RF Developments

Erk Jensen for BE-RF

The global context

From European Strategy update:

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide*.

From P5 report:

Enabling R&D

Advances in accelerators, instrumentation, and computing are necessary to enable the pursuit of the Drivers. Greater demands are being placed on the performance in all three areas, at reduced cost, necessitating continued investments in R&D. The DOE General Accelerator R&D (GARD) program and Accelerator R&D Stewardship program, as well as the new NSF Basic Accelerator Science program, form the critical basis for both long- and short-term accelerator R&D, enriching particle physics and other fields. Superconducting radio-frequency accelerating cavities, high-field superconducting magnets to bend and focus beams, advanced particle acceleration techniques, and other technologies are being developed for the required higher performance and lower cost of future accelerator concepts. Directed R&D programs, such as for the LHC Accelerator Research Program (**LARP**) and the Fermilab Proton Improvement Plan-II (**PIP-II**), will enable the next generation of accelerators. State-of-the-art test facilities at the national laboratories support activities on advanced accelerator R&D by both university and laboratory scientists. New particle

CERN goals

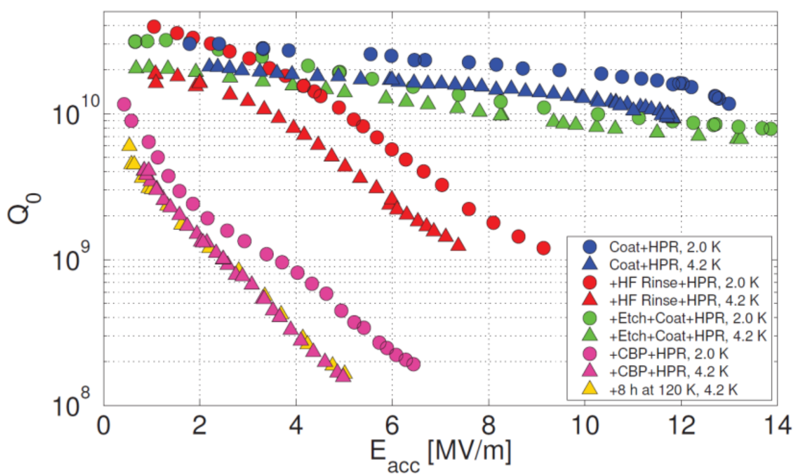
Implement the European Strategy!

- SRF clearly is a strategic key area of competency for CERN: Establish, re-establish and retain competencies in SRF!
  - Enable CERN to develop, design, build, test and operate world-class SRF!
- Undertake design studies for accelerator projects, coupled to a vigorous R&D program for … high-gradient accelerating structures
- The above should be done in collaboration with national institutes, laboratories and universities worldwide.

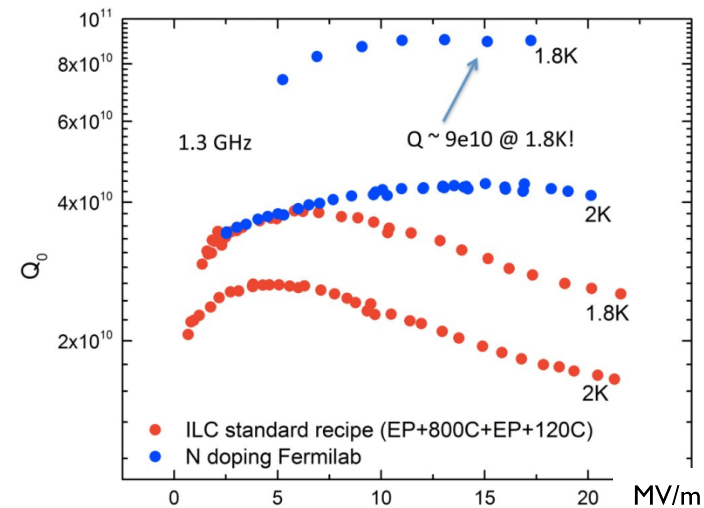
Goals of SRF R&D

- Obtain very low loss accelerating structures ($Q_0 \gg 10^{10}$) with sufficiently large accelerating gradients for continuous wave (CW) and pulsed acceleration.
- Investigate new materials and techniques that allow to
  - significantly decrease the power requirements for cryogenics (large Q_0 and/or operation at larger temperature)
  - reach larger accelerating gradients than Nb (multi-layer?)
  - ease or optimize fabrication
- Design cryomodules (CMs) for lower static losses, better magnetic shield.
- Study power couplers that allow to feed large power through the cavities to the beam.
- Study and improve HOM damping for larger I_B.
- Don’t forget ancillaries and diagnostics…

Record Q_0: recent results



Sam Posen et al.: "Recent progress in Nb3Sn SRF Cavity Development at Cornell", IPAC2014



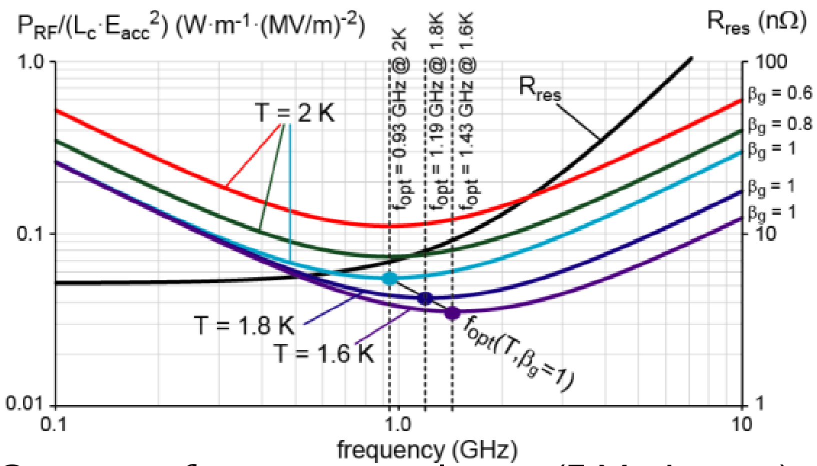
Anna Grasselino et al. (FNAL): "New Insights on the Physics of RF Surface Resistance and a Cure for the Medium Field Q-Slope", SRF 2013

Left: Nb3Sn films on Nb: Q_0 only a factor 1.5 smaller at 4.2 K than at 2 K. But cooling at 4.2 K is more than a factor 3 simpler!

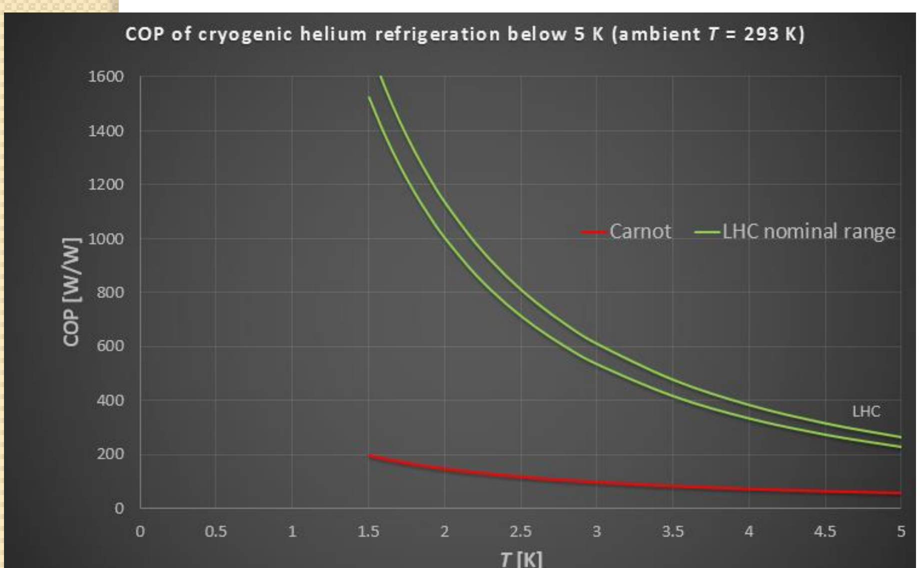
Right: Nitrogen doping seems to fight the Q-disease – very encouraging!

Some physics

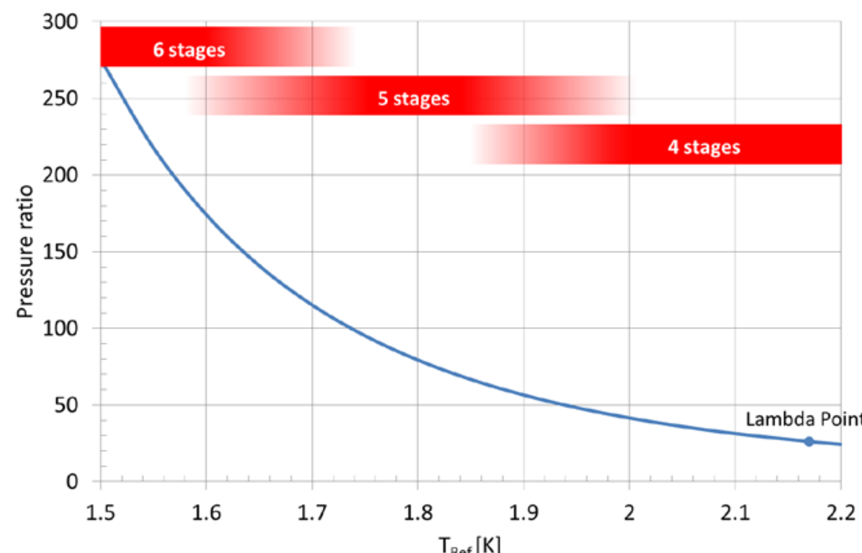
- $P_{RF} = \frac{(E_{acc}L_{act}(f))^2}{R/Q} \cdot \frac{R_{BCS}(f,T)+R_{res}(f)}{G}$
- P_{RF} is minimized for low T and has an optimum f.
- The cryo system has to cool $P_{RF} + P_{static}$, this will become very critical and expensive at low T.



Optimum f to mimimize losses (F. Marhauser)



To cool $1\ \mathrm{W}$ at $1.5\ \mathrm{K}$, $1.6\ \mathrm{kW}$ are required (P. Lebrun)



Cooling at low T is difficult, complex and expensive (P. Lebrun & L. Tavian).

CERN SRF Projects

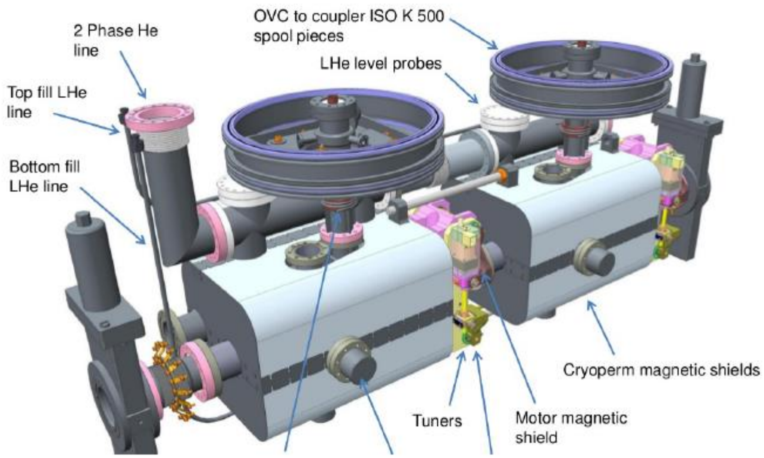
- LHC (400 MHz)
- LHC upgrade
  - Crab cavities (400 MHz)
  - Study 200 MHz, 800 MHz
- HIE-ISOLDE (100 MHz)
- SPL/ESS (704 MHz)
- LHeC ERL – ERL-TF (800 MHz)
- FCC-ee, FCC-hh (200 MHz, 401 MHz, 800 MHz)
- ILC (1.3 GHz)
- PIP-II (650 MHz, 1.3 GHz)
- "generic" SRF R&D
  - sample tests in quadrupole resonator
  - 1.5 GHz & 6 GHz single cell test cavities

HL-LHC Crab Cavities I

Three compact cavity prototypes constructed & tested

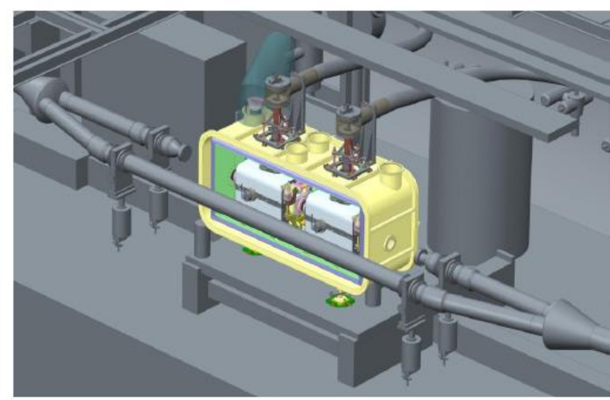
1 cavity with x2 performance

2 other cavities with moderate performance



Cryomodule concepts in advanced stage

SPS-BA4 test preparation advancing well



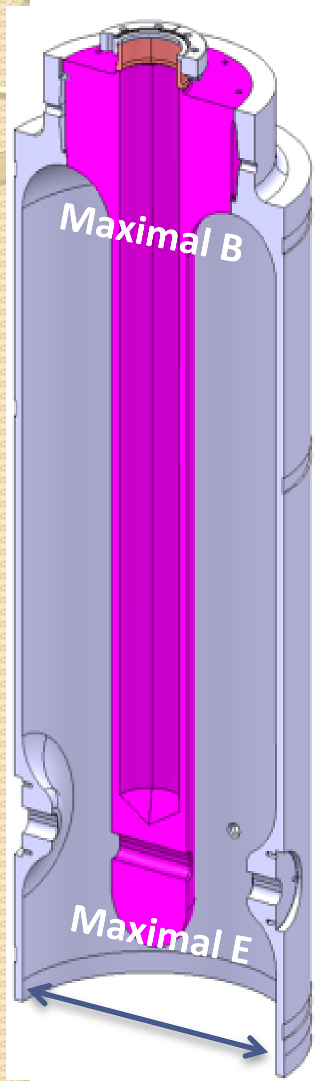
HL-LHC Crab Cavities *II*

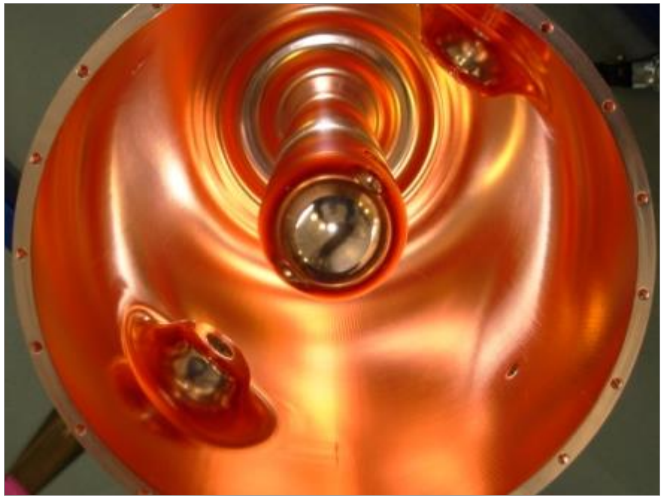
A review took place at BNL, 5-6 May 2014. Excerpt from the executive summary:

- We suggest that two cavity designs be selected for the beam tests at SPS. These cavities should incorporate complementary different HOM coupler configurations , as were presented for:
  - Double Quarter Wave (DQW) design proposed by Brookhaven National Laboratory (BNL) with Coaxial HOM Couplers, and
  - RF Dipole (RFD) design proposed by Old Dominion University (ODU) with a waveguide HOM Coupler.
- We suggest that further development and the beam test preparation be prioritized with the DQW design because the engineering design work appears to be better advanced to meet a very limited preparation time. However, we encourage the RFD cavity development to be continued with strengthening the waveguide HOM Coupler development. We note that either the DQW or the RFD could be tested first in SPS, depending on the readiness of the cavity and CM preparation.

HIE-ISOLDE /

S. Calatroni, I. Mondino, W. Venturini Delsolaro



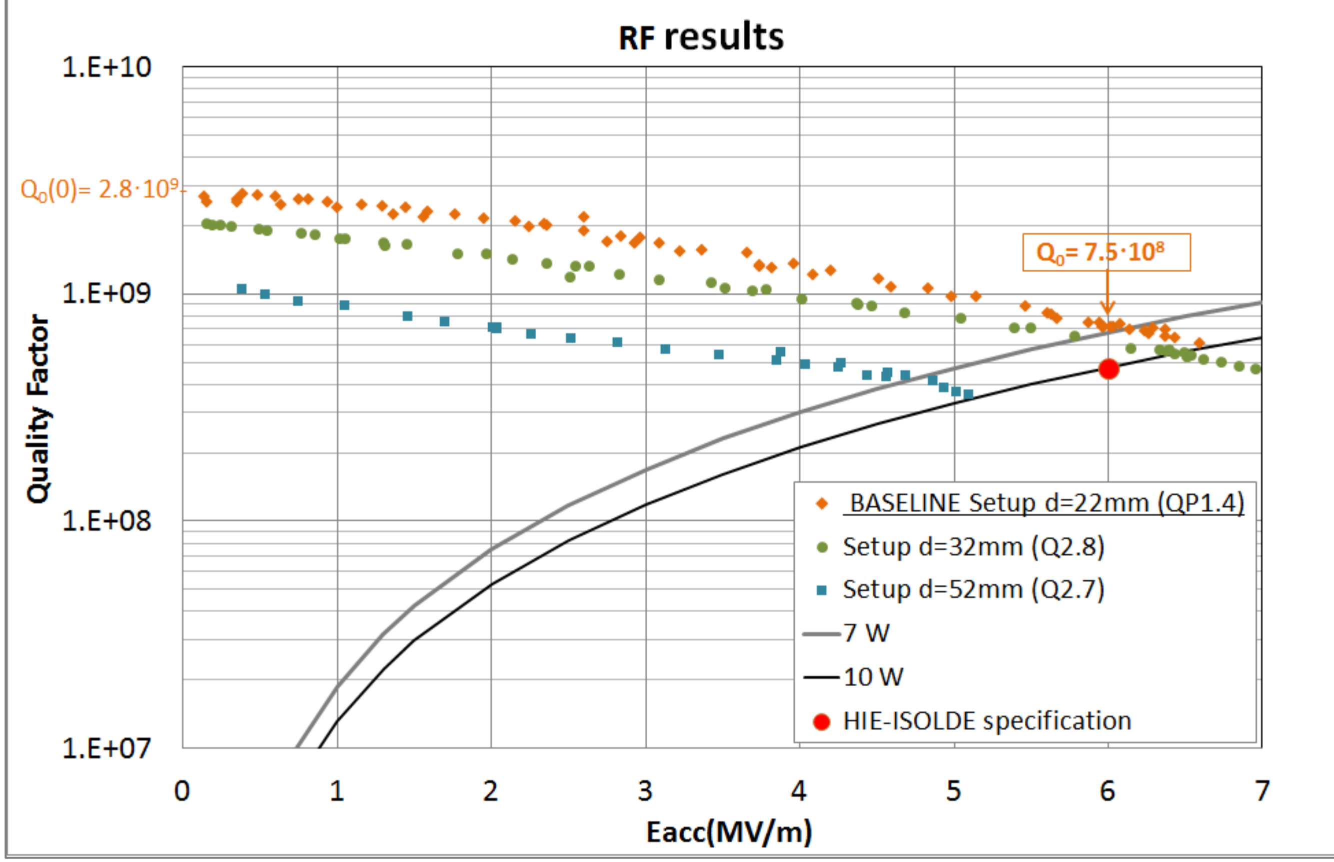


HIE-ISOLDE II

Specifications **6 MV/m** for 10 W RF power (30 MV/m peak) were exceeded after initial development phase; series production has started.

Nb-Coating

S. Calatroni, I. Mondino, W. Venturini Delsolaro



Cavities performances progress

HIE-ISOLDE III

- After a long, vigorous program, HIE-ISOLDE cavity performance now exceeds specifications (6 W loss at nominal, 10 W specified)
- Key now is the assembly of the modules, which is very complicated and has to be done in a clean-room
  $(beam\ vacuum\ =\ insulation\ vacuum)$

Existing clean room upgrade and extension — New clean room facility – HIE-ISOLDE

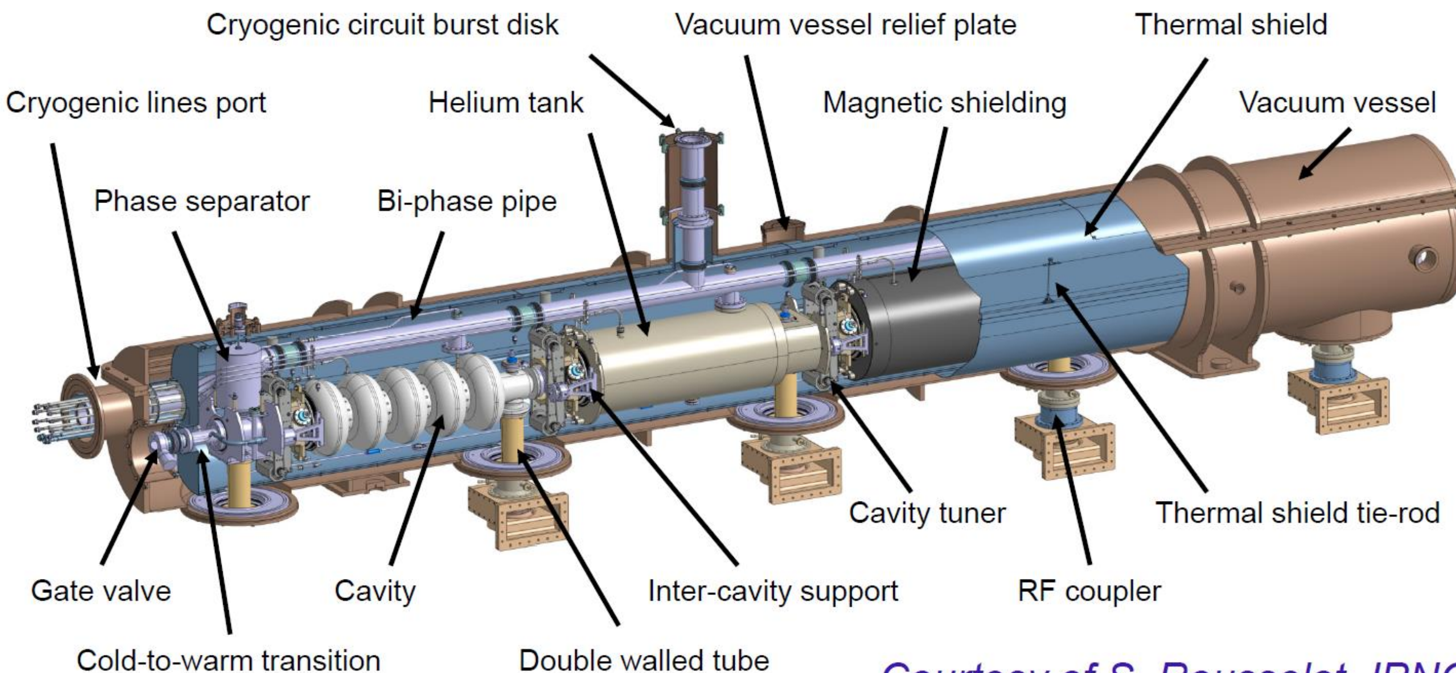
SPL and beyond I

CARE-HIPPI cavities:

- 2008: SPL part of LHC Injector Complex, R&D centred on SRF, part of FP7 CARE/HIPPI, EuCARD and CRISP.
- 2009: Synergy with ESS/Lund was clear and collaboration was established from the start.
- Short-term SPL R&D goals:
  - Complete short (4-cav) CM by end 2016
  - Develop better FPCs (fundamental power coupler)
  - Prepare CERN tests for MW-class MB-IOTs.
- The CERN CM design features a novel SS He-vessel and cavity suspension. These differ from the ESS Baseline and have large potential for savings if validated.
- Thanks to the continued R&D effort to SPL, CERN has modernized its infrastructures.

SPL and beyond II

- CERN 4-cav CM:



Courtesy of S. Rousselot, IPNO

SPL and beyond *III* (work at CERN)

Techniques/Technologies

- Basic material choices
  - bulk Nb fine-grain, large-grain Nb, Cu substrate & Nb thin film,
  - Pb, Nb_3Sn, MgB_2 techniques to be developed!
- Fabrication techniques
  - Mainly sheet metal forming (spinning, deep-drawing)
  - Machining (turning, milling), additive fabrication?
  - Joining (EBW, Vacuum brazing)
- Surface treatments
  - SUBU, BCP, EP, HPR, …
- Cryogenics, Clean room assembly, Vacuum

LHeC ERL Test Facility

- LHeC is not included in the present MTP.
- LHeC has triggered studies of the fascinating subject of Energy Recovery Linac (ERL).
- In this decade, CERN is exploiting and upgrading the LHC – but not constructing "the next big machine".
- CERN needs to study and develop the technologies to prepare for a possible next energy-frontier machine (European Strategy for Particle Physics).
- Superconducting RF is a key area – this is where this planned facility comes in.
- There is strong synergy with the work recently performed for SPL.
- An ERL Test Facility would primarily be a Test Facility for SRF!

CERN management has asked us to conduct a **Conceptual Design Study** for an Energy Recovery Linac Test Facility (ERL-TF).

We have started this study and have started to establish collaborations.

Goals of a CERN ERL-Test Facility

- Main goal: **Study real SRF Cavities with beam** – not interfering with HEP!
  - citing W. Funk ("Jefferson Lab: Lessons Learned from SNS Production", ILC Workshop 2004 http://ilc.kek.jp/ILCWS/):
    - **All problems will not be experienced until the complete subsystem is tested under realistic conditions. Be prepared to test, <u>with full rf power systems and beam,</u> all of the pre-production prototypes.**
- In addition, it would allow to study **beam dynamics & operational aspects** of the advanced concept ERL (recovery of otherwise wasted beam energy)!
- Exploration of the ERL concept with multiple re-circulations and high beam current operation
- Additional goals:
  - Gun and injector studies
  - Test beams for detector R&D,
  - Beam induced quench test of SC magnets
  - … later possibly user facility: e^- test beams, CW FEL, Compton γ-ray source …
- At the same time, it will be fostering international collaboration (JG|U Mainz and TJNAF collaborations being formalized)

Parameters of the ERL-TF

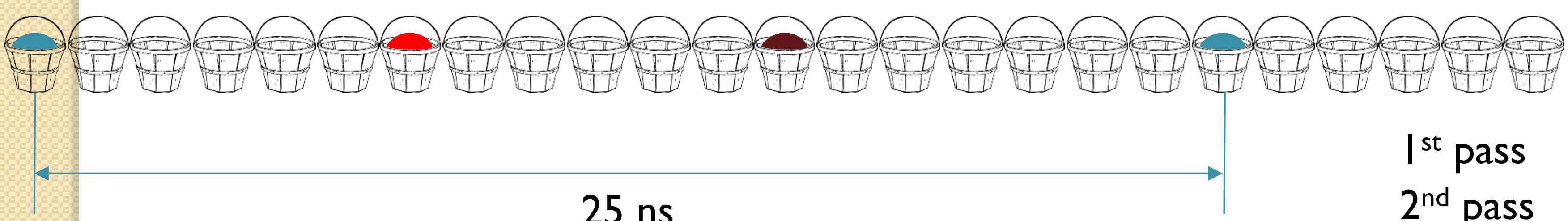
Parameter	Value	
injection energy	5 MeV	
RF f	801.59 MHz	
acc. voltage per cavity	18.7 MV	
# cells per cavity	5	
cavity length	≈ 1.2 m	
# cavities per cryomodule	4	
RF power per cryomodule	≤ 50 kW	
# cryomodules	4 *)	
acceleration per pass	299.4 MeV *)	
bunch repetition f	40.079 MHz	
Normalized emittance $\gamma\epsilon_{x,y}$	50 µm	
injected beam current	< 13 mA	
nominal bunch charge	320 pC $= 2 \cdot 10^9\ e$	
number of passes *)	2	3
top energy *)	604 MeV	903 MeV
total circulating current *)	52 mA	78 mA
duty factor	CW	

*) in stages

Post-CDR frequency choice

LHeC Meeting at Daresbury Laboratory, January 2013

802 MHz buckets (harmonic 20 of $25\ \mathrm{ns}^{-1}$)



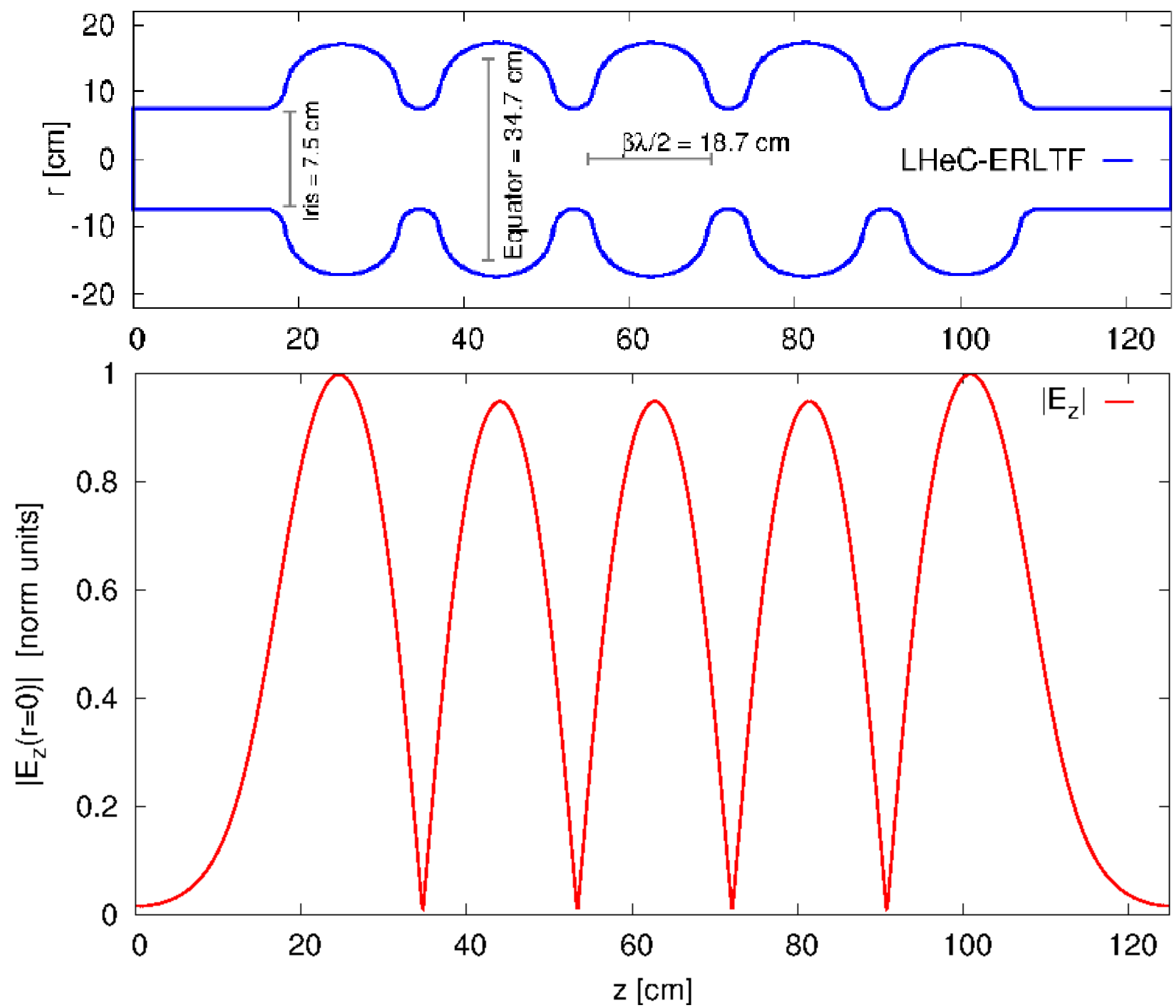
1st pass
2nd pass
3rd pass

Synergetic with CERN SPS, LHC, LHC upgrades, …
JLAB-CERN-Mainz 801.58 MHz Cavity/cryomodule now under design

802 MHz cavity: Some first choices

R. Calaga

Parameter	Value
n_{cell}	5
V_{acc}	18 MV
f_0	801.58 MHz
W	131 J
aperture Ø	75 mm
equator Ø	347 mm
R/Q	462 Ω
G	276 Ω
E_{peak}	41 MV/m
B_{peak}	86 mT
$P_{diss}\|_{2K}$	< 28 W

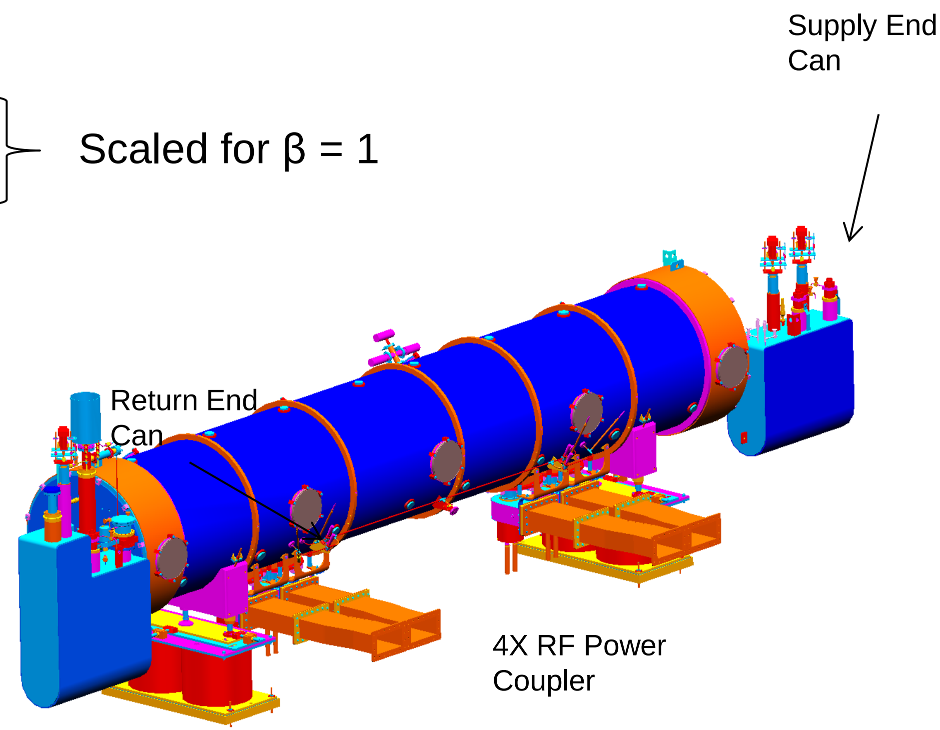


JLAB proposal: SNS style Cryomodule

- Based on SNS CM (805 MHz)
  - 5-cell low-loss shape
  - coaxial FPC
  - Single RF Window
  - DESY Style HOM coupler
  - Cold tuner drive
- Overall length: 7.524 m
- Beamline length 6.705 m

Scaled for $\beta = 1$ (Single RF Window, DESY Style HOM coupler)

- End Cans include integral heat exchanger for improved efficiency at 2 K operations



A. Hutton

Areas of R&D work

- Cavity Design (BE-RF)
  - shape optimisation
  - # cells/cavity
  - MP analysis
  - Lorentz force detuning
- Power couplers design and engineering (BE-RF)
  - RF window
  - MP suppression techniques
- HOM Damper design and engineering (BE-RF)
  - HOM power estimates, current limits
  - Filter, damping materials,
- Tuner design and engineering
- Cavity Technology
  - Sheet metal forming techniques (EN-MME)
  - New fabrication techniques (EN-MME)
  - Joining (EBW, vacuum brazing, …/EN-MME)
  - Coating (sputtering, HiPIMS, …/TE-VSC)
  - Chemistry & cleaning (SUBU, BCP, EP, HPR, …/TE-VSC)
  - Heat treatments (bakeout, N_2 doping, He processing …)
- CM Design & Engineering (EN-MME)
  - He vessel, pressure & safety
  - Magnetic shielding
  - Cavity suspension and alignment
  - Integration of tuners and HOM dampers
- Develop diagnostics (BE-RF)
  - T-mapping
  - Quench localisation
- Experimental verification (BE-RF)
  - Sample preparation
  - Cavity preparation (Clean room assembly)
  - RF tests at RT
  - RF tests in vertical cryostat
  - RF tests in horizontal cryostat
- Infrastructure operation, maintenance & upgrade (BE-RF)
  - Manufacturing, joining IS: EN-MME
  - Chemical and surface IS: TE-VSC
  - Cryogenic IS: TE-CRG
  - RF IS: 252 and SM18; planning, scheduling, operation

What is needed for what

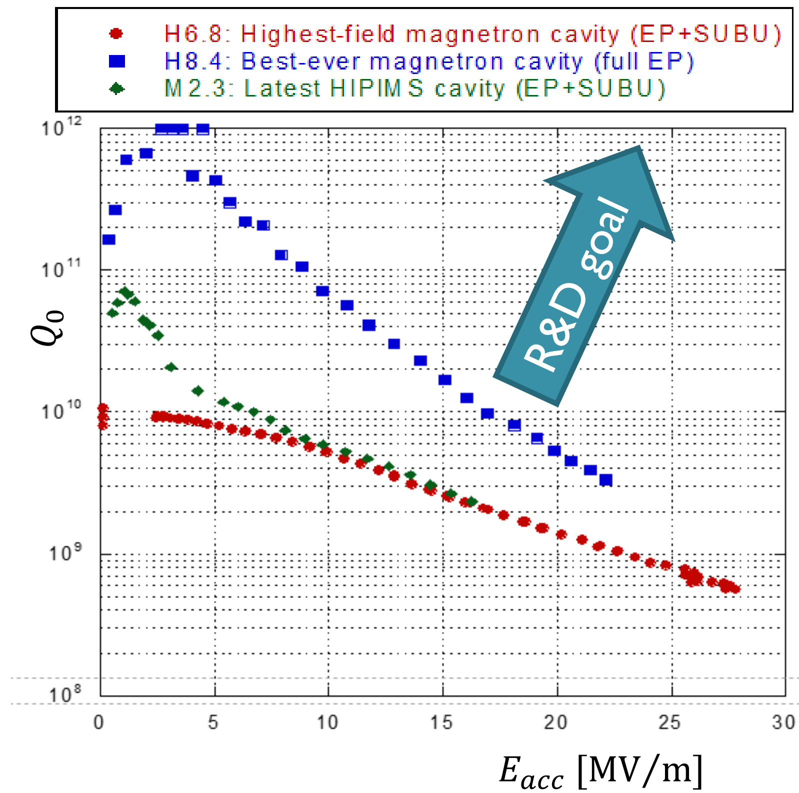
	cavity design D&E	power coupler D&E	HOM damper D&E	Tuner D&E	sheet metal forming	addit. fabrication	joining techniques	Thin-film techniques	Chemistry & cleaning	heat treatments	He-vessel	CM design	magn shield	suspension & alignment	ancillaries integration	Diagnostics	sample prep.	clean room assembly	RT tests	vertical tests	horizontal tests	operation of IS
LHC cavity rebuild					X		X	**X**	X	X	X							X		X	X	X
LHC upgrade crab cavities	X	X	X	X	X	X	X	**?**	X	X	X	**X**	X	X	X			X	X	X	X	X
LHC upgrade study 200 & 800 MHz	X		X	X				X														
HIE-Isolde QWR's	X	X		X			X	X	X	X		X						**X**		X	X	X
SPL/ESS 704 MHz	X	X	X	X			X		X		X	X	X	X	X	X		X		X	X	X
ERL-TF DS 800 MHz	**X**	**X**	**X**	**X**	X		X		X	X	X	X	X	X	X	X		X	X	X	X	X
FCC-ee and FCC-hh, 200 & 400 MHz	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ILC 1.3 GHz		**X**																X	X			
PIP-II (TBC) 650 MHz																						
Generic SRF R&D on samples	X					X		X	X	X						X	X	X	X	X	X	**X**

Promising: SRF Cavities based on Thin Films

Here: Nb sputtered on Cu

- Thin film cavities reach very high Q_0 at low field, but…
- … they suffer from Q-slope!
- There is no known physical hard limit – i.e. there is a large potential to reach much better performance.
- This technology push should be directed by TE-VSC, with BE-RF to help and conduct RF tests.
- Main project now: HIE-ISOLDE
- Thin film techniques in the focus of FCC-ee (100 MW CW, 12 GV) R&D.

S. Calatroni



Collaborations & links

- EU programs:
  - past: CARE, EuCARD, CRISP, present: EuCARD2, HiLumi-LHC
- Partners:
  - *Established:* ESS, MYRRHA (SPL), LARP, Uni Lancaster (HL-LHC)
  - *Being finalized:* JLAB, Uni Mainz (ERL), CFR Legnaro, STFC (thin film)
  - *Declared interest:* Cornell, Uni Frankfurt (ERL), CNRS/in2p3 (LAL, IPNO), CEA/irfu, BINP (FCC), PIP-II (SPL)

Annex:

Overview of SRF activities and installations at CERN

Cryolab Activities

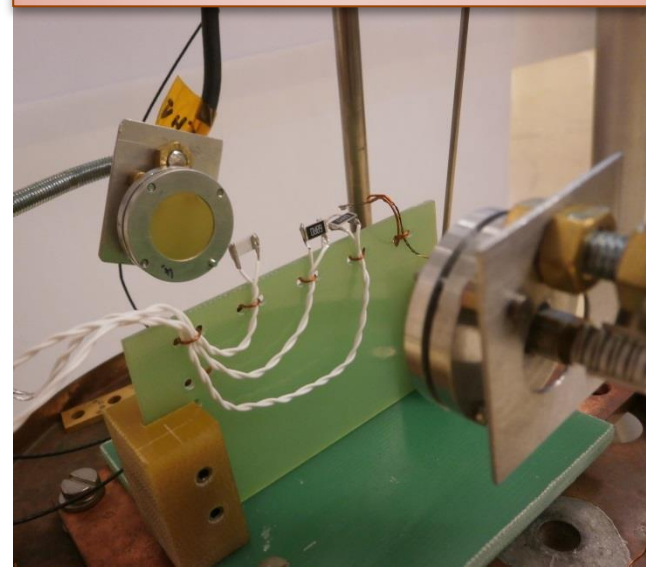
New Coating Technologies: HIPIMS on 1.3 GHz cavities

Collaboration with S. Calatroni and G. Terenziani

Fundamental SRF studies using the Quadrupole Resonator

PhD Thesis S. Aull (Univ. Siegen)
Supervisor: S. Doebert

Cavity Diagnostic Developments with OSTs



Master Thesis B. Peters (Univ. Karlsruhe)
Co-Supervisor T. Koettig

New Electron-Beam Welding Machine (EN-MME)

O. Capatina

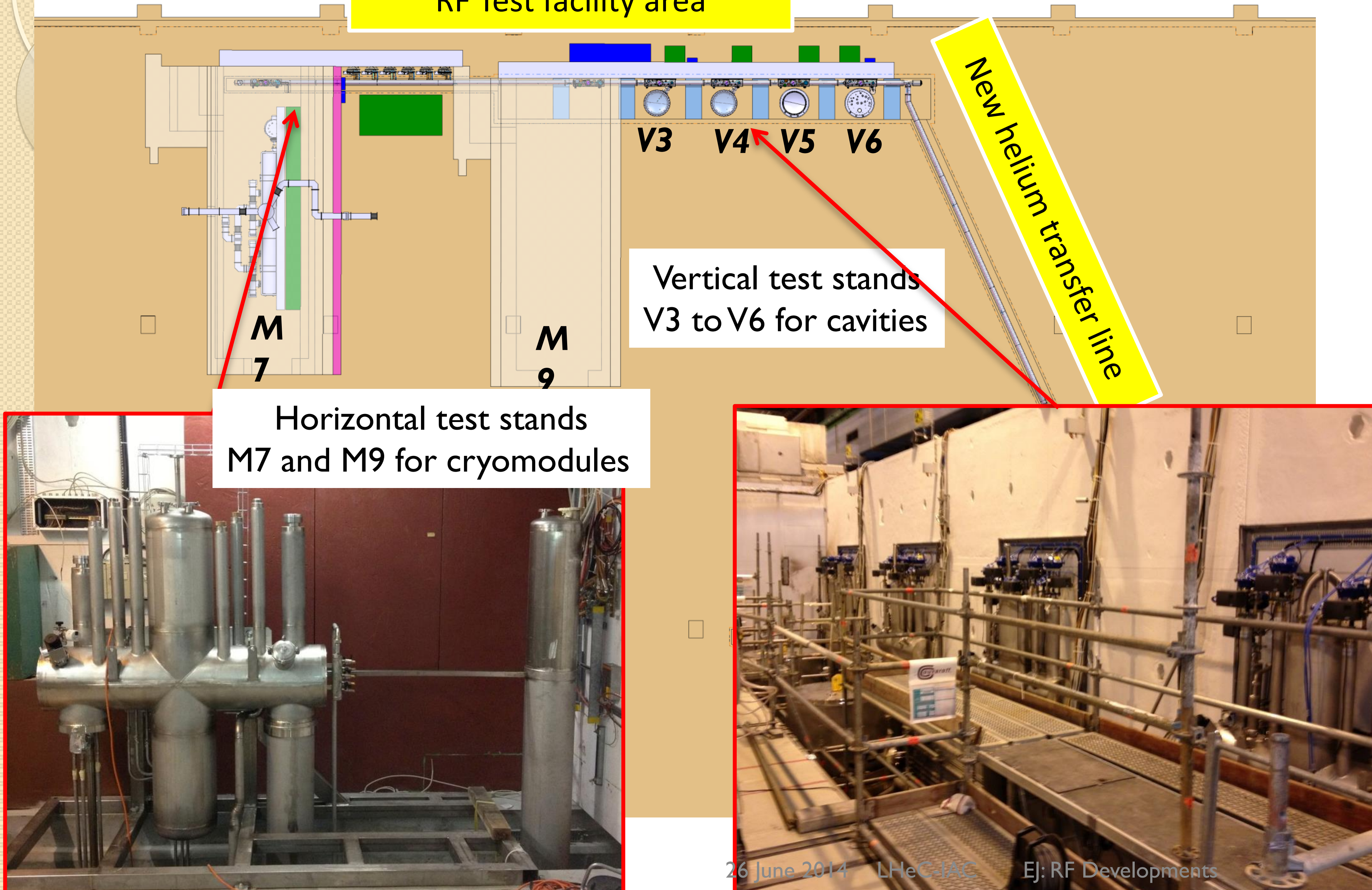
Electro-polishing

High-pressure rinsing

O. Capatina, L. Marques, K. Schirm

2 K Cryo-upgrade in SM18

T. Koettig, O. Pirotte, K. Schirm



Cavity and module test area SM18

Service module in horizontal bunker

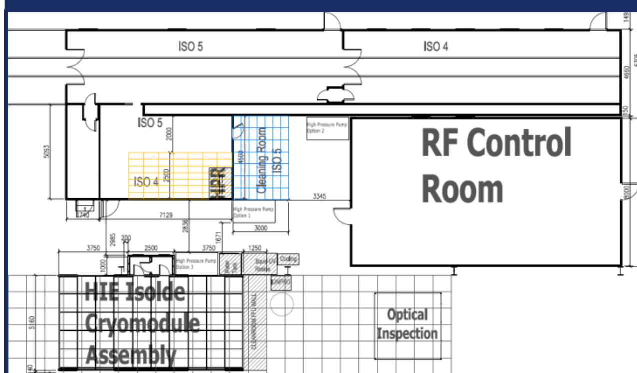
Helium tank

Cavity RF Test Area

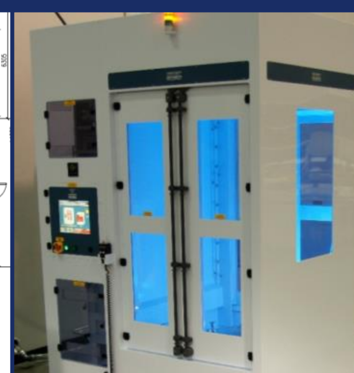
SM18: Clean room & Preparation Zone Upgrade

Existing clean room upgrade and extension

New clean room facility – HIE-ISOLDE



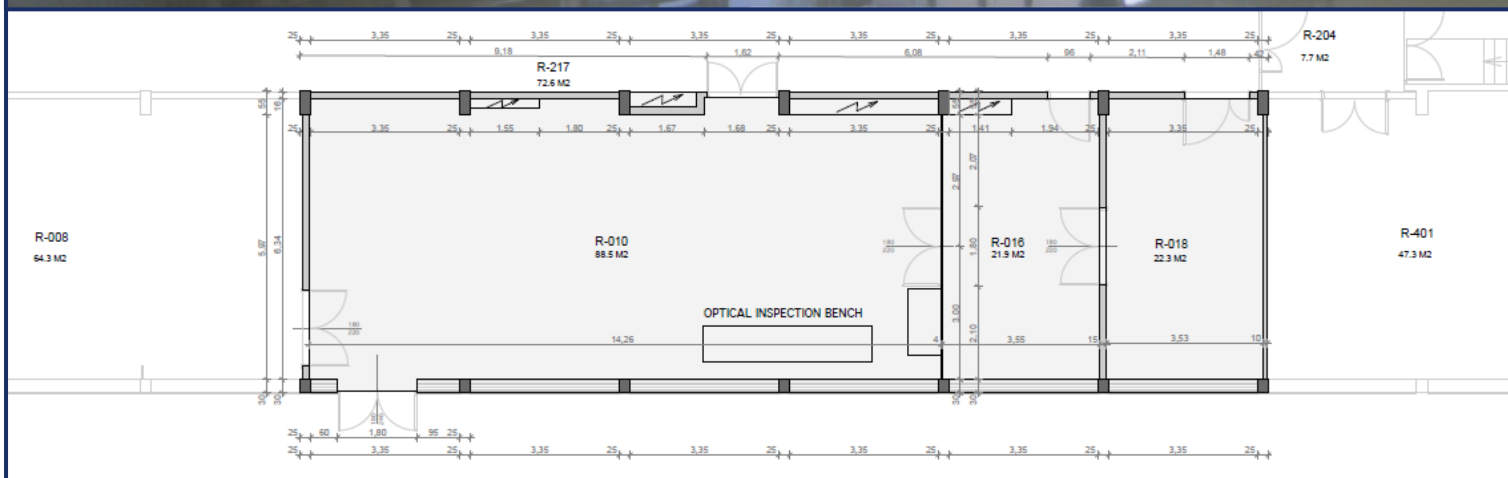
Clean room layout



High-pressure rinsing

Ultra-pure water station

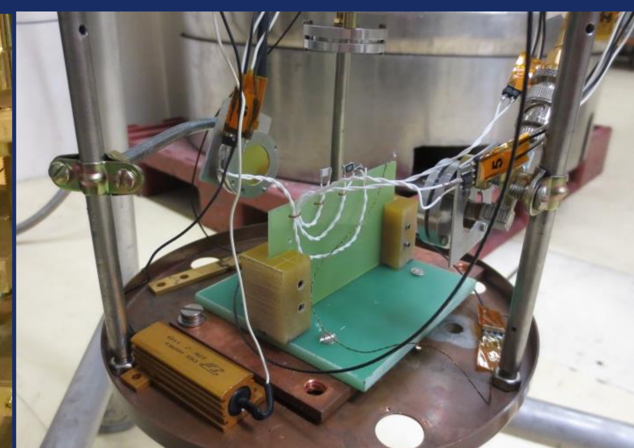
New cavity reception area



Cavity diagnostics

Optical Inspection Bench

Quench localization via second sound on SPL cavities



Fundamental research

J. Chambrillon, K. Liao, B. Peters, K. Schirm

Cavity ancillaries

Bead-pull measurement setup for field mapping

Cell-by-cell tuning system

F. Pillon, S. Mikulas, K. Schirm