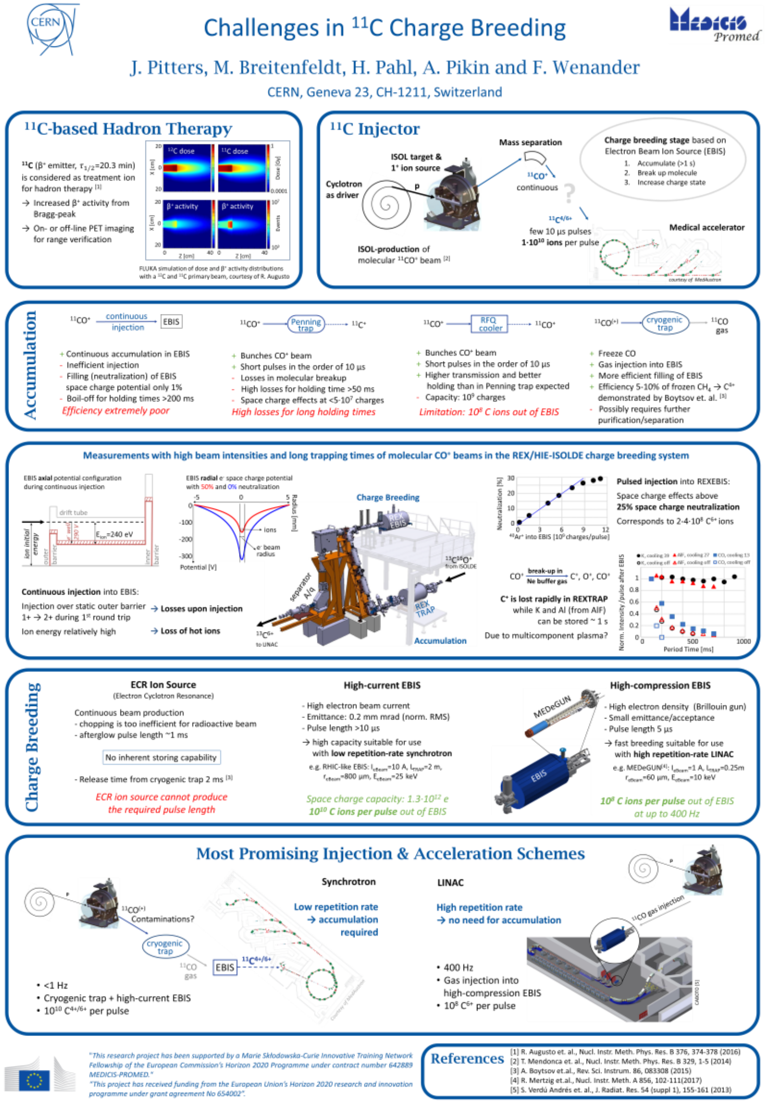
Charge breeding investigations for a future ^{11}C treatment facility



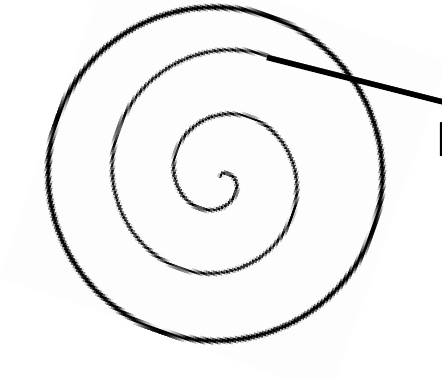
Johanna Pitters

Medicis Promed Workshop,
Wiener Neustadt

2019-01-16

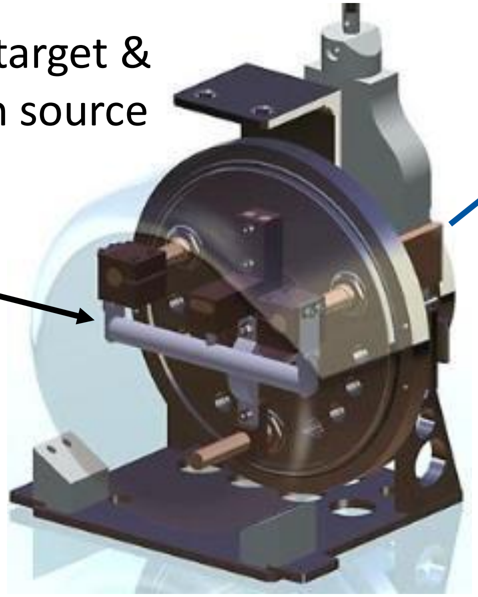
^{11}C injector

Cyclotron
as driver



p

ISOL target &
1^+ ion source



Mass separation

$^{11}CO^+$
continuous

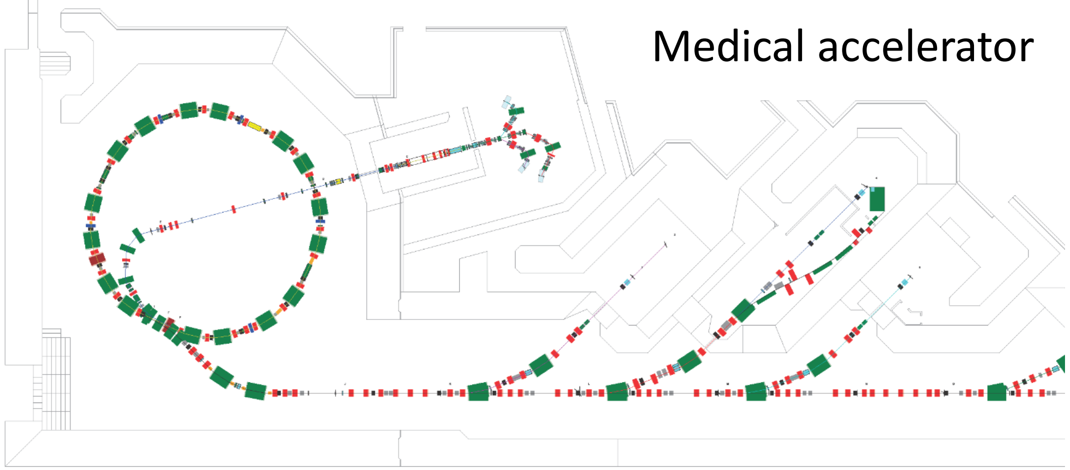
?

Charge breeding stage

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

$^{11}C^{4+}$
few 10 µs pulses
$1 \cdot 10^{10}$ ions per pulse

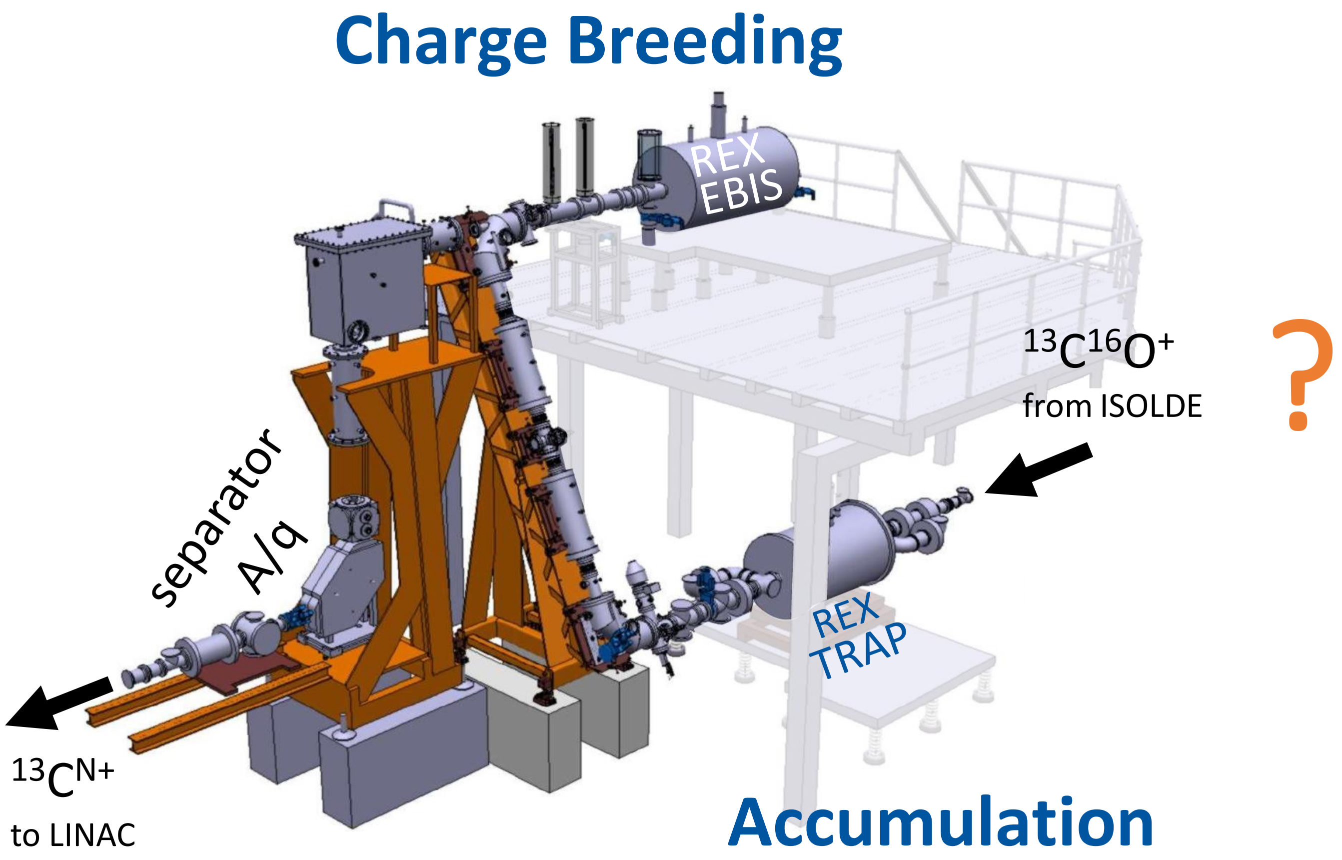
Medical accelerator



courtesy of MedAustron

ISOL-production of molecular $^{11}CO^+$ beam [*]

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



Charge breeding stage

1. Accumulate (>1 s)
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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:

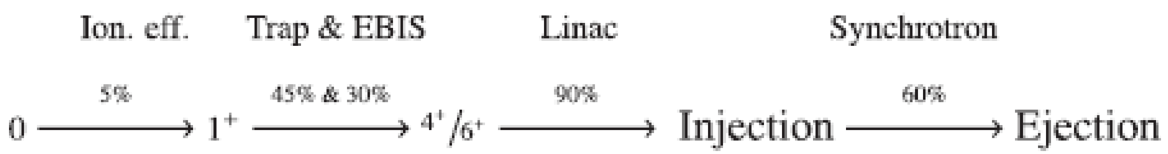

Fig. 2. Set-up taking present devices, combining present accelerator components of injection, at ISOLDE and MedAustron.

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

?

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NIRS proposal:

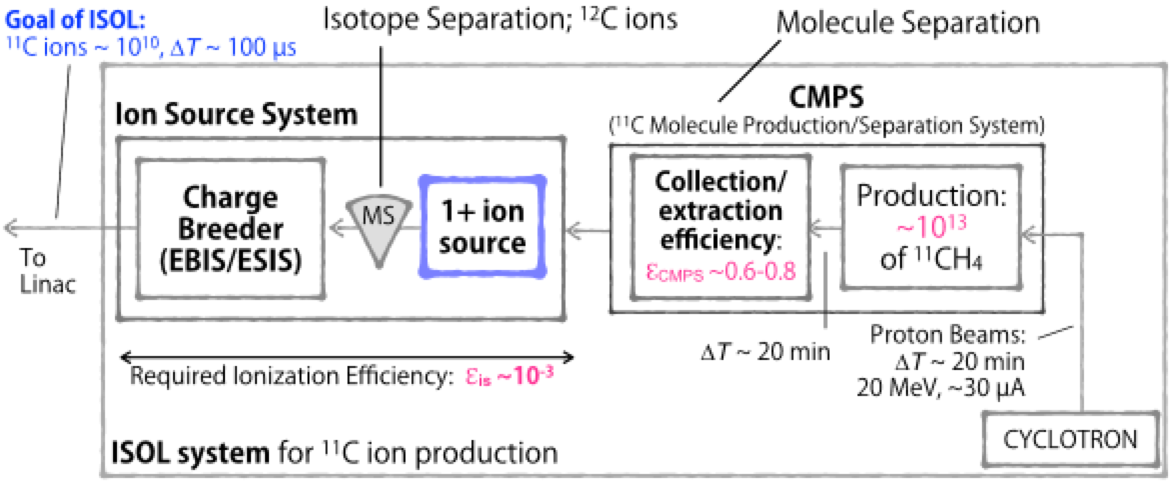

FIG. 1. A possible scheme for ^{11}C ion production.

https://aip.scitation.org/doi/pdf/10.1063/1.4935899

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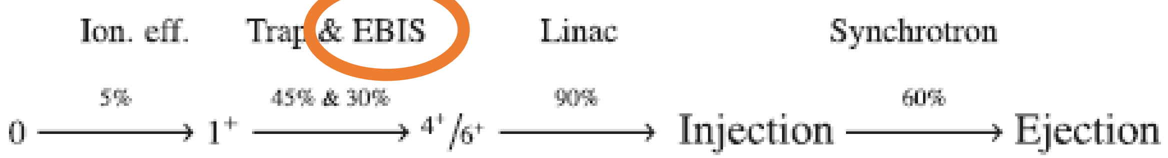

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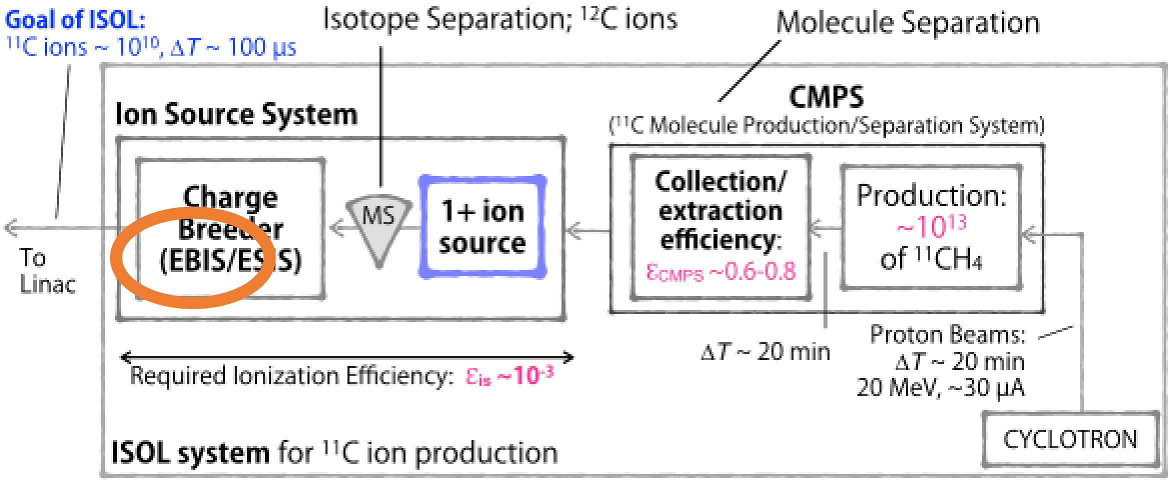

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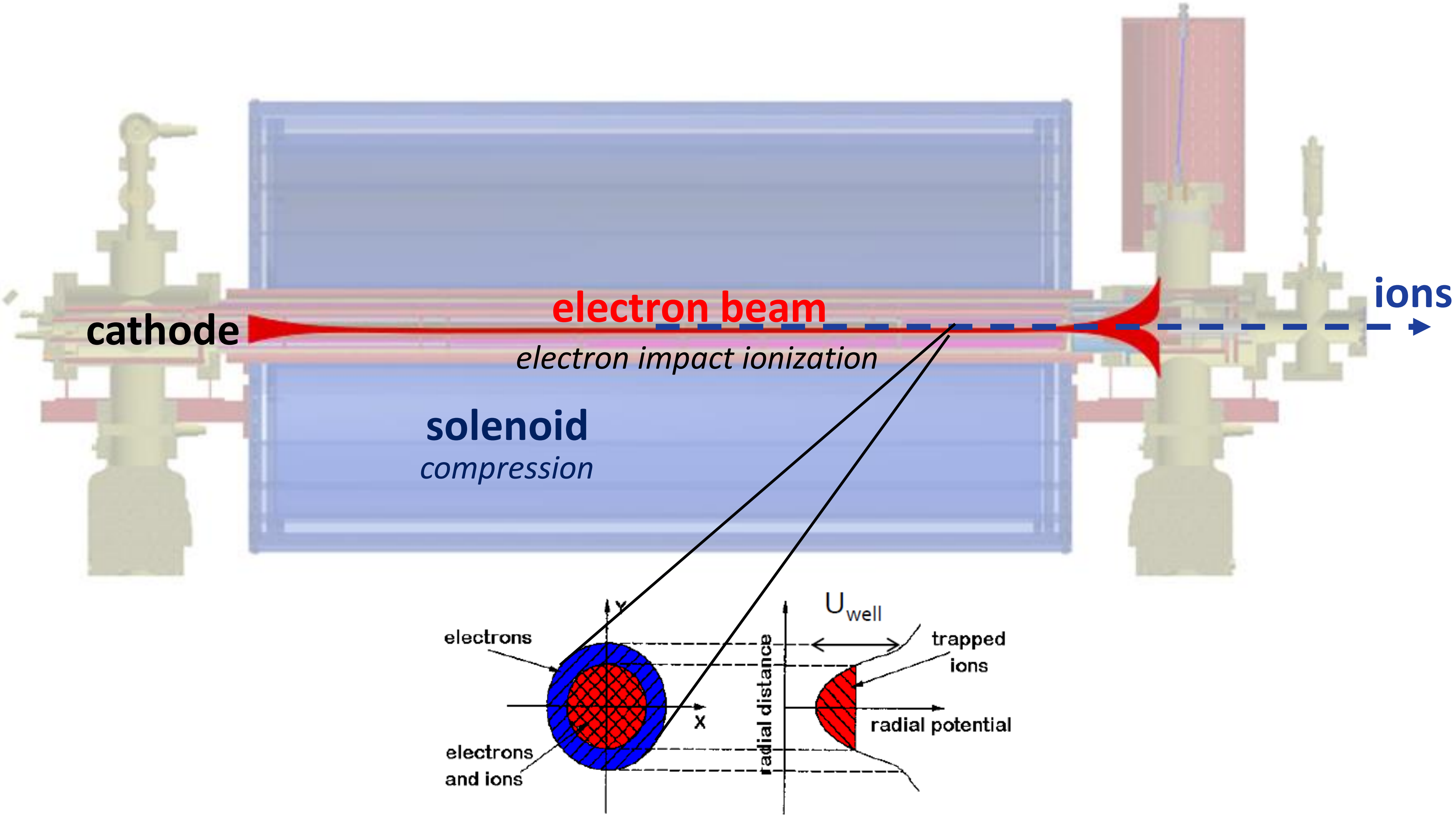
https://aip.scitation.org/doi/pdf/10.1063/1.4935899

ECR source: inefficient for radioactive beam

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

EBIS – Electron Beam Ion Source

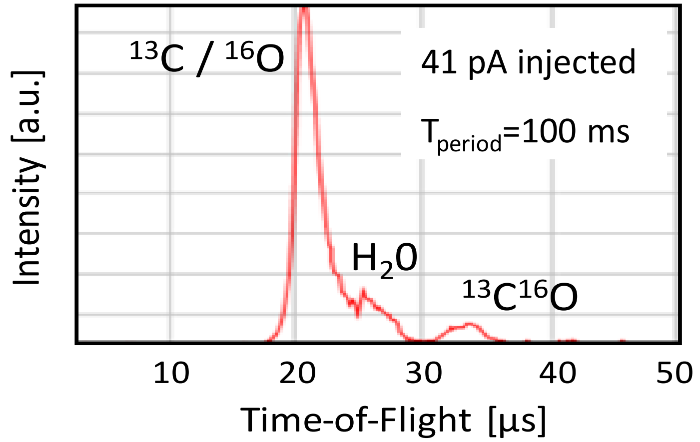


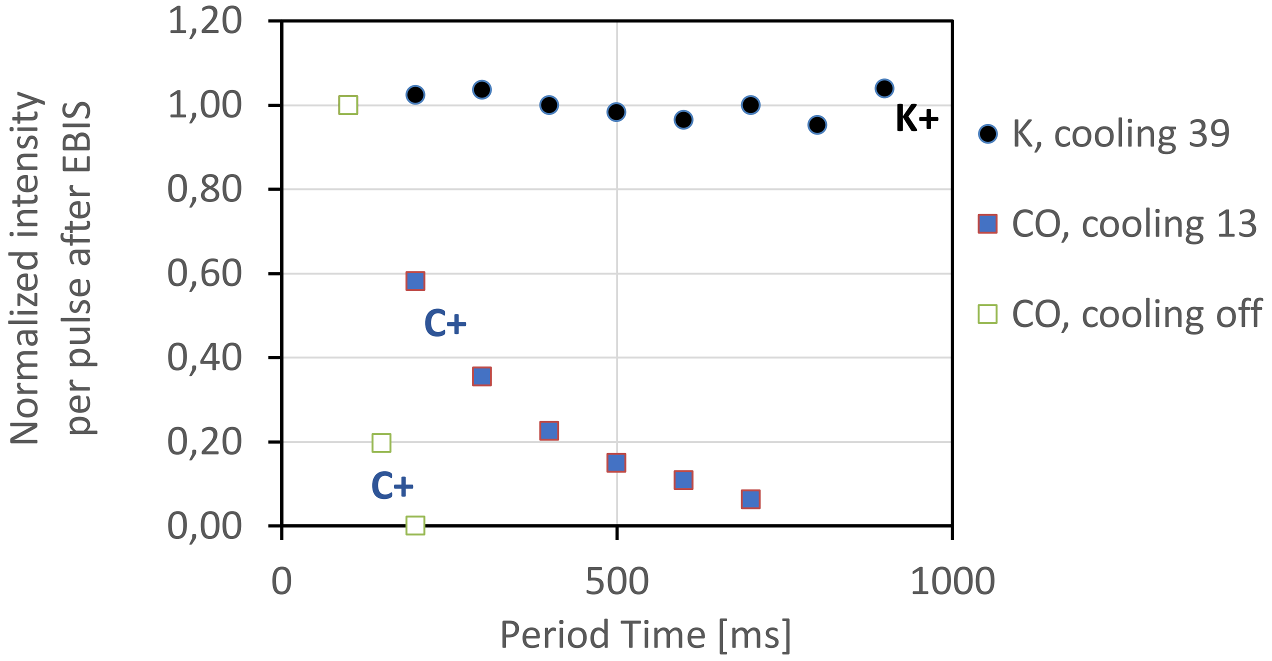
Radial potential

Beam accumulation

Accumulation alt. 1
bunching in *Penning trap*

+ 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 for $>5\cdot10^7$ charges

Accumulation alt. 2

bunching in *RFQ cooler*

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

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

? Capacity: 10^9 charges

Words of caution

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

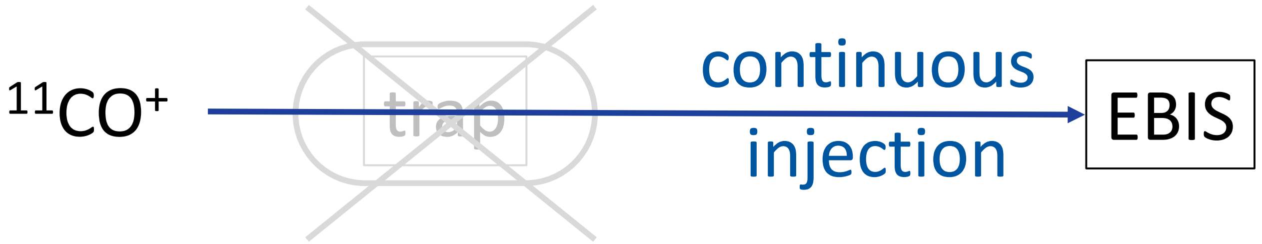
Limitation: few 10^8 C ions out of EBIS

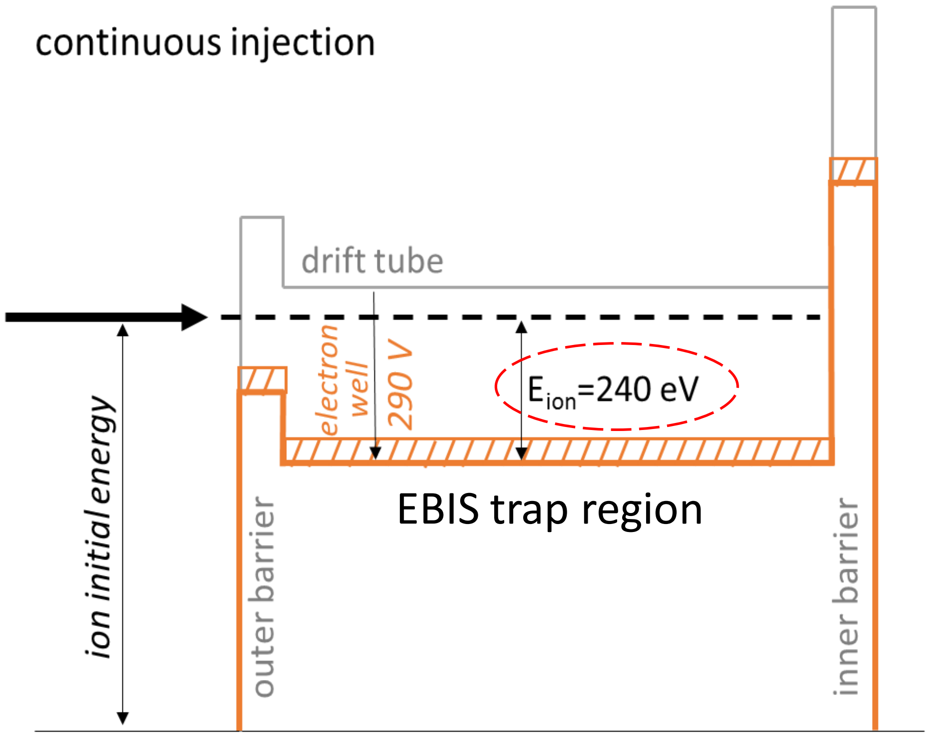
To be verified

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

Accumulation alt. 3

continuous injection into EBIS





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.

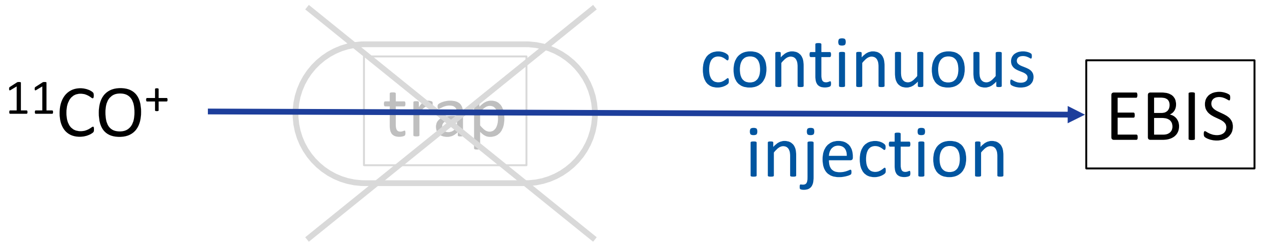
* Injection over static outer barrier

* Need $1^+ \rightarrow 2^+$ during 1^{st} round trip

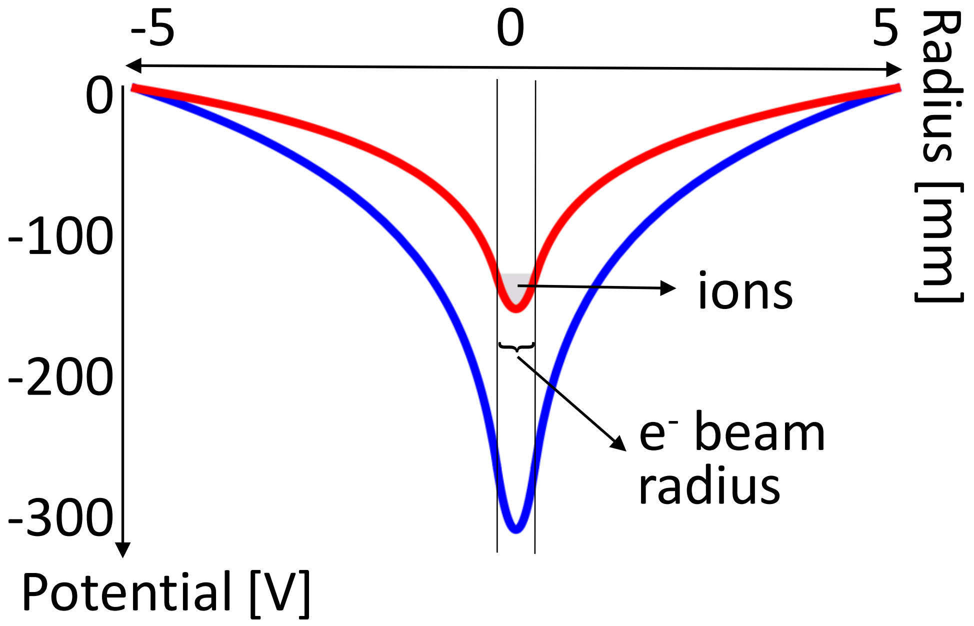
→ **Losses upon injection**

Accumulation alt. 3

continuous injection into EBIS



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



+ Continuous accumulation in EBIS

- High charge states dominate

- Inefficient injection

- Boil-off for holding times >200 ms

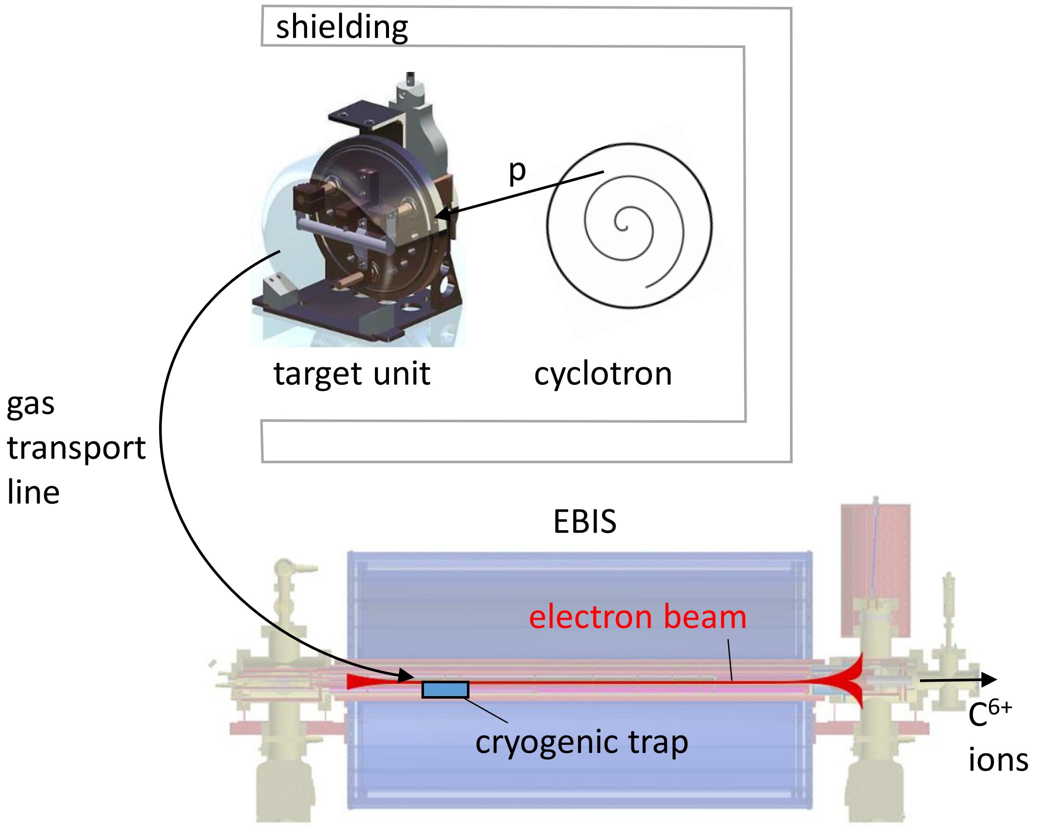
Ion energy relatively high

→ **Loss of hot ions**

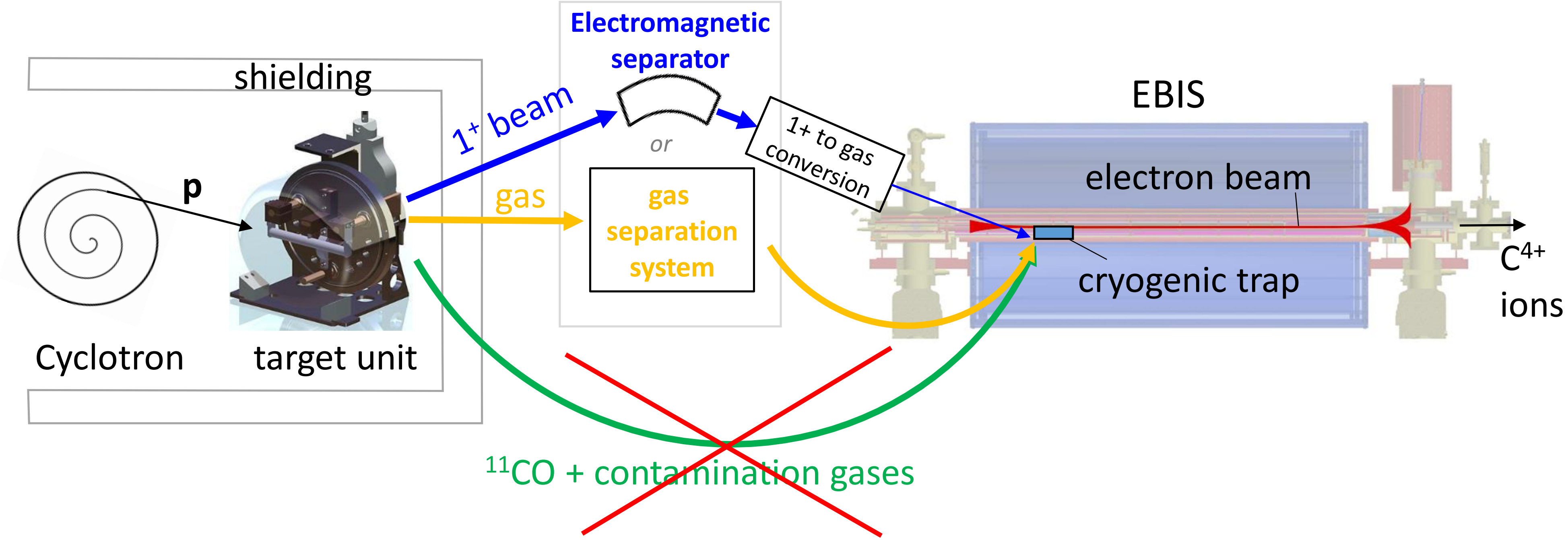
Sub-percent efficiency

Accumulation alt. 4
collection in *cryogenic trap*

- + Freeze CO for accumulation
- + Use gas injection into EBIS
- + Efficiency 5-10% of frozen $CH_4 \rightarrow C^{4+}$ demonstrated by Boytsov et al. [*]
- \- Contamination ?



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



- Contamination ?

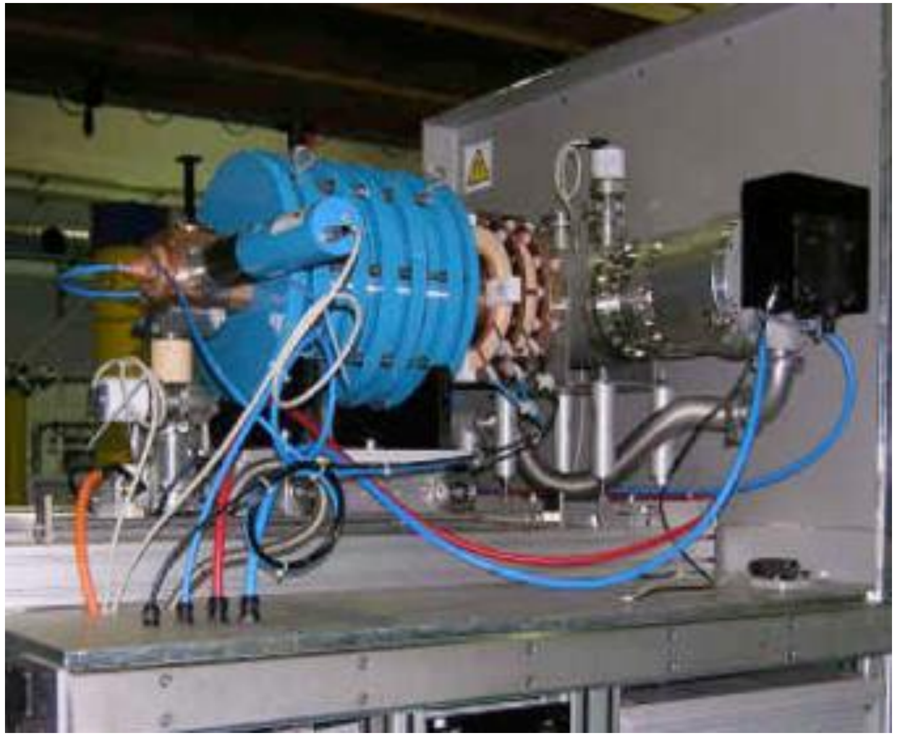
  -> separation system required[*]

[*] 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 $^{12}C^{4+}$

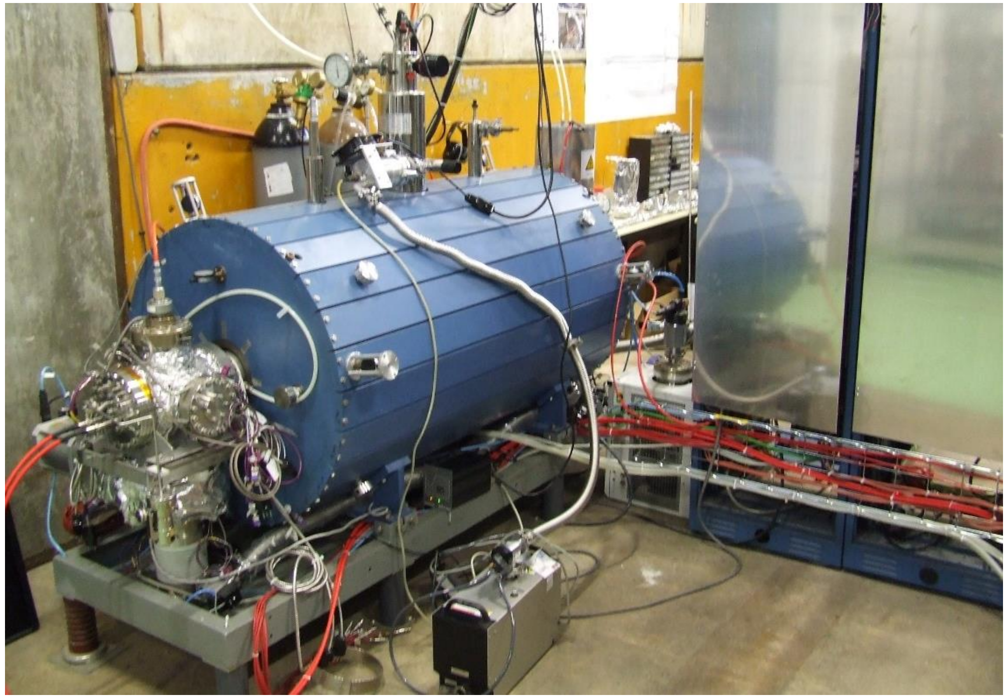
+ High capacity for continuous operation

- No inherent storing capability but
  continuous production

- Extracted pulse length 1-2 ms
  (afterglow operation)

An EBIS!

(Electron Beam Ion Source)



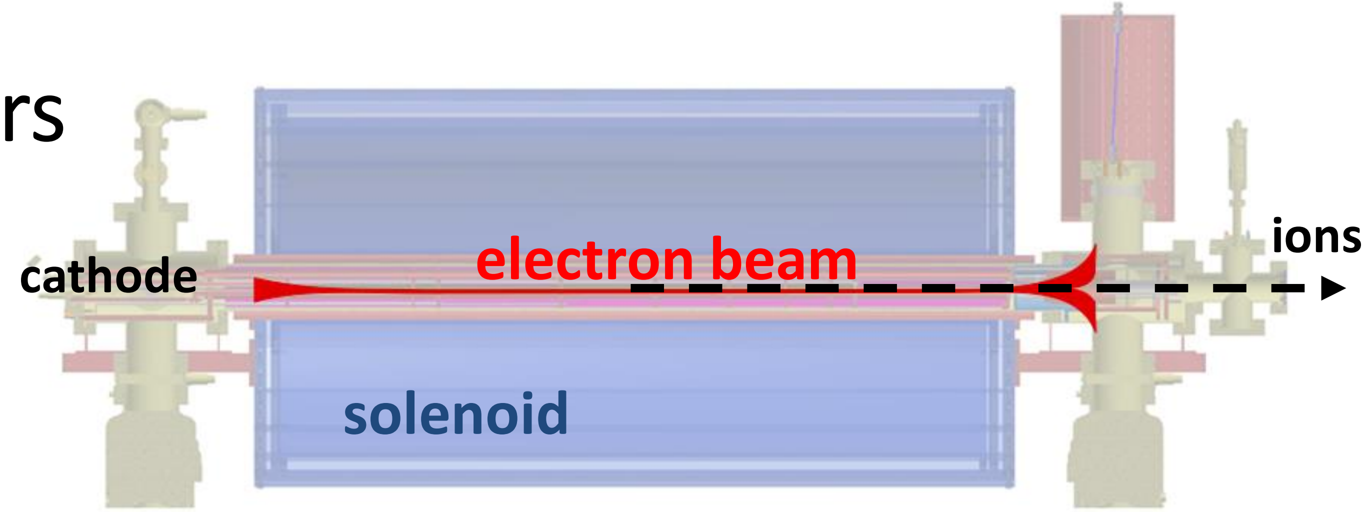
TwinEBIS test stand at CERN

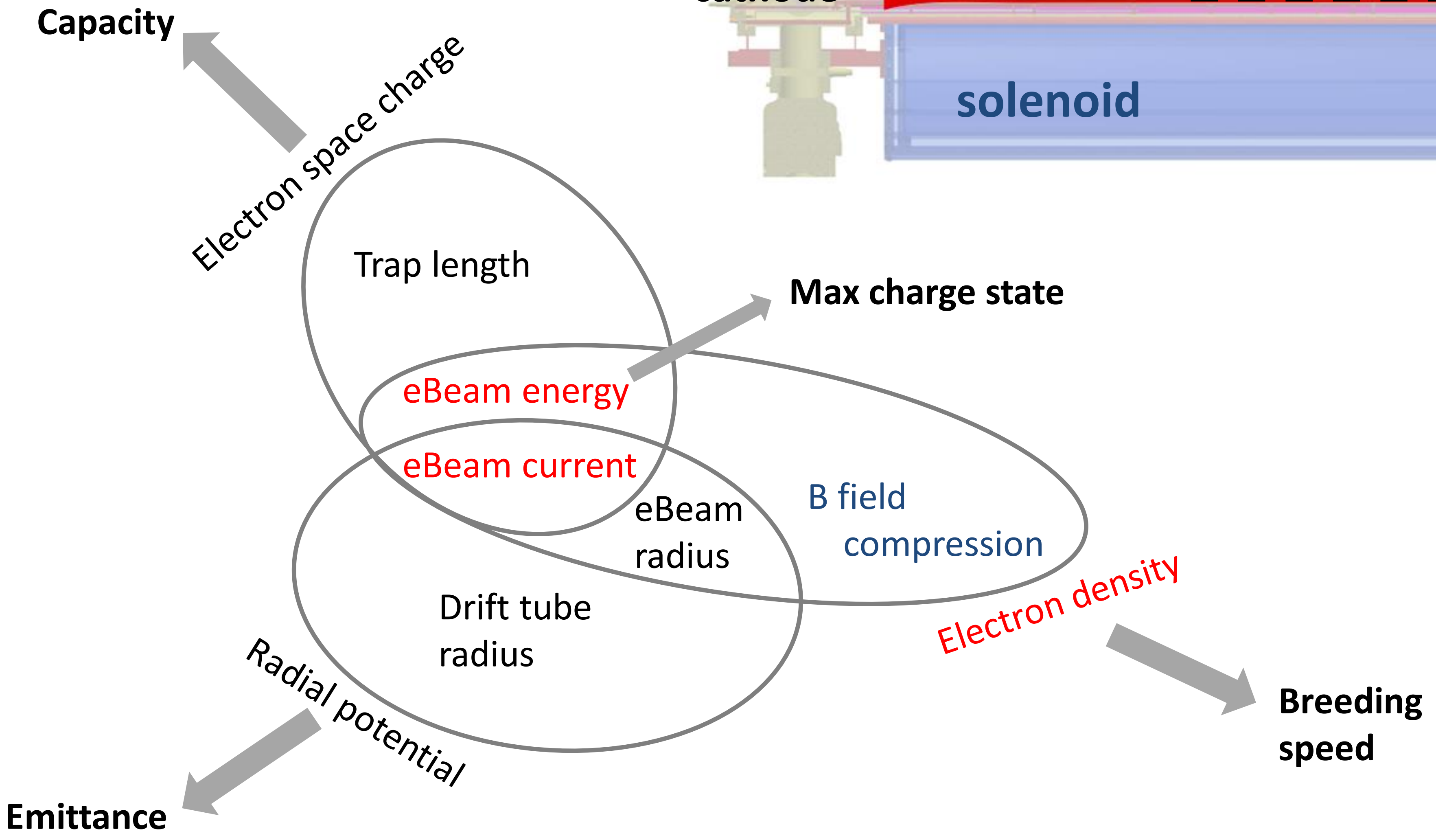
+ Inherent storing capability and pulsed production

+ Extracted pulse length few 10 μs

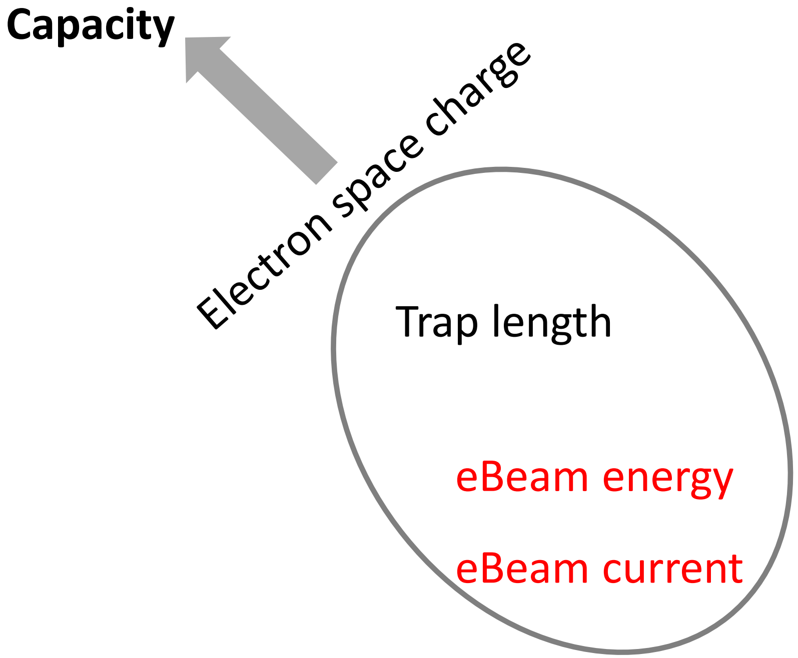
- We need:
  high efficiency → filling
  high intensity → space charge capacity

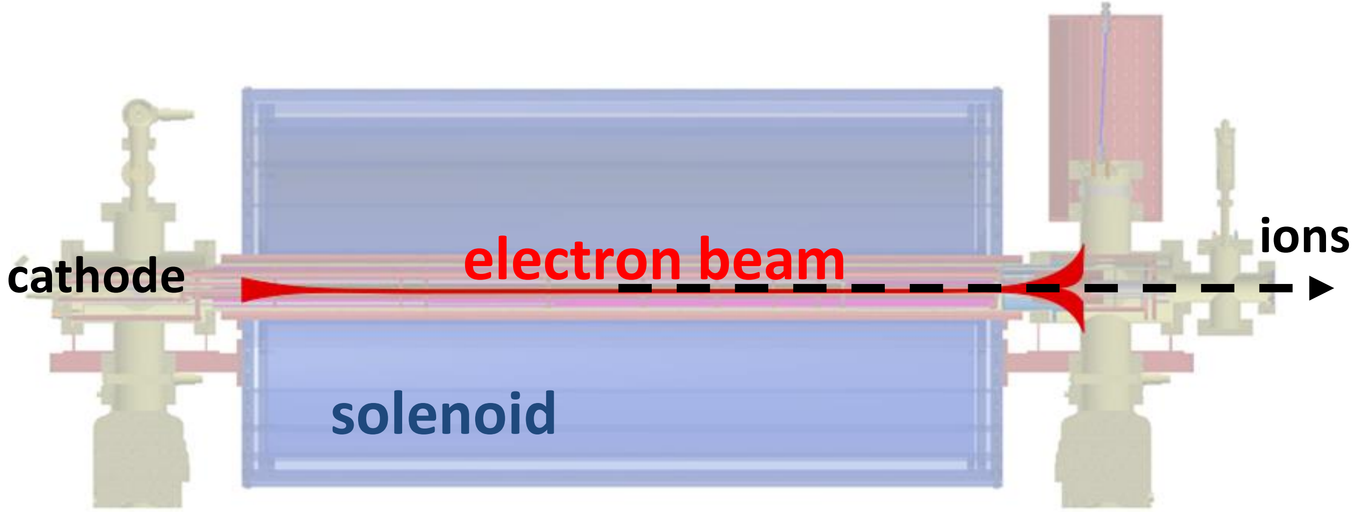
EBIS Machine Parameters





EBIS capacity





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

e.g. REXEBIS

I_e = 200 mA

E_e = 4.5 keV

L = 0.8 m

N^- = 2.3·10^{10} electrons

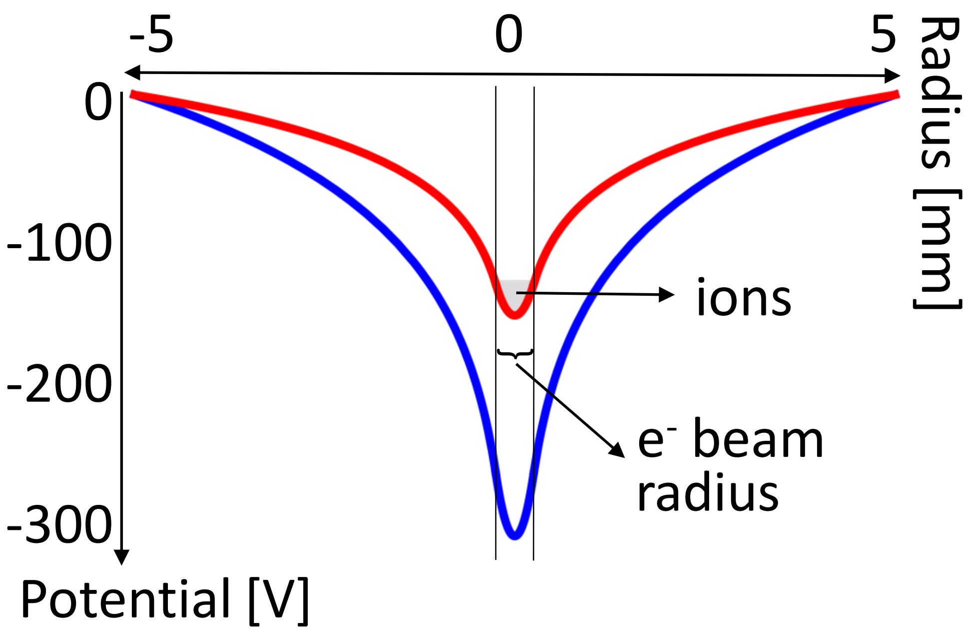
EBIS filling

Filling of EBIS

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

+

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

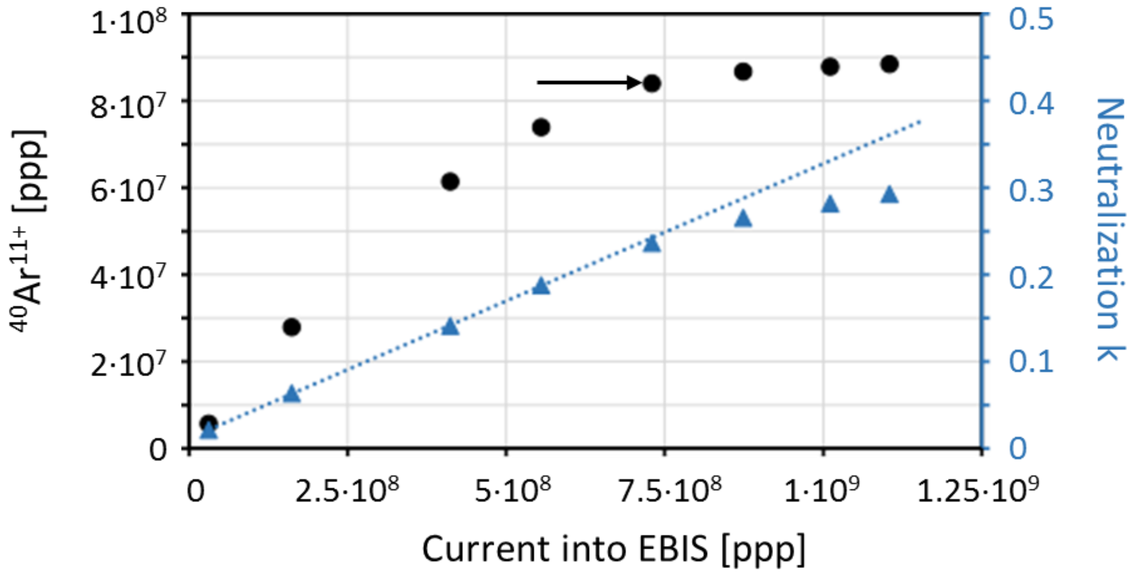
Filling of EBIS

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

+

splitting into elements and charge states

Pulsed injection into REXEBIS without using REXTRAP



REXEBIS: saturation starts at 25% filling for pulsed injection

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

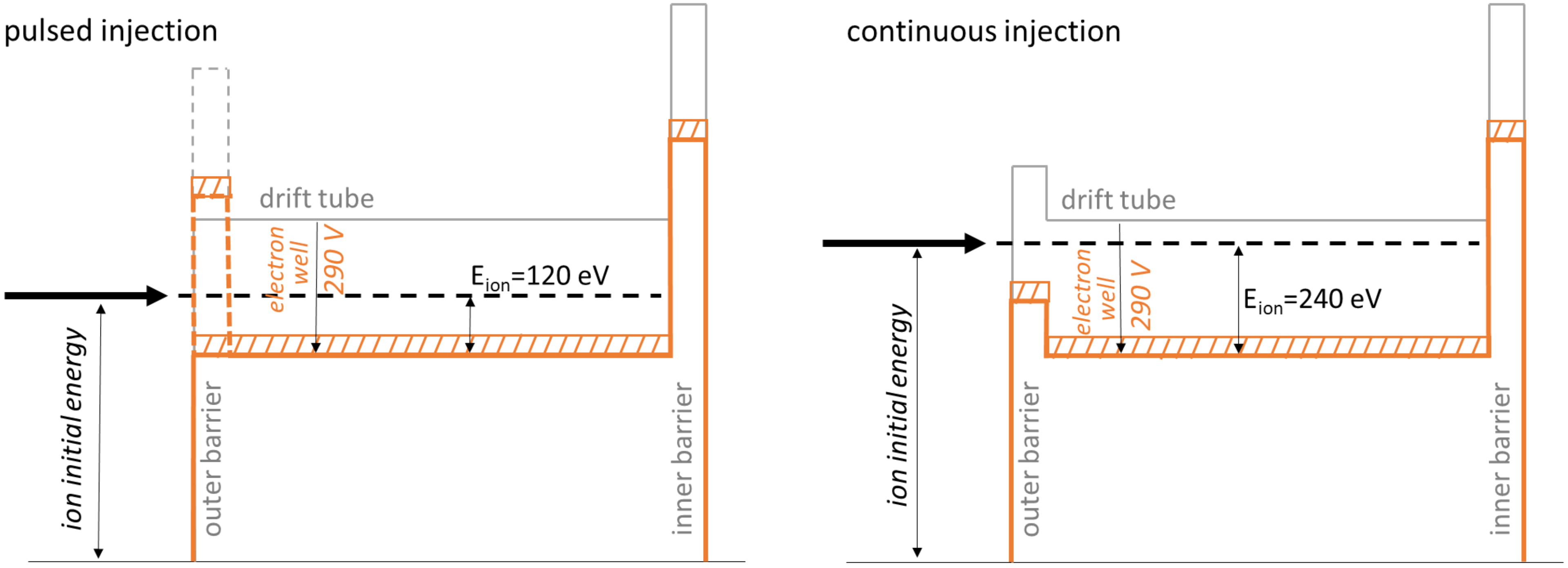
EBIS filling

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

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

Neutralization:

cw	<<	pulsed	<	gas
~ 1%		25%		>70%



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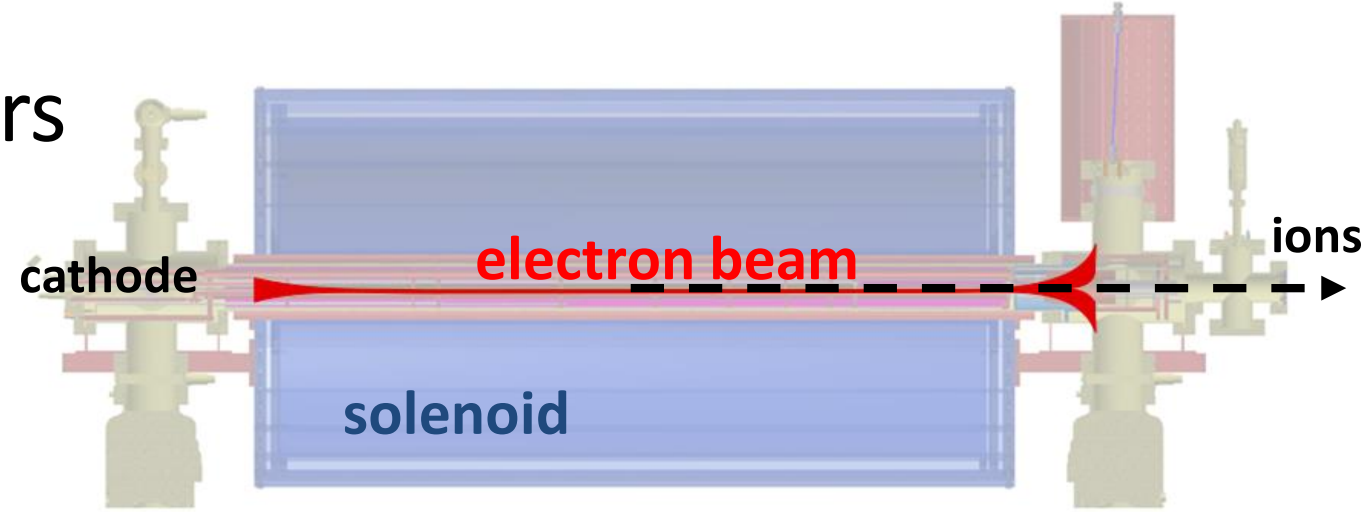
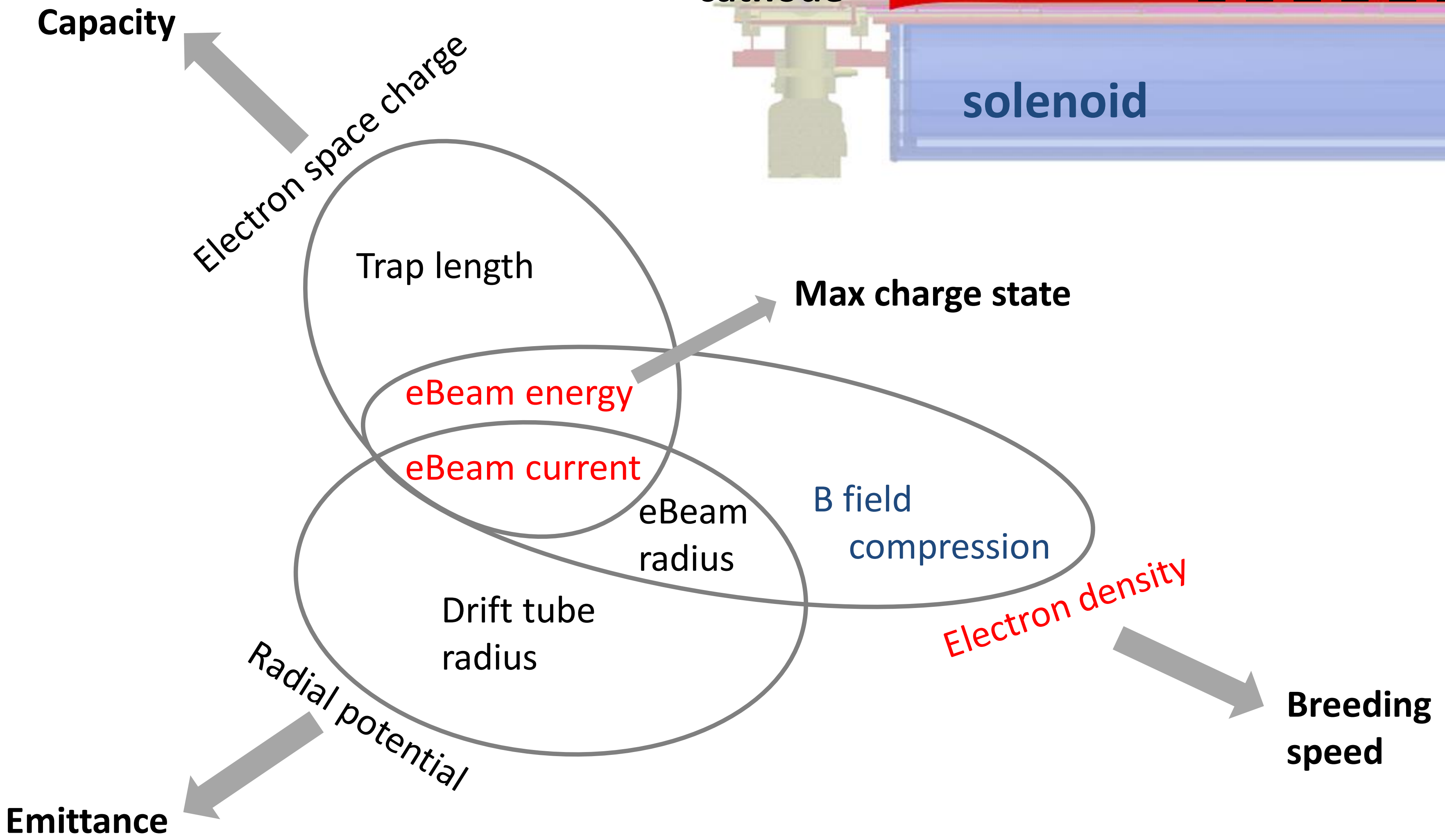


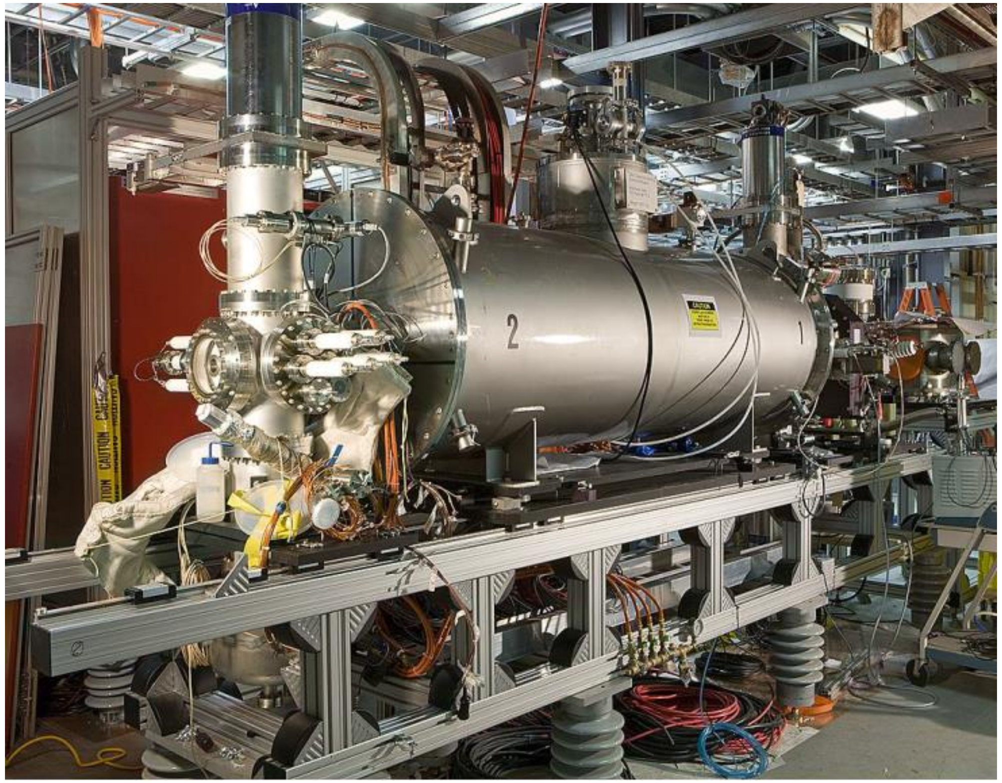


EBIS Machine Parameters

capacity vs speed

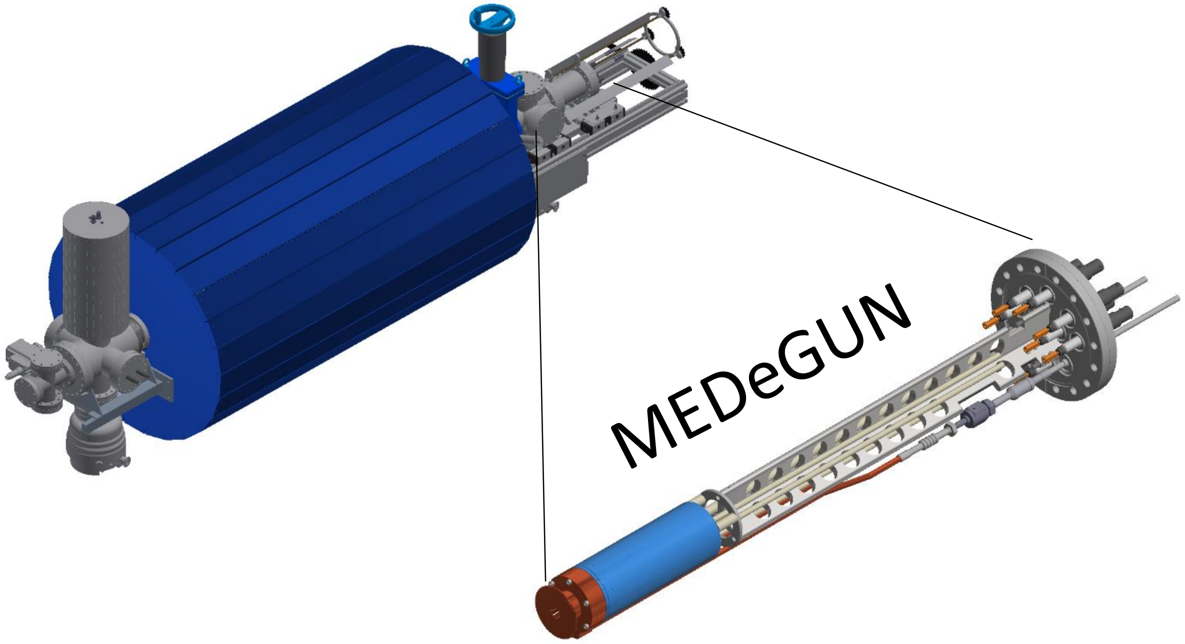
High-*current* EBIS

Courtesy of BNL



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

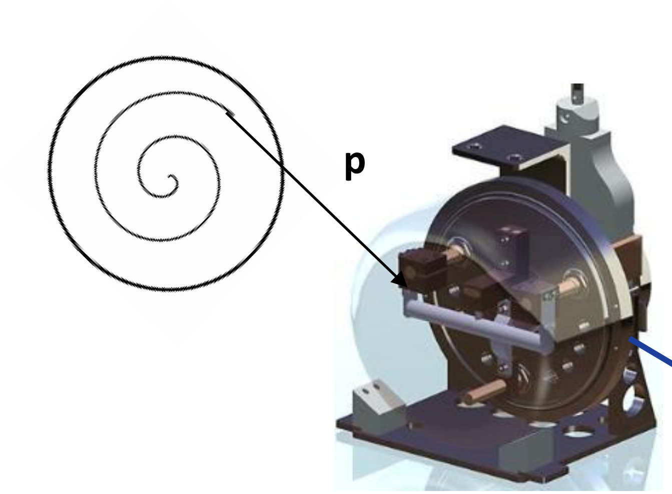
High-*compression* EBIS



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

Most Promising Injection & Acceleration Schemes

Synchrotron



$^{11}CO^{(+)}$

Contaminations?

cryogenic trap

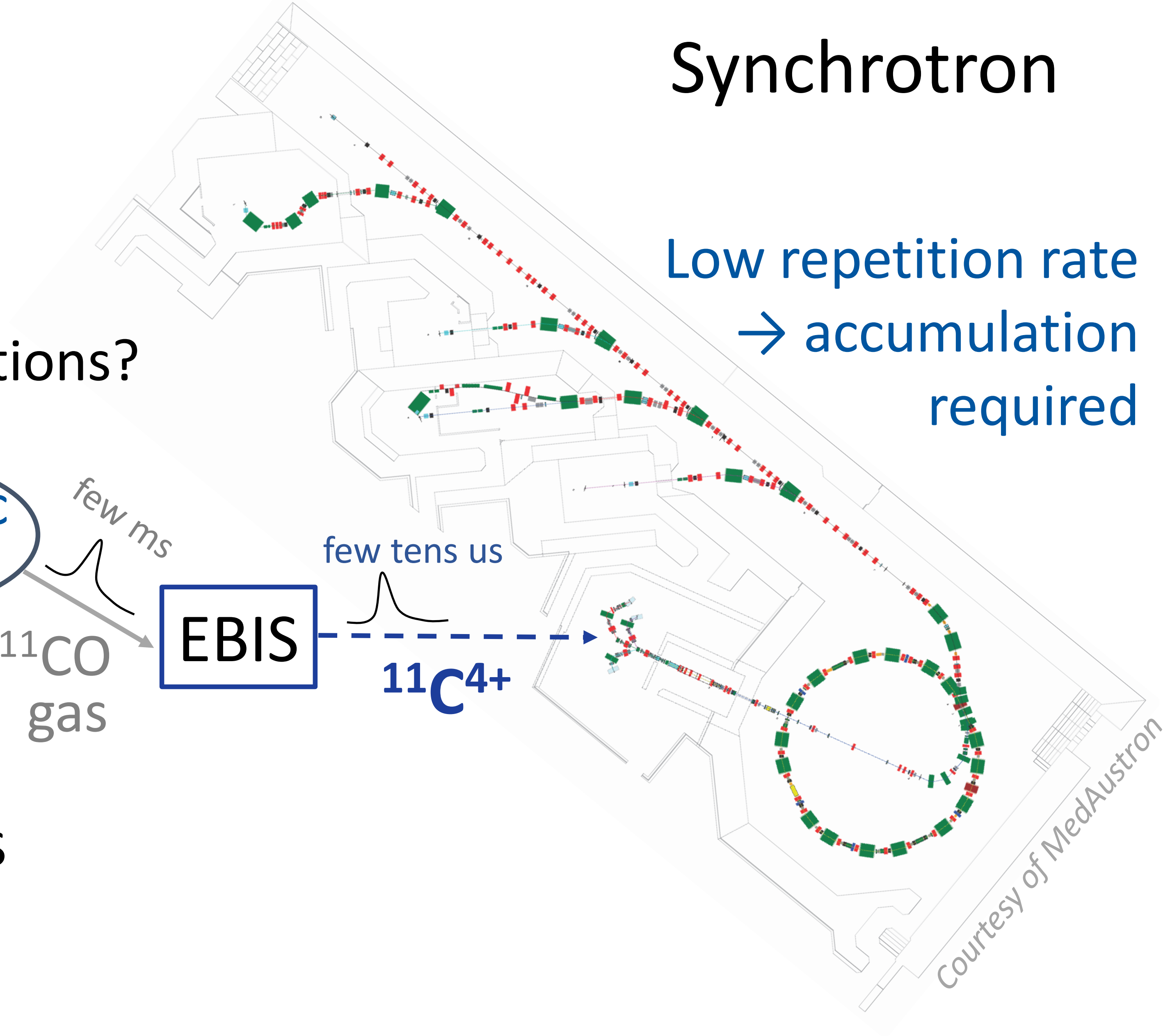
few ms

^{11}CO gas

EBIS

few tens us

$^{11}C^{4+}$



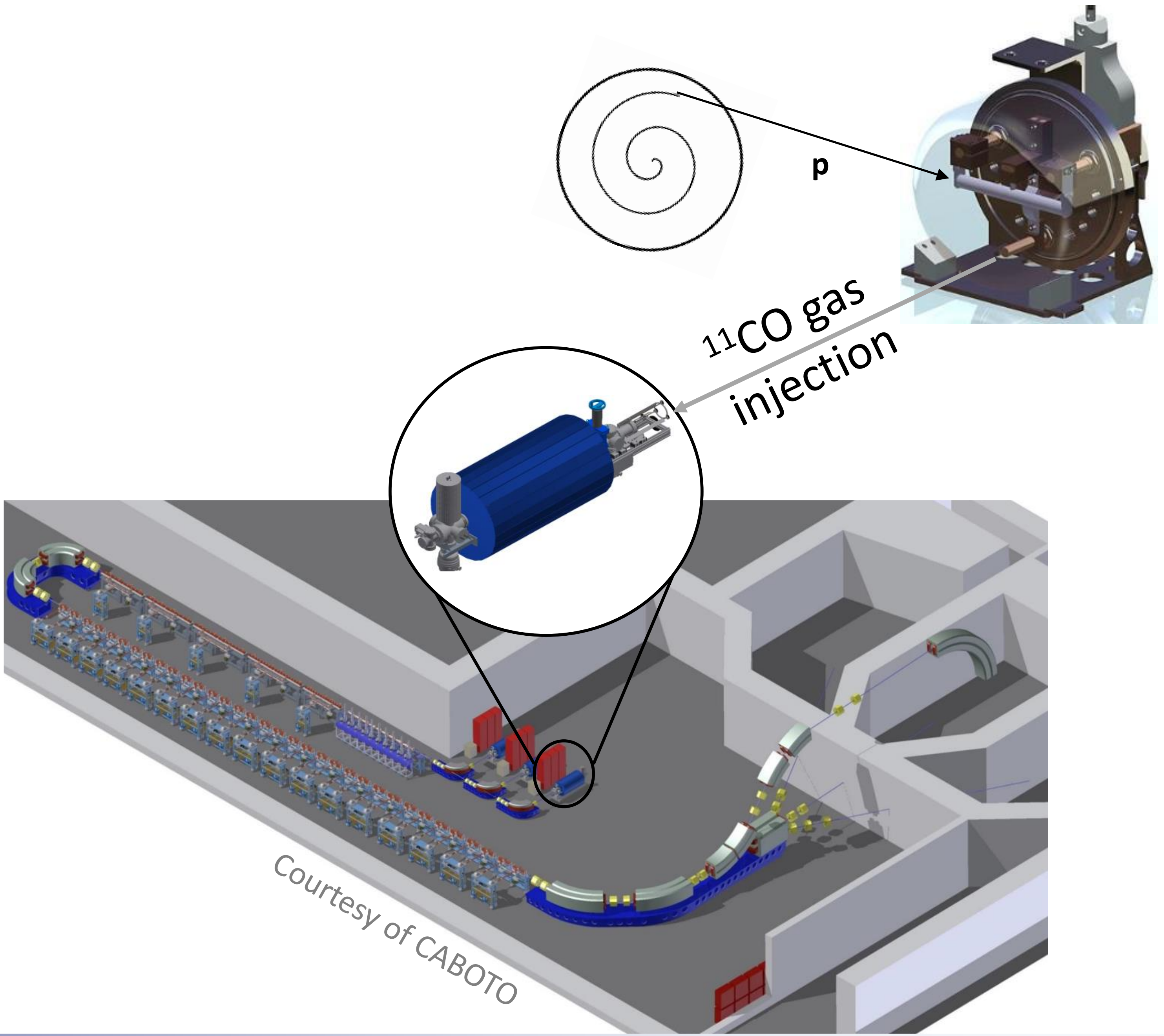
Low repetition rate
→ accumulation
required

- < 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 C^{6+} per pulse
- < 5 us pulse



Summary

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

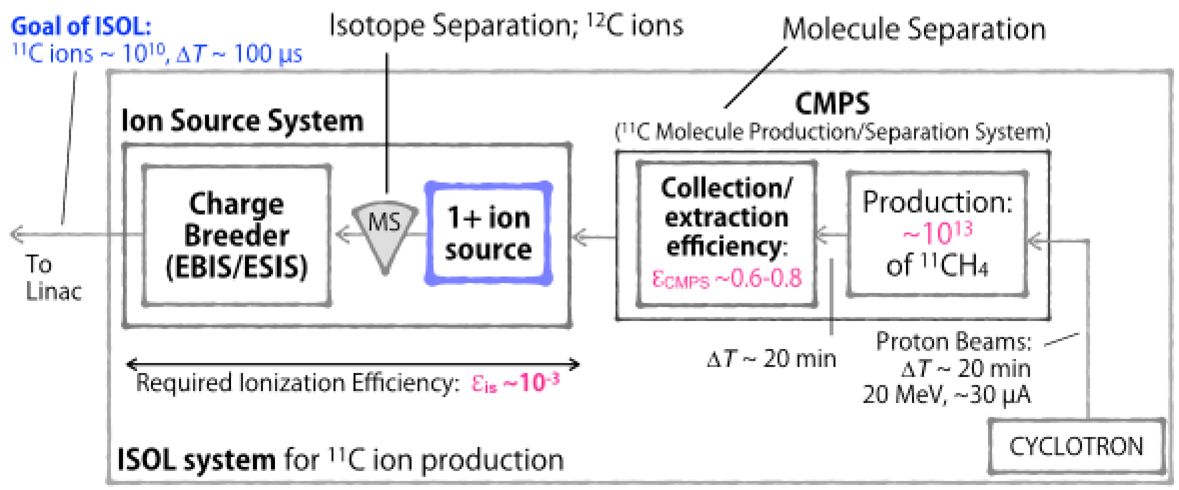


FIG. 1. A possible scheme for ^{11}C ion production.

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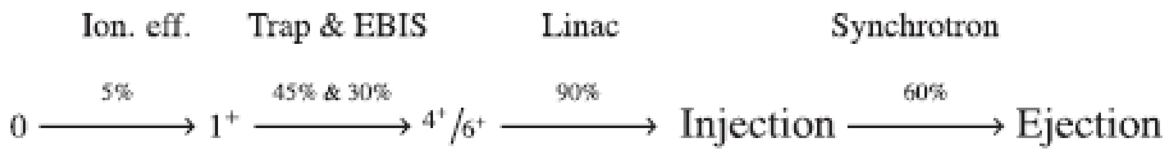

Fig. 2. Set-up taking present devices, combining present accelerator components of injection, at ISOLDE and MedAustron.

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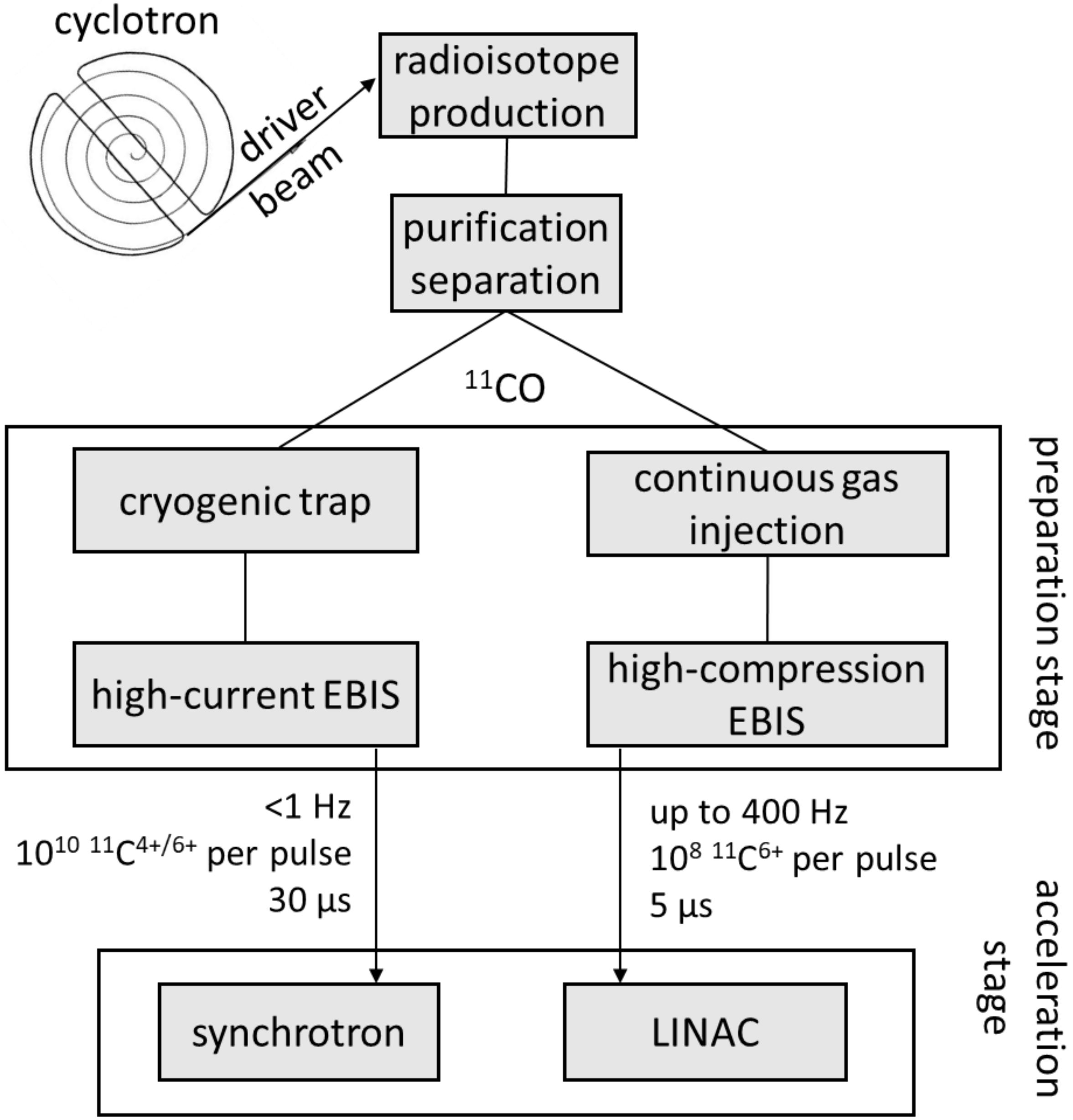
4. Synchrotron accelerator case
   - neutral gas injection via a cryogenic trap into the EBIS
   - a high-capacity EBIS with $1.3 \cdot 10^{12}$ electron charges is required

   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

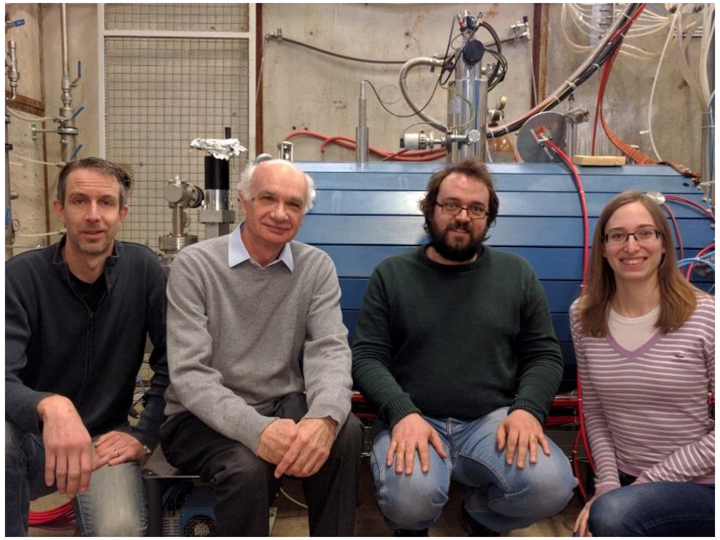
favourite

Summary



cyclotron
driver beam
radioisotope production
purification separation
11CO
cryogenic trap
continuous gas injection
high-current EBIS
high-compression EBIS
preparation stage
<1 Hz
10^10 11C4+/6+ per pulse
30 µs
up to 400 Hz
10^8 11C6+ per pulse
5 µs
acceleration stage
synchrotron
LINAC

F. Wenander, A. Pikin, M. Breitenfeldt, J. Pitters



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

H. Pahl

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