Development, Fabrication and Testing of the Rf-Kicker for the Acculinna-2 Fragment Separator

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With thanks to the many persons involved, especially

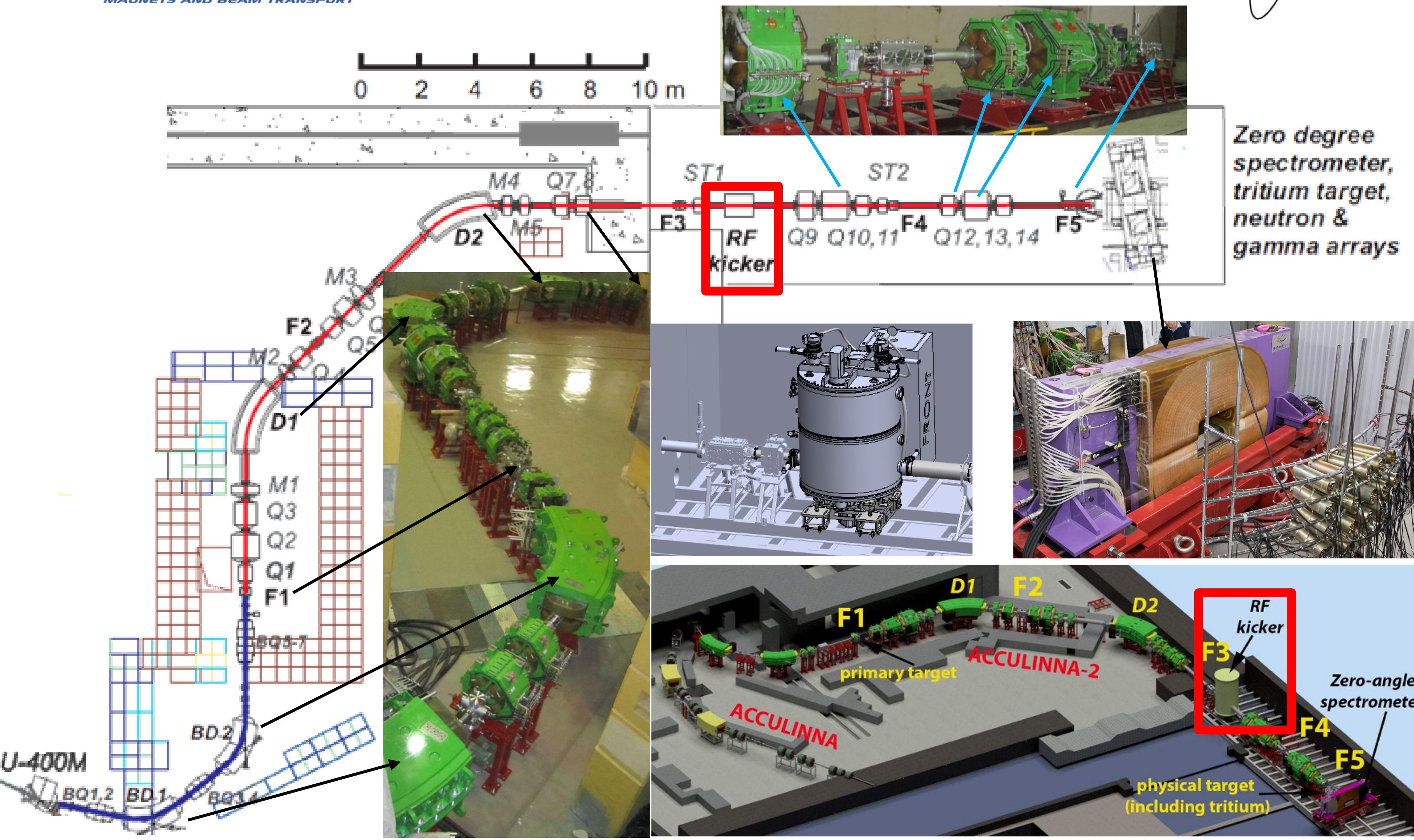
Bernard Bessot	AR France (dist QEI)	power supply
Jernej Podlipnik	COSYLAB	control system
Anna Orlova	SPE (now Jema France)	on-site debugging
Antonio Palmieri	INFN Legnaro	advices on start-up
Antonio Caruso	INFN Catania	advices on protection

And an RF master
who left us in 2020

Claude Bieth

for ideas and advices from the very start of the project

Acculinna-2 layout



Why an RF-kicker ?
Vertical deflection

Many graphs of this section are borrowed from presentation FR1PB03 by Thomas Baumann (NSCL) at the 2013 Cyclotrons conference in Vancouver.

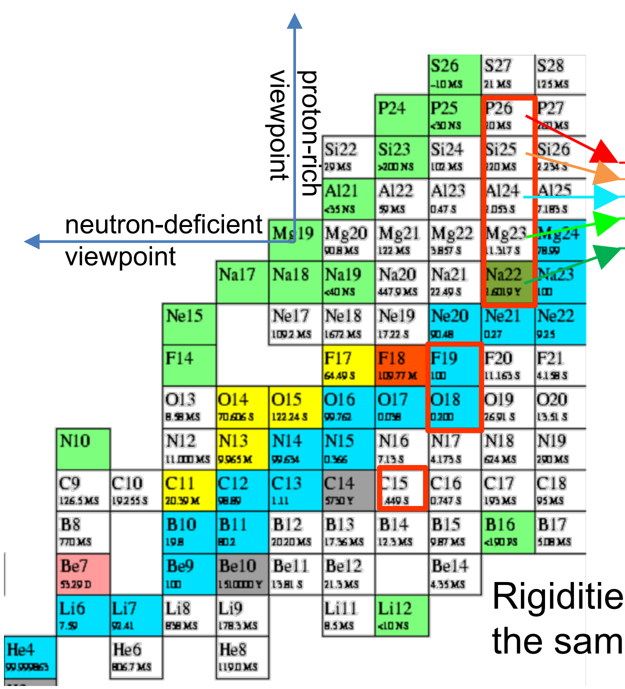
I adapted them in some way for my use but I see no point in reinventing the wheel

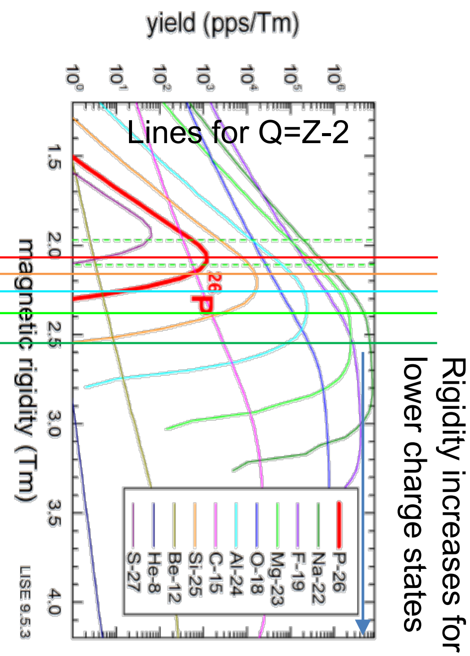
Proton-rich species

Magnetic separation is inefficient

Proton-rich (aka neutron-deficient) isotopes, are difficult to separate because

- being close to the dripline, they are usually produced with very low yields
- their (m/q) ratio is small and their magnetic rigidity is close to the rigidity of the **low energy tail** of species with higher (m/q), produced in **much larger quantities**. Hence, **they cannot be magnetically separated**





Rigidities for species with 11 neutrons and the same energy per nucleon (50 MeV/u)

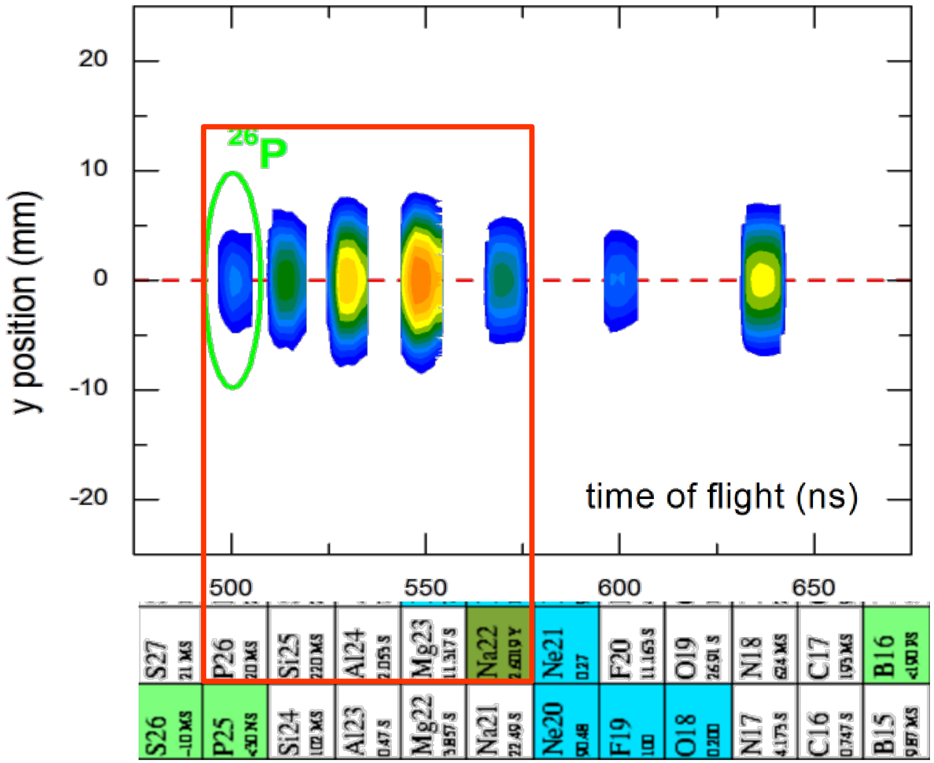
$$B\rho[Tm] \cong 10^3 \sqrt{\left(\frac{2m_0}{q}\right)} \sqrt{T\left[\frac{MeV}{u}\right]}\left(\frac{A}{Q}\right)$$

$$= 0.14397 \sqrt{50\left[\frac{MeV}{u}\right]}\left(\frac{A}{Q}\right) = 1.033\left(\frac{A}{Q}\right)$$

For a given energy per nucleon, the rigidity is proportional to the mass over charge ratio

Proton-rich species

velocities are different



$$B\rho = \left(\frac{p}{Qq}\right) = \left(\frac{mv}{q}\right)\left(\frac{A}{Q}\right) = \frac{1}{TOF}\left(\frac{Dm}{q}\right)\left(\frac{A}{Q}\right)$$

Where D is the distance between the location at which the species are produced and the kicker.

$$TOF = \left(\frac{Dm}{B\rho q}\right)\left(\frac{A}{Q}\right) = C^{ste}\left(\frac{A}{Q}\right)$$

In the case of fully-stripped ions,

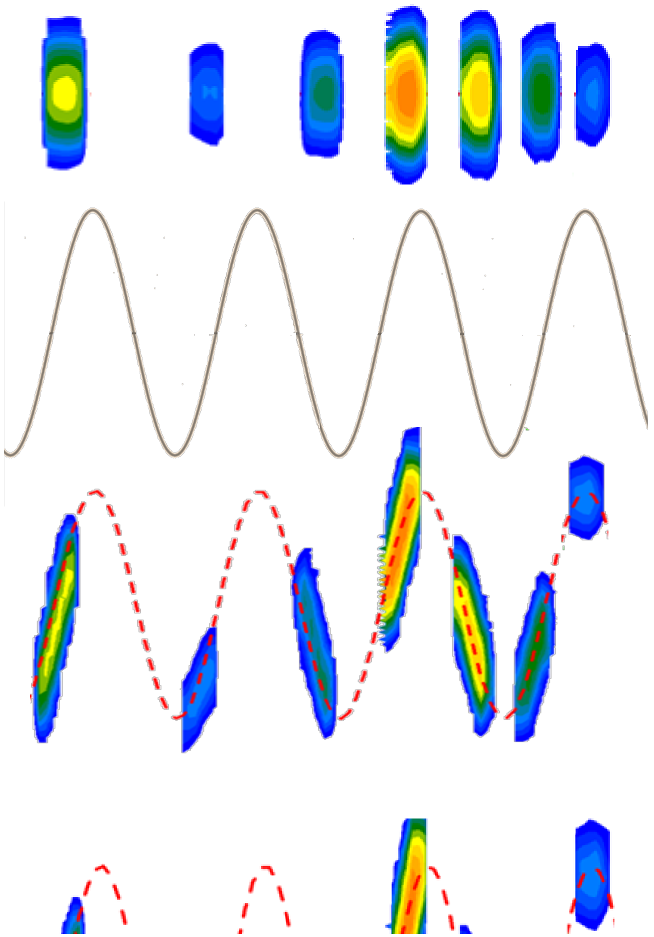
$$TOF = C^{ste}\left(\frac{Z+N}{Z}\right) = a + \frac{b}{Z}$$

offset

For species with same number of neutrons and identical rigidities, **the time-of-flight increases as atomic number decreases**.

RF kicker action

Transforming TOF to vertical position



On-axis snapshot of the beam **before the RF-kicker**
The right-hand part (short TOF) enters the kicker first
The vertical size is shown

Time variation of vertical electric field **in the kicker** in time correspondence with the different species

A snapshot **some distance away after the RF-kicker**
The different species have been kicked vertically either upwards or downwards.

The differences in TOF are transformed in differences of vertical position

Slits cut the unwanted components. Some unwanted species deflected the same way as the desired ones may remain but the desired/unwanted ratio is improved.

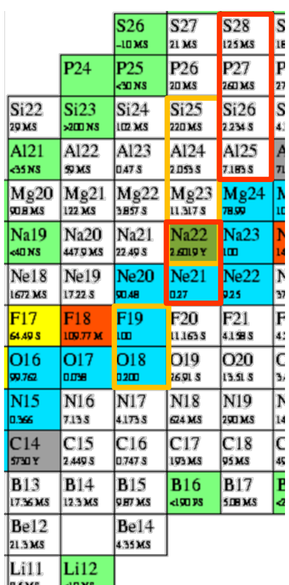
The species are separated according to their TOF

It is not that easy!

This simplified picture may not mask the role played by many other parameters in the final result

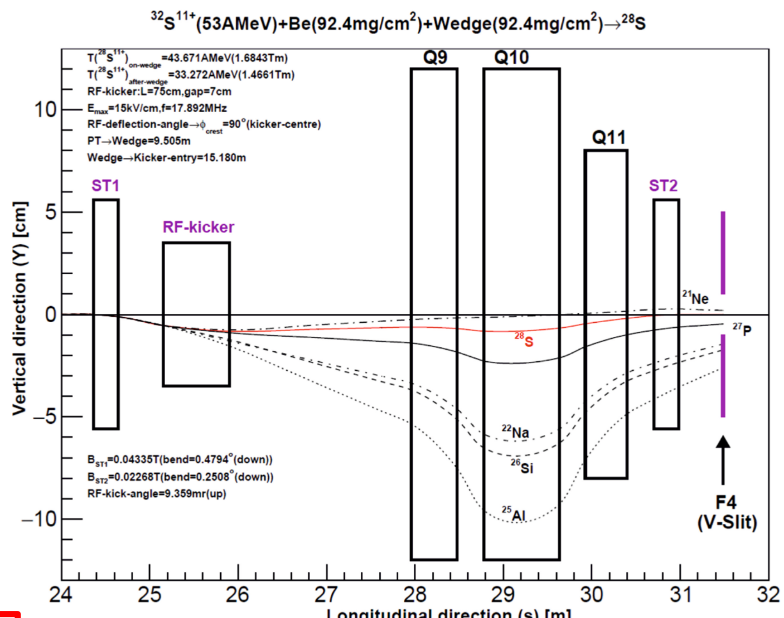
- beam energy and target thickness
- setting of the dipoles and wedge,
- quadrupoles and steerers
- RF triggering and phase

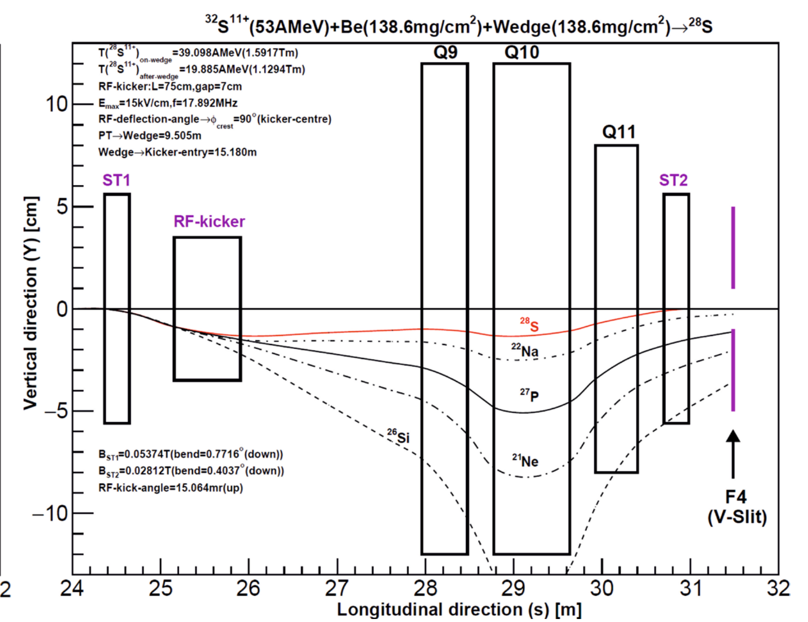
2 estimates from Lise++ in which different settings of the separator allow extracting the same ^{28}S out of its background but with 2 very different vertical rearrangement of the unwanted species.



Acculinna-2 example

NSCL example used in previous slides





Why us ?

When the improbable becomes a success

- Sigmaphi collaborates with JINR for a very long time and we studied, built, installed and started most of the Acculinna-2 facility.
- Enlarge the portfolio with an RF device … without any wish to become a manufacturer of accelerating cavities, therefore an attractive offer.
- This deflecting cavity requires a lot of R&D for a “one-of”, which is not interesting for the accelerating RF-cavity industrials.
- During 18 years as a cyclotronist, I worked on many different subjects … but RF. From a purely personal standpoint, it was the opportunity to have a dream come true.

Specifications

Low frequency	14.5	MHz
High frequency	20	MHz
Vertical gap between electrodes	70	mm
Width of electrodes	120	mm
Length of electrodes	700	mm
Max Electric field in the gap	120	kV
Max horizontal dimension	1400	mm
Max height	2300	mm
Max cavity weight	3000	kg

Some primary beam examples	$f_{cyclotron} = f_{kicker}$		
^{40}Ar	15.100	MHz (exp)	
^{32}S	17.870	MHz (exp)	
^{20}Ne	18.120	MHz (exp)	close to present maximum cyclotron frequency

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MAGNETS AND BEAM TRANSPORT

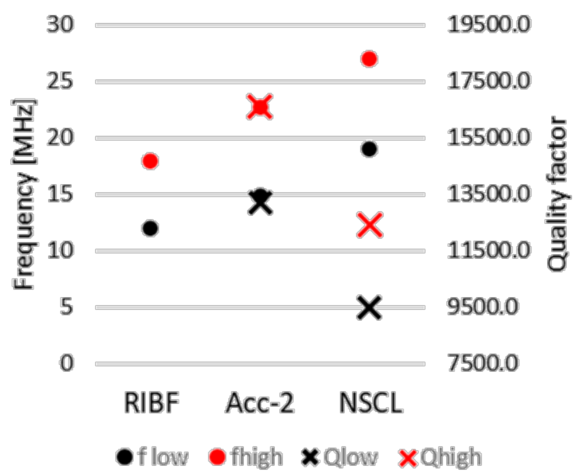
How does it compare with others?

JINR 114 Flerovium FLNR Dubna

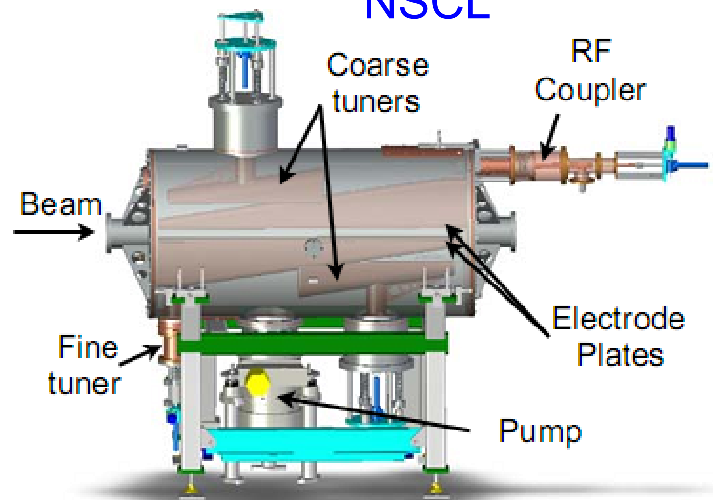
RIBF

	RIBF	Acc-2	NSCL
Type	λ/4	λ/4	λ/2
Length [mm]	1600	1650	1500
Rin cavity	800	1400	
$L_{electrode}$ [mm]	700	700	1500
$w_{electrode}$ [mm]	120	120	
gap [mm]	40	70	50
V [kV]	100	120	100
f_{low}[MHz]	12	14.8	19
f_{high} [MHz]	18	22.7	27
Q_{low}		13200	9500
Q_{high}		16600	12400

Comparison of frequency ranges and quality factors



NSCL



Frequency change
Inductive or capacitive

Inductive

- "Top-like" sliding plate around the central pillar : reduces the cavity length
- The frequency range requires 600mm stroke: mechanically complex
- Influence other functions : coupling loop, pick-ups, pumping

Capacitive

- Mechanically easier
- In the vicinity of the electrodes – little influence on other functions
  BUT
- May not deform the field pattern in the gap
- Needs a rather large space to cover the whole range
- Many different possibilities.

- For the outer conductor we tried fully cylindrical and rectangular box (RIBF)
  Rectangular box was abandoned because it induced close unwanted modes.

First dimensioning

Excel sheet with basic formulas

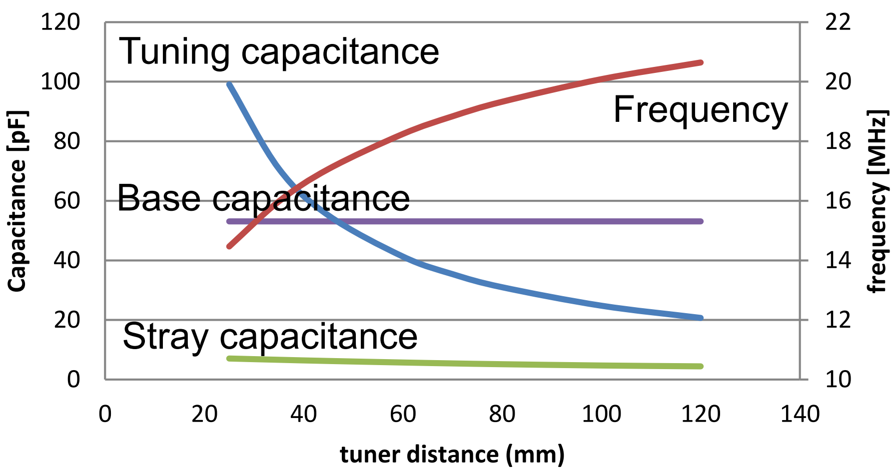
Coaxial parameters: length + inner and outer diameters govern inductance

The « base capacitance » is determined by the parallel/additive association of

- the coaxial geometry (cylindrical capacitor)
- the deflecting electrodes geometry (parallel plates capacitor)

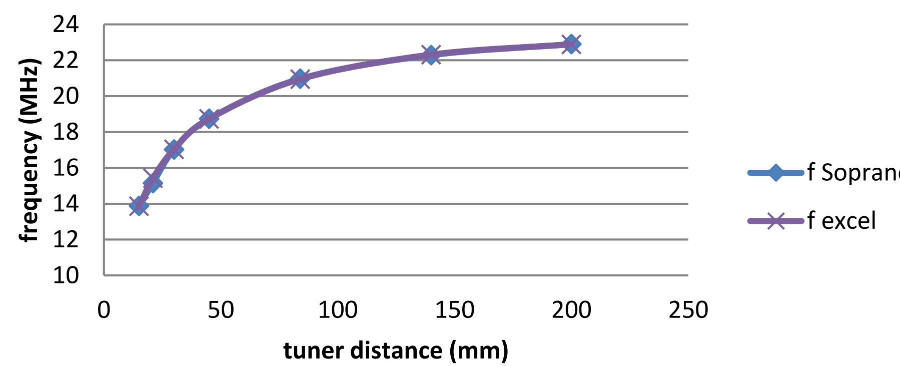
Extra capacitance in parallel permits tuning over the whole frequency range

Frequency and capacitances from basic formulas



Check with Soprano eigen solver

Frequency from Soprano and Excel vs tuner spacing for L=1.6 m



Finite elements

2 steps computation

Geometry, perfect conductors, no signal input

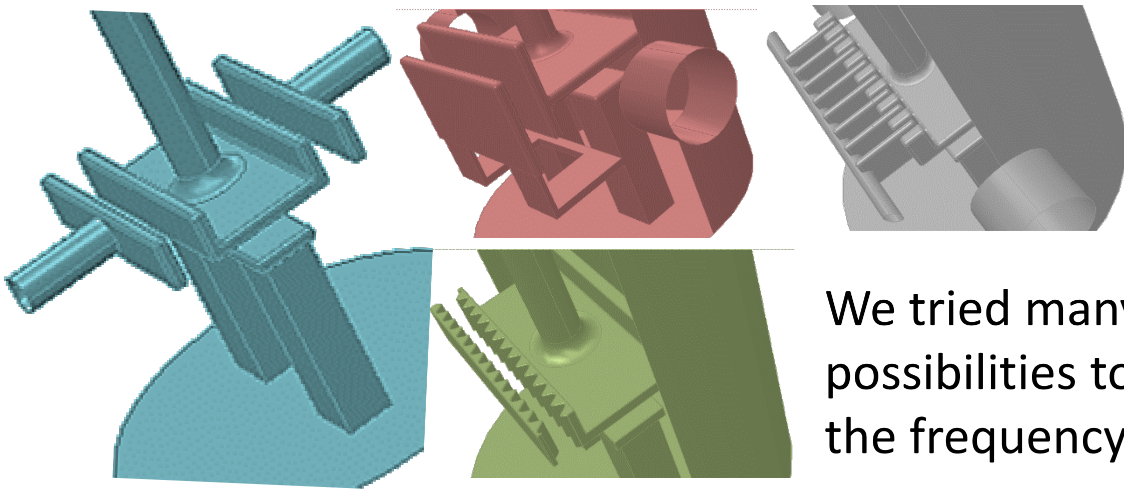
- Eigenvalues: resonant frequencies of the geometrical setup
- Eigenmodes: corresponding electric and magnetic fields distributions
- Allows deciding whether a given geometry is “promising” or not
- Rather fast, no quality factor

Geometry, realistic materials, signal input

- Solves Maxwell’s equations **at the frequency of the input signal**
- Coupling plays a role
- This frequency is not exactly the expected resonant frequency -> **redo**
- The better the Q factor, the trickier it is to find the right frequency.
  Small frequency steps to avoid “passing over” the resonance -> **many redo’s**
- Long and tedious process

Variable capacitors

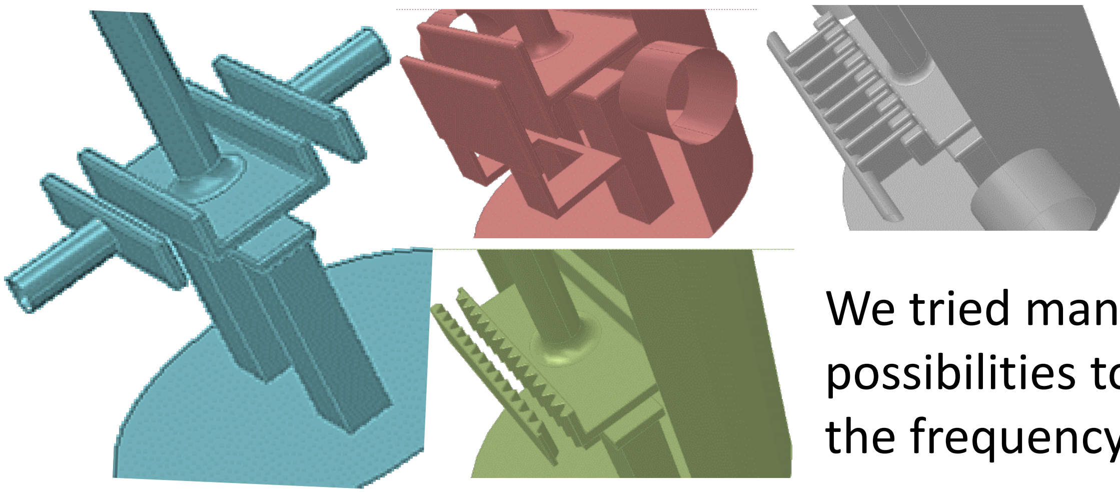
Many different ways



We tried many possibilities to vary the frequency

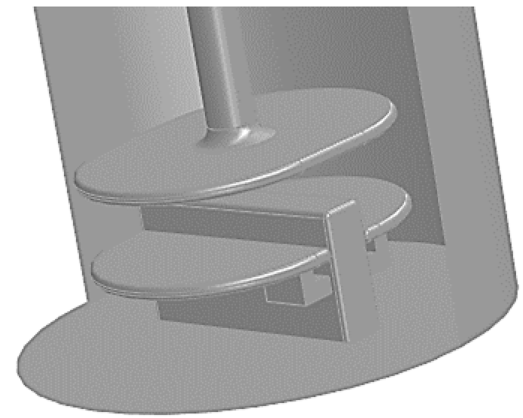
Variable capacitors

Many different ways



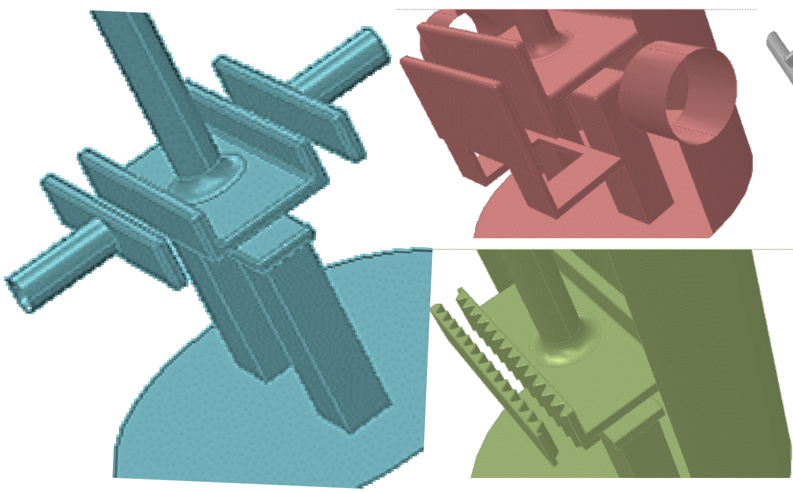
We tried many possibilities to vary the frequency

… and the winner is

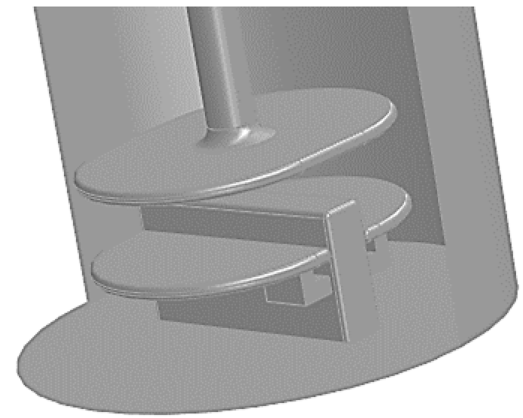


Variable capacitors

Many different ways



... **and the winner is**



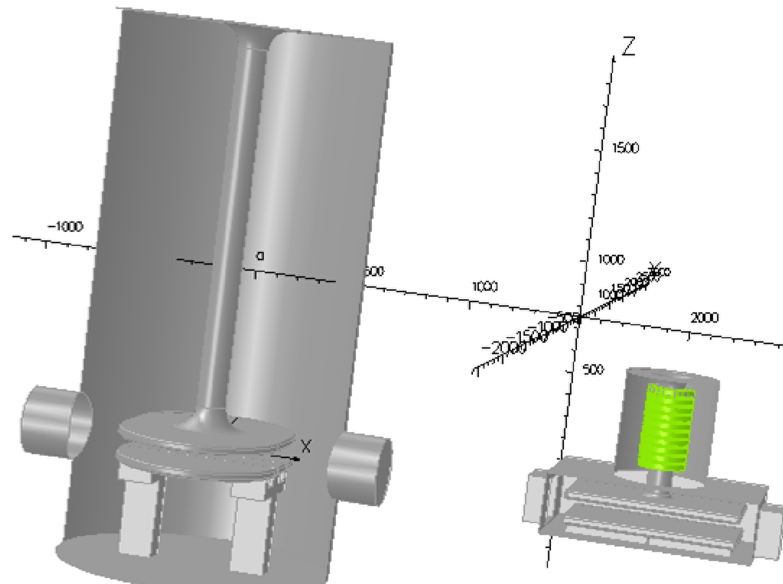
We tried many possibilities to vary the frequency

There were even more daring ideas

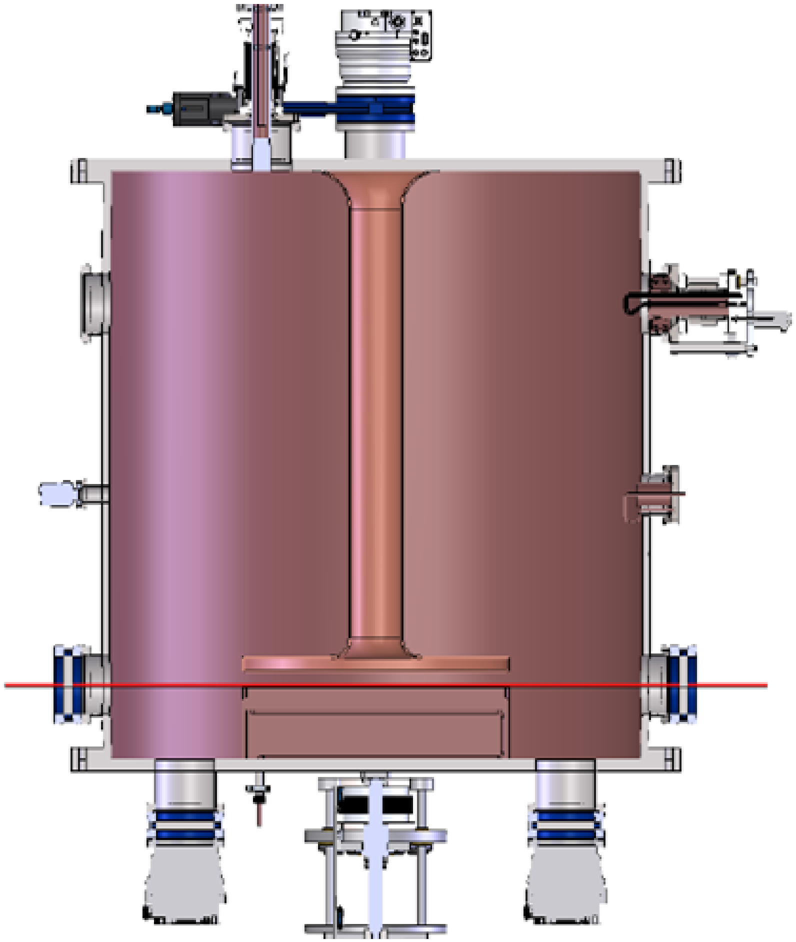
On the same scale, 2 Soprano model

- “conventional” kicker using capacitive tuning between 15 and 22 MHz
- kicker featuring saturable ferrite tuning (inductive) between 15 and 45!!! MHz

Judged “too radical” and too risky



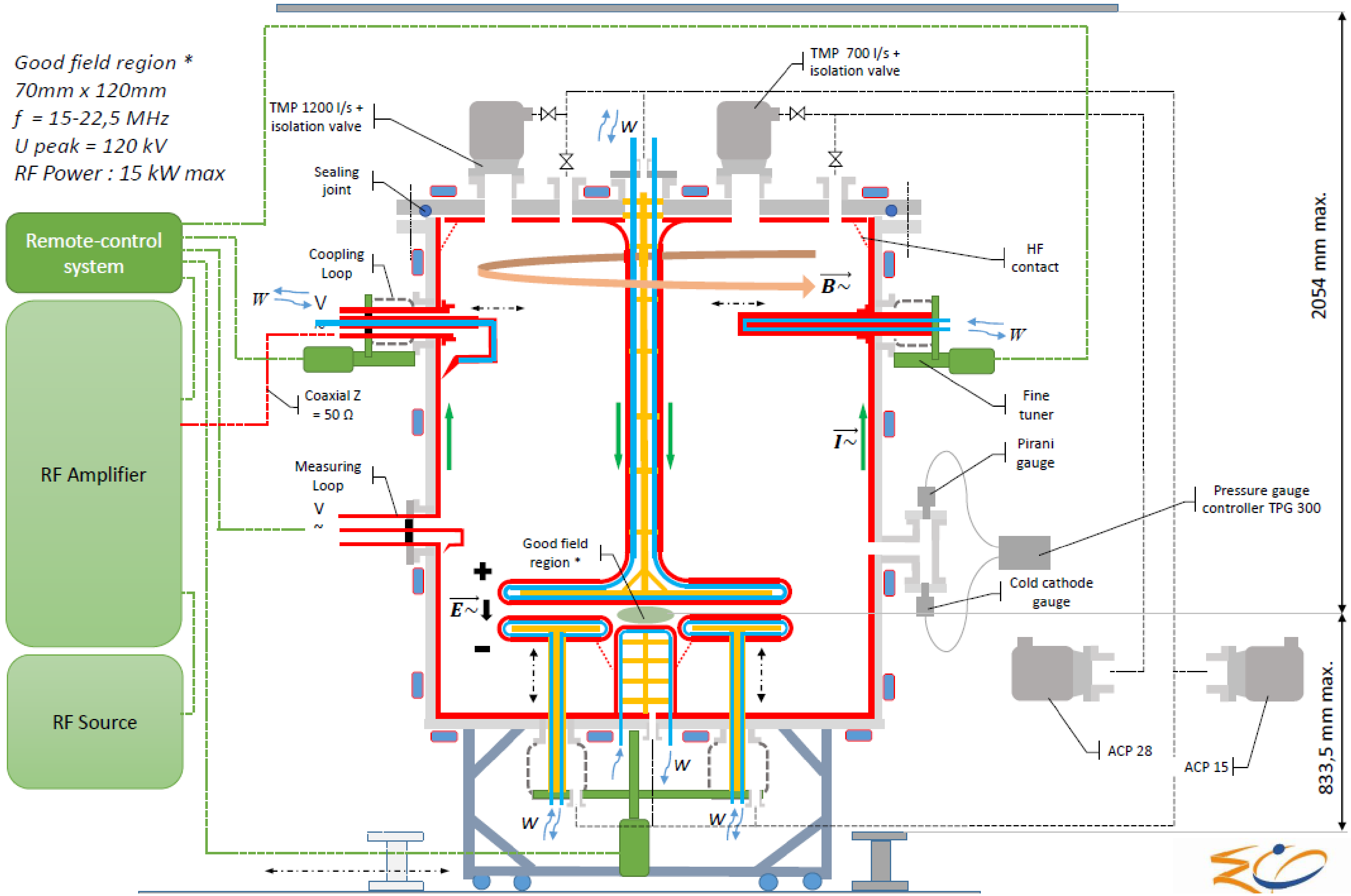
It looks so simple …



It looks so simple …
… until you include all constraints

- Functional scheme

*Good field region **
70mm x 120mm
f = 15-22,5 MHz
U peak = 120 kV
RF Power : 15 kW max



Scope of work

- RF studies
- Mechanical calculations, electro-static forces calculations
- Thermal calculations and cooling circuits definition
- Resonant cavity including vacuum vessel with special chariot
- Motorized RF tuning
- Motorized RF fine tuning
- Motorized RF coupling loop
- RF measuring loop
- Pumping system
- RF generator and RF amplifier
- Command & Control system
- Tests

Mock-up construction and tests

Mock-up construction and tests

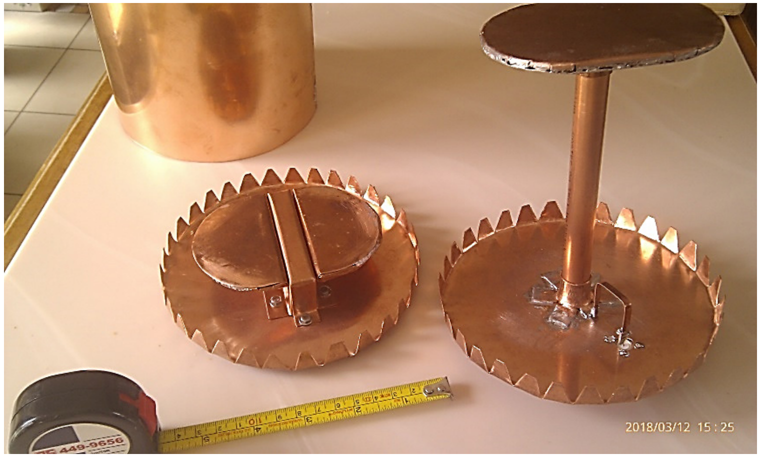
A mock-up is built for 2 main goals

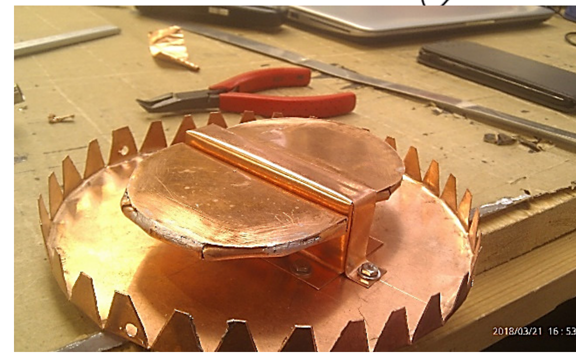
1. Reassurance that the computations were correct.

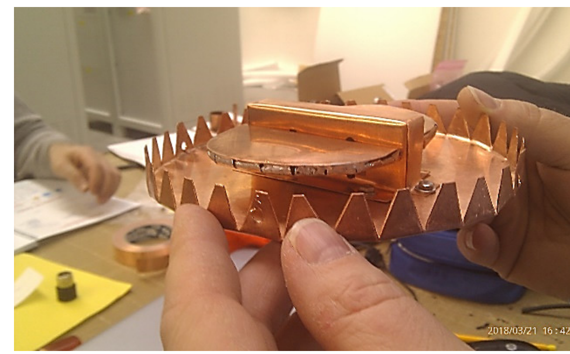
2. Learning

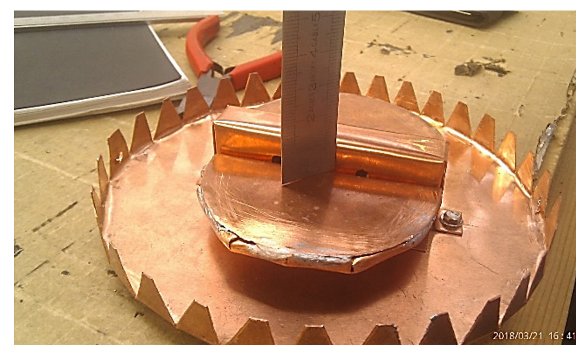
- How it works in the real world
- How to *properly* use the measuring devices
- That it is important to measure « by the book »
- That coupling is a touchy subject

Mock-up construction



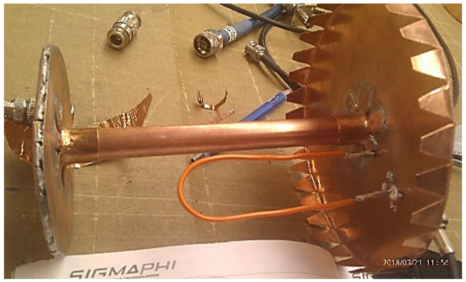




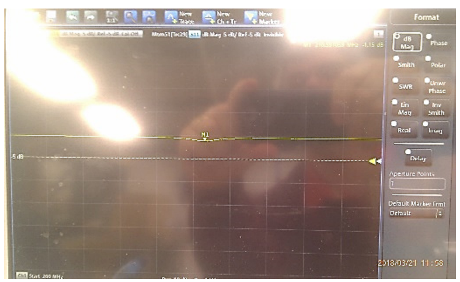


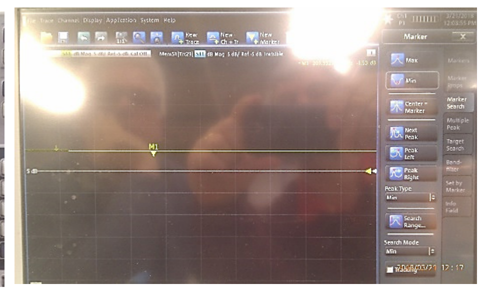
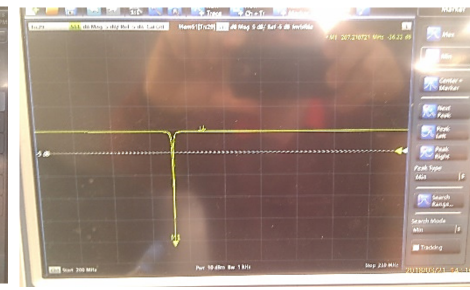
Mock-up tests
Coupling

Couplers of different sizes

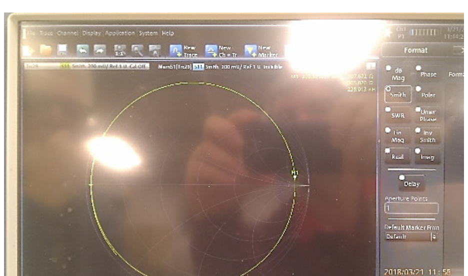


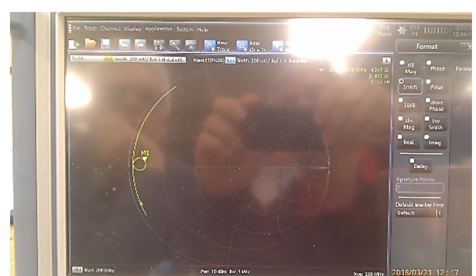
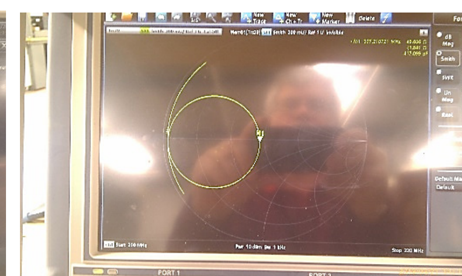

Resonance peak and Smith Chart



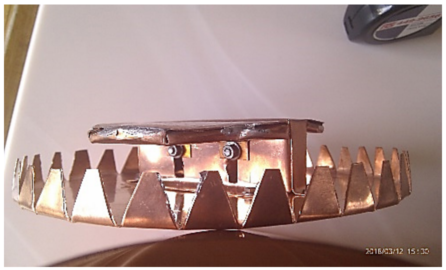
Very undercoupled | Undercoupled | Overcoupled | Ideally coupled

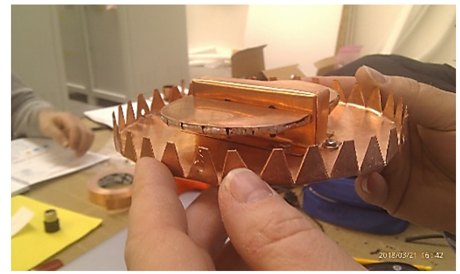


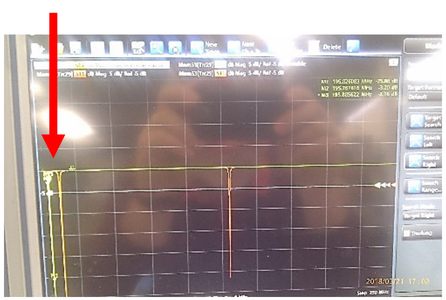
Mock-up tests
Frequency change

Changing the position of the « ears »

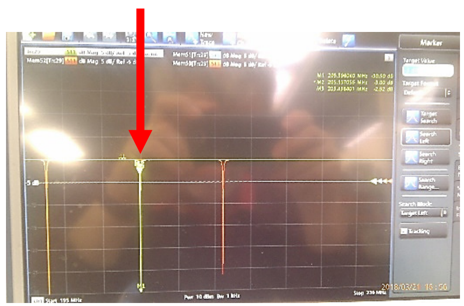




Position and intensity of the resonance peak – little change in coupling

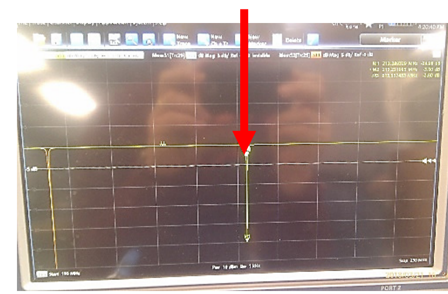


Flat – 0 mm

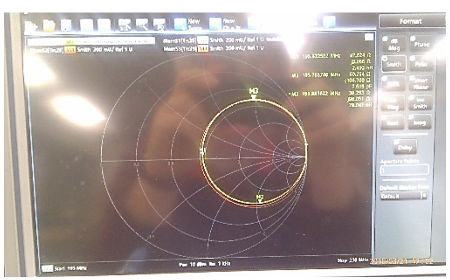


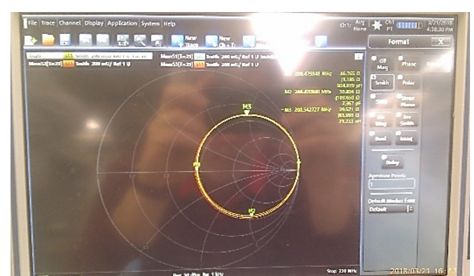
3 mm

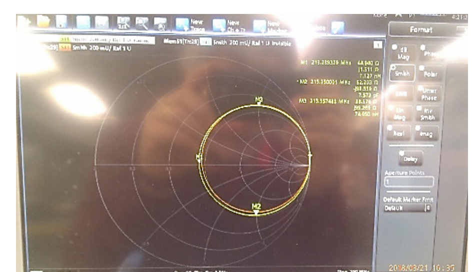
5 mm



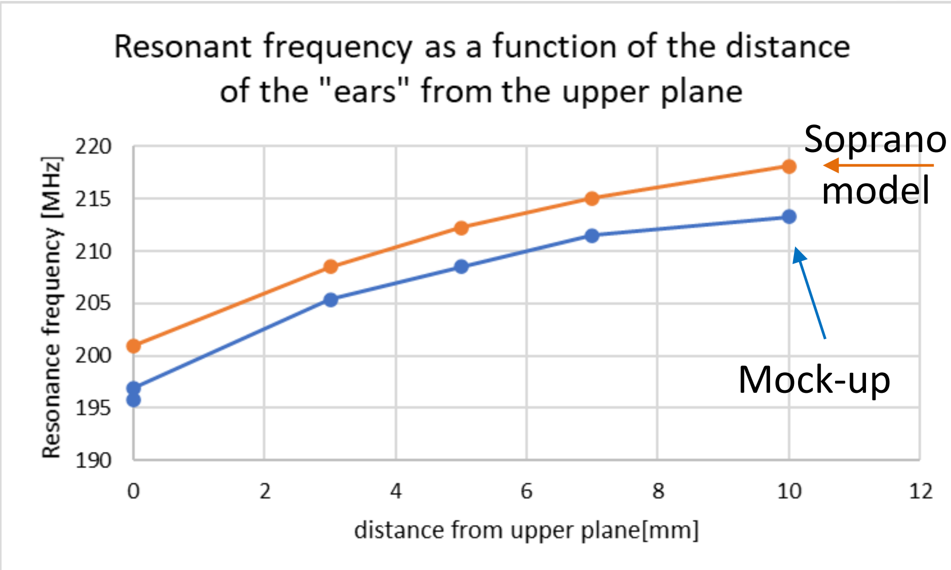
10 mm

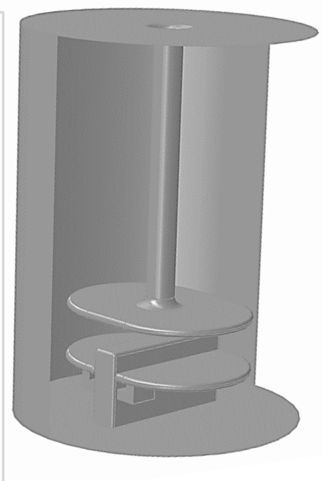






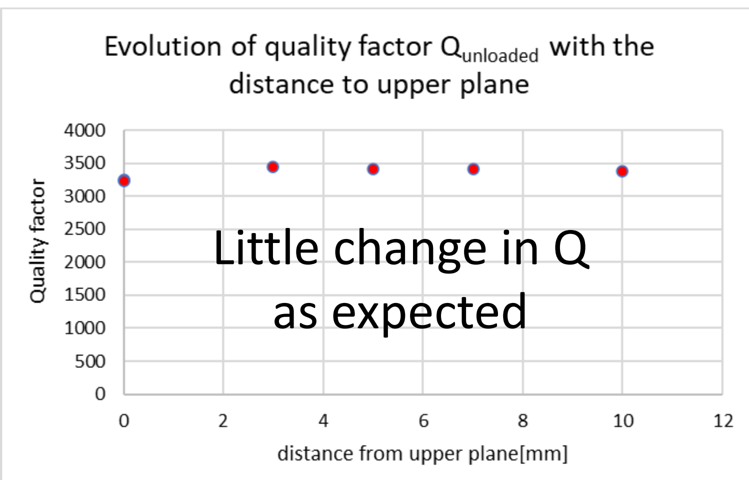
Mock-up tests
Frequency change





Differences come from

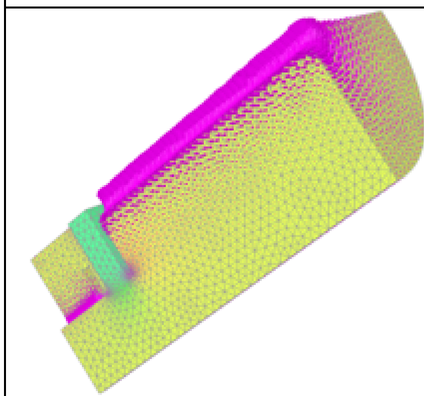
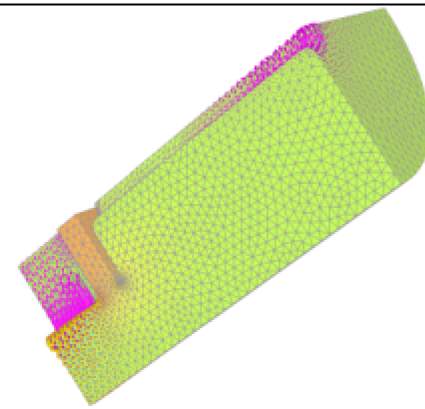
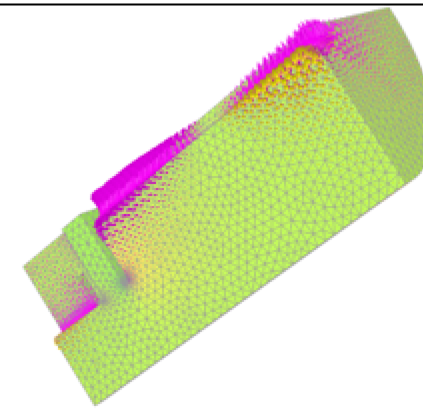
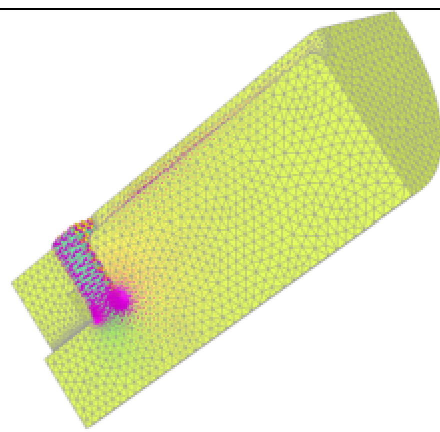
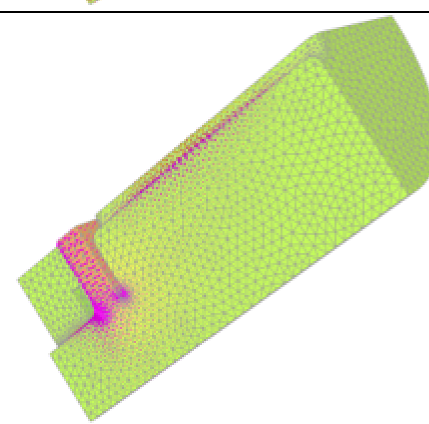
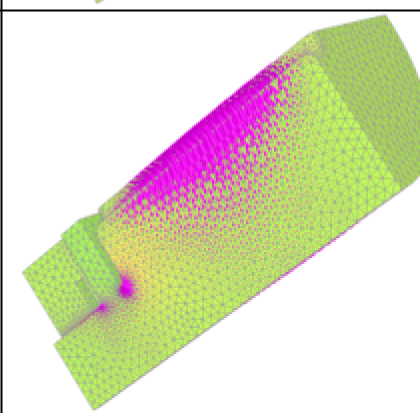
- No extra inductance from coupler in model
- Non-measurable 0.5mm difference in ear gap is enough



No change in coupling -> No tuning of coupler at different frequencies

Mock-up tests
Higher modes

Next modes are well separated from the mode of interest

	200.98 MHz	773.05 MHz	1.1258 GHz
Magnetic field			
Electric field			

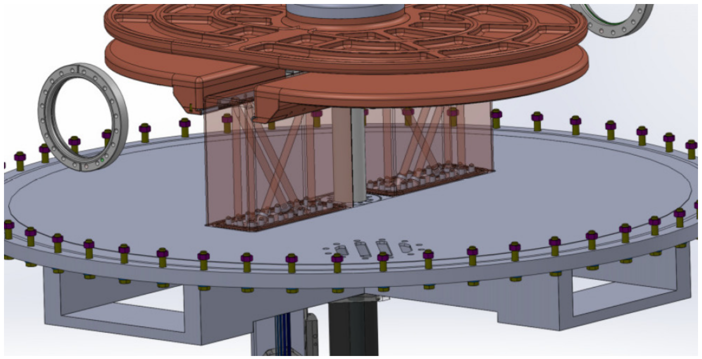
Full cross-check
and
Construction

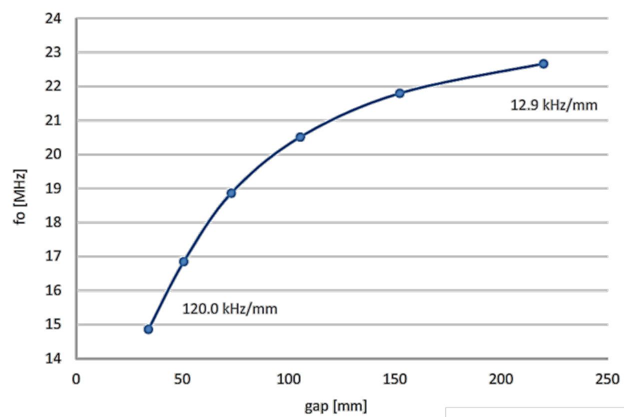
Full cross-check and detailed design

Frequency tuning system

values hold for 120 kV gap voltage	High (37 mm)	Low (220 mm)
Frequency	14.86 MHz	22.67 MHz
Total Power	8.4 kW	4.5 kW
Q	13200	16600
Tuning range df of fine tuner	14.2 kHz	23.7 kHz
Corresponding travel of ear electrode	0.12 mm (for df = 14.2kHz)	1.84 mm (for df = 23.7 kHz)
df for dV=1% (Qo = 15000)	±80 Hz	±110 Hz
Corresponding displacement of ears	±0.64 μm (for df = ±80Hz)	±8.53 μm (for df = ±110Hz)

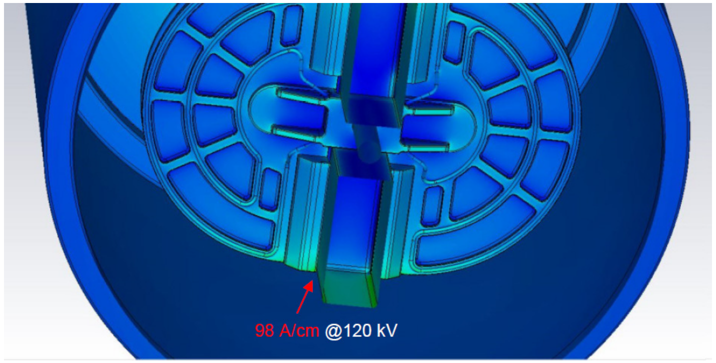
Tuning ears and central electrode



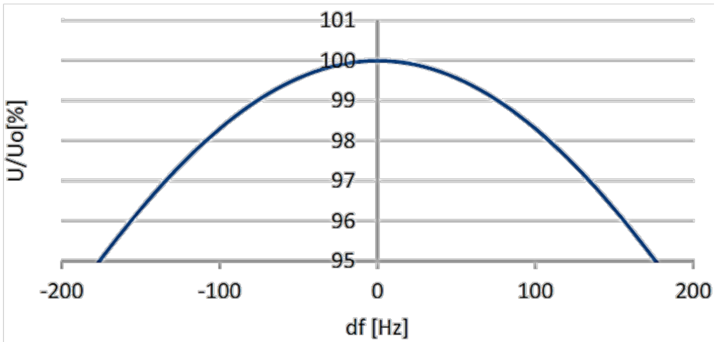


Frequency as a function of gap

Are sliding contacts at risk ?

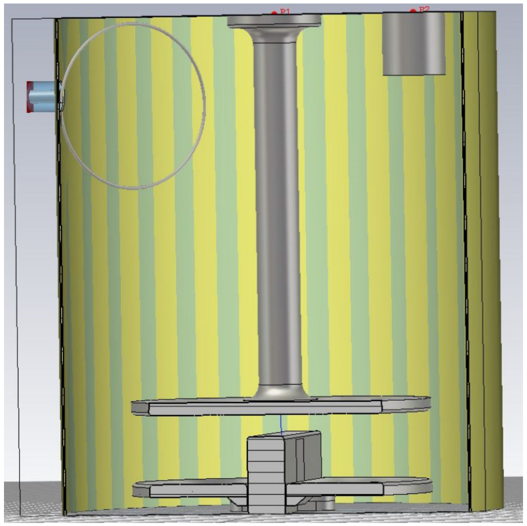


15 MHz resonance curve with Q_0=15000

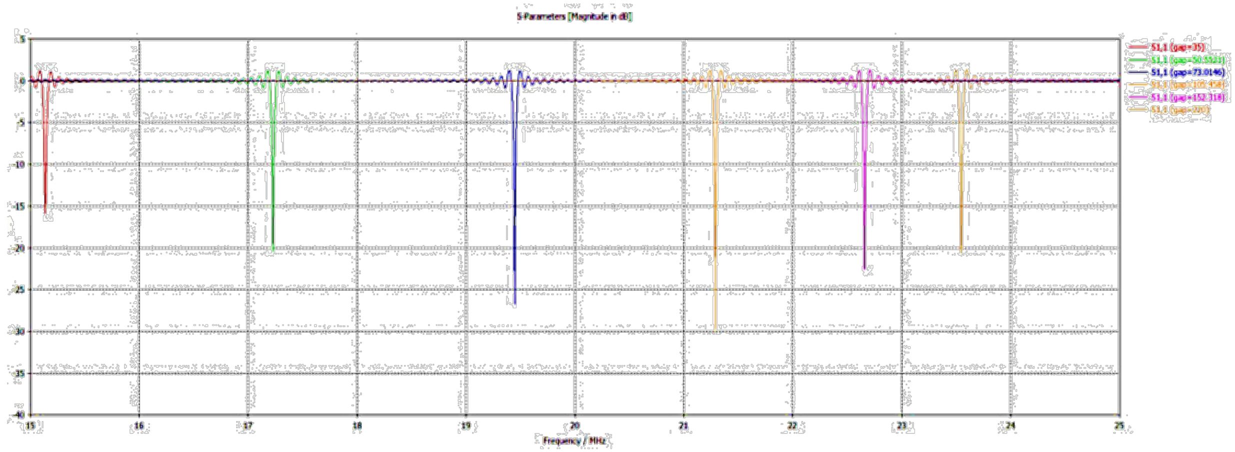


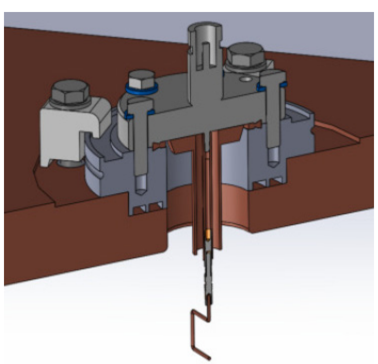
Full cross-check and detailed design

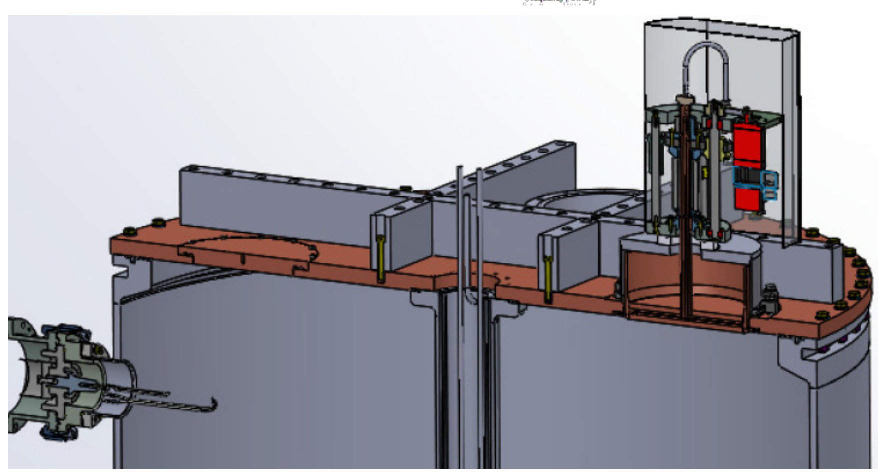
Coupling, picking and fine-tuning

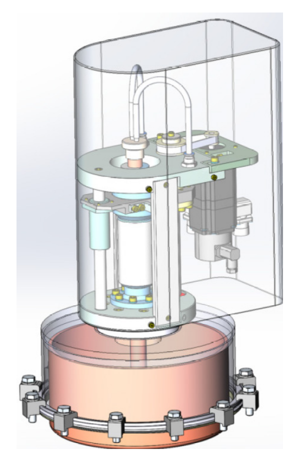


Simulation: less than -15dB reflection achieved over whole range using a single coupling loop shape and position.









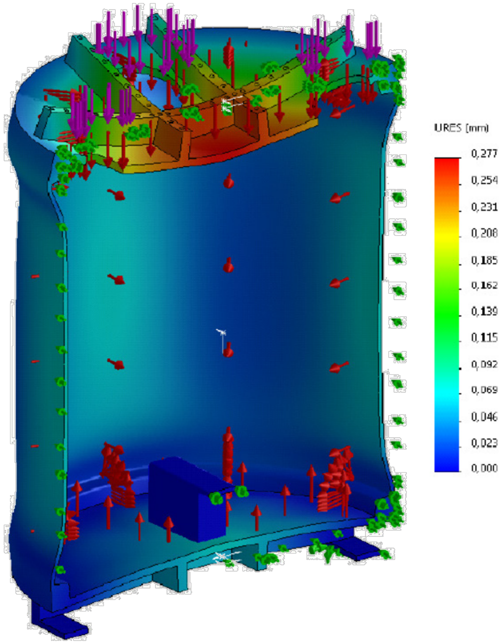
Full cross-check and detailed design

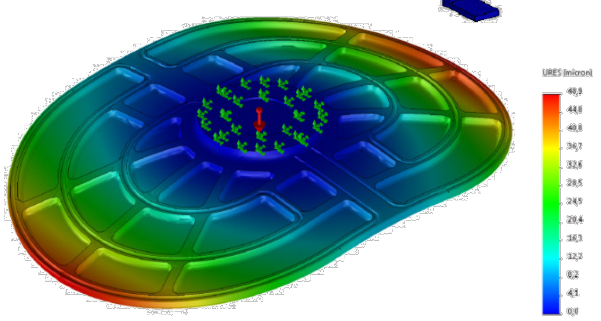
Losses and mechanics

Distribution of losses

[W]	37 mm	220 mm
tank shell	899	449
upper lid	500	305
bottom lid	205	47
upper electrode stem	5844	3366
fine tuner	30	18
upper electrode	477	235
lower static electrode	220	27
moving ear electrodes	137	29
electrode silver contact	5	1
contact holder	12	4
ear electrode combiner	25	8
sum	8403	4497

Deformations





Full cross-check and detailed design

… and last but not least comments and advices

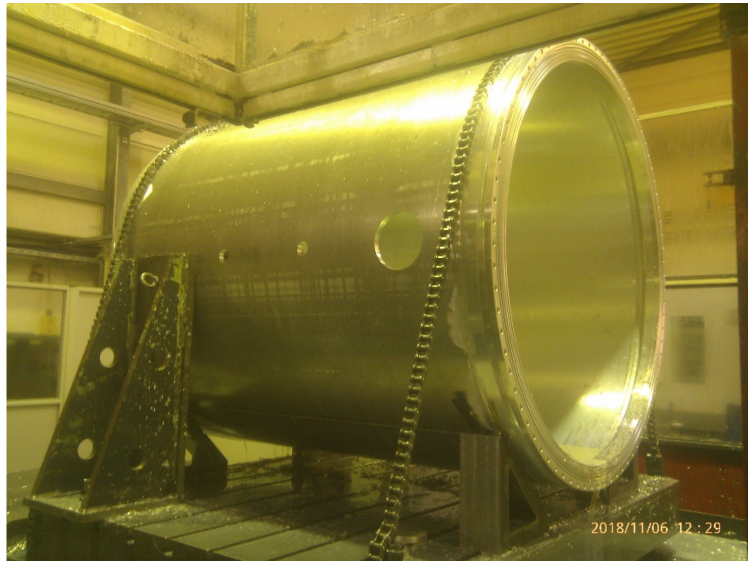
The results of the RF-simulations show that dU/U = 1% corresponds to roughly 1 µm displacement of the electrode in case of 15 MHz operation. It can be expected that such displacements can be caused by e.g. sonic vibrations from the environment of the device. In occurrence this effect can be compensated by modulating the forward power in accordance with the amplitude measured on a pickup signal. The fine tuner is to slow and would need to take over for slower frequency shifts of bigger magnitude. - On that basis it is recommended to take measures to reduce vibrations transmitted through the support system.

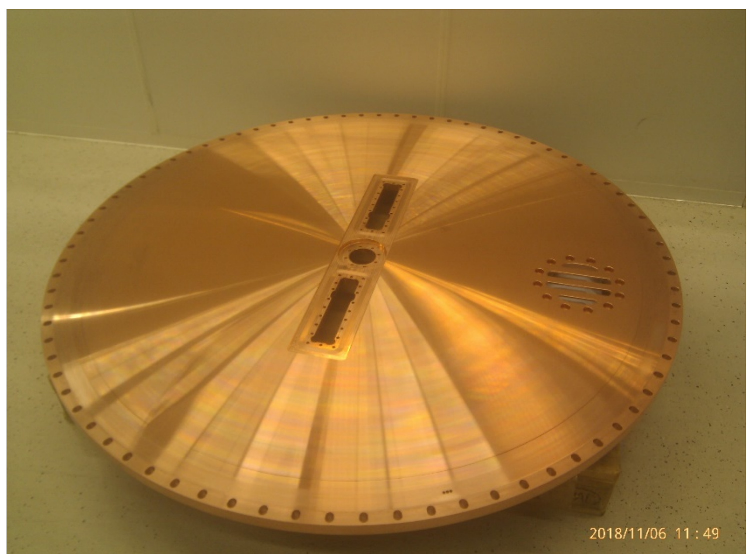
The **positioning precision of the ear electrodes** should correspond to 1/10 of the total frequency span df of the fine tuner which is roughly df/10 = 1.5 kHz or **0.01 mm** displacement of the ear electrodes at 15 MHz operation. Things are significantly more relaxed at 22 MHz operation. For finding the exact position of the ear electrodes for a certain frequency it is recommended to use a low level test RF-signal.

Fabrication - outer parts

SIGMAPHI
MAGNETS AND BEAM TRANSPORT
NTG

JINR
114 Flerovium
FLNR
Dubna

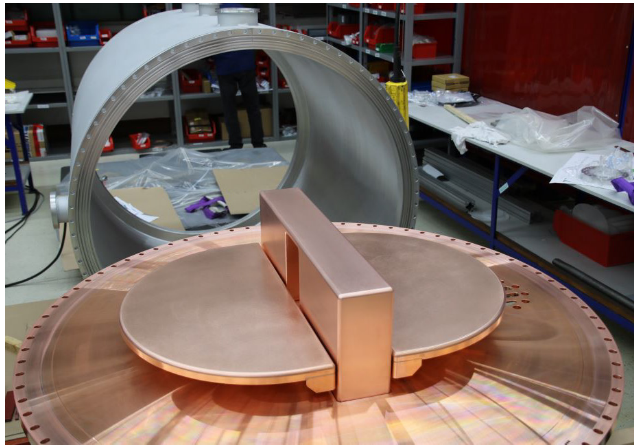


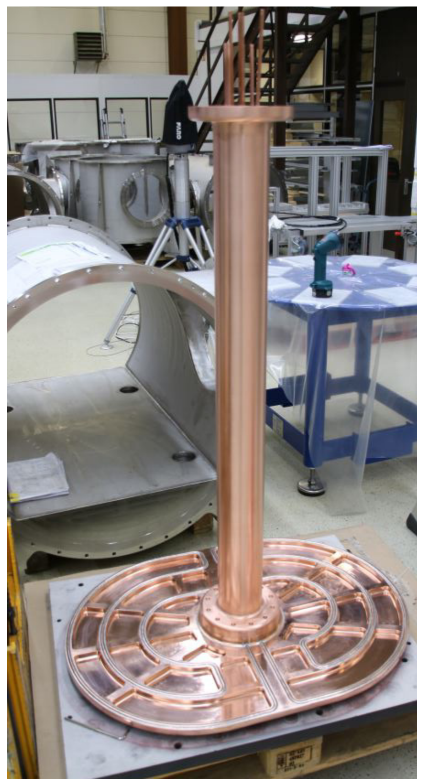


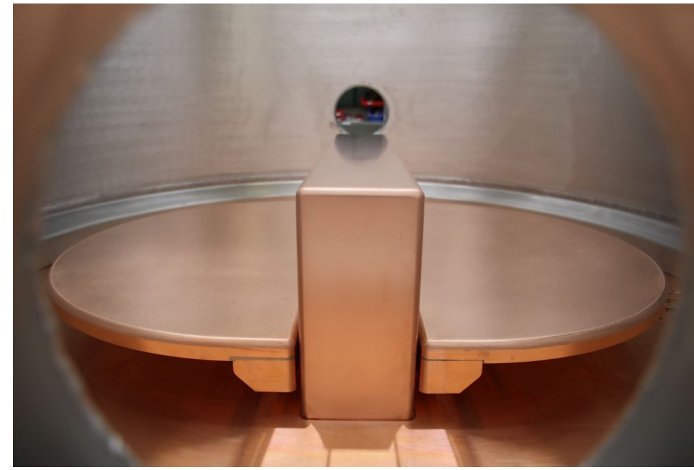
SIGMAPHI
MAGNETS AND BEAM TRANSPORT
NTG

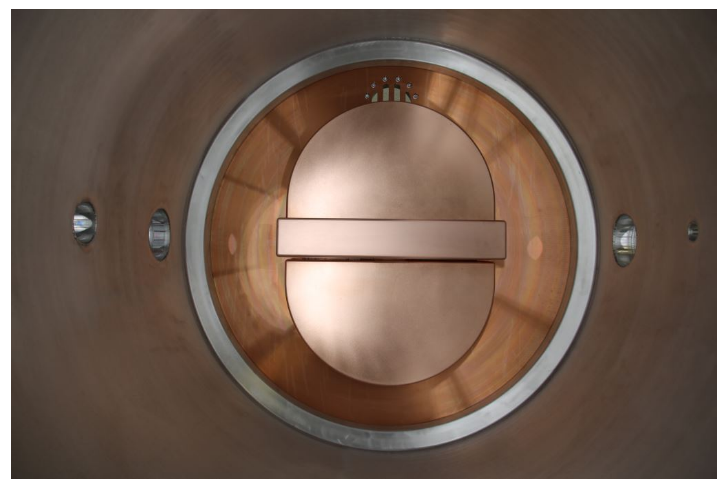
Fabrication – inner parts

JINR
114 Flerovium
FLNR
Dubna





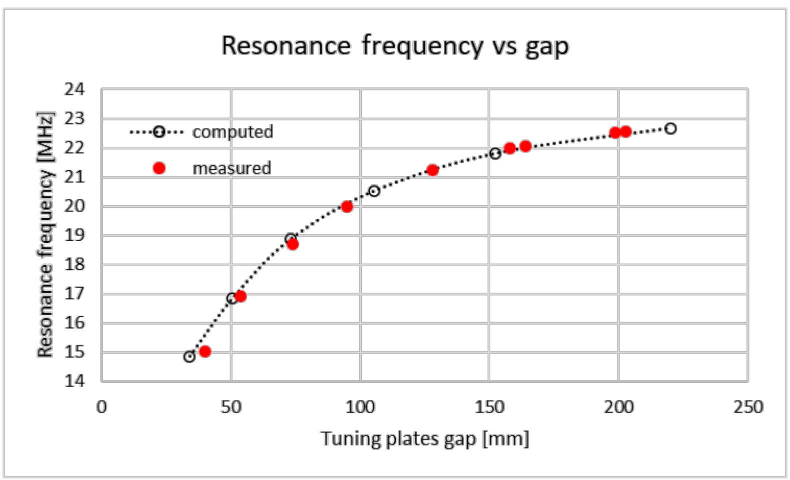


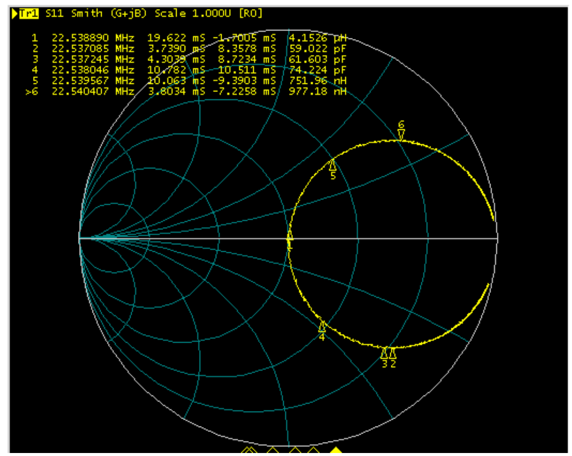


Factory tests

Tuning range and coupling loop

Measurements and model predictions of the effect of the « tuning ears » agree very well throughout the whole tuning range



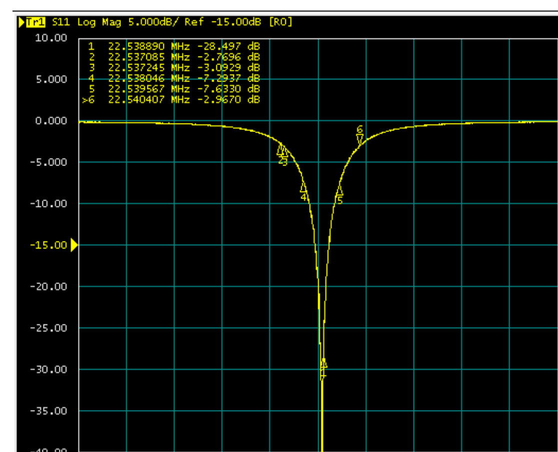


Ideal coupling is achieved at 22.539 MHz changing the orientation of the coupling loop

Q_{calc} = 14256

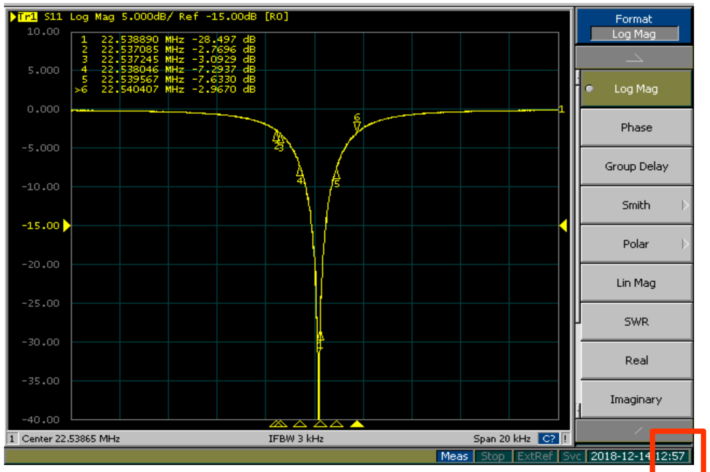
Q_{meas} = 14818

< 4% difference at 22.539 MHz

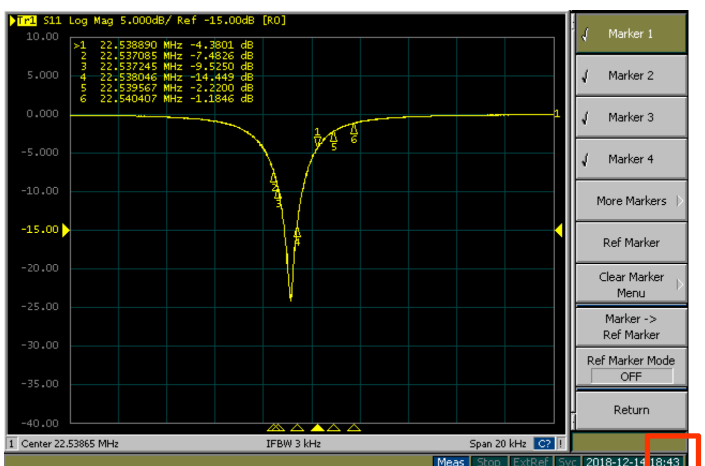


Factory tests

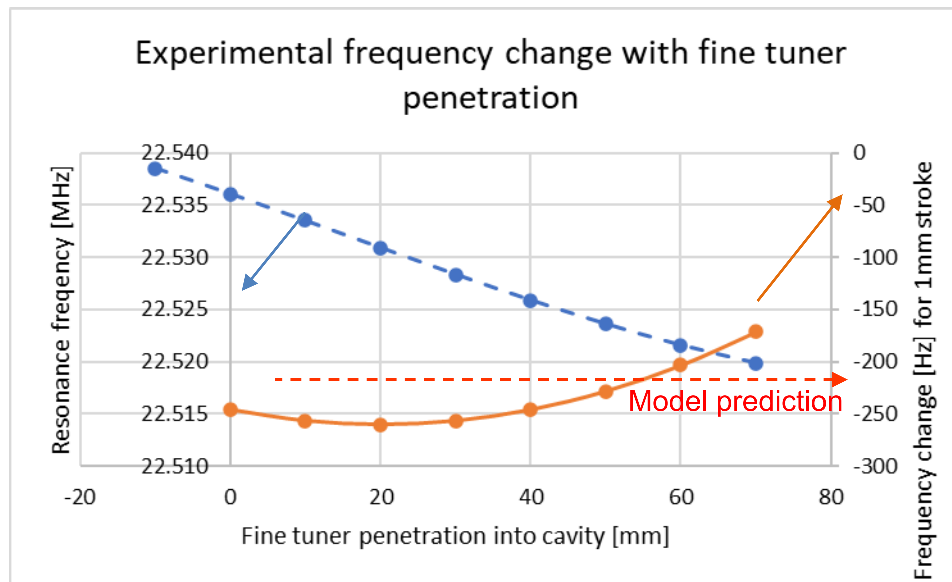
Frequency drift and fine tuning



6 hours later …



The cavity left on its own for 6 hours experienced a frequency drop by ~250 Hz. This drift can be corrected by a 1mm penetration of the fine tuner, a small fraction of the 100 mm full stroke.
This might however be unnecessary as the original -40 dB reflection is still -15 dB



RF Amplifier
&
Control system

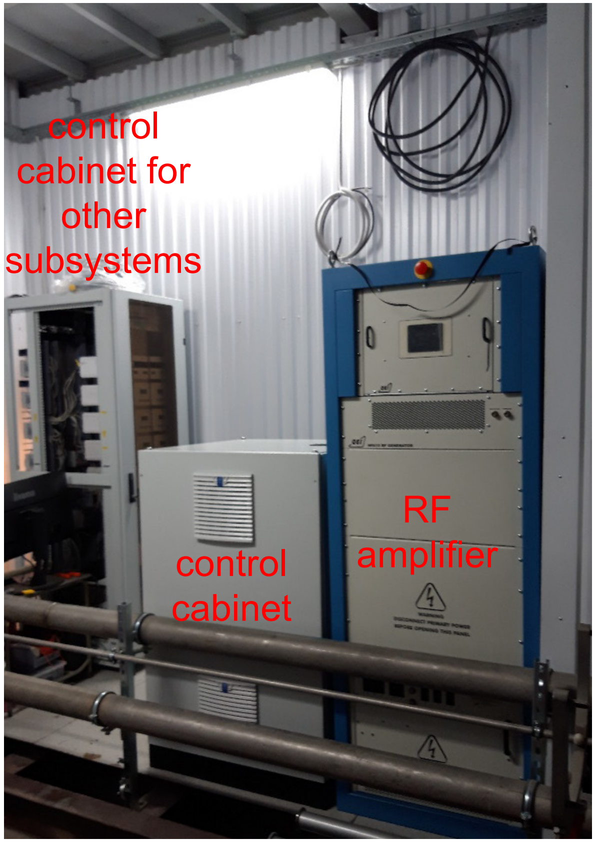
RF amplifier

AR France distributes

HFA-15 RF amplifier

Layout at installation. Because of space constraints, the control cabinet was moved elsewhere and the amplifier was rotated 90°

No.	Specification	Value	Remarks
1	Frequency Range	14-22 MHz	
2	Power Output	0-15 kW	Power adjusted by input level to amplifier
3	Mode of Operation	CW	
4	Full Power Bandwidth	Greater than 200 KHz	
5	Amplifier Tuning	Automatic tunes to desired frequency.	Motor driven variable capacitors. Software controlled.
6	Tube Compliment	3CW20,000H7	Water Cooled Triode
7	VSWR	3:1 indefinite	Infinite VSWR for 30 seconds
8	Driver Amplifier	Solid state	
9	Driver RF Output	Approximately 1 kW	
10	RF Load Impedance	50 Ohms	
11	Output Connector	1 5/8" EIA flange	
12	Input Connector	Type 'N' female	Customer can specify
13	RF Input for 15 kW Output	0 dBm	
14	Amplifier Gain	72 dB minimum	
15	Water type required	De-ionized	
16	Water flow required	25 LPM	
17	Water Connectors	¾" female union	Customer can specify connector.
18	Air Flow	8.5 cubic meters/minute	



Control system

Installation

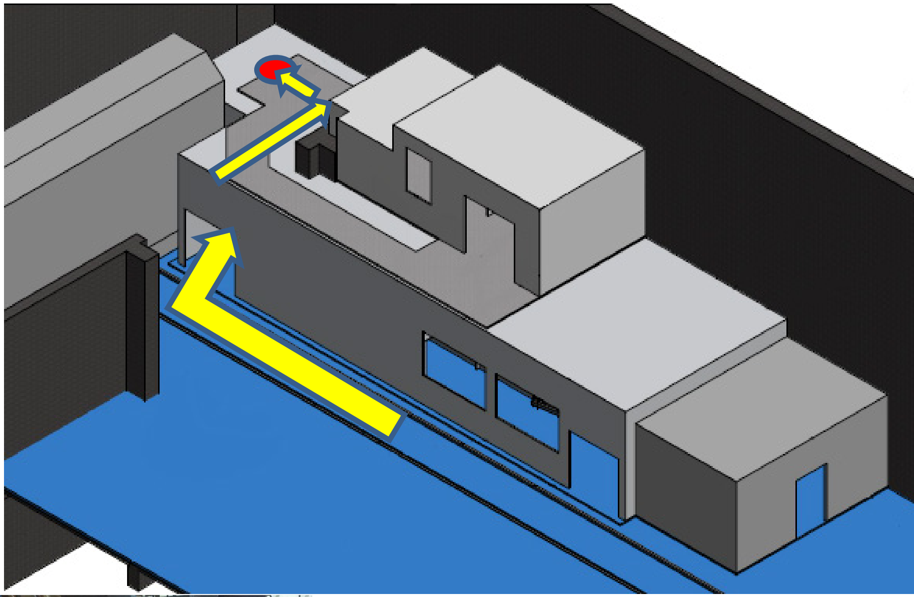
June 7th-11th 2019

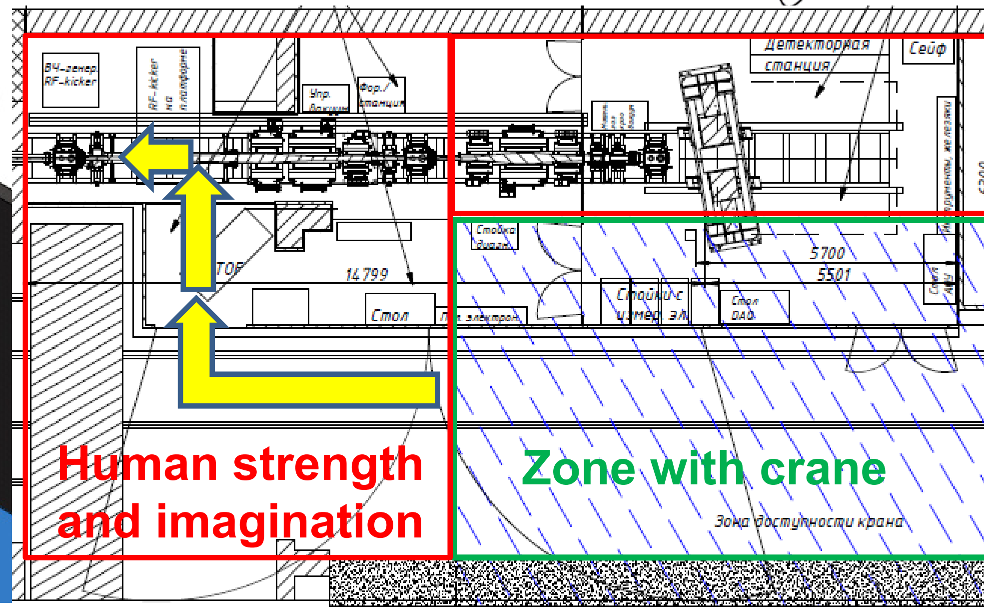
Full assembly and first test

July 21st-26th 2019

Installation

Prepare



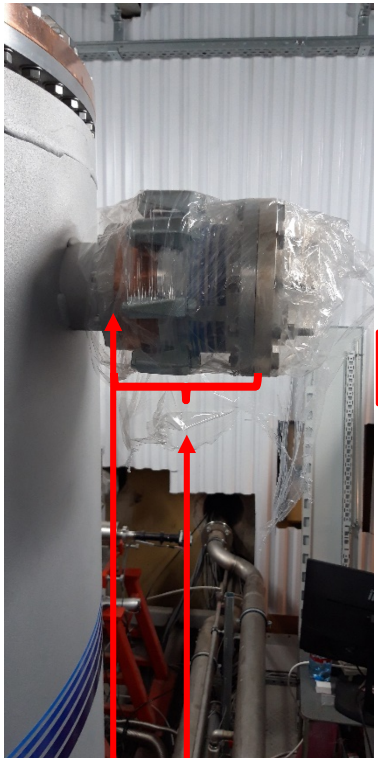


Installation

Move

Installation

Connect



Long thick and very rigid coaxial cable.

Reducer

Connecting part between extension and reducer. Hidden when assembled

Straight section between 90° bend and RF generator

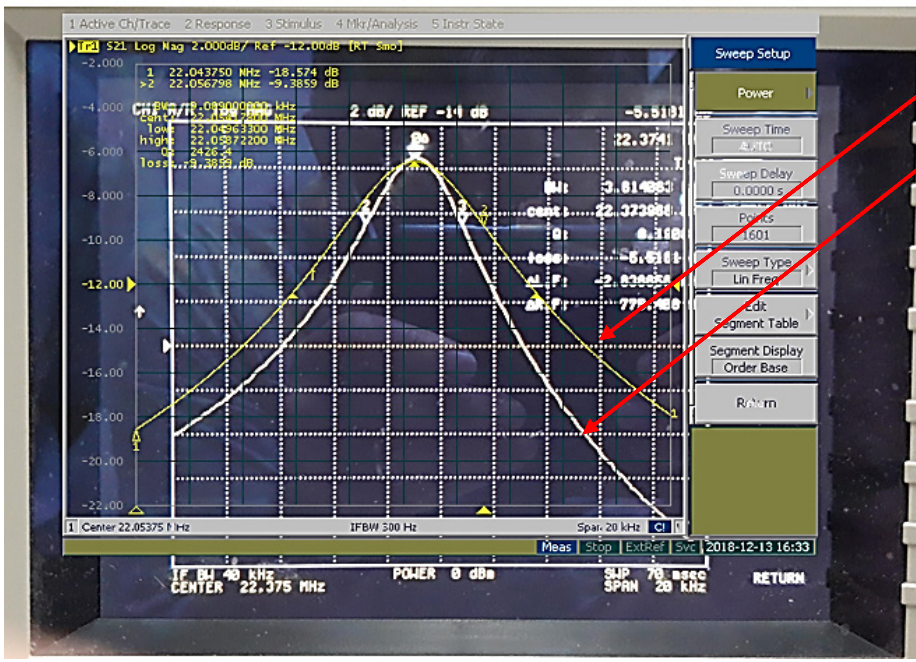
90° bend from flange to centre of elbow. Connects coax and straight

extensions

Cavity flange

First test~~s~~

For transportation, the moving electrodes are blocked in their lowest position.
The control rack is not yet operational and only 1 high frequency is available.
It compares very well with the factory test results at a close-by frequency



NTG factory	Dec 2018	22.563 MHz
JINR install	Jun 2019	22.375 MHz

2 main reasons for increase in Q

- Circular coupling loop changed to definitive shape
- Most flanges are now closed

Extended tests and power input February 10th-21st 2020

A 7-months time lag

July 2019 – February 2020 … What happened during these 7 months ?

The bad news

The U400M cyclotron was due to shut down by mid-2020 and the separator was used to accumulate data to be processed during the 2 years closing time.

A 2-weeks time window for kicker testing was only available in February 2020

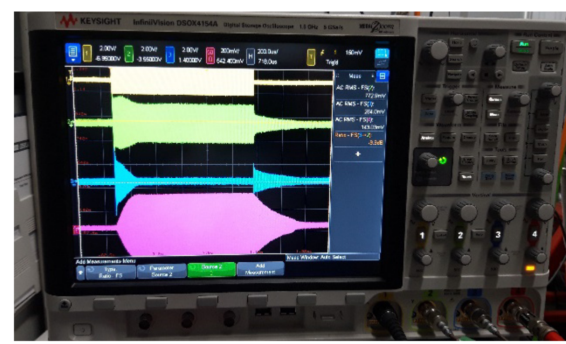
The good news

Brand new material was purchased

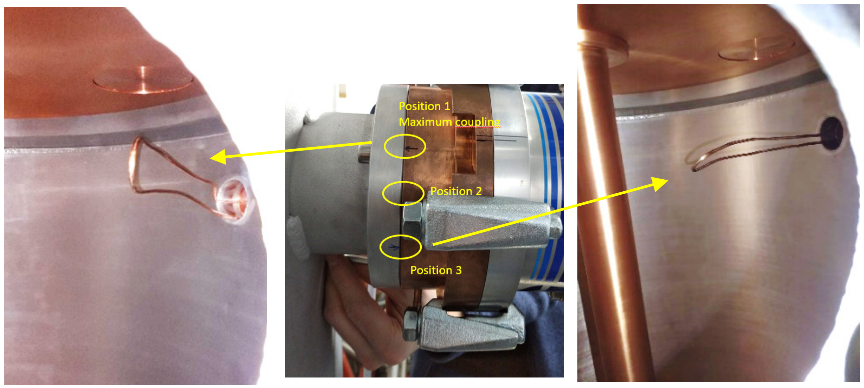
Network Analyzer
Keysight PNA-X

Frequency Generator
AKTAKOM AWG 4085

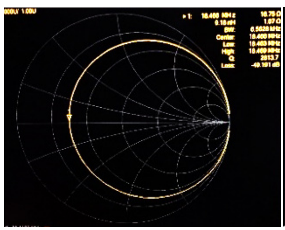
Oscilloscope
Keysight InfiniiVision
DSOX4154A



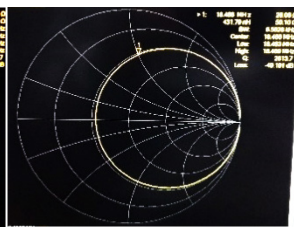
Coupling loop tuning



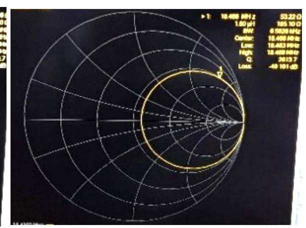
Concentrate efforts for frequencies at 18MHz and below because if time permits before U400M shutdowns, the system will be used in this range first.



Strongly Over coupled



Over coupled

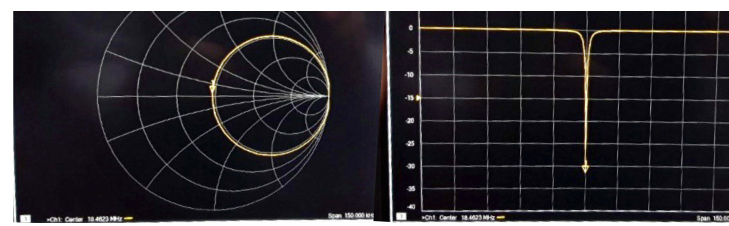


Under coupled

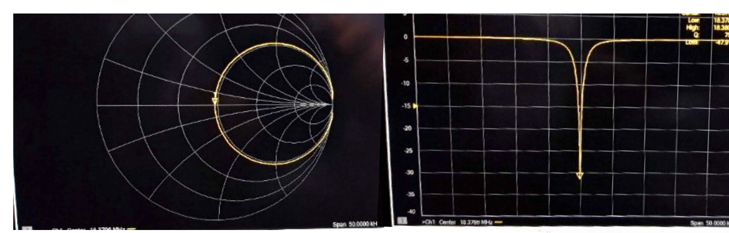
Start from position 3 and deform loop to increase its active surface

Smith chart | Transmission

Air

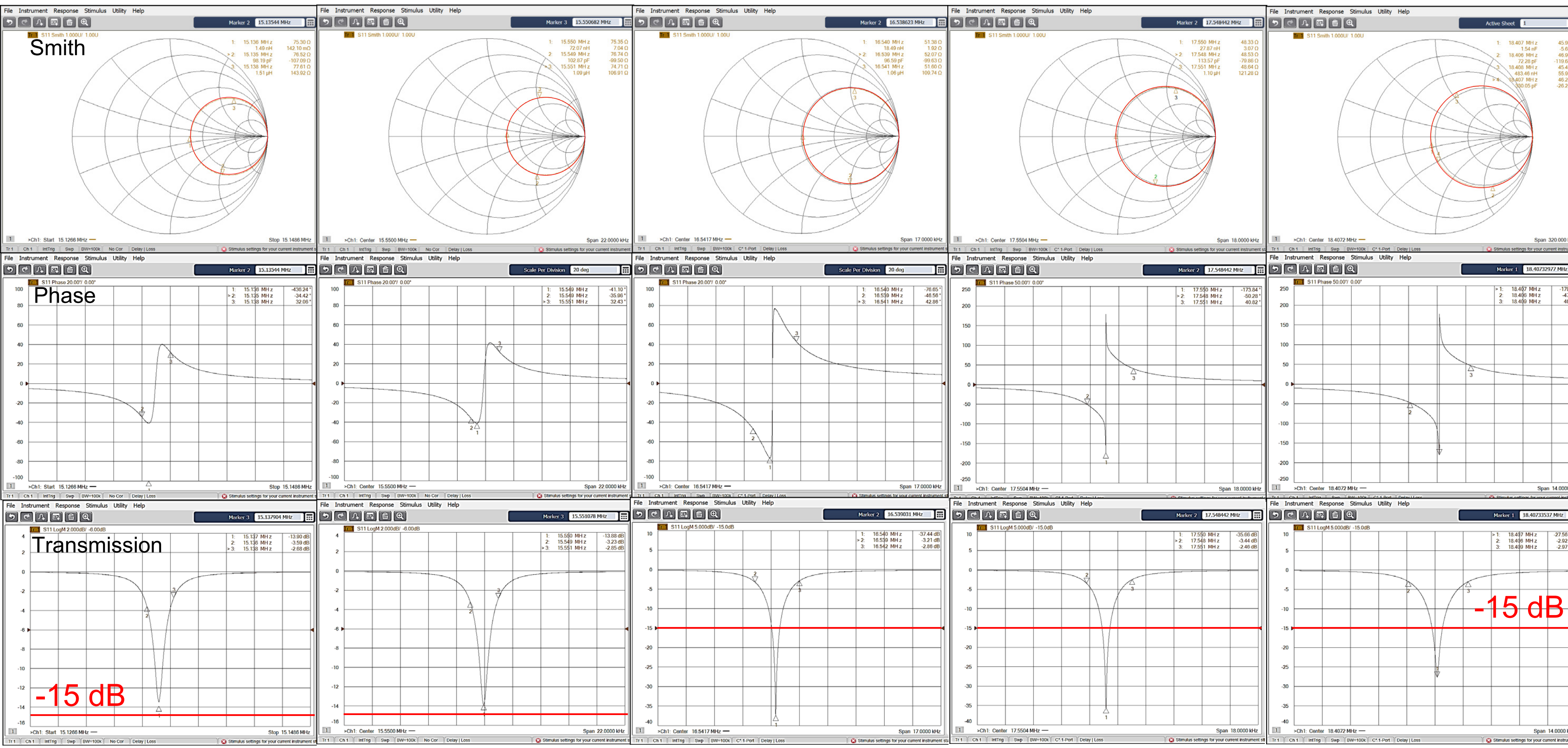


Vacuum



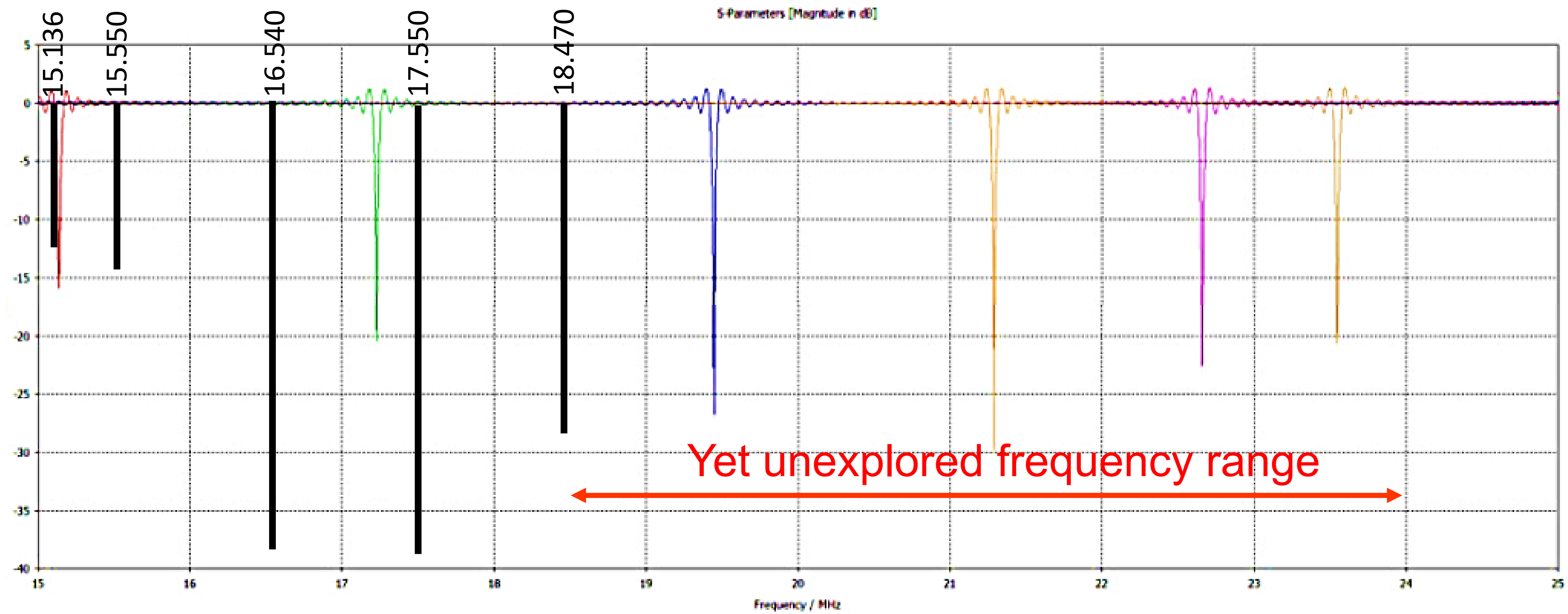
Coupling vs frequency

15.136 MHz | 15.550 MHz | 16.540 MHz | 17.550 MHz | 18.470 MHz



Under-coupled | Ideally coupled | Over-coupled

Experiment vs prediction

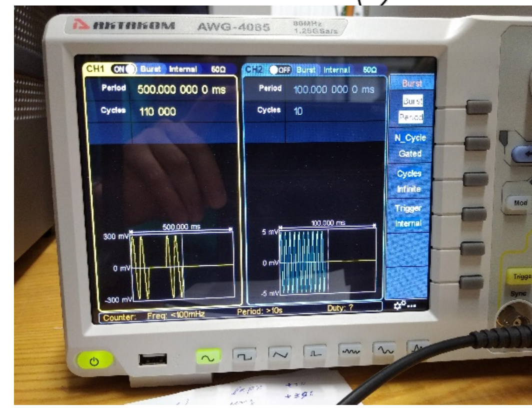


- Better transmission than expected can be reached
- The coupling must probably be retuned for the high frequency range but the present settings matches at best the cyclotron capabilities

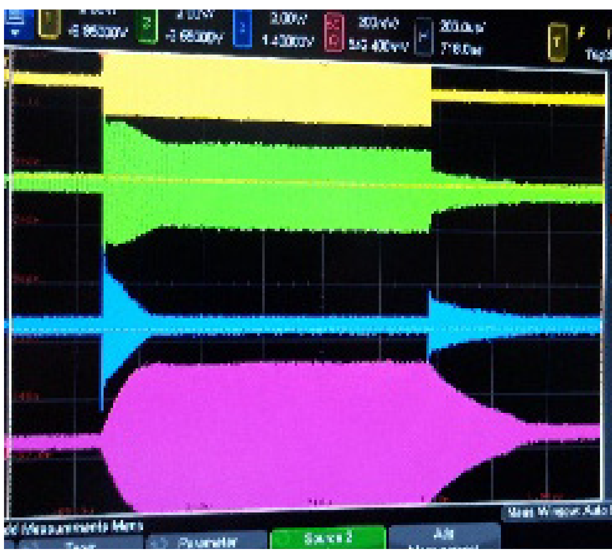
Power input (1)

To overcome multipactoring, the cavity is conditioned by short sequences of pulses separated by long «blanks».

Shown: 110 pulses, 54ns long each every 500 ms,



The number of pulses in the sequence is then increased as power is accepted by the cavity until a continuous signal can be input (shown below 20000 pulses, stable)



driving signal from frequency generator to RF amplifier input

RF amplifier signal sent to the cavity

signal reflected by the cavity at RF amplifier

pick-up loop on cavity top

Power input (2)

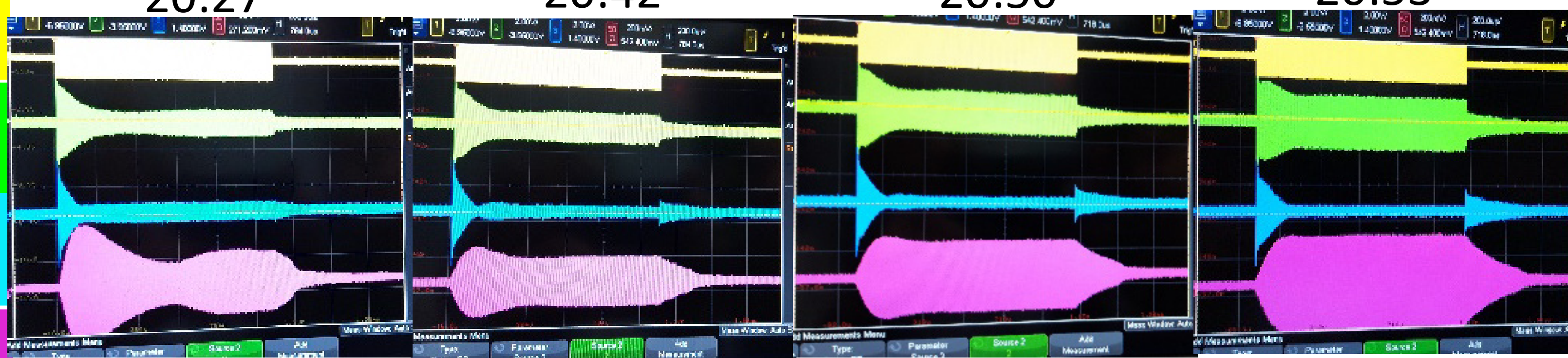
driving signal frequency generator

output signal at amplifier

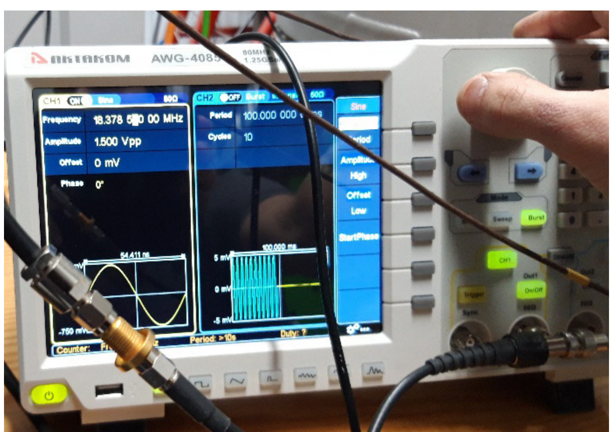
reflected signal at generator

pick-up loop on cavity top

20:27 | 20:42 | 20:50 | 20:53



f[MHz] 18.37972 | 18.37849 | 18.37830 | 18.37850



The resonance frequency changes from temperature and mechanical effects and the *input signal* is adapted to keep the resonance.

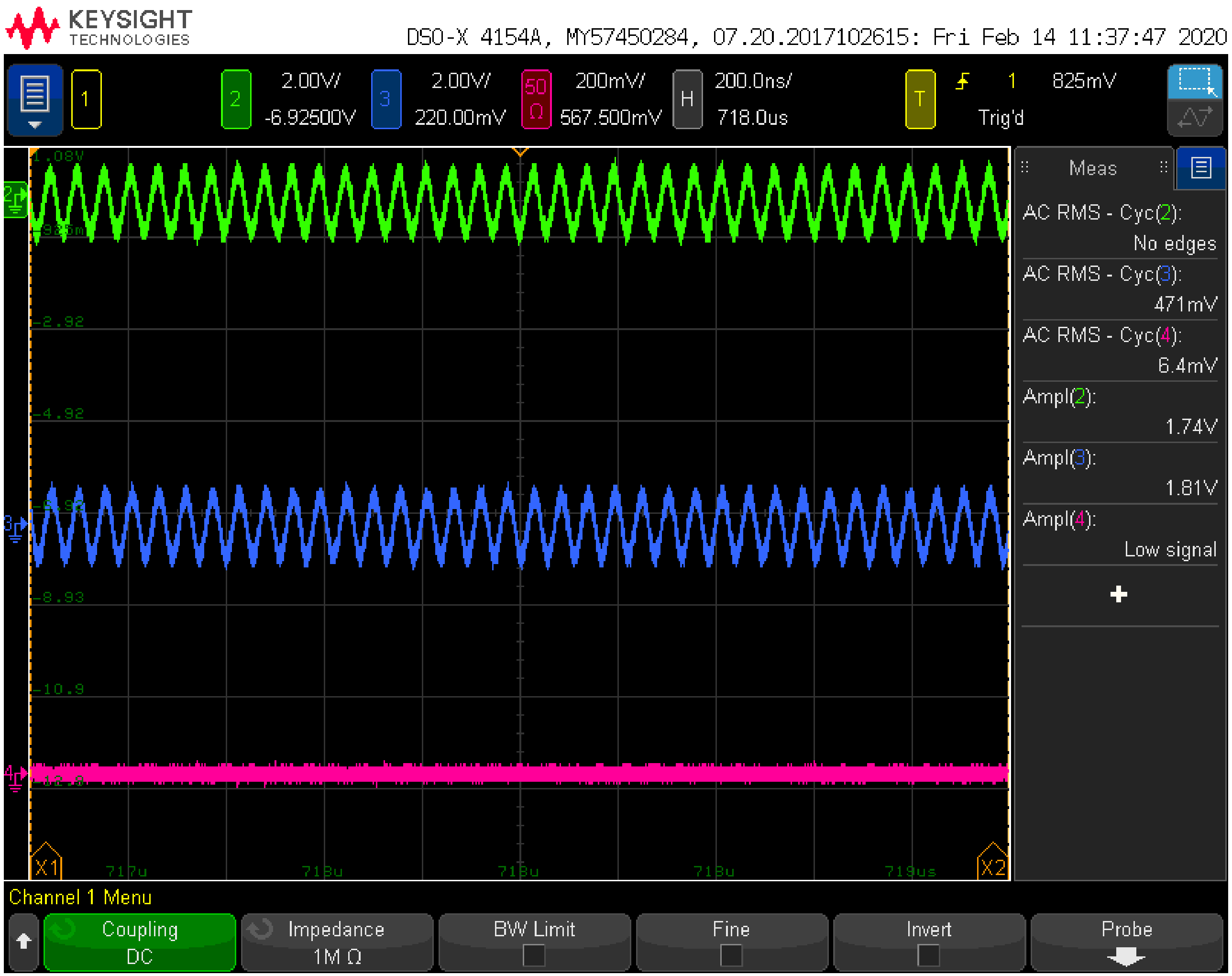
In real operation, the *frequency* must be kept constant and the cavity is automatically tuned to keep the resonance

Power input (3)

ouput signal at amplifier

reflected signal at amplifier

pick-up loop on cavity top



Fully reflected

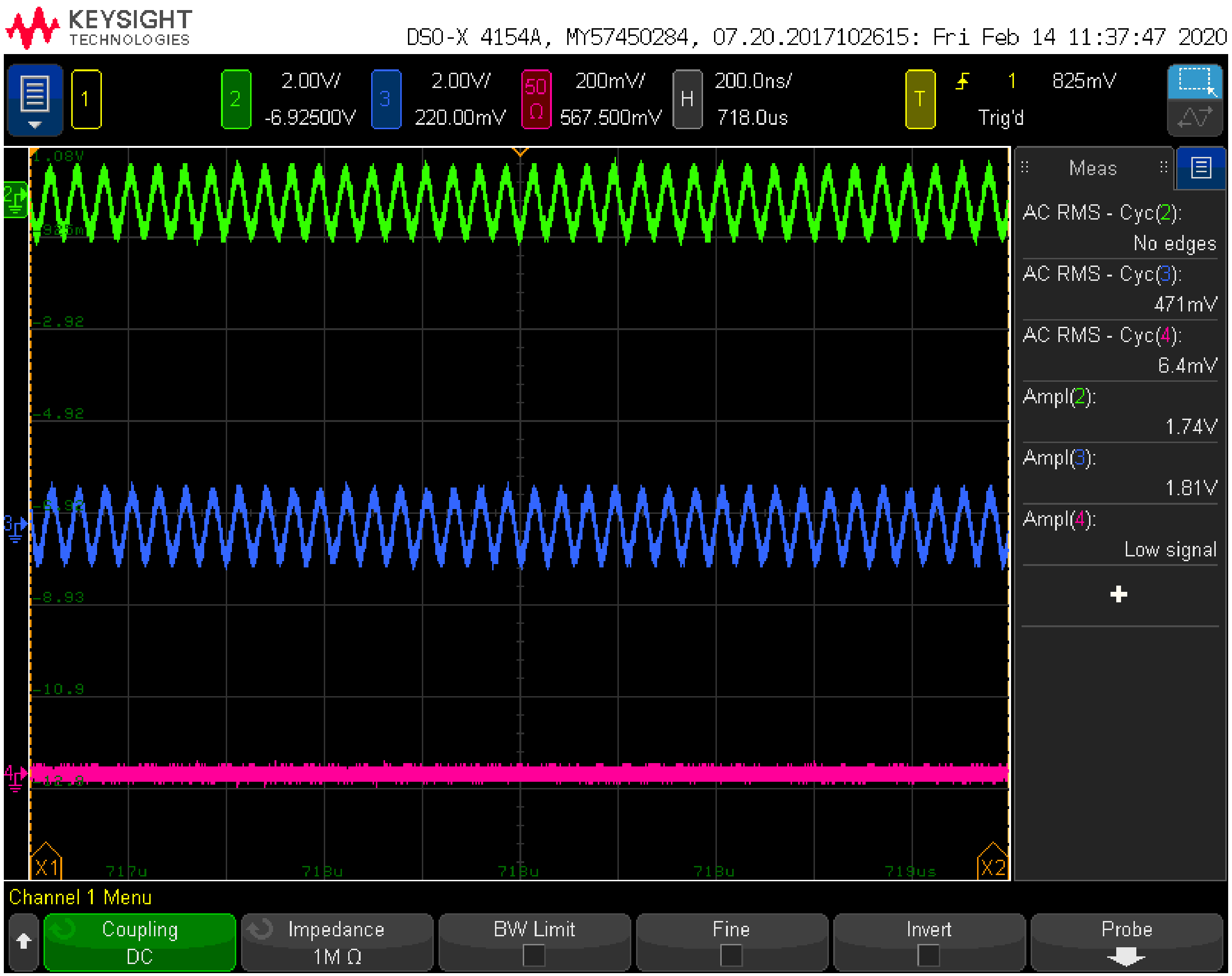
No signal in cavity

Power input (3)

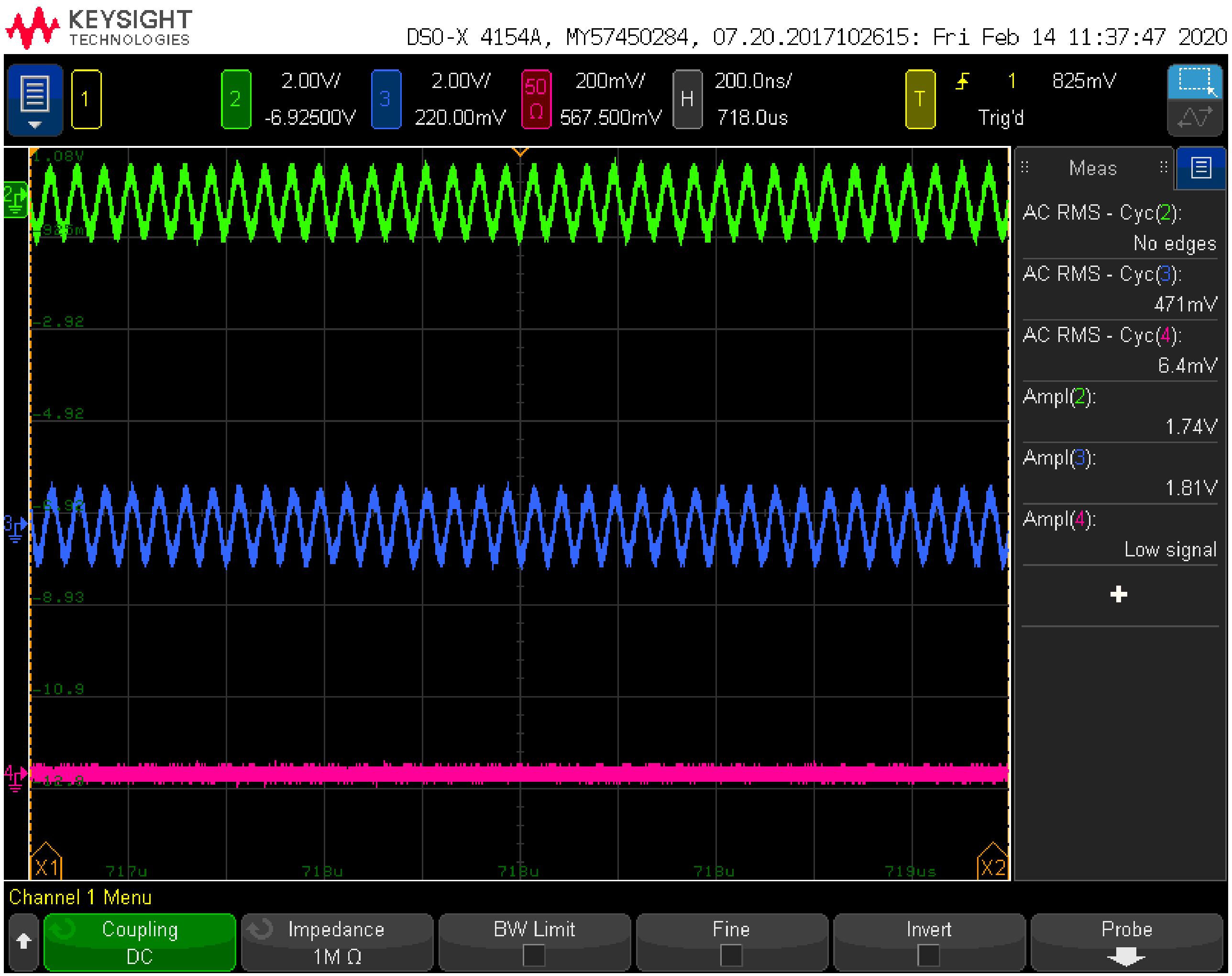
ouput signal at amplifier

reflected signal at amplifier

pick-up loop on cavity top



Power input (3)



ouput signal at amplifier

reflected signal at amplifier

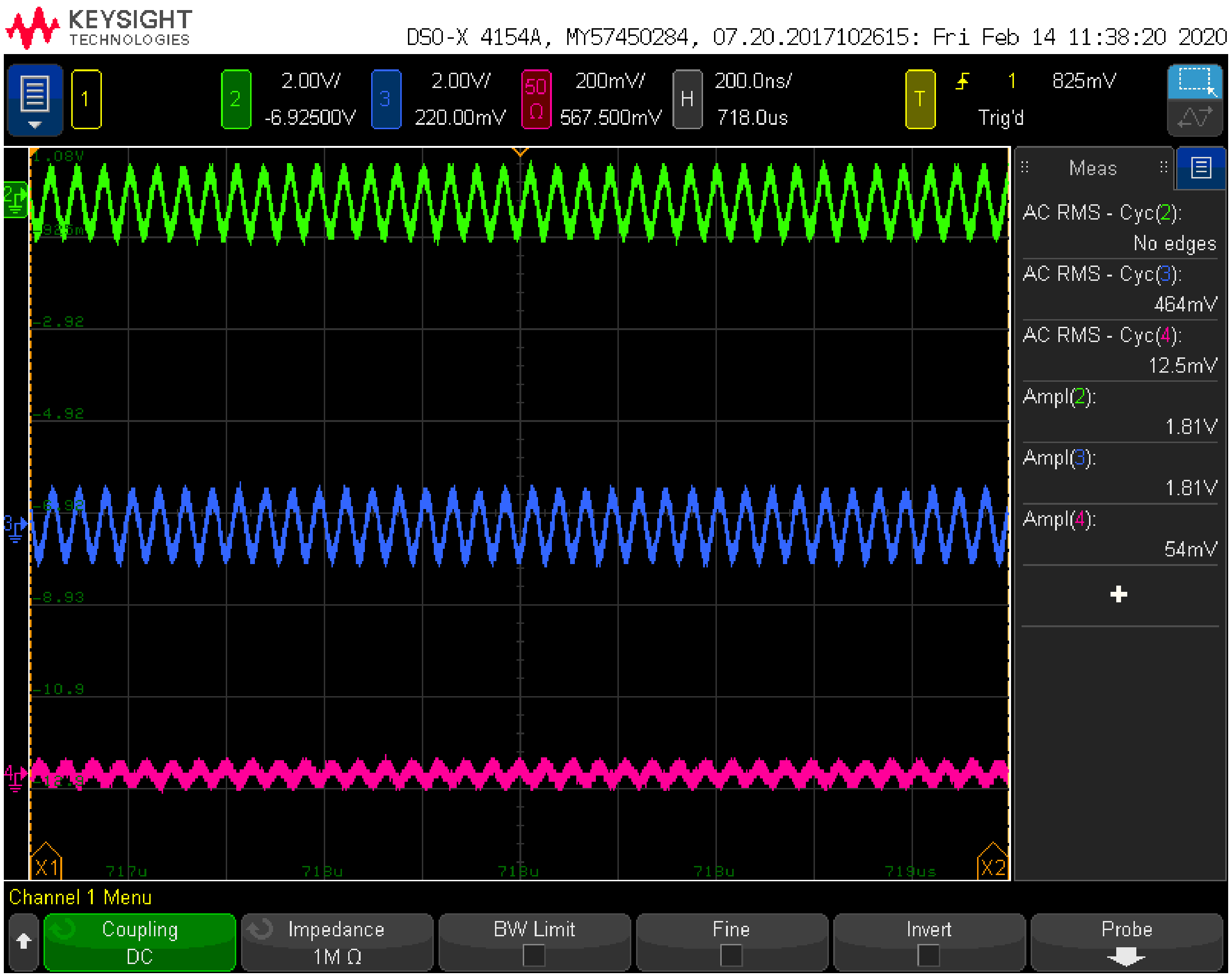
pick-up loop on cavity top

Power input (3)

ouput signal at amplifier

reflected signal at amplifier

pick-up loop on cavity top

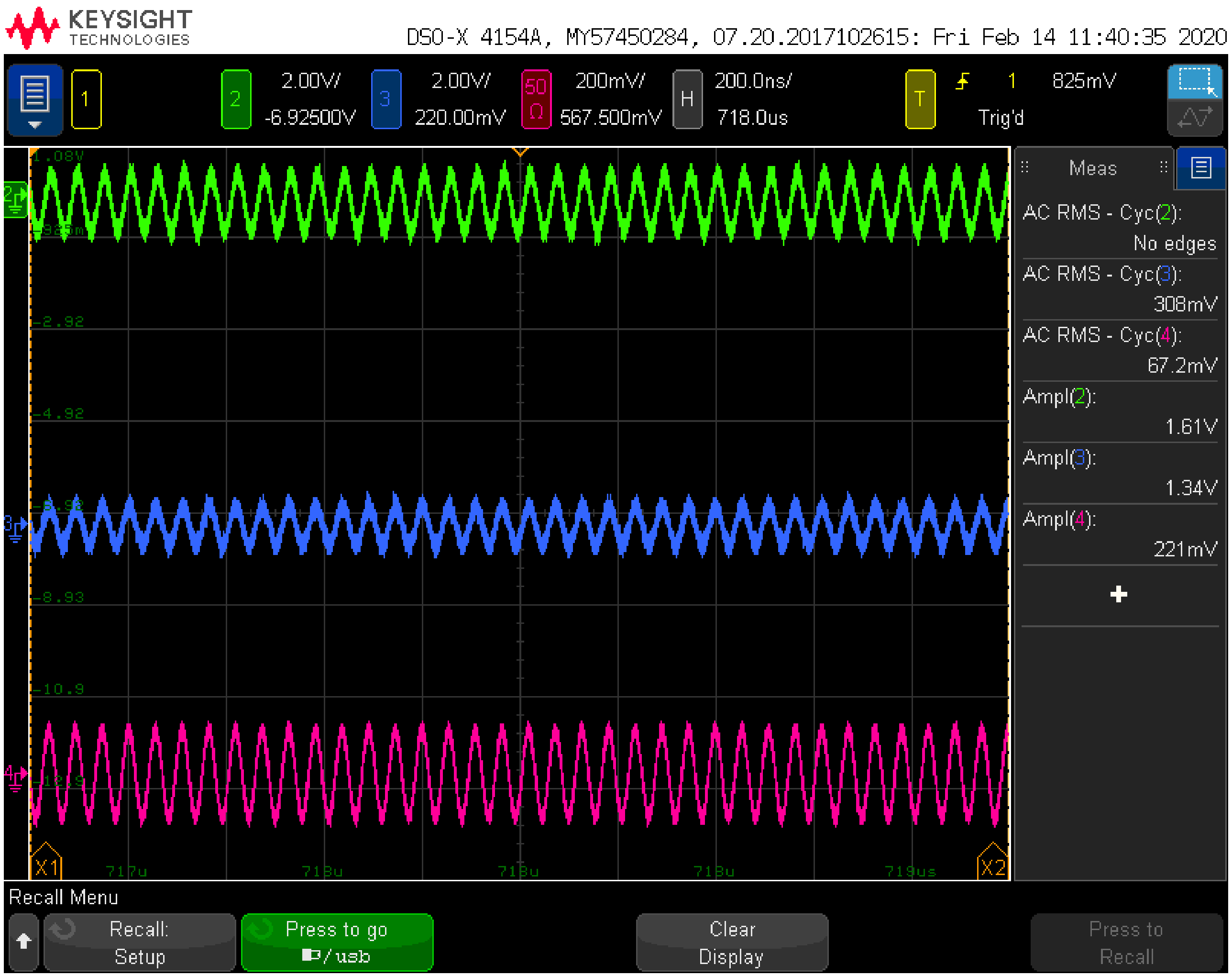


Power input (3)

ouput signal at amplifier

reflected signal at amplifier

pick-up loop on cavity top

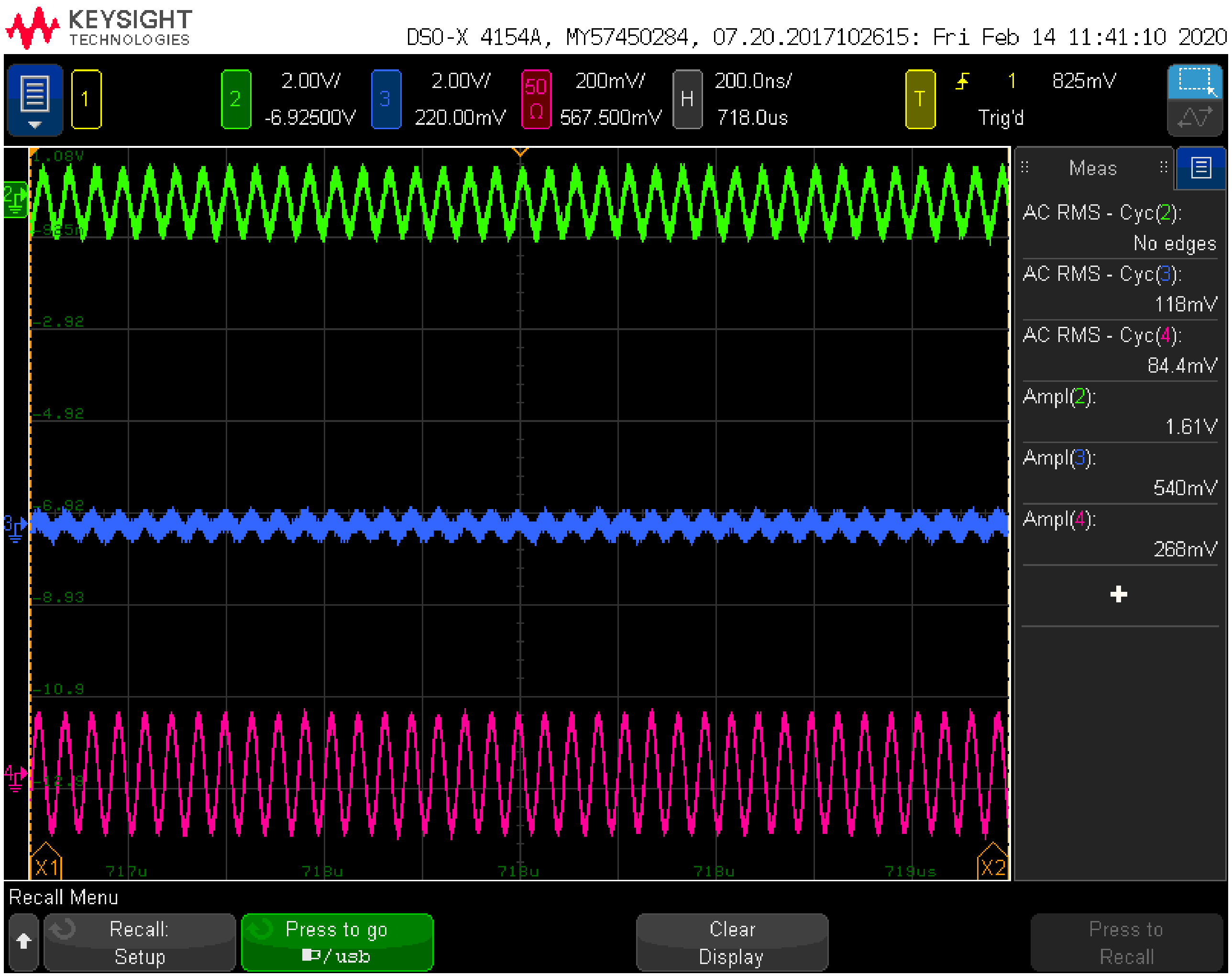


Power input (3)

ouput signal at amplifier

reflected signal at amplifier

pick-up loop on cavity top

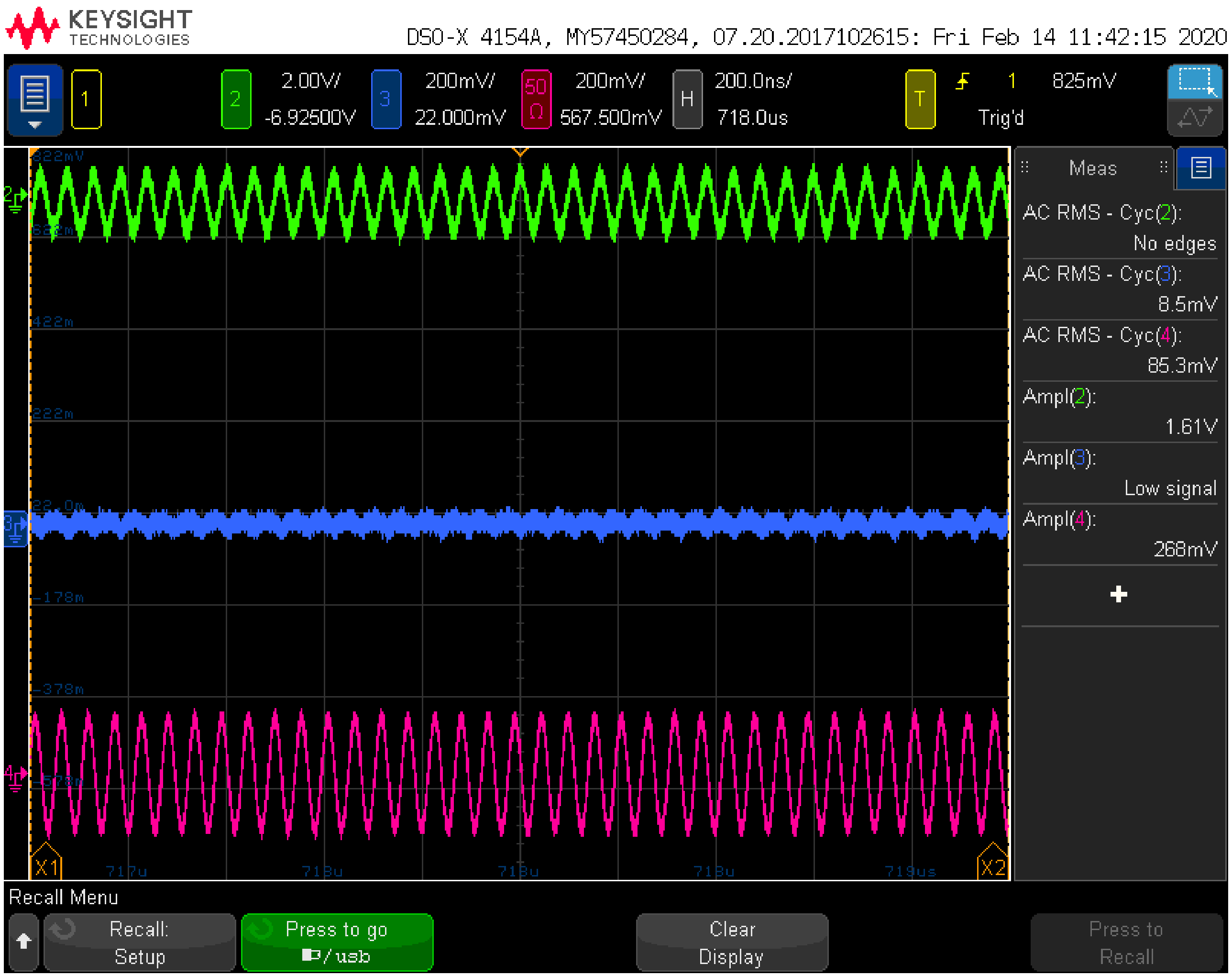


Power input (3)

ouput signal at amplifier

reflected signal at amplifier

pick-up loop on cavity top

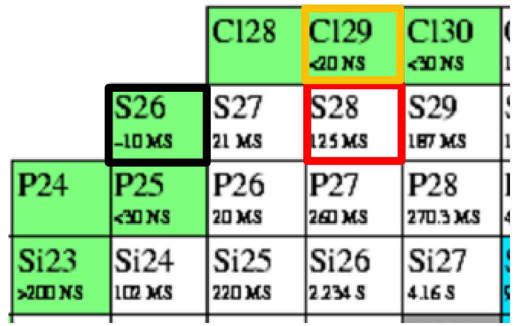


No reflection

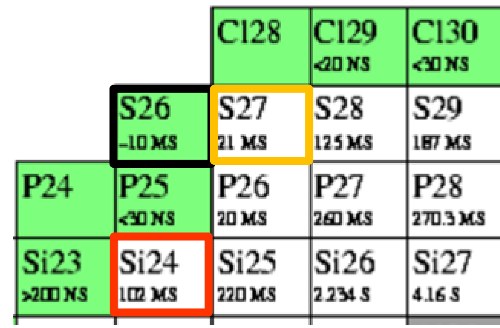
Fully accepted

Probable first experiments

^{28}S or ^{24}Si with E~25-30 AMeV, both for the study of two-proton decay properties of ^{26}S

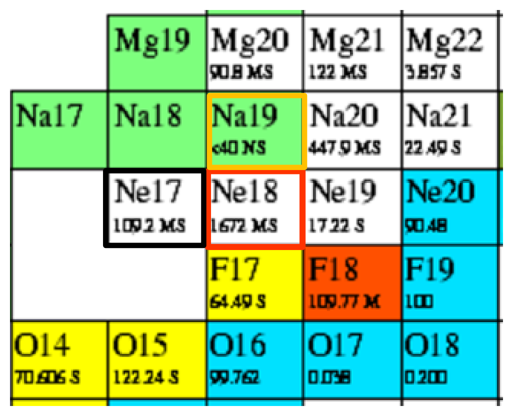


$^{28}S(^{1}H,^{3}H)^{26}S$

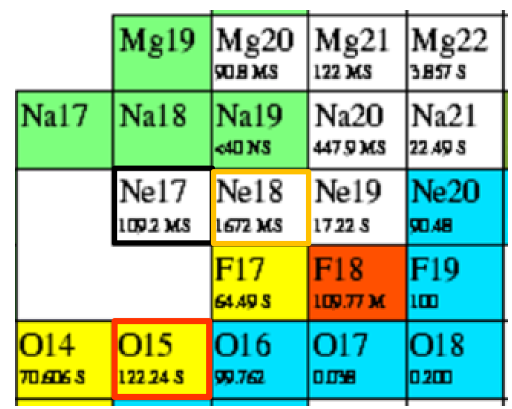


$^{24}Si(^{3}He,n)^{26}S$

^{18}Ne or ^{15}O with E~30-35 AMeV, Bypath of the ^{15}O waiting point occurring in the astrophysical rapid proton capture (rp) process



$^{18}Ne(^{1}H,^{2}H)^{17}Ne$



$^{15}O(^{3}He,n)^{17}Ne$

Conclusions

- The Acculinna-2 RF-kicker was successfully designed, built and tested. It is a collaborative achievement.
- On-site tests show equal-to or better-than expected results.
- Because of limited time slots, experiments were conducted on a limited frequency range.
- No test with beam was done yet. U400M operation should resume in the end 2022 and therefore RF-kicker operating has a high priority in day-one experiments.
- A wonderful human experience!

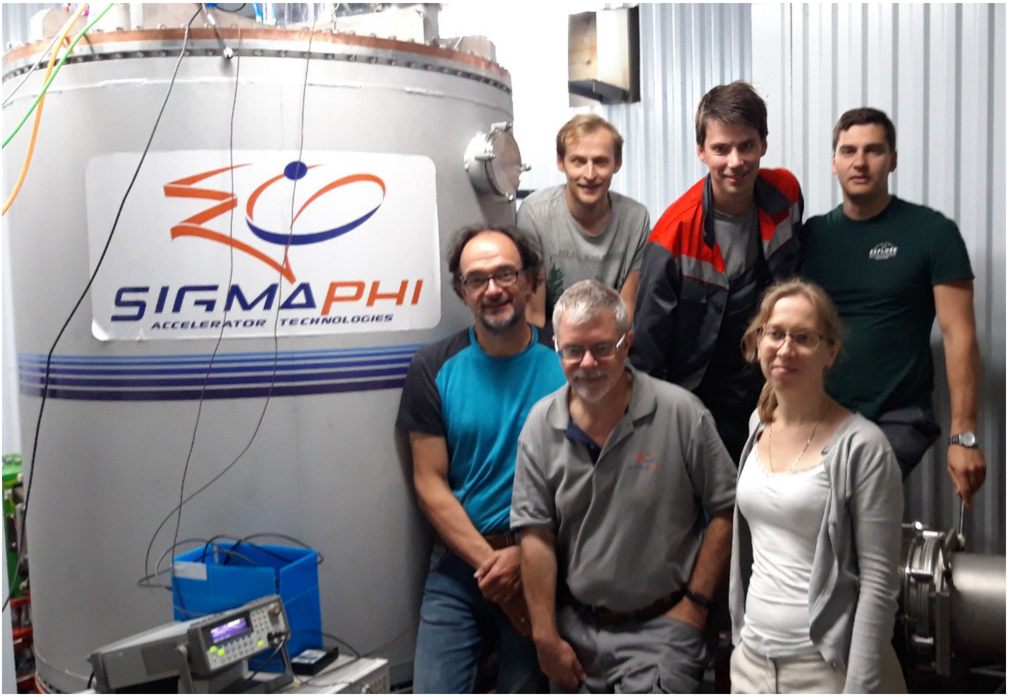
A physics jam session with players from 6 bands

Jernej Cosylab

Sacha FLNR

Sergey FLNR

Michel AML not in the picture



Alexander NTG

William Sigmaphi Magnets

Anna Sigmaphi Electronics

Andrey FLNR

Thank you

Questions ?