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

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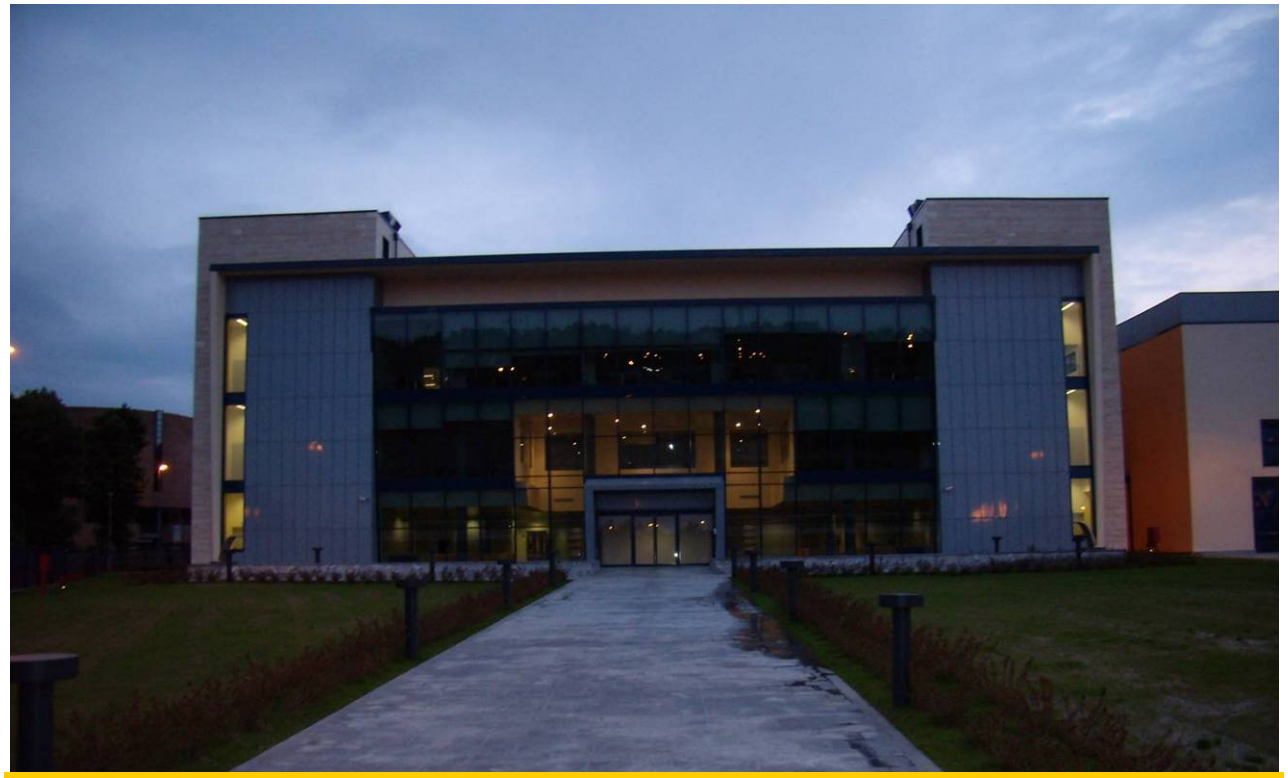
On behalf of the CNAO-GSI-INFN collaboration

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

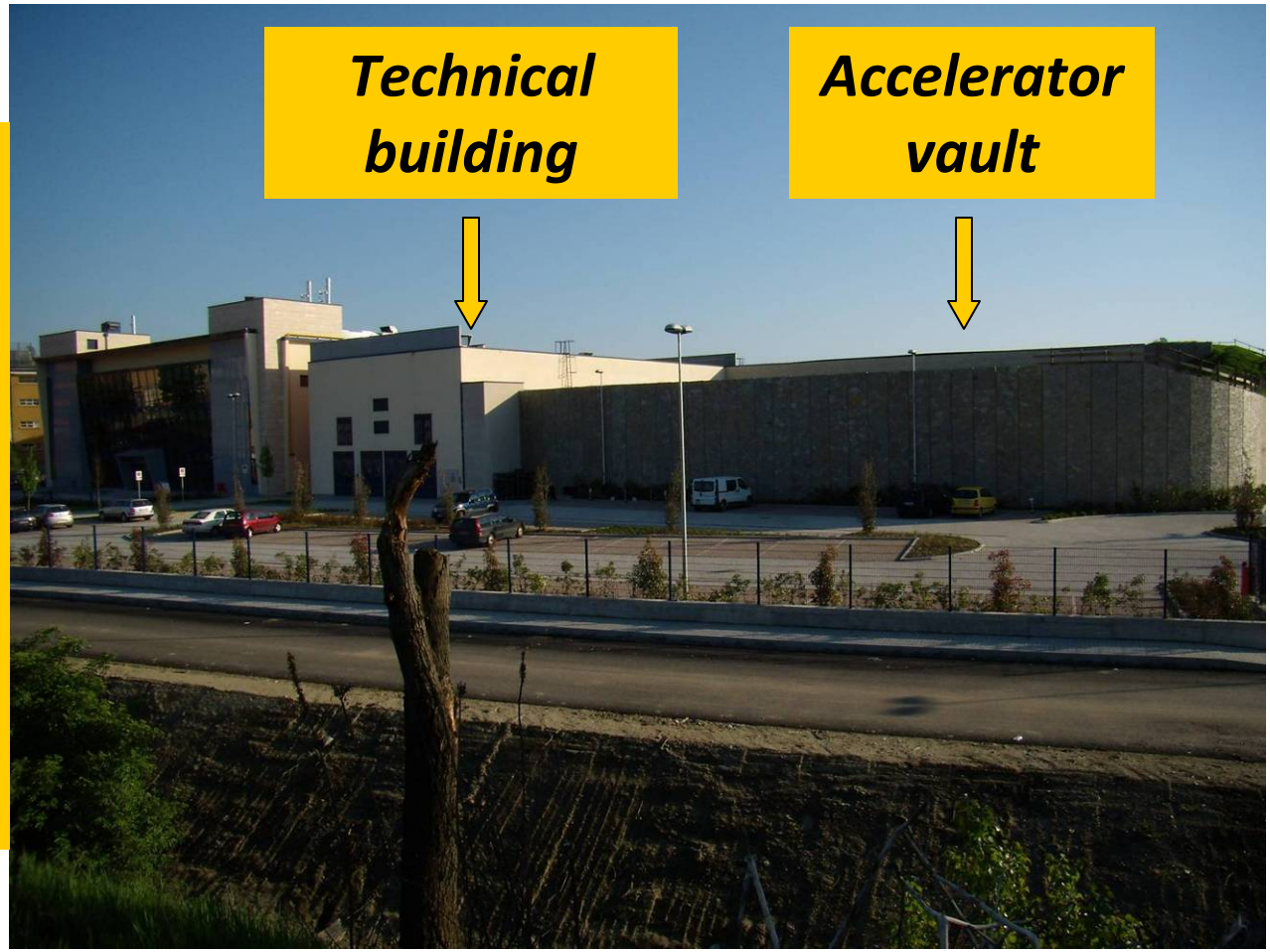
Main building:

2° floor:
auditorium & library

1° floor:
offices and laboratories

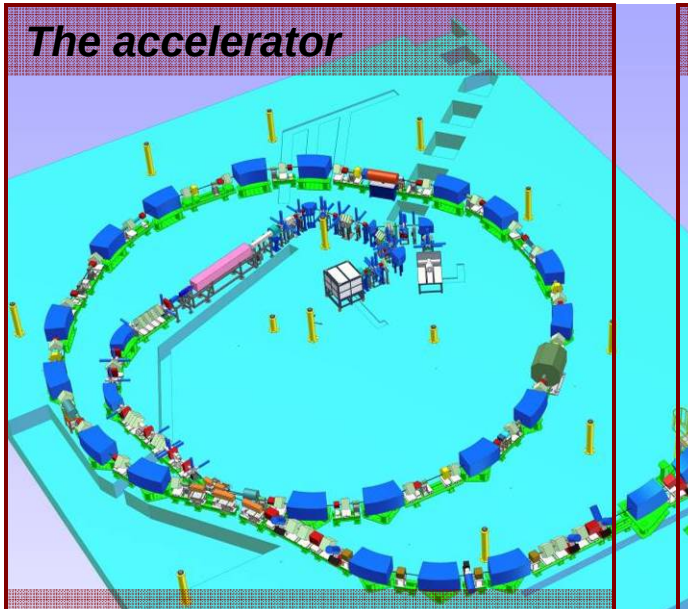
Ground floor:
Reception and
med. preparation

Basement:
3 treatment rooms



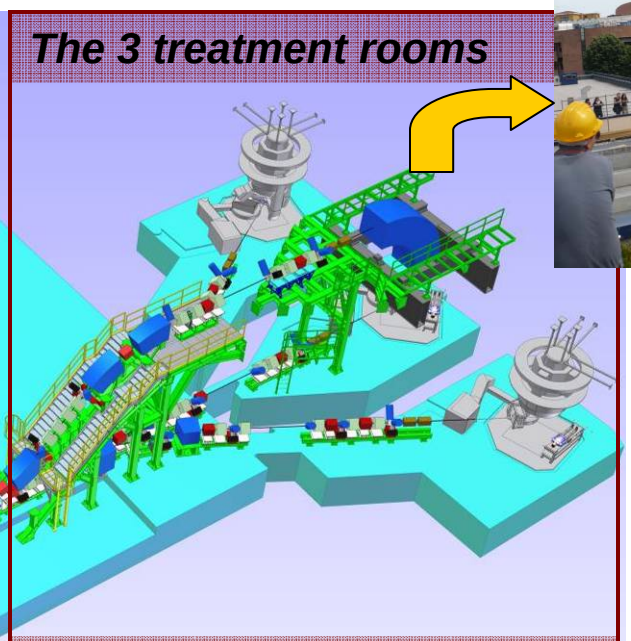
The CNAO facility

The accelerator



- Compact design
- 25 m diameter ring
- Multi turn injection
- Final energy:
  - Carbon: 2400 MeV
  - Protons: 250 MeV

The 3 treatment rooms

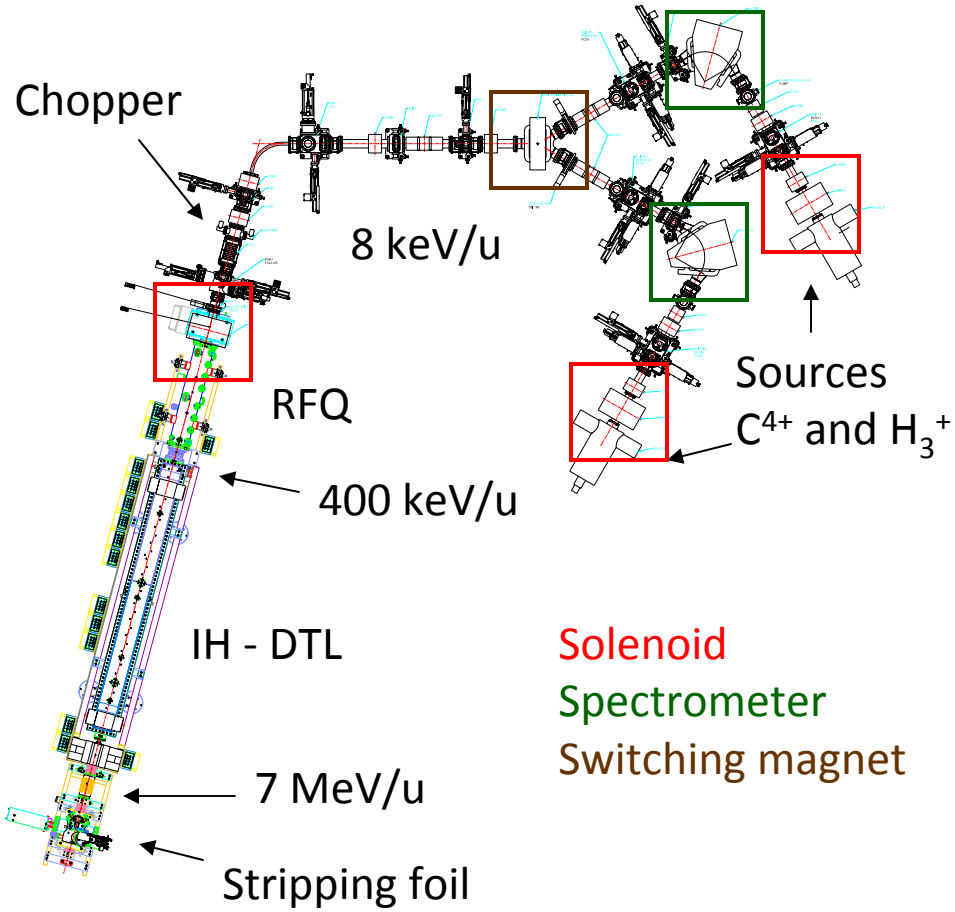


- 2 w. horizontal beam
- 1 w. hor. + vert. beam
- scanning mag. (20x20 cm)
- ~3000 patients/year
- 80% C, 20% protons

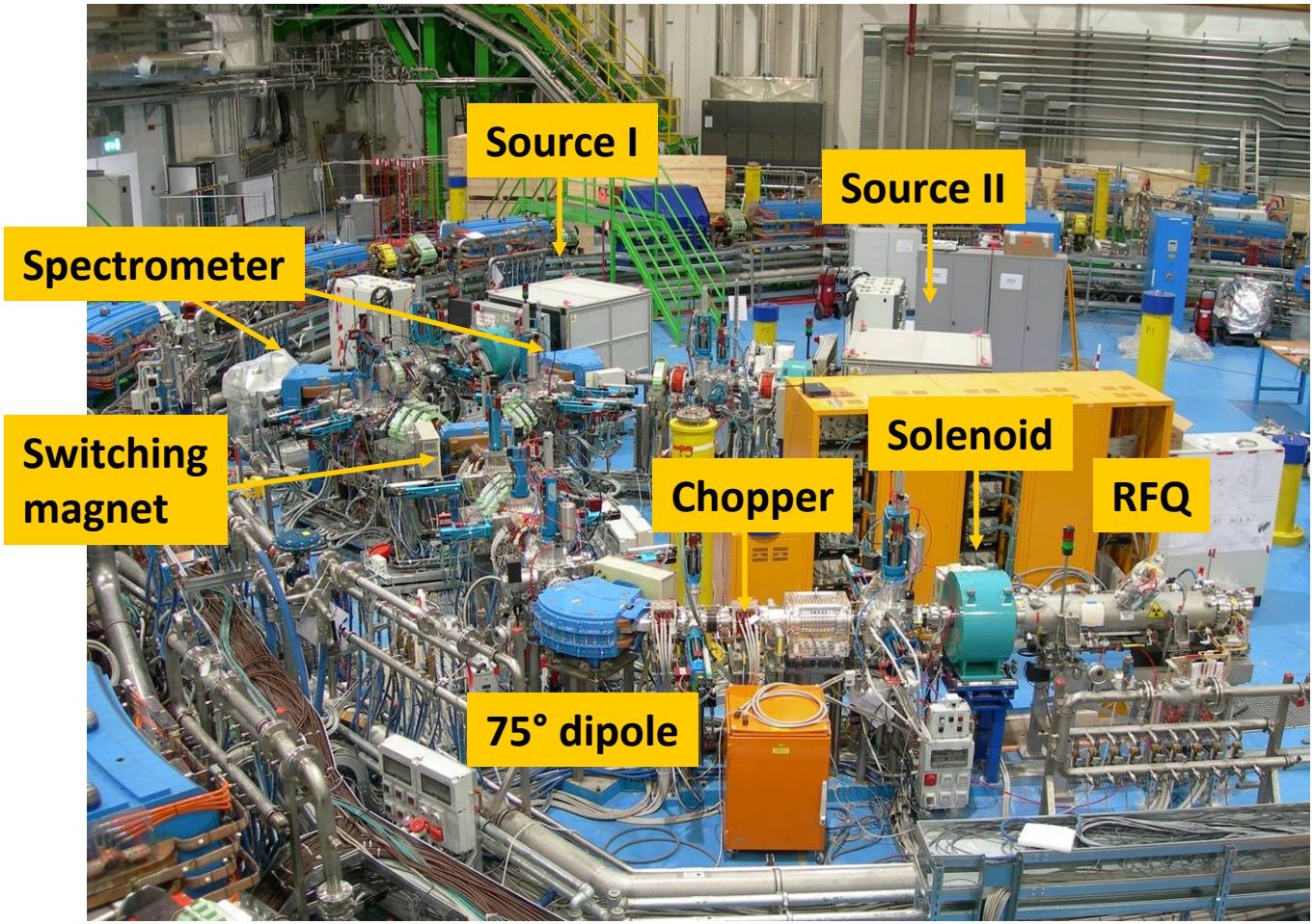
CNAO Injector:

Ion source supervised by INFN LNS
Low energy beam transport by CNAO
Linac by GSI (second version of HICAT)
supervised by INFN LNL

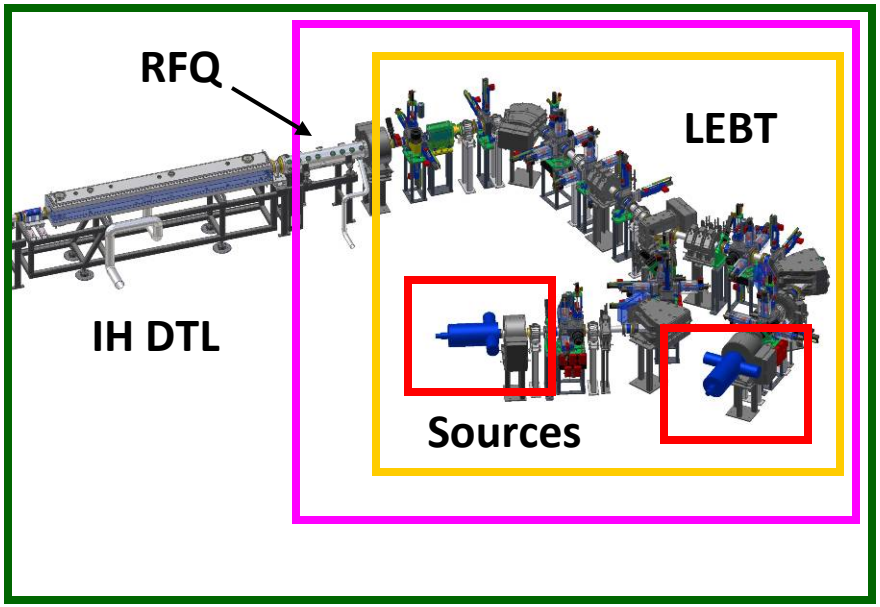
Sources Specifications	
Extraction Voltage	24 kV
Current H_3^+	> 700 µA
Current C^{4+}	> 150 µA
Transv. norm emitt. (95%)	0.5 mm mrad
LINAC Specifications	
Operating frequency	216.816 MHz
Final beam energy	7 MeV/u
Beam pulse length	≤ 300 µs
Beam rep. rate	≤ 5 Hz
Transv. norm emitt. (95%)	0.8 mm mrad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



The Injector as it was in January 2009



Injector commissioning milestones



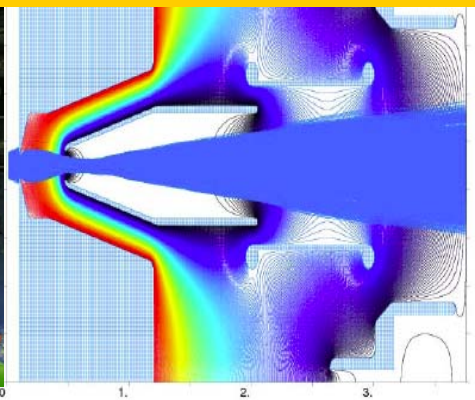
from	*to*	*Section*	*Description*
May 08	July 08	Source	Beam and LEBT Inst.
September 08	December 08	LEBT TB0	Beam
January 09	February 09	RFQ TB2	Install.
25th Feb. 09	12th Mar. 09		RF Cond.
13th Mar. 09	3rd April 09		Beam
April 09	May 09	IH DTL TB3	Install.
June 09	now		RF Cond.

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

New extraction column

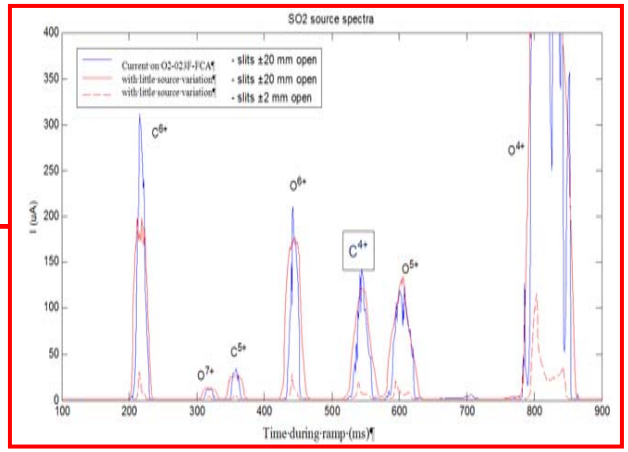


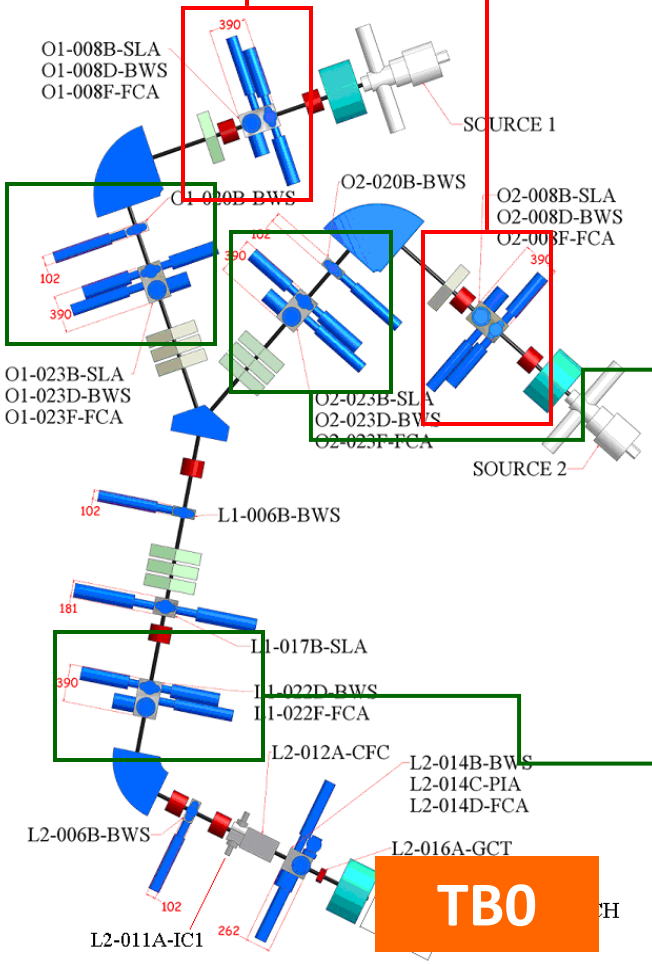
Performances

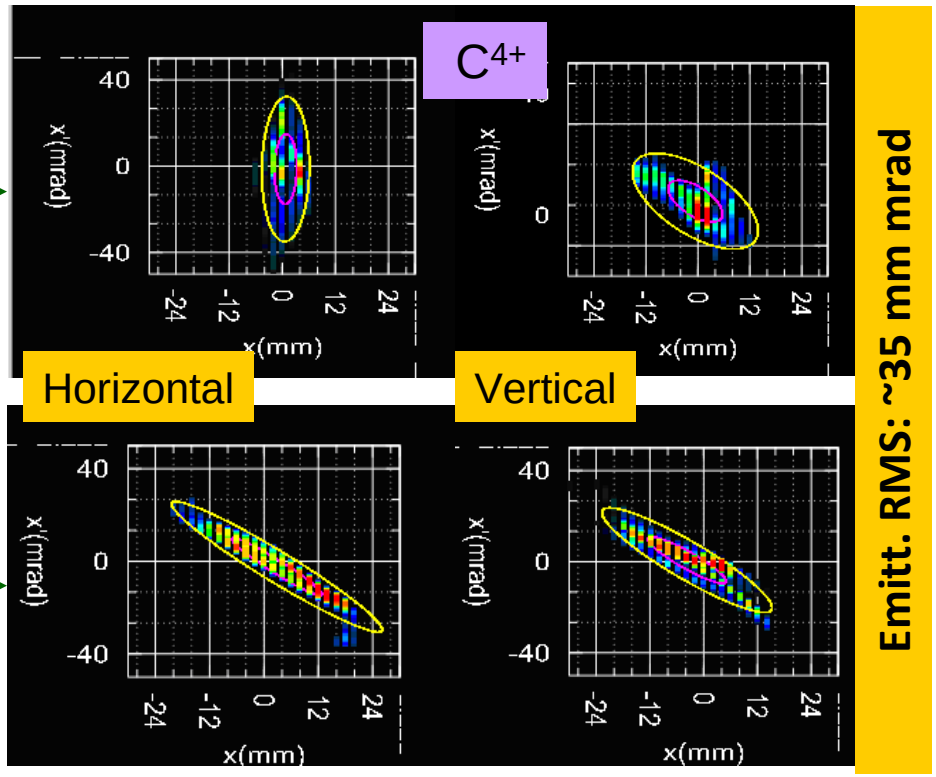
- **250 µA** for C^{4+} (25% > nominal)
- **1100 µA** for H_3^+ (50% > nominal)

→ plasma electrode hole diameter reduced to 6 mm allowing to have better emittance

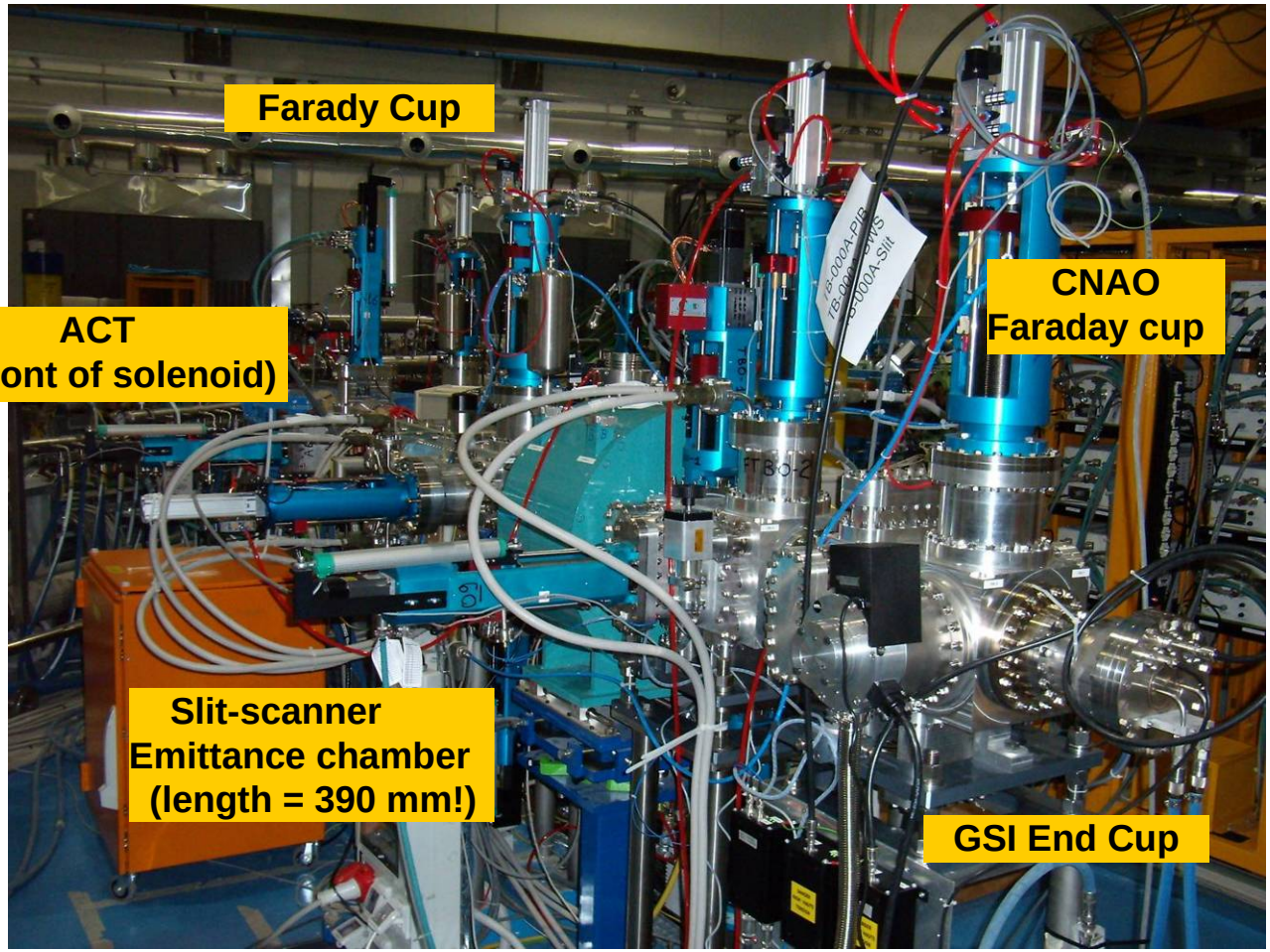
LEBT Commissioning



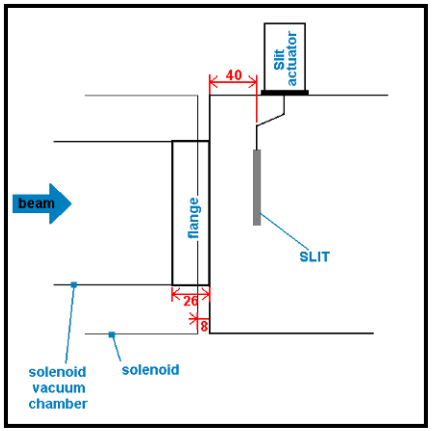


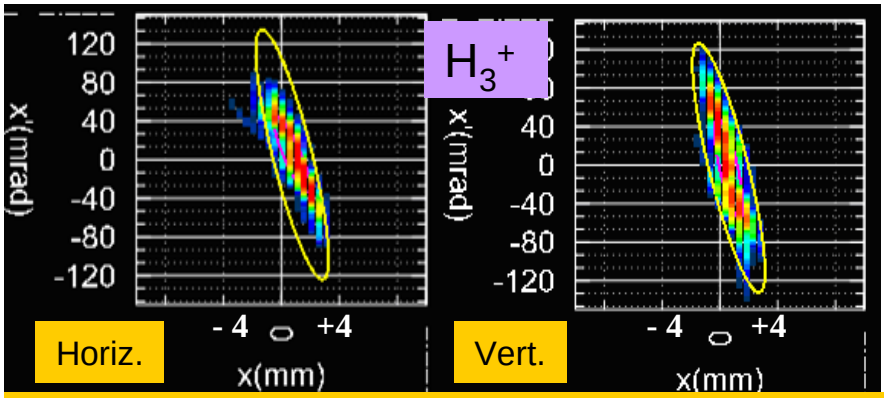


Commissioning of LEBT
TB0 (GSI & CNAO)

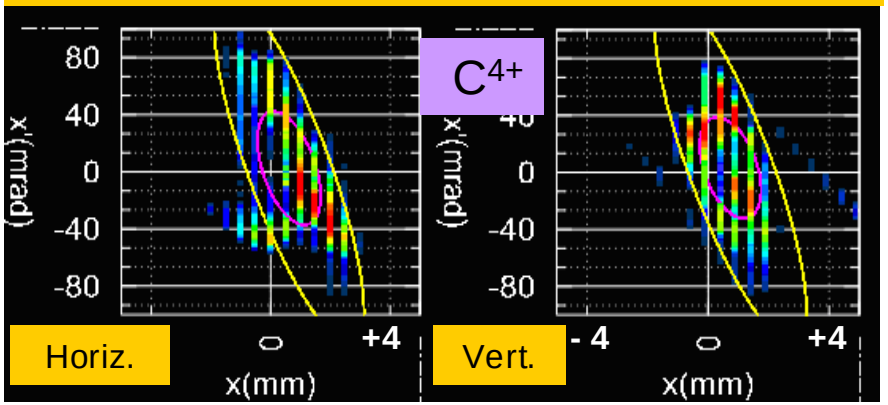


Emittance in TB0





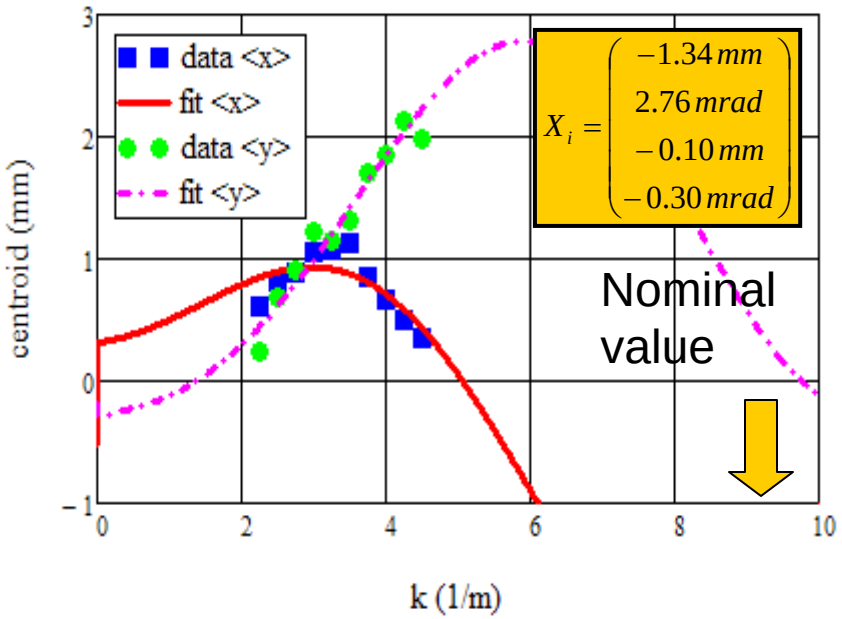
> 90% inside 180 mm mrad (yellow ellipse)



TB0:

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

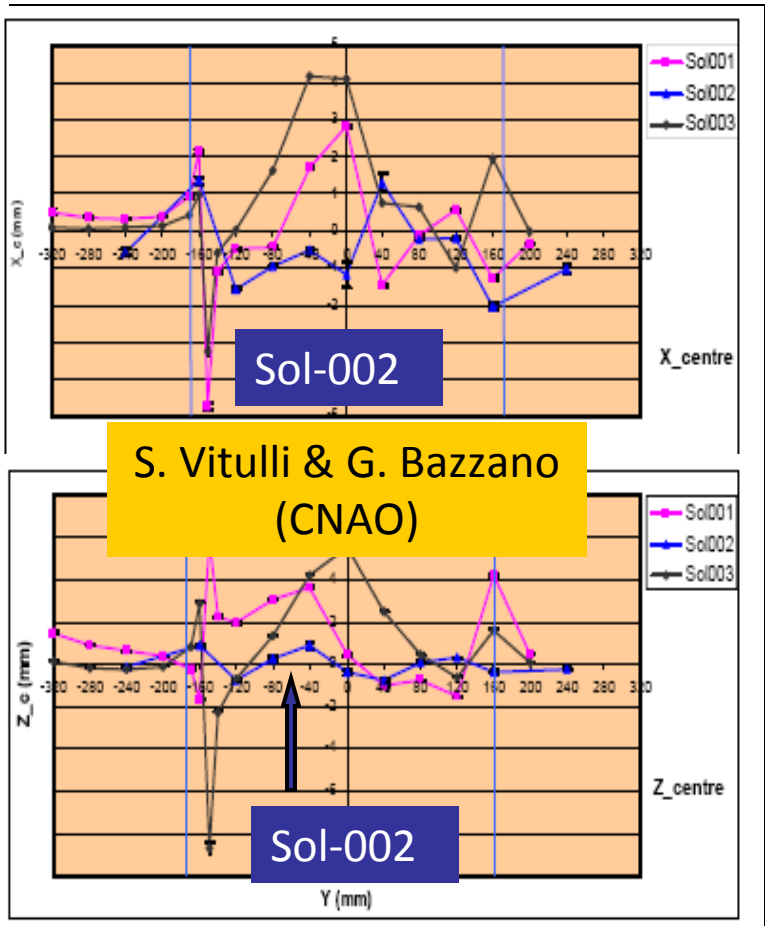
Matching solenoid



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

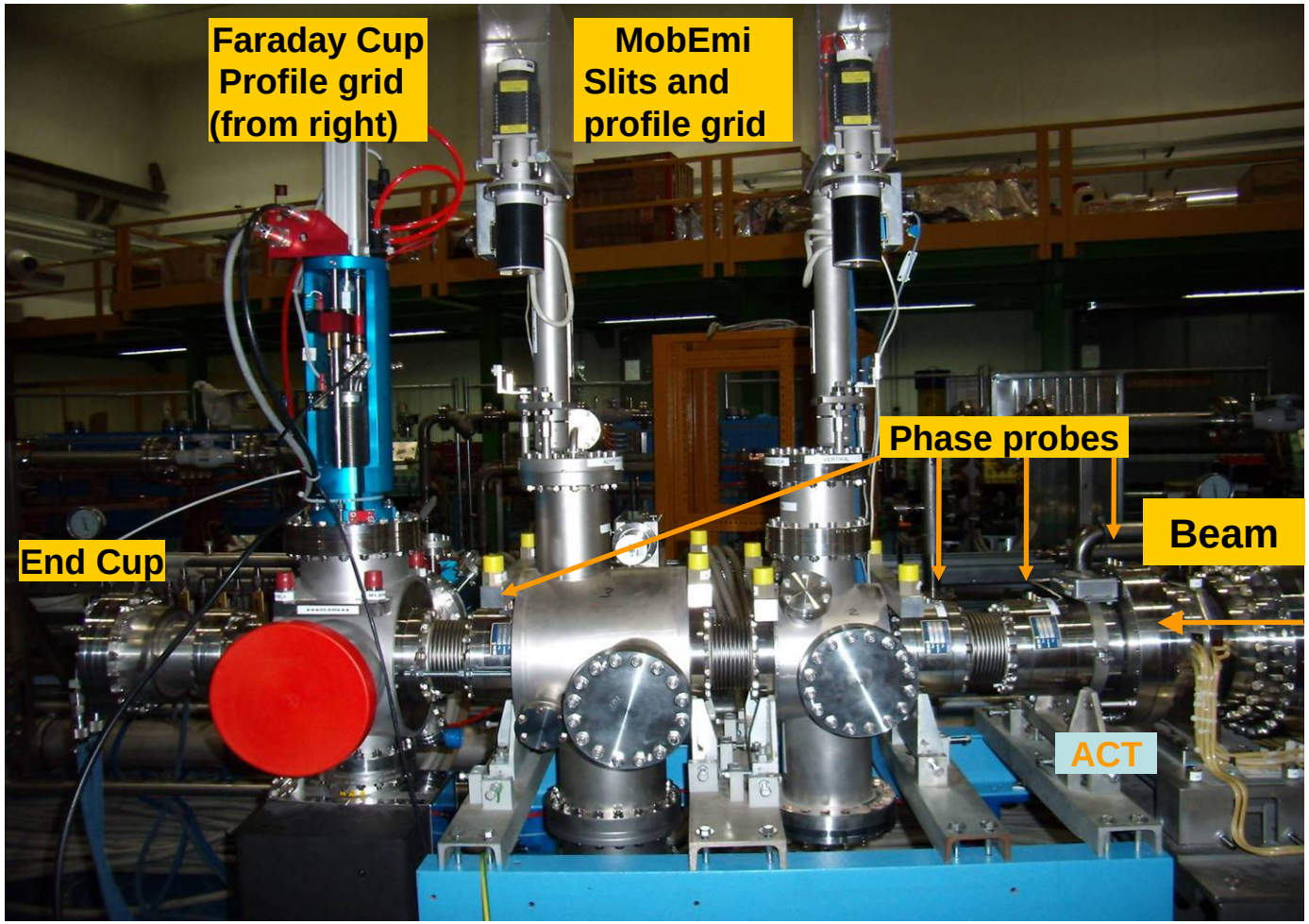
LEBT Commissioning summary TB0

- 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**

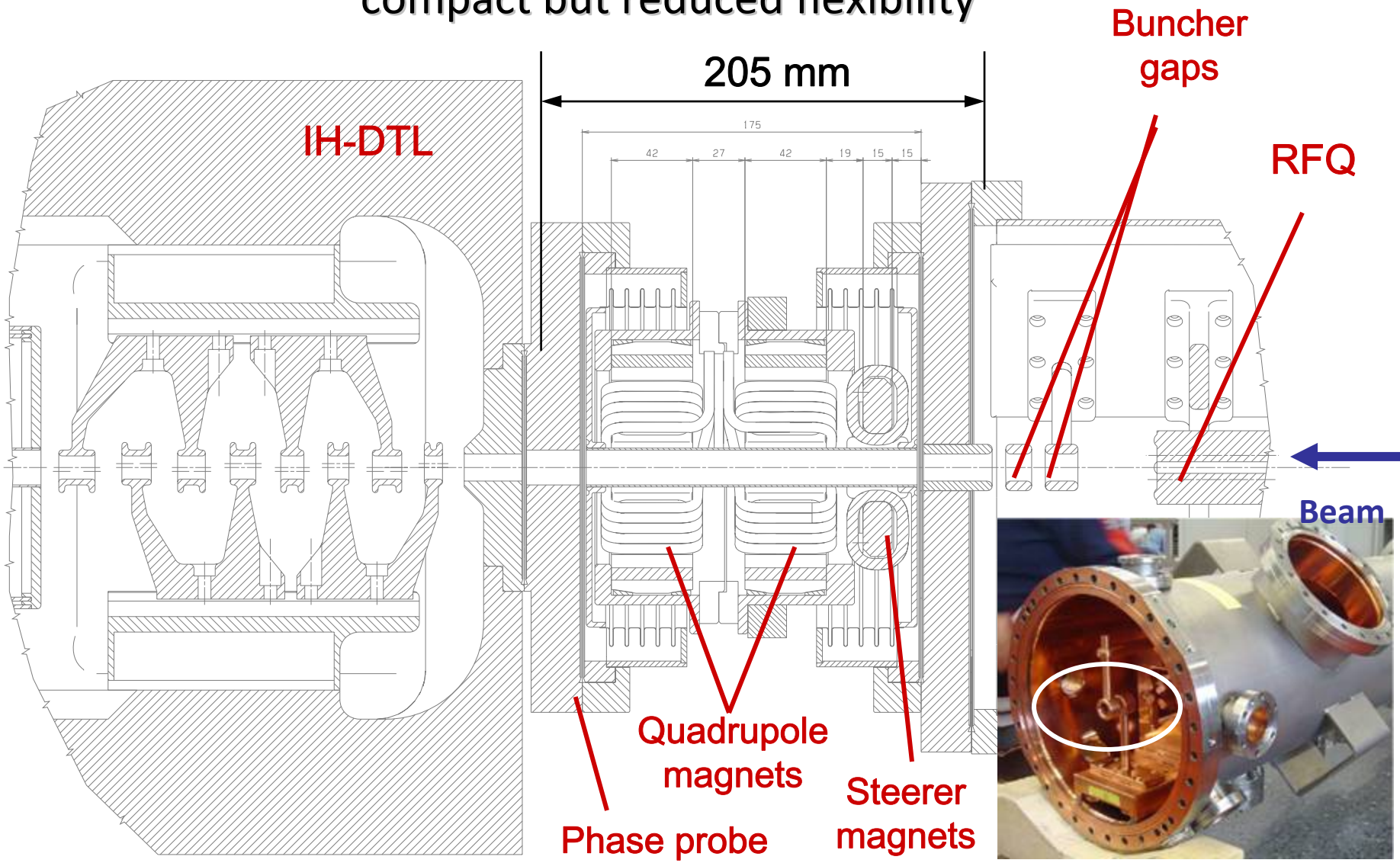
Mandatory for RFQ good performances!!!

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

Commissioning of RFQ
TB2 (GSI)



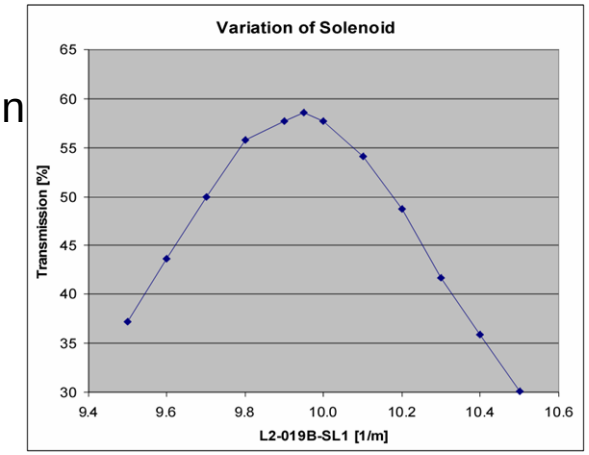
Intertank section with MEBT partly integrated in the RFQ:
compact but reduced flexibility



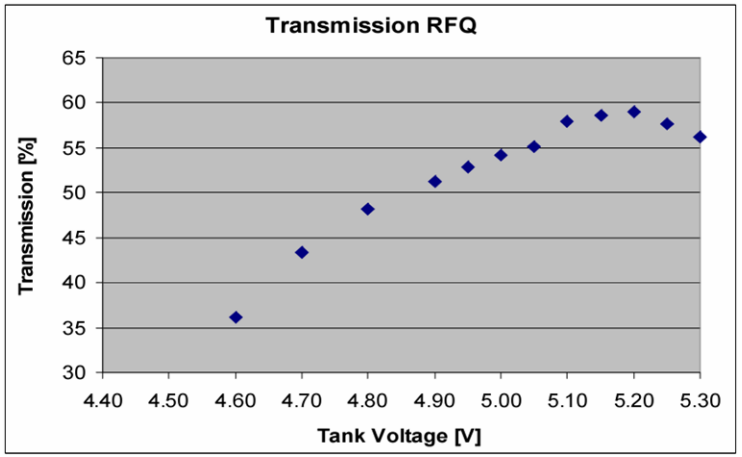
Commissioning RFQ – Results H_3^+ at 8 keV/u

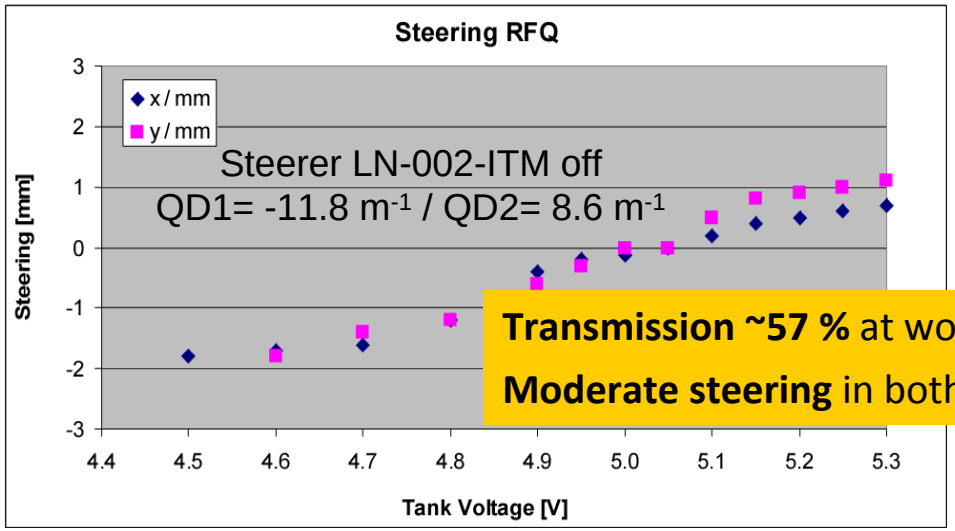
transmission, steering and energy

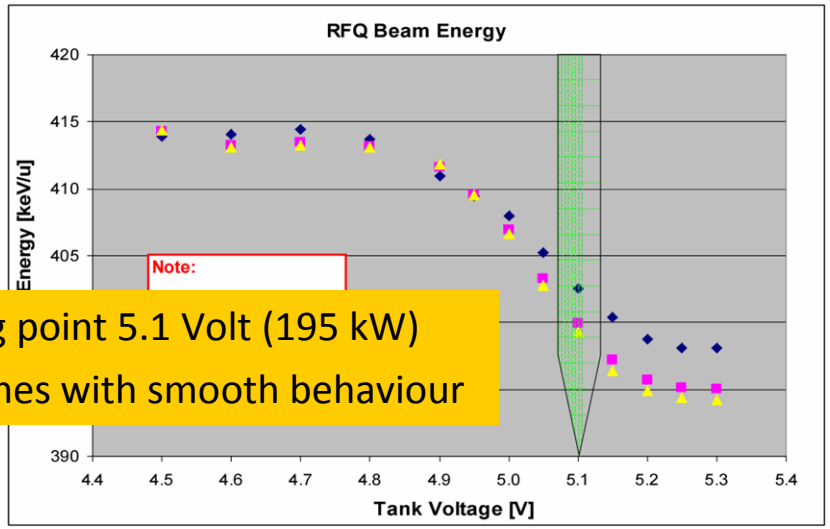
Step 1: Optimisation



Step 2: Perform standard measurements





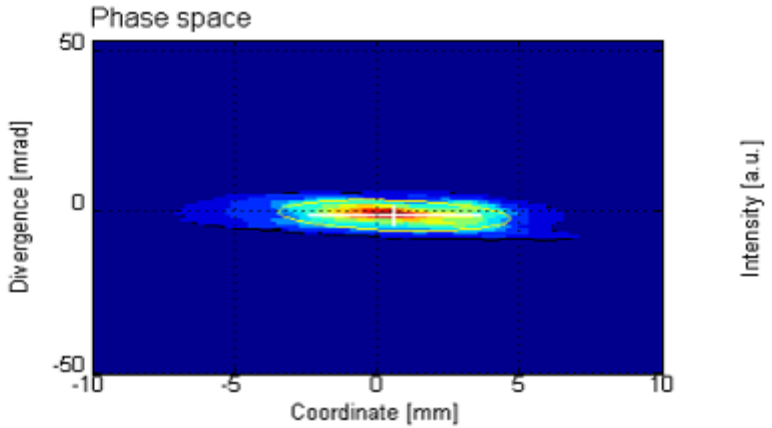


Transmission ~57 % at working point 5.1 Volt (195 kW)

Moderate steering in both planes with smooth behaviour

Commissioning RFQ – Results H_3^+ at 8 keV/u
Emittances in TB2

Horizontal Emittance

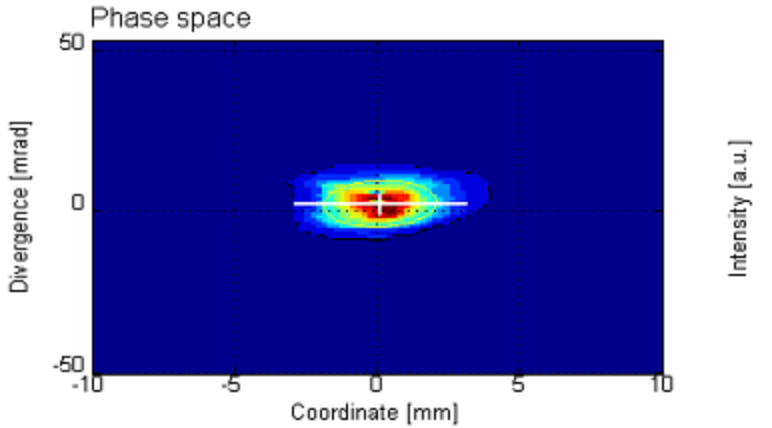


xo:	0.62
yo:	-1.26
$stdev_x$:	2.03
$stdev_y$:	2.38
$corr_{xy}$:	-0.231
ε:	**18.73**
α:	0.24
β:	0.88
γ:	1.21
KV-plane:	0.10

Threshold[%]	I_{capt}/I[%]	∑dS/▪ [mm mrad]
1.8	**99**	45.11
5.0	**95**	34.92
7.9	**90**	28.08
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		0.99

4 rms [mm mrad]

Vertical Emittance



xo:	0.11
yo:	2.27
$stdev_x$:	0.99
$stdev_y$:	3.57
$corr_{xy}$:	0.076
ε:	**14.16**
α:	-0.08
β:	0.28
γ:	3.61
KV-plane:	0.10

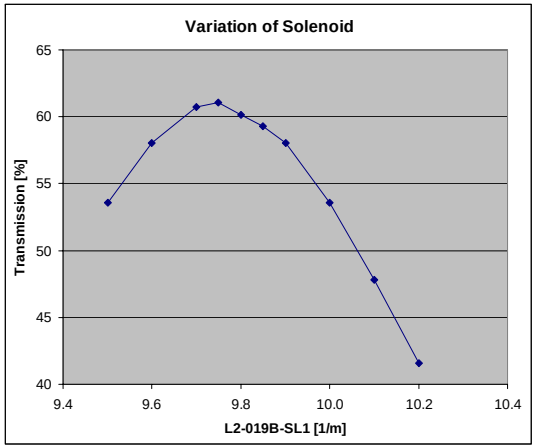
Threshold[%]	I_{capt}/I[%]	∑dS/▪ [mm mrad]
2.0	**99**	36.30
5.7	**95**	26.63
10.1	**90**	21.04
14.3	**85**	17.49
18.8	**80**	14.86
28.2	**70**	11.11
35.6	**60**	8.42
44.6	**50**	6.25
54.9	**40**	4.54
70.6	**30**	3.09
79.7	**20**	1.91
87.0		0.92

4 rms [mm mrad]

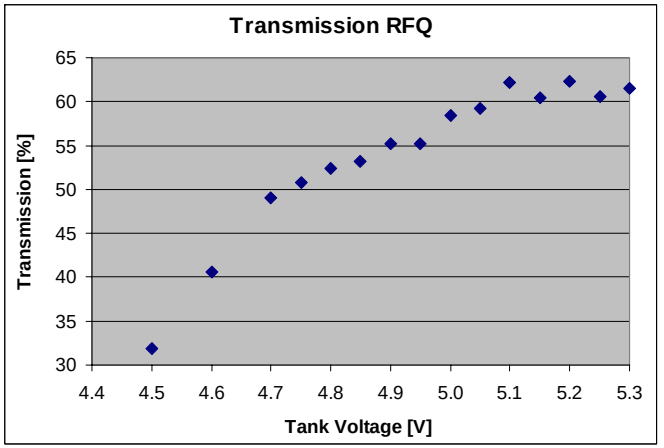
Commissioning RFQ – Results C^{4+}

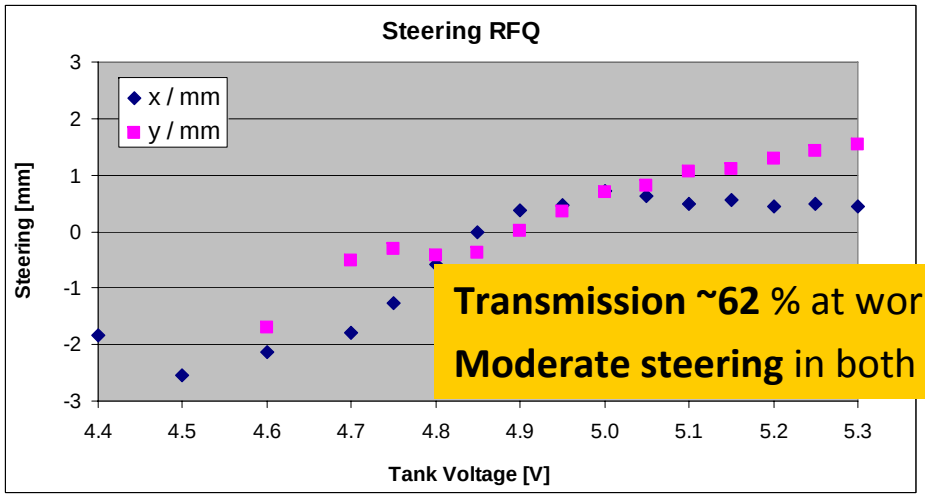
Transmission, energy und steering

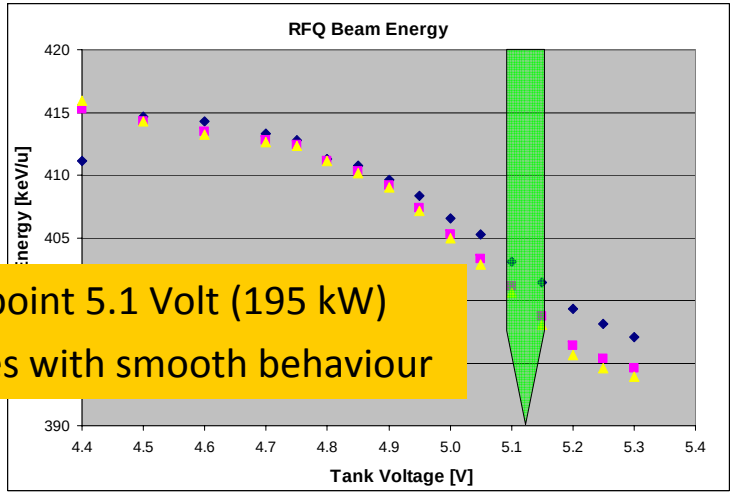
Step 1: Optimization



Step 2: Perform standard measurements







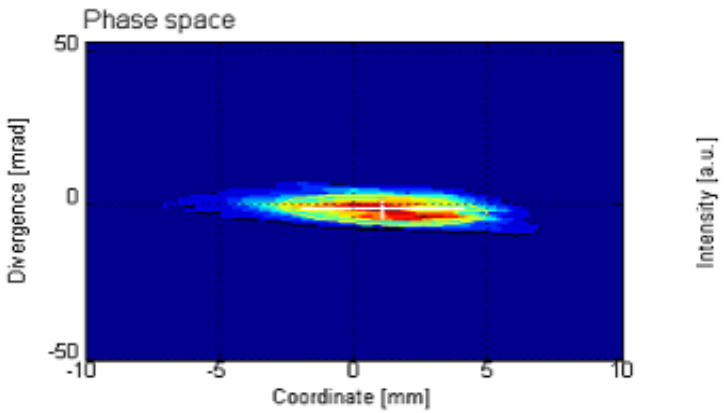
Transmission ~62 % at working point 5.1 Volt (195 kW)

Moderate steering in both planes with smooth behaviour

Commissioning RFQ – Results C^{4+}

Emittances in TB2

Horizontal Emittance

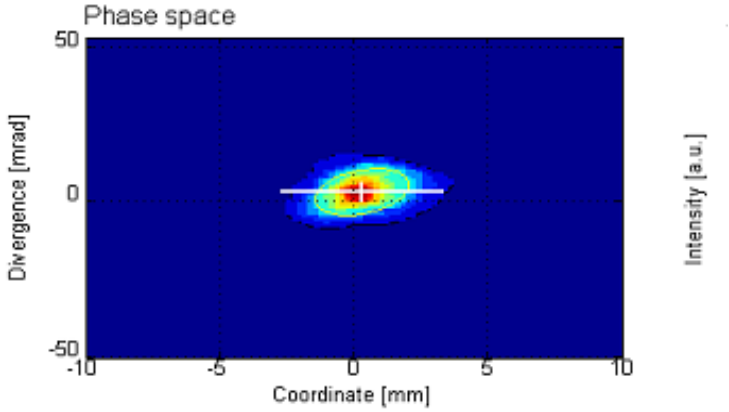


xo:	1.12
yo:	-1.63
$stdev_x$:	1.93
$stdev_y$:	2.41
$corr_{xy}$:	-0.272
ε:	**17.85**
α:	0.28
β:	0.83
γ:	1.30
KV-plane:	0.10

Threshold[%]	I_{capt}[%]	∑dS/•[mm mrad]
2.2	**99**	42.22
6.4	**95**	30.91
11.7	**90**	24.53
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		1.25

4 rms [mm mrad]

Vertical Emittance

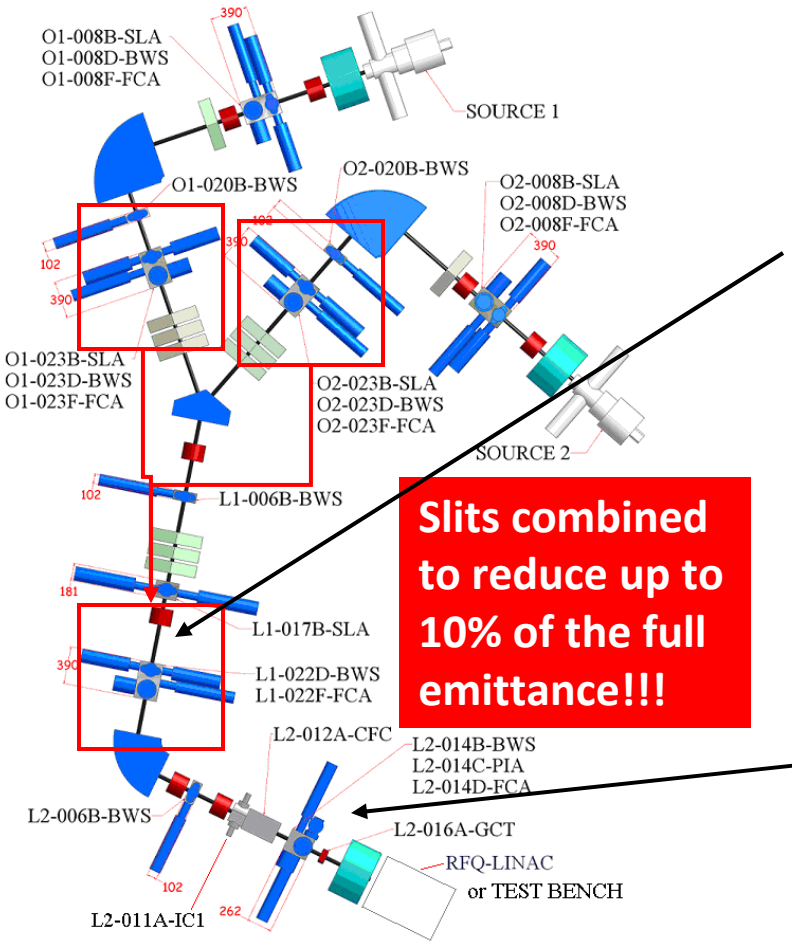


xo:	0.31
yo:	3.15
$stdev_x$:	0.86
$stdev_y$:	3.74
$corr_{xy}$:	0.316
ε:	**12.28**
α:	-0.33
β:	0.24
γ:	4.57
KV-plane:	0.10

Threshold[%]	I_{capt}[%]	∑dS/•[mm mrad]
1.7	**99**	31.30
5.2	**95**	23.02
8.9	**90**	18.41
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		0.72

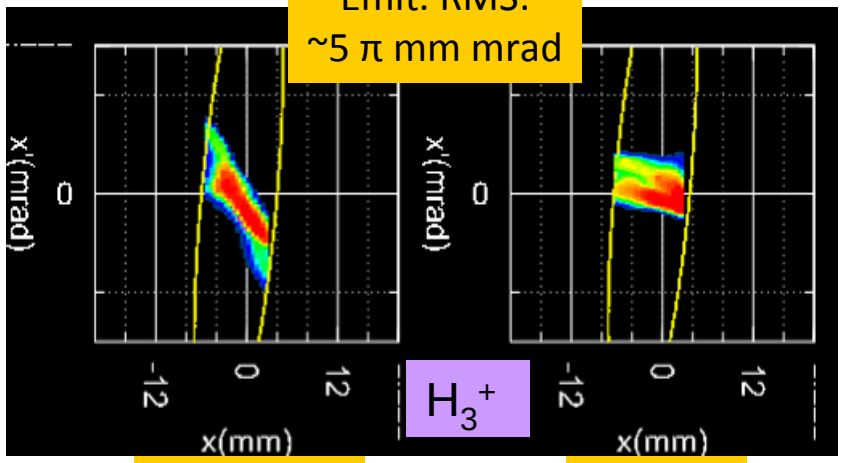
4 rms [mm mrad]

Probe beam (H_3^+)



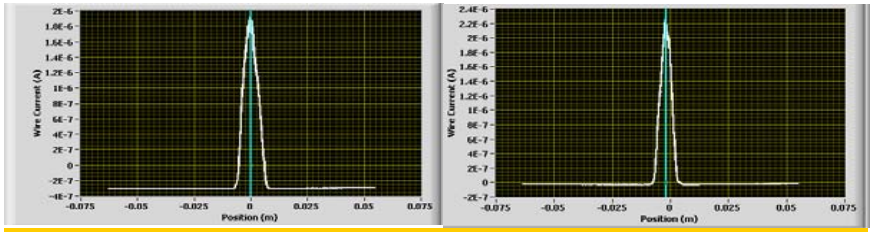
Slits combined to reduce up to 10% of the full emittance!!!

Emit. RMS:
~5 π mm mrad



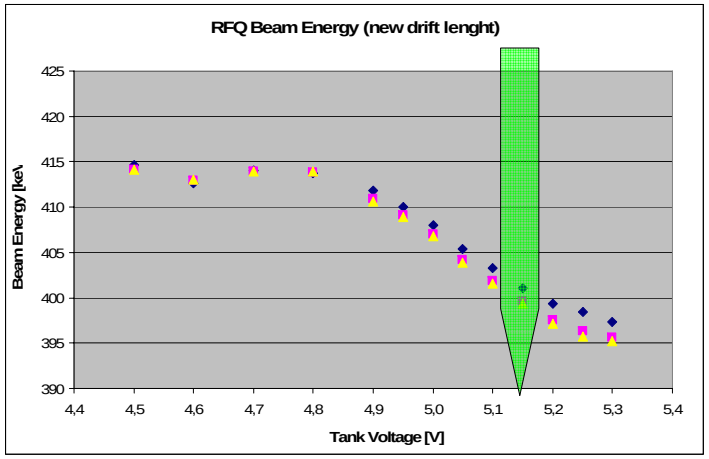
Horizontal Vertical

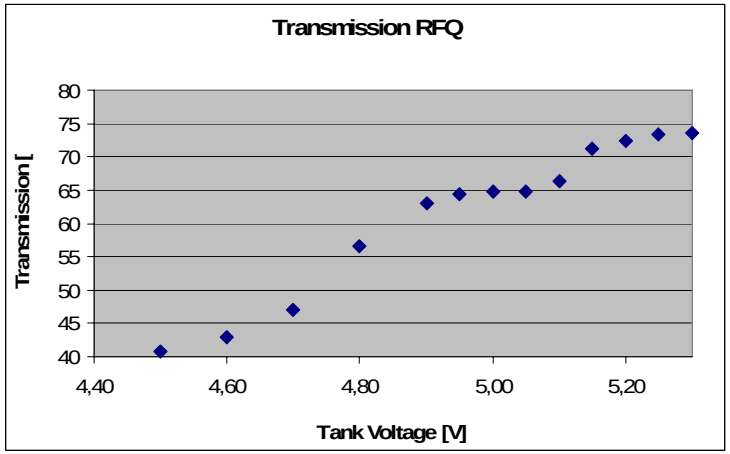
M. Pullia (CNAO)

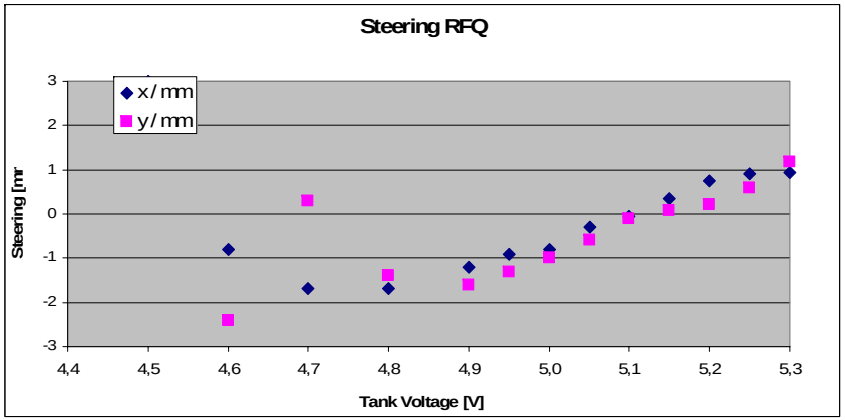


profile in L2
(~10 mm width)

RFQ: Results H_3^+ "probe beam" at 8 keV/u
Steering, energy and transmission







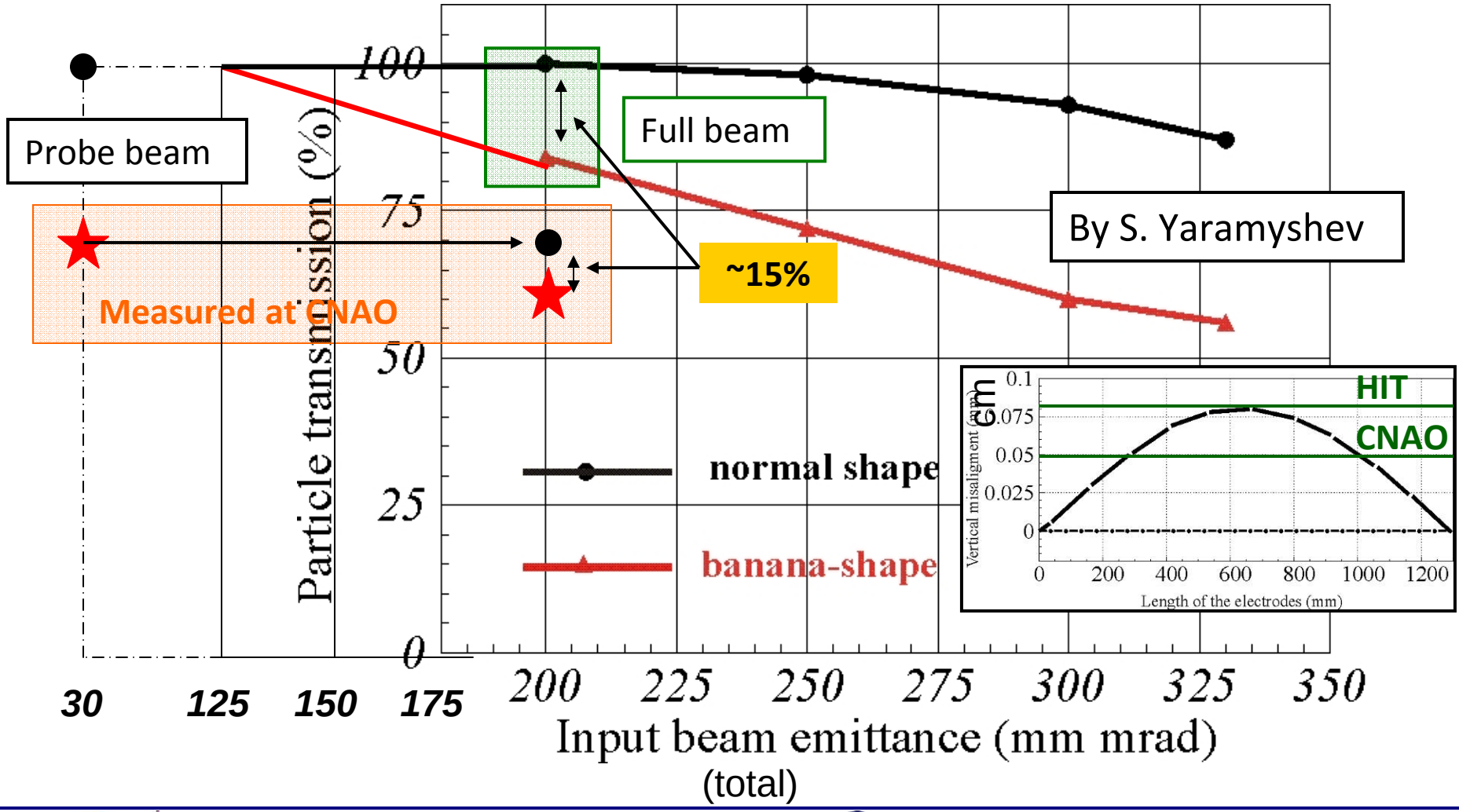
Transmission ~70 % at working point 5.1 Volt (195 kW)

Moderate steering in both planes with smooth behaviour

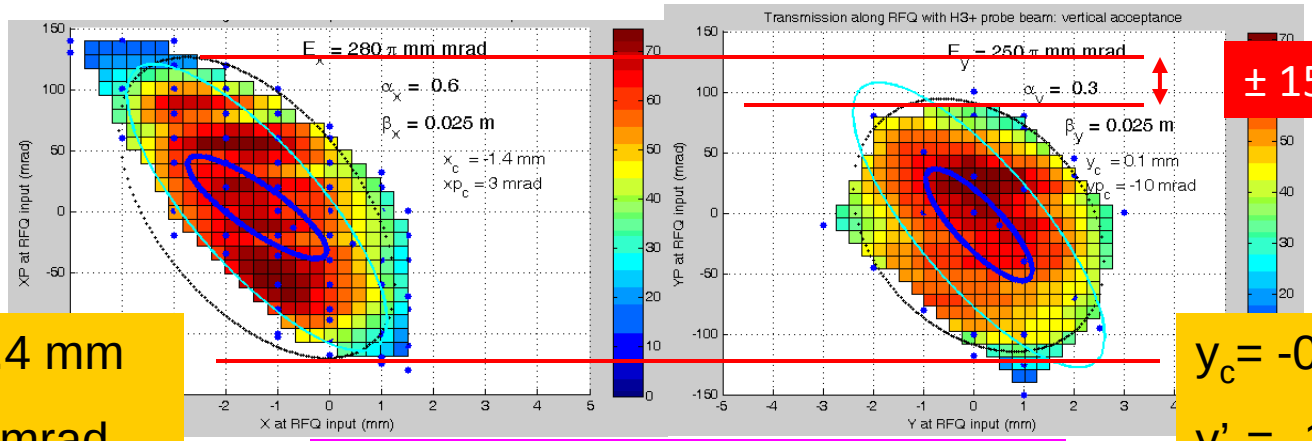
RFQ commissioning results

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



± 15 mrad!!

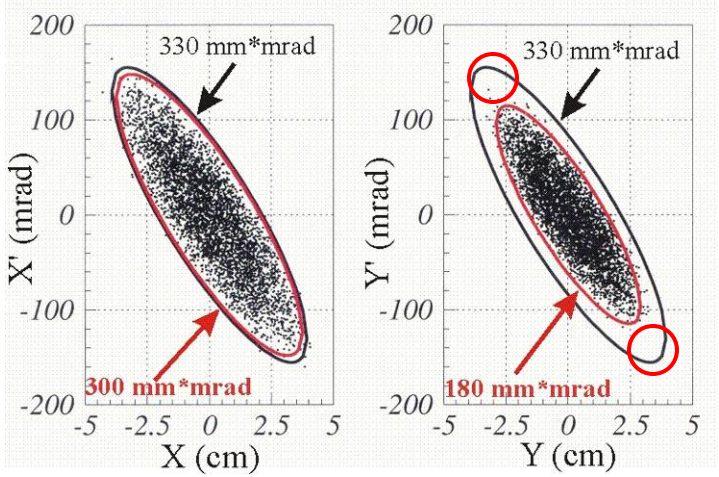
x_c= -1.4 mm

x'_c= 3 mrad

y_c= -0.1 mm

y'_c= -10 mrad

Probe beam displaced in position and angle with L2 steerers



By S. Yaramyshev

M. Pullia (CNAO) et al.

Commissioning RFQ

Summary results

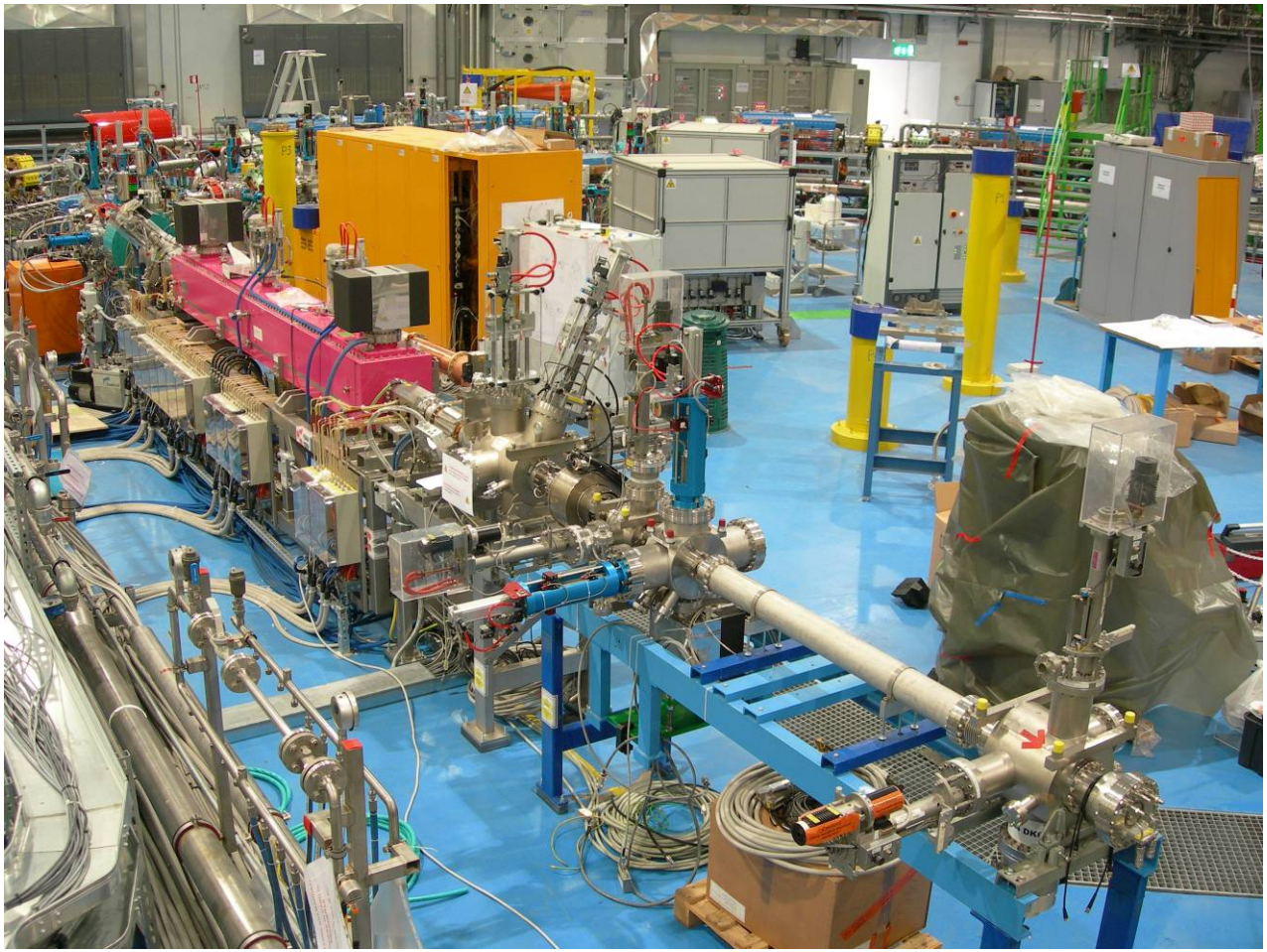
- *Working point:*
  - **Energy of 400 keV/u reached at 195 kW power**
- *Steering RFQ and quadrupole doublet:*
  - **Size acceptable and smooth behavior**
  - **during operation only small correction with steerers**
  - **very small beam losses in inter-tank section!**
- *Currents:*
  - **~500 µA (H_3^+)**
  - **~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% TRASMISSION 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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