Soreq

Operational Experience and Future Goals of the SARAF linac

Dan Berkovits, Leonid Weissman, Alex Arenshtam, Yaqir Ben Aliz, Yaniv Buzaglo, Ofer Dudovich, Yosef Eisen, Ilan Eliyahu, Gitai Feinberg, Israel Fishman, Inbal Gavish, Isaac Gertz, Asher Grin, Shlomi Halfon, Dan Har-Even, Yaara Haruvy, Tsviki Hirsh, Dan Hirschmann, Zvi Horvitz, Boaz Kaizer, Danny Kijel, Arik Kreisel, Geoffrey Lempert, Joseph Luner, Amichay Perry, Eyal Reinfeld, Jacob Rodnizki, Guy Shimel, Asher Shor, Ido Silverman, Efi Zemach

September 10th 2012

LINAC12 @ Tel-Aviv

Outline

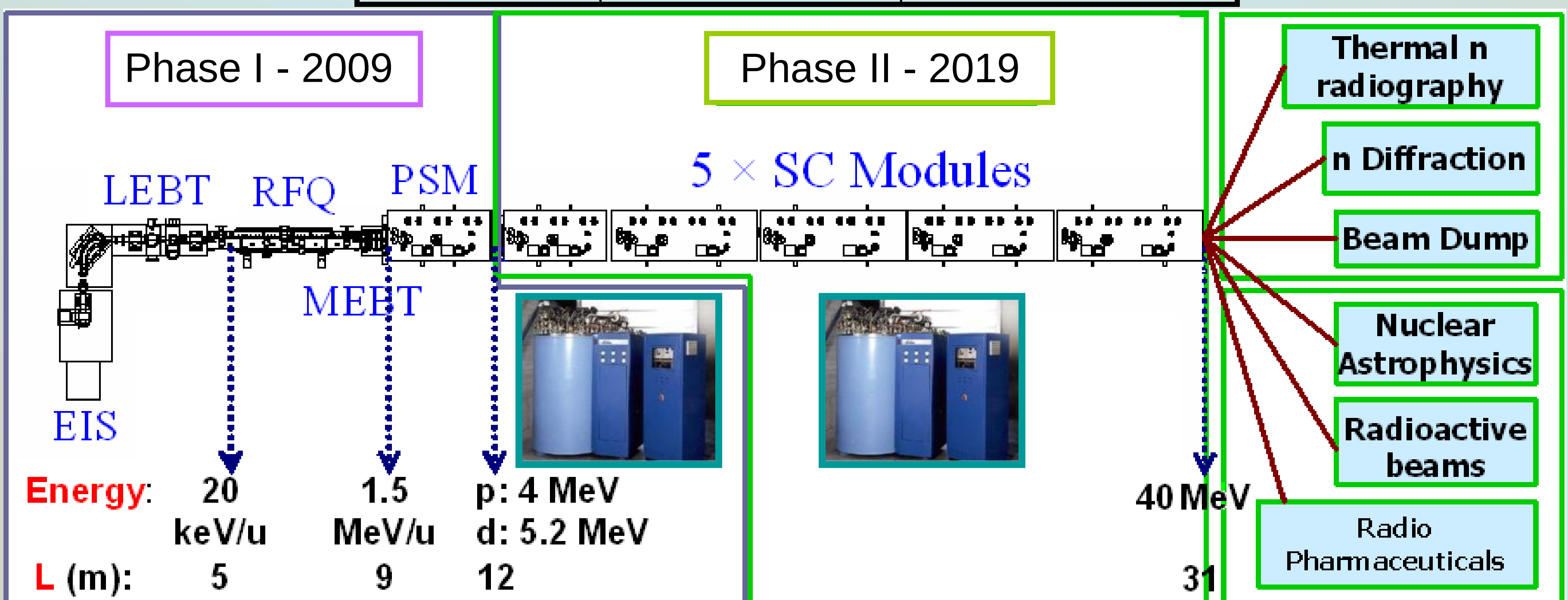
- Introduction
  - The need
  - The accelerator requirements
  - Phase-I components
- Phase-I operation experience
- Plans for Phase-II

SARAF – Soreq Applied Research Accelerator Facility

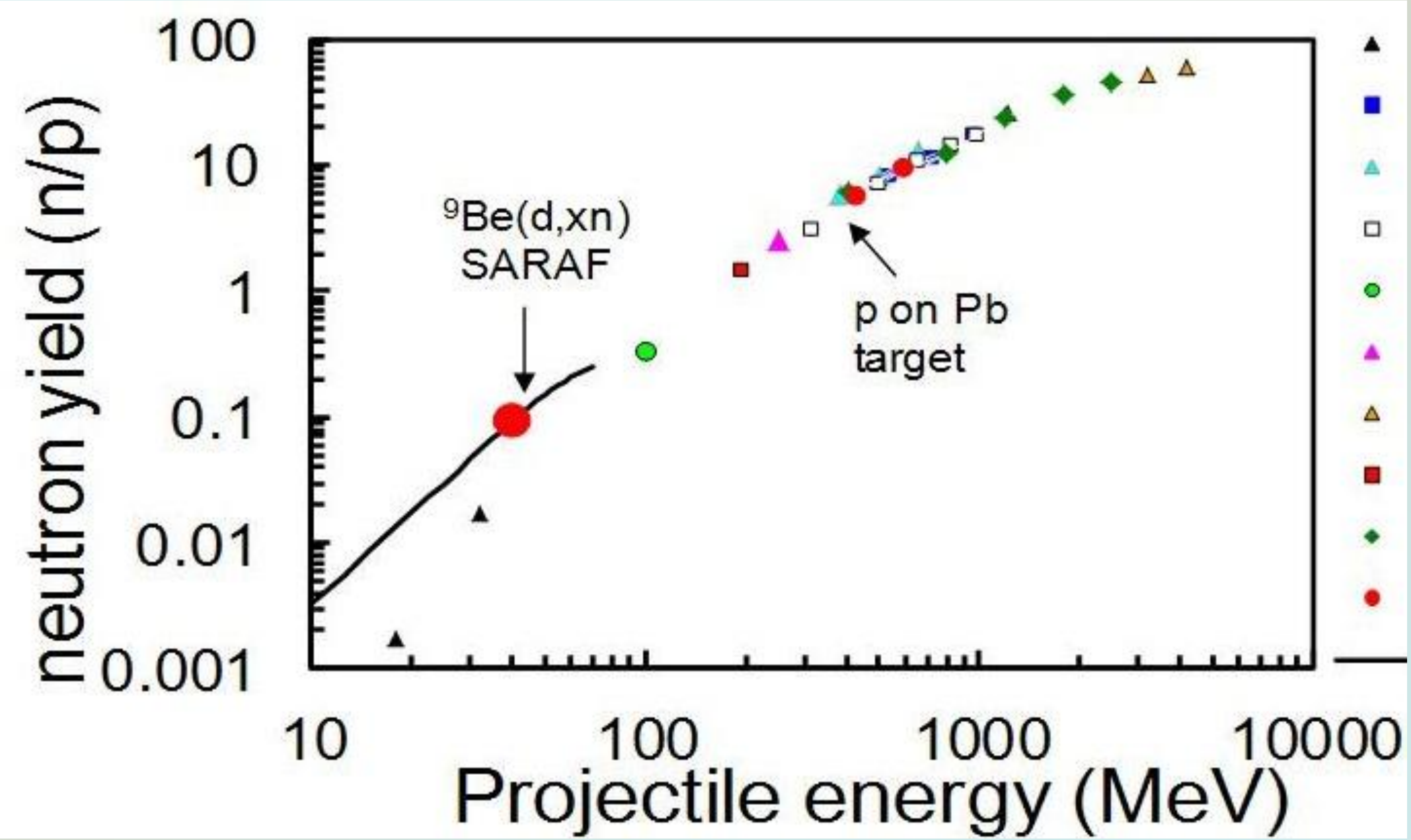
- To enlarge the experimental nuclear science infrastructure and promote research in Israel
- To develop and produce radioisotopes for bio-medical applications
- To modernize the source of neutrons at Soreq and extend neutron based research and applications

SARAF Accelerator Complex

Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	Variable energy
Current Range	0.04 – 5 mA	CW (and pulsed)
Operation	6000 hours/year	
Reliability	90%	
Maintenance	Hands-On	Very low beam loss



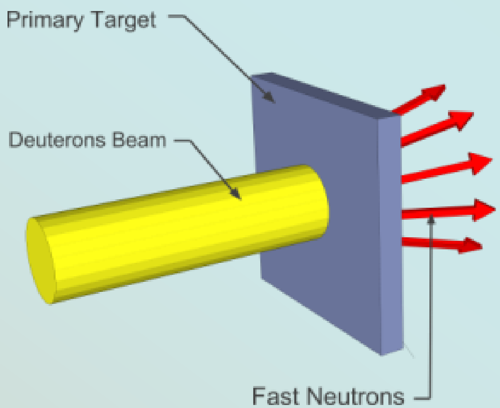
Neutron yield from d and p beams



❖ In the range of tens of MeV projectiles, neutron yield from deuterons is higher than that of protons by a factor of 3-5

K. van der Meer, M.B. Goldberg et al. NIM B (2004)

n spectrum of d-Li with 40 MeV

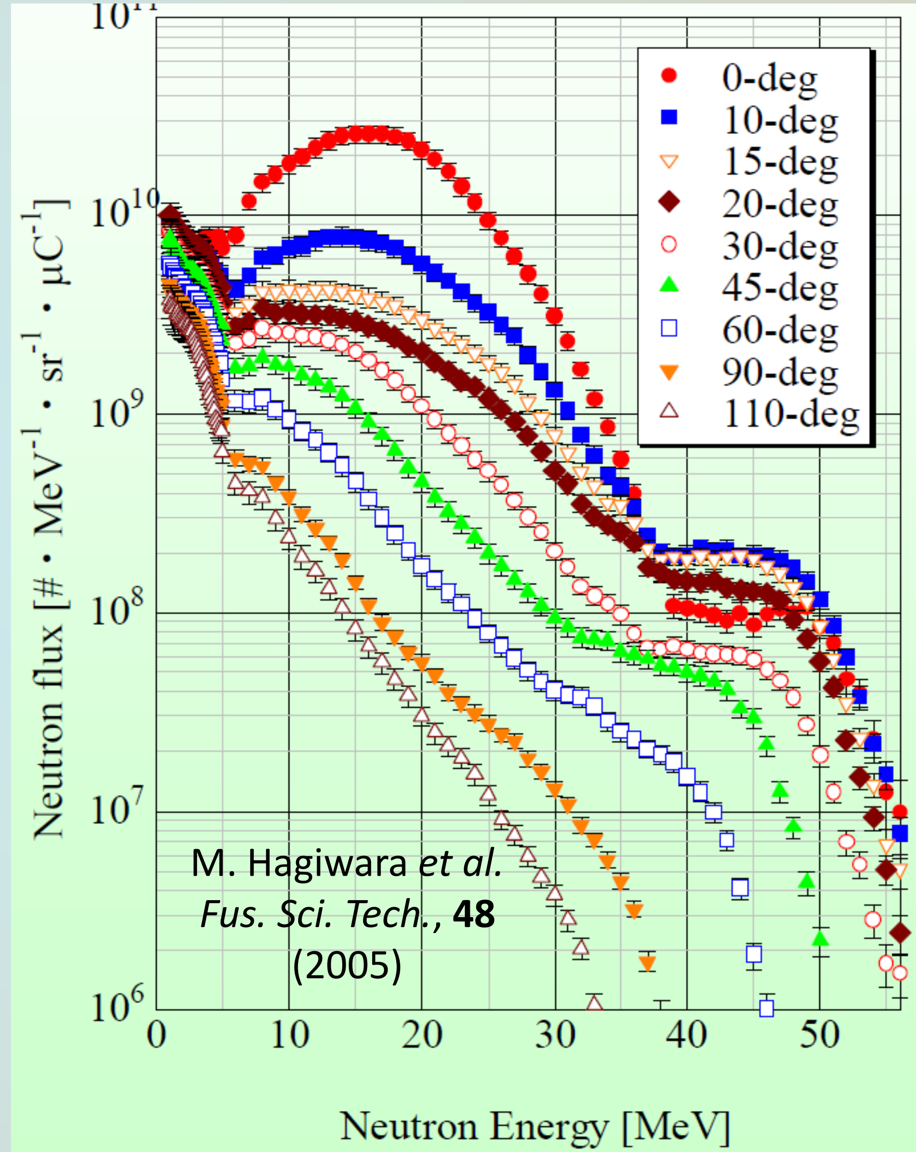


$4 \cdot 10^{14}$ n/sec/mA

<En> = 15 MeV

SARAF phase-I liquid lithium target (LiLiT)

G. Feinberg *et al.* NPA 2009
S. Halfon *et al.* App. Rad. 2011



M. Hagiwara *et al.* *Fus. Sci. Tech.*, **48** (2005)

Production of radiopharmaceutical isotopes

- Today, most radiopharmaceutical isotopes are produced by protons
- Deuterons
  - Production of neutron-rich isotopes via the (d,p) reaction (equivalent to the (n,γ) reaction)
  - Typically, the (d,2n) cross section is significantly larger than the (p,n) reaction, for A>~100

I. Silverman et al. NIM B (2007)

	Protons		Deuterons	
Target/ Product	energy range (MeV)	TTY MBq/mAh	energy range (MeV)	TTY MBq/mAh
^{103}Rh/^{103}Pd	20 → 8	12	20 → 8	22
^{186}W/^{186}Re	30 → 8	11	20 → 10	19
^{111}Cd/^{111}In	30 → 8	95	20 → 8 (^{nat}**Cd**)	20
^{114}Cd/^{114m}In	30 → 8	2,2	20 → 9	3,6
^{nat}Er/^{170}Tm	30 → 9	0,065	20 → 9	0,055
^{169}Tm/^{169}Yb	30 → 9	2,2	20 → 9	3,74
^{192}Os/^{192}Ir	20 → 9	0,18	20 → 9	0,88
^{100}Mo/^{99}Mo	40 → 8	14,3	40 → 20	16,2
^{176}Yb/^{177}Lu	NA	NA	20 → 8	1,02

Hermanne
Nucl. Data (2007)

Accelerator requirements

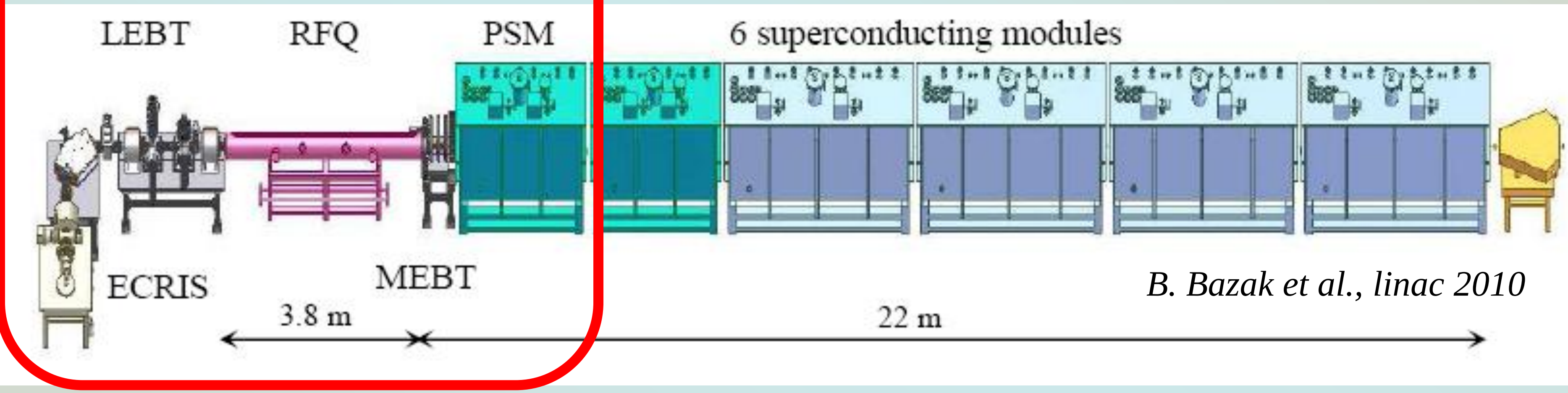
- Low energy – moderate accelerator cost
- Deuterons – be efficient in neutron production
  – enable neutron-rich isotope production
- Protons – common isotopes production
- High intensity – a n flux similar to the IRR1 TNR image plane
- Variable energy – be specific in isotopes production
- CW – avoid thermal stress in targets
- Pulsed – enable beam tuning with space charge (using slow pulses)
- Low beam loss – enable hands-on maintenance

➔ superconducting RF linear accelerator

SARAF Accelerator (2003 design view)

PSM – Prototype Superconducting Module
176 MHz HWR

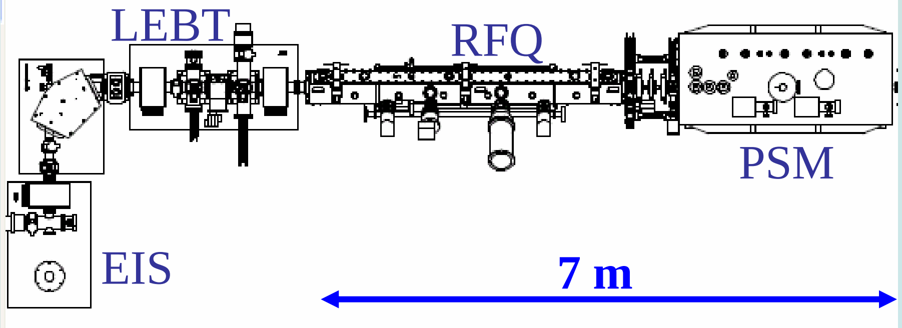
Phase-I working

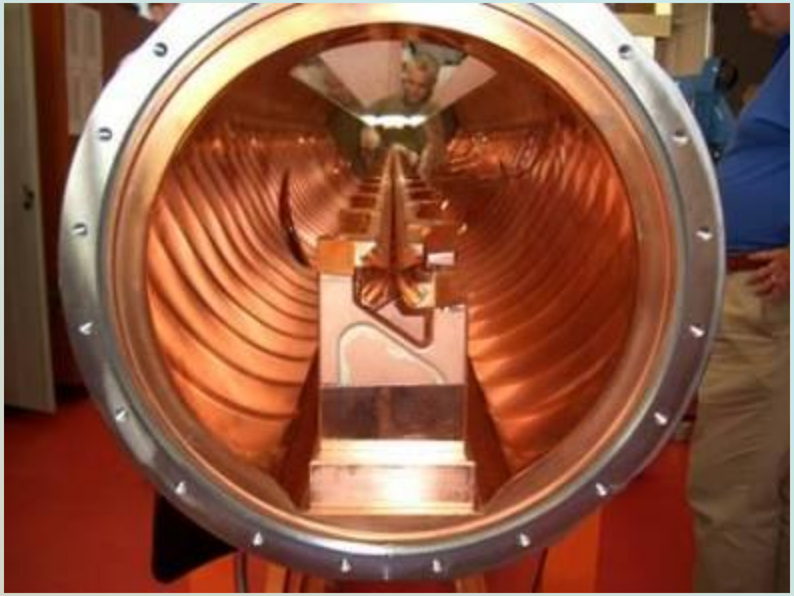


M. Pekeler, SRF 2003 (HWR)
K. Dunkel, EPAC 2004 (linac)
M. Peiniger, LINAC 2004
A. Shor, LINAC 2004 (beam dynamics)
P. Fischer, PAC 2005 (RFQ)
M. Pekeler, PAC 2005 (LLRF)
M. Pekeler, SRF 2005 (HWR)
C. Piel, PAC 2005 (ECR)
C. Piel, PAC 2005 (HPA)

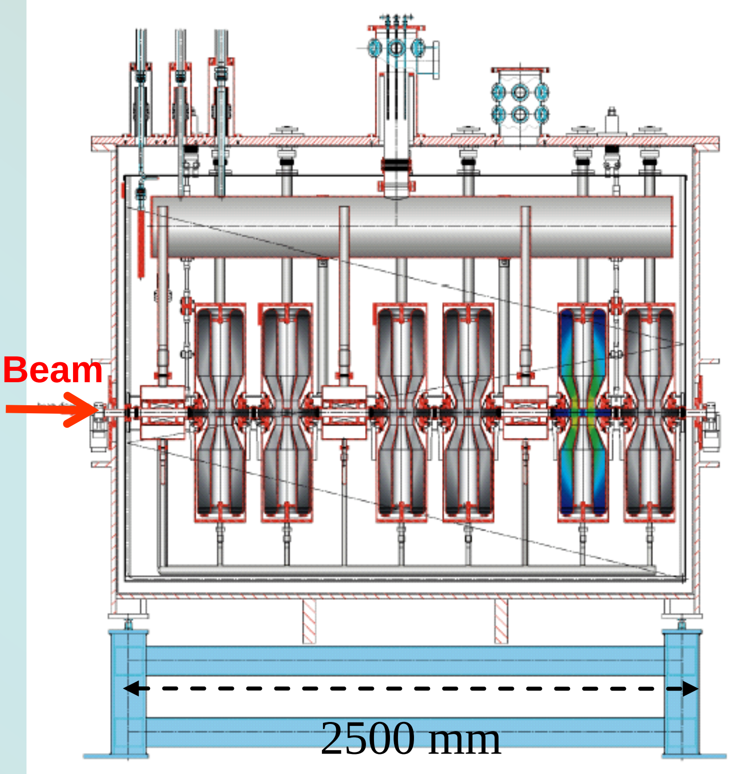
M. Pekeler, HPSL 2005 (beam dynamics)
M. Pekeler, HPSL 2005 (PSM)
P. Fischer, EPAC 2006 (RFQ)
M. Pekeler, LINAC 2006 (PSM)
C. Piel, EPAC 2006 (linac)
J. Rodnizki, LINAC 2006 (beam dynamics)
I. Mardor, LINAC 2006 (halo monitor)
I. Mardor, LINAC 2006 (FOP)
J. Rodnizki, HB 2006 (beam dynamics)

SARAF Phase-I 176 MHz linac





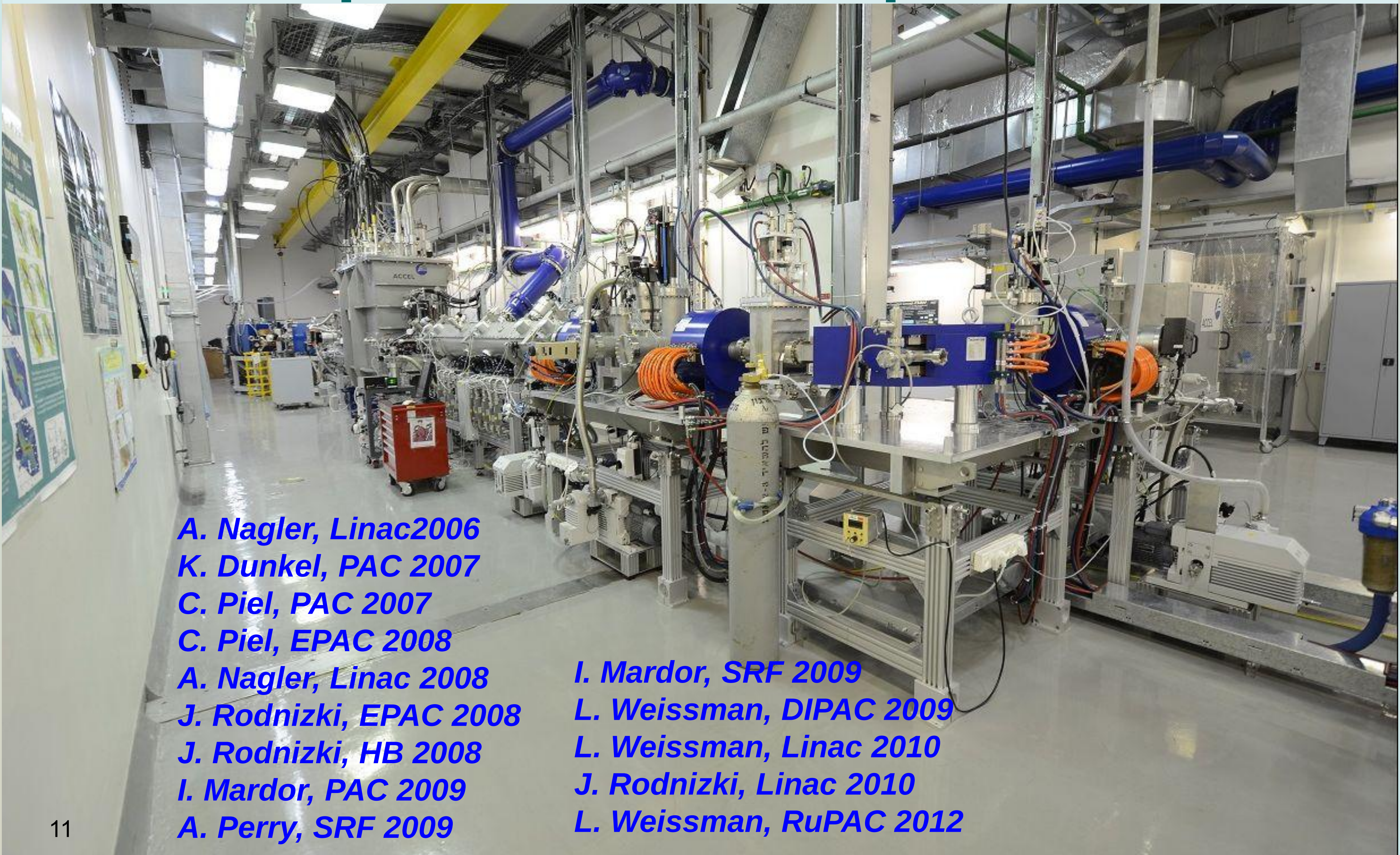
4-rod, 250 kW, 4 m, 1.5 MeV/u
P. Fischer et al., EPAC06



6 HWR β=0.09, 0.85 MV, 60 Hz/mbar
3 Solenoids 6T, separated vacuum
protons 4 MeV, deuterons 5 MeV

M. Pekeler, LINAC 2006

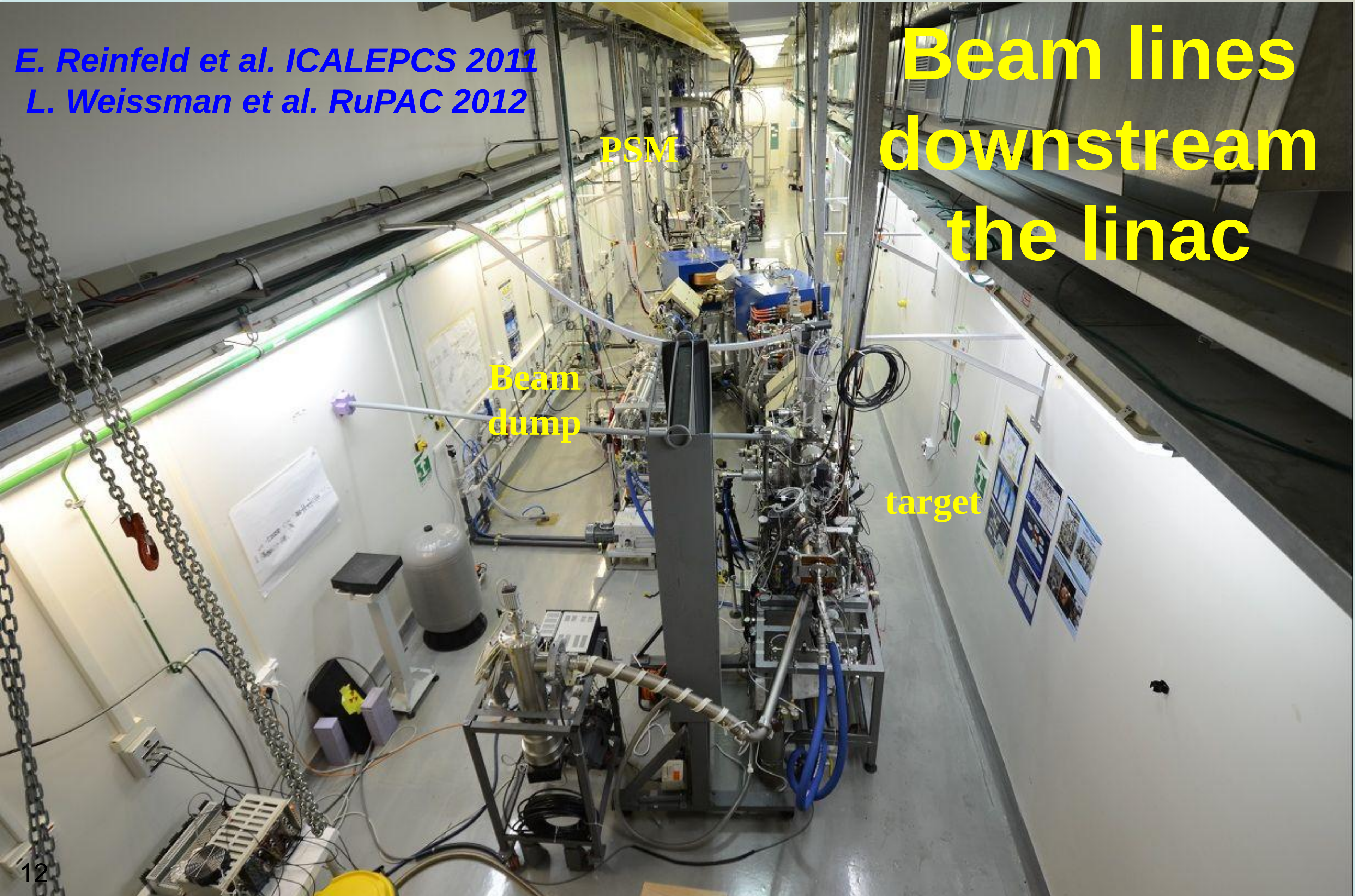
SARAF phase-I linac – upstream view



A. Nagler, Linac2006
K. Dunkel, PAC 2007
C. Piel, PAC 2007
C. Piel, EPAC 2008
A. Nagler, Linac 2008
J. Rodnizki, EPAC 2008
J. Rodnizki, HB 2008
I. Mardor, PAC 2009
A. Perry, SRF 2009
I. Mardor, SRF 2009
L. Weissman, DIPAC 2009
L. Weissman, Linac 2010
J. Rodnizki, Linac 2010
L. Weissman, RuPAC 2012

Beam lines downstream the linac

E. Reinfeld et al. ICALEPCS 2011
L. Weissman et al. RuPAC 2012



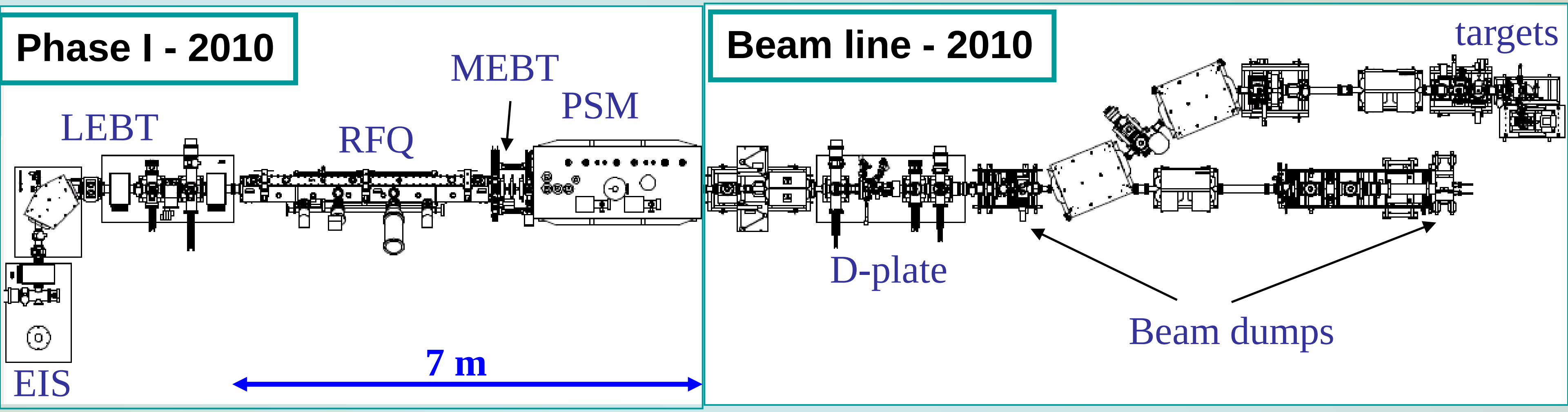
SARAF Phase-I linac status

Difficulties and challenges at high energy are caused by instabilities and space charge effects at the low energy front end

A journey of a thousand miles begins with a single step (Laozi 604 bc - 531 bc)

- SARAF Phase-I is the first to demonstrate:
  - ☑ 1 mA CW variable energy protons beam
  - ☑ Acceleration of ions through HWR SC cavities
  - ☑ Acceleration of ions through a separated vacuum SC module

SARAF summer 2012

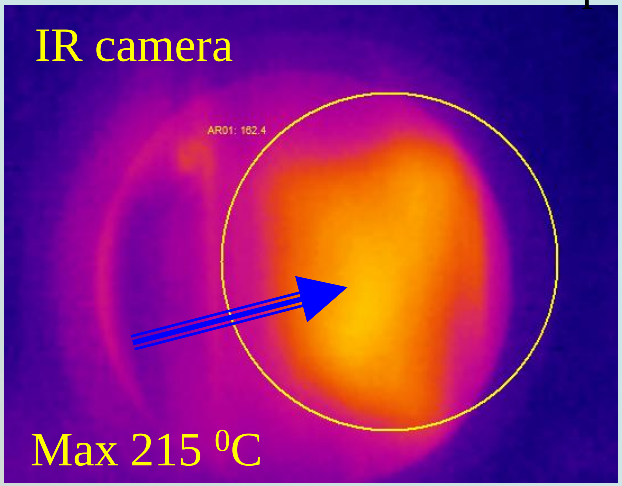


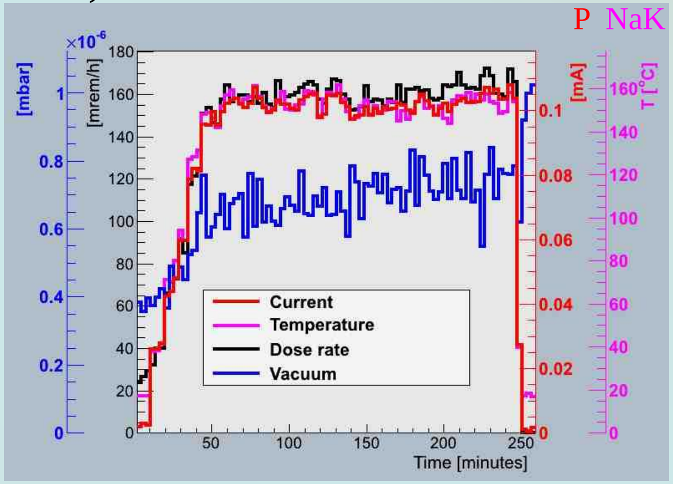
- Linac is operated routinely with CW 1mA protons at ~4 MeV
- Phase I commissioned to 50% duty cycle 4.8 MeV deuterons
- The accelerator is used most of the time to:
  - Study high intensity beam tuning
  - Interface with high intensity targets
  - Develop of high intensity targets

Production target

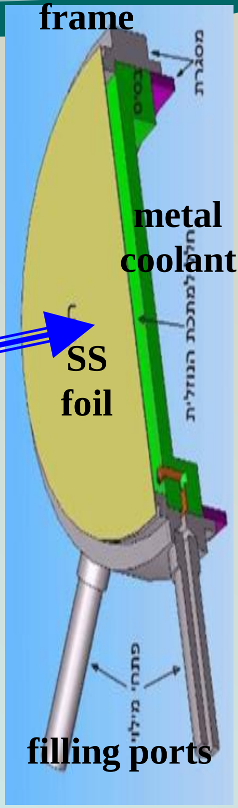
Heat removal and radiation damage tests

3.7 MeV 0.1 mA protons, 2.5 W/mm^2

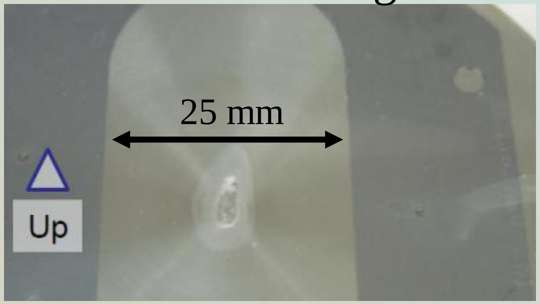




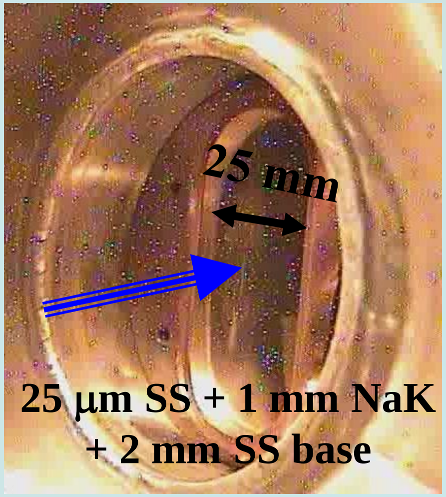
I. Silverman *et al.*
PATENT
WO/2006/035424
(2006)



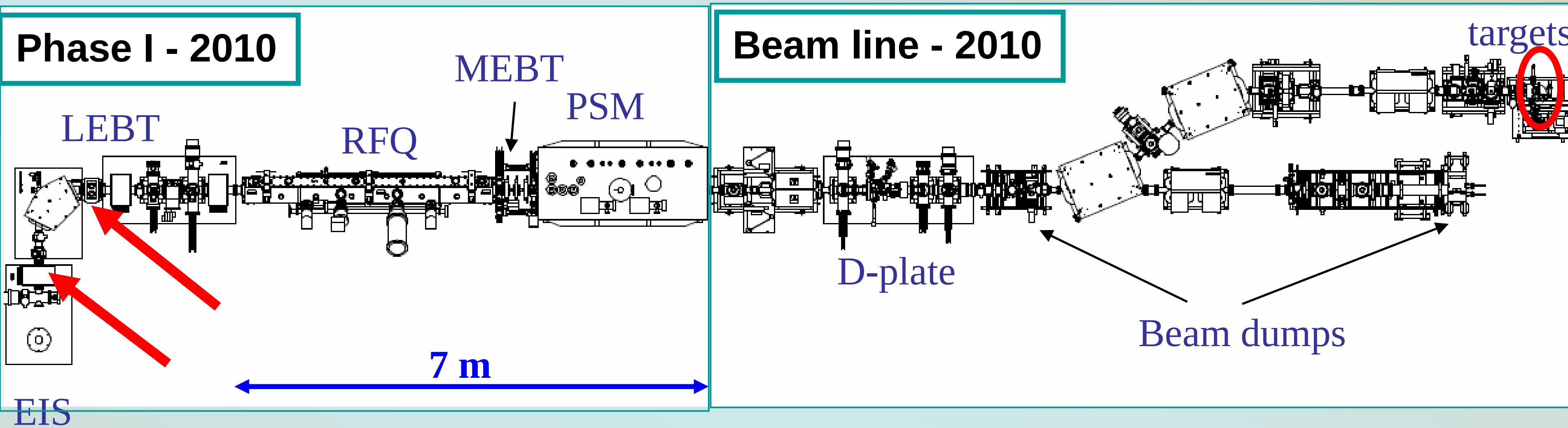
3.9 MeV 0.2 mA protons
15 W/mm^2
2 mm thick SS
water cooled target



- ➔ **The most important parameter for accelerator beam tuning are:**
- **meeting the designed beam heat flux in units of W/mm^2**
- **Intensity ramping without moving beam center neither changing the beam shape**



Beam optics study



- LINAC and beam line tune is done with a pulsed beam
- Different beam diagnostics instruments require different pulsed beam parameters (duty cycle and beam intensity)

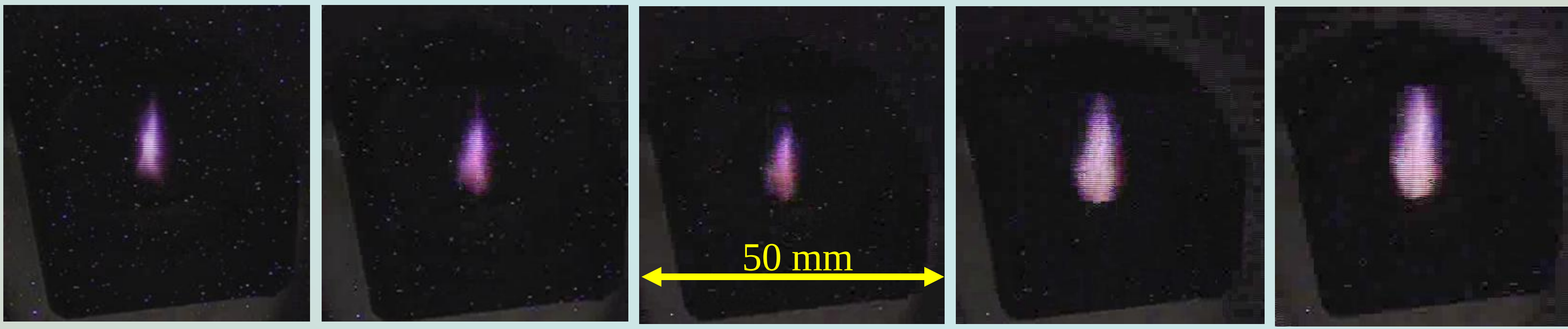
Novel LEBT chopper: A. Shor *et al.* THPB094.

- During CW beam tuning intensity is ramped by a factor of ~100.

Beam intensity control using LEBT aperture

•A quartz viewer upstream of the target, enables efficient studies of the front end parameters' influence on the beam profile near the target.

•In the example below, the effect of opening the LEBT aperture is shown:



aper=5 mm **aper=10 mm** **aper=20 mm** **aper=30 mm** **aper=50 mm**

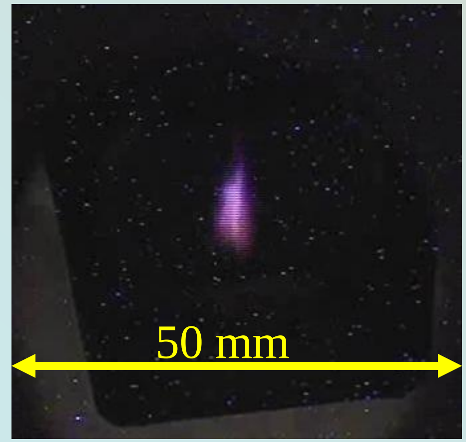
•LEBT aperture is used to vary the beam intensity within an order magnitude.

•The measurements show that to first order , **the beam position on target does is independent on the aperture opening**

Beam intensity control by LEBT solenoids

Sol1=64 A

Sol1=62 A



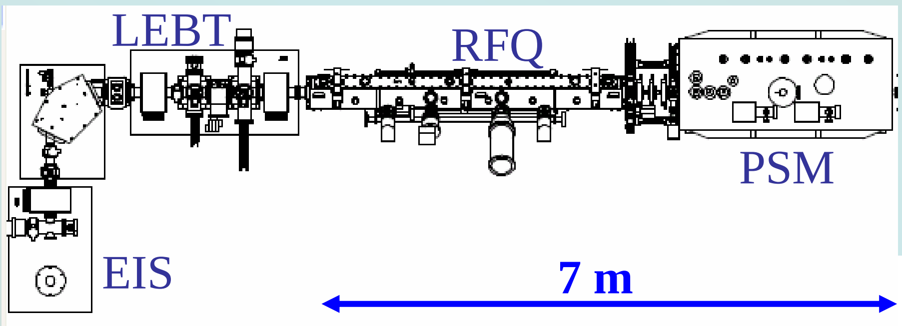
Sol1=60 A

Sol1=58 A

Varying the 1st LEBT solenoid enables increase of the beam intensity by another order of magnitude. The measurements show that **the beam position on target is independent on the solenoid current.**

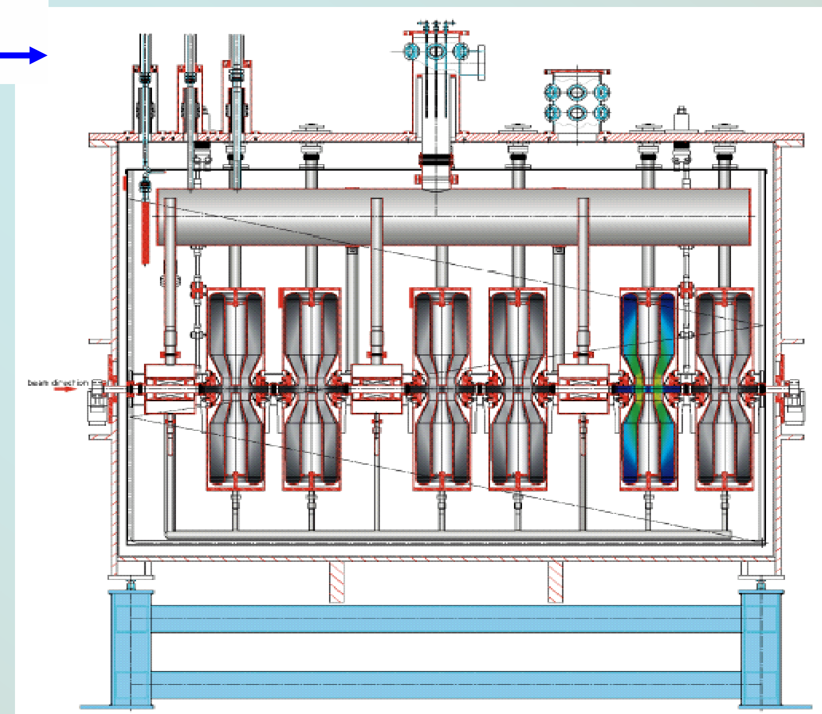
On the other hand, the measurements show some shifts of the beam position and shape with change of : the 3rd solenoid current, by using the LEBT steerers and the LEBT dipole.

Acceleration and bunching



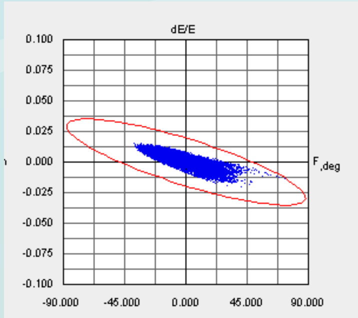
650 mm

beam

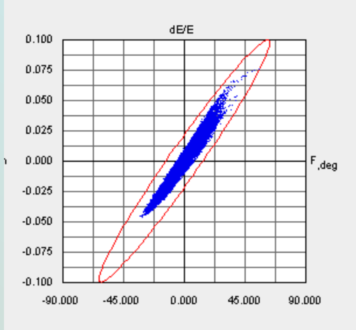


Beam Dynamics

Longitudinal phase space



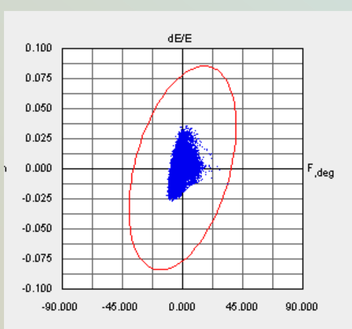
HWR1 entrance: First cavity is used as a buncher.



HWR1 exit: Forward protons are now less energetic.
A similar distribution at the entrance to HWR2, 5 cm downstream cavity 1.

Protons 0.2 mA

Component	Accel. voltage (kV)	Phase	Entr. Velocity (%c)	Exit Energy (MeV)
HWR 1	229	-90	5.7	1.52
HWR 2	459	30	5.7	1.81
HWR 3	459	-30	6.2	2.14
HWR 4	722	-20	6.8	2.76
HWR 5	833	-20	7.7	3.52
HWR 6	425	-10	8.7	3.93

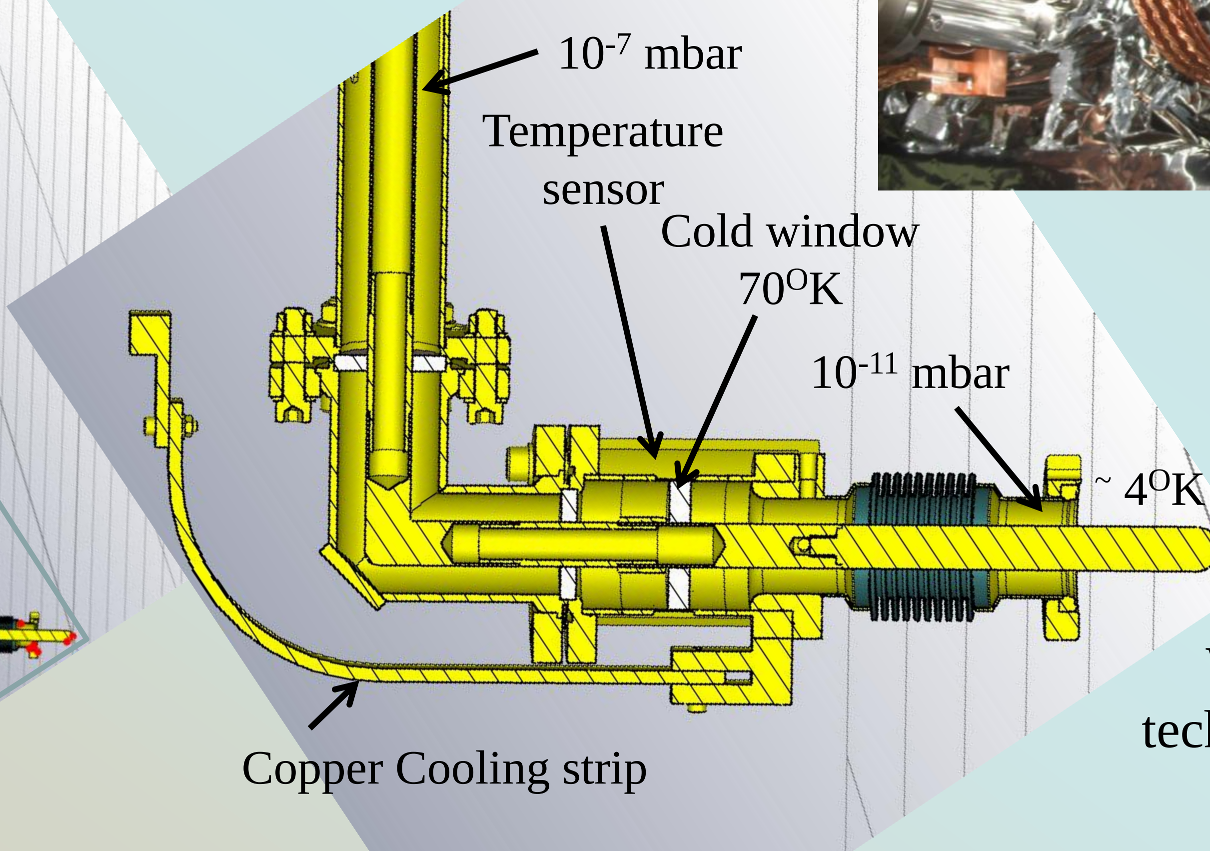


HWR2 exit: To accelerate without increasing ΔE, it is necessary to work at a positive phase in HWR2.

Some technical issues

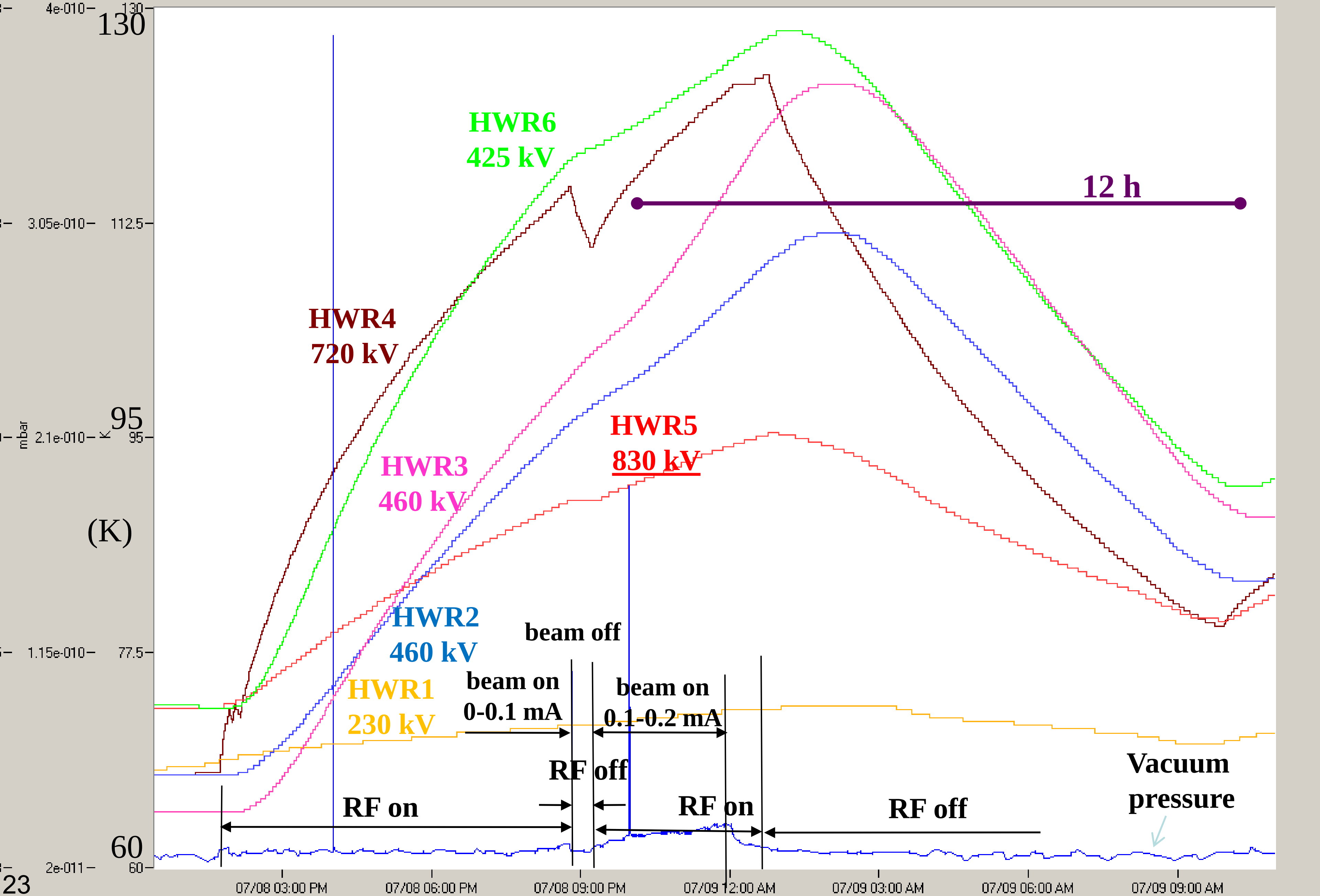
The PSM HWR 4 kW RF Coupler

M. Pekeler SRF 2003



We are studying techniques to improve coupler cooling

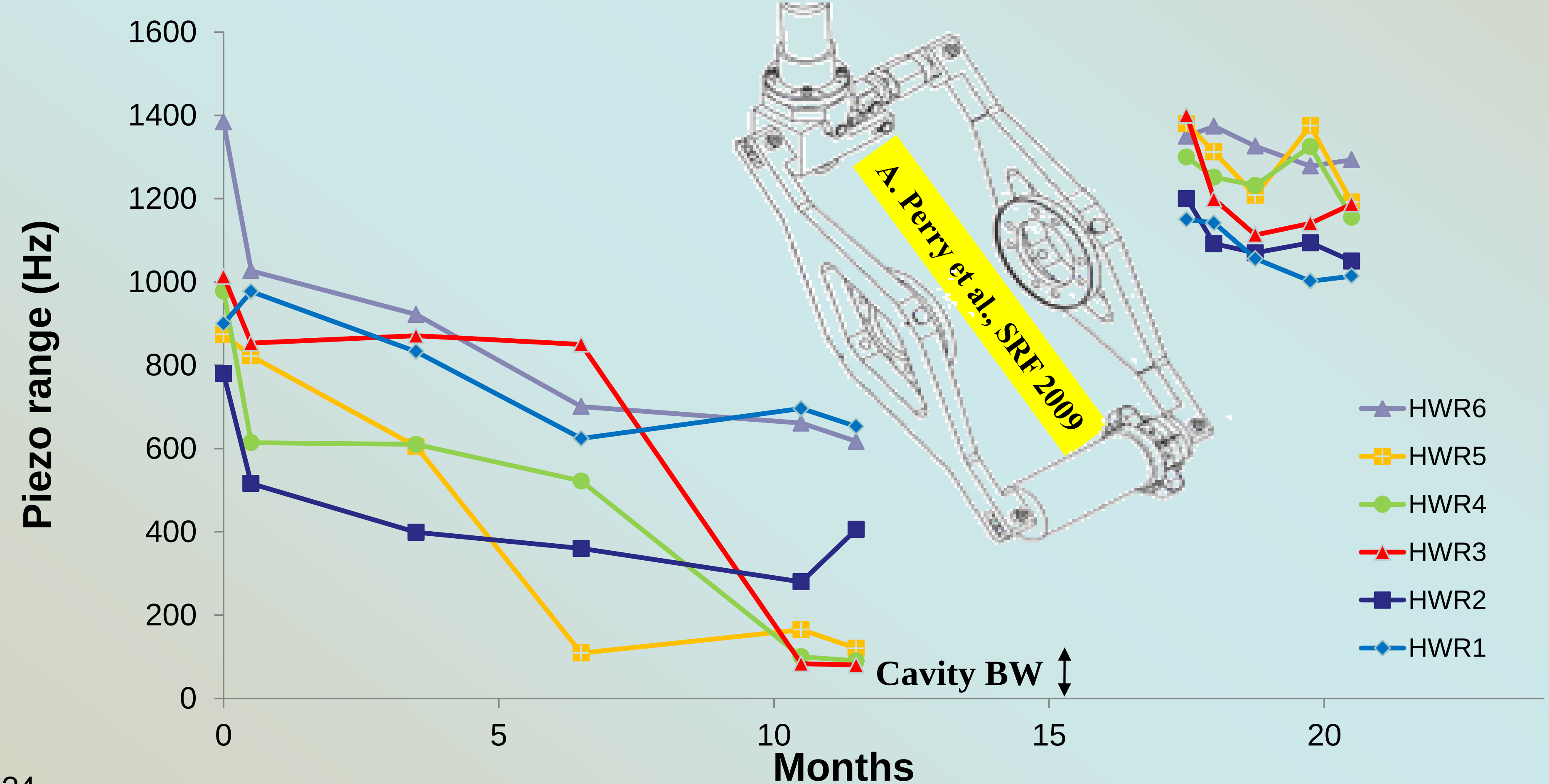
Couplers heating during 3.9 MeV p beam operation



Deterioration of the Piezo tuners

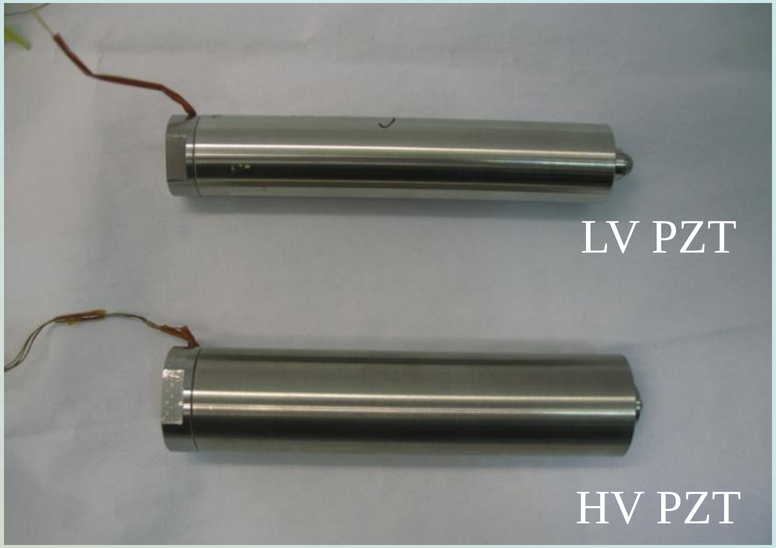
Softness of the cavities (~60 Hz/mbar) leads to high demands on cavities tuners, especially on the piezo tuners .

Dramatic deterioration in the tuning range that significantly hindered the accelerator's operation



Replacement of Piezo tuners

According to Piezomechanics recommendation, low-voltage (LV) tuners were replaced by high-voltage (HV) ones.



at room temperature

	HV PZT	LV PZT
Max. stroke[um]	130	130
Length[mm]	107	107
Capacitance[uF]	0.9	39
Stiffness[N/um]	75	40
Resonance[kHz]	20	10
Max force[N]	9750	5200

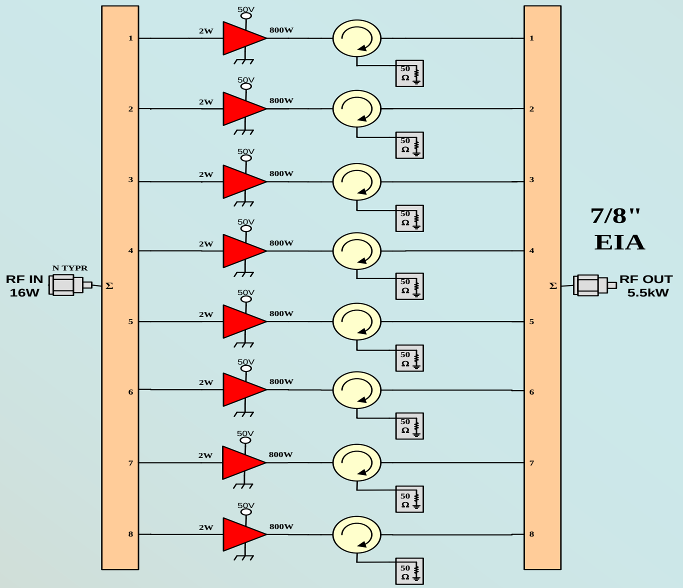
The maximum Piezo voltage (range) is limited during operation to 800V (80% of the nominal value) to avoid feed-through problems.

176 MHz RF power amplifiers development

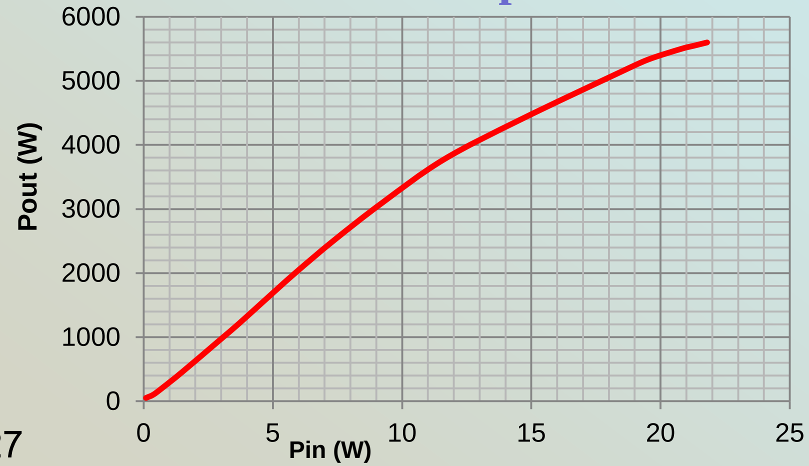
- Six 4 kW RF amplifiers are in routine operation

Basic 5.5 kW RF power amplifier

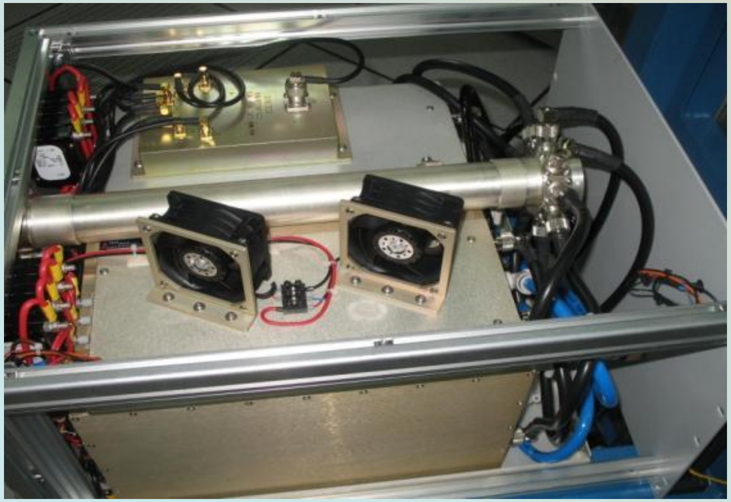
5.5 kW conceptual block diagram



5.5 kW drawer power test



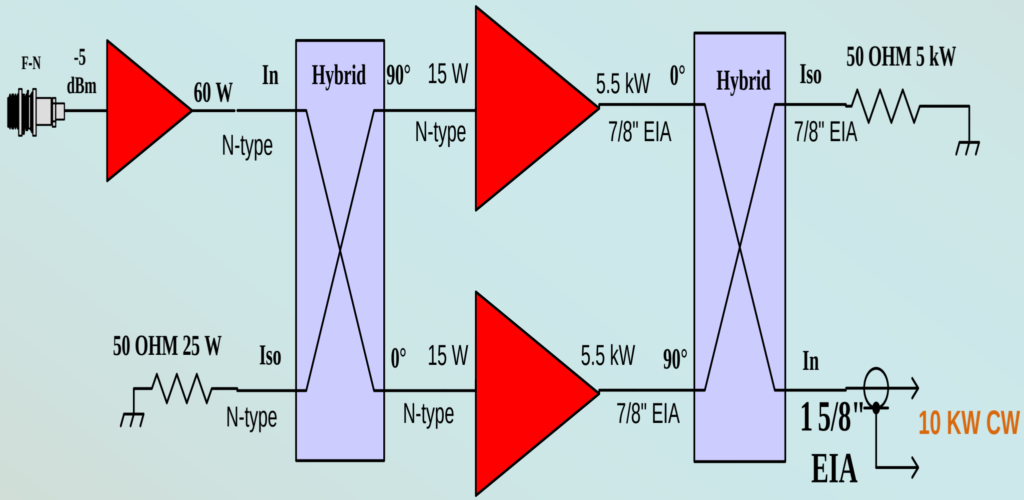
Inside view of the 5.5 kW drawer



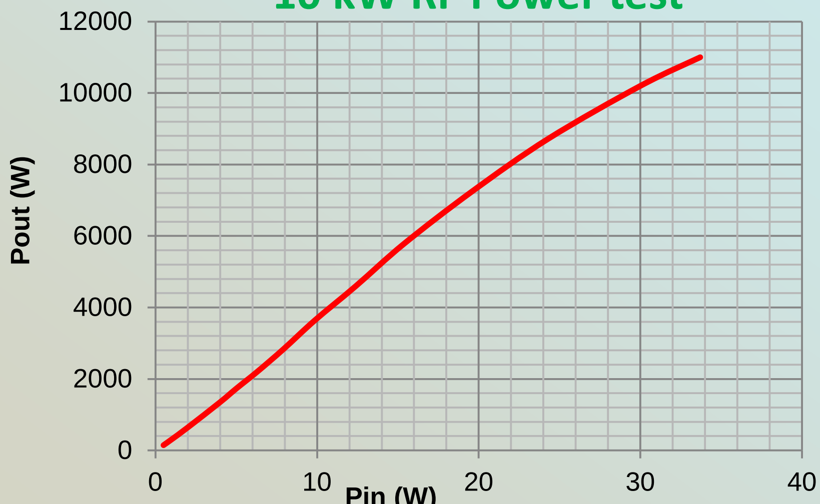
- RF frequency – [174 -178] MHz
- RF power - 5.5 kW CW (1dB)
- Power Gain – 24 dB (22 W @ 5.5 kW)
- Current consumption – 220 A (50VDC)
- Water cooling requirements – 25 l/min
- Size – 19”, 7U, 550 mm deep
- RF in connector – N-type
- RF output connector 7/8” EIA
- DC in 10 mm brass bolts
- Controls: FRD, RFL, Temp & Fault for each module

10 kW RF system

Conceptual electrical diagram



10 kW RF Power test



- Two RF 5.5 kW amplifier drawers are combined
- Can operate into infinite VSWR
- High Gain (only 35 W RF drive)
- 2 Power Supplies – 50 VDC, 220 A each
- Water cooling – 50 l/min
- Two 10 kW systems in one 48 U 25" RACK

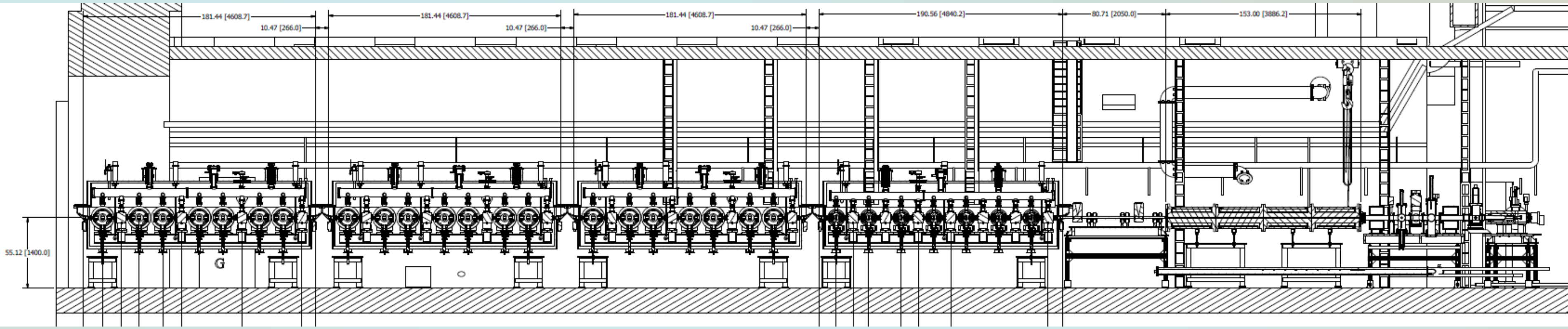
Kaizer *et al.* TUPB092

SARAF Phase-II linac plans

- Demonstrate high intensity targets durability (2012)

- Demonstrate RFQ CW operation for deuterons
  - Keep existing RFQ
    or
  - Build another RFQ
- Sign a contract with vendor(s) to design and build the linac up to 40 MeV
- Operation by 2019

ANL conceptual design (2012)



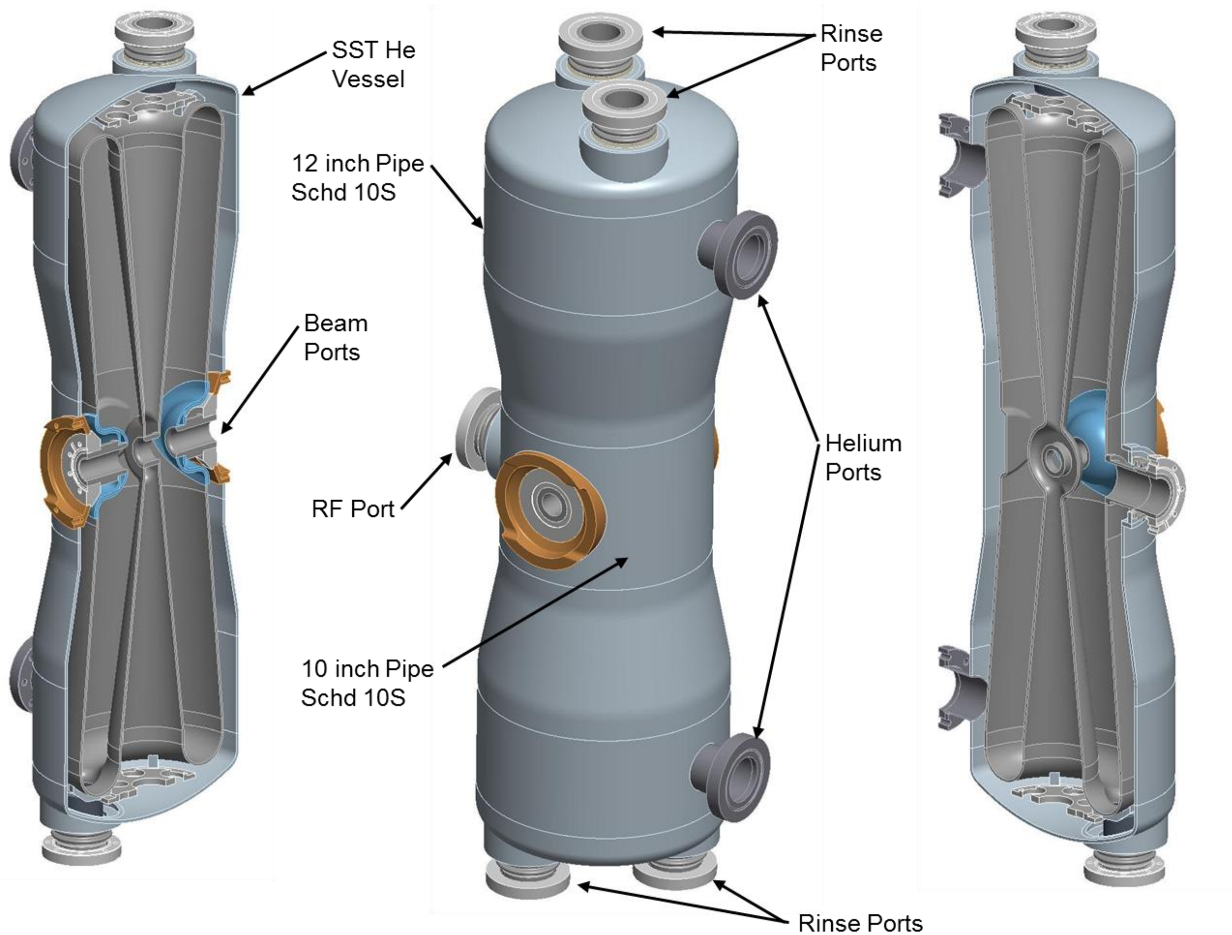
- The ion source and LEBT are in the original position
- New (RFQ) MEBT and superconducting linac
- 176 MHz β=0.09 and β=0.16 Half Wave Resonators
- Total superconducting linac = 19.47 m
- 7 low-β HWR operating at 1 MV and 21 high-β HWR operating at 2 MV
  - Beam dynamics study at **[B. Mustapha *et al.* IPAC 2012, J. Rodnizki *et al.* FR1A05]**
- Total (static and dynamic) power dissipation ~ 350 W @4K

P. Ostroumov *et al.* TUPB046

Low-β HWR ProE model

Work with AES

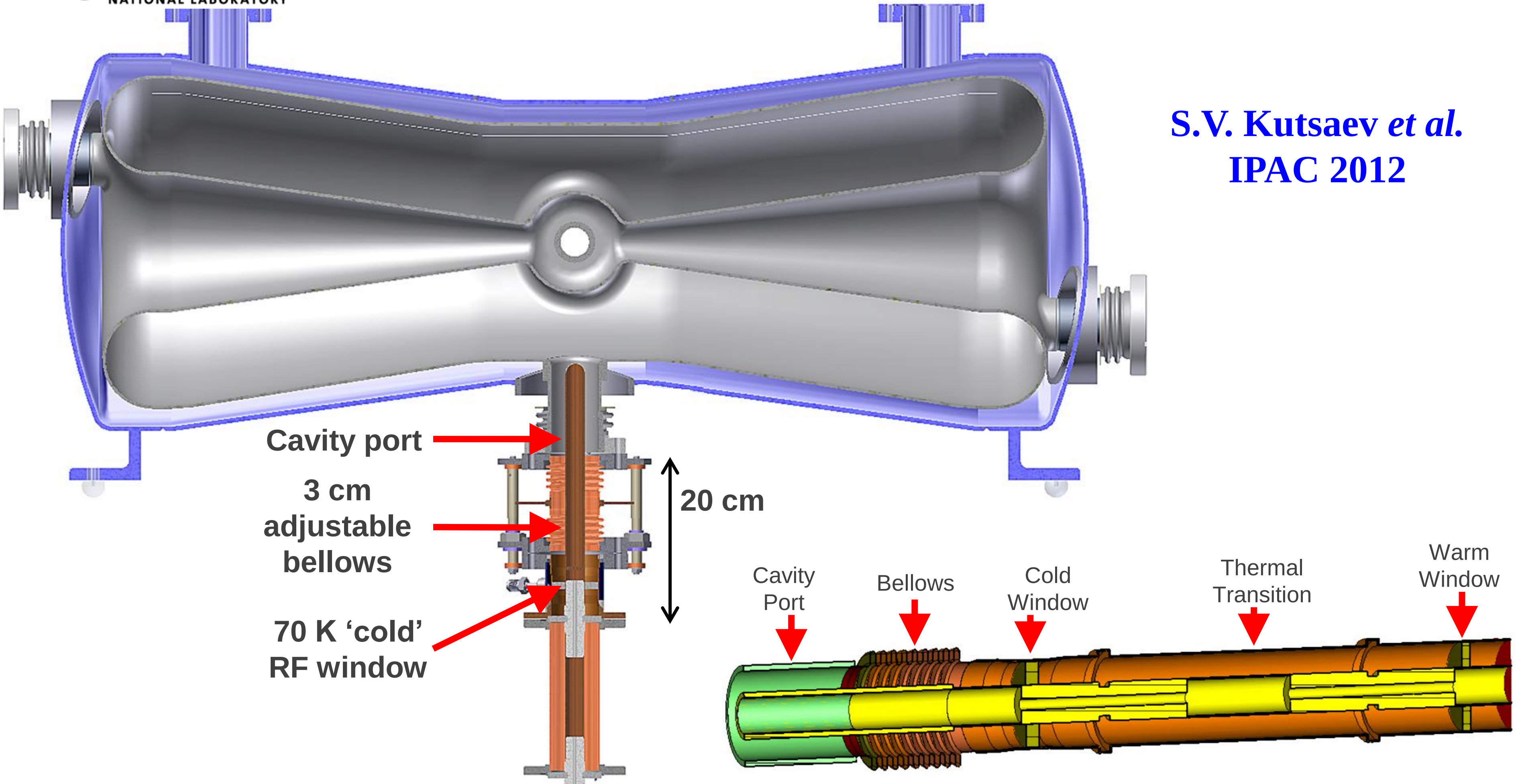
Design based on experience gained for the development of cavities for ATLAS
[Z. Conway *et al.* TUPB066]
[M. Kelly et al. MOPB073]
and for PXIE
[Z. Conway *et al.* TUPB067]
[P. Ostroumov IPAC 2012]

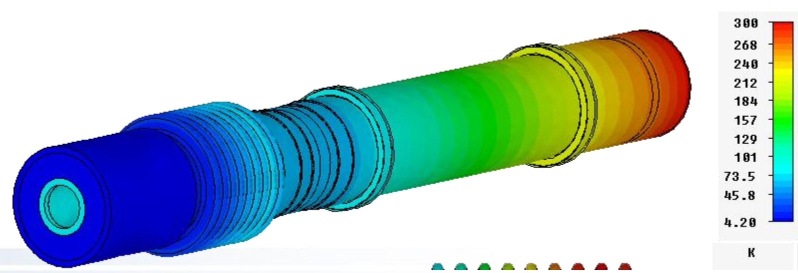


- df/dP is less than 2 Hz/mbar (and 3.5 Hz/mbar for the high β)
  - A "flat" area helps to reduce df/dP
- Slow Tuner @ 2000 lb Δf = 90 kHz

15 kW CW Power Coupler for SARAF

S.V. Kutsaev *et al.*
IPAC 2012





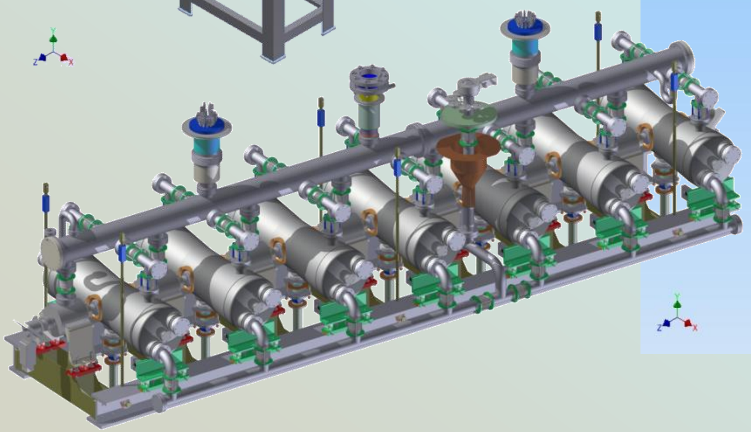
- Total heat loss to 4.2K = 1.59 W
- Transition to 79 mm (3-1/8 inch) coaxial line outside of the cryomodule

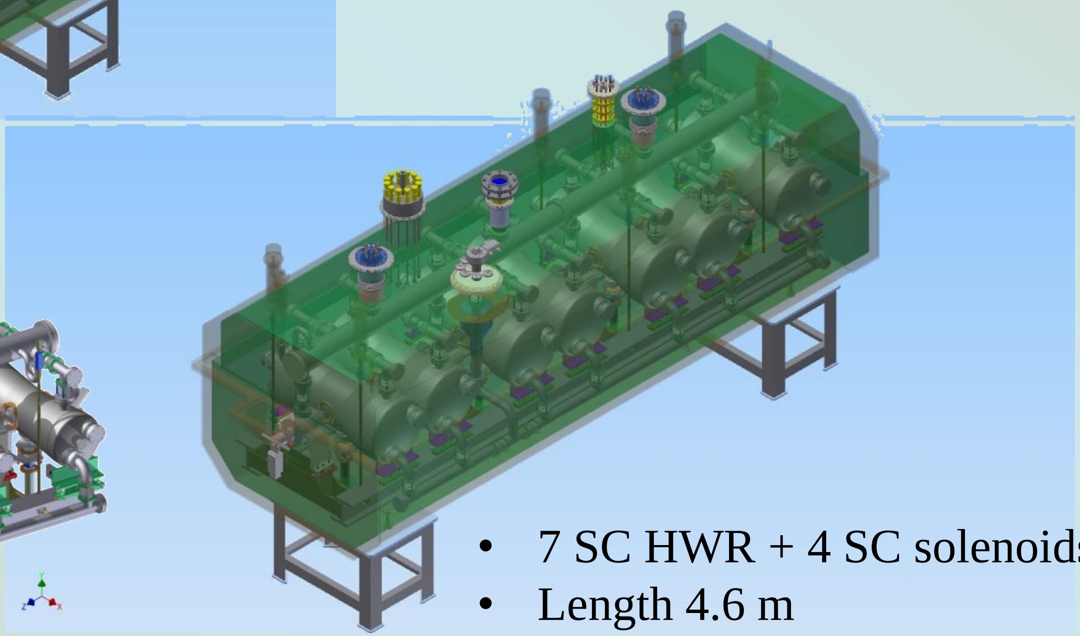
The superconducting modules

- 7 SC HWR + 7 SC solenoids
- Length 4.8 m
- Width 1.9 m
- Height 1.65 m

Z. Conway *et al.* TUPB068

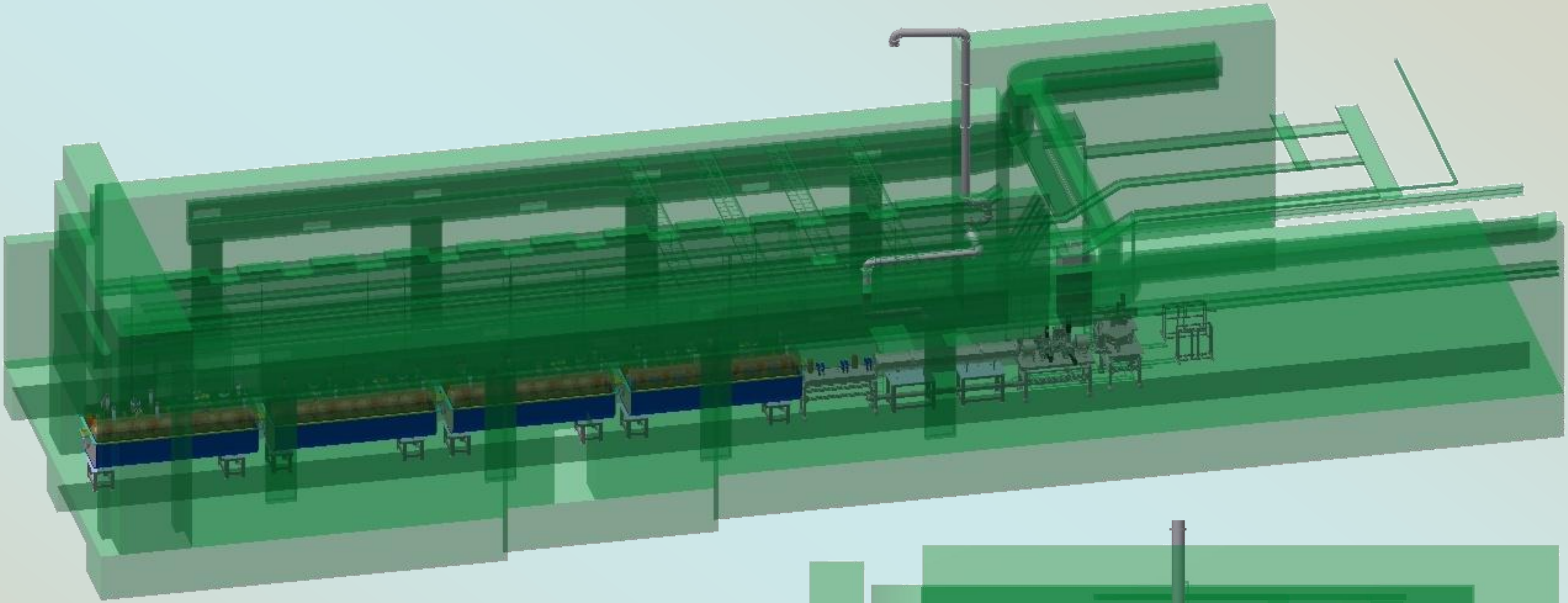
Each SC solenoid unit includes X-Y steerers and a cold BPM

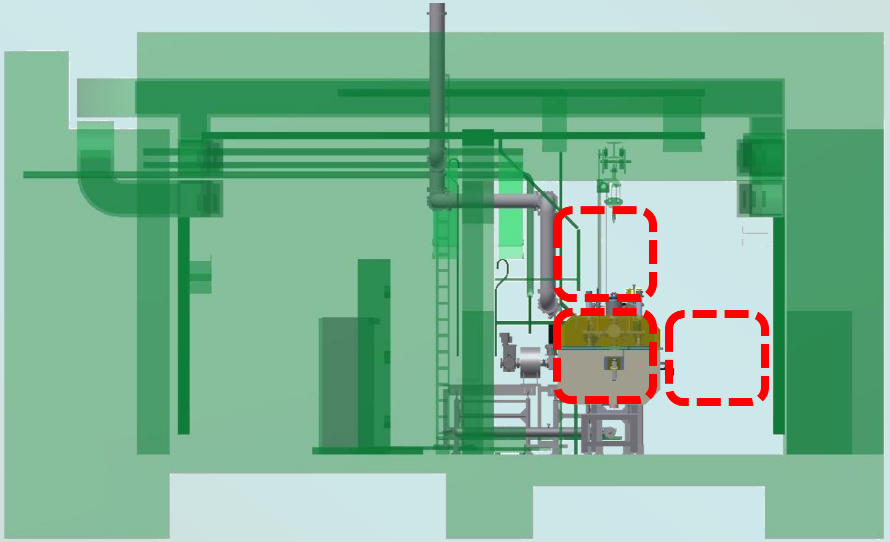




- 7 SC HWR + 4 SC solenoids
- Length 4.6 m
- Width 1.9 m
- Height 1.65 m

Interfaces with the existing building





Summary

- SARAF requires a new kind of an accelerator
  - Light ion**s**, high-intensity, CW, variable-energy
- SARAF phase-I is in routine operation with 1 mA CW protons, gaining valuable experience for CW machines
- Targets for high-intensity low-energy beams are under development and testing
- A conceptual design for Phase-II was completed

END