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

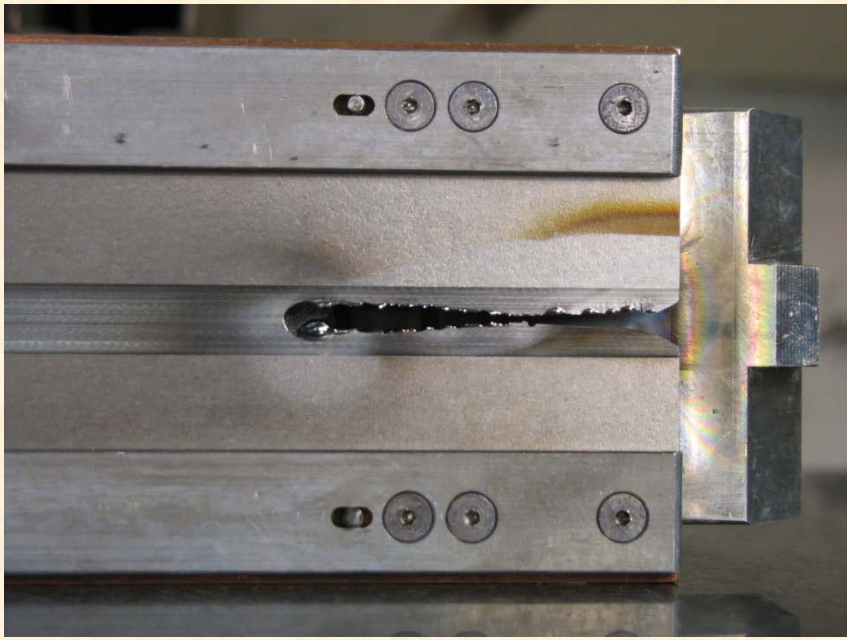
- for machine safety
- permanently
- for tuning
- at setup
- for error search
- only at commissioning

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

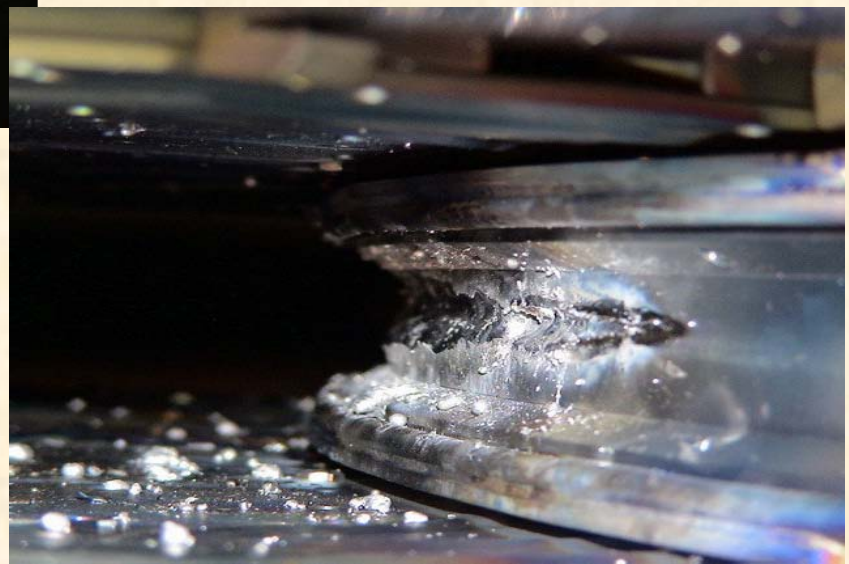
High intensity diagnostics

MSU K1200 Deflector Septum (Tungsten)

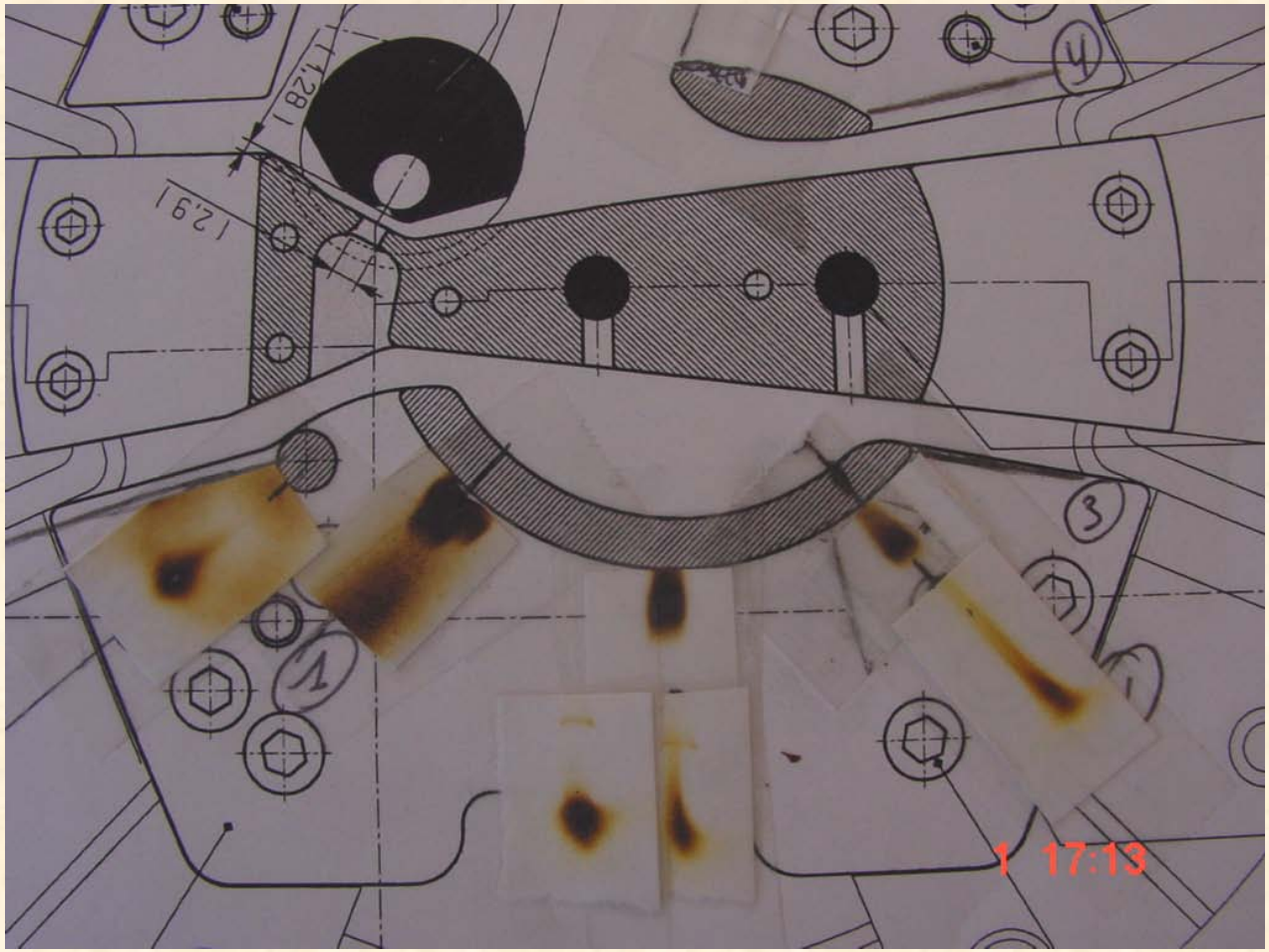


Beam induced defects with a

160 kW beam at PSI

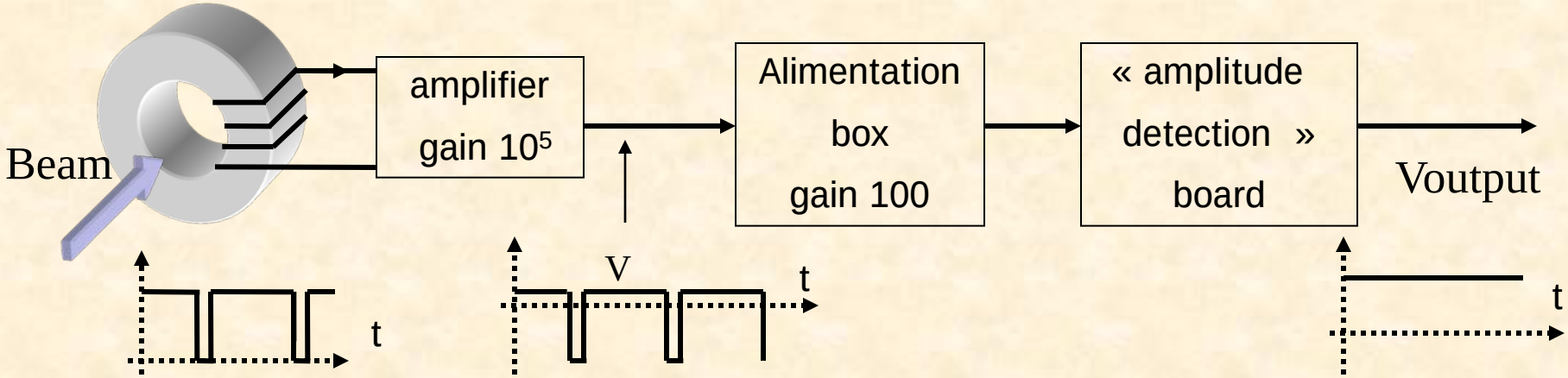


Beam Diagnostics



Current measurement (non interceptive) & (> nAe)

- Current Transformers Electronic Devices



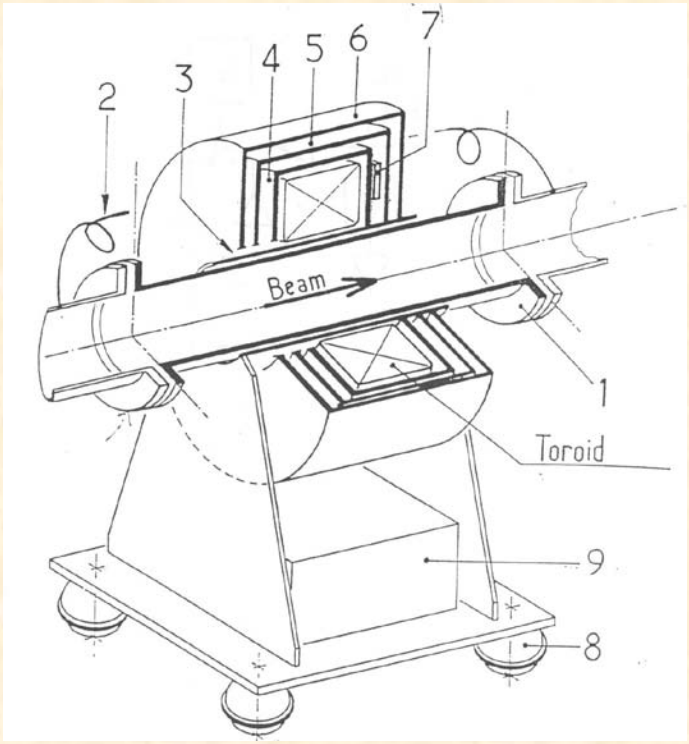
- The beam is « chopped » at a low frequency (hundred of Hz) to use this kind of diagnostics.
- Current transformer signal is amplify and measure by « amplitude detection board ».

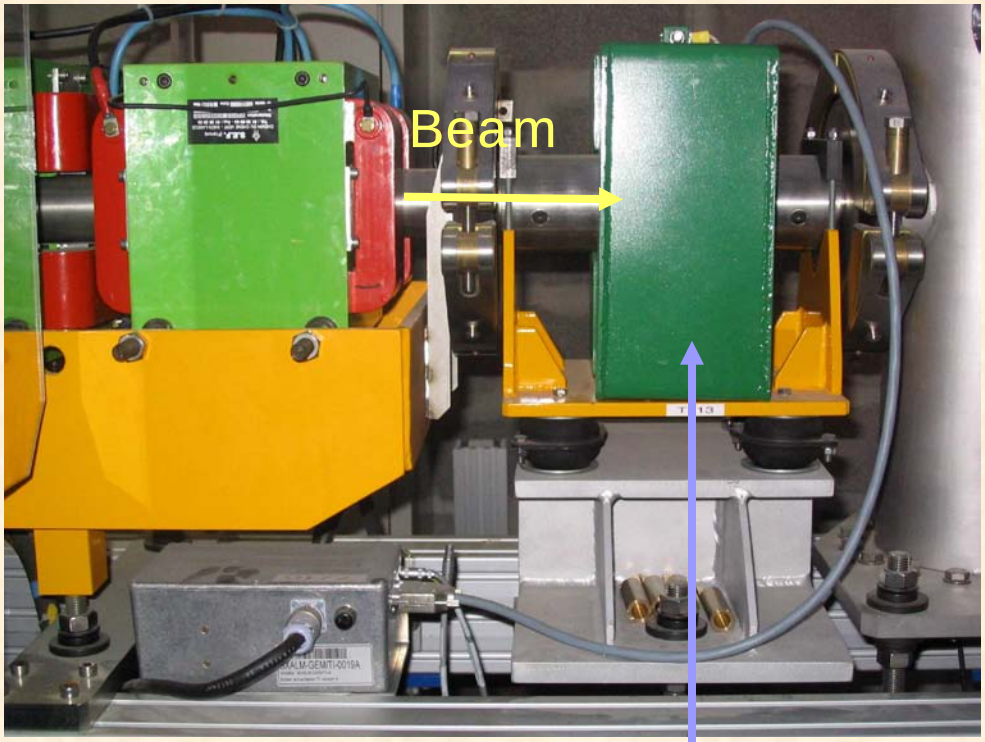
$$I\,[A] = Npps \times Q \times e$$

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

Current measurement (non interceptive)

- By Current Transformers (ACCT)

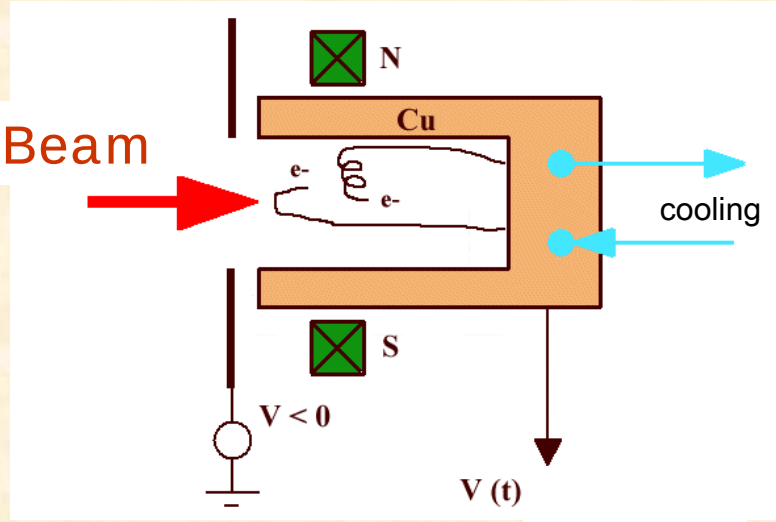


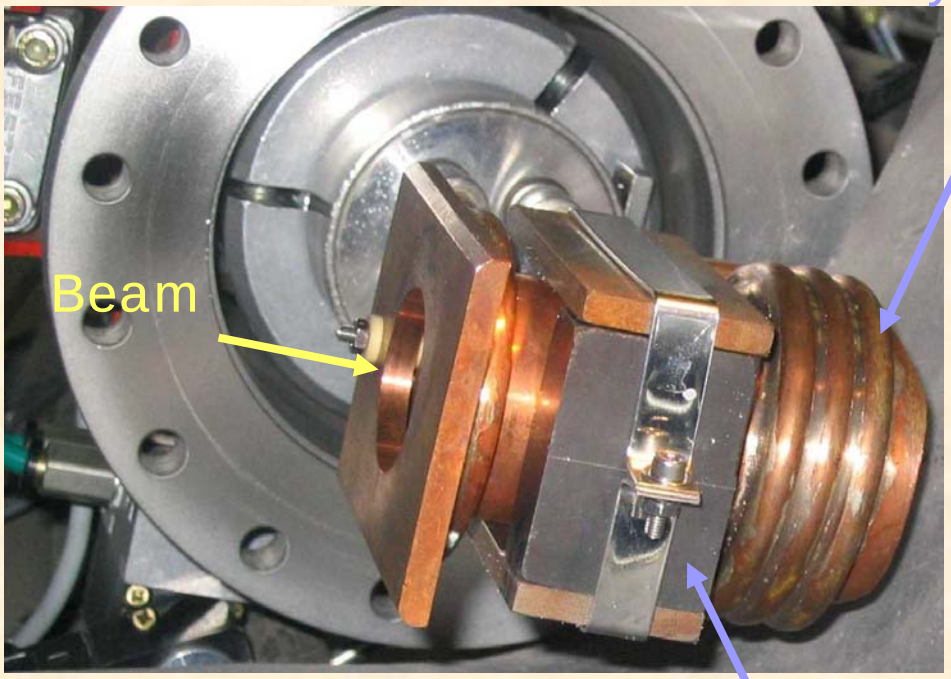


Current transformer with shielding

Current measurement (interceptive)

- By Faraday Cups

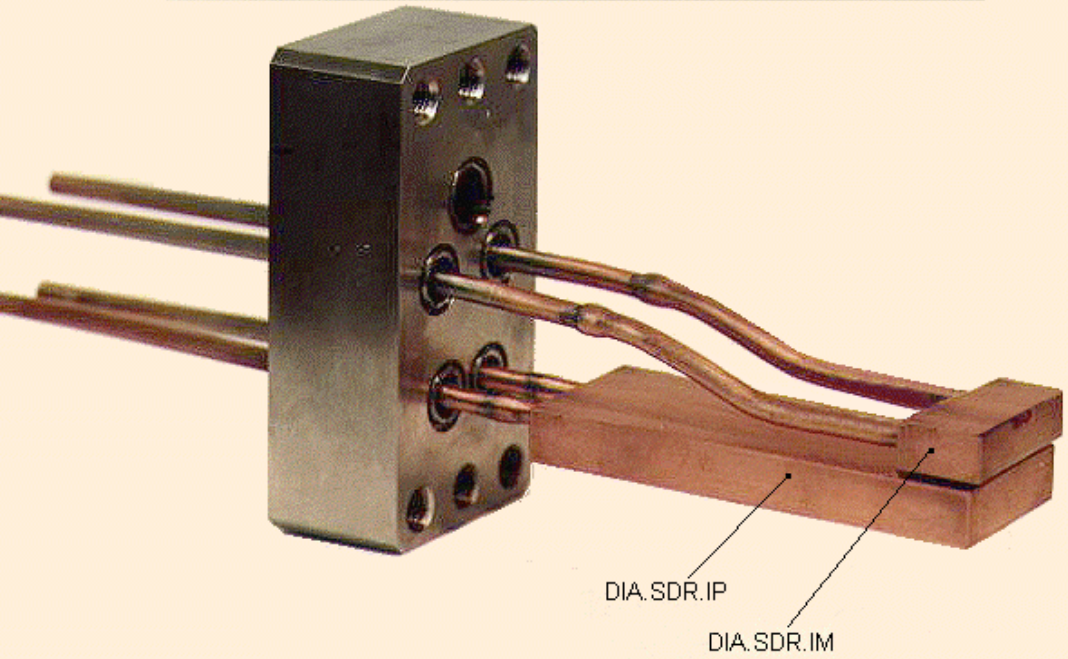


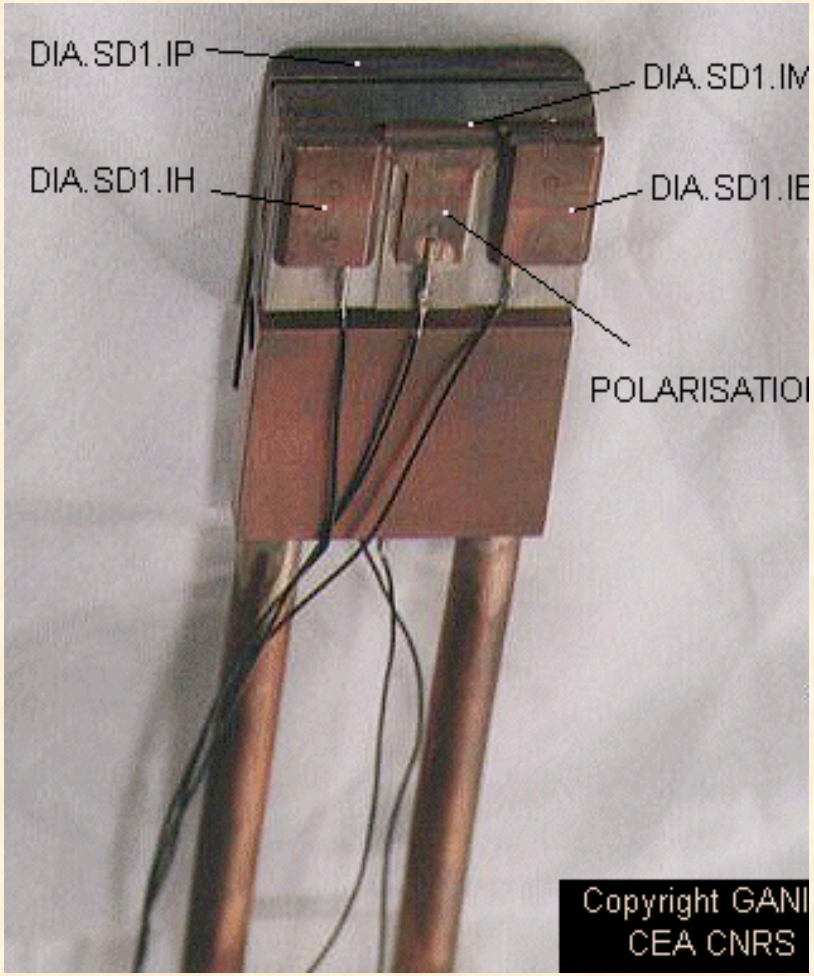


6kW cooled Faraday cup

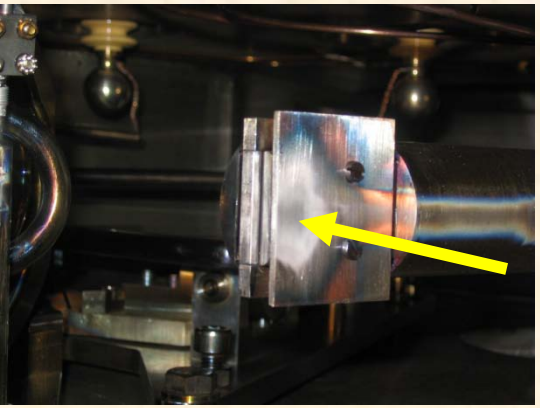
Magnet for secondary emissions

Current measurement: Radial probe

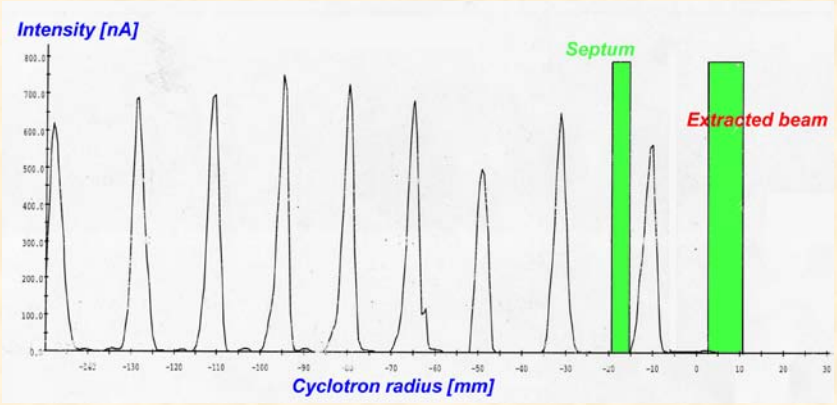


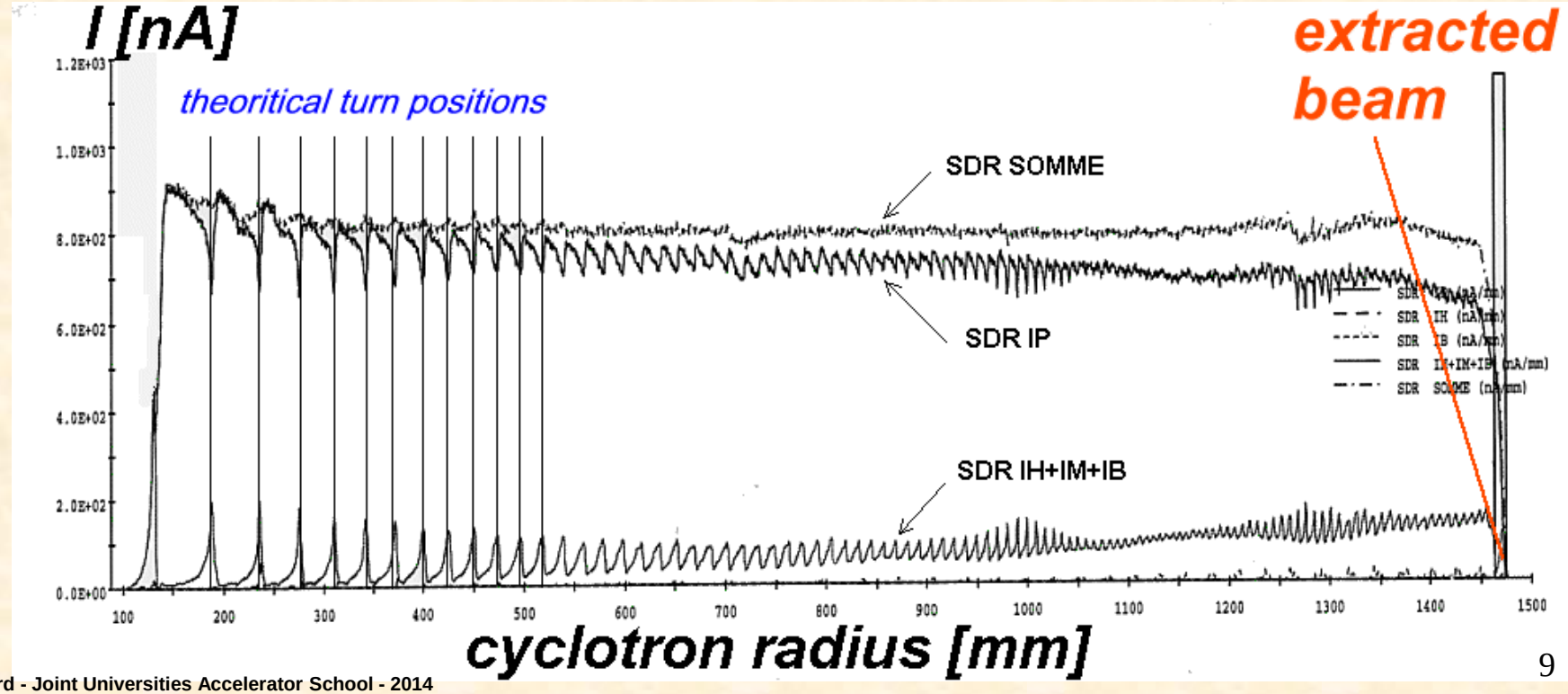


Current measurement : Beam monitoring

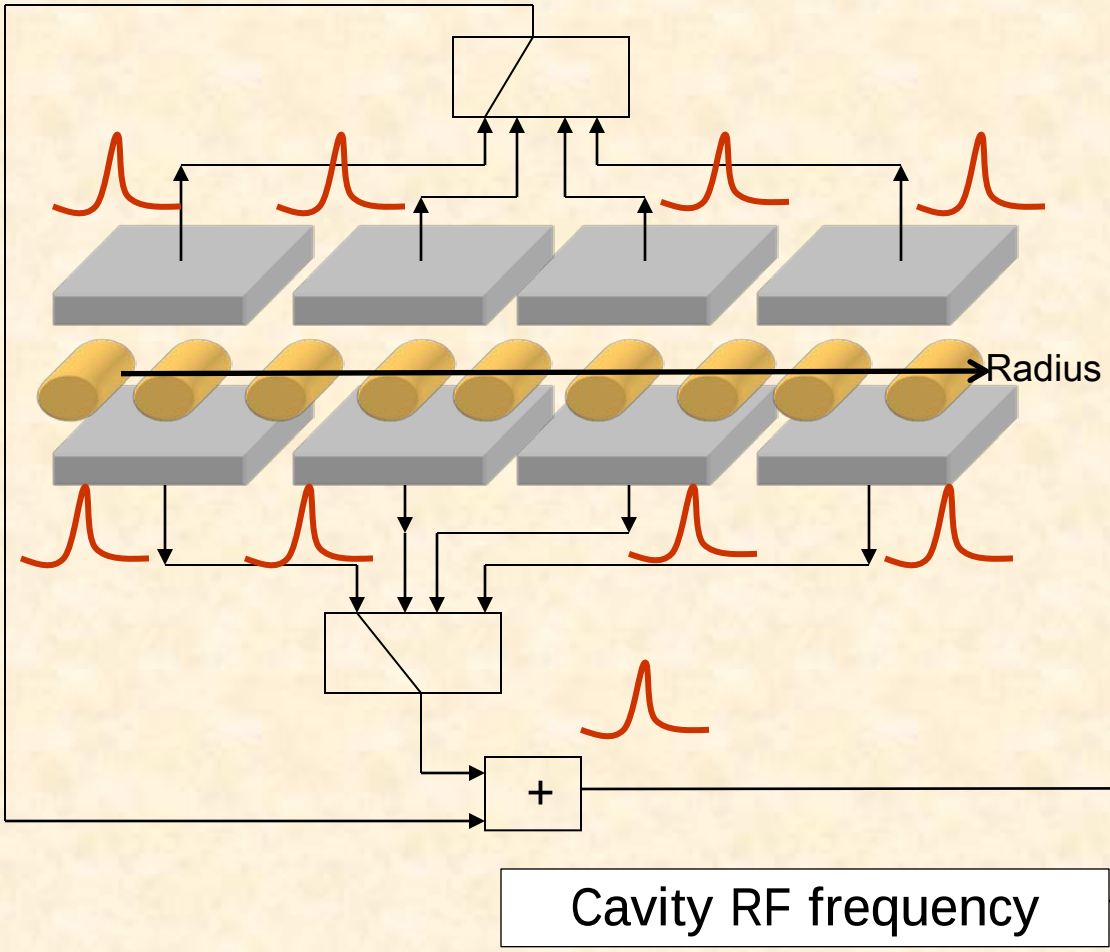


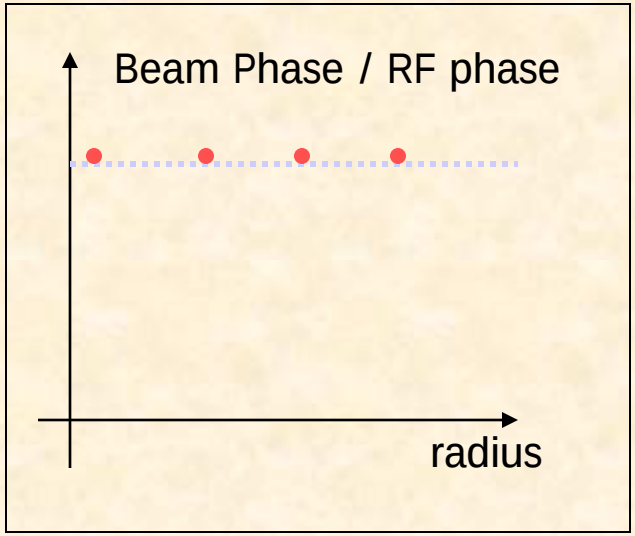
Beam



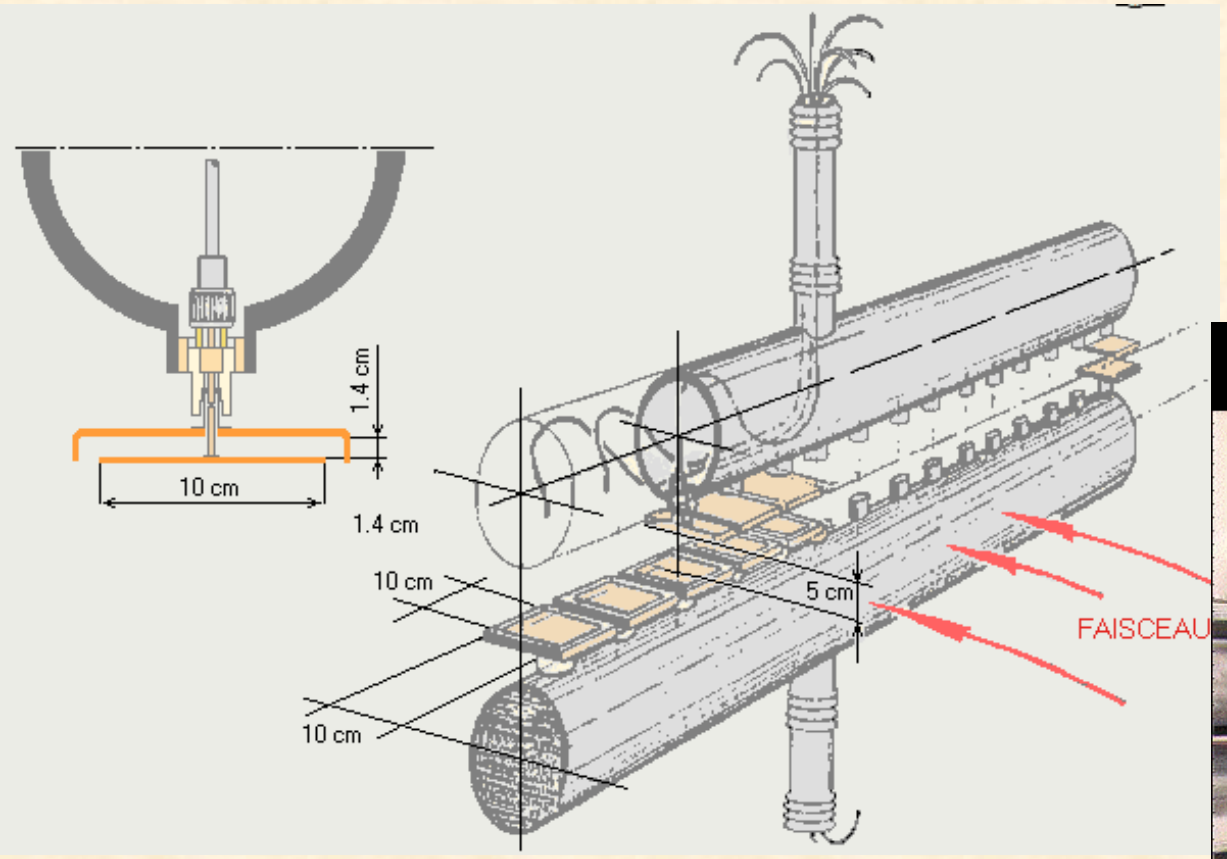


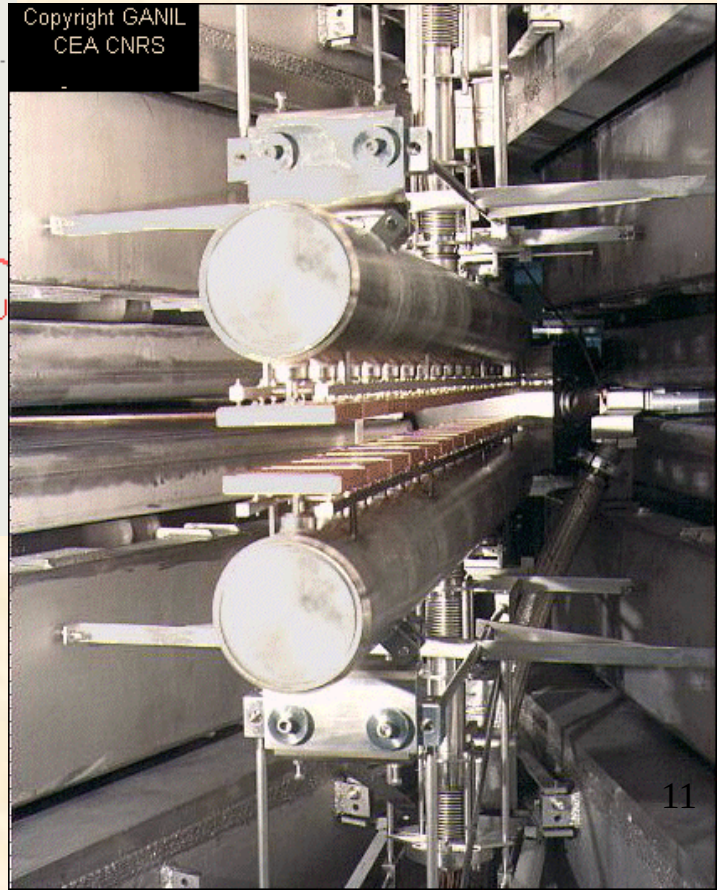
Phase measurement: Isochronism



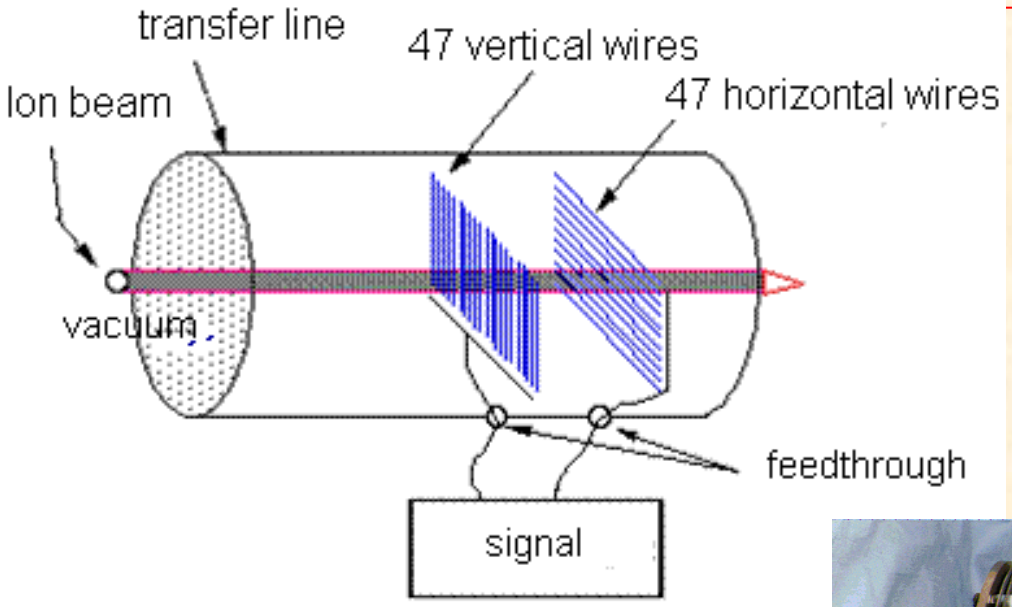


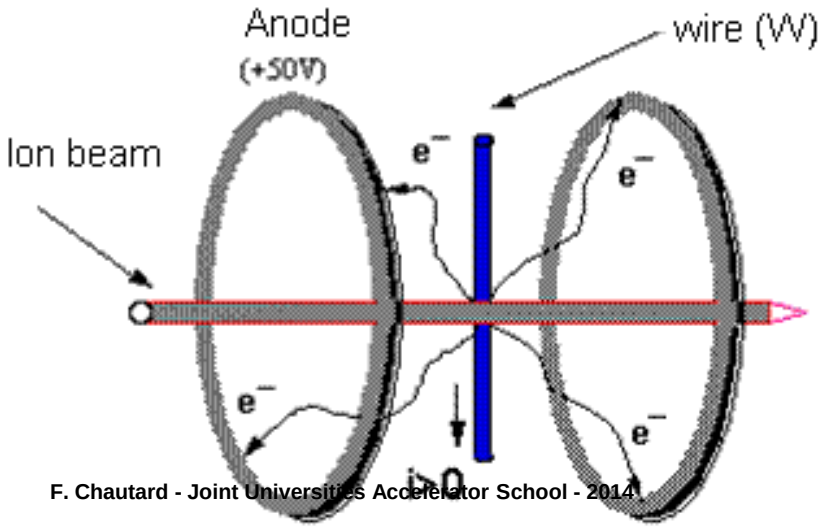
Phase measurement: Isochronism

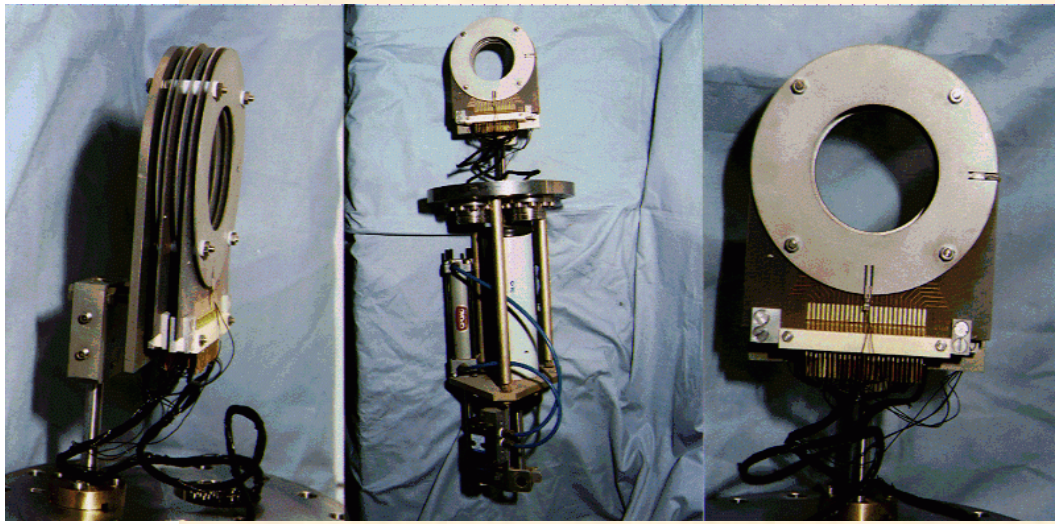




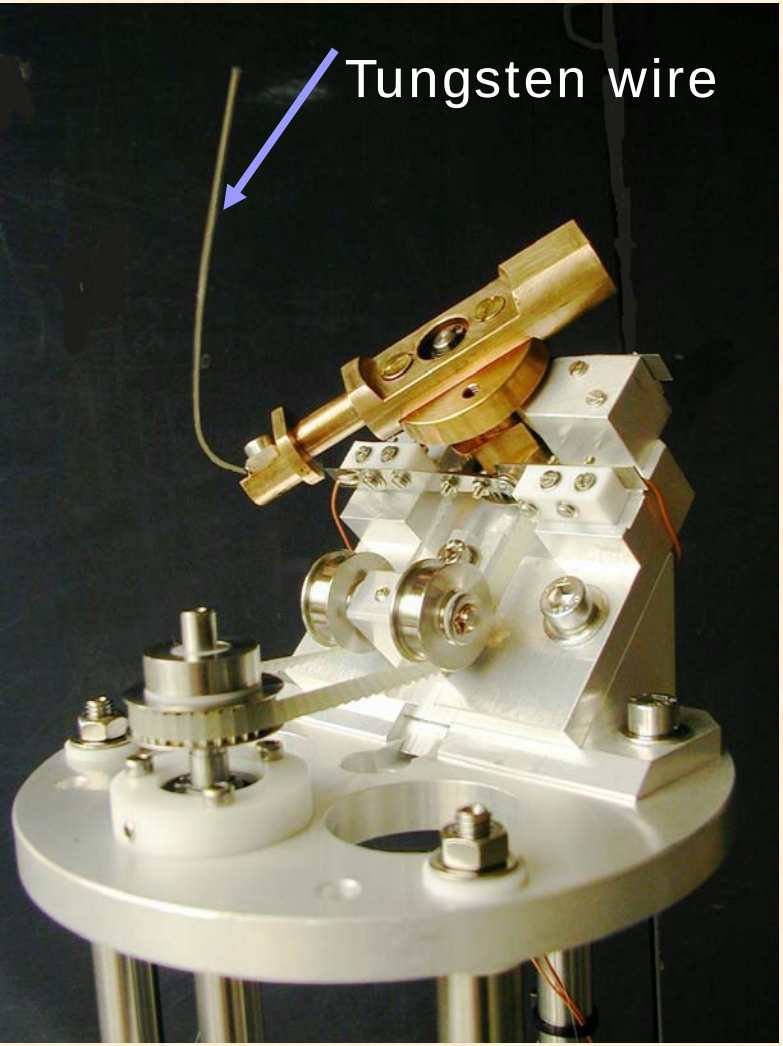
Beam Profiler: secondary emission current

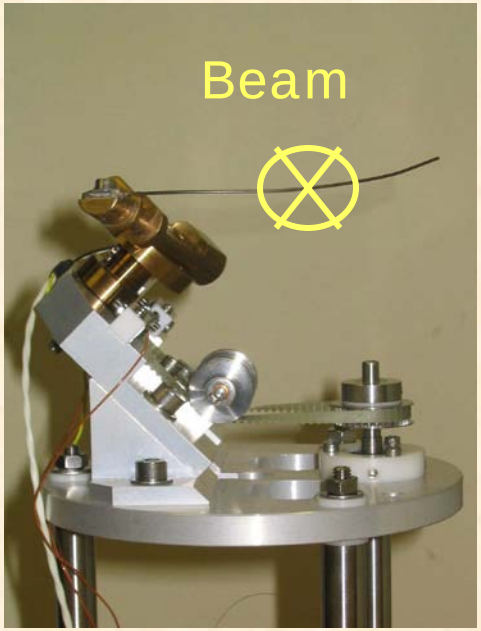




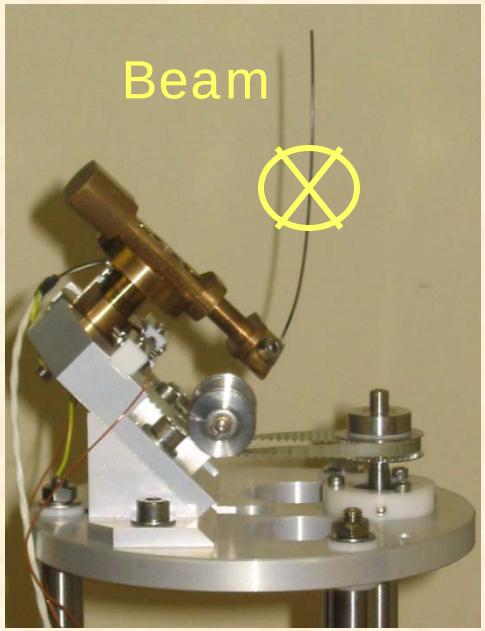


Profiler : wire scanner



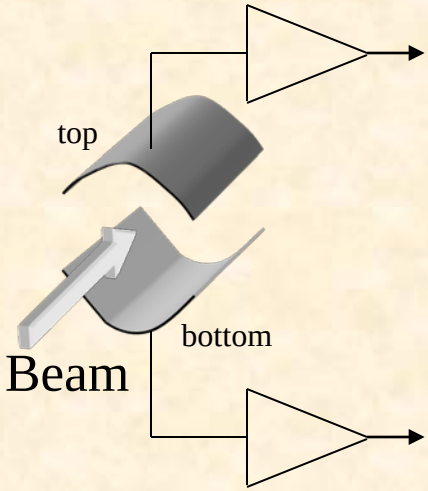


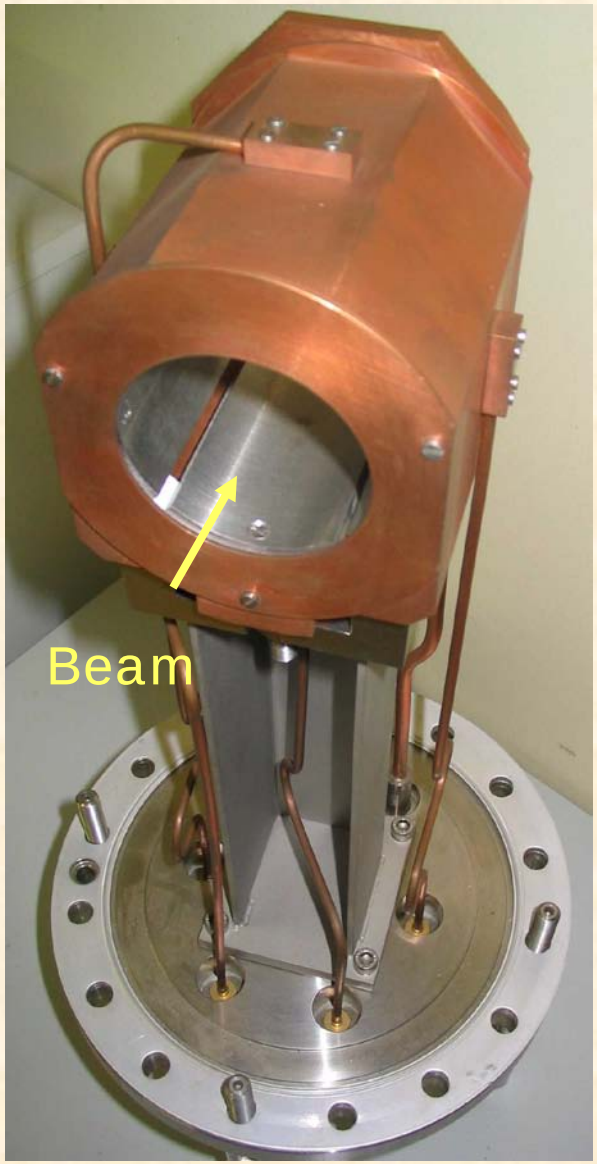
Wire in vertical position



Wire in horizontal position

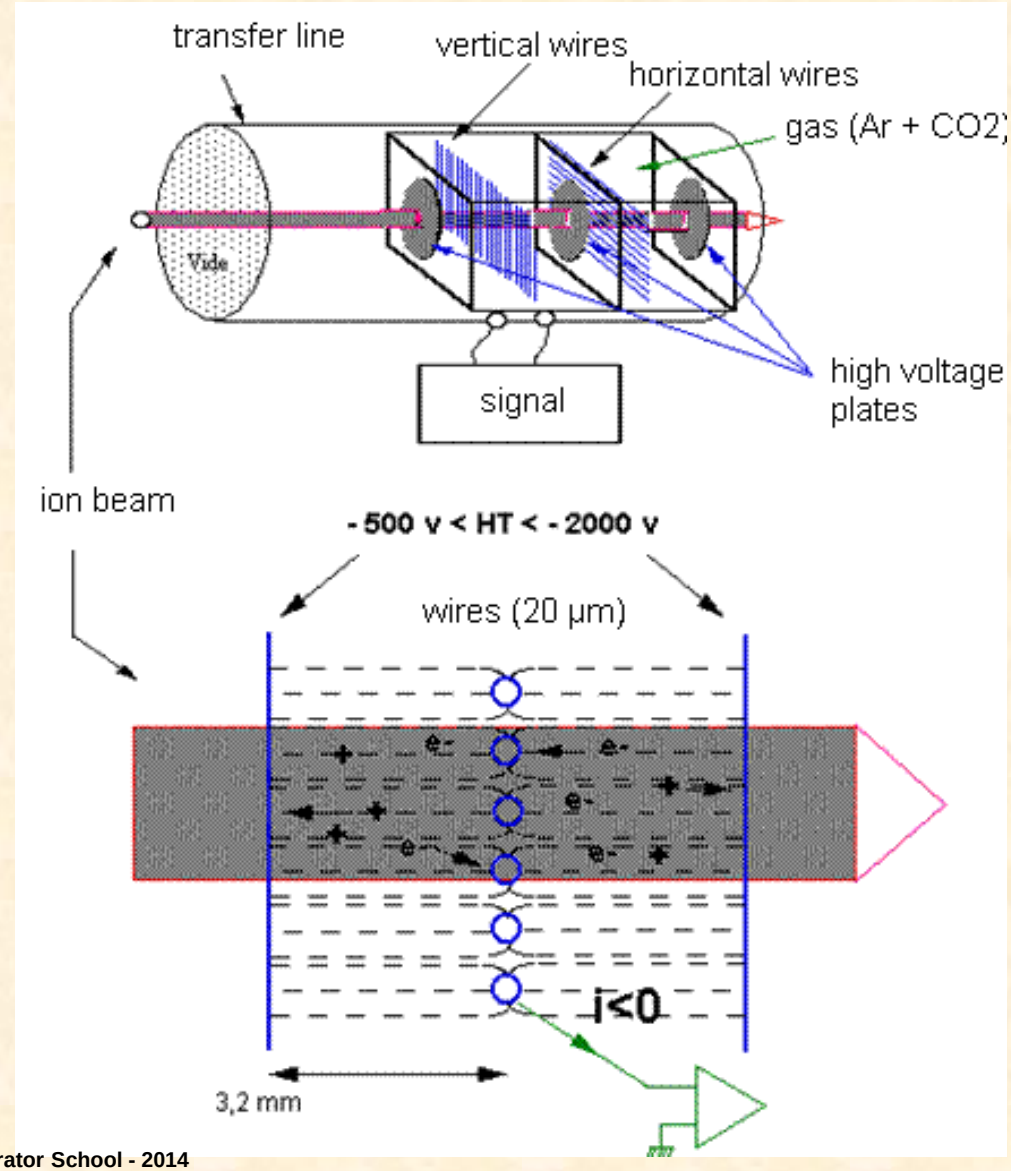
Beam position monitor



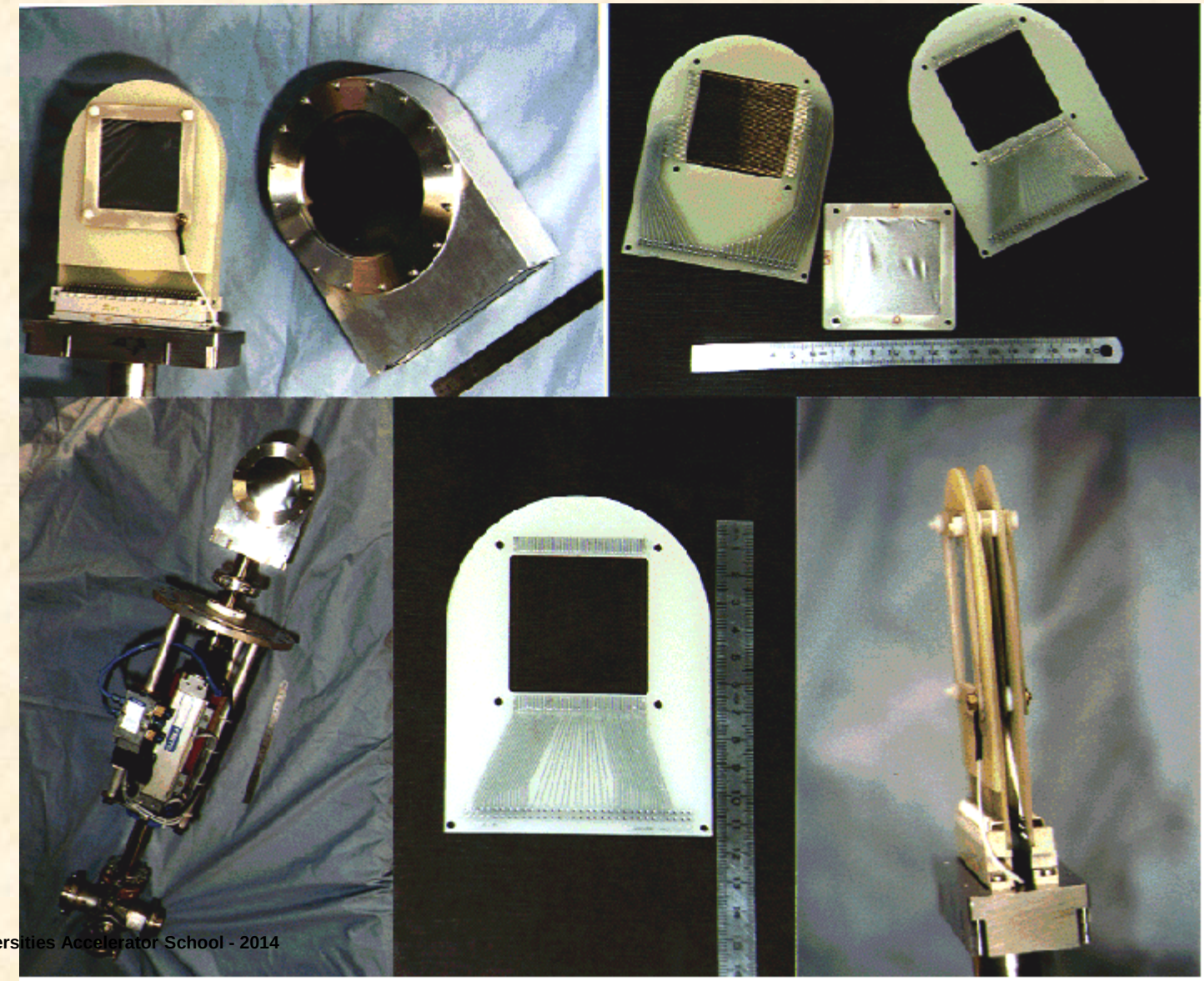


Low intensity diagnostics
$< 10^9$ pps

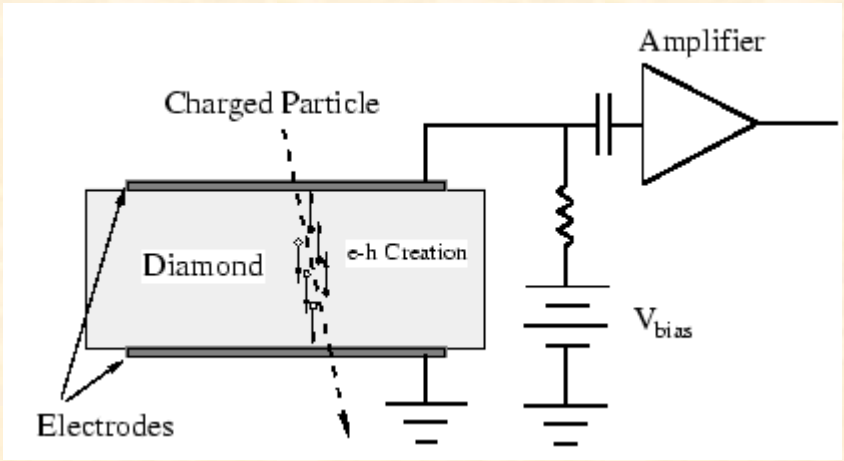
Gas Profiler

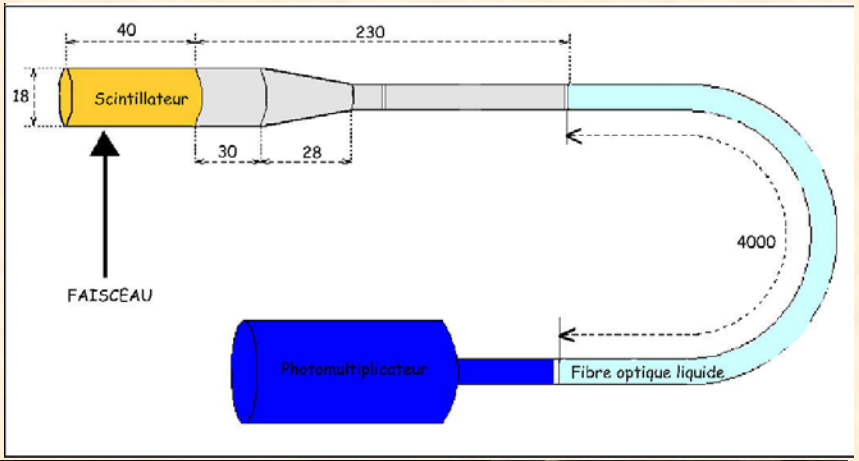


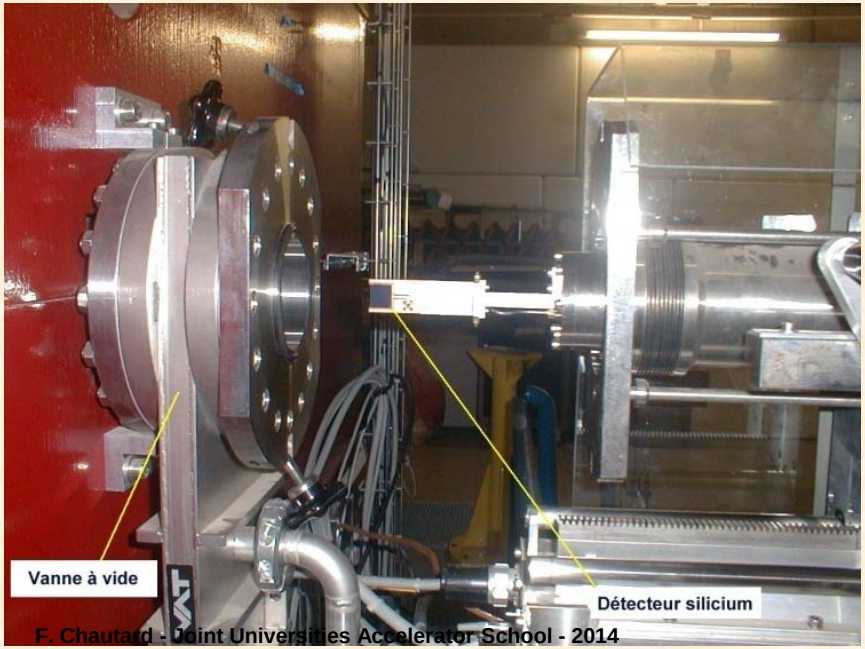
Gaz Profiler

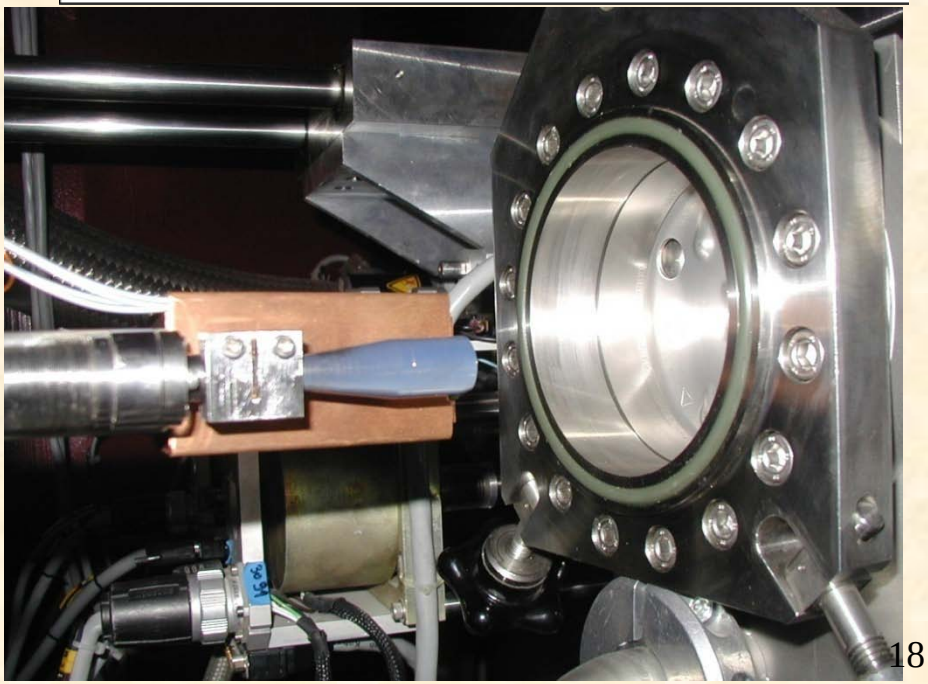


From Physics diagnostics









Back to dynamics and instabilities

Resonances

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

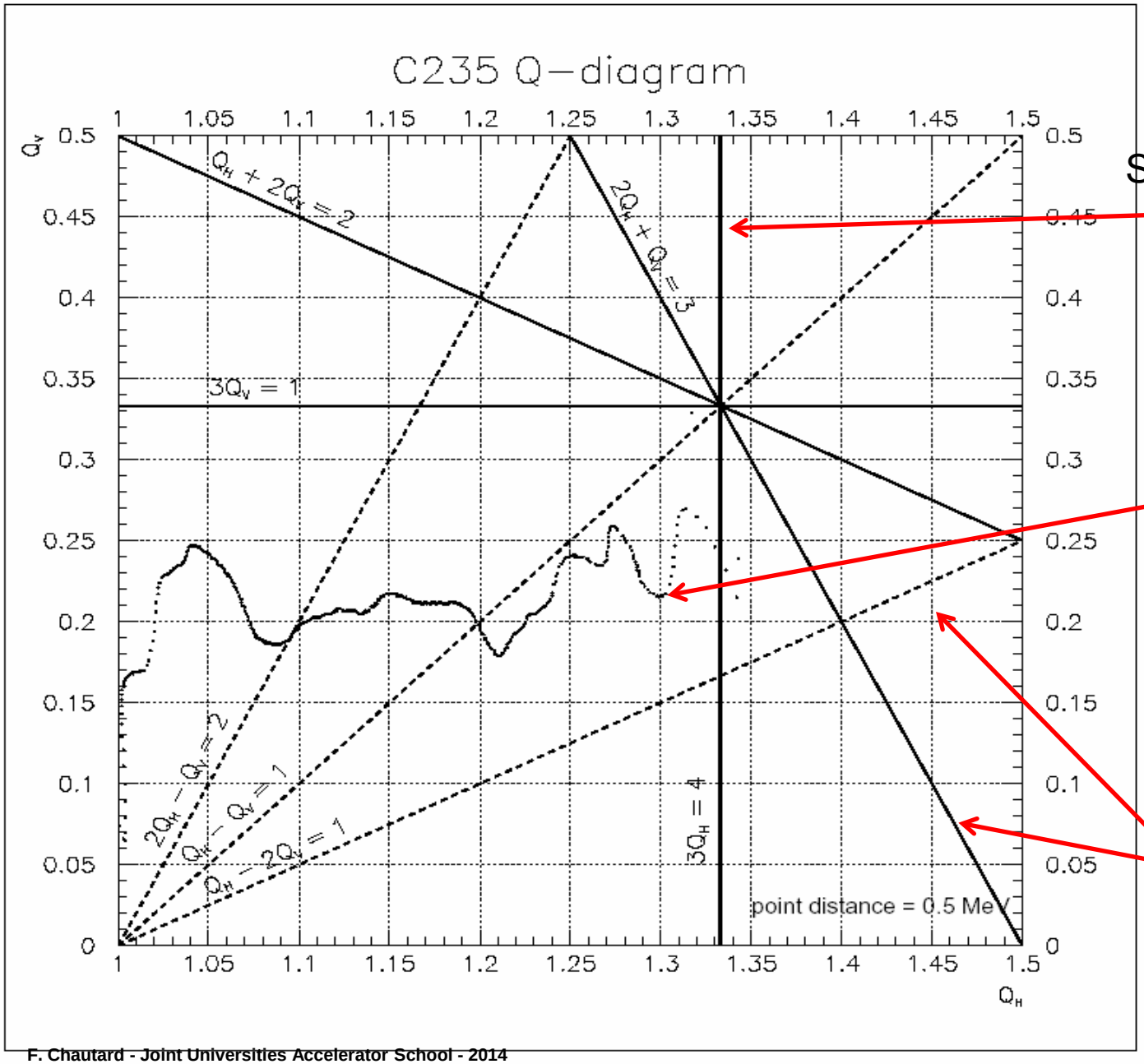
The plot of ν_r vs ν_z is called the **working point diagram.**

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

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



Systematic resonances

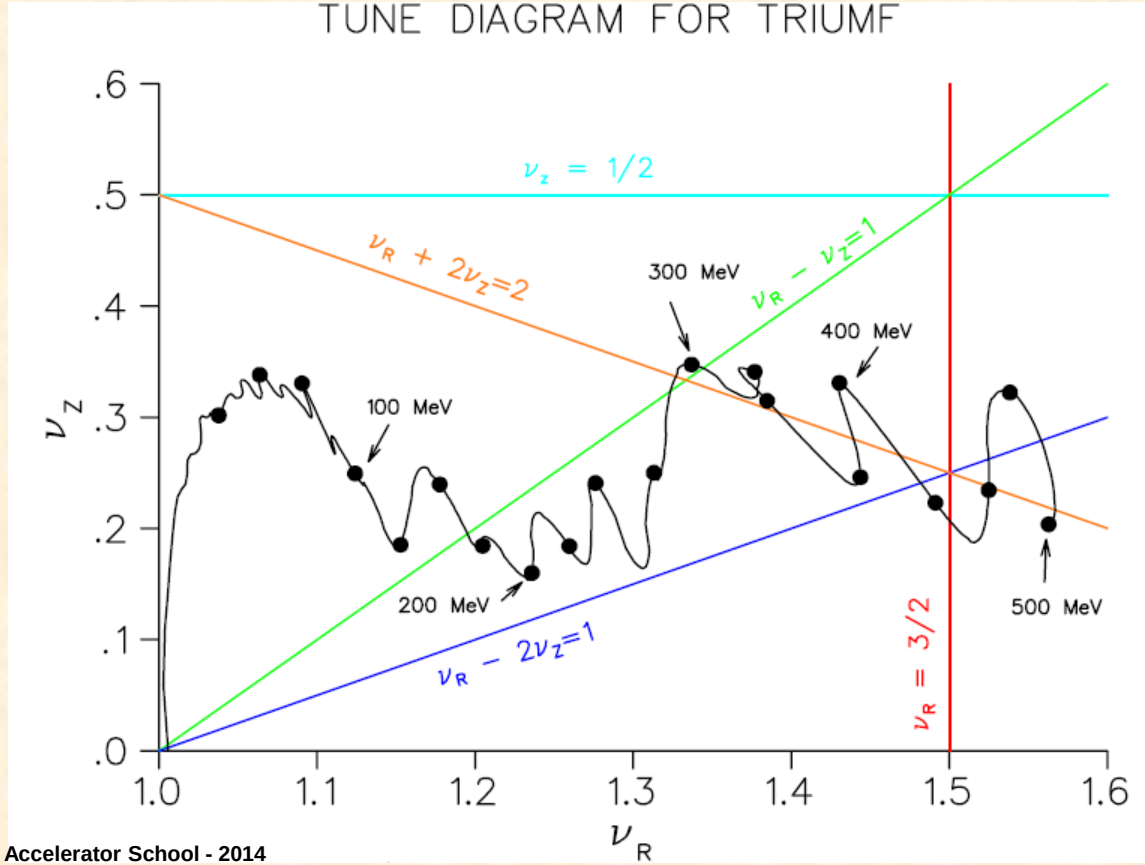
Working point curve

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 …)



$W \propto r^2$

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 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

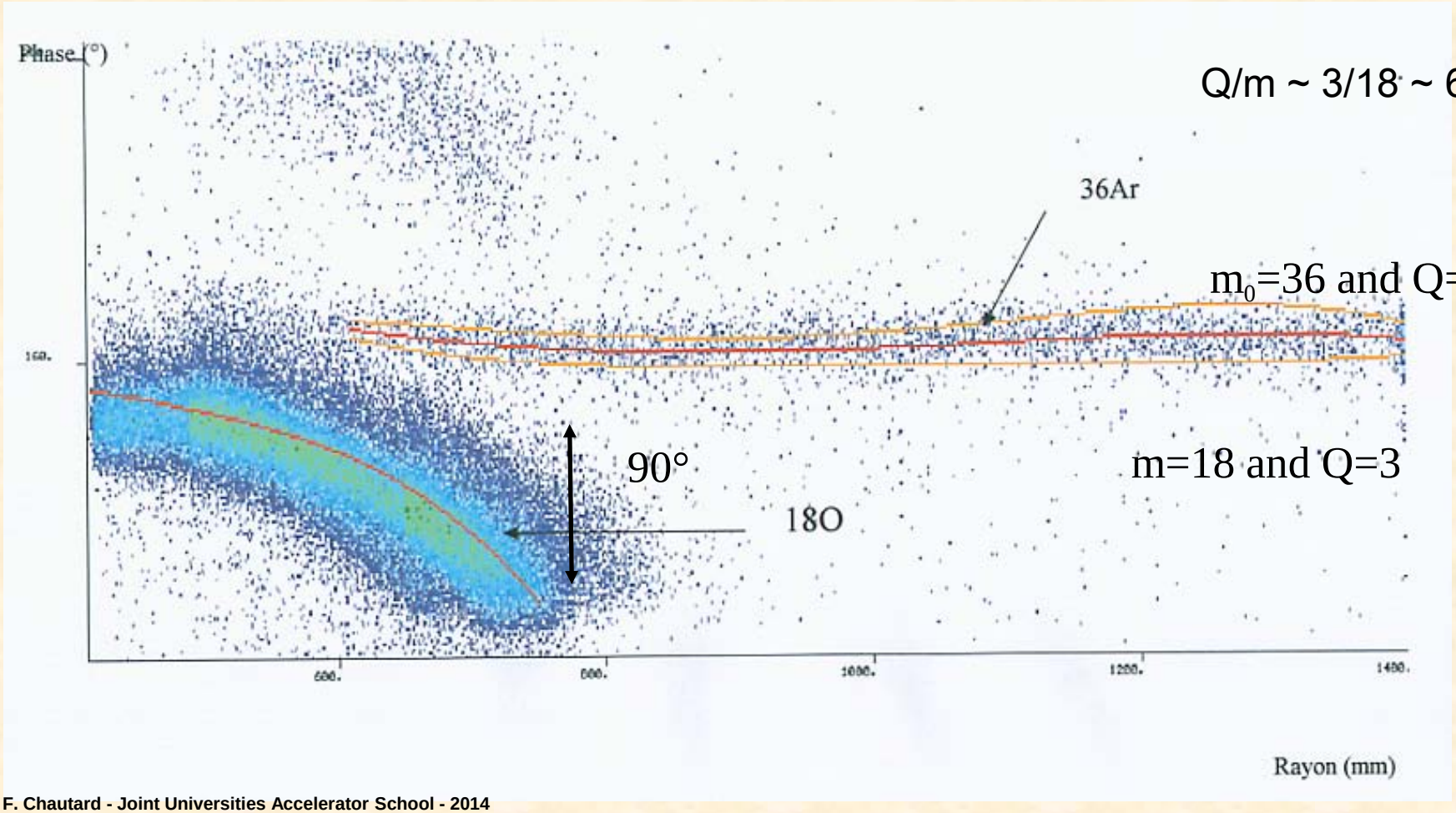
CIME example: h=3, N = 300 ⇨ R~ 10-4

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

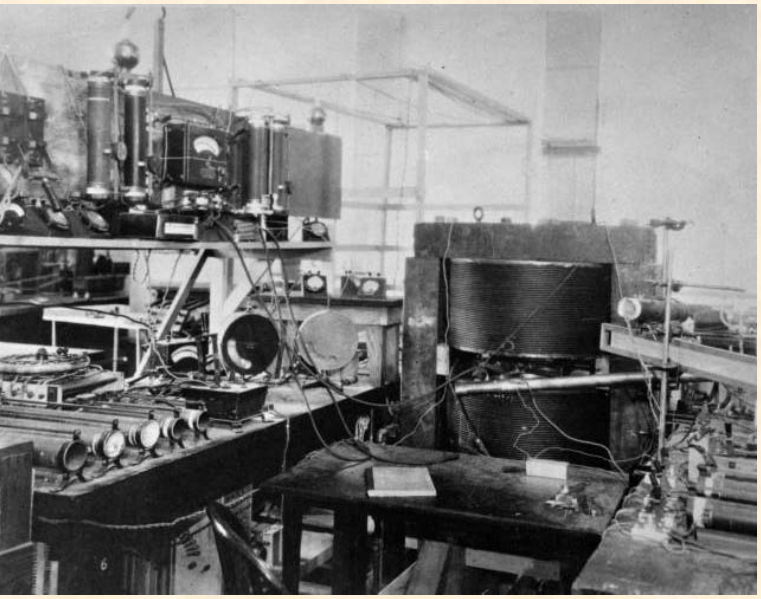
$$\Delta\varphi = 2\pi N h \frac{1}{\gamma^2} \frac{\Delta(m/Q)}{m_0/Q_0}$$



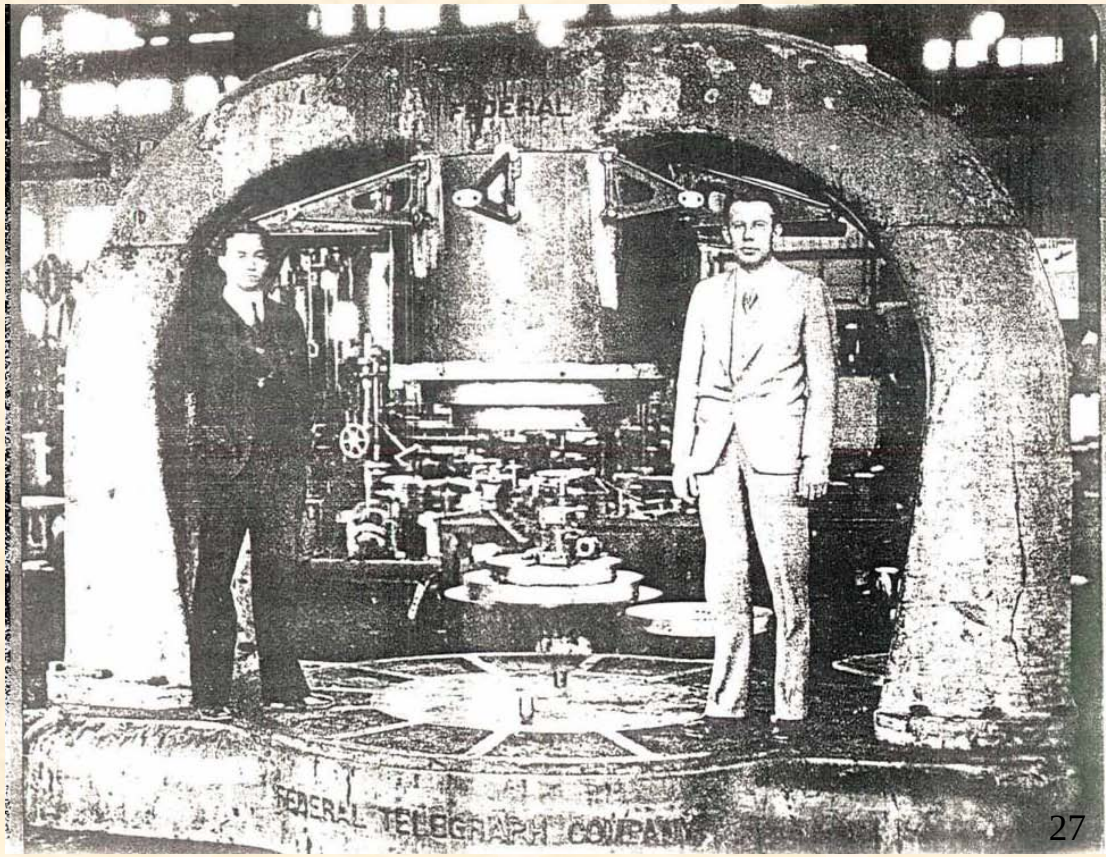
Few cyclotrons

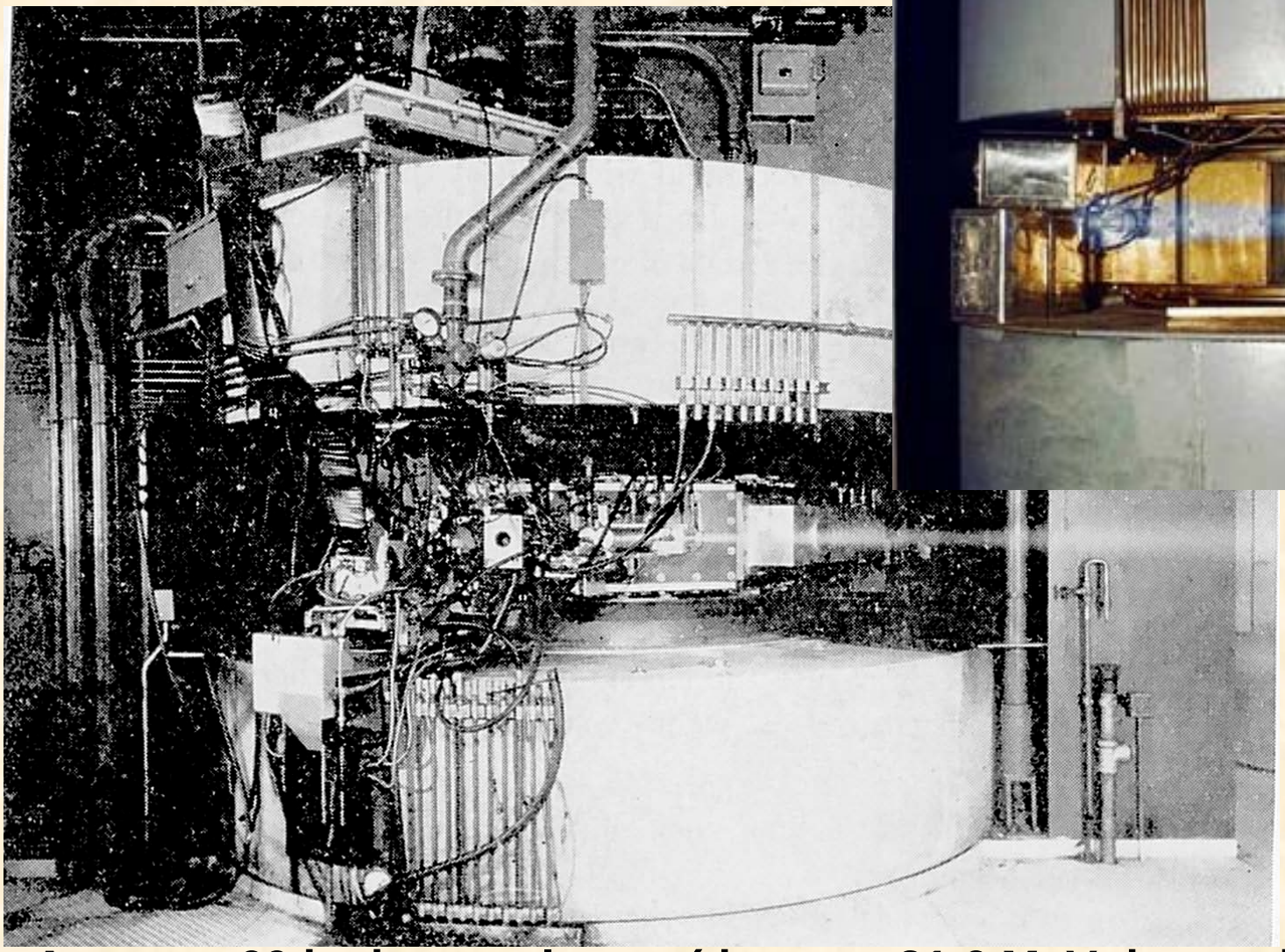
The beginning

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)

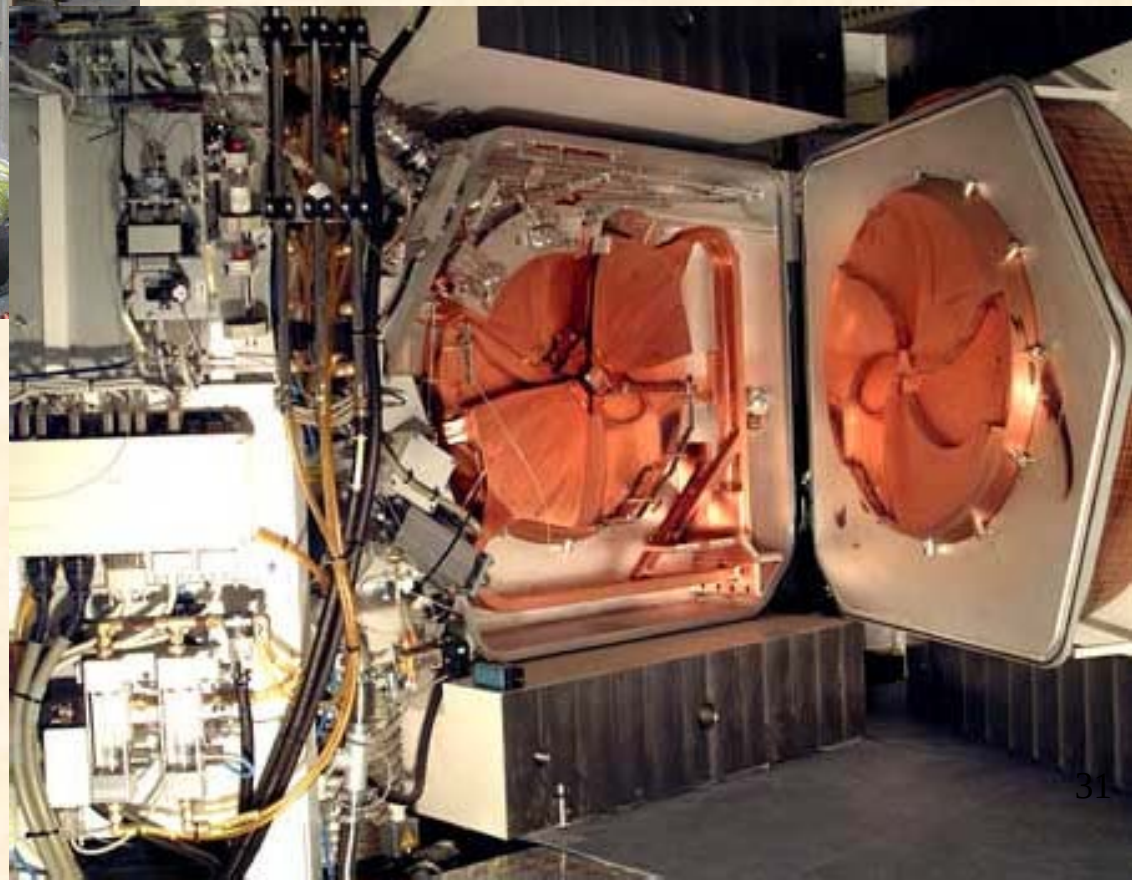
Karlsruhe cyclotron.

CYCLONE 30 (IBA) : H^- 15 à 30 MeV

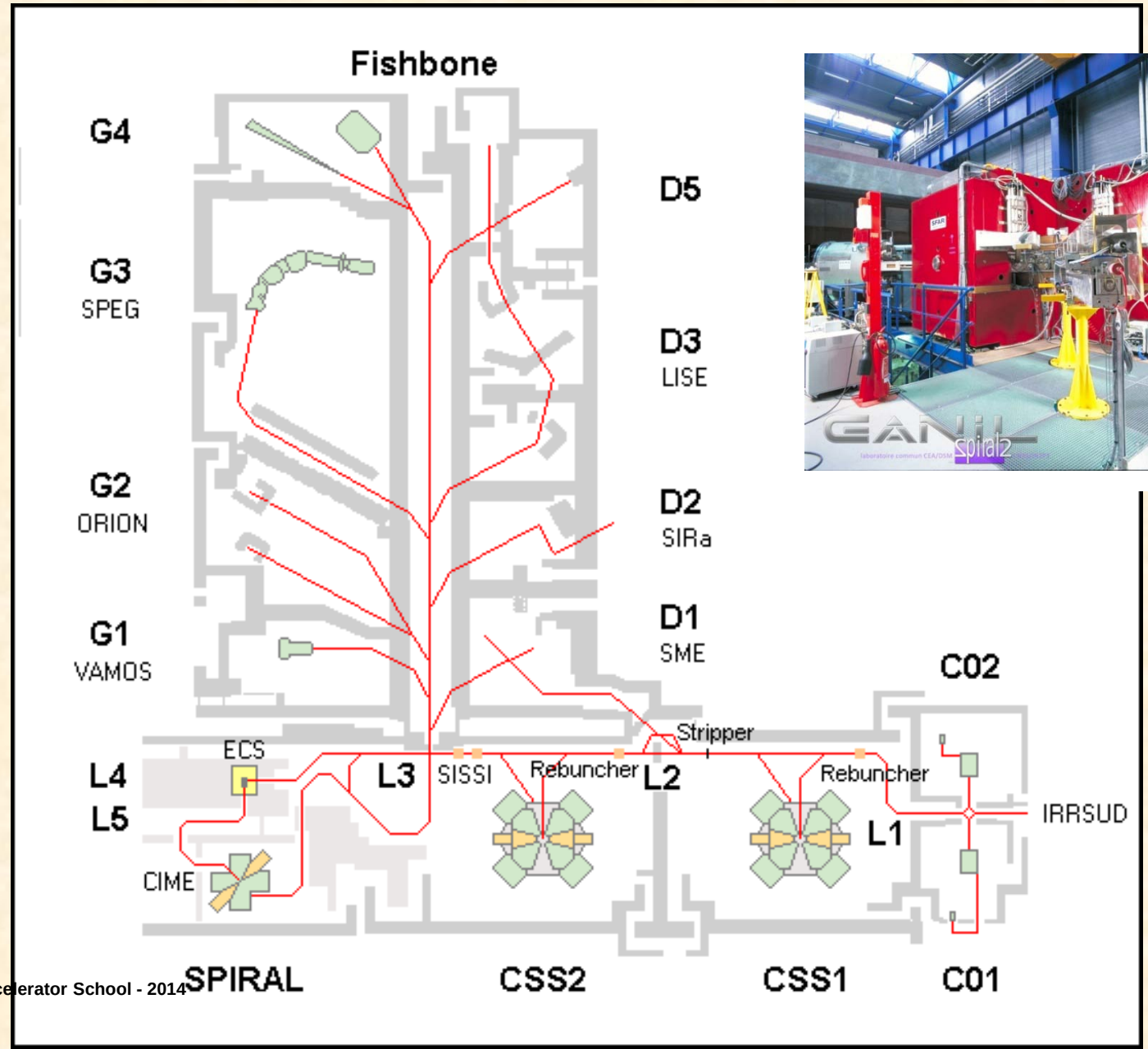
primarily designed for industrial and medical applications

Cyclone 10/5

cyclone 3D



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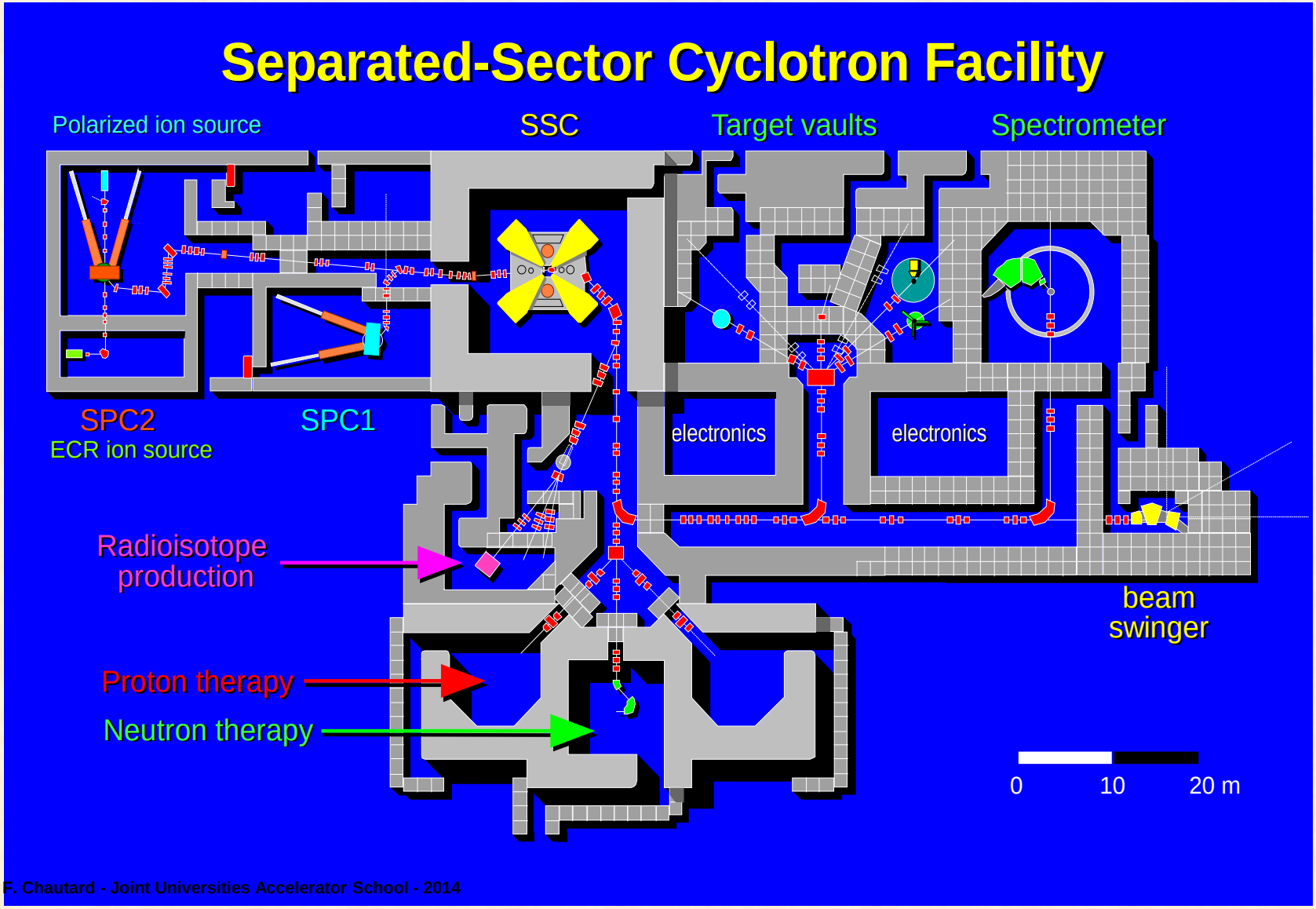
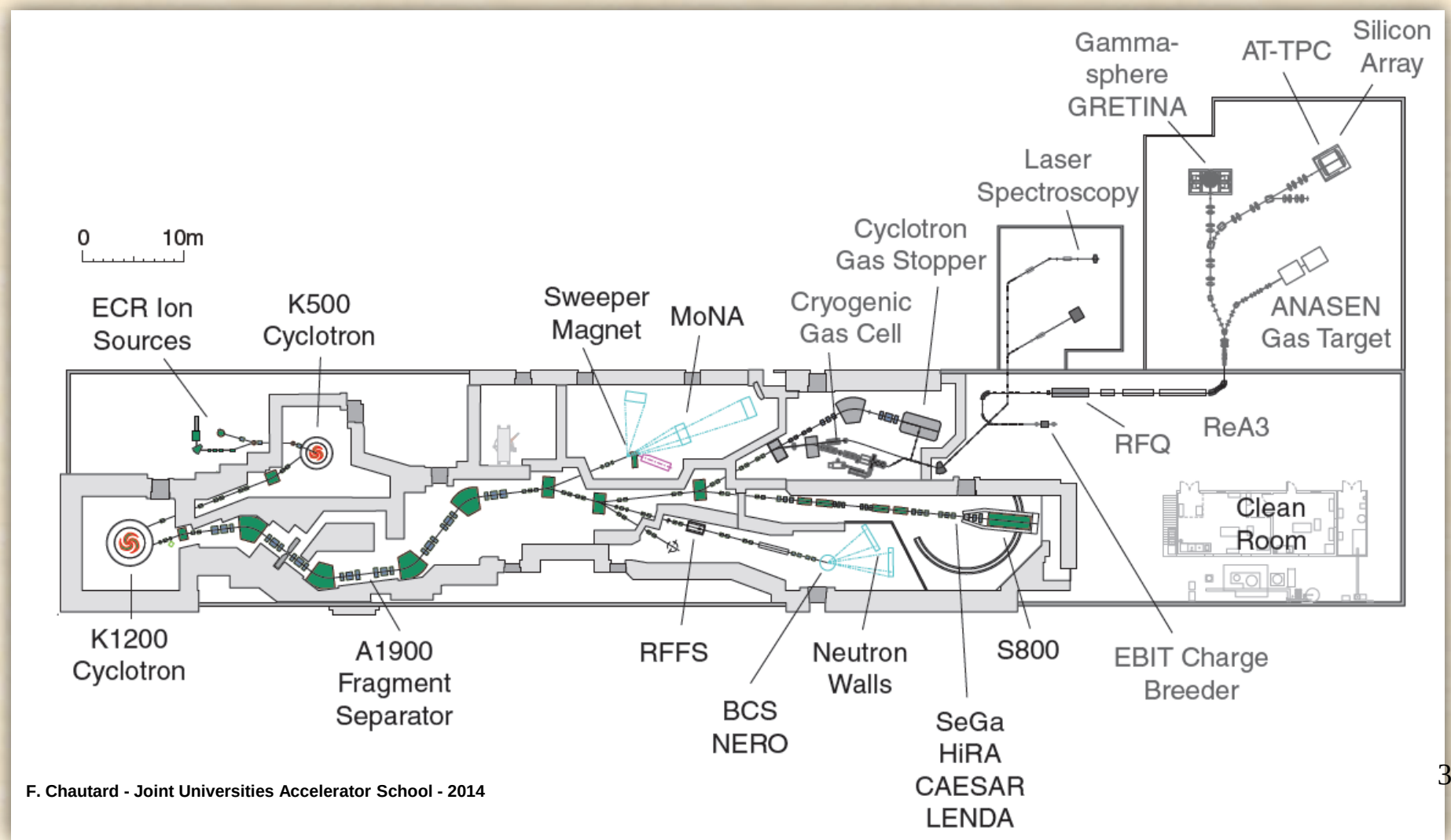
G4
G3
SPEG
G2
ORION
G1
VAMOS
D5
D3
LISE
D2
SIRa
D1
SME
C02
Stripper
ECS
L4
L5
L3
SISSI
Rebuncher
L2
Rebuncher
L1
IRRSUD
CIME
SPIRAL
CSS2
CSS1
C01

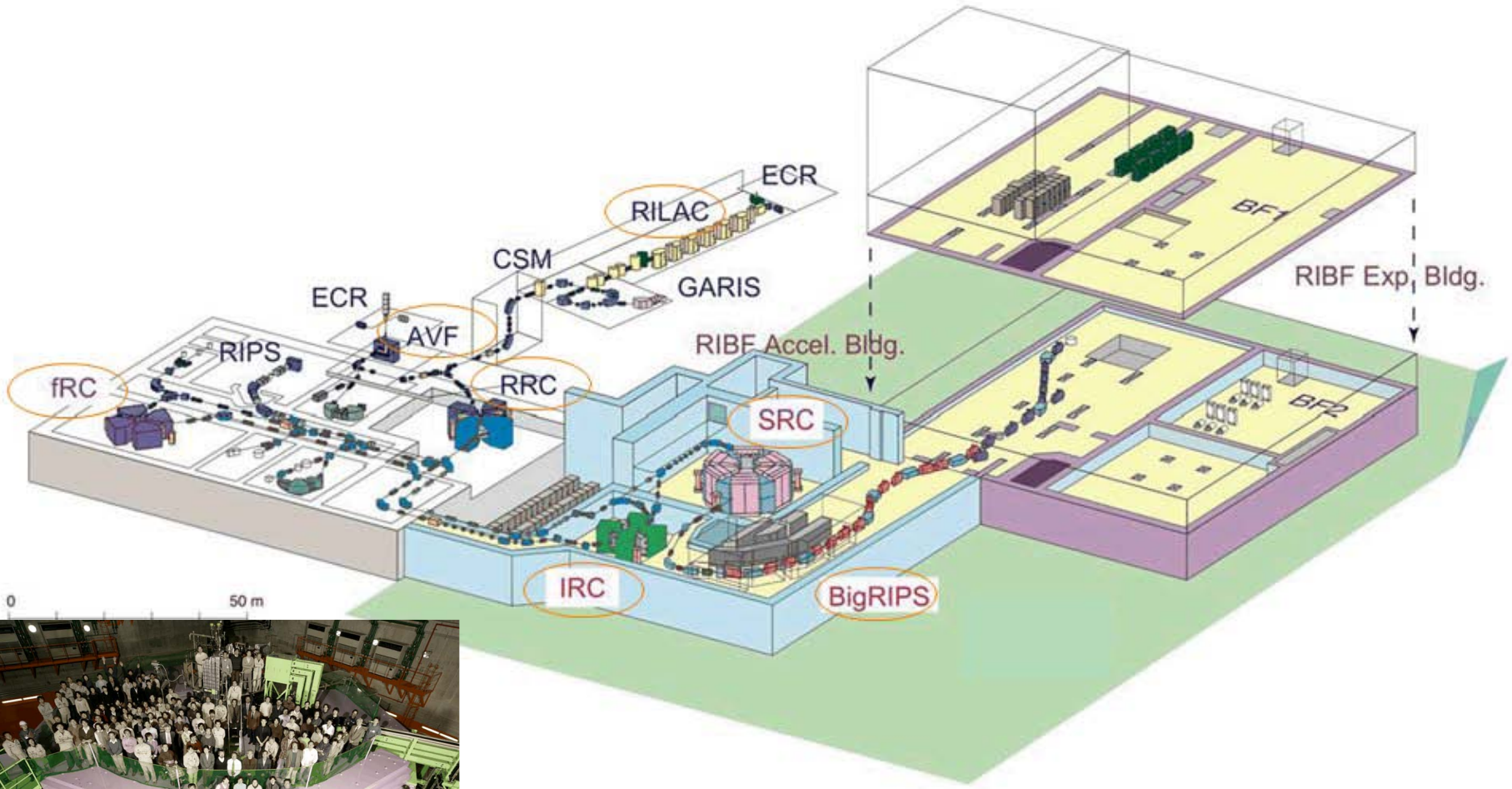
National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

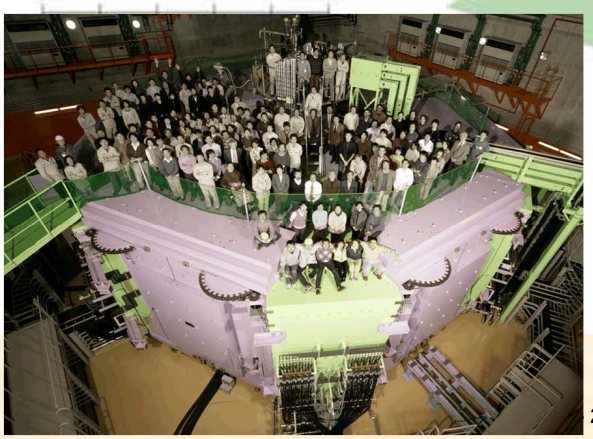
Separated-Sector Cyclotron Facility

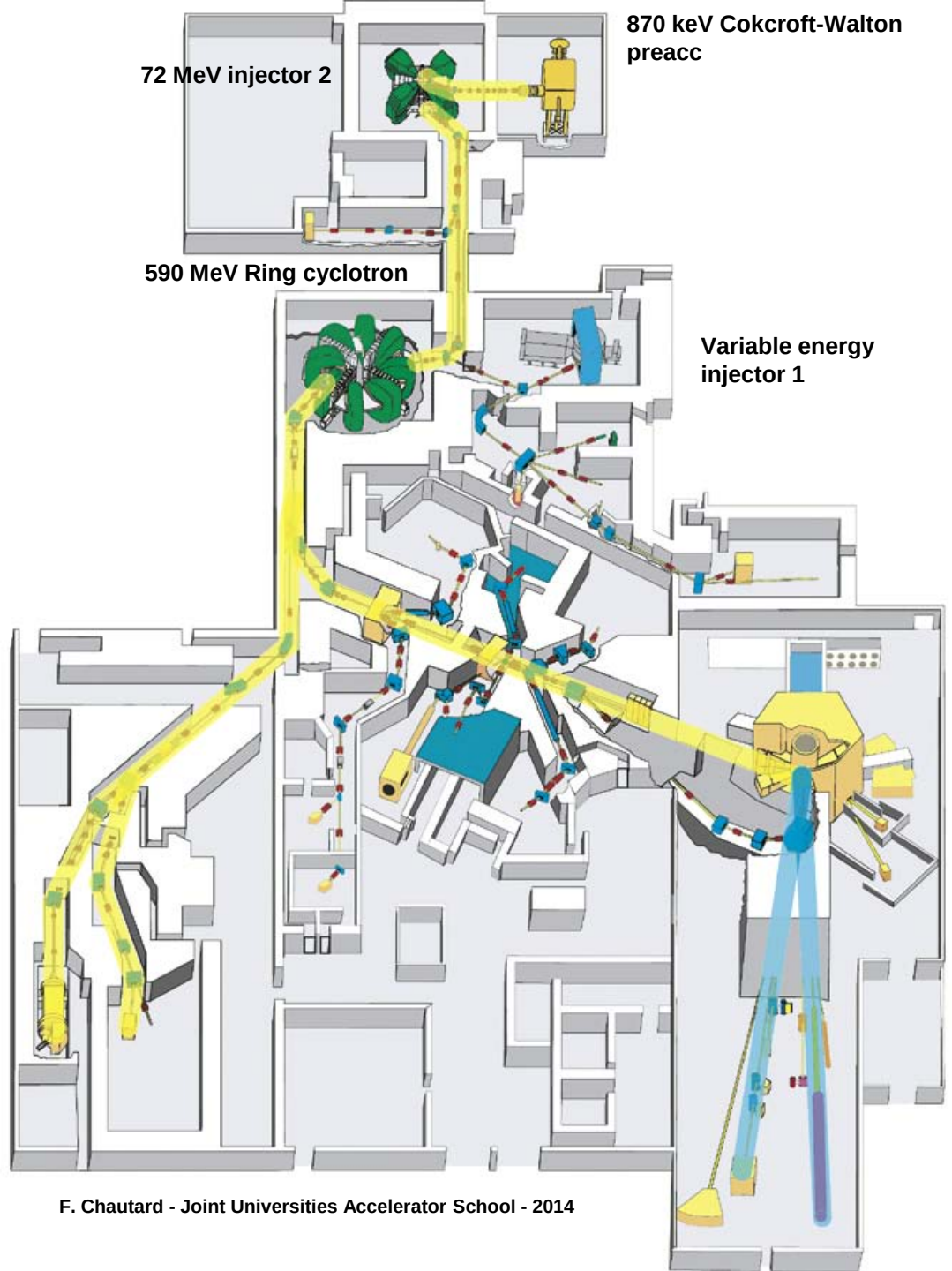


Michigan State University
Cyclotrons+A1900+Experimental Areas




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





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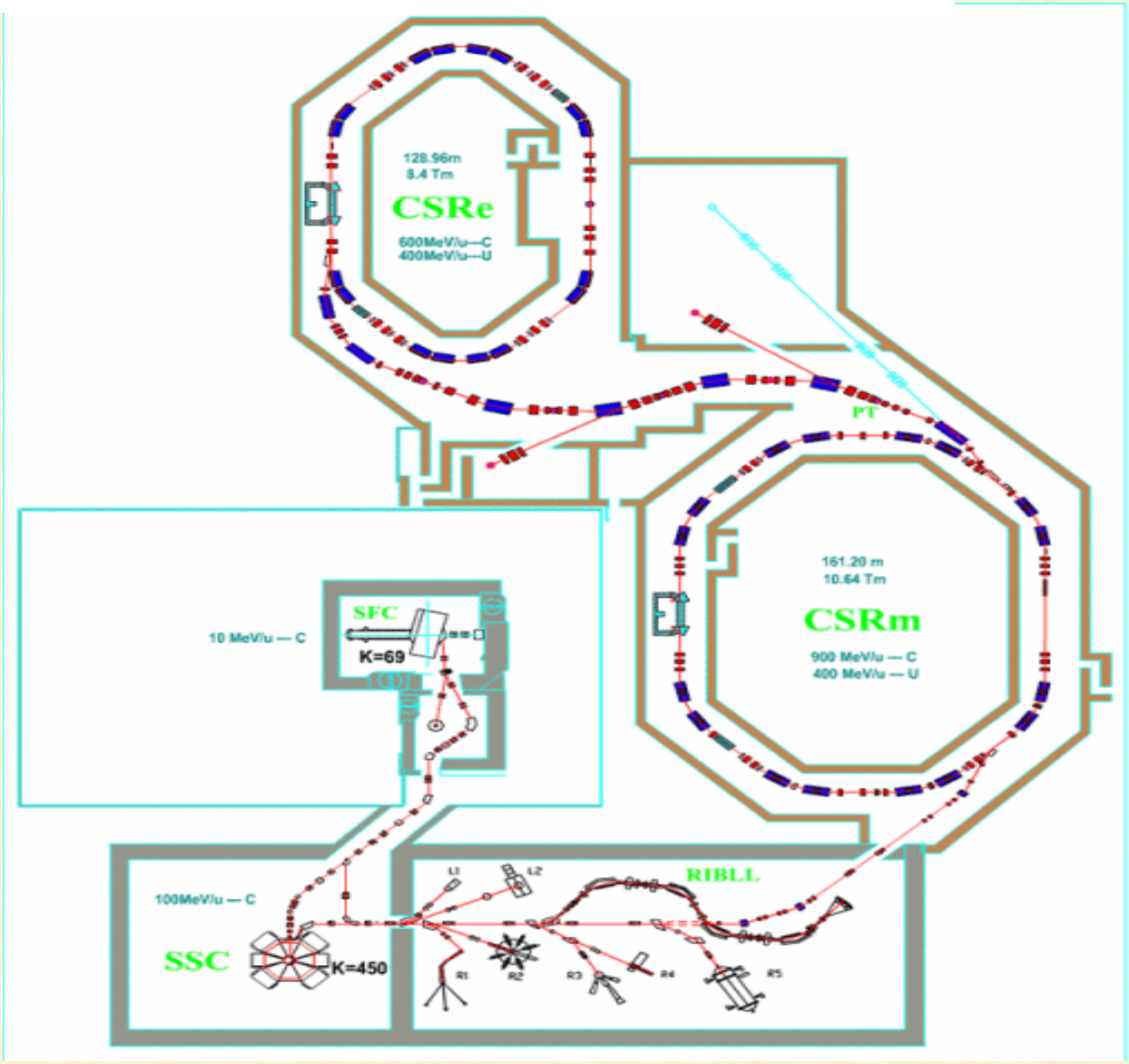
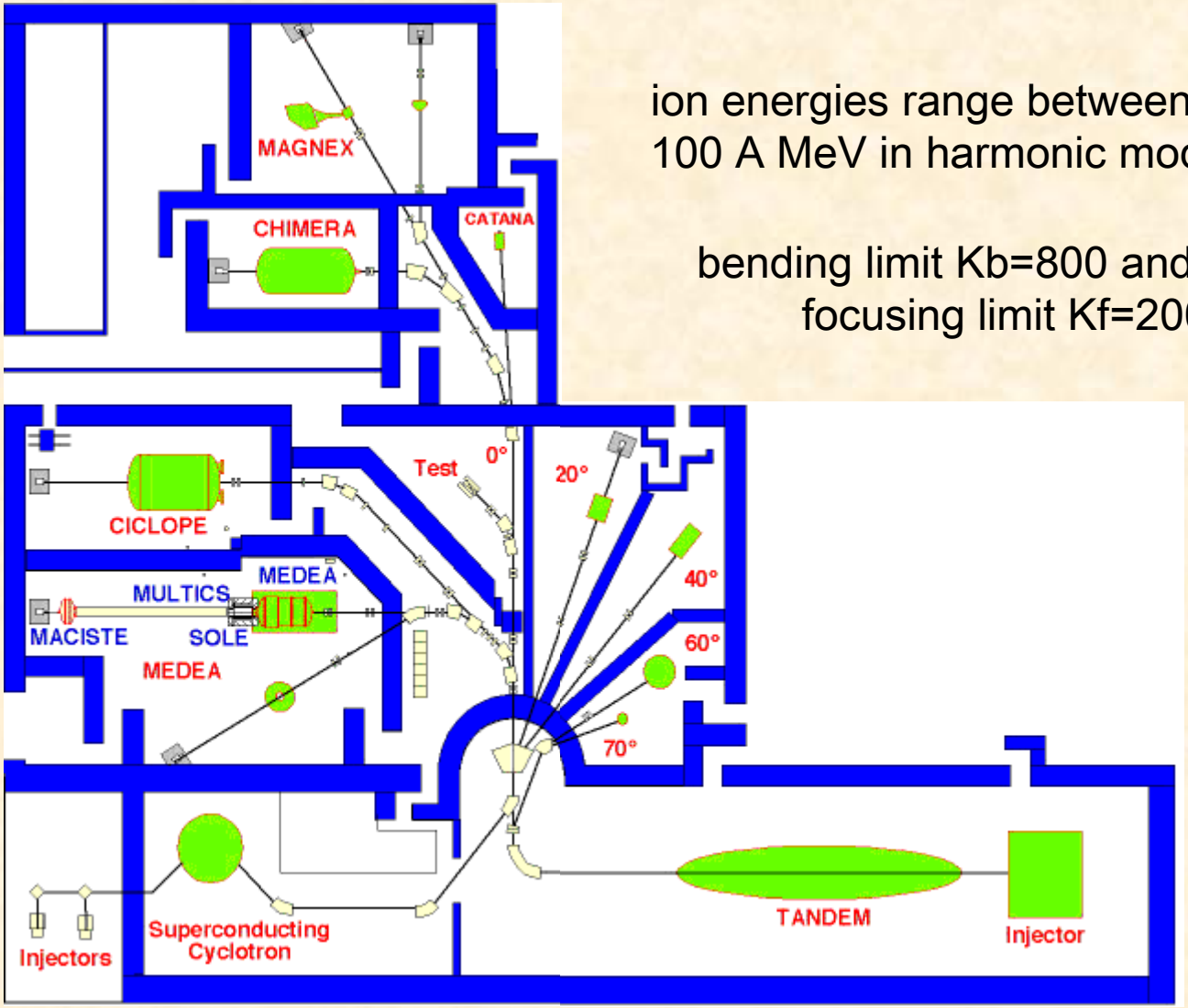
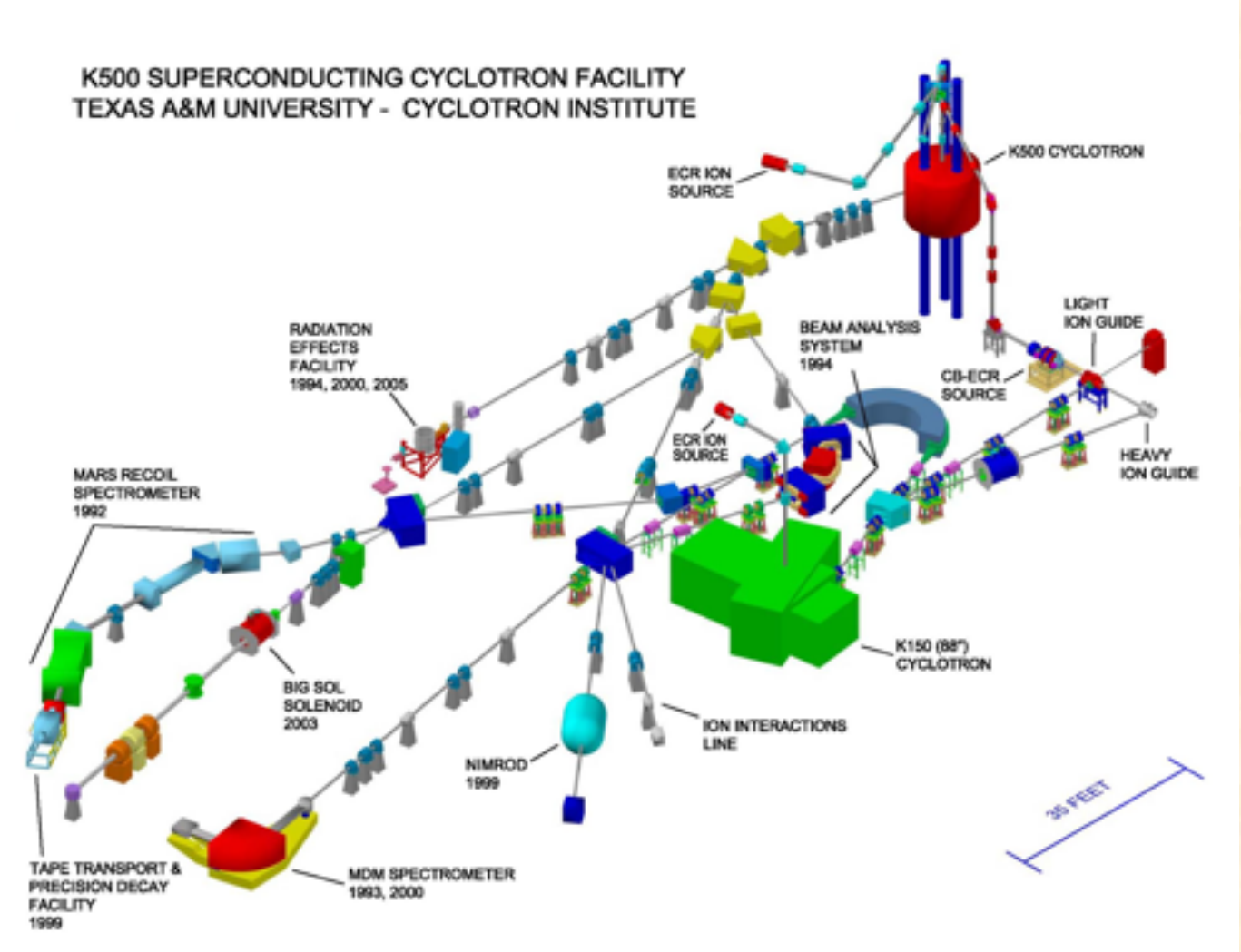
PSI


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
10 MeV/u — C
SFC
K=69
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.

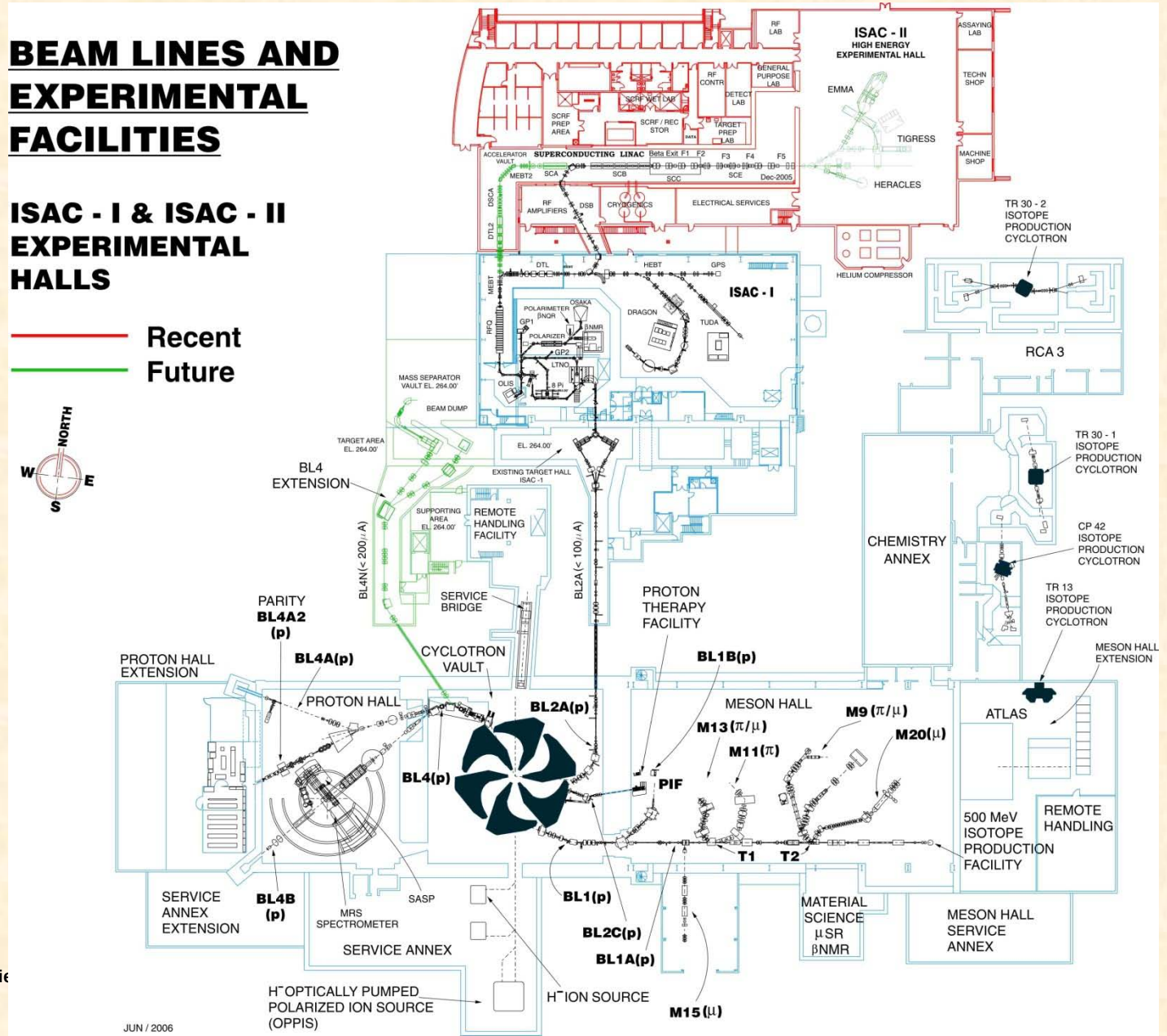

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE
ECR ION SOURCE
K500 CYCLOTRON
LIGHT ION GUIDE
RADIATION EFFECTS FACILITY 1994, 2000, 2005
BEAM ANALYSIS SYSTEM 1994
CB-ECR SOURCE
ECR ION SOURCE
HEAVY ION GUIDE
MARS RECOIL SPECTROMETER 1992
K150 (88") CYCLOTRON
BIG SOL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

BEAM LINES AND EXPERIMENTAL FACILITIES

ISAC - I & ISAC - II EXPERIMENTAL HALLS

Recent

Future



520 MeV proton, Triumf, Canada

The diameter of the machine is about 18 m

Lower half of the Main Magnet poles

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- H. Bruck, Bibl. des Scienc. Et Tech. Nucléaires 1966, Accélérateurs Circulaires de Particules.
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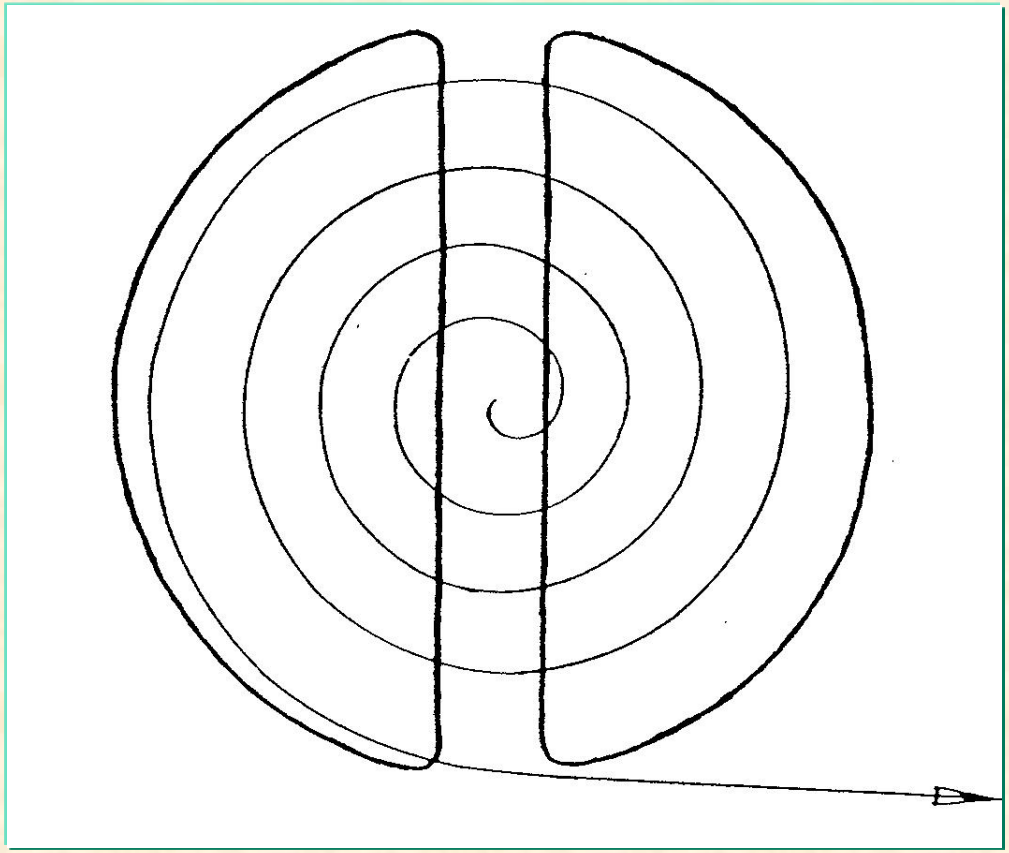
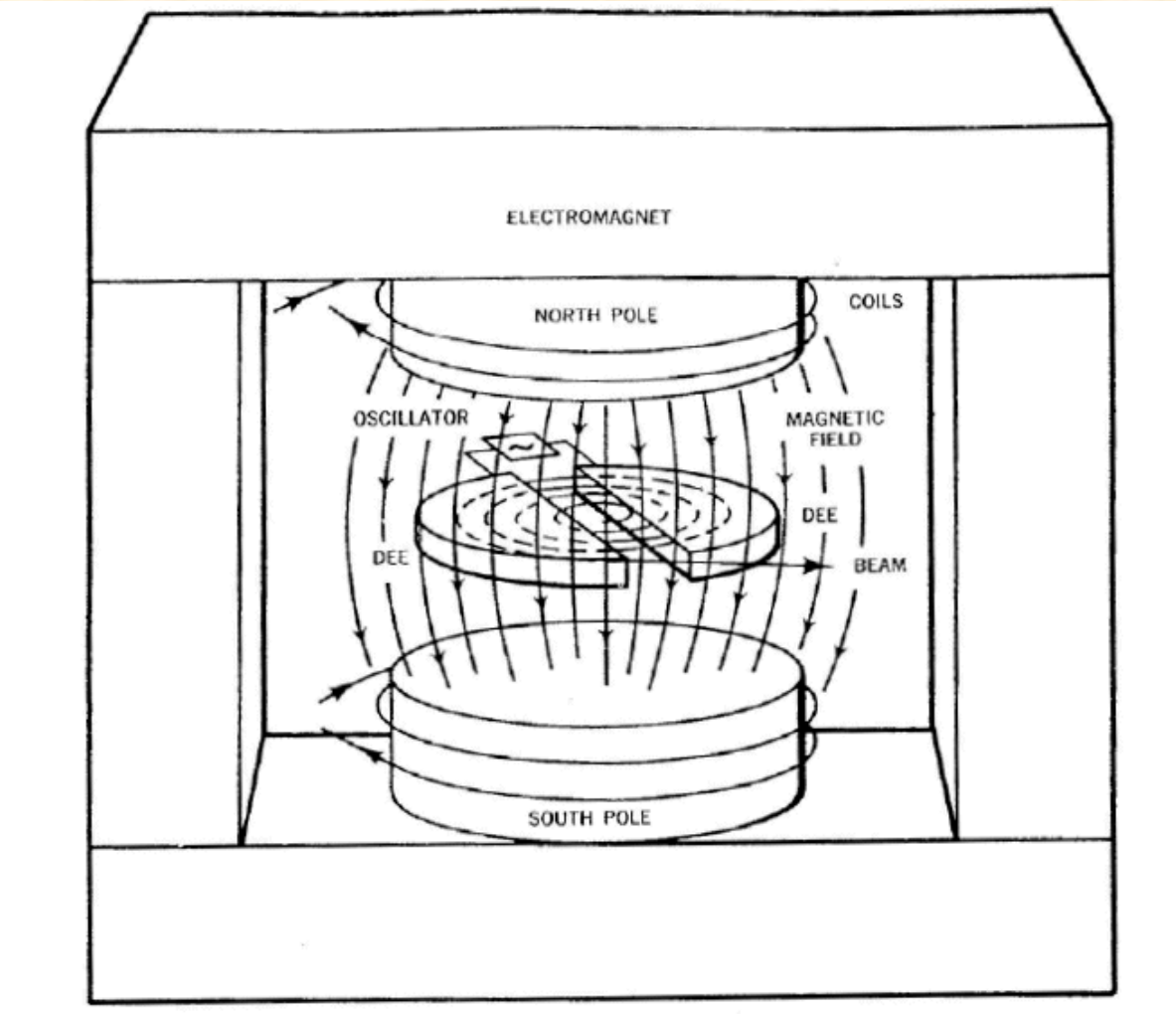
END

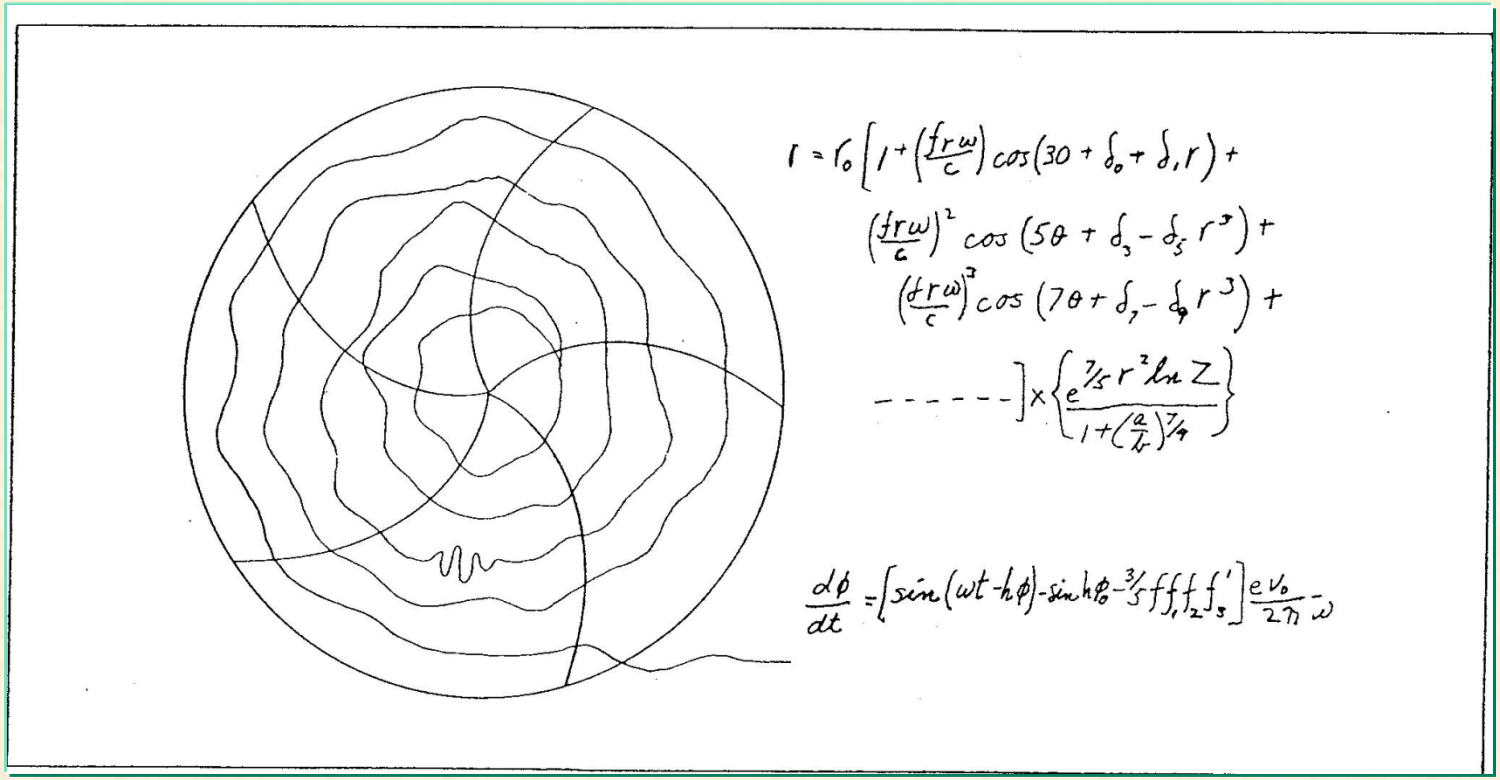
The Cyclotron as seen by the **Inventor**



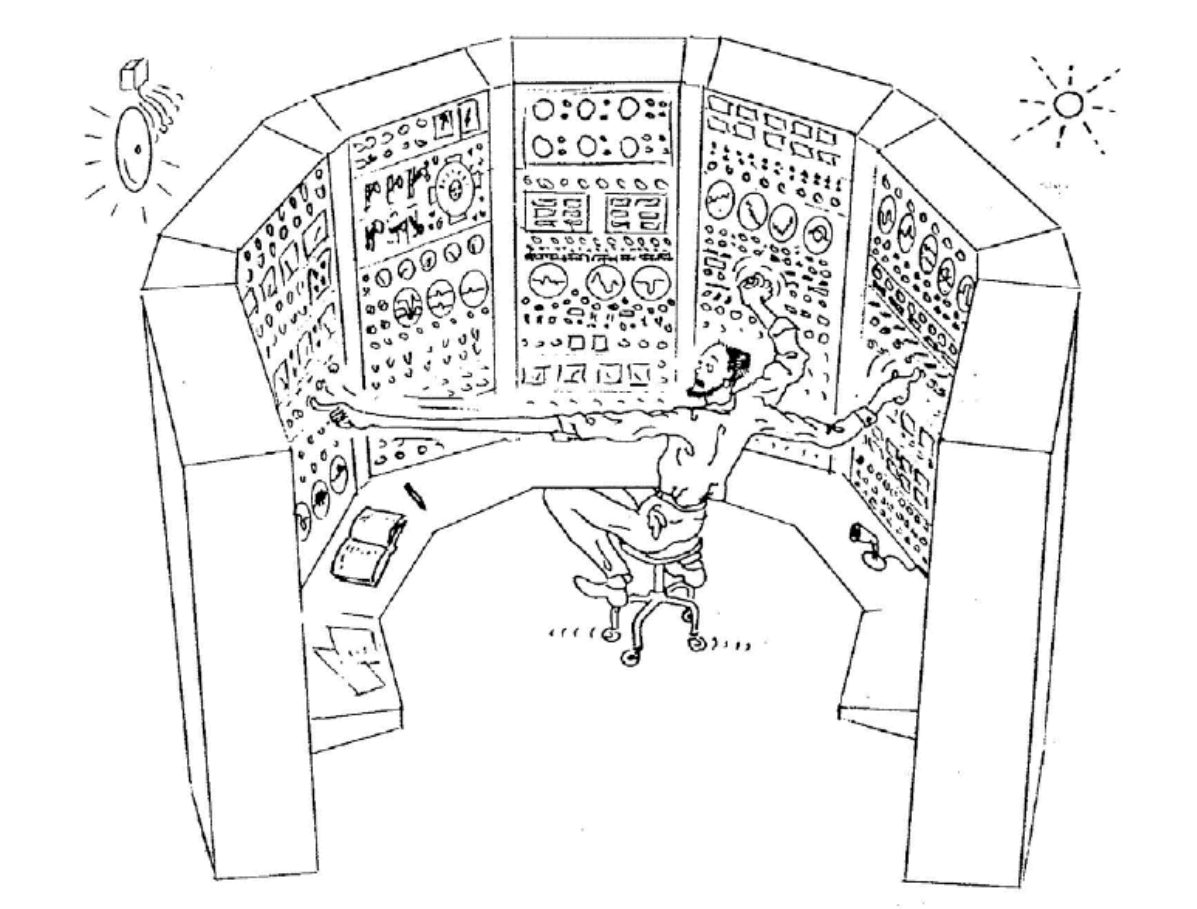
The Cyclotron as seen in the usual **text book**



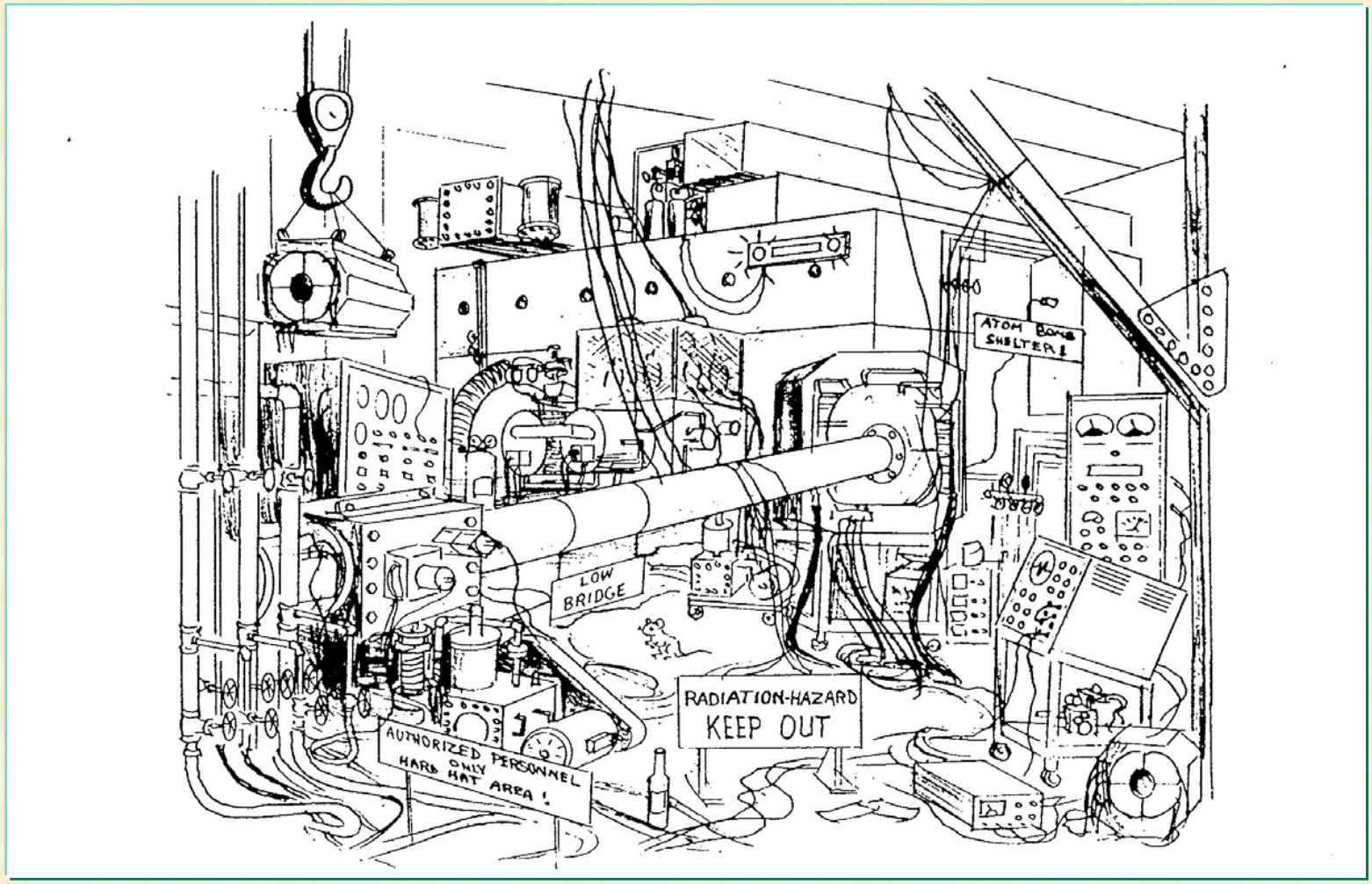
The Cyclotron as seen by the **Theorist**



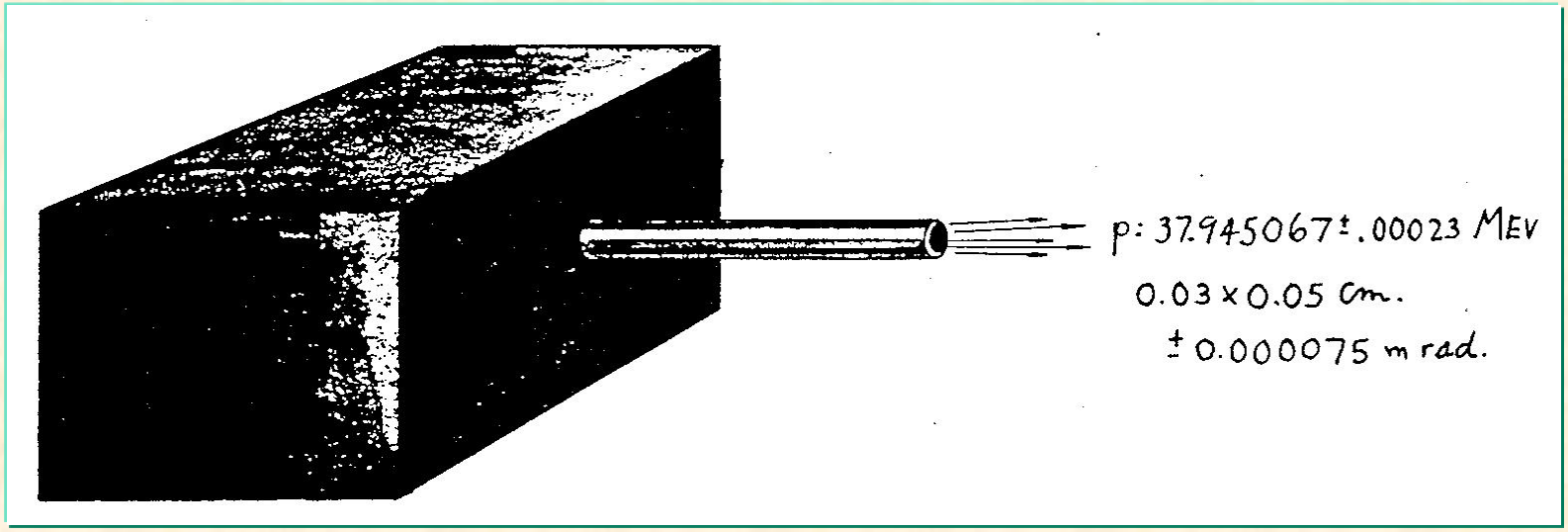
The Cyclotron as seen by the **Operator**



The Cyclotron as seen by the **Visitor**



The Cyclotron as seen by the
Experimentalist



The Cyclotron as seen by the **Student**