Istituto Nazionale di Fisica Nucleare

A NOVEL CW RFQ FOR EXOTIC AND STABLE BEAMS

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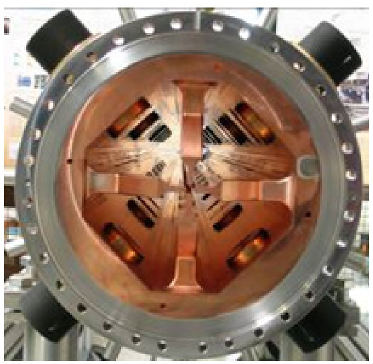
OUTLINE

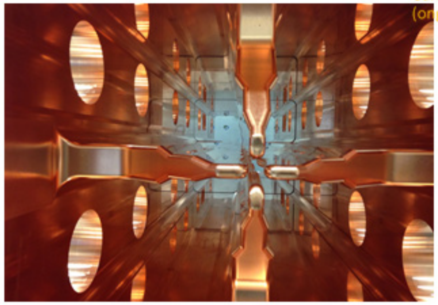
- INFN-LNL Commitment in High Power RFQs and DTLs
- The SPES Project at LNL
- Description of the RFQ for the SPES Project
- Beam Dynamics
- RF Design
- RFQ engineering
- RFQ Assembly and testing
- Conclusions

INFN-LNL Commitment in High Avg. Power RFQs and DTLs

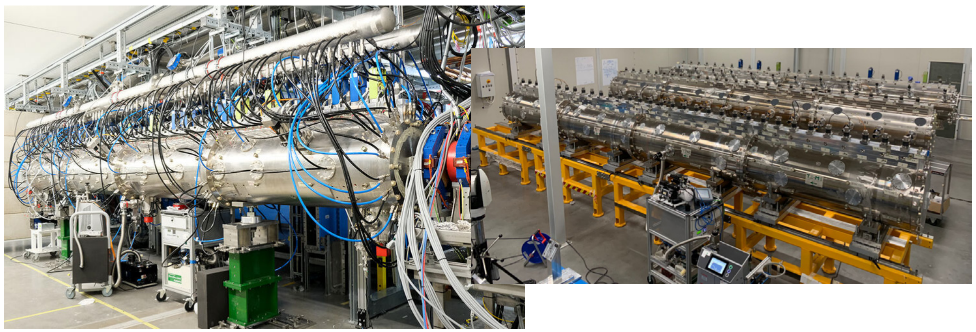
Project	Species	Wi-Wf [MeV/u]	P_{RF}[kW]	Number of cavities	f[MHz]	L[m]	Duty Cycle [%]	Ib [mA]	# of mechanical modules
MUNES RFQ (1999-)	p+	0.08-5	800	1	352.2	7.13	100	40	6
IFMIF RFQ (2007-)	d+	0.1-5	1250	1	175.0	9.81	100	130	18
ESS DTL (2012-)	p+	3.6-90	2200 (per DTL)	5	352.21	7.09-7.85	5	62.5	20 (4/DTL)



MUNES RFQ: Built and tested at full power (first two modules)



IFMIF RFQ: built and under commissioning (125 mA D+ beam on July 2019), Rokkasho (Japan)

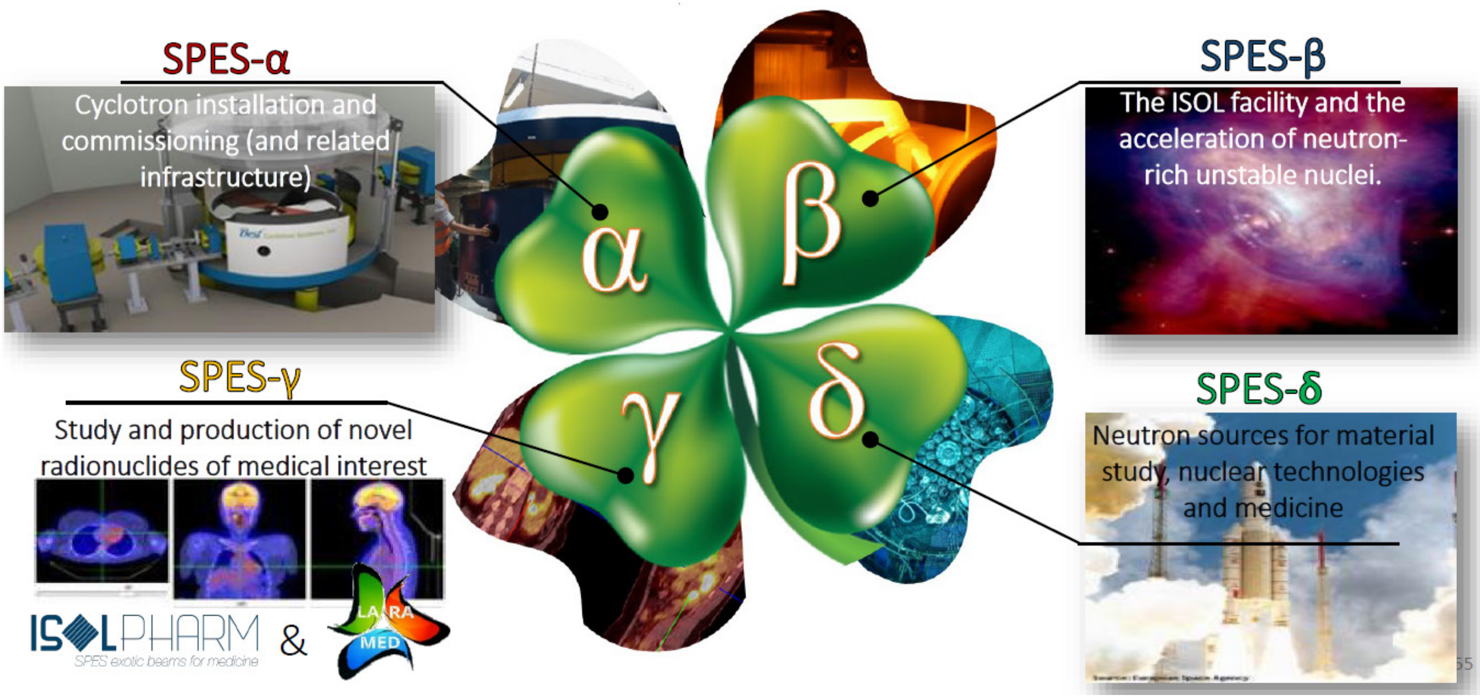


ESS DTL: in construction and testing in Lund (Sweden)

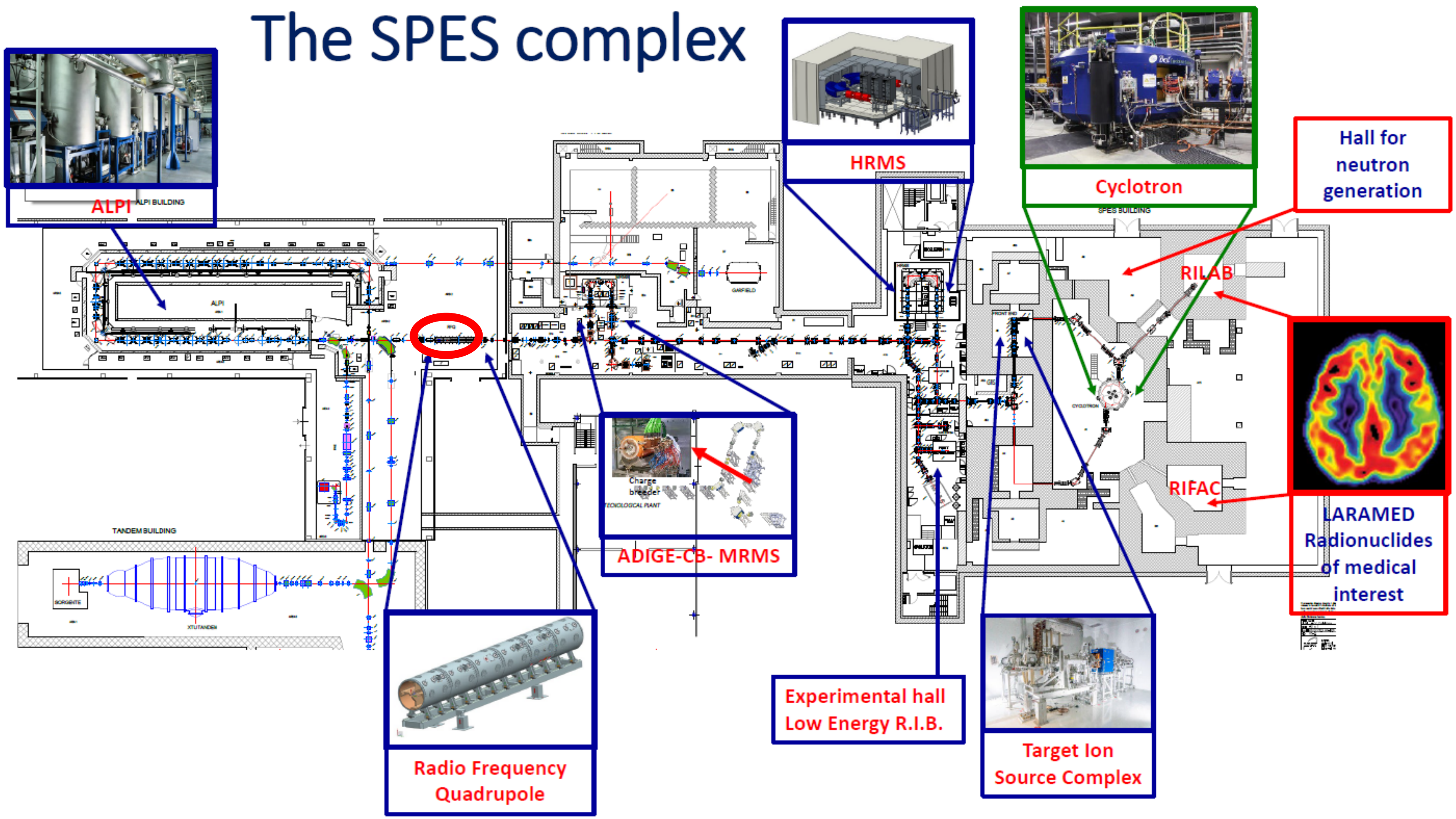
THE SPES Project at LNL

The SPES project – Selective Production of Exotic Species aims at the realization of an accelerator facility for research activity in different fields:

- Fundamental physics: nuclear physics (nuclear matter in extreme conditions) and nuclear astrophysics (stellar evolution) with radioactive ion beams
- Interdisciplinary physics: production of radionuclides of medical interest, generation of neutrons for material study, nuclear technologies, …



THE SPES Project at LNL (2)



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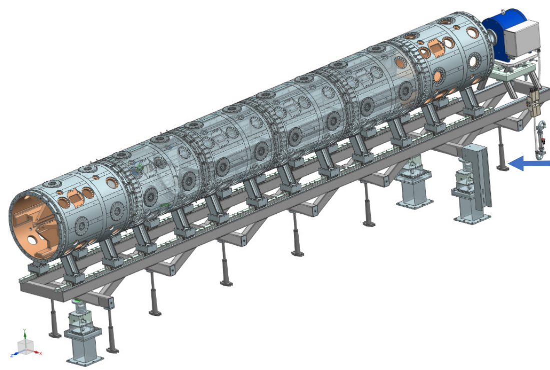
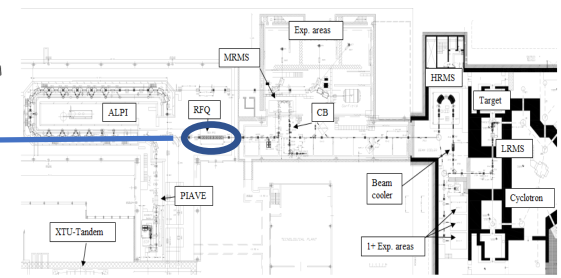
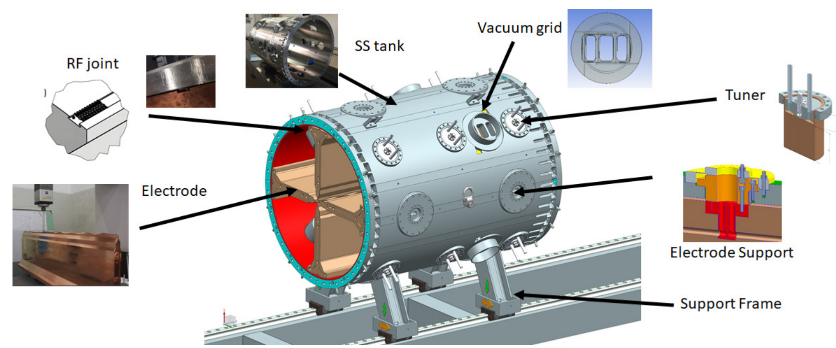
SPES RFQ Essentials: Main parameters

The SPES RFQ is designed in order to accelerate beams in CW with A/q ratios from 3 to 7. The RFQ is composed of 6 modules about 1.2 m long each. Each module is basically composed of a Stainless Steel Tank (AISI LN 304) and four OFE Copper Electrodes. A copper layer thickness is plated on the tank inner surface and a spring joint between tank and electrode is used in order to seal the RF

Paramater [units]	Design value
Frequency [MHz]	80
Duty Cycle [%]	100 (CW)
In/out. Energy [keV/u]	5.7-727 (β=0.0035-0.0359)
Intravane voltage [kV]	63.76-85.85 (A/q=7)
Beam current [mA]	0.1
Vane Length [m]	6.95
R_0[mm]	5.29-7.58
ρ/R_0	0.76
Synchronous phase (deg.)	-90 ÷ -20
Focusing Strength B	4.7 ÷ 4
Transmission [%]	94
Output Long RMS Emit [keV deg /u]	4.35







Design aspects: Beam Dynamics

Main goals:

- Minimization of longitudinal emittance to improve ALPI Linac beam performances
- Low RF power dissipation (possibility of using 1 Power Amplifier)
- Keep Surface field < 1.8 kilp.
- Maximization of Beam Transmission

Design tools:

- home-made program for main cell generation (used for CERN LINAC3 RFQ)
- full RFQ generation by LANL codes (PARI, PARMTEQM)
- multiparticle transport by PARMTEQM and TraceWin/Toutatis

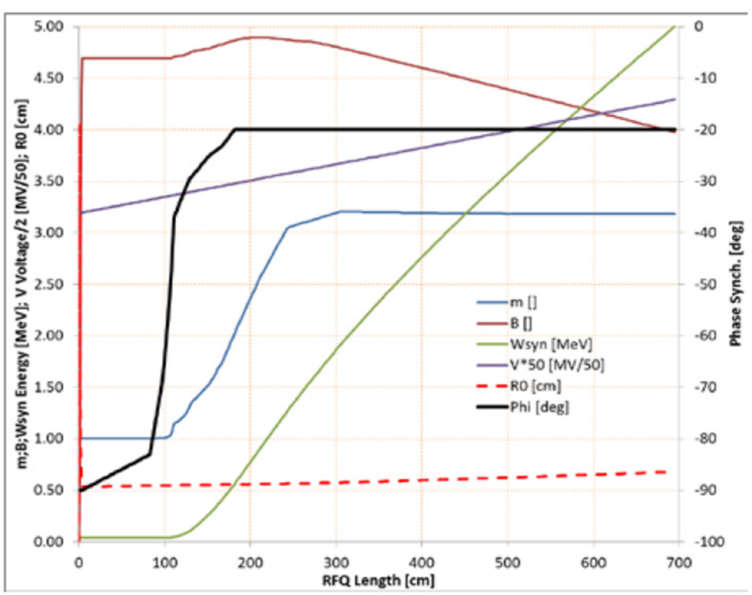
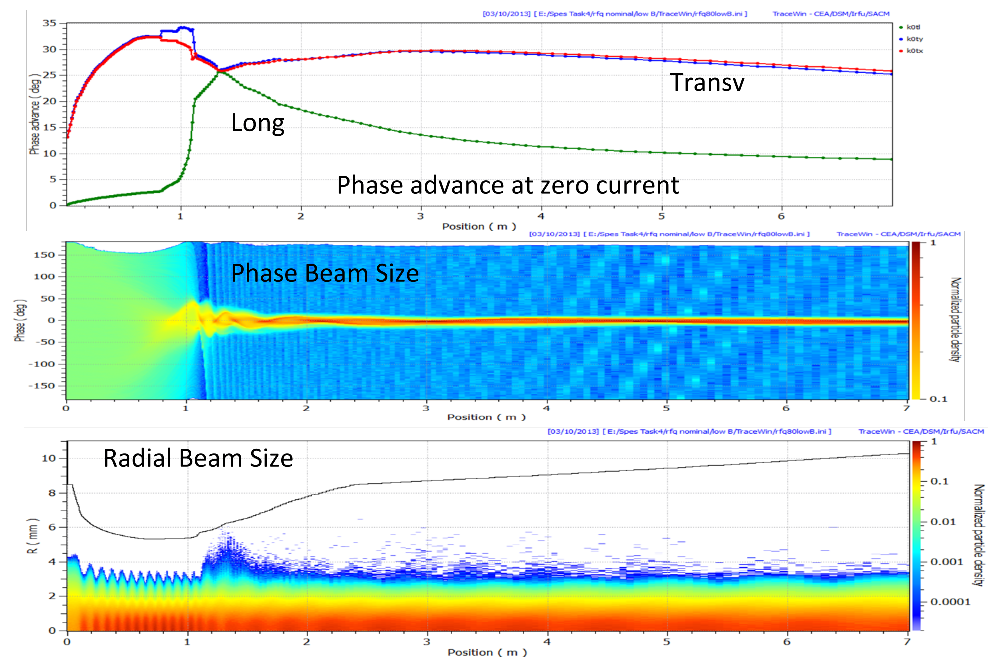


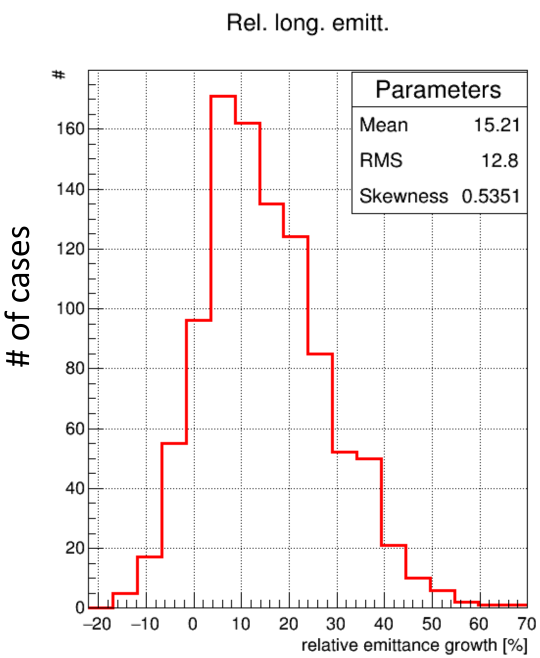
Figure 1: The main RFQ parameters vs. length.

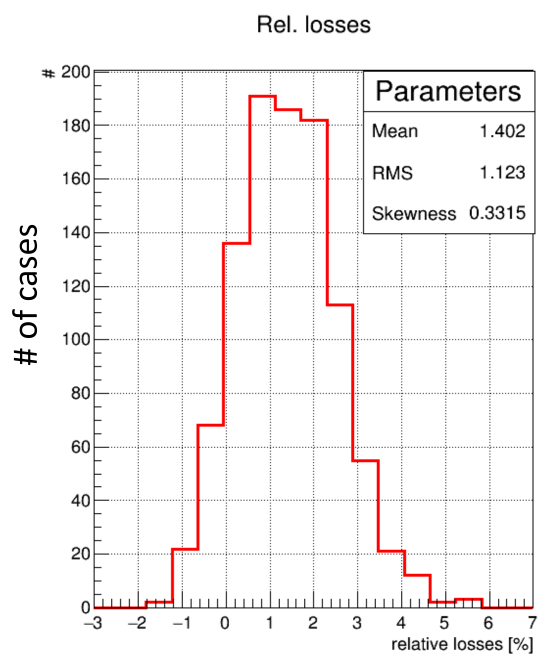


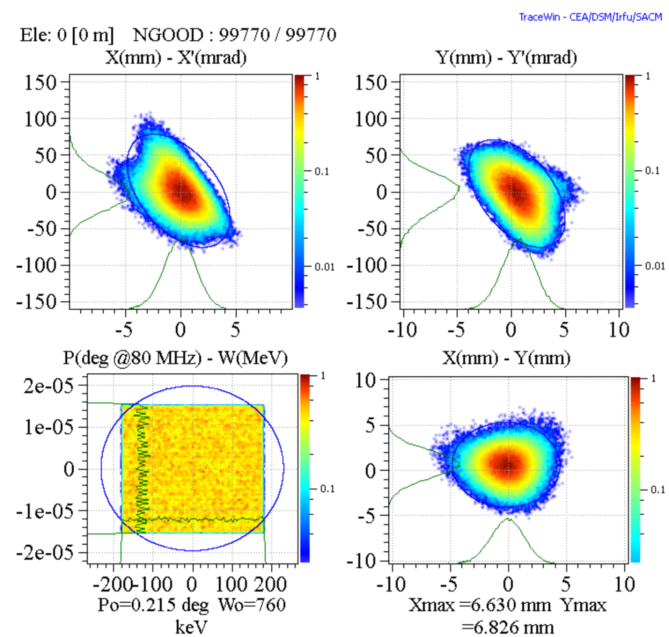
All errors together: effect on the SPES RFQ

- Statistics study on 1000 entries
- Input beam from the MRMS.
- Comparison between the nominal losses and long. Emittance

Error type	Interval error applied
Segment displacement	±0.1 mm
Segment R0 variation	±0.2 mm
Profile shape	±0.050 mm
Voltage profile (tilt)	±3%
rho	±0.020 mm





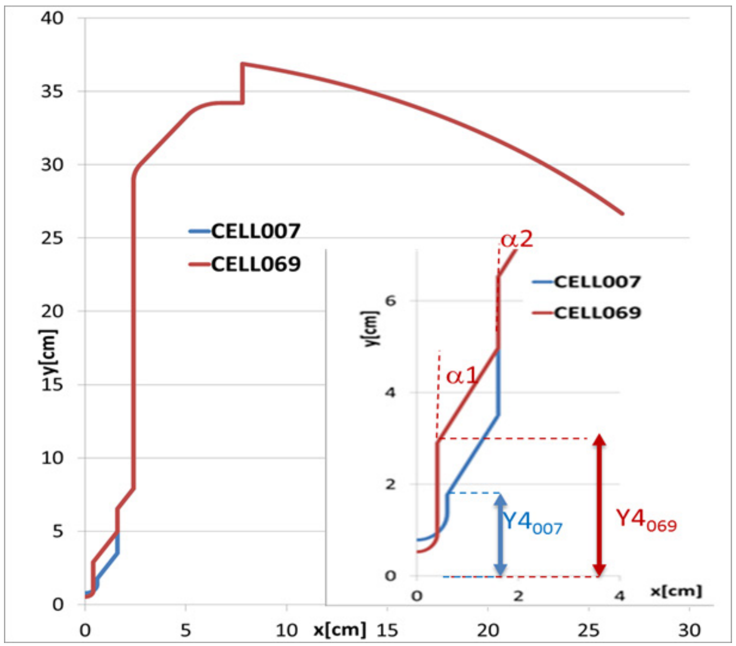


Input beam from MRMS: energy spread 10 eV

RFQ EM Design

- Four vanes (no coupling cells, L=1.9λ), ramped field (end cells detuning)
- Single coupler (<150 kW)

In order to ease machining, the capacitive region is varied along the RFQ. The electrode thickness is equal to 48 mm, the vane angles α1 and 2 are equal to 30° and the tank radius is equal to 377 mm. The voltage law is implemented by properly shaping the vane undercuts

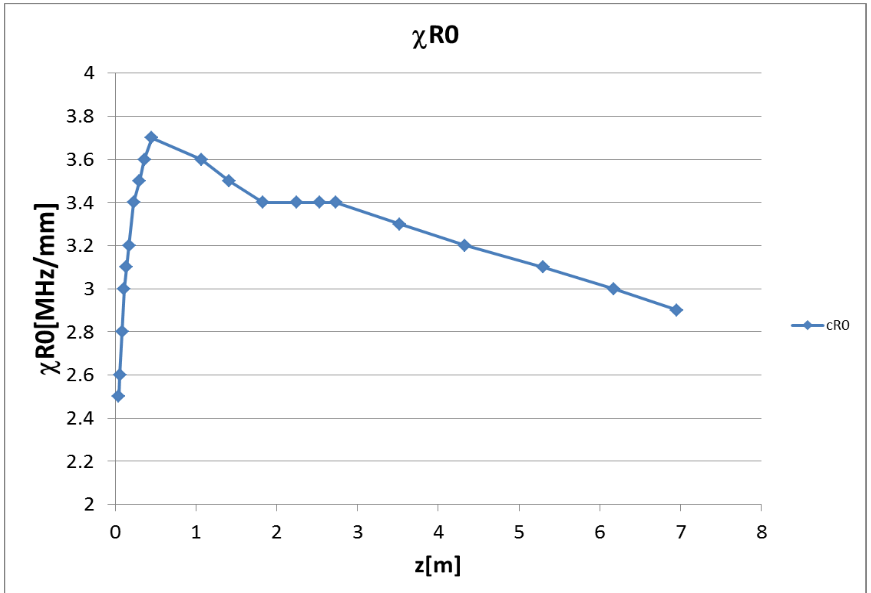


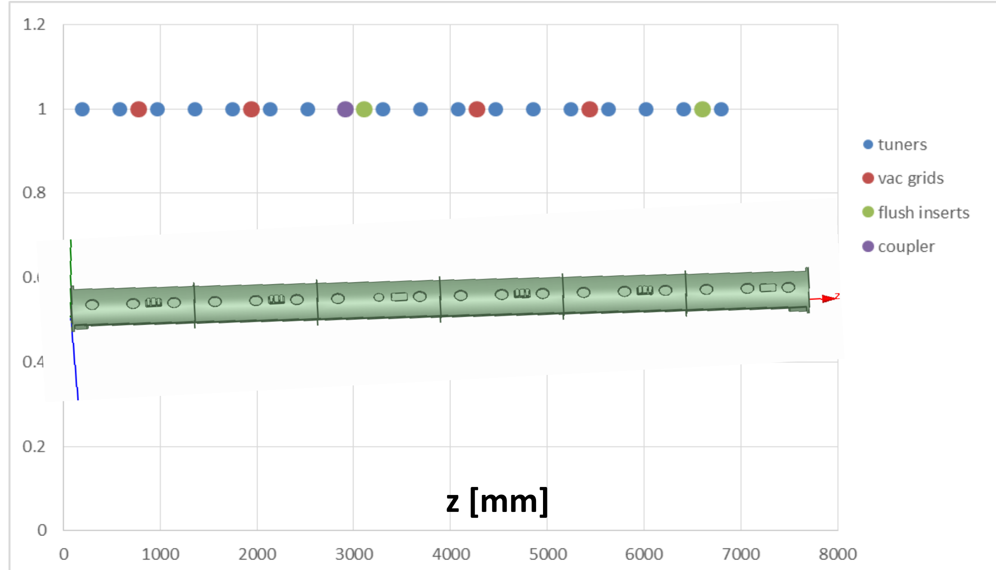
Parameter (units)	Value
Operational mode	CW
Frequency (MHz)	80
TE_{21}[TE_{11}] cut-off frequency [MHz]	79.5 [77.3]
Dipole-free region about 80 MHz	±2.2 MHz
Q_0 value	14000
Shunt Impedance times length [kΩ*m]	349-365
Dissipated Power in the cavity [kW]	100
RF power [kW]	120
Stored Energy [J]	2.87
Maximum Power density in the cavity sections [W/cm²]	0.31
Maximum Power density in the cavity undercuts [W/cm²]	11
Tank Radius R [mm]	377

$$P_{RF}=P_0\cdot a_{RF}=P_0\cdot\alpha_{RF}\cdot\alpha_{reg}=73\ \text{kW}\cdot1.35\cdot1.2=73\ \text{kW}\cdot1.62=120\ \text{kW}$$

P_0 = 2D Superfish Power
α_{RF}= margin for 3D details and RF joint
α_{reg}= margin for LLRF regulation

RFQ EM Design (2)





χ_{R0}=3.3 MHz/mm (avg)

χ_R=-200 kHz/mm

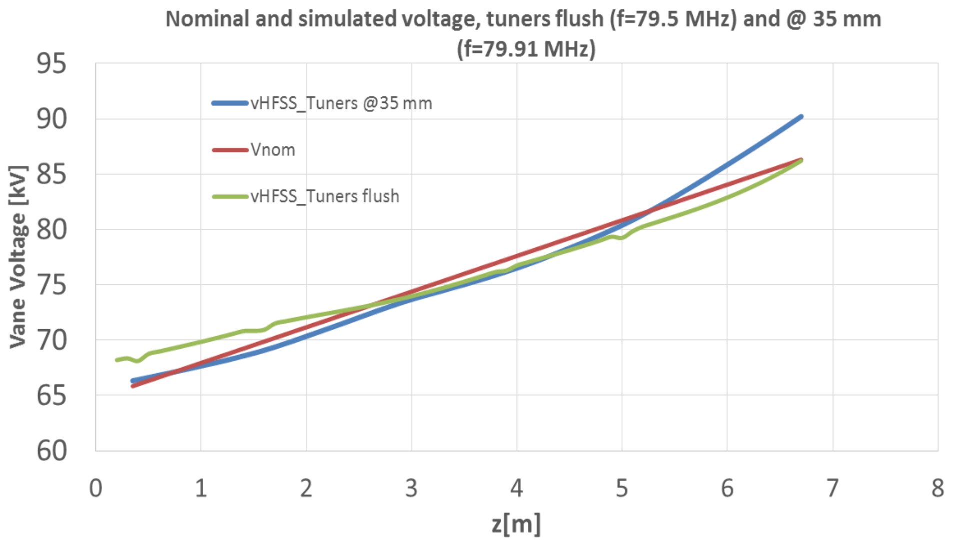
$$\delta f_0=\chi_{R0}\Delta R0+\chi_\rho\Delta\rho+\chi_R\Delta R$$

$\Delta\rho$ => construction accuracy (±(10-20) μm)
ΔR_0 => electrode positioning (errors of ± 100 μm can occur), due to alignment
ΔR => tank machining errors ((errors of ± 100 μm can occur) => R_0 errors are dominant

68 tuners (17 per quadrant), with radius a=59 mm: the average tuner sensitivity is equal to about χtun= 13 kHz/mm (all tuners), plus 3 extra tuners located at coupler position. Therefore, the tuning range can be spanned with a range of tuner depths ht=[hmin, hmax]= [-10 mm, 80 mm], corresponding to a nominal tuner position of ht0=35 mm. In this case the tuning range of 1150 kHz, corresponds to frequency range of [79.39 MHz, 80.54 MHz] and a ΔR0 range of ±0.175 mm along all the RFQ.

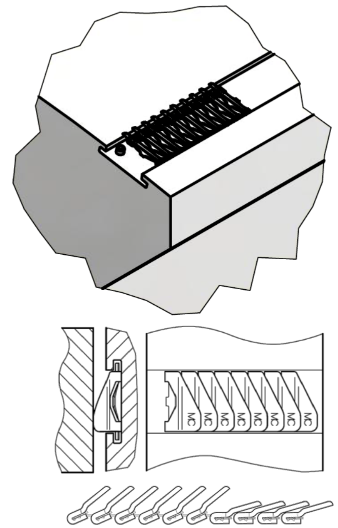
RFQ EM Design (3)

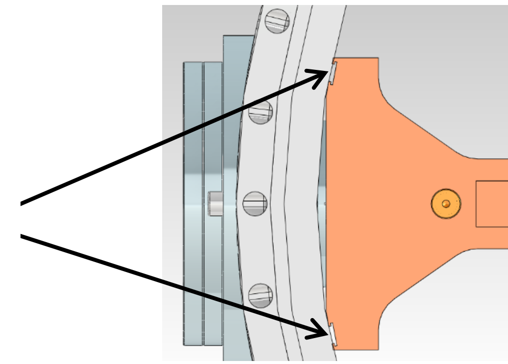
Complete 3D simulation (Ansys) incl. modulation



Maximum error ((VHFSS-Vnom)/Vnom)about 4%

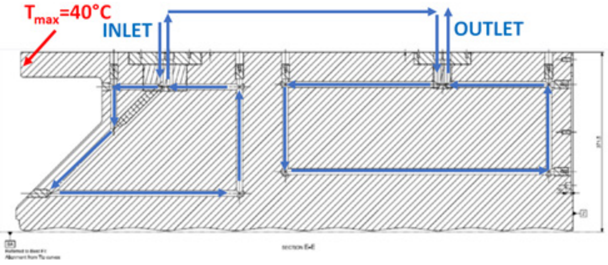
The RF joint





Multi-louver reed-shaped spring joint Contact louvers in copper, silver-plated and mounted on a stainless steel carrier., i.e. the LA-CUD/0,15 joint, by Multi-Contact®Admittable excursion=1.2mm

Electrode construction and production steps



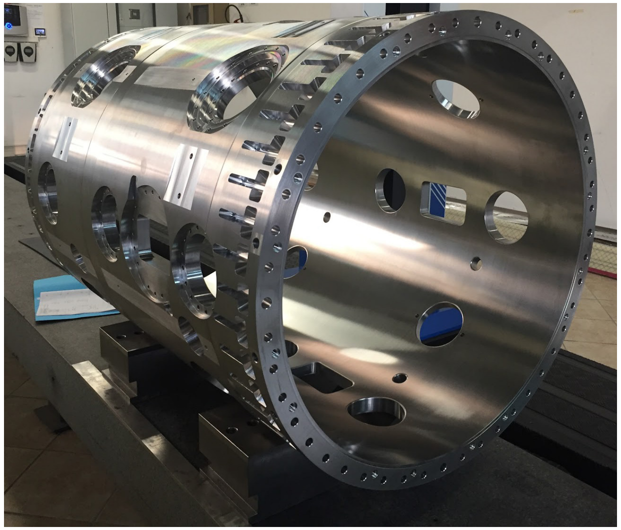
Electrode construction: CINEL STRUMENTI SCIENTIFICI S.r. l. Vigonza (PD), Italy

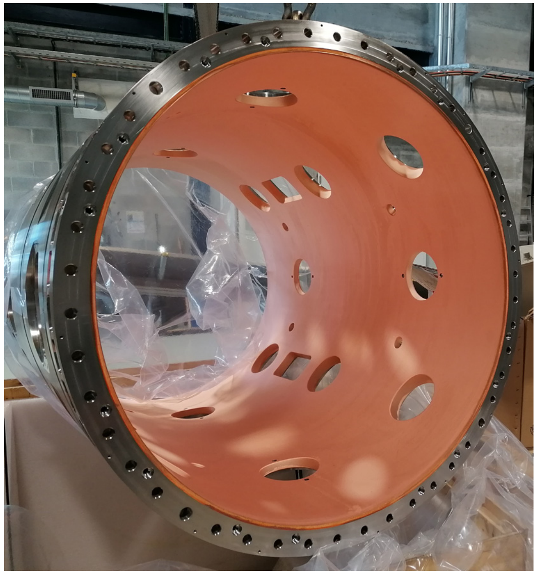
- Rough machining of the T-shaped Cu blocks
- Deep drilling
- Annealing for the stresses relaxation (3h@600°C)
- Deep holes machining and mapping with the UT and minimization of the hole deviations
- Pre-finishing of the Cu-block for the brazing
- Dimensional control of the brazing interfaces
- UHV cleaning
- Brazing
- Test: Leak and Pressure of the cooling channels, Ultra Sound of the brazed surfaces
- Finishing of the interface surfaces (support insert)
- Finishing of the modulation
- Dimensional control of the 3D-surfaces
- UHV cleaning
- Packaging and delivery

Tank construction and production steps (incl. copperplating)

Tank construction: FANTINI SUD S.p.A. Anagni (FR), Italy
(main steps)

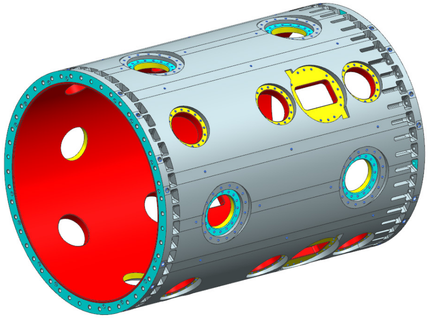
- Deep hole machining and mapping with the UT and minimization of the hole deviations
- Rough machining (e.g.: Counterbored holes for : Tuner, Support Flanges, Vacuum Grid; Slot for Bolts)
- Final machining
- UHV Cleaning
- Cu-Plating
- UHV Cleaning
- Packaging and delivery to INFN





Copper Plating : CERN

- Plating thickness 70 µm (10*δ)



Red copper plating
Cyan no be copper plating
Yellow and grey copprer plating faculatative

Assembly aspects: electrode vs tank

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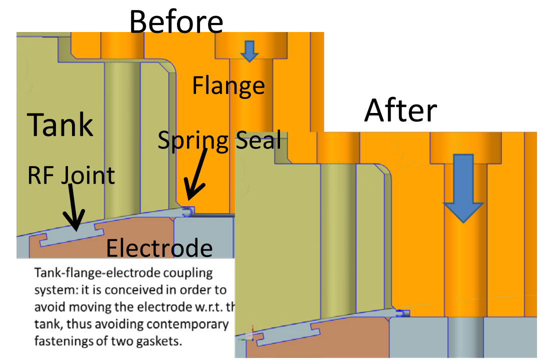
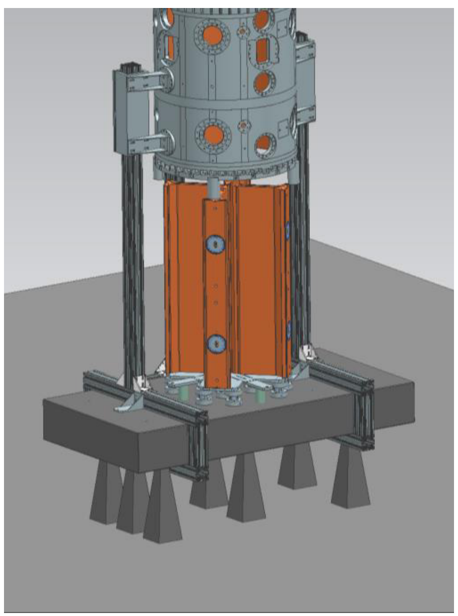
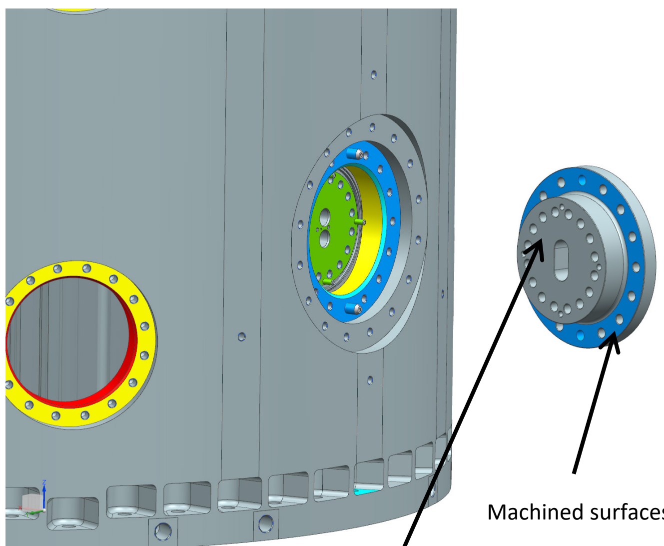
Each module (4 electrodes 1 tank) is assembled separately in a dedicated test area. The final electrode positioning (obtained by machining the interface flanges) will be confirmed with mechanical and RF measurements; then each module will be assembled in line on the support and subsequently aligned

Key ideas:

- avoid large and/or not-round gasket mounting
- decouple vacuum sealing and RF joints mounting, by avoiding simultaneous stresses on the components
- avoid dangerous stresses on the electrode, by making the assembly of one insert independent on the assembly of the other one

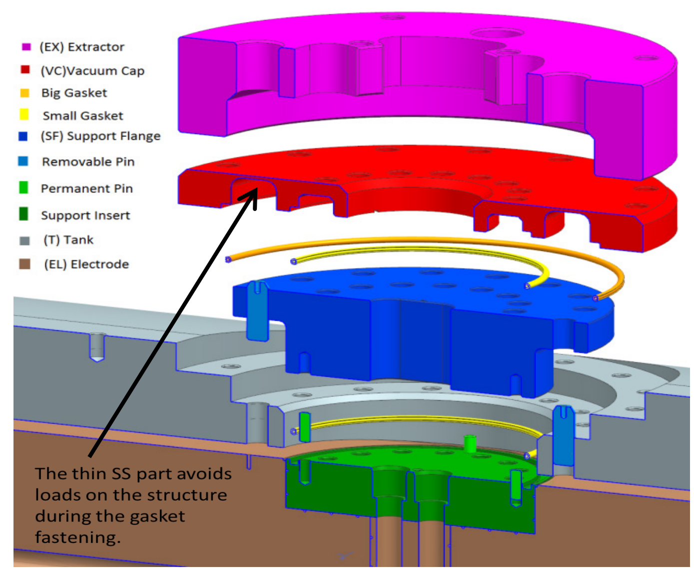






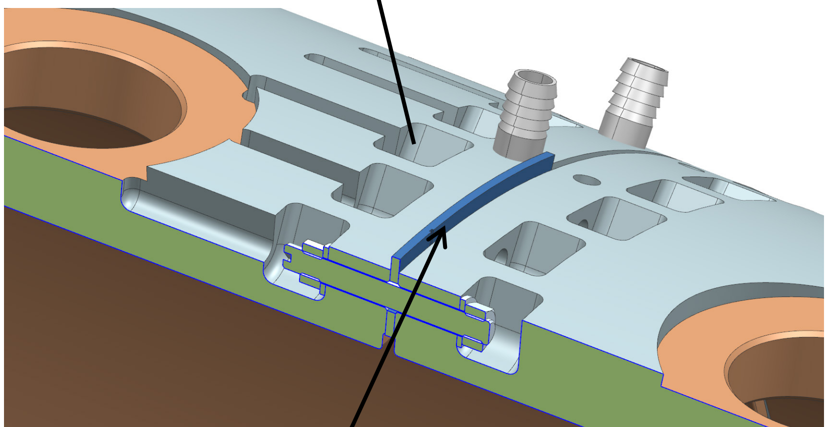
Machined surfaces

Un-machined and coupled with Support Insert



Other Assembly aspects

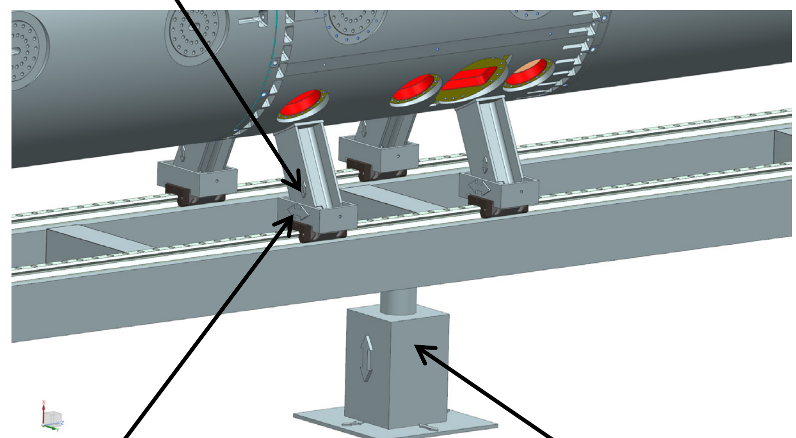
Slots for the bolt were added to increase the bending stiffness of the tank – tank interfaces.



Calibrated shims will be bolted on a front face of a tank to obtain a correct relative positioning.
Shims could also be discontinuous to permit a He-leak test on the biggest seal of the cavity. No pins are used; relative positioning is made possible by the adjustable frame tools able to support any roll, pitch, and yaw effect of the inter tank planes.

Arrows ⇔ mean adjustable displacements

Metric fine threaeded holes on pedestals (to adjust X)



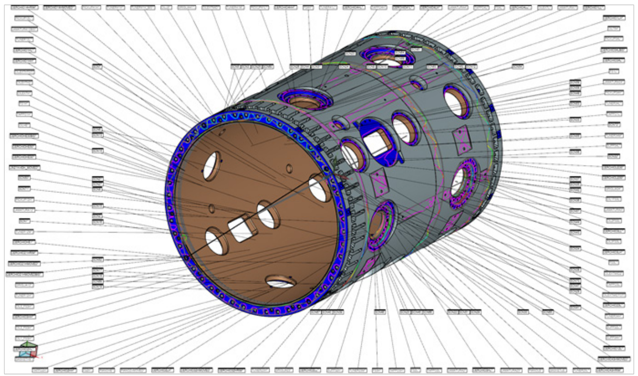
Pedestals for the RFQ positioning

Metric fine threaded holes on counter plates (to adjust Y)

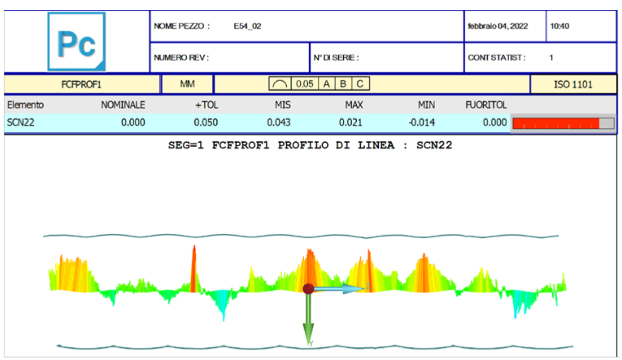
(When positioning are done, all joints can be fixed)

SPES RFQ Mechanical Measurements

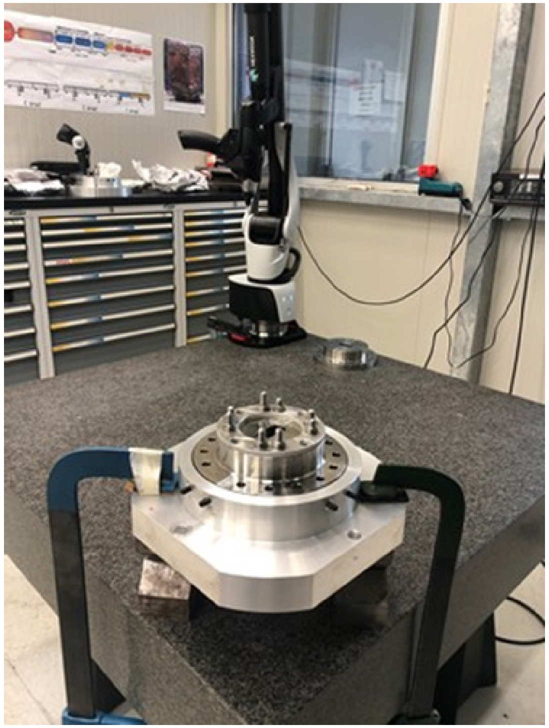
In assembly phase, tank and electrodes are completely characterized with a measuring arm, and the interface flanges are machined in order to get the correct electrode positioning in terms of pole-tip radius R_0. After final flange machining the average R_0 deviation wrt nominal value is 17 µm



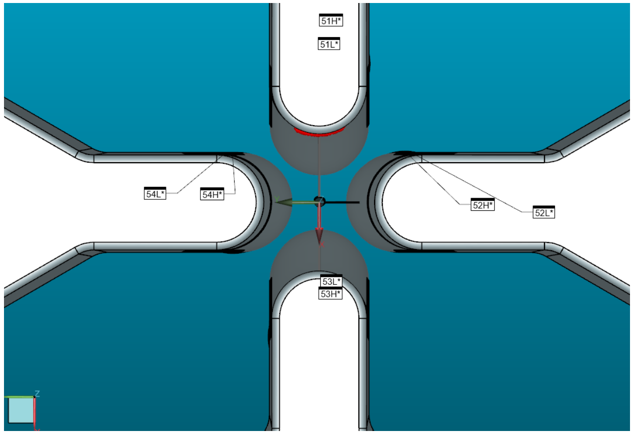
Tank characterization



Electrode characterization



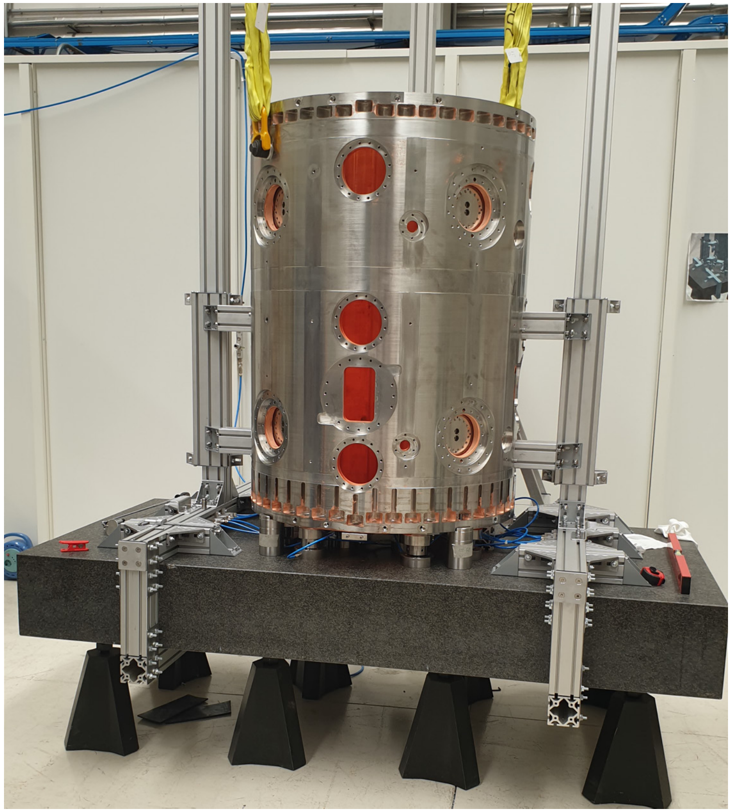
Interface flange characterization for machining



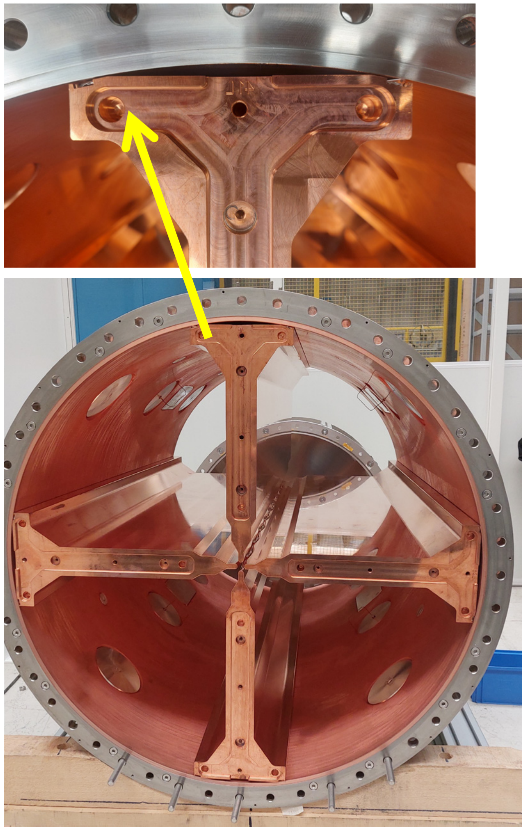
Electrode pole tip measurements after completing assembly wrt tank

SPES RFQ Module Assembly

Initial positioning of the tank vs electrodes in vertical position

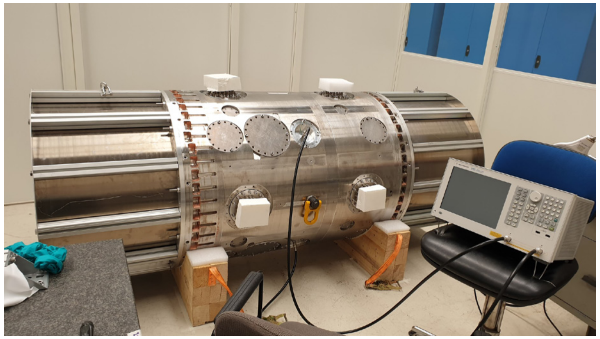


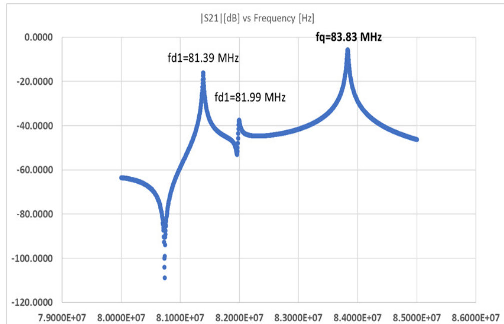
Completion of the positioning of the tank vs electrodes



Final assembly of the RFQ module in vertical position

SPES RFQ Module Assembly (2)





RFQ module connected with a pair of hollow cylinders $f_{QWG}=c_1*f_{QRFQ}+c_2$, where f_{QWG} is the frequency of the Quadrupole mode of the RFQ connected with the cylinders, while f_{QRFQ} is the frequency of the Quadrupole mode of the RFQ with perfect H boundary conditions at both ends.

After successful leak test (maximum detected leak is about $3 \cdot 10^{-11}$ mbar l/s) the RFQ module was installed on support in Area 2 (final location)

Meas no.	f_{d1}	f_{d2}	$\mathbf{f_q}$	$\mathbf{f_{qsim}}$	$\mathbf{f_q - f_{qsim}}$	$\mathbf{\Delta R_0}$**[µm]**
meas1	81.39	81.99	**83.83**	**83.802**	**0.028**	**8**
meas2	82.05	82.14	**83.82**	**83.802**	**0.018**	**5**
meas3	81.98	82.23	**83.81**	**83.802**	**0.008**	**2**

Meas 1:ruler checked alignment, no alignment pins, no machined flanges, no seals,
Meas 2: measuring arm checked alignment, alignment pins with 0.1 mm clearance, no seals,
Meas 3: measuring arm checked alignment, alignment pins with <0.05mm clearance, seals installed
Although the hollow cylinders are not optimized for Q, a Q0 value of 8415 (70% of simulated value for this particular configuration) was obtained.

Conclusions

RFQ objectives (short term)

- One RFQ module (module #5), completely assembled and characterized, is installed on the support (see following slides)
- Other two modules (#4 and #3) are on their way for assembly and characterization: in particular, for module #4 the support flanges are being machined, while for module #3, the gasket seats are being prepared
- after module #4 testing, the assembly Module#4-Module#5 on the support (with subsequent alignment) will be possible
- All remaining tanks (#1, #2 and #6) completed copper-plating at CERN, All those tanks will be shipped at once at LNL in within the end of July
- The tender for the 200 kW Solid State Amplifier tender is completed. Contract signing by Sept. 2022. Amplifier arrival by August 2023
- Module Assembly completion by November 2022
- Low Power RF measurements (tuning) by February 2023.

SPES objectives (short term)

- Authorization to operate SPES phase alfa: end 2022
- Cyclotron beam on TIS@ISOL bunker: 2023 Production of L.E. (40 keV) radioactive ion beams: 2023
- Equipment of A13 exp. hall: end 2023, Experiments with L.E. radioactive ion beams: end 2023

Time expectation (Post-Acceleration)

- Authorization to operate SPES phase beta: end 2023 ADIGE and RFQ operative: 2024
- Post acceleration operation w/o HRMS: 2024
- Installation of HRMS: 2025 Post acceleration operation with HRMS: end 2025