# SCRF DEVELOPMENT AT TRIUMF

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RUPAC 2010
Protvino

# Abstract


- TRIUMF started SCRF development with the superconducting heavy ion linear accelerator project, ISAC-II, in 2000. Since that time much work has been completed for development, prototyping and testing. The ISAC-II project was successfully completed and we now have in operation 40 superconducting bulk Nb QWR cavities assembled in eight cryomodules. The last twenty cavities, just completed, were produced by PAVAC Industries Inc. of Richmond BC; the first superconducting accelerator cavities produced in Canada.
- In 2007 TRIUMF started development towards a 50MeV electron superconducting linear accelerator to be used as a driver to produce radioactive ion beams through photofission. The accelerator is based on TTF/ILC elliptical bulk Nb cavities technology.

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# - ISAC-II Results
# - SCRF for e-LINAC

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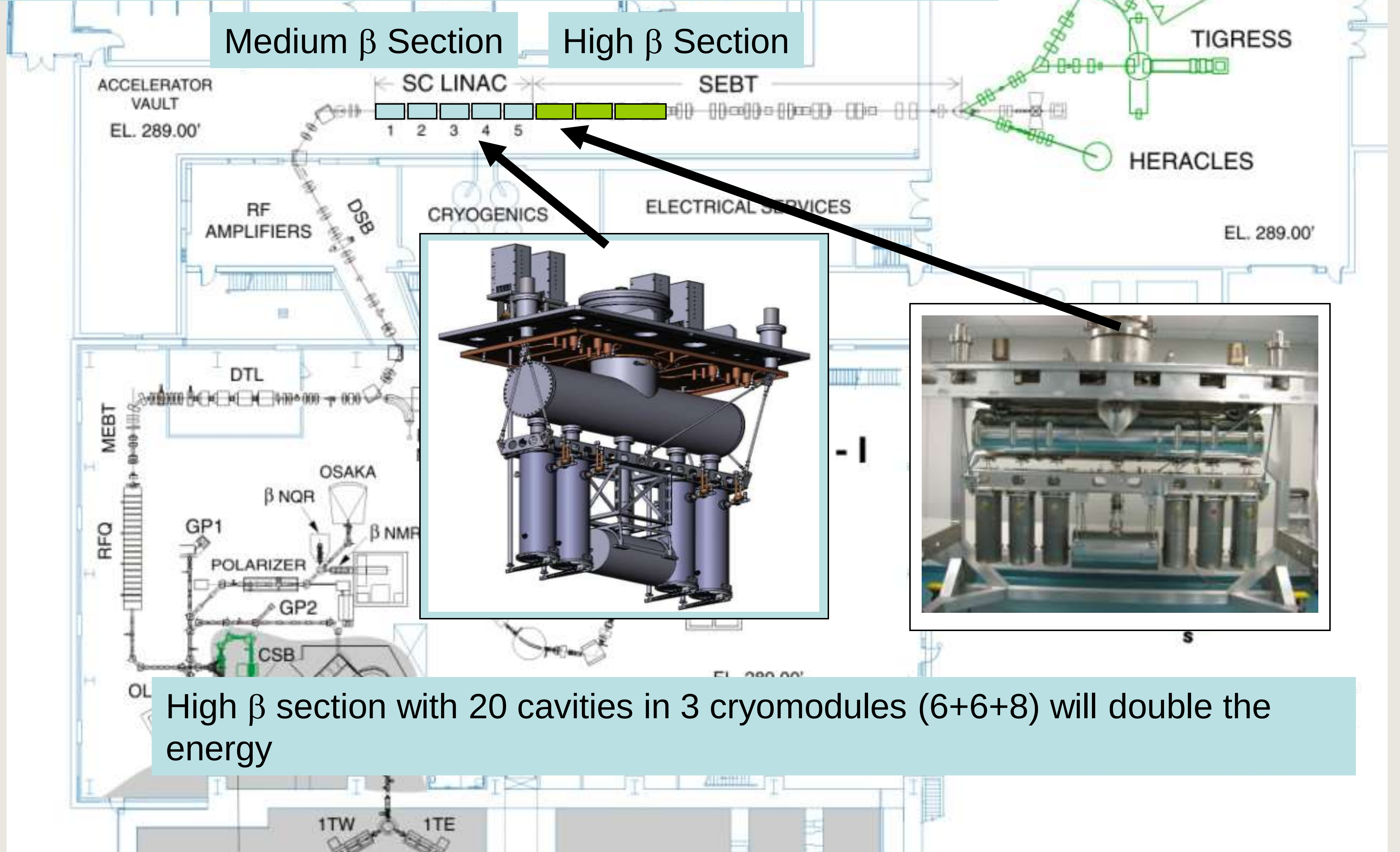
# ISAC-II Results

Design goal, the final energy is equivalent to acceleration of a beam with A/q=6 to 6.5MeV/u, is achieved at input energy 1.5 MeV/u in March 2010 after comissioning of Phase-II of the ISAC-II accelerator.

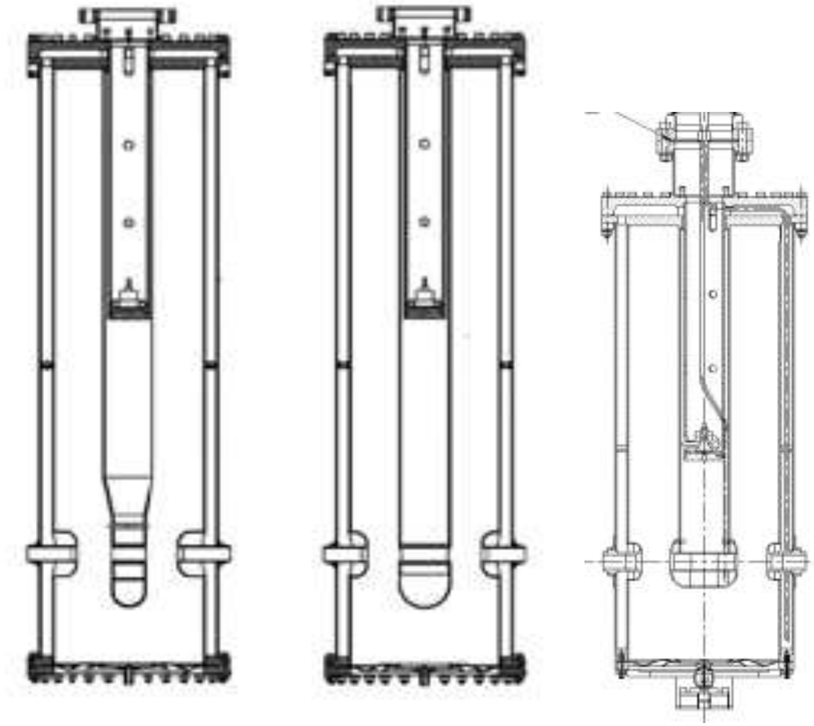
Since April 2010 ISAC-II has supported a full physics program with both stable and radioactive beams being delivered. To date stable beams of 16O5+, 15N4+, 20Ne5+ and radioactive beams (and their stable pilot beams) of 26Na, 26Al6+, (26Mg6+), 6He1+, (12C2+), 24Na5+, (24Mg5+), 11Li2+, (22Ne4+) including 74Br14+ from the charge state booster have been delivered. In addition short commissioning periods between beam delivery runs are used to characterize the machine and to satisfy licensing requirements.

Medium beta section of the ISAC-II heavy ion linear accelerator, has been in operation at TRIUMF since Apr. 2006 and high beta section since Apr. 2010




High β section with 20 cavities in 3 cryomodules (6+6+8) will double the energy

# ISAC-II QWR Cavities



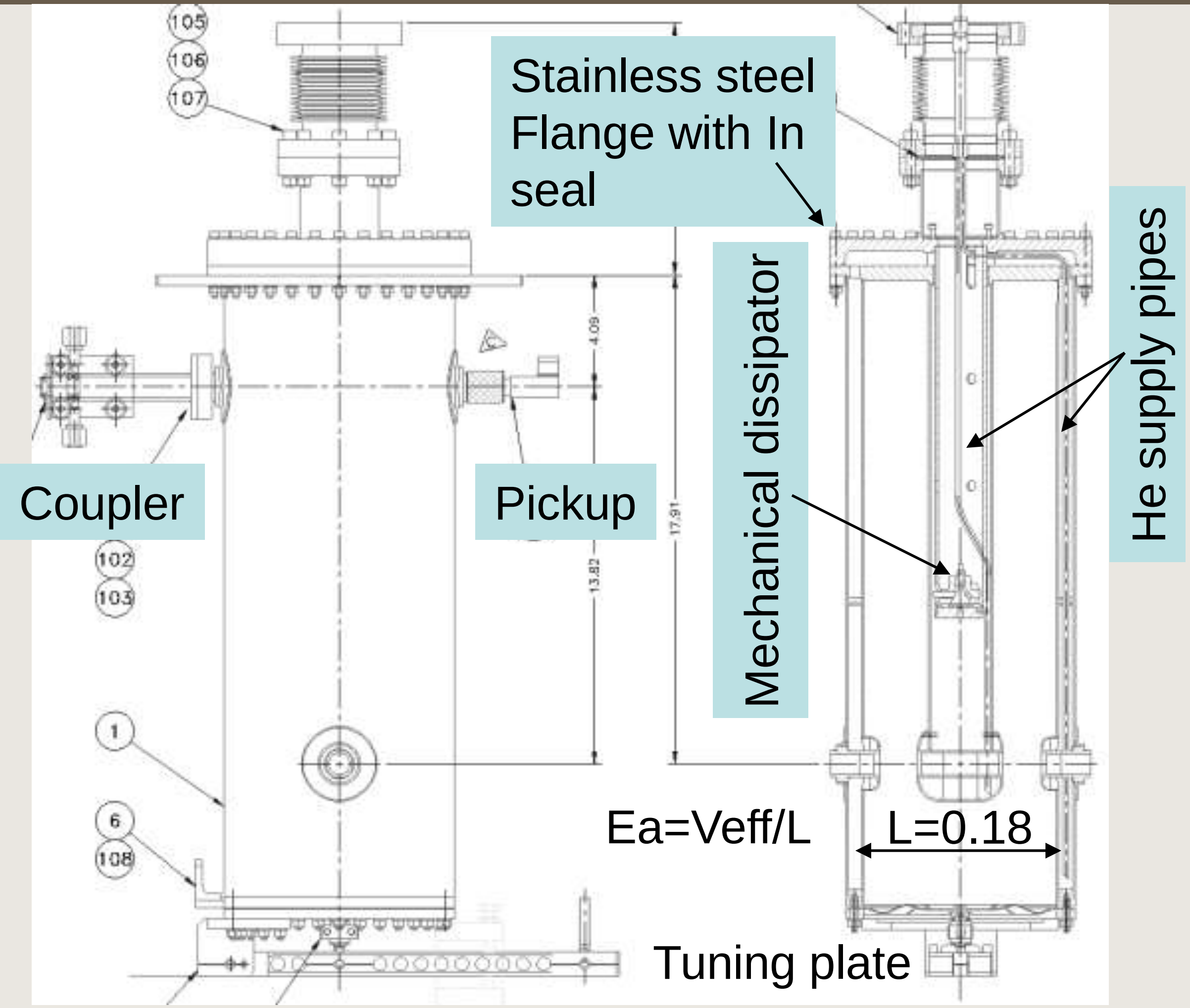
Phase-I
Zanon (Italy)

Phase-II
PAVAC (Canada)

| | flat | round | donut |
|---|---|---|---|
| f(MHz) | 106.080 | 106.080 | 141.440 |
| RsQ(Ohm) | 20.1 | 19.1 | 26.0 |
| $\beta o$ | 0.064 | 0.075 | 0.112 |
| TTFo | 0.870 | 0.898 | 0.936 |
| Ep/Ea | 5.2 | 4.7 | 4.9 |
| Bp/Ea(mT/(MV/m)) | 10.3 | 10.1 | 10.0 |
| U/Ea2 (J/(MV/m)2) | 0.100 | 0.094 | 0.067 |

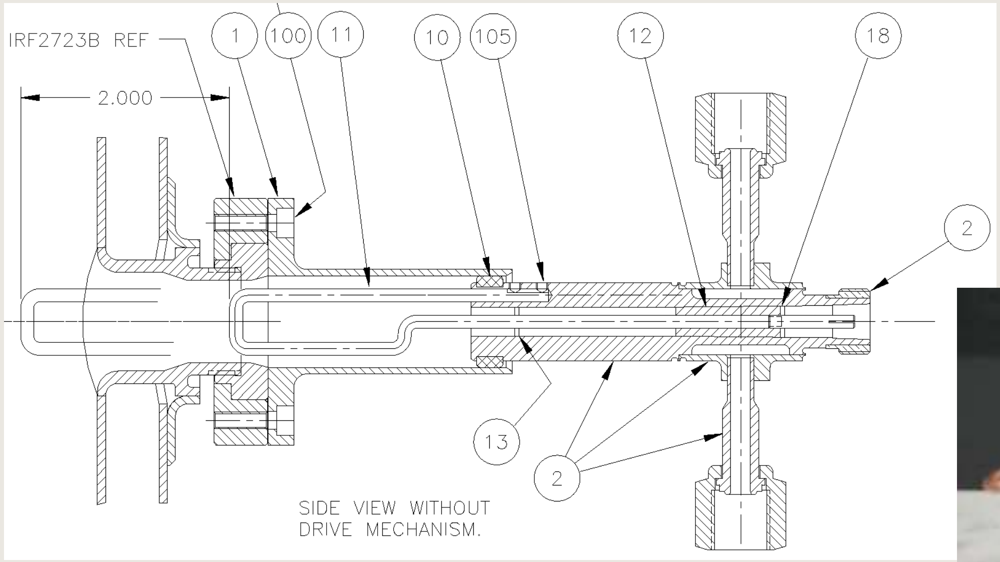
The difference between the cavities is in the beam tube region of the inner conductor. The round inner conductor shape of the beta 7.1% 106MHz is modified by squeezing to attain the 5.7% beta cavity. To provide the structure with optimum beta of 11% we went to 141MHz with corresponding decreasing of cavity length. A beam tube is added to improve the transit time factor. All cavities are specified for CW operation at 7W power dissipation with acceleration voltage 1.08MV corresponding to 30MV/m electric and 60mT magnetic peak field.

# SCC Cavity Design

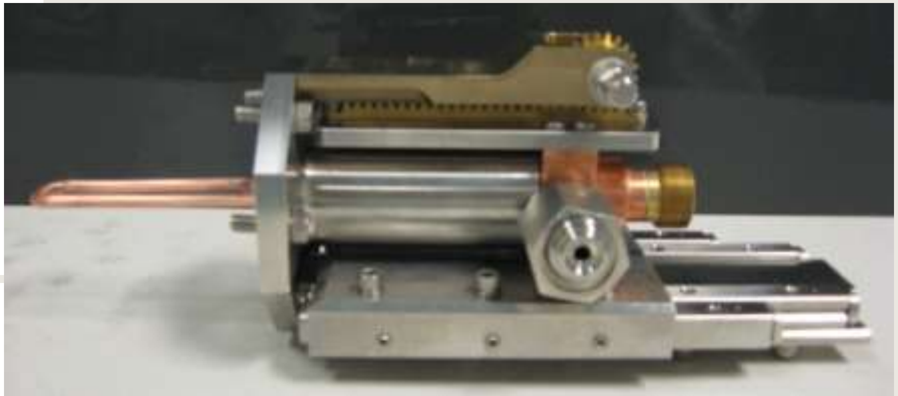


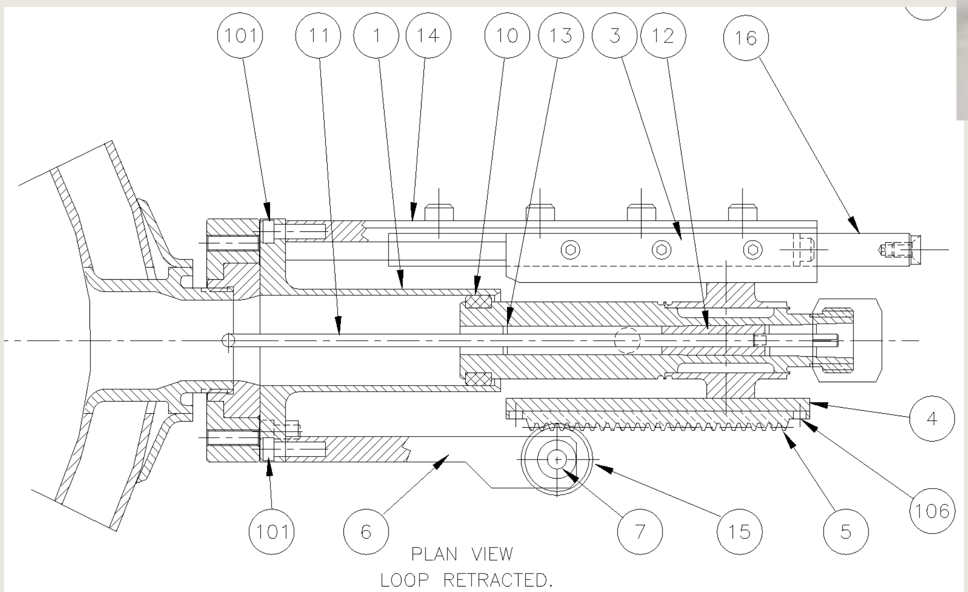

**Direct venting**
Filtered nitrogen venting instead of venting from the thermal isolation vacuum to avoid particulates drifting into cavity

# Coupler Design



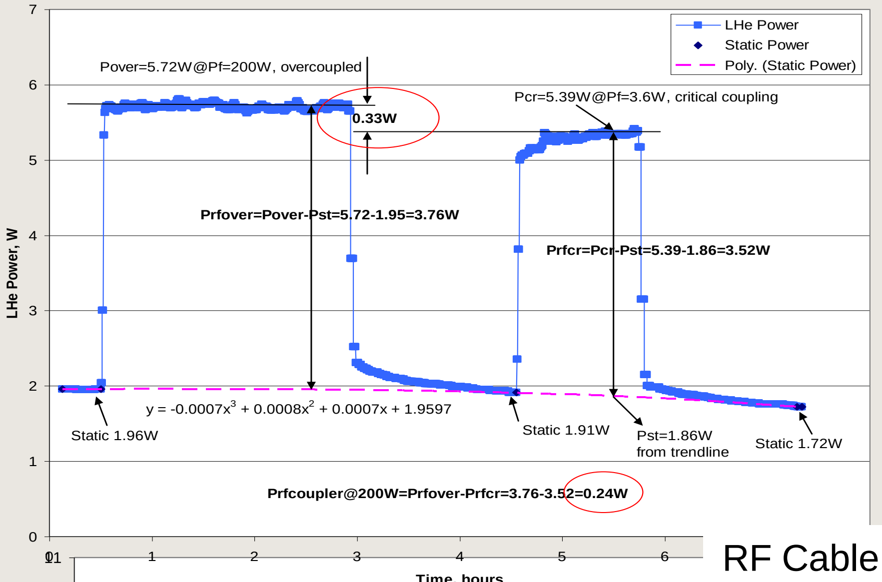

Heat sink for liquid nitrogen flux
Shapal RF window is thermal drain for inner conductor

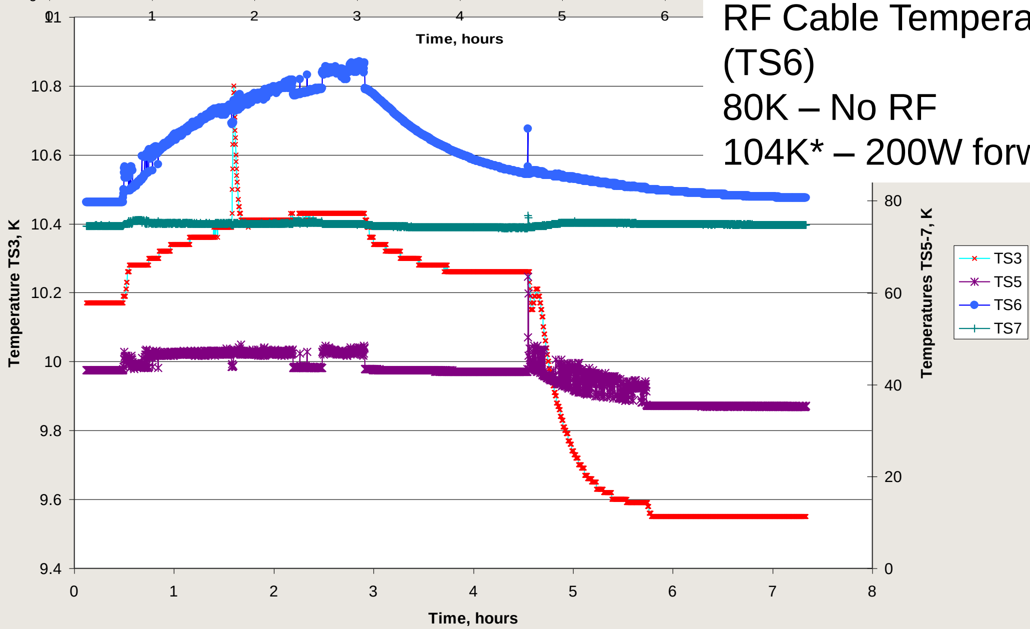




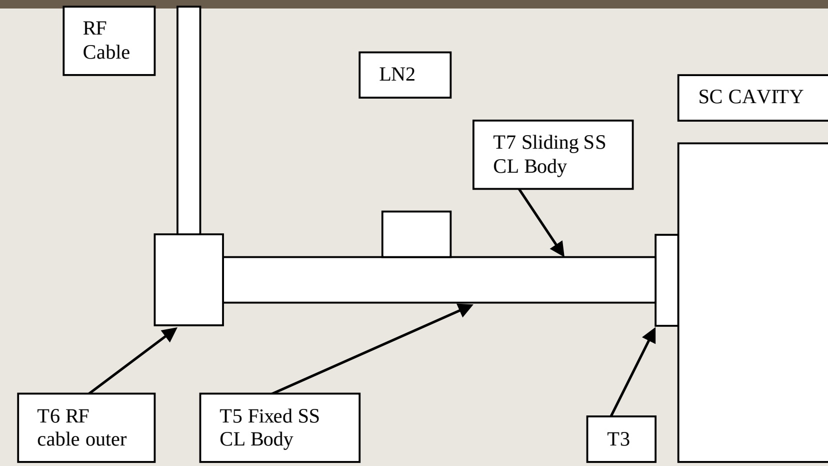

Trolley plate with cross-roller bearings provides smooth movement and holds load from rf cable and bellows with nitrogen

# Coupler Design Test

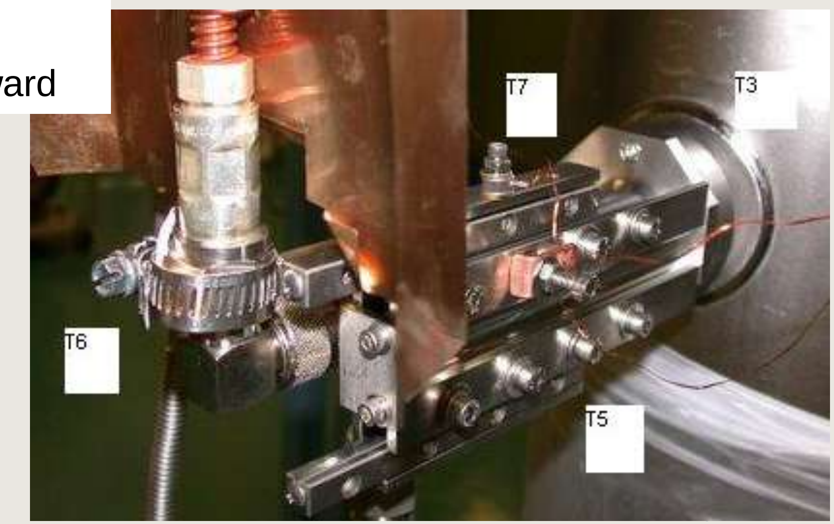


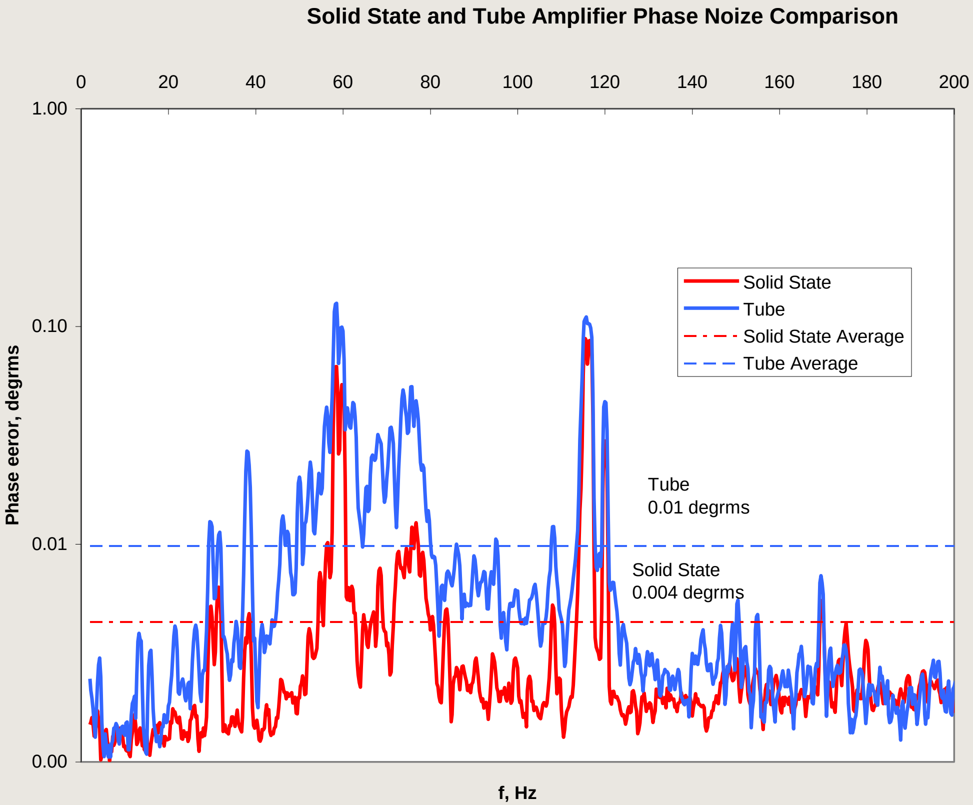

RF Cable Temperature (TS6)
80K – No RF
104K* – 200W forward




Coupler Loop Power Dissipation for He System
~0.25 W at Pf=200W



# Solid State and Tube Amplifier




Solid State Amplifier designed for High Beta ISAC-II Cavities at QEI during the test shown very good performance and twice less noise level in RF System of the cavity in comparison with tube amplifier

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# SCC Tuner

***Static Test:***

Range ~18.5 kHz, Velocity 76 Hz/s,

Resolution 0.04 Hz/step

***Dynamic tests:***

•He pressure variations

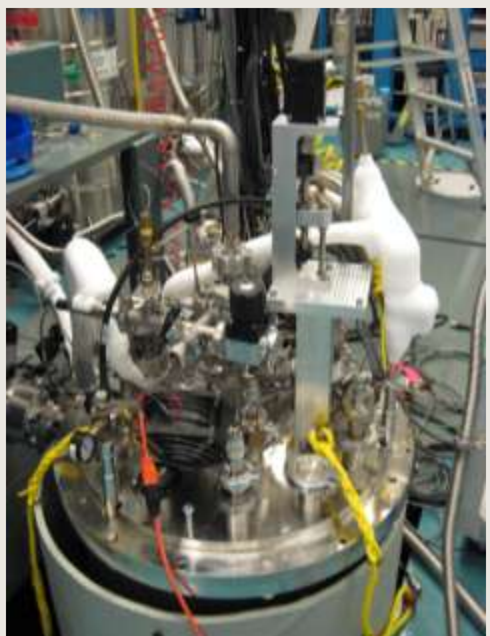
Ea= 6.4MV/m,Pf=166W, Df~40 Hz

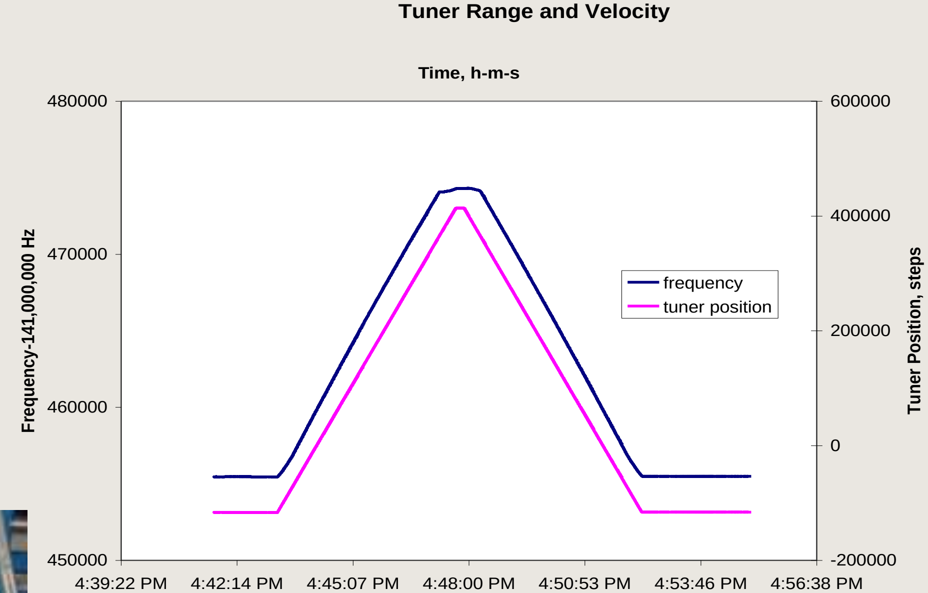
Pressure variation 137 T ->Dfo~330 Hz

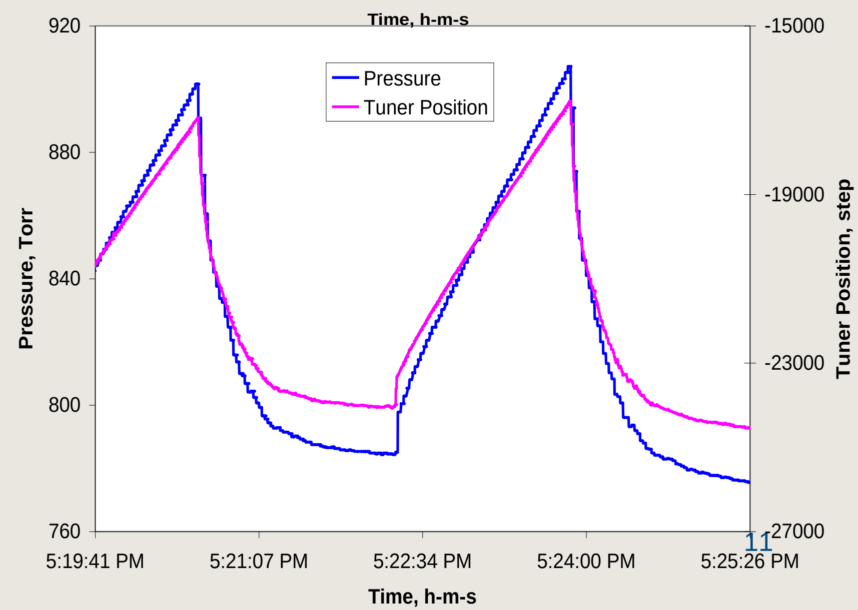
Velocity ~5.5T/s=13Hz/s

•Reference signal variations

1 Hz FM up to 10Hz deviation





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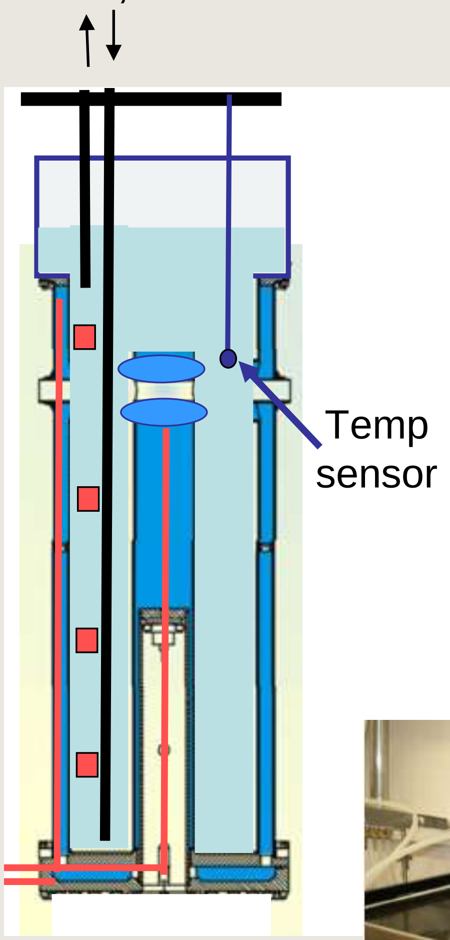
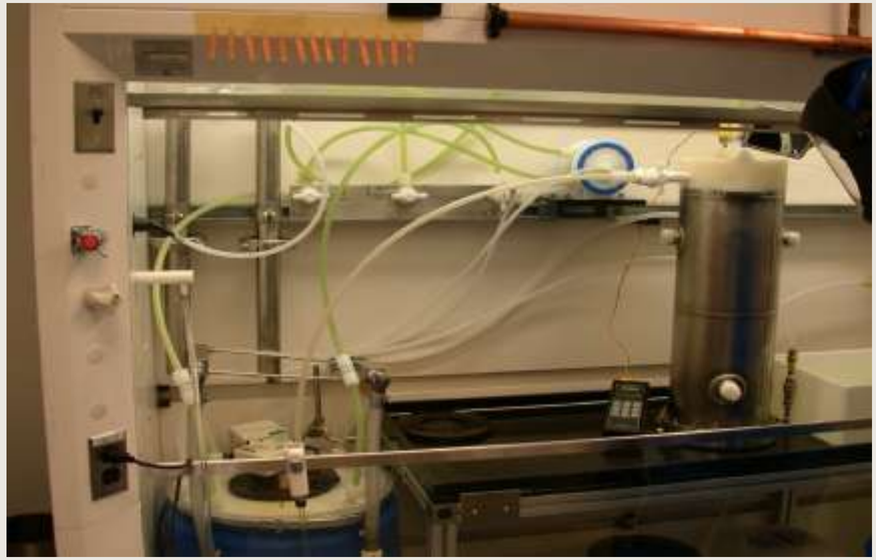
# Cavity Production at PAVAC


# BCP Etching at TRIUMF

BCP 1:1:2
HF,HNO3,H3PO4

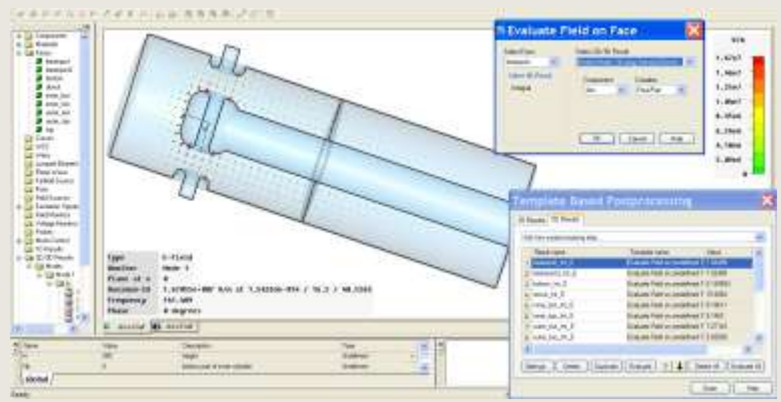



$H_2O$



~$10^0$C
~1um/min
~100um etch

Pre-weld etching ~20um

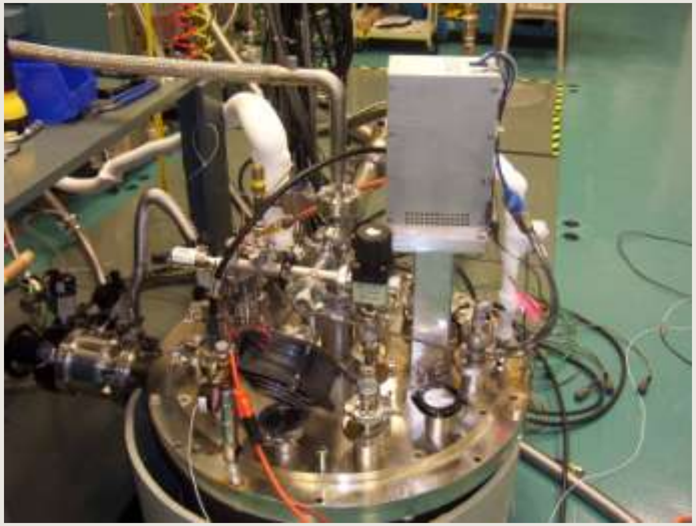



Differential etching for frequency compensation
Differential sensitivity for ½
2 kHz/um for

# Cavity Preparation

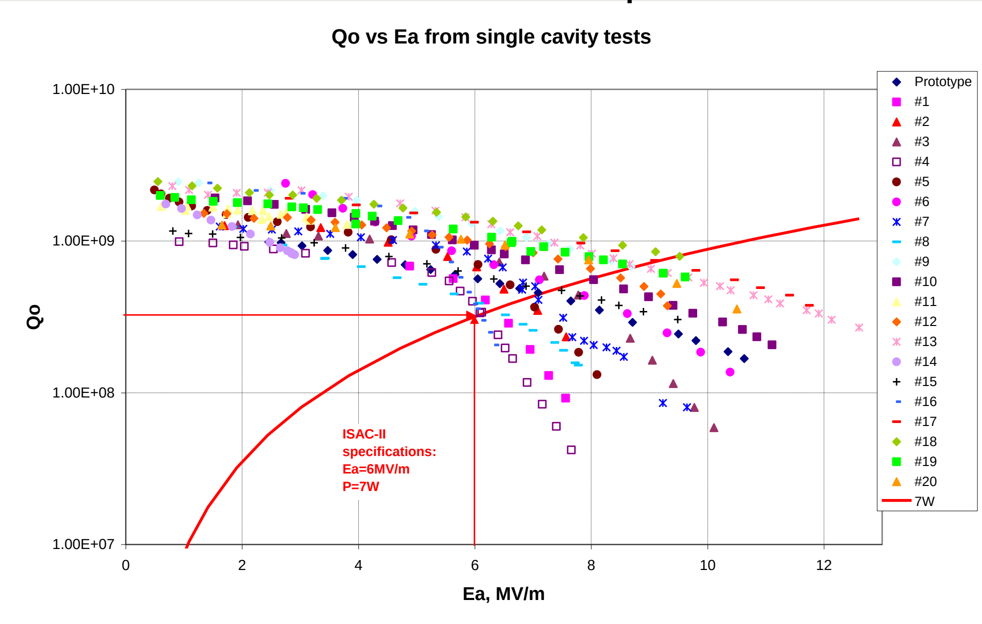
Typical treatment before the test Involves
• 40min high pressure rinse
• 24 hour air dry in a clean room

# Single cavity test

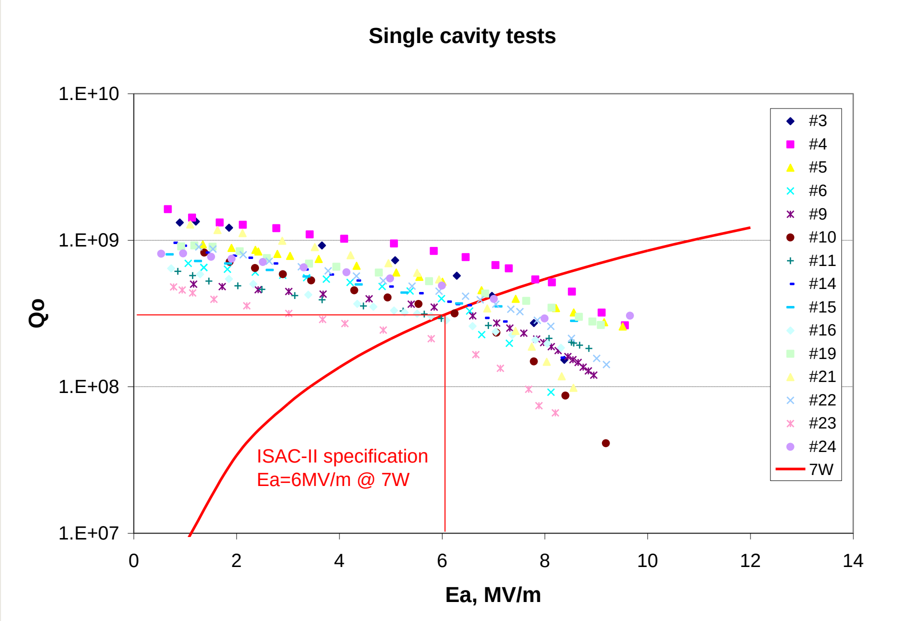


# Single cavity test results

Phase-I, Ep=

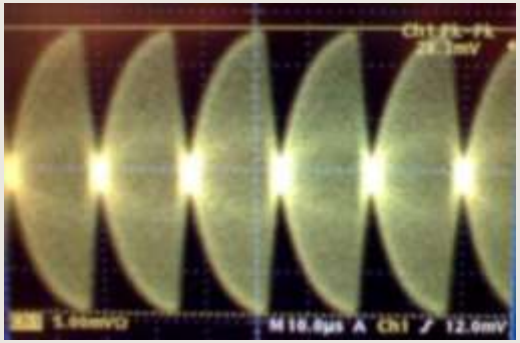



Phase-II

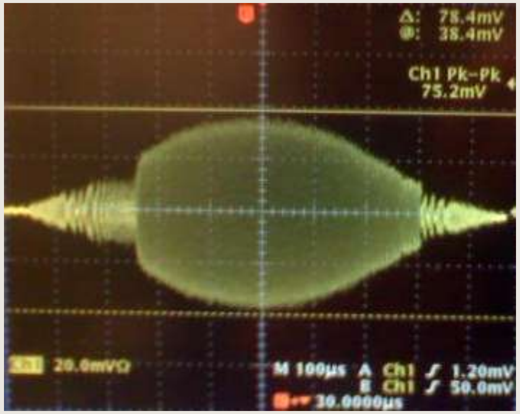



- Both Phases prepared with the same procedure : degreased, BCP etch, 40 minutes high pressure rinsing with ultra-pure water, air dried for 24h and assembled in clean room.
- Cavities are baked for 48 hours during pumpdown: single cavity cryostat 85-90C, cryomodules 70-75C.
- Thermal shield of cryomodule is pre-cooled with LN2 24h before helium cooling is started. (cavities stay above 200K).
- Fast LHe cooling to avoid Q-disease due to hydride precipitation. (cooldown rates around 80-100K/hour between 150-50K).
- Earth magnetic field shielded by warm μ-metal layer (1mm SCB and 1.5mm SCC) fastened inside vacuum vessel in cryomodule and cryoperm shield in single cavity cryostat

# Multipacting in Phase-II cavities




Multipacting in CW




Multipacting in Pulse

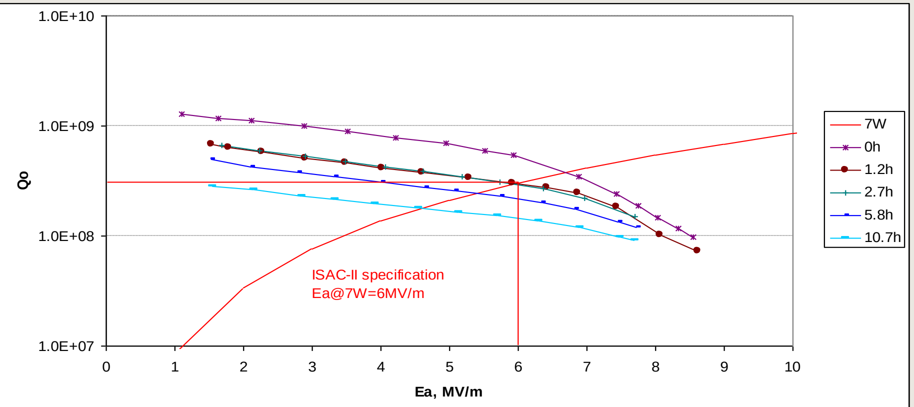
| Simulation by MultP-M code | | Measured |
|---|---|---|
| $E_a$, kV/m | Cavity region | $E_a$, kV/m |
| 12.0 – 26.0 | accelerating gap, donut – coax outer conductor | 10 – 24 |
| 27.0 – 33.0 | donut – coax outer conductor | 28 – 33 |
| 35.0 – 54.0 | coax line donut – end cap | 42 – 50 |
| 58.0 – 193.0 | donut – end cap | 77 – 80 |

**“MULTIPACTING SIMULATION IN ISAC-II SUPERCONDUCTING CAVITIES”**

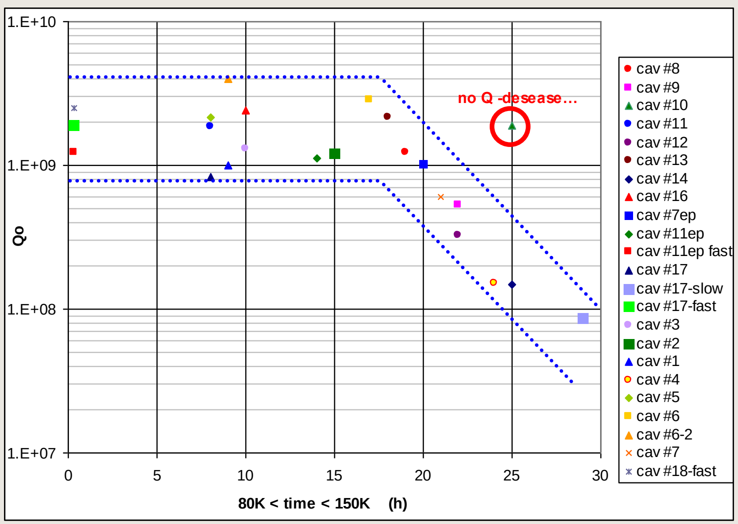
**M. Gusarova et. al., MEPhI, PAC09, FR5PFP076**

# Q-disease test

## Phase-II cavity test (typical)



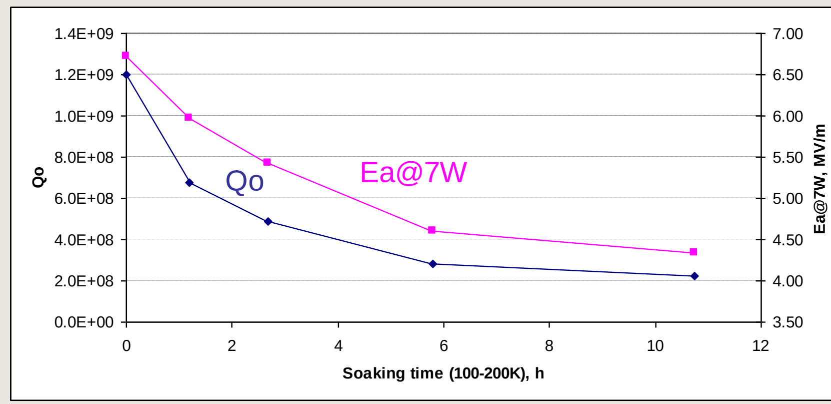

## Phase-I cavities




**Q-disease data from cavity#21 test**

| time@100K | Qo | Ea@7W |
|---|---|---|
| hours | | MV/m |
| 0 | 1.2E+09 | 6.72 |
| 1.19 | 6.76E+08 | 5.97 |
| 2.69 | 4.91E+08 | 5.43 |
| 5.8 | 2.83E+08 | 4.60 |
| 10.73 | 2.26E+08 | 4.34 |

Soaking of H for rf surface with subsequent performance degradation when cavity in the range 100-200K



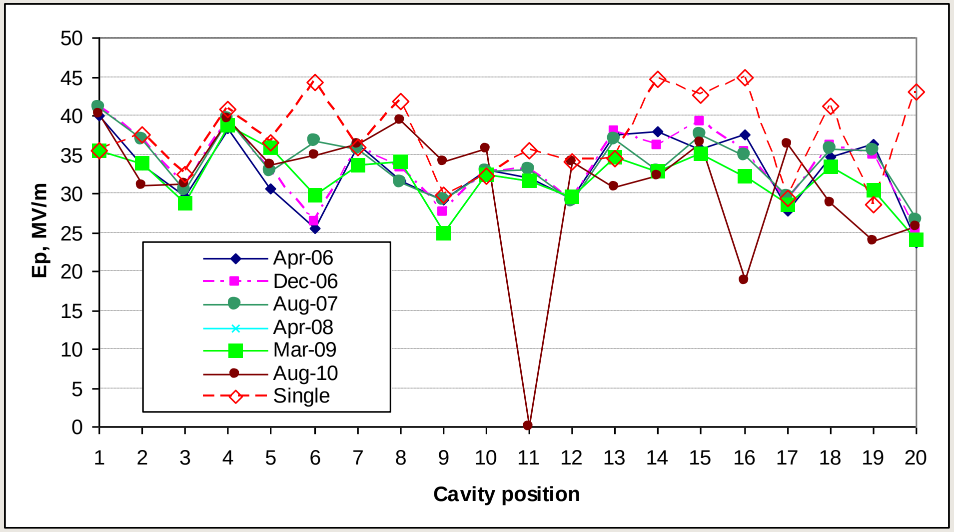

Significant degradation of Q even after 1h of soaking means big content of H in the material of Phase-II cavity (PAVAC)

**There is a sence try to anneal (600-800C in vacuum furnice)Phase-II cavities**

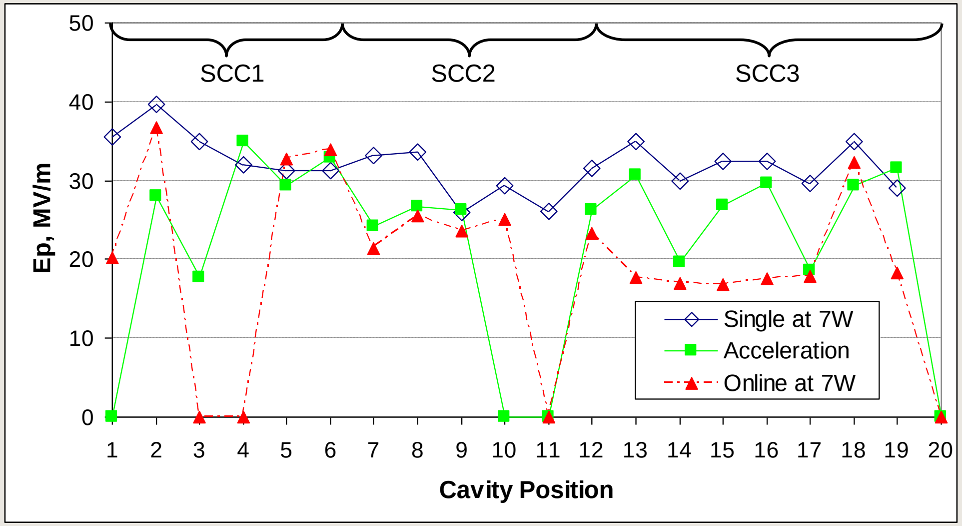
For Phase-I (Zanon) critical soaking time was 10h

# Online Performance

Phase-I




Phase-II




| Test | Metric | PHASE I (MV/m) | PHASE II (MV/m) |
|---|---|---|---|
| Single Cavity | <Ep> @ 7W | 37 | 32 |
| Installed | <Ep> @ 7W | 33 | 26 |
| Acceleration | Stable <Ep> | 30-32 | 27 |

Peak field Ep=5*Ea, Acceleration voltage Va=Ea*0.18

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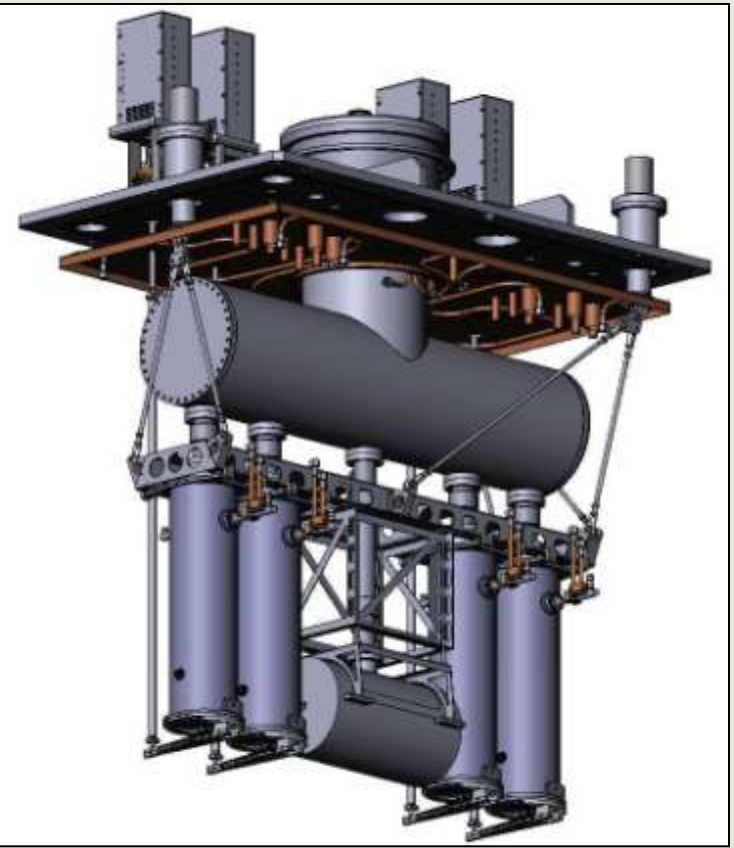
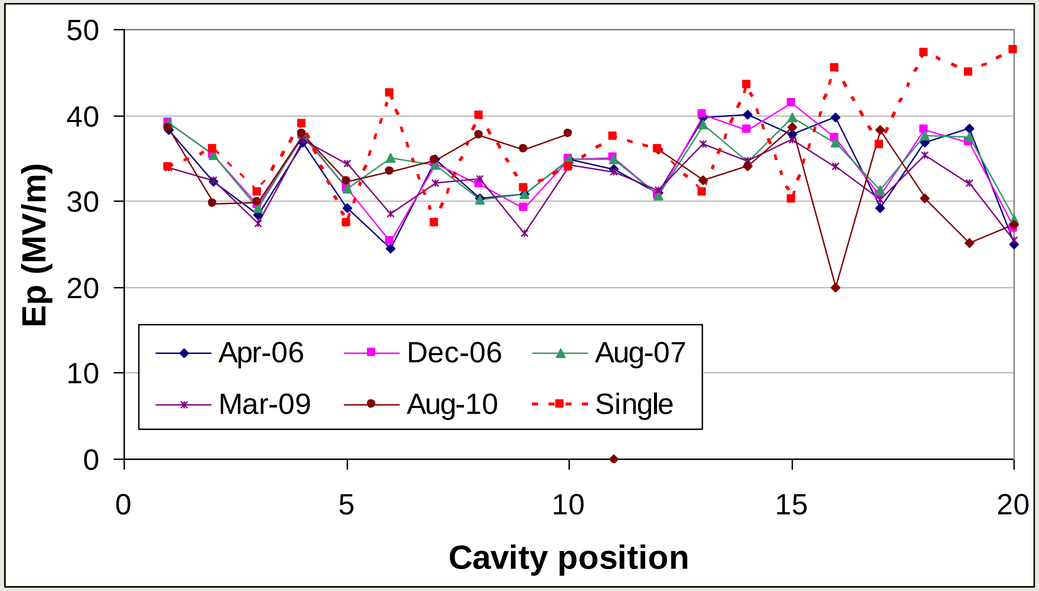
# PHASE I EXPERIENCE






- No major degradation of cavity performances over 4 years (see figure below).
- Cavities operated at an average peak electric surface field of chronologically 33.6, 34.2, 34.4, 32.5 and 33.2 MV/m at Pcav=7W. Average peak field of 37.1 MV/m during single tests.
- Degradations observed after helium delivery failures due to trapped flux (solenoid). Full recovery in two hours after warming up to 30K.
- Strong low-level multipacting makes beam tuning difficult especially after start-up. Pulse conditioning is required.
- Aging of tube amplifiers causes detuning and non-linearity in LLRF control periodically.
- One cavity is out of commission
- presently (coupler cable open circuit).

Comissioned in 2006 for 40Ca10+, 22Ne4+, 20Ne5+, 12C3+, 4He1+ and 4He2+ (A/q ratios of 5.5, 4 and 2) with final energies of 10.8, 6.8 and 5.5 MeV/u

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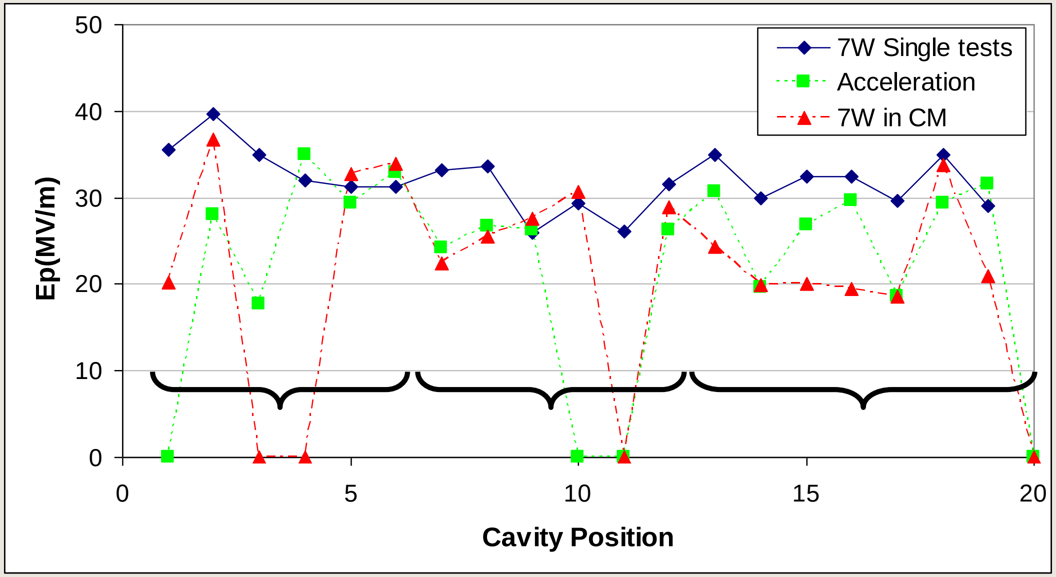
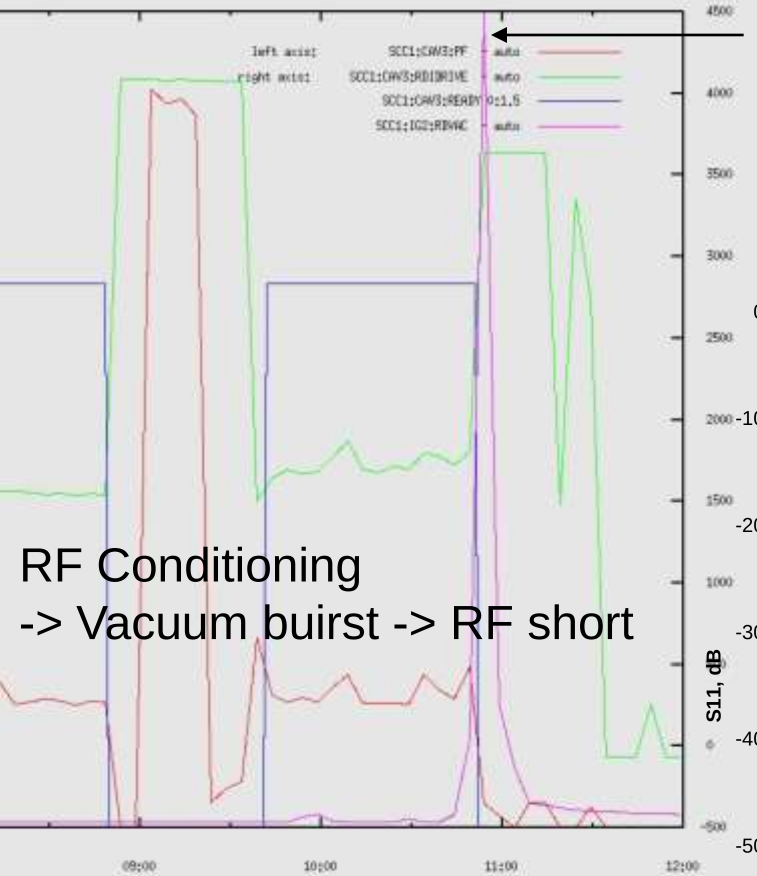
# PHASE II EXPERIENCE




16O5+ beam (A/q=3.2) from the ISAC off-line (stable) source was accelerated to 10.8MeV/u on April 24, 2010, which is equivalent to goal specification for the ISAC-II post-accelerator is to reach 6.5MeV/u for particles with A/q=6.

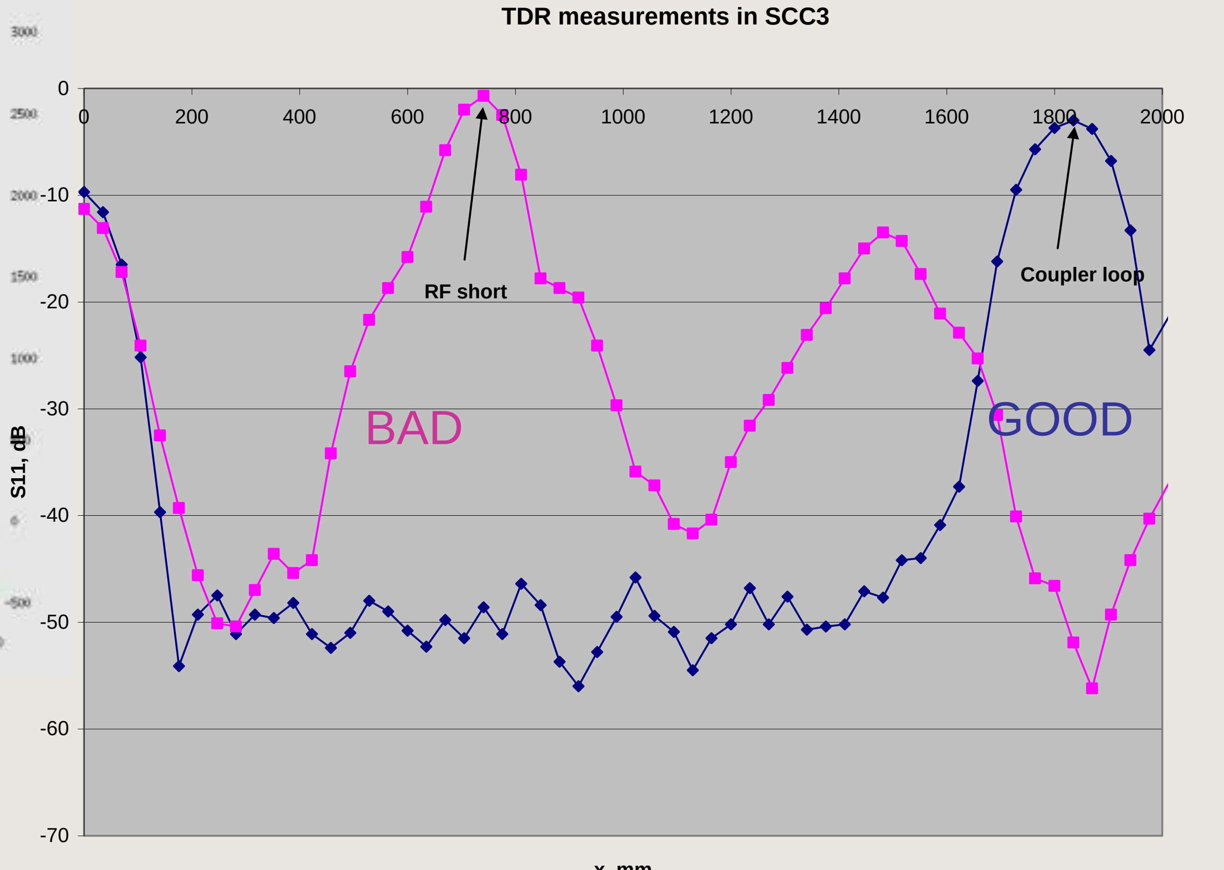
- Four cavities required rework after a vacuum leak opened during the initial BCP etching - weld joining the drift tube and the inner conductor – cavities recovered by PAVAC.
- Tight schedule imposed precautionary reduction of etching to 60 microns and four cavities installed without single cavity test.
- Average peak electric surface field dropped from 32 MV/m in single cavity test to 26 MV/m for on-line tests. Under study [6]. Theories: Single cavity performance reduced due to insufficient etch and cryomodule performance due to imperfect environment/preparation (Trapped flux, Q-disease)
- Four cavities are presently out of commission (coupler cable shorts) possibly due to too high forward power during conditioning.

# Phase-II inner cables failure



Vacuum buirst

RF short in the cable (ANDREW ETS2-50 3/8”). There are pumping holes in jacket like in Phase-I. We never had such a problem.



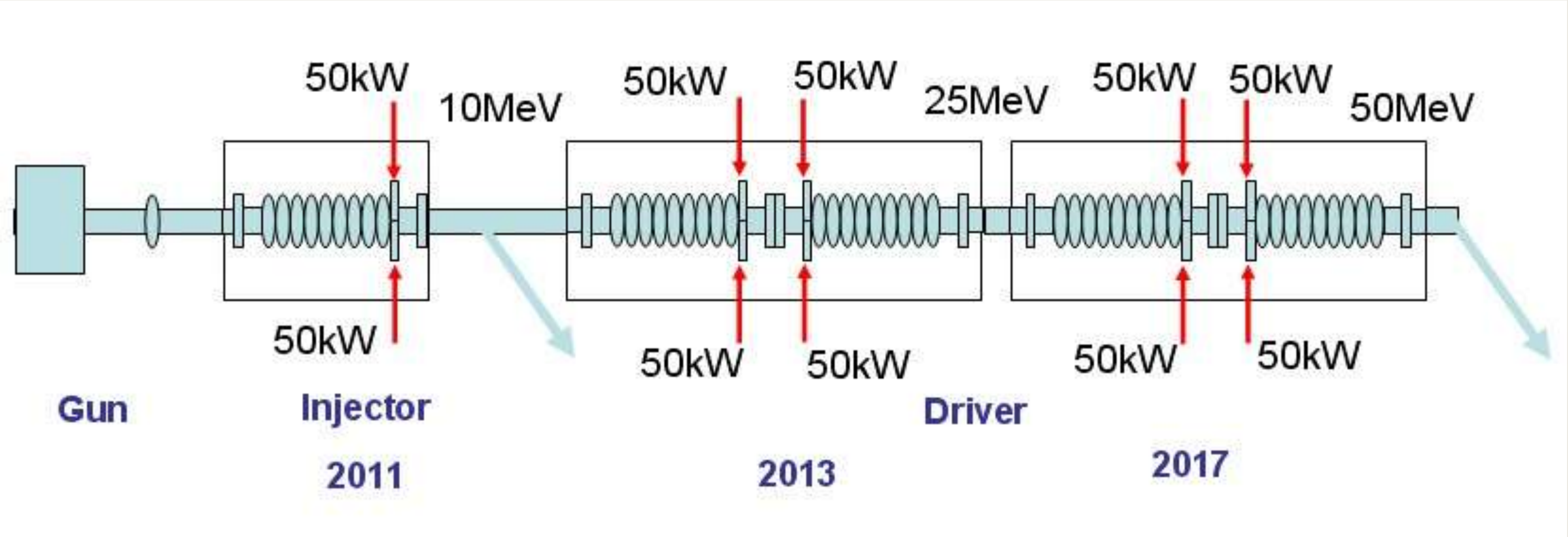

RF Conditioning
-> Vacuum buirst -> RF short

In the future we need to fix this problem in SCC cryomodules

Meantime we compensate the performance of the unavailable cavities by increasing the gradient in other cavities (at power dissipation >7W)

# SCRF Development for e-LINAC

# e-LINAC project at TRIUMF




In 2007 TRIUMF started developments toward an electron driver for photofission (Fig. 5) which will be independent and complementary to the 500MeV cyclotron. The linac is composed of five 9 cell elliptical cavities at 1.3GHz in 3 cryomodules with final goal by 2017 of 50MeV/10mA, 0.5MW beam power, CW operation.

# Cavity parameters

| Parameter | Units | Value | Value |
|---|---|---|---|
| frequency | GHz | 1.3 | 1.3 |
| Cells | | 9 | 9 |
| Veff | MV | 10 | 14 |
| Phi | Deg | -3 | -3 |
| R/Q | Ohms | 1000 | 1000 |
| Q0 | | 1e10 | 1e10 |
| Pcav | W | 10 | 20 |

Table 9: RF parameters for the multi-cell cavity.

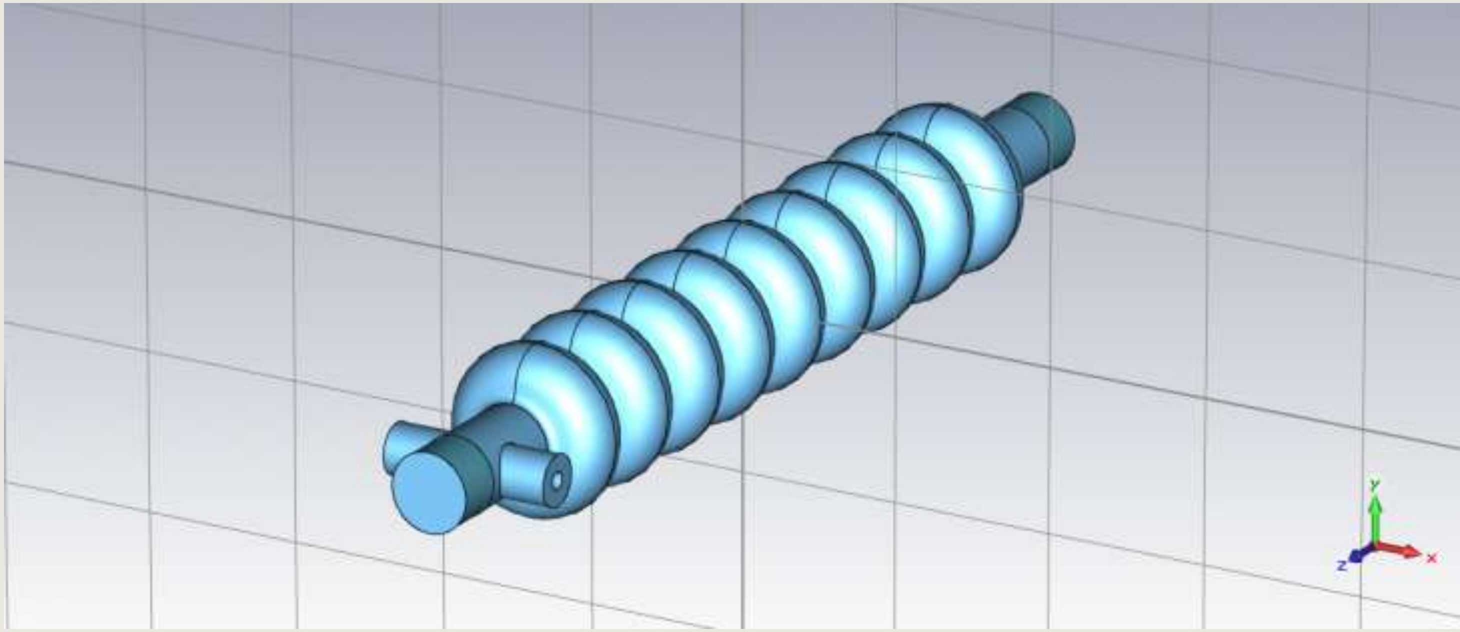
TESLA cavity

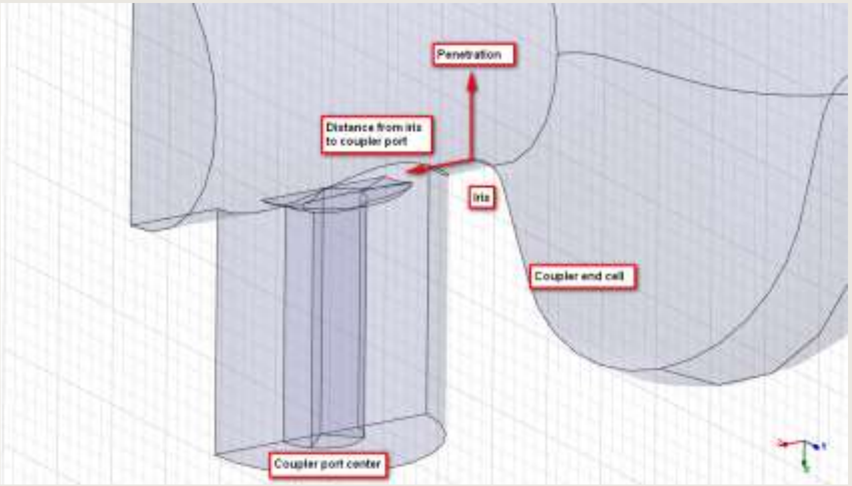
CPI 50kW coupler

# TRIUMF 9 cell cavity HOM study

Geometry details in mm:

Inner cells
sr1 = "35"
srx1 = "12"
sry1 = "19"
sr2 = "103.3"
srx2 = "42"
sry2 = "42"
sxlen2 = "57.7"
End cells
sr1 = "48"
srx1 = "10"
sry1 = "13.5"
sr2 = "103.3"
srx2 = "45"
sry2 = "40.5"
sxlen2 = "56"
Pipes
Length 117
Rings
Length 60
Coupler
R 31
Height 103.3
CPI coupler Antenna
Position 63, penetration -2.5

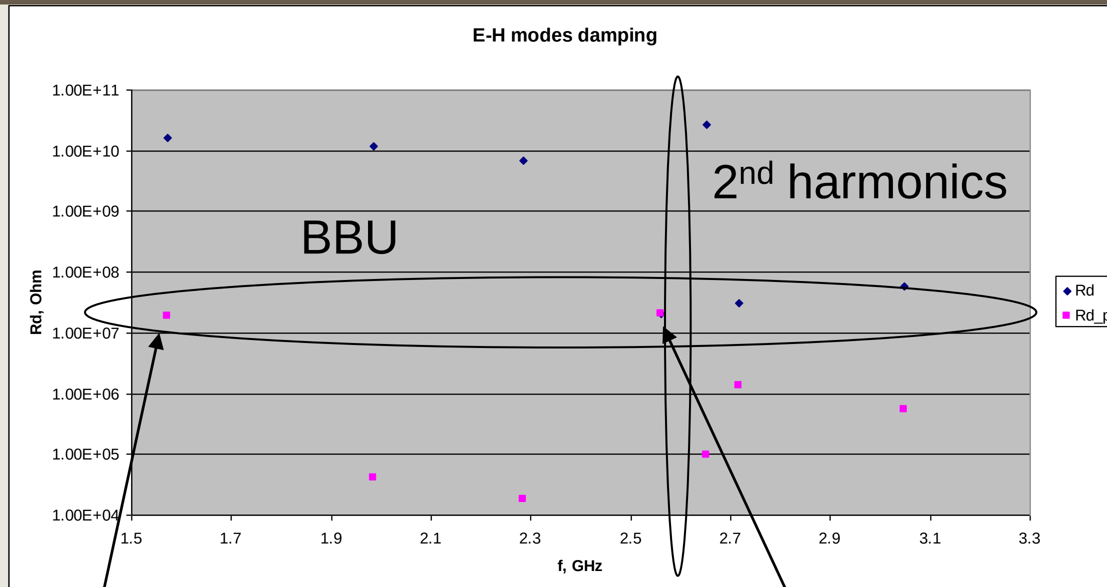


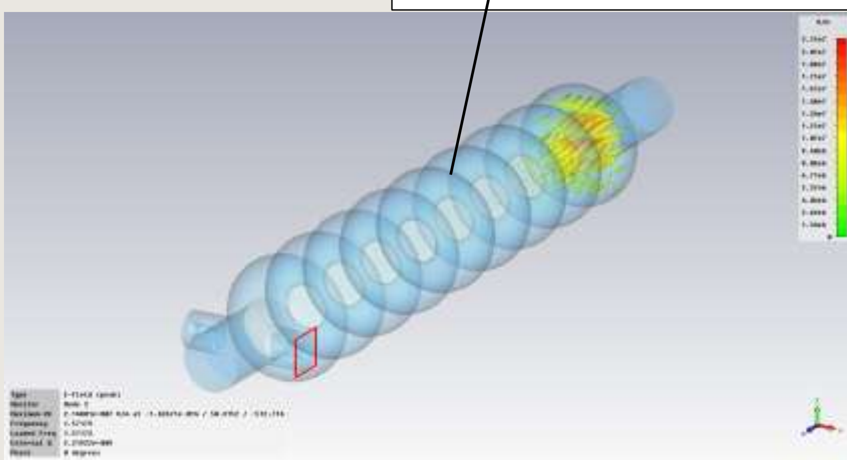


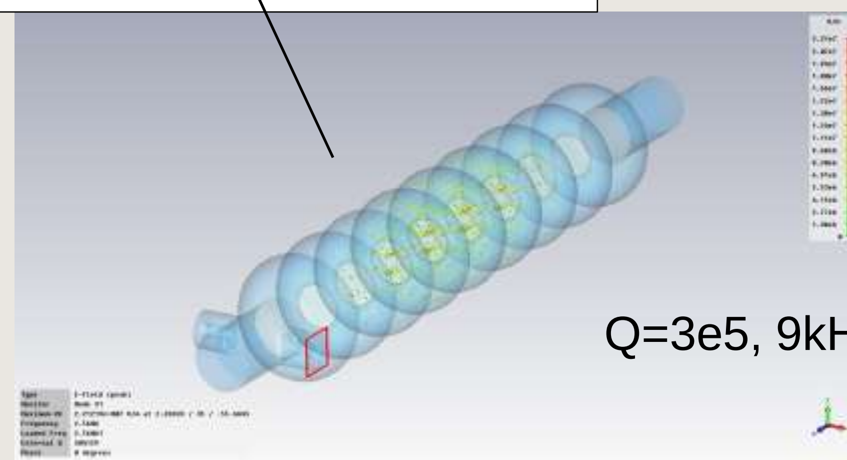
# HOM Analysis

- Studying nine-cell cavity with TESLA inner cells and 96mm entrance and exit pipe for 62mm coupler ports
- BBU threshhold set at Rd<1e7 Ohm
- Analyzing effectiveness of stainless steel rings in cavity pipe to damp modes beow threshhold
- Search for trapped dipole modes
- Analysis on-going

# Dangerous modes






Dipole TE111 1.572GHz

Trapped dipole TE111 2.56GHz No damping from pipes Rd=2e7 Ohm

# SRF Development at 1.3GHz

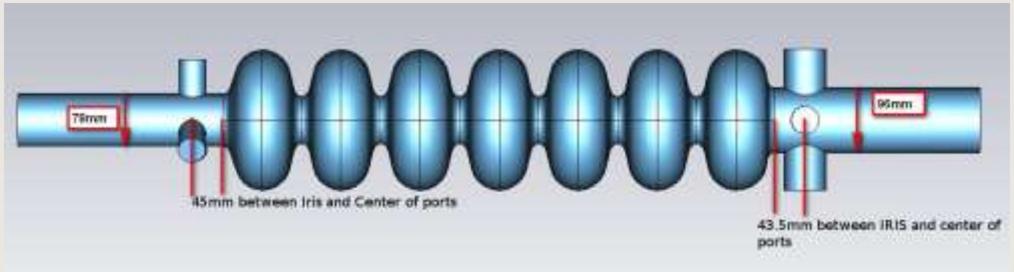
- Status of 1.3GHz cavity testing program in ISAC-II
  - Test cryostat operational for single cell testing
  - Investigating etching requirement to saturate performance
  - Quality factor now at 5e9 after 90microns of etching
  - Improving clean room procedures to reduce field emission and push gradients
- Cavity fabrication at PAVAC
  - Two Single cells produced and tested
  - PAVAC now fabricating copper seven cell for fabrication study and for student research

# Multi-cell Cavity Fabrication

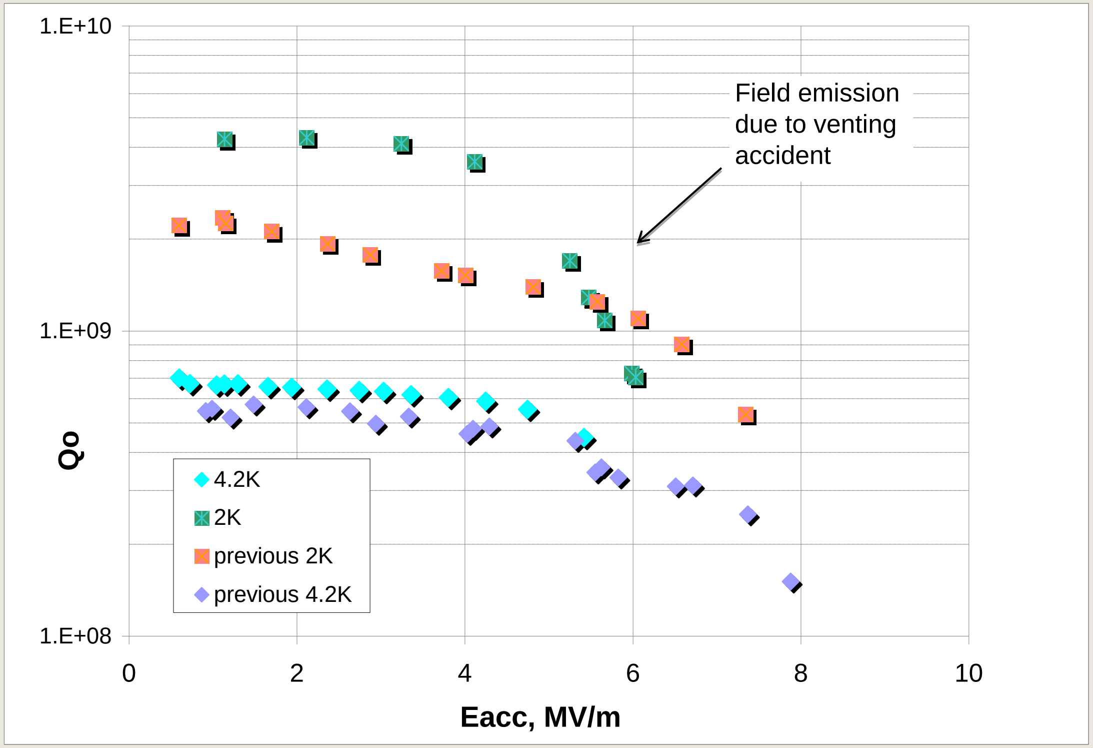
•Seven cell cavity in copper being fabricated at PAVAC

•Cavity has internal cells of TESLA nine-cell with two power coupler ports for 50kW CPI coupler and three rf ports for rf testing on tuner end

•Used both as a fabrication exercise and for student training

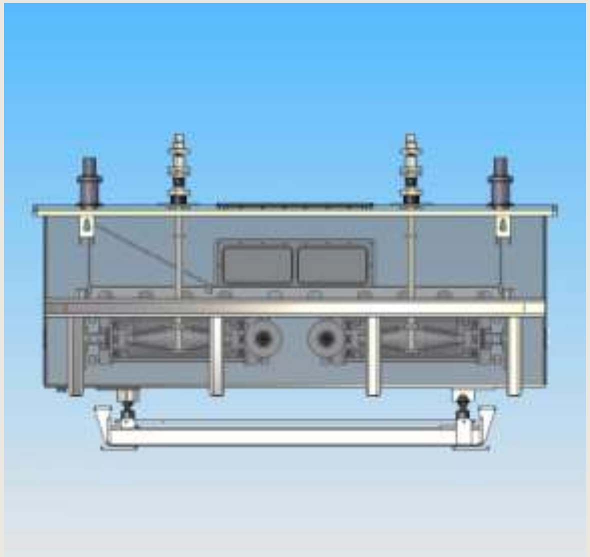



# Single cell cavity test

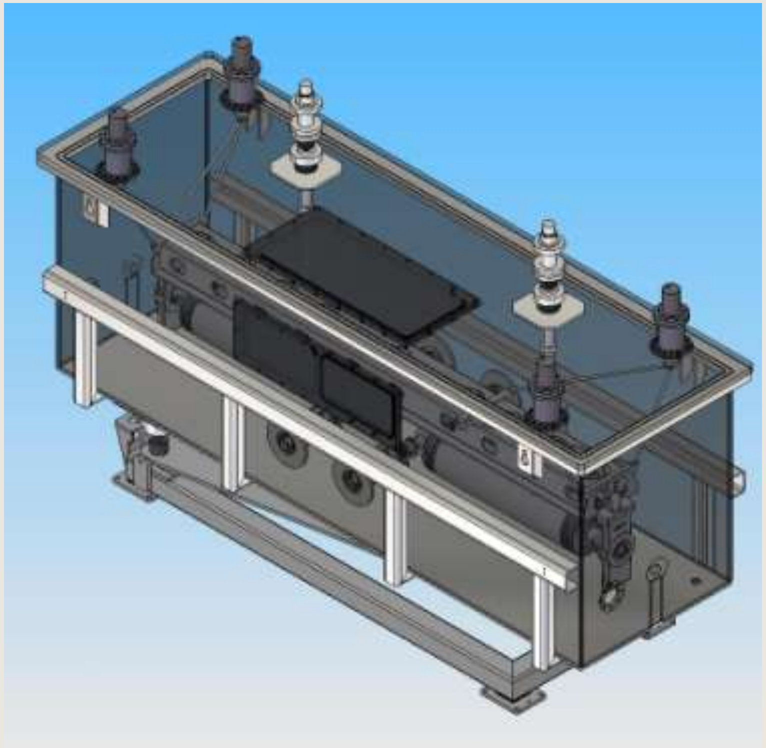


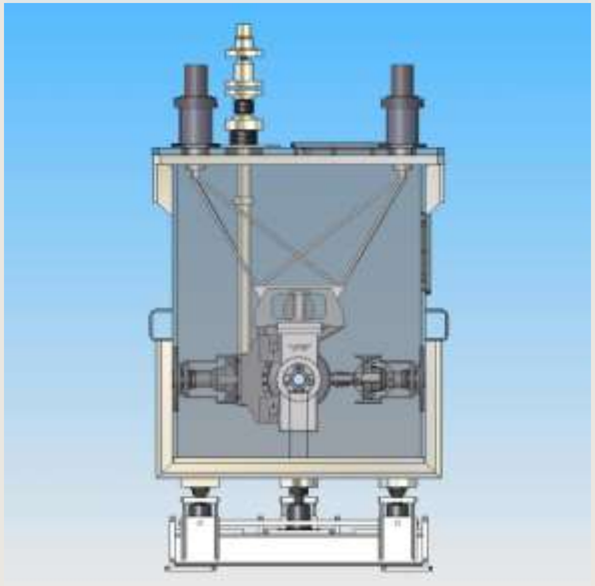

at 2K Qo~4*10$^9$ is still not enough and maximum gradient Ea~7.5MV/m is limited by field emission due to a venting accident during cavity test preparation. We already have done another etching and prepared the cavity for the next test.

# e-Linac Top-load Box Concept

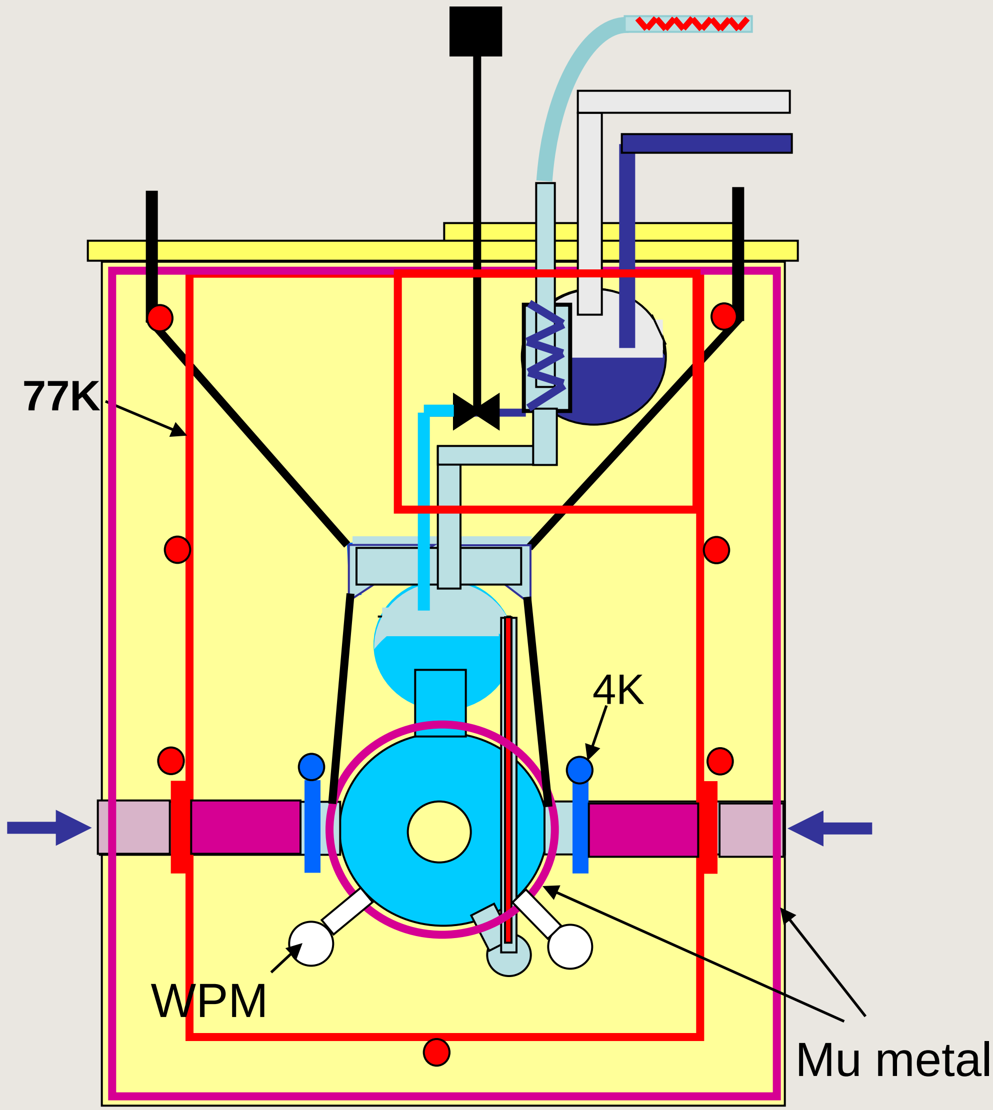


- Cold mass (cavity string, tuners) supported from strongback
- Strongback held in place by support posts strung from the lid



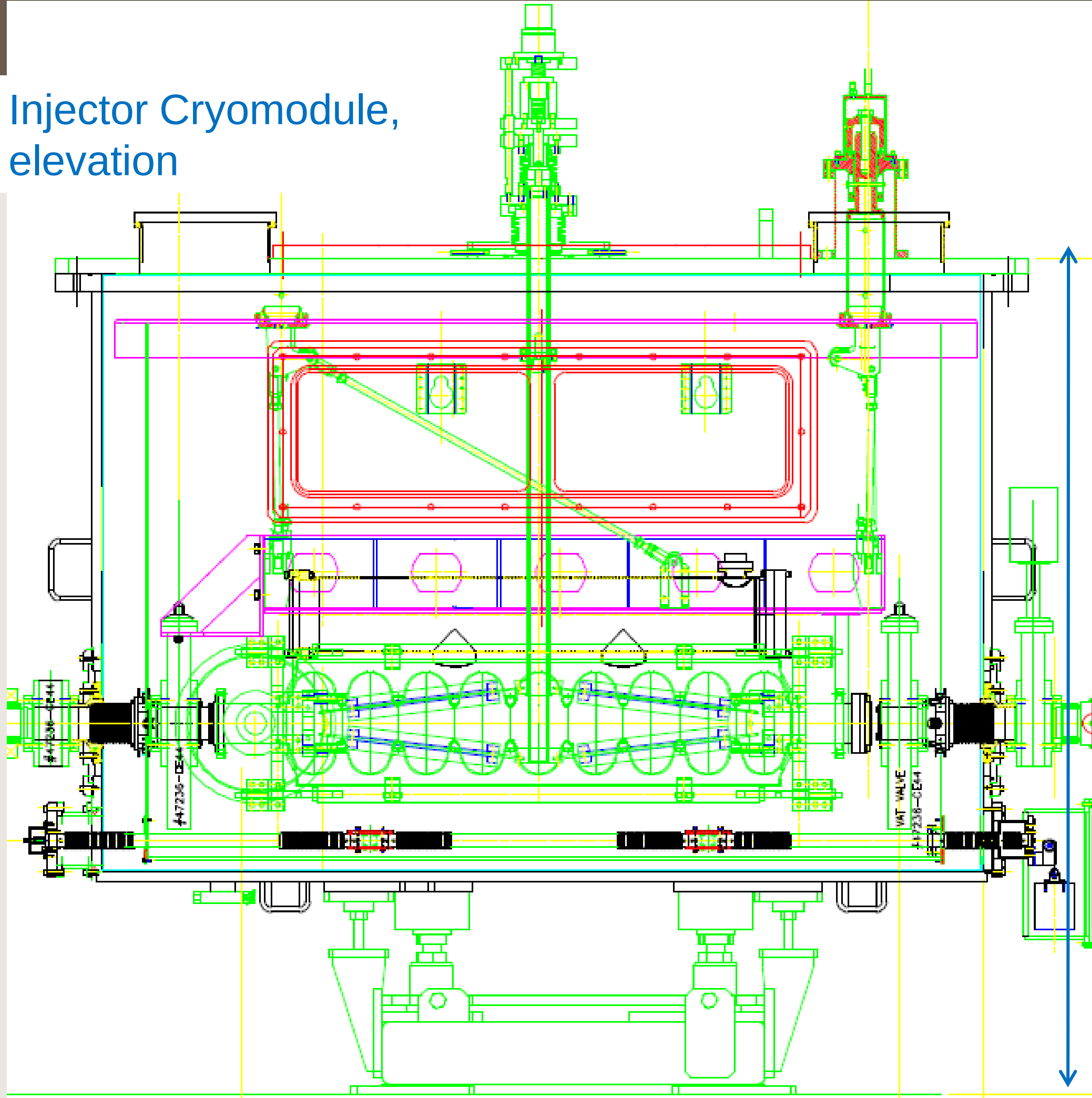


# e-Linac Cryomodule features




- •Top loading box concept
- •Cryogenic insert with 4K phase separator JT valve and heat exchanger on board to produce 2K liquid; insert removable with cryomodule in situ
- •Cold mass supported by strong-back
- •LN2 cooled thermal shield; 4K circuit for intercepts
- •Warm and cold mu-metal
- •Pair of alignment pick-ups upstream and downstream of each cavity
- •J-lab scissor tuner employed

# Injector Cryomodule, elevation



1.717 m

0.762 m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# Summary

- ICM design progressing well
  - External review Sept. 24
- SRF development in progress to support the e-Linac program
  - Multi-cell E-M modeling continues with HOM analysis
  - Seven cell cavity being fabricated in copper at PAVAC
  - PAVAC single cells now in testing rotation

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# CONCLUSIONS

- Commissioning and operational results of ISAC-II demonstrate successful operation of 20MV (20 SC QWR) from 2006. The accelerator, upgraded in 2010, now consists of 40 SC QWR cavities with independent RF systems providing high flexibility for tuning. The design goal for ISAC-II to provide 40MV acceleration voltage is achieved.
- Design, production and testing of SCRF cavities towards TTF/ILC elliptical bulk Nb cavities technology are ongoing at TRIUMF.

# THANKS!

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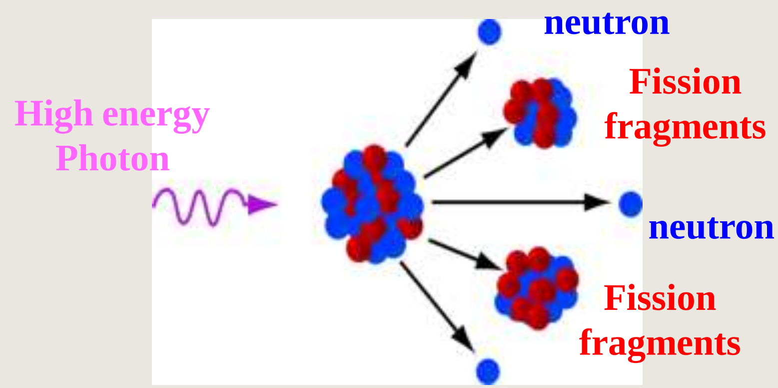
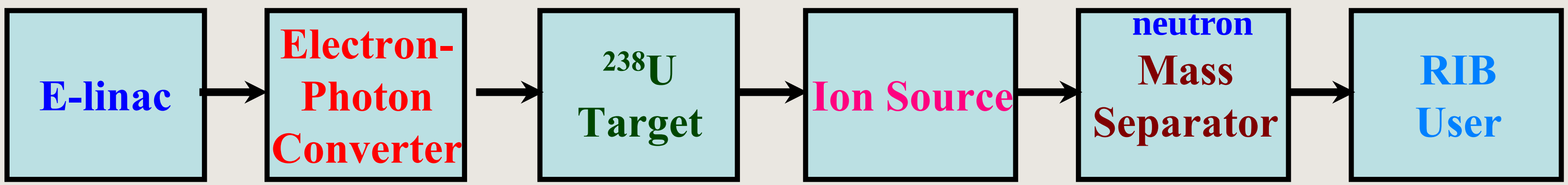
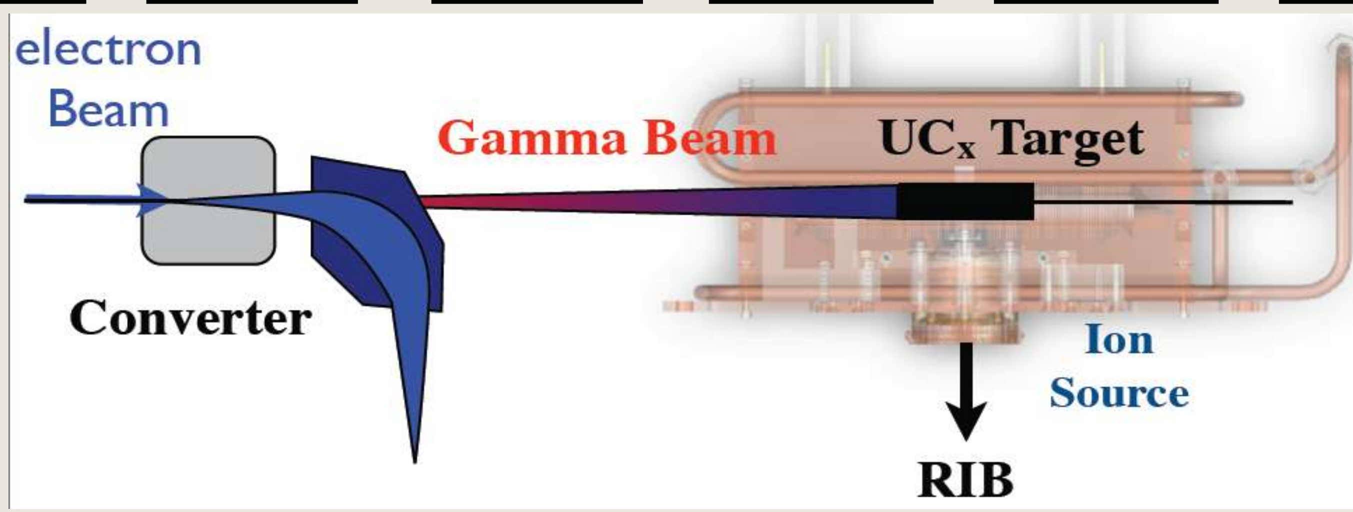
# Appendix

# Photo-fission production of RIB

Photofission of $^{238}$U was proposed by W. T. Diamond (Chalk River) in 1999 [NIM, V 432] as an alternative production method for RIB.





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# VECC Collaboration & Injector Cryomodule (ICM)

## Goal: define e-linac from 300 keV e-gun to 10 MeV, 25 kW

Challenge for beam dynamics design:

- Transport and acceleration compatible with both
  - Low brilliance thermioic gun (16 pC) - now
  - High brilliance photonic gun (100 pC) – future > 5 yrs

| Bunch vital statistics (rms=1σ) | Low brill @ Inject | High brill @ Eject |
|---|---|---|
| Normalized emittance (μm) | ≈5π | ≤10π |
| Longitudinal emittance (keV.ps) | ≈20π | ≈50π |
| Bunch length (ps) | 150 (FW) | ≈1 (rms) |
| Energy spread (rms) | 0.3 keV | <0.1% |

"at source" values for photo-fission

"at user" values for FEL