Injector linac – design choices (work in progress)

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Outlook

- Legacy linac
- New linac - need for higher energy
- Specification – open points
- Ion sources
- Expert system
- Preliminary results
- Conclusions

Legacy Linac

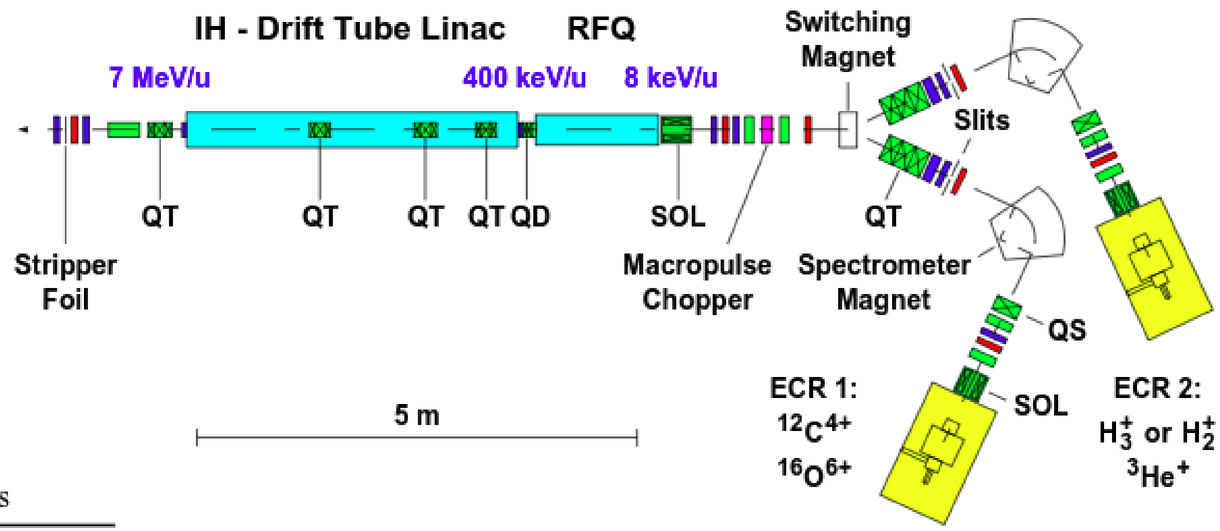


Table 1: Main Linac Design Parameters

Design ion	$^{12}C^{4+}$
Operating frequency	216.816 MHz
RFQ injection beam energy	8 keV/u
Final linac beam energy	7 MeV/u
Beam pulse length	≤ 300 µs
Beam repetition rate	≤ 5 Hz
Transv. norm. emittances (95 %) [1]	0.8 π mm mrad
Exit beam energy spread (95 %) [1]	≤ ±0.4 %
Total linac length [2]	6.95 m

[1] straggling effects in the stripper foil not included
[2] including RFQ, IH-DTL, and foil stripper section

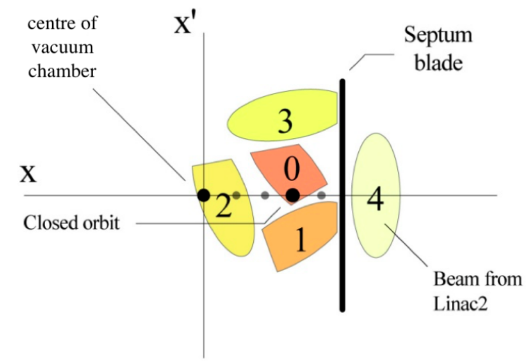
Design in late 1990s (GSI, Darmstadt), Installed in: HIT, CNAO, MIT, MedAustron and Shanghai

+ Very reliable, proven technology

- rather expensive (~10 MEUR), high power consumption (~1 MW)
- low beam intensity

New linac

- Objective: increase beam intensity in the synchrotron in order to have enough C^{6+} ions for a whole treatment session – patient comfort.
- All major centers are testing this approach and NIRS (Japan) is applying it.
- It is more critical for superconducting synchrotron with a slow ramp rate.
- The simplest way to do it is to apply so called multiturn injection
- In order to maximize injected beam intensity the beam size should be as small as possible.
- This can be achieved by:
  - Low emittance source (EBIS)
  - Higher beam energy
- Another advantages of injecting at higher energy:
  - Minimization of space-charge tune shift:
  - Smaller range of synchrotron magnet currents



$$\Delta Q_y^{SC} \approx \frac{N Z^2 r_p}{2\pi A \epsilon_y \beta_0^2 \gamma_0^3 B_f},$$

New linac specification

Design ion	C4+ or C4+/C6+ or C5+/C6+ **q/m**	Higher charge state – lower intensity from the source.
Operating frequency	216.8 MHz or 325 MHz or 352 MHz or 750 MHz	Higher frequency: larger gradient, but smaller aperture (constraint on emittance)
RFQ injection energy	8 keV/u or more	Depends on operating frequency: higher frequency, higher energy
Final linac beam energy	10 MeV/u	
Beam pulse length	< 200 us (<100 us for superconducting)	Depends on synchrotron revolution period at injection.
Beam repetition rate	5 Hz	
Transv. norm emittance (95%)	<< 0.8 pi mm mrad	Higher synchrotron intensity – smaller emittance
Exit beam energy spread (95%)	< 0.4%	
Linac length	< 10 m (but shorter is better)	

A word about ion sources

ECRIS (Electron Cyclotron Resonance Ion Source) – high intensity, large emittance.
EBIS (Electron Beam Ion Source) – lower intensity, much smaller emittance.

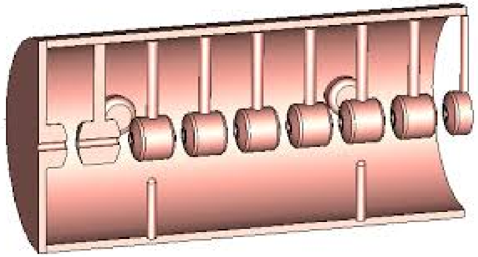
source	ion/current/ intensity in 200µs[*10^{10}]	Extraction voltage	emittance	price
SUPERNANO GAN (Pant.)	C4+/200µA/6.2	30 kV	180 mm mrad	300 kEUR
PK-ISIS (Pant.)	C4+/500µA/16 C6+/50µA/1	30 kV	As above	?
AISHA	C4+/800µA/25	30-40 kV	?	In development
MEDeGUN	C6+/?/10^9 per pulse	20 kV ?	18 mm mrad ?	In development

Components

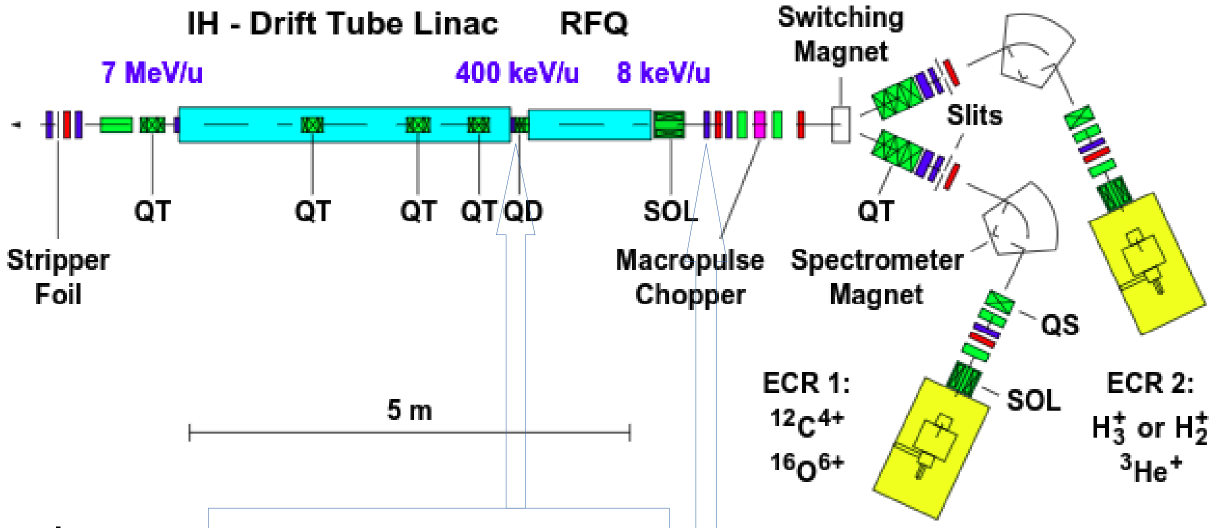
- Accelerating structures (including RFQ)
- RF sources (klystrons, tubes, solid state)

Cost drivers

- Ion sources
- Instrumentation
- Vacuum
- Timing and control system
- Power converters for magnets
- Cooling



Matching, constraints, rules, relations



For example:

Ion velocity must match to the size of the first drift tube

Ion velocity must match to the size of the first RF cell – what is the smallest possible cell?

“Expert system” for injector

- Expert system is a computer system that emulates the decision-making ability of a human expert.
- In our case the “expert system” should support (not replace) human in design process.
- There is no one good optimization, the most important criteria are: cost, simplicity, reliability, footprint, flexibility
- Expert system is made of knowledge base and inference engine.
- Main decisions:
  - Operating frequency
  - RF source technology
  - Location of stripper

Technology develops fast (this project is a part of the development) so need of **scientific guesses:**

- what will be possible in a few years?
- where to push development?

Knowledge database

- Result of talking to many people and hours of bibliographical research, translated to:
- Set of xml files for ion sources, RFQs, accelerating structures and RF sources
- Example for Pantechnik SUPERNANOGAN


```xml
<?xml version="1.0" encoding="UTF-8"?>
<IonSource>
 <Name>SUPERNANOGAN</Name>
 <Type>ECRIS</Type>
 <RFfreq unit="GHz">14.5</RFfreq>
 <Manufacturer>Pantechnik</Manufacturer>
 <Ion id="12C4+">
     <Charge>4</Charge>
     <Intensity unit="uA">200</Intensity>
     <Emittance unit="pi*mm*mrad">0.3</Emittance>
 </Ion>
 <Ion id="4He2+">
     <Charge>2</Charge>
     <Intensity unit="uA">x</Intensity>
     <Emittance unit="pi*mm*mrad">0.3</Emittance>
 </Ion>
 <ExtractionEnergy unit="kV">24</ExtractionEnergy>
 <PulseDuration unit="ms">5</PulseDuration>
 <RepRate unit="Hz">10</RepRate>
 <Cost unit="kEUR">800</Cost>
 <DataSources>
     <DataSource>
     https://indico.cern.ch/event/595518/contributions/2406543/attac
     </DataSource>
 </DataSources>
 <Remarks>
     <Remark> CW or pulsed mode. </Remark>
     <Remark> Gas: carbon oxide and helium. </Remark>
 </Remarks>
</IonSource>
```

Inference engine

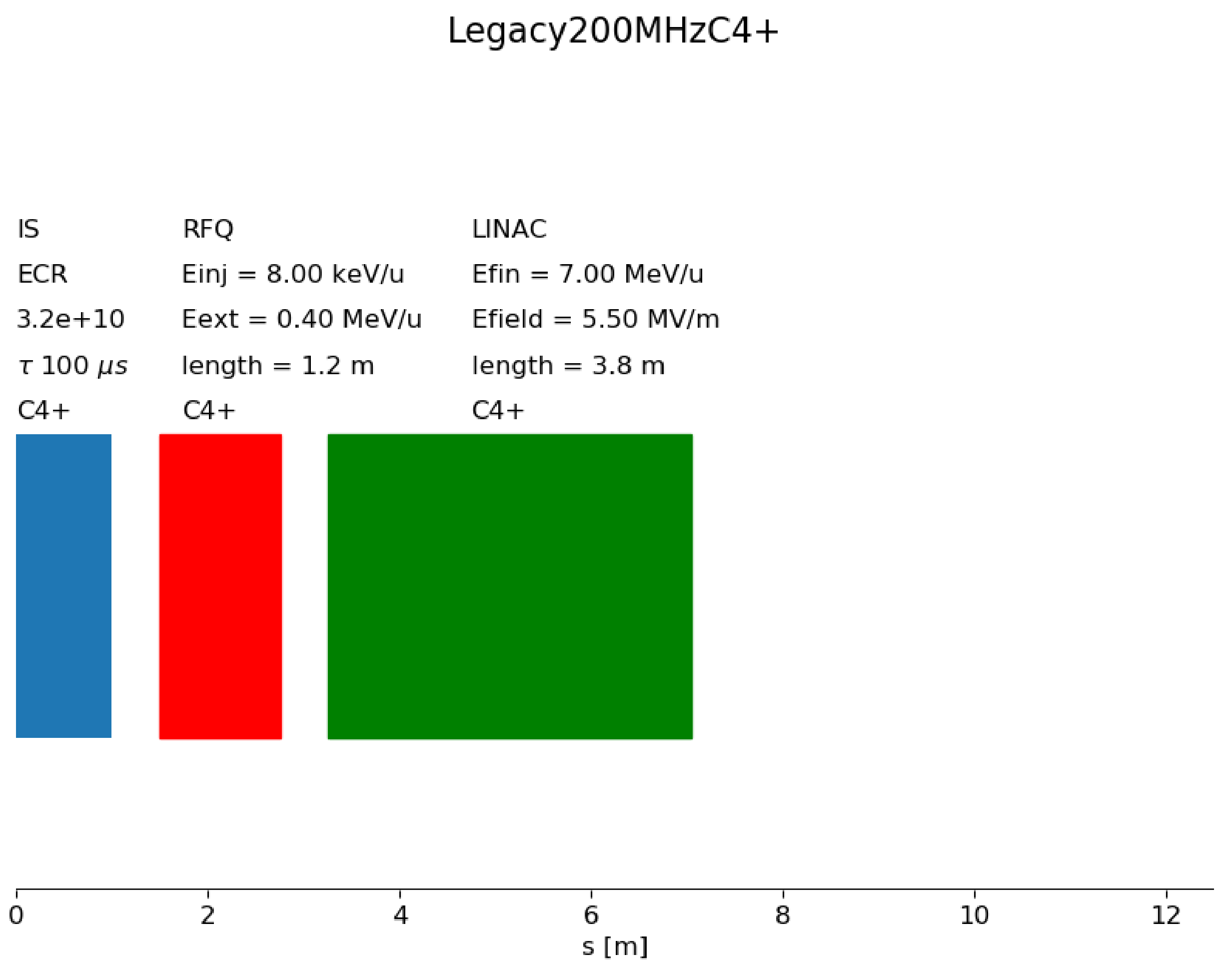
- Set of python functions grouped in a module
- Functionality:
  - calculate cost-optimized linac
  - visualize a linac
  - more will come

```
IS="IonSources/PantechnikECR.xml"
ion="12C4+"
RFQ="RFQs/HE325MHzC4plus.xml"
Linac="Linacs/CostOpt325MHzC6plus.xml"

drawLinac2("325 MHz C6+ stripping after RFQ",IS,ion,RFQ,Linac,0.5,0.5)
```

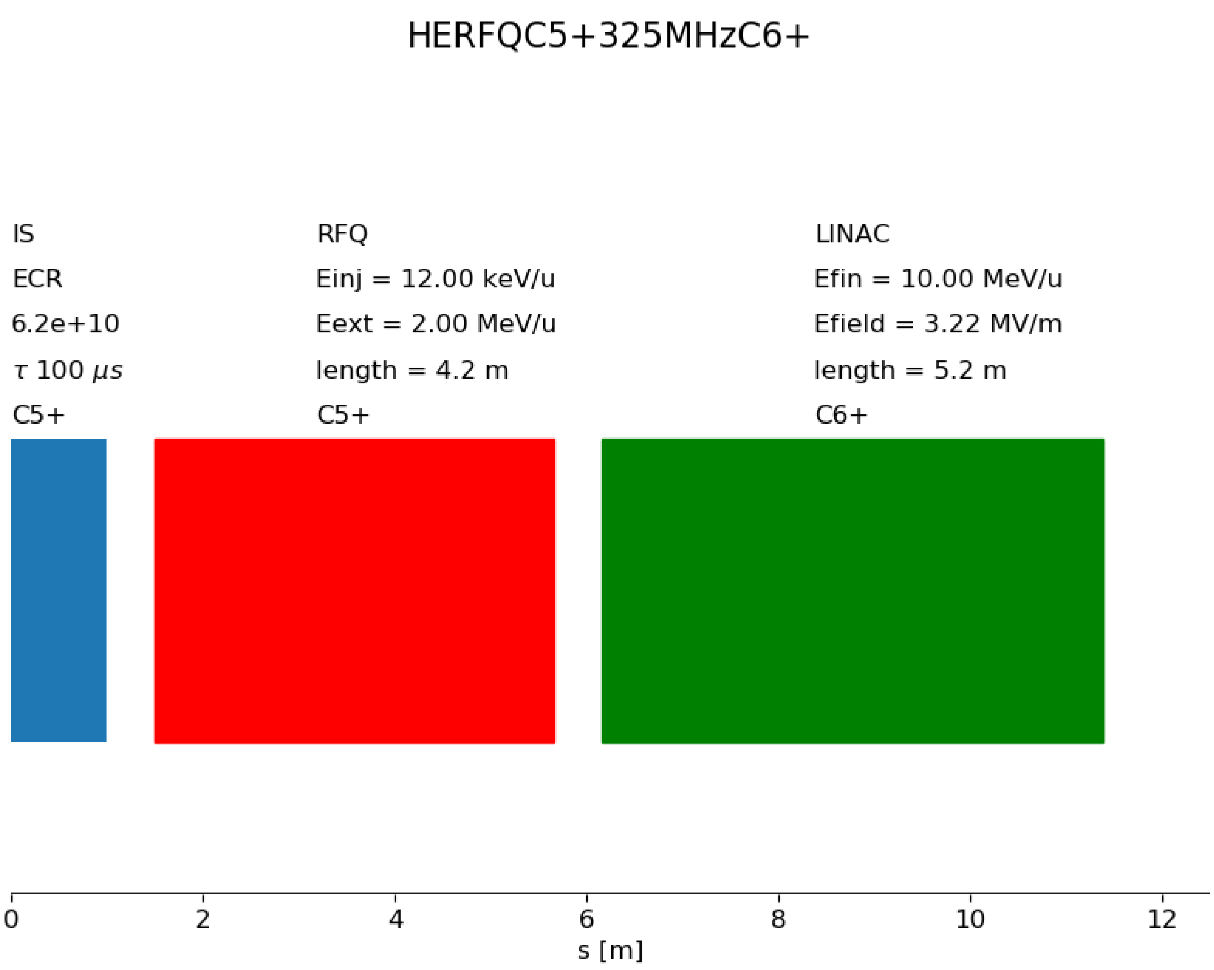
Example 1: Legacy linac

Cost (all included, source, RFQ, linac) ~10 M€



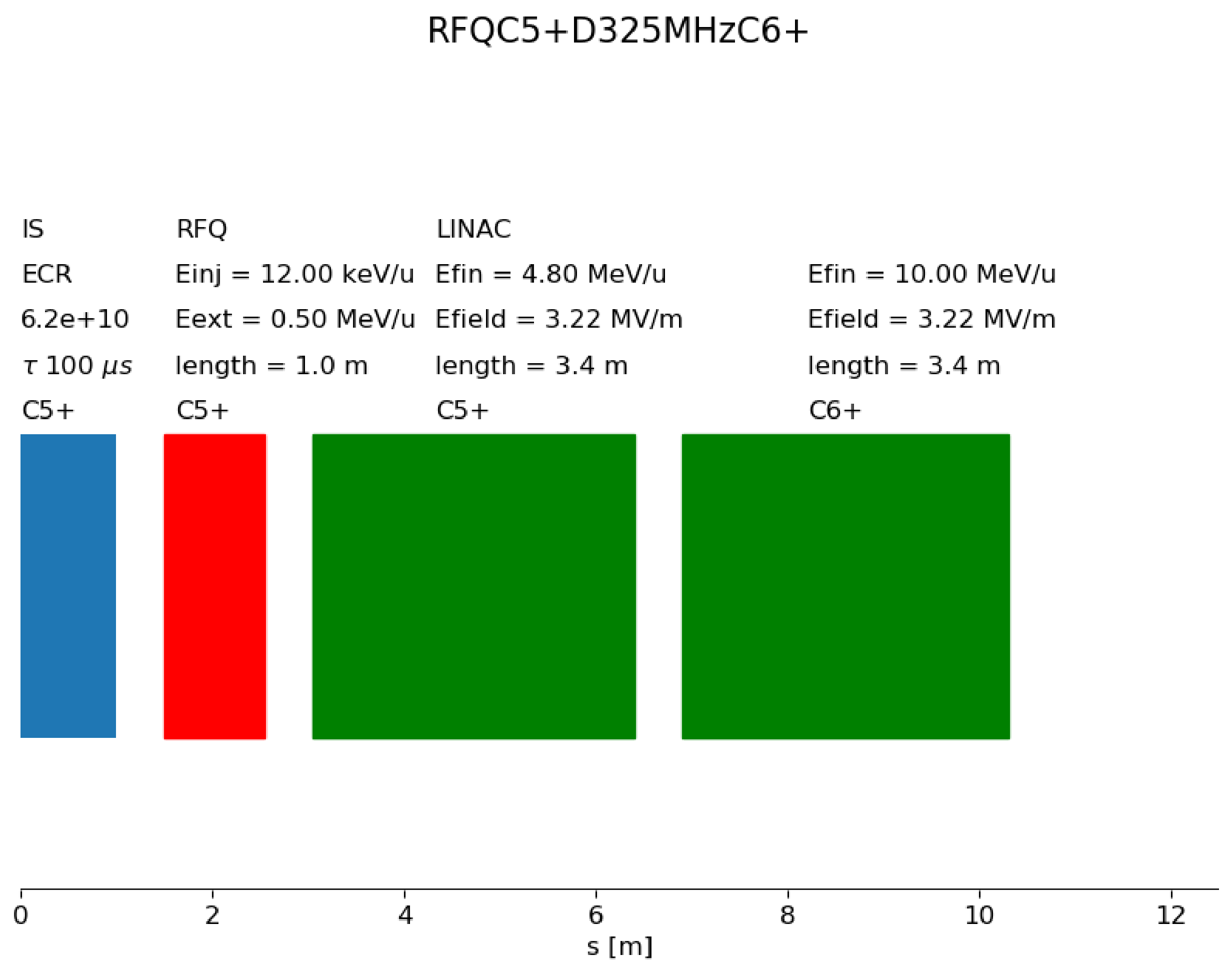
Example 2: 325 MHz C^{6+} linac, stripping after RFQ, cost-optimized

Cost (all included, source, RFQ, linac) ~6.5 M€



Example 3: 325 MHz split linac with C^{5+}/C^{6+}, stripping after first part of IH, cost-optimized

Cost (all included, source, RFQ, linac) ~3.5 M€



Conclusions

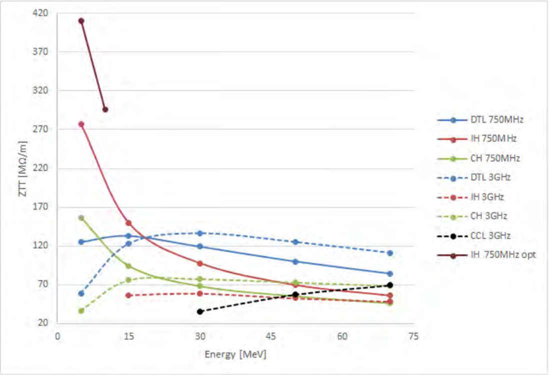


Figure 2.5 – ZTT as a function of the geometric βs for the optimized low β cavities considered.

- Lot of things still missing in “expert system”, for instance:
  - Realistic curves of shunt impedance as a function of particle velocity (need input)
  - Acceptances
- Preliminary results show that C^{5+} source is a good option
- Splitting IH is much cheaper than long RFQ
- Optimal linac, also at 325 MHz, is long (10 m)
  - probably a higher gradient at the additional cost is a way to go
- Next steps:
  - Update expert system, rerun it, choose 1-3 options
  - Design basic beam dynamic for a chosen options
  - See which is the best, iterate...