STATUS OF THE HIGH CURRENT INJECTOR PROGRAMME AT IUAC, NEW DELHI, INDIA

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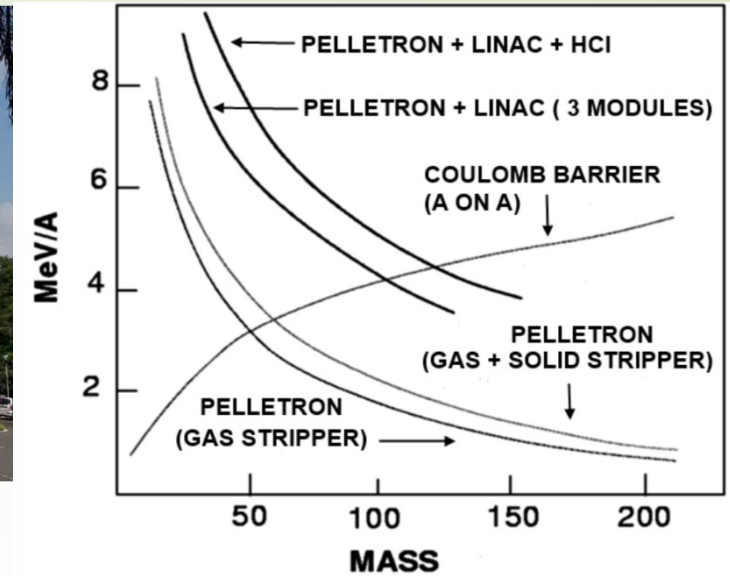
- Brief summary of the operating accelerators at IUAC
- Limitations and proposed upgrade
- <u>Development of the High Current Injector</u>
- <u>Commissioning stages and present status</u>
- <u>Existing problems and bottle necks</u>
- Future developments and Conclusions

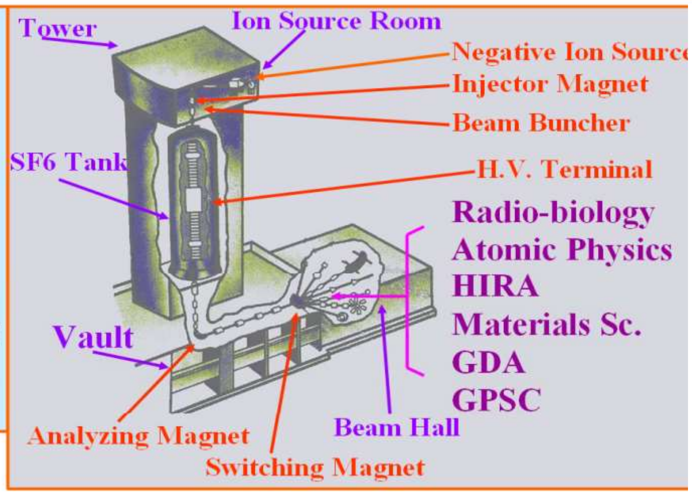


15UD Pelletron Accelerator at IUAC

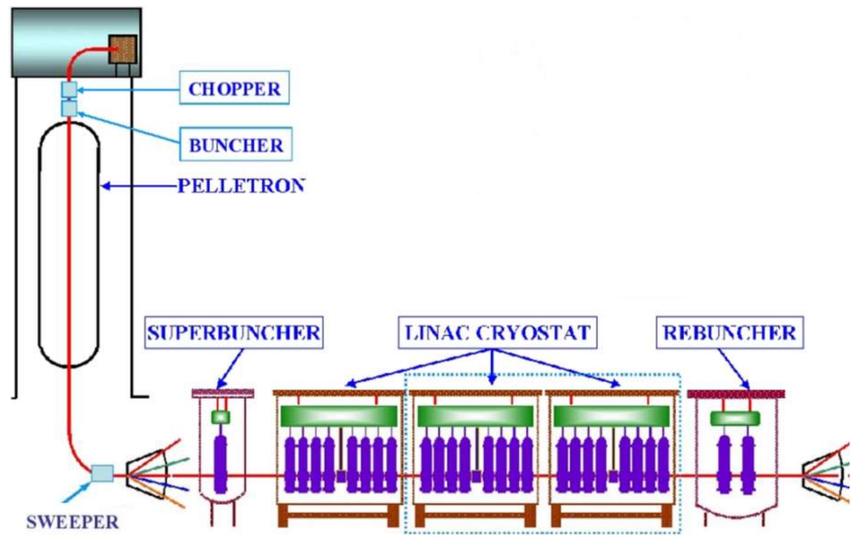
Tank height: 26.5 m
Diameter: 5.5 m
Pressure: 86 PSI
SF_6 gas

Ions accelerated:
H to Au beams

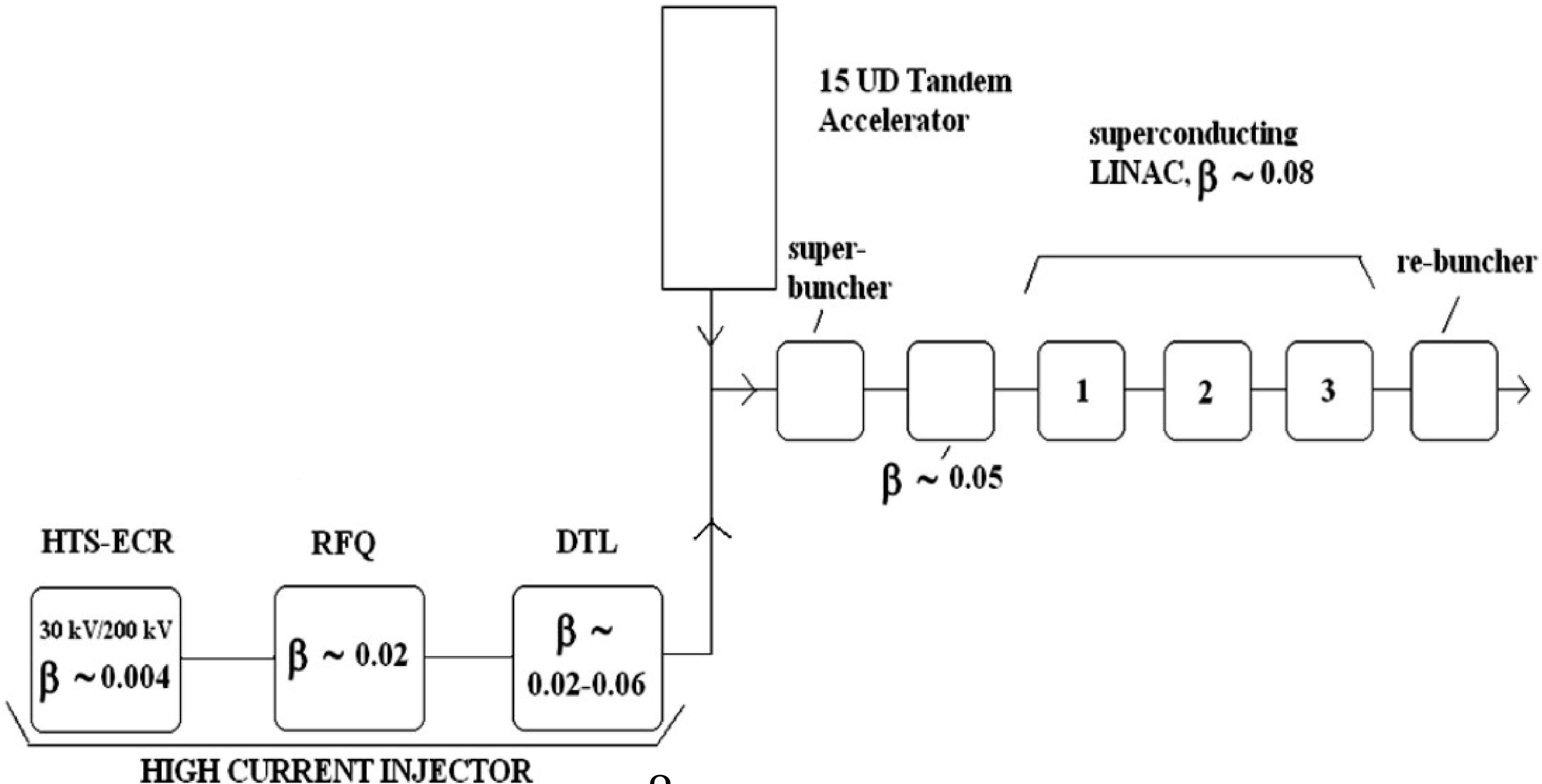
Currents: ~ 1 -50 pnA
Energy : 30 – 270 MeV



Special Features: 1. Off-set QP in Terminal
2. Earthquake Protection
3. Compressed Geometry Tubes



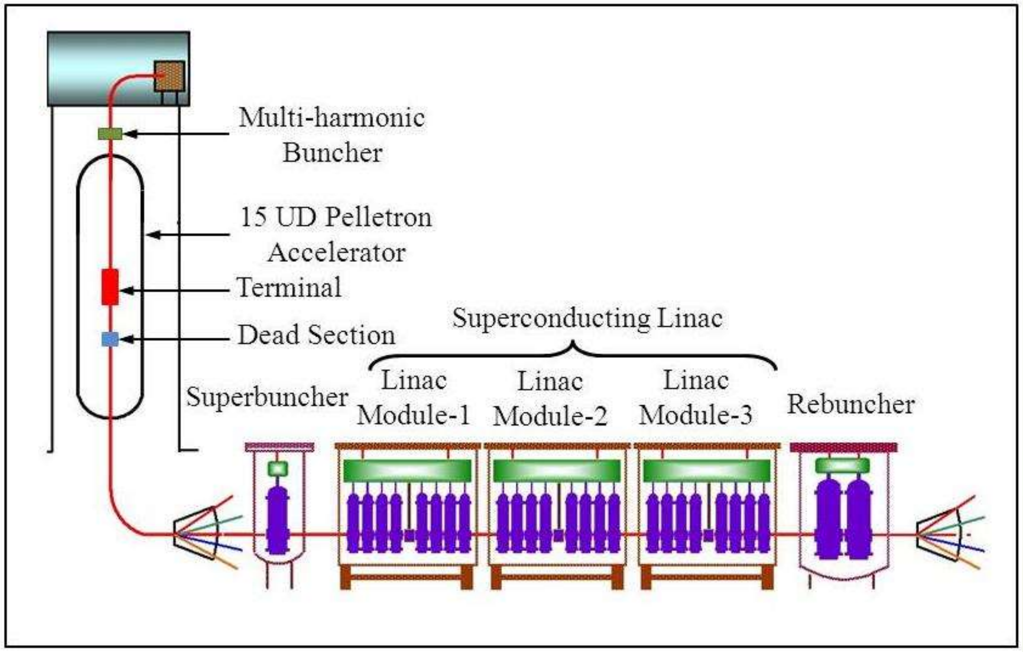
Schematic of the ECRIS based High Current Injector (HCI) with respect to the present Tandem Accelerator-Superconducting Linear Accelerator (SC-LINAC)



β is the ratio of the velocity of the charged particle to the velocity of light

Superconducting LINAC at IUAC

At the heart of the Superconducting LINAC at IUAC is a Niobium Quarter Wave Resonator (QWR) that accelerates the ion beam to high energies. The QWR operates at 97 MHz frequency.



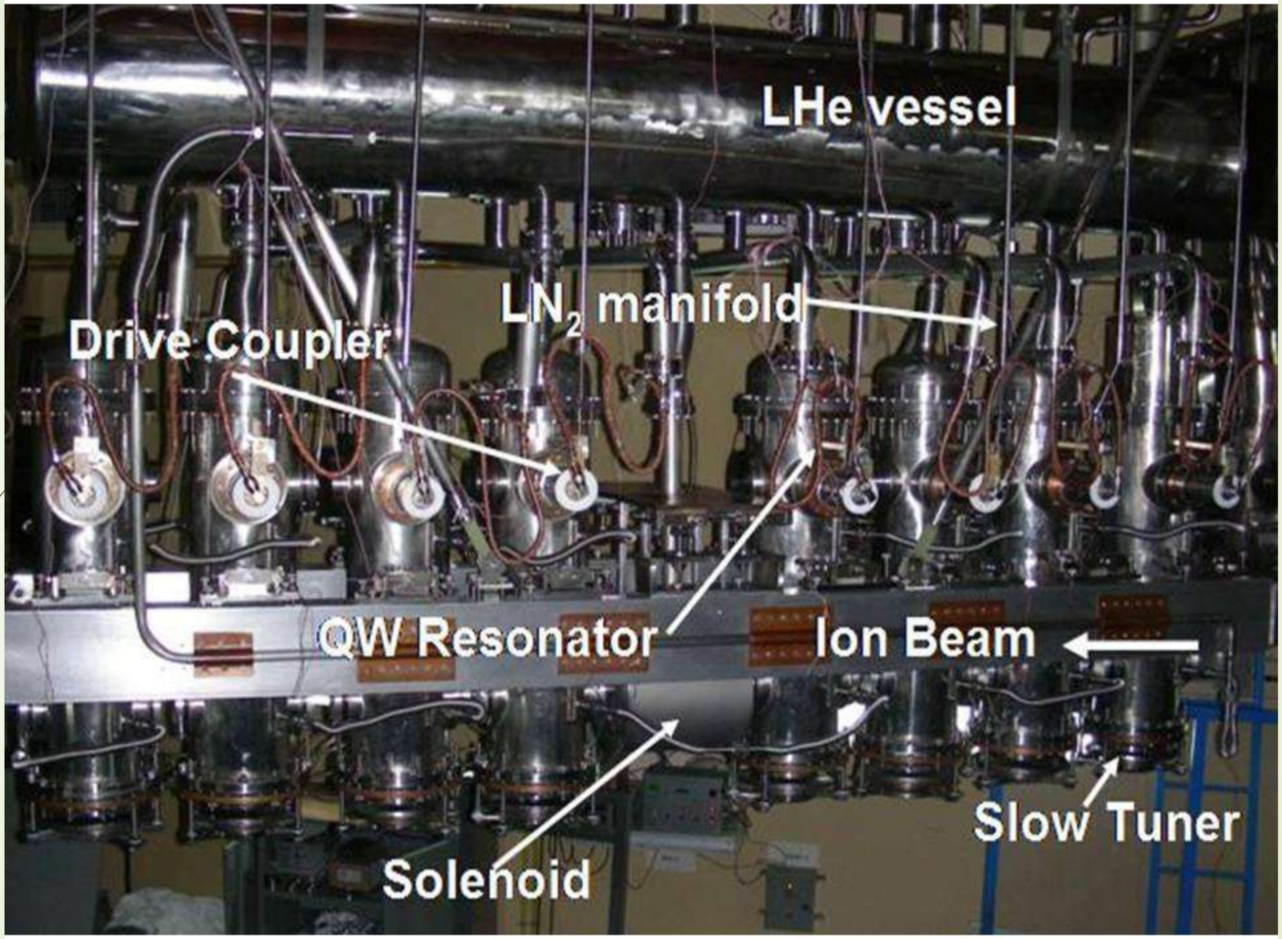
15 UD Tandem Pelletron Accelerator and Superconducting Linear Accelerator (SC LINAC)

Quarter Wave Resonator: β=0.08; the operating temp. is 4.2 K

SC LINAC Modules

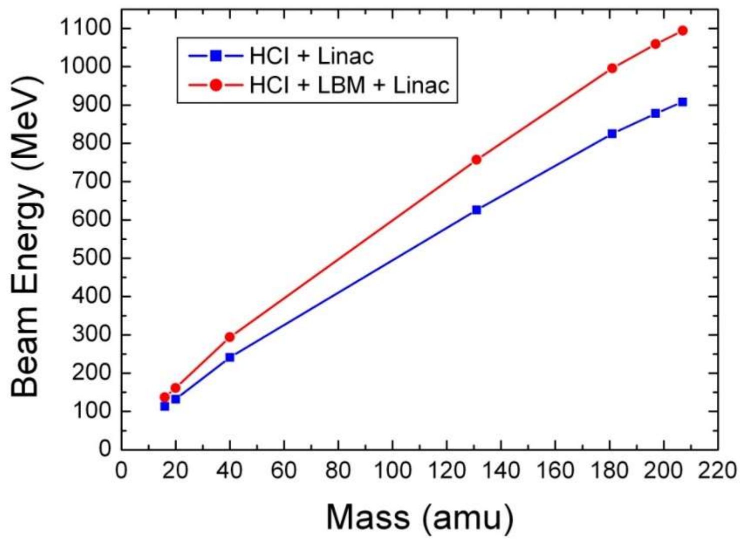
The Superconducting LINAC at IUAC. It has been in operation for the past several years and experiments are being done regularly using this facility.

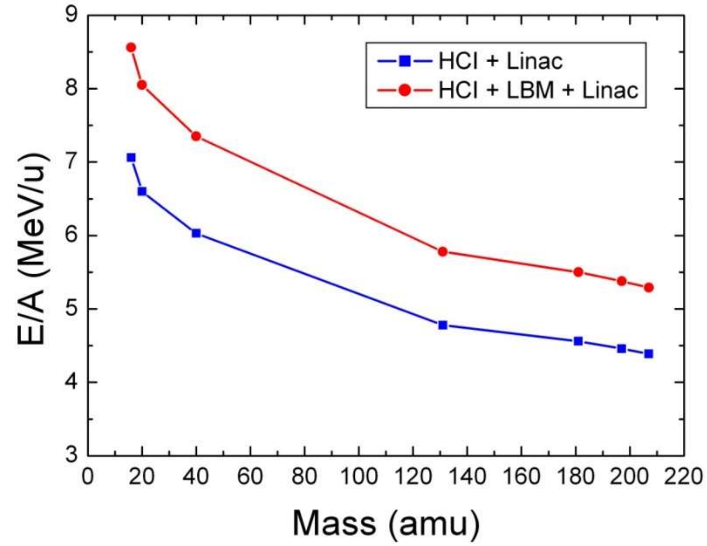
Inside View of the Module



The inside of a LINAC Cryomodule at IUAC. Each Module has eight QWRs and a superconducting solenoid magnet to focus the ion beams.

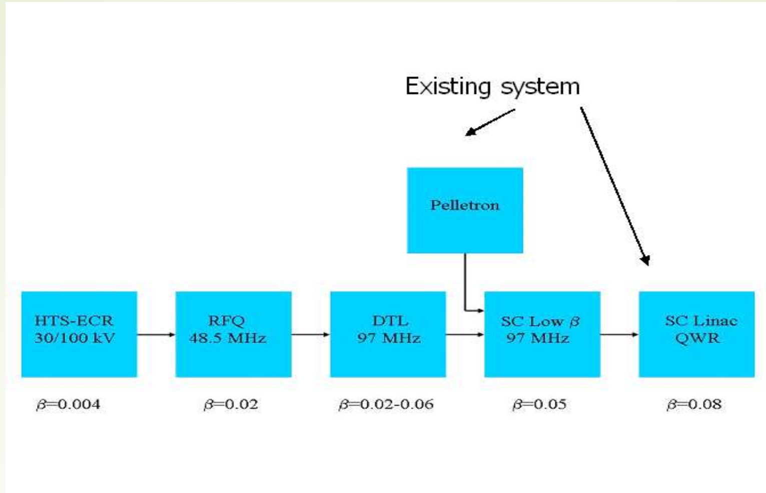
HCI + SC LINAC Energy Gain

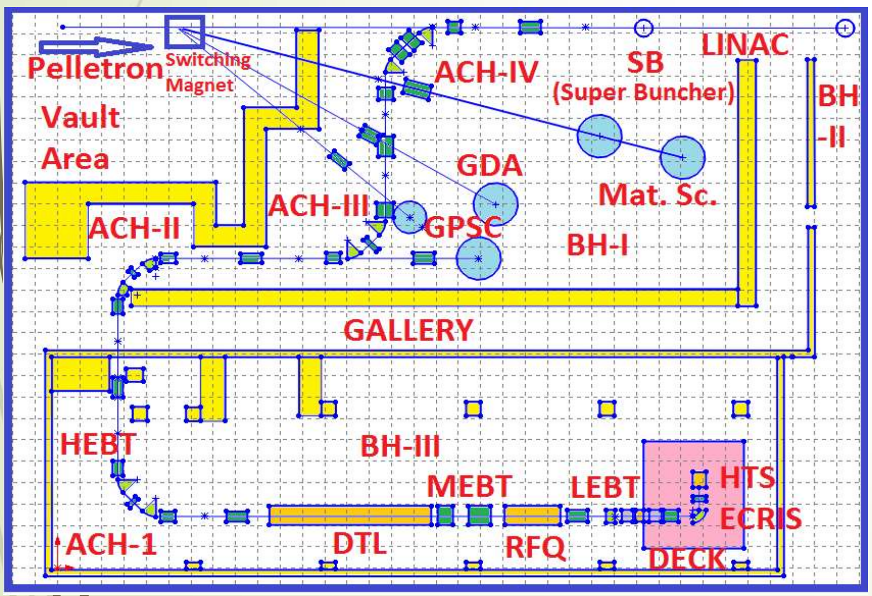


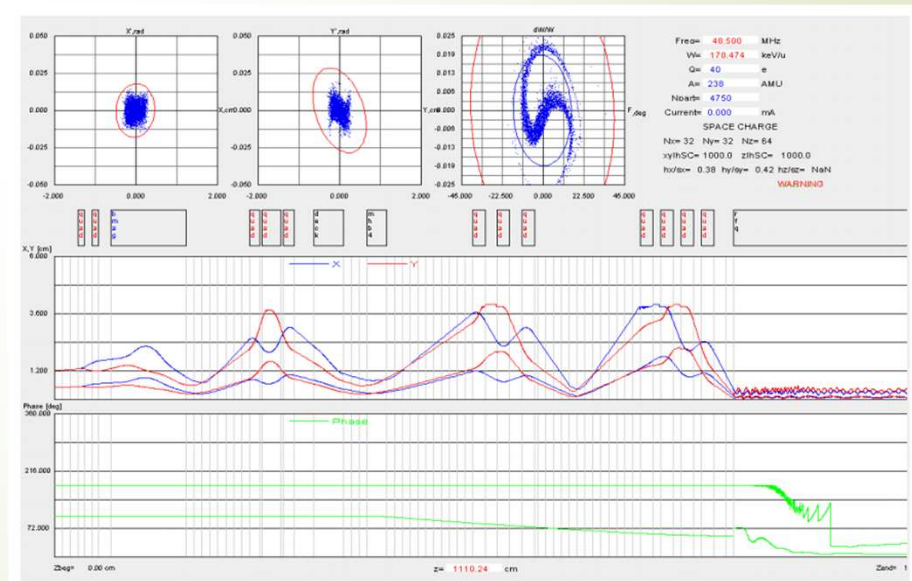


Energy Gain (left) and Energy per nucleon (right) as a function of ion mass for the High Current Injector (HCI) + Superconducting Linac, and High Current Injector + Low beta Module (LBM) + Superconducting Linac. A foil stripper is assumed between HCI and LBM in both the cases. The calculations are done with the Low Beta Resonators in the LBM operating at 6 MV/m accelerating gradient and the QWRs in the SC Linac at 3.5 MV/m accelerating gradient.

High Current Injector Programme

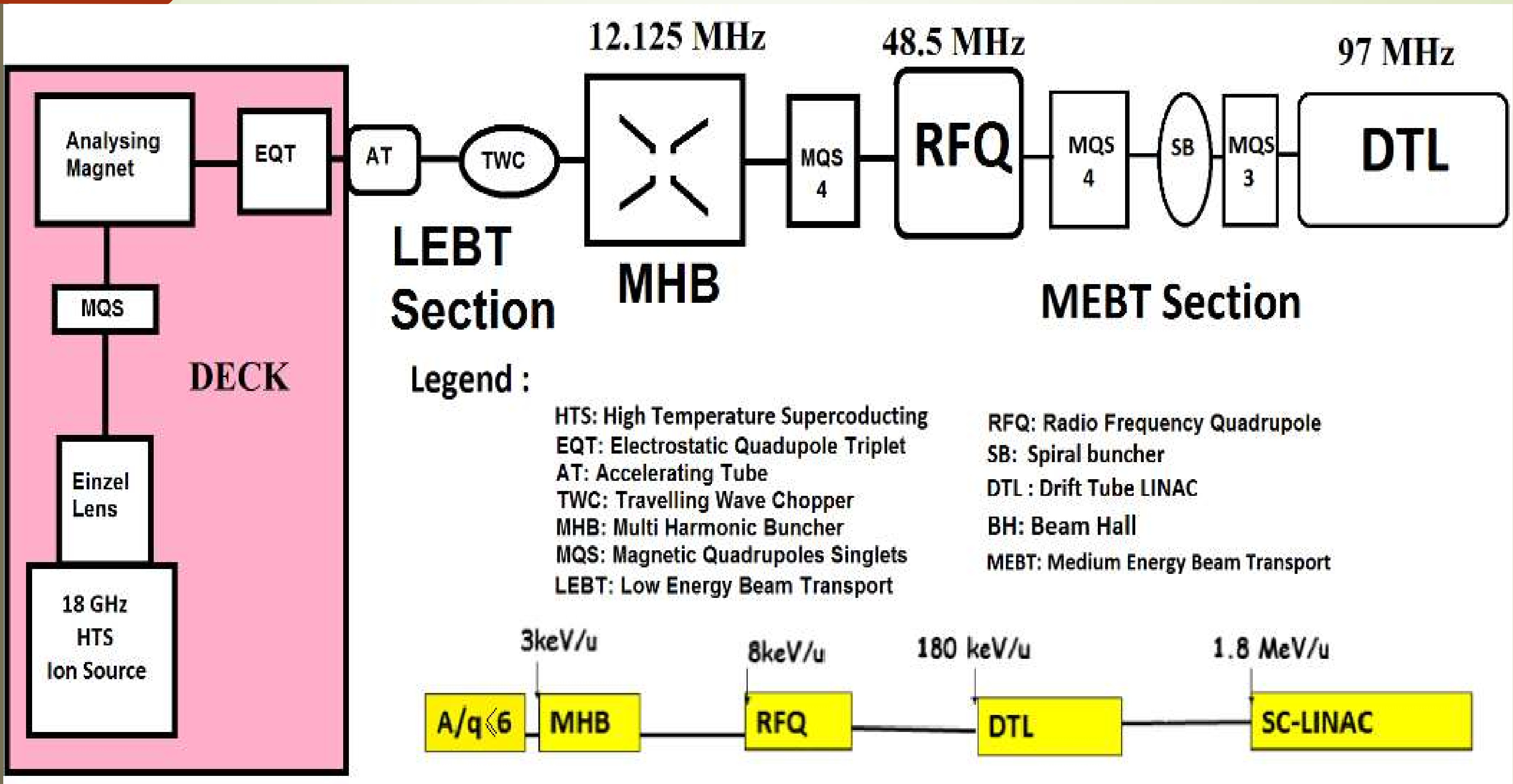




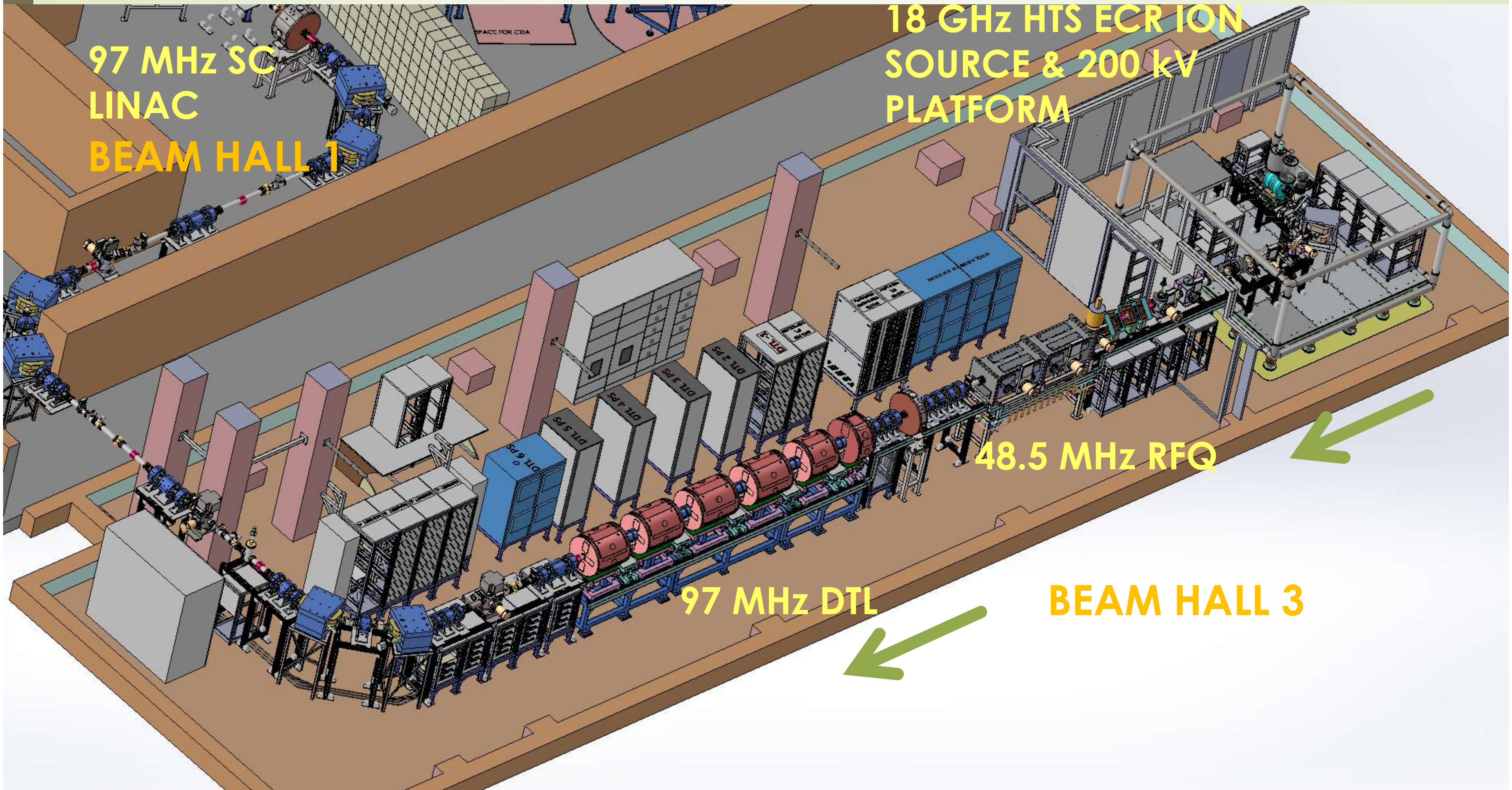


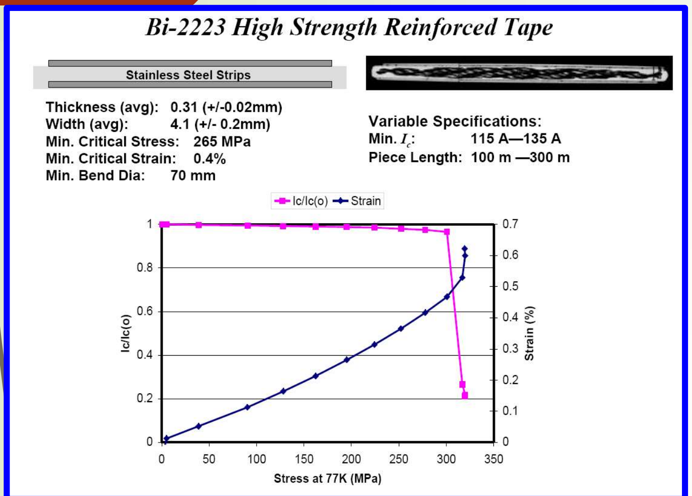
TRACK simulation of $^{238}U^{40+}$ from ECR upto RFQ exit

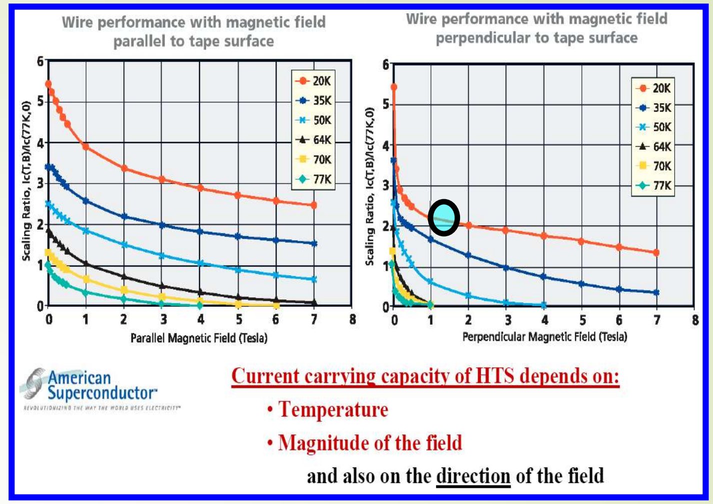
Schematic layout of the High Current Injector



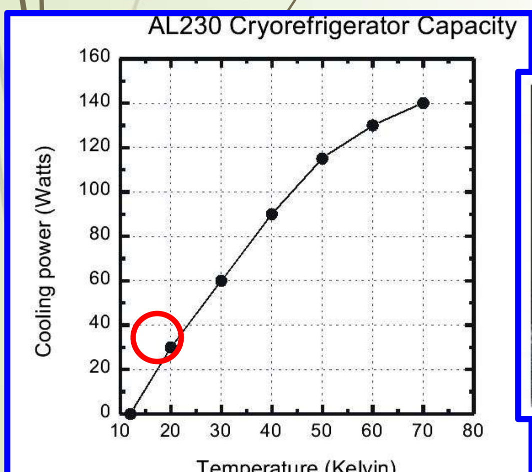
LAYOUT OF HIGH CURRENT INJECTOR (HCI) BEAMLINE







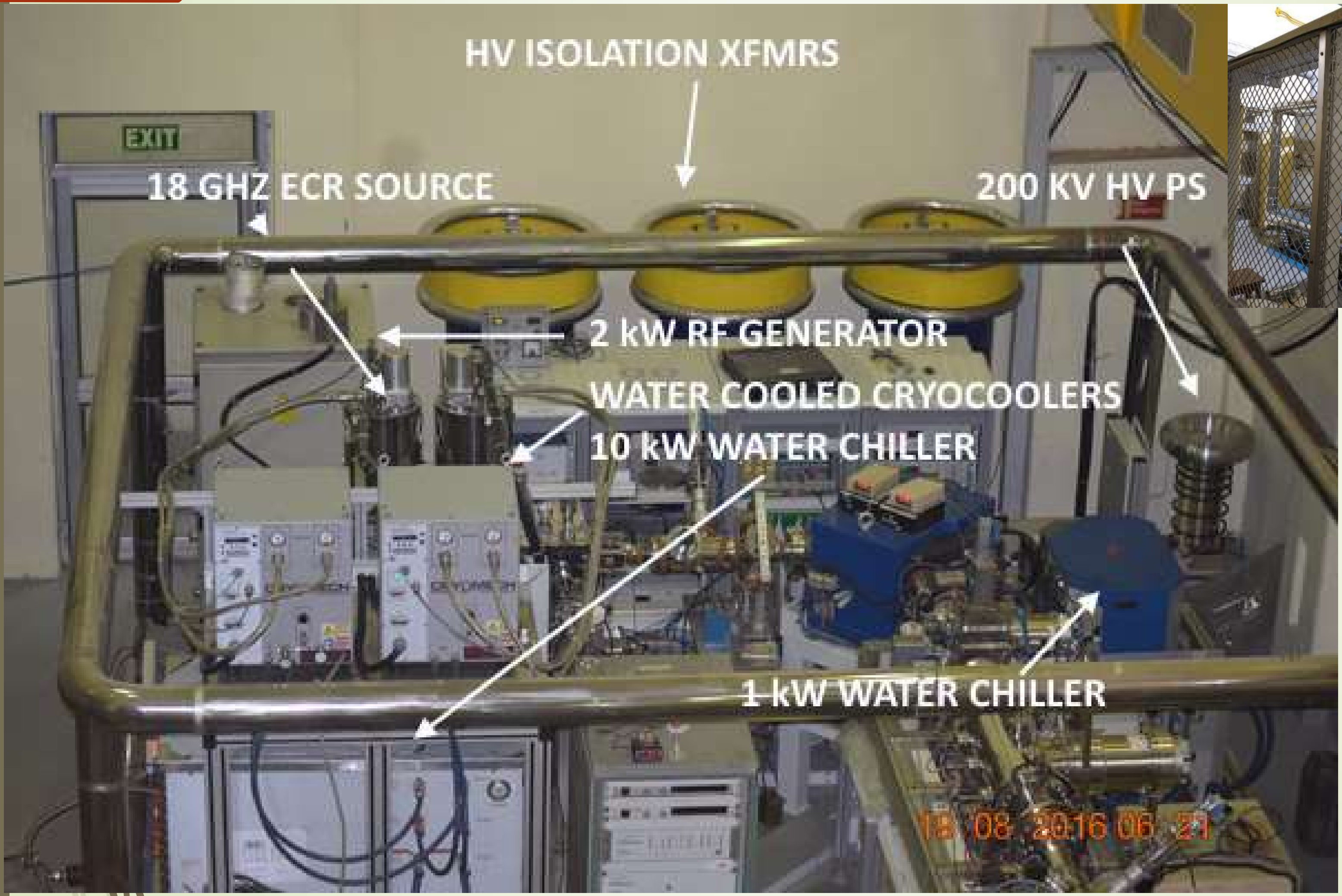
Parameter	Value
Conductor type	BSCCO-2223
Operating temperature (at field)	23 K
Operating current	181 A (injection coil)
	145 A (extraction coil)
Maximum field on the axis	1.8 T
Maximum field on the conductor	3.0 T
Maximum radial field on the conductor	1.4 T
Total length of conductor per coil	950 m
Inner coil diameter	240 mm
Outer coil diameter	320 mm



Maximum operating current 181 A
Maximum radial field 1.4 T
I_c @ 77 K,0B 110 A

Richard McMahon , Stephen Harrison, Steve Milward, John Ross, Robin Stafford Allen, Claude Bieth, Said Kantas and Gerry Rodrigues, **IEEE Transactions on Applied Superconductivity, Vol.14, No.2, June 2004**

View of the sub-systems on the 200 kV high voltage platform

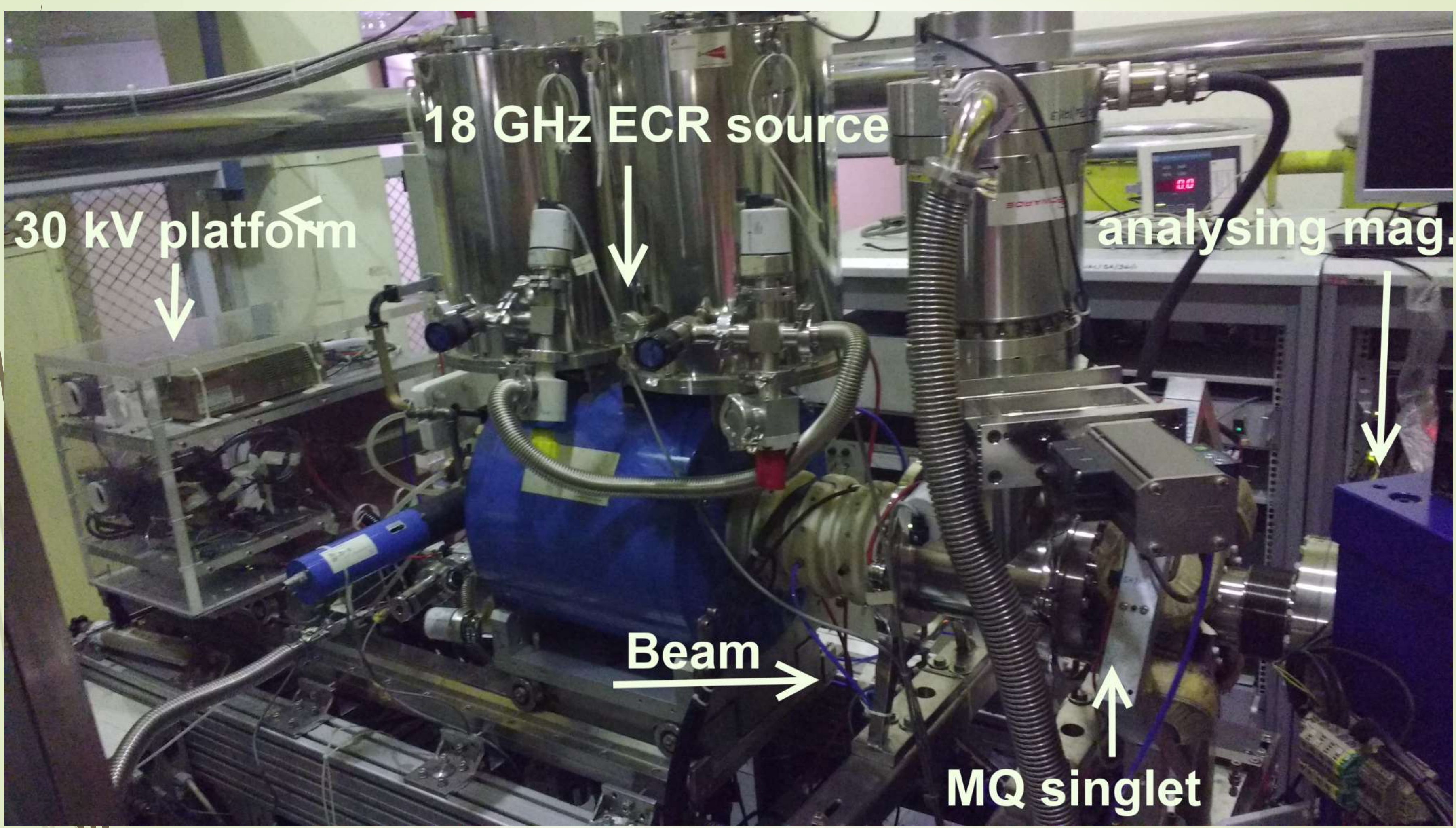


SPECIFICATIONS OF THE 18 GHz HTS ECR ION SOURCE

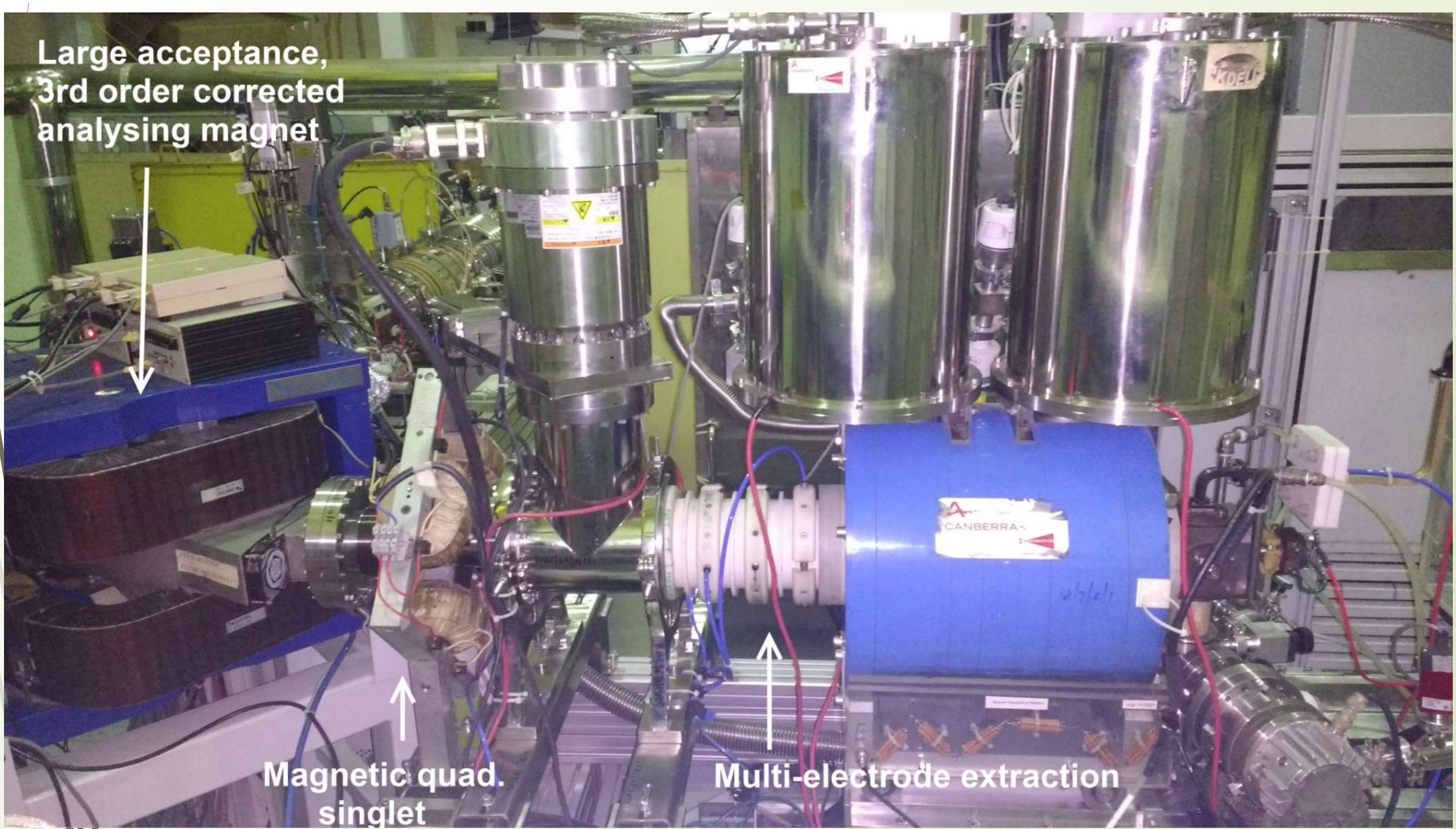
HTS coils operational temperature :	22 K (Coil former @ 20 K)
Cryo-coolers:	Cooled using chillers
Cryostat vacuum (INJ & EXT):	2 x 10^{-6} mbar
Maximum axial field at injection:	1.8 T
Maximum axial field at extraction:	1.5 T
Multipole:	36 sector Hexapole ('Halbach' configuration)
RF injection:	transverse to co-axial coupling
Plasma chamber:	multi-mode cavity
RF generator :	Klystron 1.7 kW, air cooled
Multi-electrode extraction	
Extraction voltage:	Maximum 30 kV
Gas injection, oven, sputter probe	
Negative DC bias probe:	Maximum – 1 kV
Base injection vacuum:	7 x 10^{-8} mbar
Base extraction vacuum:	3 x 10^{-8} mbar

C. Bieth, S. Kantas , P. Sortais, D. Kanjilal , G. Rodrigues , S. Milward , S. Harrison , R. Mc Mahon, Nucl.Instrum.Methods. B 235 (2005) 498

View of the 18 GHz HTS ECR ion Source



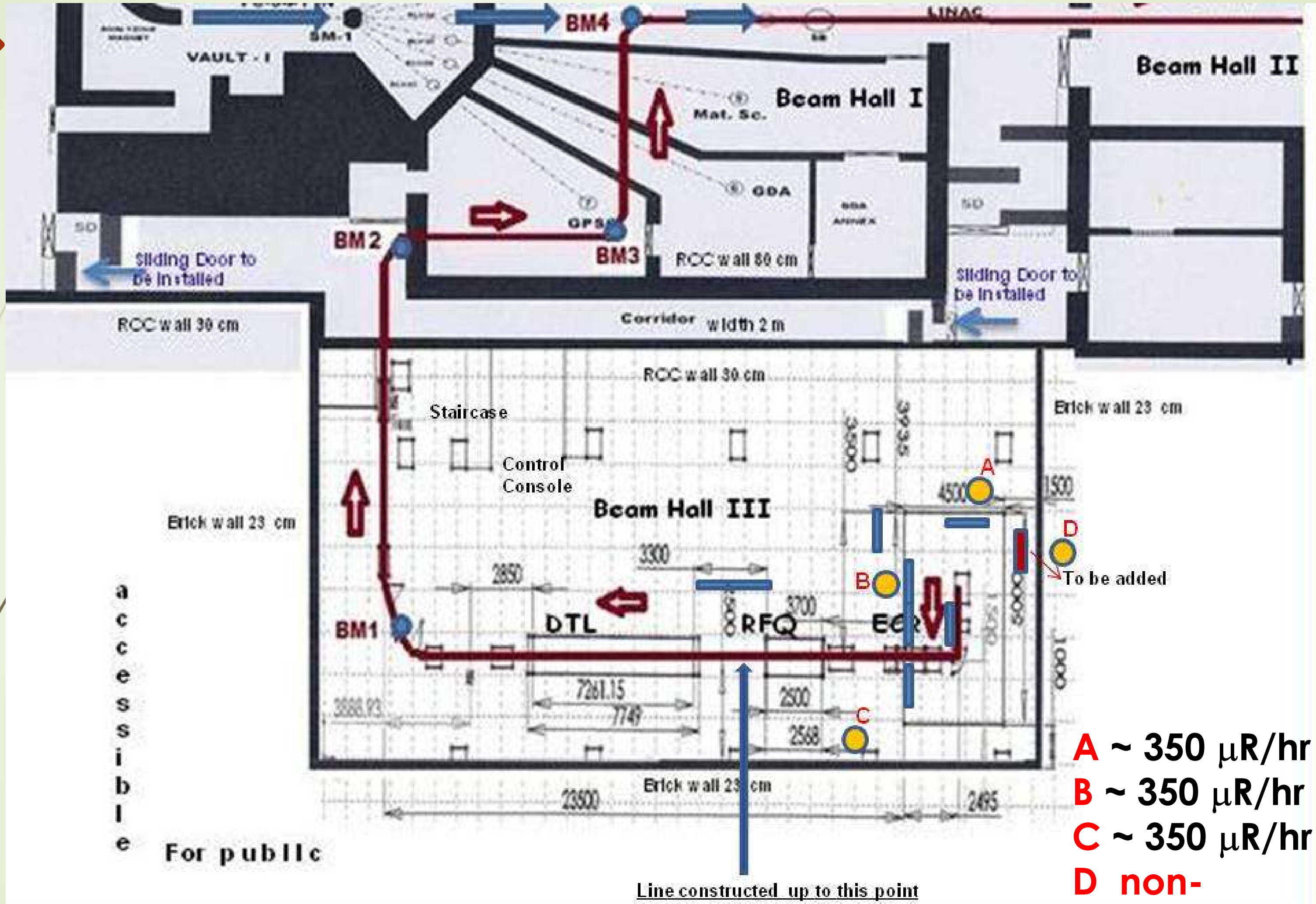
View of the 18 GHz HTS ECR ion Source coupled to the LEBT



BEAMS EXTRACTED FROM THE 18 GHz HTS ECR ION SOURCE

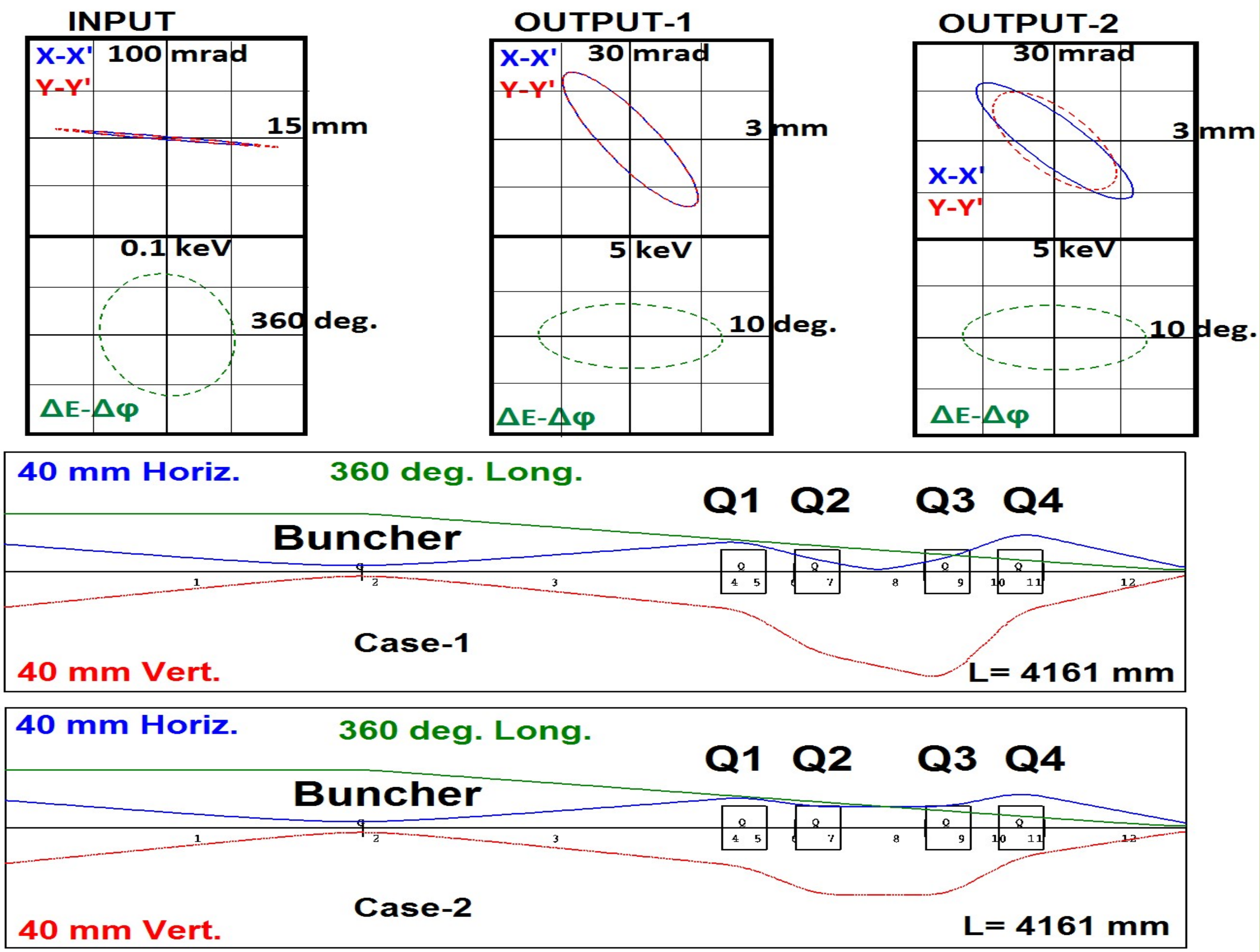
ION	A/Q = 6	A/Q = 7	A/Q = 8	A/Q = 9
^{12}C	Q=2+, I > 2 mA 2 mA			
^{16}O			Q=2+, I ≥ 2 mA 2.037 mA	
^{20}Ne		Q=3+, I > 1mA 1.533 mA		Q=2+, I ≥ 2 mA 2.044 mA
^{40}Ar	Q=7+, I ≥ 600 µA 600 µA			Q=4+, I ≥ 1 mA 1.023 mA
^{129}Xe	Q=21+, I ≥ 20 µA 28 µA			Q=14+,I ≥ 150 µA 157 µA
^{180}Ta		Q=25+,26+, I ≥ 25 µA 27 µA		Q=20+, I ≥ 30 µA 65 µA
^{197}Au		Q=28+, I ≥ 10 µA 10 µA		Q=21+, I ≥ 15 µA 28 µA
^{208}Pb		Q=29+, I ≥ 12 µA 12 µA		Q=21+, I ≥ 15 µA 65 µA

Proximity of beam hall III and beam hall I

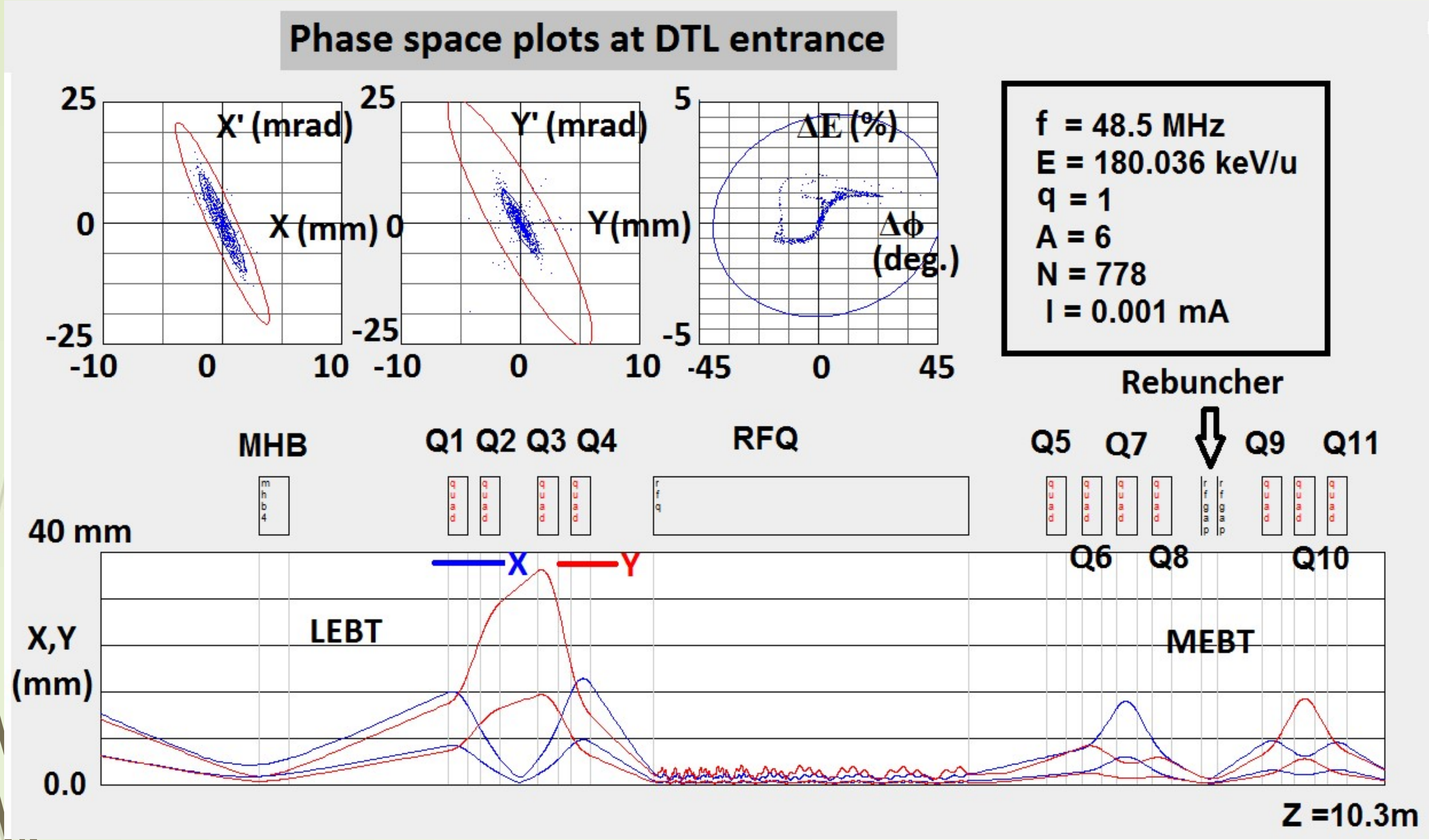


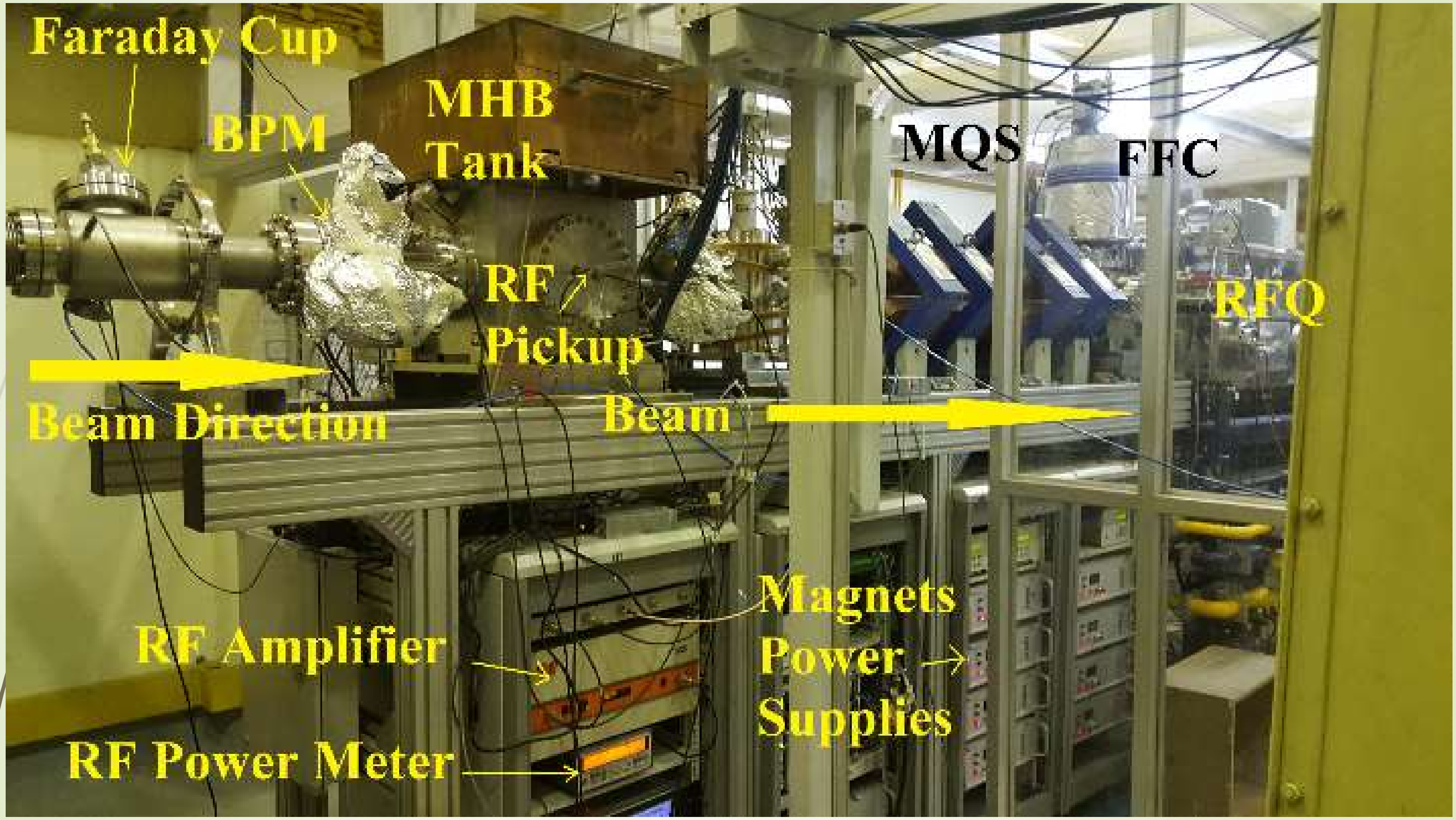
A ~ 350 μR/hr
B ~ 350 μR/hr
C ~ 350 μR/hr
D non-permissable

Transverse and longitudinal optics before RFQ using a Multi-Harmonic Buncher



Multiparticle TRACK simulation upto entrance of DTL




Faraday Cup
BPM
MHB
Tank
MQS
FFC
RF
Pickup
RFQ
Beam Direction
Beam
Magnets
Power
Supplies
RF Amplifier
RF Power Meter

Bunching using the 12.125 MHz Multi Harmonic Buncher

CRITERIA FOR BEAM BUNCHING OPERATION AND MEASUREMENTS

1. The ion beam should have a sharp waist in transverse dimension at the RF gap formed by the grids of the buncher.

2. The electric field must be uniform across the pair of grids forming the RF gap.

3. The energy spread of the beam from the ECR source must be minimum for proper bunching.

4. The bunching grids, tank circuit coils, and RF amplifier should be water cooled for continuous operation to avoid any temperature related drifts.

5. The saw-tooth voltage responsible for bunching must be stable in terms of amplitude and phase. This is ensured by monitoring the pick-up signal triggered by the master clock.

6. The beam hall environment should be noise free in order to measure the beam bunches on CRO using the amplified signal from the fast faraday cup.

PROBLEMS ENCOUNTERED

1. The FFC signal for measuring bunch width was very sensitive to any noise and RF pick-up. The background signal were minimized by averaging over 50 – 100 samples for stable measurements.

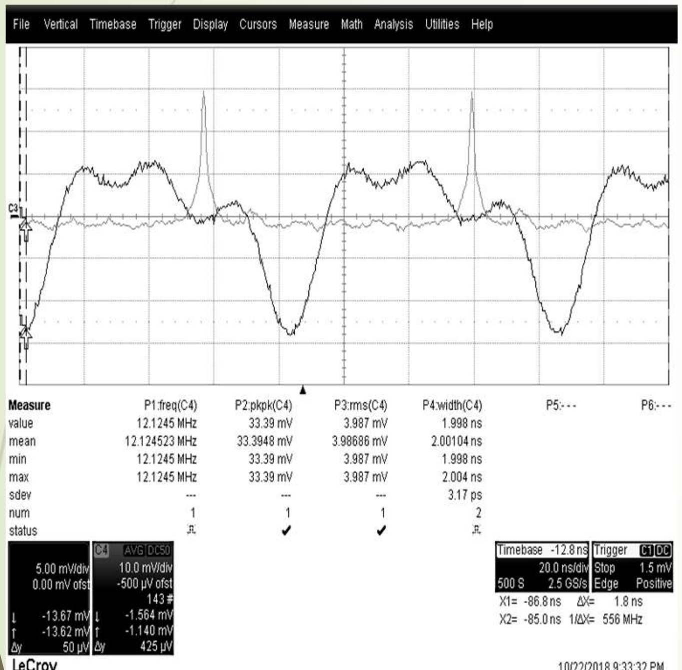
2. The pre-amplifier coupled to the FFC is also very sensitive and prone to damage for any RF pick-ups. It was thus turned off whenever RFQ was on. The measurement of beam bunches were made only when RFQ was off.

3. For cooling of the grids and tank circuit coils, the flow and temperature of the de-ionised water cooling system had to be maintained accurately for smooth operation.

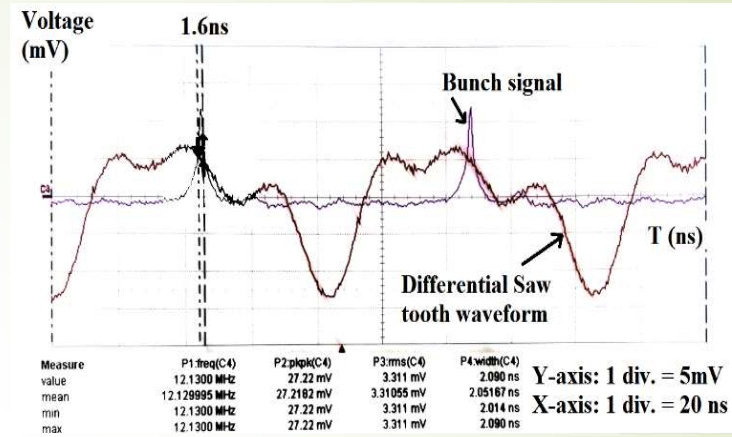
4. All the bunched width measurements were done on a 500 MHz oscilloscope. Measurements of FFC timing signals on 4 - 6 GHz oscilloscope would yield much better results.

Bunched widths of various beams

Bunched Spectrum of O^{6+}

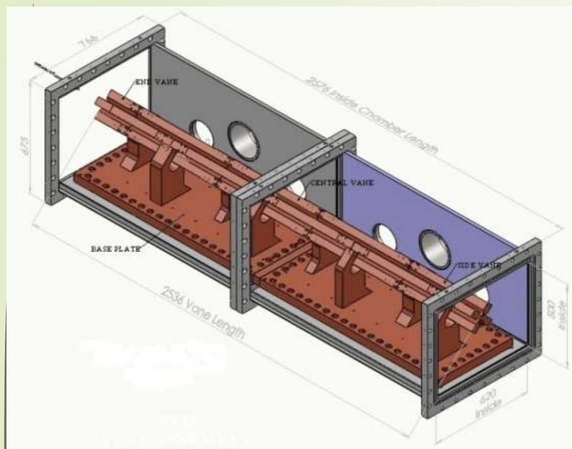


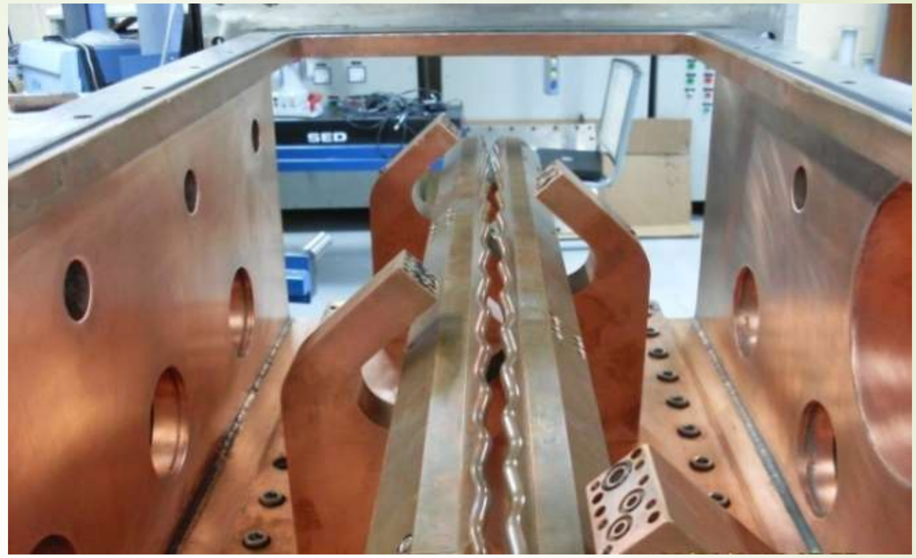
Bunched Spectrum of Ne^{8+}



Bunched spectrum of N^{5+}

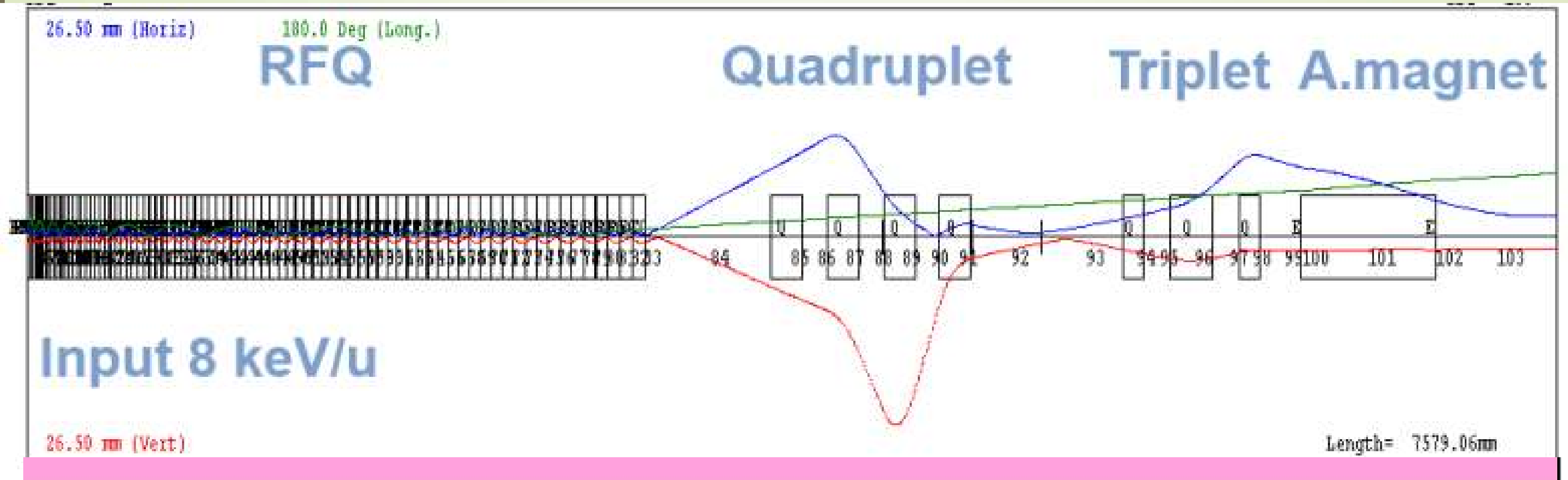
48.5 MHz RADIO FREQUENCY QUADRUPOLE

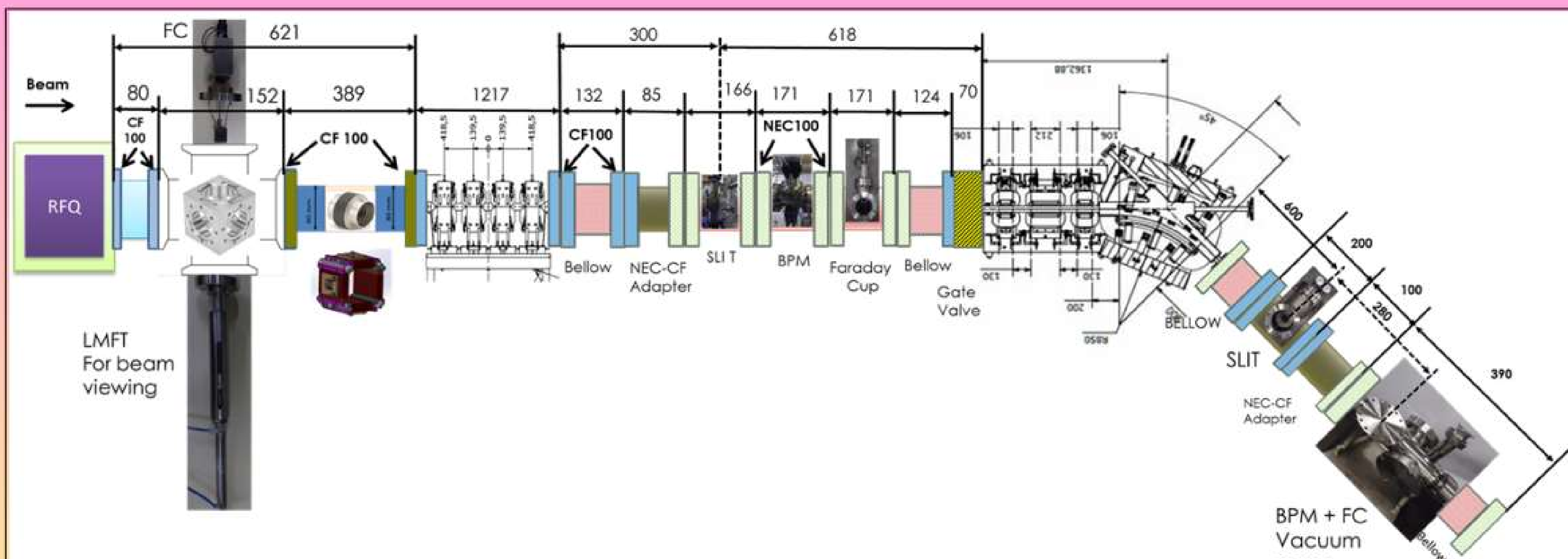




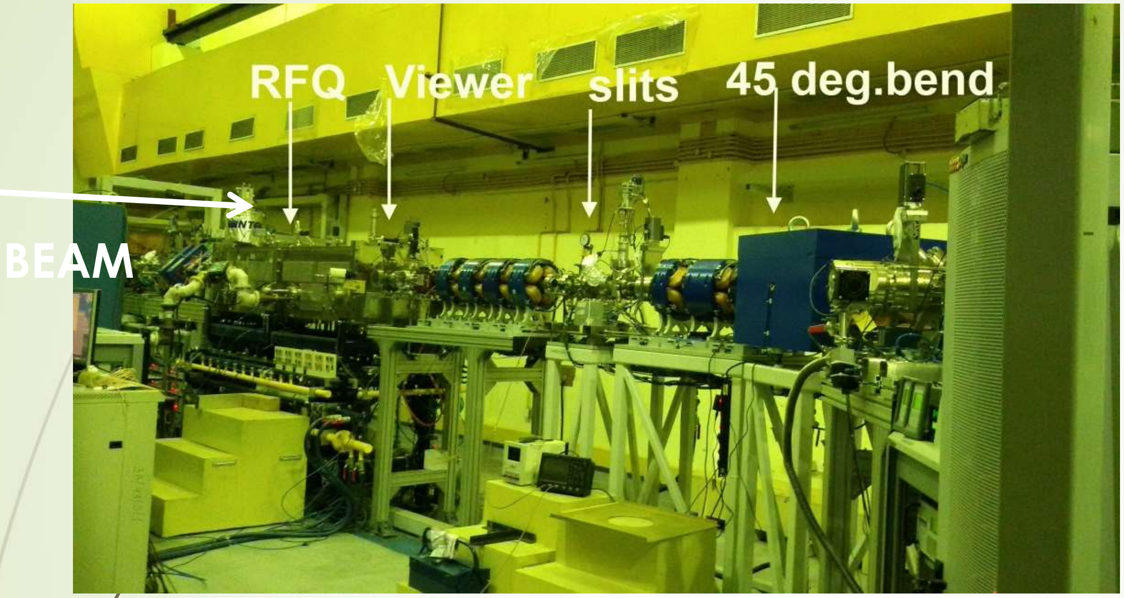
RFQ type	Rod
Frequency	48.5 MHz
Design A/q	<= 6
Input design energy	8 keV/u
Output design energy	180 keV/u
Total Length (without buncher)	2.536 m
Transmission	> 90 %

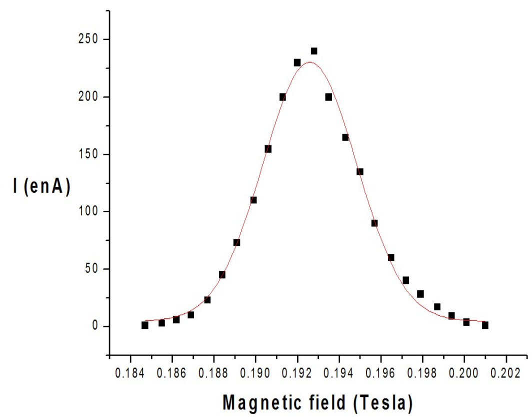
Layout to test the Energy gain through RFQ





Test of Energy gain through the RFQ cavity





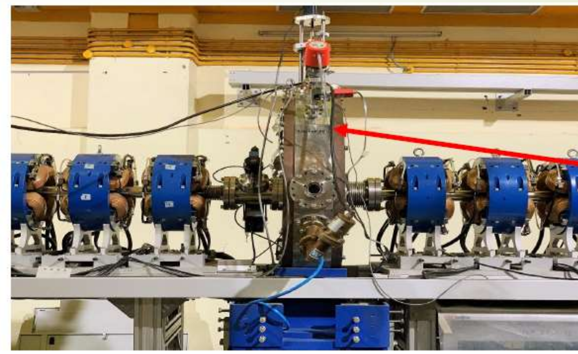
- **A Gaussian fit to the distribution gives an final energy of $^{16}O^{5+}$, 180.5 keV with an energy spread of FWHM of 4.97 keV (3 mm slit at object and image planes)**
- **Spiral Buncher and DTL cavities were operated in 'drift' mode and the bunch width after the RFQ could not be measured due to lack of a time diagnostic.**

ACCELERATION TESTS OF VARIOUS BEAM THROUGH THE RFQ

Beam	A/q	E_{in}(keV)	E_{out}(keV)	Cavity Pickup (mV)	Peak Power (kW)
He^{2+}	2.0	32	707 ± 3.0	38.2	13.2
Ne^{8+}	2.5	160	3640 ± 2.8	43.0	18.0
O^{6+}	2.67	128	2896 ± 2.7	43.5	18.3
N^{5+}	2.8	112	2520 ± 2.5	44.8	19.2

48.5 MHz SPIRAL BUNCHER (MEBT SECTION)

- MEBT spiral buncher cavity has been designed, developed, characterized, tested, and commissioned in the HCI beamline. High Vacuum of ~low 10^{-7} mbar was achieved.
- The buncher cavity has been powered several times more than its design value to check it's stability at high-power.
- The cavity was tested with various ion beams to validate it's electrical design.
- The transmission has been improved be a factor of ~ two, when MEBT spiral buncher cavity was on (old beamline).
- Beam testing continues in the new beamline, transmission further improved using the tuning of spiral buncher.



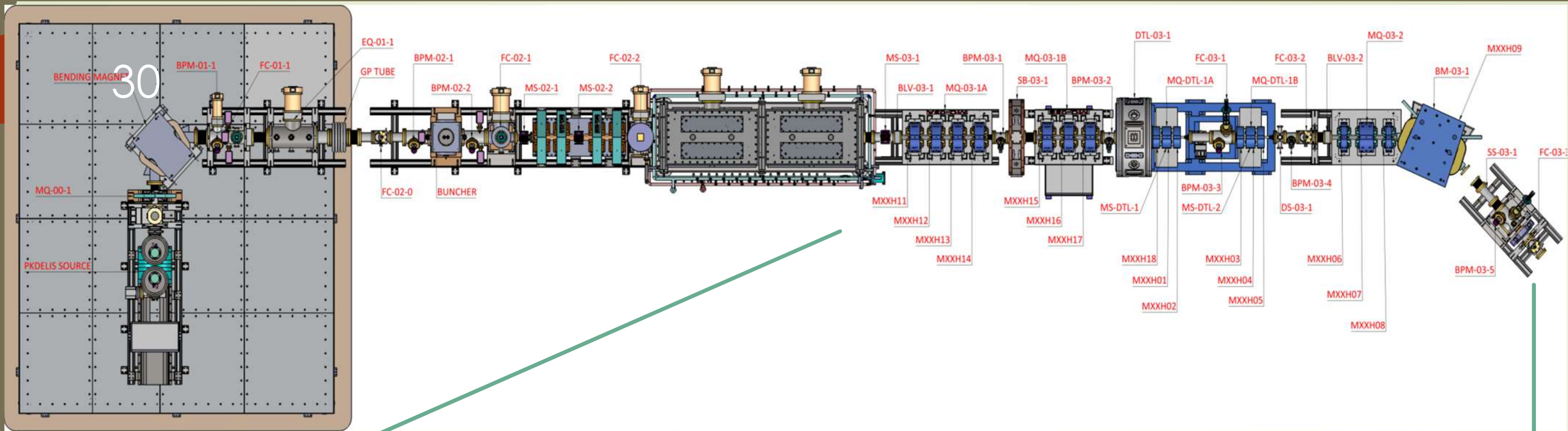
Spiral Buncher cavity installed in the MEBT Section of the HCI

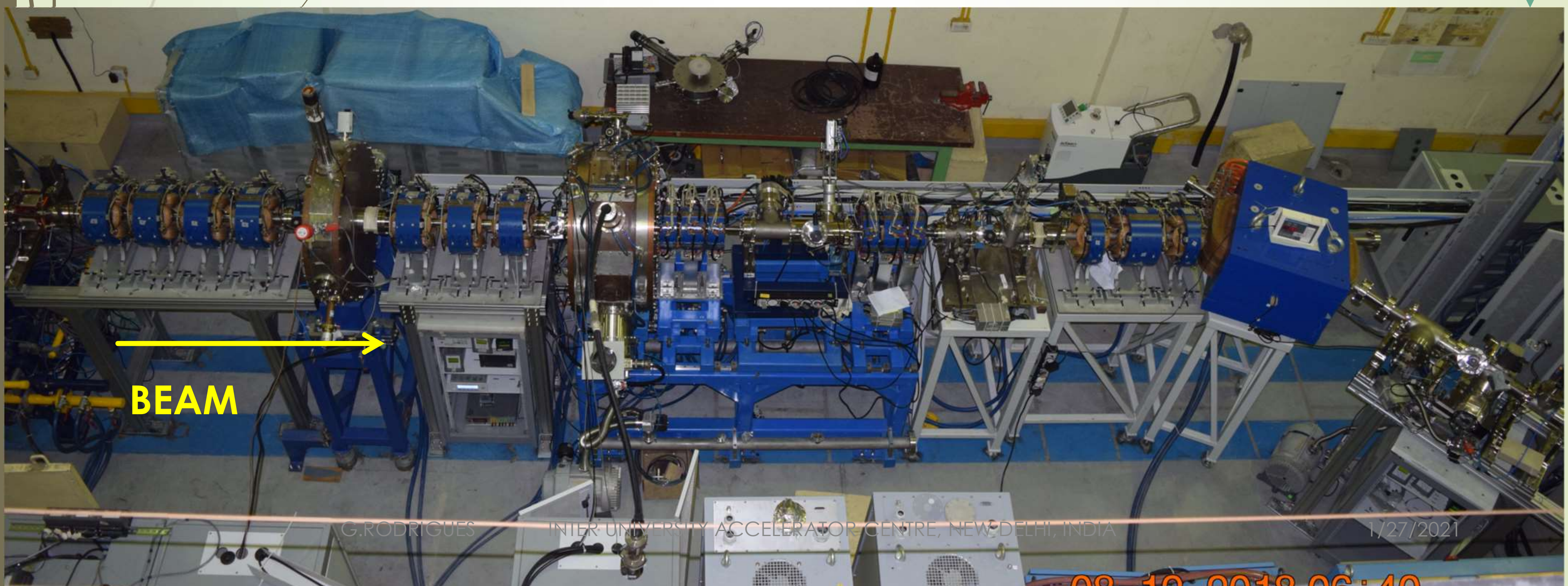
Ion Beam	Before Spiral	After Spiral	Comments
Ne^{+8}	2.3 nA	4.3 nA	(Old Beamline) Current became almost double when the spiral buncher kept on
	2.1 nA	4.4 nA	

Ion Beam	After RFQ	After DTL	Comments
N^{+5}	1300 nA	460 nA	(New Beamline) Transmission has been increased by a factor of ~two by tuning the spiral buncher.
	1500 nA	650 nA	

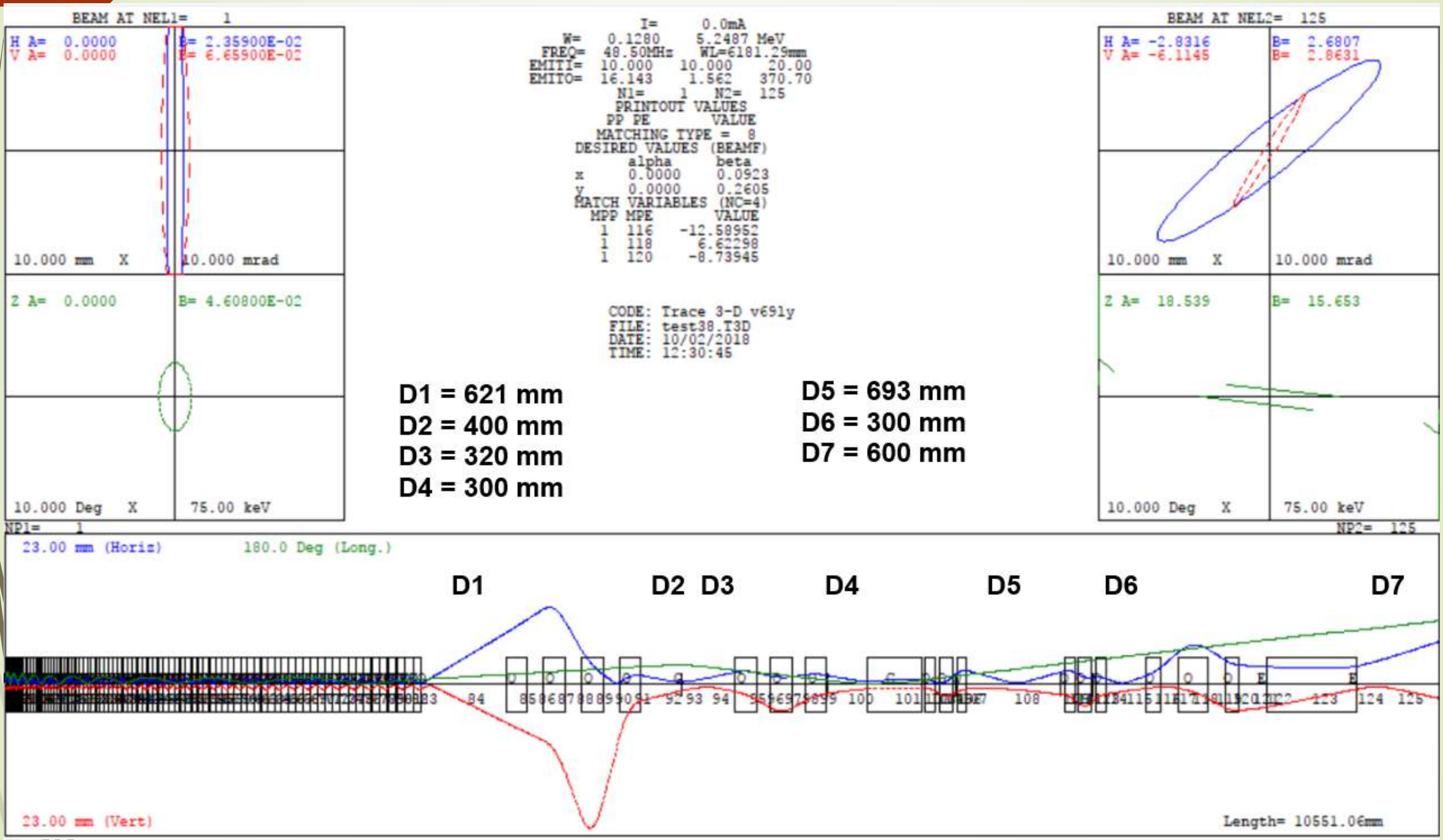
Beam Test Results

Layout of components for testing the first DTL cavity





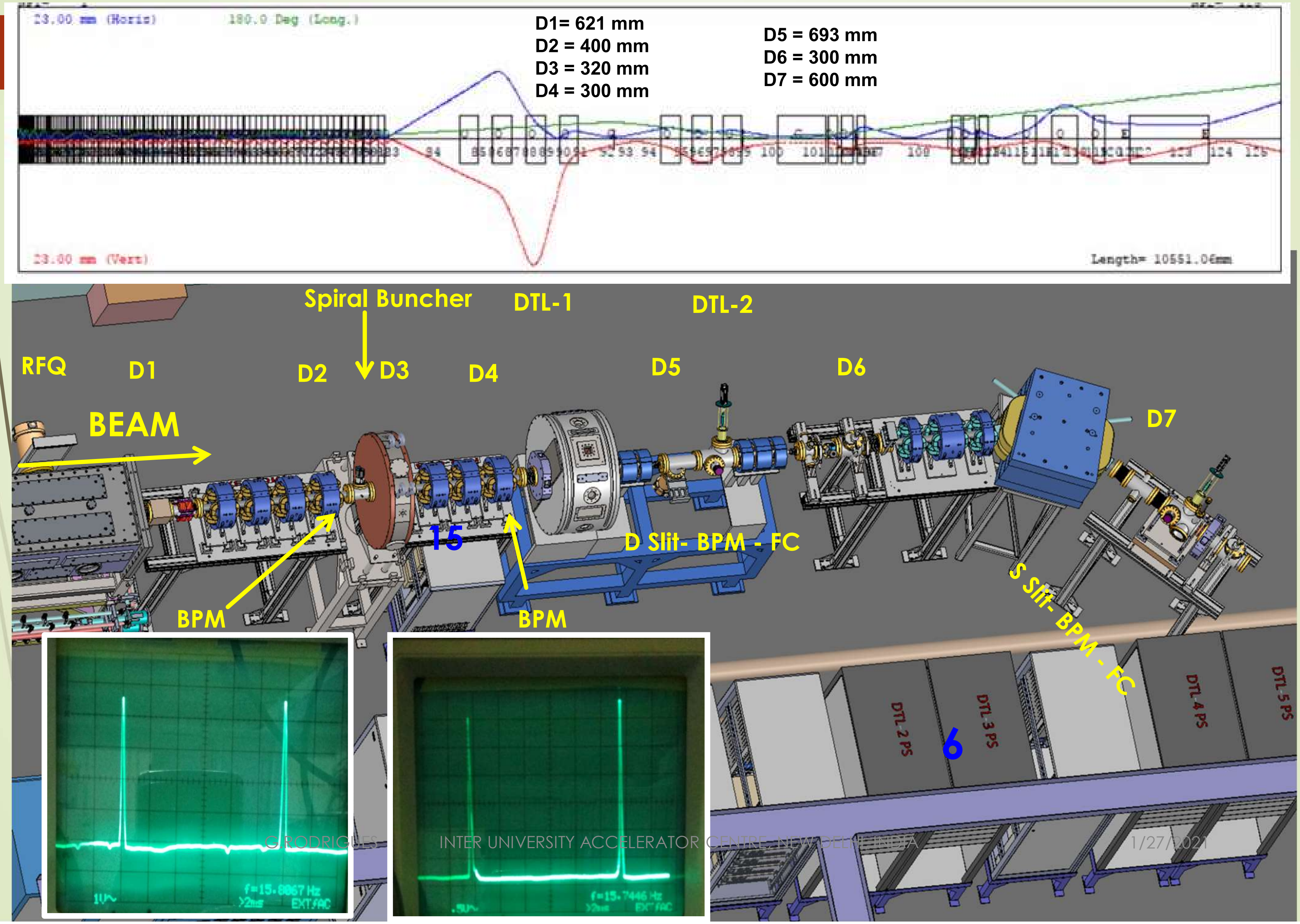
Beam optics for RFQ--SB--DTL-1 with provision DTL-2 Layout beam test



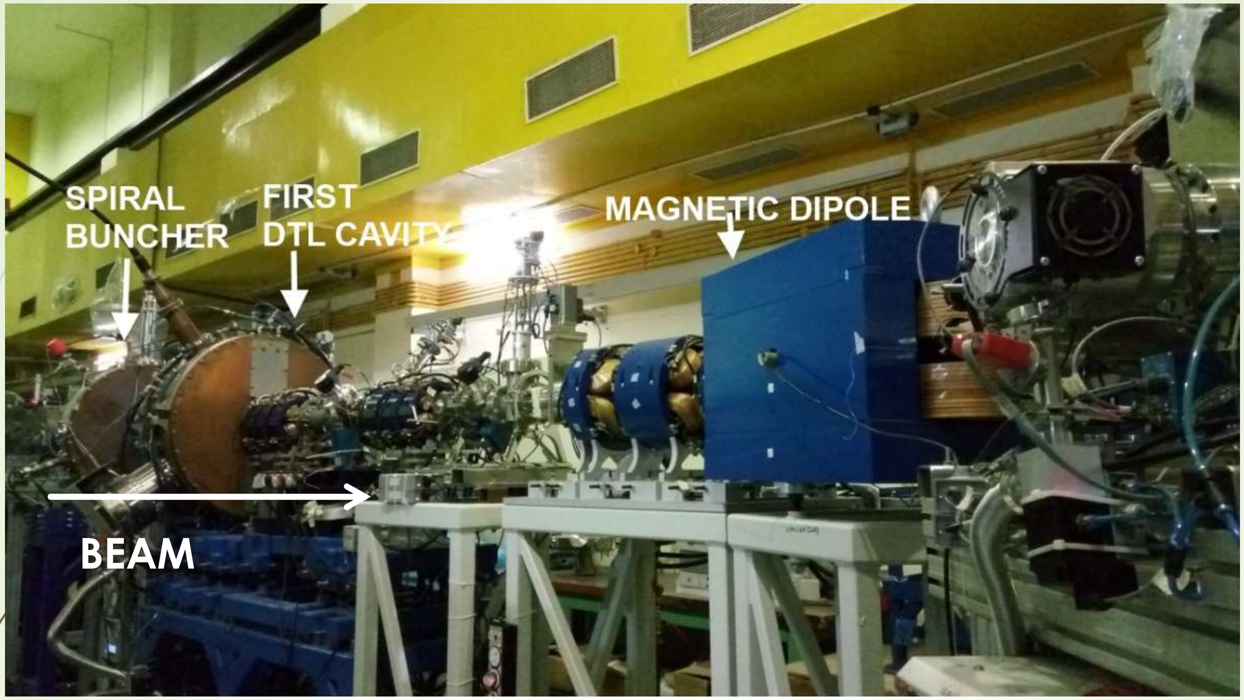
D1 = 621 mm
D2 = 400 mm
D3 = 320 mm
D4 = 300 mm

D5 = 693 mm
D6 = 300 mm
D7 = 600 mm

RFQ--SB--DTL-1 with provision DTL-2 Layout beam test

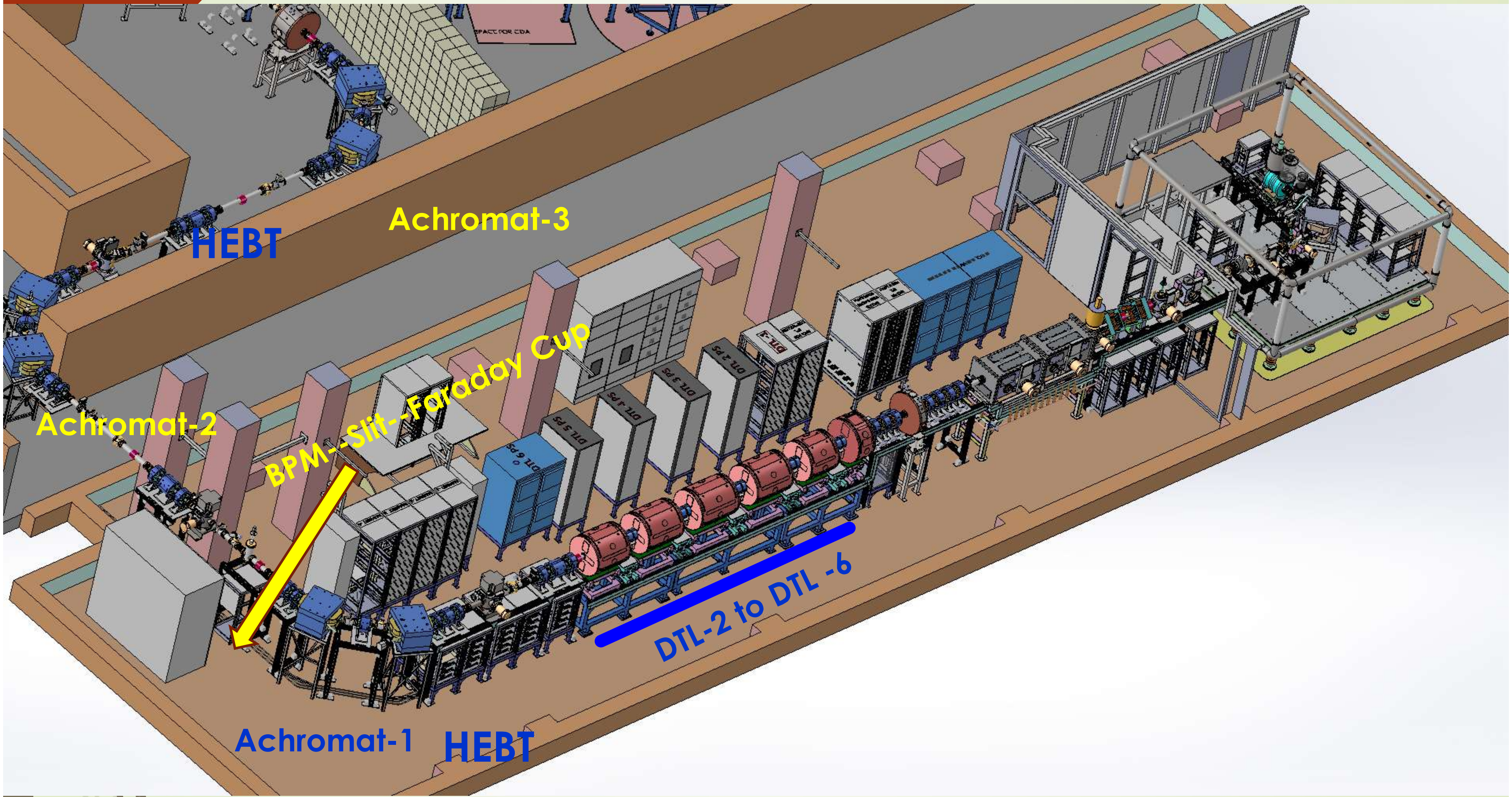


Test of Energy gain through the first DTL cavity

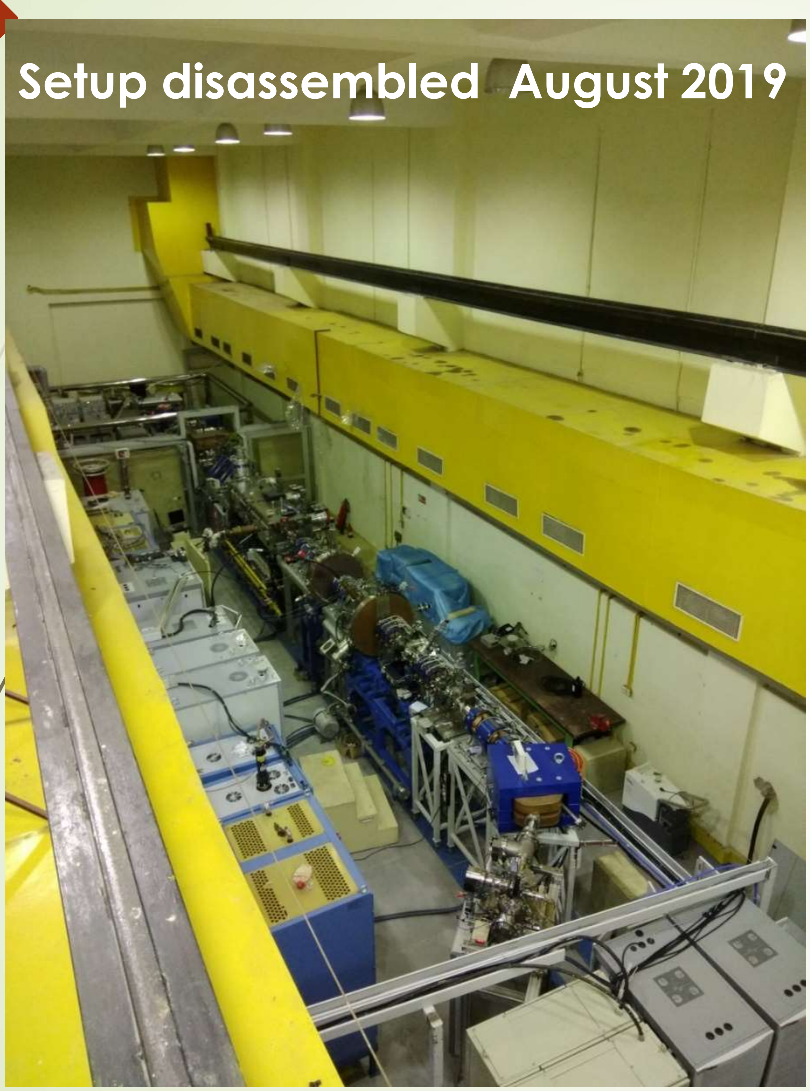


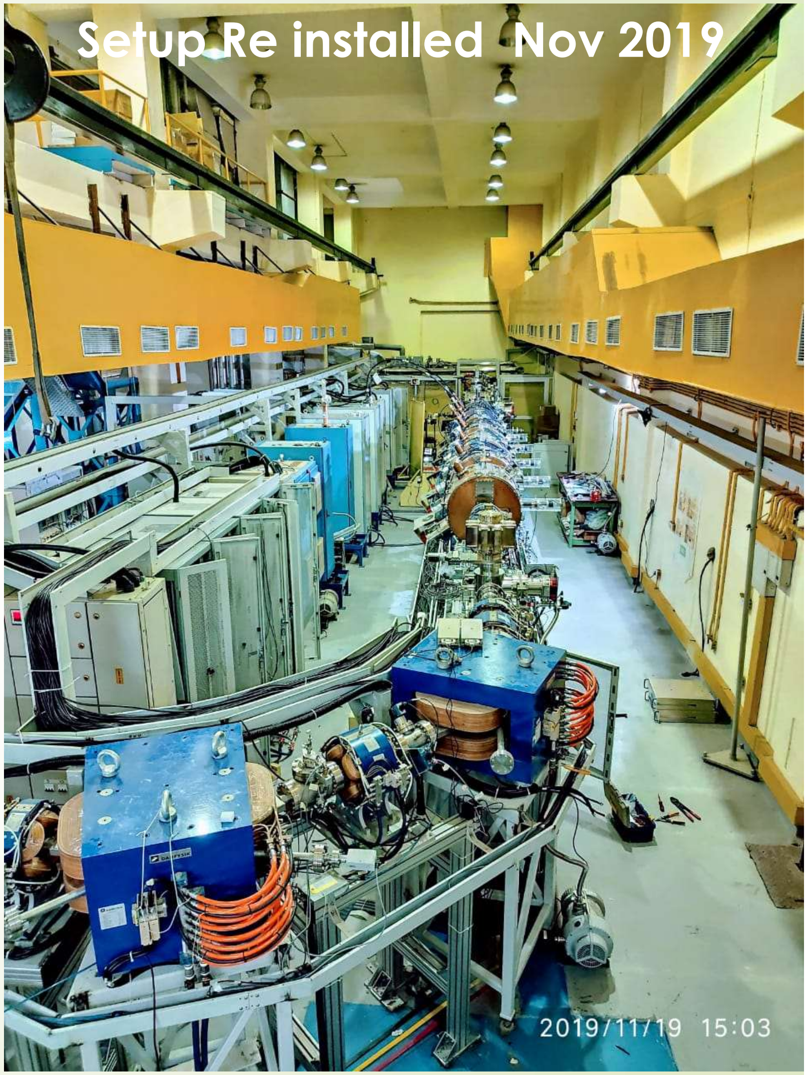
- spiral buncher was put initially in "drift" mode
- DC beam of Ne^{8+} (8 keV/u) was accelerated through the RFQ with an energy gain of 3.76 MeV (188 keV/u, slightly higher)
- Further accelerated by the DTL to an energy of 6.962 MeV (348 keV/u).
- To test the spiral buncher together with the DTL cavity, a 2.42 ns bunched beam of Ne^{8+} was accelerated by the RFQ to 3.949 MeV and further bunched using the spiral buncher.
- The final acceleration through the DTL cavity was determined to be 7.148 MeV.

Installation DTL-2 to DTL -6, HEBT, Achromate-1 and beam diagnostic component for energy gain measurement in Dec 2019

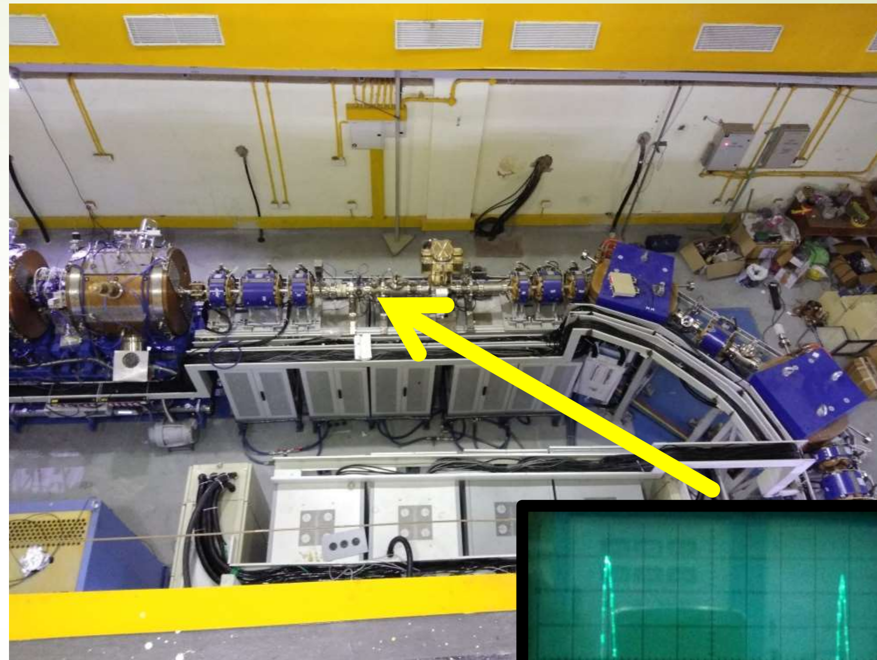


Views of the system in Beam Hall 3 at different times





Test of Energy gain through the second DTL cavity



- All cavities following the second cavity were in “drift” mode
- All miniature quadrupole triplets were used to transport the beam and analyzed using the first Achromat
- Energy gain from second cavity of DTL was determined using the Achromat to be 234 keV/u in “Energy Dispersive Mode”
- Maximum bunched beam transmission from RFQ exit to the first Achromat 36 %

Beam tuning and diagnosis

- DC transmission of 20 % and bunched beam transmission was 32 % after RFQ in old configuration
- A maximum DC beam transmission of 25% and 36% transmission for bunched beam were achieved through RFQ by analysing using the first achromat in new configuration.
- It is likely that some dedicated diagnostics at close to the entrance of RFQ and all along the downstream of RFQ and DTL may help to further improve the beam tuning and overall transmission.
- Beam tuning has been rigorous and time consuming due to enormous amount of active elements. However, a lot of effort has been put in, especially to study the optics and scale from the predicted values
- Repeatibility of beam tuning is important

Future plans and Goals

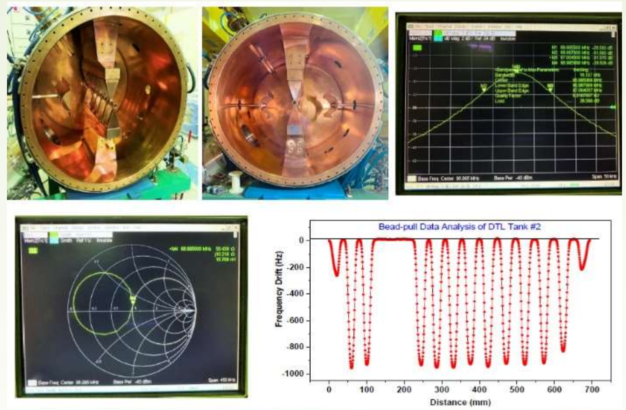
- Commissioning of time diagnostic devices for ease of beam tuning and improvement of beam transmission before injection into SC-LINAC
- Acceleration tests of following DTL cavitie
- Foil/gas stripping tests before injection into SC-LINAC

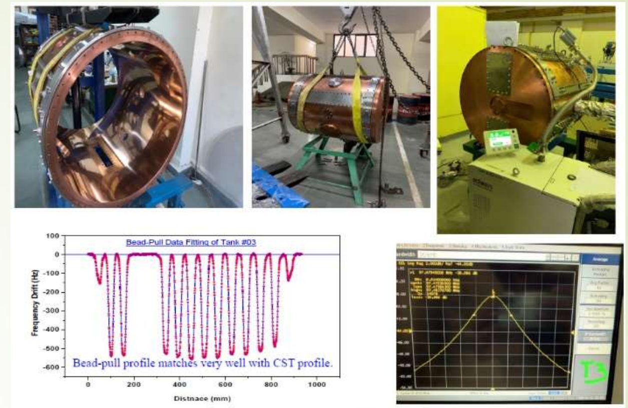
Thank You for your Kind Attention

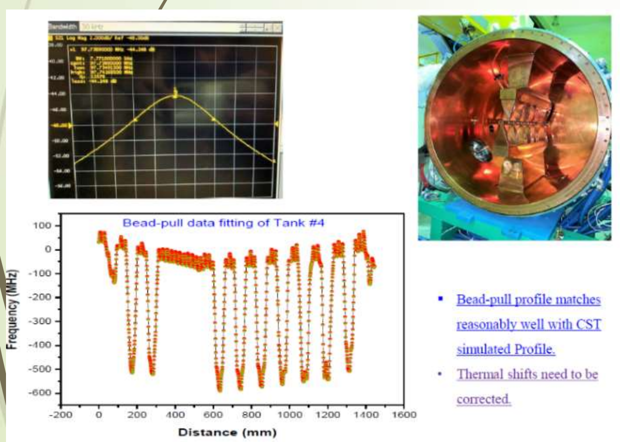
ELECTRICAL DESIGN PARAMETERS OF 6 DTL CAVITIES

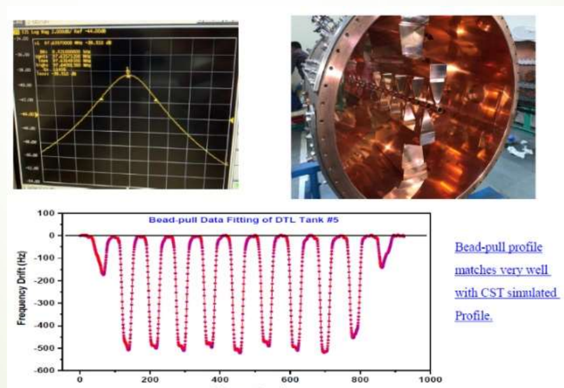
#	Length	Egain	Vz(Lana)MV	Vz (MWS)MV	Ppeak(KW)	Ez^2/P	Vratio	Ppeak(KW)/2
1	38.7	0.137	0.971	3.361	109	103	0.092	5
2	69.3	0.234	1.758	3.587	83	155	0.265	11
3	89.6	0.312	2.318	3.450	74	161	0.498	18
4	93.6	.276	2.045	2.984	68	130	0.518	18
5	91.7	.344	2.453	3.074	67	142	0.702	24
6	82	.336	2.202	2.688	67	107	0.740	25

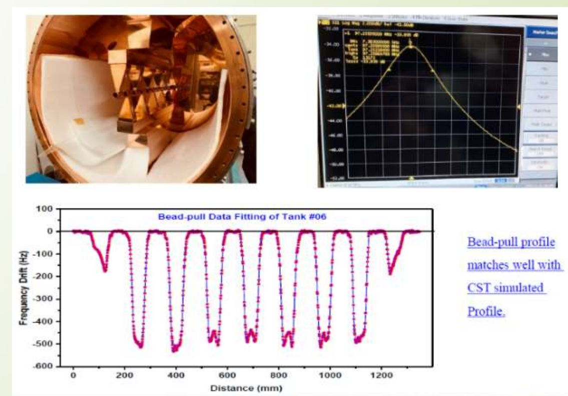
DTL CAVITIES : BEAM PULL & HIGH POWER TESTS



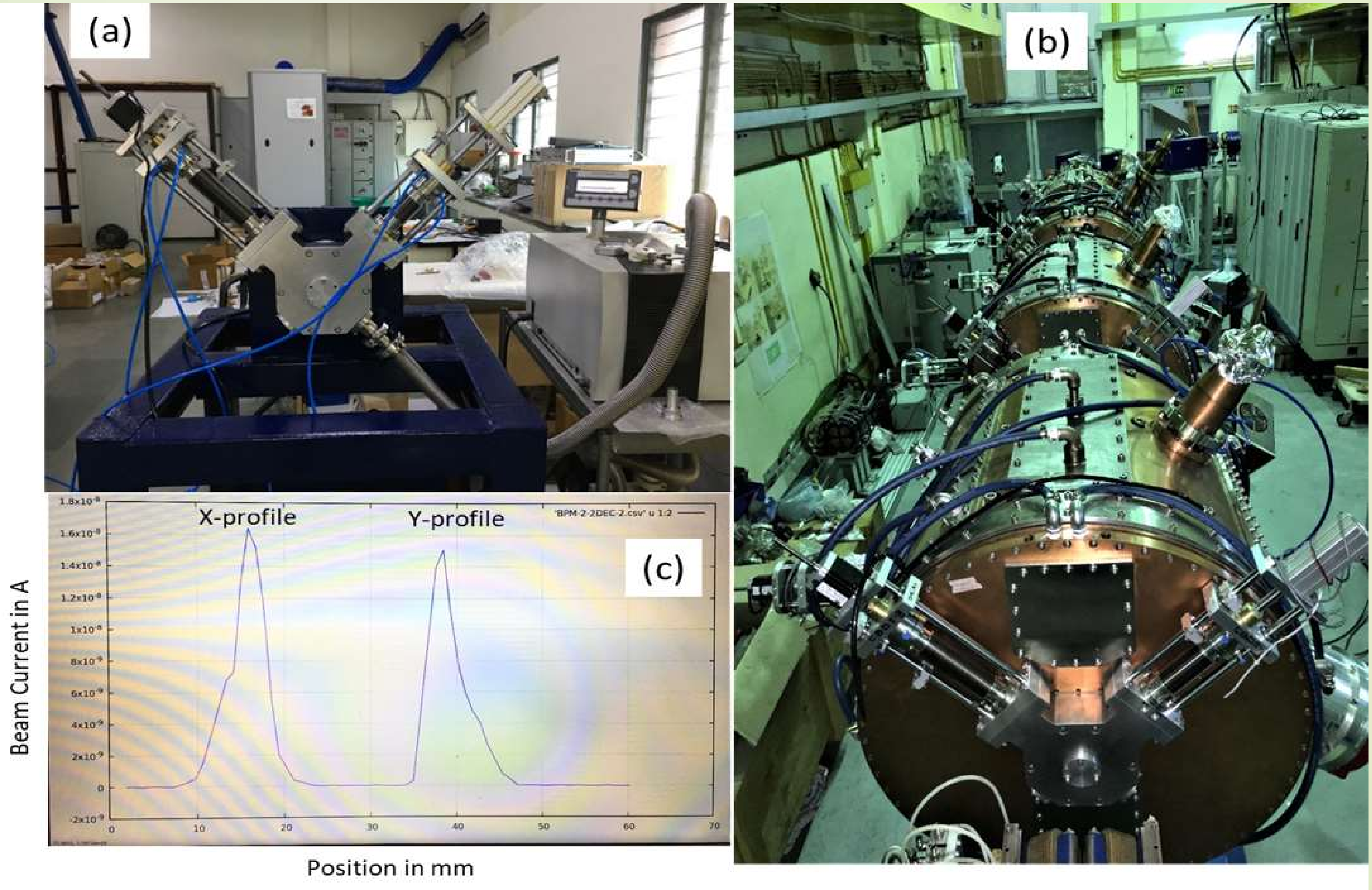








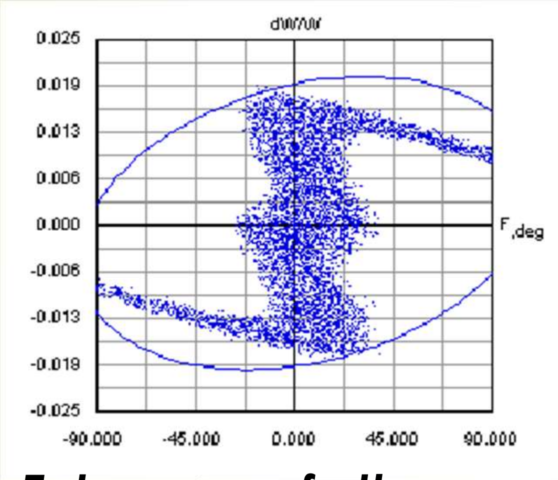
COMPACT BEAM DIAGNOSTIC SYSTEM (used between the DTL cavities)



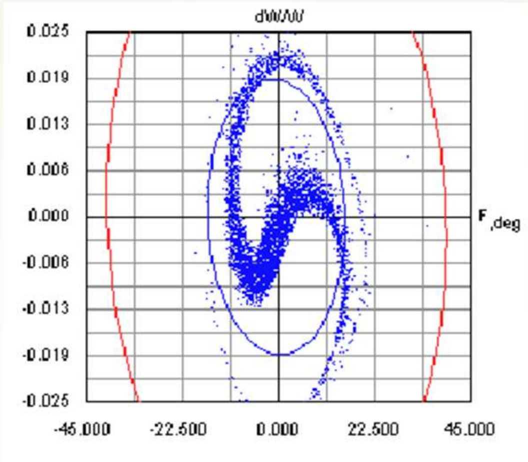
TRACK simulation of the longitudinal phase space at the entrance and exit of the RFQ situated 4.0 m downstream from the multi-harmonic buncher

Injector stability

$$\frac{\Delta V}{V} = \frac{\Delta \phi}{\pi} \frac{\beta \lambda}{h L_{\mathrm{drift}}}$$



Entrance of the RFQ



Exit of the RFQ

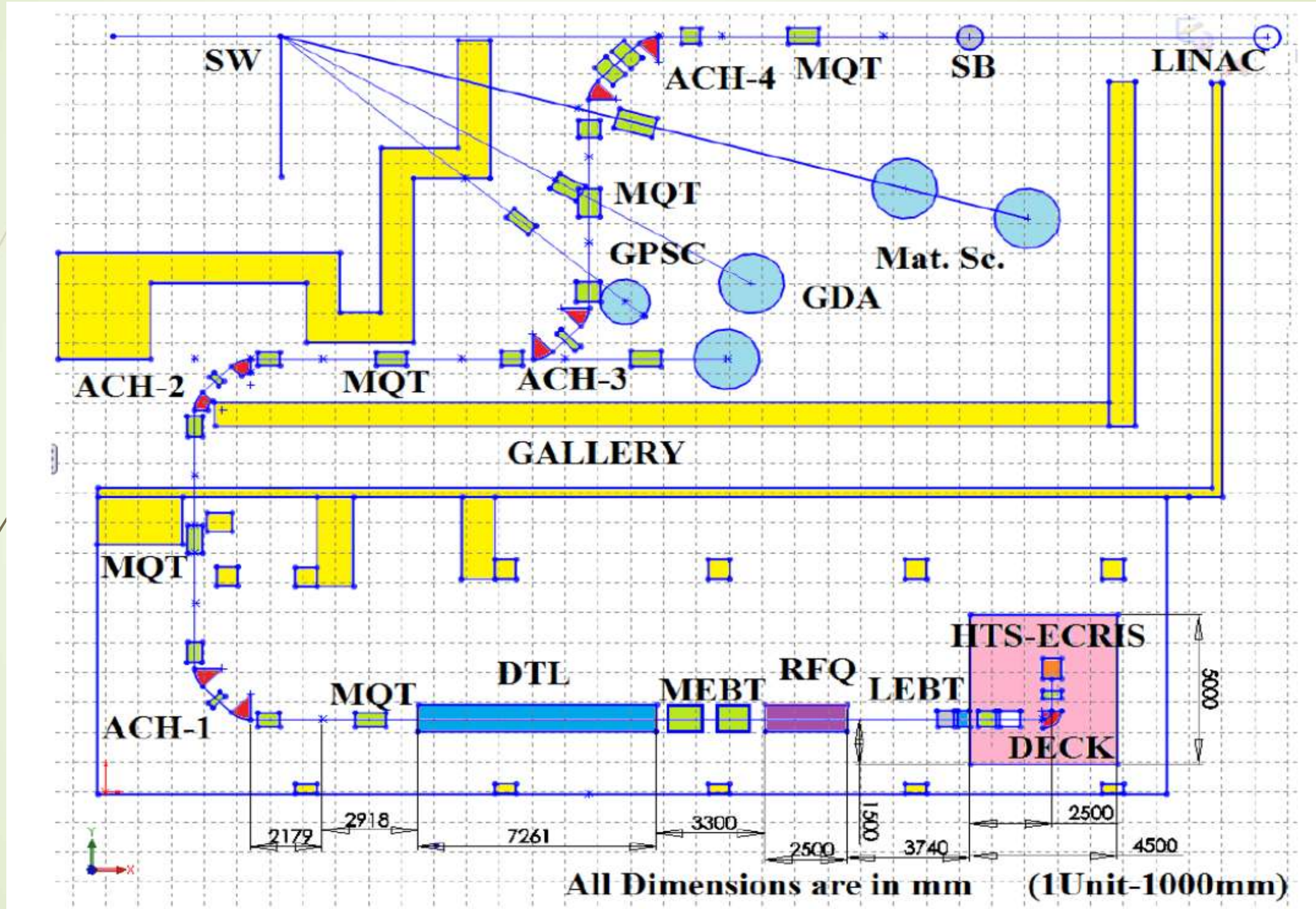
Calculated from formula →Phase spread +/- 25.6°
From TRACK simulation → +/- 22.5°

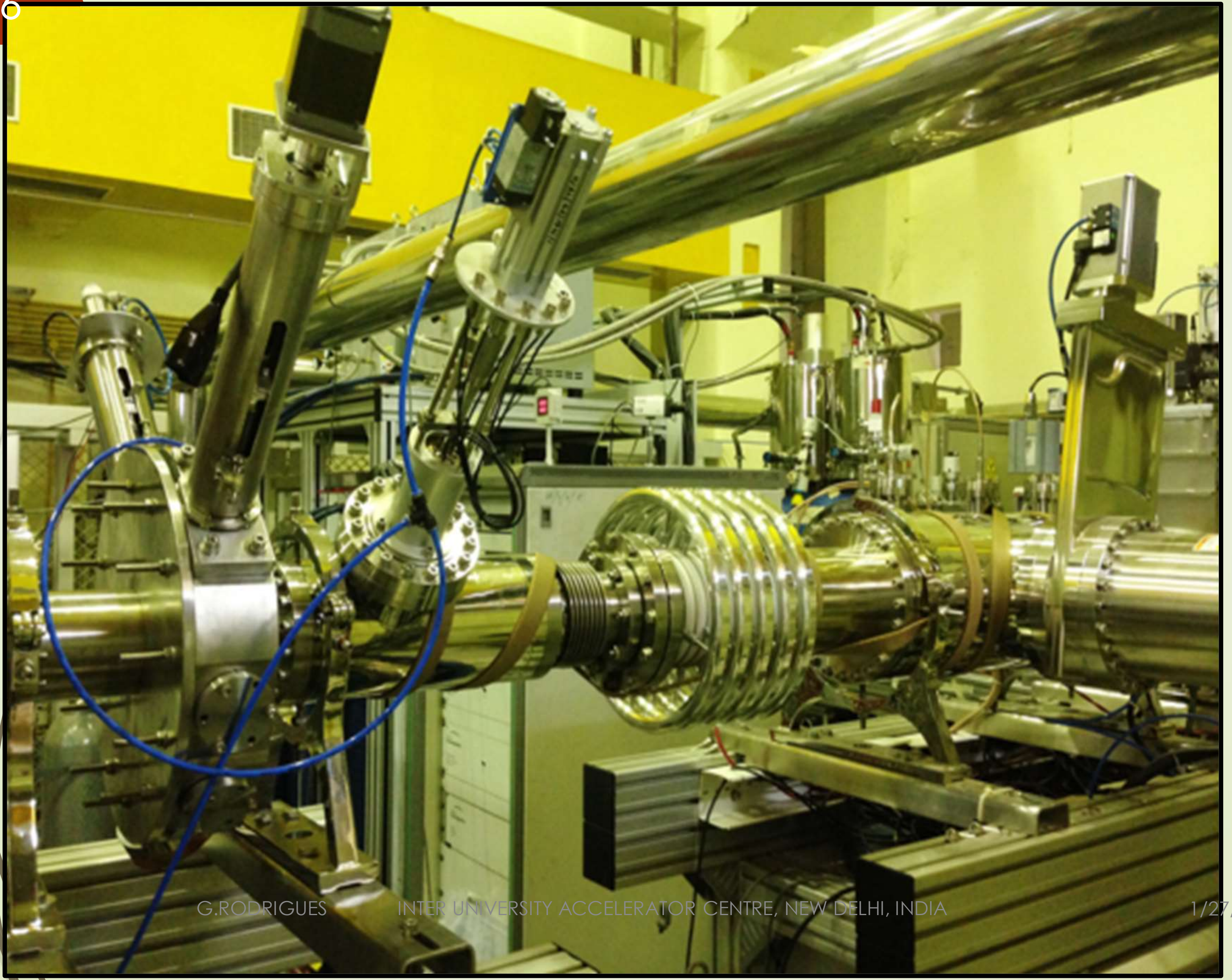
- For the heaviest ion measured, Vp ~ 40 V @ 20 kV
- Energy spread is 0.11 %
- 16 % loss in transmission through RFQ besides 15 % loss through MHB due to grids (from TRACK)

G.Rodrigues, R.Baskaran, S.Kukrety, Y.Mathur, Sarvesh Kumar, A.Mandal, D.Kanjilal and A.Roy, **Rev.Sci.Instrum. 83,p.033301(2012)**

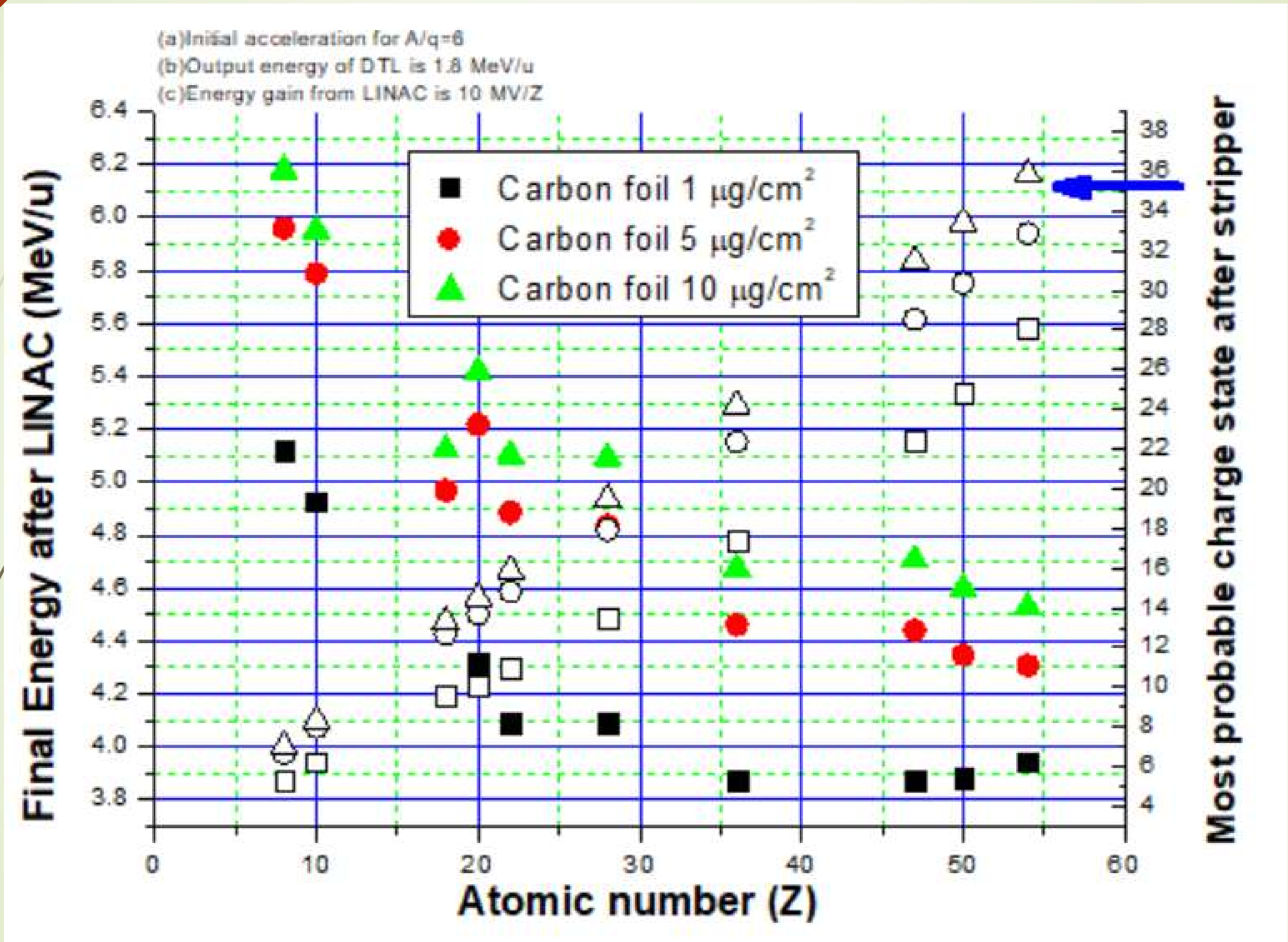
HYPERNANOGAN 180 kW

PKDELIS 15 kW


SW
ACH-4
MQT
SB
LINAC
MQT
GPSC
Mat. Sc.
GDA
ACH-2
MQT
ACH-3
GALLERY
MQT
HTS-ECRIS
DTL
RFQ
MQT
MEBT
LEBT
ACH-1
DECK
5000
1500
2500
2179
2918
7261
3300
2500
3740
4500
All Dimensions are in mm
(1Unit-1000mm)



RF parameters	Designed Value	Simulated	Experiment
Resonance Frequency (f0)	48.5 MHz	-	44.12
Quality Factor (Q)	-	-	5524
Shunt impedance (Rsh)	-	90k-ohm	87k-ohm
Power Required (Pin)	-	-	80kW/m


(a)Initial acceleration for A/q=6
(b)Output energy of DTL is 1.8 MeV/u
(c)Energy gain from LINAC is 10 MV/Z
Carbon foil 1 μg/cm²
Carbon foil 5 μg/cm²
Carbon foil 10 μg/cm²
Final Energy after LINAC (MeV/u)
Most probable charge state after stripper
Atomic number (Z)
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
0
10
20
30
40
50
60
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38