Upgrade SARAF 4 rods RFQ

L. Weissman on behalf of SARAF and NTG teams

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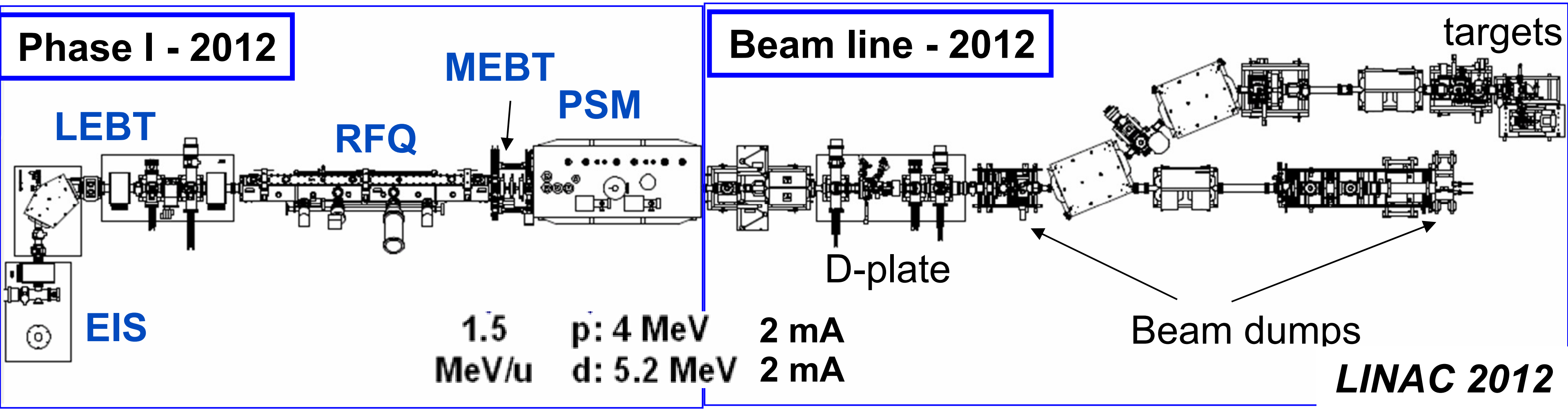
Outline:

- Brief history of SARAF RFQ, motivation for RFQ upgrade
- Installation of the new 4-rod structure
- RFQ conditioning
- Beam characterization with pulsed beams
- Operation of high intensity CW deuteron beam
- Summary and plans for future

SARAF now and tomorrow



- The linac is operated with CW/pulsed protons and pulsed deuterons beams.

  For CW proton beam : 1mA at ~3.7 MeV~ 10 hours/trip

  2 mA at ~ 2 MeV ~ 2 hours/trip

- The accelerator is used to:

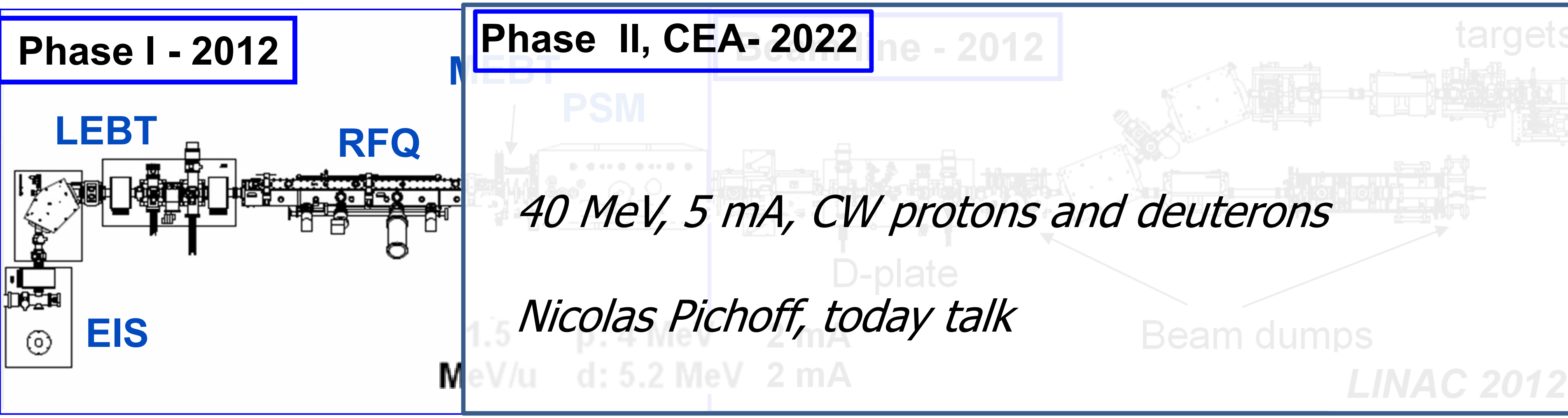
  Collecting expertise with high intensity beams

  Development with high intensity targets

  Research in nuclear astrophysics, physics, material science and medicine

I. Mardor et al. Eur. Phys. J. A (2018)

SARAF now and tomorrow



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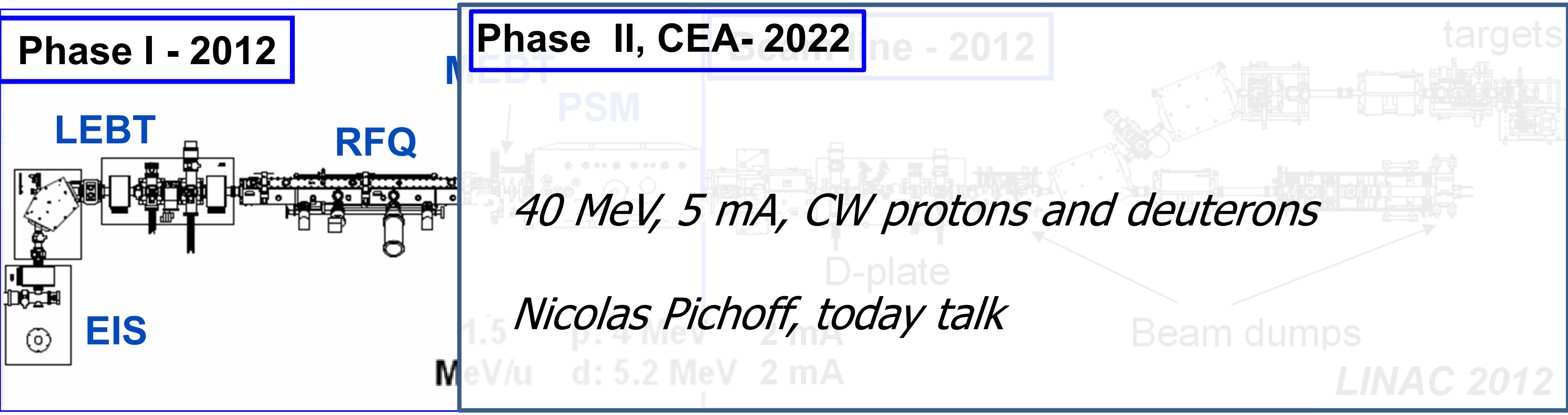
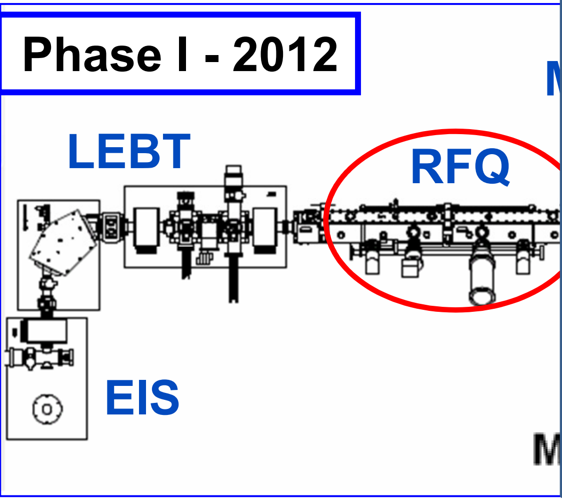


The Phase I components EIS/LEBT/RFQ will serve as injector for Phase II

RFQ - 5 mA CW protons/deuterons

SARAF now and tomorrow



Phase II, CEA- 2022

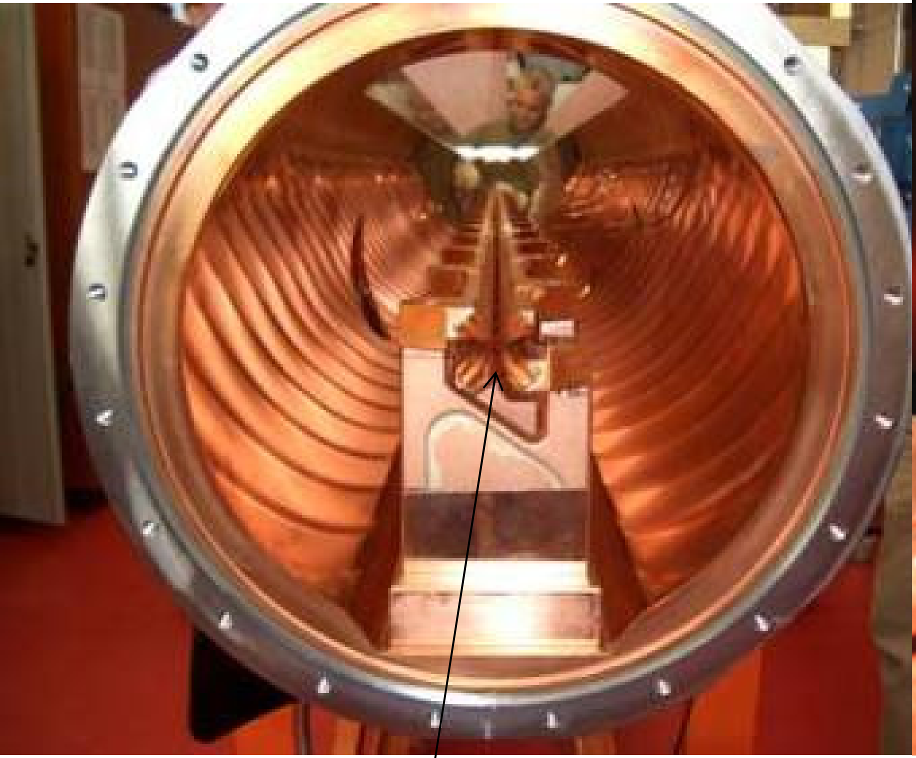
40 MeV, 5 mA, CW protons and deuterons

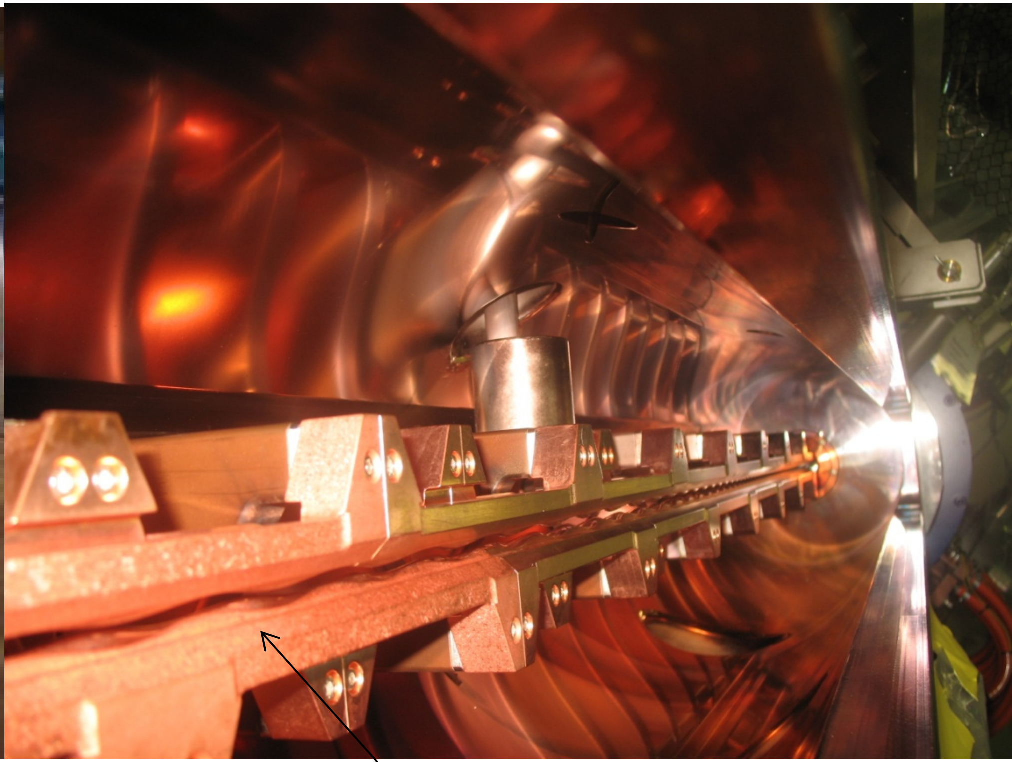
Nicolas Pichoff, today talk

The Phase I components EIS/LEBT/RFQ will serve as injector for Phase II

RFQ - 5 mA CW protons/deuterons

Radio Frequency Quadruple injector





4 rods structure traps and transport the low-energy beam

Acceleration and bunching is performed by sophisticated modulation of the rods

built by NTG/U. Frankfurt

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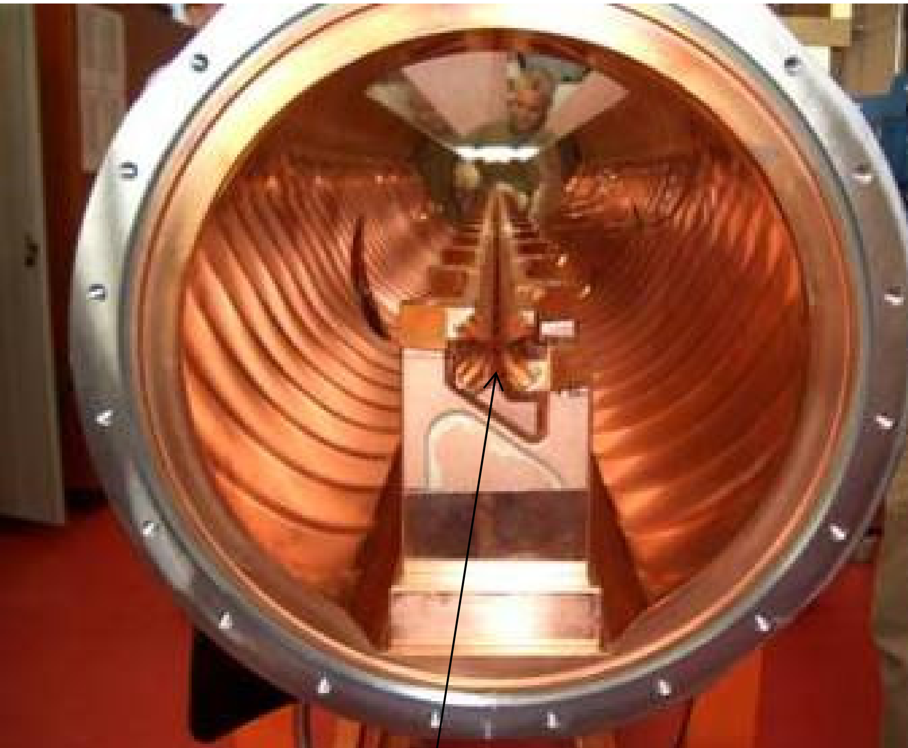

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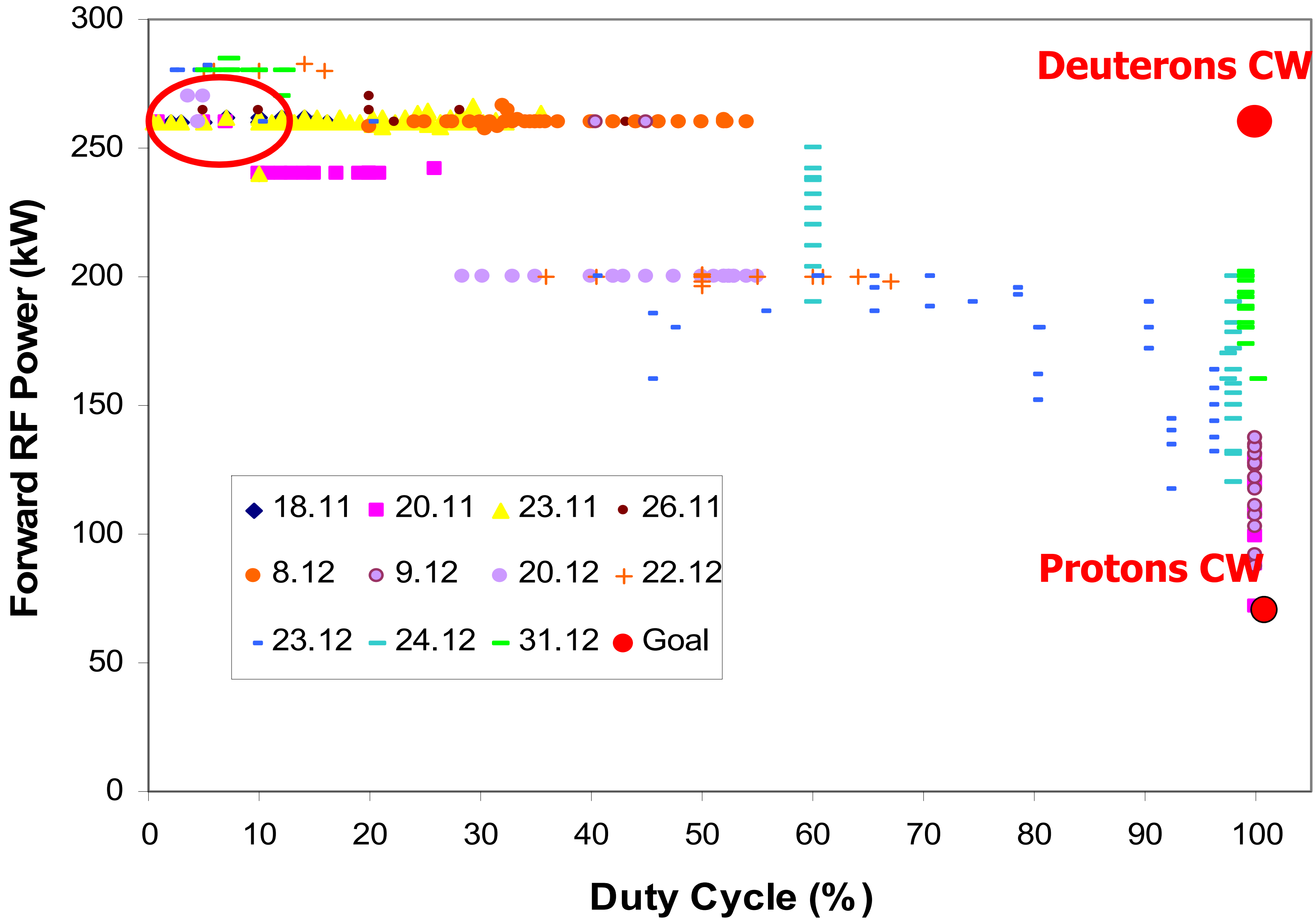
RFQ worked, but ….

Old RFQ conditioning



Stable operation of deuterons only at low DC(<20%)

Old RFQ conditioning

Soreq NRC

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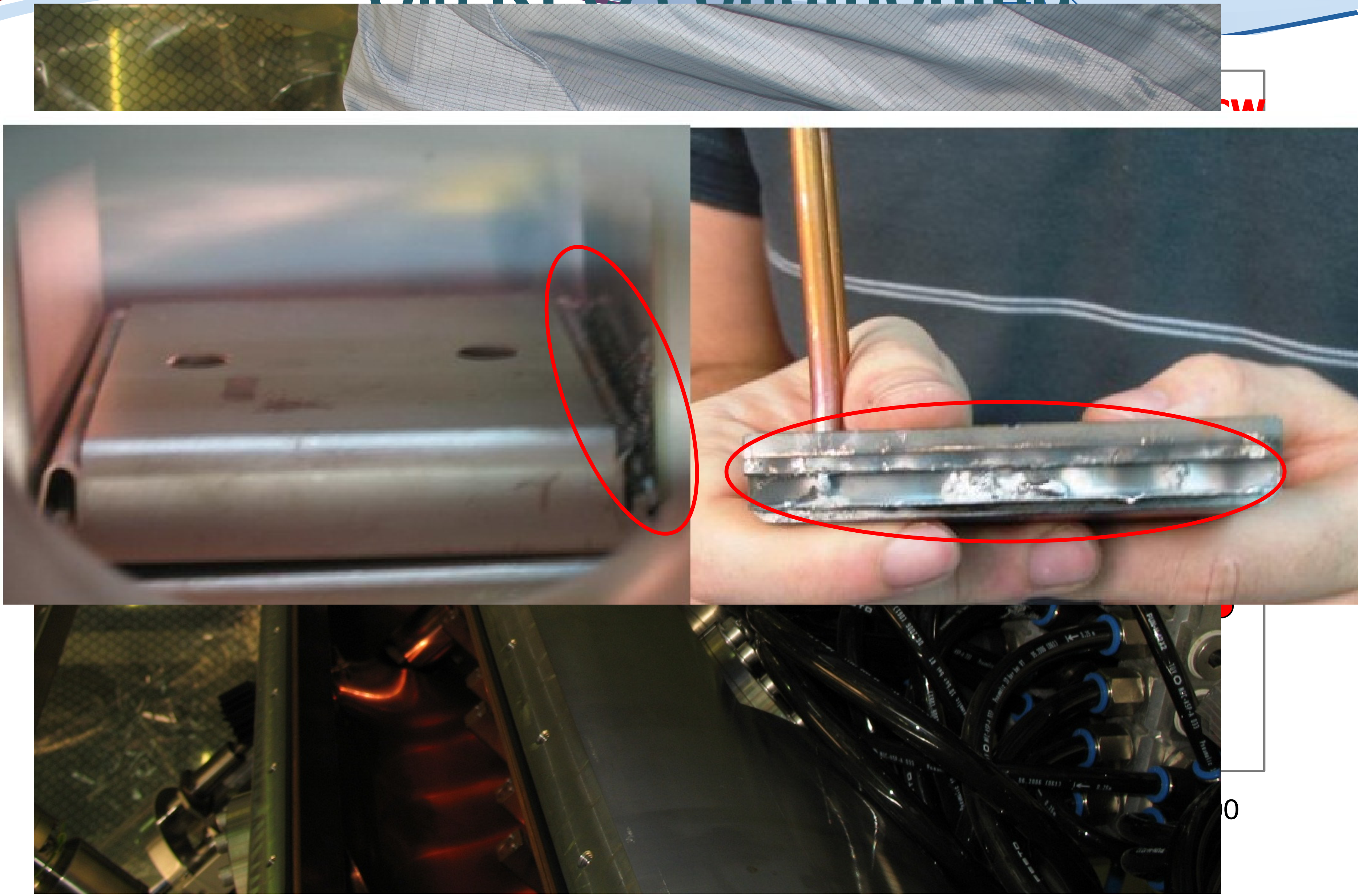

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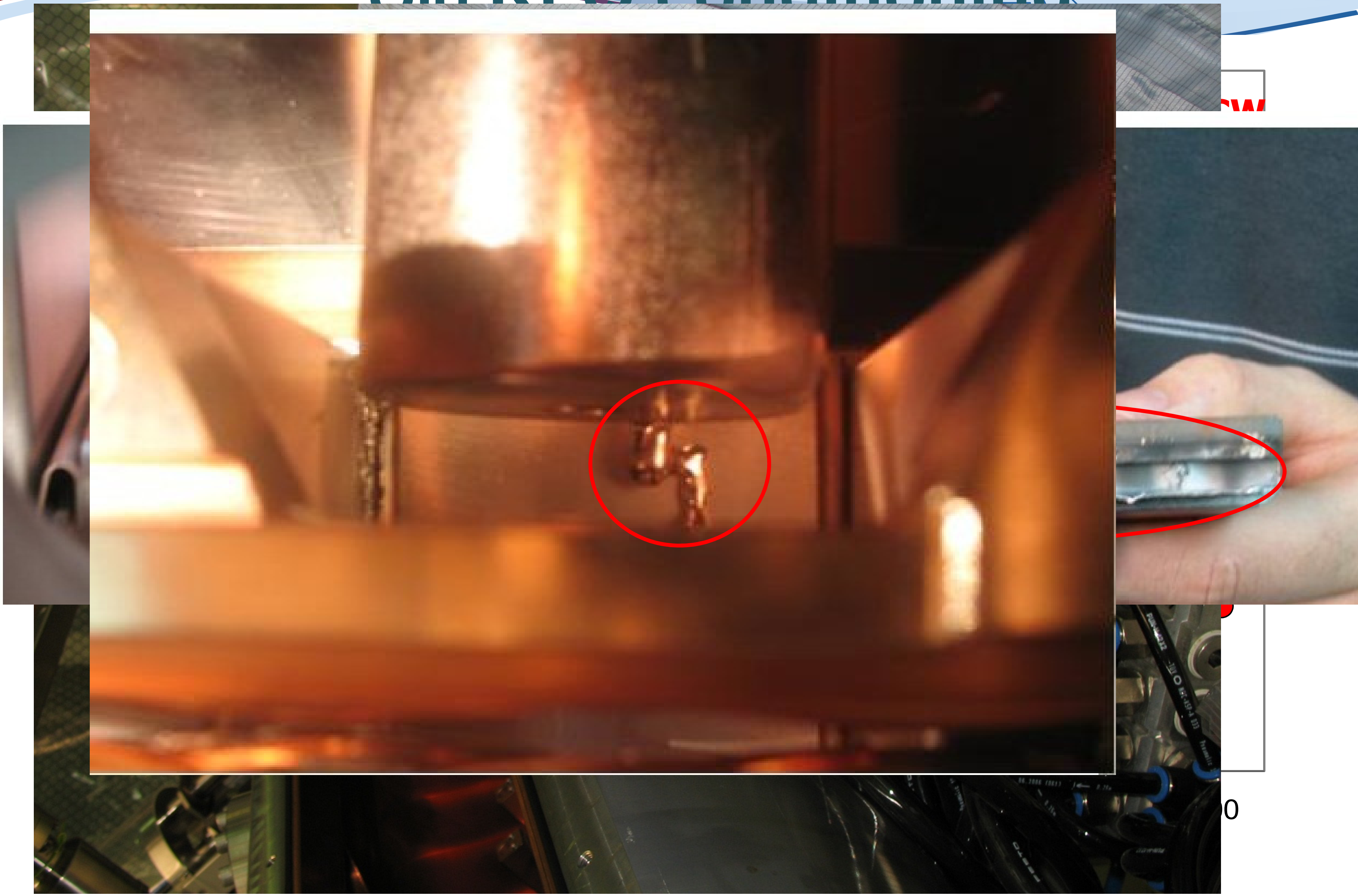

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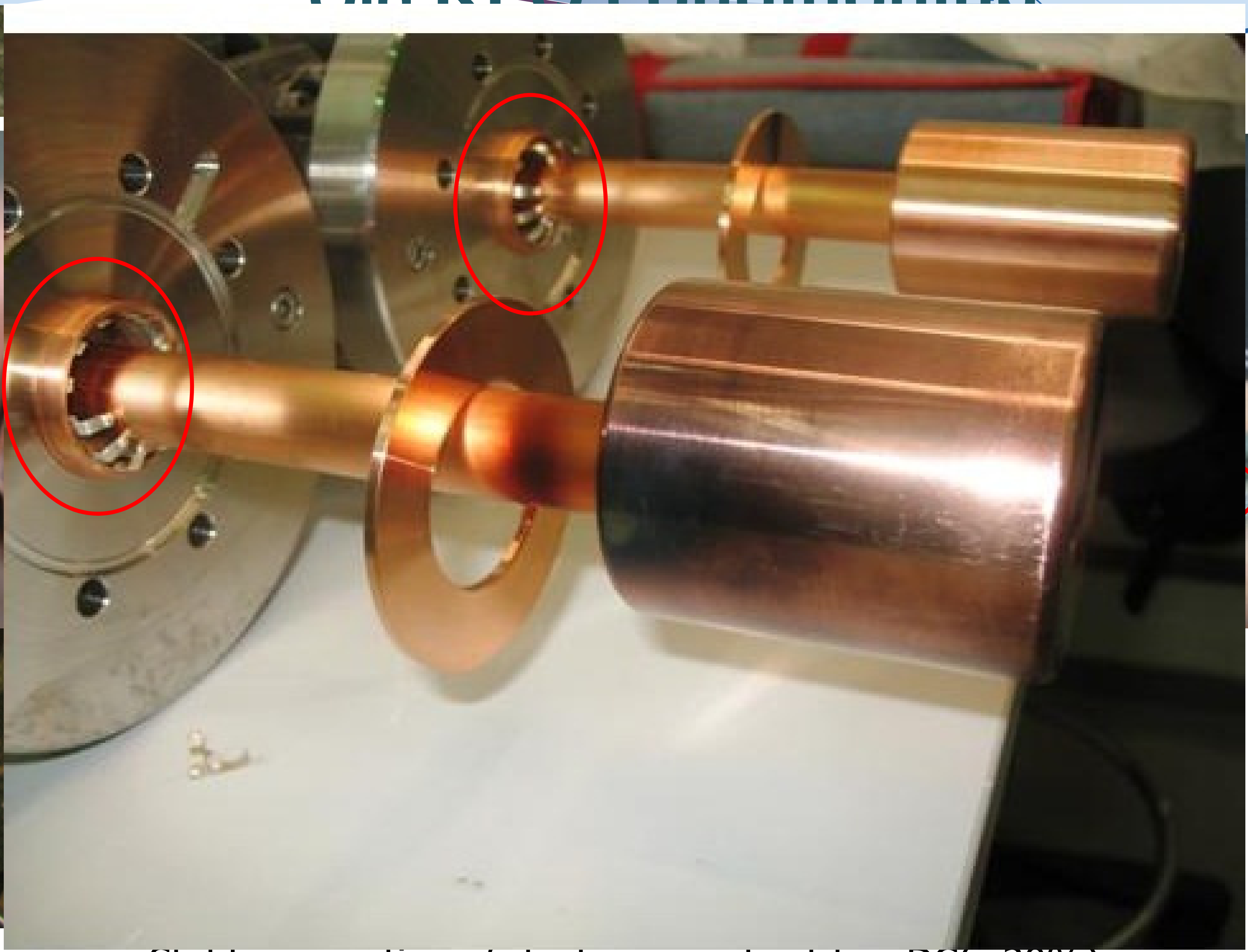

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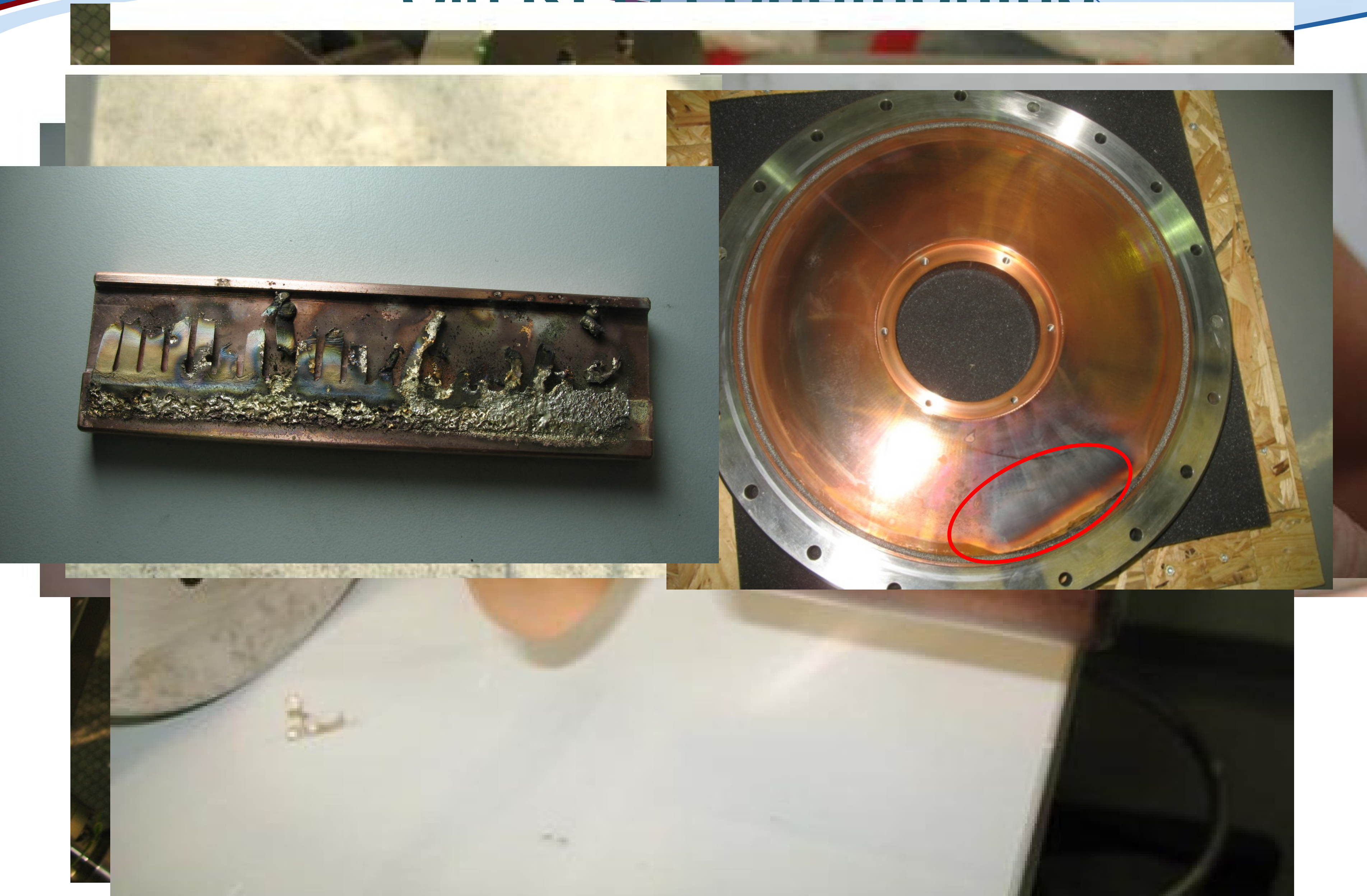

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Stable operation of deuterons only at low DC(<20%)


Beam

Modification of RFQ

- New modulation with lower inter-electrode voltage has been designed
- Reduction of power required for deuteron operation below 200kW
- Scale down of existing solution, same transverse focusing

	old	new
Power/deuterons (kW)	250	**185**
Voltage (kV)	65	**56**
Kilpatrick	1.54	1.52
Exit energy (MeV/u)	1.50	**1.28**
RF couplers	1	2

A. Shor et al., SNRC internal report

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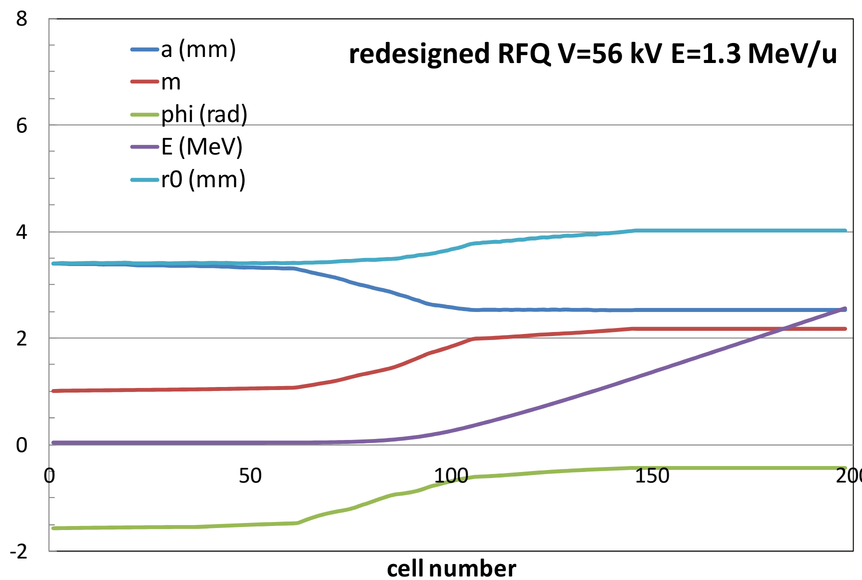

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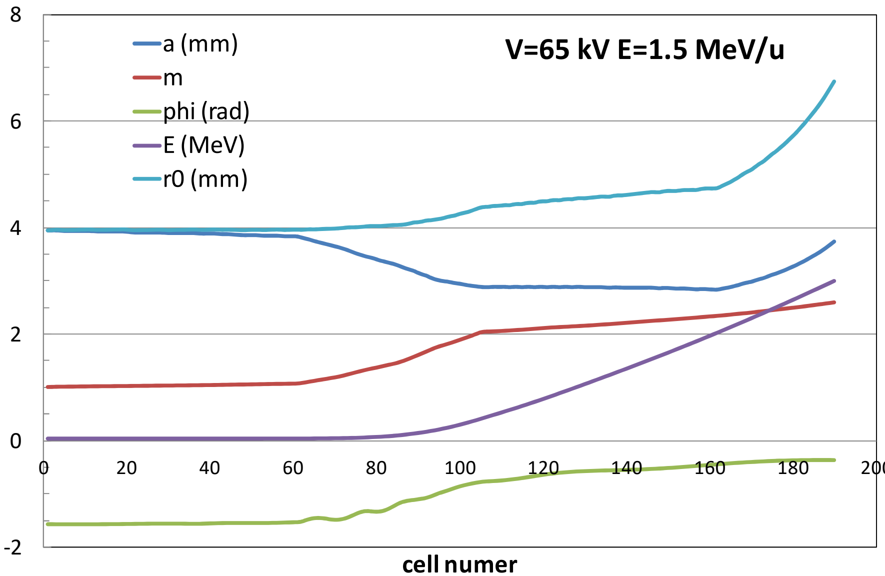

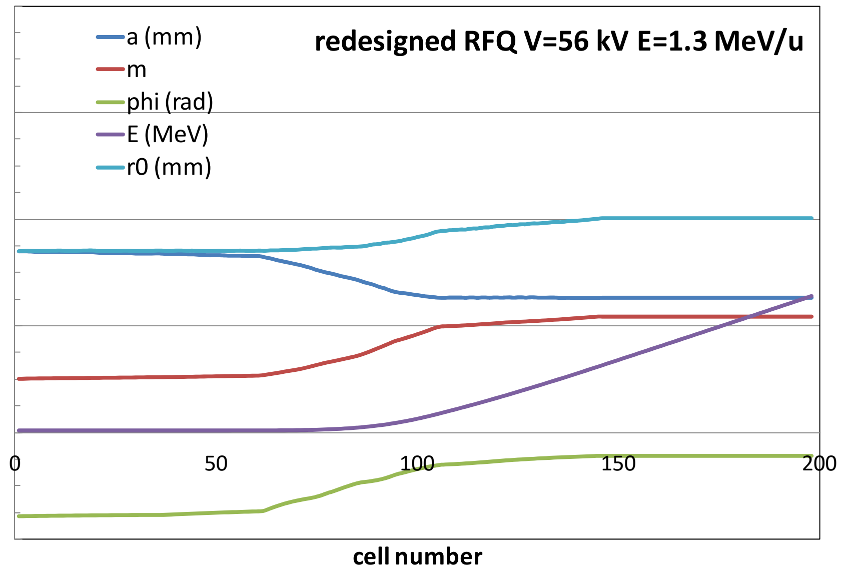

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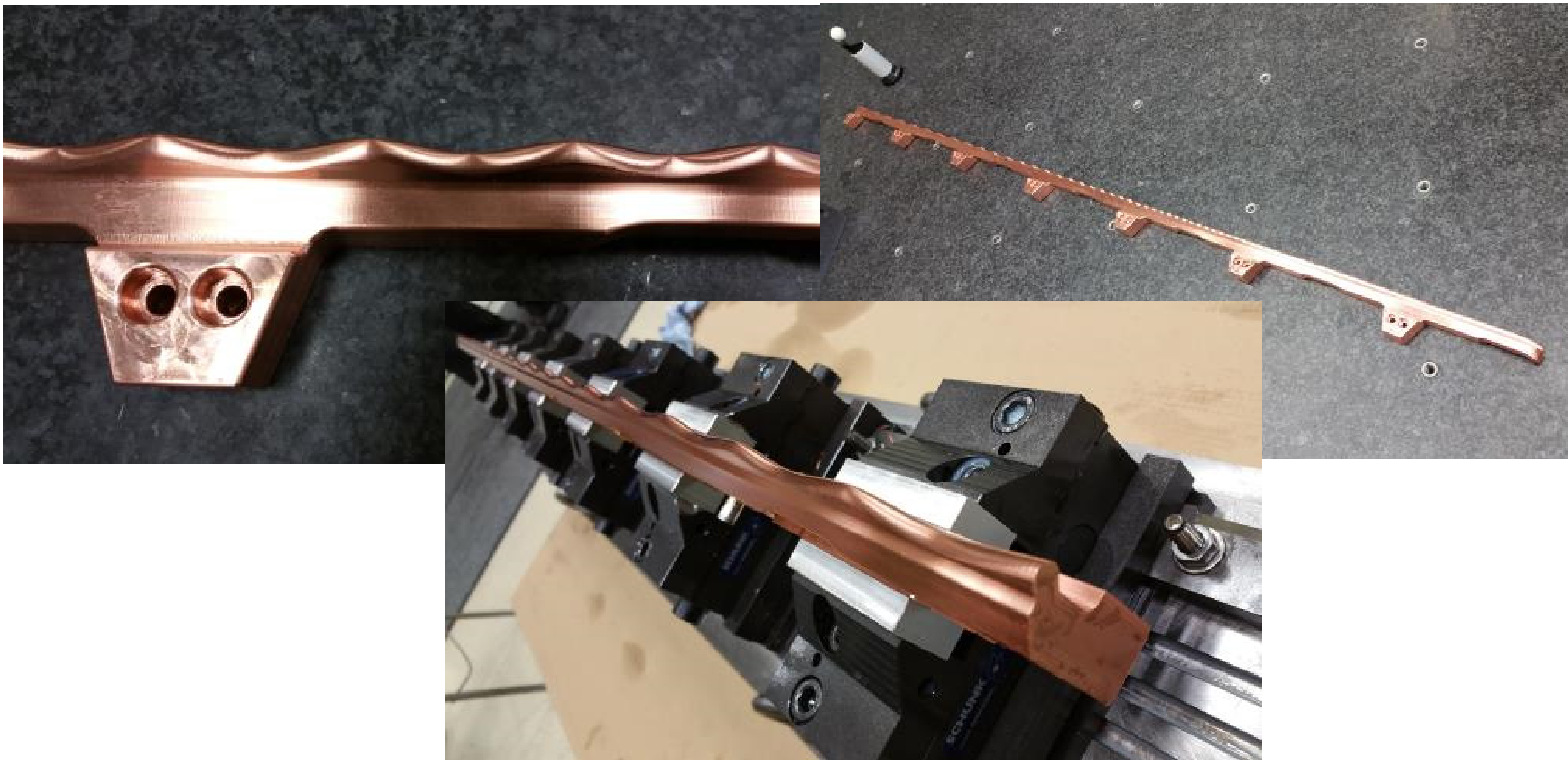
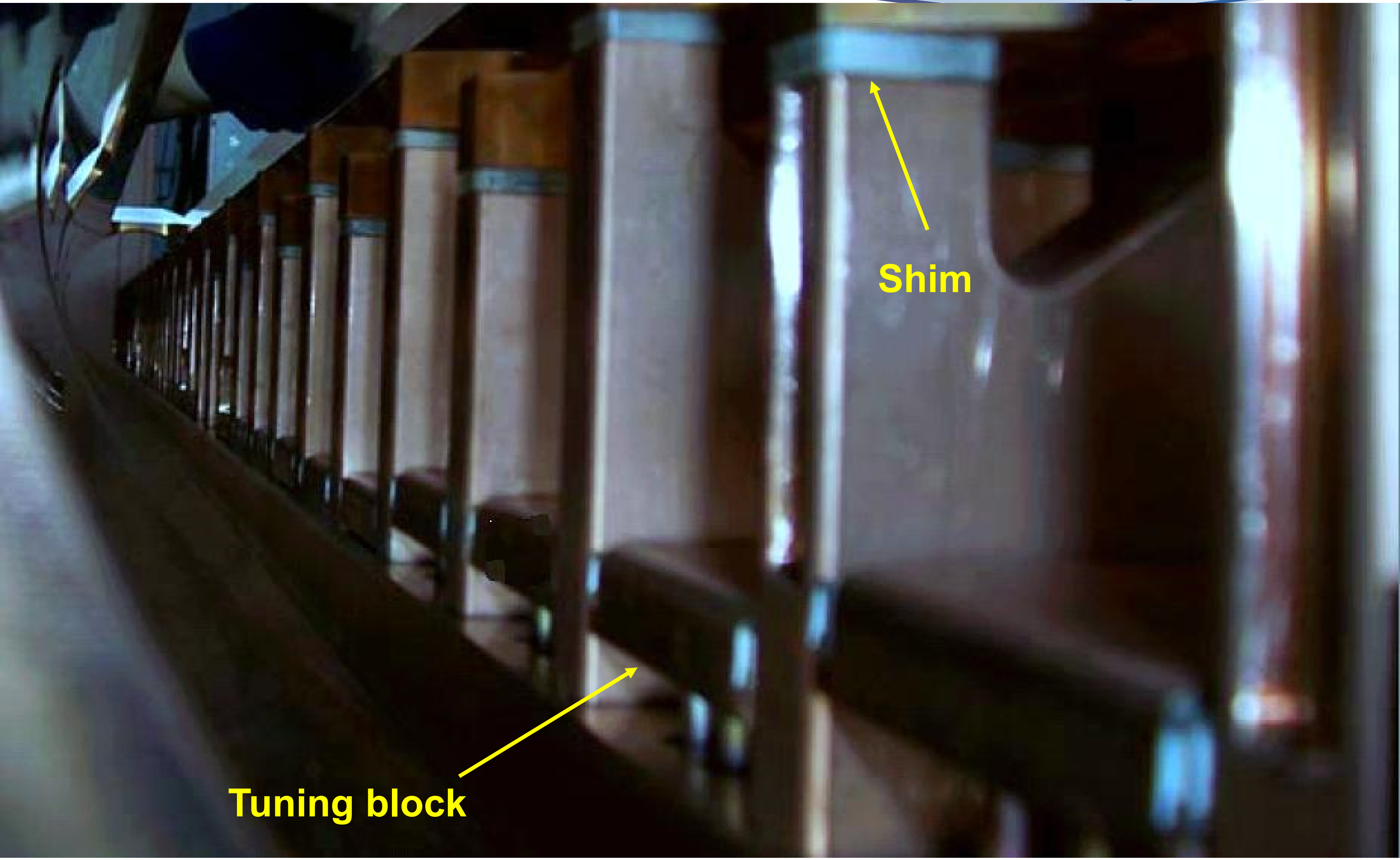
Modified RFQ

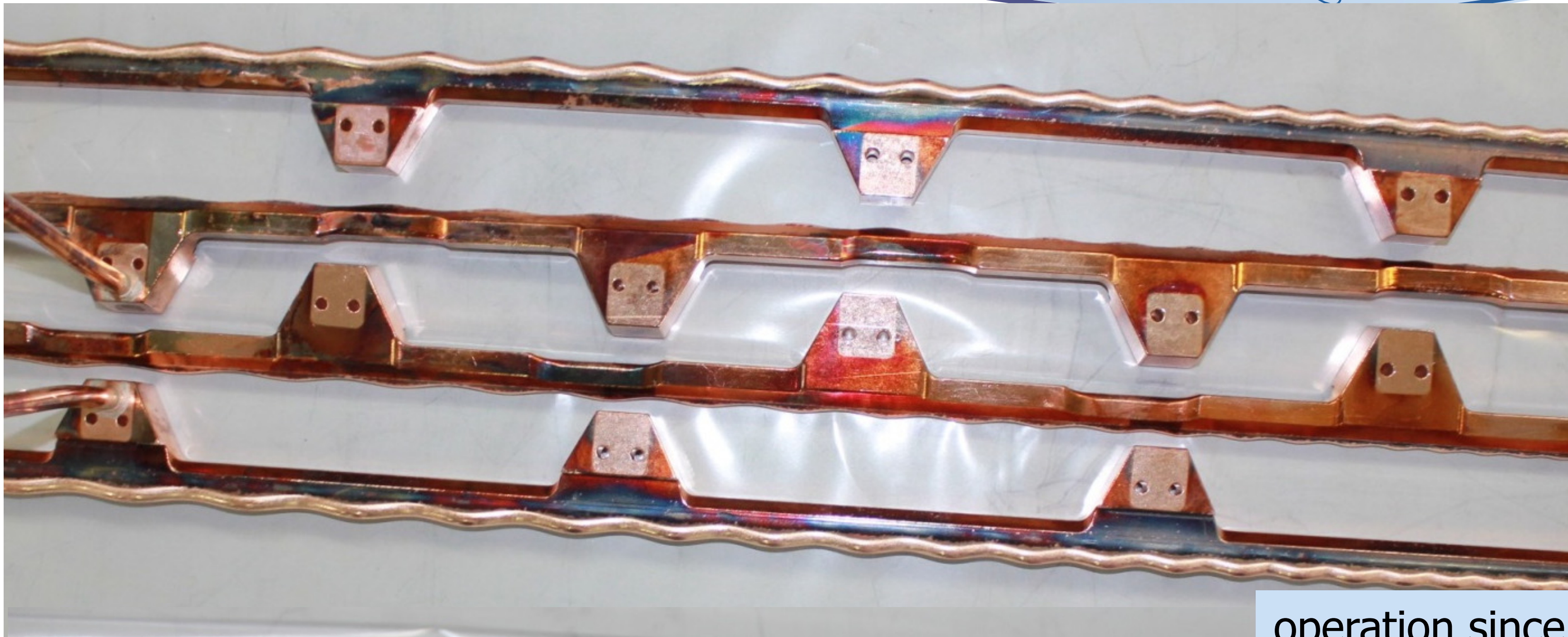


New rods modulation designed by A. Shor (SNRC)

Fabricated by Neue Technologien Beteiligungs (NTG, Germany)

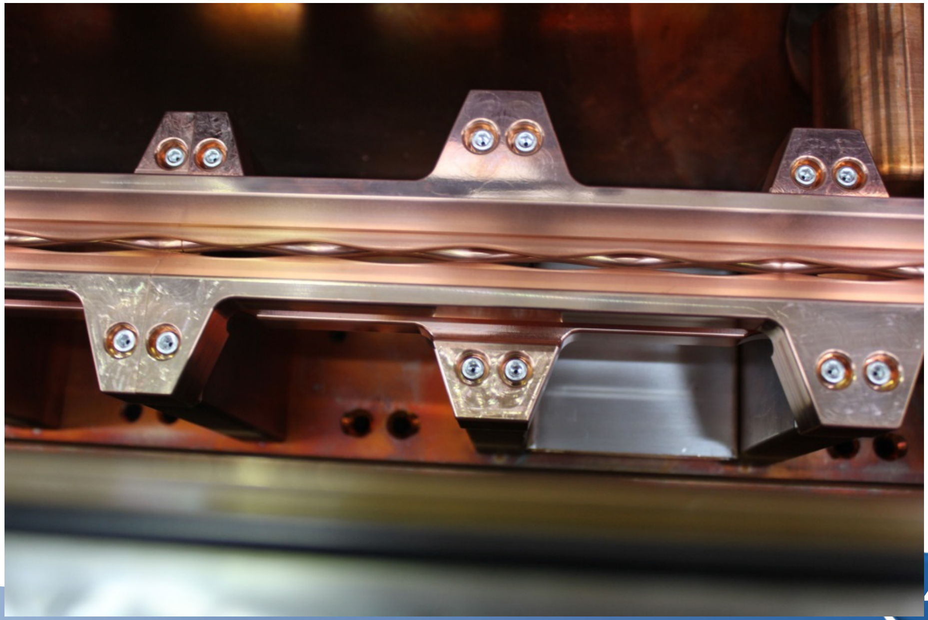

Shim
Tuning block

Disassembly of the old rods

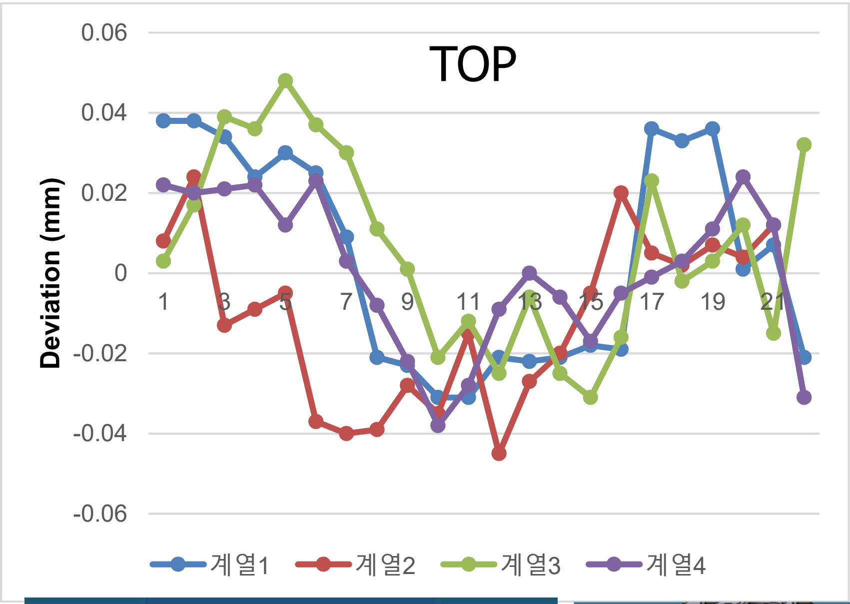


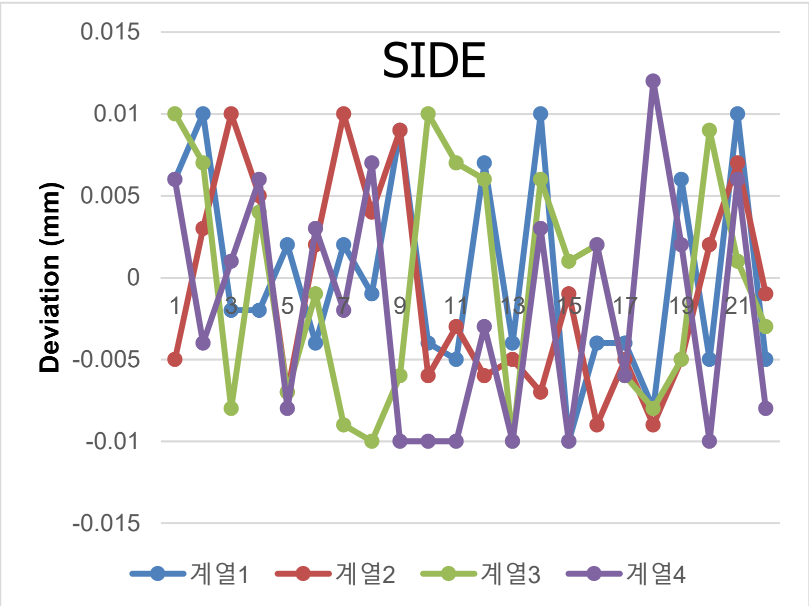
operation since 2009
more than 200 mA h

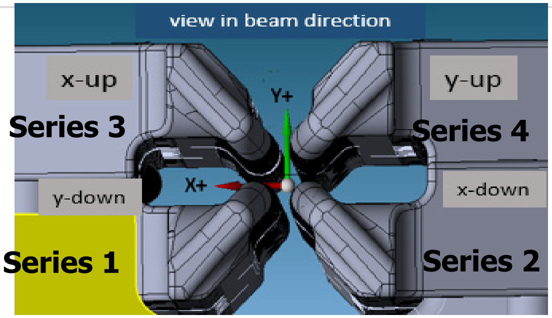
Assembly of the new rods

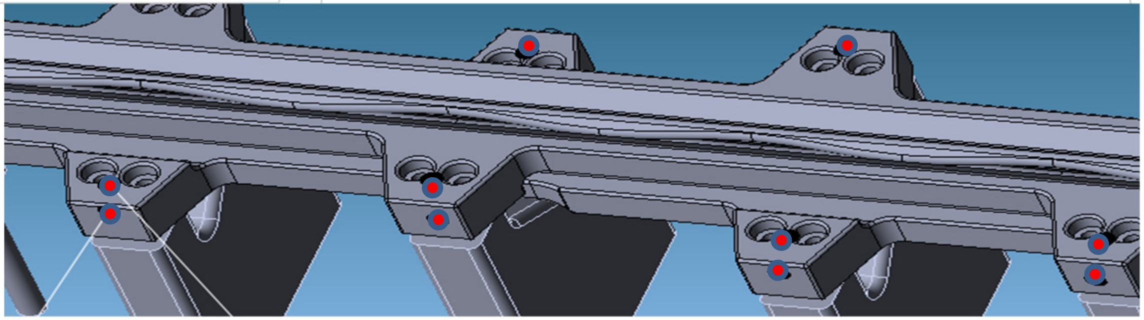


Results of the alignment measurements









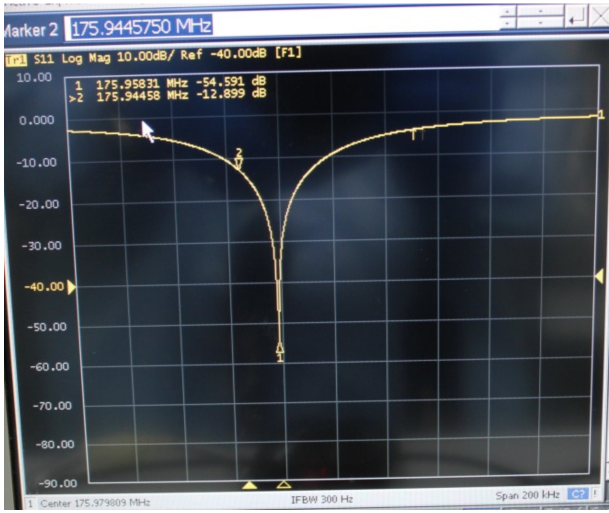
Arrangement of the tuning plates

Introduction of dummy TB in the precalculated positions

Establishing the couplers positions to obtain good coupling

Measuring the field homogeneity using perturbation method

Optimizing the resonance frequency and field homogeneity
 by shifting dummy TB heights (iterative process)



Exchanging the dummy TB to high power ones (critical point : cutting the the water tubes)

Final measurement and tuning

Arrangement of the tuning plates

Int

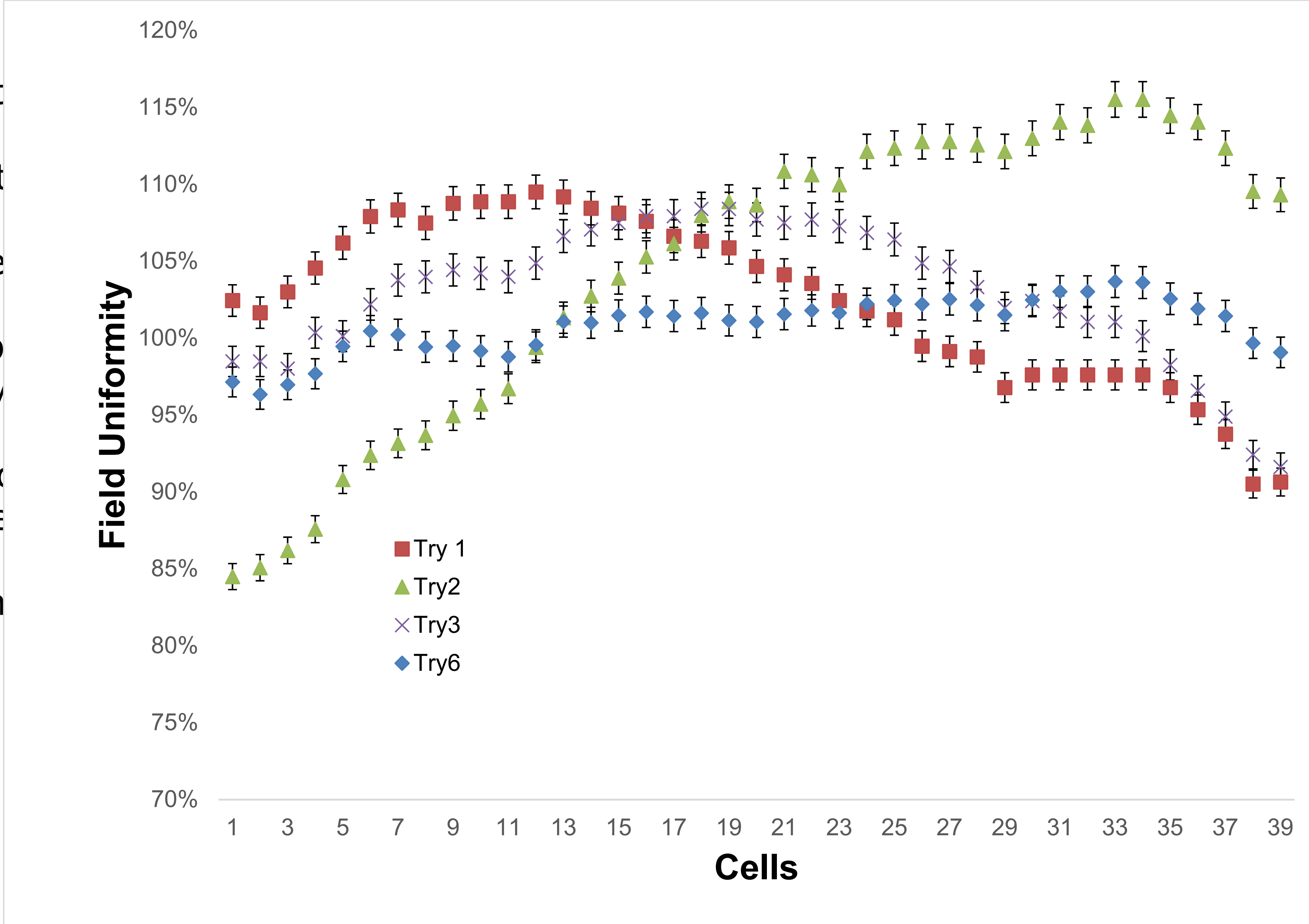
Est

Me

Op
by

Exc
the

Fin



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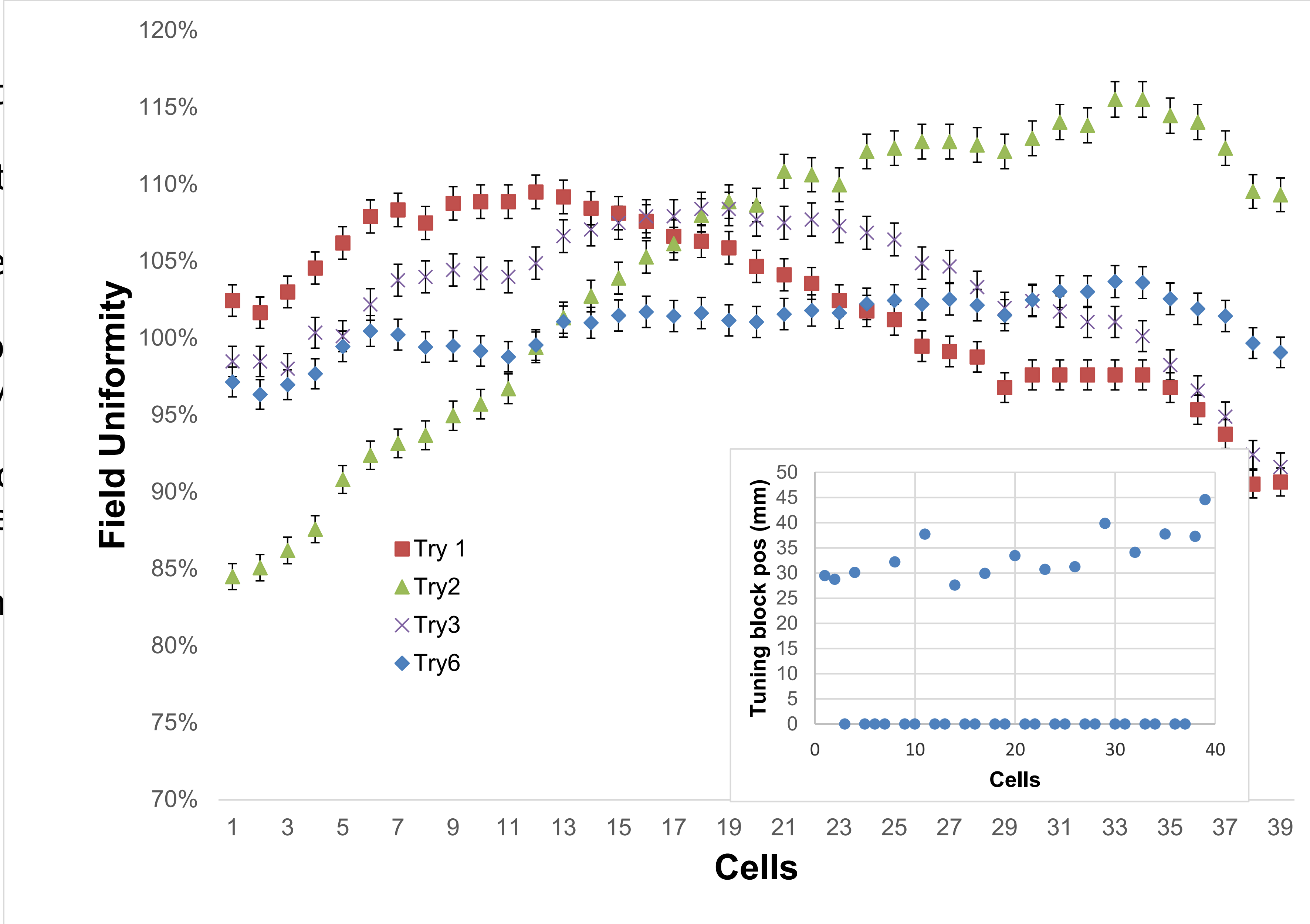

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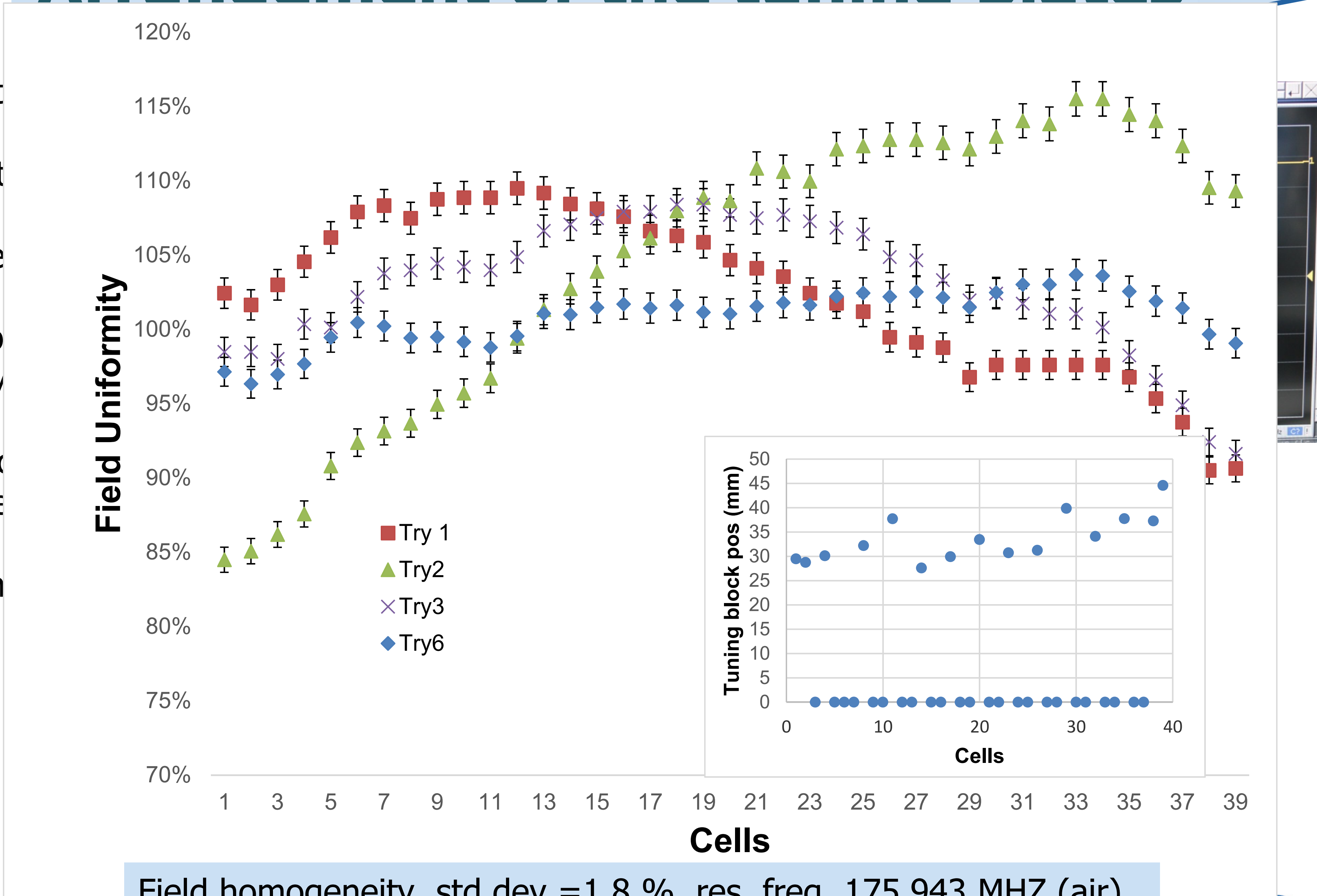
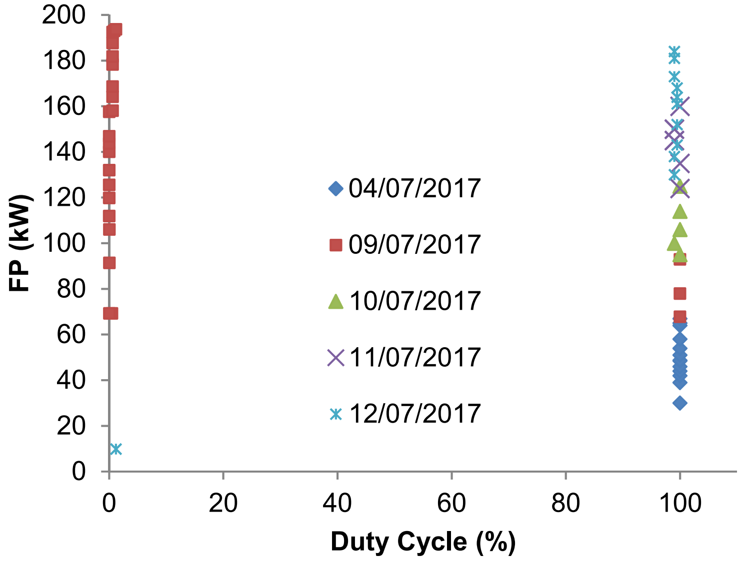


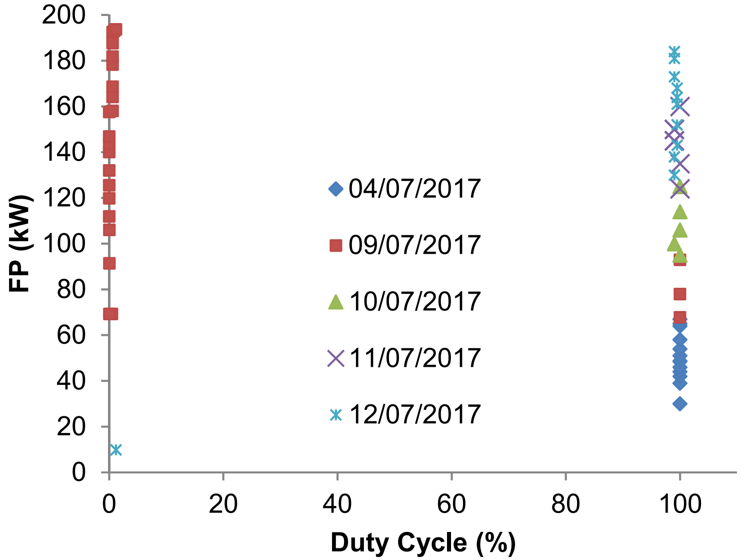
Field homogeneity std dev =1.8 %, res. freq. 175.943 MHZ (air)
In the old rods std dev =2.7 %

High power conditioning



High power conditioning

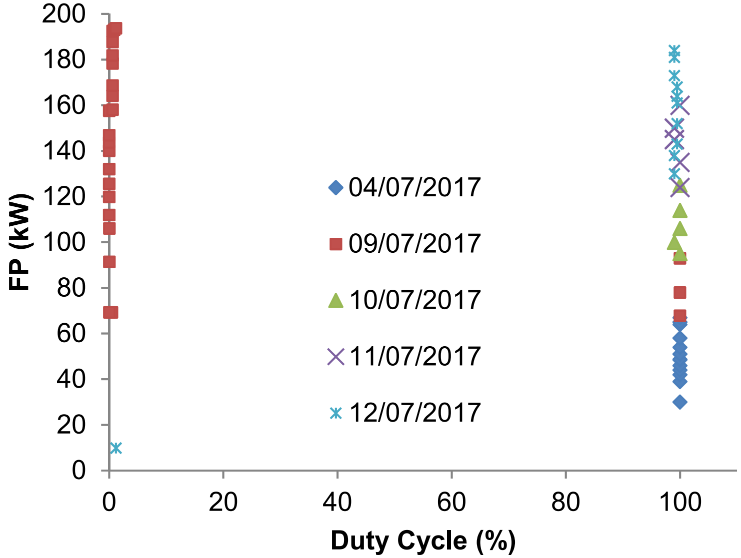
Soreq NRC



Conditioning to 180 kW (36 net hours)

High power conditioning

180 kW ~6 h w/o trip



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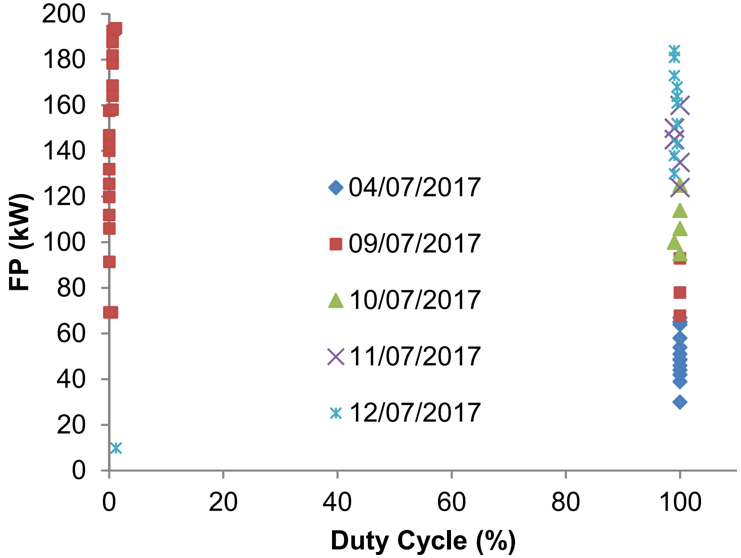

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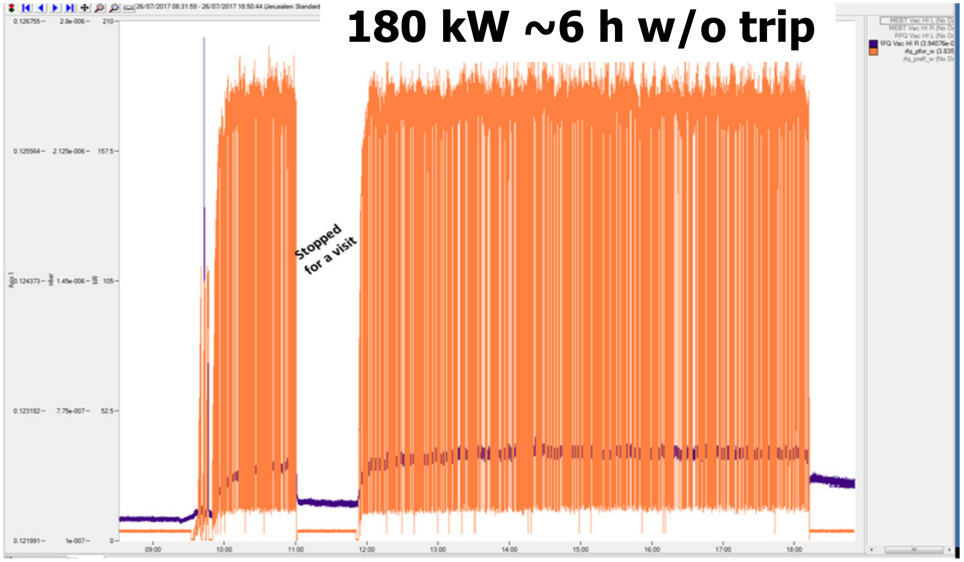

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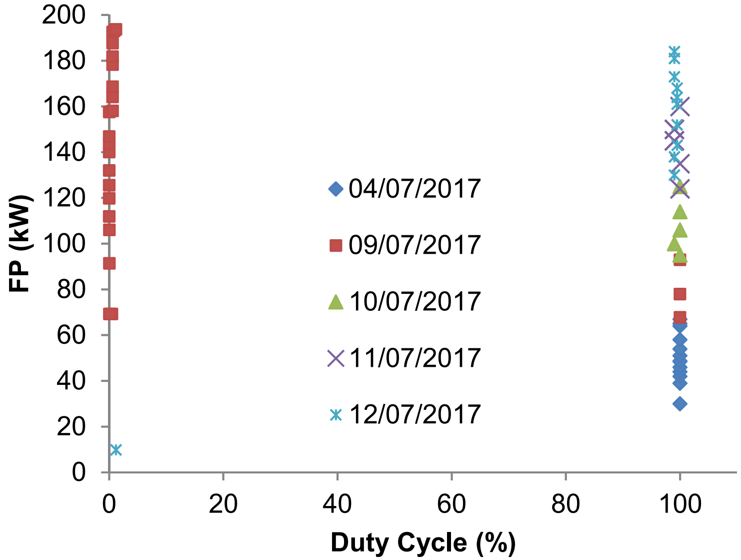

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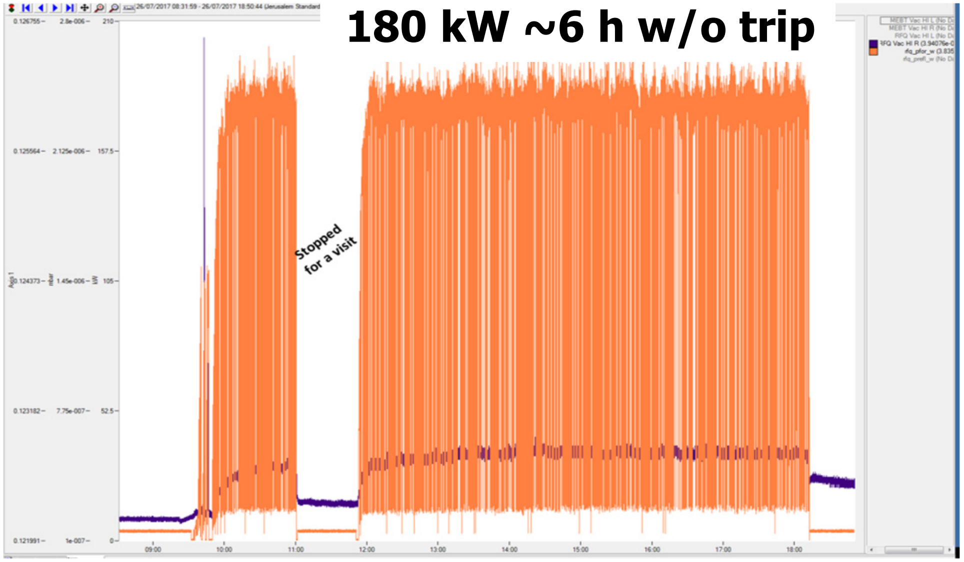

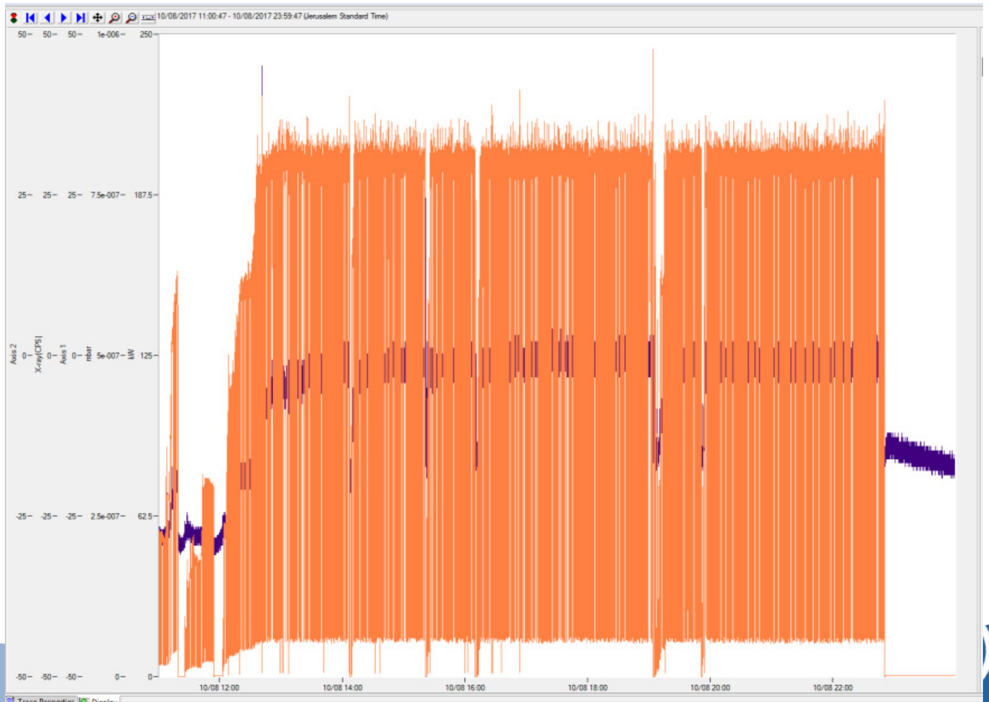

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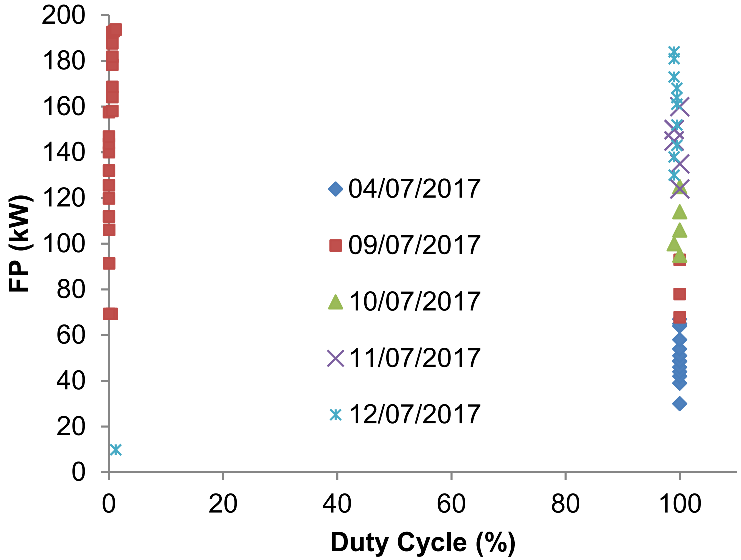

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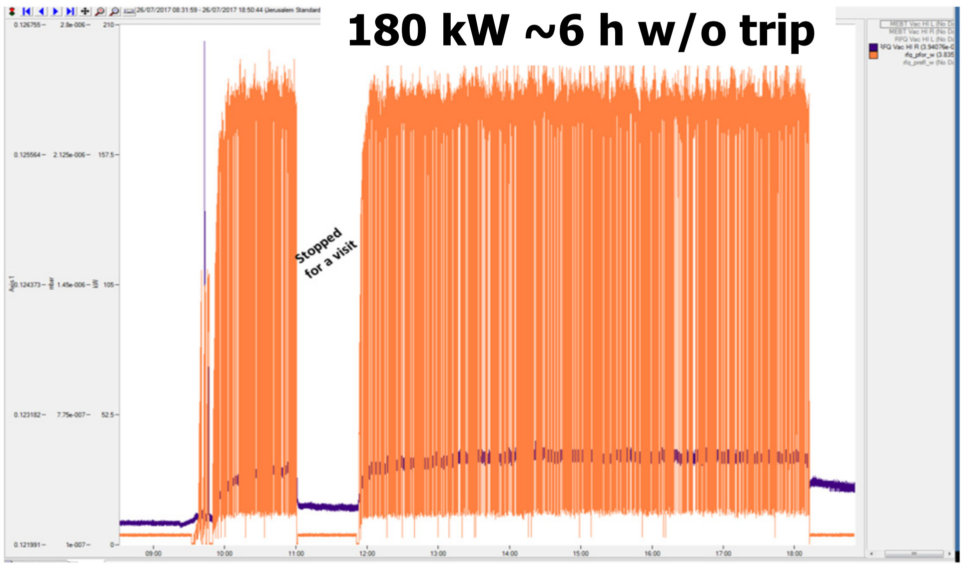

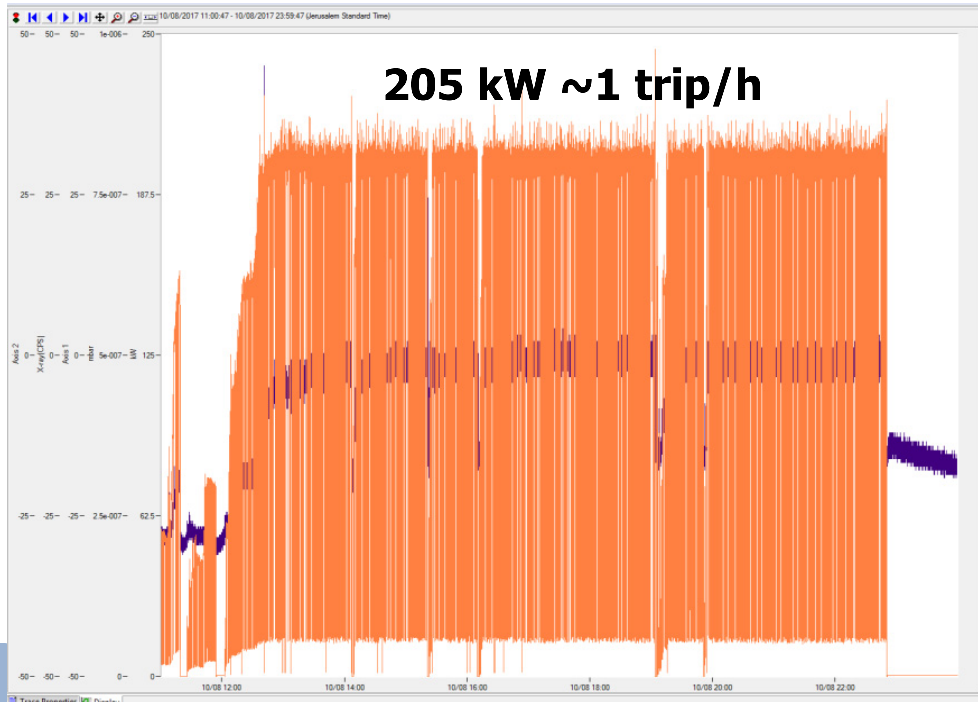

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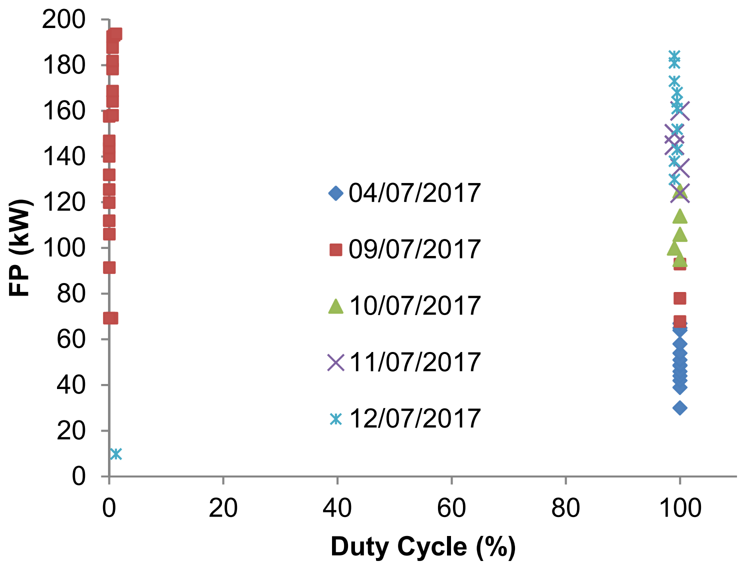

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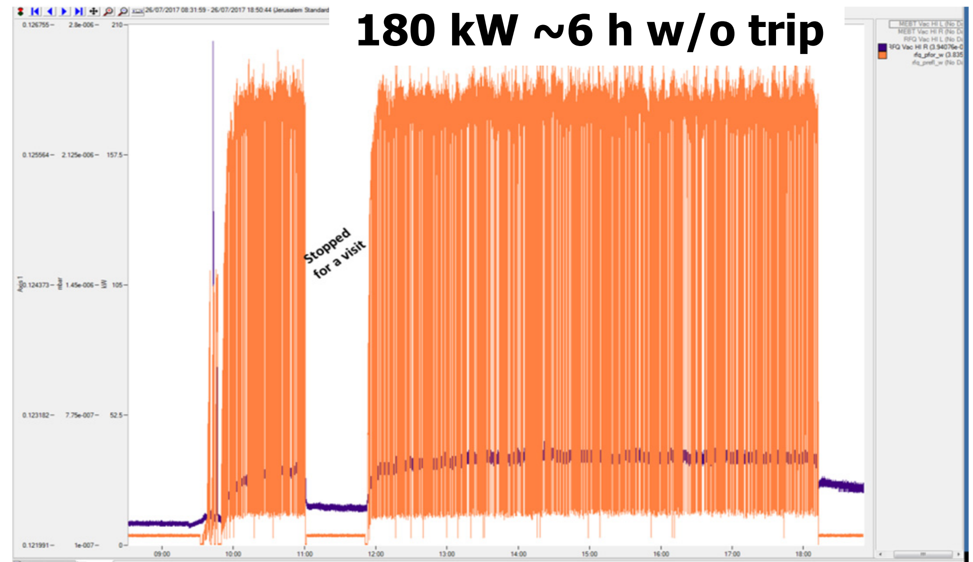
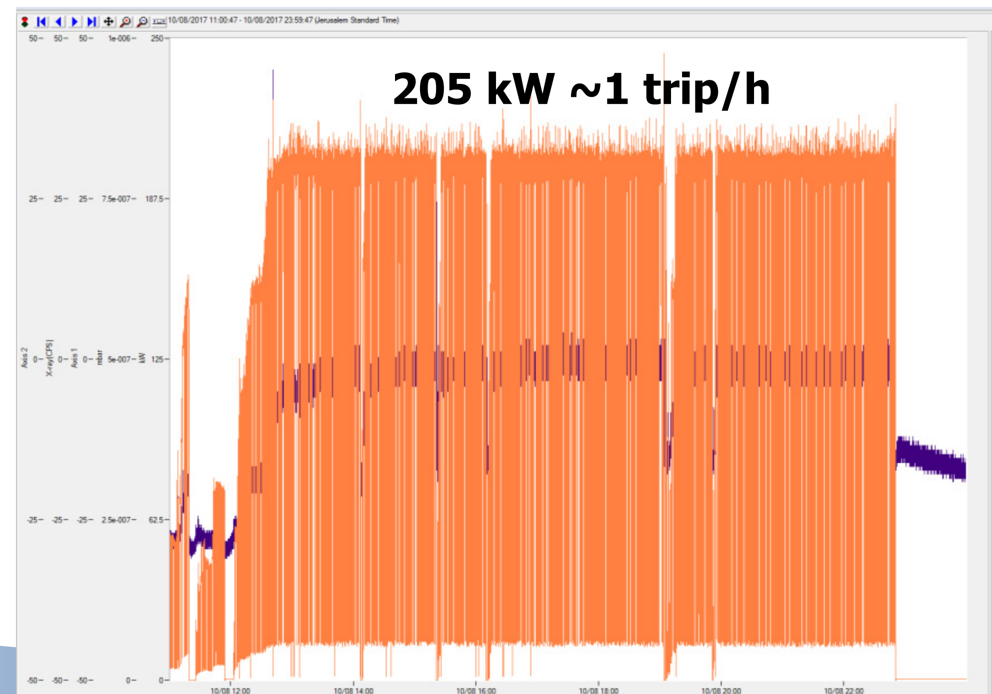
Another 35 net hours





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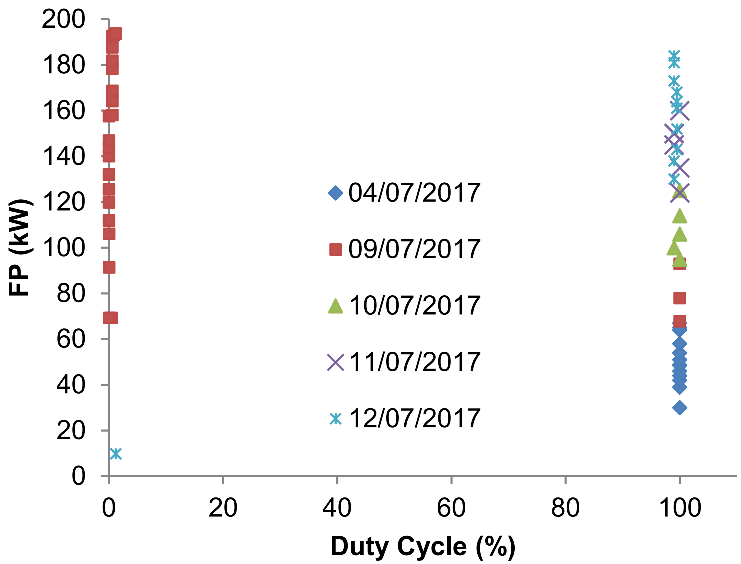

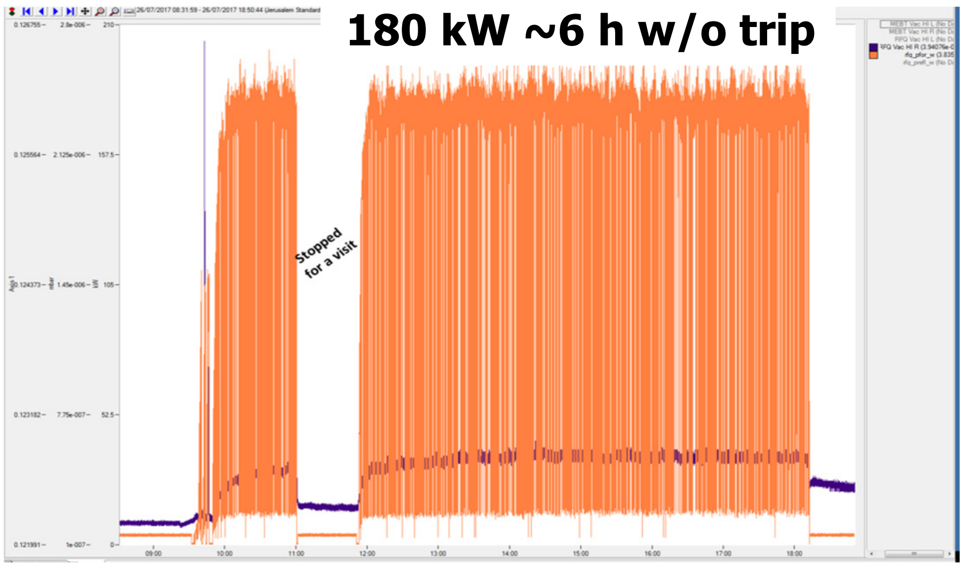

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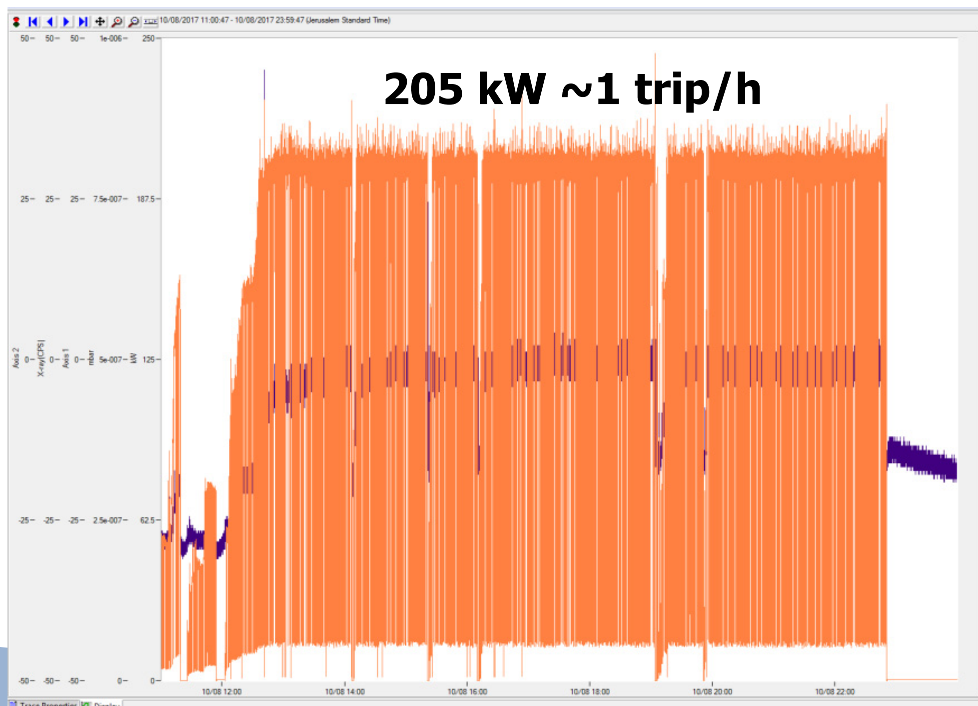
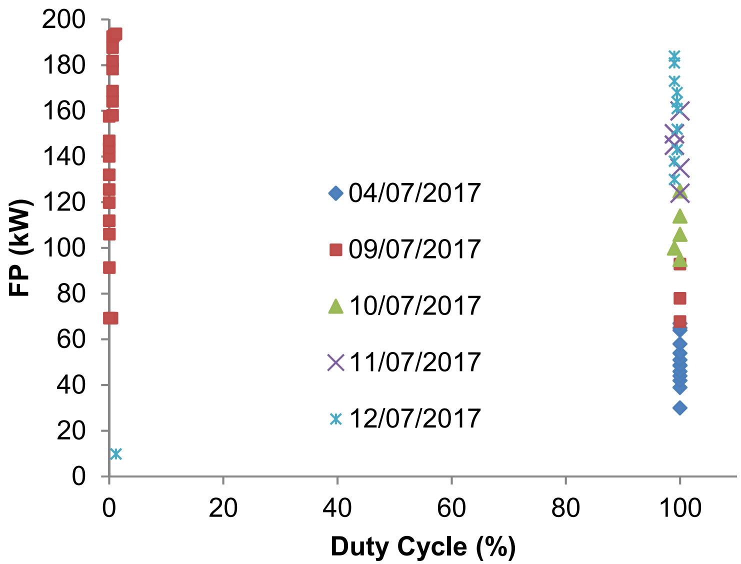
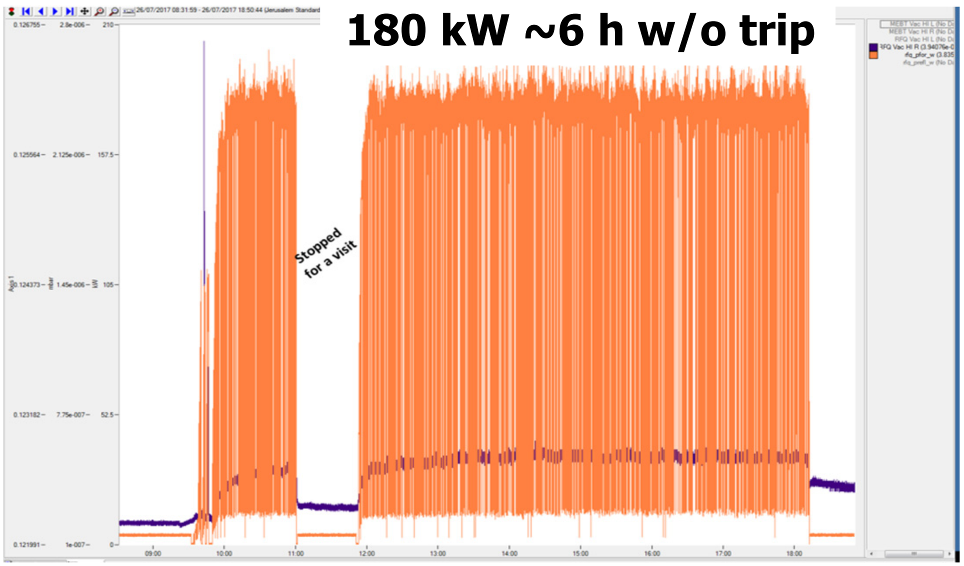


In fact, had to vent RFQ 3 times: Vacuum problems and rearrangement of the tuning range of the plungers

High power conditioning





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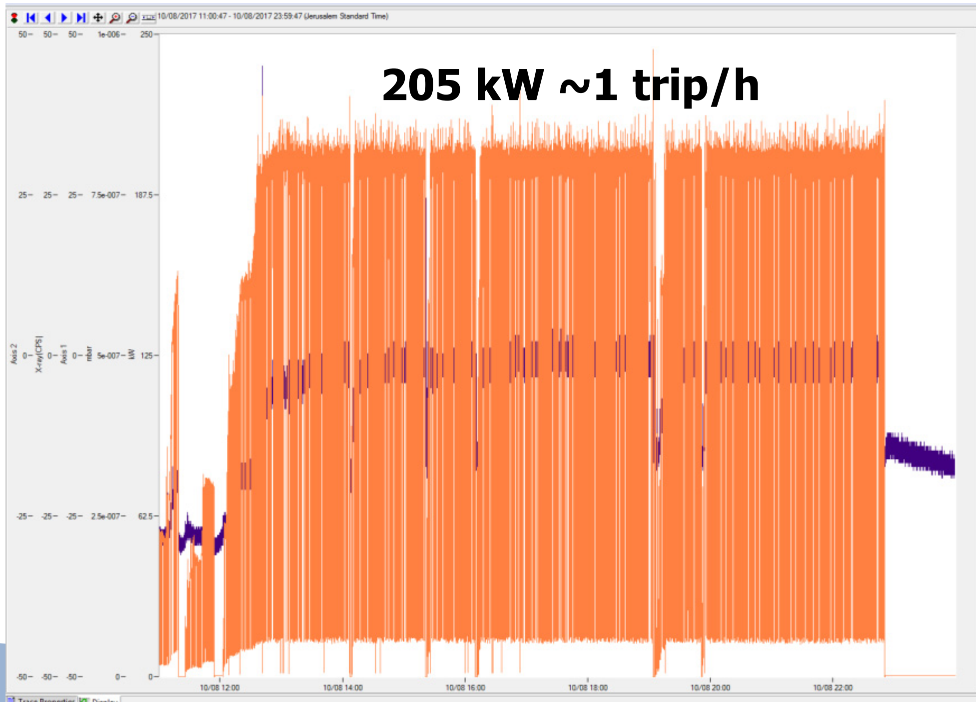
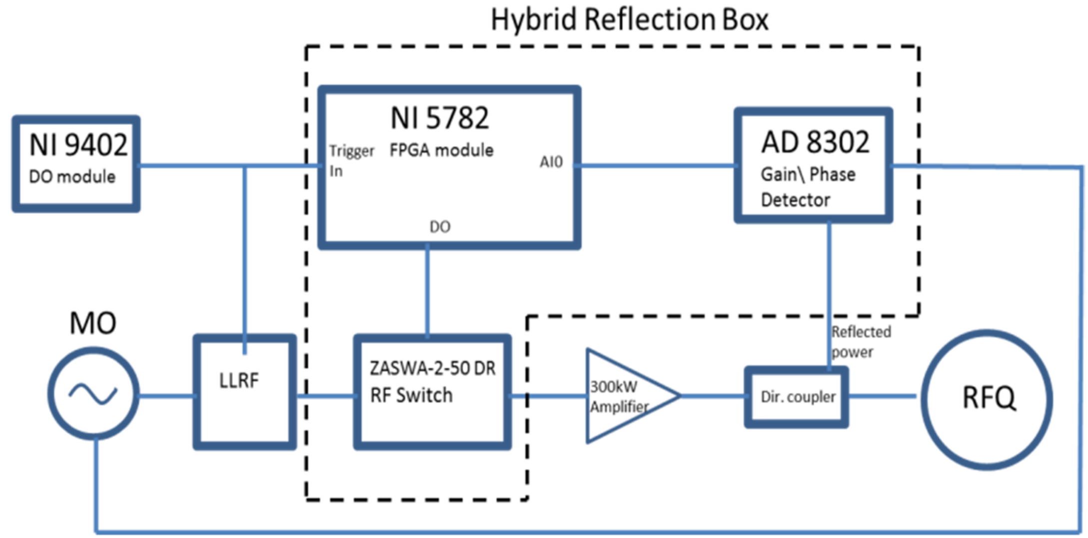


In fact, had to vent RFQ 3 times:
Vacuum problems and rearrangement of the tuning range of the plungers

In terms of the electrical field:
200 kW with new rods corresponds to 260 kW of the old rods RFQ

Reflection events protection



A. Perry & B. Kaizer

Elements used for RFQ beam characterization

EIS
BB

LEBT
Aperture
FC/slits/wire
Slow chopper

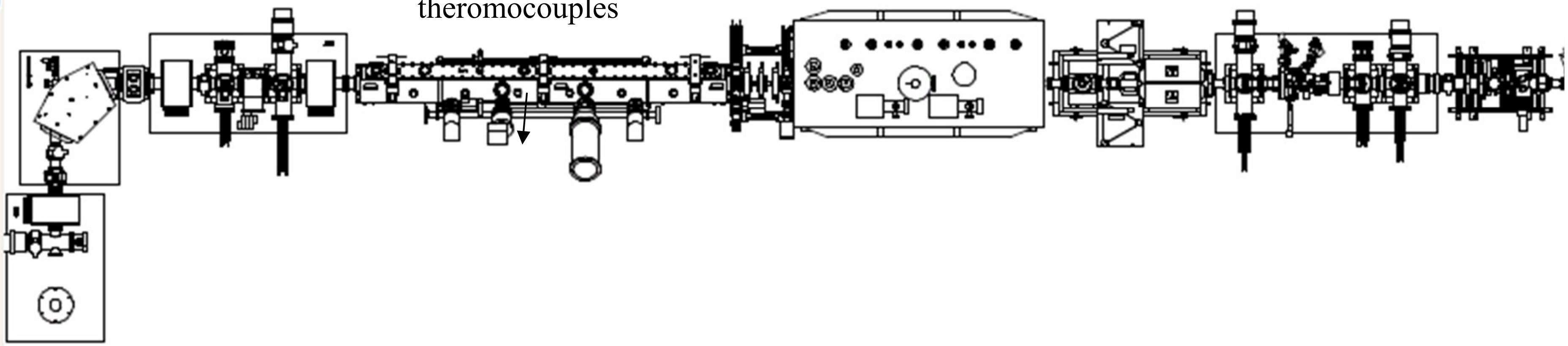
RFQ
Entrance col.
X-rays det
cameras
theromocouples

MEBT
BPMs
BB/col.
wires

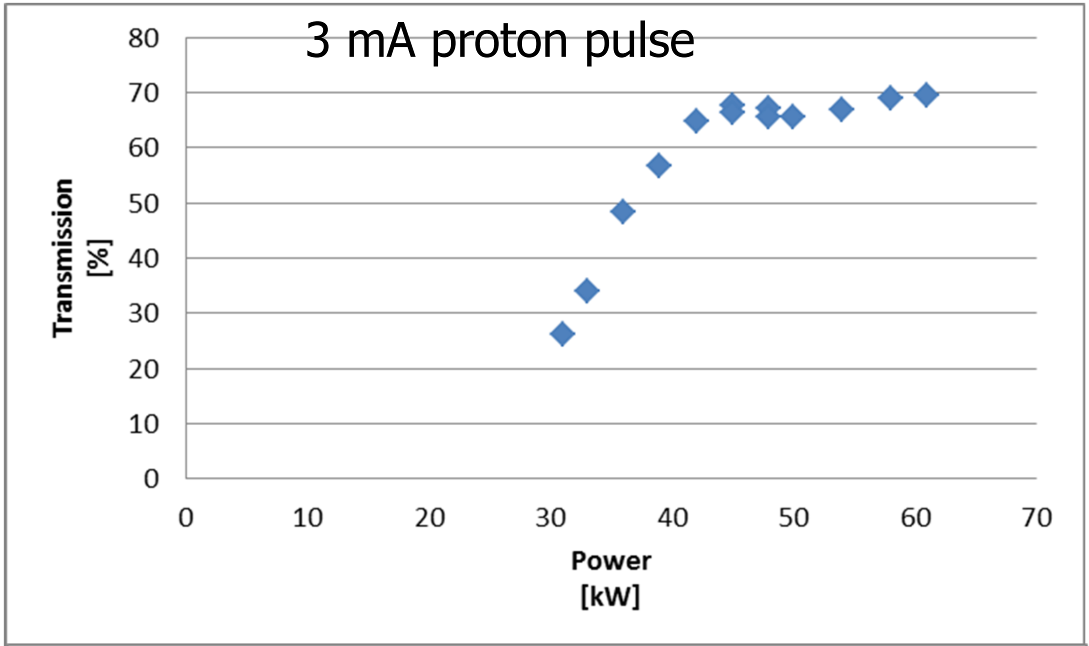
PSM

D-plate
slits/wires
phase probes
RBS/BEM
FFCs

Beam dump
FC/col

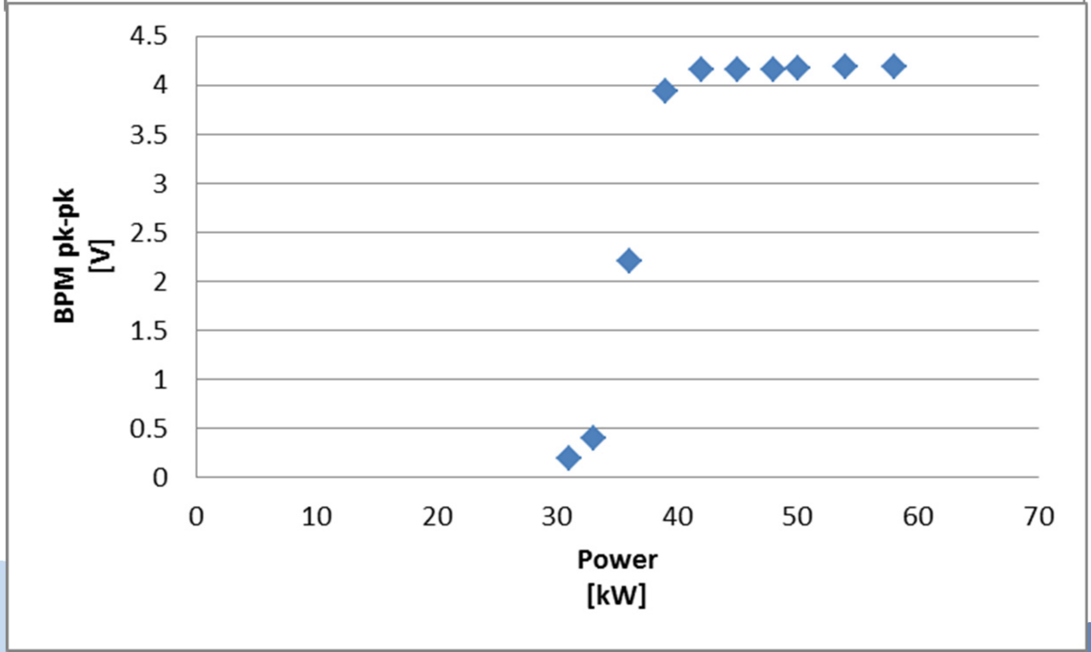


First beam through new RFQ



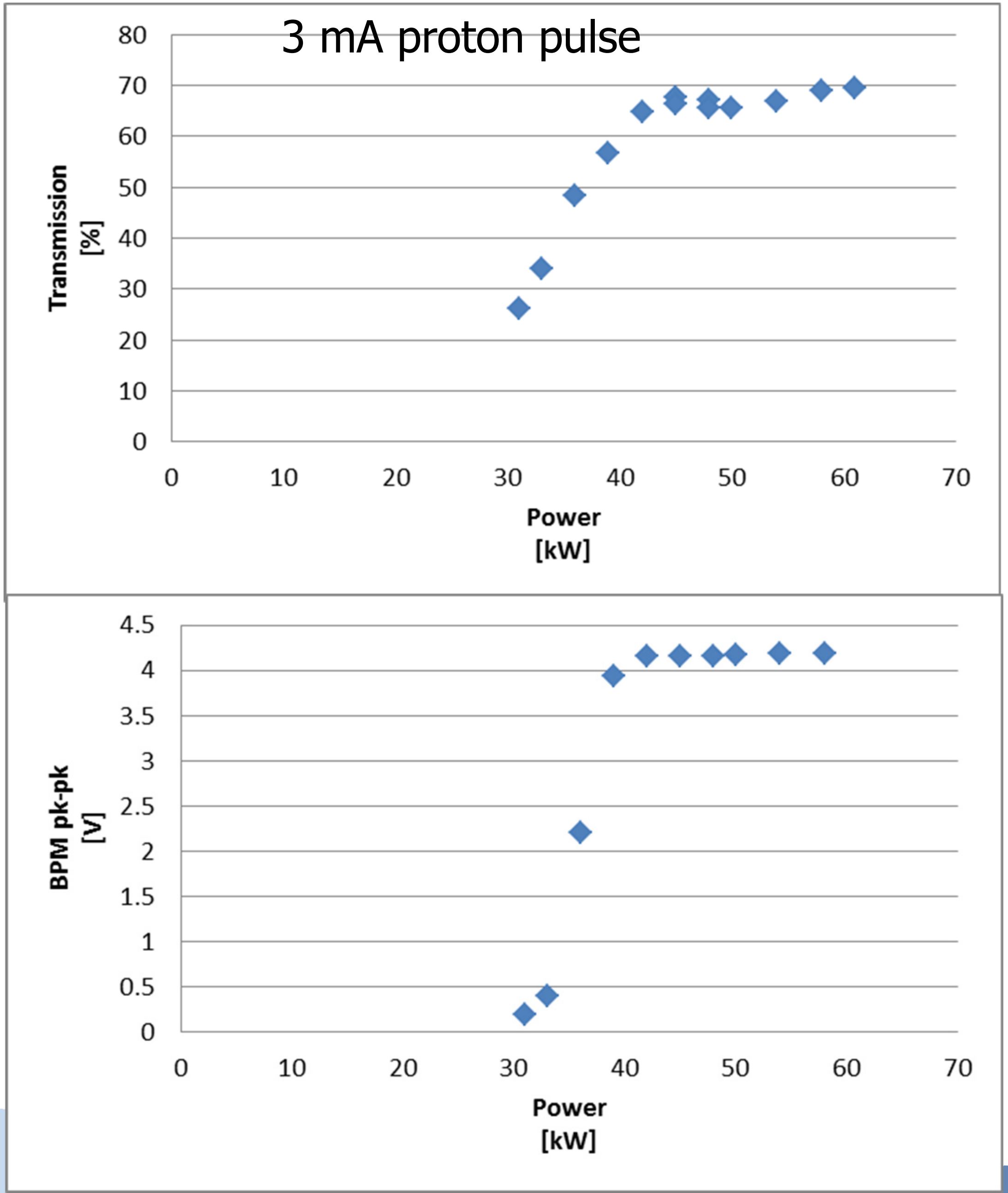
Measurements MEBT BB cryomodule on maintenance

Beam current sensitive to non accelerated particles



BPM signal sensitive to beam bunching

First beam through new RFQ



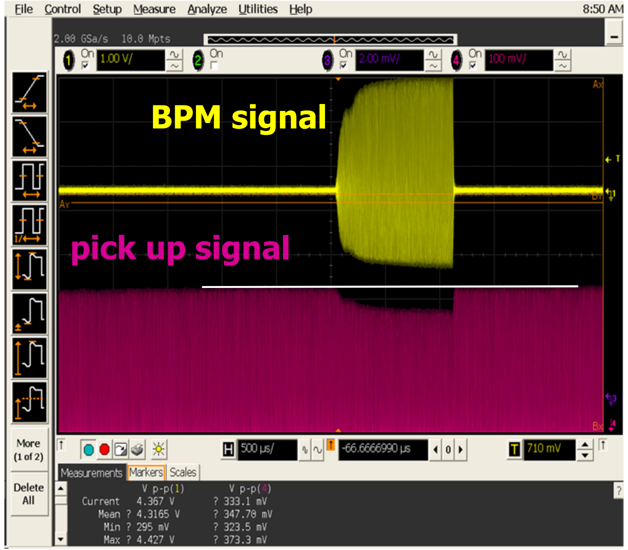
Measurements MEBT BB cryomodule on maintenance

Beam current sensitive to non accelerated particles

BPM signal sensitive to beam bunching

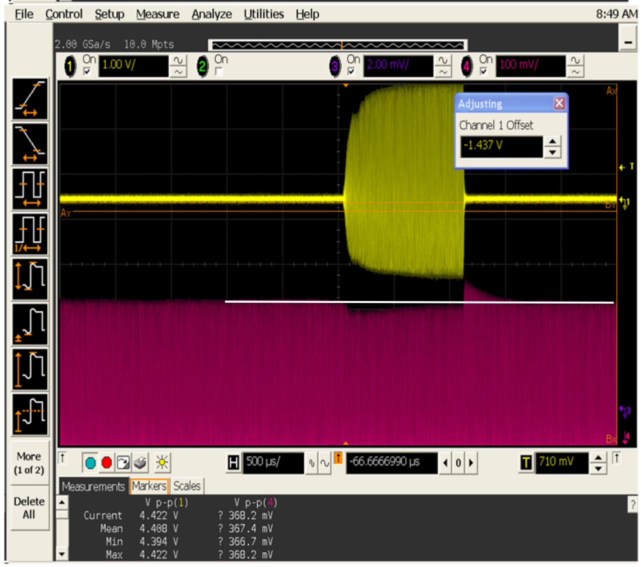
The optimum FP is ~ 45 kW

Beam loading, high intensity beam



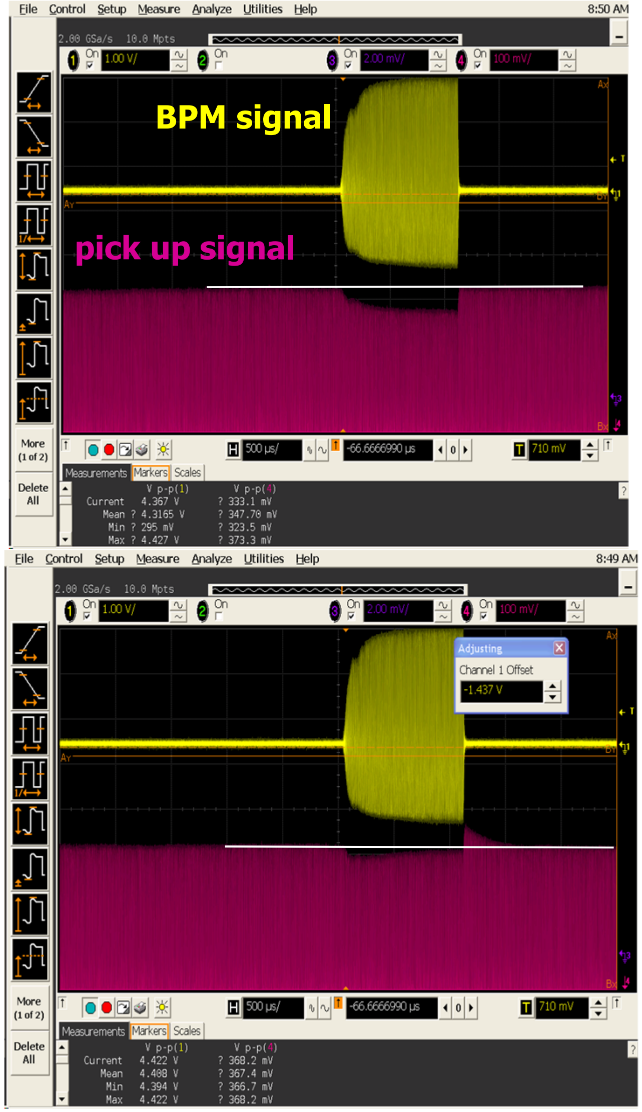
5 mA beam loading on RF field

Without analog loop



With analog loop locked

Beam loading, high intensity beam



5 mA beam loading on RF field

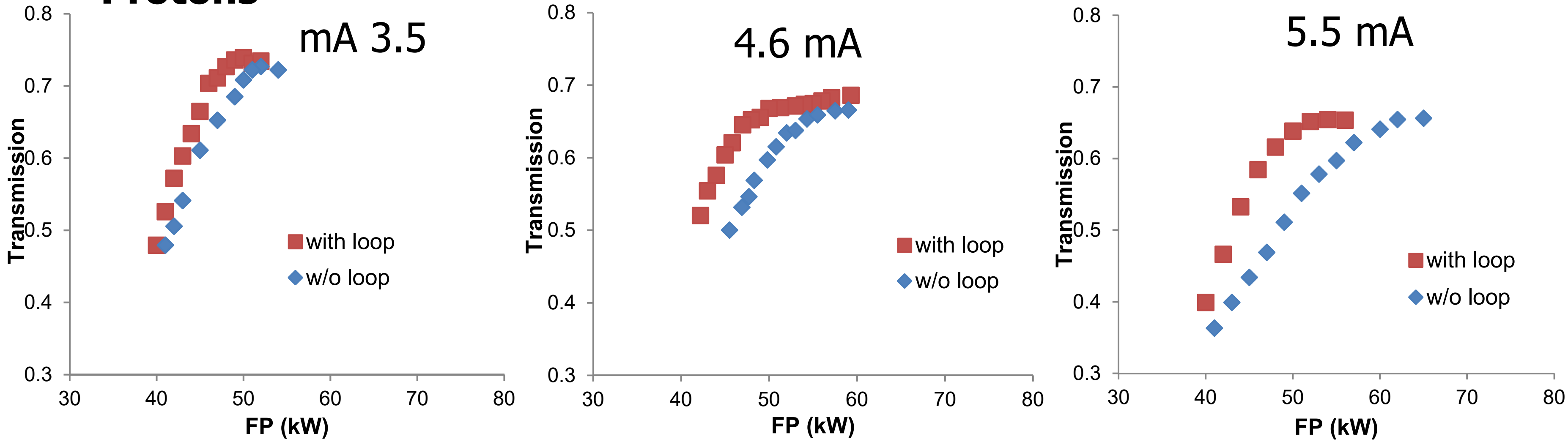
Without analog loop

With analog loop locked

Operation of RFQ w/o analog loop effectively requires higher average RF power

Transmission studies; beam loading effect

Protons



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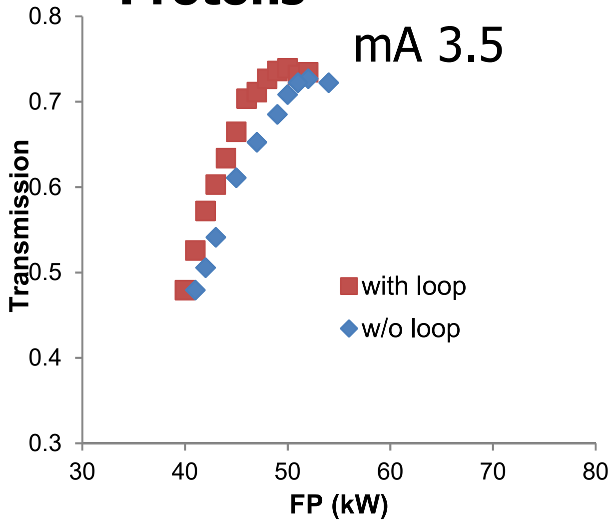
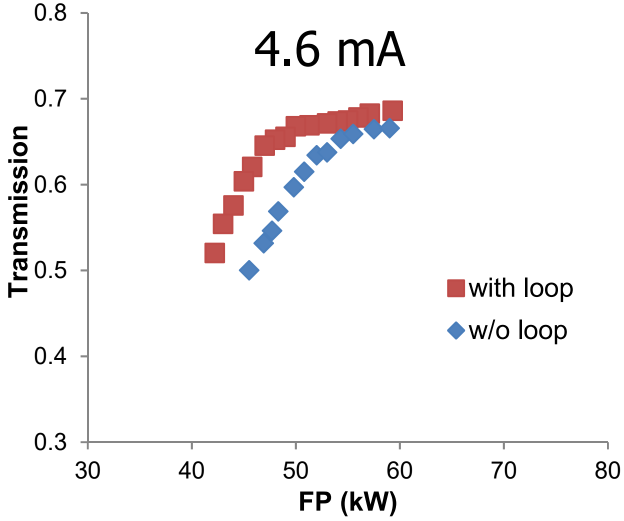
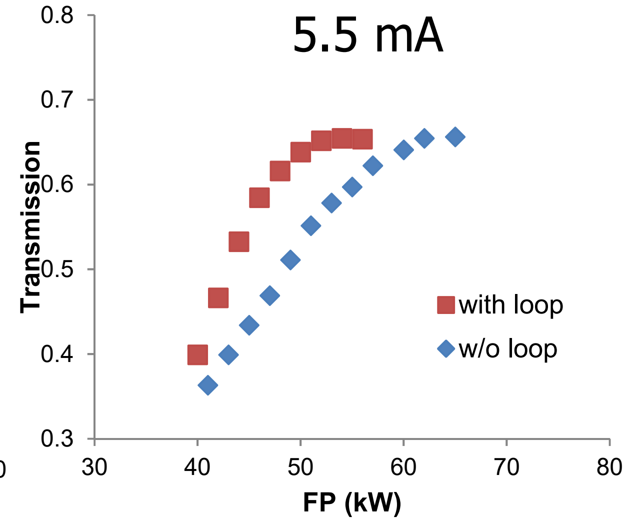


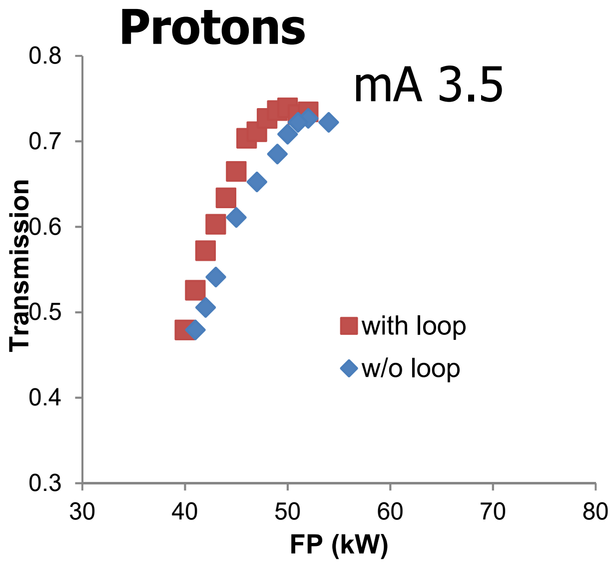


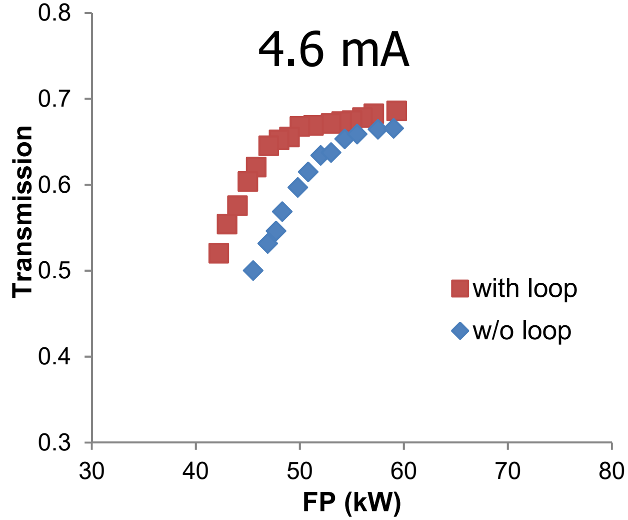


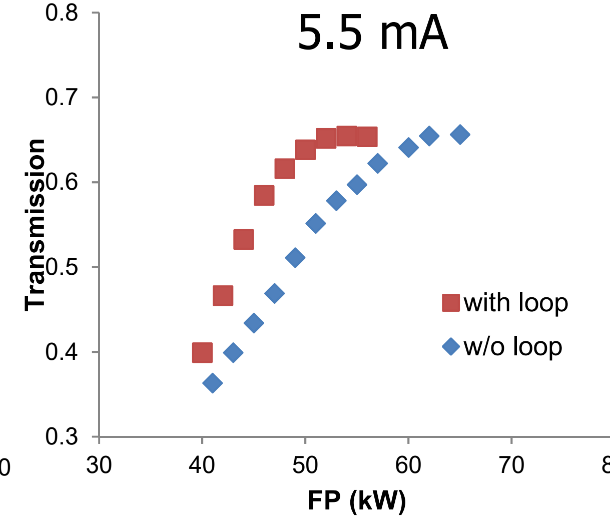
with loop

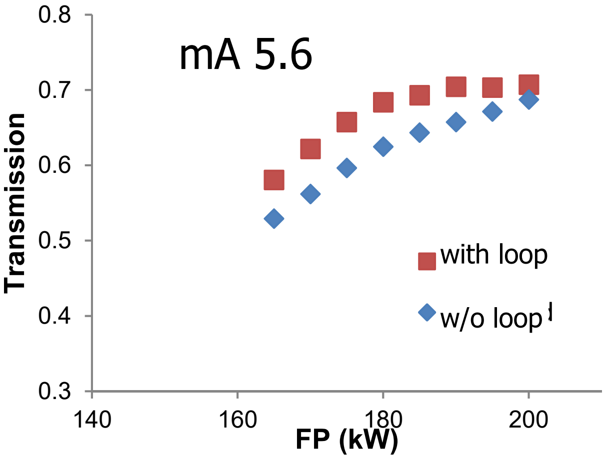
w/o loop

Transmission studies; beam loading effect



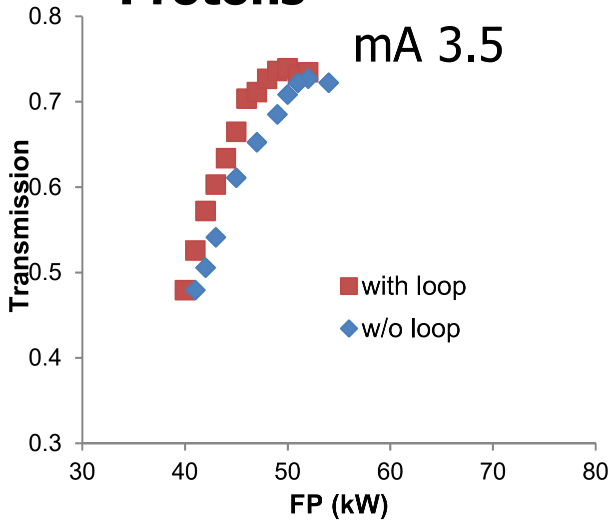


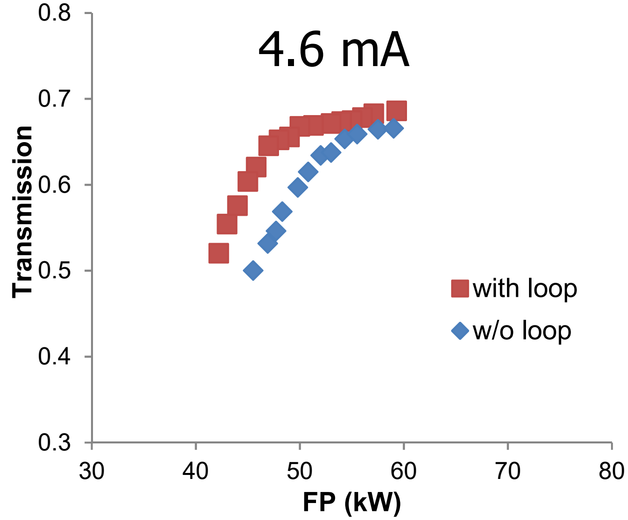


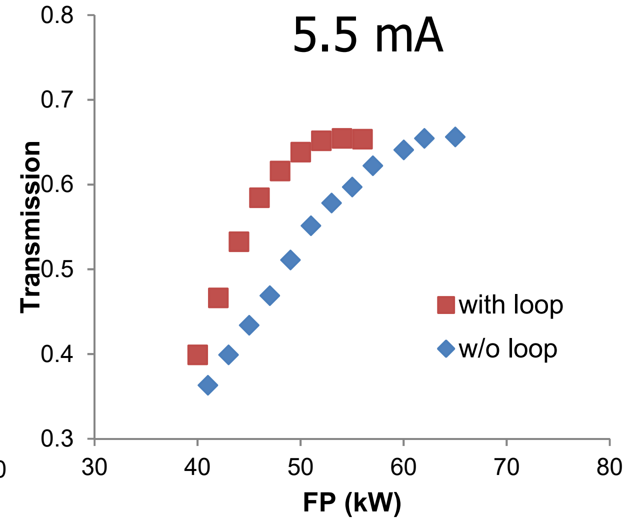


Transmission studies; beam loading effect

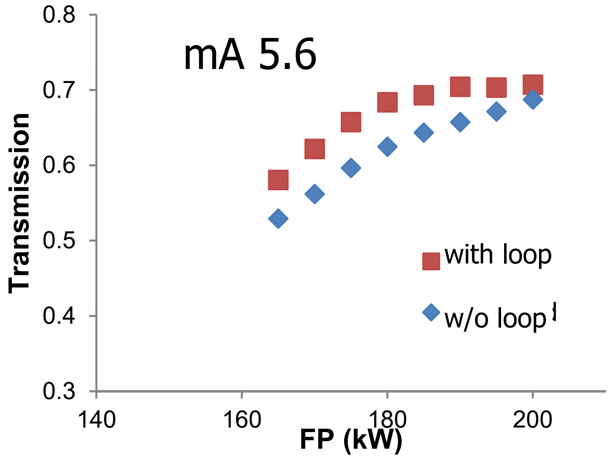
Protons



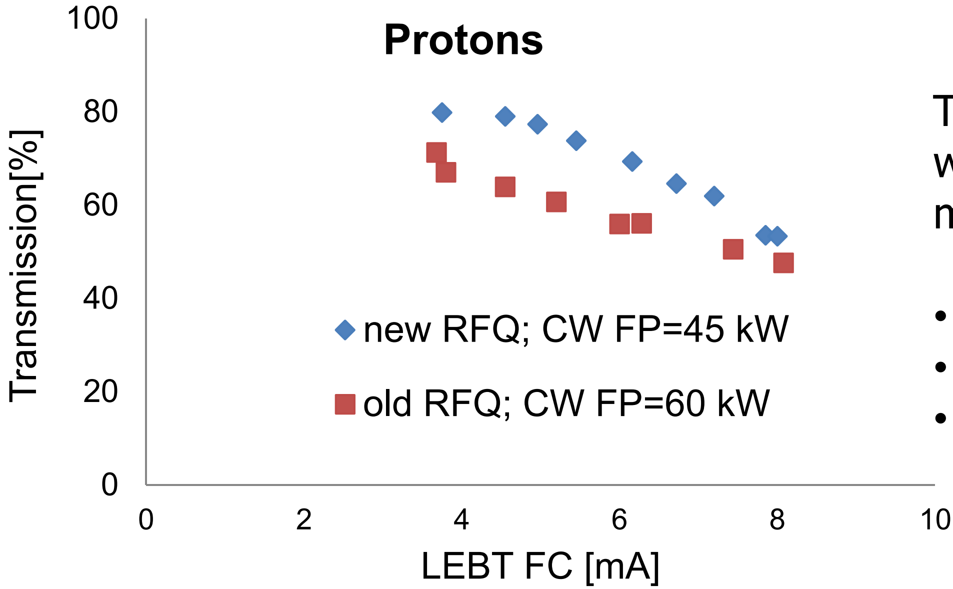


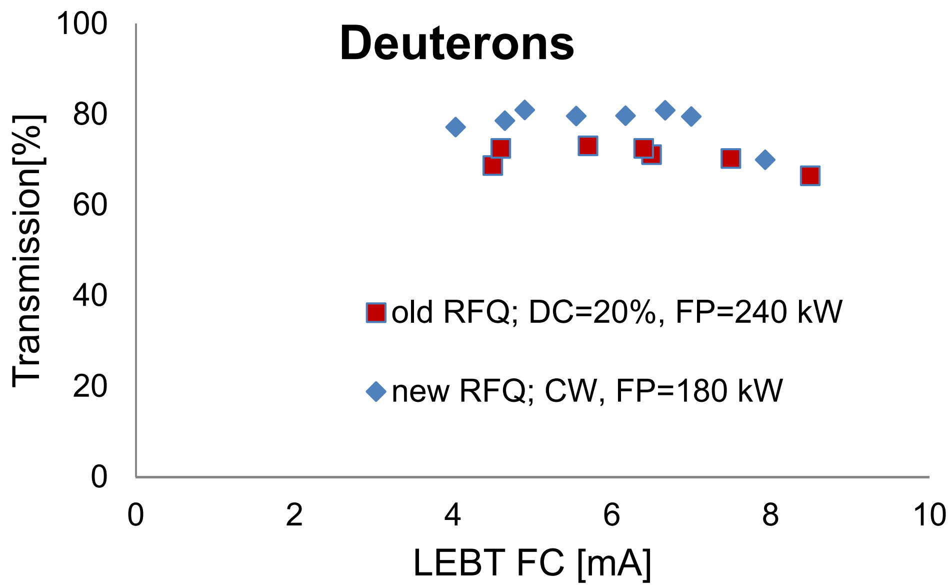


Deuterons



Transmission vs LEBT current; new vs old

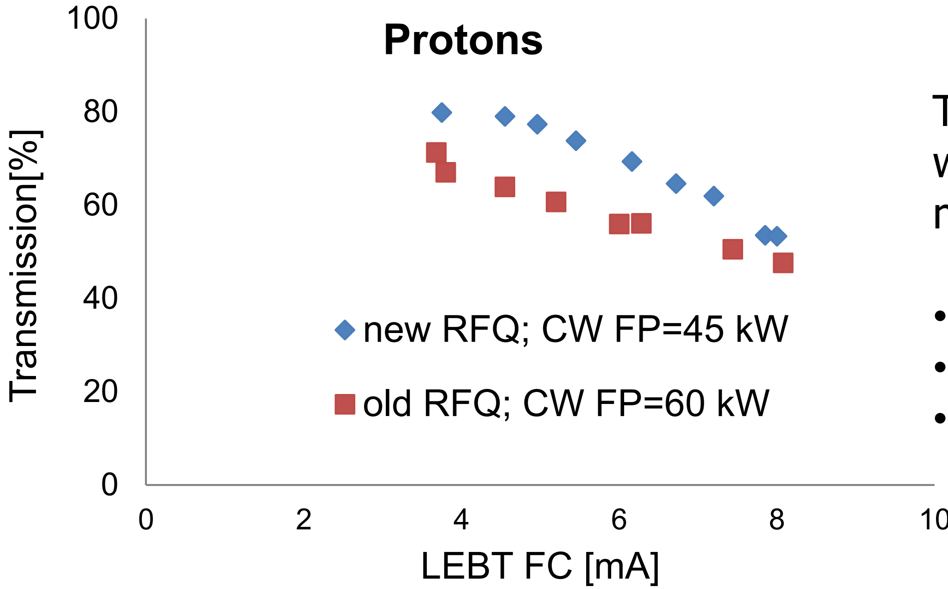




The measurements with old rods was made in Dec 2015 in the same manner:

- MEBT measurements,
- similar LEBT optics,
- the LEBT current was changed only by varying RF power of the ion source

Transmission vs LEBT current; new vs old



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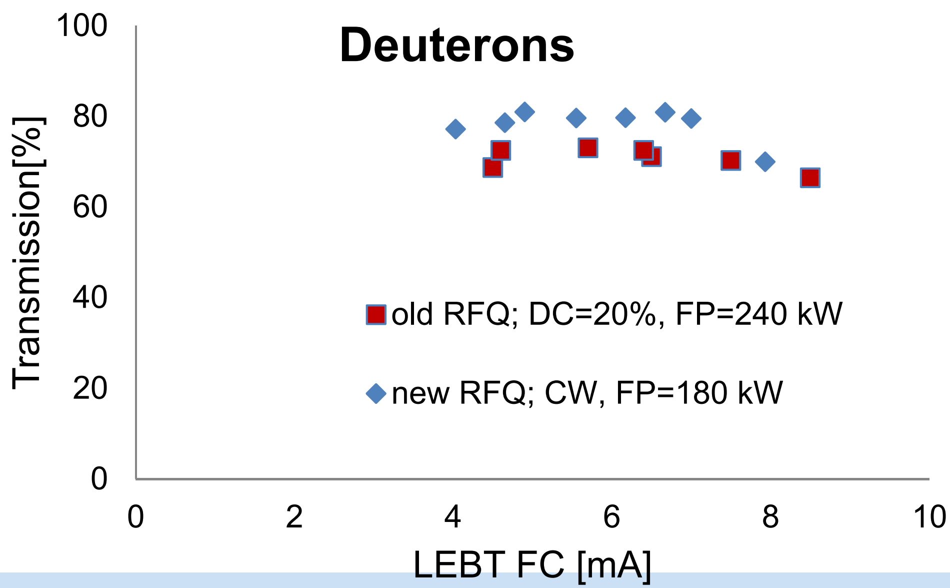
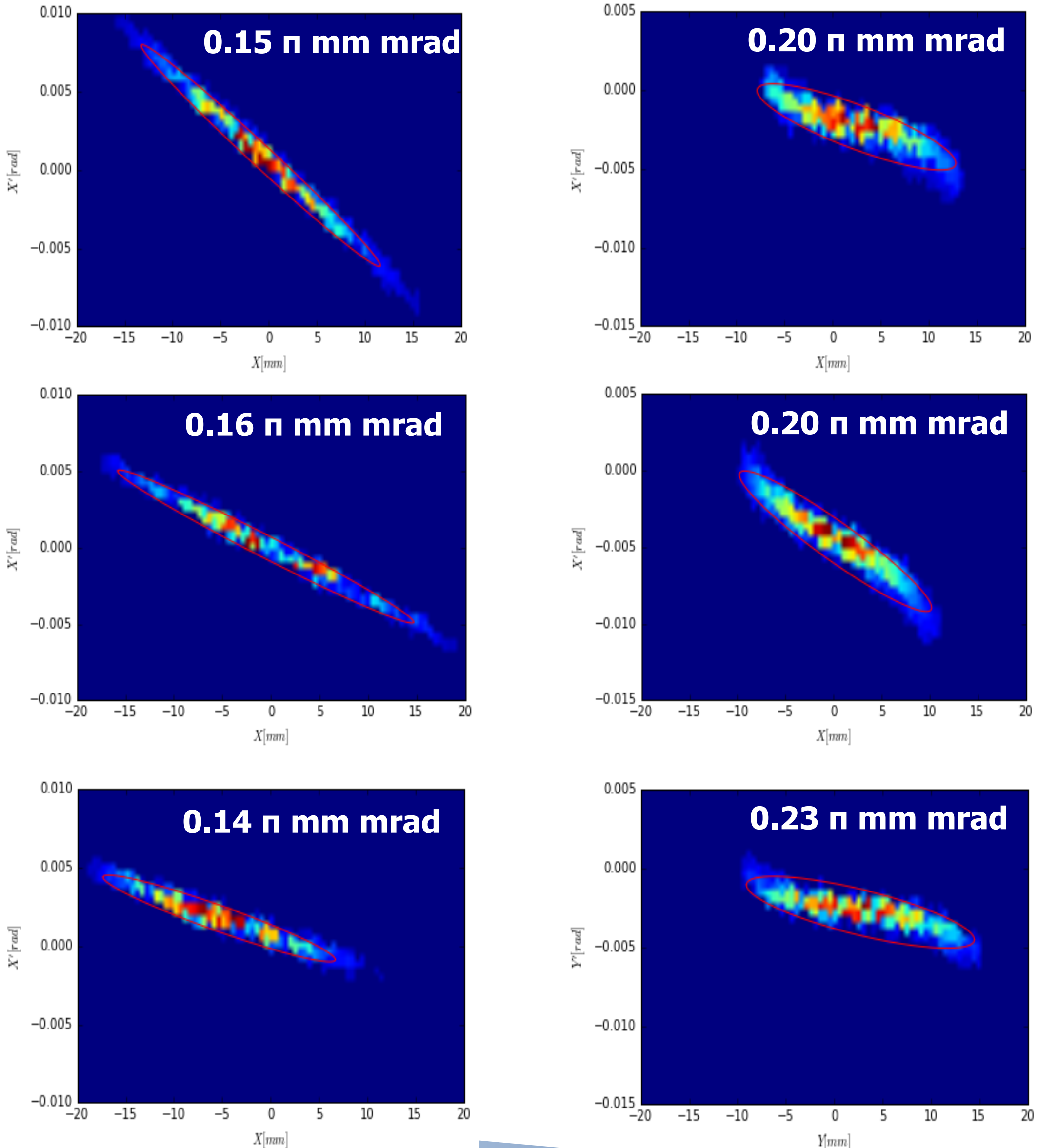


Some improvement in the transmission in spite the fact that the geometrical aperture between rods was reduced by 30 %

Transversal emittance

x-x′ y-y′



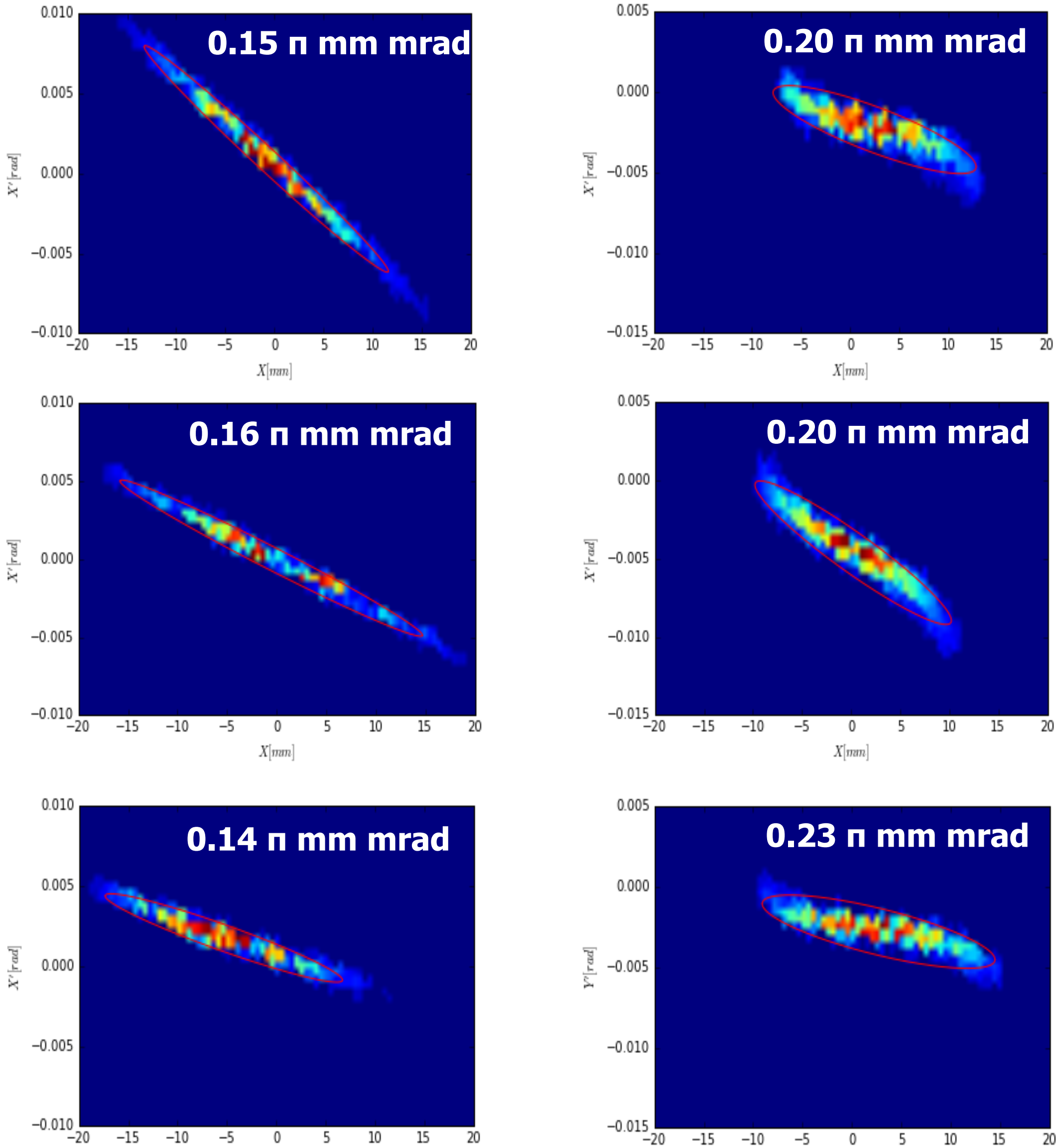
Protons 4.3 mA

Protons 5.5 mA

Deuterons 5.0 mA

Transversal emittance

x-x'　　　　y-y'



Protons 4.3 mA

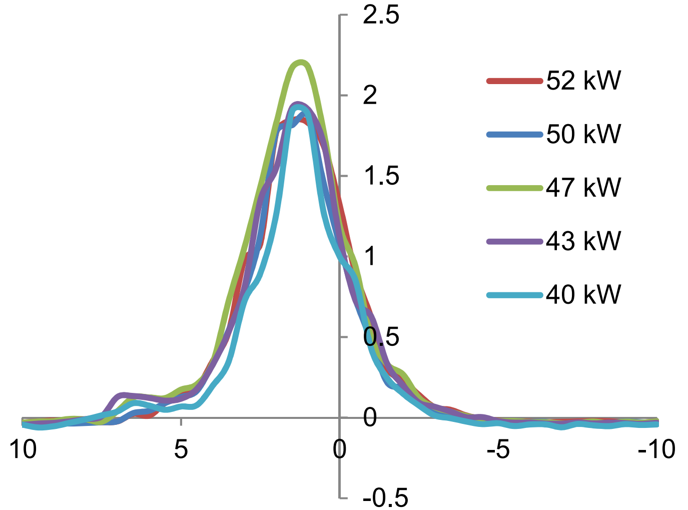
Protons 5.5 mA

Deuterons 5.0 mA

Transversal emittance is within the specification

Profiles at the RFQ exit new rods

MEBT profiles
New rods



MEBT profiles
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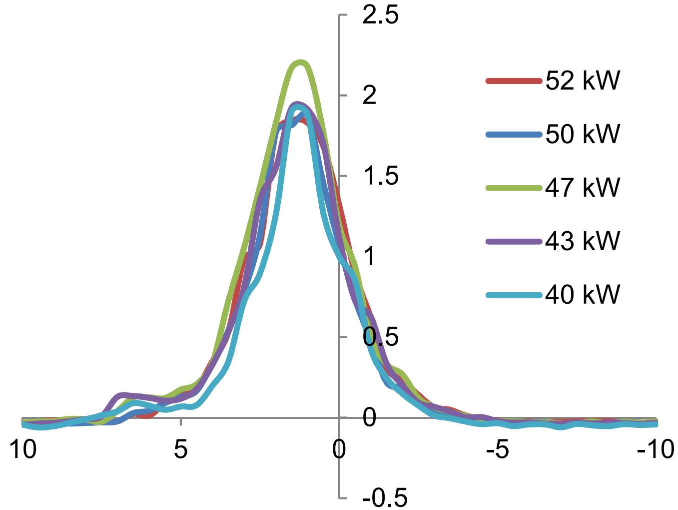
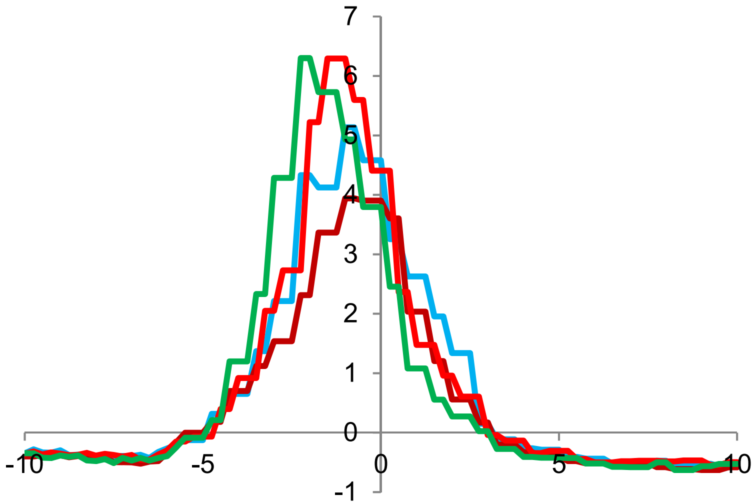
Profiles at the RFQ exit new rods

MEBT profiles
New rods



MEBT profiles
Old rods



Profiles at the RFQ exit new rods

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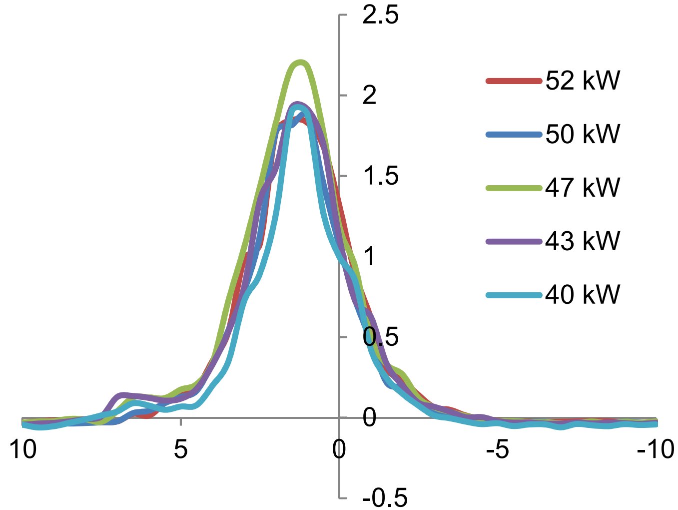
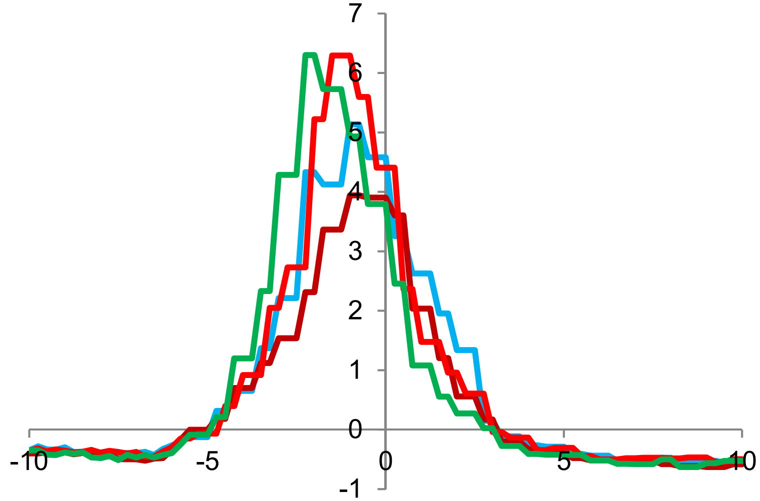
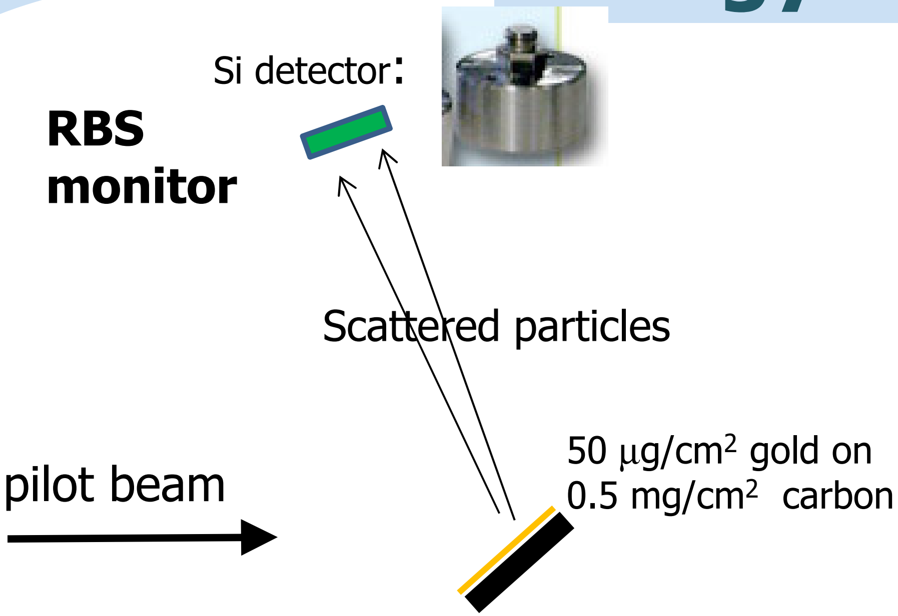


MEBT profiles
Old rods

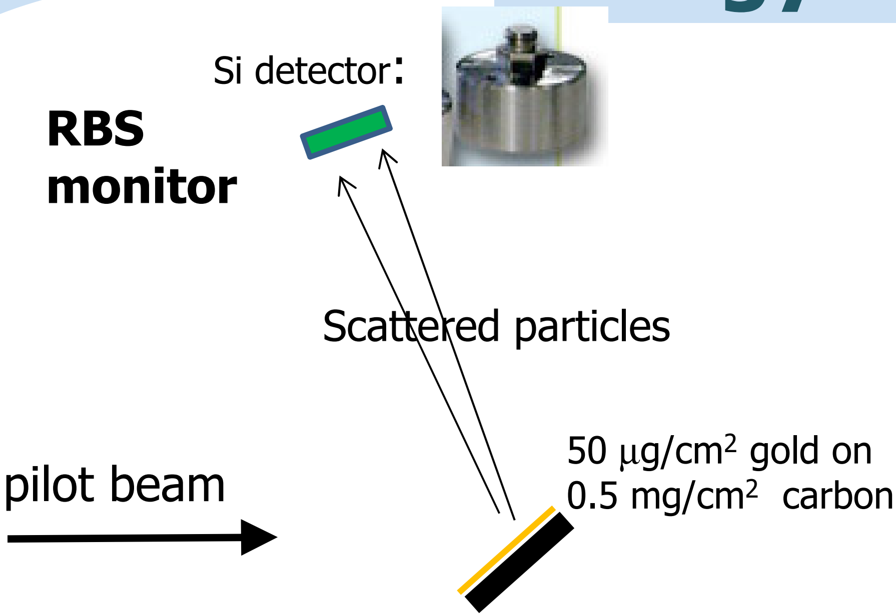


Do not observe power related steering effects

Energy measurement



Energy measurement

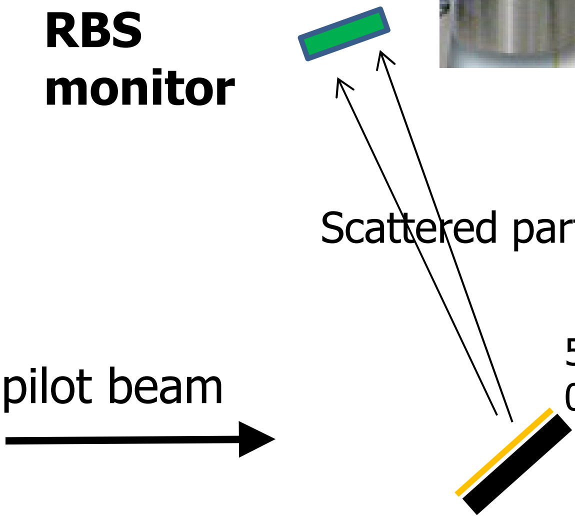


Detector is carefully calibrated in-situ with ^{148}Gd and ^{228}Th alpha sources

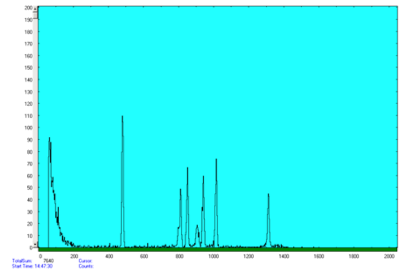
Energy measurement

RBS monitor

Si detector:



50 $\mu g/cm^2$ gold on
0.5 mg/cm^2 carbon



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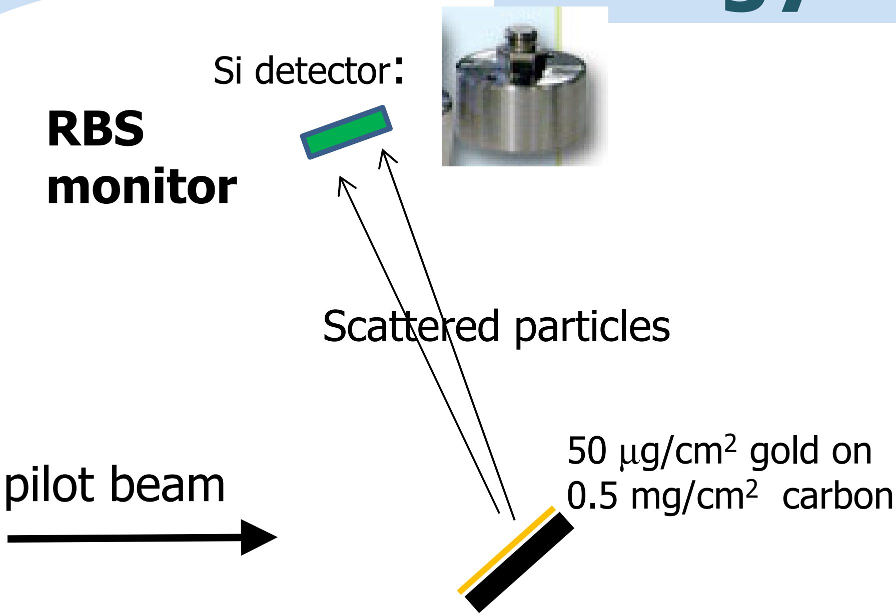
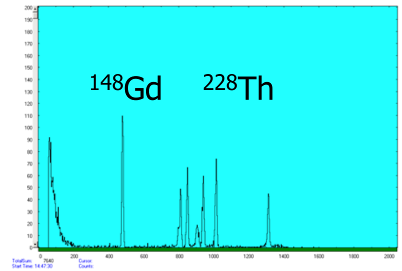
Energy measurement





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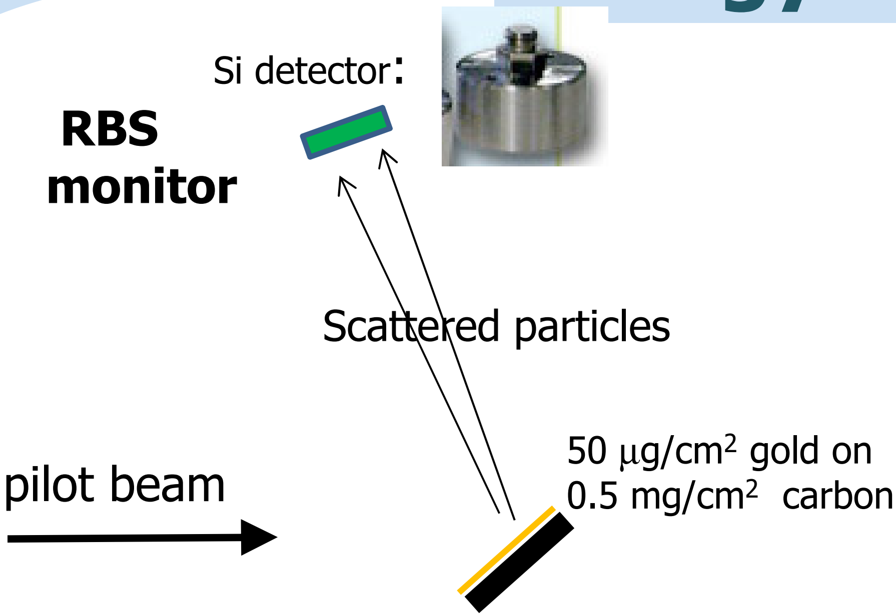
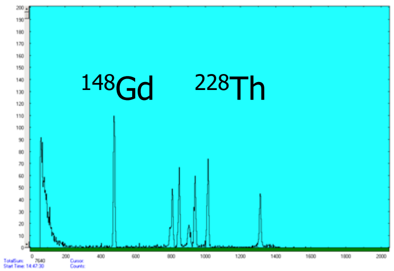
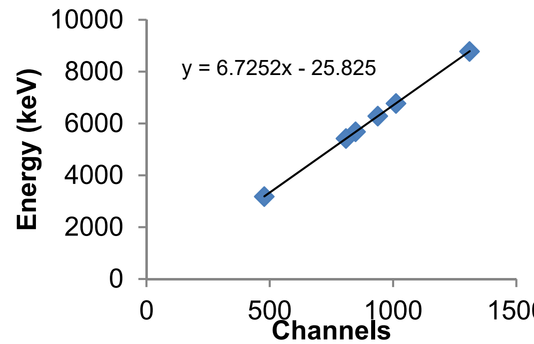
Energy measurement







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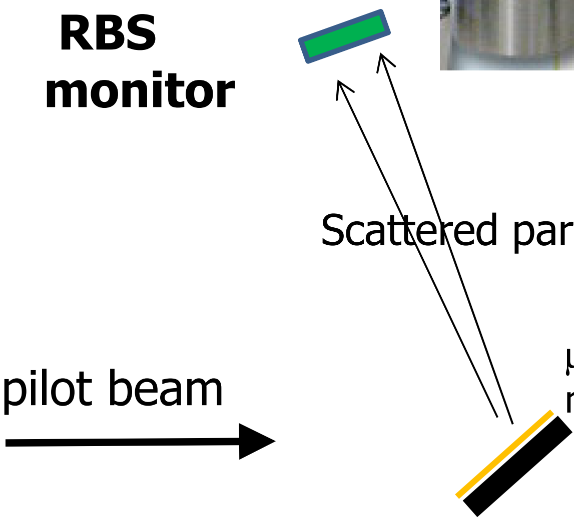
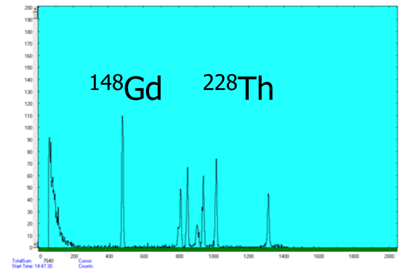
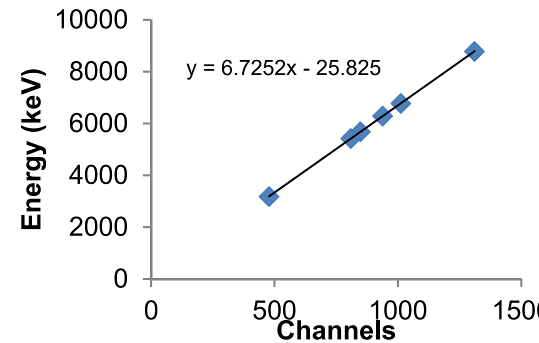
Energy measurement







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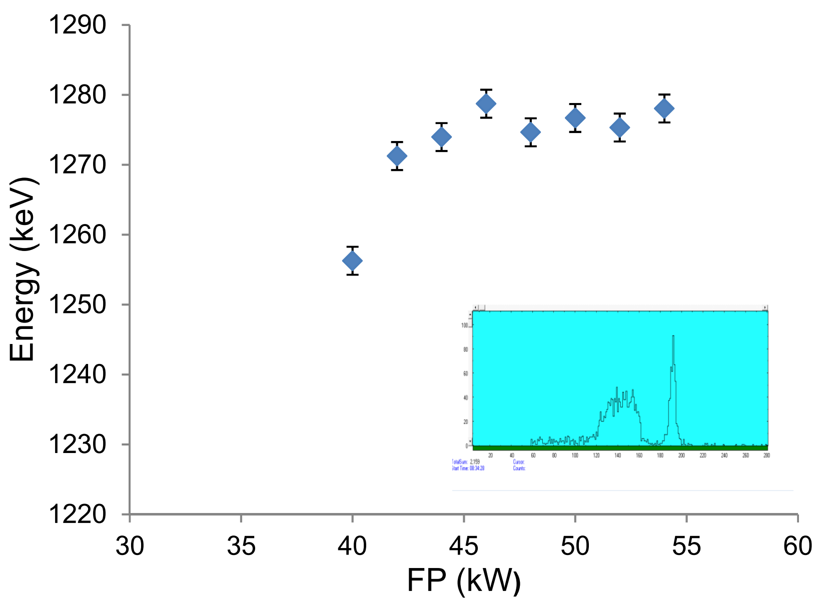
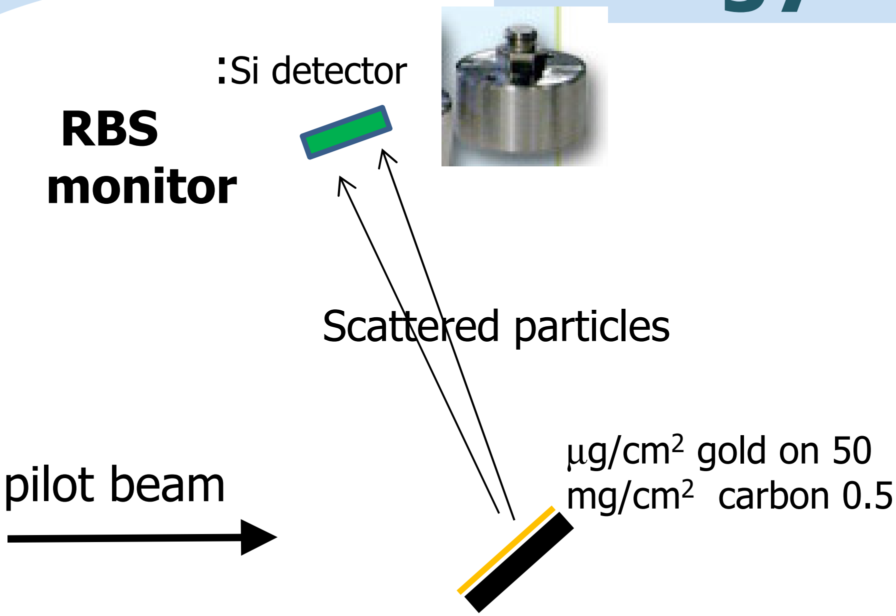
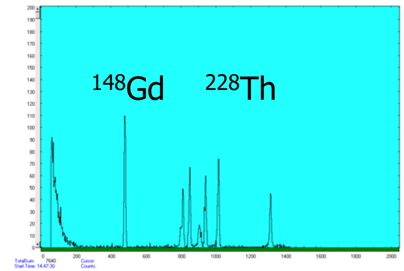
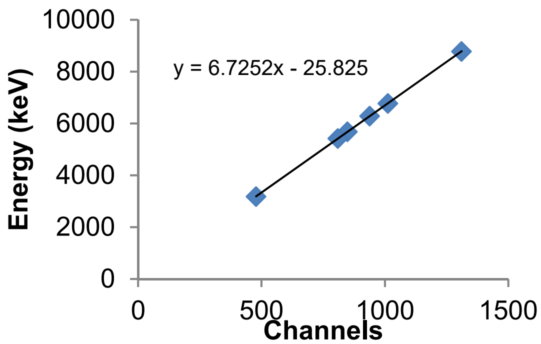


Energy measurement







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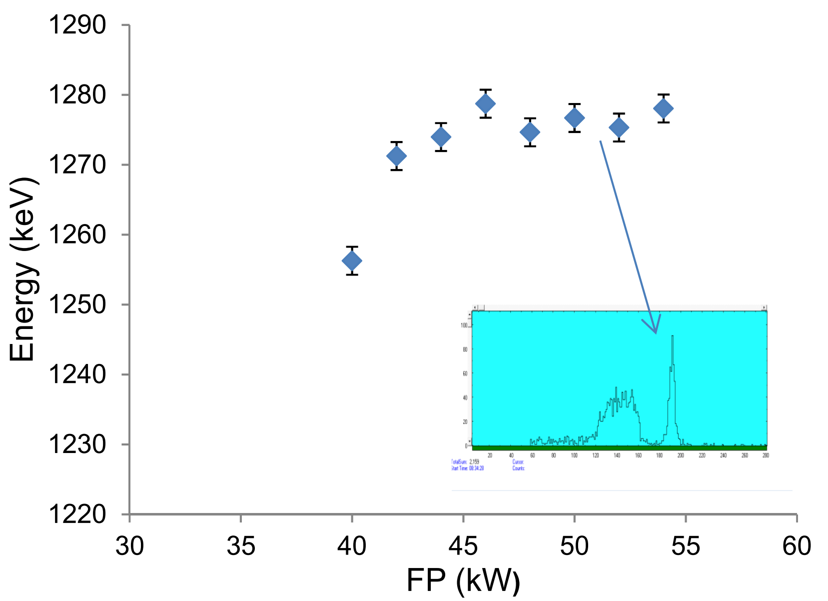
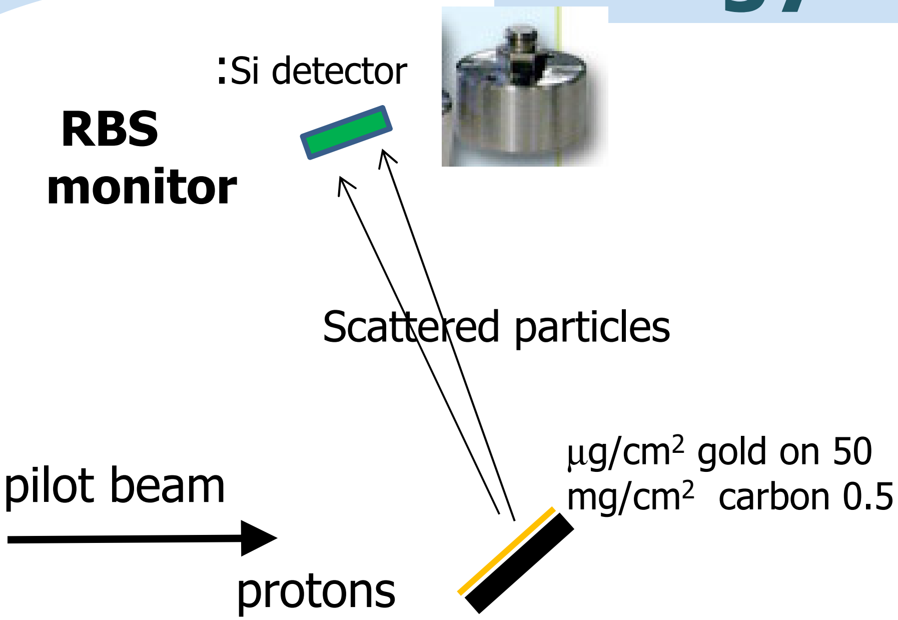
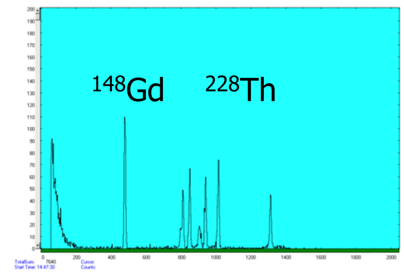
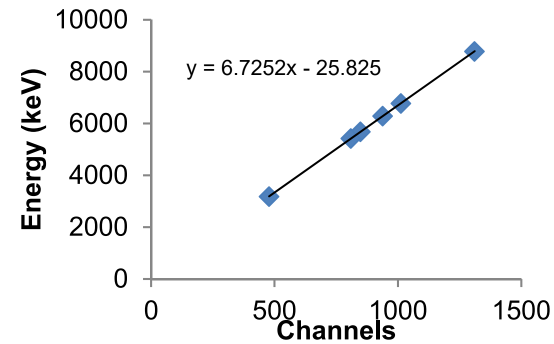


Energy measurement

Soreq NRC







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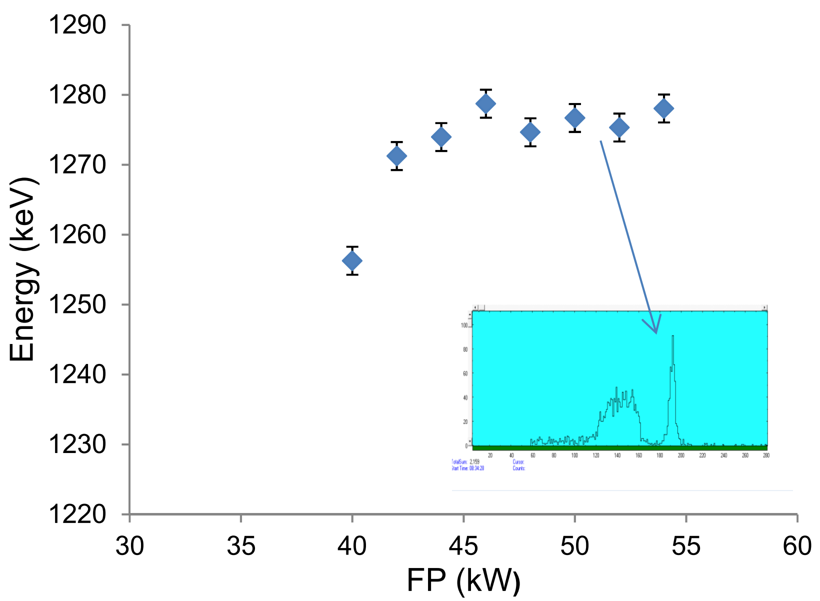
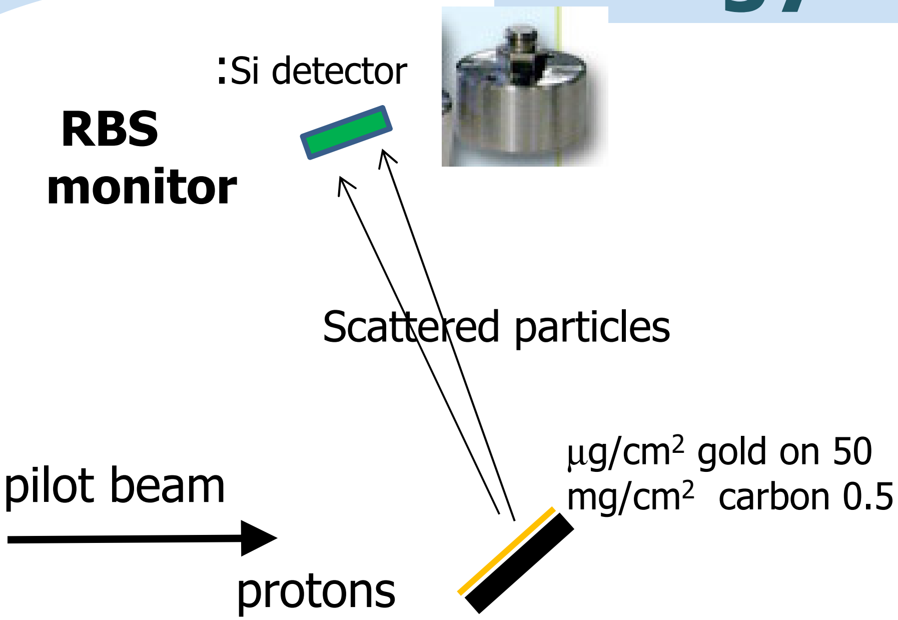
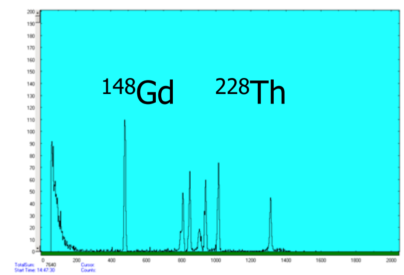
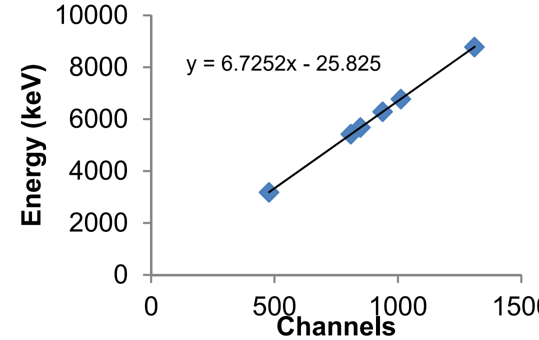


Energy measurement

Soreq NRC







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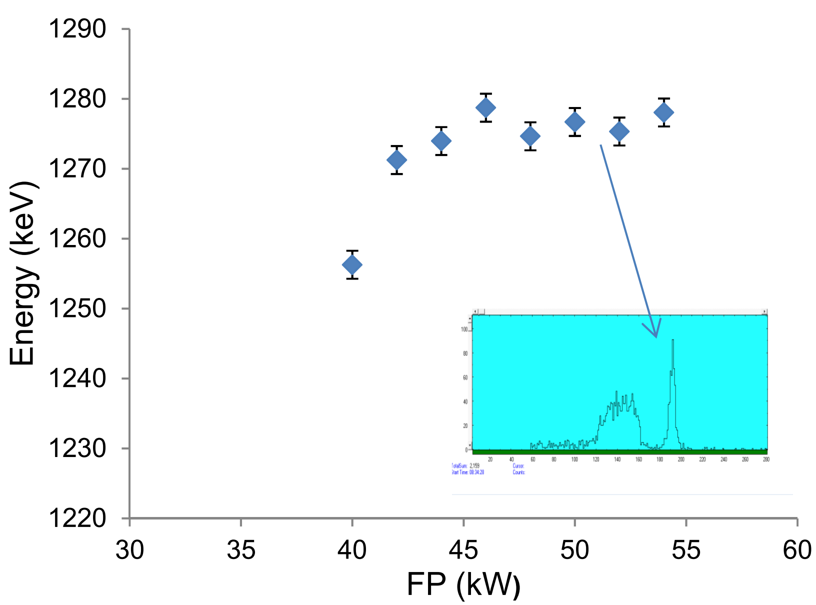

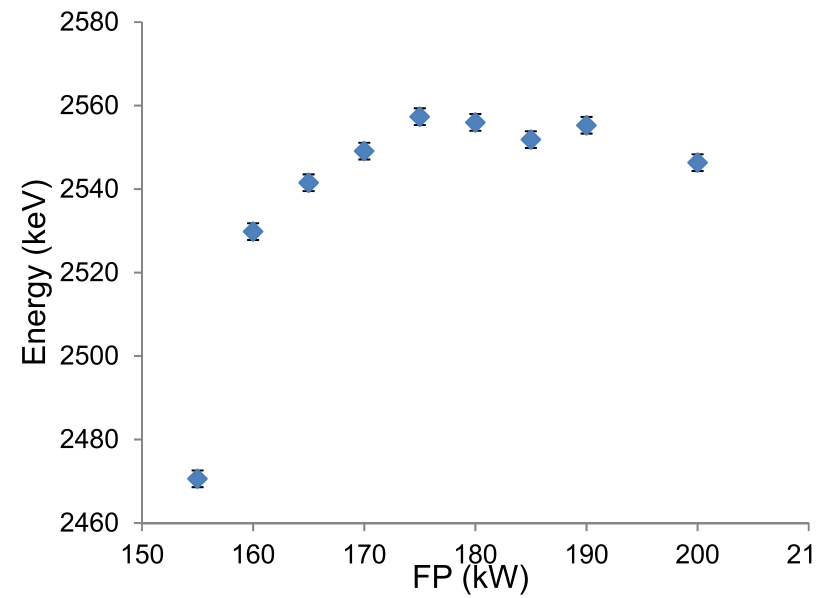

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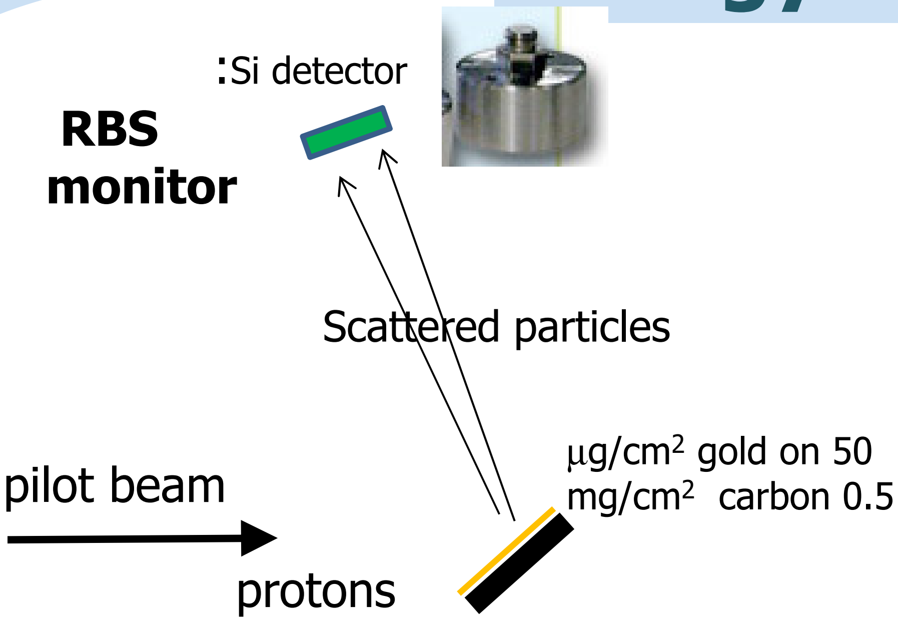

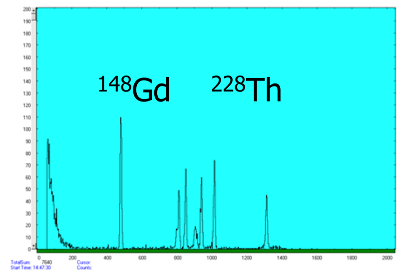

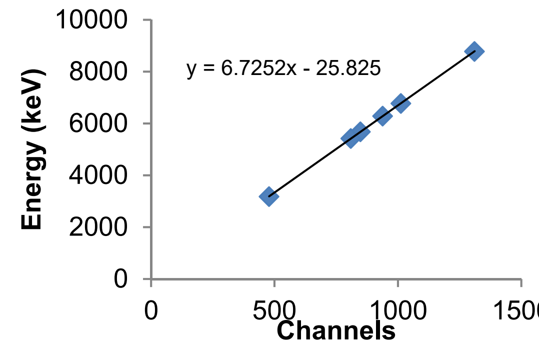

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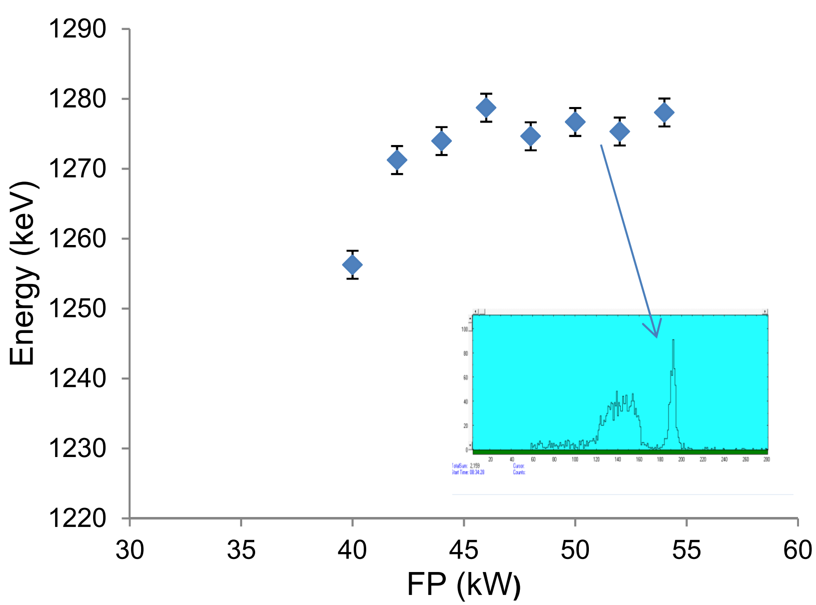

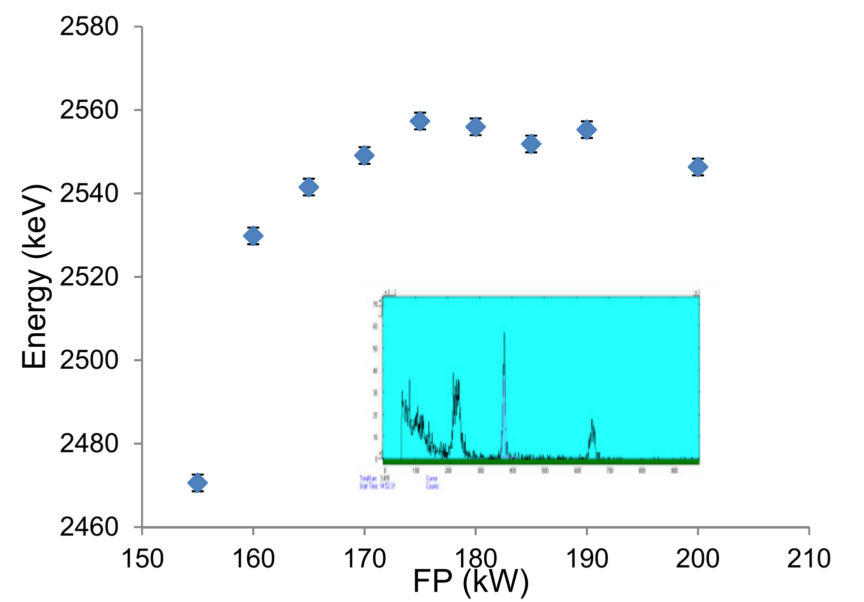

Energy measurement

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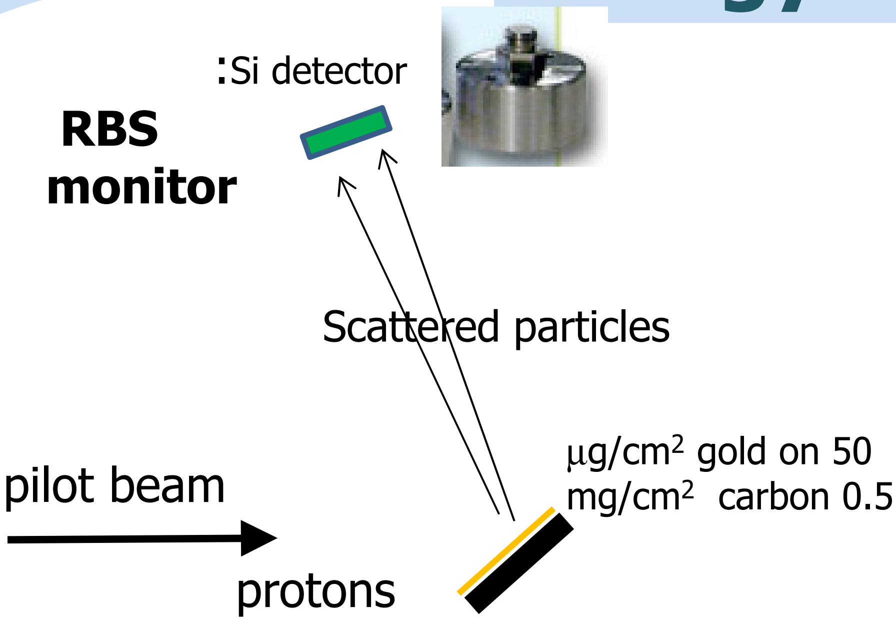

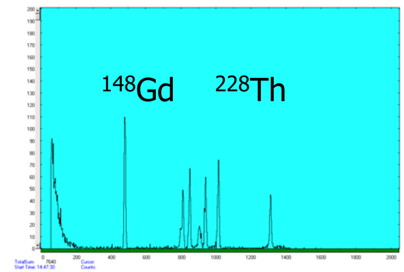

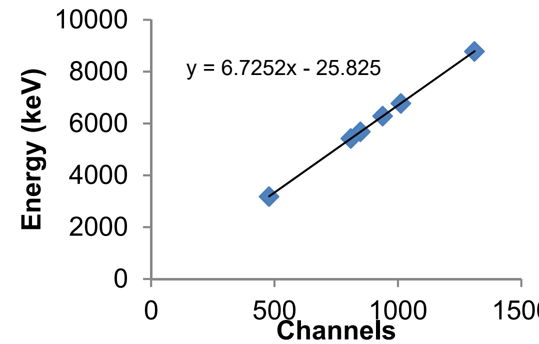

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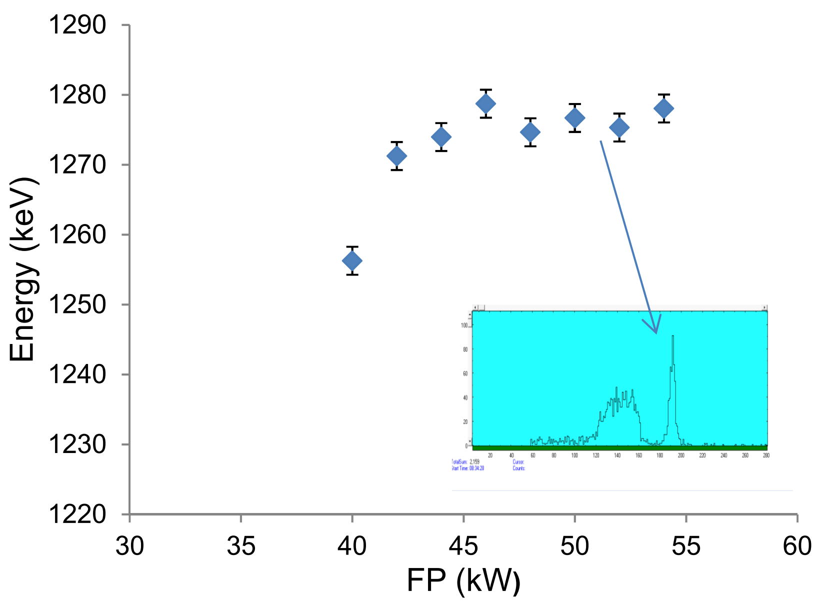
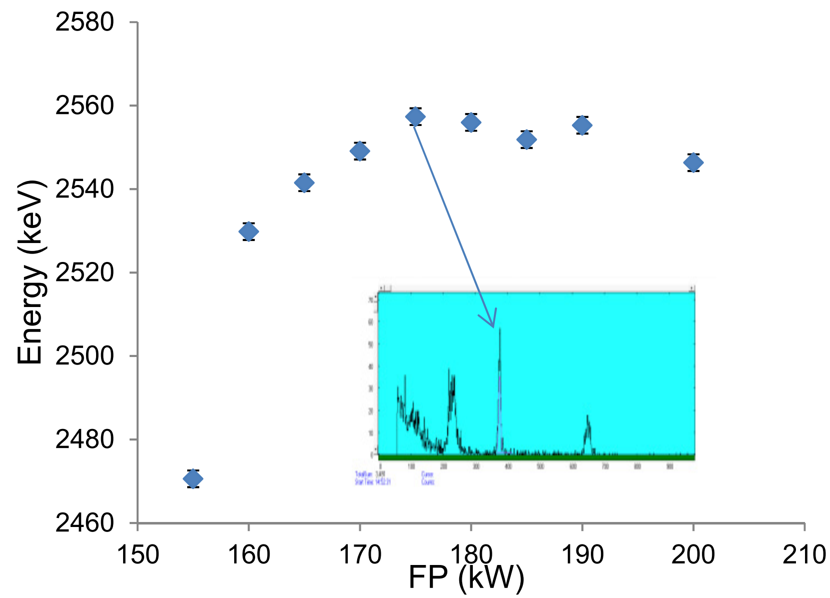
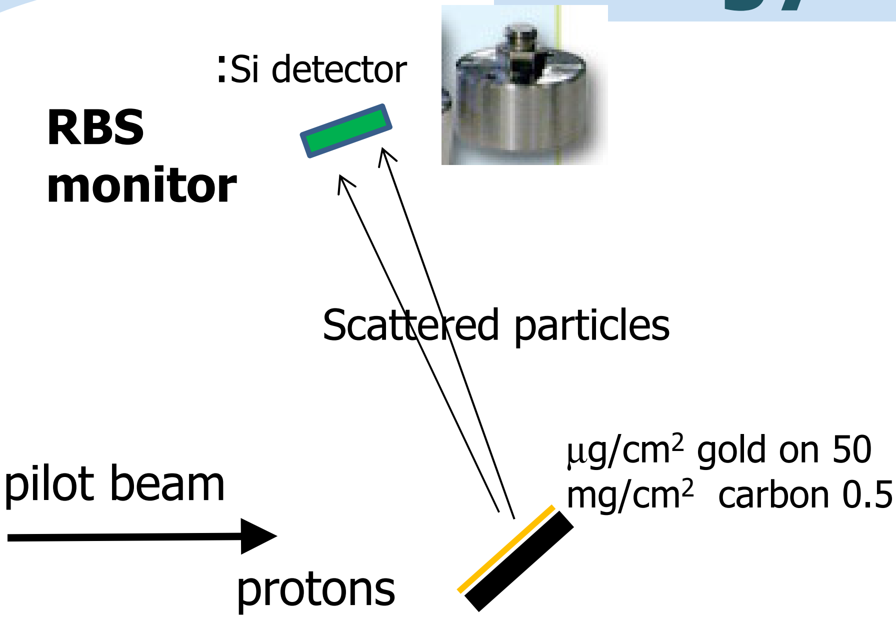
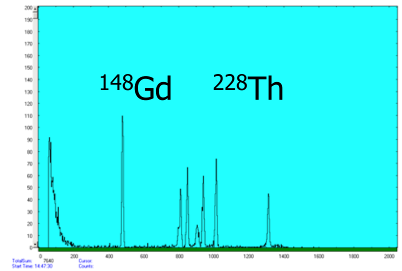
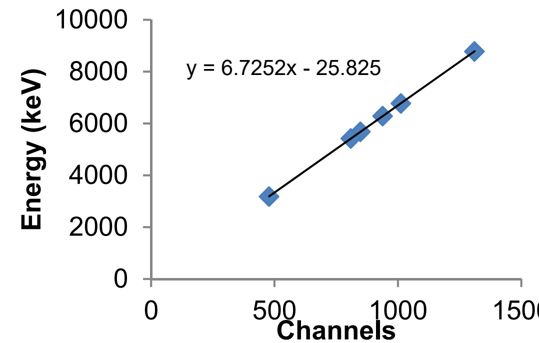




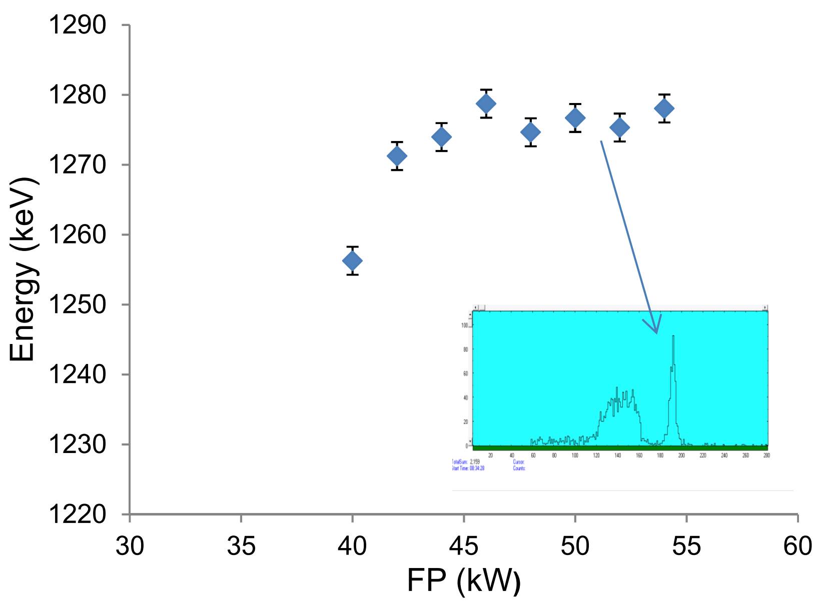
Energy measurement

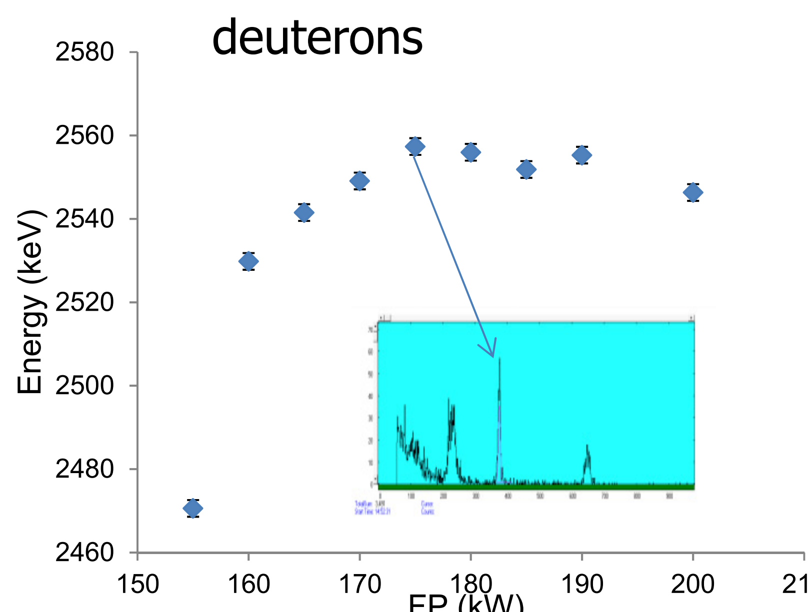






Detector is carefully calibrated in-situ with ^{148}Gd and ^{228}Th alpha sources



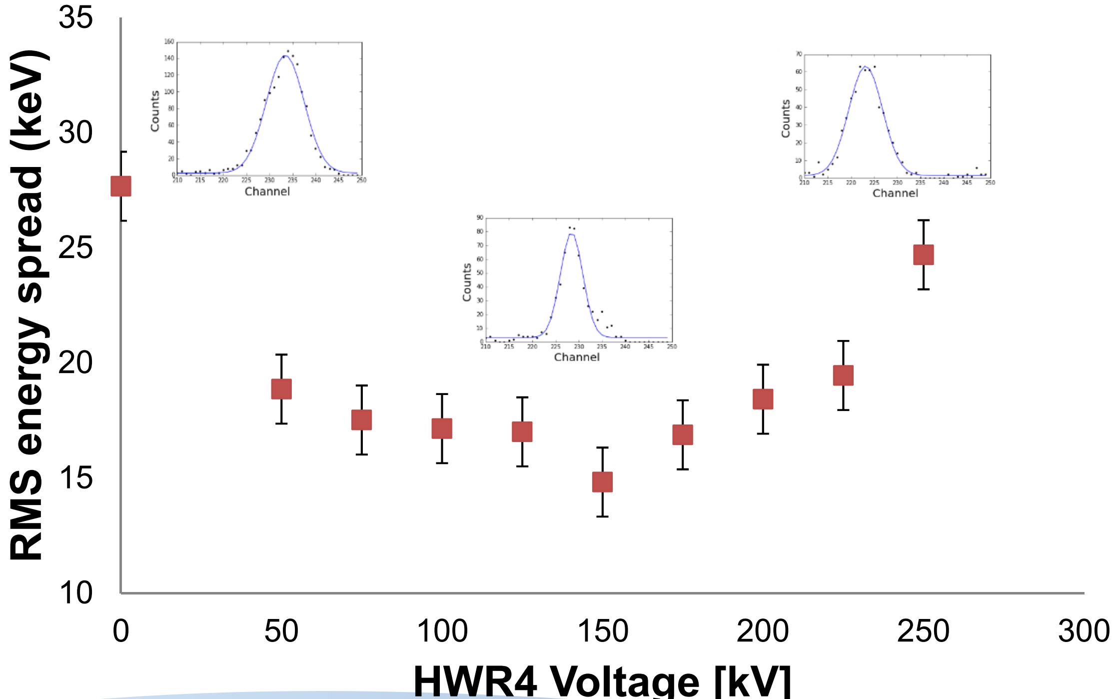


Measurement longitudinal emittance

RBS measurements have some sensitivity to energy spread
Attempt measurement of longitudinal emittance
by variation of longitudinal focusing with a cavity

Tune:	HWR1 300 kV	-90^{o}
	HWR2 500 kV	$+40^{o}$
	HWR4 0-300 kV	-130^{o}

This tune should not increase too much (~ 20%) the original emittance at RFQ exit

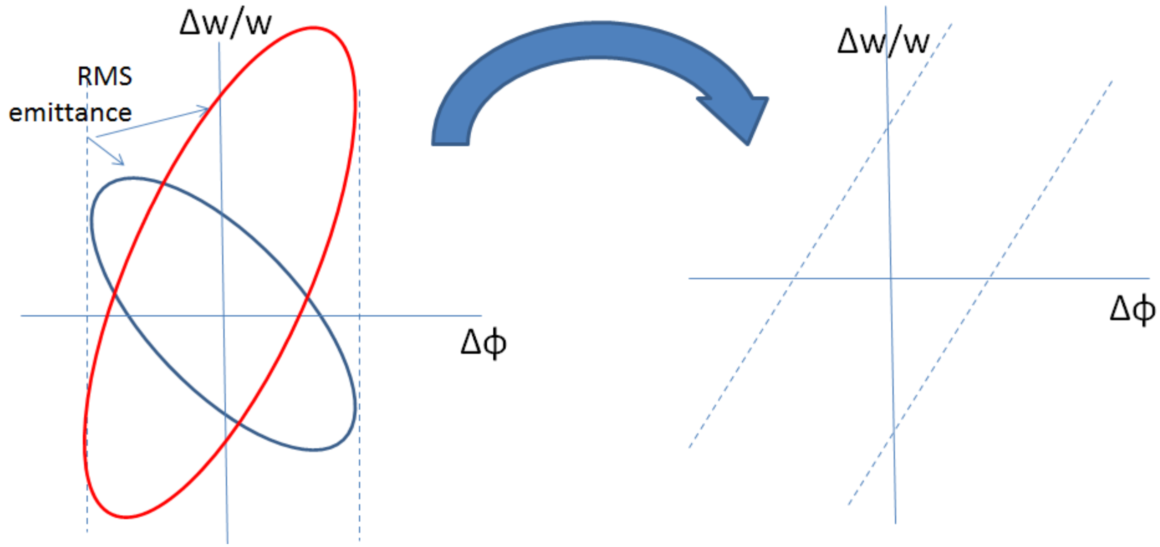


The energy and bunch profiles are measured for different HWR4 bunching voltages

Measurement method

From RBS measurements
we know that RMS emittance
is bond in the limits at the
measuring position

We approximately matrix
transformation and can
calculate how thes boundary
look like at HWR4



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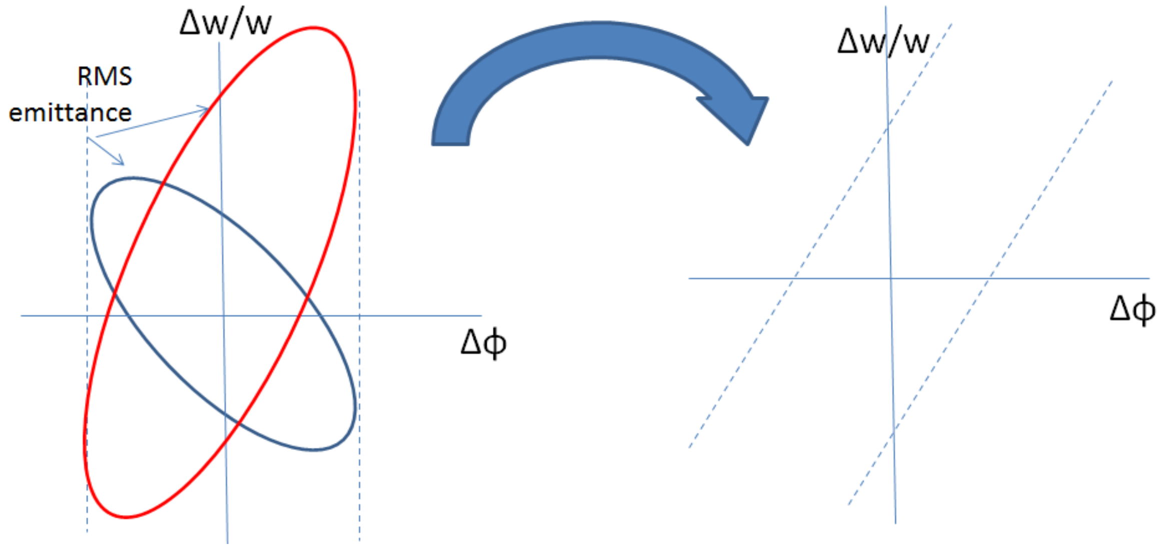

Making this transformation
for different bunching
HWR4 voltages we find
the limits of the RMS
emittance at HWR4 position

Measurement method

From RBS measurements
 we know that RMS emittance
 is bond in the limits at the
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We approximately matrix
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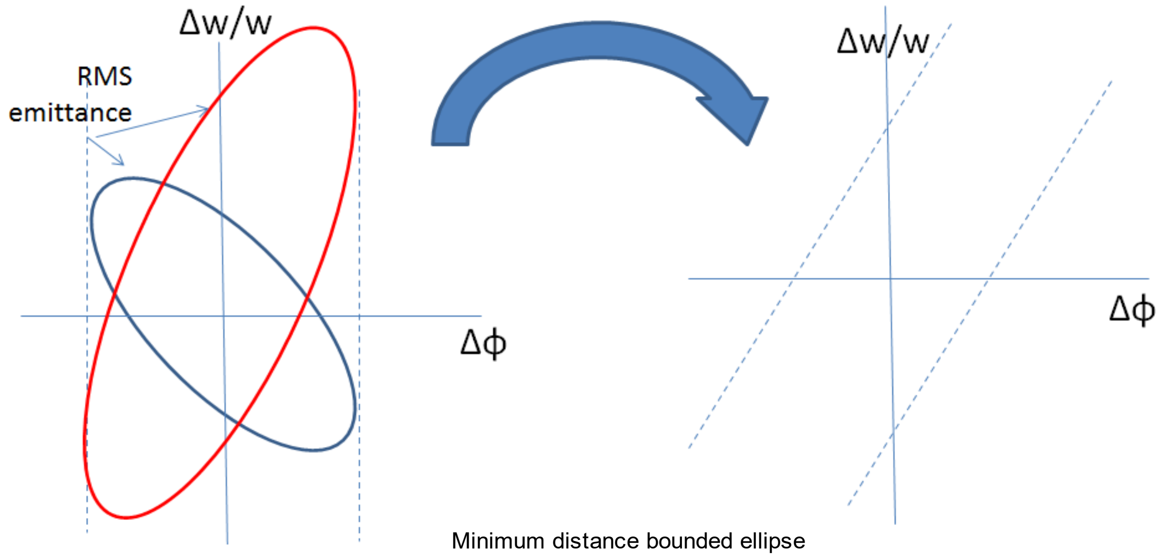

Making this transformation
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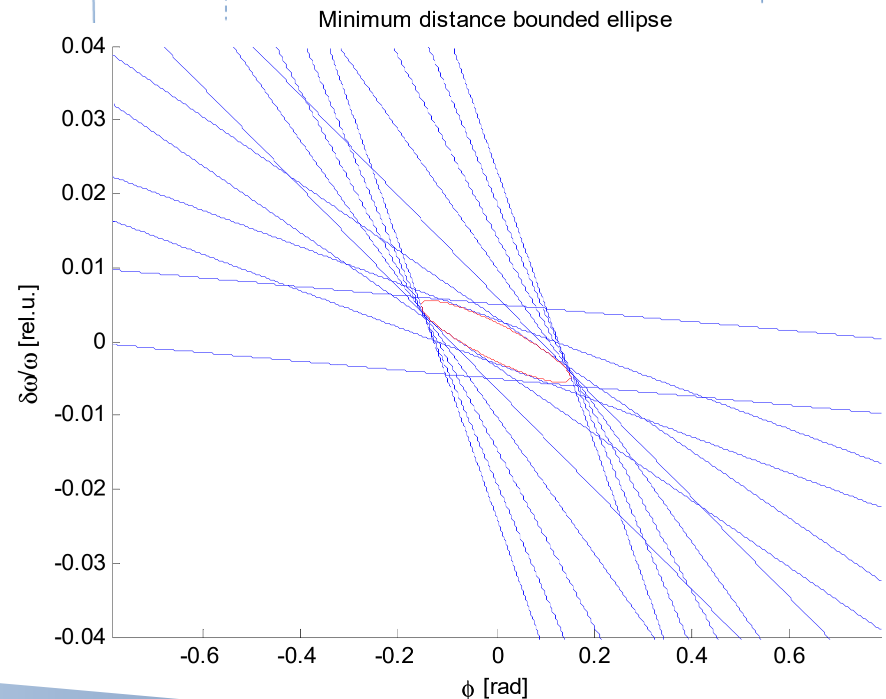
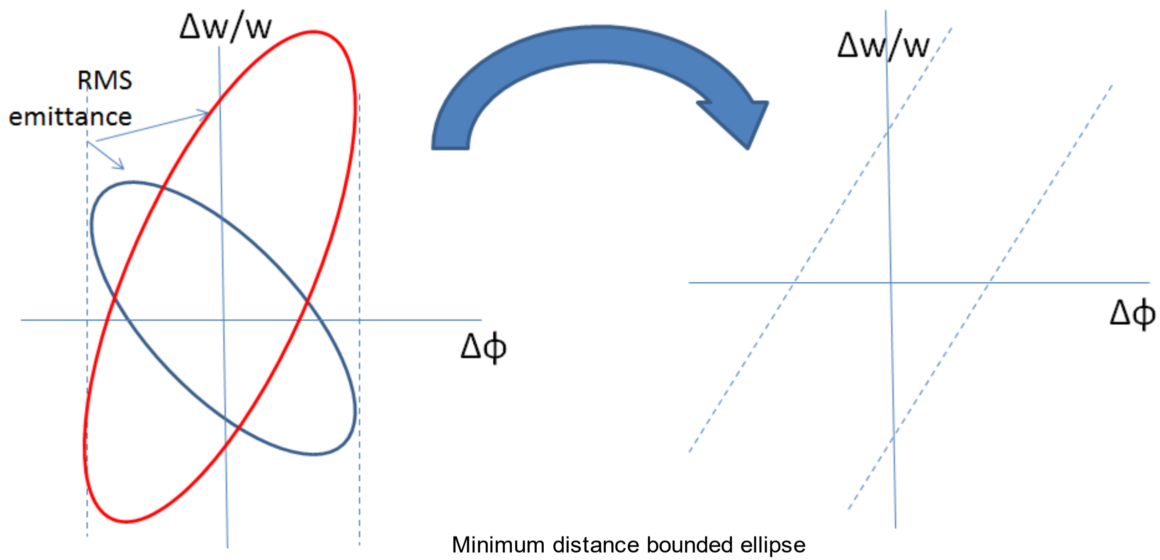
the limits of the RMS
emittance at HWR4 position



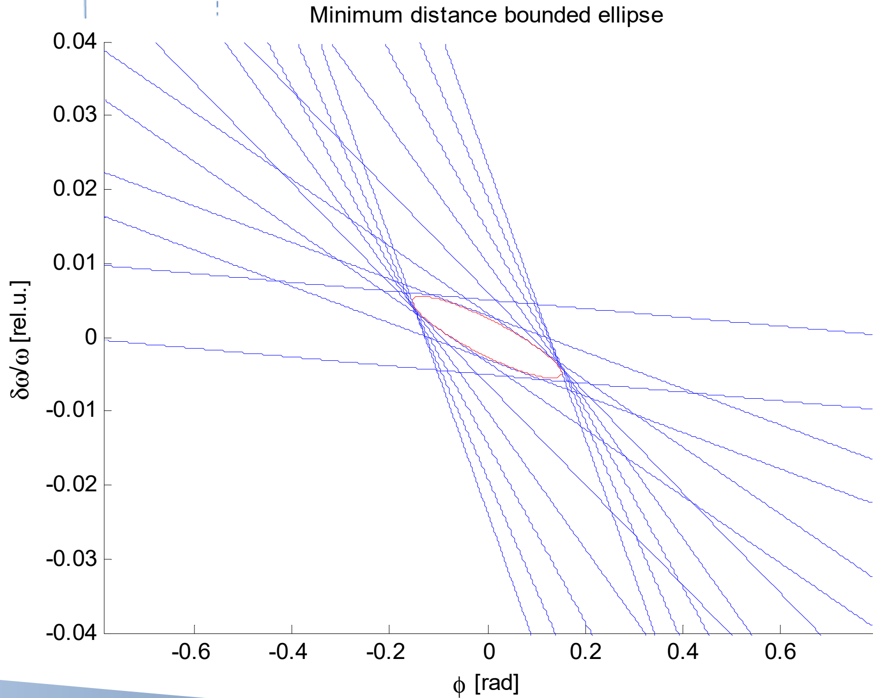
Measurement method

From RBS measurements
we know that RMS emittance
is bond in the limits at the
measuring position

We approximately matrix
transformation and can
calculate how thes boundary
look like at HWR4

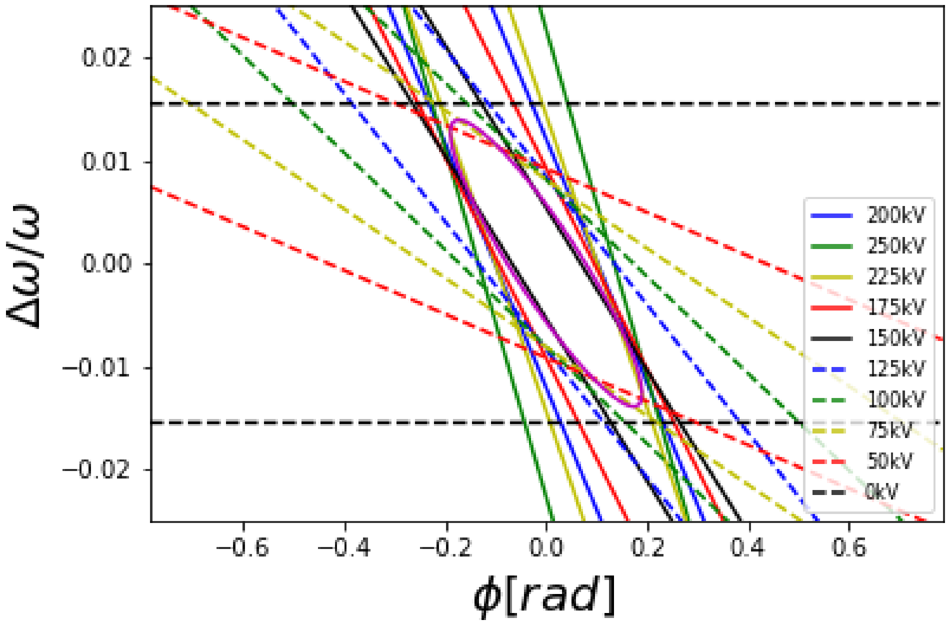


Making this transformation
for different bunching
HWR4 voltages we find
the limits of the RMS
emittance at HWR4 position



'Beam Instrumentation and Diagnostics', P. Strehl. Pg. 267 & 325

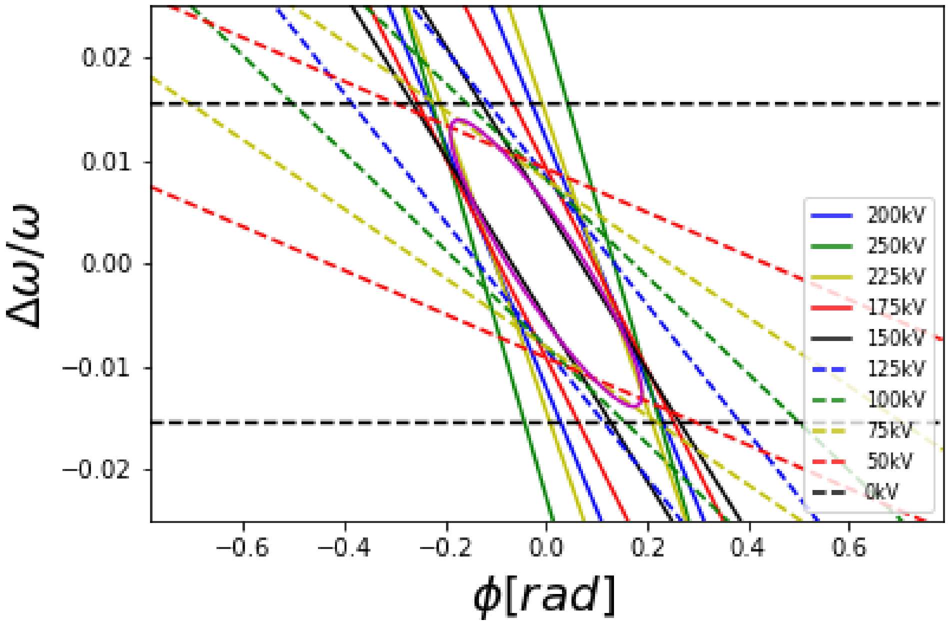
Results protons



resolution RBS 15 keV

analysis by A. Perry

Results protons



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ε_z [RMS, π keV/u nsec]	1.3
α_z [rad]	2.2
β_z [deg/(%ofΔw/w)]	19

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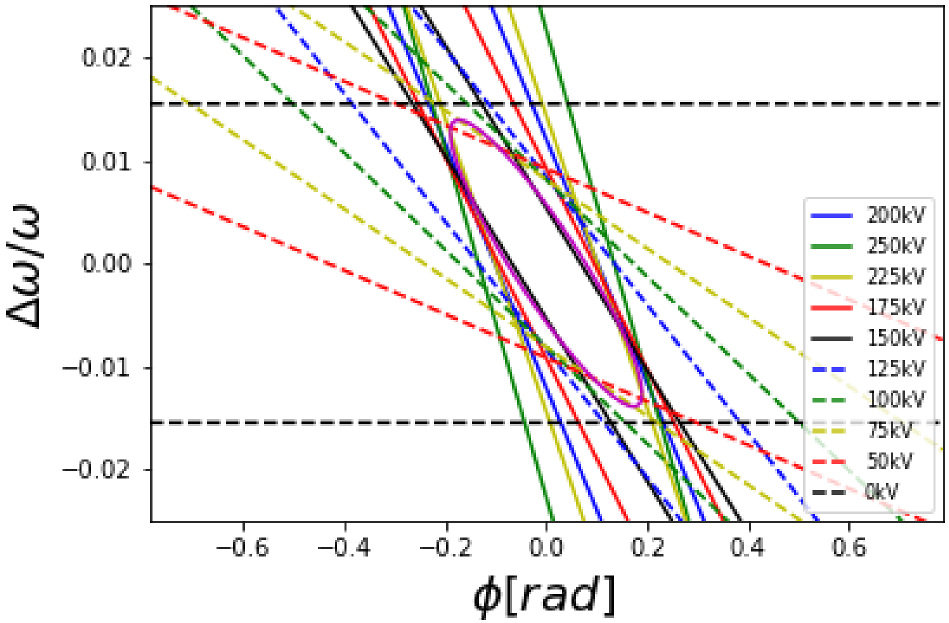

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The RBS results for emittance RMS ~ **1.3** [π keV nsec] at HWR4 pos.

analysis by A. Perry

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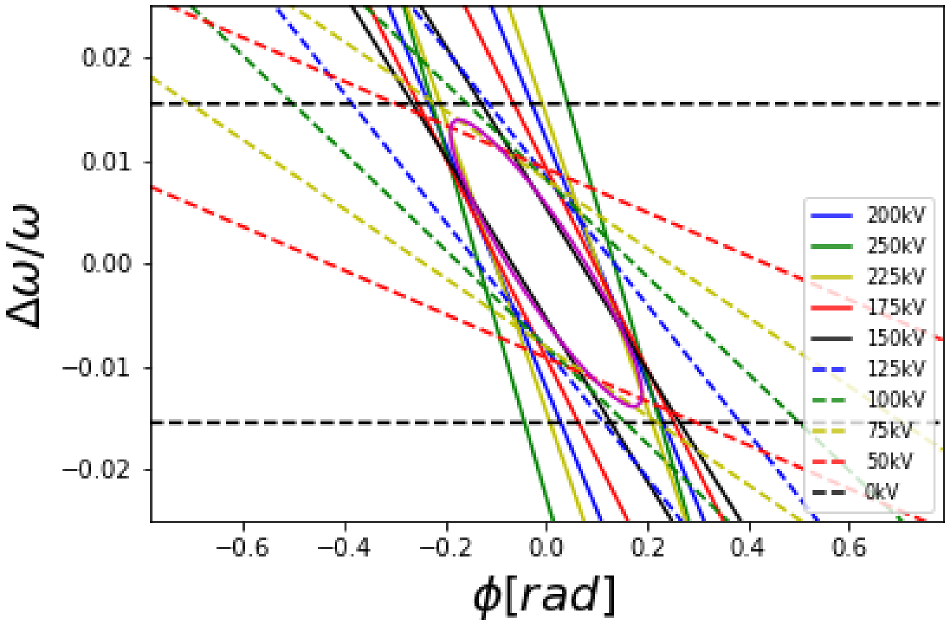

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The RBS results for emittance RMS ~ **1.3** [π keV nsec] at HWR4 pos.

Emittance at RFQ exit is 23 % lower ~**1.1** [π keV nsec]

According to simulations emittance is ~**1.3** [π keV nsec] for low current

~**0.85** [π keV nsec] for high current

analysis by A. Perry

Summary of the RFQ specifications

Parameter	Designed value	Measured value
Energy (keV/u)	1.275	1.275(5)
Working power protons (kW)	46.5	45-50
Working power deuterons (kW)	186	180-190
Transmission protons (%)	93	**60** (for 5 mA)
Transmission deuterons (%)	93	**70** (for 5 mA)
Transversal emittance protons (p·mm·mrad)	0.2	≤0.2 (for 5 mA)
Transversal emittance deuterons (p·mm·mrad)	0.2	≤0.2 (for 5 mA)
Longitudinal emittance protons (π keV/u nsec)	0.85	1.1 (low current)
Longitudinal emittance deuterons (π keV/u nsec)	0.85	non measured yet

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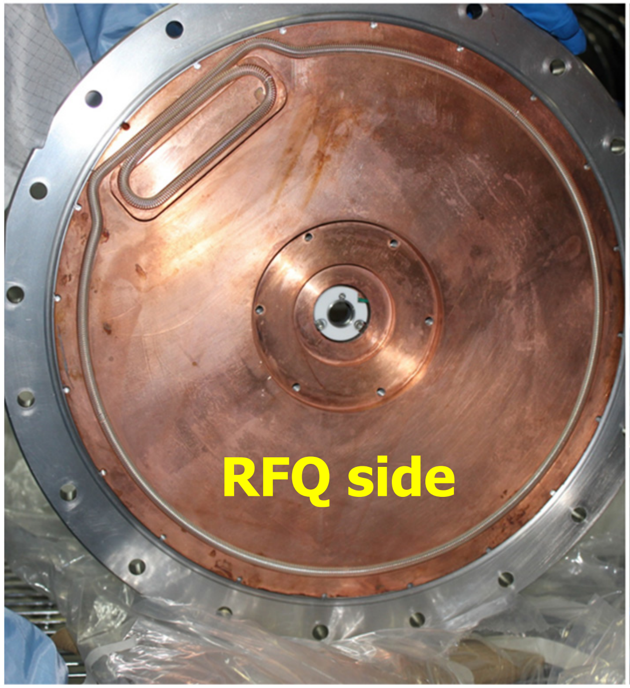
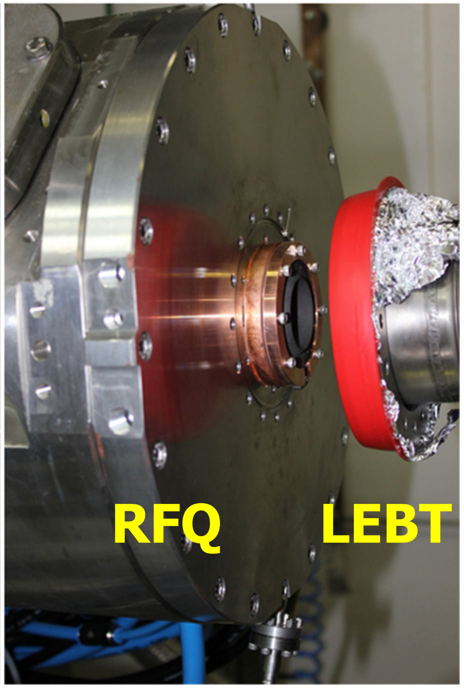
RFQ entrance (new flange)





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Metallic vacuum seals
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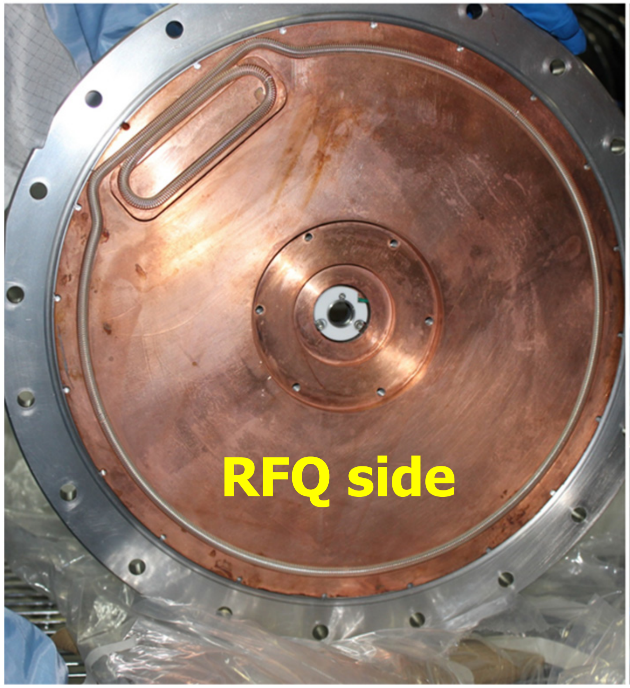

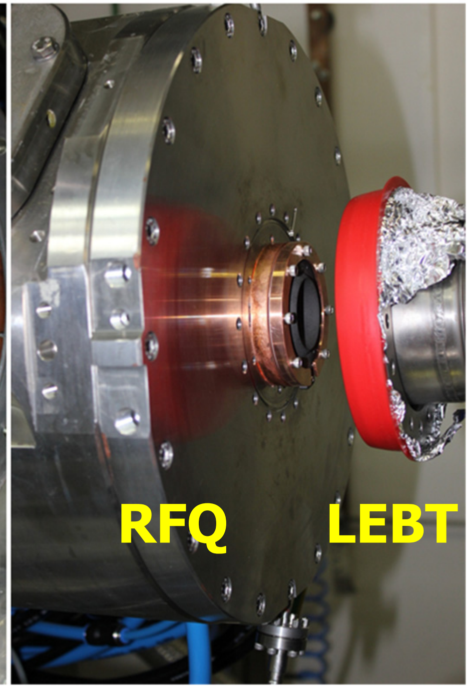

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80

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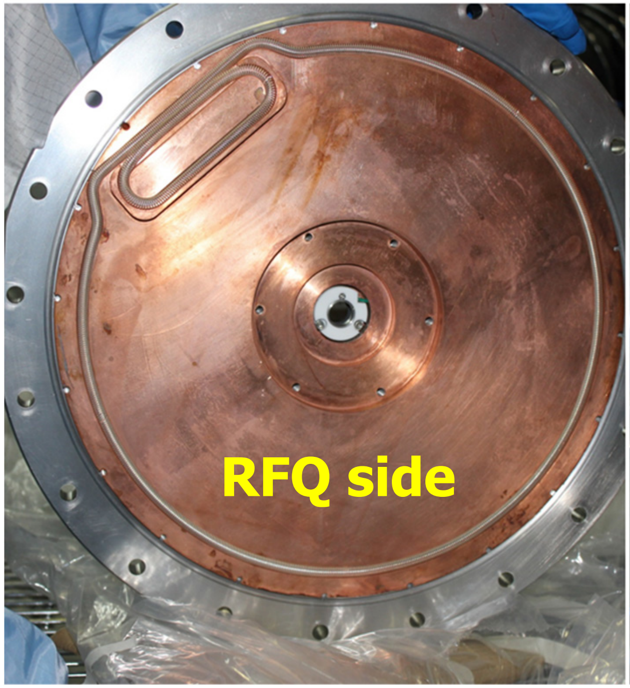

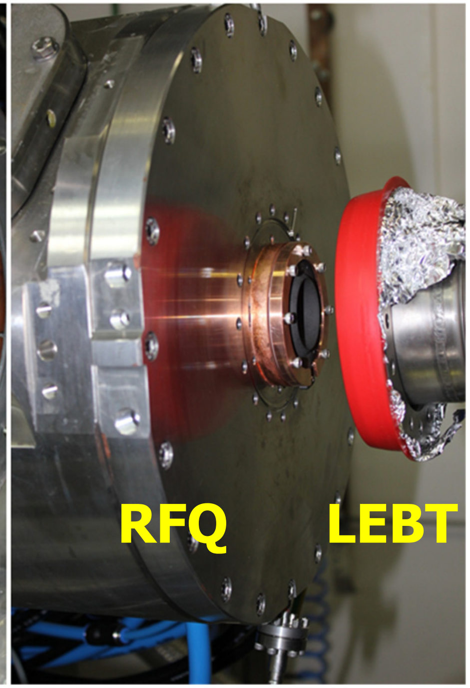

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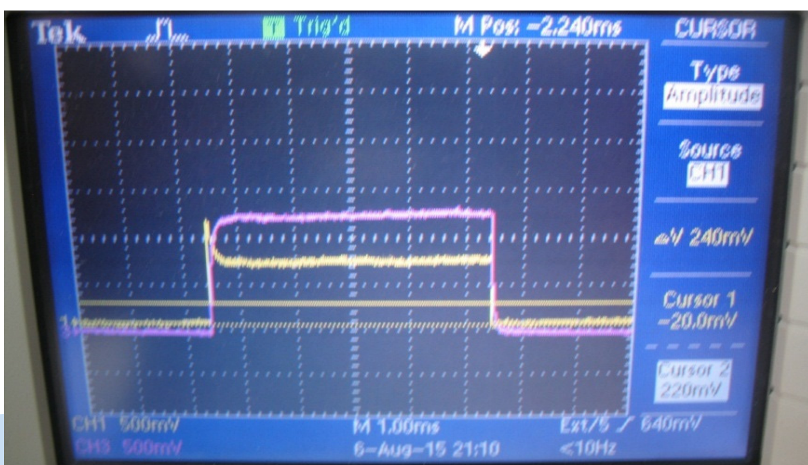

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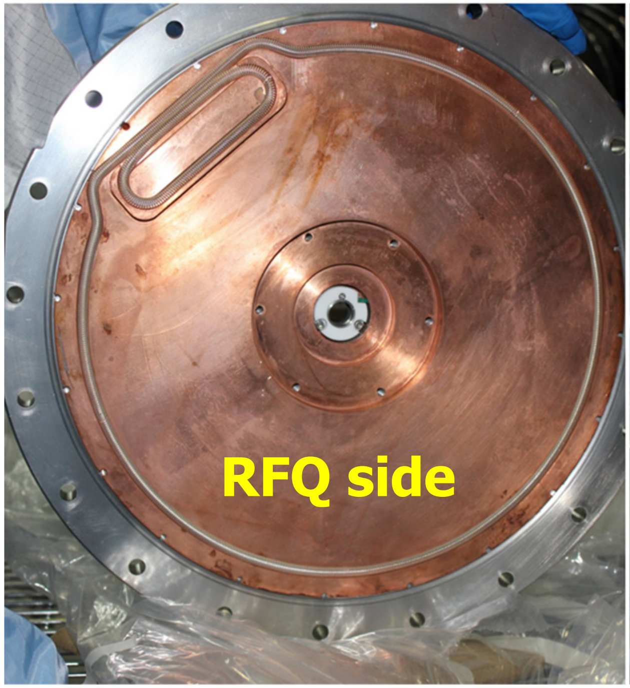

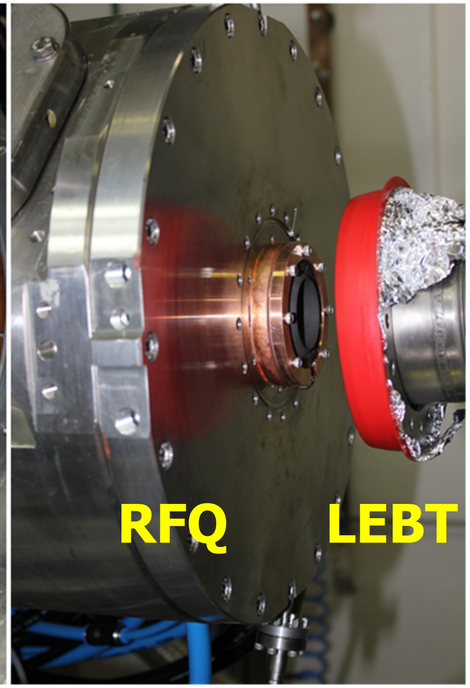

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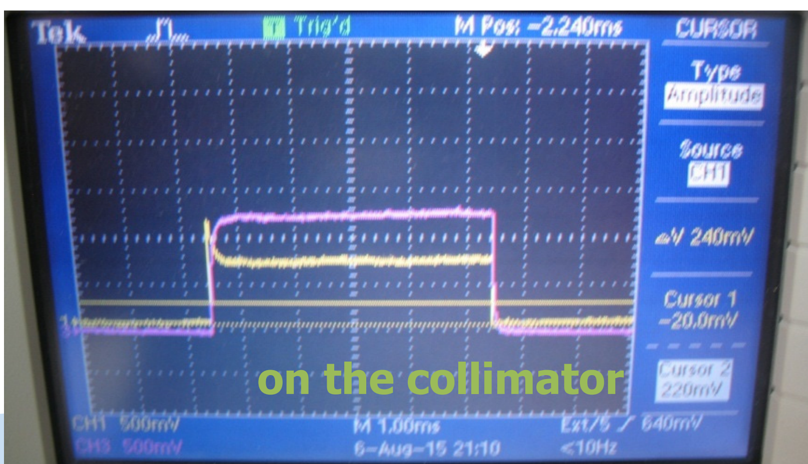

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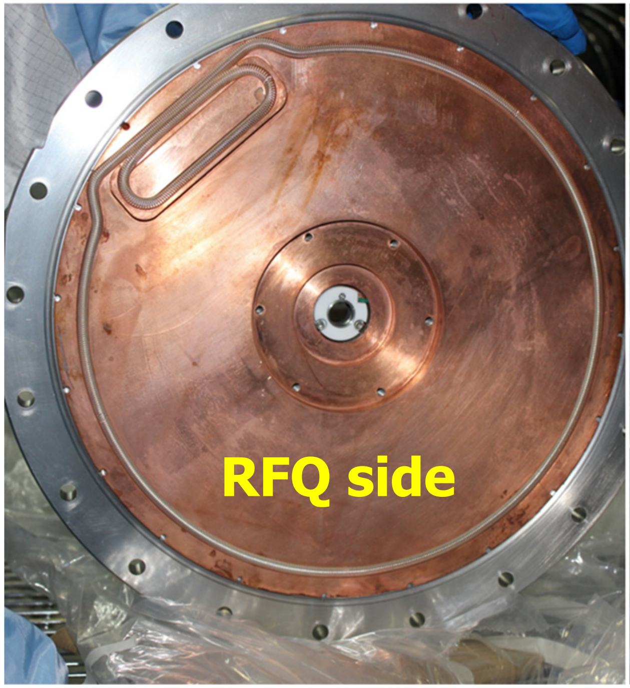

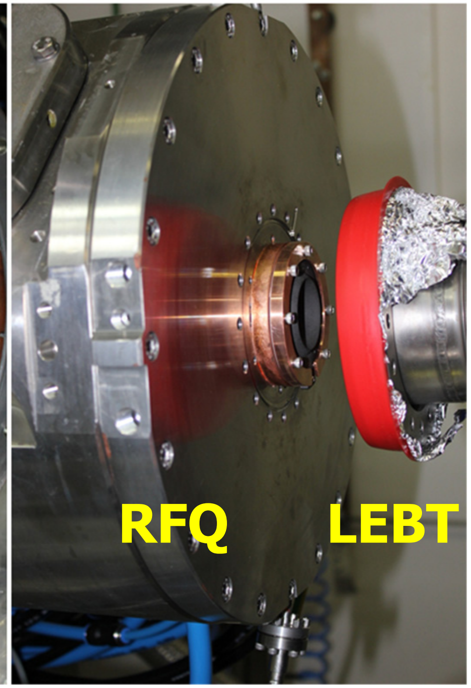

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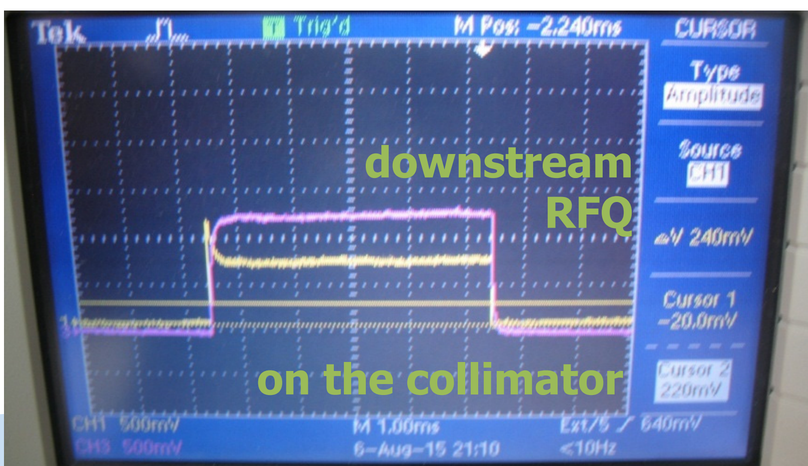

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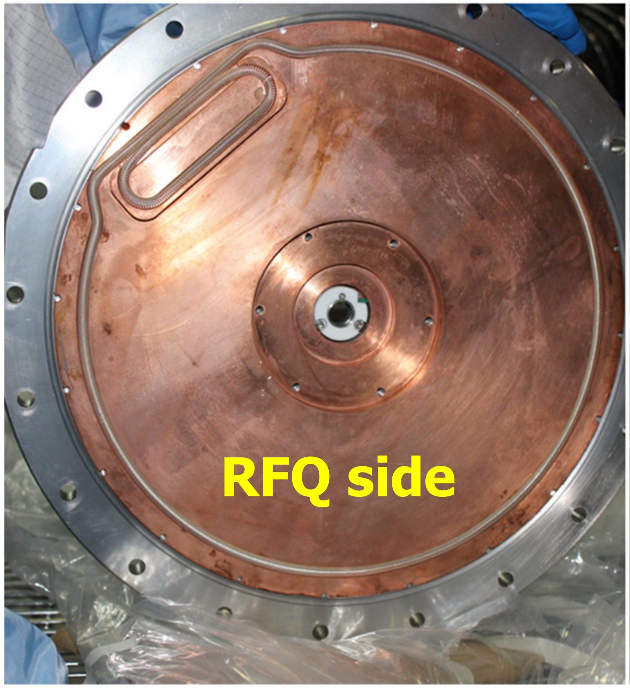

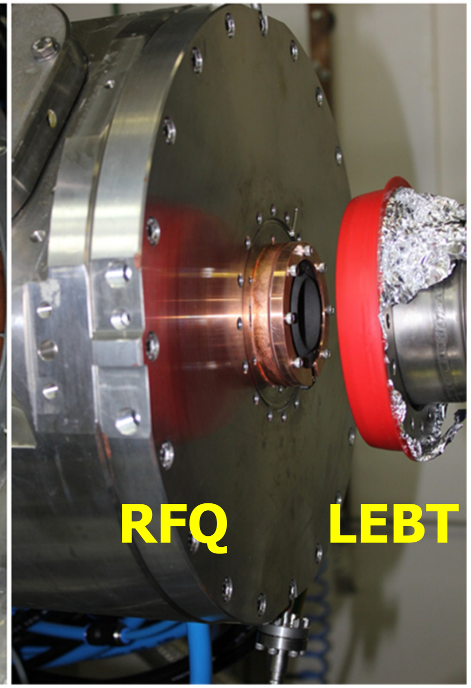

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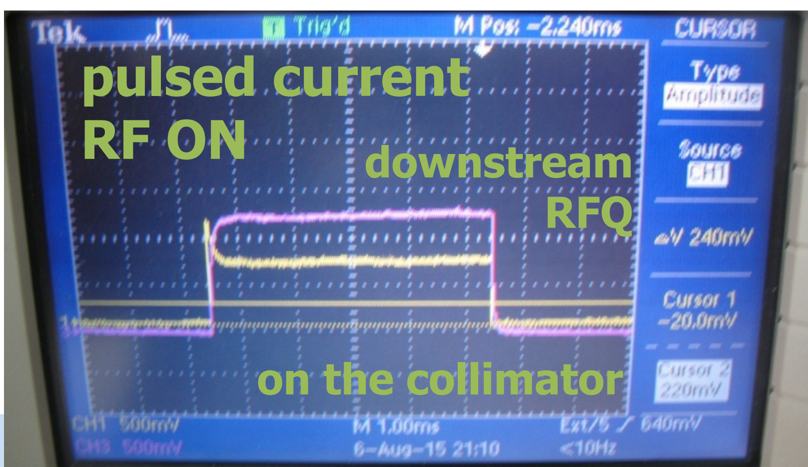

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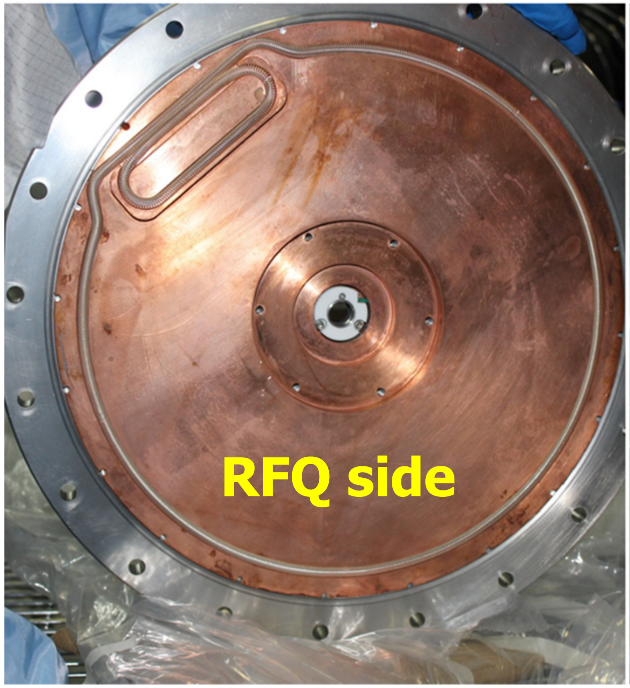

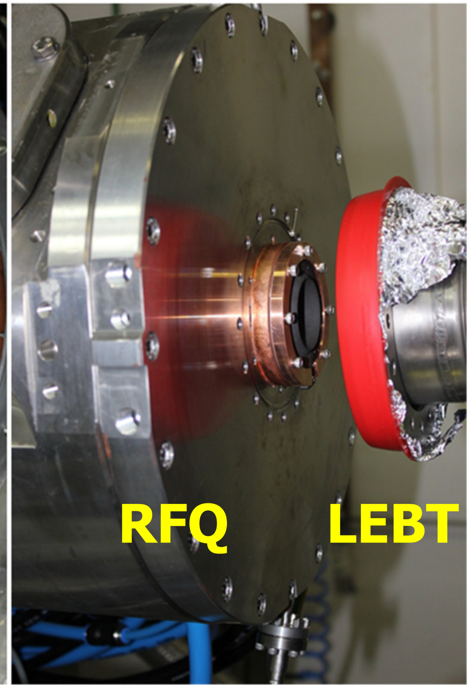

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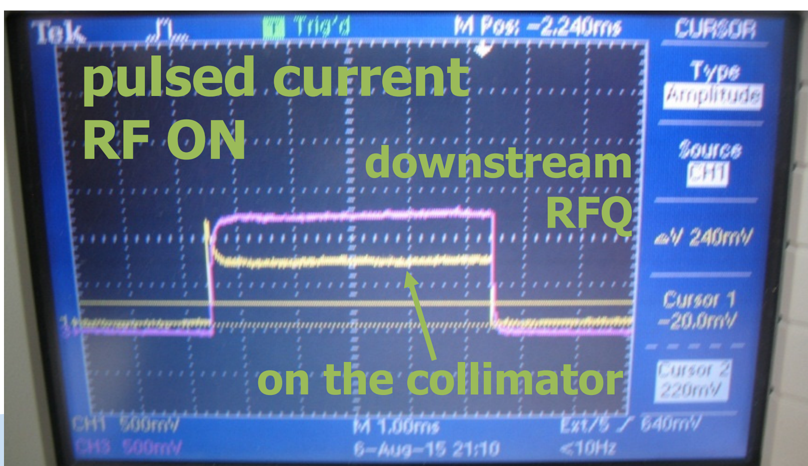

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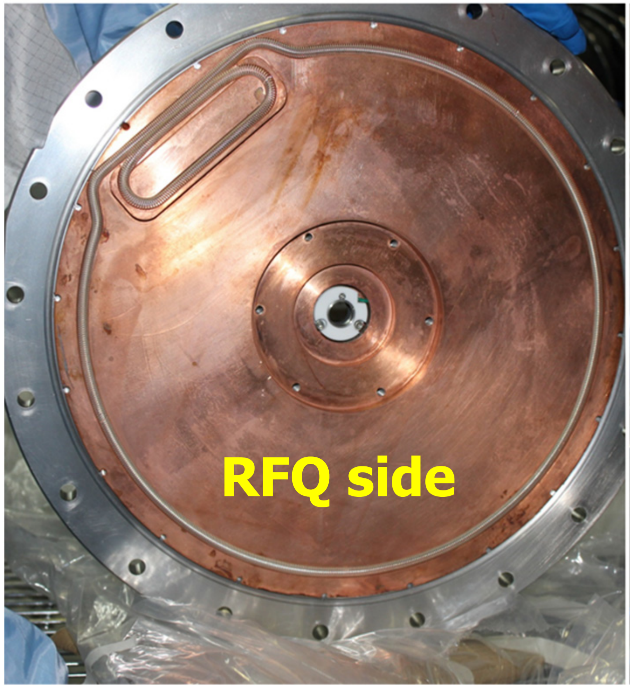

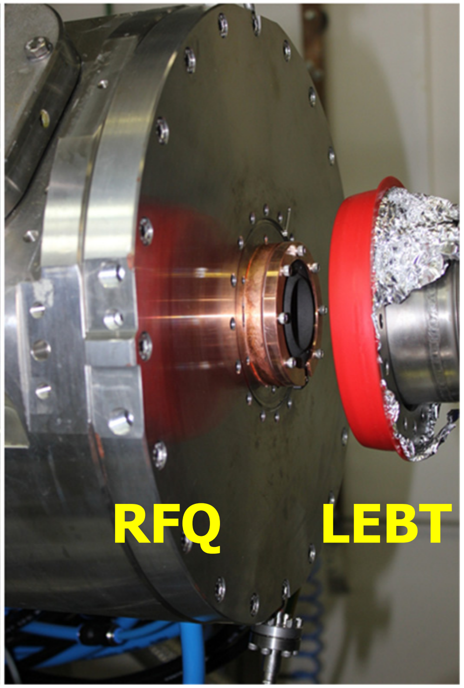

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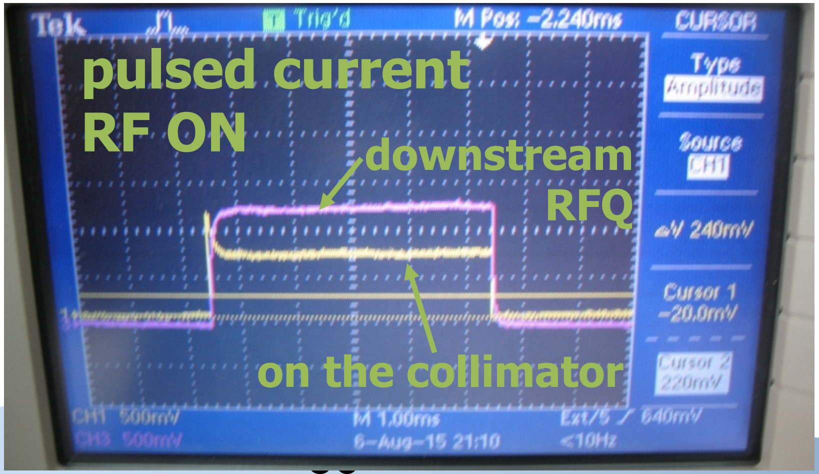

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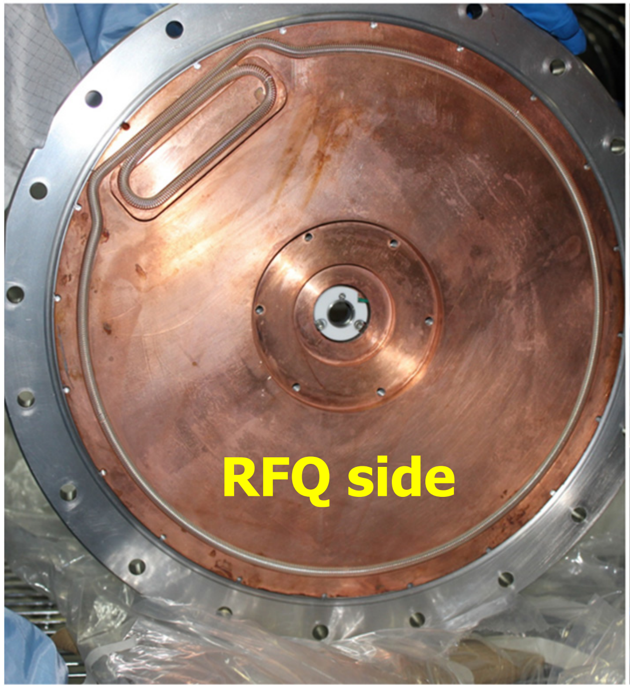

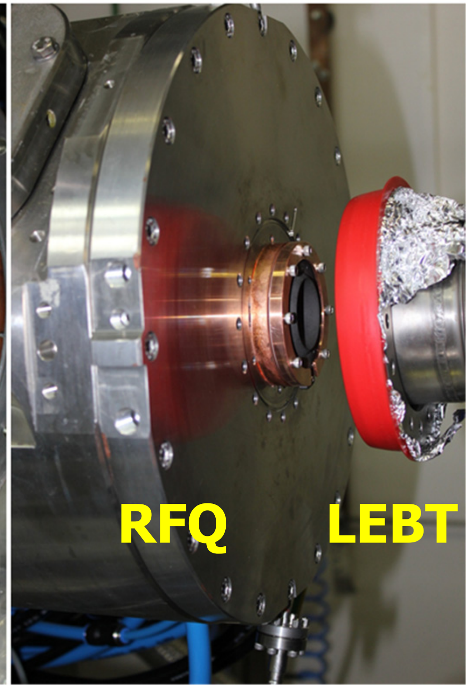

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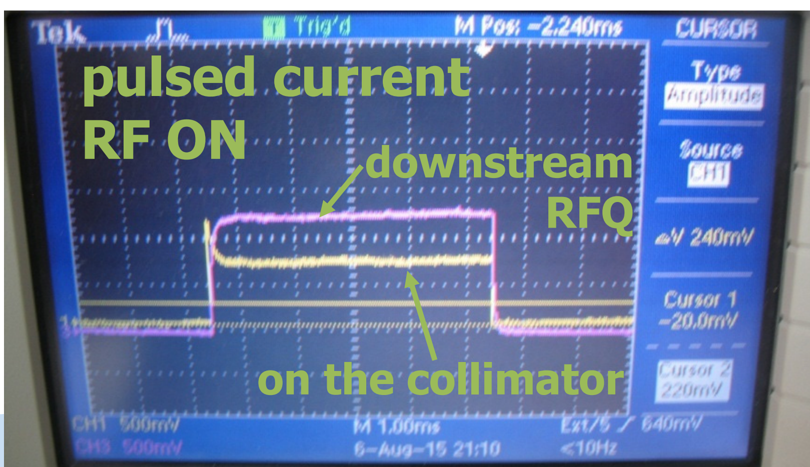

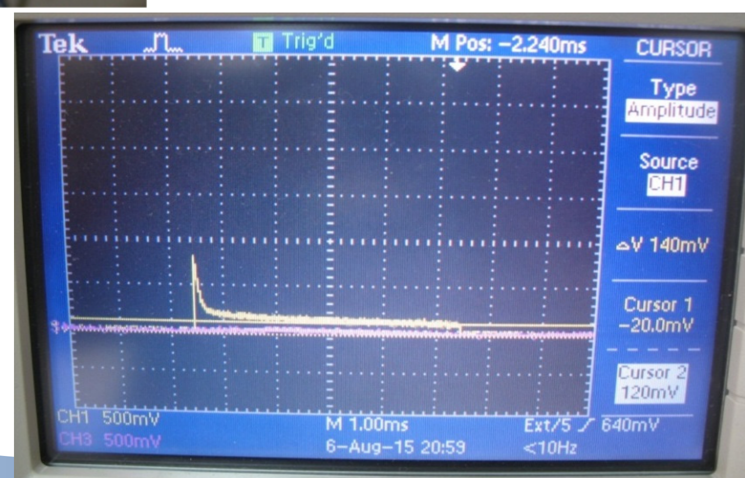

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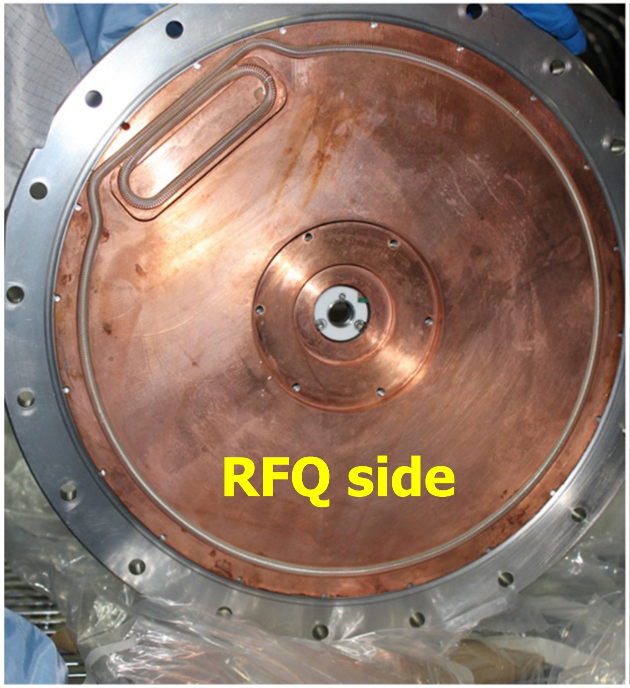

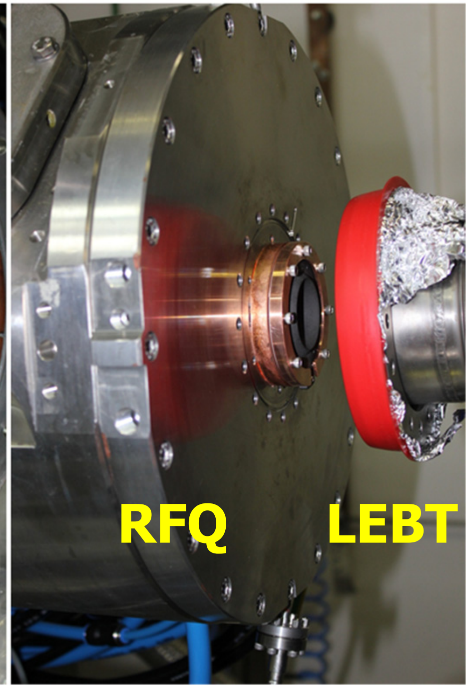

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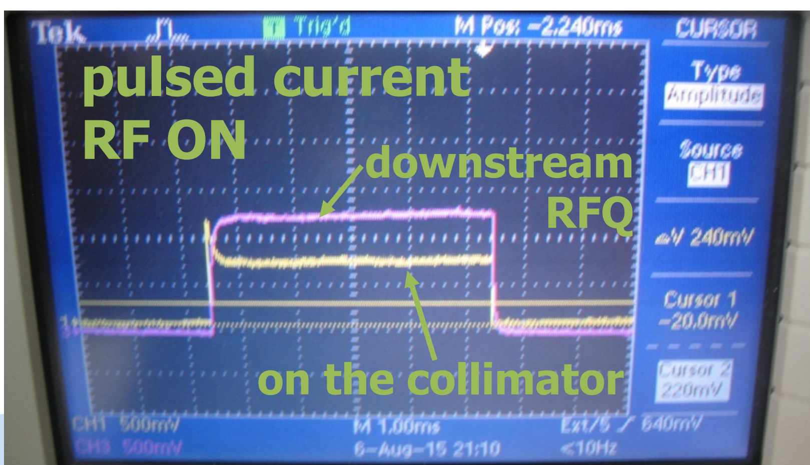
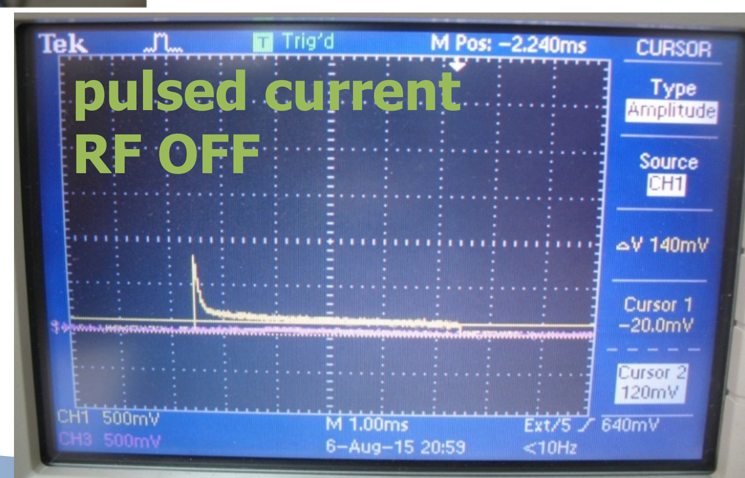
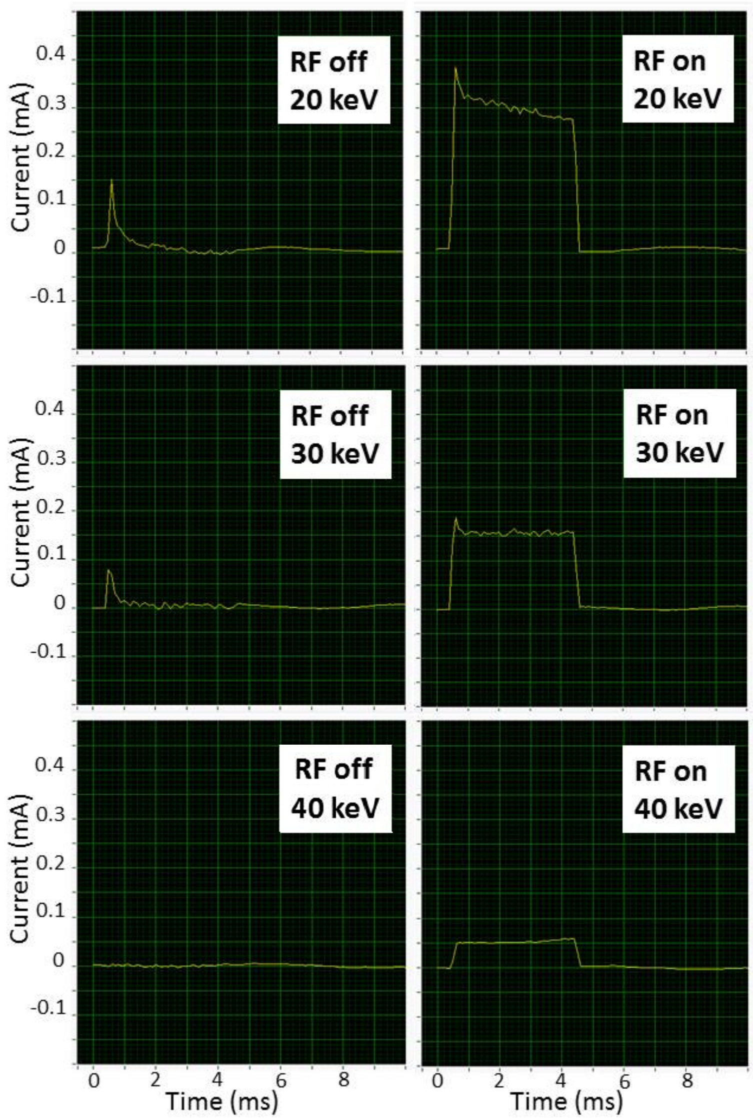




RF field effect vs proton energy

RFQ entrance collimator beam current



L. Weissman et al., ICIS 2017

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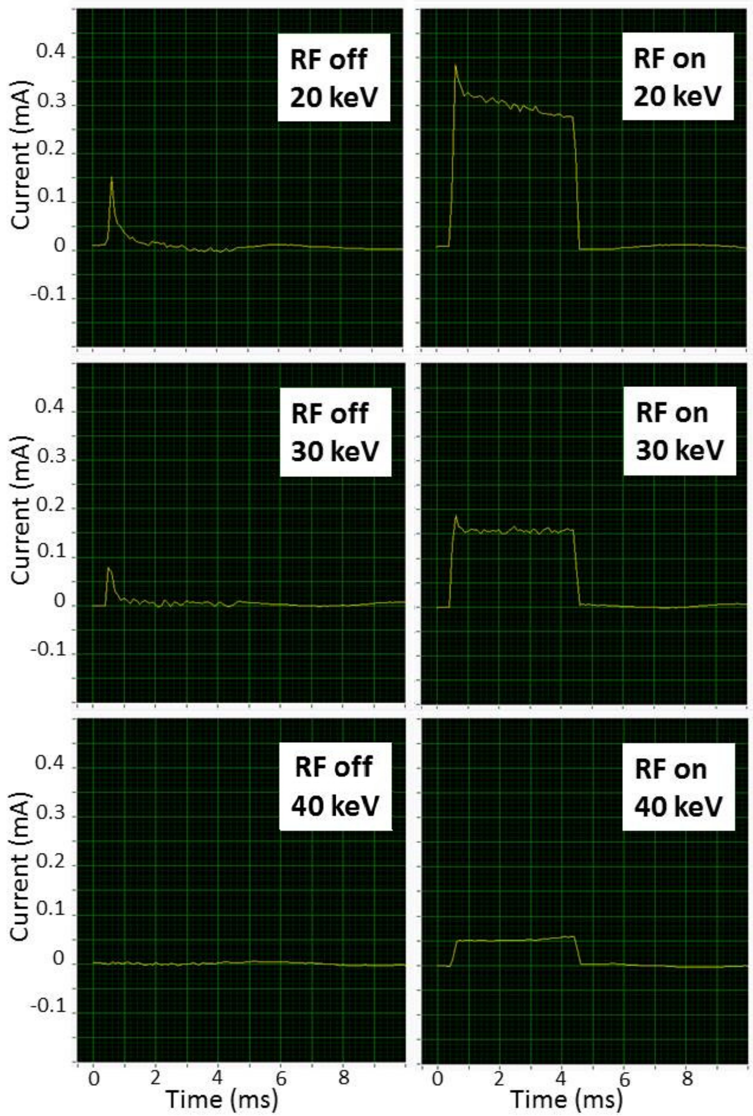
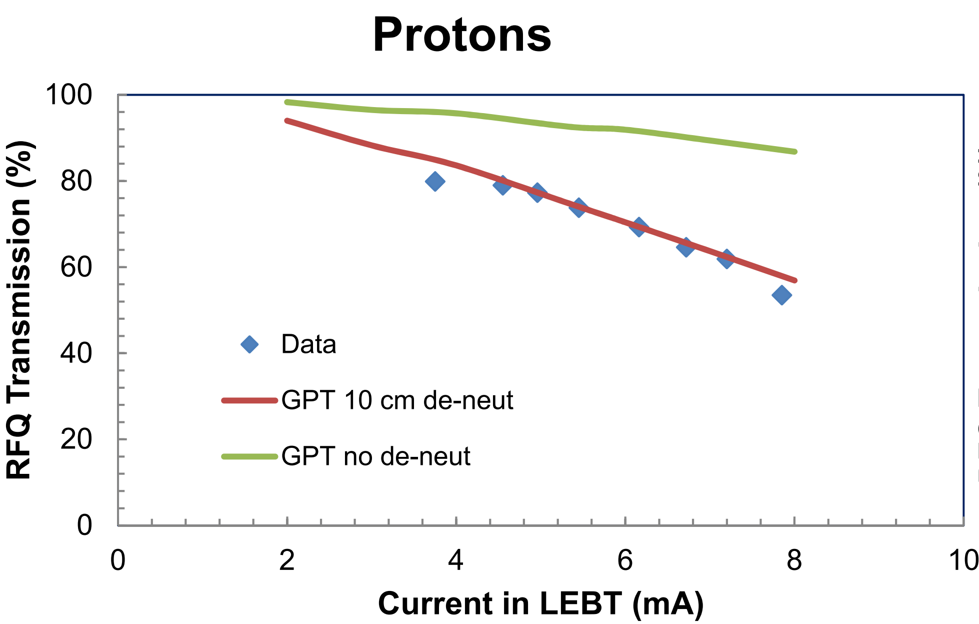
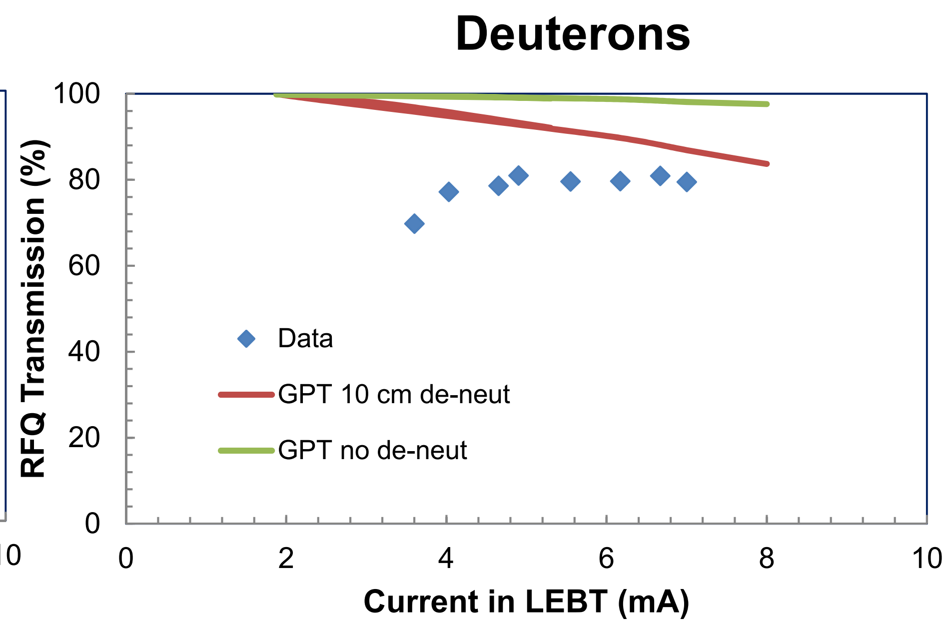


The effect depends on LEBT beam energy indicating its space-charge nature.
Most likely it is associated with compromising beam neutralization at the LEBT end

L. Weissman et al., ICIS 2017

Loss of neutralization at the LEBT end





Soreq NRC

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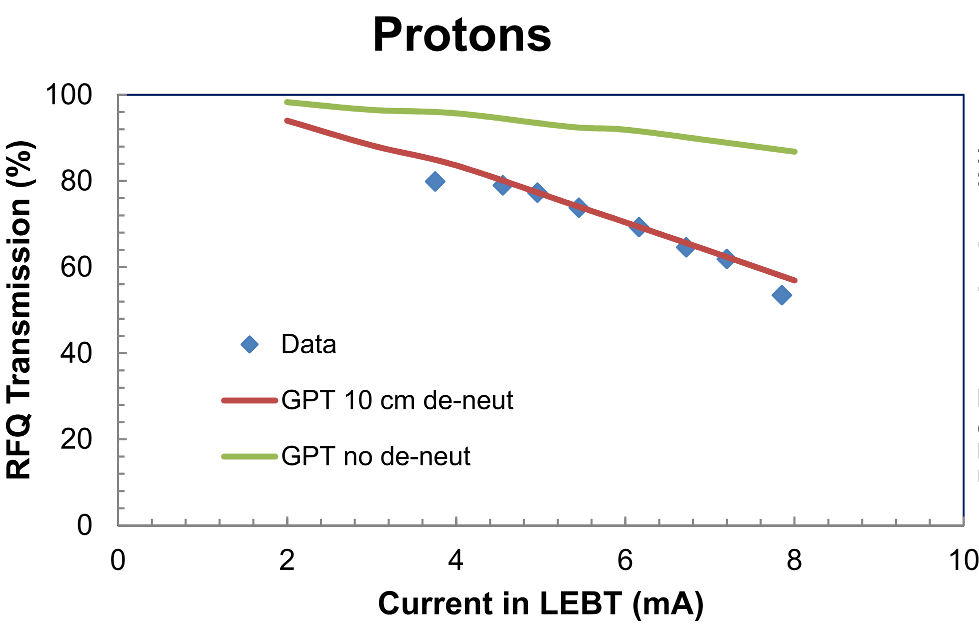
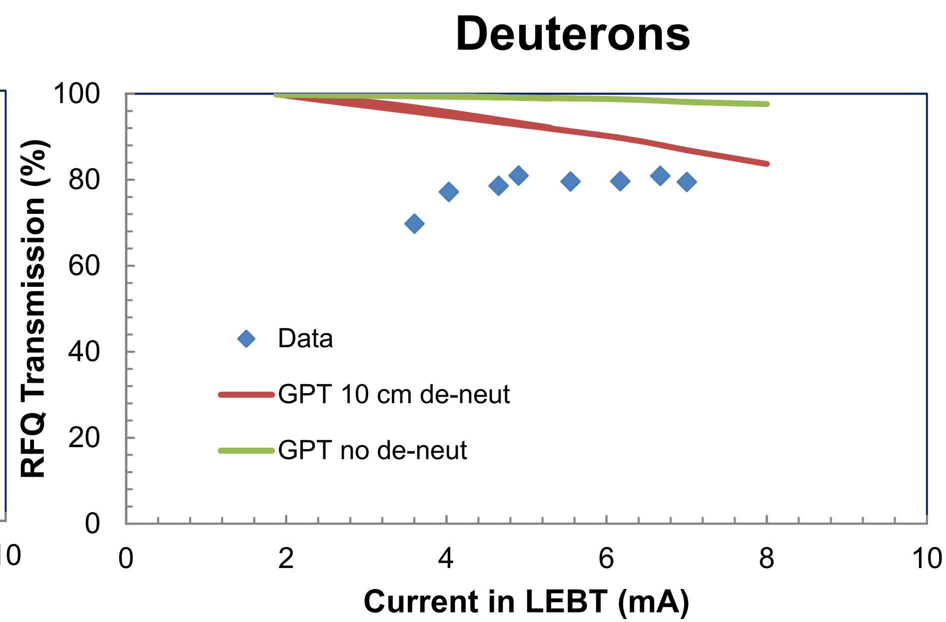
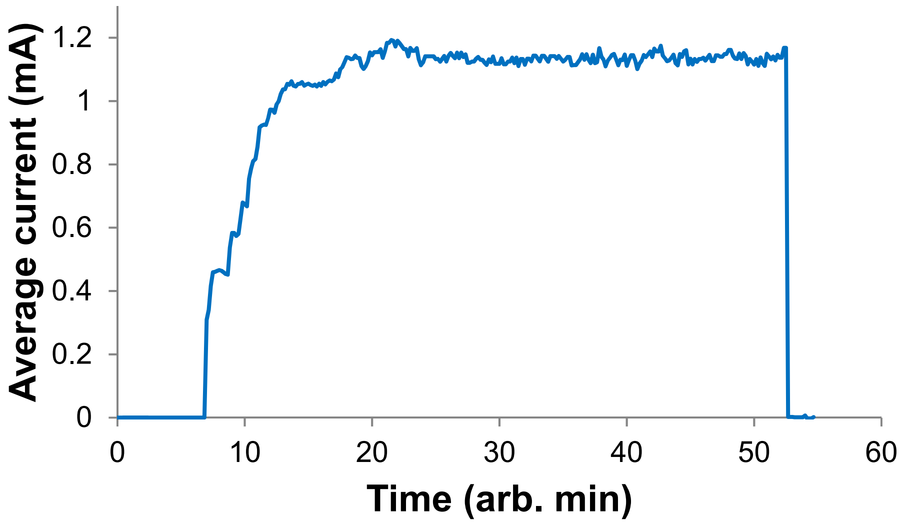




Need somehow to preserve neutralization at the LEBT end

Demonstration deuteron CW operation



RFQ at pseudo CW 99.5 %

1.15 mA low duty cycle pulsed deuteron beam to the dump

Increased beam DC to 98 % and kept beam on the dump for ~ 30 min

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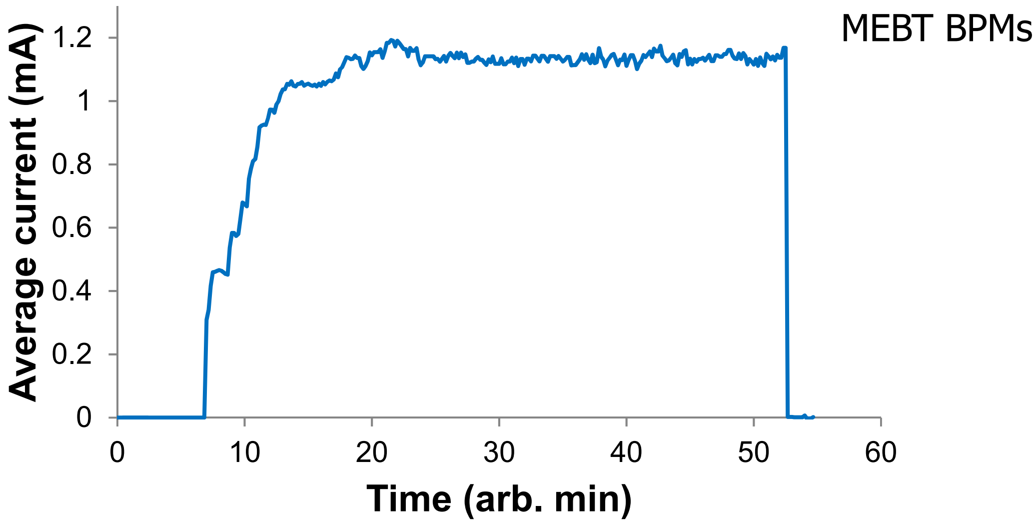

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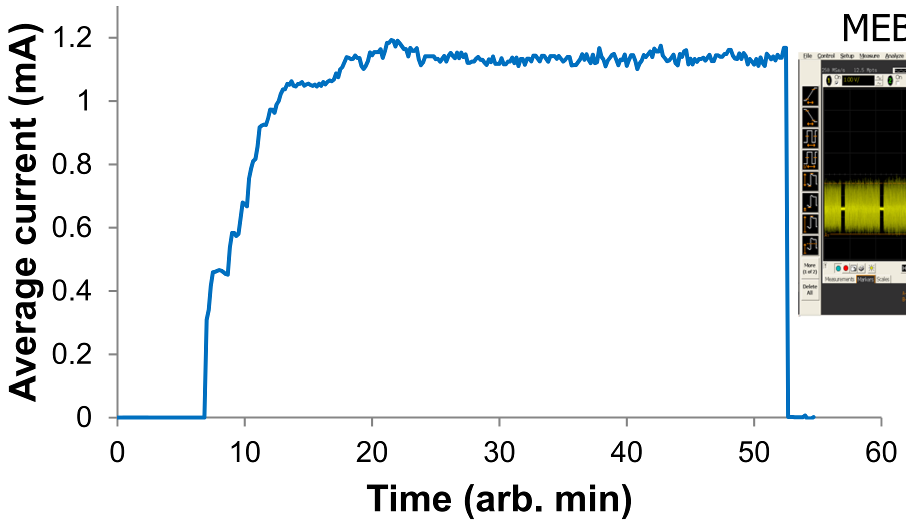
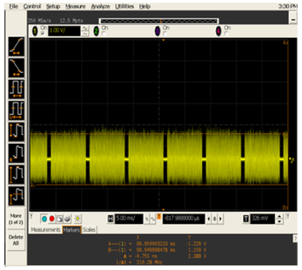


MEBT BPMs



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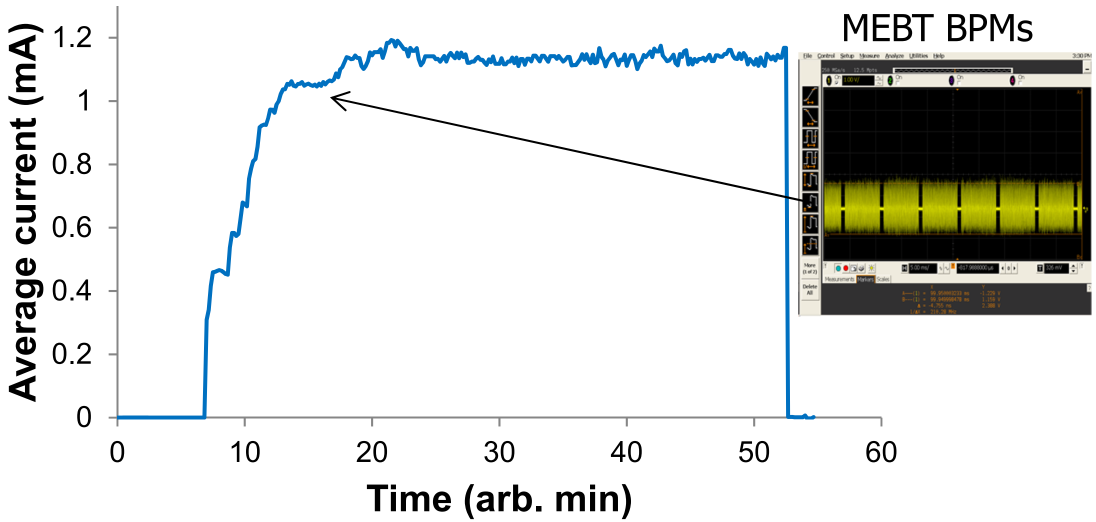

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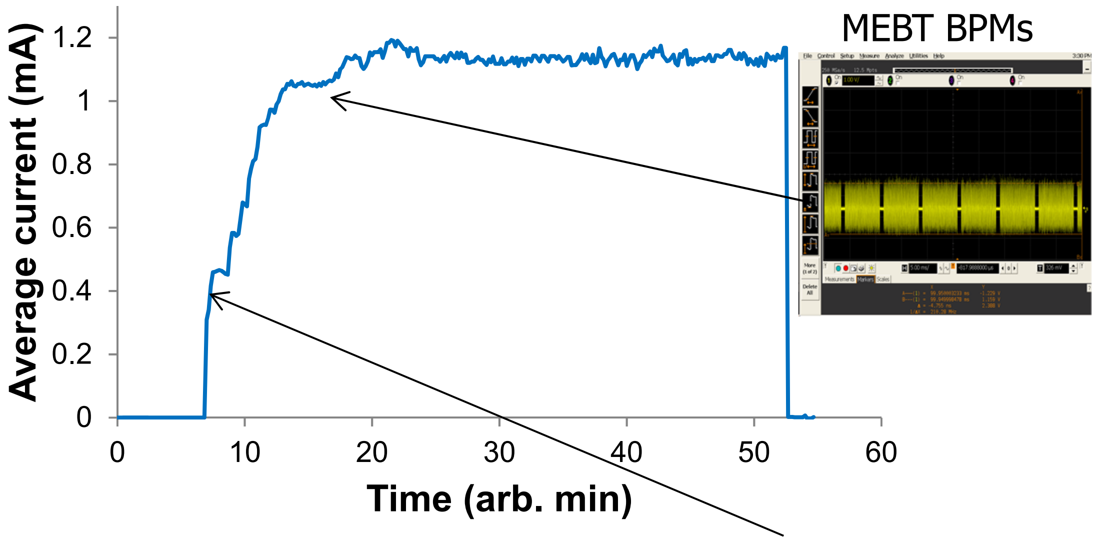

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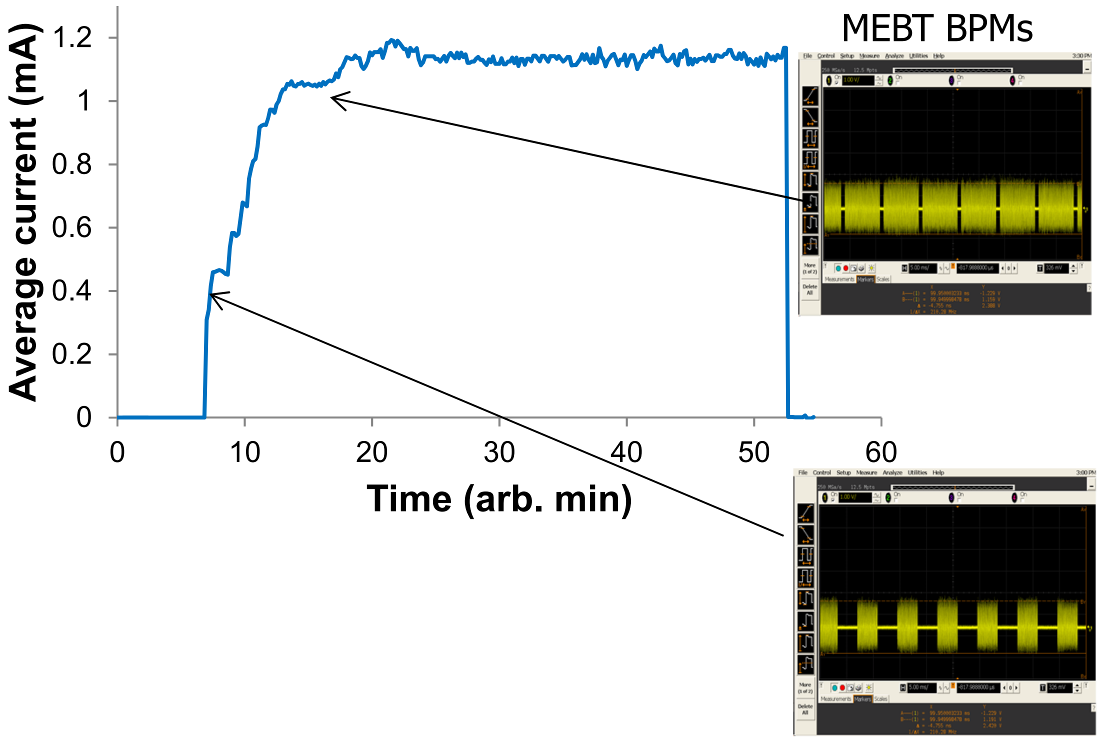

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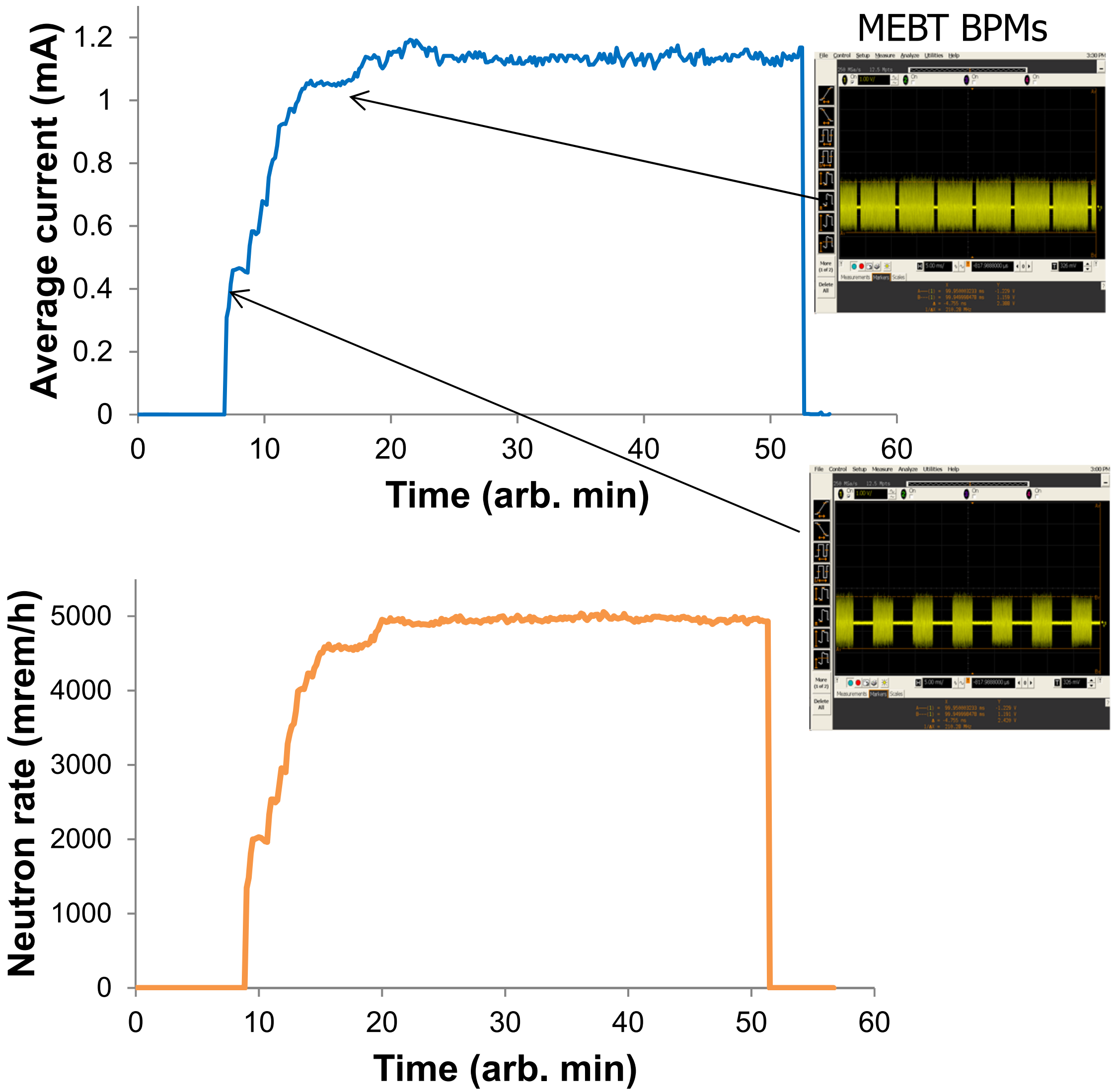

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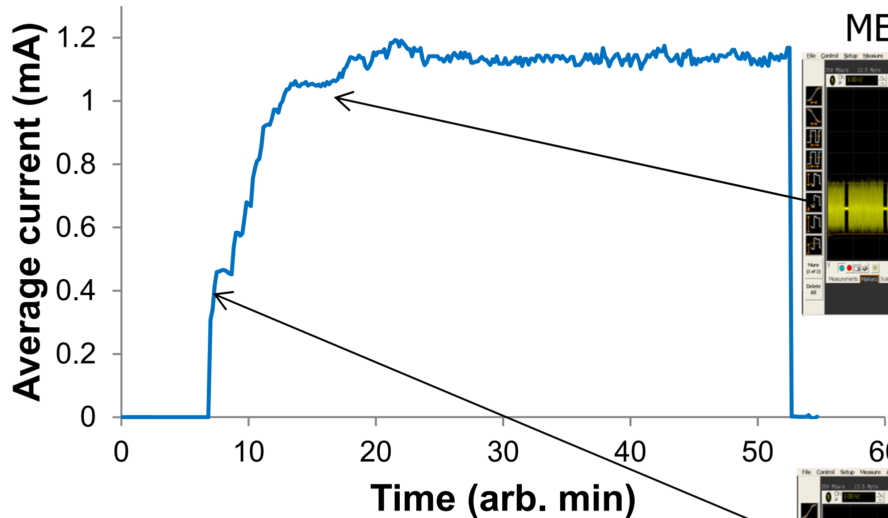

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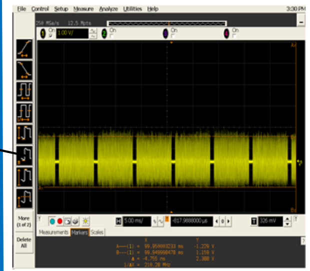

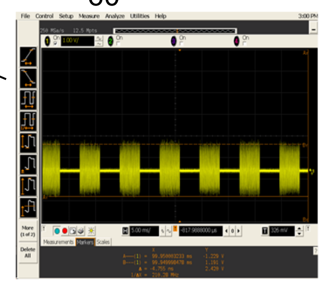

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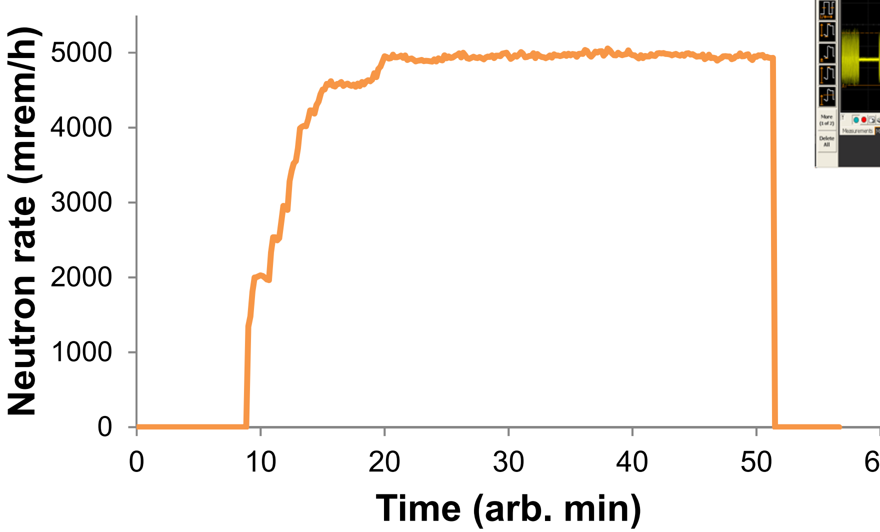
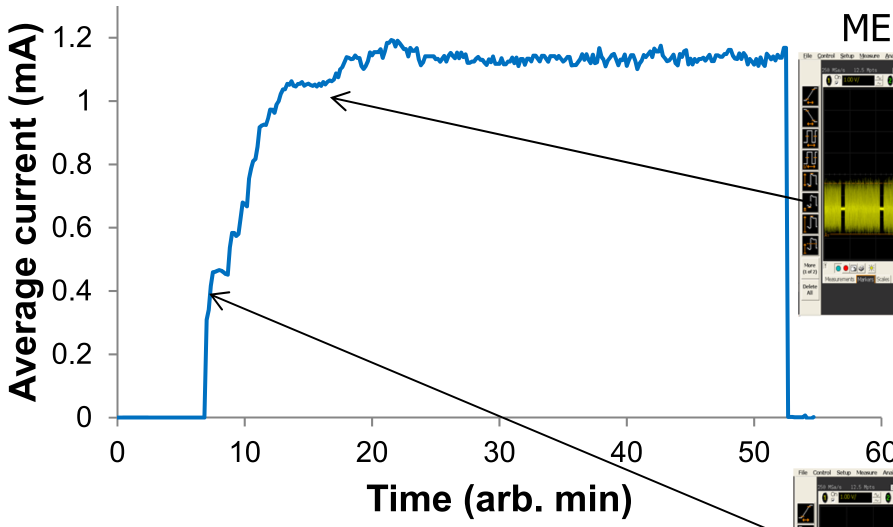


Neutron dosimeter ~10 m away from the beam dump

Demonstration deuteron CW operation



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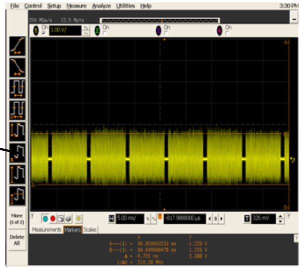
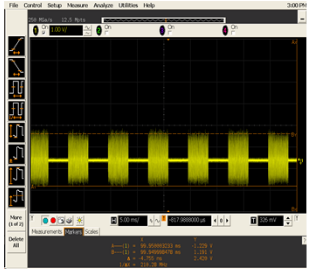
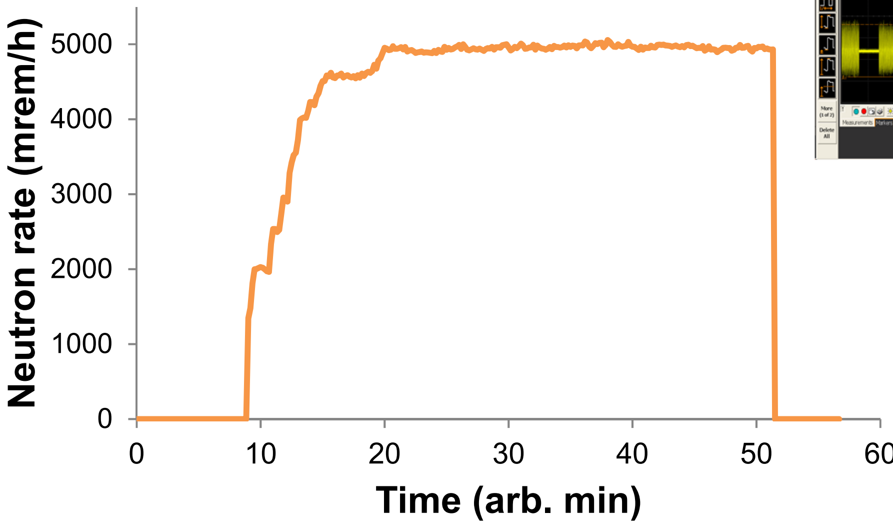




RFQ at pseudo CW 99.5 %

1.15 mA low duty cycle pulsed deuteron beam to the dump

Increased beam DC to 98 % and kept beam on the dump for ~ 30 min



Neutron dosimeter ~10 m away from the beam dump

! First deuteron CW beam

Summary

Soreq NRC

- The RFQ rods were manufactured and installed successfully
- The field homogeneity was improved; improvement of optics (less steering effects, a slightly better transmission)
- RFQ conditioning up to 210 kW was performed successfully
- Beam commissioning showed that the most of beam properties correspond to the designed values
- Transmission of pulsed 5 mA deuterons at CW RFQ power for the first time
- Operation of 1.1 mA CW deuteron beam was demonstrated for the first time

L. Weissman et al. JINST 2018

Summary

SARAF RFQ today is at much better state to serve as a reliable injector for Phase II linac. However, there is still a lot to be done to that end.

- RFQ conditioning exposed some operational problems:

  Instabilities of the amplifiers;
  The problems with o-rings damage
  Conflict between different control loops
  Still some problems with coupler

- Low RFQ transmission 65-70 %
- Beam matching to the superconducting linac
- Operation with 5 mA CW protons and deuteron to be demonstrated yet

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We have strong commitment and sufficient expertize to ensure that the SARAF Phase I RFQ will serve as an reliable injector for SARAF Phase II linac