IFMIF-LIPAc diagnostics and its challenges

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Overview

IFMIF, LIPAc: a brief introduction

Injector overview

- Allison scanner for emittance

Diagnostics at “high” energy (downstream RFQ)

- Radiation background
- Profilers: IPM & FPM
- Losses: BLoM & μLoM
- BPMs
- Slits

Summary

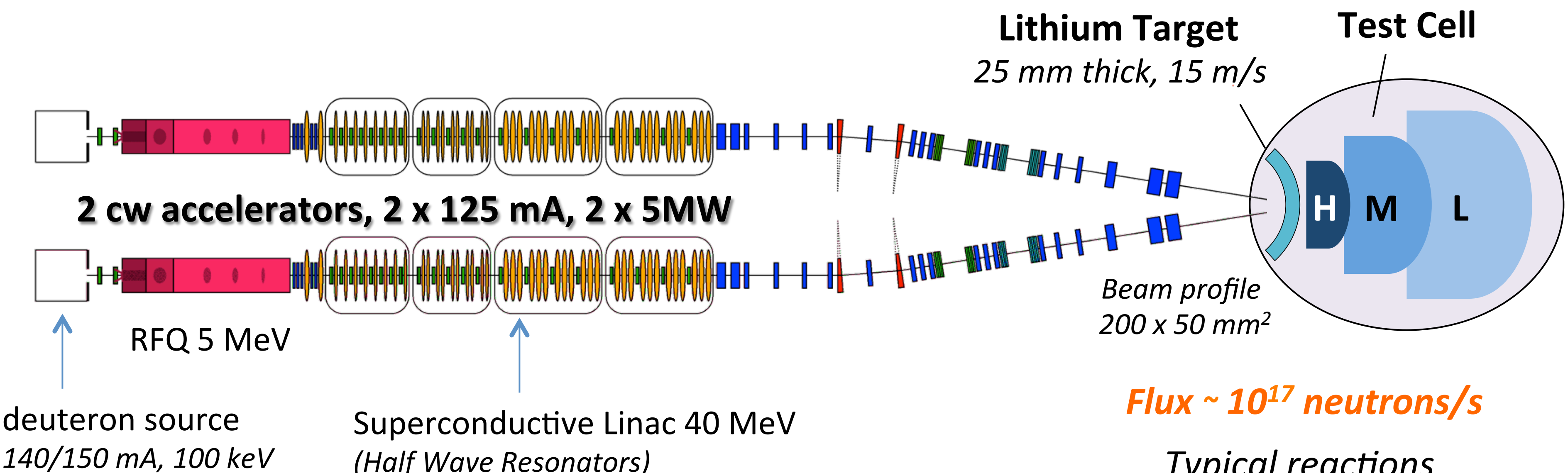
IFMIF

(International Fusion Materials Irradiation Facility)

International agreement of the **BA** (JAEA+F4E in Feb. 2007)
= IFMIF + IFERC + JT60-SA

IFMIF* : to test materials submitted to very high neutron fluxes for future **Fusion** Reactors.

High	> 20 dpa/y	0.5 l
Medium	> 1 dpa/y	6 l
Low	1 dpa/y	> 8 l



Flux ~ 10^{17} neutrons/s

Typical reactions

$^{7}Li(d,2n)^{7}Be$

$^{6}Li(d,n)^{7}Be$

$^{6}Li(n,T)^{4}He$

LIPAc

(Linear IFMIF Prototype Accelerator)

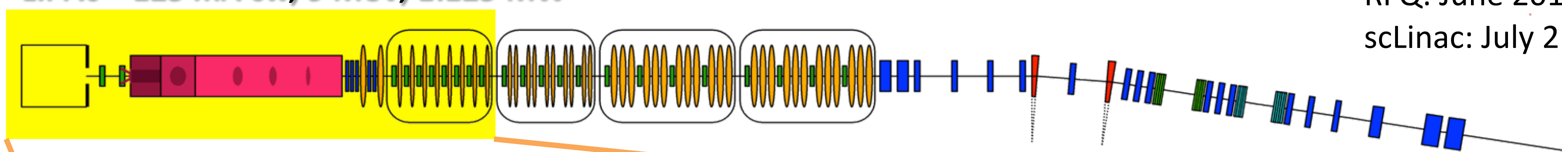
Validation phase:

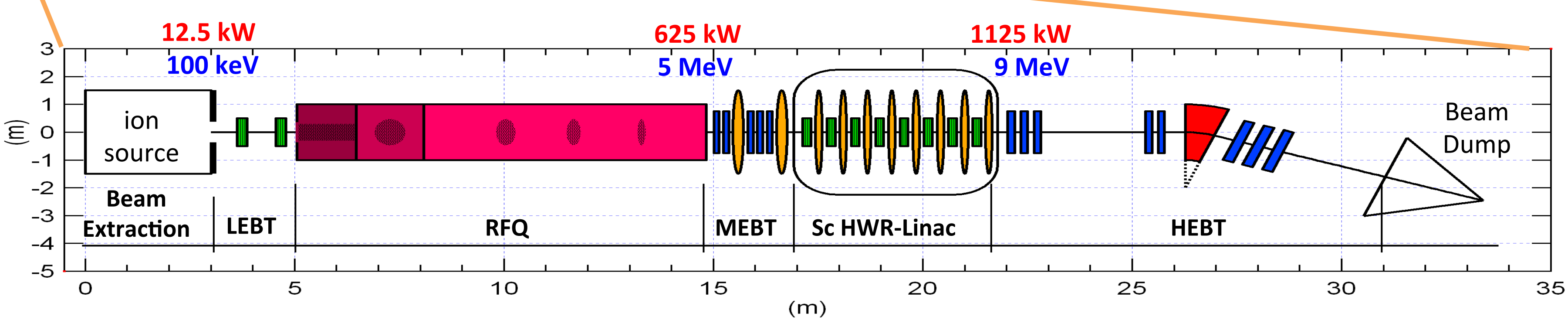
prototype accelerator → LIPAc (Rokkasho – Japan)

Commissioning at Rokkasho beginning:

Injector: March 2013
RFQ: June 2015
scLinac: July 216

LIPAc = 125 mA cw, 9 MeV, 1.125 MW

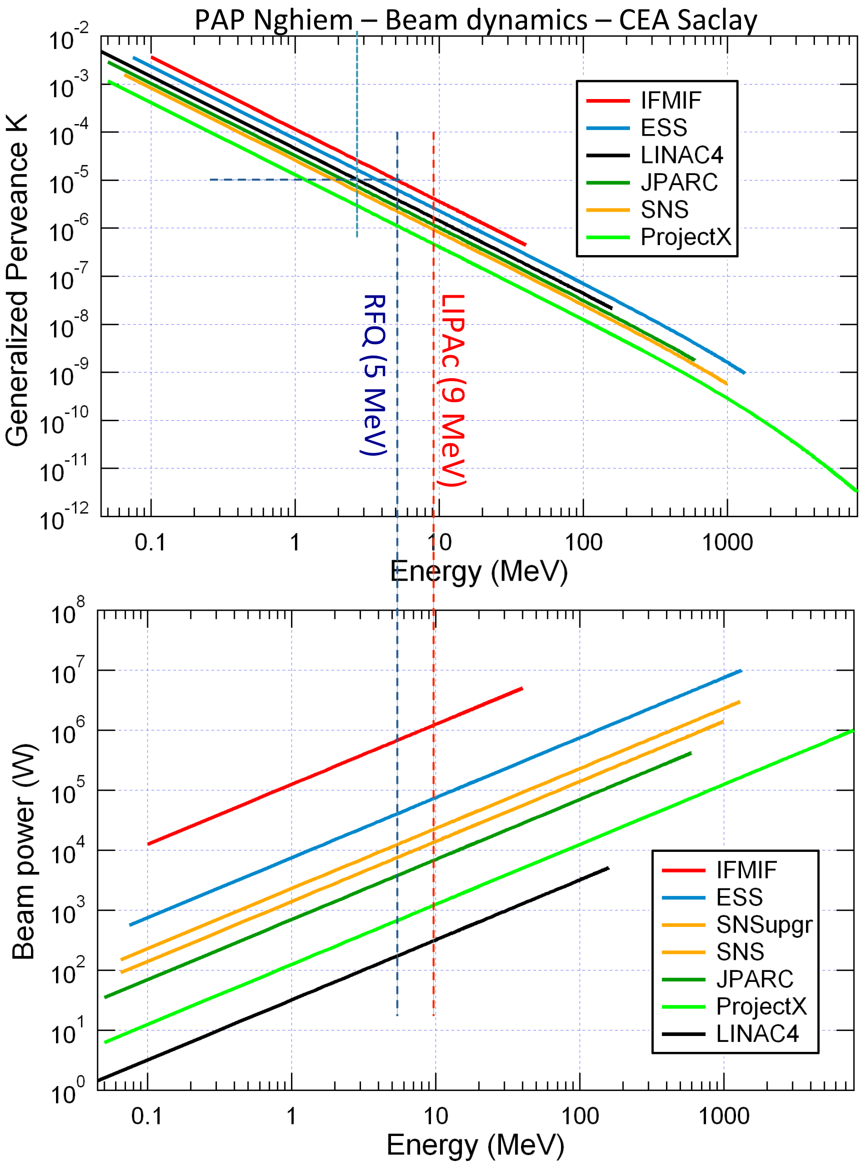




LEBT / **MEBT** / **HEBT** = **L**ow / **M**edium / **H**igh **E**nergy **B**eam **T**ransport
RFQ = **R**adio **F**requency **Q**uadruple

1.125 MW ≡ ability for the Beam Dump to evacuate the whole energy of the LHC beams every 11 minutes!

Challenges



highest intensity (125 mA cw)

highest beam power

highest space charge

⇓

↑ RFQ length to ↓ SC
for beam injection in the SRF Linac

⇓

longest RFQ (0.1 to 5 MeV)
~ 10 m

⇓

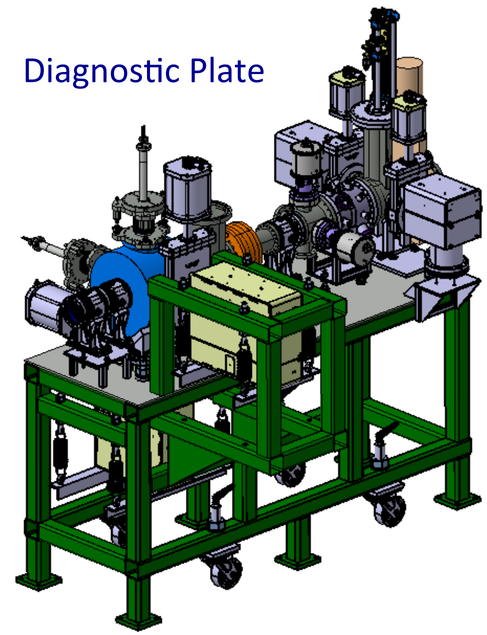
Validation Phase: LIPAc

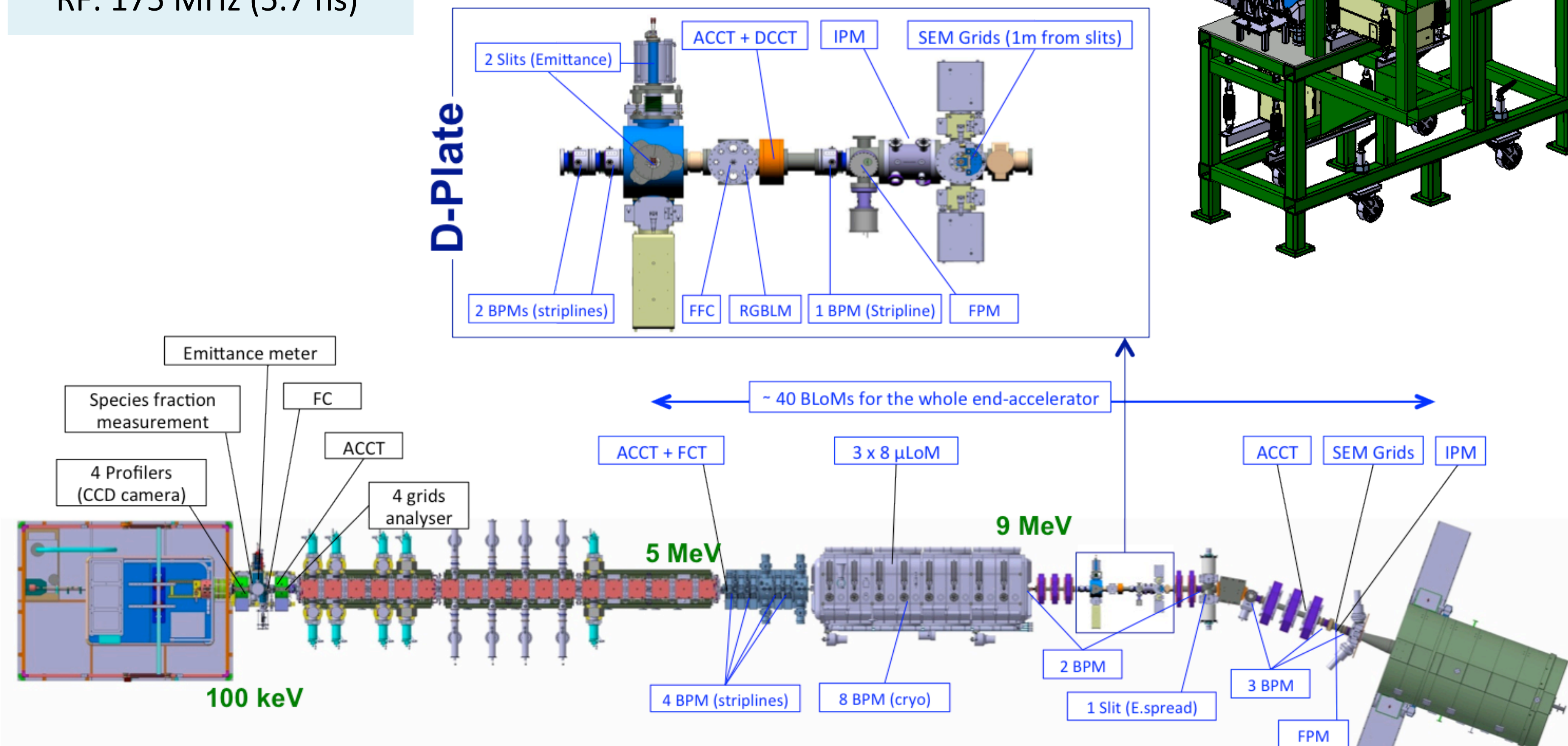
LIPAc Beam Instrumentation Layout

deuteron beam:

E_{max} = 9 MeV
I = 125 mA
P_{max} = 1.125 MW
Duty Cycle: <10^{-4} to cw
RF: 175 MHz (5.7 ns)

Diagnostic Plate





Injector

Injector challenges (0 to 100 keV)

E_{max} = 100 keV & I ~ 150 mA

High Space Charge: shorten the LEBT* length for minimizing emittance growth
⇒ lack of space

- ➜ Limited number of diagnostics: only 1 diagnostic box shared with pumping…
- ➜ not enough room for DCCT: no RFQ transmission measured in cw mode.

Low energy (100 keV):

Cons:

- High space charge to be overcome with Kr injection (few 10^{-5} Torr)
  → enlarge the beam diameter (few cm)
- Numerous secondary electrons → non uniformity of charge compensation

Pro:

- High interaction with residual gas → intensely emitted light (but important reflection on the walls)

High intensity (150 mA):

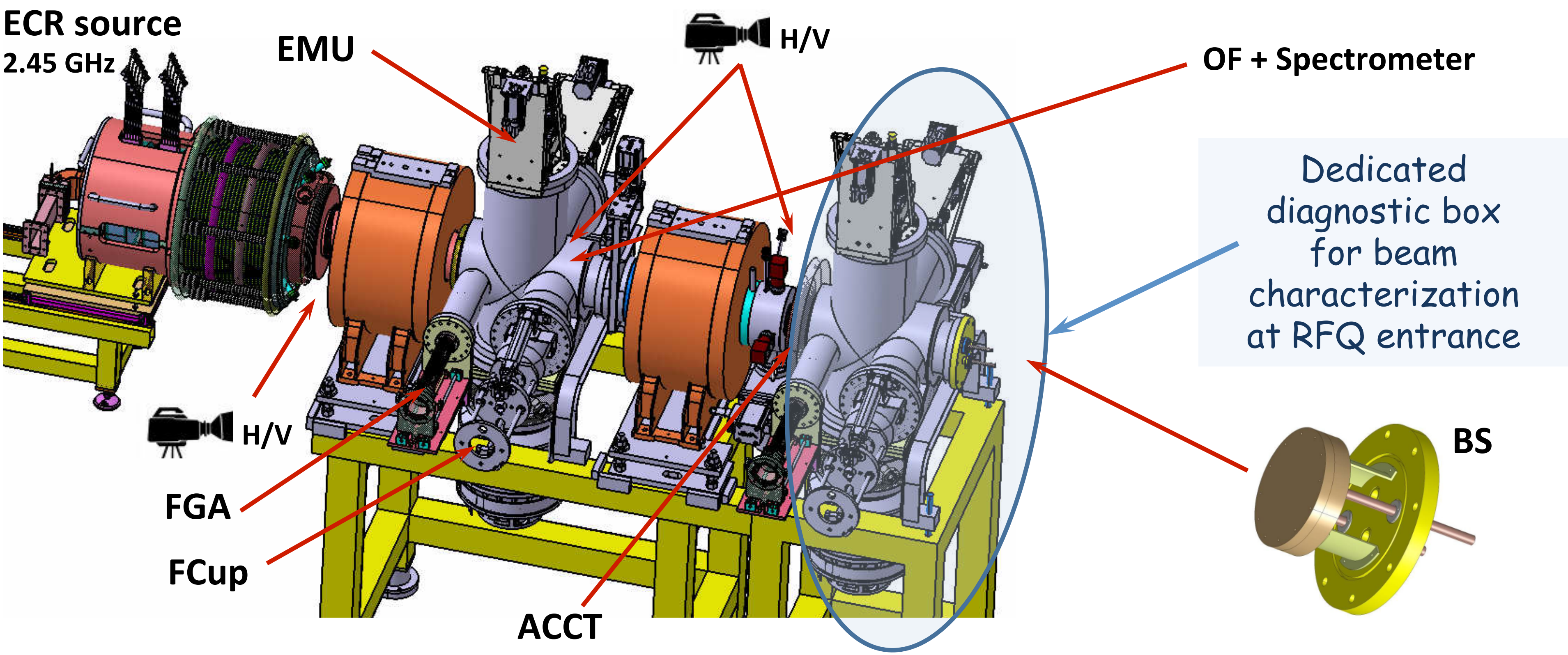
→ 15 kW continuous beam → important water cooling

*LEBT: Low Energy Beam Transport

LEBT diagnostics

- Particle loss: thermocouples on electrodes
- Space charge analysis: 1 FGA (4 Grid Analyzer)
- Beam current:
  - 1 ACCT (at RFQ entrance -> transmission)
  - 1 "Faraday Cup", Beam Stopper
  - → Calorimetric measurements (FC, BS and Cone)
- Emittance (Allison): 4 positions for 1 Emittancemeter EMU
- Transverse beam profiles (fluorescence): 6 CID cameras
- Beam purity species: 1 deported spectrometer with optic fiber

Note: a beam chopper will be installed between the 2 solenoids → adding a new apparatus!



Emittance: Allison scanner

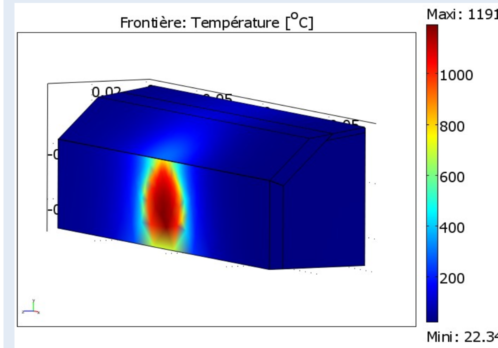
cw mode → 15 kW (Max)

Emittance measurement made on LIPAc injector (CEA Saclay, 08/2012)

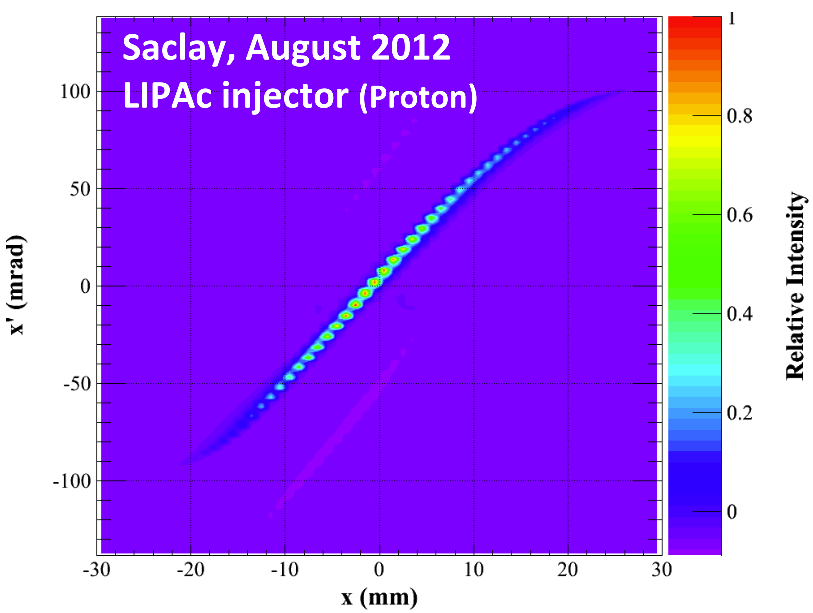
- with a proton beam to avoid injector activation
- E_p = 50 keV and $I_B/2$ (to keep SC constant)

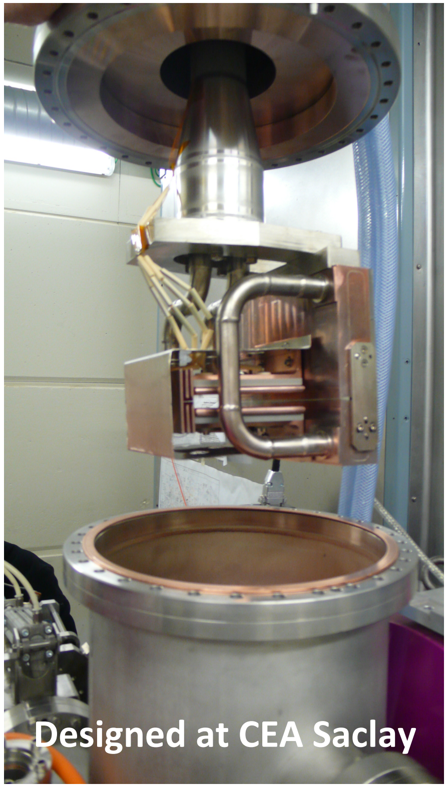
⇒ $\varepsilon_x = 0.29\ \pi$.mm.mrad

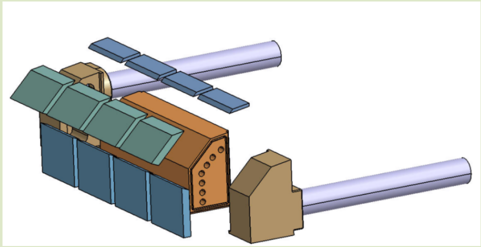
RFQ acceptance $\varepsilon_{x,y} = 0.30\ \pi$.mm.mrad (0.25 specification)



- Thermal simulation (COMSOL)
- Critical case: T_{max}=1191 °C on W surface







- Cu block covered by W tiles
- Internal water cooling system
- Brazing technique for Cu/W assembly

Diagnostics downstream the RFQ 5 to 9 MeV

Challenges at 5 to 9 MeV energy

High Space Charge ⇒ compact design

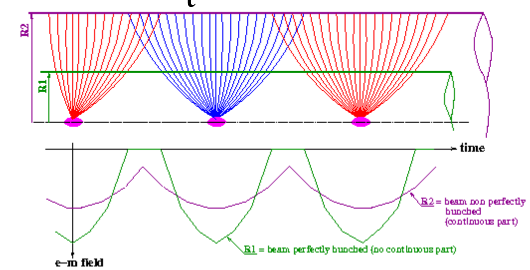
➞ reduce available space for diagnostics (i.e. no DCCT in the MEBT)

Low energy:

Cons:

- Low β effect (β<0.1)
  - ➝ bunch overlapping ("de-bunching") effect
  - ➝ challenging for BPMs, FCT…
- superficial deposition (short penetration and small beam size)
  - ➝ slits, SEM grid, Faraday cup…
  - ➝ **fast chopper for interceptive needed**
- beam particle stopped in beam pipe (D {9MeV} ⇒ 140 μm Fe)
  - ➝ only neutral secondaries (γ, n) ➝ beam losses

$$\sigma_t \approx R/\sqrt{2}\beta\gamma c$$



Pro:

- "high" ionization & fluorescence processes
  - ➝ good for profilers based on beam – residual gas interaction

High intensity (125 mA cw):

- high power deposition (interceptive diagnostics very challenging)
- beam losses for MPS are crucial (10 μs)
- huge space charge effects ➝ IPM
- huge amount of radiation background (~ 7 kSv/h on IPM close to the BD)

but, good S/N ratio for BPMs

MEBT/HEBT:
Medium/High Energy
Beam Transport

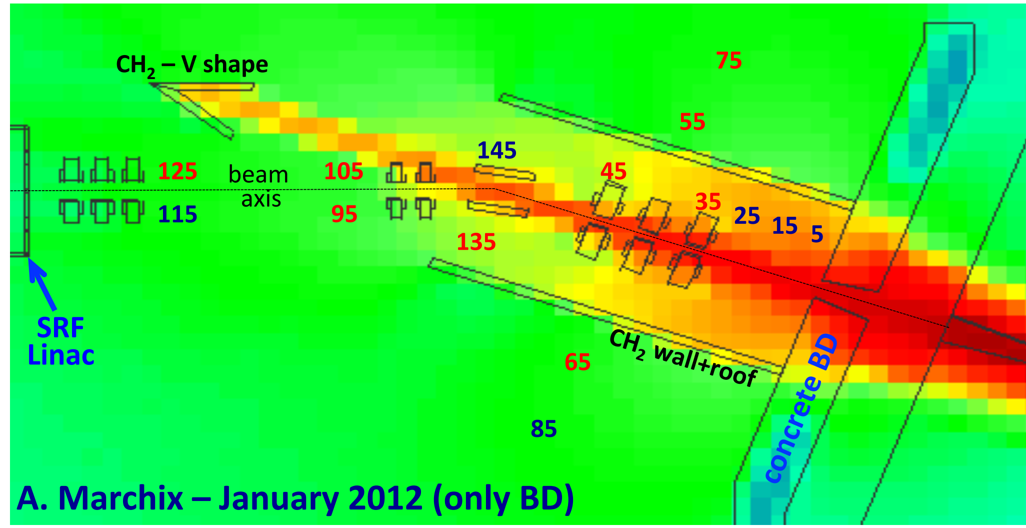
Radiation background

Shielding (polyethylene disks, plates…)

➟ neutrons

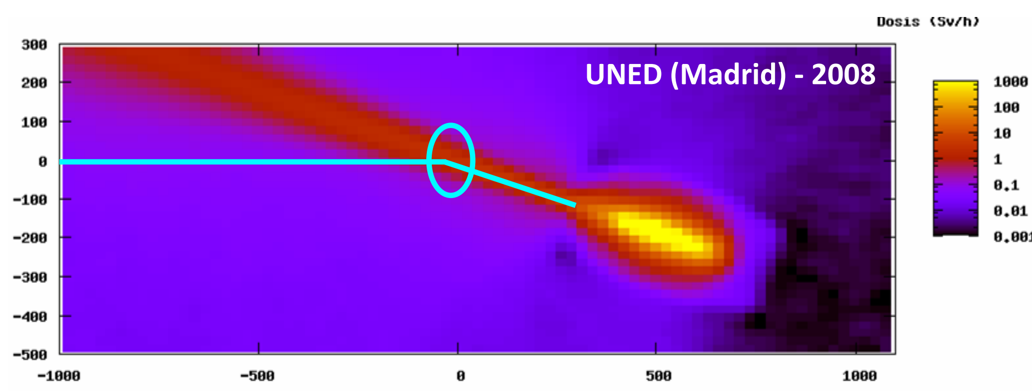
Fluence, calculated over **1 month cw**

Point #	**5**	**15**	**25**	**145**	**115**	**85**
$n/cm^2/s$	$7\ 10^8$	$6\ 10^8$	$5\ 10^8$	$4\ 10^7$	$6\ 10^6$	$4\ 10^6$
Fluence *n/cm^2*	$2\ 10^{15}$	$2\ 10^{15}$	$1\ 10^{15}$	$1\ 10^{14}$	$2\ 10^{13}$	$1\ 10^{13}$



Electronic radiation hardness

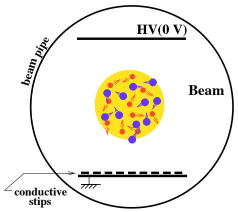
- high energy neutrons (~ MeV) ⇒ electronic trouble for Fluence > 10^{11} n/cm^2



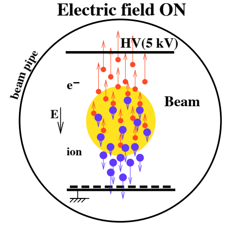
IPM: Ionization Profile Monitor

Jan Egberts's thesis, defended on September 25th, 2012

Electric field OFF

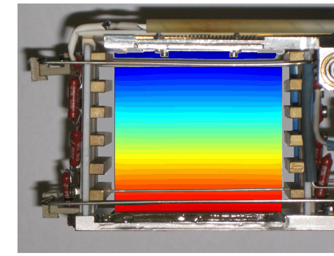


Electric field ON



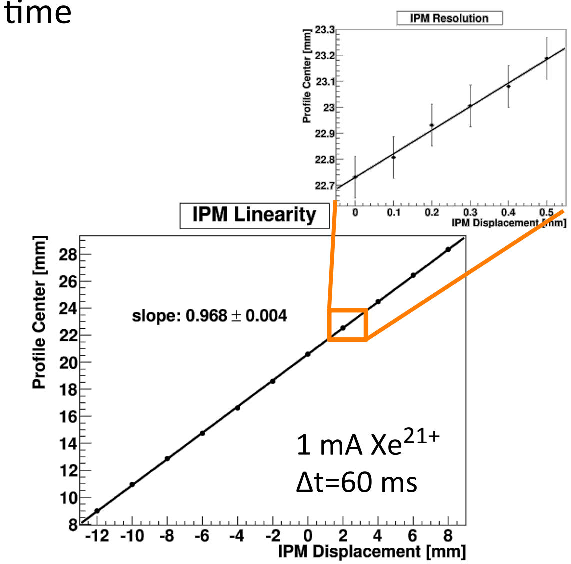
Design & manufacturing of an IPM prototype

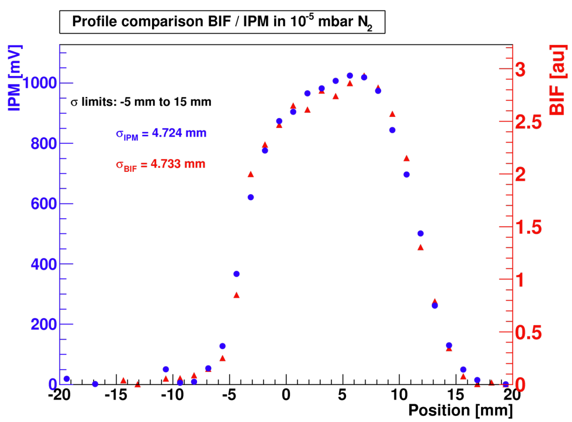
- 6 x 6 cm^2 aperture
- electric field homogeneity (Lorenz) → degraders
- HV ~ 5 kV (E=833 V/cm)

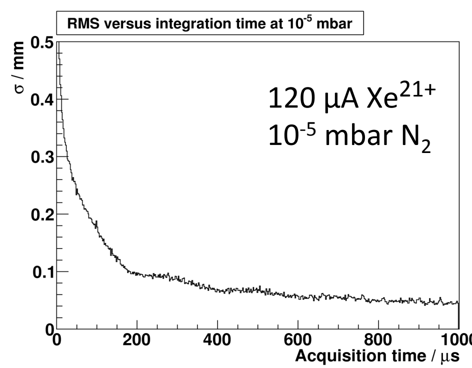


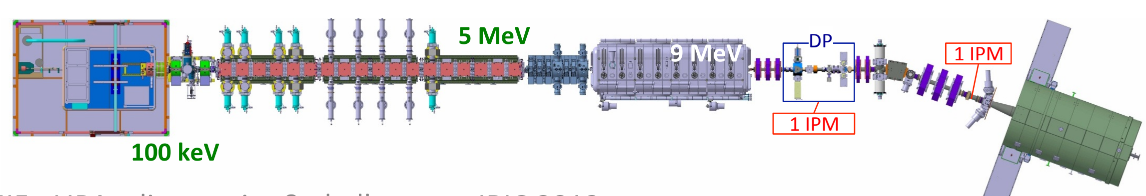
and tested at GSI Darmstadt

- linearity (step motor): 100µm well resolved
  → very good field homogeneity
- Position resolution of beam center vs data acquisition time
  → σ <100 µm after Δt~0.2 ms
- Profile comparison IPM / FPM
- extrapolation to LIPAc beam conditions → Ok







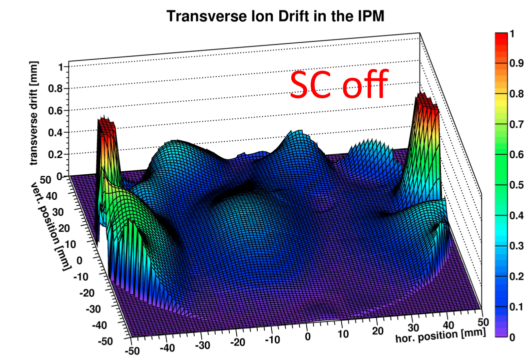


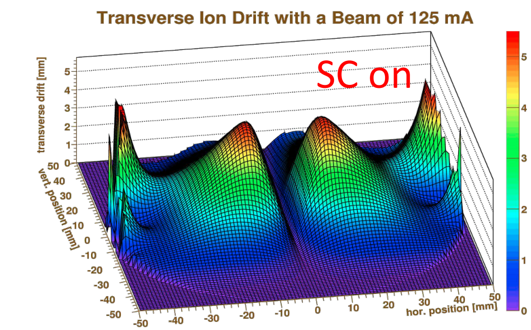
IPM (Space Charge)

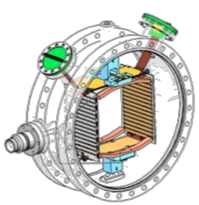
Design & manufacturing the HEBT IPM
- 15 x 15 cm^2 aperture
- HV ~ 10 kV (E=667 V/cm)

Particle tracking within a 125 mA beam
- no SC → transverse displacement < 300µm
- SC applied → transverse displacement > 5 mm

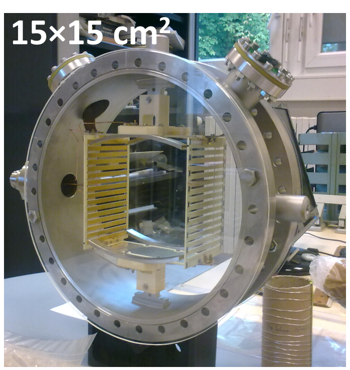
How to overcome
- ↑Electric field, but beam deviation…
- magnetic field for guidance, but no room…
- apply correction **algorithm**
  - hypothesis:
    - generalized Gaussian beam distribution
    - round beam shape
  - distribution iteration until self consistent solution is found

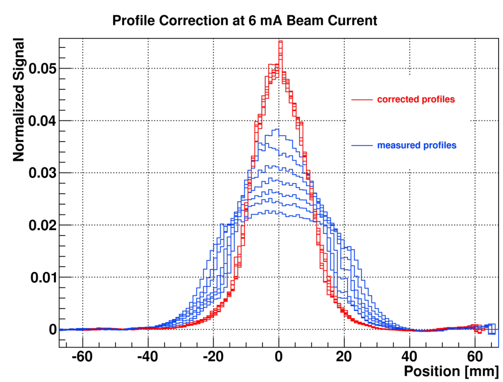


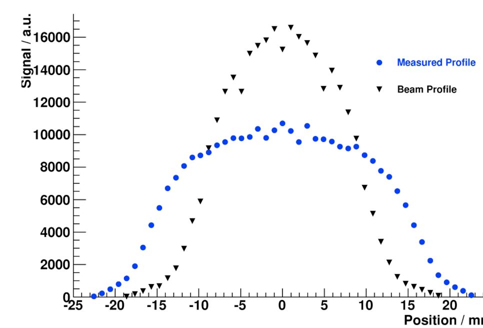


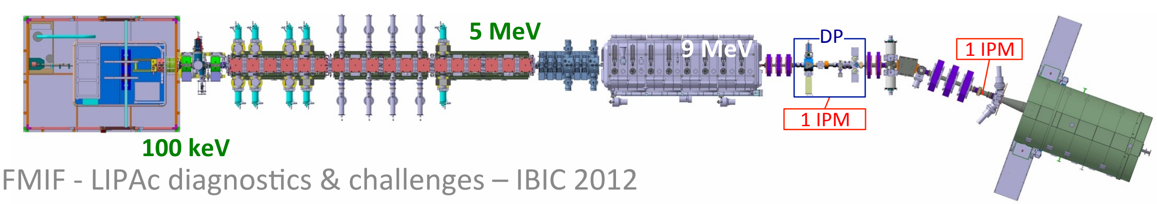


Silhi proton source
(CEA Saclay)
- E_p = 95 keV
- I_{max}=6 mA cw









FPM: Fluorescence Profile Monitor

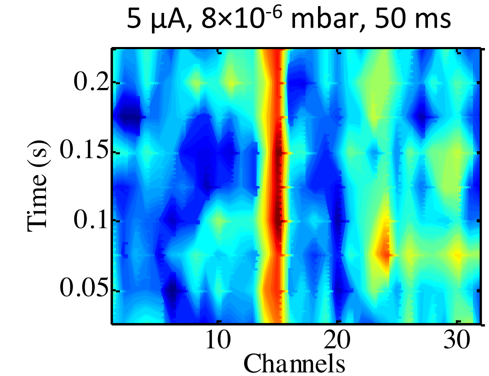
Design & manufacture at CIEMAT Madrid

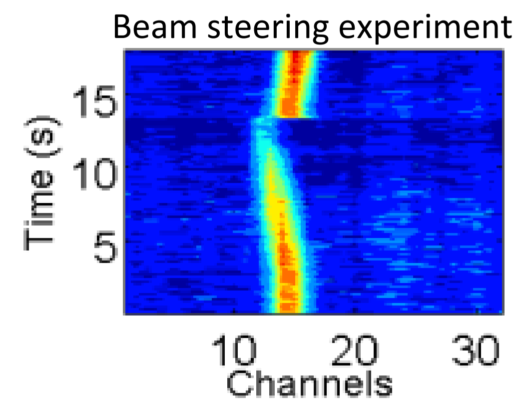
2 FPM prototypes: Image Intensifier CID camera & Multichannel PMT

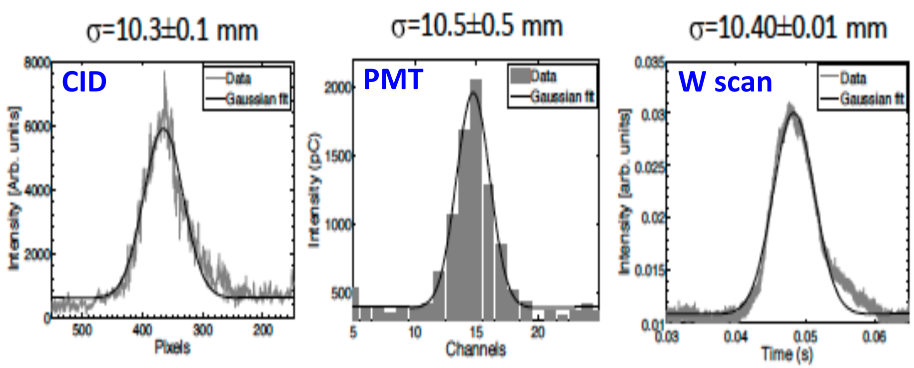
Tests done at CNA Sevilla: 9 MeV deuteron beam (up to 40 µA)

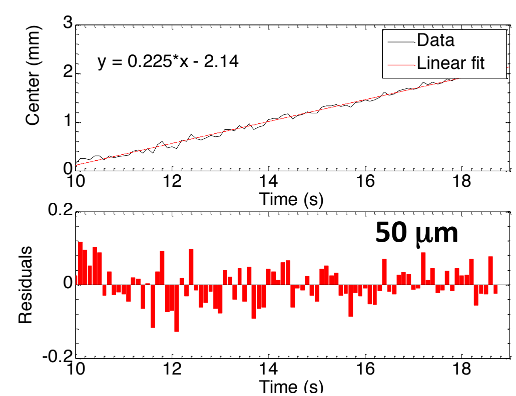
- ➞ linearity with I_{beam} and with pressure: Ok
- ➞ extrapolation to LIPAc beam conditions: Ok
- ➞ good agreement FPMs / wire scanner for various gas (N_2, Xe, Ar, Ne)
- ➞ beam shape evolution with time: Ok
- ➞ beam tracking capabilities for steered beams : Ok
- ➞ Position resolution of 50 µm achieved

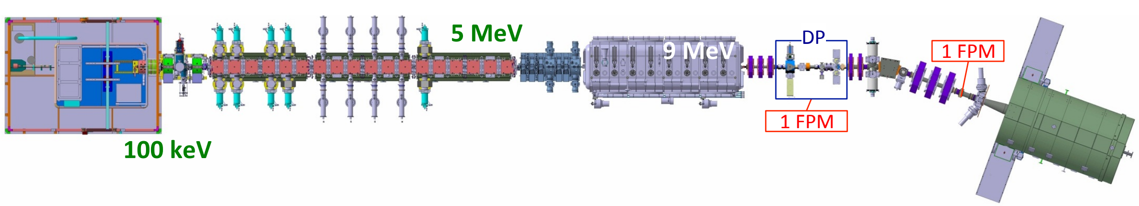
due to high radiation background ➞ PMT











BLoM: Beam Loss Monitors

Objectives

- Machine Safety ➞ provide an interlock signal to MPS in less than 10 µs
- Monitoring the beam losses

Monitors: LHC Ion Chambers (~40 ICs)

Low energy

- only neutrons and γ's exit the beam pipe (secondary)
  ➞ low IC response!

High beam intensity

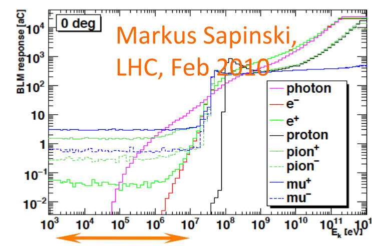
- huge background

Feasibility study

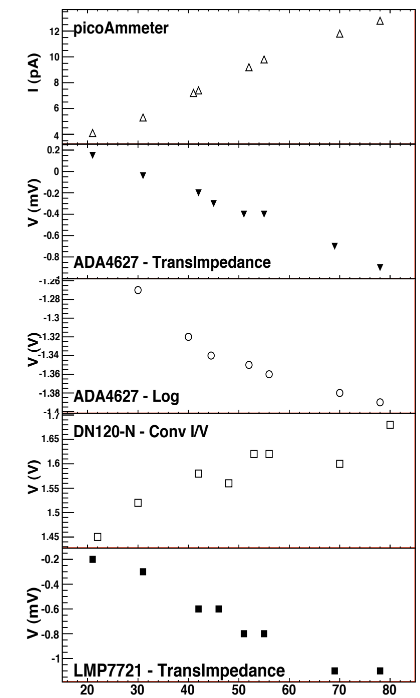
- simulation ➞ I_{IC}~2 pA for 1W/m losses in worst case
- experimental test in neutron and γ ➞ LHC calibration: OK
- MPS ➞ threshold 1 to 10 nA: 30 µs to stop LIPAc, not harmful

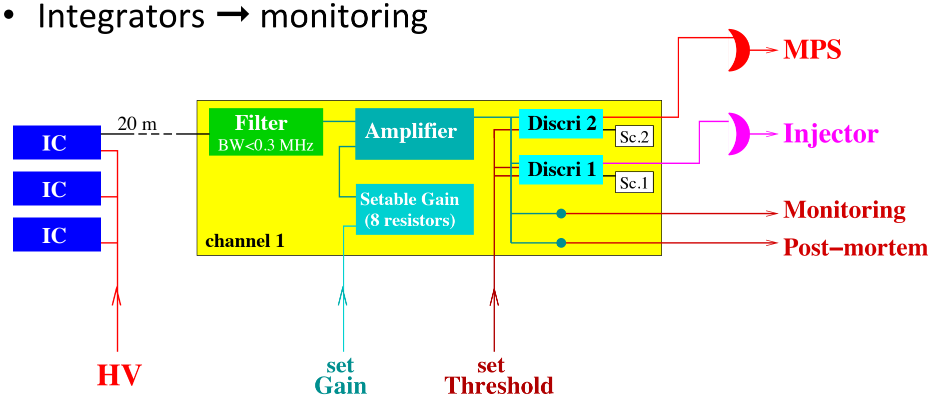
Electronics

- Fast ➞ MPS
- Integrators ➞ monitoring

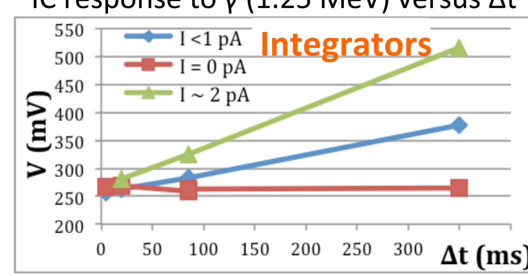


neutron calibration (3 MeV)





IC response to γ (1.25 MeV) versus Δt



µLoM: micro-Loss Monitors

Motivation: due to high beam power, beam dynamics group chooses an innovative strategy for beam tuning.

→ instead of minimizing the beam core, they will tune the beam to optimize the halo contribution.

→ very good sensitivity for beam losses are required

Ideal monitor:

→ sensitive to neutrons, less to X-rays and γ produced by sc cavities

→ reasonable counting rates in ~minutes

→ ability to work at 4.5K

→ very good reliability (no possibility of dismounting) and radiation hardness

→ compromise: single crystalline **CVD diamond** (Chemical Vapor Deposit)

Objective: 3 diamonds/ensemble (8×cavity+solenoid+BPM)

→ improve reliability

→ better transverse localization

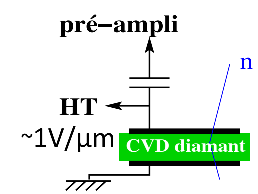
CVD Diamond

Size ~ $4 \times 4 \times 0.5$ mm^3

Active area(measured) = **9.2** mm^2

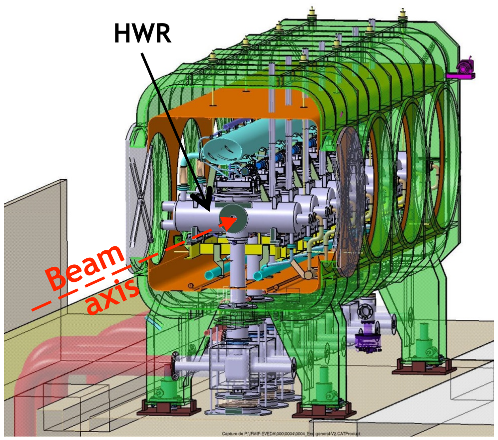
e^-/hole pair production ≈ 13.2 eV

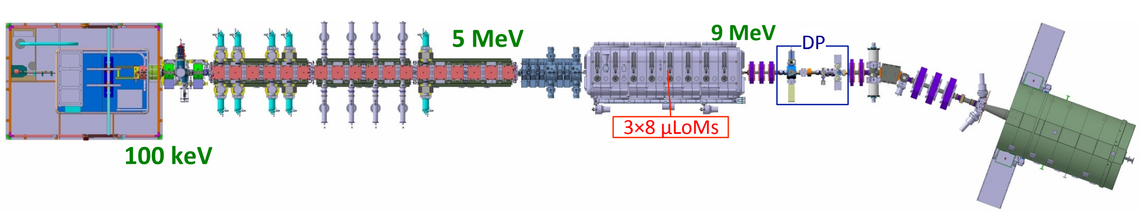
Band gap = 5.5 eV



Feasibility study:

→ simulation for 1W/m losses





Counting rates & radiation background

Rate versus the electronic threshold (keV) for neutron & γ (*1W/m*)
(Background is low wrt 1W/m)

Threshold (keV)	γ+n (kHz)
100	4.3
200	2.7
300	2.1

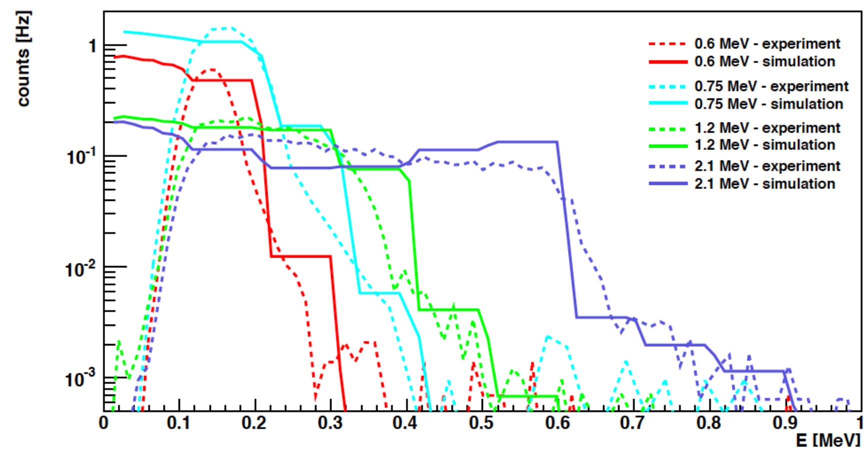
Neutron tests made with a Van de Graaff (CEA Bruyères-le-Châtel):

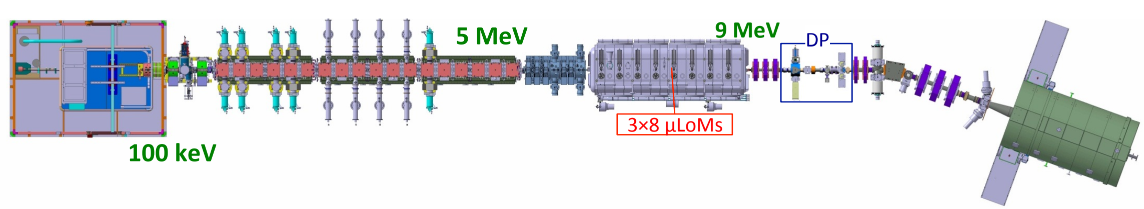
- E_n = 0.2, 0.6, 0.75, 1.2, 2.1, 3.65, 6, 16 MeV
- Goal: diamond response (energy deposit…)
- Room temperature

neutron/γ discrimination ➞ time of flight

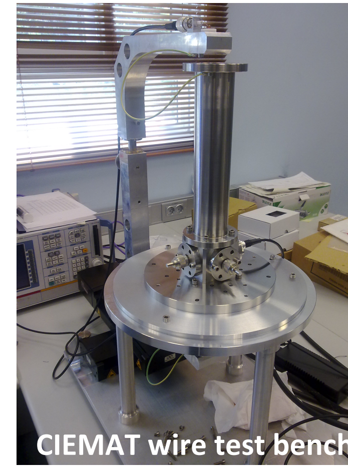
Conclusion

- Threshold is ≈ 100 keV, but short cable
- Simulation fits quite well data
  - ⇒ more confidence in previous counting rates.





BPM: Beam Position Monitor


CIEMAT wire test bench

Several types of BPMs have to be designed

- MEBT (4 striplines): inserted inside the quads due to lack of space
- SRF Linac cryostat: 8 BPMs (button-type) in cryogenic environment
- DPlate (3 striplines): beam energy measurement using ToF technique
- HEBT (2+3): steering of the beam to the Beam Dump. Debunching and big chamber issue

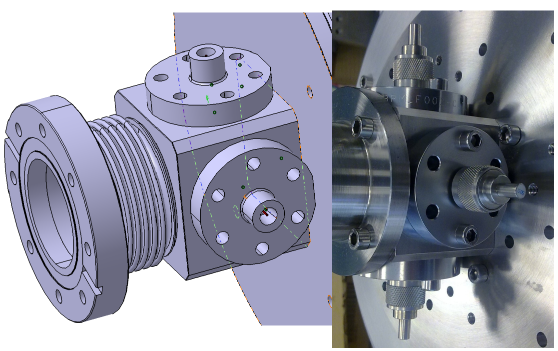
Test

- A wire bench test has been constructed and commissioned in CIEMAT for characterization of all LIPAC BPM's

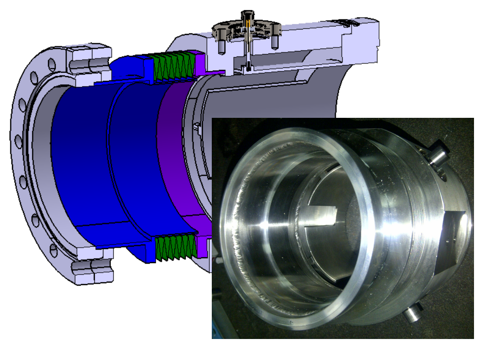
Electronics

- based on IQ demodulation of the 1st or 2nd harmonic
- automatic calibration to minimize phase and amplitude errors in the cables (~70 m)

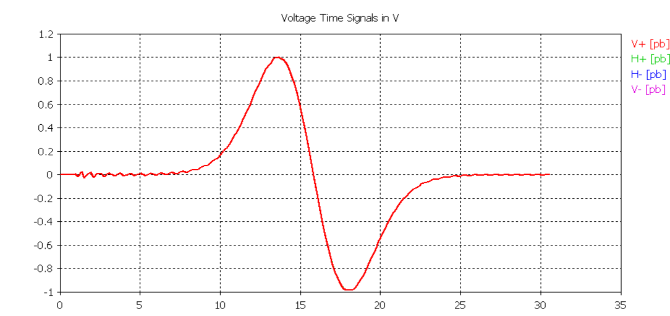
cryogenic BPM (SRF Linac)

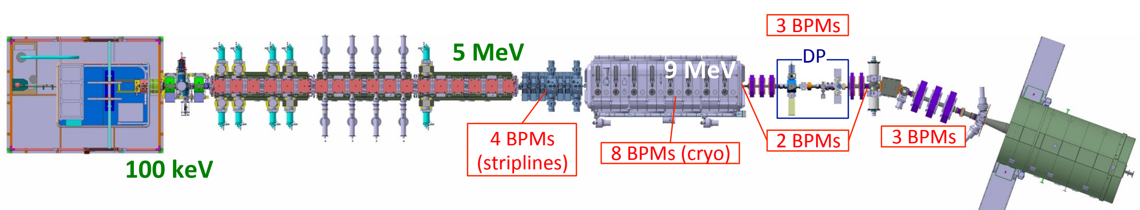


stripline for E measurement



signal (CST PS) for the last BPM (upstream the BD)





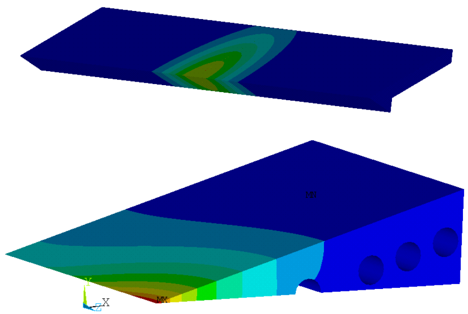
Slits (Emittance & Energy spread)

Emittance

2 slits in DP (vertical & horizontal) + SEM grid (1)

Energy spread (using the dipole)

1 slit in DP (vertical) + 1 slit (dipole) + SEM grid (2)



Thermal study done at CIEMAT Madrid

hypothesis:

Δt = 100 µs / 1 s (10^{-4} duty cycle)

Carbon forbidden (superconductive cavities)

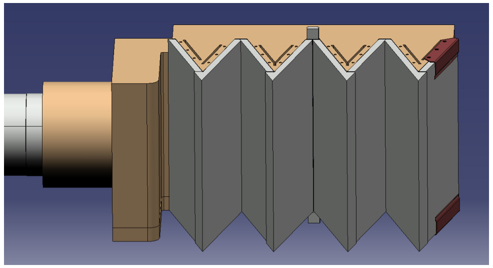
surface power density: 1.5 GeV/m^2

→ Plates of high fusion temperature: W, TZM (molybdenum alloy)

→ radiator with water cooling system

slit prototype

based on LINAC4 design



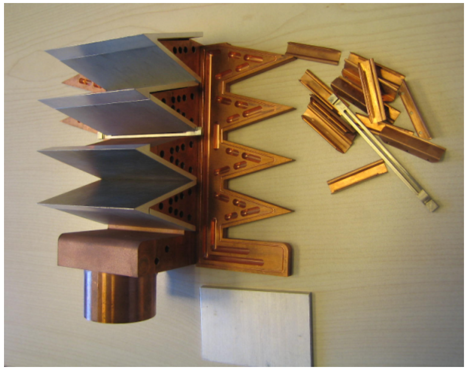
Outcomes from thermo-mechanical analysis:

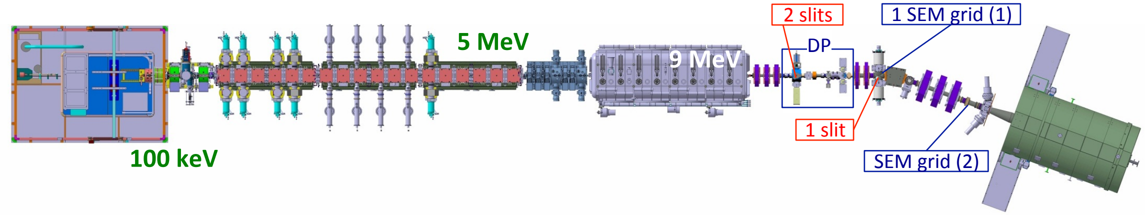
graphite plates (removable) for commissioning at 5 MeV (no sc Linac)

TZM plates (15°) for commissioning at 9 MeV

Copper body for cooling channeling

Prototype manufactured at CIEMAT Madrid





Summary

LIPAc: very challenging facility

- highest beam power (1.125 MW cw deuteron beam)
- strongest space charge
- longest RFQ
- very high radiation background

Few challenging diagnostics

- Allison scanner → high beam power (15 kW to allow cw beam)
- IPM → strong space effects (profile distortion / algorithm)
- FPM → radiation hardness
- BLoM & µLoM → low beam energy (neutral detection = medium sensitivity)
- BPM → cryogenic temperature, mechanical insertion in quad, debunching
- Slits → huge surface power density

Future

- switch on electronics, daq & control system
- RFQ commissioning (summer 2015)
- SRF Linac + HEBT + BD (summer 2016)

Thank you for your attention

Thanks to

GSI diagnostics group and UNILAC GSI people
SILHI – IPHI group at CEA Saclay
CoCase group at Saclay (^{60}Co irradiator)
CNA Sevilla accelerator group
B. Dehning for IC lend and advises

Organizing committee to give us the word

and of course, many thanks to

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CIEMAT Madrid: J. Calvo, ***J.M. Carmona***, P. Fernandez, A. Guirao, D. Iglesias, C. Oliver, I. Podadera, A. Soleto

INFN Legnaro: M. Poggi

Backups

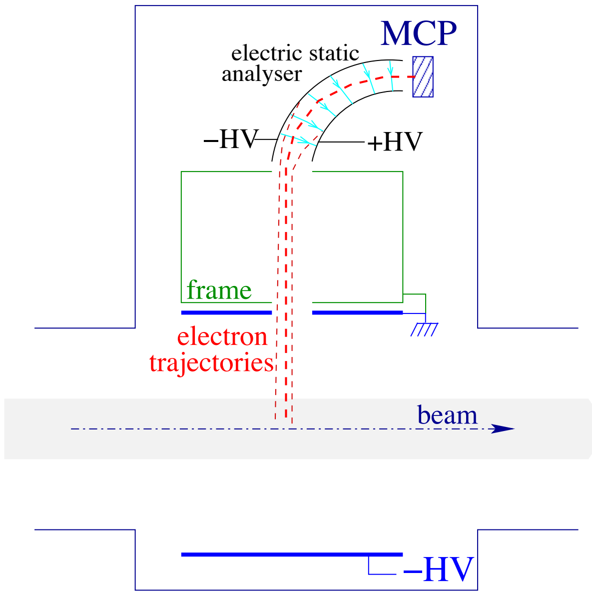
Bunch Length Monitor

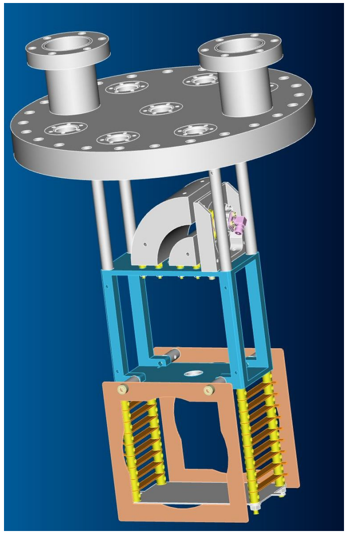
RGBLM (Residual Gas Bunch Length Monitor)

- non interceptive
- residual gas ionization
- electron extraction (homogeneous Electric field) through a hole
- electric static analyser: to sort specific electron energy
- MCP: electron detection and ToF measurement wrt RF

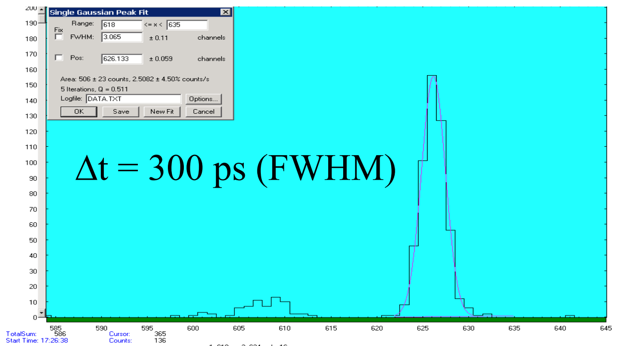
Prototype design, manufacture and tests at INFN Legnaro

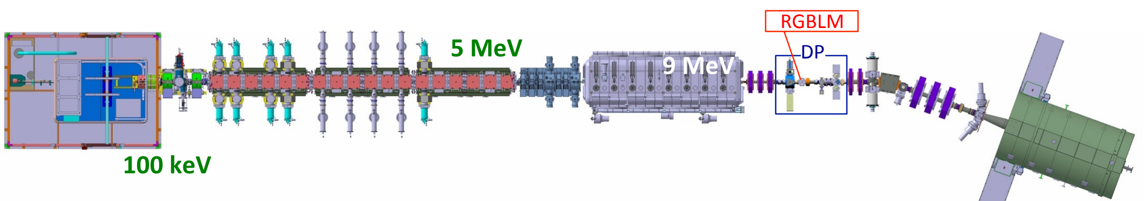
Test on $^{136}Xe^{28+}$ beam at 546 MeV → Δt = 300 ps (FWHM)



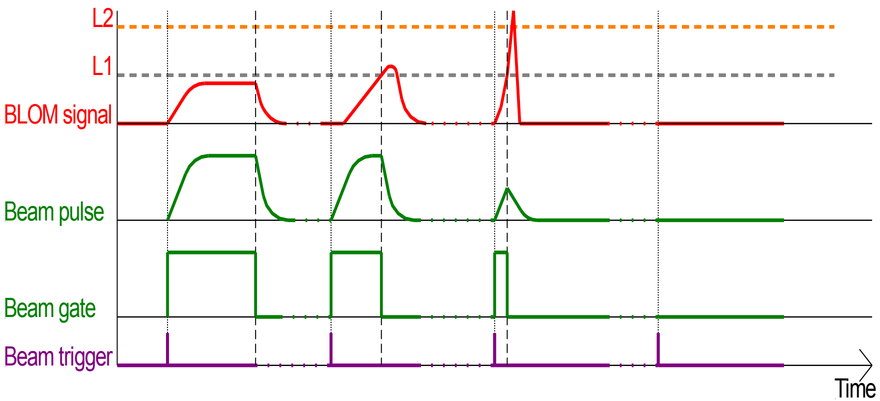


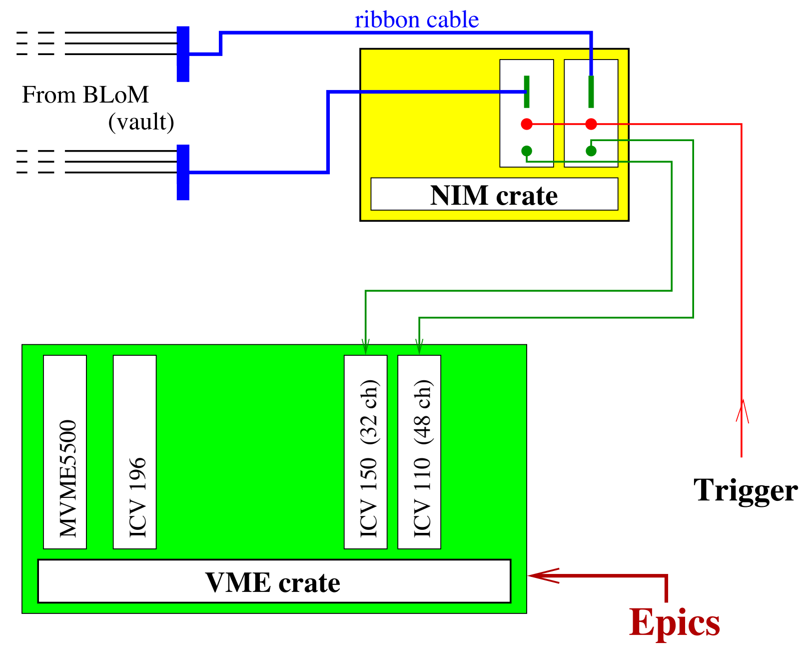
10×10 cm^2 aperture

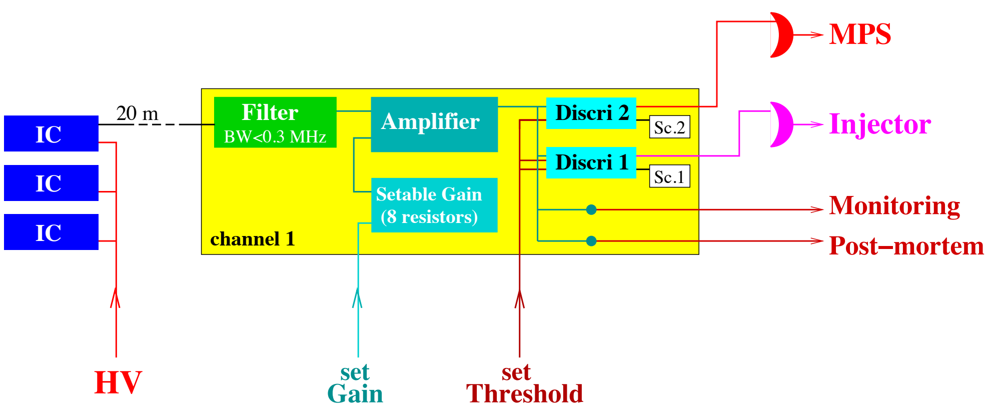




Beam Loss Monitor



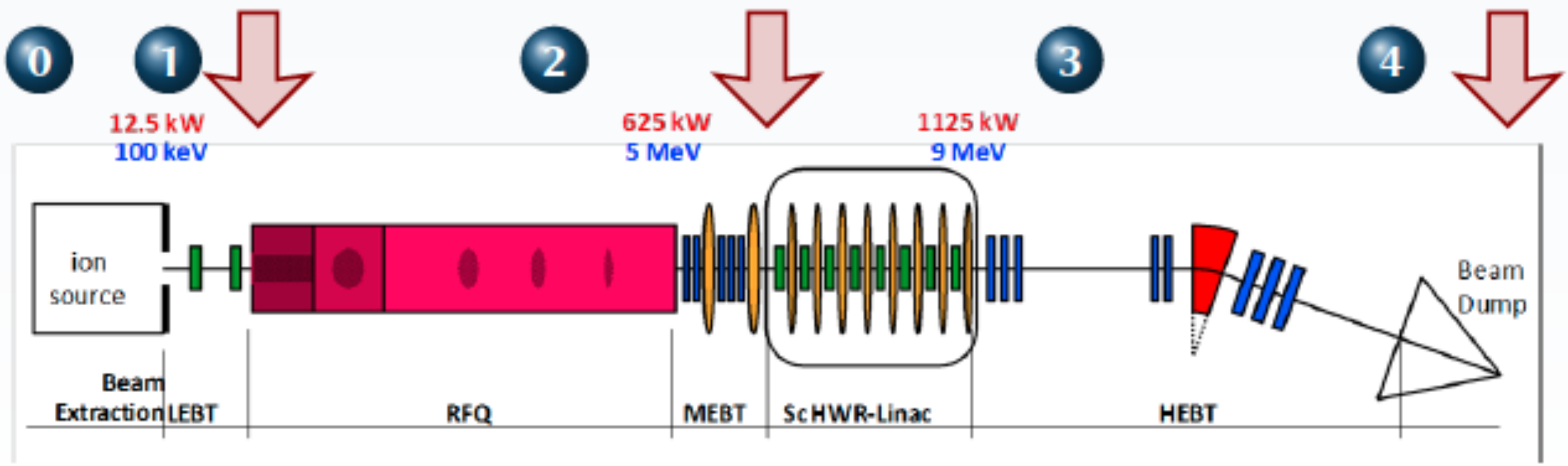




LIPAc Commissioning

(N. Chauvin, June 26th 2012)

- **Stage 0:** Source + LEBT + LPBD in Saclay (full intensity, CW)
- **Stage 1:** Source + LEBT + LPBD in Rokkasho (full intensity, CW)
- **Stage 2:** RFQ + MEBT + D-Plate + LPBD (full intensity, pulsed mode)
- **Stage 3:** SRF linac + HEBT + Beam Dump (full intensity, pulsed mode)
- **Stage 4:** Ramp up to full power of the whole accelerator.



Pulsed mode (max duty cycle = 10^{-3}): $\Delta t < 1$ ms (1 Hz).

SC Algorithm

1- Idea

- calculate the Space Charge force
- determine ion displacement at each position
- correct the profile

2- Hypothesis

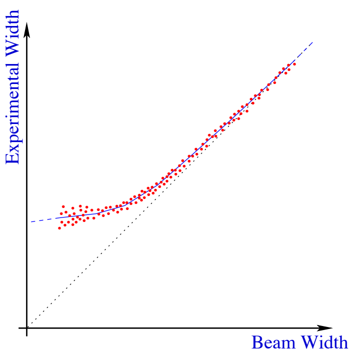
- D^+
- round beam
- profiles have a generalized Gaussian shape
- I_{beam}

3- Approach

- apply statistics

  $\rightarrow g(x') = \Sigma\, p_{x'}(x,y)\cdot(x,y)$

  where $p_{x'}(x,y)$ is given by beam distribution



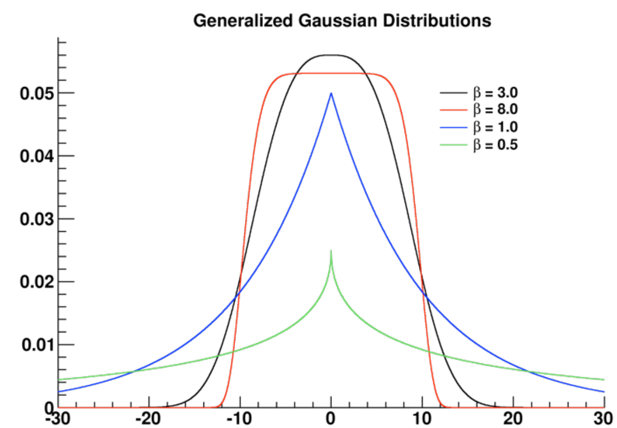
Generalized Gaussian distribution

- µ: profile center
- Two degrees of freedom

  σ: 2^{nd} moment

  β: kurtosis, 4^{th} moment

$$p_{\alpha,\beta,\mu}(x) = \frac{\beta}{2\alpha\,\Gamma(1/\beta)} e^{-\left(\frac{|x-\mu|}{\alpha}\right)^{\beta}}$$



SC Algorithm (2)

4- First parameter to initiate iteration process

- fit of the experimental profile using a generalized Gaussian to **extract**
  - → $\sigma_0 = \sigma_{exp}$
  - → $ß_0 = ß_{exp}$
- beam intensity given by CT