The production of ^{9}C beam in the Secondary Beam Line at HIMAC and its potential application in cancer therapy

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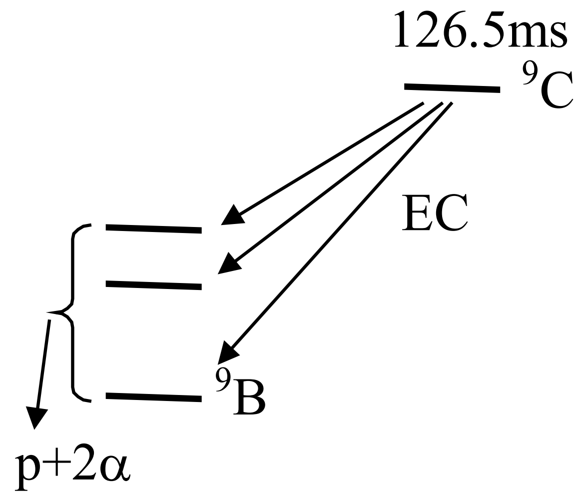
- **Advantages of ^{9}C beam**
- **Experimental setup**
- **Production rate and purity**
- **Momentum distribution under the optimal condition**
- **Uniform irradiation field made by the wobbling magnets**
- **Conclusion**

Advantages of ^{9}C beam

decay scheme of ^{9}C nuclide



decay mode: EC-delayed particle emission

emitted particle energy: 2.9MeV for alpha particles
(range in water 18μm)
3.5~12.3MeV for protons
(range in water 192μm~1.73mm)

Advantages of ^9C beam

characteristics of the emitted particles:

- action range of the emitted particles are confined in a limited region
- the emitted particles have large RBEs due to their low energies

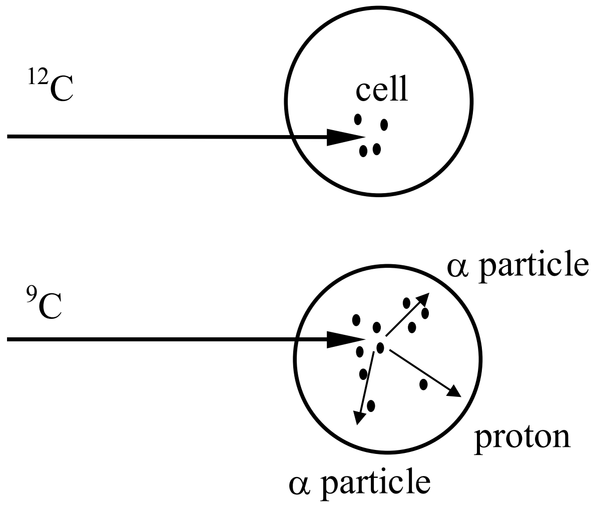
advantages of ^9C beam:

- enhance the cure efficacy of heavy ions by increasing the cell-killing rate
- reduce the damage of heavy ions to normal tissue at the entrance channel

^9C beam = external heavy-ion radiation + internal particle radiation
a double radiation source

Advantages of ^{9}C beam

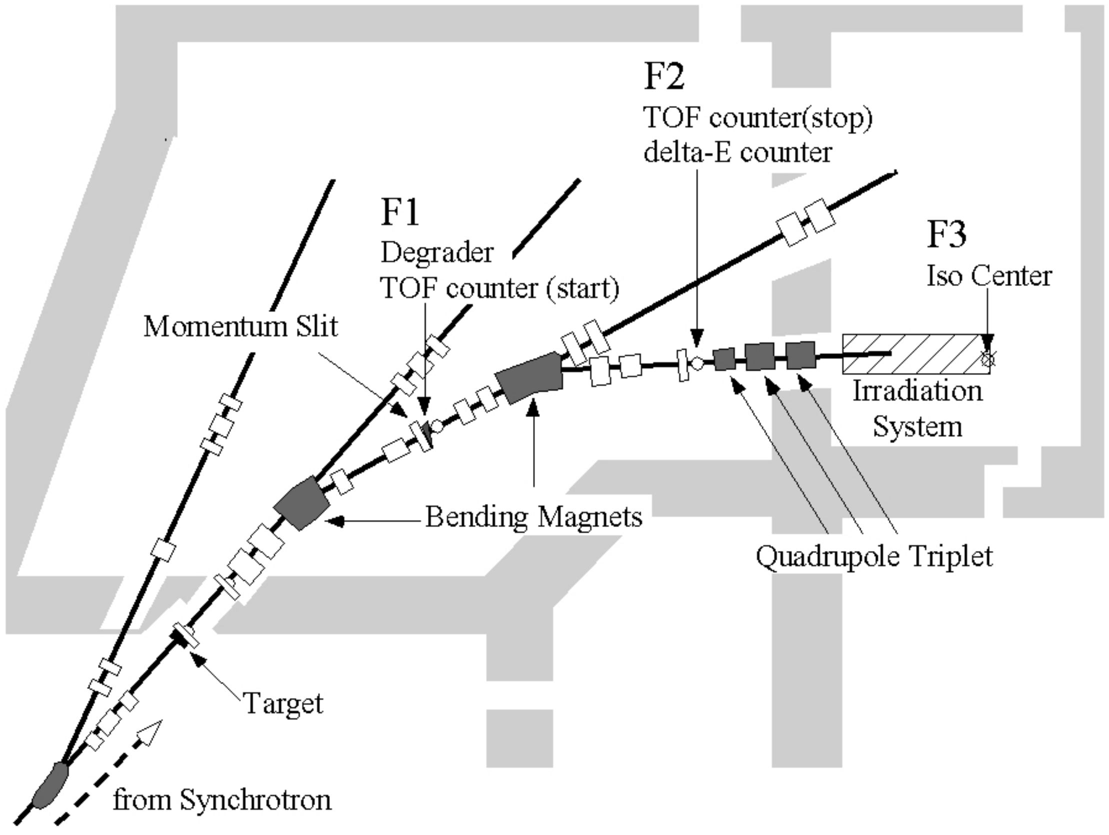
Comparison of ^{12}C with ^{9}C



Up to 23% extra biological effect (cell killing) can be caused by the emitted particles (*Q.Li, et al. Phys Med Biol. 48, 2003:2971~2986.*)

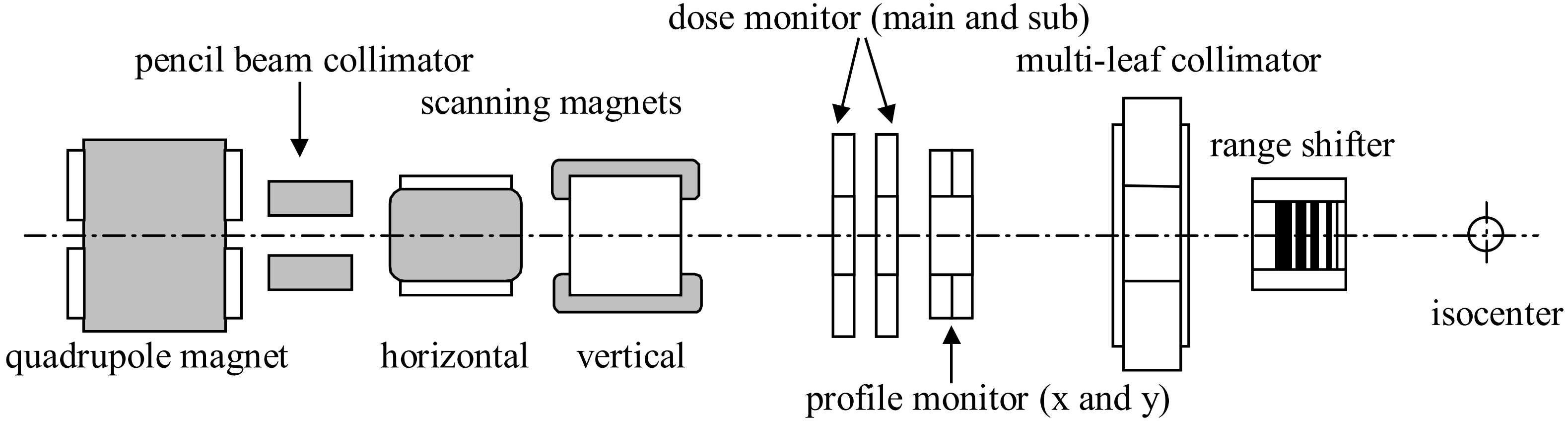
Other potential β-delayed particle decay beams: ^{8}B, ^{8}Li
(double radiation sources in oncology radiotherapy)

Experimental setup



The layout of the Secondary Beam Line at HIMAC

Experimental setup



The irradiation system in the SBL

Experimental setup

measurement method

- production rate and purity with TOF-ΔE counters and a SEM
  TOF start counter: a 0.5mm thick plastic scintillator
  TOF stop counter: a 0.5mm thick plastic scintillator
  10m flight distance
  ΔE counter: a silicon semiconductor detector of 0.3mm in thickness
  SEM: a secondary emission monitor
  to count the total particles of the primary beam

- irradiation field uniformity with a PSD detector
  PSD: position-sensitive semiconductor detector
  0.5mm thick silicon detector (Hamamatsu Photonics S5378-03)

Experimental setup

making irradiation field

With the scanning magnets, operating in the wobbler mode, in the irradiation system of the SBL, beams could be expanded laterally. Because of the relatively large beam spot and low intensity for the produced ^{9}C beam in the SBL, no scatterer was used in making uniform irradiation field in combination with the wobbling magnets

Results — production rate and purity

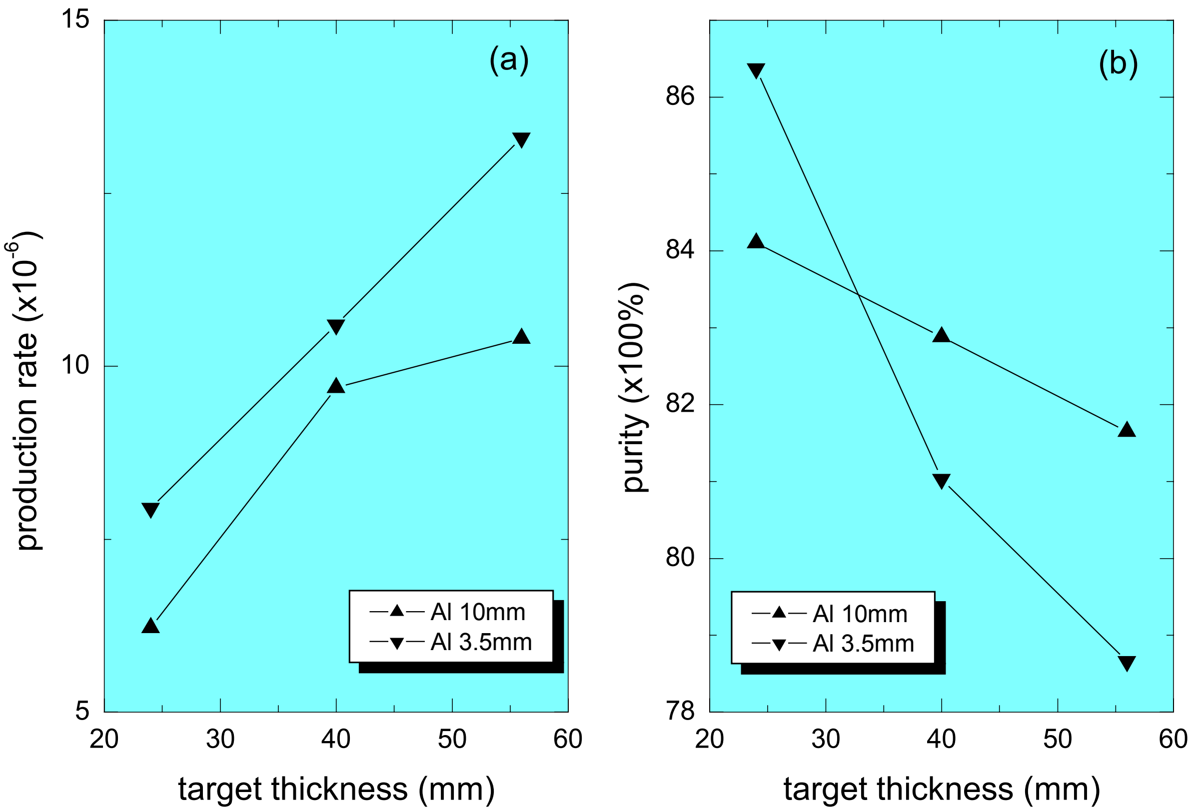
In order to produce a ^{9}C beam in the SBL with higher production rate and purity, different targets and degraders were tested.

Production target: Beryllium - 24mm, 40mm, 56mm in thickness
Degrader: Aluminum - 3.5mm, 10mm in thickness

Using each combination of these targets and degraders, the production rate and purity of produced ^{9}C beam were measured at the full momentum acceptance of 5%. In each measurement, the magnetic rigidities of the ^{9}C ions in the bending magnets were respectively changed with a step of 0.5% in order to obtain a largest production rate or highest purity in that case.

Results — production rate and purity

The maximum production rates and the corresponding purity under different combinations of the targets and degraders



Conditions:

- 56mm thick target
- 3.5mm thick degrader

Production rate:

- 1.33×10^{-5}

Purity:

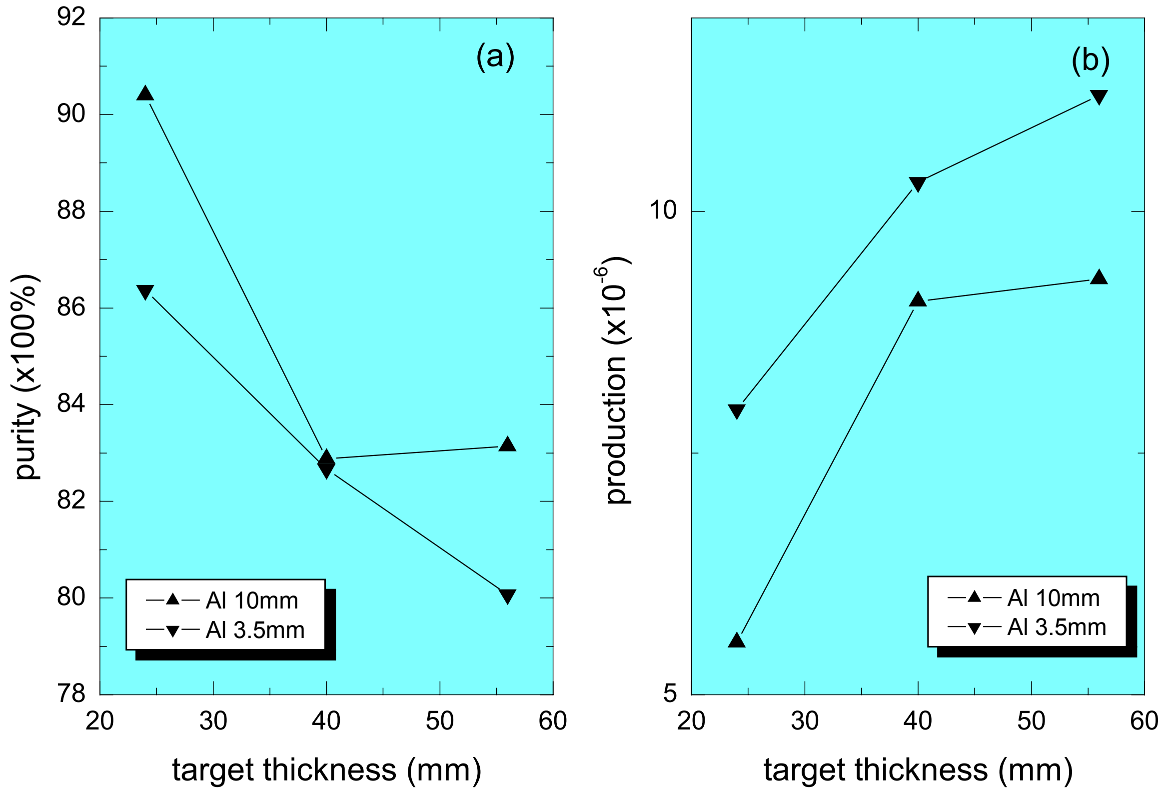
- 78.66%

Result:

- largest production rate but lowest purity

Results — production rate and purity

The maximum purity and corresponding production rates under different conditions



Conditions:
- 24mm thick target
- 10mm thick degrader

Production rate:
- 5.54×10^{-6}

Purity:
- 90.4%

Result:
- highest purity
- but smallest production rate

Results — production rate and purity

The best condition to produce a ^{9}C beam with higher production rate and purity:

target thickness 40mm

degrader thickness 10mm

Under this condition:

production rate = 9.07×10^{-6}

purity = 82.88%

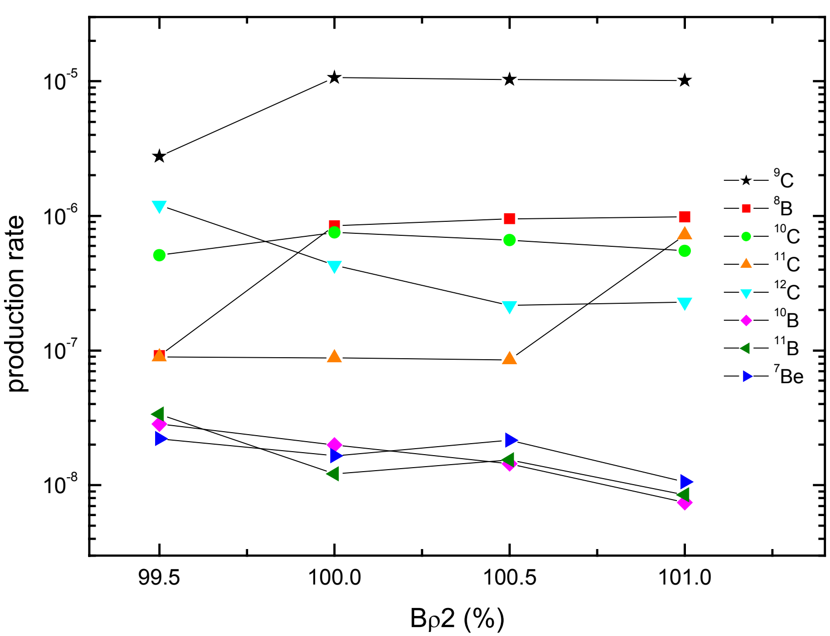
Main contamination in the produced ^{9}C beam:

^{12}C(3.00%), ^{10}C(3.13%) and ^{8}B(8.72%) ions

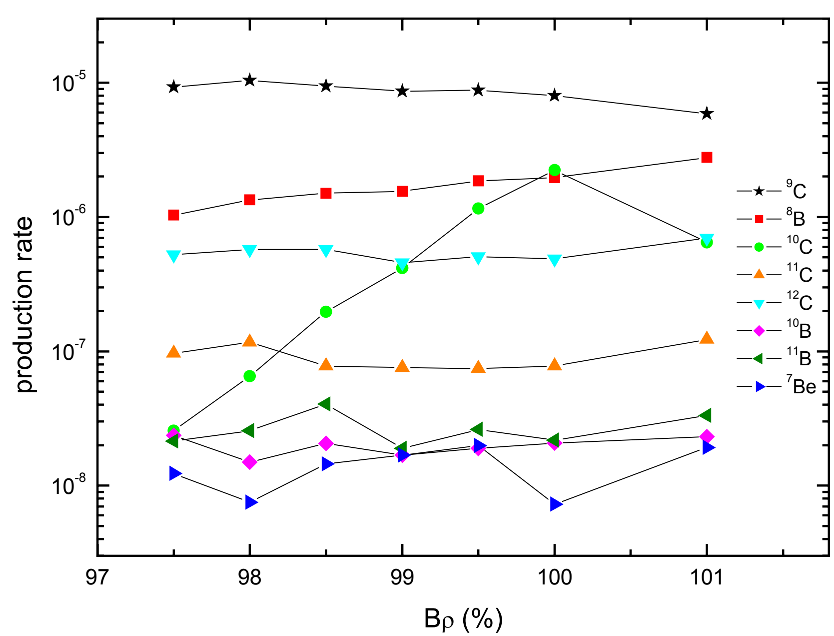
Results — production rate and purity

Examples of ion spectra in the produced ^{9}C beams under different conditions

Bρ=98.5%, Be=40mm, Al=3.5mm, momentum acceptance=5%

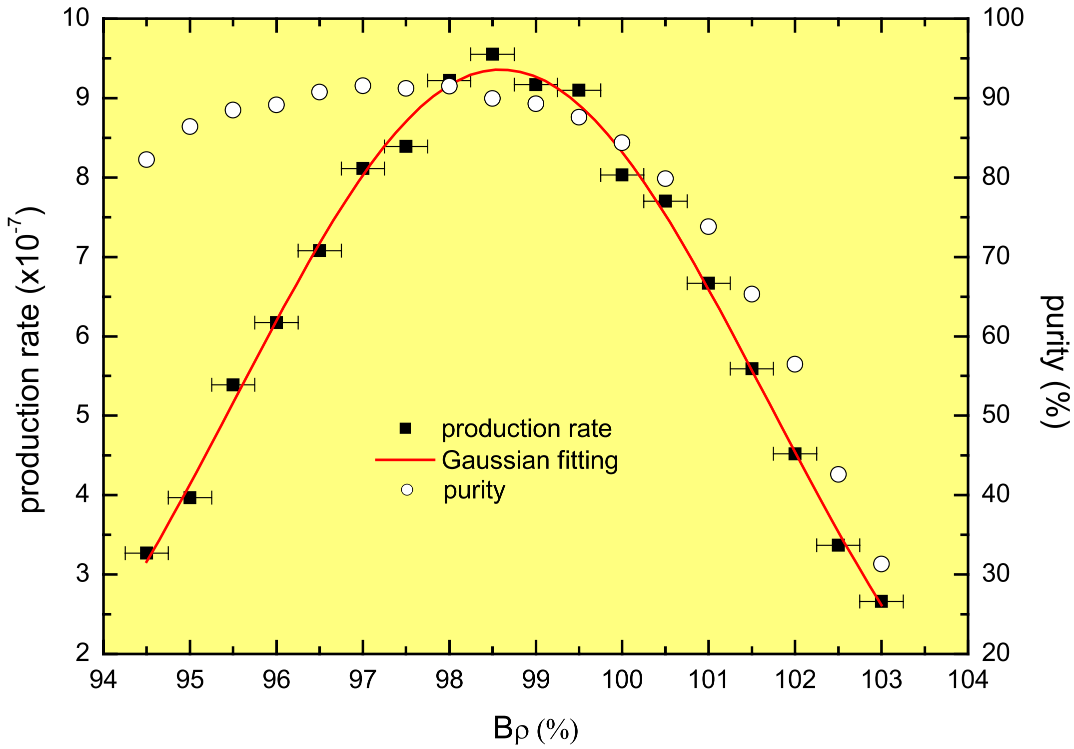


Bρ2=100%, Be=56mm, Al=10mm, momentum acceptance=5%



Results — momentum distribution

Momentum distribution under the optimal production condition

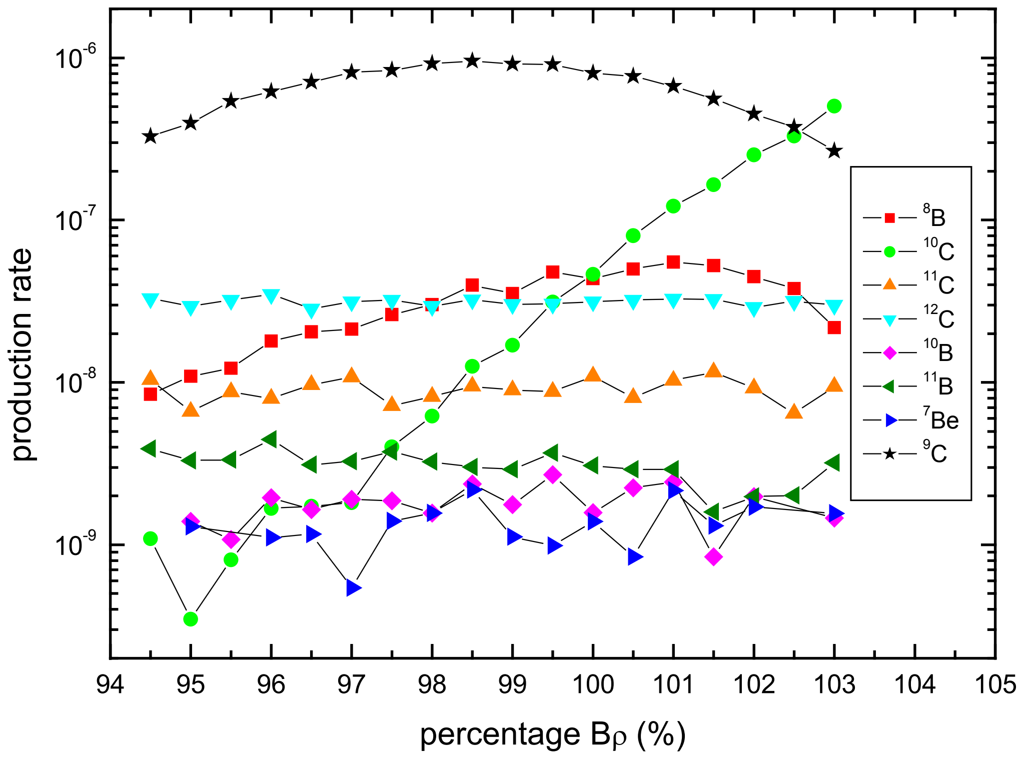


Profile:
nearly Gaussian

Maximum component:
Bρ= ~98.5%

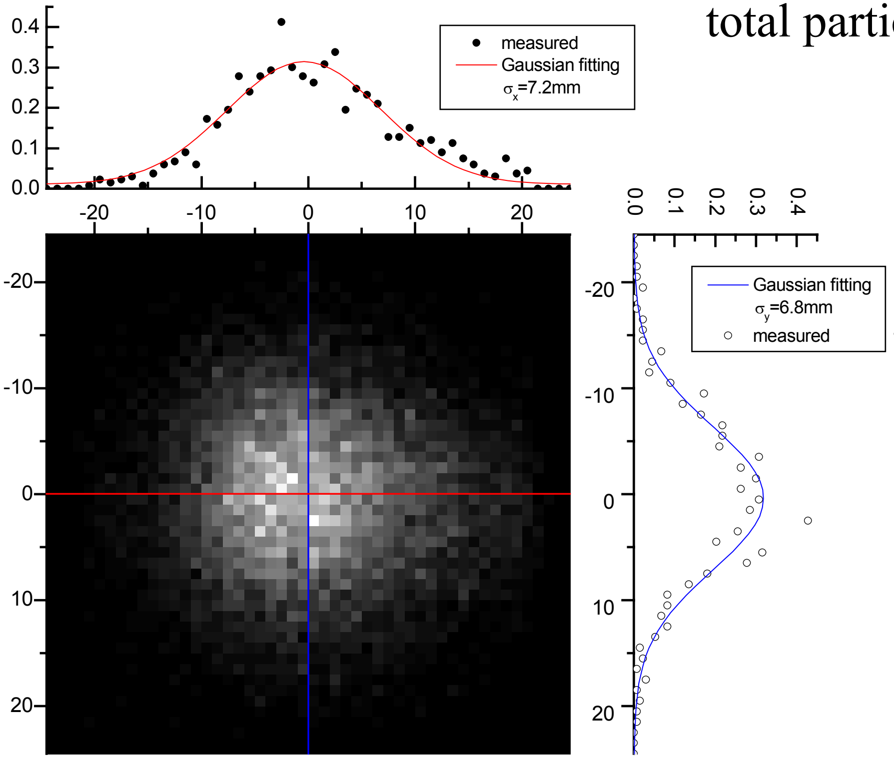
Results — momentum distribution

Ion spectra in the ^{9}C beam produced under the optimal condition

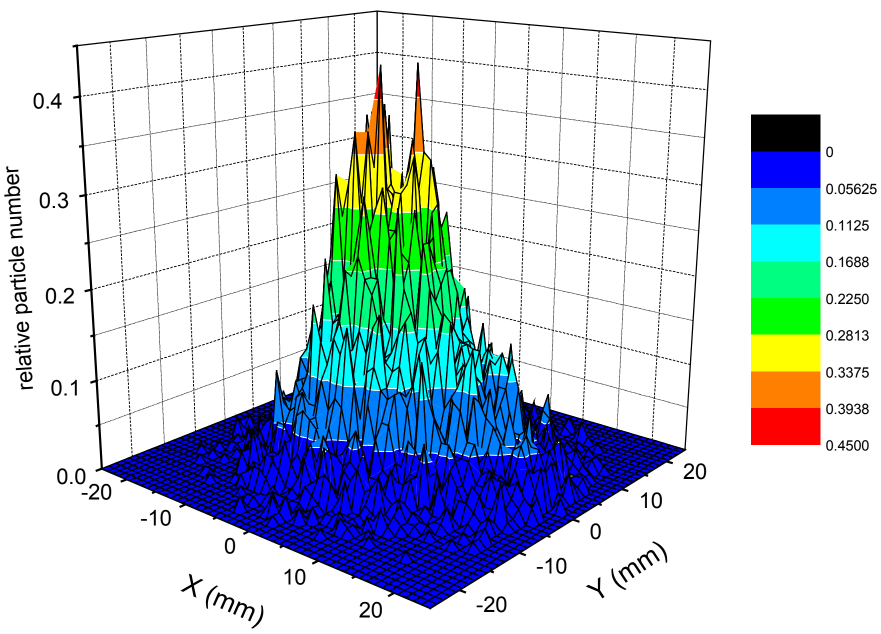


Results — uniform irradiation field

Before using the wobbling magnets a nearly Gaussian beam spot was obtained by tuning the quadrupole magnets in the SBL (total: σ_x=7.2mm, σ_y=6.8mm)

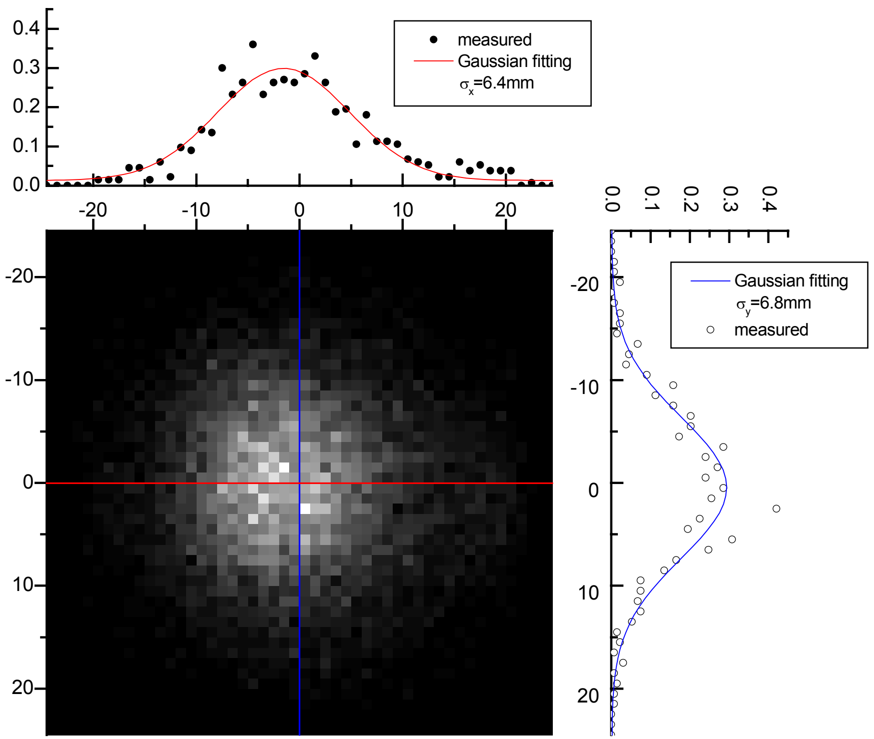


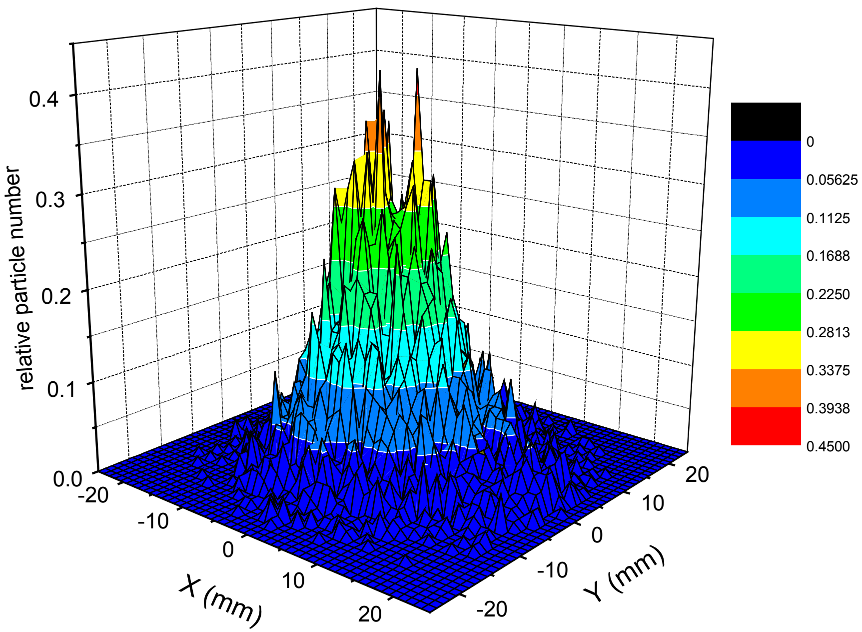
total particle distribution



Results — uniform irradiation field

^{9}C ion lateral distribution (σ_x=6.4mm, σ_y=6.8mm)

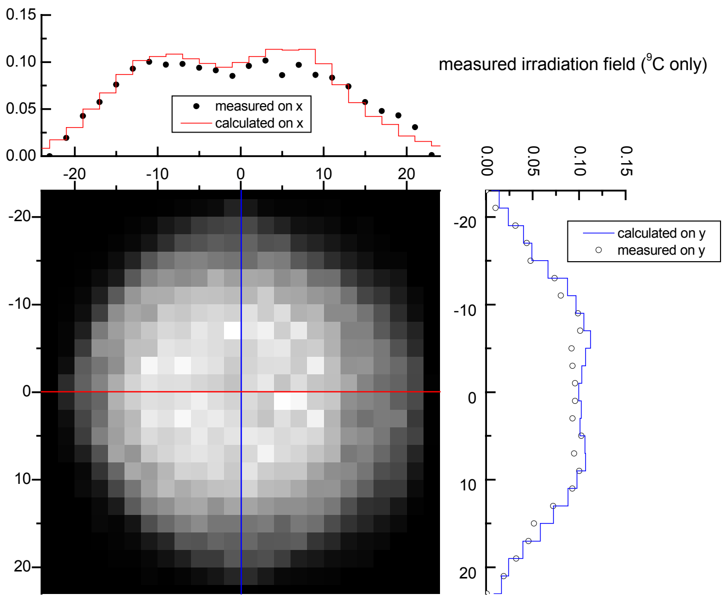


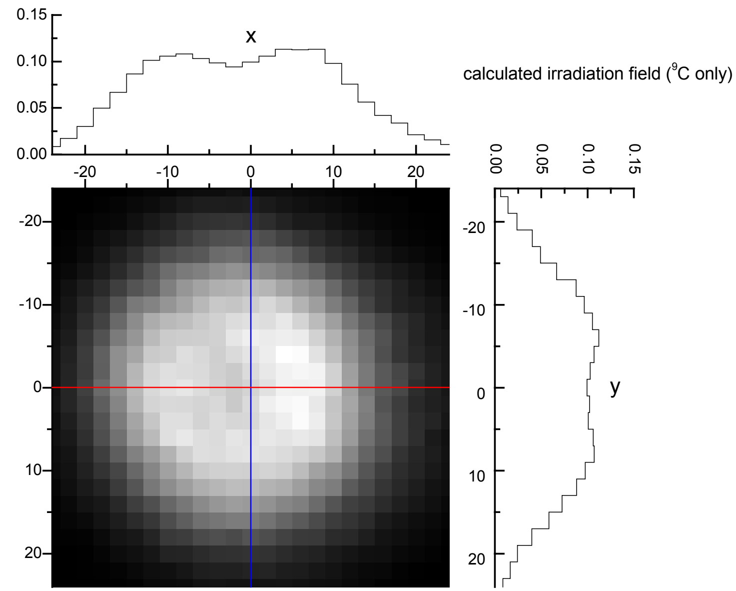


Results — uniform irradiation field

Using the wobbling magnets (horizontal: 36.8A; vertical: 50.3A)

measured (^{9}C events) calculated (^{9}C events)



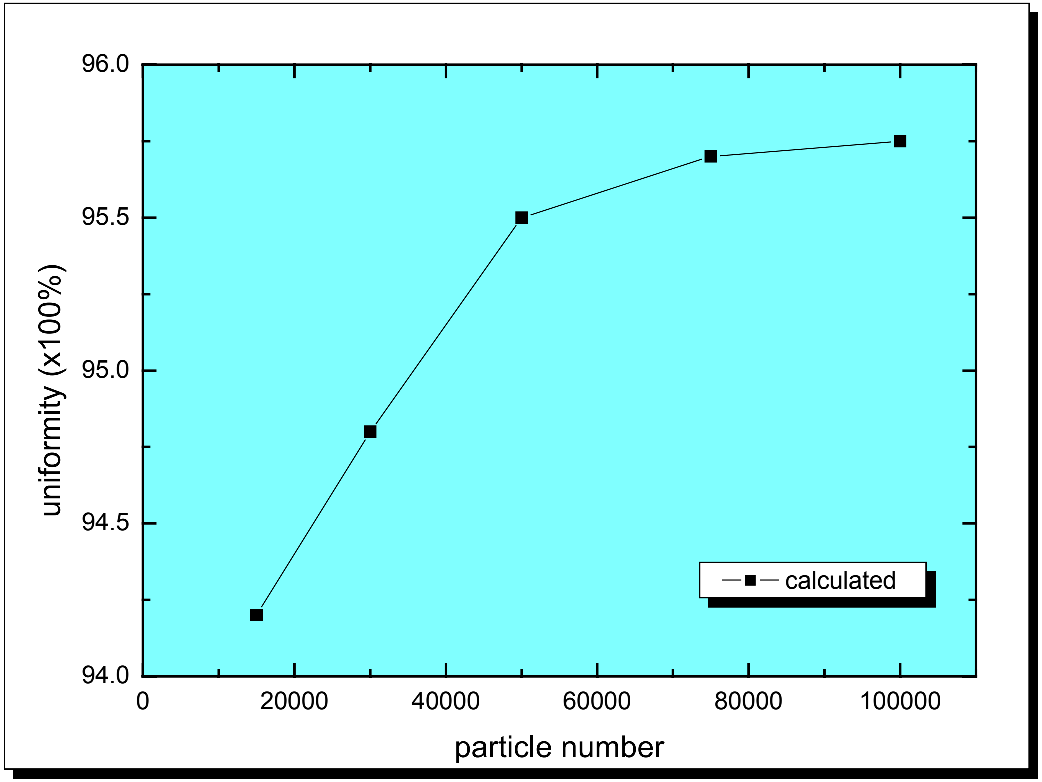


uniformity 93.8% 94.2%

(inside the central region of 20mm diameter)

Results — uniform irradiation field

Further calculation shows the uniformity of the irradiation field increases with the number of the particles counted by the PSD



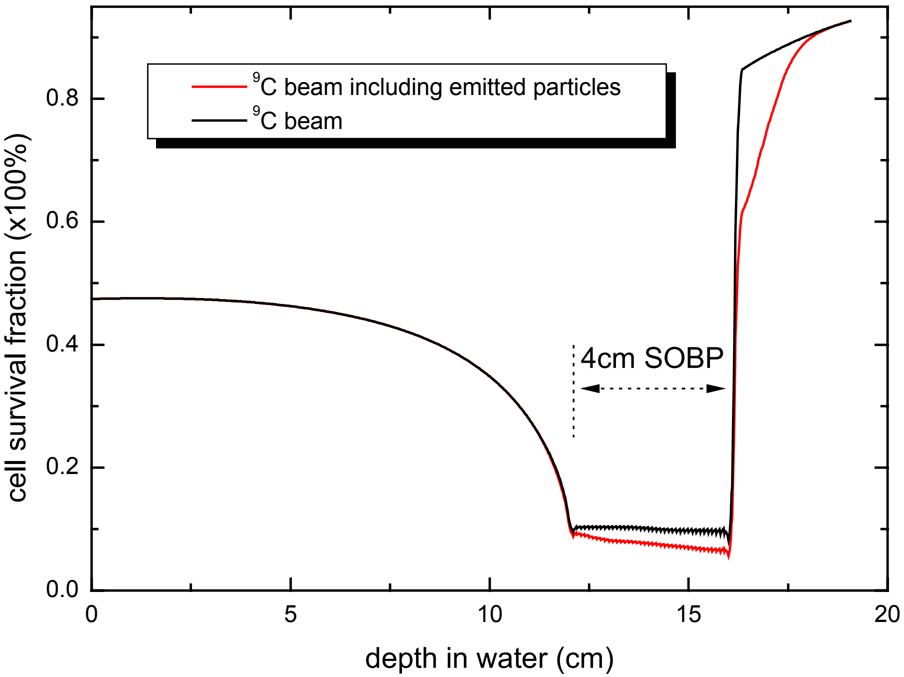
A saturated uniformity of 95.8% could be achieved when the particle number was over 80000

Considering the statistical error of about 1% in the measured data and actual particles required in the future experiment, the irradiation field is good enough to be appropriate to future radiobiological experiments

Results — uniform irradiation field

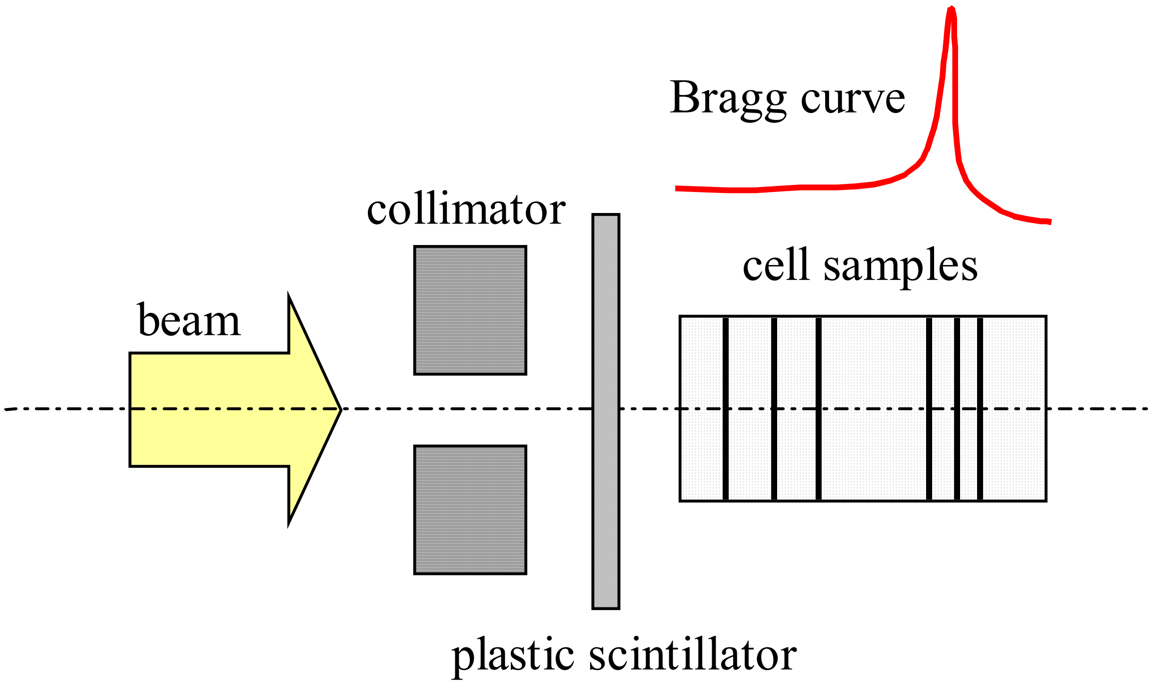
- statistical fluctuation about 1% in the measured data;
- large and detectable difference in biological effect (see right figure)

The uniform irradiation field is good enough to be appropriate to future radiobiological experiments



Results — uniform irradiation field

Radiobiological experiment with the uniform irradiation field



Dosimetry with the plastic scintillator

Conclusion

- for the first time ^{9}C beams were produced in the SBL at HIMAC;
- the optimal conditions to produce ^{9}C beam were obtained;
- production rates and purity for ^{9}C beams were measured;
- the momentum distribution was measured under the optimal conditions;
- uniform irradiation field was made with the wobbling magnets.