Report on SRF 2003

- A Personal Selection-

P. Kneisel

Oct. 10, '03

11. Workshop on RF Superconductivty

• 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

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

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

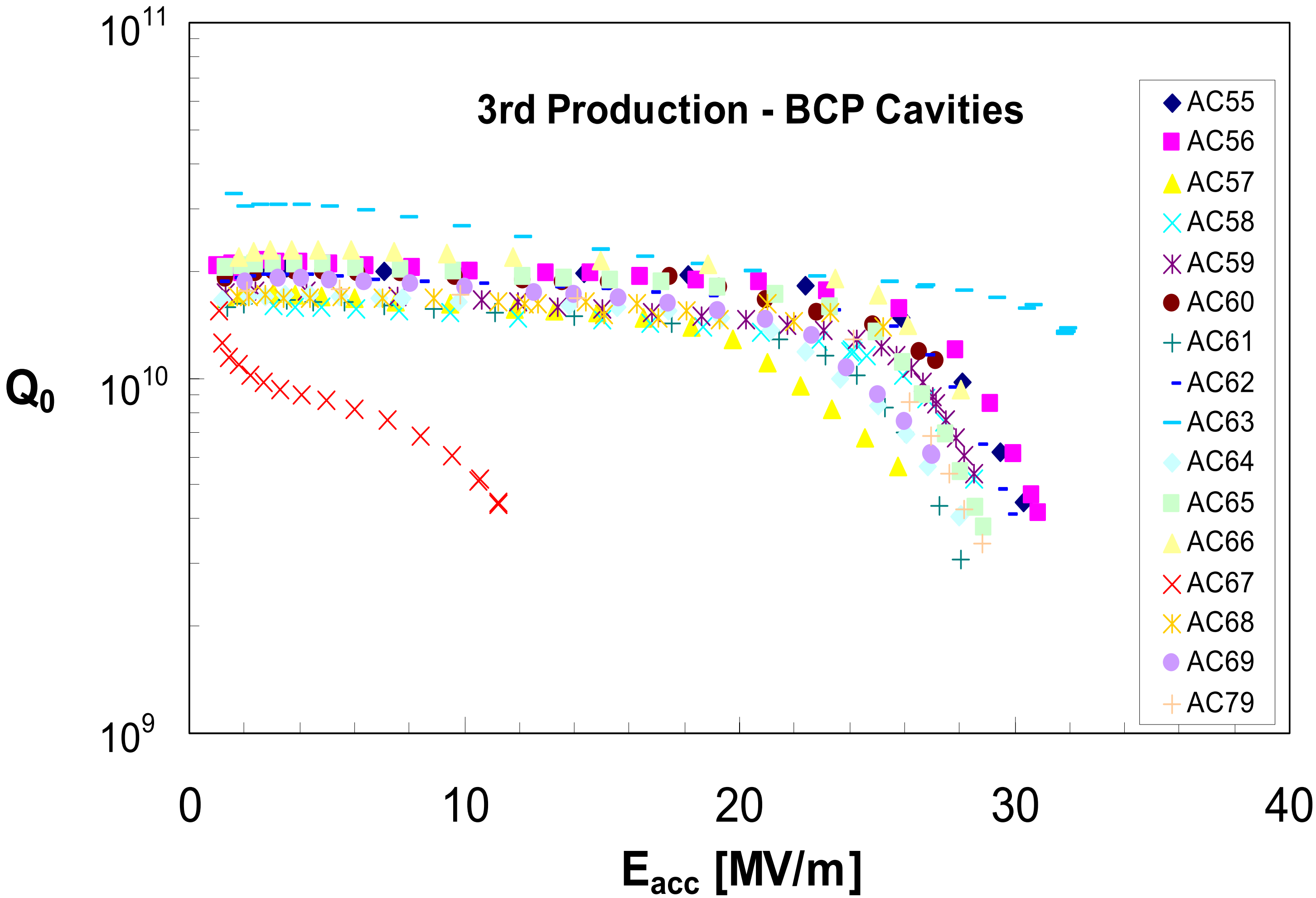
- Typically 100-200 μm of damage layer are removed to obtain high gradients
  - etching is still the most commonly used method
  - electropolishing – due to the impressive results at KEK on single-cells – becomes more and more popular (for good reasons – see below)
- One major limitation of cavities 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, Epeak = 27.5 – 35 MV/m))
  - KEK/JAERI:J-Parc (600 MHz, 5-cells, 0.604, Epeak = 40 MV/m;

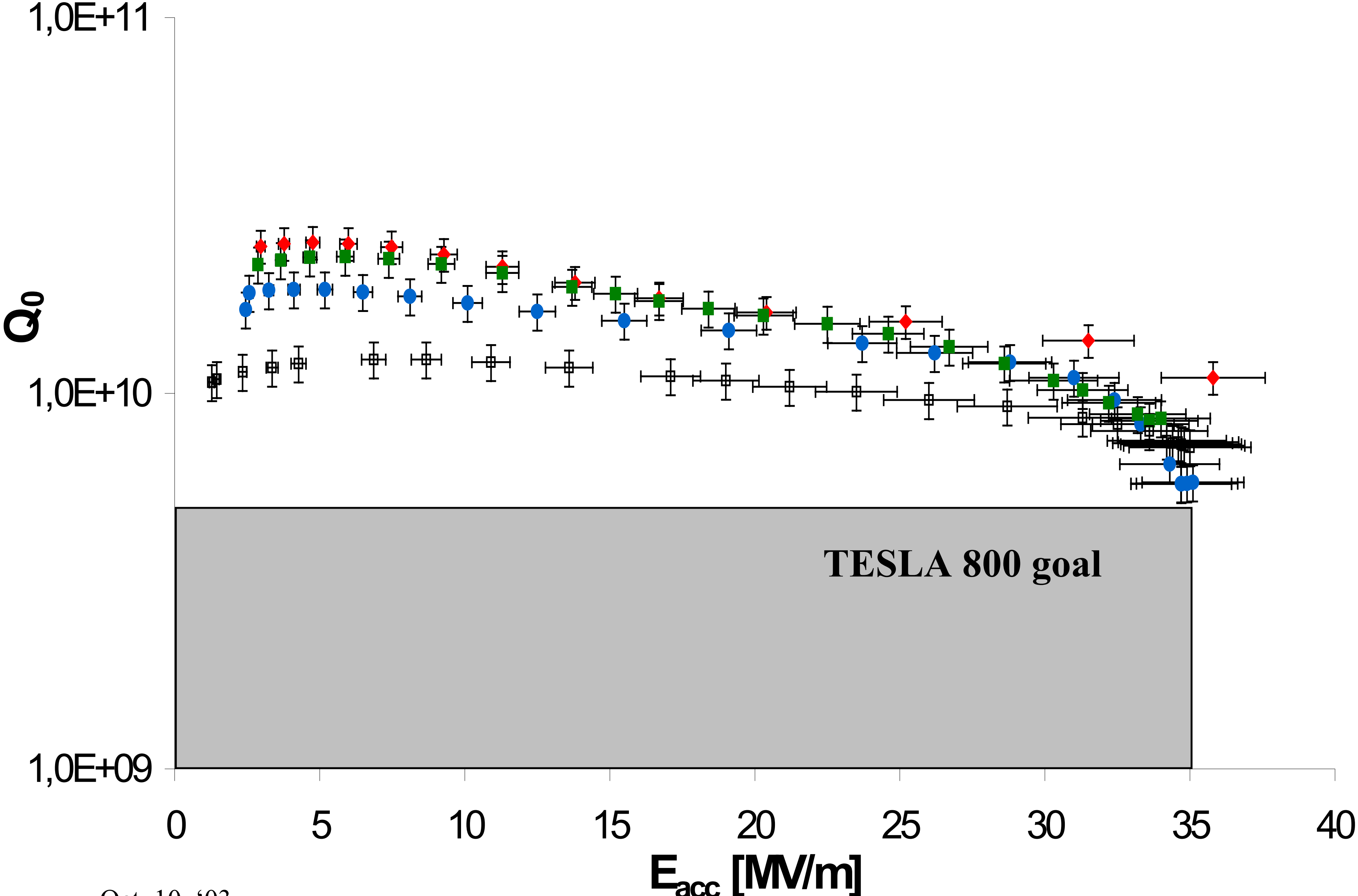
    972 MHz, 9-cells, 0.725, Epeak =30 MV/m)
  - Eurosol/XADS: 700 MHz, 5-cell, 0.65, Eacc = 16 MV/m)
  - RIA (805 MHz, 6 cells, 0.47, Epeak >~ 40 MV/m)

TESLA: Etched cavities



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

Nine-cell Cavities for TESLA-800



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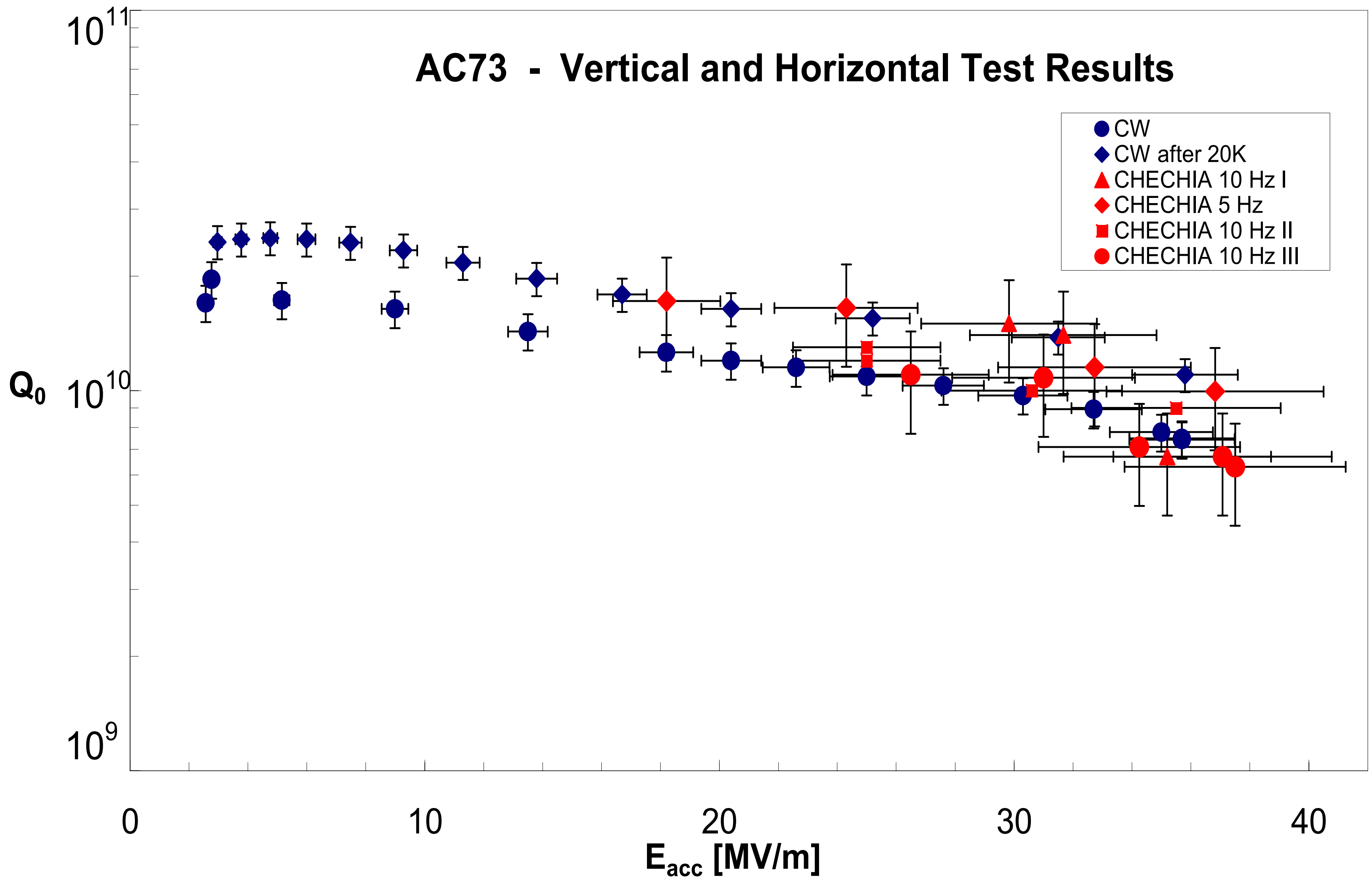
Results of Vertical Test (last Production):

- 6 out of 9 nine-cell cavities with $E_{acc} \geq$ 30MV/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 $7*10^9$ stable, comparable to continuous wave test
  - max. gradient >36 MV/m
  - field emission observable only above 35 MV/m

High Power Test of an Electropolished nine-cell cavity



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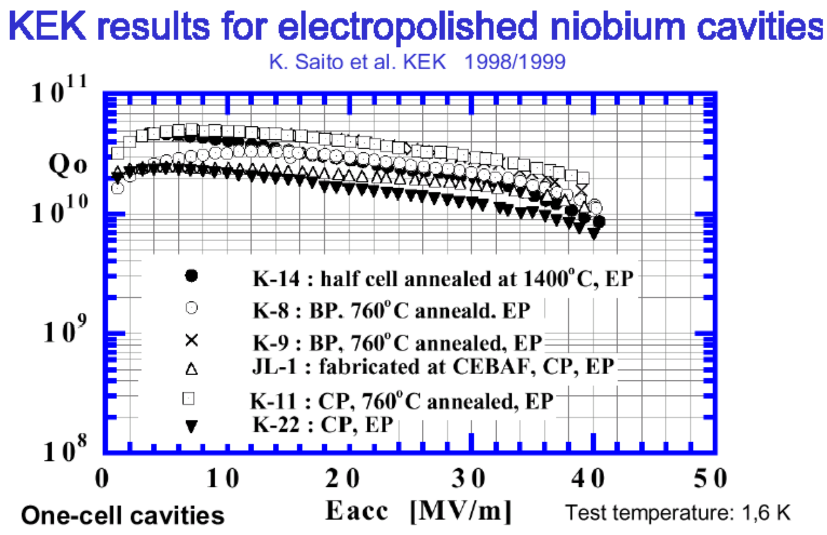
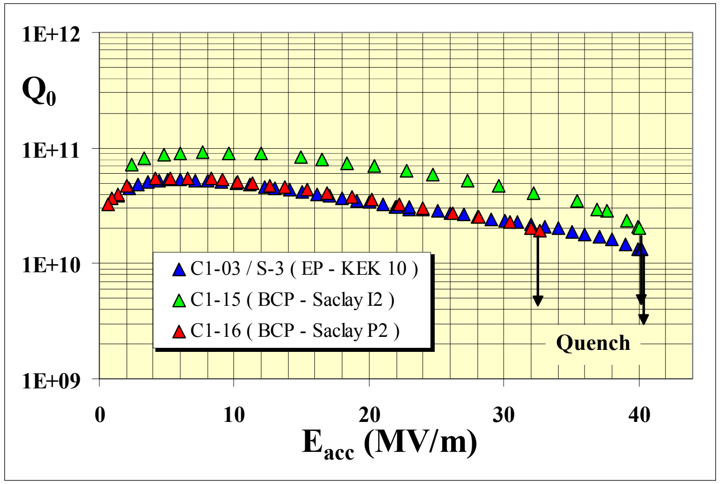
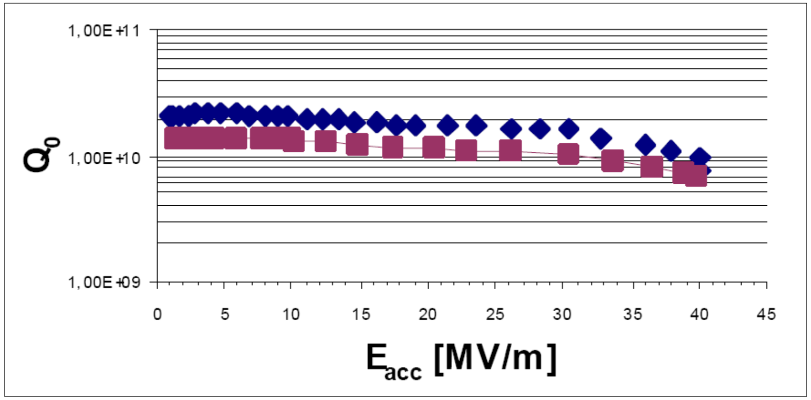
Single Cell Performances: Eacc ~ 40 MV/m







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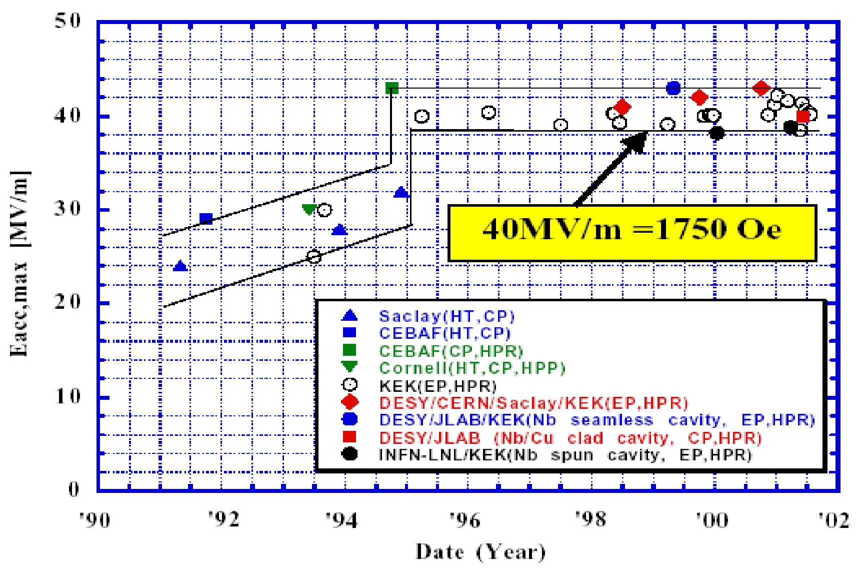
Critical Field for RF Application (K.Saito, KEK)

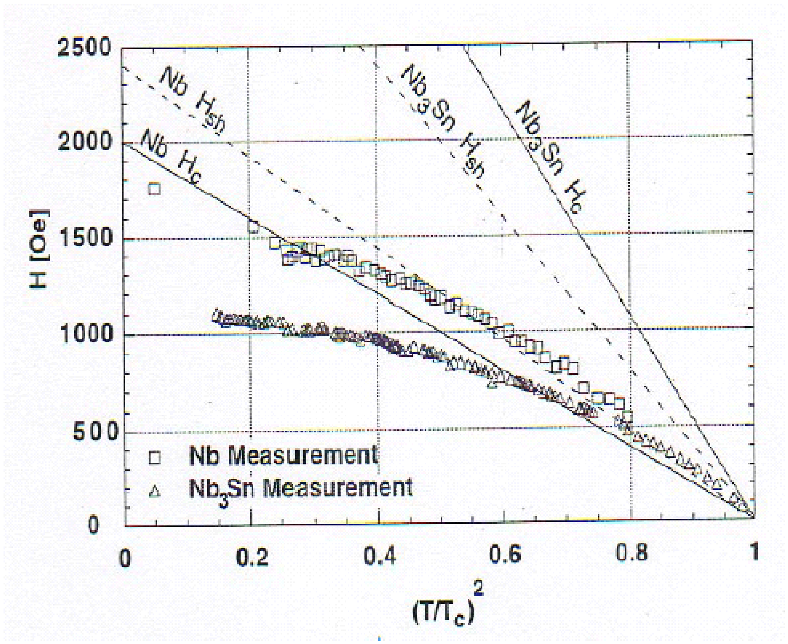
Experimental CW

Saturation around 40 MV/m (KEK)



Experimental, pulsed

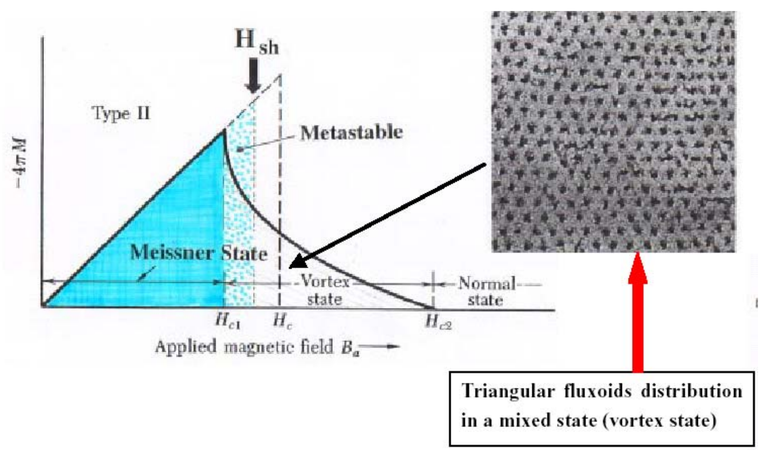
RF critical measurement (Cornell)

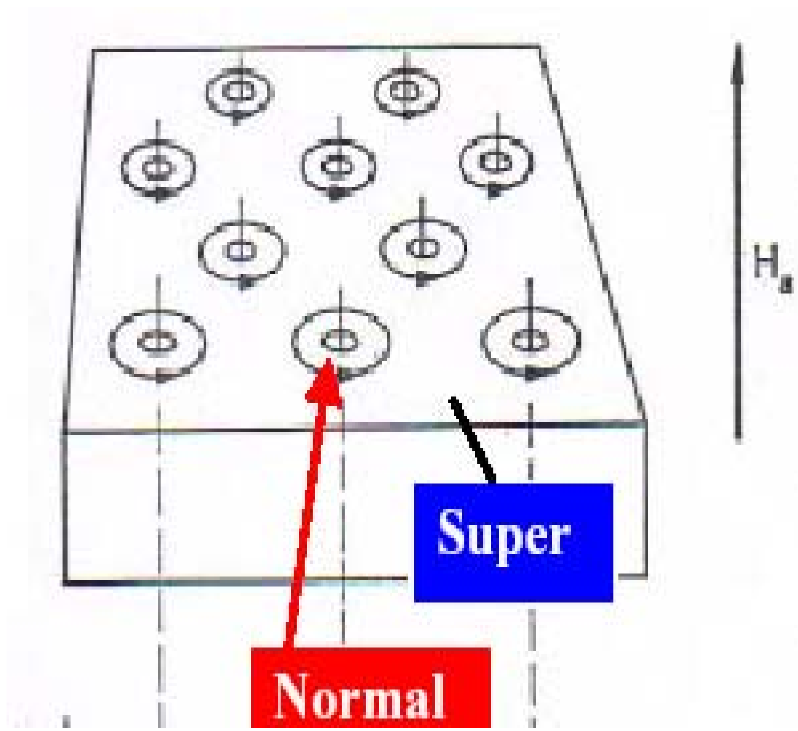


Critical Field for RF Application (K.Saito, KEK)

Theoretical

There exists a solution (metastable) in the GL equation, which keeps the Meissner state up to a field Hsh >Hc1 (type-II) or Hc (type-I). The field is called as superheating field.





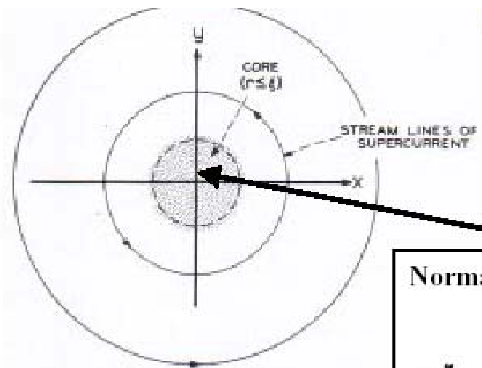
Critical Field for RF Application (K.Saito, KEK)

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

$$H_{SH} = \text{sqrt}(2)/\kappa(T) * H_C \qquad \kappa = \frac{\lambda}{\xi}$$

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

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



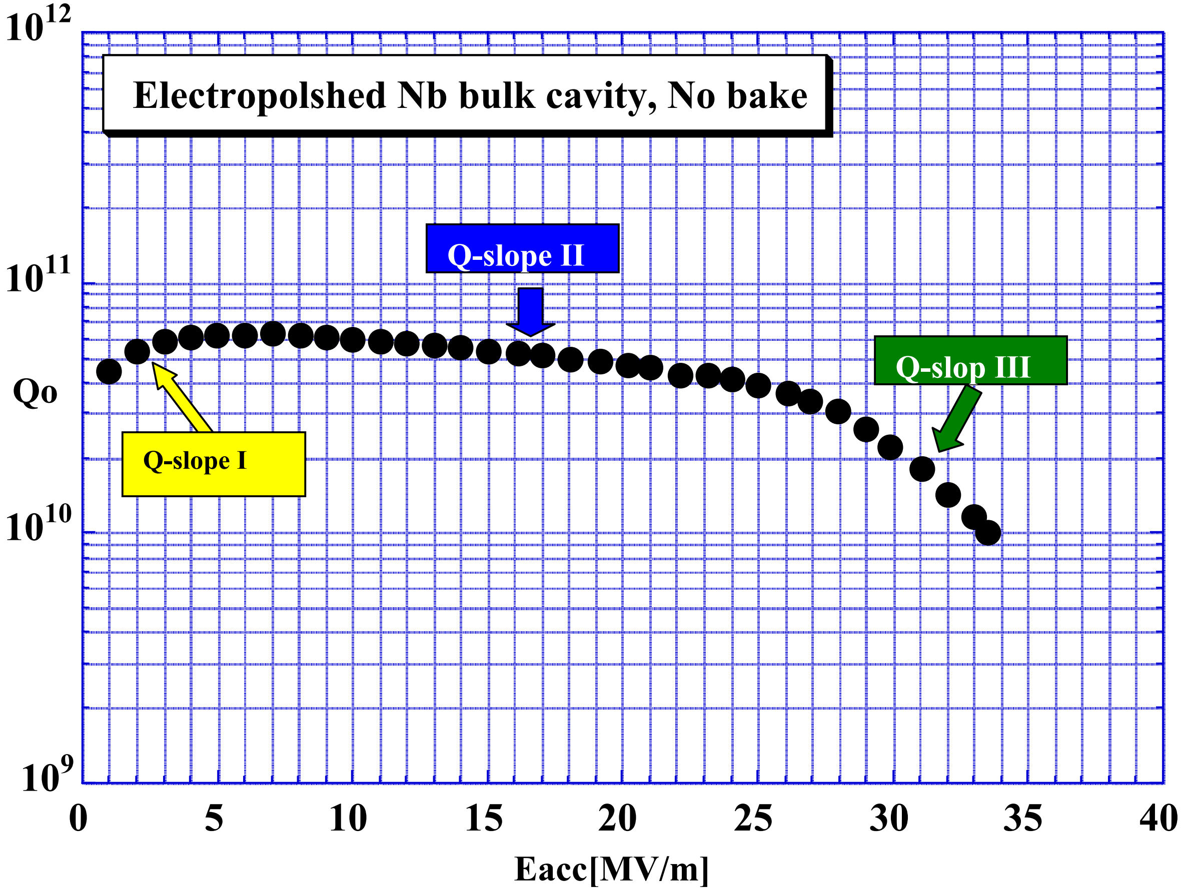
Fluxoid core

Flux line nucleation $f = f_{core} + f_{mag} = -\pi\xi^2 \frac{H_c^2}{8\pi} + \pi\lambda^2 \frac{H_c^2}{8\pi} \leq 0$

Normal core : condensation energy	magnetic energy
$r \sim \xi$ $f_{core} = -\pi\xi^2 \frac{H_c^2}{8\pi}$	$f_{mag} = \pi\lambda^2 \frac{H_c^2}{8\pi}$

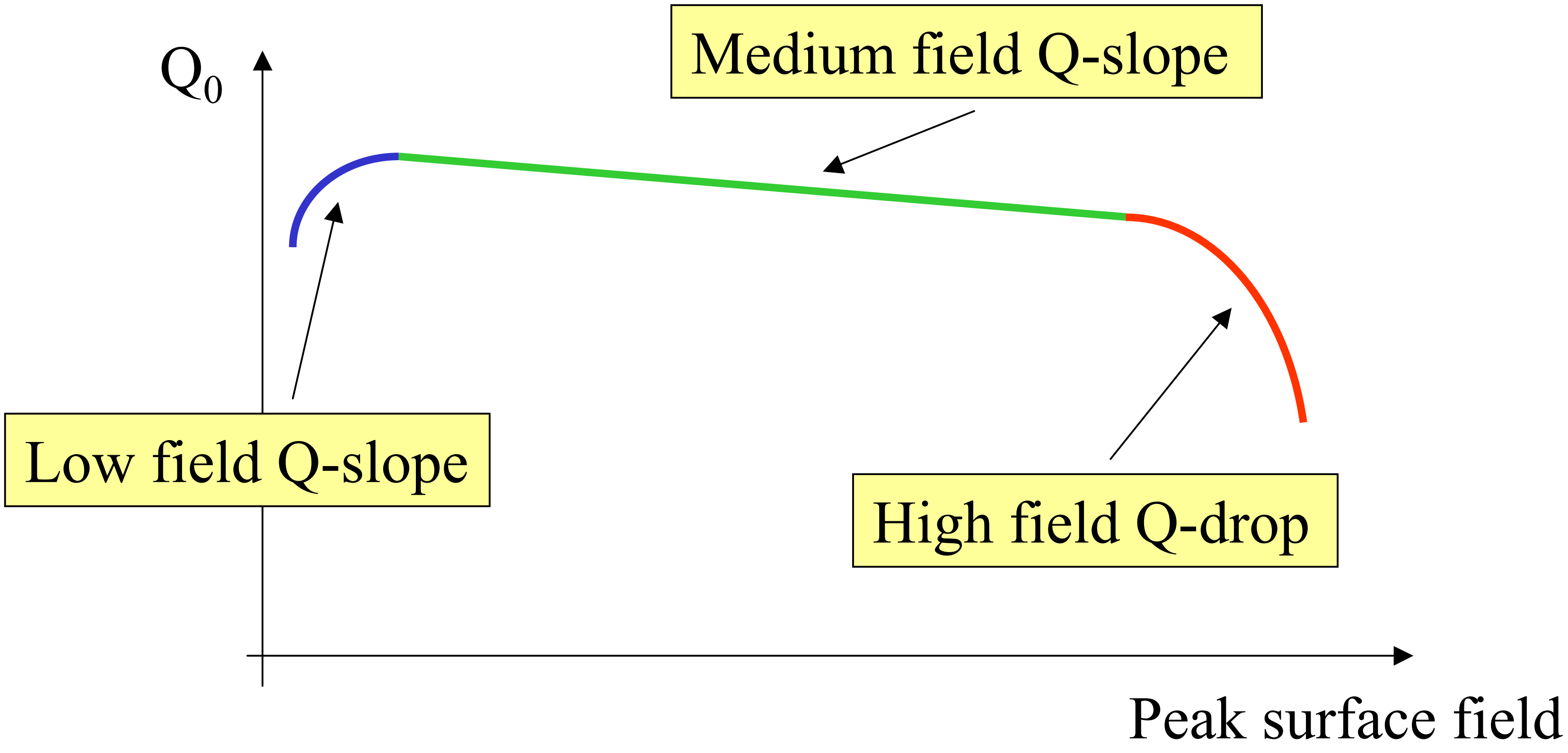
Q vs Eacc

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



Q vs E_{acc} (G. Ciovati)

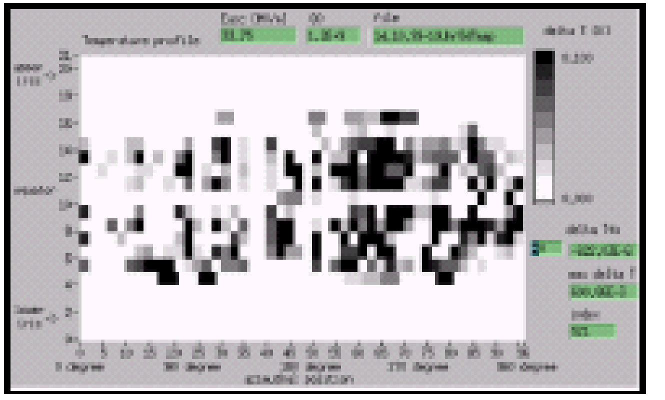
Excitation curves of bulk Nb cavities show 3 different "anomalous behaviors" in absence of field emission:



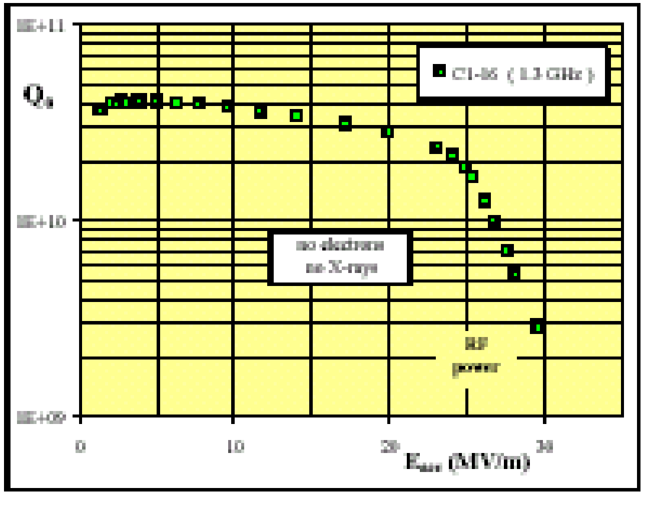
"Q – Slope" (B. Visentin, CEA Saclay)

quality factor ⇨ strong degradation

- E_{acc} > 20 MV/m TTF cavities (B_p > 85 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



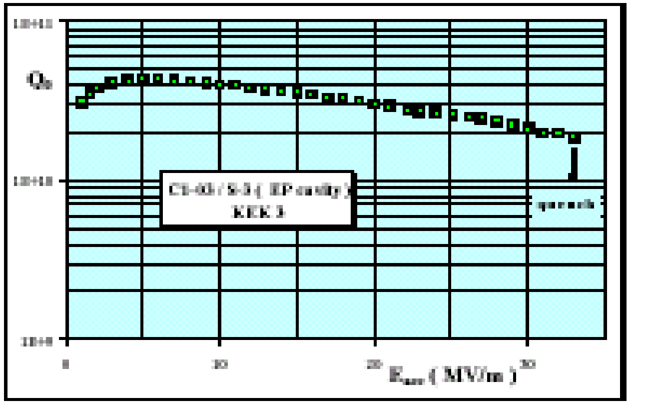
(L. Lilje *et al.* - SRF '99 - Santa Fe)



(Nb 1-cell cavity)

"European Headache"
superiority of EP
without Q-slope

K. Saïto *et al.*
SRF '97
(Abano Terme)



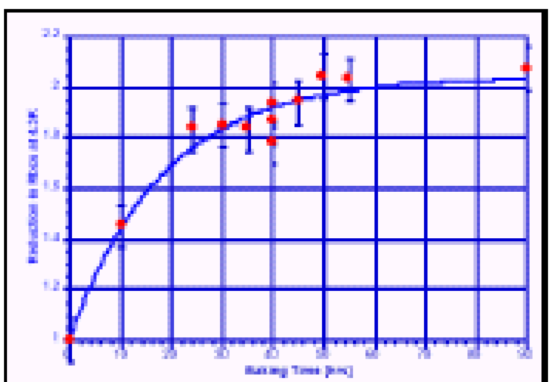
(E. Kako *et al.* - SRF '99 - Santa Fe)

“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

$$R_{BCS} = A(\lambda_L, \xi_F, \ell)\frac{\omega^2}{T} e^{-\Delta/kT}$$

R_{BCS} ⇩ (baking time) ⇨ saturation

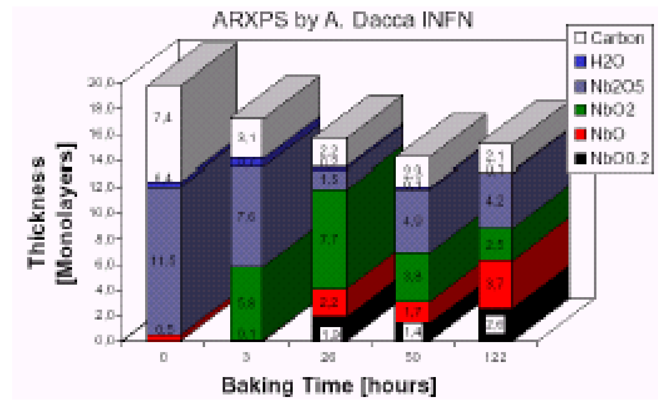


diffusion process

(300 nm)

{ R_{BCS} @ T = 4.2 K
T_{bake} = 145°C

Oc (P. Kneisel - SRF '99 - Santa Fe)



(A. Daccà - sample 4 - T=150°C)

Change
of the structure oxide
after baking
(Nb_2O_5 ⇩ and NbO - $NbO_{0.2}$ ⇧)

"Q – slope"

Several models have been proposed to explain the Q-drop

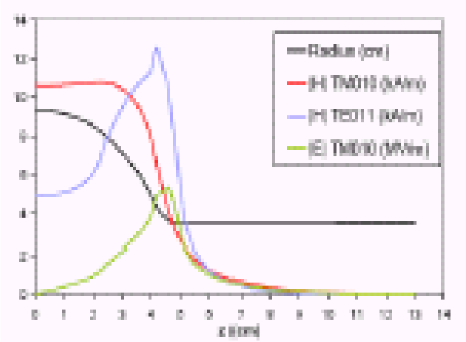
- Field enhancement at grain boundaries(K.Knobloch et al)
- Interface tunnel exchange in Nb/oxide interface (J. Halbritter)
- Thermal feedback :T-dependence of R_{BCS} (E. Haebel)
- Magnetic field dependence of energy gap (K.Saito)
- Granular Superconductivity: Grain boundery contribution to R_{BCS}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

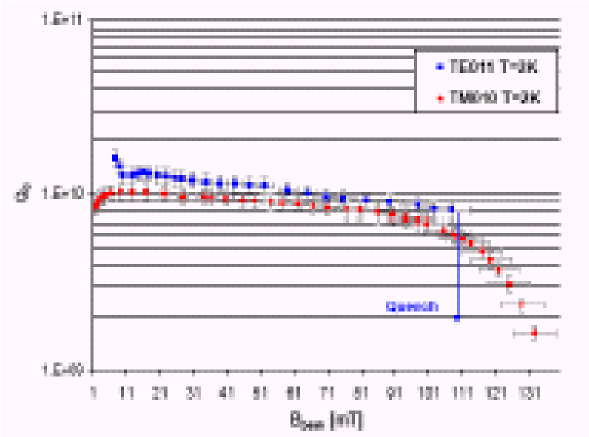
Q – slope (G. Ciovati et al)

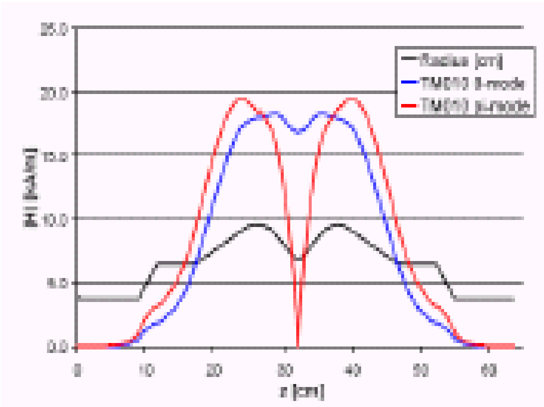
" H enhancement at grain bound. " ⇔ " Interface Tunnel Exchange "

- Single cell cavity (BCP - EP - w/o Baking) excited in modes TM_{010} or TM_{011} : H_S
- Two cell cavity 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)

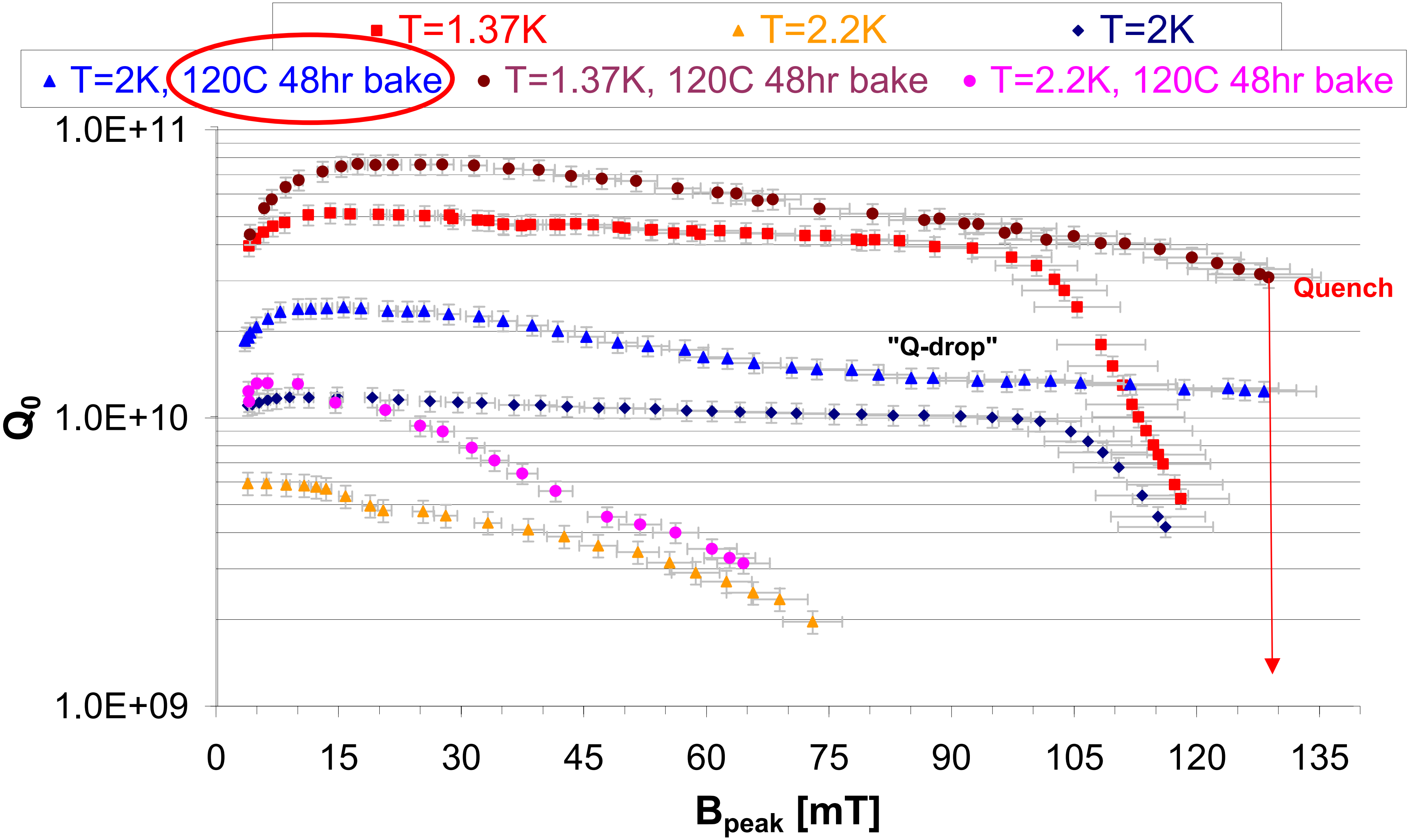






Q – slope (G. Ciovati et al)

Results: Effect of Baking (G. Ciovati)

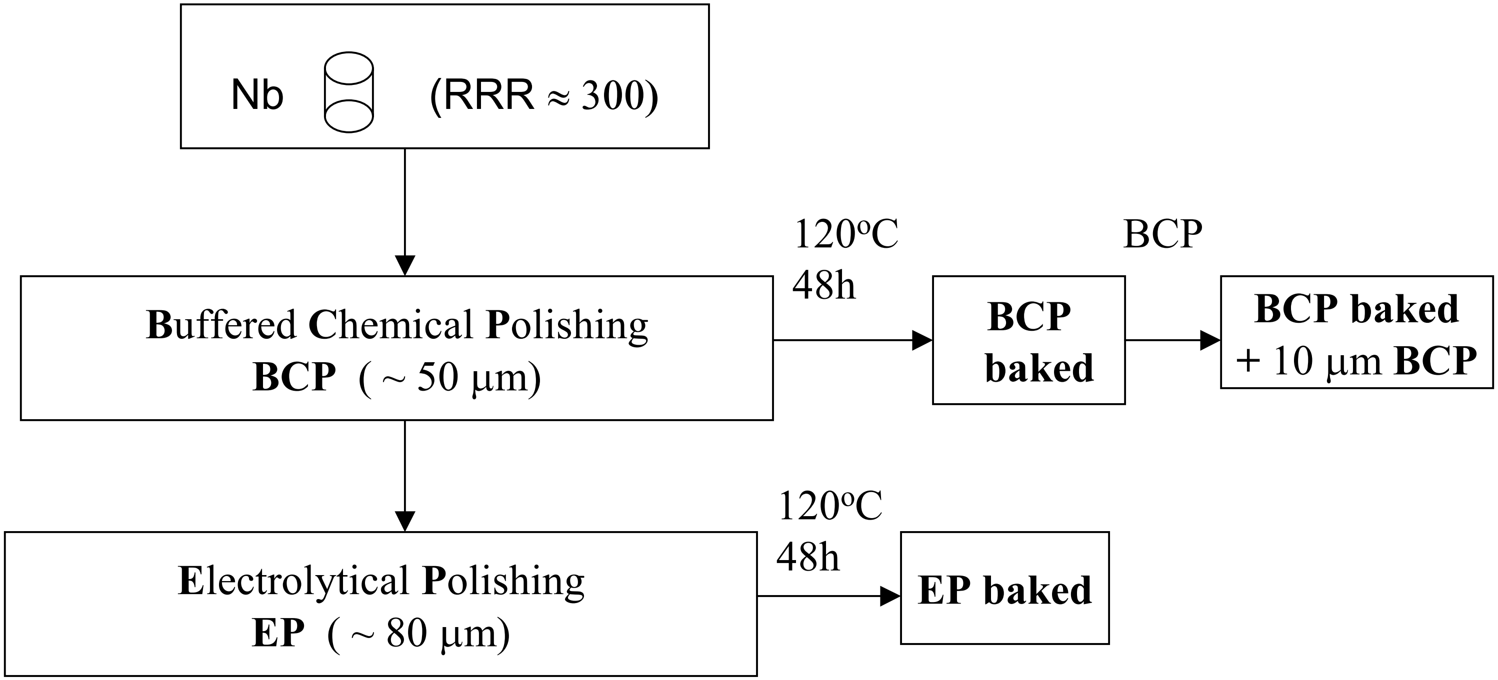


Superconductivity above H_{C2} as a probe for Niobium RF-cavity surfaces

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

Institute of Applied Physics and Microstructure Research Center
University of Hamburg

10.09.03 SRF2003



-Volume characterization

-Surface characterization: $\cdot\, \chi(H, H_{AC}, \omega, T) \Rightarrow H_{C3}$

$\cdot\, M(H) \Rightarrow J_C$

-Conclusions

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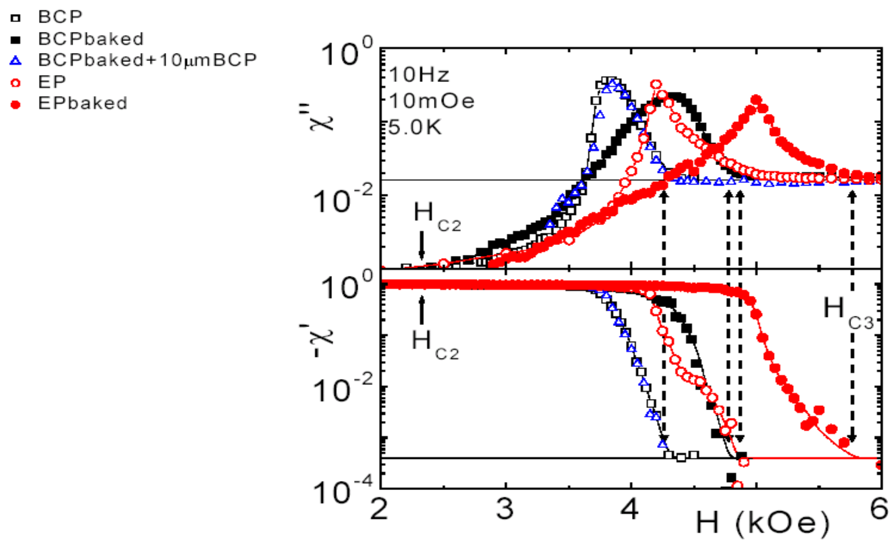
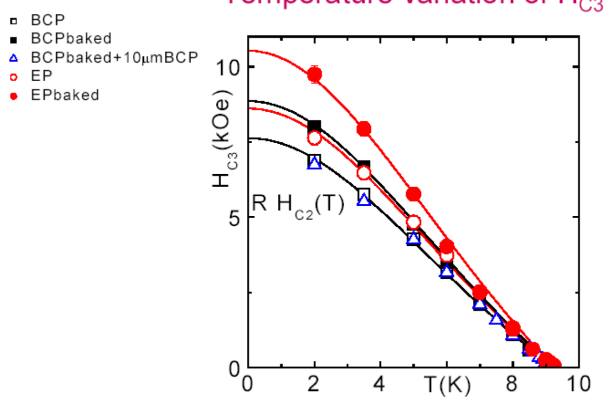
Surface Superconductivity(S.Casalbuoni)

Nucleation of surface superconductivity: H_{C3}



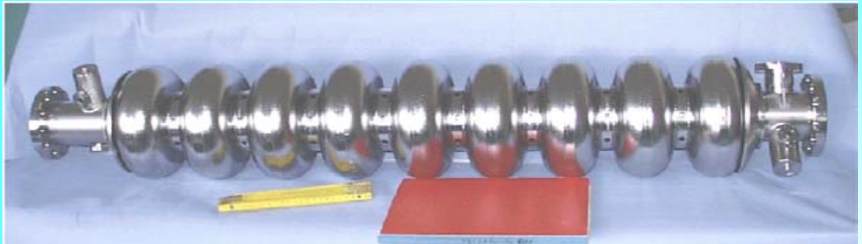
Temperature variation of H_{C3}



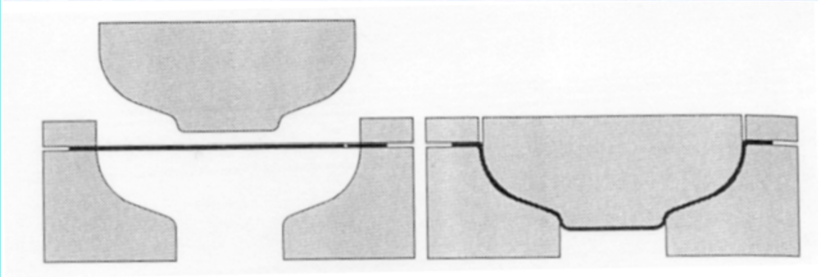
	BCP	BCPbaked	EP	EPbaked	BCPbaked + 10μmBCP
H_{C3}/H_{C2}	1.86(3)	2.16(3)	2.10(3)	2.57(2)	1.86(3)

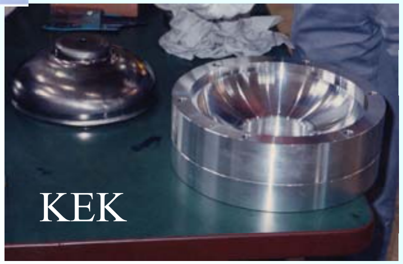
H_{C3} is increased by baking for EP and BCP
H_{C3} is increased by EP
EP+baking gives the larger H_{C3}

Conventional cavity fabrication (TESLA shape)

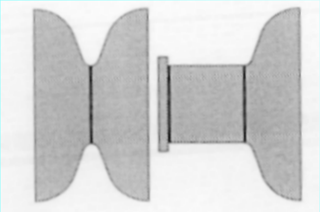


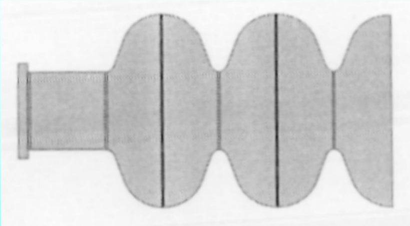
TESLA 9-cell Niobium Cavity





Deep drawing a niobium disk into a half cell

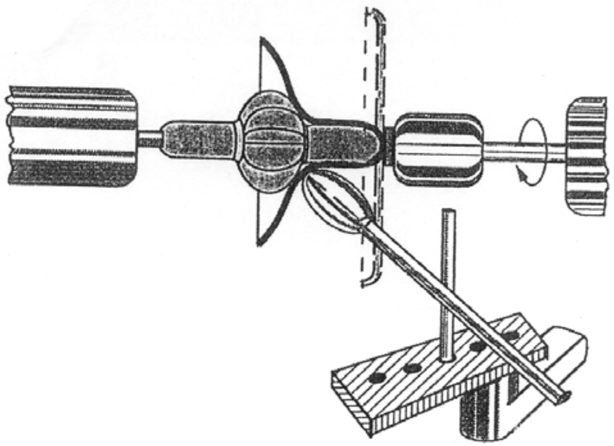


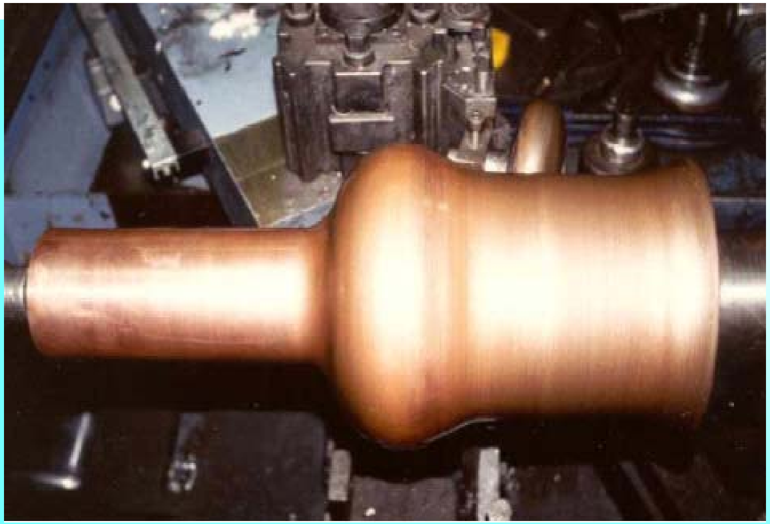


Electron beam welding of a cavity. Iris welds (inside), equator welds (outside)

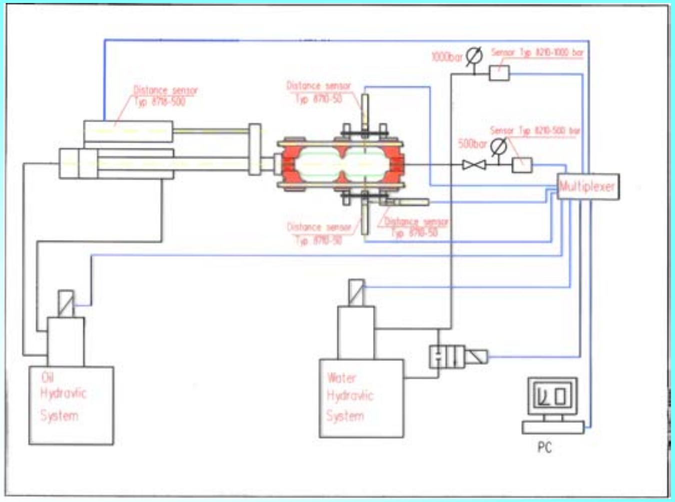
Well developed procedure

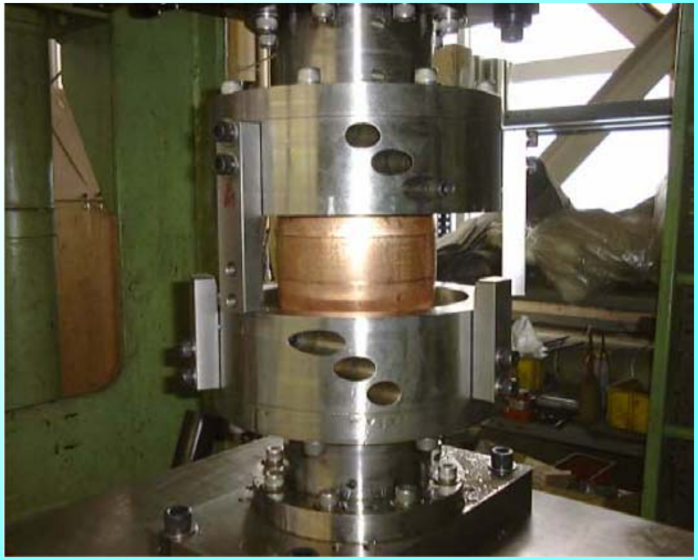
Spinning (V.Palmieri, INFN Legnaro)





Hydroforming, DESY, KEK

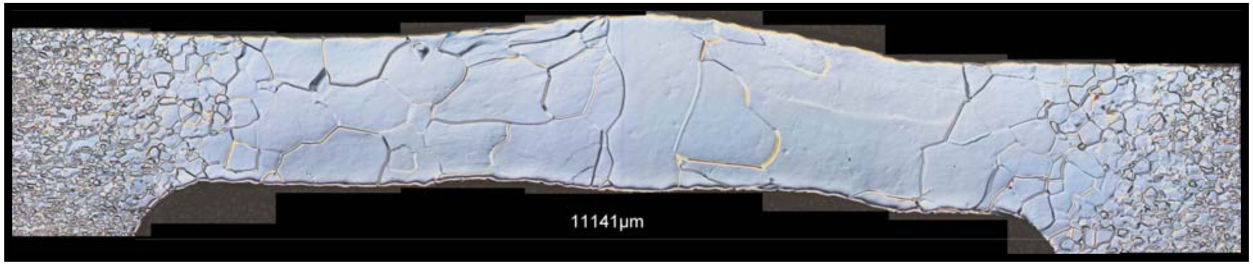


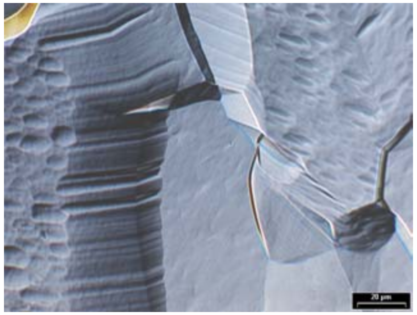


Seamless Cavities

Why seamless cavities?

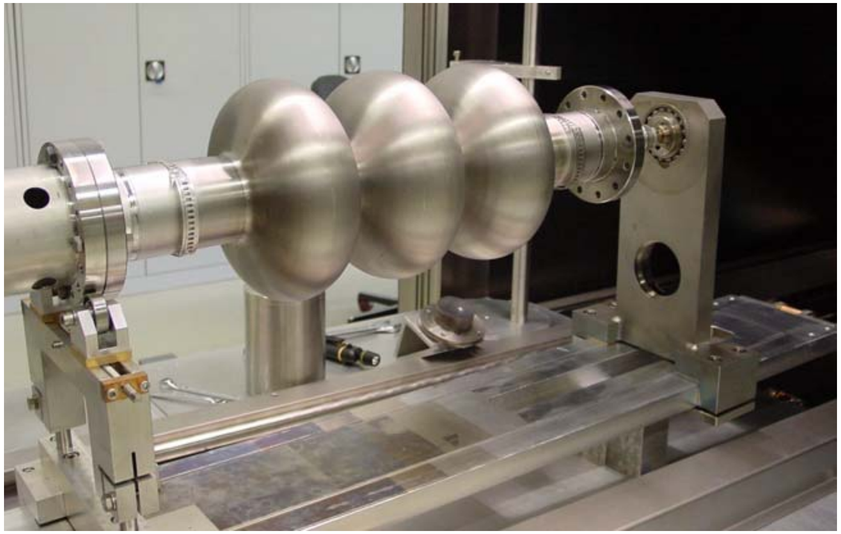
- EBW can cause RRR degradation in weld and heat effected zone: highest H – field region
- Grain growth can lead to field enhancement at grain boundaries: “quench” and defects “ bubbles”
- Reduced machining,chem. Cleaning,QA
- Faster manufacturing (8 hrs/9cell cavity)
- In principal accurate frequency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





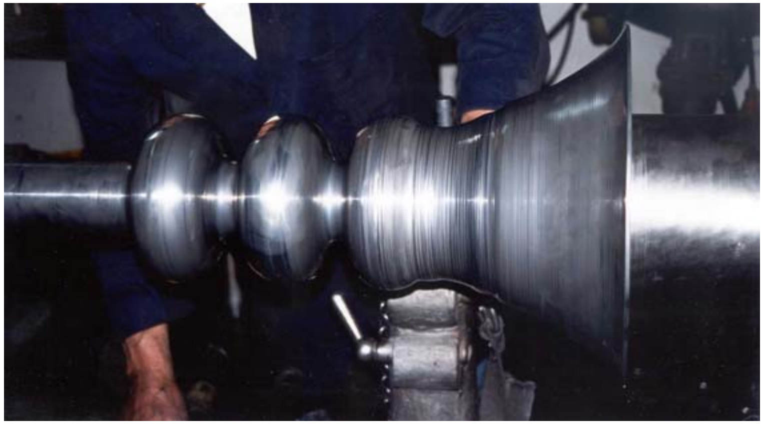
Spinning (Poster TuP26)

First spun 9-cell cavity



Spun 3-cell cavity

Spinning from tube

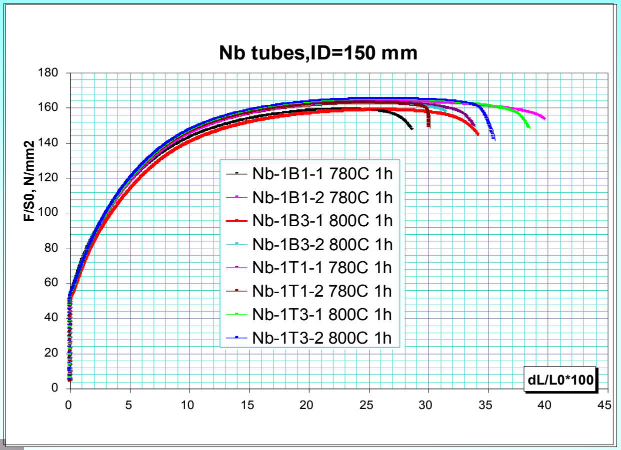


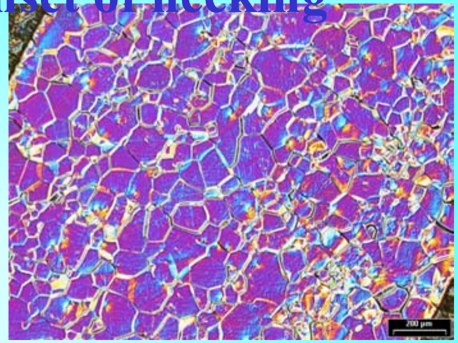
Spinning from disk

Hydroforming

Combination of spinning with flow forming gives seam less 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
.





Microstructure of Nb tubes produced by combination of spinning and flow forming

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

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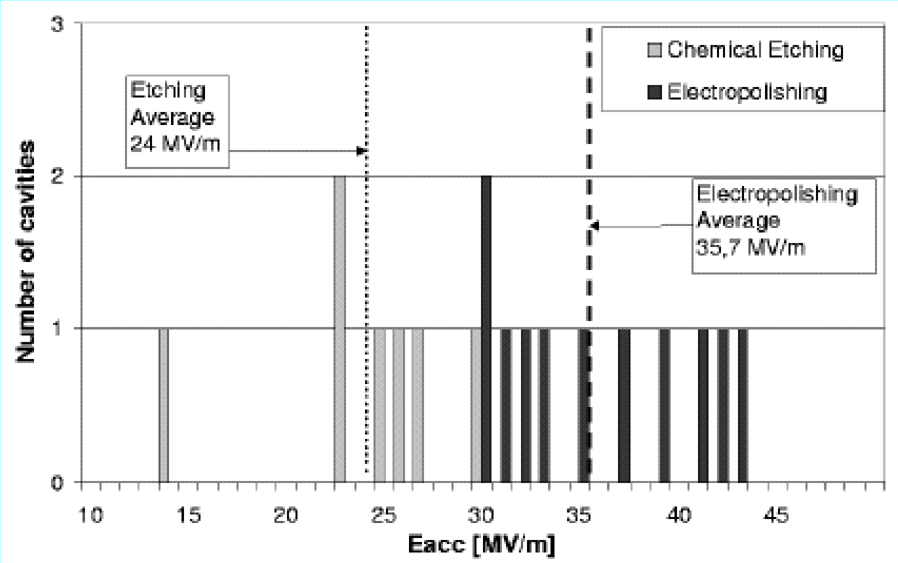
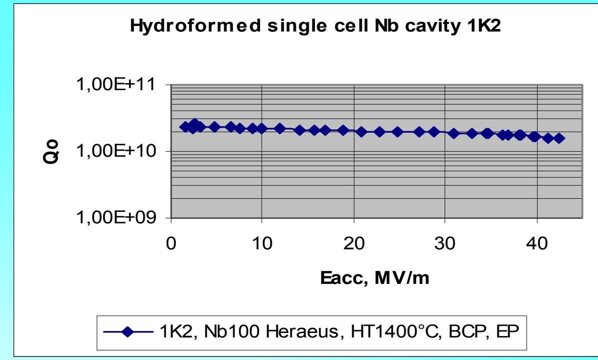
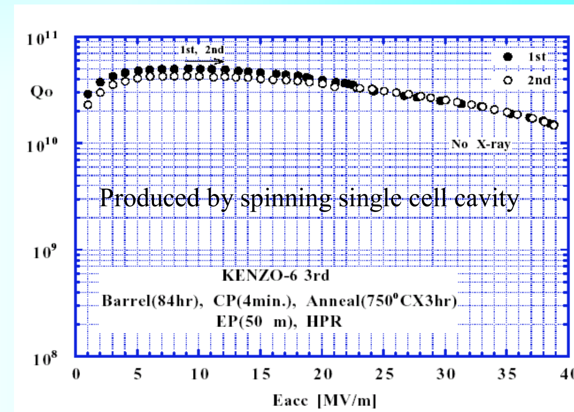
Waldemar Singer, 11th SRF Workshop, September 2003

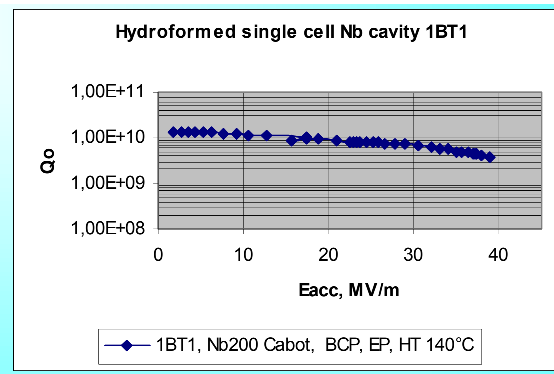


Distribution of the maximal accelerating gradients of etched and electropolished single-cell cavities (L.Lilje, SRF 2001).



Record single cell cavity (talk of H. Padamsee SRF 2003)





Some best seam less single cell cavities. Prepartion and RF tests: K.Saito, P.Kneisel

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.

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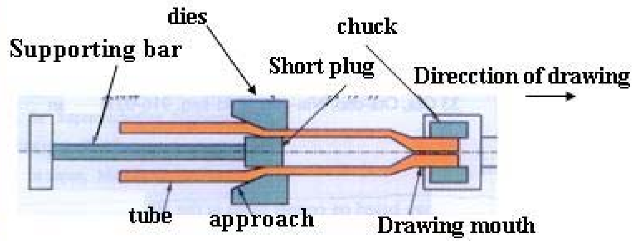
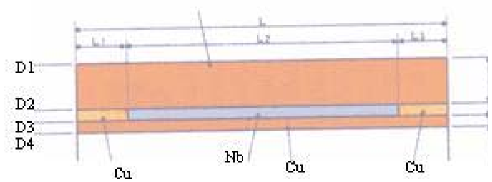
• Coextruded NbCu tubes (Poster TuP40)



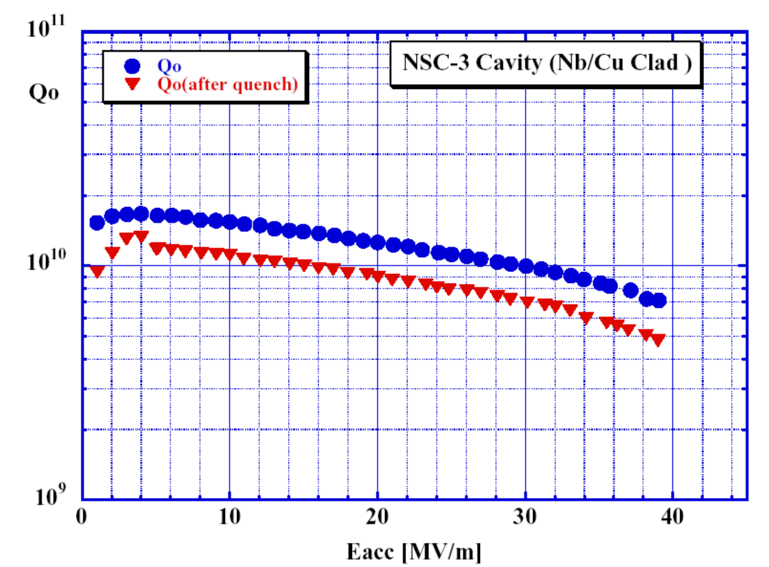
Fabrication principle of sandwiched Cu-Nb-Cu tube

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

Principle of the tube drawing technology



Cu-Nb-Cu Sandwiched Tubes (KEK)

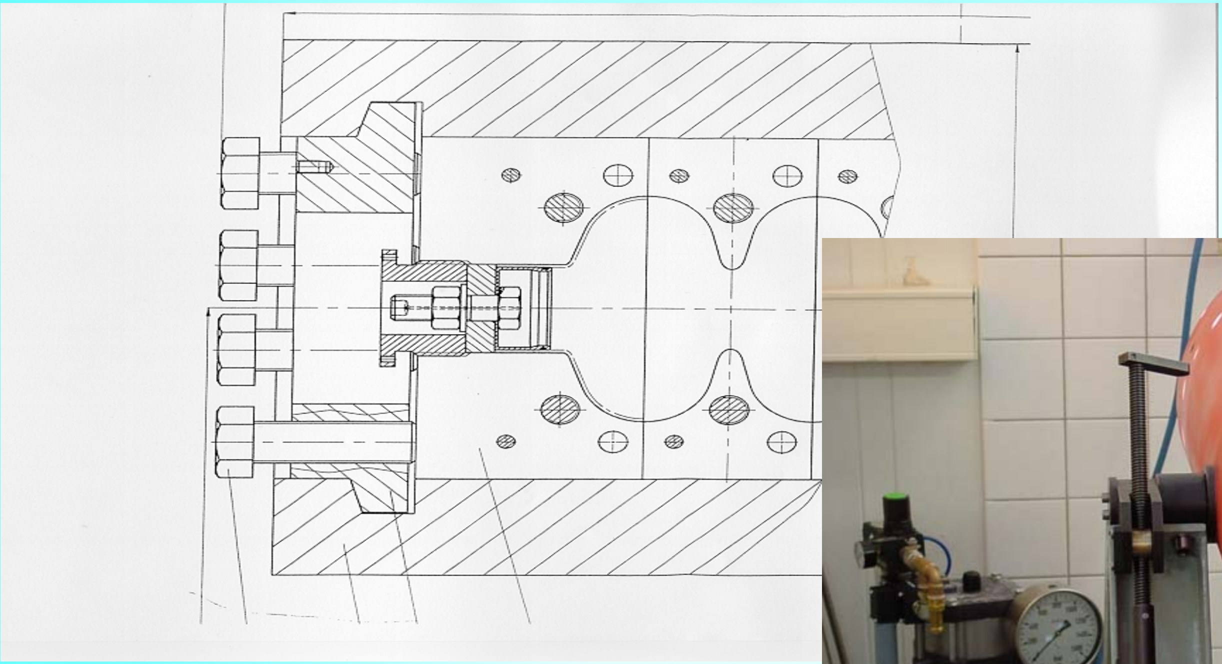


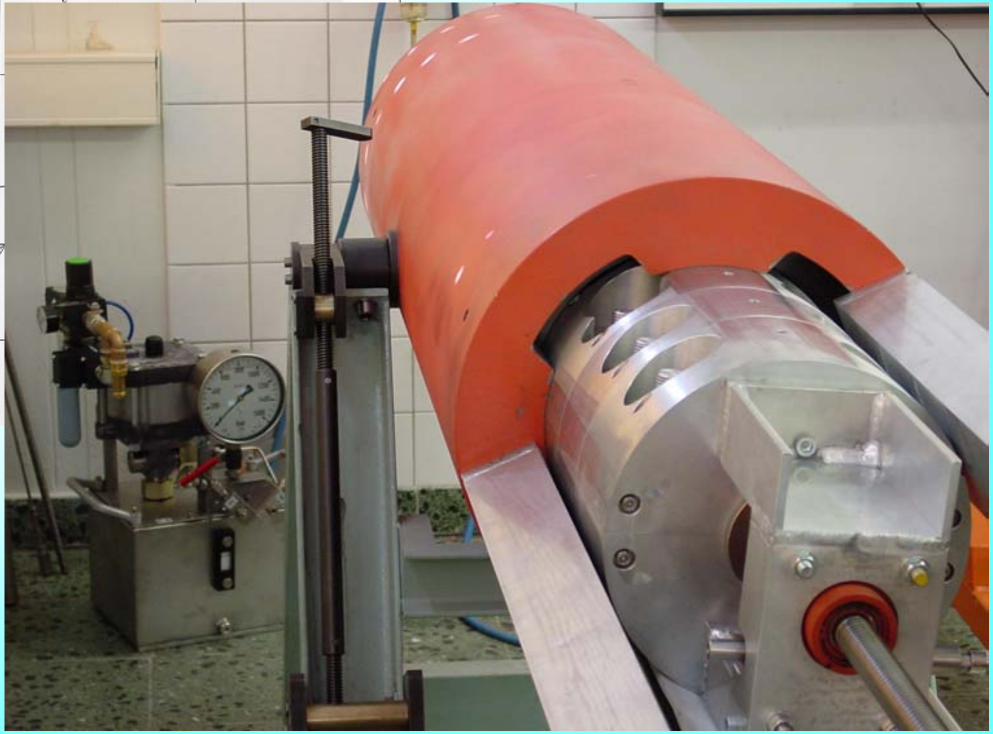
Single cell NbCu cavities produced at DESY from KEK sandwiched tube.

E_{acc} of best sputtered NbCu cavities is <25 MV/m

Oct. 10, ‘03

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

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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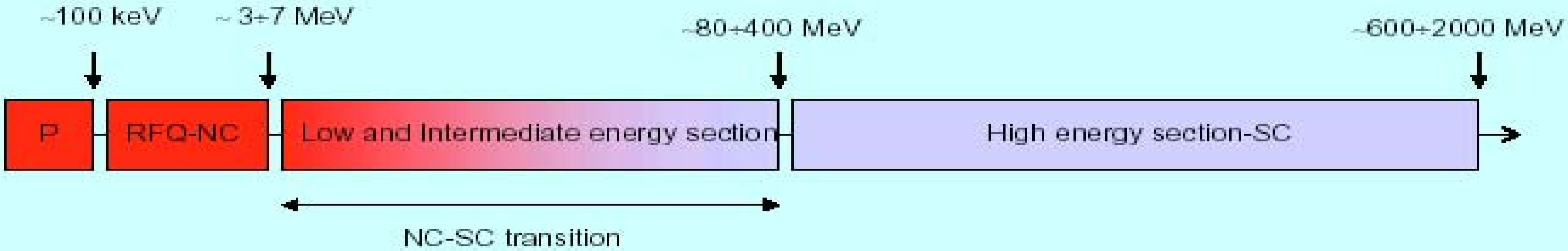
High Intensity Proton Sources

High Intensity Superconducting Proton Linacs

(**HISPL** from now on)



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-β 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!

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High Intensity Proton Sources

HISPL projects worldwide: High-β

Linac	E_{in}/ E_{out} MeV	I_{peak} mA	duty cycle, %	Rep. rate, Hz	N.cav. (types)	rf freq. MHz	Notes	Status
SNS USA	187 / 1000	26	6.25	60	81 (2)	805	H-	Construct. started operation 2006
ESS Europe	200 / 1330	114	6	50	137 (2)	704	H-, p	Proposal
Concert Europe	200 / 1330	114	6	50	137 (2)	704	H-,p	Project Study (closed)
J-PARK Japan	400 / 600	30	1.25	25	22 (1)	972	H-	Construction started R&D
APT USA	211 / 1030	100	100	CW	242 (2)	700	p	Project Study, R&D (closed)
ADTF H.E. USA	109 / 600	13	100	CW	133 (2)	700	p	Proposal R&D
XADS H.E. Europe	95 / 600	10	100	CW	88 (3)	700	p	Preliminary design Study, R&D
TRASCO H.E. Italy	100 / 1000	30	100	CW	124 (3)	704	p	Project Study R&D
EURISOL H.E. Europe	85 / 1000	5	100	CW	134 (3)	700	p	Project Study R&D
SPL CERN	120 / 2200	22	14	50	202 (3)	352	H-	Project Study R&D
KOMAC Korea	100 / 1000	20	100	CW	90 (3)	700	p	Proposal R&D
FNAL 8 GeV USA	87 / 8000	25	1	10	384 (4)	805/ 1207.5	H-, p	Proposal
AGS upgrade USA	200/ 1200	28	0.18	2.5	92 (3)	805/ 1610	p	Proposal

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High Intensity Proton Sources

HISPL projects worldwide:
Low-β

Linac	E_{in}/ E_{out} MeV	I_{peak} mA	duty cycle, %	Rep. rate, Hz	Cavities N. (types)	rf freq. MHz	Notes	Status
ADTF L.E. USA	6.4 / 109	13	100	CW	128 (3)	350	p	Proposal R&D
XADS L.E. France	5 / 95	10	100	CW	96 (2)	350	p	Prelim. design study, R&D
TRASCO L.E. Italy	5 / 100	30	100	CW	230 (1)	352	p	Prelim. design study, R&D
SPES Italy	5 / 100	3	100	CW	113 (3)	352	p (d, A/q=3)	Proposal R&D
COSY INJ Germany	2.5 / 52	2	0.1	2	44 (2)	160/32 0	p, d	Proposal R&D
SARAF Israel	1.5 / 40	2	100	CW	48 (2)	176	p, d	Under constr. operation 2008

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High Intensity Proton Sources

Low-β cavities

1 gap reentrant- LNL
352 MHz, β>0.1

2 gap spoke- LANL
352 MHz, β=0.2

2 gap spoke- IPN Orsay
352 MHz, β=0.36

2 gap spoke- 345 MHz β=0.4
ANL for RIA

- short cavities, wide β 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

3 gap SPOKE, β=0.4
345 MHz
ANL for RIA

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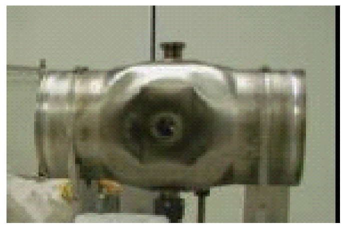
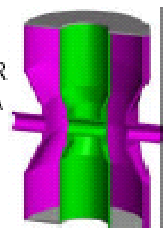
High Intensity Proton Sources

Low-β Coaxial Half–Wave

350 MHz, β=0.12
ANL

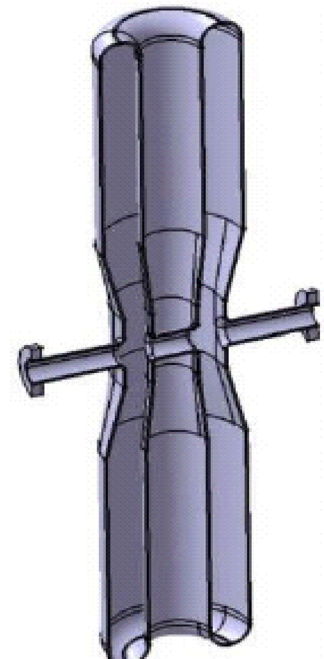


322 MHz,
β=0.28 HWR
MSU for RIA



352 MHz, β=0.31
HWR - LNL

160 MHz, β=0.12 HWR
For the COSY injector



- 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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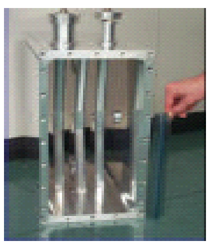
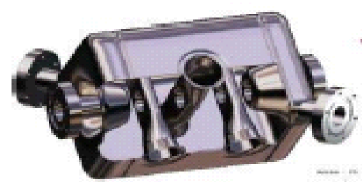
High Intensity Proton Sources

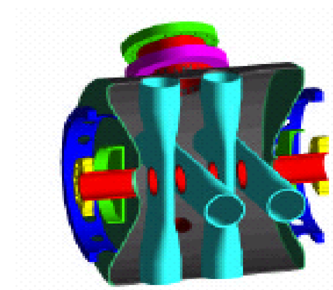
4-gap SC cavities development
The Low-β zoo is still growing

4 gap ladder,
352 MHz, $\beta=0.12$
INFN-LNL



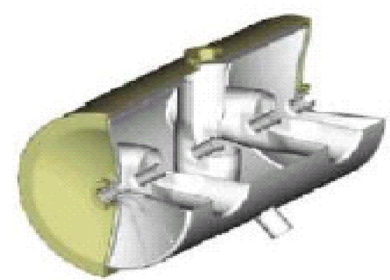
$\beta=0.2$
784 MHz
IKF Juelich





$\beta=0.12$
352 MHz
LANL

- 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 $\beta=0.5$ multicell



4 gap SPOKE, $\beta=0.5$
345 MHz - ANL for RIA

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Cavity/Structure Developments

- For β – values >~ 0.5, cavities with elliptical cross sections are still the preferred cavity type
- However, there is increasing interest in "spoke cavities" for intermediate β – values and in the case of the ANL proposal for RIA the β- range for spoke resonators has been extended as far as β ~ 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 ®
- Small number of degrees of freedom

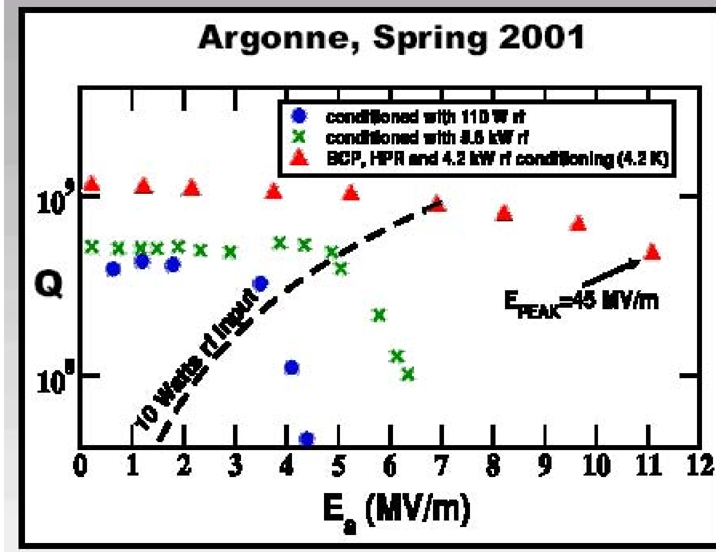
Spoke cavities:positive features

- 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 β
- Large number of degrees of freedom

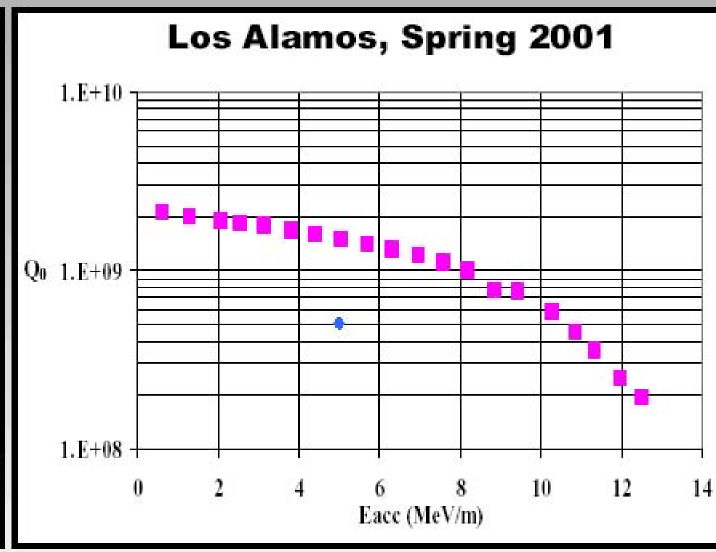
Cavity/Structure Developments

Results

ANL β=0.3 and β=0.4 Prototype Spoke Cavity Results

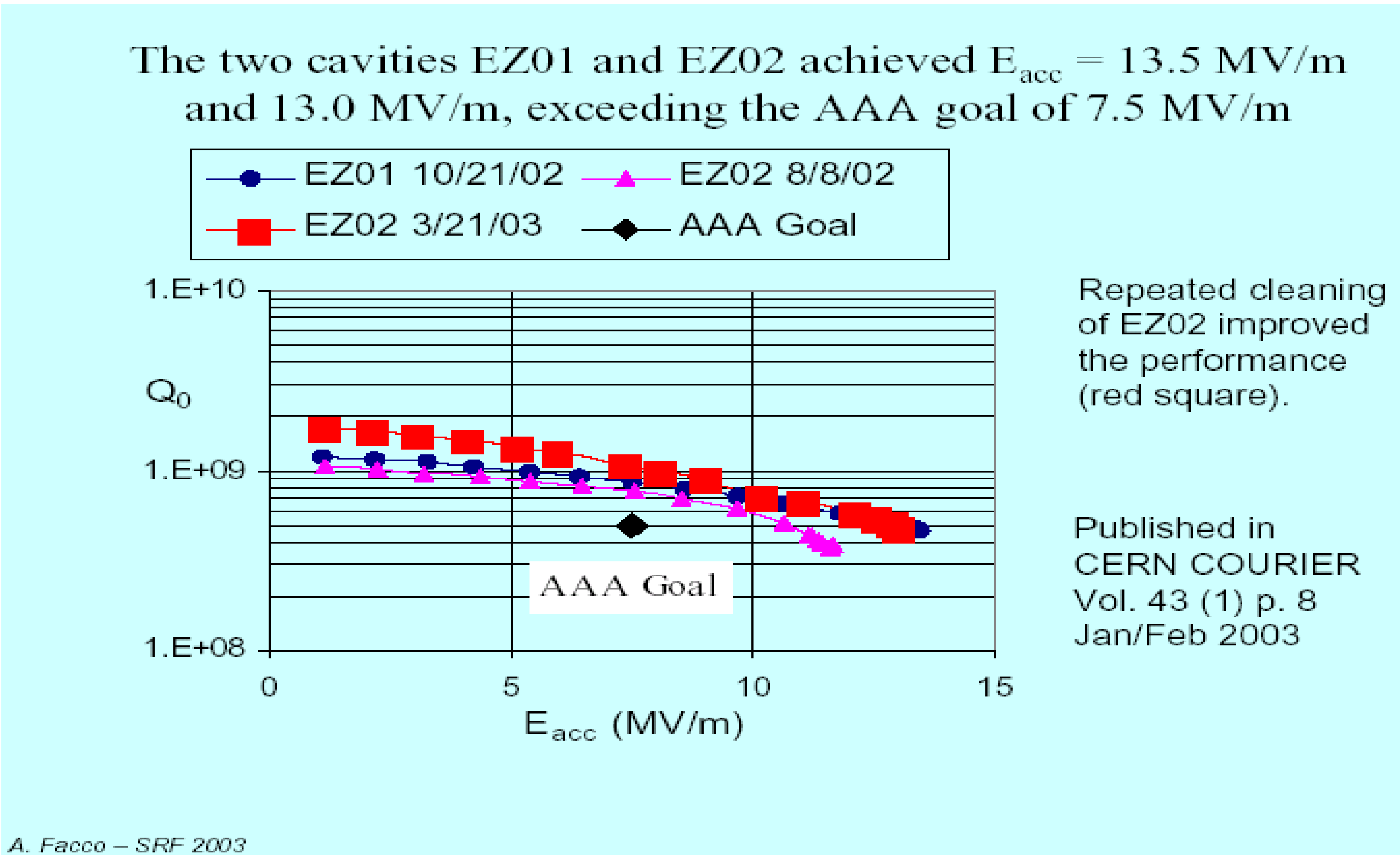


Argonne Result β=0.4 cavity



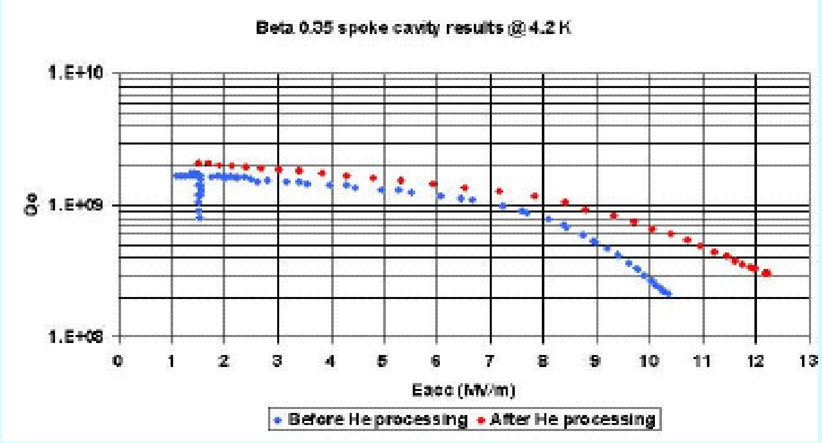
Los Alamos Result β=0.3 cavity

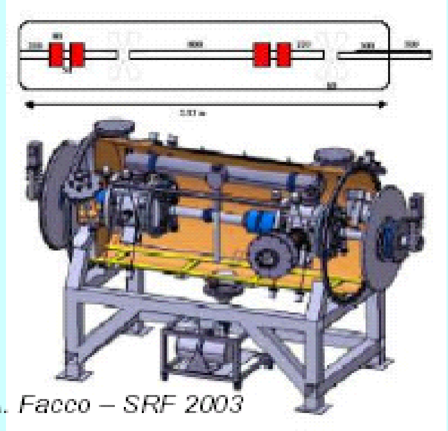
Results(LANL)



Results (IPN)

IPN Orsay β=0.35, 352 MHz Spoke resonator





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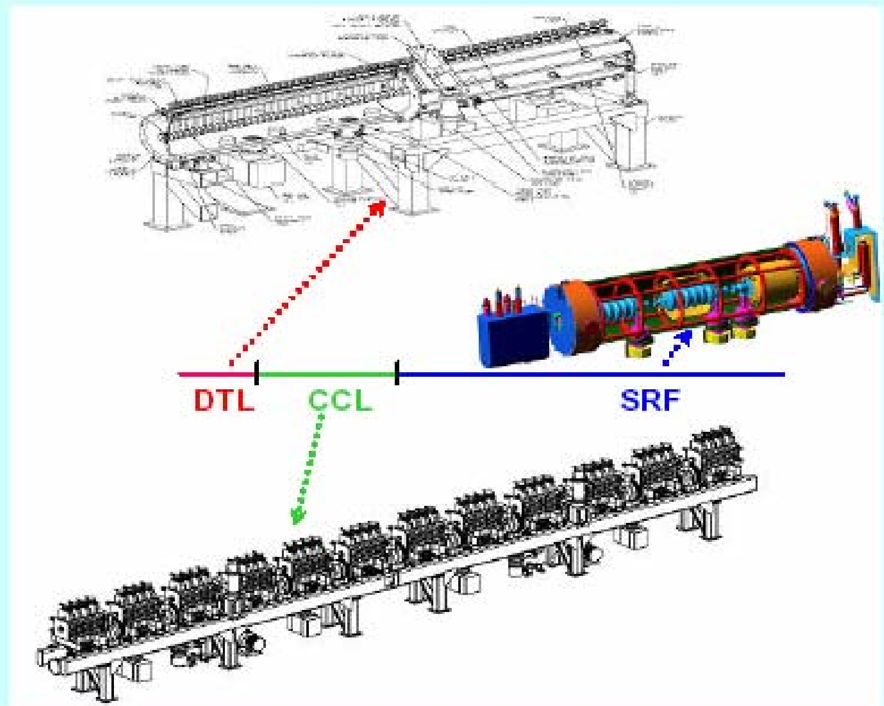
Fault tolerant Spoke cavity Linac:

- 5÷ 80 MeV
- 84 cavities: 30 β=0.12 and 54 β=0.35
- Cavity aperture 60 mm
- Superconducting quadrupole doublets
- SC Linac length : 91 m
- Possible injector for XADS

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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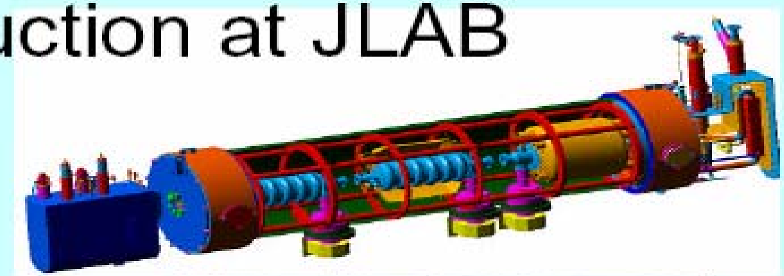
High Intensity Proton Sources

Cryomodule Production at JLAB



High Intensity Proton Sources

EURISOL Driver

European Radioactive Ion Beam Facility Proton Driver

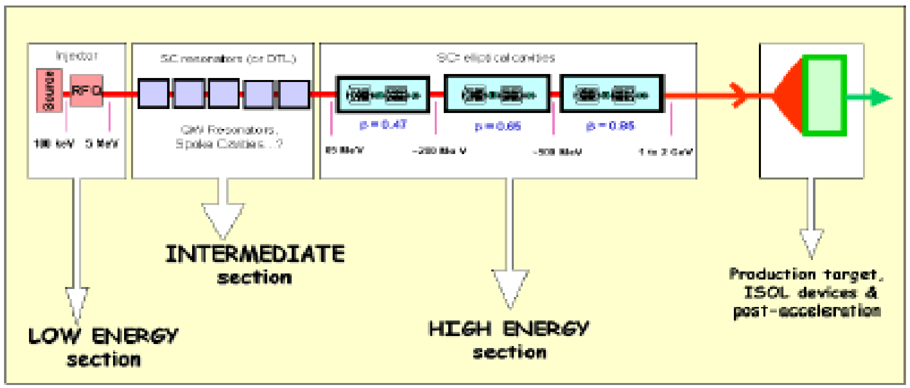


Fig. 3.1: General layout of the EURISOL proton driver accelerator.

	β=0.47 section	β=0.65 section	β=0.85 section
Input energy (MeV)	85	192	481
No. of cavities per module	2	3	4
Lattice length (m)	4.1	5.65	8.1
No. of modules	15	16	14
No. of cavities	30	48	56
Section length (m)	61.5	90.4	113.4
E_{acc} (MV/m)	4.6 to 9.1	5.7 to 10.7	8.8 to 12.6

- 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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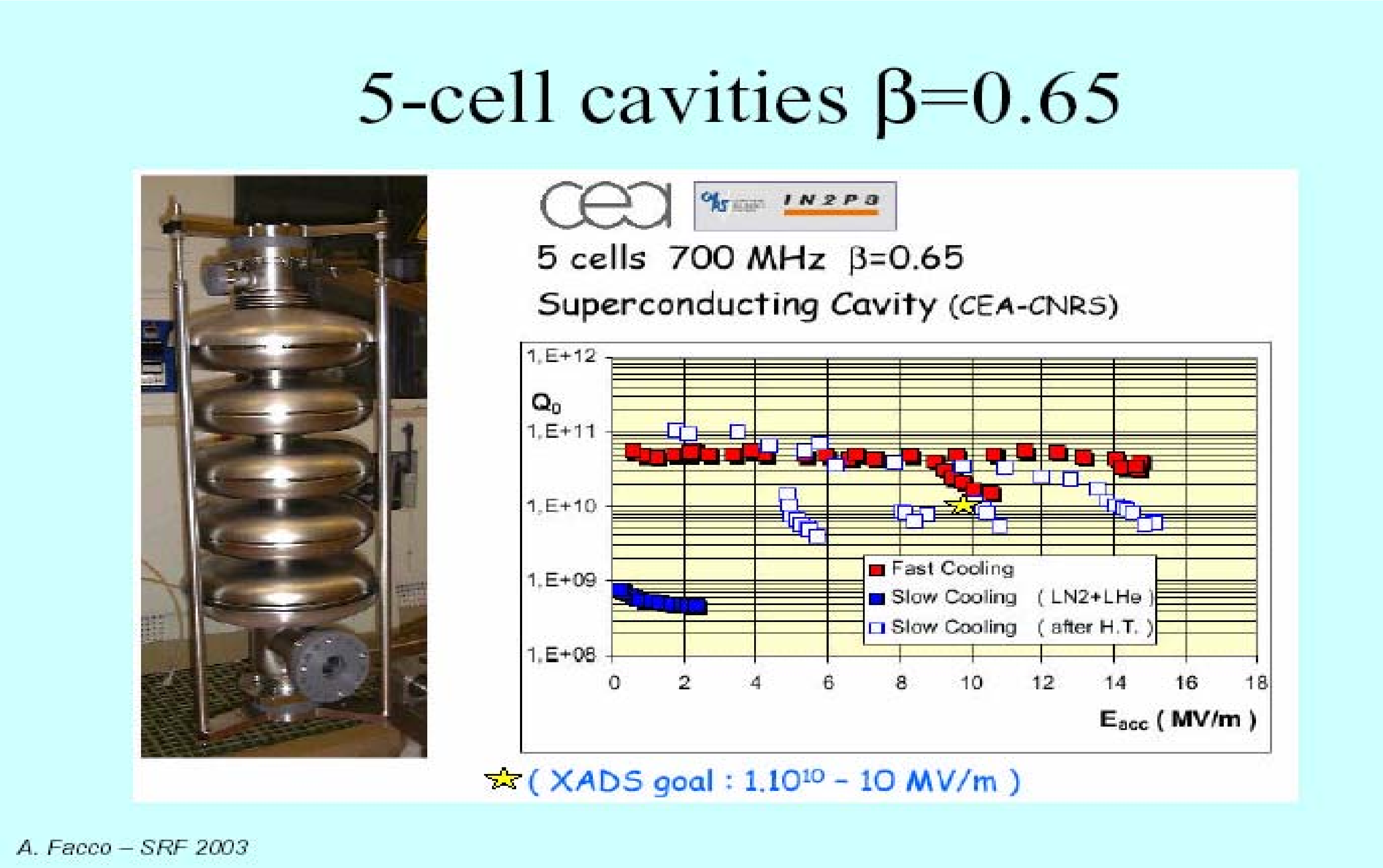
High Intensity Proton Sources



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 cavites 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

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 sourses 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/mrad^2/mm^2)
- 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

RF linacs!

3.5th gen

FEL

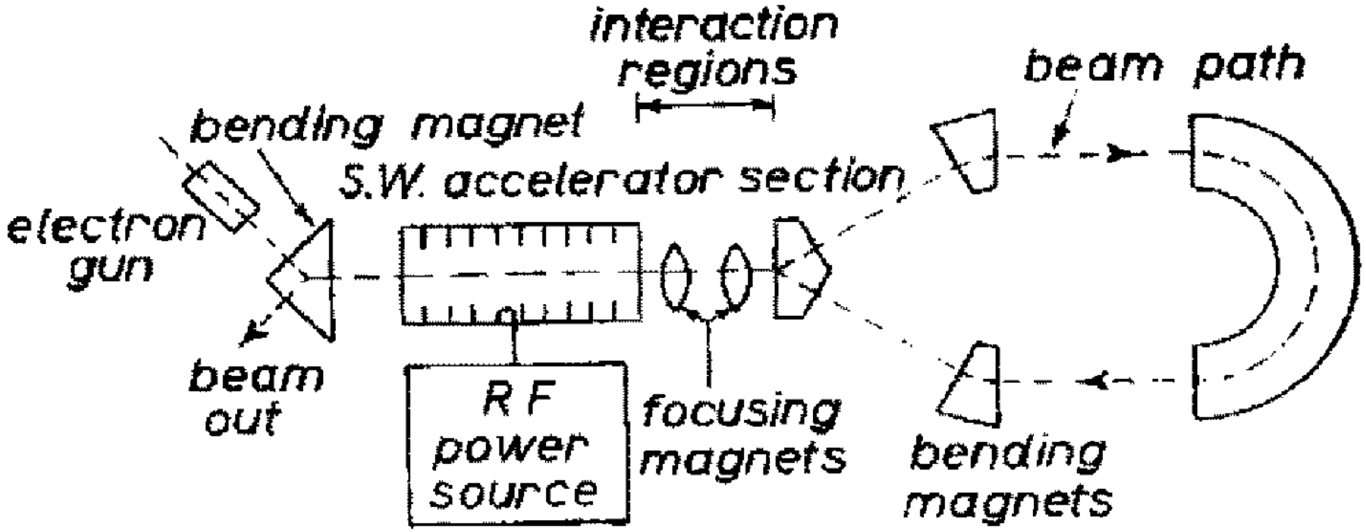
ERL

?

Linac Light Sources: How to get high currents?
High Current Layout (SLS-ERL, FEL-ERL)

- **High photon flux ⇒ 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?

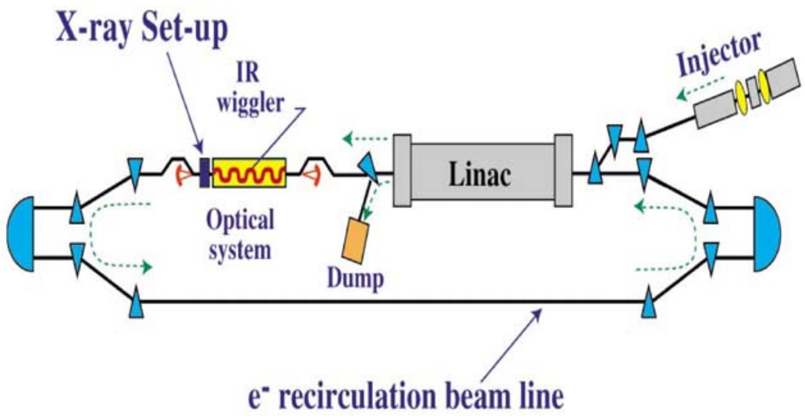
- ***Re-use energy of beam after SR generation.***
- ***Recirculate beam and pass it through the linac a second time, but 180 deg. out of phase to decelerate beam.***
- ***⇒ "Energy Storage Ring" but not "Beam Storage Ring".***

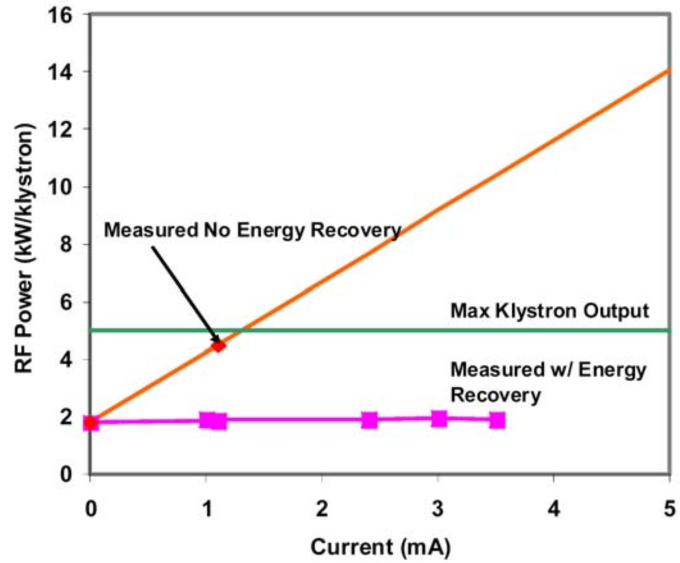
↓

- **Emittance defined by source/gun (not ring equilibrium) $\varepsilon < 10^{-10}$ m·rad 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**

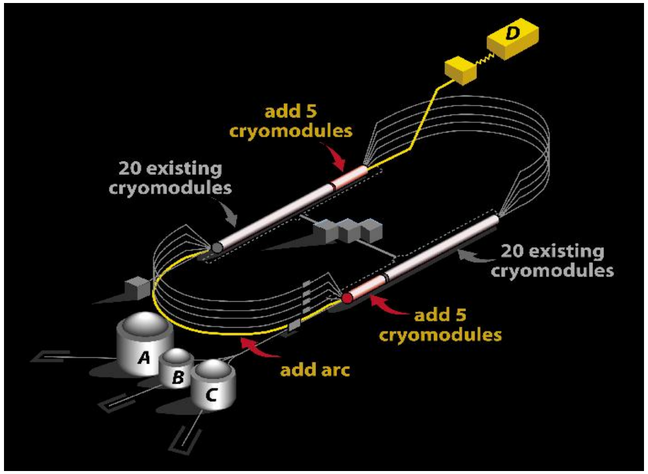
ERLs: It works!

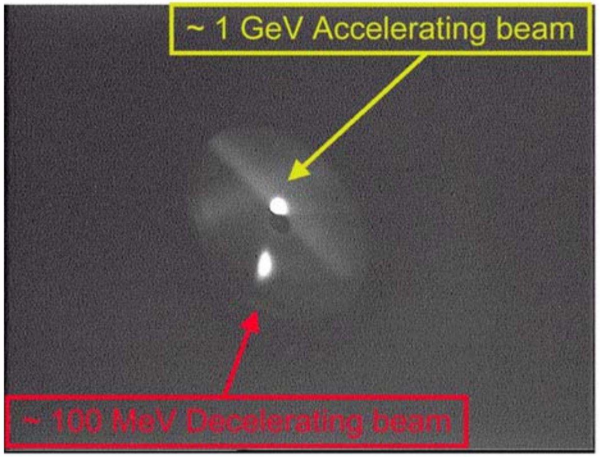
- ***JLAB FEL-ERL, 40 MeV, 5 mA:***





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





Energy Ratio of up to 1:50 tested (20 MeV $\rightleftarrows$ 1 GeV)

S. Chattopadhyay, G. Krafft et al.

ERLs Worldwide (FEL-ERLs and SR-ERLs)

1960

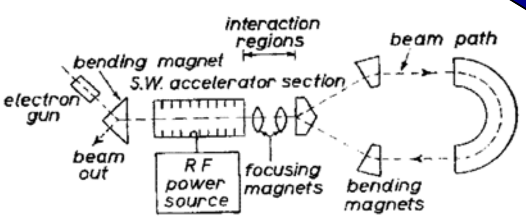
1970

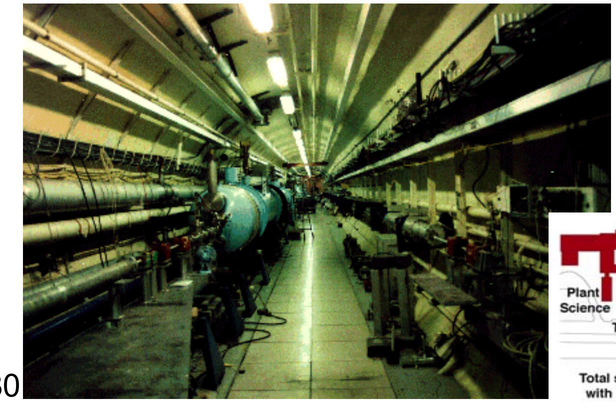
1980

1990

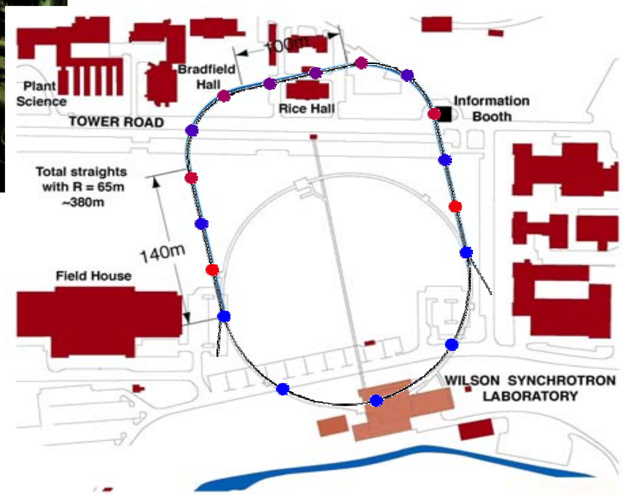
2000

M. Tigner, 1965

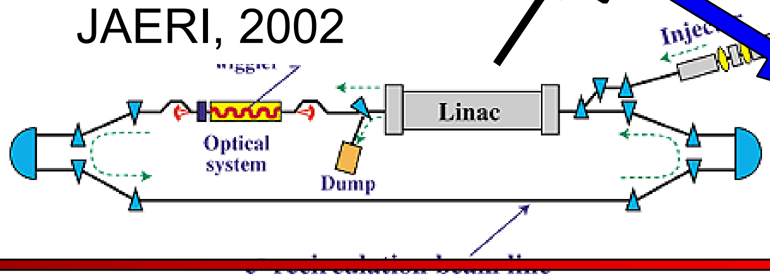




SCA, Stanford, 1986

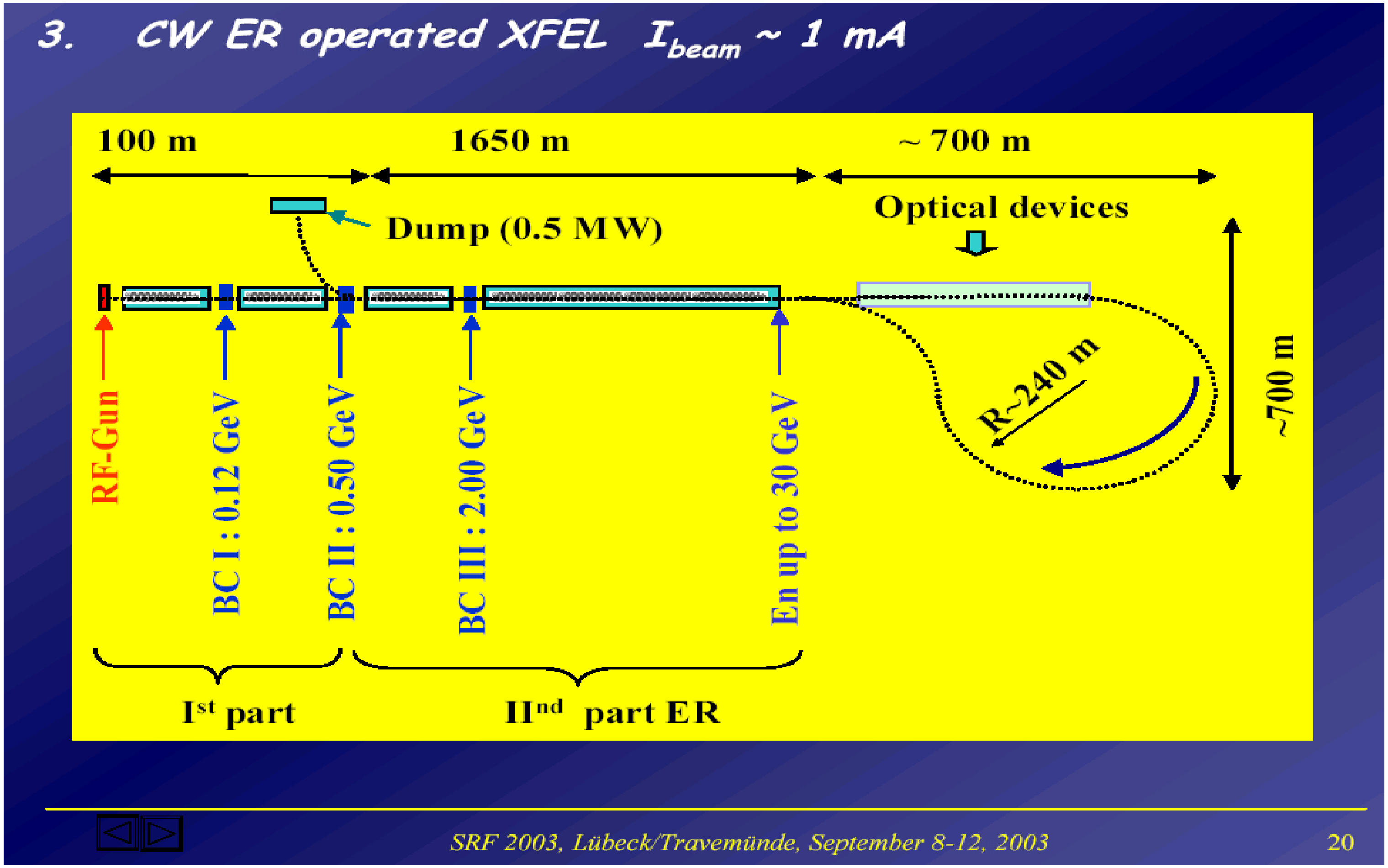


S-DALINAC, 1990
IR FEL Jlab, 1999
JAERI, 2002



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_{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

- short bunches (X-FELs): radiate at high frequencies up to THz

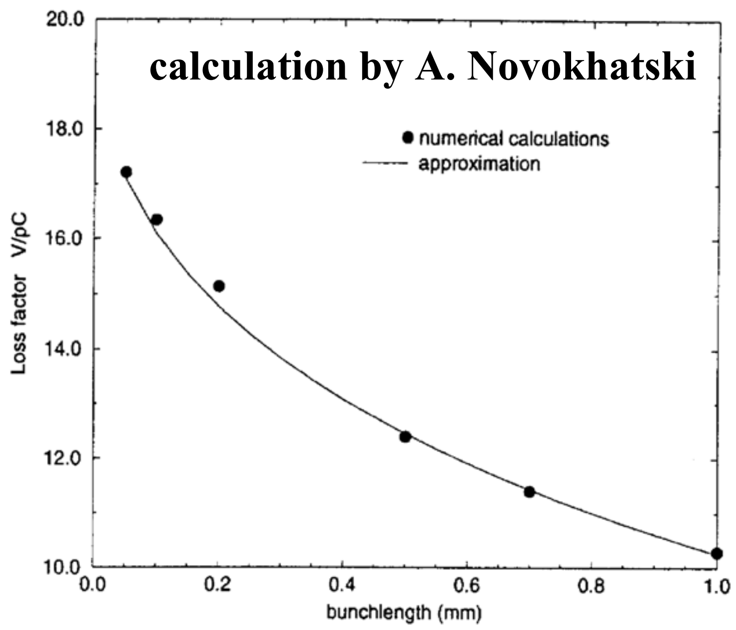
- High beam current:
  - HOM power extraction at temperature with good cryo-efficiency
  - beam stability limit

Strong HOM damping

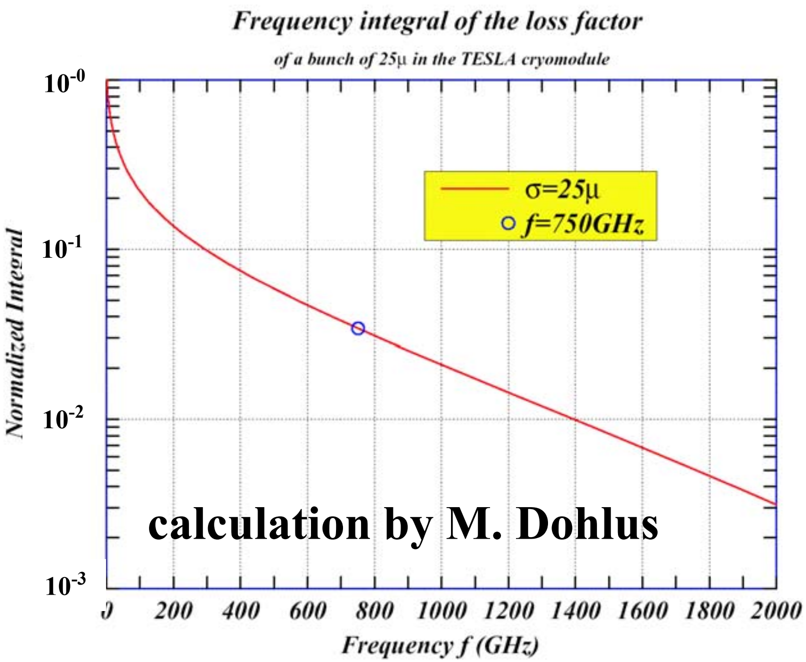
Short Bunches

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

⇒ **Higher loss factor:**

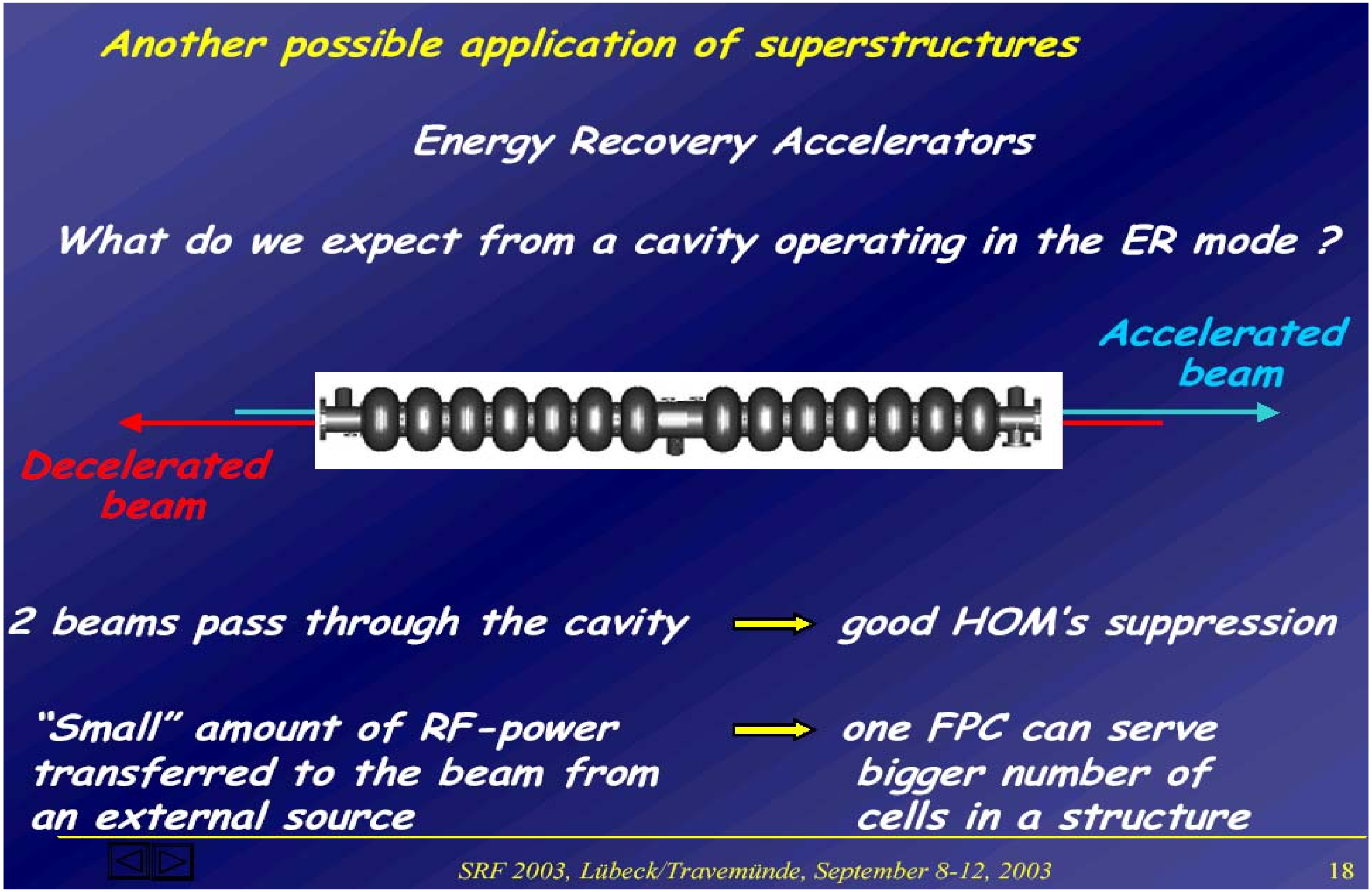


⇒ **Higher frequencies (up to THz):**

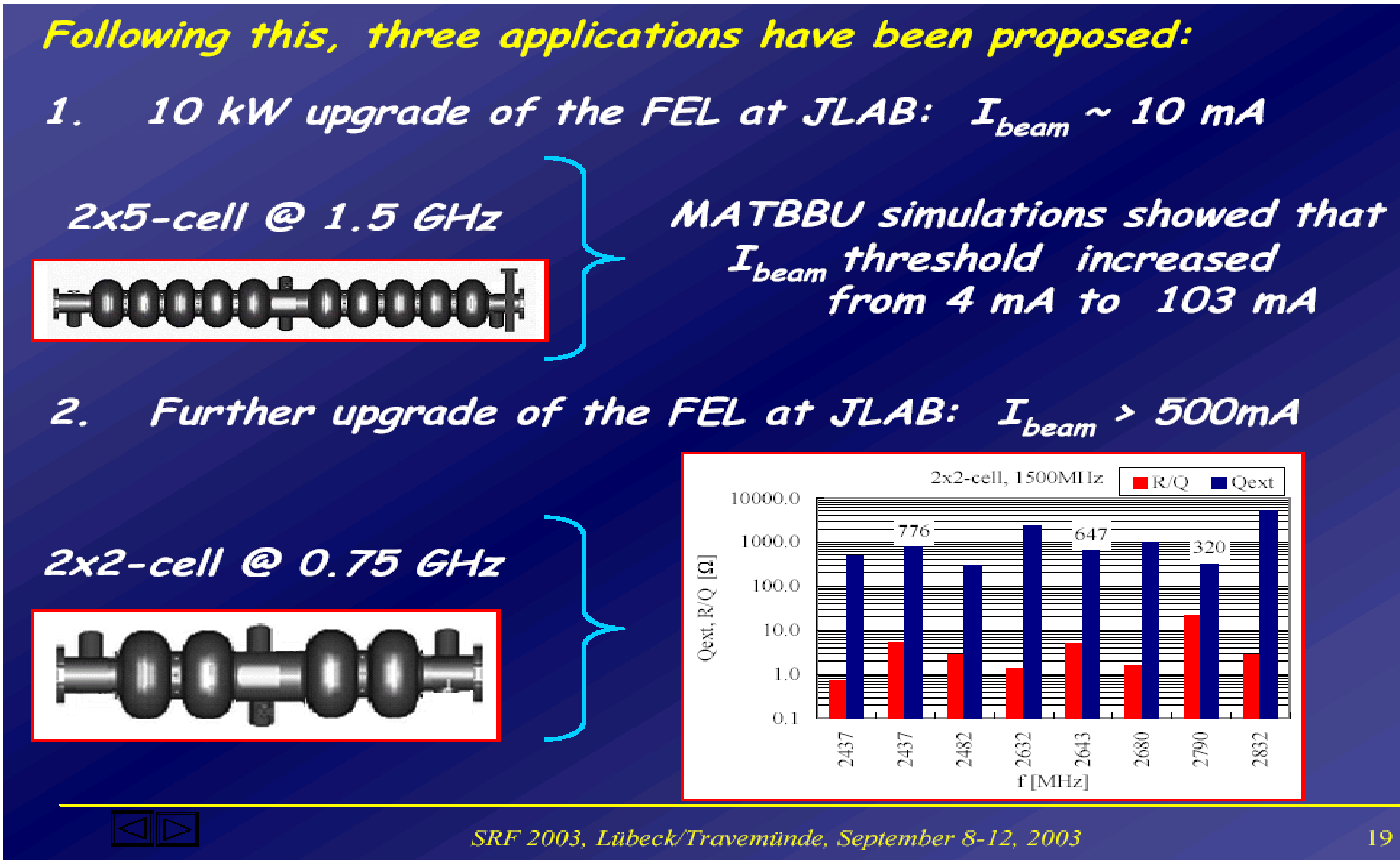


- **Where is the high frequency RF power absorbed? (s.c.walls for f > 750 MHz; n.c. walls, e.g. tubes bellows, input coupler ; RF absorber)**
- **Best broadband absorber material?**

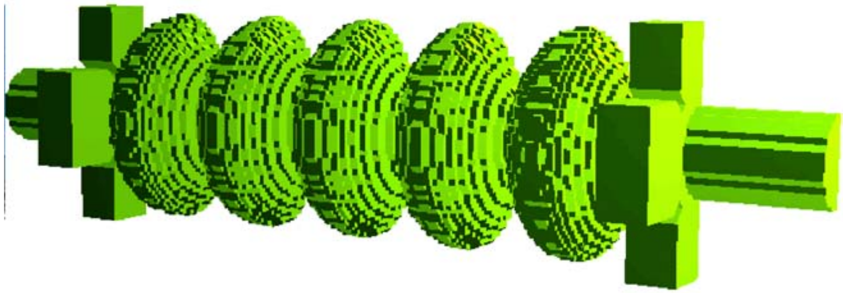
Super-Structures (J.Sekutowicz)

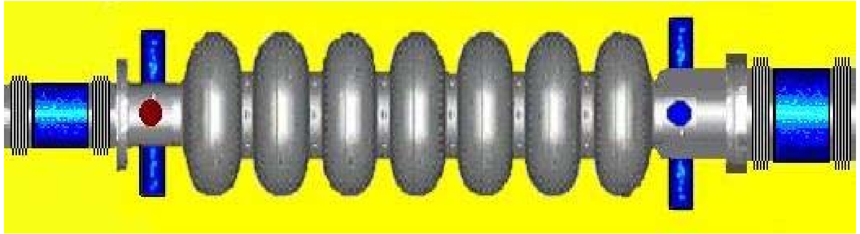


Super-Structures (J.Sekutowicz)

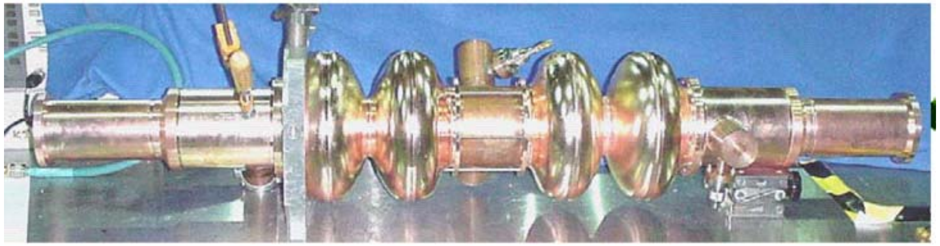


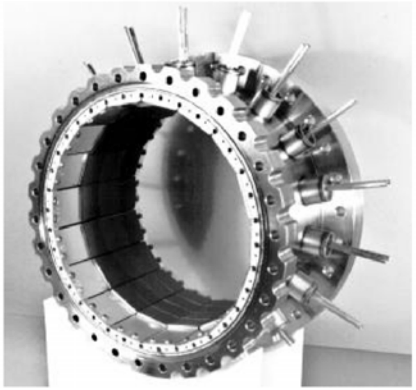
Achieving Strong HOM Damping





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





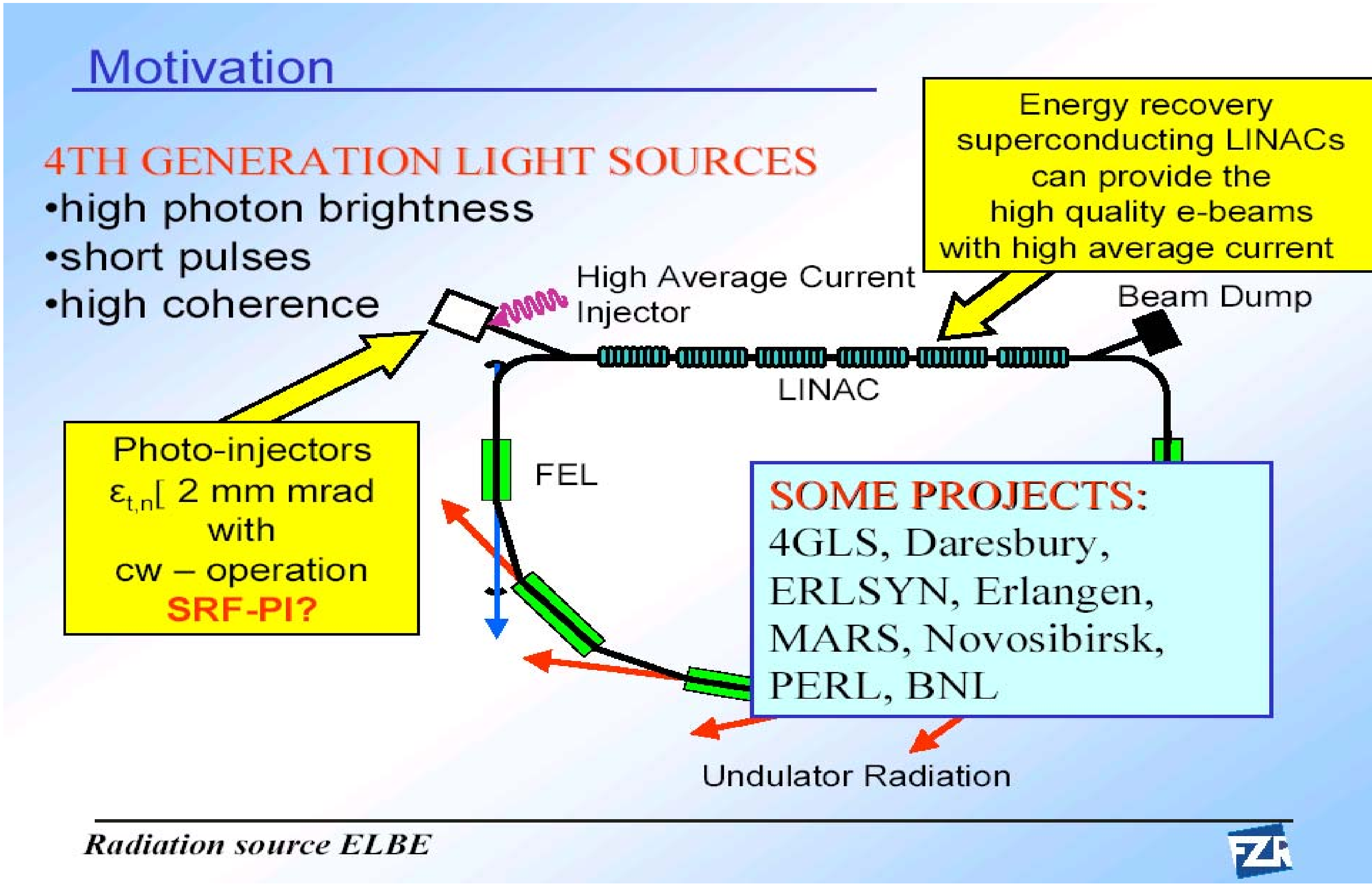
Cryogenic losses

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

$$P_{diss} = \frac{V_{acc}^2}{R/Q \cdot G} R_S$$

  - Cavity treatment for high Q_0
  - Optimal bath temperature?

SC Photo-Injector Status (J. Teichert)



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.

Radiation source ELBE

FZR

SC Photo-Injector Status

Summary

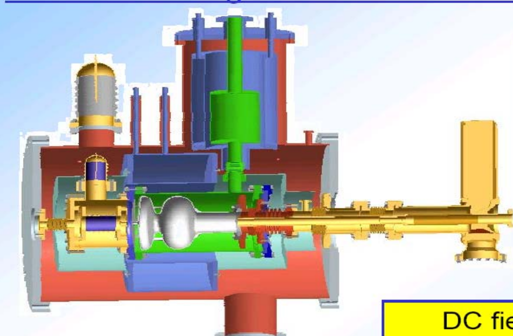
Overview of the SRF-PI Projects

	Peking Univ.	BNL	Rossendorf	
Type	DC-SC Gun	All Niobium	NC Cathode in SC Cavity	
Cell	1+1/2	1/2	1/2	3+1/2
Cathode	Cs_2Te	Laser-cleaned Nb	Cs_2Te	Cs_2Te
Q.E. @262 nm	0.01	5×10^{-5}	0.0025	0.05
Contamination	no	no	not found	?
transv. emittance	bad	good	good	best
Status	cool down to 4 K	Q measured at 4 K	**operated at 4 K**	Project started (cavity design)

Radiation source ELBE

SC Photo-Injector Status

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



1.5 cell, 1.3 GHz
Field: 15 MV/m (5 kW)
DC voltage: 70 kV
DC gap: 15 mm
Charge: 60 pC
Simulation:
Energy: 2.6 MeV
Trans. emittance:
12.5 mm mrad

DC field at cathode causes high emittance

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

Radiation source ELBE

SRF-PI: BNL All-Niobium SC Gun

No contamination from cathode particles

1/2 cell, 1.3 GHz
Maximum Field: 45 MV/m

Q.E. of Niobium @ 248 nm
with laser cleaning
before: 2×10^{-7}
after: 5×10^{-5}

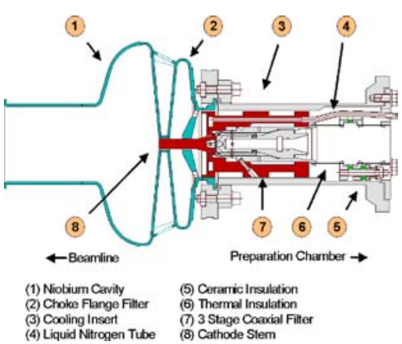
Thermal analysis:
maximum laser power of 1 W/cm^2
& low Q.E. limit current

T. Srinivasan-Rao et al., PAC 2003
I. Ben-Zvi, Proc. Int. Workshop, Erlangen, 2002

Radiation source ELBE

SRF-PI: Rossendorf SC ½ Cell Gun

normal-conducting cathode inside SC cavity

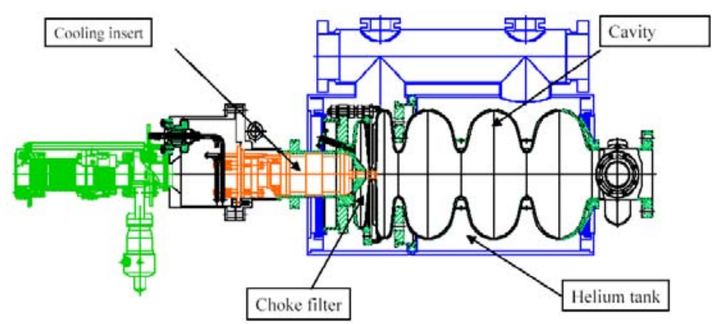


Cavity:
Niobium ½ cell, TESLA Geometry
1.3 GHz
Cathode:
Cs_2Te (262 nm, 1 W laser)
thermally insulated, LN_2 cooled

D. Janssen et al., NIM-A, Vol. 507(2003)314

SRF-PI: Rossendorf 3½ Cell Gun Project

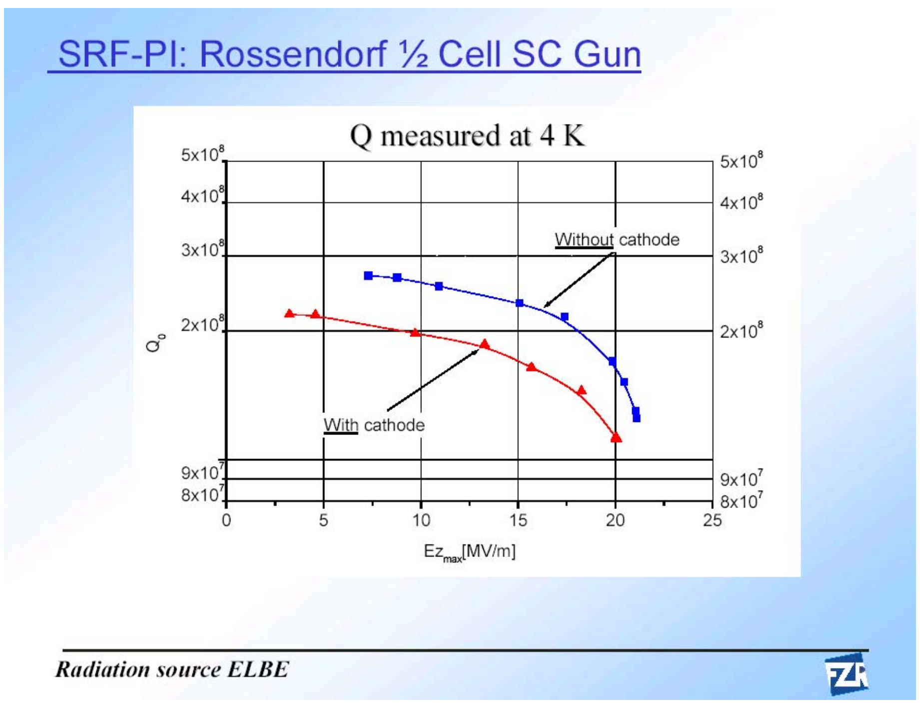
J.Stephan, D. Janssen, FZR, S.Kruchkov BINP

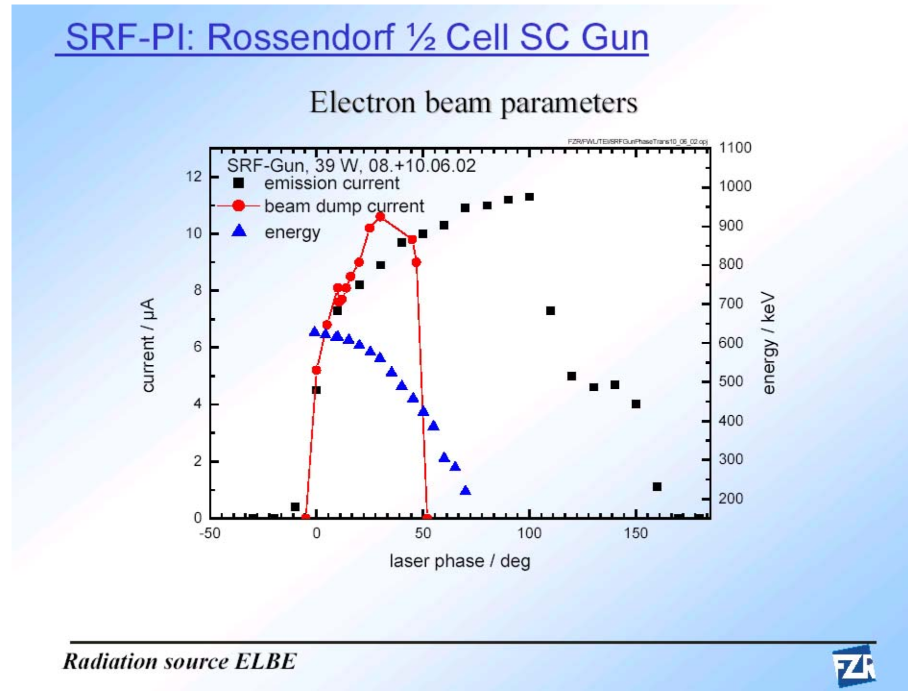


Radiation source ELBE

SC Photo-Injector Status

Proof of principle experiment at FZ Rossendorf





Conclusion(1)

- Proliferation of technology: HEP to e-storage rings to low β : proton machines, light sources,FEL,ERL's,RIA,sc photo-injectors
- Highlights: E_{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

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.