SARAF linac experience with CW mA beams

at low variable energy

Dan Berkovits on behalf of SARAF linac team

HB 2016, Malmo

July 5th 2016

Outline

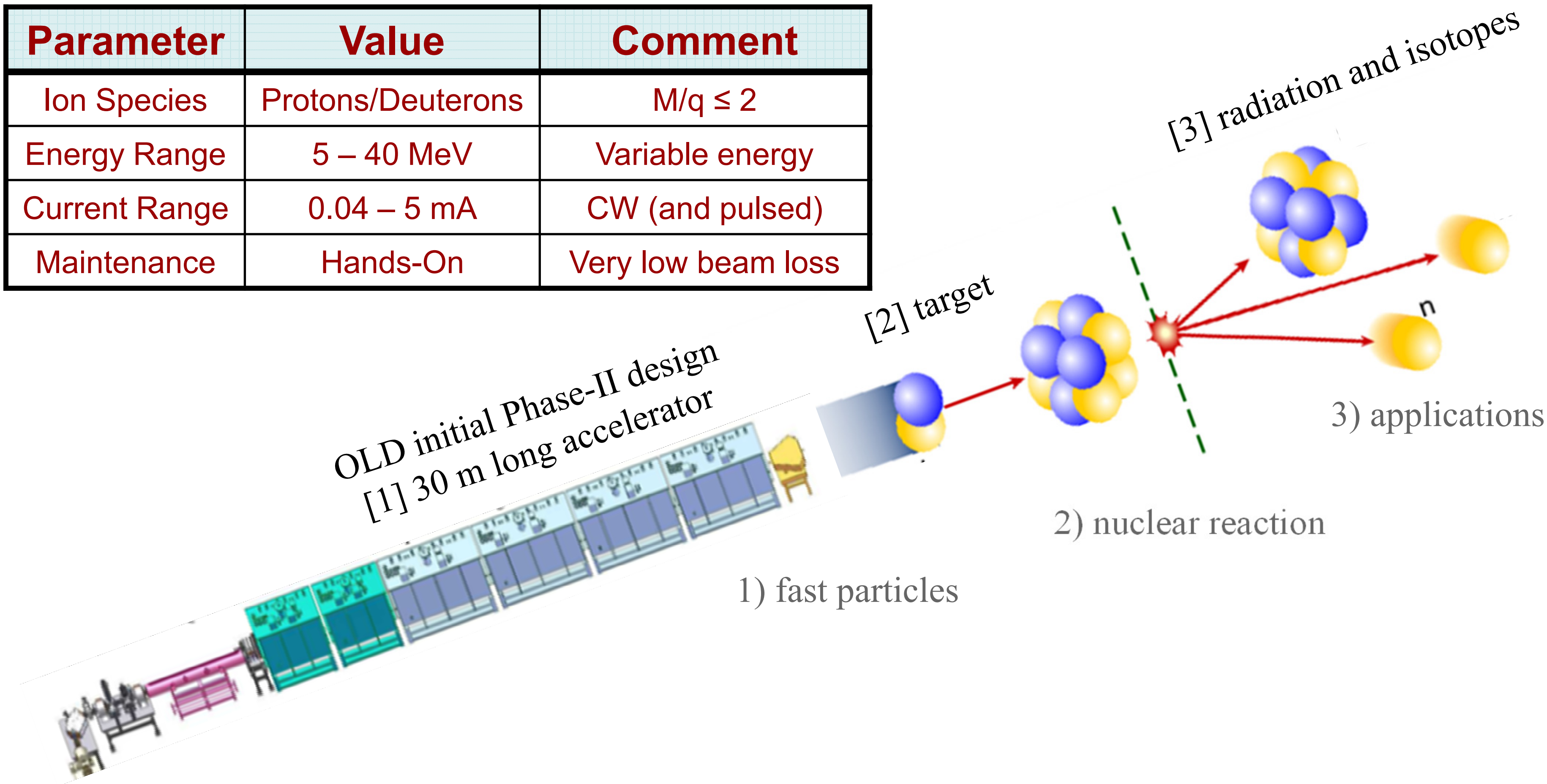
- Introduction:
- Phase-I experience
  - LEBT
  - RFQ
  - HEBT
- Initial versus latest Phase-II lattice design

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 concept and top level requirements

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)
Maintenance	Hands-On	Very low beam loss



SARAF concept and top level requirements

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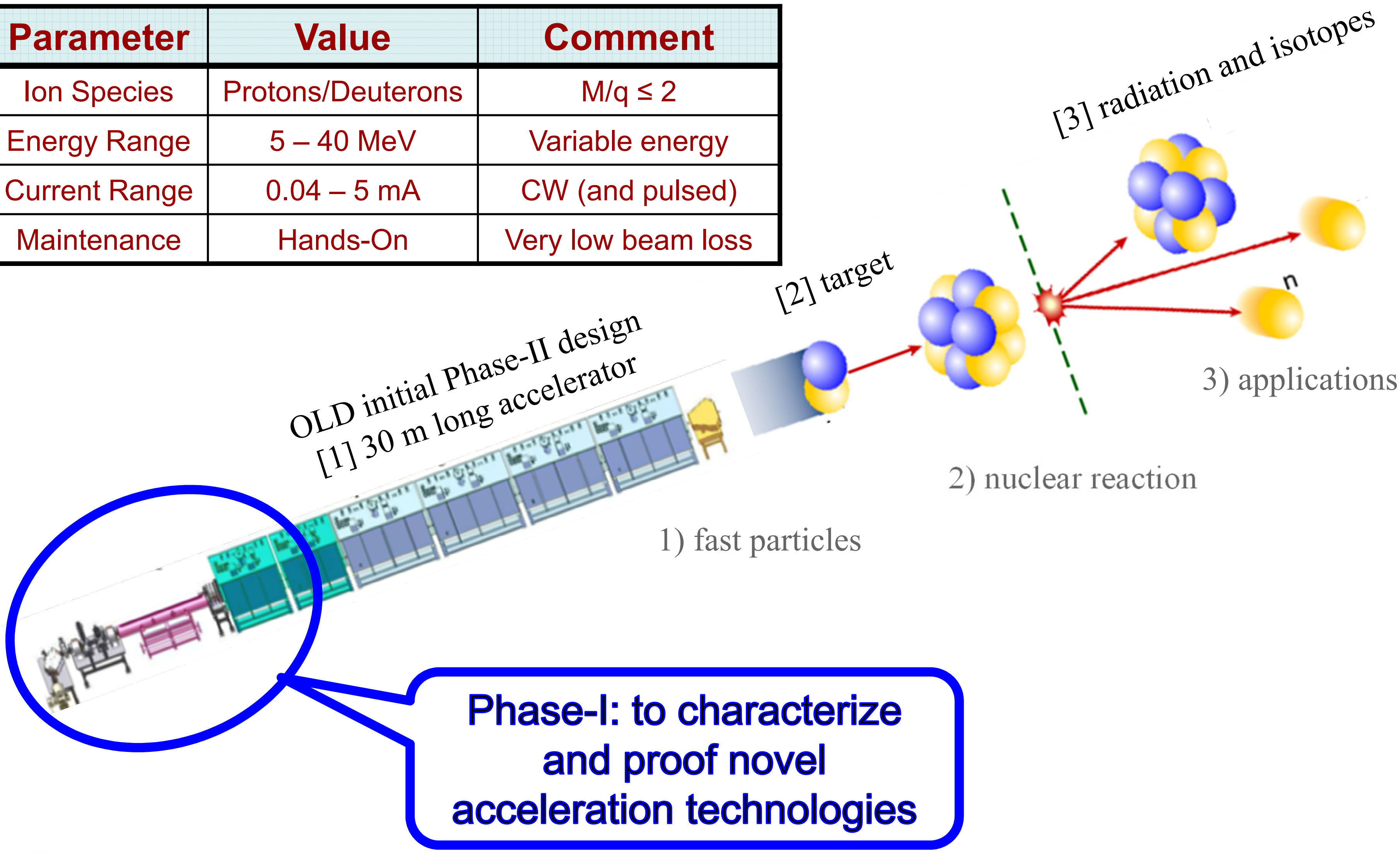

SARAF concept and top level requirements

Parameter	Value	Comment
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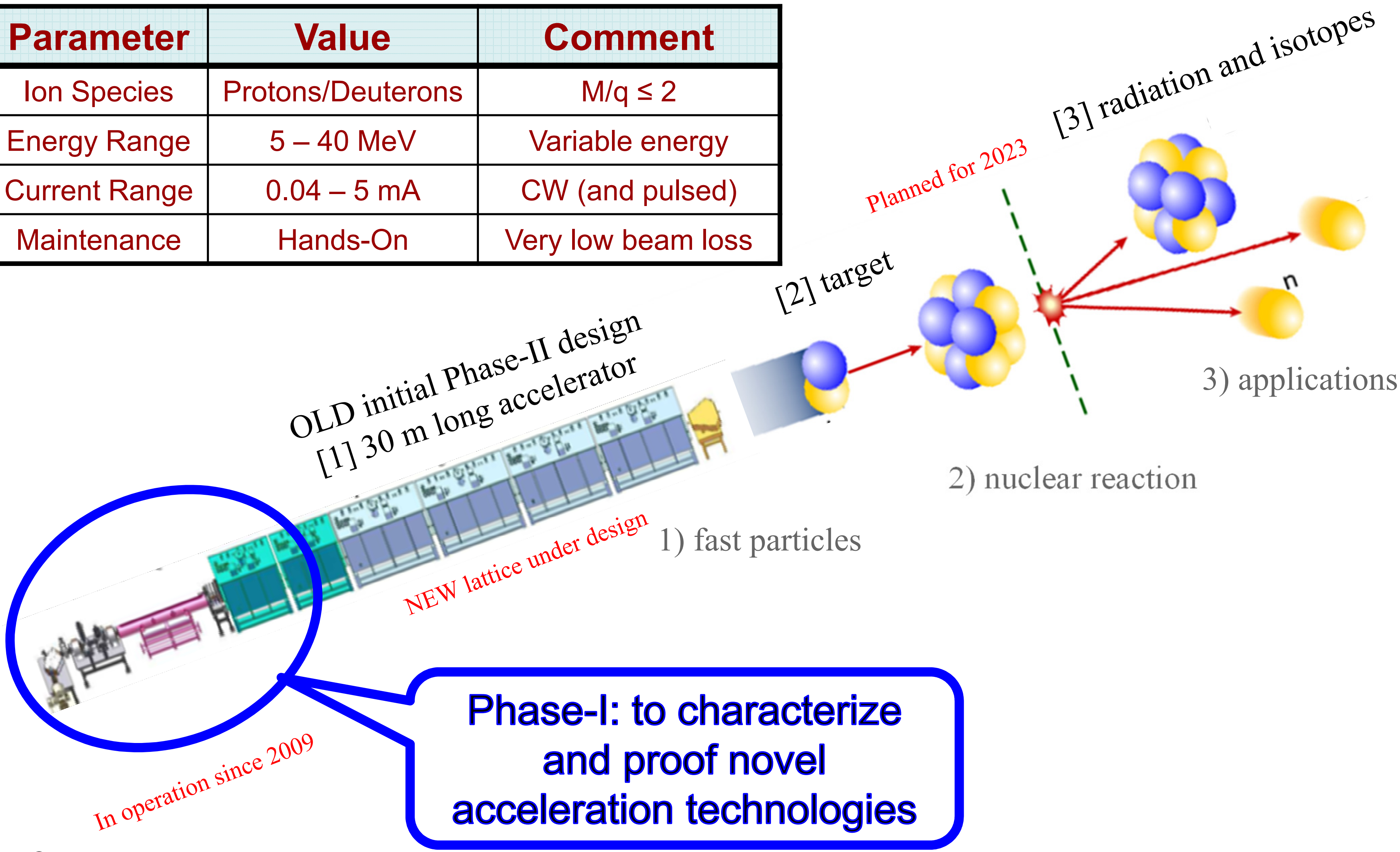
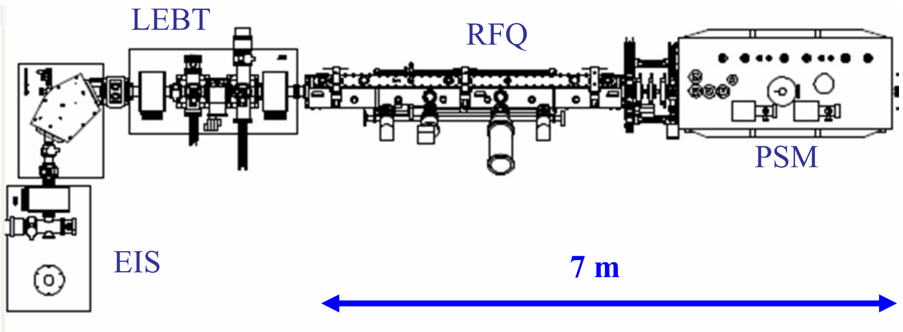
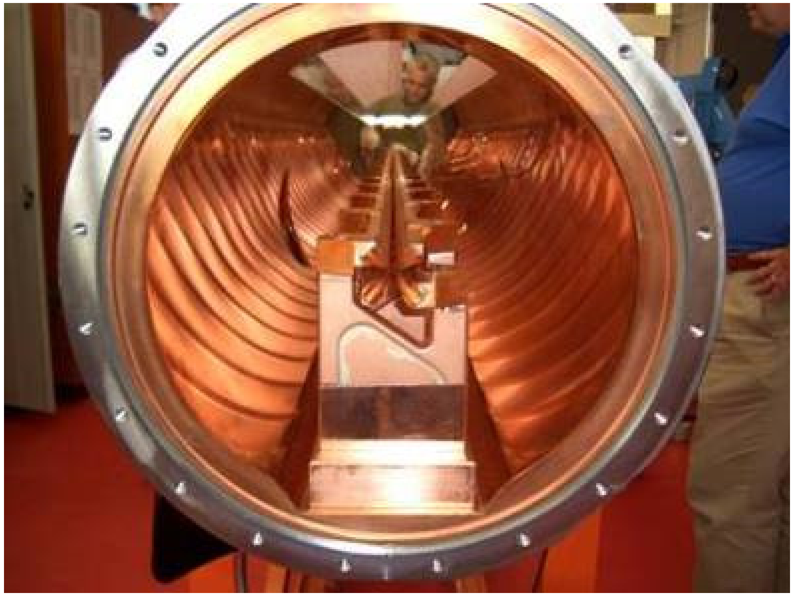
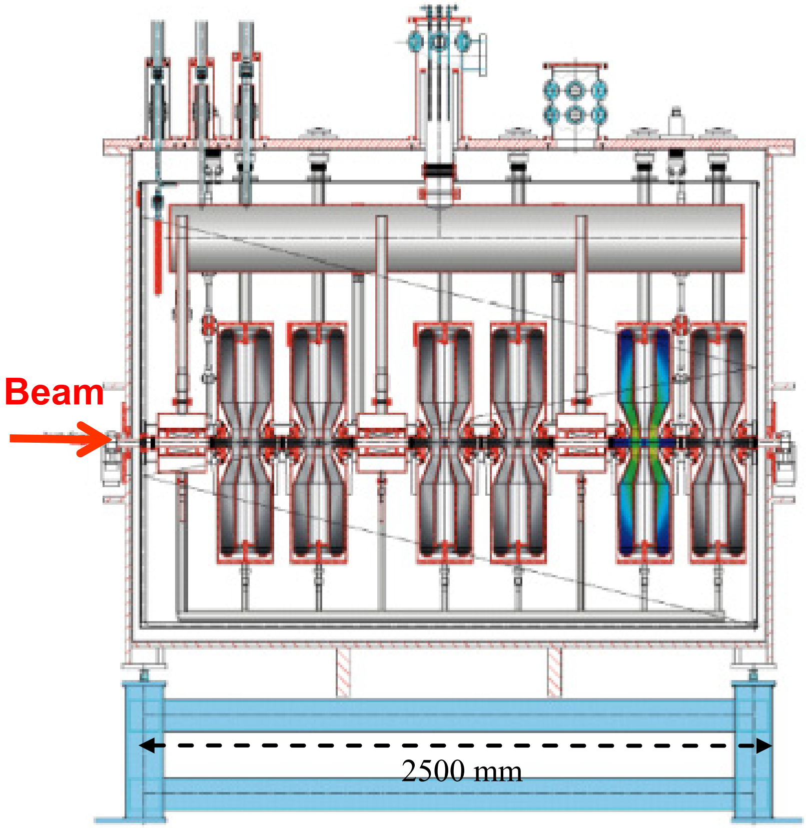


SARAF Phase-I 176 MHz linac





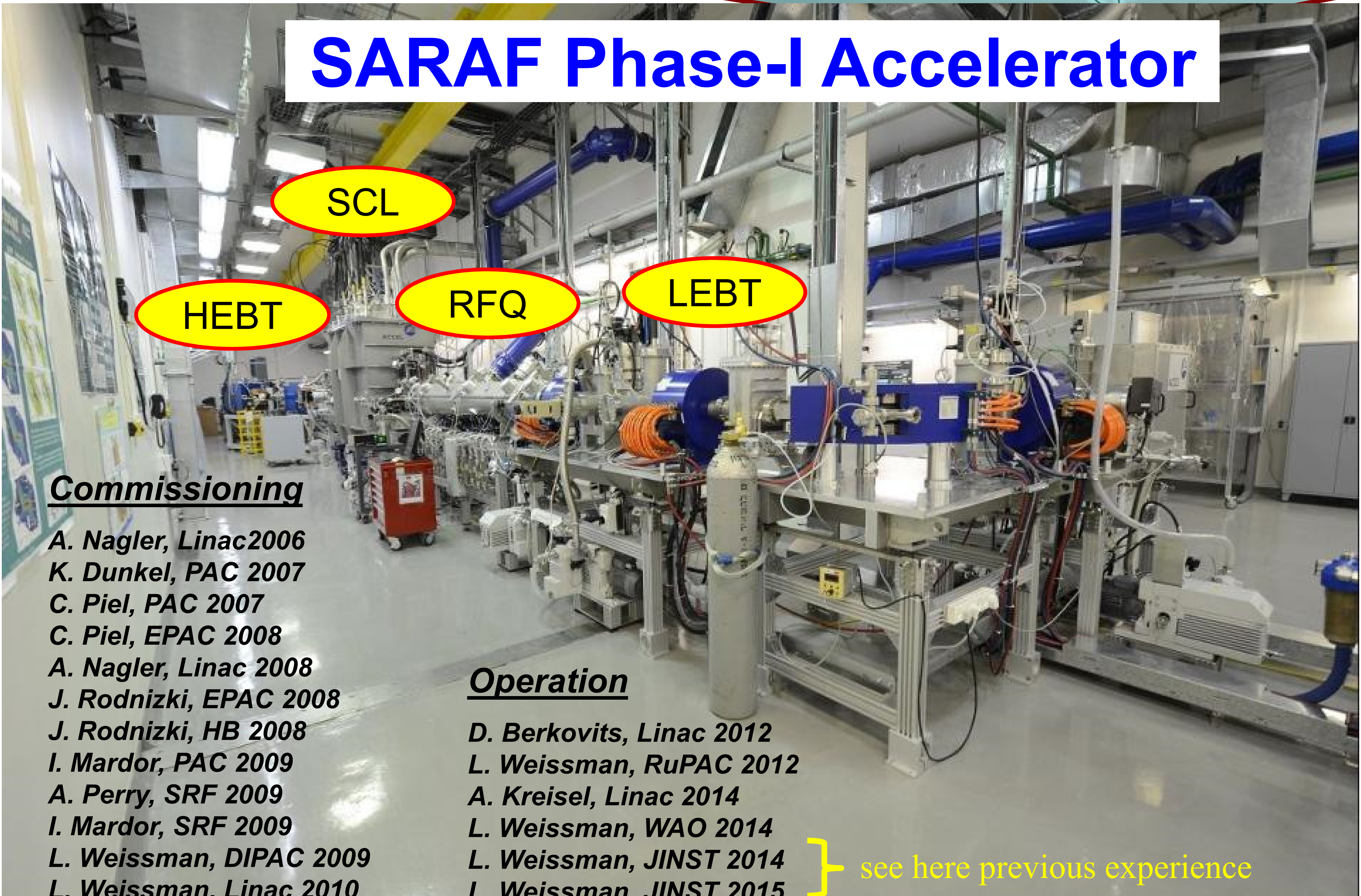
4-rod, 250 kW, 4 m, 1.5 MeV/u
P. Fischer et al., EPAC06



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 Accelerator



Commissioning

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

Operation

D. Berkovits, Linac 2012
L. Weissman, RuPAC 2012
A. Kreisel, Linac 2014
L. Weissman, WAO 2014
L. Weissman, JINST 2014
L. Weissman, JINST 2015

} see here previous experience

… see therein several contributions regarding components design, upgrades and development

SARAF Phase-I linac status

- SARAF Phase-I is the first to demonstrate:
  - ☑ 2.1 mA CW variable energy protons beam
  - ☑ Acceleration of ions through HWR SC cavities
  - ☑ Acceleration of ions through a separated vacuum SC module
  - ☑ 1.7 mA CW proton irradiation of a liquid lithium jet target for neutron production

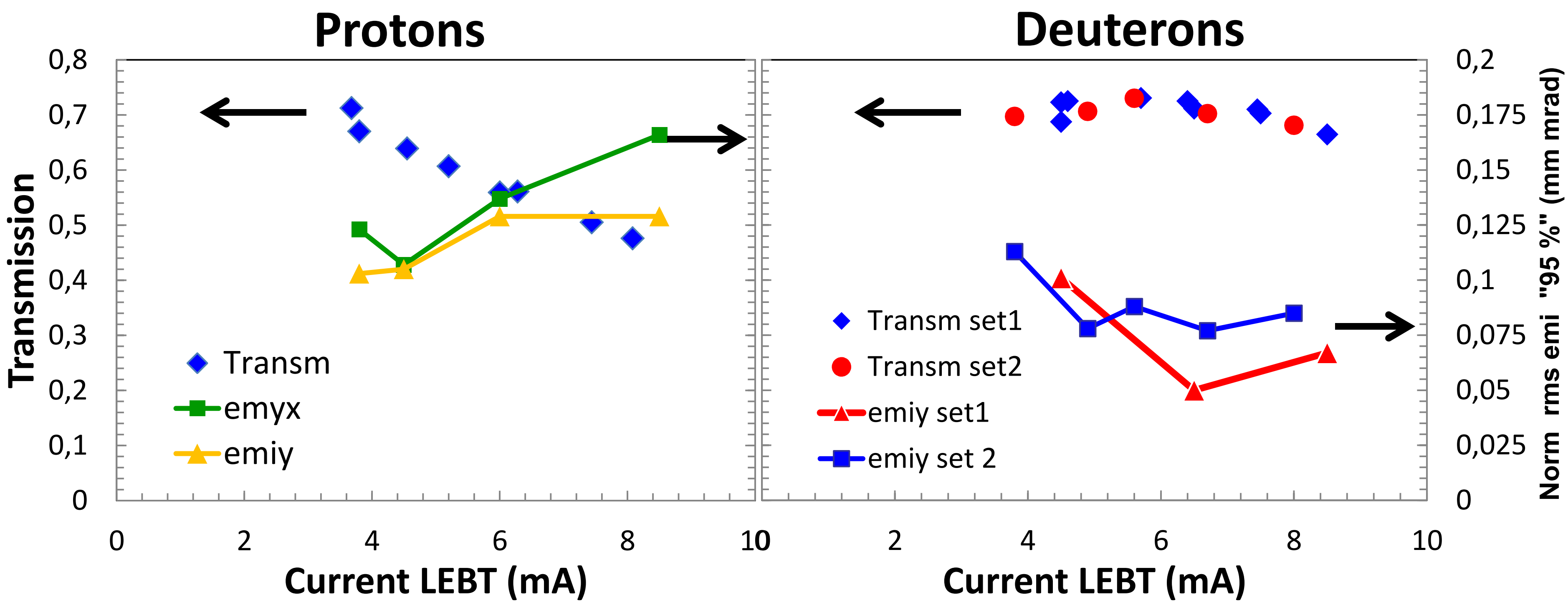
Case 1

LEBT

Space charge effect

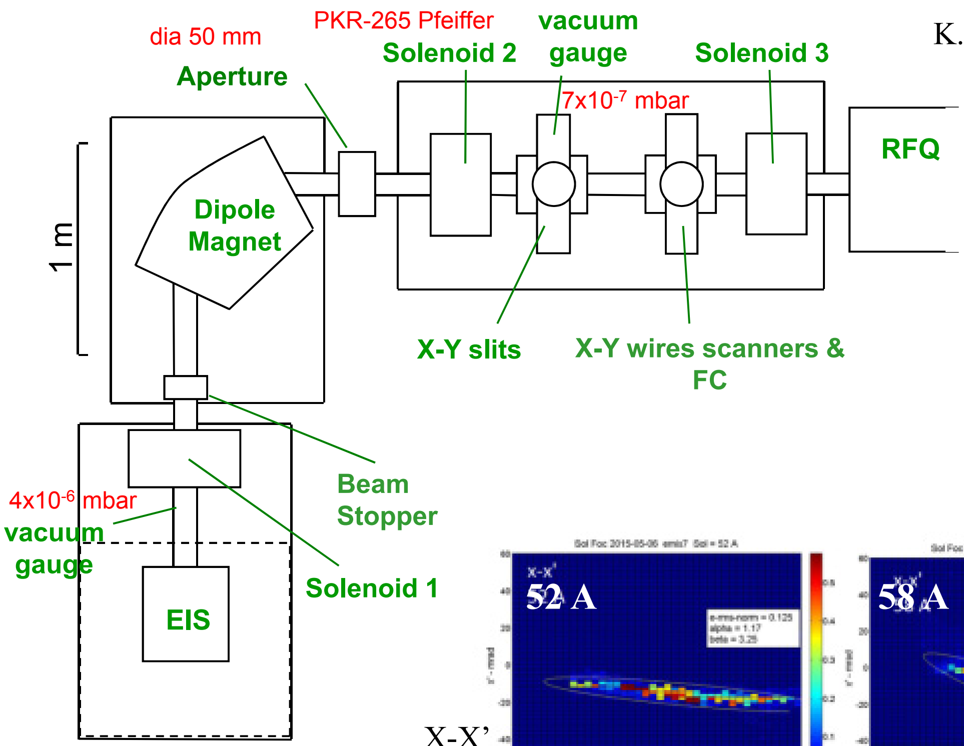
by Leo Weissman and Asher Shor

RFQ transmission study



Why RFQ transmission is not sensitive, in a wide range, to LEBT some beam optic, LEBT vacuum and entrance flange electron suppressor voltage?
Protons are more sensitive to space charge. What is the LEBT space charge effect?

Study of LEBT beam matching to RFQ



K. Dunkel, PAC 2007

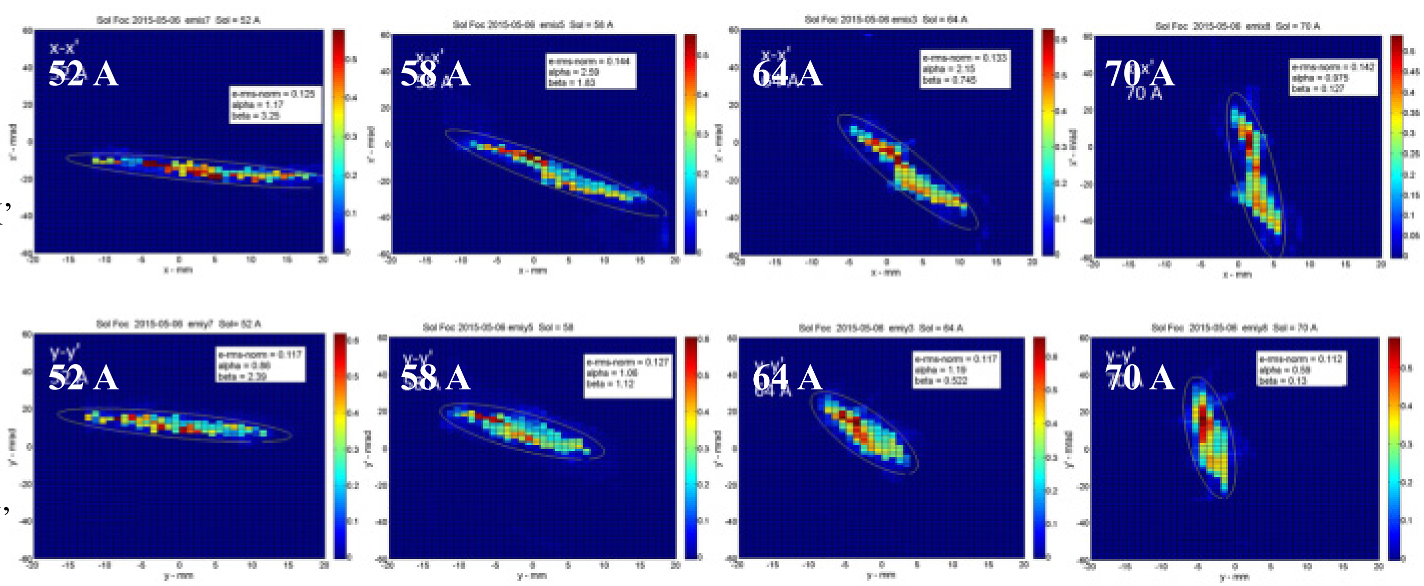
phase space measured by slit and wire
for 20 keV 5 mA protons beam
as function of solenoid #2 current.
Results: rms norm. emittance is constant

ε_x=0.14±0.01 ε_y=0.12±0.01 π mm mrad

space charge neutralization time ~0.2-2 ms << pulses of 20 ms

X-X'

Y-Y'



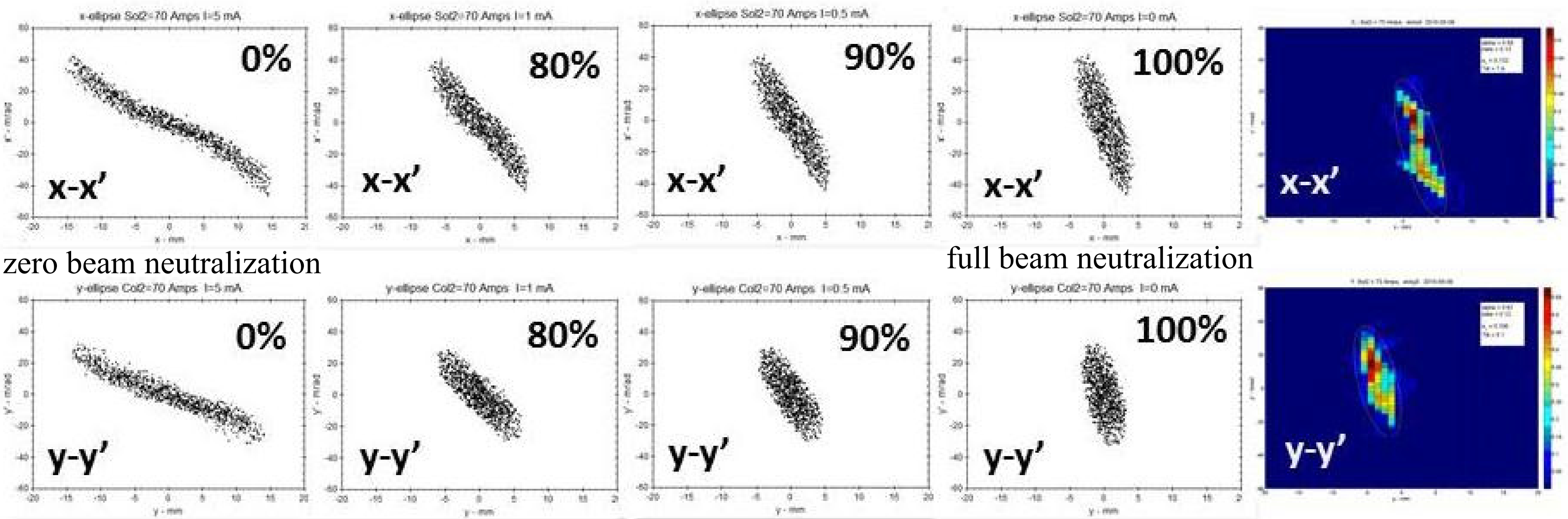
A. Shor and L. Weissman
accepted for publication in
JINST 2016

LEBT simulation
Twiss parameters as function of space charge

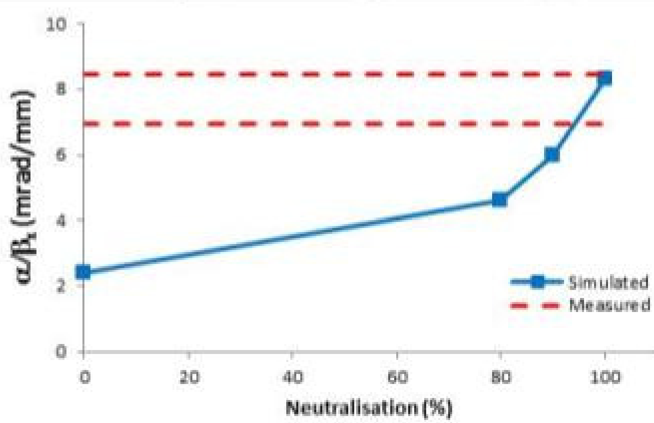
simulated

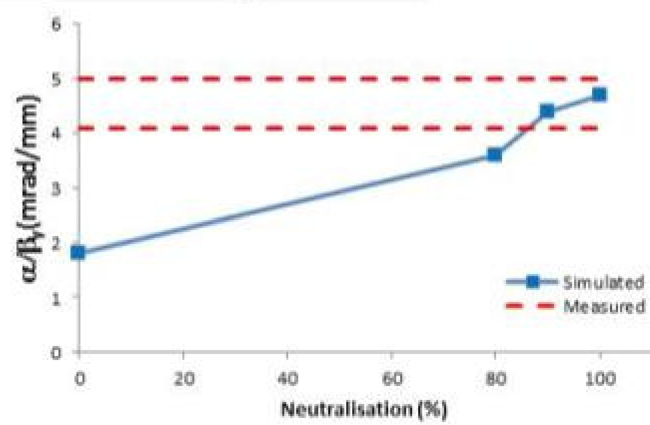
Solenoid #2 @ 70 A

measured



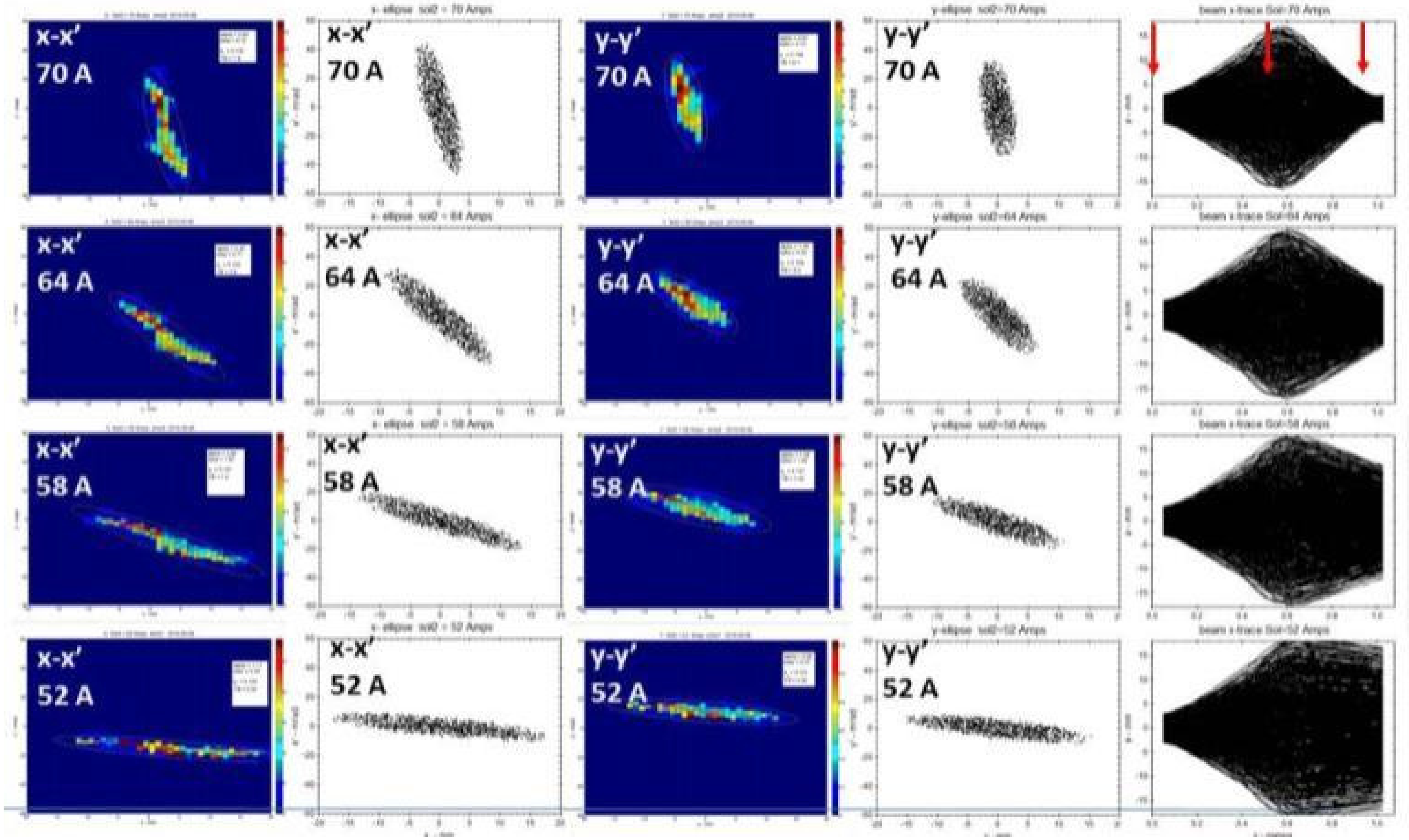
Simulation input:
4D Waterbag 5 mA
protons @ 20 keV





LEBT simulation
Twiss parameters as function of focusing

Simulated with 100% beam neutralization



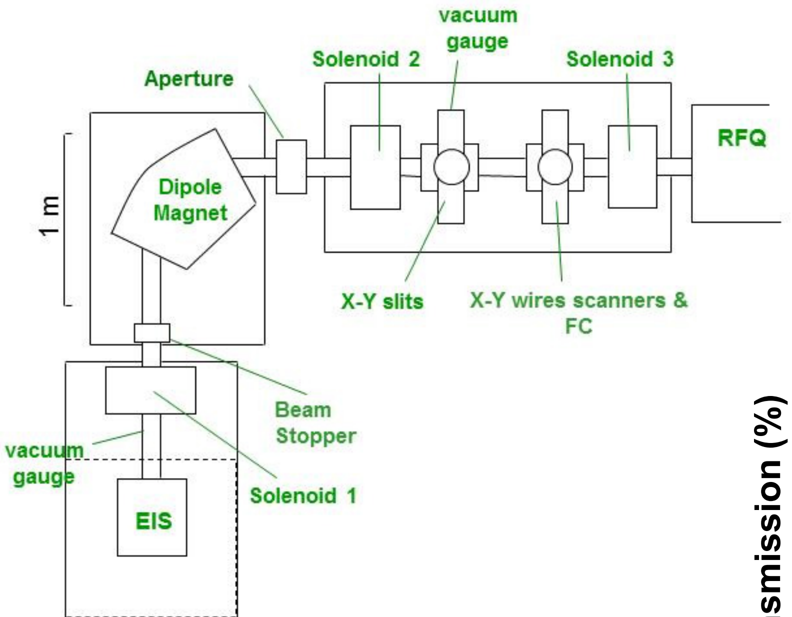
➔ Beam is fully neutralized at the LEBT @ ~1x10^{-6} mbar

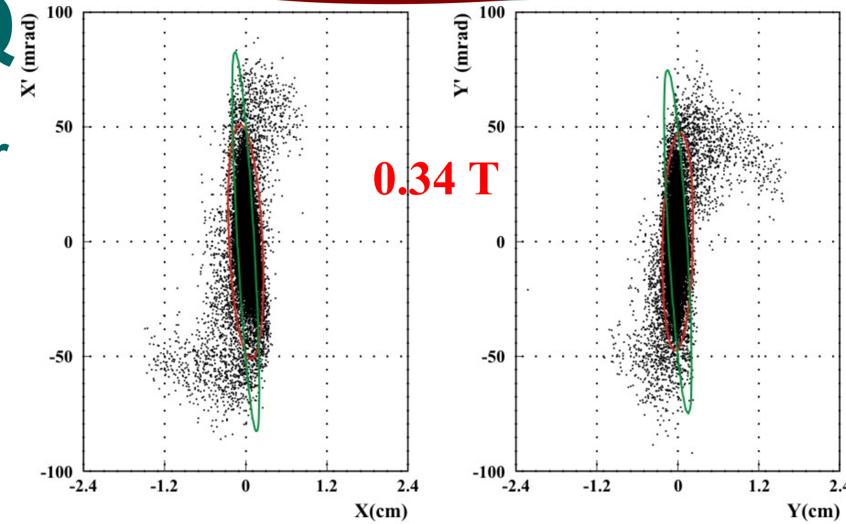
➔Beam focusing at RFQ entrance is not a direct cause for RFQ transmission reduction

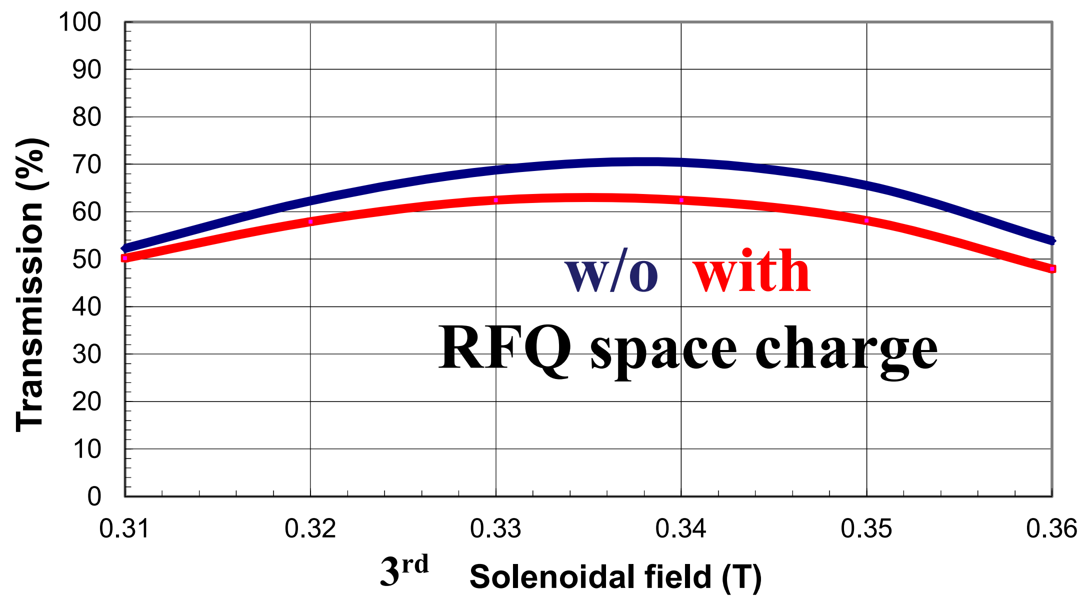
LEBT matching to RFQ

RFQ beam dynamic transmission simulation as function of solenoid power

by Stepan Yaramyshev







- ➔ increase degree of freedom to shape the beam in the LEBT <+5% trans.
  - ➔ change the RFQ input radial matcher to higher acceptance / wider <+20%

Case 2

RFQ

New modulation

by Asher Shor

RFQ new modulation

Why the 4 m 4-rod RFQ cannot sustain its original designed power / field at CW?

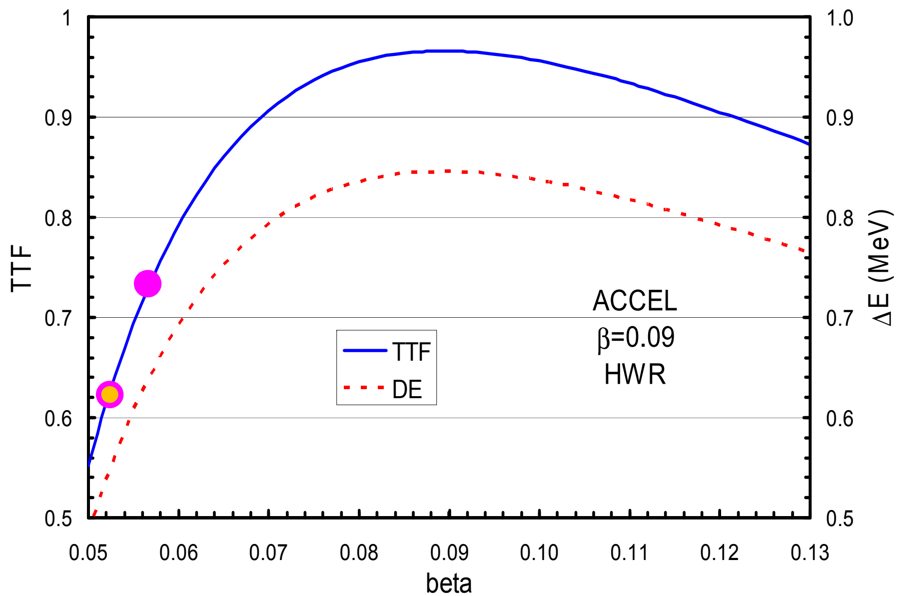
The 4-rod RFQ sustains CW power of 200-210 kW for long periods
➔ A new modulation at a moderated power is performed

For deuterons		exist	new
Power	kW	250	185
Voltage	kV	65	56
Kilpatrick		1.54	1.52
Exit energy	MeV/u	1.50	1.28
RF couplers		1➔2	2

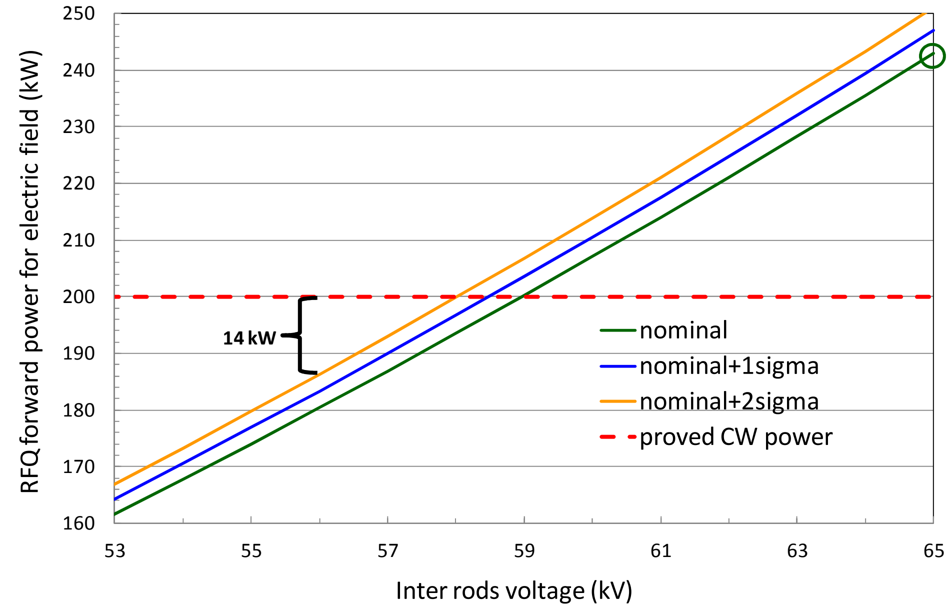
Existing design – see P. Fischer et al. EPAC 2006 and LINAC 2006
New RFQ RF coupling and conditioning - see J. Rodnizki et al. LINAC 2016
New 4-rod modulation – see A . Shor INS27 (http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/45/114/45114733.pdf?r=1)

RFQ limits for new modulation

1) Lower limit
beta mismatch at 1st SC cavity



2) Upper limit
max power and field≤1.5 Kp



Working points: existing RFQ 1.5 MeV/u new lattice 1.3 MeV/u

Working point at the existing RFQ calibrated using nominal deuterons beam and 4x protons beam

4-rod advantage: replacement of rods is ~100 k€ and ~1 month of in situ maintenance

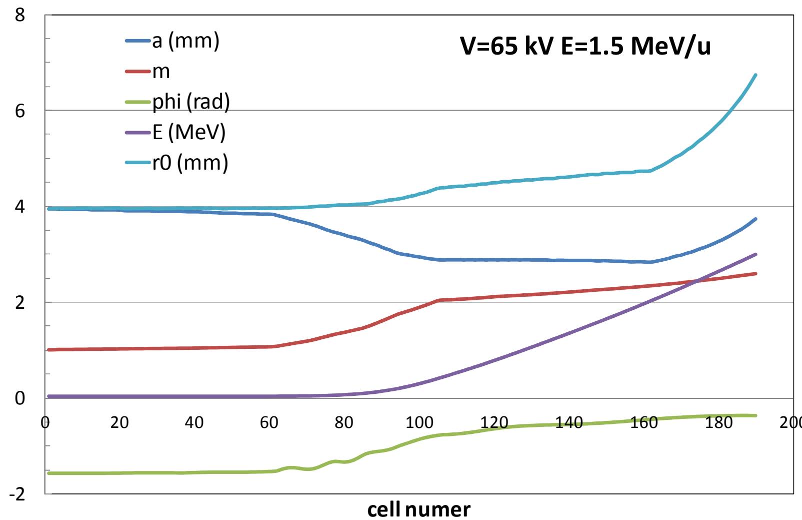
4-rod challenge: design is very limited by voltage/power.

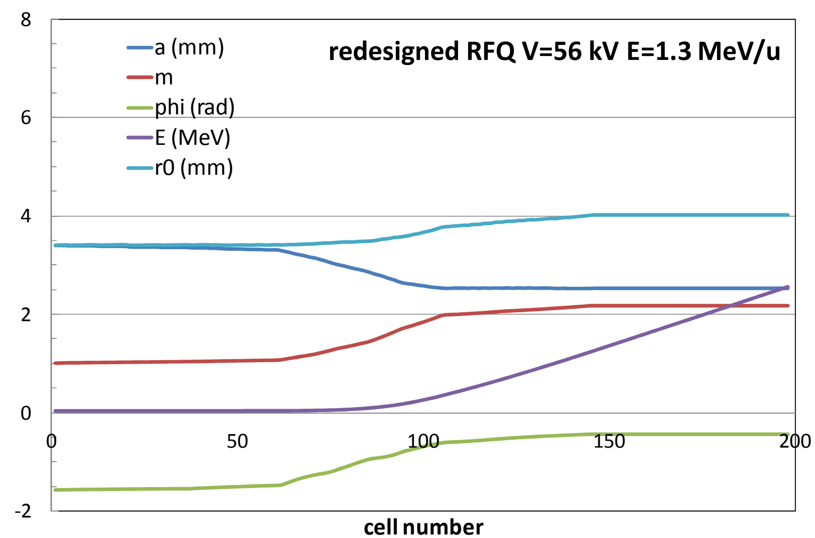
4-vane RFQ designed for SARAF have a working point at 70-75 kV/~150 kW [S. V. Kutsaev et al. PR-AB 2014 , N. Pichoff et al. IPAC 2015]

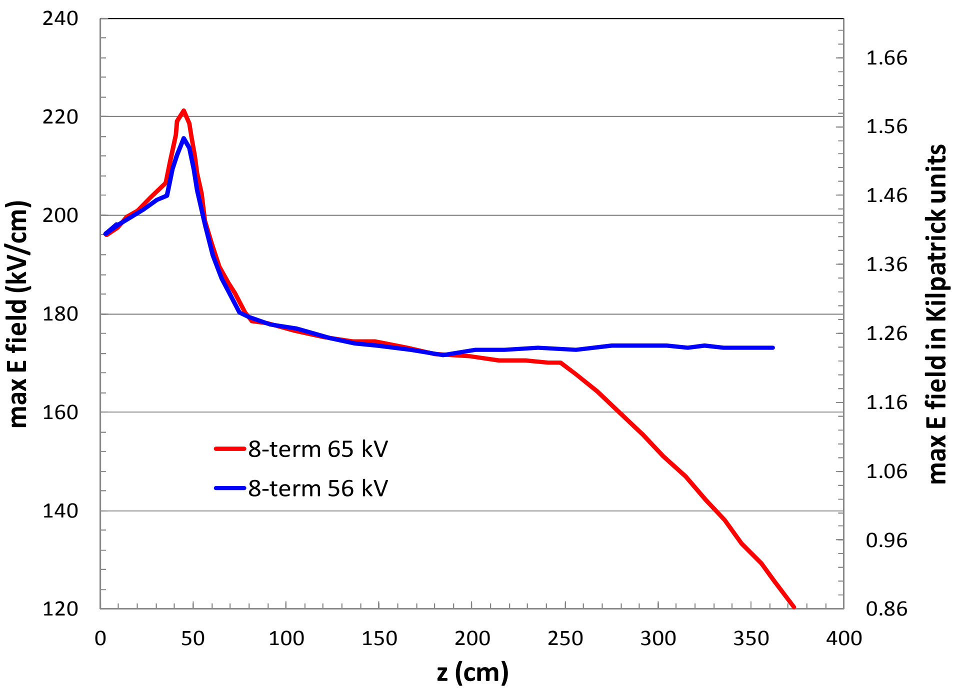
3) Exit particle distribution within the acceptance of the SC LINAC

RFQ new modulation

Scale down of original solution keeping the same transversal focusing and the same capacitance







Kilpatrick criterion is calculated using the equation

$$f = 1.643\, E_s^2 e^{-(8.5/E_s)}$$

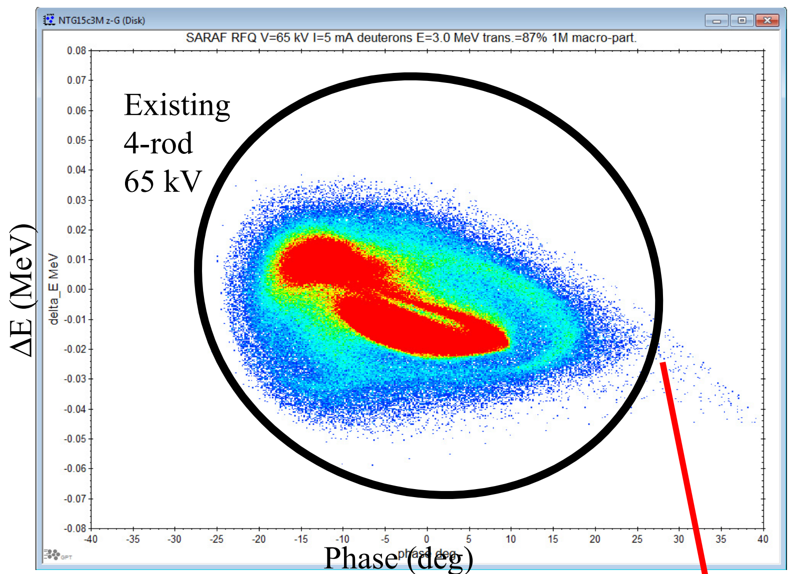
for E_s, the surface field in MV/m

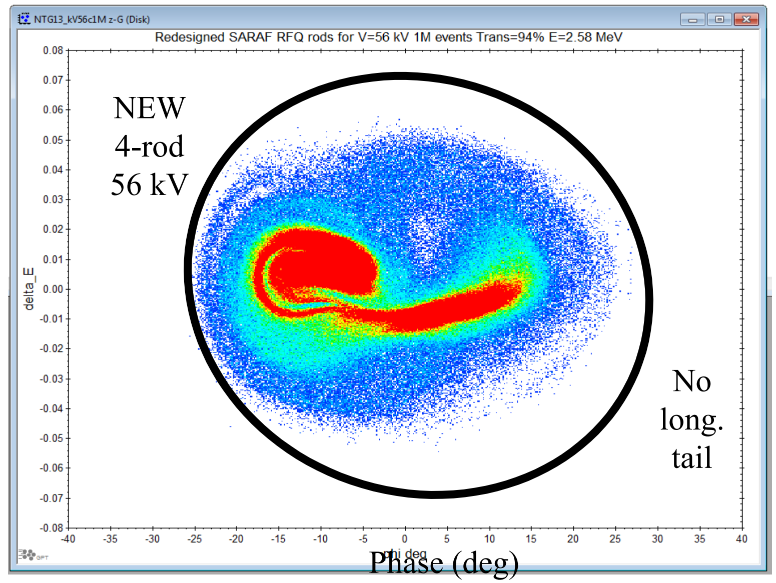
[J. Staples, Handbook of accelerators, 2013]

Effort is done to design a modulation with a smaller peak field

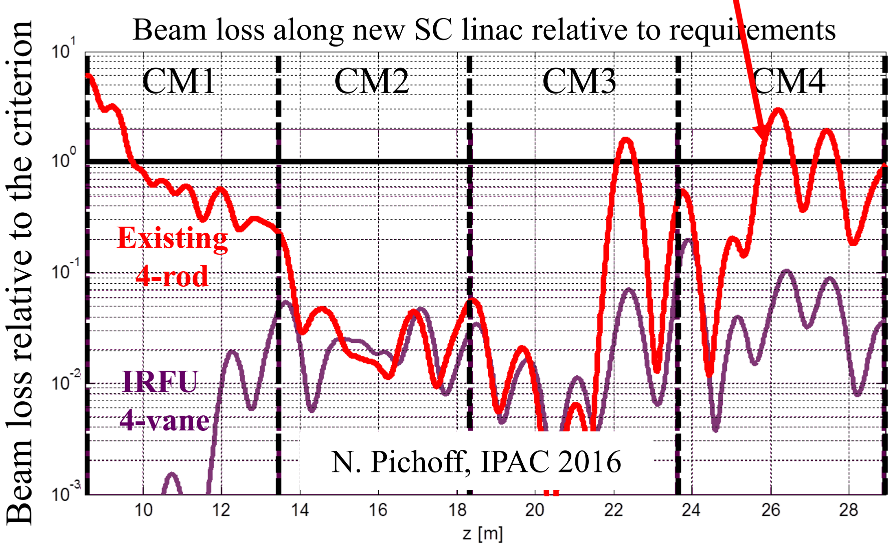
RFQ exit long. beam distribution

by A. Shor





4-rod RFQ exit 5 mA 1 M macro Deuterons longitudinal phase space in the SC linac acceptance



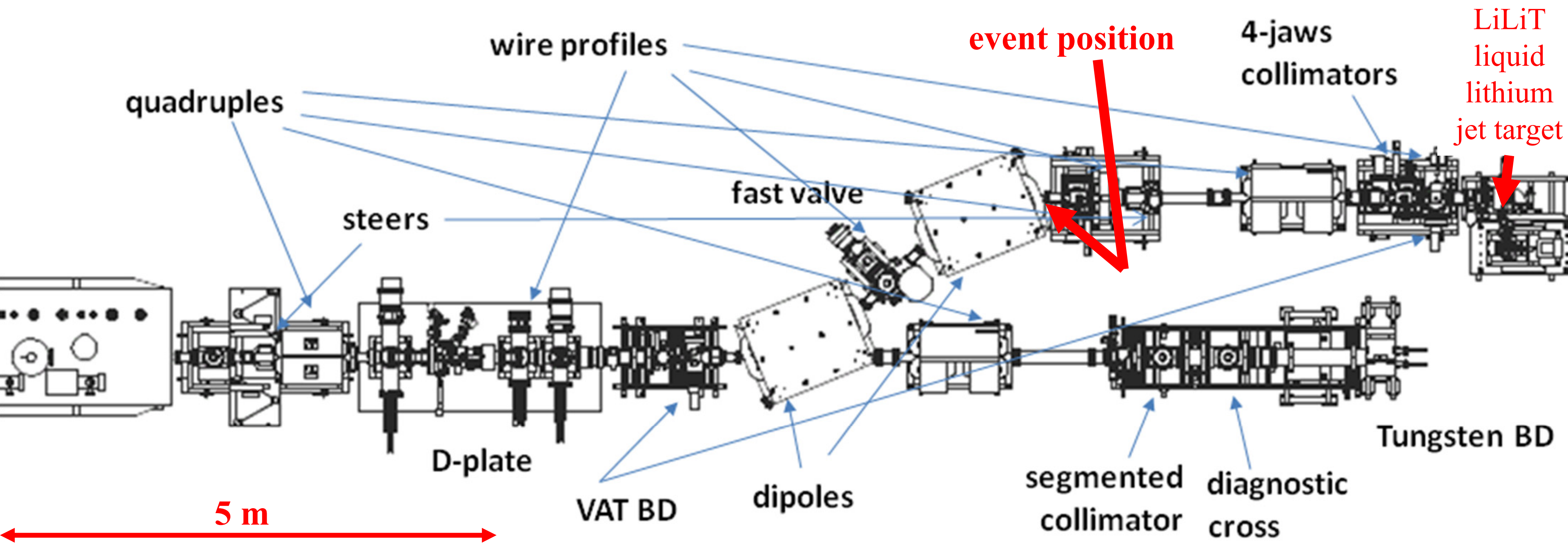
4-rod RFQ	New	Exists
Optimization HV (kV)	56	65
Kilpatrick criterion	1.52	1.54
Norm. RFQ RF power $250*(HV/65)^2$	185.6	250
Norm. RFQ RF power $240*(HV/65)^2$	178.1	240
Transmission (%)	94	87
Longitudinal loss (%)	0.7	2.8
Energy deuterons (MeV)	2.56	3.0
Maximum E – field (kV/cm)	215	225
Trans. Norm. rms emittance (π mm mrad)	0.209	0.202
Long. Norm. rms emittance (π keV deg)	105	89

Case 3

HEBT (HE in this case is 2 MeV)

Beam drilled vacuum chamber incident

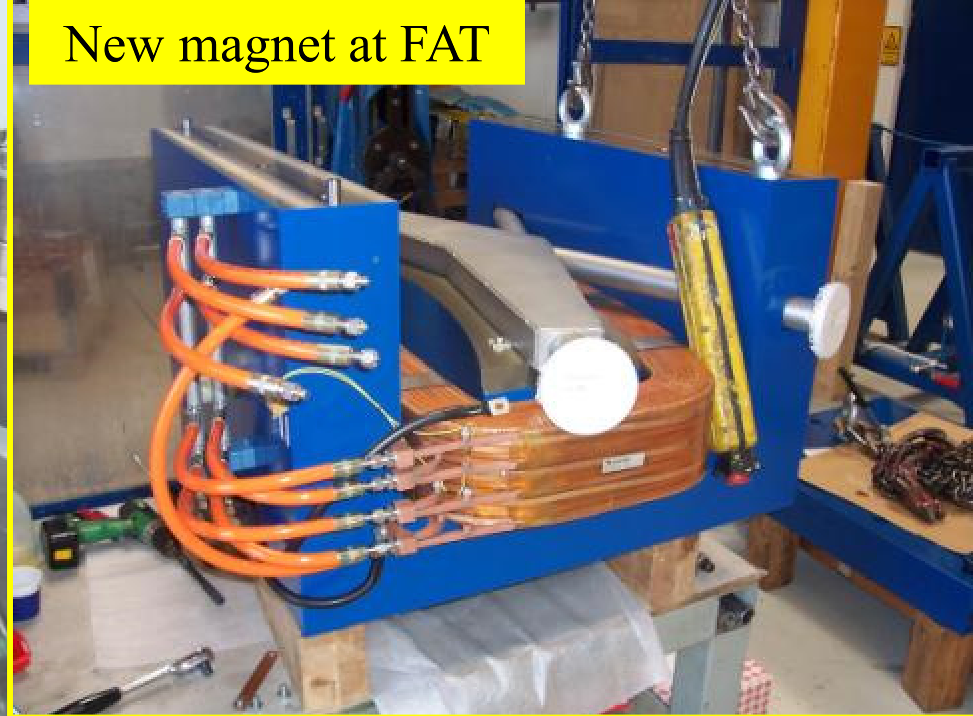
The event – untuned beam drilled a hole

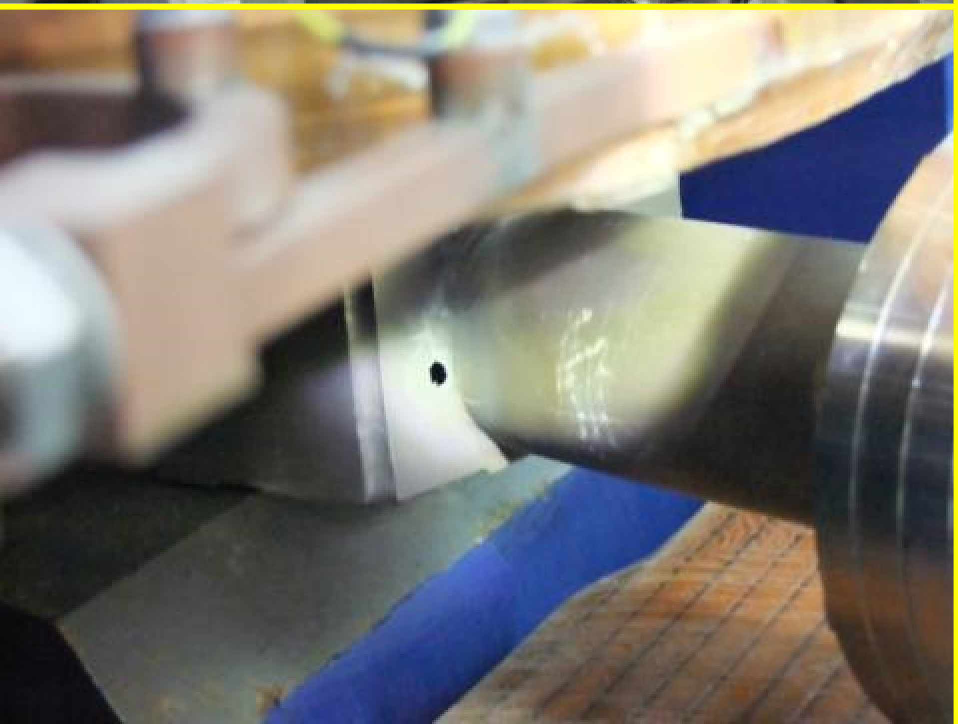


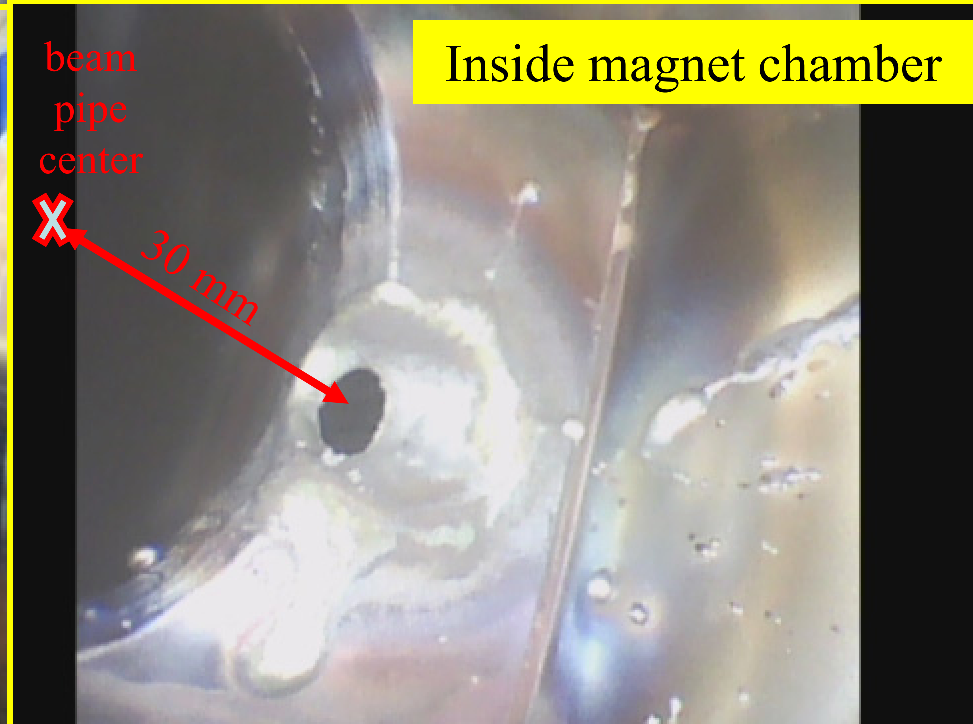
A 2 MeV x 1.5 mA CW proton beam jumped 30 mm to its right and drilled a hole in the bending magnet vacuum chamber, during neutron production experiment using LiLiT.

✘ HZARDS: 1) humid air ignites the hot lithium 2) air contaminates the SC cavities.

✓ RESULTS: all safety measured worked well. LiLiT &LINAC vacuum didn't exceed the limits.


New magnet at FAT

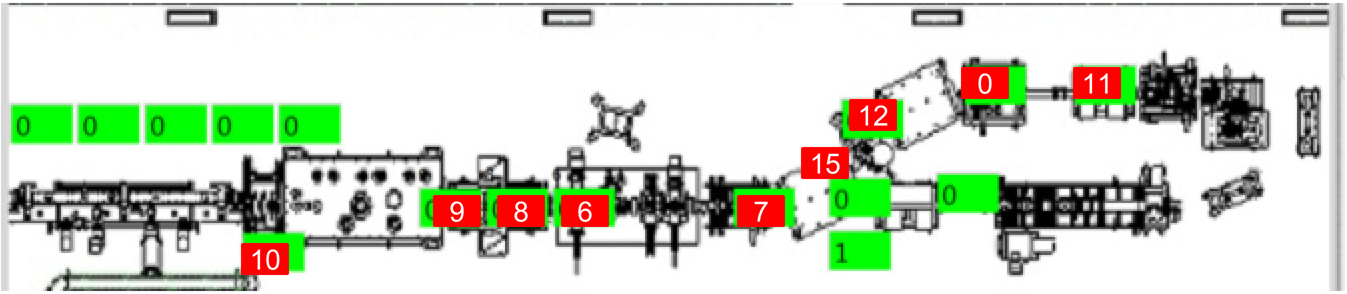



Inside magnet chamber
beam pipe center
30 mm

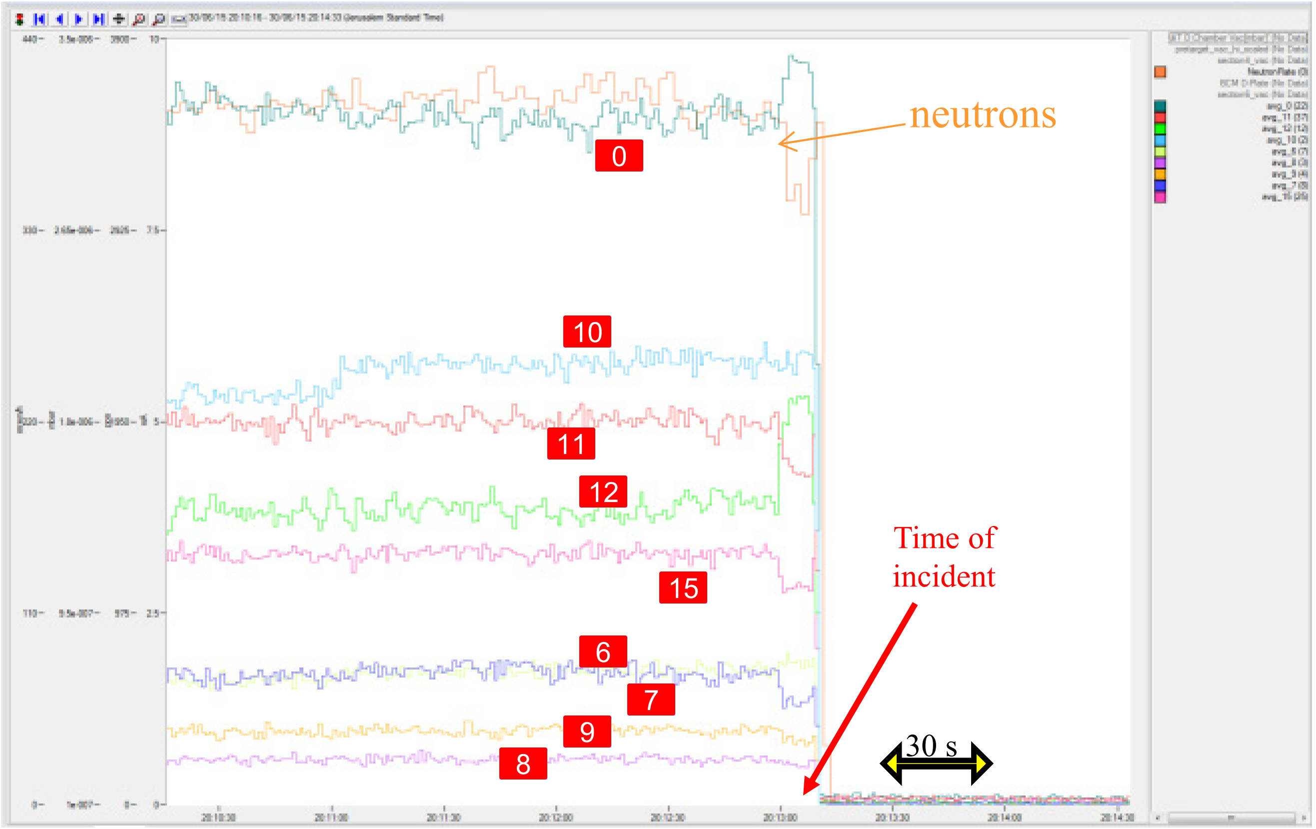
Incident investigation

- About 40 accelerator beam operation values, that are recorded in the database, were investigated and found to be very stable prior and up to the incident
  - RFQ: 1-power, 2-vacuum, 4-X ray
  - HWRs: 6-FP, 6-voltage, 6-phase
  - Magnets: 3-MEBT, 3-SC solenoid, 5-HEBT
  - and more
- One magnetic steerer values were not recorded in the database
- Beam dynamics simulations couldn’t predict, in any case, a beam displacement of 30 mm !!
- The reason for the incident was not found at that time and until now, a year later !
- Conclusion: more beam diagnostic is needed

Beam loss monitor last few min just before the incident



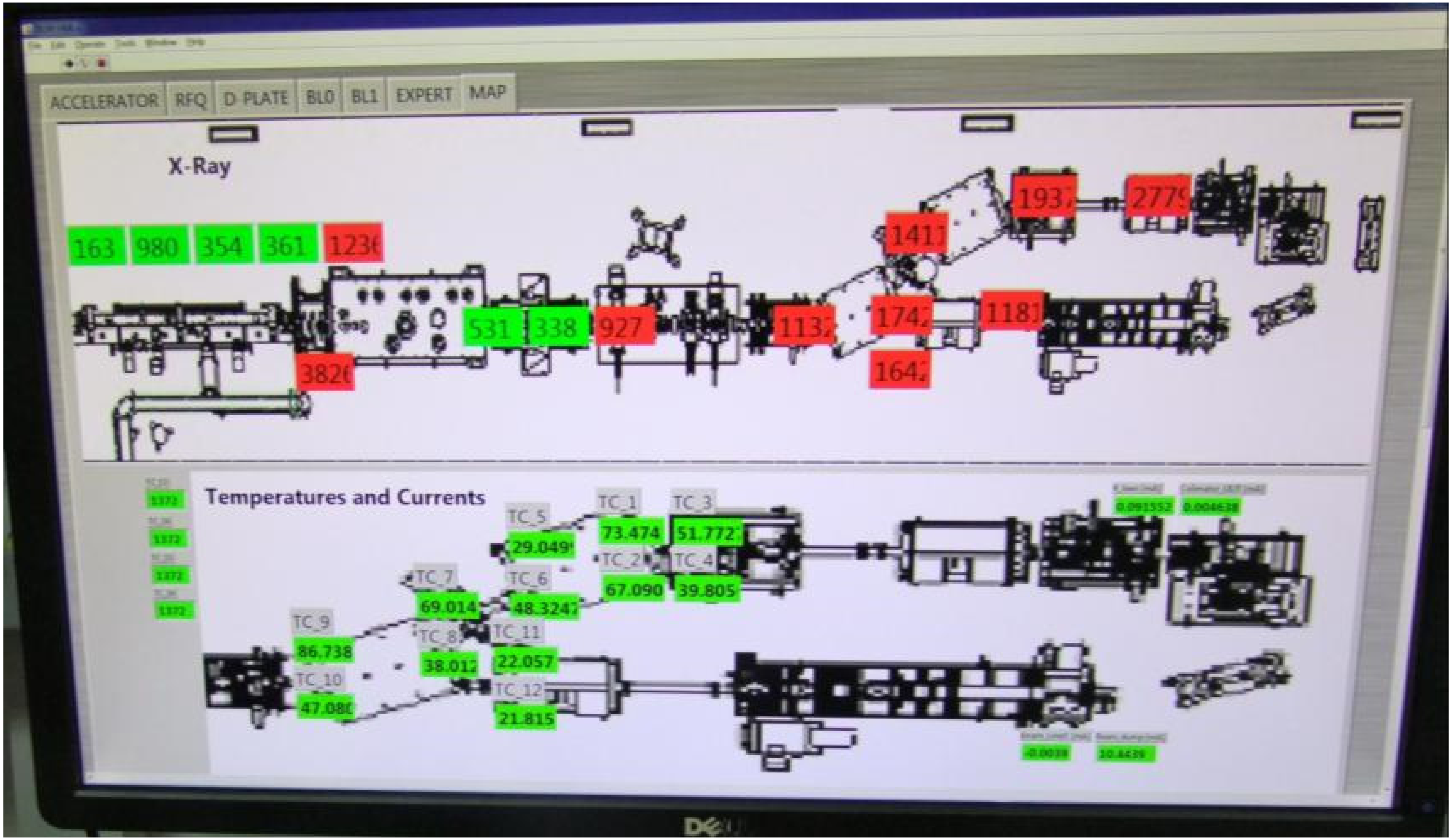
Loss monitors are based on Saint Gobain G1200 Geiger



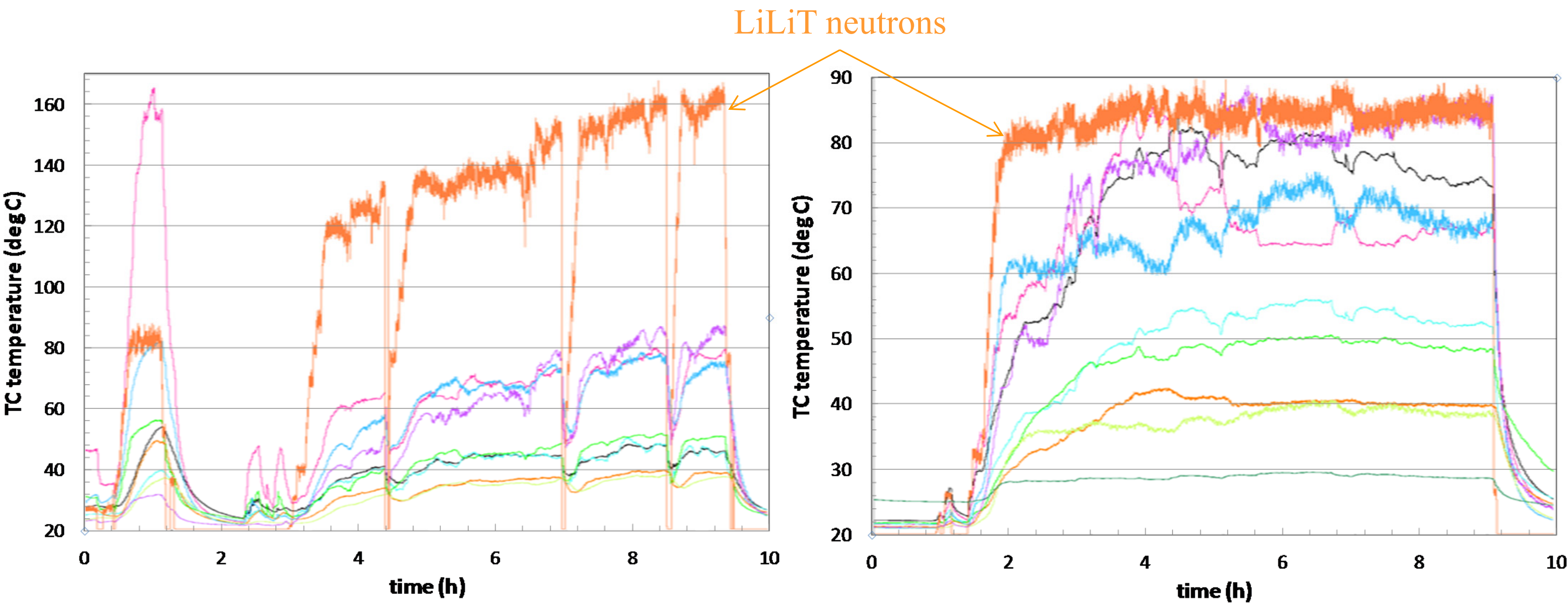
Beam loss monitors that are near to the experimental irradiation target typically measure high radiation from the experiment and are less sensitive to beam loss changes

Improvements as the result of the incident

- Thermocouples were added along the beam line, serve as slow beam loss monitors and help beam tuning



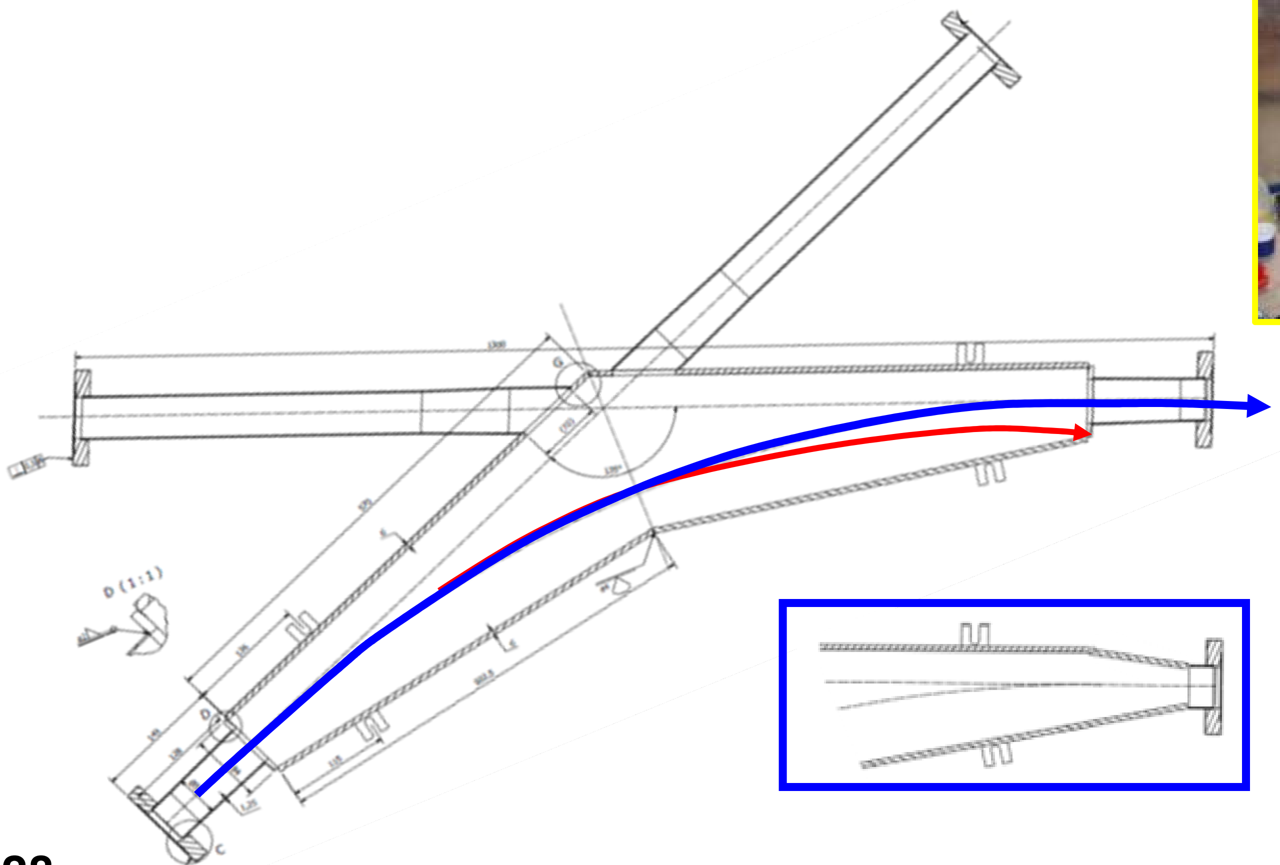
Tune with the help of the new TC



✓ With the help of the TC a significantly better beam optics is found

Recommendation

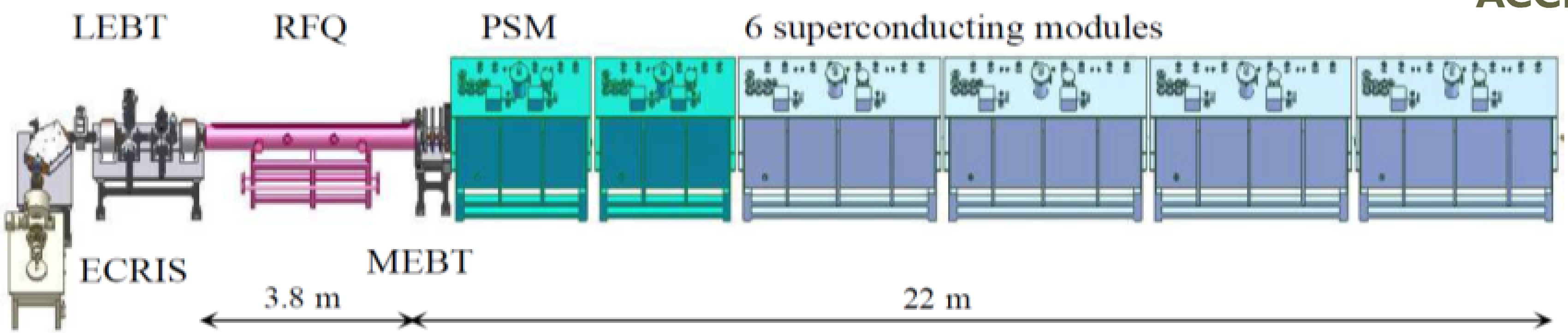
- Avoid surface perpendicular to beam along the beam pipe



Case 4

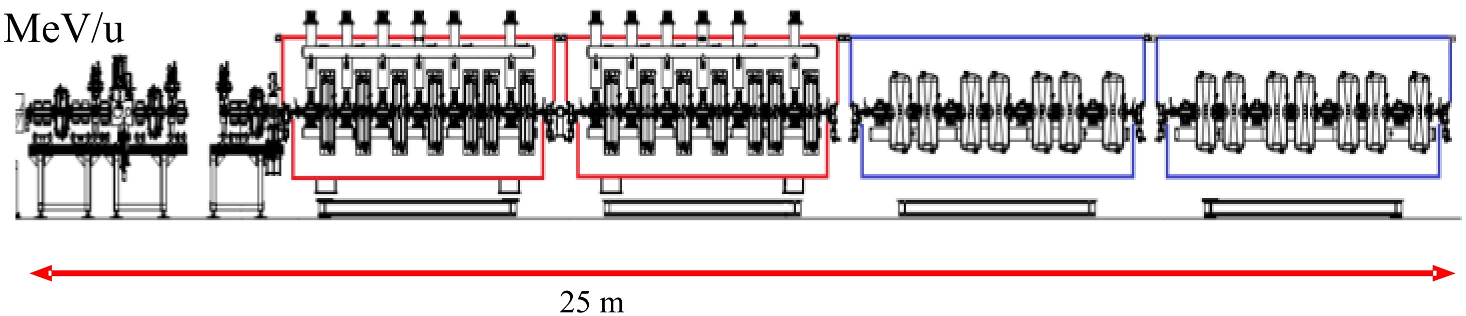
Design of the SC LINAC lattice

linac lattice design in 2006 and today



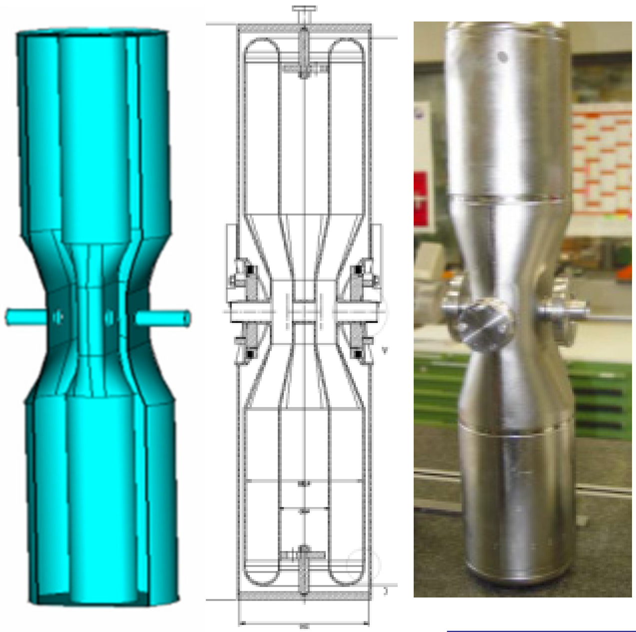
1.5 MeV/u

1.3 MeV/u



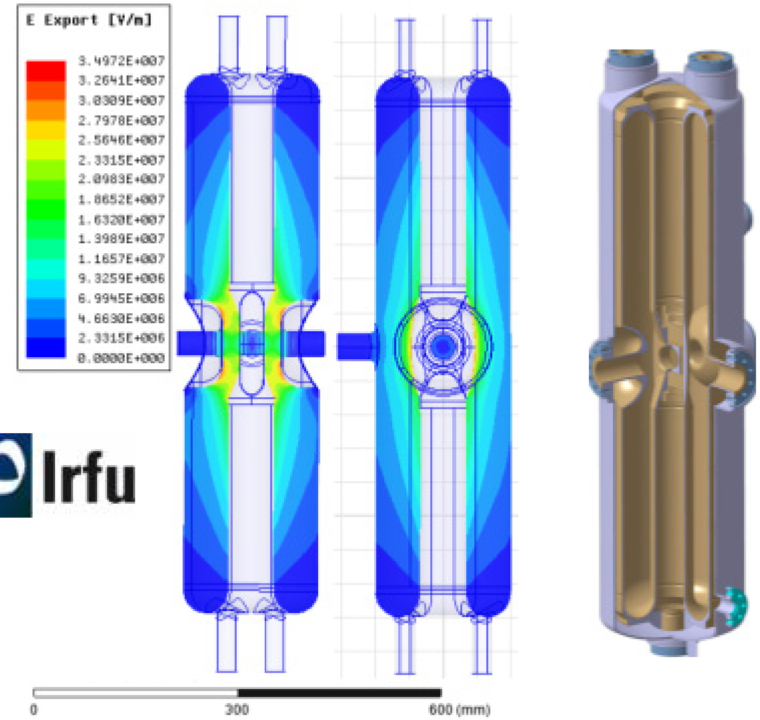
Today designed lattice from N. Pichoff et al IPAC 2016

176 MHz β_0=0.09 HWR



ACCEL

Irfu



Single 3 mm Nb wall in SS vessel

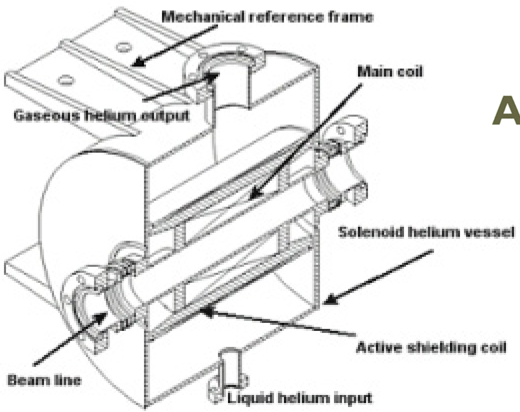
		ACCEL Phase-I	IRFU Phase-II
E_{peak}	MV/m	25	32
Bore dia.	mm	30	36
$E_{acc}(@E_{peak})$	MV/m	8.6	6.5
$B_{peak}(@E_{peak})$	mT	53	61
$\Delta V(@E_{peak})$	MV	0.85	1.0
Sensitivity	Hz/mbar	56	5

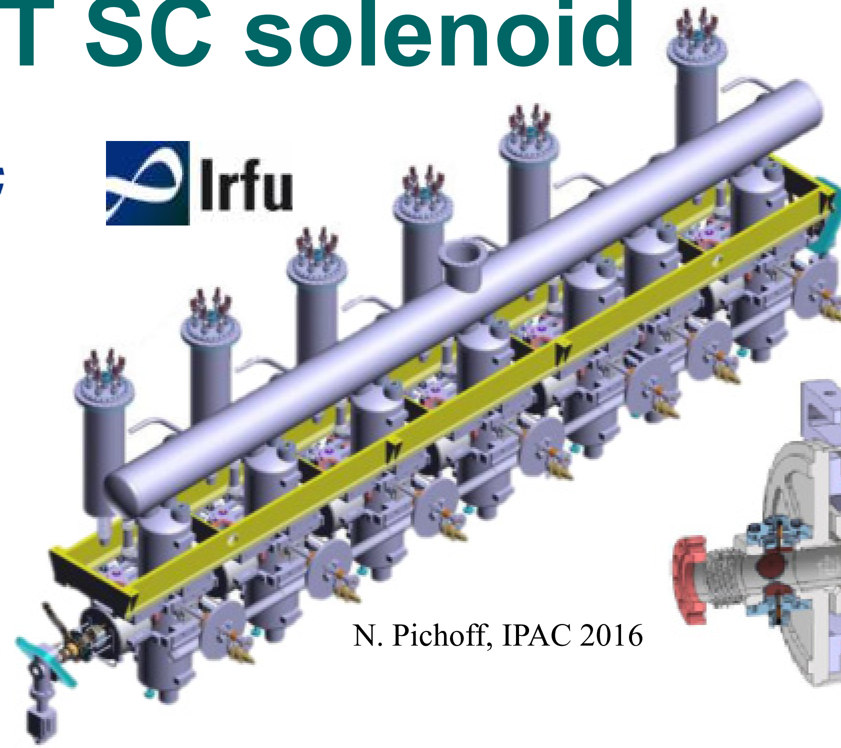
Single 3 mm Nb wall in Ti vessel. Nb and Ti are connected in several places

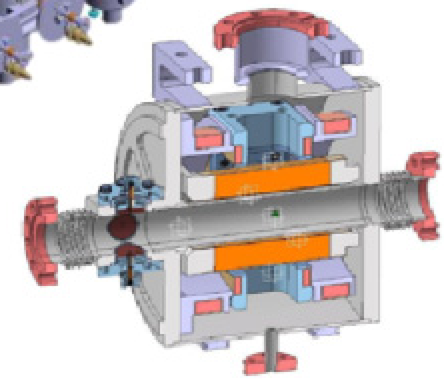
M. Peiniger, LINAC 2004
M. Pekeler, SRF 2005

G. Ferrand, IPAC 2016
N. Pichoff, IPAC 2016

Cryomodule & 6T SC solenoid







N. Pichoff, IPAC 2016

Solenoid		ACCEL Phase-I	IRFU Phase-II
Field_{peak}	T	6.0	5.8
Bore dia.	mm	38	40
x,y,z misalignment	mm	0.2	1.0
Steerer		no	yes
BPM		no	yes

Not measurable

 M. Pekeler, SRF 2003 and APAC 2007

linac lattice parameters 2009 vs. 2016

		Ion	RFQ		cavity type 1				cavity type 2	
linac lattice										
type		ECR	4-rods (mini-		HWR ACCEL		Irfu		HWR ACCEL	Irfu
β_0					0.09		0.091		0.15	0.181
Conductor type			Normal-		SC-Nb				SC-Nb	
RF frequency (MHz)		DC	176		176				176	
#		1	1		12		12		32	14
Cavities per Solenoid					2		1		2	2
max ε_{peak} (MV/m)			22	22	25		32		25	33
Acceleration voltage (kV)	p	20	32.5	30	850		1000		1175	2300
	d	40	65	56						
Beam at exit of component										
CW current (mA)		5 7	4	5	4		5		4	5
Ion energy (MeV)	p	0.02	1.5	1.3	4	9	3	7.1	40	35
	d	0.04	3	2.6	5.2	8.8	6.7	11.4	40	40
velocity β (%c)	P		5.6	5.2	9.2	14	8	12.3	28.4	26.7
	d	0.655			7.5	9.7	8.5	11	20.4	20.4
transversal emittance (π mm mrad)		0.2	0.3		0.4				0.4	
Longitudinal emittance (π deg keV/u)			120		150				150	

ACCEL IRFU

Thanks for your attention