Beam dynamics simulation in SARAF phase-I proton/deuteron 4 MeV linac commissioning

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HB2010, Morschach, Switzerland

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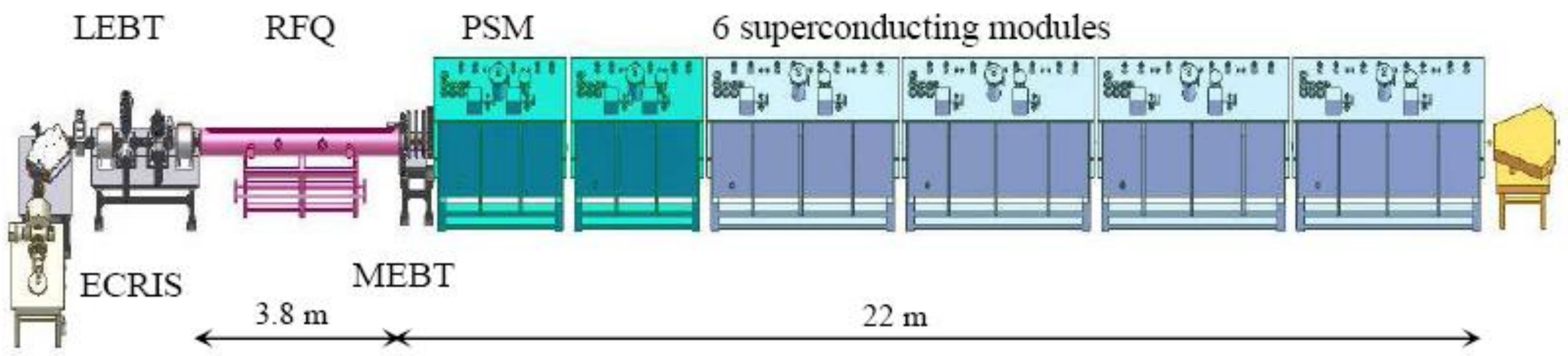
Presentation Outline

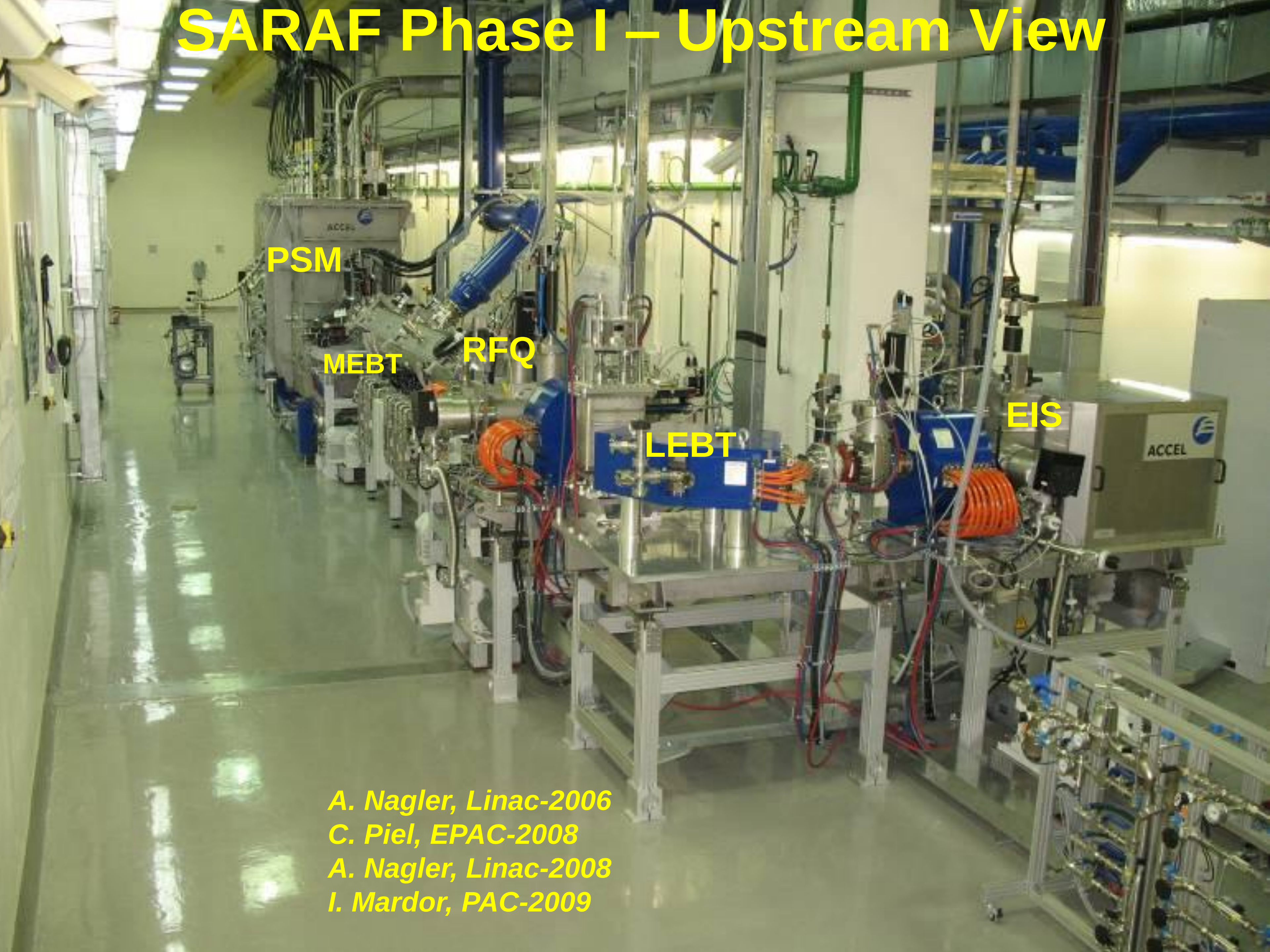
- Overview
- SARAF Linac Phase I components
  - ECR ion source + LEBT
  - RFQ
  - Prototype Superconducting Module (PSM)
- Beam operation modifications by beam dynamics analysis
- Outlook

SARAF Accelerator 40 MeV proton/ deuteron 4 mA linac



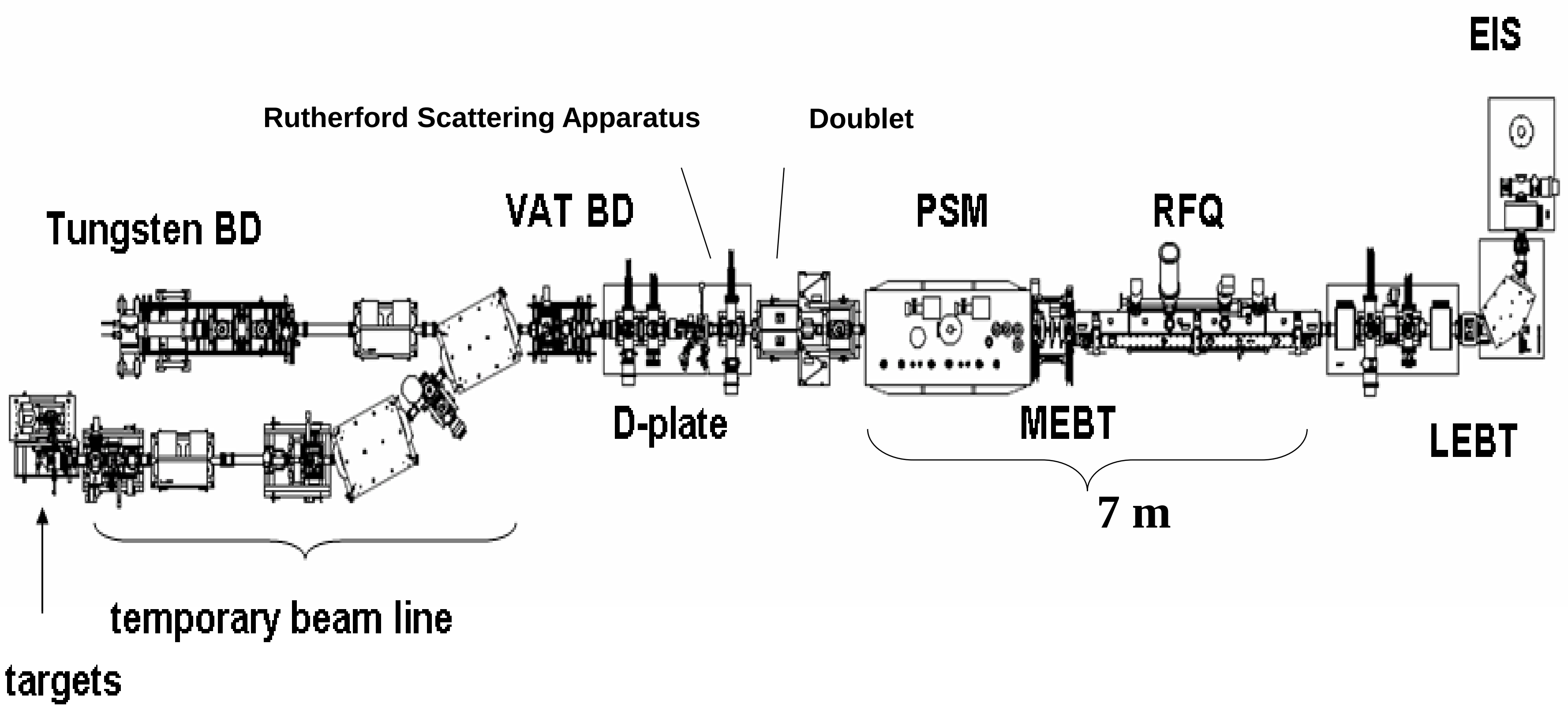
B. Bazak *et al.* 2008

SARAF Phase I – Upstream View



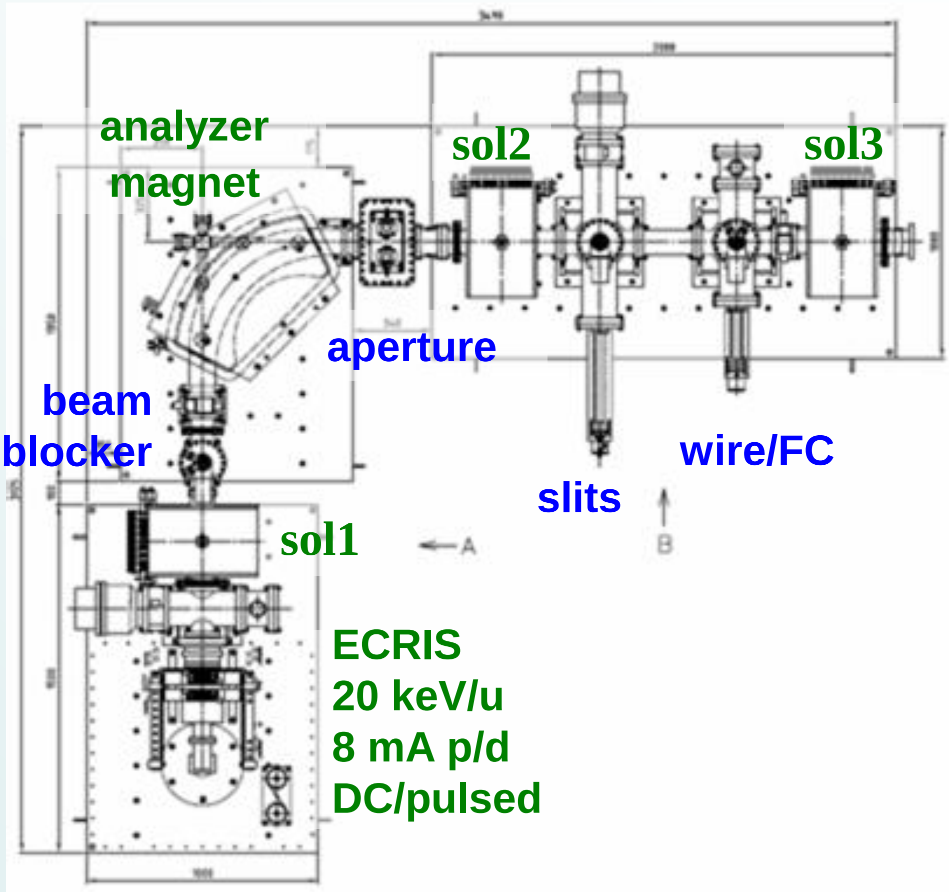
A. Nagler, Linac-2006
C. Piel, EPAC-2008
A. Nagler, Linac-2008
I. Mardor, PAC-2009

A layout of SAREF phase-1



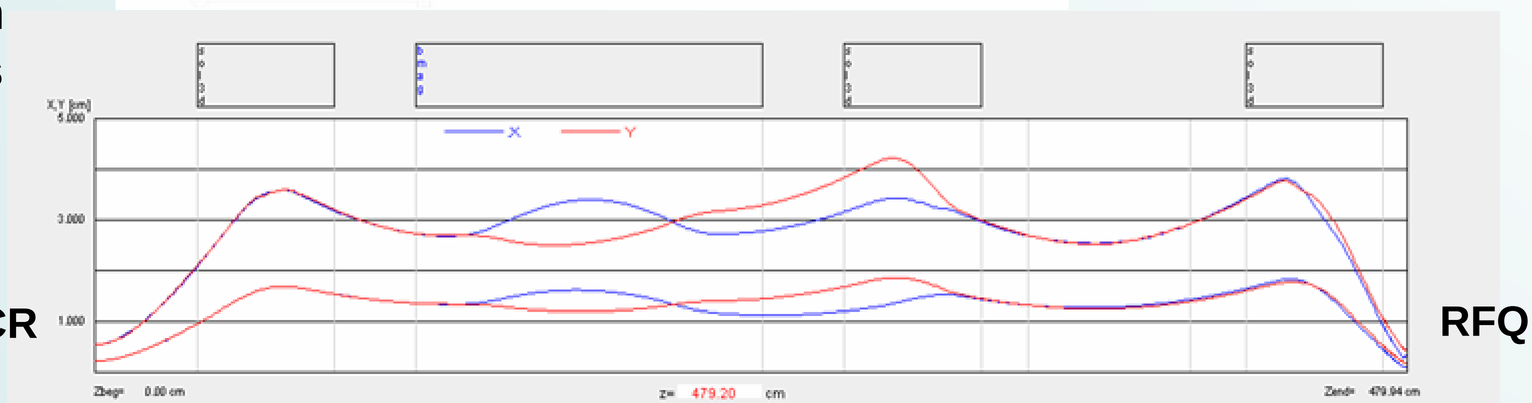
ECR/LEBT

Build by RI (ACCEL)
K. Dunkel PAC 2007



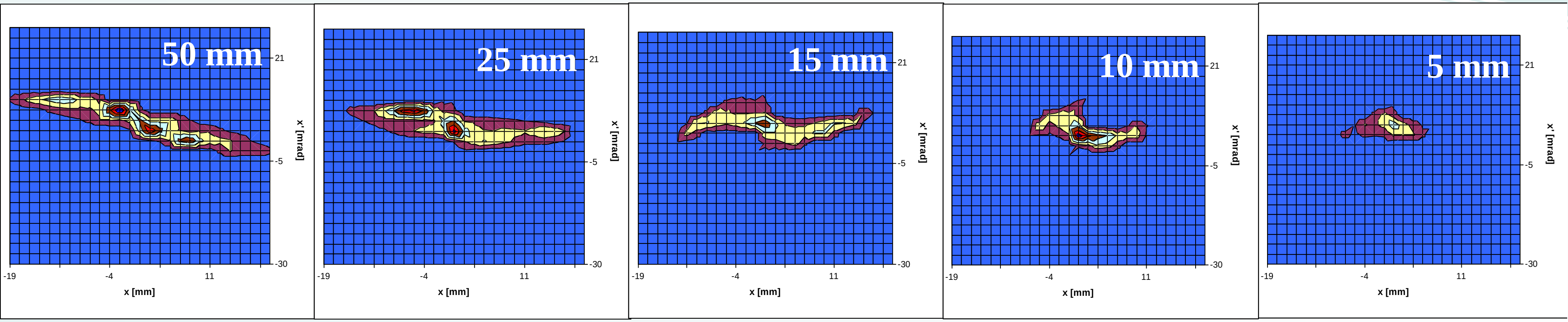
5 mA proton beam optics

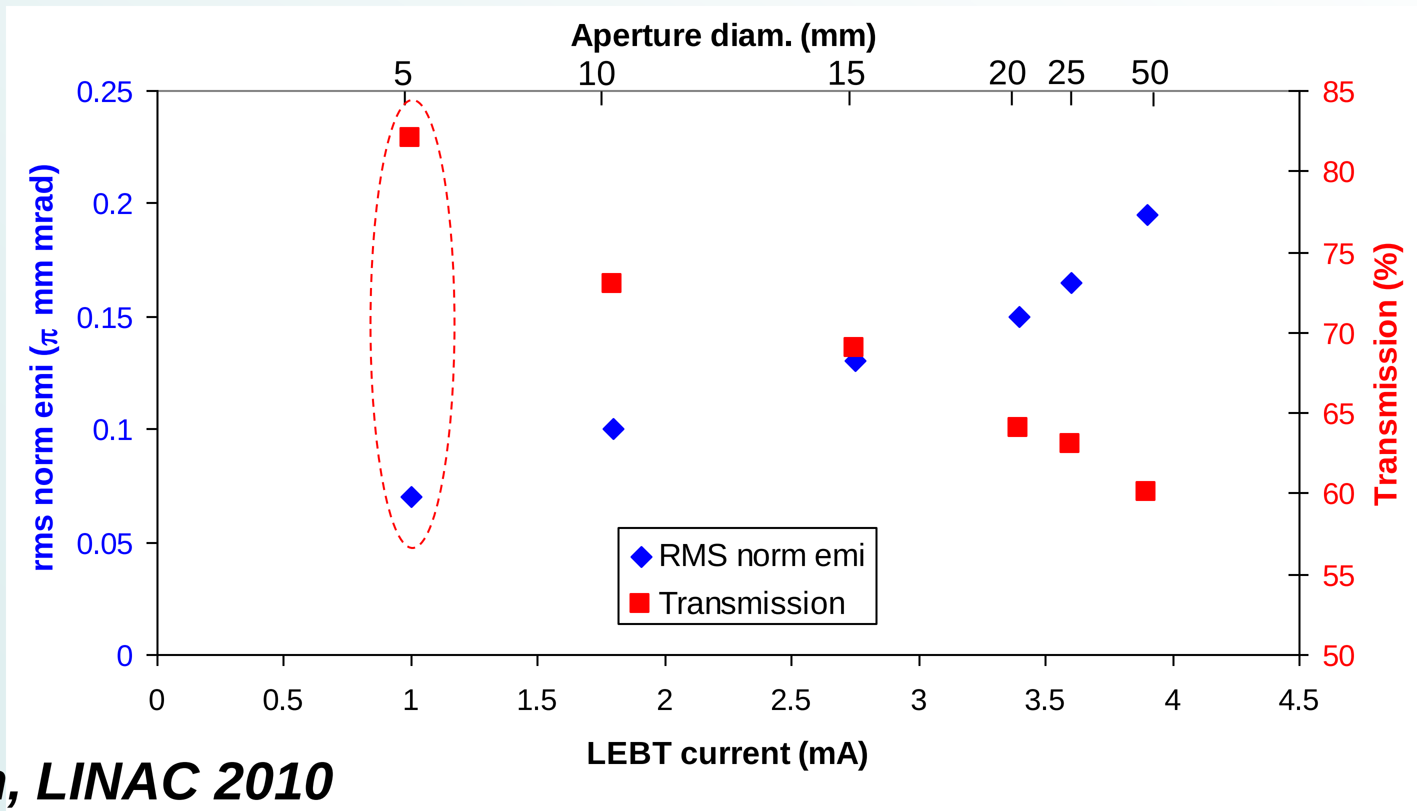
Large beam minimize space charge (TRACK)



LEBT aperture

Manipulating beam size, current and emittance using the LEBT aperture





L. Weissman, LINAC 2010

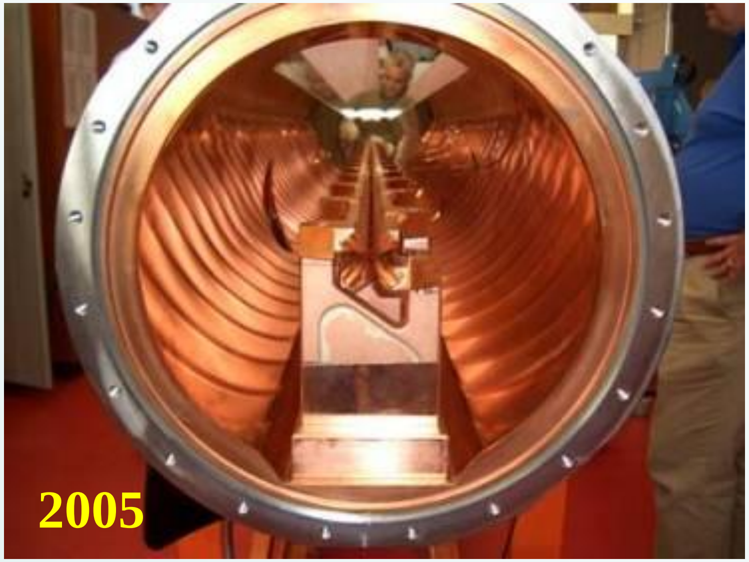
176 MHz 4-Rod CW RFQ

RFQ Beam Properties		
Beam Parameter	Protons	Deuterons
Energy (MeV)	1.5 (1.5)	3.0 (3.0)
Maximal current [mA]	4.0 (CW) (4.0)	2.5 (10^{-2}) (4.0)
Transverse emittance, r.m.s., normalized, 100% [π·mm·mrad] (0.5 mA, closed LEBT aperture)	0.17 (0.30)	0.16 (0.30)
(4.0 mA, open LEBT aperture)	0.25 / 0.29 (0.30)	NM
Longitudinal emittance, r.m.s., [π·keV·deg/u] (3.0 mA/0.4 mA)	90 (120)	200 (120)
Transmission [%] (0.5 mA)	80 (90)	NM
(2.0 mA)	70 (90)	NM
(4.0 mA)	65 (90)	70 (90)

RF Conditioning Status	
Input Power [kW]	Duration [hrs]
190 (CW)	12
210 (CW)	2
240 (CW)	0.5
260 (DC = 80%)	0.5

Deuteron CW operation requires conditioning up to 260 kW (65 kV)

Power density: average ~ 25 W/cm^2



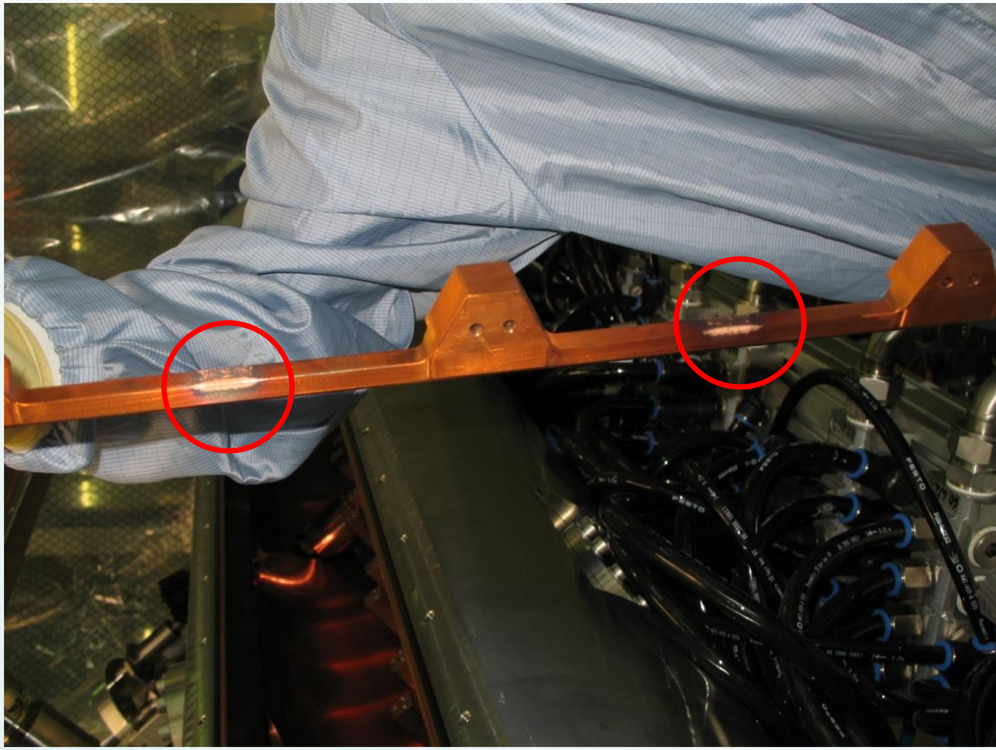
J.Rodnizki HB2010

I. Mardor, SRF 2009

Discharge between the rods and stems

Non-linearity of voltage response, High x-ray background

Discharge between back of the rods and stems

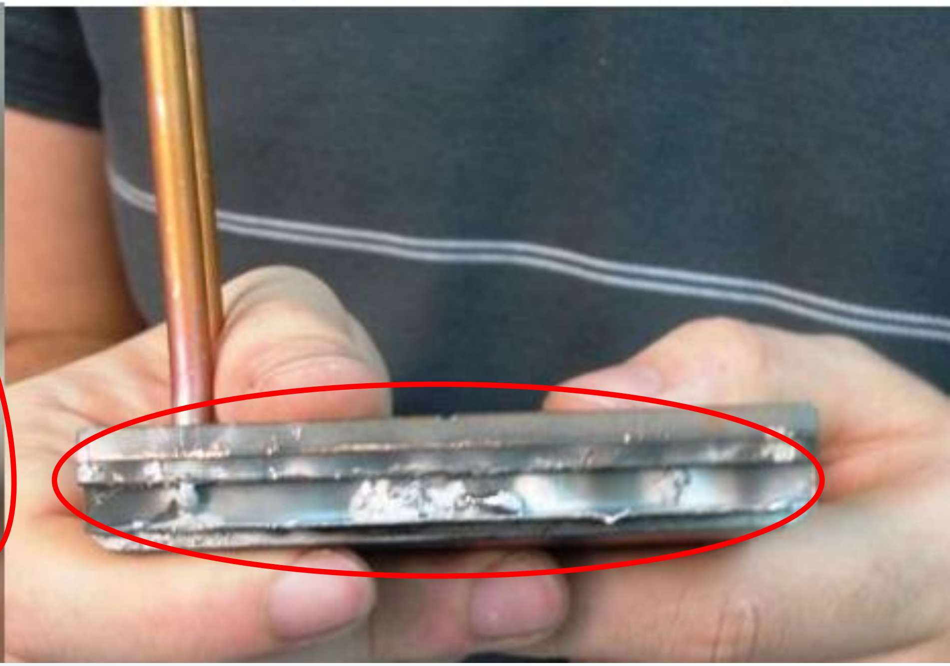


In spring 2009 the rods were modified locally to reduce the parasitic fields.

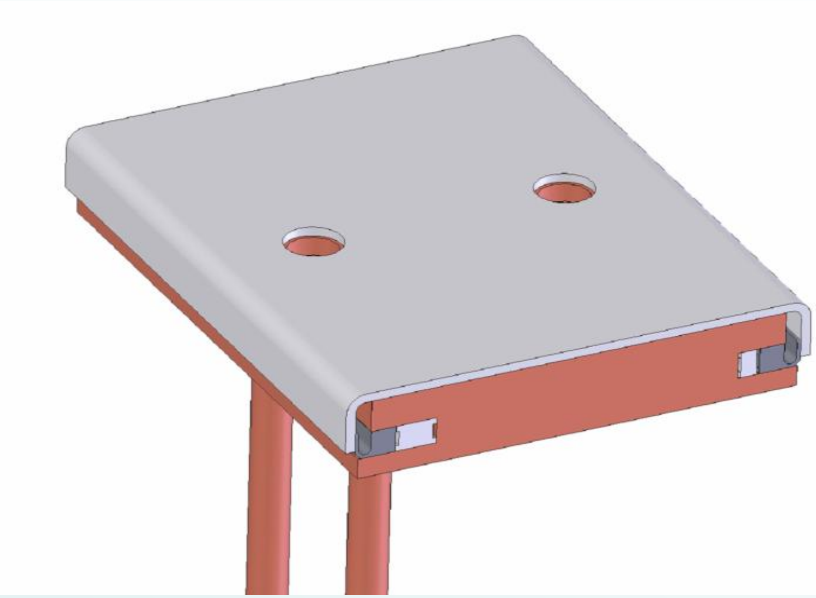
This solved the problem of discharge.

However, field realignment was required (later in the talk).

Burning of tuning plates



Contact springs of tuning plates were burned twice

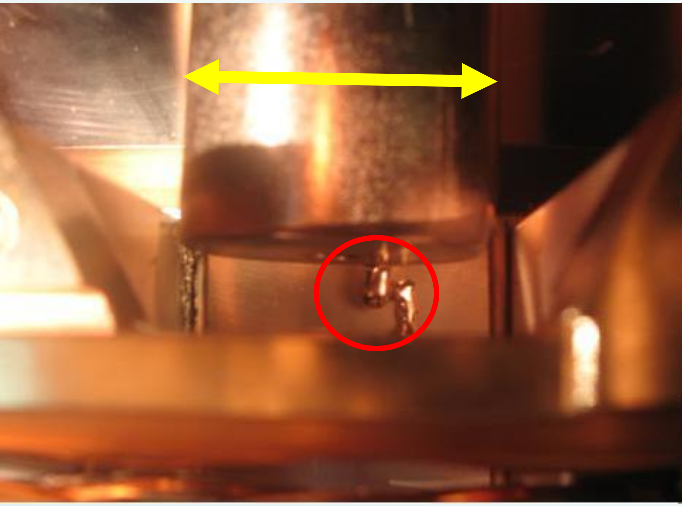


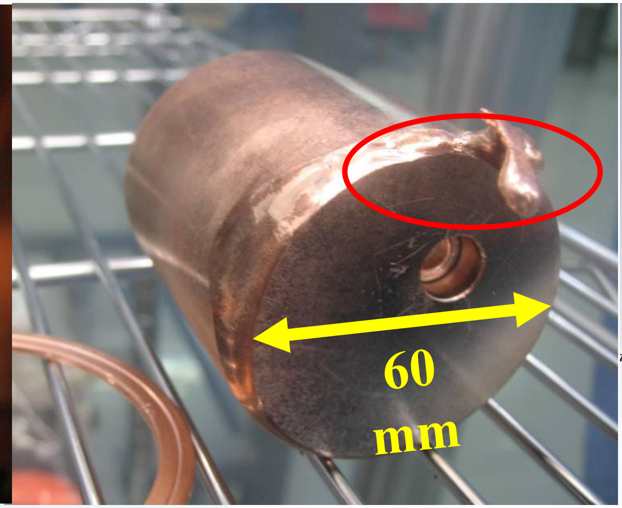
<u>New design</u> :

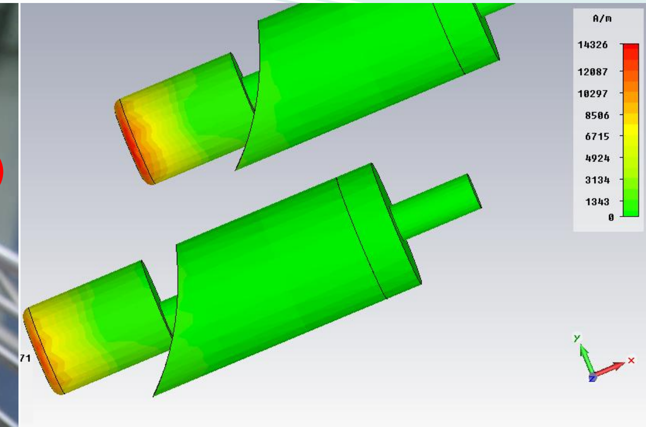
massive silver plate for better current and thermal conductivity,

mechanical contact with stems by a splint system

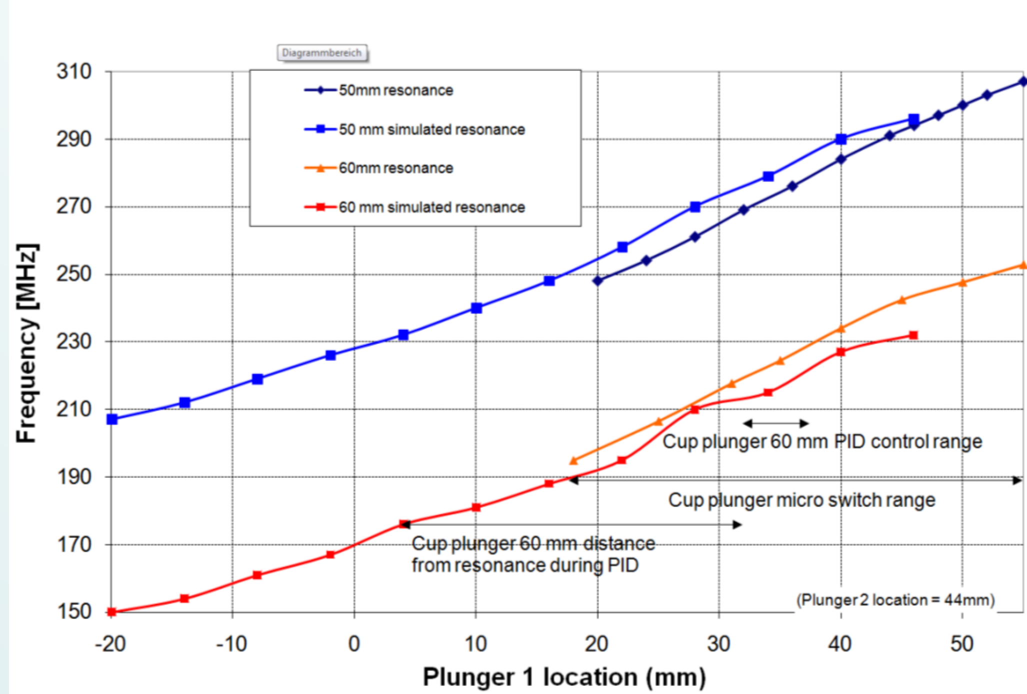
Melting of plunger electrode



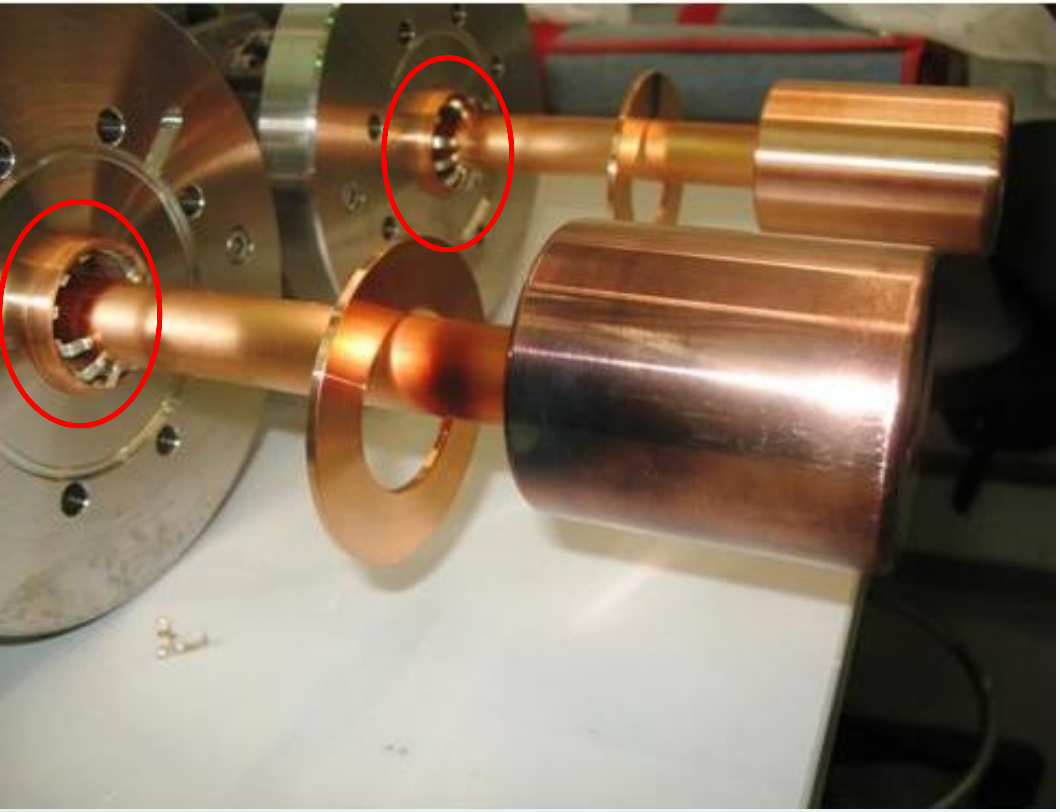


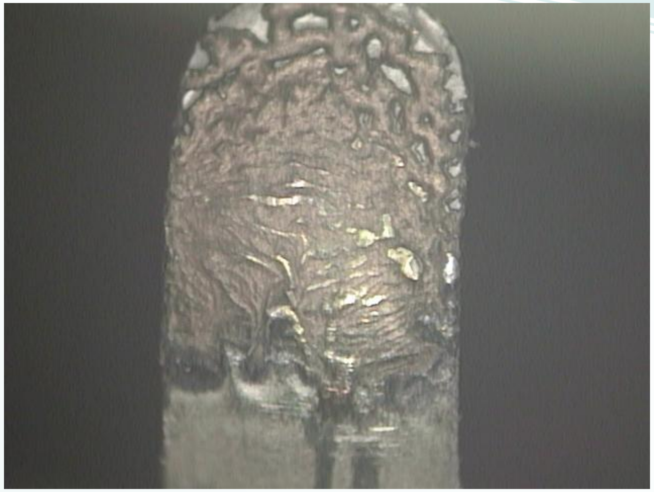


The low-energy plunger electrode has been melted.
It was verified that this was not due to a resonance phenomenon.
New design:
plunger was reduced by size (twice less thermal load), cooling capacity was improved (the plunger and cooling shaft made from one block)



Plungers RF sliding contacts





Cu/Be silver plated

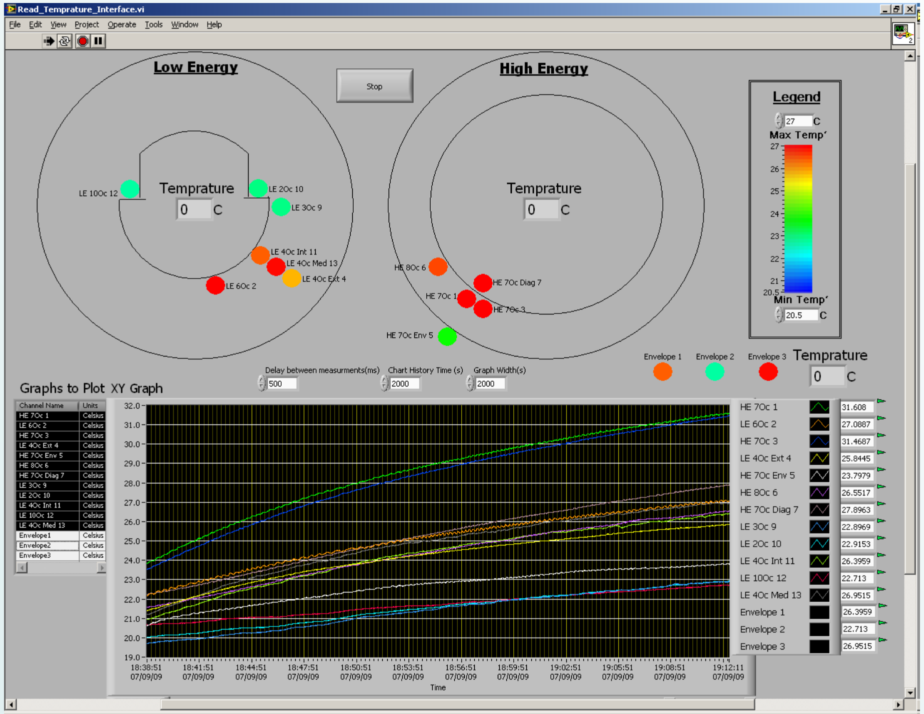
Broken and deformed RF fingers of the plunger sliding contacts.
The sign analysis of the finger surface showed melting signs.

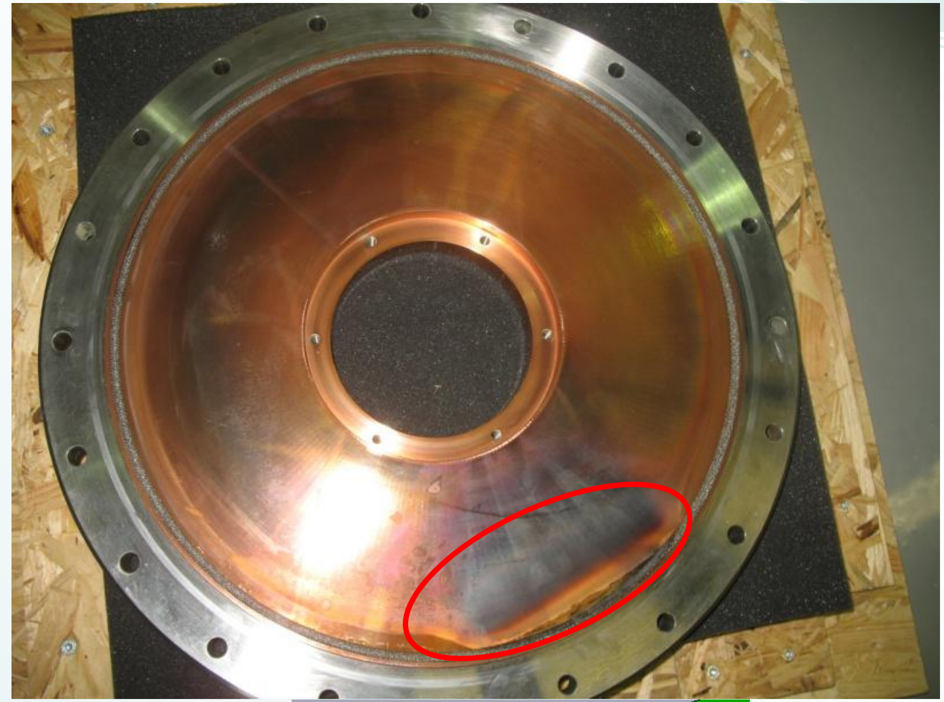
New design :

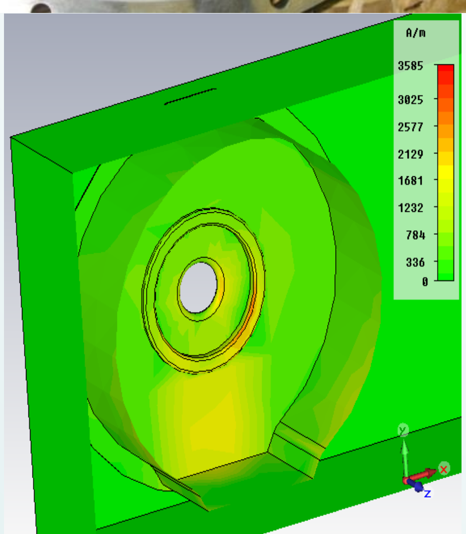
new type of RF contact with more rigid fingers
shafts plated by rhodium to avoid cold welding
rigid alignment of the plunger providing uniform contact pressure

Heating of end flanges

SOREQ







Heating of RFQ end flanges (not water cooled). Coloration of flanges was observed.

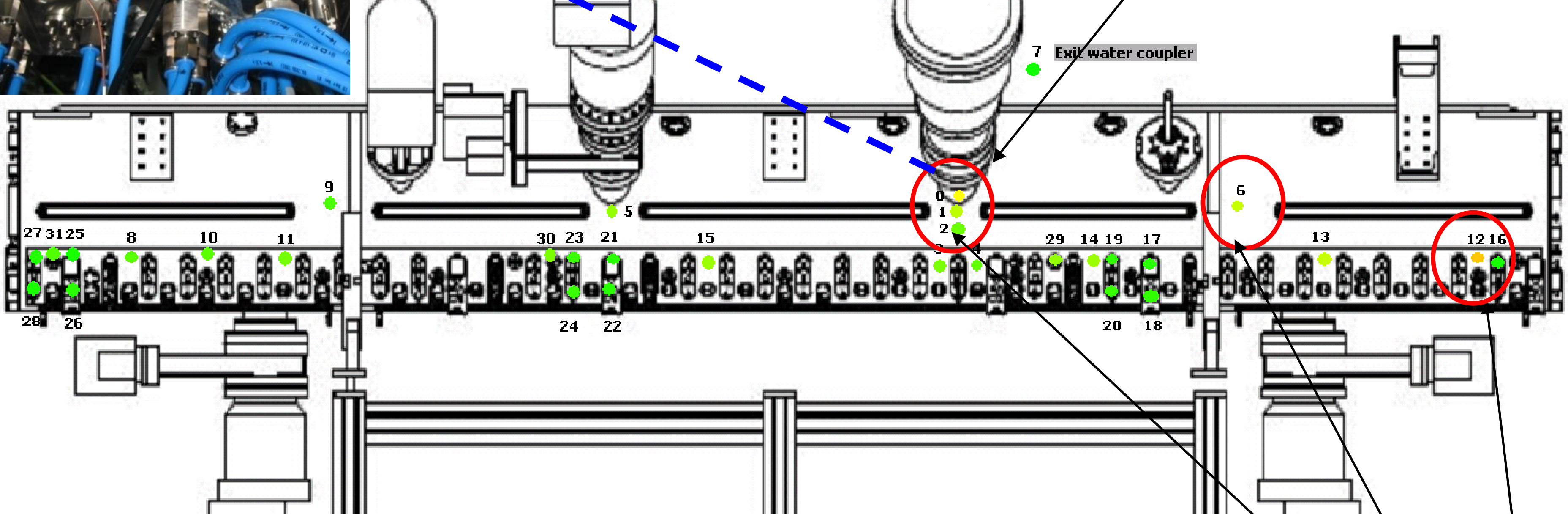
<u>New design</u>:

efficient cooling lines were drilled at the end flanges

improved RF contact between the flanges and the base plate

RFQ tank hot spots

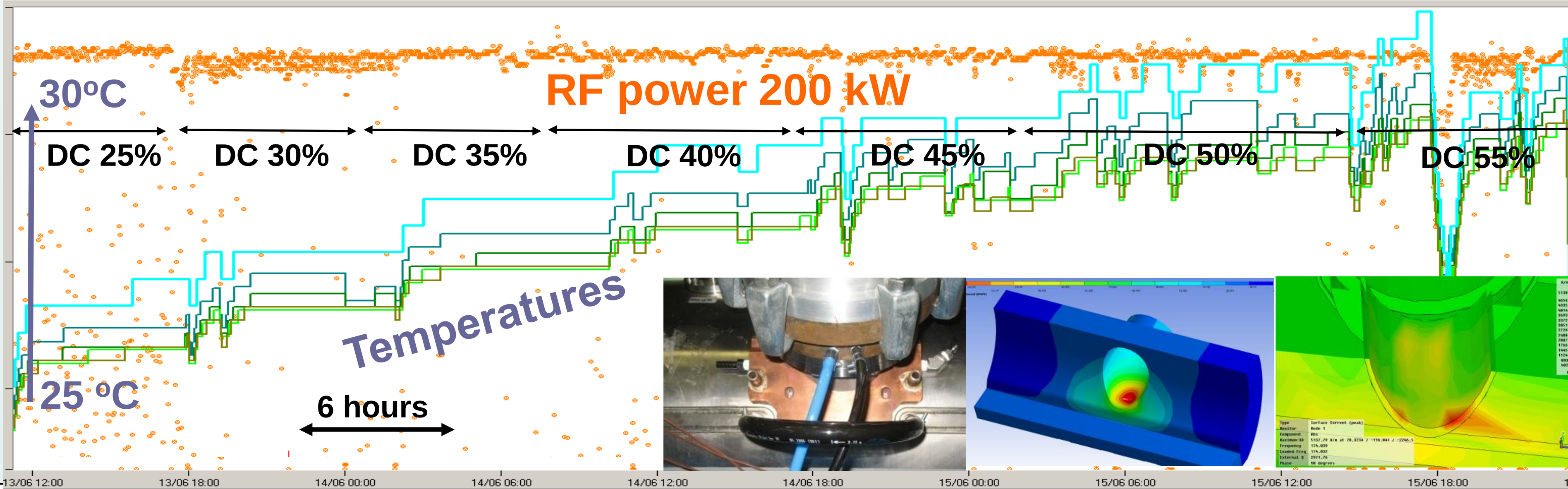
A fan was install in front of the coupler

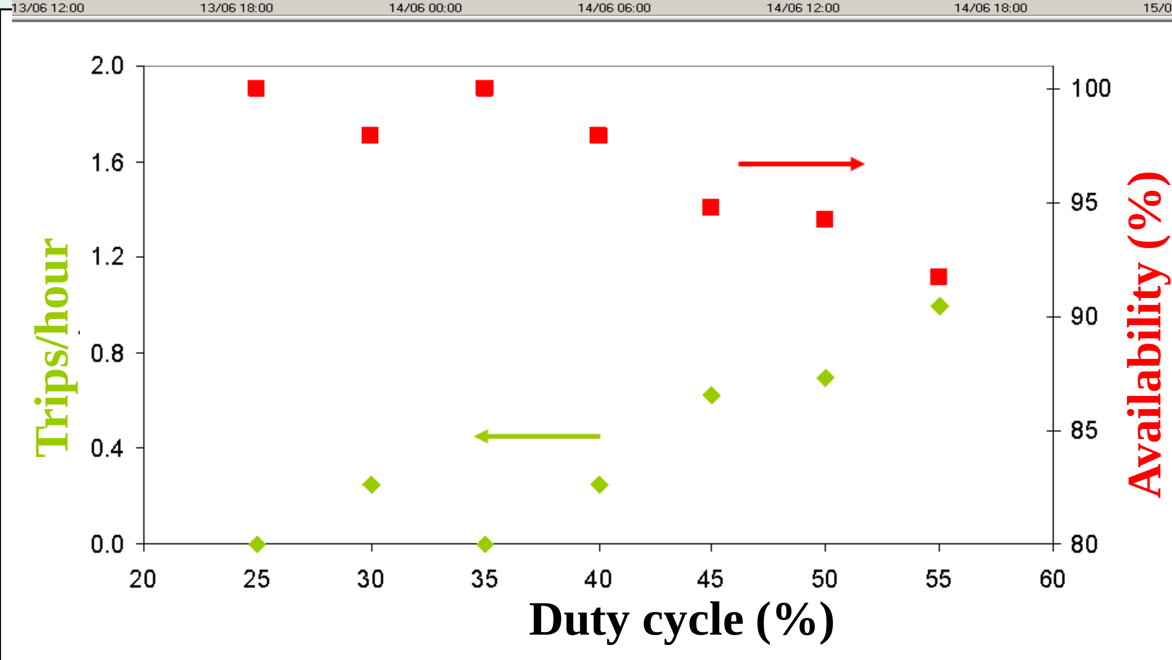


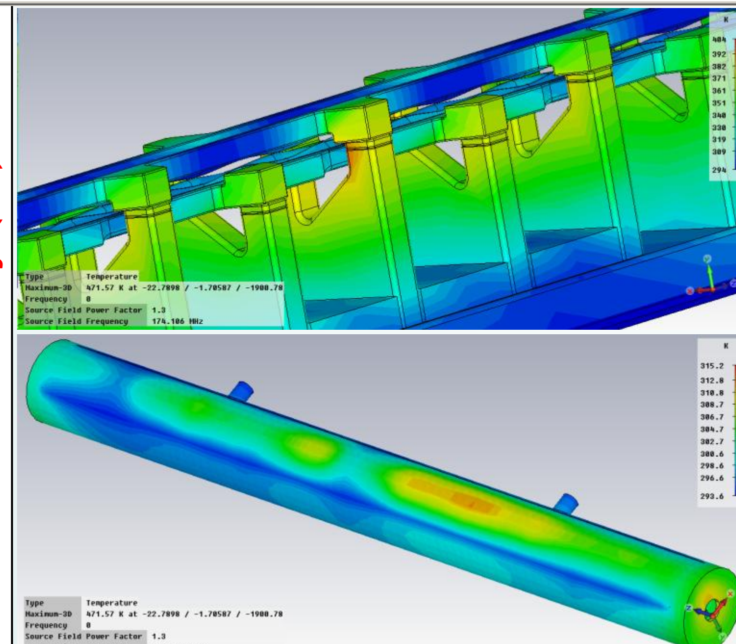
Further RFQ temperature mapping showed problematic regions:

1. the area of the break of tank cooling line especially in the vicinity of the coupler
   this problem is well understood by simulation, external cooling blocks were installed.
2. The region closed to high energy end
   probably due to lack of tuning plates at the last section- surface currents on base plate.

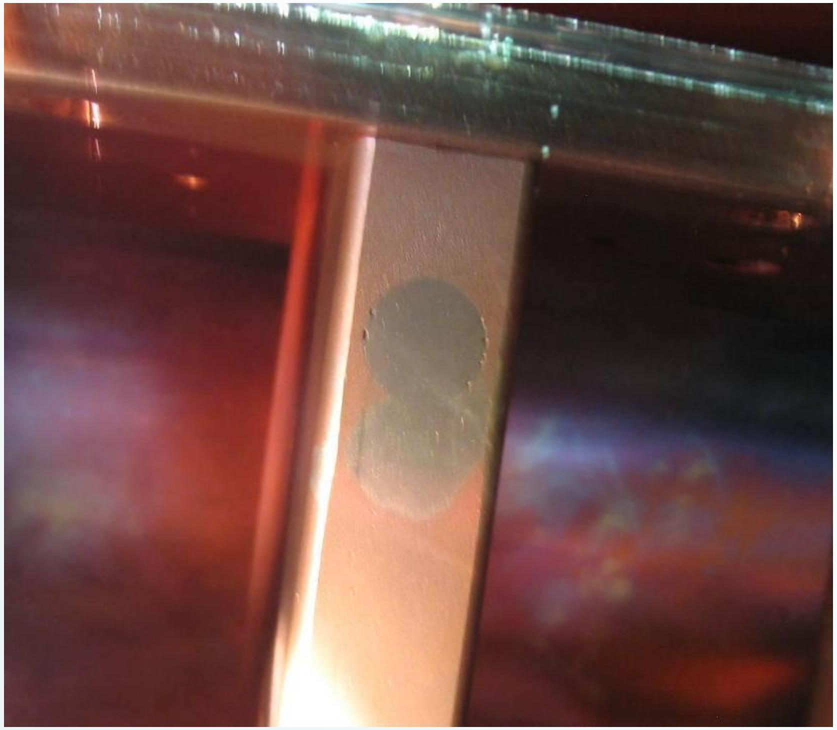
RFQ stability/availability







Findings from the last conditioning effort At 200 kW, 50% duty cycle

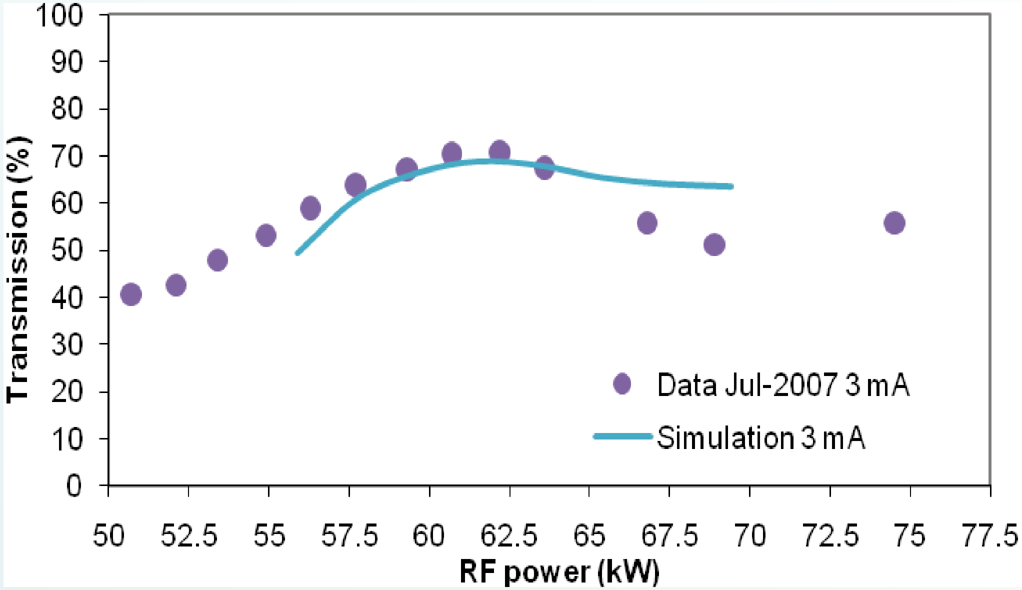


- Bridge between end flange and base plate, RF fingers were melted.
- Stem 5, leak at the brazing of the water cooling line.

Beam dynamics analysis as a vital tool to improve beam operation at the SARAF linac

- The CST MWS simulation and the TRACK beam dynamics simulation package were used to study the reduction in the RFQ current transmission during 2009.
- The reduction in transmission occurred following local cutting of the RFQ bottom electrodes to reduce parasitic fields that prevent RFQ operation at high power needed for a CW deuteron beam operation.
- Beam dynamics analysis demonstrated transmission reduction due to the distorted field flatness, an outcome of the local cutting.
- Reestablish of field flatness based on CST MWS simulation enables a stable CW, 1 mA, 3MeV proton beam at the SARAF linac on April 2010.
- The operating fields and phases were derived and set by the beam dynamics TRACK simulations.

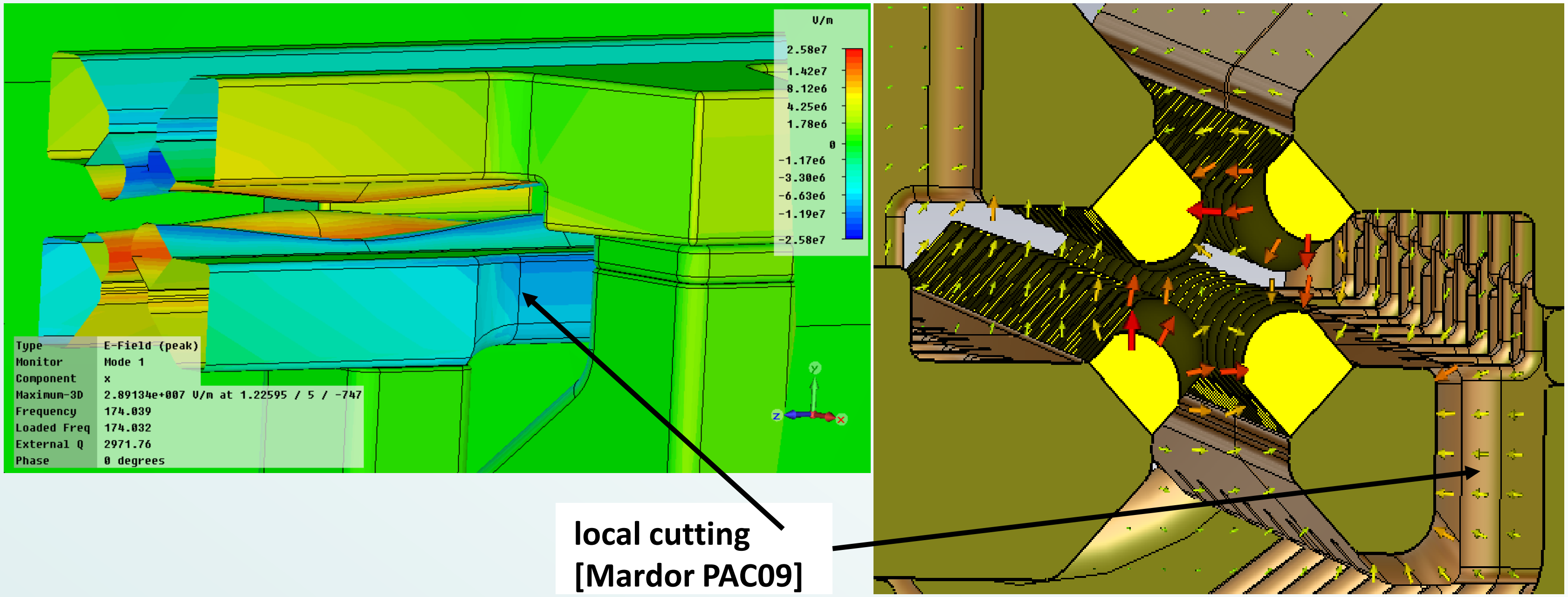
SARAF RFQ transmission at 2007



Beam dynamics simulation vs. measurements 2007

- a good agreement at the low power region
- a reduction in the measured transmitted current in the high power region.

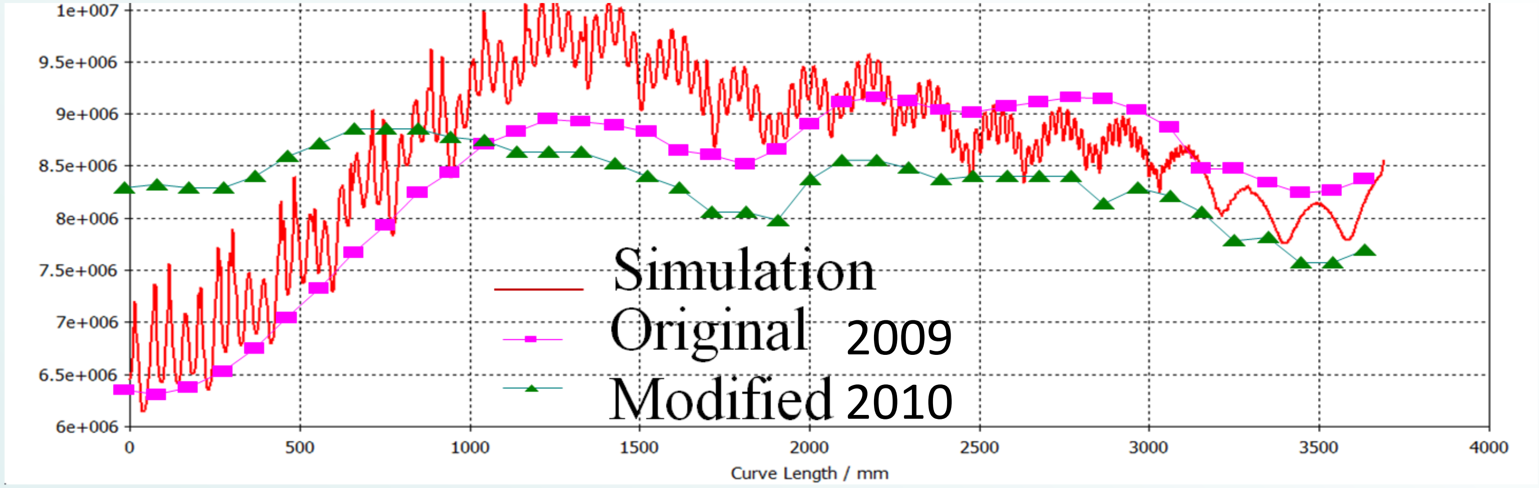
Local cut at the bottom electrodes at 2009



Eliminate high parasitic fields between the bottom electrodes and the stems with the negative polarity.

- **Enable to double the RFQ power towards d operation**
- **The field flatness along the RFQ was distorted**

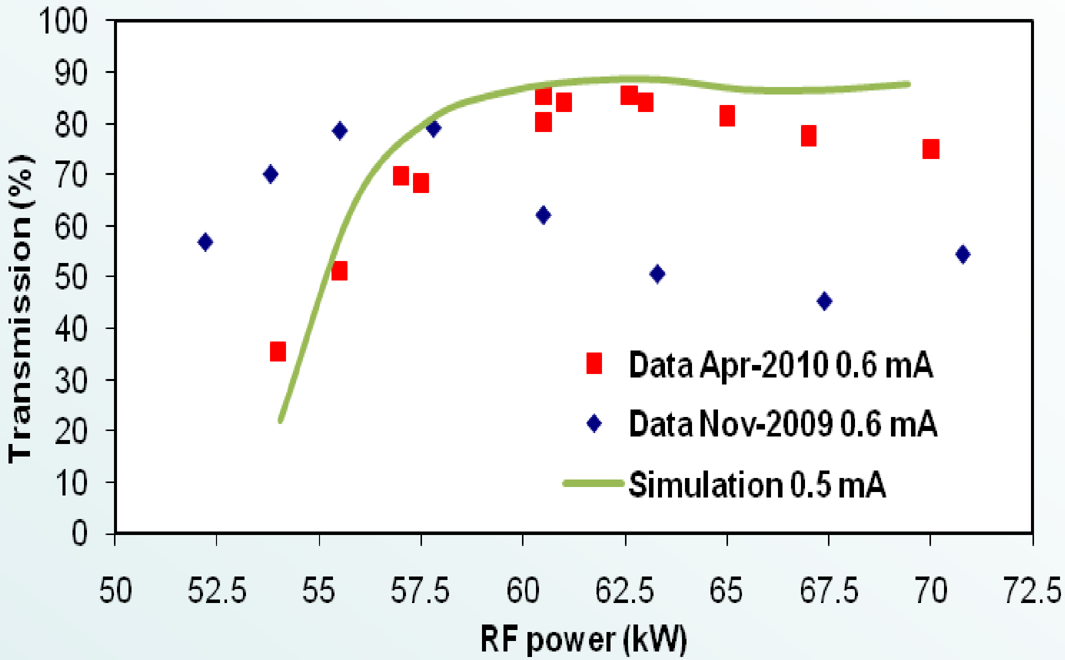
Field flatness along the RFQ



At 2009, the electrodes capacity at the high modulation section was reduced behind the tuning plate range.

- **The field flatness was distorted**
- **The RFQ transmission was reduced.**

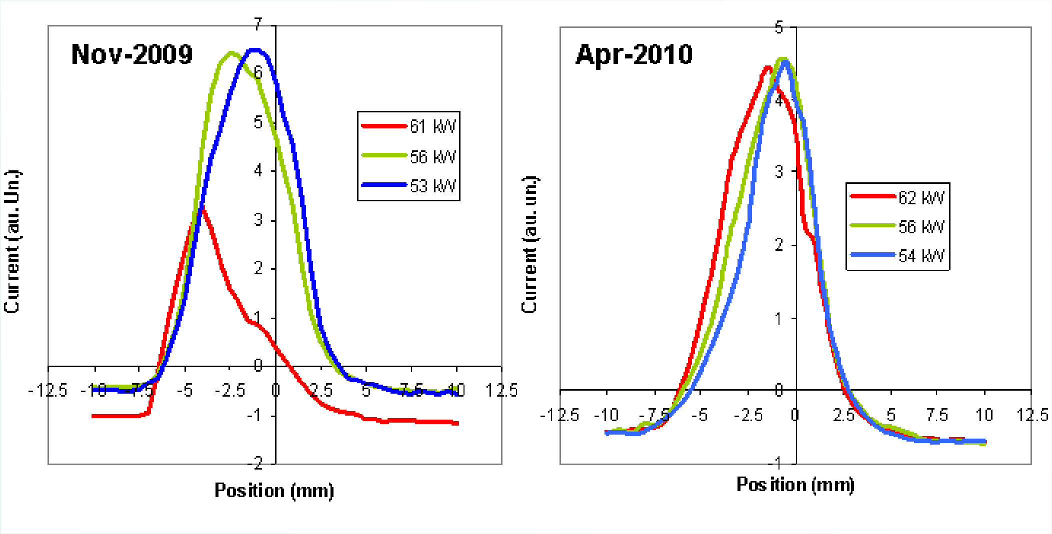
SARAF RFQ transmission at 2009



Beam dynamics simulation vs. measurements 2009

- **A significant reduction in the RFQ transmission**
- **Beam dynamics predicted increase in the losses at the high energy section of the RFQ.**

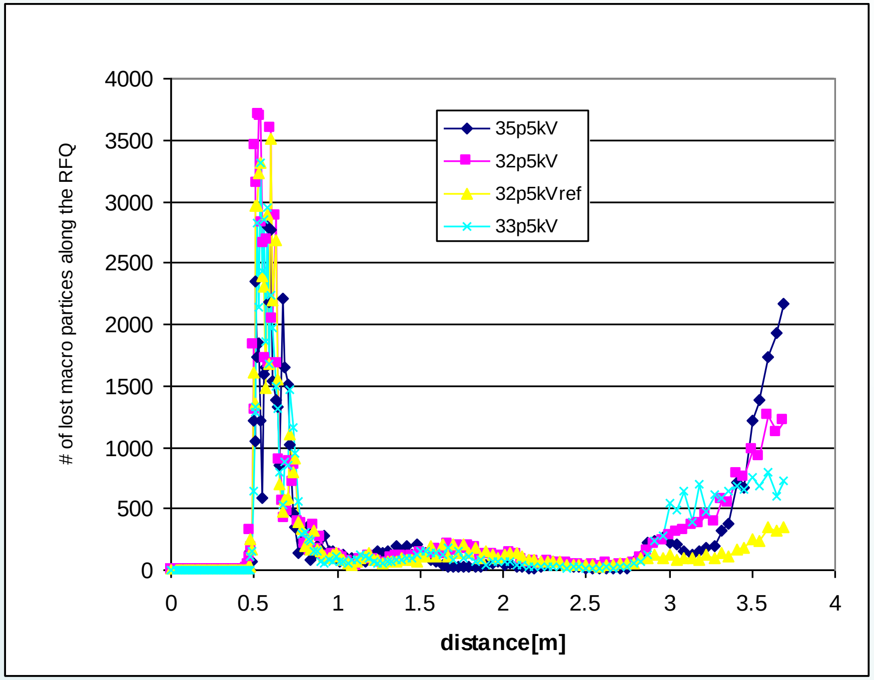
MEBT wire scanner profile measurements



2009 profile scan at the RFQ exit presented

- Beam losses at a high RFQ power and a wide beam profile

Macro particles losses along the RFQ
As function of field configuration



2009 distorted field configurations [32,5, 33.5, 35.5] kV vs. a nominal 32.5 kV flat field configuration.

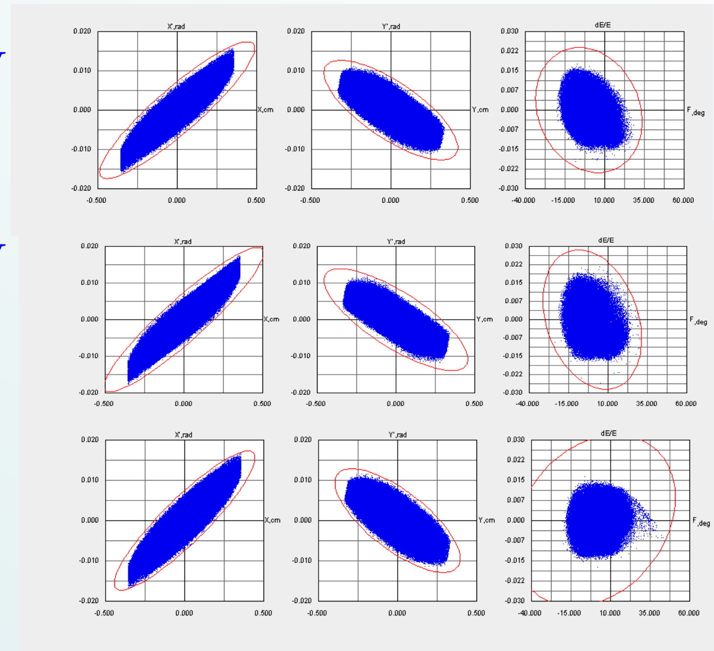
- **higher losses at the RFQ exit section for the distorted field configurations.**

Transverse phase spaces at the RFQ exit as function of field configuration

2009 32.5 kV

2009 35.5 kV

32.5 kV Reference Field



- **Wider transverse phase spaces envelopes at the RFQ exit for the distorted field configurations.**

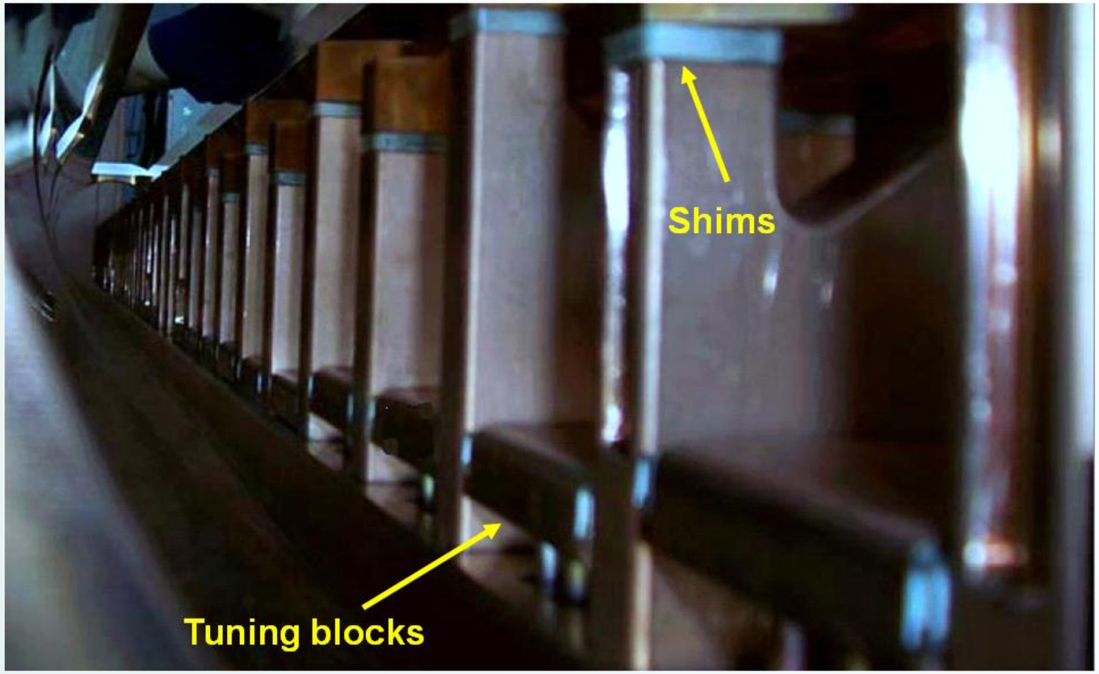
Due to the local cutting of the bottom electrodes in 2009:

- All the tuning plates at the last section were removed
- The horizontal distance between the electrodes was reduced by 400 micron

To re achieve field flatness CST MWS simulation showed that field flatness can be achieved by:

- Further reduction of 600 micron in the vertical plane
- Re installing of a tuning plate at the last section

RFQ modifications towards field flatness



On 2010 following CST MWS simulations study

- The shims at the last section were replaced and the vertical rod distance was enlarged by 400 micron
- The horizontal distance was further extended by 200 micron
- A tuning plate was reinstalled at the last section

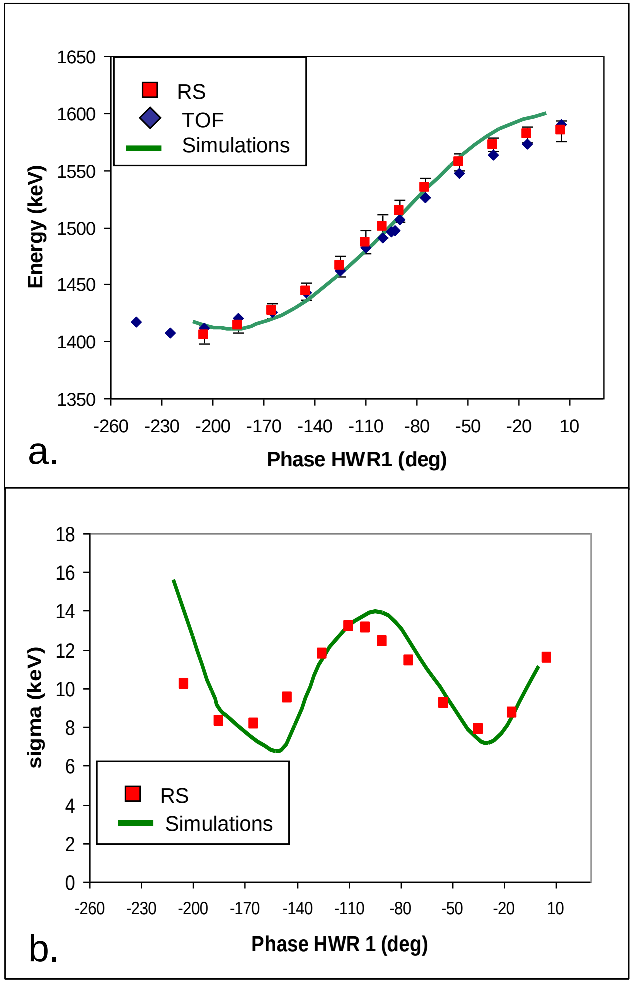
April 2010 RFQ modifications

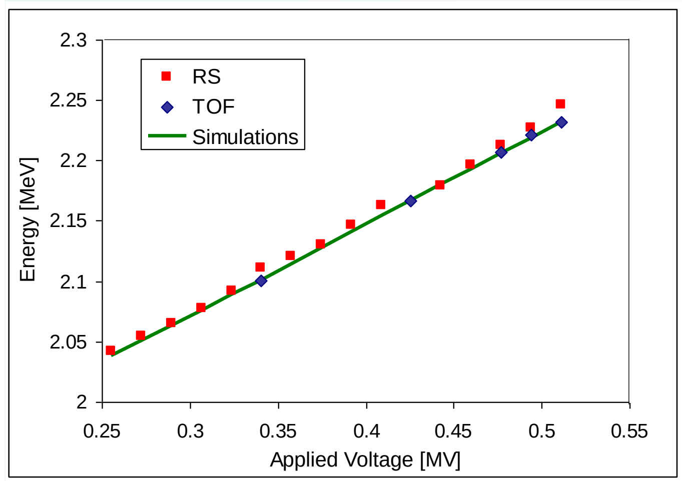
- A Field flatness along the RFQ was reestablished
- The RFQ transmission as function of RFQ power is in good agreement with beam dynamics simulations
- The transversal losses at RFQ exit as shown in the wire profile measurements for high RFQ power were occurred
- The increase in the PSM pressure for CW beam operation with a proton beam was reduced
- The entire field tune configuration set downstream the RFQ, along the MEBT and the PSM, was derived and calibrated by beam dynamics simulations.
- A stable CW, 3 MeV, 1mA proton beam operation through the PSM was established.

Energy and energy spread measurements

Time Of Flight (TOF) and Rutherford Scattering (RS) techniques were used.

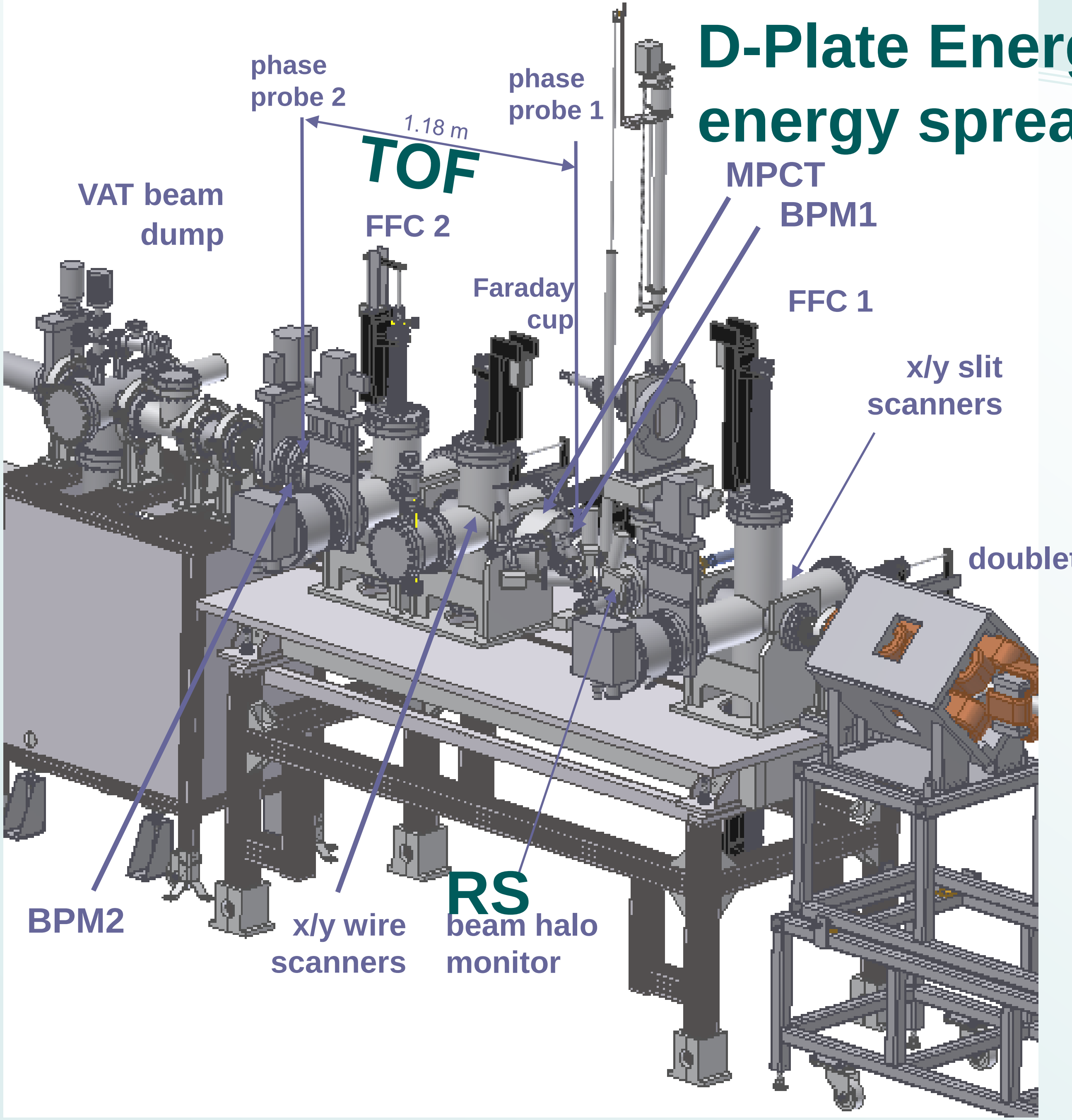
- Good agreement between both methods and simulations for beam energy measurements
- The RS measured the beam spread and used for a longitudinal emittance reconstruction





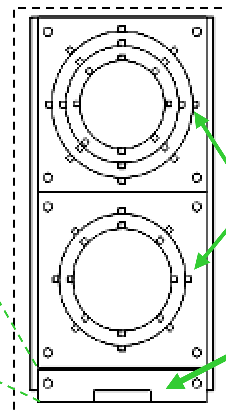
The PSM beam operation was based on beam dynamics design combined with TOF and RS measurements.

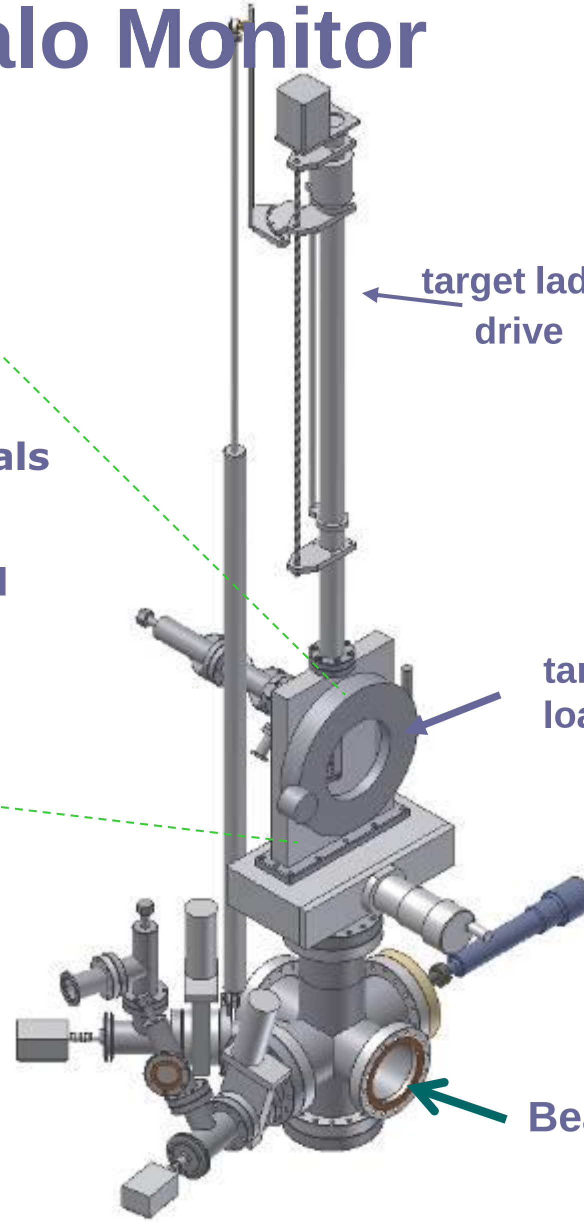
D-Plate Energy and energy spread measurements



L. Weissman DIPAC 2009

Beam energy at the Halo Monitor





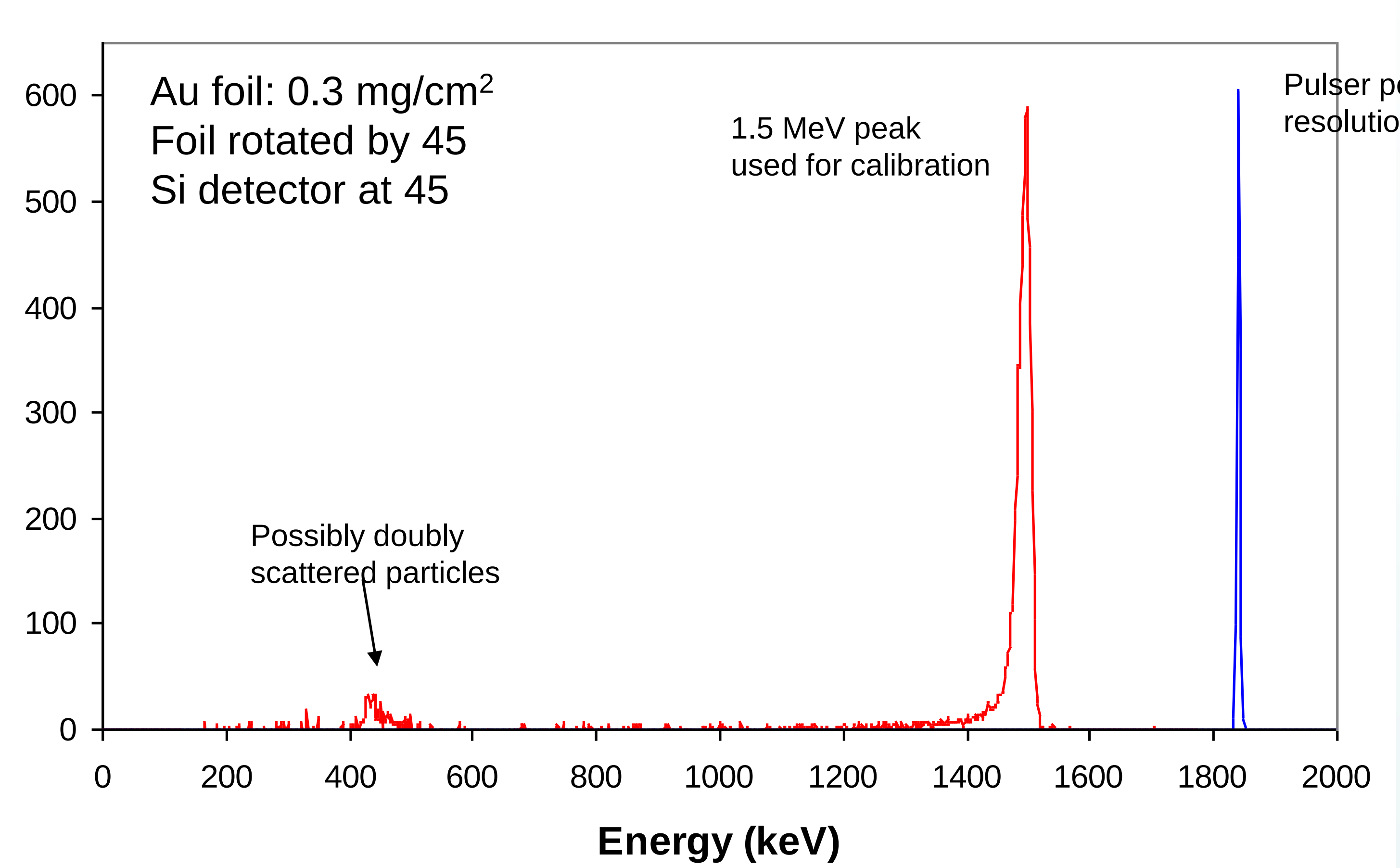
Energy measurements are possible because FFC and beam dynamics simulation show that the energy distribution on the beam side is similar to the core

I. Mardor *et al*, LINAC 2006

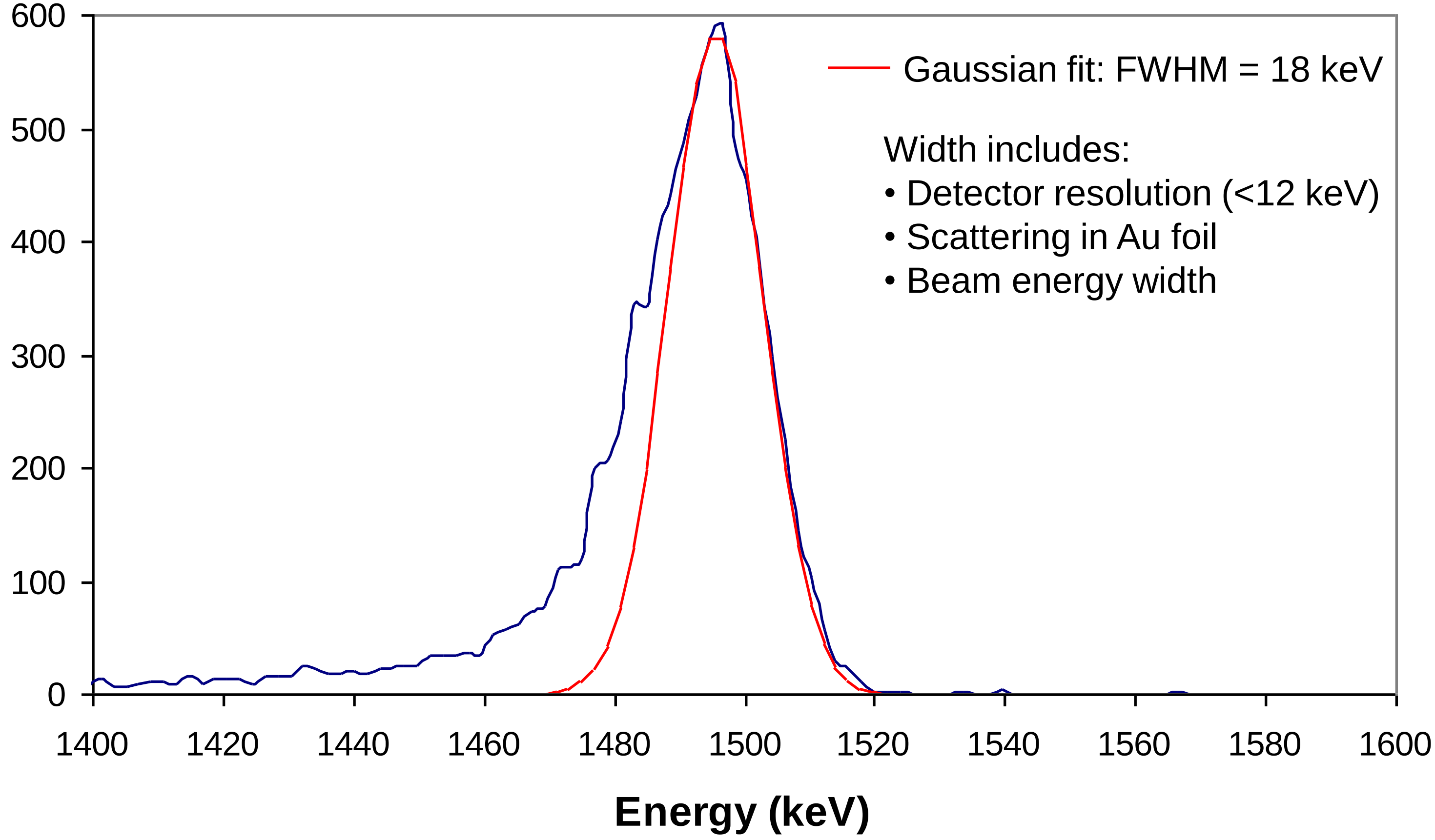
L. Weissman *et al*, DIPAC 2009

Proton beam energy measurement using Rutherford scattering (RS)

Typical spectrum without cavity voltages (RFQ only). Background (removed foil) was subtracted.

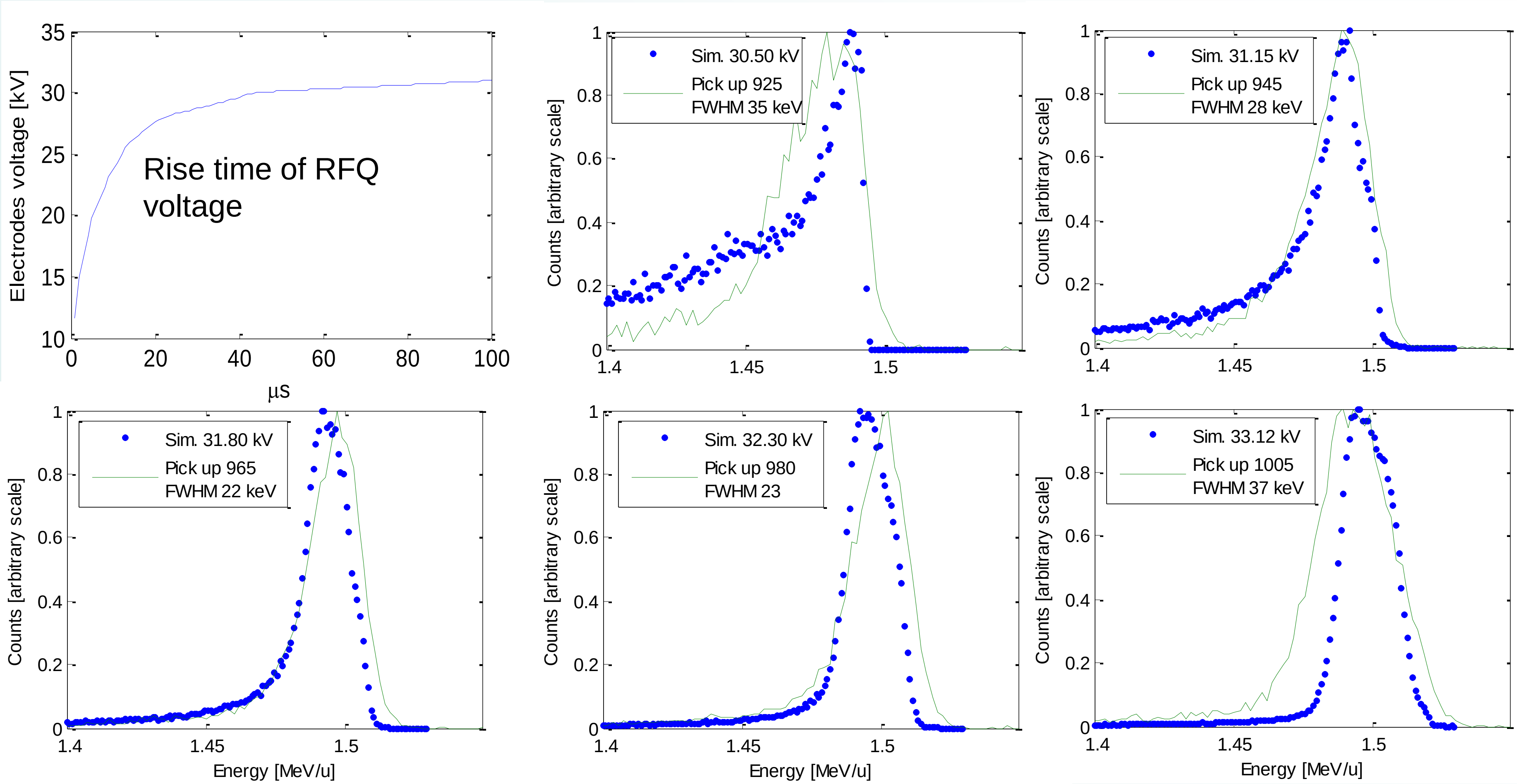


Proton beam energy measurement using Rutherford scattering



The low energy tail is most probably enhanced due to rise time of RFQ voltage pulse (Si detector not gated). This is supported by beam dynamics simulations.

Proton beam energy measurement using Rutherford scattering vs. beam dynamics simulations



The simulations were based on RFQ voltage as function of time during the 100 µs proton beam pulse length, the low energy tail is most probably enhanced due to rise time of the pulse (Si detector not gated).

Longitudinal emittance construction

- The energy spread is measured with the RS technique
- The variance of the energy spread measured as a function of the diagnostic cavity energy gain per degree, denoted as X, is a quadratic polynomial
- The RS apparatus variance contributions (5.8 keV)^2– (7.4 keV)^2 are not extracted from the measurements

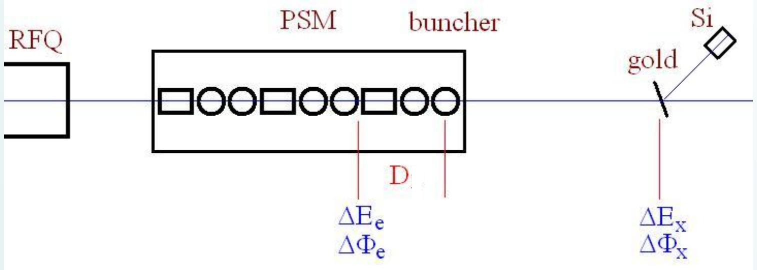
$$\sigma_{66x}(X) = (\sigma_{55e} + 2Y\sigma_{56e} + Y^2\sigma_{66e})X^2 + 2(\sigma_{56e} + Y\sigma_{66e})X$$

$$+\sigma_{66e} = p_1 X^2 + p_2 X + p_3$$

$$\sigma = \varepsilon \begin{bmatrix} \hat{\beta} & -\hat{\alpha} \\ -\hat{\alpha} & \hat{\gamma} \end{bmatrix} = \begin{bmatrix} \sigma_{55} & \sigma_{56} \\ \sigma_{65} & \sigma_{66} \end{bmatrix}$$

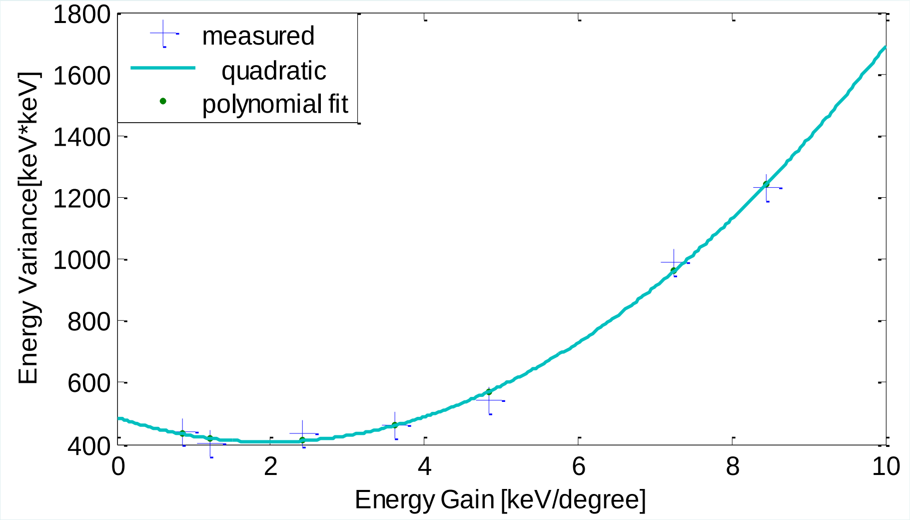
$$X = Uacc * 2\pi / 360$$

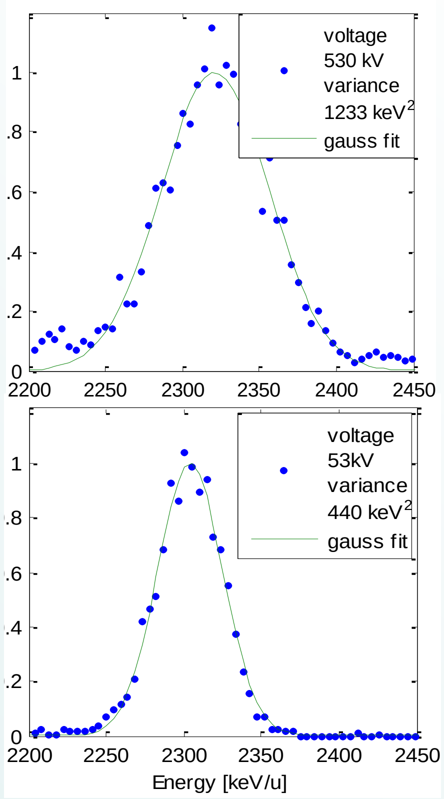
$$Y = -\left(\left(360/T\right)*\left(D/\beta c\right)\right)/(mc^2\gamma^3\beta^2)$$



Longitudinal emittance construction at the PSM proton beam operation

- The PSM 6th- last cavity was operating as a buncher for various cavity voltages [53-530] keV
- The 5th cavity was turned off and detuned
- Cavity 1-4 were locked according to the beam dynamics design for a 3.1 MeV at the PSM exit as described above
- The constructed emittance value was 90 5 π degree keV vs. 60 π degree keV the beam dynamics predicted value.





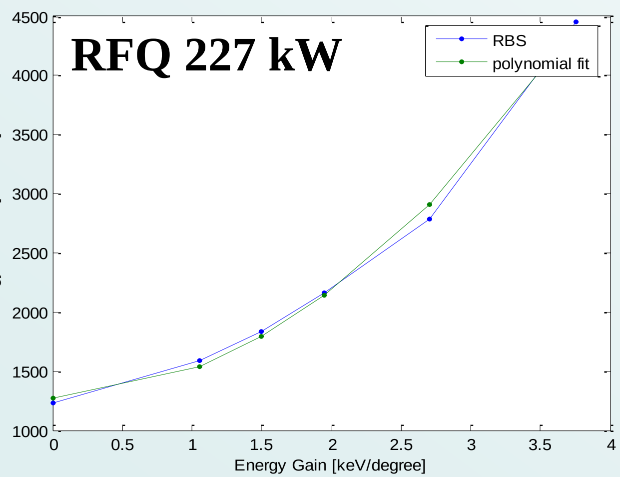
RFQ Longitudinal emittance measurement

Example : Deuteron beam

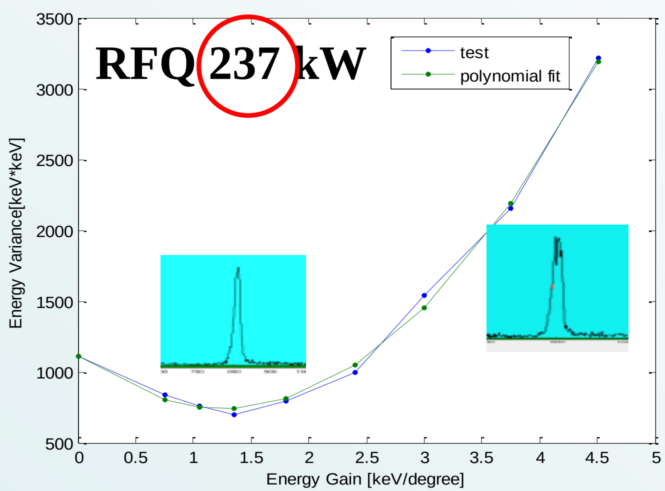
RFQ + 1st cavity

The cavity was set to -90 (bunching mode) and its voltage is varied

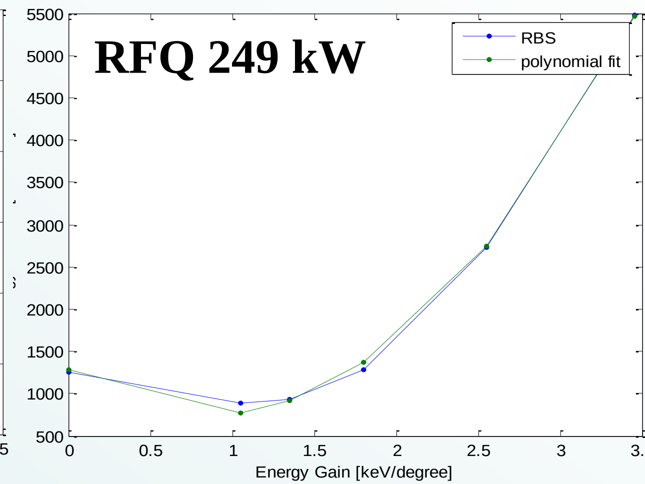
Evaluation of longitudinal emittance via measuring energy width of the peak as a function of the cavity voltage



Long. Emittance
260 π deg keV/u



Long. Emittance
210 π deg keV/u



Long. Emittance
365 π deg keV/u

Summary and Outlook

- First proton and deuteron beams were accelerated by a HWR based SC Linac

- Proton and Deuteron **low duty cycle** beams were accelerated up to **3.7 MeV** and **4.3 MeV**

- Protons **CW ~1 mA** beams accelerated up to **3.1 MeV**

- Phase I is still in its commissioning stage.

  1. Actions to improve beam operation :

     RFQ alignment

     MEBT scrapper

     Upgrade of tuners control and cavities amplifiers

  2. CW Deuteron operation has not been achieved yet

- Design of Phase II is underway

People involved

SARAF team (including students, advisers and partially affiliated personal) :

A. Nagler , I. Mardor, D. Berkovits, A. Abramson , A. Arenshtam, Y. Askenazi, B. Bazak (until 2009), Y. Ben-Aliz, Y. Buzaglo, O. Dudovich, Y.Eisen, I. Eliyahu, G. Feinberg, I. Fishman, I. Gertz, A. Grin, S. Halfon, D. Har-Even, D. Hirshman, T. Hirsh, A. Kreisel, D. Kijel, G. Lempert, A. Perry, R. Raizman (until 2010), E. Reinfeld, J. Rodnizki, A. Shor, I. Silverman, B. Vainas, L. Weissman,Y. Yanay (until 2009).

Red font : persons who joined recently

RI&Varian /(former ACCEL):

H. Vogel, Ch. Piel, K, Dunkel, P. Von Stain, M. Pekeler, F. Kremer, D. Trompetter, many mechanical and electrical engineers and technicians

Cryoelectra :

B. Aminov, N. Pupeter, …

NTG/ Frankfurt Univ:

A. Bechtold, Ph. Fischer, A. Schempp, J. Hauser