FROM RESEARCH TO INDUSTRY

RFQ DEVELOPMENTS AT CEA/IRFU

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www.cea.fr

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- Design flow for RFQ @CEA (SPIRAL2 RFQ example)
- Fabrication and installation of SPIRAL2 RFQ
- Conditioning and commissioning of SPIRAL2 RFQ
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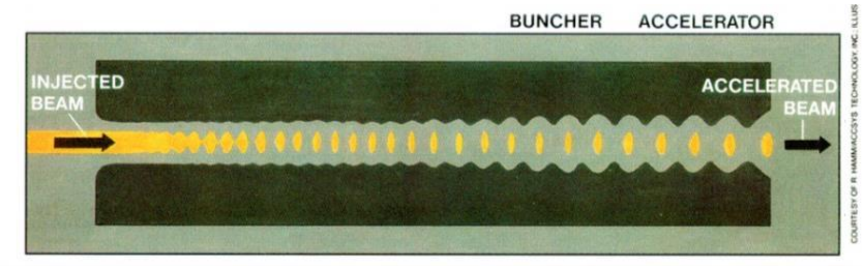
  - IPHI
  - LINAC4
  - ESS
- Conclusion

Introduction

Functions of the RFQ:

- Beam transverse focusing
- Particle bunching at RF frequency
- Beam acceleration



3 main steps for a RFQ development

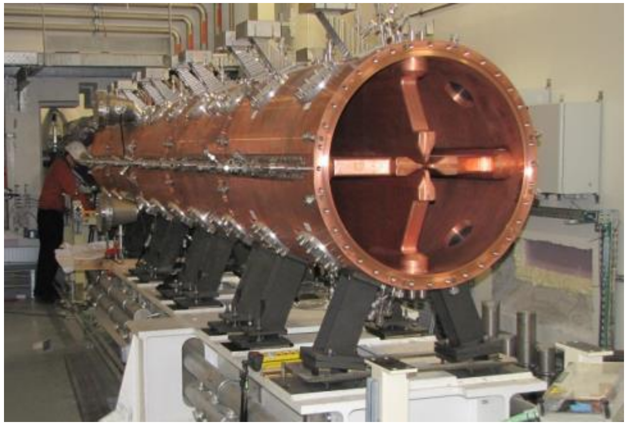
RFQ design → **RFQ fabrication and installation** → **Conditioning and commissioning**

RFQ design:
Beam dynamics
RF design
Thermo-mechanical studies

RFQ fabrication and installation:
Control and tuning of voltage law → RFQ design

Conditioning and commissioning:
Control of voltage law with RF power
Verification of beam dynamics performances
→ RFQ design

Tools developed at CEA are used for the design and for the RFQ validation



CEA is involved in the design and fabrication of 4 RFQs (IPHI, SPIRAL2, LINAC4 and ESS)

→ Example of SPIRAL2 RFQ development at CEA

Introduction

SPIRAL2 accelerator:

- Major extension of GANIL (CAEN in Normandy France)
- New Multi-purpose Accelerator facility
- New experimental rooms for nuclear physics

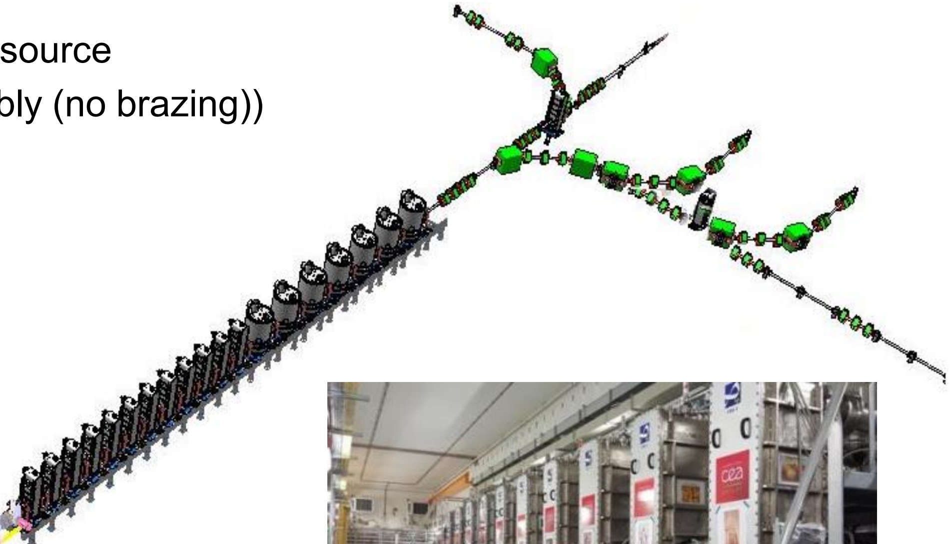
Introduction

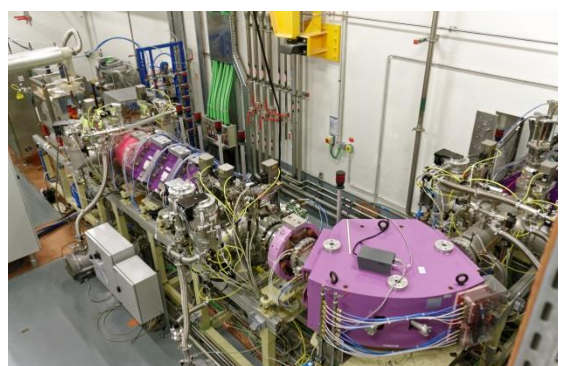
SPIRAL2 accelerator:

- 2 sources: Heavy ion source and proton/deuteron source
- RFQ (4 vane RFQ type, with a mechanical assembly (no brazing))
- 3 re-buncher cavities
- 19 cryomodules with 26 superconductive cavities

Main parameters of the RFQ

Frequency	88.05 MHz
Output energy	3 MeV
Peak current	5mA
Length	5 m
Voltage	100 to 113 kV
RF power	180 kW CW





Contents

Design flow for RFQ

Beam Dynamics

•Voltage profile.

•Vane modulations

•Error analysis

RF Calculations

•Cross-section geometry.

•TLM parameters.

•Dissipated power.

•End circuits.

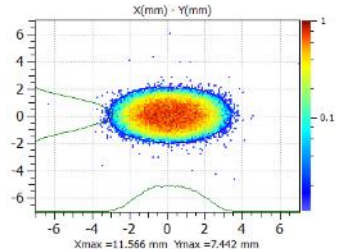
•Slug tuners.

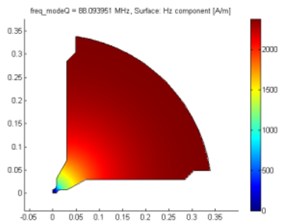
•RF power coupler.

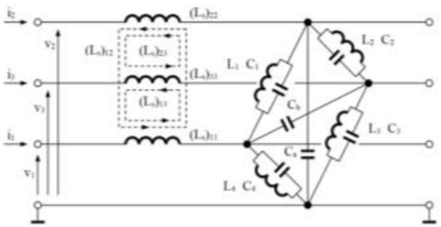
Error Analysis

•"RF stability"

i.e. sensitivity to Tolerance requirements for RFQ construction







Thermo-mechanical simulations

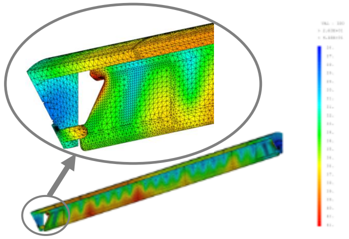
•Definition of cooling system required to maintain geometry within tolerances during RF operation

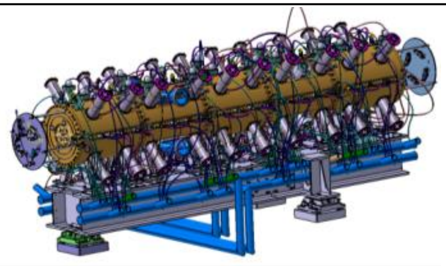
Mechanical Design

•Drawings.

•Definition of machining and assembly processes satisfying tolerance requirements.

•Design of RFQ support and tools for assembly





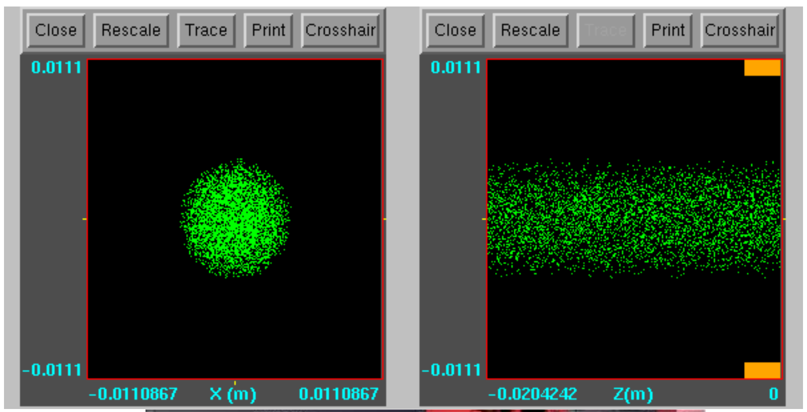
Design flow for RFQ

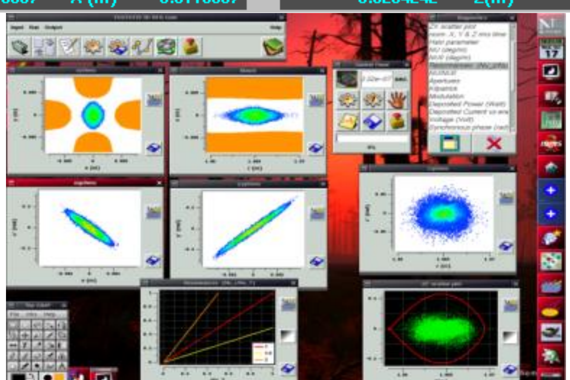
Beam Dynamics

- Voltage profile.
- Vane modulations.
- Error analysis

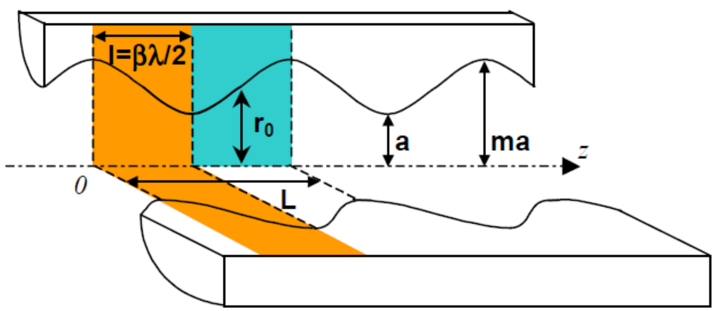
TOUTATIS code: An accurate tool to simulate RFQ

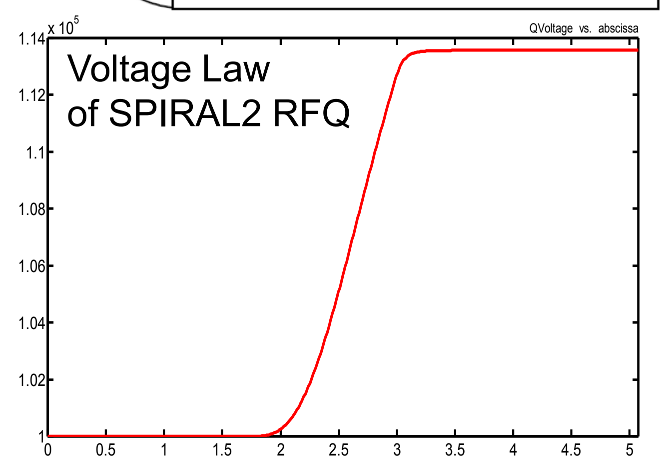
- The fields are computed using 3D grid via a Poisson solver allowing to compute image effect, space charge force.
- TOUTATIS code can take into account real shapes of electrodes including mechanical defects, coupling gaps and RFQs extremities





Design of vane ends and voltage law for the RFQ

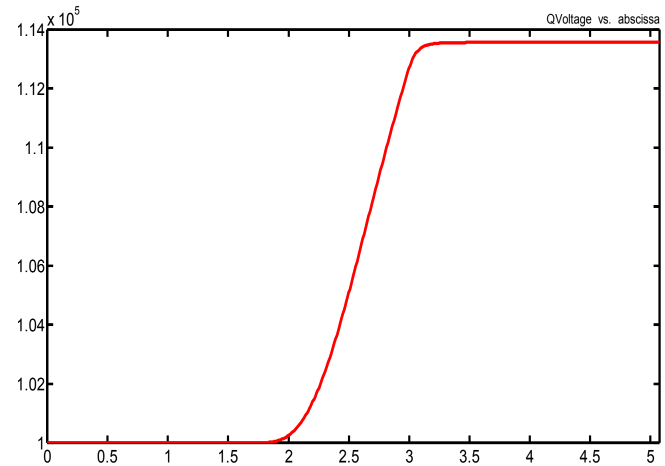




Design flow for RFQ

RF Calculations

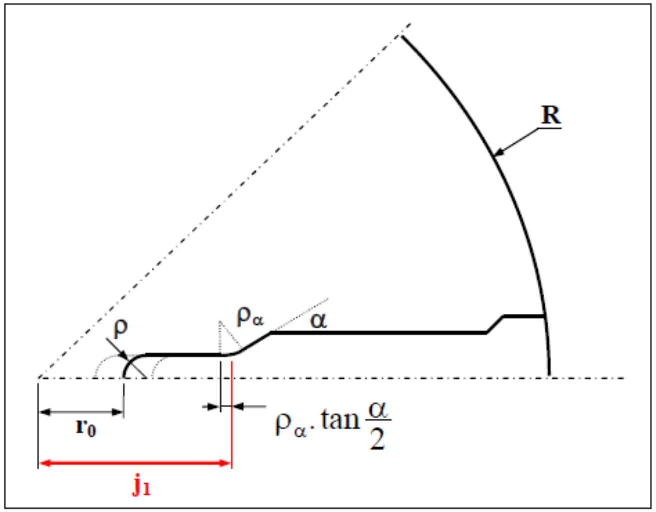
- •Cross-section geometry.
- •TLM parameters.
- •Dissipated power.
- •End circuits= extremities
- •Slug tuners.
- •RF power coupler.

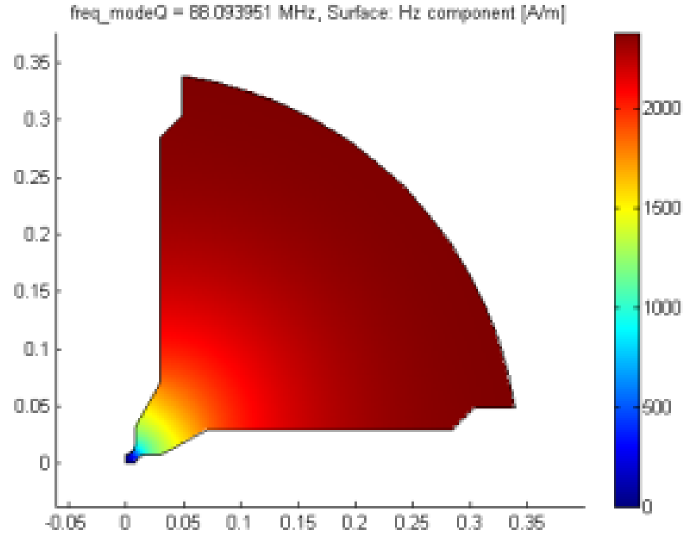


Variable Voltage law involves to a frequency variation of 2D cross section of the RFQ

2D RF calculations give the cross-section geometry vs. abscissa, achieving specified voltage profile

SPIRAL2 cross section

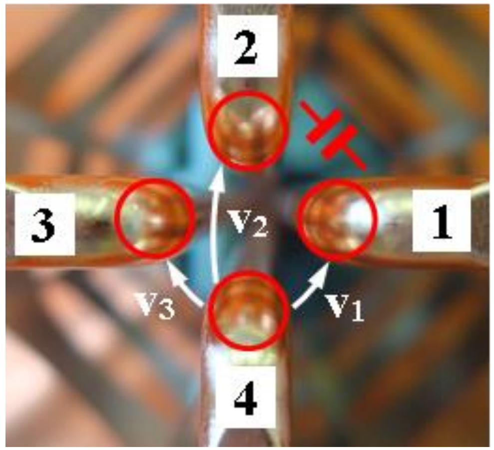


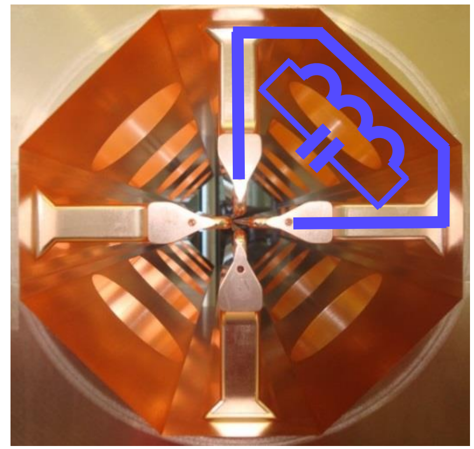


Design flow for RFQ

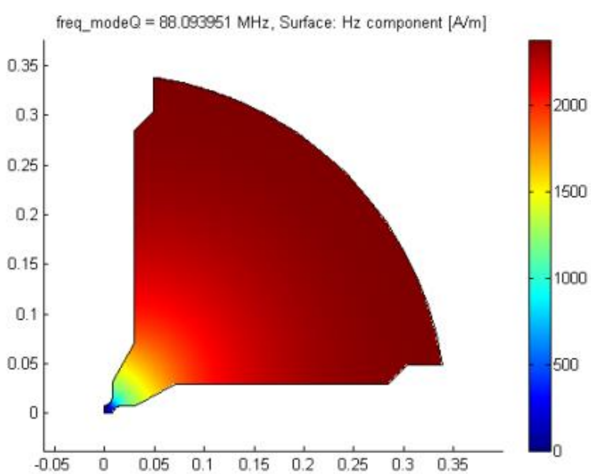
4-wire transmission line model (TLM)

The RFQ 4-wire transmission line model (TLM) is primarily used for error analysis (tuning range) and RFQ tuning.

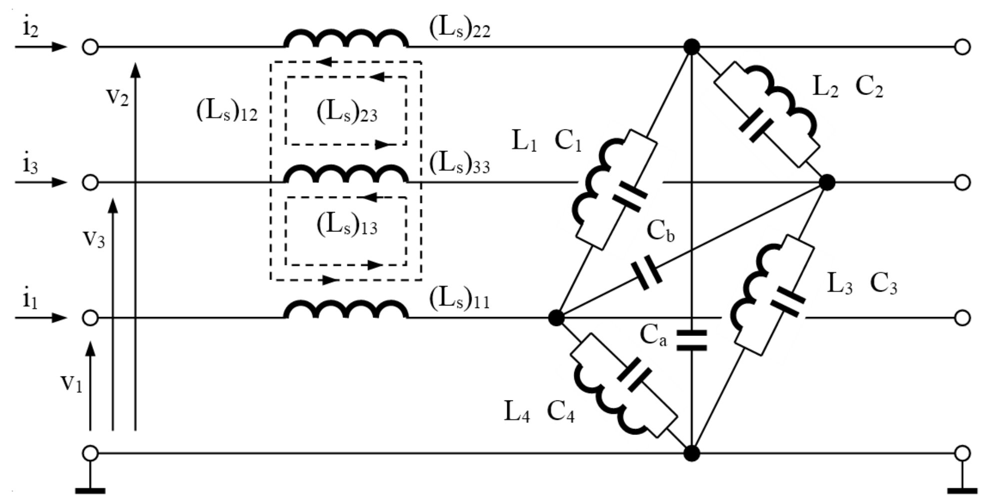




2D RF simulations of the cross-section vs. abcsissa



Electrical parameters of RFQ vs. abscissa in order that TLM mimics physical RFQ



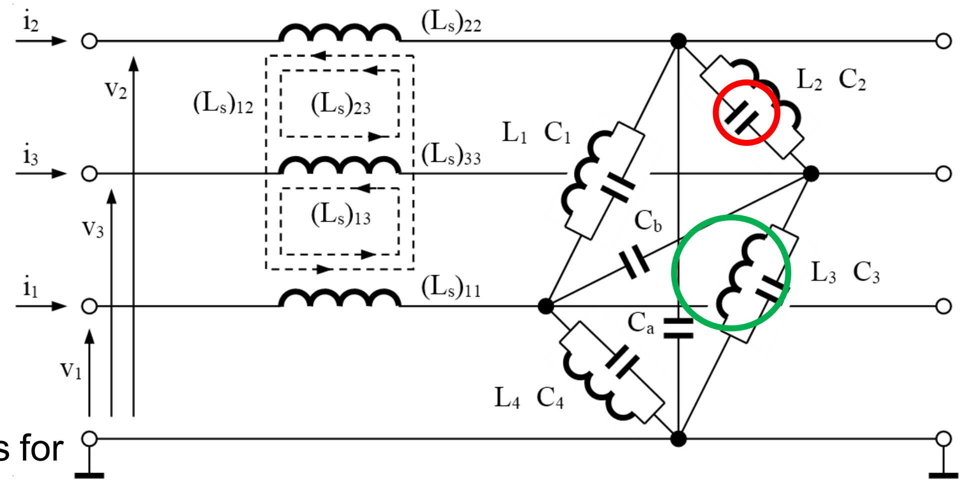
Design flow for RFQ

Error Analysis

"RF stability"

i.e. sensitivity to:

Tolerance requirements for RFQ construction



- TLM are used to define tolerance requirements for RFQ construction according to the tuner position

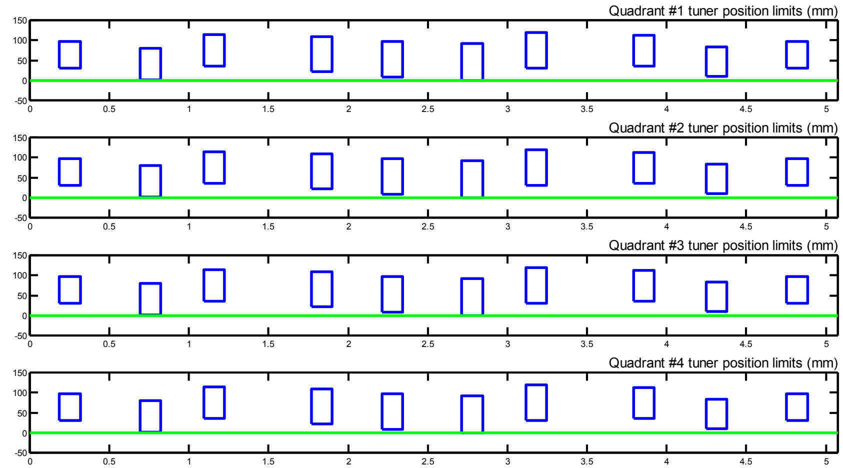
Geometry errors ~ capacitance perturbations derived from RF calculations

Tuning slugs located in the bottom of the cross section ~ inductance perturbations derived from RF calculations

Slug tuning range according to construction errors

Compromise between construction tolerances and power losses

Tuning range of SPIRAL2 RFQ :
40 slugs, for ±90 µm tolerance:
Max position is 140 mm inside cavity



Construction tolerances ↘ ➡ Length of tuner ↗ ➡ Power and cooling ↗

Design flow for RFQ

Thermo-mechanical simulations

- Geometrical deformation vs. power.
- Definition of cooling system required to maintain geometry within tolerances.

The cooling system is designed to maintain geometry within tolerances in order to:

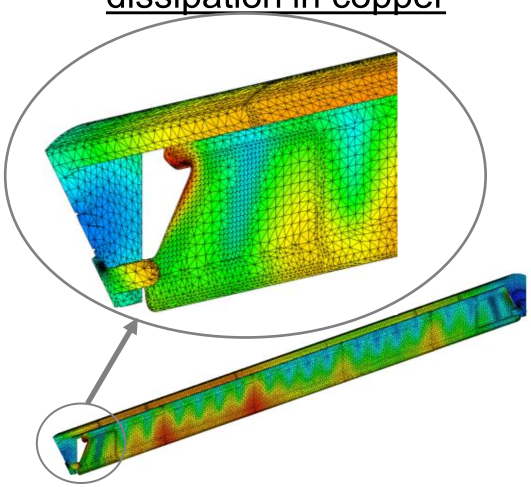
1) minimize transverse deformation of the RFQ to preserve the voltage law

2) minimize the frequency shift between the RF on/off states

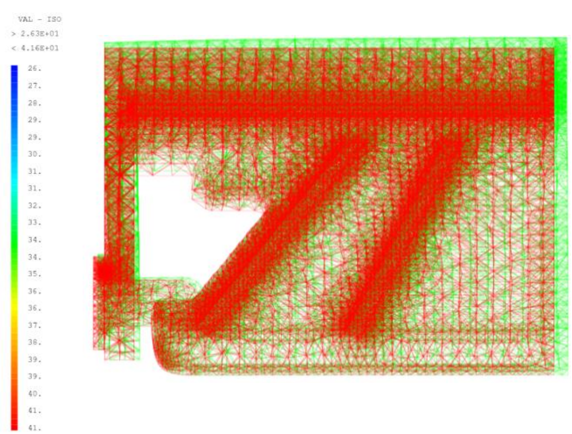
RF losses obtained with RF code are used as input for thermal and mechanical calculation (ANSYS solution or RF code + CASTEM (CEA code)) → Optimization of the cooling channel position, sizes, temperatures and fluid velocity → **Definition of cooling skid**

SPIRAL2: 2 independently temperature-controlled circuits: tubes and vanes

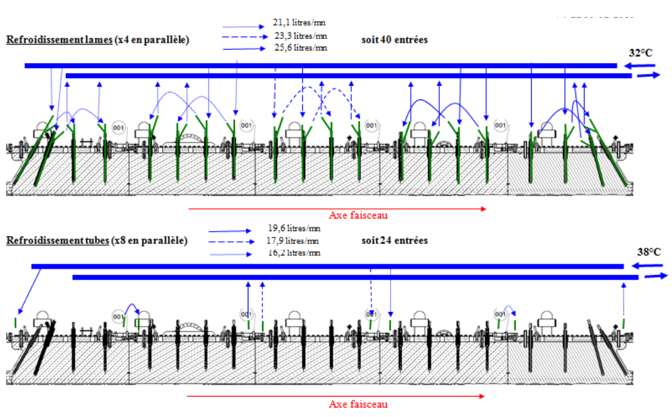
Heating induced by RF power dissipation in copper



RFQ deformations (× 200)



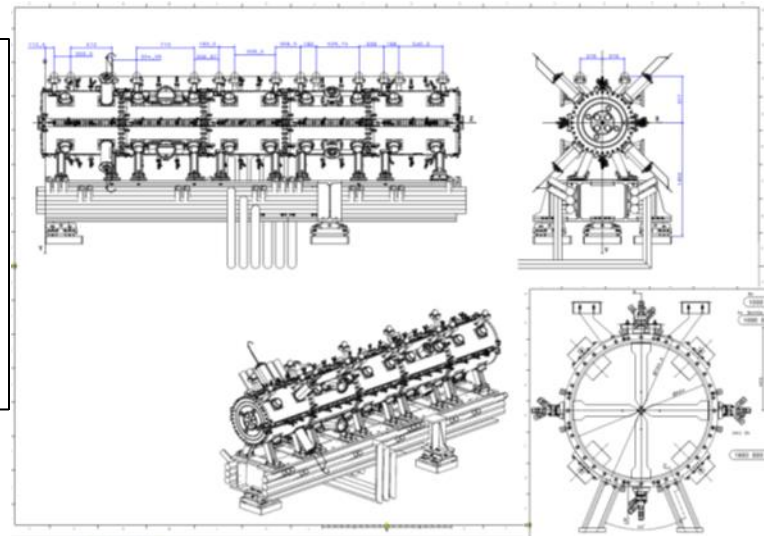
Layout of the cooling system

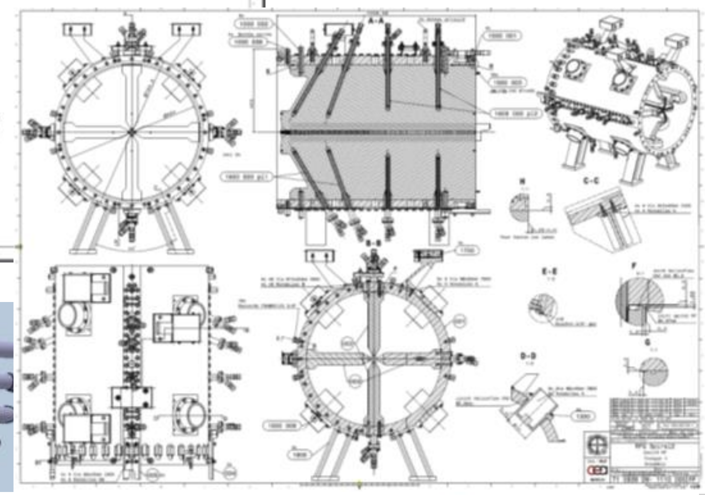


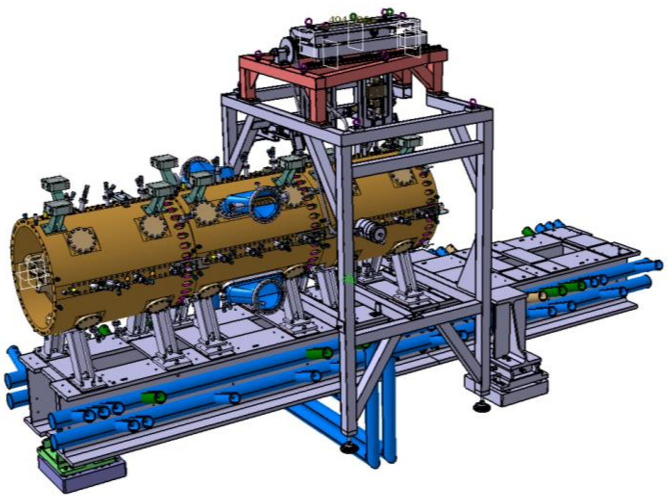
Design flow for RFQ

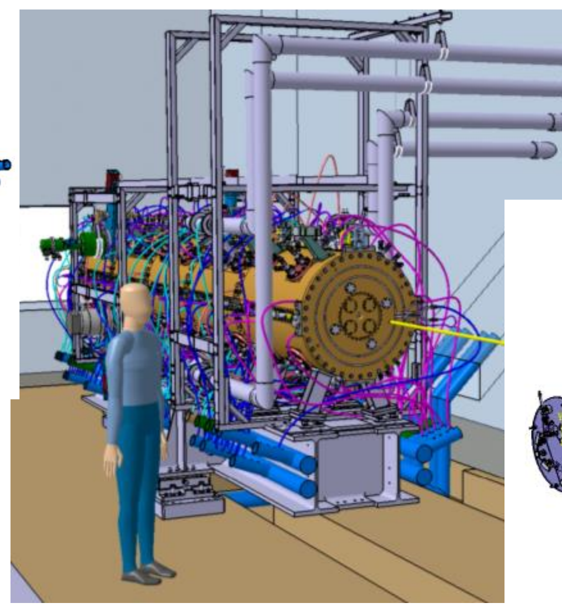
Mechanical Design

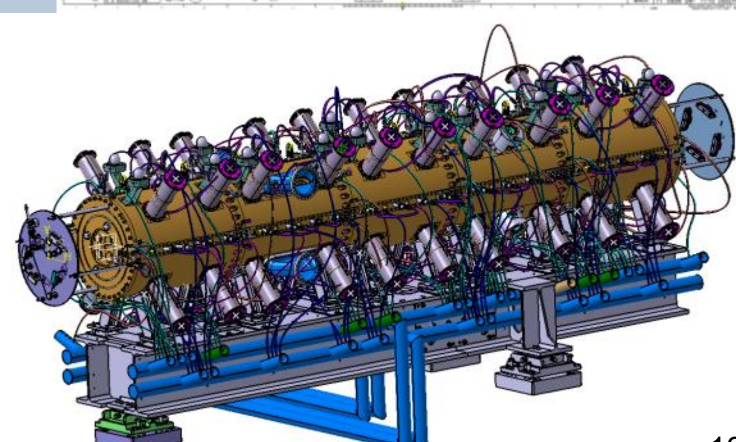
- Drawings.
- Definition of machining and assembly processes satisfying tolerance requirements.
- Design of RFQ support, tools for assembly, tuning system…











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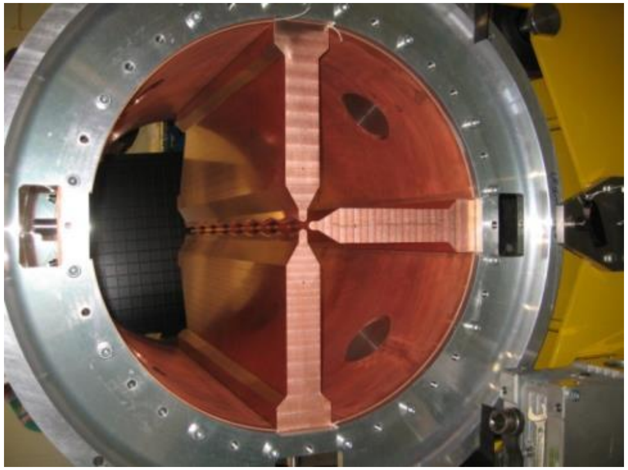
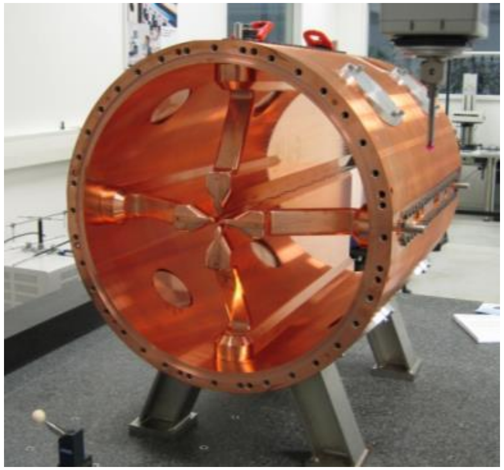
Machining/assembly (Research Instruments GmbH)

➤ Fabrication of five 1-meter RFQ sections (800 mm diameter)

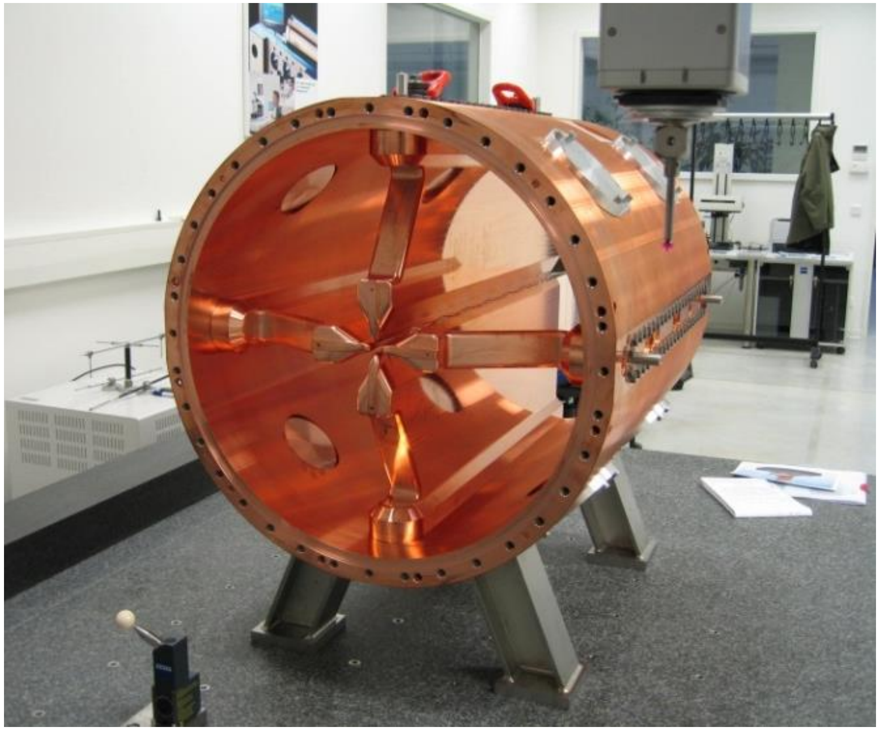
➤ Assembling 4 vanes in a tube (only with seals)

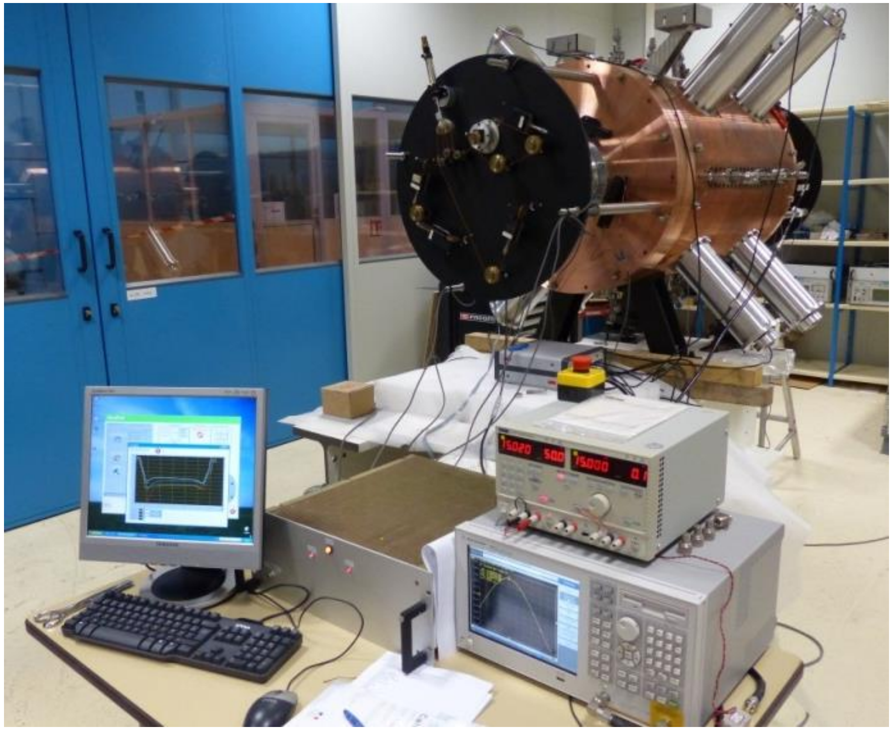




Control during fabrication

- Control with CMM and beadpull measurements





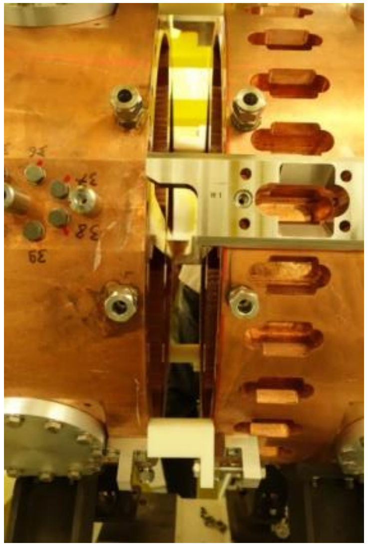
CMM measurement for the control of the geometry of vane

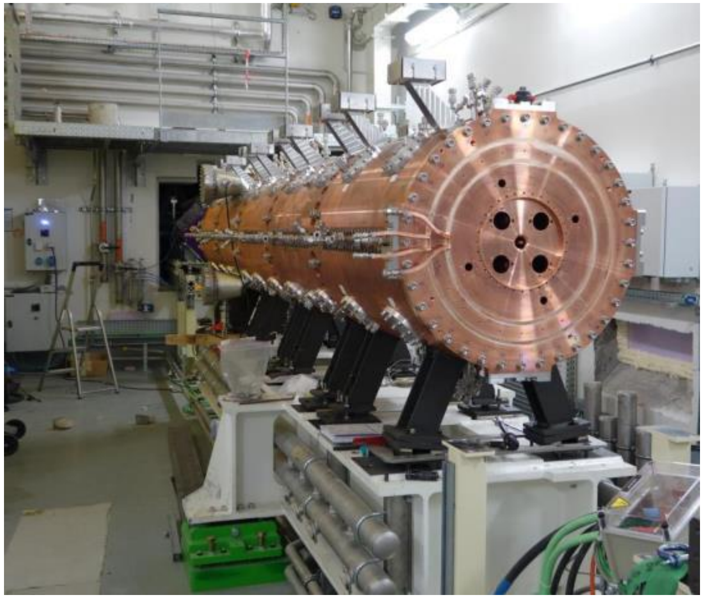
Beadpull measurements to check the RF design

These results could be used as inputs for new beam dynamic calculations with TOUTATIS code in case of non-conformity during fabrication

Installation at GANIL by CEA team



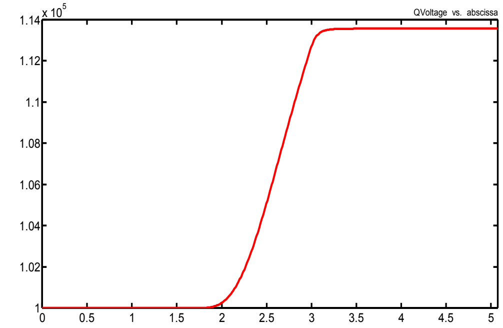


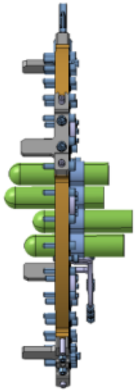
RF Tuning

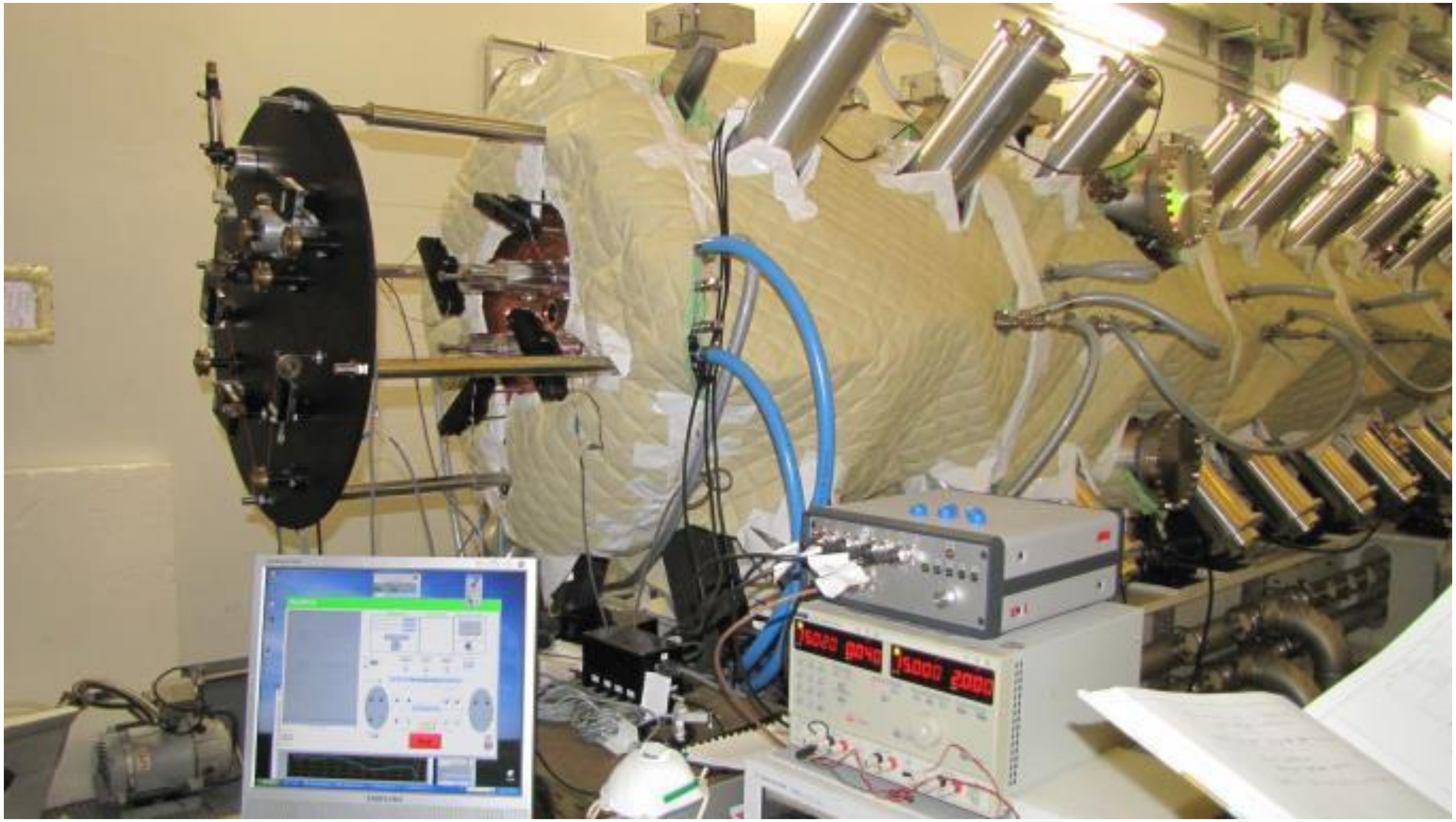
RF tuning (beadpull measurement)

Compensation of mechanical defaults (machining and assembly errors) by the tuning of end cells (Quadripolar rods) and 40 tunable slugs

Voltage law required by the beam dynamic



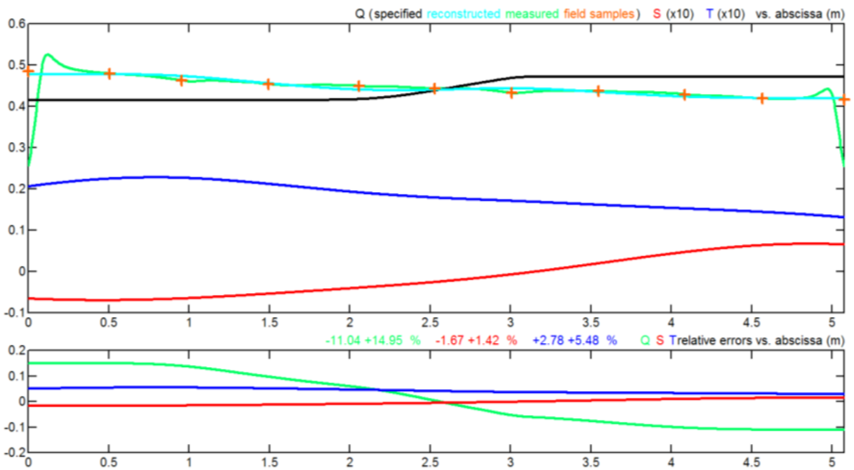


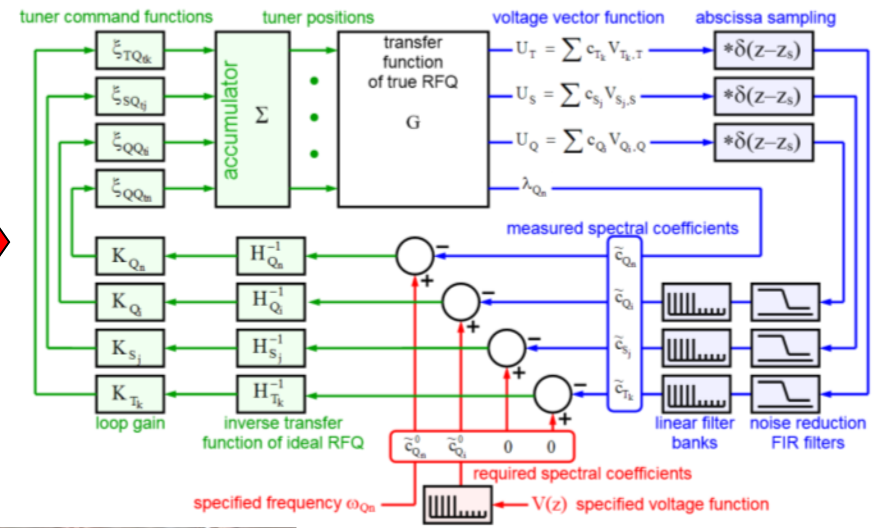


RF Tuning

Typical tuning iteration:

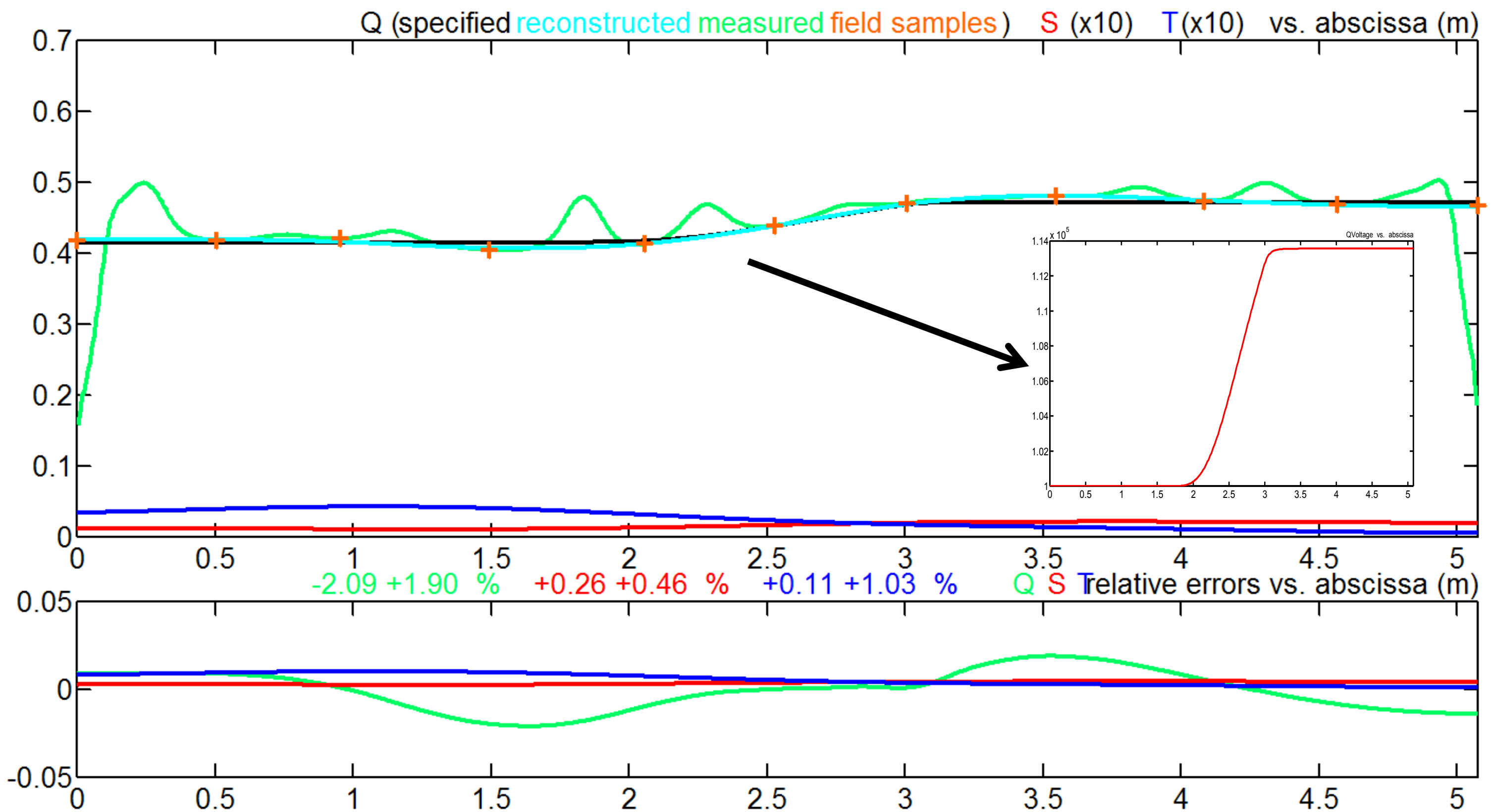
1) Beadpull measurement to obtain voltage law
2) Comparison with TLM model
3) TLM model gives the length for the 40 tuners to obtain the nominal voltage law
4) Tuning of the tunable slugs





Final beadpull measurement

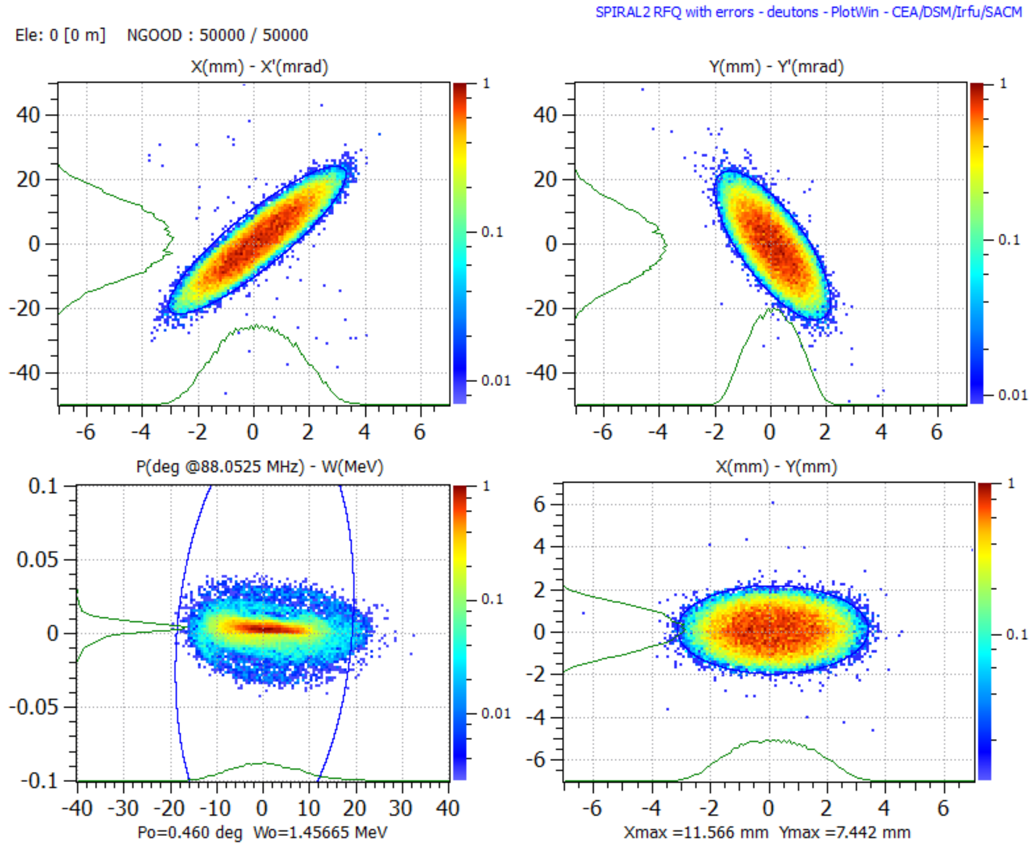
- After final copper slugs have replaced adjustable slugs and after vacuum and temperature tests



	Q	S	T
Un-tuned	15	1.7	2.8
Tuned, with adjustable tuners	1.0	0.5	1.4
Tuned, with copper slugs	1.0	0.6	1.3
After vac. & temp. test	2.1	0.5	1.0

Beam dynamic calculations

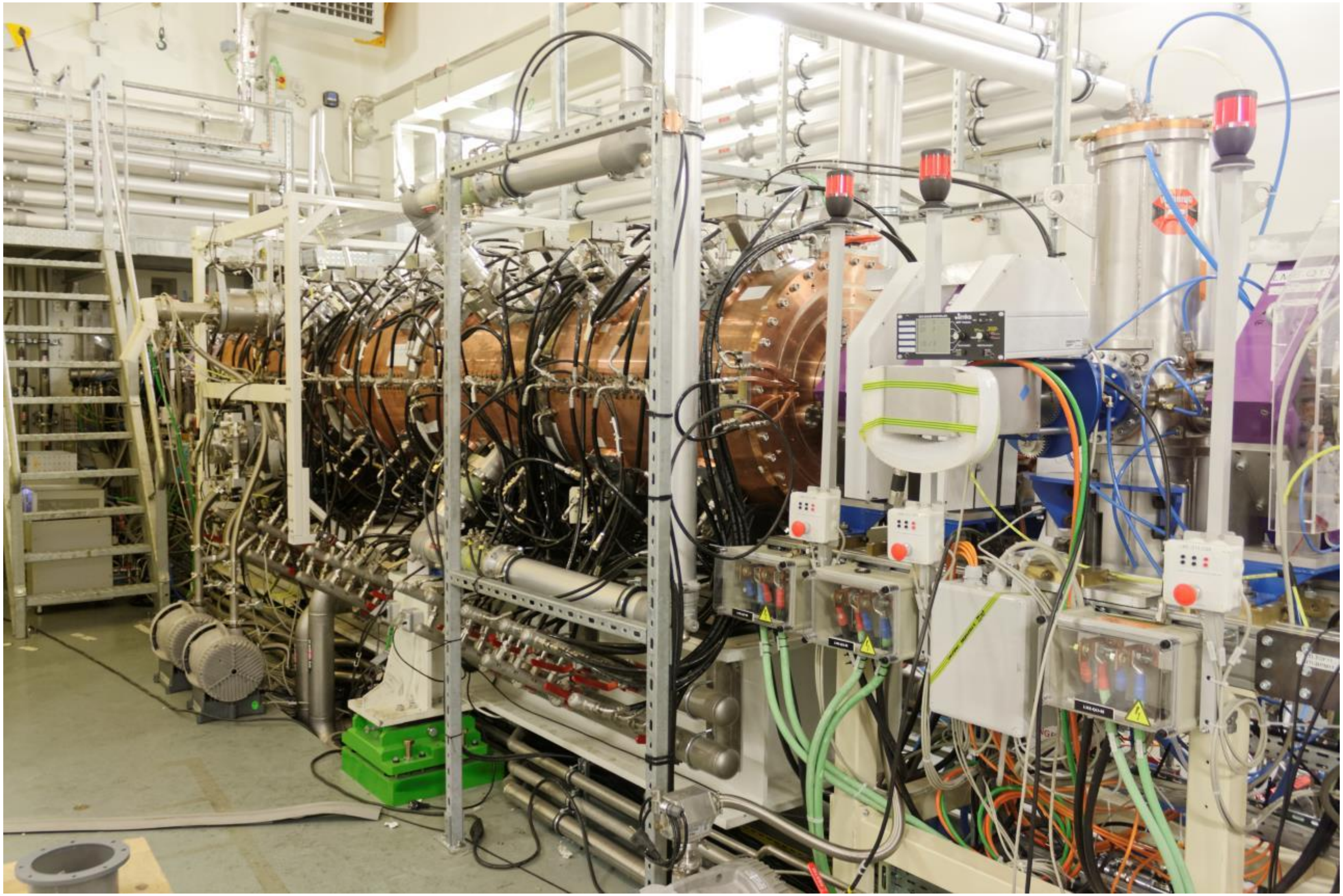
➢ Voltage measured with the last beadpull used as input for new beam dynamic simulation with TOUTATIS code:



➡ No degradation of the performances of the RFQ for the transverse and longitudinal emittance and for the RFQ transmission.

RFQ installation

RFQ connected to the water cooling system, RF and LLRF systems, pick-up acquisition system and to the beam line



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Conditioning

- Start of conditioning: **15th November 2015** only with 3 amplifiers because one has a failure
- The maximum of power achieved in the cavity was 110 kW (85kV for the cavity voltage (nominal at 113kV))
- Control the voltage law with the pick-ups acquisition system

- 16 pick-ups along the RFQ in order to measure the voltage law
- Calibration of pick-ups measurement at low power (according the last bead-pull measurement)
- Voltage reconstruction using the TLM

A variation of ±0.2% for the nominal voltage is measured when the voltage changes from 20 kV to 80 kV.

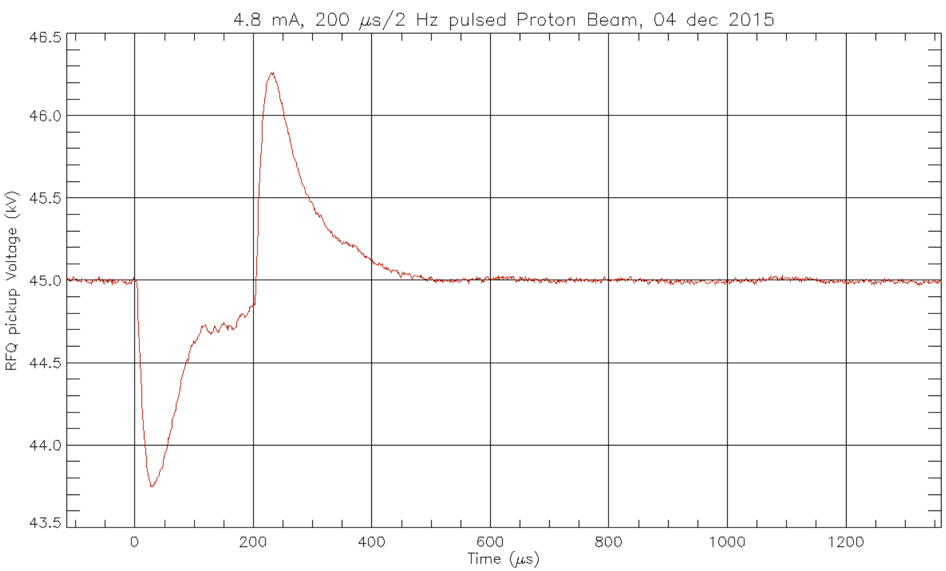
voltage errors

Check of no degradation of the voltage law obtained after the RF tuning and RF conditioning
Behavior is repeatable along the time

Commissioning

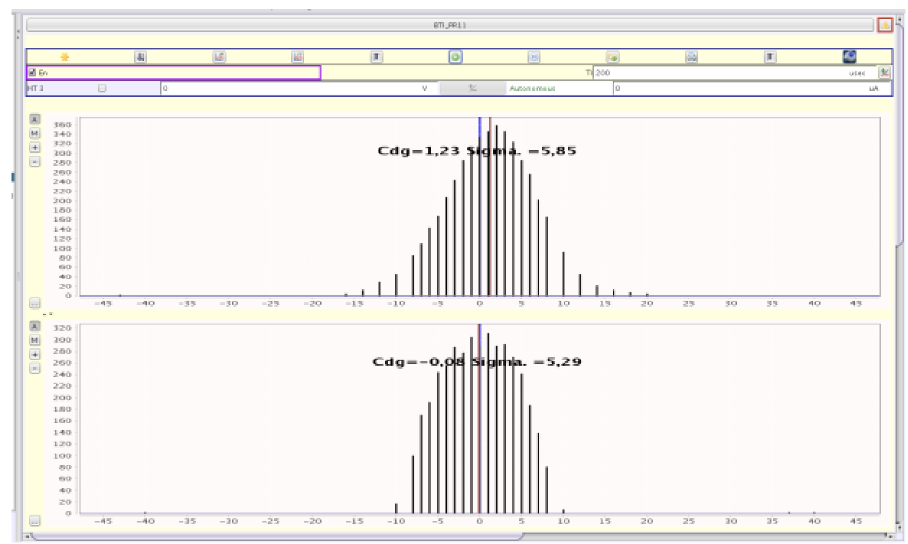
- **First proton beam the 5th December 2015**

(5mA of proton, 200µs/2Hz, 50kV for the maximum of the voltage law)



Perturbation of the RF voltage with a 200µs, 5mA pulse of proton

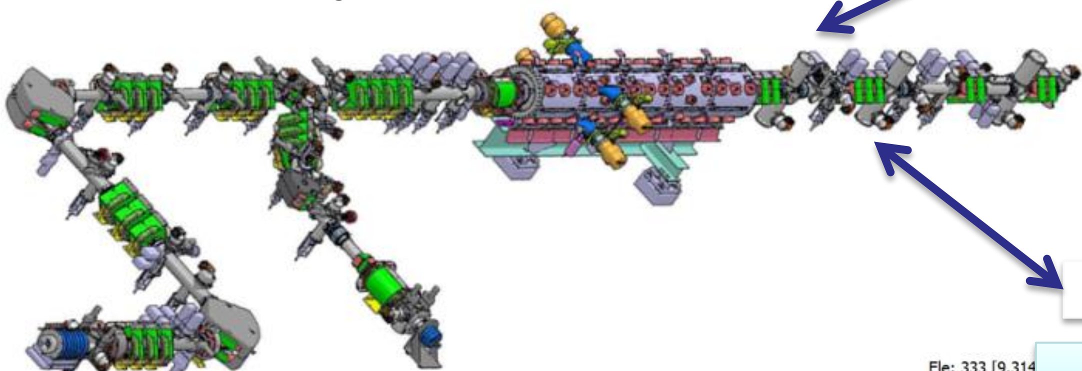
CW beam with 5mA of proton (50kV) the 10th December 2015

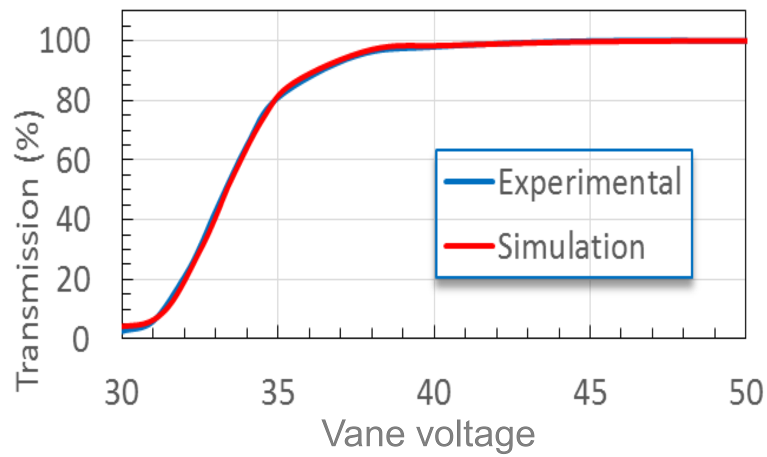


Commissioning

Some results with proton beam

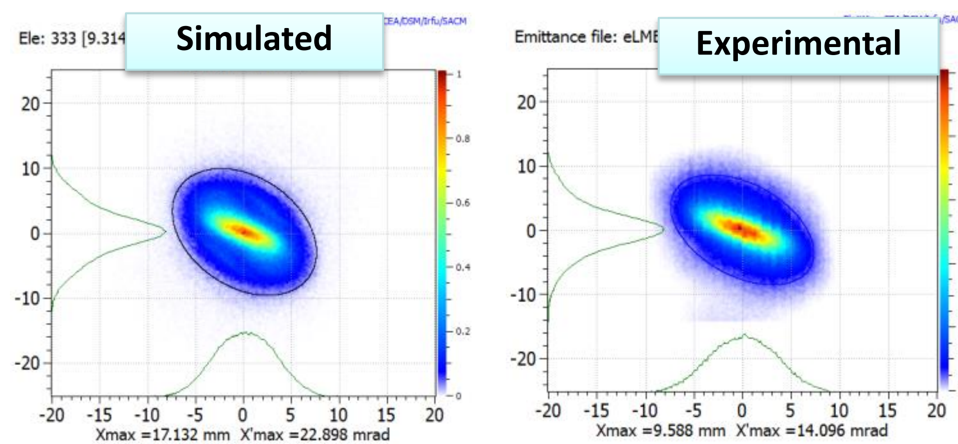
- Measurement of the beam characteristics with several diagnostics
- Comparison with simulation results (TOUTATIS)
  - RFQ transmission
  - Transverse Emittance
  - Longitudinal Emittance



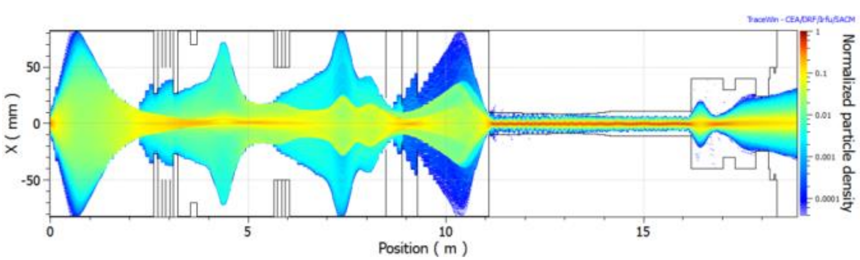


Proton
5 mA, CW

LME XX' emittance



Simulation with TraceWin and Toutatis codes



Good agreement between beam dynamics simulation and measurements

Future work

- RFQ qualification with Beam (**DONE**)

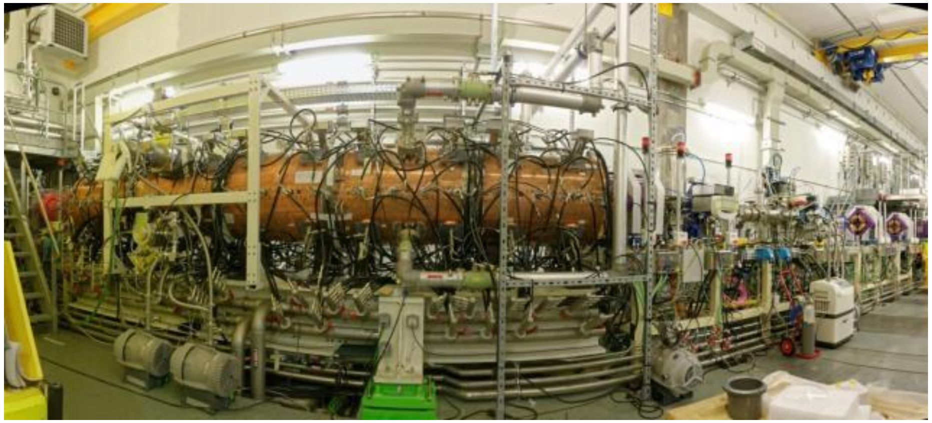
December 2015	**Proton (A/Q = 1)**	**Voltage= 50 kV**	**Power = 35 kW**
March 2016	**Helium $^{4}He^{2+}$ (A/Q = 2)**	**Voltage = 80 kV**	**Power = 89 kW**

- Fourth amplifier has been fixed 3 weeks ago

Today: Conditioning until:

100kV in CW mode
119kV In pulsed mode (5% of DC)

(Nominal value: 113kV)



- To be done in the next weeks

Mai 2016	**Complete the conditioning**		
June 2016	**Oxygene $^{18}O^{6+}$ (A/Q = 3)**	**Voltage = 113 kV**	**Power = 178 kW**
September 2016	**Deuteron (A/Q = 2)**	**Voltage = 80 kV**	**Power = 89 kW**

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- Design flow for RFQ @CEA (SPIRAL2 RFQ example)
- Fabrication and installation of SPIRAL2 RFQ
- Conditioning and commissioning of SPIRAL2 RFQ
- **RFQs developed at CEA**

  - IPHI

  - LINAC4

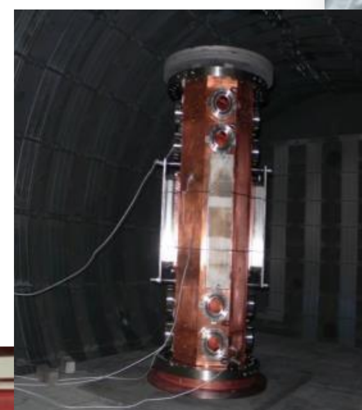
  - ESS
- Conclusion

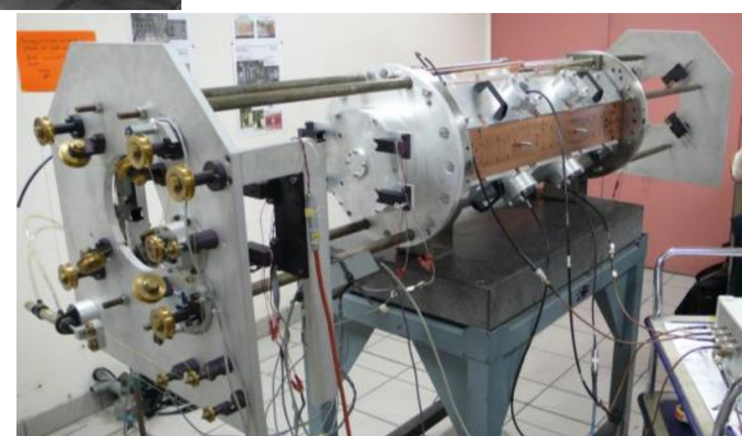
IPHI RFQ

CEA, CERN and CNRS collaboration to build a 3 MeV, 100 mA, continuous proton accelerator at CEA/Irfu for R&D purposes (beam diagnostics, neutron production and moderation, …)

- First RFQ completely designed, built and implanted at CEA
- This RFQ has permit to validate machining and brazing procedures (±30µm of tolerance), RF design and RF tuning methods used for all the RFQ developed by CEA

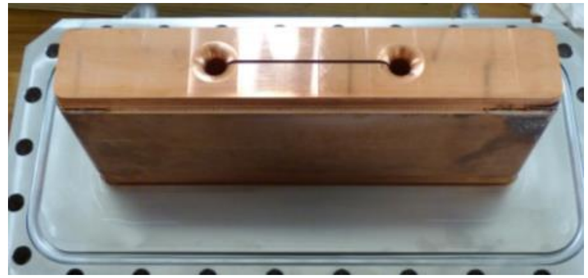
Frequency	352.2 MHz
Output energy	3 MeV
Peak current	100mA
Length	6 m (segmented RFQ)
Voltage	80 to 120 kV
RF power	1.2 MW CW



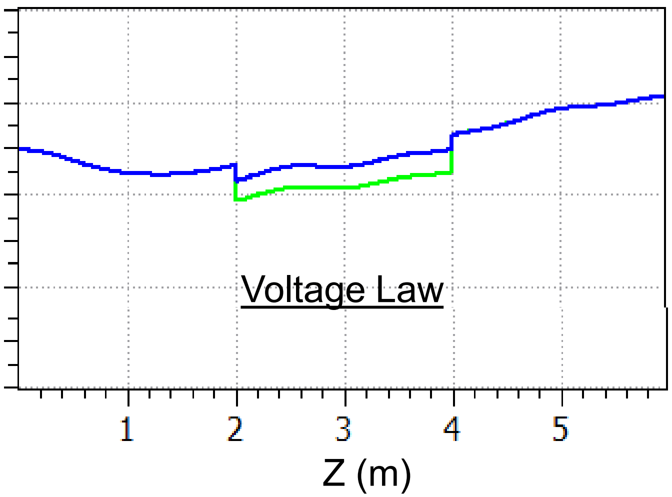


Conditioning

- Conditioning started in April 2015 limited by the cooling system of the RFQ (duty-cycle limited to 1%)
- RF seals have been burned for 2 RF inputs at 900kW peak

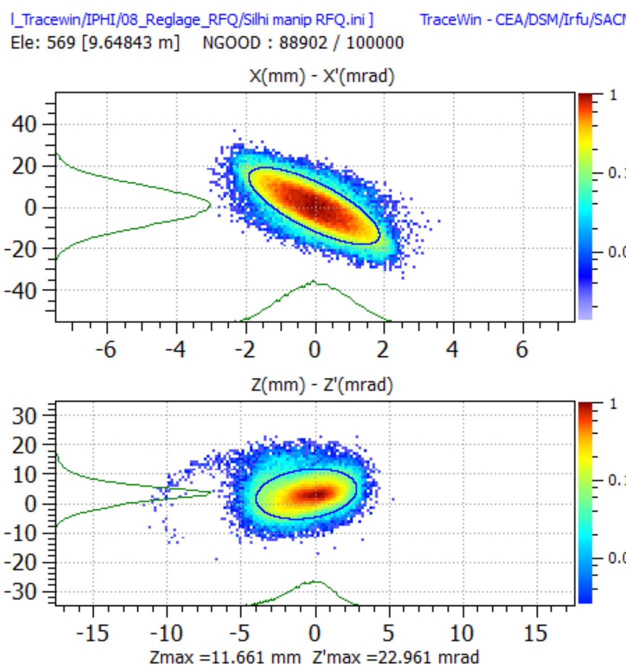


→ RF detuning of 50kHz
Abnormal heating of this 2 RF inputs
10% of error for the voltage law in the section 2 of the RFQ
measured with 96 pick-ups along the RFQ



RF voltage law used as input for beam dynamics calculations

→ **Degradation of the emittance and transmission**



- Reparation: New seal and new design for groove for the 4 RF inputs
- Conditioning restarted in February 2016 until 1.2MW peak with 0.5% of duty cycle

→ **First beam 25th march 2016**

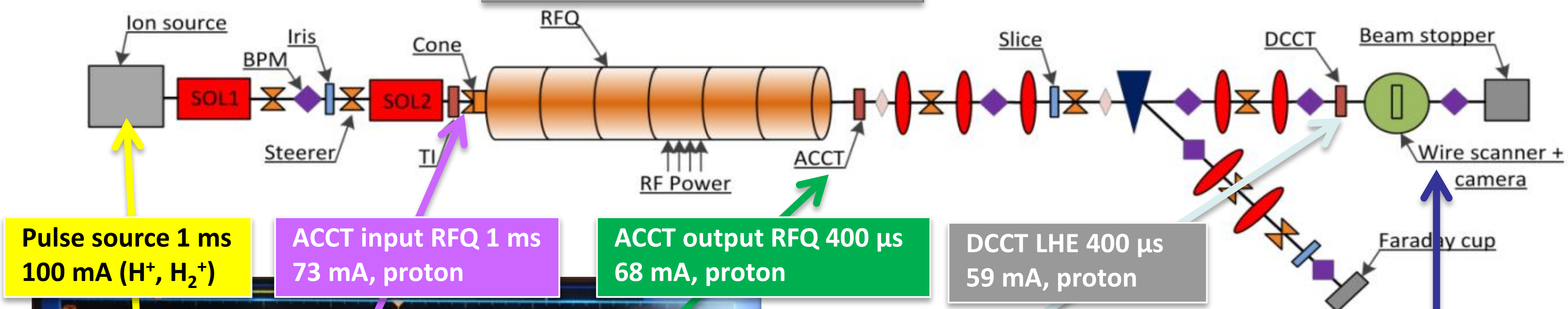
IPHI RFQ

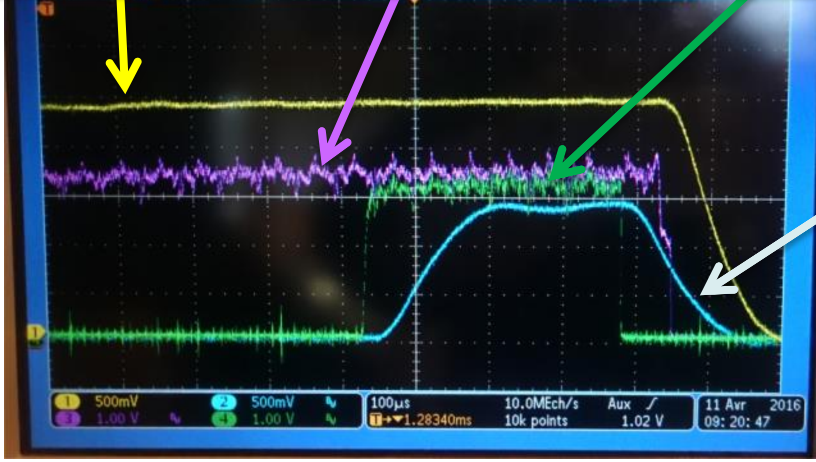
First results obtained 2 weeks ago:

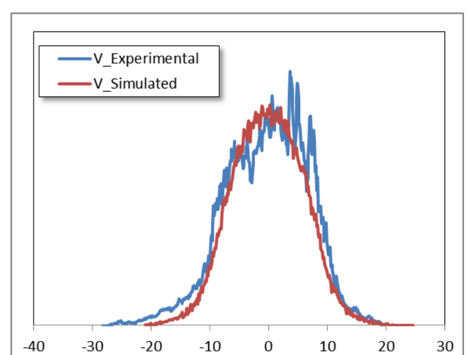
- Measurements of beam characteristics with several diagnostics
- Comparison with simulation results (TOUTATIS)

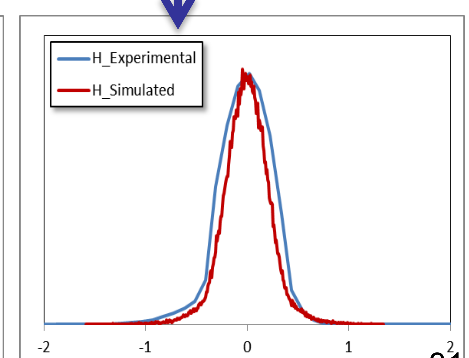
Transmission	Simulated	Experimental
RFQ	98 %	93 %
LHE	100 %	92 %

Pulsed RF @ 400µs/s









➡ **Optimize the beam at the input of the RFQ**
CW mode expected at the end of this year

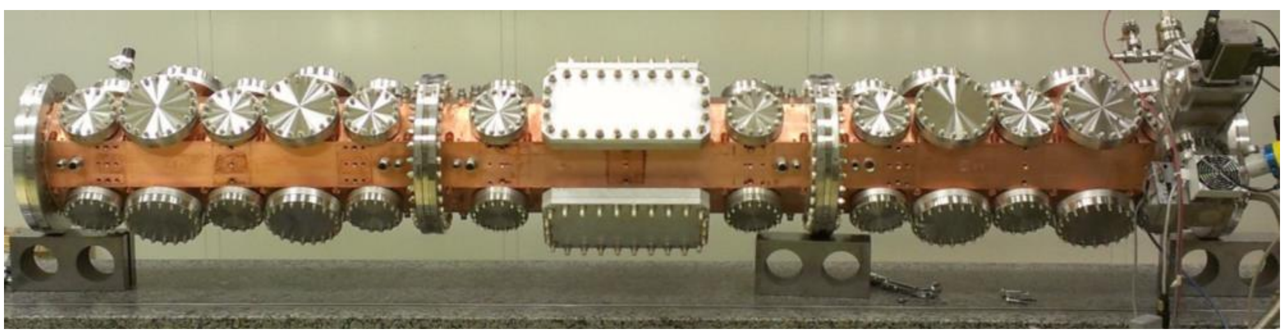
LINAC4 RFQ

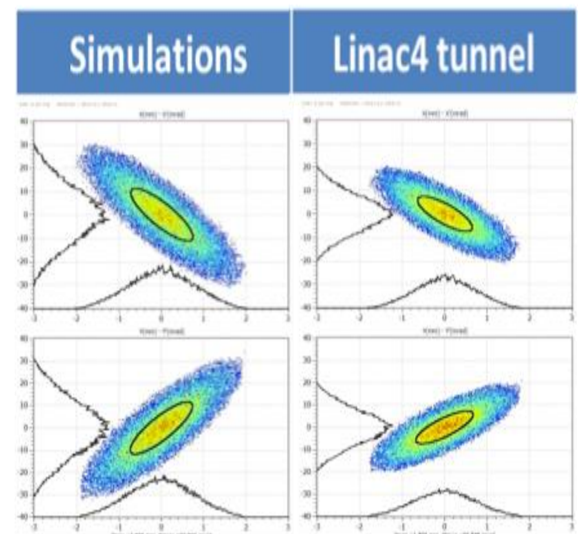
CERN decided to build a new RFQ for LINAC4 accelerator in collaboration with CEA in 2007

- RFQ machined and brazed in CERN with the technics developed during IPHI fabrication

- CEA contributions:
  - RF and thermo-mechanical design
  - RF tuning
  - Measurement of voltage profile during operation vs. RF power, module temperatures, with and without beam

Frequency	352.2 MHz
Energy	3 MeV
Max current	80 mA
Max duty cycle	7.5%
Length	3.06 m
Voltage	78kV
RF power	430 kW





beam transverse emittance profiles

Conditioning and commissioning done in 2013 without difficulties
Performances actually limited by the emittance coming out of the source which is bigger than the RFQ acceptance

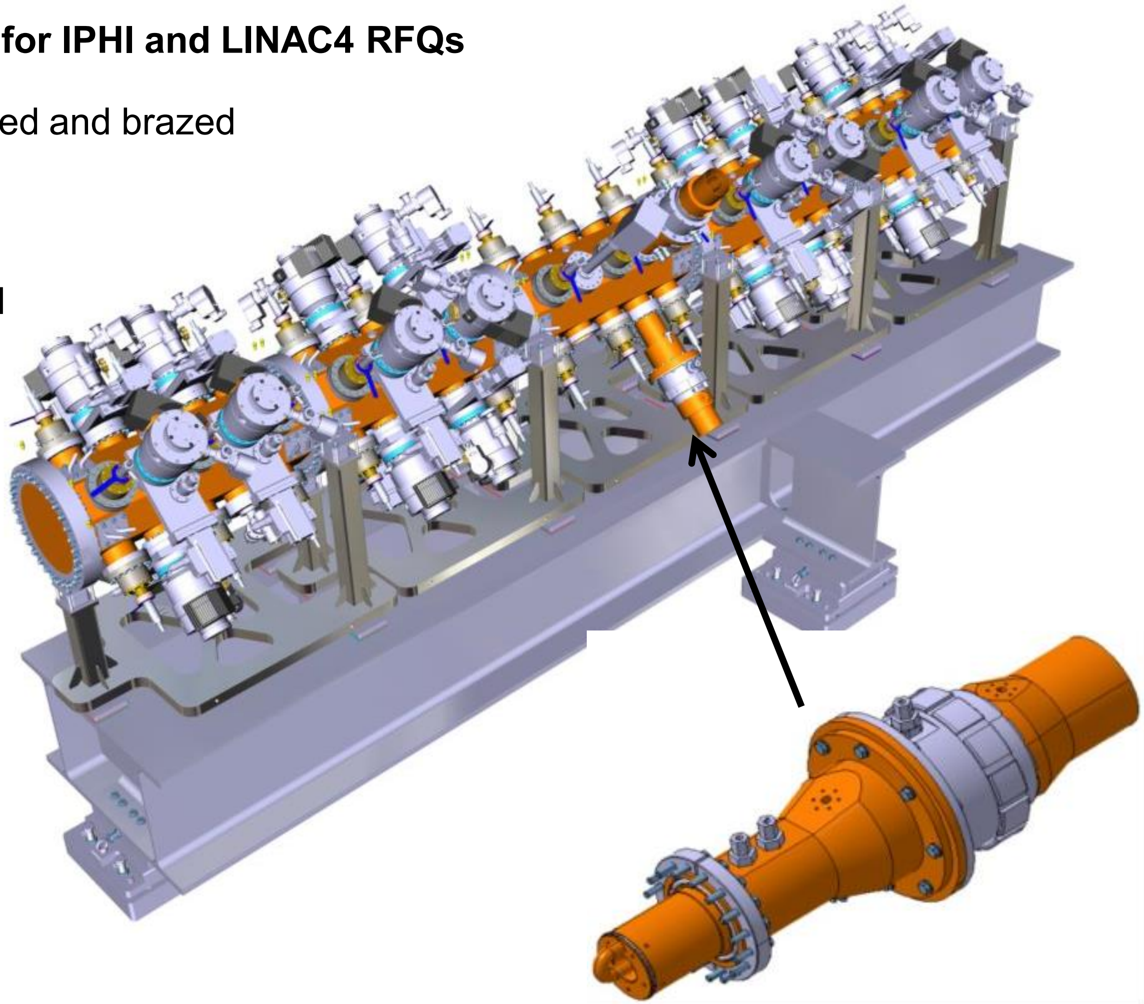
ESS RFQ

Use all the developments done by CEA for IPHI and LINAC4 RFQs

- Five 1-meter long modules machined and brazed

- CEA contributions:
  - RF and thermo-mechanical design
  - Fabrication and installation at Lund
  - Conditioning and commissioning

Frequency	352.2 MHz
Energy	3.62 MeV
Max current	70 mA
Max duty cycle	5%
Length	4.54 m
Voltage	80kV to 120kV
RF power	1300 kW



- Major change compared to IPHI and LINAC4 RFQs: RF power loop (as SPIRAL2 RFQ)

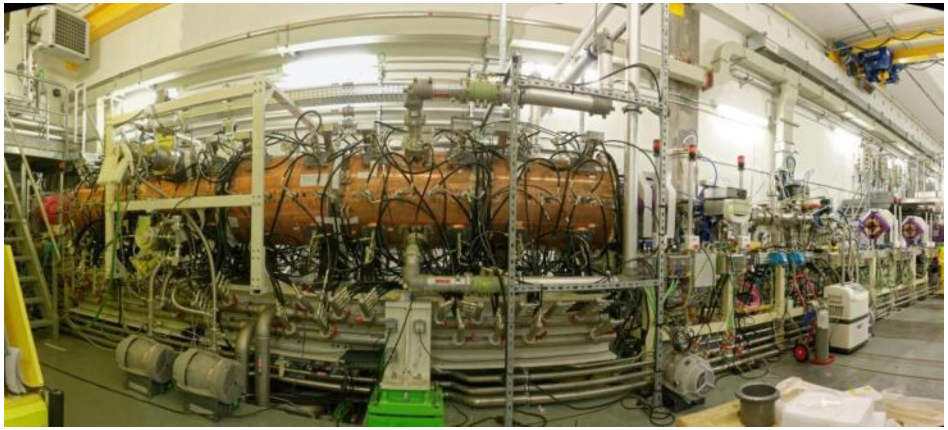
➡ Start of the conditioning expected in April 2018

Poster Today: MOPOY054

Contents

Conclusion

CEA is involved in the design and fabrication of 4 RFQs (IPHI, SPIRAL2, LINAC4 and ESS)



- **Same tools developed at CEA are used for the design and the RFQ validation**:

  1) Toutatis code for beam dynamics
  2) TLM for RF tuning and measurements

- **CEA skills:**

  Beam dynamics simulation
  RF tuning
  Mechanical engineering
  Fabrication (brazing or not)
  Conditioning
  Commissioning

- **Strong program for the next months:**

  1) End of conditioning and commissioning of 2 CW RFQs: IPHI and SPIRAL2
  2) Start of the fabrication of the ESS RFQ