Novel linear accelerator design for injection of helium ions into a particle therapy synchrotron and parallel radioisotope production

Presenter: **Lazar Nikitovic (CERN/RTU)**
Supervisors: Maurizio Vretenar (CERN)
Toms Torims (RTU)

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- ❑ Facility and linac layout
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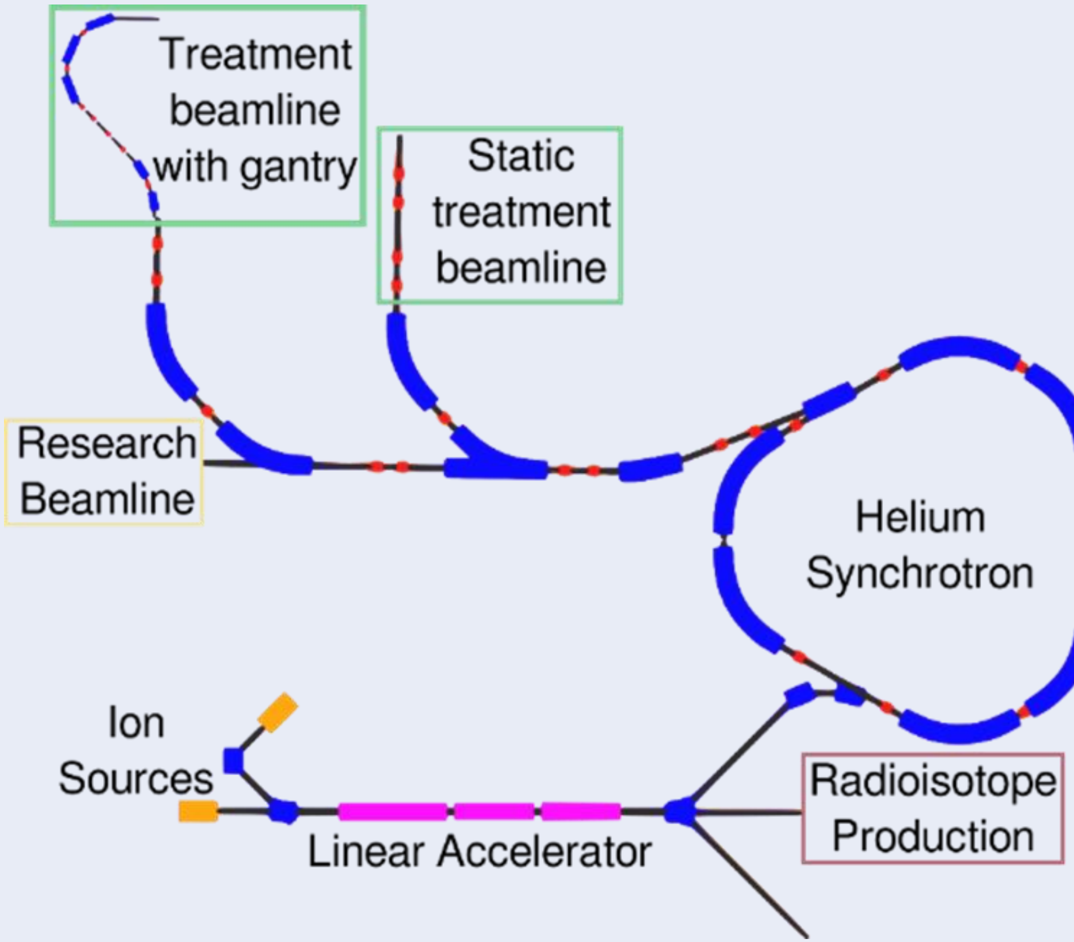
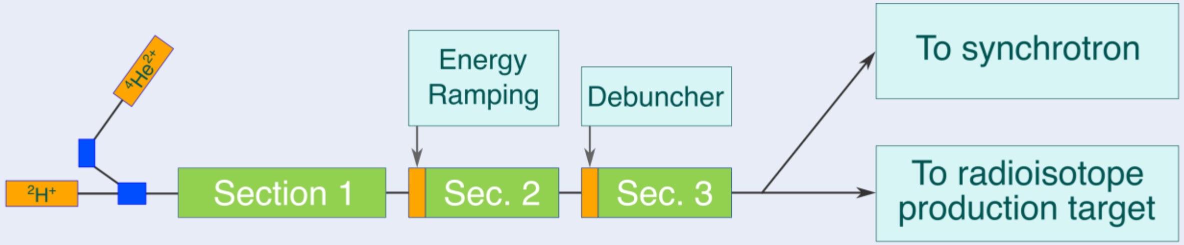
Aims of the study

- **To develop a dual function linac that can:**
  - Inject helium ions into a cancer therapy synchrotron, and
  - Produce in parallel a wide range of therapeutic radioisotopes.

Facility layout



Linac layout



Sections 2 and 3 are powered **only** for isotope production

Maximum duty cicle: **10%**

2 Ion Sources:

- $^4He^{2+}$, 5 - 35 mA, 0.25 π·mm·mrad
- $^2H^+$, 35 mA, 0.25 π mm mrad

LINAC sec. 1:

- A/q = 2
- W_{in} = 15 keV/u
- W_{out} = 5 MeV/u

Frequency: **352 MHz**

LINAC sec. 2:

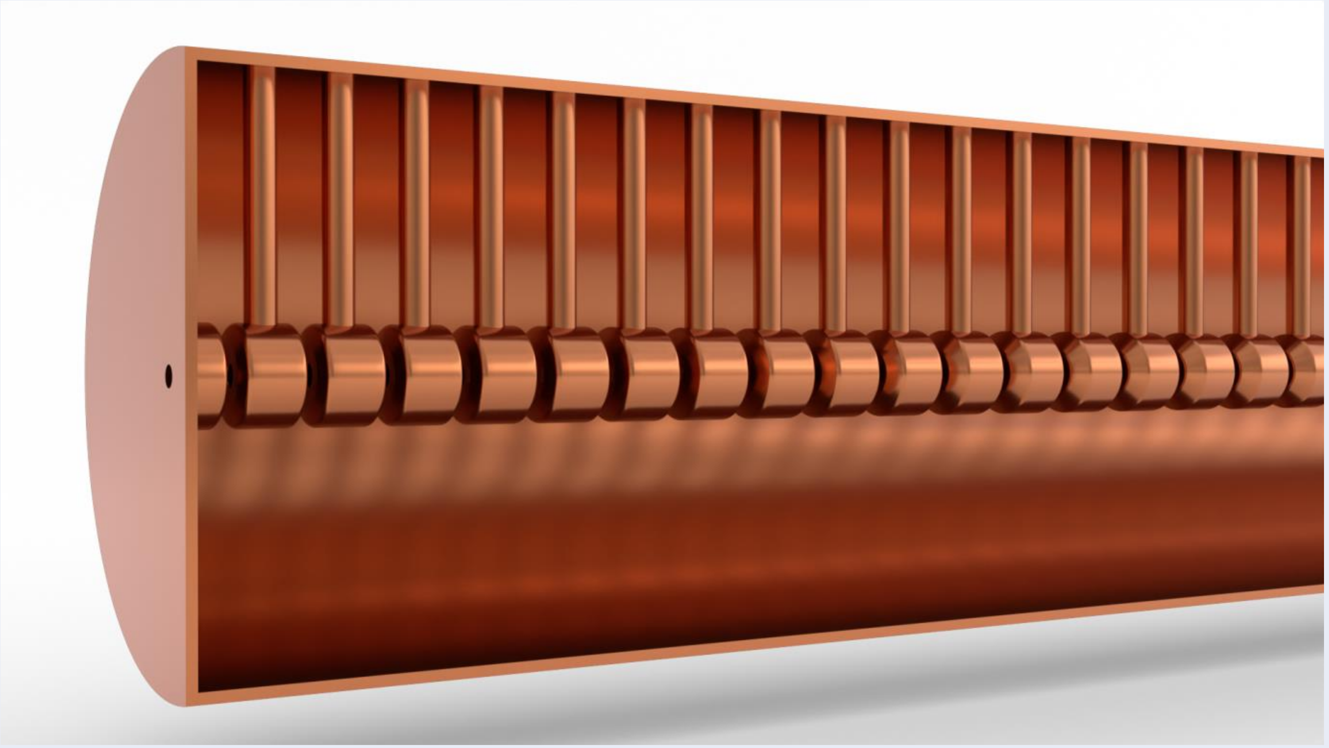
- A/q = 2
- W_{in} = 5 MeV/u
- W_{out} = 7.1 MeV/u

LINAC sec. 3:

- A/q = 2
- W_{in} = 7.1 MeV/u
- W_{out} = 10 MeV/u

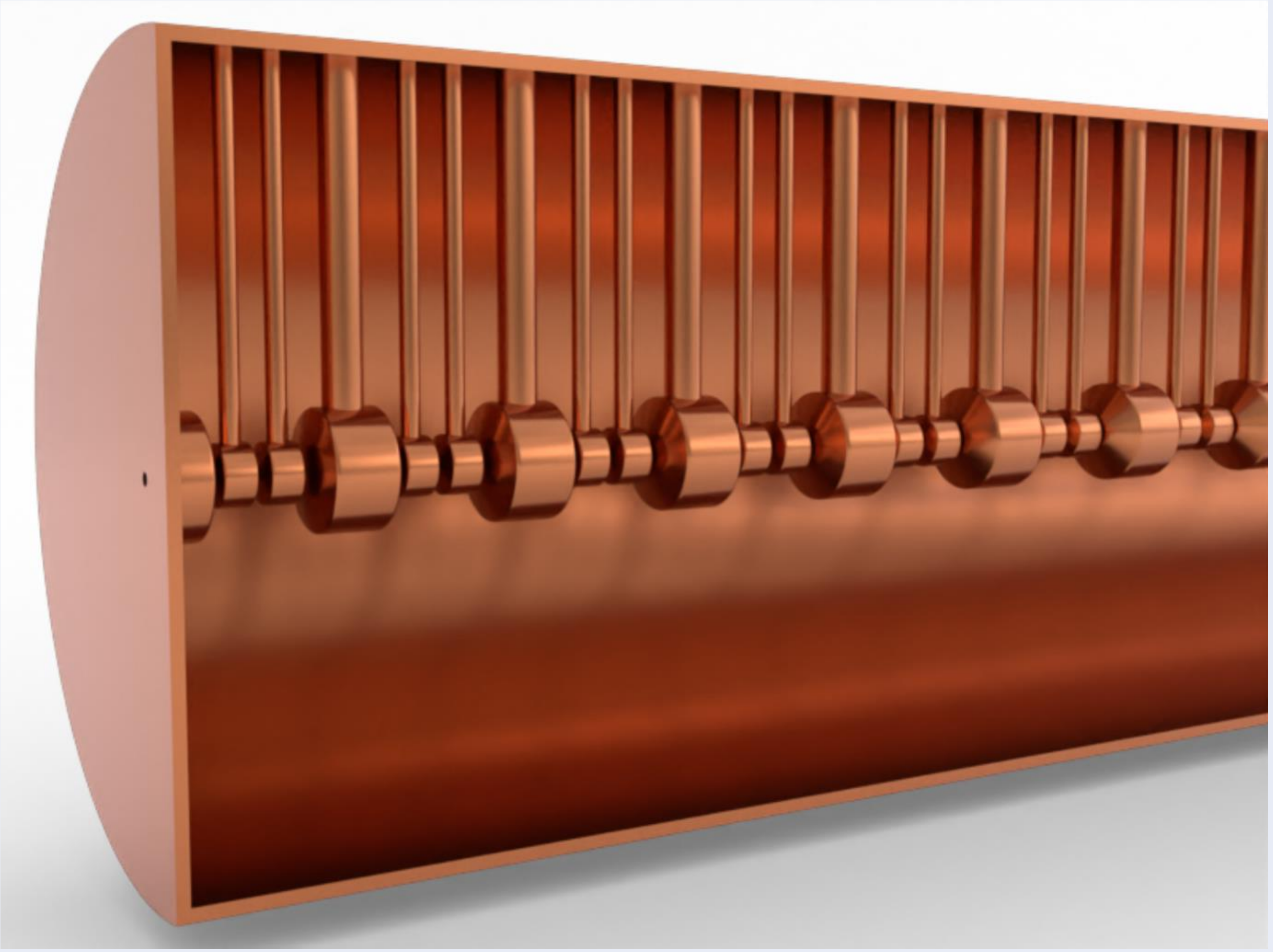
Alvarez Drift Tube Linac (DTL)

- Simplest 0-mode structure;
- Every drift tube (DT) contains permanent magnet quadrupole (PMQ);
- Strong transversal focusing;
- Isn’t suitable for acceleration of low energy particles;



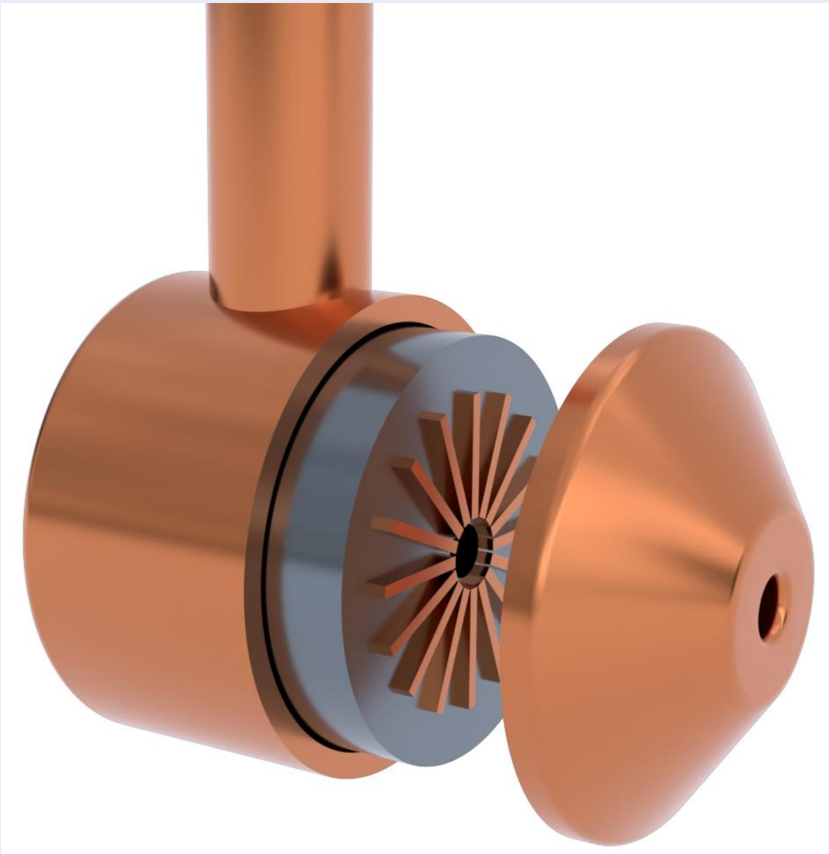
Quasi-Alvarez Drift Tube Linac (QA-DTL)

- Modification of Alvarez DTL;
- Every third DT contains PMQ;
- DTs containing PMQ are 2 times longer than the ones present in Alvarez DTL;
- Due to DTs length the lower energy particles can be accelerated in comparison to standard Alvarez DTL;



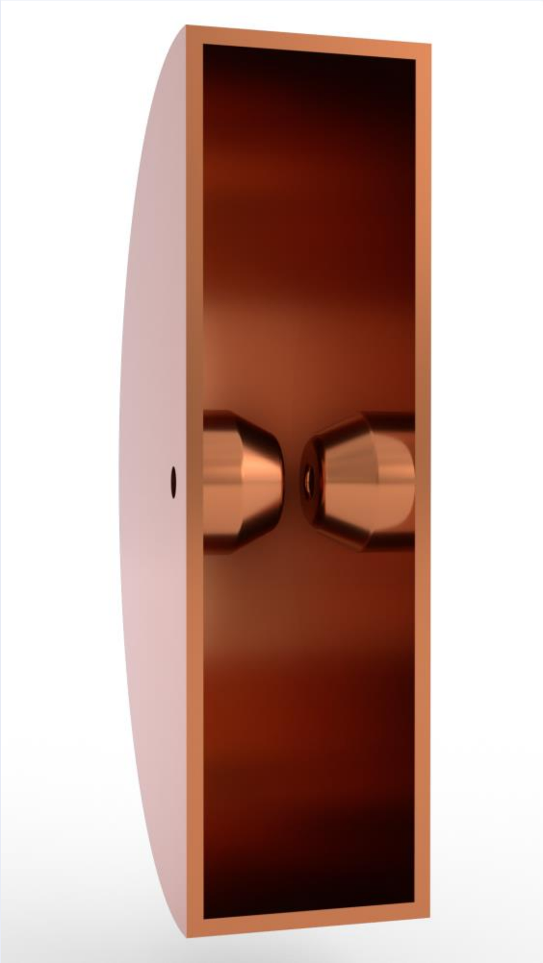
QA-DTL drift tube with PMQ

- The overall dimensions of each DT is carefully designed;
- Special complexity creates the DTs consisting PMQ;
- The Halbach quadrupole with 16 sections placed inside longer DT;

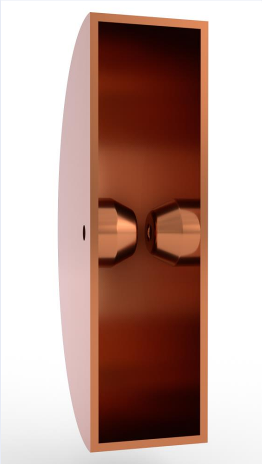


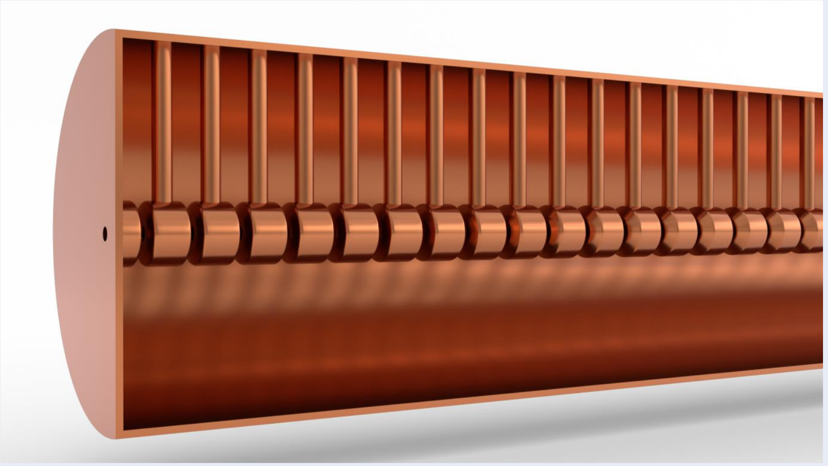
Energy Ramping (ER) & Debunching (DB) cavities

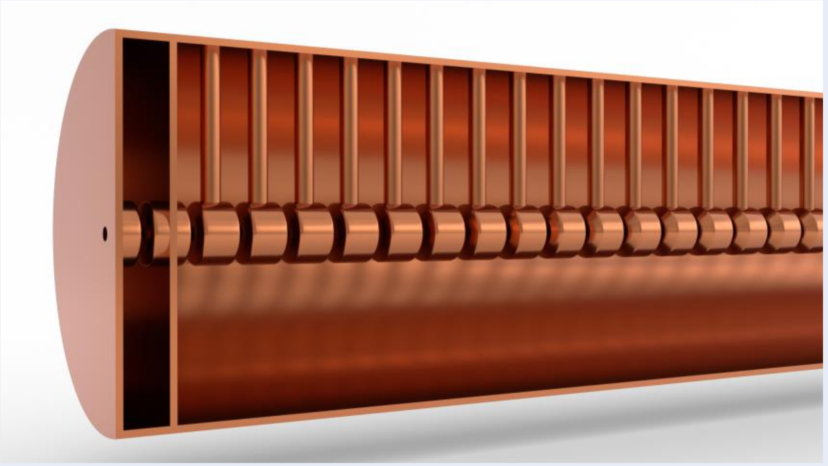
- Both ER and DB cavities consist of one or multiple cells, depending on required voltage and size of energy ramping step;
- Both ER and DB cavities can be 0-mode or pi-mode structures;
- For ER cavity the manipulation of synchronous phase is crucial;
- For DB cavity the voltage needs to be chosen carefully;



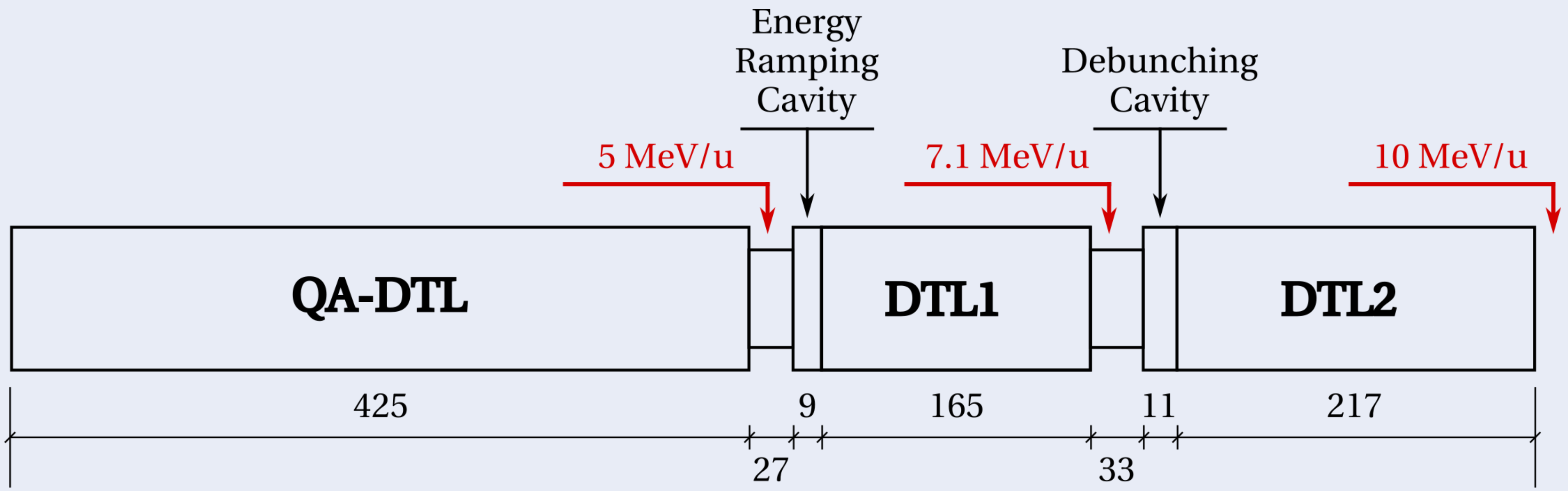
Energy Ramping (ER) & Debunching (DB) cavities







Proposed linac design



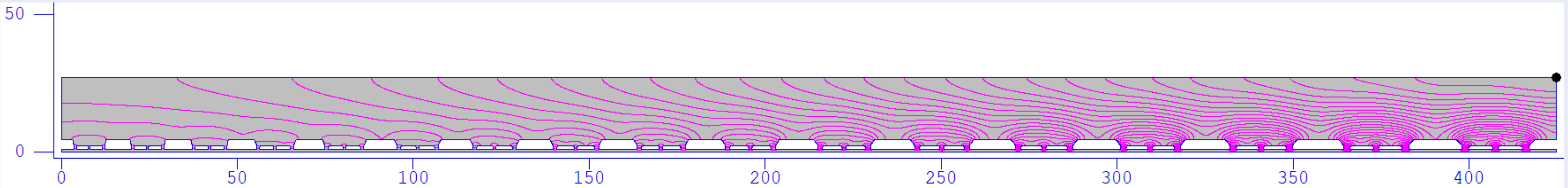
All the units are in [cm].

Linac as synchrotron injector

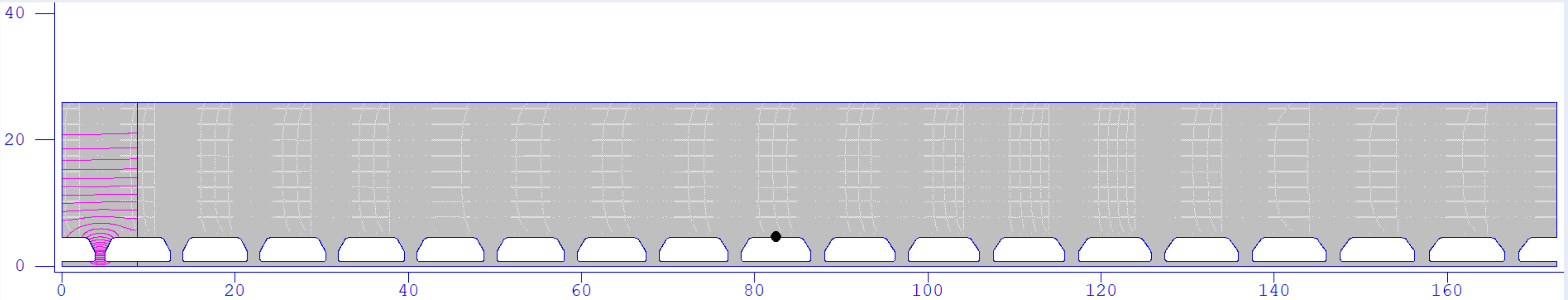
- The linac as synchrotron injector must deliver 5 mA of helium ions at the energy of 5 MeV/u;
- Since multiturn injection in the synchrotron at relatively high intensity requires a careful control of the longitudinal beam parameters, two short RF cavities are included as separate sections in the DTL1 and DTL2:
  - Energy Ramping (ER) cavity providing a fast ramping of beam energy for longitudinal painting, and
  - Debunching (DB) cavity to minimize energy spread;

RF design of linac as synchrotron injector

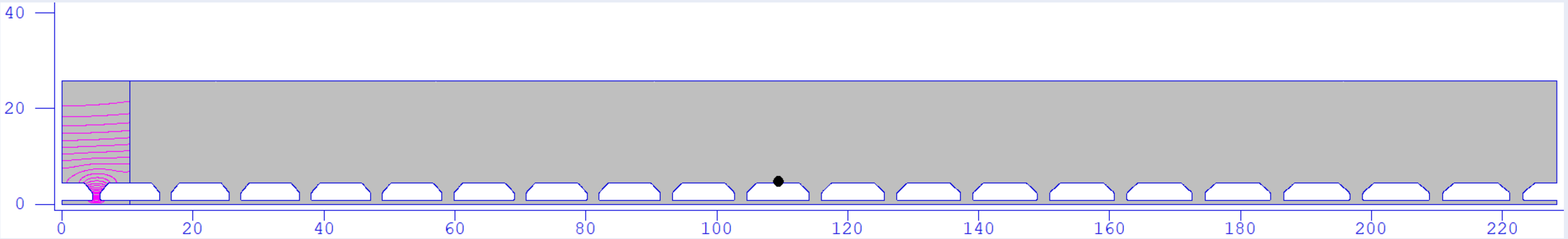
QA-DTL
(Section 1)



ER
(Section 2)



DB
(Section 3)



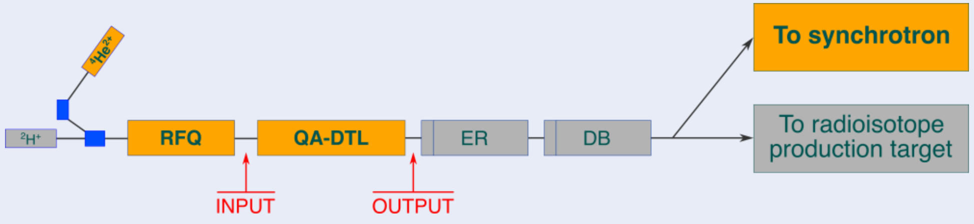
All the units are in [cm].

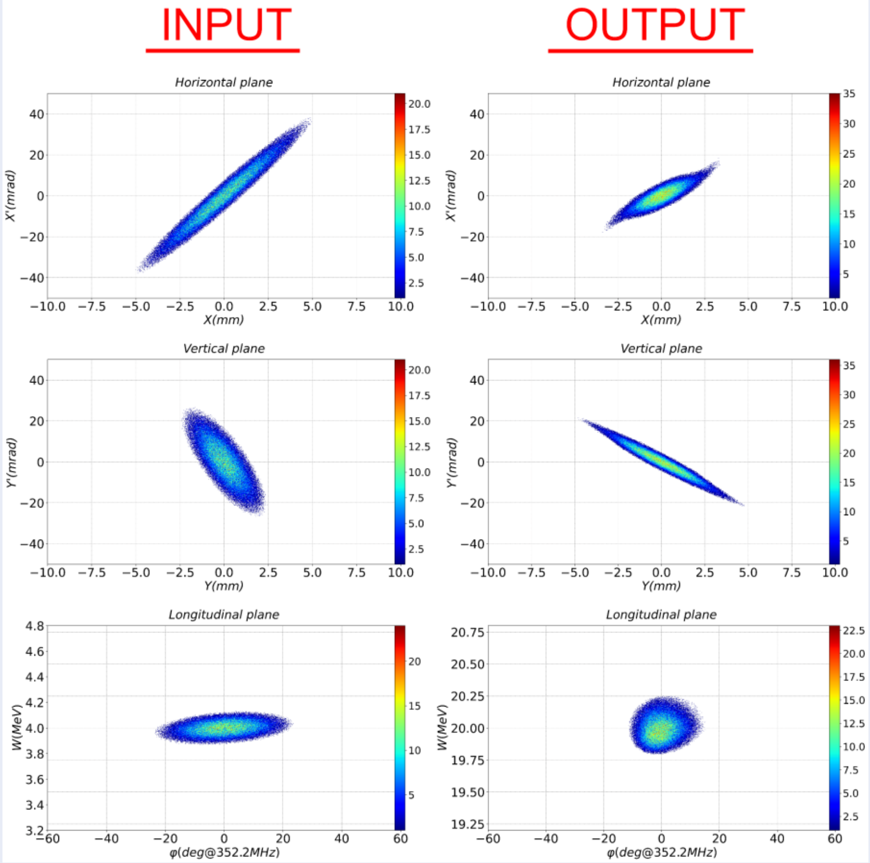
RF design of linac as synchrotron injector

	QA-DTL	ER	DB	Units
Designed ions	$^{4}He^{2+}$			-
RF frequency	352.2			MHz
Length	425	9	11	cm
Input energy	1	-	-	MeV/u
Output energy	5	-	-	MeV/u
Max. surface field	1.8	1.3		kp
Synchronous phase	-35 to -24	-146.9 to -33.1	-90	°
RF power	535	35	38	kW
Avg. axial el. field	3.5	3.1		MV/m
No. of cells/superperiods*	17	1	1	-

Beam optics of linac as synchrotron injector

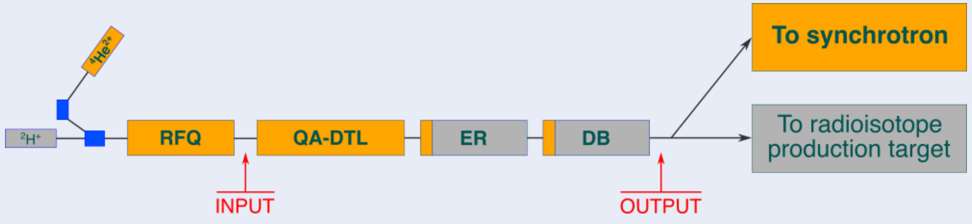
	LINAC	Units
Beam current	5	mA
Energy ramping	-	MeV/u
In. trans. norm. emit. [rms] (xx’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (xx’)	0.265	π.mm.mrad
In. trans. norm. emit. [rms] (yy’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (yy’)	0.259	π.mm.mrad
In. long. norm. emit. [rms]	0.394	π.deg.MeV
Out. long. norm. emit. [rms]	0.401	π.deg.MeV
Energy spread	±1.02	%
Transmission	100	%

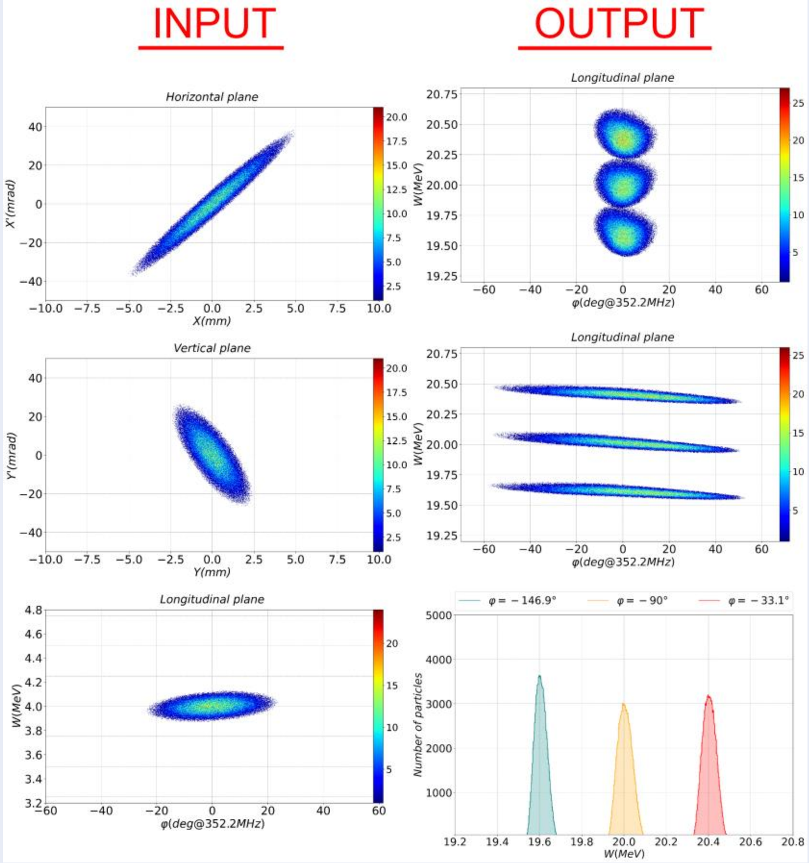




Beam optics of linac as synchrotron injector

	LINAC	Units
Beam current	5	mA
Energy ramping	-0.1 to 0.1	MeV/u
In. trans. norm. emit. [rms] (xx’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (xx’)	0.264	π.mm.mrad
In. trans. norm. emit. [rms] (yy’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (yy’)	0.261	π.mm.mrad
In. long. norm. emit. [rms]	0.394	π.deg.MeV
Out. long. norm. emit. [rms]	0.403	π.deg.MeV
Energy spread	±0.37	%
Transmission	100	%



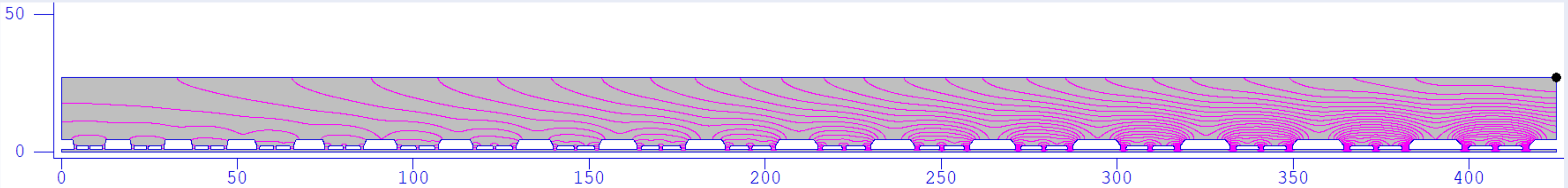


Linac for radioisotope production

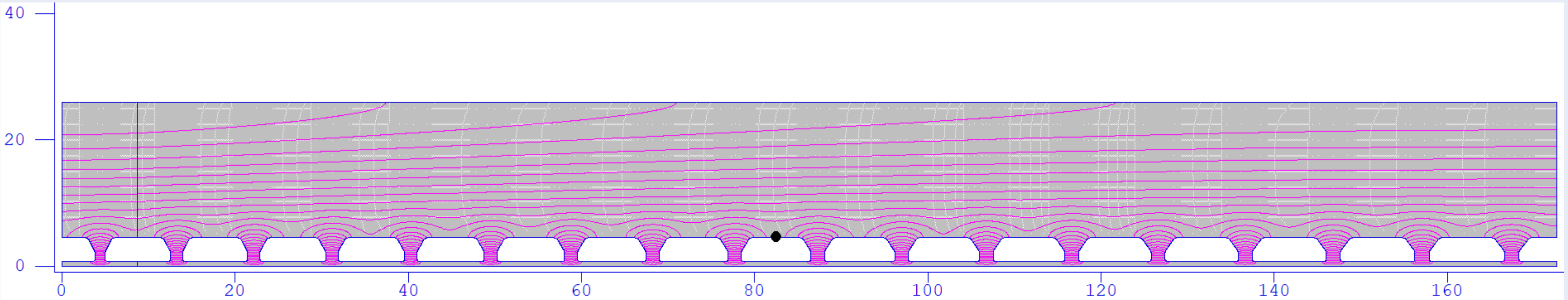
- The linac needs to provide both alpha particles and deuterons at 2 energies:
  - **7.1 MeV/u** for production of ^{211}At, the most promising alpha emitter, used for Targeted Alpha Therapy (TAT);
  - **10 MeV/u** for production of other radioisotopes like ^{47}Sc, ^{67}Cu and ^{123}I;

RF design of linac for radioisotope production

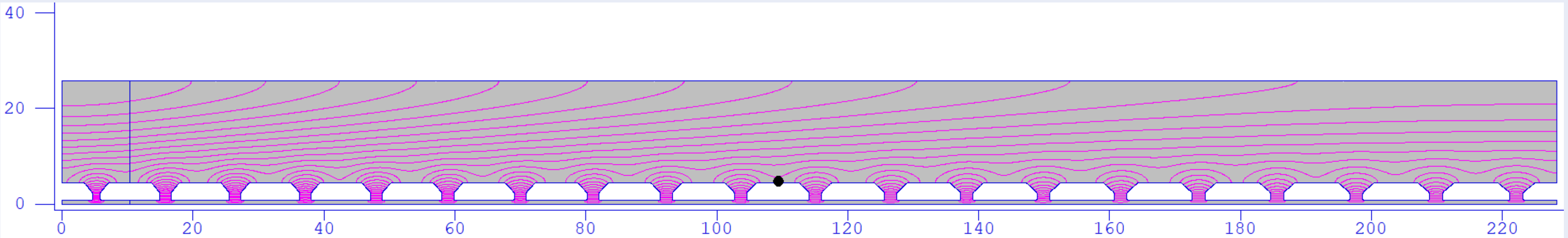
QA-DTL
(Section 1)



DTL1
(Section 2)



DTL2
(Section 3)



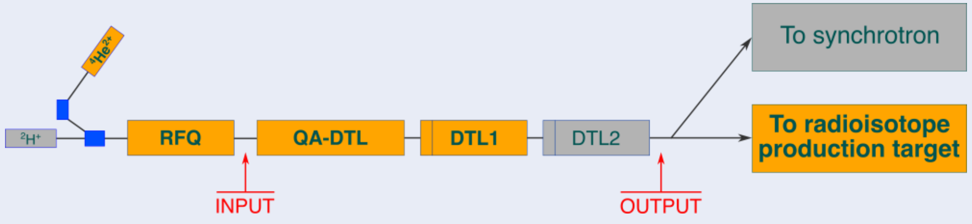
All the units are in [cm].

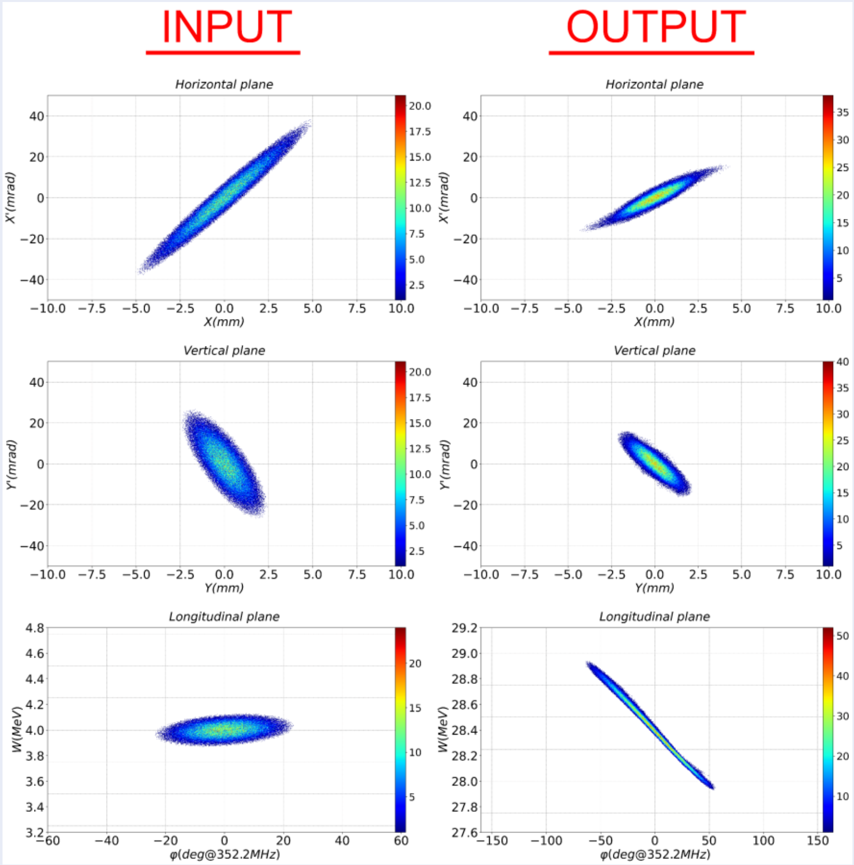
RF design of linac for radioisotope production

	QA-DTL	DTL1	DTL2	Units
Designed ions	$^{4}He^{2+}$ / $^{2}H^{+}$			-
RF frequency	352.2			MHz
Length	425	174	228	cm
Input energy	1	5	7.1	MeV/u
Output energy	5	7.1	10	MeV/u
Max. surface field	1.8	1.3		kp
Synchronous phase	-35 to -24	-24		°
RF power	535	235	300	kW
Avg. axial el. field	3.5	3.1		MV/m
No. of cells/superperiods*	17	18	20	-

Beam optics of linac for radioisotope production

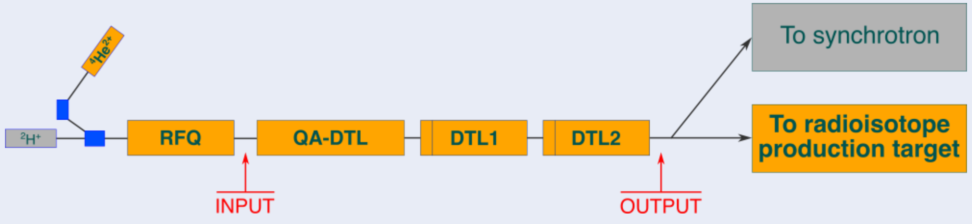
	LINAC	Units
Beam current	35	mA
Energy ramping	-	MeV/u
In. trans. norm. emit. [rms] (xx’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (xx’)	0.283	π.mm.mrad
In. trans. norm. emit. [rms] (yy’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (yy’)	0.279	π.mm.mrad
In. long. norm. emit. [rms]	0.394	π.deg.MeV
Out. long. norm. emit. [rms]	0.466	π.deg.MeV
Energy spread	±2.31	%
Transmission	100	%

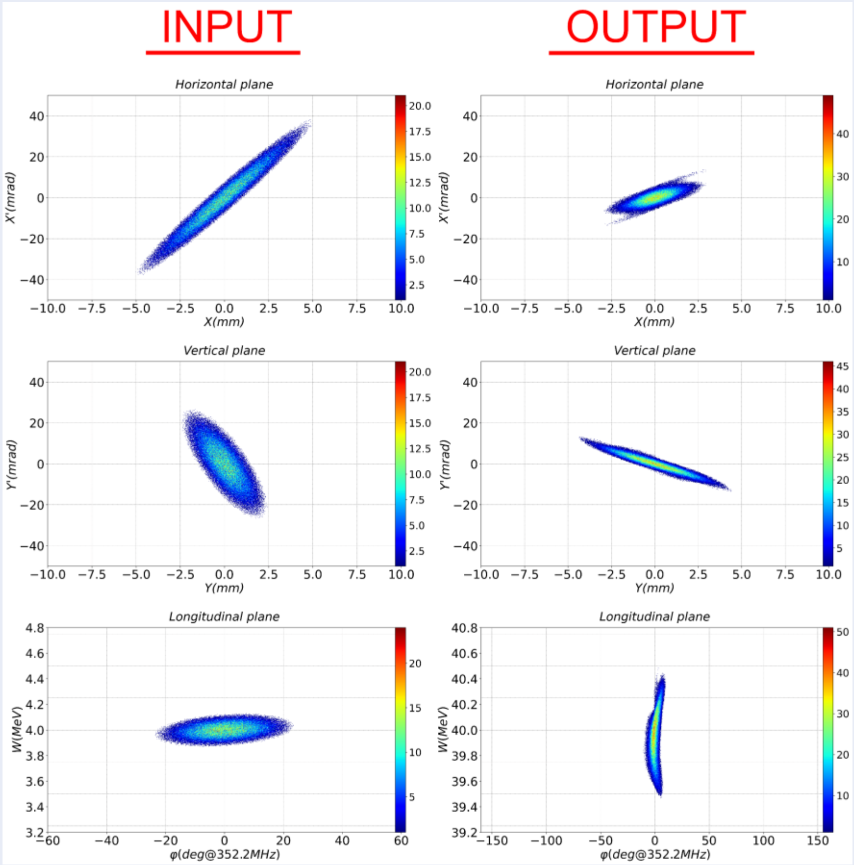




Beam optics of linac for radioisotope production

	LINAC	Units
Beam current	35	mA
Energy ramping	-	MeV/u
In. trans. norm. emit. [rms] (xx’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (xx’)	0.287	π.mm.mrad
In. trans. norm. emit. [rms] (yy’)	0.250	π.mm.mrad
Out. trans. norm. emit. [rms] (yy’)	0.287	π.mm.mrad
In. long. norm. emit. [rms]	0.394	π.deg.MeV
Out. long. norm. emit. [rms]	0.534	π.deg.MeV
Energy spread	±1.03	%
Transmission	100	%





Summary

- RF design and beam optics studies of E-mode DTL structures (DTL and QA-DTL) as injector for helium therapy synchrotron and for radioisotope production in parallel have been done;
- RF design and beam optics studies of Energy Ramping and Debunching cavities before helium ions injection into therapy synchrotron have been accomplished;
- Radioisotope production with proposed Linac;

Further steps

- RF design and beam optics study of different types of H-mode DTL structures and its adaptation to 176 MHz frequency;
- The comparison between E-mode and H-mode DTL structures for acceleration of alpha particles for injection into therapy synchrotron and for radioisotope production in parallel;

Thank you!