IFMIF High energy beam line design and beam expansion using non-linear multipole lenses and "step-like" magnet

N. Chauvin [1] R. Duperrier [1] P.A.P. Nghiem[1] J. Y. Tang[2] D. Uriot[1] Z.Yang[2]

[1]Commissariat à l'Energie Atomique et aux Energies Alternatives, DSM/Irfu; F-91191 Gif-sur-Yvette, France.

[2]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Monday 26th March 2012

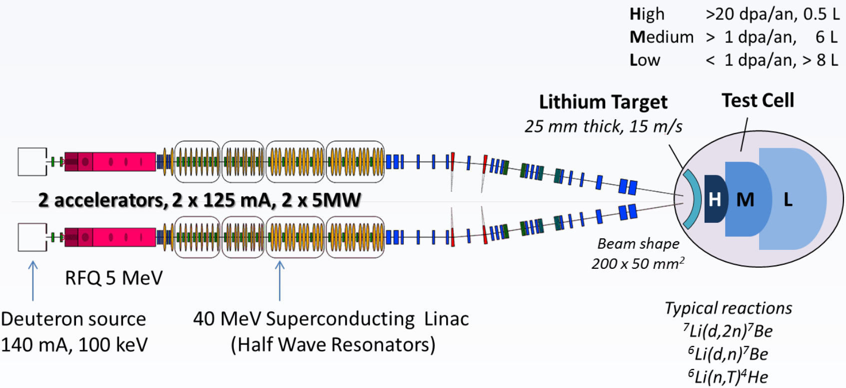
Outline

1. IFMIF accelerator overview
2. Beam dynamics simulations for LIPAc
3. Beam dynamics simulations for IFMIF
4. Beam expansion in IFMIF HEBT with high-order multipoles
5. Beam expansion with step-like field magnets (Zheng YANG's work)
6. Conclusions and perspectives

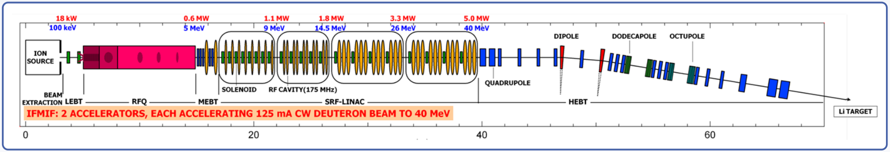
Outline

1. IFMIF accelerator overview
2. Beam dynamics simulations for LIPAc
3. Beam dynamics simulations for IFMIF
4. Beam expansion in IFMIF HEBT with high-order multipoles
5. Beam expansion with step-like field magnets (Zheng YANG's work)
6. Conclusions and perspectives

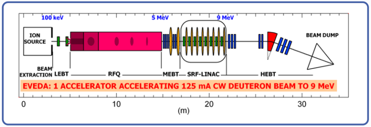
IFMIF principle



IFMIF & LIPAc



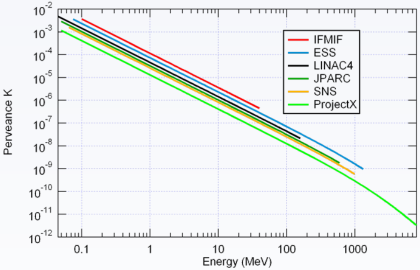
IFMIF Accelerator: 2×5 MW

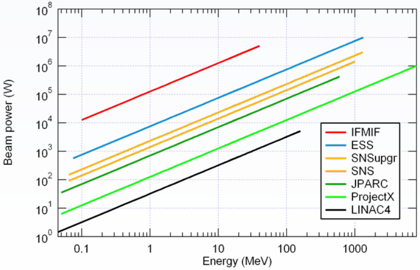


Linear IFMIF Prototype Accelerator (LIPAc): 1.125 MW

IFMIF accelerator characteristics & orders of magnitude

- Deuteron beam.
- Intensity: 125 mA, c.w. (5 MW @ 40 MeV).
- Energy: 40 MeV $(\beta = 0.166)$.
- Energy: 9 Mev $(\beta = 0.094)$ for LIPAc.
- Minimize the losses along the accelerator.
- Keep a good beam quality.
- Final beam spot on target 200×50 mm, with $\pm$ 5 % uniformity.





Outline

1. IFMIF accelerator overview
2. **Beam dynamics simulations for LIPAc**
3. Beam dynamics simulations for IFMIF
4. Beam expansion in IFMIF HEBT with high-order multipoles
5. Beam expansion with step-like field magnets (Zheng YANG's work)
6. Conclusions and perspectives

Codes used

Linac beam dynamics simulations

- **GenLinWin**: SC linac design.
- **Toutatis**: RFQ simulation.
- **TraceWin**:
  - multi-particles (10^6 particles) simulations in space charge regime.
  - errors studies.
  - LIPAc start-to-end simulations.

Codes used

Linac beam dynamics simulations

- **GenLinWin**: SC linac design.
- **Toutatis**: RFQ simulation.
- **TraceWin**:
  - multi-particles (10^6 particles) simulations in space charge regime.
  - errors studies.
  - LIPAc start-to-end simulations.

Source extraction and LEBT simulations

- **AXCEL-INP**: source extraction system simulation.
- **SOLMAXP**:
  - Self-consistant code to simulate beam transport with space charge compensation.
  - Simulation of the physical processes that occur in the LEBT (ionisation, secondary electrons, charge exchange).

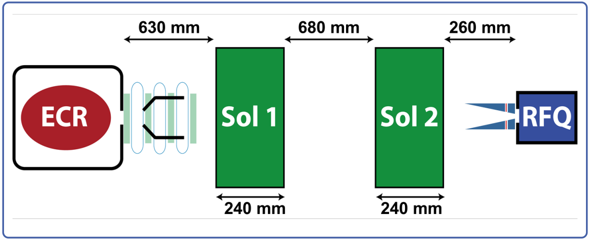
The LIPAc injector

Main parameters

- D^+ beam.
- Energy : 100 keV.
- Intensity : 140 mA.
- Final emittance : $\leqslant 0.25\ \pi$ mm.mrad

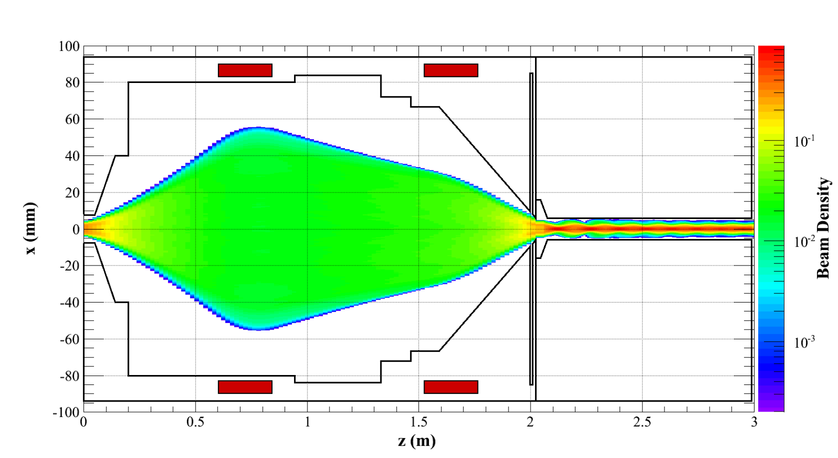
IFMIF injector

- SILHI-like source.
- 4 electrodes extraction system.
- LEBT with 2 solenoids.
- Kr injection in the LEBT for space charge compensation.



Total lenght: 2.05 m

LIPAc injector beam dynamics results

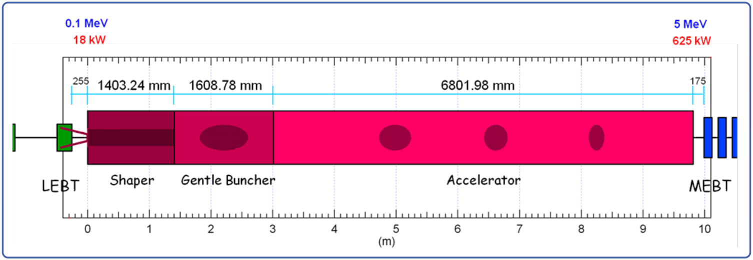


LEBT output: $\epsilon_{RMS} = 0.16\ \pi$ mm.mrad
RFQ transmission: 96 % (5 % mismatch)

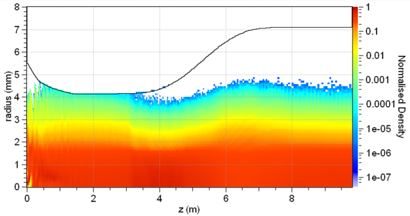
LIPAc RFQ (M. Comunian, INFN Legnaro)

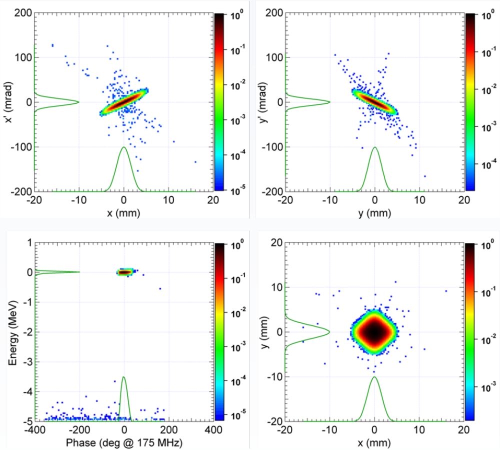
Some RFQ parameters

- Frequency: 176 MHz.
- Input energy: 100 keV.
- Output energy: 5 MeV.
- Total length: 9.814 m.
- Number of cells: 486.
- Maximum modulation: 1.8.
- Minimum aperture: 3.47 cm.
- Maximum field: 24.7 MV/m (1.76 kp).



RFQ beam dynamics results (M. Comunian, INFN Legnaro)





RFQ transmission: 96 %

Output emittance:

- $\epsilon_{trans.}$ = 0.20 π mm.mrad.
- $\epsilon_{long.}$ = 0.47 π mm.mrad.

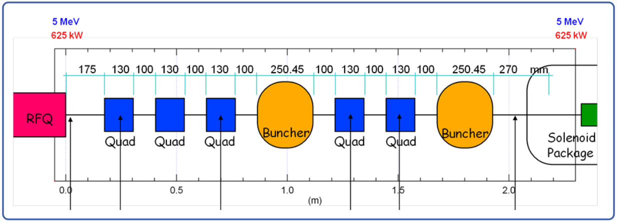
LIPAc Medium Energy Beam Transport line

MEBT purposes

- Transport the beam from the RFQ to the SC linac.
- Adapt the beam for the linac (longitudinally and transversally).
- Beam scrapping.

MEBT elements

- 5 quadrupoles.
- 2 bunchers.
- 4 BPMs.
- 3 scrappers.



Total length: 2.18 m

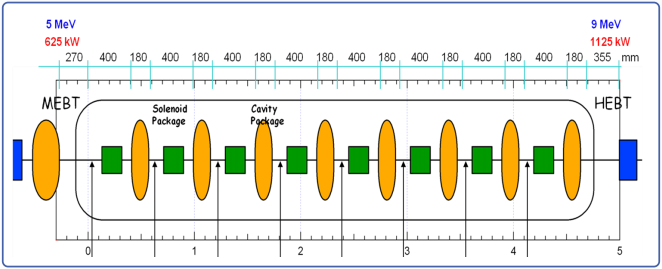
LIPAc superconducting accelerating section

Specifications

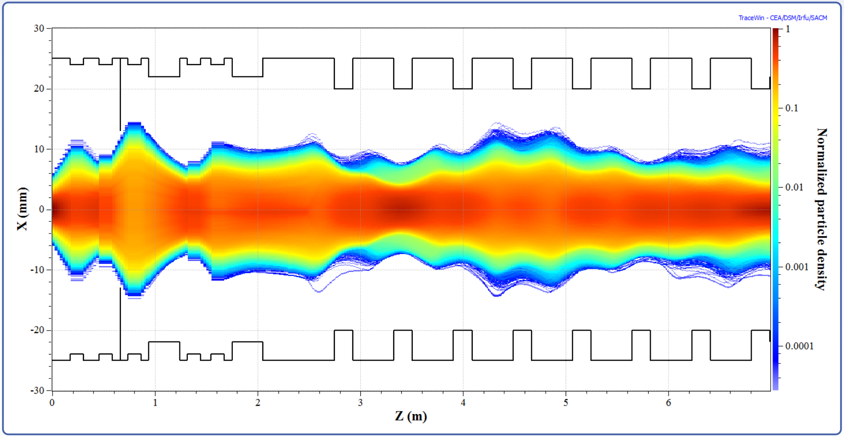
- Acceleration from 5 MeV to 9 MeV.
- Beam intensity : 125 mA.
- Minimize the beam losses (< 1 W/m).

SC section

- 1 cryomodule.
- 8 periods.
- Trans. focusing: 1 solenoid/period.
- Acceleration: 1 HWR cavitiy/period ($\beta = 0.094$).

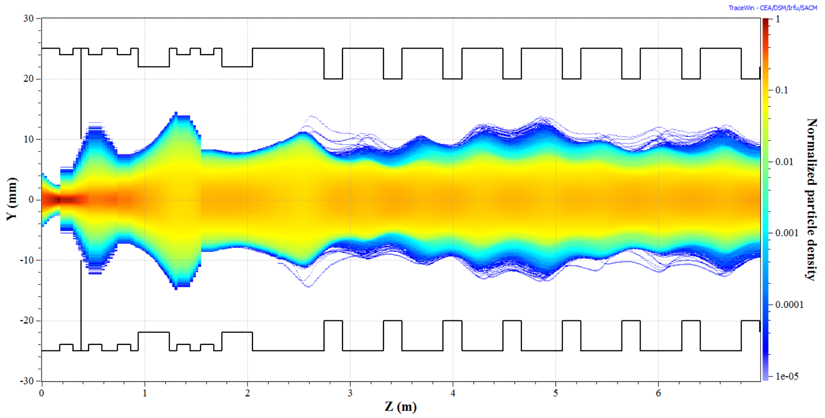


LIPAc MEBT and SC section BD results



Beam Density – X plane

LIPAc MEBT and SC section BD results

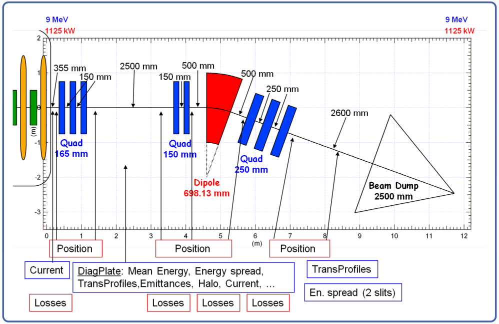


Beam Density – Y plane

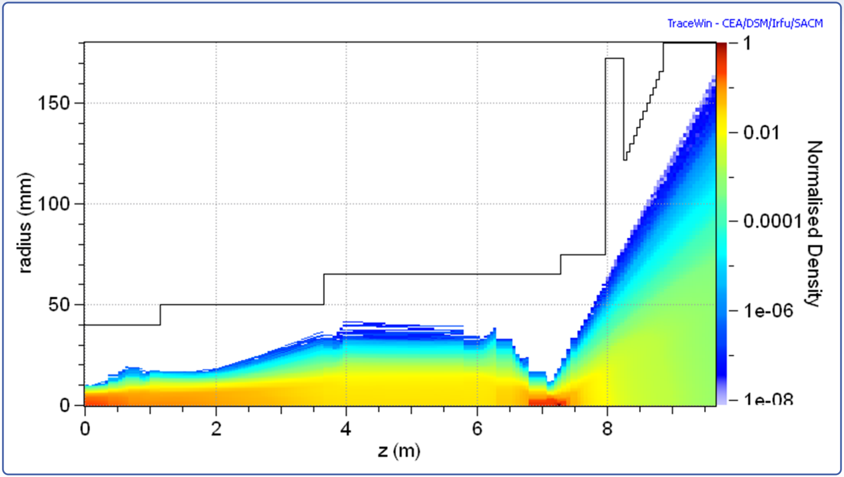
LIPAc High Energy Beam Transport line (designed by C. Olivier, CIEMAT Madrid)

HEBT purposes

- Beam diagnostics ("D plate") for LIPAc characterisation.
- Beam transport to the beam dump.
- Beam expansion to the beam dump (≤ 300 W/cm^2).

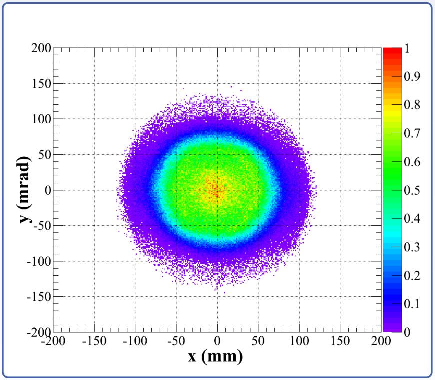


LIPAc HEBT beam dynamics results

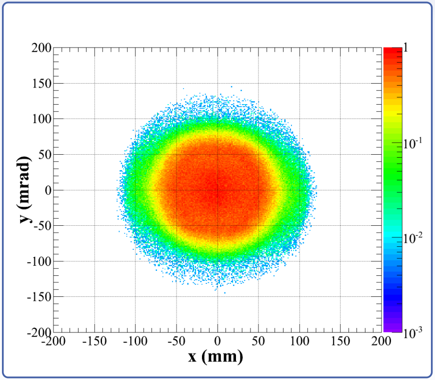


R beam density

LIPAc HEBT beam dynamics results



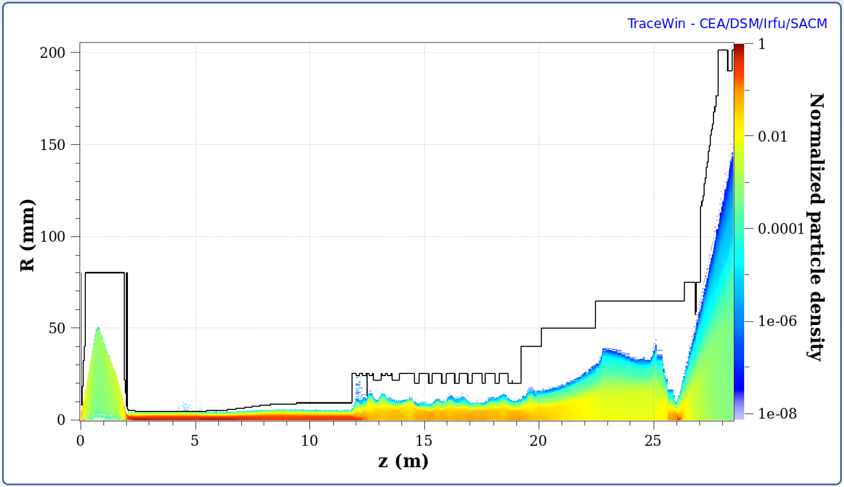
Linear scale



Log. scale

Beam distribution on the beam dump

LIPAc start-to-end dynamics results



R beam density

Outline

1 IFMIF accelerator overview

2 Beam dynamics simulations for LIPAc

3 **Beam dynamics simulations for IFMIF**

4 Beam expansion in IFMIF HEBT with high-order multipoles

5 Beam expansion with step-like field magnets (Zheng YANG's work)

6 Conclusions and perspectives

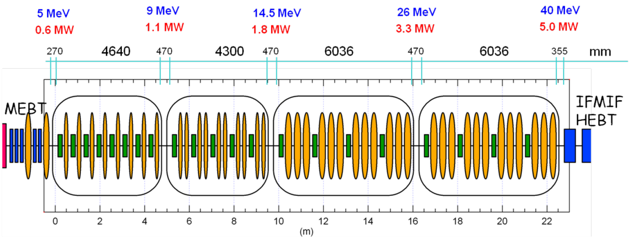
IFMIF superconducting accelerating section

Specifications

- Acceleration from 5 MeV to 40 MeV.
- Beam intensity : 125 mA.
- Minimize the beam losses (< 1 W/m).

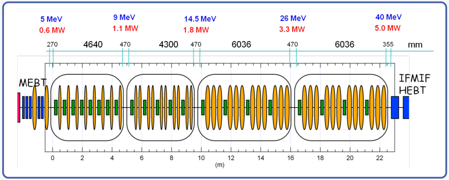
SC linac parameters

- 4 cryomodules.
- Transverse focusing: solenoids.
- 2 types of HWR cavities (β = 0.094 et β = 0.166)



IFMIF superconducting linac

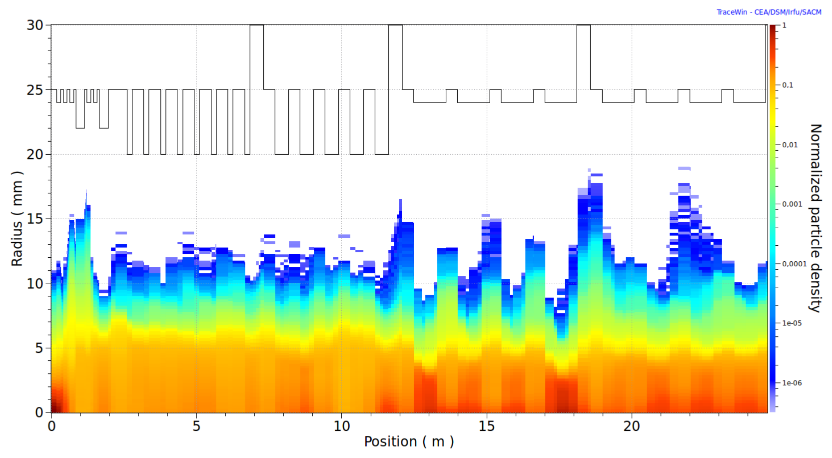
Cryomodules	1	2	3 & 4
Cavity β	0.094	0.094	0.166
Cavity Length (mm)	180	180	280
Beam Aperture (mm)	40	40	48
Nb cavity/period	1	2	3
Nb cavity/cryostat	1×8	2×5	3×4
Cryostat Length (m)	4.64	4.30	6.03
Output Energy (MeV)	9	14.5	26/40



Beam dynamics optimisations

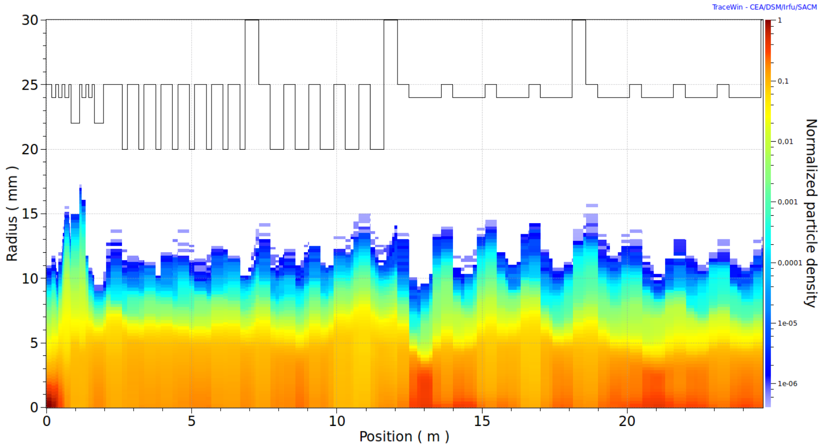
- Beam in the MW range and losses < 1 W/m $\Rightarrow$ **simulations with at least 10^6 particles**.
- Optimisations $\Rightarrow$ **losses minimization** ("halo matching" rather than "RMS matching").

IFMIF SC-linac beam dynamics results



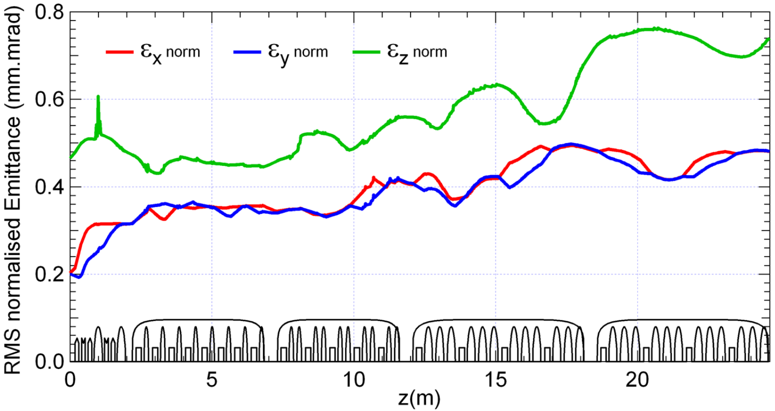
Beam density with "RMS matching"

IFMIF SC-linac beam dynamics results



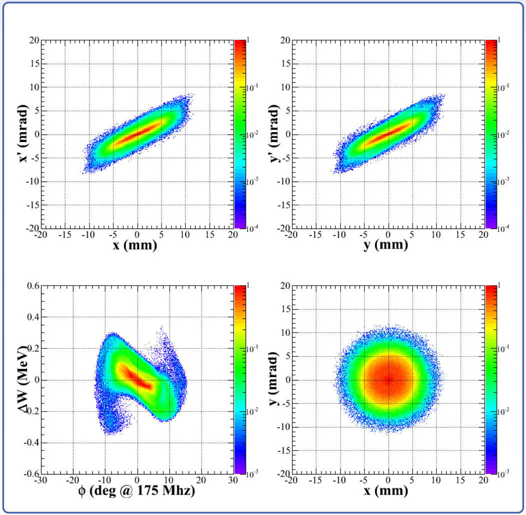
Beam density with "halo matching"

IFMIF SC-linac beam dynamics results



Final Transverse emittance: 0.45 πmm.mrad.

IFMIF SC-linac beam dynamics results



Beam distribution after the IFMIF SC-linac.

Outline

1. IFMIF accelerator overview
2. Beam dynamics simulations for LIPAc
3. Beam dynamics simulations for IFMIF
4. **Beam expansion in IFMIF HEBT with high-order multipoles**
5. Beam expansion with step-like field magnets (Zheng YANG's work)
6. Conclusions and perspectives

IFMIF HEBT

Requirements

- Transport the 125 mA – 40 MeV beam from the linac to the Li target.
- Beam footprint: rectangular with dimensions of 200×50 mm.
- Beam homogenity: 5% (to be reconsidered).
- Minimizing beam losses in the HEBT.
- Bending angle to protect the accelerator from the back streamed neutrons.

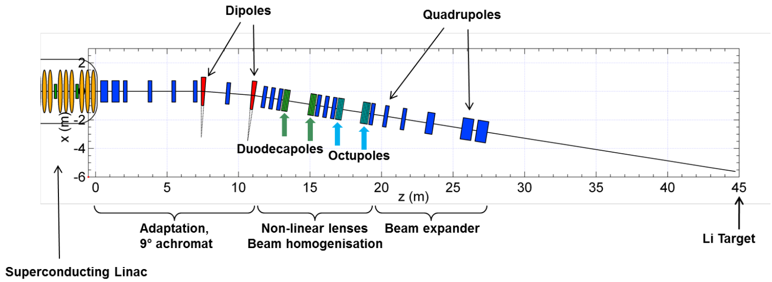
Simulations

- Multi-particles simulations are necessary.
- Recent development of a new diagnostic for TraceWin:

```
MY_DIAG(Beam_Homogeneity) n Target_Value Dimension_X Dimension_Y
Relative_Weight_Dimension/homogenity
```

IFMIF HEBT

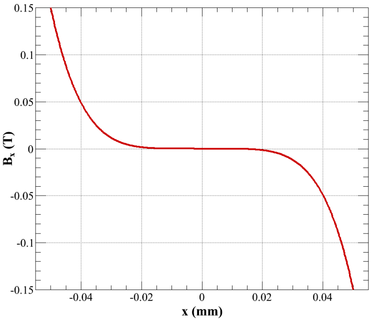
Design based on non-linear multipoles[Duperrier et al., 2004].

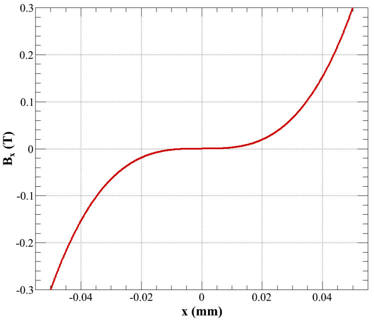


R. Duperrier, J. Payet and D. Uriot (2004).
The IFMIF High Energy Beam Transport line.
In *Proceedings of EPAC 2004*, Lucerne, Switzerland.

Non-linear Multipole field maps

1D Field Maps



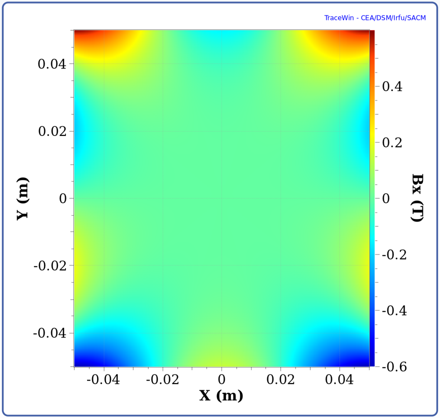


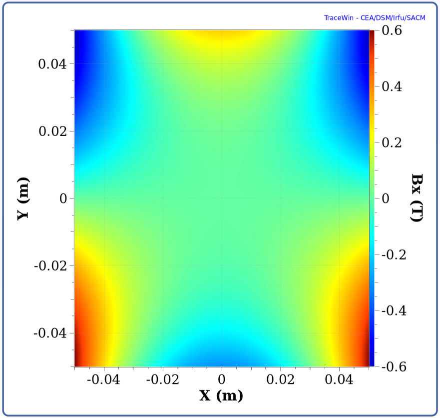
Duodecapoles – 50 mm radius

Octupoles – 50 & 80 mm radius

Non-linear Multipole field maps

2D Field Maps

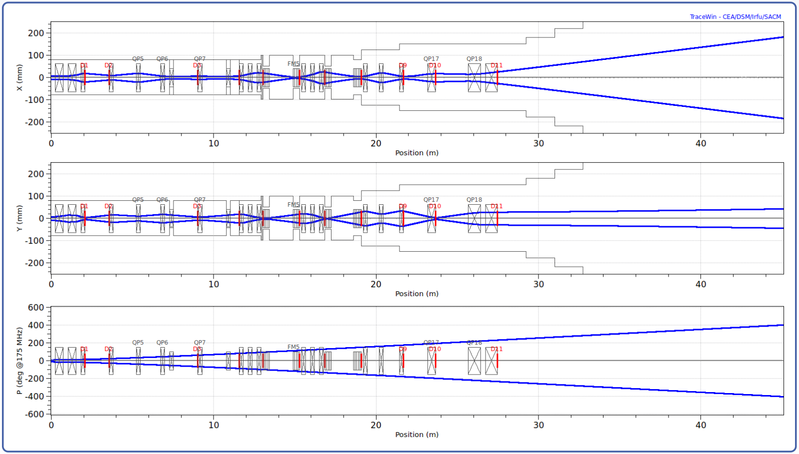




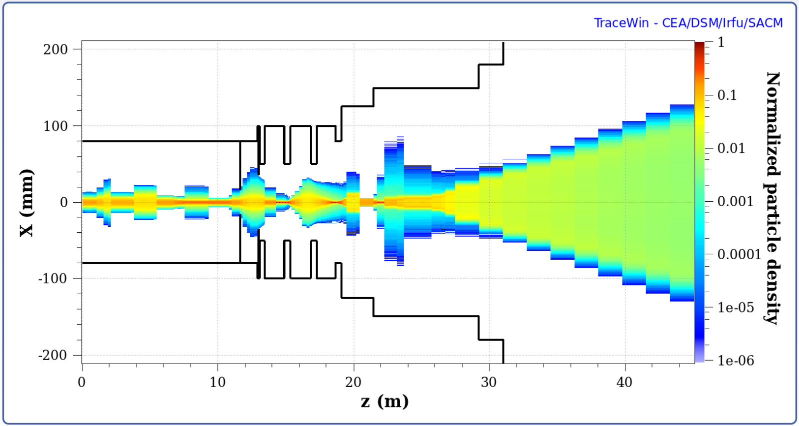
Duodecapoles – 50 mm radius

Octupoles – 50 & 80 mm radius

Beam Envelope (3σ) in IFMIF HEBT

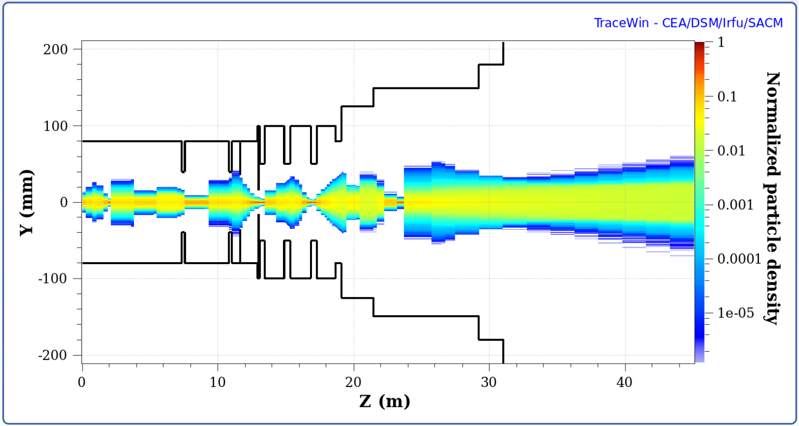


Beam Density in IFMIF HEBT



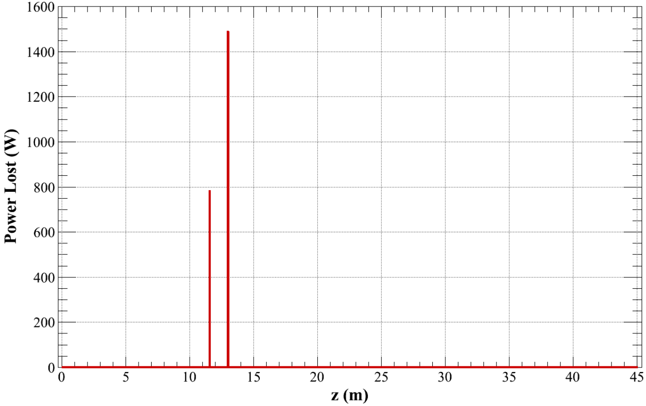
Beam Density – X plane

Beam Density in IFMIF HEBT



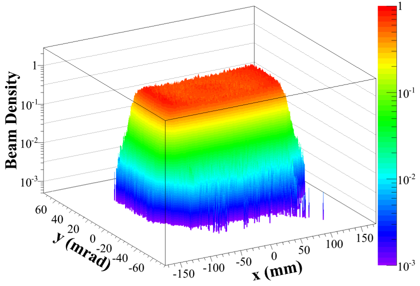
Beam Density – Y plane

Power lost in the IFMIF HEBT



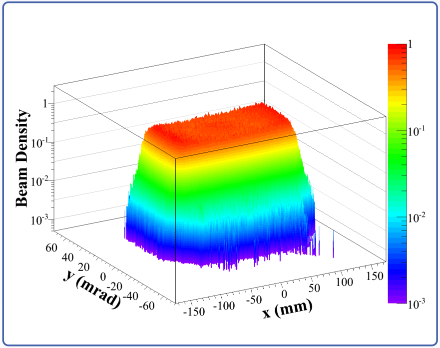
Total power lost: 2.276 kW – Losses on scrappers

Beam Distribution on target

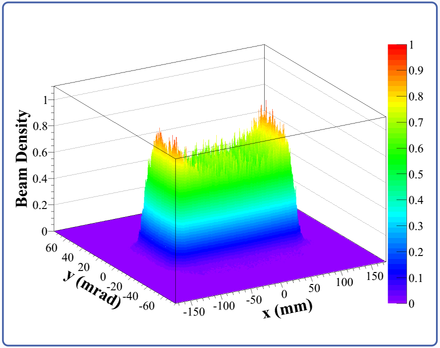


Log. scale

Beam Distribution on target

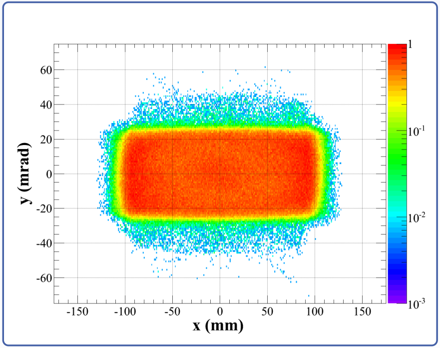


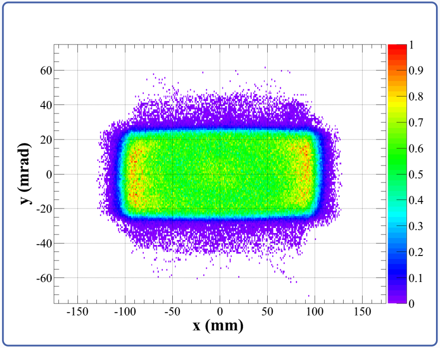
Log. scale



Linear scale

Beam Distribution on target





Log. scale

Linear scale

Errors study

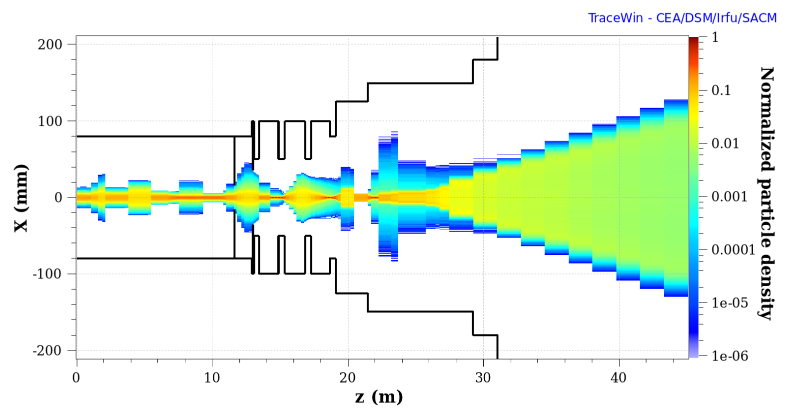
Errors applied (orders of magnitude)

- Static errors:
  - Magnetic elements Misalignment [x,y] : ± 0.1 mm.
  - Magnetic elements Tilt [φ_x,φ_y]: ± 0.5 mrad
  - Magnetic elements Tilt [φ_z]: ± 8.7 mrad
  - Magnetic elements Gradient: ± 0.25 %
  - BPMs Measurement Accuracy: ± 0.1 mm
- Dynamic errors: $\approx$ 10% of the static errors.
- Monte-Carlo simulation method: 10^6 particles through 200 HEBTs.

Correction scheme

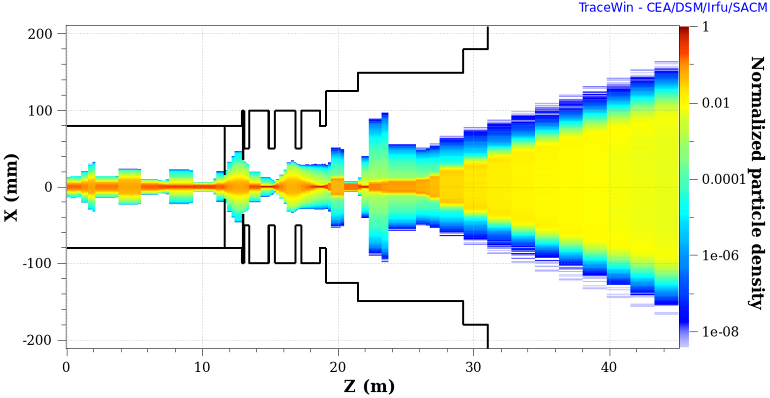
- 12 steerers and 12 BPMs in the beam line (working by pairs).
- Orbit correction.
- No re-tuning of the magnetic elements.

IFMIF HEBT: Errors study results



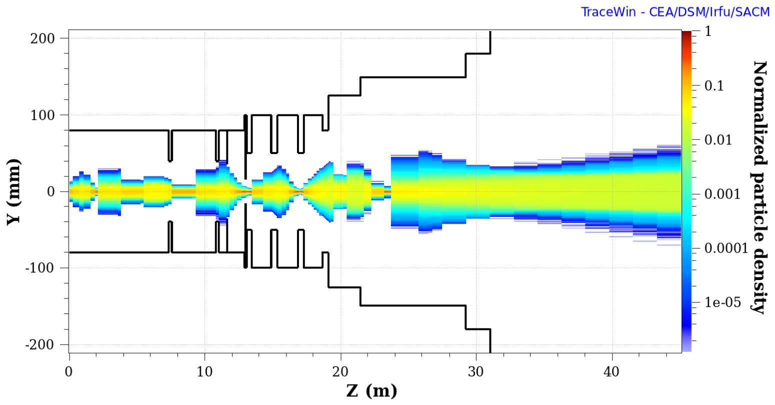
Beam Density – X plane – WITHOUT error

IFMIF HEBT: Errors study results



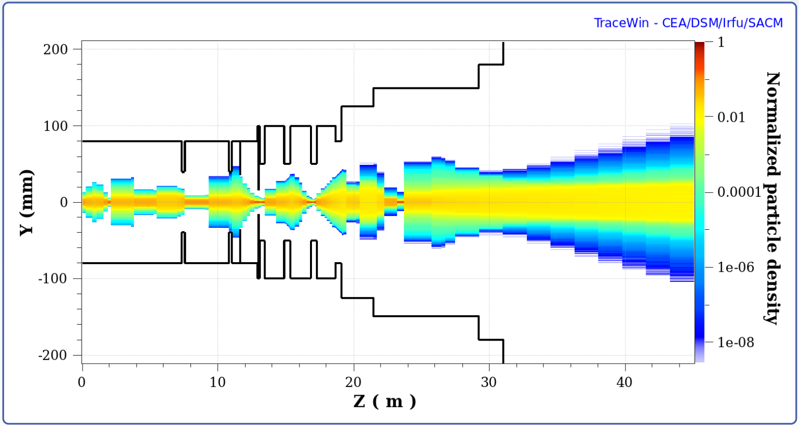
Cumulated Beam (200 runs) Density – X plane – WITH errors

IFMIF HEBT: Errors study results



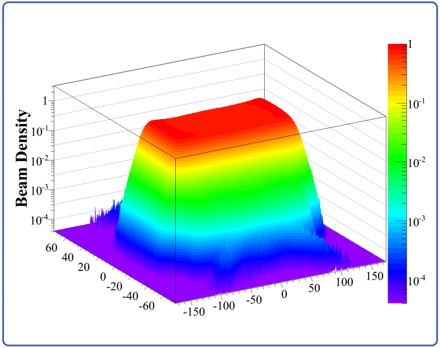
Beam Density – Y plane – WITHOUT error

IFMIF HEBT: Errors study results

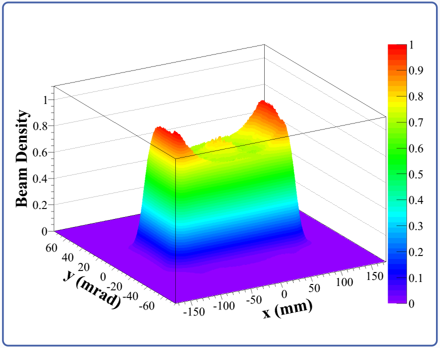


Cumulated (200 runs) Beam Density – Y plane – WITH errors

IFMIF HEBT: Errors study results

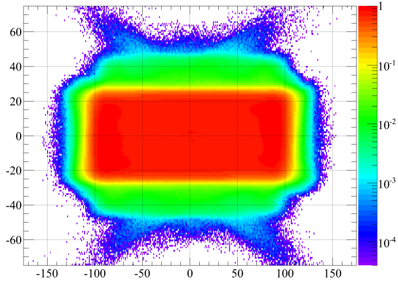


Cumulated beam distribution
(200 runs) on target
Log. scale

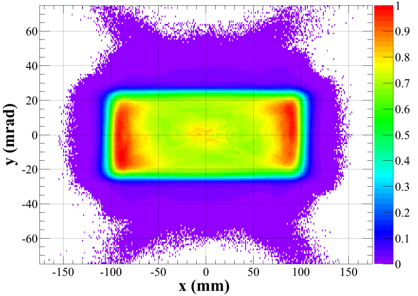


Cumulated beam distribution
(200 runs) on target
Linear scale

IFMIF HEBT: Errors study results



Cumulated beam distribution (200 runs) on target Log. scale



Cumulated beam distribution (200 runs) on target Linear scale

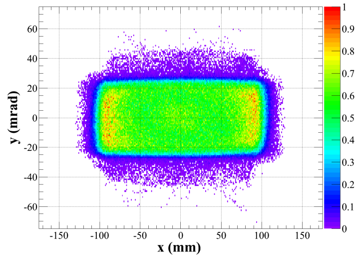
IFMIF HEBT with non-linear multipoles: Pros and Cons

Pros

- Well-known solution.
- Flexibility of the beam line (tuning).

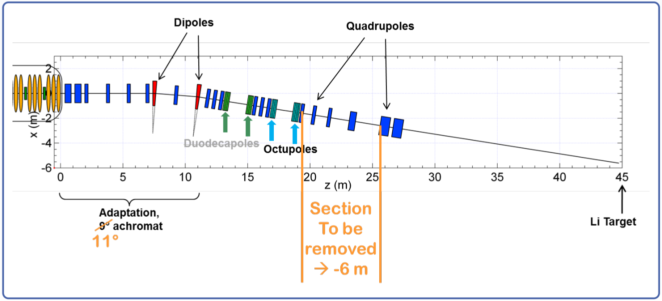
Cons

- The beam line tuning is challenging.
- Small radius of the non-linear elements.
- Beam scrapping is needed.



IFMIF HEBT with non-linear multipoles: to be studied

- More optimizations for the presented HEBT design are needed.
- A new design with a shorter/simpler HEBT will be proposed:

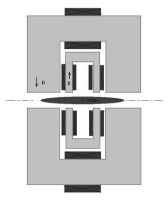


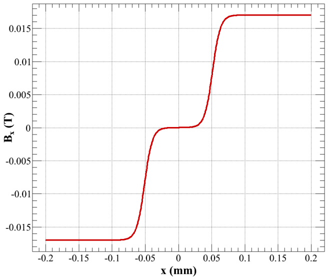
Outline

1. IFMIF accelerator overview
2. Beam dynamics simulations for LIPAc
3. Beam dynamics simulations for IFMIF
4. Beam expansion in IFMIF HEBT with high-order multipoles
5. **Beam expansion with step-like field magnets (Zheng YANG's work)**
6. Conclusions and perspectives

IFMIF HEBT with SFM magnets (Zheng YANG)

Design based on Step-Like Field non-linear Magnets [Tang et al., 2004].

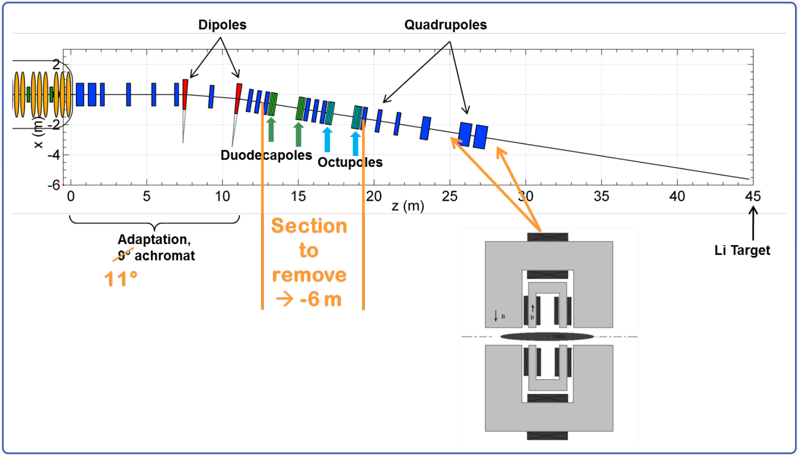




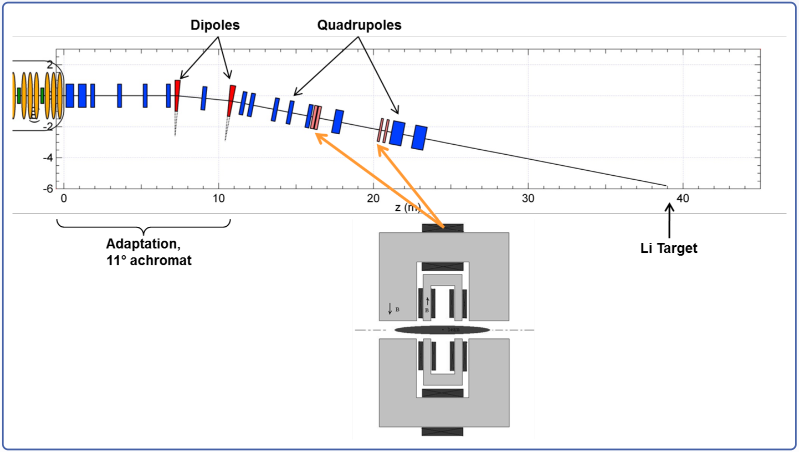
$$B_x = \frac{B_0}{1 + e^{-b(|x| - X_0)}}$$

J.Y. Tang, H. H. Li, S.Z. An, and R. Maier (2004).
Distribution transformation by using step-like nonlinear magnets.
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 532(3):538 – 547.

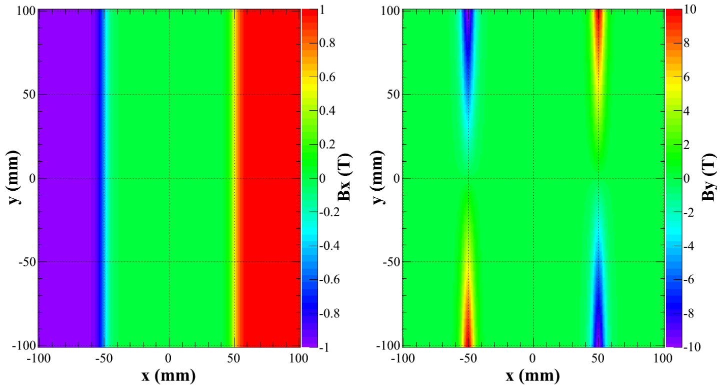
IFMIF HEBT design with SFM magnets (Z. YANG)



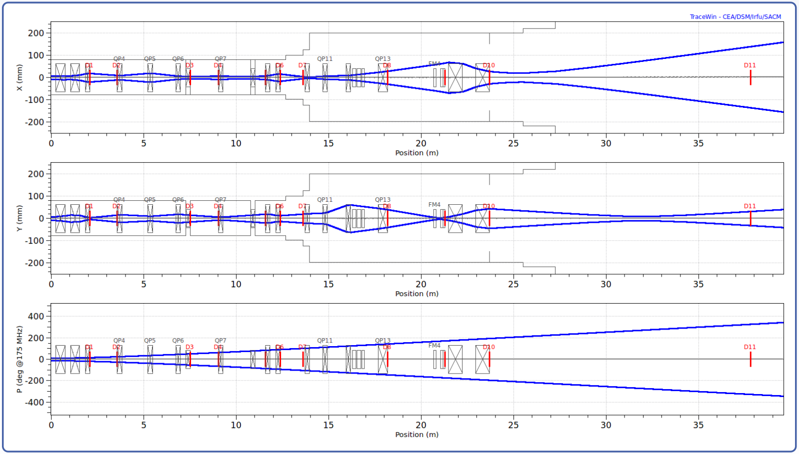
IFMIF HEBT design with SFM magnets (Z. YANG)



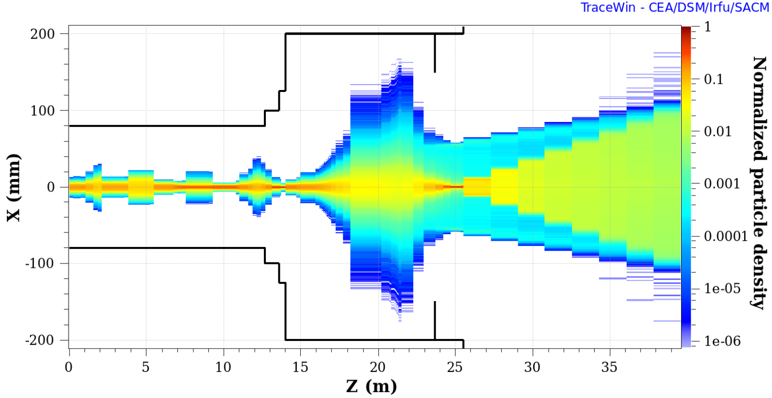
Step-Like Field magnet field map (Z. YANG)



Beam Envelope (3σ) in IFMIF HEBT (Z. YANG)

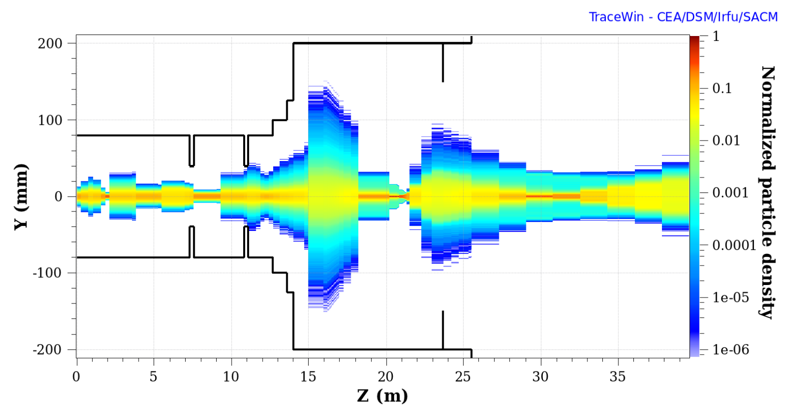


Beam Density in IFMIF HEBT (Z. YANG)



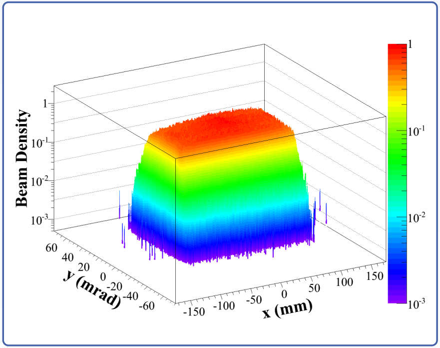
Beam Density – X plane

Beam Density in IFMIF HEBT (Z. YANG)

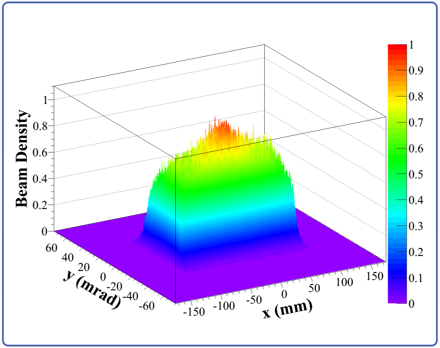


Beam Density – Y plane

Beam Distribution on target (Z. YANG)

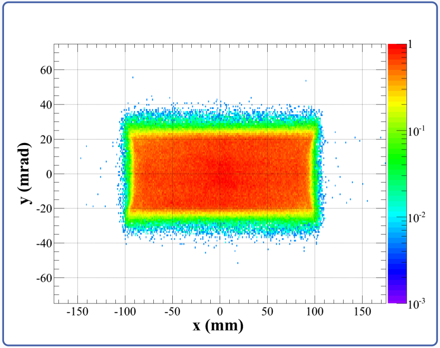


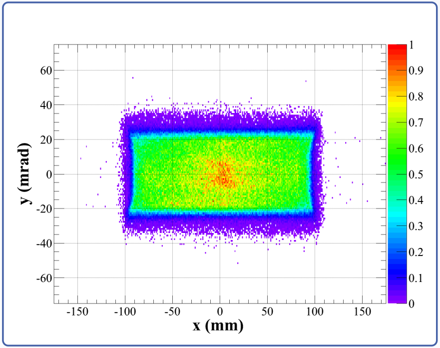
Log. scale



Linear scale

Beam Distribution on target (Z. YANG)

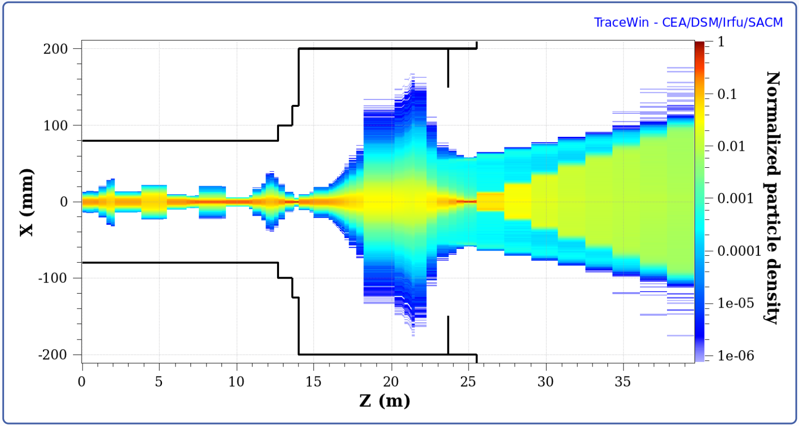




Log. scale

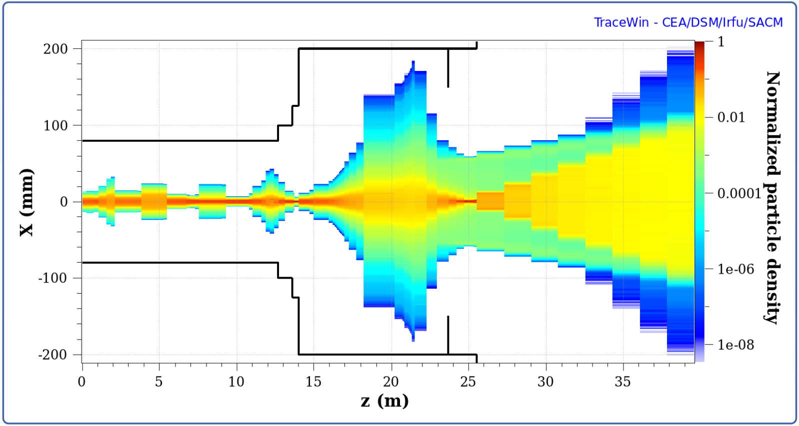
Linear scale

IFMIF HEBT with SFM: Errors study results (Z. YANG)



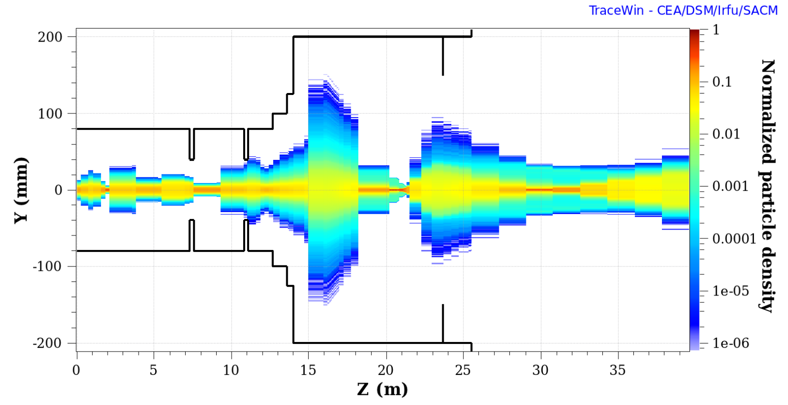
Beam Density – X plane – WITHOUT error

IFMIF HEBT with SFM: Errors study results (Z. YANG)



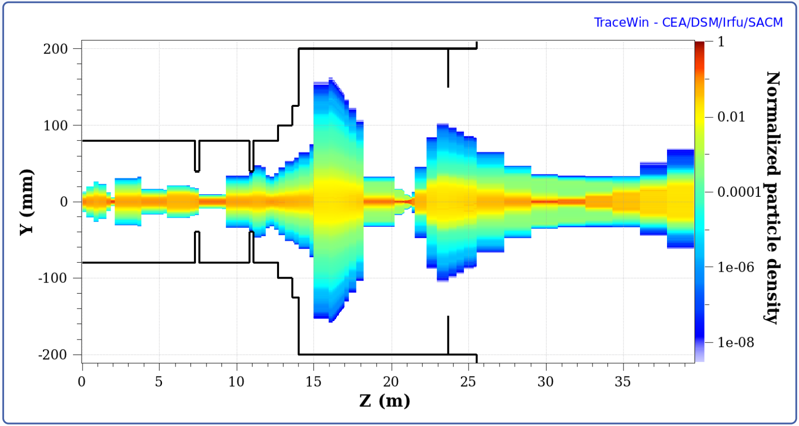
Cumulated (200 runs) Beam Density – X plane – WITH errors

IFMIF HEBT with SFM: Errors study results (Z. YANG)



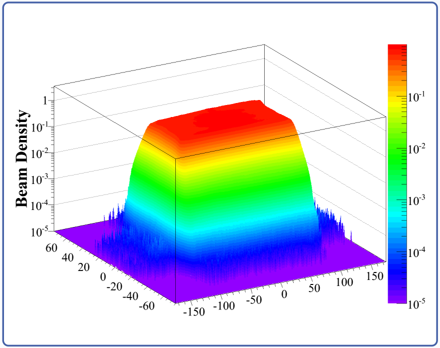
Beam Density – Y plane – WITHOUT error

IFMIF HEBT with SFM: Errors study results (Z. YANG)

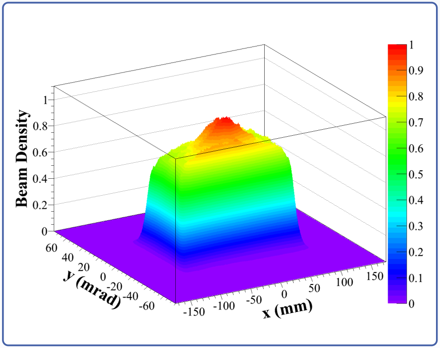


Cumulated (200 runs) Beam Density – Y plane – WITH errors

IFMIF HEBT with SFM: Errors study results (Z. YANG)

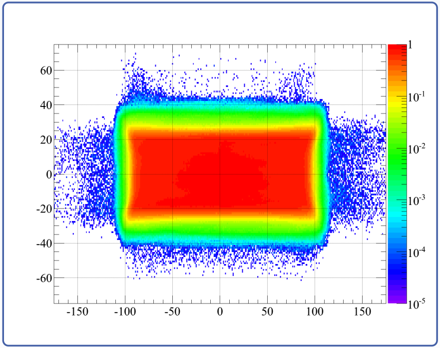


Cumulated beam distribution (200 runs) on target
Log. scale

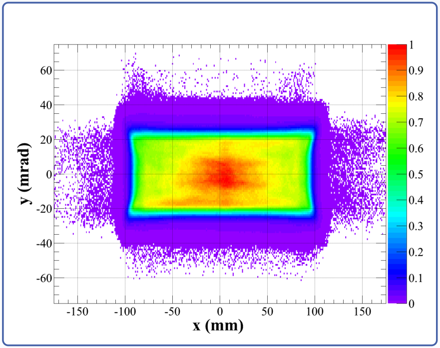


Cumulated beam distribution (200 runs) on target
Linear scale

IFMIF HEBT with SFM: Errors study results (Z. YANG)



Cumulated beam distribution (200 runs) on target
Log. scale



Cumulated beam distribution (200 runs) on target
Linear scale

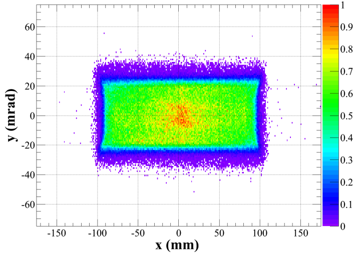
IFMIF HEBT with Step-Like Field Magnets : Pros and Cons

Pros

- "Easier" beam line tuning.
- Large beam pipe aperture (low field).
- Steps can be adapted to the beam halo.
- STM are easy to manufacture.

Cons

- Slope (b) and step position (X_0) are fixed.
- Non-homogeneous zone seems to be in the center of the footprint.



Outline

1. IFMIF accelerator overview
2. Beam dynamics simulations for LIPAc
3. Beam dynamics simulations for IFMIF
4. Beam expansion in IFMIF HEBT with high-order multipoles
5. Beam expansion with step-like field magnets (Zheng YANG's work)
6. **Conclusions and perspectives**

Conclusions and Perspectives

Conclusions

- Two methods have been tested to expand the beam on the IFMIF liquid Lithium target.
- The step-like field magnets solutions looks very promising.
- A diagnostic has been implemented for TraceWin to optimize the beam line parameters.

Conclusions and Perspectives

Conclusions

- Two methods have been tested to expand the beam on the IFMIF liquid Lithium target.
- The step-like field magnets solutions looks very promising.
- A diagnostic has been implemented for TraceWin to optimize the beam line parameters.

Perspectives

- More optimizations have to be performed.
- Design of shorter and simpler beam HEBTs.
- HEBT tuning feasibility with real beam diagnostics.
- Develop beam diagnostics suitable for high radiation environment.