Technical Design Report for a Carbon-11 Treatment Facility

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Solid ground for Science

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OVERVIEW

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- **Motivation**
  - PET imaging
- **Facility Layout**
  - Past results
    - Key accelerator components
- **Integration Possibilities**
  - Integration at existing facilities MedAustron, CNAO

Motivation: PET imaging

Range uncertainties

INDEPENDENT on dose calculation:
- Beam reproducibility
- Patient positioning and setup
- Measurements in water for commissioning

DEPENDENT on dose calculation:
- CT calibration
- Tissue conversion
- Mean ionization energy estimation
- Range degradation for complex inhomogeneities

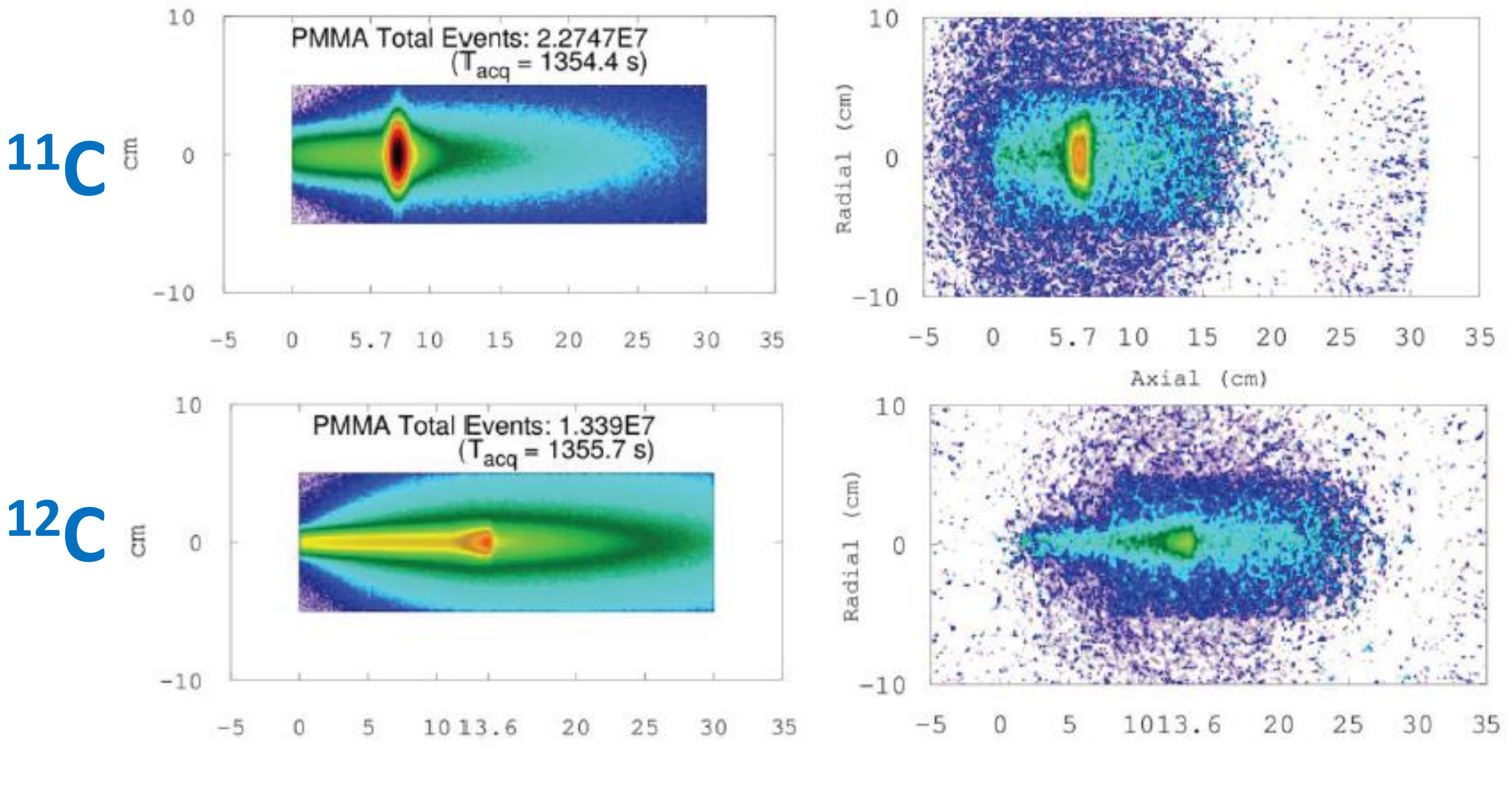
Treatment verification via PET device

- Off-line (PET/CT)
- In-room (PET or PET/CT)
- In-beam (PET)

Limitations of the PET imaging

- Noisy image from positron emitters produced by projectile fragmentation
- Long acquisition times (~2% of the primary beam undergo nuclear reactions, per cm)

Imaging performance



FLUKA Simulation: Annihilation events at rest

Experimental data (A.U.)

^{11}C advantages:
- Higher relative concentration of signal in the Bragg peak vicinity
- A factor of two sharper peak
- Higher number of events (by one order of magnitude)

FLUKA simulation:
- FLUKA PET tools
- Estimation of the annihilation events at rest

EXPERIMENTAL data:
- openPET whole-body scanner (QST/NIRS)
- Beam irradiation in PMMA phantoms
- ^{11}C: 5.4x10^{7} particles (3 spills)
- ^{12}C: 9x10^{7} particles (5 spills)

Past results

Lawrence Berkeley National Laboratory

^{11}C via projectile fragmentation, 250 MeV/u, 2 ·10^7 per pulse

- Primary beams: ^{12}C, 350 MeV/u; ^{18}O, 800 MeV/u
- Target: Be

11 MeV PET-cyclotron, N_2 gas target

HIMAC/NIRS

^{11}C via projectile fragmentation, 355 MeV/u, 7.2 ·10^6 per pulse

- Primary beam: ^{12}C, 430 MeV/u; ^{16}O, 800 MeV/u
- Target: Be

Centre de Recherche du Cyclotron

^{11}C at 120MeV/u, 1·10^8 ions/s

30 MeV cyclotron; Targets: BN, B_2O_3

CERN ISOLDE

^{11}C without post-acceleration, intensities $\leq 7.7 \cdot 10^8$ ions/s

1.4GeV protons; Targets: multiple types

ISAC/TRIUMF

^{11}C without post-acceleration, intensities $\leq 10^7$ ions/s

500 MeV protons; Target: NiO/Ni

FACILITY LAYOUT: specifications and challenges

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SPECIFICATIONS: the same as for ^{12}C treatment facilities

SPILLS:

0.1 to 10 seconds

ENERGIES:

C^{6+}: 120 to 400 MeV/u

- *Energies corresponding to 3-37 cm penetration depth in human tissue*
- *~1 minute to deliver 2 Gray in 1 L tumor volume*

INTENSITIES:

C^{6+}: $\leq 4 \cdot 10^8$ particles/spill

(4 intensity steps for each beam species)

BEAM SIZES:

4 to 10mm

(4 size steps)

The main CHALLENGES to solve for a ^{11}C facility

- Production of ^{11}C
- Accumulation of ^{11}C
- Stable and reproducible performance

FACILITY LAYOUT: key components/stages

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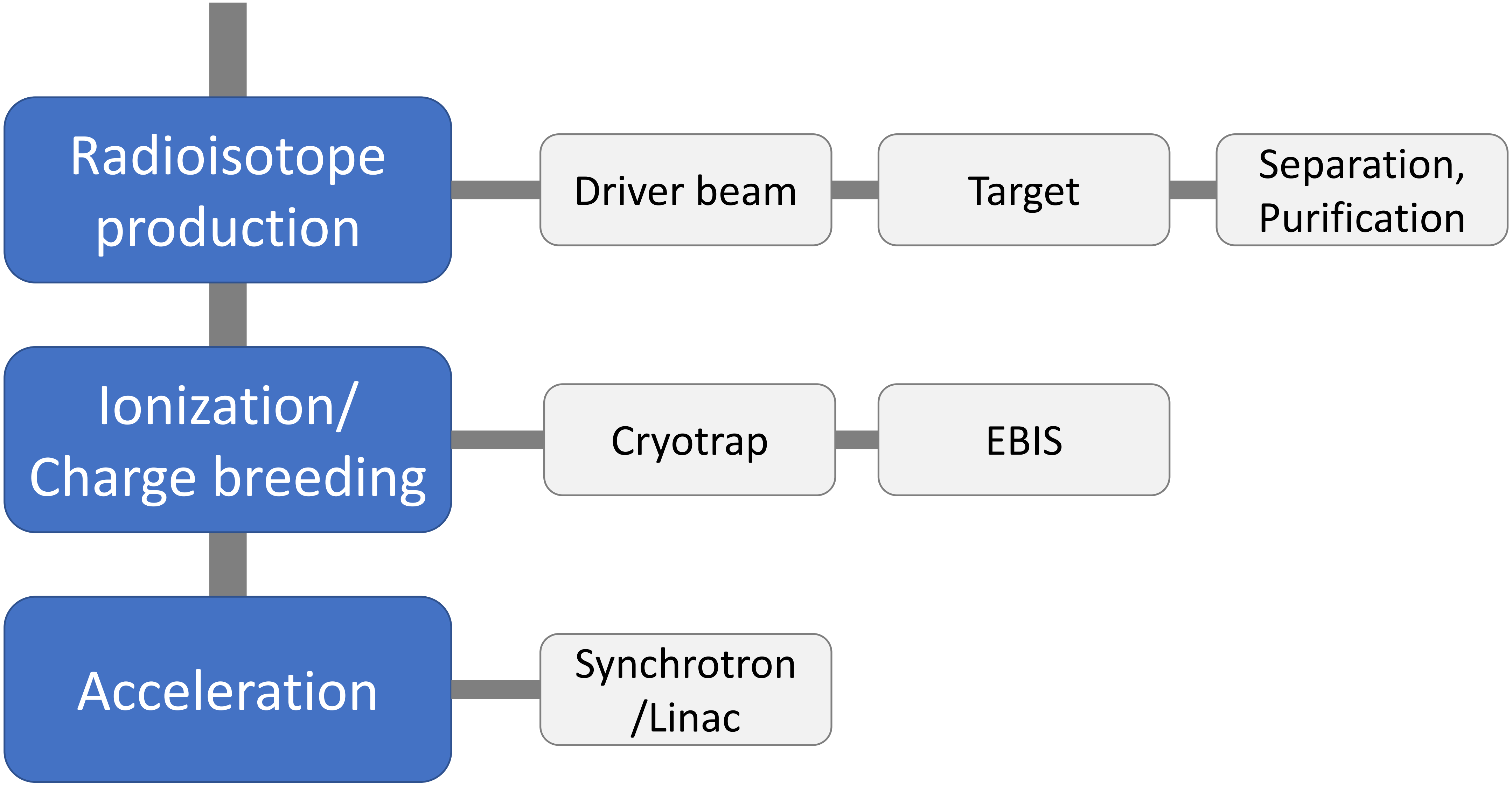

Radioisotope production

Driver beam — Target — Separation, Purification

H^+

OPTIONS:
- 7 MeV (existing facilities)
- 18 MeV (IBA KIUBE)
- 250 MeV (VARIAN ProBeam)

N_2 *vs.* BN

N_2:
- Gaseous
- PET type
- Batch operation

BN:
- Solid
- ISOL type
- cw operation

neutral *vs.* 1+

neutral:
- Gas mixing in the target (O_2 or N_2)
- Chromatography gas separation (of $^{11}CO_2$ or $^{11}CH_4$)

1+:
- ^{11}CO delivered to a ECR ion source
- Beam deceleration

- In-target production yields (FLUKA)
- Isotope release efficiencies

OPTIONS
- Feasible intensity of primary beam
- Target geometry
- Molecular sideband

- Starting contaminants…
- Trapping efficiency
- Transport efficiency
- Process duration
- Remaining contaminants

The resulting numbers are given in the talk of Simon Stegemann

^{11}C Production: summary for N_2 targets

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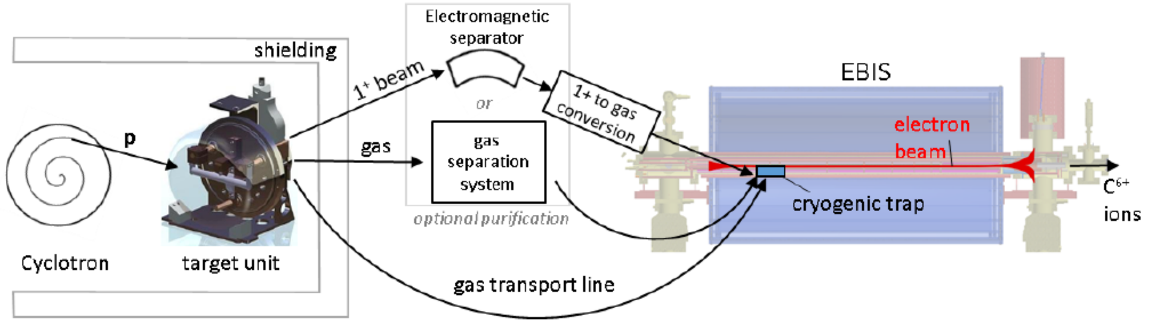
Accelerator	LEBIT-Linac	CYCLONE® **KIUBE**	VARIAN ProBeam™
Particle	proton	proton	proton
Energy[MeV]	7	18	250
Intensity [μA]	7	50	0.8
Pulse structure	dc/ x Hz-y ms	dc/ x Hz-y ms	dc/ x Hz-y ms
Beam cross section [mm^2]	Gauss 8.24^2	Gauss 8.24^2	Gauss 8.24^2
batch/extraction time [min]	30 + 4 + 1	30 + 4 + 1	30 + 4 + 1
Target size, geometry [S · L] [cm]	40 cm^3 1.8·11.26 · 5.7	40 cm^3 1.8·11.26 · 5.7	40 cm^3 1.8·11.26 · 5.7
Target material	N_2/O_2	N_2/O_2	N_2/O_2
In-target yield EOB [GBq]	0.7	262 (176)	0.35
Technique	CGS	CGS	CGS
Separation efficiency [%]	40	40	40
Molecular sideband	CO_2	CO_2	CO_2
Residual impurities	$^{12}CO_2$, (N_2, O_2)	$^{x}CO_2$, (N_2, O_2)	$^{x}CO_2$, (N_2, O_2)
Injection EBIS [molecules]	$5 \cdot 10^{11}$	$2 \cdot 10^{14}$ ($1 \cdot 10^{14}$)	$2 \cdot 10^{11}$

^{11}C Production: summary for BN targets

Accelerator	LEBIT-Linac		CYCLONE®**KIUBE**		VARIAN ProBeam™	
Particle	proton		proton		proton	
Energy[MeV]	7		18		250	
Intensity [μA]	7		50		0.8	
Pulse structure	dc/ x Hz-y ms		dc/ x Hz-y ms		dc/ x Hz-y ms	
Beam cross section [mm^2]	Gauss 8.24^2		Gauss 8.24^2		Gauss 8.24^2	
batch/extraction time [min]/cw	cw		cw		cw	
Target size, geometry [S · L] [cm]	cyl. 7.1·34.2		cyl. 7.1·34.2		cyl. 7.1·34.2	
Target material	BN		BN		BN	
In-target yield EOB [GBq]	12		593		63.4	
Release efficiency [%]	5	5	5	5	5	5
Technique	ISOL	CGS	ISOL	CGS	ISOL	CGS
Separation efficiency [%]	5	40	5	40	5	40
Molecular sideband	CO	CO_2	CO	CO_2	CO	CO_2
Residual impurities	$^{13}N^{14}N$	$^{x}CO_2$	$^{13}N^{14}N$	$^{x}CO_2$	$^{13}N^{14}N$	$^{x}CO_2$
Injection EBIS	$5 \cdot 10^{10}$ [molecules/s]	$4 \cdot 10^{11}$ [molecules]	$3 \cdot 10^{12}$ [molecules/s]	$2 \cdot 10^{13}$ [molecules]	$3 \cdot 10^{11}$ [molecules/s]	$2 \cdot 10^{12}$ [molecules]

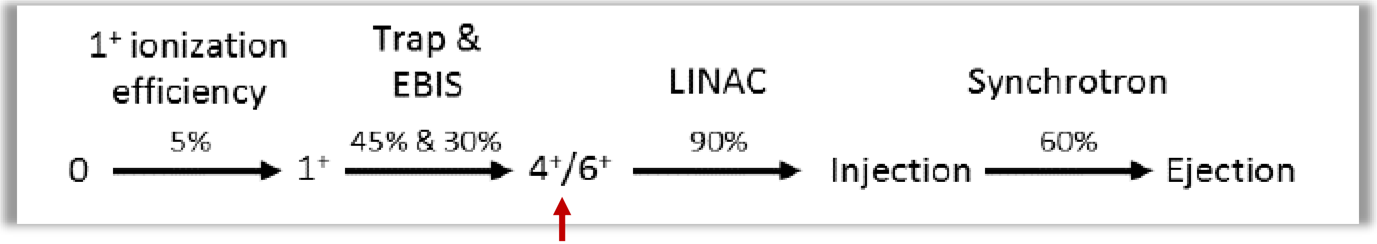
Ionization / Charge breeding

Cryotrap — EBIS



How we got to this conclusion:

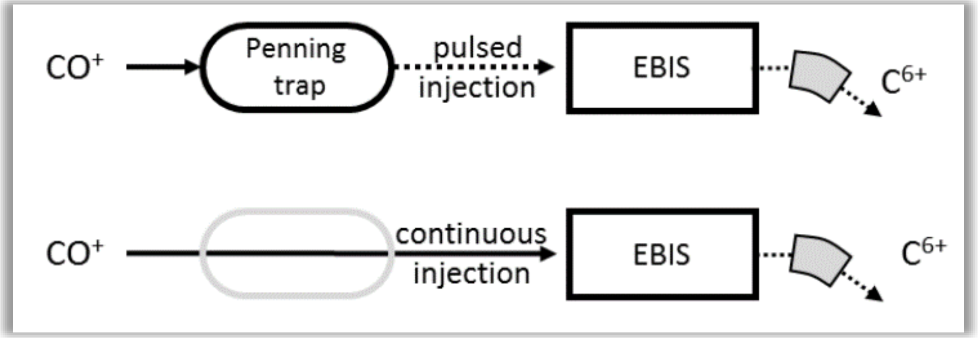
Initial evaluation:



$5{\cdot}10^9$ particles per pulse

- Too optimistic efficiencies

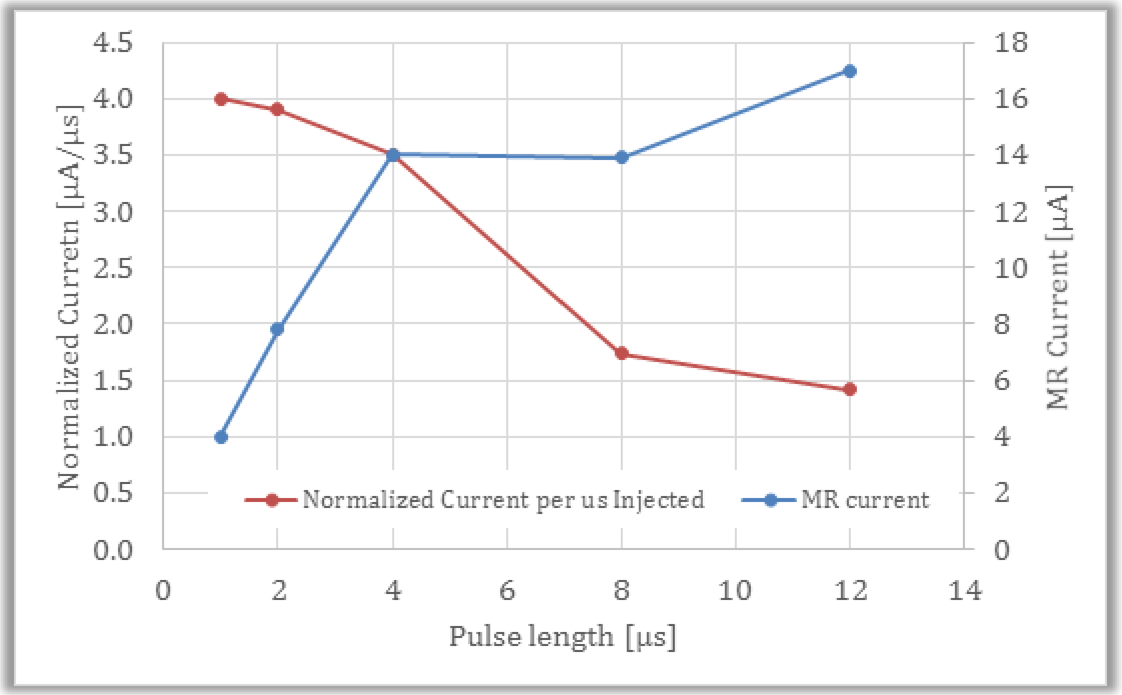
In-depth investigations:

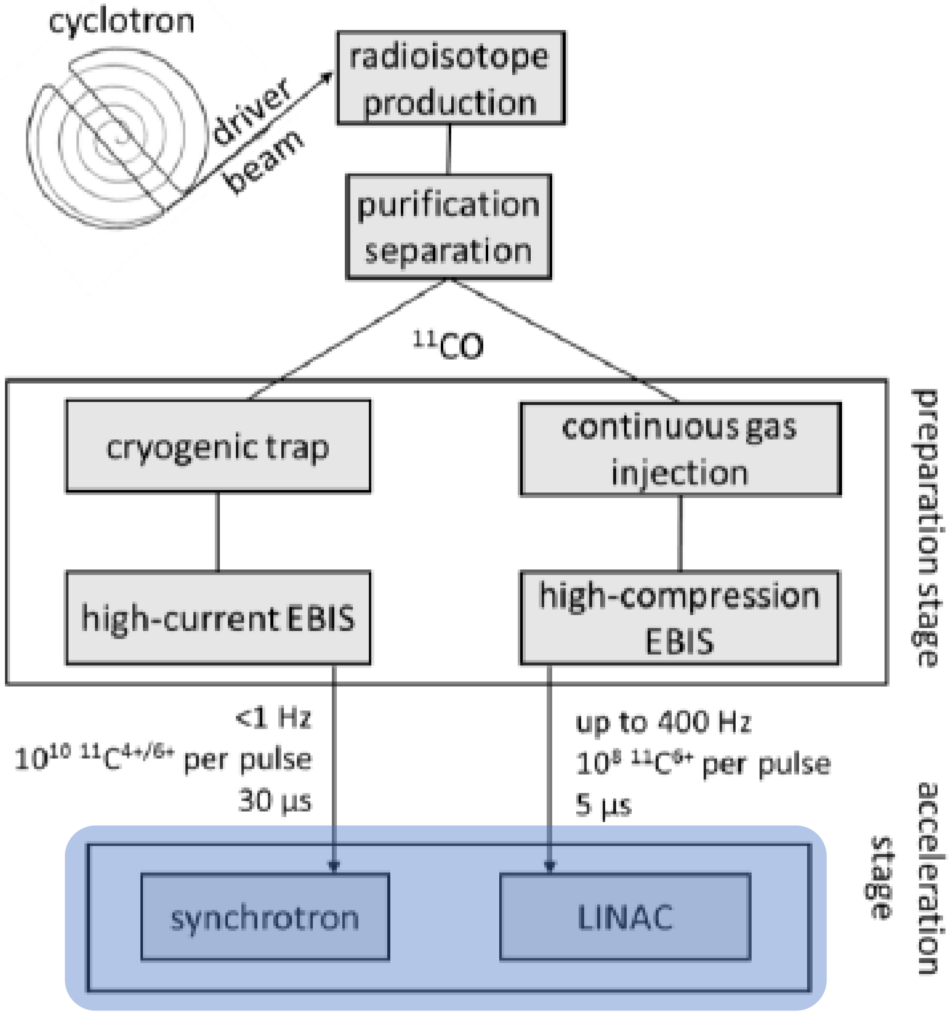


- EBIS performance is technically possible
- The limitation comes mostly from the trapping process

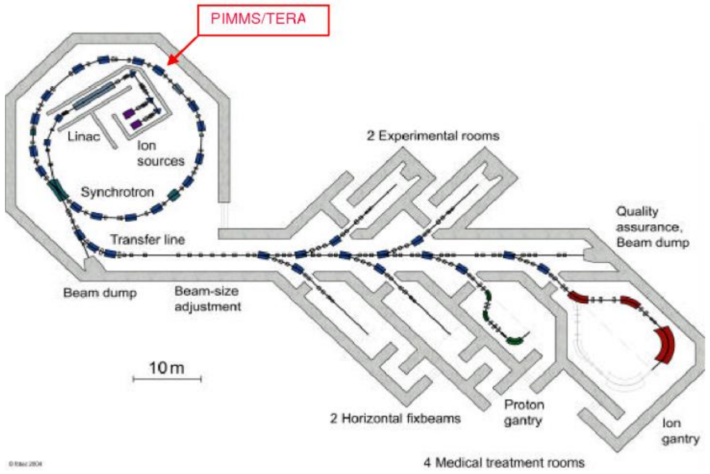
- **SYNCHROTRON: for existing facilities**
- **LINAC: an attractive alternative**

The pulse length:
a key parameter for the injection into the synchrotron

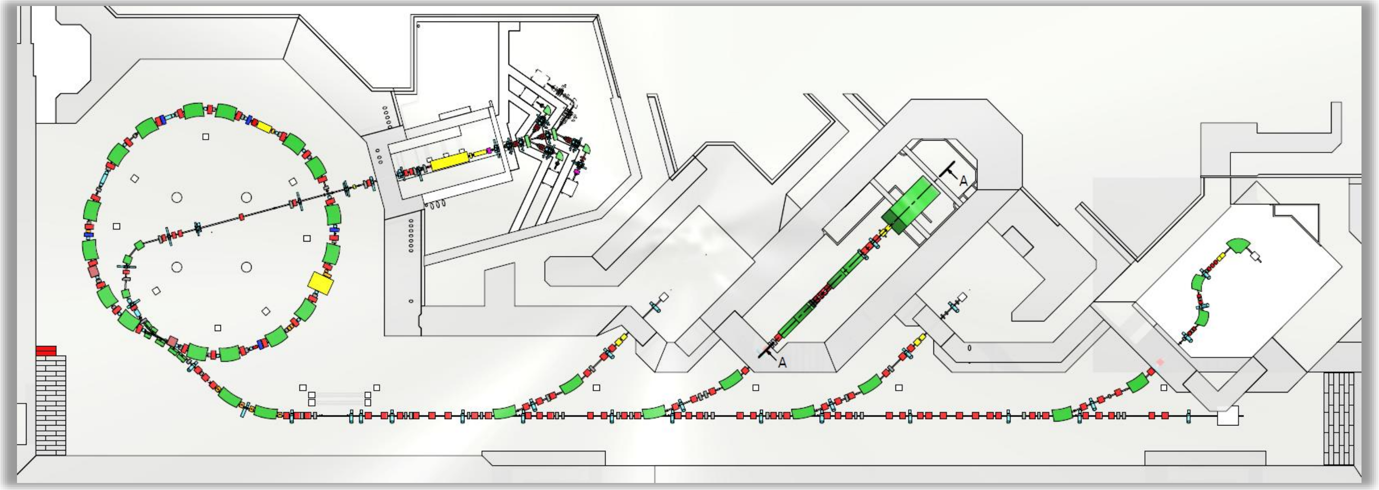




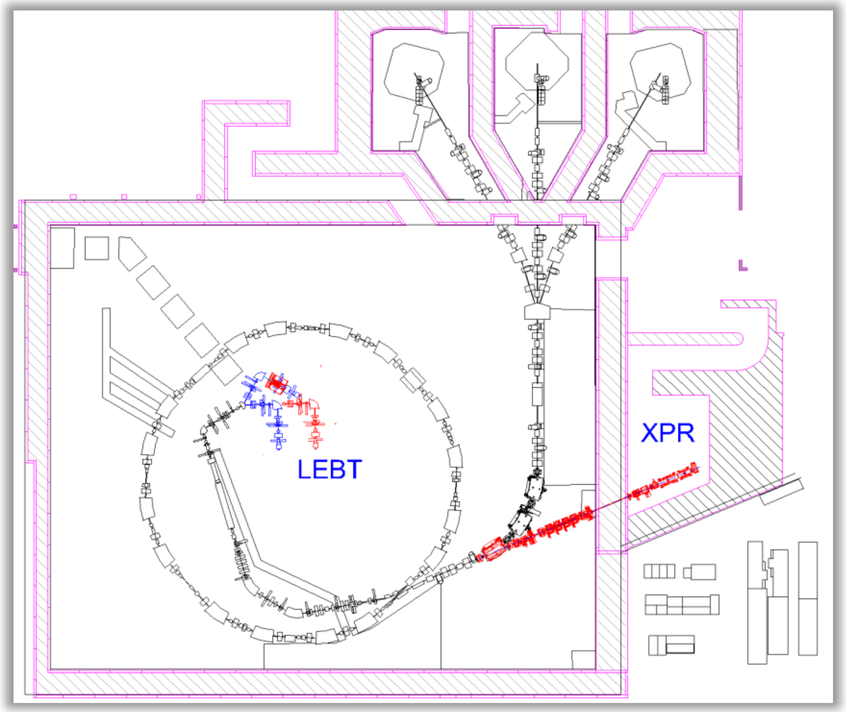
Integration to existing facilities



MedAustron



CNAO



The MedAustron case: potential scenarios

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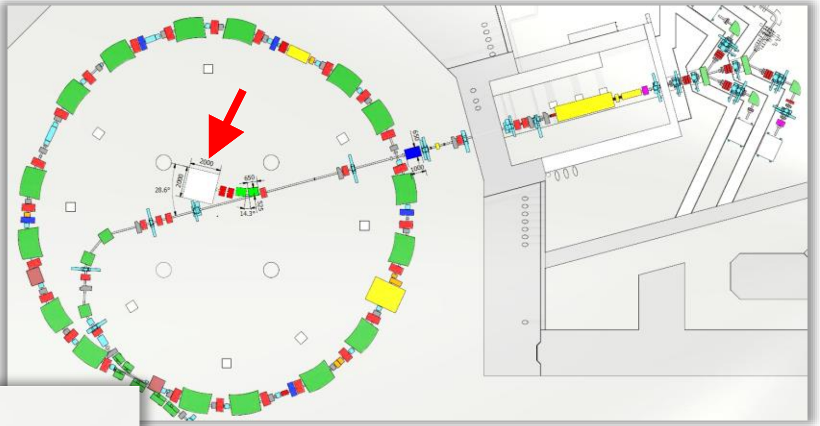
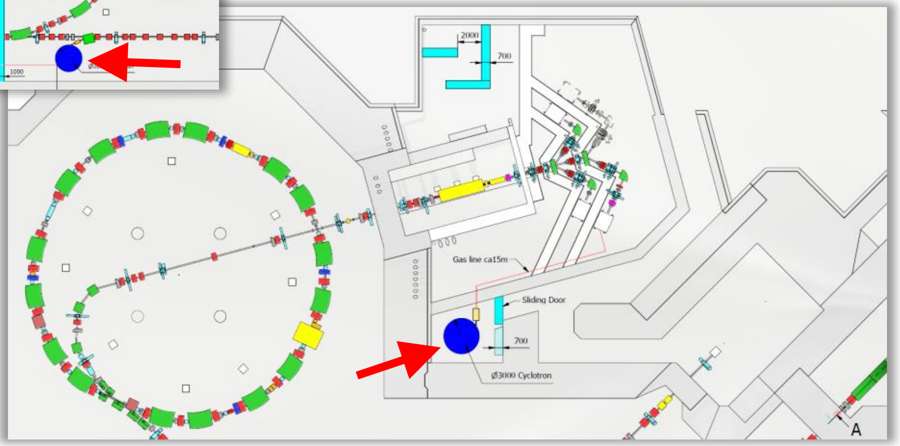
LINAC production

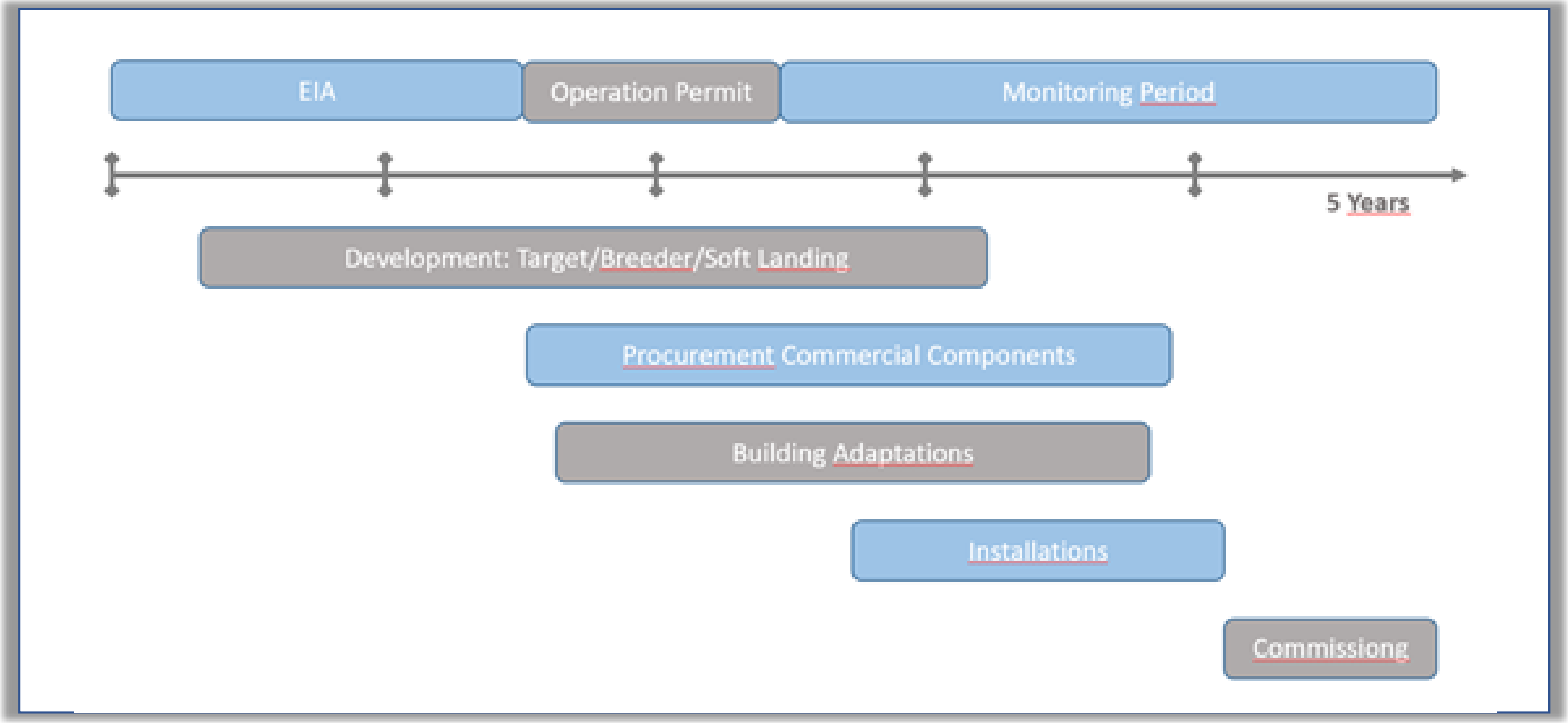


Medical cyclotron

Radiopharma cyclotron



MedAustron: potential timeline



- Additional RP measures possible to implement
- A new Environmental Impact Analysis (EIA) needed

Next steps

Network with following expertise

- Cryotrap
- High-capacity EBIS
- Deceleration / soft landing
- Commercial partners

Tests at a partner facility