LIPAc beam diagnostics

LIPAc: Linear IFMIF Prototype Accelerator

Ditanet topical workshop, 26th & 27th September 2011, on:

« High intensity proton beam diagnostics »

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Overview

IFMIF, LIPAc: a brief introduction

LEBT diagnostics: a summary

Diagnostics downstream to the RFQ:

- CT
- BPM
- BLM
- Profilers
- BLoM
- µ-Loss

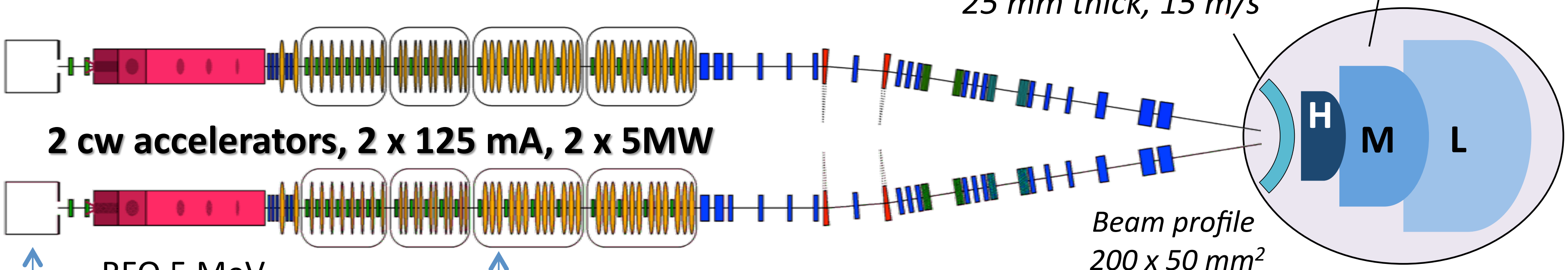
IFMIF

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

*International Fusion Materials Irradiation Facility

international agreement of the **BA** (JAEA+F4E) = **IFMIF** + IFERC + JT60-SA

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



Lithium Target

25 mm thick, 15 m/s

Test Cell

2 cw accelerators, 2 x 125 mA, 2 x 5MW

Beam profile
200 x 50 mm^2

RFQ 5 MeV

deuteron source
140 mA, 100 keV

Superconductive Linac 40 MeV
(Half Wave Resonators)

Flux ~ 10^{17} neutrons/s

Typical reactions

$^7Li(d,2n)^7Be$
$^6Li(d,n)^7Be$
$^6Li(n,T)^4He$

LIPAc

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

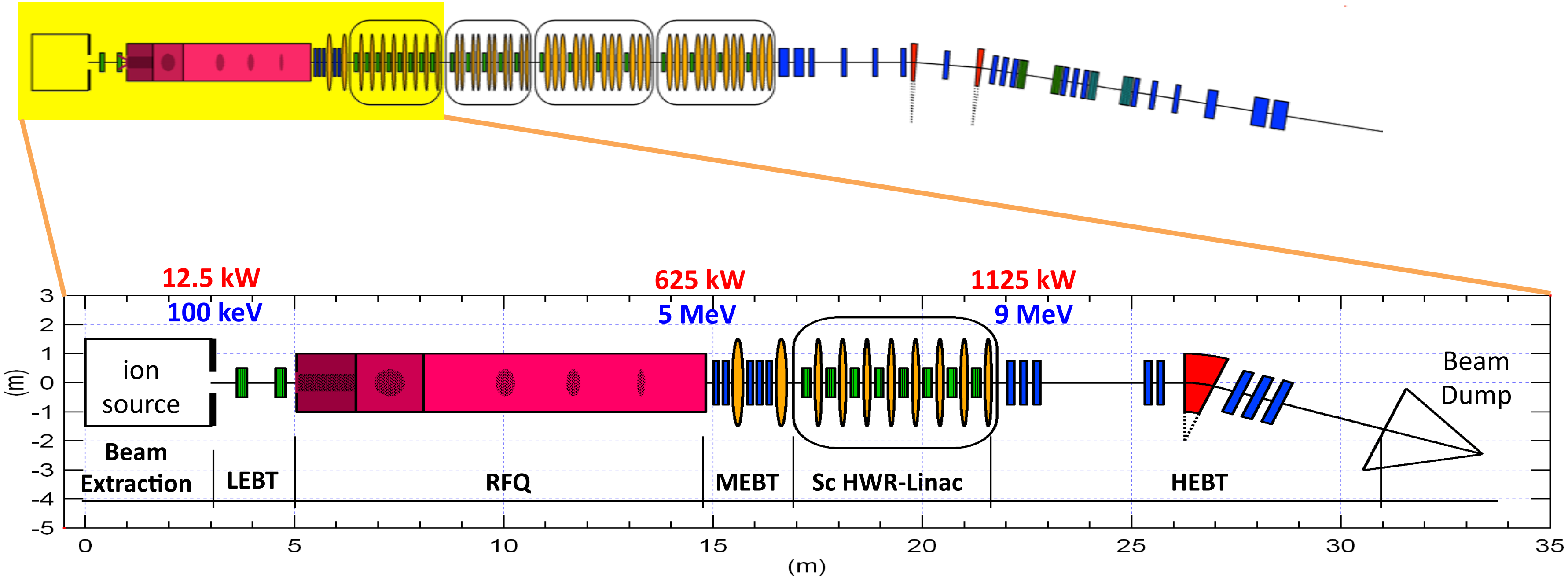
Validation phase: prototype accelerator → LIPAc*

*Linear IFMIF Prototype Accelerator

Commissioning at Rokkasho (Japan) beginning:

Injector: March 2013
RFQ: July 2014
scLinac: May 2015

LIPAc = 125 mA cw, 9 MeV, 1.125 MW



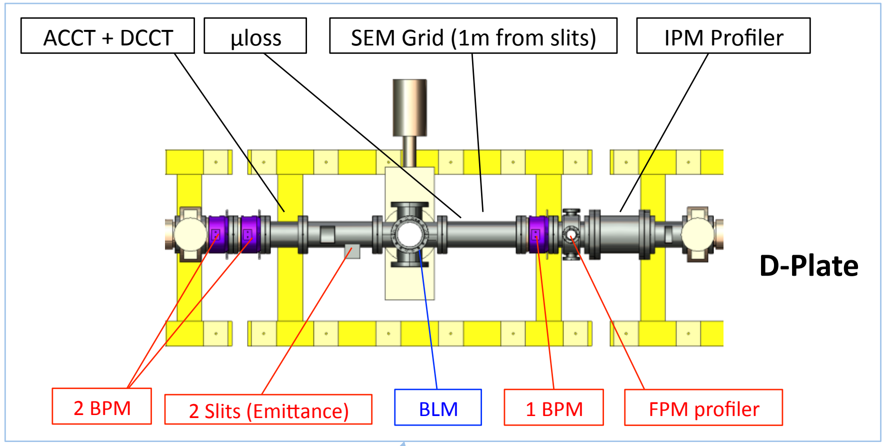
Beam Instrumentation Layout

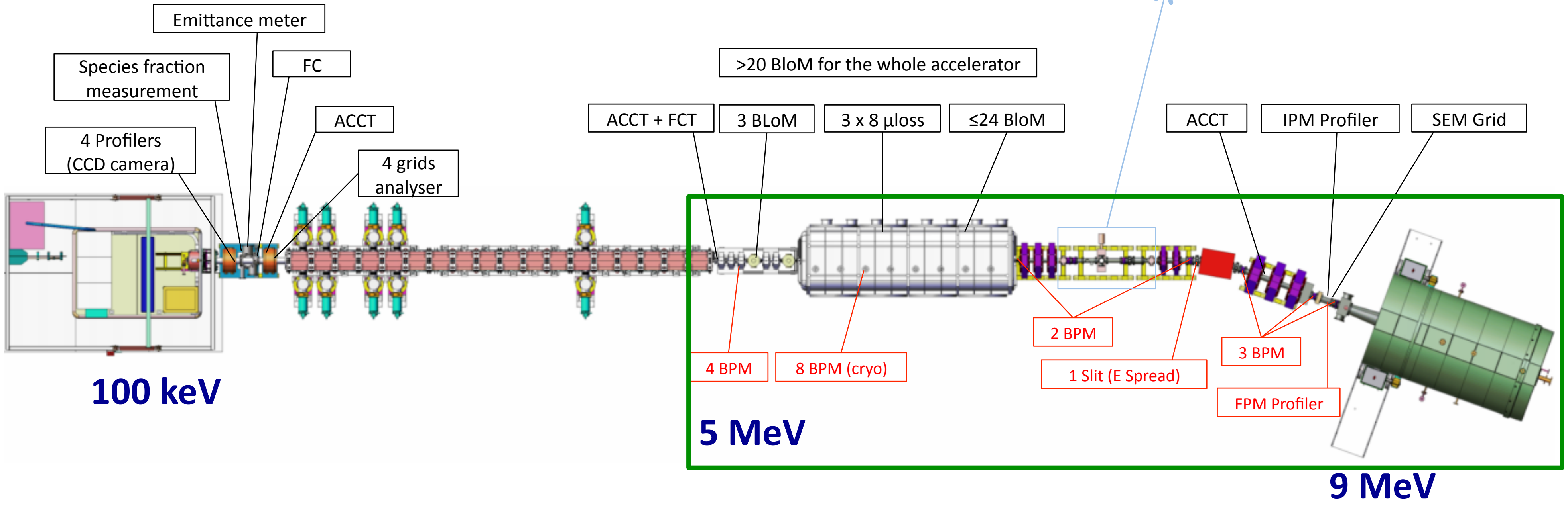
deuteron beam:

E_{max} = 9 MeV
I = 125 mA
P = 1.125 MW (cw)
RF: 175 MHz (5.7 ns)

Glossary:

ACCT: AC Current Transformer
BLoM: Beam Loss Monitor
BLM: Bunch Length Monitor
BPM: Beam Position Monitor
DCCT: DC Current Transformer
FC: Faraday Cup
FCT: Fast Current Transformer
IPM: Ionization Profile Monitor
FPM: Fluorescence Profile Monitor





LEBT diagnostics

0 to 100 keV

LEBT challenges (0 to 100 keV)

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

Lack of space due to short length of LEBT to minimize emittance growth:

→ Limited number of diagnostics and only 1 diagnostic box shared with pumping…

Low energy (100 keV):

Cons:

- High space charge to be overcome:
  - → with Kr injection (few 10^{-5} Torr)
  - → enlarging the beam diameter (few cm)
- Only ACCT due to space lacking: cw beam → no beam current measurement
- Numerous secondary electrons → non uniformity of charge compensation

Pro:

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

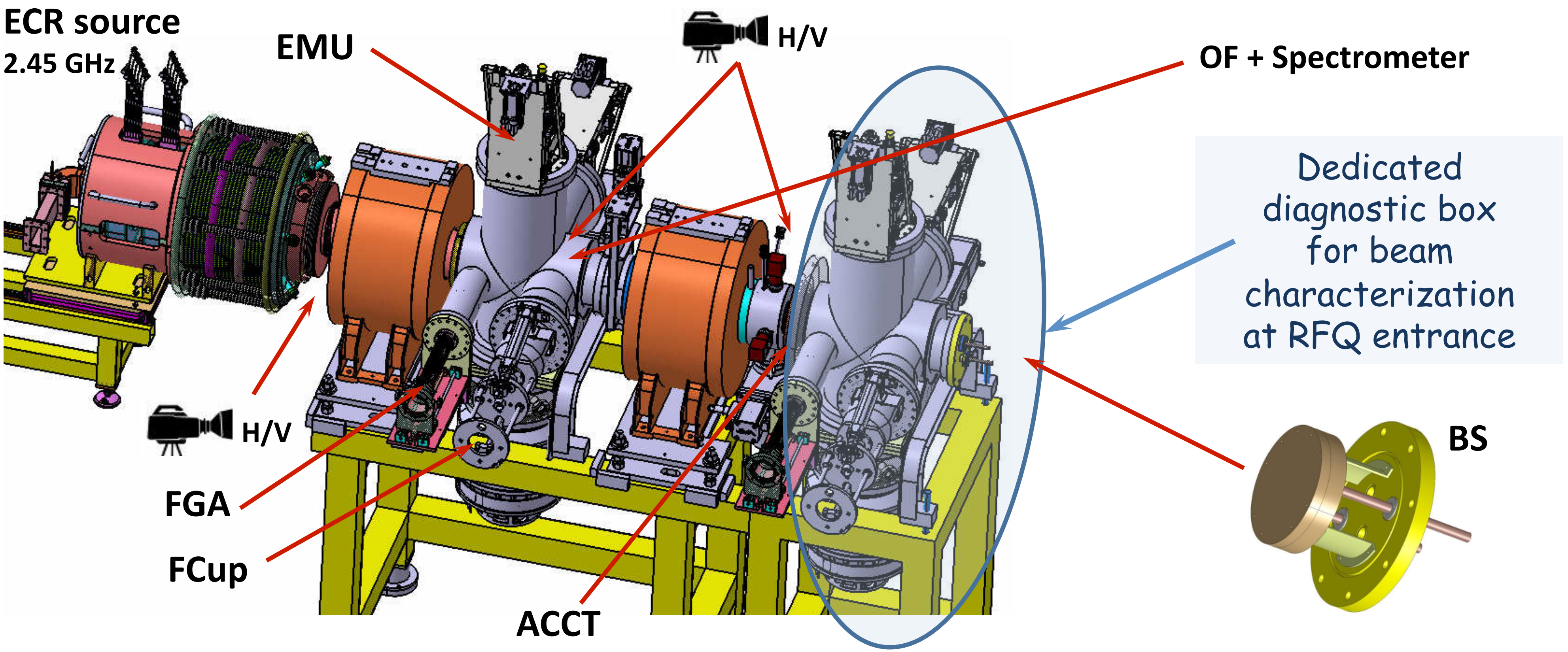
High intensity (150 mA):

→ 15 kW continuous beam → important water cooling

Injector 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 (residual gas fluorescence): 6 CID cameras
- Beam purity species: 1 deported spectrometer with optic fiber

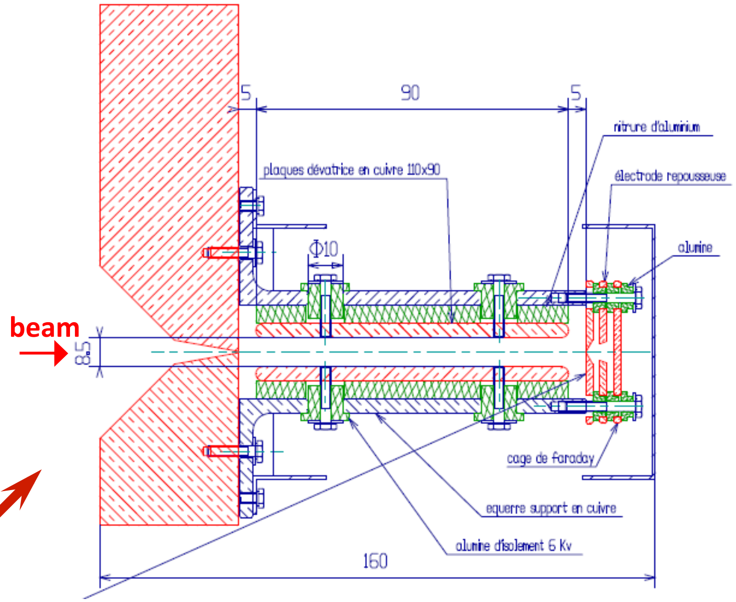
Note: a beam chopper will be installed between the 2 solenoids
→ adding a new apparatus!

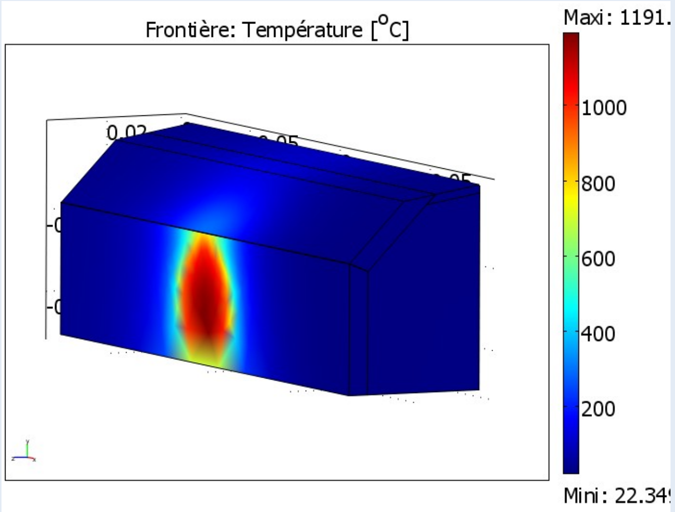


Dedicated diagnostic box for beam characterization at RFQ entrance

Emittance meter

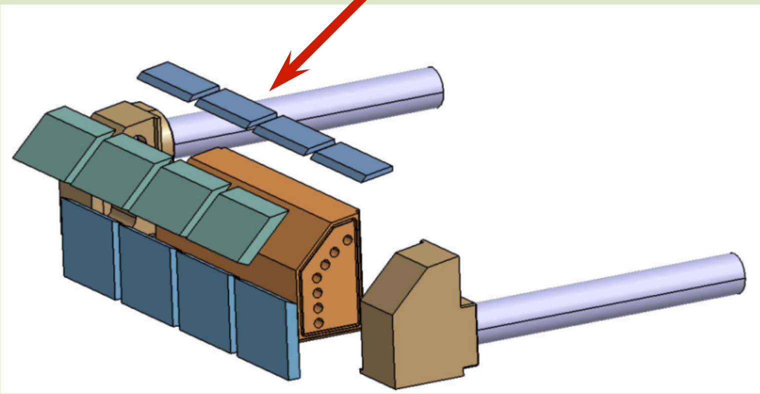
- ➢ Allison scanner design completed
- ➢ Linear translation system
- ➢ Thermal screen simulations
- ➢ Cold model to validate the brazing technique
- ➢ Thermal screen manufacturing in progress



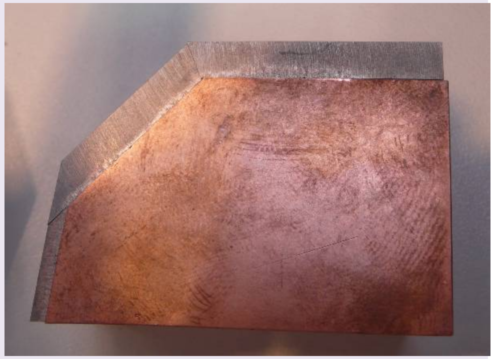


- ☐ Thermal simulation with Comsol
- ☐ Critical case shows

Tmax = 1191 °C on tungsten surface



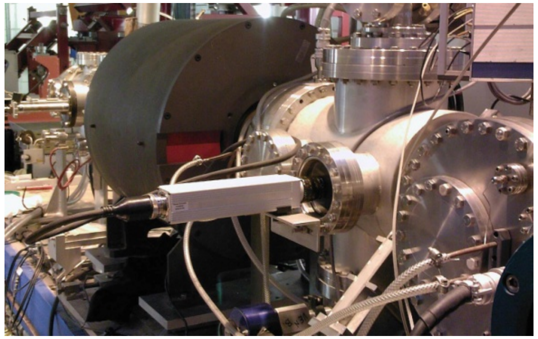
- ☐ Cu block covered by W tiles
- ☐ Internal water cooling system
- ☐ Brazing technique for Cu/W assembly



- ☐ Tests for brazing technique validation are still in progress with small models

Optical beam diagnostics

based on residual gas excitation by the beam



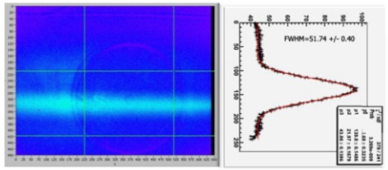
CID camera on the SILHI source

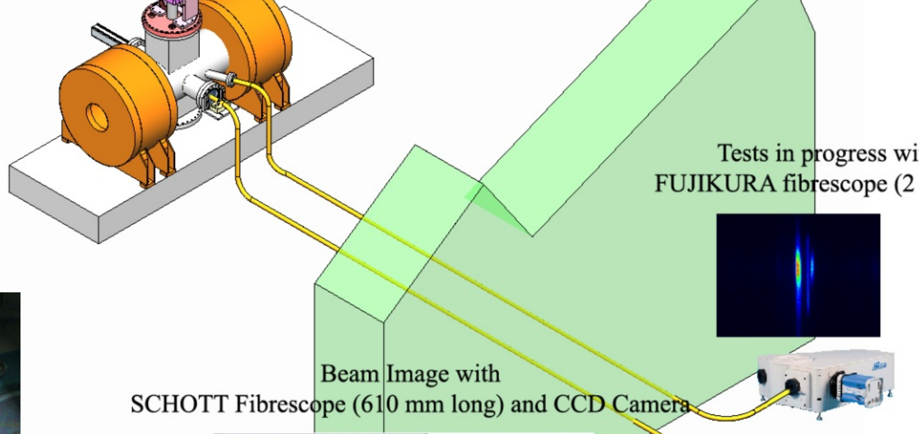
Devices allow getting ion beam characteristics:

With CID Cameras (Hardened radiations ~ 30 kGy)
or SCHOTT fibrescope + CCD (not retained):

- Beam current proportional to fluorescence intensity
- Beam size
- Beam center position
- Transverse beam profile
  - → see Cherry May Mateo talk

Beam Image with CID cameras



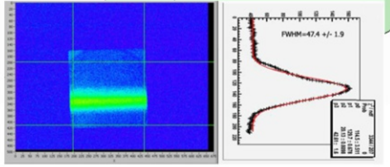


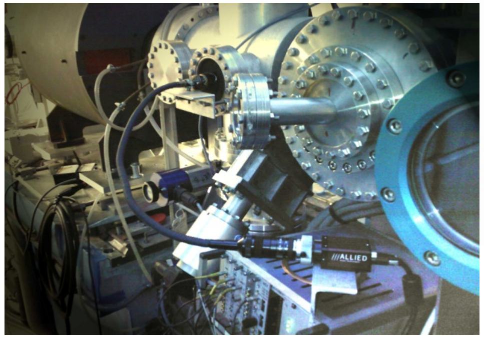
Tests in progress with
FUJIKURA fibrescope (2 m long)

With FUJIKURA fibrescope (Hardened radiations)
+ monochromator (Doppler shift analysis):

- Species fraction beam
- Profile species fraction beam
- Source impurities

Beam Image with
SCHOTT Fibrescope (610 mm long) and CCD Camera





SCHOTT fibrescope on the SILHI source

Diagnostics downstream to the RFQ

5 to 9 MeV

Challenges at 5 to 9 MeV energy

Lack of space (space charge forcing compact beam dynamics):

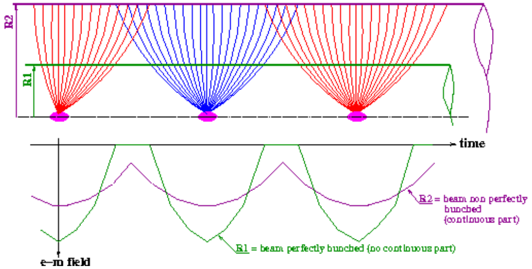
compromise:

- minimizing the diagnostics number,
- save space ➝ replace DCCT (> 12 cm) / ACCT (~ 4 cm)…

Low energy:

Cons:

- e.m. field spread ($\beta<0.1$): $\sigma_t \approx R/\sqrt{2}\beta\gamma c$ ➝ bunch overlapping (“de-bunching”) effect (FCT, BPM ➝ Ivan Podadera)
- high energy density deposit in material (small material penetration and small transverse beam size)➝ slits, SEM grid, Faraday cup… ➝ **chopper**
- beam particle stopped in beam pipe (D {9MeV} ⇒ 140 µm Fe) ➝ only neutral secondaries (γ, n) ➝ BLoM



Pro:

- “high” ionization & fluorescence processes ➝ profiler

High intensity (125 mA):

➝ weight the low energy cons and pros!

\+ huge space charge effects ➝ IPM ➝ Jan Egberts talk

\+ huge amount of radiation background (~ 7 kSv/h on IPM close to the BD)

Current Transformers

Around RFQ:

transmission → measured only in pulsed mode (ACCT)

FCT: insures that cw beam passing through

DPlate:

1 ACCT + 1 DCCT in a single setting (1 ceramics cut off)

only 1 cw current monitor

HEBT:

1 ACCT downstream to the dipole

Magnetic shielding: difficult ($B_{\perp}$ ~ 30 mT for MEBT)

BW:

DCCT (0 to 10 kHz)

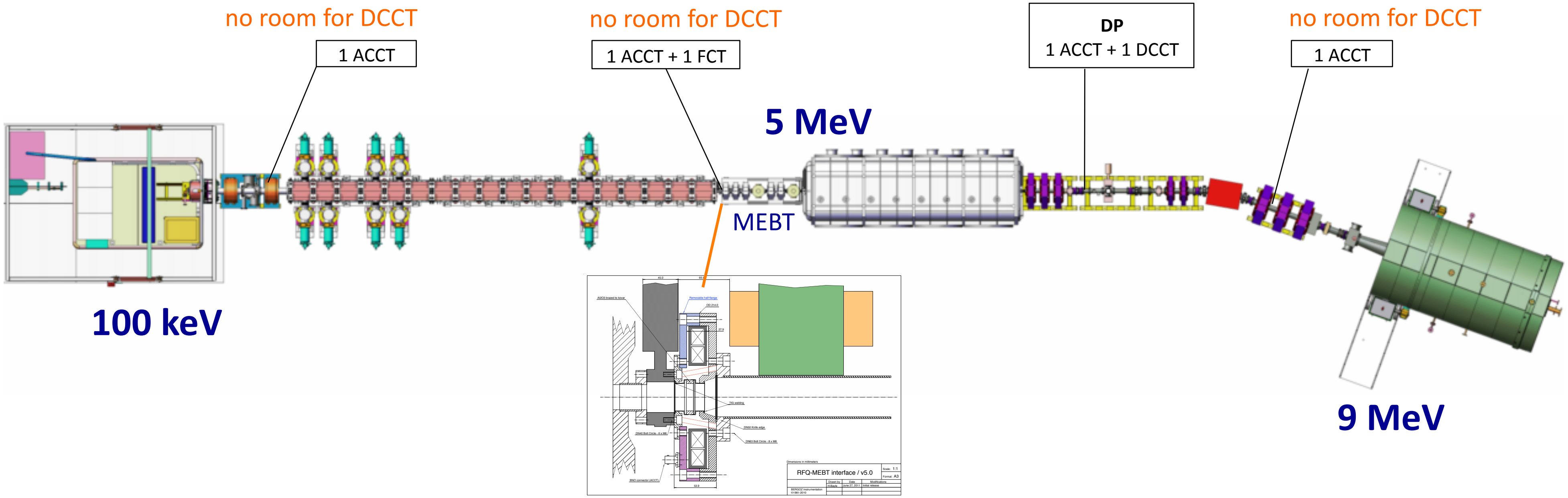
ACCT (3 Hz to 300 kHz)

FCT (10 kHz to > 1 GHz)

RFQ exit (5 MeV):

Beam radius ~ 3σ = 38°

R=2 mm → 2.7 ns (< $F_{RFQ}/2$)



no room for DCCT

1 ACCT

no room for DCCT

1 ACCT + 1 FCT

DP

1 ACCT + 1 DCCT

no room for DCCT

1 ACCT

5 MeV

MEBT

100 keV

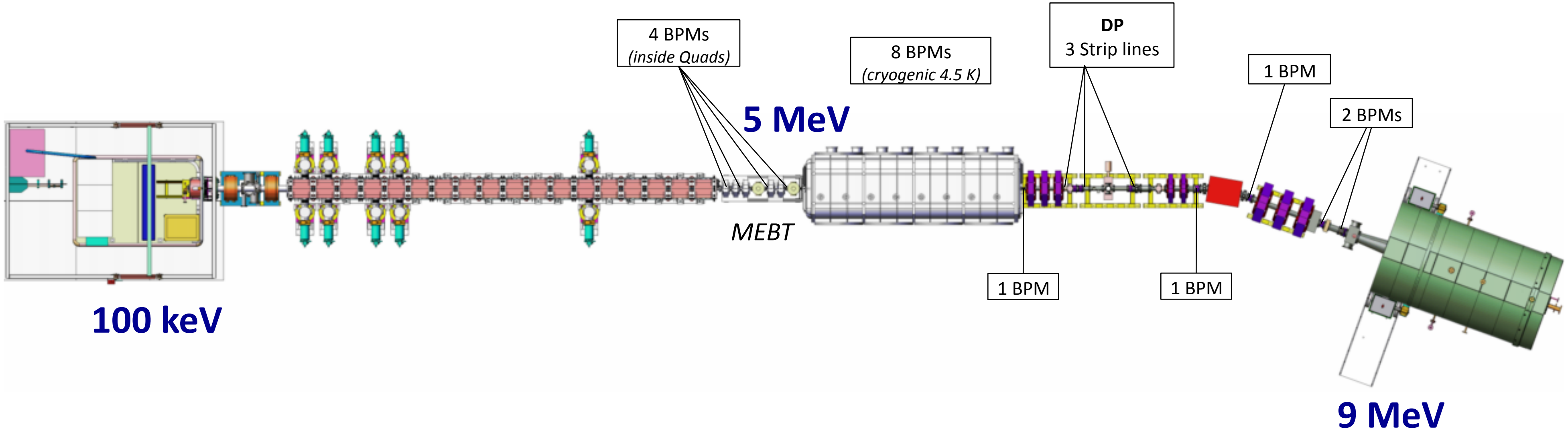
9 MeV

Beam Position Monitors

20 BPMs:

- 8 cryogenics
- 12 room temperature

See **Ivan Podadera** talk tomorrow (low β effect)



Bunch Length Monitors

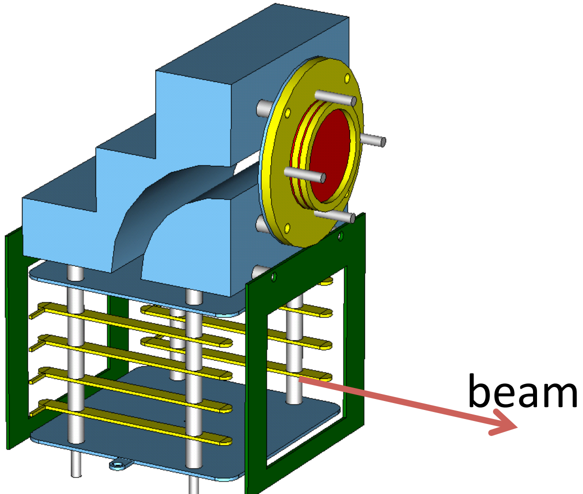
Non interceptive:

Residual Gas Bunch Length Monitor *(based on GSI monitor)*

1) collected e^- from ionized particles are filtered with a spectrometer
2) e^- are multiplied by a MCP
3) $t_{RFQ} - t_{MCP}$ → beam bunch time structure

Expected resolution → FWHM ~ 200 ps

Design and tests are in progress

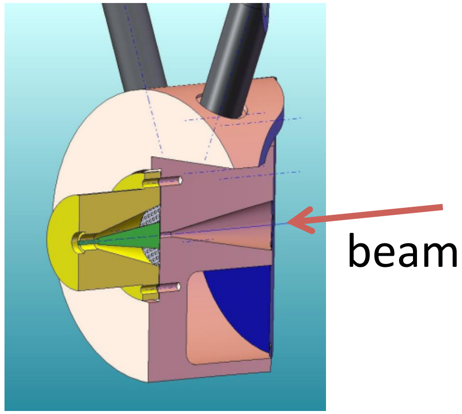


(not shown the collecting 50 Ω anode)

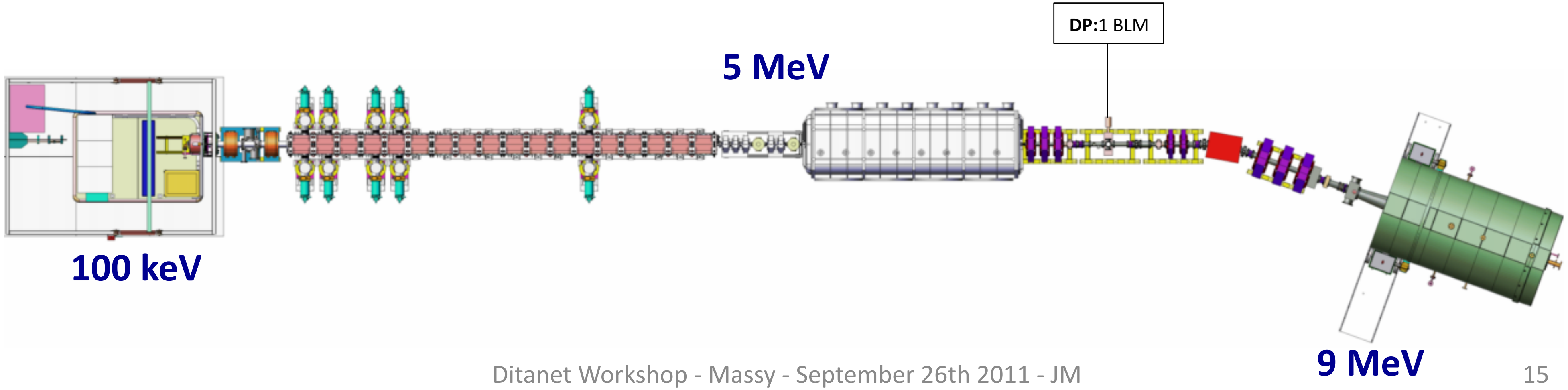
Interceptive:

Fast Faraday Cup

goal: FWHM ~ 200 ps



fast cup in green and yellow
cooling system in front of



Slits: emittance & energy spread

Interceptive (removable mechanism):

emittance: *2 scanning slits at 90°*

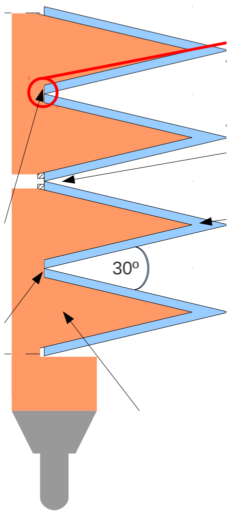
energy spread: *1 fixed slit*

Worst case: RFQ exit (5 MeV) and σ < 4 mm

Thermal study is under progress (ANSYS) →

- slit shape similar to Linac4 (see Benjamin Cheymol)
- material: W (C is forbidden) + Cu
- angle < 20°
- water cooling
- time structure (chopper): 50 to 100 µs/s

Prototype will be designed

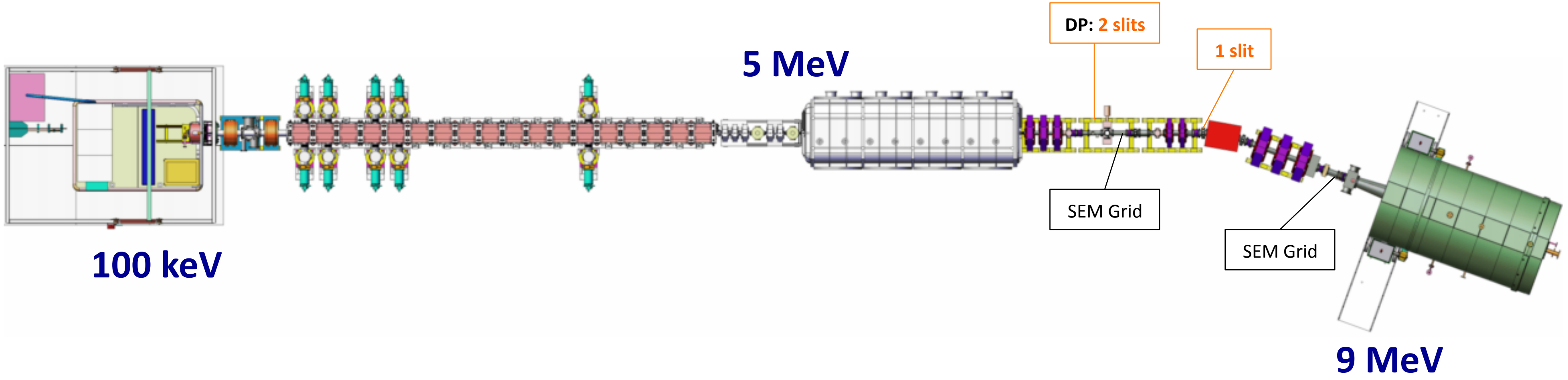


Non-interceptive:

Quad scanning (last quads triplet)

Feasibility is under progress

→ 0.1 mm profile resolution for 5% emittance precision!



SEM grids

Thermal study (ANSYS):

tungsten wire (carbon forbidden)

worst case: RFQ exit and σ < 4 mm (5MeV→43µm & 9MeV→103µm)

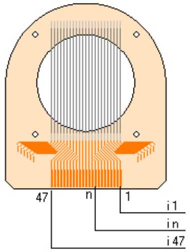
Mechanics + electronics (Spiral2 → Jean-Luc Vignet, Ganil):

47 channels / plane

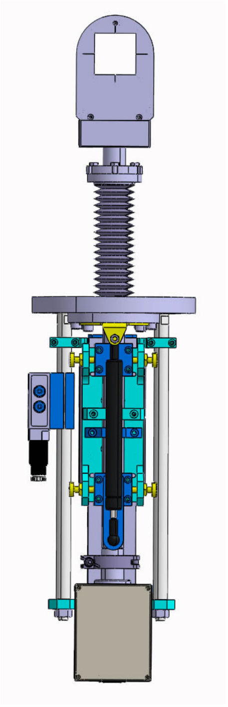
Require modifications to adapt them:

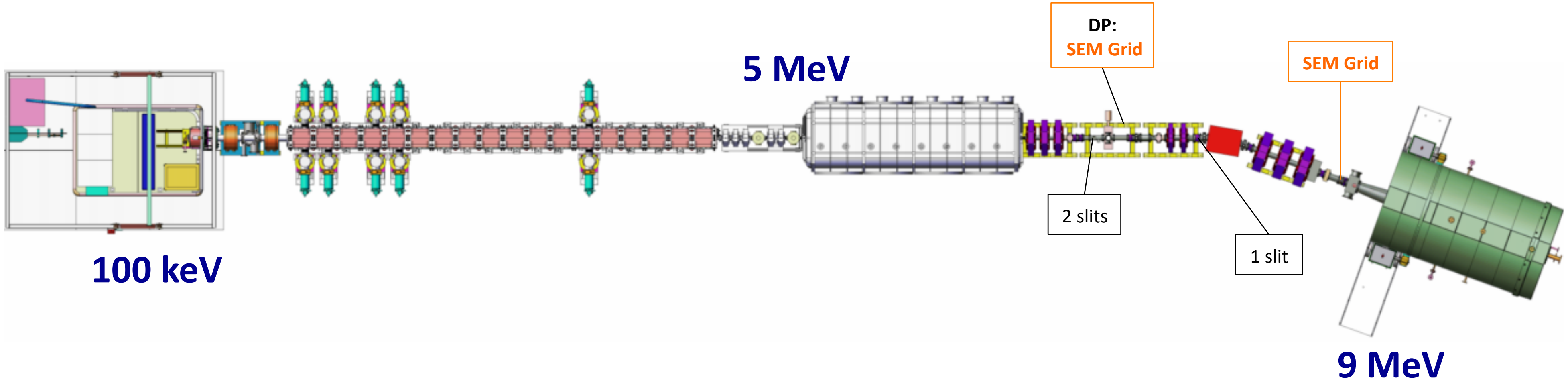
- piston, vacuum box...
- wires (material, diameter)

Note: huge background at BD position (~ 7 kSv/h)



Spiral2





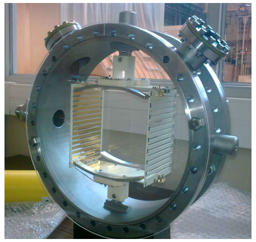
Non interceptive profilers

2 types are developed:

FPM (Fluorescence)

IPM (Ionization)

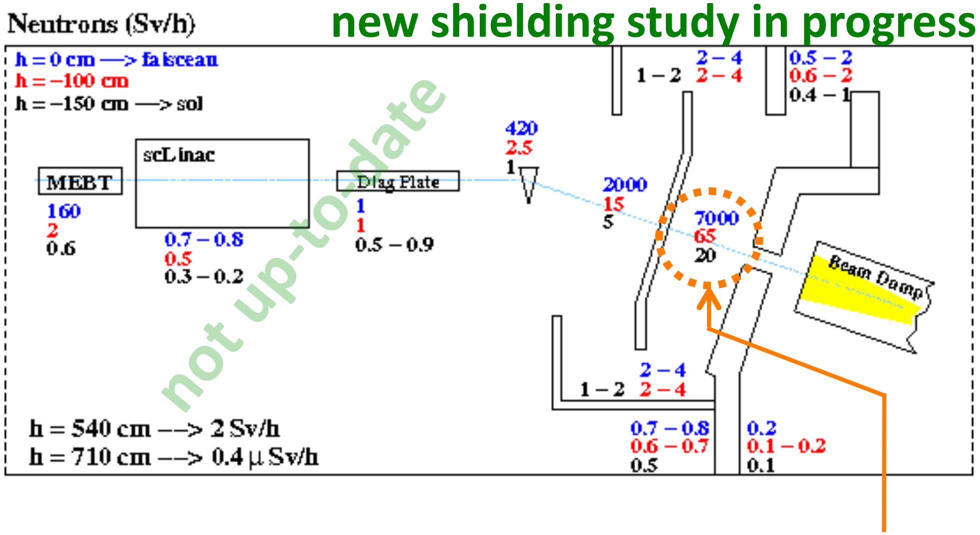
→ Jan Egberts talk



Characteristics:

Apertures:

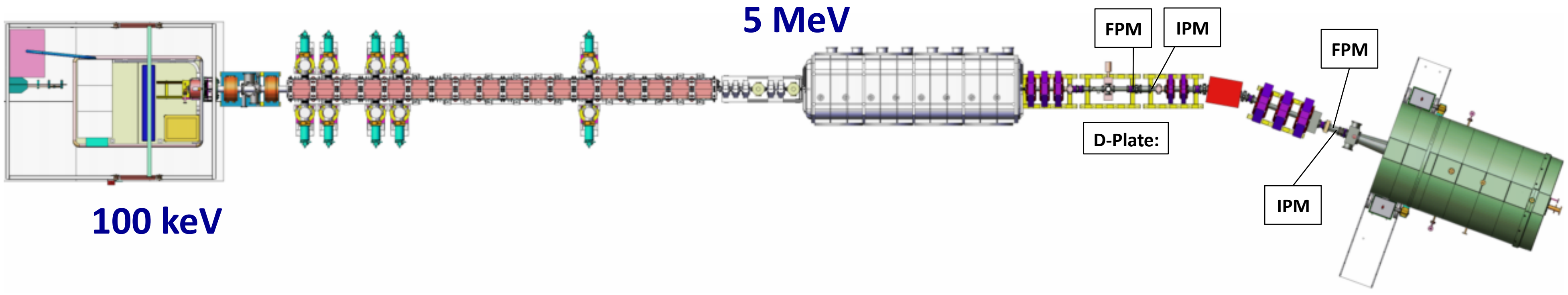
- >10 cm for DP
- >15 cm for HEBT



new shielding study in progress

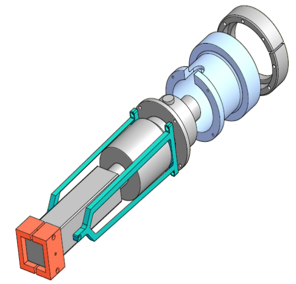
not up-to-date

IPM / FPM
SEM grid
position



9 MeV

Fluorescence Profiler



Campaign tests at CNA Sevilla:

D$^+$: 9 MeV

H$^+$: 18 MeV

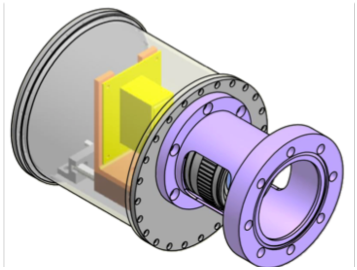
2 read-out types were tested:

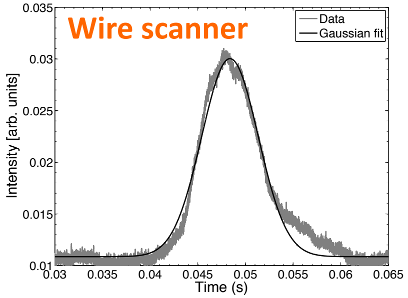
- ICID (Intensified Charge Injection Device) camera (MCP + CID):
  - - CID radiation tolerance: 30 kGy
  - - HV$_{MCP}$ = 1580 V
  - - integration time (Δt) = 20 ms
- PMT: multi anode 32 channels linear array (H7260)
  - - HV = 900 V
  - - Δt = 5 ms
- Gas: N$_2$, Ar, Xe

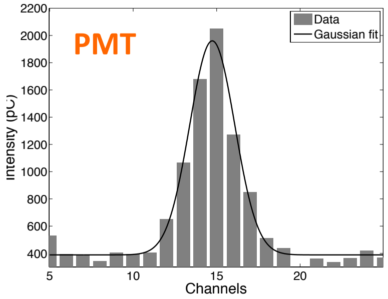
Extrapolation to LIPAc conditions (125 mA):

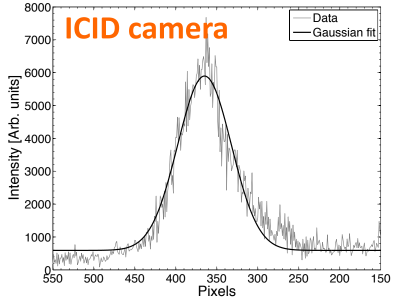
- 10^{-6} mbar → 0.01 % dc (100 μs/s)
- 10^{-8} mbar → 1% dc (10 ms/s)

Note: these conditions are not the minimum values to get a clear profile, but similar to the right plots !









Profiler	**FWHM** (95% CL)
Wire Scanner	**2.44 ± 0.03 cm**
PMT	**2.4 ± 0.3 cm**
ICID	**2.42 ± 0.07 cm**

Beam Loss Monitors

Goal:

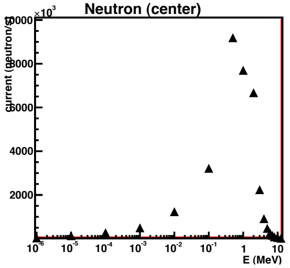
alert MPS (Machine Protection System) to avoid machine damage providing a stop signal in less than **10 µs**.
→ good reliability

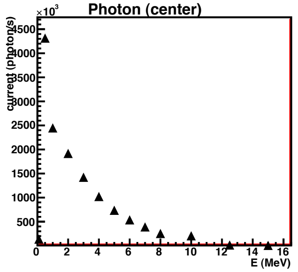
Choice: Ionization Chamber LHC type (IC)
Particles: neutrons and γ (few keV – 10 MeV)

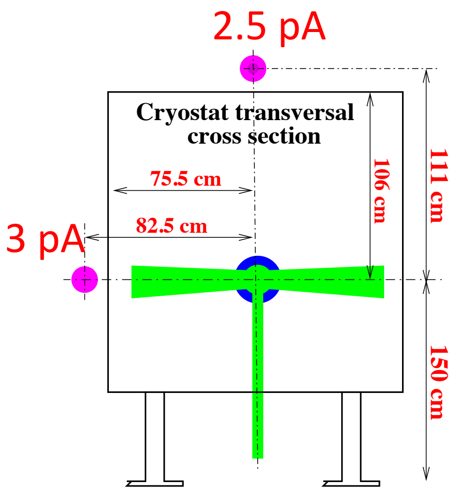
Feasibility study:

Simulation *(A. Marchix, Saclay, Sept. 2010)*:
Loss: **1 W/m** with Thalis + neutron transports
$D^+ + Fe \rightarrow$ neutron (or γ) + X

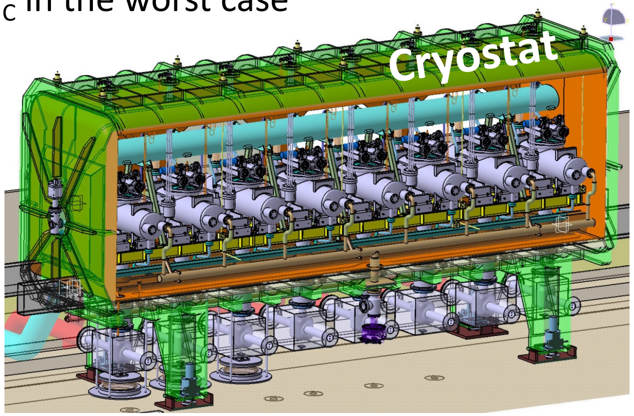
IC current using LHC responses *(M. Sapinski, Feb. 2010)* → I_{IC}

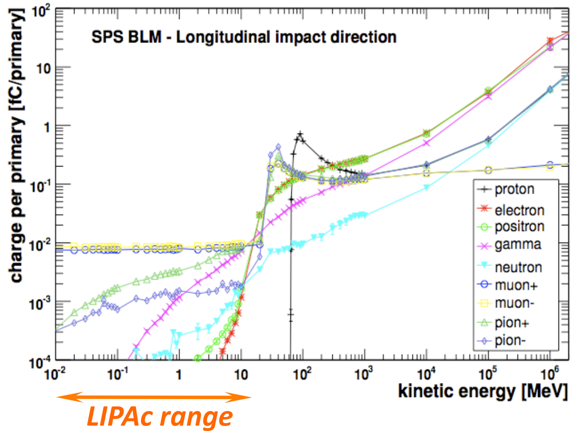






I_{IC} in the worst case





Ion Chambers

Calibration → good agreement with LHC

- γ (^{60}Co 1.25 MeV)
- neutron (3 & 14.7 MeV)

IC as beam loss monitor for LIPAc?

Hypothesis:

2 pA → 1 W/m (worst case)
20 µs to stop the injector source

I_{IC}	2 pA	1 nA	100 nA
dP (W/m)	1	500	50000
dE in 30 µs	30 µJ	15 mJ	1.5 J

Comparisons with energy deposited on spots

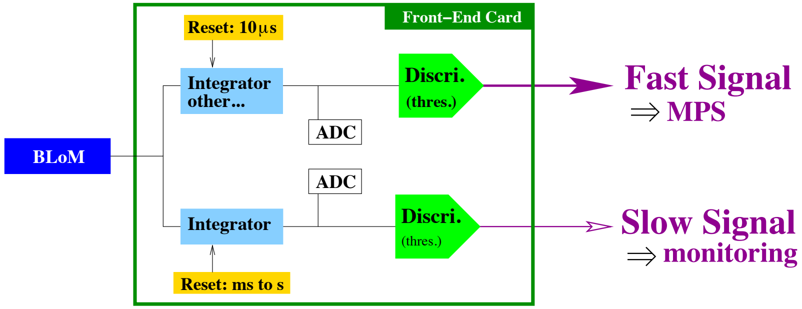
Slits for LINAC4 (B. Cheymol, EPAC 2010):

- E_p=3 MeV – I=65mA – σ=3.5/9.1 mm – Δt=100 µs/s
- graphite blade

→ T_{Max} = 1200 °C @ $\theta_{incident}$=15° / 1615°C @ θ=90°
→ dE = 19.5 J

Signal processing:

- MPS → ability to deliver an emergency signal < 10 µs
- Integrating signal (> 10 ms) → monitor current fluctuations



Amplifier:

- Choice: transimpedance, logarithmic…
- BW ~ 100 kHz

^{60}Co irradiation tests (Friday)

→ current fluctuations → threshold limit (dE)

µ-Loss Monitors

Goal: provide a very sensitive tool for very low losses (< 10^{-6} of the beam) on the beam pipe, in a reasonable time (few seconds) and with a quite good loss location, in order to tune accurately the scLinac.

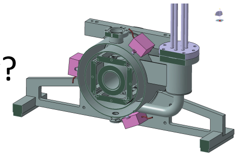
Why: only 1 BPM for each Cavity + Solenoid set (x8) in the scLinac cryomodule.

Ideal monitor: sensitive only to neutrons in order to avoid γ and X-rays emitted by RF cavities (fake signal) and T ~ 4.5 K

Choice (compromise): CVD diamond (Chemical Vapor Deposition)

3 diamonds per Solenoid

- → transverse localization + reliability
- → convertor foil to improve neutron sensitivity?



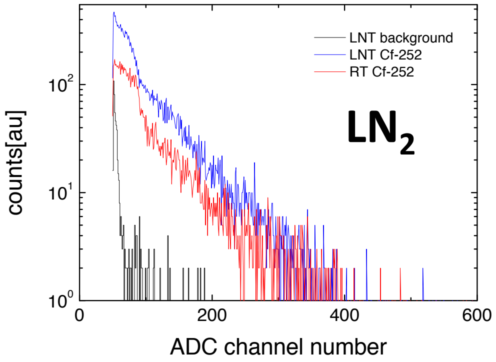
Cryogenic tests:

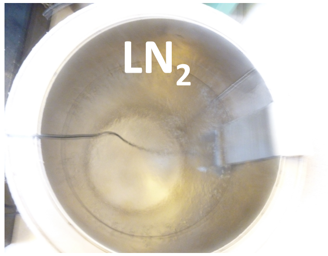
^{252}Cf: neutrons and γ

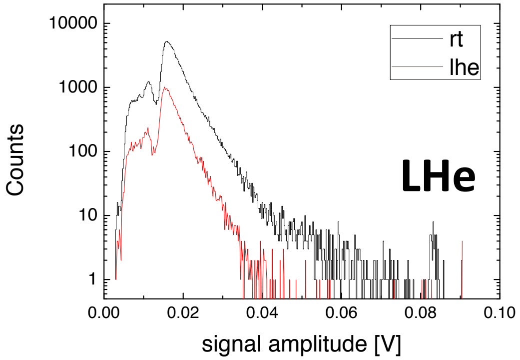
LN_2 (77K): December 2010

LHe (4.2 K): May 2011

- → signal (γ) at both temperatures. Ok
- → Workshop Cryo-BLM @ CERN (B. Dehning)







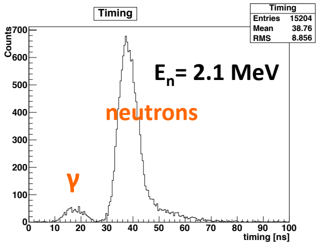
Neutrons tests at room temperature (Van de Graaff – CEA Bruyères-le-Châtel):

E_n = 0.2, 0.6, 0.75, 1.2, 2.1, 3.65, 6, 16 MeV

Goal: recoil energy spectra

ToF for neutron/γ discrimination

Analysis in progress



Challenges for LIPAc diagnostics

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

LEBT: **E_d < 100 keV**

Upstream RFQ: **5 < E_d (MeV) < 9**

Lack of Space (space charge forcing compact beam dynamics)

due to short length of LEBT to minimize emittance growth
⇒ Limited number of diagnostics and only 1 diagnostic box shared with pumping…

Compromise:

- minimizing the diagnostics number,
- save space ➝ replace DCCT (> 12 cm) / ACCT (~ 4 cm)…

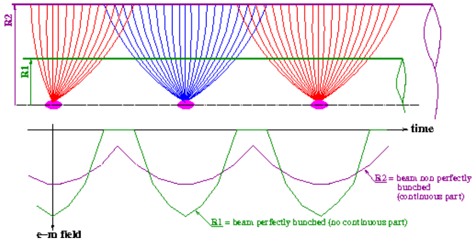
Low energy beam

Cons:

- High space charge to be overcome:
  - ➝ with Kr injection (few 10^{-5} Torr)
  - ➝ enlarging the beam diameter (few cm)
- Only ACCT due to space lacking: cw beam ➝ no beam current measurement
- Numerous secondary electrons ➝ non uniformity of space charge compensation

Pro:

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



Cons:

- e.m. field spread (low β effect): $\sigma_t \approx R/\sqrt{2}\beta\gamma c$ ➝ bunch overlapping or "de-bunching" effect (FCT, BPM)
- high energy density deposit in material ➝ slits, SEM grid, Faraday cup…
  ⇒ chopper
- beam particle stopped in beam pipe (D {9MeV} ⇒ 140 µm Fe) ➝ only neutral secondaries (γ, n) ➝ BLoM

Pro:

- "high" ionization & fluorescence processes ➝ profiler

High beam intensity (125 mA)

➝ 15 kW continuous beam ⇒ important water cooling

➝ weight the low energy cons and pros!

\+ huge charge space effects ➝ IPM

\+ huge amount of radiation background (~ 7kSv/h on IPM close to the BD)

Extra slides

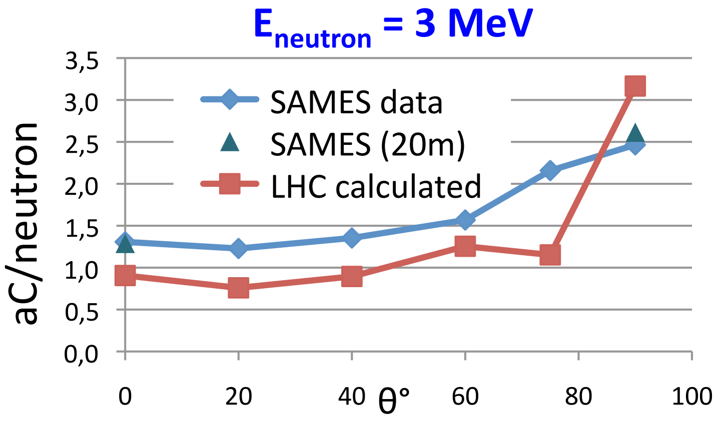
Neutron calibration: CEA Valduc

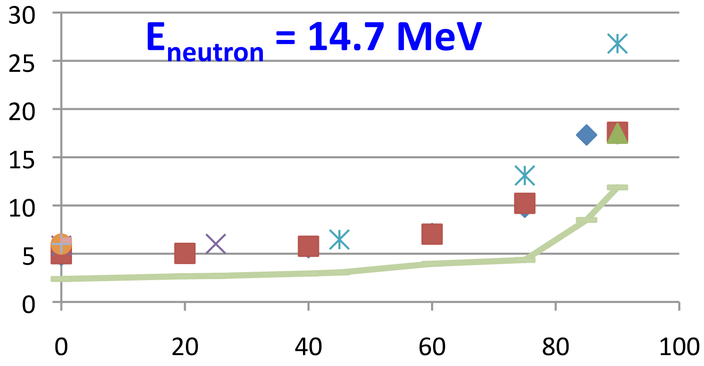
^{2}H accelerator (May 2010) :

$^2H + ^2H \rightarrow X + n$ (3 MeV)

$^2H + ^3H \rightarrow X + n$ (14.7 MeV - IFMIF)

neutron calibration in agreement with LHC simulation.





Very good linearity