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

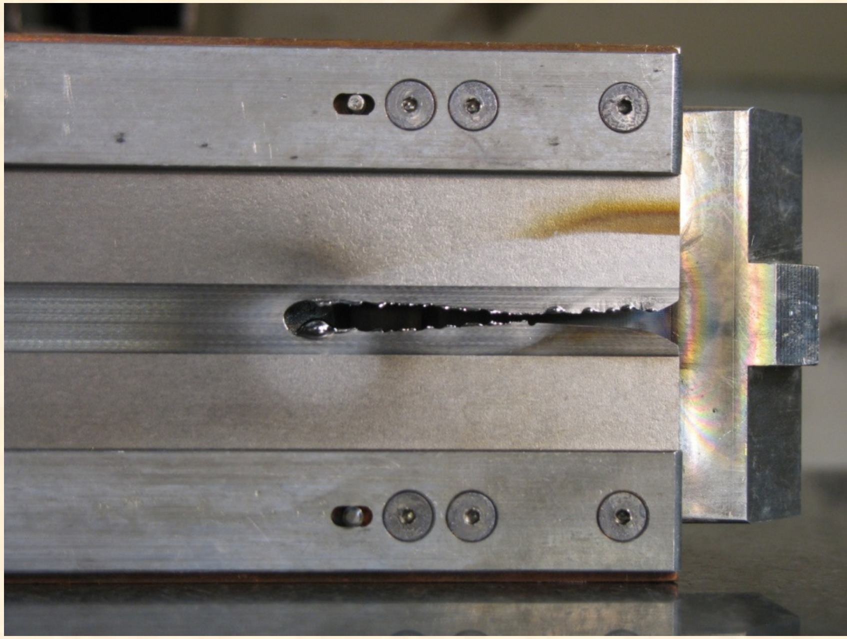
- for machine safety
- permanently
- for tuning
- at setup
- for error search
- only at commissioning

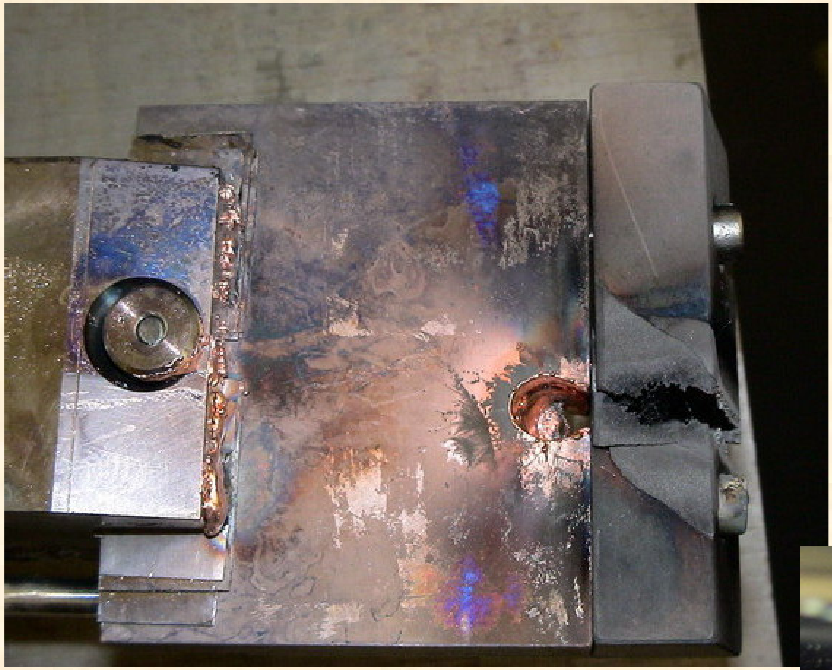
familiar monitors

- 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

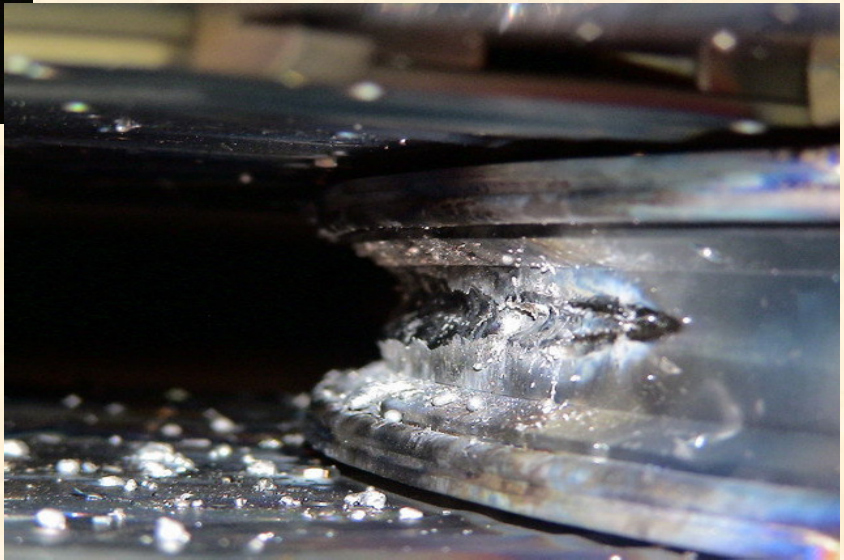
MSU K1200 Deflector Septum (Tungsten)



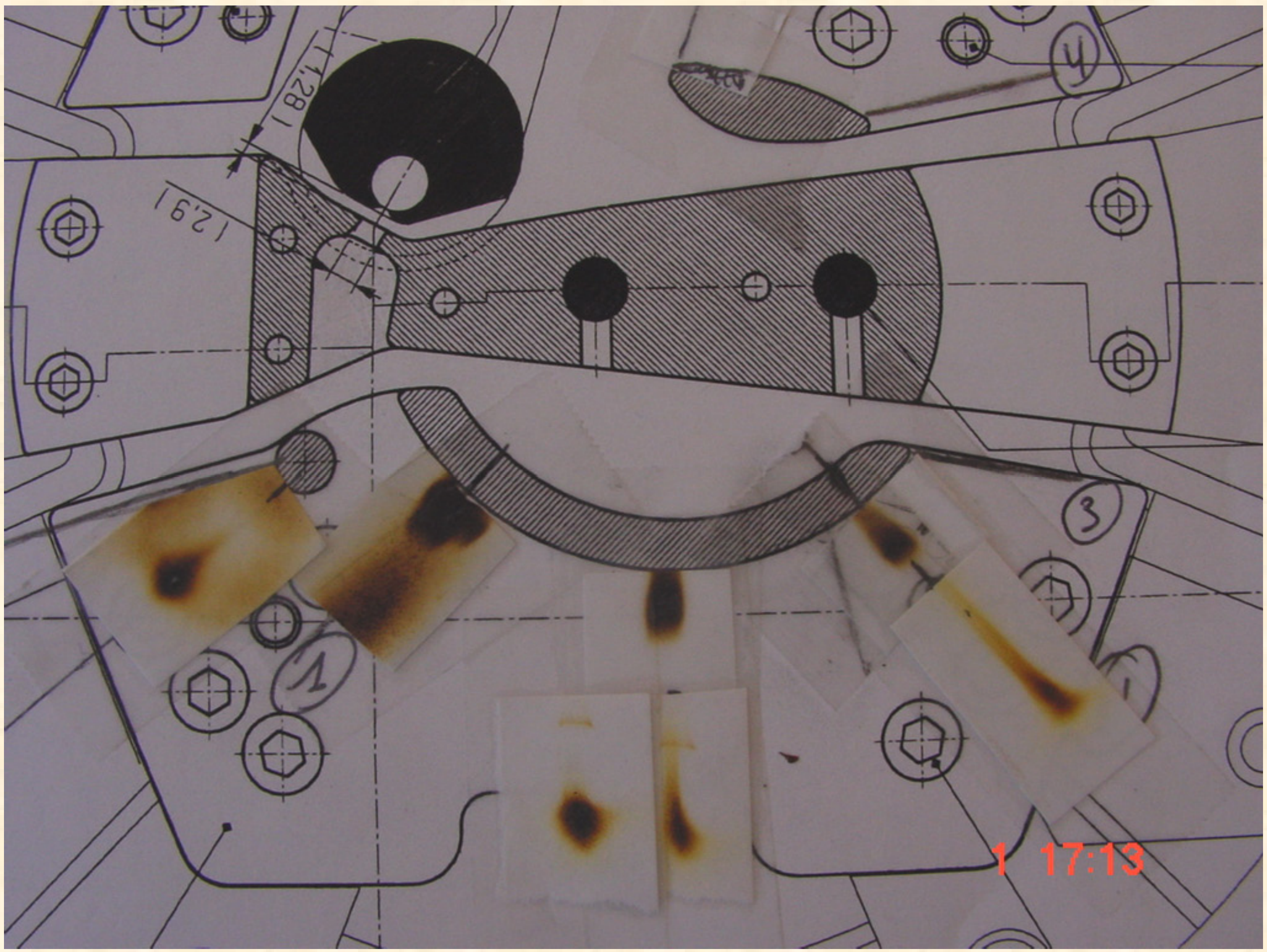


Beam induced defects with a

160 kW beam at PSI

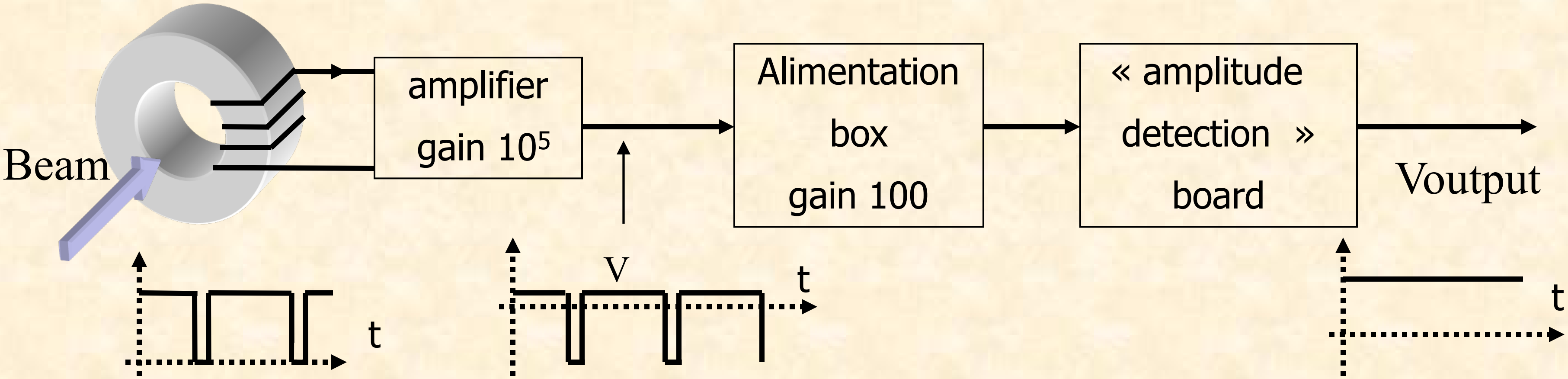


Beam Diagnostics



Current measurement (non interceptive) & (> nAe)

- Current Transformers Electronic Devices



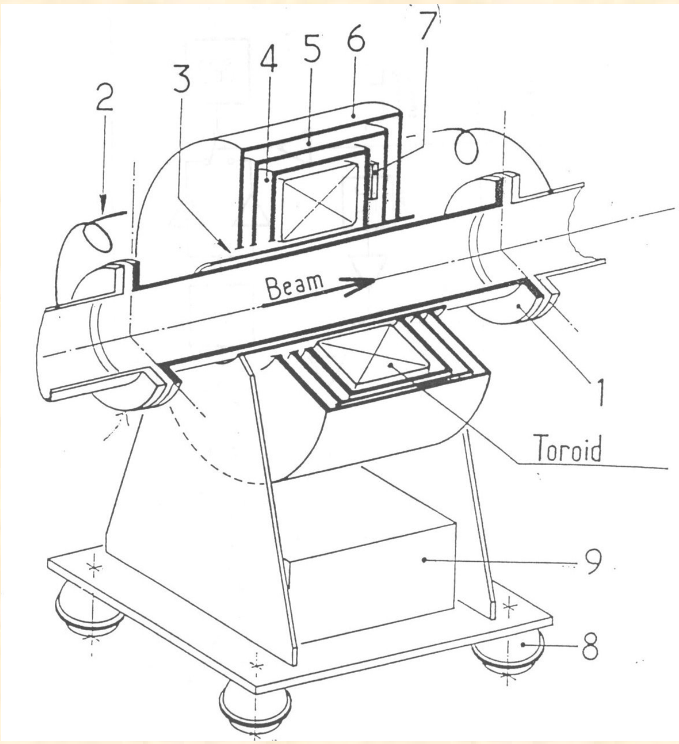
- The beam is « chopped » at a low frequency (hundred of Hz) to use this kind of diagnostics.
- Current transformer signal is amplify and measure by « amplitude detection board ».

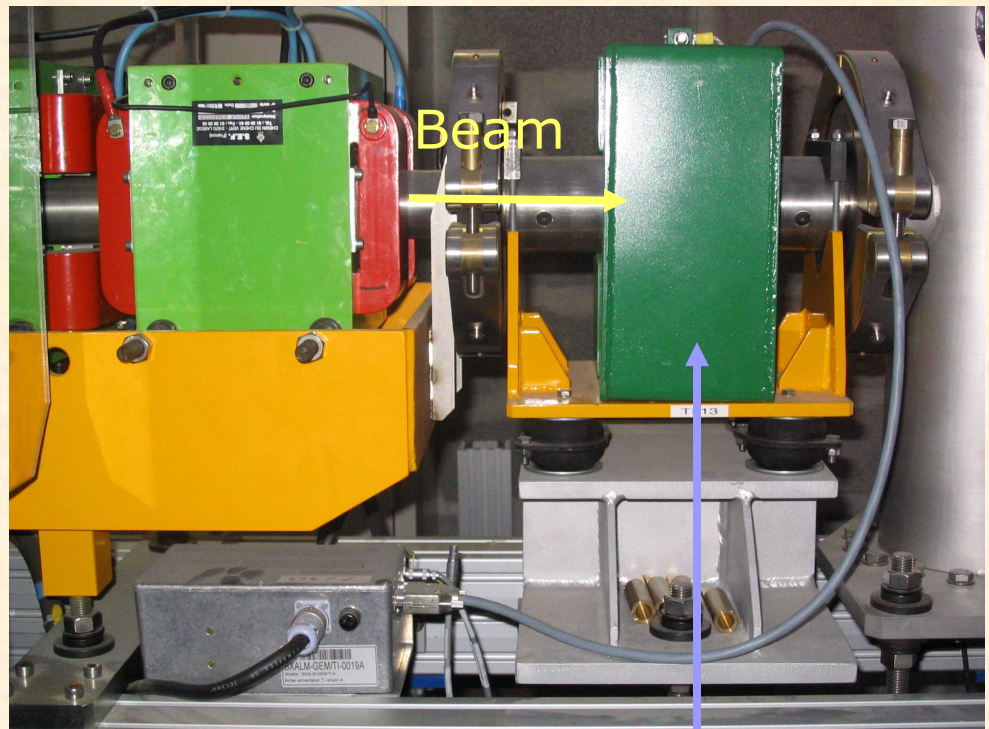
$I\,[A] = Npps \times Q \times e$

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

Current measurement (non interceptive)

- By Current Transformers (ACCT)

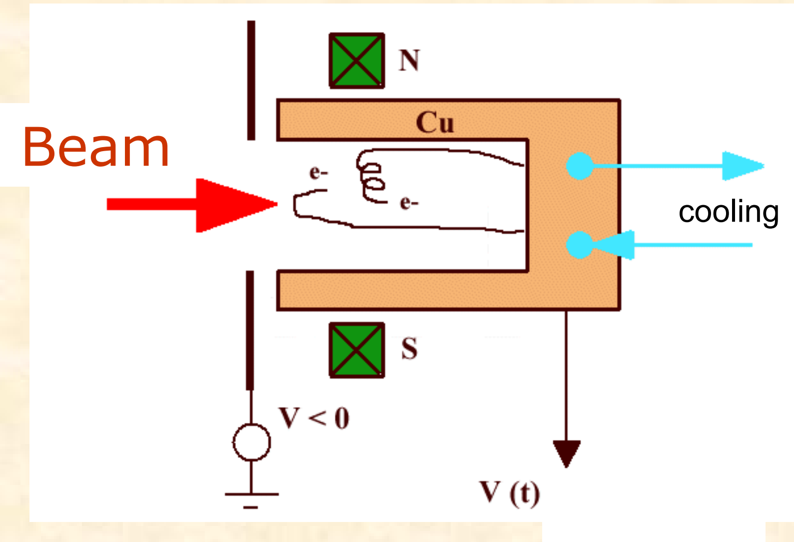




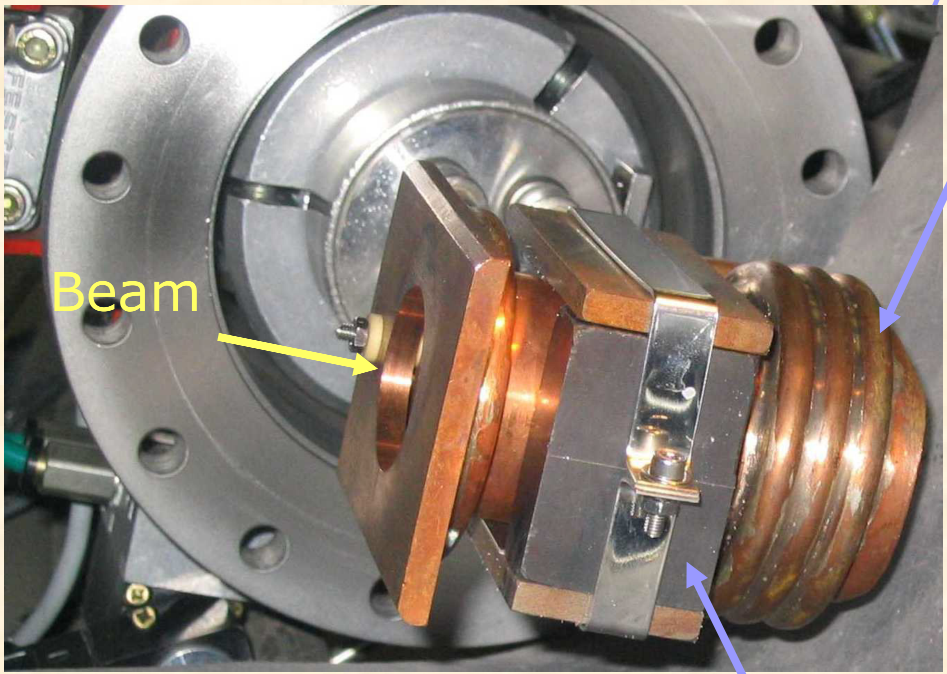
Current transformer with shielding

Current measurement (interceptive)

- By Faraday Cups

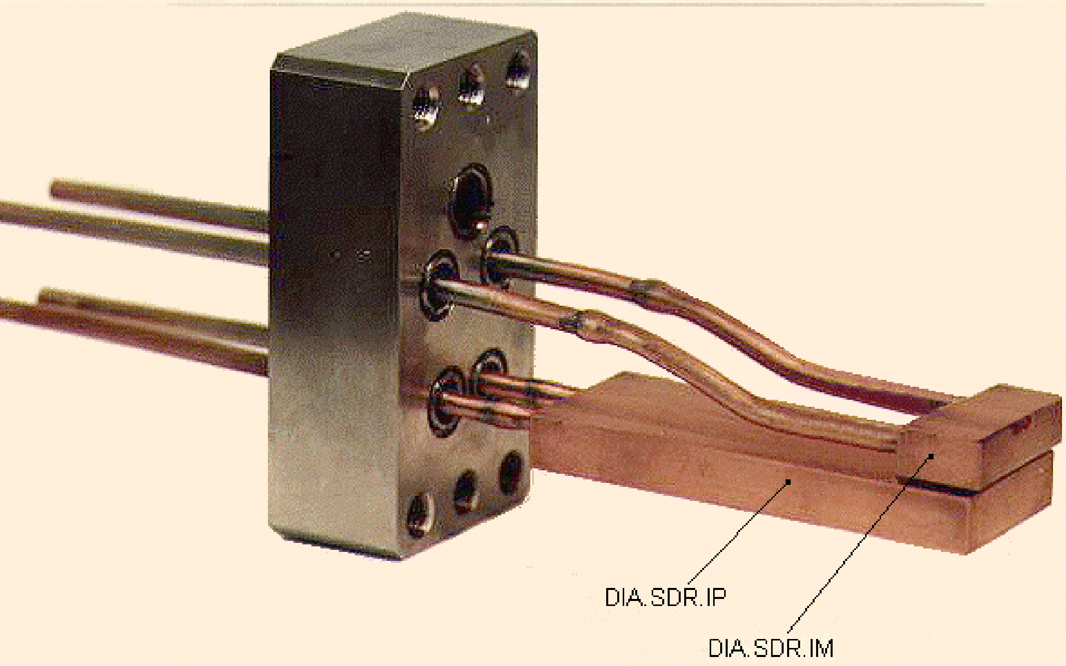


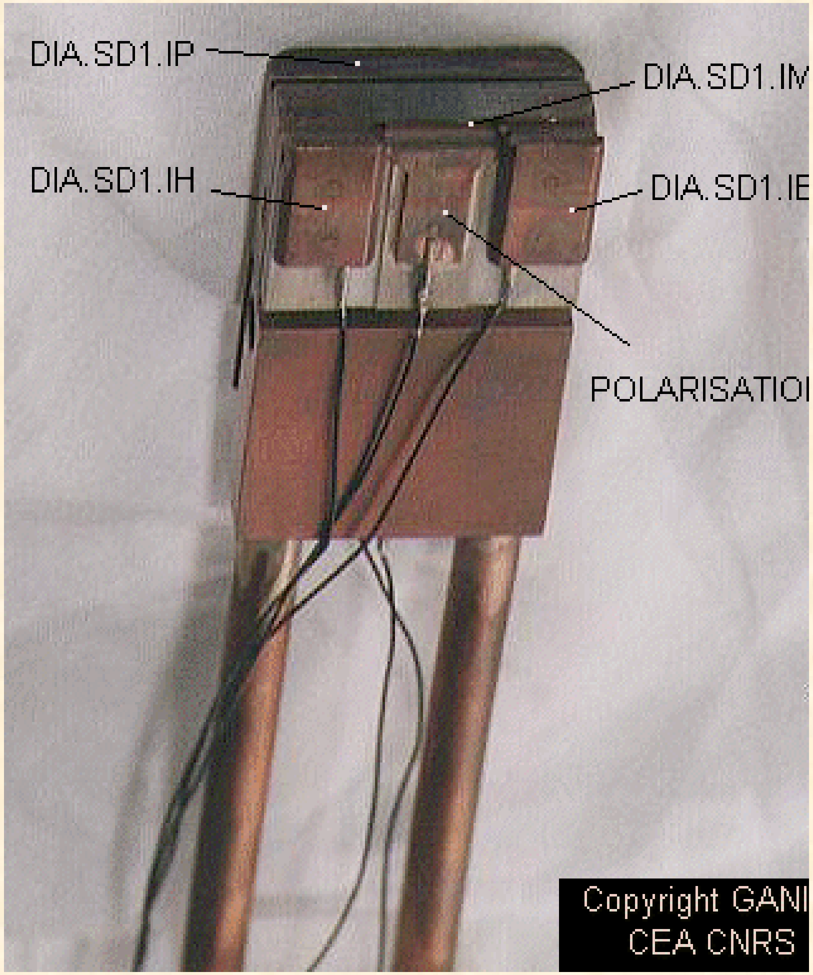
6kW cooled Faraday cup



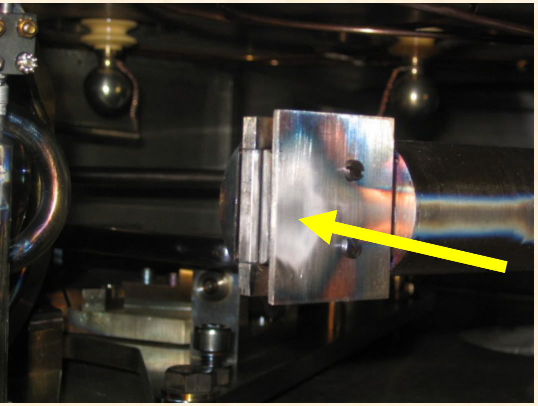
Magnet for secondary emissions

Current measurement: Radial probe

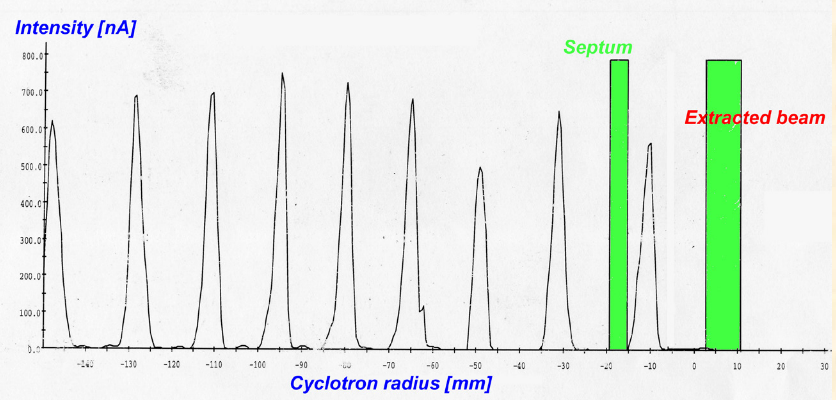


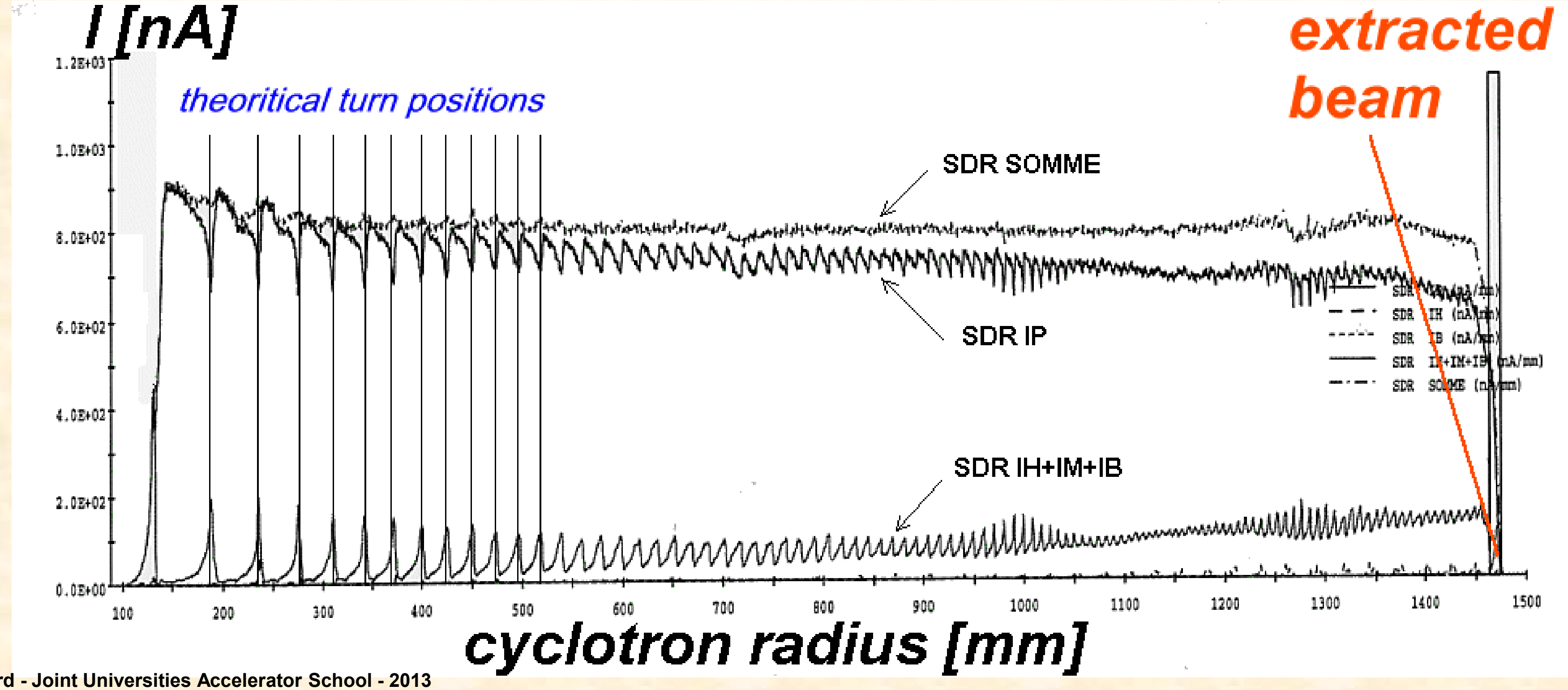


Current measurement : Beam monitoring

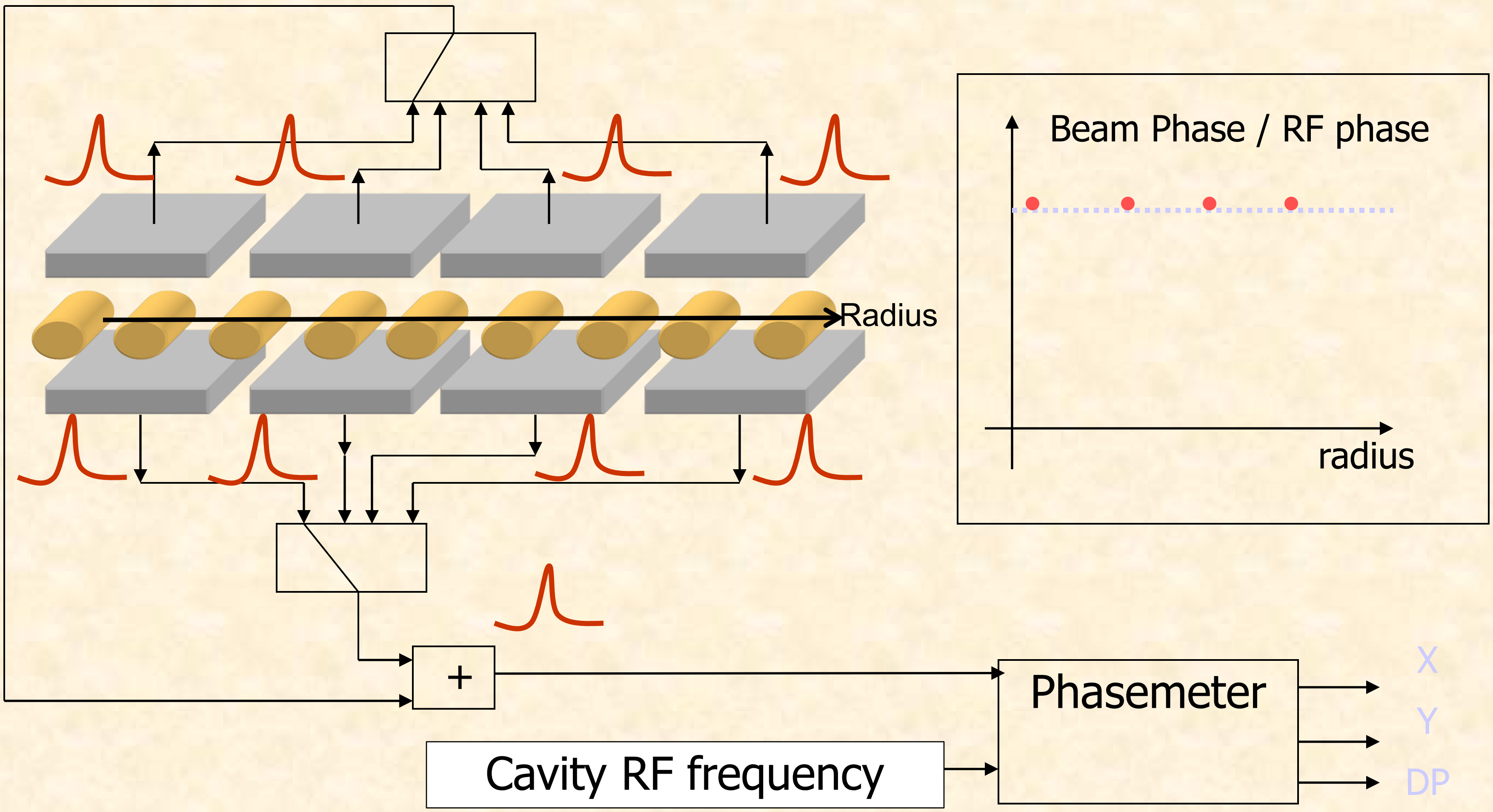


Beam

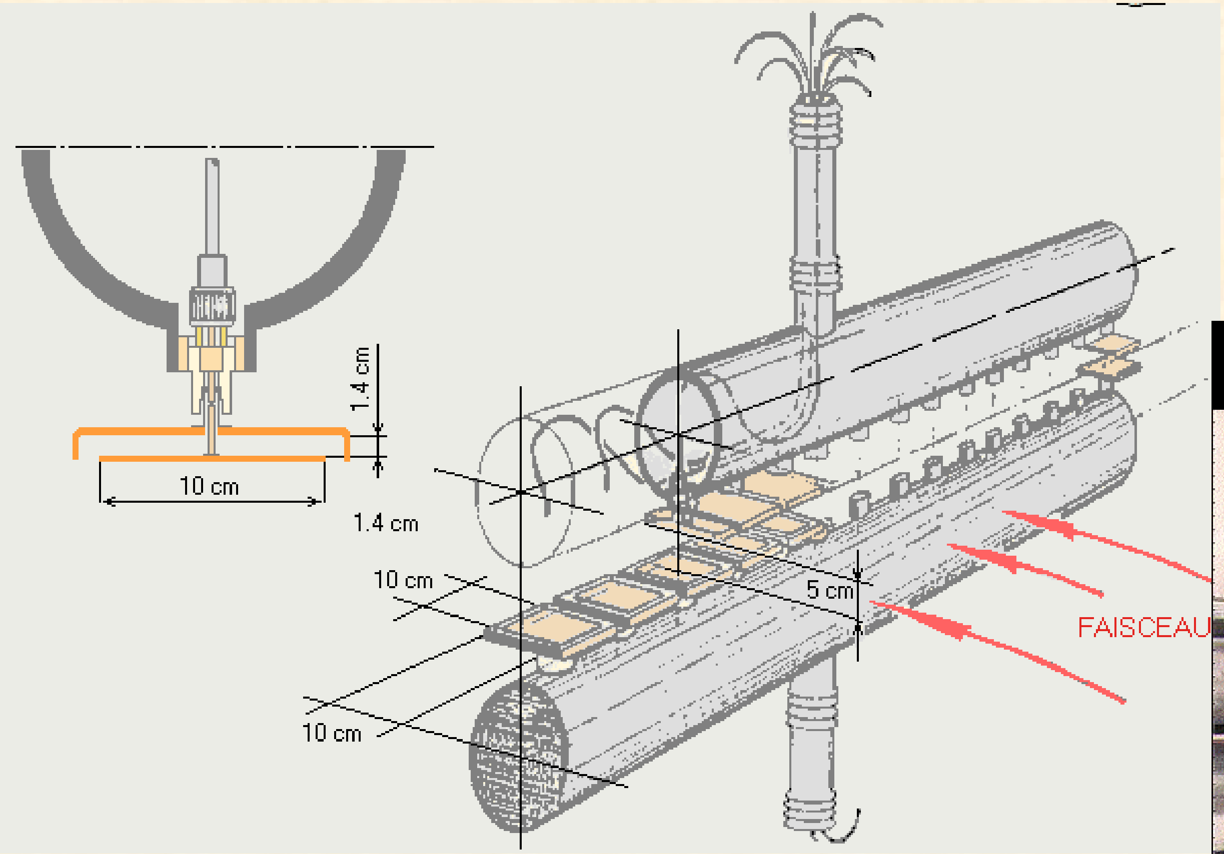


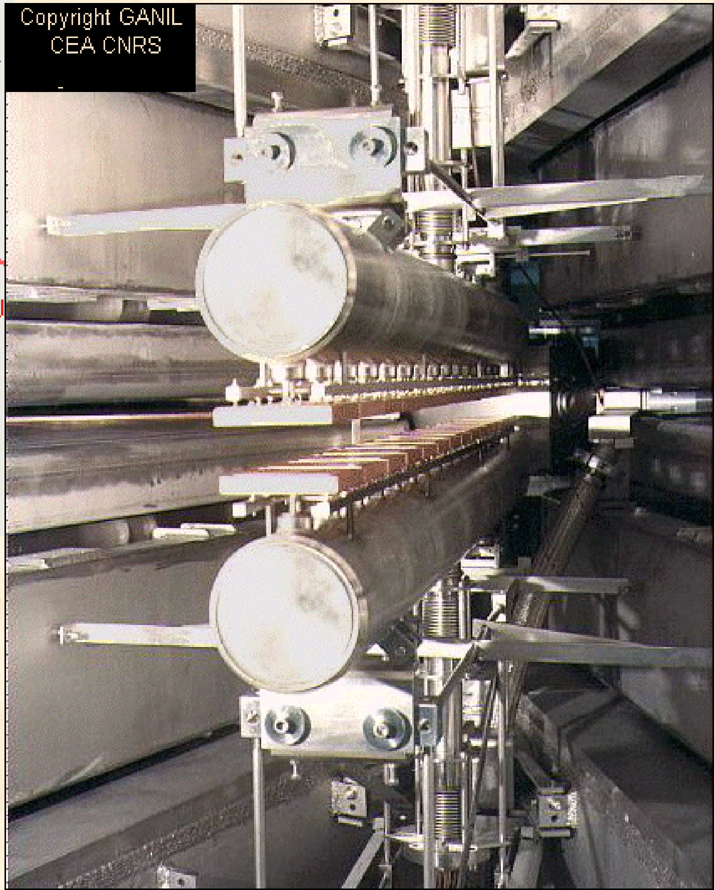


Phase measurement: Isochronism

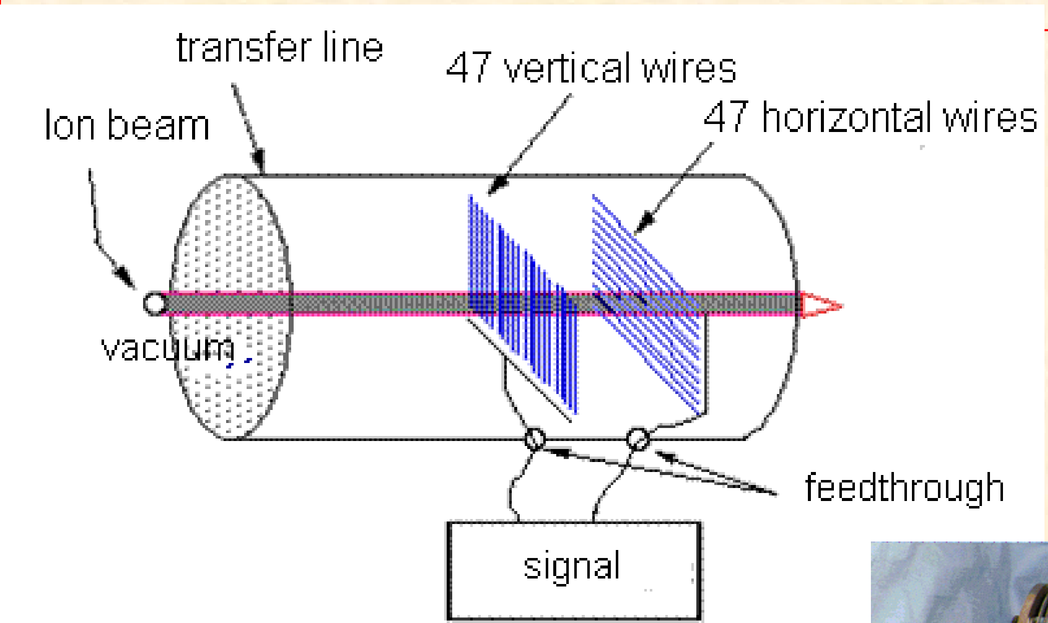


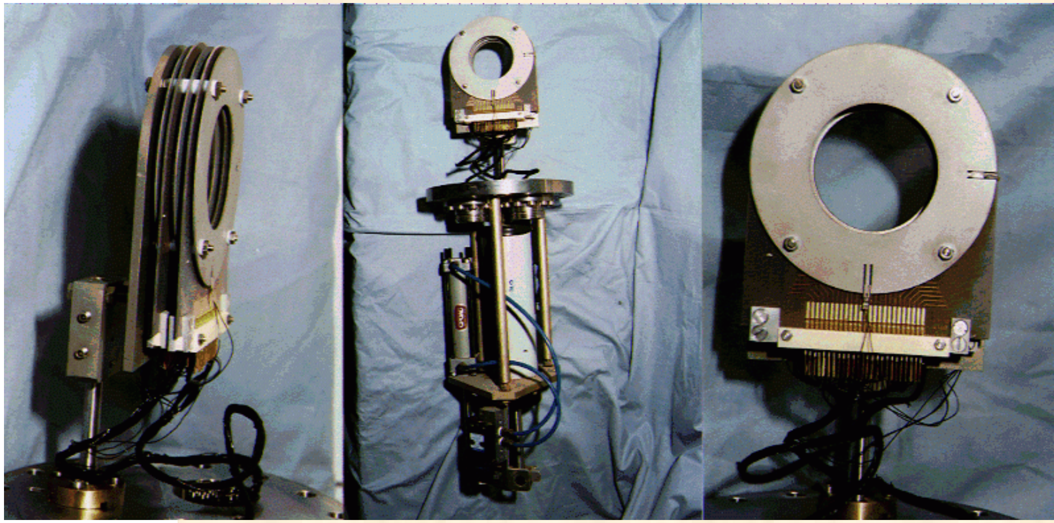
Phase measurement: Isochronism

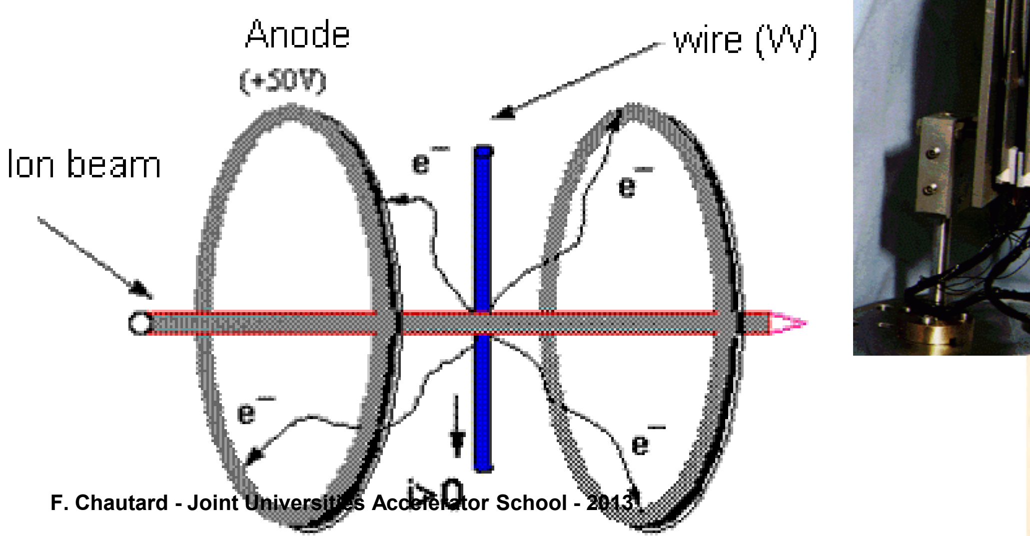




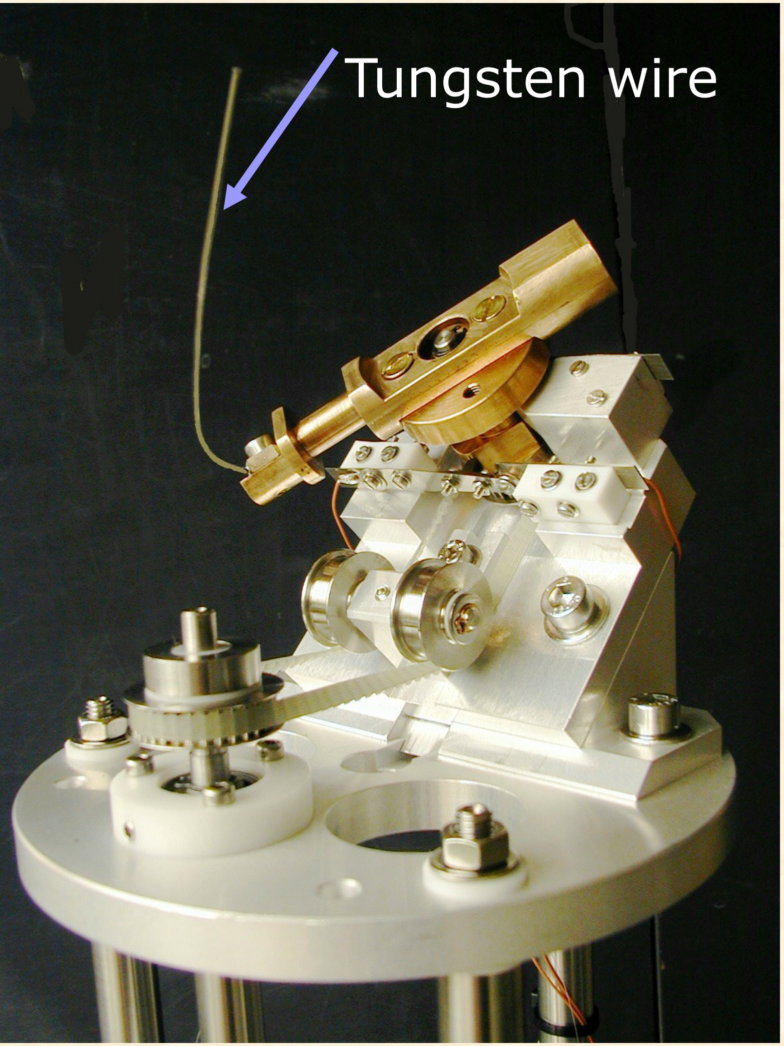
Beam Profiler: secondary emission current

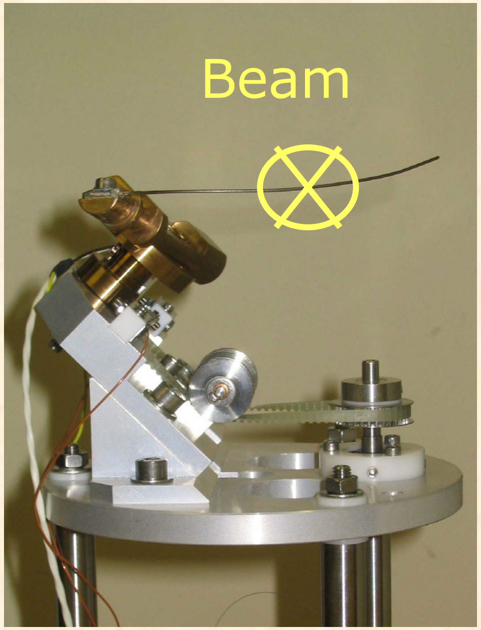




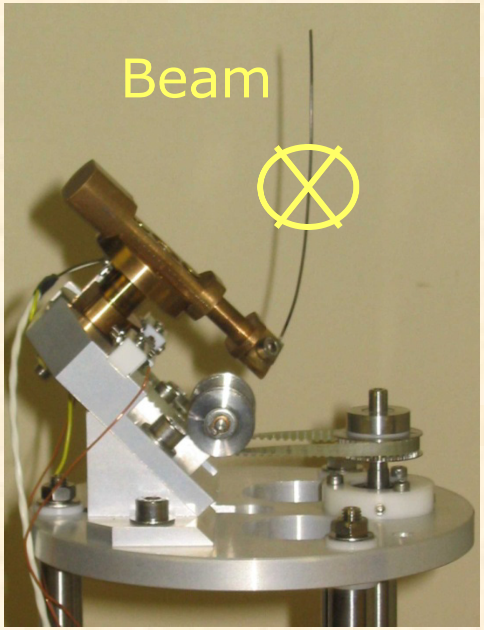


Profiler : wire scanner



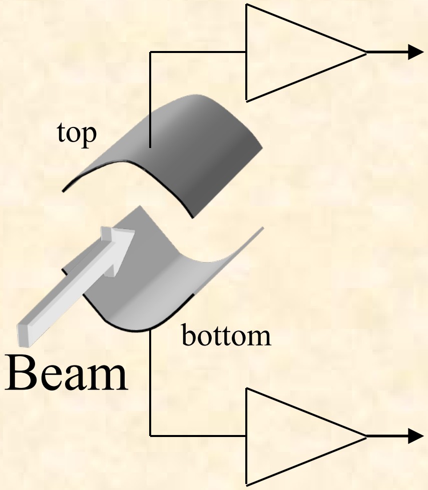


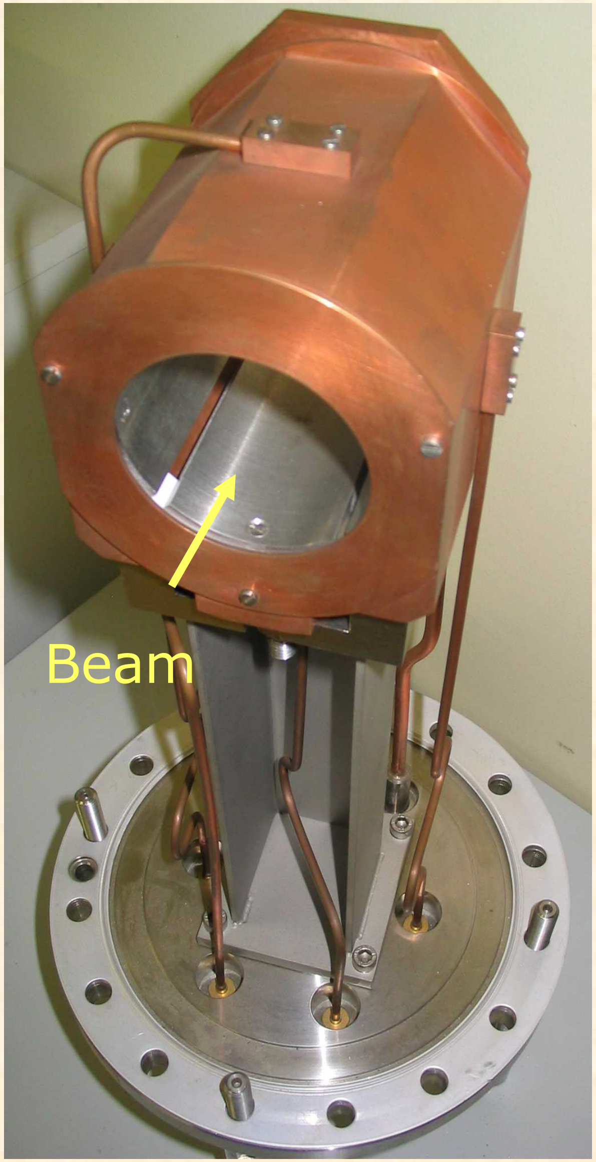
Wire in vertical position



Wire in horizontal position

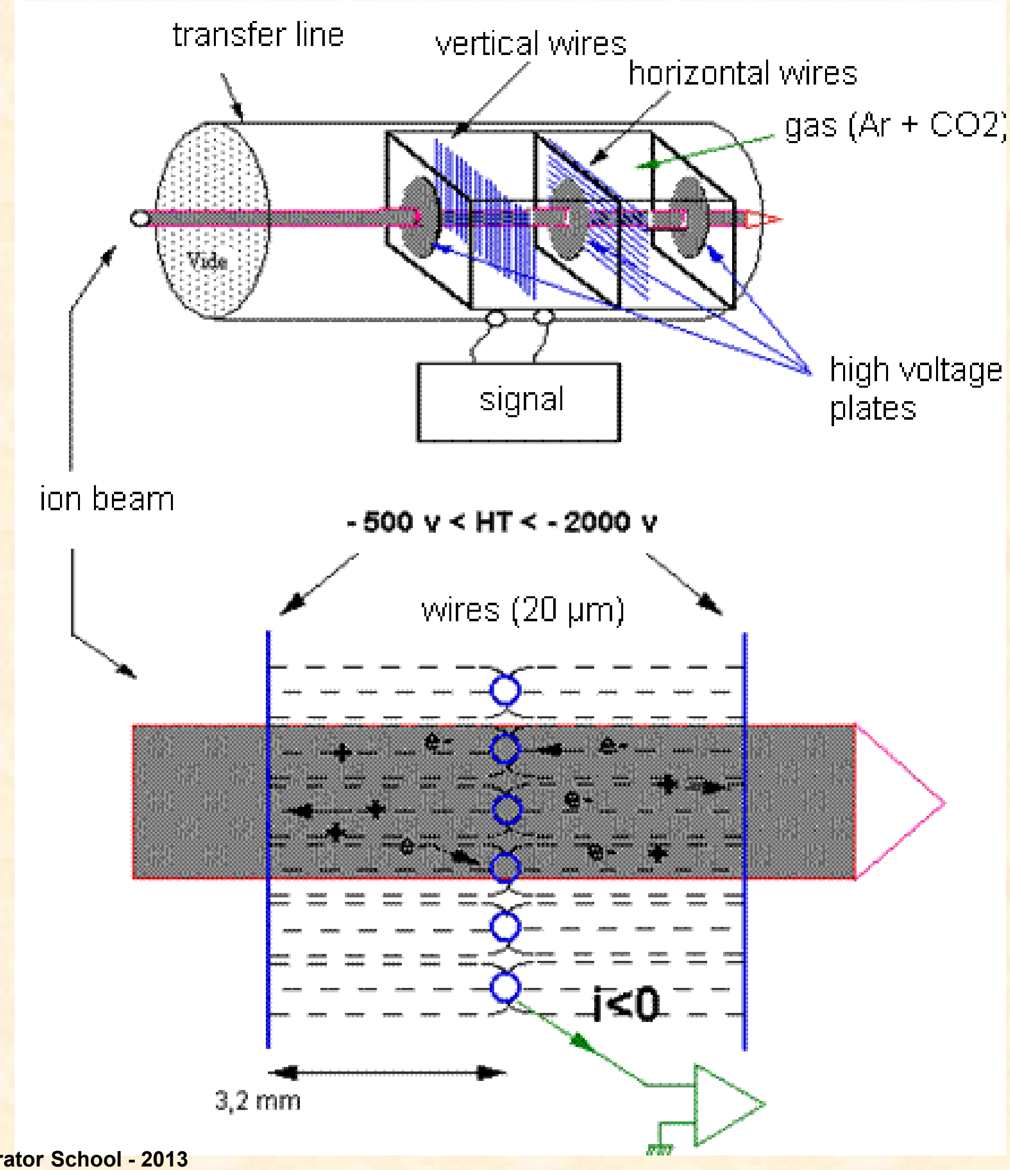
Beam position monitor



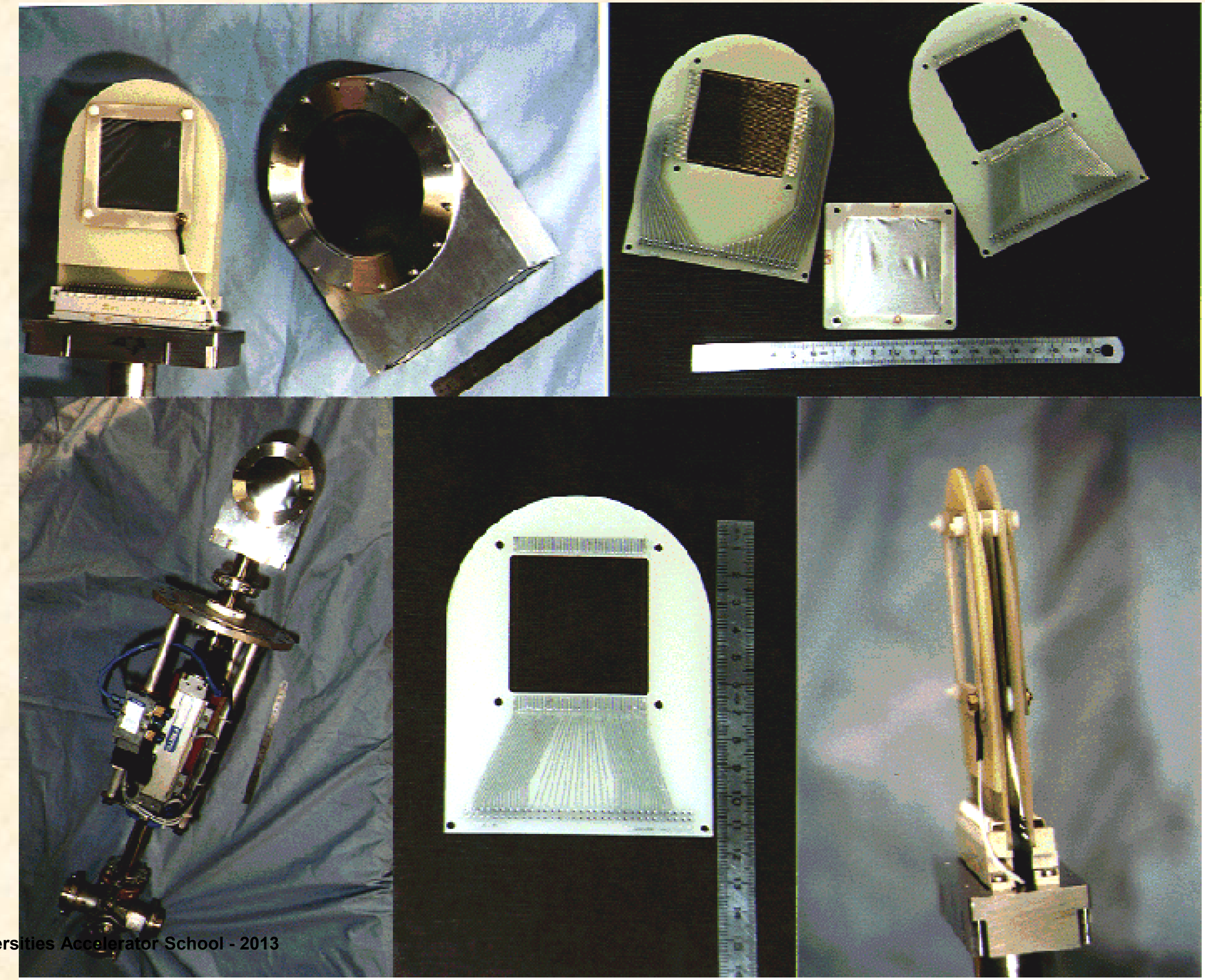


Low intensity diagnostics
$< 10^9$ pps

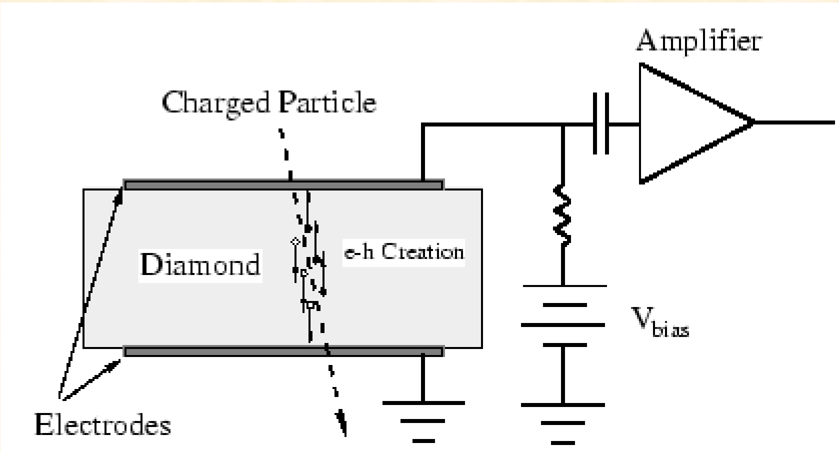
Gas Profiler

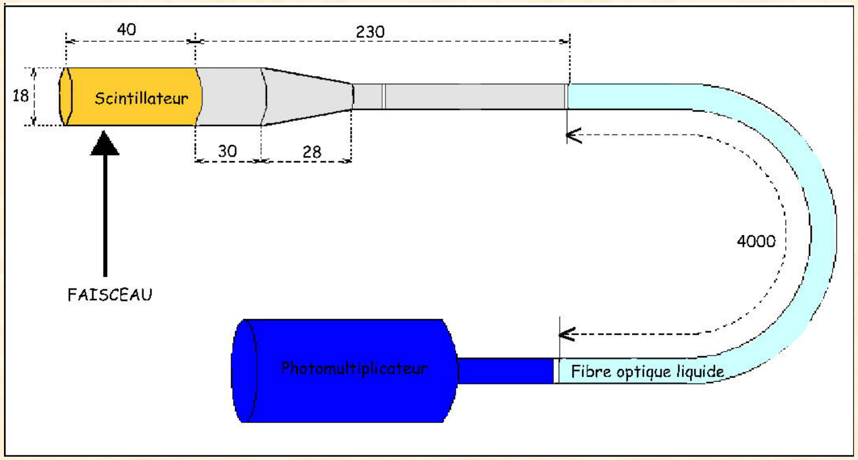


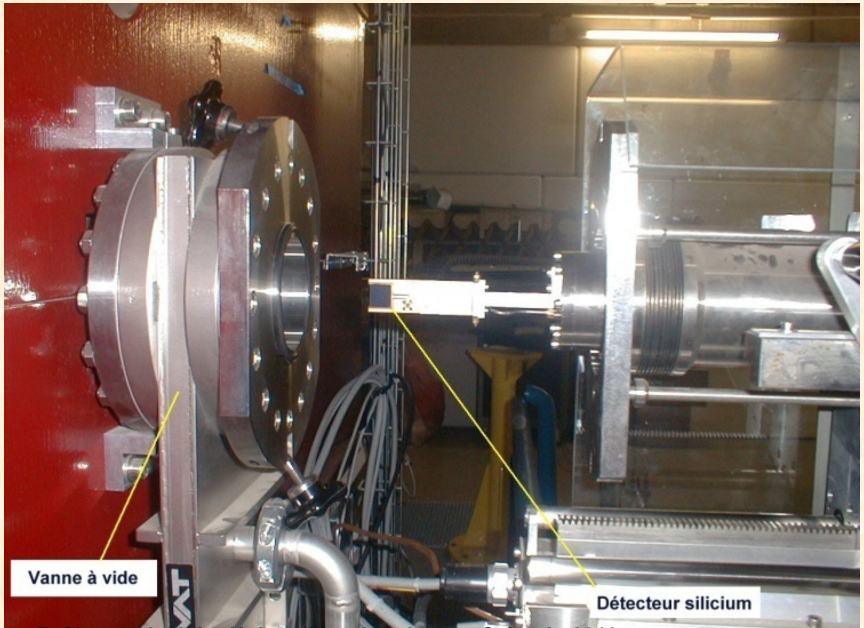
Gaz Profiler

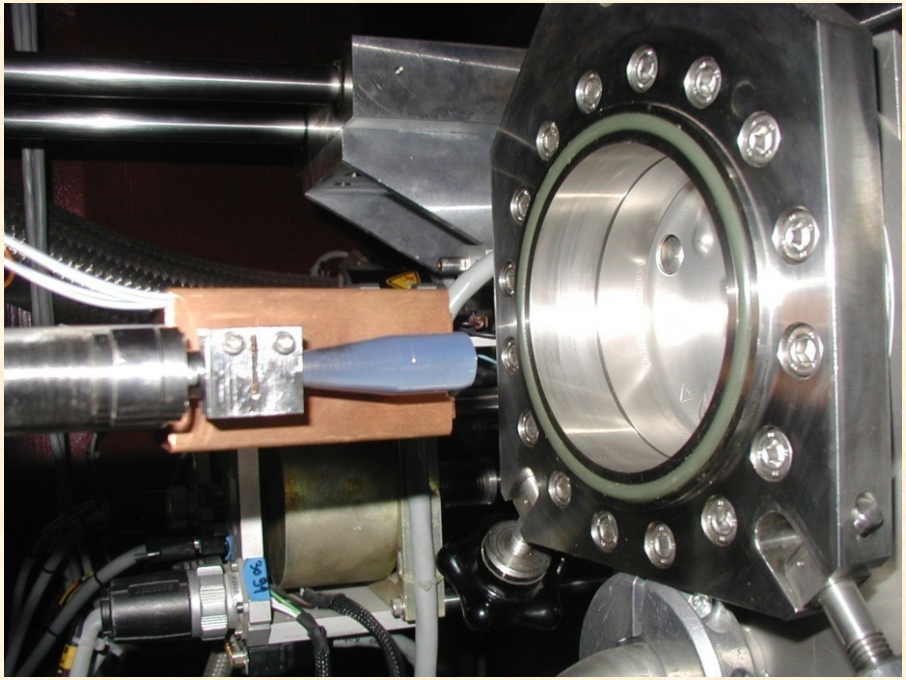


From Physics diagnostics









Back to dynamics and instabilities

Resonances

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

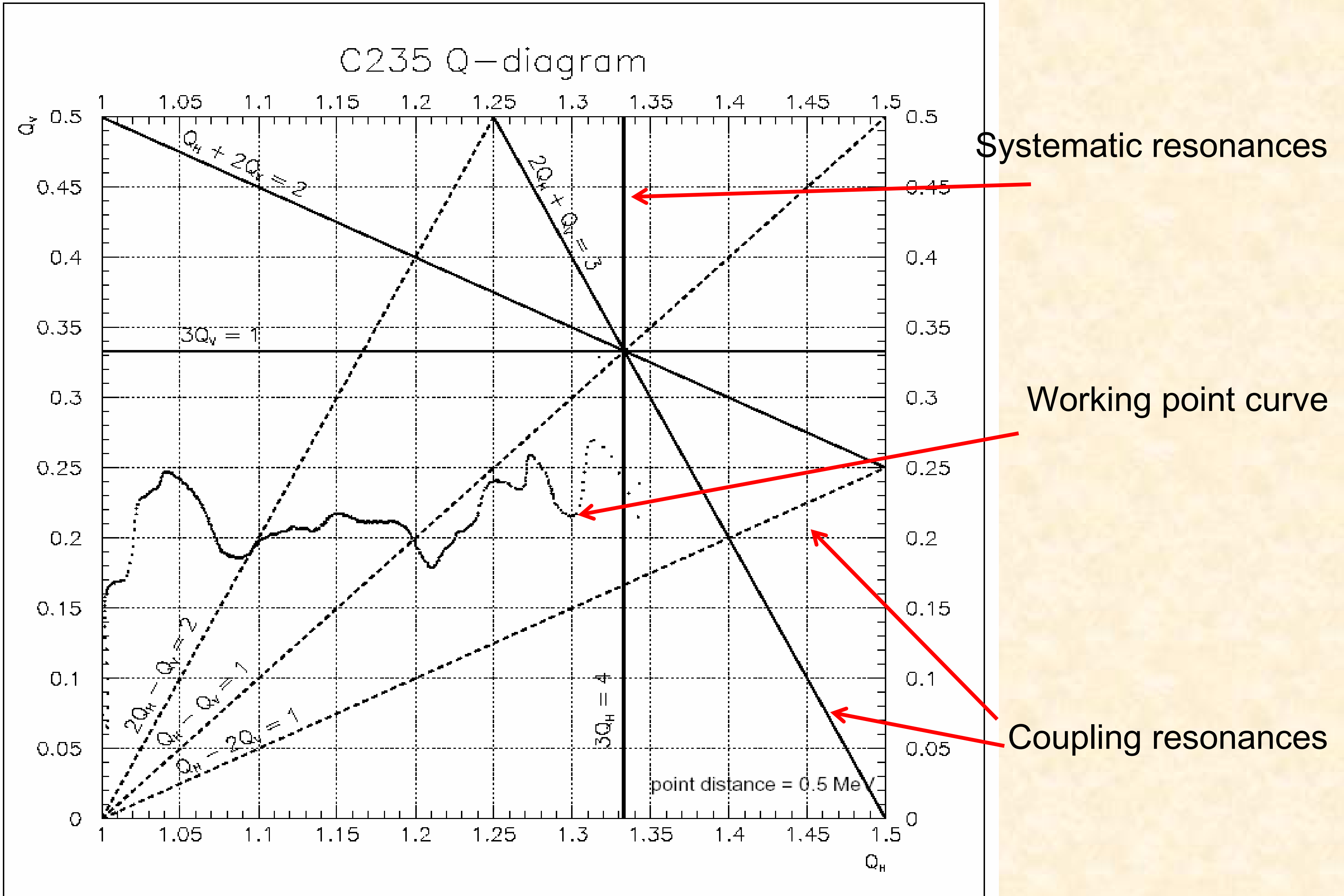
The plot of ν_r vs ν_z is called the **working point diagram.**

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 ($K.\nu_r + L.\nu_z = P$).**

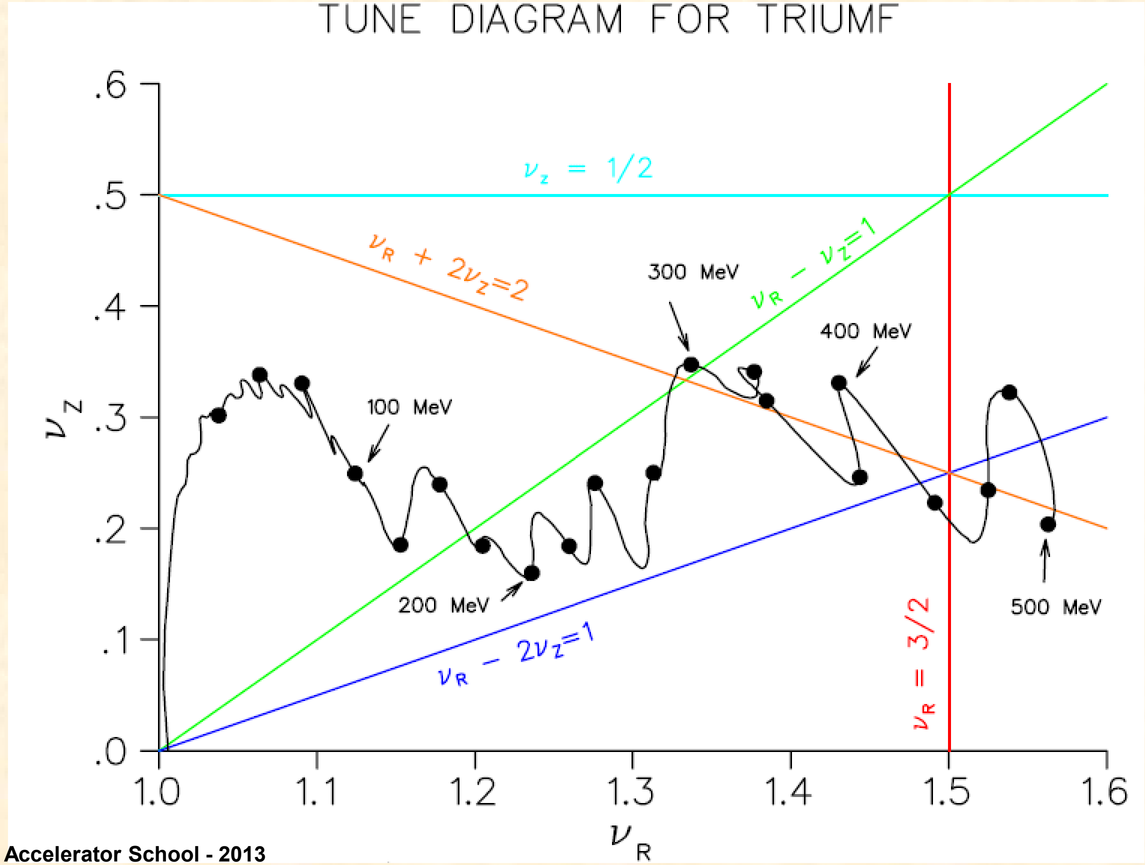
The particle's working point curve should avoid or cross as fast as possible those lines.


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

Tunes and resonances

$$K.\nu_r + L.\nu_z = P$$

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



$W \propto r^2$

Cyclotron as a separator

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

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

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

when the phase φ 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

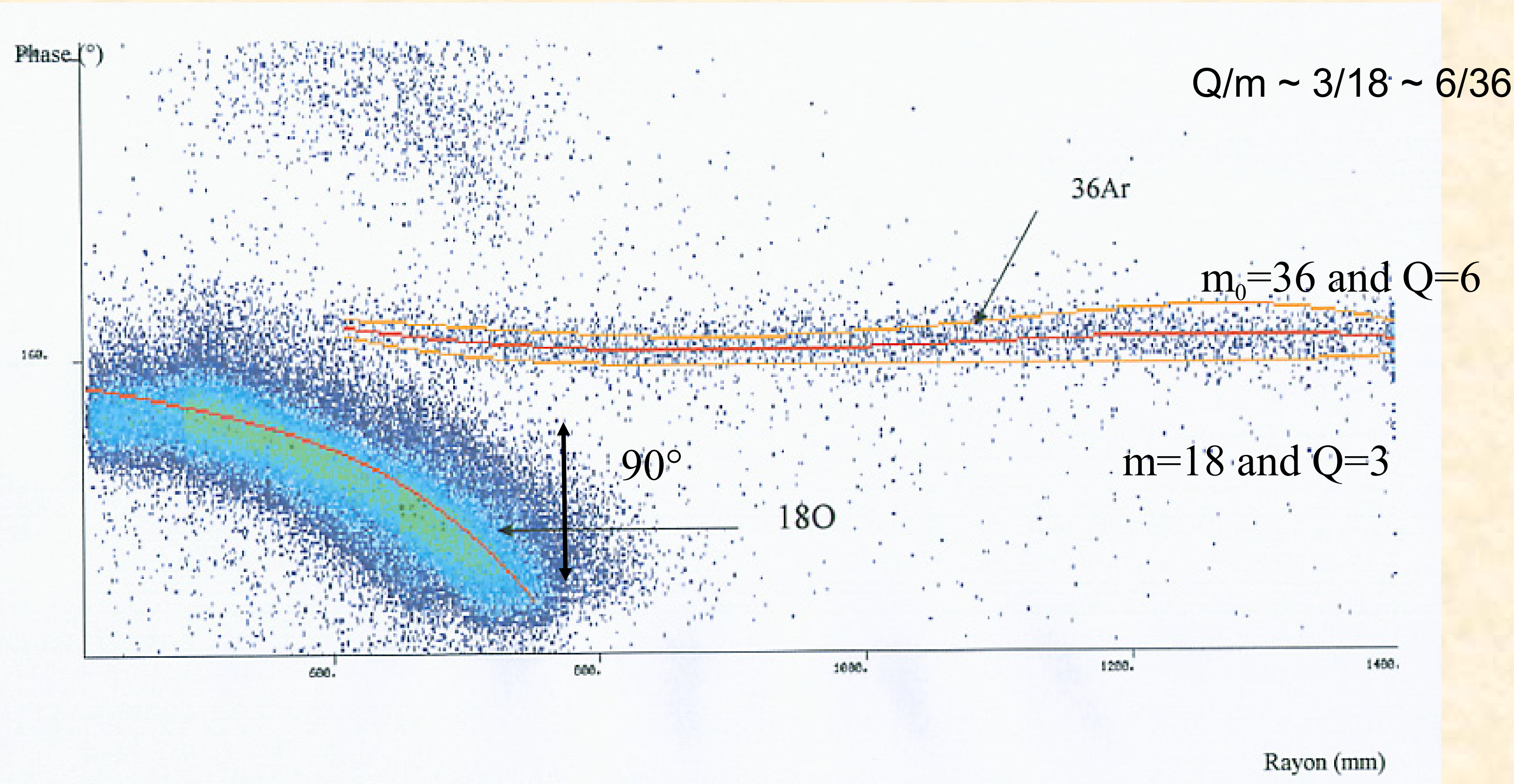
CIME example: h=3, N = 300 ⇨ R~ 10-4

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

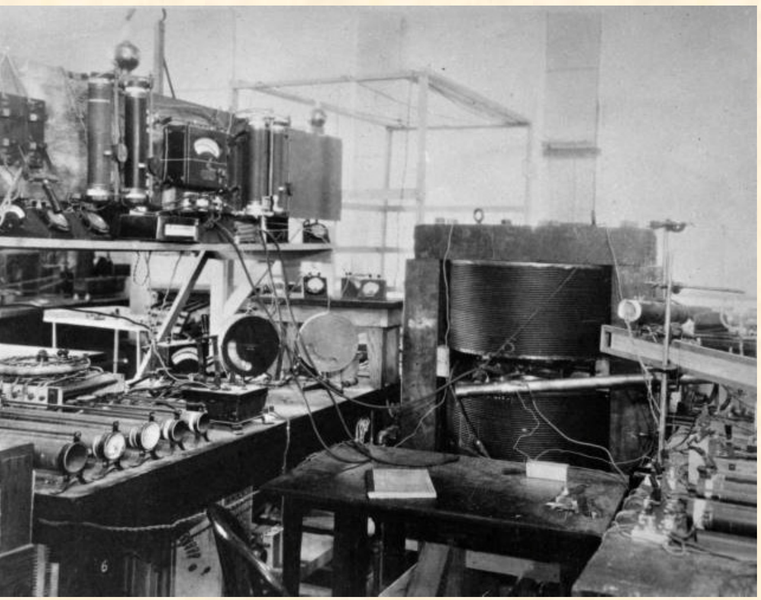
$$\Delta\varphi = 2\pi N h \frac{1}{\gamma^2} \frac{\Delta(m/Q)}{m_0/Q_0}$$



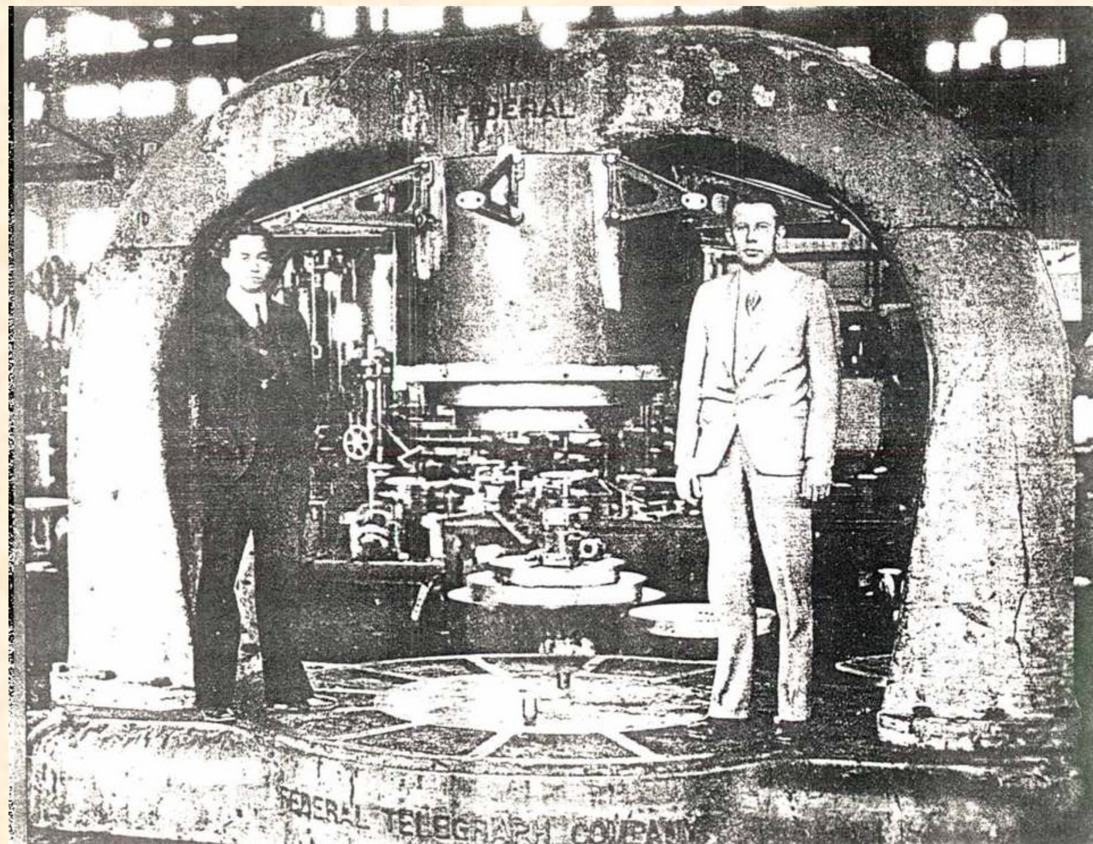
Few cyclotrons

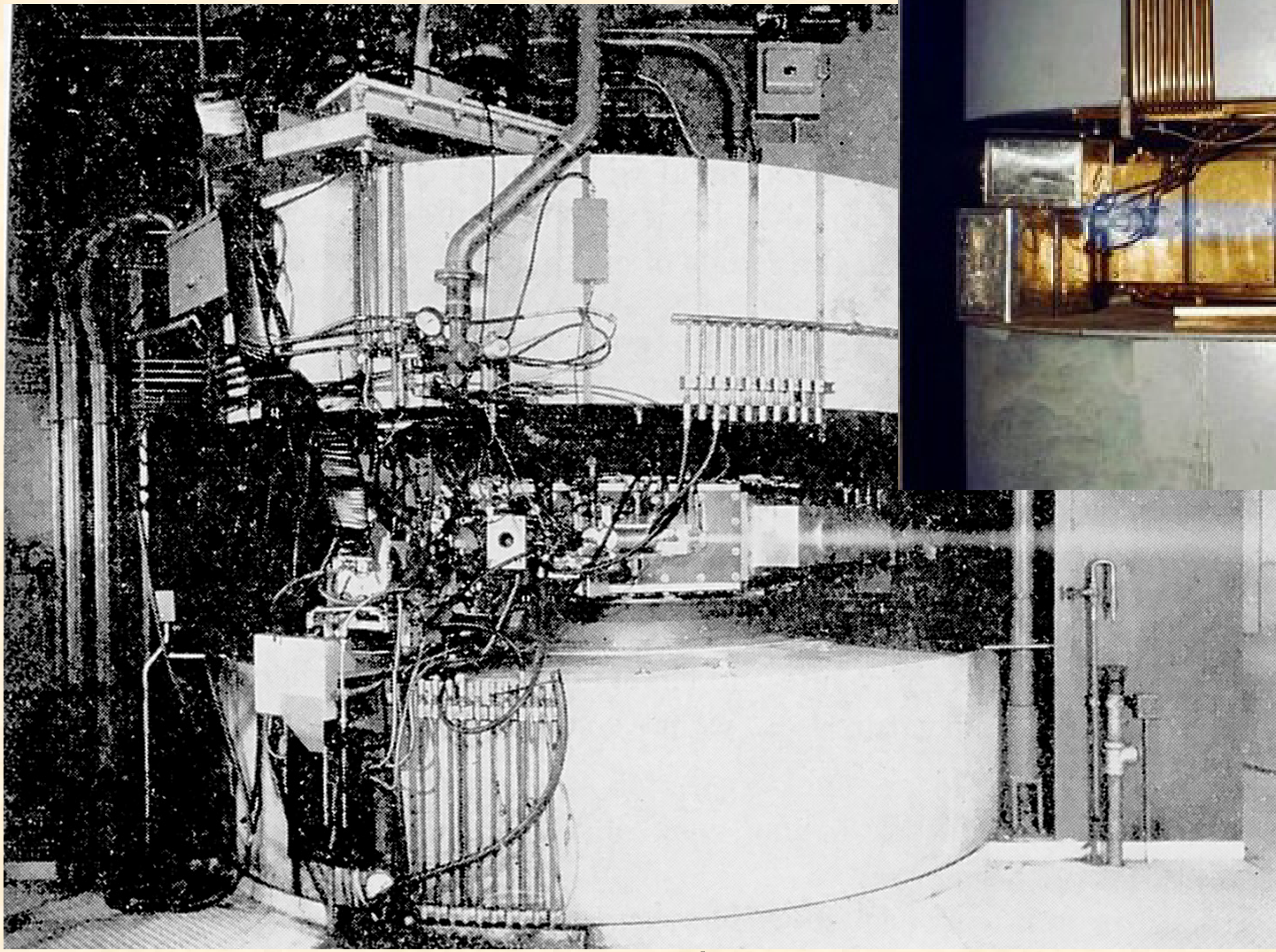
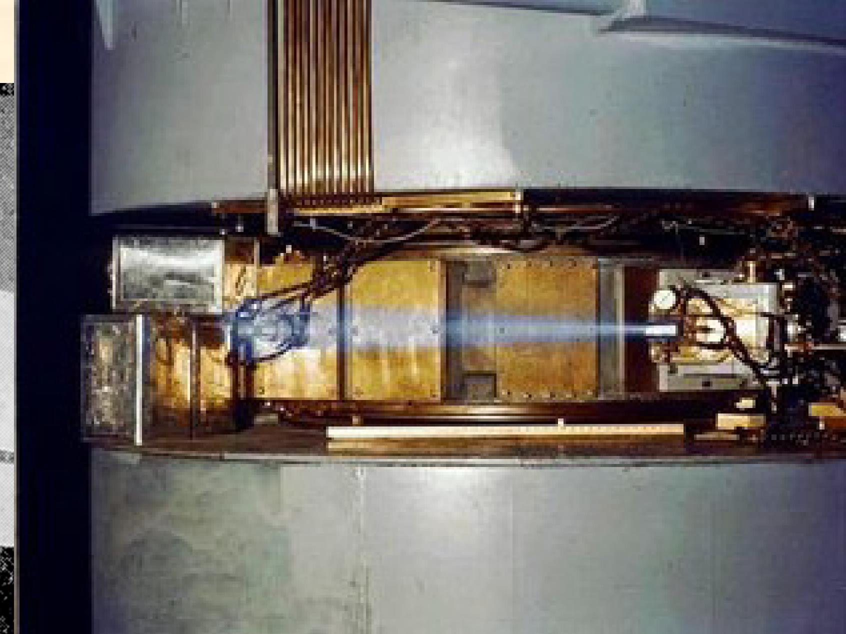
The beginning

The 11-inch cyclotron and lab bench equipment.



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



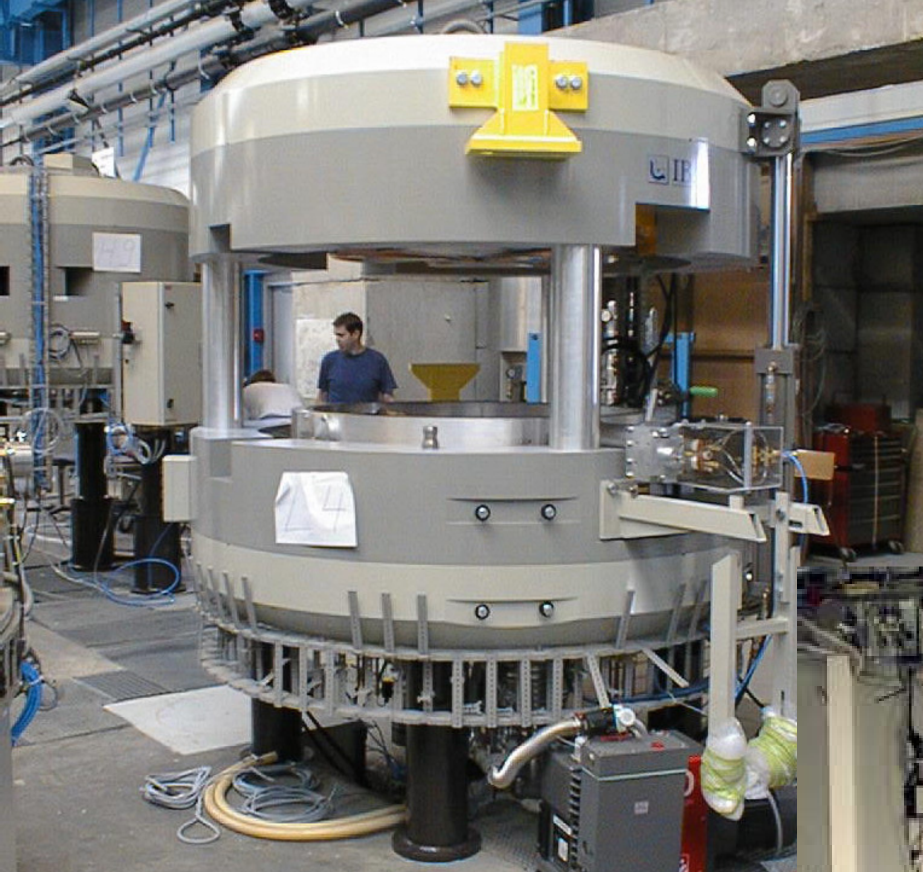



Argonne 60 inches cyclotron (deutons 21,6 MeV deuton beam out of an aluminium foil)

Karlsruhe cyclotron.

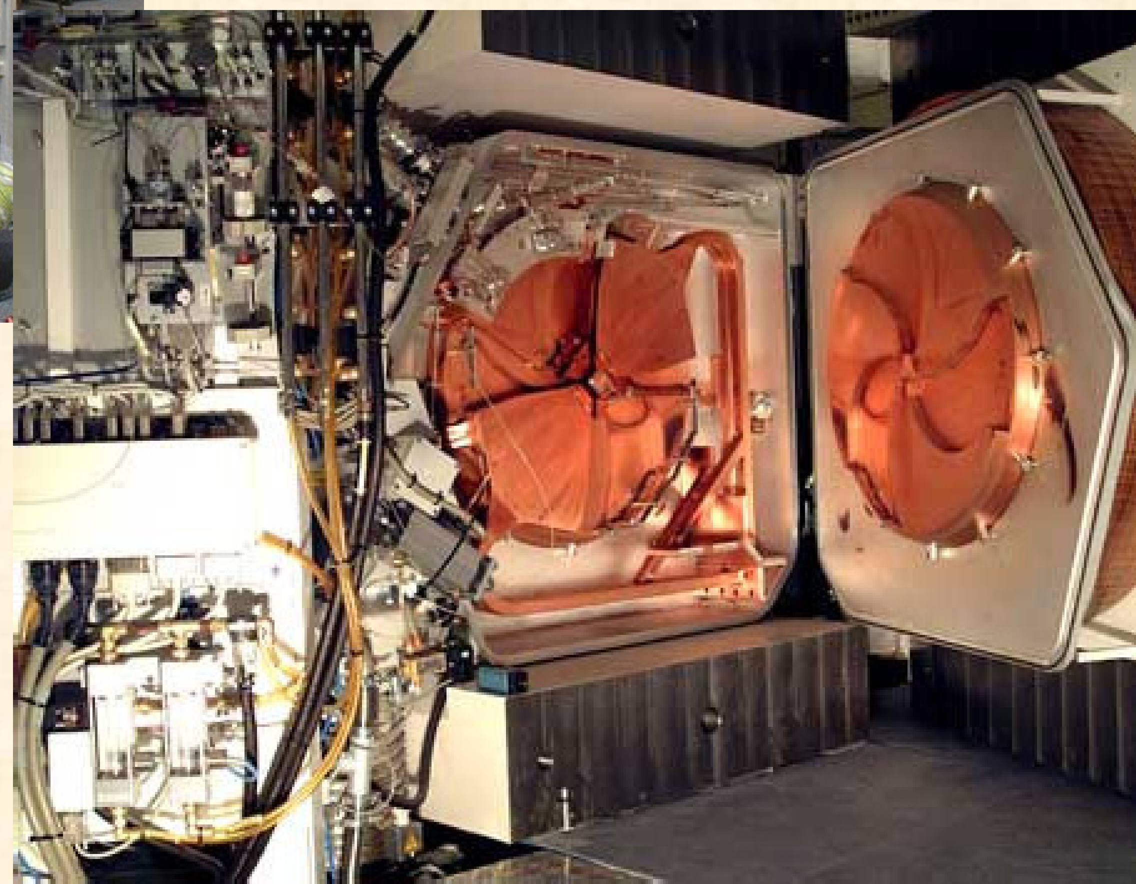
CYCLONE 30 (IBA) : H^- 15 à 30 MeV

primarily designed for industrial and medical applications

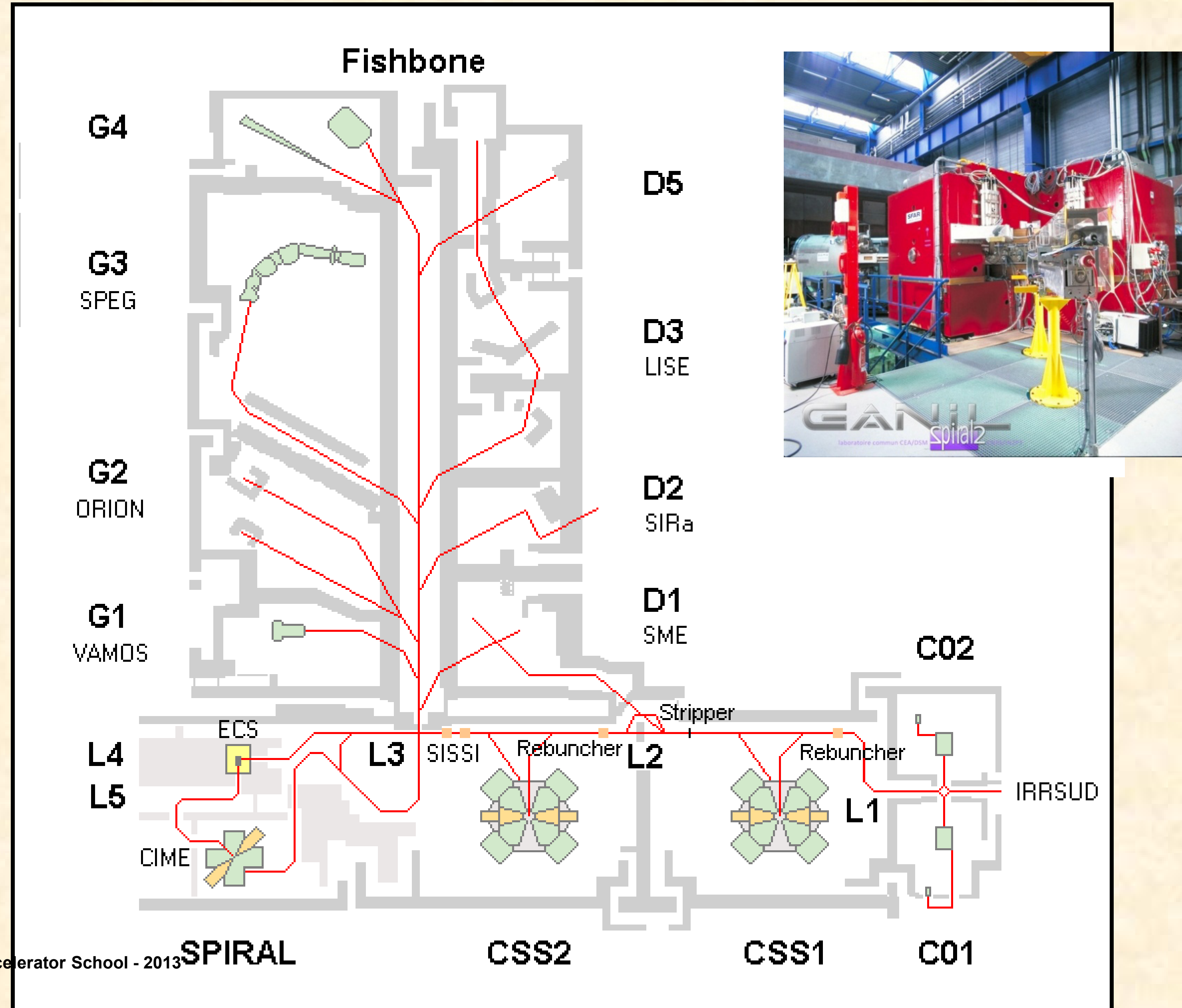


Cyclone 10/5

cyclone 3D



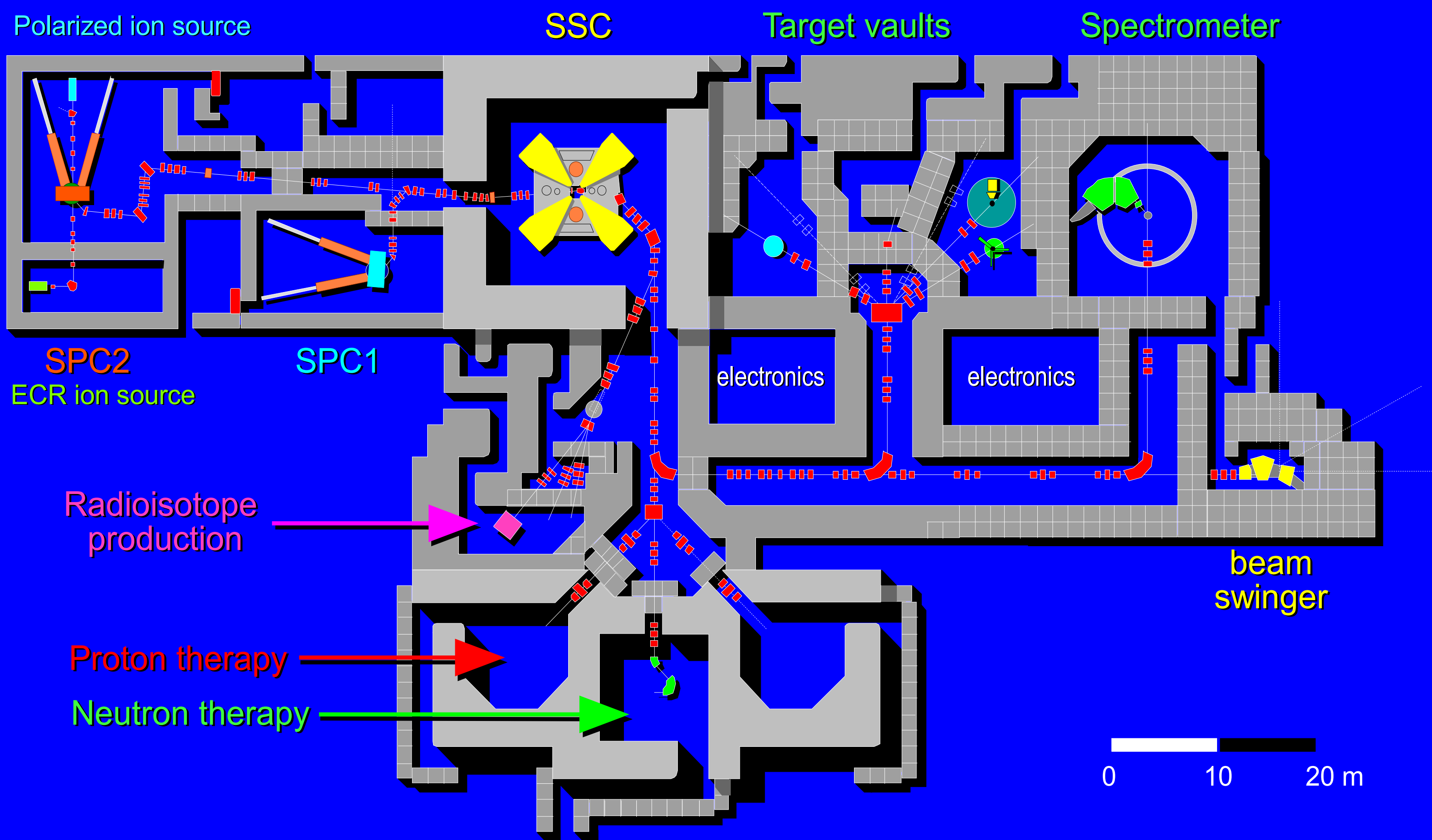
Cyclotron laboratories


Fishbone
G4
G3
SPEG
G2
ORION
G1
VAMOS
D5
D3
LISE
D2
SIRa
D1
SME
C02
Stripper
ECS
L4
L5
L3
SISSI
Rebuncher
L2
Rebuncher
IRRSUD
L1
CIME
SPIRAL
CSS2
CSS1
C01

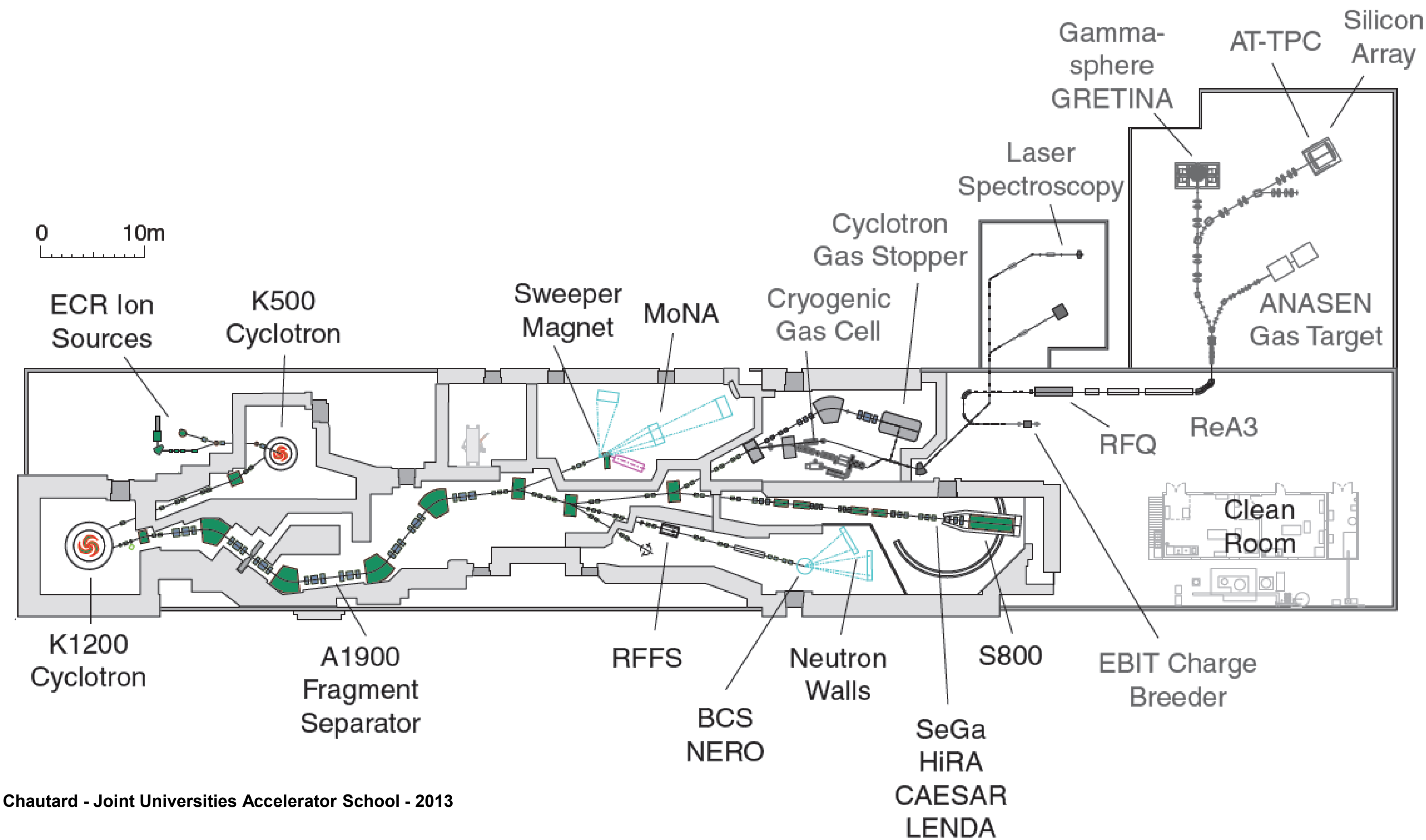
NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

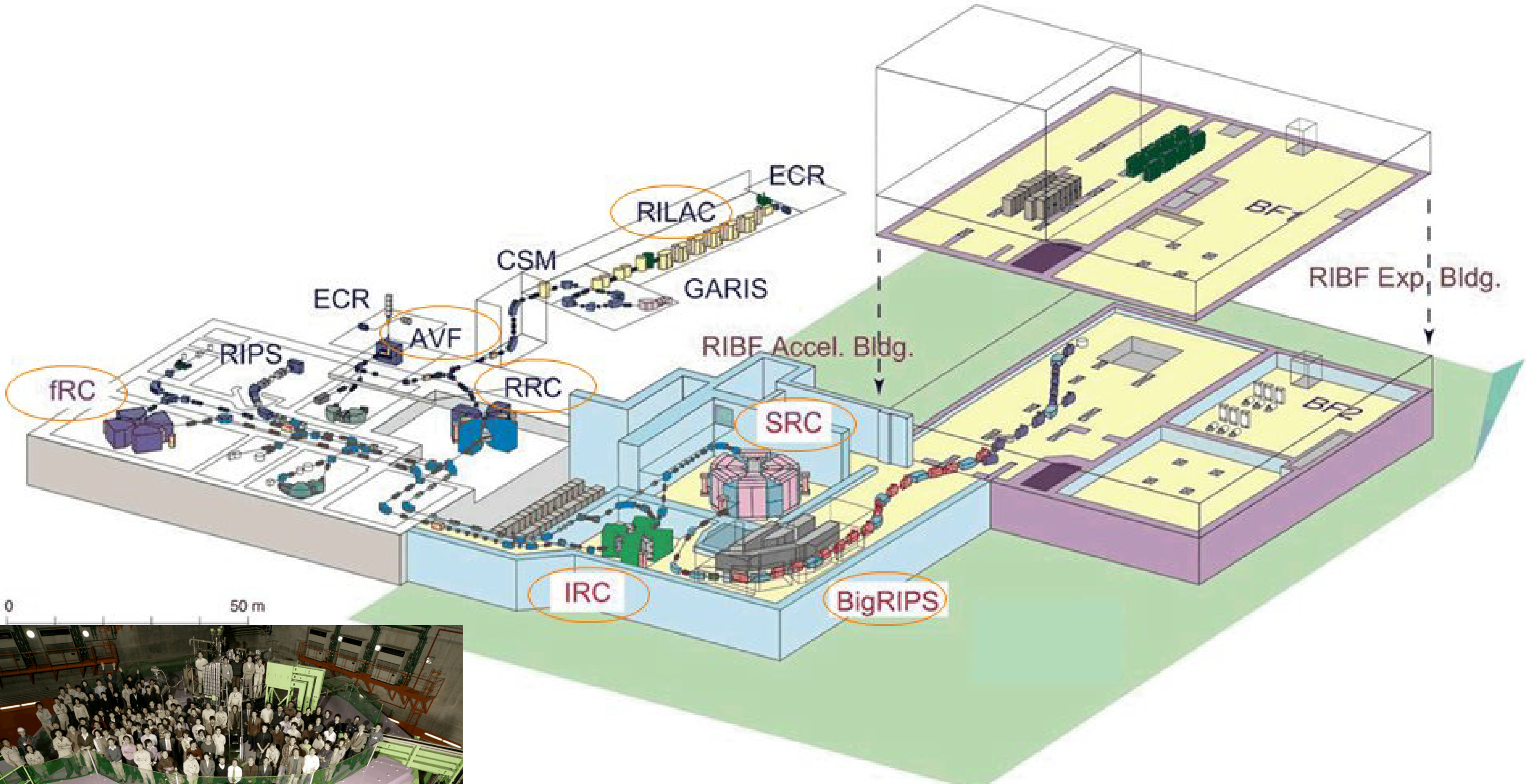
Separated-Sector Cyclotron Facility

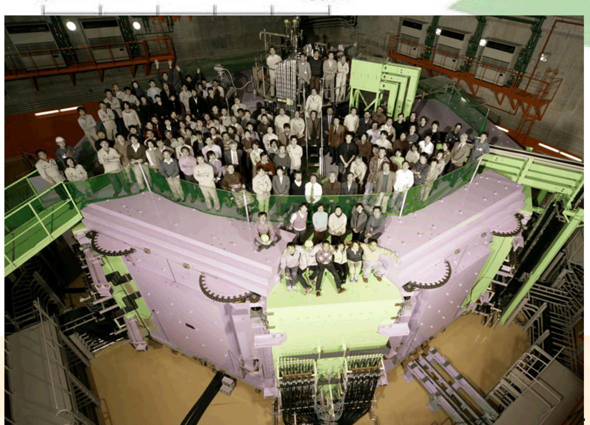


Michigan State University
Cyclotrons+A1900+Experimental Areas



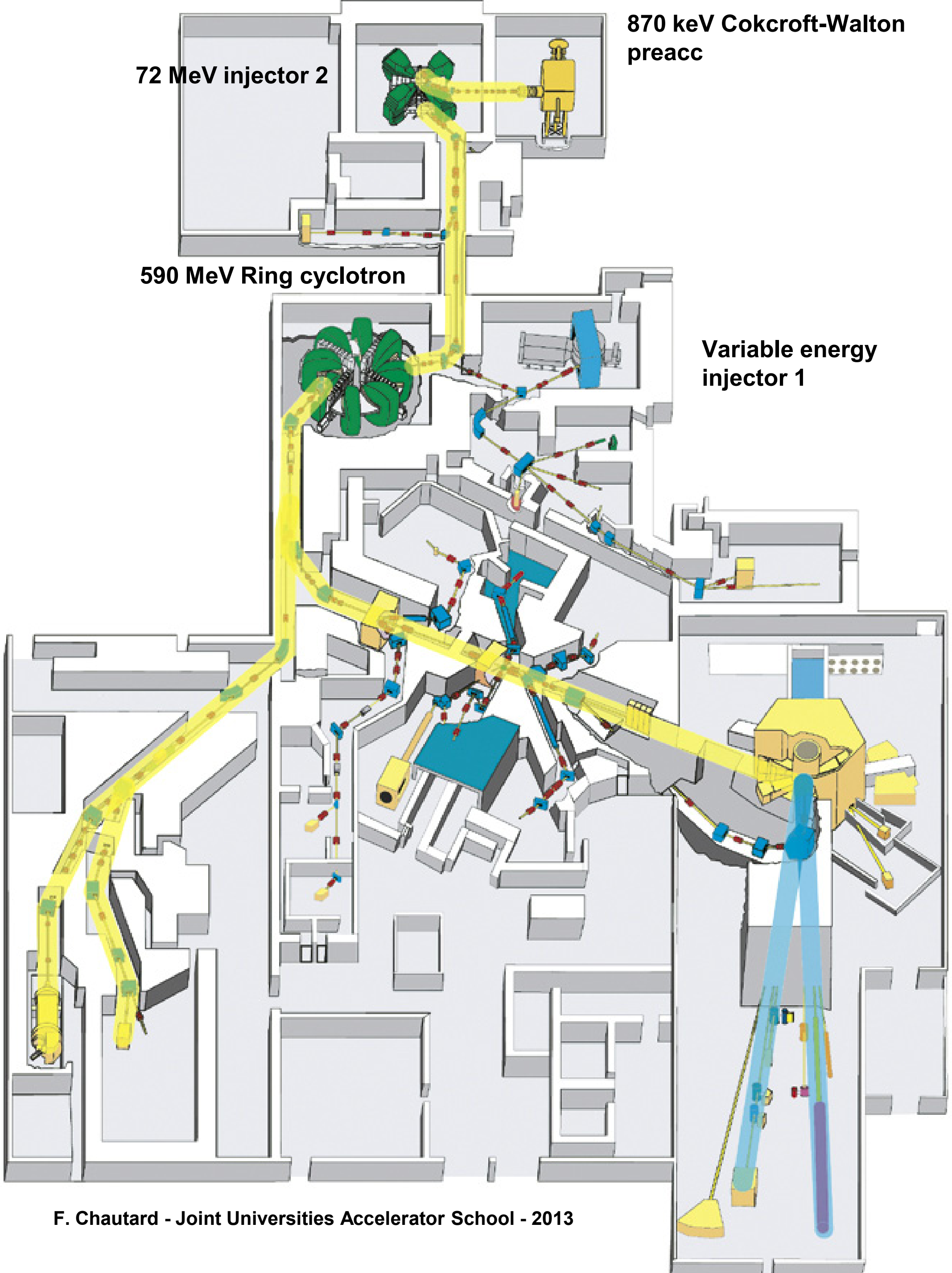
F. Chautard - Joint Universities Accelerator School - 2013


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

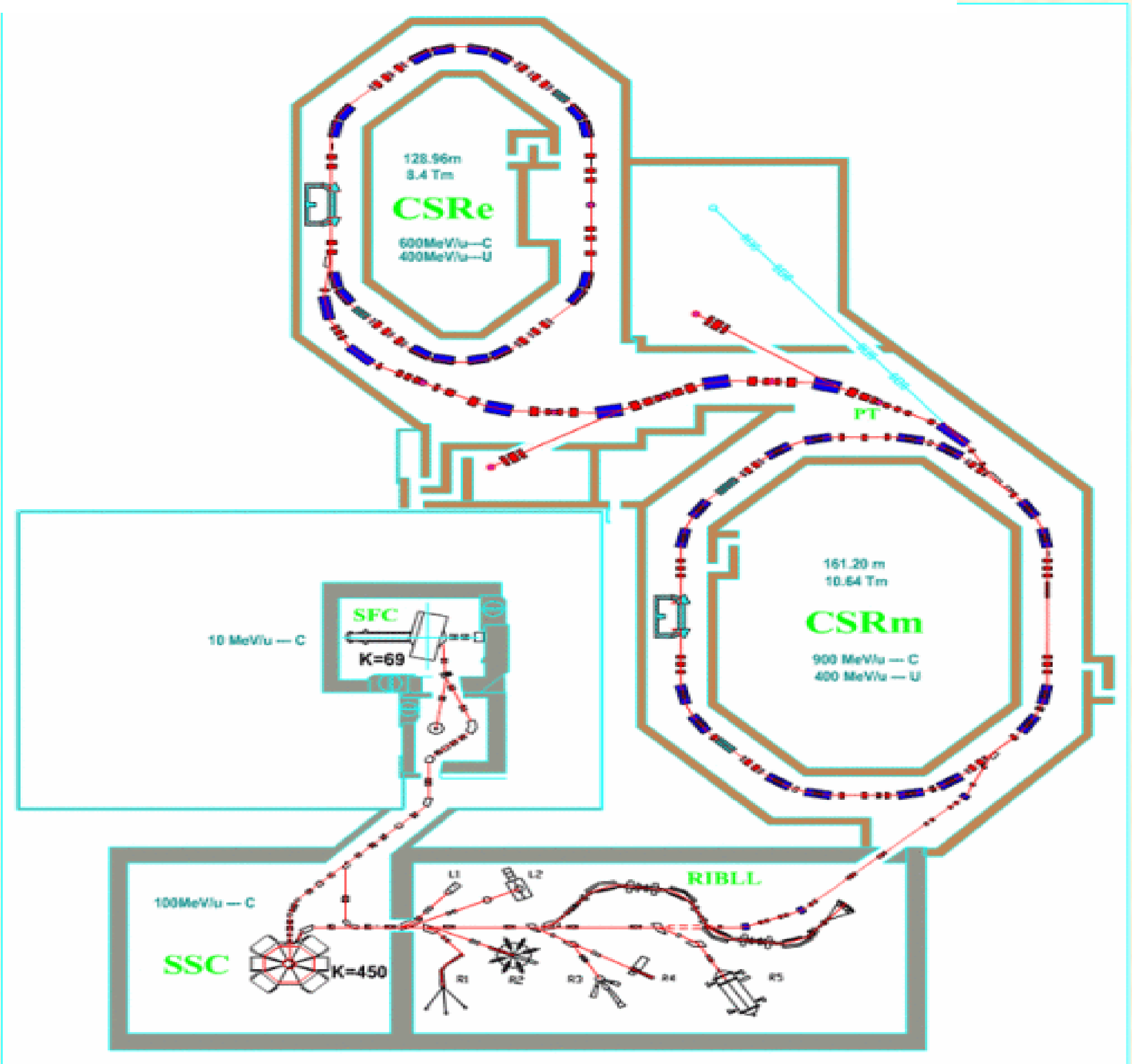


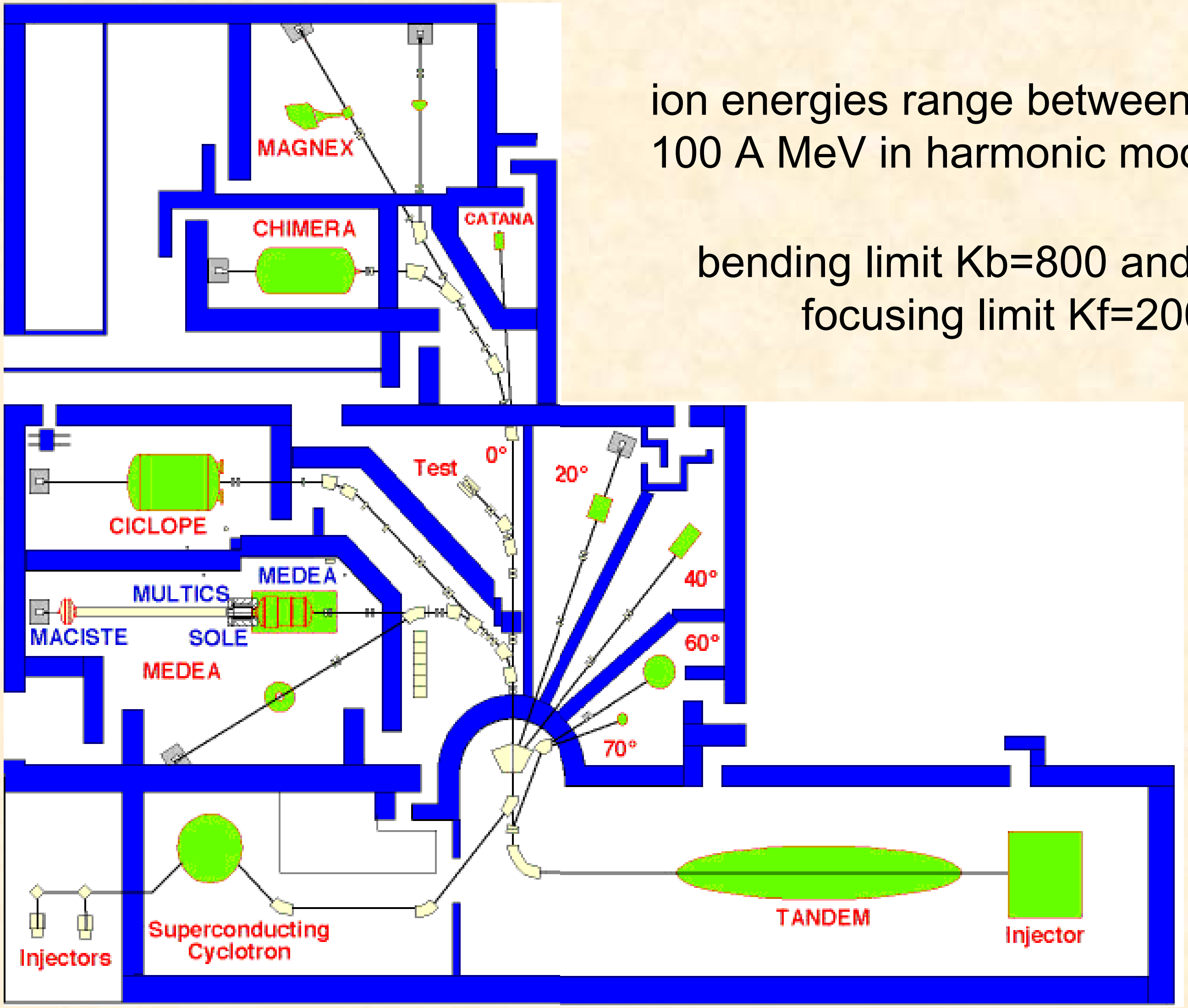
2013

PAUL SCHERRER INSTITUT PSI



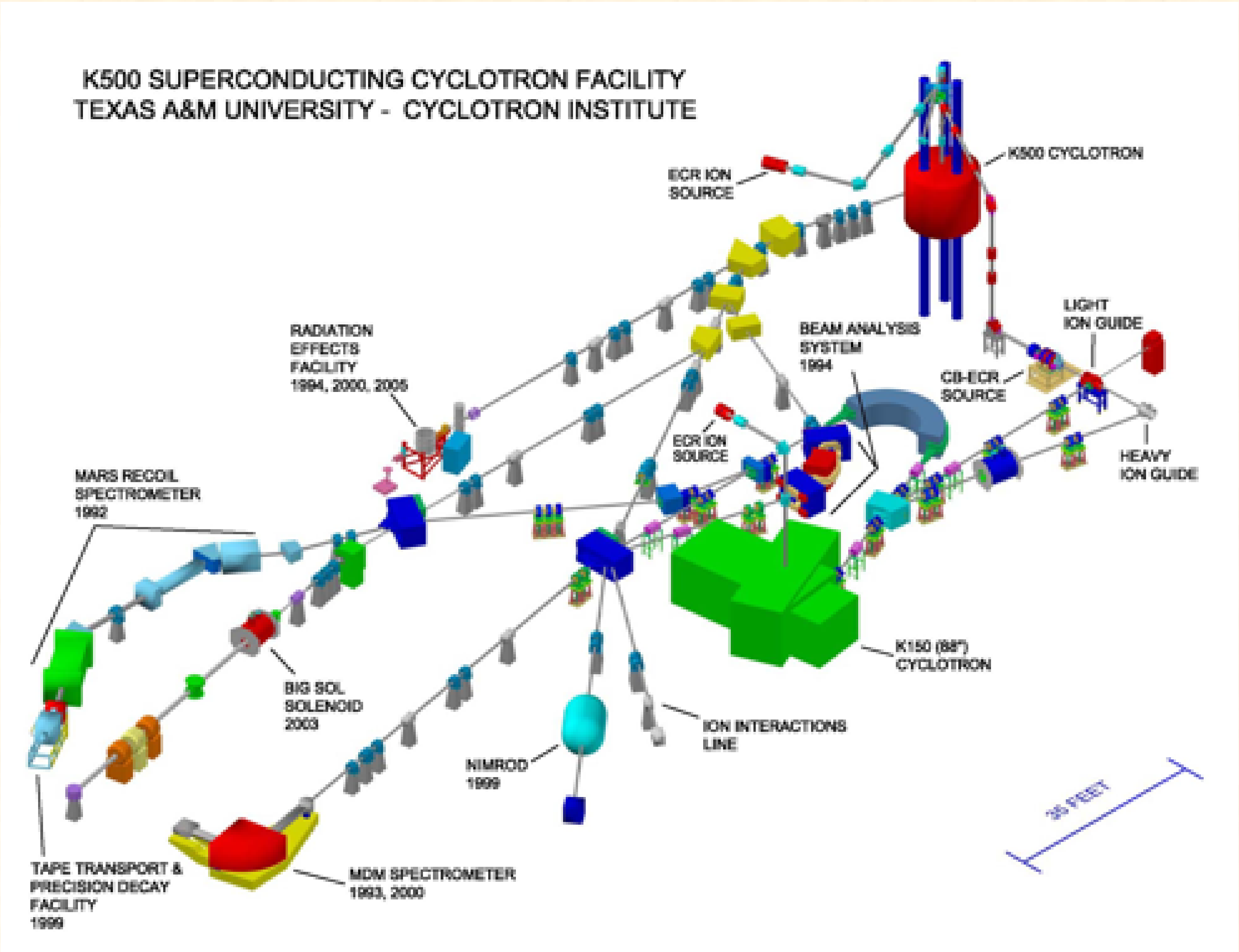
Institute of Modern Physics, Chinese Academy of Sciences



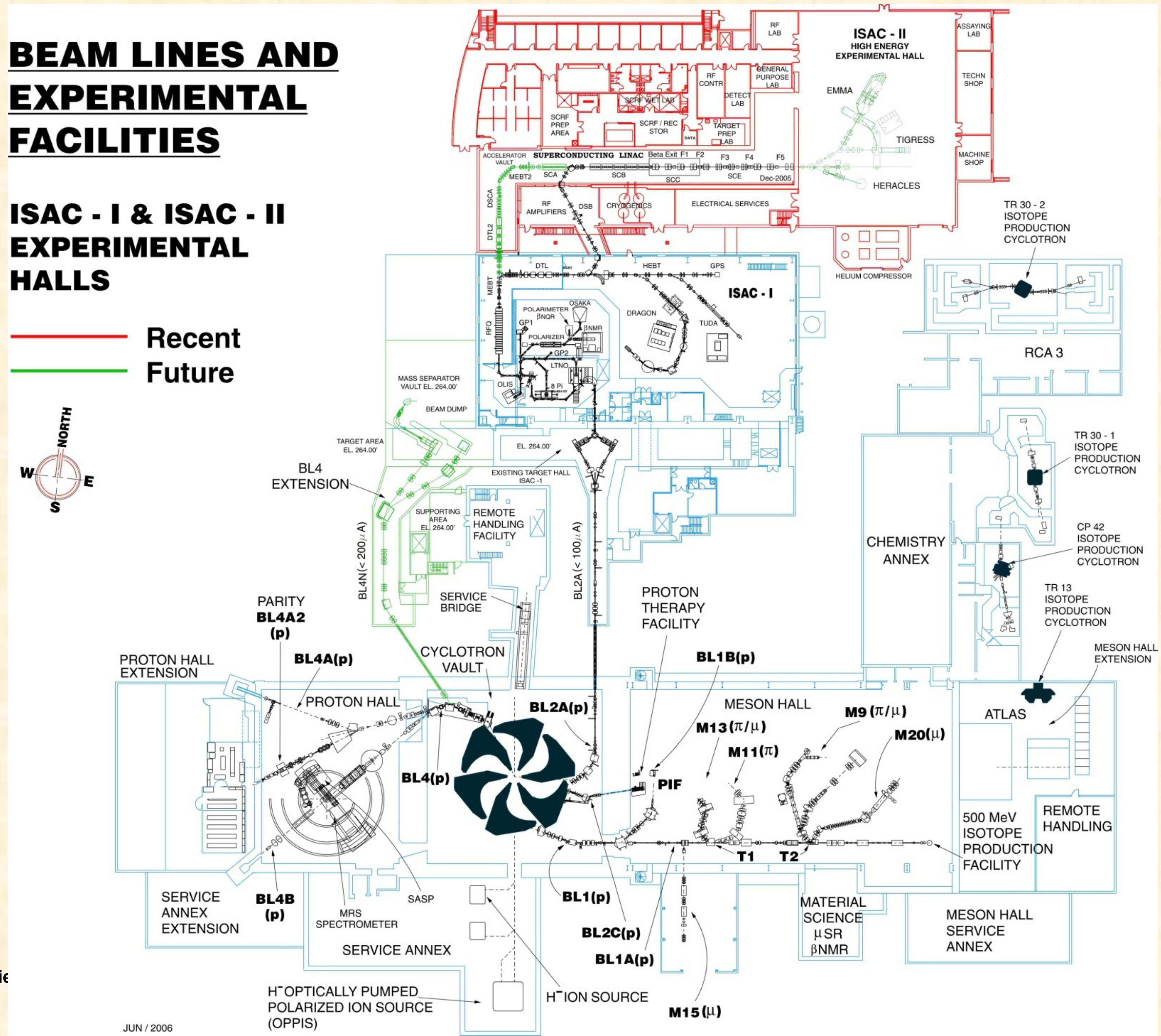


ion energies range between 8 and 100 A MeV in harmonic mode h=2

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
ASSAYING LAB
TECHN SHOP
MACHINE SHOP
RF LAB
GENERAL PURPOSE LAB
RF CONTR
DETECT LAB
SCRF WET LAB
SCRF PREP AREA
SCRF / REC STOR
TARGET PREP LAB
DATA
ACCELERATOR VAULT
SUPERCONDUCTING LINAC
Beta Exit F1 F2 F3 F4 F5
MEBT2
SCA
SCB
SCC
SCE
Dec-2005
DSCA
DTL2
RF AMPLIFIERS
DSB
CRYOGENICS
ELECTRICAL SERVICES
HELIUM COMPRESSOR
TR 30 - 2 ISOTOPE PRODUCTION CYCLOTRON
DTL
HEBT
GPS
ISAC - I
MEBT
RFQ
POLARIMETER βNQR
OSAKA
GP1
βNMR
POLARIZER
GP2
LTNO
OLIS
8 Pi
DRAGON
TUDA
RCA 3
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
TR 30 - 1 ISOTOPE PRODUCTION CYCLOTRON
CP 42 ISOTOPE PRODUCTION CYCLOTRON
TR 13 ISOTOPE PRODUCTION CYCLOTRON
CHEMISTRY ANNEX
PROTON THERAPY FACILITY
PARITY BL4A2 (p)
PROTON HALL EXTENSION
BL4A(p)
CYCLOTRON VAULT
BL1B(p)
MESON HALL EXTENSION
PROTON HALL
BL2A(p)
MESON HALL
M9 (π/μ)
ATLAS
M13 (π/μ)
M20(μ)
M11(π)
BL4(p)
PIF
500 MeV ISOTOPE PRODUCTION FACILITY
REMOTE HANDLING
T1
T2
SERVICE ANNEX EXTENSION
BL4B (p)
MRS SPECTROMETER
SASP
BL1(p)
MATERIAL SCIENCE μSR βNMR
MESON HALL SERVICE ANNEX
SERVICE ANNEX
BL2C(p)
BL1A(p)
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**

- S. Humphries, jr., J. Wiley & Sons 1986, Principles of Charged Particle Acceleration.
- 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**

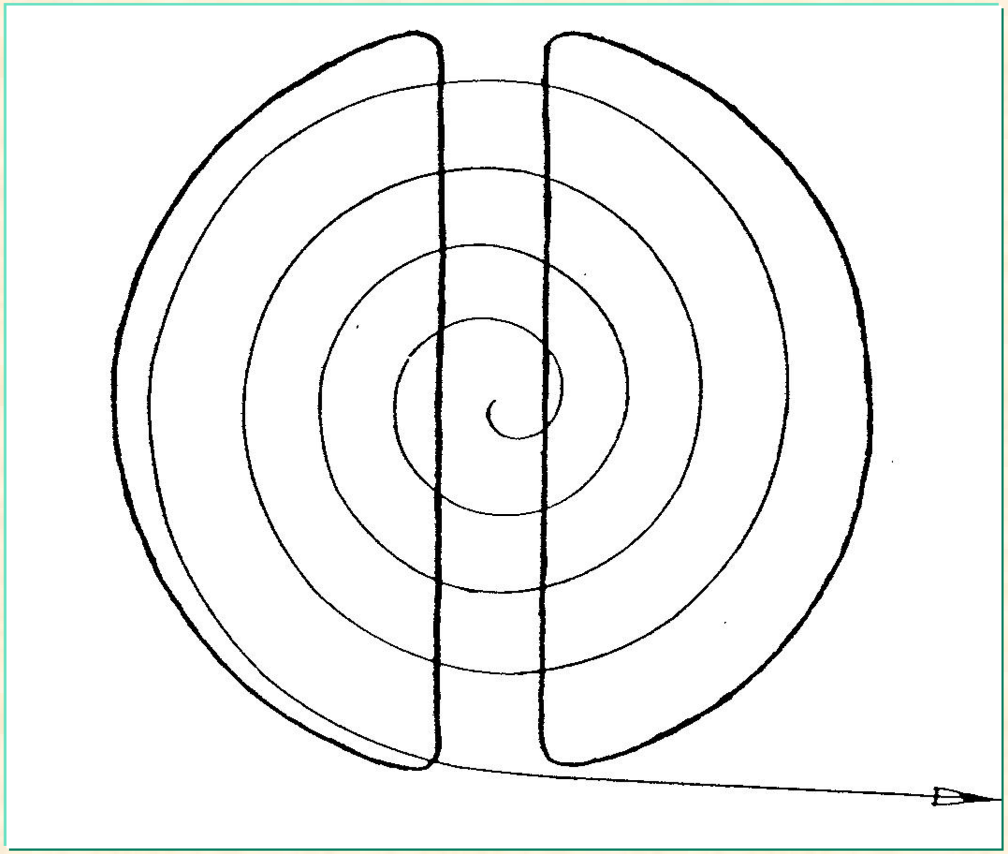
- Proceedings of the International Conferences on Sector-focused Cyclotrons and on Cyclotrons and their application :
- ICC1, Informal Conference on sector-focused Cyclotrons 1959 in Sea Island, NAS-NRC, Publ.656 (1959)
- ICC2, Int. Conference 1962 in Los Angeles, Nucl. Inst.& Meth. 18, 19 (1962)
- ICC3, Int. Conference 1963 in Geneva, CERN 63-19 (1963)
- ICC4, Int. Conference 1966 in Gatlinburg, IEEE Trans. NS-13(4) (1966)
- ICC5, 5th Int. Cyclotron Conference 1969 in Oxford, McIllroy, Butterworth (1971)
- ICC6, 6th Int. Cyclotron Conference 1972 in Vancouver, AIP Conf. Proc. N°9 (1972)
- ICC7, 7th Int. Cyclotron Conference 1975 in Zürich, Birkhäuser (1975)
- ICC8, 8th Int. Cyclotron Conference 1978 in Bloomington, IEEE Trans. NS-26(2) (1979)
- ICC9, 9th Int. Cyclotron Conference 1981 in Caen, les Editions de Physique (1982)
- ICC10, 10th Int. Cyclotron Conference 1984 in East Lansing, IEEE, New York (1984)
- ICC11, 11th Int. Cyclotron Conference 1986 in Tokyo, Ionics Publishing Tokyo (1987)
- ICC12, 12th Int. Cyclotron Conference 1989 in Berlin, World Scientific Publ. (1991)
- ICC13, 13th Int. Cyclotron Conference 1992 in Vancouver, World Scientific Publ. (1993)
- ICC14, 14th Int. Cyclotron Conference 1995 in Cape Town, World Scientific Publ Co. (1996)
- ICC15, 15th Int. Cyclotron Conference 1998 in Caen, Institute of Physics Publ. (1999)
- ICC16, 16th Int. Cyclotron Conference 2001 in East Lansing, American Inst. of Ph., New York (2001)

- **Contribution to CERN Accelerator Schools**

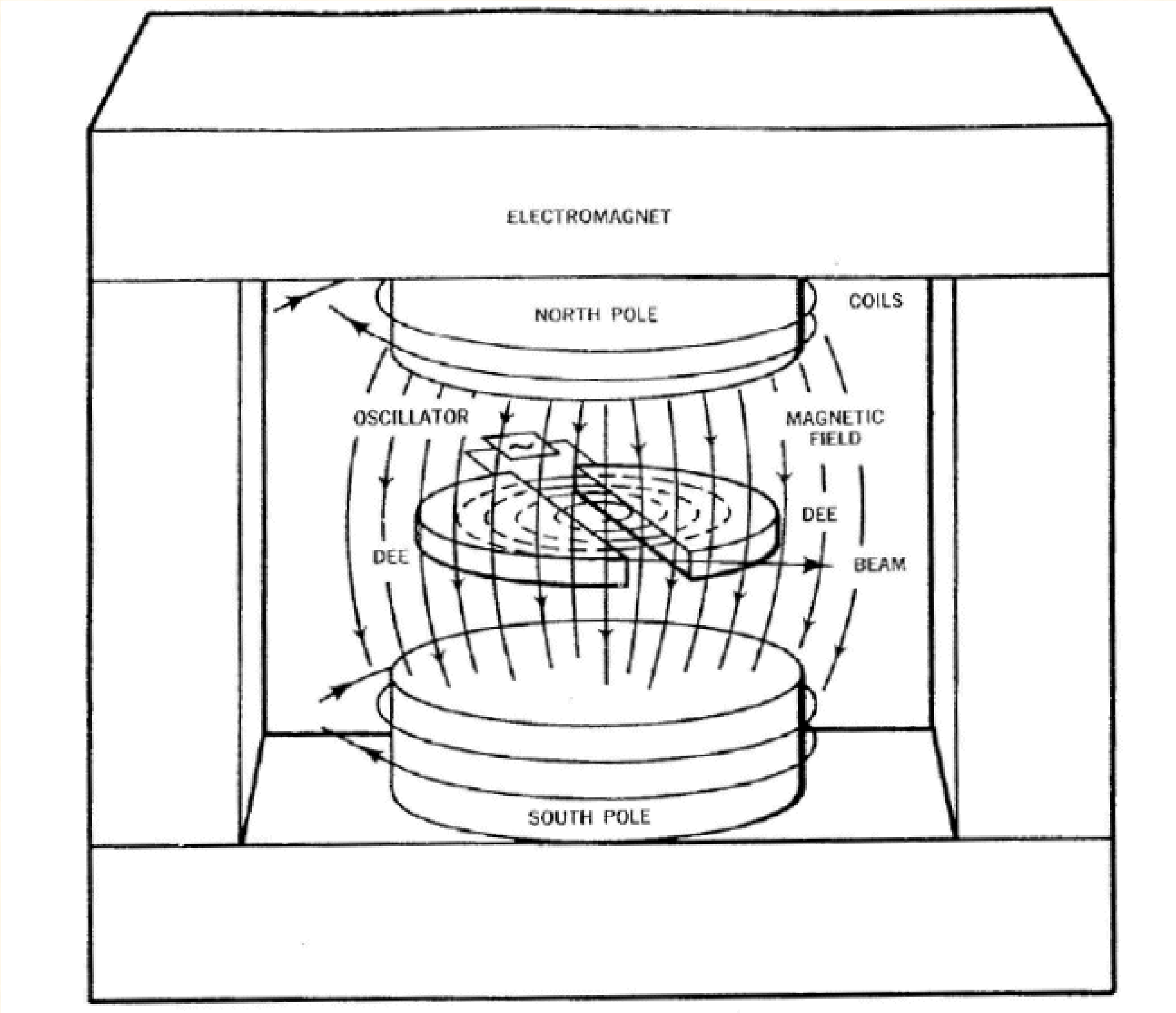
- W. Joho, CAS Aarhus 1986, CERN 87-10 (1987) 1 “Modern Trends in Cyclotrons”
- H.L. Hagedoorn et al., CAS Jülich 1990, CERN 91-04 (1991) 323 “Introduction to Cyclotron”
- H.L. Hagedoorn et al., CAS Leewenhorst 1991, CERN 92-01 (1992) 1 “Hamilton Theroy”
- P. Heikinnen, CAS Jyväskylä 1992, CERN 94-01 (1994) “Cyclotrons“ and “Injection and Extraction“
- T. Stammbach, CAS La Hulpe, 1994, CERN 96-02 (1996) “Introduction to Cyclotrons“
- F. Chautard, CAS Zeegse, CERN-2006-012 (2005) “Beam dynamics for cyclotrons”

END

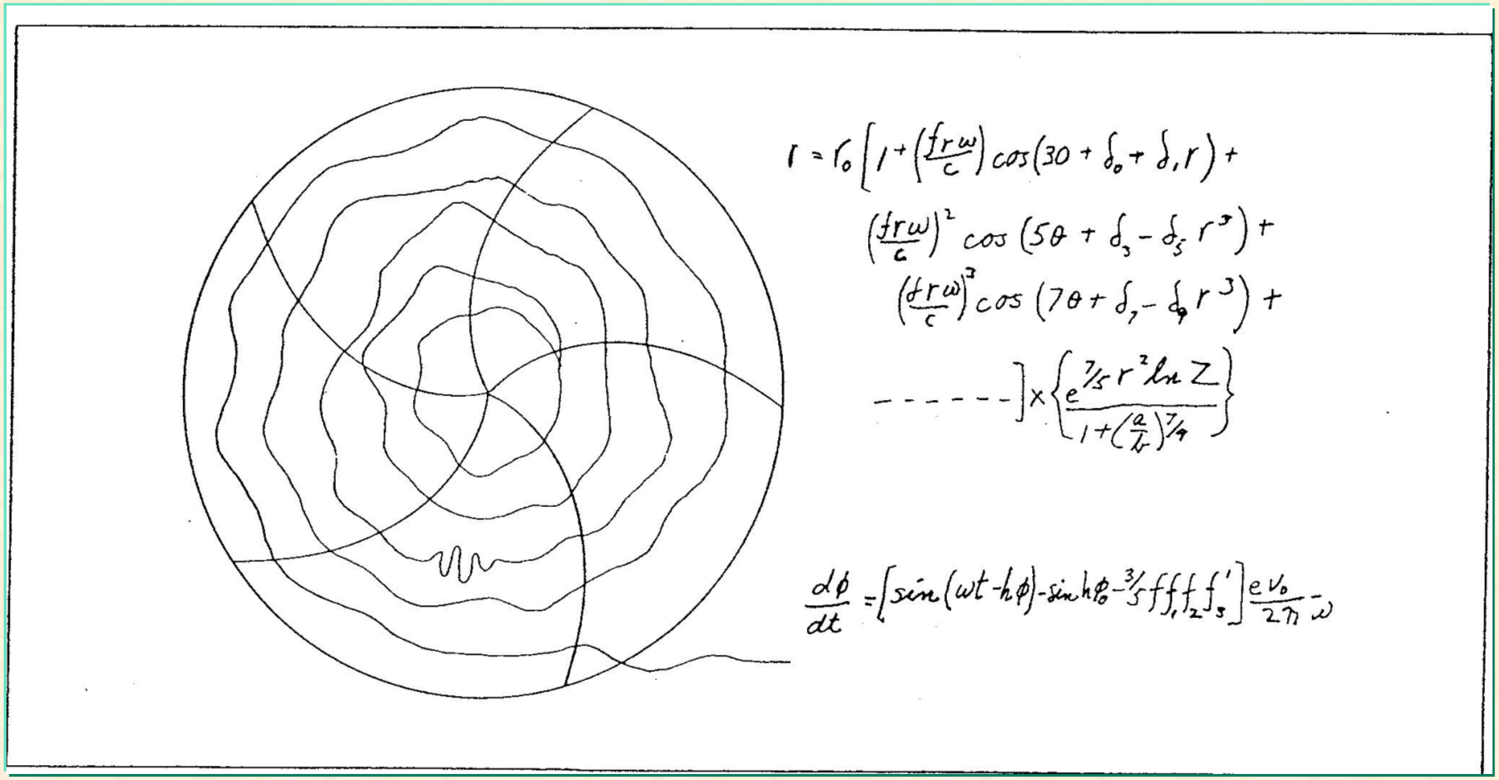
The Cyclotron as seen by the **Inventor**



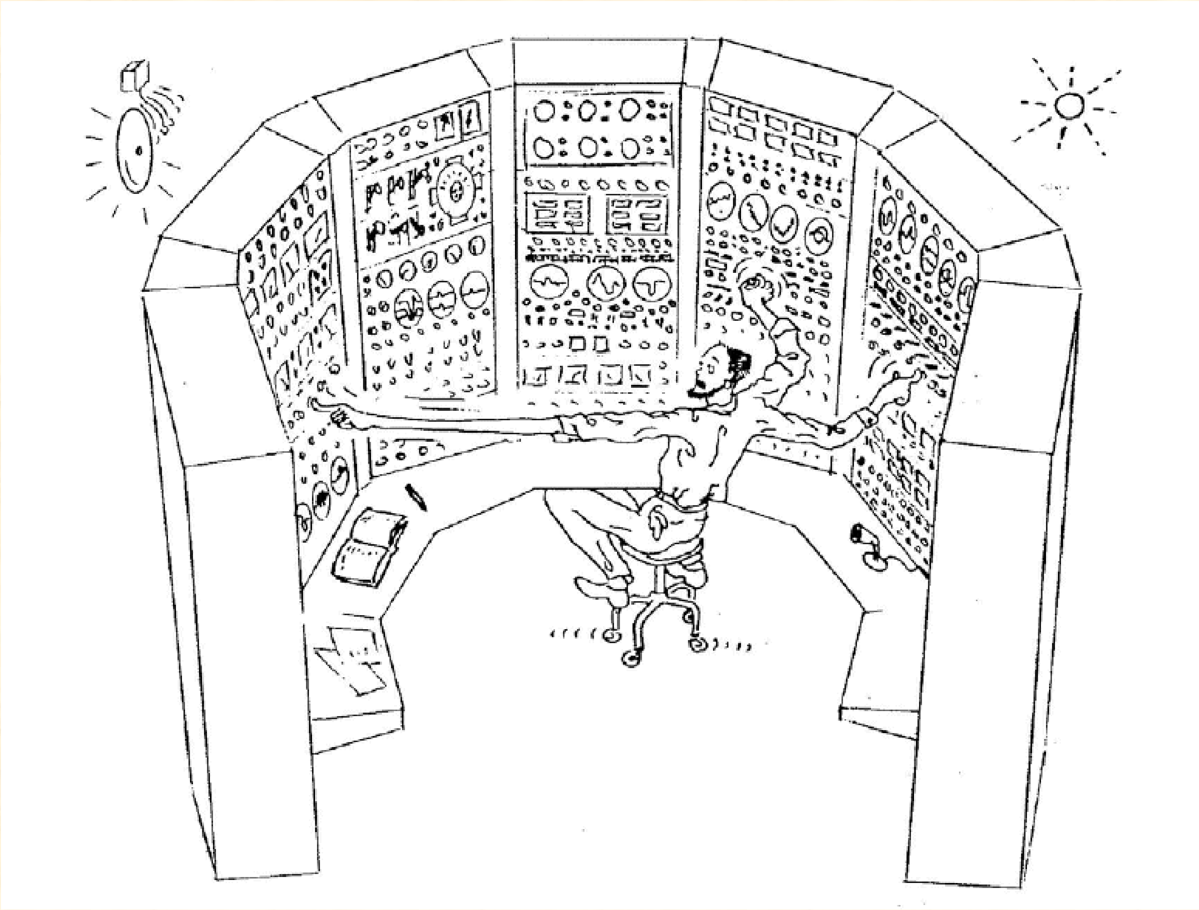
The Cyclotron as seen in the usual **text book**



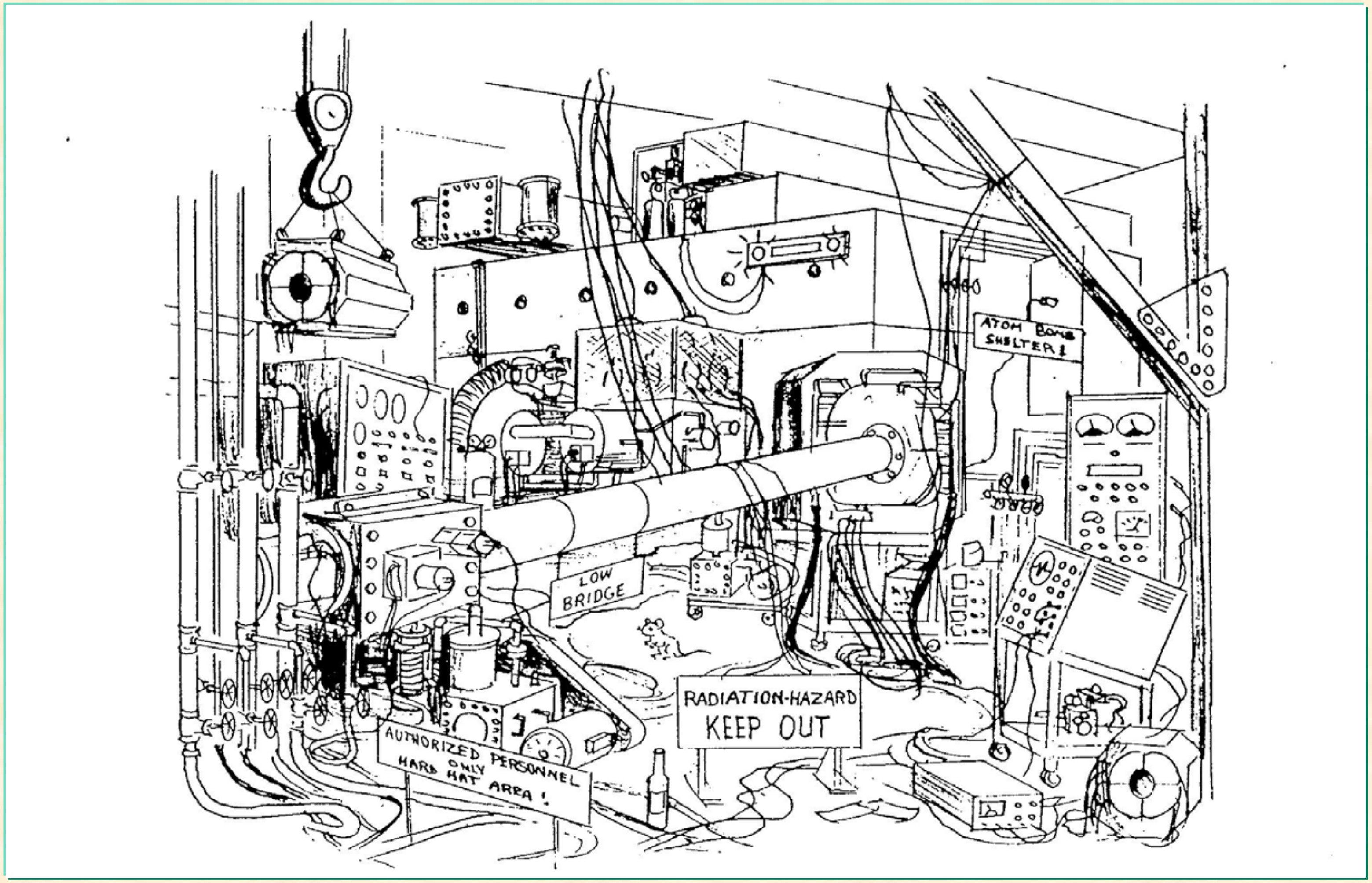
The Cyclotron as seen by the **Theorist**



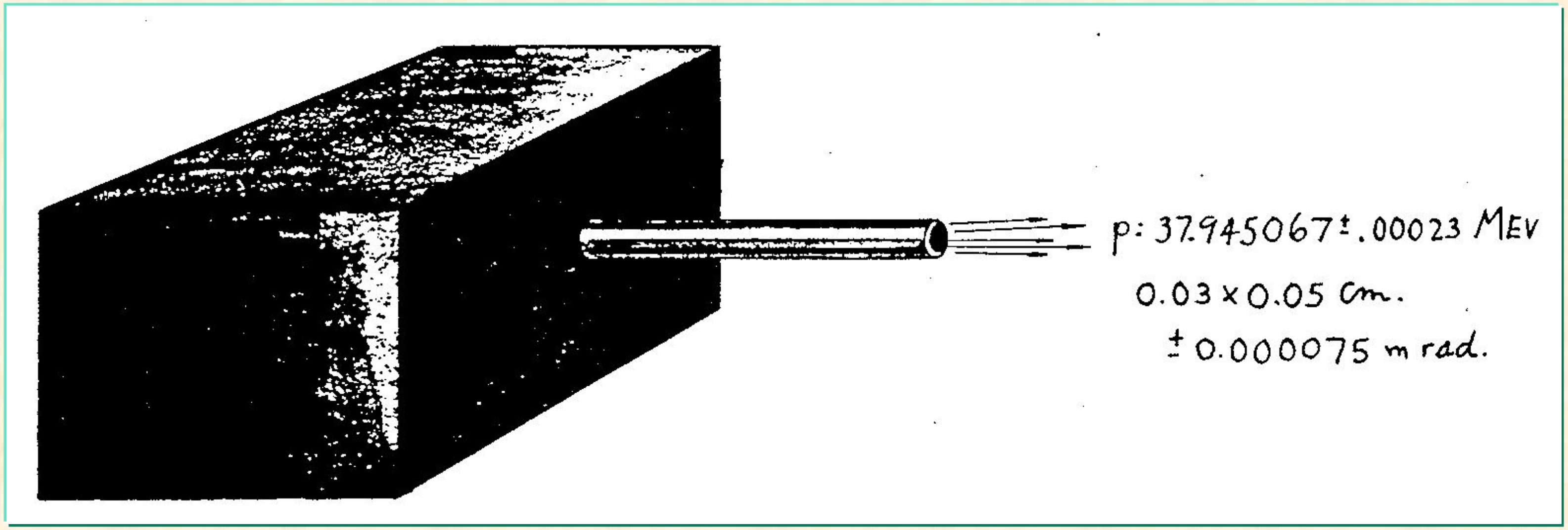
The Cyclotron as seen by the **Operator**



The Cyclotron as seen by the **Visitor**



The Cyclotron as seen by the
Experimentalist



The Cyclotron as seen by the **Student**