

PAUL SCHERRER INSTITUT



Markus Schneider :: RF group :: Paul Scherrer Institut

# Upgrade of the PSI Injector 2 Cyclotron

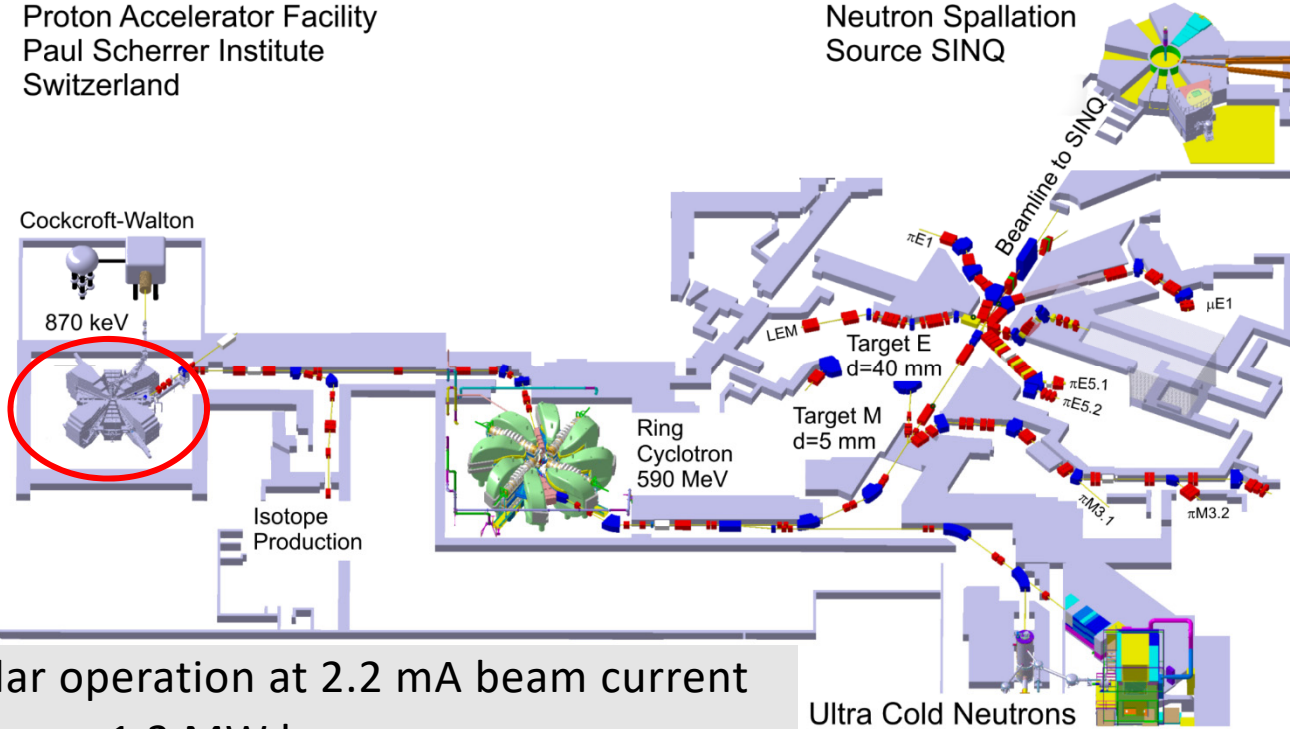
International Conference on Cyclotrons and their Applications (CYC2019), Cape Town

- Overview of HIPA
- The Injector 2 cyclotron
- Project goals
- The new RF system
  - 50 MHz Resonator
  - Amplifiers
  - Digital LLRF System

# Overview High Intensity Proton Accelerator

Proton Accelerator Facility  
Paul Scherrer Institute  
Switzerland

Injector 2  
Cyclotron



Regular operation at 2.2 mA beam current  
1.3 MW beam power  
Tested up to 2.4 mA beam current

# The Ring cyclotron

Injection energy: 72 MeV

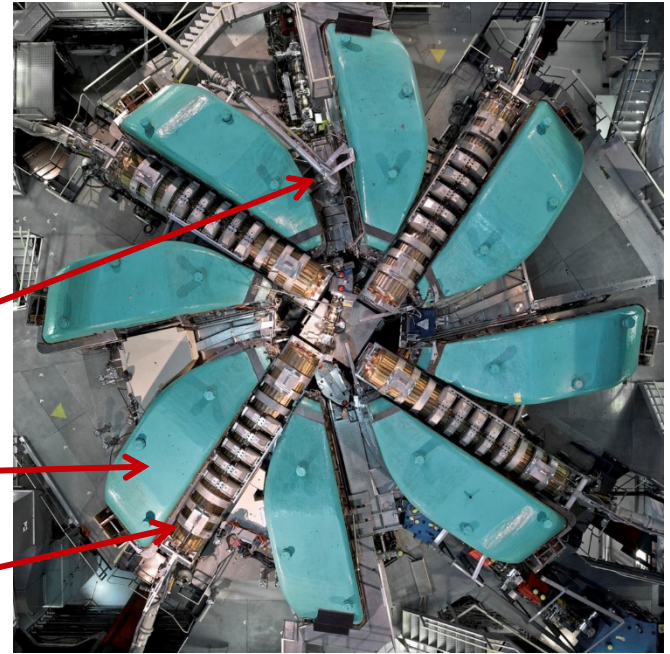
Extraction energy: 590 MeV

Number of turns: 186

Flattop cavity

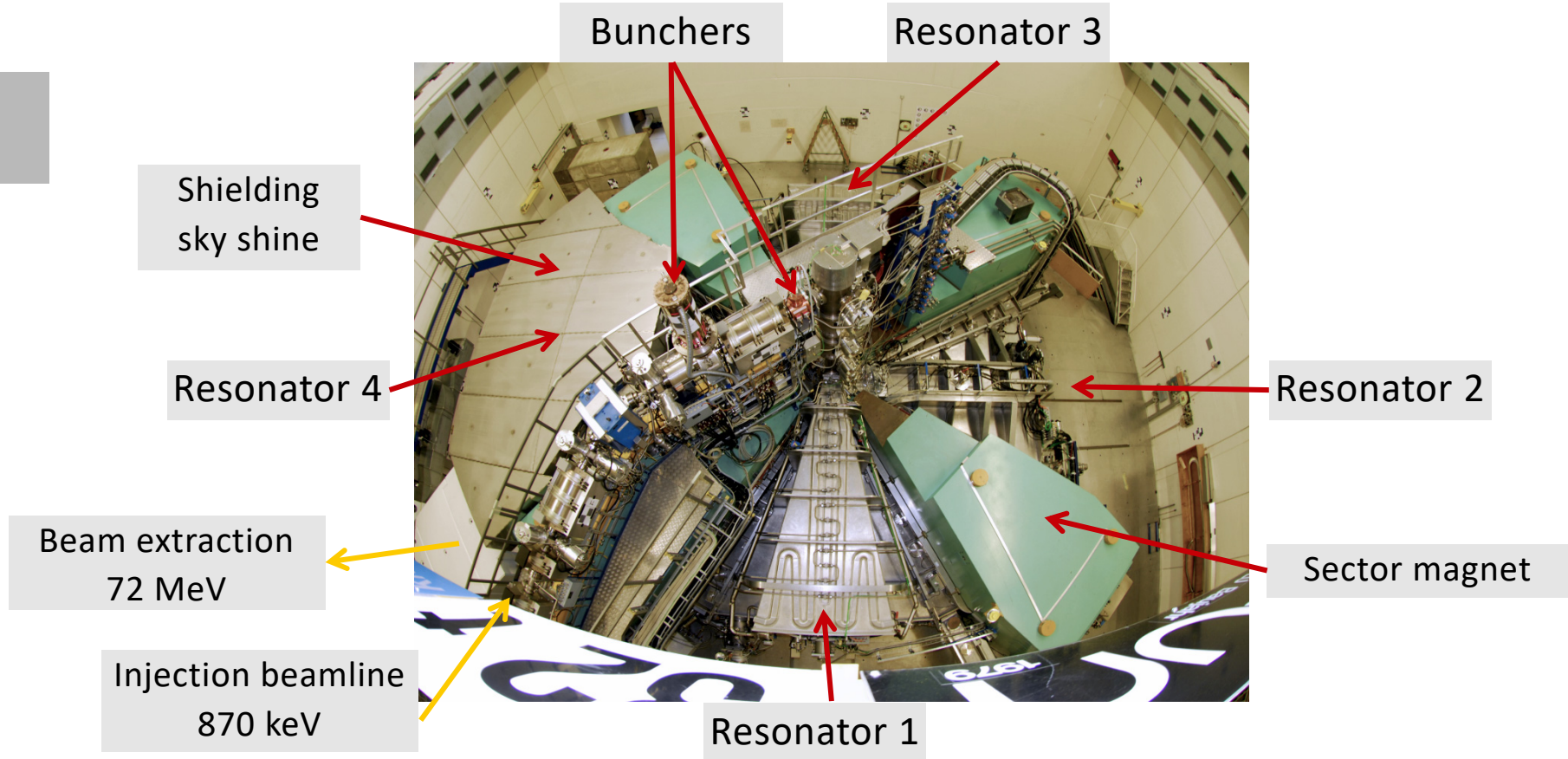
Sector magnet

Copper cavity

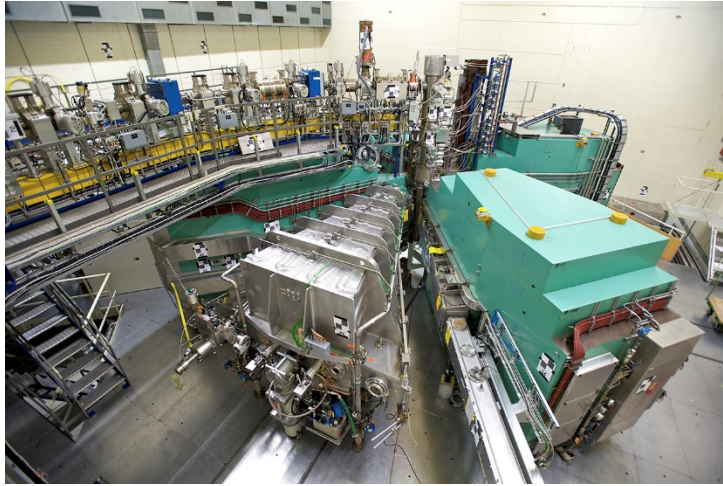


numbers	type	material	frequency	gap voltage	Wall losses in cavity	incident power @ 2.4 mA beam
4	Main cavity	copper	50 MHz	~ 850 kVp	~ 250 kW	~ 600 kW
1	Flattop cavity	aluminum	150 MHz	555 kVp	~ 90 kW	~ - 30 kW

# The Injector 2 cyclotron: status 2017



# The Injector 2 cyclotron



Injection energy: 870 keV  
Extraction energy: 72 MeV  
Number of turns: 83

Resonator	type	material	frequency	gap voltage	Wall losses in cavity	incident power @ 2.4 mA Beam
1 & 3	Double gap cavity	aluminum	50 MHz	~ 420 kVp (kV peak)	~ 150 kW	~ 225 kW
2 & 4	Flattop cavity	aluminum	150 MHz	~ 31 kVp	~ 5 kW	~ 14 kW
2 & 4 new	Single gap cavity	aluminum	50 MHz	~ 400 kVp @ extraction	~ 50 kW	~ 100 kW

# Motivation for the Injector 2 upgrade

## project goal:

Defined about 14 years ago:

**dreams of 4+ mA beam current**

&

renewal of RF-systems

today:

$\leq 3$  mA beam current

&

**renewal of RF-systems**

Increase energy gain per turn

-> less turns -> better turn separation ->  
lower extraction losses

2010 Thales:

End of production of smaller tetrodes  
-> last order in 2010  
-> finite time of operation

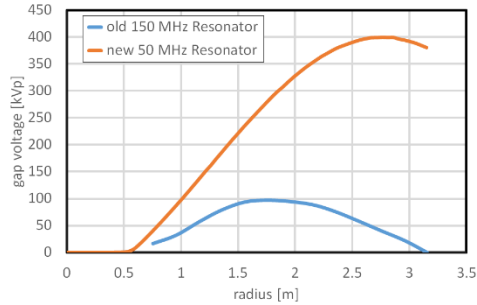
-> new RF-cavities

&

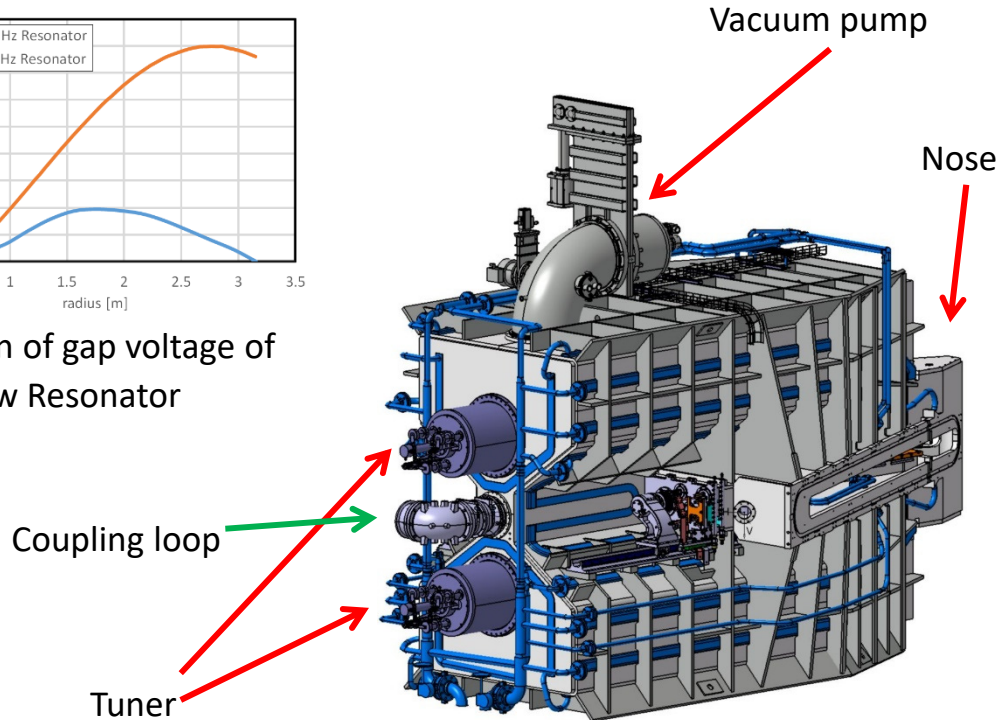
-> replacement of old amplifiers & LLRF

REI2 -> Resonator Exchange Injector 2

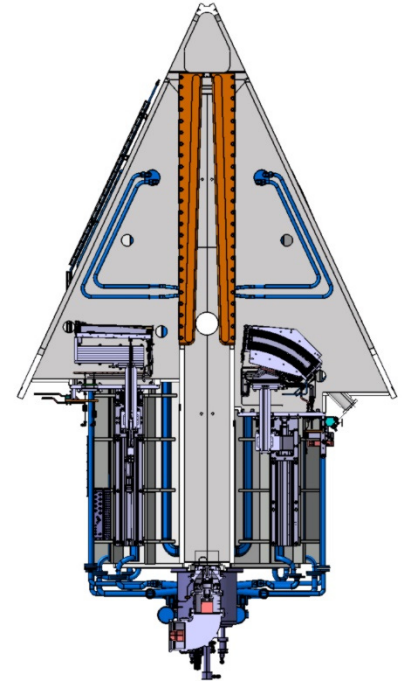
# The new 50MHz Resonator



Comparison of gap voltage of old and new Resonator

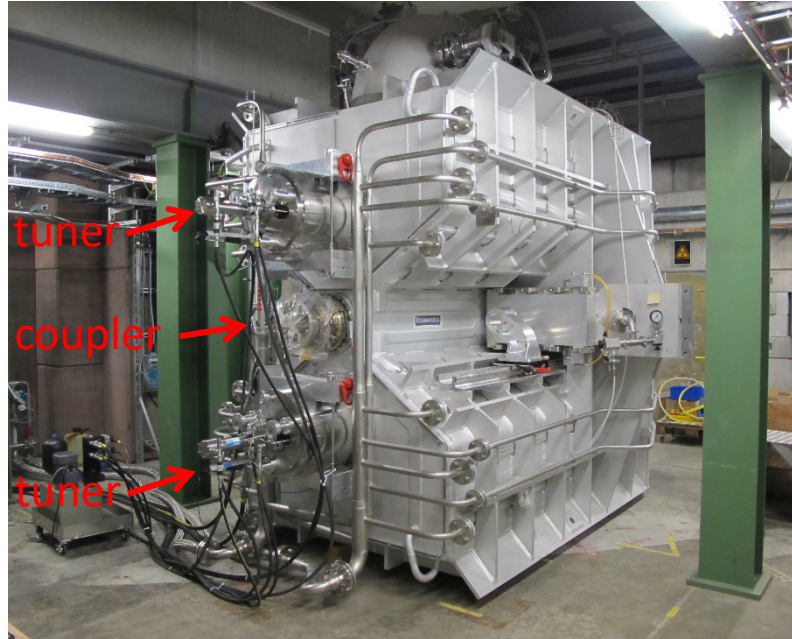


Isometric view of Resonator 4



Cross section horizontal mid plane Resonator 4

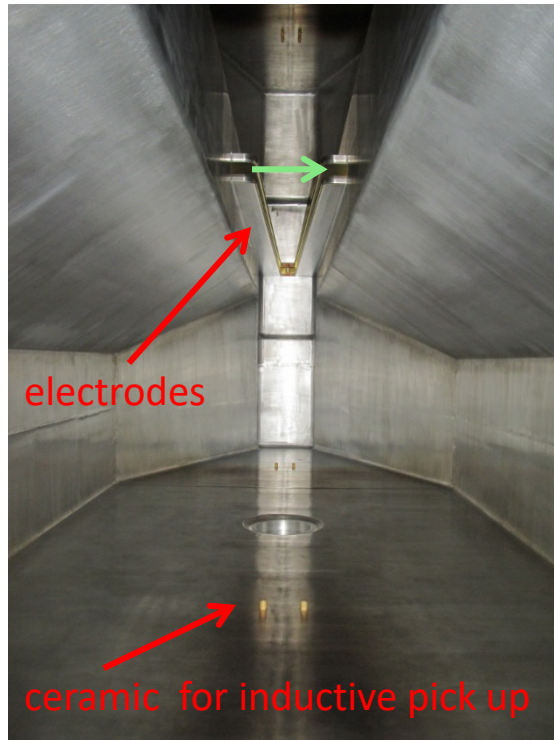
# The new 50MHz Resonator



Resonator 4 in test bunker

resonance frequency	50.6328 MHz
$Q_0$	24'500
Gap voltage (nominal)	400 kVp
dissipated power	50 kW @ 400 kVp
Tuning range	200 kHz
material cavity RF-wall	EN AW 1050
material structure	EN AW 5083
cooling water flow	15 m <sup>3</sup> /h
dimension	5.6 x 3.3 x 3 m
weight	7000 kg

# Inside Resonator 2



Pictures taken at inspection of Resonator 2 after power tests. View towards nose.

# Reduction of RF radiation into vacuum chamber



Capacitive pickup in Resonator wing to measure the RF radiation out of the beam slit

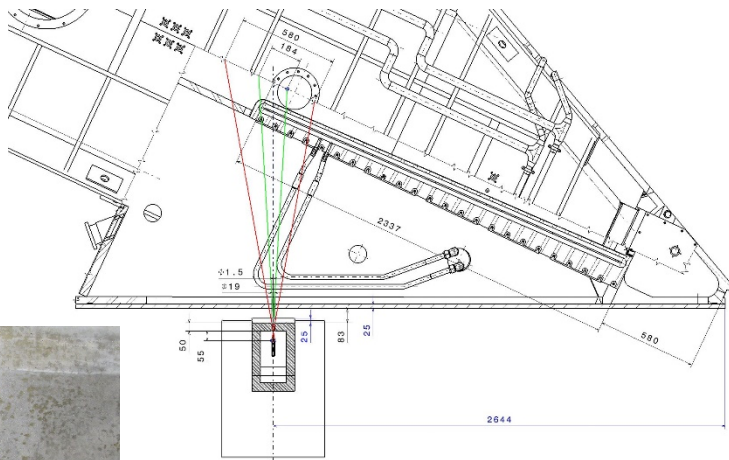
	RF power	before shifting	after shifting
Pickup in wing Beam exit side	50 kW	233.5 mV	22.2 mV
Pickup in wing Beam exit side	70 kW	271.8 mV	25.1 mV
Pickup in wing Beam entrance side	50 kW	41.7 mV	25.0 mV
Pickup in wing Beam entrance side	70 kW	33.3 mV	30.4 mV

By shifting the lower right electrode at the outer radius of 1.45 mm the measured signal on the pickup was reduced by 20 dB.

The radiation on both sides is now symmetrical.

Coupling between power coupler and pickup is -96 dB.

# Calibration of gap voltage



## Positioning of detector

Two different hole in lead housing  
( $\varnothing 19$  mm,  $\varnothing 1.5$  mm)  
-> different aperture angle of detector

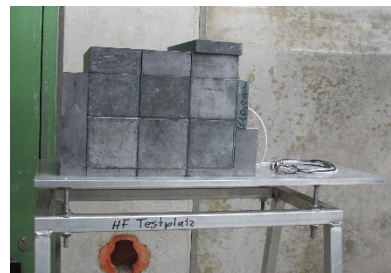
RF power	Voltage on reference pickup	Zero crossing in bremsstrahlung spectrum
35 kW	2.936 V	323 keV
46 kW	3.402 V	382 keV
56 kW	3.714 V	422 keV
66 kW	4.040 V	467 keV
75 kW	4.280 V	483 keV
85 kW	4.560 V	500 keV

Simulation cavity:

400 kV -> 50kW

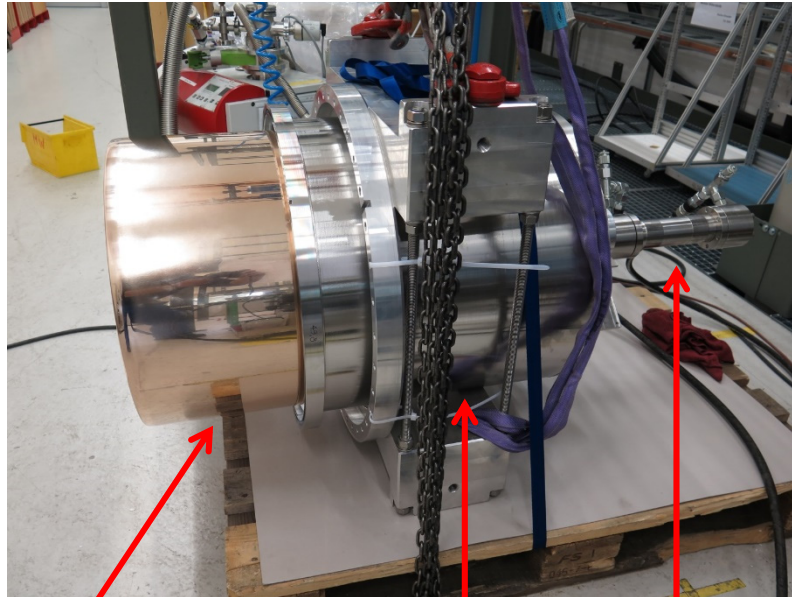
Bremsstrahlung:

400 keV -> 50.3kW



Lead housing holding the SPEAR™-detector (CZT-detector) of kromek

# Tuning system for Resonator



plunger

vacuum vessel with  
mounting structure

hydraulic cylinder

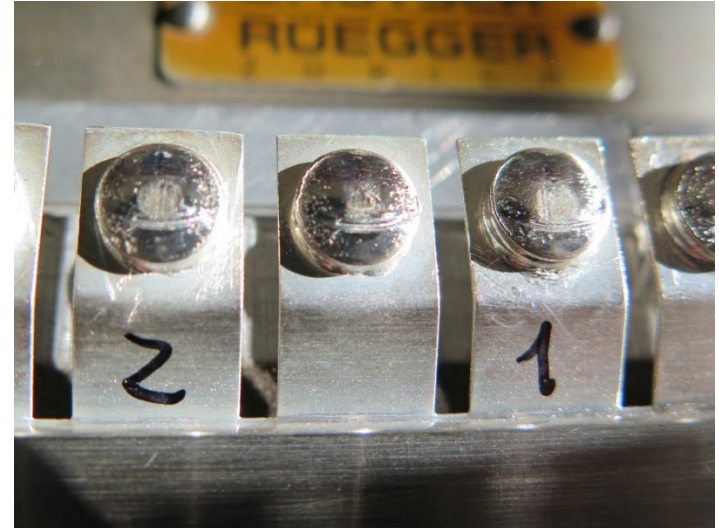
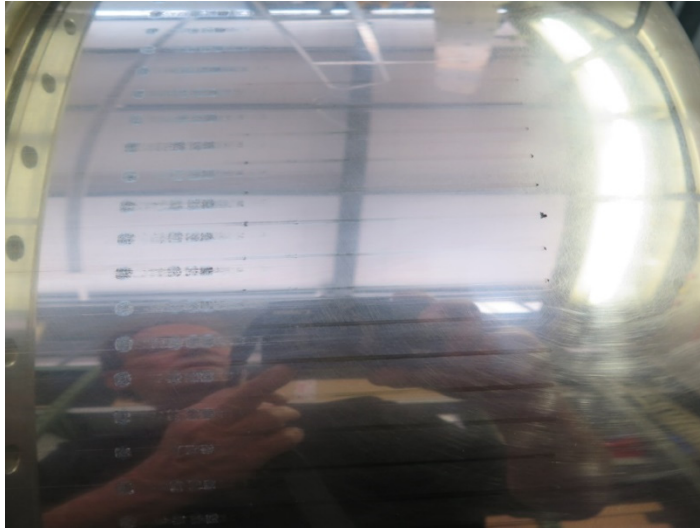
tuning range	200 kHz
way	200 mm
diameter of plunger	508 mm
speed of plunger	10 mm/s
current density on finger contacts	15 A/cm
cooling	water

Master/slave tuning system.  
Position of master controls the slave position.  
Slave moves slower than master.

# Development of finger contacts

Marks from first test

Only small amount of graphite

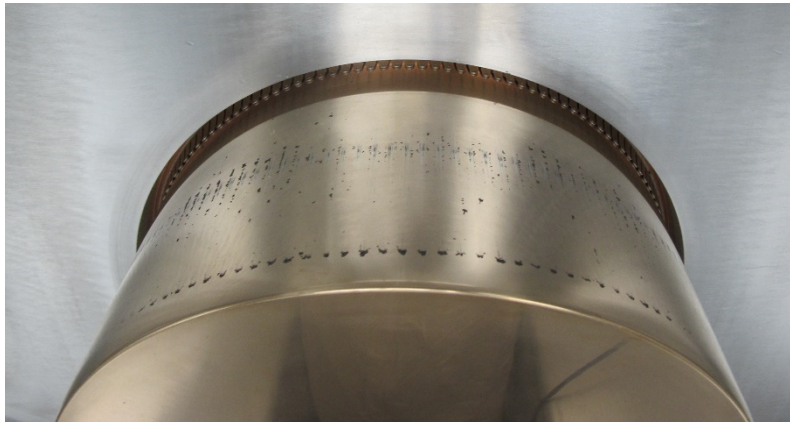
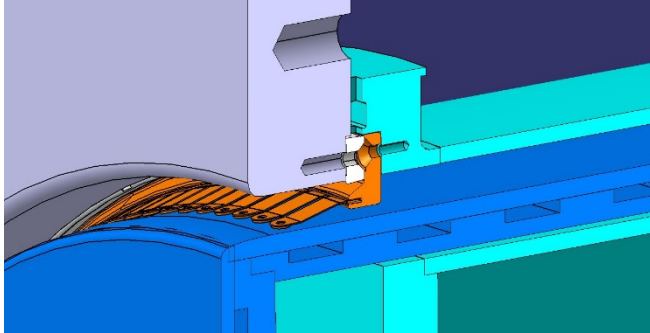


Plunger: copper with  $4\mu\text{m}$  hard gold plating

Finger contacts from: Sumitomo Heavy Industries, Ltd, Japan  
(Material: silver and graphite, 97/3)

Reduced pressure on each finger (**0.3kg / 0.3mm way**).

# Tuner development



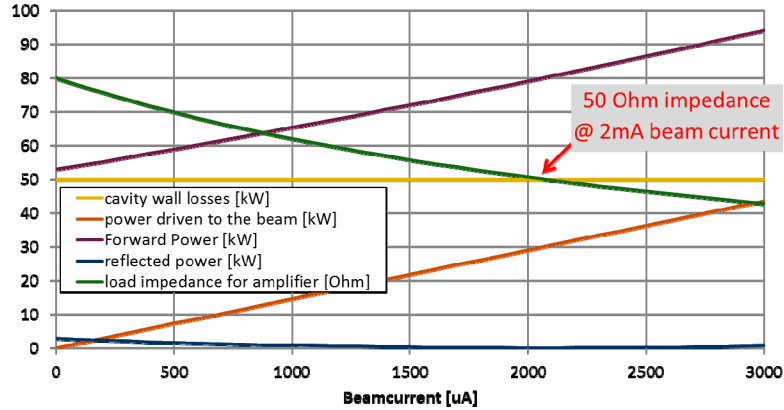
PSI finger contact design:  
Silver / graphite powder of finger contacts on  
tuner after one week of testing

Upgrade of the PSI Injector 2 Cyclotron, CYC2019, Cape Town

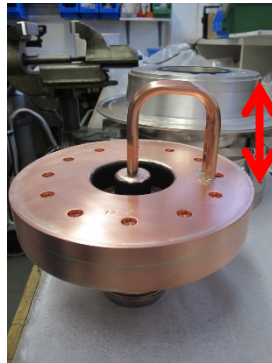
- Present finger contact design not suitable for operation.
- New design doubling the number of finger contacts in production. Lower current on each contact.
- A preliminary version without finger contacts under test.

# Coupling loop

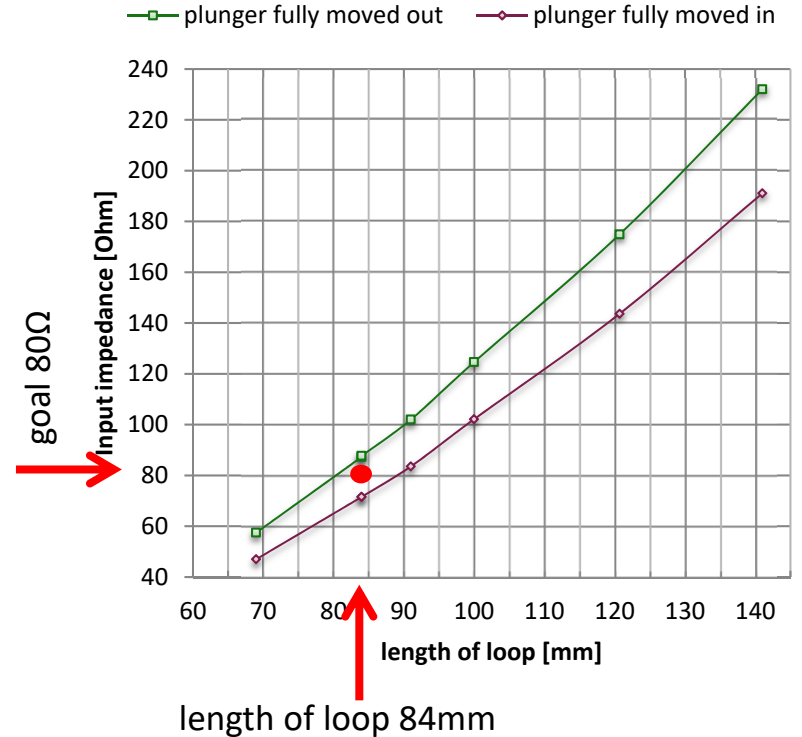
## Calculation of Input Impedance versus Beam Current



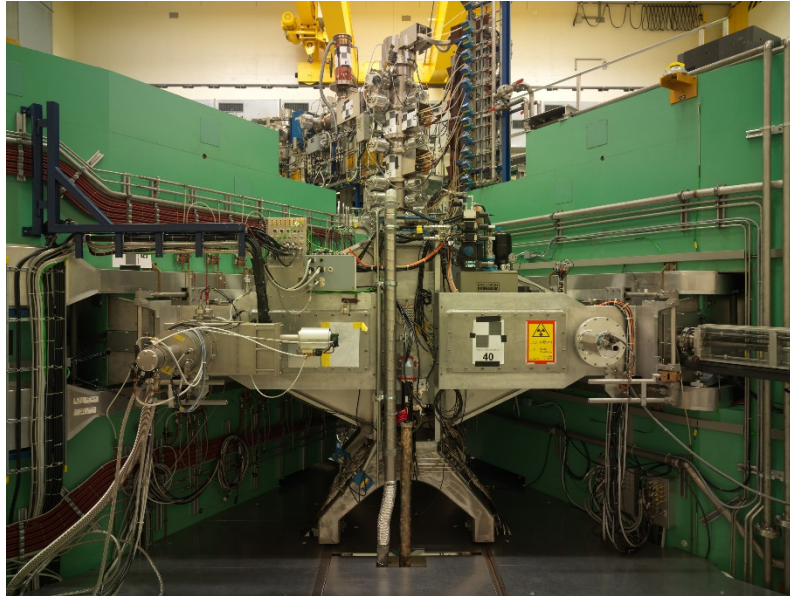
Coupler with soldered coupling loop.  
Length of loop 84mm.  
Impedance 81 Ohm



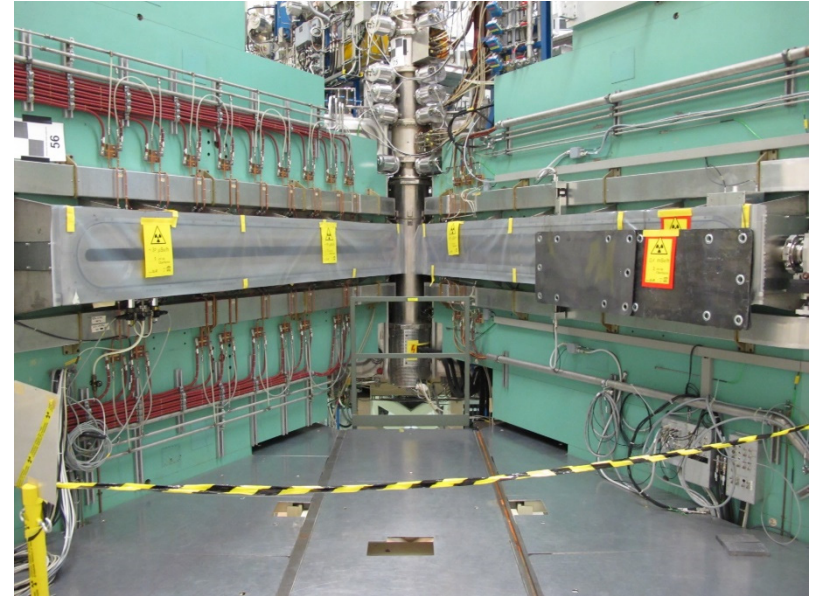
## Measurement Input Impedance versus Loop Length



# Replacement of old Resonator 2



Old 150 MHz Resonator 2



Open sector of the Injector 2 cyclotron

# Bringing the new Resonator into the Injector 2 bunker



Bringing the new Resonator in the Injector 2 bunker



Passing trough the wall  
(only about 10 cm left in height)

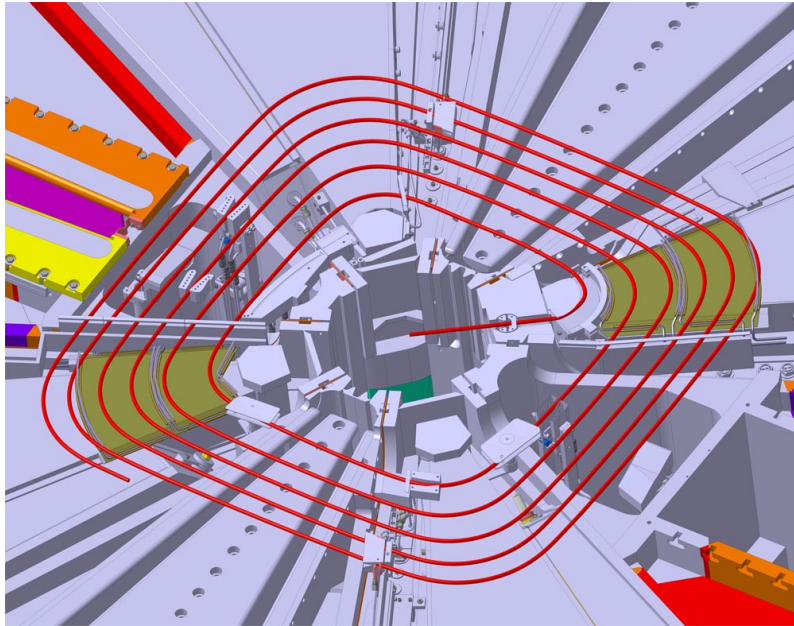
# And finally sitting in the right place



20.02.2018 first time new 50 MHz Resonator 2 installed in the Injector 2 cyclotron

# Installation of central region components

Resonator 2



Resonator 1

Resonator 3

CAD model of central region with first few turns in the cyclotron

KIP5

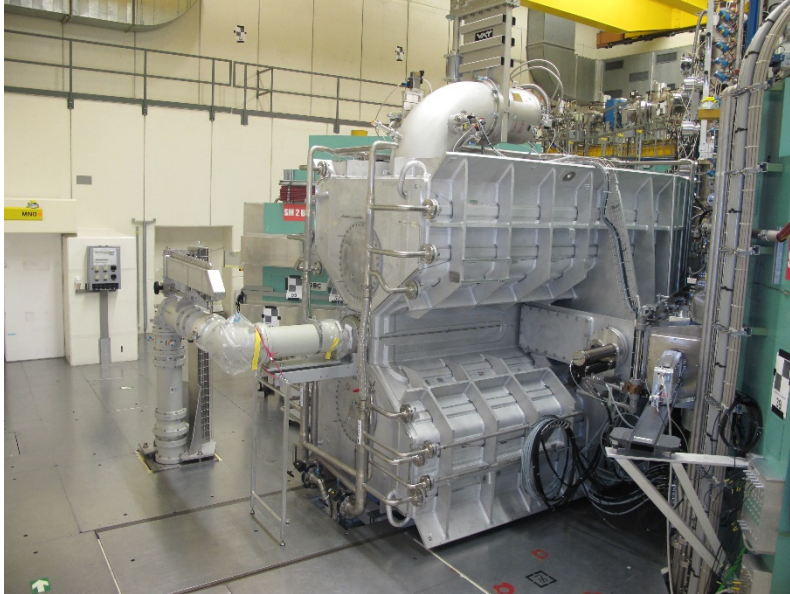
KIP4

KIR3

KIP2



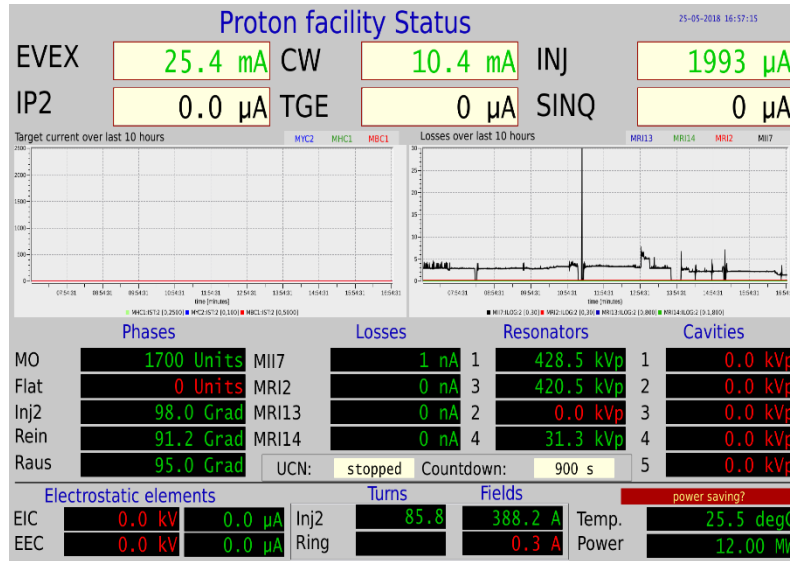
Collimators in the nose of Resonator 2



New Resonator 2 in INJ.2

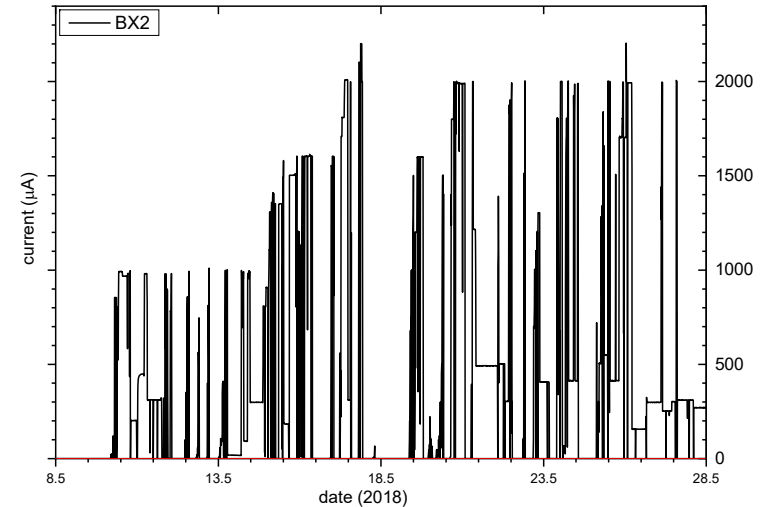
- Vacuum pump
- Cooling
- Cables for pickups, tuning system, thermocouples
- RF power line
  
- Tuners and coupling loop are not installed

# First tests with beam on 9th May 2018



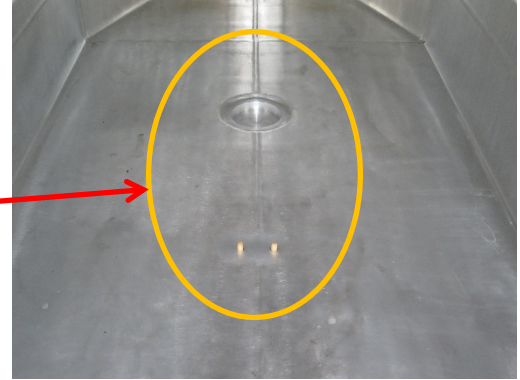
Setup with 3 Resonators (1,3,4)

New 50 MHz Resonator only installed as vacuum chamber

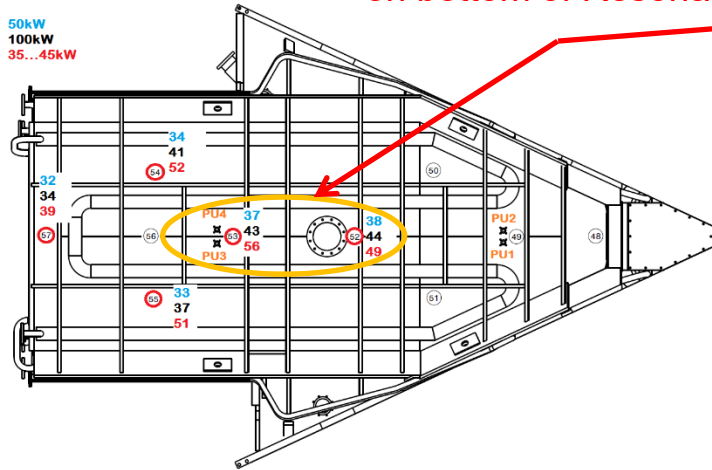


Beam current at the beam dump after the Injector 2 cyclotron (BX2)

# Problems on Resonator 4



Hot area  
on bottom of Resonator 4

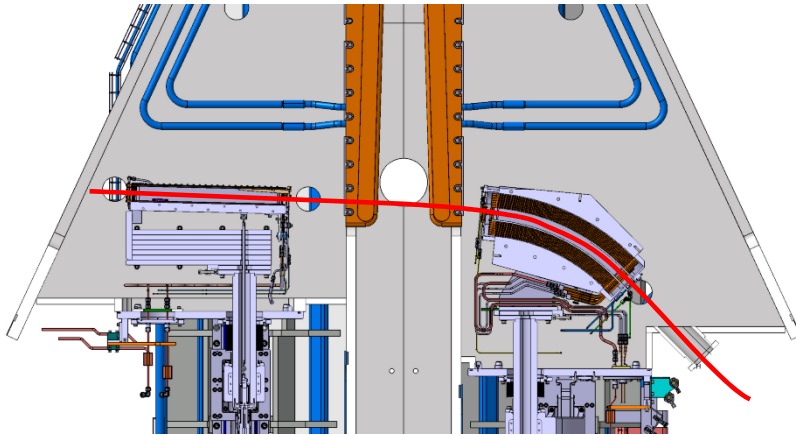


Thermocouple on the bottom of Resonator

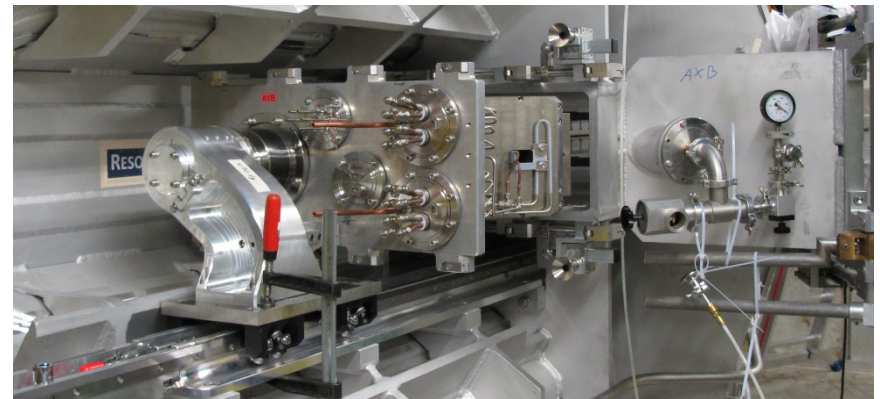
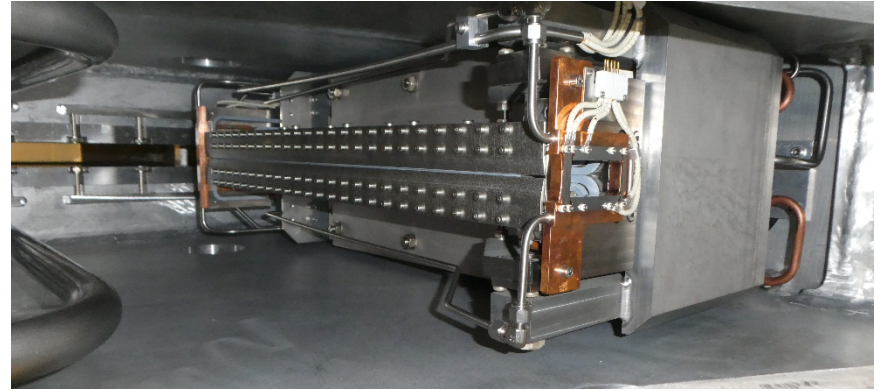
Power	Temperature top Resonator	Temperature bottom Resonator
35 kW	38 °C	50 °C
60 kW	39 °C	76 °C

Discharges in cavity. Possible contamination after the first high power test campaign. Treatment of wall surface needed by cleaning or painting with Aquadag®.

# Extraction magnets in Resonator 4

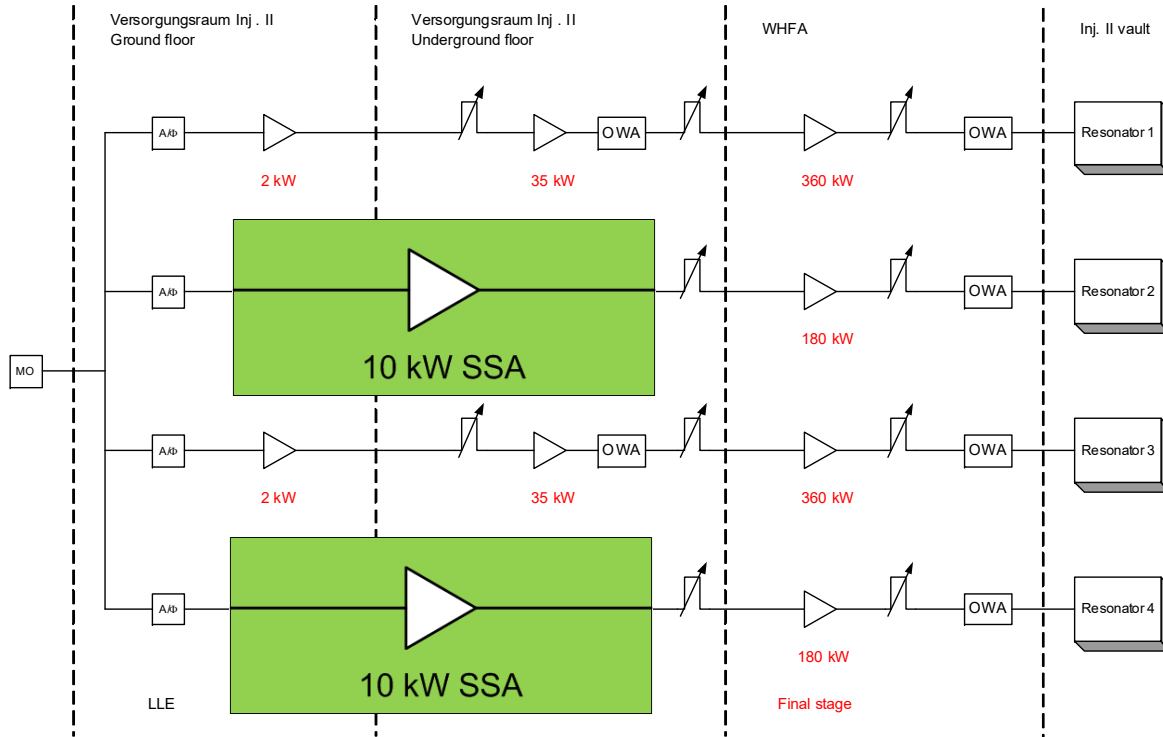


Cross section of Resonator 4 at horizontal Mid plane with the Magnets AXA and AXB for the Beam Extraction.



Extraction Magnets AXA (top Picture) and AXB during test assembly in the new Resonator 4

# Upgrade of the Amplifier chain



Phase 1: 10 kW SSA of the shelf. Sufficient power for 2.4 mA for Res. 2 & 4

# 10kW Solid-State Amplifier



- BBL200-A10000 (40 – 60 MHz)  
Rohde & Schwarz
- Two amplifiers are installed and tested on load.
- System integration has to be done.  
(controls, signal cables, RF power connection to final stage)

# New power amplifiers for the Injector 2

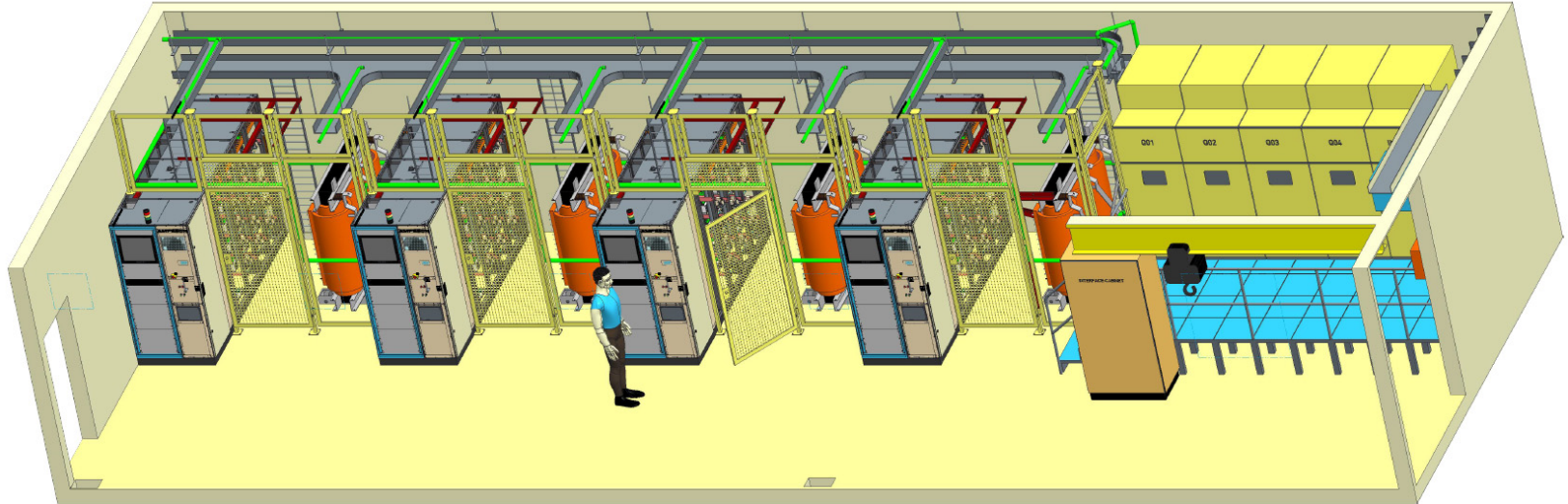


Power amplifiers installed on ground floor in WHFA

- 4 + 1 spare 50 MHz 1MW tetrode based coaxial cavity amplifier running in grounded grid configuration on a reduced power level. Working point adapted to needed power.
- Tetrode RS2074HF, Thales
- In house design
- Size of amplifier trolley 1m x 1m x 3m. Can be replaced within 3 hours.
- Same design as used for Ring cyclotron. Amplifiers are useable on both machines.

# First floor WHFA (Anode power supplies)

16kV-main distribution



4 x Anode power supplies 15kV, 40 A

Supplier: Ampegon

Technology: PSM9

Efficiency: 96%

4 similar power supplies  
crowbar less system

# First floor WHFA (Anode power supplies)



APS Ampegon 15kV, 40A



16kV-main distribution

# Power amplifiers: ongoing activities

- Control rack, power rack (UG1, UG2, filament PS, auxiliary), interface rack final stage
- Cabling
- APS: finish cabling, commissioning and SAT
- Control system (software) for power amplifier
- Air cooling for amplifier (RF circuits and tube)
  
- Start of commissioning in June 2020

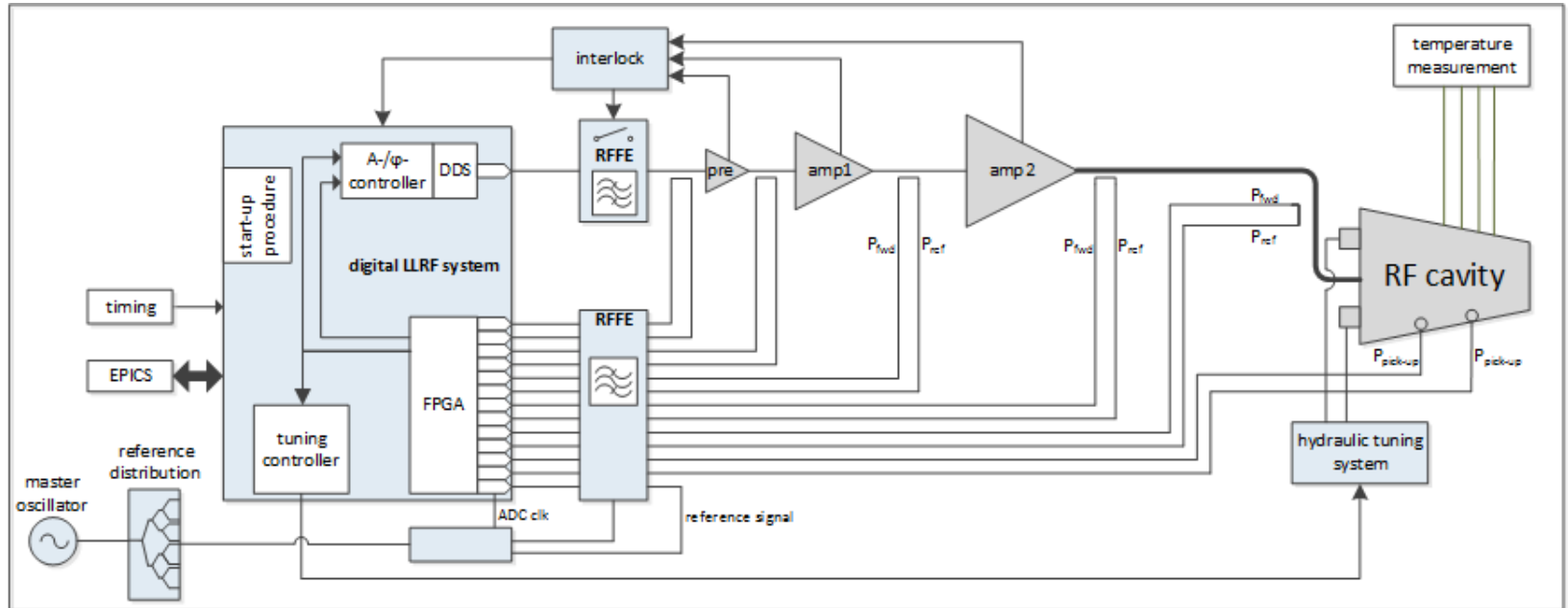
# New digital LLRF system



Installation for new LLRF system

- Replacement of 30 years old analog LLRF system.
- New LLRF based on PSI's standard processing board, FMC mezzanine cards and a specific RF front-end to condition the RF signal for direct sampling
- Control amplitude and phase of cavity
- Startup sequencer
- Master/slave tuning system
- Interlock system

# New digital LLRF system



Overview Layout of an RF station

Courtesy A. Hauff

- Due to the operation of the Injector 2 with only 3 Resonators the beam current is at the moment limited to 2 mA.
- The new Resonator 2 was successfully tested and characterized under full power.
- Different redesign options to solve the issues with the finger contacts on the tuners are under investigation.
- The installation of the amplifier chain and new digital LLRF system should be finished until summer 2020 for the commissioning of the new system in the second half of 2020 and to demonstrate the operation of Resonator 2 with beam. This will allow to operate on higher beam currents.
- Complete upgrade with the implementation of Resonator 4 and renew the amplifiers and LLRF for Resonator 1 & 3.

## My thanks go to my RF colleagues:

- Markus Bopp
- Oliver Brun
- Hansruedi Fitze
- Sebastian Jetzer
- Roger Kalt
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- Marco Pedrozzi
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- Andreas Stadler
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- Wolfgang Tron
- Erich Wüthrich

**and all other groups who  
support this project**

