The SARAF CW 40 MeV Proton/Deuteron Accelerator

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Accel Instruments, Bergisch Gladbach, Germany

LINAC08, MO203, September 29th, 2008

SARAF – Soreq Applied Research Accelerator Facility

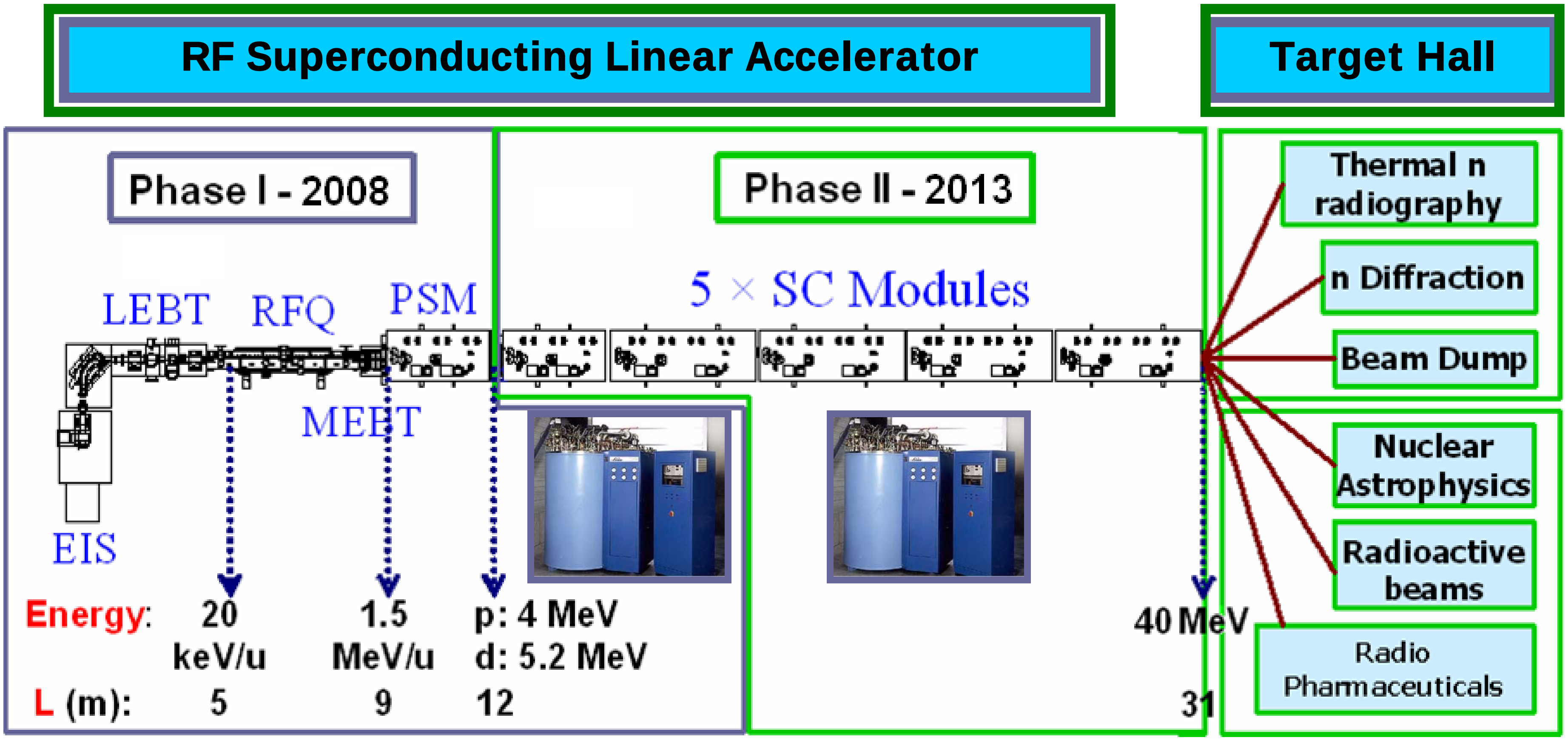
- To modernize the source of neutrons at Soreq and extend neutron based research and applications.
- To develop and produce radioisotopes primarily for bio-medical applications.
- To enlarge the experimental nuclear science infrastructure and promote the research in Israel.

Accelerator Basic Characteristics

A RF Superconducting Linear Accelerator

Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	
Current Range	0.04 – 2 mA	Upgradeable to 4 mA
Operation mode	CW and Pulsed	PW: 0.1-1 ms; rep. rate: 0.1-1000 Hz
Operation	6000 hours/year	
Reliability	90%	
Maintenance	Hands-On	beam loss < 1 nA/m

SARAF Layout



A. Nagler et al., LINAC 2006

SARAF project organization

Construction and Commissioning of a **(Beyond-)State-of-the-Art accelerator** within an **international business collaboration**

- Accelerator – Accel Instruments (Germany)
- Cryogenics – Linde Kryotechnik (Switzerland)
- Building and Infrastructure – U. Doron (Israel)
- Applications - Soreq

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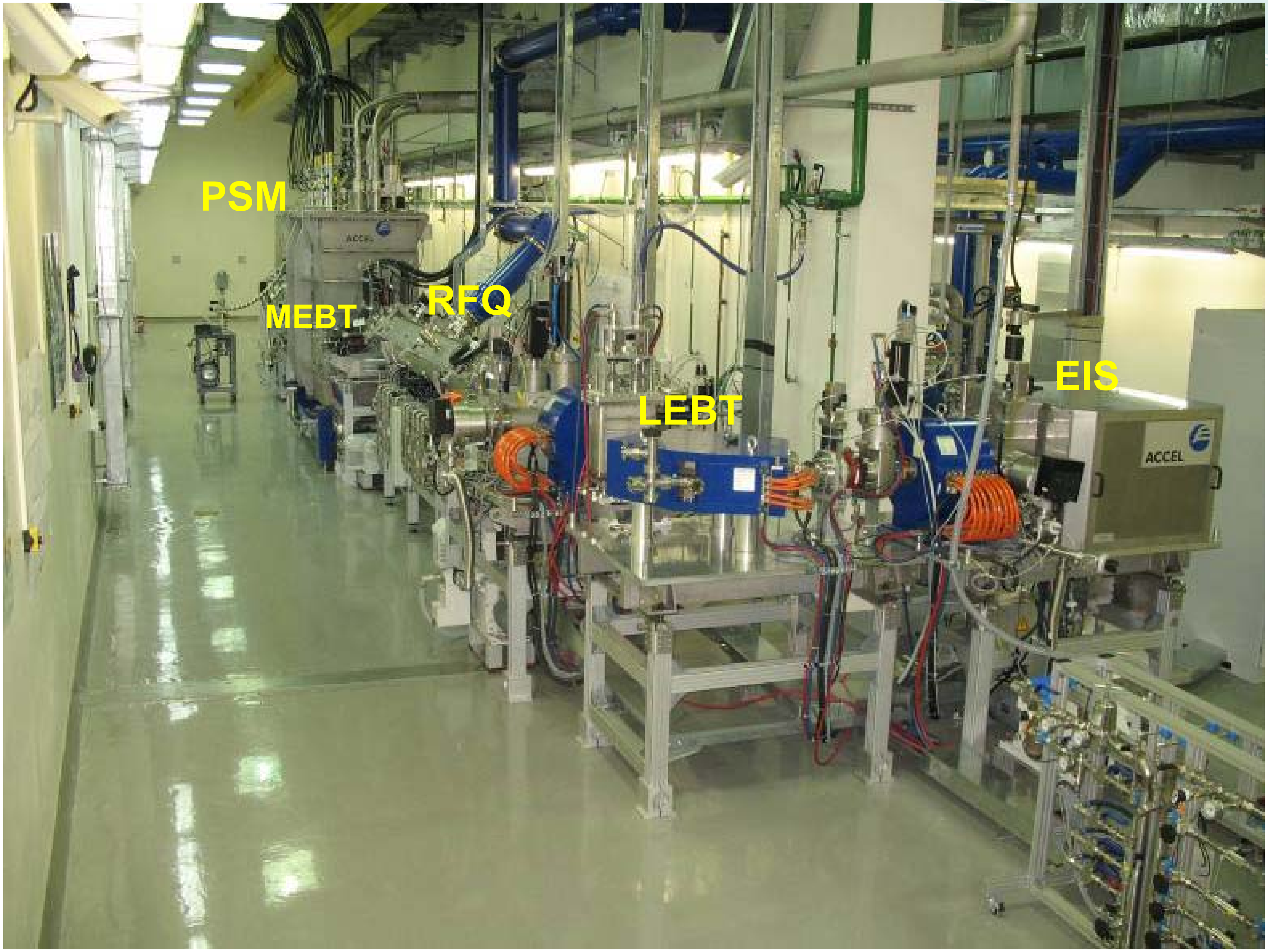
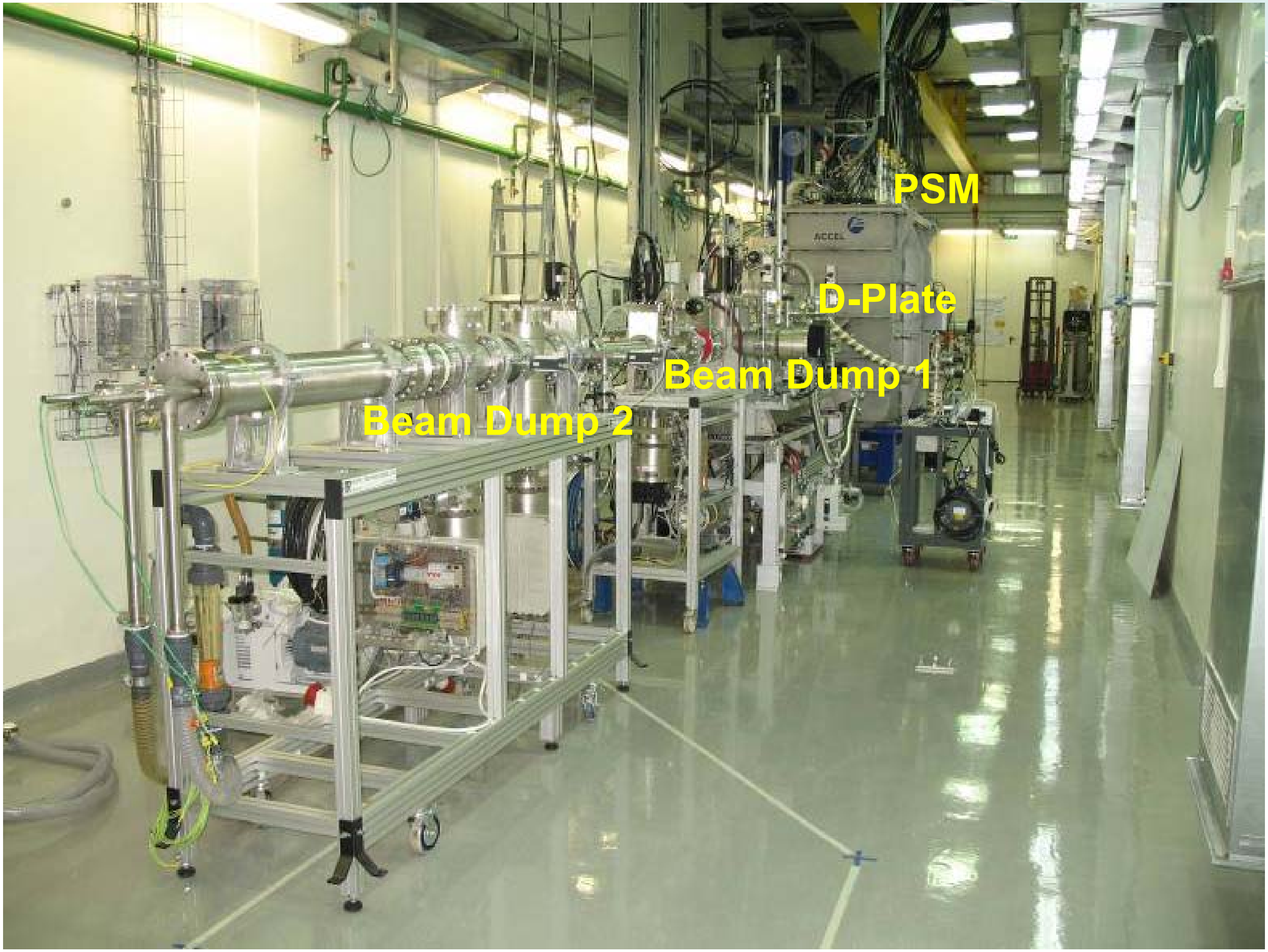
Overall Integration – Soreq

SARAF Phase I – Upstream View



SARAF Phase I – Downstream View

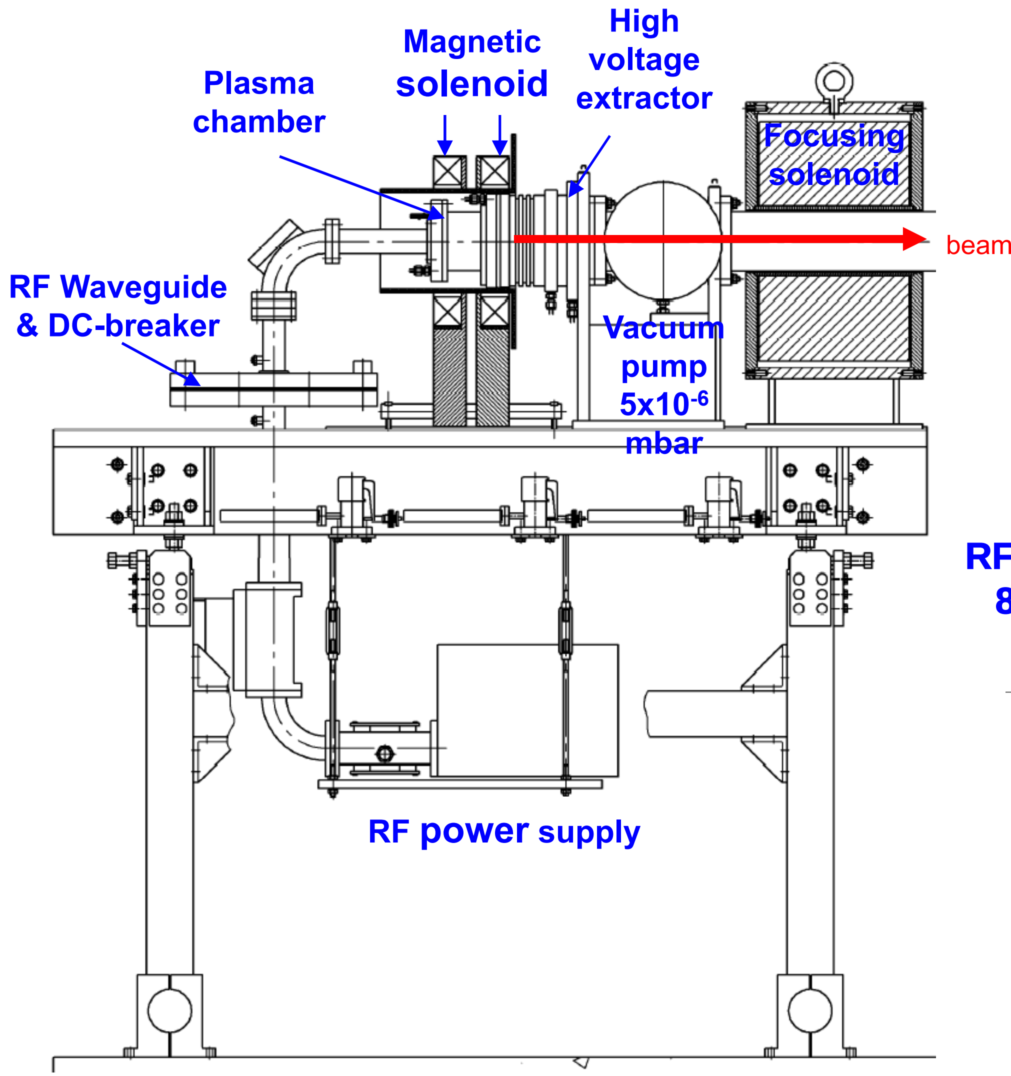


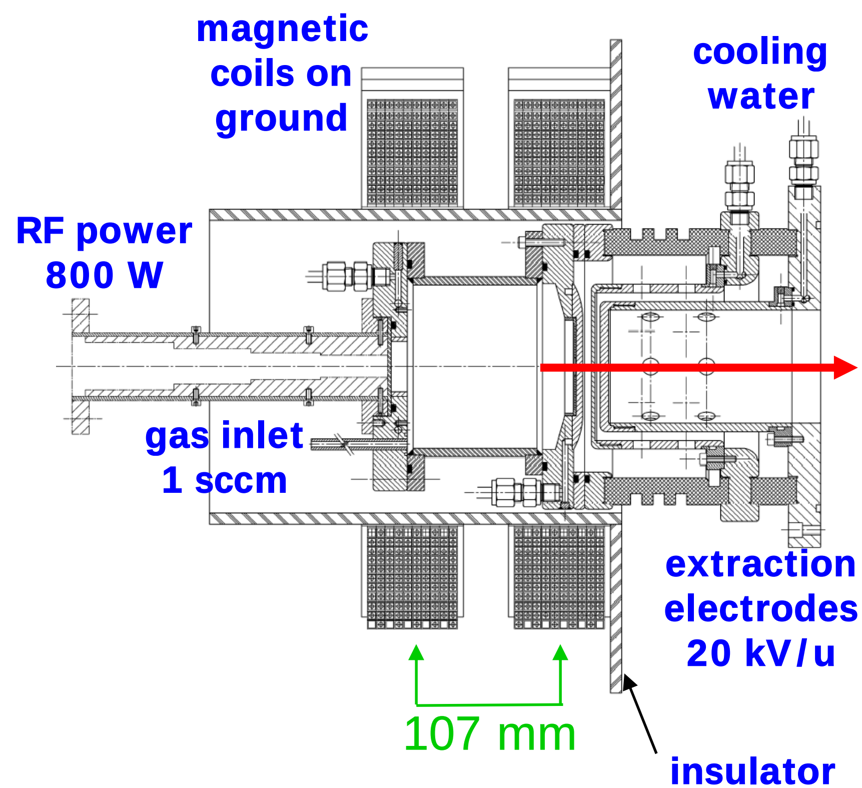
ECR Ion Source (ECRIS)

C. Piel EPAC 2006

F. Kremer ICIS 2007

K. Dunkel PAC 2007





LEBT – emittance measurement

C. Piel EPAC 2006

F. Kremer ICIS 2007

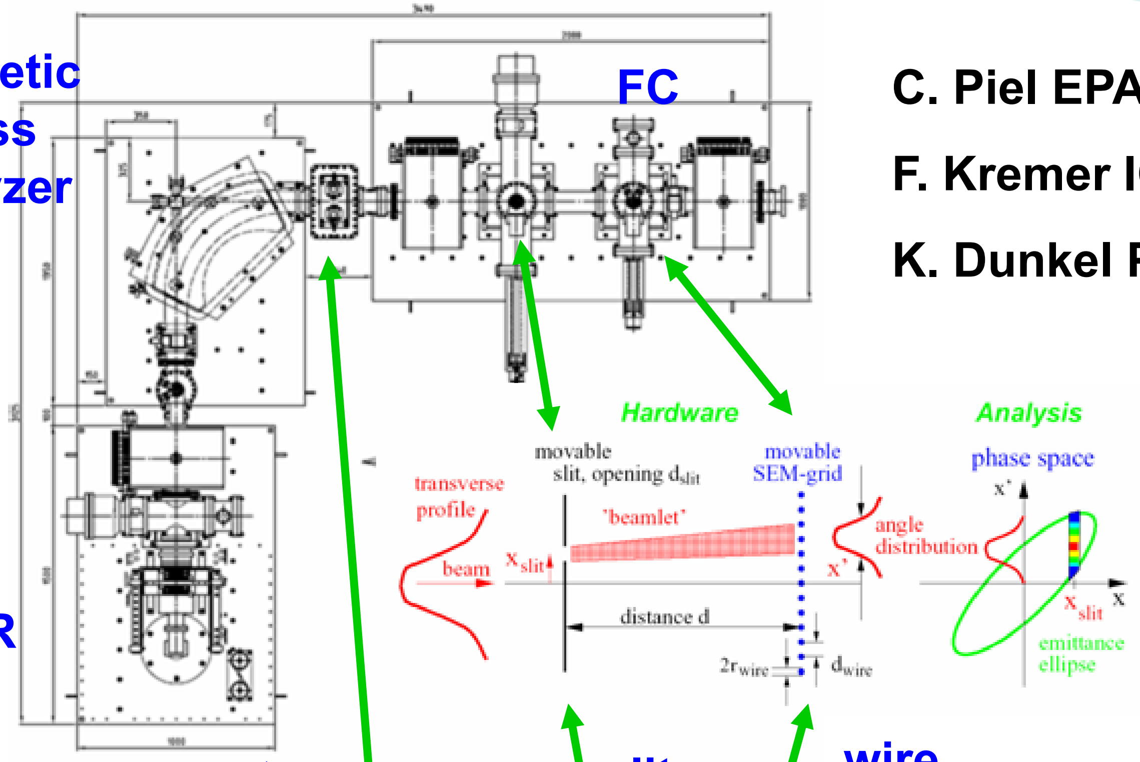
K. Dunkel PAC 2007

magnetic mass analyzer

FC

aperture

ECR

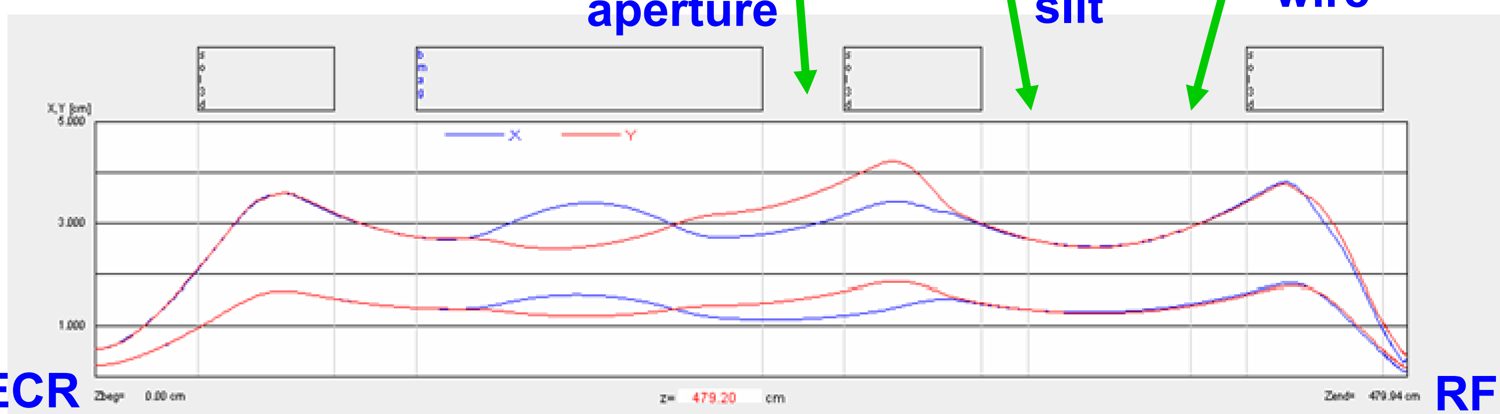


P. Forck JUAS 2003

aperture

slit

wire



5 mA proton beam optics

ECR

RFQ entrance

EIS: measured emittance values

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

Particles Beam current	Protons X / Y	H_2^+ X / Y	Deuterons X / Y
5.0 mA	0.20 / 0.17	0.34 / 0.36	0.13 / 0.12
2.0 mA	0.13 / 0.13	0.30 / 0.34	0.14 / 0.13
0.04 mA	0.18 / 0.19		0.05 / 0.05

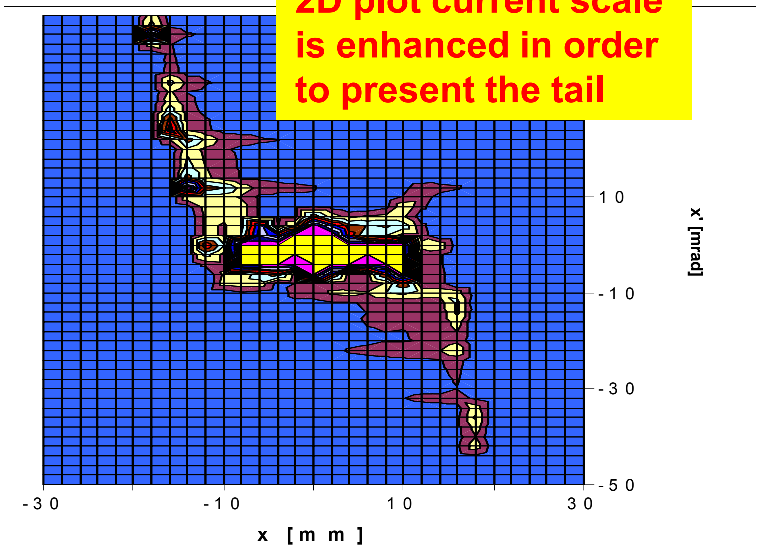
Specified value = 0.2 / 0.2 [π mm mrad]

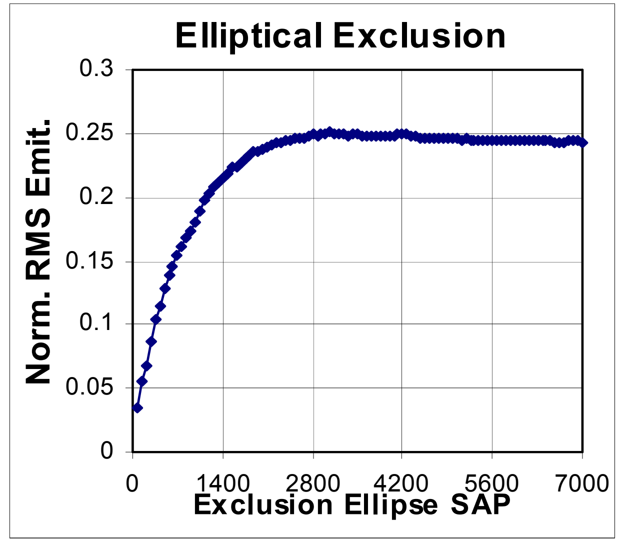
deuterons emittance results

SOREQ

π mm mrad

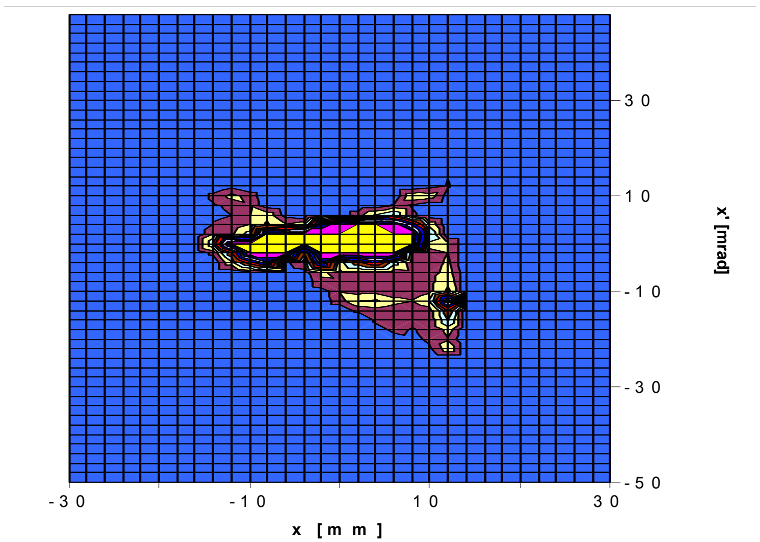
2D plot current scale is enhanced in order to present the tail

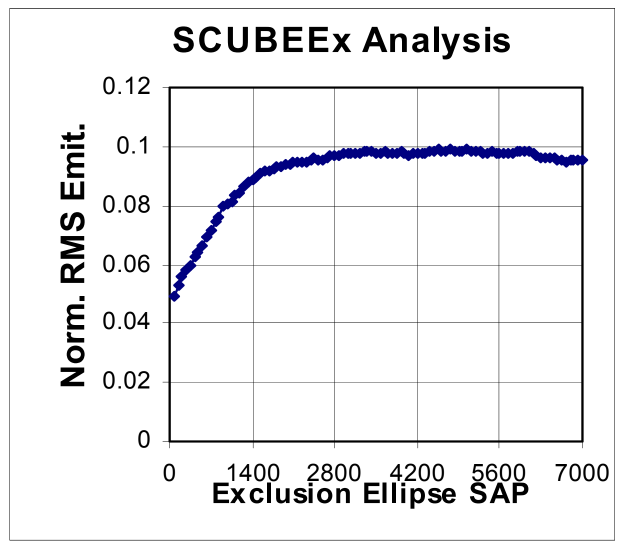




deuterons

6.1 mA open aperture



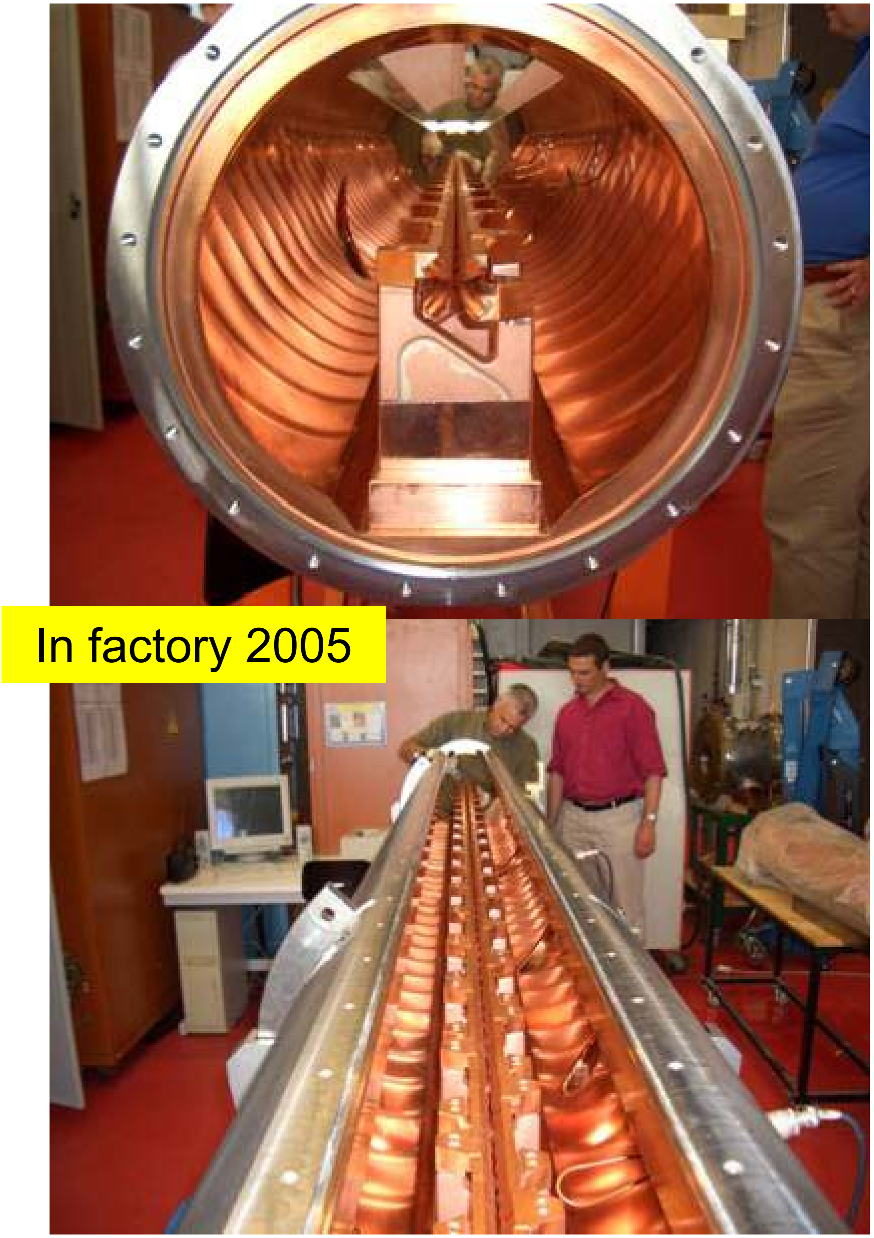


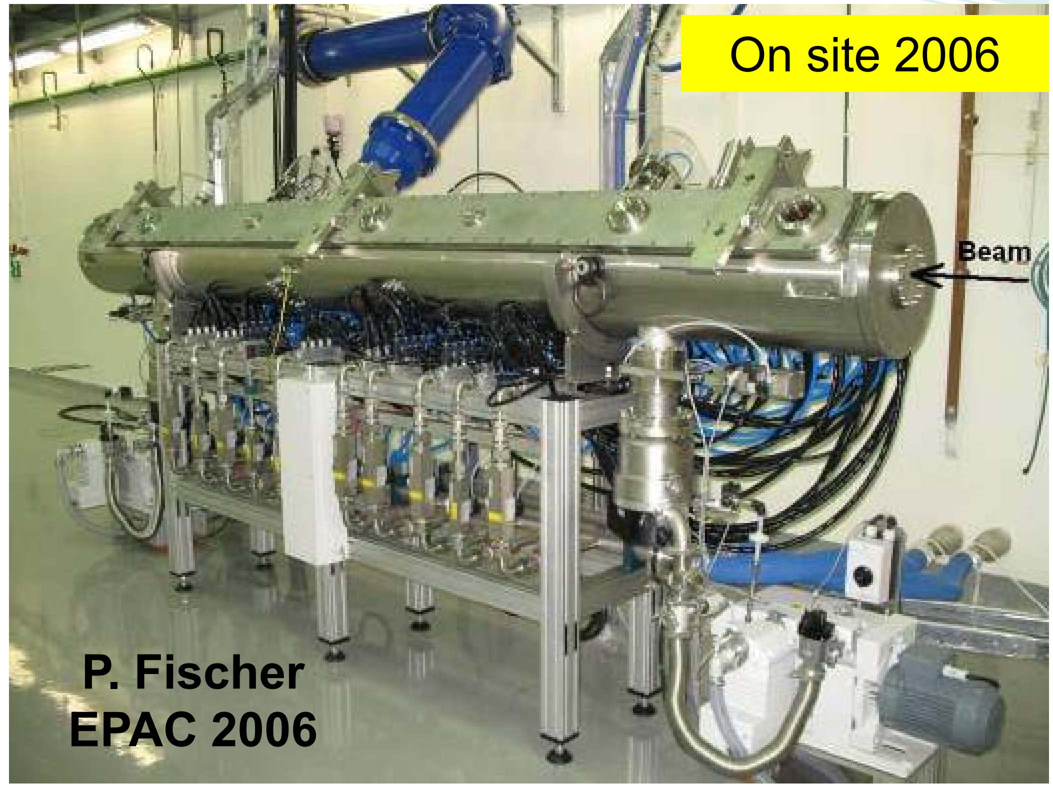
B. Bazak JINST 2008

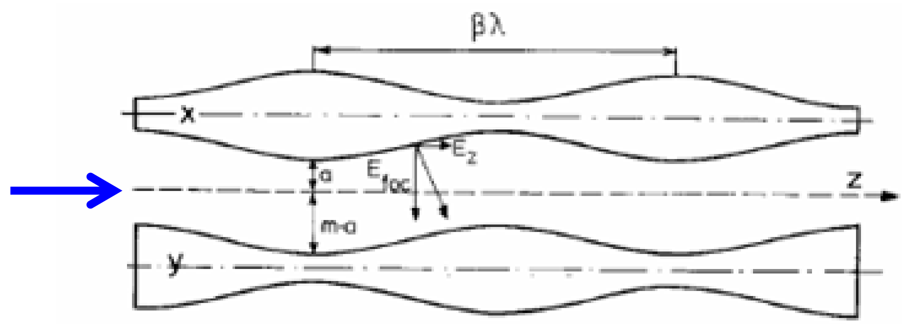
aperture cut to 5.0 mA

emittance analysis with the SCUBEEx code by M. P. Stockli and R.F. Welton, Rev. Sci. Instr. 75 (2004) 1646

176 MHz Radio Frequency Quadrupole





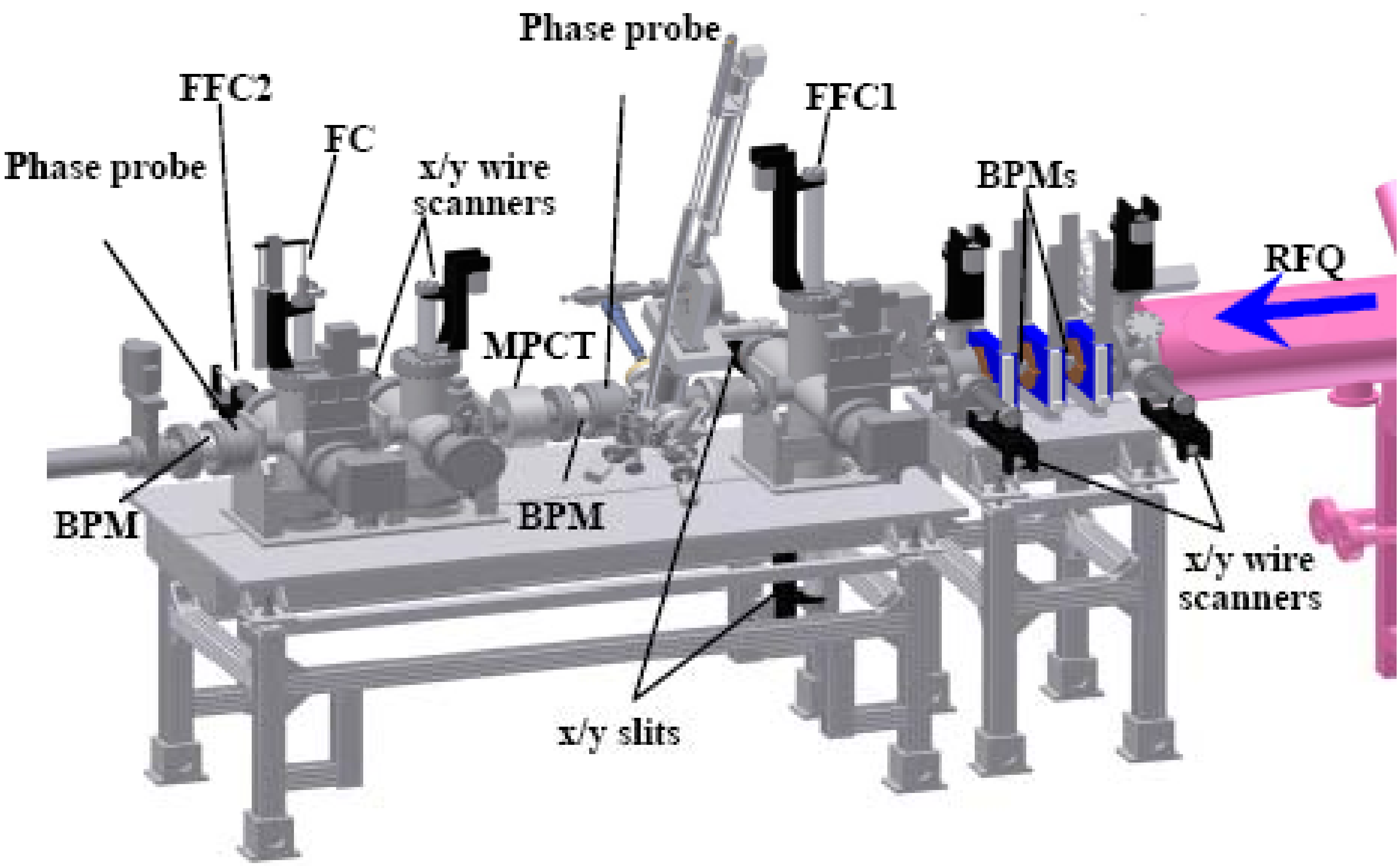


RFQ commissioning results

Specifications in parentheses

Parameter	Protons
Output energy **[MeV/u]**	1.5 **(1.5)**
Maximal CW current **[mA]**	4.0 **(4.0)**
Transverse emittance, r.m.s., normalized, 100% **[π·mm·mrad]**	
(at 0.5 mA, closed LEBT aperture)	0.17 **(0.30)**
(at 4.0 mA, open LEBT aperture)	0.25 / 0.29 **(0.30)**
Longitudinal emittance, r.m.s **[π·keV·deg/u]** (at 3.0 mA)	30 **(120)**
Transmission **[%]** (at 0.5 mA)	80 **(90)**
(at 2.0 mA)	70 **(90)**
(at 4.0 mA)	65 **(90)**
Required RF power (protons) **[kW]**	62 **(55)**
(deuterons) **[kW]**	248 **(220)**

Diagnostic plate (D-Plate) for beam commissioning

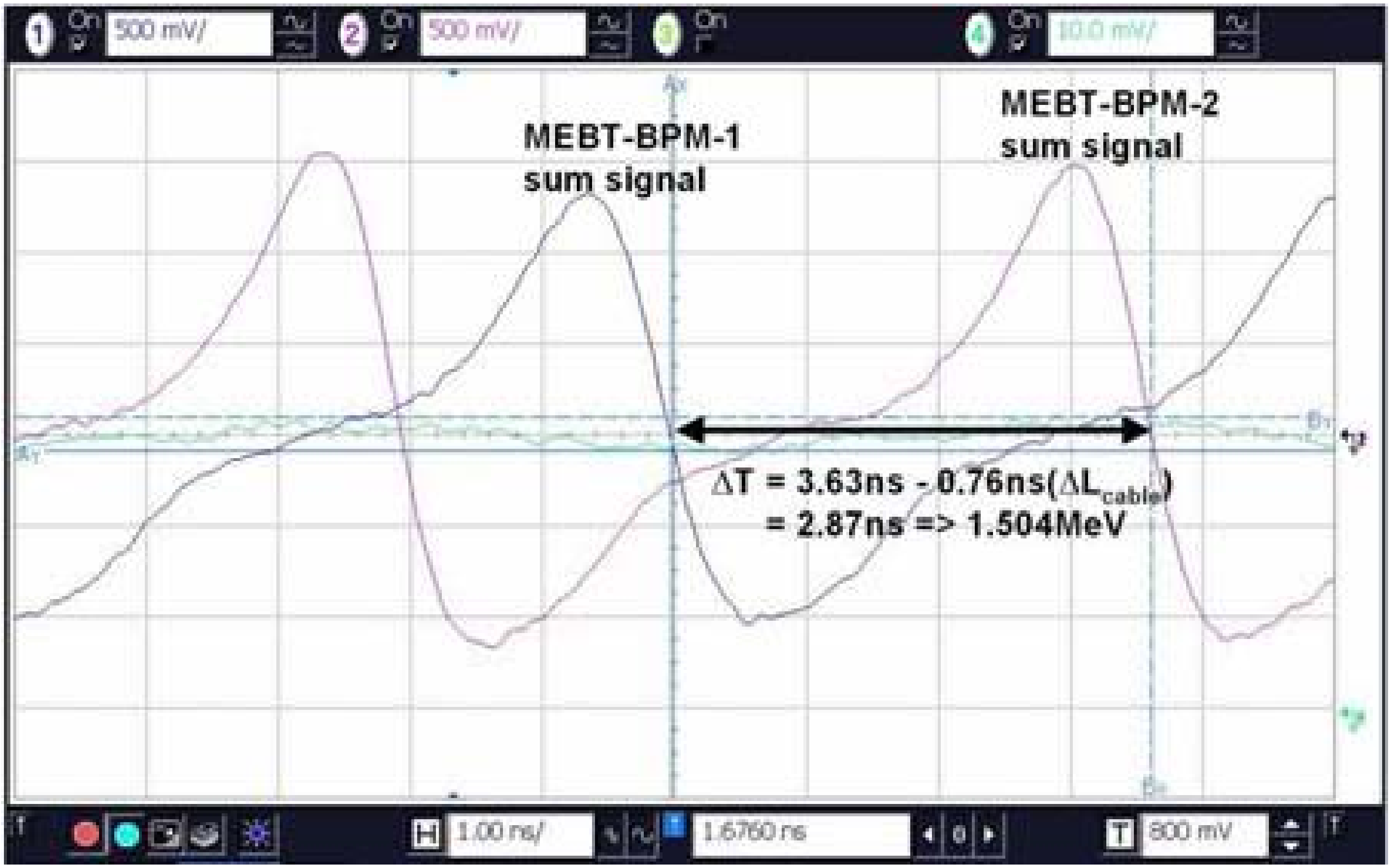


Proton energy at RFQ exit by TOF

Beam Energy Measurement using TOF between 2 BPMs sum signals, 145 mm apart,

E = 1.504 ± 0.012 MeV

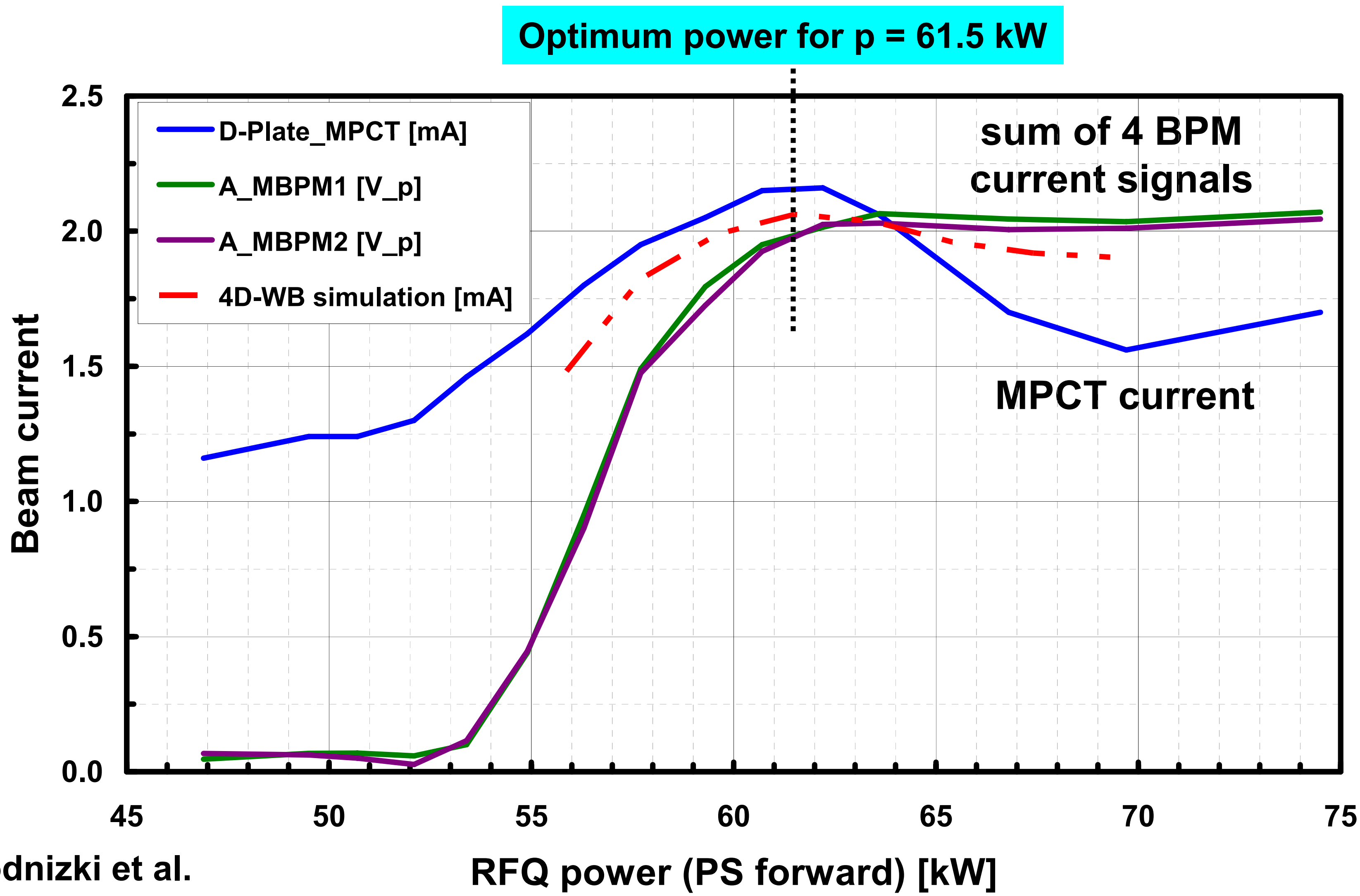
C. Piel PAC 2007



Button pickup for 2 mA pulse and 15 mm bore radius gives a signal high above noise.

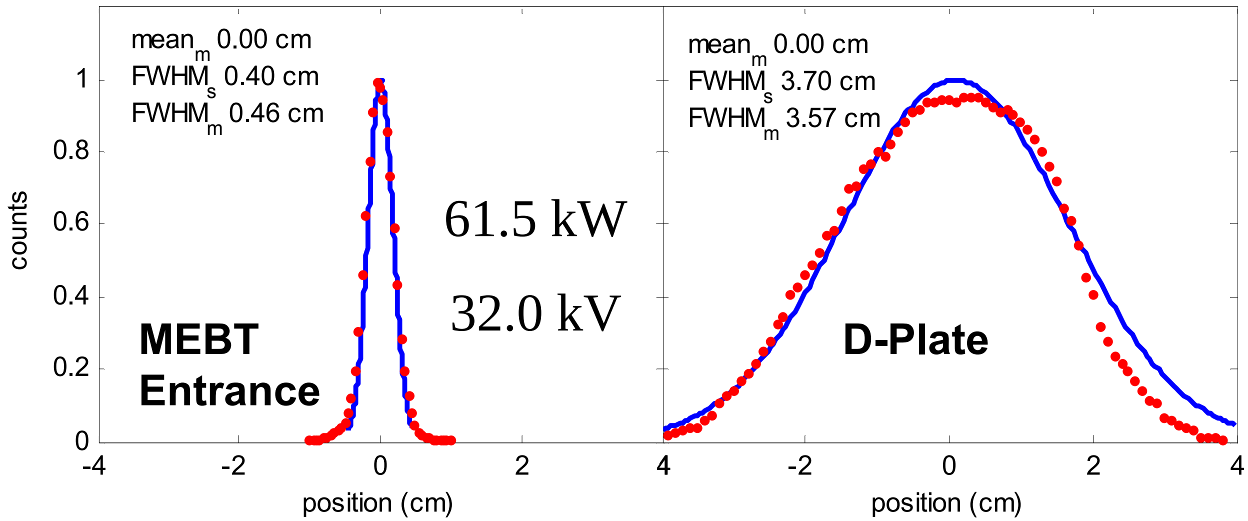
Bunch width measured at β=0.056 is larger than the predicted value due to the induced charge broadening.

Current downstream RFQ vs. RFQ forward power for 3 mA injection



J. Rodnizki et al.
EPAC 2008

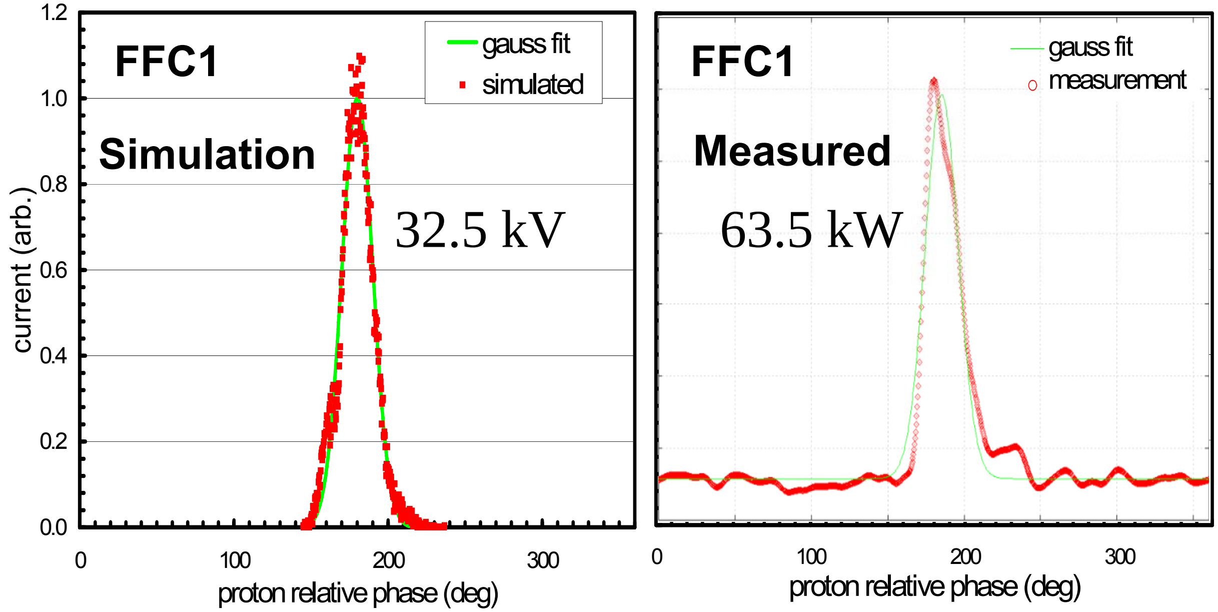
RFQ: Bunch profiles measurements



Wire scan profiles

C. Piel PAC 2007

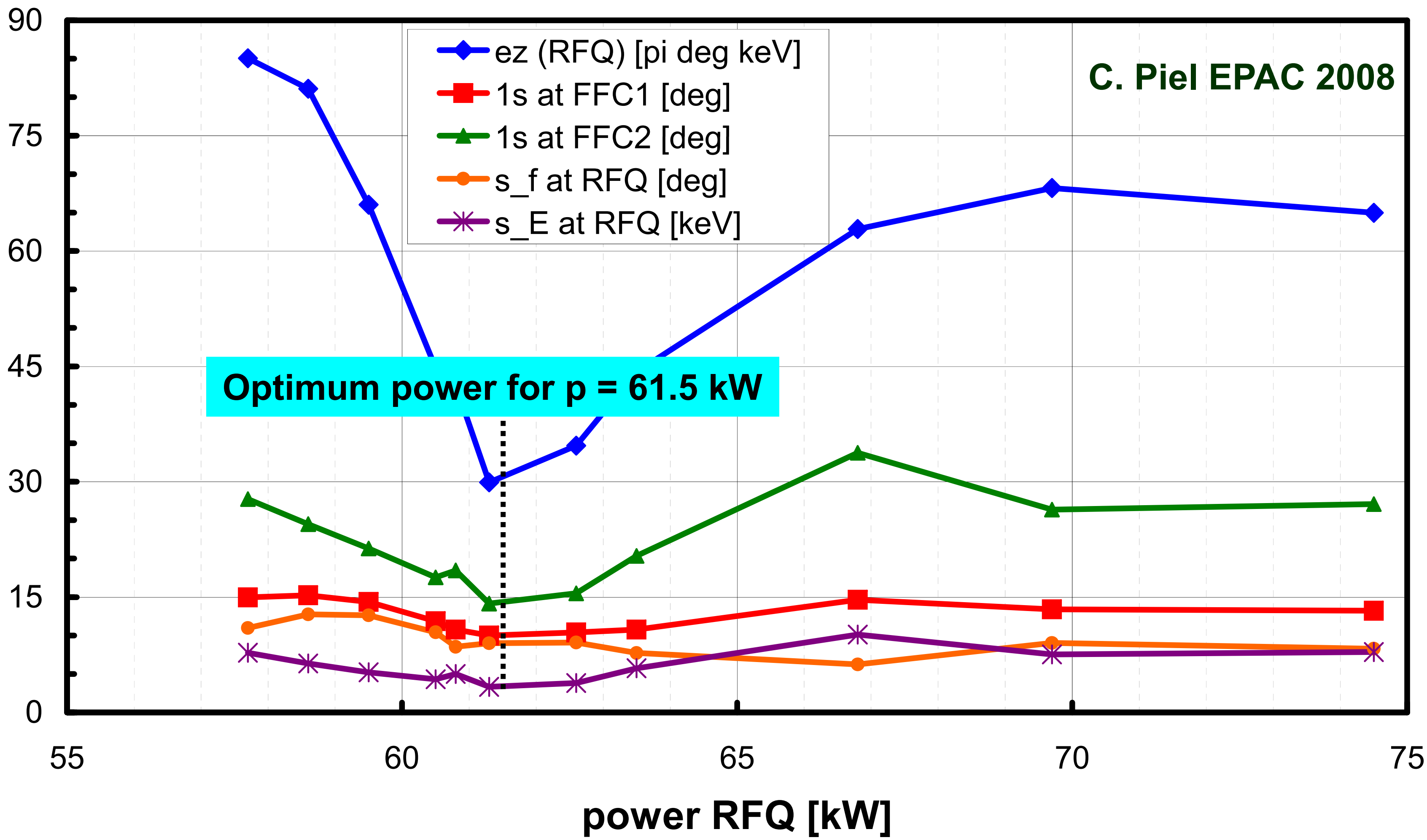
Measurement results are backed up by simulations (TRACK)



FFC time profiles

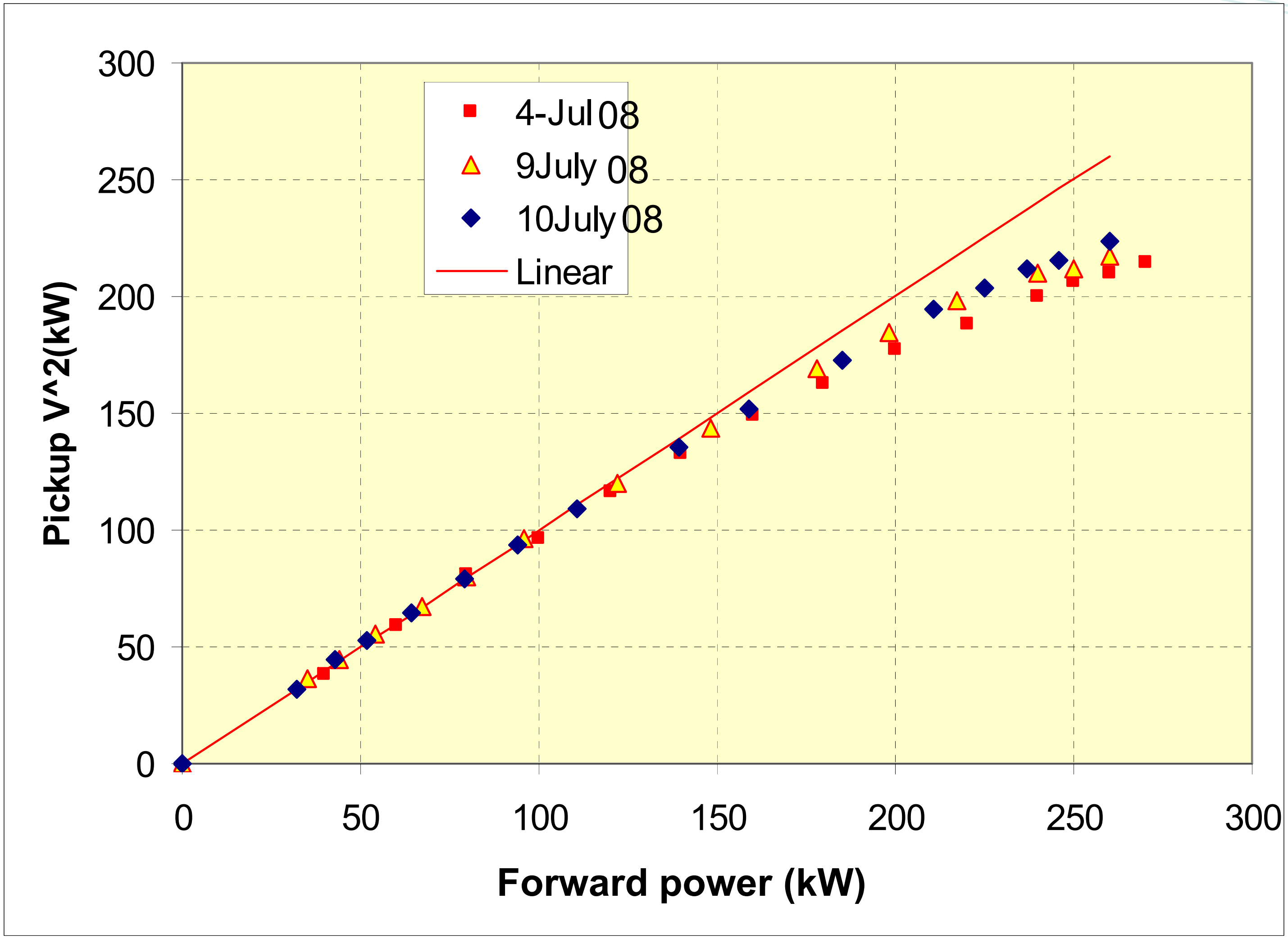
Rodnizki et al.
EPAC 2008

Approximated rms ε_Z extracted from bunch width measurements



Specified rms ε_Z = 120 π deg keV Value for simulations = 74 π deg keV

RFQ voltage squared vs. forward power



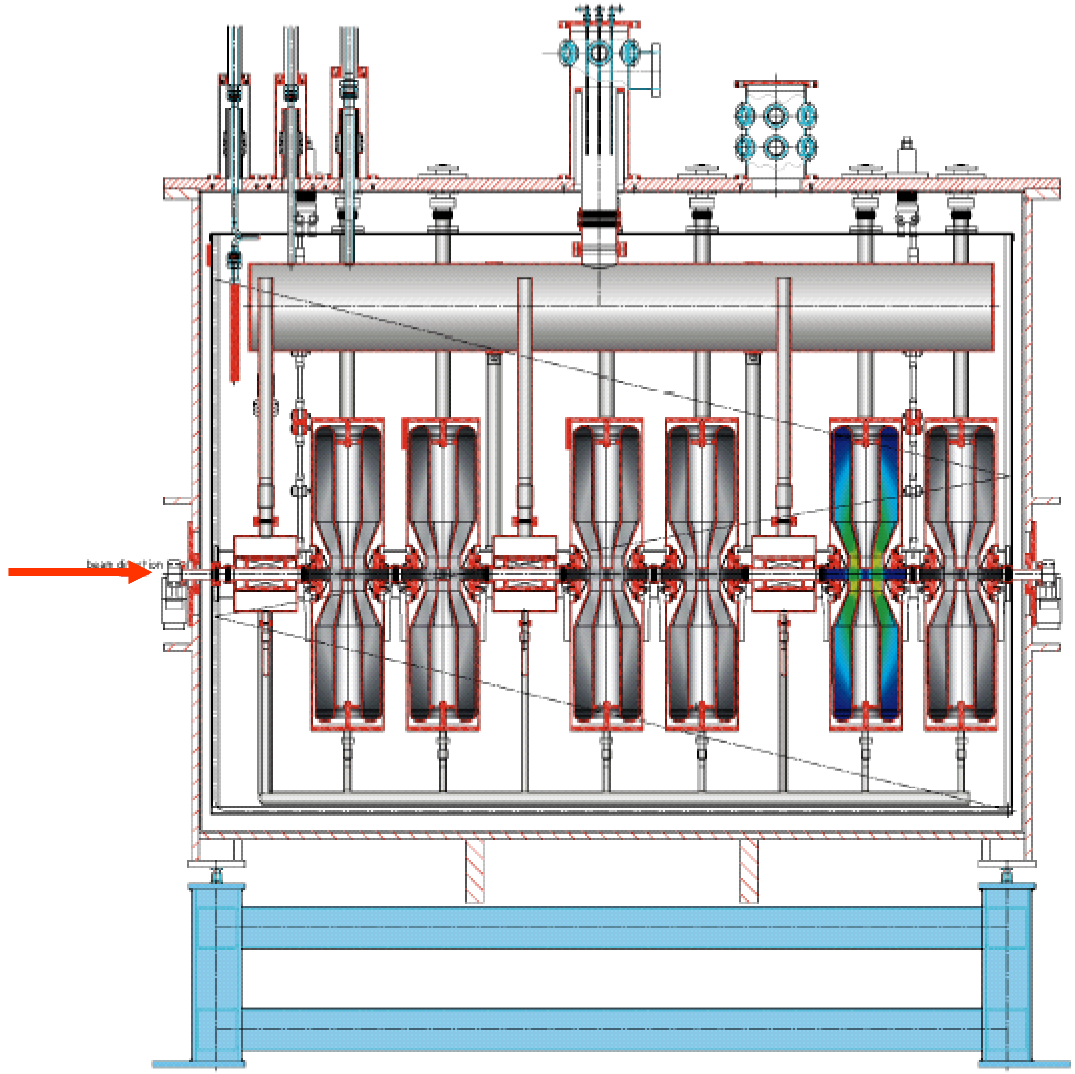
Parting from the linear relation indicates onset of dark current due to poor conditioning

RFQ Conditioning – current status

- A few hundred conditioning hours for two years
- Conditioning schemes
  - Set maximum power and increase duty cycle
  - Set CW duty cycle and increase power
- Special actions to improve conditioning rate:
  - Rounding off sharp edges of rods bottom part
  - Cleaning of rods
  - Installation of circuit for fast recovery after sparks
- Maximal power reached so far:
  - **195 kW CW**
  - **280 kW** with duty cycle of **15%**

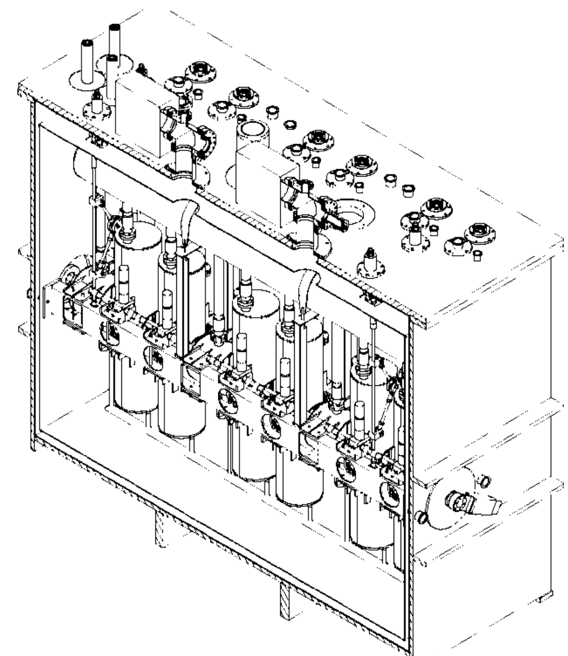
75°C baking performed recently for 3 days. Effect on conditioning tp be measured soon

Prototype SC Module (PSM)



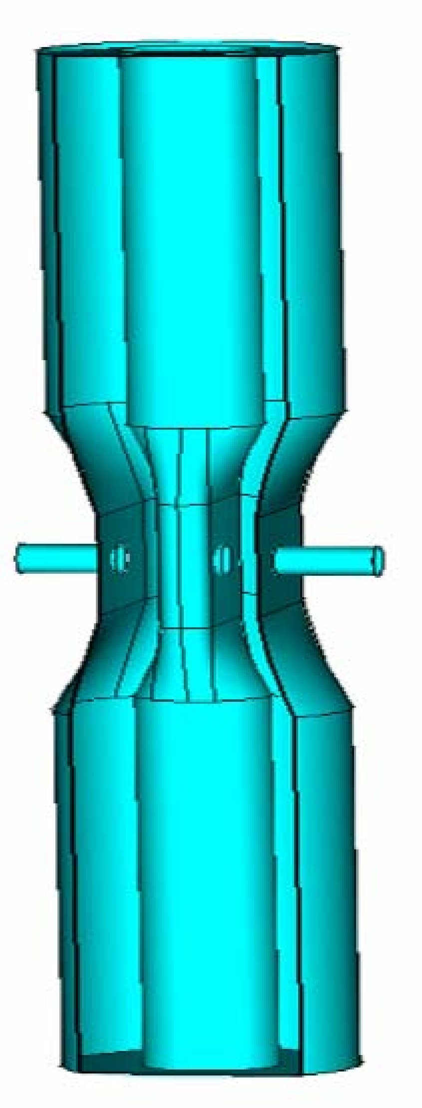
General Design:

- **Houses 6 HWR and 3 superconducting solenoids**
- **Accelerates protons and deuterons from 1.5 MeV/u on**
- **Very compact design in longitudinal direction**
- **Cavity vacuum and insulation vacuum separated**



M. Peiniger, LINAC 2004 M. Pekeler, SRF 2003 M. Pekeler, LINAC 2006

HWR – Basic parameters



- f = 176 MHz & bandwidth ~ 130 Hz
- height ~ 85 cm high
- Optimized for
  β=0.09 @ first 12 cavities (2 modules)
  β=0.15 @ 32 cavities (4 modules)
- Bulk Nb 3 mm @ 4.45 K
- $E_{peak, max}$ = 25 MV/m & E_{peak} / E_{acc} ~ 2.5
- $Q_0 \sim 10^9$
- Designed cryogenic Load < 10 W (@E_{max})

HWR measured fields and dissipated power

Closed loop operation with a voltage controlled oscillator (VCO)

At Accel (single cavity) | **At Soreq (inside PSM)**

Cavity		vertical Test			max field	limit	Q at	Q at	losses at	losses at
location	name	max field	losses at	Q at			20 MV/m	25 MV/m	20 MV/m	25 MV/m
		[MV/m]	25 MV/m	25 MV/m	[MV/m]				[W]	[W]
			[W]							
HWR1	**LB-2**	40	7,3	6,0E+08	30		8,0E+08	7,0E+08	3,5	6,3
HWR2	**LB-3**	43	7,3	6,0E+08	28	coupler temp.	2,0E+08	1,4E+08	14,1	31,4
HWR3	**LB-5**	33	6,3	7,0E+08	32		4,0E+08	2,0E+08	7,0	22,0
HWR4	**LB-7**	46	6,3	7,0E+08	29		4,0E+08	2,0E+08	7,0	22,0
HWR5	**LB-4**	36	5,5	8,0E+08	31		7,0E+08	4,0E+08	4,0	11,0
HWR6	**LB-6**	38	7,3	6,0E+08	29	coupler temp.	7,0E+08	3,0E+08	4,0	14,7
		sum	40,0					Σ	39,7	107,3
Target values		**25**		**4.7E+08**	**25**			**4.7E+08**		**72**

C. Piel *et al.* EPAC 2008

Phase and amplitude stability results

SARAF LLRF:

Generator driven resonator (GDR) cavity tuning loop

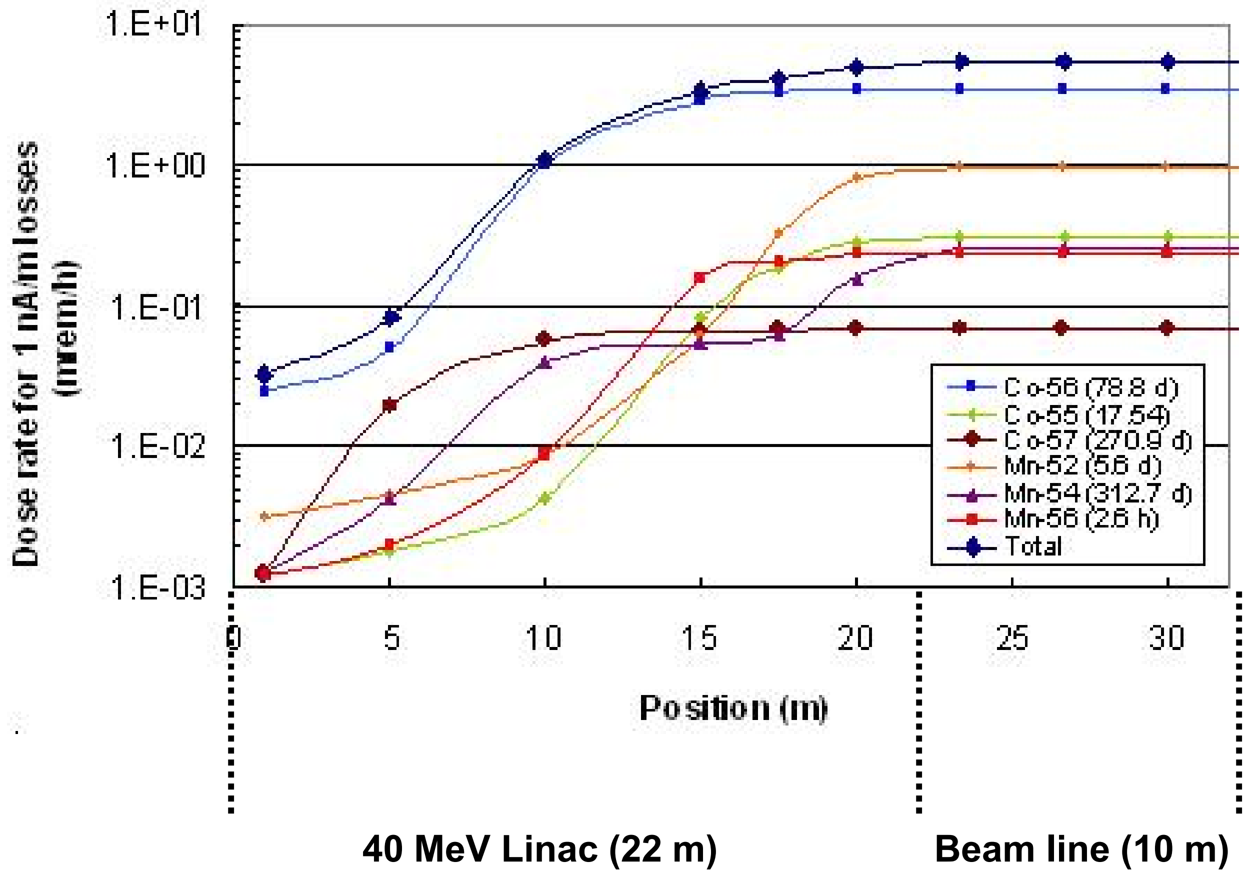
Cavity	Vcav, MV	Epeak, MV/m	Phase Stab.,°	Ampl. Stab., %
HWR 1	0.8	23.5	±0.3	0.5
HWR 2	0.7	20.6	±0.3	0.5
HWR 3	1.0	29.5	±0.3	0.5
HWR 4	0.9	26.5	±0.3	0.5
HWR 5	1.14	33.5	±0.2	0.5
HWR 6	1.03	30.3	±0.3	0.3

- **Above results are for operation of one cavity at a time**
- **Stability measurement period was a few minutes for each cavity**
- **Stability values are peak-to-peak and are limited by ADC least significant bit**

Recent commissioning: simultaneous operation of 6 HWRs at ~20 MV/m for several hours

Residual activation from beam loss

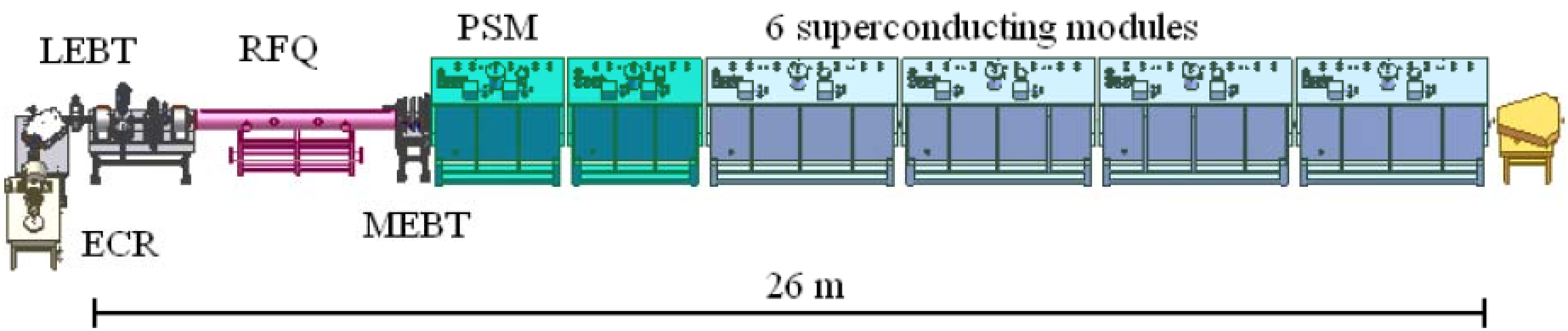
- A beam loss value of **0.4 nA/m** at 40 MeV generates **2 mRem/hr** after a 1 year irradiation



Conditions

- 30 cm from beam line
- 4 hours after shutdown
- Effects of 40 MeV applied for entire linac
- Accelerator is operating 365 days per year (~65%)
- Run deuterons at 40 MeV all the time (25-50%)
- Accelerator made entirely of stainless steel (~50% Nb)

SARAF Phase II simulations with error analysis



Simulations shown in next slides:

- 4 mA deuterons at RFQ entrance.
- Last macro-particle=1 nA

B. Bazak *et al.*, Submitted for Publication
J. Rodnizki *et al.*, HB2008

Component	Error	Static	Dyn.
Quadrupole Magnets	Misalignment x,y,z [mm]	± 0.2	
	Rotation θ [mrad]	± 3	
	Magnetic field [%]	± 2	0.5
Solenoids	Misalignment x,y,z [mm]	± 0.2	
	Magnetic field [%]	± 2	0.5
HWR	Misalignment x,y,z [mm]	± 0.4	
	Rotation θ [mrad]	± 6	
	Field strength [%]	± 2	0.5
	Phase [degree]	± 1	0.25

Errors are double than in: J. Rodnizki *et al.* LINAC 2006, M. Pekeler HPSL 2005

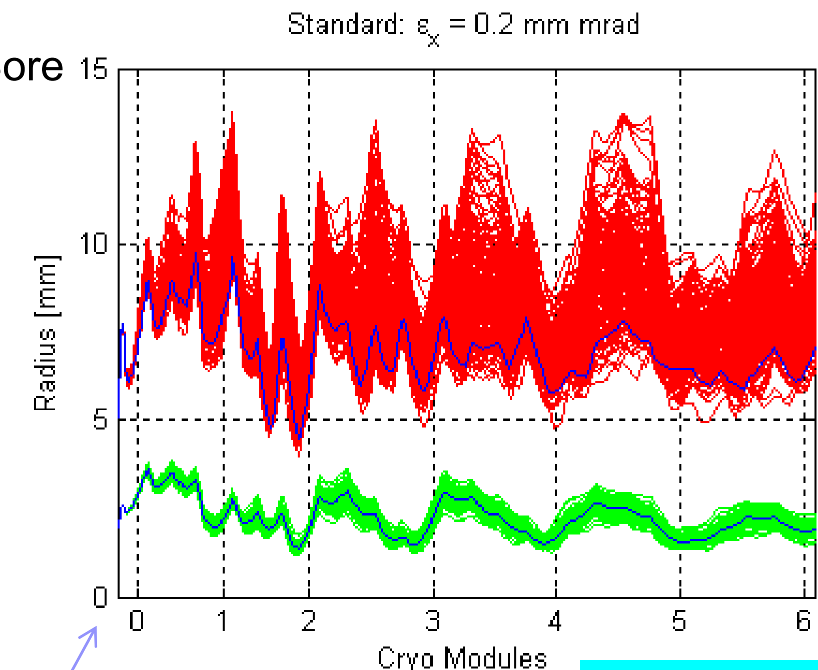
Deuteron beam envelope radius at SARAF SC Linac

Solenoids **19**

Tail emphasis simulations

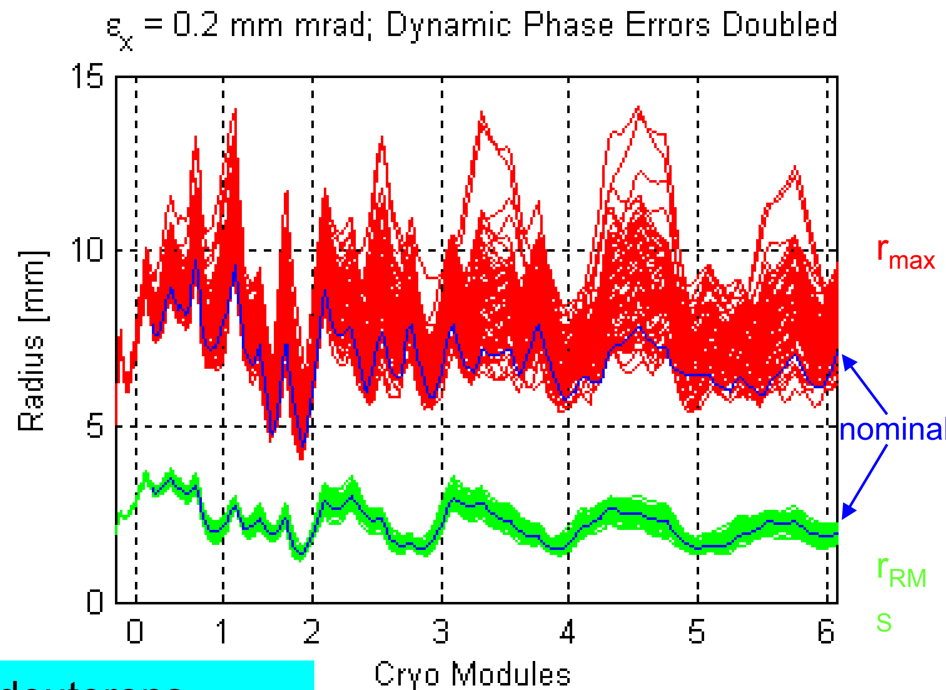
200 realizations

Bore



RFQ exit

70 realizations



3.4 mA deuterons
32k/193k particles in core/tail
Last macro-particle = 1 nA

B. Bazak *et al.*, Submitted for Publication
J. Rodnizki *et al.*, HB2008

General Particle Tracer 2.80 2006, Pulsar Physics S.B. van der Geer, M.J. de Loos http://www.pulsar.nl/

Summary and Outlook

- SARAF Phase I Commissioning status:
  - Extensive proton beam commissioning through RFQ performed
  - First deuteron and H_2^+ beams accelerated in RFQ
  - On-going RFQ RF conditioning to enable CW deuteron and H_2^+ beams
  - RF commissioning of the PSM to enable beam acceleration through it
- Simulations of Phase II
  - Beam loss criterion for hands-on maintenance is 0.4 nA/m at 40 MeV
  - Tail emphasis simulations indicate beam loss below 1 nA/m