SPES RFQ

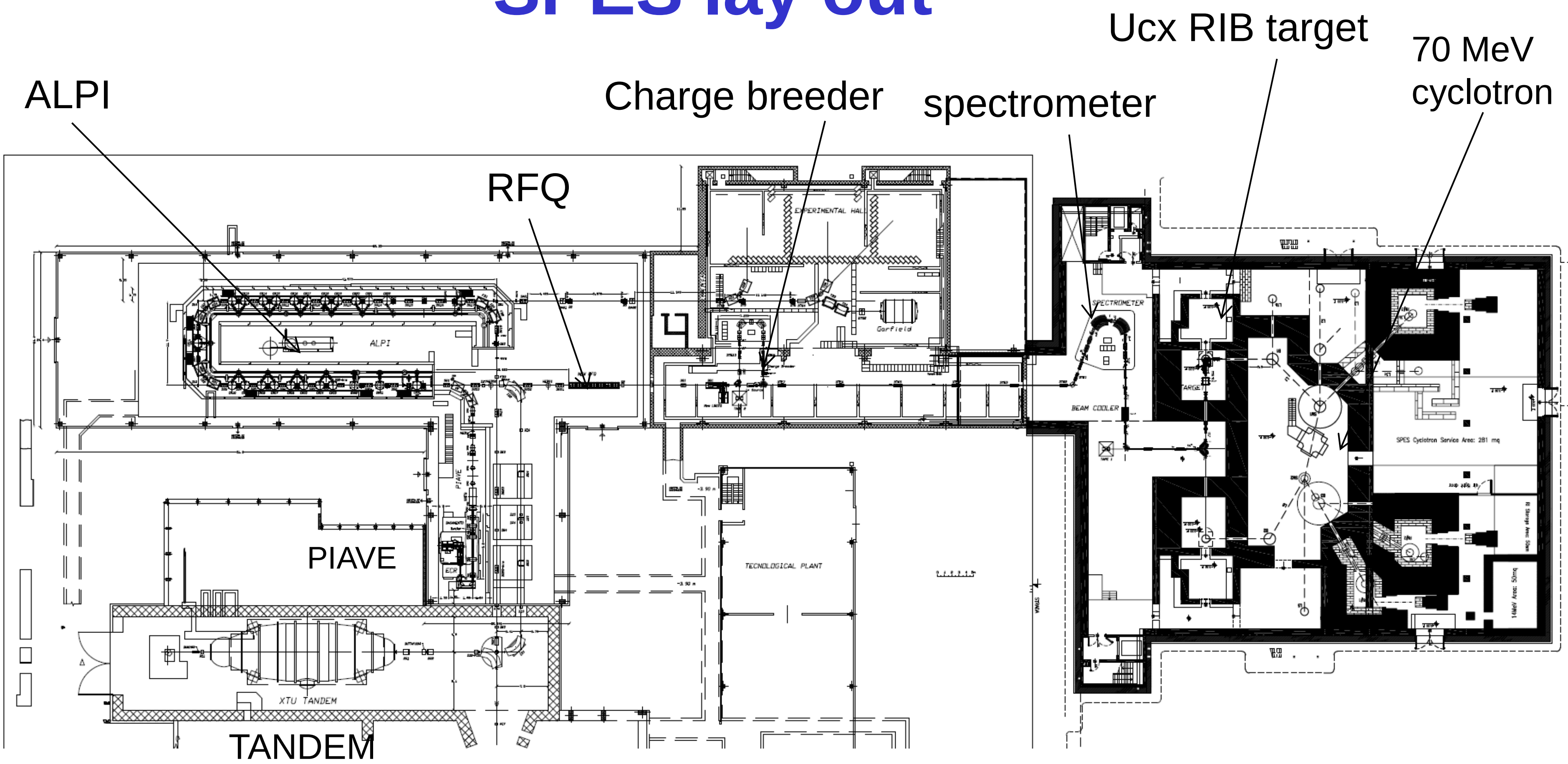
Main contributors to preliminary design

A.Pisent, M. Comunian (Beam Dynamics), A. Palmieri (RF design and thermo-mechanical simulations, RF contacts selection), C Roncolato (3d drawings, material specs, vacuum and brazing)

Thanks to useful discussions and participation to meetings: A. Pepato, L. Ferrari, M. Rossignoli, A.Facco, G. Bisoffi, F. Grespan, E. Fagotti, R. Baruzzo (Cinel s.r.l.)

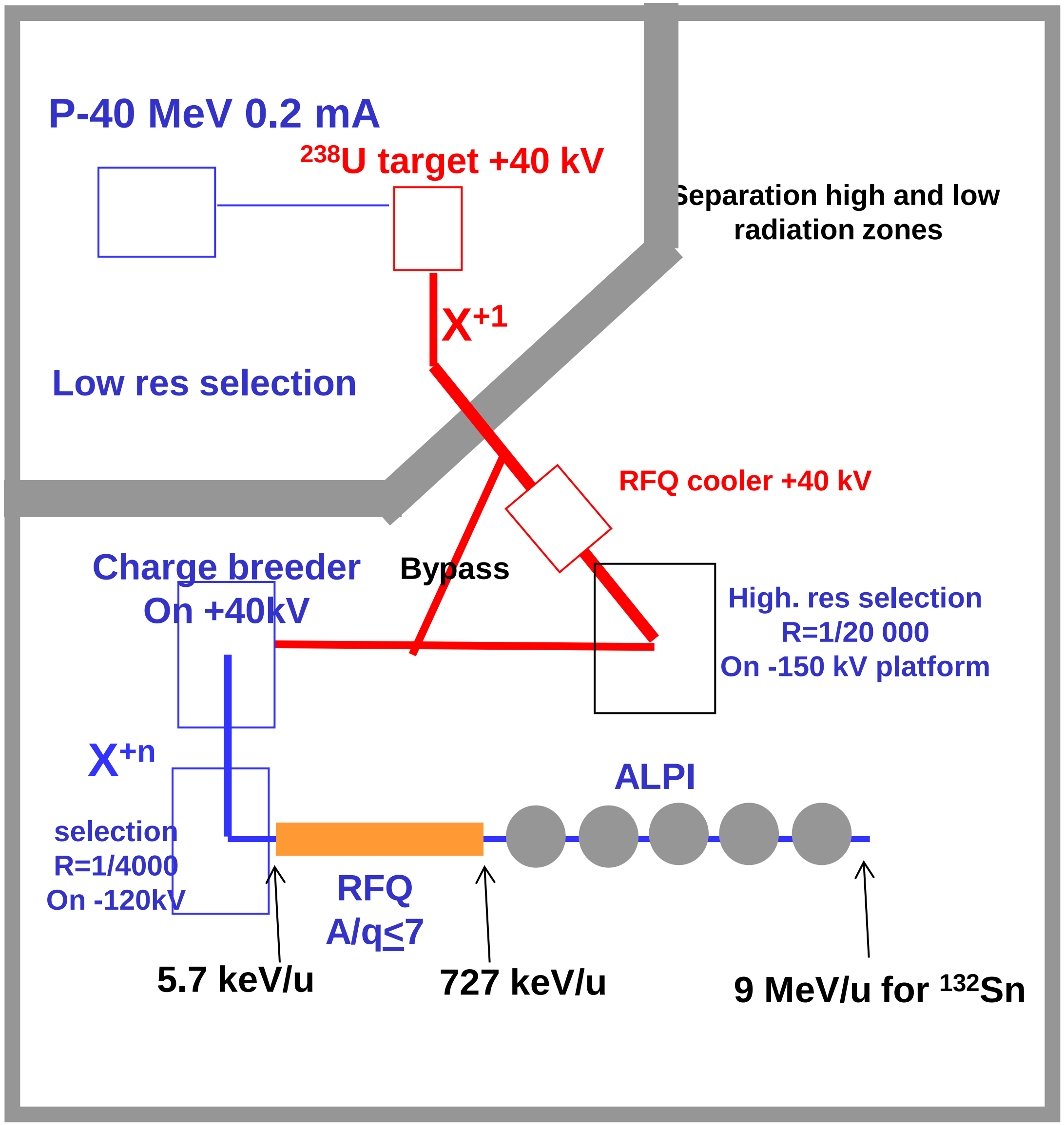
The working group for the engineering design and realization is not yet formally set (but competences from IFMIF experience are available).

SPES lay out

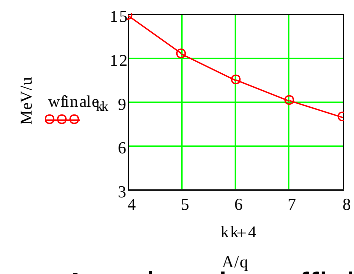


- New lay out: for A/q=7 the extraction voltage is 40 kV, after the breeder the beam is accelerated by a new 80 MHz cw RFQ, internal bunching
- Low longitudinal emittance and larger final energy for better injection into ALPI
- Maximum possible current 100 uA

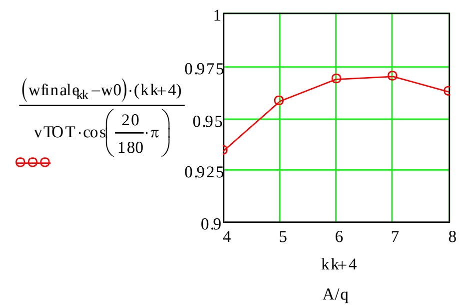
Functional scheme for SPES post acceleration



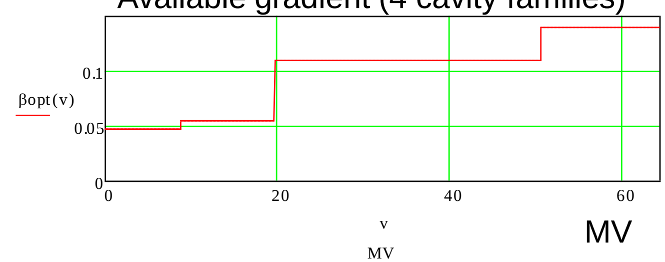
Final energy



Acceleration efficiency



Available gradient (4 cavity families)



vTOT = 64.4112

History

- 1**988-1994** development of the low intensity codes for CERN Linac3 (M. Weiss, GD Amendola, M. Comunian thesis, AP)
- **2010** decision of the straight beam line design with a new normal conducting RFQ
- **End 2011** first mechanics idea for the four vane RFQ, evolution of SPIRAL2 RFQ.
- **Jan 2012** Preparation of a feasibility study for an offer to MSU of an RFQ produced by Italian Industry
- **Sept 2012** Linac Conference in Tel Aviv definition of the Physical Design
- **March 2012** decision to built a test stand for IFMIF RFQ at LNL. The high power source and the infrastructures will be used for SPES RFQ.
- **2013** preliminary design (thermo-mechanics and mechanics)
- **End 2013** Ordered components for the prototype.

Comparison PIAVE-new RFQ

Parameter [units]	PIAVE SRFQ	NEW RFQ
A/q	8.5	7.0
Input Tr. Norm. RMS emittance [mmmrad]	0.071	0.1
Output Energy [keV/u]	587 (β=0.0355)	727 (β=0.0395)
Output RMS Long. emittance [degkeV/u]	4.5	4.8
Output 90% Long. emittance [degkeV/u]	29.3	26
Transmission [%]	65	95
QWR 0.047 TTF	0.85	0.95
QWR 0047 DY' [mrad]	-0.48	-0.32
Power consumption [kW]	0.03 [4 deg K] **30**	100 kW RF **250**
Intervane voltage	148-280	64-86
Length [m]	1.38+0.75	7
Max surface field [MV/m]	25	1.8 Ekp 18.9
Stored Energy [J]	1.8+3.5	3

SPES RFQ

Table 2: RFQ design parameters

Parameter (units)	Design
Inter-vane voltage V (kV, A/q=7)	63.8 – 85.84
Vane length L (m)	6.95
Average radius R_0 (mm)	5.33 – 6.788
Vane radius ρ to average radius ratio	0.76
Modulation factor m	1.0 – 3.18
Min small aperture a (mm)	2.45
Total number of cells	321
Synchronous phase (deg.)	-90 – -20
Focusing strength B	4.7 – 4
Peak field (Kilpatrick units)	1.74
Transmission (%)	95
Input Tr. RMS emittance (mmmrad)	0.1
Output Long. RMS emittance (mmmrad) / (keVns/u)/(keVdeg/u)	0.055 / 0.15 / 4.35

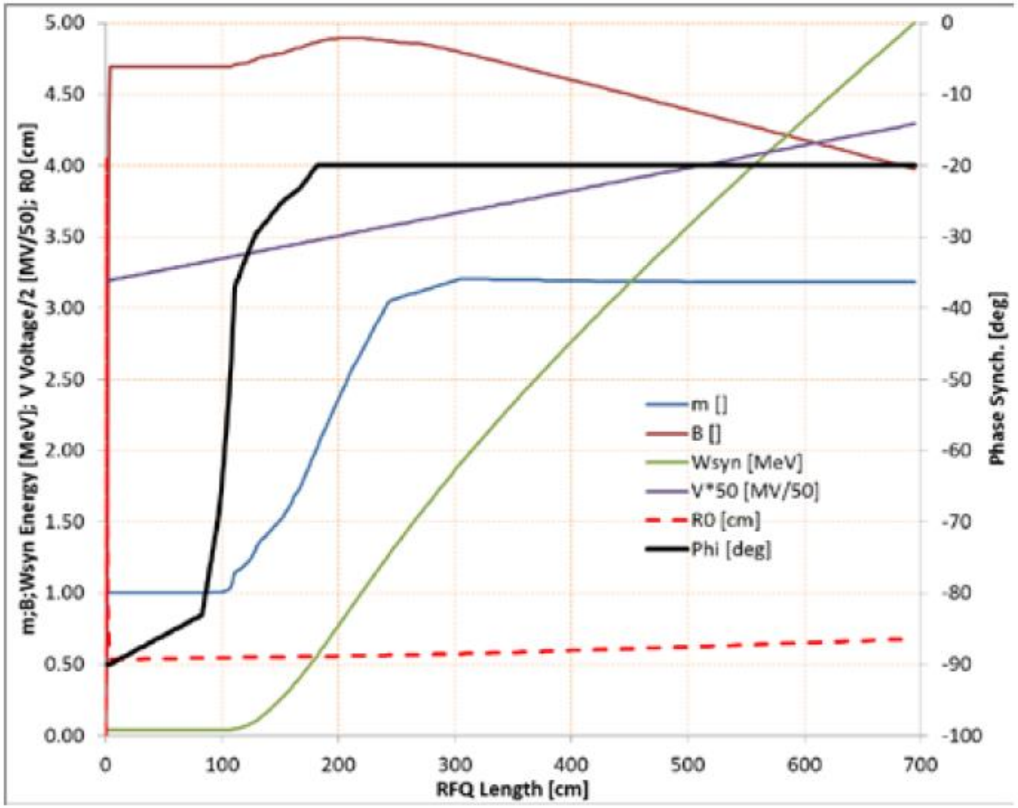
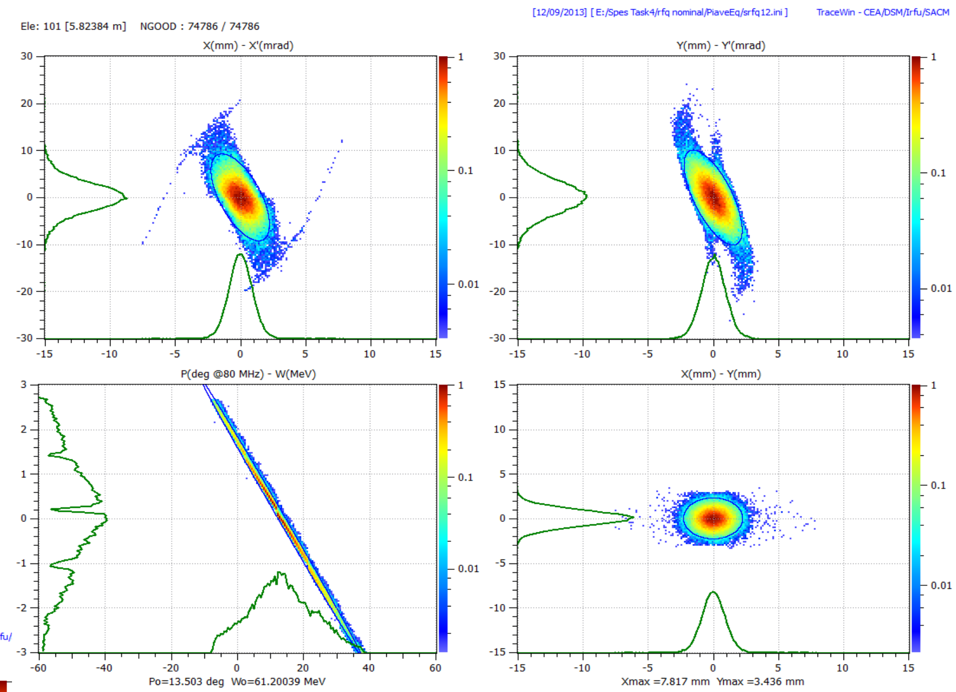


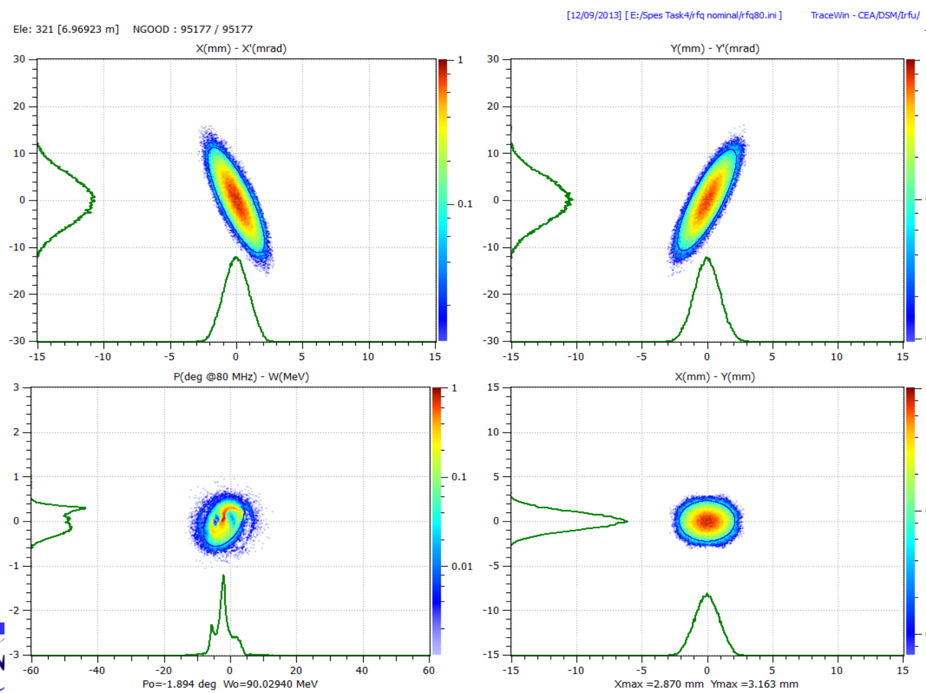
Figure 1: The main RFQ parameters vs. length.

BEAM DYNAMICS

Comparison PIAVE- SPES RFQ: input tr. Gaussian 3σ

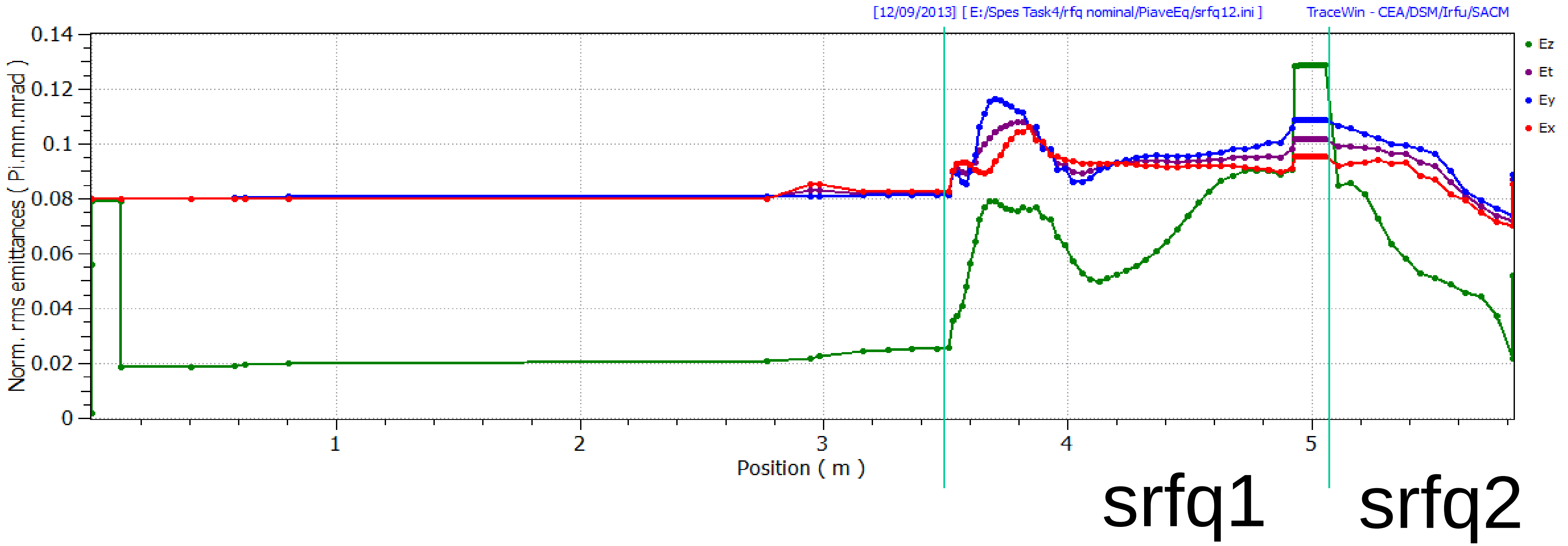
PIAVE:
Emit T in=0.08 mmmrad
W=587 keV/u
Tr=75%
EmitL rms=4.5 degkeV/u
EmitL 95%=29.3 degkeV/u

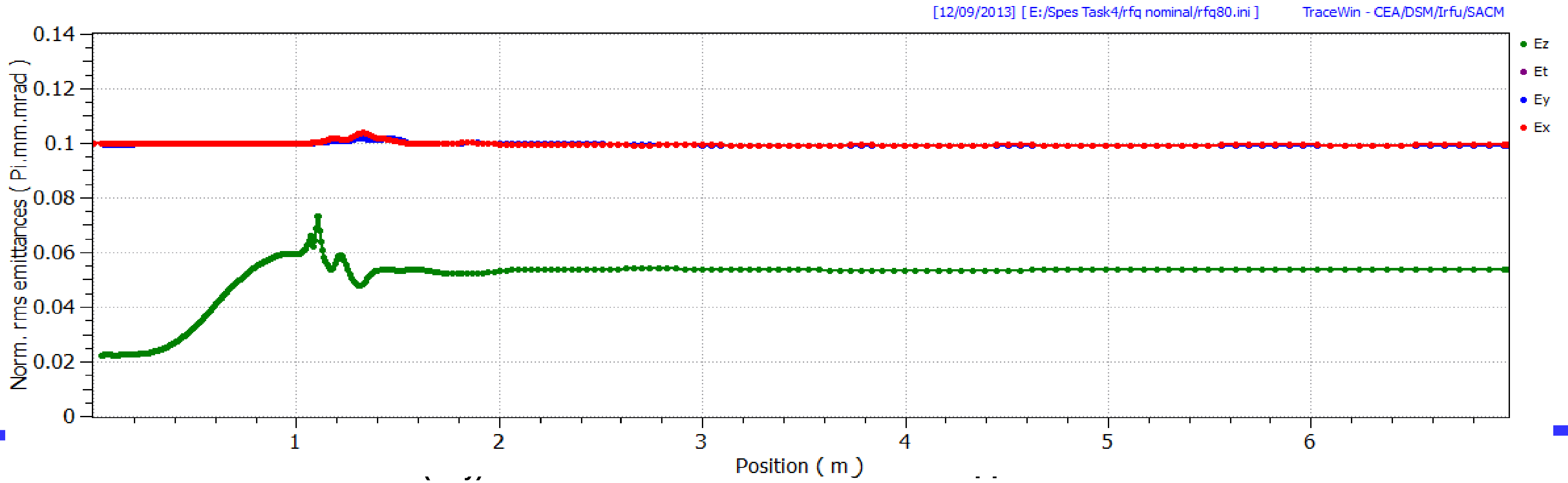




SPES-RFQ:
Emit T in=0.1 mmmrad
W= 727 keV/u
Tr=95%
EmitL rms=4.8 degkeV/u
EmitL 95%=26 degkeV/u

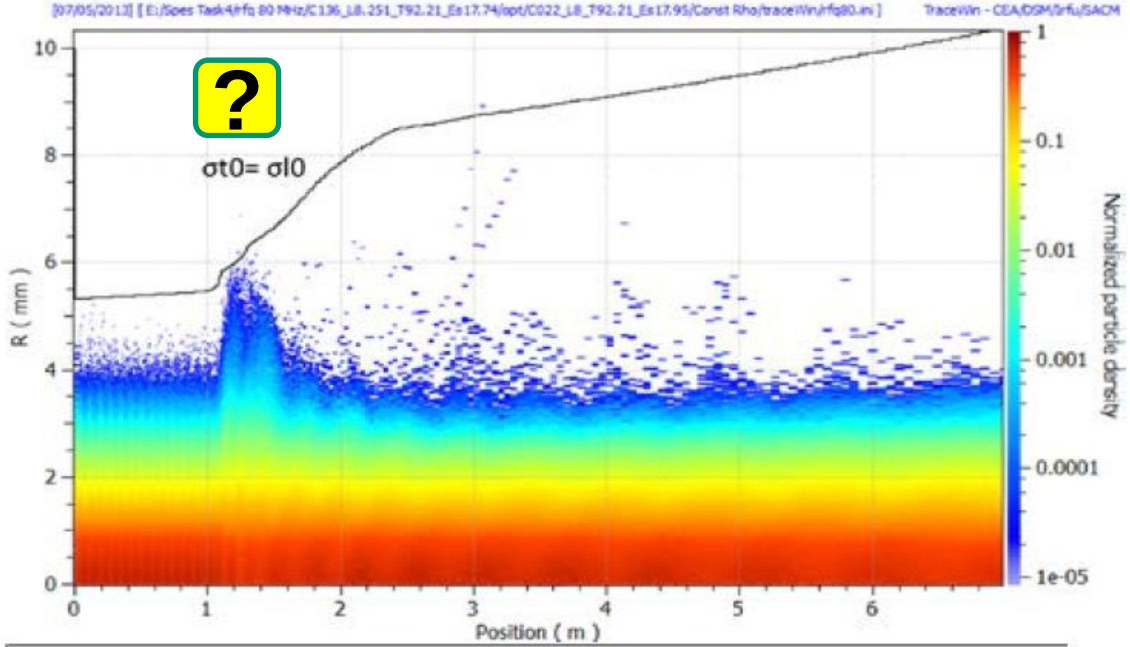
Comparison PIAVE – SPES RFQ

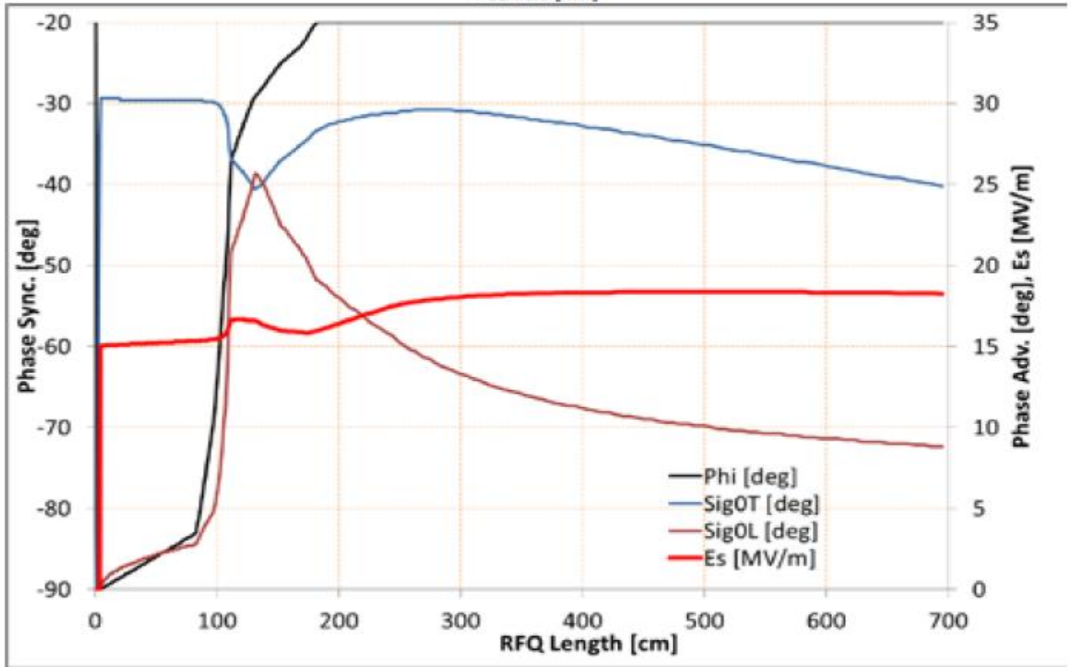




INFN

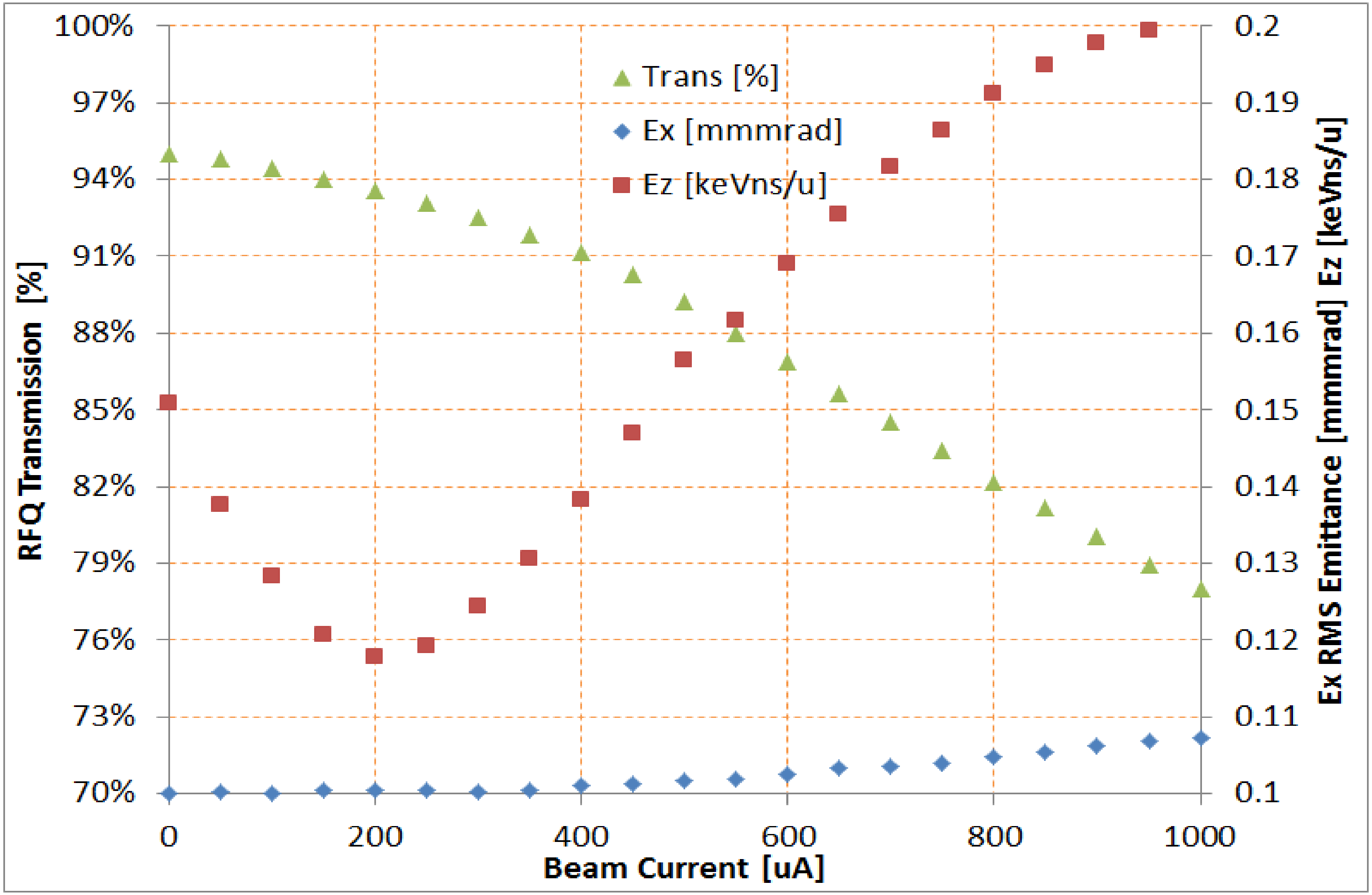
Design parameters





Input distribution 6σ gaussian

Performances



RFQ transmission and emittance as function of beam current

Performances

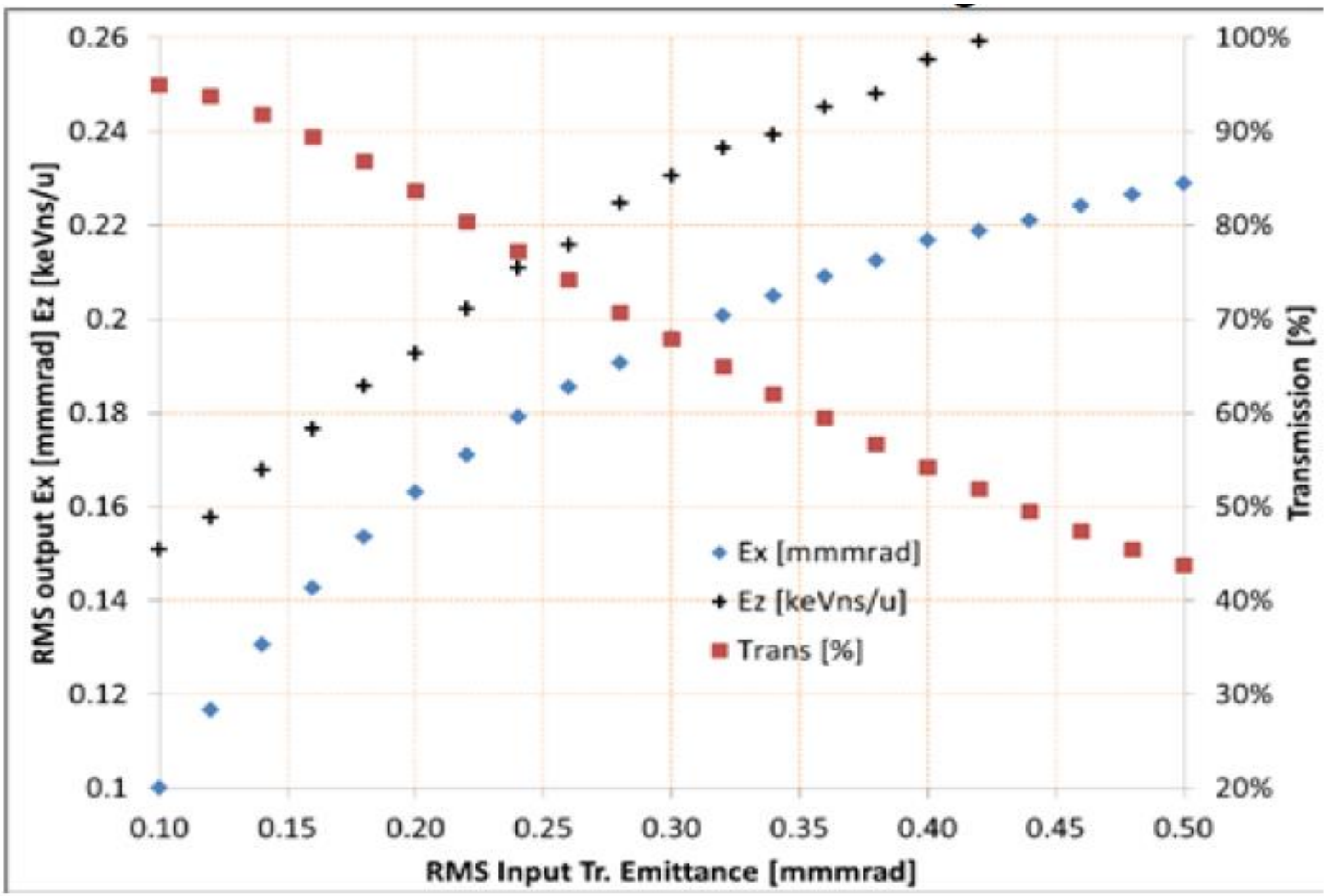


Figure 3: Output emittance as function of input emittance.

Input distribution 6σ gaussian

Performances

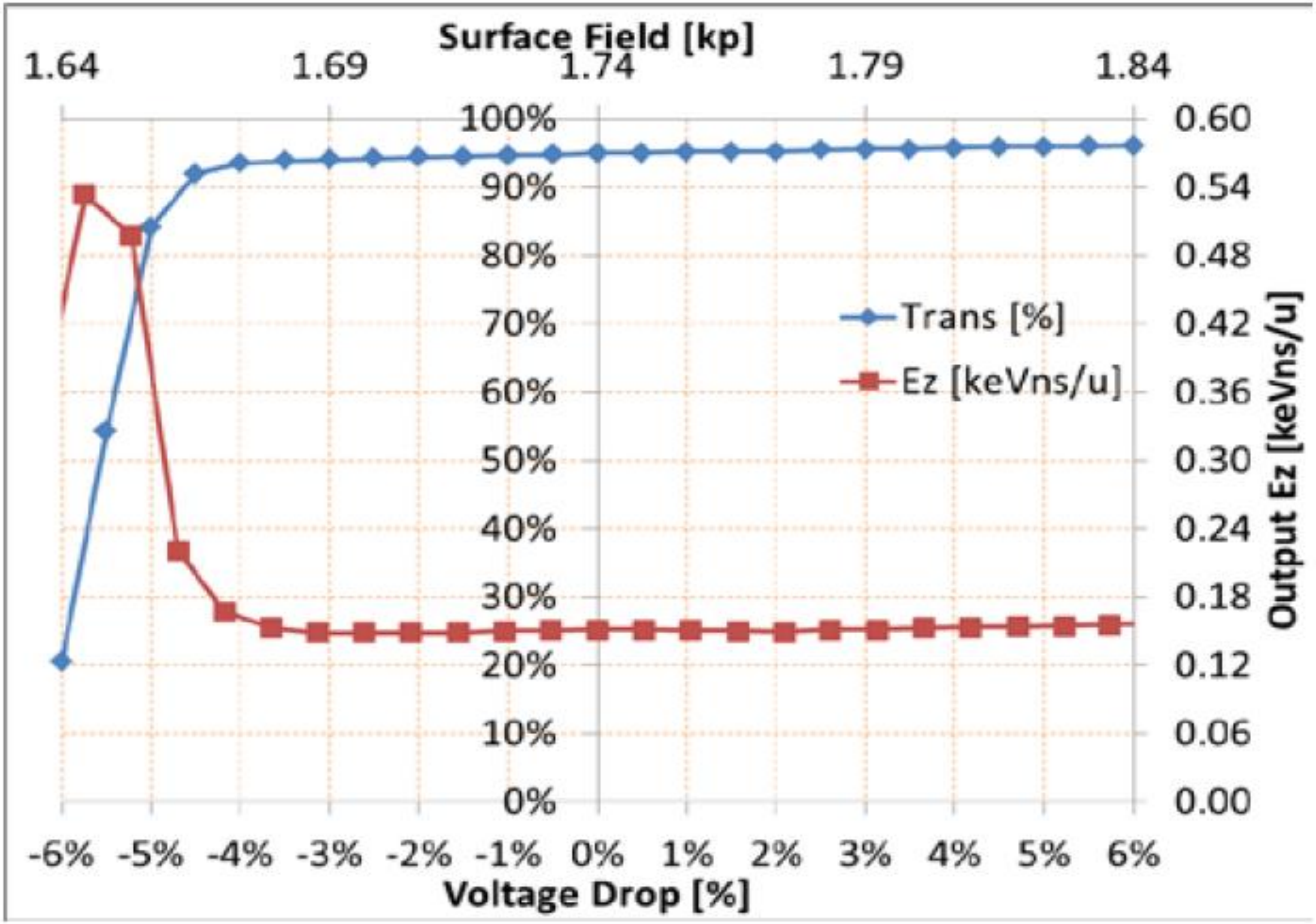
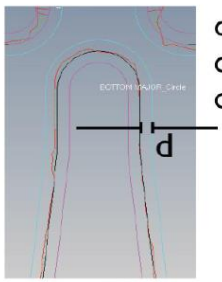


Figure 4: Transmission as function of RFQ voltage.

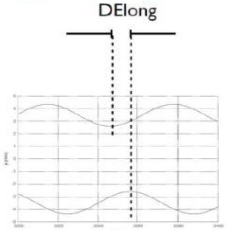
Possible errors study

RFQ errors

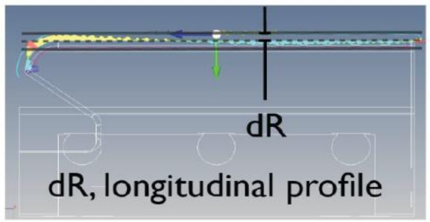
ERROR_RFQ_CEL_NCPL_STAT *N, r(0/1/2), dR(mm), d (mm), E(%),φ(°), TEpe(mm), TEpa(mm), DEpe(mm), DEpa(mm), DELong(mm) TSVerti(mm), TSHori(mm), DSVerti(mm), DSHori(mm), DSLong(m)*



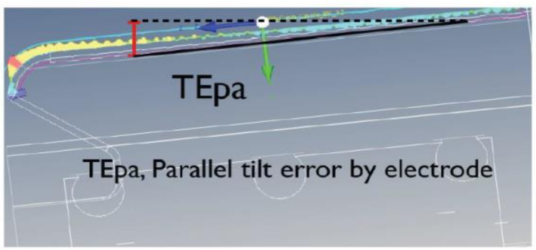
d, transverse curvature of the electrode



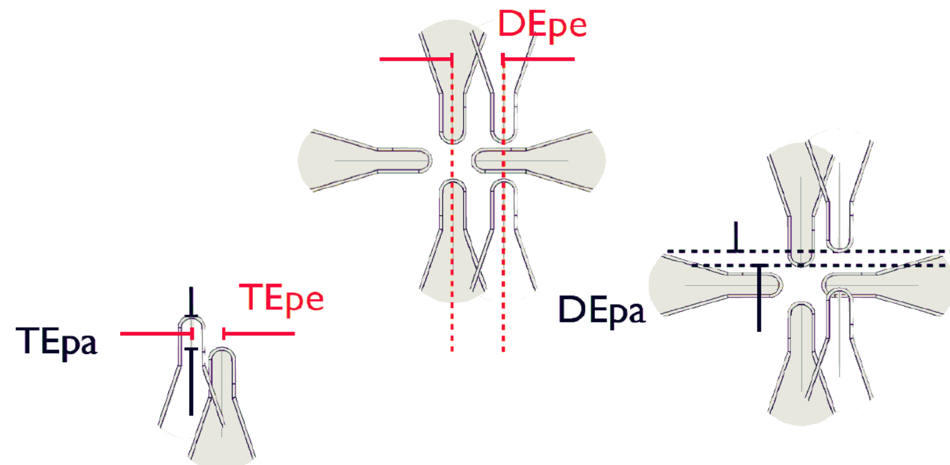
DElong, Longitudinal displacement error by electrode



dR, longitudinal profile



TEpa, Parallel tilt error by electrode

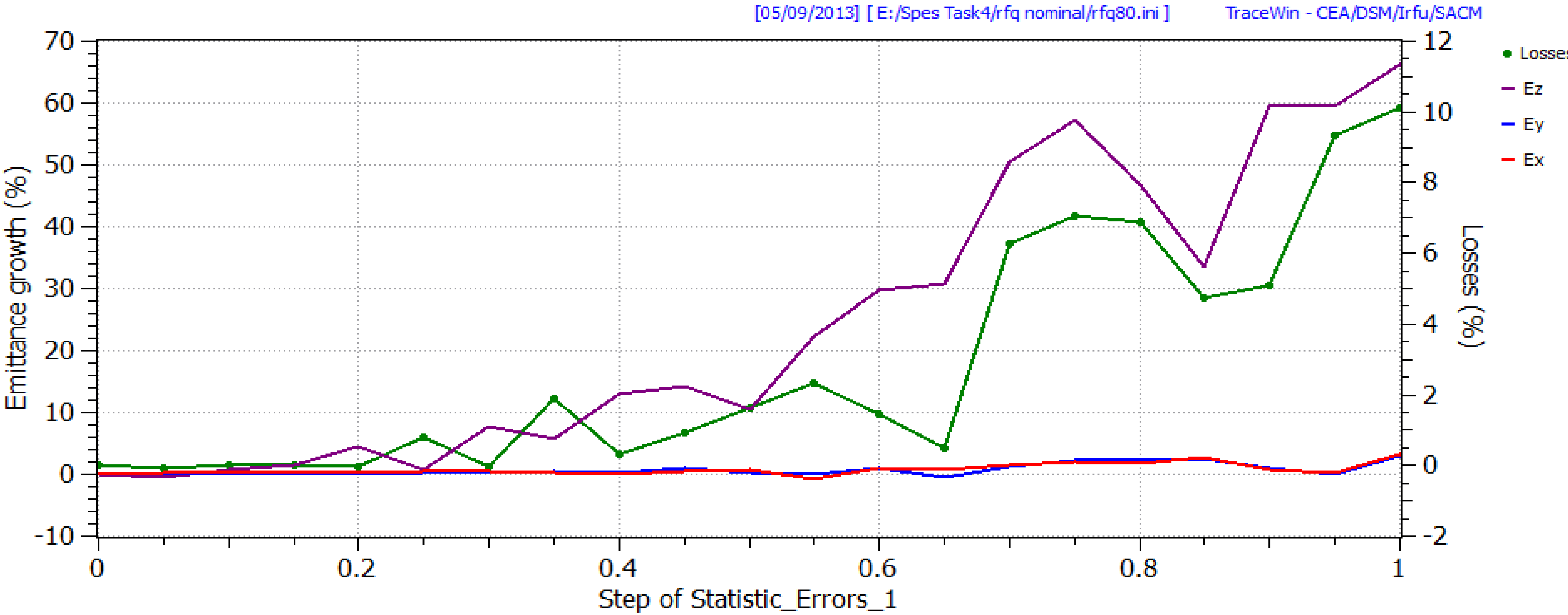


TEpa, Parallel tilt error by electrode
TEpe, Perpendicular tilt error by electrode
DEpa, Parallel displacement error by electrode
DEpe, Perpendicular displacement error by electrode

These errors are applied in the N elements following this command, excepted, if a new error command appears. The error distribution depends on the *r* parameter:

- *r = 0*, the errors are constant and equal to each value of the command line (only envelope mode).
- *r = 1*, the errors are uniformly distributed (±); each value of the command line is the maximum range error.
- *r = 2*, the errors are Gaussian distribute; each value of the command line is rms value of the distribution.

Initial error study on dR

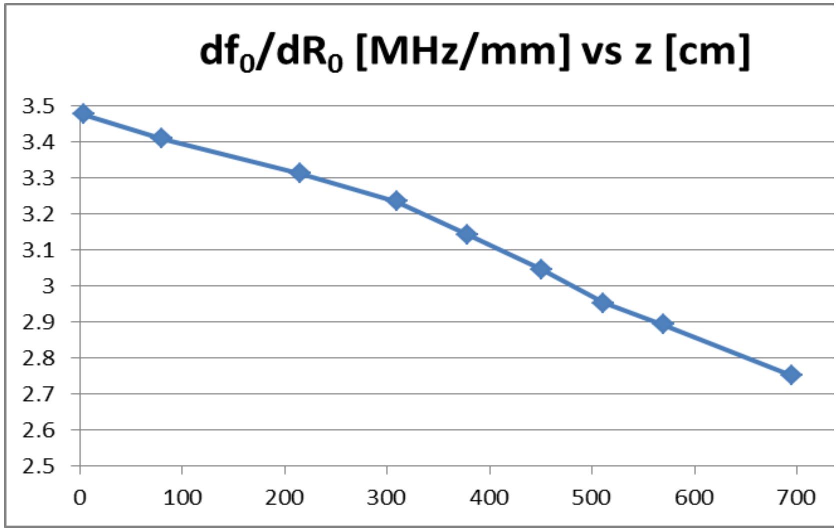


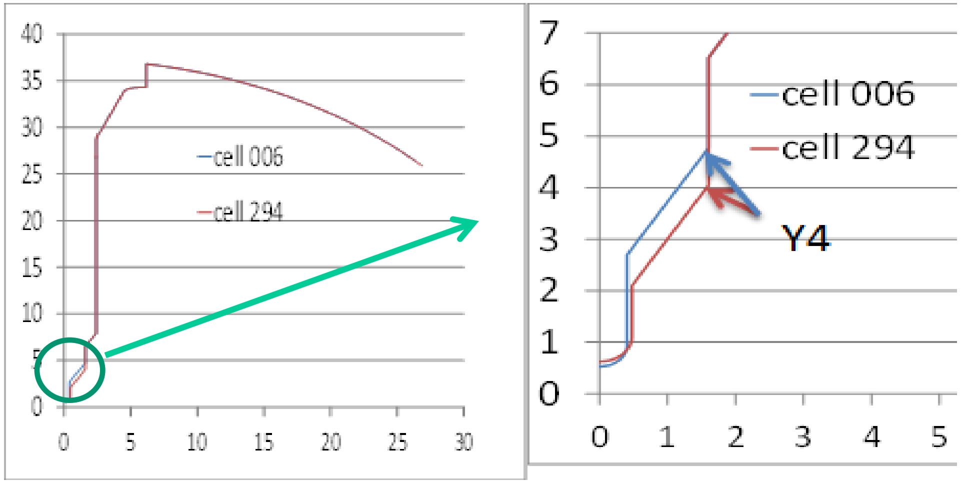
Step 1==+/- 0.2 mm; statistics on 10 runs with uniform error distribution;

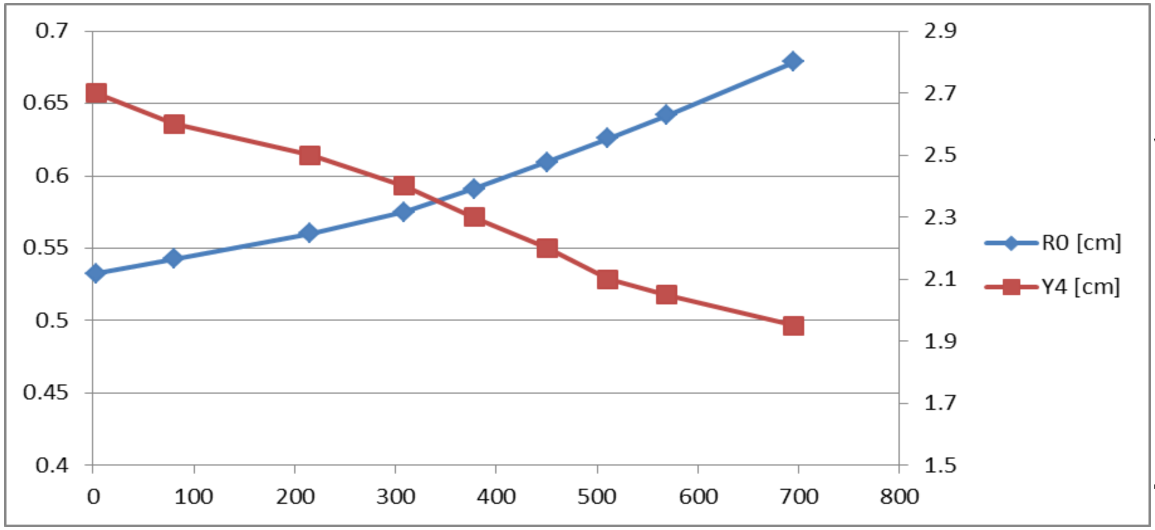
Gaussian input beam distribution.

RF CAVITY

RF Study of SPES RFQ







In order to compensate the f_0 variations due to R_0 variations the Y4 dimension is varied at each RFQ section, in order to have a constant value of f_0 throughout the RFQ. The linear voltage profile will be implemented by simply shaping the vane undercuts at the RFQ ends. **The electrode thickness equals 48 mm and the tank inner radius equals 375 mm.**

RF Study (2): parameters

Shunt Impedance times length R_{sh} (SF)	538-552	kΩ·m
Q_0 (SF)	20000	
Copper power P_0 (SF)	74	kW
Stored Energy U	3.0	J
Max H field (2D)	1633	A/m
Max Power Density (2D)	0.31	W/cm^2
Dissipated power $P_d=\alpha_{3D}* P_0$ (α_{3D} = 1.3, margin for 3D losses)	96	kW
RF power $P_{RF}=\alpha_{RF}* P_d$ (α_{RF} = 1.2, margin for RF system)	115	kW
f_0	79.5	MHz

The difference between the operating frequency f=80 MHz and the TE_{21} cut-off frequency f_0=79.5 MHz defines the tuning range, [-500 kHz, 500 kHz] in our case: in this study the usage of 4 tuners per quadrant and per meter of 89 mm diameter (same as IFMIF). This corresponds to [0 cm, 10 cm] tuning range.

RF Study (3): The RF amplifier

The RF power source is a tetrode amplifier based on the TH781 200 kW tube. This amplifier is, de facto, the same installed in the 3rd Exp. Hall for the High Power Tests of the 175 MHz IFMIF RFQ (DB Elettronica) and such amplifier is undergoing the comissioning phase. In order to allow 80 MHz operation, only the cavity and the 12 kW driver amplifier will need to be refurbished, while the AC/DC converter, the tube and the controls will remain unchanged.

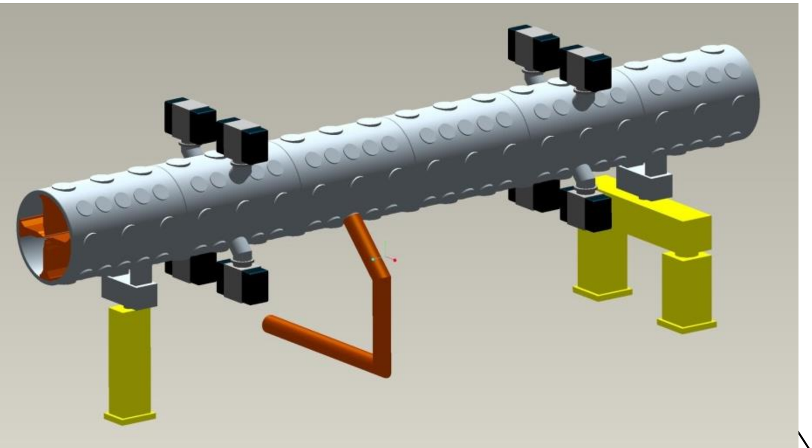
Parameter	Value	Unit	comment
Modes of operation	CW and pulsed		
Max Output forward power (CW)	200	kW	CW
Linearity	±1	dB	
Babdwidth (1 dB)	±1	MHz	
Harmonics	<-30	dBc	
Spurious	<-60	dBc	
Cooling type	Deionized water, forced air		
Power regulation	0-100 %		
Anode voltage	13	kV	
Input power	0	dBm	
Efficiency (RF power/Grid power)	>	50%	

Final stage 220 kW
(under test now)

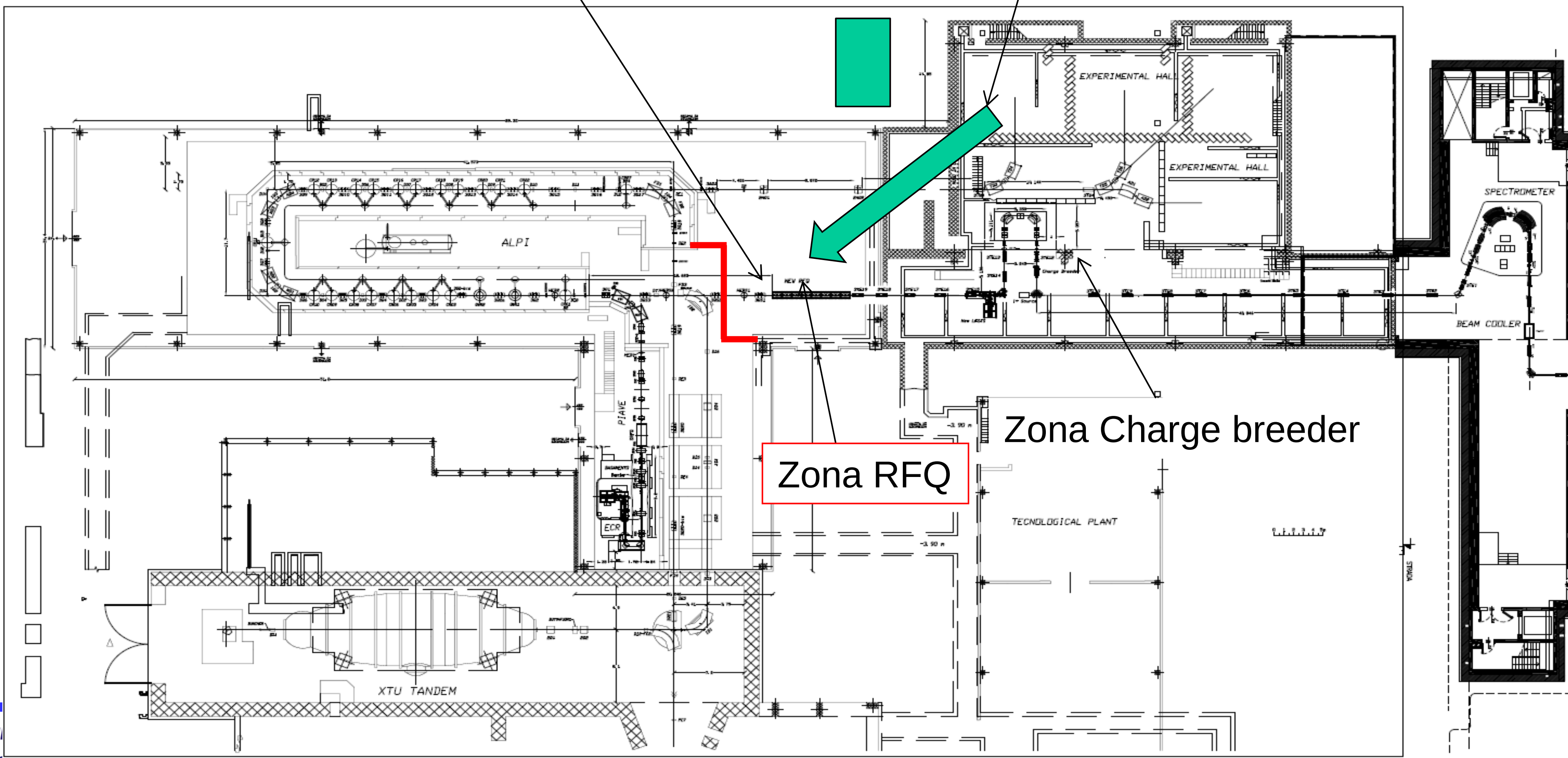
Linear Power Supply
Nominal Output: 12 KV DC 28 A (336 KVA)
Maximum Output: 19 KV DC 37 A (703 KVA)

Two solid state stages: Driver & IPA
Driver output power: 20 W
IPA output power: 4 X 3 kW = 12 KW
IPA maximum output power: 16 KW

location



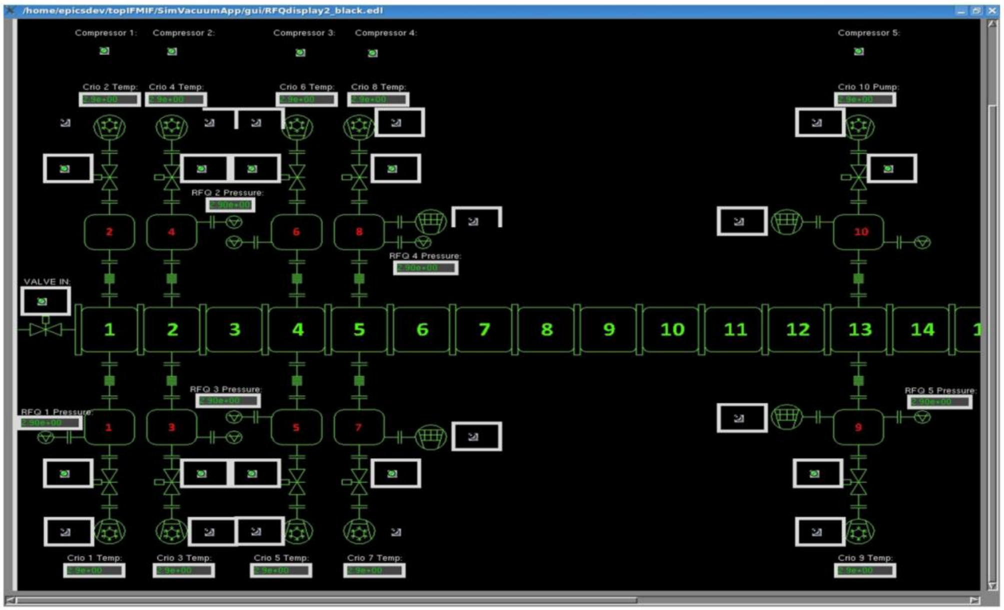
RF system and cooling system

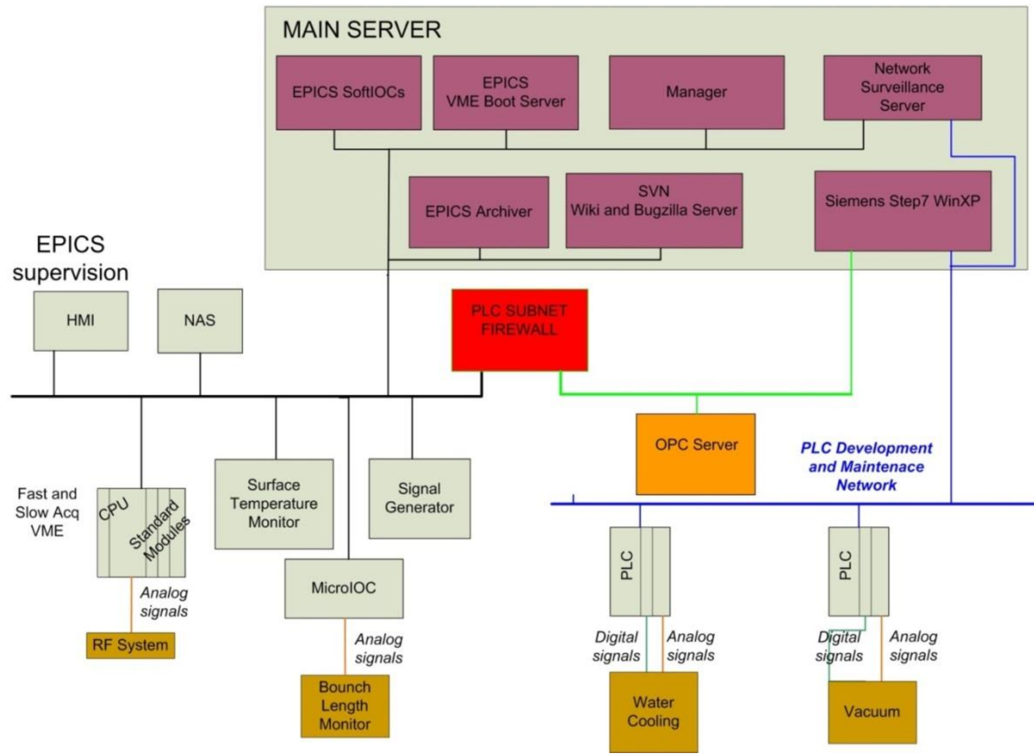


Control system

- LLRF based on the new 80 MHz digital controller (D. Bortolato, M. Bellato)
- Vacuum, cooling, RF signals mutuated from IFMIF RFQ architecture PLC + EPICs (M. Giacchini, L Antoniazzi, M. Montis)

EPICS Vacuum Control System (Simulation)





Preliminary Thermo-Structural Calculations

Goals

- Preliminary determination of the channel number, dimension and position, as well as the inlet water temperatures, in order to
  1. Remove the RF heat load
  2. Keep the RF frequency constant during operation by compensating the RF heat load induced deformation
  3. Determinare the frequency sensitivities as a fanction of water temperature and duty cycle

Tool

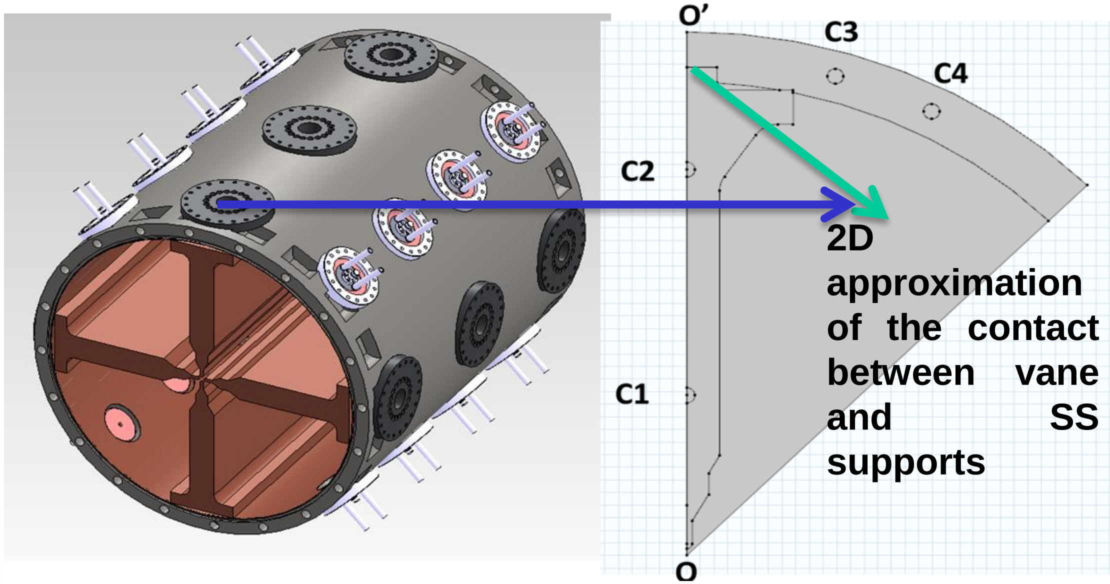
2D joint RF and thermo-structural simulations with COMSOL v. 4.3

Case studies

- initial (R_0=5.327 mm, V=63.9 kV) and final (R_0=6.788 mm, V=85.8 kV) sections.

Material used

Copper for the electrode, LN 304 Steel for the tank.



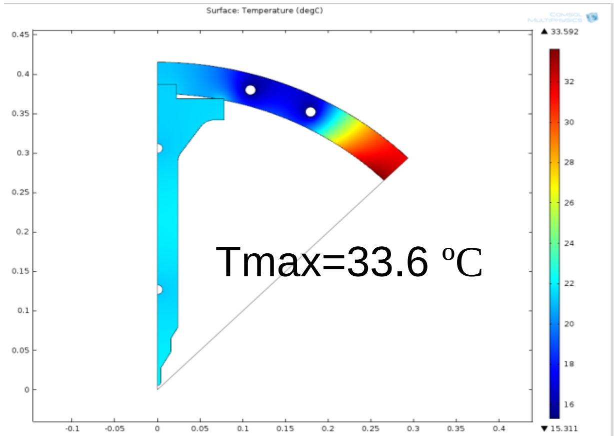
Main assumptions

All the channels are set at 6 mm radius and 10000 W/(m2*K) heat exch. Coeff., and v=3m/s water speed. The positions of the channels C1 and C32 are always the same, while the positions of C3 and C4 (defined by thei angles $\alpha 3$ and $\alpha 4$ with the OO' axis) are varied according to the sections

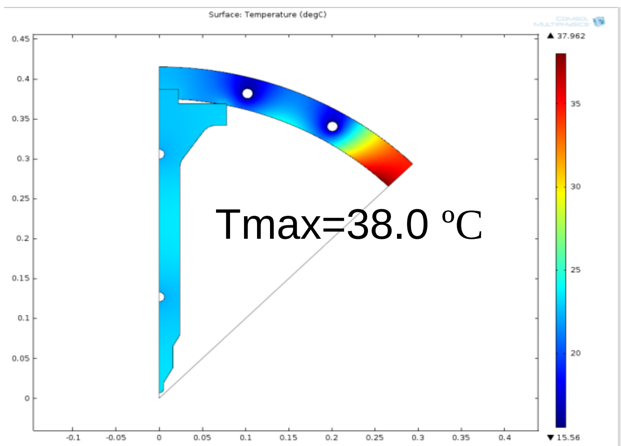
The inlet water temperatures are always 15º C for the tank and 20 º C for the vane channels respectively.

Preliminary Thermo-Structural Calculations (2)

Output data: Temperature

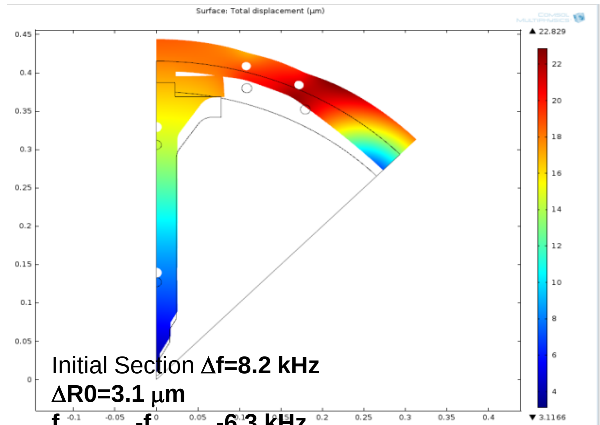


Initial Section α**3 =16° C** α**4=27°**

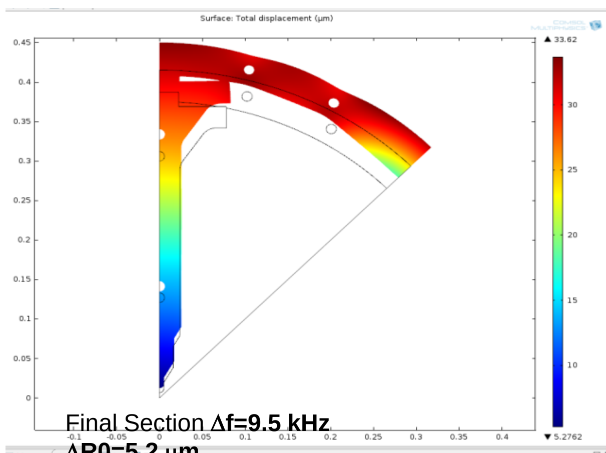


Final Sectionα**3 =15° C** α**4=30.5°**

Output data: Deformation

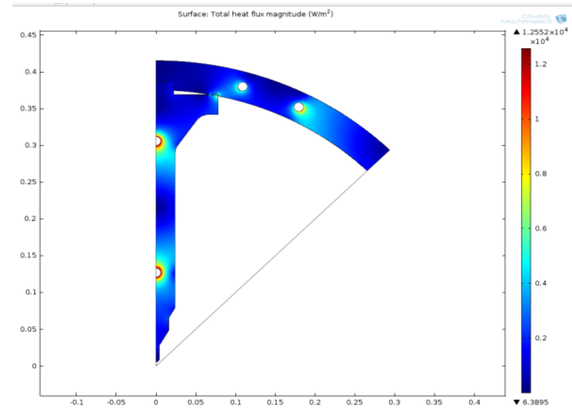


Initial Section **Δf=8.2 kHz**
ΔR0=3.1 µm
f_{out_water}-f_{in_water}-6.3 kHz

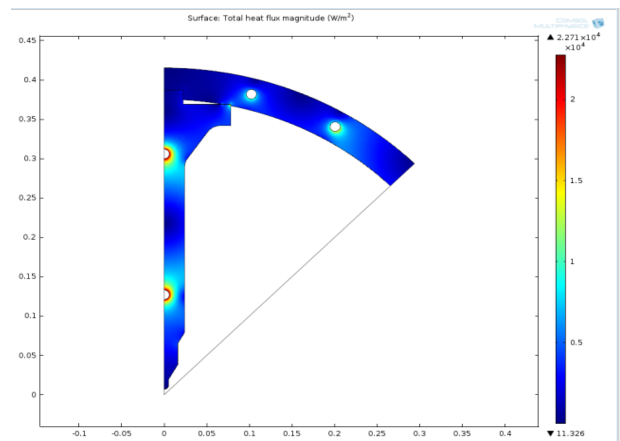


Final Section **Δf=9.5 kHz**
ΔR0=5.2 µm
f_{out_water}-f_{in_water}-8.5kHz

Output data: Heat Flux



Initial Section (per meter) **ΔT1=0.3° C, ΔT2=0.3° C, ΔT3=0.1° C, ΔT4=0.2° C**

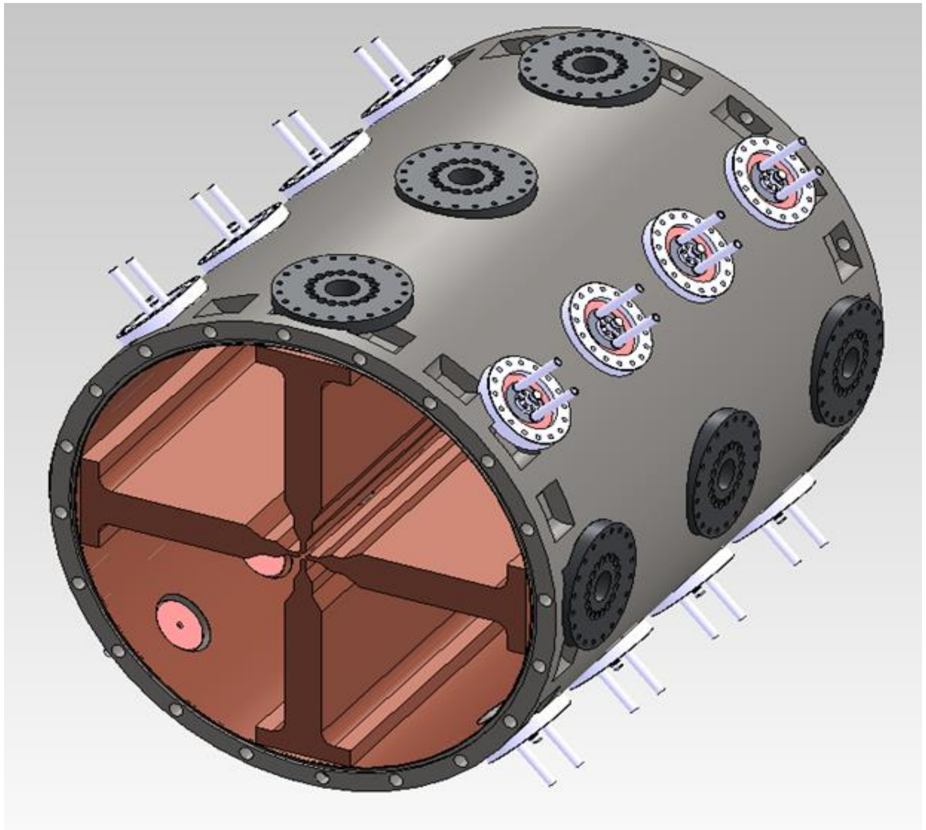


Final Section (per meter) **ΔT1=0.6° C, ΔT2=0.6° C, ΔT3=0.2° C, ΔT4=0.3° C**

Preliminary Thermo-Structural Calculations (3)
Some observations

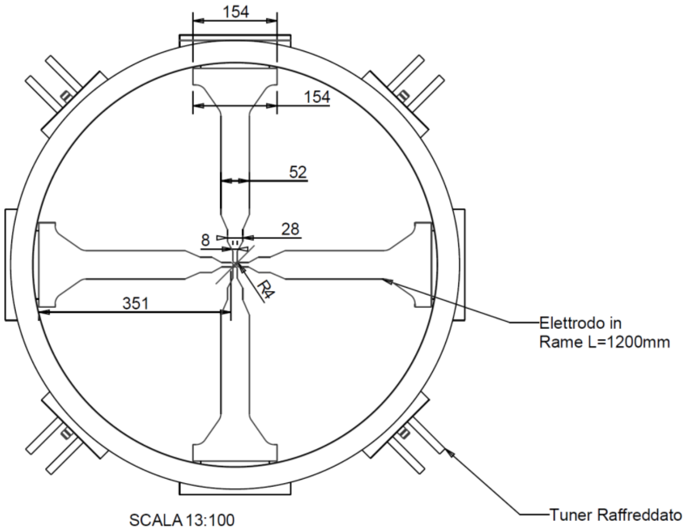
1. The overall water flux on the 24 channels (8 on the vane and 16 on the tank) is equal to about 500 l/min
2. The gfrequency difference between RF ON and RF OFF is in the order of 120 kHz.
3. The frequency tuning of the cavity with water temperature is obtained by keeping T_{tank} fixed and by mixing the inlet and outlet water of the vane channels: in this way the frequency range that can be corrected by varying the inlet vane temperature of the water is equal to $f+\partial f/ \partial(\Delta T)*(T_{tank}-T_{vane})$ =-25 kHz/ºC*(15ºC-20ºC)= 125 kHz. Therefore a tuning range of [- 125 kHz, 125 kHz], corrisponds to a T_{vane} range of[15ºC-25ºC]. Notice that, due to the fact that the two frequency gradients (one with respect to T and another one with respect to PRF) have opposite signs, the mixing of the water actually stabilizes the RFQ frequency
4. In order to increase the efficiency of such tuning system, by connecting in series the water cooling tubes of 3 or 4 modules, supposed to be in the order of 1 m long, one can have an overall ΔT of about 2°C.
5. The simulations performed hitherto have assumed a perfect thermal contact between the electrode and the tank. The lack of this kind of contact can lead to a frequency variation of about 60 kHz. Therefore the possibility of having a thermal isolation between electrode and tank is being studied.

Mechanical concept



Bolted electrodes, copper plated iron tank, metallic circular joints, brazing of electrodes and other components before assembly

Tank inner radius 375 mm, 40 mm thickness



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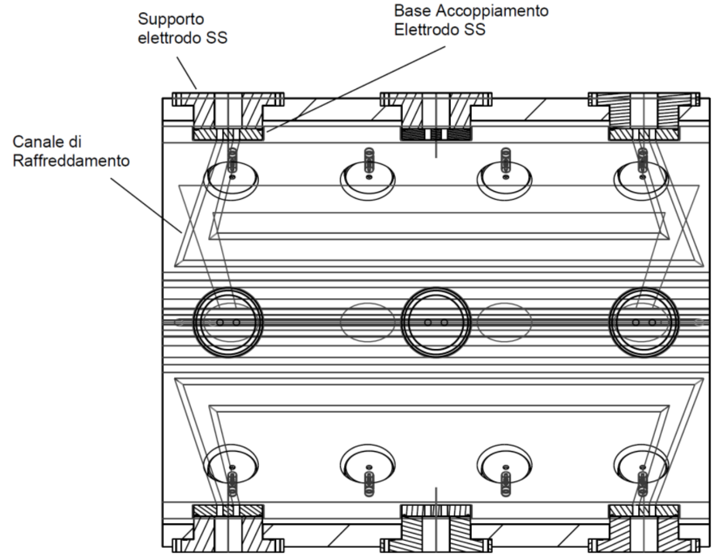
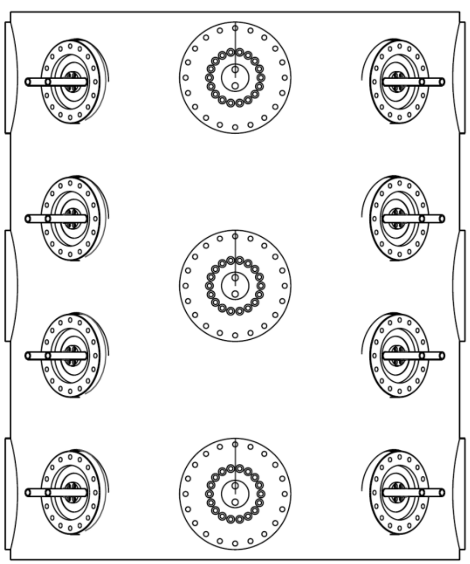
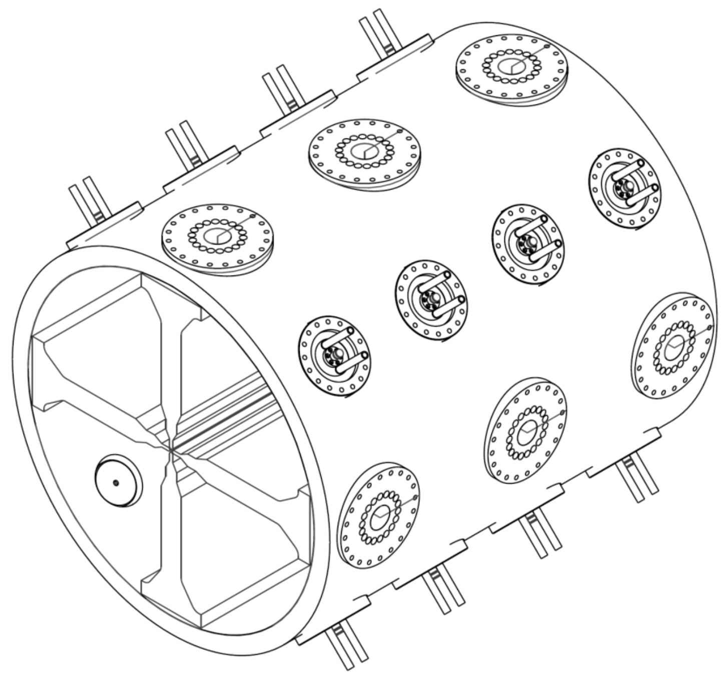


SEZIONE PROVA-PROVA





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Designed by
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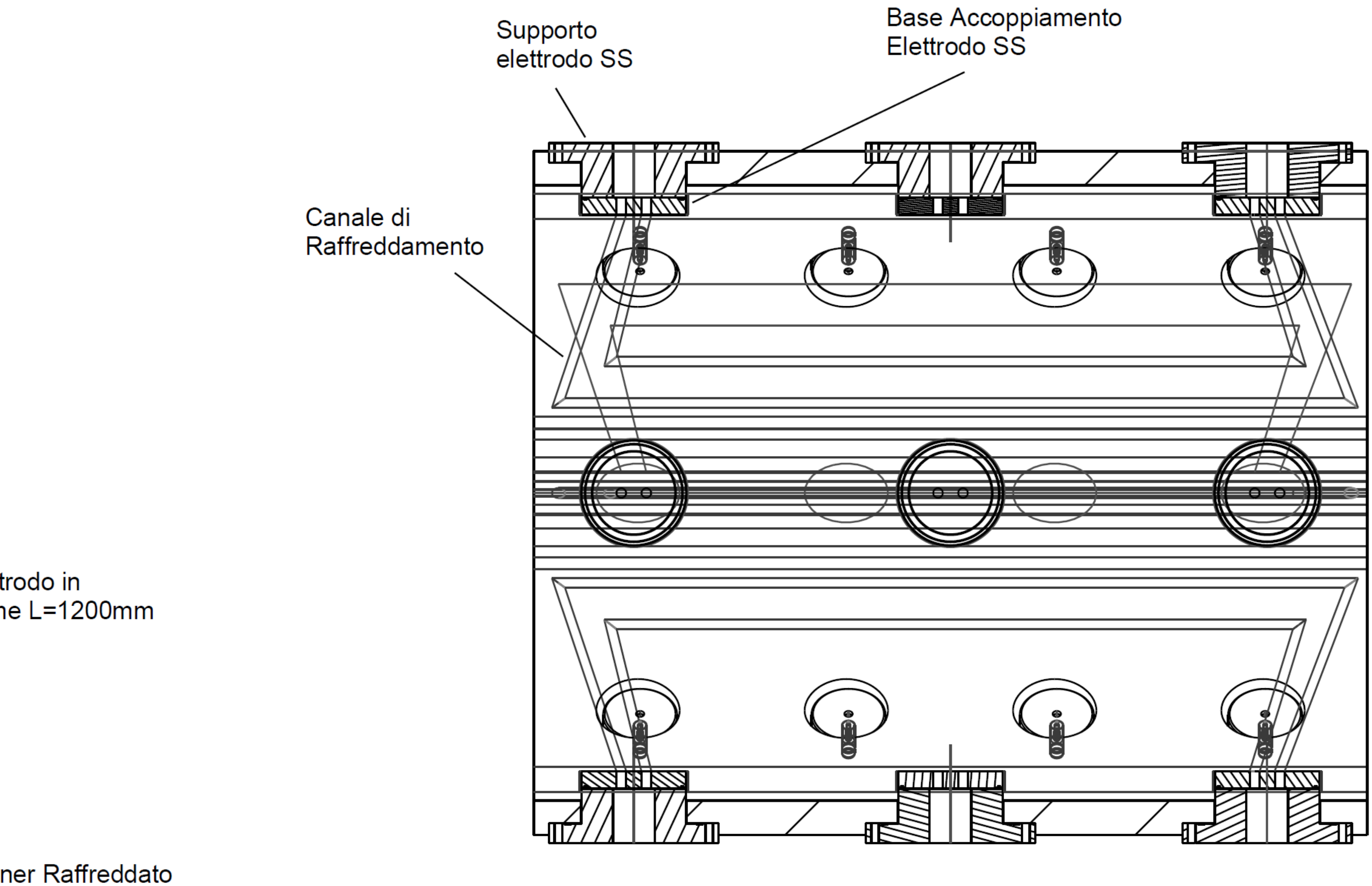
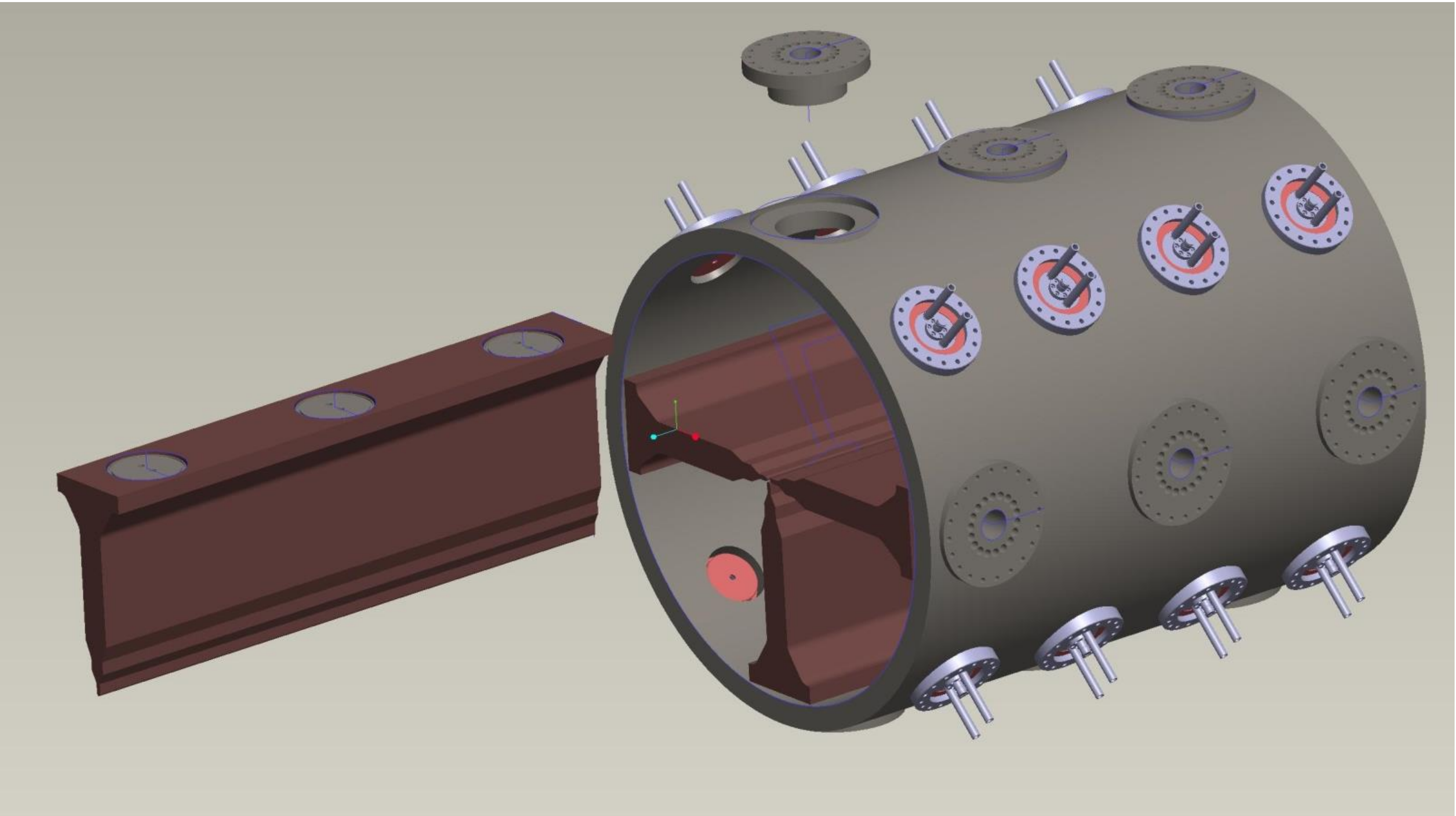


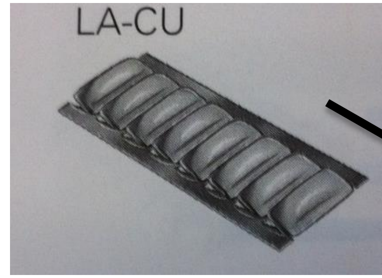
SEZIONE PROVA-PROVA

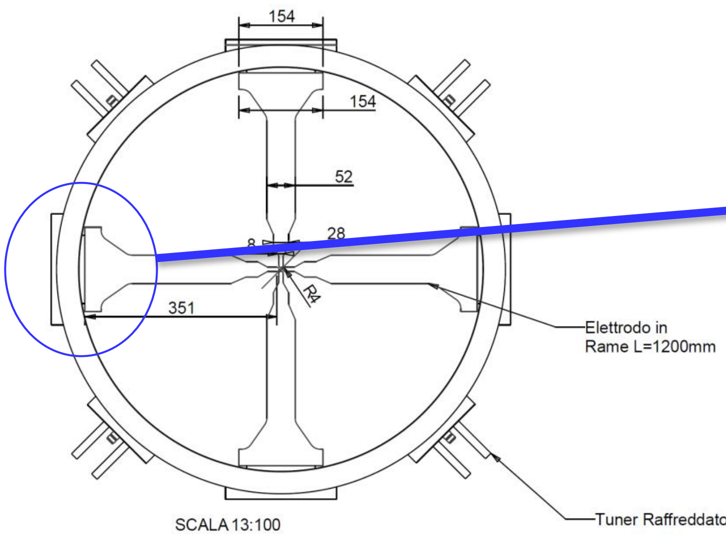
Electrode assembly concept

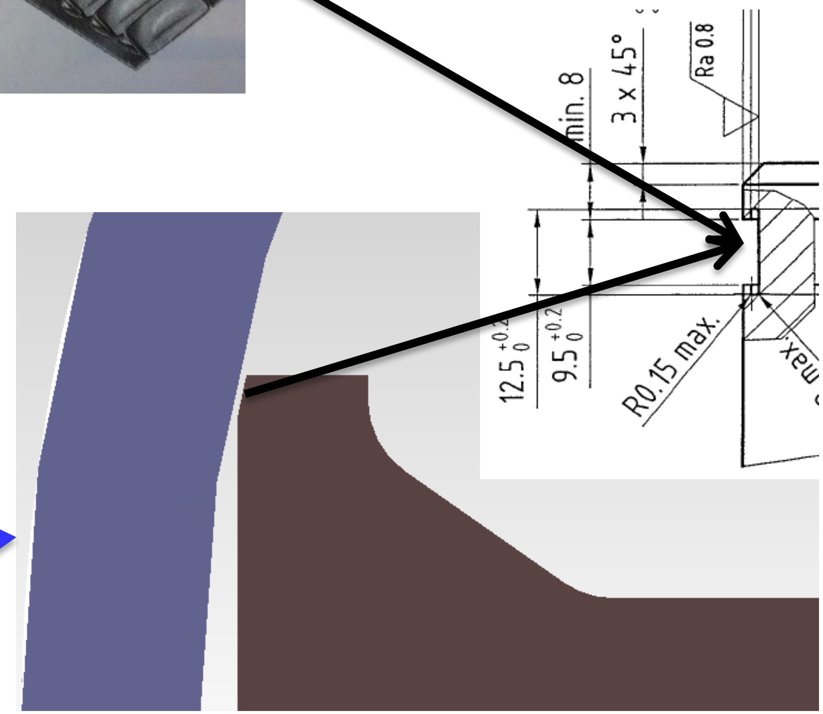


RF contacts

- HFSS simulations showed that on the electrode base, where the RF joint is foreseen to be inserted, the maximum current does not exceed the **16 A/cm** 2D values.
- A possible solution is the usage of a multi-louver reed-shaped spring joint, i.e. the LA-CU joints,by Multi-Contact® (**385 louvers/m**).
- Guarantees regulation **(±0.6 mm, nominal)** and a shrinkage force in the range of **(200 ÷320) kg per meter of spring joint**



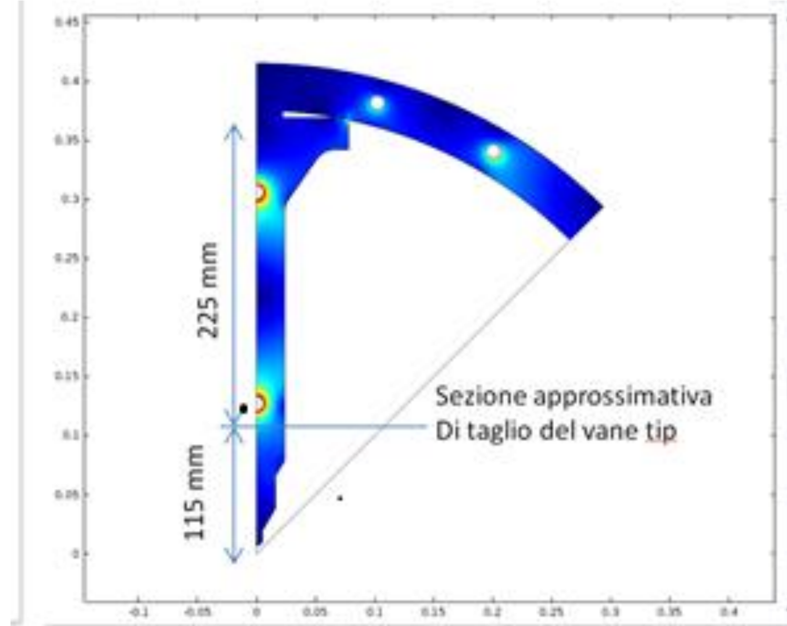




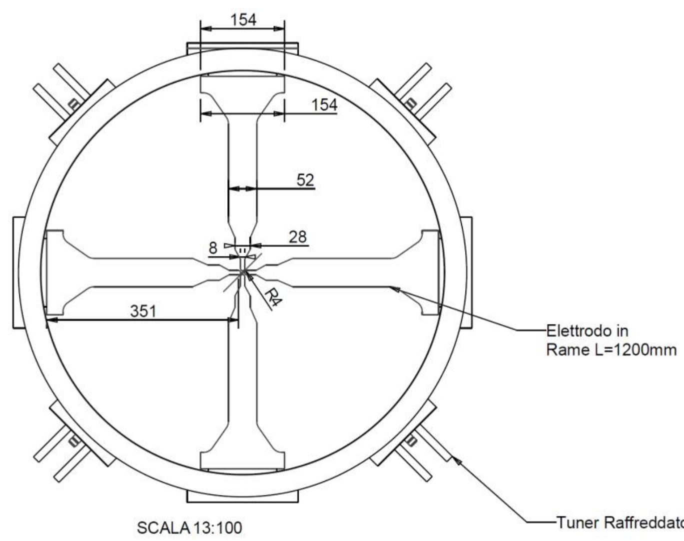
Detail of the groove for the spring joint (under the hypothesis of machining the groove on the electrode

Key manufacturing issues

- Electrodes mounted and bolted
- Tank forged SS (304 L or 316 L) to be copperplated [same technology as for ESS DTL]
- Reference and groove planes external to the tank
- Electrodes in OFE copper, cooling channel and coupling SS planes brazed (brazing possible at LNL or Cinel oven)
- 3d modulation of the electrodes (1200 mm long) possible with new 5 axis center at Cinel, or in two pieces at INFN Pd.
- RF contacts at electrode bases
- Elicoflex metal joints for module connection, viton or metal for all the lateral apertures (can be substituted)

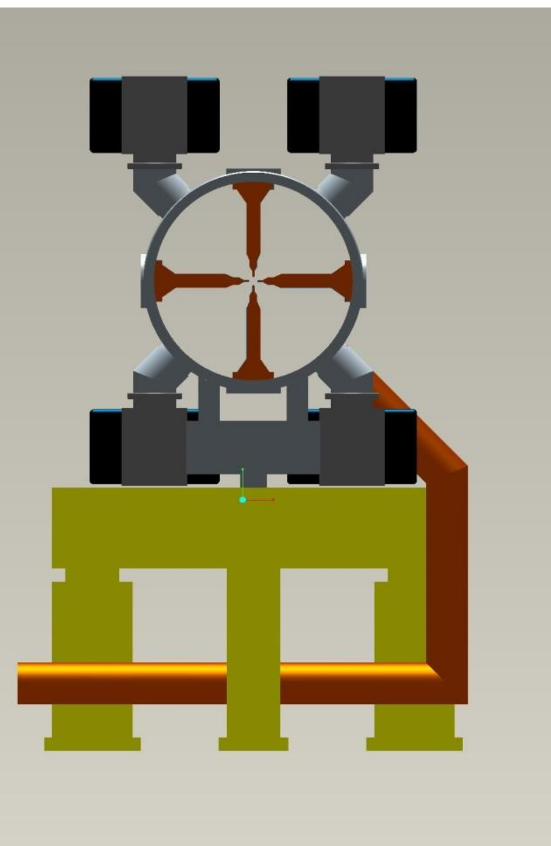


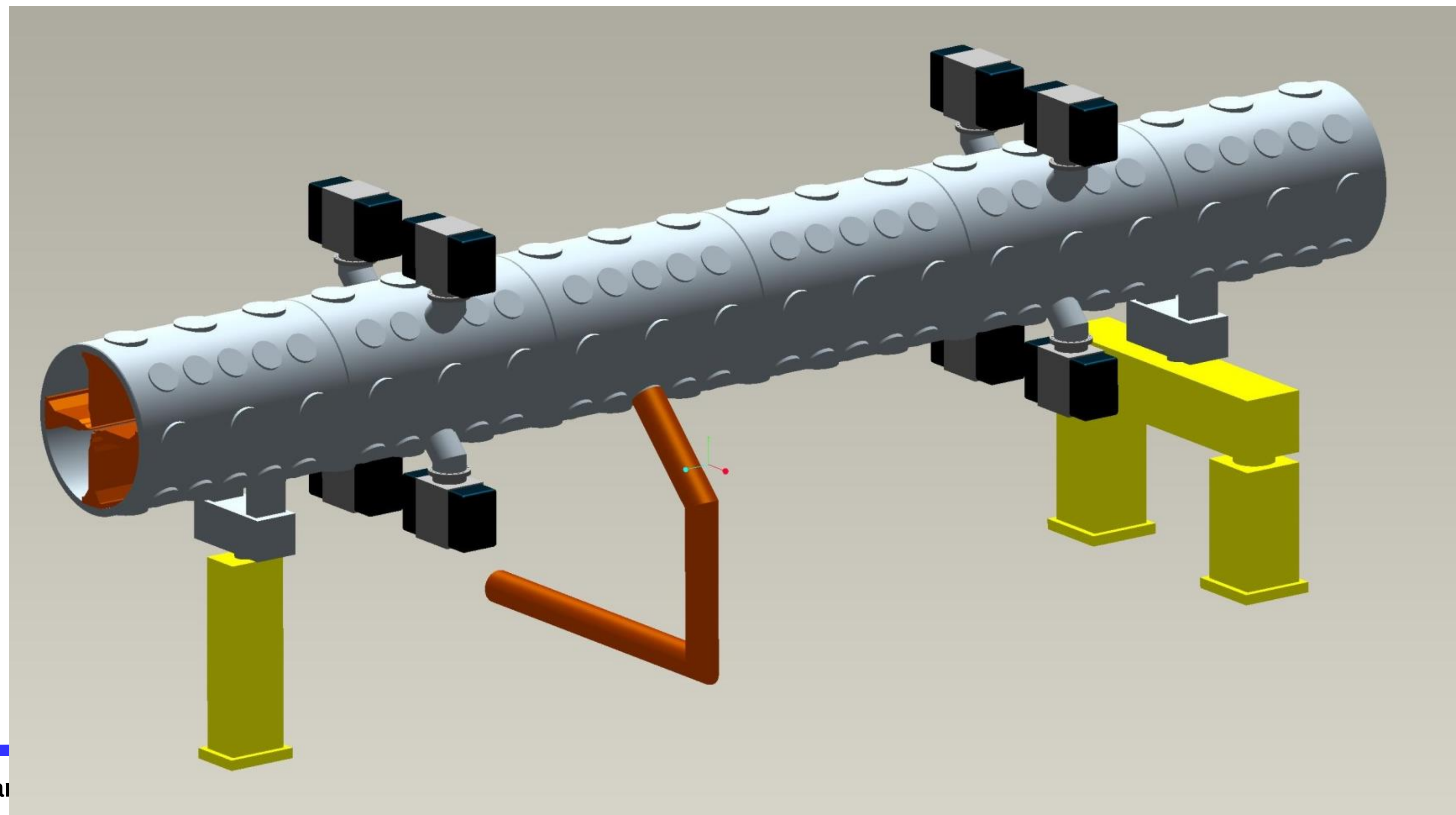
Sezione finale



Overall design

- 6 modules self-sustained (10 Tons)
- About 120 tuners with IFMIF design
- Isostatic support with separate assembly (vertical or horizontal) TBC.
- 1 RF coupling loop and coaxial line distribution
- Ionic pumps with short manifolds distributed in four quadrants
- RF pick ups in the tuners TBC





Conclusions

- The Physical design and the mechanical concept of the RFQ are established.
- With the RF system, cooling system and electrical infrastructures there is a substantial contribution to SPES from the synergy with the power test stand (dedicated to IFMIF and ESS in next future).
- During 2014 (IFMIF RFQ will be delivered to Japan at the end of the year) prototypes of critical aspects of the mechanical conception will be tested (tank ordered, electrodes…)
- An approximate time plan
  - 2014 prototypes and start of material procurement
  - 2015 preparation of the specs, preparation of the tender for the construction of the RFQ (construction contract within end 2015)
  - 2016-17 construction and gradual commissioning
  - 2018 RFQ beam into ALPI