The MYRRHA LEBT
Commissioning & Space Charge Compensation Experiments

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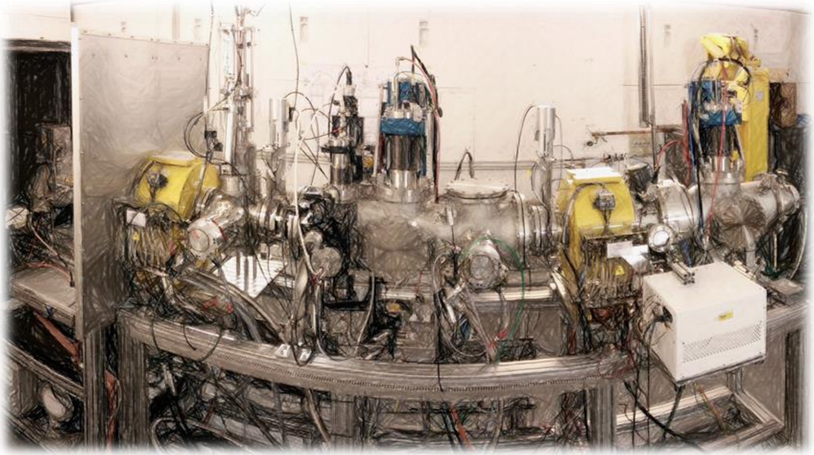

IPAC'17 Conference
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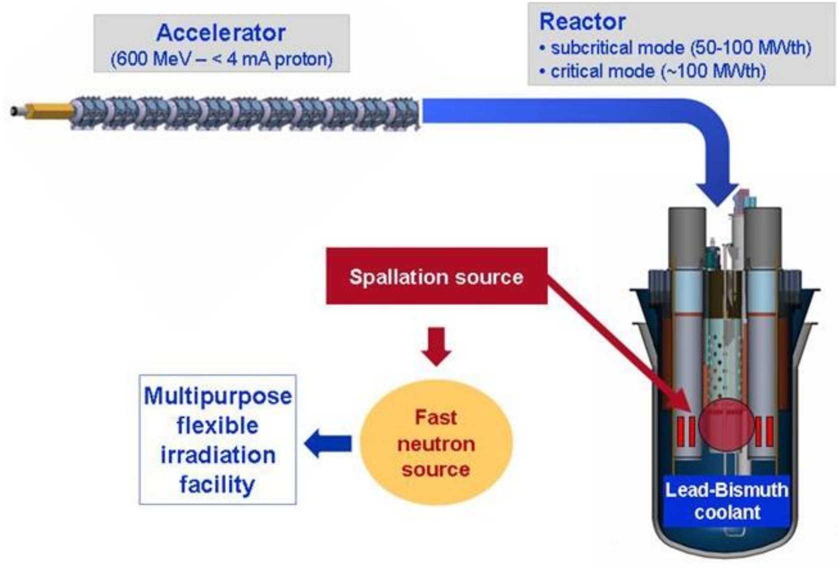
MYRRHA

Multi-purpose hYbrid Research Reactor for High-tech Applications At Mol (Belgium)

Demonstrate the physics and technology of an Accelerator Driven System (ADS) for transmuting long-lived radioactive waste



Accelerator
(600 MeV – < 4 mA proton)

Reactor
- subcritical mode (50-100 MWth)
- critical mode (~100 MWth)

Spallation source

Fast neutron source

Multipurpose flexible irradiation facility

Lead-Bismuth coolant

High power proton beam (up to 2.4 MW)

Proton energy	600 MeV
Peak beam current	0.1 to 4.0 mA
Repetition rate	1 to 250 Hz
Beam duty cycle	10^{-4} to 1
Beam power stability	< ± 2% on a time scale of 100ms
Beam footprint on reactor window	Circular ∅85mm
Beam footprint stability	< ± 10% on a time scale of 1s
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited

Extreme reliability

- to minimise thermal stress and fatigue on target, reactor core,…
- to ensure 80 % availability (reactor re-start procedures : ~20 h).

MYRRHA Linac Design

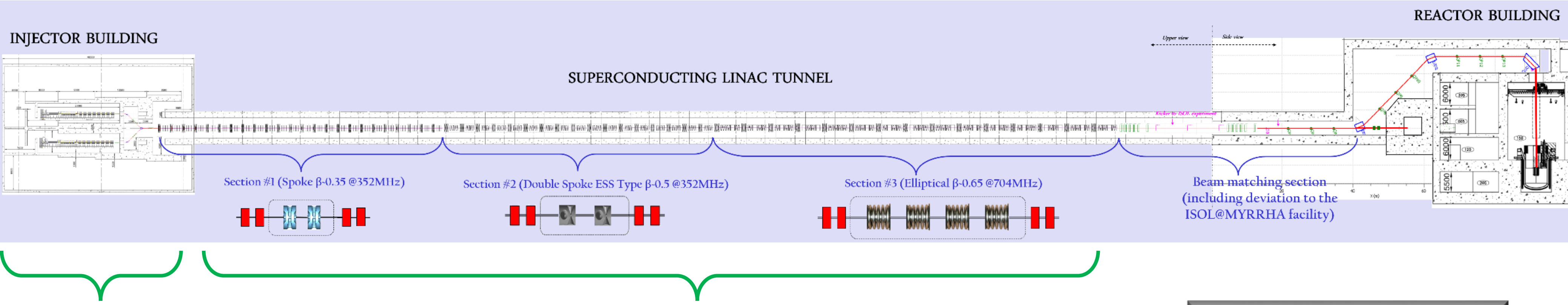
- **Reliabilty guidelines for an ADS accelerator design:**

➲ Robust design i.e. robust optics, simplicity, low thermal stress, operation margins…

➲ Redundancy (serial where possible, or parallel) to be able to tolerate/mitigate failures

➲ Repairability (on-line where possible) and efficient maintenance schemes

- Layout of the MYRRRHA linac : **Double injector + Superconducting linac**



Parallel redundancy

Serial redundancy

Courtesy of J.-L. Biarrotte

Accelerator Background & Project Support

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

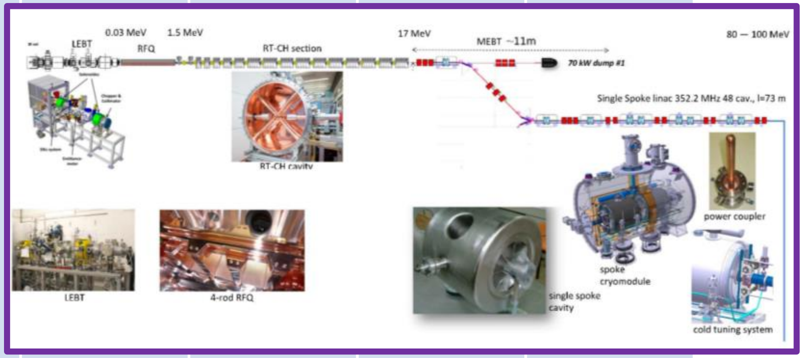
← *End 90's : 1st accelerator projects for ADS (APT/AAA, TRASCO, …)*
2002-2005 : MYRRHA as one of the 3 reactor designs within the PDS-XADS FP5 project

Eurotrans (FP6)
MYRRHA : XT-ADS demo.
Linac 600 Mev –
R&D on reliability-
GUINEVERE & GENEPI-3C

MAX (FP7)

- Start-to-end reference design w. error study
- Prototyping : elliptical and spoke cavity, RF ampli., RFQ mock-up, CH-DTL cavities
- Reliability model
- Design Review

MYRRHA PHASE 1 (100 MeV)
Construction & Commissioning of the first Accelerator section -> 100 MeV



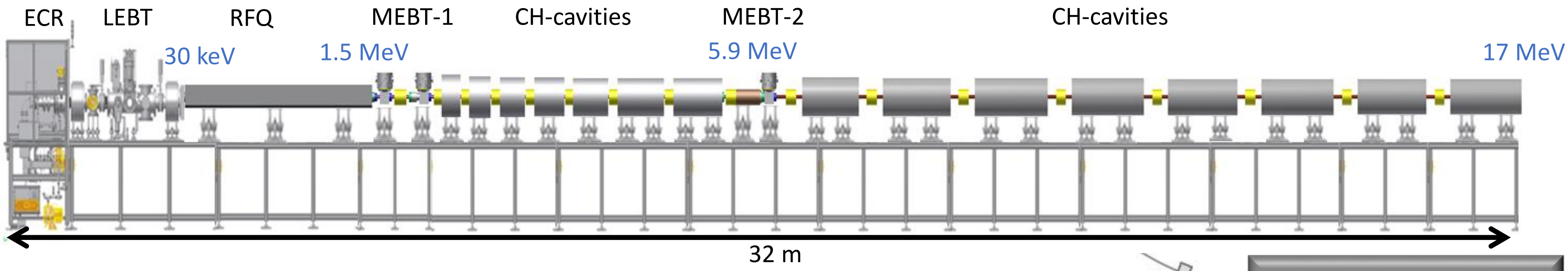
CDT (FP7) – HEBT design

MARISA (FP7)
LEBT construction – 176 MHz RF amplifier–

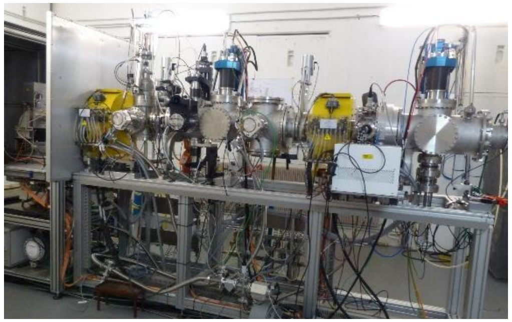
MYRTE (H2020)

- Injector construction & commissioning
- Beam Characterisation & Control
- SRF cavities (spoke Cryomodule – CH)
- Reliability & specific R&D

MYRRHA Linac injector

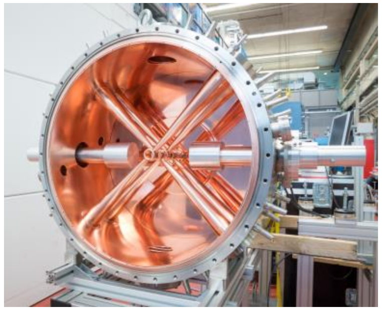


Courtesy of H. Podlech



Source & LEBT

176.1 MHz 4-Rod RFQ



RT CH-DTL Prototype

TUPVA062 : *Construction of the MYRRHA Injector*, D. Mäder et al.
TUPVA068 : *The New Injector Design for MYRRHA*, K. Kümpel et al.

THPVA006 : *Space-Charge Compensation in the Transition Area Between LEBT and RFQ*, P. Schneider et al.

TUPVA070 : *Dipole Compensation of the 176 MHz MYRRHA RFQ*, K. Kümpel et al.

TUPVA071 : *The MYRRHA RFQ: Status and First Measurements*, H. Podlech et al.

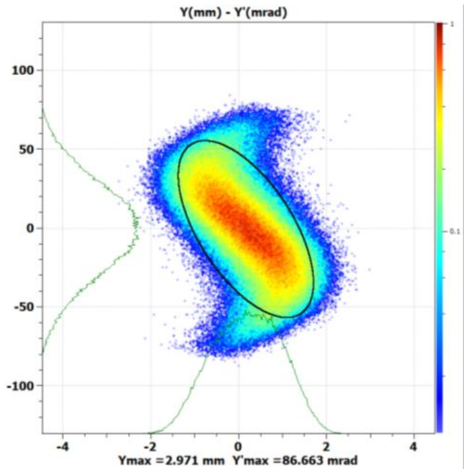
TUPVA069 : *Test of a High Power Room Temperature CH DTL Cavity*, N. F. Petry et al.

LEBT Functions

- The Low Energy Beam Transfer line (LEBT) is the first 3 meters of the MYRRHA accelerator

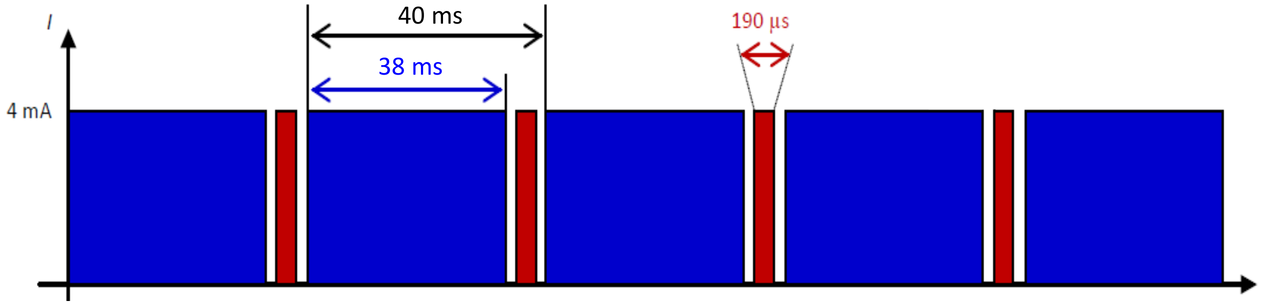
- Ensure the 'safe' beam transport from the source to the RFQ :
  - Minimise the beam losses → Increased Reliability

- Condition the beam for the RFQ
  - Required parameters at the RFQ entrance : $\varepsilon_{RMS.norm.proton} \leq 0.2\ \pi.mm.mrad$
    $\beta = 0.04\ mm/\pi.mrad$ & $\alpha = 0.88$



- 'Clean' the proton beam from other species (H_2^+,H_3^+)
  - The Ion source produces protons but also H_2^+,H_3^+ (ionisation of H_2 gas)

- Give/Create the temporal beam time structure ('holes' / pseudo-pulsed beam / power mitigation)



Proposed MYRRHA beam time structure for operation:

-> long blue pulses are sent to the reactor (mean power is adjusting with pulse length)

-> short red ones are sent to ISOL experiment

MYRRHA LEBT Design and Construction

- Design, Construction & Commissioning funded by EU projects (MAX, MARISA, MYRTE) and SCK-CEN

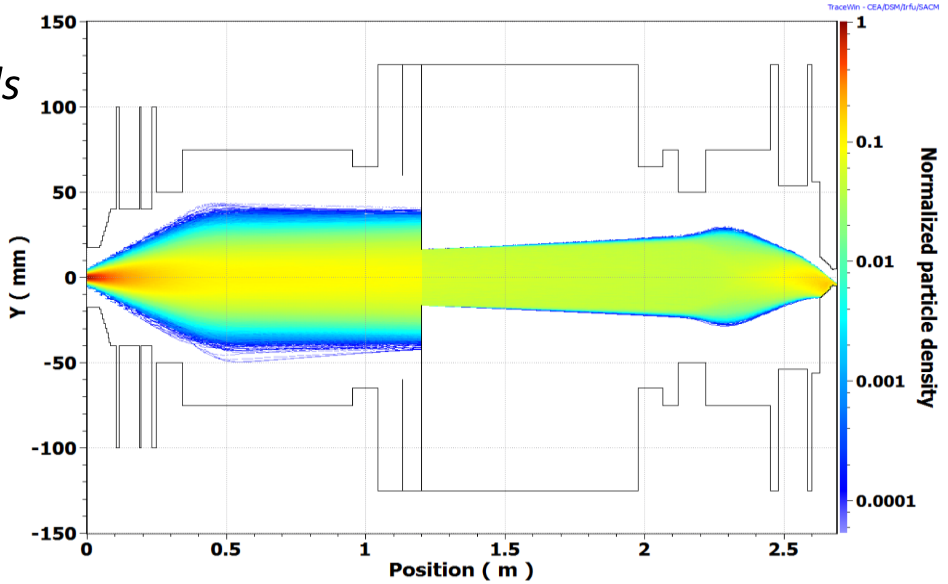
- Collaboration :
  - **LPSC (CNRS)** : solenoid design, collimation , vacuum chamber, experimental area, part of the control system,…
  - **SCK-CEN** : Chopper + collimation cone, …
  - **Cosylab (+ADEX)** : Specific control system developments

TUPAB092 : *MYRRHA Control System Development*, R. Modic et al.

- *Compact design : ~ 3 meters long with two solenoids*

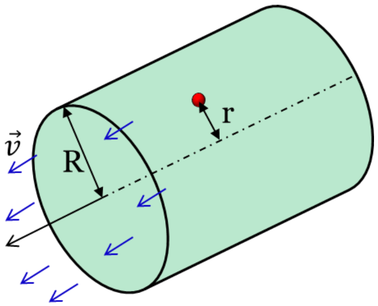
👍 A minimum of elements/magnet to tune (Reliability)
👍 Simple design (Reliability)
👍 Minimise the number of electrostatic elements (Reliability)
👍 Shorter Space Charge Compensation transients than in a longer version
👎 No 'clean' ions separation to ensure a direct proton current monitoring

J-L Biarrotte, MAX technical note + Deliverable 1.2



Beam dynamics : Space Charge & Compensation

- Defocusing effect : Coulomb repulsion of charged particles inside the beam
- 2 contributions (Lorentz):
  - ◆ Electrostatic : repelling Force
  - ◆ Magnetic : attractive Force (charged particles in movement)

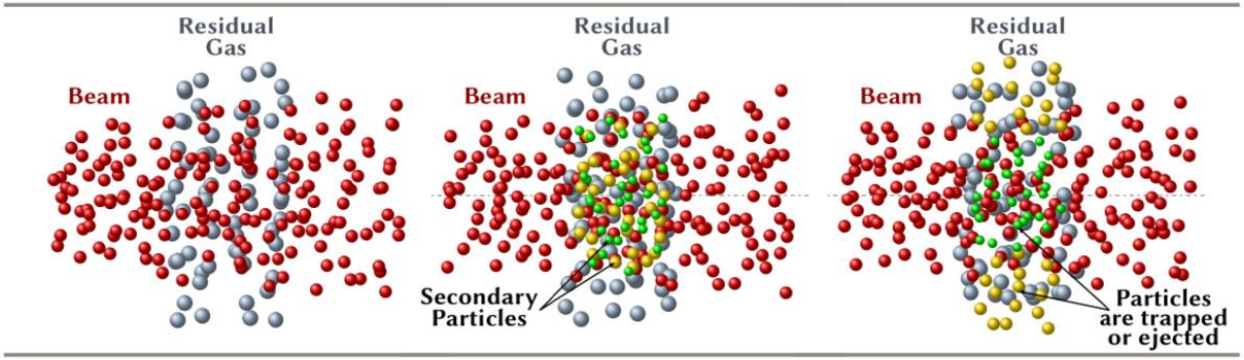


Radial force seen by one particle of a continuous (DC) cylindrical and homogenous beam

$$F_r = \frac{(1-{\beta_L}^2)}{\beta_L}\frac{qI}{2\pi\,\varepsilon_0\,c}\cdot\frac{r}{R^2}\ (\mathrm{r} < \mathrm{R})$$

β_L : *reduced speed*
ε_0 : vacuum permittivity
q : *charge*
I : beam current

- **Complex phenomena, difficult to model, depends on many parameters :** influence of the vacuum chamber walls, beam transverse and longitudinal distribution, different species/ions, residual gas interaction, etc.

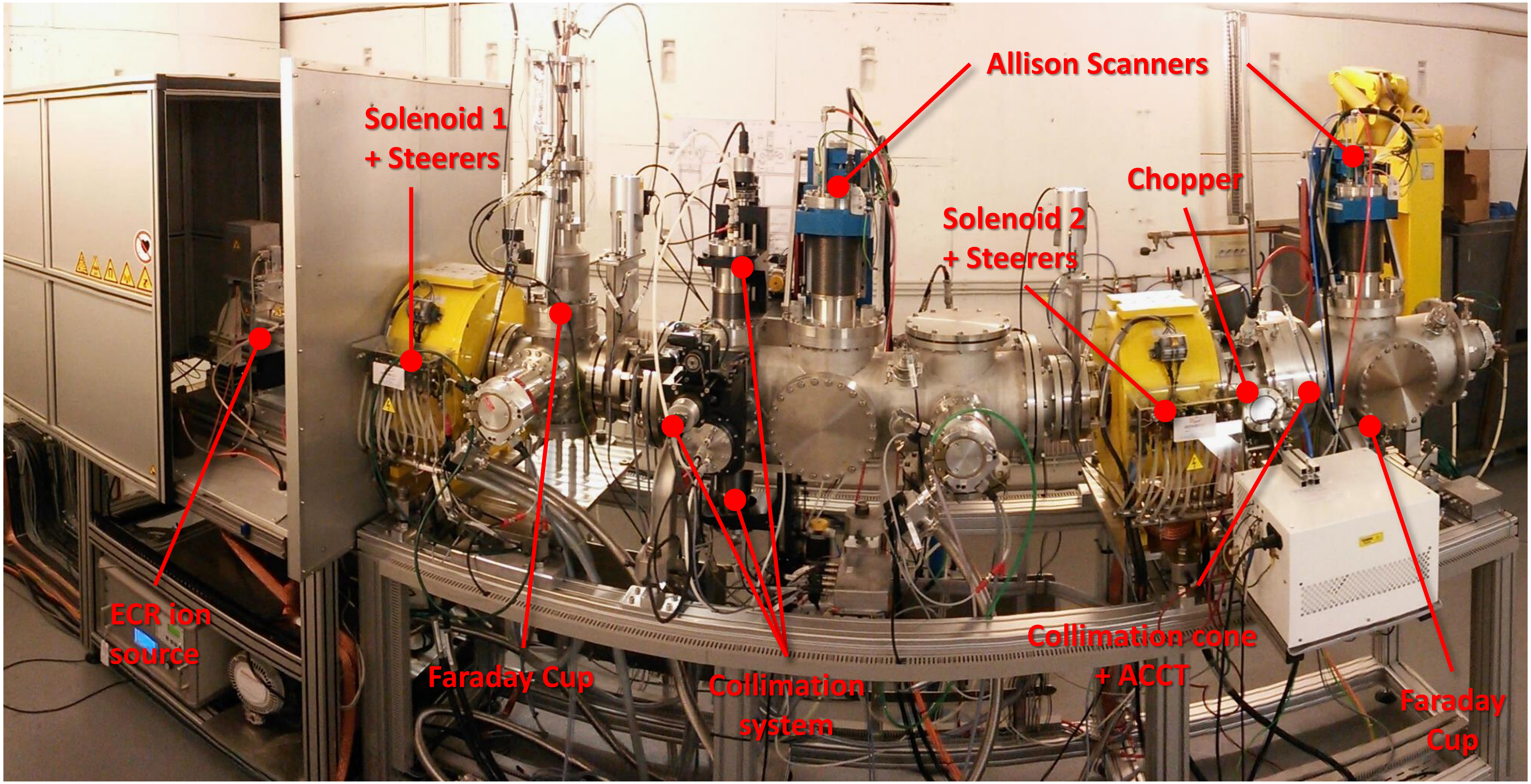


Courtesy of N. Chauvin

- A solution to compensate the beam diverging effect in the LEBT :

→ Use the Ionisation of the residual gas in the vacuum chamber.

The LEBT installed at LPSC Grenoble



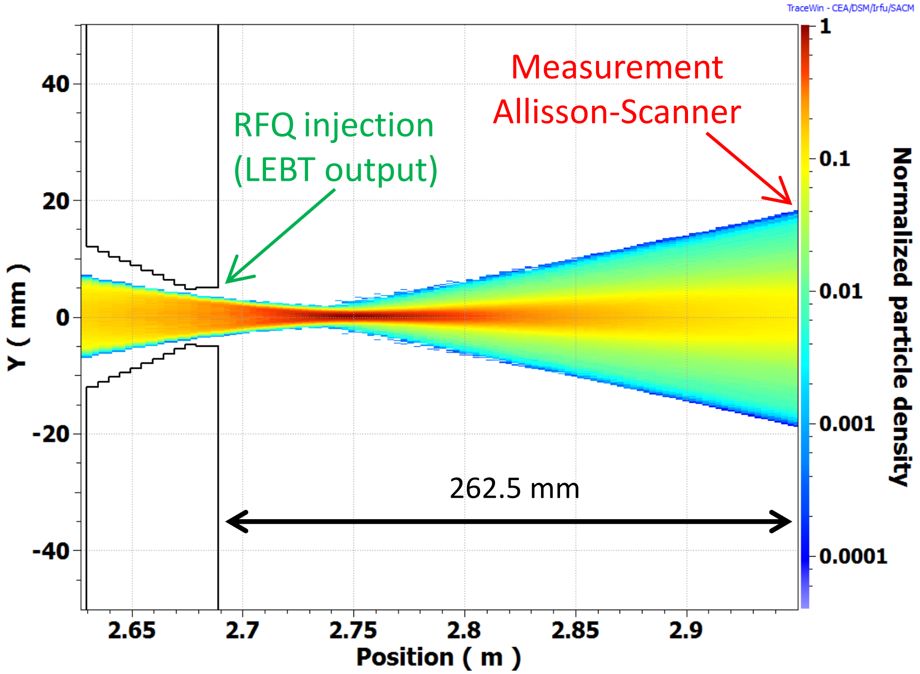
LEBT tuning

- **Goal : tune the solenoids & steerers settings to optimise the transmission through the LEBT and to match the beam into the RFQ**

- **Solenoid scan on the beam transmission**

➢**I$_{\text{source}}$ set at 9 mA**, hard to regulate below this value (dropout in an other plasma mode)

➢ Beam current & Twiss parameters measured 26.2 cm after the hole of the collimation cone (FC + Allisson scanner)



➢ Estimation of the beam parameters to be expected at the Emittance-meter location with TraceWin (SCC comp. : ~ 85% , $\varepsilon_{\text{RMS.norm.proton}}$ = 0.1 mm.mrad)

Requirement at RFQ input

-> β =0.04 mm/mrad & α = 0.88

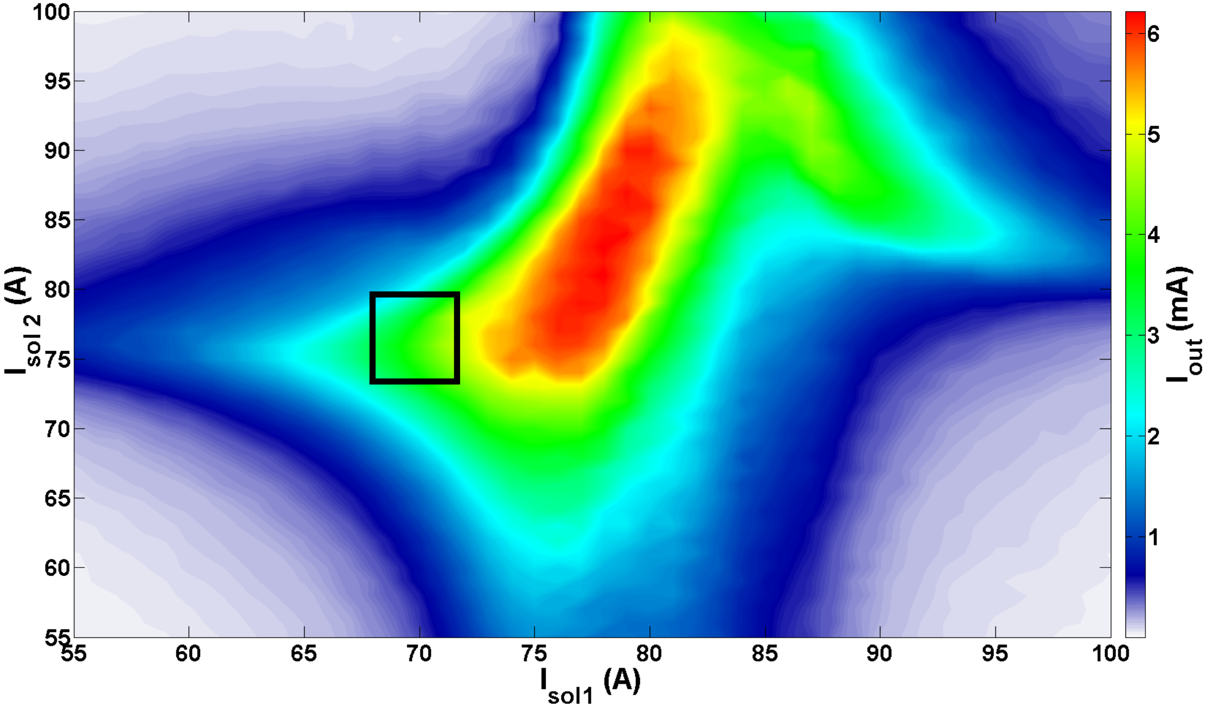
Estimation : 262.5 mm after the RFQ injection hole

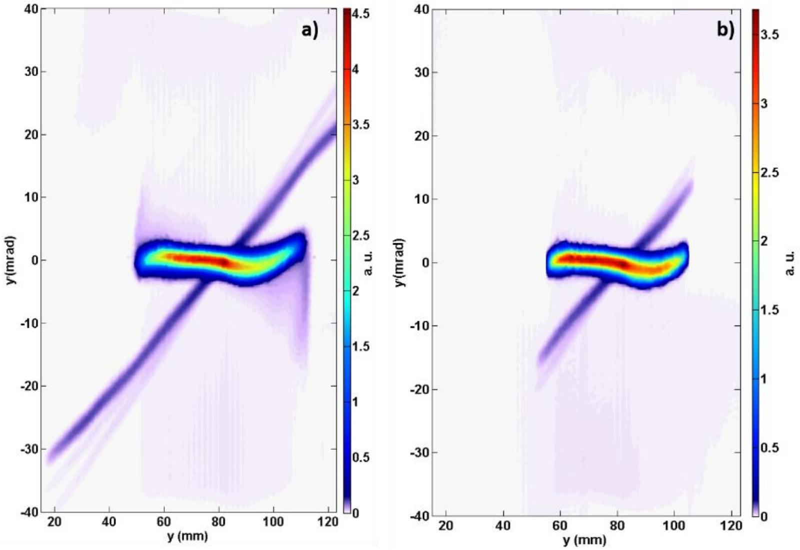
-> β ~ 2.9 mm/mrad & α ~ -12.5

Transmission map : Tuned LEBT

- I_{source} = 9 mA
- P = 7 10^{-6} mbar

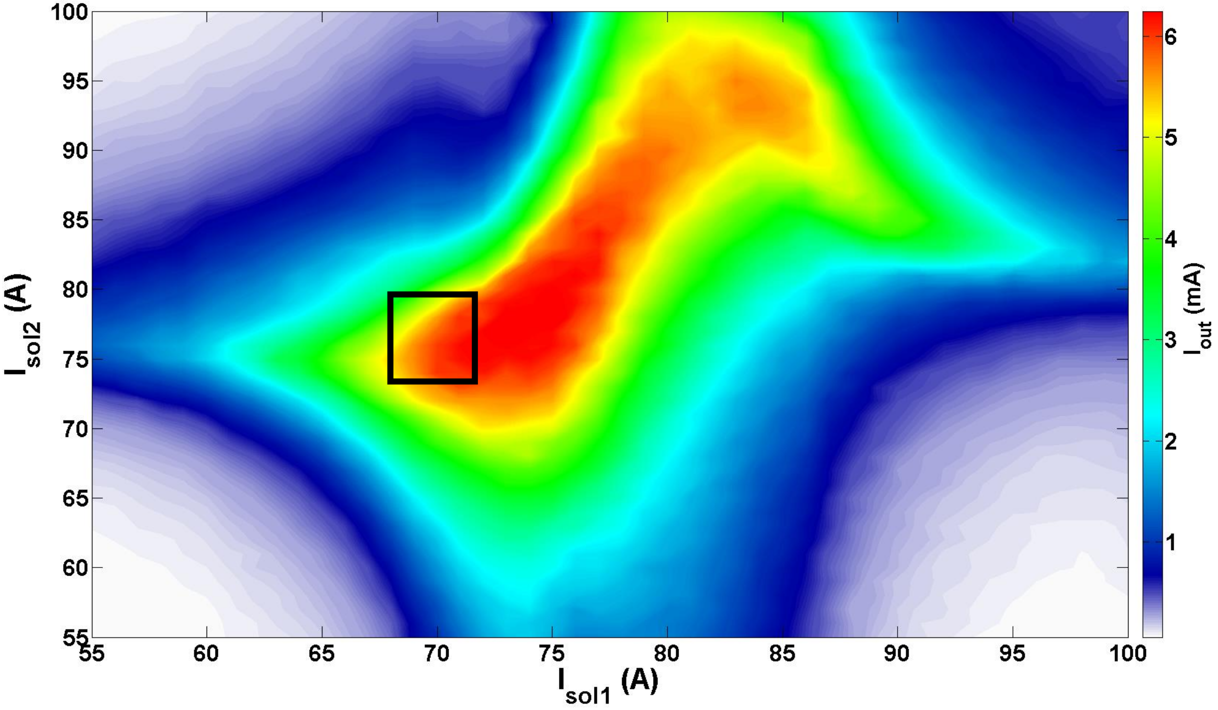
- Collimator aperture : 48 mm
- Steerers settings inside solenoid 2 :
  - $I_{steererH}$ = -0.5 A
  - $I_{steererV}$ = 2 A





a) No collimation
b) With collimation

Transmission map : Tuned LEBT + Kr injection



- I_{source} = 9 mA
- **P = 2.4 10^{-5} mbar (Kr injection)**

- Collimator aperture : 48 mm
- Steerers settings inside solenoid 2 :
  - ➢ $I_{steererH}$ = -0.5 A
  - ➢ $I_{steererV}$ = 2 A

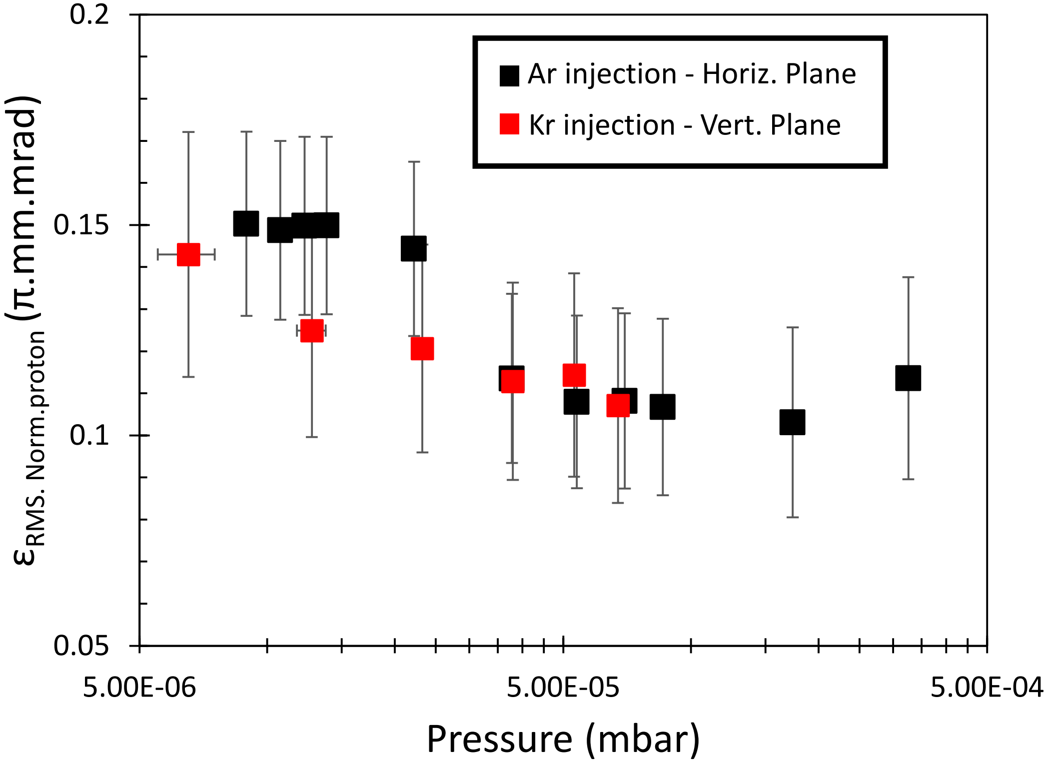
➢ Gas injection (pressure, type) has an effect on the transmission in steady state and therefore on the space charge neutralisation

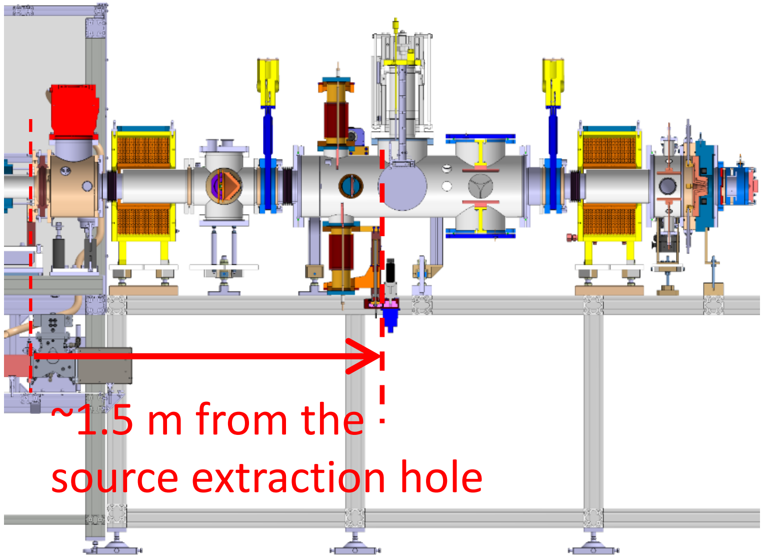
➢ Already observed on several experiements :

_ R. Hollinger et. al. , “High current proton beam investigation at the SILHI-LEBT at CEA Saclay ”, TU3001, Proceedings of LINAC2006 , Knoxville, Tennessee, USA,2006
_ D. Winklehner, D. Leitner, "A space charge compensation model for positive DC ion beams." Journal of Instrumentation 10.10 (2015): T10006.
_ R. Ferdinand et al. , “Space-charge neutralization measurement of a 75 keV, 130 mA hydrogen-ion beam”, Proceedings of PAC’97, Vancouver, B.C., Canada,1997

Space charge compensation

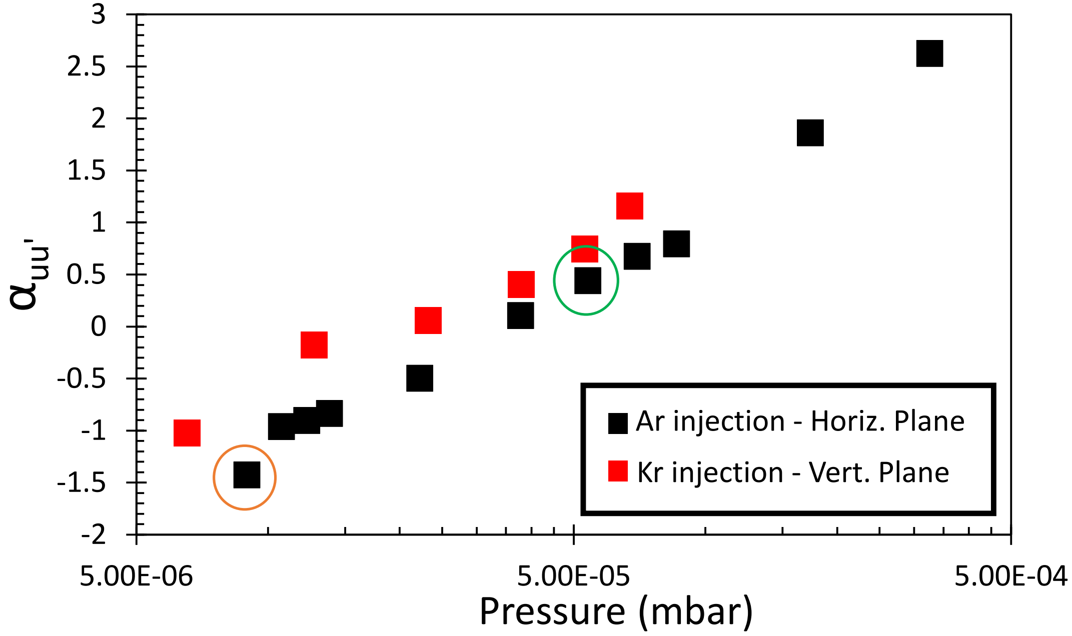
- Evolution of the Emittance in the middle of the LEBT as function of the gas pressure
  - the focussing strength of the solenoid is kept constant (I_{sol}=69A)
  - Argon or Krypton gas injected
  - The beam current is kept constant at the emittance measurement location : $I_{proton} \approx 8.5$ mA





- In steady state we observed that the emittance decreases while residual gas pressure is increased

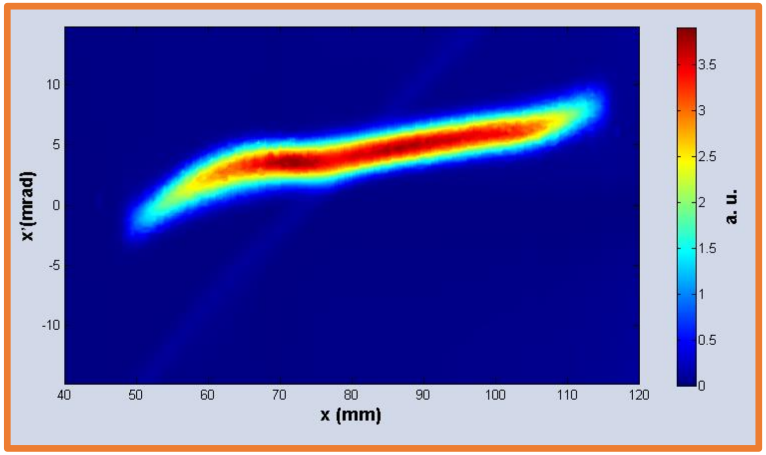
Space charge compensation



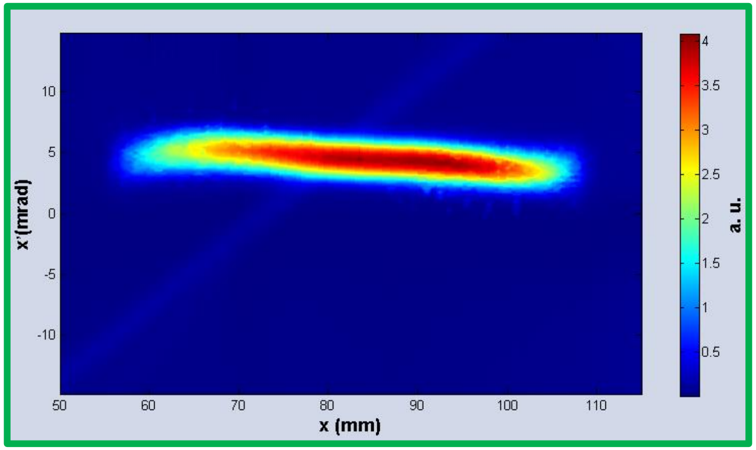
- For a given focussing strength of the solenoid :

→ the beam divergence is changing with the gas pressure

P = 9.2 10^{-6} mbar

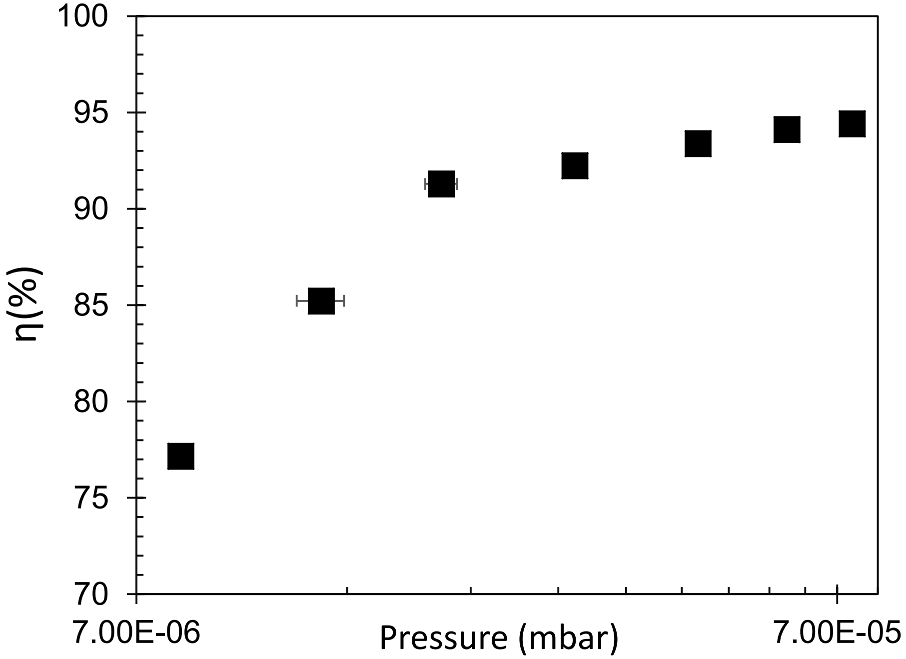


P =5.4 10^{-5} mbar

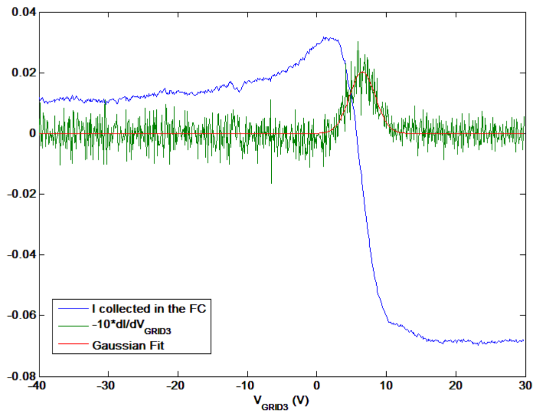


Space charge compensation degree

- Measurement of the space charge neutralisation degree with Kr injection: $\eta = 1 - \frac{\phi_c}{\phi_0}$



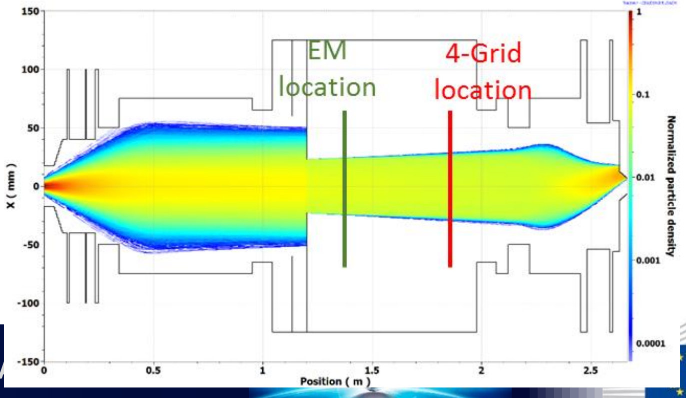
- Careful – several assumptions :
  - 4-grid analyser (low and noisy signal)



  - Beam distribution assumed Gaussian

$$\phi(0) = \frac{I}{4\pi\varepsilon_0\, \beta c\left(1 - e^{-r_b^2/2.\sigma_b^2}\right)} \left[-\frac{\ln\left(2.\sigma_b^2\right)}{2} - \frac{1}{2}\ln\left(\frac{r_b^2}{2.\sigma_b^2}\right) + \frac{1}{2}\sum_{k=1}^{+\infty}\frac{(-1)^{k+1}\ \left(-r_b^2/2.\sigma_b^2\right)}{k.k!} + \left(1 - e^{-r_b^2/2.\sigma_b^2}\right).ln\left(\frac{r_{vac.chamb}}{r_b}\right) + \ln(r_b)\right]$$

  - Beam radius calculated from emittance measurements



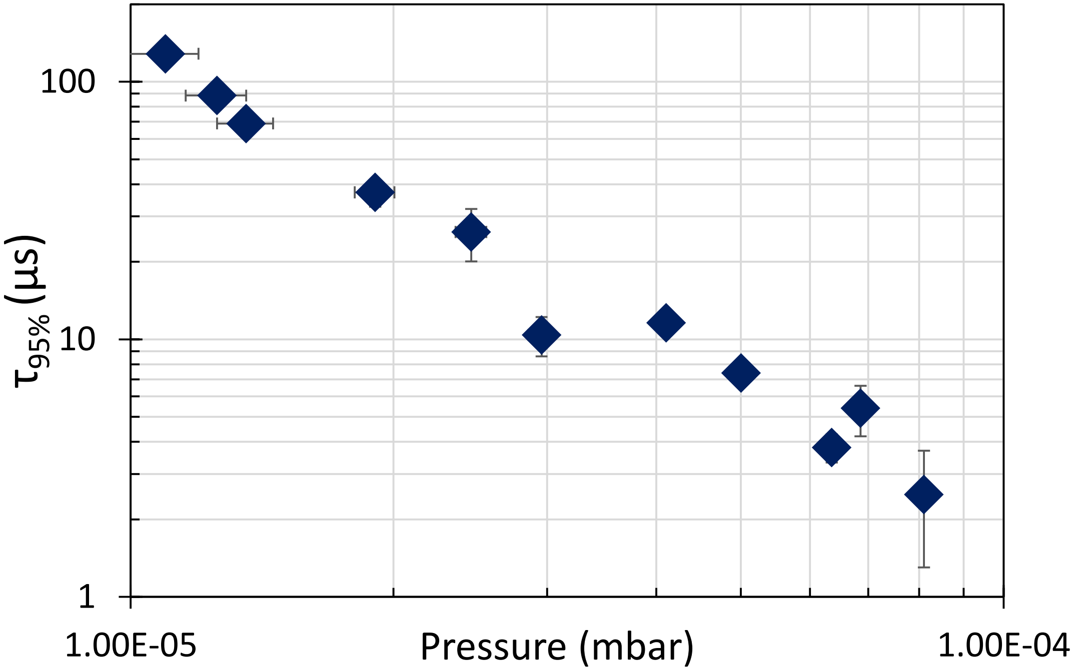
Chopper & SCC Transients

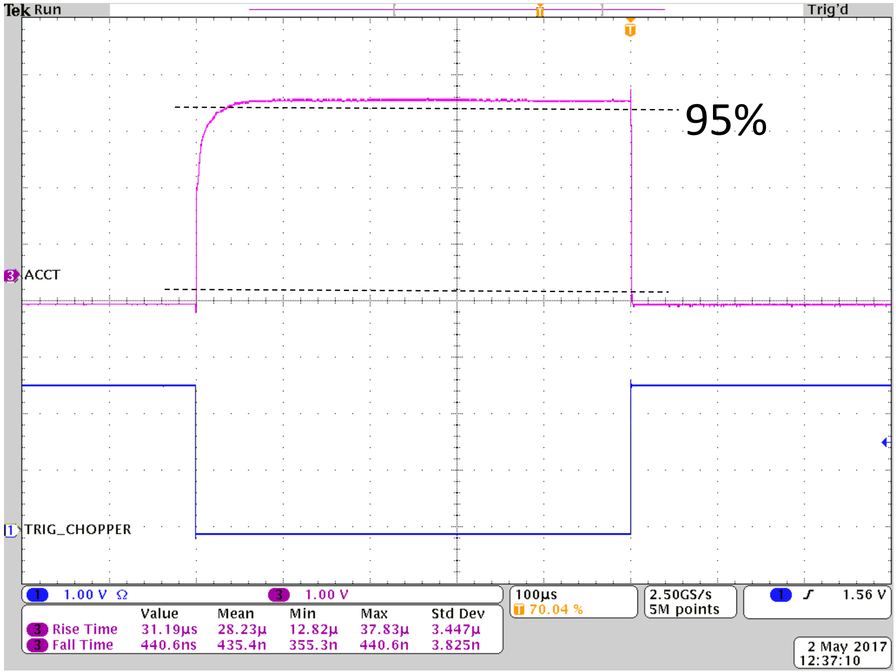
- Space charge compensation time measured as function of the pressure (Kr injection)

➢ Beam current measured with the ACCT in the final collimation cone

➢ $\tau_{95\%}$: time to reach 95 % of the maximum value

➢ Chopper rise time : ~400 ns



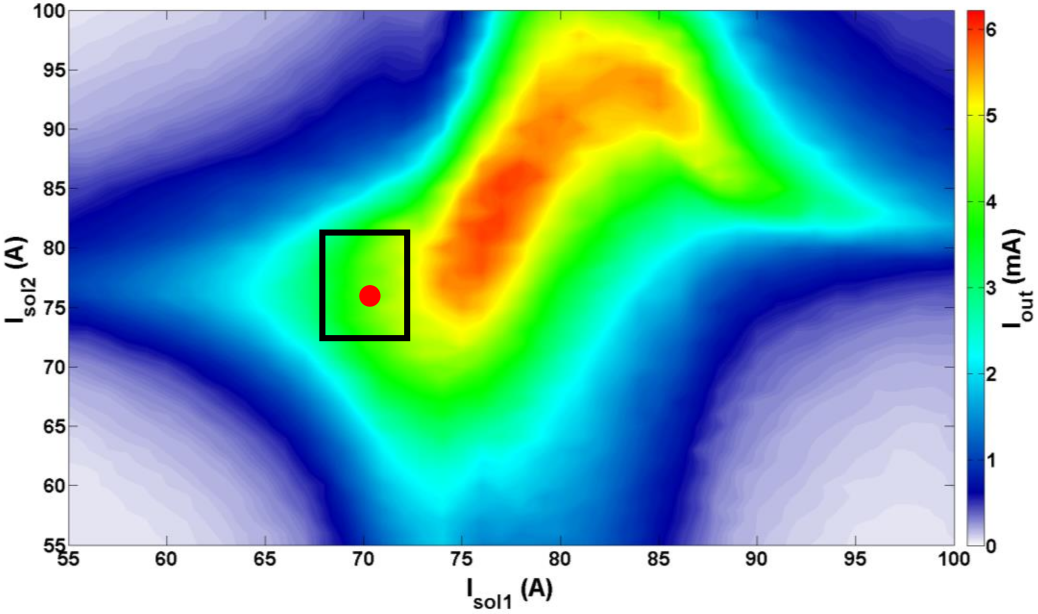


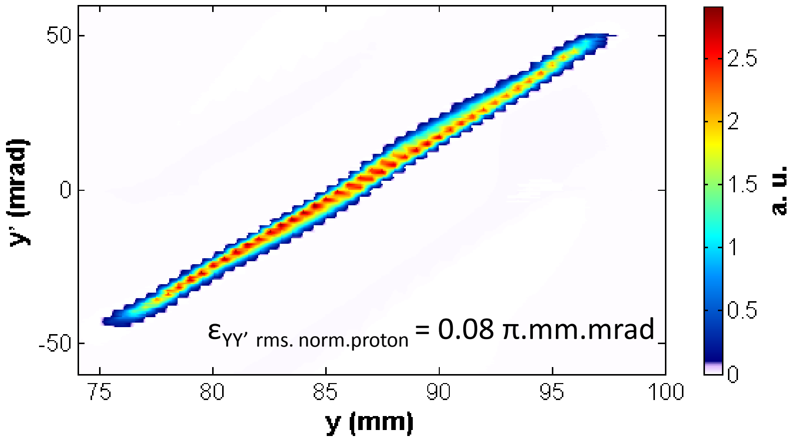
	Value	Mean	Min	Max	Std Dev
3 Rise Time	31.19µs	28.23µ	12.82µ	37.83µ	3.447µ
3 Fall Time	440.6ns	435.4n	355.3n	440.6n	3.825n

500 µs macro-pulse

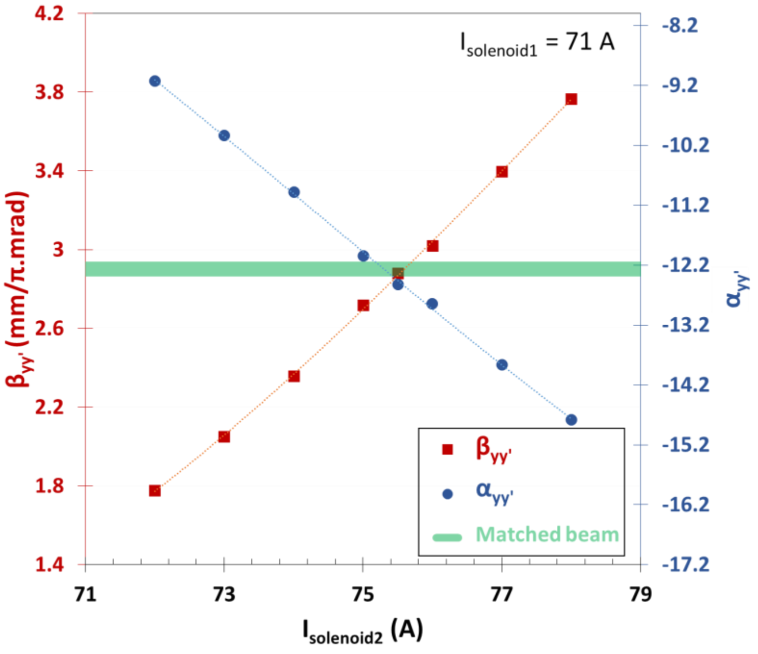
LEBT final tuning

- I_{source} = 9 mA
- **P = 2.4 10^{-5} mbar (Kr injection)**
- **Collimator aperture : 37 mm**
  - ➢ I_{out} = 4.5 mA
- Steerers settings inside solenoid 2 :
  - ➢ $I_{steererH}$ = -0.5 A
  - ➢ $I_{steererV}$ = 2 A





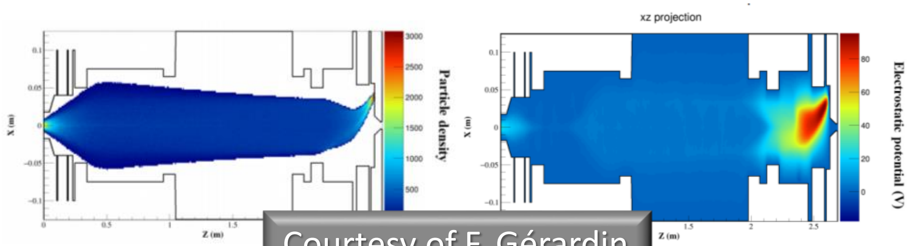
$\varepsilon_{YY'\ rms.\ norm.proton}$ = 0.08 π.mm.mrad



CONCLUSIONS & Future work

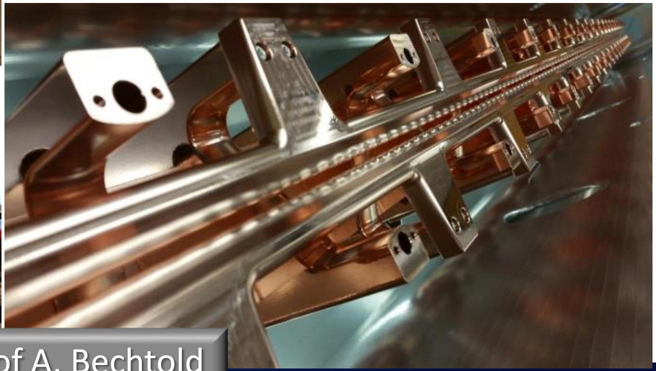
- The MYRRHA LEBT is fully commissioned
  - ➢ Effect of gas on Space charge compensation experimentally measured
  - ➢ Tuned to provide the right beam parameters (Twiss, emittance) at RFQ input

- Analysis of experimental data for SCC studies in progress
  - ➢ Model development With WARP for a better understanding of the Physical process of SCC in the LEBT
    - - As studied for example on **LINAC4** ***C. A. Valerio-Lizarraga et al., Phy.Rev. ST Accelerator & beams, 2015***
    - - Assess the effect of Emittance-meter on measurement accuracy
    - - **Phd thesis of Frédéric Gérardin at CEA Saclay**
  - ➢ To anticipate on the future re-tuning & operation



Courtesy of F. Gérardin

- Next step : LEBT will be moved to Louvain-la-Neuve for RFQ and injector commissioning (2018)



Courtesy of A. Bechtold

Thank you to

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Thank You for your Attention