SARAF 4-rod RFQ RF power line splitting design and test

LINAC 2016

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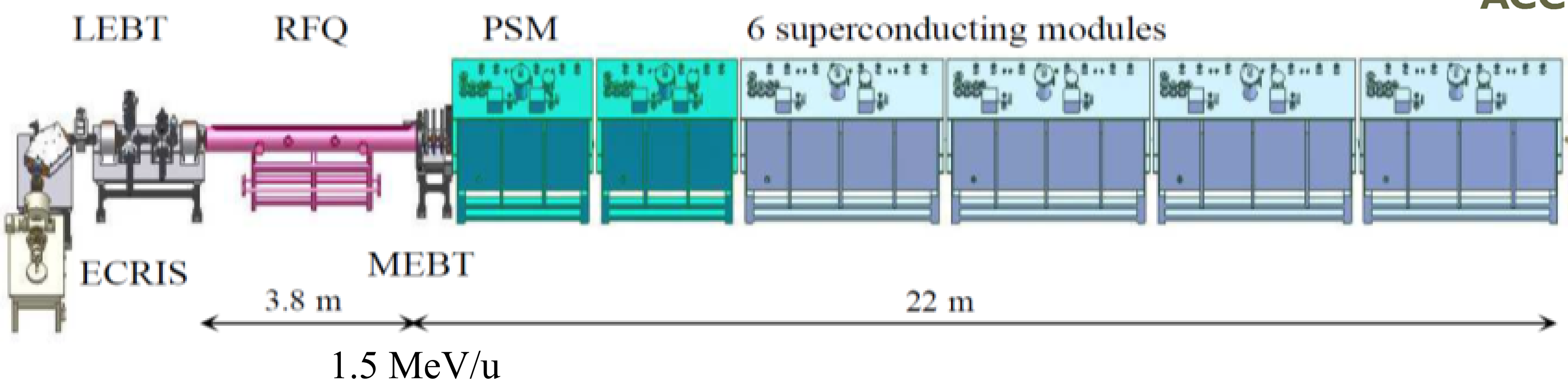
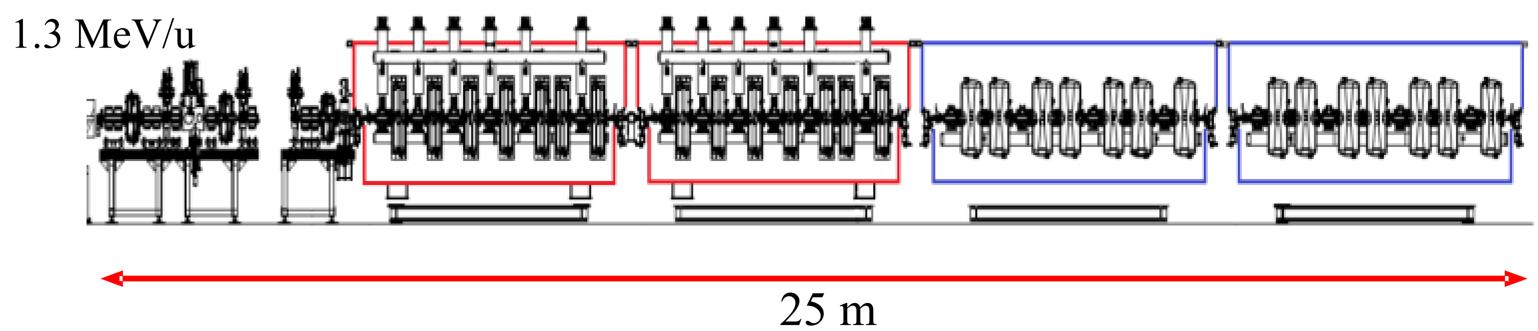
SARAF Soreq NRC

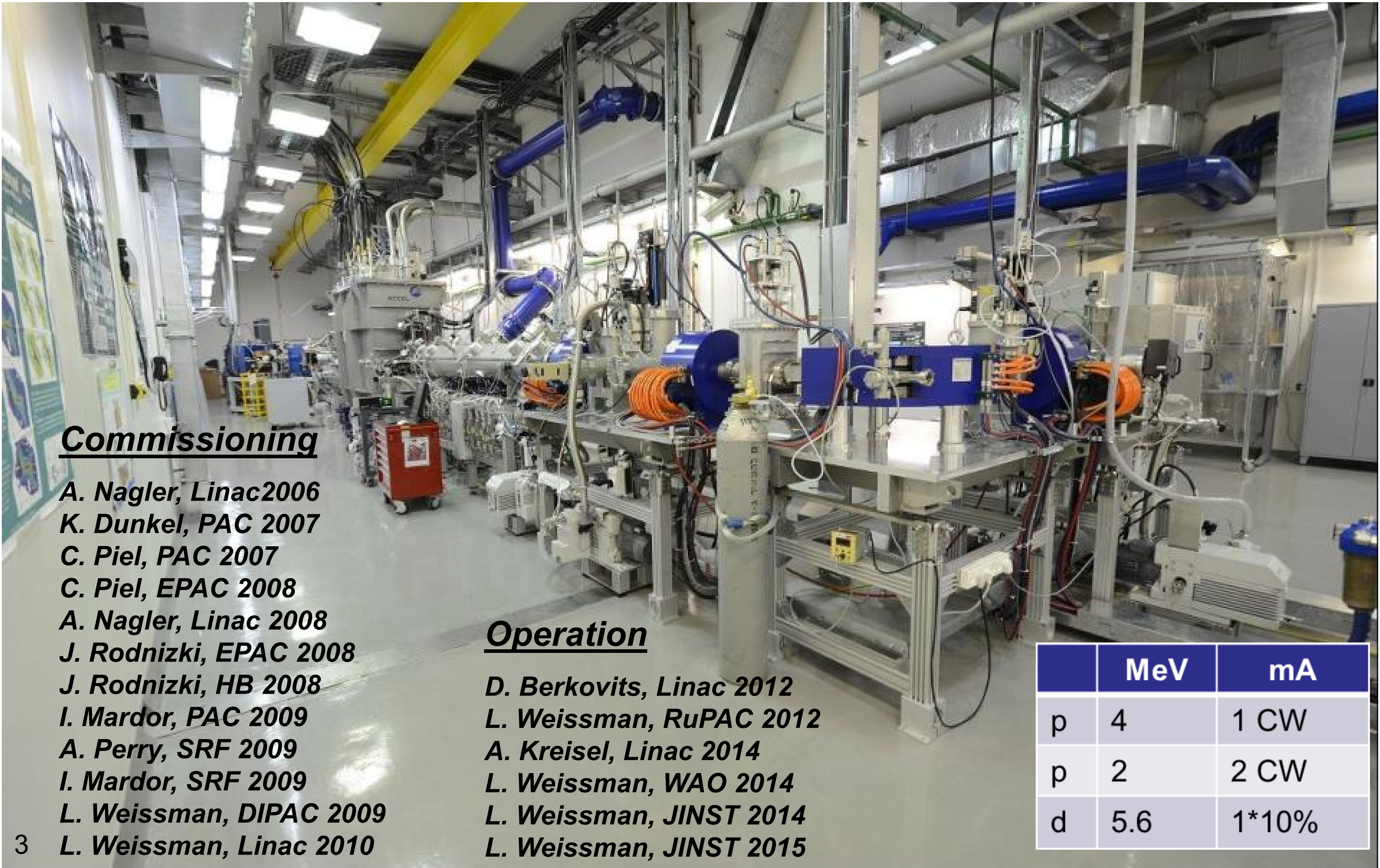
linac lattice in 2006 and today





SC linac status	N. Pichoff	MOPOY053
SC HWR physical design	G. Ferrand	MOPRC025
SC HWR mechanical design	N. Misiara	MOPRC026
NC MEBT rebuncher	B. Kaizer	MOPLRO050

SARAF Phase-I Accelerator



Commissioning

A. Nagler, Linac2006
K. Dunkel, PAC 2007
C. Piel, PAC 2007
C. Piel, EPAC 2008
A. Nagler, Linac 2008
J. Rodnizki, EPAC 2008
J. Rodnizki, HB 2008
I. Mardor, PAC 2009
A. Perry, SRF 2009
I. Mardor, SRF 2009
L. Weissman, DIPAC 2009
L. Weissman, Linac 2010

Operation

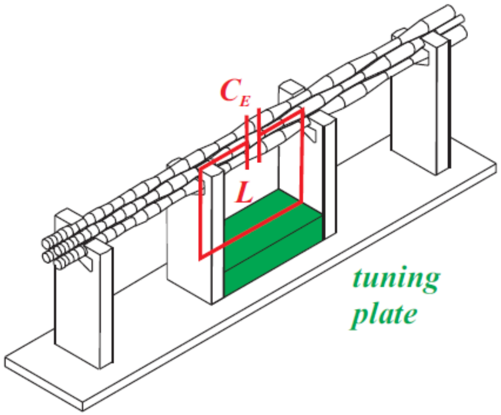
D. Berkovits, Linac 2012
L. Weissman, RuPAC 2012
A. Kreisel, Linac 2014
L. Weissman, WAO 2014
L. Weissman, JINST 2014
L. Weissman, JINST 2015

	MeV	mA
p	4	1 CW
p	2	2 CW
d	5.6	1*10%

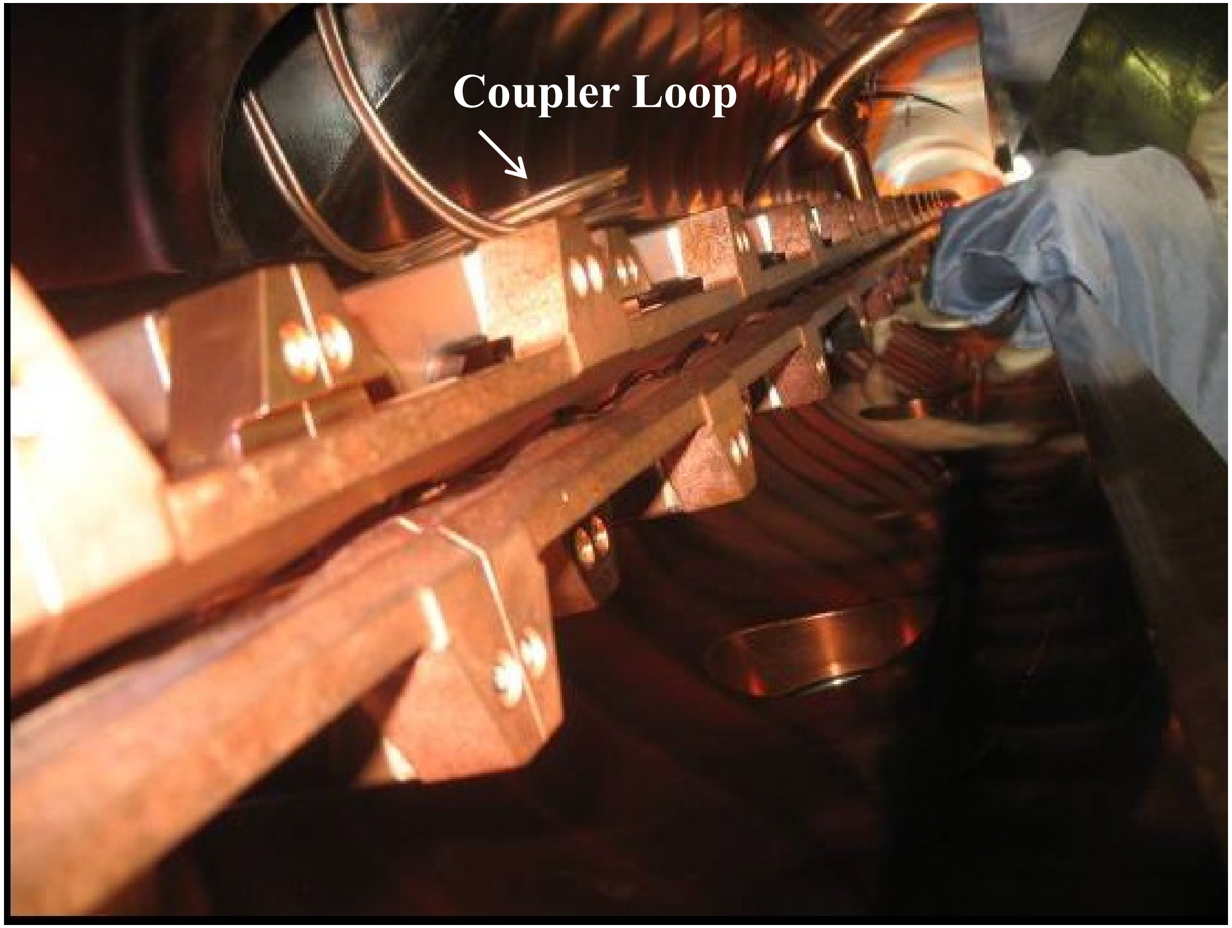
CW 4-rod RFQ - design Parameters

Injection/output energy	20 / 1500 keV/u
Isotope	deuterium
Frequency	176 MHz
electrode voltage	65 kV
RFQ length	3.8 m
inner diameter	280 mm
min. aperture	2.7 mm
max. modulation	2.7
power consumption	250 kW
input emittance $\epsilon_{x,y}$	160 π mm mrad
a / b	0.85 / 0.28 mm mrad^{-1}
number of cells	199
number of stems	40
long. output emittance ϵ_l	75 π deg. keV/u
transmission 0 / 5mA	98 / 96 %

- P.Fischer, *A.Schempp Linac 2006*



The SARAF 4-rod RFQ coupler



- The RFQ includes one coupler with an antenna loop to supply the 260 kW needed to accelerate 5 mA CW deuteron beam

Recent years main limitations

- Following conditioning campaigns the RFQ was capable to reach 200 kW CW dissipated power for few times
- During RFQ operation we faced deteriorations of the RFQ performance
- The RFQ coupler was found to be the bottle neck that prevented long term CW operation at high dissipated power.

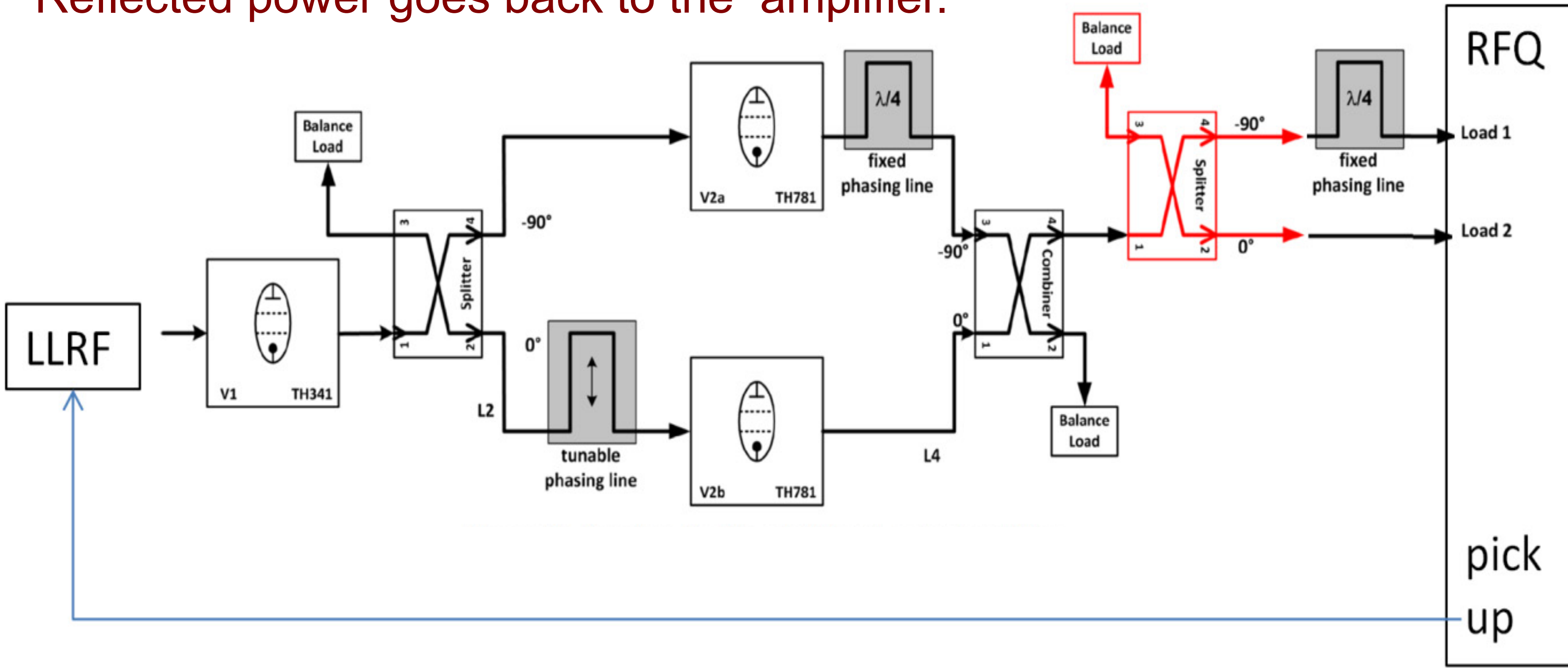
2015 RFQ RF splitting roadmap

- Splitting the RFQ RF line to two couplers to reduce the RF load on each coupler
- Improve the coupler design to eliminate potential failures
- Couplers loop design and matching
- Conditioning the RFQ to find the available CW dissipated power to reach long term stable operation in the new configuration with reduced fields and dissipated power in the range of 170-200 kW
- RFQ deuteron beam operation test
- An accomplished step will be a design of new rods modulation with reduced fields and dissipated power to gain a long term CW RFQ operation.

Splitting the RFQ RF line to two couplers to reduce the RF load on each coupler

RF design for operation with two couplers

- LLRF control scheme is not effected
- Fixed phasing line to reach RF loops synchronization
- The 3dB splitter avoids cross talk
- Coupling is reached during the installation stage
- Directional couplers pickup output is presented and recorded
- Reflected power goes back to the amplifier.

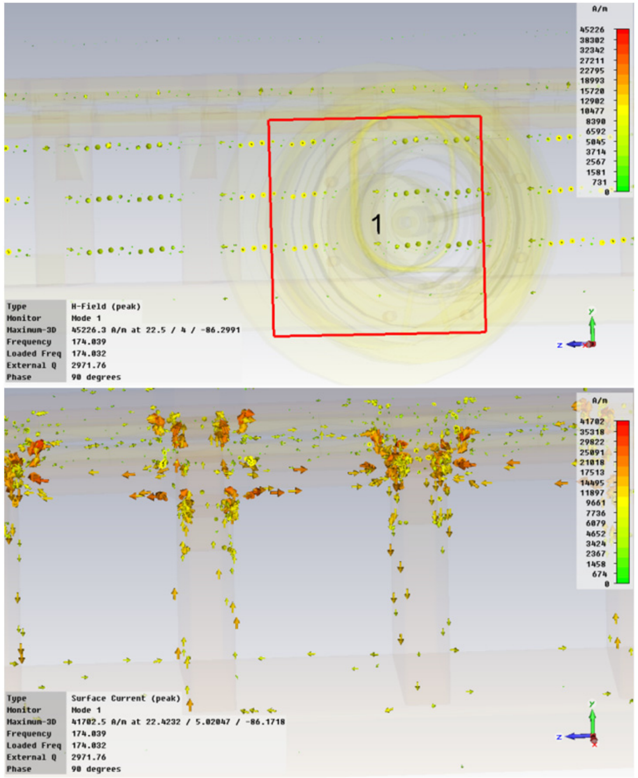


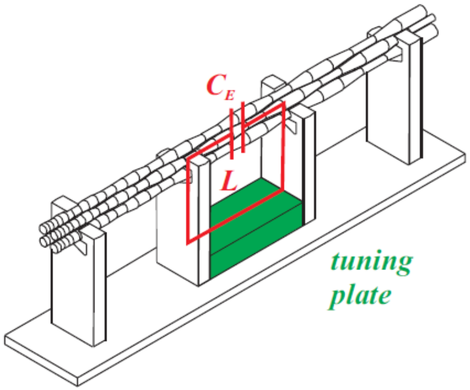
The synchronization phase between the ports

- The eigenmode magnetic field change sign between adjacent RF cells
- The synchronized RF phase between the couplers ports is 180º due to even # of cells between the ports
- 1º deviation in phase at 176 MHz ~5 mm deviation in the fixed phasing line length →
- $A\cos(wt-\alpha/2)+A\cos(wt+\alpha/2)$ $=2A\cos(wt)\cos(\alpha/2)$

$$\frac{Pf_{synchronised}}{Pf}=\cos^2\left(\frac{\alpha}{2}\right)=0.9999$$

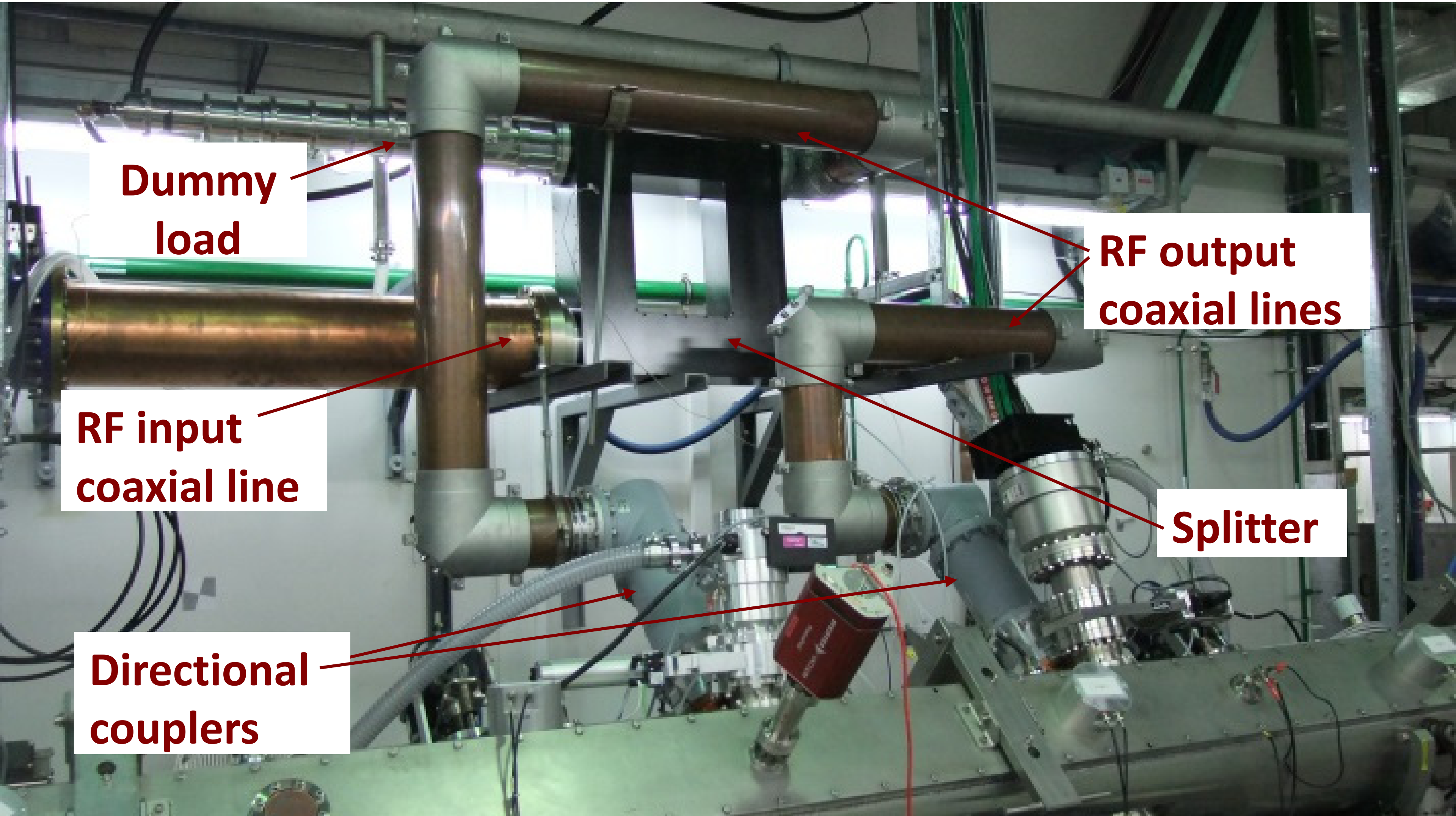
where $H_1=A\cos(wt+\alpha/2)$ and
$H_2=A\cos(wt-\alpha/2)$
$\alpha=1°$





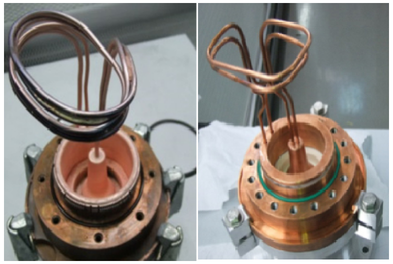
If the fixed rigid line is not matched properly that will result in additional reflected power. However for phase deviation of 1°, the additional reflected power is negligible.

Splitting the RFQ RF line with the new designed couplers

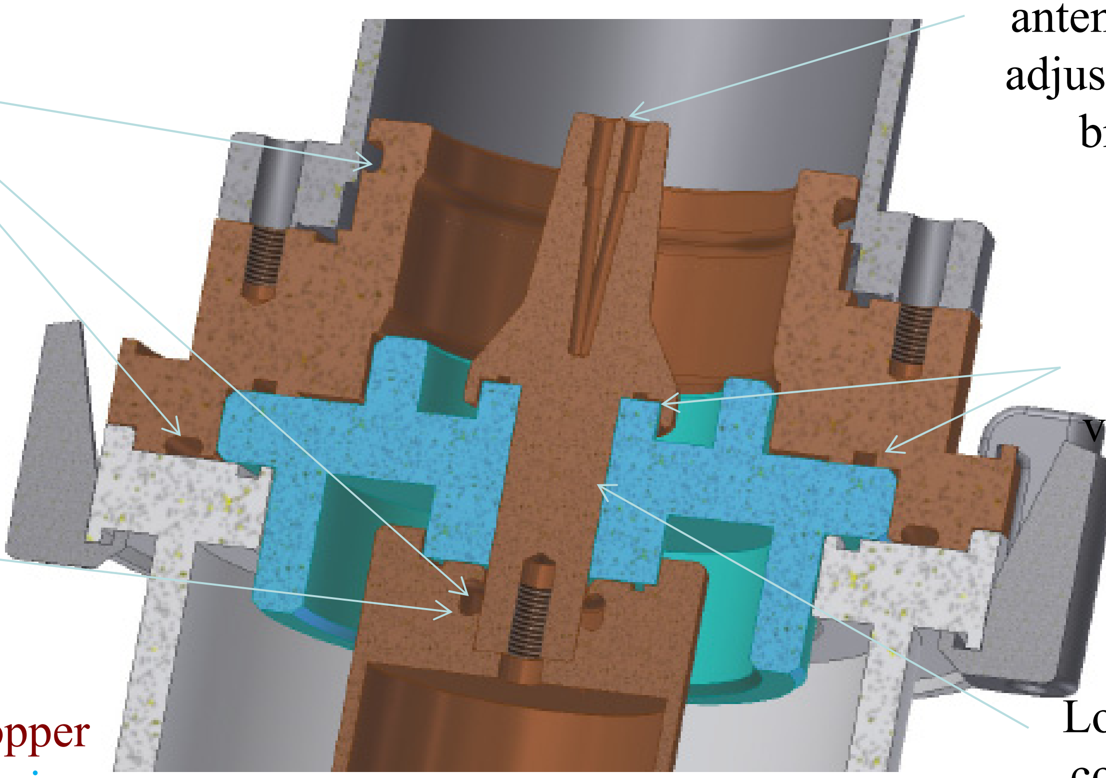


Improve the coupler design to eliminate potential failures

New coupler design



Former design | New design

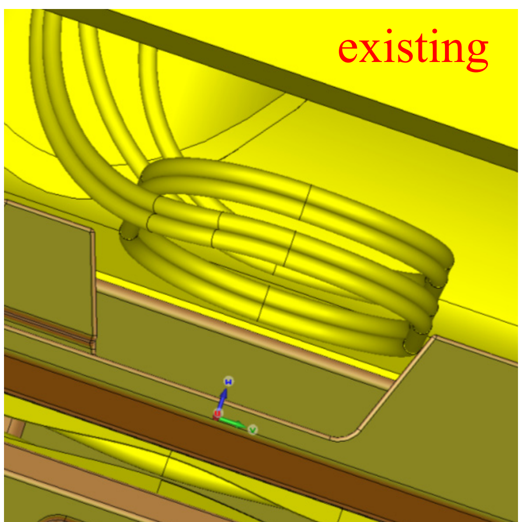


Brown – copper
Blue - ceramic
Gray – SS or aluminum

Couplers loop design and matching

Antenna design

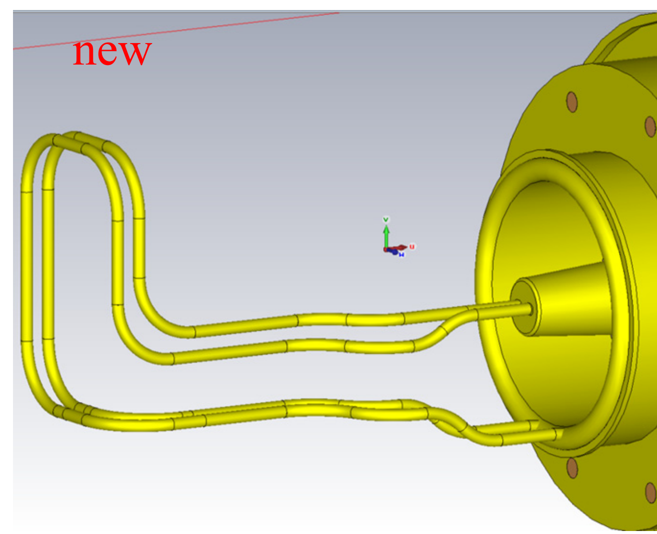
- One loop antenna advantages:
  - Lower coupling is required, due to the installation of 2 couplers
  - Simplifies the manufacturing procedure
  - Improving the antenna reliability
  - Enable the separation between in\out water tubes (no silver brazing)



Simulation the existing RFQ coupler coupling to Q_{ext}=4000

→

Derive the required configuration to reach Q_{ext}= 8000 (for two couplers)

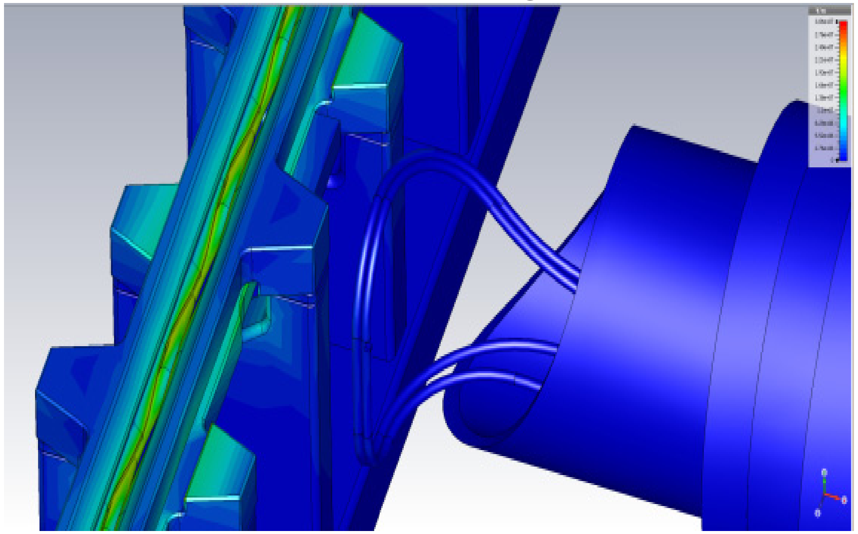


One loop Antenna design

- Loop geometry considerations
  - Antenna tuning by rotation or by bending
  - Adequate coupling
  - Antenna reliability

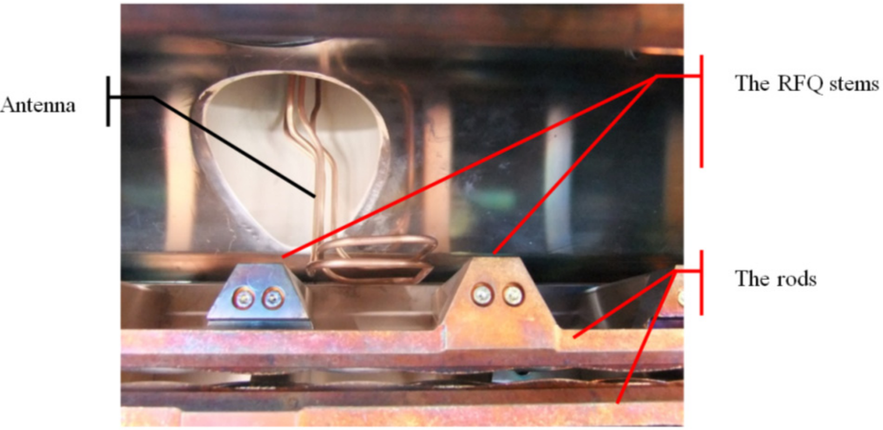
Vertical configuration

parallel configuration



Adequate coupling was achieved only with a “parallel” (to the rods) configuration

Coupling matching procedure



Critical coupling with one antenna is reached by insertion of the antenna between stems

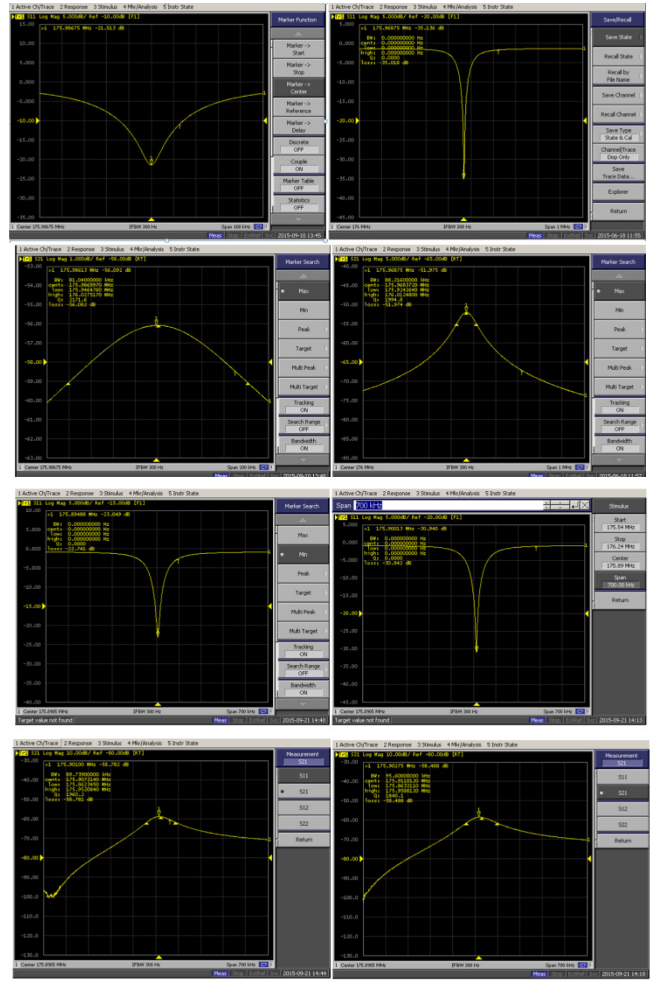
For S_{11}<-40 dB the Q_{load} is evaluated with a network analyser. At this configuration $Q_{ex}=Q_0=2\ Q_{load}$

Each antenna is cut further to reach $Q'_{load}= (4/3)Q_{load}$

Since: $1/Q'_{load}=1/(Q'_{ex})+1/Q_0$
$Q'_{ex}= 2Q_{ex}$

Assembling both together, critical coupling is reached by fine tuning; $Q''_{ex}\sim=Q_{ex}$

intermediate   final



The former antenna reflected S_{11} and pickup S_{21} power as function of the forward power

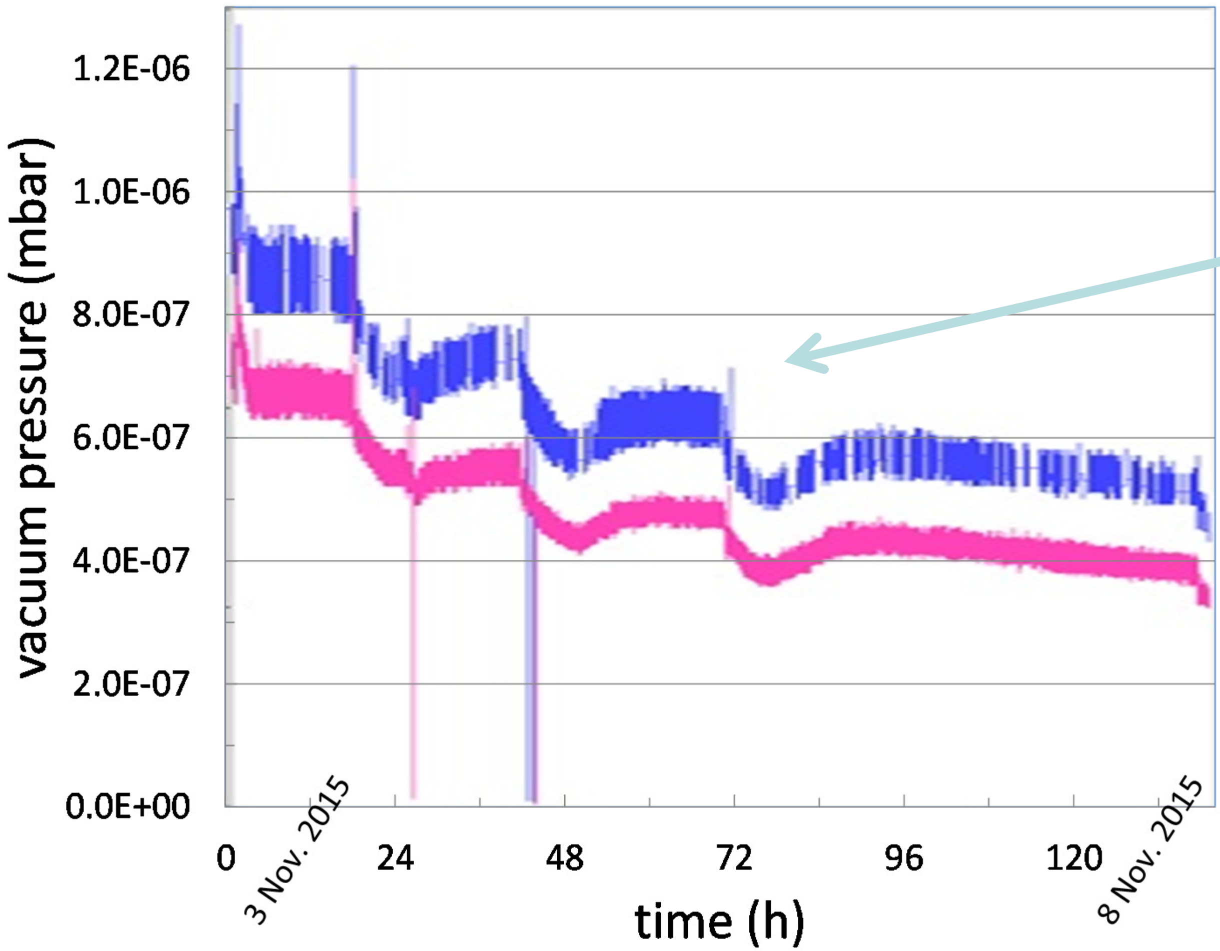
The new antenna reflected S_{11} and pickup S_{21} power as function of the forward power

Conditioning the RFQ to find the available CW dissipated power

RFQ pre conditioning steps

- The chamber was cleaned, rods polished with tissue socked by alcohol
- Diagnostics devices were mounted:
  - a few CCD cameras at the viewports in front of couplers and rods
  - a few x-rays detectors in front of the viewports for monitoring x-ray
  - several thermocouples attached to- tank, water feedthroughs and RF lines
- Chamber was pumped for one week to avoid partial virtual leaks

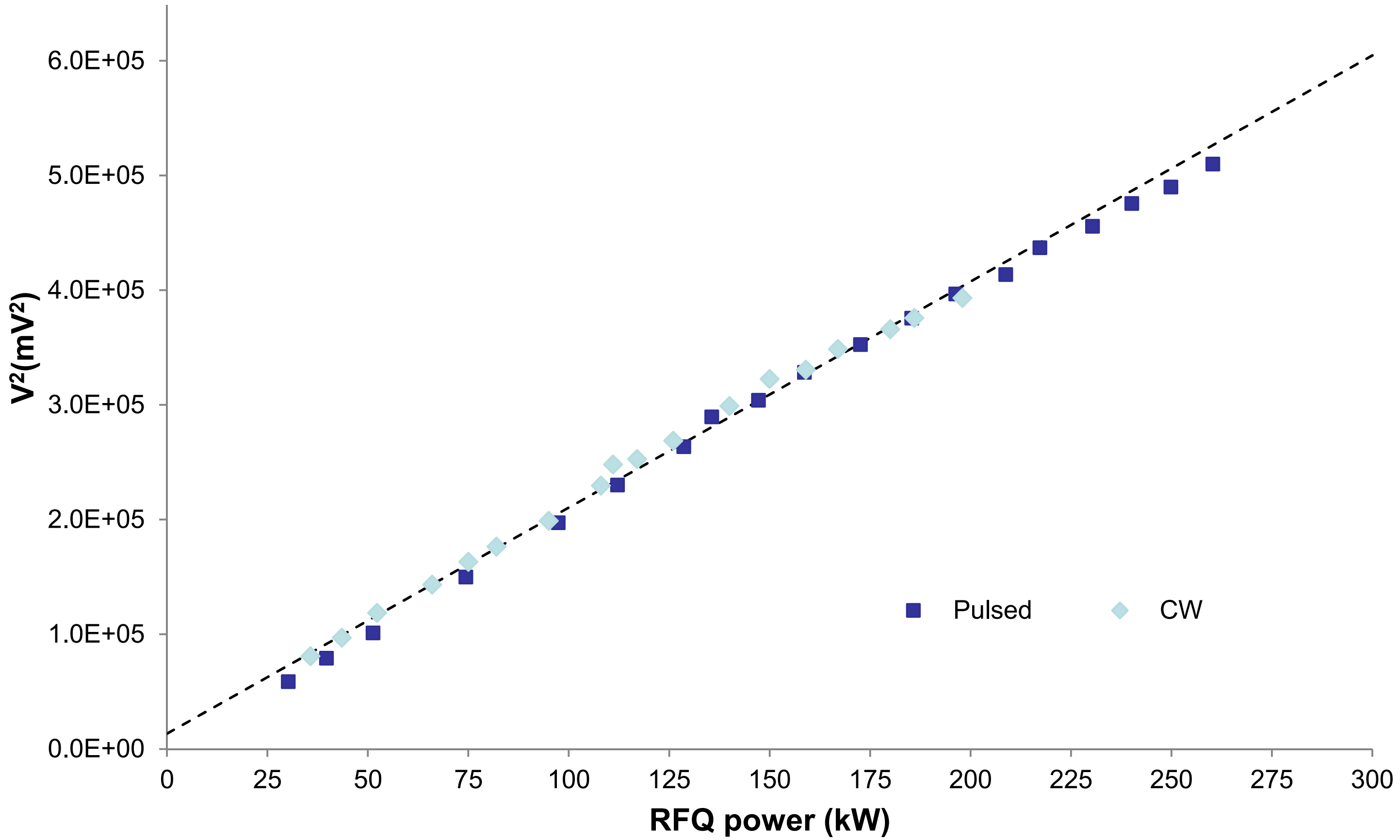
Vacuum development along the first week



when cooling water were cycled vacuum level was improved due to lower surface degassing rate

now the base vacuum level is $2*10^{-7}$ mBar

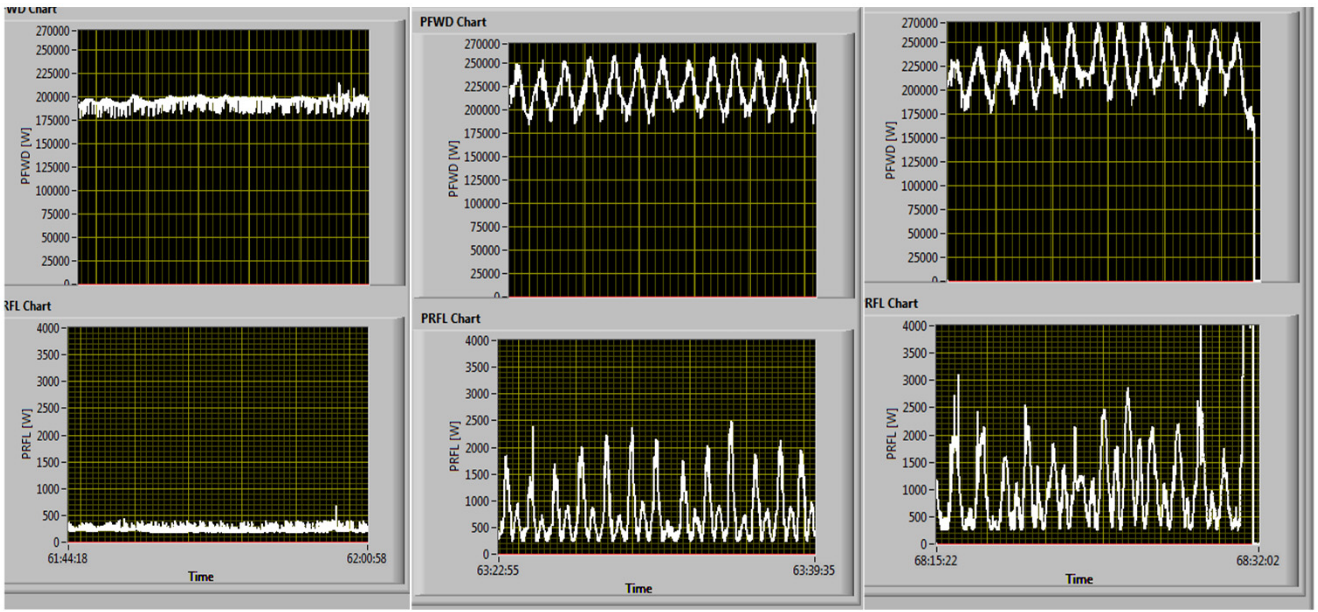
RFQ pickup voltage as function of the forward power



- Linear dependence between the square RFQ pickup voltage to the forward power
- Max deviation 4%

RFQ conditioning campaign

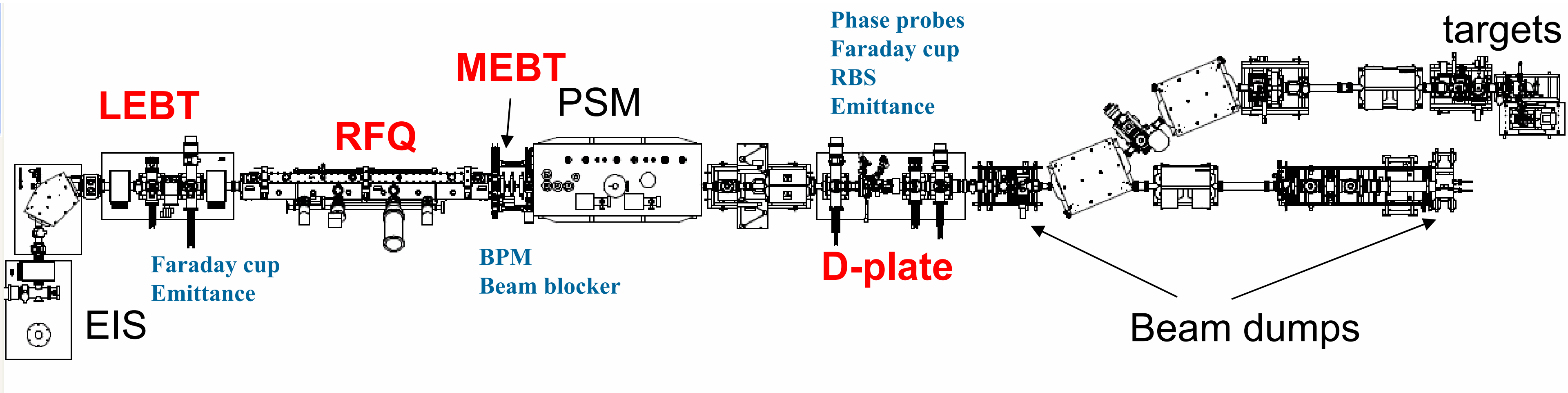
- The conditioning was performed most of the time at CW mode.
- The forward power was increased at low rate to achieve a quasi static thermal behavior of the RFQ, inspected by the thermocouples output temperatures.
- The vacuum level in RFQ RF breaks usually did not increase above 10^{-5} to 10^{-6} mbar.
- Stable and long term operation were systematically demonstrated at 200 kW CW forward power, with 0.2% reflected power and 98% availability.
- Above 200 kW CW forward power, onset of forward and reflected power oscillations initiated. Other 4 rods RFQ projects report on mechanical vibration of the rods at high loads:



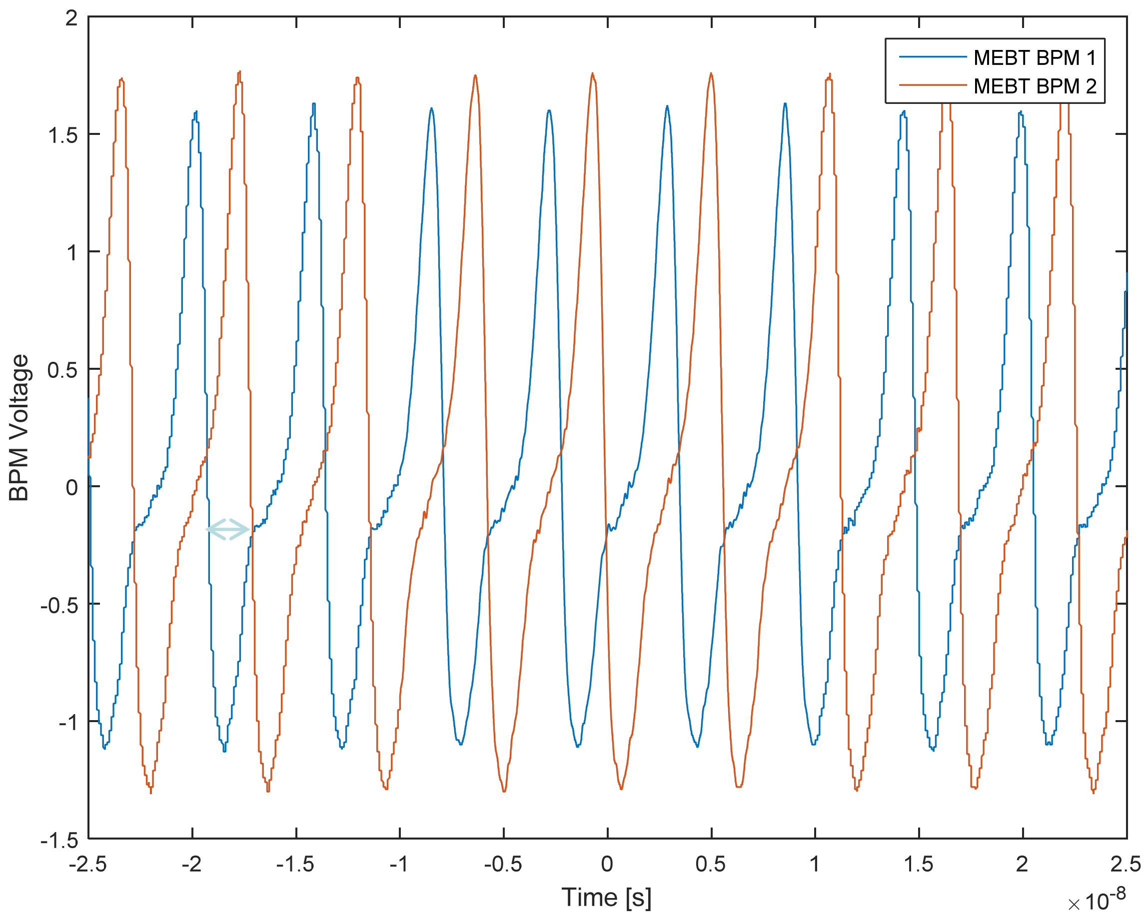
- 50-80% duty cycle were demonstrated at 250 kW incident forward power (the required dissipated power for a deuteron beam operation).

RFQ deuteron beam test

Beam diagnostics along the test

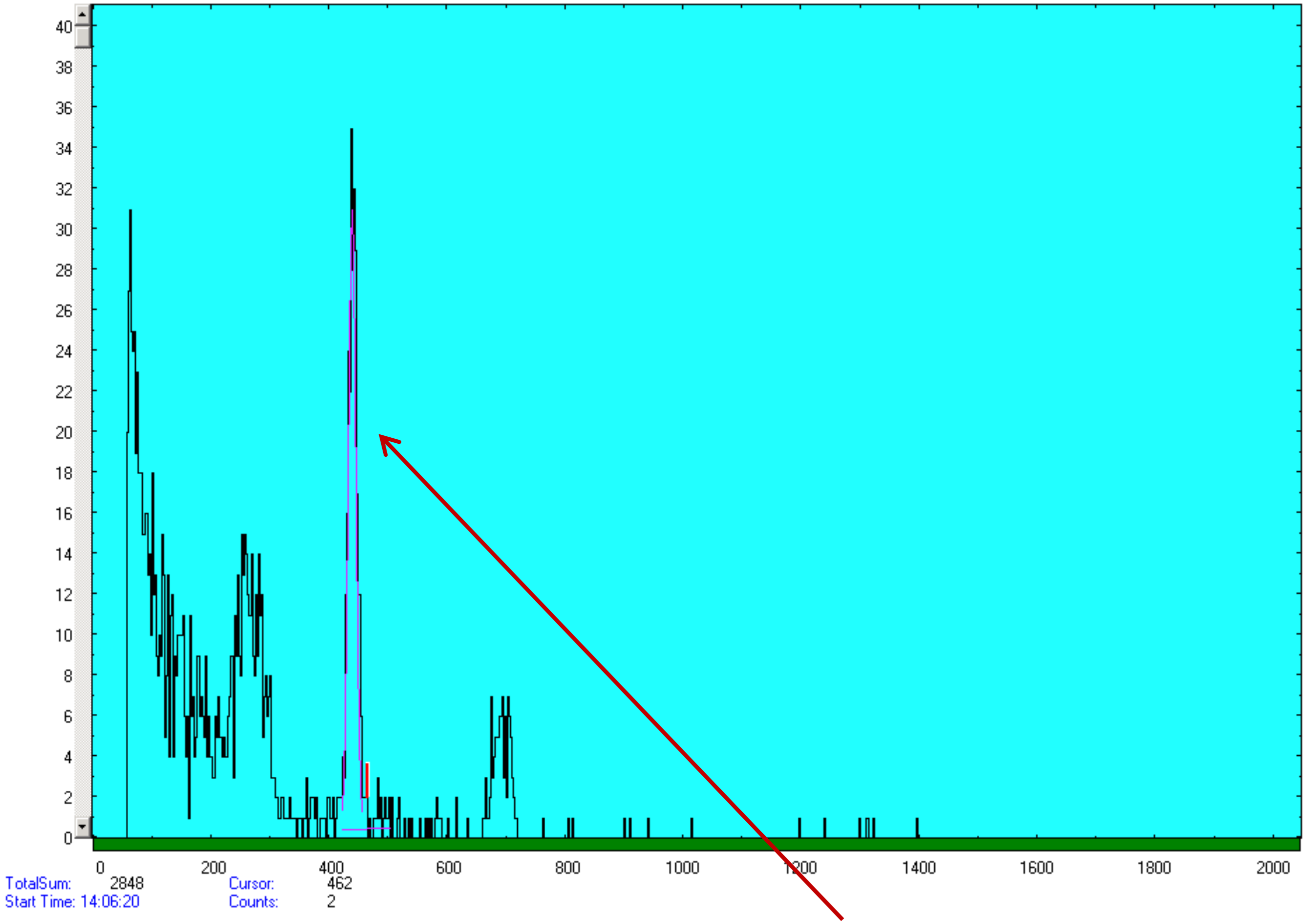


The deuteron beam TOF



The Time Of Flight measurement between the MEBT BPMs confirmed that the deuteron energy downstream the MEBT is 1.5±0.1 MeV/u

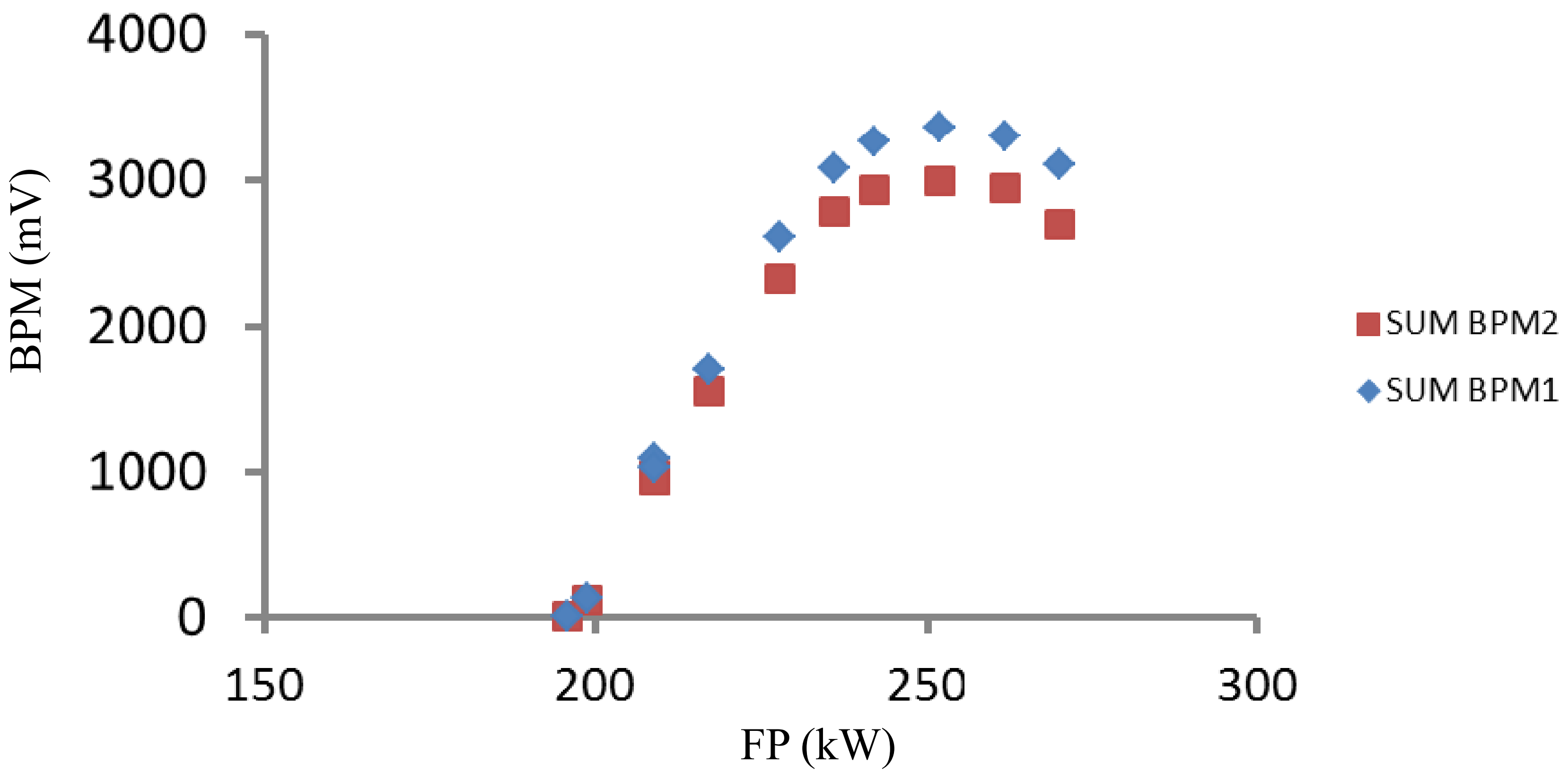
The deuteron Energy distribution RBS measurement



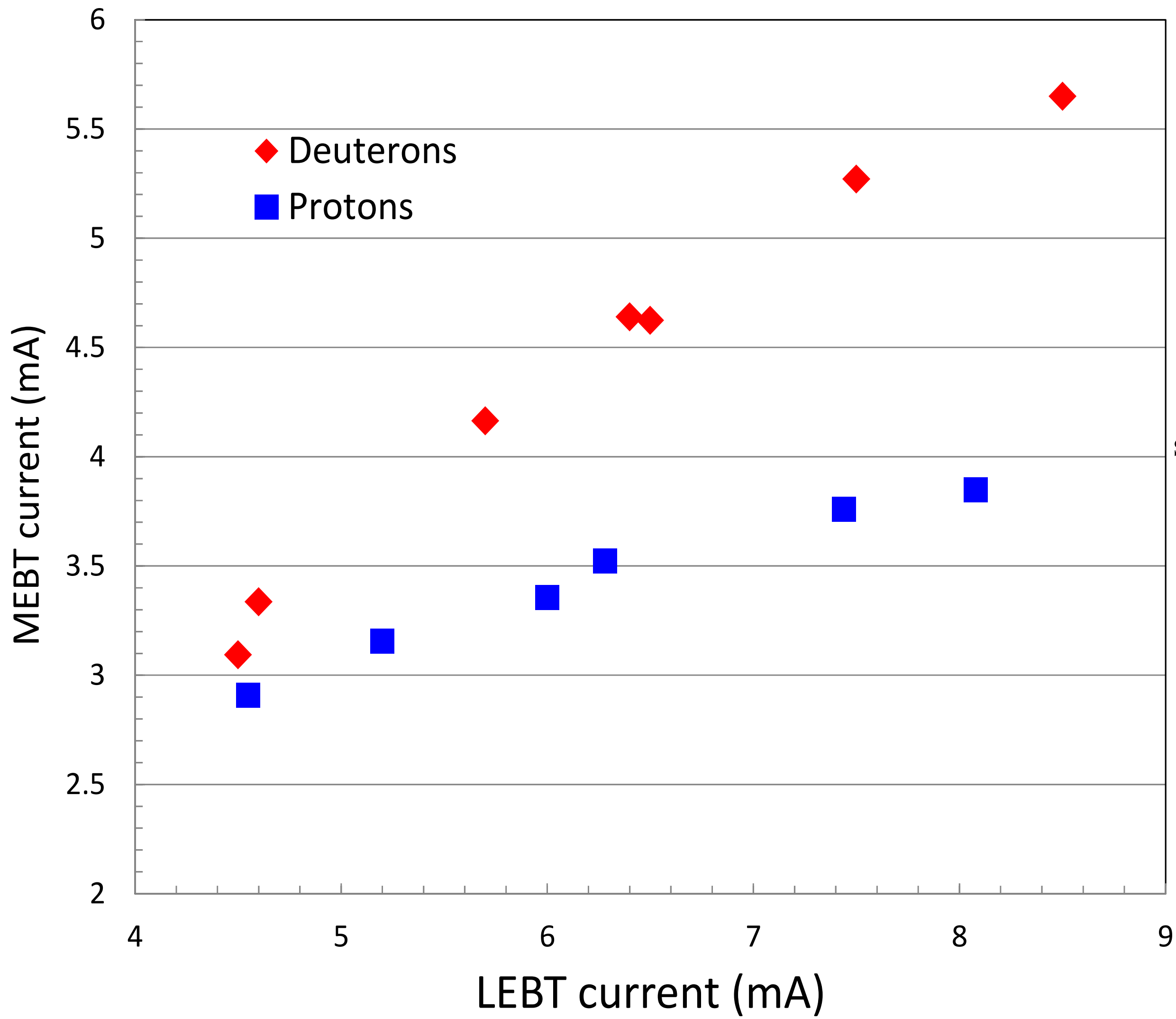
The measurement method is described in L. Weissman et al. DIPAC 2009

RBS measurements of deuteron energy distribution verified that the mean beam energy is 1.50±0.01 MeV/u

BPM 1 (blue) and BPM 2 (red) amplitude as function of RFQ power for 8.5 mA LEBT injected deuteron current



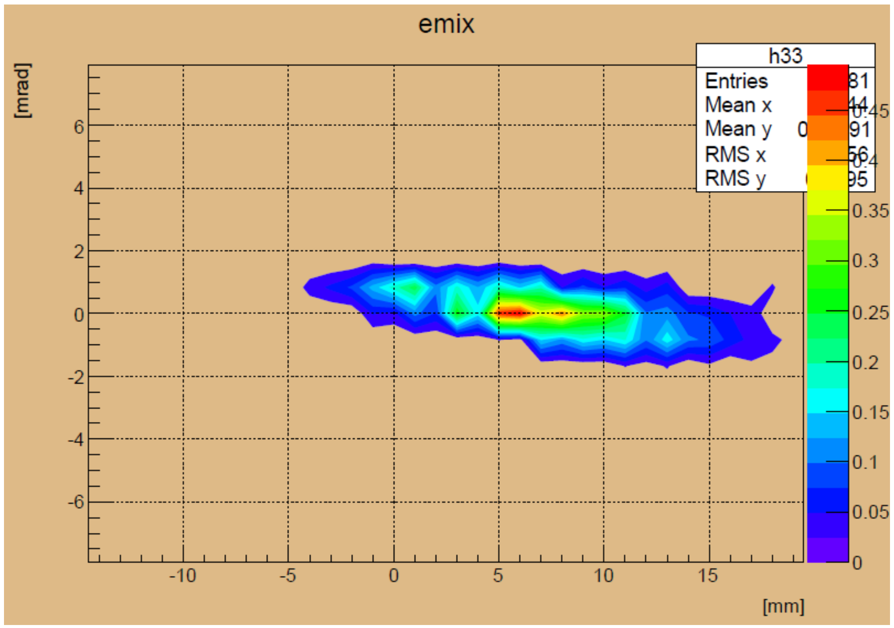
RFQ transmission as function of injected current for a proton and a deuteron beam

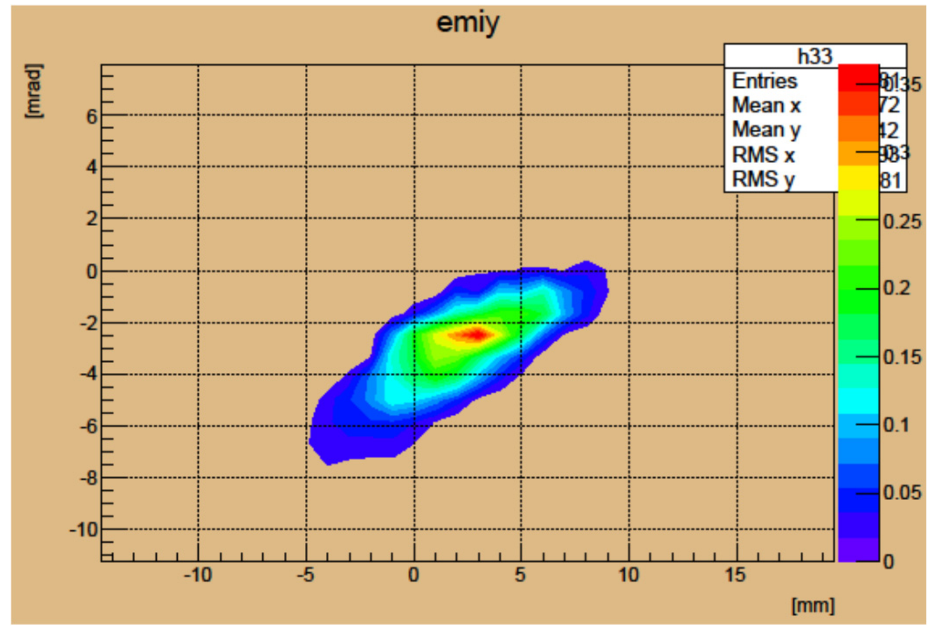


LEBT current is LEBT FC minus RFQ entrance collimator current (0.05-0.15 mA)

MEBT current measured without suppression and corrected assuming 20% secondary electrons yield

RMS emittance measurements for 3.6 mA deutrons at the beam dump downstream the D-Plate (5.9mA at the LEBT FC)





Em x n	alpha	beta
mm mrad		mm/mrad
0.136	-0.701	9.27

Em y n	alpha	beta
mm mrad		mm/mrad
0.162	1.18	2.73

Summary

- New two couplers configuration was proposed design implemented and conditioned at SARAF 4–rod RFQ
- The RFQ reached systematically up to 200 kW dissipated power, with long term stability
- Operation of up to 5.5 mA Deuteron pulsed beam was demonstrated
- The preliminary results of 0.15 mm-mrad RMS normalized transverse emittance measured at the D-Plate downstream the PSM for a 3.6 mA deuteron beam are very encouraging
- The accomplish step is a design of new rods modulation in the range of 200 kW dissipated power with 1.3 MeV/u beam energy
- This pioneer study may contribute to other projects which intend to run CW beams with high power dissipation like FRANZ and MYRRHA 4-rod RFQ.

END

Acknowledgement:

Mr. L. Dadon for the couplers brazing works

Dr. A. Kreisel for his assistance in the beam emittance analysis.

The SARAF team for their support during the work on this project

Personnel of the Soreq workshop for their assistance during manufacturing and installations phases