

STATUS OF LINAC BEAM COMMISSIONING FOR THE ITALIAN HADRON THERAPY CENTER CNAO

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On behalf of the CNAO-GSI-INFN
collaboration

Welcome to CNAO

(Centro Nazionale Adroterapia Oncologica)



The CNAO has been conceived to perform treatment of deep seated tumours with light ion beams (proton, Carbon ions and others) and to clinical and radiobiological research

CNAO from outside

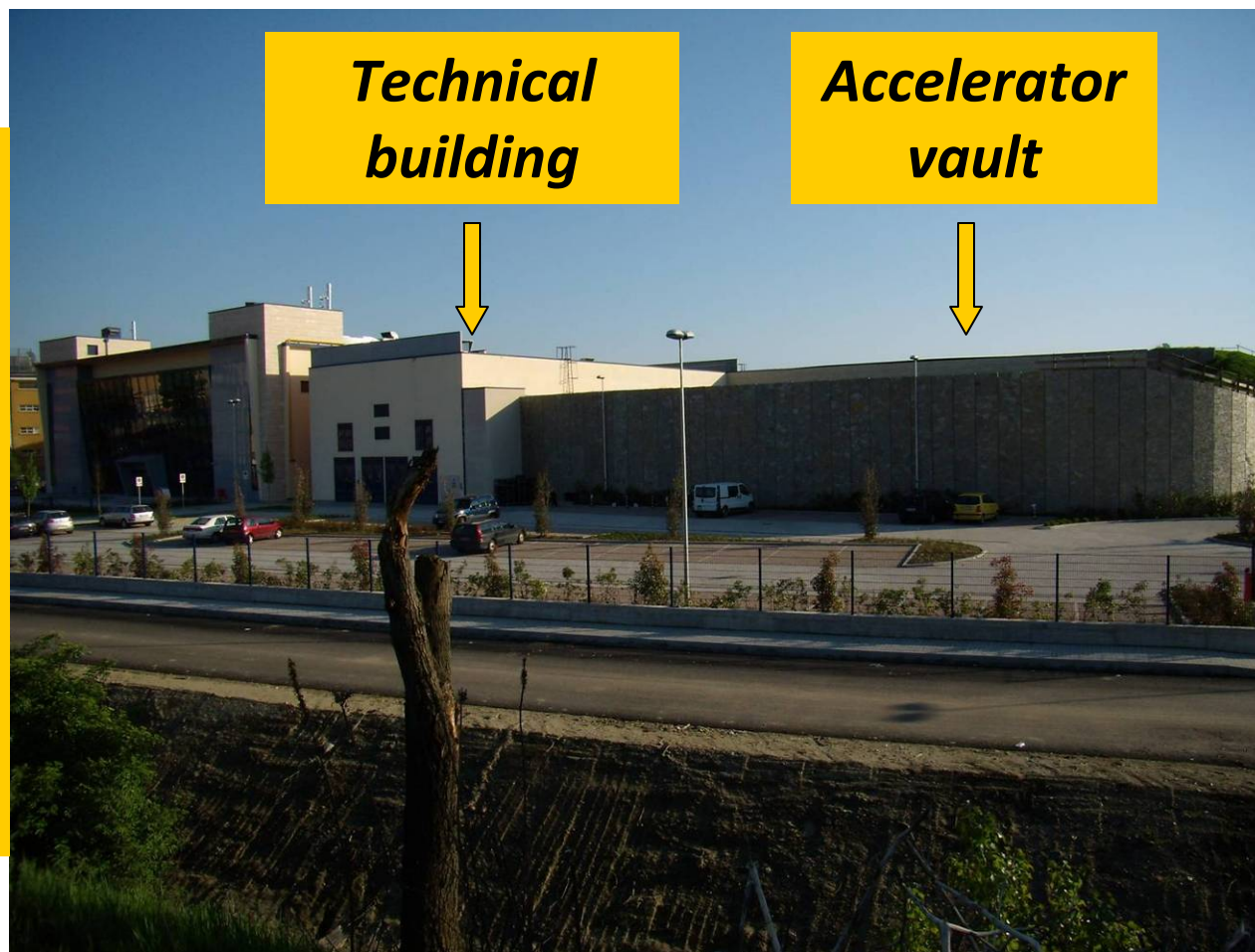
Main building:

2° floor:
auditorium & library

1° floor:
offices and laboratories

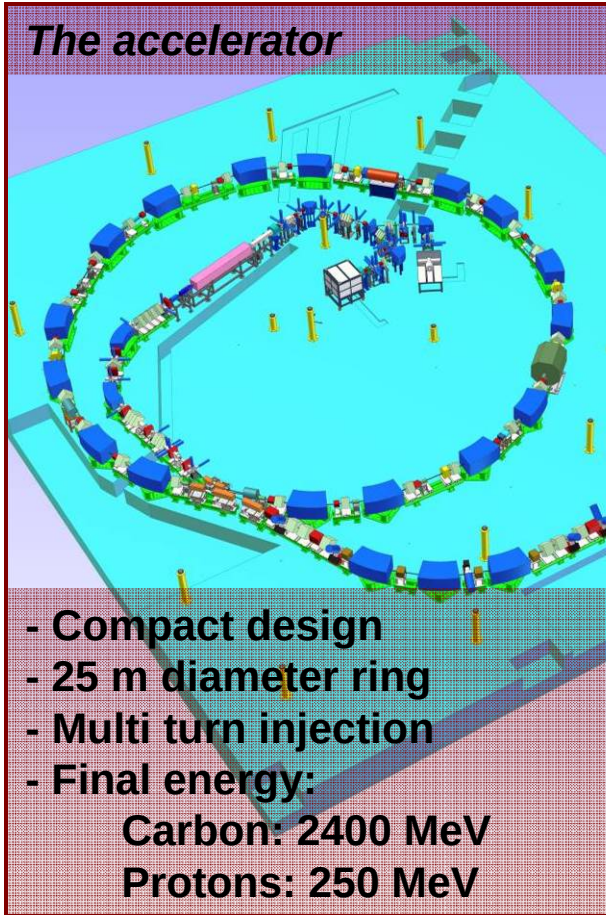
Ground floor:
Reception and
med. preparation

Basement:
3 treatment rooms

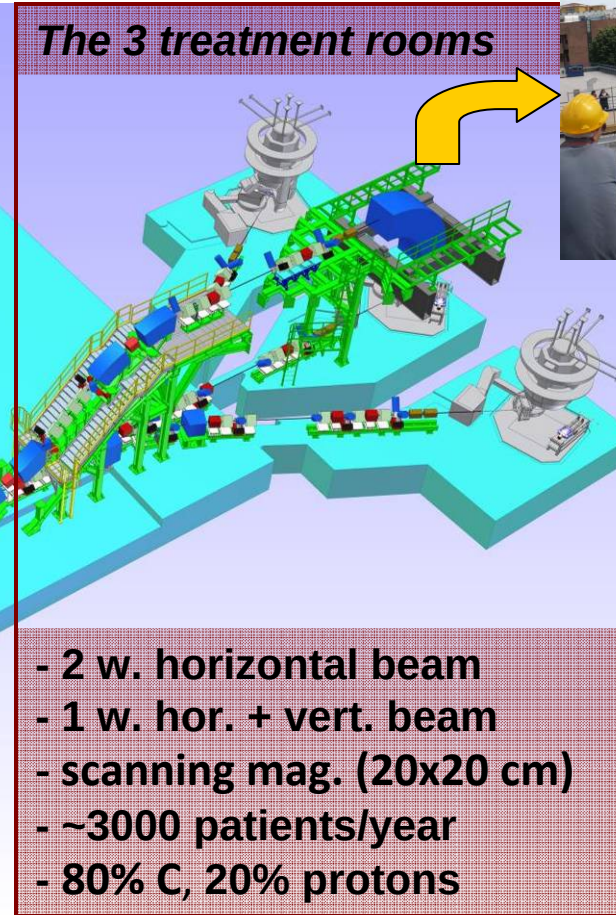


The CNAO facility

The accelerator



The 3 treatment rooms



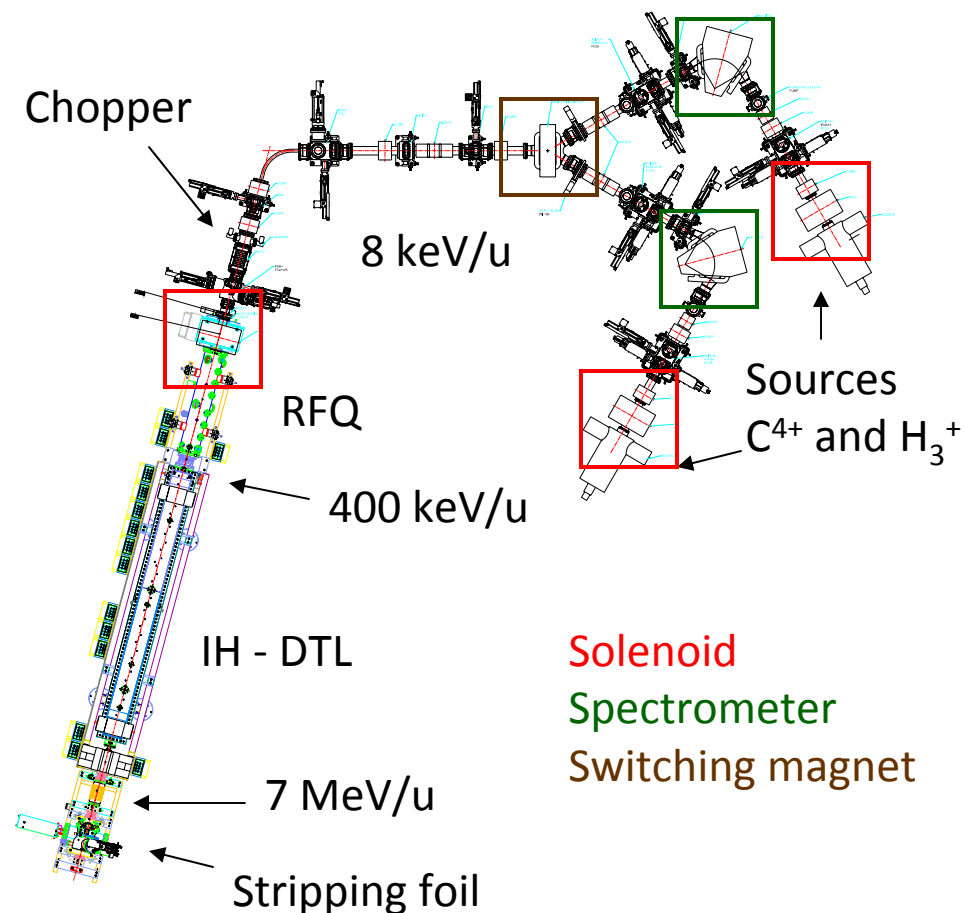
CNAO Injector:

Ion source supervised by **INFN LNS**

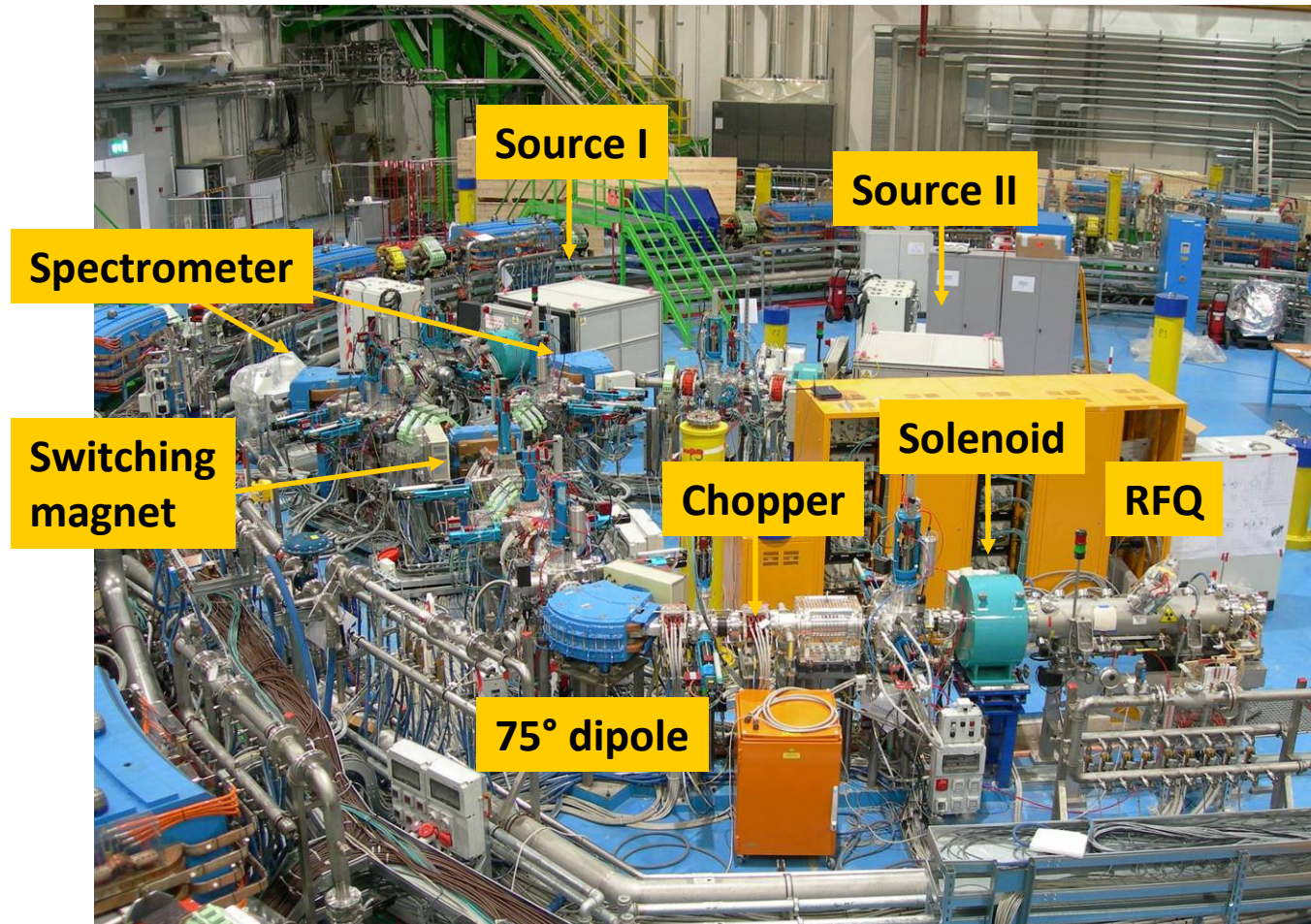
Low energy beam transport by **CNAO**

Linac by **GSI** (second version of HICAT)
supervised by **INFN LNL**

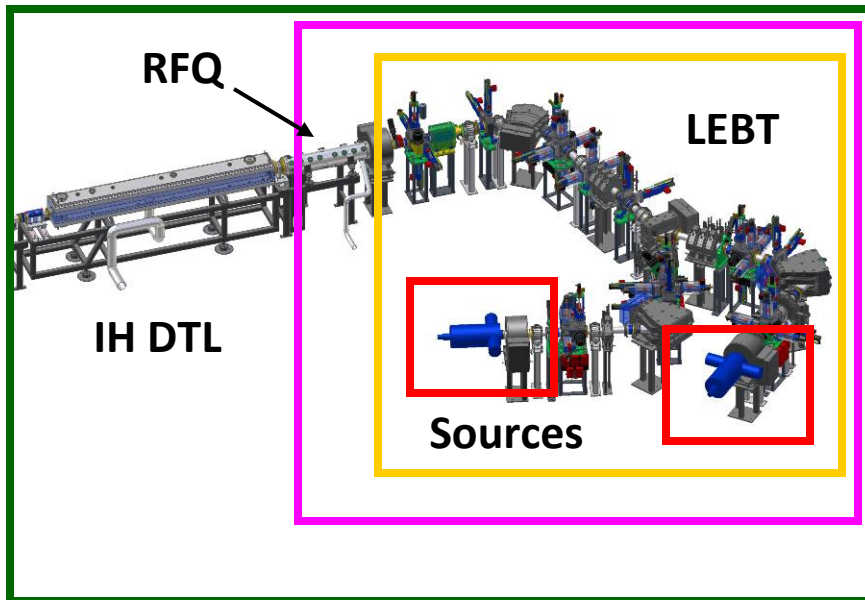
Sources Specifications	
Extraction Voltage	24 kV
Current H_3^+	$> 700 \mu A$
Current C^{4+}	$> 150 \mu A$
Transv. norm emitt. (95%)	0.5 mm mrad
LINAC Specifications	
Operating frequency	216.816 MHz
Final beam energy	7 MeV/u
Beam pulse length	$\leq 300 \mu s$
Beam rep. rate	$\leq 5 \text{ Hz}$
Transv. norm emitt. (95%)	0.8 mm mrad
Exit energy spread	$\pm 0.3\%$
Total injector length	$\sim 19 \text{ m}$



The Injector as it was in January 2009



Injector commissioning milestones

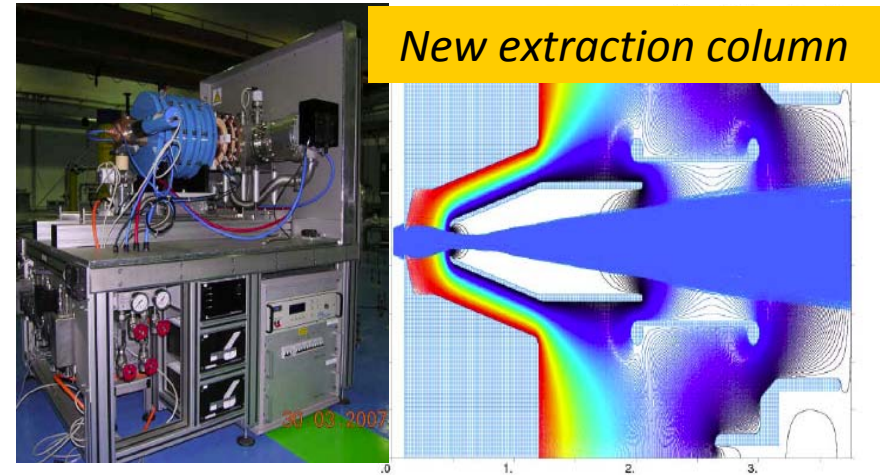


<i>from</i>	<i>to</i>	<i>Section</i>	<i>Description</i>
May 08	July 08	Source	Beam and LEBT Inst.
September 08	December 08	LEBT TB0	Beam
January 09	February 09	RFQ TB2	Install.
25 th Feb. 09	12 th Mar. 09		RF Cond.
13 th Mar. 09	3 rd April 09		Beam
April 09	May 09	IH DTL TB3	Install.
June 09	now		RF Cond.

Ion Sources Performances

Improvements (in 2007)

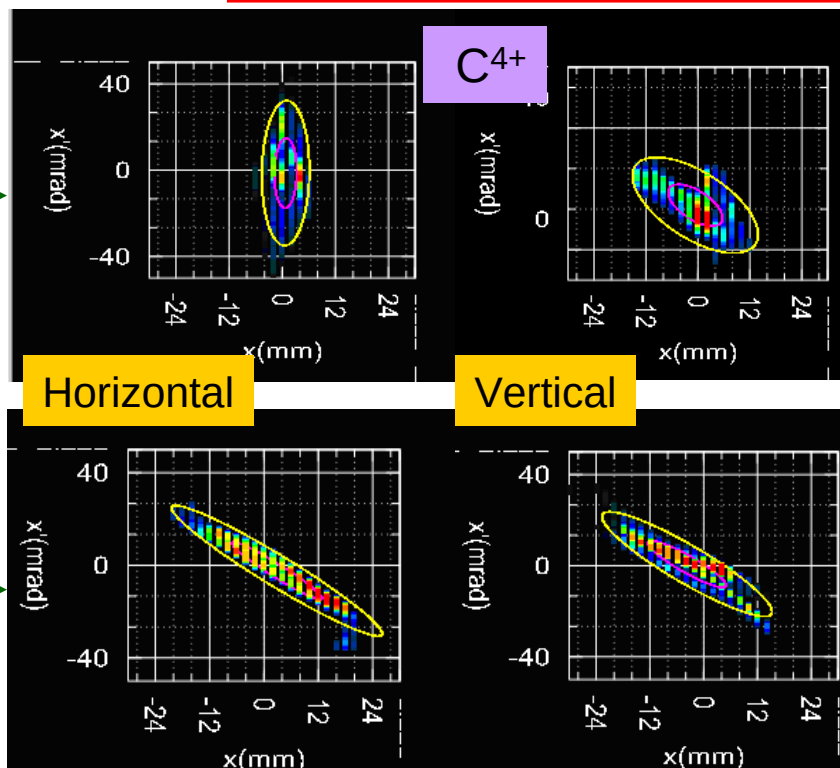
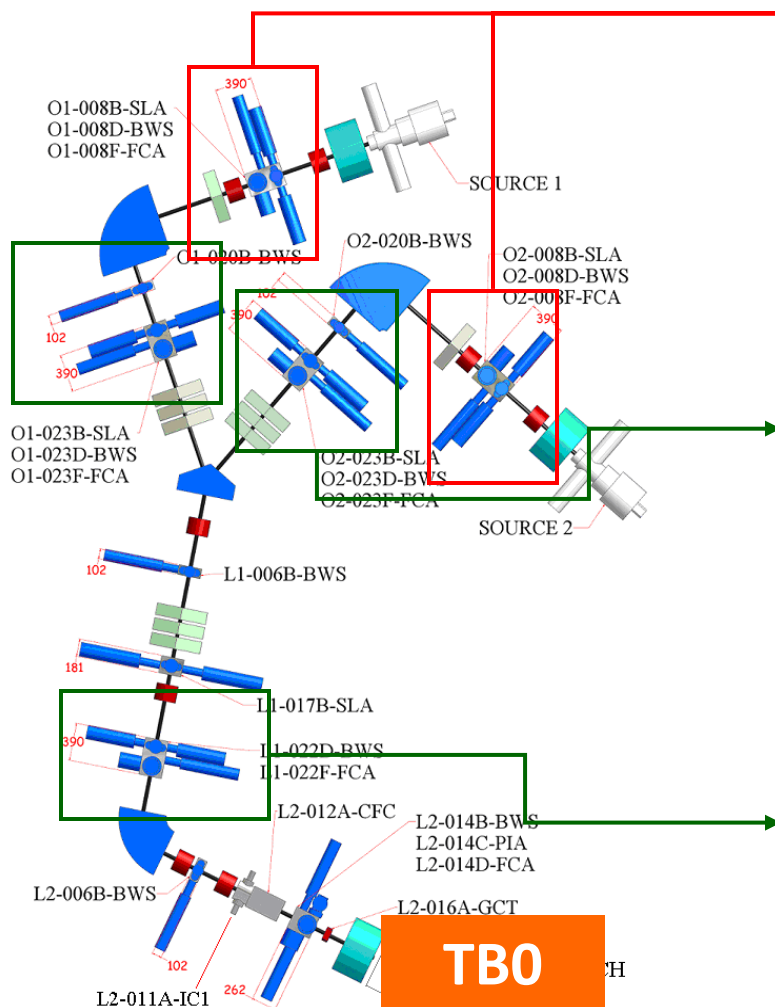
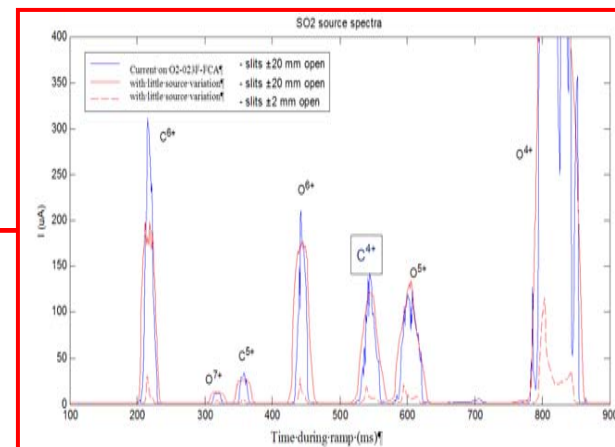
- the gas injection system has been modified in order to improve the stability
- extraction gap distance modified to improve beam emittance and stability
- a lead shield 10 mm thick all around the source instead of a 5 mm one for improving radiation safety
- the noise of electronics has been reduced



Performances

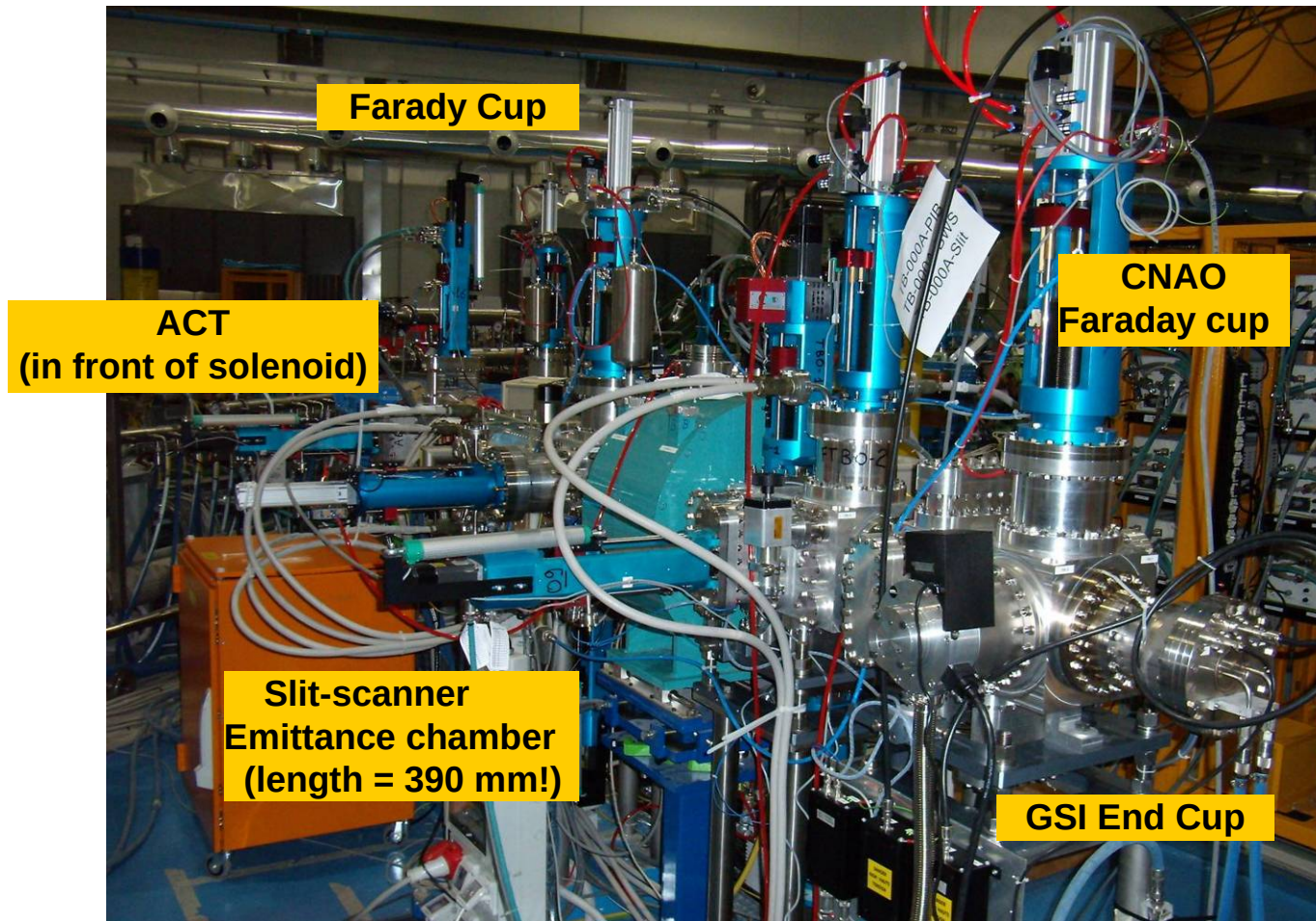
- 250 μA** for C^{4+} (25% > nominal)
 - 1100 μA** for H_3^+ (50% > nominal)
- plasma electrode hole diameter reduced to 6 mm allowing to have better emittance

LEBT Commissioning

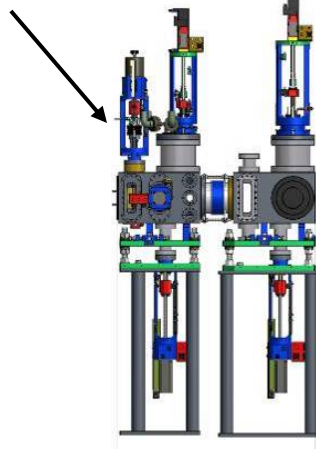
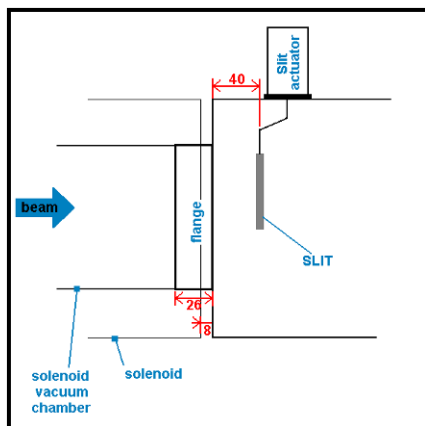


Emitt. RMS: ~ 35 mm mrad

Commissioning of LEBT TB0 (GSI & CNAO)

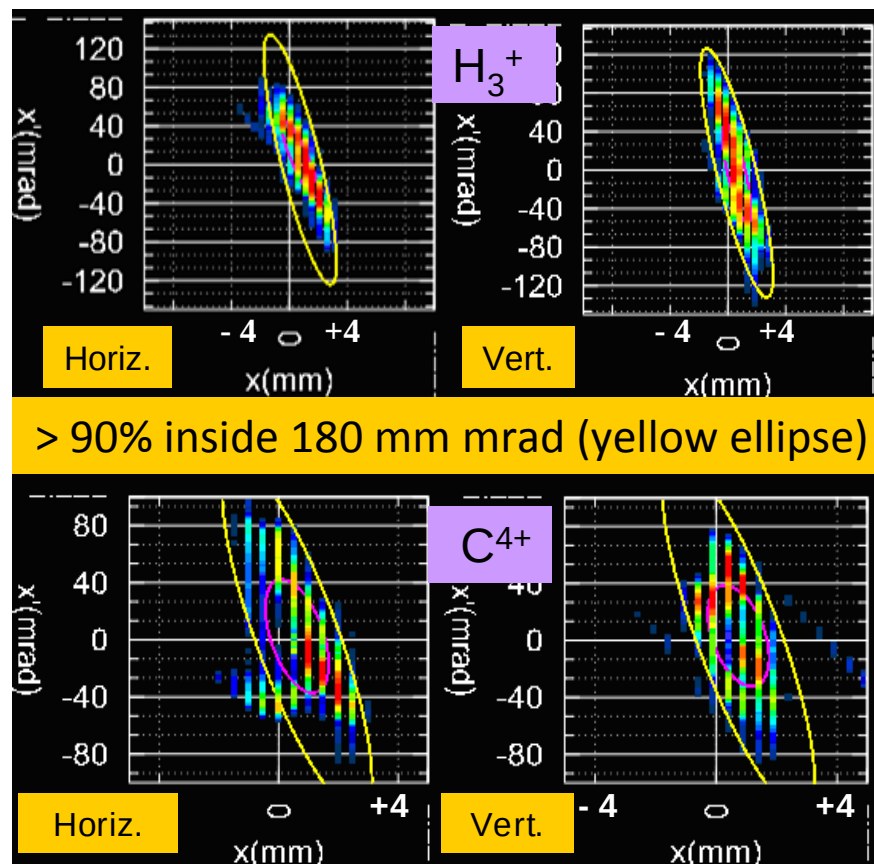


Emittance in TB0

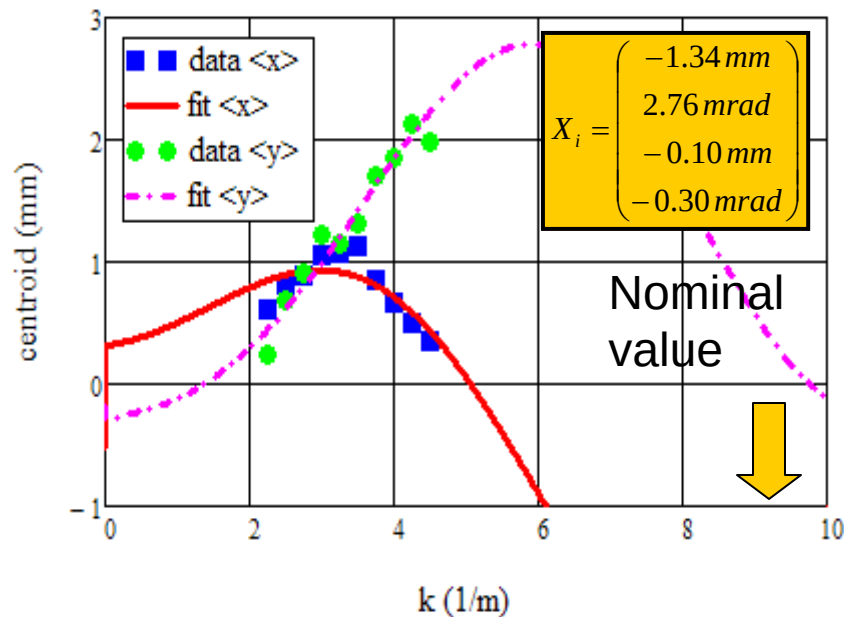


TB0:

- AC/DC current
- AC/DC profiles
- **DC emittance exactly at the RFQ matching point!!!**



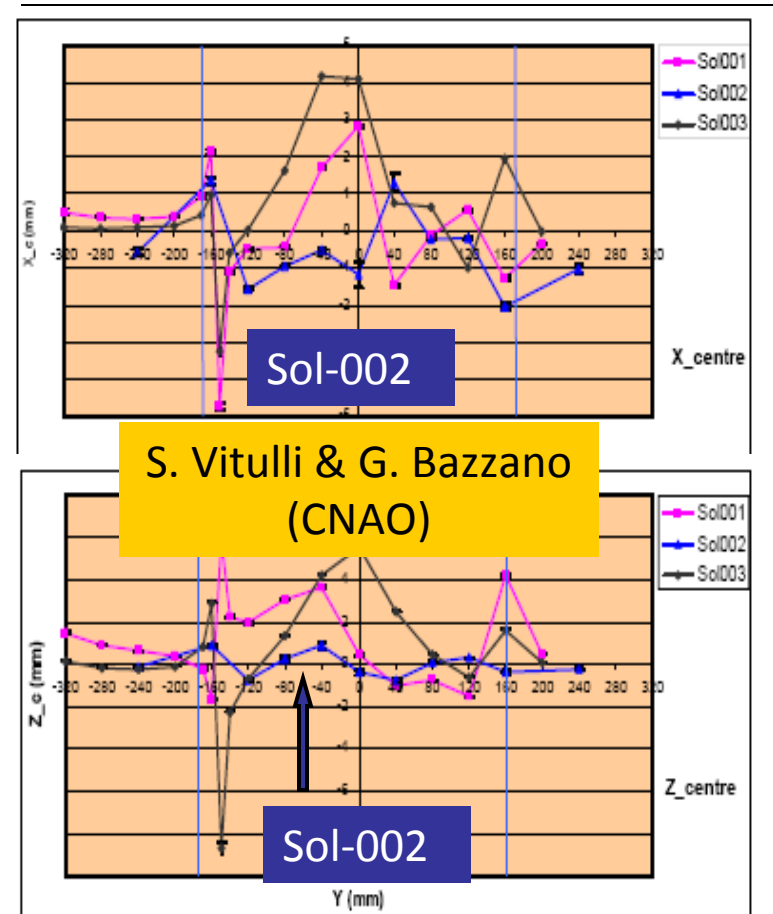
Matching solenoid



Example of beam steering at TB0 grid as function of the solenoid strength

Results:

- Very accurate centroid displacement correction (~ 1 mm over 3 cm wide beam!!!)
- Linear response



The 3 solenoids build by SigmaPhi:
magnetic field along the axis
measurements at INFN Frascati

LEBT Commissioning summary

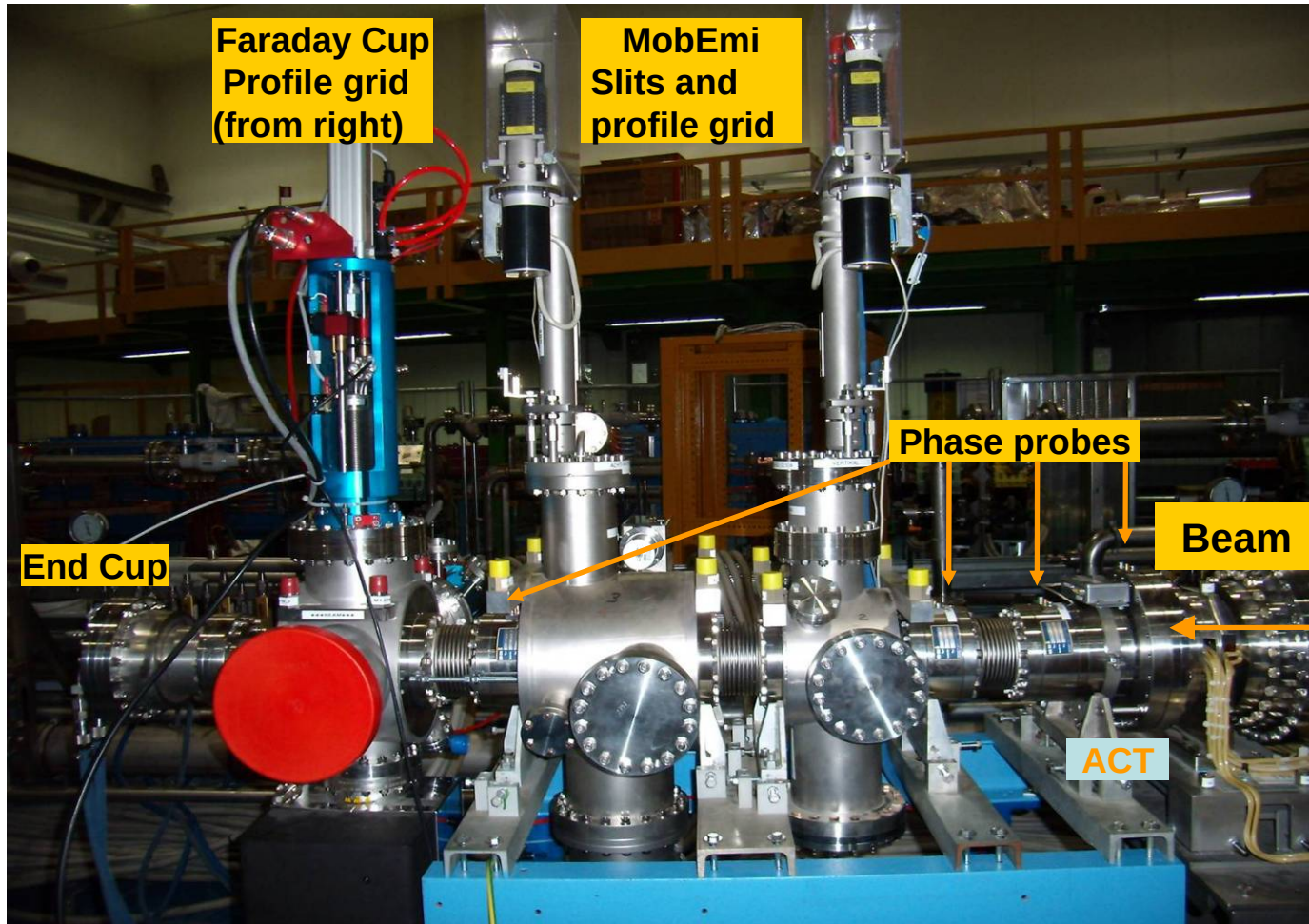
TBO

- Comparison current measurements (GSI/CNAO & DC/AC)
 - **Consistency**
- Comparison of profiles (grid/scanner)
 - **Consistency**
- Beam position as function of solenoid field
 - **Steering at RFQ entrance**
- Profiles for long and short macro pulses at
 - **Neutralisation, Space**
- Different times within pulse (H_3^+/C^{4+})
 - **Charge, verification of DC emittances**

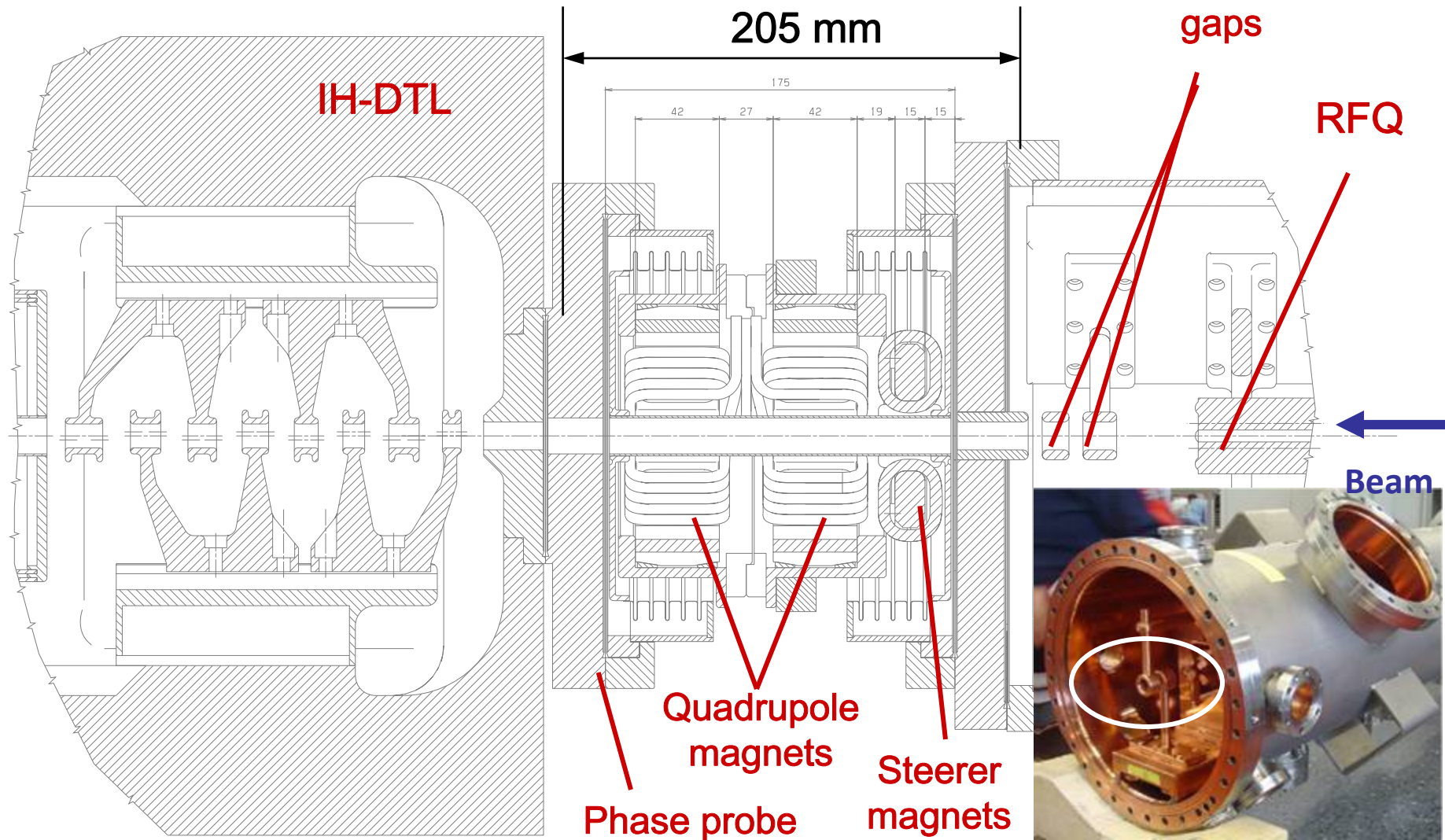
- Transmission, Twiss-Parameter and emittances
 - **Matching RFQ**
 - **Definition of LEBT operating parameters**
 - **Pre-condition for RFQ commissioning**

Mandatory for RFQ good performances!!!

Commissioning of RFQ TB2 (GSI)



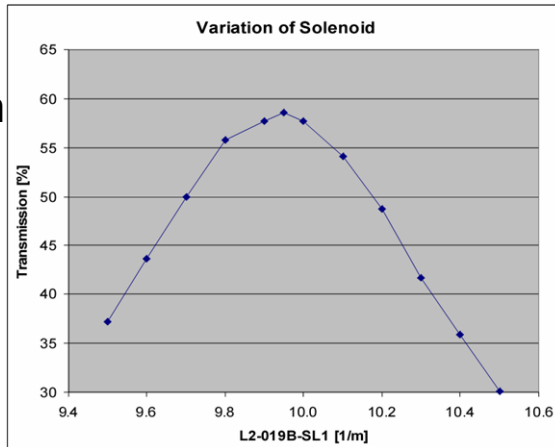
Intertank section with MEBT partly integrated in the RFQ: compact but reduced flexibility



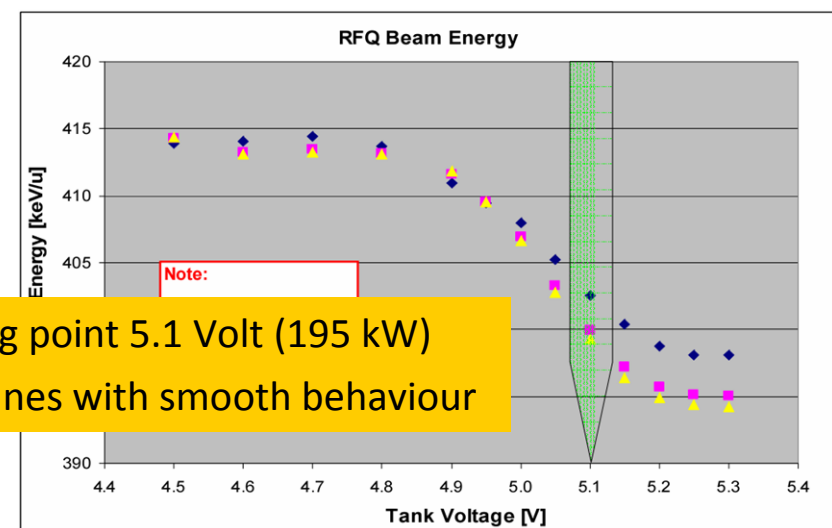
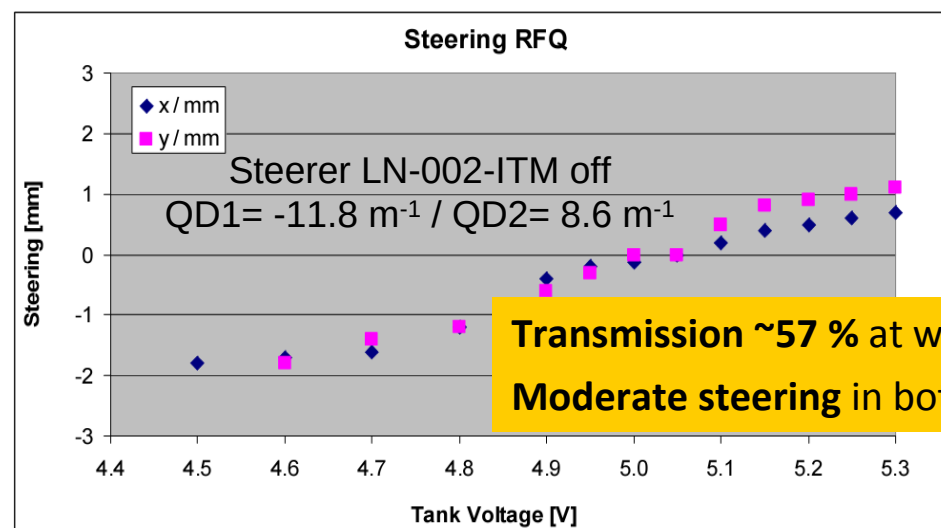
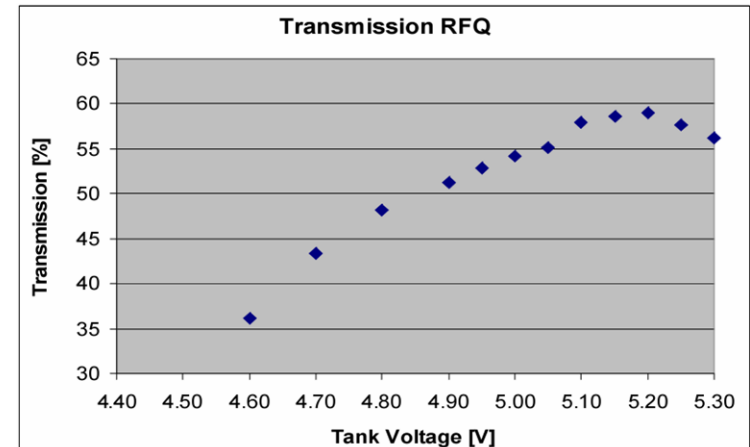
Commissioning RFQ – Results H_3^+ at 8 keV/u

transmission, steering and energy

Step 1:
Optimisation



Step 2:
Perform
standard
measurements

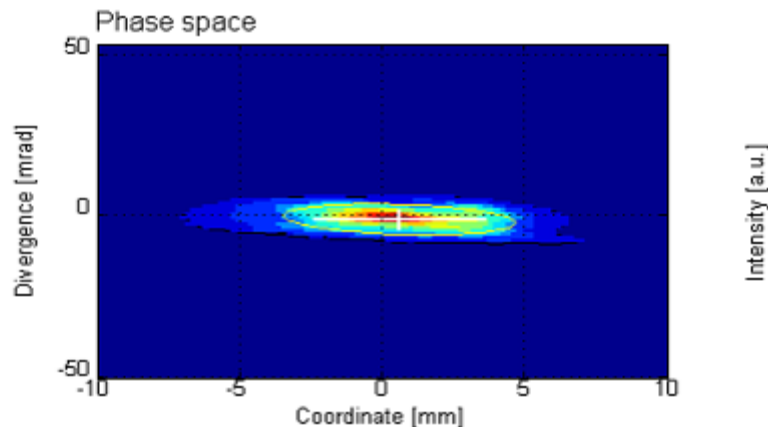


Transmission ~57 % at working point 5.1 Volt (195 kW)
Moderate steering in both planes with smooth behaviour

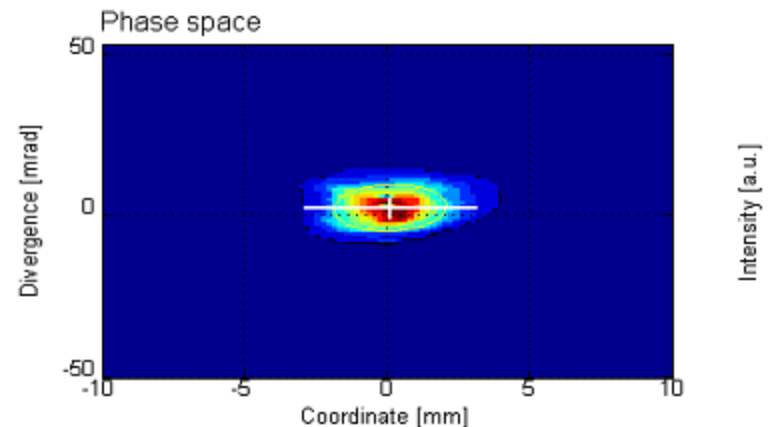
Commissioning RFQ – Results H_3^+ at 8 keV/u

Emittances in TB2

Horizontal Emittance



Vertical Emittance



x0:	0.62	Threshold[%]	$I_{\text{capt}}[\%]$	$\Sigma dS/^\circ$ [mm mrad]	
y0:	-1.26	1.8	99	45.11	→
stdev _x :	2.03	5.0	95	34.92	
stdev _y :	2.38	7.9	90	28.08	
corr _{xy} :	-0.231	10.5	85	23.34	
		13.8	80	19.79	
		20.0	70	14.66	
		27.2	60	11.05	
		32.7	50	8.15	
		39.7	40	5.79	
		48.1	30	3.81	
		61.0	20	2.24	
		78.1	10	0.99	
ϵ :	18.73				
α :	0.24				
β :	0.88				
γ :	1.21				
KV-plane:	0.10				

4 rms [mm mrad]

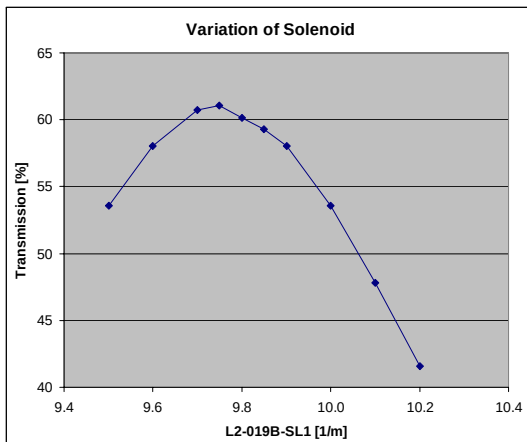
x0:	0.11	Threshold[%]	$I_{\text{capt}}[\%]$	$\Sigma dS/^\circ$ [mm mrad]	
y0:	2.27	2.0	99	36.30	→
stdev _x :	0.99	5.7	95	26.63	
stdev _y :	3.57	10.1	90	21.04	
corr _{xy} :	0.076	14.3	85	17.49	
		18.8	80	14.86	
		28.2	70	11.11	
		35.6	60	8.42	
		44.6	50	6.25	
		54.9	40	4.54	
		70.6	30	3.09	
		79.7	20	1.91	
		87.0	10	0.92	
ϵ :	14.16				
α :	-0.08				
β :	0.28				
γ :	3.61				
KV-plane:	0.10				

4 rms [mm mrad]

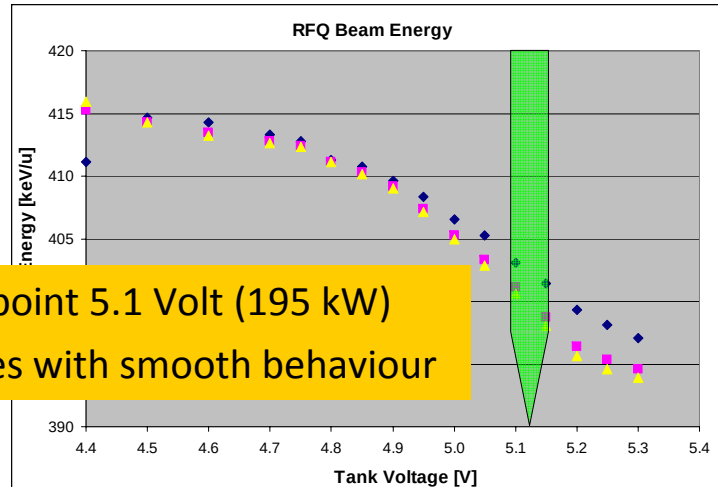
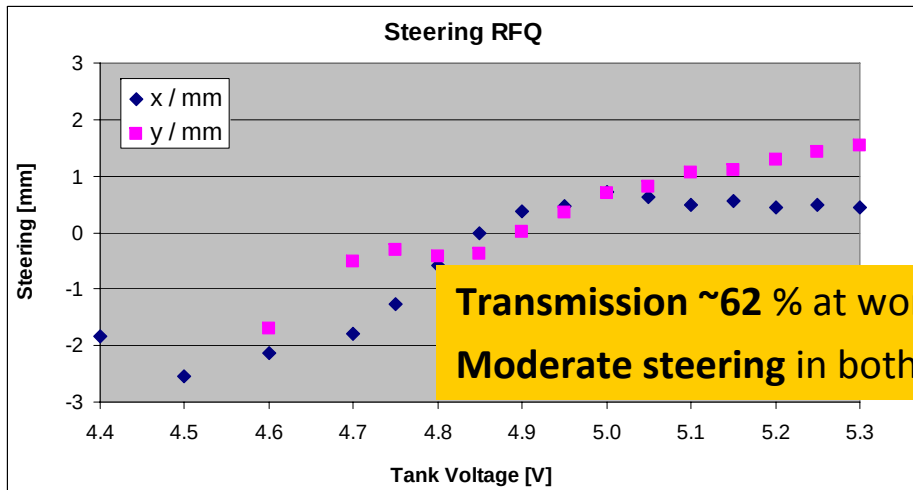
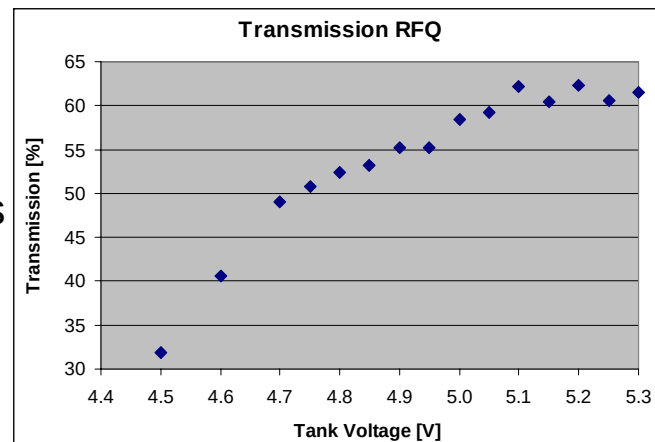
Commissioning RFQ – Results C⁴⁺

Transmission, energy und steering

Step 1:
Optimization



Step 2:
Perform
standard
measurements

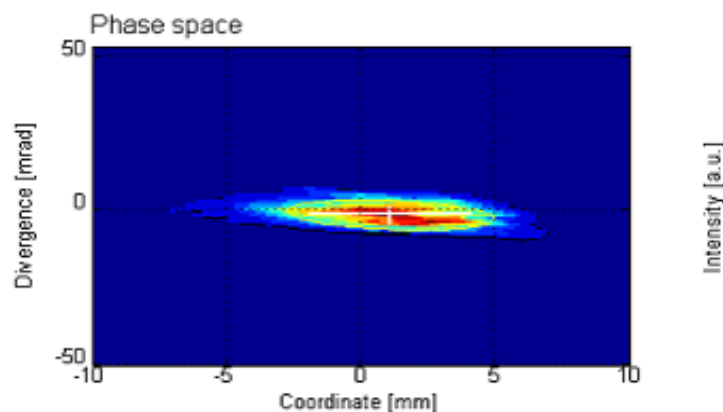


Transmission ~62 % at working point 5.1 Volt (195 kW)
Moderate steering in both planes with smooth behaviour

Commissioning RFQ – Results C⁴⁺

Emittances in TB2

Horizontal Emittance



x0:	1.12	Threshold[%]	$I_{\text{capt}}[\%]$	$\Sigma dS/^\circ$ [mm mrad]	
y0:	-1.63	2.2	99	42.22	→
stdev _x :	1.93	6.4	95	30.91	
stdev _y :	2.41	11.7	90	24.53	
corr _{xy} :	-0.272	16.5	85	20.52	
		22.6	80	17.62	
		32.4	70	13.48	
		43.5	60	10.52	
		51.1	50	8.09	
		60.7	40	6.05	
		68.1	30	4.27	
		74.1	20	2.70	
		80.8	10	1.25	

ϵ : **17.85**

α : 0.28

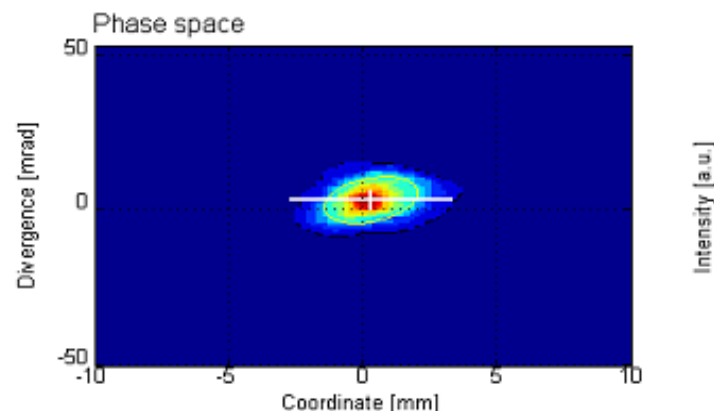
β : 0.83

γ : 1.30

KV-plane: 0.10

4 rms [mm mrad]

Vertical Emittance



x0:	0.31	Threshold[%]	$I_{\text{capt}}[\%]$	$\Sigma dS/^\circ$ [mm mrad]	
y0:	3.15	1.7	99	31.30	→
stdev _x :	0.86	5.2	95	23.02	
stdev _y :	3.74	8.9	90	18.41	
corr _{xy} :	0.316	12.9	85	15.45	
		16.3	80	13.22	
		23.5	70	9.93	
		29.5	60	7.50	
		37.4	50	5.52	
		45.6	40	4.01	
		55.6	30	2.70	
		64.8	20	1.64	
		81.2	10	0.72	

ϵ : **12.28**

α : -0.33

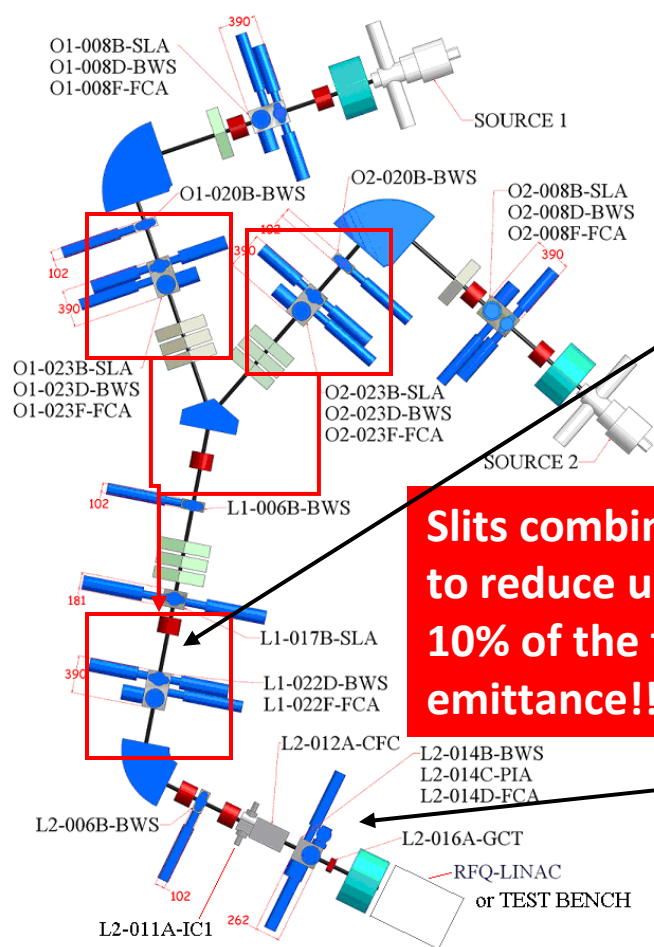
β : 0.24

γ : 4.57

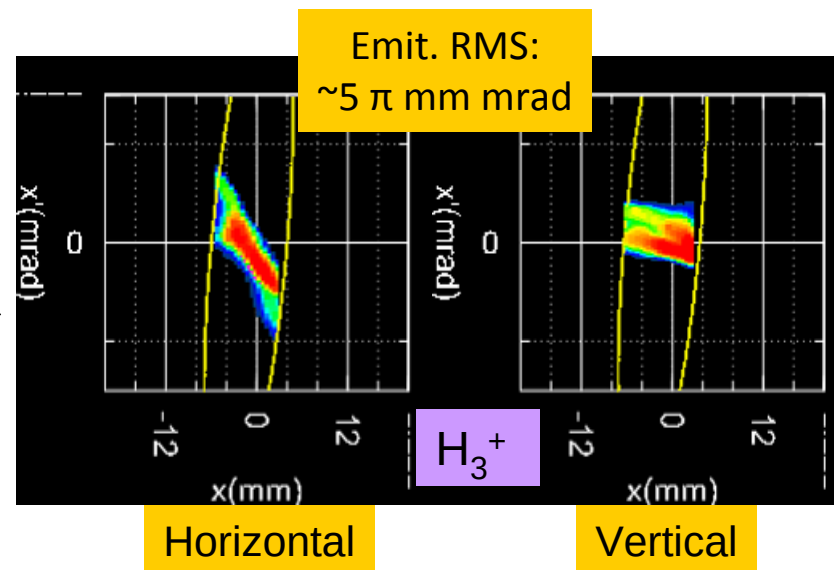
KV-plane: 0.10

4 rms [mm mrad]

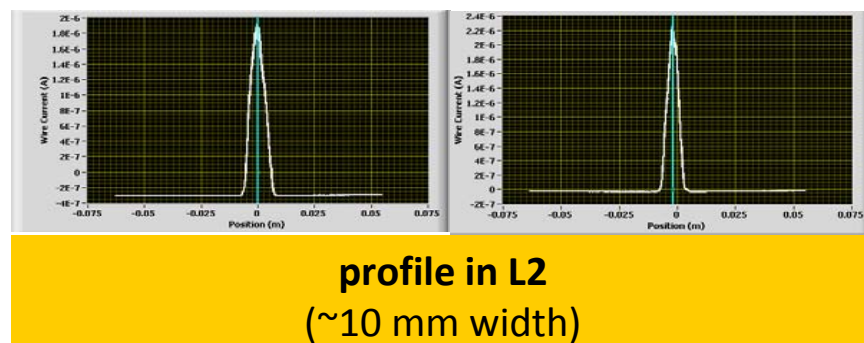
Probe beam (H_3^+)



**Slits combined
to reduce up to
10% of the full
emittance!!!**

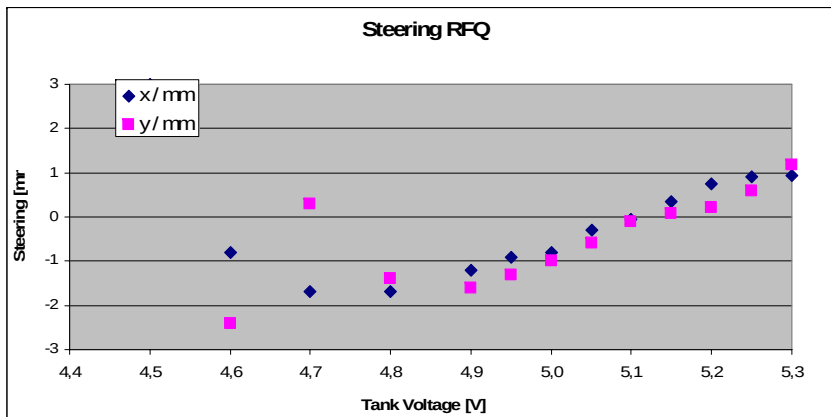
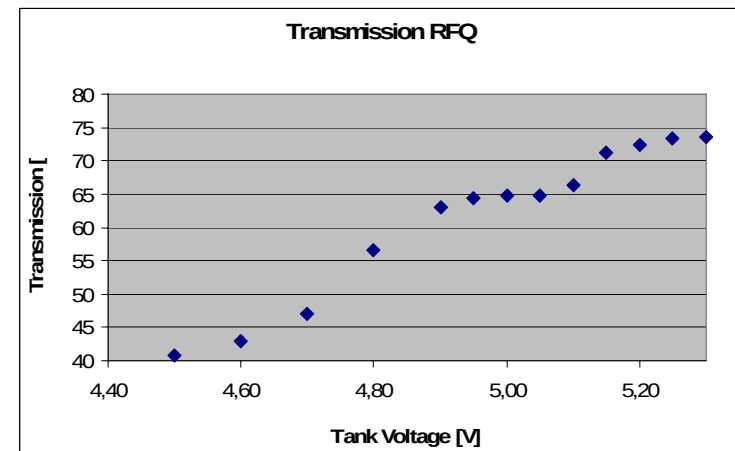
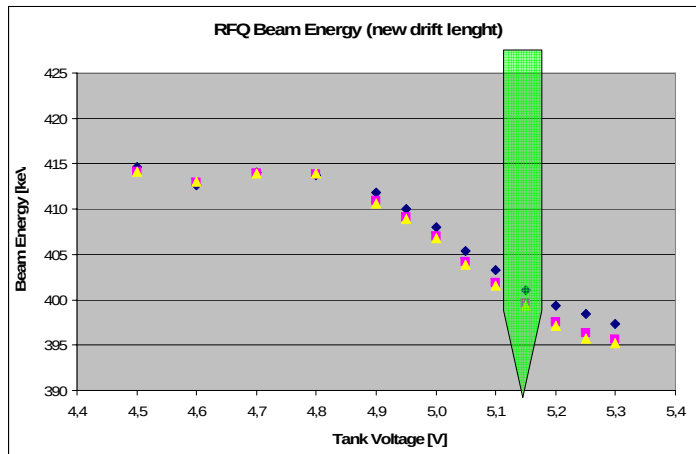


M. Pullia (CNAO)



RFQ: Results H_3^+ “probe beam” at 8 keV/u

Steering, energy and transmission



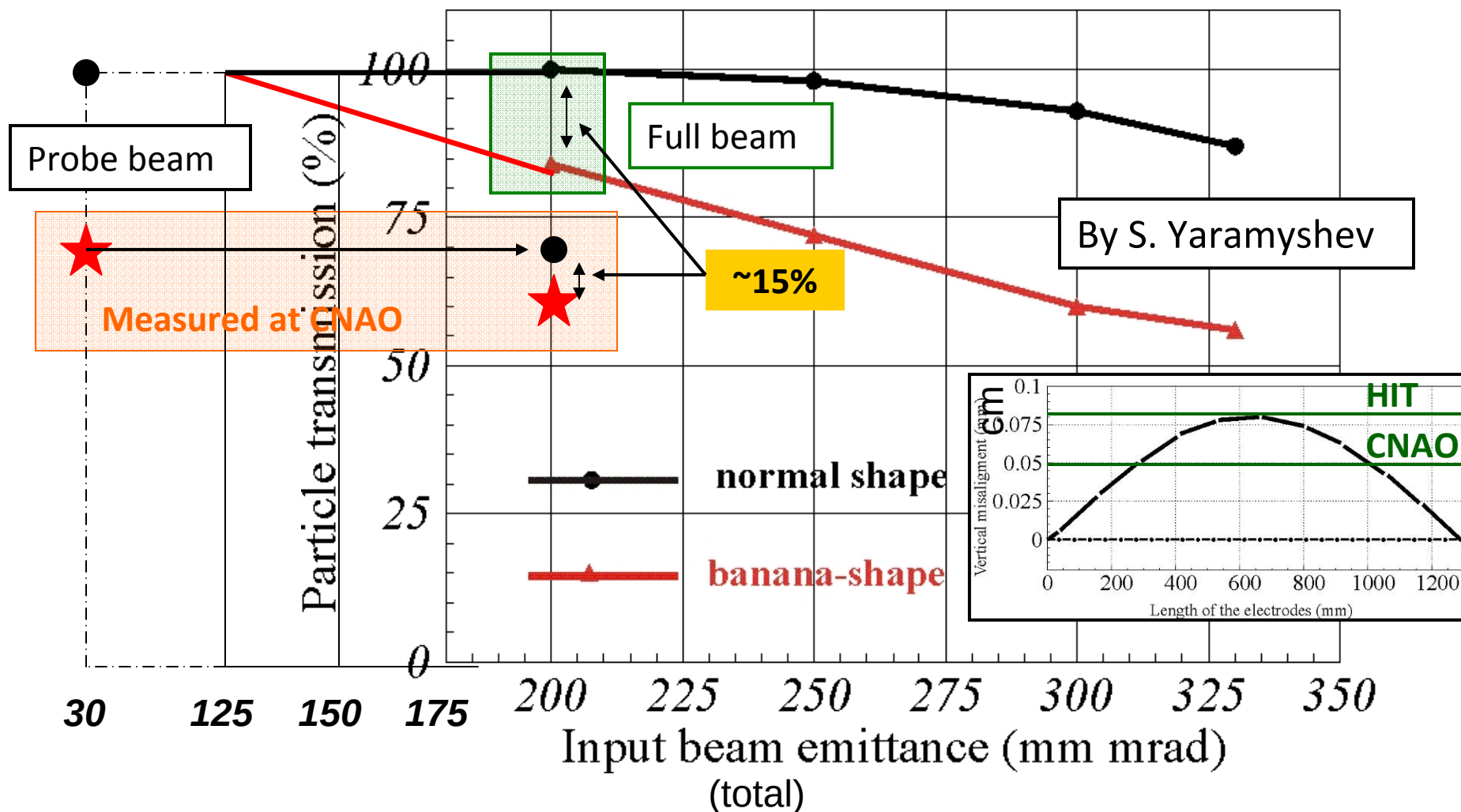
Transmission ~70 % at working point 5.1 Volt (195 kW)

Moderate steering in both planes with smooth behaviour

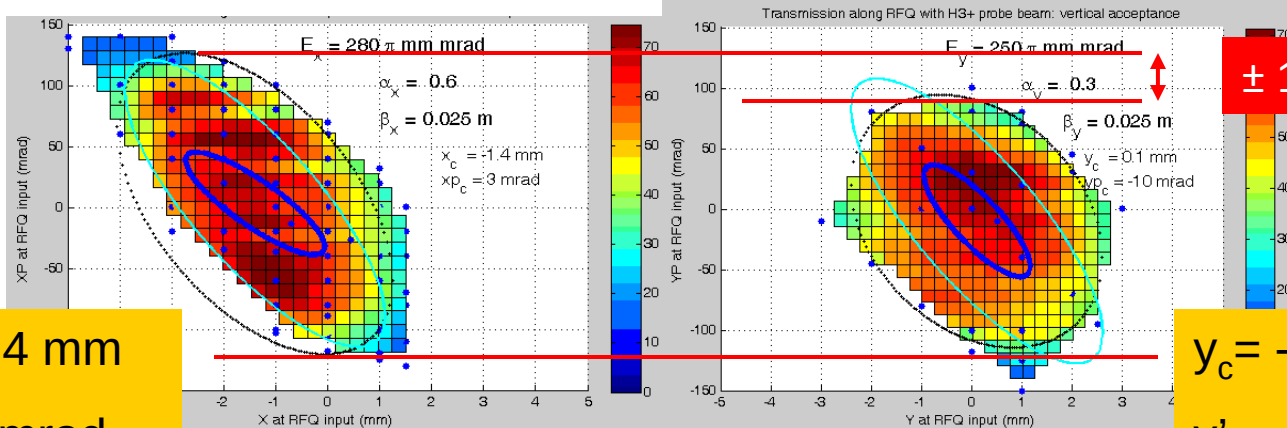
RFQ commissioning results

Ion	H_3^+			C^{4+}
Energy (keV/u)	7.5	8.0	8.5	8.0
Working point (V)	5.15	5.10	5.15	5.10
Max. transm. full beam	4.6%	58%	59%	62%
Max. transm. probe beam	3.4%	71%	69%	-
x rms emit. (4 rms [mm mrad])	-	18.7	21.6	17.9
y rms emit. (4 rms [mm mrad])	-	14.2	13.7	12.3

Effect of the bend electrodes on RFQ acc.



Exp. RFQ acceptance at 8 keV/u



$\pm 15 \text{ mrad!!}$

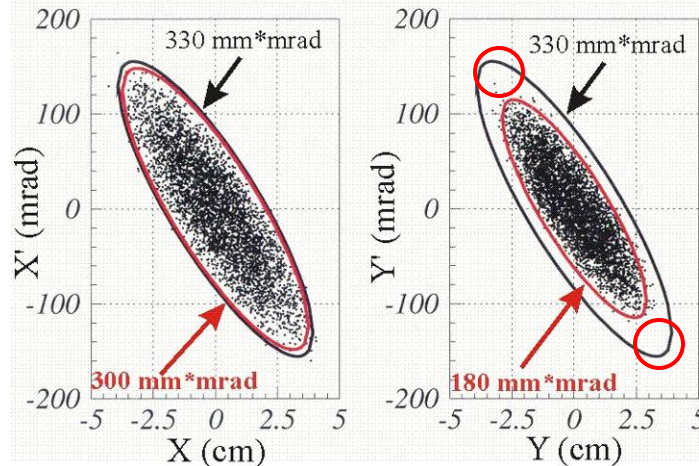
$x_c = -1.4 \text{ mm}$

$x'_c = 3 \text{ mrad}$

$y_c = -0.1 \text{ mm}$

$y'_c = -10 \text{ mrad}$

Probe beam displaced in position and angle with L2 steerers



By S. Yaramyshev

M. Pullia (CNAO) et al.

Commissioning RFQ

Summary results

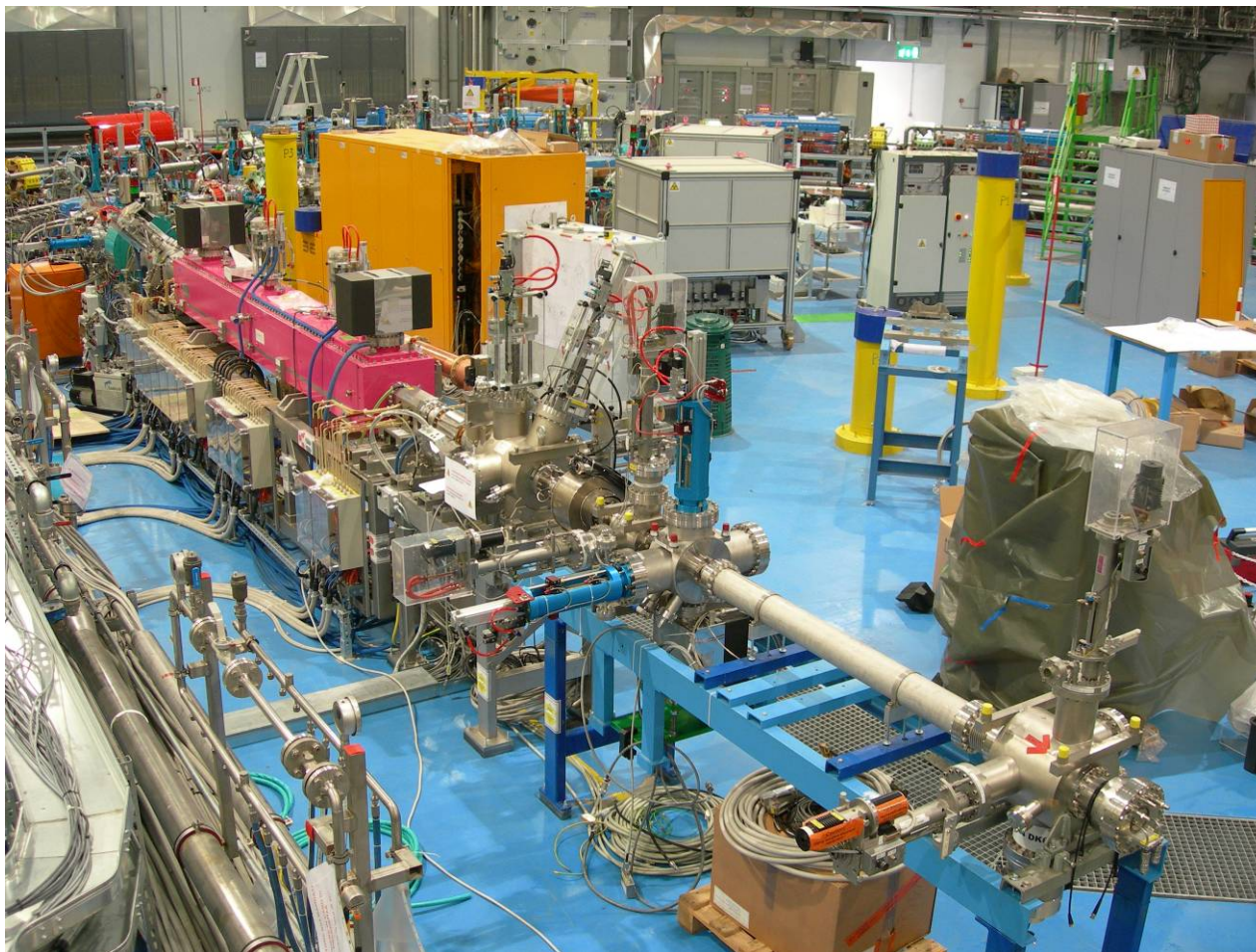
- *Working point:*
 - Energy of 400 keV/u reached at 195 kW power
- *Steering RFQ and quadrupole doublet:*
 - Size acceptable and smooth behavior
 - during operation only small correction with steerers
 - very small beam losses in inter-tank section!
- *Currents:*
 - ~500 μA (H_3^+)
 - ~75 μA (C^{4+})
 - transmissions up to 60 %
- *Transverse emittances:*
 - H_3^+ : Hor - Ver(90%) = 19 / 14 π mm mrad
 - C^{4+} : Hor - Ver(90%) = 18 / 12 π mm mrad
 - within acceptance of IH-DTL (~50 mm mrad)
- *RFQ operating parameters:*
 - Established for H_3^+ and C^{4+} beams

Commissioning RFQ

Summary of further measurements

- Variation of LEBT energy: Measurements with 7.5, 8.0 and 8.5 keV/u
 - **At 7.5 keV/u no useful results**
 - **At 8.5 keV/u results are similar to 8.0 keV/u case but at higher RFQ power level**
- Stability of energy over 1.5 h:
 - **variation in 2 keV/u region**
- Measurement (Hor. and Vert.) of RFQ acceptance at 8.0 and 8.5 keV/u:
 - **both measurements consistent**
- Optimization of LEBT settings with respect to centers of measured acceptance
 - **higher transmission**
 - **reduced steering and emittance after RFQ**
- WHY ONLY 70% TRANSMISSION AT MAX, with pencil beam ?
 - **Probably longitudinal losses, the RFQ is not able to capture and accelerate more than 70% of particles even for on axis particles!**

Now: IH – DTL! TB3 (GSI)



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