MID 42329

PART II:

Cyclotrons for radioisotope production

Why cyclotrons for isotope production?

- Cost-effective machines for achieving:
  - required energies (<100 MeV) and
  - high currents (< 1000 μA)
  - Constant particle revolution frequency in a uniform magnetic field => same accelerating structure used multiple times
- Compact =>
  - magnet and RF integrated into one system
  - Single stage => no injector accelerator needed
- Moderate magnetic fields up to 1 to 2 Tesla
- Simple RF system:
  - Constant RF-frequency (10-100 MHz) => CW operation
  - Moderate voltages (10-100 kVolt)
- Relative easy injection (internal ion source or axial injection)
- Simple extraction (stripping for H^- ions)

Major milestones in cyclotron development (1)

1. Classical cyclotron (Lawrence)
   - Uniform magnetic field => loss of isochronism due to relativistic mass increase => energy limited
   - CW but weak focusing => low currents
2. Synchro-cyclotron (McMillan-Veksler)
   - B-uniform but time varying RF frequency => high energies achievable
   - Pulsed operation and weak focusing => very low currents
3. The isochronous AVF cyclotron (Thomas focusing)
   - Azimuthally varying magnetic fields with hills and valleys
   - Allows both isochronism and vertical stability
   - CW-operation, high energies and high currents
   - Radial sectors => edge-focusing
   - Spiral sectors => alternating focusing

Major milestones in cyclotron developoment (2)

4. The separate sector cyclotron (Willax)
   - No more valleys=> hills constructed from separate magnets
   - More space for accelerating cavities and injection elements
   - Example PSI-cyclotron at Villingen-Switserland
   - Very high energy (590 MeV) and very high current (2 mA) => 1 MWatt
5. H^- cyclotron (Triumf)
   - Easy extraction of H^- by stripping
   - Low magnetic (center 3 kG) field because of electromagnetic stripping
   - Triumf is largest cyclotron in the world (17 m pole diameter)
6. Superconducting cyclotron: Fraser/Chalk River/Blosser/MSU
   - High magnetic field (up to 5 Tesla) => high energies at compact design
7. Superconducting synchrocyclotrons (Antaya-Wu-Blosser)
   - Very high magnetic fields (9 Tesla)
   - Very compact => cost reduction => future proton therapy machines?

Market and suppliers of 30 MeV cyclotrons

Name	country	30 MeV beam	Year of Op.
IBA Cyclone 30	Belgium	400 - 800 - 1200 µA	1986 / 2010
ACS TR-30	Canada (Triumf lab)	500 – 1200 µA	1990 / 2000
SHI HM-30	Japan	1 mA (BNCT)	2009
MCC 30/15	*Russia (Efremov inst.)*	*100 µA*	*2010*
Kirams-30	*Korea (university based)*	*500 µA*	*2007*


Cyclotron conference, ECPM , web brochures

IBA **Cyclone-30 for production of** SPECT **isotopes**

First IBA machine

30 MeV - 500 µA

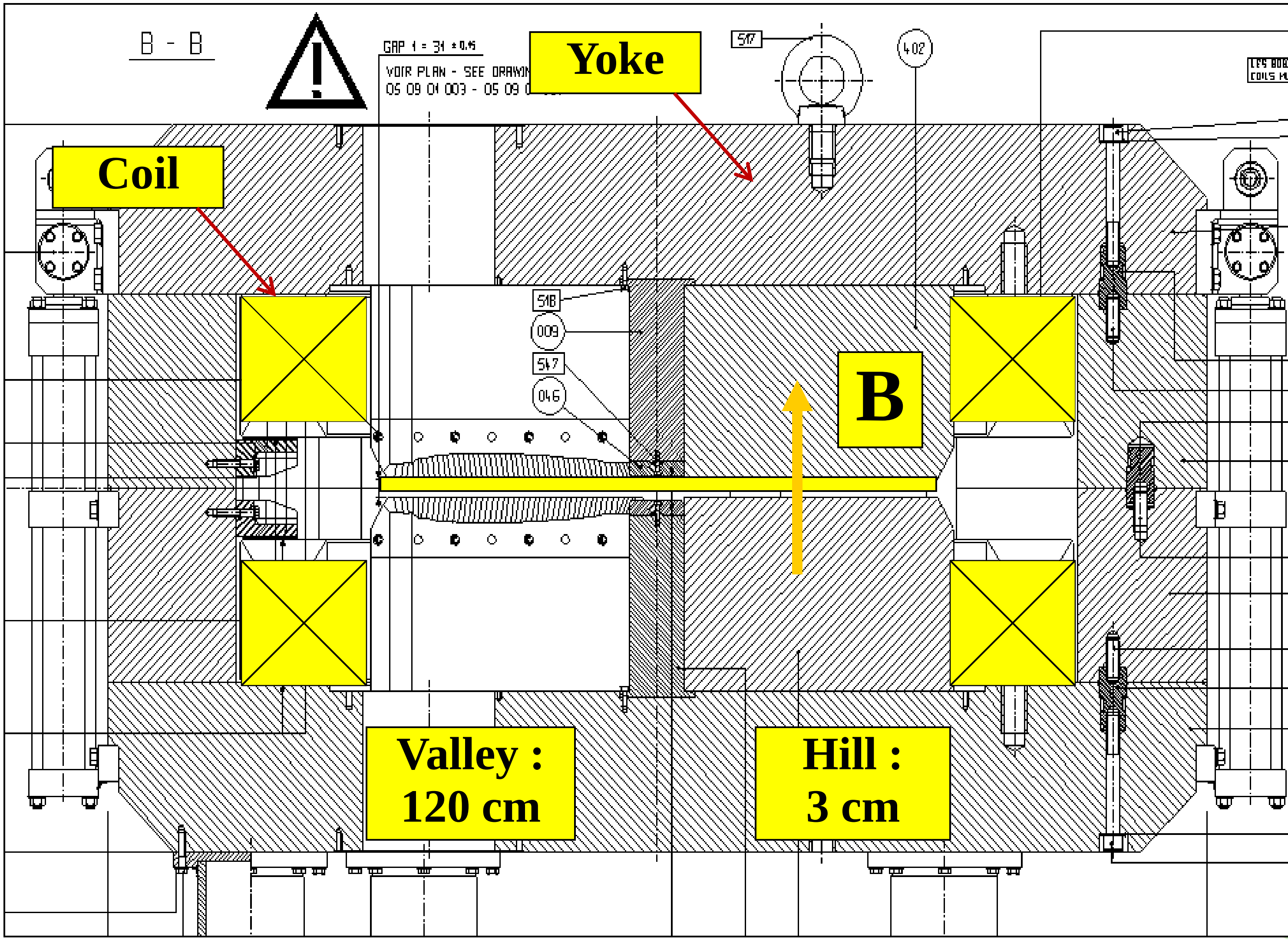
1986

Used by many (all) radiopharmaceutical producers

IBA medical cyclotrons: some general features

- Deep-valley magnetic structure
  - Strong azimuthal variation of B ⇒ Strong focussing
  - Small gap requiring low power dissipation
  - Yoke completely closed ⇒ providing some shielding
- 4-fold symmetry
  - Two accelerating structures (dees) in two valleys ⇒
  - Very compact; two other valleys for pumping, ESD….
- Acceleration of negative ions (H^- or D^-) ⇒
  - Beam extraction by stripping
  - Very easy using thin carbon foil
  - 100% extraction efficiency
- Injection from internal PIG-source (PET-isotopes) or with a spiral inflector (SPECT => cyclone 30)

Deep-valley Cyclotron Magnet Design



Extraction of the beam from the cyclotron

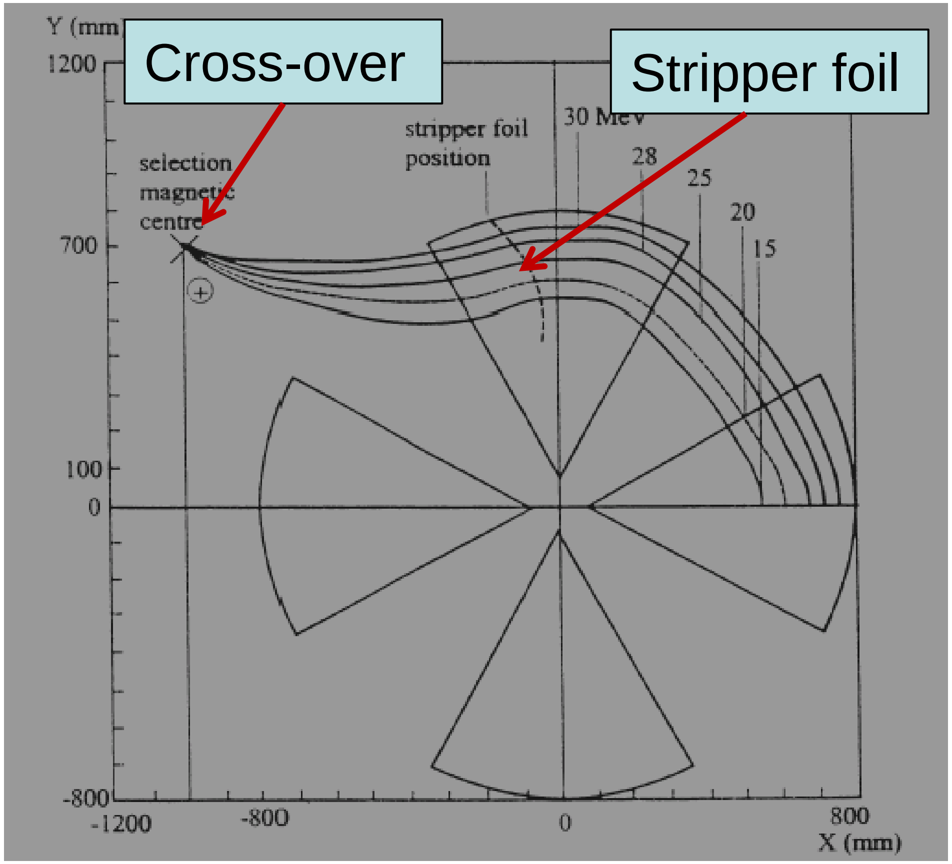
Extraction is always a major concern in cyclotrons => how to get the beam out of the magnetic field

1. No extraction at all => place an internal target
2. Stripping extraction (H^- cyclotrons)
3. Extraction with an electrostatic deflector (ESD)
   - Proton therapy cyclotrons
4. Self-extraction => suitable shaping of the magnetic field
5. Regenerative extraction => synchrocyclotron

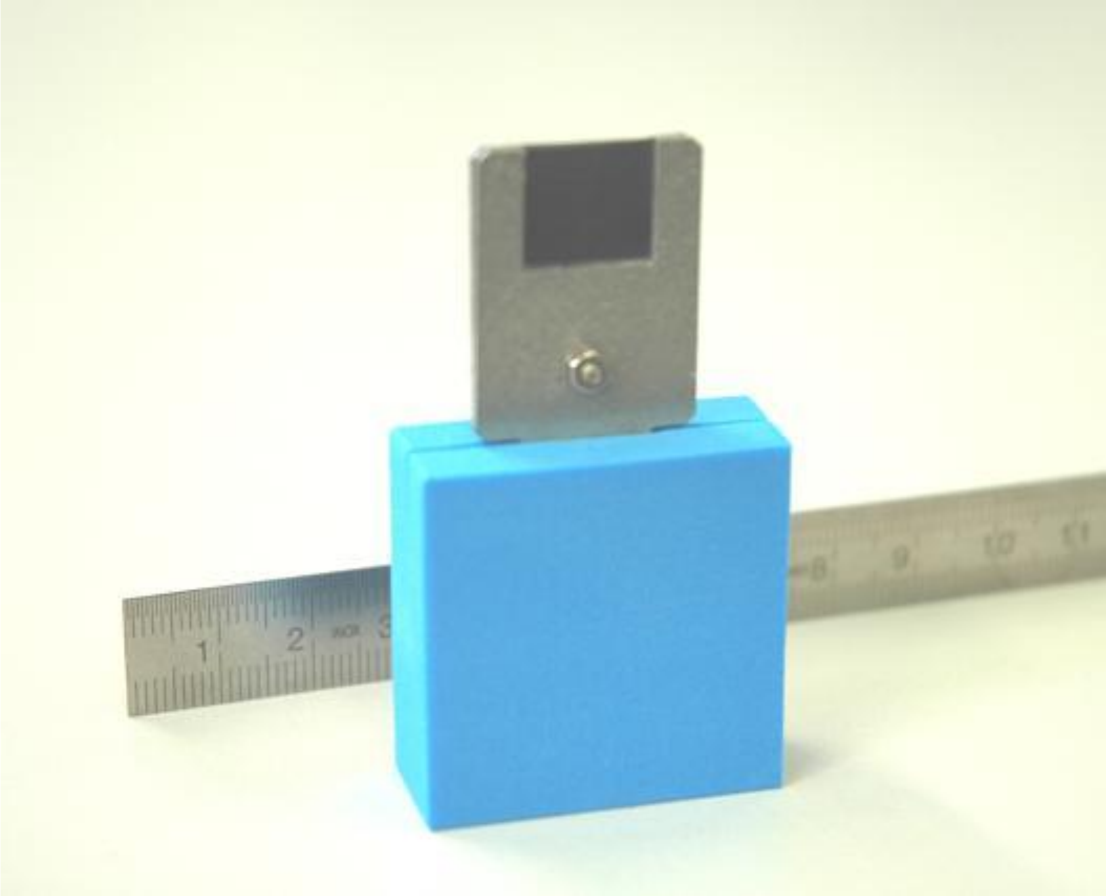
Some examples will be shown later

Extraction by stripping (Cyclone 30)

- Stripper foil removes the two electrons of the H^- ion
- Orbit curvature changes sign after stripping foil
- Simple =>high extraction yield and little internal activation
- Energy variation by moving stripper position
- All energies go to one crossover point by proper foil azimuthal position
- Place combination magnet at crossover
- Ideal solution for industrial cyclotrons



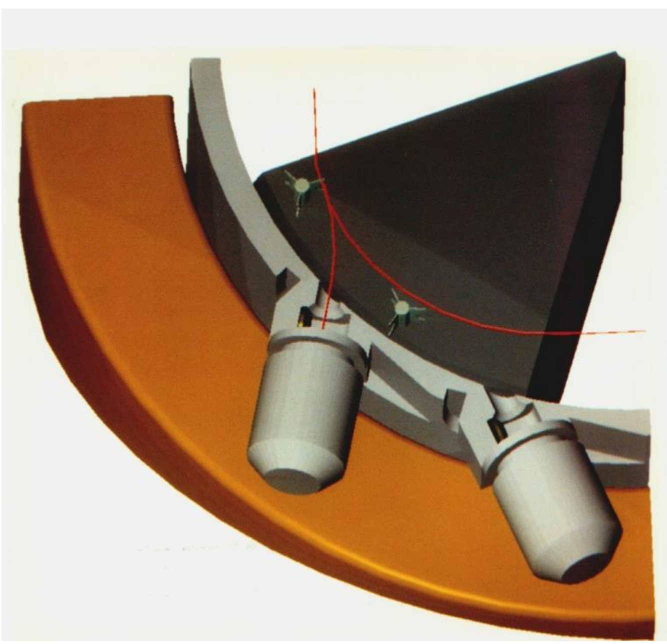
Extraction by stripping: carbon stripping foil

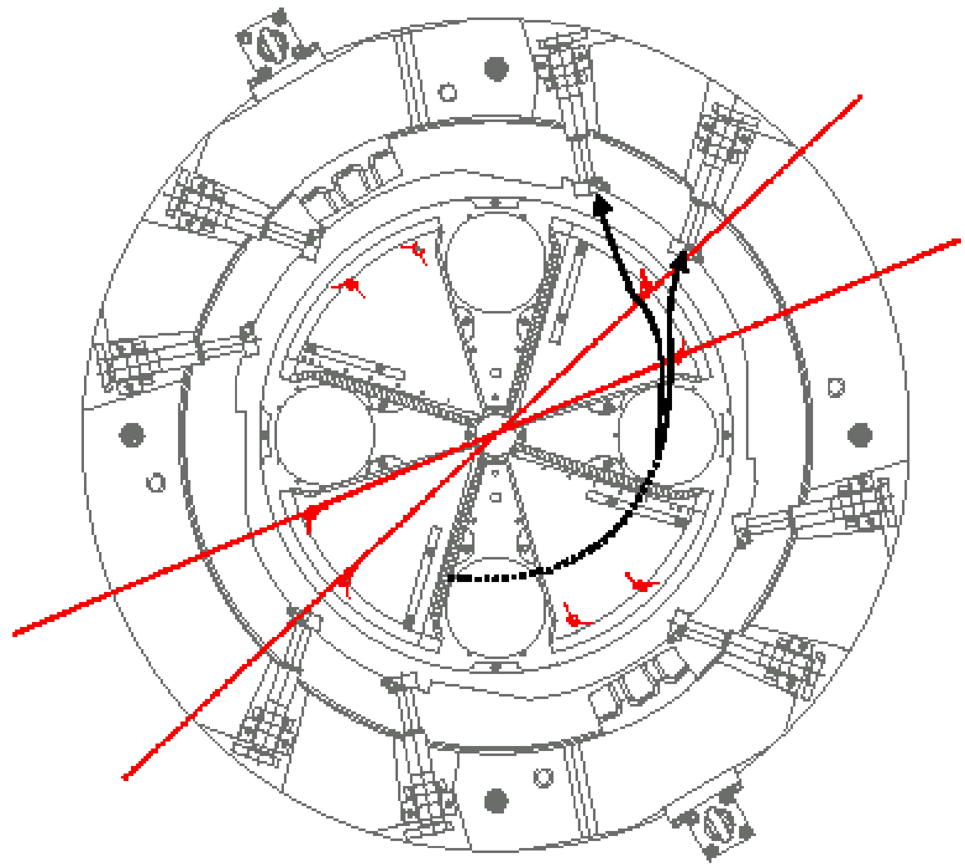


Simpler than this is not possible

Extraction by stripping (Cyclone-18/9)

- Fixed foil position => constant energy but
- Multiple extraction ports around the machine
- Dual beam capability





An Internal Ion Source

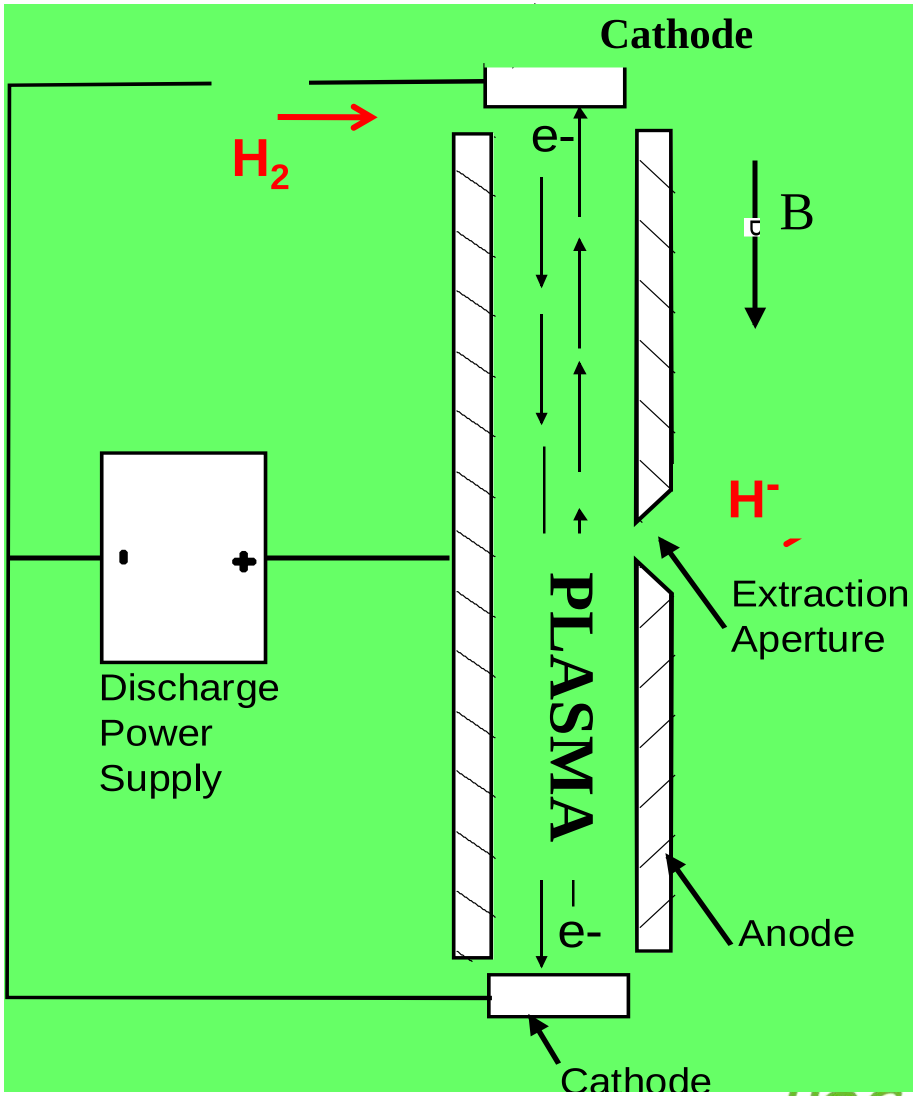
- Some advantages
  - Simple and cheap: No injection line needed
  - Compact: two ion sources can be placed simultaneously
  - Cost considerations are essential in this market

- Some limitations
  - Moderate beam intensities
  - Simple ion species (H^+,H^-,deuterons,He-3, He-4)
  - Gas-leak directly into the cyclotron (stripping of negative ions)

- Carefull CR design is needed in order to obtain good centering and focusing

Cold Cathode PIG Ion Source => how does it work

- Electron emission due to high initial electrical potential on the cathodes
- Electron confinement due to the magnetic field along the anode axis
- Electrons produced by thermionic emission and ionic bombardment
  - Start-up: 3 kV to strike an arc
  - Operating point 100V
- cathodes heated by the plasma (100 V is enough to pull an outer e- off the gas atoms)



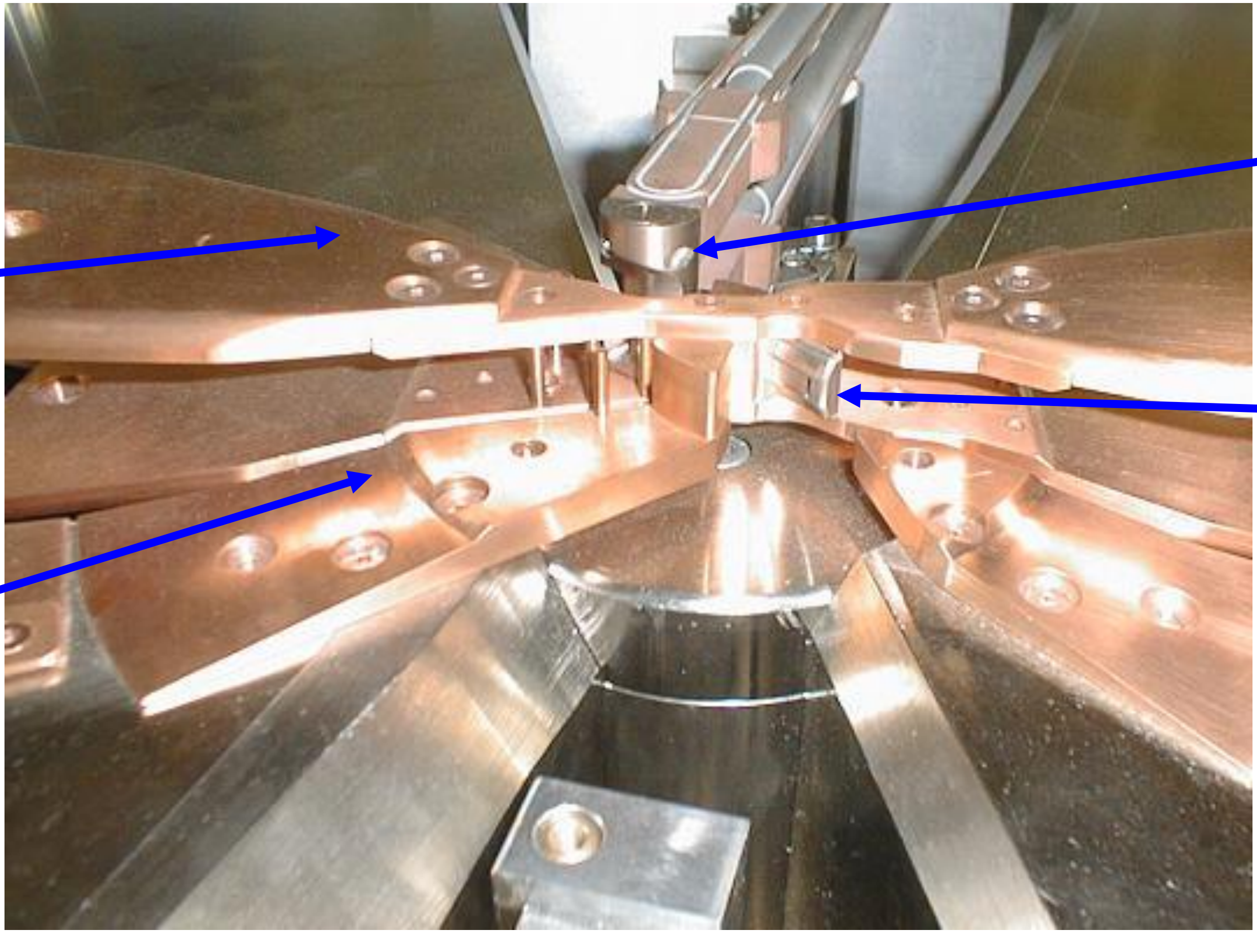
Chimney cathodes and puller

Chimney: copper-tungsten ⇒ good heat properies; machinable

Cathodes: tantallum ⇒ high electron emission (low workfunction)

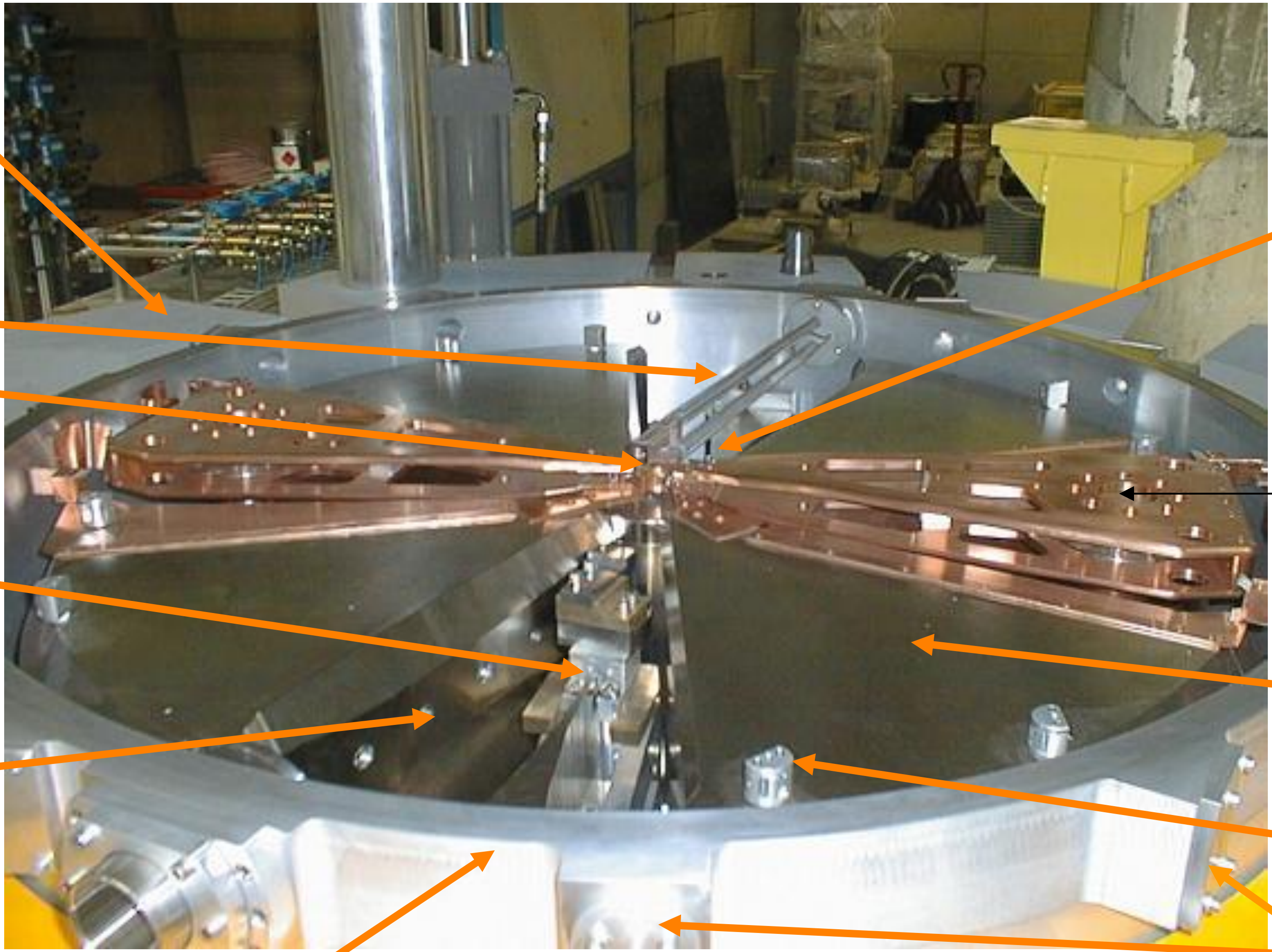
iba Particle Therapy

The cyclotron central region with an internal source



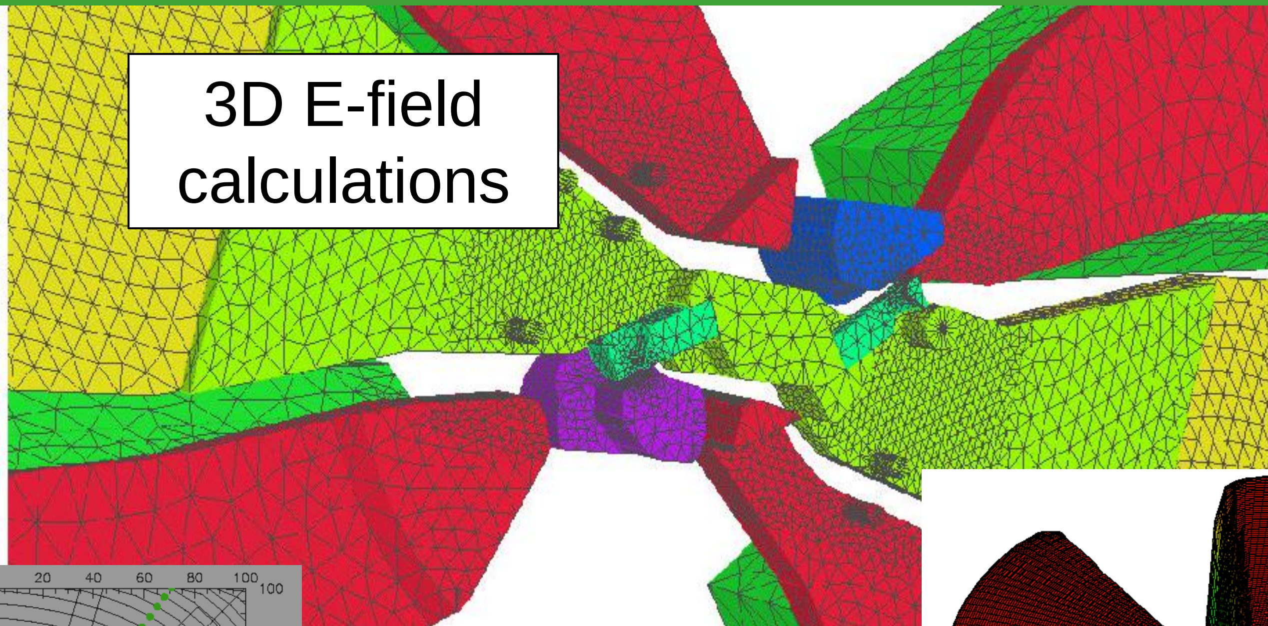
Two ion sources can be placed symmetrically

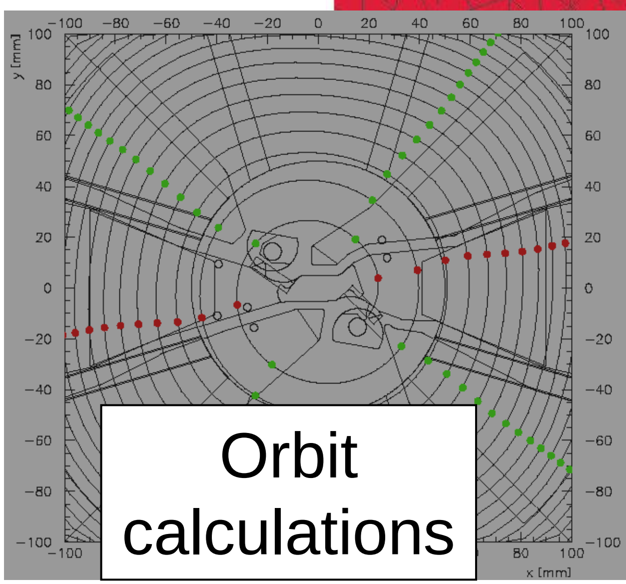
Compact Deep-valley Cyclotron Design



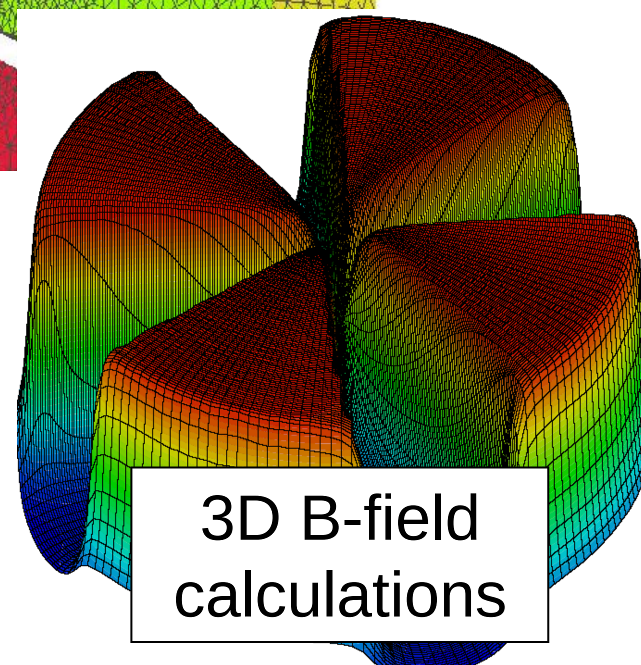
iba Particle Therapy

3D EM and beam-dynamics simulations



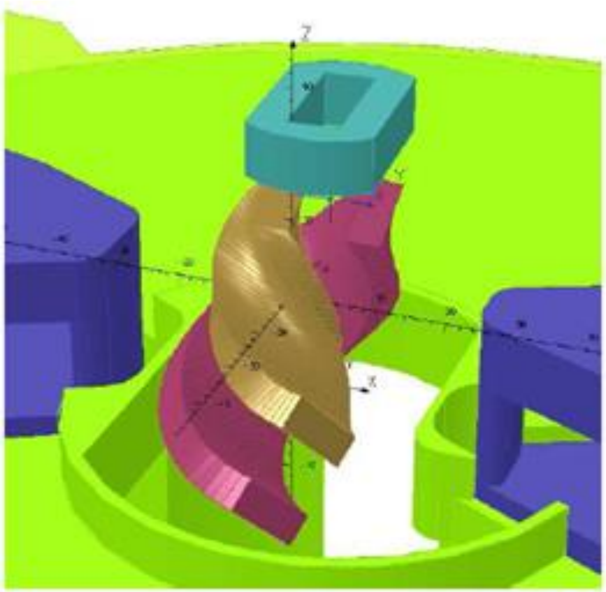


Essential in cyclotron design



External Ion Source => Axial Injection

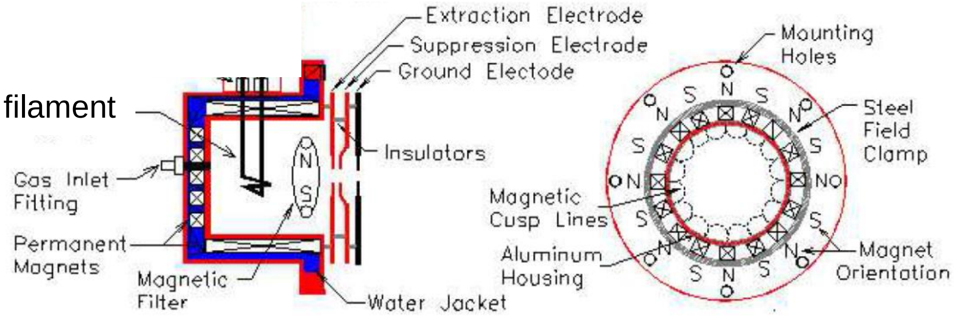
- External ion source => beam injection along the vertical axis
- Bend from vertical to horizontal with an electrostatic inflector
- Higher currents can be achieved
- More different ion species can be injected
- Better cyclotron vacuum (less stripping losses for H^{-})
- Injection line needed with buncher, lenses, diagnostics, pumping…



iba Particle Therapy

Ion source: considerations for axial injection

- H^- is a very fragile ion =>ion source requires carefull design and optimization to get good performance
- Multicusp volume ion source with special 3D magnetic field shape (permanent magnets) to maximize plasma-confinement
- A separate zone of lower plasma temperature is made with magnetic filter, where H^- can be formed and stabilized



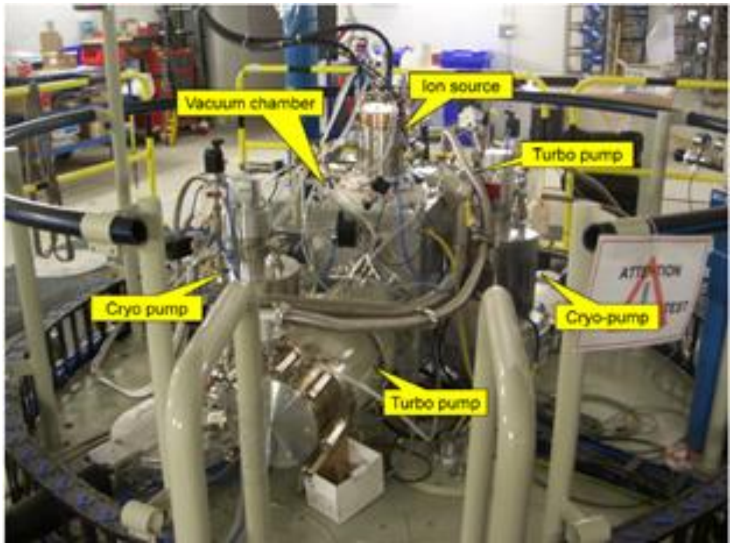
- Multiple extraction electrodes for beam divergence adjustment
- High current: 15 mA
- Good emmittance: 100 π mm-mrad (4-rms) at 30 keV

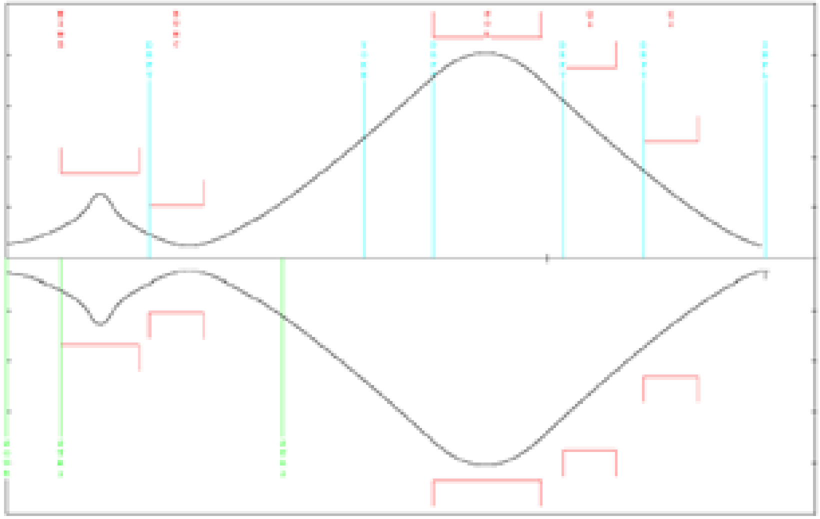
iba Particle Therapy

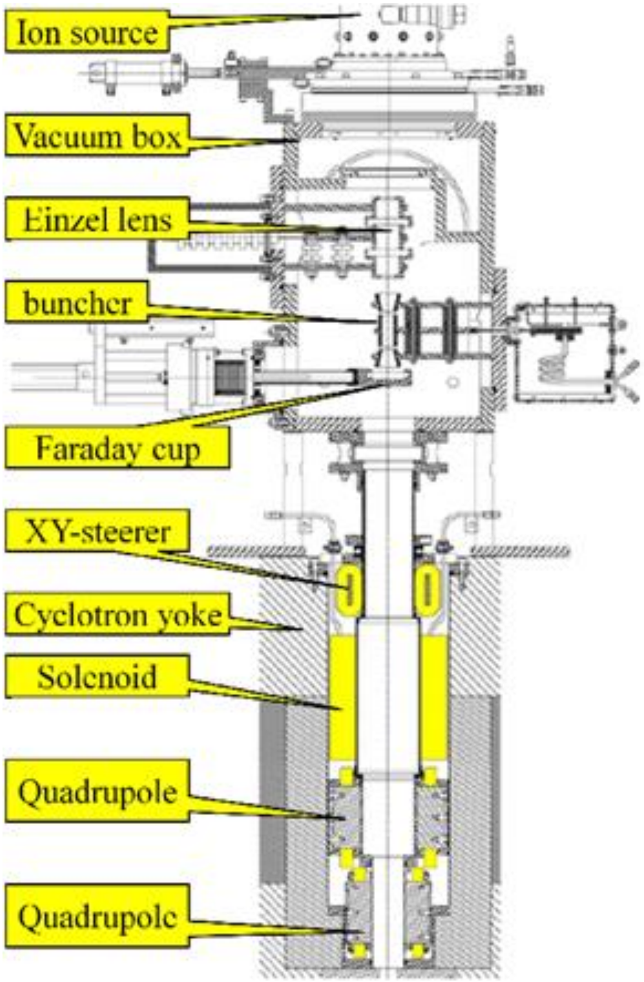
Considerations for the injection line

- Good vacuum to minimize stripping losses (H^-)
- Differential pumping to separate ion source vacuum from beam line
- Source is DC but Cyclotron is RF => matching needed
  - Bunching to increase injection efficiency
- Focusing: small beam spot at the entrance of the inflector => space charge effects
- Steering: good alignment of beam spot on inflector
- Beam diagnostics needed
- Compact (short) design to reduce stripping and space charge
  - Install several elements in the return yoke

An example of an injection line and ion source







C30-HC achieved 1.2 mA extracted beam with this injection line

Automized Magnetic Field Mapping

Precise mapping and iron pole shimming is needed in order to isochronize the magnetic field

- Move Hall-probe on a 2D polar grid to obtain a full fieldmap in the median plane of the cyclotron
- Analyse the magnetic field on equilibrium orbits in order to evaluate isochronism
- Shim the hill sectors of the iron in order to improve the isochronism (reduce RF phase slip)

iba Particle Therapy

A family of cyclotrons for isotope production

PET | PET+SPECT | Multi-purpose

30 units — C10/5

160 units — C18/9

27 + 2 units — C30-family

2 units — C70

Particle Therapy

Baby-cyclotron 11 MeV

- **11 MeV proton.. limited capacity for PET**
- **H^- (proton only) - 120 μA ~ 1300 watts**
- **Usually hospital based 18F- 11C system**

External shielding for neutrons and gammas

IBA Cyclone11

Medium energy Cyclone 18

- **18 MeV proton (9 MeV deuteron) or TWIN proton**
- **H^{--} (proton) 150 µA ~ 2700**
- D^{-} (deuteron) 50 µA
- **Access to common PET**
  - 18F
  - 11C
  - 13N
  - 15O
- **And new RI**
  - 64Cu,89Zr,124I,..
  - Also 123I solid tgt

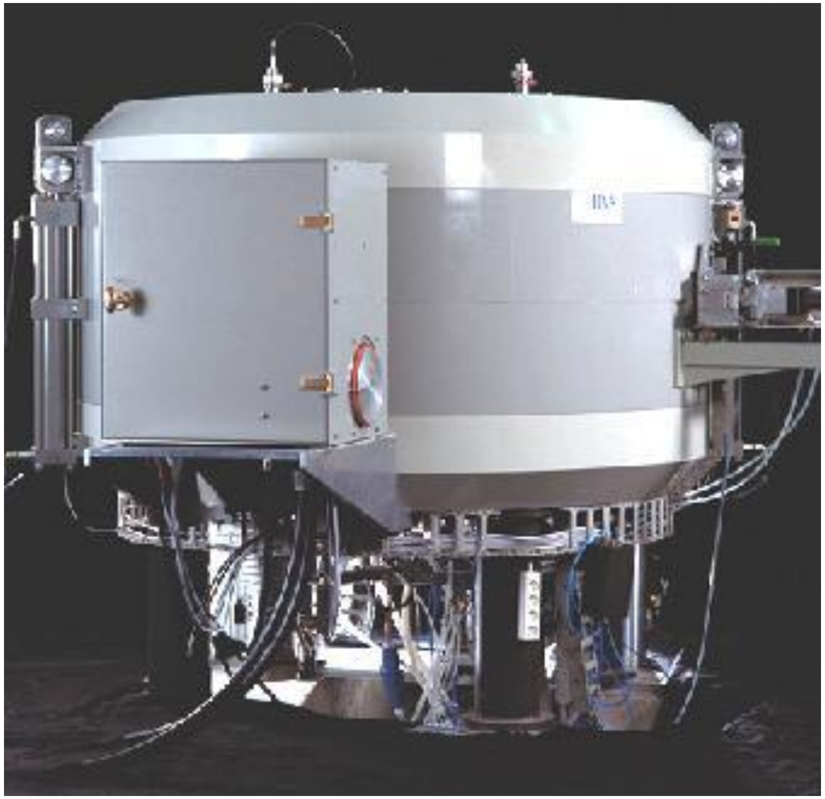
Cyclone 18 with an external beam line

More diverse target technologies for external beams

Cyclone 18+ for Pd-103 production (Brachyterapy)

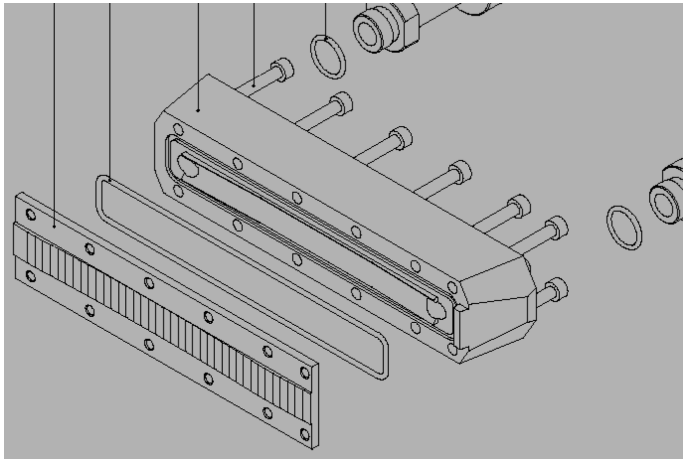
- Large doses, lower cross-section require high current operation: example
- 18 MeV p @2mA on internal target
- 14 cyclotrons in the same factory
- 30 kW of beam with 100 kW of electrical power ⇒ 30 % accelerator efficiency

$^{103}Rd(p,n)^{103}Pd$

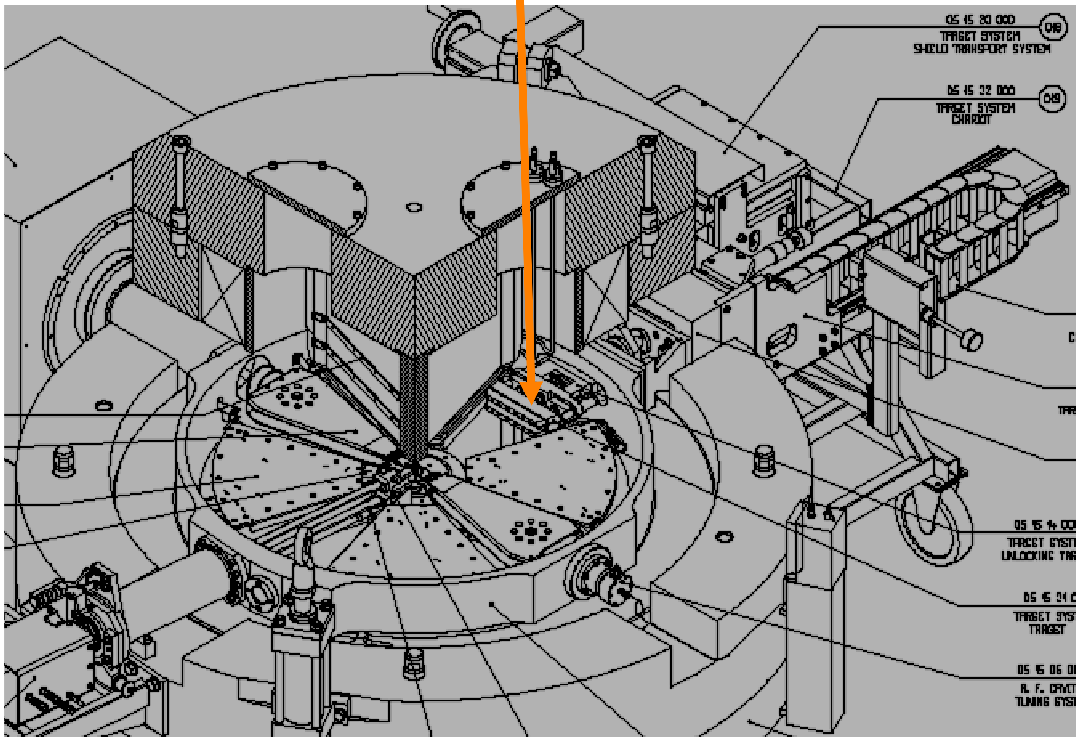


80% of the RF power is for beam acceleration; 20 % for building the accelerating field

IBA C18+ with internal target for Pd-103



Rhodium target



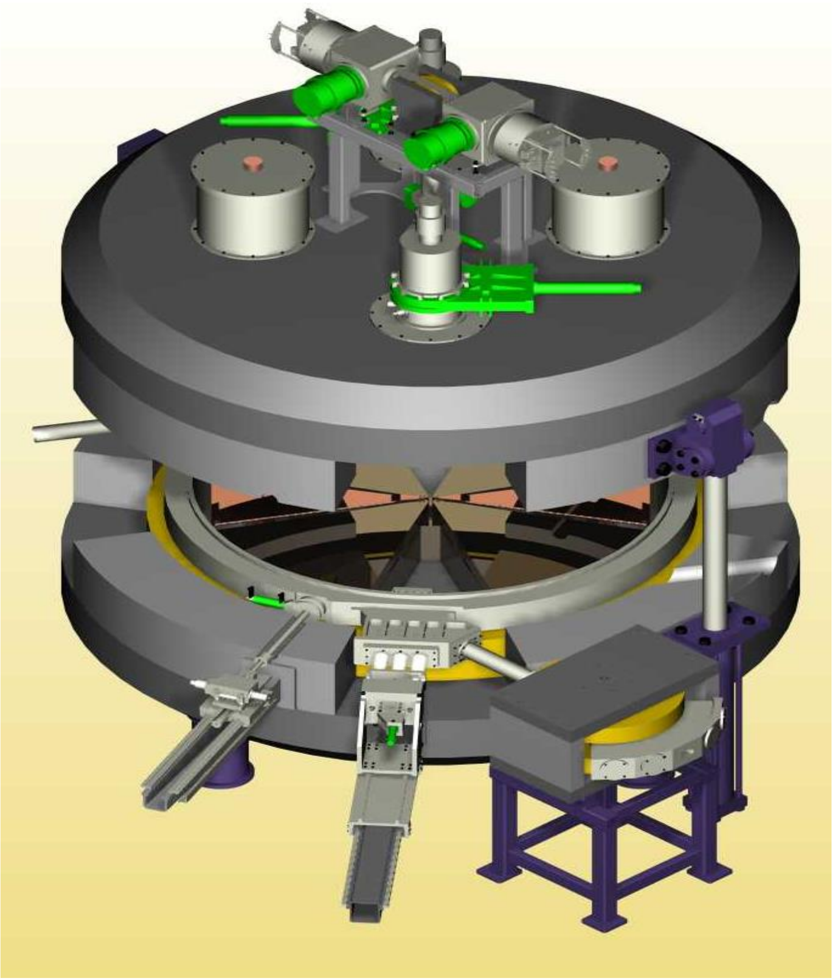
- Target surface at a small angle wrt the beam =>
- Increase beam spot but
- Try to minimize beam reflection

The C14SE self-extraction cyclotron for 103-Pd

- Accelerate high intensity 14 MeV protons
- Good vacuum not required
  - Internal ion source
  - Less expensive pumping
- High current protons
  - ESD not possible
  - Extraction completely from magnetic design
  - IBA patented
- The ion source reached 15mA on internal beam stop.
- Extracted beam intensities reached 1.4 mA
- On target reached 0.8 mA

IBA is currently studying if SE principle can be more widely applied for PET-cyclotrons

The C70 cyclotron for Arronax



- Multi-purpose isotope production cyclotron
- Routine PET and SPECT
- Radio-chemistry research
- Therapeutic isotopes
  - ^{211}At, alpha emitters
  - ^{67}Cu, ^{177}Lu, beta emitters
  - Pulsed alpha (research)

Accelerated Beam	RF mode	Extraction	Extracted Beam	Extracted Energy (MeV)	Beam Intensity (μeA)	Exit Ports
H^-	2	stripping	H^+	30–70	750	dual
D^-	4	stripping	D^+	15–35	50	dual
$^4He^{2+}$	4	ESD	$^4He^{2+}$	70	70	single
HH^+	4	ESD	HH^+	35	50	single

iba Particle Therapy

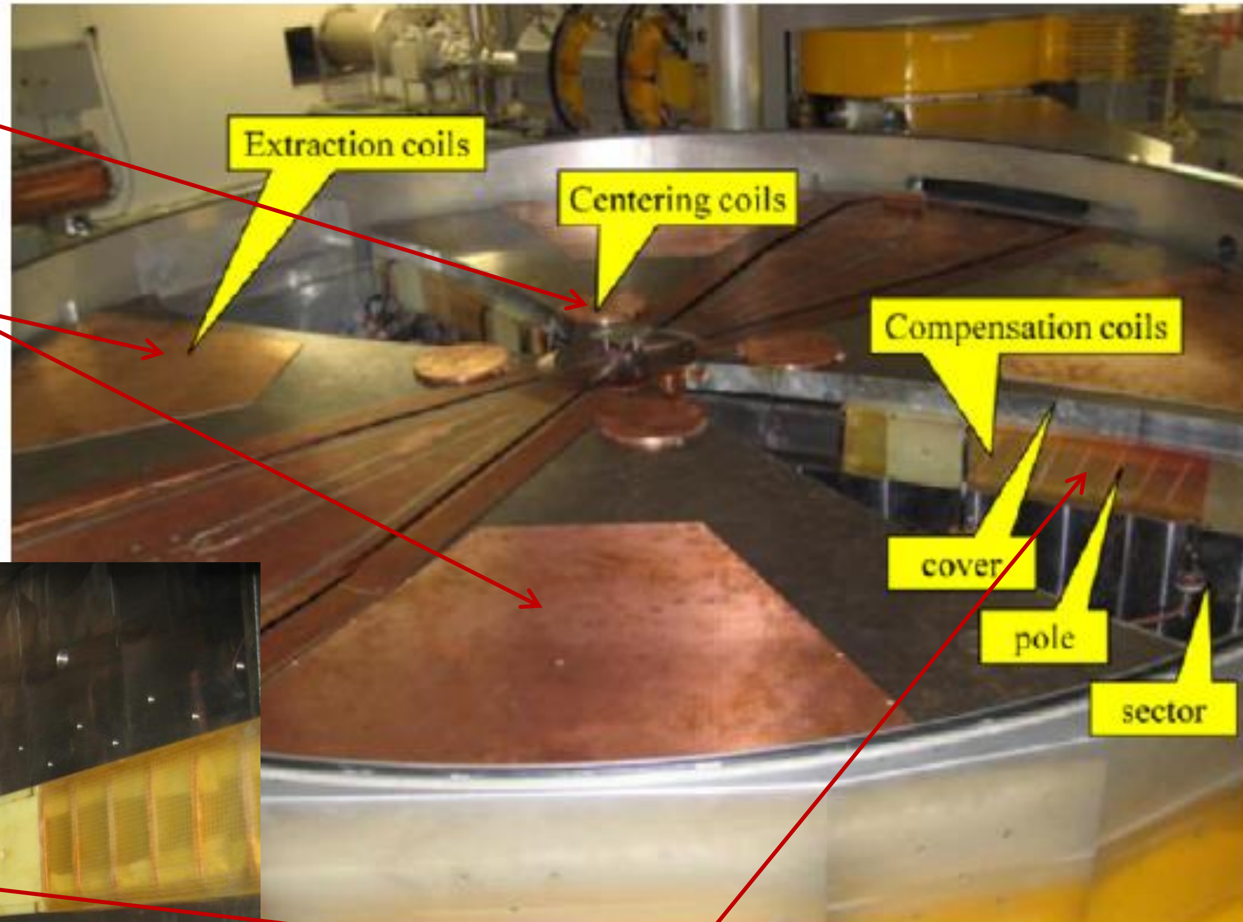
C70 multiple particles => additional complexity

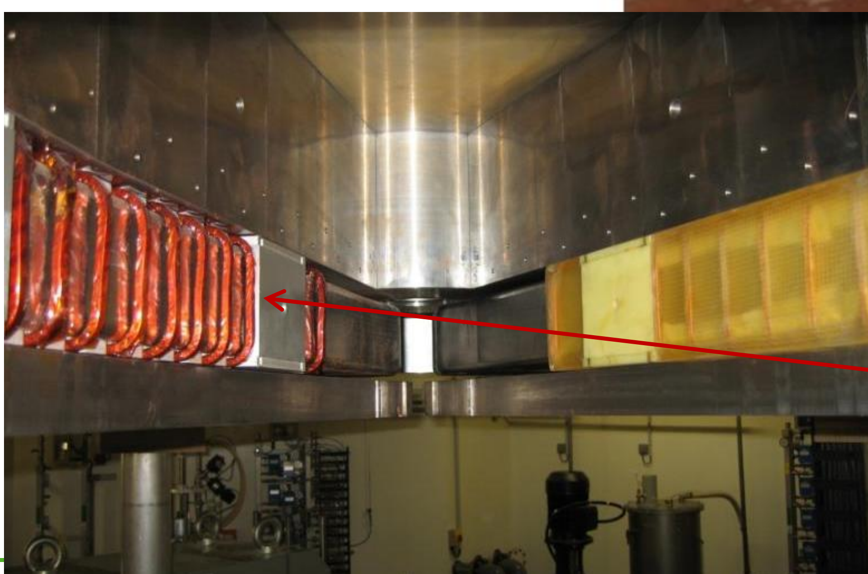
- Particles with different charge sign
  - B-field must be inversed between + and – particles
  - Two different types of ion sources (multicusp vs ECR)
- Particles with different q/m ratio (1/1 and 1/2)
  - Isochronous field shape not the same for both types
  - Central region geometry not the same for both types
  - Harmonic mode of acceleration not the same types
- Different methods of extraction needed
  - Stripping for H^- and D^-
  - ESD for α and H_2^+
- High intensity H^- requires very good vacuum

C70 => additional complexity of magnetic field

centering coils

extraction coils

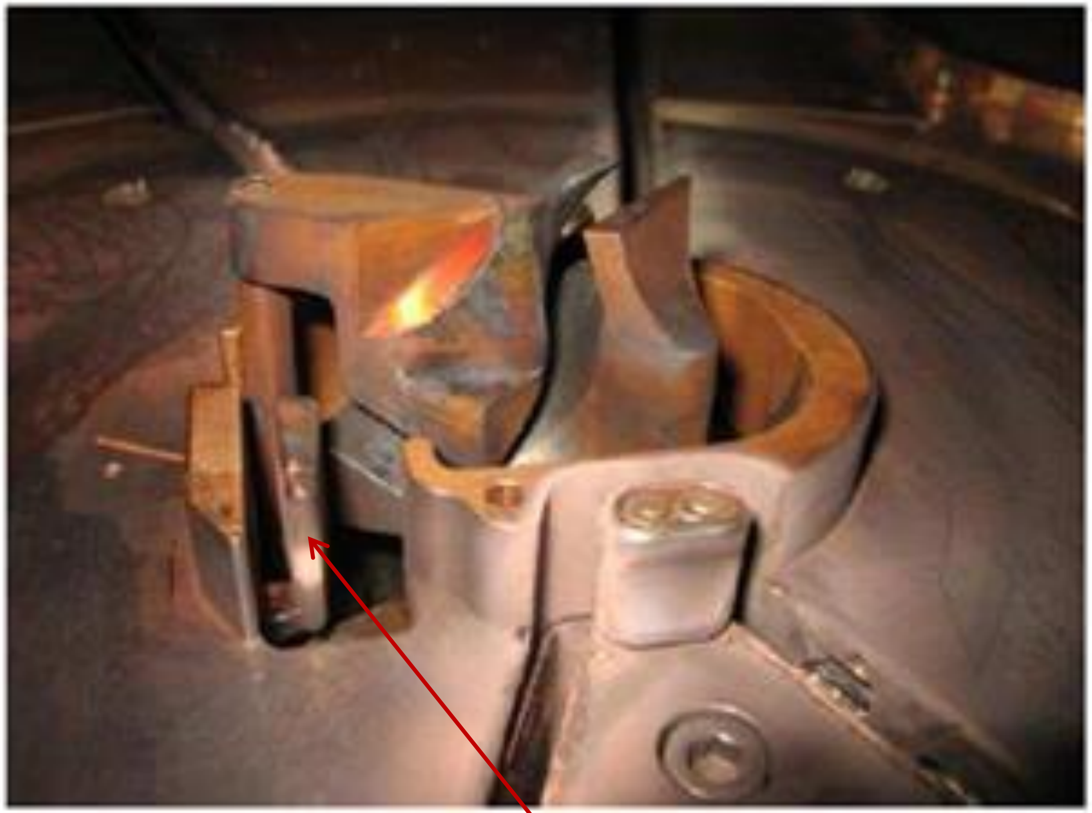




Isochronization coils

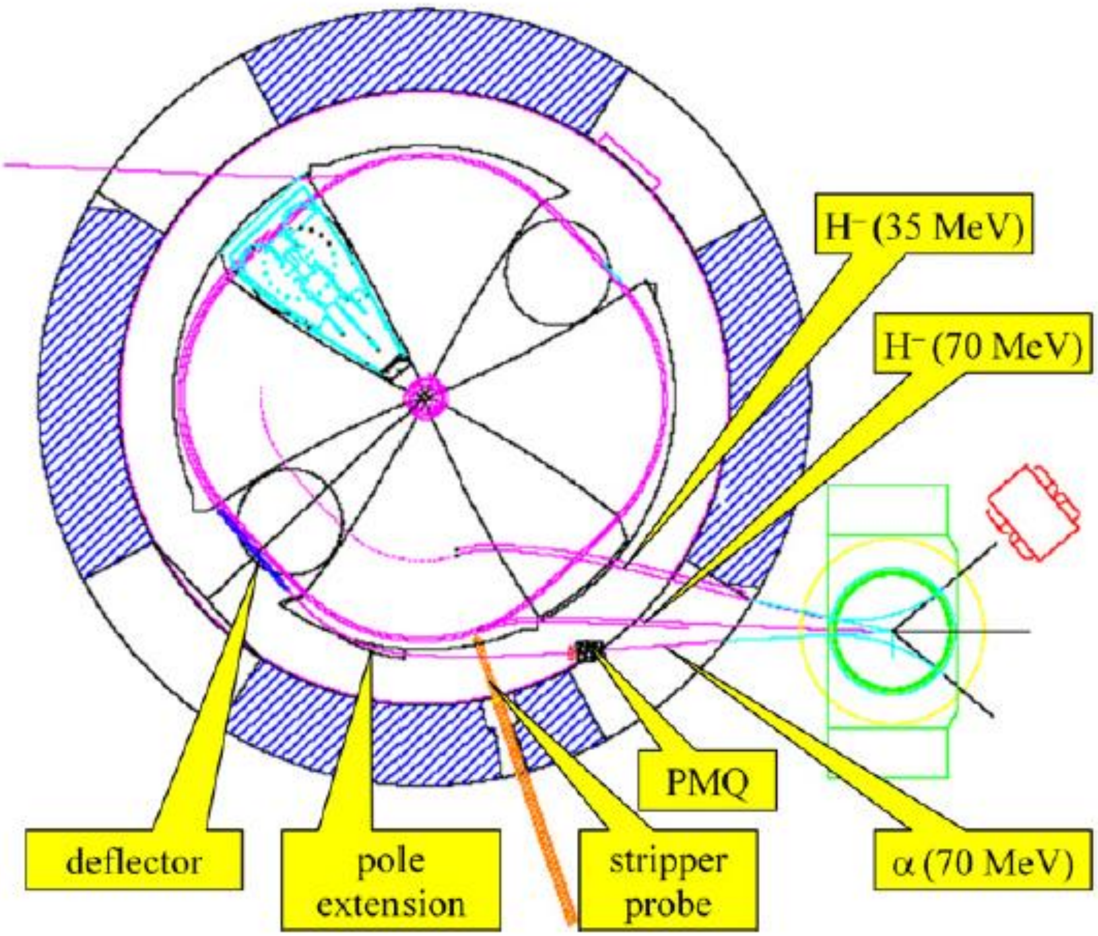
Particle Therapy

C70 => additional complexity of central region



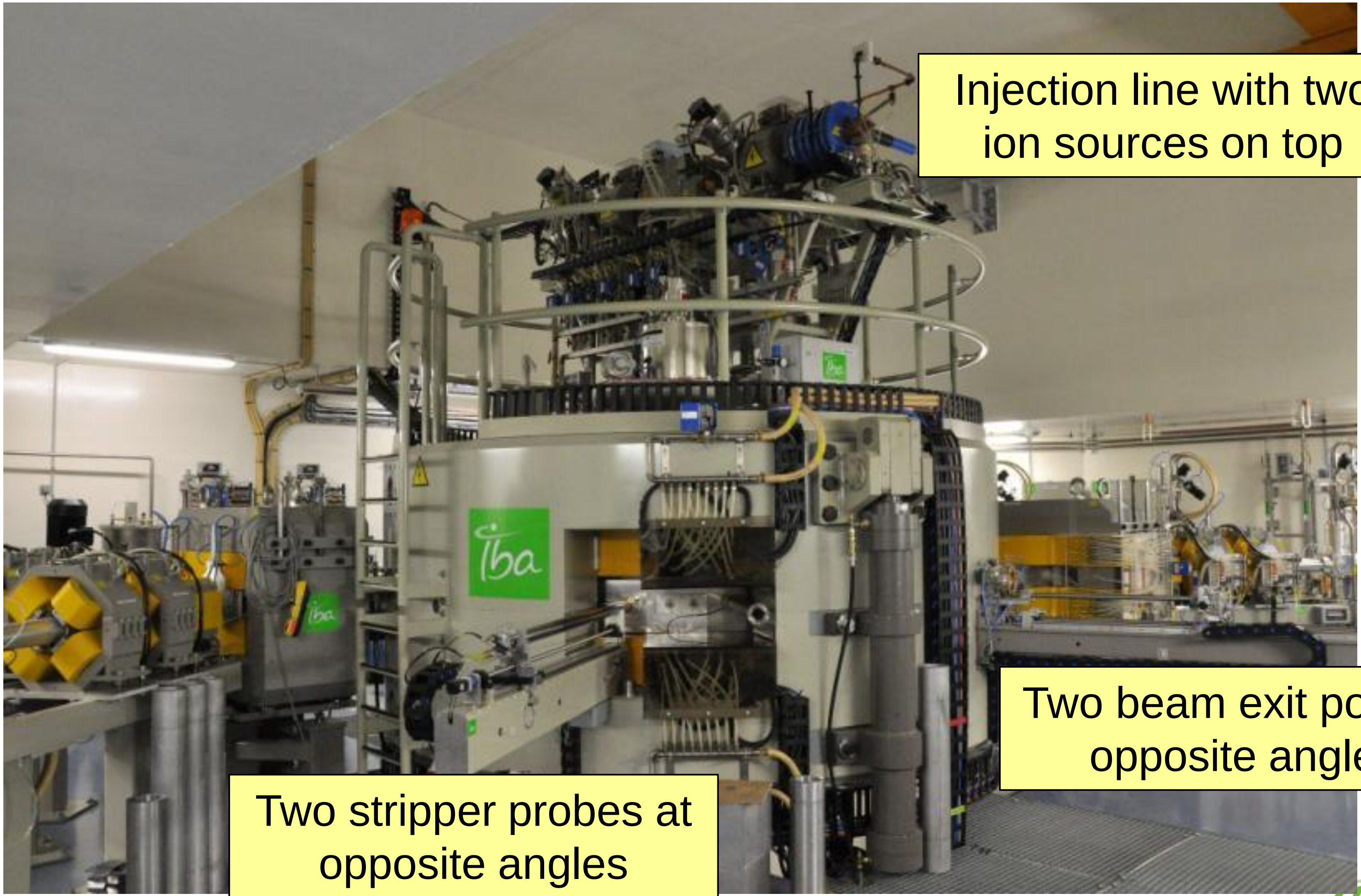
Horizontal deflector at exit of the inflector needed to place different both particle types on the equilibrium orbit (orbit centering)

Illustration of the C70 dual extraction system

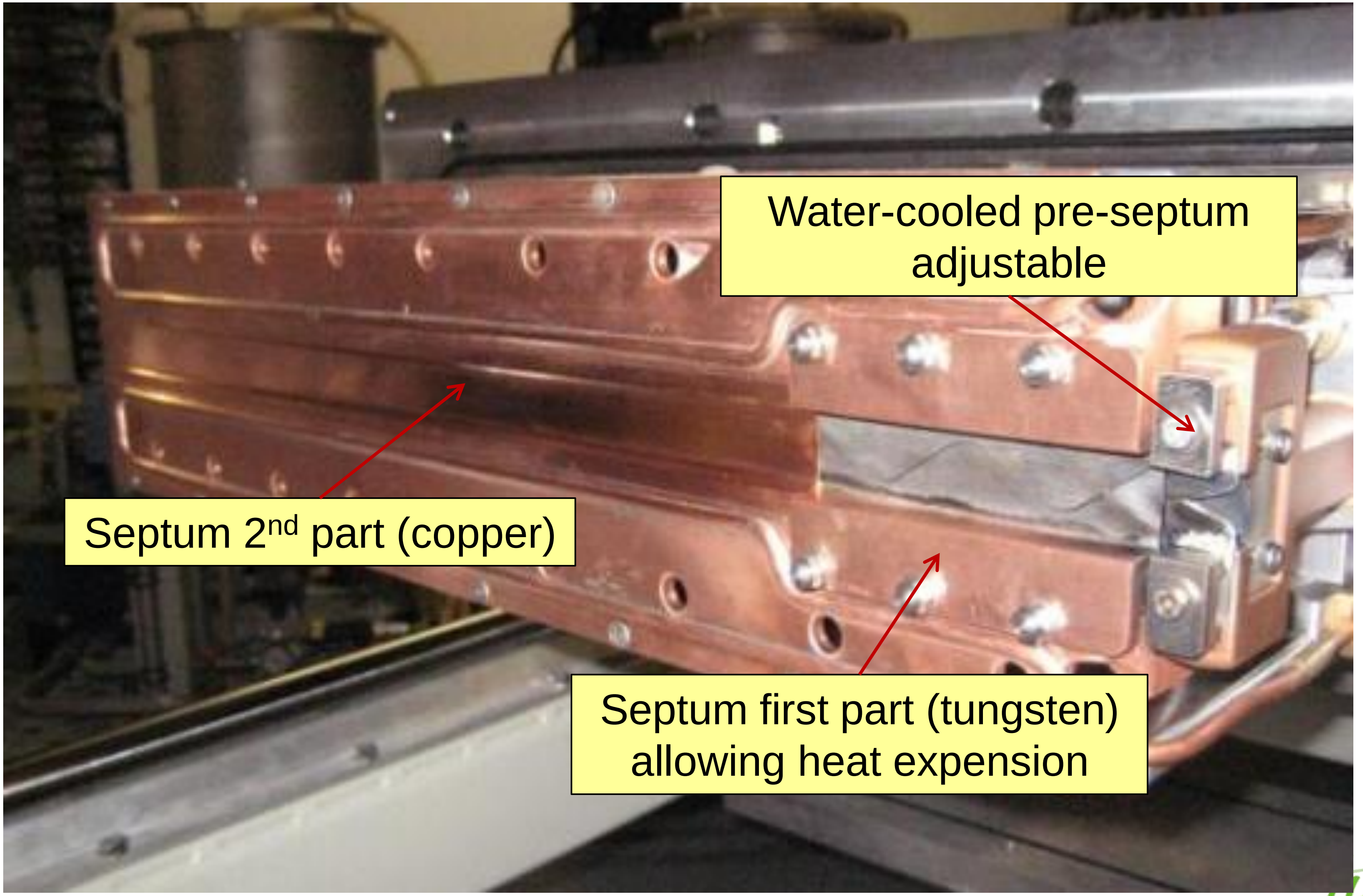


- Stripping extraction for negative particles
- ESD for α-particle
- Two opposite exit ports
- Simultaneous dual beam capability for H- and D-
- Variable energy for H- and D-
- External switching magnet to direct different energies and particle into the beam lines

The C70 multiple particle cyclotron



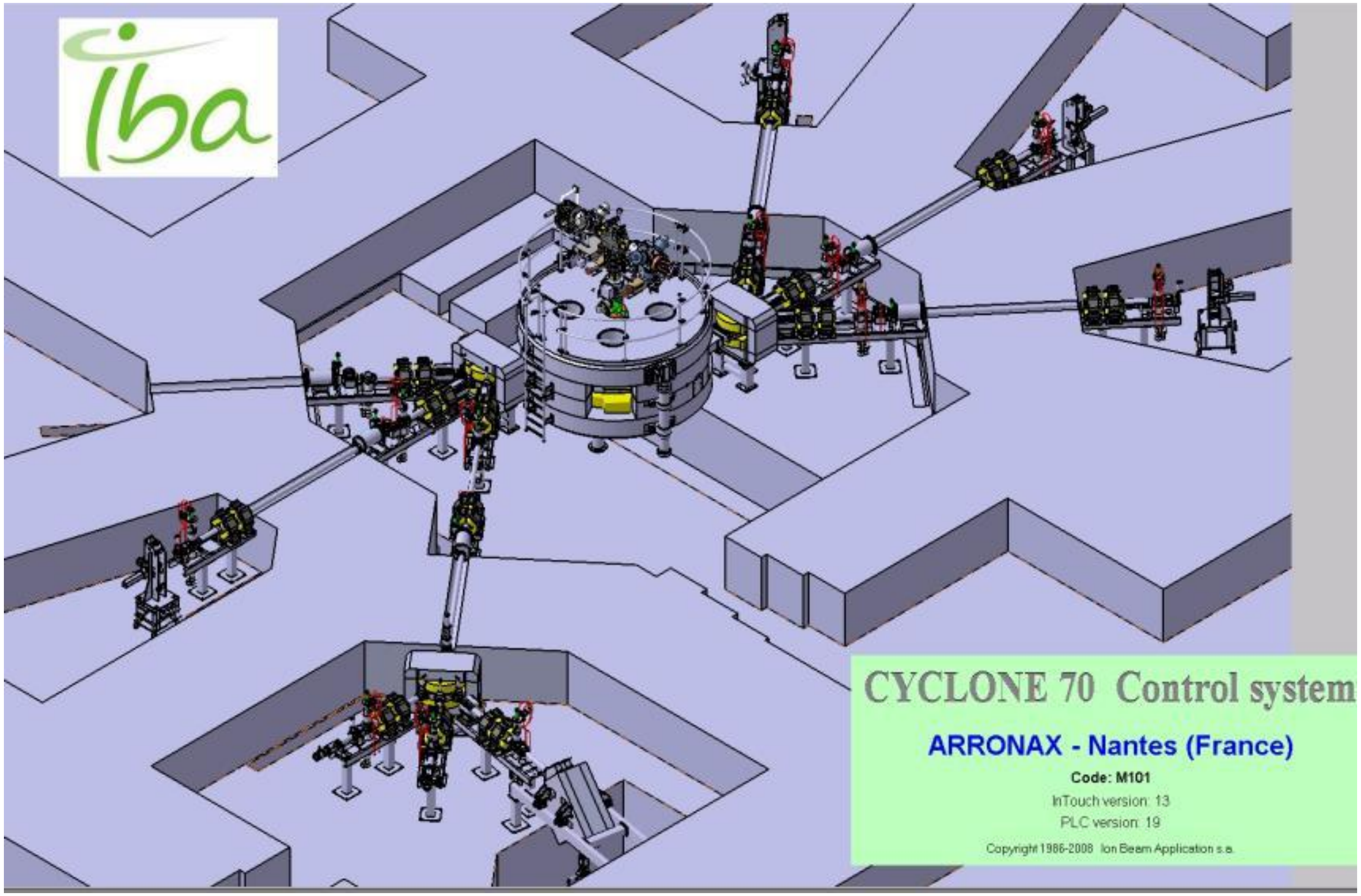
The C70 electrostatic deflector (ESD)



The ESD if you don't do it right

α - beam 5kWatt
extraction efficiency 90%
500 Watt on thin septum

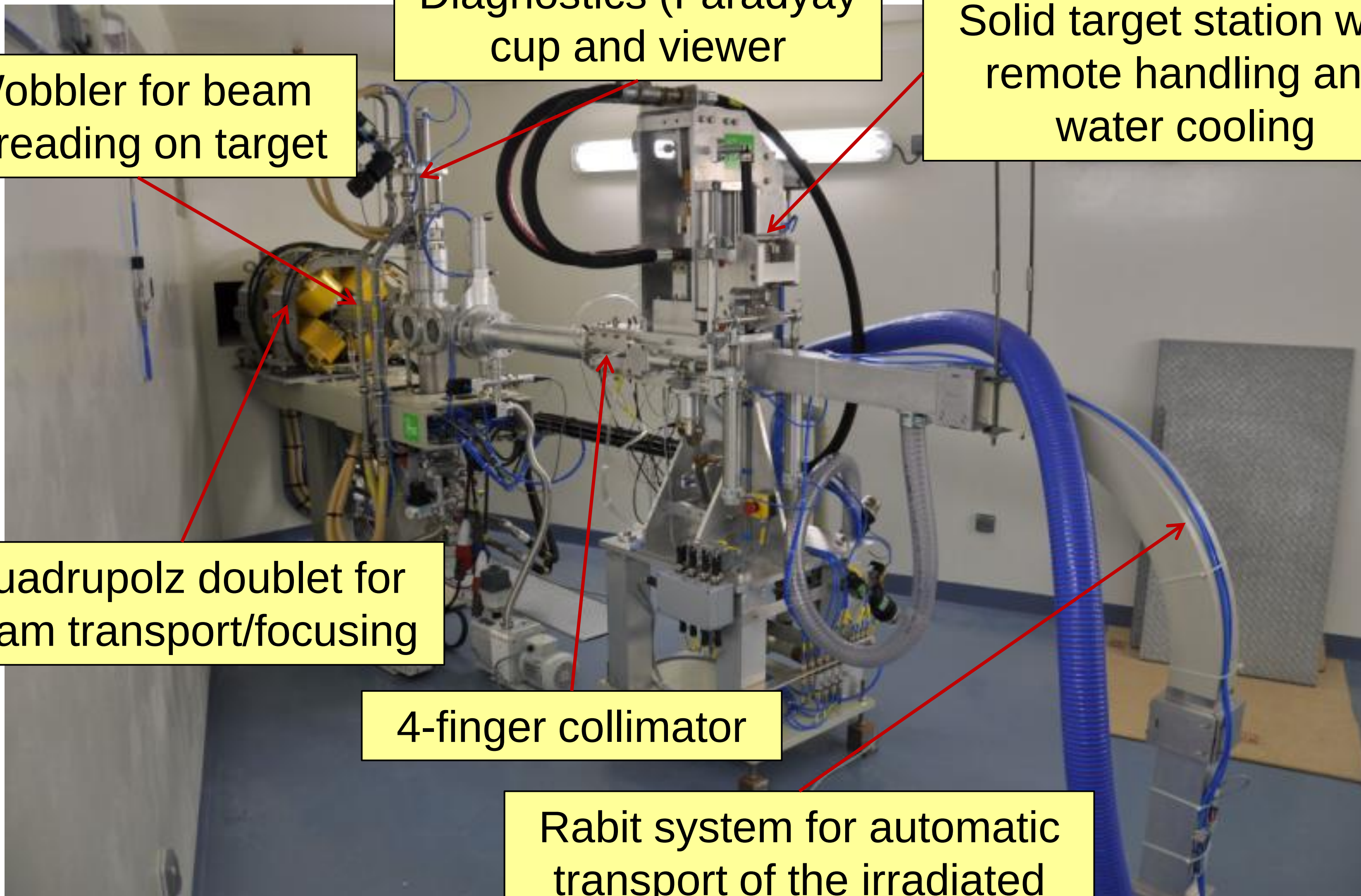
C70 at Arronax => a versatile RI production site



Six different vaults for routine RI production, development and research

iba Particle Therapy

A typical RI Production beam line



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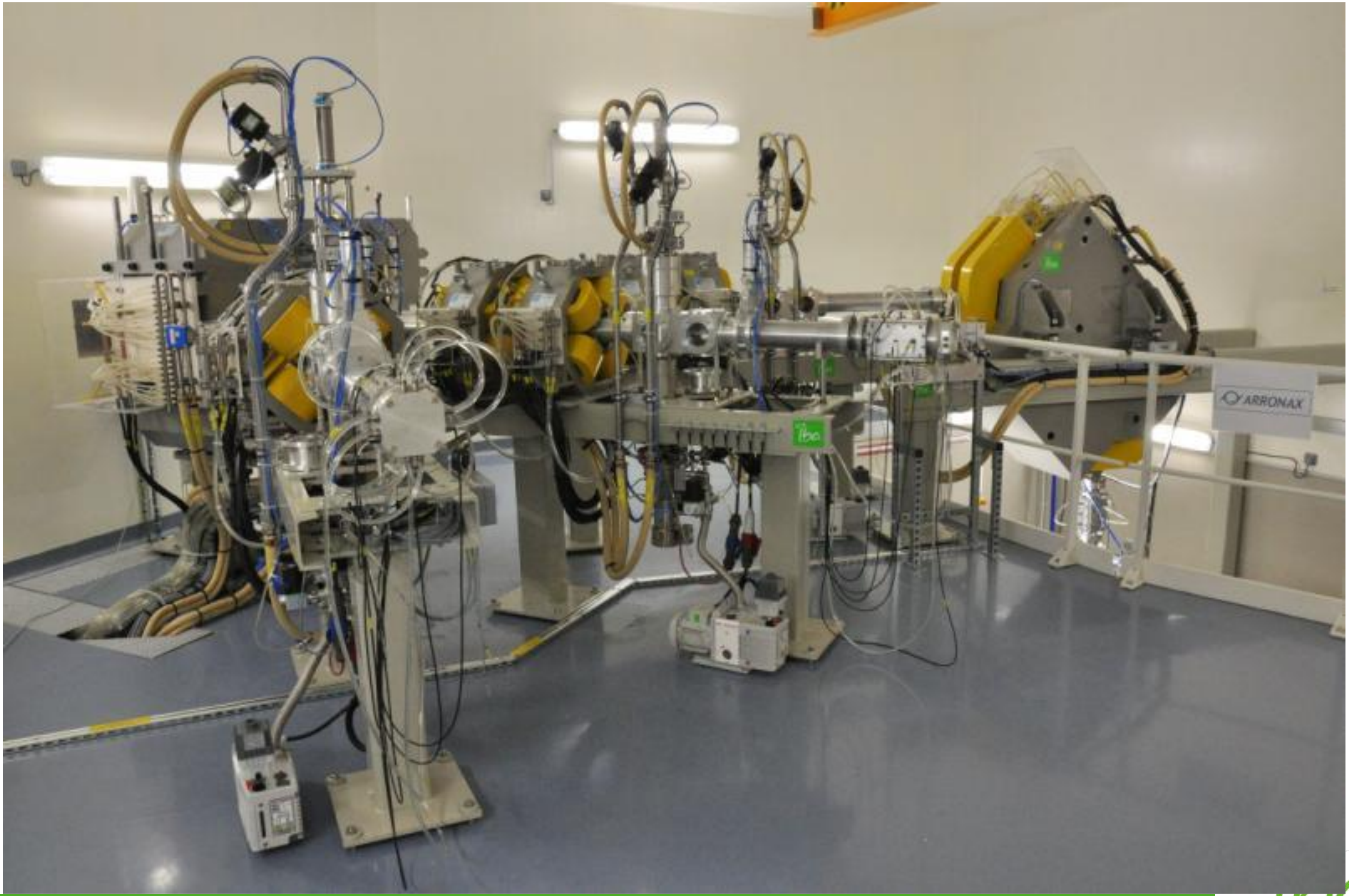
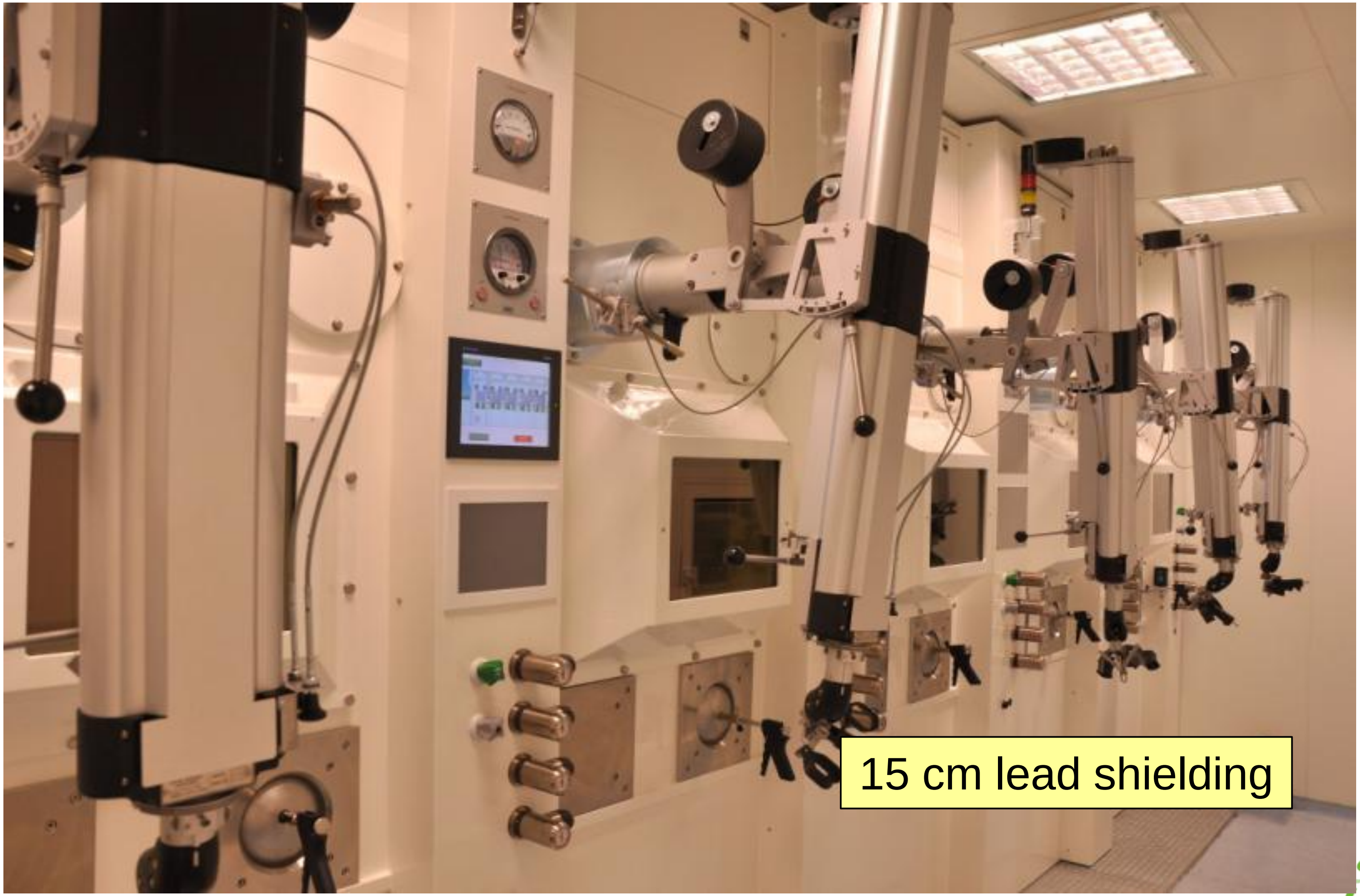
Experimental vault at Arronax Nantes



Hot-cells are needed for the remote handling of irradiated target material

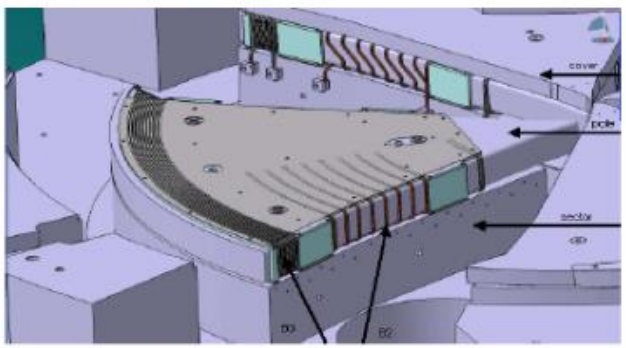


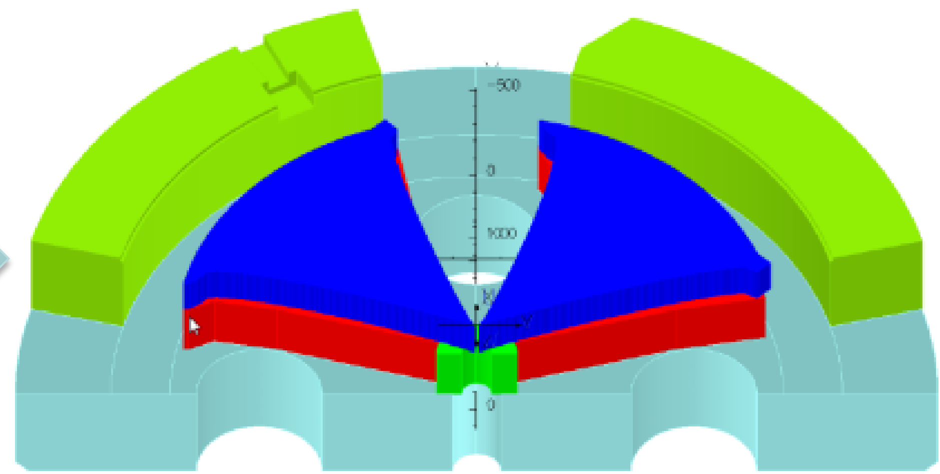
15 cm lead shielding

A simpler version of the Cyclone 70 => proton only Zevacor Molecular USA

- Optimize proton acceleration => currently under development at IBA

- Starting from Cyclone 70 XP installed in Arronax, France
- Optimize : Magnet : isochronism for proton only
  - Compensation coils not needed => simplifies magnet considerably



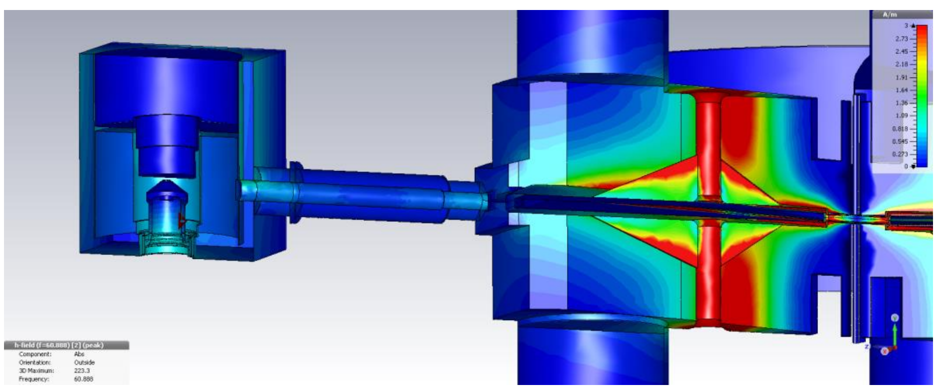


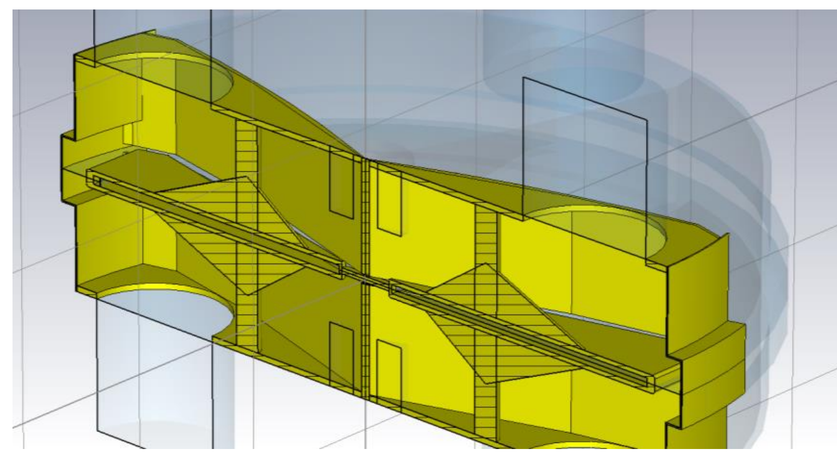
3D Tosca finite element design of the magnetic structure

Cyclone 70 proton only

- Optimize proton acceleration mode for high intensity
- Optimize : RF for proton only : 35-70 MeV , > 750 µA ,
- Accelerate H- at Harmonic 4 => less turn, lower losses

3D CST finite element design of the accelerating structure





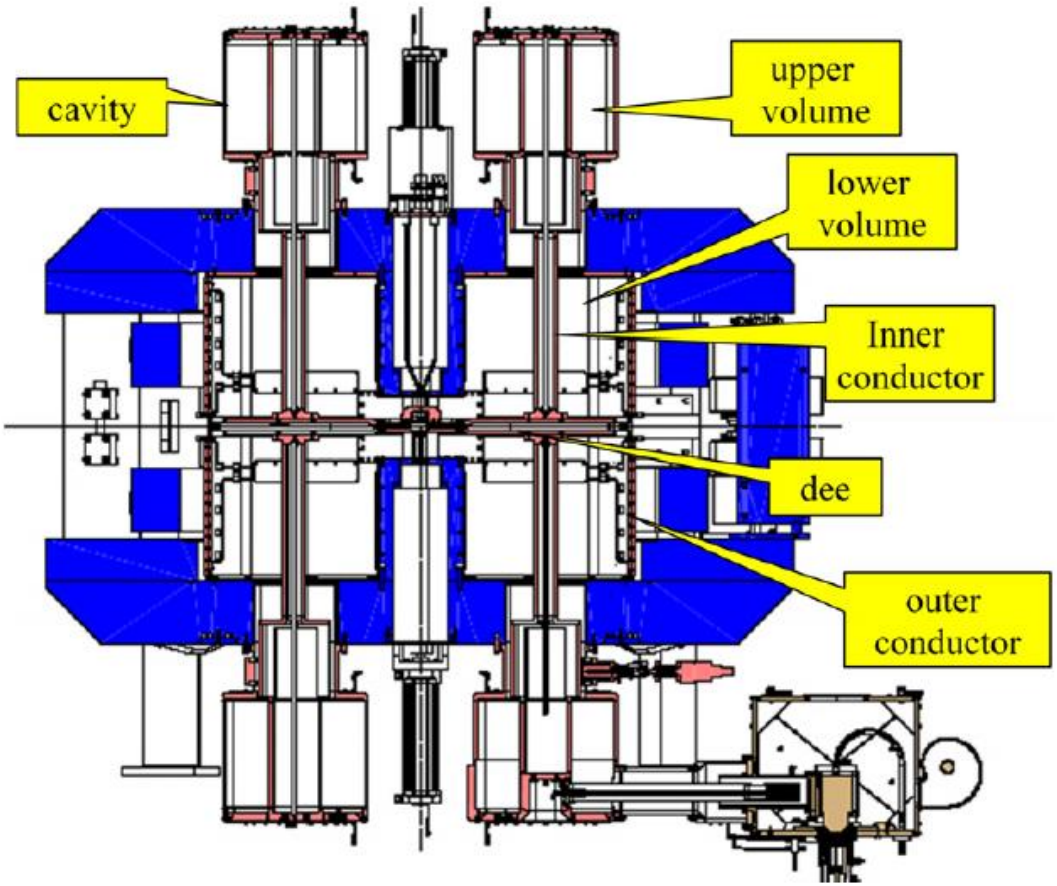
Vacuum stripping in a high intensity H^{-} cyclotron

- H^{-} interacting with rest-gas may loose its electron
- Neutral H-atom moves on straight line and hits vacuum chamber wall
- Extra out-gassing on the walls induced by the beam
- May lead to an avalanche effect
  - Vacuum deteriorates with current => more stripping losses => more outgassing
  - Max extracted current is limited by vacuum
- How to reduce stripping losses
  - Better base vacuum => more pumping
  - Less outgassing => local cooling of vacuum chamber walls
  - More efficient acceleration => less turns in the machine
- Choose optimum harmonic mode of acceleration H
  - 4-fold symmetric cyclotron => dee-angle 45° => H=4

The C30XP cyclotron

- Very similar to the C70 (multi-purpose, multiparticle) but 30 MeV instead of 70 MeV
- Most important difference is the RF-system
  - Can operate in two modes with frequencies that exactly differ with a factor 2 (dual frequency)
  - Allows to accelerate all four particles at the same optimum harmonic mode H=4
  - Minimum turns => minimum stripping losses

Dual frequency RF system



dual band IMPA + FPA

66 and 33 MHz on the same cavities

Without any moving RF parts

- coaxial cavity made up of two resonating volumes which are coupled by a capacity.
- Low frequency mode is the quarter wave ($\lambda/4$) mode
- High frequency mode as the $3\lambda/4$ mode.
- By proper dimensioning of the structure, the condition of frequency-doubling is obtained.

iba Particle Therapy

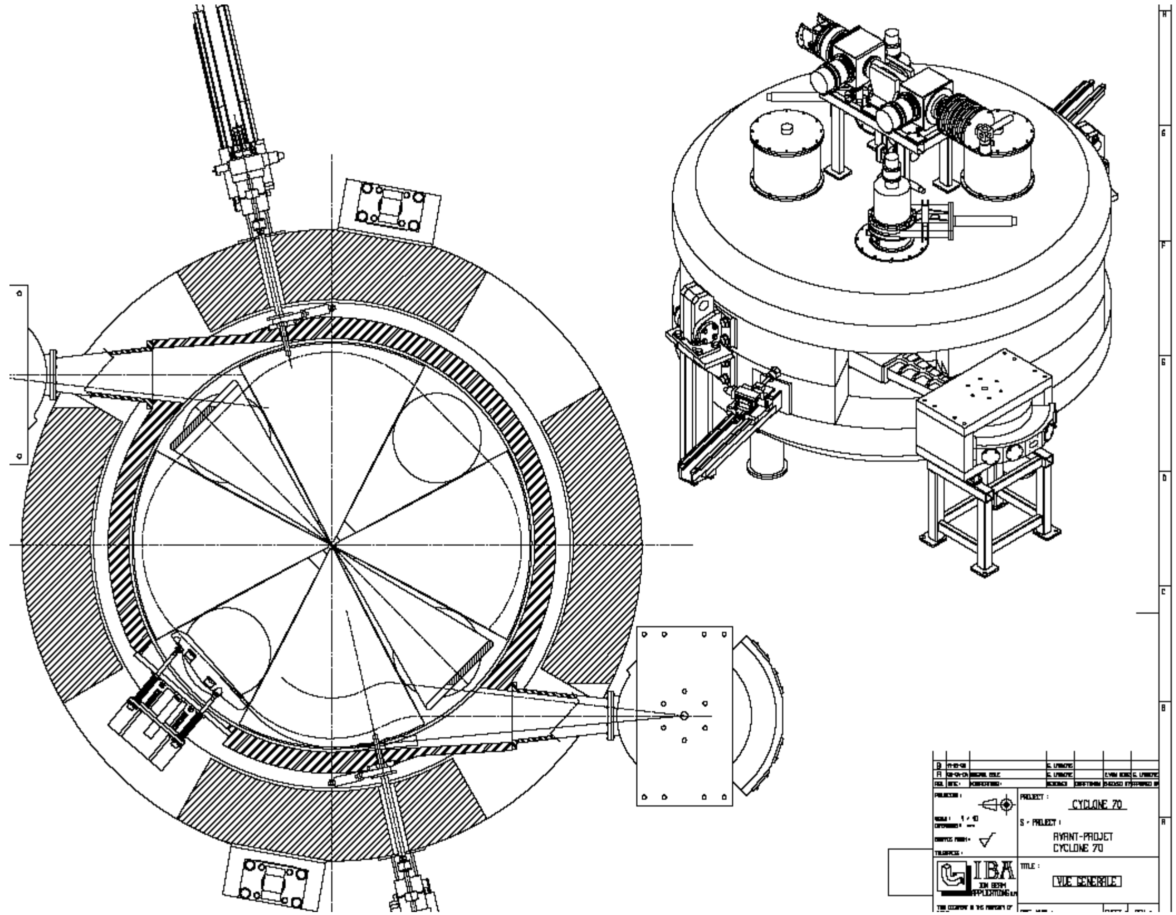
Cyclone® 30 XP ; proton- deuteron- alpha

- based on the successful Cyclone® 30; eXtra Particles

Proton (H- accelerated)
18 - 30 MeV   350µA
2 exits , H+ (proton)

Deuteron (D- accelerated)
9 - 15 MeV; 50 µA
2 exits, D+ (deuteron)

Alpha   (He2+ accelerated)
30 MeV, 50 µAe
1 common exit with H+
Electrostatic deflector

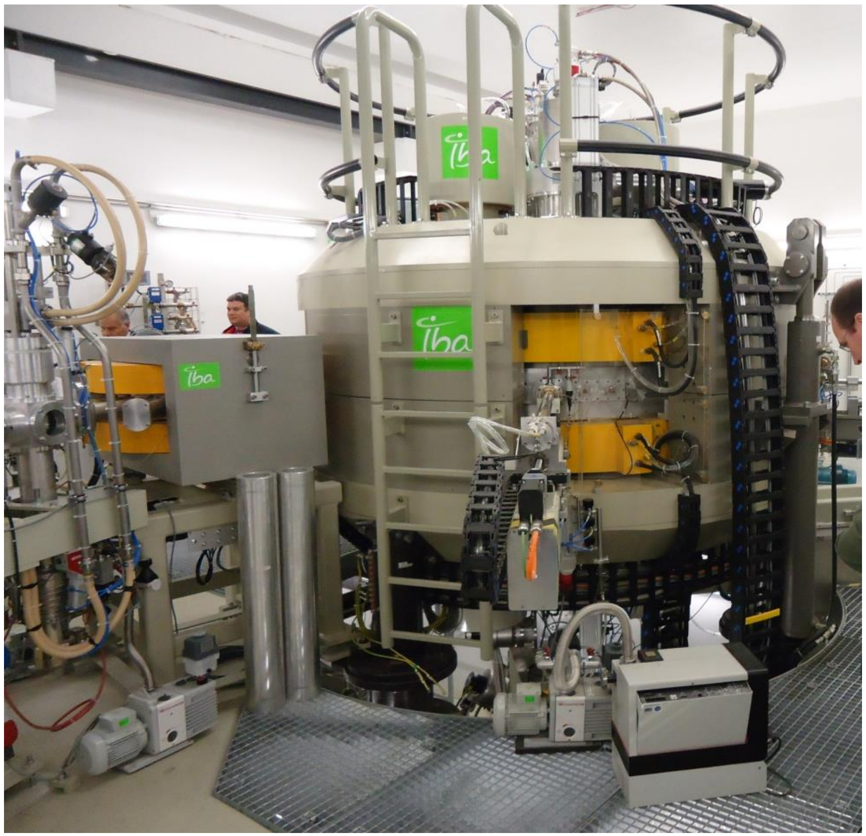


Ref: ECPM 2012; Cyclone 30 multiparticles status

Cyclone 30 XP :

- 30 MeV proton – alpha – deuteron machine

- **Cyclotron fully installed with 2 long beam lines, one short line in Jülich <u>Waiting for beam license</u>.**



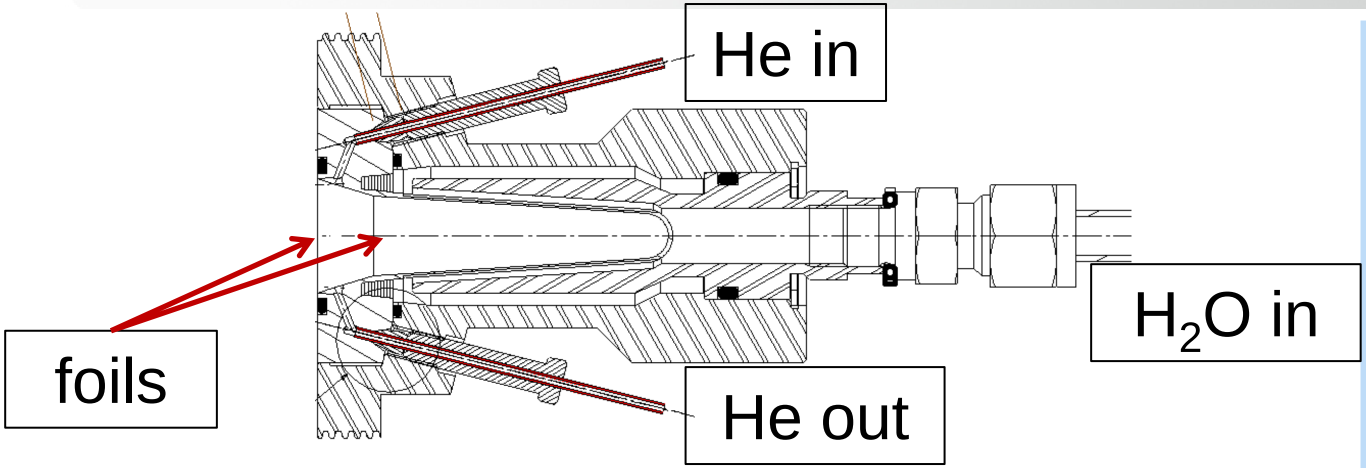
Beam lines and targets

- Cyclone 30XP with Solid target high current + PET system

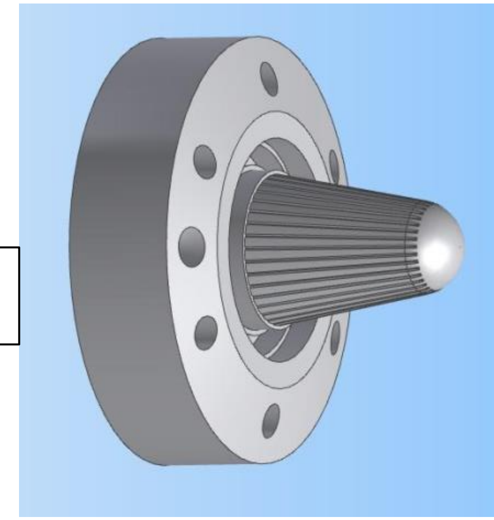
Target technologies
1. Liquid targets
2. Solid targets
3. Gas-targets

18F target development => liquid target

IBA new Conical shaped [^{18}O] water targets



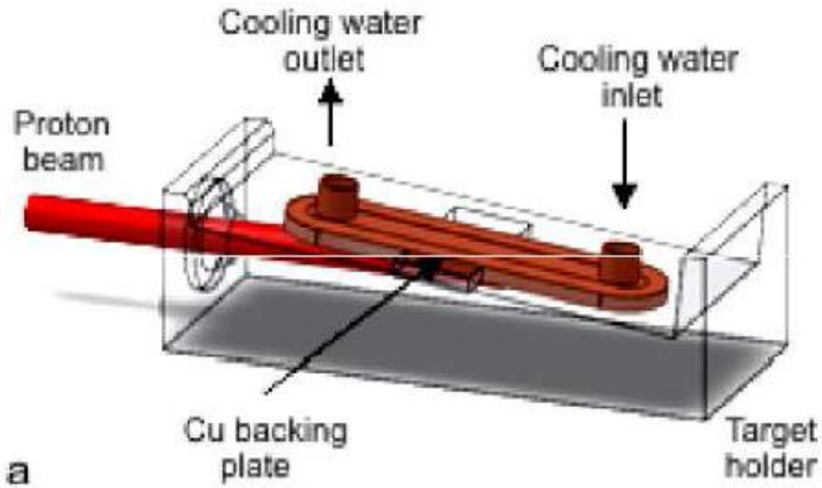
$^{18}O(p,n)^{18}F$

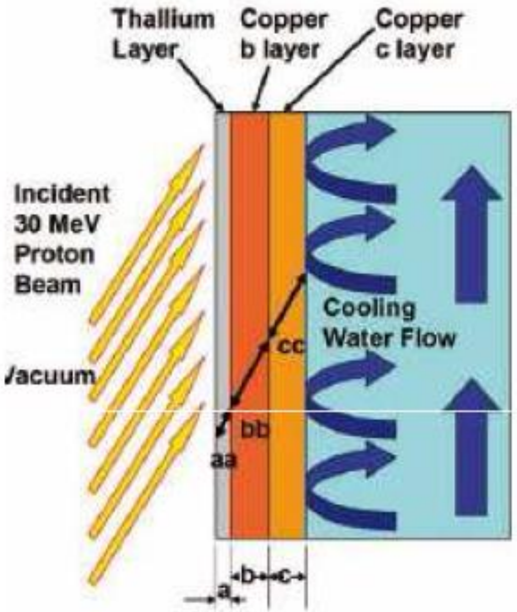


Enriched $H_2{}^{18}O$
150 µA, 4ml => 18 Ci ^{18}F
High pressure (50 bar)
He-window cooling
Water cooiling

Solid target irradiation

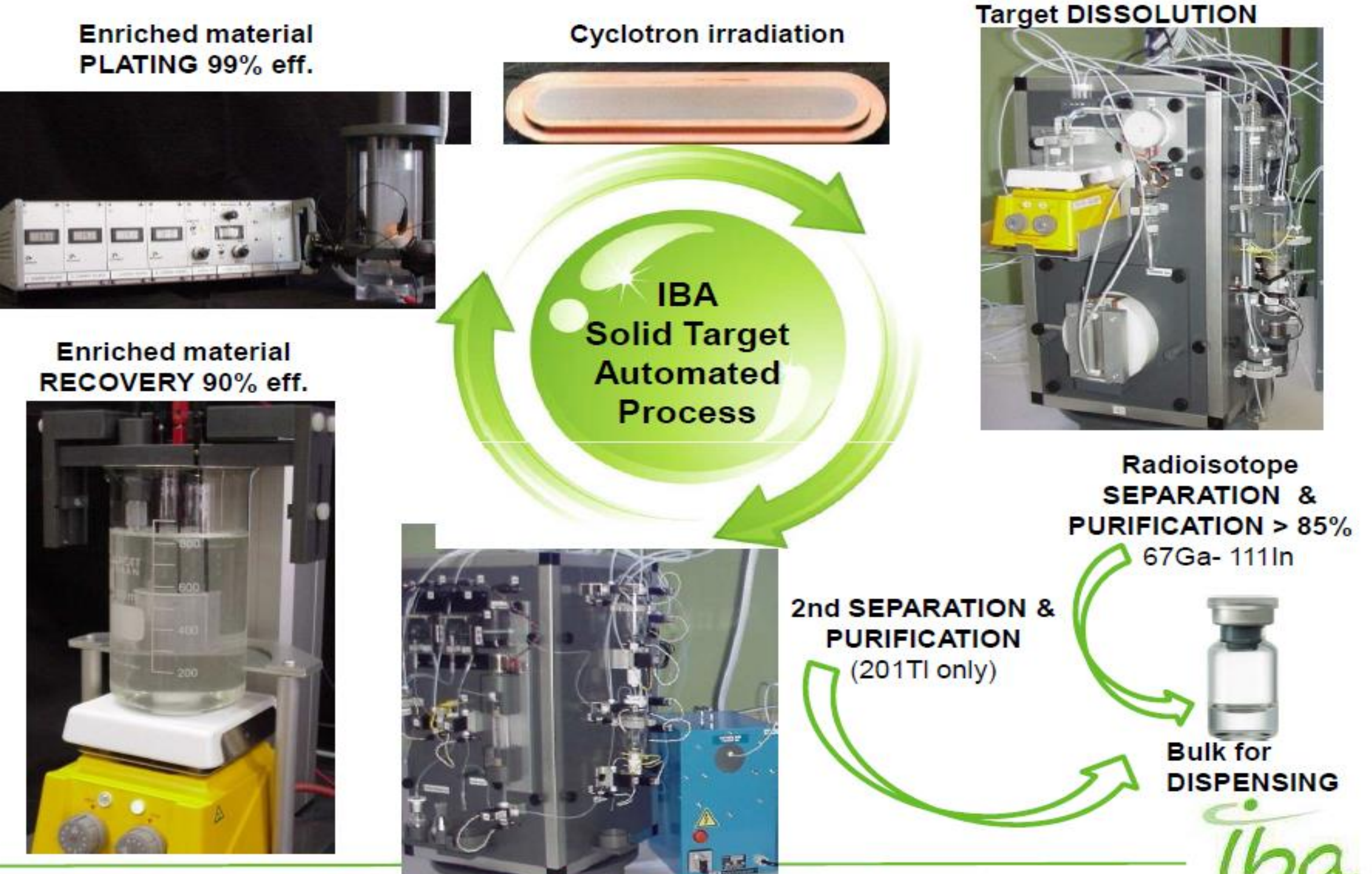
- Avoid melting/evaporation





Element	Density ($g \cdot cm^{-3}$)	Melting point (°C)	Thermal conductivity ($W \cdot cm^{-1} \cdot K^{-1}$)
Copper	8.96	1083	4.03
Thallium	11.85	303	0.46

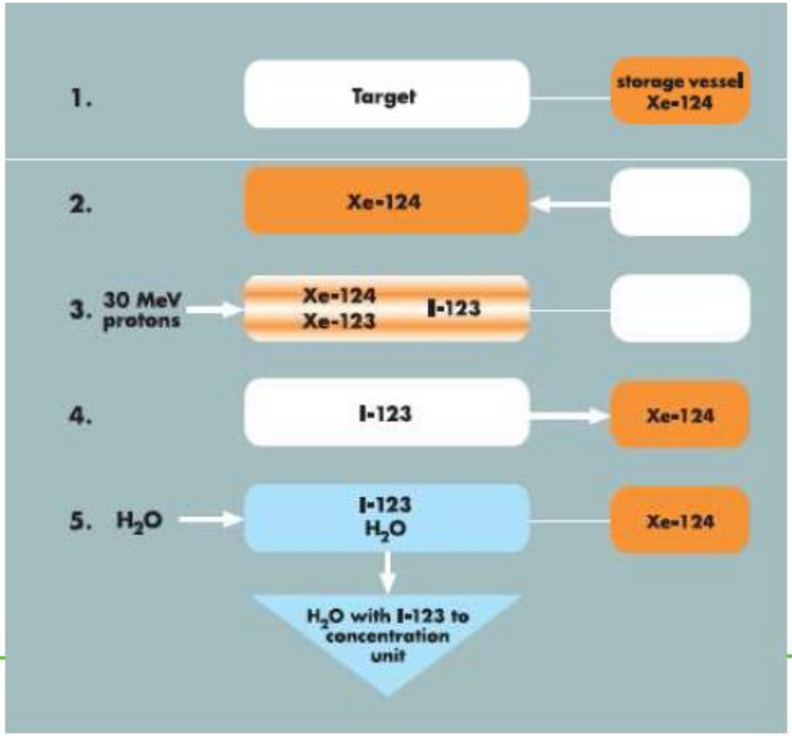
Solid target: $^{203}Tl(p,3n)^{201}Pb \Rightarrow {}^{201}Tl$



^{123}I production using ^{124}Xe gas target

$^{124}Xe(p,pn)^{123}Xe \Rightarrow ^{123}I$

- High power targetry
- High yield and ultrapure 123I
- Closed-loop and full recovery of 124Xe (liquid N_2)



- Kipros 120 (200) – ZAG Zyklotron