IFMIF-LIPAc diagnostics
and its challenges

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**INFN Legnaro:** M. Potti
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.

<table>
<thead>
<tr>
<th>Level</th>
<th>Flux (dpa/y)</th>
<th>0.5 l</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>&gt; 20</td>
<td>0.5 l</td>
</tr>
<tr>
<td>Medium</td>
<td>&gt; 1</td>
<td>6 l</td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
<td>&gt; 8 l</td>
</tr>
</tbody>
</table>

Typical reactions:
\[ ^7\text{Li}(d,2n)^7\text{Be} \]
\[ ^6\text{Li}(d,n)^7\text{Be} \]
\[ ^6\text{Li}(n,T)^4\text{He} \]

Lithium Target
25 mm thick, 15 m/s

Test Cell

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

deuteron source
140/150 mA, 100 keV

Superconductive Linac 40 MeV
(Half Wave Resonators)

Beam profile
200 x 50 mm²

Flux \( \sim 10^{17} \) neutrons/s
LIPAc
(Linear IFMIF Prototype Accelerator)

Validation phase:
prototype accelerator → LIPAc (Rokkasho – Japan)

LIPAc = 125 mA cw, 9 MeV, 1.125 MW

Commissioning at Rokkasho beginning:
- Injector: March 2013
- RFQ: June 2015
- scLinac: July 2016

LEBT / MEBT / HEBT = Low / Medium / High Energy Beam Transport
RFQ = Radio Frequency Quadruple

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
deuteron beam:
\[ E_{\text{max}} = 9 \text{ MeV} \]
\[ I = 125 \text{ mA} \]
\[ P_{\text{max}} = 1.125 \text{ MW} \]
Duty Cycle: \(<10^{-4}\) to cw
RF: 175 MHz (5.7 ns)
Injector
Injectors challenges (0 to 100 keV)

\[ E_{\text{max}} = 100 \text{ keV} \quad & \quad I \sim 150 \text{ mA} \]

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!
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)
  ⇒ $\varepsilon_x = 0.29 \, \pi \, \text{mm.mrad}$

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

- Thermal simulation (COMSOL)
- Critical case: $T_{\text{max}} = 1191 \, ^{\circ}\text{C}$ on W surface
- Cu block covered by W tiles
- Internal water cooling system
- Brazing technique for Cu/W assembly

designed at CEA Saclay

Saclay, August 2012
LIPAc injector (Proton)
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

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
Radiation background

**Shielding** (polyethylene disks, plates...)

- neutrons
- Fluence, calculated over 1 month cw

<table>
<thead>
<tr>
<th>Point #</th>
<th>5</th>
<th>15</th>
<th>25</th>
<th>145</th>
<th>115</th>
<th>85</th>
</tr>
</thead>
<tbody>
<tr>
<td>n/cm²/s</td>
<td>7 $10^8$</td>
<td>6 $10^8$</td>
<td>5 $10^8$</td>
<td>4 $10^7$</td>
<td>6 $10^6$</td>
<td>4 $10^6$</td>
</tr>
<tr>
<td>Fluence n/cm²</td>
<td>2 $10^{15}$</td>
<td>2 $10^{15}$</td>
<td>1 $10^{15}$</td>
<td>1 $10^{14}$</td>
<td>2 $10^{13}$</td>
<td>1 $10^{13}$</td>
</tr>
</tbody>
</table>

Electronic radiation hardness

- high energy neutrons (~ MeV) ⇒ electronic trouble for Fluence > $10^{11}$ n/cm²
IPM: Ionization Profile Monitor

Design & manufacturing of an IPM prototype
- 6 x 6 cm² 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

![Profile comparison BIF/IPM in 10^7 mbar N₂](image)
![RMS versus integration time at 10^-5 mbar](image)
![IPM Linearity](image)

120 µA Xe^{21+}
10^-5 mbar N₂

1 mA Xe^{21+}
Δt=60 ms
IPM (Space Charge)

Design & manufacturing the HEBT IPM
- 15 x 15 cm² 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)
- \( E_p = 95 \text{ keV} \)
- \( I_{\text{max}} = 6 \text{ mA cw} \)
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 $I_{\text{beam}}$ 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 $\rightarrow$ 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 → $I_{IC} \sim 2 \text{ pA}$ 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

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[Illustration of the BLoM system with labels for ICs, Amplifier, Filter, HV, and Injector.]
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

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)

<table>
<thead>
<tr>
<th>Threshold (keV)</th>
<th>γ+n (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>4.3</td>
</tr>
<tr>
<td>200</td>
<td>2.7</td>
</tr>
<tr>
<td>300</td>
<td>2.1</td>
</tr>
</tbody>
</table>

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

-\[ E_n = 0.2, 0.6, 0.75, 1.2, 2.1, 3.65, 6, 16 \text{ MeV} \]
- 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
  \[ ⇒ \text{more confidence in previous counting rates.} \]
BPM: Beam Position Monitor

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 1\textsuperscript{st} or 2\textsuperscript{nd} 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:
\[ \Delta t = 100 \, \mu s / 1 \, s \times 10^{-4} \text{ duty cycle} \]
Carbon forbidden (superconductive cavities)
surface power density: 1.5 GeV/m²

→ Plates of high fusion temperature: W, TZM (molybdenum alloy)
→ radiator with water cooling system

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
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 (\(^{60}\text{Co}\) 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


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

**INFN Legnaro:** M. Poggi
Backups
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 $^{136}\text{Xe}^{28+}$ beam at 546 MeV $\rightarrow \Delta t = 300$ ps (FWHM)
Beam Loss Monitor

- Beam Loss Monitor

- IFMIF - LIPAc diagnostics & challenges – IBIC 2012

- L1
- L2
- BLOM signal
- Beam pulse
- Beam gate
- Beam trigger
- Time
- Monitoring
- set Gain
- set Threshold
- HV
- 20 m
- Filter
- Amplifier
- Discr 2
- Discr 1
- Settable Gain (8 resistors)
- 8 resistors
- MVME5500 (vault)
- NIM crate
- ICV 196
- ICV 150 (32 ch)
- ICV 110 (48 ch)
- Trigger
- Epics
- NIM crate
- ribbon cable
- From BLoM (vault)
- Injector
- Monitoring
- Post-mortem
- MPS
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}): Δt < 1 ms (1 Hz).
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
• \( \mu \): profile center
• Two degrees of freedom
  \( \sigma \): 2\(^{nd}\) moment
  \( \beta \): kurtosis, 4\(^{th}\) moment

\[
p_{\alpha,\beta,\mu}(x) = \frac{\beta}{2\alpha \Gamma(1/\beta)} e^{-\left(\frac{|x-\mu|}{\alpha}\right)^{\beta}}
\]
4- First parameter to initiate iteration process

- fit of the experimental profile using a generalized Gaussian to extract
  \[ \sigma_0 = \sigma_{\text{exp}} \]
  \[ \beta_0 = \beta_{\text{exp}} \]
- beam intensity given by CT

Parameter iteration
\( \sigma_i - \text{Kurtosis} (\beta_i) \)

Hypothesis:
Beam: D', I, \( \sigma_i, \beta_i \)
IPM: HV (E field)
Algorithm
\[ \sigma_{\text{exp}}, \beta_{\text{exp}} \]

Test: not OK

Fit

\( \sigma_{\text{cal}} = \sigma_{\text{exp}} \)
\( \beta_{\text{cal}} = \beta_{\text{exp}} \)

Test = OK