SOREQ

The SARAF 40 MeV Proton/Deuteron Accelerator

I. Mardor, D. Berkovits, I. Gertz, A. Grin, S. Halfon,
G. Lempert, A. Nagler, A. Perry, J. Rodnizki, L. Weissman

Soreq NRC, Yavne, Israel

K. Dunkel, M. Pekeler, C. Piel, P. vom Stein

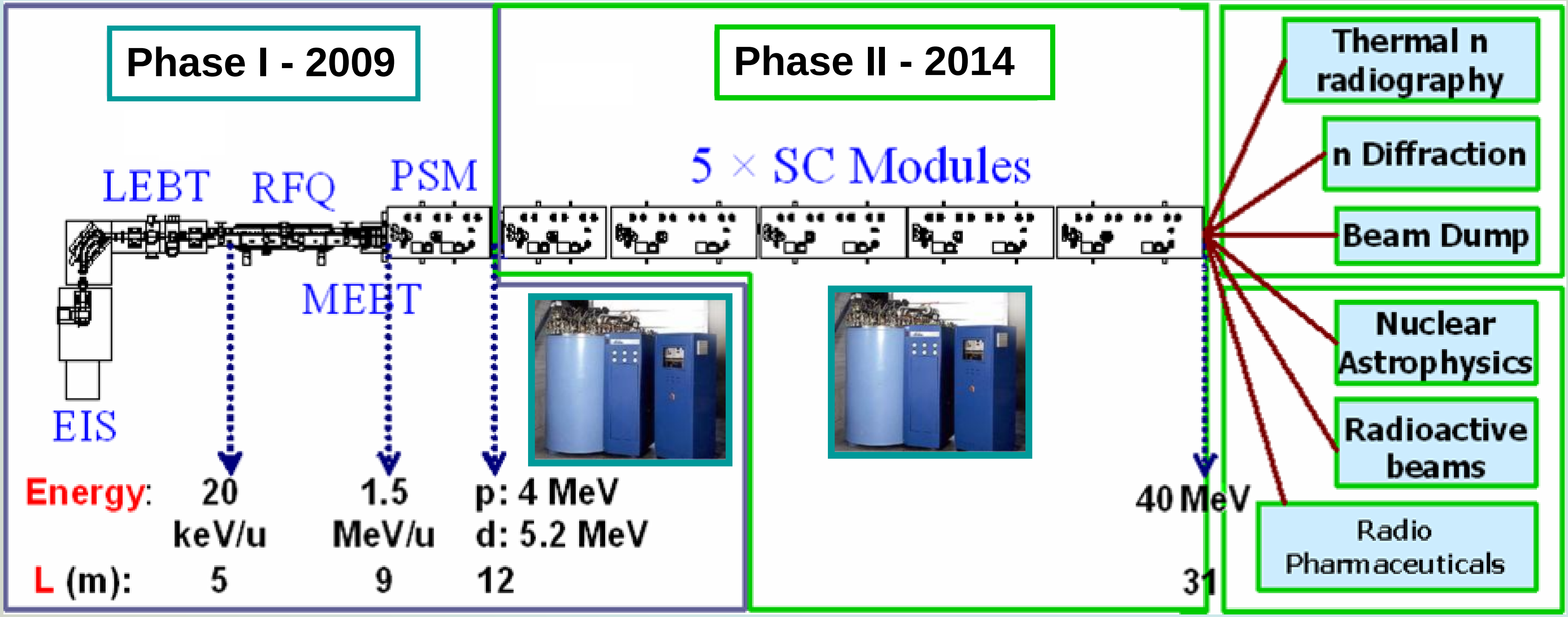
RI Research Instruments, Bergisch Gladbach, Germany

SRF09, Berlin-Dresden

MOODAU04, September 21th, 2009

Soreq Applied Research Accelerator Facility

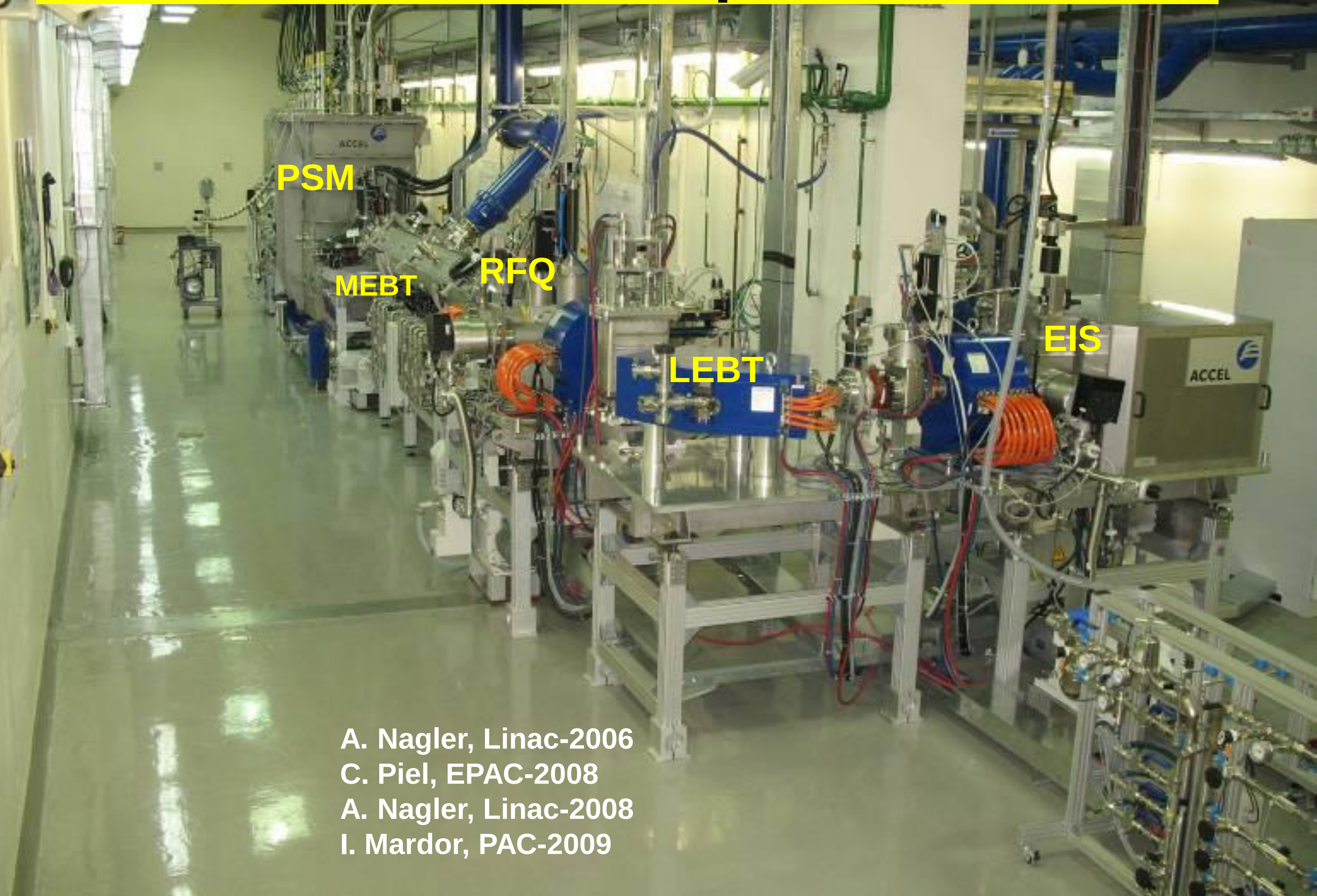
RF Superconducting Linear Accelerator | **Target Hall**



Current Range	0.04 – 2 mA (4 mA)
Operation mode	CW and Pulsed
Maintenance	Hands-On (beam loss < 1 nA/m @ 40 MeV)

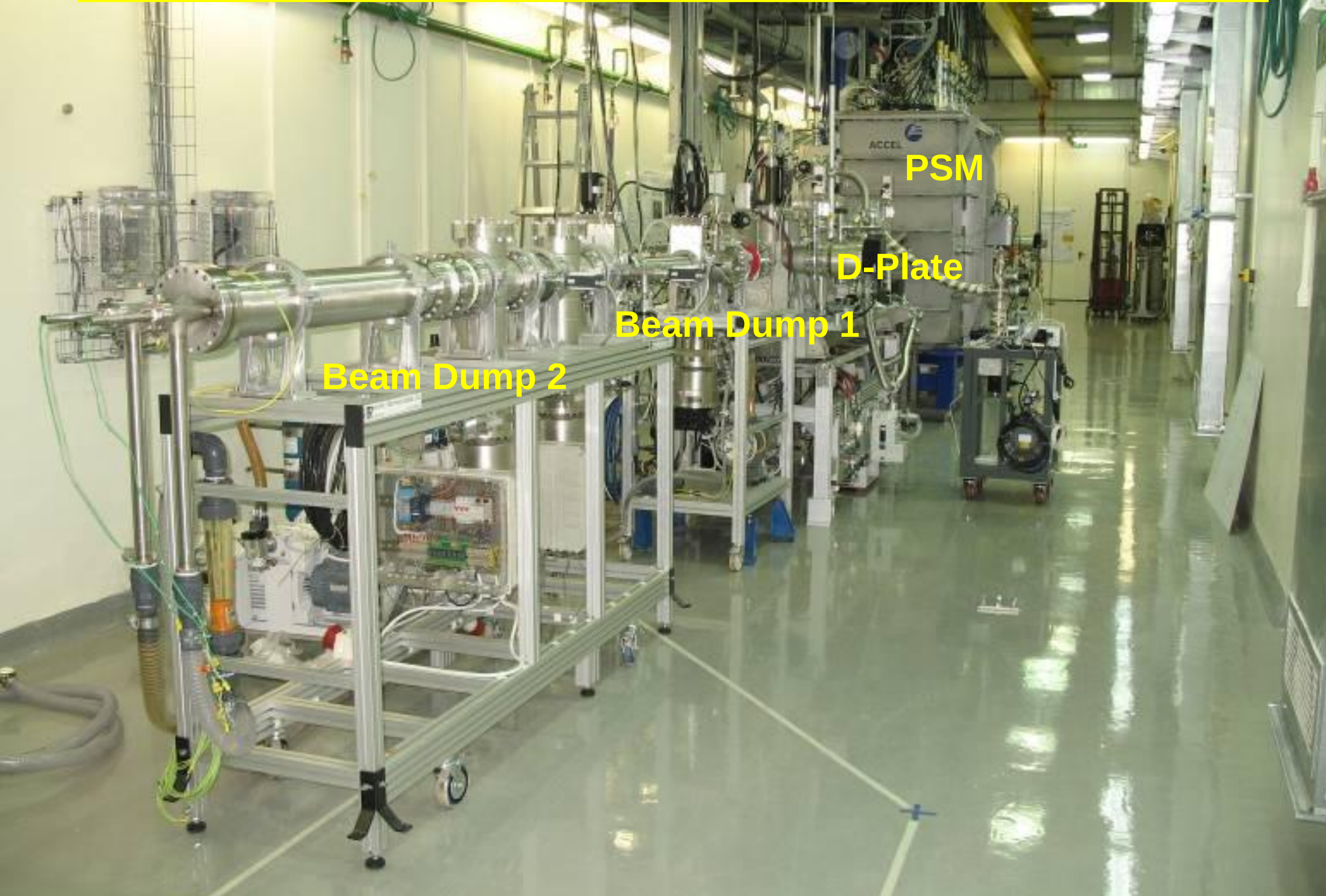
A. Nagler et al., LINAC 2006

SARAF Phase I – Upstream View



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

SARAF Phase I – Downstream View



EIS: measured emittance values

EIS has been in routine operation since 2006

$\varepsilon_{rms\_norm.\_100\%}$ [π mm mrad]

Particles Beam current	Protons X / Y	Deuterons X / Y
5.0 mA	**0.20 / 0.17**	**0.13 / 0.12**
2.0 mA	**0.13 / 0.13**	**0.14 / 0.13**
0.04 mA	**0.18 / 0.19**	**0.05 / 0.05**

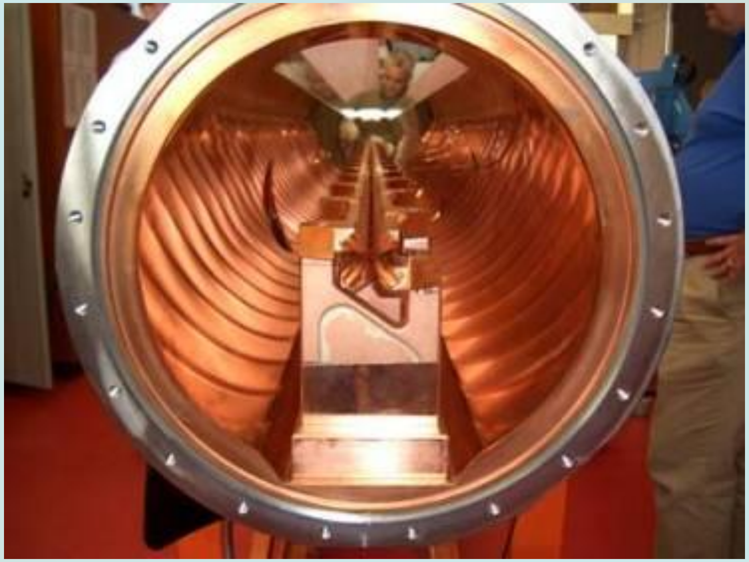
Specified value = 0.2 / 0.2 [π mm mrad]

176 MHz 4-Rod RFQ

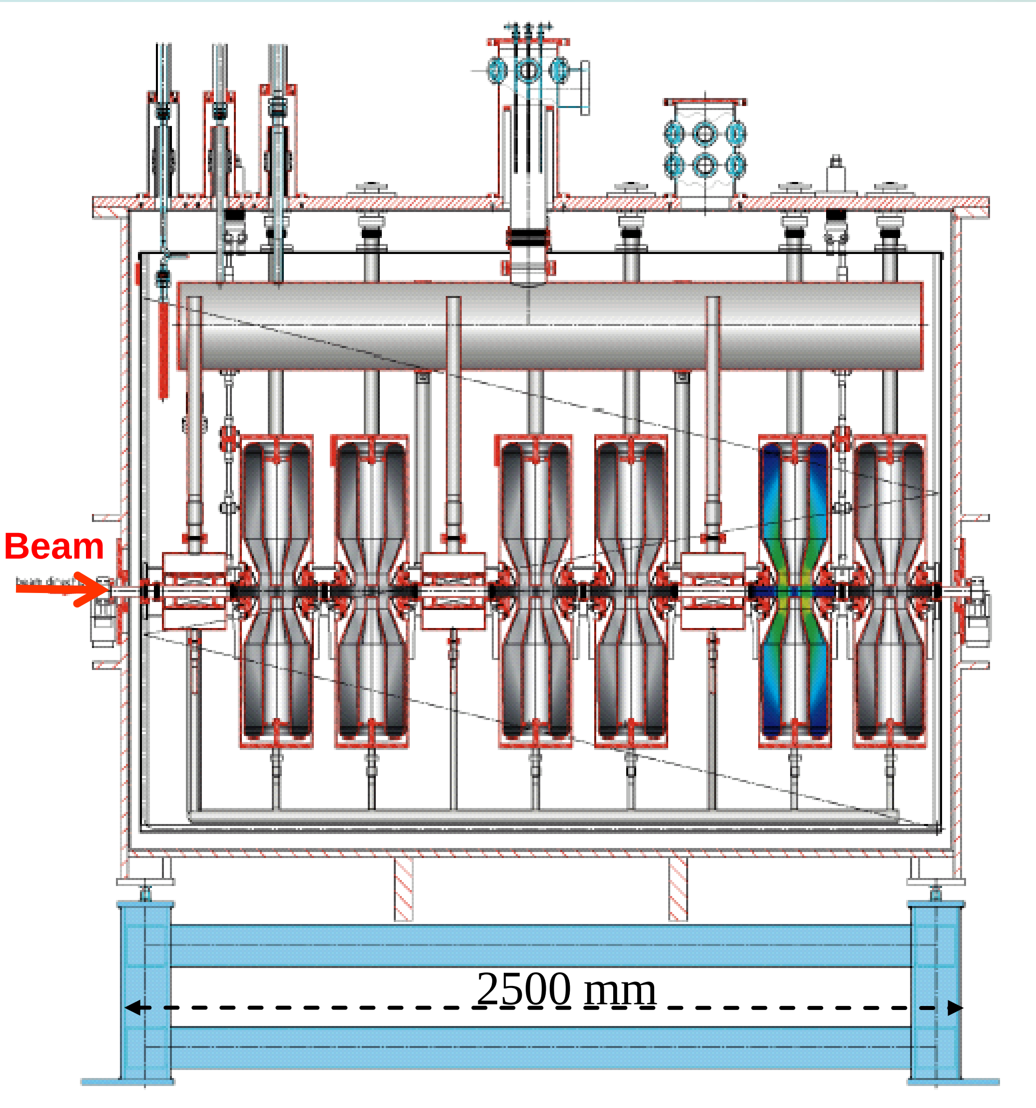
RFQ Beam Properties		
Beam Parameter	Protons	Deuterons
Energy (MeV)	1.5 (1.5)	3.0 (3.0)
Maximal current [mA]	4.0 ***(CW)*** (4.0)	2.5 ***(10^{-4})*** (4.0)
Transverse emittance, r.m.s., normalized, 100% [π·mm·mrad] (@ 0.5 mA, closed LEBT aperture)	0.17 (0.30)	NM
(@ 4.0 mA, open LEBT aperture)	0.25 / 0.29 (0.30)	NM
Longitudinal emittance, r.m.s., [π·keV·deg/u] (@ 3.0 mA)	30 (120)	NM
Transmission [%] (@ 0.5 mA)	80 (90)	NM
(@ 2.0 mA)	70 (90)	NM
(@ 4.0 mA)	65 (90)	70 (90)

Deuteron operation requires 260 kW CW over 3.8 m rods (65 kV)

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



Prototype SC Module (PSM)



General PSM Design:

- Houses 6 176 MHz β=0.09 HWRs and 3 sc solenoids
- Accelerates protons and deuterons from 1.5 MeV/u
- Very compact design in longitudinal direction
- Cavity vacuum and insulation vacuum are separated

Linac Lattice:

- 2 SC modules
  - Each housing 6 β=0.09 HWRs
- 4 SC modules
  - Each housing 8 β=0.15 HWRs
- Total of 44 SC cavities

M. Pekeler, LINAC 2006

HWR peak fields and dissipated power

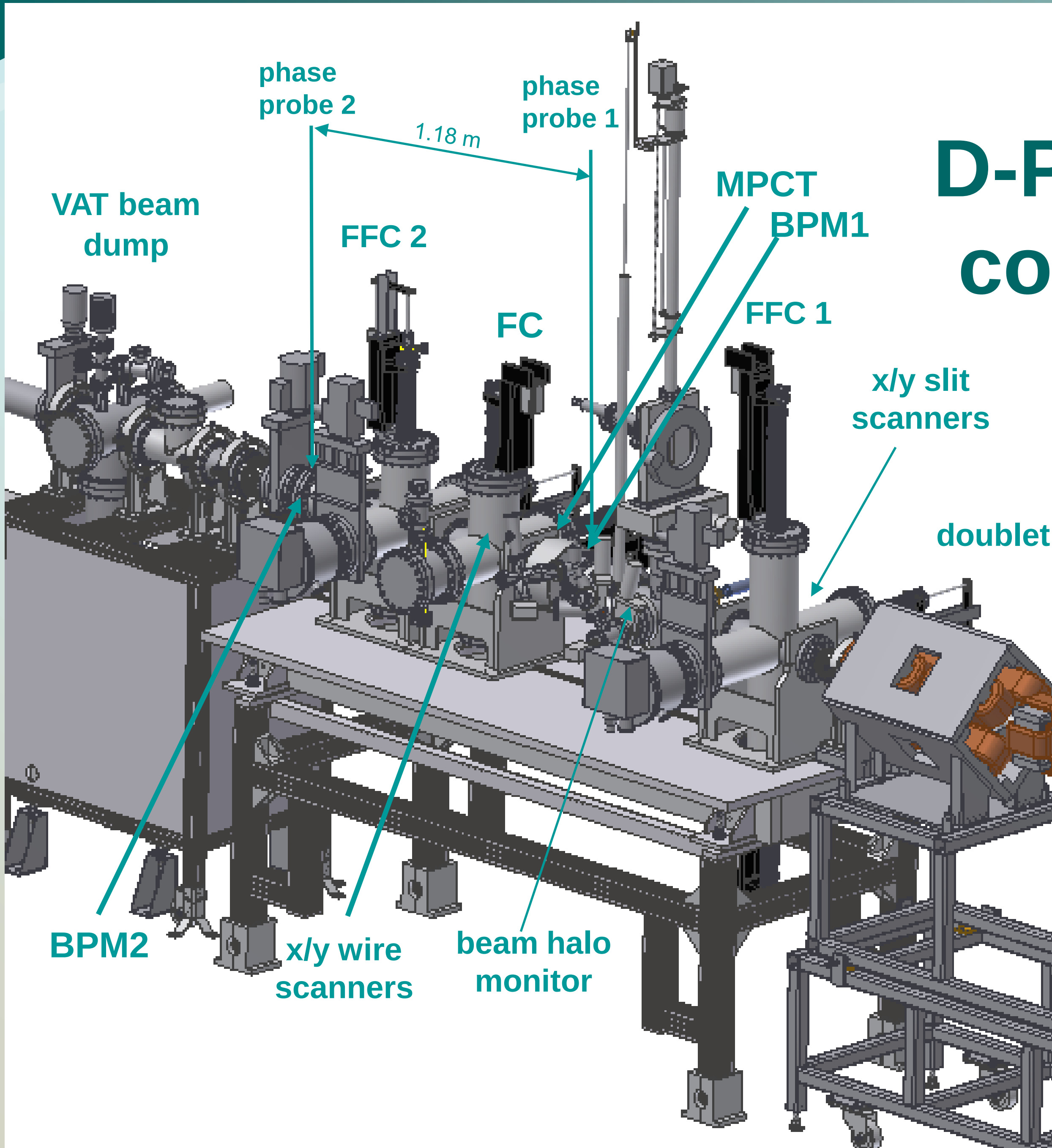
Cavity #	Vertical Test [W] (At RI (single cavity))	Before Processing [W] (At Soreq (inside PSM))		After Helium Processing [W] (At Soreq (inside PSM))	
	25 MV/m	20 MV/m	25 MV/m	20 MV/m	25 MV/m
1	7.3	1.9	7	2.2	5.5
2	7.3	3.0	6.3	4.8	8.7
3	6.3	12.3	16.8	7.0	14.8
4	6.3	11.1	---	3.9	10.6
5	5.5	5.4	15.1	3.3	8.8
6	7.3	9.6	---	5.4	10.7
Total	40	43.3	---	26.6	59.1
Target	72		72		72

RF Processing:
Closed loop operation with a voltage controlled oscillator (VCO)

He Processing:
99.9999% purity
4×10^{-5} mbar
Pulsed 43 MV/m

More details:
A. Perry, TUPPO027

D-Plate for beam commissioning



C. Piel, PAC 2007
L. Weissman, DIPAC 2009

Deuteron beam operation through PSM

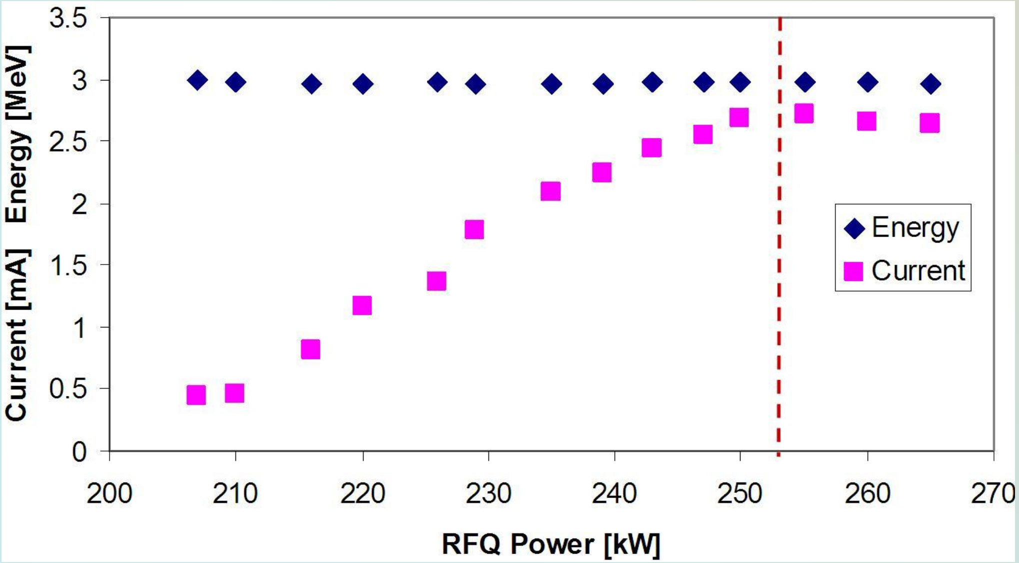
- A deuteron beam was passed through a detuned PSM
  - Measure the needed RFQ power for deuteron operation
  - Check alignment of all Phase I components

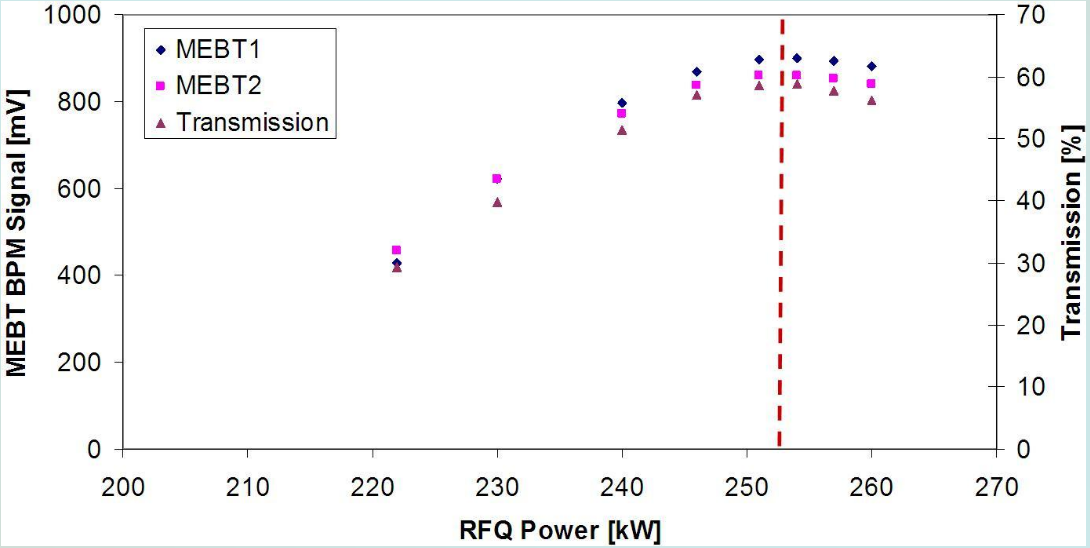
E_d [MeV]	3.0
Beam Duty Cycle [%]	0.01
I_d @ LEBT [mA]	4.6
I_d @ D-Plate [mA]	2.7
RFQ RF Duty Cycle [%]	10 - 30
PSM RF Duty Cycle [%]	100

Transmission = 59%

Deuteron beam – RFQ power and transmission

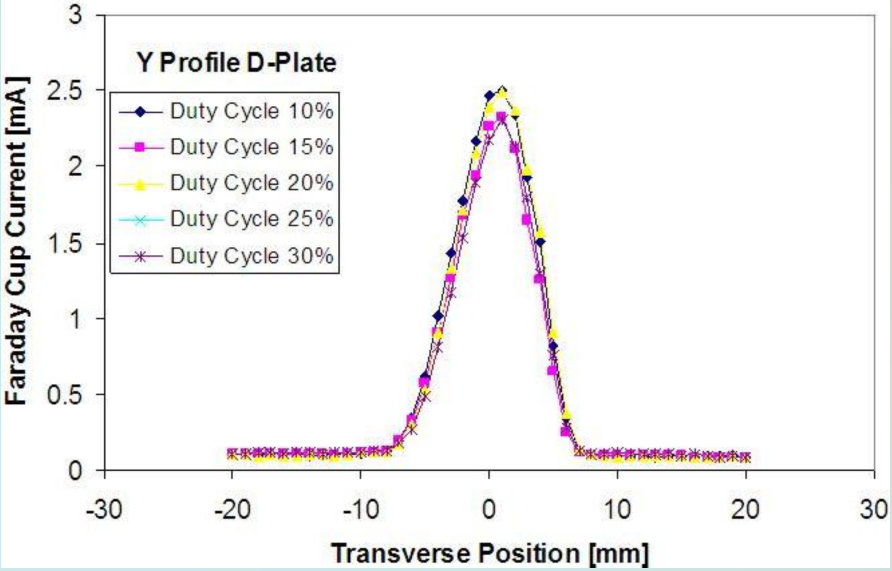
- Energy reaches its nominal value at lower power.
- D-Plate FC current and MEBT BPMs mark the nominal value
- Nominal deuteron power is **252-253 kW**, (including ~7 kW of beam loading)
- Higher than 4×58 = 232 kW
- Similarity of MEBT and D-Plate FC curves indicate that beam transmission is dominated by RFQ

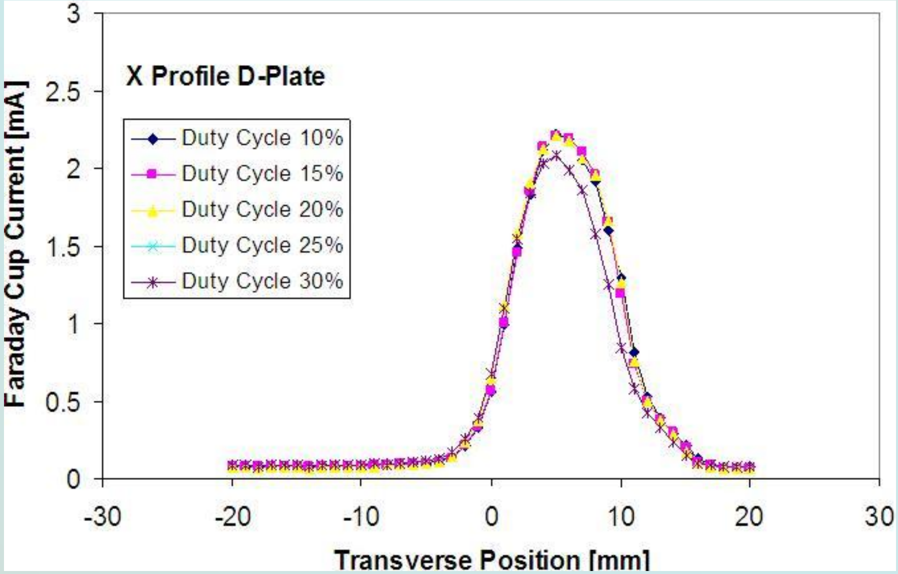




Deuteron beam – transverse alignment

- The Y profile was centered by adjusting the field in the quadrupole between the PSM and the D-Plate
- The X profile was less sensitive to this device
  - Beam entered that quadrupole off its axis in the Y plane
- The steerers down stream of the PSM were not used
- Up to DC = 30% In the RFQ power, there is hardly an effect on the beam profiles
  - No significant thermal movements of the rods in the average power range of **26** through **78 kW**.





Proton beam operation through PSM

- A proton beam was accelerated through the PSM with all 6 cavities in locked operation
  - Check stability of cavities and LLRF
  - Compare measurements to beam dynamics simulations

E_p [MeV]	3.7
Beam Duty Cycle [%]	0.01
I_p @ LEBT [mA]	5.0
I_p @ D-Plate [mA]	2.1
RFQ RF Duty Cycle [%]	100
PSM RF Duty Cycle [%]	100

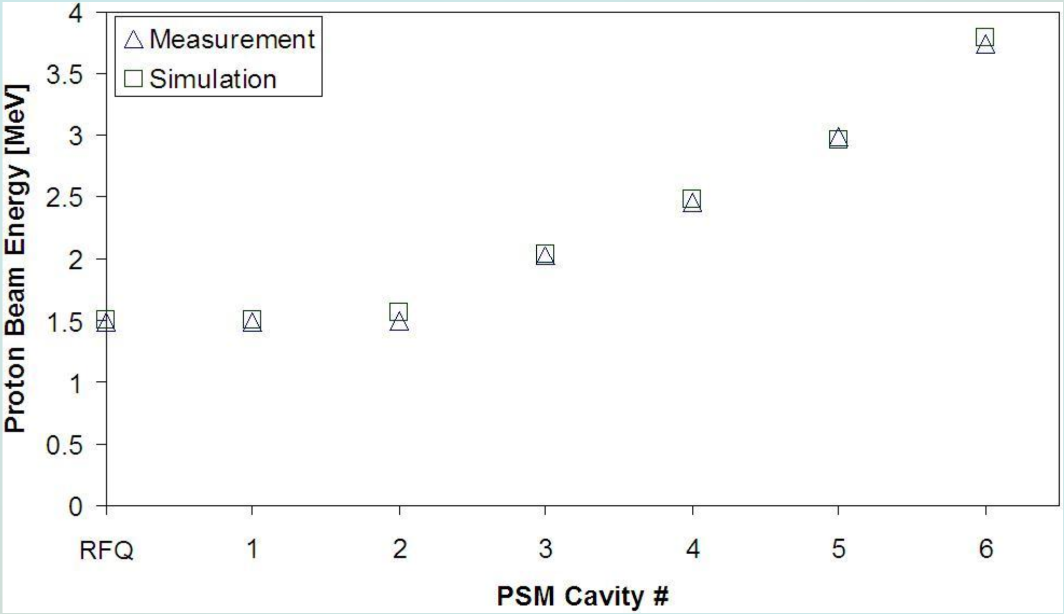
Transmission = 42%

Subsequent runs with lower LEBT current yielded higher transmission, up to 70%

Proton beam – fields, phases, beam energy

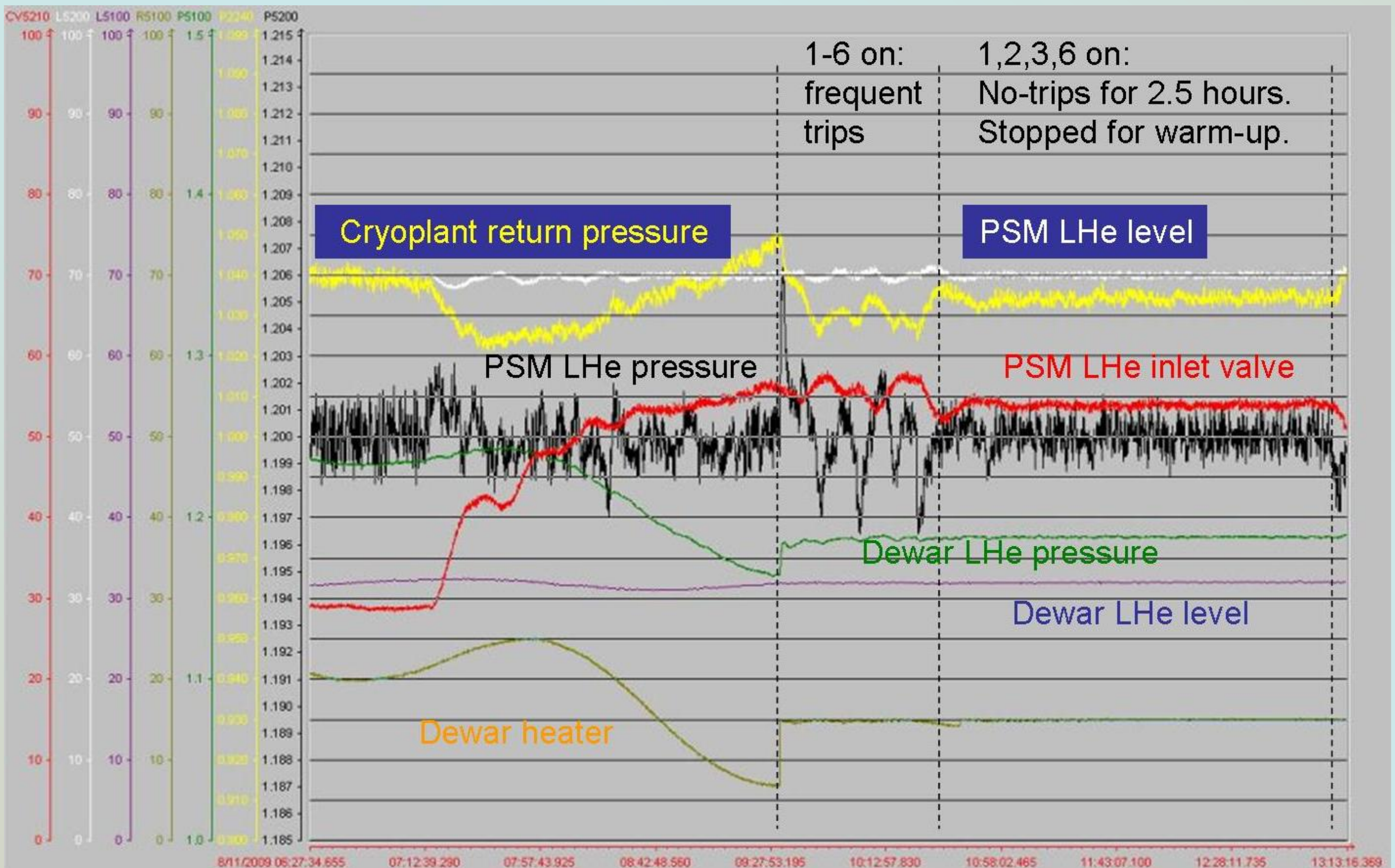
- Synchronous phase was found for each cavity by maximizing energy
- Fields, phases and magnet currents were set according to simulations
- The first cavity is used for bunching
- Energy was measured by ToF and compared to simulations

HWR	V_{acc} [kV]	E_{peak} [MV/m]	E_{acc} [MV/m]	Sync. Phase [deg]
1	150	4.5	0.9	-95
2	85	2.6	0.5	0
3	700	21.0	4.3	0
4	550	16.5	3.4	-20
5	550	16.5	3.4	-20
6	900	27.0	5.6	-20



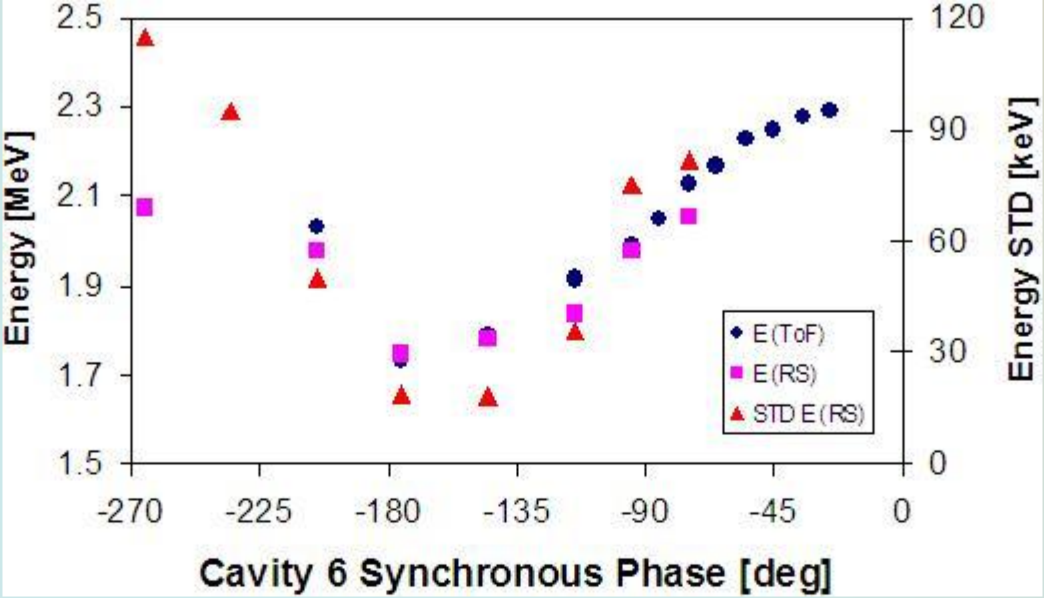
Proton beam – cavities and LLRF stability

- 6 cavity operation tripped every 15-20 minutes, mainly due to cavities 4 and 5
- Detuning 4 and 5 increased stability to many hours
- Observe correlation between cryoplant and cavities stability



Proton beam – Longitudinal emittance

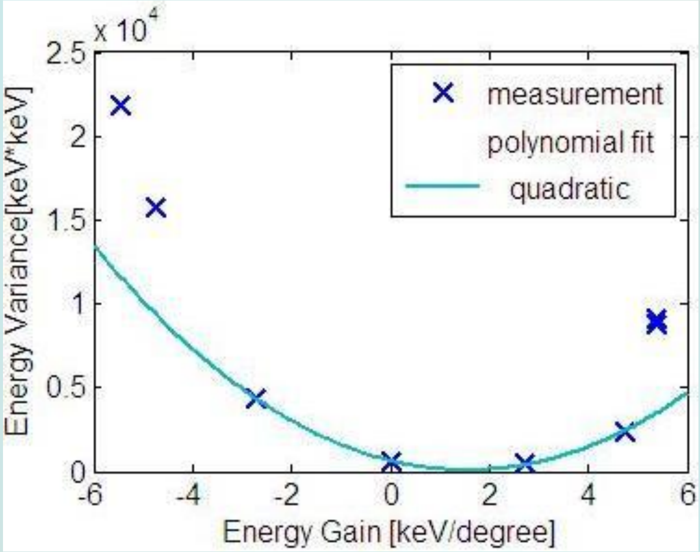
- ❖ HWRs 4 and 5 detuned. HWRs 1 – 3 in nominal value
- ❖ Measured energetic width using Rutherford scattering
- ❖ Varied HWR 6 phase and extracted beam matrix at HWR 3 exit



$$\begin{bmatrix} \sigma_{55x} & \sigma_{56x} \\ \sigma_{65x} & \sigma_{66x} \end{bmatrix} = R * \begin{bmatrix} \sigma_{55e} & \sigma_{56e} \\ \sigma_{65e} & \sigma_{66e} \end{bmatrix} R_T \;;\quad R = \begin{bmatrix} 1 & Y_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ X_1 & 1 \end{bmatrix} \begin{bmatrix} 1 & Y_1 \\ 0 & 1 \end{bmatrix}$$

$$\boxed{\sigma_{66x}(X_1) = (\sigma_{55e} + 2Y_1\sigma_{56e} + Y_1^2\sigma_{66e})X_1^2 + 2(\sigma_{56e} + Y_1\sigma_{66e})X_1 + \sigma_{66e}}$$

X_1 = Energy gain per degree



- **Longitudinal emittance extracted from polynomial fit parameters**
- **Non polynomial behavior indicates <u>non linear operation region</u>**

ε_z = 120 ± 5 π·deg·keV/u (30 at RFQ exit in 2008)

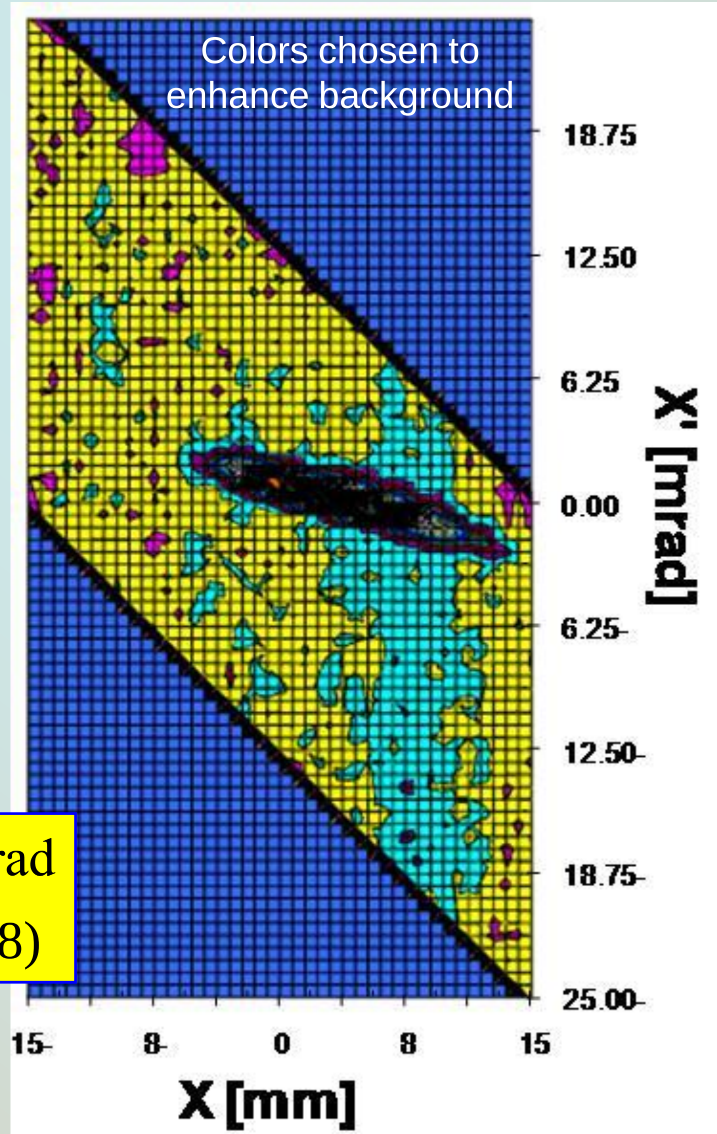
Proton beam - Transversal emittance

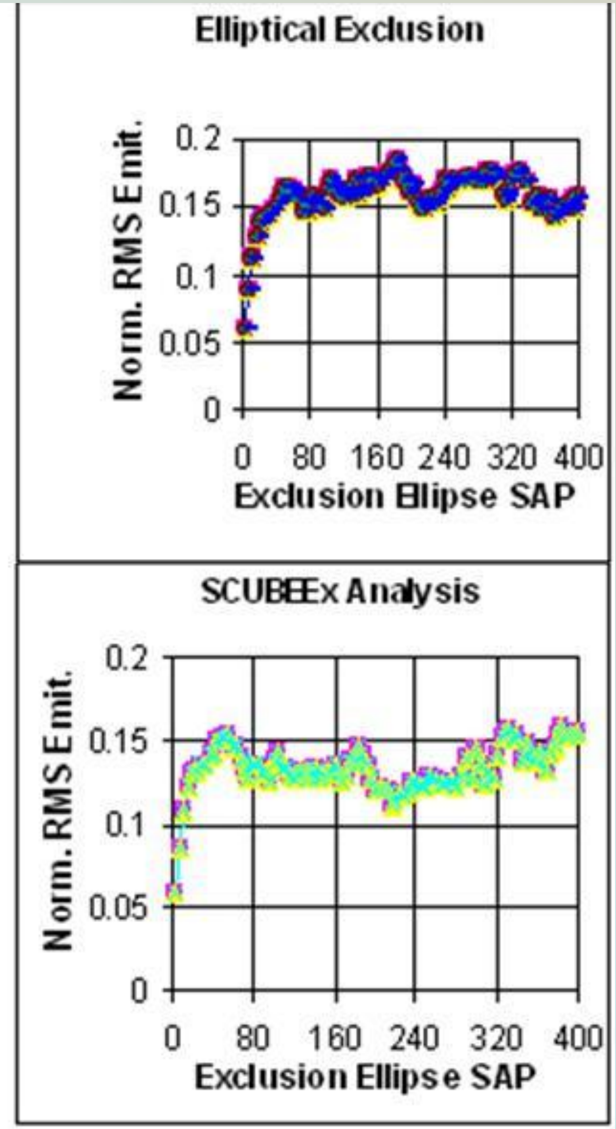
- Cavities 4-6 detuned
- Measurements with D-Plate slit-wire system
- X-X' plot and emittance values generated by SCUBEEx and internal Soreq algorithm
- Beam ellipse and satellite distribution recognized
- Emittance value extraction excluded the effect of the satellite distribution

$\varepsilon_t = 0.14 \pm 0.02\ \pi\cdot\text{mm}\cdot\text{mrad}$

(0.30 at RFQ exit in 2008)

Low RFQ transmission might be cutting off phase space





Summary and Outlook

- 2.7 and 2.1 mA deuteron and proton beams (DC = 10^{-4}) have been accelerated through the RFQ and PSM up to energies of 3.0 and 3.7 MeV
- RFQ Transmission is low
  - **Probable causes**: high LEBT emittance, LEBT-RFQ mis-alignment, non-uniform RFQ field
- Longitudinal emittance is high
  - **Probable causes**: choice of non-linear conditions, non-uniform RFQ field
- Transversal emittance is low
  - **Probable cause**: Low transmission cuts off part of the beam's phase space
- Proton and Deuteron beam commissioning continuing
- RFQ conditioning with new internal parts is ongoing
- Continuation to Phase II is foreseen for the beginning of 2010