OPTIMIZING THE RADIOISOTOPE PRODUCTION WITH A WEAK FOCUSING COMPACT CYCLOTRON

Concepción Oliver

On behalf of

Accelerator Technology Group at CIEMAT (Spain)

concepcion.oliver@ciemat.es

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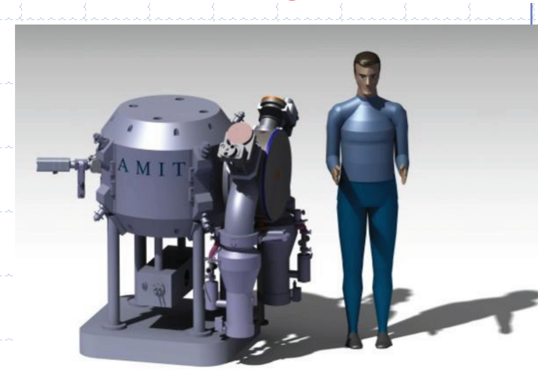
AMIT cyclotron



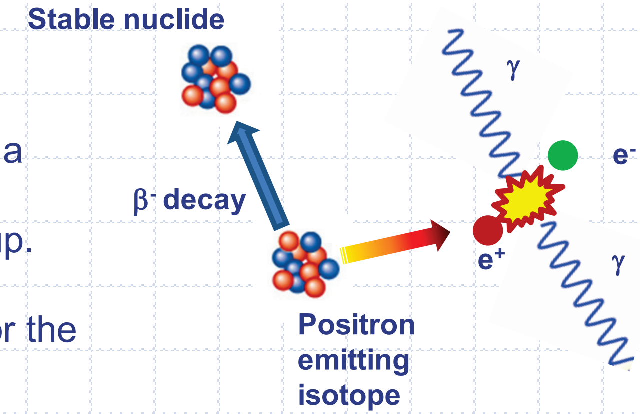
OPTIMIZING THE RADIOISOTOPE PRODUCTION WITH A WEAK FOCUSING COMPACT CYCLOTRON

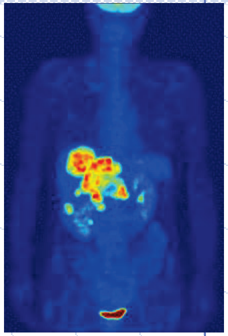
And simple…

Why weak focusing machines (again)?

E. Lawrence

Why a weak focusing machine?





Whole-body PET scan using ^{18}F-FDG

- PET technique is broadly used around the world as a diagnostic tool and for treatment planning and follow-up.
- Cyclotrons are the most widely used accelerators for the production of positron emitter isotopes

- **Technology requirements** for future radiopharmaceuticals production:
  - To minimize building requirements:
    - -cyclotron with the minimal weight/size
    - -lowest possible energy to produce radioisotopes but reducing machine activation (shielding)
  - To reduce cost of cyclotron (more adjustable to on-site needs)
  - Low power consumption
  - Possibility to produce new markers with short half- life (^{11}C, 20 min)
  - …

Compact (SC) cyclotron ⟵ **AMIT cyclotron**

AMIT project: Advanced Molecular Imaging Technologies

- Work supported by the Spanish Ministry of Science and Innovation
- CDTI (Center for Industrial Technology development) funded project (CENIT CIN/1559/2009)
- **Target: brain pathologies, in particular, those derived from mental diseases.**
- In addition to other workpackages related with miniaturized radiopharmacy, PET instrumentation or advanced molecular software imaging, one of the goals is the development of a **compact minicyclotron for ^{11}C and ^{18}F single doses production**

- CIEMAT is the scientific leader of this cyclotron project
- Close collaboration with Spanish industry
- External collaboration as CERN

SEDECAL: responsible for the development of the prototype

ANTEC: Responsible for the electromagnetic part

CIEMAT: Responsible for the design, integration, tests and qualification.

HGGM: Support on the specifications and management

Biomagune: support on targets

CNIO: support on clinical and preclinical applications

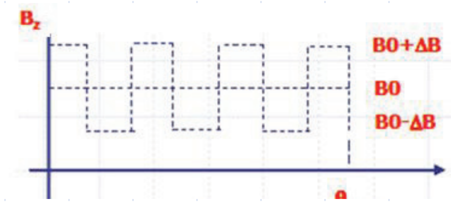
AMIT as a weak focusing machine

INTRODUCTION

- ❑ Compactness requirement → high magnetic field

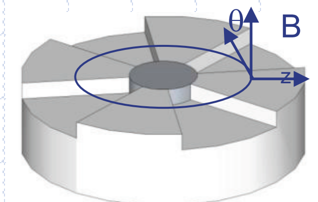
  → 4 Tesla → Superconducting machine

Beam focusing in cyclotrons:



❑ In isochronous machines, focusing forces arise from the azimuthal magnetic field variation introduced by the "valley-hill" configuration

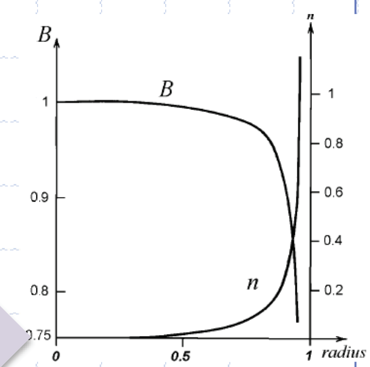
❑ In our 4T cyclotron, the magnetic field is so high that iron will be saturated and the magnetic field difference between valleys and hills is small, resulting in a small flutter



❑ Magnetic elements with higher saturation level will result in expensive machines

❑ Classical cyclotron becomes a good option for compact machine, given its simplicity

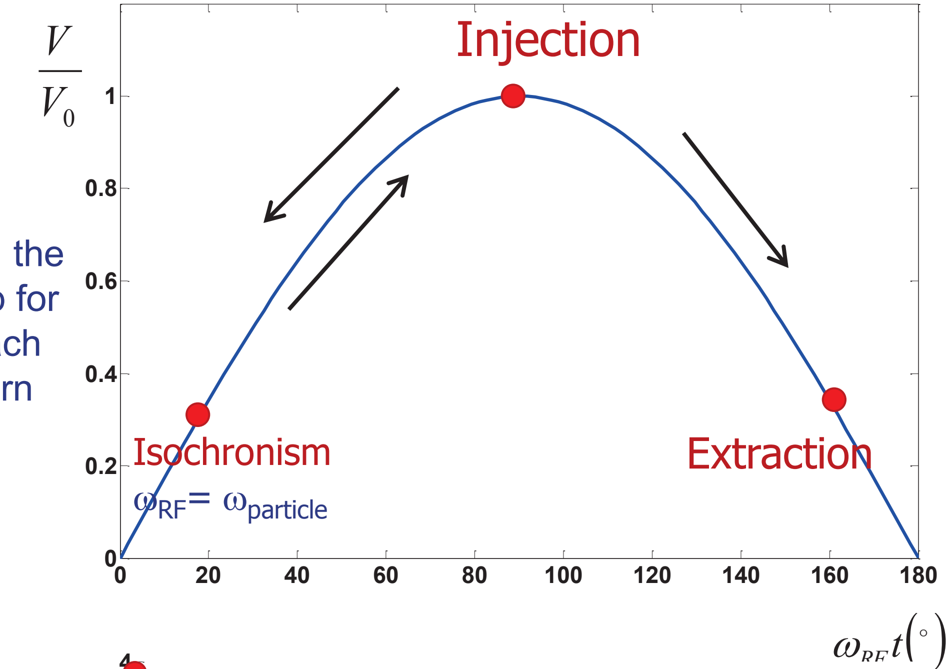
❑ In a classical cyclotron magnetic forces are only produced by **the slightly decreasing radial magnetic field** configuration



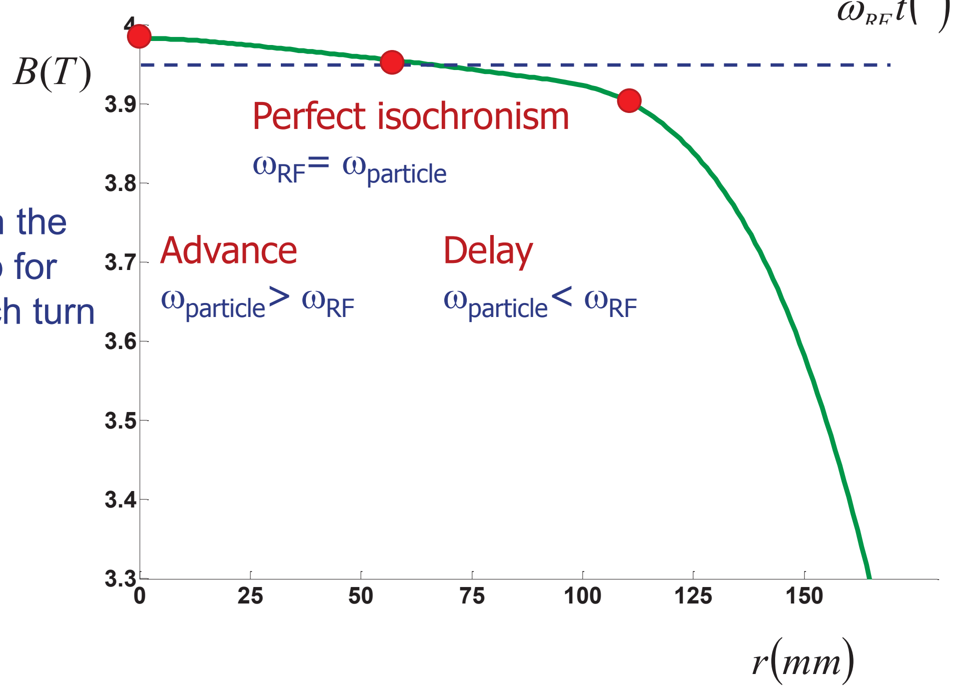
Compact Machine: 4 T → **Focusing forces: low flutter for a 4 T isochronous machine** → **Classical Cyclotron**

AMIT: weak focusing machine

V in the gap for each turn



B in the gap for each turn

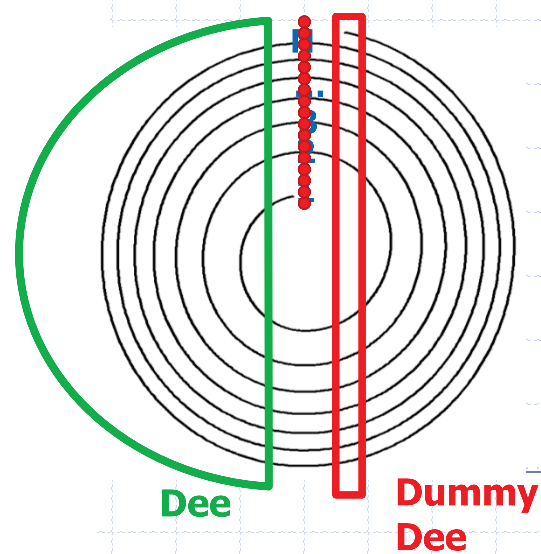


- The orbital frequency decreases with radius

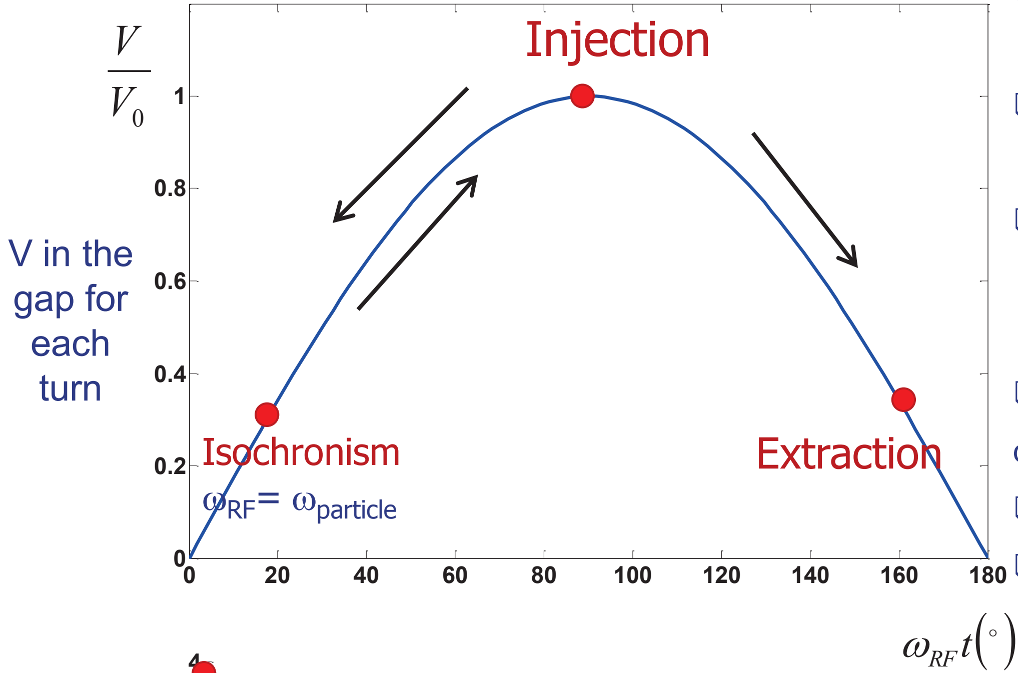
$$\omega_{particle} = \frac{qB}{m} = \frac{qB(r,\theta)}{\gamma m_0}$$

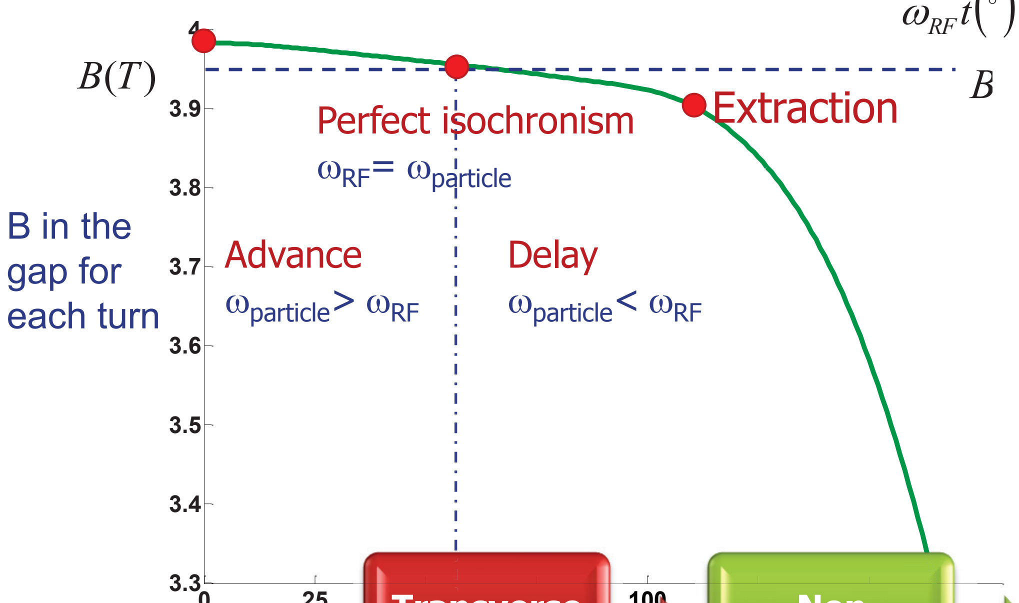
- Fixed RF frequency → **Non particle-RF isochronism**
- RF frequency chosen to be equal to particle frequency in an intermediate radius $\mathbf{r_{synch}}$ → **intermediate energy**

$$\omega_{RF} = \omega_{particle}(r_{synch}) = \frac{qB(r_{synch})}{m(r_{synch})}$$



AMIT: weak focusing machine





- Due to transverse stability, there is non RF-particle synchronism
- The energy gain will be lower than the maximum one (qV_{peak})
- The time that the particle can be accelerated is limited–> **limitation on the maximum energy** at extraction in a classical cyclotron
- ω_{RF} such as particle reaches r_{synch} before being decelerated
- Extraction before deceleration
- To get the maximum output beam energy :
  - **High accelerating voltages** are required (low number of turns)
  - The **field gradient of magnetic field** has to be **limited** → worse axial stability → higher vacuum pipe or higher losses
  - An optimum value for the RF frequency value should be carefully chosen

Transverse stability → **Non isochronism** → **Limited energy** → **High voltage**

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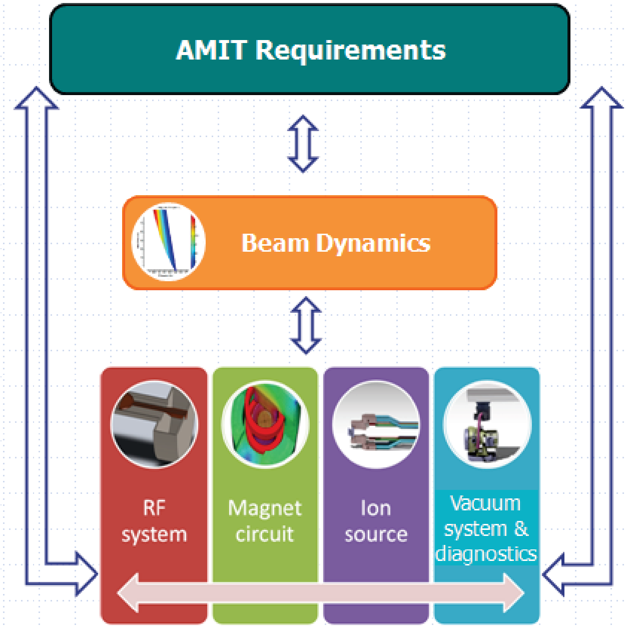
AMIT cyclotron: main specifications

GENERAL	
Cyclotron Type	Classical
Energy	>8.5 MeV
Current	>10 μA
MAGNET	
Type	Low Tc Superconductor
Configuration	Warm Iron
Superconductor	NbTi
Central Field	4 T
RF SYSTEM	
Configuration	One 180º Dee
Peak Voltage	60 kV
RF frequency	~ 60 MHz
ION SOURCE	
Type	Internal
Ions	H^-
EXTRACTION	
Extraction	Stripping foil at 110 mm
Target	Nitrogen gas (^{11}C) , ^{18}O enriched water (^{18}F)
Position	External



OPTIMIZING ISOTOPE PRODUCTION

IN CLASSICAL CYCLOTRON

RADIOISOTOPE PRODUCTION

- Radioisotope production for a given target depends on:
  - Incident beam current → lineal dependence
  - Incident particle energy → strongly dependent

$$A = A_{sat}(E_{particle}) \cdot I_{particle}$$

- An increase of beam energy and/or current could give us more margin in the total radioisotope production and in the production time
- To maximize radioisotope production in the weak focusing AMIT cyclotron

Central region design:

- To optimize phase acceptance resulting in a high transmitted beam current, taking into account the electric (de)focusing forces and the impact in the output energy
- Reduced dimensions due to high B

High voltage + Small distances = Sparks!! ⇐ Careful mechanical design of CR

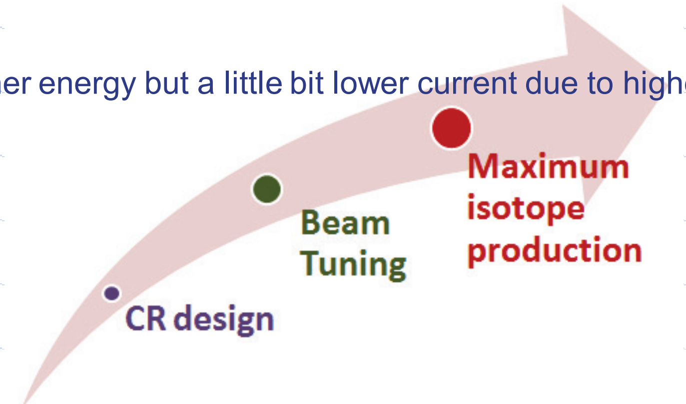
Beam tuning

RF frequency choice to control synchronous phase

- Small synchronous phase → higher energy but higher number of turns (vacuum stripping losses) and defocusing electric forces (axial losses)

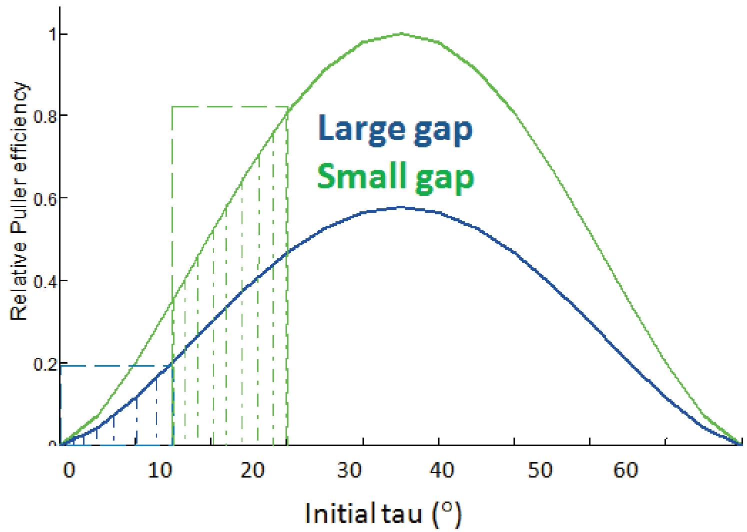
Stripping foil location:

- Higher radius results in higher energy but a little bit lower current due to higher stripping losses



	Maximizing E	Maximizing I
	$\sum_{i=1}^{2N_{turns}} \Delta E^{i}_{gap}$	$I_{output} = I_{H^-}(puller) \cdot K_{vac\_strip} \cdot K_{losses} \cdot K_{extraction}$ $I_{H^-}(\tau_i) \propto \left(\frac{V_{peak} \sin \tau_i}{d_{IS\_puller}} \right)^{3/2}$
▪ High peak voltages	▪ Higher energy gain	▪ Higher extracted current
▪ Initial phase acceptance close to peak	▪ Larger phase excursion	▪ Higher extracted current
▪ Small ion source-puller gap	-----	▪ Higher extracted current & optimum phase acceptance

- Ion source-puller gap as small as possible to:
  - move the phase range with small energy spread close to the peak (90º) → higher beam current
  - to increase the electric field → higher current
  - stronger bunching in orbit centers and energy
- From ANSYS ↔ CYCLONE simulations: 6 mm



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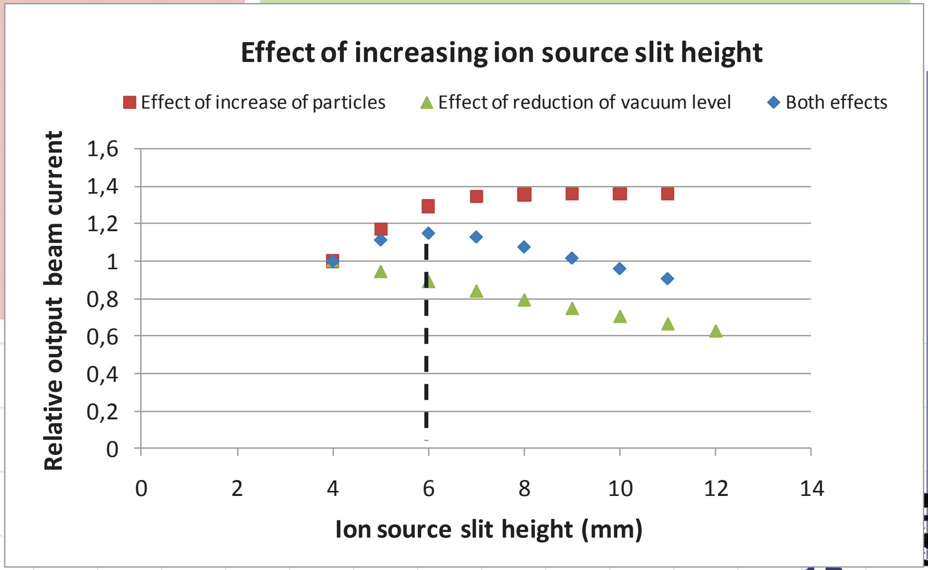
▪ Ion source slit	------	▪ Optimum value to increase extracted current but reducing losses by stripping or axial losses

Ion source slit→

Optimum 0.5 mm wide x 6 mm high



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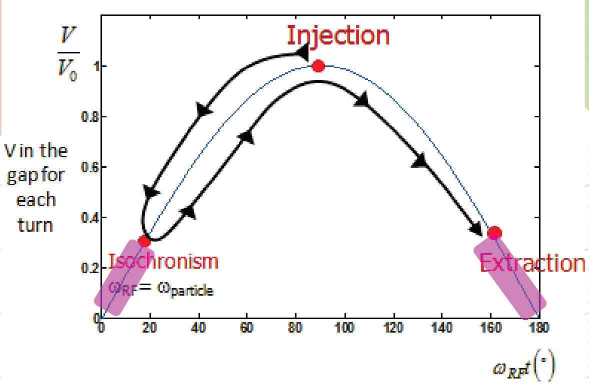
▪ Phase excursion	▪ To maximize phase excursion ⟷	▪ Limited to avoid losses by vacuum stripping and by electric defocusing forces



	Maximizing E	Maximizing I
	$\sum_{i=1}^{2N_{turns}} \Delta E_{gap}^{i}$	$I_{output} = I_{H^-}(puller)\cdot K_{vac\_strip}\cdot K_{losses}\cdot K_{extraction}$ $I_{H^-}(\tau_i) \propto \left(\frac{V_{peak}\sin\tau_i}{d_{IS\_puller}}\right)^{3/2}$
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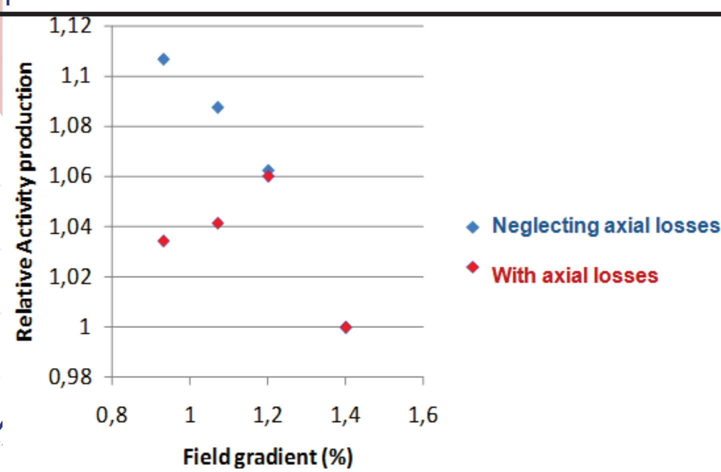
▪ Phase excursion	▪ To maximize phase excursion	▪ Limited to avoid losses by vacuum stripping and by electric defocusing forces
▪ Field gradient	▪ Small to reduce phase shift → larger phase excursion	▪ Large for beam focusing

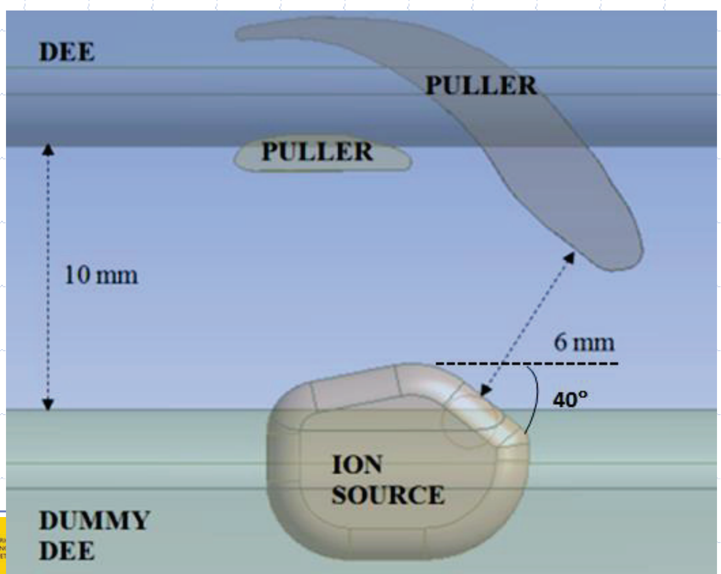


CR design

CENTRAL REGION

AMIT cyclotron

Compact machine	Internal ion source	-Beam can not be matched to the optimum conditions -Interaction with plasma geometry: uncertainty about initial beam position -Particles should save the ion source → limited size -Slit aperture: limited by electric defocusing forces and radial miscentering
Compact machine	Superconducting machine	- Small orbit radius in first turns → very compact design (mechanical effort) - Puller should be located very close to the ion source to result in high energy gain and therefore get enough available space for the ion source
Classical cyclotron	High peak voltage	-Required not only to result in high output beam energy, but also to increase the energy gain in the first turn → available space for IS -As result of the high magnetic field and peak voltage, high electric fields will be obtained in the central region - Careful design of IS-puller gap
Classical cyclotron	Weak focusing forces	-Small magnetic focusing forces. Electric focusing forces are very important at low energy and phase acceptance should be chosen to optimize them



- **Longer first half turn:** The ion source and puller are offset by about 40º from the Dee edge → the first half turn is lengthened from the usual 180º to 220º → particles are accelerated on the decreasing side of the Dee voltage after one half turn
  - High difficult related to the phase dependent effect and the long acceleration time with negative phases

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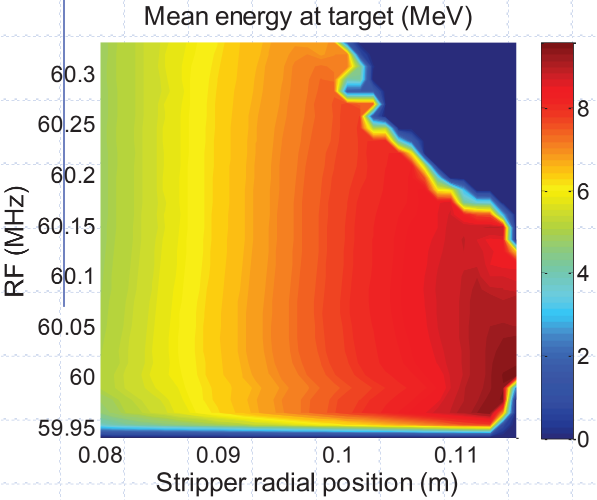
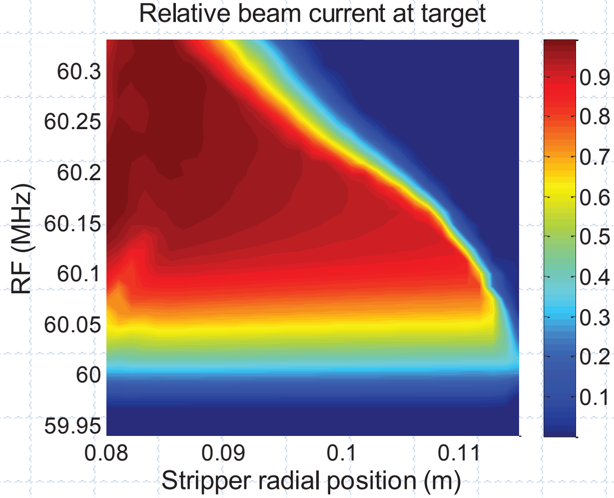
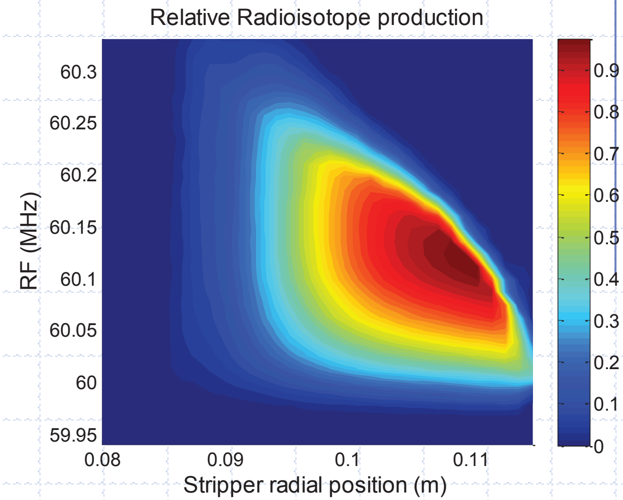
Cyclotron tuning: RF frequency and stripper location

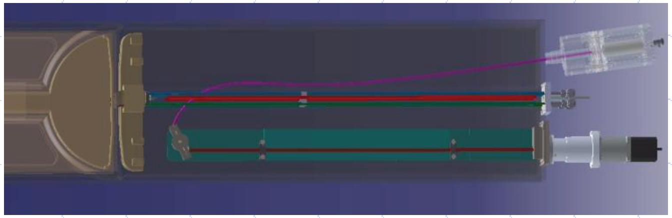
Effects of beam tuning (RF frequency and stripper location) on the mean energy and relative current at and the impact on the relative radioisotope production

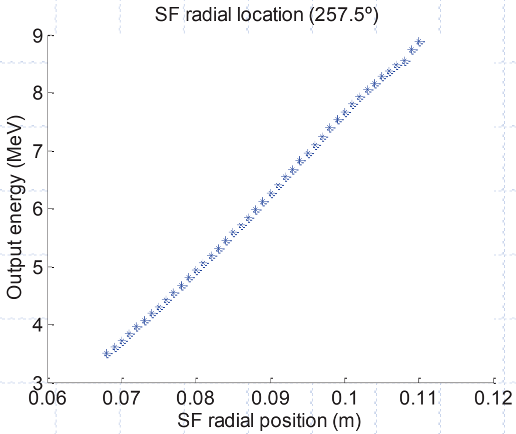


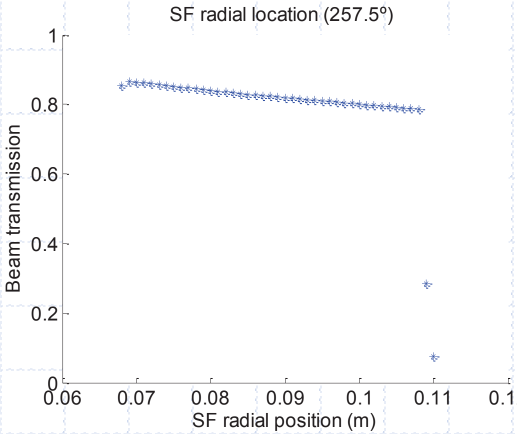


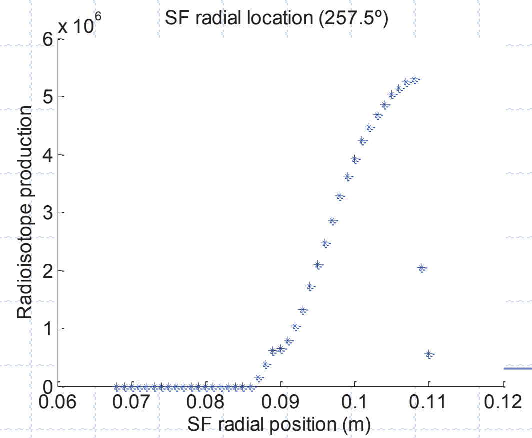


- ❑ For **a given RF frequency** (60.1 MHz) as the stripper is located at higher radius, the mean energy increases whereas the output beam current is slightly reduced by vacuum stripping losses, being the beam fully lost if we move to very large radius.

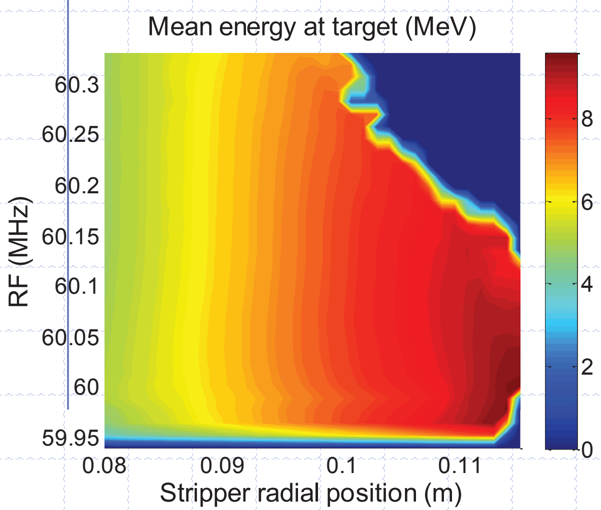


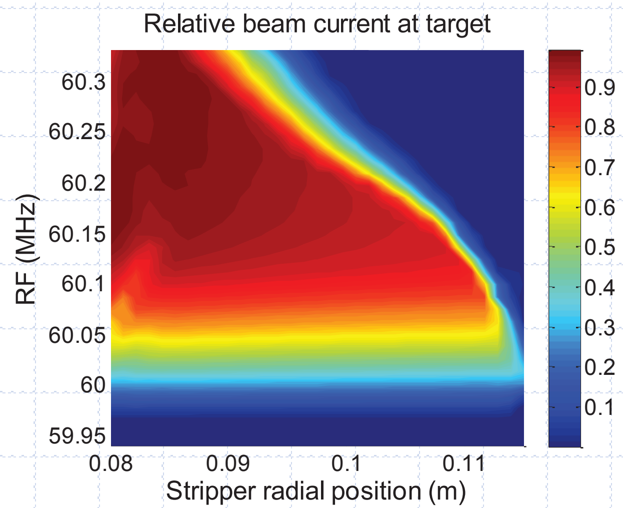


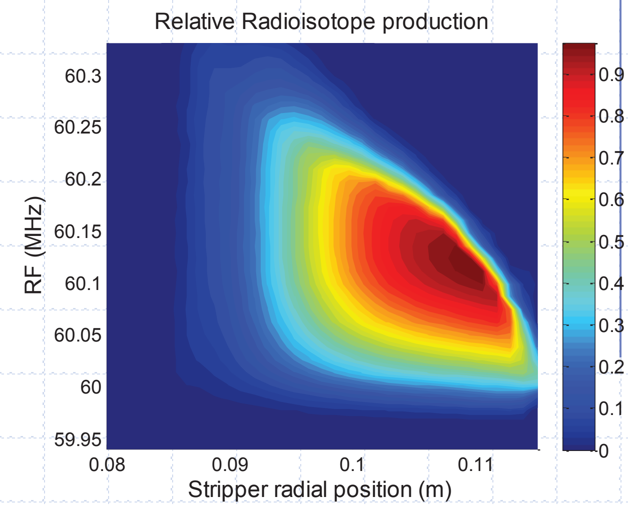




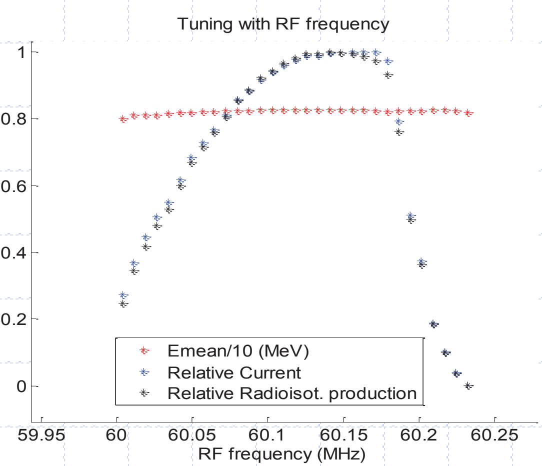
Cyclotron tuning: RF frequency and stripper location



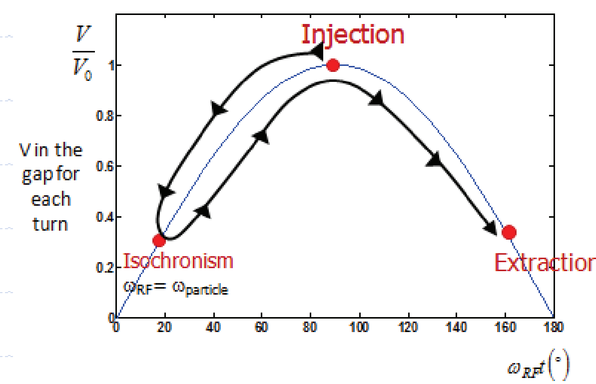




Fixed SF radial position



- Output energy fixed by the SF location (only mean energy of particles arriving at target)
- Optimum RF frequency resulting in maximum radioisotope production
- For higher RF frequencies, synchronous point is reached very early → some particles do not achieve enough energy to get the SF
- For lower RF frequencies, synchronism occurs later→ longer number of turns → higher stripping vacuum losses
- For much lower RF frequencies, some particles are decelerated before reaching the synchronous point



Conclusions

- Classical cyclotrons can be used as simple machines for compact cyclotrons producing radioisotopes
- Main drawback: the high required peak voltage in combination with the high B
- A careful design of the central region is needed to control electric field peaks and to achieve optimum initial beam conditions for the further acceleration
- An optimum RF frequency-stripper location tuning should be performed to get the maximum energy-current resulting in the optimum radioisotope production
- AMIT cyclotron is in the manufacturing phase

Many thanks for your attention!!!

C. Oliver, P. Abramian, B. Ahedo, P. Arce, J.M. Barcala, J. Calero, E. Calvo, L. García-Tabarés, D. Gavela, A. Guirao, J.L. Gutiérrez, J.I. Lagares, L.M. Martínez, T. Martínez, E. Molina, J. Munilla, D. Obradors, F. Olivert, J. M. Pérez, I. Podadera, E. Rodríguez, L. Sánchez, F. Sansaloni, F. Toral, C. Vázquez

concepcion.oliver@ciemat.es