# Cyclotrons

## Chapter 4

- Beam diagnostics review (becomes technical…)
- Instabilities
- Cyclotron as a mass separator
- Few cyclotrons examples

**Beam properties**

- current of full beam
- transverse position of full beam
- phase of bunch center
- transverse profile – projection 2D
- transverse emittance - 1D-2D
- longitudinal profile
- longitudinal emittance
-beam ion energy distribution

**Monitor properties**

- resolution
- temporal resolution / rate
- destructive vs. non-destructive (loss of beam up time, machine activation)
- low current limit (sensitivity, noise)
-high current limit (thermal damage, outgassing/sputtering)
- life time (radiation damage/hardness)
-reliability, cost, ....

**Special „cyclotron environment“ for monitors, drives, cooling**

-high magnetic field / stray field (particularly compact cyclotrons)
- little space (particularly compact cyclotrons) compact monitors, no radiation shielding, nearby activated components,RF nearby

**usage**

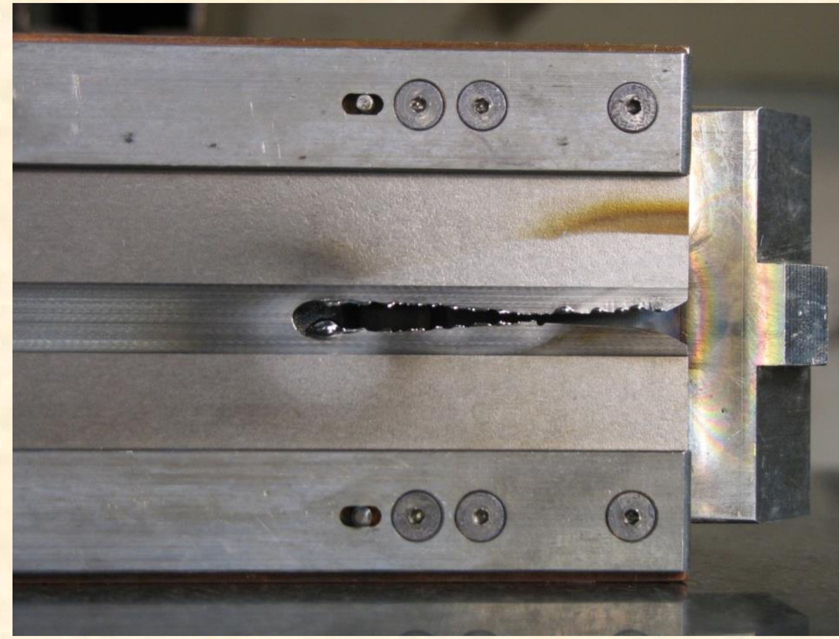
- for machine safety
- permanently
- for tuning
- at setup
- for error search
- only at commissioning

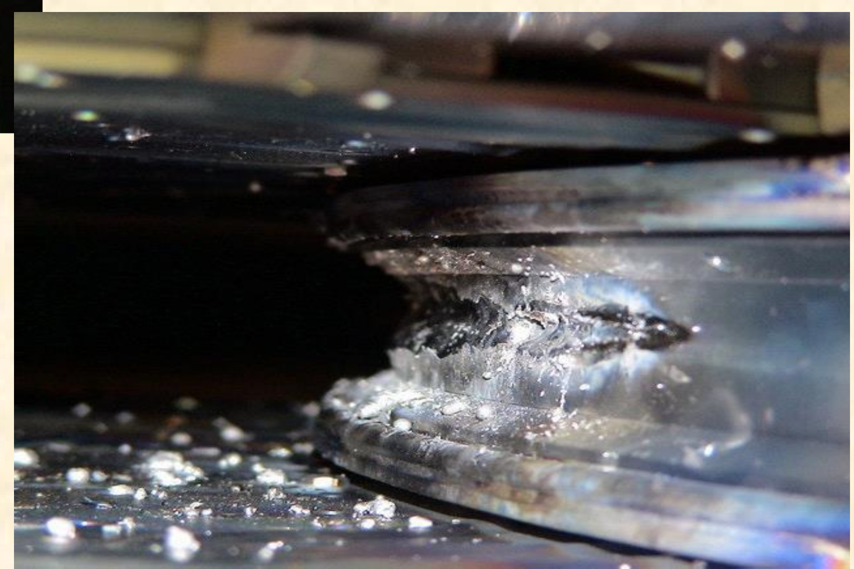
**familiar monitors**

- current transformer (DCCT, ACCT), Faraday-cup
-beam position monitor (BPM capacitive or inductive coupling)
- phase probe (capacitive coupling)
- wire monitor, wire grid
- screen
- emittance measurement device (slit-slit/slit-grid/Allison/3 profile/Q-pole variation) pepperpot

# High intensity diagnostics

MSU K1200 Deflector Septum (Tungsten)

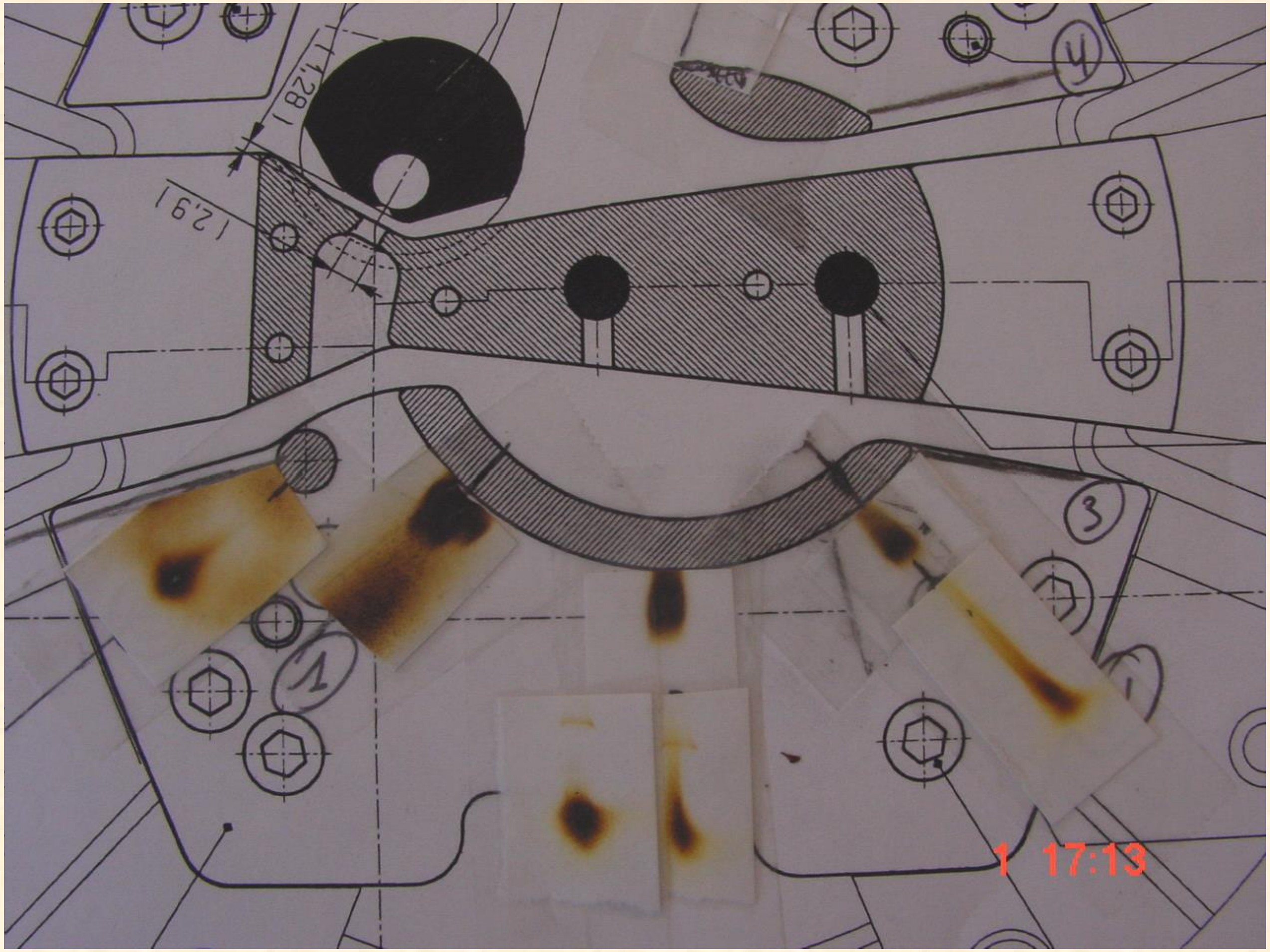




Beam induced defects with a

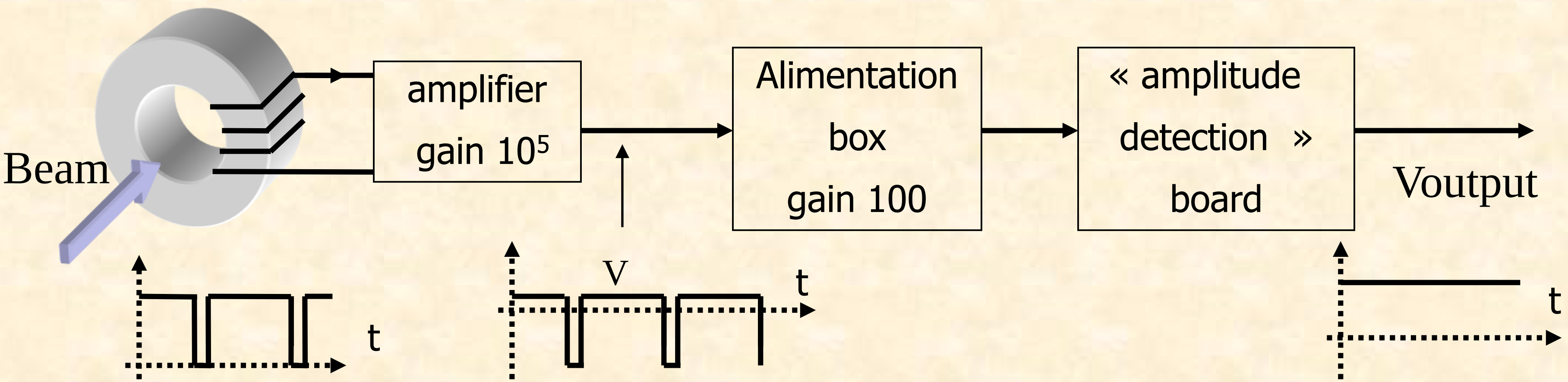
160 kW beam at PSI

# Beam Diagnostics



# Current measurement (non interceptive) & ( > nAe )

- Current Transformers Electronic Devices



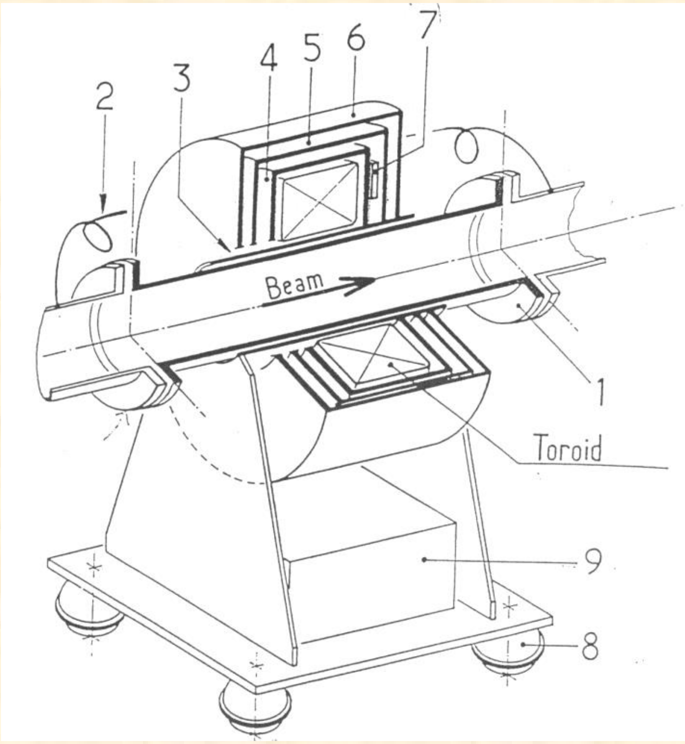

- The beam is « chopped » at a low frequency (hundred of Hz) to use this kind of diagnostics.
- Current transformer signal is amplify and measure by « amplitude detection board ».

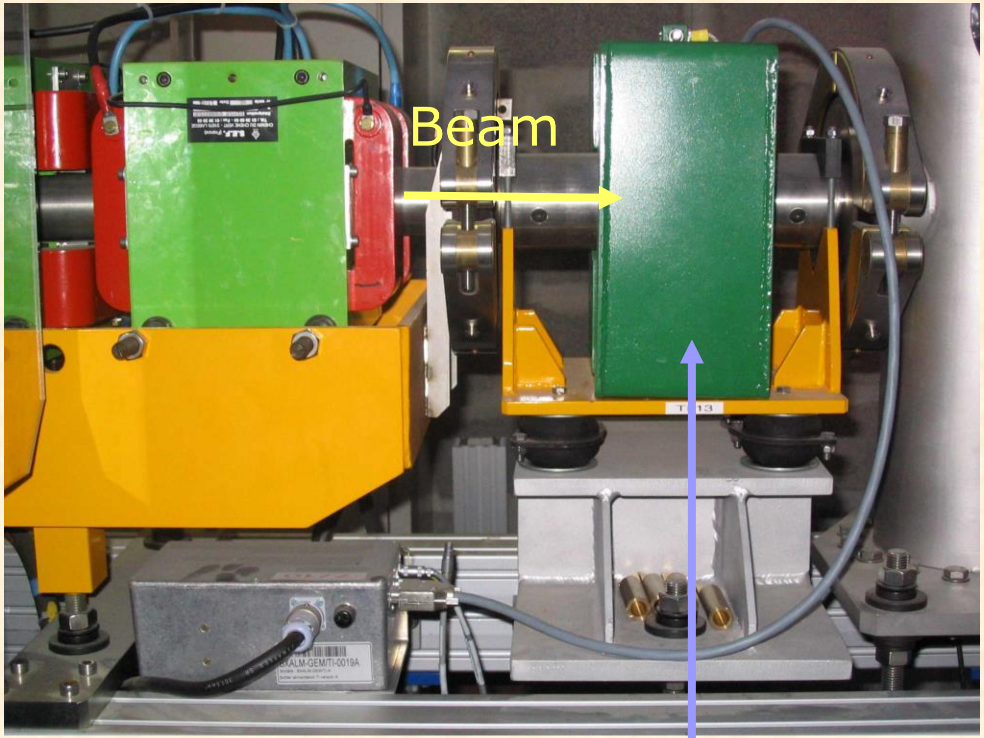
$I\ [A] = Npps \times Q \times e$

$e = 1.6\ 10^{-19}\ C$

# Current measurement (non interceptive)

- By Current Transformers (ACCT)

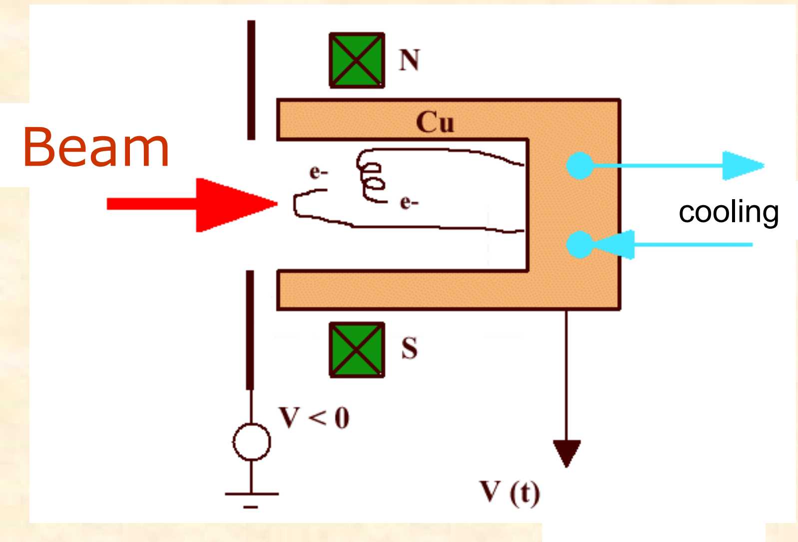


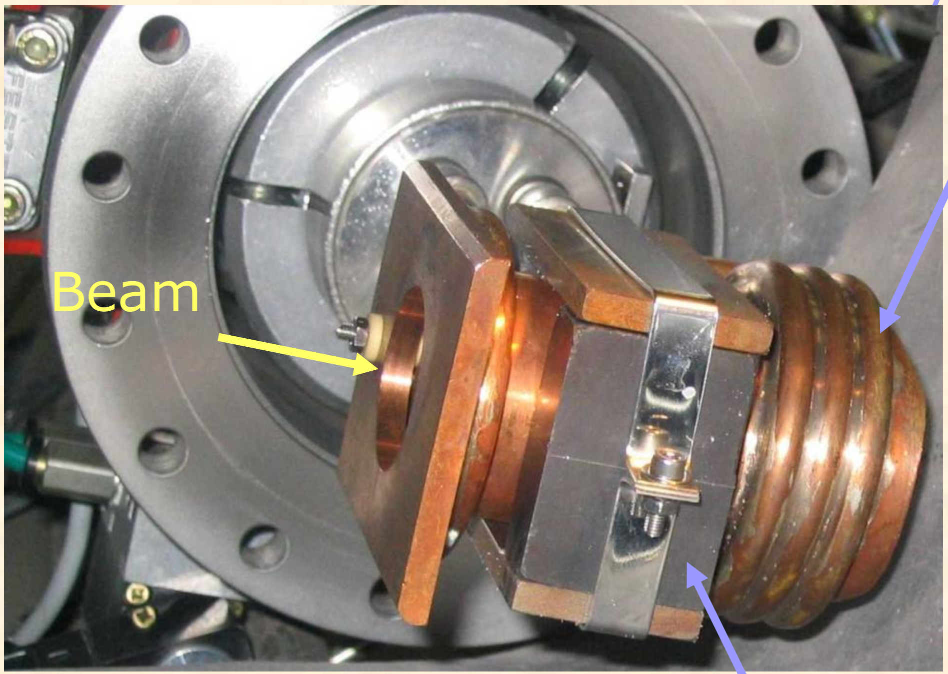

Current transformer with shielding

# Current measurement (interceptive)

- By Faraday Cups

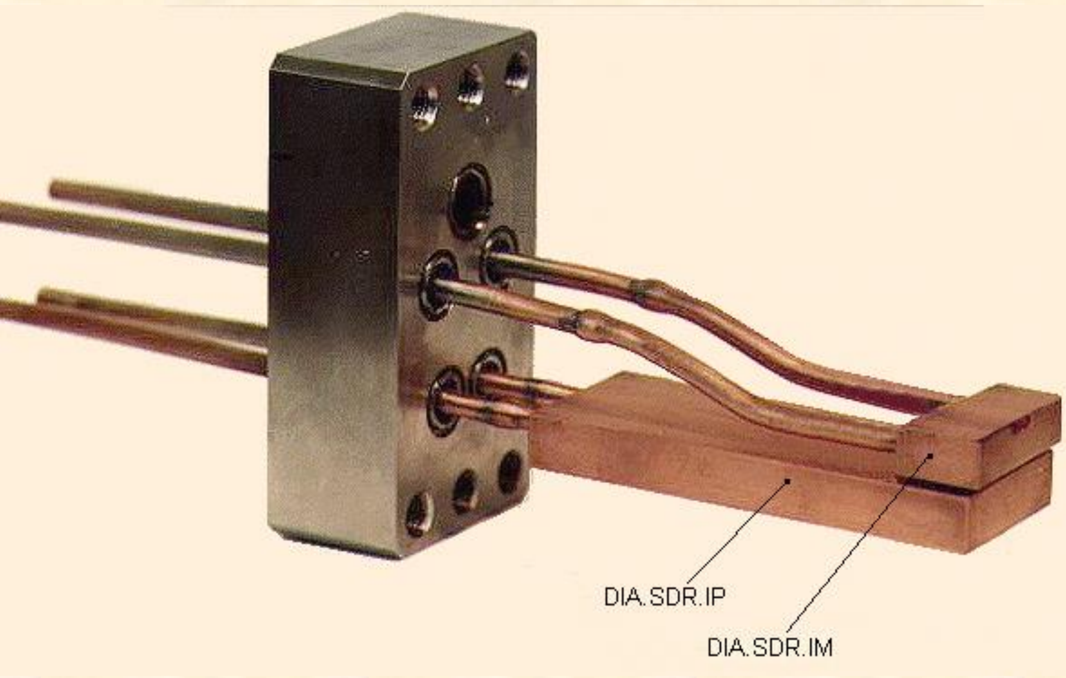


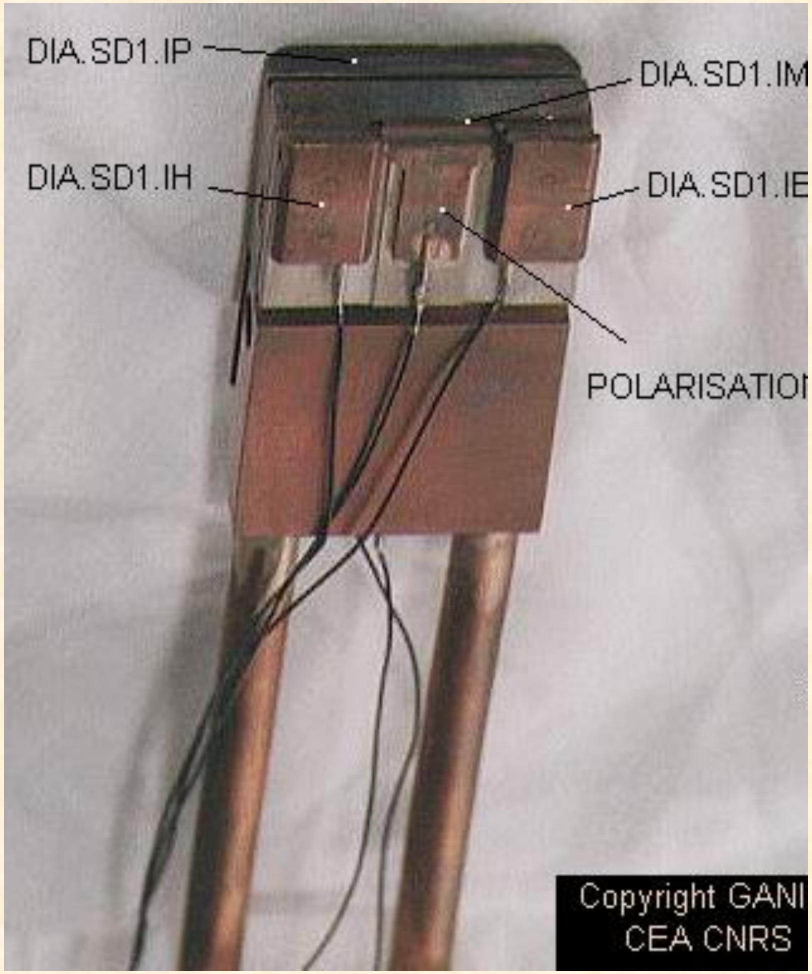

6kW cooled Faraday cup



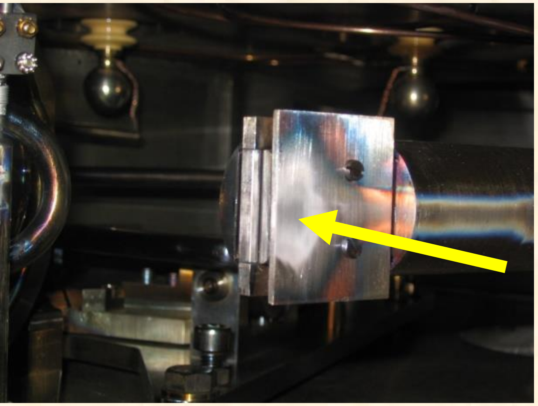

Magnet for secondary emissions

# Current measurement: Radial probe

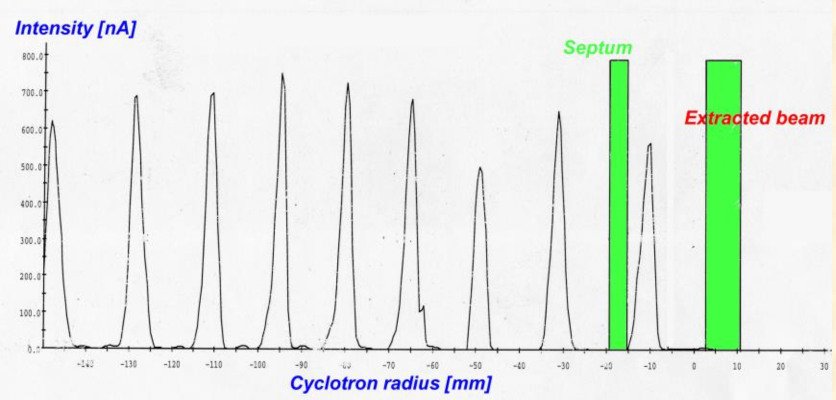


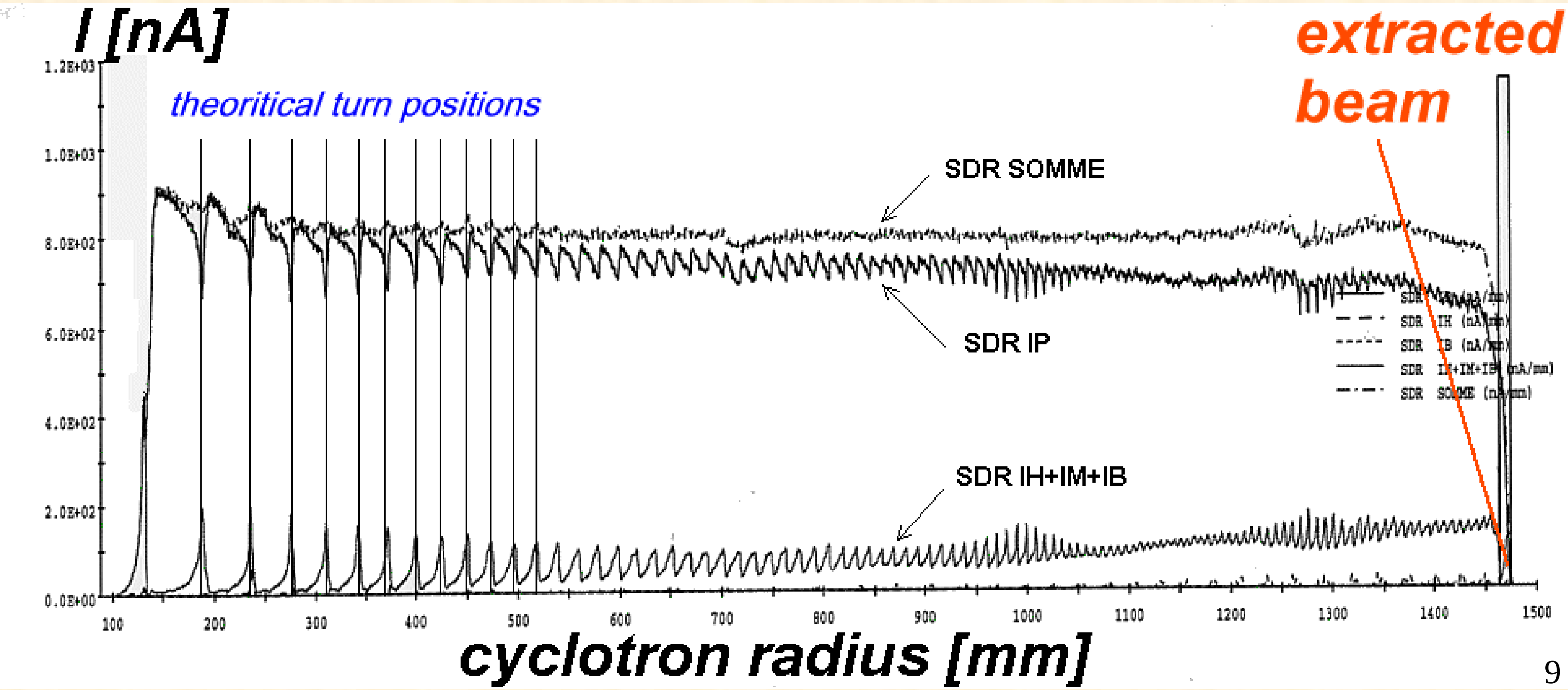



# Current measurement : Beam monitoring

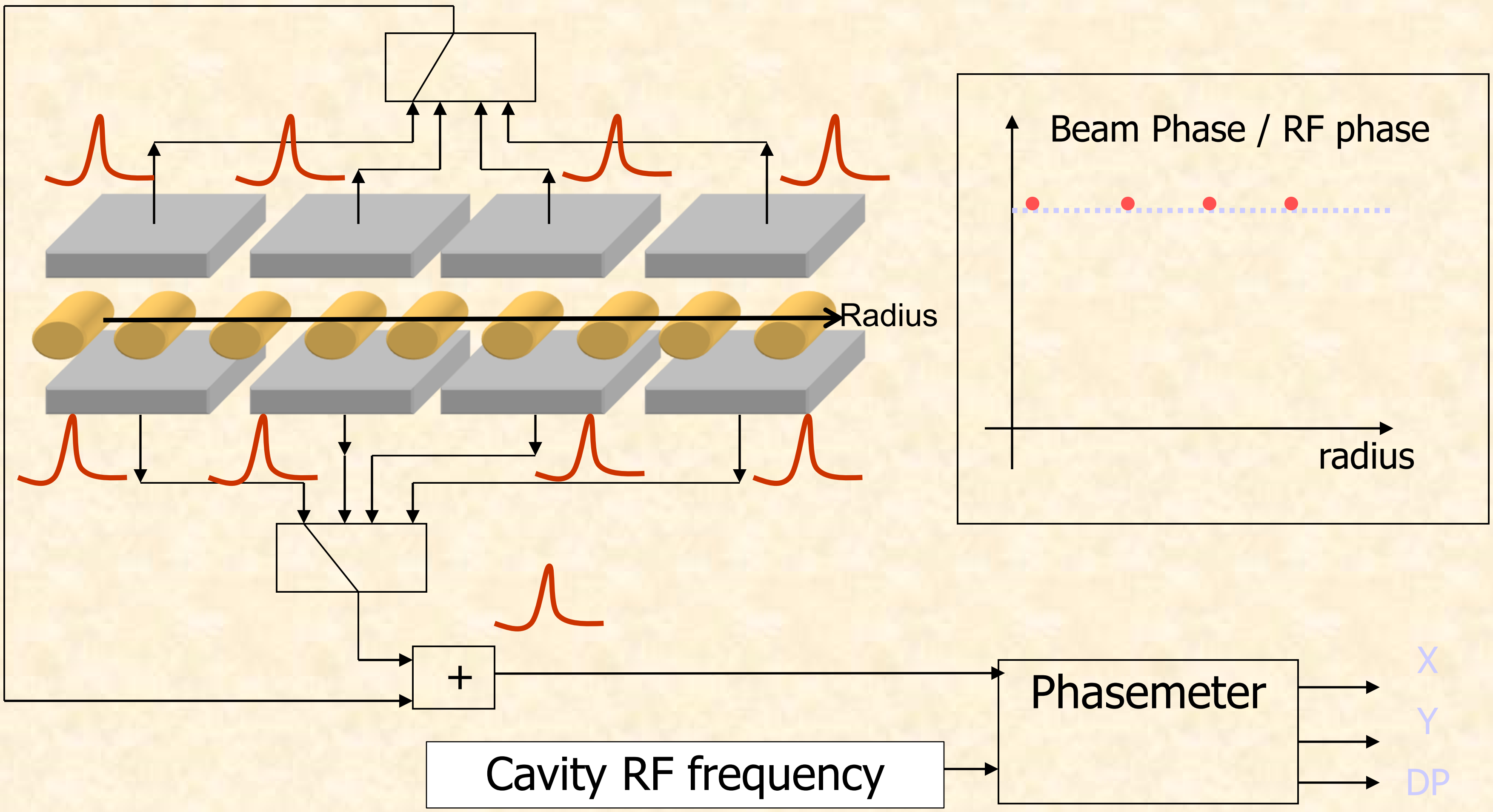


Beam

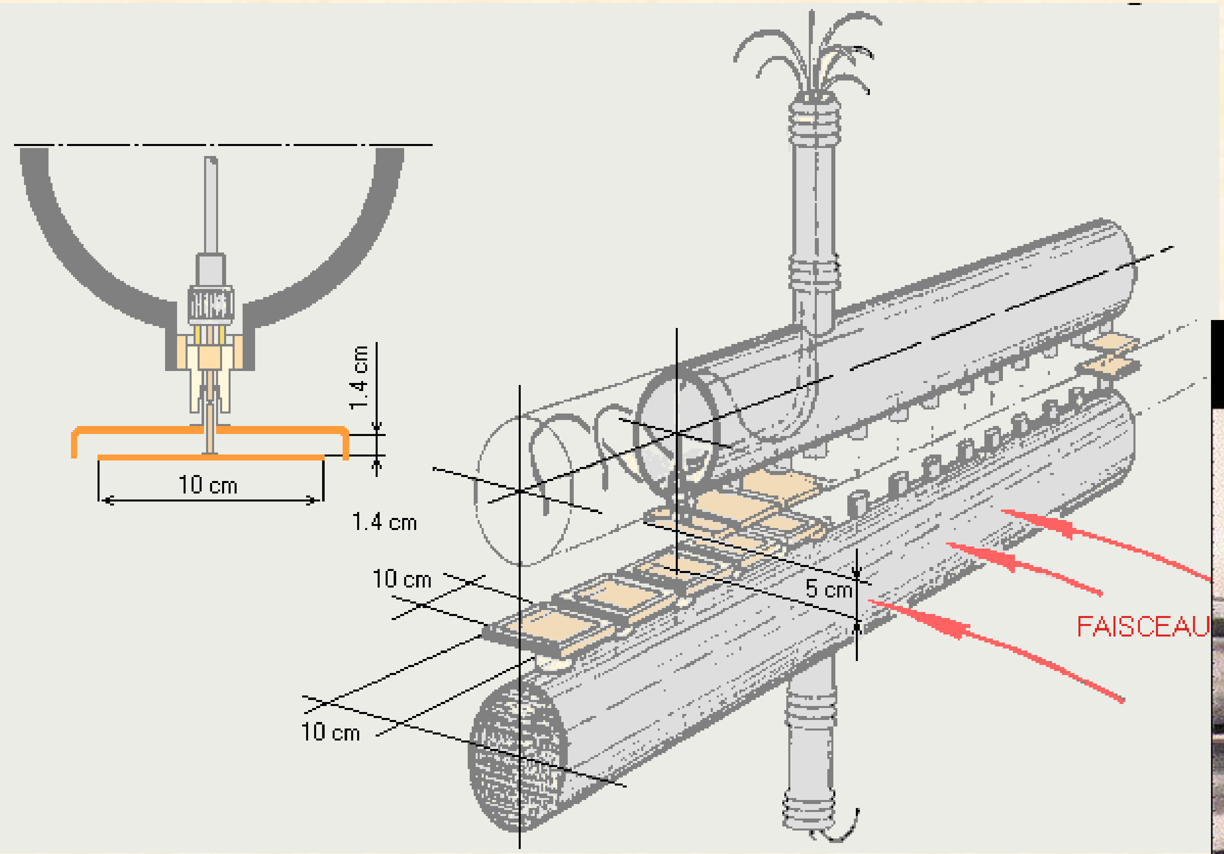


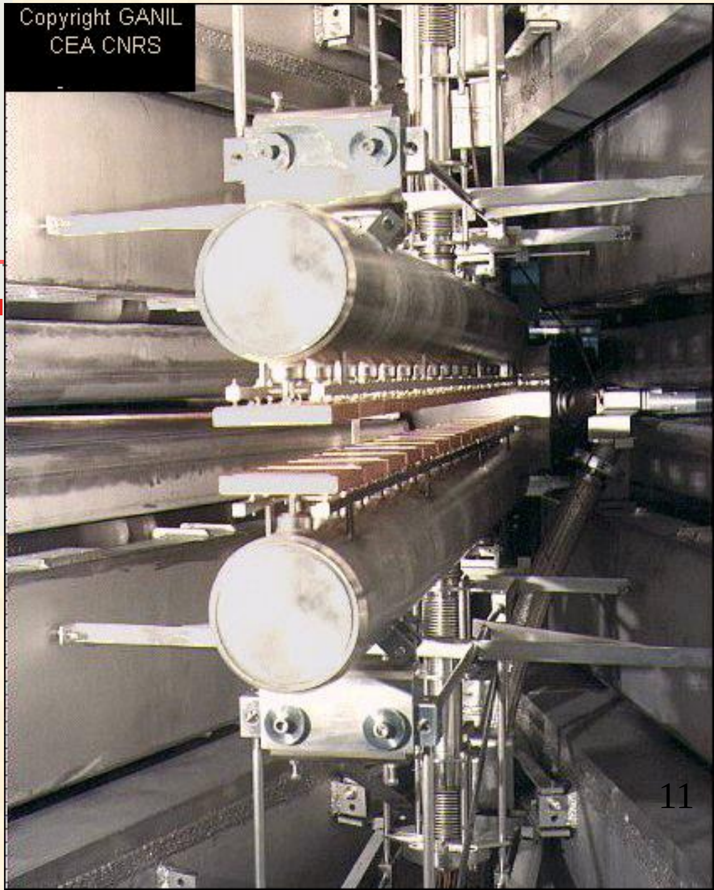



# Phase measurement: Isochronism

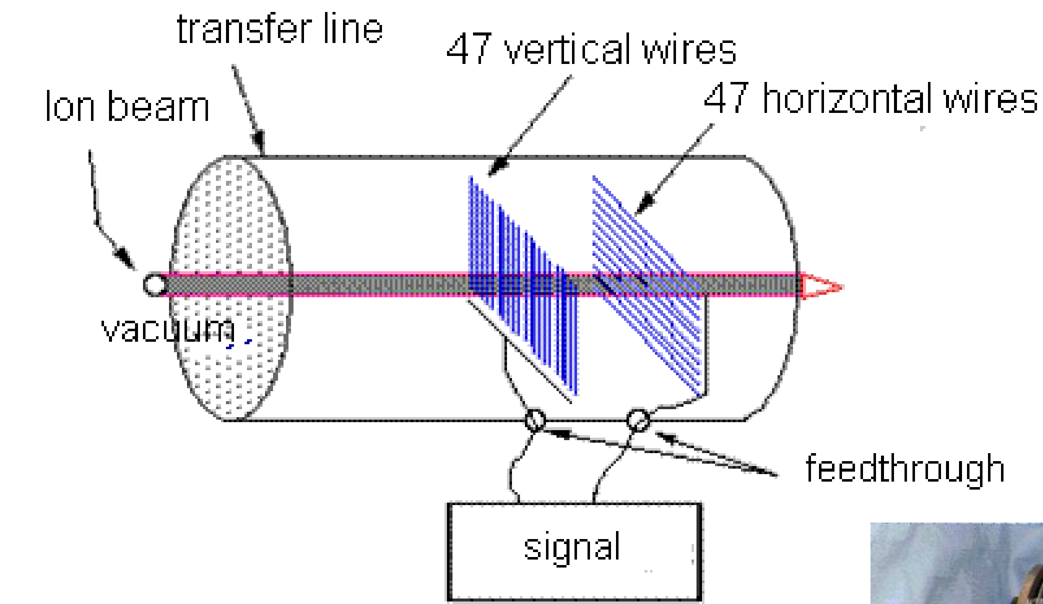


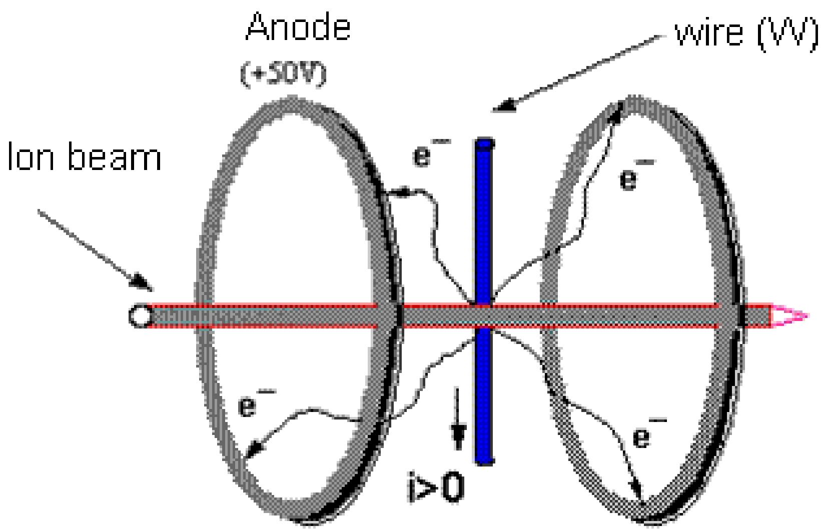
# Phase measurement: Isochronism



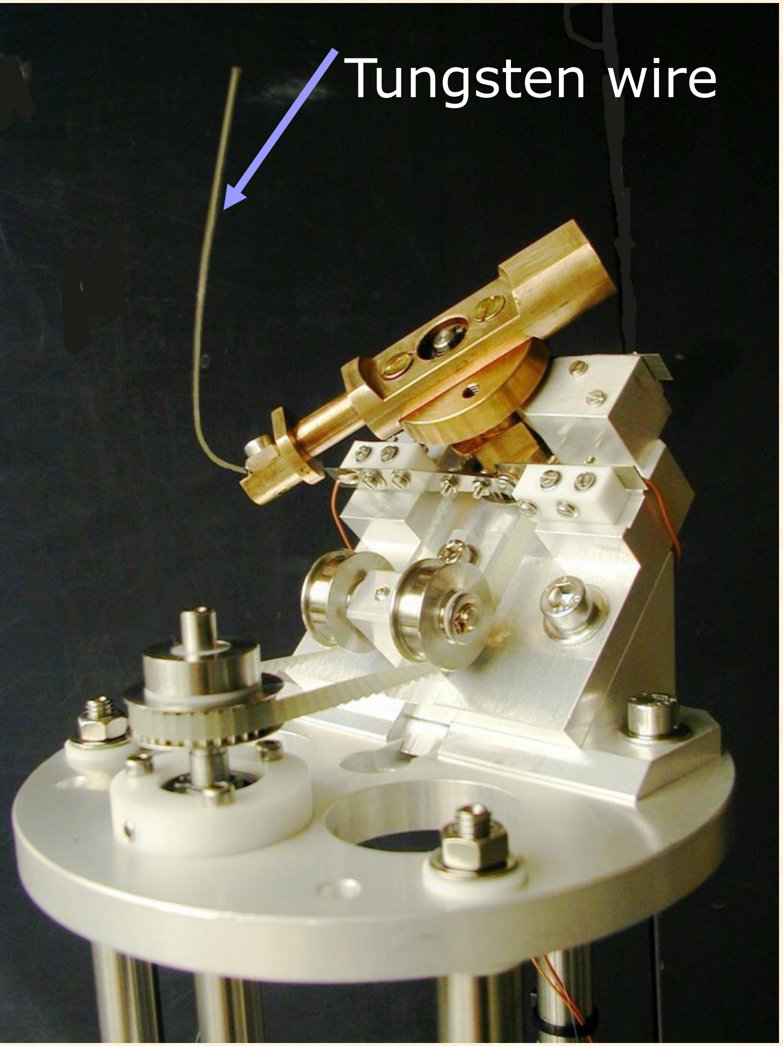



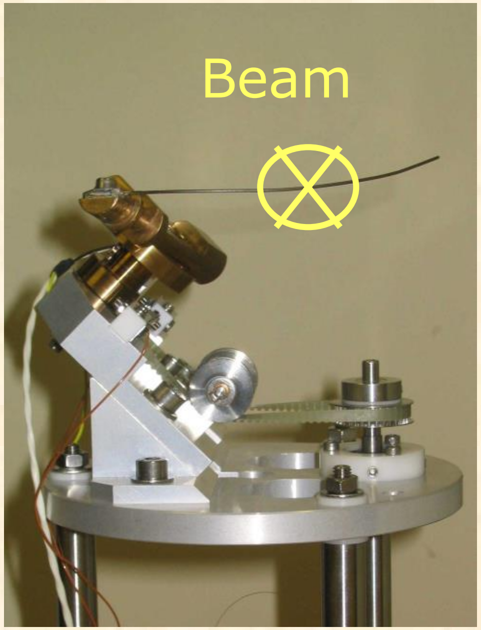
# Beam Profiler: secondary emission current



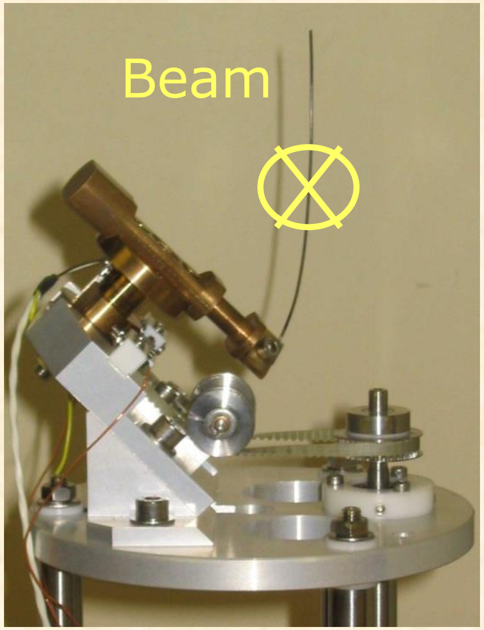




# Profiler : wire scanner



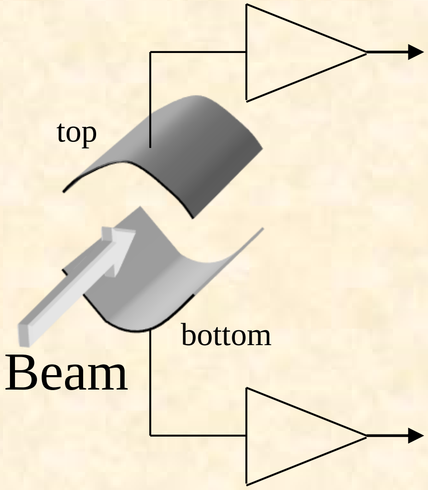



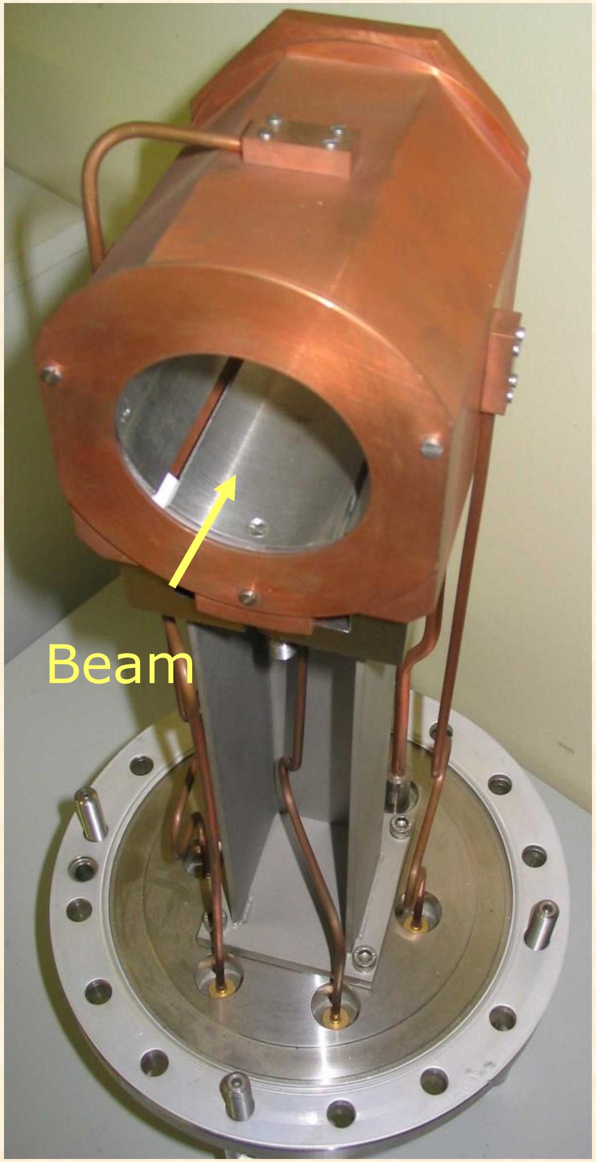

Wire in vertical position




Wire in horizontal position

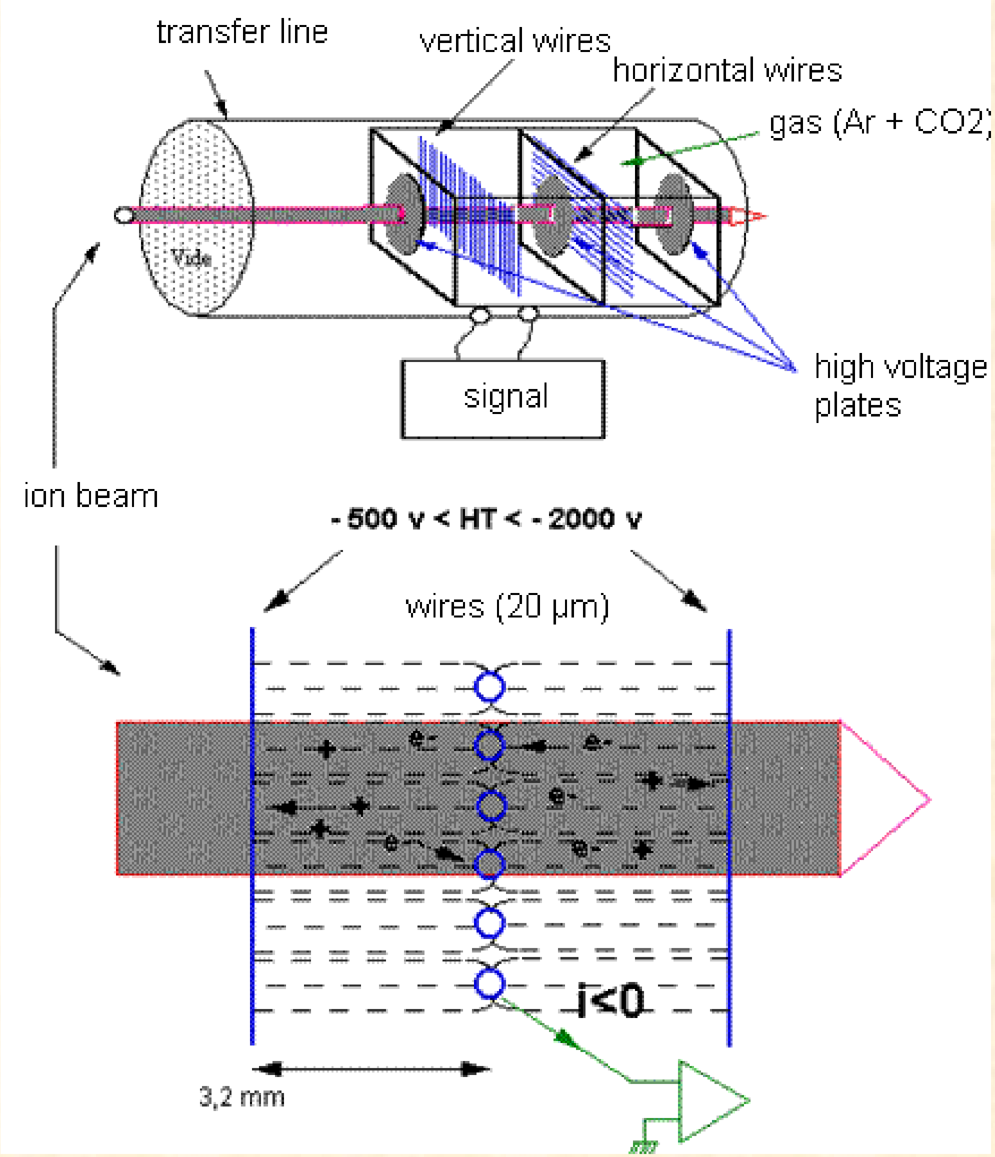
# Beam position monitor



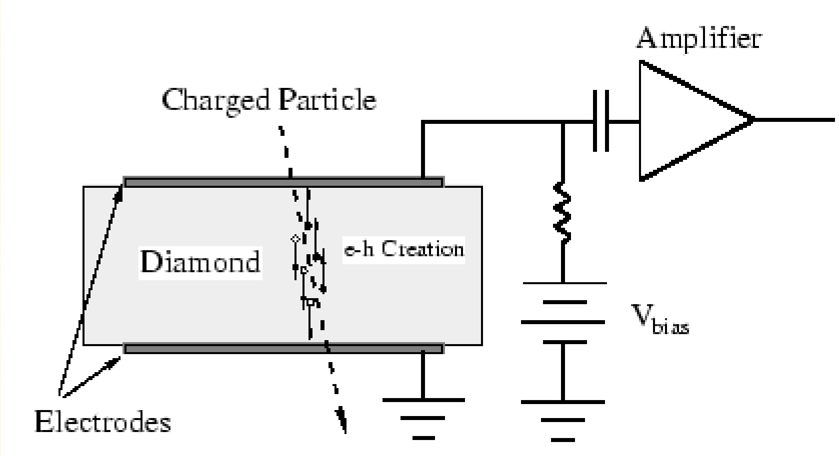
# Low intensity diagnostics
# $< 10^9$ pps

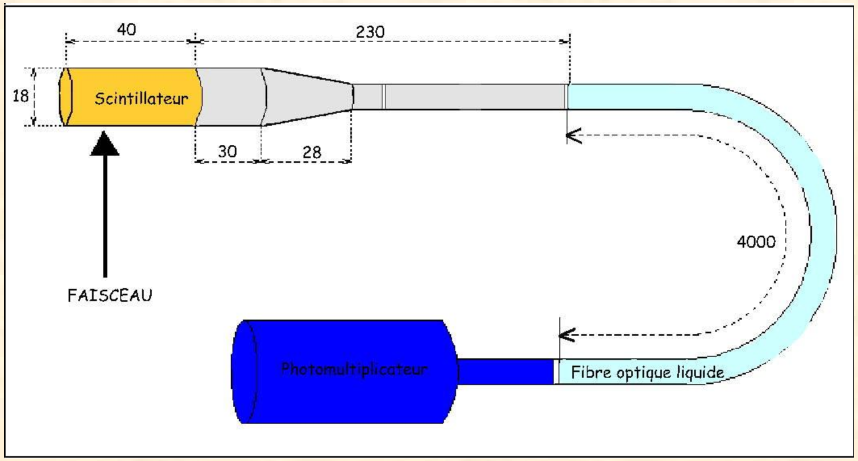
# Gas Profiler

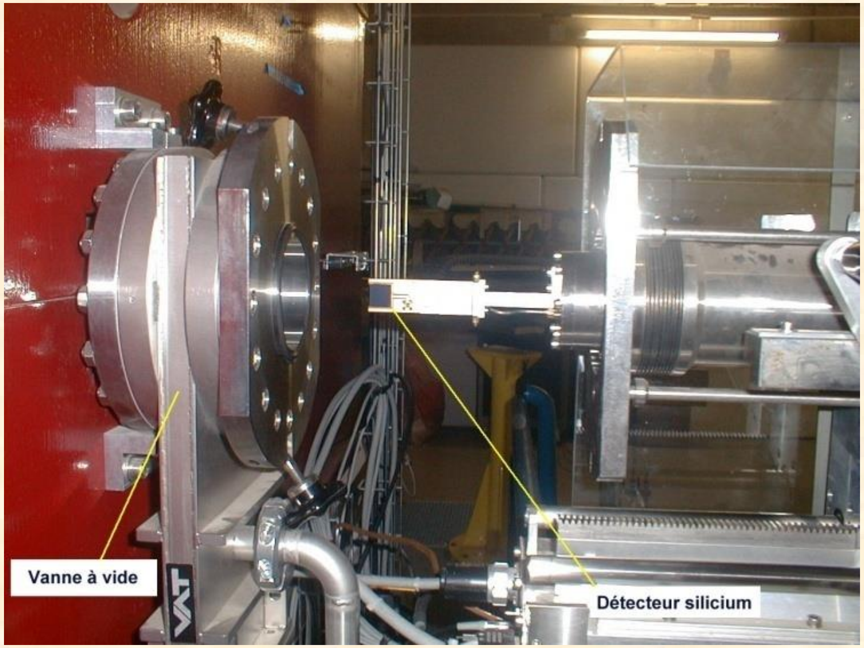


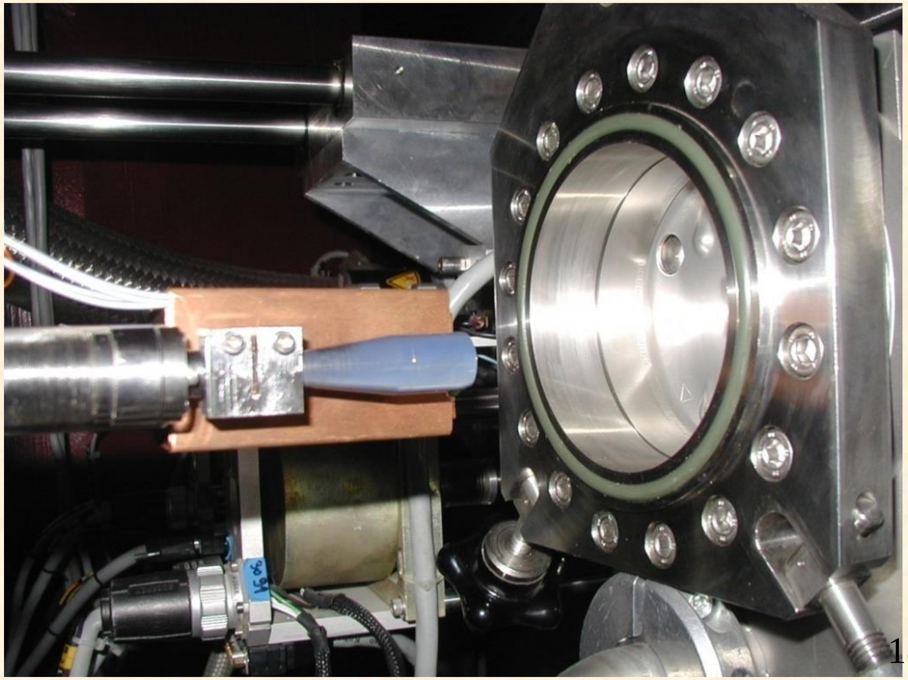
# Gaz Profiler

# From Physics diagnostics



# Back to dynamics and instabilities

# Resonances

During the acceleration, $\nu_r$ and $\nu_z$ change because $\nu_{r,z} \propto B(r)$

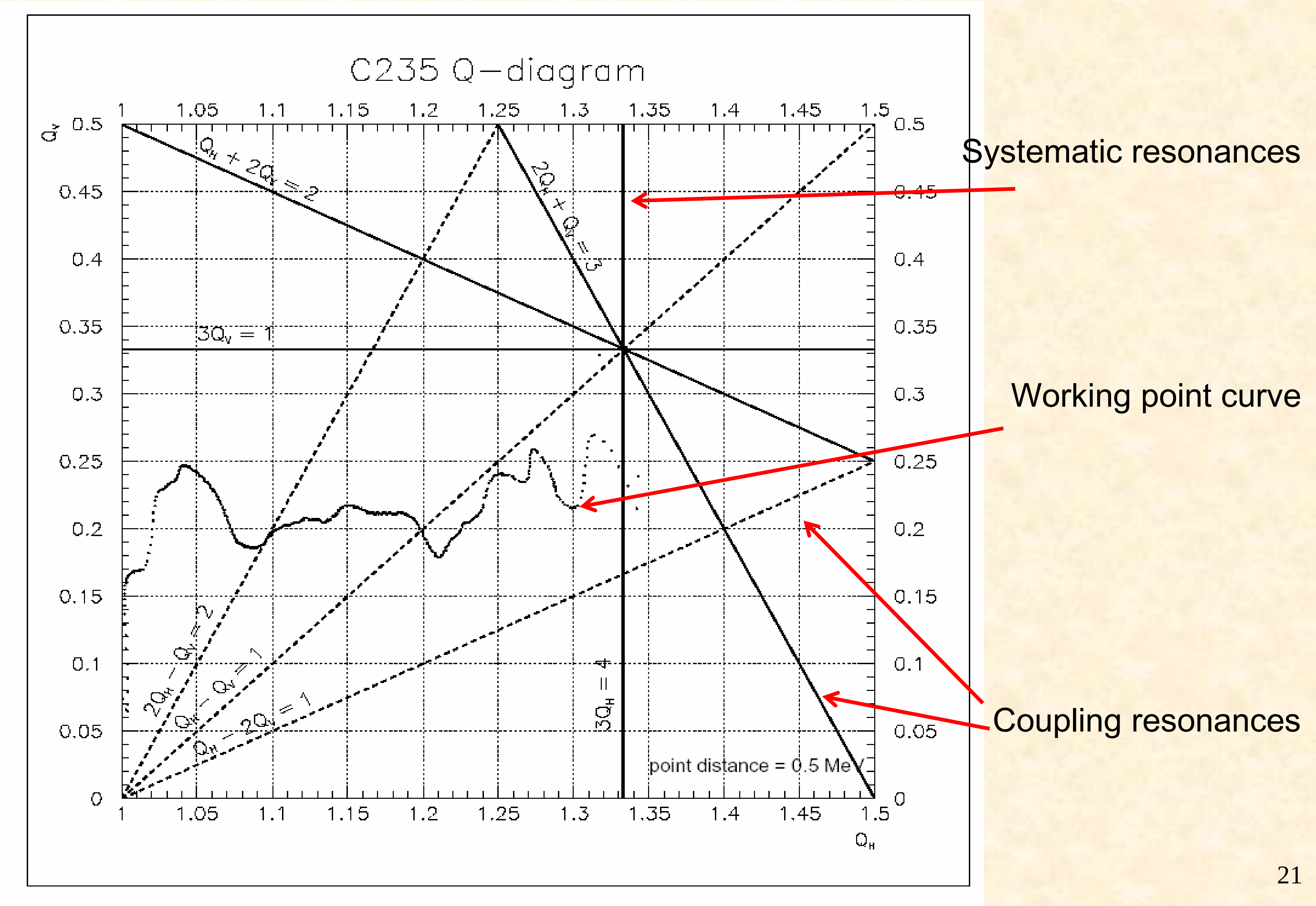
The plot of $\nu_r$ vs $\nu_z$ is called the **working point diagram.**

Like any oscillatory phenomenon, the amplitude of a betatronic motion can grow uncontrolled whenever an external source excites it with its own frequency.

This **resonance occurs as the betatronic** frequency is a multiple of the "geometrical frequency" of the cyclotron. In this case, any kick given to the particle because of its particular position will be experienced again and again. These are known as **systematic resonances**

Under proper circumstances and frequency ratios, the 2 oscillators can be coupled and the energy stored in one motion, transferred to the other. These are **coupling resonances ($K.\nu_r + L.\nu_z = P$).**

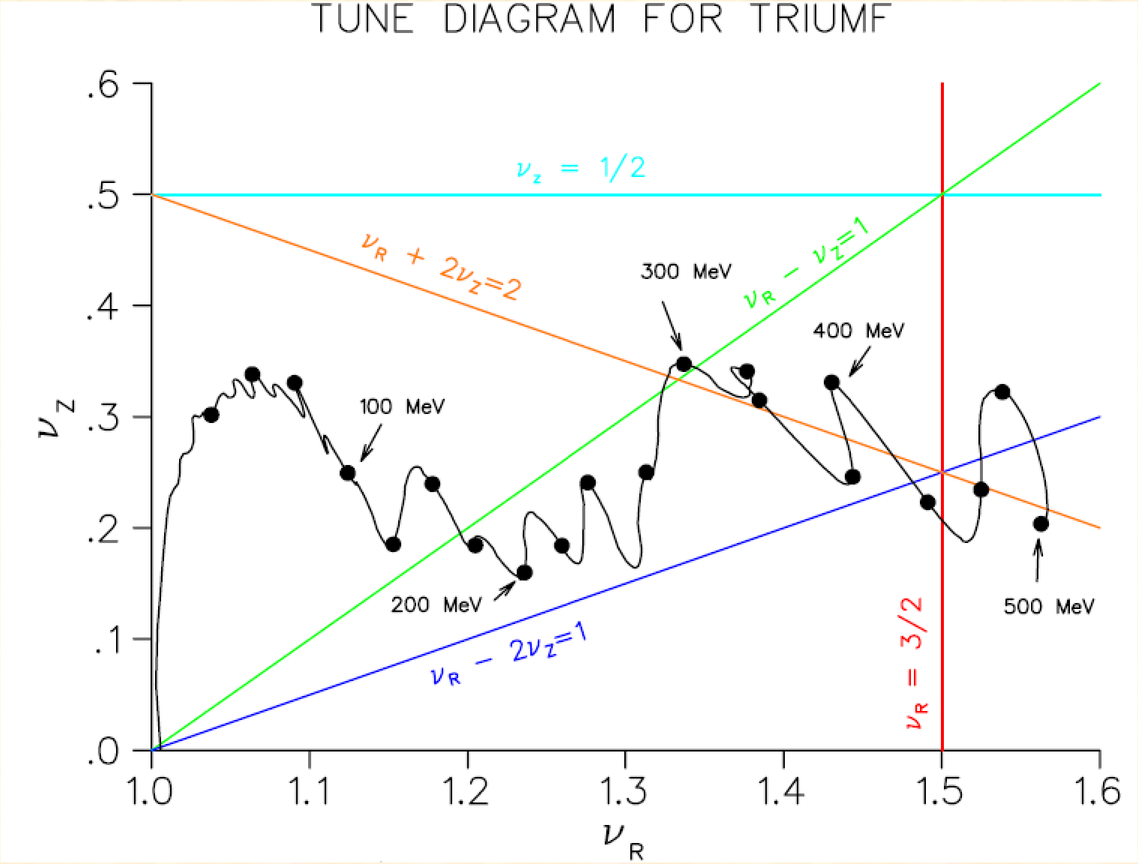
The particle's working point curve should avoid or cross as fast as possible those lines.


C235 Q−diagram
$Q_V$
$Q_H$
$Q_H + 2Q_V = 2$
$2Q_H + Q_V = 3$
$3Q_V = 1$
$3Q_H = 4$
$2Q_H - Q_V = 2$
$Q_H - Q_V = 1$
$Q_H - 2Q_V = 1$
point distance = 0.5 MeV
Systematic resonances
Working point curve
Coupling resonances

# Tunes and resonances

$$\mathbf{K.\nu_r + L.\nu_z = P}$$

- K, L and P integer
- |K| + |L| is called the resonance order (1, 2, 3 …)




W ∝ r²

# Cyclotron as a separator

For an isochronous ion ($Q_0$, $m_0$): $\omega_{rev} = \dfrac{Q_0 \; B(r)}{m_0 \; \gamma}$

Constant energy gain per turn: $\delta T \approx QV_0 \cos(\varphi)$

For ions with a Q/m different from the isochronous beam $Q_0/m_0$, $\omega \neq \omega_{rev}$

There is a phase shift of this ion compared to the RF field during acceleration

$$\Delta\varphi = 2\pi N h \frac{1}{\gamma^2} \frac{\Delta(m/Q)}{m_0/Q_0}$$

when the phase $\varphi$ reaches 90°, the beam is decelerated and lost.

# Cyclotron resolution

There is the possibility to have out of the source not only the desired ion beam ($m_0$,$Q_0$) but also beams with close Q/m ratio.

If the mass resolution of the cyclotron is not enough, both beams will be accelerated, extracted and sent to the physics experiments.

Mass resolution:

$$R = \frac{\Delta\left(\frac{m}{Q}\right)}{\frac{m_0}{Q_0}} = \frac{1}{2\pi\ h N}$$

We want R small ⇨separation of close ions

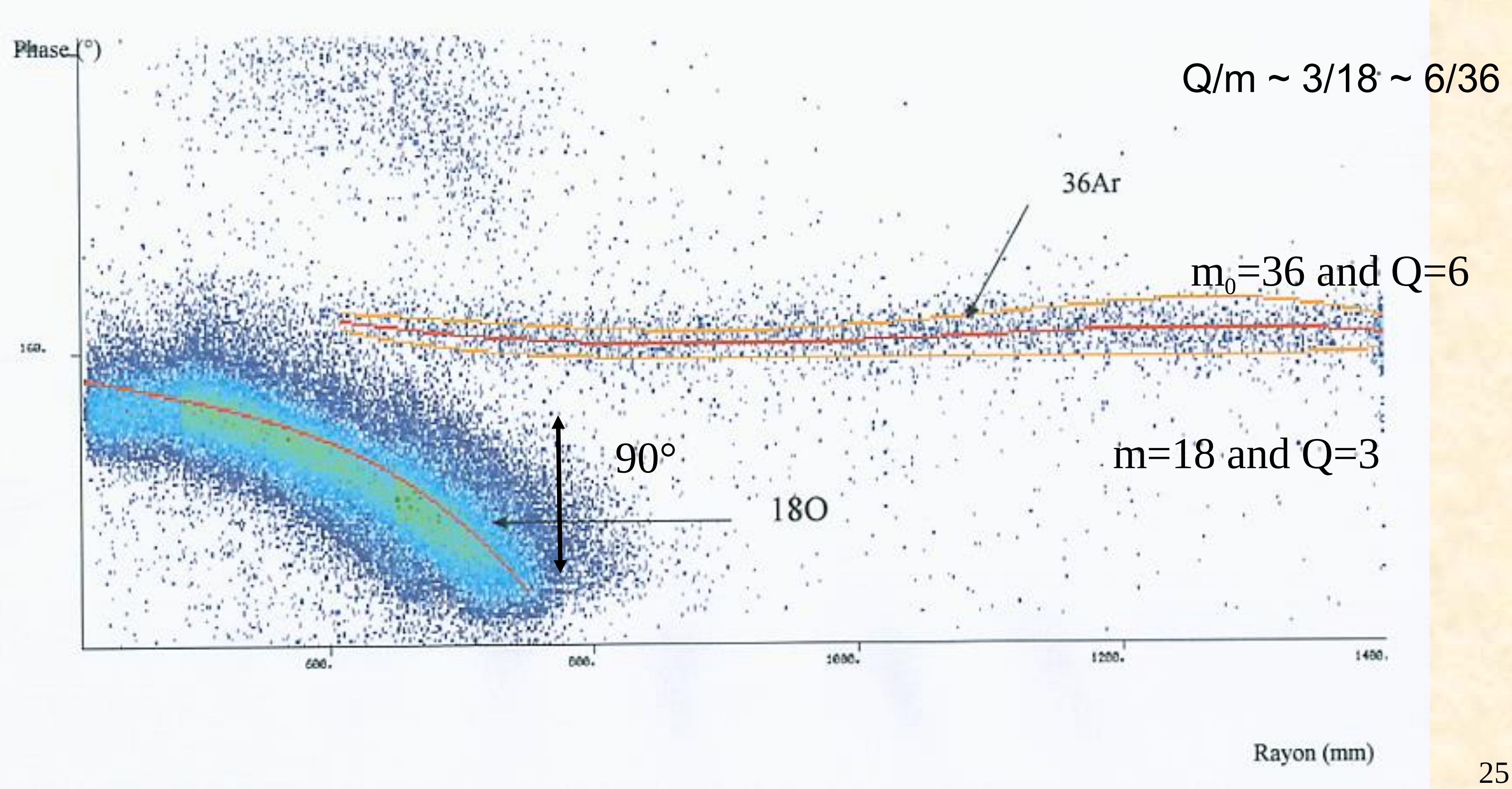
CIME example: h=3, N = 300 ⇨ R~ 10-4

Meaning that ions with a m/Q > 1.0001×m0/Q0 will not be extracted

To have R small for a given harmonic h, the number of turn N needs to be increased ⇨ lowering the accelerating voltage ⇨ small turn separation ⇨ poor injection and/ or extraction (great problems for new exotics beam machines : isobar and contamination for new machine…)

# Cyclotron as a separator

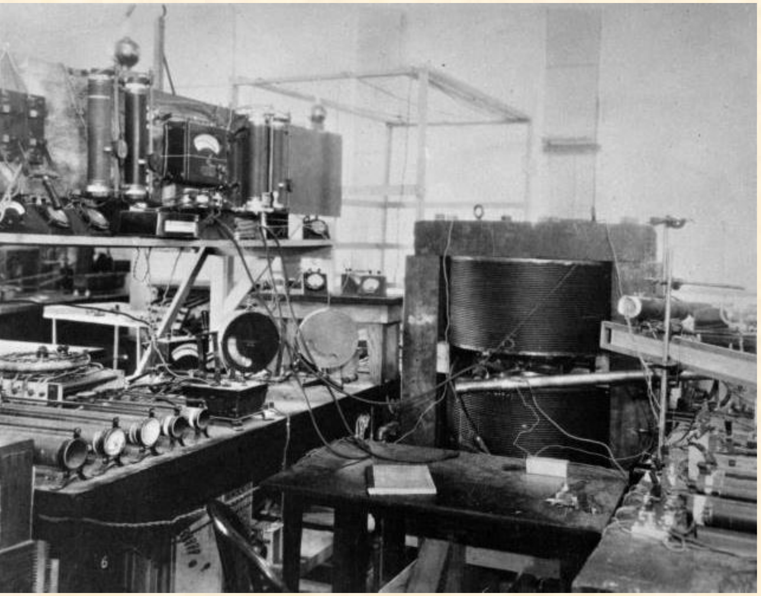
$$\Delta\varphi = 2\pi N h \frac{1}{\gamma^2} \frac{\Delta(m/Q)}{m_0/Q_0}$$



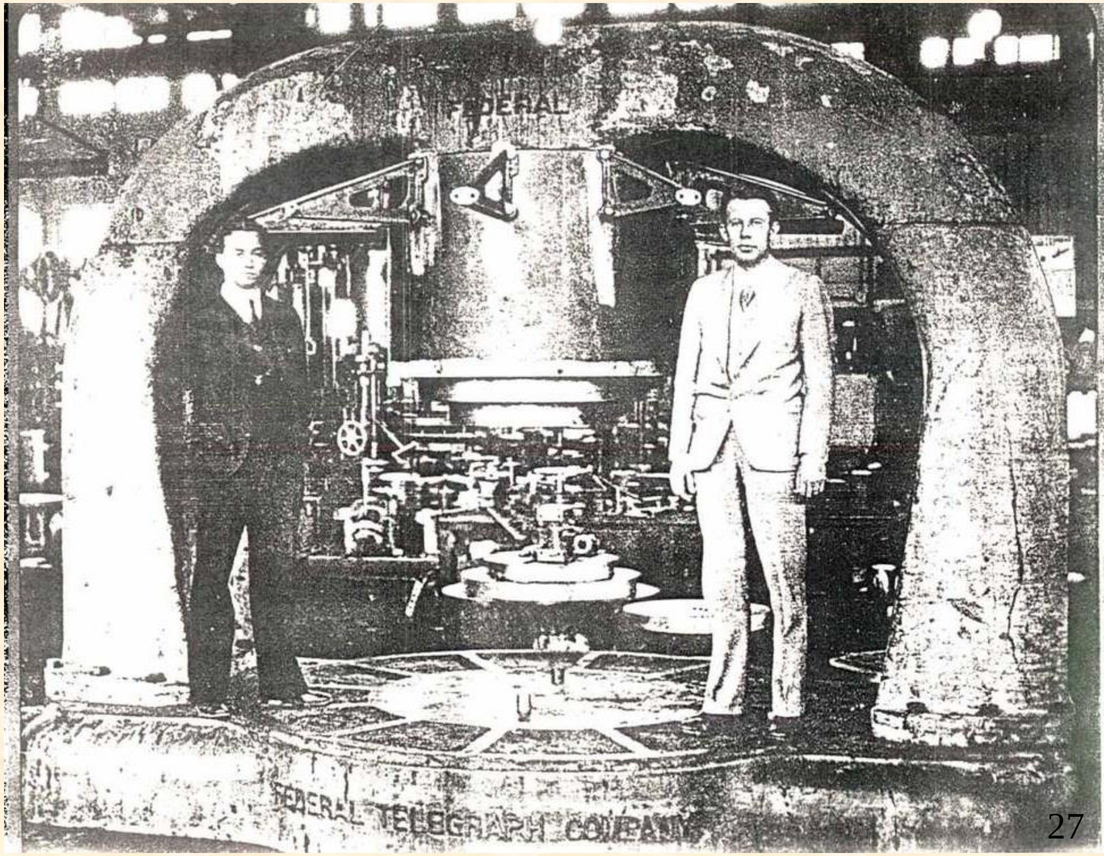
# Few cyclotrons

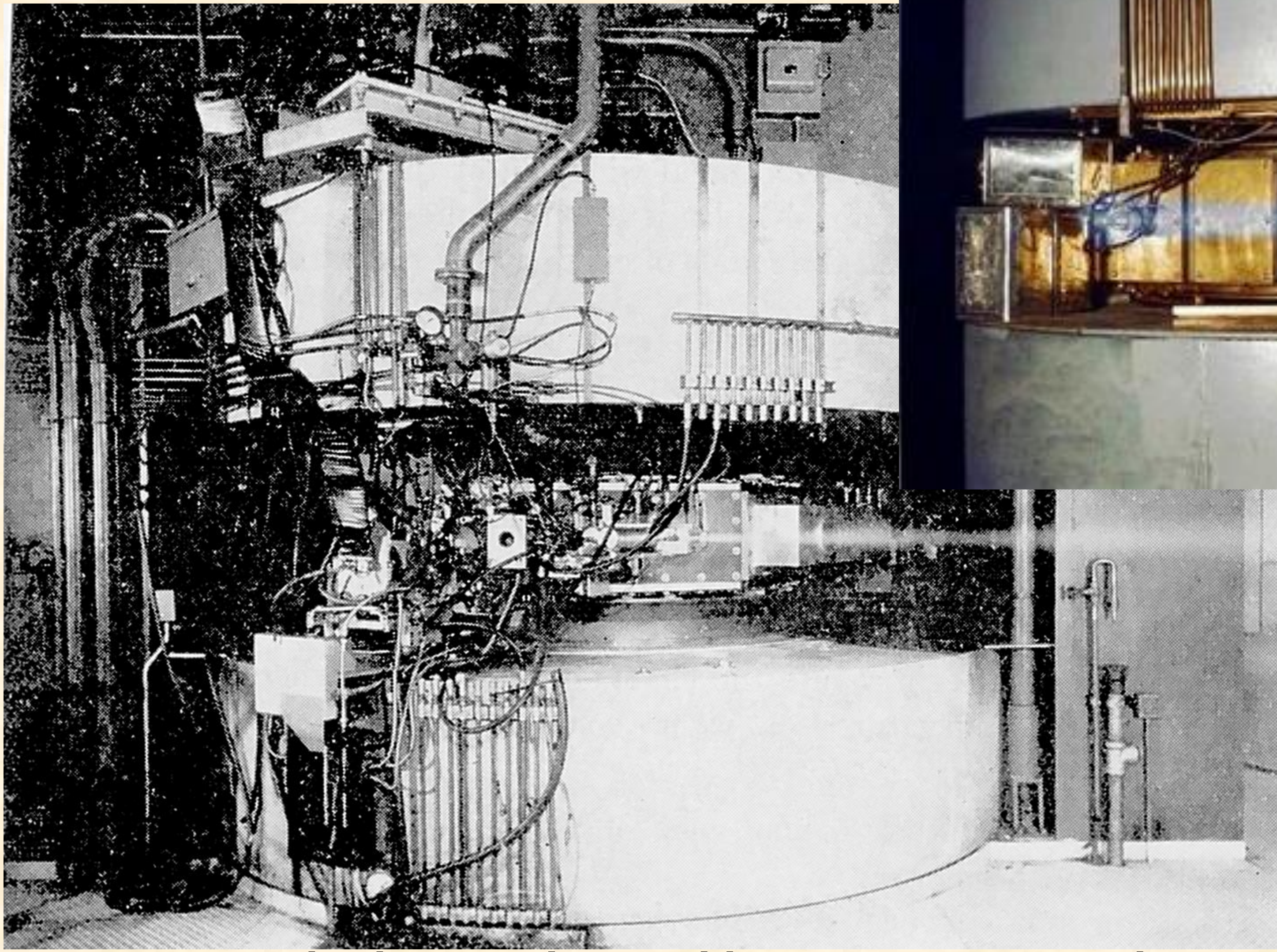
# The beginning

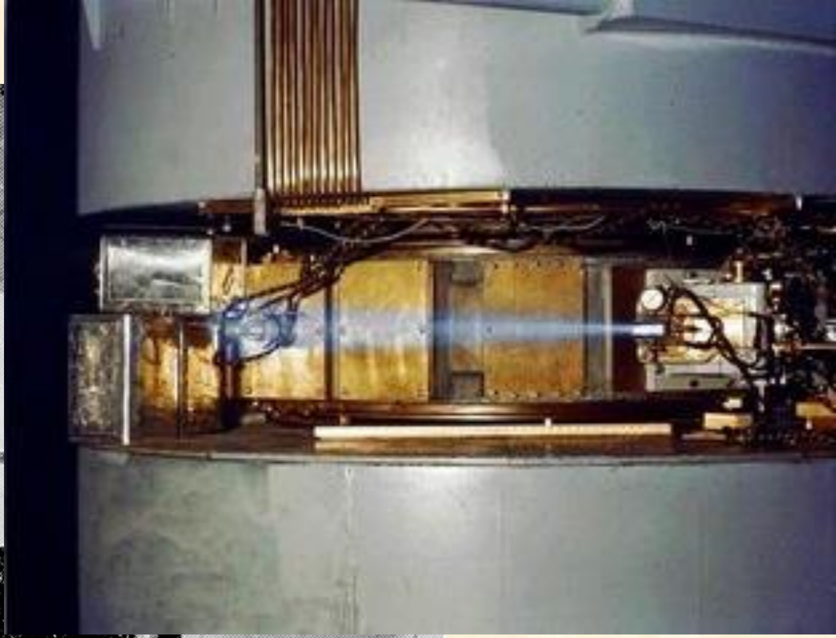
The 11-inch cyclotron and lab bench equipment.



1933 : Livingston (left) and Lawrence with the 27-inch (later 37-inch) cyclotron.





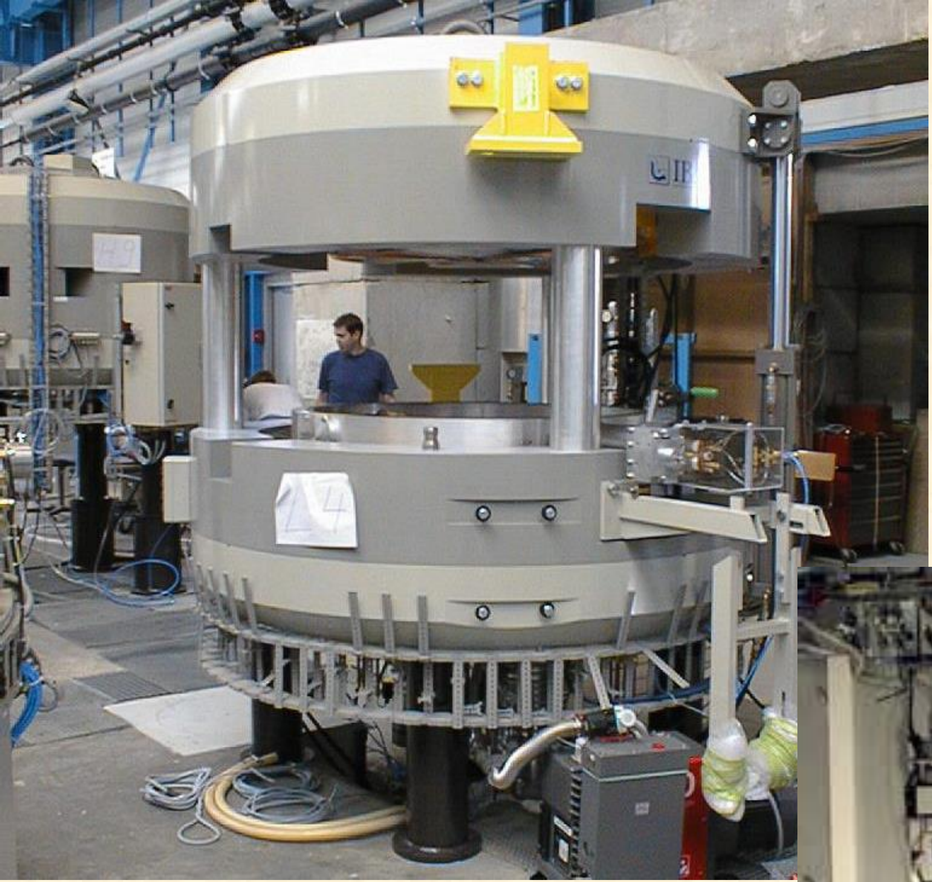


**Argonne 60 inches cyclotron (deutons 21,6 MeV deuton beam out of an aluminium foil)**


**Karlsruhe cyclotron.**

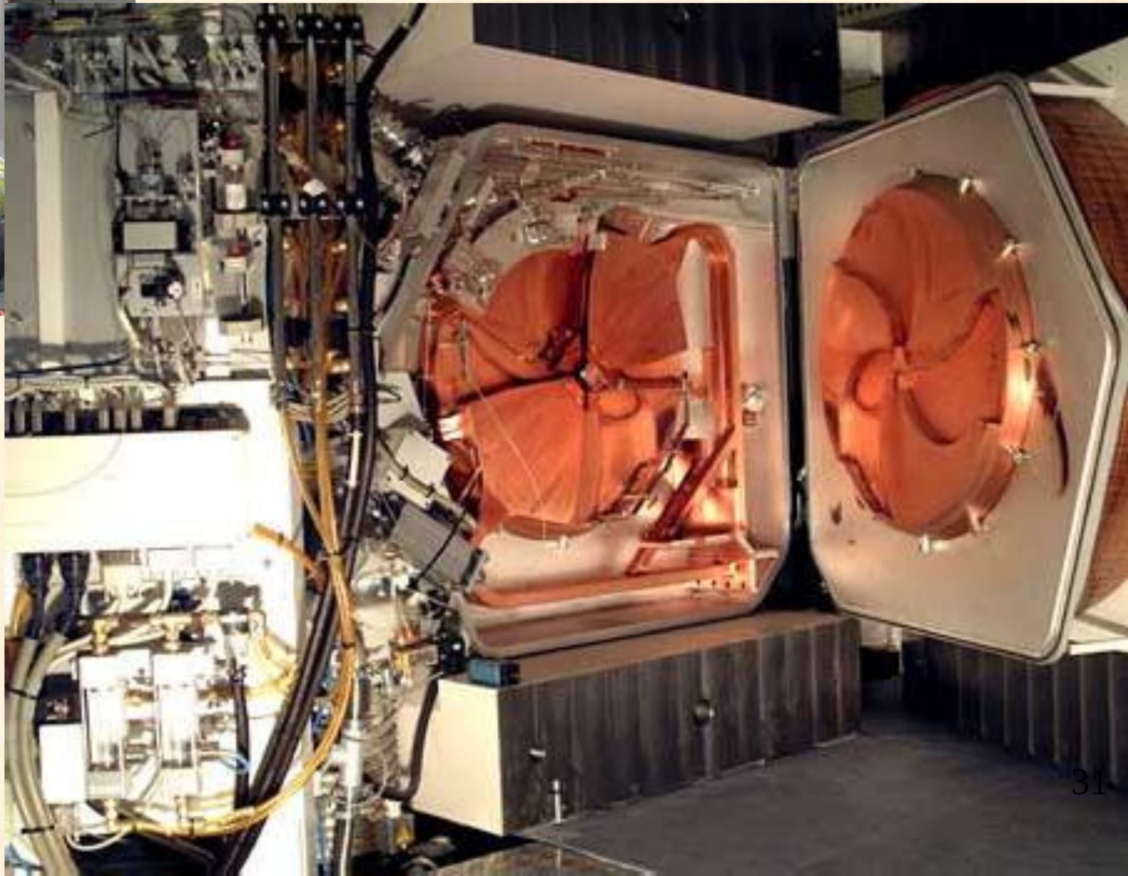
**CYCLONE 30 (IBA) : $H^-$ 15 à 30 MeV**

**primarily designed for industrial and medical applications**



Cyclone 10/5

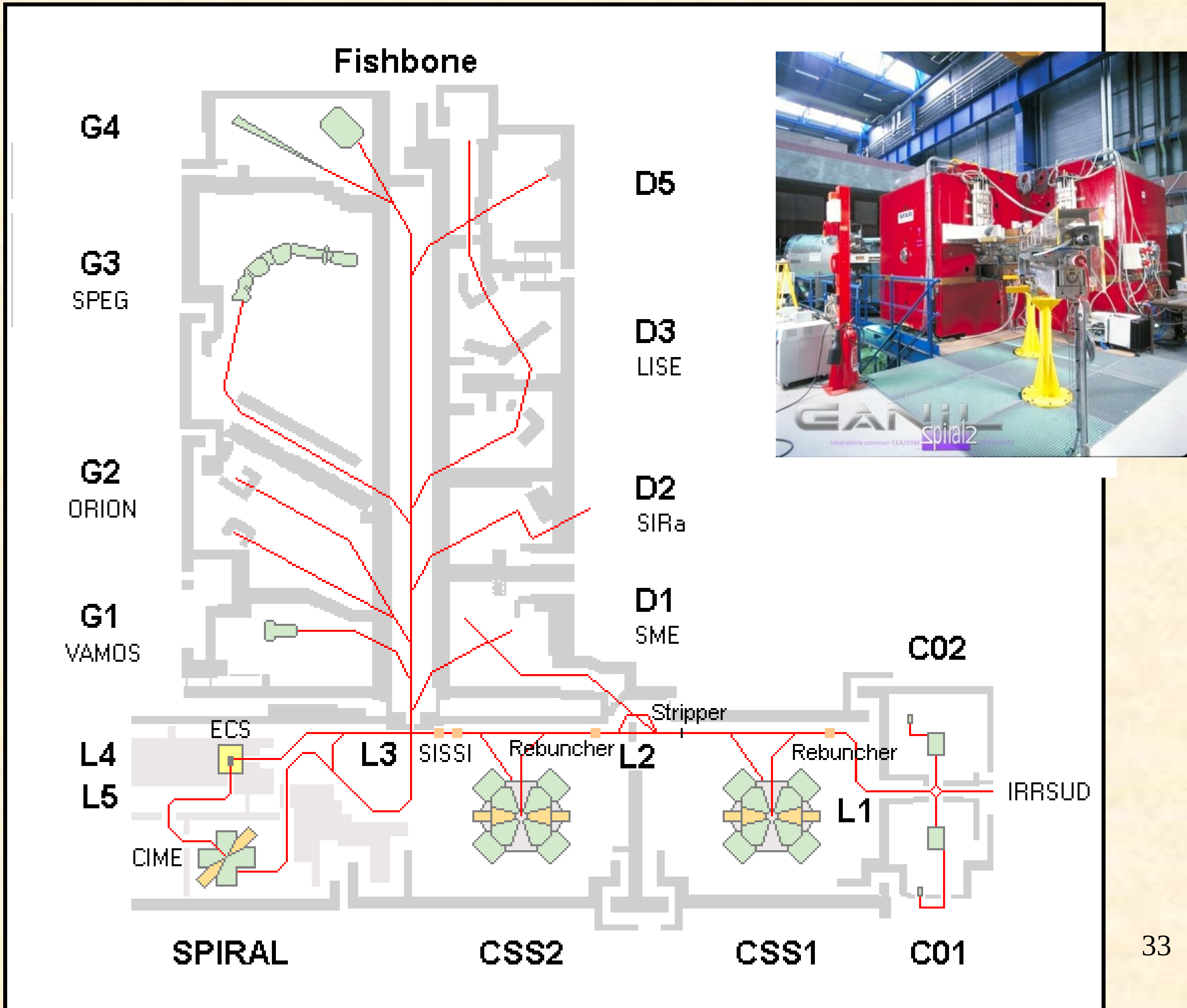
cyclone 3D



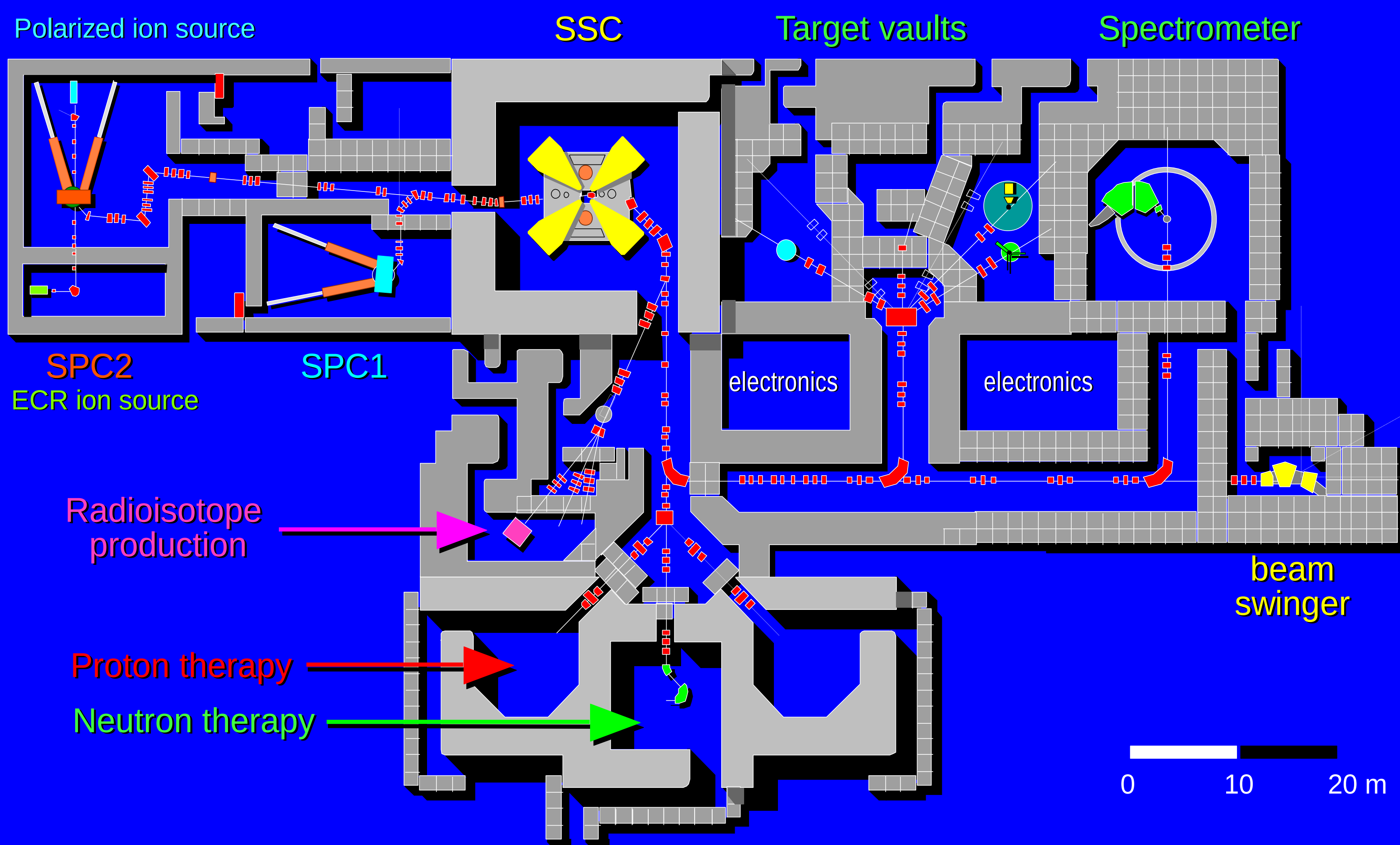
# Cyclotron laboratories

GANIL spiral2

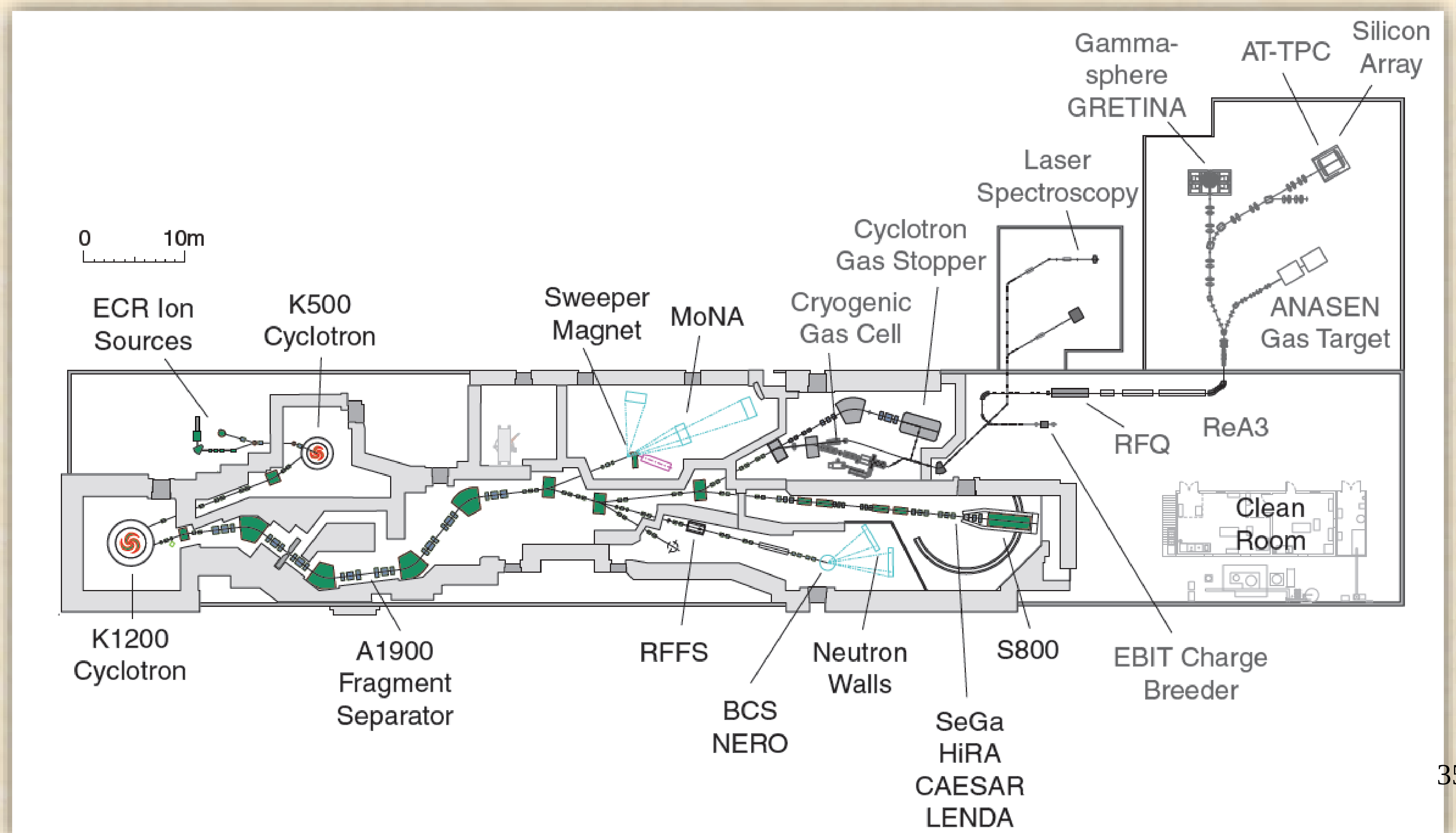
laboratoire commun CEA/DSM CNRS/IN2P3

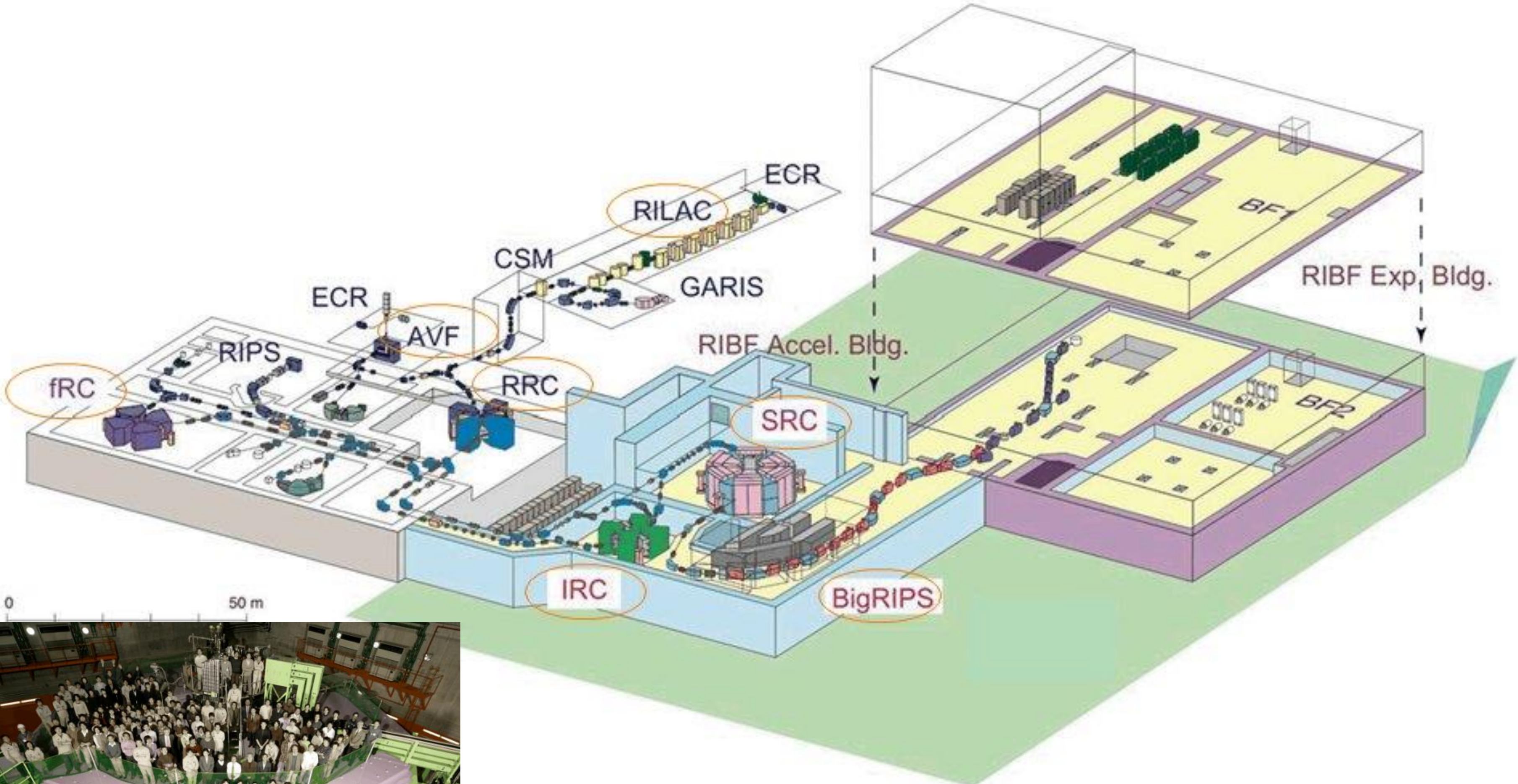


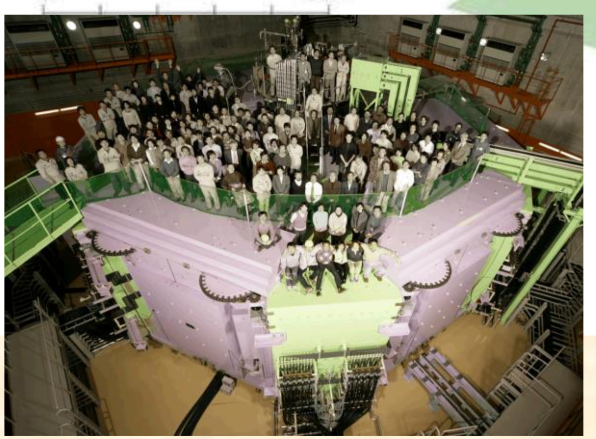
# Separated-Sector Cyclotron Facility

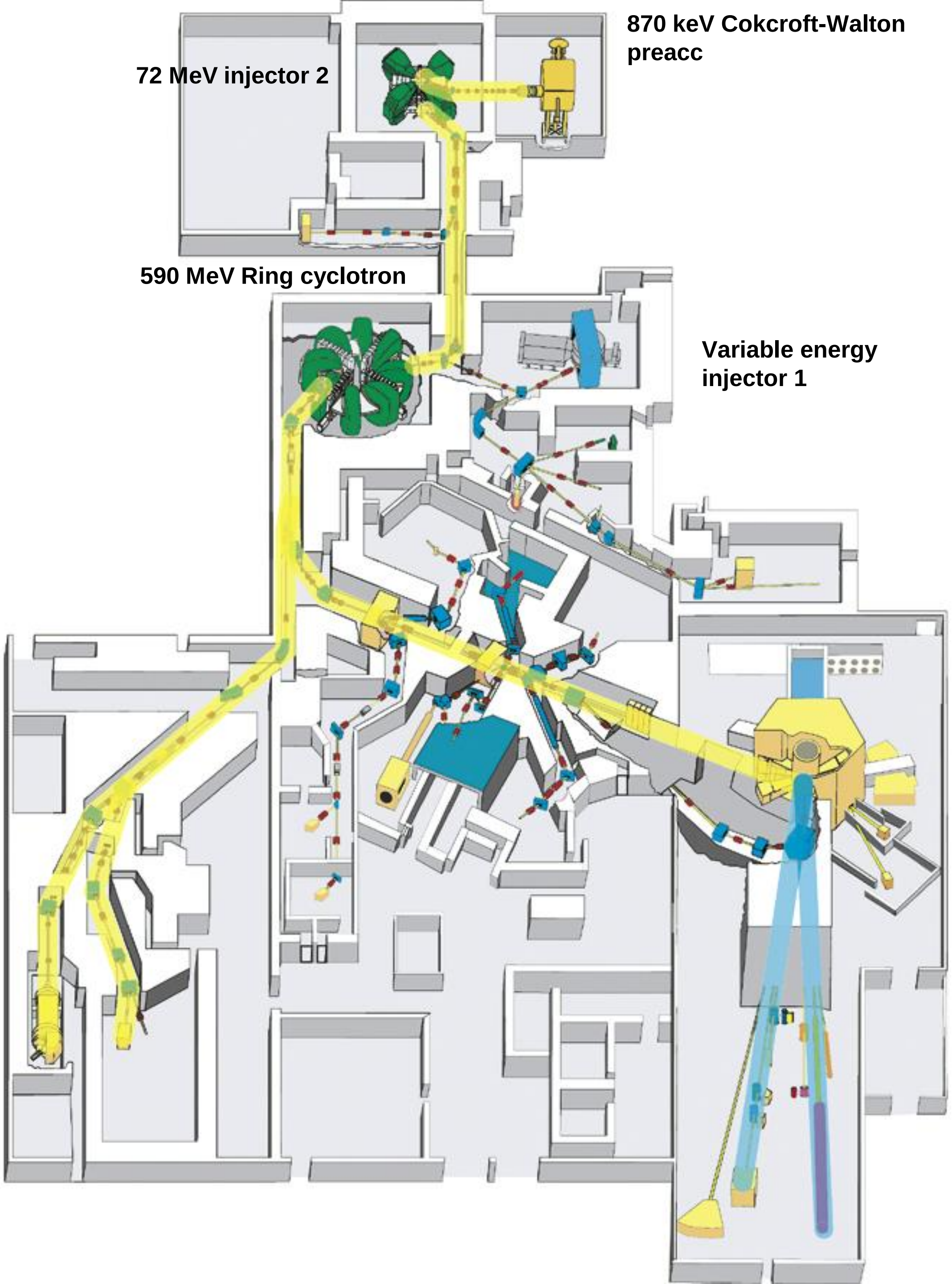


# Michigan State University
# Cyclotrons+A1900+Experimental Areas



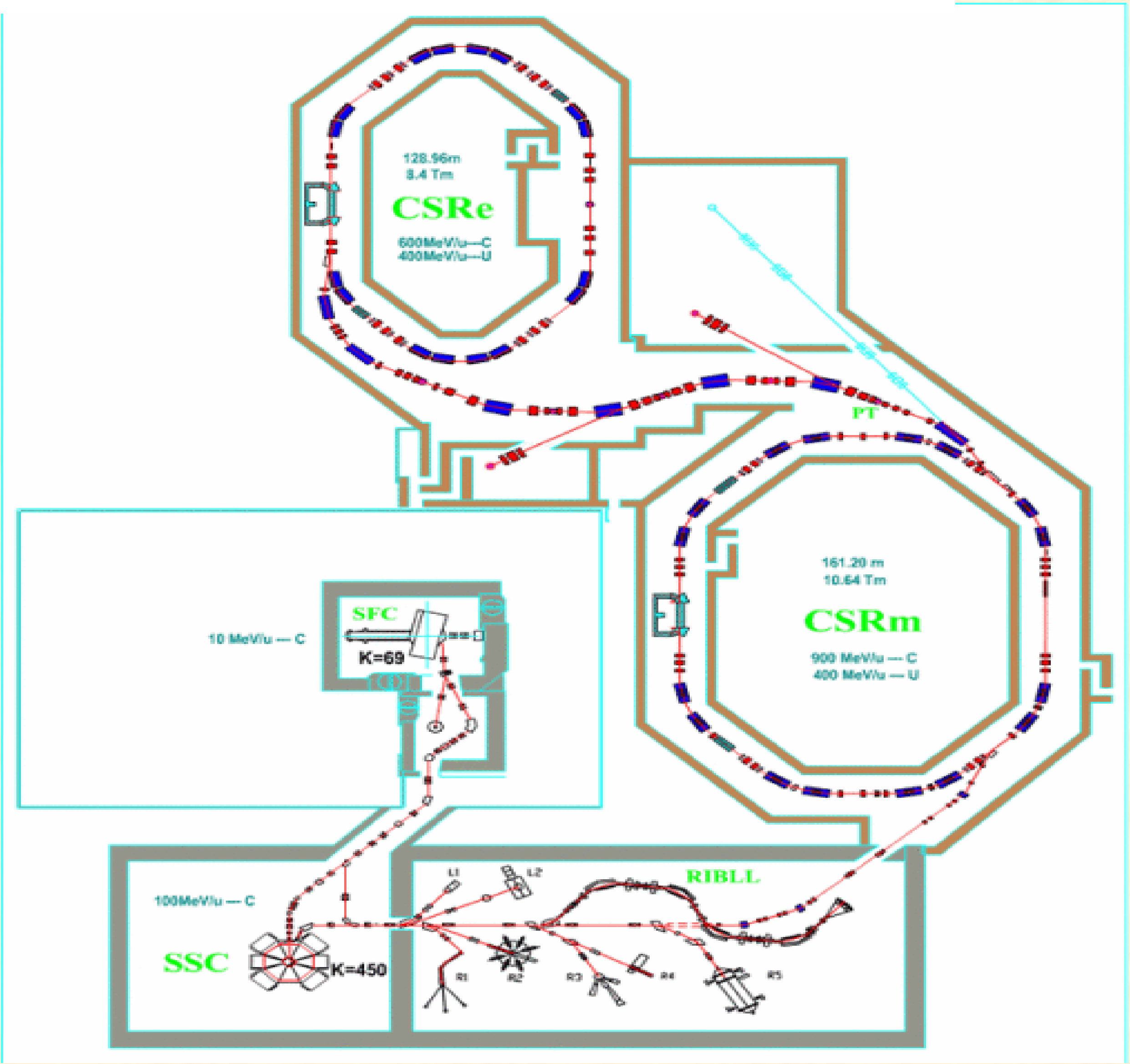

ECR
RILAC
CSM
GARIS
ECR
AVF
RIPS
fRC
RRC
RIBF Accel. Bldg.
SRC
IRC
BigRIPS
BF1
BF2
RIBF Exp. Bldg.
0
50 m

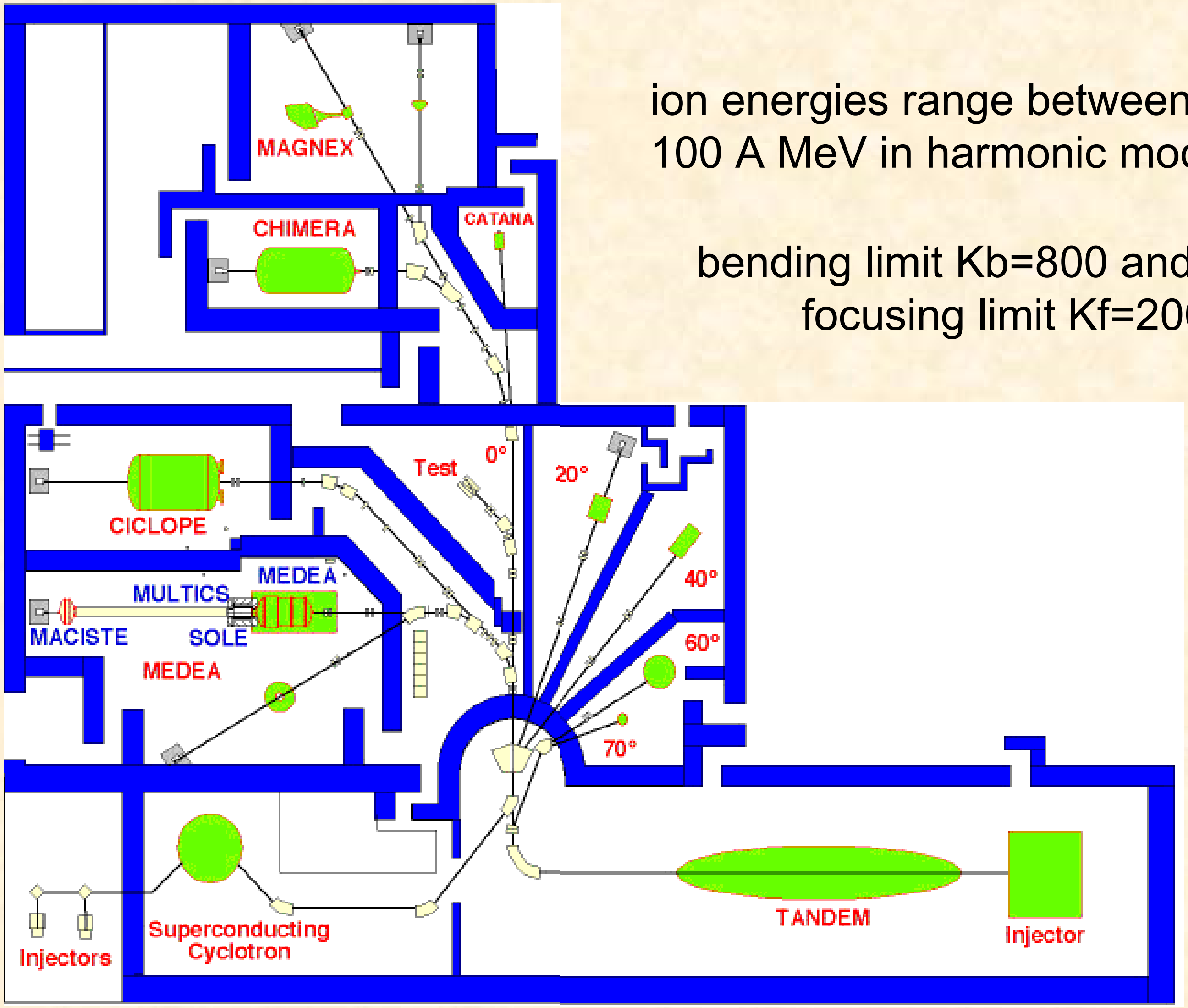





PAUL SCHERRER INSTITUT

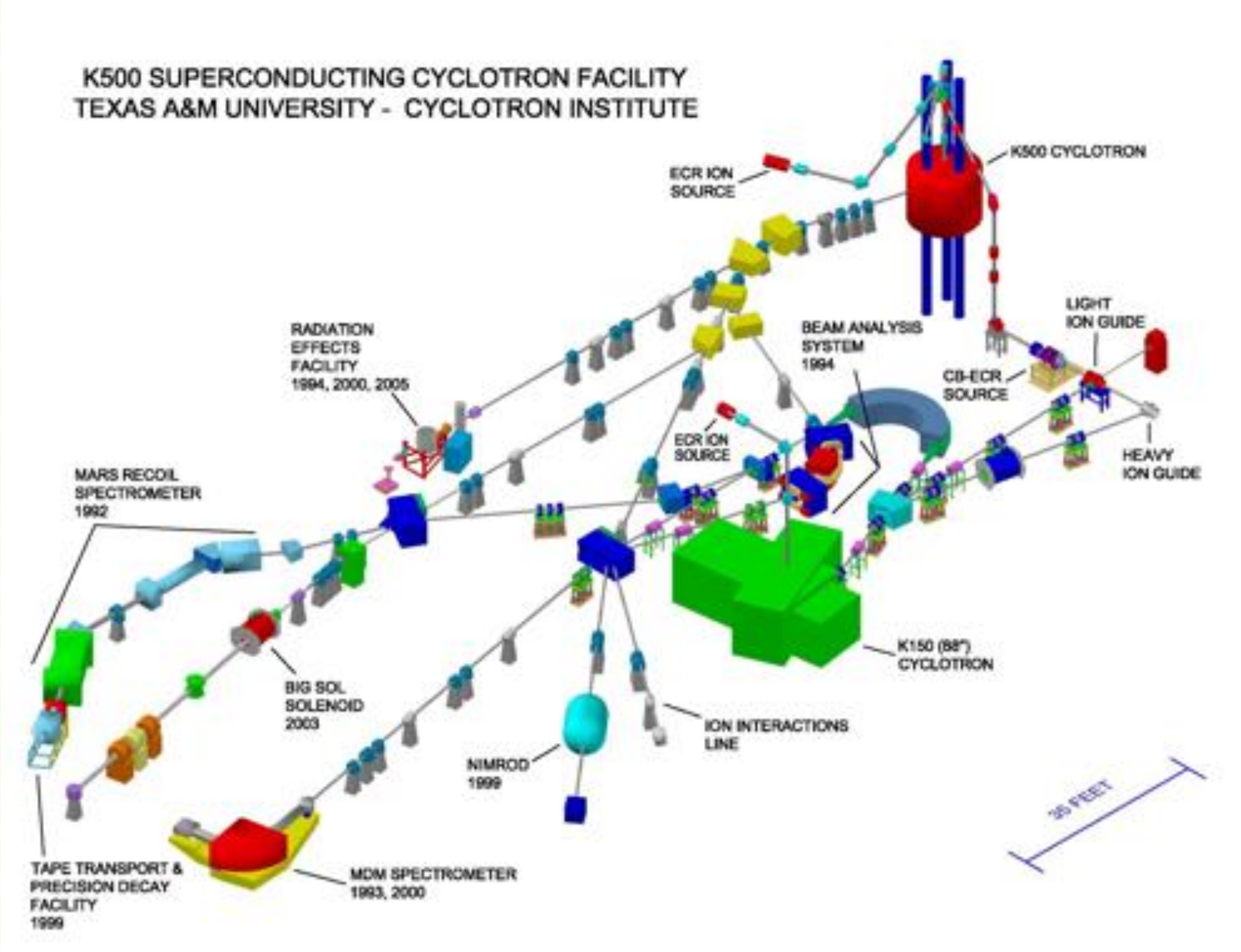
PSI


128.96m
8.4 Tm
CSRe
600MeV/u---C
400MeV/u---U
PT
161.20 m
10.64 Tm
CSRm
900 MeV/u --- C
400 MeV/u --- U
SFC
K=69
10 MeV/u --- C
100MeV/u --- C
SSC
K=450
RIBLL

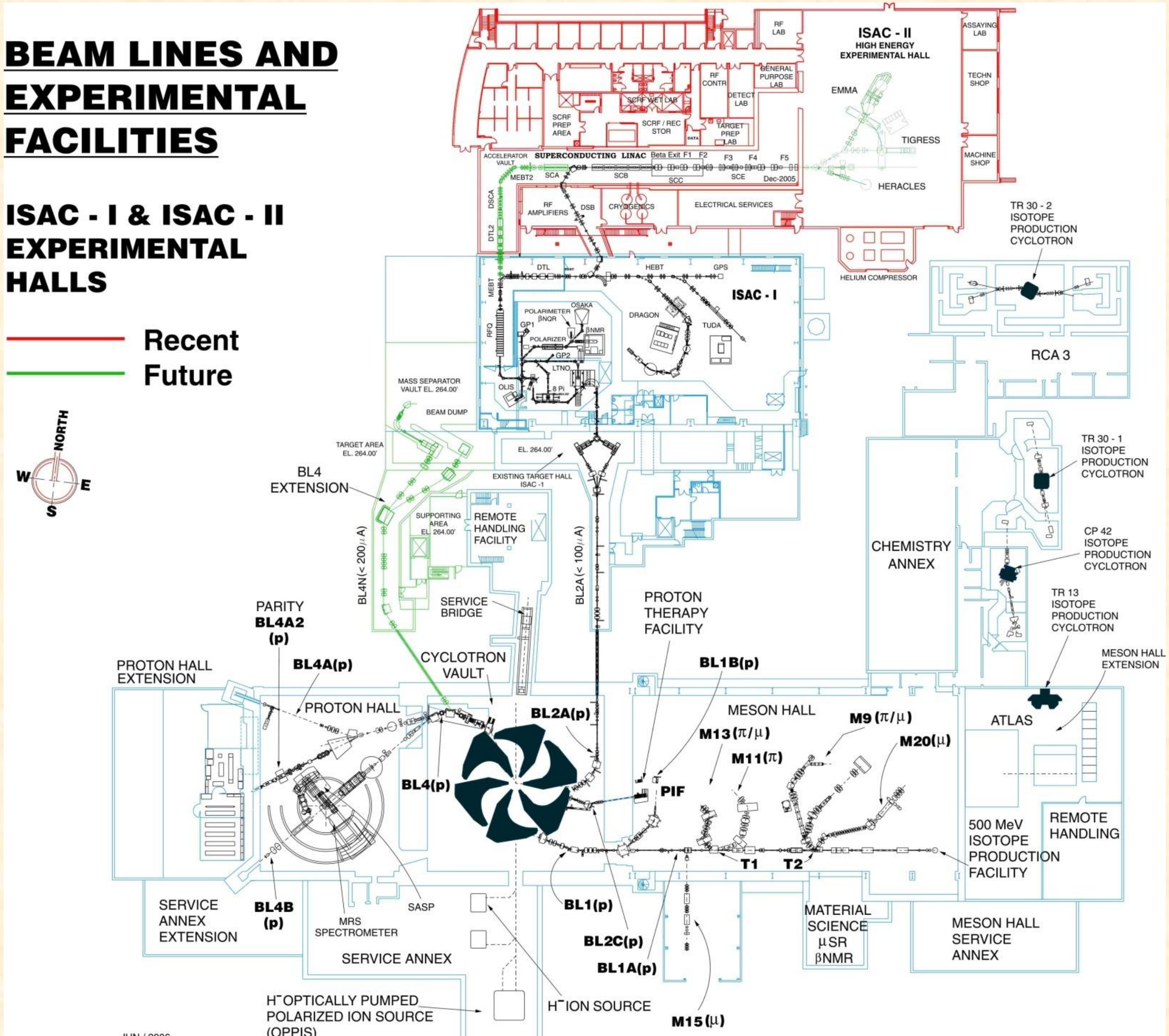



ion energies range between 8 and 100 A MeV in harmonic mode h=2

bending limit Kb=800 and by the focusing limit Kf=200.


K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE
ECR ION SOURCE
K500 CYCLOTRON
RADIATION EFFECTS FACILITY 1994, 2000, 2005
BEAM ANALYSIS SYSTEM 1994
LIGHT ION GUIDE
CB-ECR SOURCE
ECR ION SOURCE
HEAVY ION GUIDE
MARS RECOIL SPECTROMETER 1992
BIG SOL SOLENOID 2003
K150 (88") CYCLOTRON
ION INTERACTIONS LINE
NIMROD 1999
35 FEET
TAPE TRANSPORT & PRECISION DECAY FACILITY 1999
MDM SPECTROMETER 1993, 2000

TRIUMF



BEAM LINES AND EXPERIMENTAL FACILITIES
ISAC - I & ISAC - II EXPERIMENTAL HALLS
Recent
Future
NORTH
W
E
S
ISAC - II
HIGH ENERGY EXPERIMENTAL HALL
EMMA
TIGRESS
HERACLES
SUPERCONDUCTING LINAC
ACCELERATOR VAULT
SCRF PREP AREA
SCRF / REC STOR
SCRF WET LAB
RF CONTR
DETECT LAB
TARGET PREP LAB
GENERAL PURPOSE LAB
RF LAB
ASSAYING LAB
TECHN SHOP
MACHINE SHOP
RF AMPLIFIERS
DSB
CRYOGENICS
ELECTRICAL SERVICES
HELIUM COMPRESSOR
Dec-2005
TR 30 - 2
ISOTOPE PRODUCTION CYCLOTRON
RCA 3
ISAC - I
DRAGON
TUDA
HEBT
GPS
DTL
MEBT
RFQ
POLARIMETER
βNQR
OSAKA
POLARIZER
βNMR
GP1
GP2
LTNO
OLIS
8 Pi
MASS SEPARATOR VAULT EL. 264.00'
BEAM DUMP
TARGET AREA EL. 264.00'
EL. 264.00'
EXISTING TARGET HALL ISAC -1
BL4 EXTENSION
SUPPORTING AREA EL. 264.00'
REMOTE HANDLING FACILITY
BL4N(< 200μA)
BL2A(< 100μA)
SERVICE BRIDGE
PROTON THERAPY FACILITY
CHEMISTRY ANNEX
TR 30 - 1
ISOTOPE PRODUCTION CYCLOTRON
CP 42
ISOTOPE PRODUCTION CYCLOTRON
TR 13
ISOTOPE PRODUCTION CYCLOTRON
MESON HALL EXTENSION
PARITY
BL4A2 (p)
PROTON HALL EXTENSION
BL4A(p)
CYCLOTRON VAULT
BL1B(p)
PROTON HALL
BL2A(p)
MESON HALL
M9 (π/μ)
M13 (π/μ)
M20(μ)
M11(π)
ATLAS
BL4(p)
PIF
500 MeV ISOTOPE PRODUCTION FACILITY
REMOTE HANDLING
T1
T2
SERVICE ANNEX EXTENSION
BL4B (p)
MRS SPECTROMETER
SASP
BL1(p)
BL2C(p)
BL1A(p)
MATERIAL SCIENCE
μSR
βNMR
MESON HALL SERVICE ANNEX
SERVICE ANNEX
H⁻ OPTICALLY PUMPED POLARIZED ION SOURCE (OPPIS)
H⁻ ION SOURCE
M15(μ)
JUN / 2006

520 MeV proton, Triumf, Canada

The diameter of the machine is about 18 m

Lower half of the Main Magnet poles

# BIBLIOGRAPHY


**Textbooks**

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- H. Bruck, Bibl. des Scienc. Et Tech. Nucléaires 1966, Accélérateurs Circulaires de Particules.
- J. J. Livingood, D. van Nostrand Comp. 1961, Principles of Cyclic Particle Accelerators.

**Conference Proceeding**

- Proceedings of the International Conferences on Sector-focused Cyclotrons and on Cyclotrons and their application :
- ICC1, Informal Conference on sector-focused Cyclotrons 1959 in Sea Island, NAS-NRC, Publ.656 (1959)
- ICC2, Int. Conference 1962 in Los Angeles, Nucl. Inst.& Meth. 18, 19 (1962)
- ICC3, Int. Conference 1963 in Geneva, CERN 63-19 (1963)
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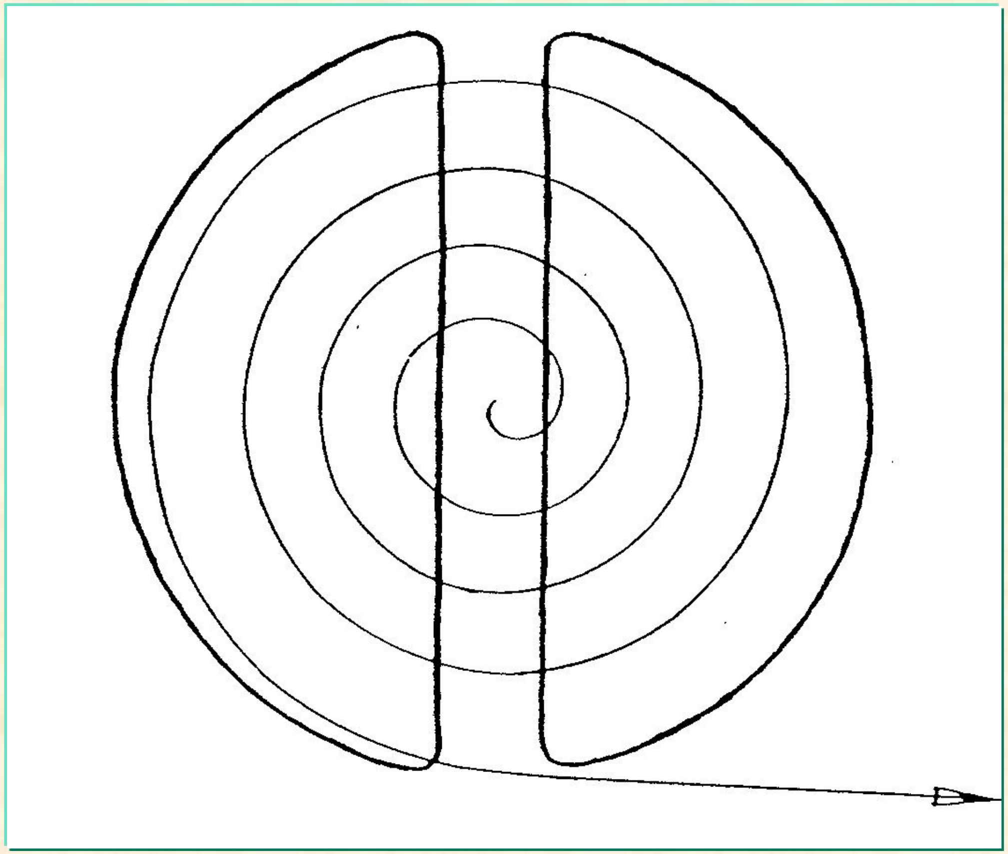
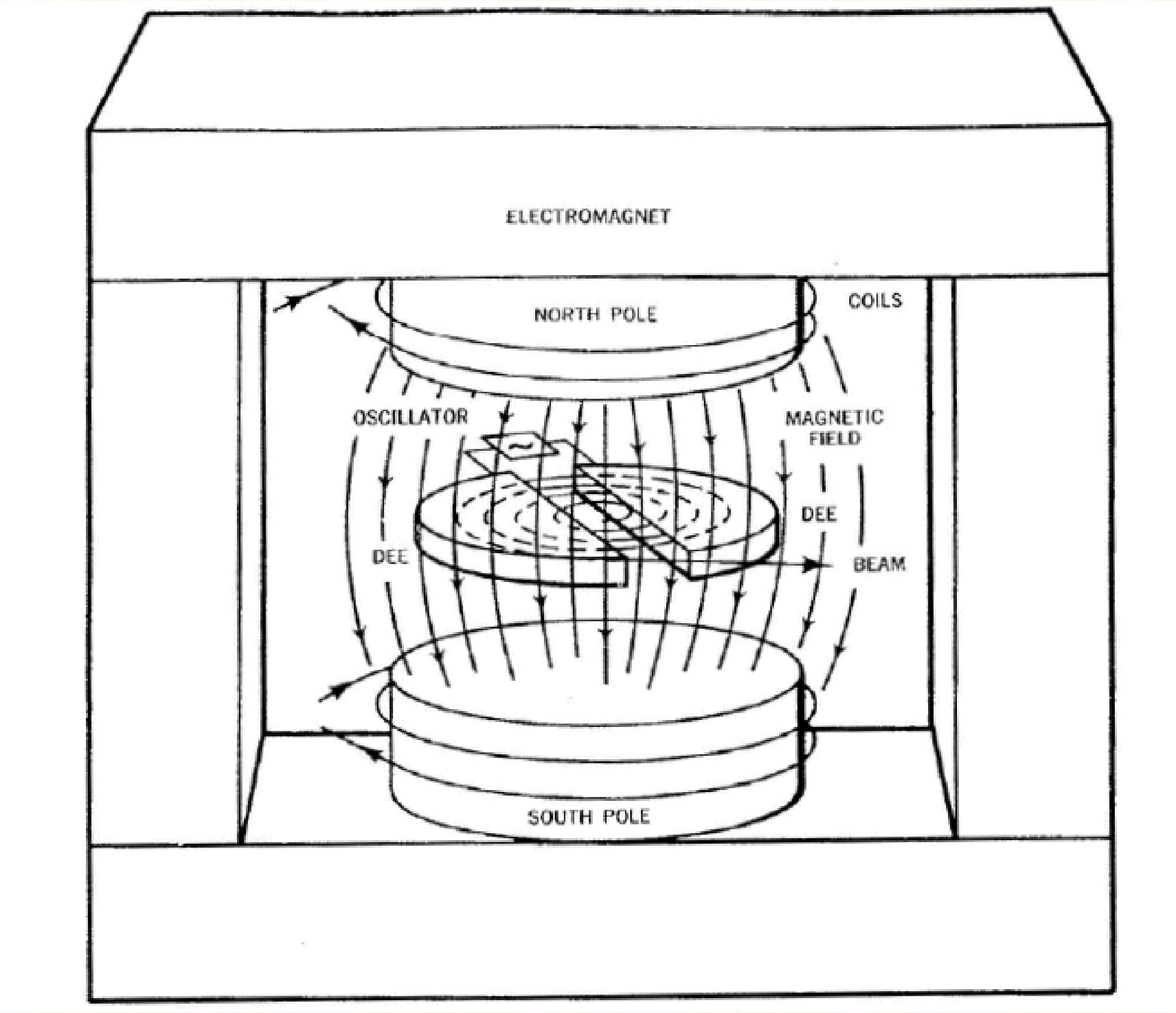
END

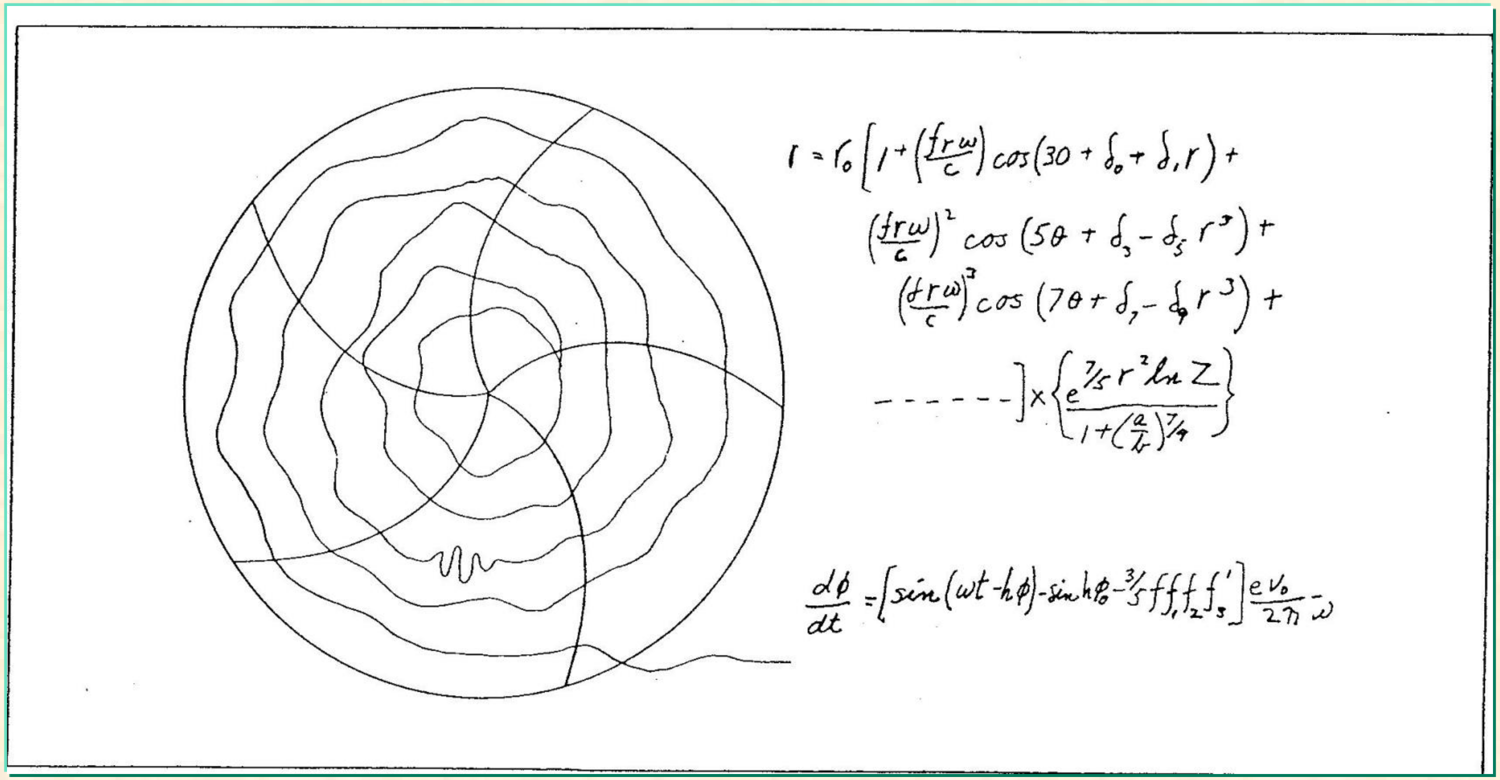
The Cyclotron as seen by the **Inventor**



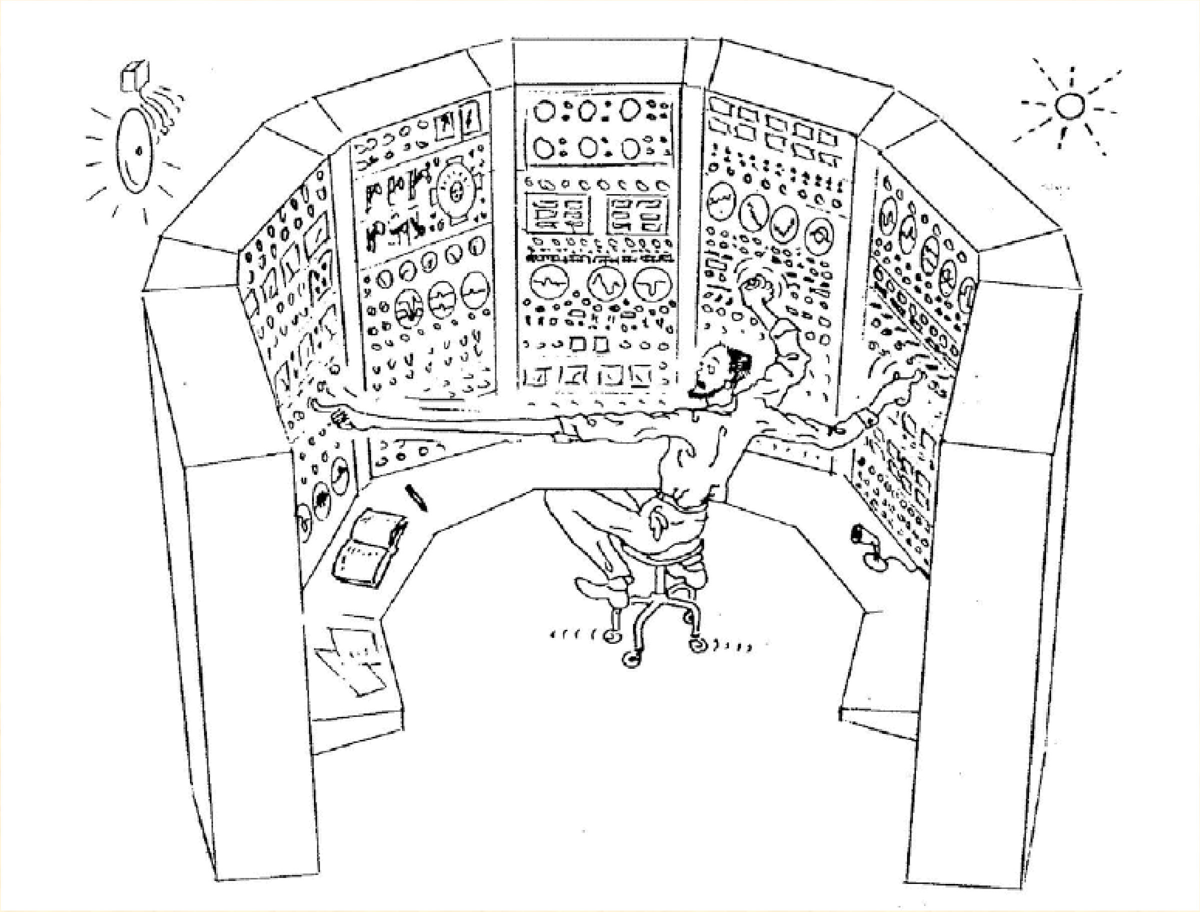
The Cyclotron as seen in the usual **text book**



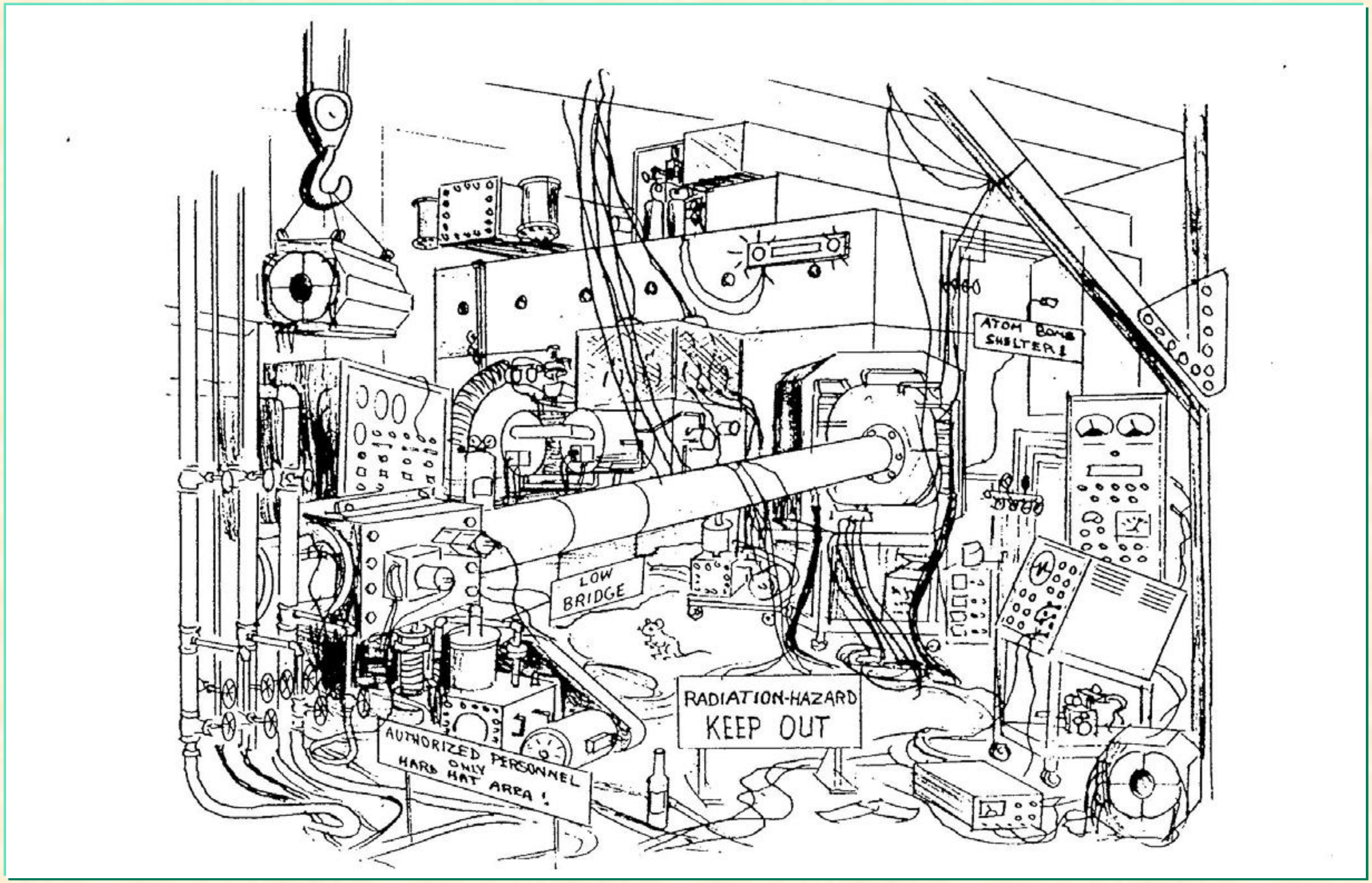
The Cyclotron as seen by the **Theorist**



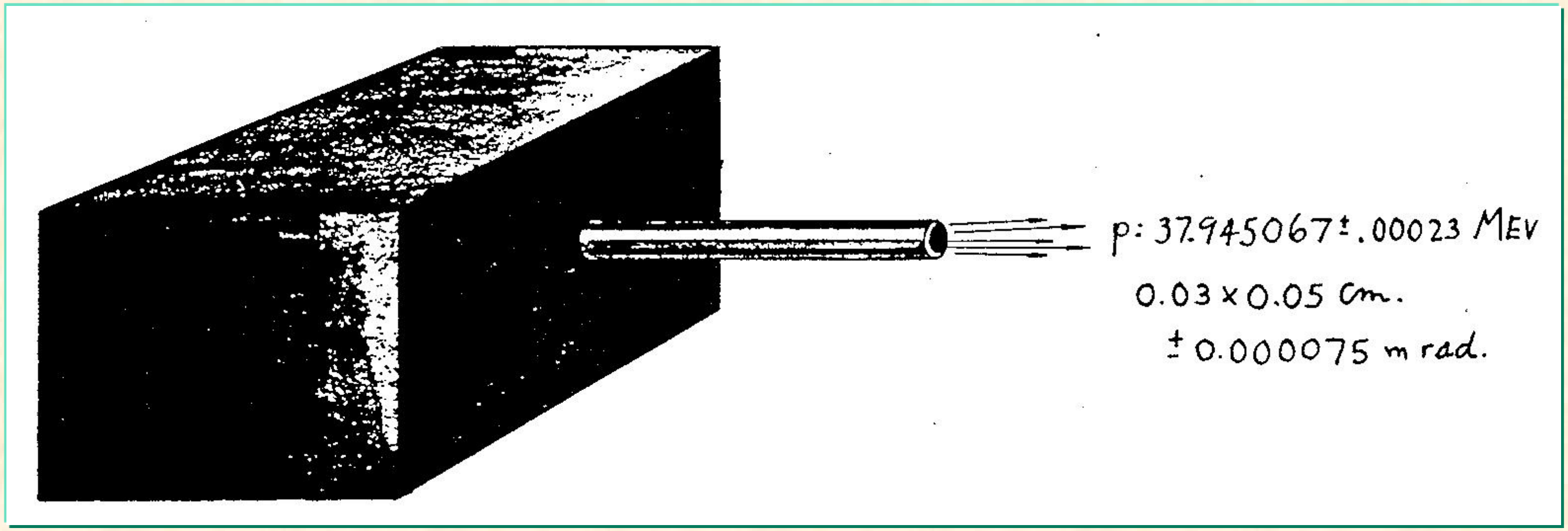
The Cyclotron as seen by the **Operator**



The Cyclotron as seen by the **Visitor**



The Cyclotron as seen by the
**Experimentalist**



The Cyclotron as seen by the **Student**