

Charge breeding investigations for a future ^{11}C treatment facility

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Wiener Neustadt

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Challenges in ^{11}C Charge Breeding



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^{11}C -based Hadron Therapy

^{11}C (β^+ emitter, $t_{1/2} = 20.3$ min) is considered as treatment ion for hadron therapy [1].

- Increased β^+ activity from Bragg-peak
- On- or off-line PET imaging for range verification

[1] R. Augusto et al., Nucl. Instr. Meth. Phys. Res. B 376, 374-378 (2016)

^{11}C Injector

ISOL production of molecular $^{11}\text{CO}^+$ beam [2]

Mass separation

Charge breeding stage based on Electron Beam Ion Source (EBIS)

- Accumulate (~ 1 s)
- Break up molecule
- Increase charge state

Medial accelerator

Accumulation

Continuous injection EBIS	Penning trap	RFQ cooler	Cryogenic trap
<ul style="list-style-type: none"> Continuous accumulation in EBIS Inefficient injection Filling (neutralization) of EBIS space charge potential only 1% Boil-off for holding times >200 ms Efficiency extremely poor 	<ul style="list-style-type: none"> Bunches CO^+ beam Short pulses in the order of 10 μs Losses in molecular breakup High losses for holding time >50 ms Space charge effects at <math>5 \cdot 10^7</math> charges High losses for long holding times 	<ul style="list-style-type: none"> Bunches CO^+ beam Short pulses in the order of 10 μs Higher transmission and better holding than in Penning trap expected Capacity: 10^7 charges Limitation: 10^6 C ions out of EBIS 	<ul style="list-style-type: none"> Freeze CO Gas injection into EBIS More efficient filling of EBIS Efficiency from frozen $\text{CH}_4 \rightarrow \text{C}^{4+}$ demonstrated by Boytsov et al. [3] Possibly requires further purification/separation

Measurements with high beam intensities and long trapping times of molecular CO^+ beams in the REX/HIE-ISOLDE charge breeding system

EBIS axial potential configuration during continuous injection

EBIS radial e- space charge potential with 10% neutralization

Charge Breeding

Accumulation

Pulsed injection into REXEBIS: Space charge effects above 25% space charge neutralization corresponds to $2-4 \cdot 10^7$ C^{4+} ions

break-up in No buffer gas C^+ , O^+ , CO^+

C^+ is lost rapidly in REXTRAP while K and Al (from AIF) can be stored ~ 1 s

Due to multicomponent plasma?

Charge Breeding

ECR Ion Source	High-current EBIS	High-compression EBIS
<ul style="list-style-type: none"> Continuous beam production chopping is too inefficient for radioactive beam afterglow pulse length ~ 1 ms No inherent storing capability Release time from cryogenic trap 2 ms [4] ECR ion source cannot produce the required pulse length 	<ul style="list-style-type: none"> High electron beam current Emission: 0.2 mm mrad (norm. RMS) Pulse length >10 μs high capacity suitable for use with low repetition-rate synchrotron e.g. REX-like EBIS: $I_{\text{beam}}=10$ A, $I_{\text{beam}}=2$ m, $I_{\text{beam}}=900$ μm, $E_{\text{beam}}=25$ keV Space charge capacity: $1.3 \cdot 10^{11}$ e 10^{10} C ions per pulse out of EBIS 	<ul style="list-style-type: none"> High electron density (Brillouin gun) Small emittance/acceptance Pulse length 5 μs fast breeding suitable for use with high repetition-rate LINAC e.g. MEDISGUN [5]: $I_{\text{beam}}=1$ A, $I_{\text{beam}}=0.25$ m, $I_{\text{beam}}=90$ μm, $E_{\text{beam}}=10$ keV 10^8 C ions per pulse out of EBIS at up to 400 Hz

Most Promising Injection & Acceleration Schemes

Synchrotron	LINAC
<ul style="list-style-type: none"> Low repetition rate → accumulation required • <math>1</math> Hz • Cryogenic trap + high-current EBIS • 10^{10} C^{4+} per pulse 	<ul style="list-style-type: none"> High repetition rate → no need for accumulation • 400 Hz • Gas injection into high-compression EBIS • 10^8 C^+ per pulse

*This research project has been supported by a Marie Skłodowska-Curie Innovative Training Network Fellowship of the European Commission's Horizon 2020 Programme under contract number 842881 MEDICIS-PROMED.

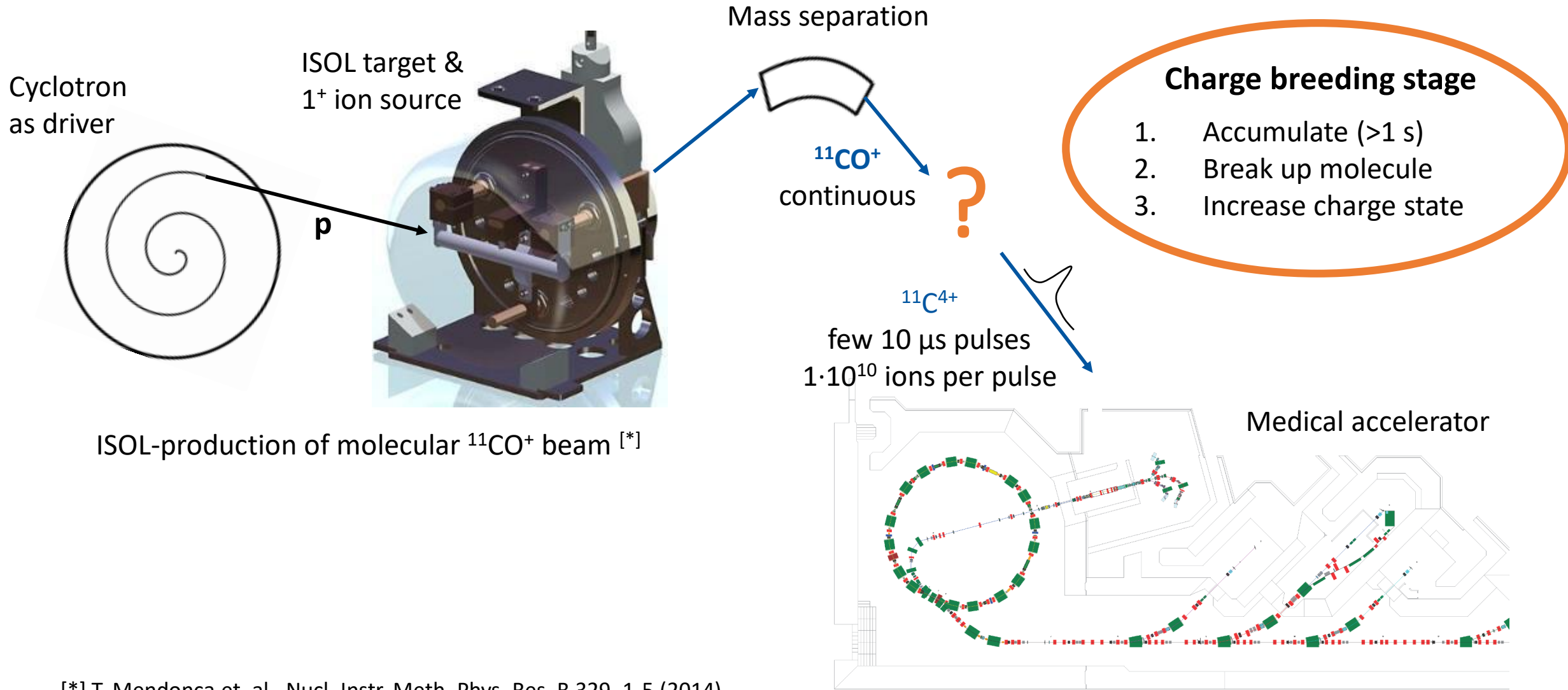
**This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 644804.

References

- [1] R. Augusto et al., Nucl. Instr. Meth. Phys. Res. B 376, 374-378 (2016)
- [2] T. Mendonça et al., Nucl. Instr. Meth. Phys. Res. B 329, 1-5 (2014)
- [3] A. Boytsov et al., Rev. Sci. Instrum. 86, 083301 (2015)
- [4] R. Mering et al., Nucl. Instr. Meth. A 506, 102-112 (2003)
- [5] S. Venkú András et al., J. Radiat. Res. 54 (suppl 1), 155-161 (2013)

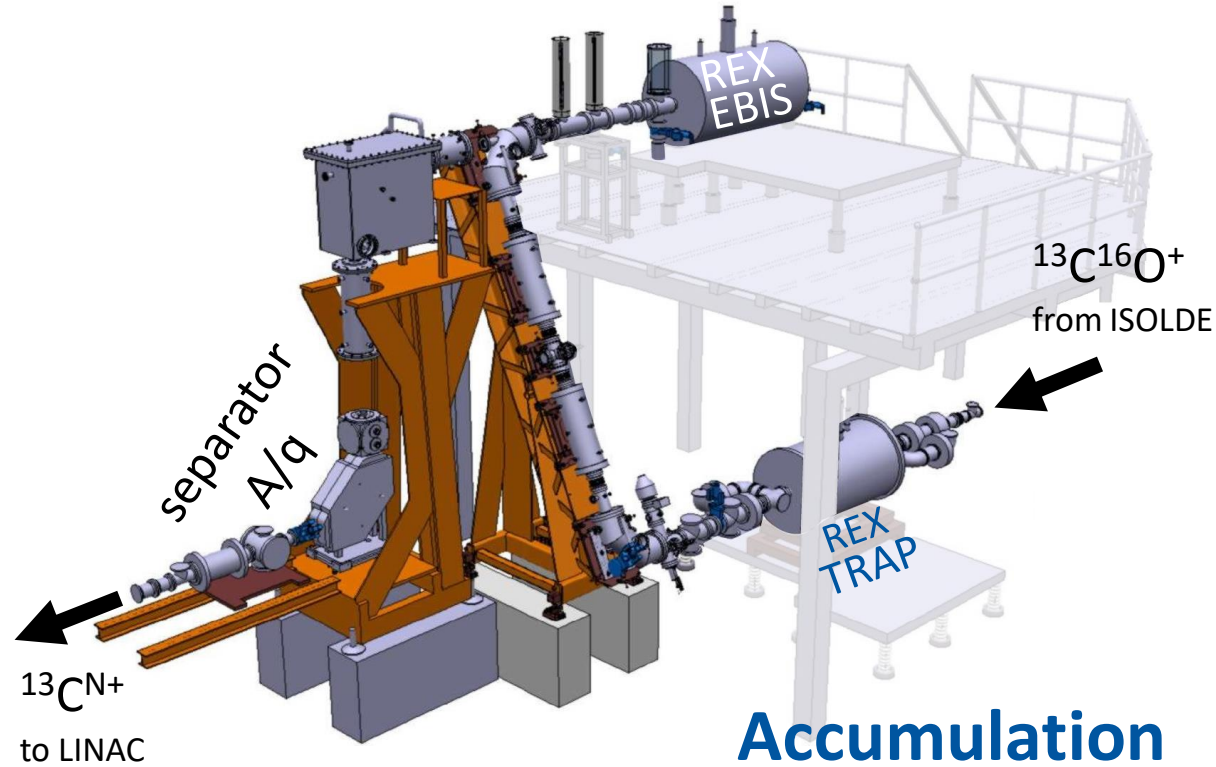


^{11}C injector



[*] T. Mendonca et. al., Nucl. Instr. Meth. Phys. Res. B 329, 1-5 (2014)

Charge Breeding



Charge breeding stage

1. Accumulate (>1 s)
2. Break up molecule
3. Increase charge state

Tests at **REX-ISOLDE** to understand limitations for high-intensities, molecular beams and long accumulation time

Initial proposal for Medicis Promed:

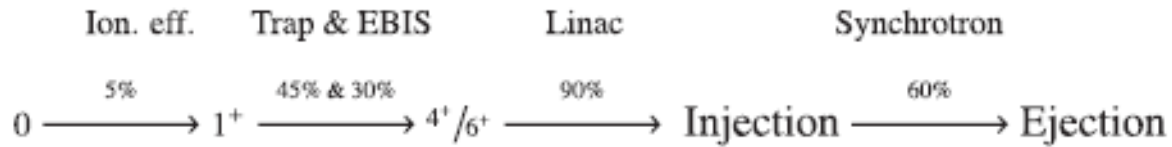


Fig. 2. Set-up taking present devices, combining present accelerator components of injection, at ISOLDE and MedAustron.

Augusto et al. (2016) <https://doi.org/10.1016/j.nimb.2016.02.045>



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NIRS proposal:

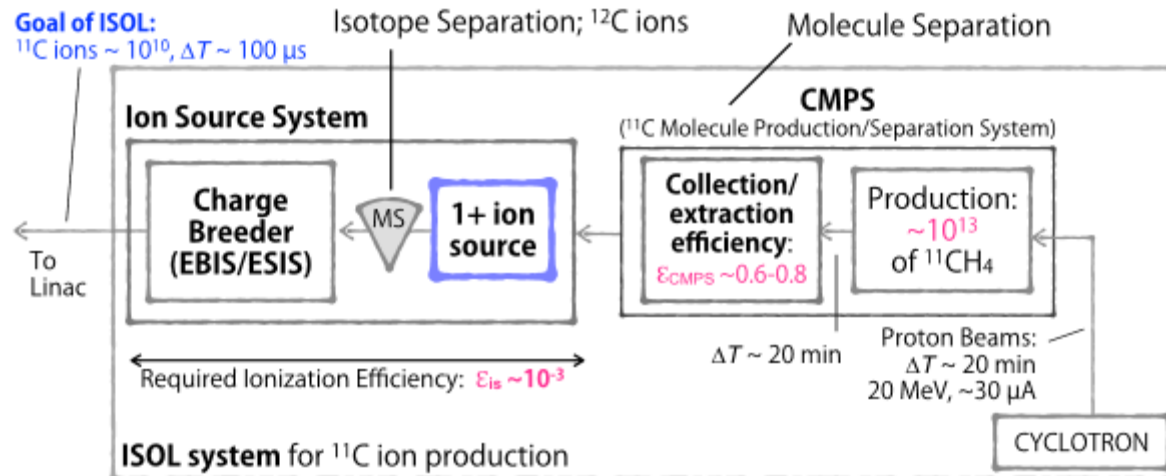


FIG. 1. A possible scheme for ¹¹C ion production.

Initial proposal for Medicis Promed:

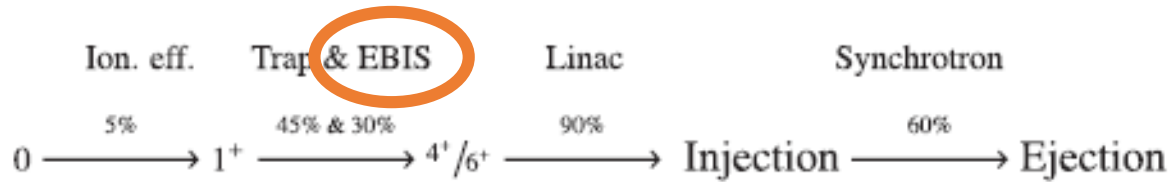


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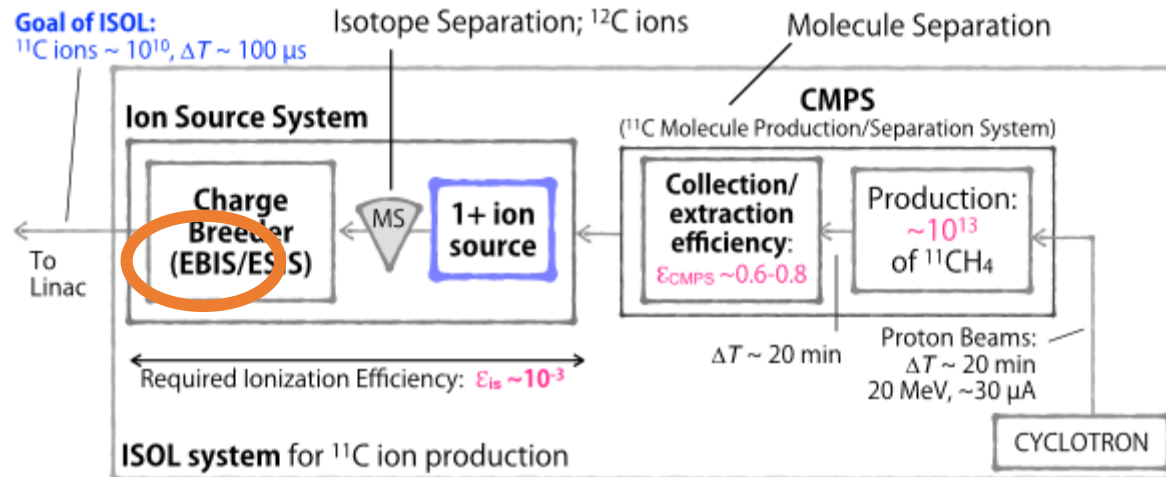


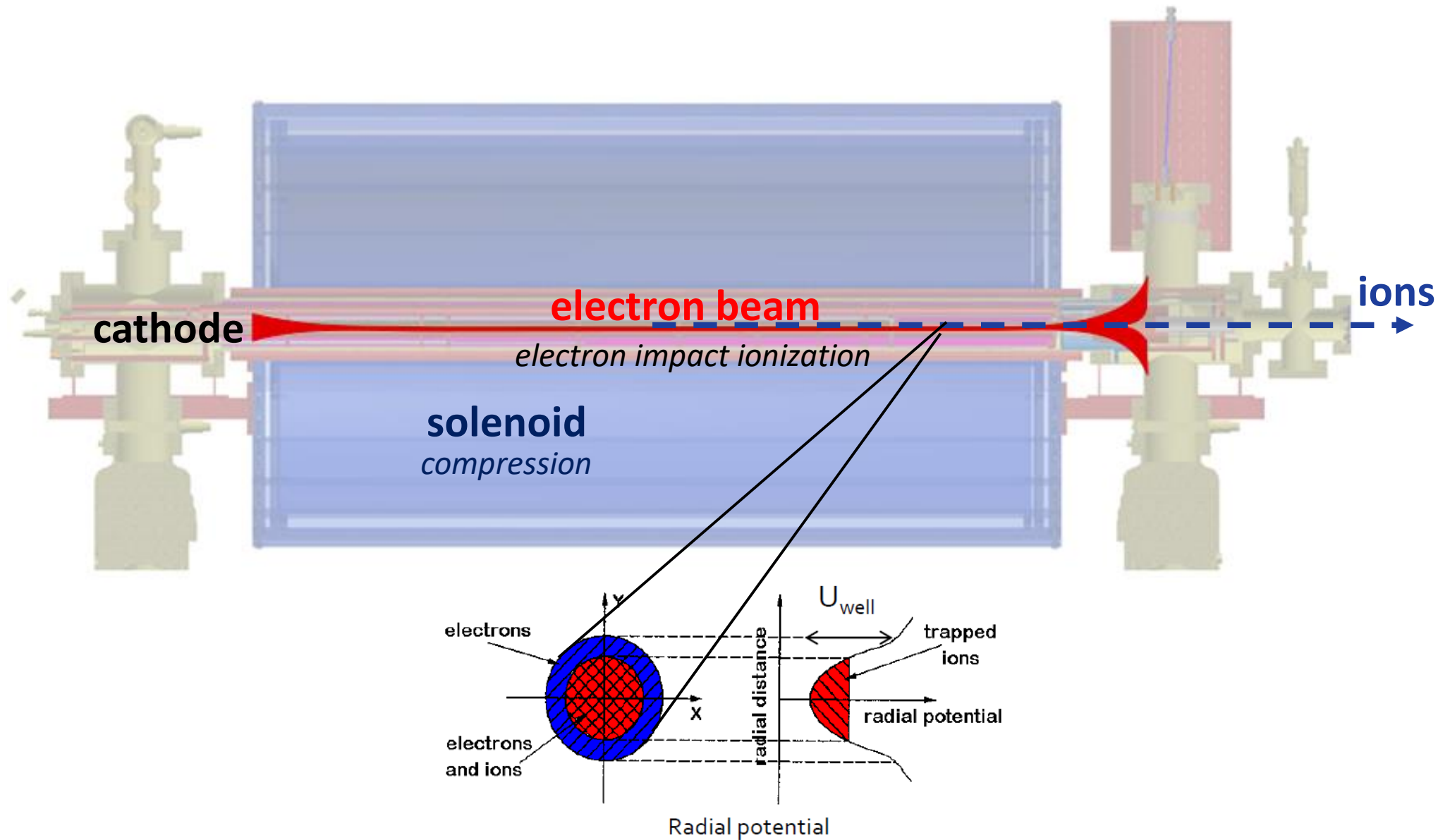
FIG. 1. A possible scheme for ¹¹C ion production.



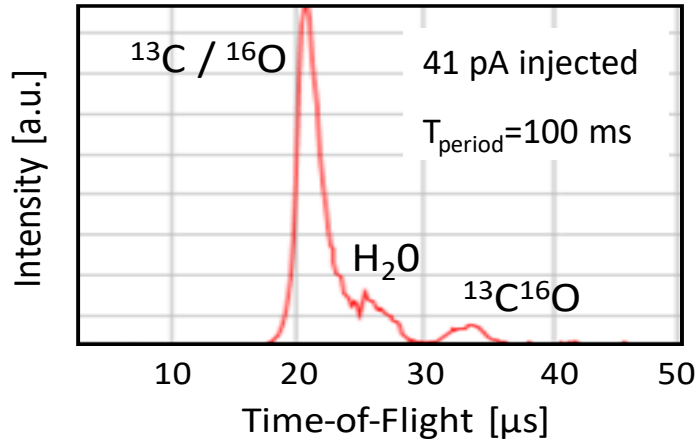
ECR source: inefficient for radioactive beam

EBIS: short pulse length
-> no ions have to be cut away

EBIS – Electron Beam Ion Source



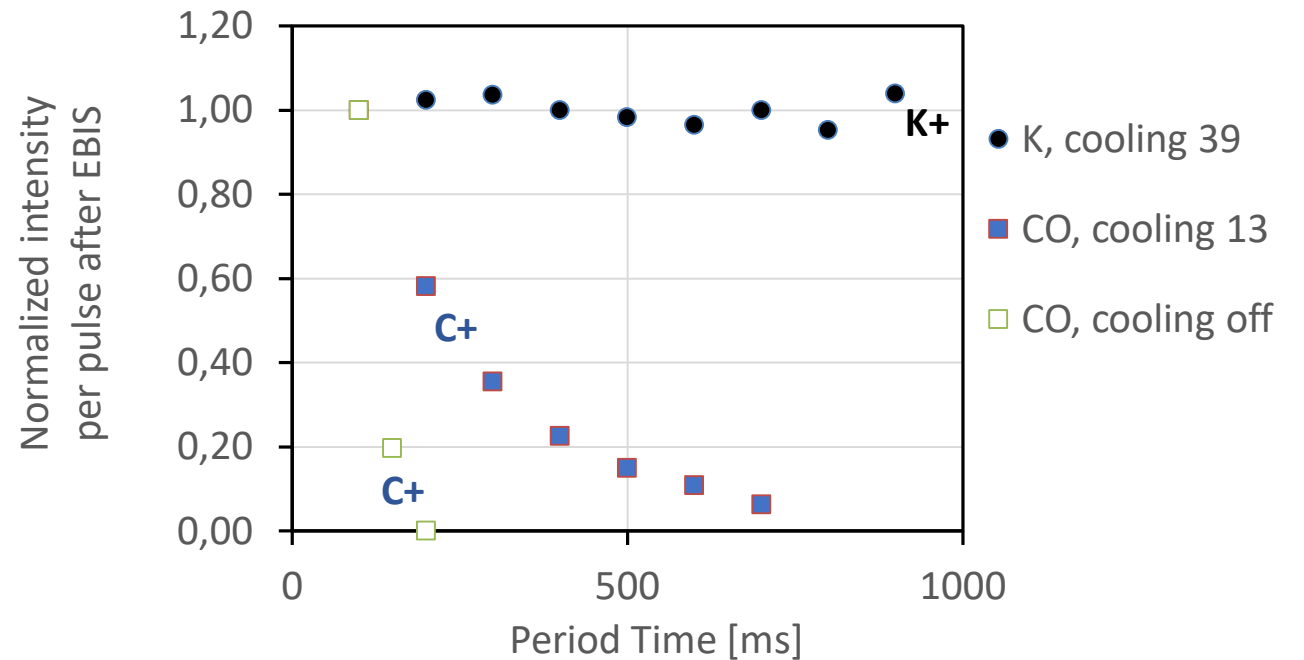
Beam accumulation



- Losses in molecular breakup
- High losses for holding time >50 ms
- Space charge effects for $>5 \cdot 10^7$ charges

Accumulation alt. 1 bunching in *Penning trap*

- + Bunches CO^+ beam
- + Short pulses in the order of 10 μs





Accumulation alt. 2 bunching in *RFQ cooler*

- + Bunches CO^+ beam
- + Short pulses in the order of $10\ \mu\text{s}$

? Higher transmission and better holding time than in Penning trap?

? Capacity: 10^9 charges

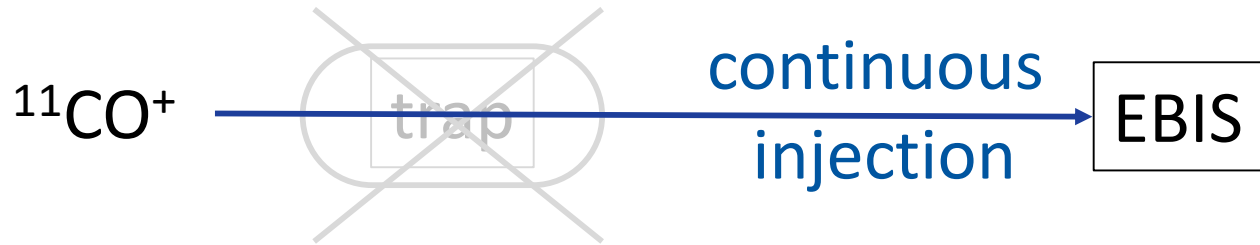
Words of caution

- kV potential on the RF rods
- low mass challenging for RF setup
- Emittance prop. to extracted current^[*]

Limitation: few 10^8 C ions out of EBIS

To be verified

[*] R. Boussaid et al., Phys. Rev. ST Accel. Beams 18 (2015) 072802)

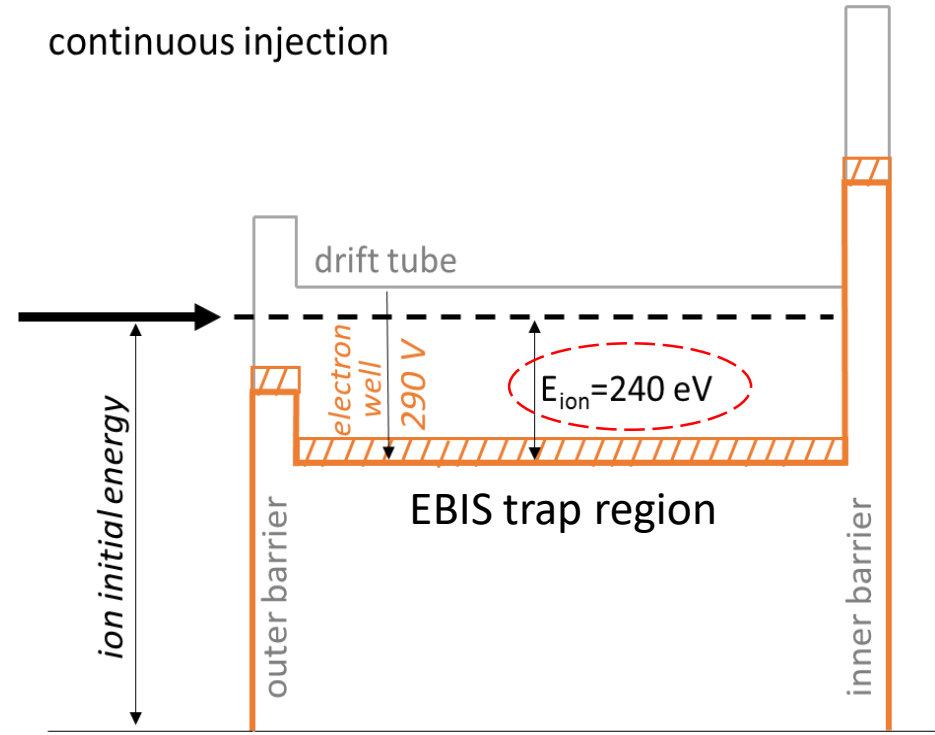


Accumulation alt. 3

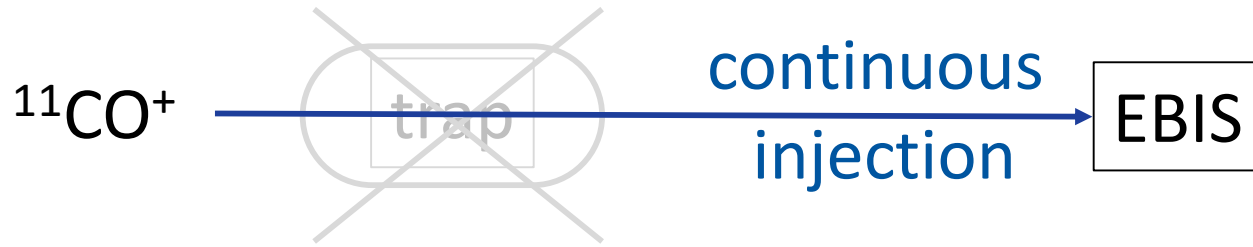
continuous injection into EBIS

- * Injection over static outer barrier
- * Need $1^+ \rightarrow 2^+$ during 1st round trip

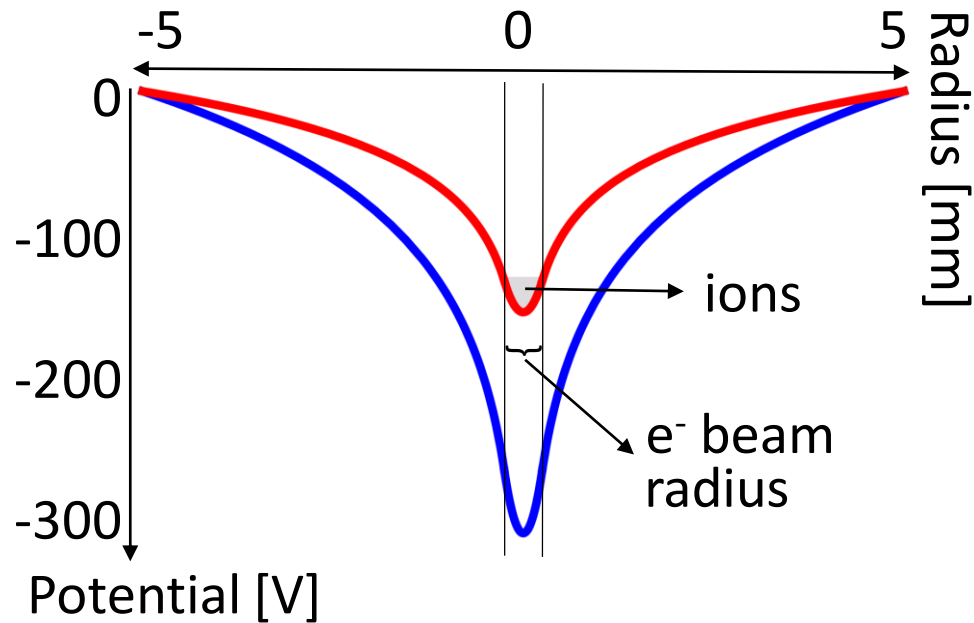
→ **Losses upon injection**



Schematic drawing of potentials for continuous injection into the EBIS. The dashed region indicates the radial potential depth of the electron beam, in this case 40 V.



EBIS *radial* e^- space charge potential with 50% and 0% neutralization



Accumulation alt. 3 *continuous injection* into EBIS

- + Continuous accumulation in EBIS
- High charge states dominate
- Inefficient injection
- Boil-off for holding times >200 ms

Ion energy relatively high

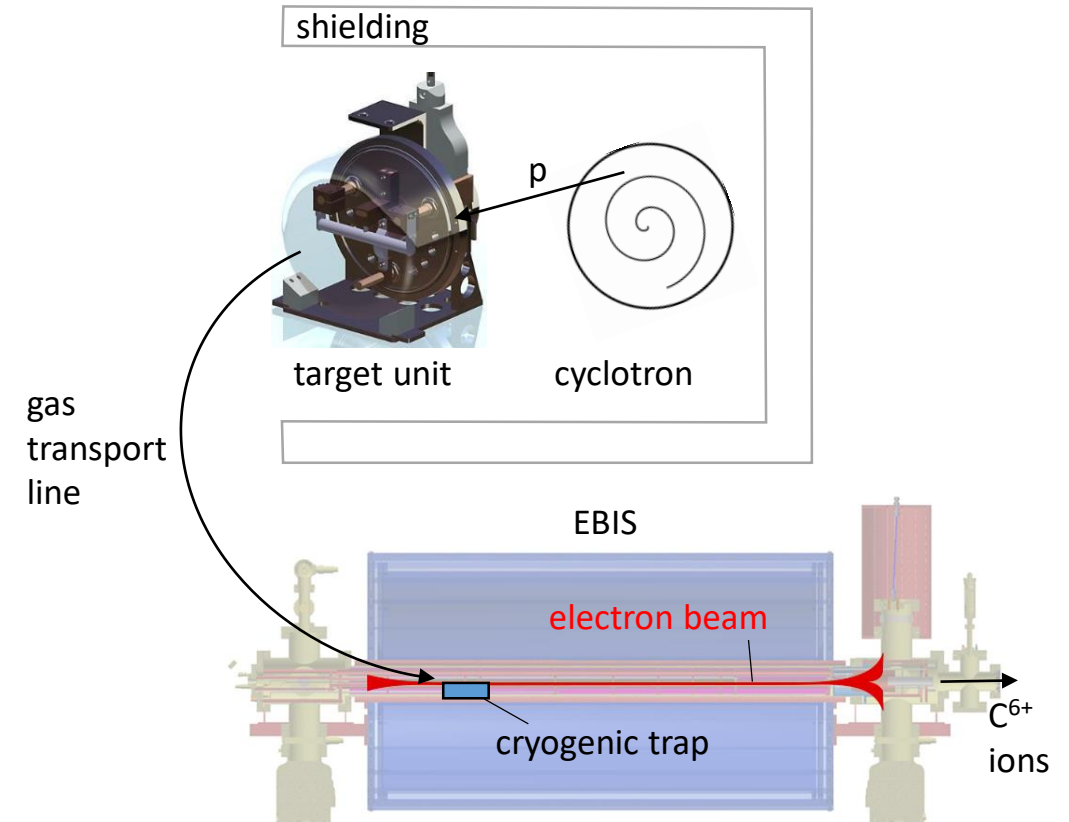
→ **Loss of hot ions**

Sub-percent efficiency

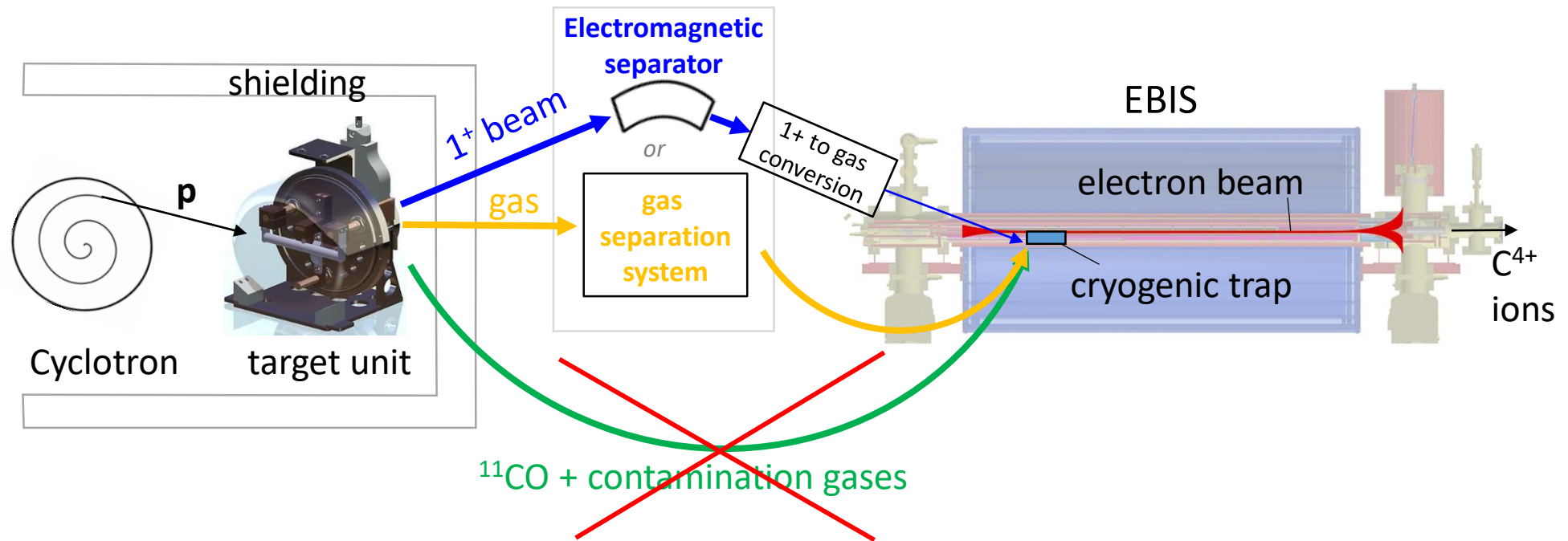


Accumulation alt. 4 collection in *cryogenic trap*

- + Freeze CO for accumulation
- + Use gas injection into EBIS
- + Efficiency 5-10% of frozen $\text{CH}_4 \rightarrow \text{C}^{4+}$ demonstrated by Boytsov et al. [*]
- Contamination ?



[*] A. Boytsov et.al., Rev. Sci. Instrum. 86, 083308 (2015)



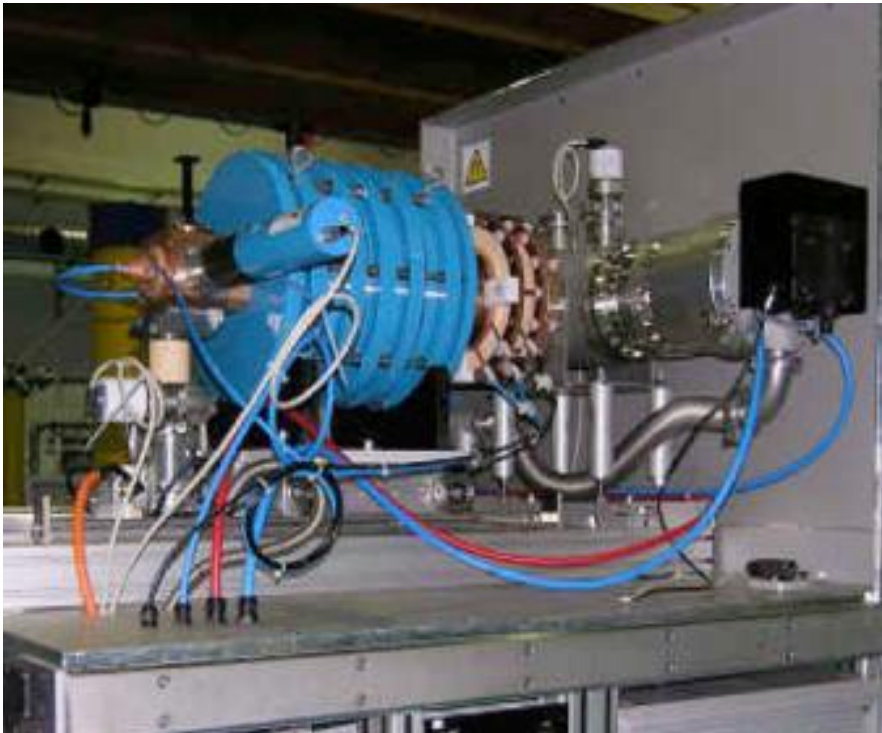
- Contamination ?
 -> separation system required^[*]

[*] Katagiri et al. (2015) <https://doi.org/10.1063/1.4937593>

Charge breeding

An ECR ion source?

(Electron Cyclotron Resonance)

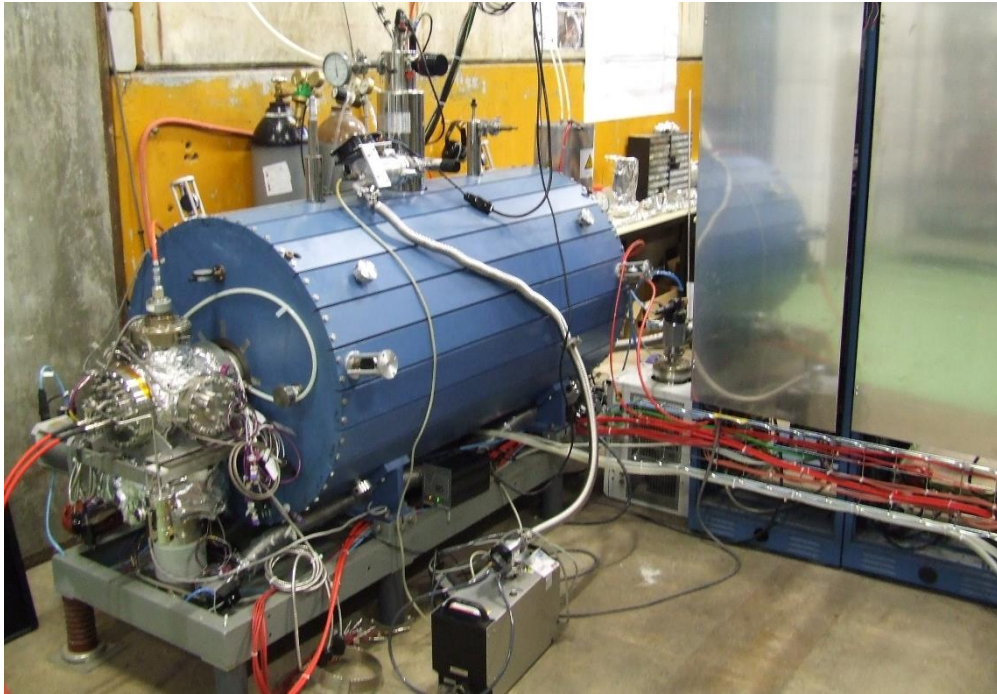


Used at CNAO and MedAustron
for stable $^{12}\text{C}^{4+}$

- + High capacity for continuous operation
- No inherent storing capability but continuous production
- Extracted pulse length 1-2 ms (afterglow operation)

An EBIS!

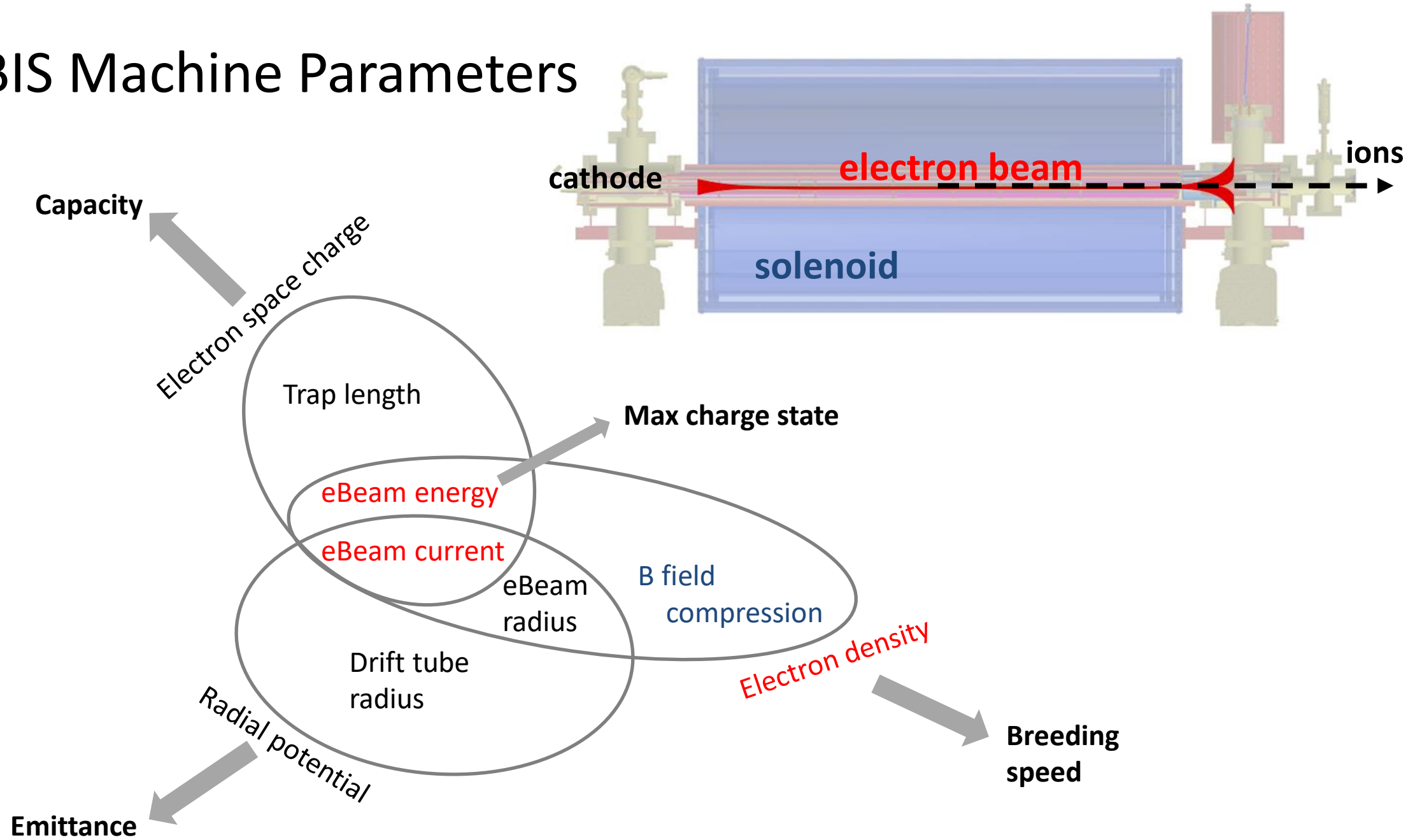
(Electron Beam Ion Source)



TwinEBIS test stand at CERN

- + Inherent storing capability and pulsed production
- + Extracted pulse length few $10 \mu\text{s}$
- We need:
 - high efficiency
 - high intensity → filling space charge capacity

EBIS Machine Parameters



EBIS capacity

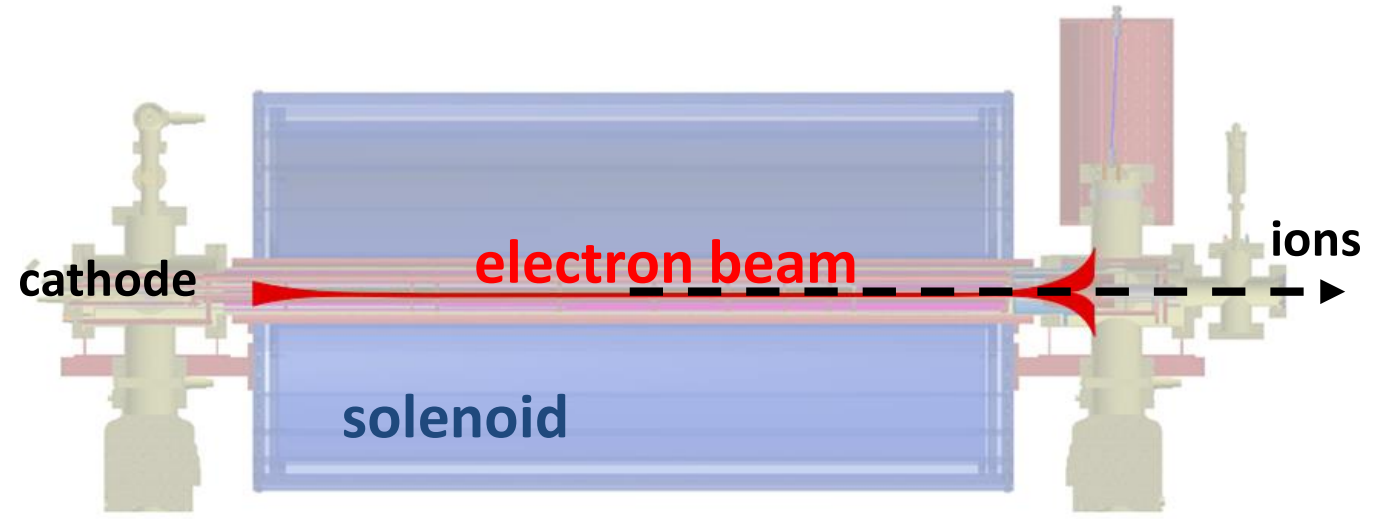
Capacity

Electron space charge

Trap length

eBeam energy

eBeam current



$$N^- = \frac{L \cdot I_e}{e} \cdot \sqrt{\frac{m_e}{2E_e}}$$

e.g. REXEBIS

$$I_e = 200 \text{ mA}$$

$$E_e = 4.5 \text{ keV}$$

$$L = 0.8 \text{ m}$$

$$N^- = 2.3 \cdot 10^{10} \text{ electrons}$$

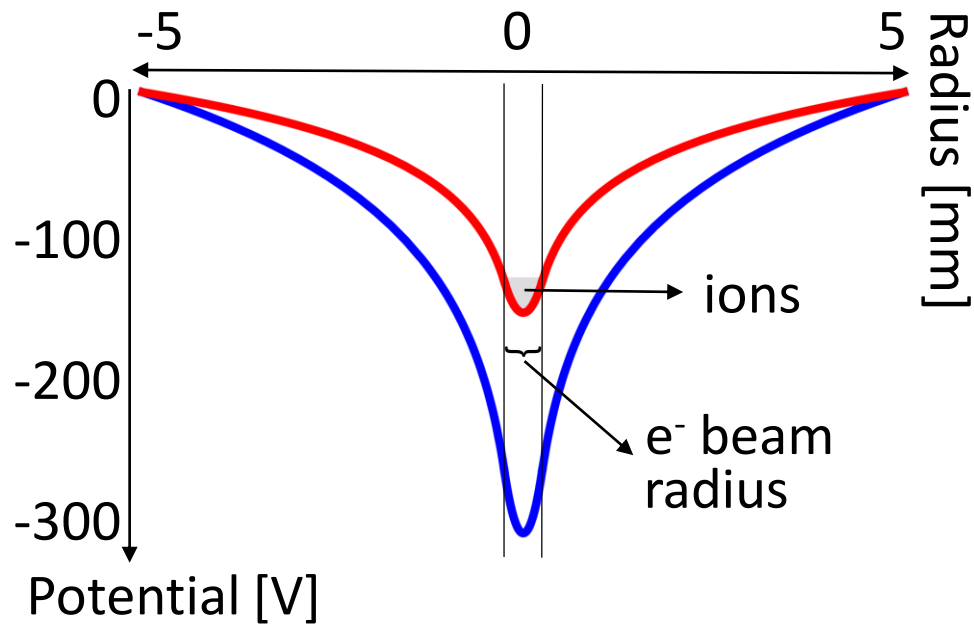
EBIS filling

Filling of EBIS

$$k = \frac{\text{ion charges}}{\text{electrons}}$$

+

splitting into
elements and
charge states



Ions neutralize the electron space charge

EBIS *radial* e⁻ space charge potential with 50% and 0% neutralization

EBIS filling

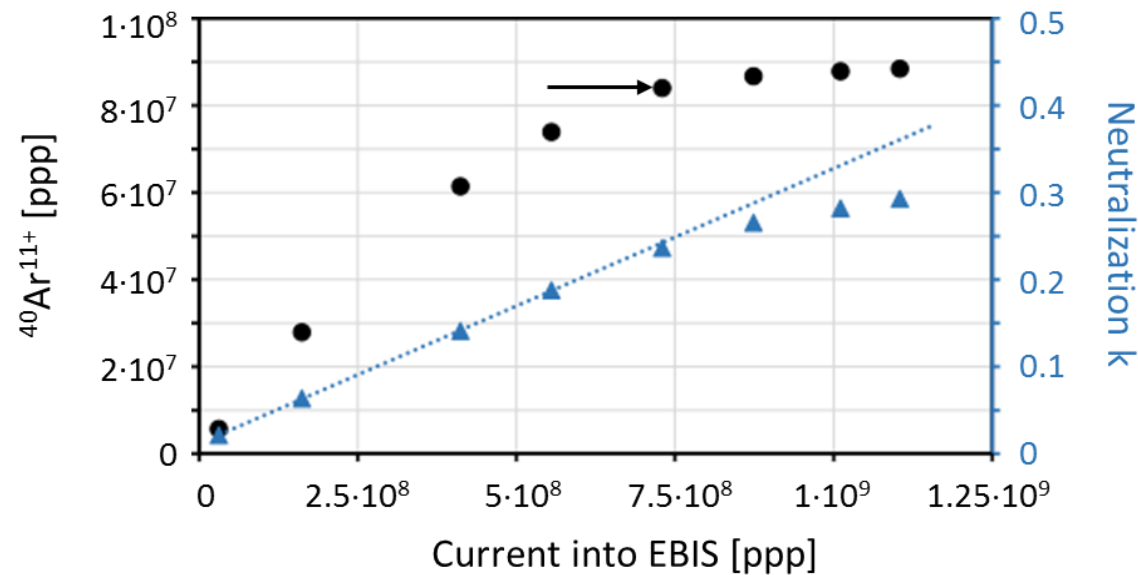
Filling of EBIS

$$k = \frac{\text{ion charges}}{\text{electrons}}$$

+

splitting into
elements and
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Pulsed injection into REXEBIS without using REXTRAP



REXEBIS: saturation starts at 25%
filling for pulsed injection

Translate to CO^+ injection ->
 $\sim 2 \cdot 10^8 \text{ C}^{6+}$ extracted per pulse

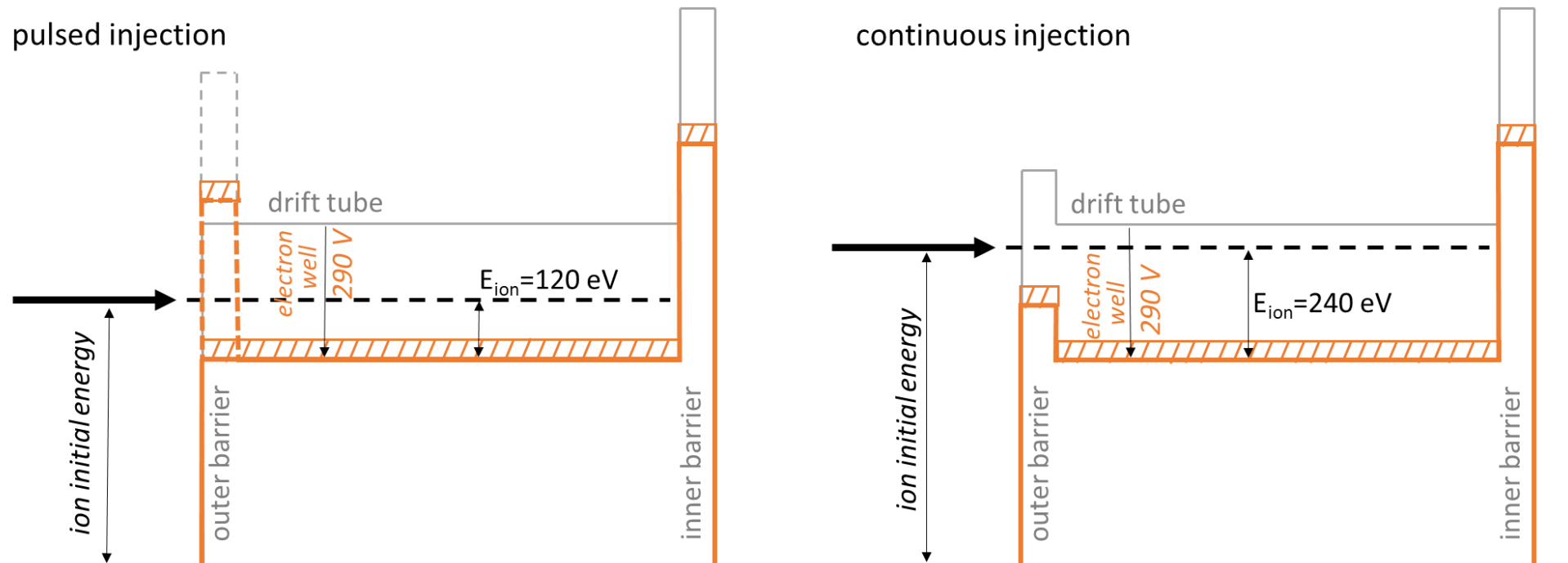
EBIS filling

$$k = \frac{\text{ion charges}}{\text{electrons}}$$

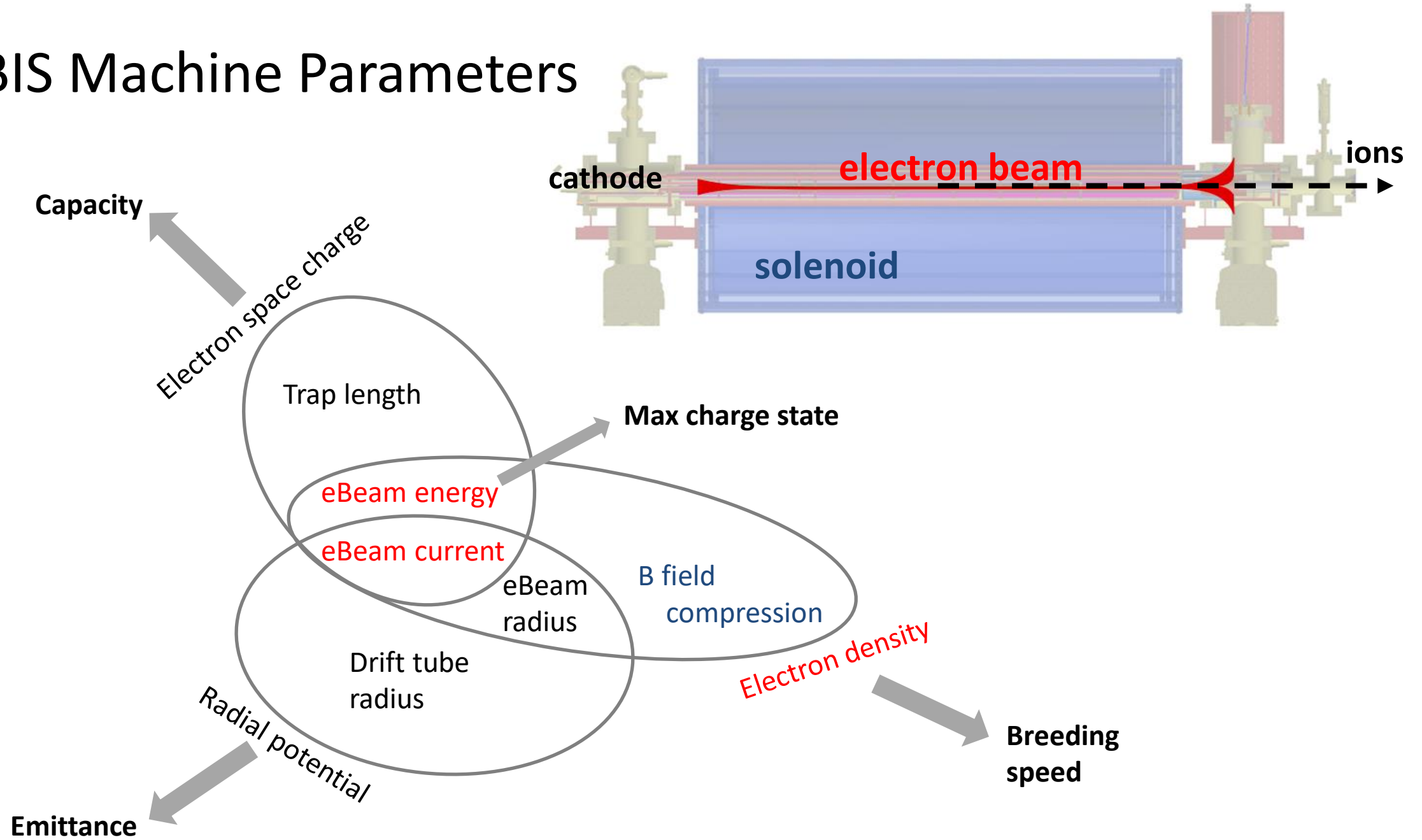
Filling depends a lot on injection mechanism:
Continuous injection, **pulsed** injection or **gas** injection

Neutralization:

cw \ll pulsed $<$ gas
 $\sim 1\%$ 25% $>70\%$



EBIS Machine Parameters

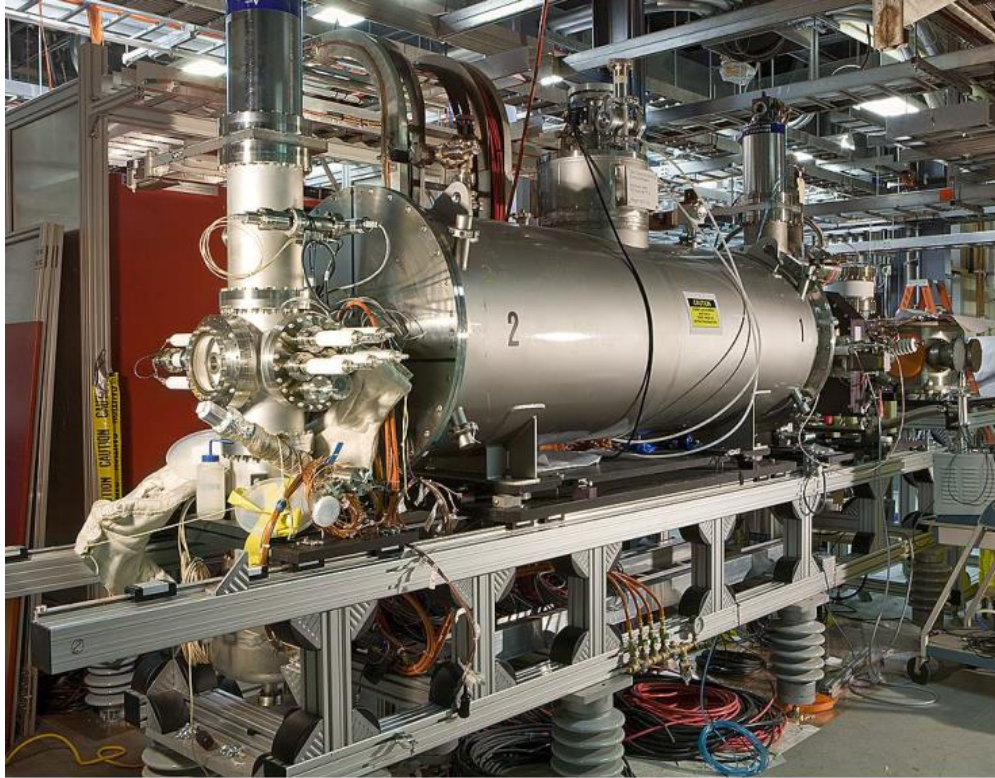


EBIS Machine Parameters



capacity vs speed

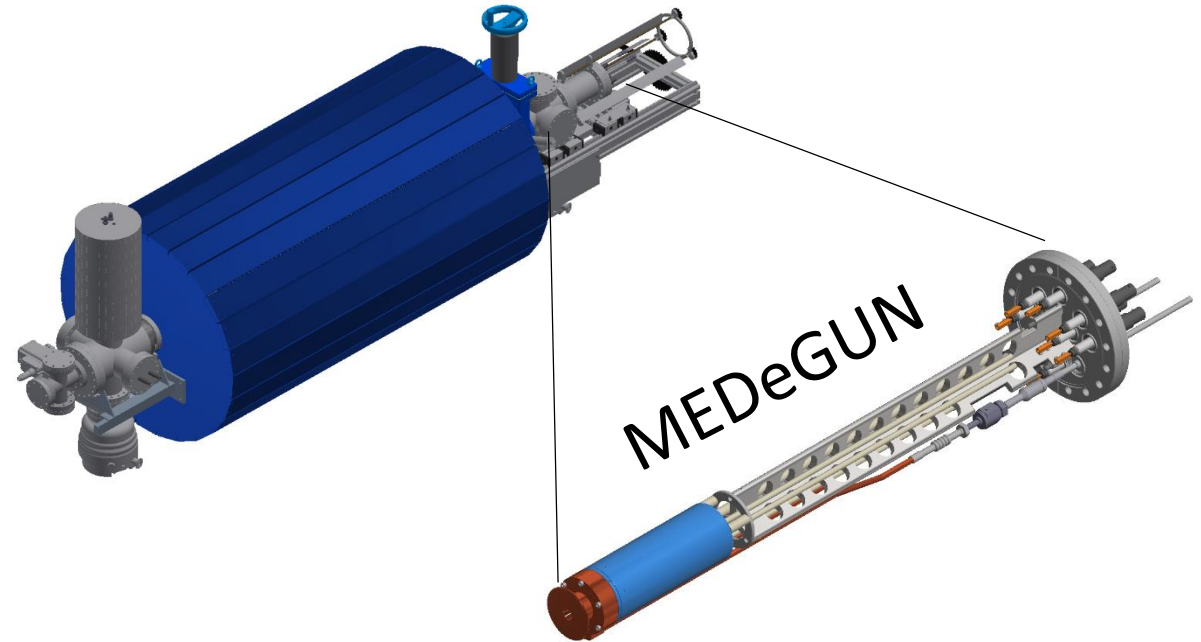
High-current EBIS



Courtesy of BNL

- 10 A e-beam (immersed gun)
- Pulse length $< 30 \mu\text{s}$
- Breeding time 10-15 ms
- Storage capacity $1.3 \cdot 10^{12}$ charges

High-compression EBIS

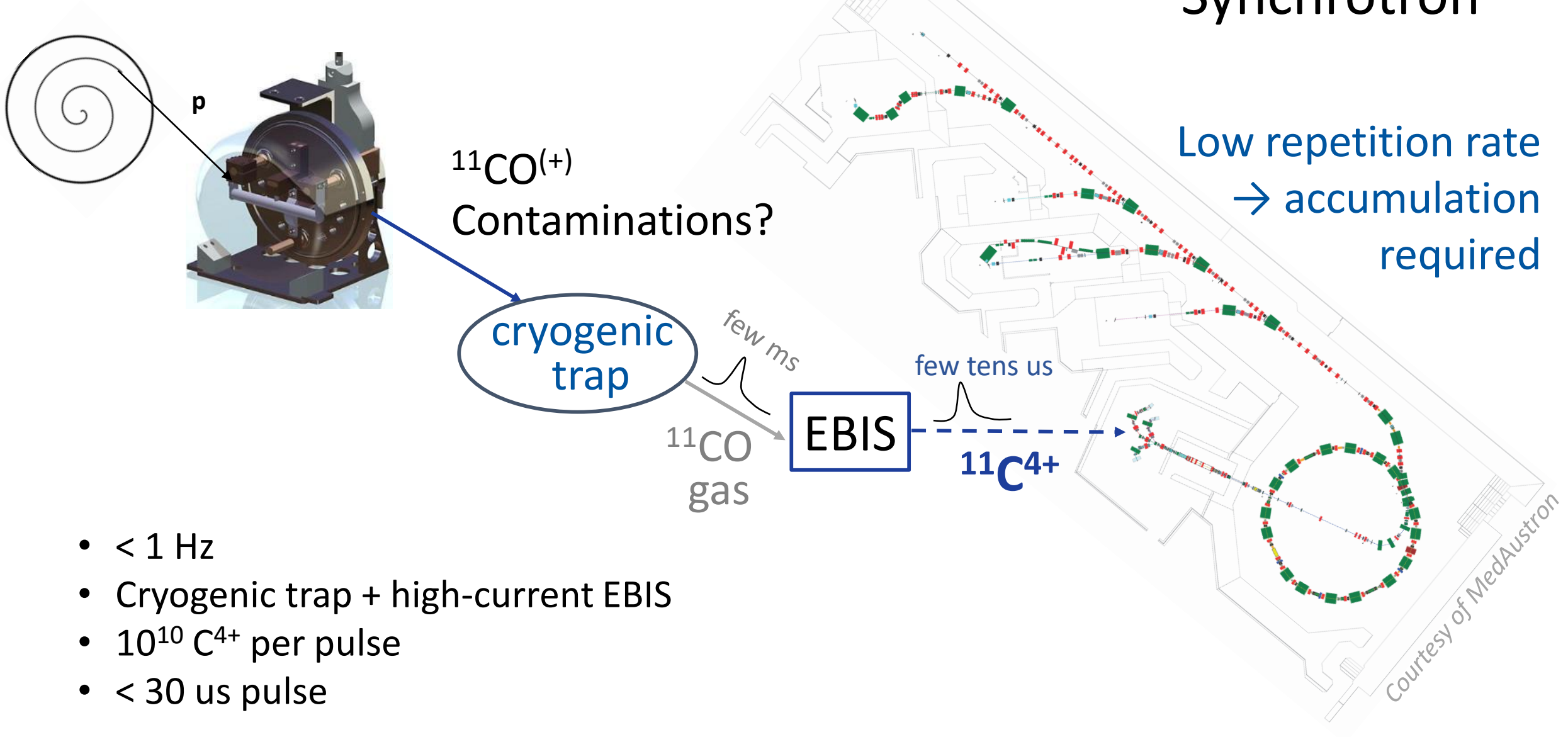


- $>1000 \text{ A/cm}^2$ e-beam (Brillouin gun)
- Pulse length $5 \mu\text{s}$
- Breeding time 2.5 ms
- Storage capacity $3 \cdot 10^{10}$ charges

Most Promising Injection & Acceleration Schemes

Synchrotron

Low repetition rate
→ accumulation
required

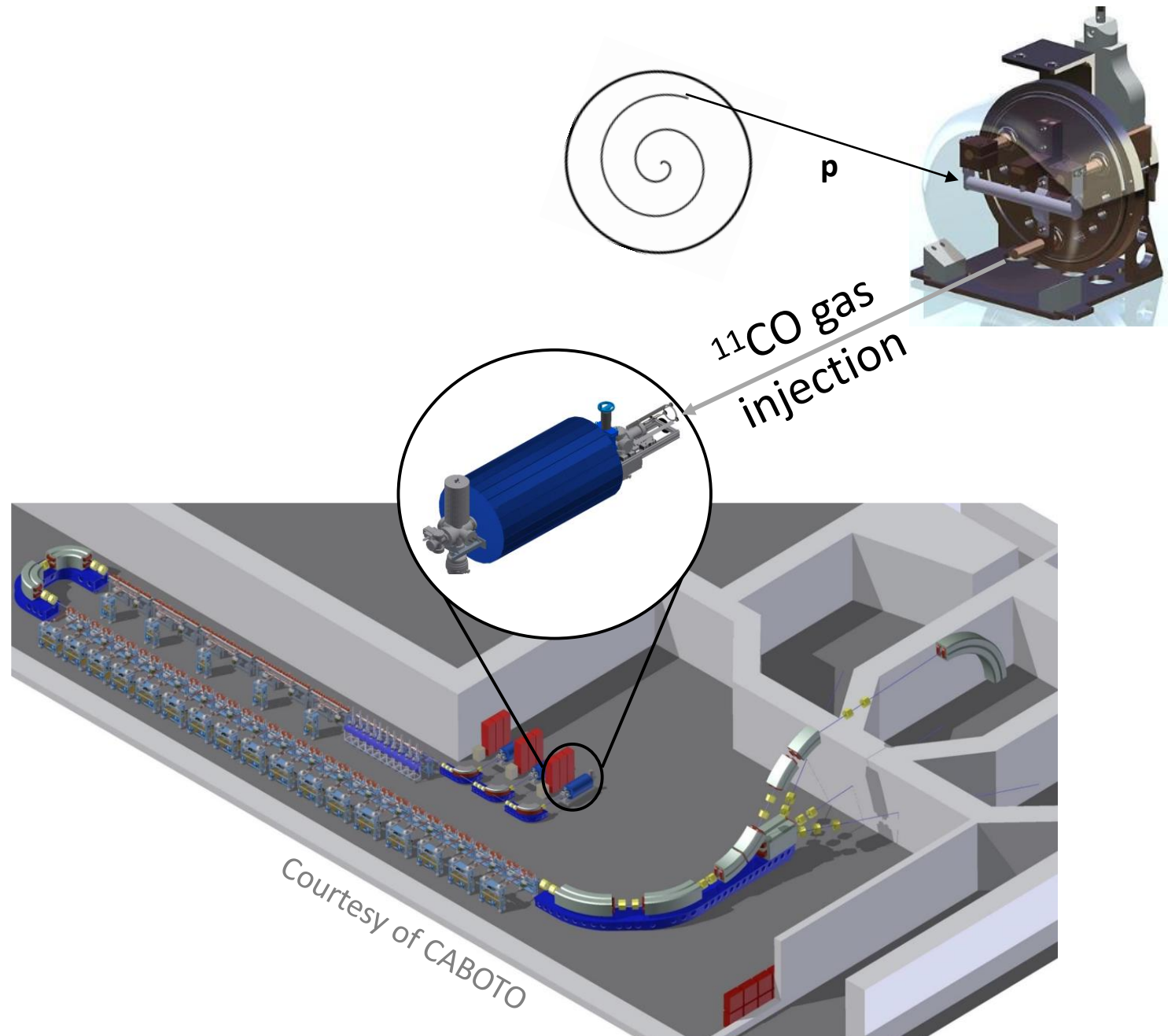


- < 1 Hz
- Cryogenic trap + high-current EBIS
- 10^{10} C^{4+} per pulse
- < 30 us pulse

LINAC

High repetition rate
→ no need for accumulation

- 400 Hz
- Gas injection into high-compression EBIS
- 10^8 C⁶⁺ per pulse
- < 5 us pulse



1. Continuous injection into the EBIS can be excluded due to low efficiency and low output, as the EBIS cannot be filled properly.

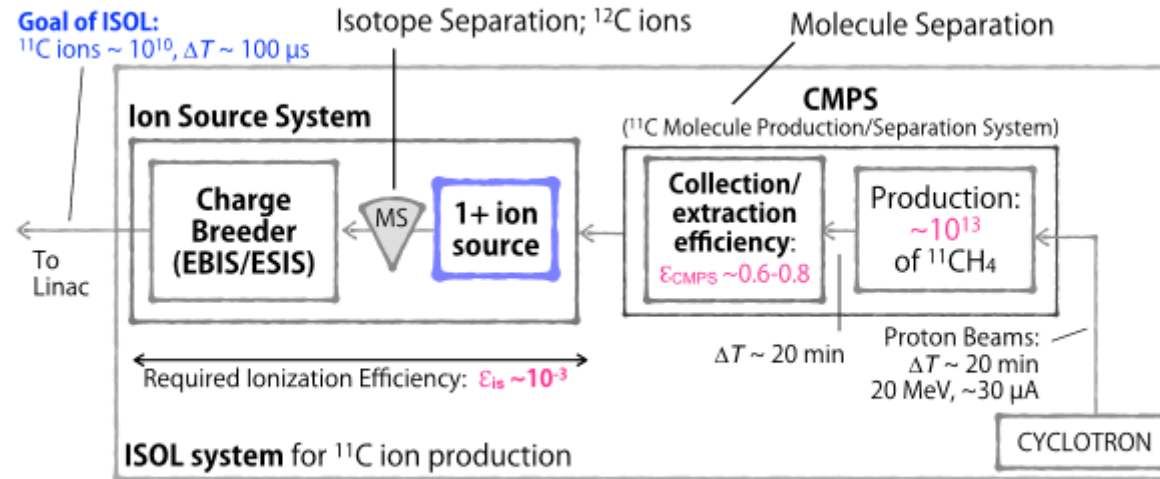


FIG. 1. A possible scheme for ^{11}C ion production.

1. **Continuous injection into the EBIS can be excluded** due to low efficiency and low output, as the EBIS cannot be filled properly.
2. A **Penning trap can be excluded** due to its low capacity and inability to store molecular CO beam.

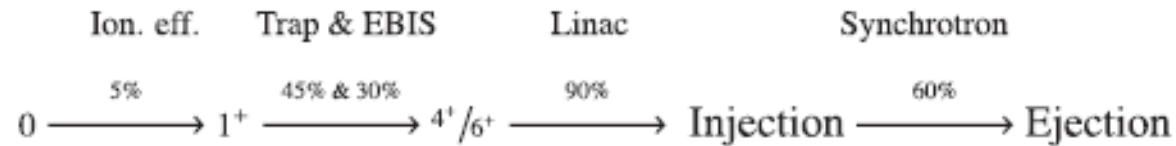
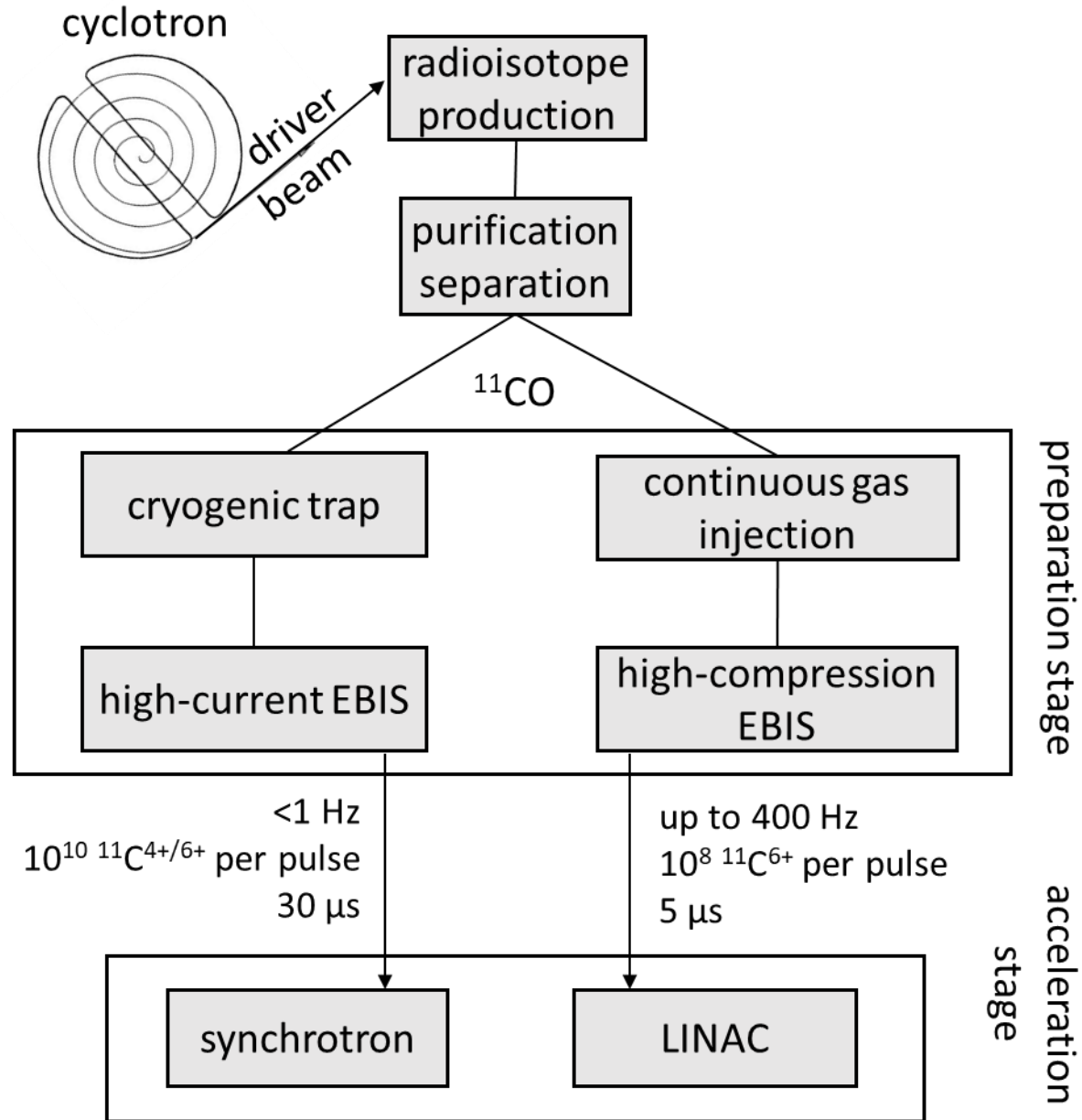


Fig. 2. Set-up taking present devices, combining present accelerator components of injection, at ISOLDE and MedAustron.

1. **Continuous injection into the EBIS can be excluded** due to low efficiency and low output, as the EBIS cannot be filled properly.
2. A **Penning trap can be excluded** due to its low capacity and inability to store molecular CO beam.
3. An **RFQ ion beam cooler** and an EBIS is also limited in capacity.

1. **Continuous injection into the EBIS can be excluded** due to low efficiency and low output, as the EBIS cannot be filled properly.
2. A **Penning trap can be excluded** due to its low capacity and inability to store molecular CO beam.
3. An **RFQ ion beam cooler** and an EBIS is also limited in capacity.
4. **Synchrotron** accelerator case
 - neutral gas injection via a **cryogenic trap** into the EBIS
 - a **high-capacity EBIS** with $1.3 \cdot 10^{12}$ electron charges is required
 - All-linac** accelerator case (high repetition rate relaxes the per-pulse intensity-requirement)
 - cryogenic trap not required as **gas can be injected continuously**
 - smaller electron space charge** capacity is sufficient
 - high-current density EBIS** required for fast charge breeding

Summary



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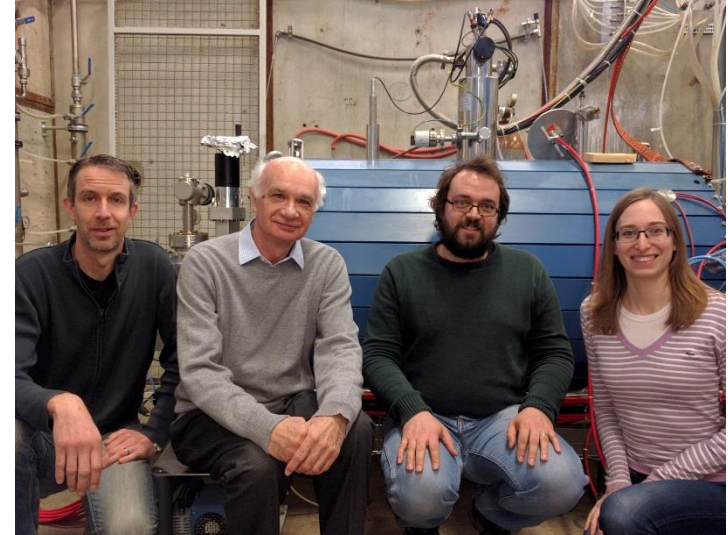
For the full story see:

J. Pitters et al., 'Summary of charge breeding investigations for a future ^{11}C treatment facility', CERN-ACC-NOTE-2018-0078

For an executive summary see:

J. Pitters et al., 'Challenges in ^{11}C charge breeding', proceedings EMIS 2018

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