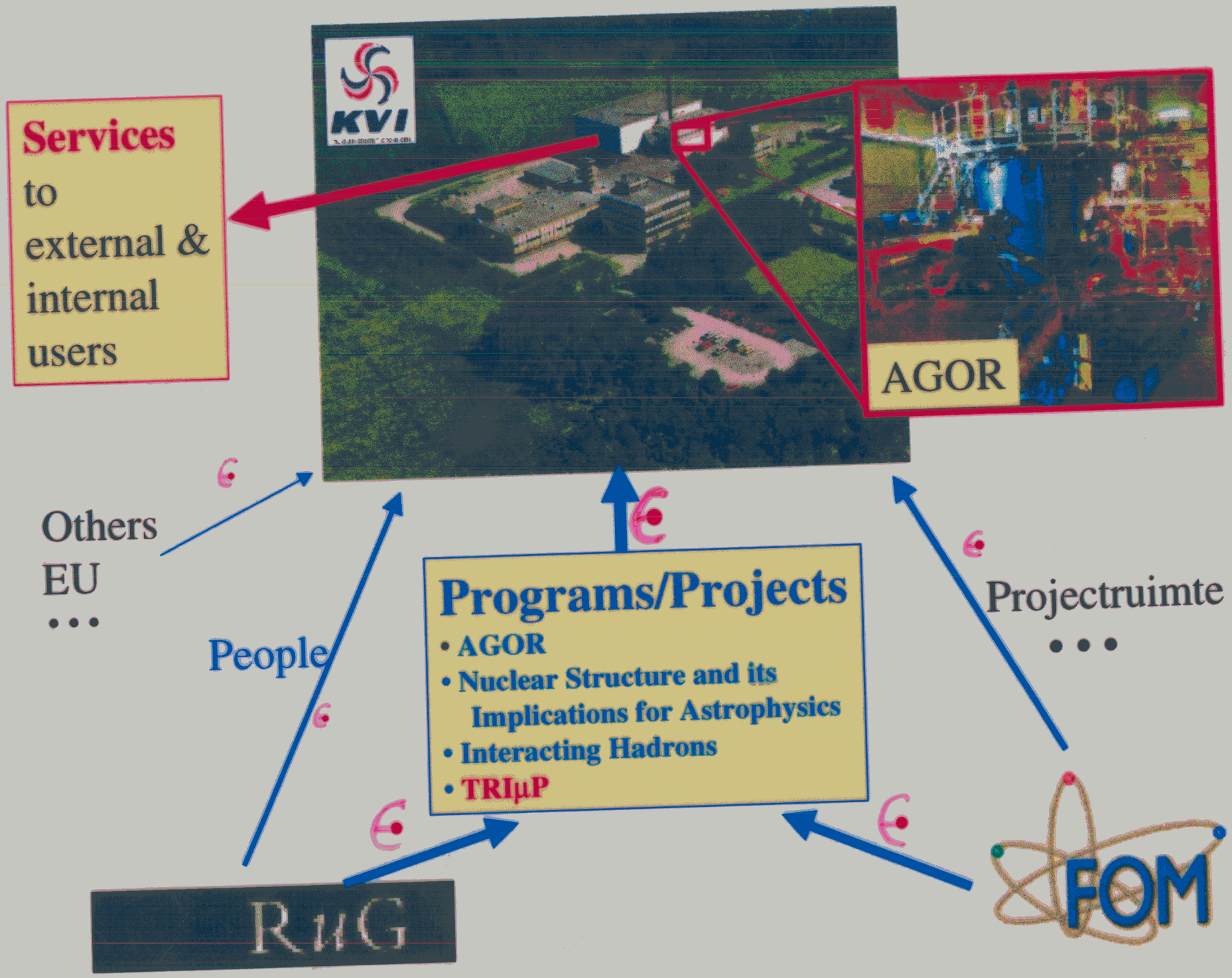
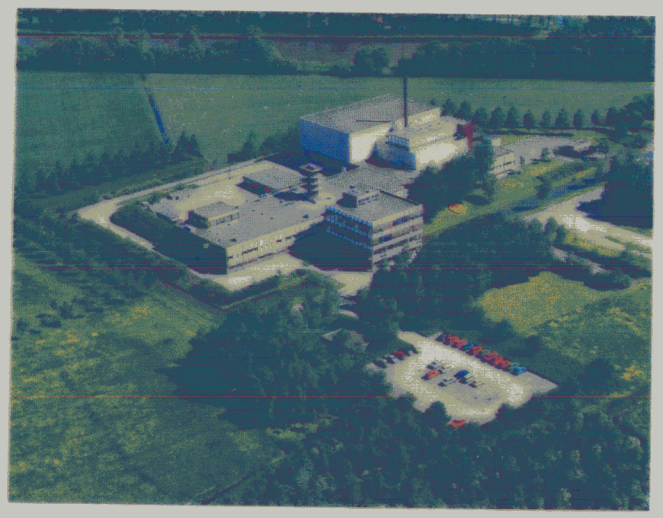

Services
to
external &
internal
users
KVI
AGOR
Others
EU
...
People
Programs/Projects
• AGOR
• Nuclear Structure and its
Implications for Astrophysics
• Interacting Hadrons
• TRIμP
Projectruimte
...
RuG
FOM

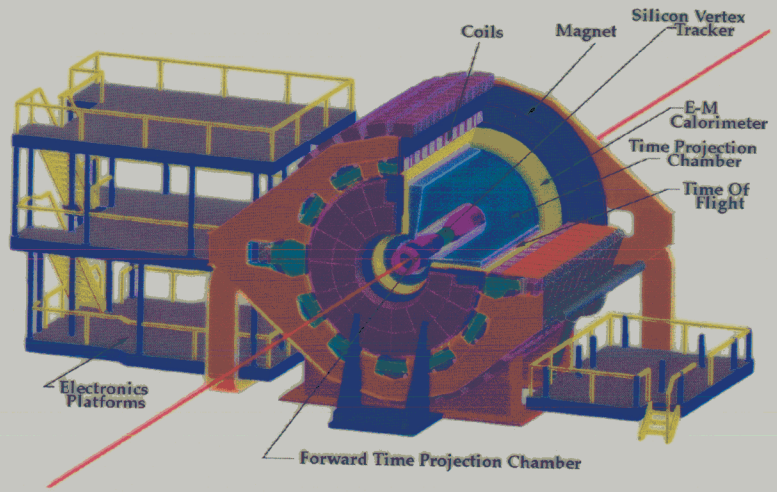
TRIμP

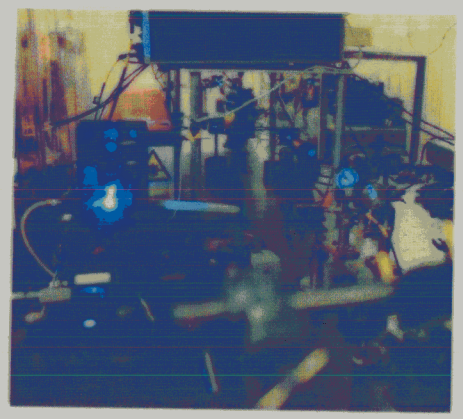
Possibilities to Test New Models

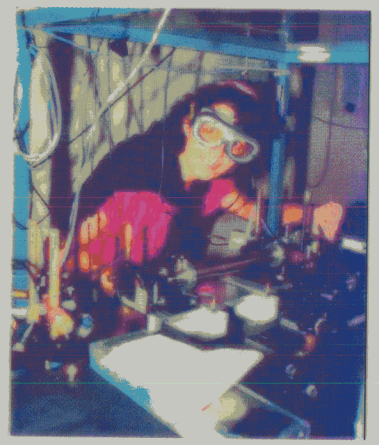
KVI

STAR Detector









High Energies
& direct observations

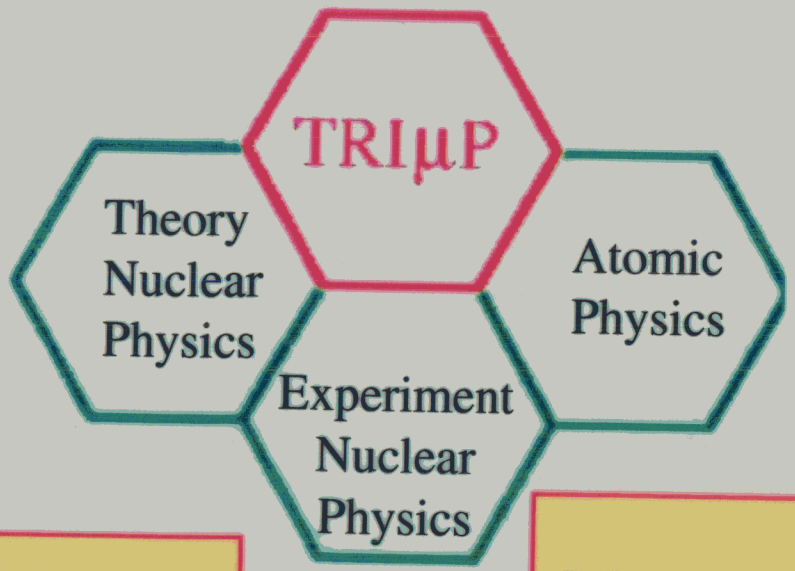
Low Energies
& Precision Measurement

TRIμP

A new Facility to Investigate Fundamental Interactions with Optically Trapped Radioactive Atoms

Klaus Jungmann

ICHEP02, Amsterdam, 24-31 July 2002



funding:

FOM RuG

people :

G. Berg, P. Dendooven, O. Dermois, M. Harakeh, R. Hoekstra, S. Hoekstra, K. Jungmann, S. Kopecky, R. Morgenstern, R. Rogachevsky, M. Sanchez-Vega, , R. Timmermans, E. Traykov, S. Umakanth, M. van Veenhuizen, H. Warringa, L. Willmann, H. Wilschut

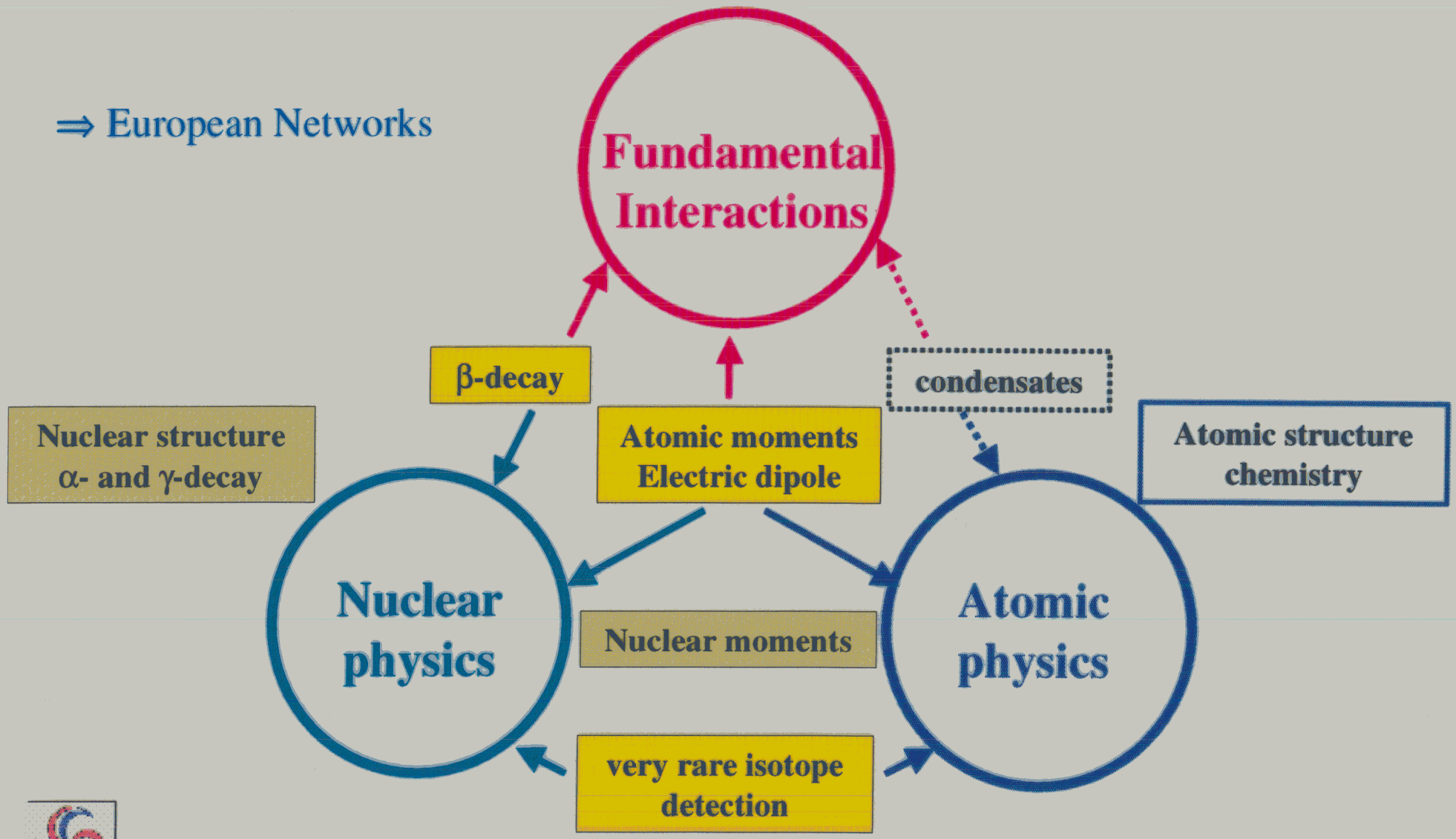
+ many more

project ⇒ program

2001 ⇒ 2013

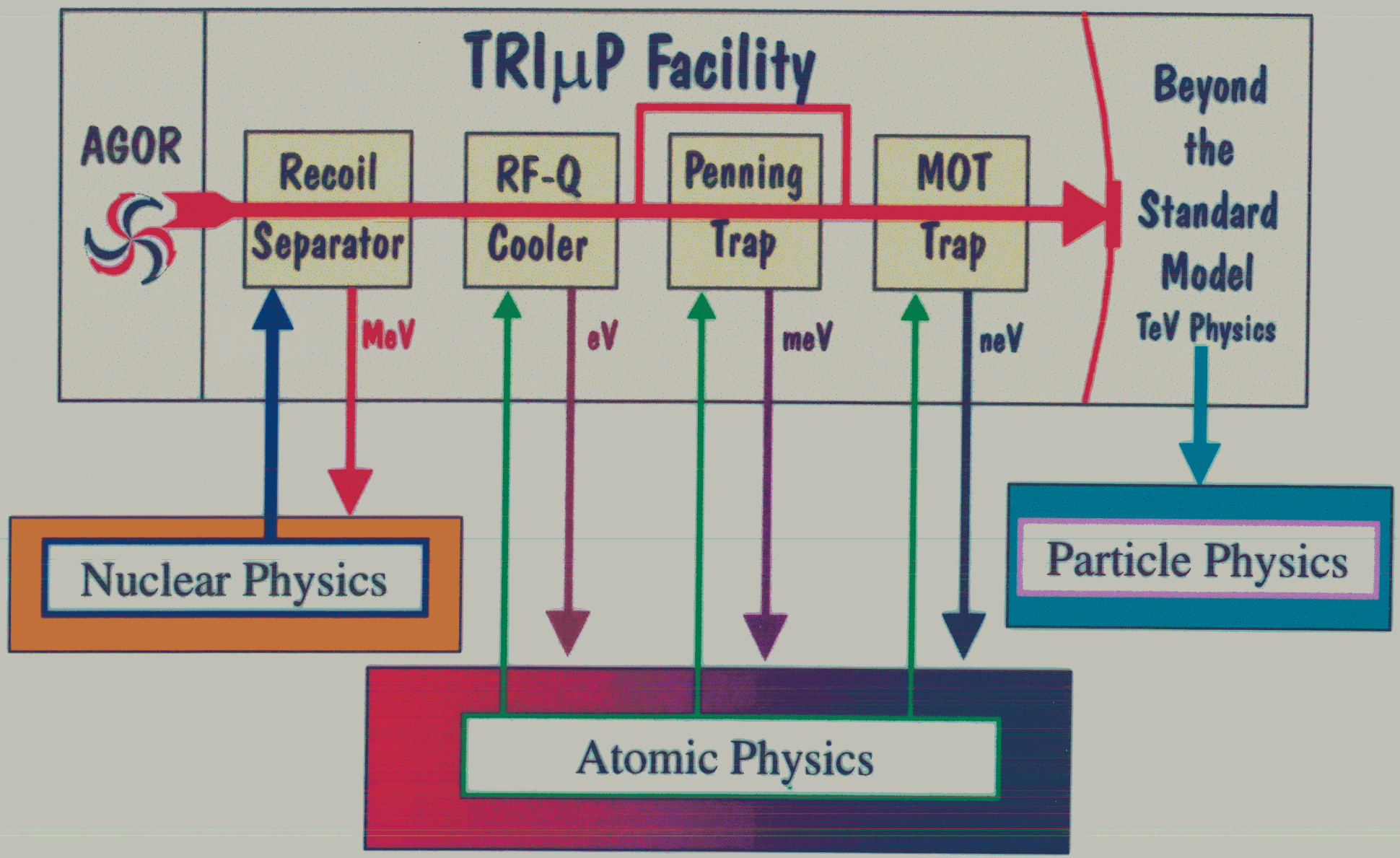
Physics Possibilities with Atomic Traps

⇒ European Networks

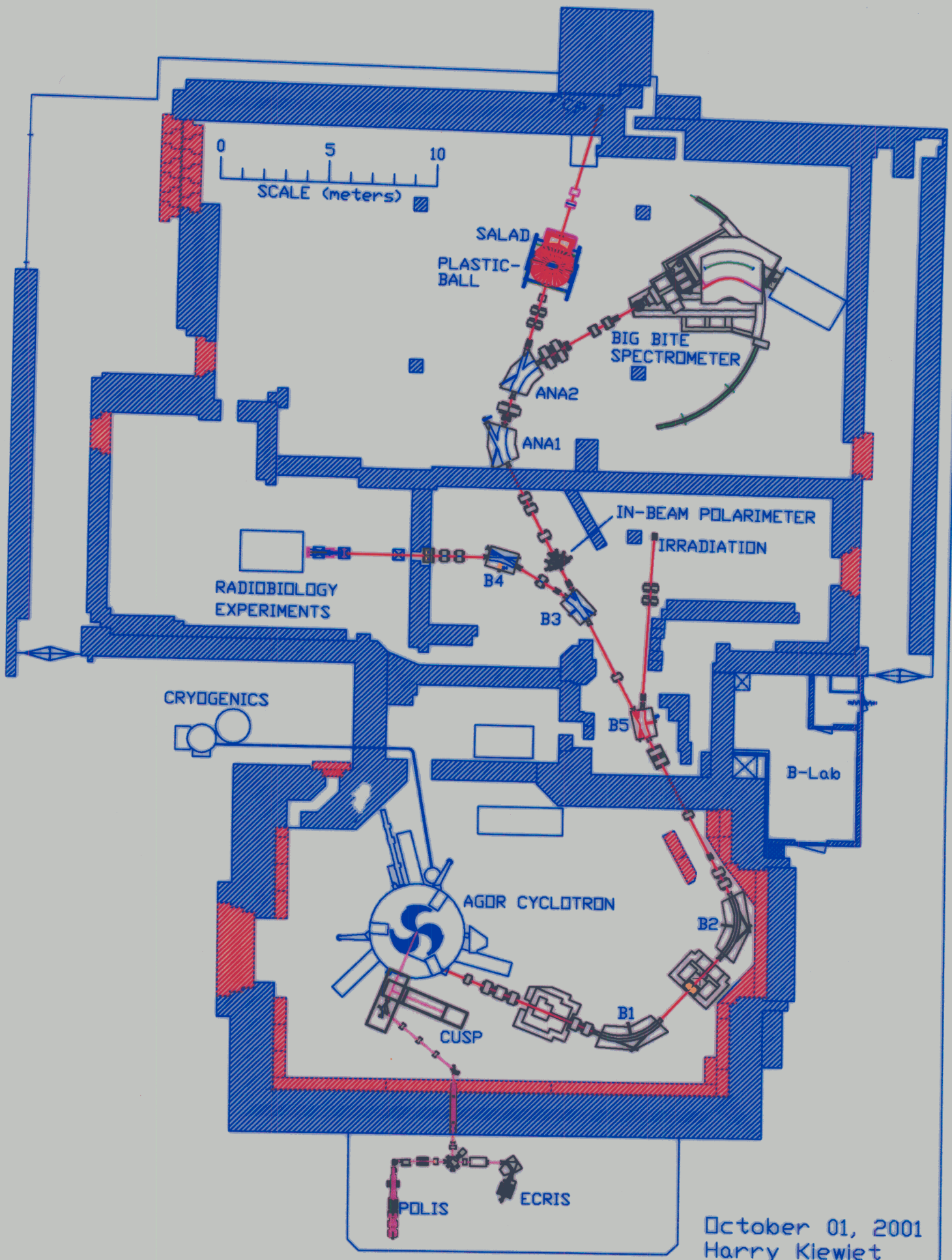


Covered by TRIμP

TRIμP

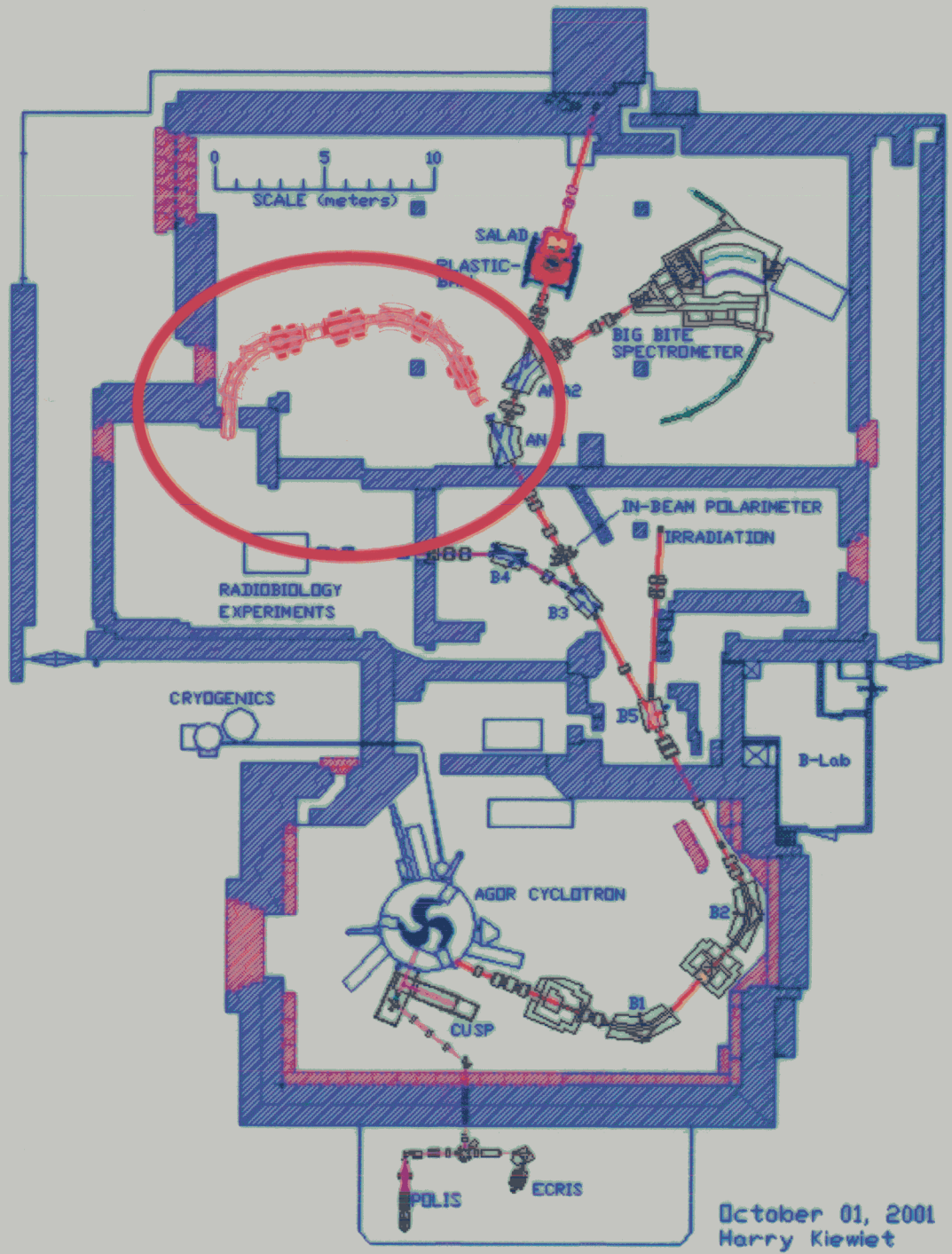

TRIμP Facility
AGOR
Recoil Separator
RF-Q Cooler
Penning Trap
MOT Trap
Beyond the Standard Model
TeV Physics
MeV
eV
meV
neV
Nuclear Physics
Atomic Physics
Particle Physics

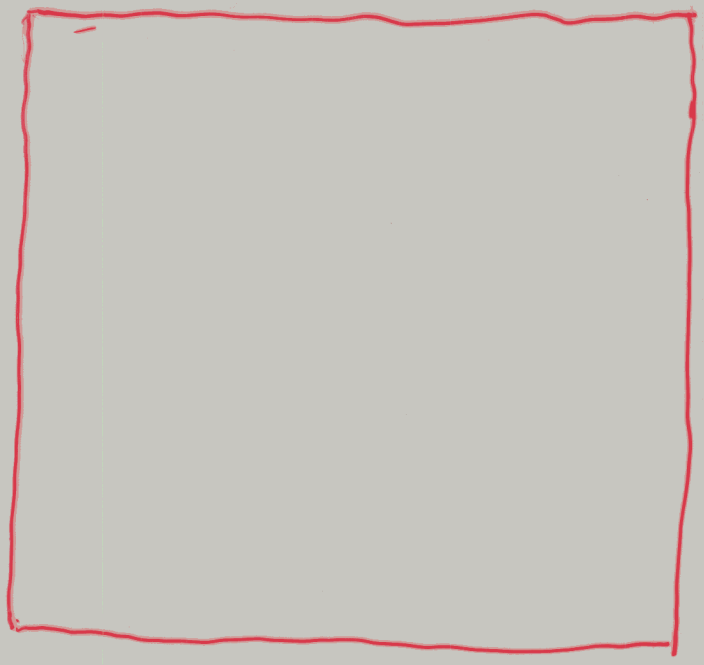
VIEW ON THE AGOR CYCLOTRONVAULT AND EXPERIMENTAL AREA



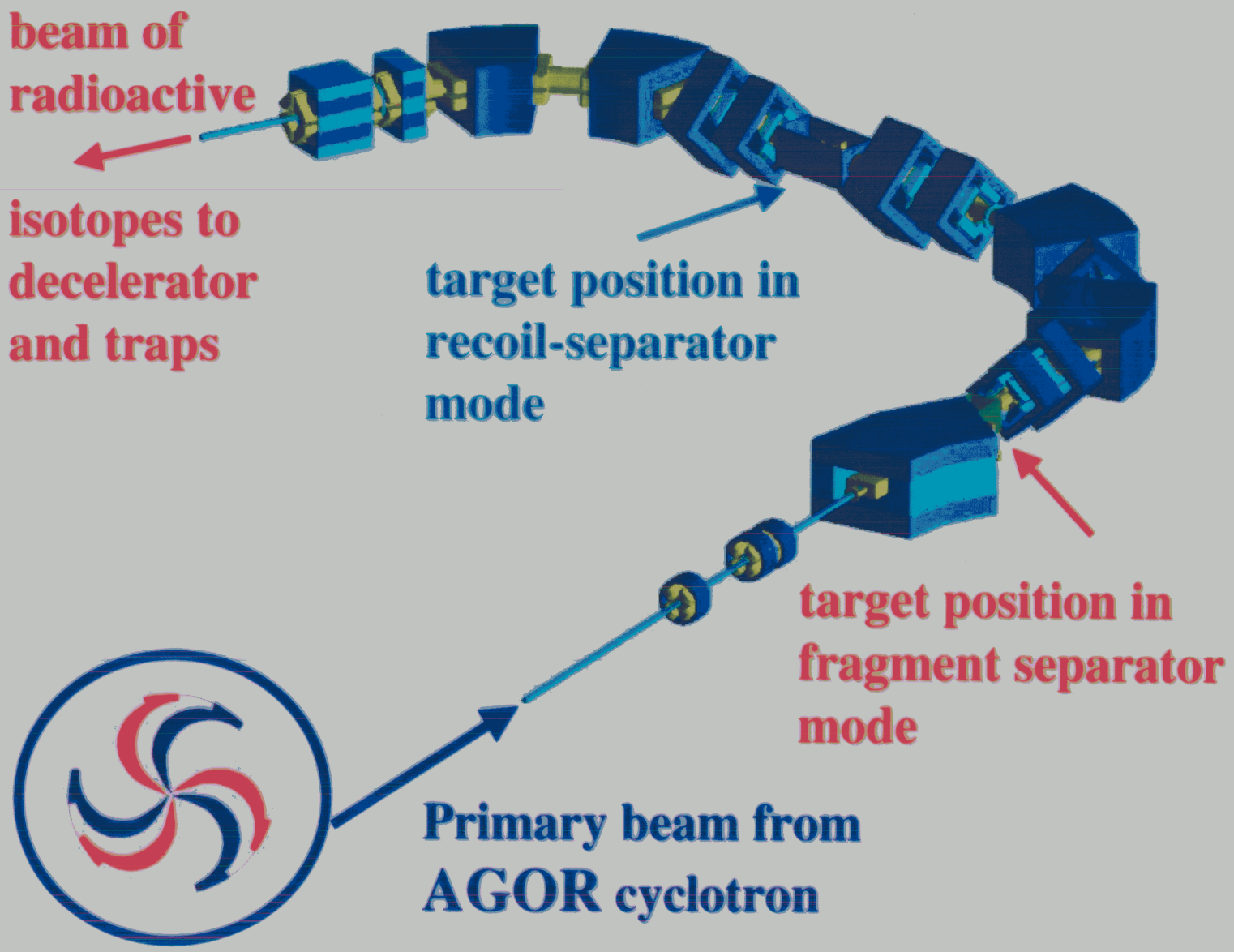
October 01, 2001
Harry Kiewiet

TRIμP


0
5
10
SCALE (meters)
SALAD
PLASTIC-
BIG BITE
SPECTROMETER
IN-BEAM POLARIMETER
IRRADIATION
RADIOBIOLOGY
EXPERIMENTS
B4
B3
B5
B-Lab
CRYOGENICS
AGOR CYCLOTRON
B2
B1
CUSP
POLIS
ECRIS
October 01, 2001
Harry Kiewiet



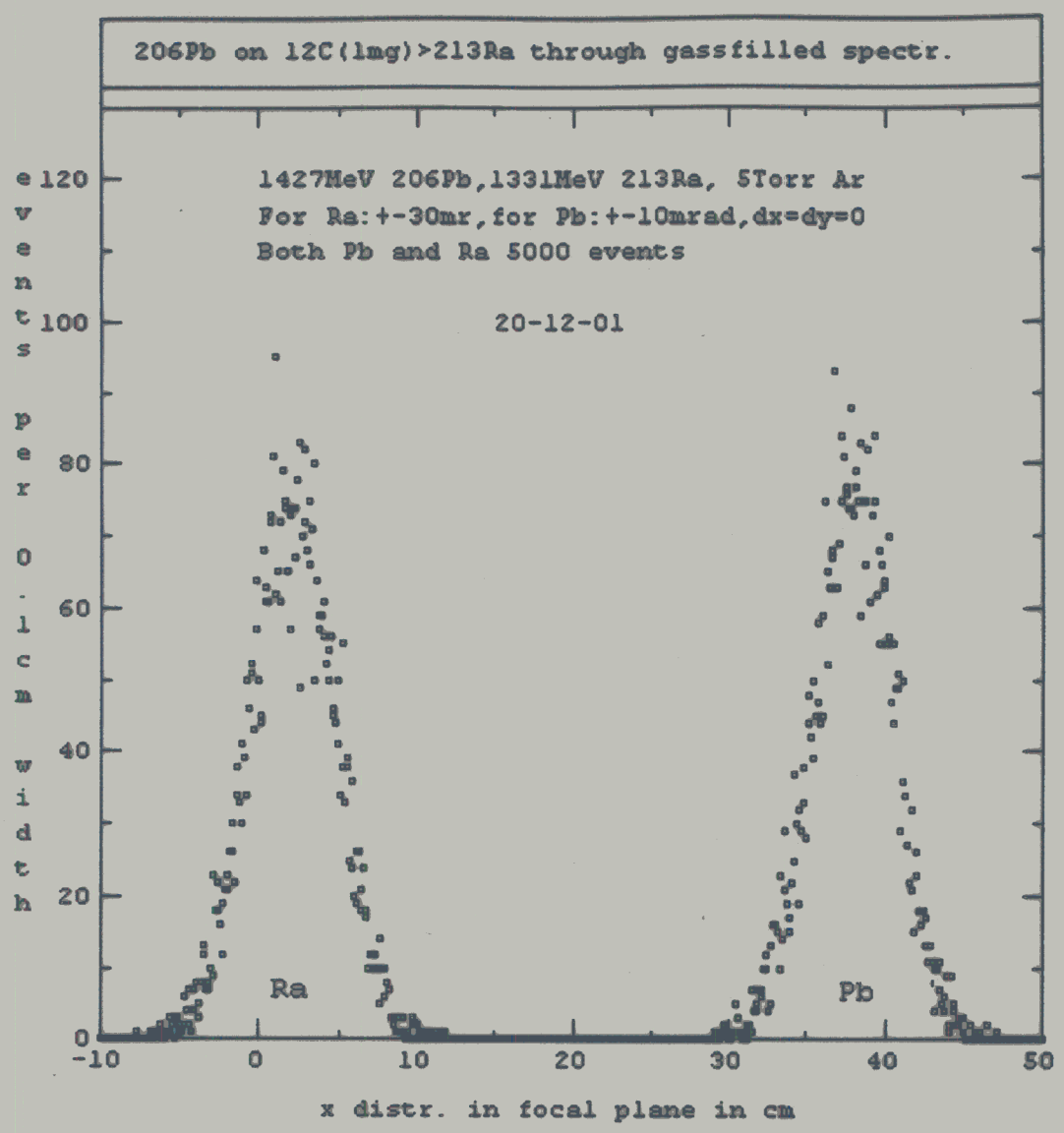
TRIμP


beam of
radioactive
isotopes to
decelerator
and traps
target position in
recoil-separator
mode
target position in
fragment separator
mode
Primary beam from
AGOR cyclotron

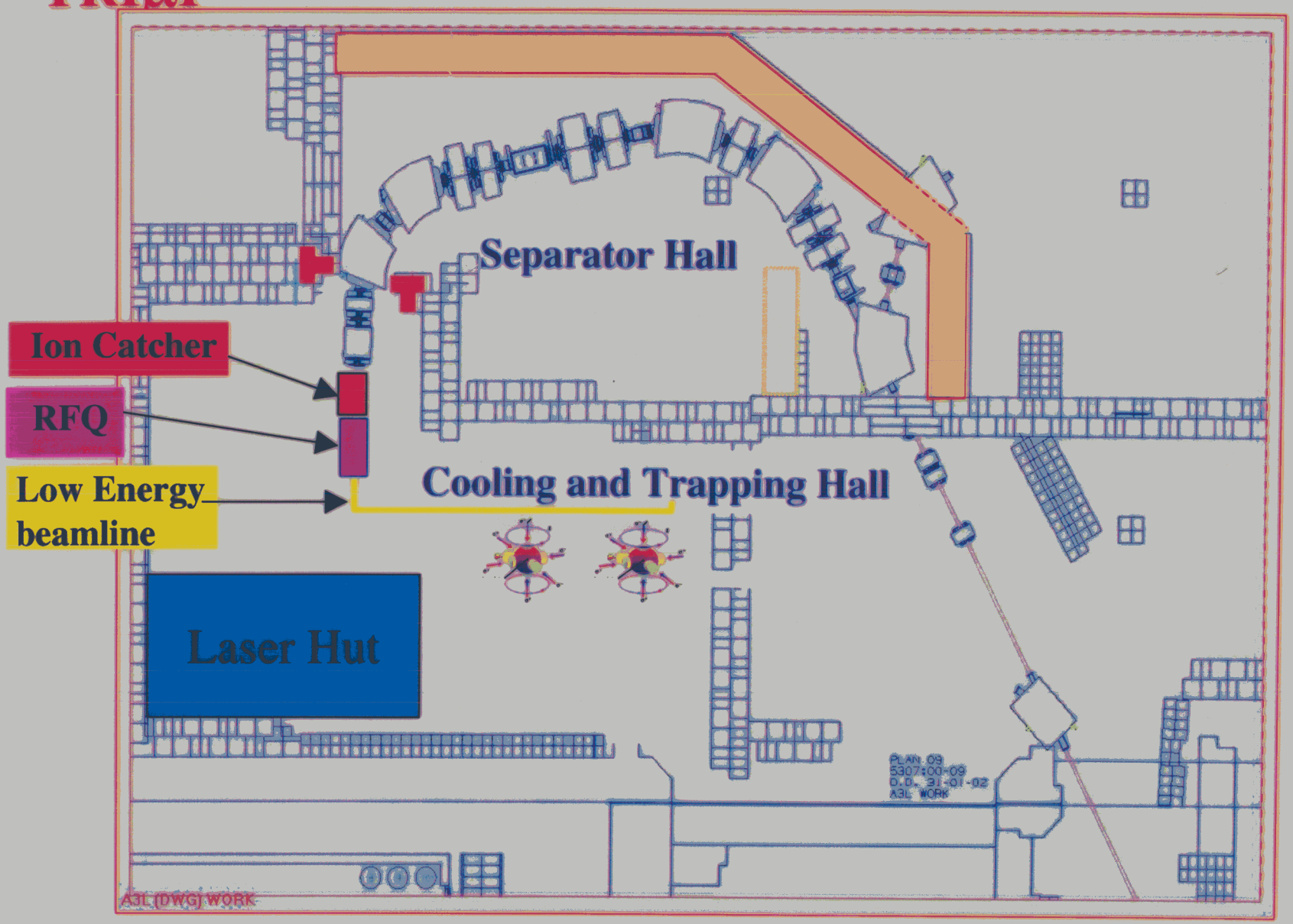
Production methods and rates

1 Fusion-evaporation	gas-filled mode
2 (Semi-)direct reactions	fragment. mode
3 Fragmentation	fragment. mode

Method	product	beam	E/nucl (MeV)	target	rate /s/kW
1	Ra	^{208}Pb	8	^{12}C	10^7
2	^{20,21}Na	^{20}Ne	10-20	p,d	10^8-10^9
3	^{32}Ar	^{36}Ar	40-70	Be	10^3-10^4
3	^{36}Si	^{40}Ar	40-70	Be	10^3-10^4


206Pb on 12C(1mg)>213Ra through gassfilled spectr.
1427MeV 206Pb,1331MeV 213Ra, 5Torr Ar
For Ra:+-30mr,for Pb:+-10mrad,dx=dy=0
Both Pb and Ra 5000 events
20-12-01
events per 0.1cm width
Ra
Pb
x distr. in focal plane in cm

TRIuP


Separator Hall
Ion Catcher
RFQ
Low Energy beamline
Cooling and Trapping Hall
Laser Hut
PLAN.09
5307:00-09
D.D. 31-01-02
A3L WORK
A3L [DWG] WORK

Key Experiments

- **TRIμP** will be a ***user facility***
  ⇒ ***open to outside users***

- **KVI** will concentrate *first* on
  ⇒ ***electroweak tests***
  * ***β - decay ($^{20,21}Na$, ^{19}Ne)***
  * ***electric dipole moments (Ra)***
  * ***parity violation (Fr, Ra^+)***
  ⇒ ***applications***
  * ***ALCATRAZ (rare Ca isotope detection)***

- **Networks** will jointly address
  ⇒ ***technology*** and ***science*** issues
  * ***NIPNET, BETANET, ION Catcher***

KVI

Goals of TRIμP

- Study fundamental interactions using radioactive isotopes in traps
- A facility will be created for in house and outside users

General Time Lines

- Project started 2001; setup facility in 4 years
- TRIμP became a managed program in July 2001
- Exploitation of facility until 2013
- TRIμP will evolve into a 50% user of ARGOR
- Midterm review in 2008

TRIμP

TRIμP Organization (Technical)

KVI

• Separator
(design stage)

project leader:	Otto Dermois /Georg Berg
ass. proj. lead:	Harry Kiewiet
slow control :	Dick Damstra
design:	Lambertus Slatius
vaccum:	Harry Timersma

• RFQ cooler and LEB
(design stage)

project leader :	Lorenz Willmann
ass. proj. lead:	N.N.
slow control :	Peter Kroon
design:	Lambertus Slatius
vaccum:	Henk Gorter

• Cryo target
(orientaton phase)

projectleader :	Hans Wilschut
	N.N.

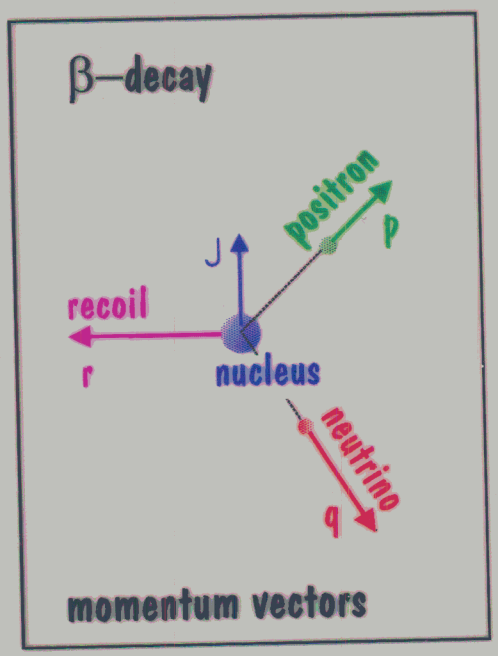
• MOT & Laser Laboratory
(design stage)

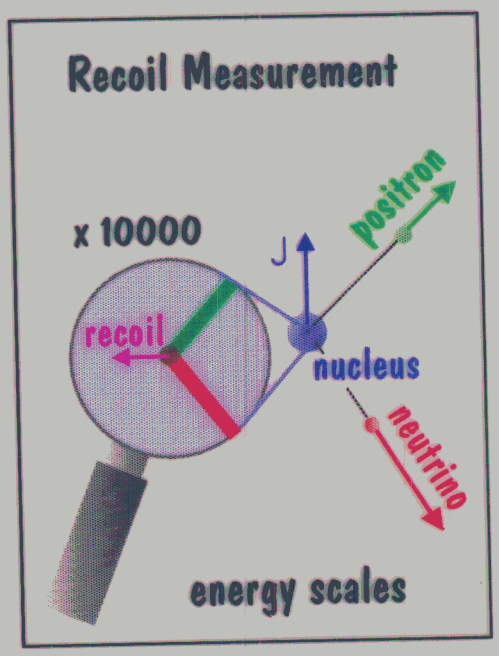
project leader:	Lorenz Willmann
ass. proj. lead:	Jan Mulder
slow control :	Henk van der Duin
design:	Bastian Duinsveld
vaccum:	Henk Gorter
optics&lasers:	Hassan Karaer

• Infrastructure
(design stage)

project leader:	Harry Kiewiet
radiation safety:	Hans Beijers
design:	Bastian Duinsveld
building services:	Jans Sijbring
cooling:	Steven van der Veen
electro-technics:	Piet Wieringa

Why Traps?





$$\langle \vec{J} \cdot \vec{p} \times \vec{q} \rangle \neq 0 \ ?$$

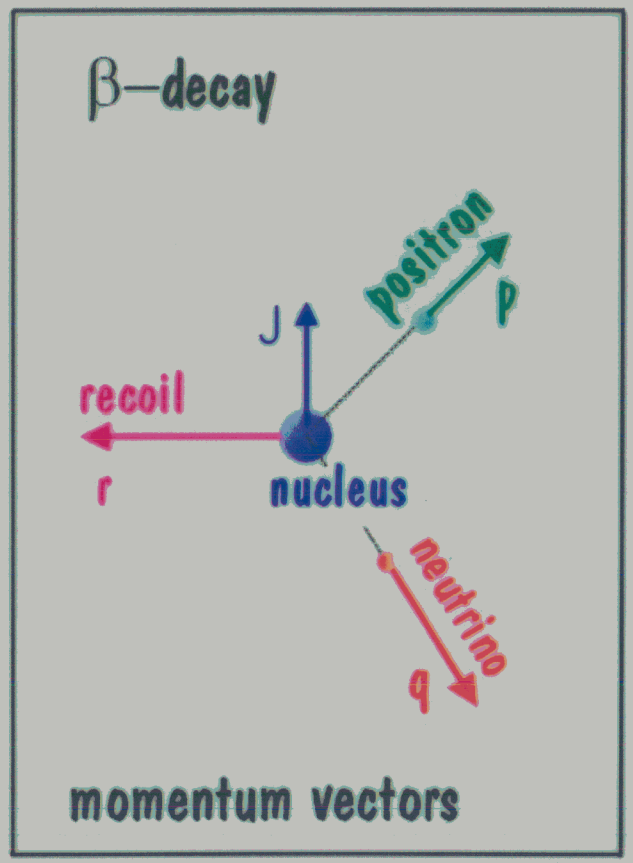
$$E_{recoil} = \frac{(\vec{p} + \vec{q})^2}{2M_{recoil}} < 100\,\mathrm{eV}$$

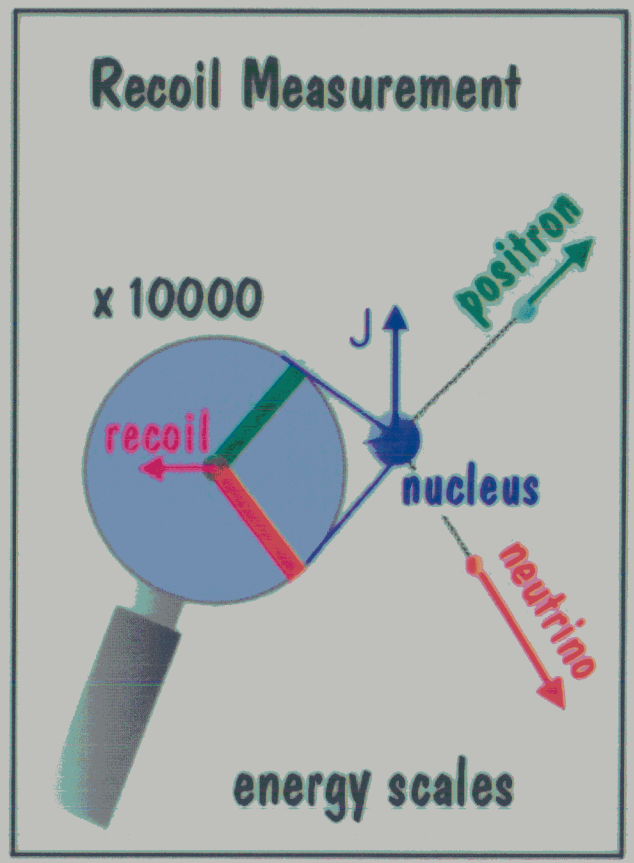
Correlation coefficients in β-decay:

$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\frac{p \cdot \hat{q}}{E} + b\Gamma\frac{m_e}{E}$$
$$+ \langle J \rangle \cdot \left[A\frac{p}{E} + B\,\hat{q} + D\frac{p \times \hat{q}}{E}\right]$$
$$+ \langle \sigma \rangle \cdot \left[G\frac{p}{E} + Q\langle J \rangle + R\langle J \rangle \times \frac{p}{E}\right]$$

Maximal experimental control

Why traps?





$$\langle \vec{J} \cdot \vec{p} \times \vec{q} \rangle \neq 0 \ ?$$

$$E_{recoil} = \frac{(\vec{p} + \vec{q})^2}{2M_{recoil}} < 100\,\text{eV}$$

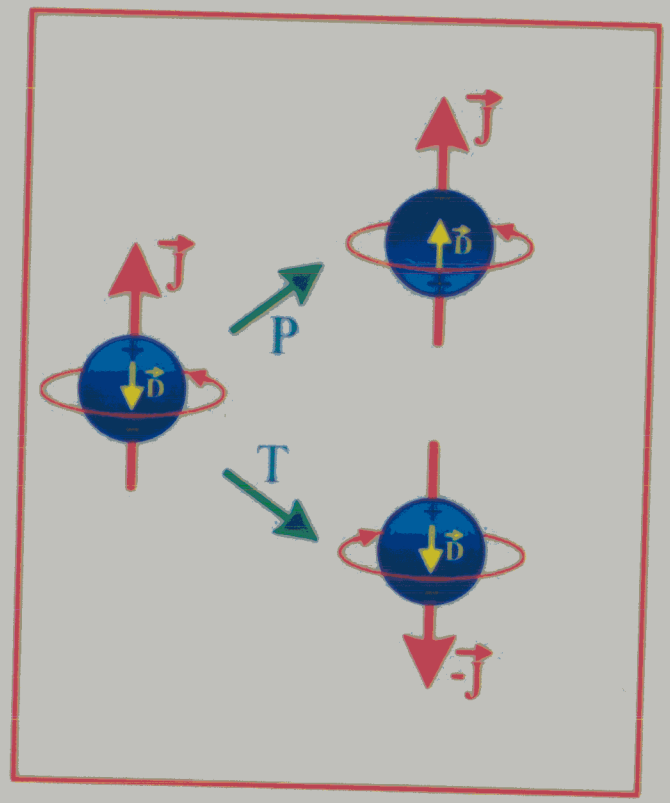
Maximal experimental control

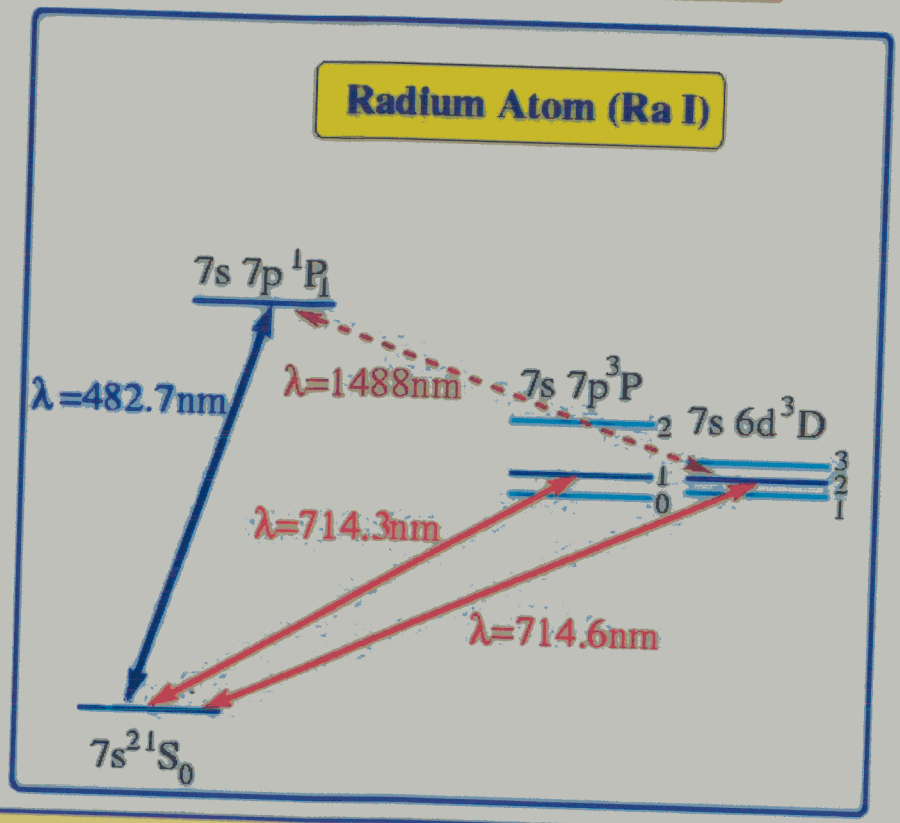
TRIμP

KVI
RIJKSUNIVERSITEIT GRONINGEN

TRIμP

Radium Permanent Electric Dipole Moment





EDMs violate
- Parity
- Time Reversal
- CP Symmetry

Advantage over "best" atom so far (^{199}Hg)

- close states of opposite parity
  ⇒ several 10 000 enhancement possible
- some nuclei strongly deformed
  ⇒ may give nuclear enhancement

history

- AGOR cyclotron operational since 1996

- design and construction 1985 - 1994
  - collaboration KVI - IPN Orsay (France)
  - investment
    - 25 MEuro mainly KVI (FOM-NWO)
    - 500 manyear 75 % IPN Orsay; 25 % KVI
  - initial commissioning in Orsay 1994
  - installation and commissioning at KVI 1995 - 1996

- 20 % share of beamtime for French proposals

design goals

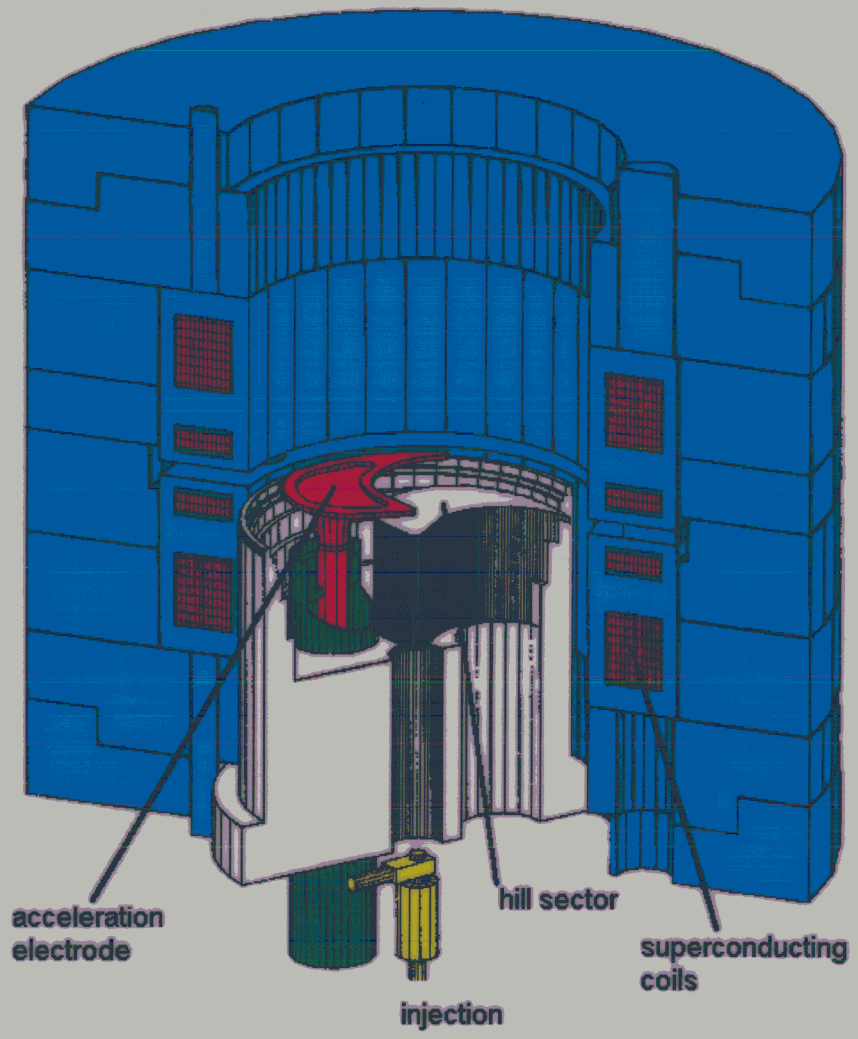
- general purpose accelerator for nuclear physics
- accelerate all elements of periodic system
  - protons up to E ~ 200 MeV
  - ions with Q/A = 0.5 up to E/A ~ 95 MeV
  - heavy ions down to E/A ~ 6 MeV
- 'optimum' solution
  - compact superconducting cyclotron
  - external ECR ion source

cyclotron basics

- longitudinal phase space
  - orbital period independent of velocity
    - relativistic effects impose

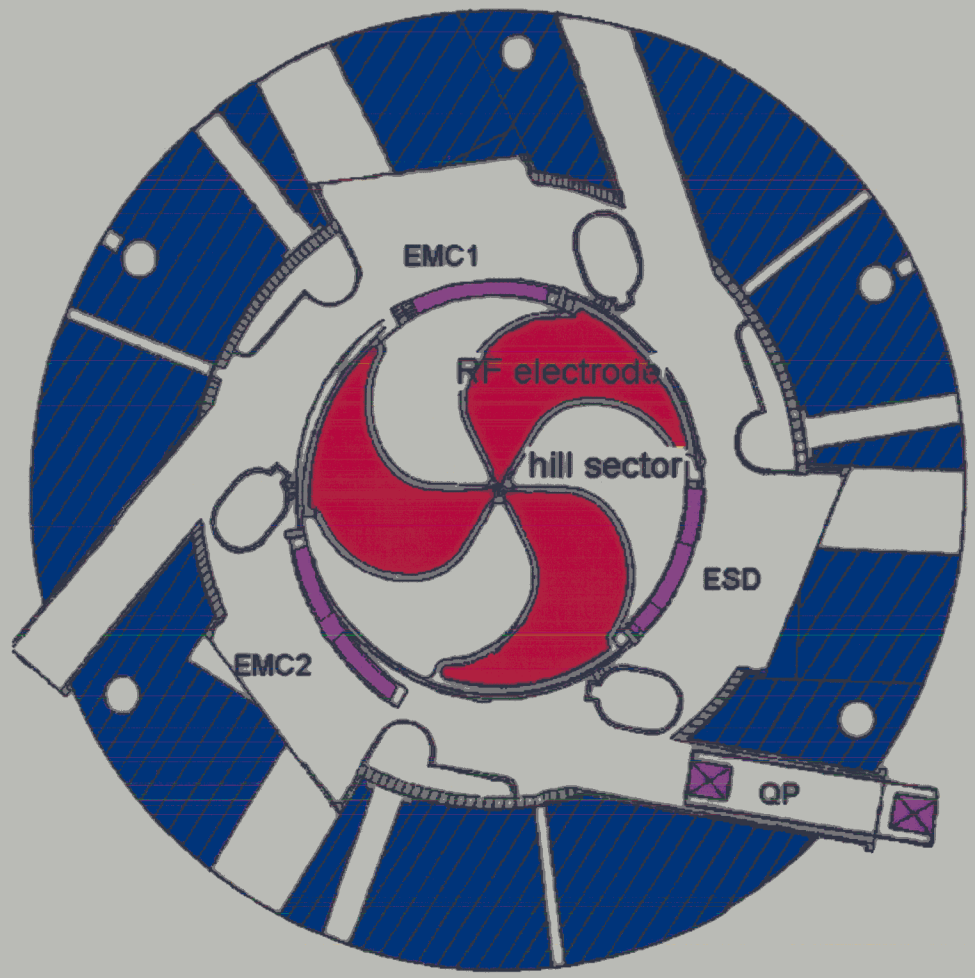
$$n = \frac{r}{B}\frac{dB}{dr} = \gamma - 1 > 0$$

  - acceleration with fixed frequency RF voltage
  - no stability: overall accuracy magnetic field better 10^{-4}



cyclotron basics

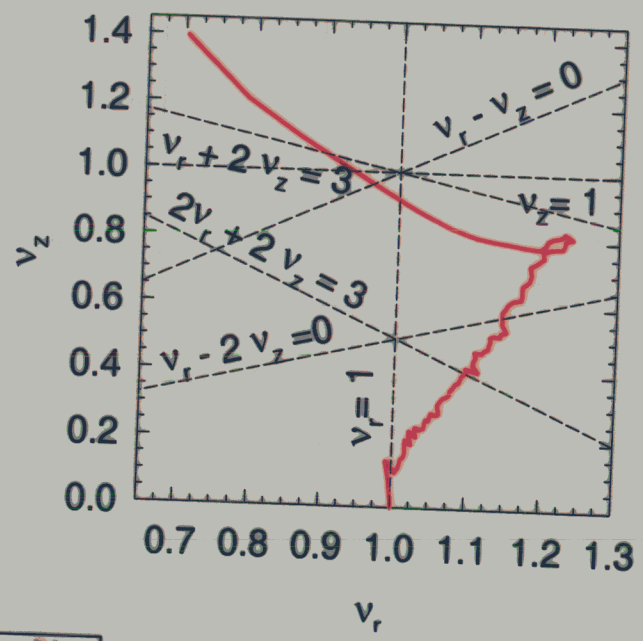
- transverse phase space
  - radial stability: intrinsic
  - vertical stability: interplay between
    - defocussing due to $n > 0$
    - focussing by azimuthal field variation $\Delta B/B(\vartheta)$ by hill and valley configuration magnet poles



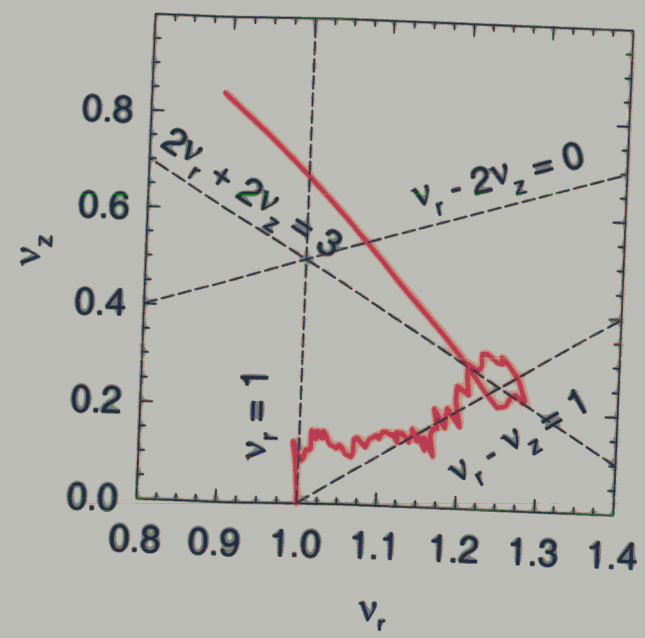
orbit dynamics

- betatron frequencies ν_r and ν_z measure of focussing strength
  - number of oscillations around equilibrium orbit per turn
- resonances occur at $k\nu_r + l\nu_z = m$; k, l, m, integer
  - excited by small perturbations

120 MeV protons



190 MeV protons



KVI

superconducting coils

- high magnetic field: 2 - 4 T
  - coil contribution to magnetic field 50 - 75 % .
  - compact machine

- iron poles saturated: M = 2.1 T
  - very good reproducibility
  - constant amplitude azimuthal field variation
    - at high E/A loss of vertical focussing ($\nu_z = 0$)
    - at low E/A too strong vertical focussing; coupling resonance $\nu_r + 2\nu_z = 3$
  - geometry determines operating diagram

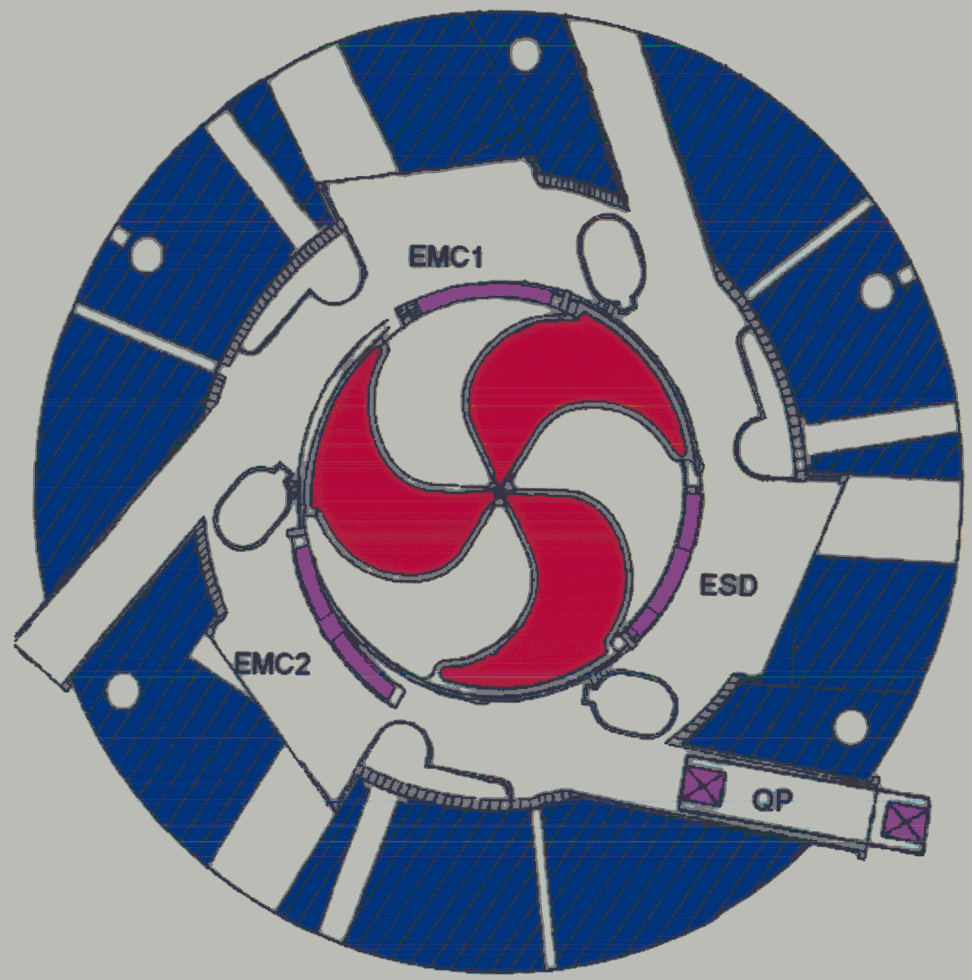
- relativistic corrections: two main coils needed

extraction

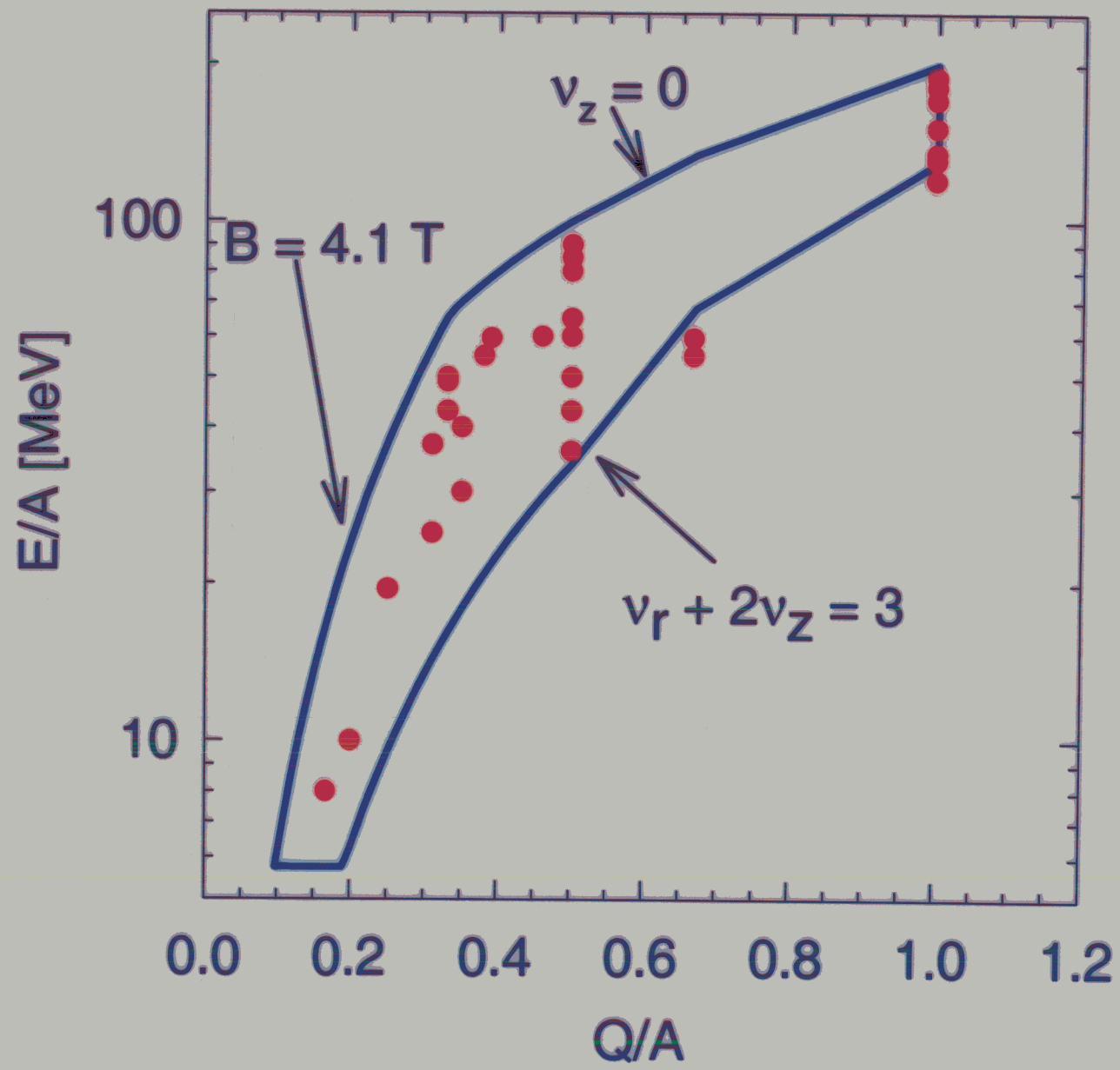
- turn separation too small to insert extraction device
- induce precession movement with first harmonic at $\nu_r = 1$
  - large turn separation around $\nu_r = 0.8$
- high magnetic field
  - large fringe field region
  - long extraction path
  - several elements with bending and focussing
    - movable to adjust to beam trajectory

extraction

- ESD <100 kV/cm
- EMC1
  - dipole 0.25 T
  - quadrupole 13 T/m
- EMC2
  - superconducting
  - dipole 0.4 T
  - quadrupole 22 T/m
- QP
  - superconducting
  - quadrupole 35 T/m



performance



performance

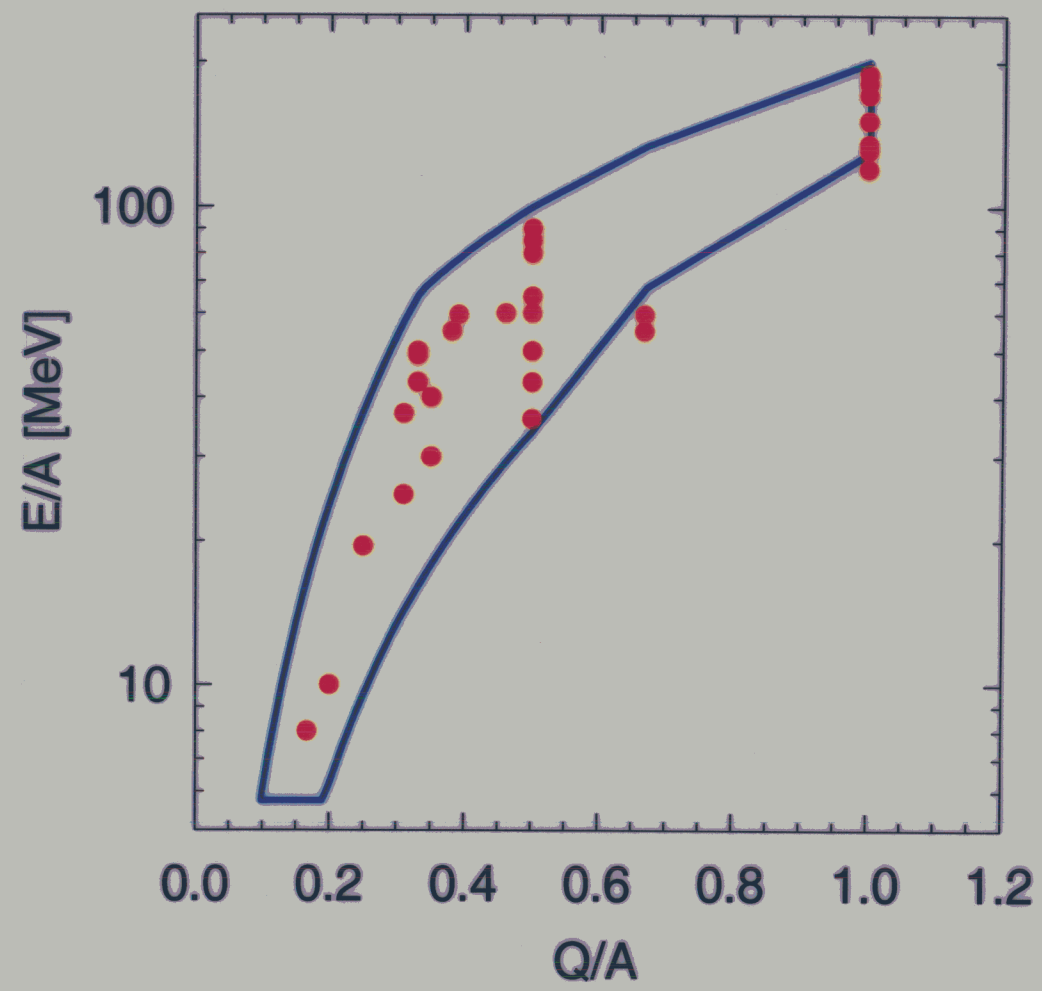
- extraction efficiency
  - 50 - 90 %
- transmission ion source - target
  - 10 - 25 %
- beam dynamics
  - good agreement with calculation

- design validated by operating experience

- operation
  - 3200 hours beam on target per year
  - 80 % availability

beams

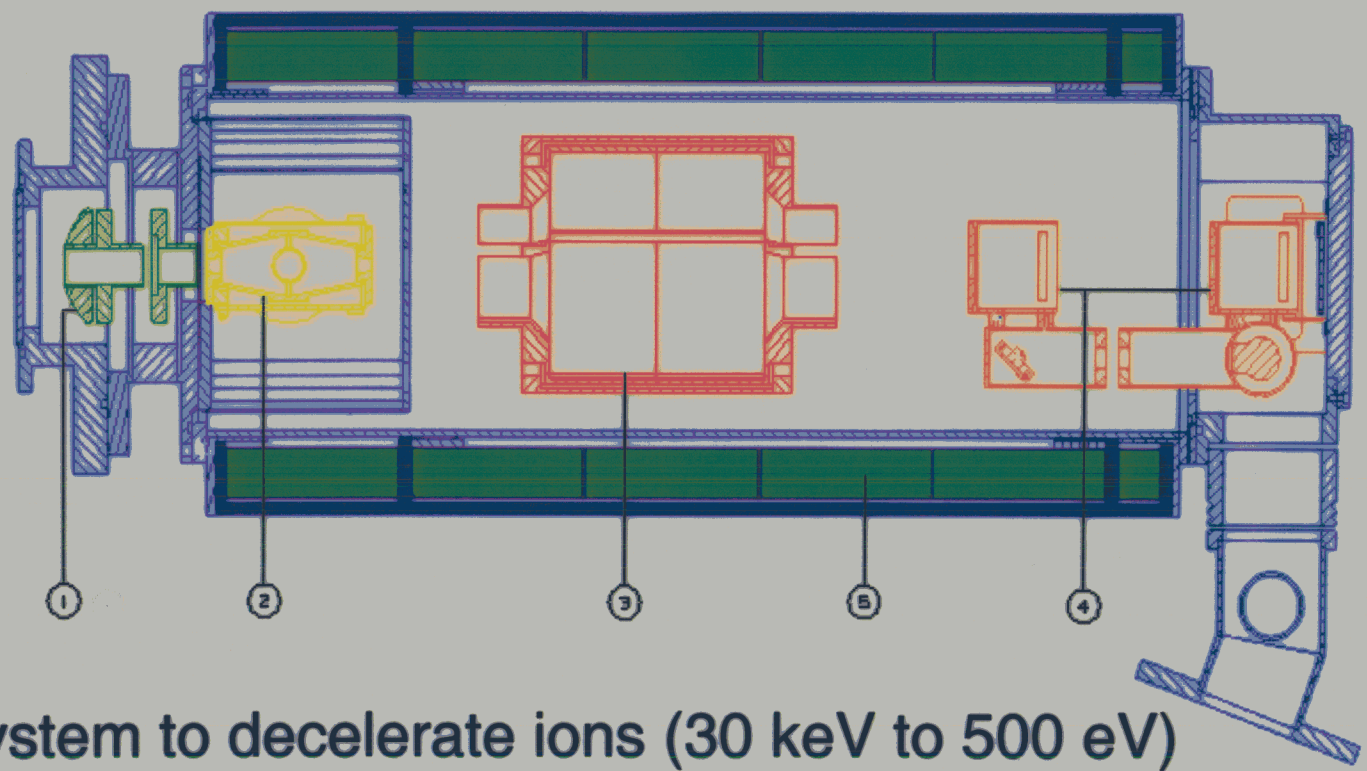
- present
  - polarized protons
    P = (80 %)
  - polarized deuterons
    P_z and P_{zz} ~ 75 %
  - tritons
  - heavy ions up to ^{40}Ar
- development
  - heavy ions up to ^{208}Pb



conclusion

- cyclotron complies with design specifications
  - good agreement theory and experiment
  - good transmission
- versatile tool for nuclear physics research
  - many different ions
  - large energy range
- experimental setups allow many types of experiments

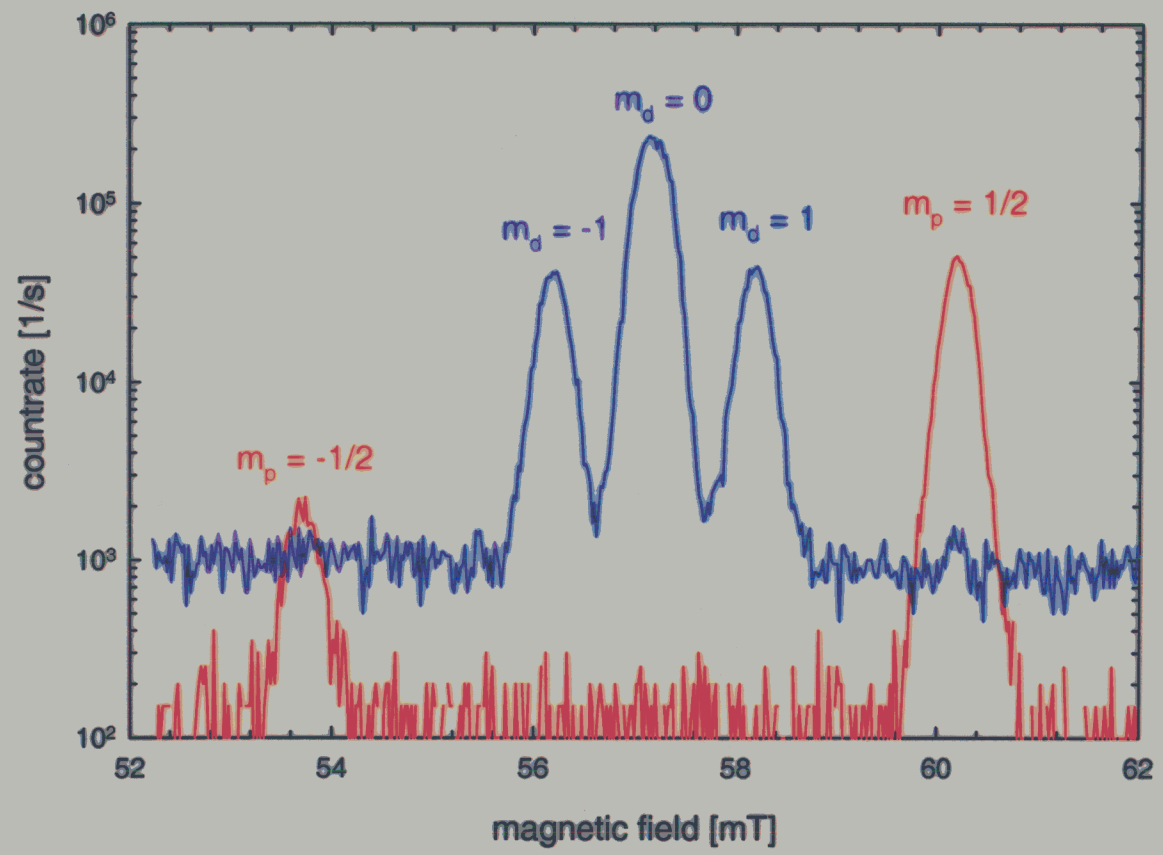
Lamb-shift polarimeter: lay-out



1: lens system to decelerate ions (30 keV to 500 eV)
2: Cs vapor cell to convert ions in metastable atoms
3: 1609 MHz cavity with DC dipole field to quench metastable atoms
4: detection of surviving metastable ions
5: solenoid to scan over resonance

KVI

Lamb-shift polarimeter: first measurements



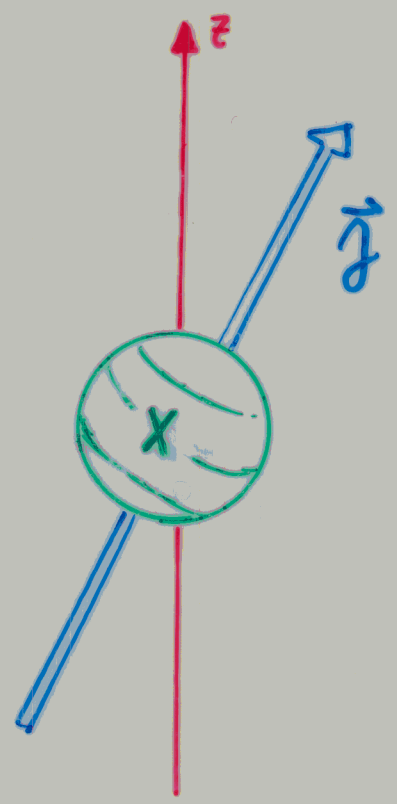
- polarisation deuteron $P_z = 0.005\ (0)$, $P_{zz} = -1.34\ (-2)$
- polarisation proton $P_y = 0.92\ (1)$
- in brackets: theoretical value

Longitudinal deuteron
polarization: 80%
current : 1 μA

KVI

sb/NNV_DPG140302/14

Permanent Electric Dipole Moment (e d m)



$\vec{J}$ is the only vector characterizing a non degenerate quantum system: any additional vector would bring in additional quantum numbers, i.e. degeneracy.

- magnetic moment

$$\vec{\mu} = g \cdot \mu_x \cdot \vec{J} \; ; \quad \mu_x = \frac{q\hbar}{2 m_x}$$

- perm. electric dipole moment

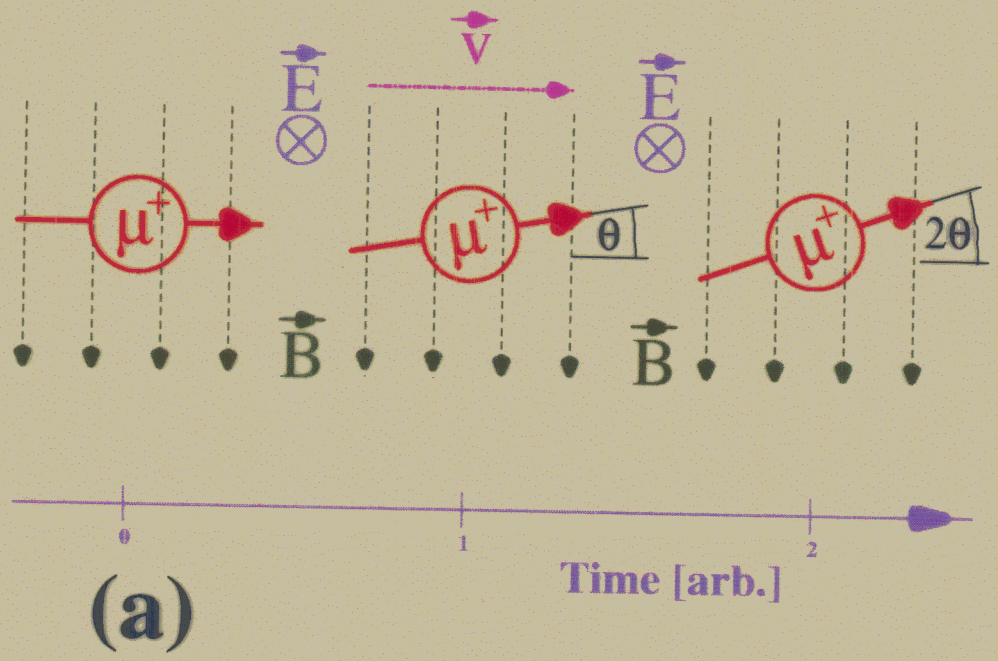
$$\vec{d} = \eta \cdot c^{-1} \mu_x \cdot \vec{J}$$

by definition $\vec{d} = q \vec{r}_0$

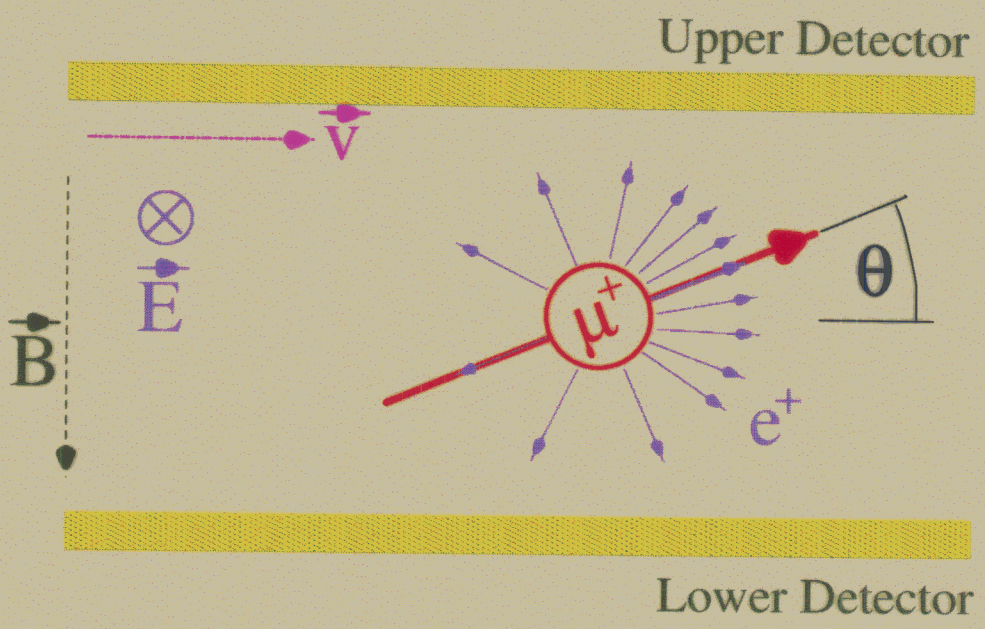
- η contains all physics
- Non Standard Model Theory: $\eta \propto m_x^2, m_1^2, \ldots$

$$c^{-1} \mu_x \cdot J_z = \begin{cases} 9.7 \cdot 10^{-12} \; e \cdot cm & \text{electron} \\ 4.7 \cdot 10^{-14} \; e \cdot cm & \text{muon} \\ 5.3 \cdot 10^{-15} \; e \cdot cm & \text{nucleon} \end{cases}$$

EDM Experiments in Storage Rings



(a)



(b)

- Possible for muons and nuclei
- Sensitivity better 10^{-24} e cm

Nuclear EDM

- Enhancement relative to d_n
  - ⇒ CP-Odd mixing of opposite parity nuclear levels
  - ⇒ Induced T- and P-Odd Potentials

    Enhancement $3\pi\left(m_\pi^2 U_0 r_0^3\right)^{-1} \approx 60$
  - ⇒ T- and P-Odd Nuclear Multipoles

    Enhancement $\sim \frac{Z}{A^3} \frac{U_0 W^2}{\Delta E^3} \approx \ldots 100$

- Could be sensitively measured in a setup similar to d_μ @BNL

Suitable Candidate Nuclei

- basic constraint through

$$E = \frac{a\, v\, B}{1-(1+a)\left(\frac{v}{c}\right)^2}$$

$$a = \frac{g_{eff}-2}{2} = \frac{\frac{\mu}{\mu_K}\cdot\frac{A}{Z}\cdot\frac{1}{J}}{2} - 1$$

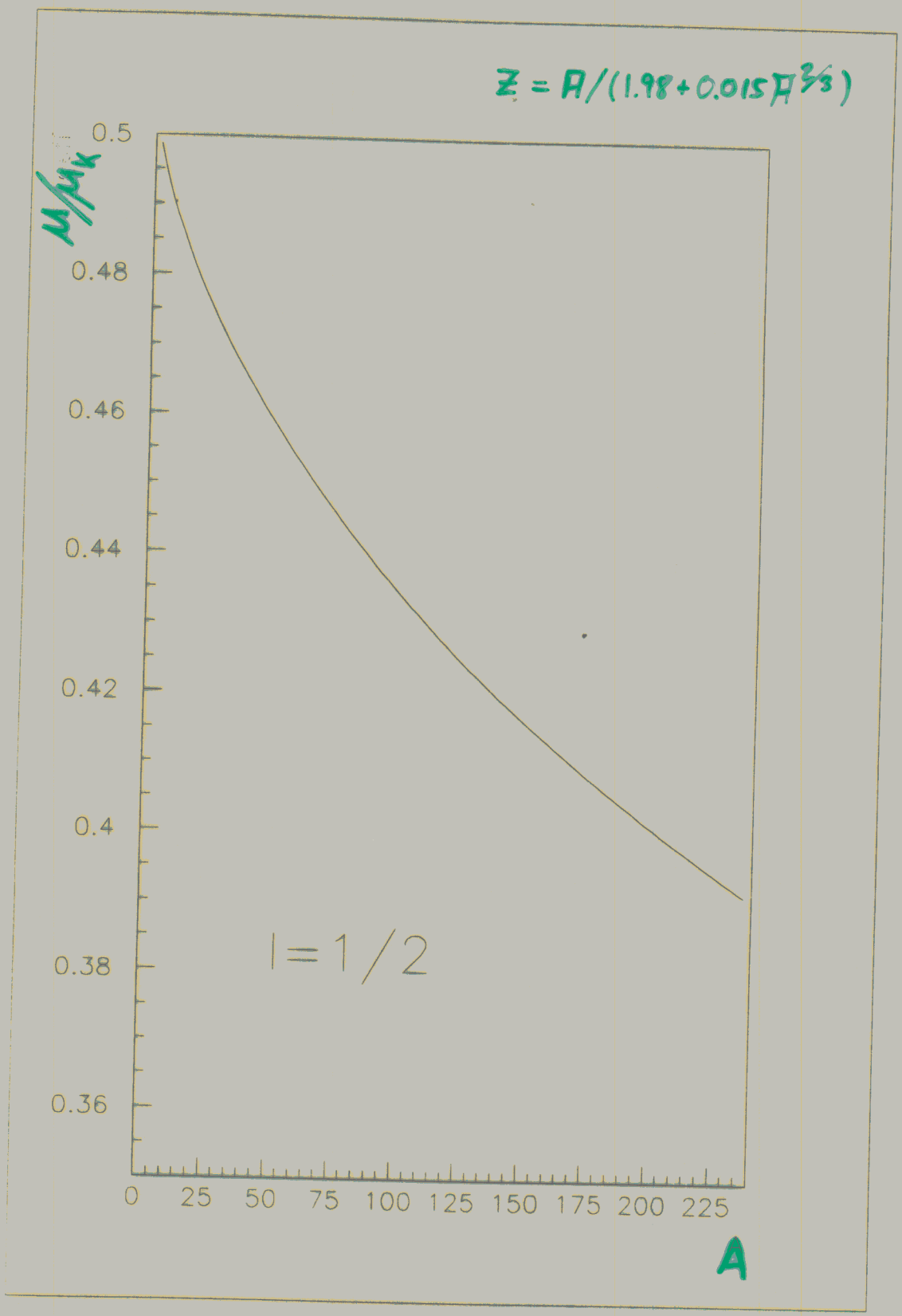
Example: $B = 1\,T$, $\frac{v}{c} = 75\%$, $a = 0{,}1$

$\Rightarrow E = \frac{80\,kV}{cm}$

- $|a| \lesssim 0.1$
- $\mu > 0$

- Preferred Properties
  - $J = 1/2$ (no quadrupole moment)
  - $a \ll 1$

(o maybe β-radioactive)


Z = A/(1.98+0.015A^2/3)
μ/μk
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
I=1/2
0
25
50
75
100
125
150
175
200
225
A

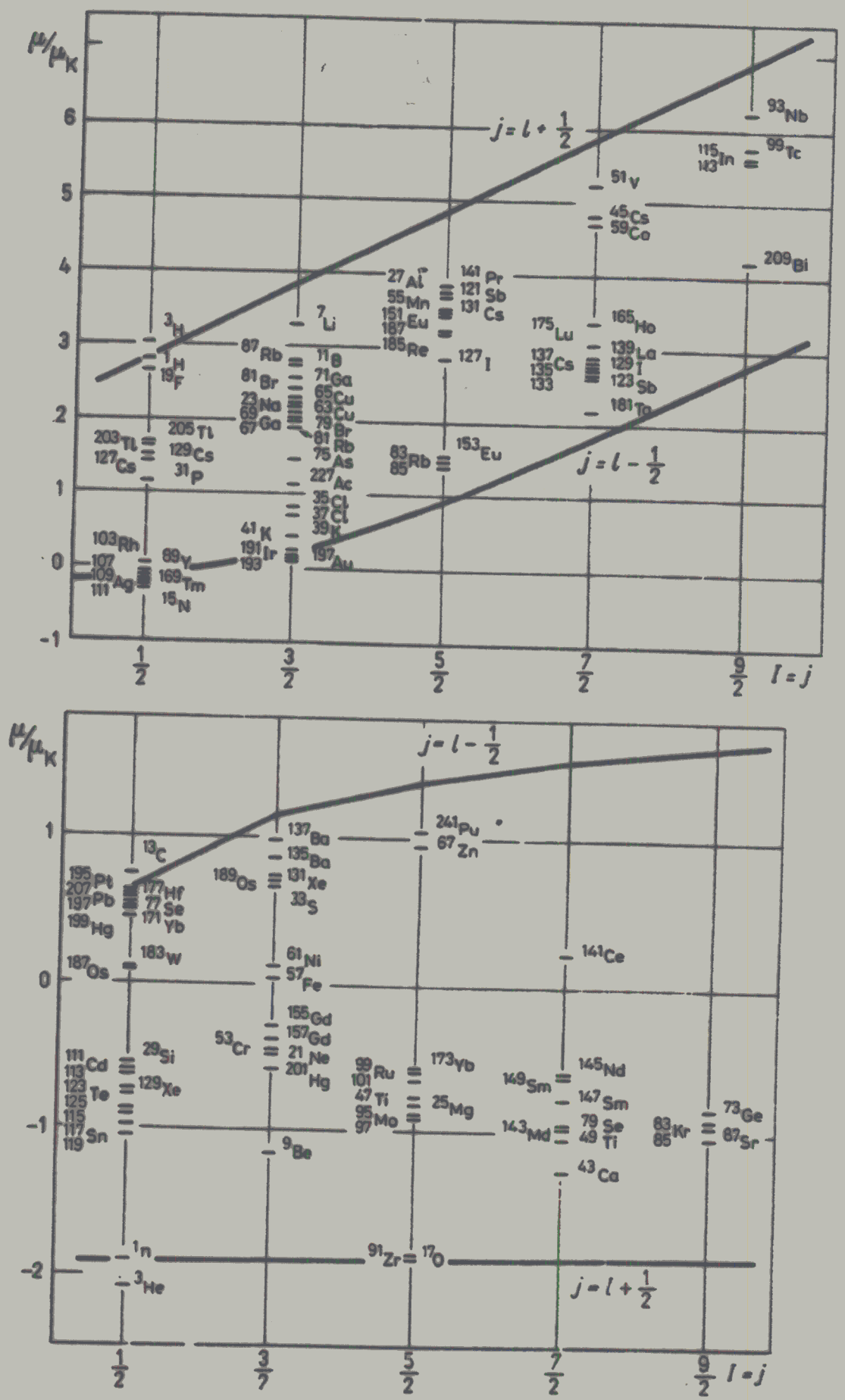


Abb. 8.14
Schmidtsche Linien und magnetische Dipolmomente
a) für uZ-Kerne, b) für uN-Kerne

Candidate Nuclei

	J	μ/μ_K	a	$\tau_{1/2}$
$^{139}_{57}La$	$7/2$	$+2.783$	-0.0305	
$^{123}_{51}Sb$	$7/2$	$+2.550$	-0.1215	
$^{75}_{33}As$	$3/2$	$+1.4395$	0.0905	
$^{6}_{3}Li$	1	$+0.8220$	-0.1779	
$^{171}_{70}Yb$	$1/2$	$+0.49367$	0.2060	
$^{2}_{1}H$	1	$+0.8574$	0.1426	
$^{31}_{16}S$	$1/2$	± 0.4880	0.055	2.6s
$^{75}_{32}Ge$	$1/2$	$+0.510$	0.195	82.8m
$^{157}_{69}Tm$	$1/2$	$+0.476$	0.083	3.6m
$^{137}_{55}Cs$	$7/2$	$+2.8413$	0.0119	30y
$^{223}_{87}Fr$	$3/2$	$+1.17$	<0.02	22 min

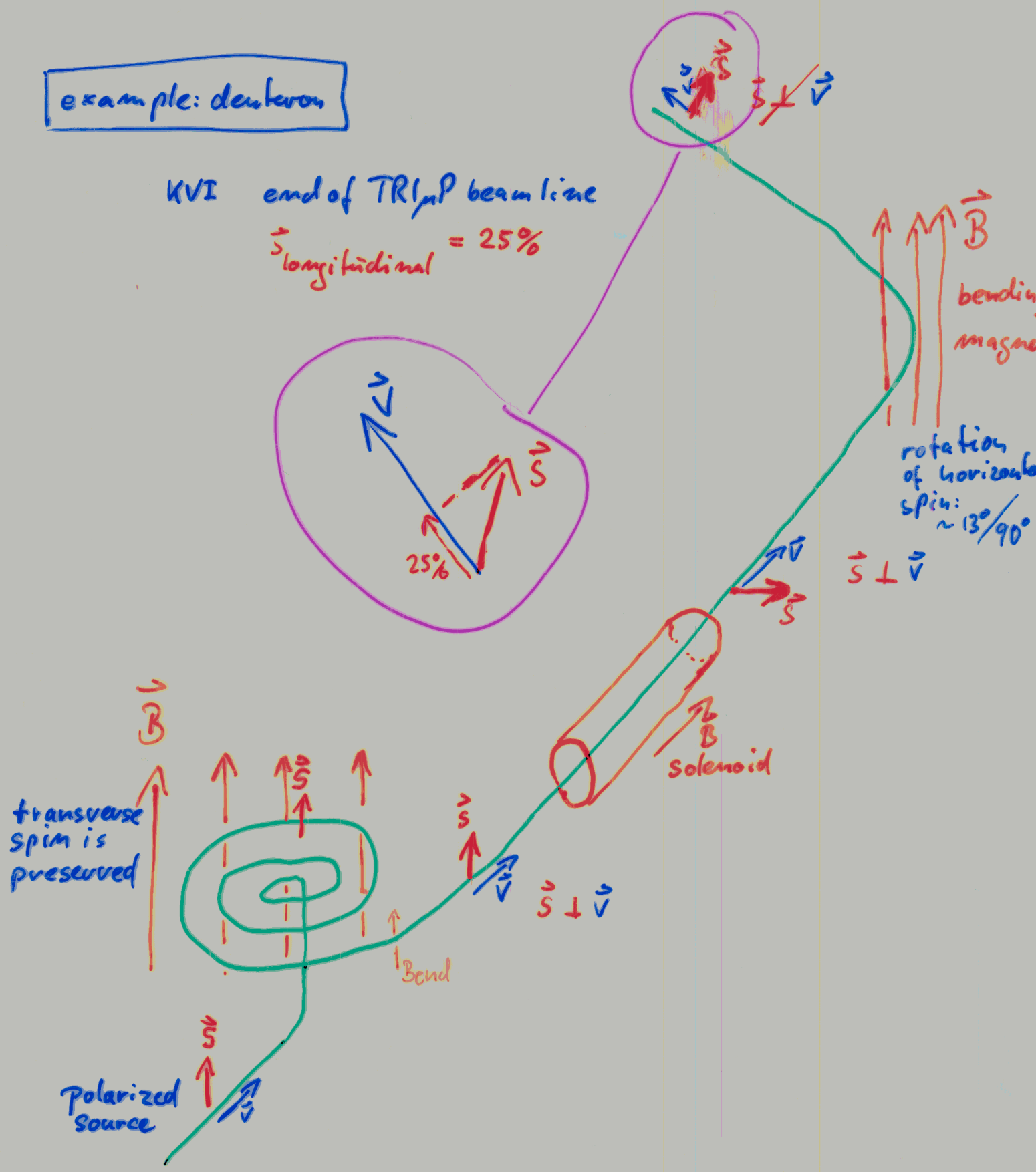
P. Raphavan, At. & Nucl. Data 42, 189 (1989)

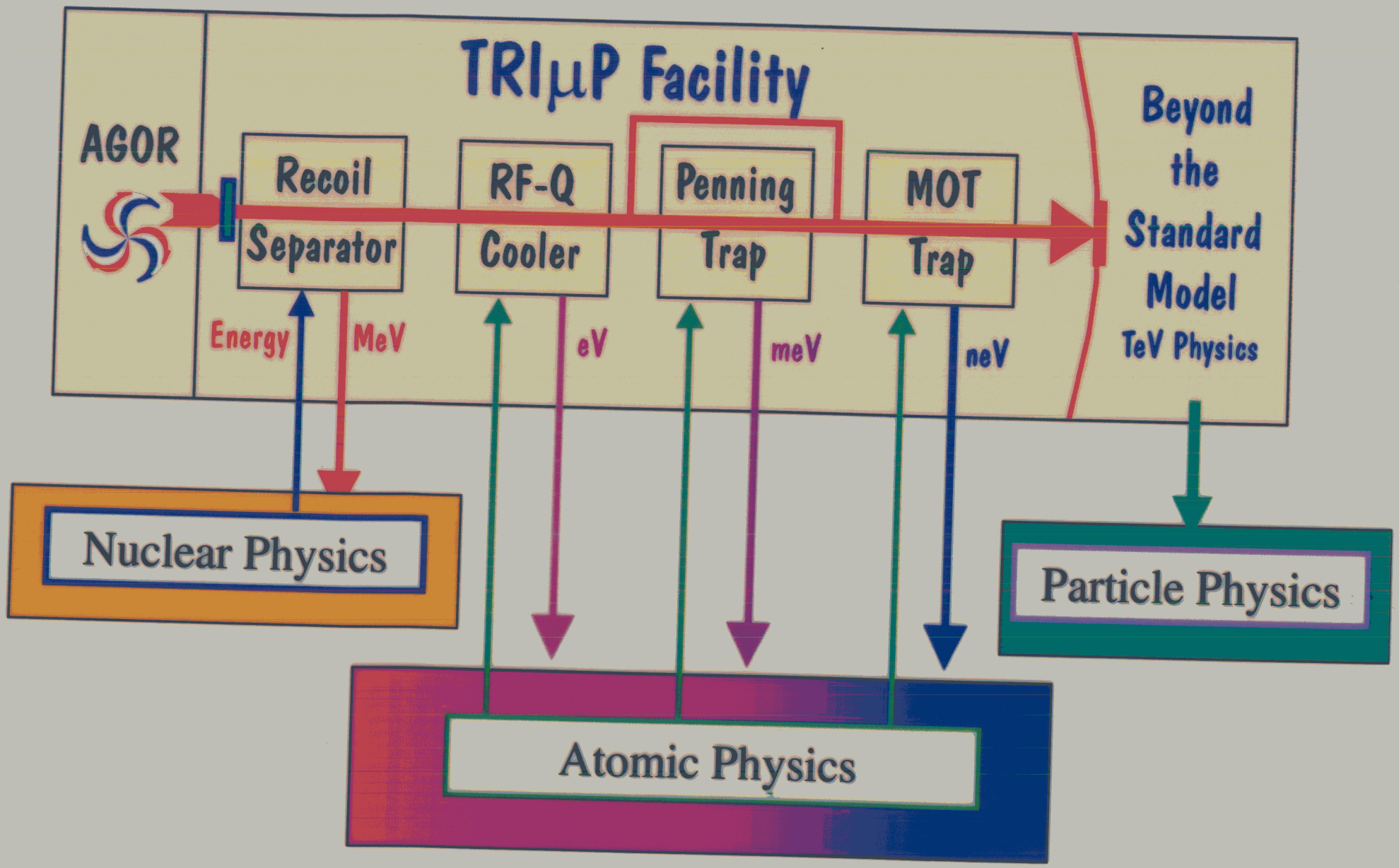
Spin in a circular accelerator

example: deuteron

KVI end of TRIμP beam line

$\vec{s}_{longitudinal} = 25\%$

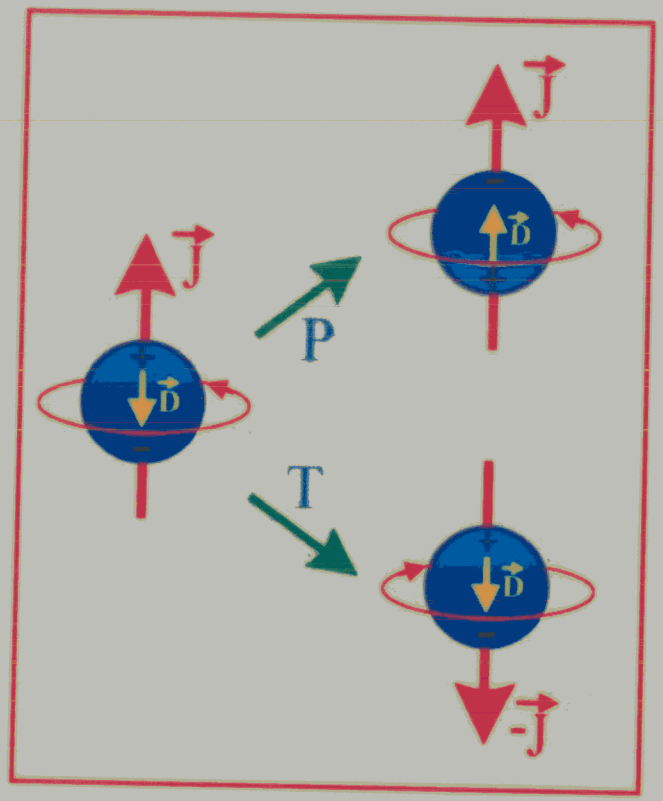



TRIμP Facility
AGOR
Recoil Separator
RF-Q Cooler
Penning Trap
MOT Trap
Beyond the Standard Model
TeV Physics
Energy
MeV
eV
meV
neV
Nuclear Physics
Atomic Physics
Particle Physics

TRIμP

Permanent Electric Dipole Moments

KVI



There can be only one vector in the system

$$\Rightarrow \quad \vec{D} = \eta \bullet \mu_x \bullet c^{-1} \bullet \vec{J}$$

Spin precession in an Electric Field E

$$\Rightarrow \quad \vec{\omega} = \frac{\vec{D} \bullet \vec{E}}{\hbar} \frac{\vec{E} \times \vec{J}}{|\vec{E} \times \vec{J}|}$$

Sensitivity of spin precession experiments proportional to:

$$\frac{1}{\text{Polarization}^2 \bullet \text{efficiency} \bullet \sqrt{\text{number}} \bullet \text{time}}$$

EDMs violate
- Parity
- Time Reversal
- CP Symmetry

① Different Systems give different answers

EDM searches

leptons	electrons, muons, Taus	intrinsic edm, comes CP-violation with 2nd ge
nucleons	proton, neutron	intrinsic quark edm, CP violating gluon interac
light nuclei	^3H, ^6Li	edm through electroweak nuclear forces edm through nuclear loop effects
heavy nuclei	^{199}Hg, ^{225}Ra	enhancement by CP violating nuclear forces
atoms		induced edm of constituents, enhance
molecules		induced edm of constituents, enhan

Generic edm Experiment

Preparation of "pure" $\vec{J}$ state	→	Interaction with $\vec{E}$-field	→	Analysis of state
Polarization		Spin Rotation		Determination of Ensemble Spin Average

Interaction with $\vec{E}$-field

$$\vec{d} = \eta \cdot c^{-1} \cdot \mu_x \cdot \vec{J}$$

Precession frequency:

$$\vec{\omega}_e = \frac{\vec{d} \cdot \vec{E}}{\hbar} \cdot \frac{\vec{E} \times \vec{J}}{|\vec{E} \times \vec{J}|}$$

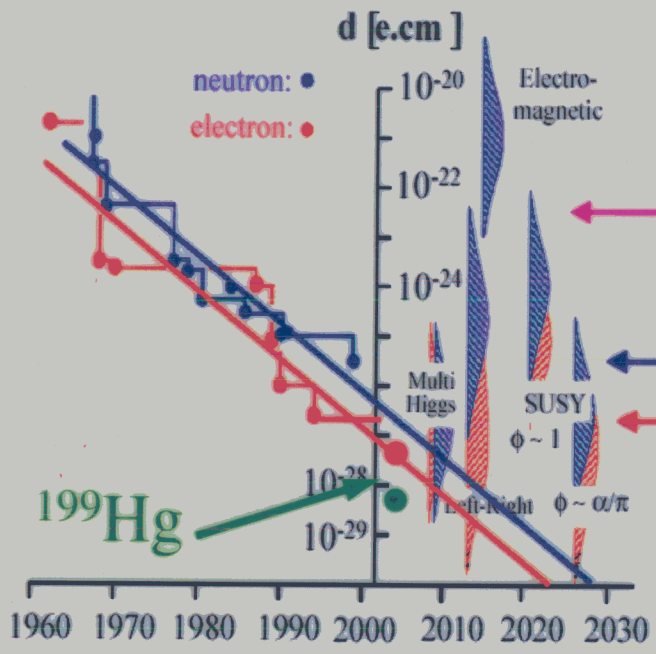
$\vec{E} \perp \vec{J}$; i.e. $\vec{E} \parallel J_z$

$$\boxed{\omega_e = \eta \cdot c^{-1} \cdot \mu_x \cdot E \cdot \frac{J_z}{\hbar}}$$

Example: $d = 10^{-24}$ ecm ; $E = 100 \frac{kV}{cm}$; $J = \frac{1}{2}$

$$\omega_e = 15{,}2 \text{ mHz}$$

Some EDM Experiments compared



d(muon) < 7×10^{-19}

d(proton) < 6×10^{-23}

d(neutron) < 6×10^{-26}

d(electron) < 1.6×10^{-27}

Many Systems with unique Physics Potential

- leptons
- nucleons
  - neutrons
  - protons
- nuclei
  - light
  - heavy
- atoms
- molecules

Possible Experiment @ GSI

$\boxed{\text{J state preparation}} \rightarrow \boxed{\text{Interaction with } \vec{E} \text{ field}} \rightarrow \boxed{\text{Analysis of state}}$

- polarized nuclei source
- optical pumping?
- cooling in ESR
- $\frac{v}{c} \approx 75\%$ ($> 10\%$)
- $N_N \approx 10^5 \ldots 10^6$/sec
- $\frac{\Delta p}{p} \leq 10^{-4}$

  $\frac{\Delta p}{p} \sim 10^{-6}$ possible!

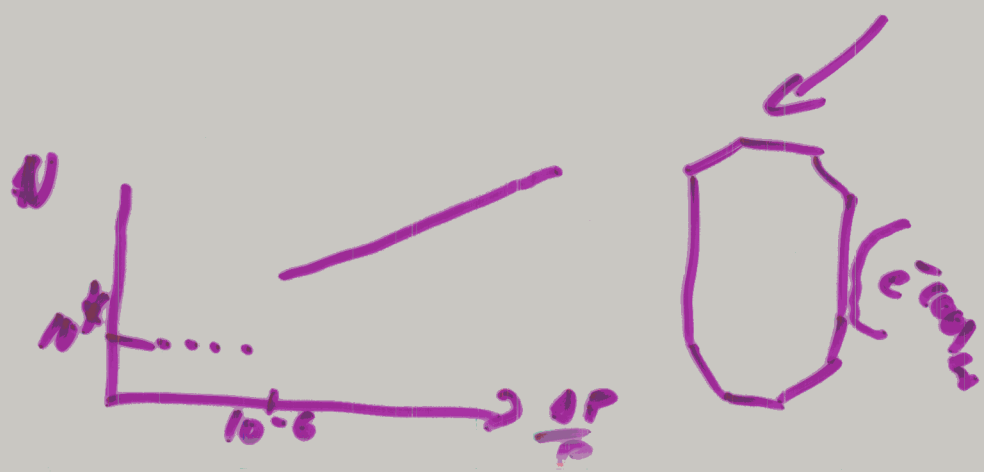
- special storage ring
- $r \approx 2$ m
- $B \approx 1 \ldots 1.5$ T
- Interaction time $\tau_i \lesssim 1$ sec
- Spin rotation angle @ $d_N \approx 10^{-24}$ ecm

  $\vartheta_e \approx 2$ mrad

- scattering analyzing power 0.1

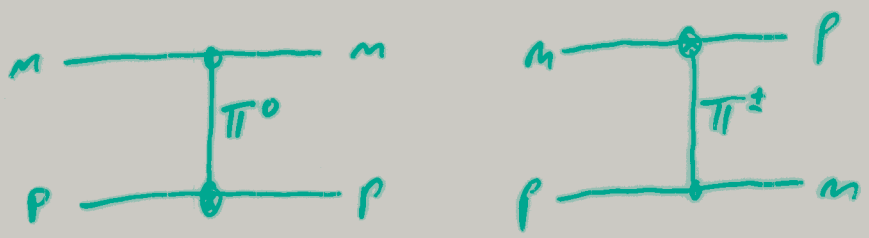
  or

- β-asymmetry
  - counters in ring
  - counters after extraction



Deuteron edm

- proton + neutron edm
- nuclear part



$\Rightarrow$ ~ 1. o.m. enhancement over nucleon

10^{-24} e cm in ^2H are equivalent to

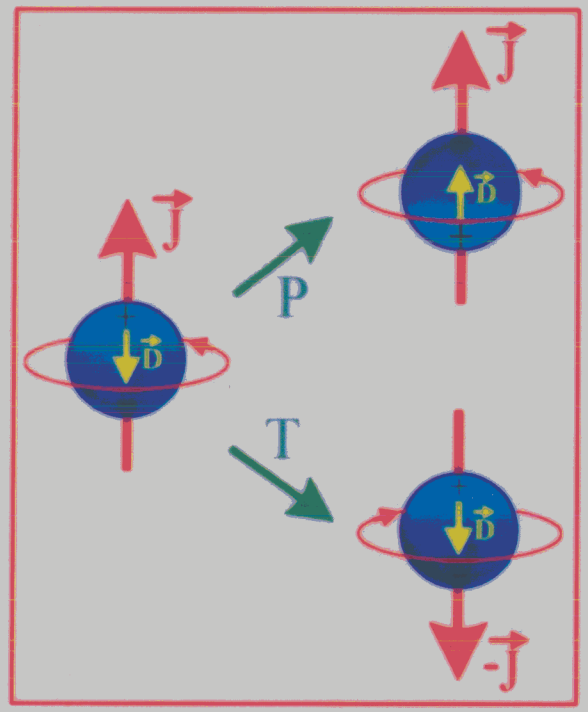
10^{-25} e cm in neutron

10^{-28} e cm in Hg atom

$\Rightarrow$ Khriplovich & Korkin, nucl-th/9904081:

$$\vec{d}_d = \frac{e g g_1}{12\pi m_\pi} \frac{1+\xi}{(1+2\xi)^2} \vec{\eta} \qquad \begin{array}{l} \xi \approx 0.32 \\ g \approx 13 \end{array}$$

Permanent Electric Dipole Moments



S. Weinberg (1993):

" may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments ... seem to me to offer one of the most exciting possibilities for progress in particle physics."

R.L. Jaffe (2001)

"Electric dipole moments (EDM's) fascinate both theorists and experimenters. They probe CP violation, one of the most poorly understood aspects of the Standard Model. If all CP-violation is encoded in the CKM matrix, EDM's are too small to measure. For this reason EDM's are an excellent place to look for CP-violation beyond the Standard Model. The problem of baryogenesis in the early Universe continues to suggest that other sources of CP-violation are waiting to be discovered."

EDMs violate
- Parity
- Time Reversal
- CP Symmetry

$\Rightarrow$ **Just do it**