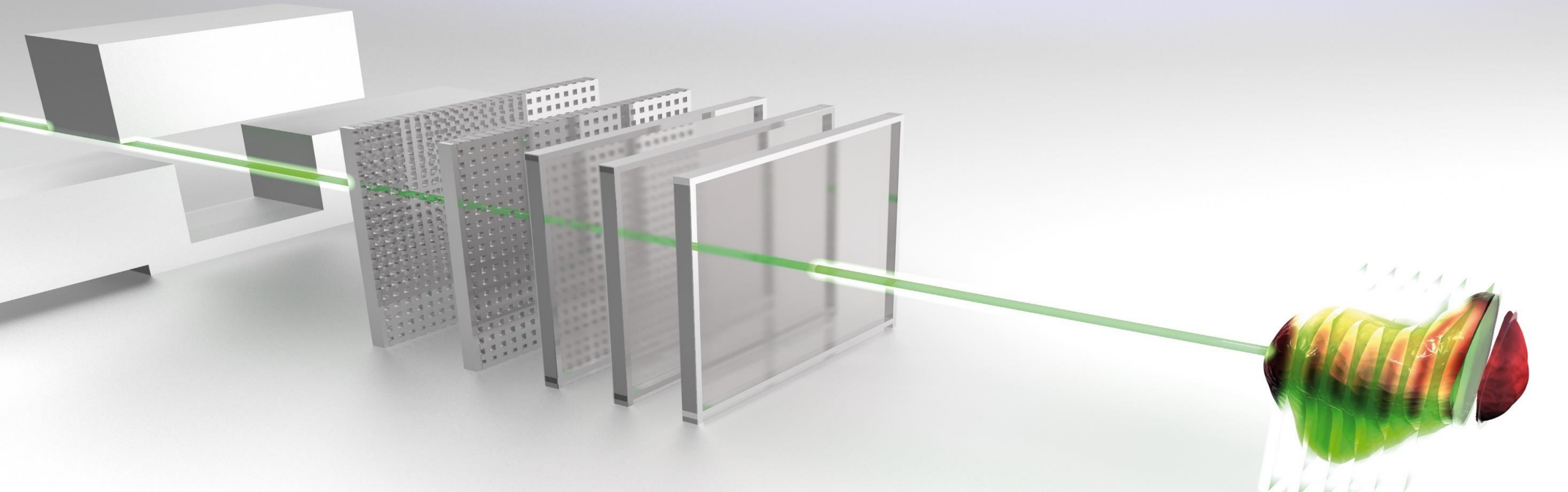
Photo credits HIT Heidelberg



Design of a ‘bent linac’ for carbon ion therapy

V. Bencini

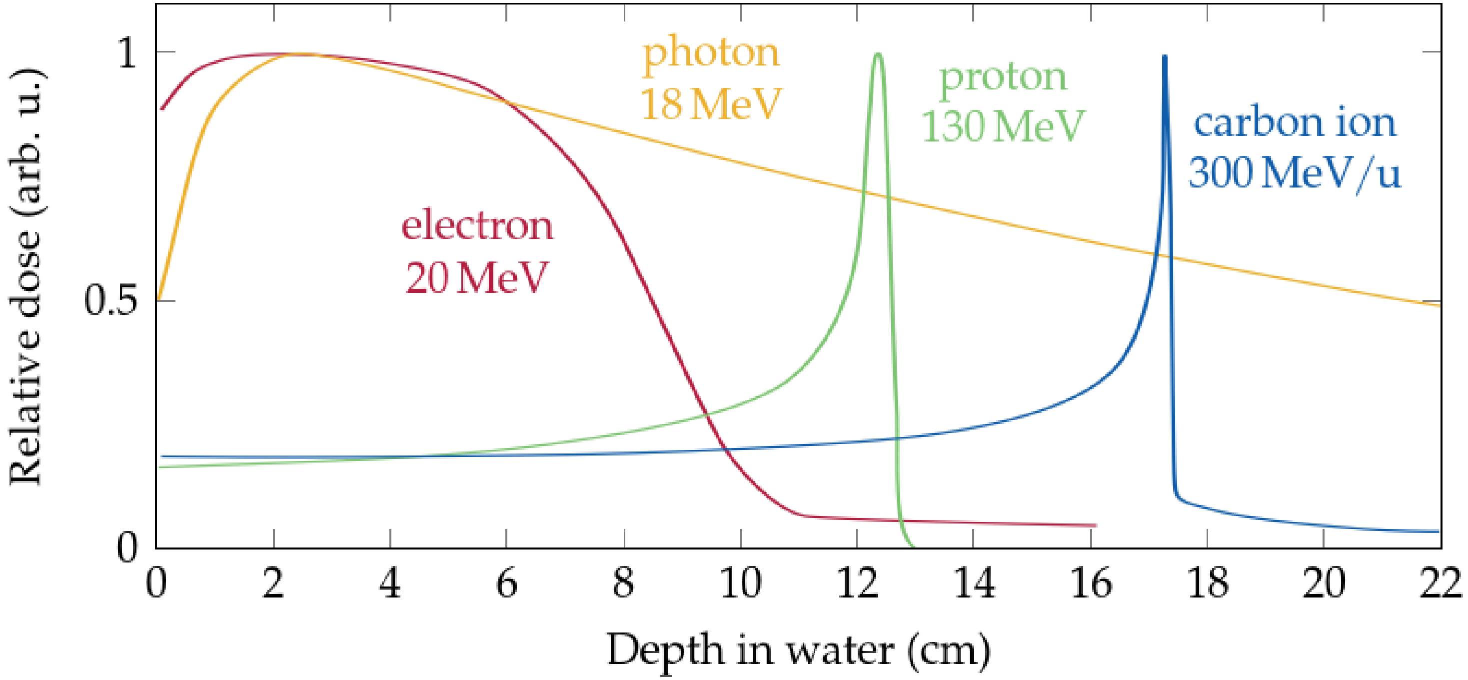
CERN

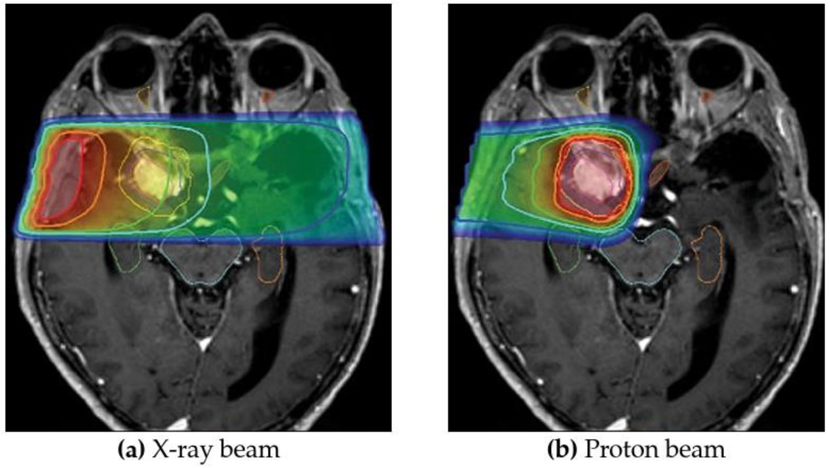
SAPIENZA
UNIVERSITÀ DI ROMA

A quick intro to hadron therapy

Hadron therapy exploits Bragg peak to precisely target tumor cells, sparing the surrounding healthy tissue

- Particularly beneficial when treating solid tumors in critical regions (liver, brain, spinal column)
- Carbon ion therapy specifically tailored to treat radioresistant tumors (narrower Bragg peak)





Emory Proton Therapy Center, http://news.emory.edu/features/2018/11/proton-therapy-center/index.html, 2020

Why don't we use just hadron therapy?

A hadron therapy treatment costs at least 2 times a radiotherapy one.

How to address the problem

<u>A hadron therapy treatment costs at least 2 times a radiotherapy one</u>.

Hadron therapy accelerators must be designed aiming for high treatment quality and low cost.

Low cost

- Small footprint (reduce facility costs)
- Reduced cost components (highly modular, available on the market)
- Low operational costs (power, maintenance)

What we do need

<u>A hadron therapy treatment costs at least 2 times a radiotherapy one</u>.
Hadron therapy accelerators must be designed aiming for high treatment quality and low cost.

Low cost

- Small footprint (reduce facility costs)
- Reduced cost components (highly modular, available on the market)
- Low operational costs (power, maintenance)

High beam quality

- Small spot size (small emittance, small divergence)
- Ideally monochromatic (small distal error)
- Short treatment time (fast energy modulation)

Linacs are very promising

<u>A hadron therapy treatment costs at least 2 times a radiotherapy one</u>.
Hadron therapy accelerators must be designed aiming for high treatment quality and low cost.

Low cost

- Small footprint (reduce facility costs)
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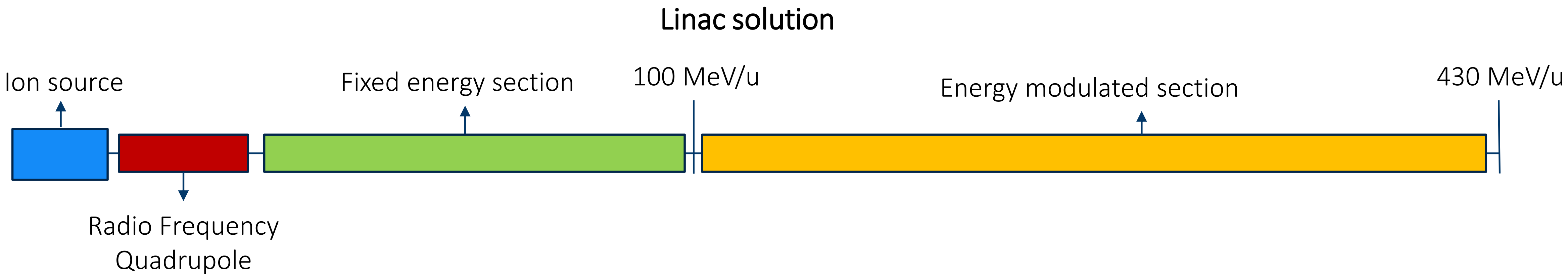
High beam quality

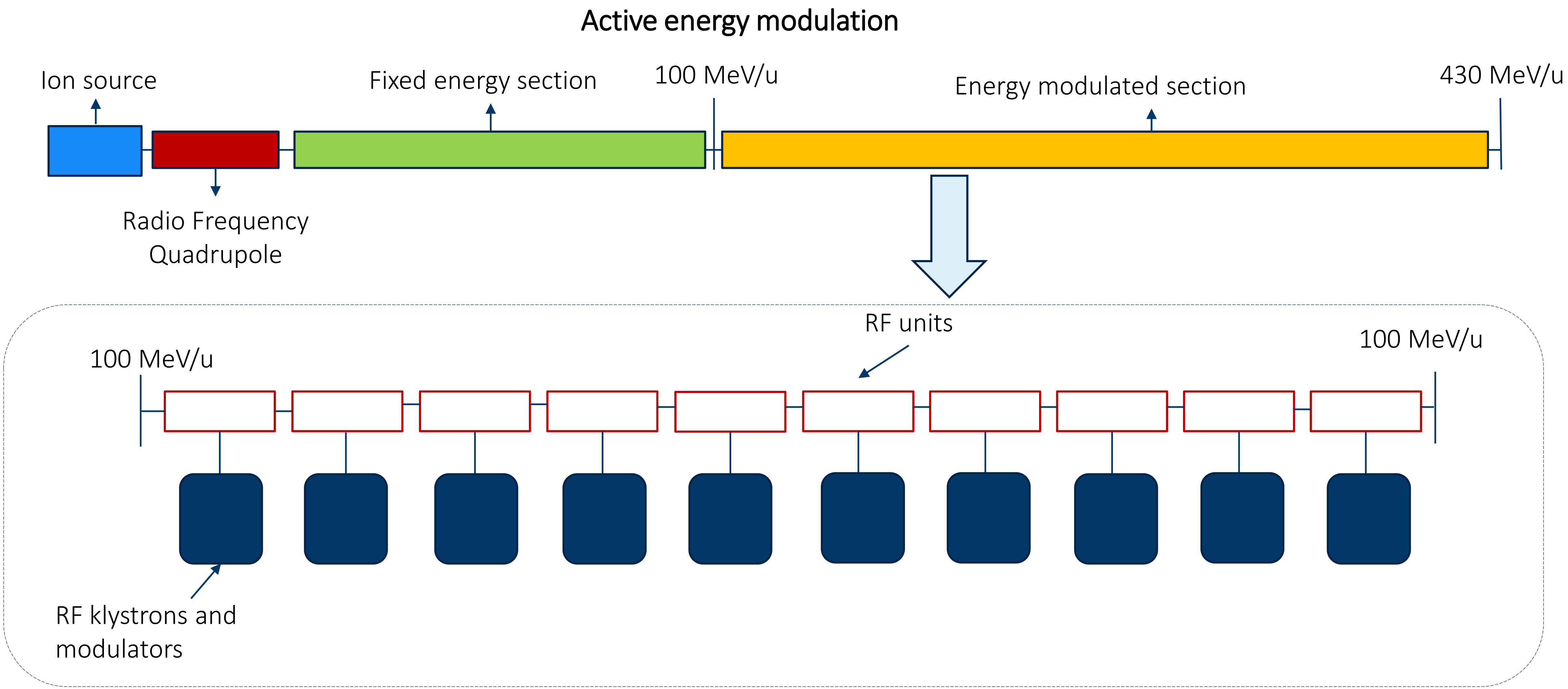
- Small spot size (small emittance, small divergence)
- Ideally monochromatic (small distal error)
- Short treatment (fast energy modulation)

LINACS ARE A GREAT COMPROMISE BETWEEN HIGH QUALITY AND LOW COST!

How linacs look like

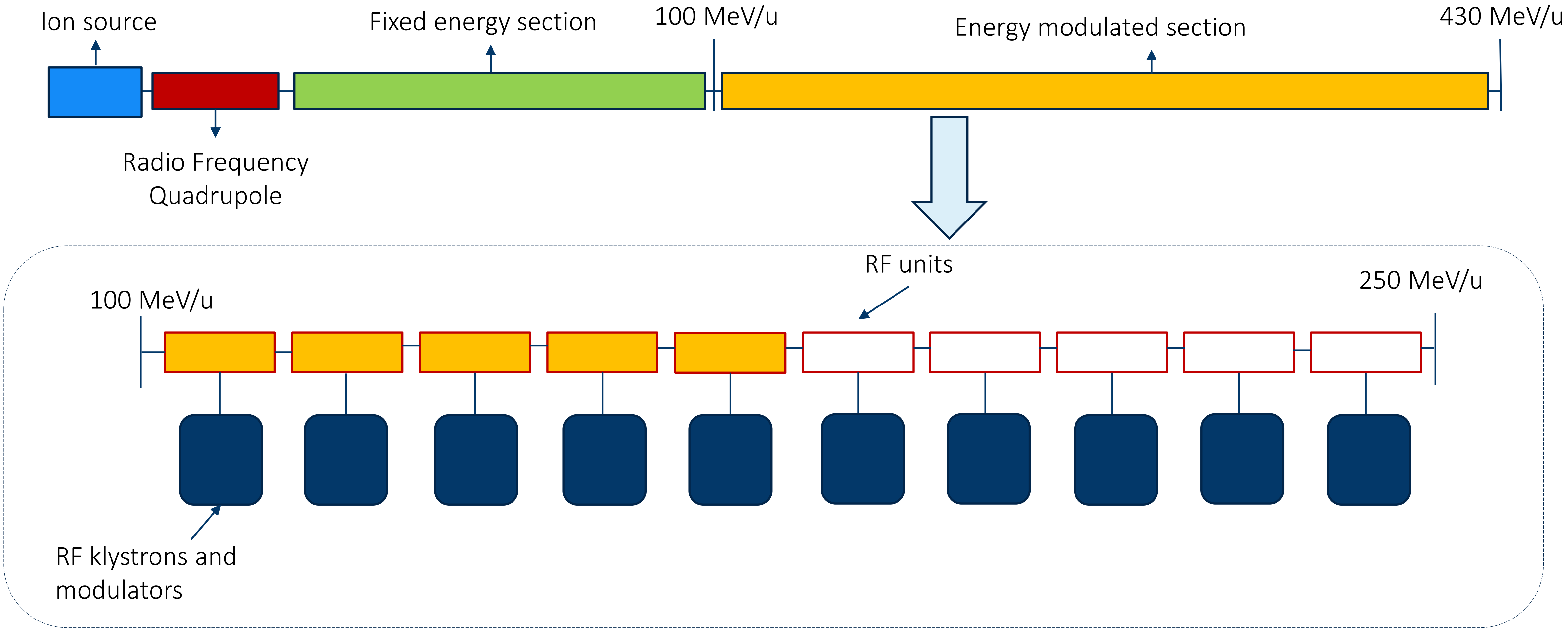


The special feature of hadron therapy linacs



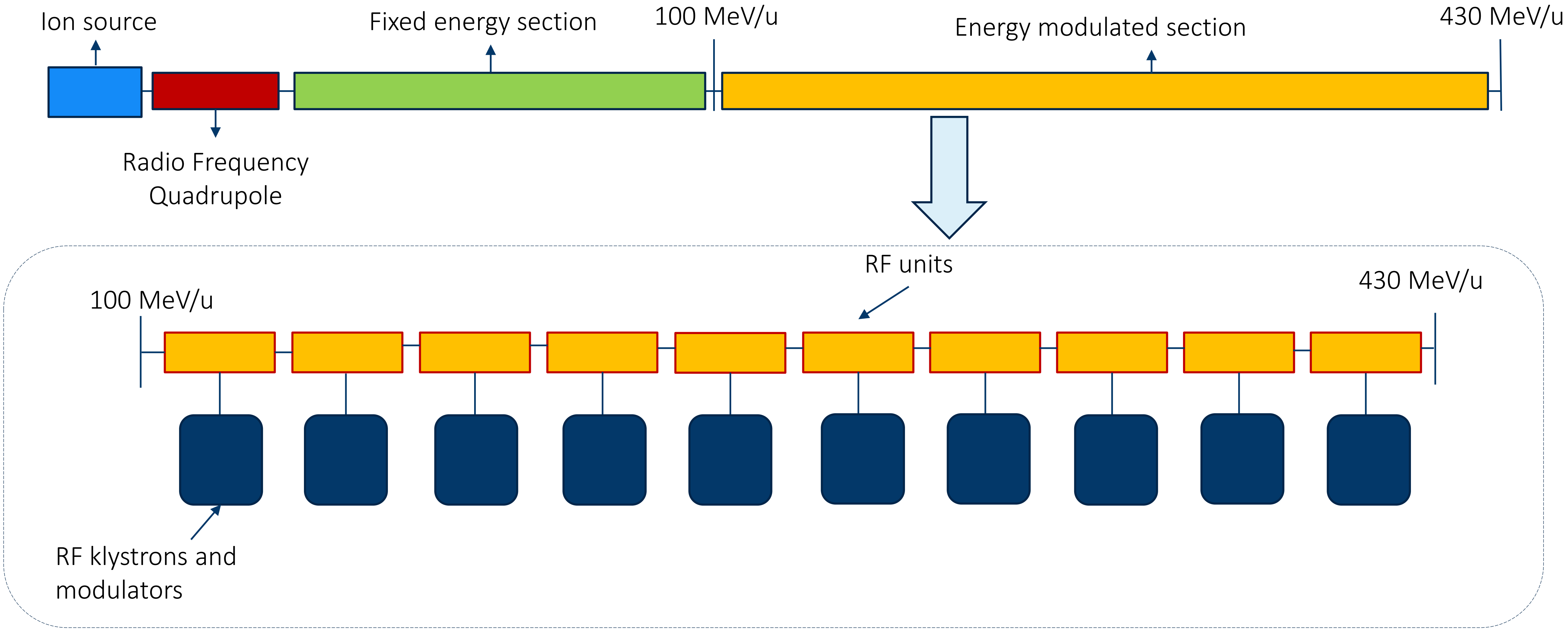
The special feature of hadron therapy linacs

Active energy modulation



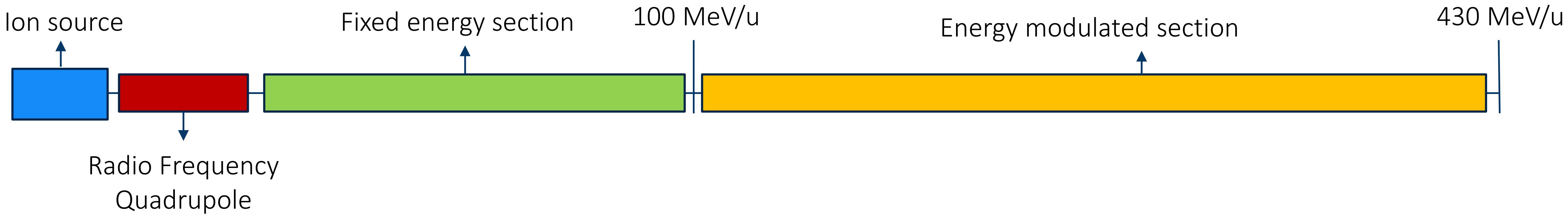
The special feature of hadron therapy linacs

Active energy modulation



A few numbers

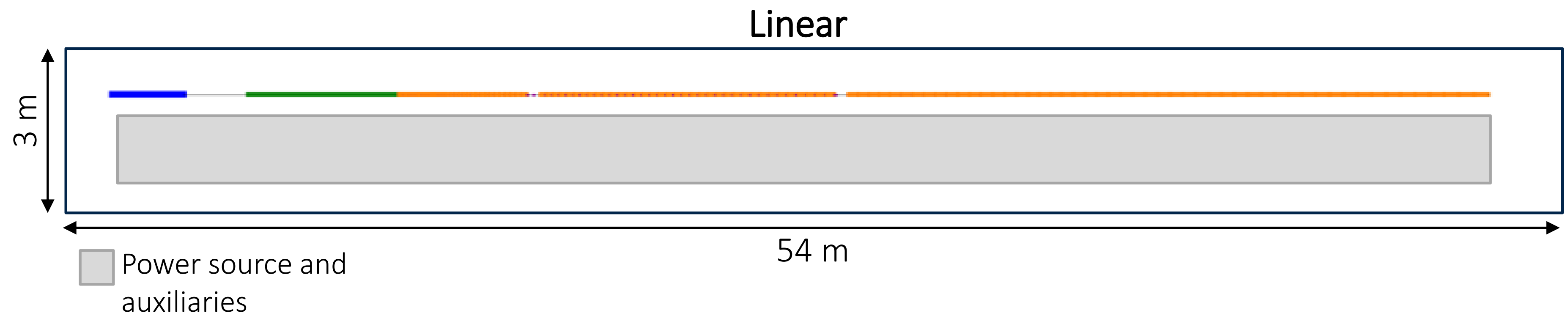
Linac features



	Linac	Features
Energy modulation	Active	Prevent activation issues
Time for energy modulation	5 ms	Pulse to pulse
Footprint	440 m^2	Small compared to synchrotrons
Magnets	Permanent	Reduced power consumption
Beam emittance RMS Norm.	0.02 π mm mrad	Extremely precise treatment

Why would we bend a linac?

How the footprint is occupied is critical to fit the accelerator into a hospital facility

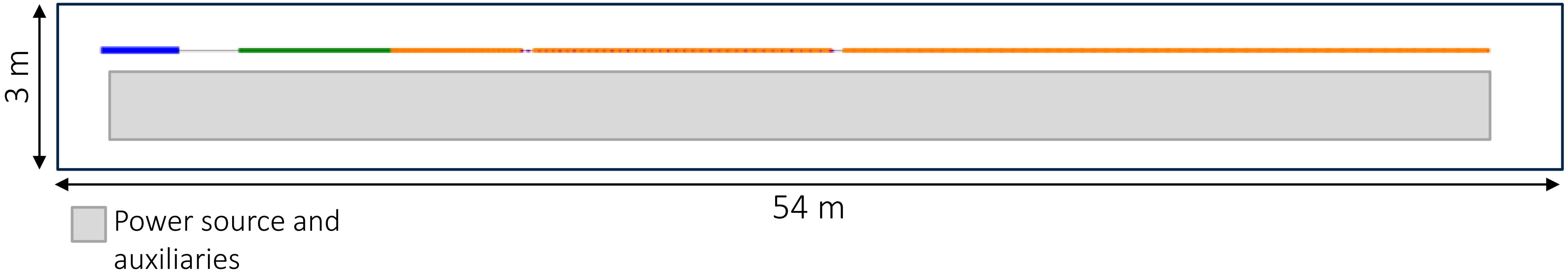


	Shape	Beam dynamics
Linear	✘	✓

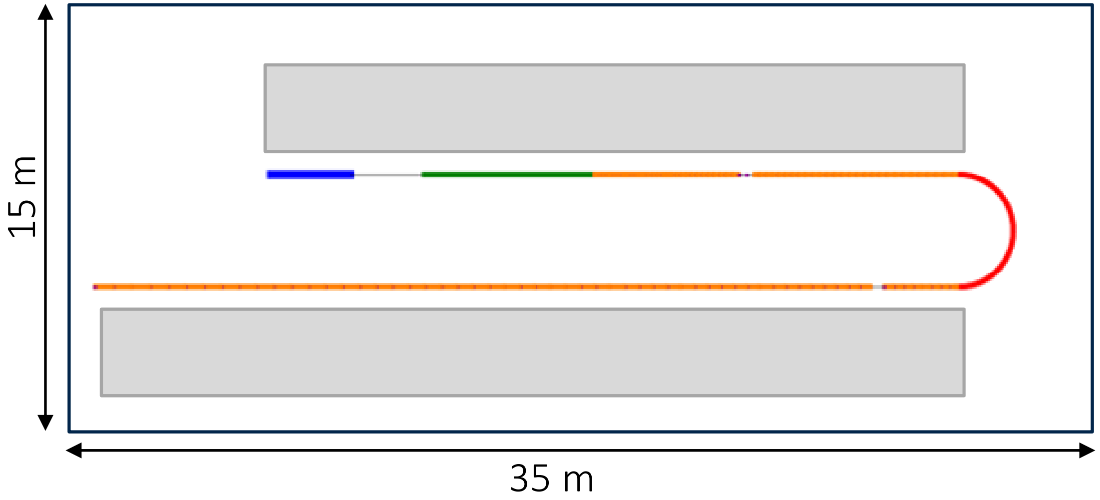
The footprint problem

How the footprint is occupied is critical to fit the accelerator into a hospital facility

Linear



Single bend

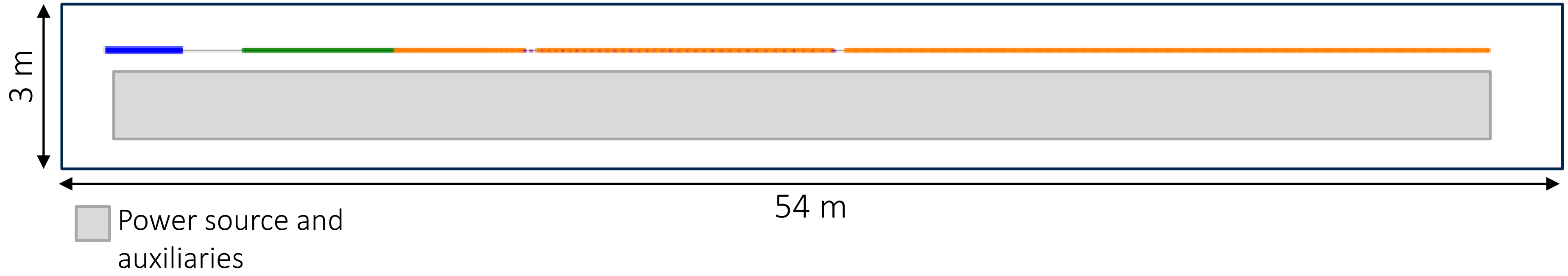


	Shape	Beam dynamics
Linear	✗	✓
Single bend	✓	✗

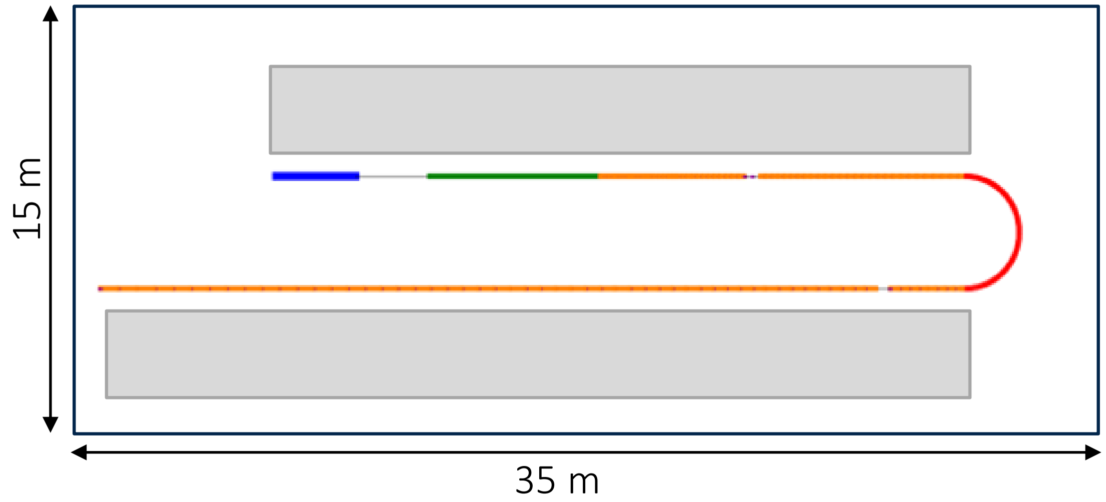
The footprint problem

How the footprint is occupied is critical to fit the accelerator into a hospital facility

Linear



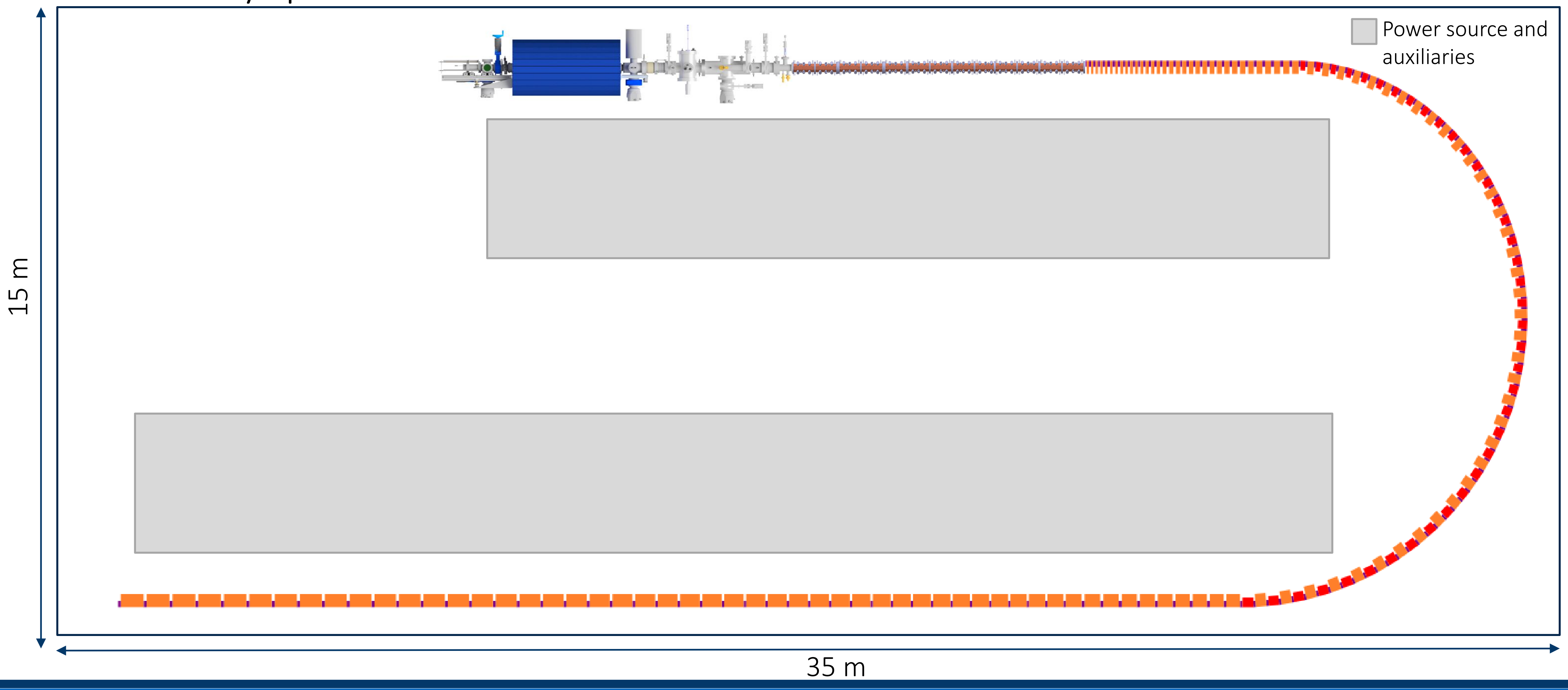
Single bend



	Shape	Beam dynamics
Linear	✗	✓
Single bend	✓	✗
Bent linac	✓	✓

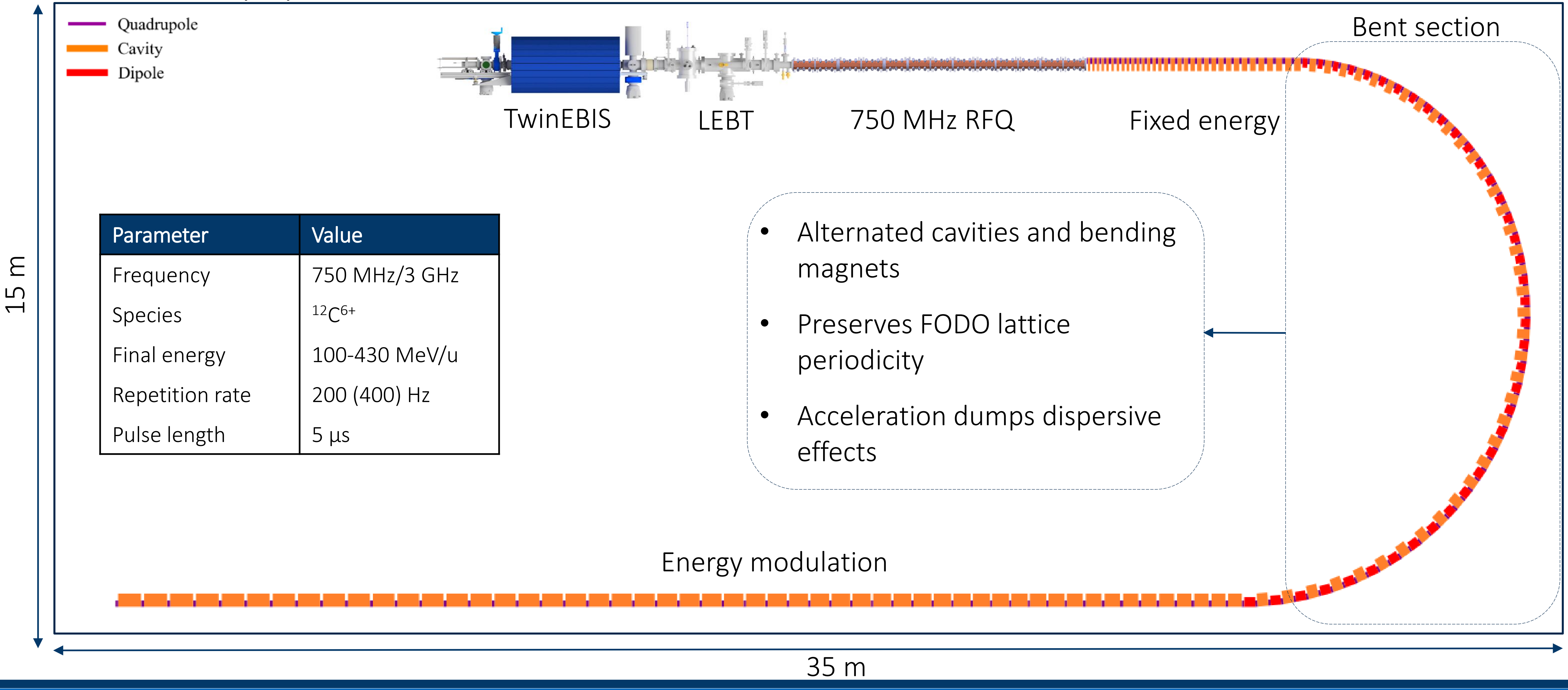
The bent linac solution

Interlaced cavity-dipole scheme



Linac layout

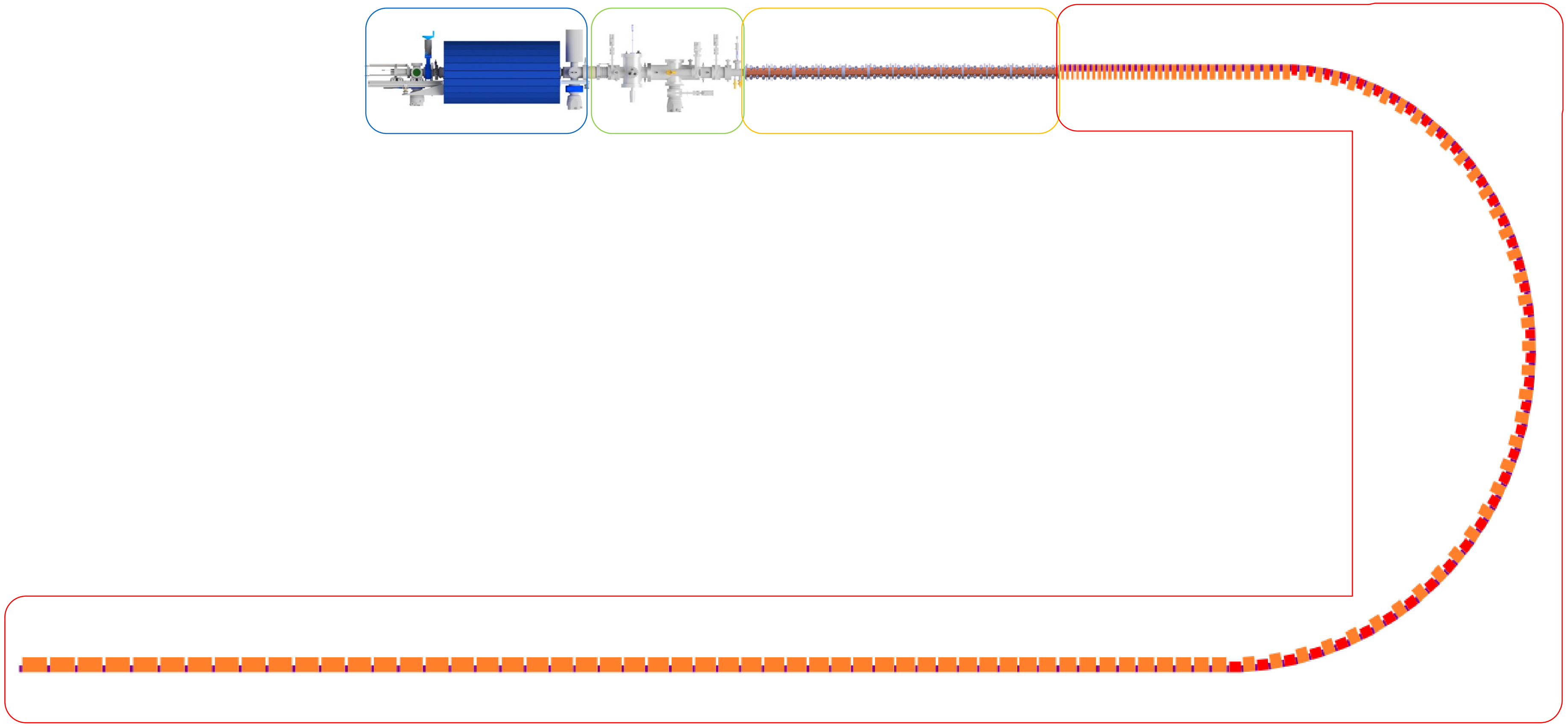
Interlaced cavity-dipole scheme



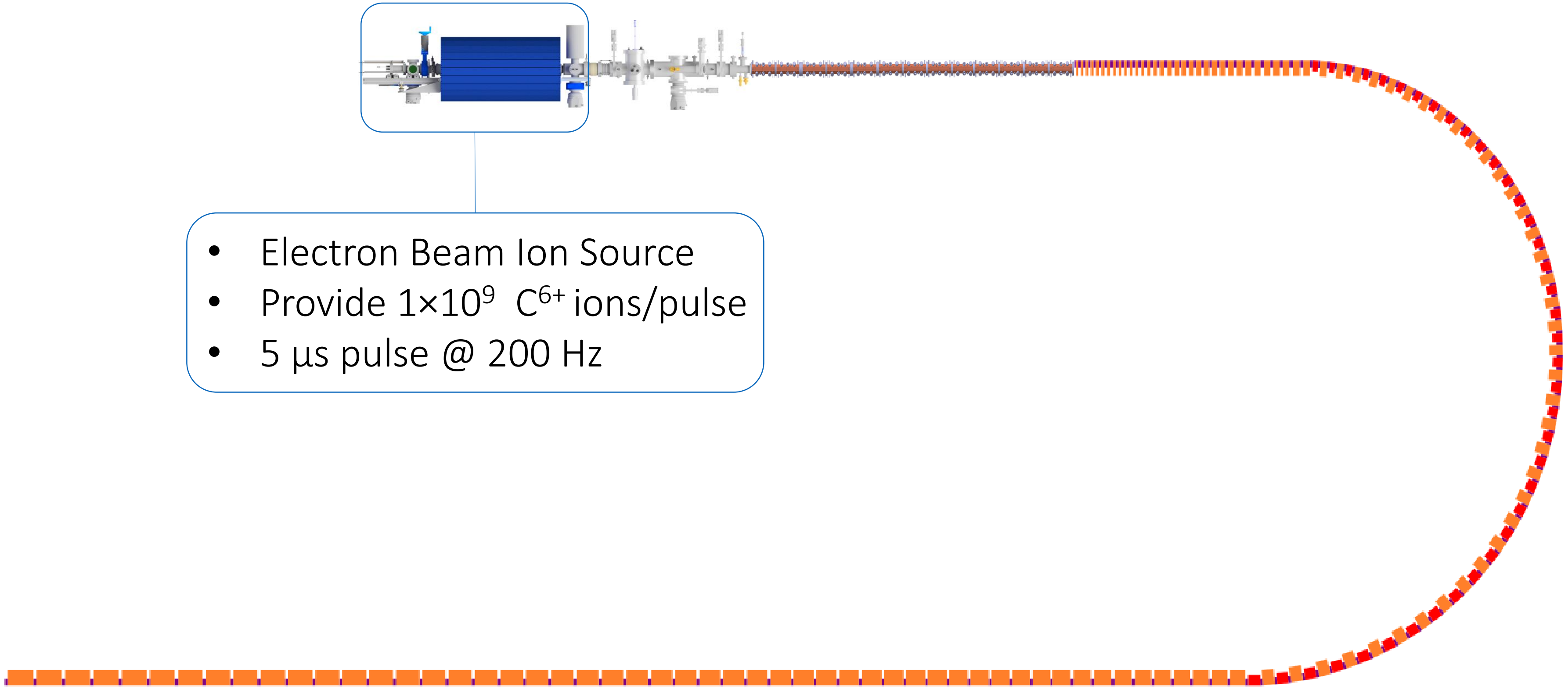
Parameter	Value
Frequency	750 MHz/3 GHz
Species	$^{12}C^{6+}$
Final energy	100-430 MeV/u
Repetition rate	200 (400) Hz
Pulse length	5 µs

- Alternated cavities and bending magnets
- Preserves FODO lattice periodicity
- Acceleration dumps dispersive effects

The bent linac



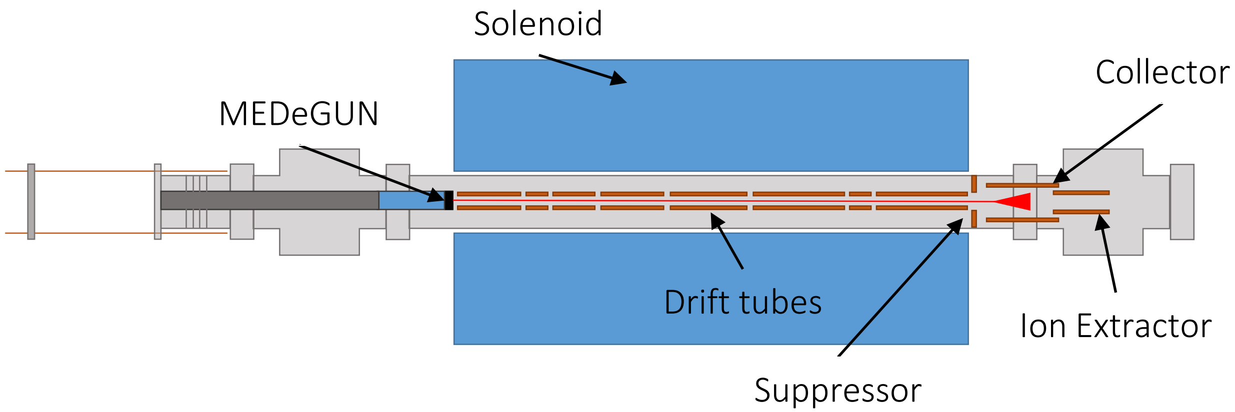
TwinEBIS source



- Electron Beam Ion Source
- Provide 1×10^9 C^{6+} ions/pulse
- 5 µs pulse @ 200 Hz

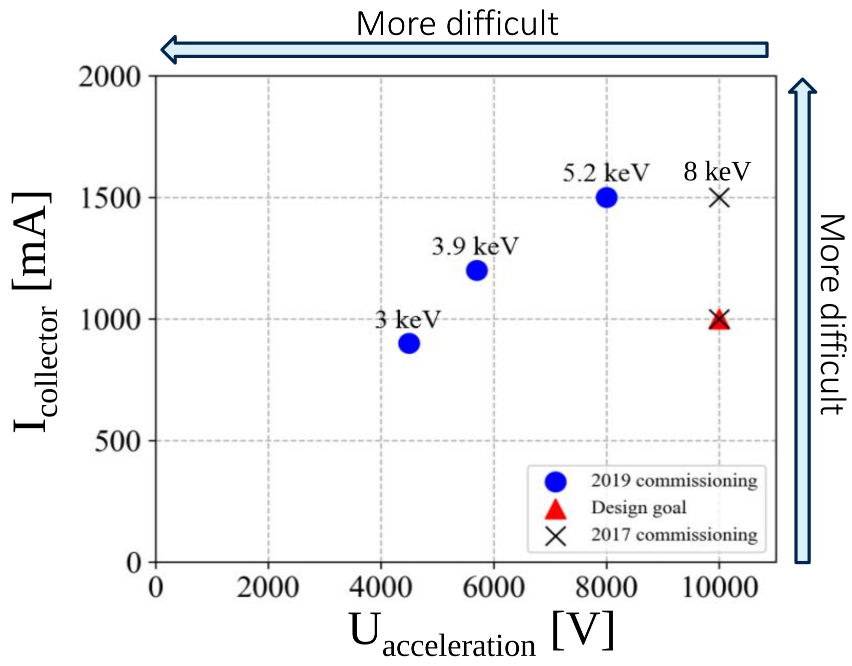
MEDeGUN commissioning

2019 Commissioning



Where we were

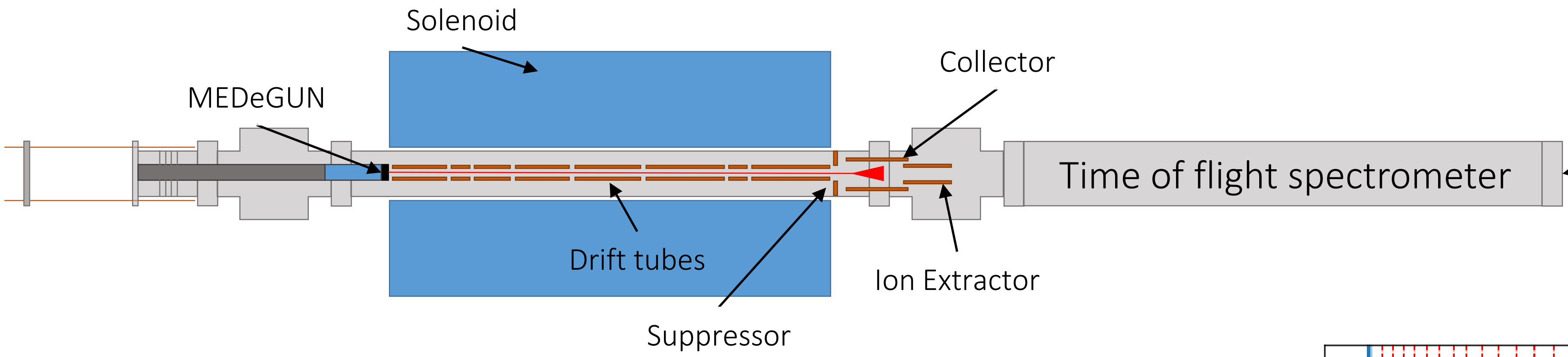
- Stable reproducible operation above nominal current
- Energy decreased to the lower theoretical limit
- Minimized losses (<1.5 mA)
- Calculation of expected ion current



Electron energy [keV]	N_{Ions} [ions/pulse]	N_{6+} [ions/pulse]
3	3.6×10^9	2.6×10^9
3.9	3.2×10^9	2.2×10^9
5.2	2.7×10^9	1.7×10^9

Ion extraction

2020/2021 ion commissioning



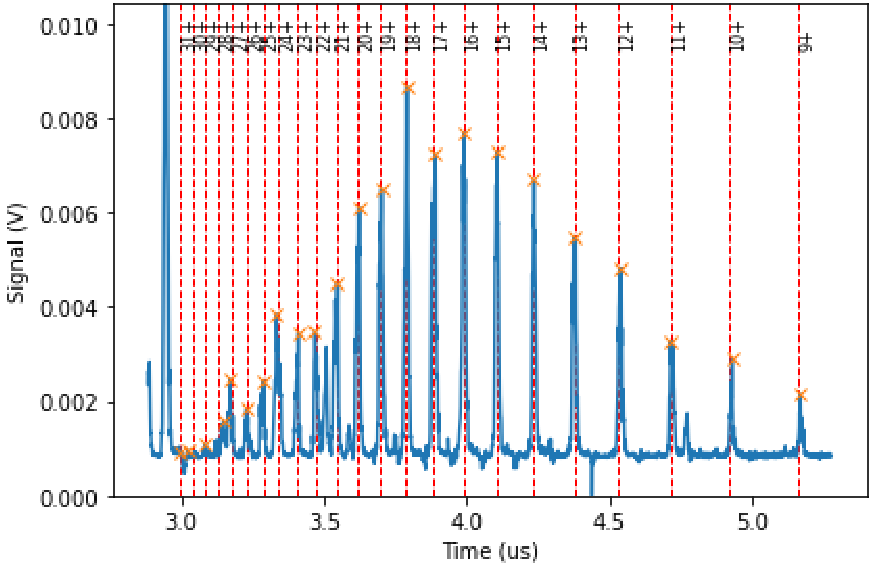
Time of Flight spectrometer was installed to record ions charge distribution spectra

Where we were

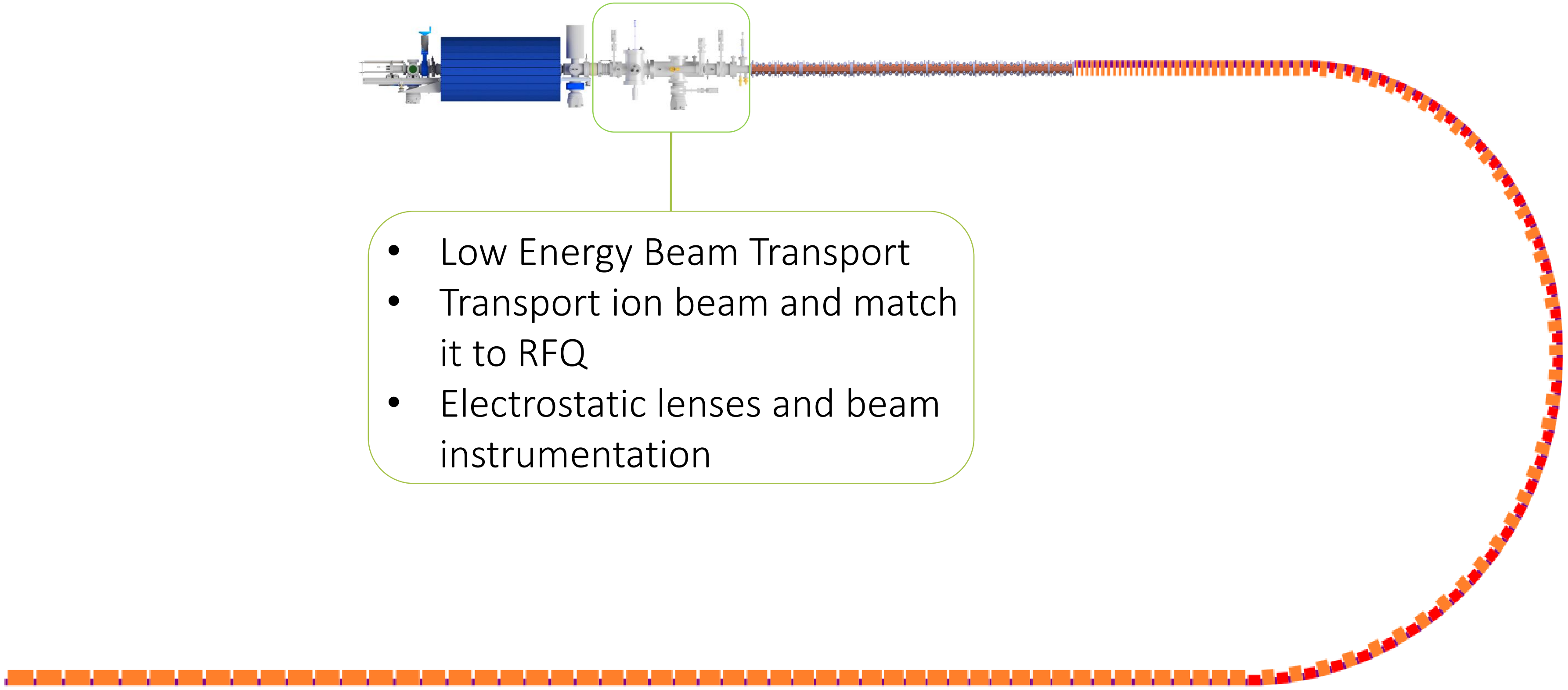
- Test and commissioning of ToF spectrometer
- Measured ion spectra for Ar and Xe
- Better understanding of TwinEBIS physics

Next step

- Few upgrades needed before CH_4 injection

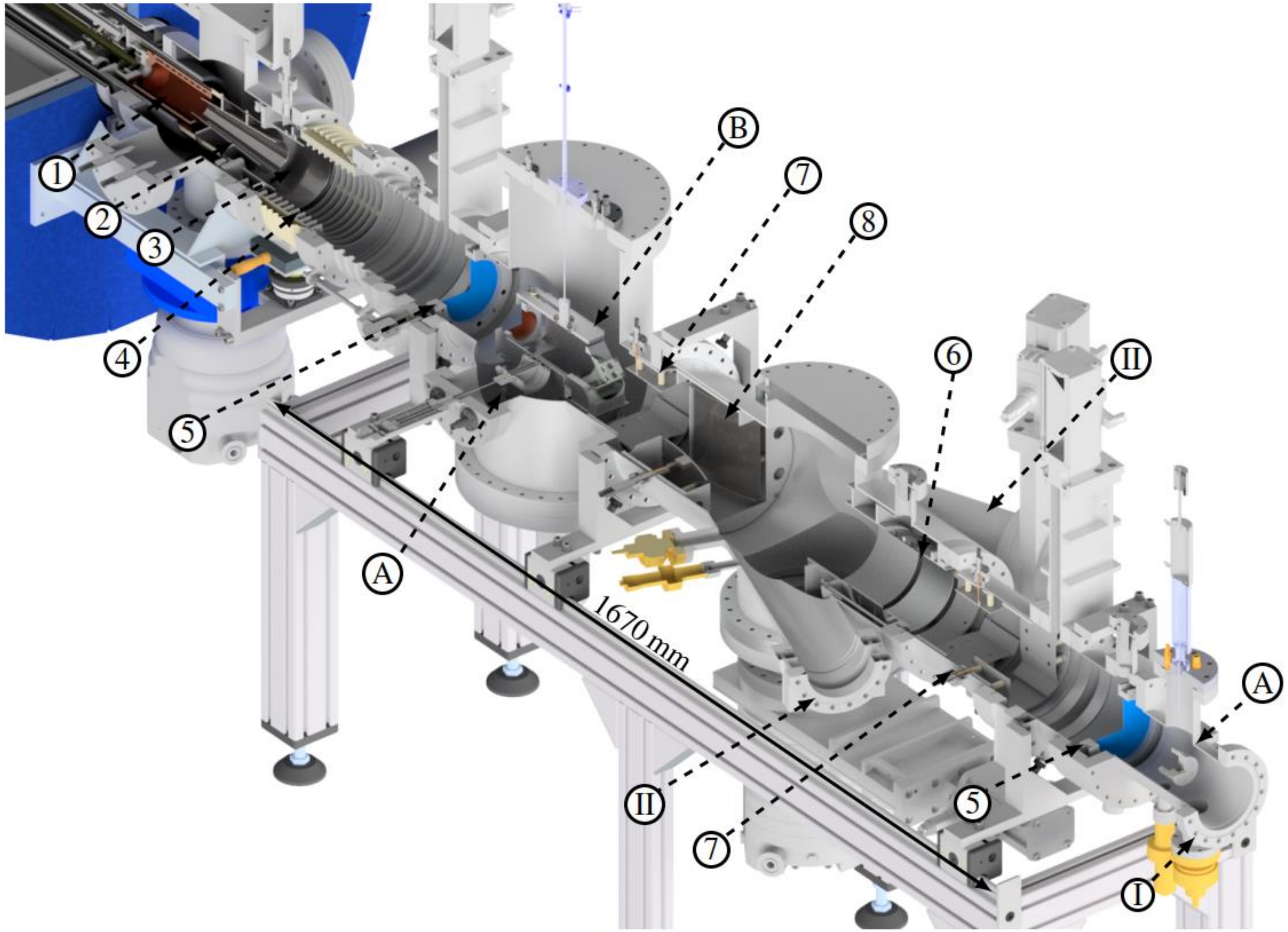


LEBT beam matching



- Low Energy Beam Transport
- Transport ion beam and match it to RFQ
- Electrostatic lenses and beam instrumentation

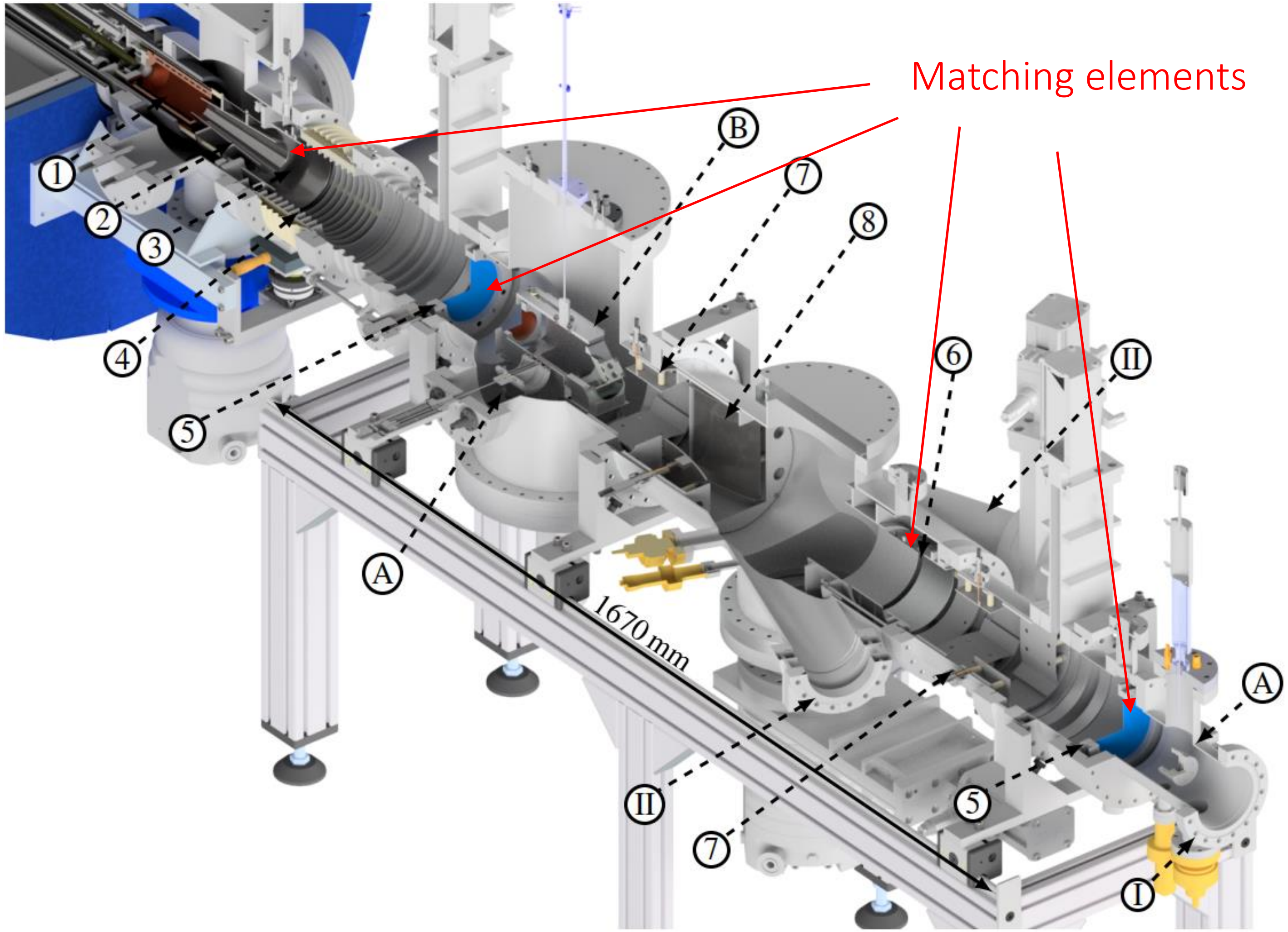
LEBT beam matching



1) Collector
2) Extractor
3) Adaptor
4) Rings
5) Gridded lens
6) Einzel lens
7) Switchyard
8) Deflector

Courtesy of H. Pahl

LEBT beam matching



1) Collector
2) Extractor
3) Adaptor
4) Rings
5) Gridded lens
6) Einzel lens
7) Switchyard
8) Deflector

Main goals

- Simulate beam dynamics in the LEBT
- Beam matching to the RFQ
- Assess flexibility of the system

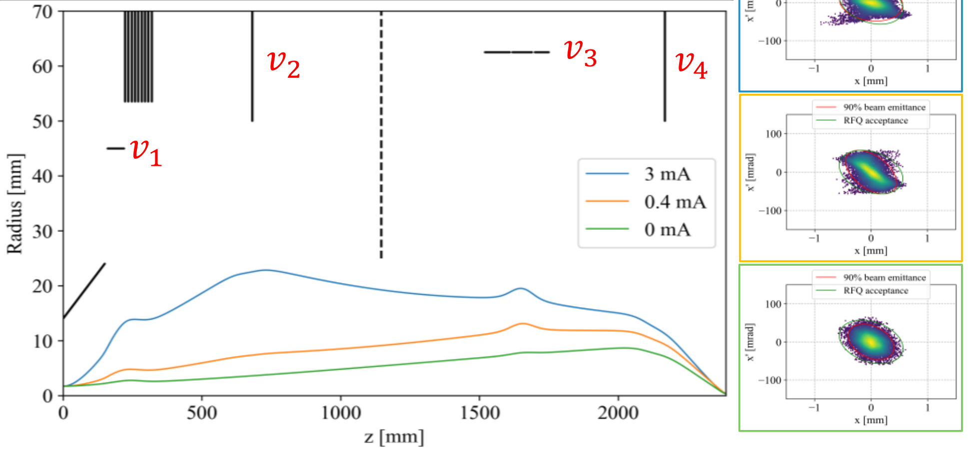
Courtesy of H. Pahl

LEBT beam matching

Where we are

- Beam matching purpose was to maximize transmission in RFQ acceptance

Beam current	0 mA	0.38	3 mA
Particles into acceptance	99%	96%	88%



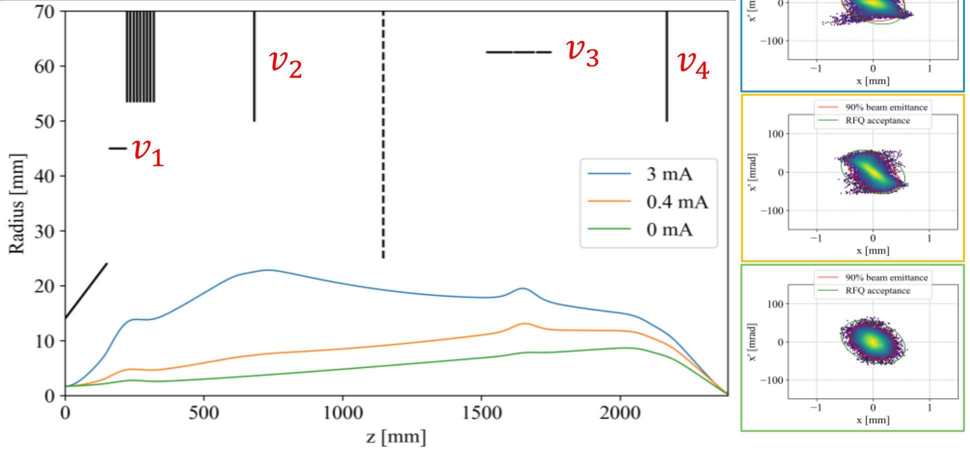
Einzel lens [kV]

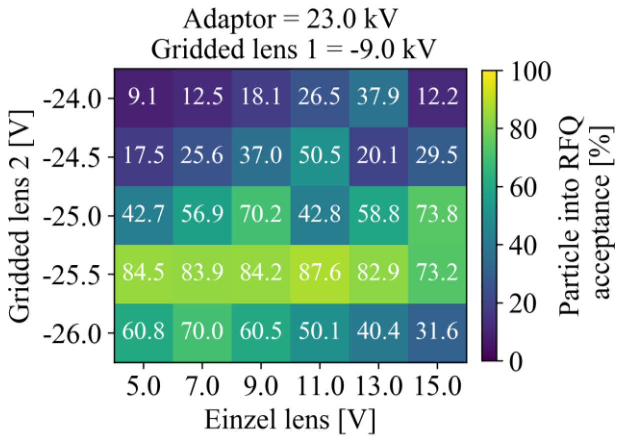
LEBT beam matching

Where we are

- Beam matching purpose was to maximize transmission in RFQ acceptance
- Development of optimization routine to find the best operational settings

Beam current	0 mA	0.38	3 mA
Particles into acceptance	99%	96%	88%





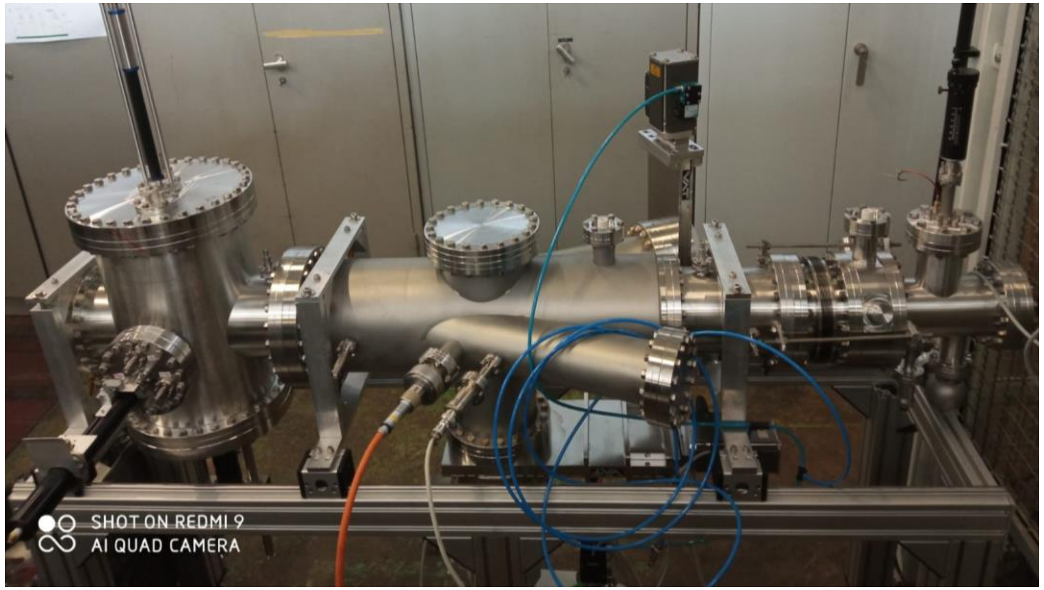
LEBT beam matching

Where we are

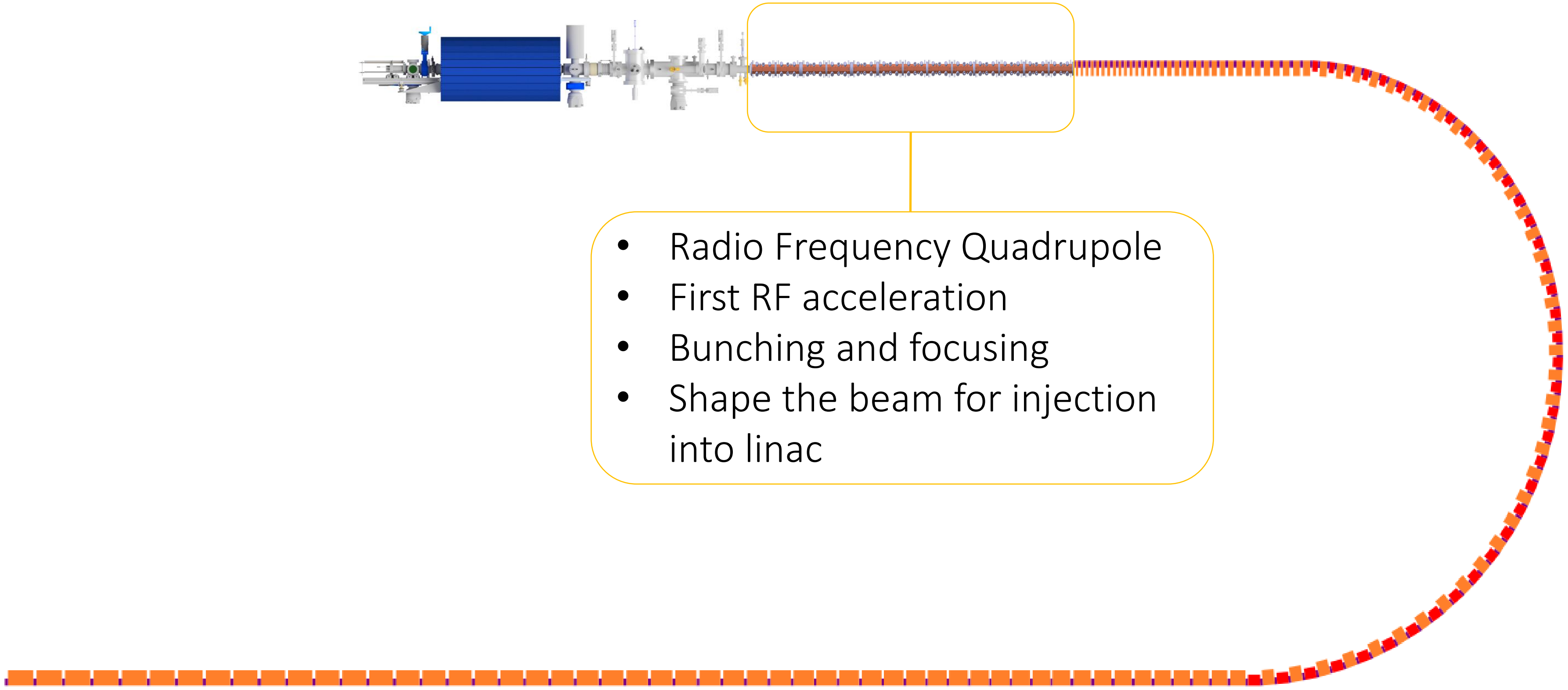
- Beam matching purpose was to maximize transmission in RFQ acceptance
- Development of optimization routine to find the best operational settings
- LEBT has been assembled and is now under vacuum

What's next?

- The LEBT is ready to be branched to TwinEBIS
- Measurements will be used to validate simulations



750 MHz RFQ design

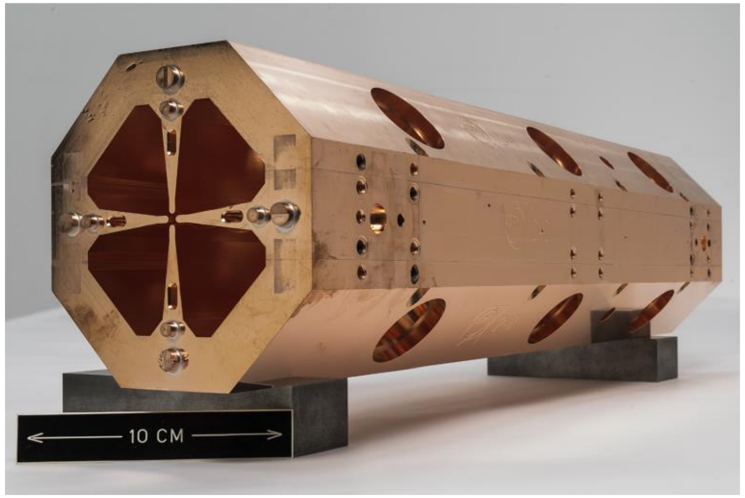


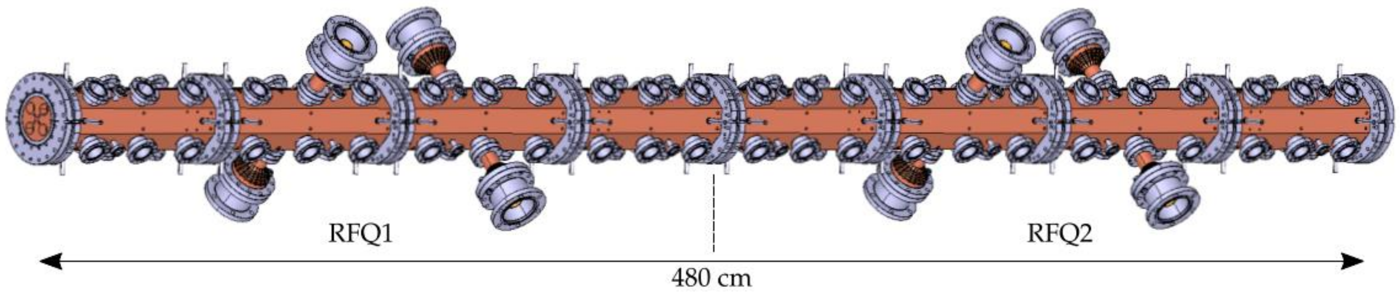
- Radio Frequency Quadrupole
- First RF acceleration
- Bunching and focusing
- Shape the beam for injection into linac

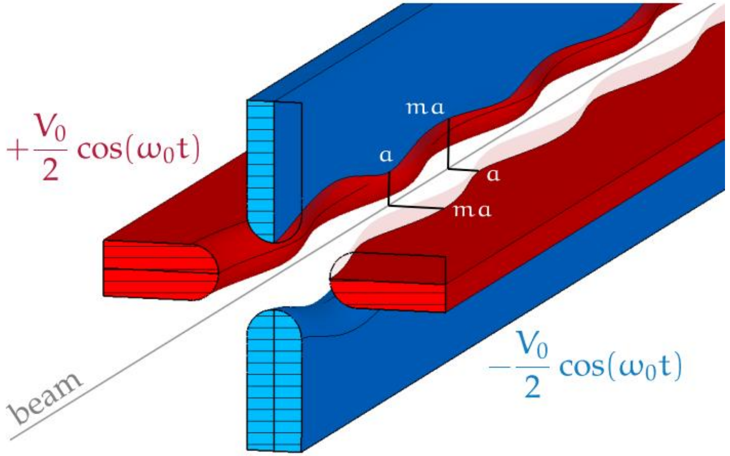
What is a RFQ?

RF resonating cavity hosting four vanes at alternating voltages

- transverse focusing (FODO-like)
- modulation on electrodes produces longitudinal electric field for acceleration
- accepts continuous input beam from particle source, structures it into bunches







A compact RFQ for carbon ion therapy

750 MHz RFQ designed to be compact and operate at low power (reduce cost!)

Where we are

- Designed on purpose to have 50 % transmission

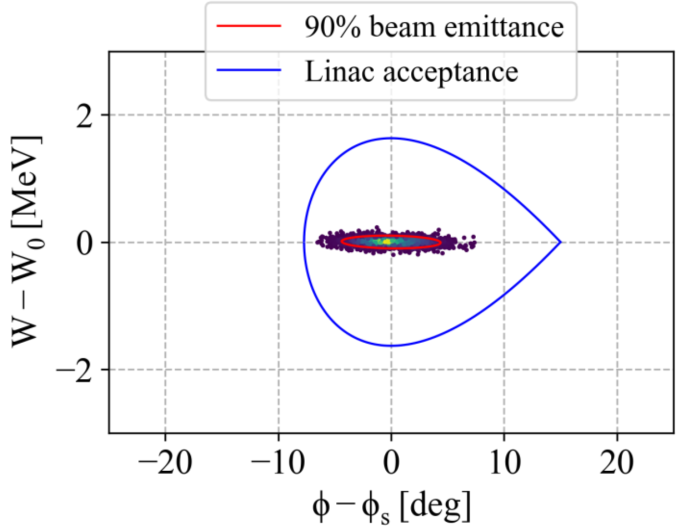
Courtesy of H. Pommerenke

A compact RFQ for carbon ion therapy

750 MHz RFQ designed to be compact and operate at low power (reduce cost!)

Where we are

- Designed on purpose to have 50 % transmission
- Shape the beam for injection into the 3 GHz bent linac



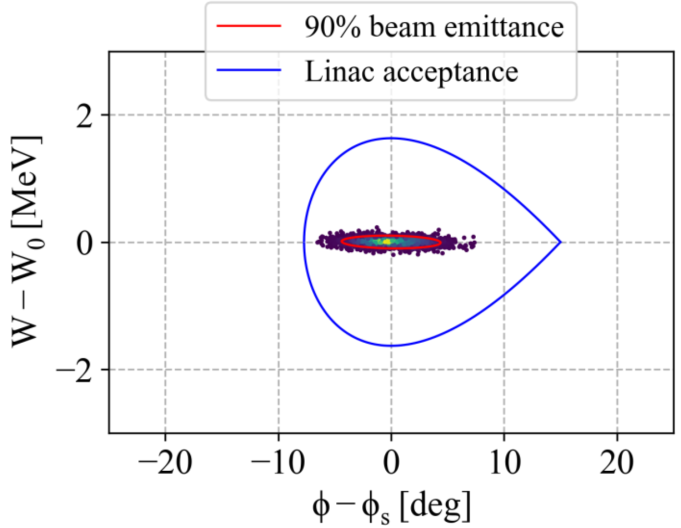
Courtesy of H. Pommerenke

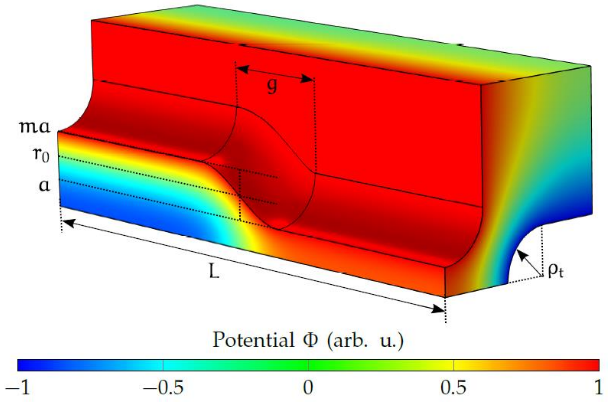
A compact RFQ for carbon ion therapy

750 MHz RFQ designed to be compact and operate at low power (reduce cost!)

Where we are

- Designed on purpose to have 50 % transmission
- Shape the beam for injection into the 3 GHz bent linac
- Trapezoidal vanes for higher efficiency





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A compact RFQ for carbon ion therapy

750 MHz RFQ designed to be compact and operate at low power (reduce cost!)

Where we are

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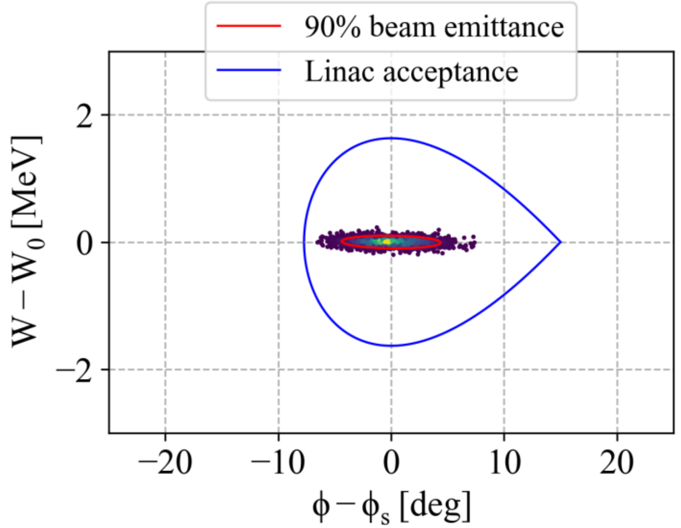
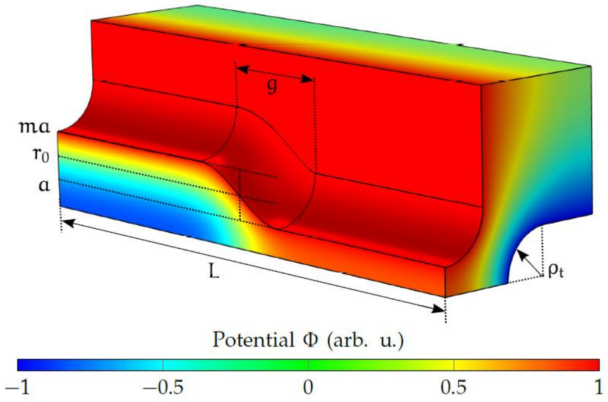
- Trapezoidal vanes for higher efficiency

What's next?

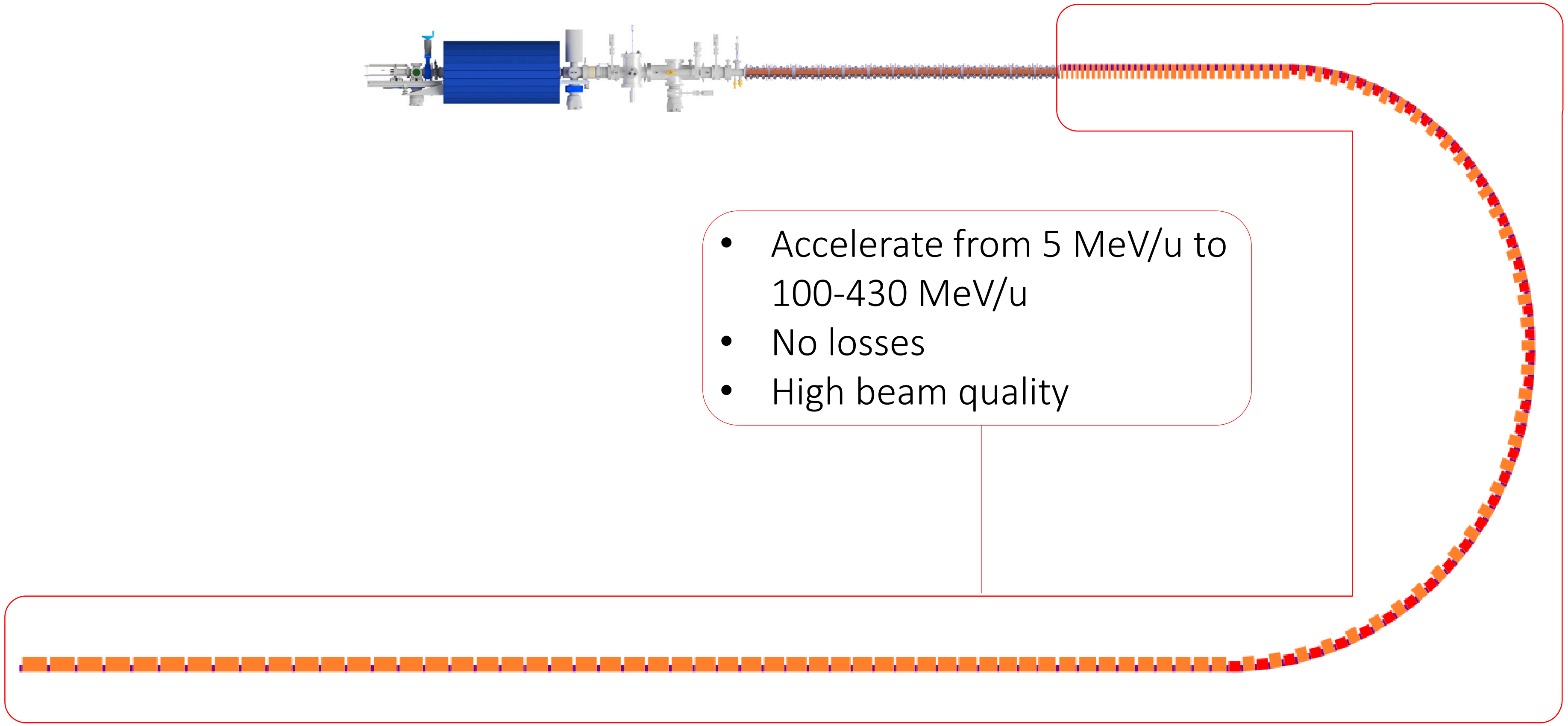
- The RFQ design was the result of a great collaboration between Beam dynamics and RF people!
- RFQ is presently under construction in the framework of a collaboration with CIEMAT





Courtesy of H. Pommerenke

The bent linac design



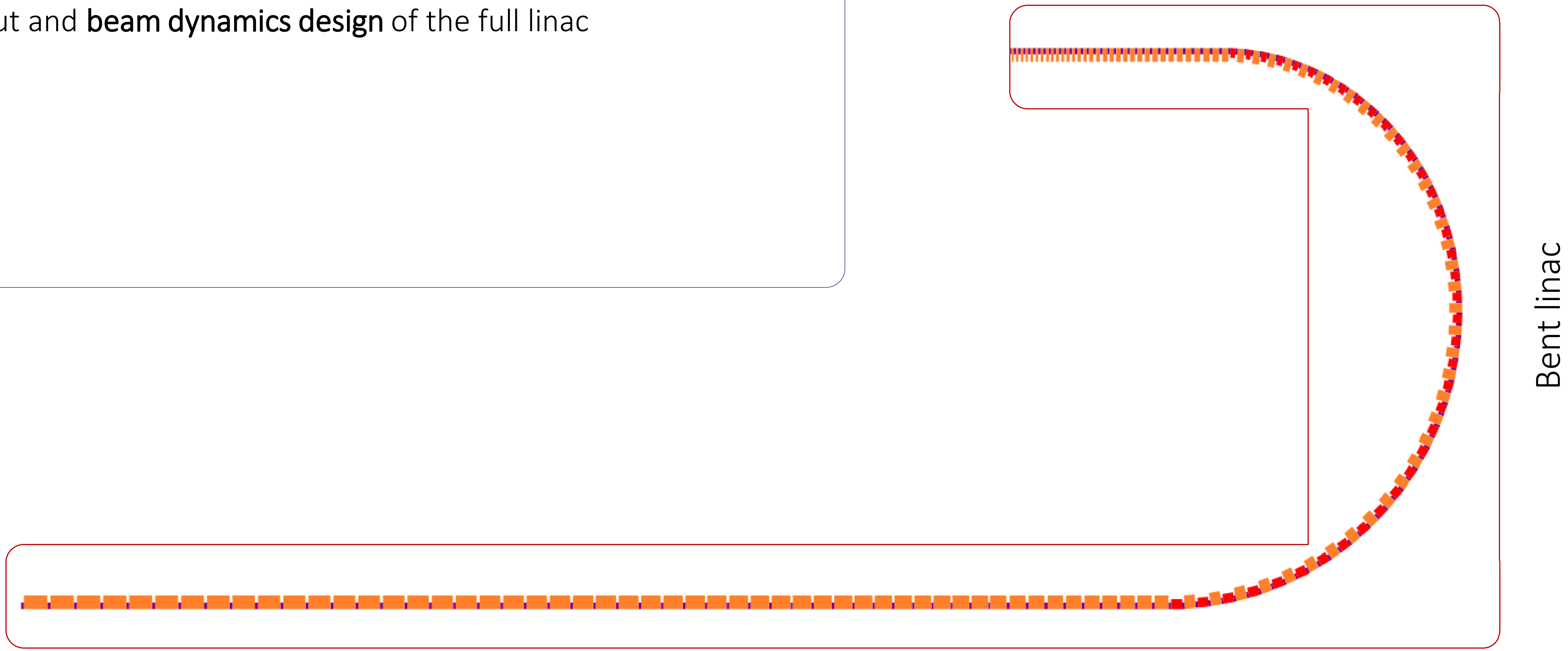
- Accelerate from 5 MeV/u to 100-430 MeV/u
- No losses
- High beam quality

The bent linac in practice

Design of a 3 GHz linac for carbon ion therapy

Where we are

- Layout and **beam dynamics design** of the full linac

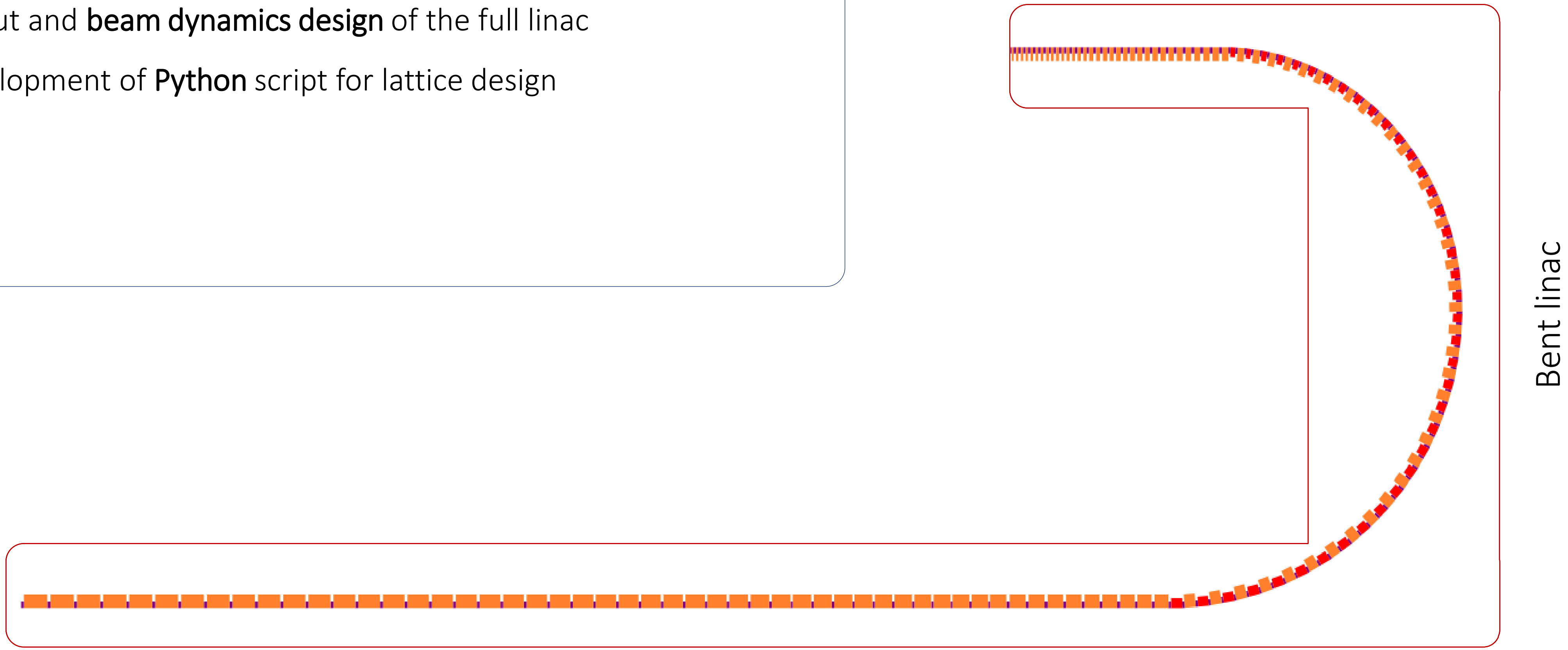


The bent linac in practice

Design of a 3 GHz linac for carbon ion therapy

Where we are

- Layout and **beam dynamics design** of the full linac
- Development of **Python** script for lattice design



The bent linac in practice

Design of a 3 GHz linac for carbon ion therapy

Where we are

- Layout and **beam dynamics design** of the full linac
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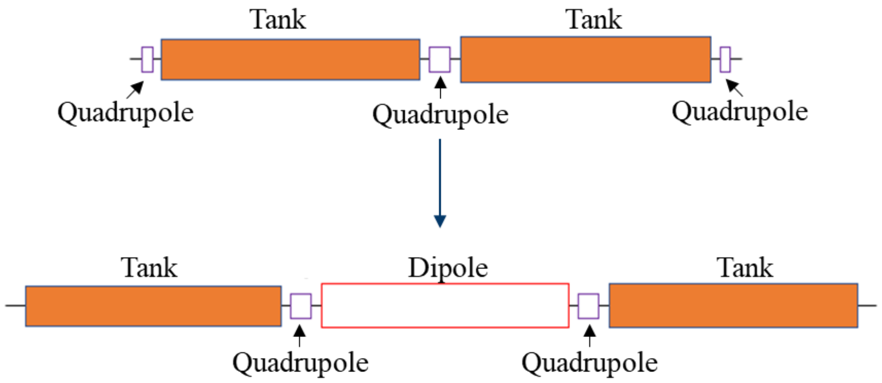
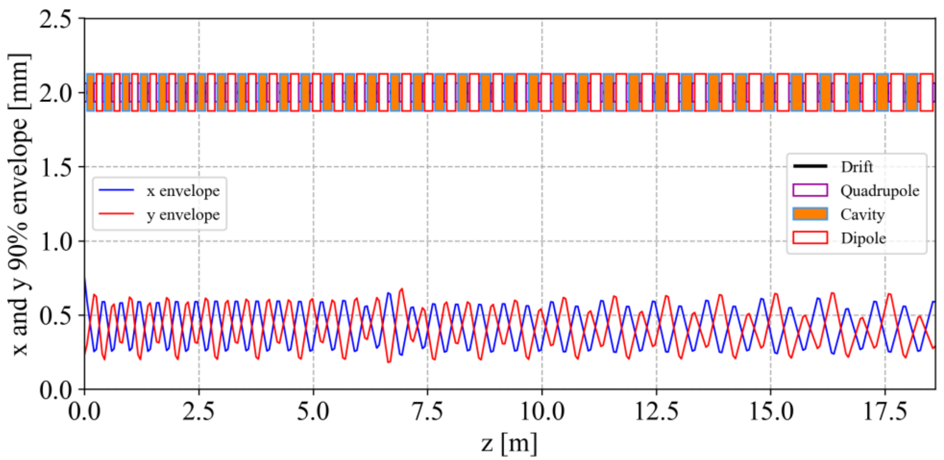
- Concept and beam dynamics of **bent section** scheme





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Design of a 3 GHz linac for carbon ion therapy

Where we are

- Layout and **beam dynamics design** of the full linac
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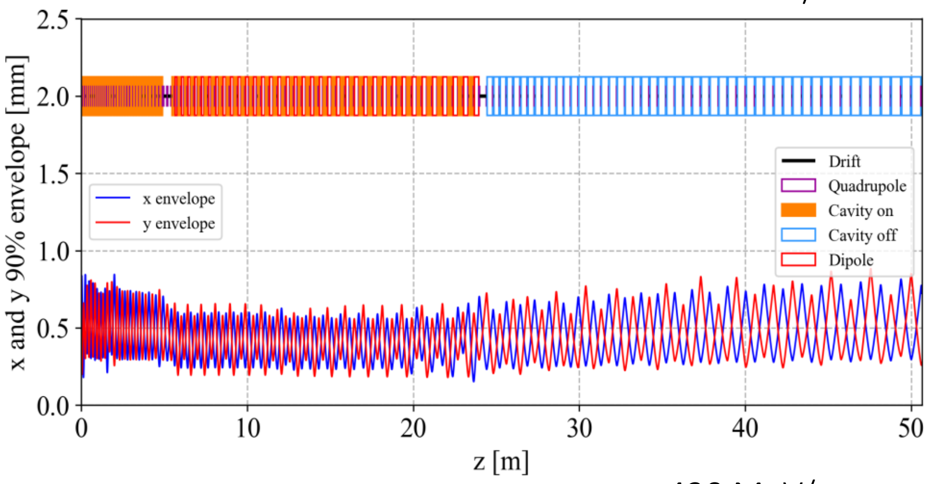
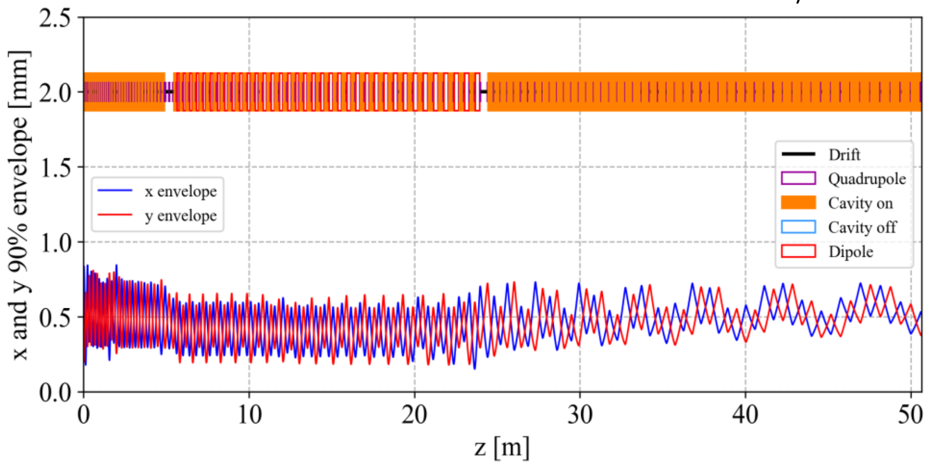
- End-to-end tracking for design validation

100 MeV/u



430 MeV/u



The bent linac in practice

Design of a 3 GHz linac for carbon ion therapy

Where we are

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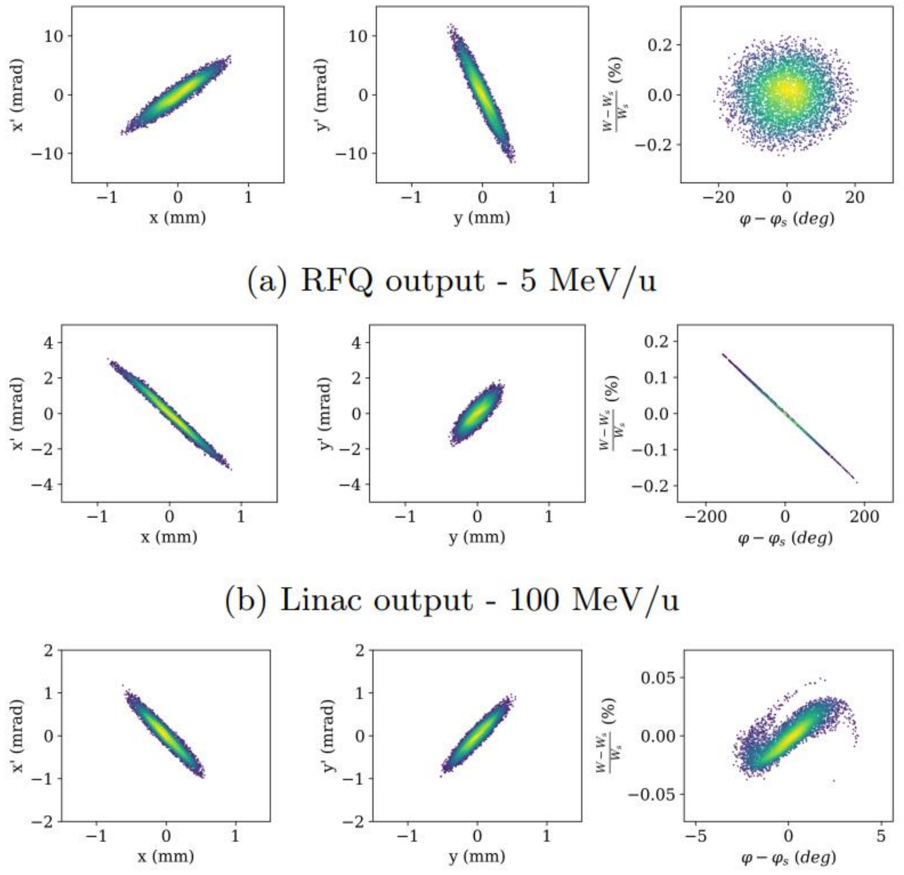
	Energy modulated	
	100 MeV/u	430 MeV/u
$\varepsilon_{xx',RMS,norm.}(\pi\ mm\ mrad)$	0.0284	0.0279
$\varepsilon_{yy',RMS,norm.}(\pi\ mm\ mrad)$	0.0269	0.0268
$\varepsilon_{\varphi W,RMS,norm.}(\pi\ deg\ MeV)$	0.6220	0.6230



(a) RFQ output - 5 MeV/u

(b) Linac output - 100 MeV/u

(c) Linac output - 430 MeV/u

The bent linac in practice

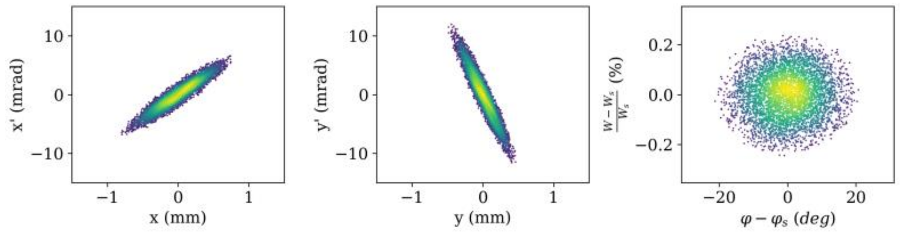
Design of a 3 GHz linac for carbon ion therapy

Where we are

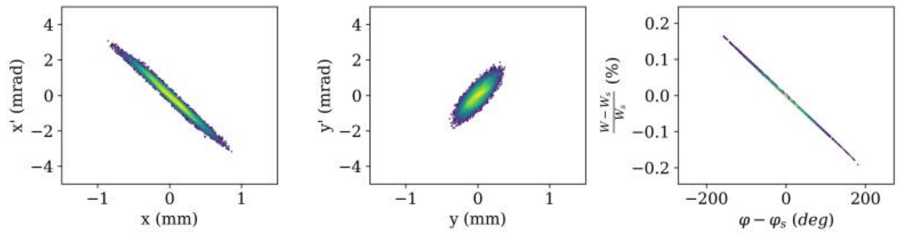
- Layout and **beam dynamics design** of the full linac
- Development of **Python** script for lattice design
- Concept and beam dynamics of **bent section** scheme
- End-to-end tracking for design validation

What's next

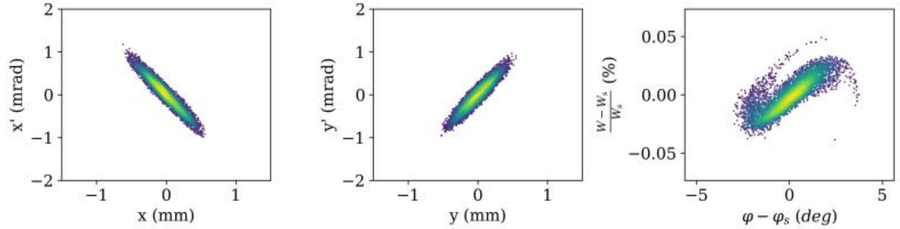
- RF design of the accelerating cavities, error studies, beam instrumentation specs definition, etc..
- Adjust the design to measured beams



(a) RFQ output - 5 MeV/u



(b) Linac output - 100 MeV/u



(c) Linac output - 430 MeV/u

To conclude…

- The pre-injector, under construction by CIEMAT, will stand as a demonstrator of the feasibility of the low energy section of the machine

- The simulation and design work on the different components of the machine indicate the capability of the bent linac of providing a high-quality beam widely within treatment specifications.

- The bent section of the machine introduces a new approach to linac design and a new degree of flexibility in rearranging the shape of a linac to fit into a hospital facility.

Last but not least…

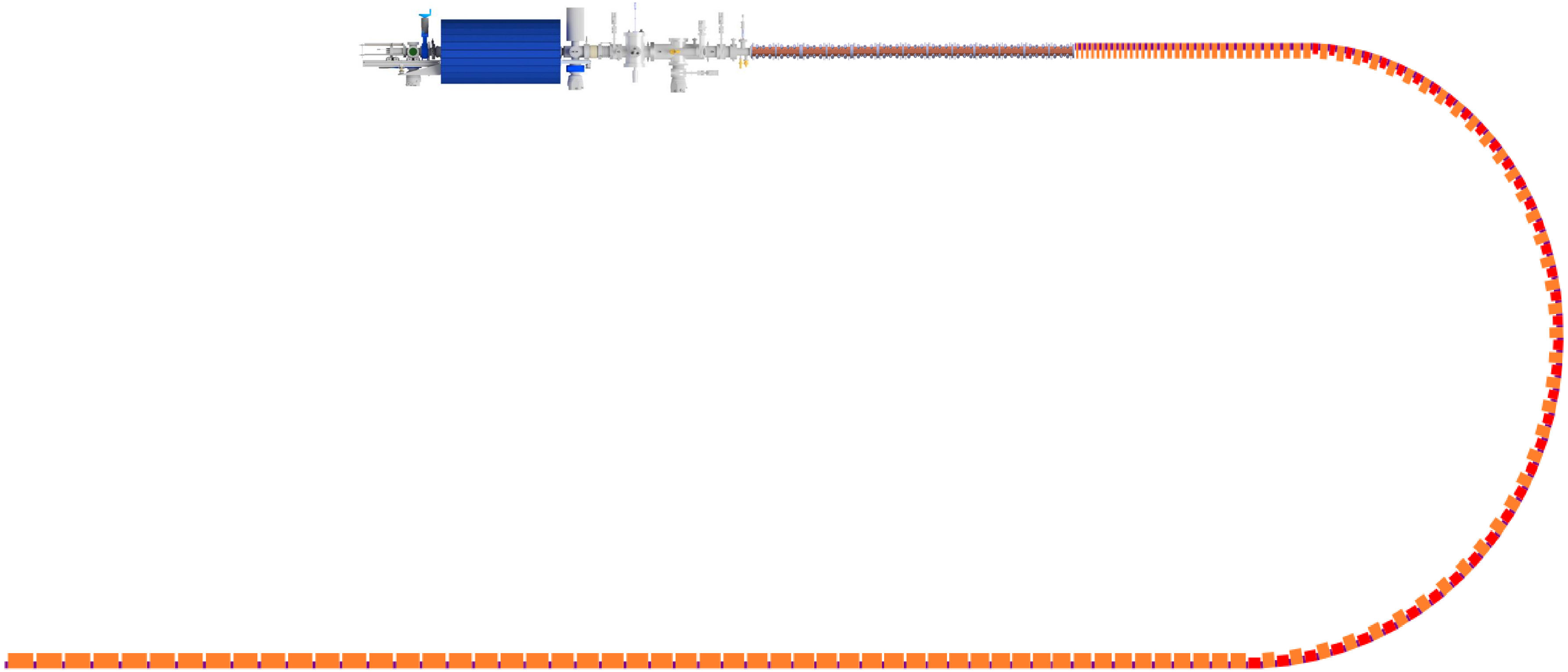
- My adventure working on the bent linac came to an end…

- It was a great experience to work on such a beautiful project and with so many incredible people!

Thanks to all the people from many groups (RF, KT, BE, EN…) who collaborated to this project:

F. Wenander, H. Pahl, J. Pitter, A. Pikin, G. Khutri, A. Lombardi, J.B. Lallement, H. Pommerenke, A. Grudiev, M. Cirilli, S. Matot, the TwinEBIS team and the Linac4 team!

Thank you!



The RFQ was proposed in 4 versions

Energy	Parameter	High Transmission	Compact
2.5 MeV/u	Transmission [%]	99	54
	Length [m]	4.6	2.7
	Power [kW]	470	280
5 MeV/u	Transmission [%]	99	54
	Length [m]	7.7	5.8
	Power [kW]	790	600

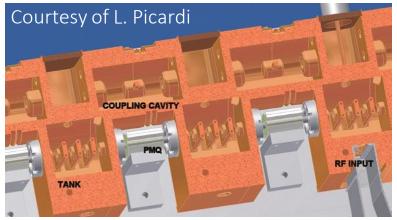
High Transmission → Experimental activities

Compact → Carbon ion therapy

2.5 MeV/u Compact → 750 MHz IH-structure

Courtesy of S. Benedetti

5 MeV/u Compact → 3 GHz SCDTL structure

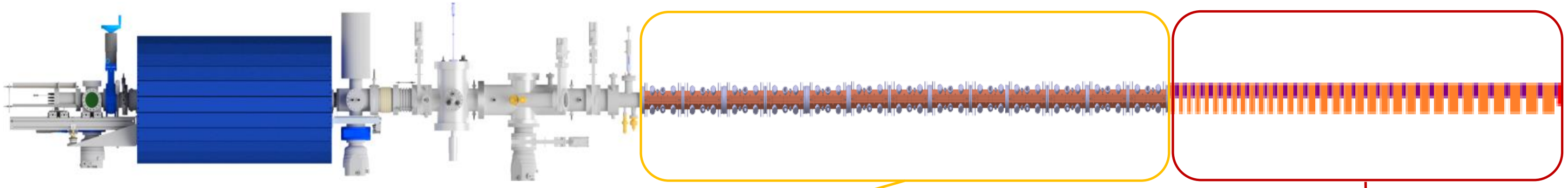


IH = Interdigital H-type

SCDTL = Side Coupled Drift Tube Linac

The fixed energy section

Baseline design



RFQ

Parameter	Value
Frequency	750 MHz
Energy	0.015-5 MeV/u
Length	4.5 m

Side Coupled DTL

Parameter	Value
Frequency	3 GHz
Energy	5-30 MeV/u
Length	5 m (1.5 m to 10 MeV/u)

The IH-structure option

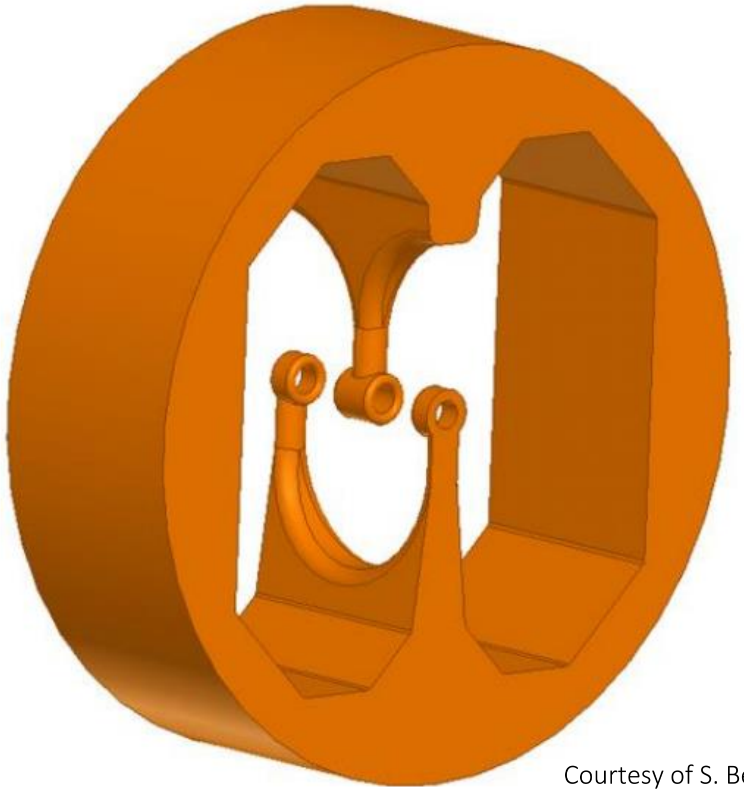
In the framework of the collaboration with CIEMAT two alternative layouts have been proposed that consider an IH-structure at 750 MHz instead of the 3 GHz SCDTL.

Advantages

- Same frequency of the RFQ (easy injection)
- High efficiency (ZTT) in the considered energy range, thus lower power consumption

Drawbacks

- More difficult transverse matching (symmetric beam due to triplet focusing)



Courtesy of S. Benedetti

IH-structure design

Two options (1 and 2) with different voltage configurations (A and B) for a total of 4 configurations:

Option 1

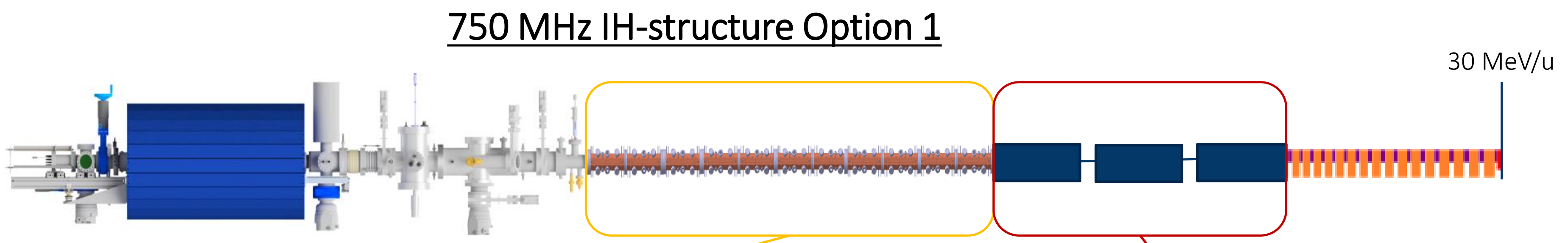
- OPTION (1A): RFQ2 (up to 5 MeV/u) + IH-KONUS (constant voltage per gap 150 kV)
- OPTION (1B): RFQ2 (up to 5 MeV/u) + IH-KONUS (more conservative voltage per gap between 120-140 kV)

Option 2

- OPTION (2A): Only IH-KONUS cavities (constant voltage per gap 150 kV)
- OPTION (2B): Only IH-KONUS cavities (more conservative voltage per gap between 100-140 kV)

The IH design is based on KONUS dynamics configuration, which includes RF gaps and quadrupole magnets.

The IH-structure option



RFQ

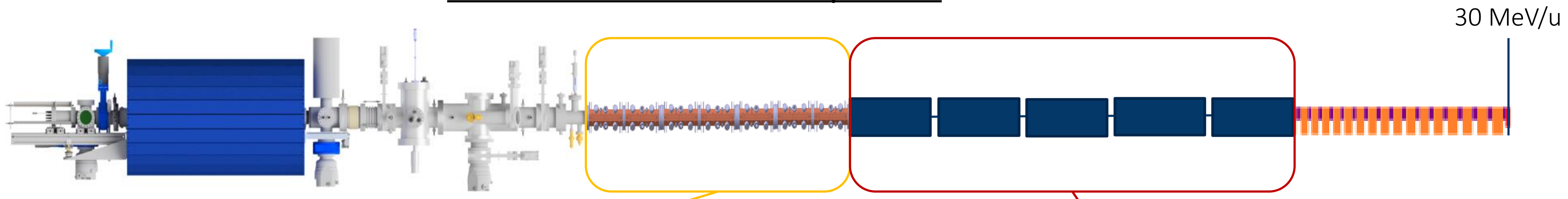
Parameter	Value
Frequency	750 MHz
Energy	0.015-5 MeV/u
Length	4.5 m

IH - structure

Parameter	Value
Frequency	750 MHz
Energy	5-10 MeV/u
Length	2.8 (A)/3.1 (B) m

The IH-structure option

750 MHz IH-structure Option 2



RFQ

Parameter	Value
Frequency	750 MHz
Energy	0.015-2.5 MeV/u
Length	2.5 m

IH - structure

Parameter	Value
Frequency	750 MHz
Energy	2.5-10 MeV/u
Length	4.7 (A)/4.3 (B) m