SRF Challenges for Improving Operational Electron Linacs

C. E. Reece

Outline

What is the real growing-edge experience with SRF systems for operational electron linacs?

- **Contamination control** → field emission and heat
- **Magnetic field environment** → heat
- **Seals and gaskets** → vacuum leaks
- **Cavity processing protocol** → reliable peak results
- **Fabrication tolerances and HOM damping** → BBU
- **Heat management** → operational limitations & cost
- **Microphonics management** → power efficiency

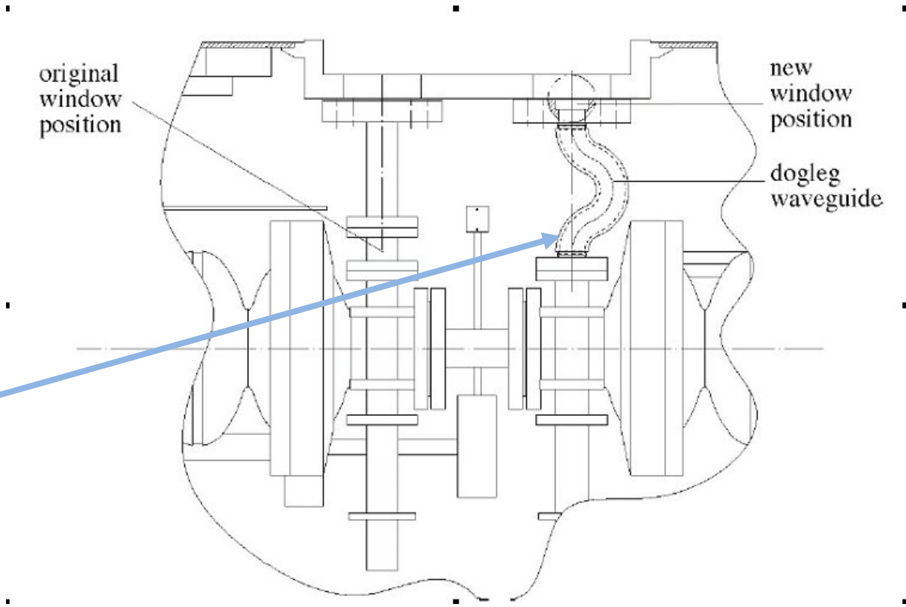
Outline

- CEBAF
  - Reworking 20-year-old cryomodules -- **C50**
  - Learning from upgrade prototype cryomodules
  - 12 GeV Upgrade project
- S-DLINAC
  - Improving *Q*'s and increasing energy
- ELBE
  - Field emission limited energy
  - Developing SRF gun

Rework of CEBAF Cryomodules – C50 program

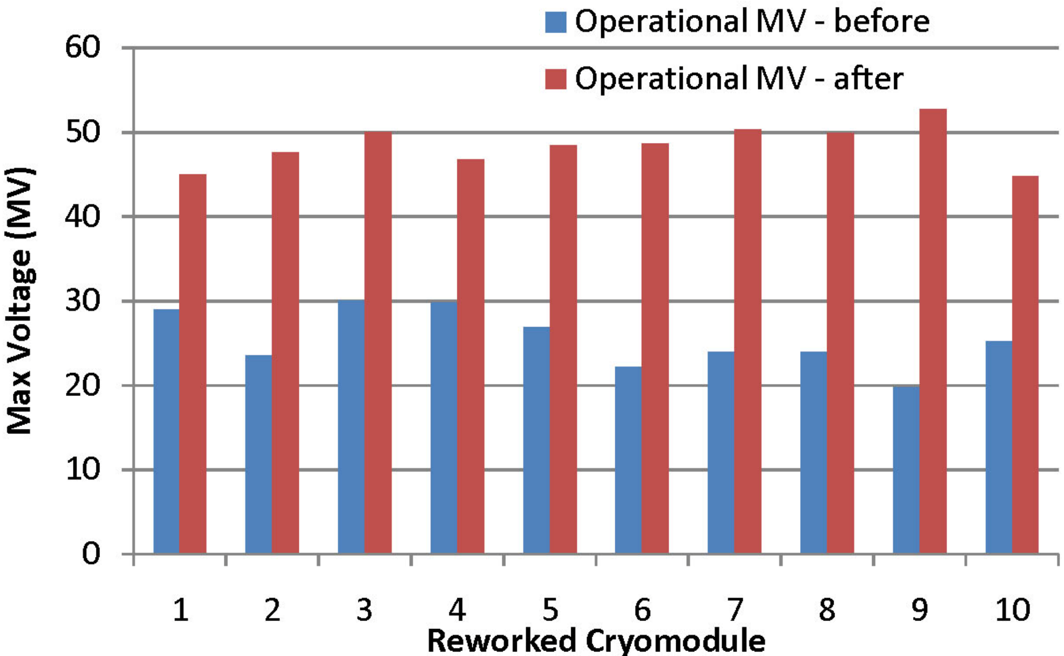
- **Objective**
  - **Clean-up field emission**
  - **Raise useful gradients from ~5.5 MV/m to 12.5 MV/m**

- Ten cryomodules were fully disassembled
- Cavities (fabricated 1991)
  - Baked @ 600°C
  - Tuned
  - 30 μm BCP
  - HPR UPW
- Cold rf window moved outboard of new "dogleg" waveguide section
- Cavity pairs assembled under improved cleanroom conditions
- Cryomodules were reassembled, tested, and reinstalled in CEBAF



M. Drury, et al., "Summary Report for the C50 Cryomodule Project" TPU108, PAC2011

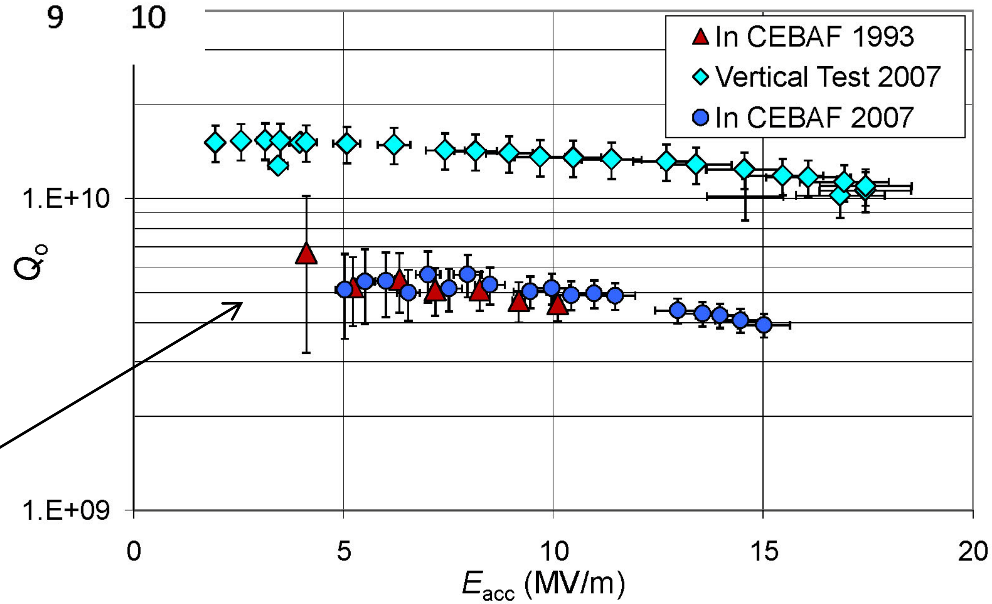
Rework of CEBAF Cryomodules – C50 program



Operating range in CEBAF is limited to 13.5 MV/m by RF power

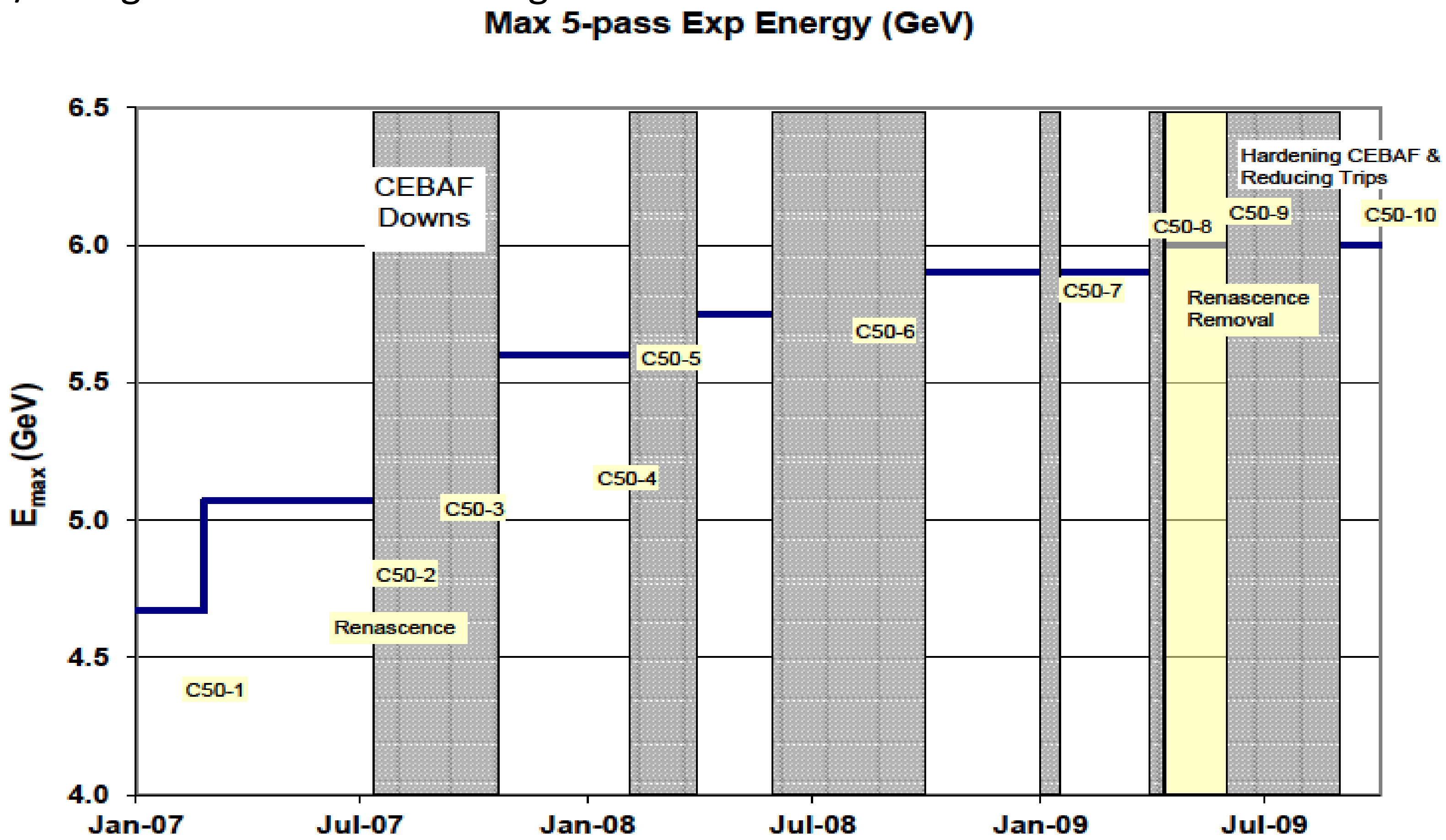
- Excellent improvement in gradient, FE effectively eliminated
- But *Q*'s still low in cryomodule – now attributed to **unrecognized magnetized CM components**

Example



Rework of CEBAF Cryomodules – C50 program

- Established a solid 6 GeV base for the 12 GeV upgrade, but cryo heat load is higher than expected
- Operational setup now considers cavity 2K W/MV as well as MV/m in gradient distribution algorithm



Evolution of CEBAF energy with C50 progress

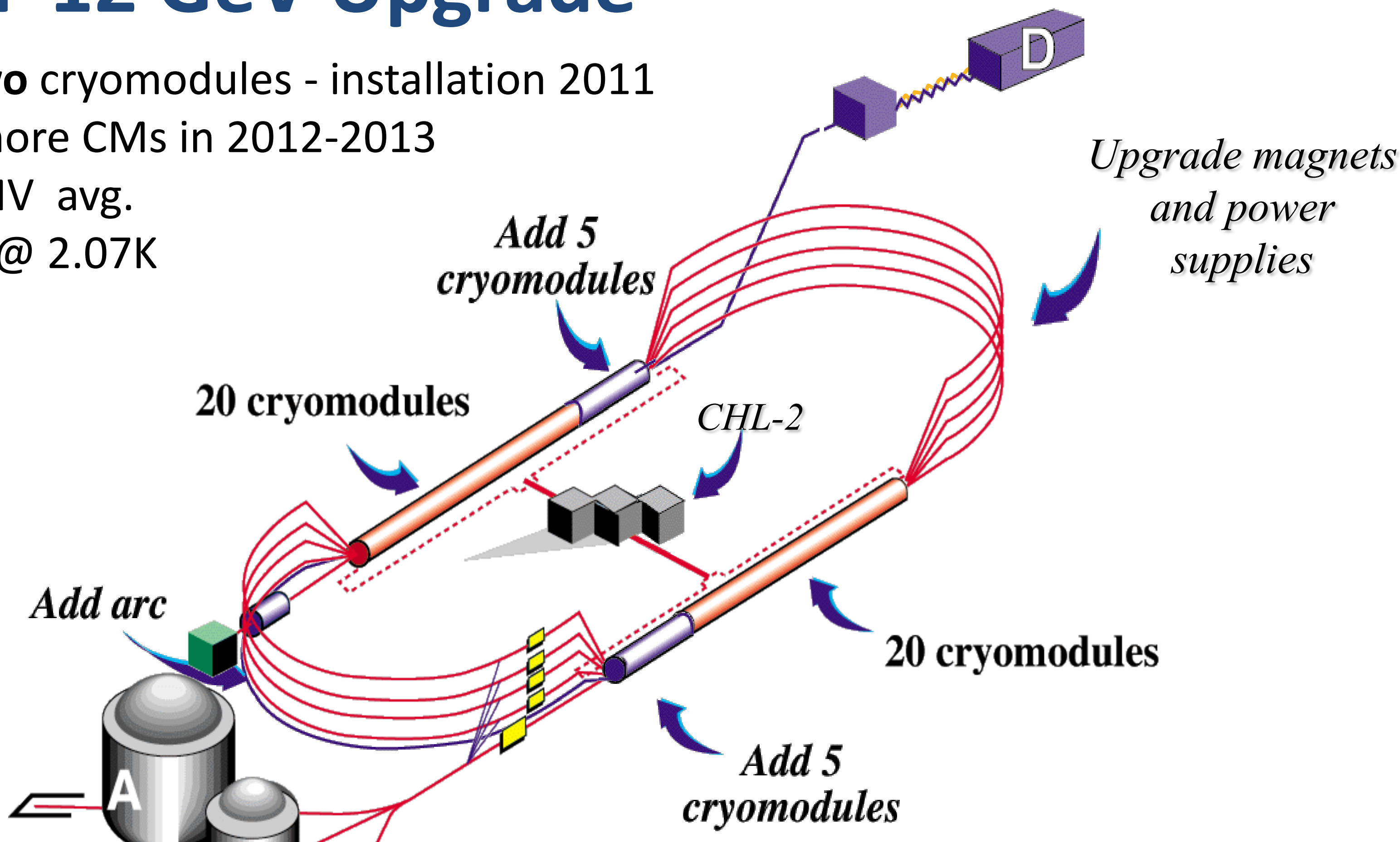
CEBAF Prototype Upgrade Cryomodule Challenges

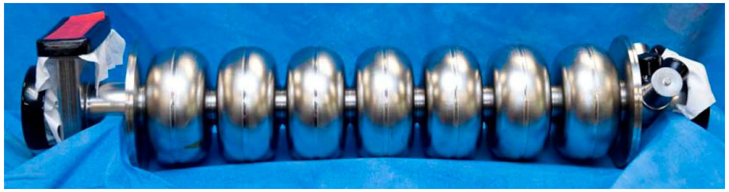
- **New CM design** – 8-cavity string suspended in space frame
- **New cavity designs** – "HG" and "LL"
- **New Tuners** – two designs tested, "scissor-jack" selected
- **Feedthroughs** – leak tight and thermally stable
- **RF waveguide windows -** leak tight and thermally stable
- **Cu-plated SS waveguide** – low rf loss, low static loss, no particulates
- **Flange seals** – cavity waveguide coupler – serpentine gasket
- **Cavity fabrication tolerances** – HOM damping → BBU

- A.-M. Valente, et al., *Production and Performance of the CEBAF Upgrade Cryomodule Intermediate Prototypes.* TUPKF072, EPAC2004
- C. E. Reece et al., *Performance of the CEBAF Prototype Cryomodule Renascence,*"WEP32, SRF2007
- F. Marhauser , *JLab Cavity Fabrication Errors, Consequences, and Lessons Learned* JLab TN-10-021
- R. Kazimi, et al., *Observation and Mitigation of Multiturn BBU in CEBAF* WEPP087, EPAC08
- F. Marhauser et al. *Critical Dipole Modes in JLab Upgrade Cavities,* THP009, LINAC10

CEBAF 12 GeV Upgrade

First **two** cryomodules - installation 2011
Eight more CMs in 2012-2013
≥108 MV avg.
300 W @ 2.07K





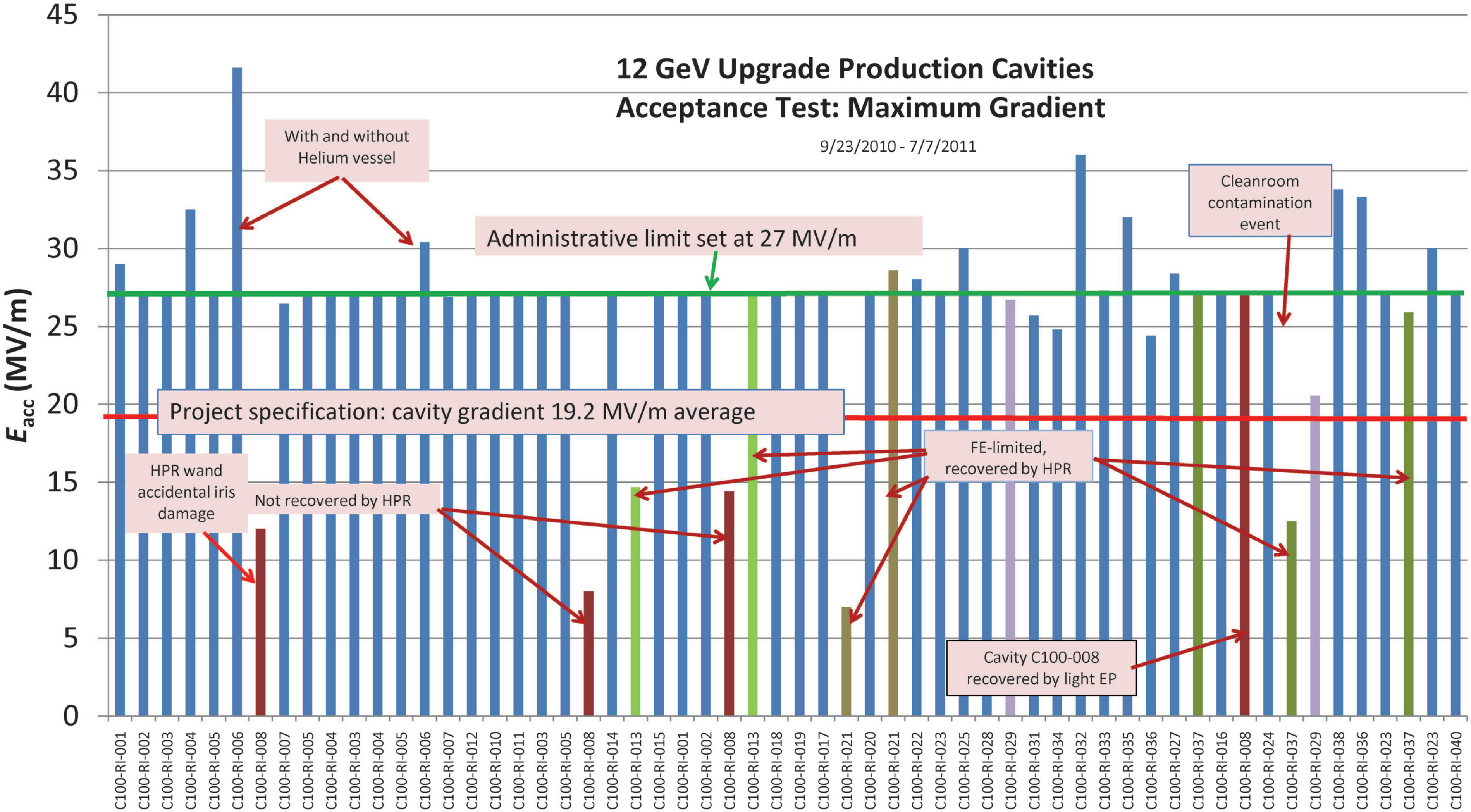
Cavity: 0.7 m, "Low loss" cell shape, 1.497 GHz
8 cavities/cryomodule

12 GeV Upgrade Cavities

- **Production process** – press for reliable efficiency
  - **160 µm BCP** and pre-tuned **by vendor**
  - Receipt inspection – mechanical and rf
  - US >> Bake: 600 C, 10 hrs
  - US >> EP: **30 µm, @20°C** regulated by external water spray
  - US >> Tune
  - Helium vessel welding
  - Flange lapping
  - HPR
  - Partial assembly
  - HPR >> dry in Class 10 cleanroom
  - Final assembly, leak check
  - Bake: **120° C, 24 hrs**
  - Vertical test @ 2.07 K
  - HPR >> dry in Class 10
  - String assembly

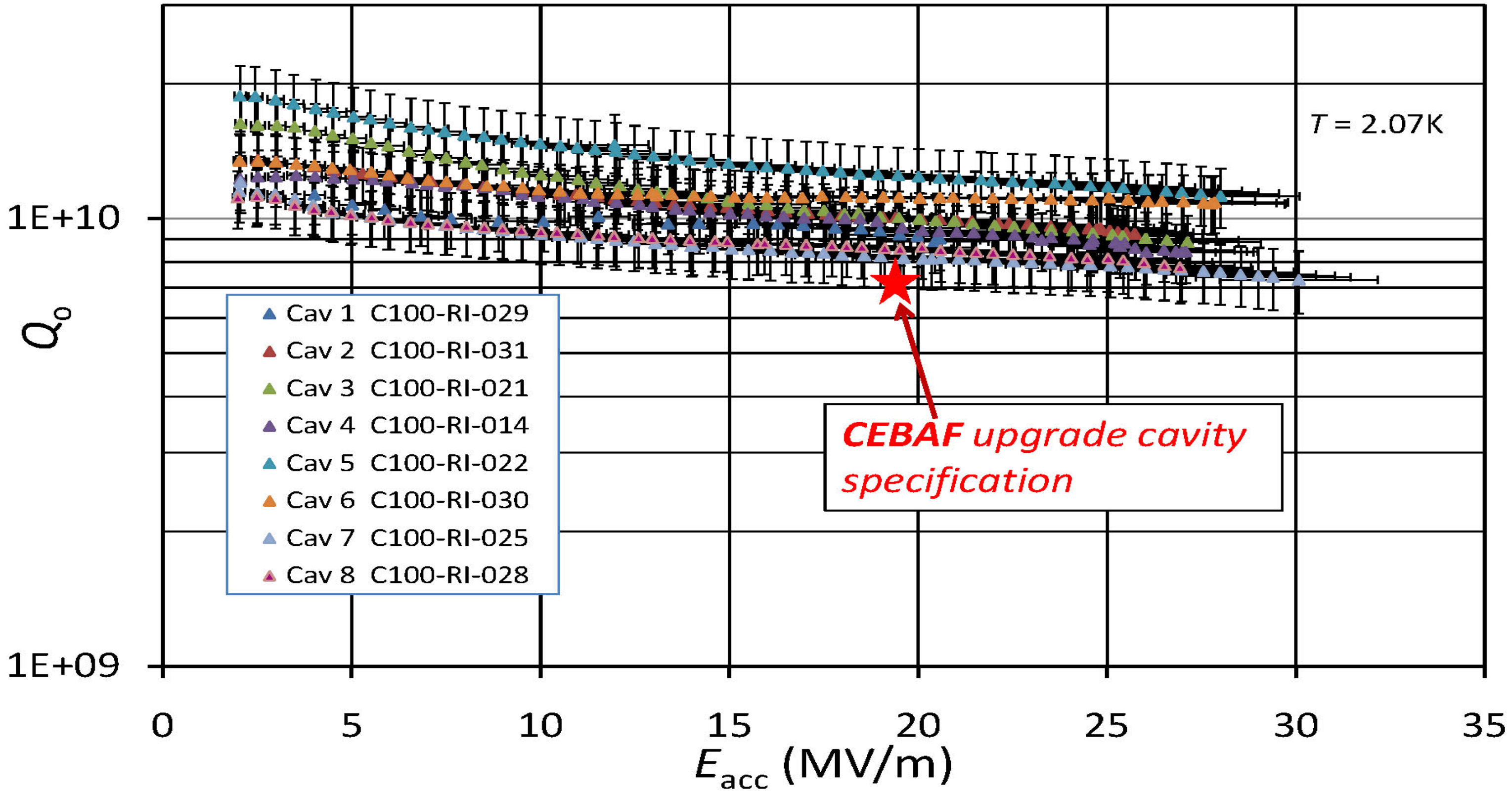
A. Reilly et al., *Preparation and Testing of the SRF Cavities for the CEBAF 12 GeV Upgrade,"* **TUPO061** this conference.

12 GeV project cavities – to date



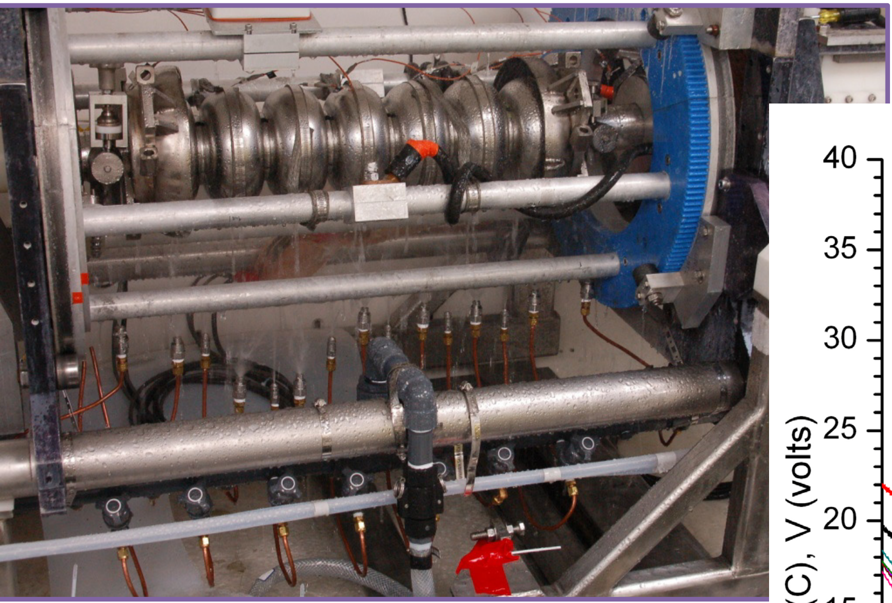
12 GeV project cavities

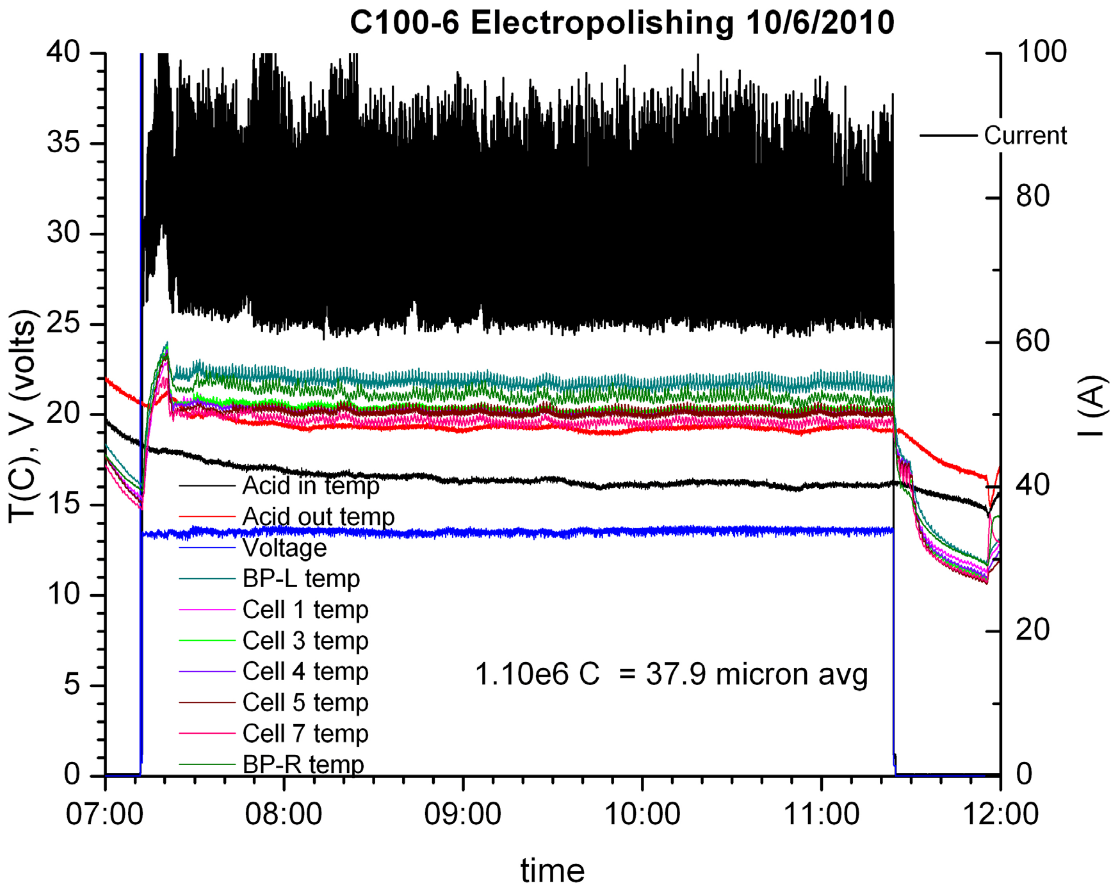
Vertical acceptance test of the 8 cavities in C100 string #3



12 GeV Upgrade Cavities

- Improved electropolishing process is now standardized and controlled

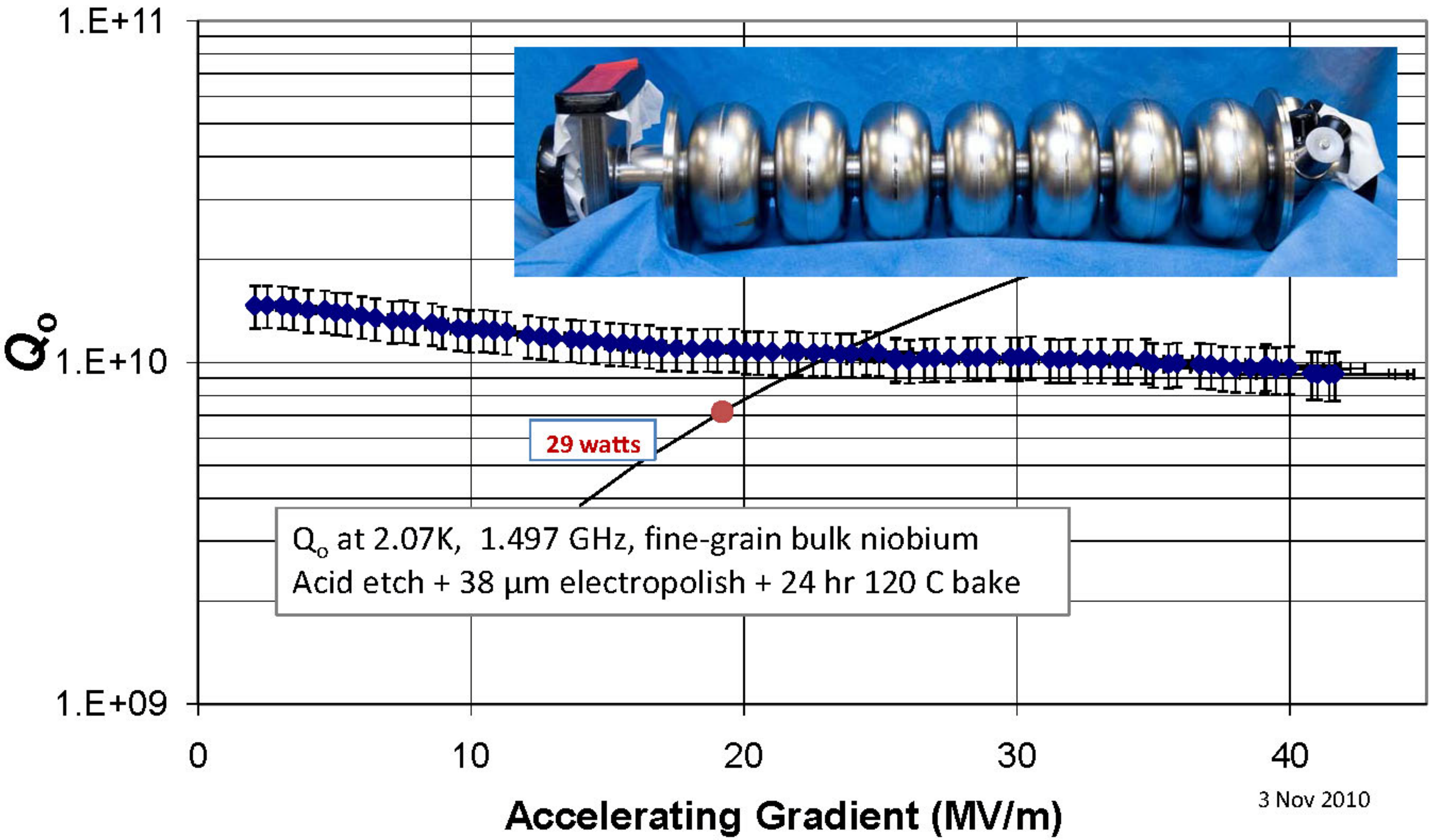




C. E. Reece and H. Tian, *Exploiting New Electrochemical Understanding of Niobium Electropolishing for Improved Performance of SRF Cavities for CEBAF*
THP010, LINAC10

State-of-the-art production SRF cavity

C100-6



(Q is BCS-limited)

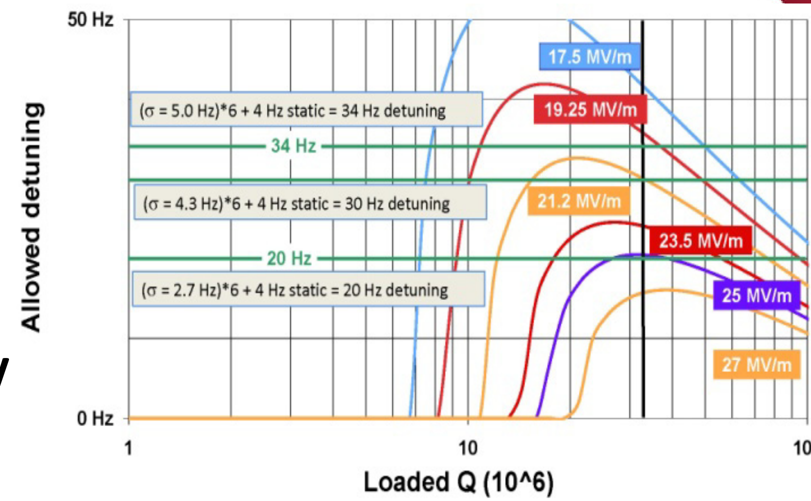
12 GeV Upgrade Cryomodule

First cavity string @ completion

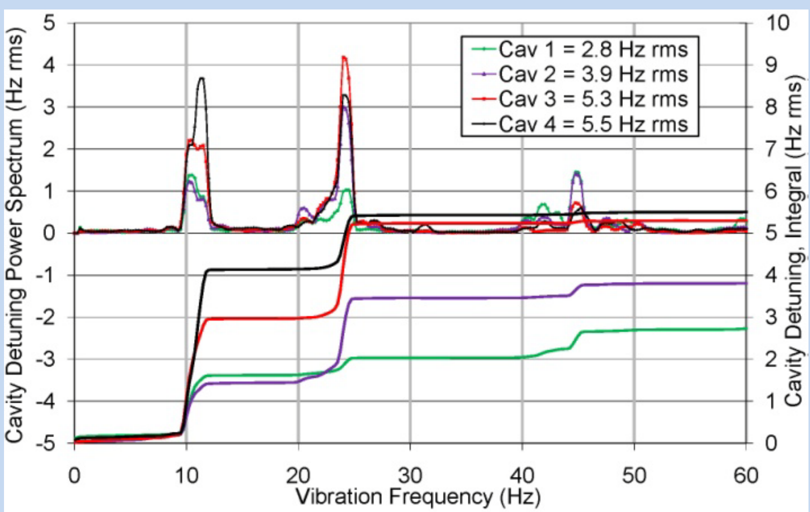
Installation of super-insulation on upgrade cryomodule

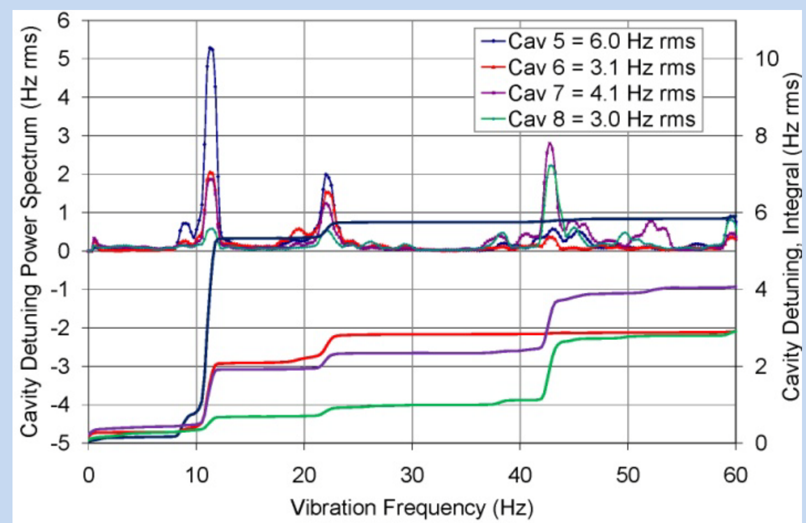
Other CEBAF Upgrade SRF Challenges

- Found weak specification on SS helium vessel material
  - High permeability, **degraded cavity *Q***
  - Found early, material replaced
  - Issue was resolved quickly
- Higher than expected **microphonic sensitivity** found in first cryomodule
  - Investigation guiding attention to string longitudinal modes
  - Microphonic detuning **budget is 5 Hz RMS**



Detuning limit of C100 cavities with 12 kW of available rf power at several different operating gradients, with 460 μA design beam current





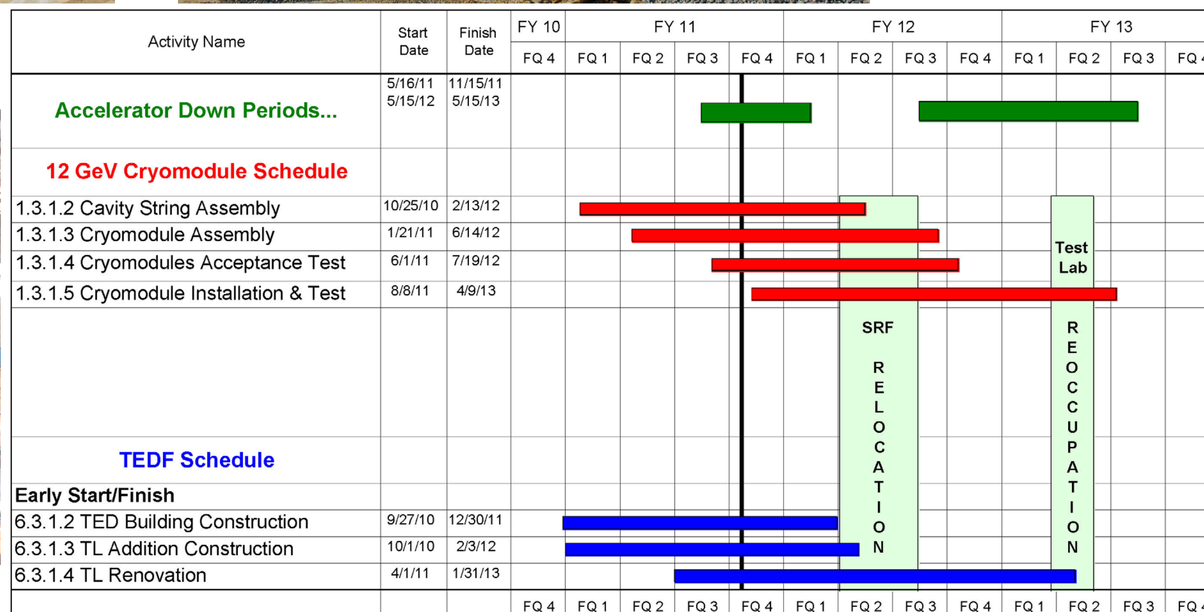
Initial test data from C100-1 CM in CEBAF June 2011 - courtesy Kirk Davis

CEBAF Upgrade Challenge – Simultaneous Facility Upgrade

Reliable acid transfer?

Cryomodule assembly?

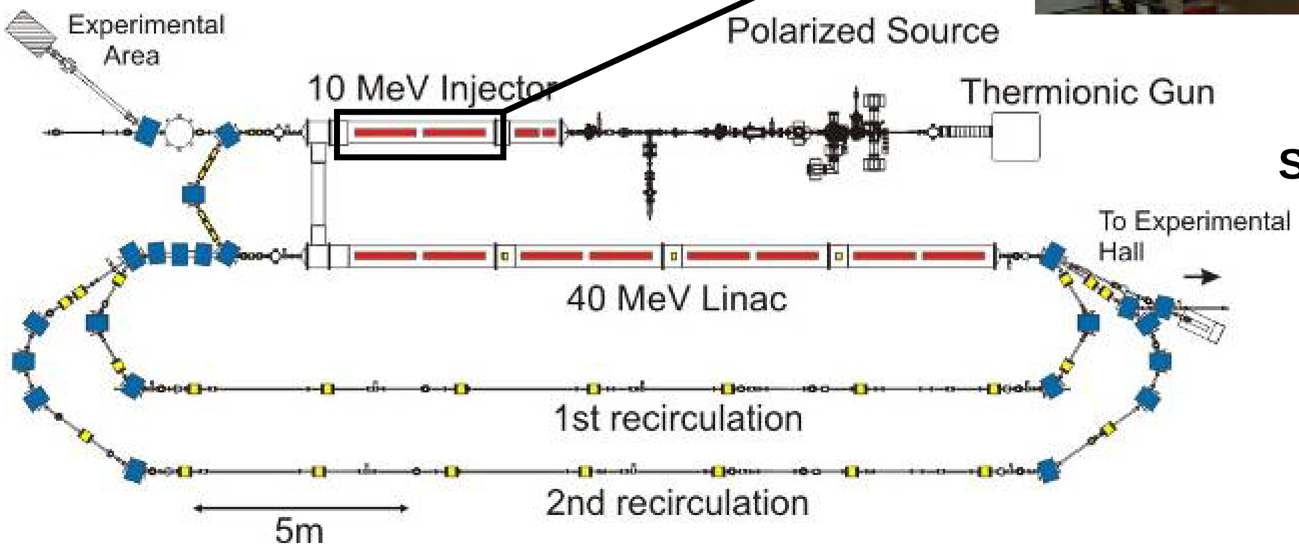
New cleanroom?



C. E. Reece and A. Reilly, *A New Home for SRF Work at JLab--the Technology and Engineering Development Facility*, **TUPO061** this conference.

Injector Upgrade Program

- Energy increase in the injector section from 10 up to 14 MeV
- Increase in current from 60 μA to 150 – 250 μA



Kürzeder et al., Adv. in Cryog. Eng. ***55A*** *(2010) 831*

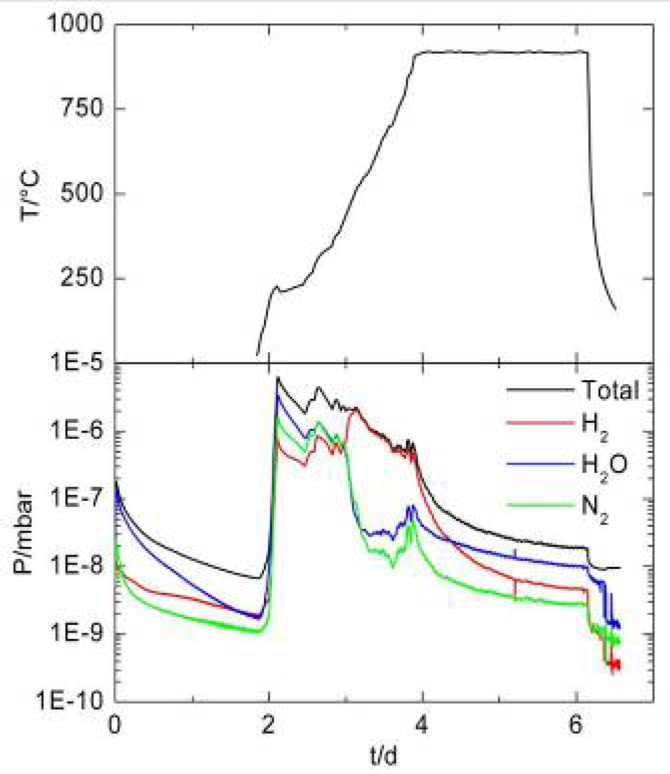
S-DALINAC

Freq.:	3 GHz
Duty cycle:	cw
Temp.:	2 Kelvin
Max. E.:	130 MeV
Max. curr.:	20-60 μA

In operation since 1991

Cavity improvements by firing

Improvement of the quality factor



Status:

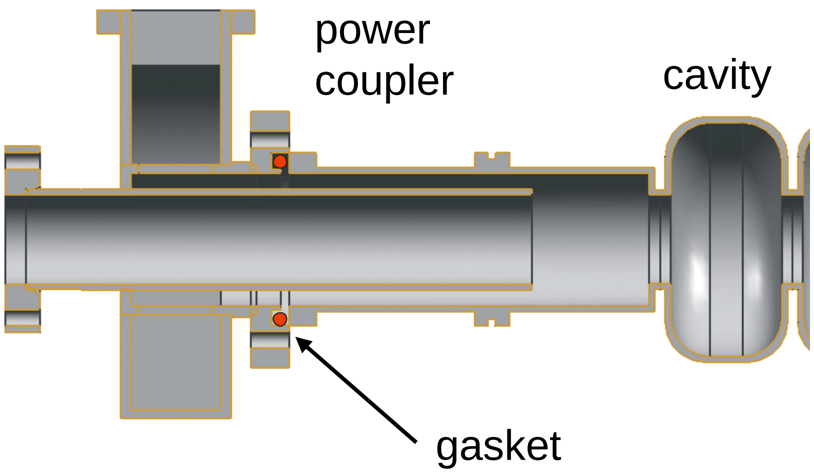
- 7 of 14 cavities fired
- Q increased from typ. **$8*10^8$** to **$1.5*10^9$**

Effect on accelerator performance (combined with other measures):

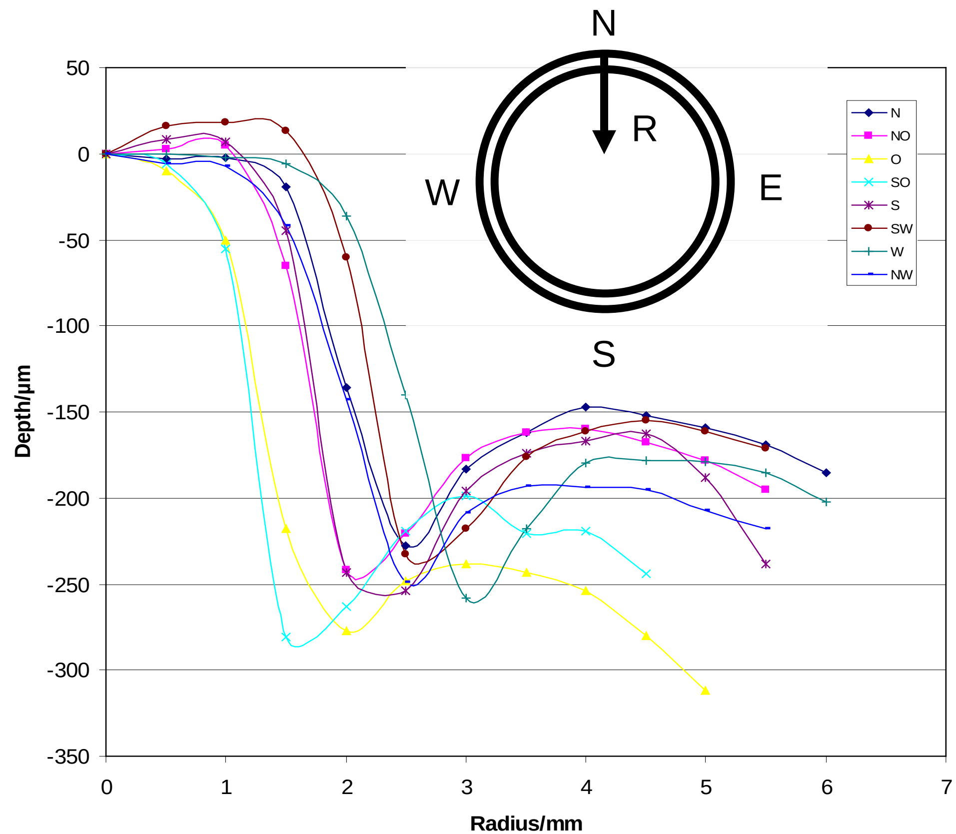
Increased energy
60 MeV (2007)
80 MeV (2008)

R. Eichorn et al., Proc. LINAC 2008 (2008) 395

Cold leaks related to helicoflex gaskets

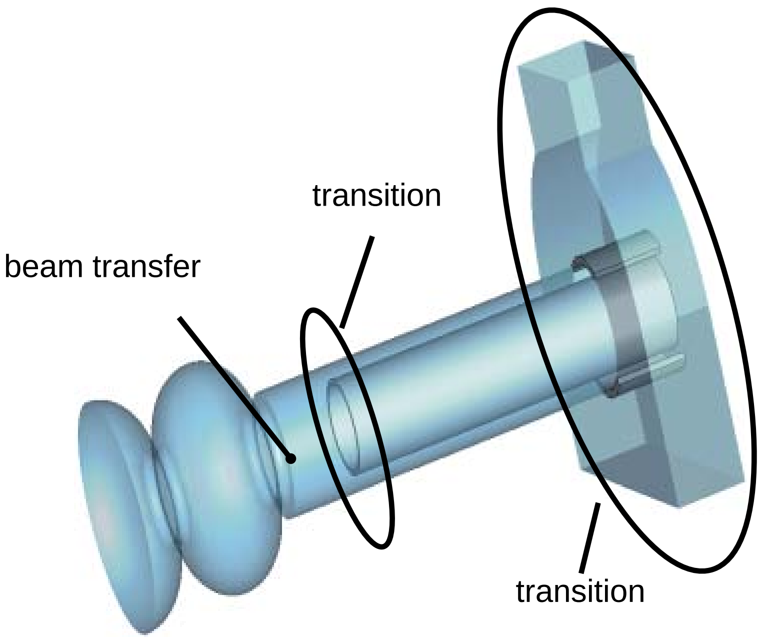


Imprint on the cavity flange



R. Eichhorn et al., Cryo-Opps Workshop 2010

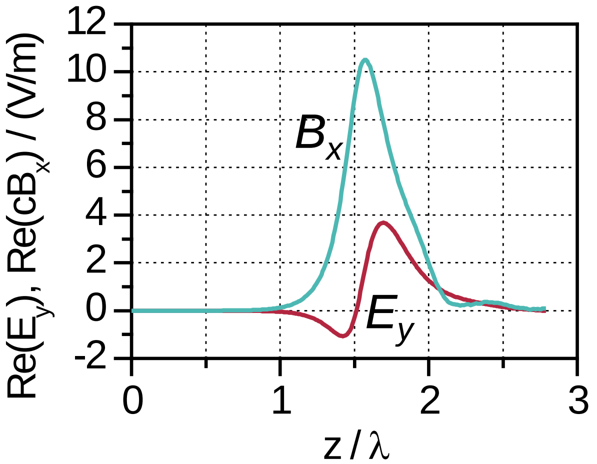
Waveguide to coaxial power coupler with low transversal fields

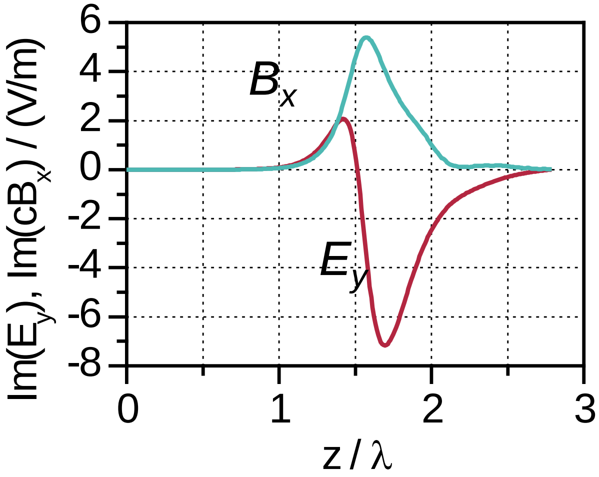


$V_{acc} \approx 7$ MV

$Q_{ext} \approx 5 \cdot 10^6$

kick $\approx$ $-(2{,}2 + i \cdot 3{,}2) \cdot 10^{-6}$





M. Kunze et al., Proc. LINAC 2004 (2004) 736

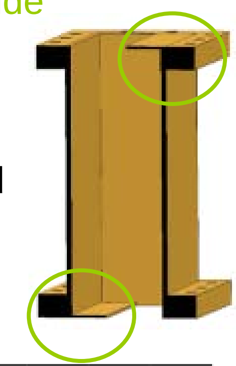
Waveguide cold-warm transition

Special waveguide to reduce heat radition

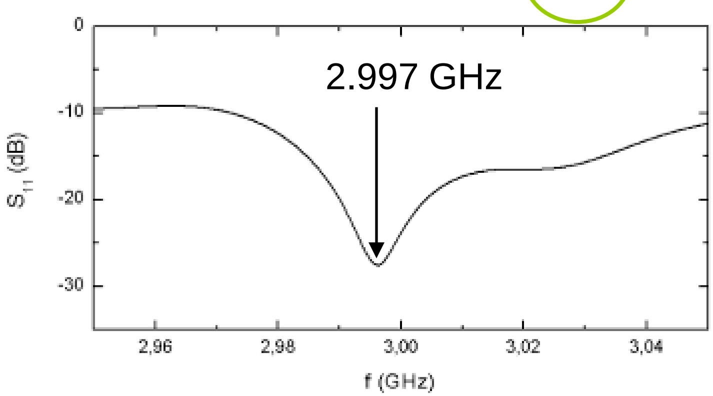
Flexible WR-284 waveguides (custom product)

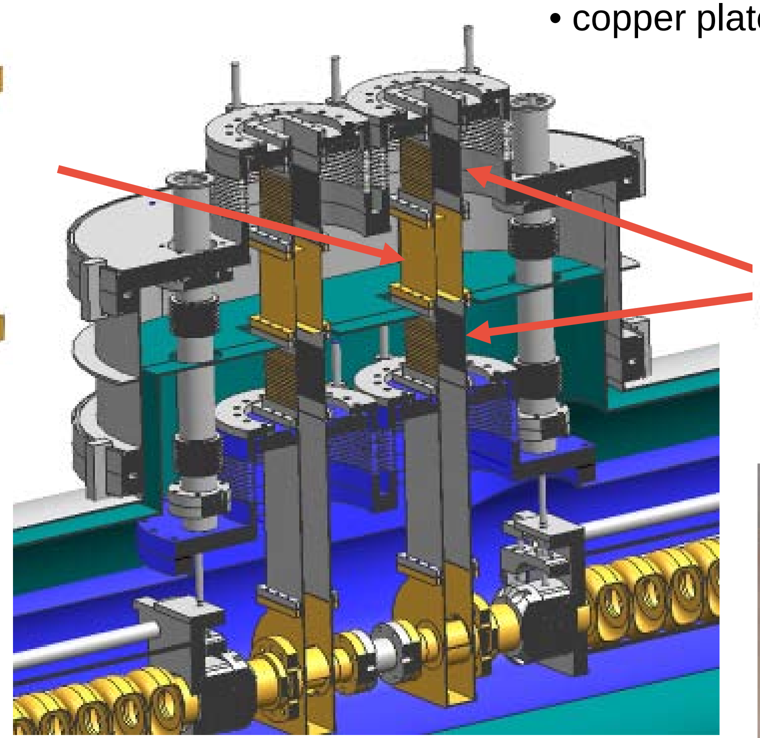
- stainless steel
- copper plated

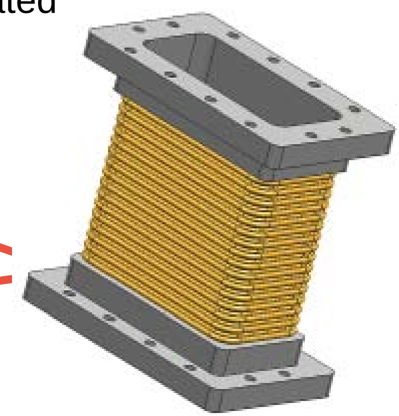
small bars inside the waveguide cooled down to 77 K



with the appropriate distance the RF reflection is minimized at working frequency





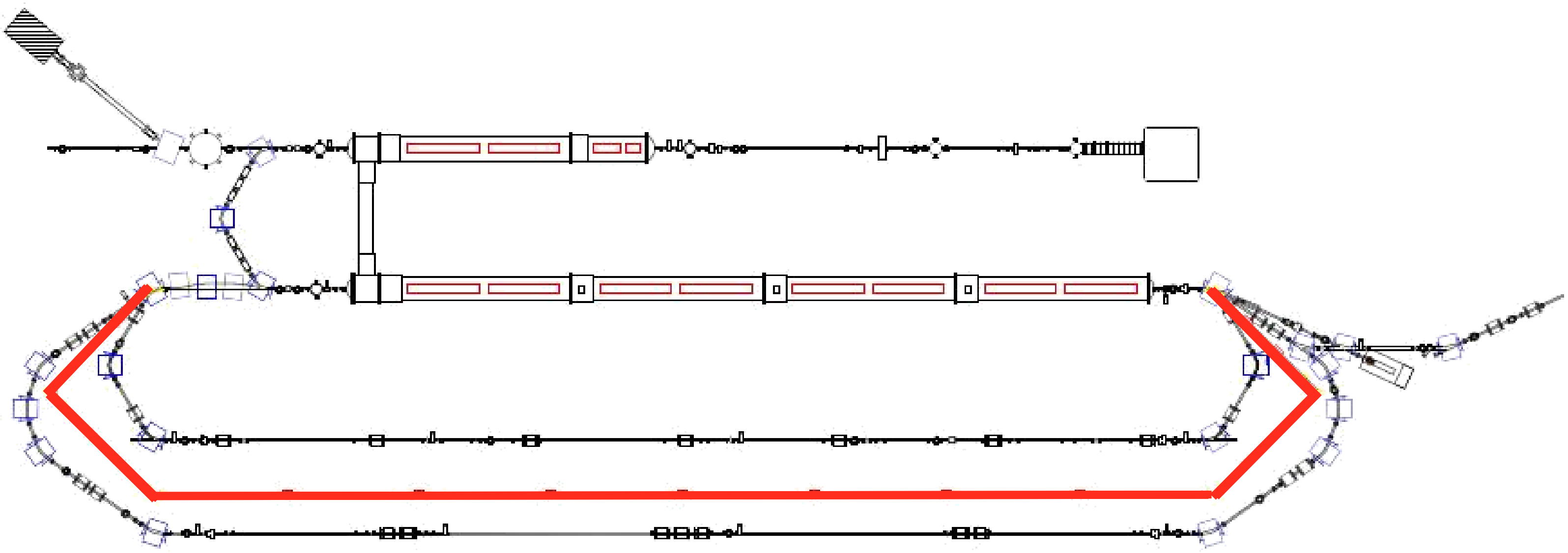


-> Poster: R. Eichhorn et. al.

Upcoming Upgrades (2011-2013), fully financed

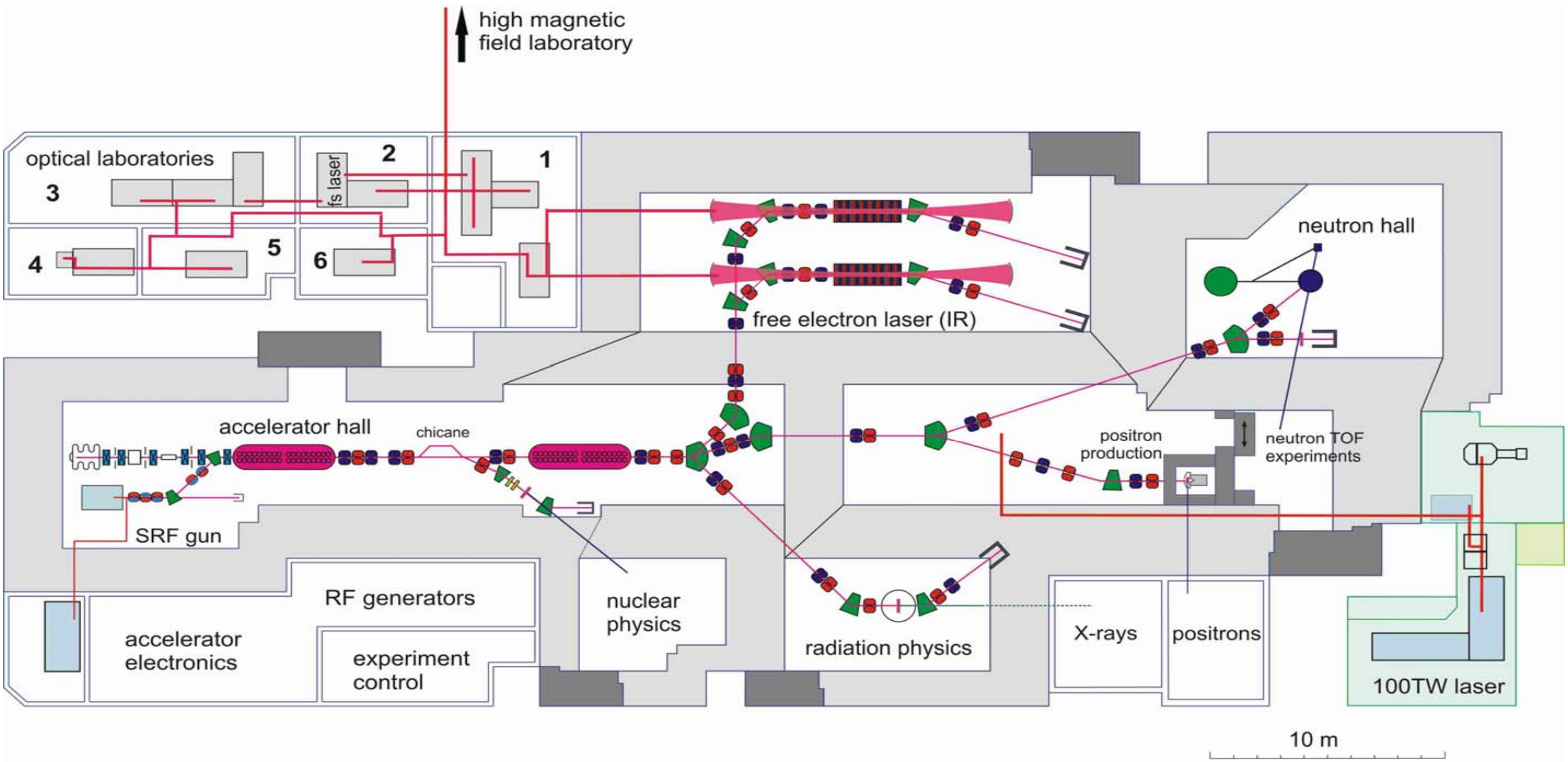
TECHNISCHE UNIVERSITÄT DARMSTADT

- Installation of a third recirculation path allows 130 MeV in cw operation (currently 85 MeV)

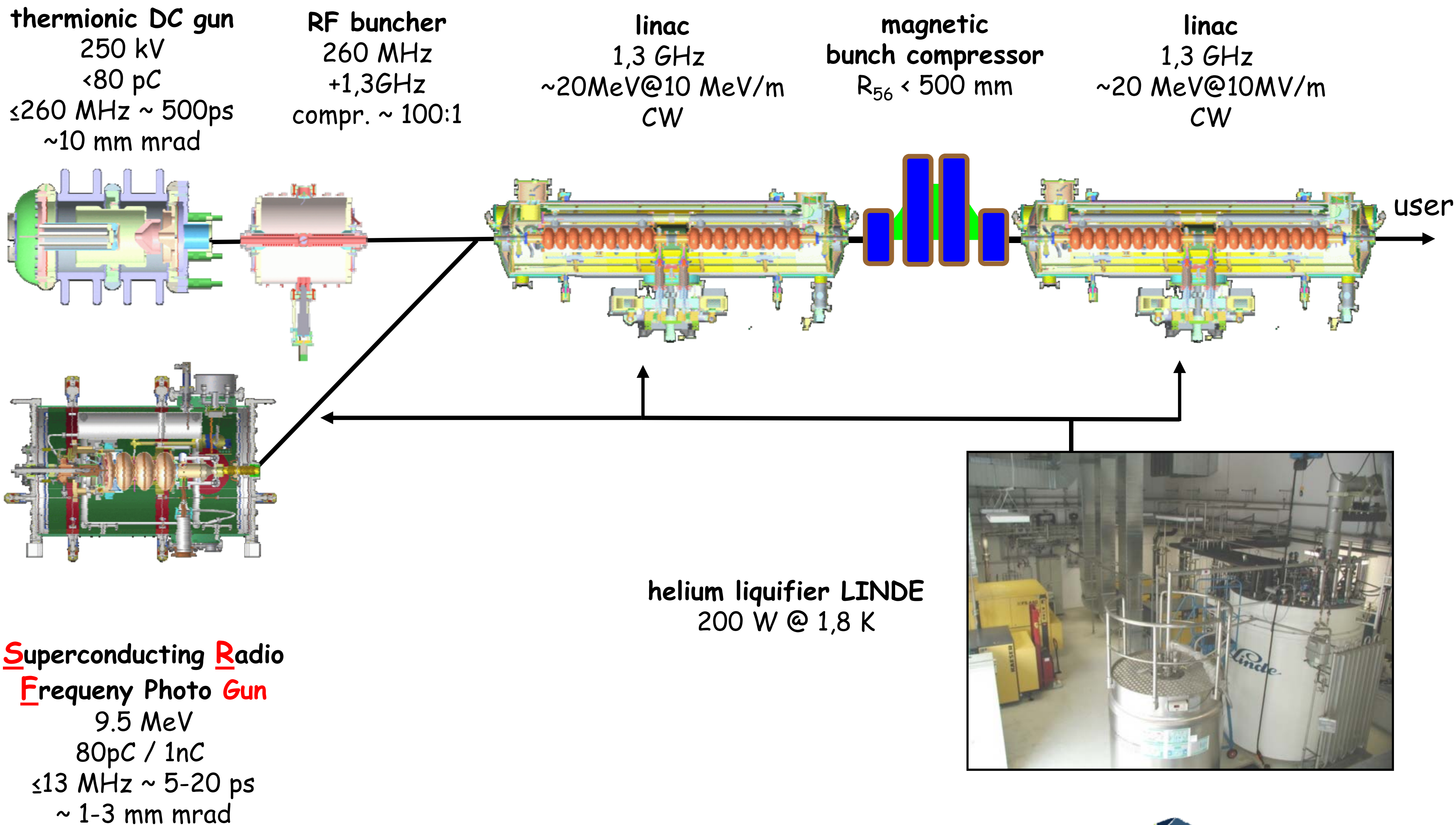


- Installation of two scraper systems (injector arc and extraction beam line: halo free beam with excellent energy definition
- Improvement of the LLRF system and non-isochronous beam dynamics

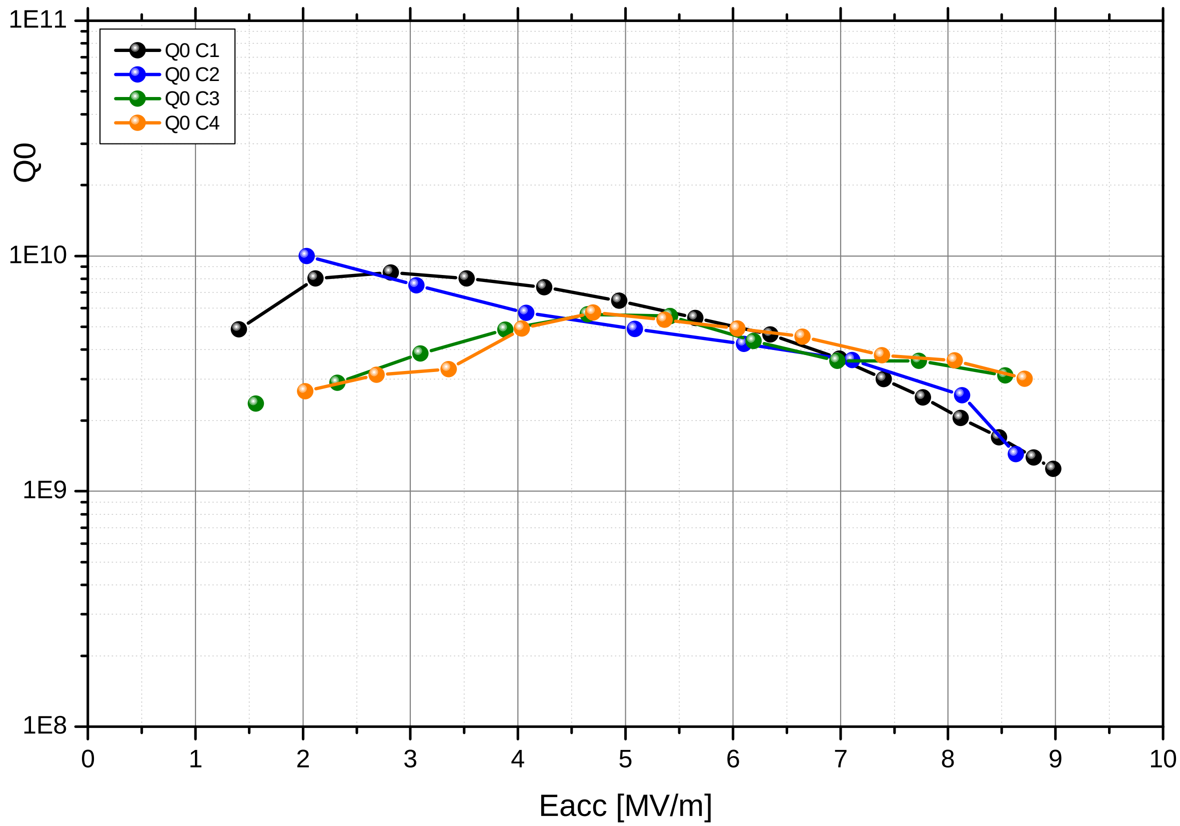
radiation facility ELBE



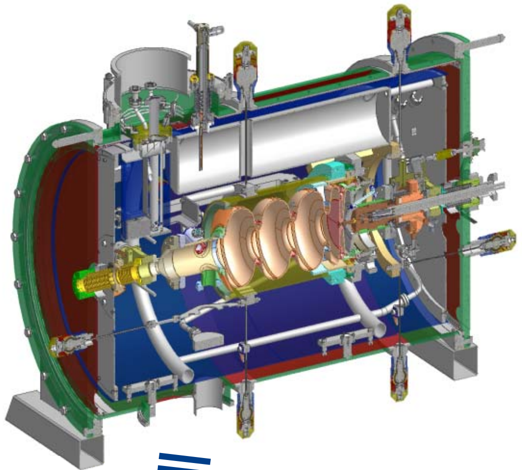
1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Time-resolved semiconductor spectroscopy, THz-spectroscopy
4: FTIR, biological IR experiment
5: Near-field and pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal deflection spectroscopy


thermionic DC gun
250 kV
<80 pC
≤260 MHz ~ 500ps
~10 mm mrad
RF buncher
260 MHz
+1,3GHz
compr. ~ 100:1
linac
1,3 GHz
~20MeV@10 MeV/m
CW
magnetic
bunch compressor
R56 < 500 mm
linac
1,3 GHz
~20 MeV@10MV/m
CW
user
helium liquifier LINDE
200 W @ 1,8 K
Superconducting Radio
Frequeny Photo Gun
9.5 MeV
80pC / 1nC
≤13 MHz ~ 5-20 ps
~ 1-3 mm mrad

• performance of the four TESLA cavities @ ELBE

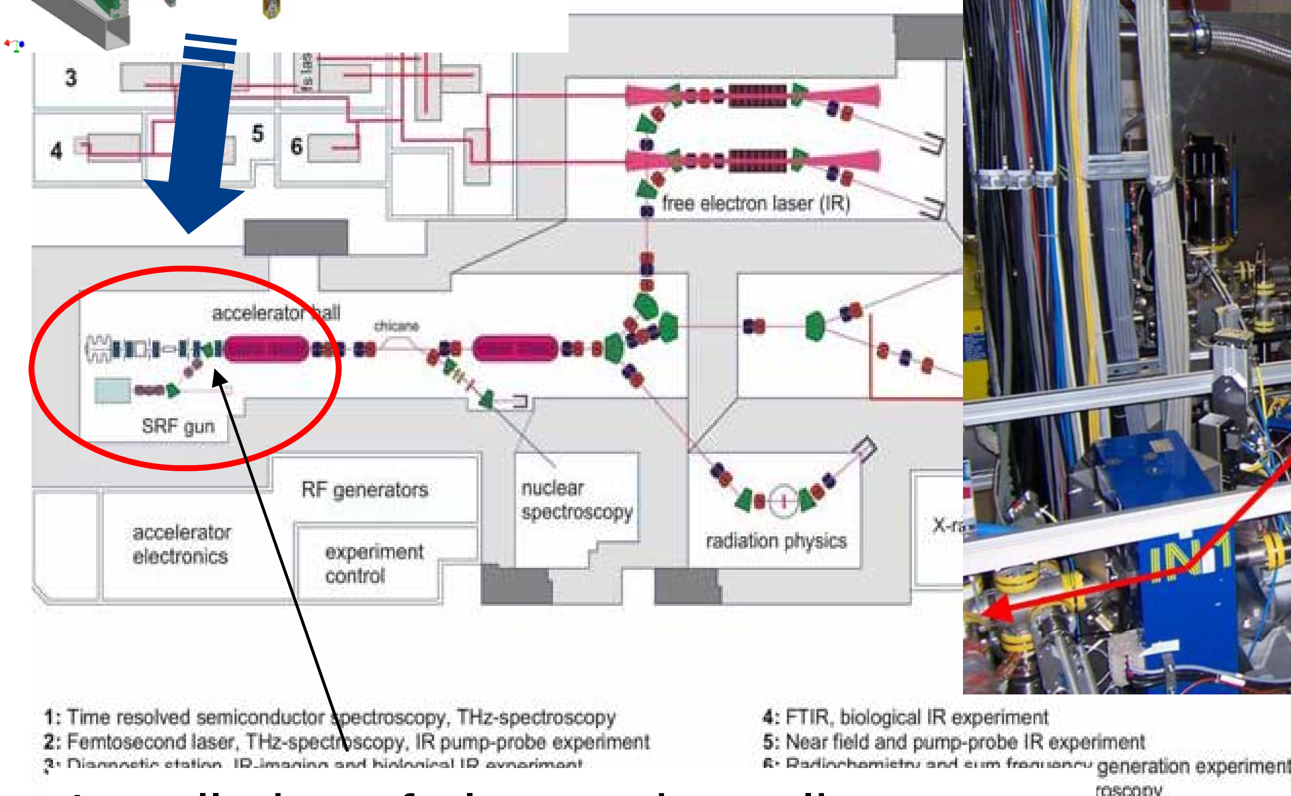


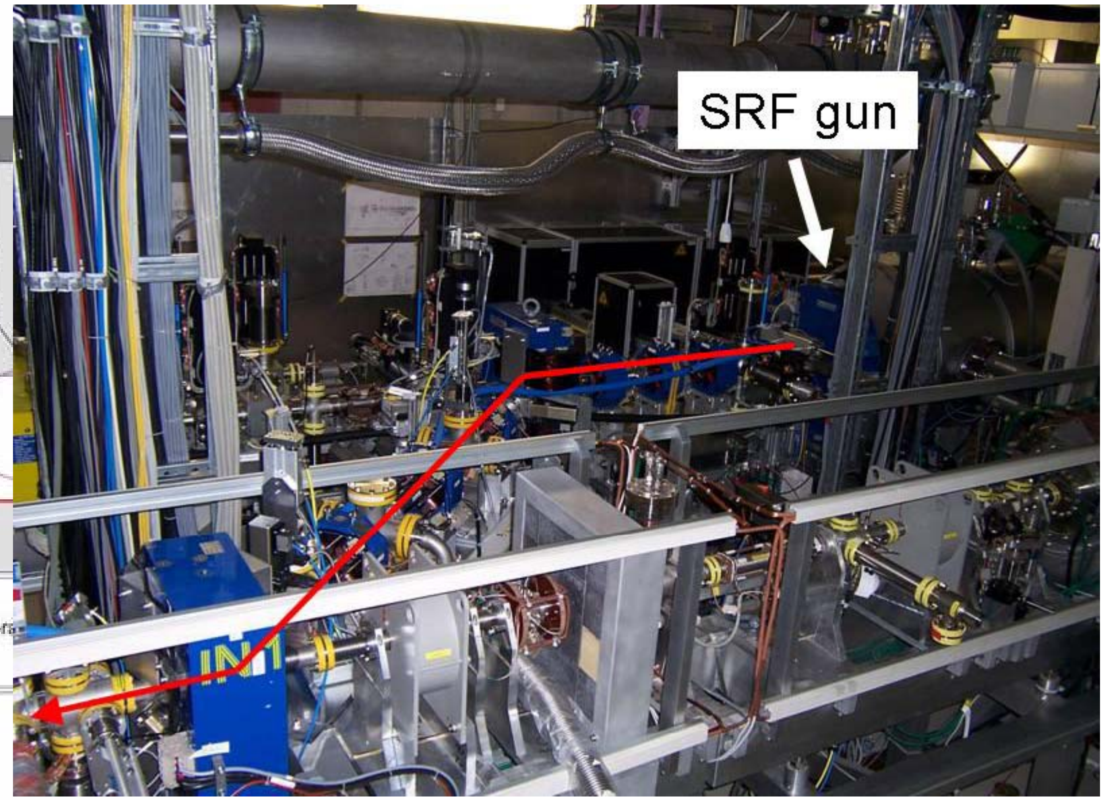
Cavities produced by ACCEL Instruments
In CW operation since 2002 (cavities C1, C2) and 2005 (C3, C4)
Gradient limit is field emission



ELBE Superconducting RF Photoinjector

- New Injector for the ELBE SC Linac
- Test Bench for SRF Gun R&D

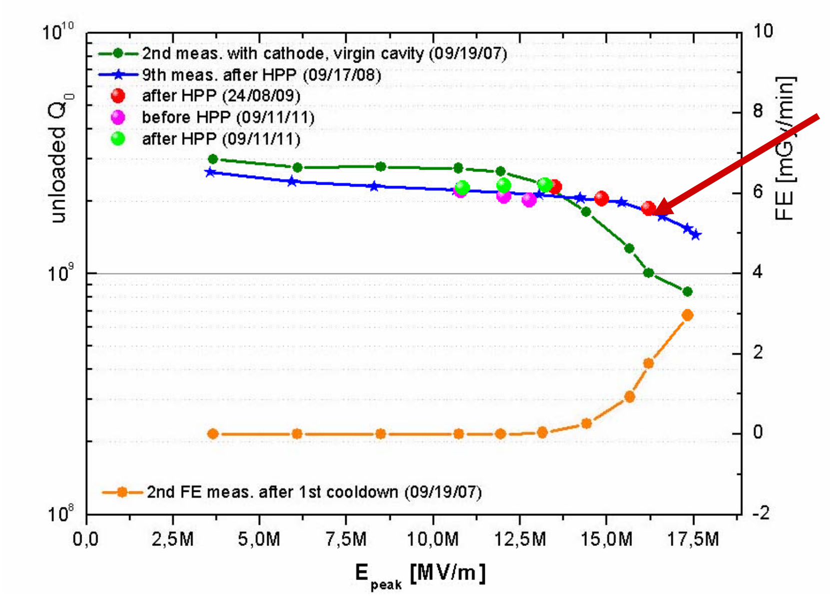




Installation of electron beamline
to ELBE (dogleg) was finished in 2010

SRF gun gradient and beam energy

- **SRF Gun cavity performance**

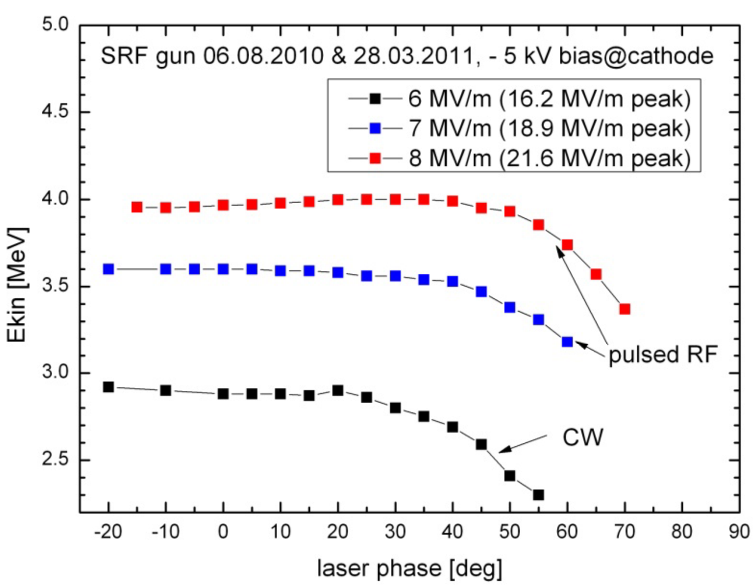


In CW:
Max. 16 MV/m peak field
= 6 MV/m acc. gradient
= 3 MeV beam energy

Improvement
requires new cavity
JLab collaboration

standard
RRR 300
Nb cavity

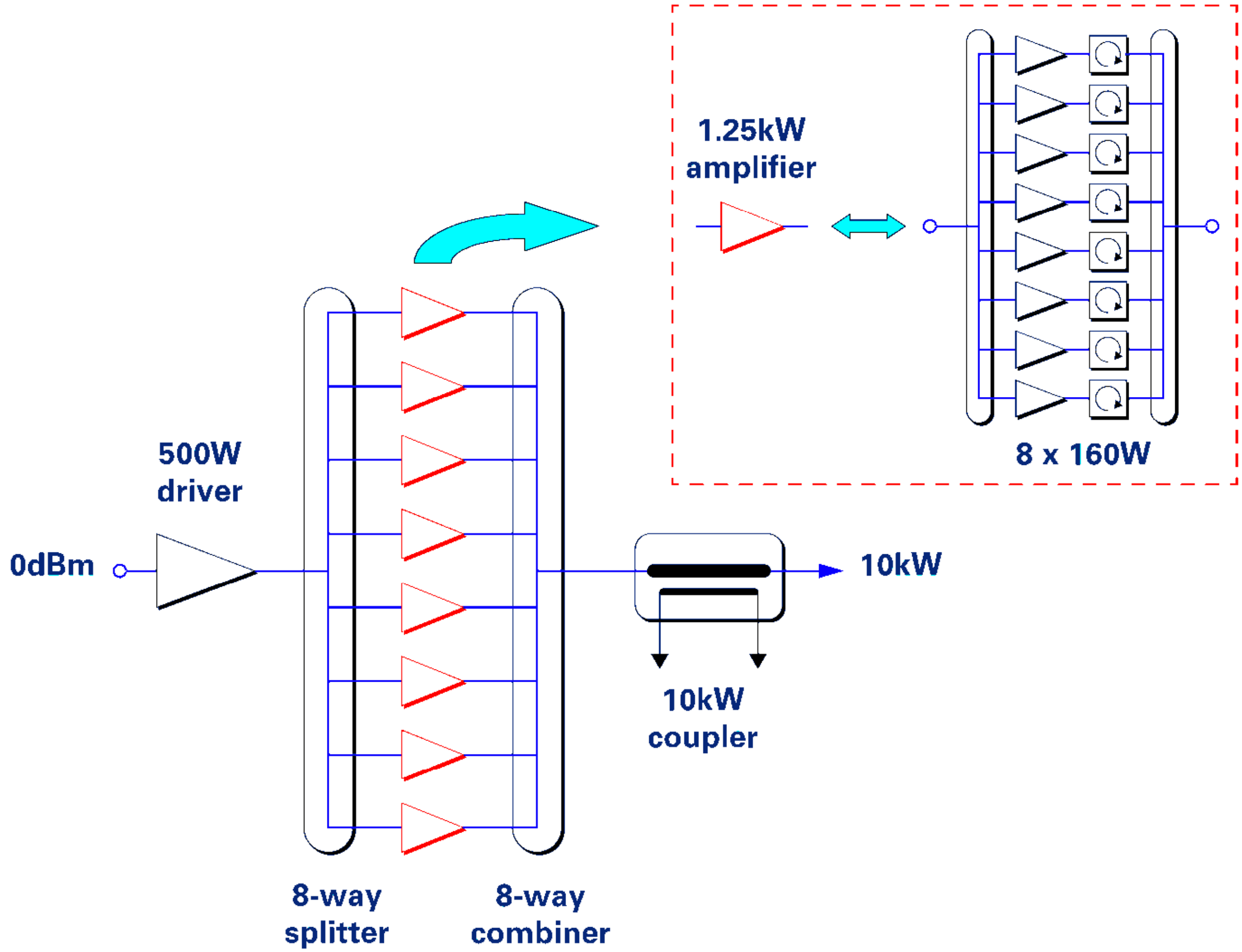
large grain
Nb cavity



Cavity gradient strongly determines
beam energy, maximum bunch charge & beam quality

10 kW Solid State Power Amplifier

Bruker BioSpin S.A. Wissembourg, France



Two amplifiers has been in routine operation since 2010

Acknowledgements

- **Mike Drury** served as the project manager of the C50 project
- **Kirk Davis** is the source of all microphonic characterization measurements at JLab
- *Many* other members of the Jefferson Lab staff also made numerous vital contributions to the JLab work summarized here
- **Ralf Eichhorn** provided information on progress at S-DALINAC
- **Jochen Teichert** provided information regarding recent ELBE activities

SRF Challenges to Operational Electron Linacs

Conclusion

- While designs and technology continue to develop, the very real challenges of affording thoroughly vetted designs and effective quality assurance remain quite present in multiple domains that are crucial to the operational success of SRF-based particle accelerators.
- The pressure to realize peak performance reliably and efficiently in this context is unrelenting – but a worthy challenger with which to contend.