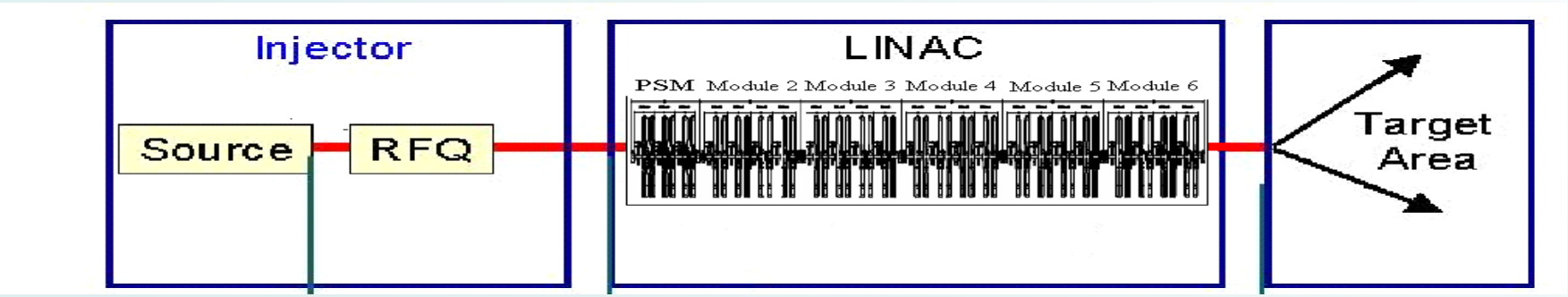
The 40 MeV proton / deuteron linac at SARAF

August 27th, 2008

Jacob Rodnizki on behalf of SARAF team

Content of the talk

1. Introduction
2. SARAF accelerator - technologies and commissioning process
3. Beam dynamics simulation and lost estimation
4. Derivation of a safety criterion
5. Diagnostics box along the linac



SARAF – Soreq Applied Research Accelerator Facility

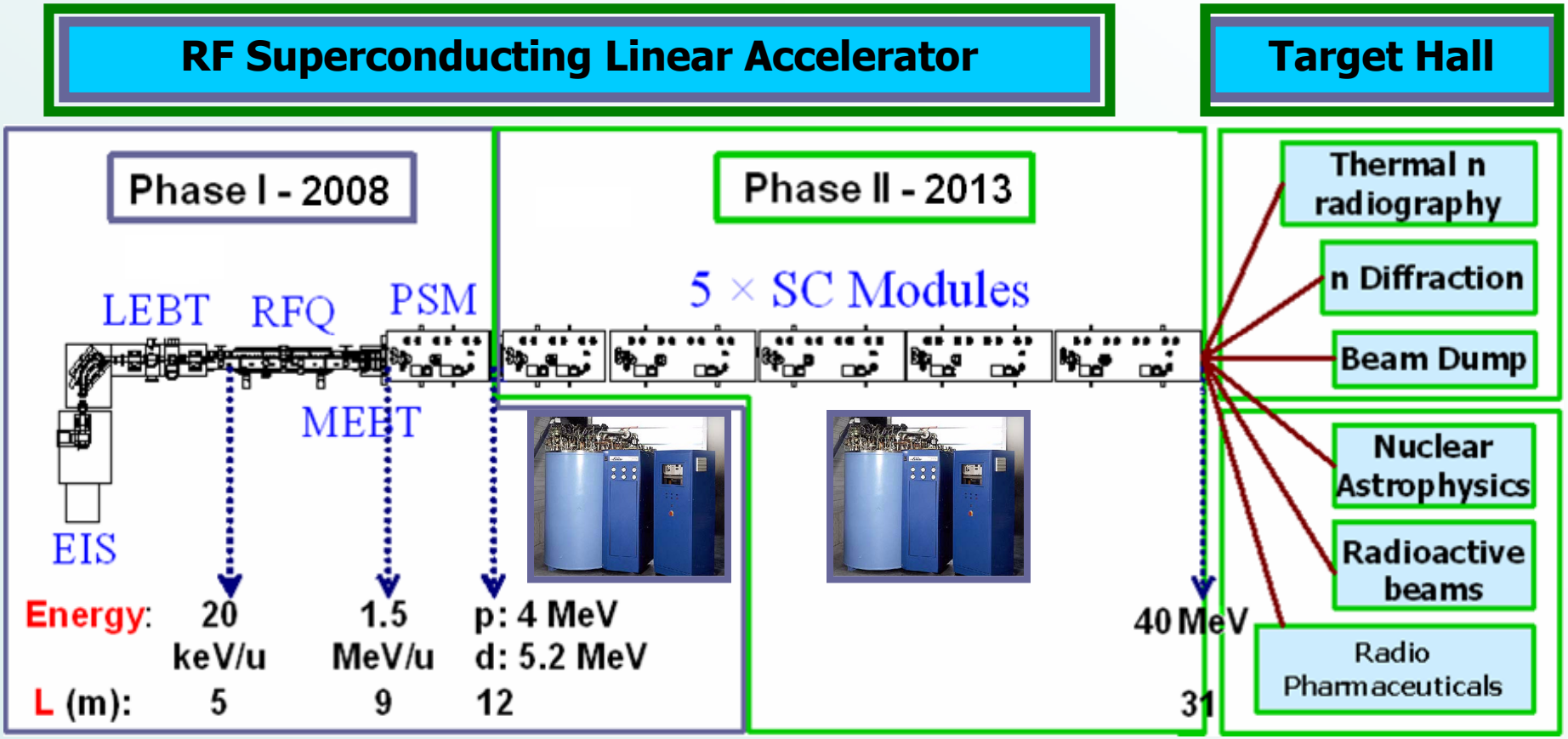
- To modernize the source of neutrons at Soreq and extend neutron based research and applications.
- To develop and produce radioisotopes primarily for bio-medical applications.
- To enlarge the experimental nuclear science infrastructure and promote the research in Israel.

A RF Superconducting Linear Accelerator

Accelerator Basic Characteristics

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	Very low beam loss

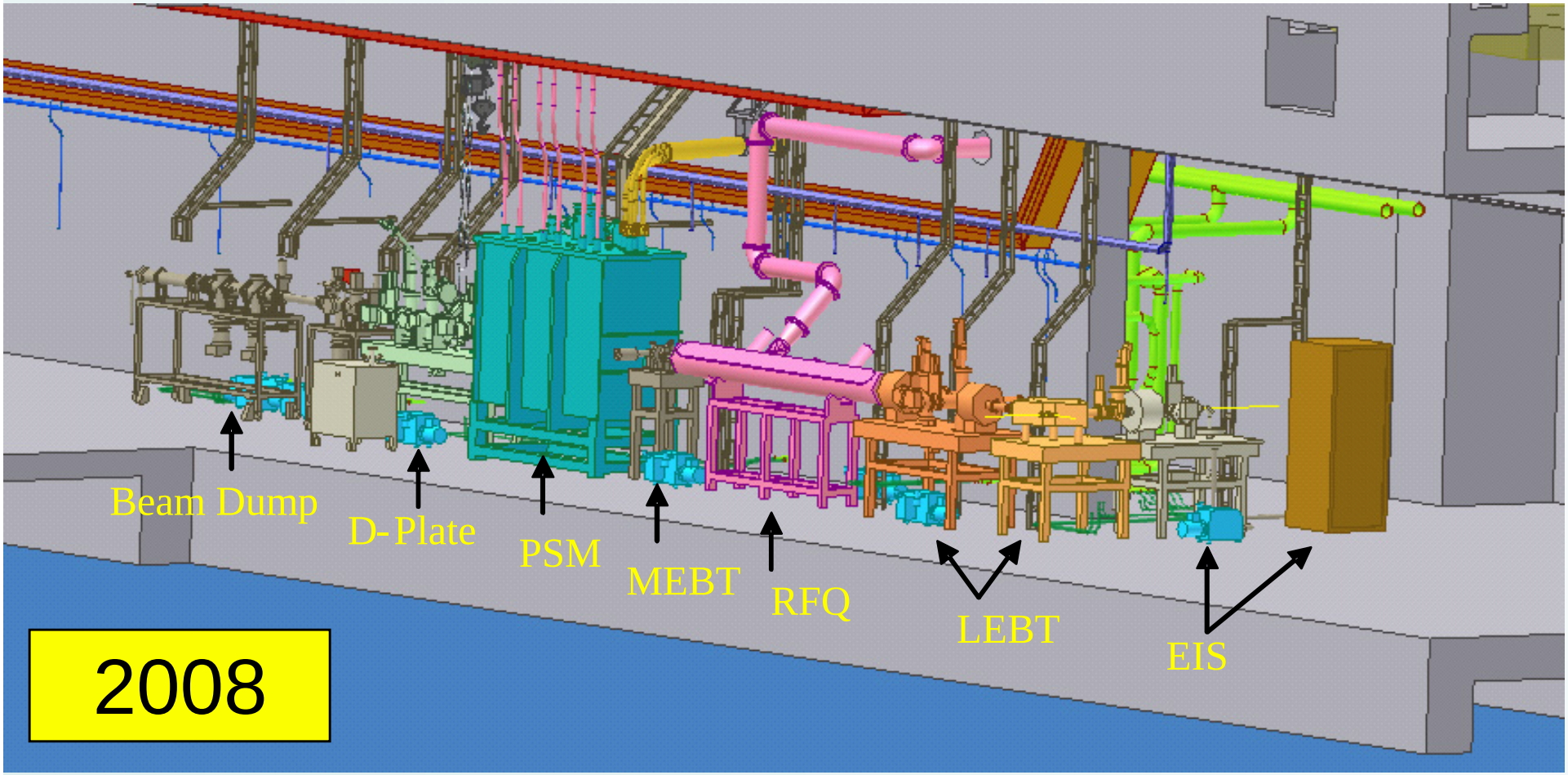
SARAF Layout

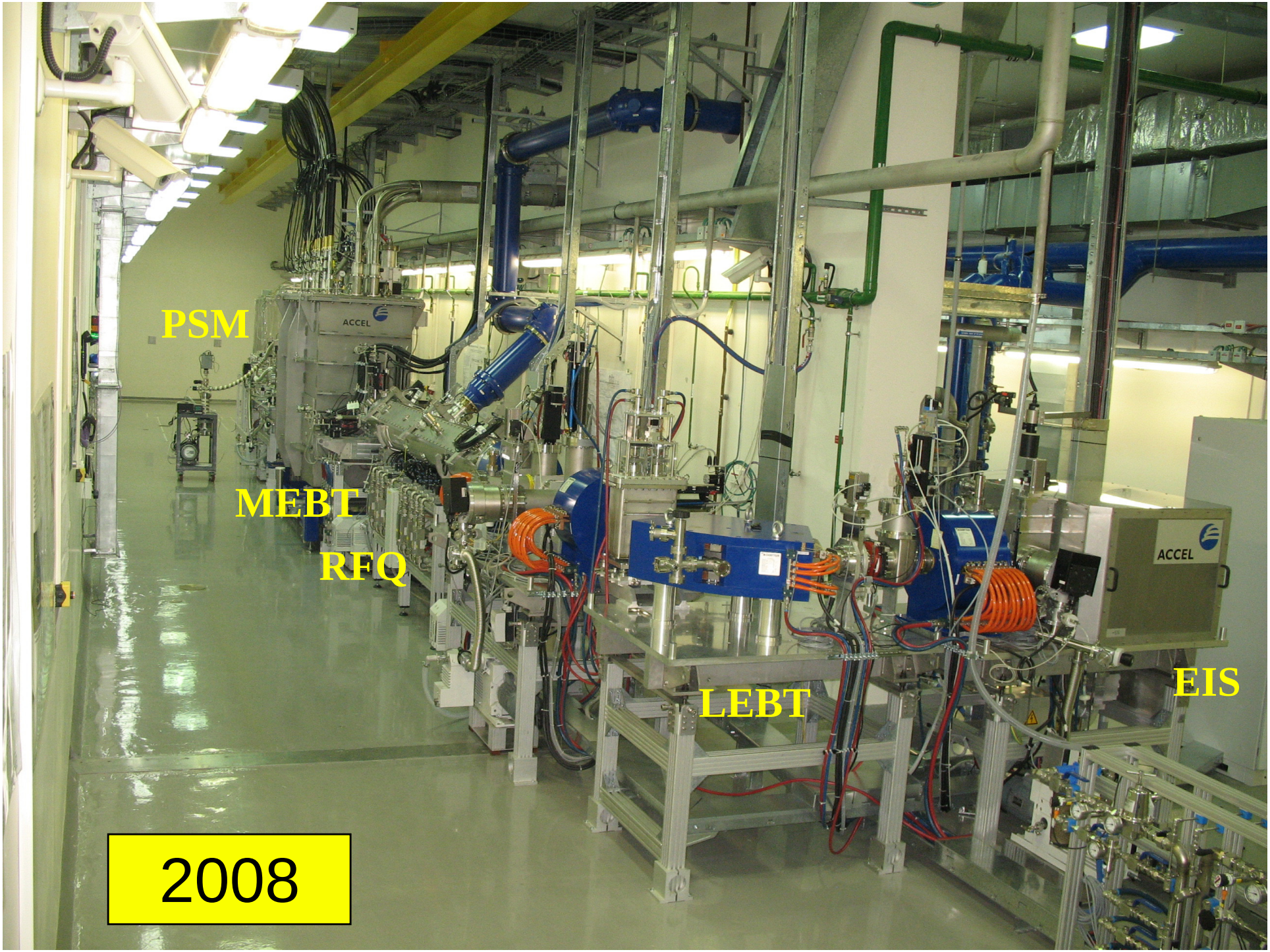


A. Nagler et al., LINAC 2006


2005
Beam and Service Corridors

Set up for beam characterization




PSM
MEBT
RFQ
LEBT
EIS
ACCEL
ACCEL
2008

Phase-I technologies and commissioning

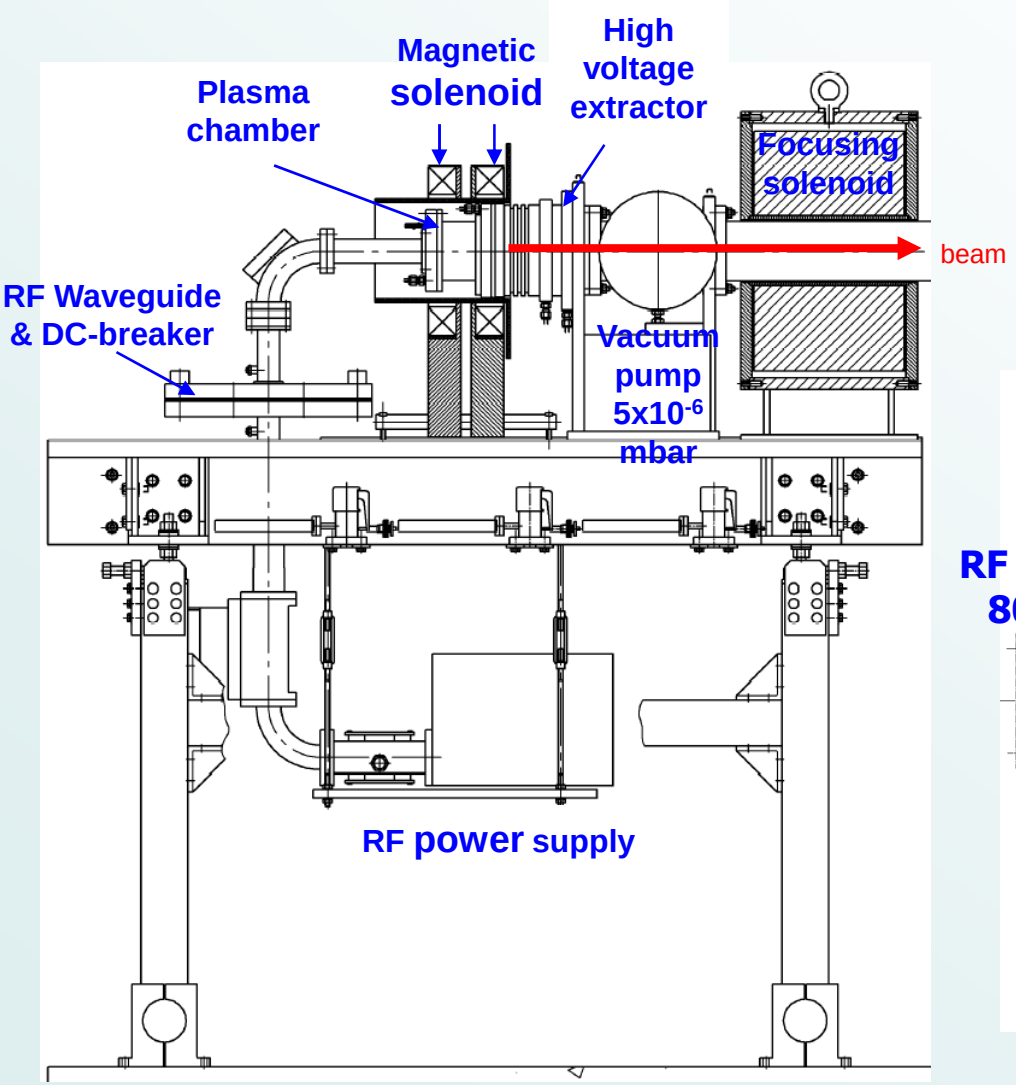
LEBT

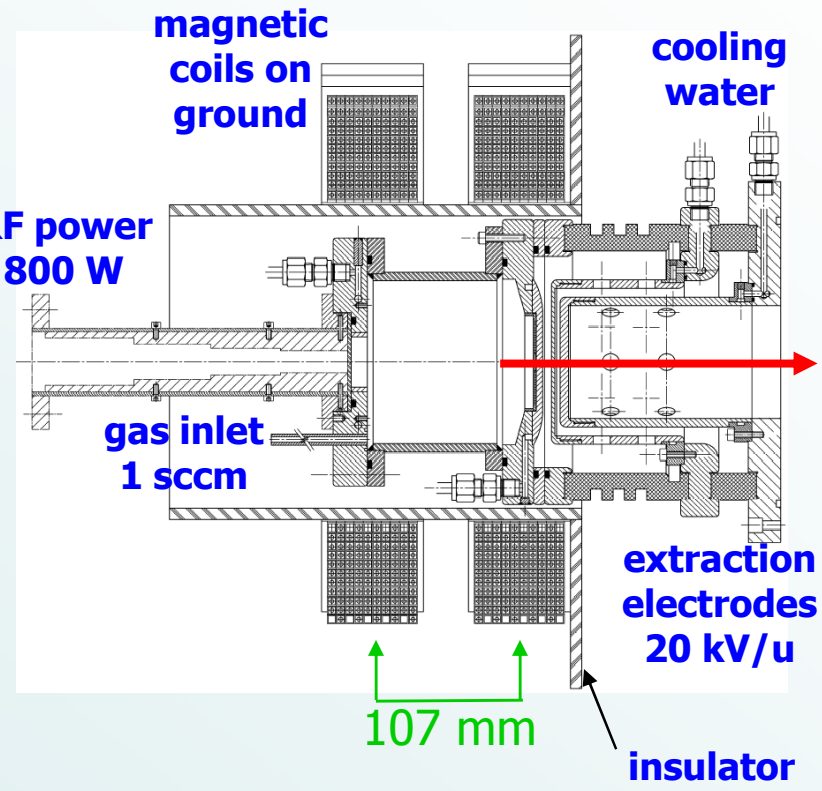
ECR Ion Source (ECRIS)

C. Piel EPAC 2006

F. Kremer ICIS 2007

K. Dunkel PAC 2007

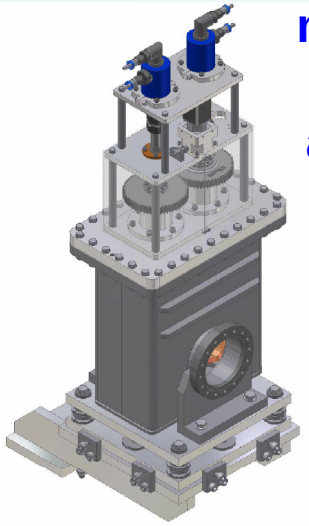




SARAF Electron Cyclotron Resonator Ion Source (ECRIS) Design Parameters

Ion Species	p, d, H_2^+
Extraction Energy	20 keV/u
Energy ripple	±0.03 keV/u
Current range	0.04 – 5 mA
Current ripple (max current)	±2%
Transverse emittance (norm, r.m.s.)	0.2 π·mm·mrad

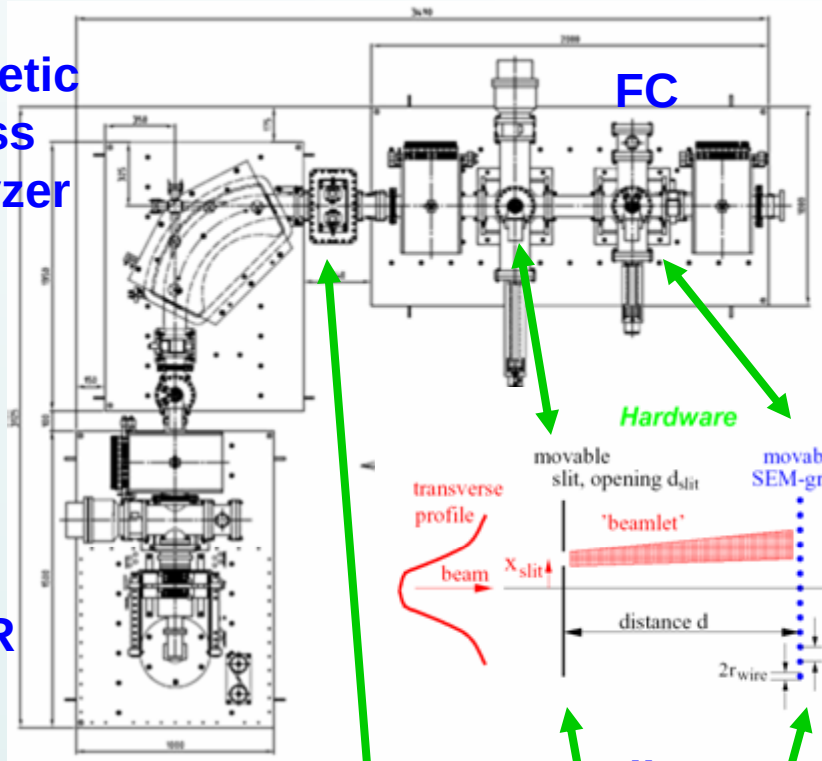
LEBT – emittance measurement



aperture

magnetic mass analyzer

ECR

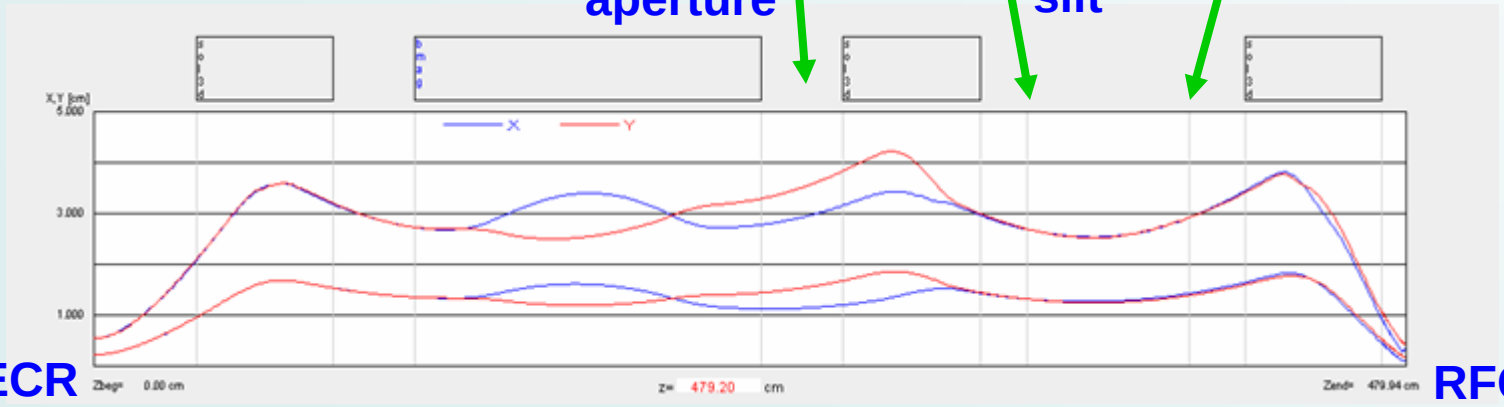


C. Piel EPAC 2006

F. Kremer ICIS 2007

K. Dunkel PAC 2007

P. Forck JUAS 2003

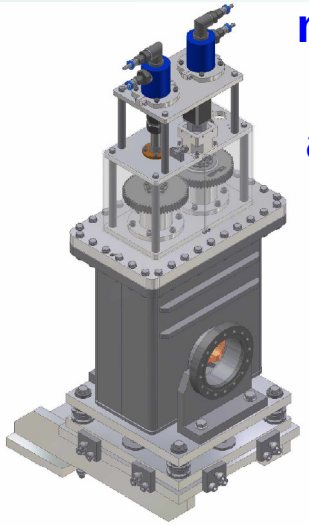


5 mA proton beam optics

ECR

RFQ entrance

LEBT – emittance measurement

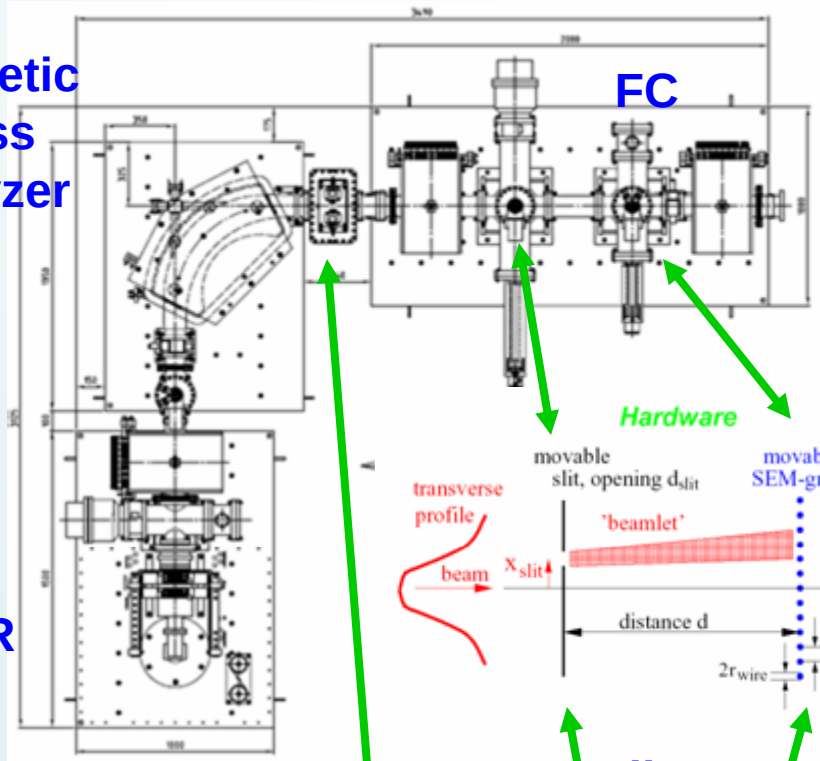


magnetic mass analyzer

FC

aperture

ECR



aperture

slit

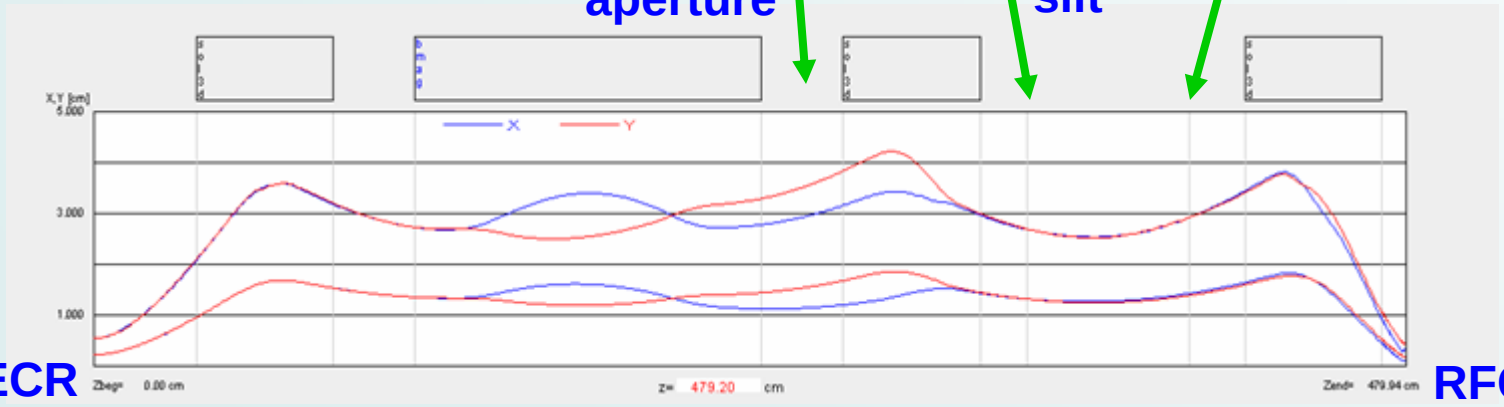
wire

C. Piel EPAC 2006

F. Kremer ICIS 2007

K. Dunkel PAC 2007

P. Forck JUAS 2003



5 mA proton beam optics

ECR

RFQ entrance

EIS: emittance values during FAT

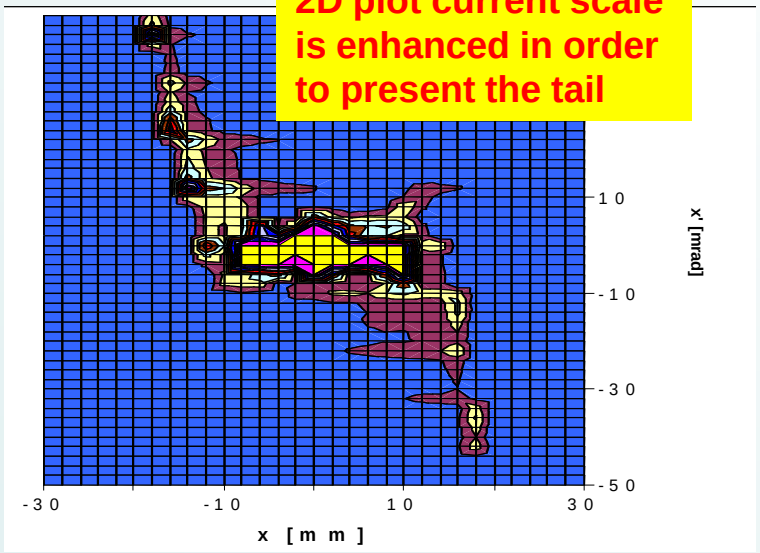
$\varepsilon_{rms_norm._100\%}$ [π mm mrad]

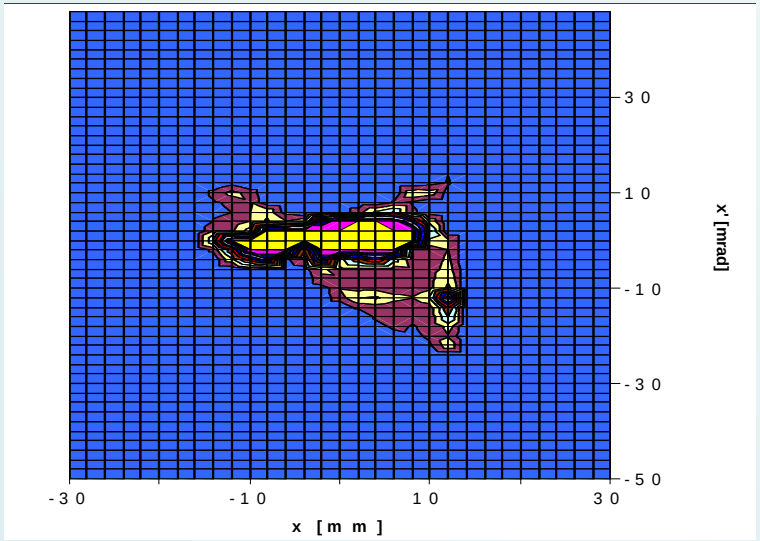
Particles Beam current	Protons X / Y	H_2^+ X / Y	Deuterons X / Y
5.0 mA	**0.2 / 0.17**	**0.34 / 0.36**	**0.13 / 0.12**
2.0 mA	**0.13 / 0.13**	**0.30 / 0.34**	**0.14 / 0.13**
0.04 mA	**0.18 / 0.19**		**0.05 / 0.05**

Specified value = 0.2 / 0.2 [π mm mrad]

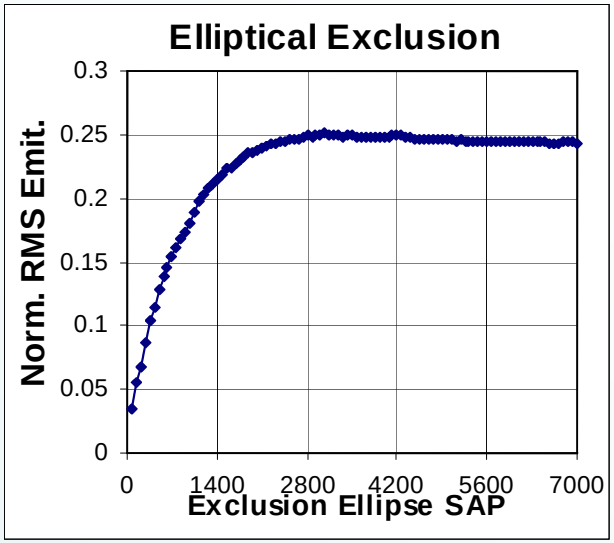
deuterons emittance results

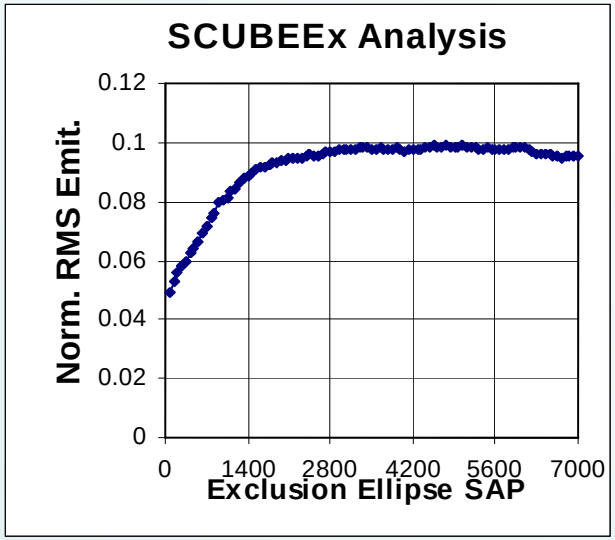
2D plot current scale is enhanced in order to present the tail





π mm mrad





deuterons

6.1 mA open aperture

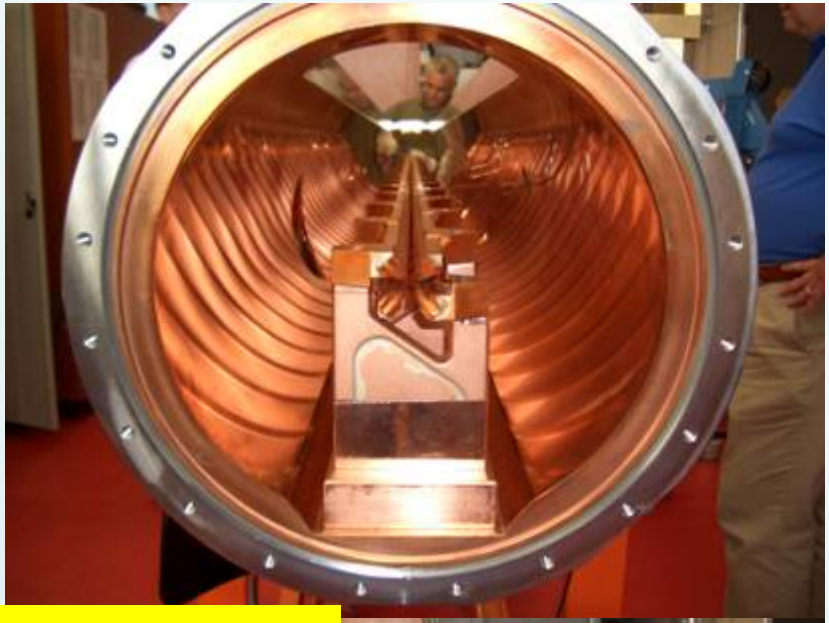
B. Bazak JINST 2008

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

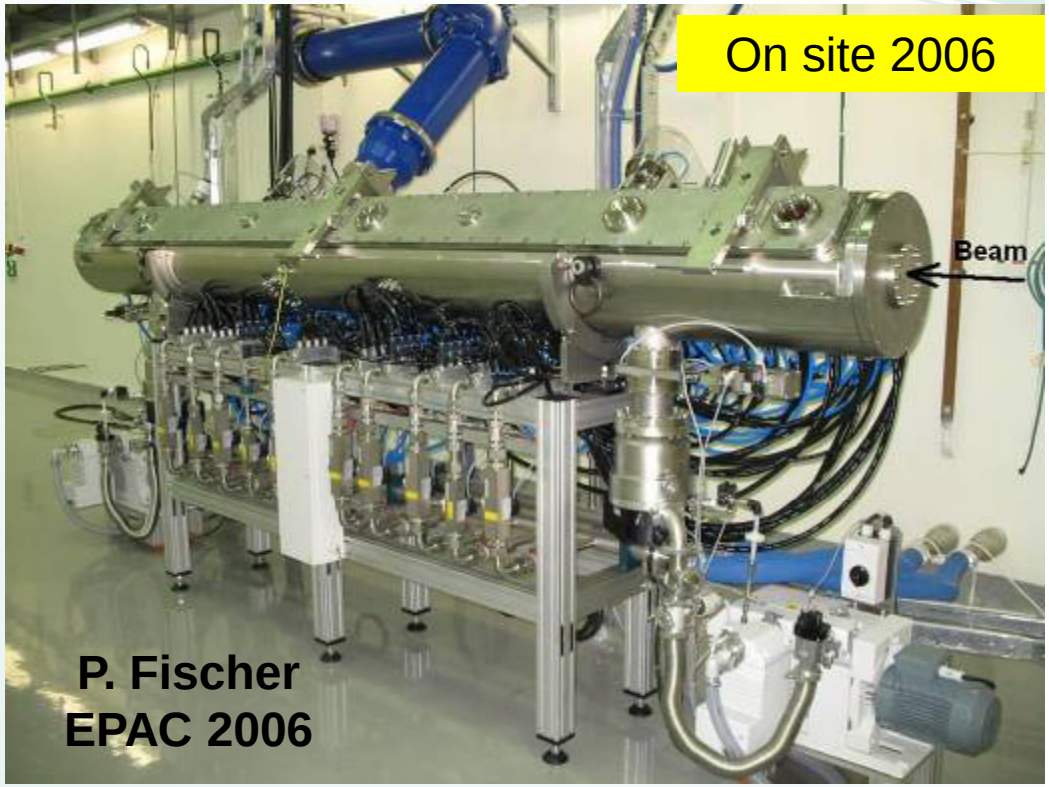
RFQ

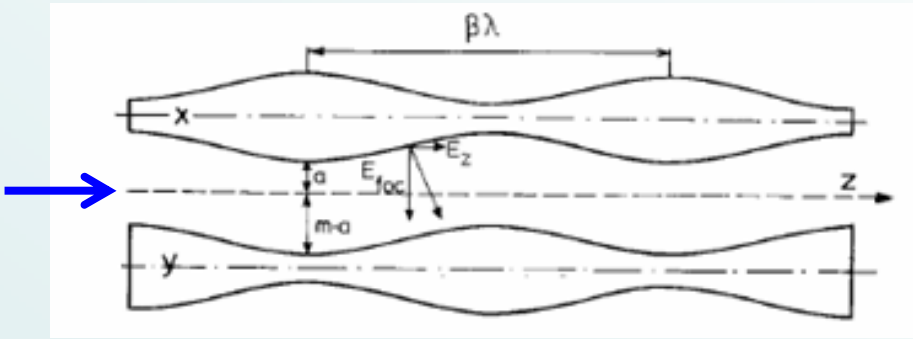
176 MHz Radio Frequency Quadrupole



In factory 2005



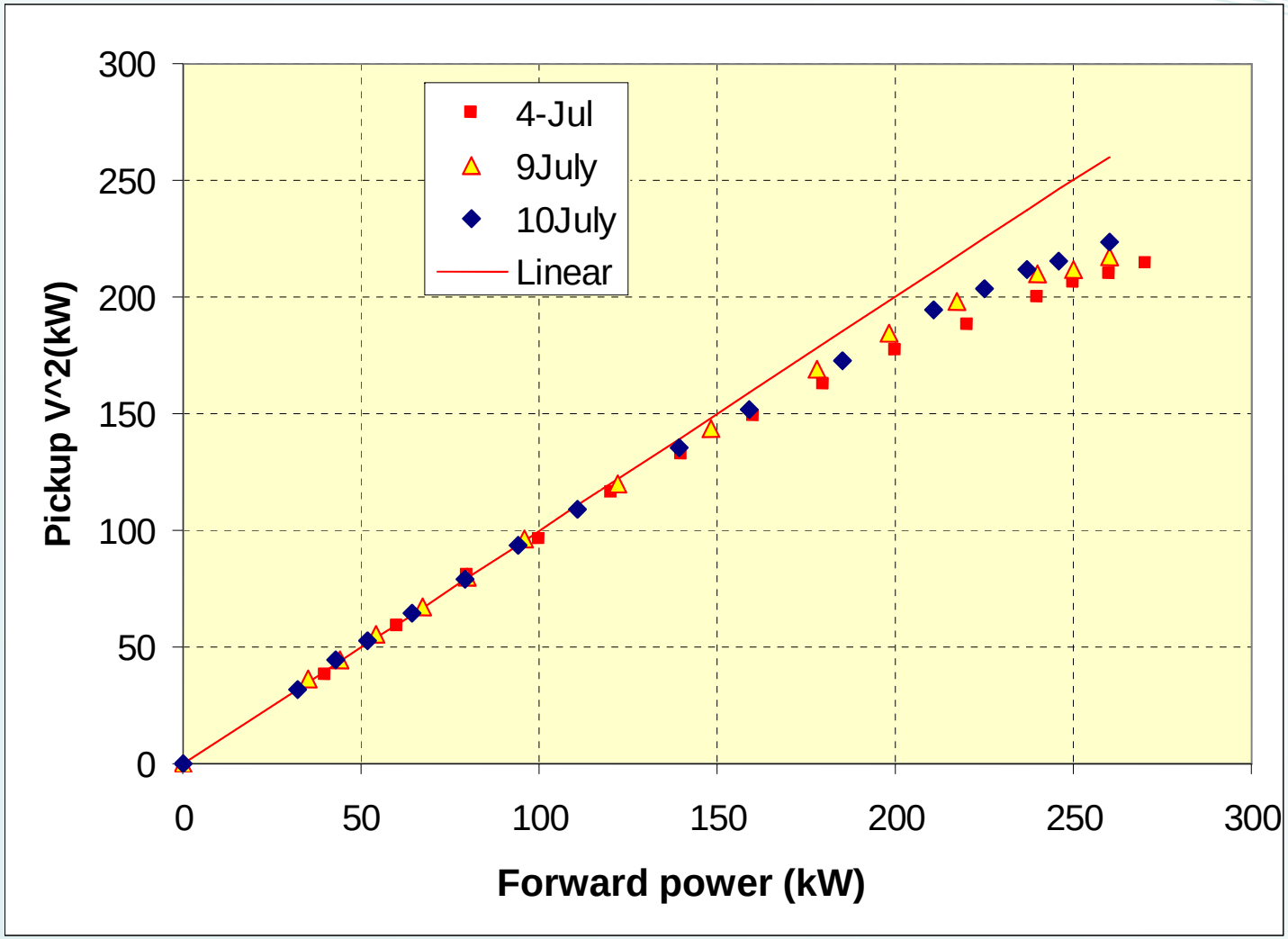




SARAF Radio Frequency Quadrupole (RFQ) Parameters

Input energy	20 keV/u
Output Energy	1.5 MeV/u
Energy ripple	±0.03 MeV/u
Maximal Current	4 mA
Transverse emittance (norm, r.m.s.)	0.3 π·mm·mrad
Longitudinal emittance (r.m.s.)	120 π·keV·deg/u
Transmission	90% (70-80%)
Length	3.8 meters
RF Power (p,d)	55, 220 kW (60,240)
Quality factor	2000 (3600)

RFQ power gain vs. forward power

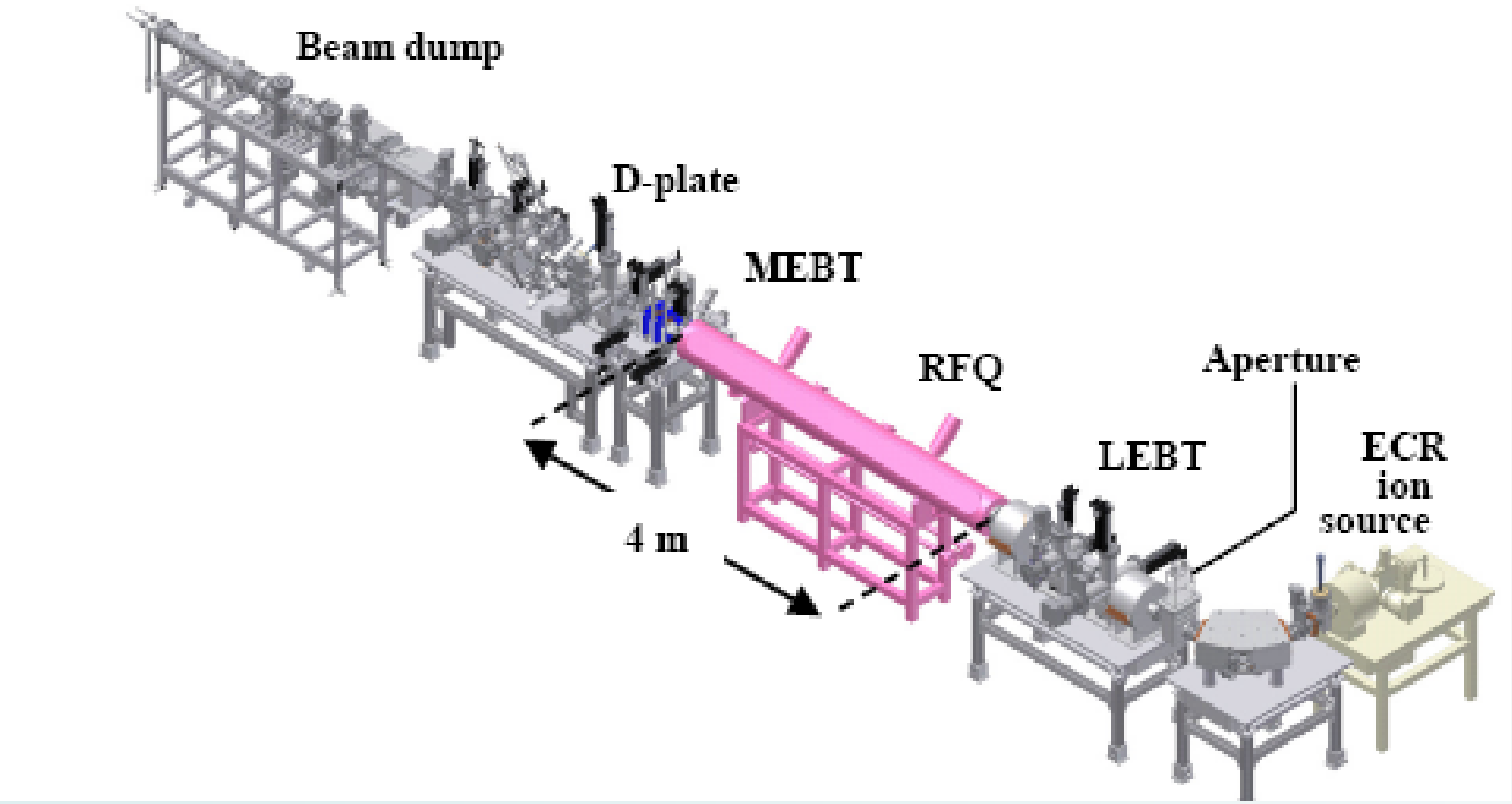


RFQ voltage squared as a function of RFQ input power. Parting from the linear relation indicates onset of dark current due to poor conditioning

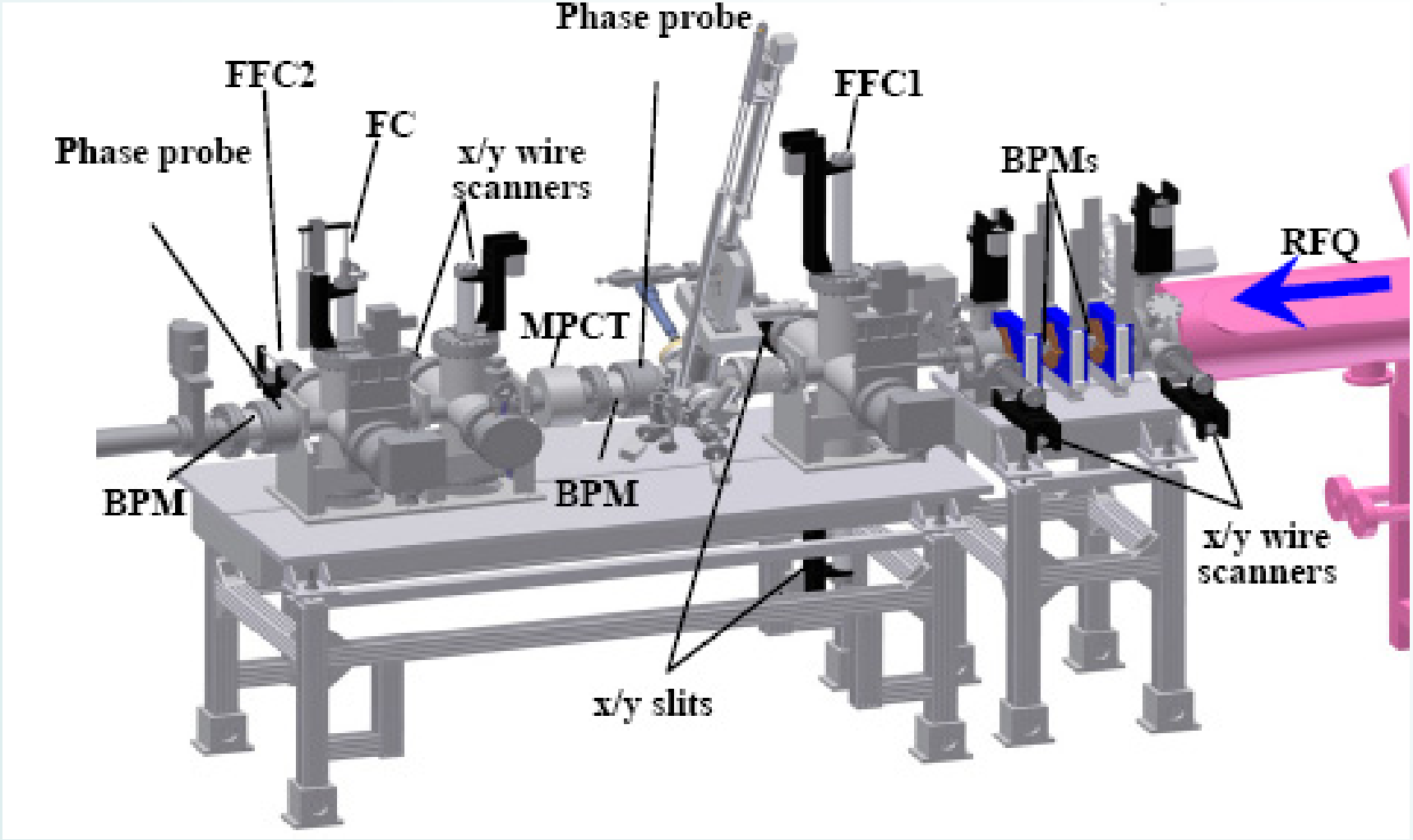
RFQ Conditioning – current status

- Expected conditioning rate improvement:
  - Rounding off sharp edges of rods bottom part
  - Cleaning of rods
  - Installation of circuit for fast recovery after sparks
- But the Reached power:
  - **195 kW CW**
  - **280 kW** with duty cycle of **15%**

RFQ Test system configuration



RFQ Test Setup

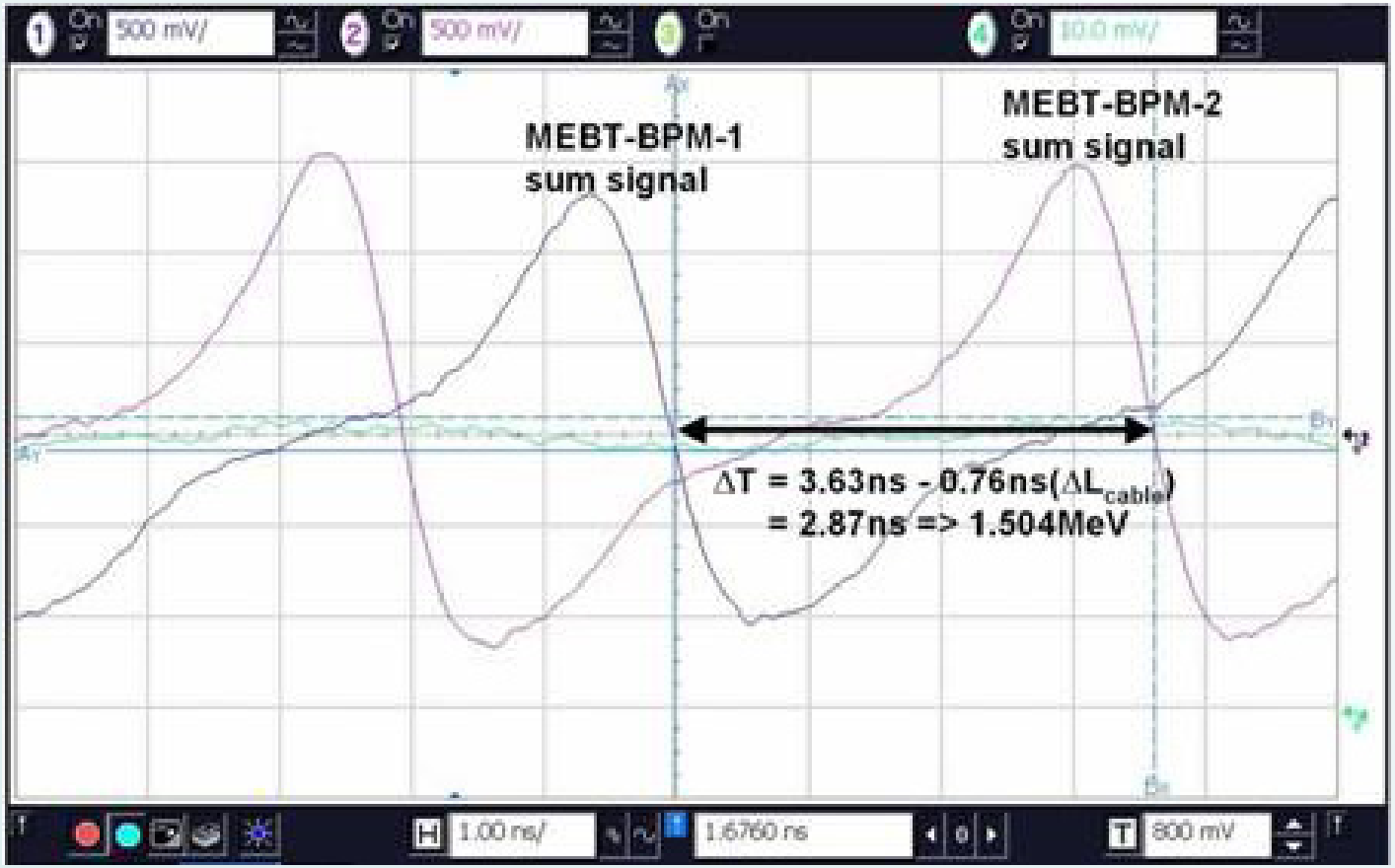


Proton energy at RFQ exit by TOF

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

E = 1.504 ± 0.012 MeV

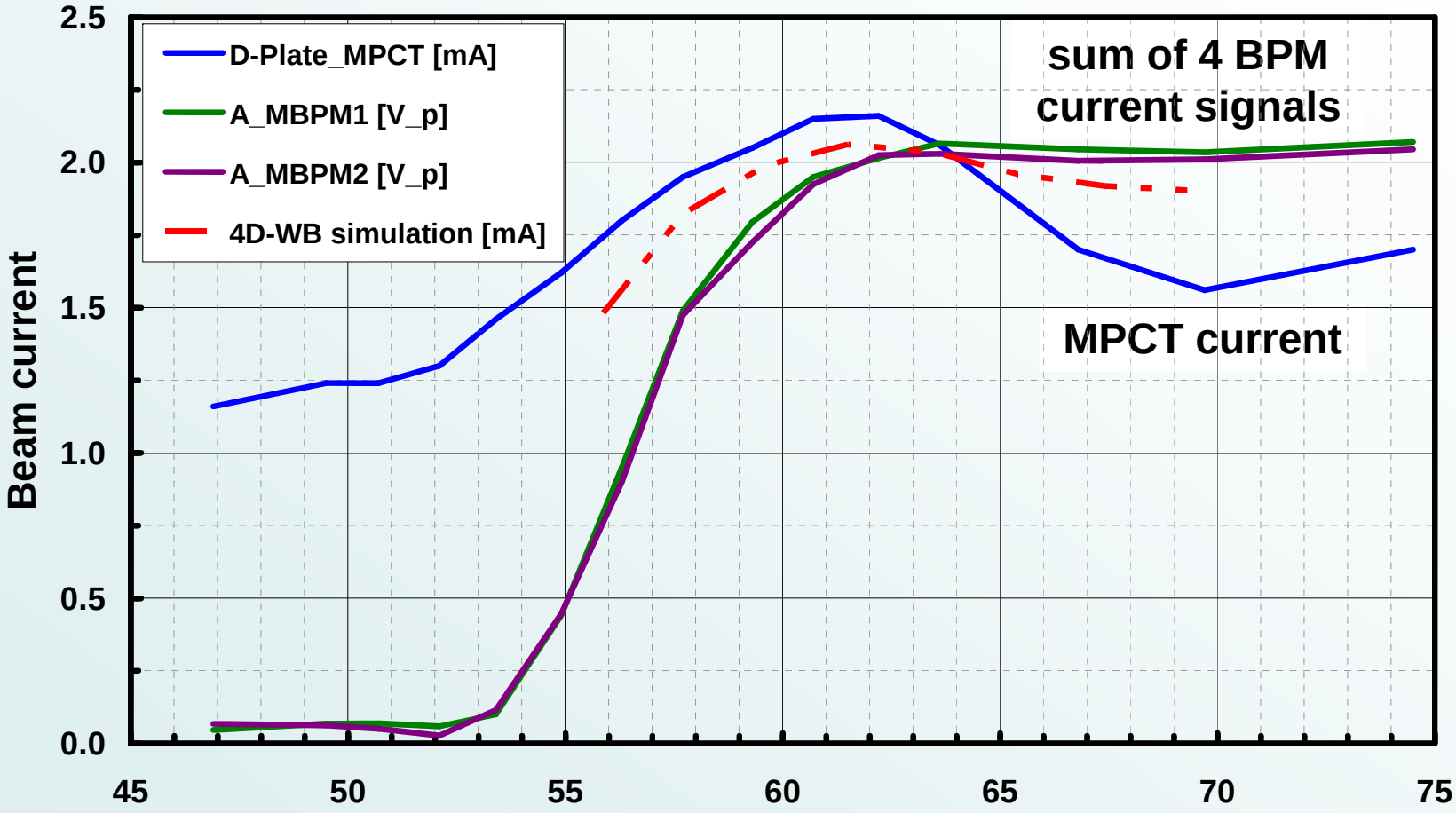
C. Piel PAC 2007



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

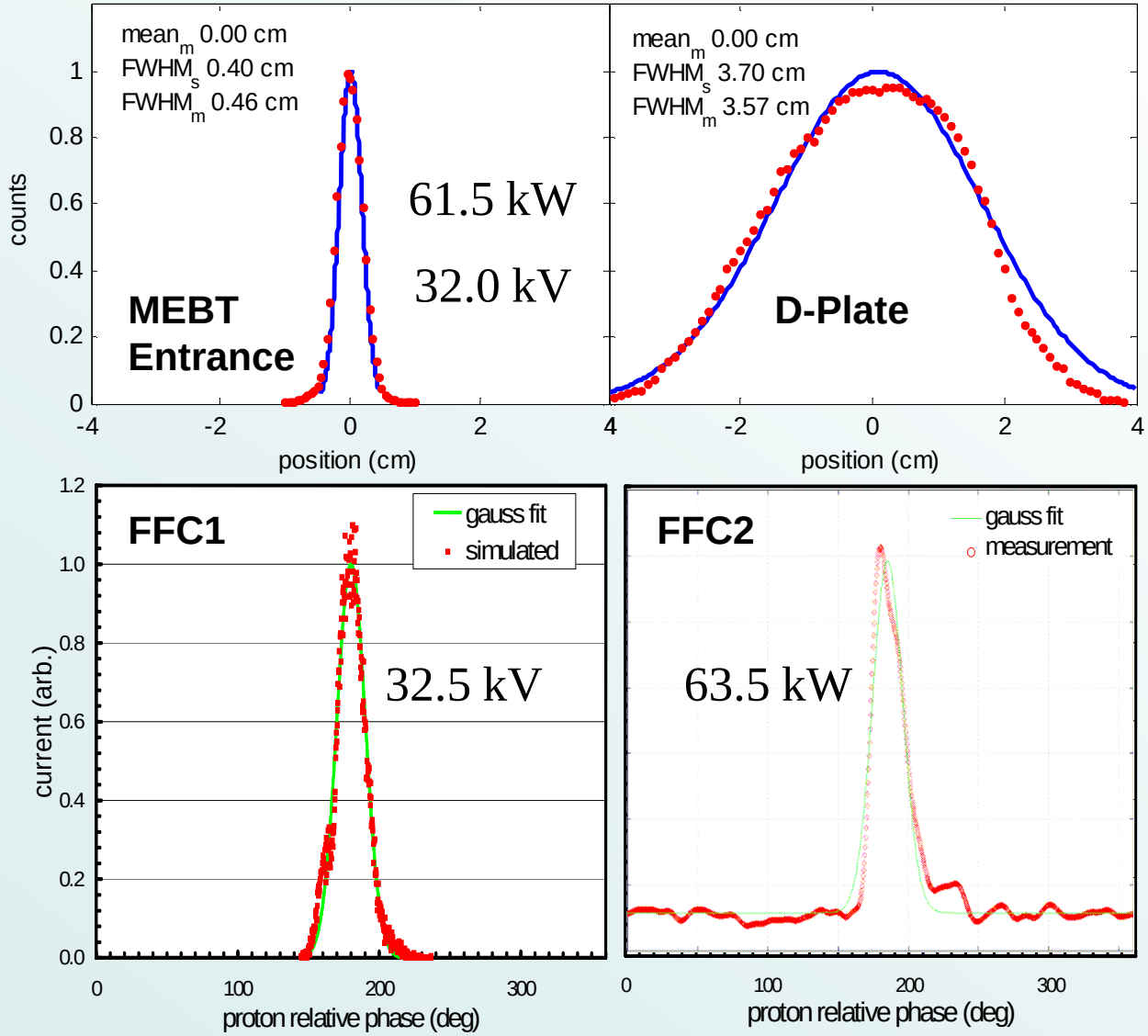
Bunch width measured at β=0.056 is larger than the predicted value due to the induced charge broadening.

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



J. Rodnizki et al.
EPAC 2008

RFQ: Bunch profiles measurement



Wire scan profile

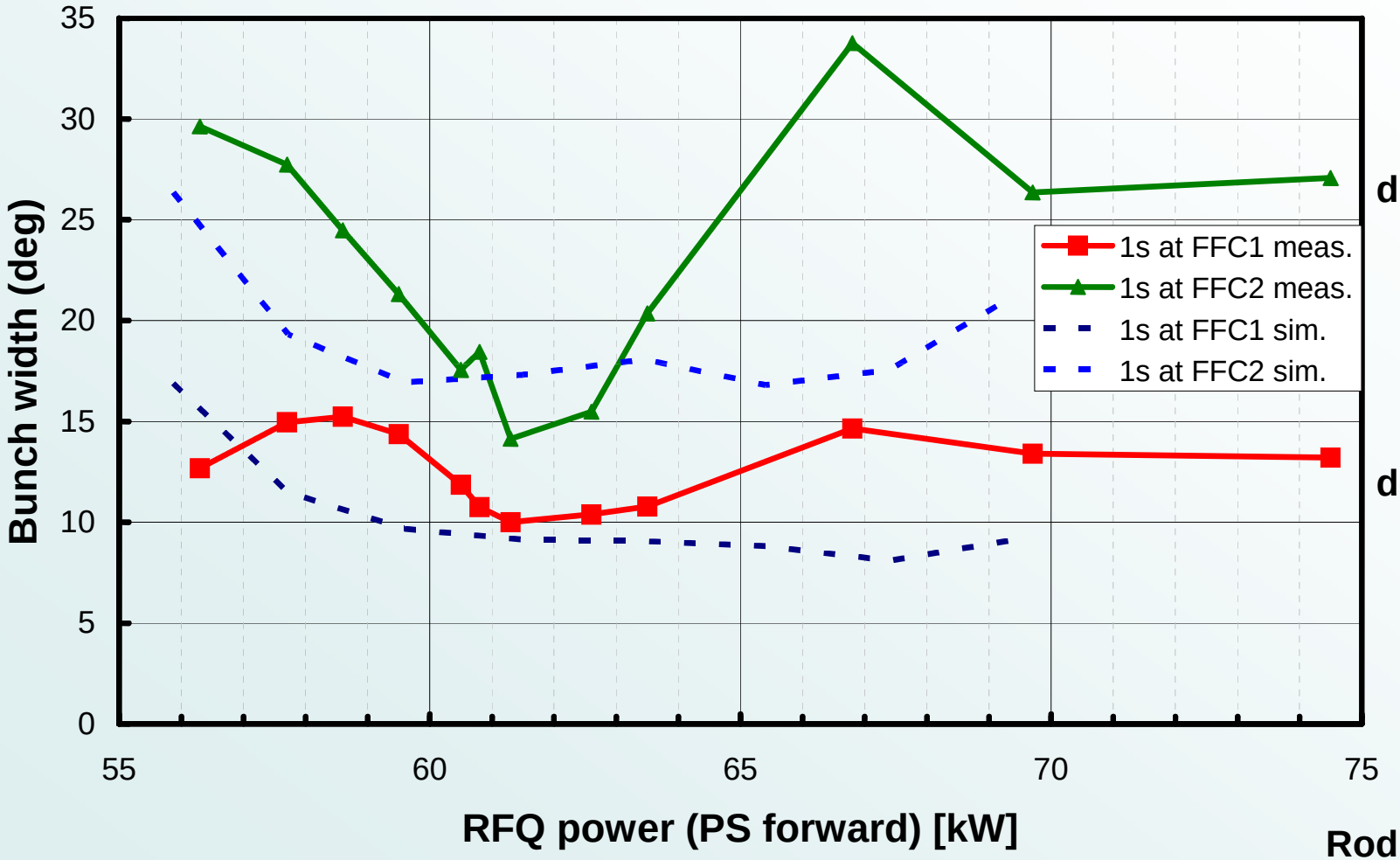
C. Piel PAC 2007

Measurement results are backup by simulations (TRACK)

FFC time profile

Rodnizki et al. EPAC 2008

Proton bunch width (by FFCs) vs. RFQ forward power

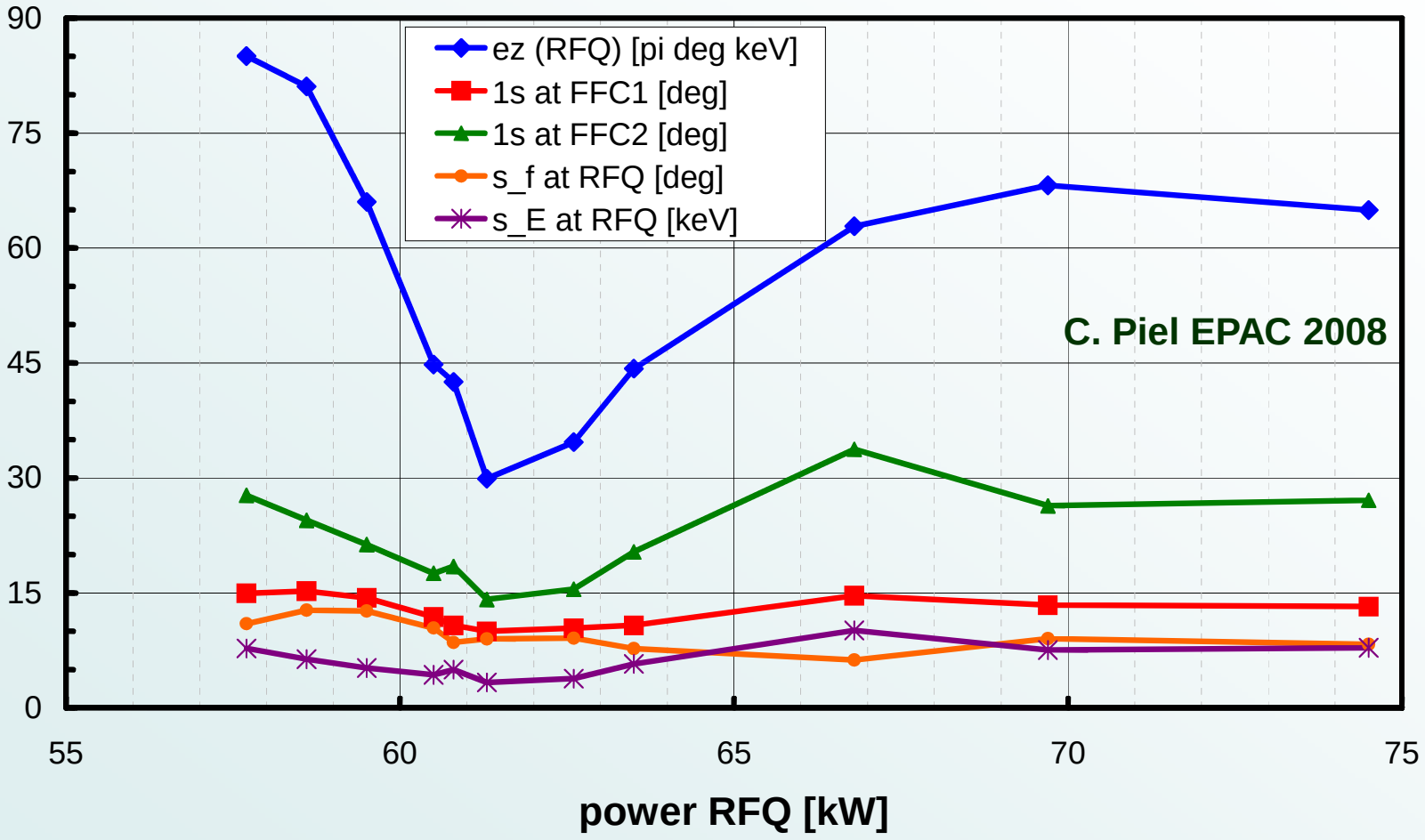


265 cm downstream the RFQ

106 cm downstream the RFQ

Rodnizki et al. EPAC 2008

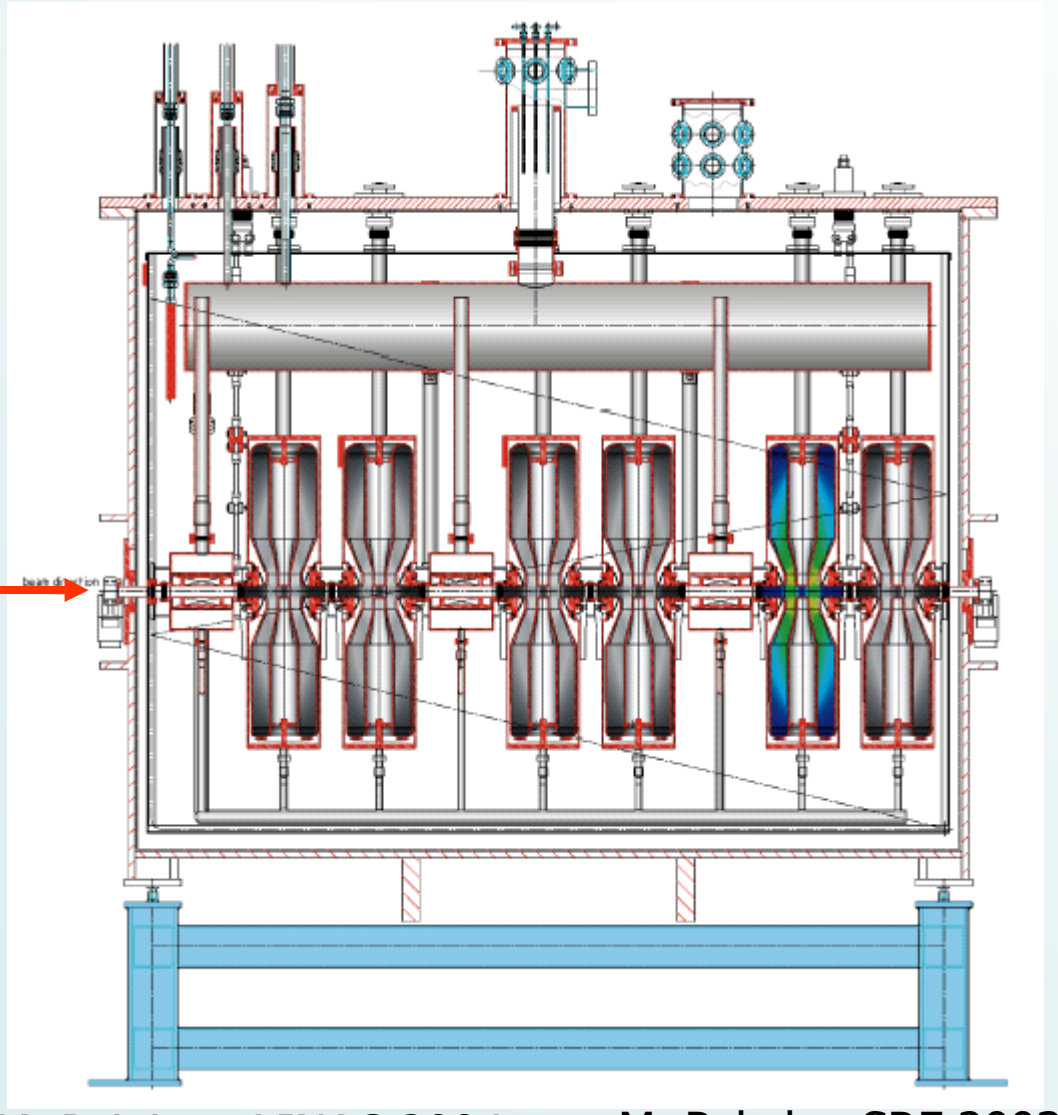
Approximated longitudinal rms emittance extracted from bunch width measurements



Specified longitudinal rms emittance = 120 π deg keV, realistic value 74 π deg keV

PSM

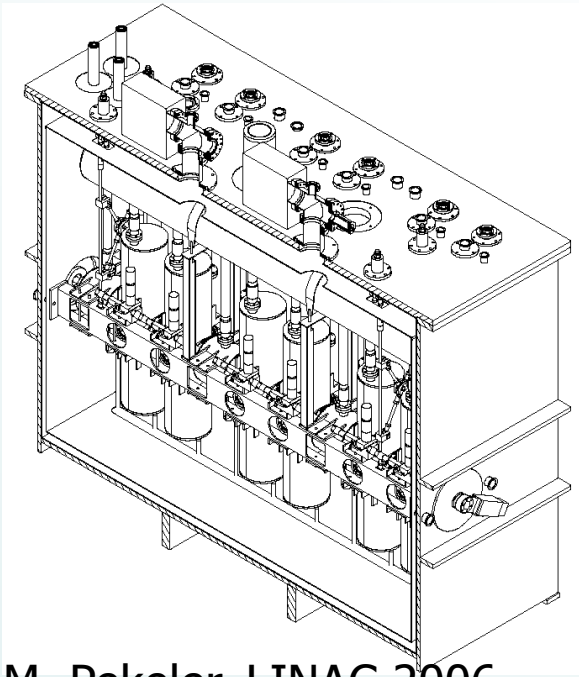
Prototype SC Module (PSM) developed by ACCEL



M. Peiniger, LINAC 2004

General Design:

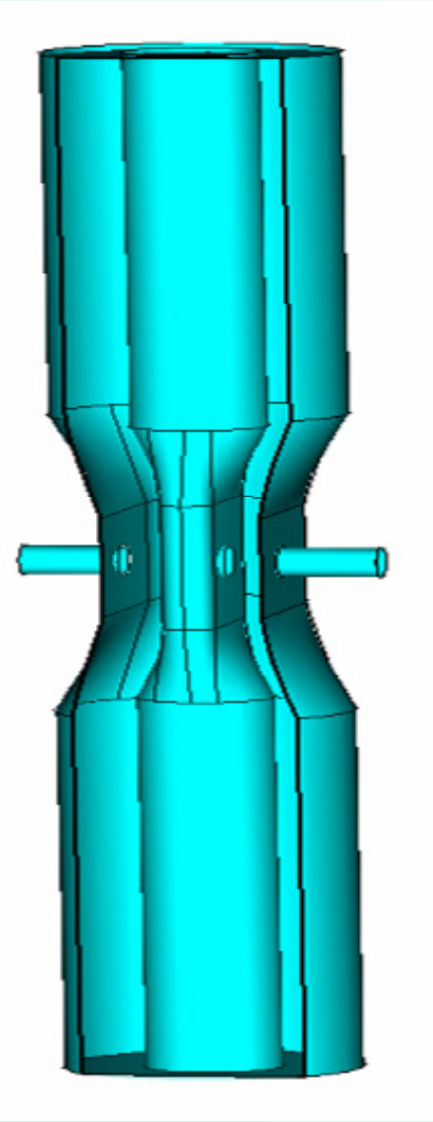
- **Houses 6 HWR and 3 superconducting solenoids**
- **Accelerates protons and deuterons from 1.5 MeV/u on**
- **Very compact design in longitudinal direction**
- **Cavity vacuum and insulation vacuum separated**



M. Pekeler, SRF 2003

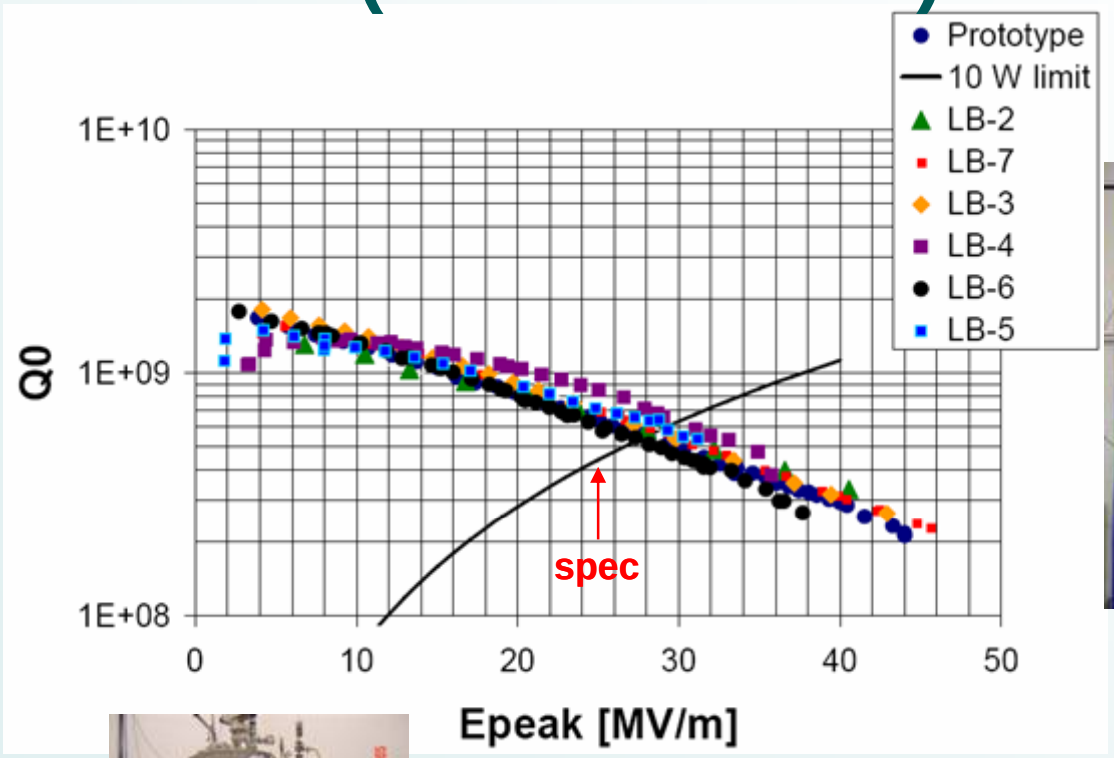
M. Pekeler, LINAC 2006

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})

PSM: Summary of cavity test results (vertical dewar)











Cavity performance:

- LB-2, LB-7, LB-3, and LB-4 tested before helium vessel welding
- LB-6 and LB-5 tested after helium vessel welding
- In all test of series cavities, multipacting was much reduced compared to the prototype cavity
- Field emission only seen at very high field levels

M. Pekeler, LINAC 2006

HWR field and dissipated power recent measurements with phase lock loop

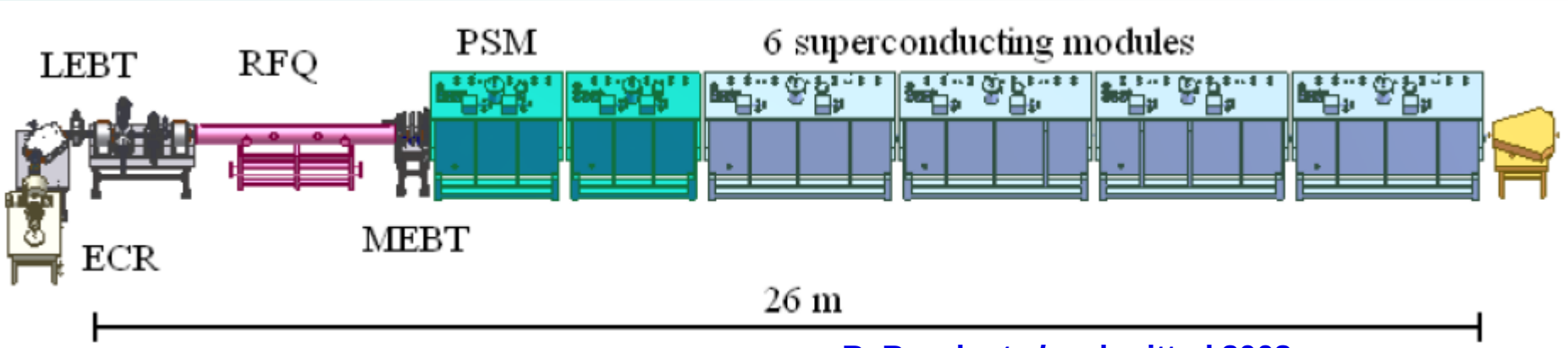
Cavity		vertical Test			10/2007 PSM Test			03/2008 PSM Test	
location	name	max field	losses at	Q at	max field	losses at	Q at	losses at	Q at
		[MV/m]	25 MV/m	25 MV/m	[MV/m]	25 MV/m	25 MV/m	25 MV/m	25 MV/m
			[W]			[W]		[w]	
HWR1	LB-2	40	7,3	6,0E+08	30	6,3	7,0E+08	6	8,00E+08
HWR2	LB-3	43	7,3	6,0E+08	28	31,4	1,4E+08	9	5,00E+08
HWR3	LB-5	33	6,3	7,0E+08	32	22,0	2,0E+08	24	2,00E+08
HWR4	LB-7	46	6,3	7,0E+08	29	22,0	2,0E+08	39	2,00E+08
HWR5	LB-4	36	5,5	8,0E+08	31	11,0	4,0E+08	13	4,00E+08
HWR6	LB-6	38	7,3	6,0E+08	29	14,7	3,0E+08	42	1,00E+08
		sum	40,0			107,3		133	

Target values: 72 4.7E8

C. Piel *et al.* EPAC 2008

Beam dynamics error simulations for phase-II

Superconducting linac simulation with error analysis



B. Bazak *et al.* submitted 2008

Simulations shown in next slides. 4 mA deuterons at RFQ entrance. Last macro-particle=1nA:

1. RFQ entrance norm rms $\varepsilon_{x,y}$=0.2 π mm mrad
2. Similar to 1 with double dynamic phase error
3. Similar to 1 with RFQ exit norm rms expanded to $\varepsilon_{x,y}$=0.3 π mm mrad

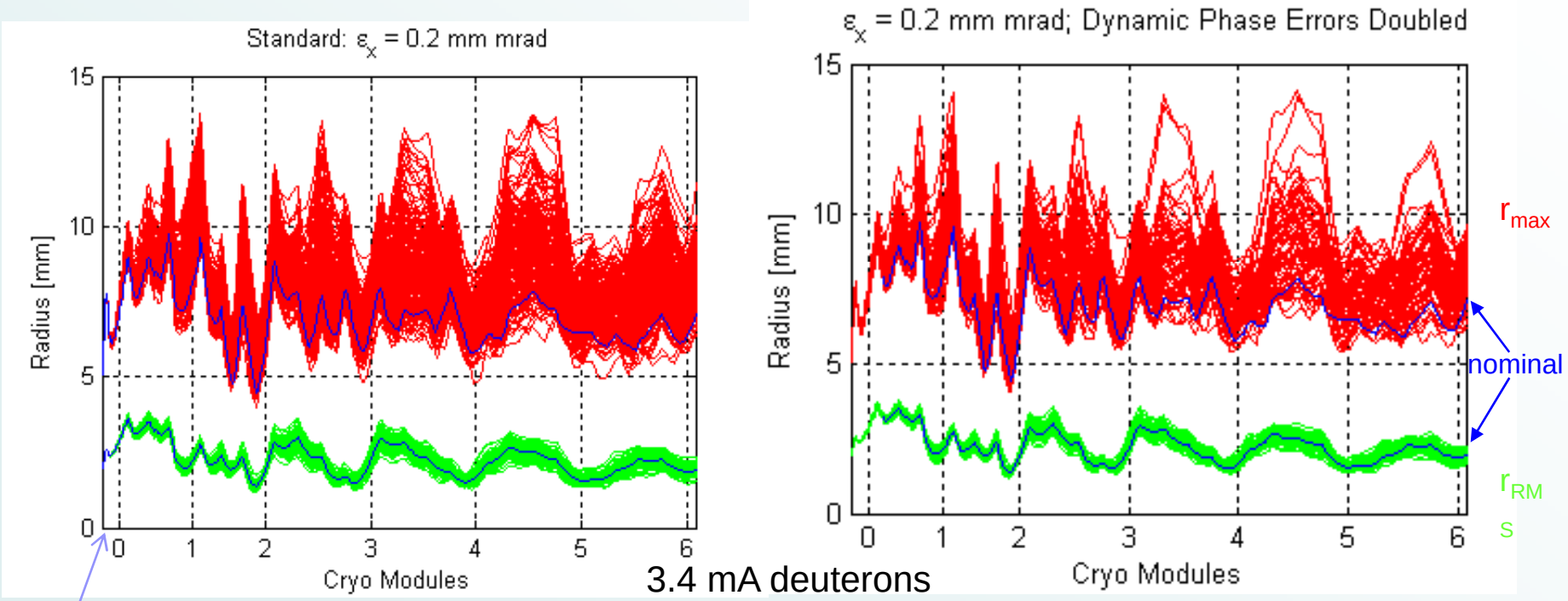
Component	Error	Static	Dyn.
Quadrupole Magnets	Misalignment x,y,z [mm]	± 0.2	
	Rotation θ [mrad]	± 3	
	Magnetic field [%]	± 2	0.5
Solenoids	Misalignment x,y,z [mm]	± 0.2	
	Magnetic field [%]	± 2	0.5
HWR	Misalignment x,y,z [mm]	± 0.4	
	Rotation θ [mrad]	± 6	
	Field strength [%]	± 2	0.5
	Phase [degree]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

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

d beam envelope radius along the SC linac

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

Asymmetric lattice



3.4 mA deuterons

200 realizations — 32k/193k particles in core/tail — 70 realizations

Last macro-particle = 1 nA

RFQ exit

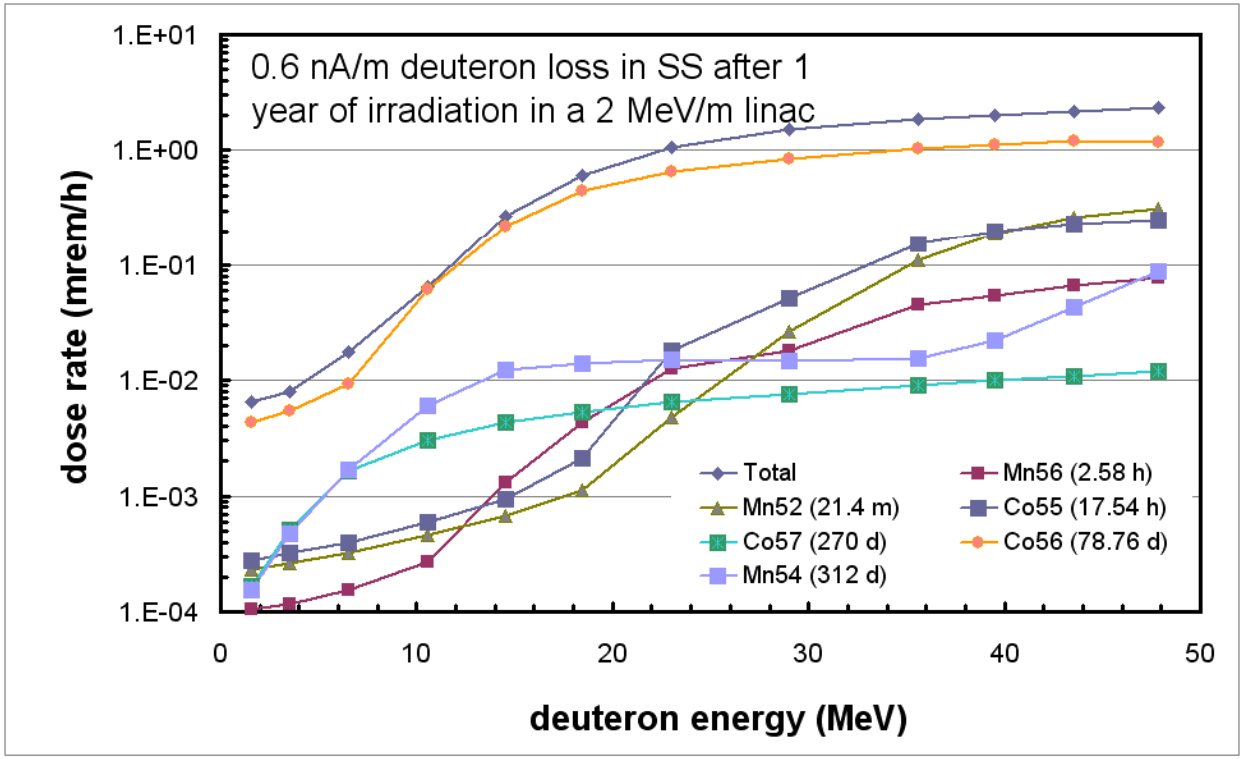
HWR bore radius = 15 mm

SC solenoids bore radius = 19 mm

Loss limit

Guidelines for beam loss calculations

- All calculations assume a beam loss of **0.6 nA/m**. This value was deduced from a limit on residual activation



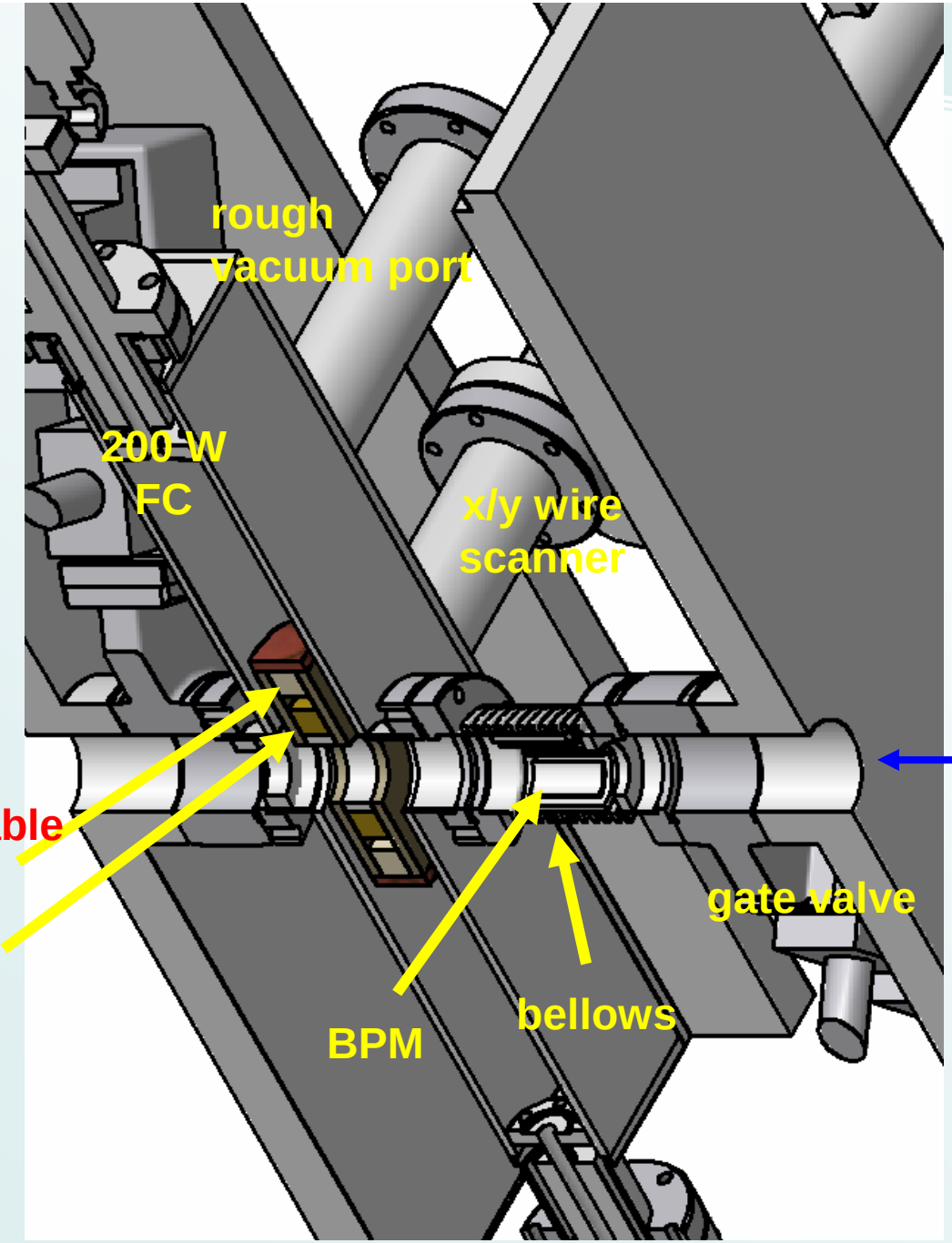
Determination of 0.6 nA/m limit (1)

- This limit was determined in order to limit the dose to 2 mrem/h (100 h of hands-on maintenance per technician per year gives 10% of the annual dose limit) at:
  - 30 cm away from beam line
  - 4 hours after accelerator shutdown
  - After the accelerator has been operating for a year
- Conservative assumptions leading to this limit:
  - 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)

Determination of 0.6 nA/m limit (2)

- Comparison of our calculations and Delayen *et al* (PAC 1993)
  - SARAF: Stainless Steel sets the 0.6 nA/m limit at 40 MeV
  - Delayen: Niobium sets the 1 nA/m limit at 35 MeV
- Calculations show that SARAF can tolerate losses of ~5 nA/m at 10 MeV, but criterion not changed

Diagnostics between cryostats


rough
vacuum port
200 W
FC
x/y wire
scanner
beam
Retractable
FCT
TCT
gate valve
BPM
bellows

END

Intermodule diagnostic box

