to field enhancement at grain boundaries: “quench” and defects “bubbles”
• Reduced machining, chem. Cleaning, QA
• Faster manufacturing (8 hrs/9cell cavity)
• In principal accurate frequency adjustment
Spinning (Poster TuP26)

First spun 9-cell cavity

Spun 3-cell cavity

Spinning from tube

Spinning from disk

Oct. 10, '03
Waldemar Singer, 11th SRF Workshop, September 2003
Hydroforming

Combination of spinning with flow forming gives seamless tubes appropriate microstructure of and rather high strain before onset of necking.

Stress-strain curves and microstructure of Nb tubes produced by combination of spinning and flow forming. Tensile tests done in circumferential direction.

Seamless Nb tubes produced by combination of spinning and flow forming and multi cells produced from tubes.

Two and three cell cavities hydroformed at DESY.

Waldemar Singer, 11th SRF Workshop, September 2003
Distribution of the maximal accelerating gradients of etched and electropolished single-cell cavities (L.Lilje, SRF 2001).

The highest achieved accelerating gradient is the same for both versions (ca. 40 MV/m). Is the limitation the same for both versions? T-mapping of seam less cavity is missing, would help for understanding of the limitation mechanism.

Oct. 10, ’03

Waldemar Singer, 11th SRF Workshop, September 2003
Coextruded NbCu tubes (Poster TuP40)

Fabrication principle of sandwiched Cu-Nb-Cu tube

NSC-3: Barrel polishing, CP(10microns), Annealing 750°C x 3h, EP(70microns) by K.Saito

Cu-Nb-Cu Sandwichted Tubes (KEK)

Single cell NbCu cavities produced at DESY from KEK sandwiched tube.

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Waldemar Singer, 11th SRF Workshop, September 2003

E_{acc} of best sputtered NbCu cavities is <25 MV/m
Do we change the material properties by applying high pressure to the cavity?

High pressure device for cavity calibration. Pressure ca. 1 kbar

Oct. 10, ‘03

Waldemar Singer, 11th SRF Workshop, September 2003
High Intensity Proton Sources

HIPS applications

Many applications, both as standalone machines or as injectors:

- Spallation neutrons sources (pulsed power)
- Sub-critical nuclear reactor powering (avg power, reliability)
- Nuclear waste transmutation (“)
- Production of tritium (military applications) (avg power)
- Radioactive ion beams production (“)
- Neutrino factories (“)
- Production of radioisotopes for medical use (“)
- …

Possible significant impact in research but also in everyday life: increasing interest in large communities

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Oct. 10, ‘03
High Intensity Proton Sources

High Intensity Superconducting Proton Linacs

(HISPL from now on)

- $\sim 100$ keV
- $\sim 3\text{+}7$ MeV
- $\sim 80\text{-}400$ MeV
- $\sim 600\text{+}2000$ MeV

P RFQ-NC Low and Intermediate energy section High energy section-SC

NC-SC transition

The consolidated scheme of modern HIPS includes
- a proton ($H^+, H^-$) injector and a normal conducting RFQ
- a SC high energy linac with multicell, elliptical cavities
- A low and intermediate energy linac, either NC (DTL, CCL), SC (low-$\beta$ elliptical, spoke, half wave coaxial, reentrant...) or both

Although one is under construction and activity in the field is growing fast,

no HISPL exists yet!

A. Facco – SRF 2003

Oct. 10, ‘03
# High Intensity Proton Sources

## HISPL projects worldwide: High-β

<table>
<thead>
<tr>
<th>Linac</th>
<th>$E_p / E_{cut}$ MeV</th>
<th>$I_{peak}$ mA</th>
<th>duty cycle, %</th>
<th>Rep. rate, Hz</th>
<th>N.cav. (types)</th>
<th>rf freq. MHz</th>
<th>Notes</th>
<th>Status</th>
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<tbody>
<tr>
<td>SNS, USA</td>
<td>187 / 1000</td>
<td>26</td>
<td>6.25</td>
<td>60</td>
<td>81 (2)</td>
<td>805</td>
<td>H-</td>
<td>Construct. started operation 2006</td>
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<tr>
<td>ESS, Europe</td>
<td>200 / 1330</td>
<td>1114</td>
<td>6</td>
<td>50</td>
<td>137 (2)</td>
<td>704</td>
<td>H-p</td>
<td>Proposal</td>
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<tr>
<td>Concert, Europe</td>
<td>200 / 1330</td>
<td>114</td>
<td>6</td>
<td>50</td>
<td>137 (2)</td>
<td>704</td>
<td>H-p</td>
<td>Project Study (closed)</td>
</tr>
<tr>
<td>J-PARK, Japan</td>
<td>400 / 600</td>
<td>30</td>
<td>1.25</td>
<td>25</td>
<td>22 (1)</td>
<td>972</td>
<td>H-</td>
<td>Construction started R&amp;D</td>
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<tr>
<td>APT, USA</td>
<td>211 / 1030</td>
<td>100</td>
<td>100</td>
<td>CW</td>
<td>242 (2)</td>
<td>700</td>
<td>p</td>
<td>Project Study, R&amp;D (closed)</td>
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<td>ADT H.E., USA</td>
<td>109 / 600</td>
<td>13</td>
<td>100</td>
<td>CW</td>
<td>133 (2)</td>
<td>700</td>
<td>p</td>
<td>Proposal R&amp;D</td>
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<tr>
<td>XADS H.E., Europe</td>
<td>95 / 600</td>
<td>10</td>
<td>100</td>
<td>CW</td>
<td>88 (3)</td>
<td>700</td>
<td>p</td>
<td>Preliminary design Study, R&amp;D</td>
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<tr>
<td>TRASCO H.E., Italy</td>
<td>100 / 1000</td>
<td>30</td>
<td>100</td>
<td>CW</td>
<td>124 (3)</td>
<td>704</td>
<td>p</td>
<td>Project Study R&amp;D</td>
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<tr>
<td>EURISOL H.E., Europe</td>
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<td>5</td>
<td>100</td>
<td>CW</td>
<td>134 (3)</td>
<td>700</td>
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<td>SPL, CERN</td>
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<td>28</td>
<td>0.18</td>
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<td>92 (3)</td>
<td>805/1610</td>
<td>p</td>
<td>Proposal</td>
</tr>
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</table>

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Oct. 10, ‘03
High Intensity Proton Sources

HISPL projects worldwide: Low-β

<table>
<thead>
<tr>
<th>Linac</th>
<th>$E_{in}/E_{out}$ MeV</th>
<th>$I_{peak}$ mA</th>
<th>duty cycle, %</th>
<th>Rep. rate, Hz</th>
<th>Cavities N. (types)</th>
<th>rf freq. MHz</th>
<th>Notes</th>
<th>Status</th>
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<td>ADT F. L.E. USA</td>
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<td>13</td>
<td>100</td>
<td>CW</td>
<td>128 (3)</td>
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<td>XADS F. L.E. France</td>
<td>5 / 95</td>
<td>10</td>
<td>100</td>
<td>CW</td>
<td>96 (2)</td>
<td>350</td>
<td>p</td>
<td>Prelim. design study, R&amp;D</td>
</tr>
<tr>
<td>TRASCO F. L.E. Italy</td>
<td>5 / 100</td>
<td>30</td>
<td>100</td>
<td>CW</td>
<td>230 (1)</td>
<td>352</td>
<td>p</td>
<td>Prelim. design study, R&amp;D</td>
</tr>
<tr>
<td>SPES Italy</td>
<td>5 / 100</td>
<td>3</td>
<td>100</td>
<td>CW</td>
<td>113 (3)</td>
<td>352</td>
<td>p (d, Aνq=3)</td>
<td>Proposal R&amp;D</td>
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<td>0.1</td>
<td>2</td>
<td>44 (2)</td>
<td>160/320</td>
<td>p, d</td>
<td>Proposal R&amp;D</td>
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<tr>
<td>SARAF Israel</td>
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<td>2</td>
<td>100</td>
<td>CW</td>
<td>48 (2)</td>
<td>176</td>
<td>p, d</td>
<td>Under constr., operation 2008</td>
</tr>
</tbody>
</table>

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Oct. 10, ‘03
High Intensity Proton Sources

Low-$\beta$ cavities

- Short cavities, wide $\beta$ acceptance
- 1-2-3 gap cavity prototypes successfully developed by ANL, INFN Legnaro, LANL, IPN Orsay
- High power rf couplers not fully developed yet, as well as tuners

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High Intensity Proton Sources

Low-\(\beta\) Coaxial Half-Wave

- Developed first for heavy ion linacs
- Short real estate length, steering-free
- Alternative to QWRs and Spoke especially for \(150< f <350\) MHz

Dedicated prototypes for HIPS under development at INFN Legnaro, IKF Juelich, Accel

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High Intensity Proton Sources

4-gap SC cavities development
The Low-β zoo is still growing

- 4-gap cavities under development at ANL, INFN-Legnaro, LANL, IKF-Juelich
- Higher energy gain, lower velocity acceptance
- The 4-gap spoke was proposed in place of the the β=0.5 multicell

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Cavity/Structure Developments

- For $\beta$ – values $\gtrsim 0.5$, cavities with elliptical cross sections are still the preferred cavity type
- However, there is increasing interest in “spoke cavities” for intermediate $\beta$ – values and in the case of the ANL proposal for RIA the $\beta$- range for spoke resonators has been extended as far as $\beta \sim 0.7$, eliminating the need for SNS type elliptical cavities
- Developments of spoke resonators (single spoke to multi-spoke) are taking place at ANL, LANL, IPN, FZ Juelich
Cavity/Structure Developments

Elliptical Cavities: positive features

• Geometrically simple
• Familiar
• Large knowledge base
• Good modeling tools
• Low surface fields at high $\beta$
• Small number of degrees of freedom

Spoke cavities: positive features

• Compact, small size
• High shunt impedance
• Robust, stable field profile (high cell-to-cell coupling)
• Mechanically stable, rigid (low Lorentz coefficient, microphonics)
• Small energy content
• Low surface fields at low $\beta$
• Large number of degrees of freedom
Cavity/Structure Developments

Results

ANL $\beta=0.3$ and $\beta=0.4$ Prototype Spoke Cavity Results

Argonne, Spring 2001

Los Alamos, Spring 2001

Argonne Result $\beta=0.4$ cavity

Los Alamos Result $\beta=0.3$ cavity

Oct. 10, ‘03
Results (LANL)

The two cavities EZ01 and EZ02 achieved $E_{acc} = 13.5$ MV/m and 13.0 MV/m, exceeding the AAA goal of 7.5 MV/m.

Repeated cleaning of EZ02 improved the performance (red square).

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Jan/Feb 2003

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Oct. 10, ‘03
Results (IPN)

IPN Orsay $\beta=0.35$, 352 MHz Spoke resonator

Fault tolerant Spoke cavity Linac:
- 5–80 MeV
- 84 cavities: 30 $\beta=0.12$ and 54 $\beta=0.35$
- Cavity aperture 60 mm
- Superconducting quadrupole doublets
- SC Linac length: 91 m
- Possible injector for XADS

Oct. 10, '03
High Intensity Proton Sources

The first HISPL: SNS

- SNS is a DOE-BES multi-lab construction project to create the world’s leading neutron-scattering science facility at ORNL

- SNS is Constructed by Six US-DOE-Laboratories: ANL, BNL, JLAB, LBNL, LANL and ORNL

- Cost: 1.4 B$

- SNS will be the first High Intensity Superconducting Proton Linac in operation from 2006

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High Intensity Proton Sources

Cryomodule Production at JLAB

Oct. 10, '03
High Intensity Proton Sources

EURISOL Driver
European Radioactive Ion Beam Facility Proton Driver

- Large international collaboration supported by the European Community
- French-Italian-German SC cavity technology
- 5 mA cw
- 1 GeV
- $P_{rf} \leq 50$ kW/cavity
- SC above 5÷85 MeV
- below 85 MeV few possible options

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High Intensity Proton Sources

5-cell cavities $\beta=0.65$

5 cells 700 MHz $\beta=0.65$
Superconducting Cavity (CEA-CNRS)

$Q_0$

$E_{\text{acc}}$ (MV/m)

Fast Cooling
Slow Cooling (LN2+LHe)
Slow Cooling (after H.T.)

(XADS goal: $1.10^{10} - 10$ MV/m)

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Oct. 10, ‘03
High Intensity Proton Sources

Conclusions

- The HISPL field is more active than ever with many laboratories involved.
- SNS in an advanced stage of construction, other projects are starting and new proposals are coming for new applications.
- High beta HISPL: the design is mature and all components developed.
- Low beta HISPL:
  - Different competing design schemes.
  - Linac design and cavities are in continuous positive evolution.
- New kinds of problems related to high power and reliability requirements must be faced: a lot to do and a promising future.

Thanks to M. White, T. Tajima, D. Schrage, H. Padamsee , R. Toelle, A. Ruggiero, P. Pierini and all people who helped me in preparing this talk.

A. Facco – SRF 2003

Oct. 10, ‘03
Challenges for Future Light Sources

Or: ERLs and FELs:
A Bright Future for Superconducting Cavities

Matthias Liepe
Cornell University
Today's Workhorse Light Sources: Storage Rings

- **1st generation**
  parasitic SR on high energy physics storage rings
- **2nd generation**
  dedicated bending magnet sources, designed for high flux SR
- **3rd generation**
  dedicated undulator sources optimized for brilliance, using high current, low emittance

Some rings use superconducting RF

Storage ring light sources give:
- Repetition rate
- Stability
- Tunability
- Polarisation
- High flux, brilliance – average/peak
... More Demands: What do we need in the future?

1. High average and high peak
   - Brilliance (photons/s/0.1% bw/mrad²/mm²)
   - Flux (photons/s/0.1% bw)

2. Coherence

3. Flexible pulse structure
   - Programmable pulse trains (interval, bunch size)
   - Adjustable pulse lengths down to the femtosecond regime

3. Small x-ray source size of desired shape, e.g. circular

4. Flexibility of source operation
   - No fill decay
   - Stability & robustness
   - Easily upgraded
Linac Light Sources: How to get high currents?

High Current Layout (SLS-ERL, FEL-ERL)

- High photon flux \(\Rightarrow\) need high current
- But: With a simple linac you’d go broke!!
- Example: 5 GeV * 100 mA = 500 MW

Solution: Use energy recovery. First proposed by M. Tigner in 1965.
RF Linacs: Why SRF?

SRF linacs can deliver beams of superior quality:

- Smaller emittance (lower impedance) ⇒ higher brilliance
- Better RF control and stability ⇒ lower energy spread
- CW operation at high gradient ⇒ flexibility in pulse train, lower impedance, cost saving

In addition, SRF gives

- Higher power conversion efficiency
- ERL option (very low wall losses) ⇒ high beam current, high flux
**ERLs: What is the trick?**

- Re-use energy of beam after SR generation.
- Recirculate beam and pass it through the linac a second time, but 180 deg. out of phase to decelerate beam.
- ⇒ “Energy Storage Ring” but not “Beam Storage Ring”.

- Emittance defined by source/gun (not ring equilibrium)
  \[ \varepsilon < 10^{-10} \text{ m rad} \text{ possible, close to diffraction limit} \]
- Small pulse length < 100 fs possible (not ring equilibrium)
- Potential for brilliance ≥ storage rings
- High beam current possible ⇒ high flux SR, high power FELs
- SC linac; RF power: independent of current
ERLs: It works!

- **JLAB FEL-ERL, 40 MeV, 5 mA:**

  X-ray Set-up
  - IR wiggler
  - Optical system
  - Dump
  - Linac
  - e⁻ recirculation beam line

- **CEBAF: First Energy Recovery Experiment at High Energy**

  Energy Ratio of up to 1:50 tested (20 MeV → 1 GeV)

  S. Chattopadhyay, G. Krafft et al.

Oct. 10, '03

CORNELL UNIVERSITY
Matthias Liepe 09/12/03
ERLs Worldwide (FEL-ERLs and SR-ERLs)

M. Tigner, 1965

SCA, Stanford, 1986

S-DALINAC, 1990
IR FEL Jlab, 1999
JAERI, 2002

Cornell ERL
LUX (LBL)
PERL (NSLS)
4 GLS (Daresbury)
ERLSYN (Erlangen)
KEK
CW Energy Recovery Operation of an XFEL
(J. Sekutowicz, A. Bogacz et al)
Challenges for ERL’s

• Generation and preservation of low emittance beams
cw gun, superconducting?

• RF and beam control
  small $\Delta E/E$
  high $Q_{\text{loaded}}$ – microphonics

• HOM damping
  Beam break up
  high current operation
  extraction of HOM’s with good cryo-efficiency

• CW operation
  high $Q$ – values at high gradients
  optimized mechanical design (stiffness, mech. resonances)
HOM Damping

- **Strong HOM damping**

- **High beam current:**
  - HOM power extraction at temperature with good cryo-efficiency
  - Beam stability limit

- **Short bunches (X-FELs):** Radiate at high frequencies up to THz
Short Bunches

- Especially X-FELs require to accelerate very short bunches (down to some 10 μm):

  ⇒ Higher loss factor:

  ⇒ Higher frequencies (up to THz):

  - Where is the high frequency RF power absorbed? (s.c. walls for f > 750 MHz; n.c. walls, e.g. tubes bellows, input coupler; RF absorber)

  - Best broadband absorber material?
Another possible application of superstructures

Energy Recovery Accelerators

What do we expect from a cavity operating in the ER mode?

2 beams pass through the cavity → good HOM’s suppression

“Small” amount of RF-power transferred to the beam from an external source → one FPC can serve bigger number of cells in a structure
Super-Structures (J. Sekutowicz)

Following this, three applications have been proposed:

1. 10 kW upgrade of the FEL at JLAB: $I_{beam} \sim 10 \text{ mA}$
   - 2x5-cell @ 1.5 GHz
     - MATBBU simulations showed that $I_{beam}$ threshold increased from 4 mA to 103 mA
   - 2x2-cell @ 0.75 GHz

2. Further upgrade of the FEL at JLAB: $I_{beam} > 500 \text{ mA}$
Achieving Strong HOM Damping

- Open beam pipes to propagate HOMs
- More loop couplers, waveguide couplers, broadband absorbers
- Smaller number of cells
- Superstructure concept
- ...
Cryogenic losses

- High gradient cw operation: dynamic head load dominates: Example: $20 \text{ MV/m}, Q_0 = 10^{10} \Rightarrow 40 \text{ W/m}$

- Module design:
  - Heat transfer through LHe
  - Mass transport of helium gas
  - HOM losses

- Cavity:
  - Design: Maximize $R/Q$ and $G$ for the accelerating mode
    \[ P_{\text{diss}} = \frac{V_{\text{acc}}^2}{R/Q \cdot G} R_S \]
  - Cavity treatment for high $Q_0$
  - Optimal bath temperature?
SC Photo-Injector Status (J. Teichert)

Motivation

4TH GENERATION LIGHT SOURCES
• high photon brightness
• short pulses
• high coherence

Photo-injectors $\varepsilon_{t,n}[2 \text{ mm mrad with } \text{cw – operation SRF-PI?}]

Energy recovery superconducting LINACs can provide the high quality e-beams with high average current

SOME PROJECTS:
4GLS, Daresbury, ERLSYN, Erlangen, MARS, Novosibirsk, PERL, BNL

Radiation source ELBE

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SC Photo-Injector Status

Superconducting Photo-Injectors

Main Advantage:

- low RF power losses & cw operation

Problems and Open Questions:

- Cavity contamination by particles sputtered from cathode (fast Q degradation, low gradient).
- Specific geometry of the SC cavity (cathode insert). Can we reach the high gradient?
- Operation of the photo cathode itself at cryogenic temperature.
- Not possible to do the emittance compensation like in a NC RF gun.
## SC Photo-Injector Status

### Summary

**Overview of the SRF-PI Projects**

<table>
<thead>
<tr>
<th></th>
<th>Peking Univ.</th>
<th>BNL</th>
<th>Rossendorf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>DC-SC Gun</td>
<td>All Niobium</td>
<td>NC Cathode in SC Cavity</td>
</tr>
<tr>
<td><strong>Cell</strong></td>
<td>1+1/2</td>
<td>1/2</td>
<td>1/2</td>
</tr>
<tr>
<td><strong>Cathode</strong></td>
<td>Cs$_2$Te</td>
<td>Laser-cleaned Nb</td>
<td>Cs$_2$Te</td>
</tr>
<tr>
<td><strong>Q.E. @262 nm</strong></td>
<td>0.01</td>
<td>5x10^{-5}</td>
<td>0.0025</td>
</tr>
<tr>
<td><strong>Contamination</strong></td>
<td>no</td>
<td>no</td>
<td>not found</td>
</tr>
<tr>
<td><strong>transv. emittance</strong></td>
<td>bad</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td><strong>Status</strong></td>
<td>cool down to 4 K</td>
<td>Q measured at 4 K</td>
<td><strong>operated at 4 K</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Project started (cavity design)</td>
</tr>
</tbody>
</table>

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**Radiation source ELBE**

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SC Photo-Injector Status

**SRF-PI: Peking Univ. DC-SC Photo-Injector**

- **Cavity:** Niobium ½ cell, TESLA Geometry
- **Cathode:** Cs$_2$Te (262 nm, 1 W laser) thermally insulated, LN$_2$ cooled


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**SRF-PI: Rossendorf SC ½ Cell Gun**

- **Cavity:** Niobium ½ cell, TESLA Geometry
- **Cathode:** Cs$_2$Te (262 nm, 1 W laser) thermally insulated, LN$_2$ cooled

B.C. Zhang et al., SRF Workshop 2001

**SRF-PI: BNL All-Niobium SC Gun**

- **Cavity:** No contamination from cathode particles
- **Cathode:** Maximum Field: 45 MV/m
- **Q.E. of Niobium:** @ 248 nm with laser cleaning:
  - before: $2 \times 10^{-7}$
  - after: $5 \times 10^{-7}$

T. Srinivasan-Rao et al., PAC 2003


**SRF-PI: Rossendorf 3½ Cell Gun Project**

- **Cavity:** Cooling insert
- **Cathode:** Helium tank

J. Stephan, D. Janssen, FZR, S.Krutikov, BINP
SC Photo-Injector Status
Proof of principle experiment at FZ Rossendorf

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Conclusion(1)

- **Proliferation of technology:** HEP to e-storage rings to low $\beta$ : proton machines, light sources, FEL, ERL’s, RIA, sc photo-injectors
- **Highlights:** $E_{\text{acc}} = 35$ MV/m, high Q, 9-cell cavity
  - ERL: prove of principle at Jab, new proposals
  - large variety of low beta sc structures
  - Nb dominant material for cavity application
  - EP for high cavity performance
  - strong interest in input couplers and cw cryostat designs

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Conclusion (2)

A”Dream”:

- 2005 Decision in favor of “cold” linear collider
- 2006 Approval of RIA project
- 2007 Construction start for X-FEL
- 2008 Approval of TESLA
- 2009 Approval of 5 GeV ERL

Next workshop 2005 at Cornell University
The sunset of this talk.
The sunrise of a bright future for s.c. cavities.