Spectral functions in exotic nuclei – prospects at next-generation RIB facilities

I. Present-days experimental methods

II. Opportunities at next-generation RIB facilities

Spectroscopic factors / Momentum distributions
- unstable nuclei -

Experimental methods as presently applied:

(see this ECT Workshop)*

Transfer reactions (p,d) .... (Orsay, GANIL)

(Q,L matching → 10 – 30 MeV/u)

H.I. induced single (few) nucleon knockout (MSU)

Coulomb (and diffractive) dissociation (RIKEN, GSI)

large cross sections (10mb – 1b)

high energy, 50 -500 MeV/u

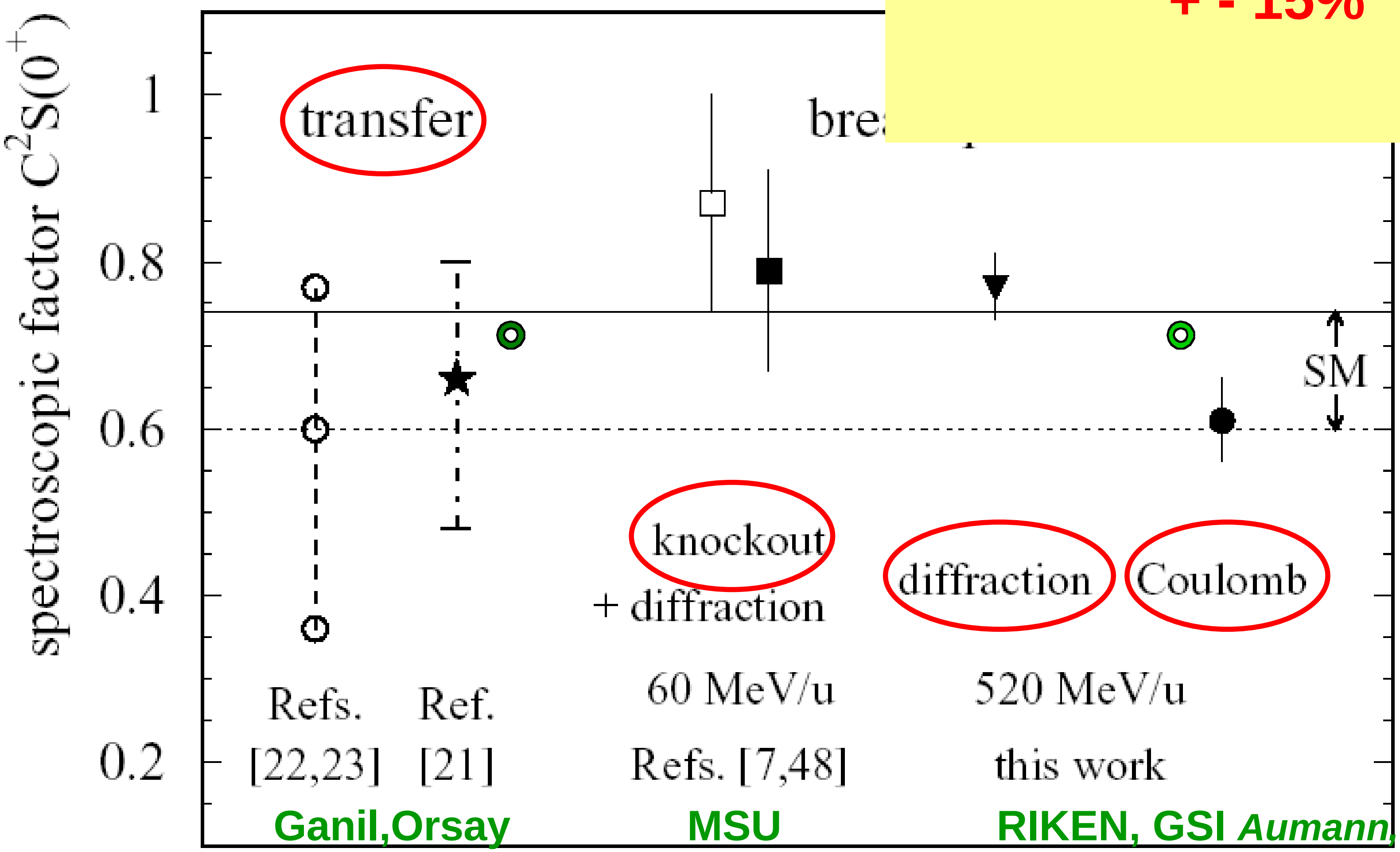
→ *luminosity*

→ *solid angle coverage*

→ *theoretical description*

^{11}Be

Results consistent within + - 15%



Otsuka et al.

A. Brown

Ganil,Orsay *(d,p) Delaunay*

MSU *Hansen*

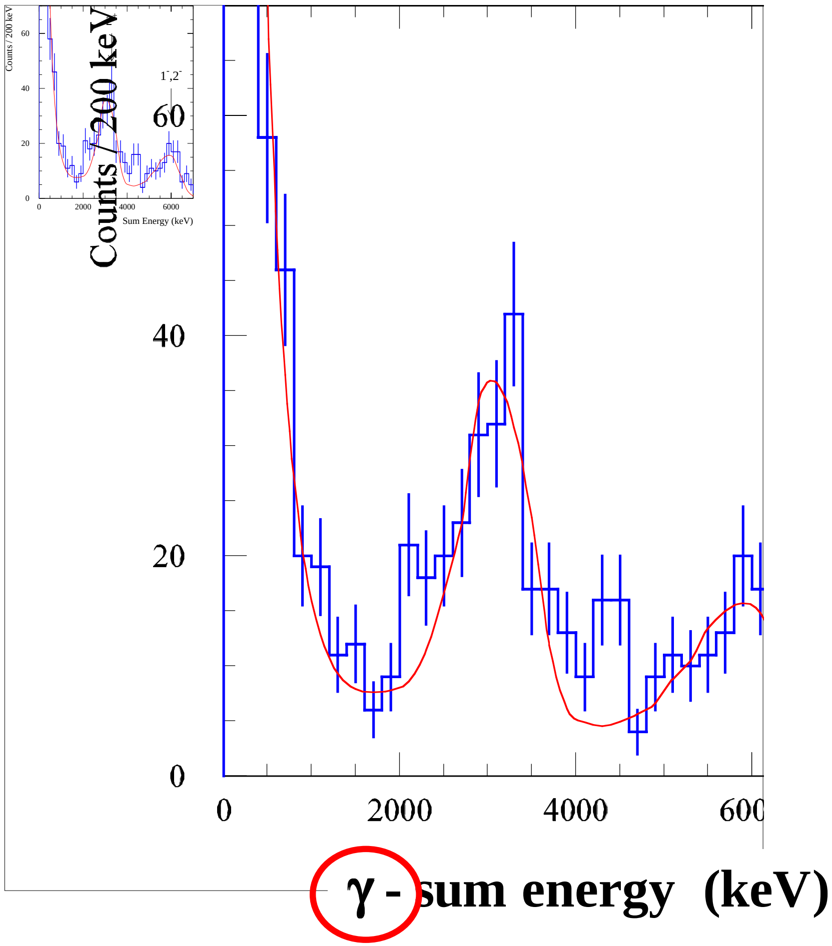
RIKEN, GSI *Aumann, Nakamura*

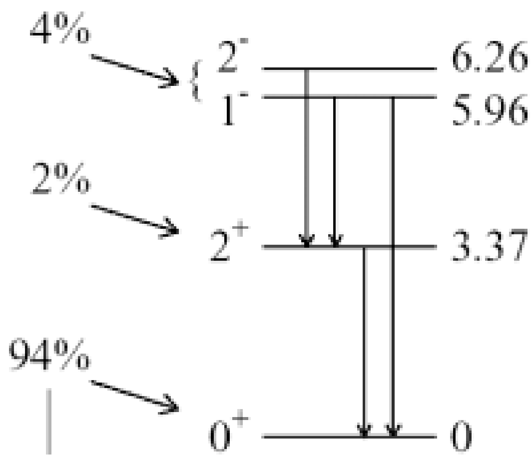
GSI

Coulomb breakup of ^{11}Be

$|^{11}Be\rangle = \sqrt{S(2^+)}\,|^{10}Be(2^+) \otimes 1d_{5/2}\rangle + \sqrt{S(0+)}\,|^{10}Be(0^+) \otimes 2s_{1/2}\rangle + \ldots$

$^{11}Be + Pb \rightarrow {}^{10}Be + \gamma + n$





Final state from γ-ray spectroscopy !!

R. Palit et al., Phys. Rev. C 68 (2003)

Knockout from Two-Neutron Halo Nuclei

Aim: single-particle structure and (pairing) correlations

In sudden approximation:

momentum distribution:

$w(p_1) = w(p_{4He} + p_2)$

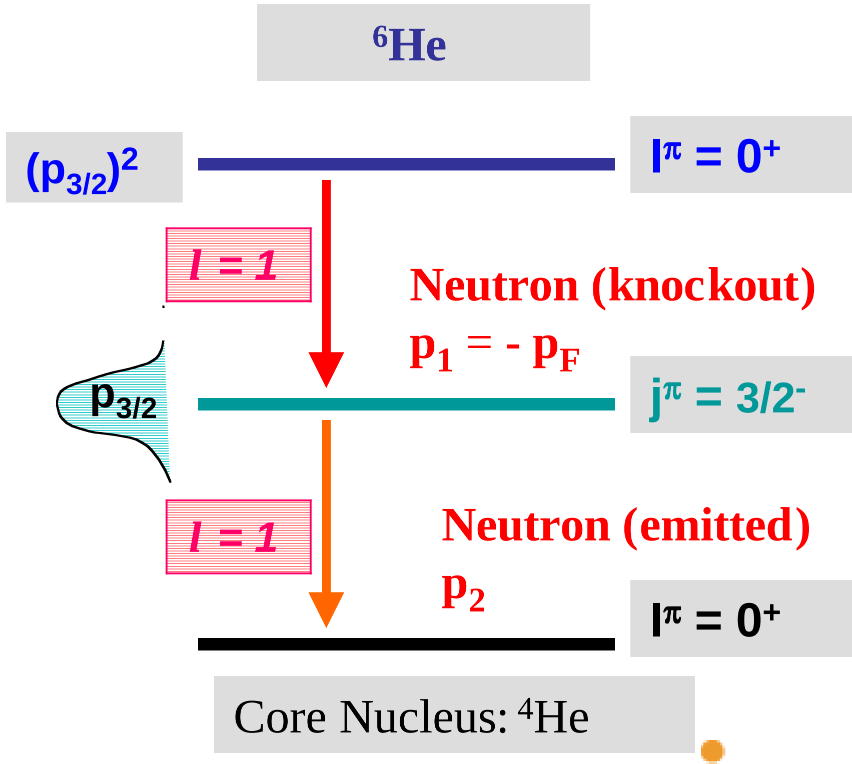
intermed. state energy E_{rel}:

^{5}He ground state resonance ($j^\pi = 3/2^-$)

angular correlation (p_1,p_2):

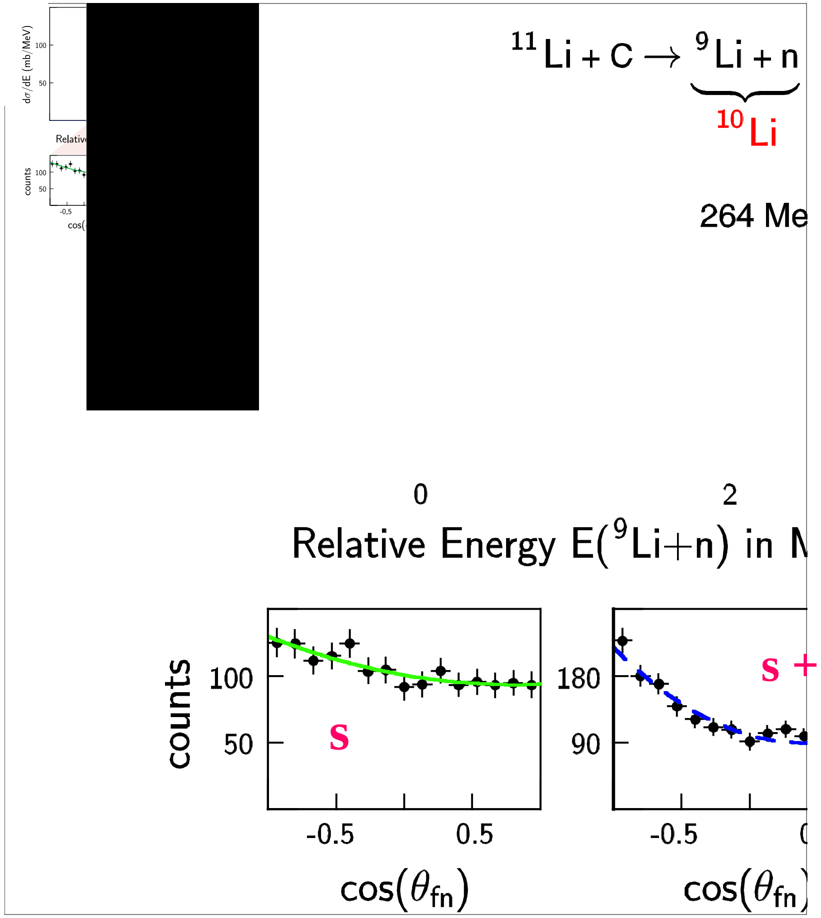
order of Legendre polynomil: min($2l$, 2j)

even terms only (good parity)

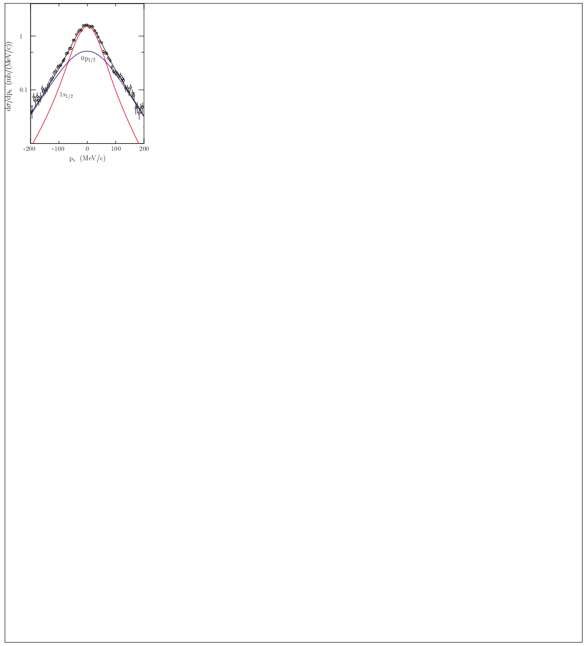


The halo of ^{11}Li: *s* and *p* waves

Angular correlations



Momentum distribution



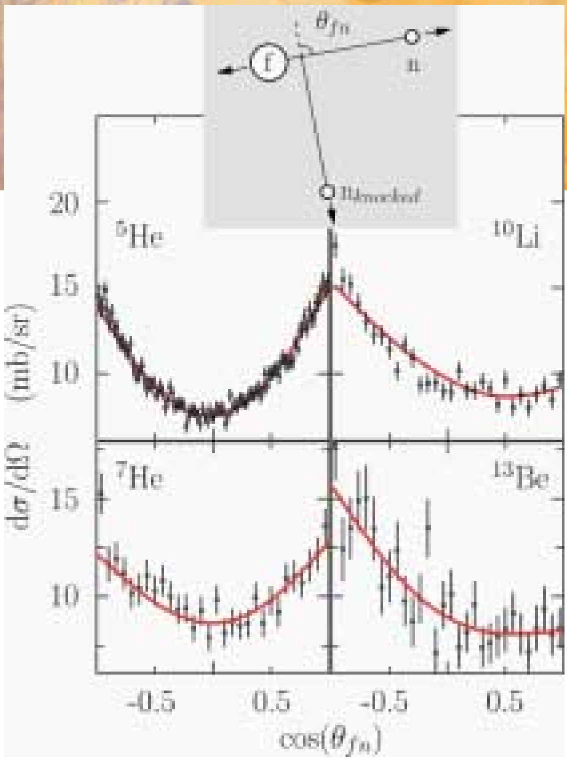
Asymmetric angular distribution

⇒ Direct evidence for the mixture of

***s* and *p* waves (~1:1) in ^{11}Li ground state**

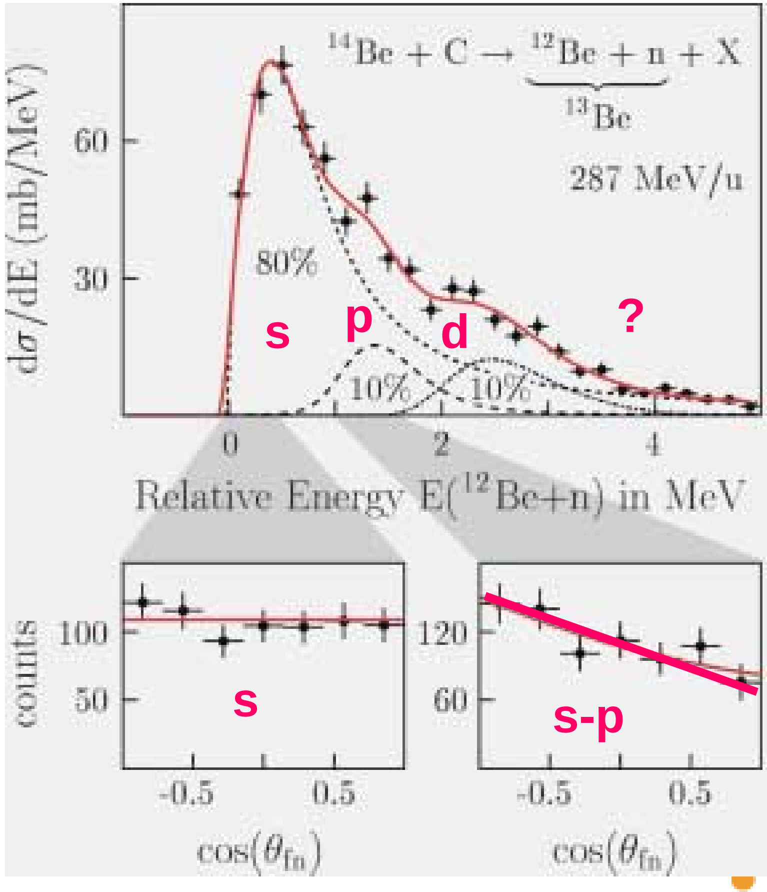
→ STRONG PAIRING

H. Simon et al., Phys. Rev. Lett. 83 (99) 496



^{14}Be:

s – p – d waves



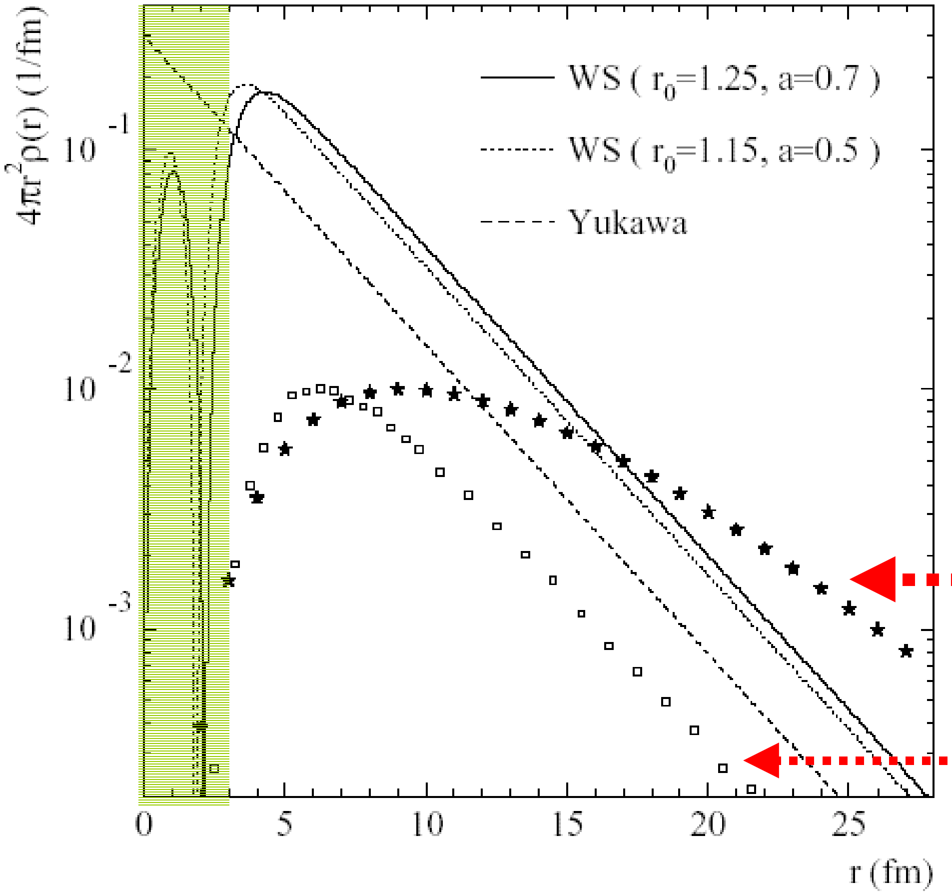
^{6}He: $(p_{3/2})^2$

^{8}He: $(p_{3/2})^2 + (p_{1/2})^2$

^{11}Li: $(p_{1/2})^2 + (s_{1/2})^2 +$

^{14}Be: $(p_{1/2})^2 + (s_{1/2})^2 + (d_{5/2})^2$

2s neutron bound state (^{11}Be)



Sensitivity:

Coulomb

diffraction (knockout)

Limitations:

light nuclei   A < 50   (luminosity)

applicable to loosely bound valence nucleons

➔ halo, skin structure

of interest (not only valence sector):

shell structure

spin-orbit splitting

short - / long-range correlations

(pairing, cluster....)

we may need to return to quasifree scattering !

(i.e., elastic scattering off the constituents of a composite system
..... *electrons in atoms... nucleons in nuclei .... quarks in nucleons* ..)

electromagnetic probes :

electrons

γ – rays

hadronic probes :

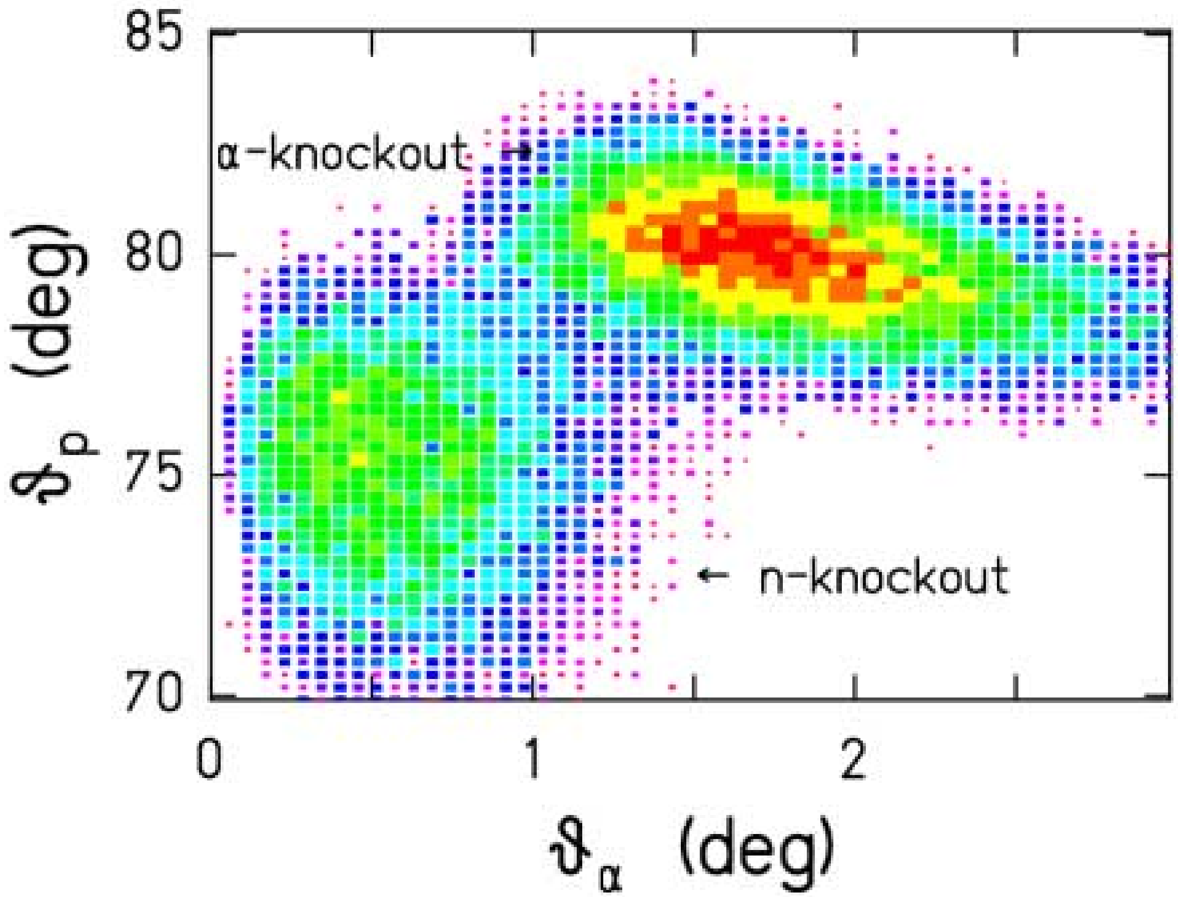
protons, neutrons

pions

antiprotons ....

- single-particle spectral functions S(**k**,_)
- cluster structures
- in-medium interactions (here: isospin part)

Cluster knockout



$^6He \rightarrow LH_2$

L. Chulkov et al.
Petersburg-Kurchatov-TU Darmstadt-GSI

Call for Letters of Intent (April 15, 2004)

STORIB (STOred Rare-Isotope Beams) Collaboration

- **Light-ion induced scattering experiments in storage rings**
- **Electron – Heavy Ion Collider**
- **Antiproton – Heavy Ion Collider**
- **Backscattered Photon facility**

*** Approved by German government as an International Facility in Europe (Feb.2003)**
~ 25 % external contribution expected

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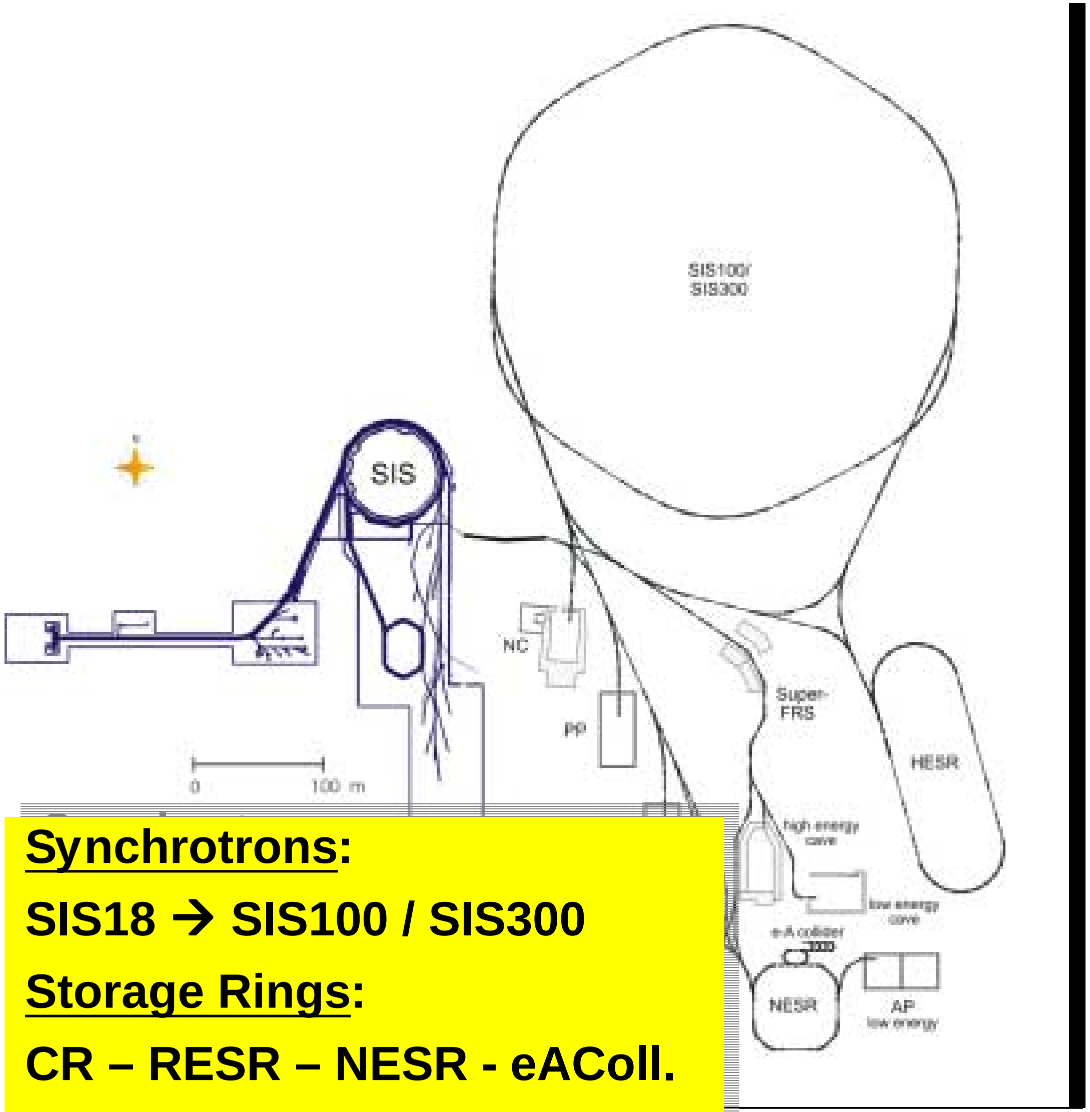
Accelerators and Storage Rings



Synchrotrons:

SIS18 → SIS100 / SIS300

Storage Rings:

CR – RESR – NESR - eAColl.

and HESR (pbar)

Primary Beams

- High primary beam intensity e.g. **10^{12}** s^{-1} ^{238}U **at 1.5 GeV/u**
- Proton beam energy ~ 90 GeV
- Ion-beam energy: ~ 30 GeV/u

Secondary Beams

- **Intense RIB** beams , ~ 2 GeV/u
- **Stored and cooled RIB** beams
- **Stored and cooled antiprotons**, 15 GeV

- Internal targets for high-luminosity in-ring experiments
- Electron-RIB collider

R & D

- Fast cycling superconducting magnets
- Electron cooling
- Fast stochastic cooling .....

- → **new experimental concepts !**

The Rare-Isotope Beam Facility

SIS 100/300 in **High-Intensity Mode**, driving

an **IN-Flight Rare-Isotope Beam facility**, comprising the:

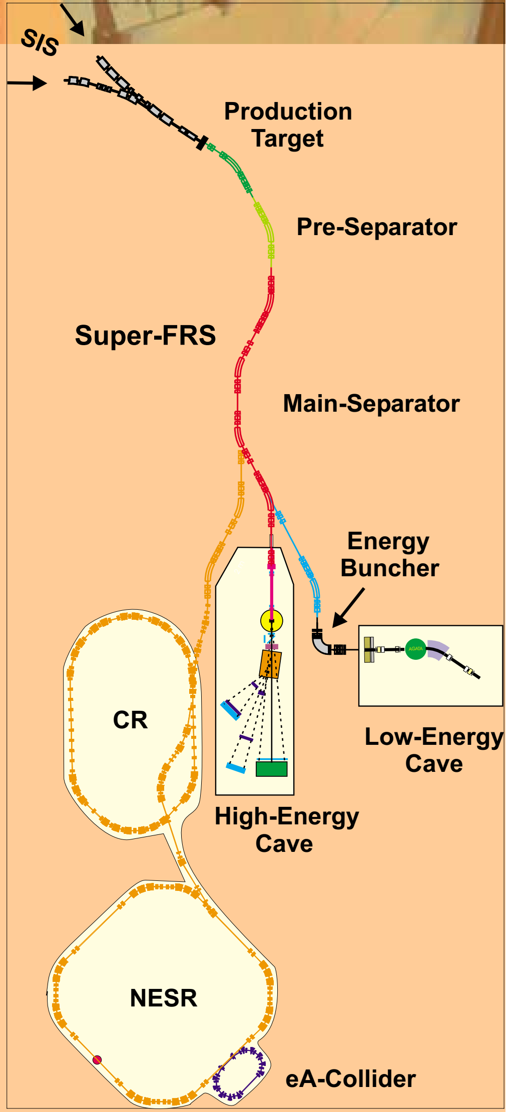
Key characteristics :
- *all elements, H to U*
- *intensity > 10^{12} ions/sec.*
- *high energy, 1.5 GeV/u*
- *pulsed and CW beams*

Superconducting FRagment Separator

High-Energy Reaction Setup

Multi-Storage Rings (CR, RESR, NESR, eA)

Energy-Bunched Stopped Beams

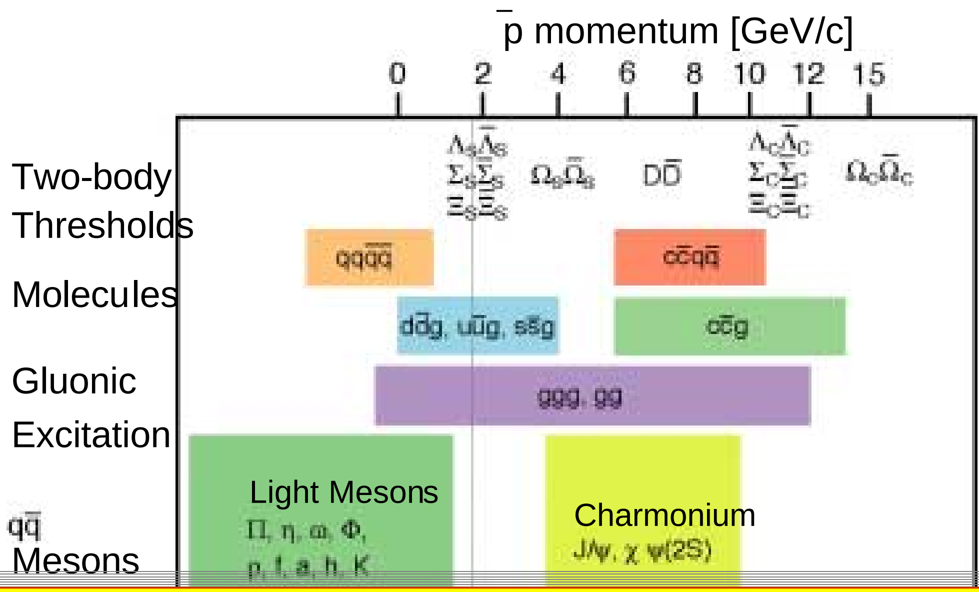


Antiproton Facility

<u>Hadron Physics with Antiproton Beams</u>

Quark gluon structure and dynamics of “strong” interacting particles;

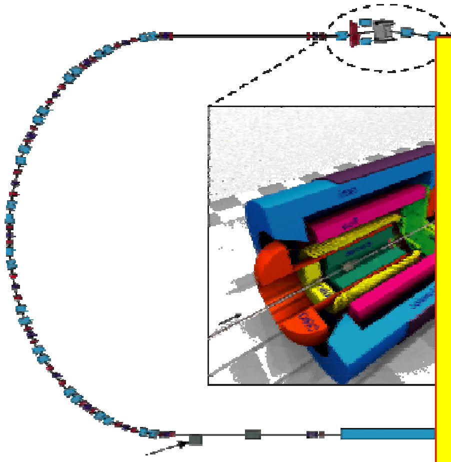
Origin of the confinement and mass of hadrons



HESR: 3 – 15 GeV antiprotons

L = 2 x 10^{32} / cm^2 s

cooling: Δp = 2 x 10^{-5} / 2 x 10^{-4}



Nuclear Structure Aspects:

Neutron skin from

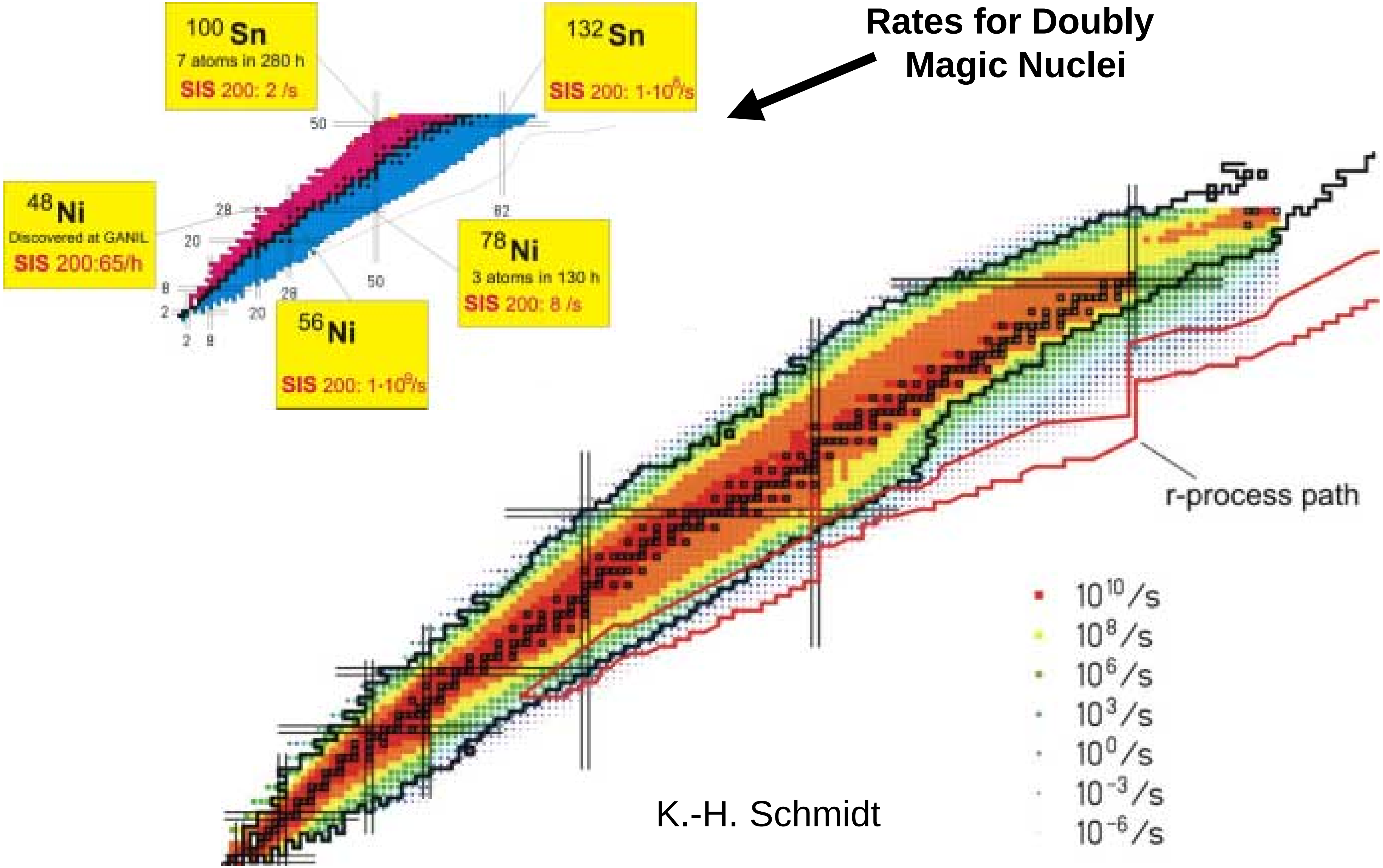
→Antiproton annihilation at rest (CERN)

→Antiproton annihilation in flight – COLLIDER mode

(P.Kienle)

Expected secondary beam intensities

Rates for Doubly Magic Nuclei



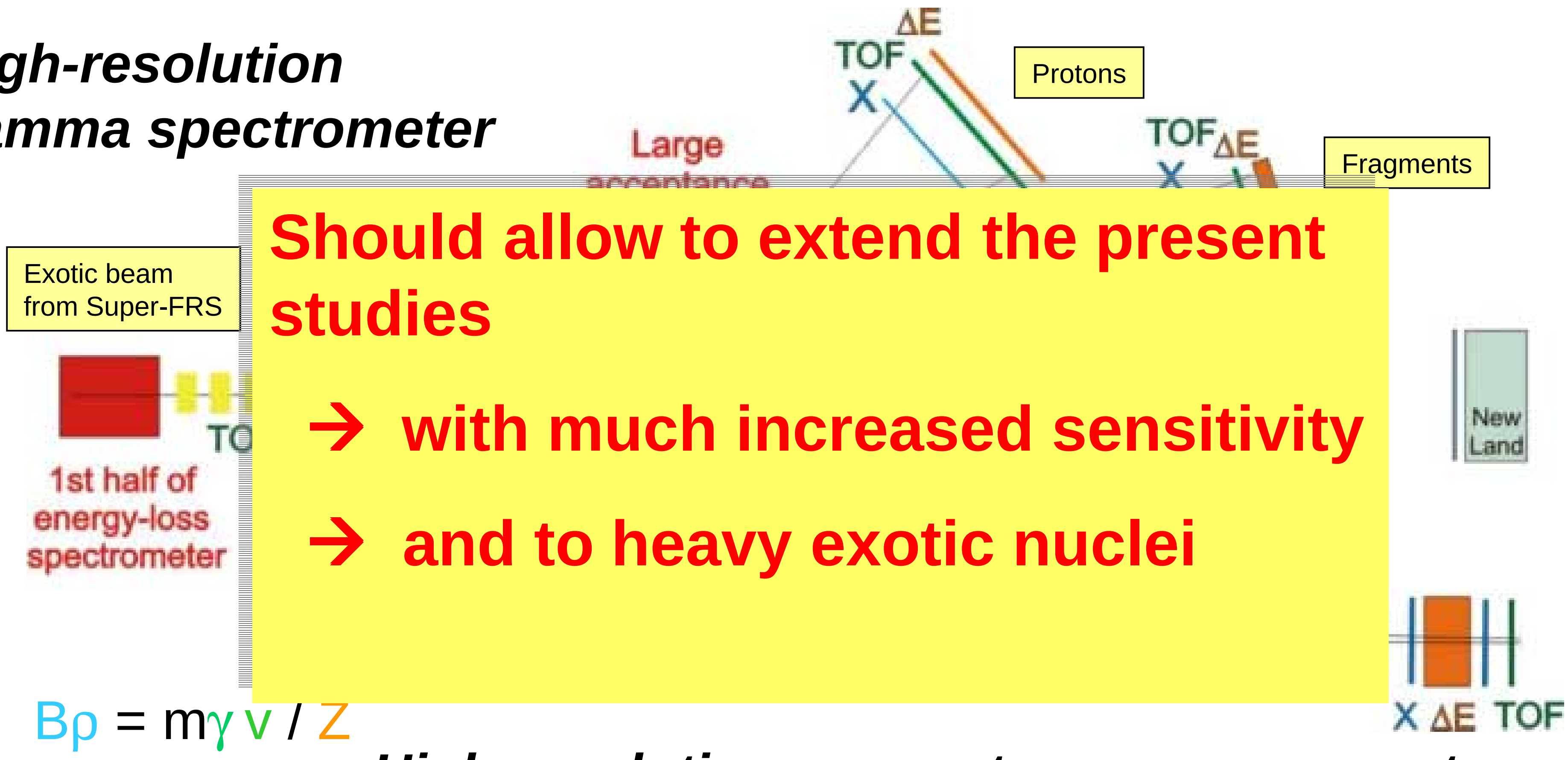
K.-H. Schmidt

HEAVY-ION Scattering

The High Energy Experimental Setup

Large-acceptance measurements

High-resolution gamma spectrometer



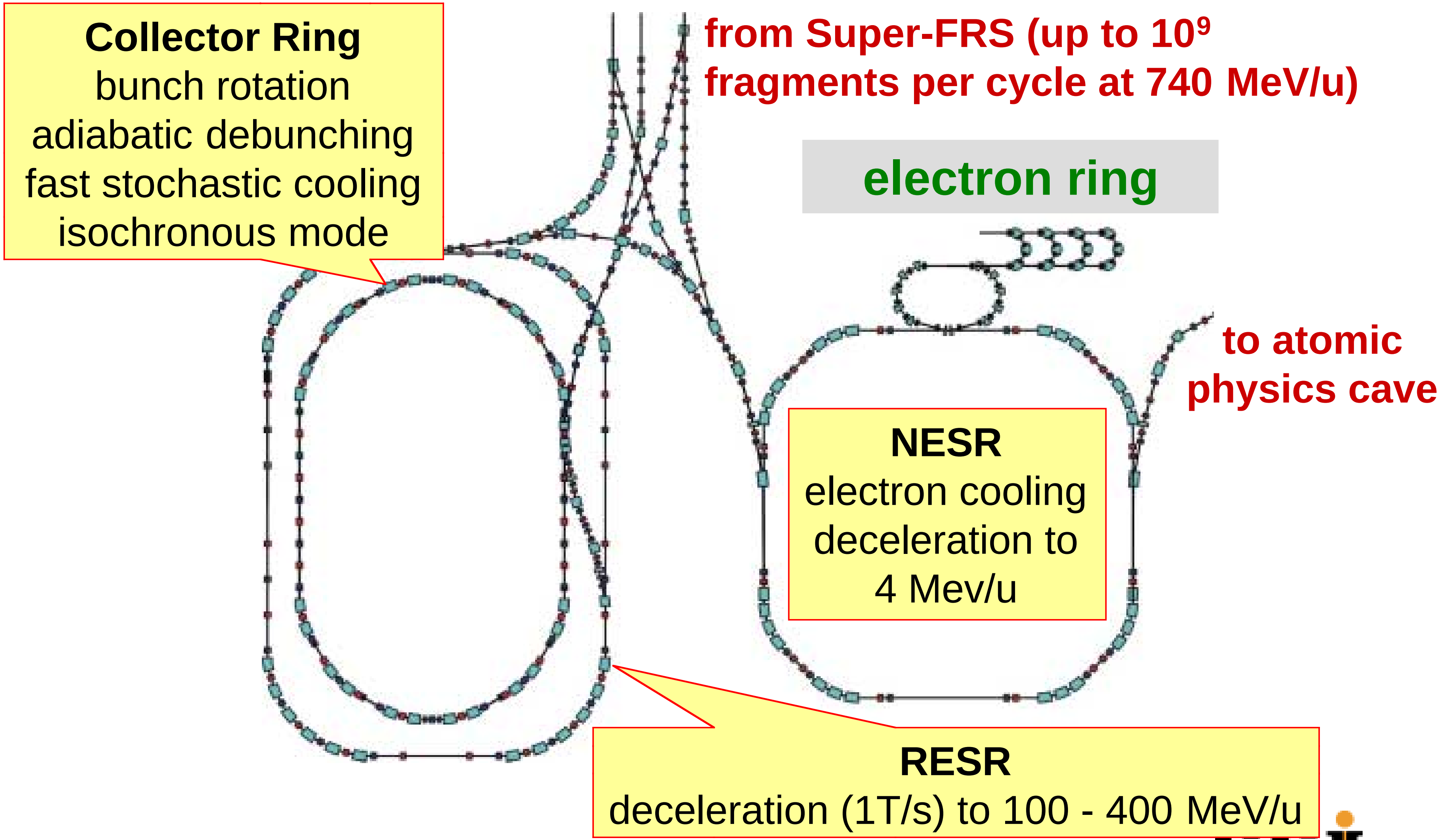
Should allow to extend the present studies

- → **with much increased sensitivity**
- → **and to heavy exotic nuclei**

$B\rho = m\gamma v / Z$

High-resolution momentum measurement

The Storage Rings



Quasifree scattering (p,2p), (p,pn), (p,pα) ... in a storage ring ?

Why ?

$\mathbf{q = p_1 + p_2 - p_o}$

$E_s = T_0 - T_1 - T_2 - q^2/2M_{A-1}$

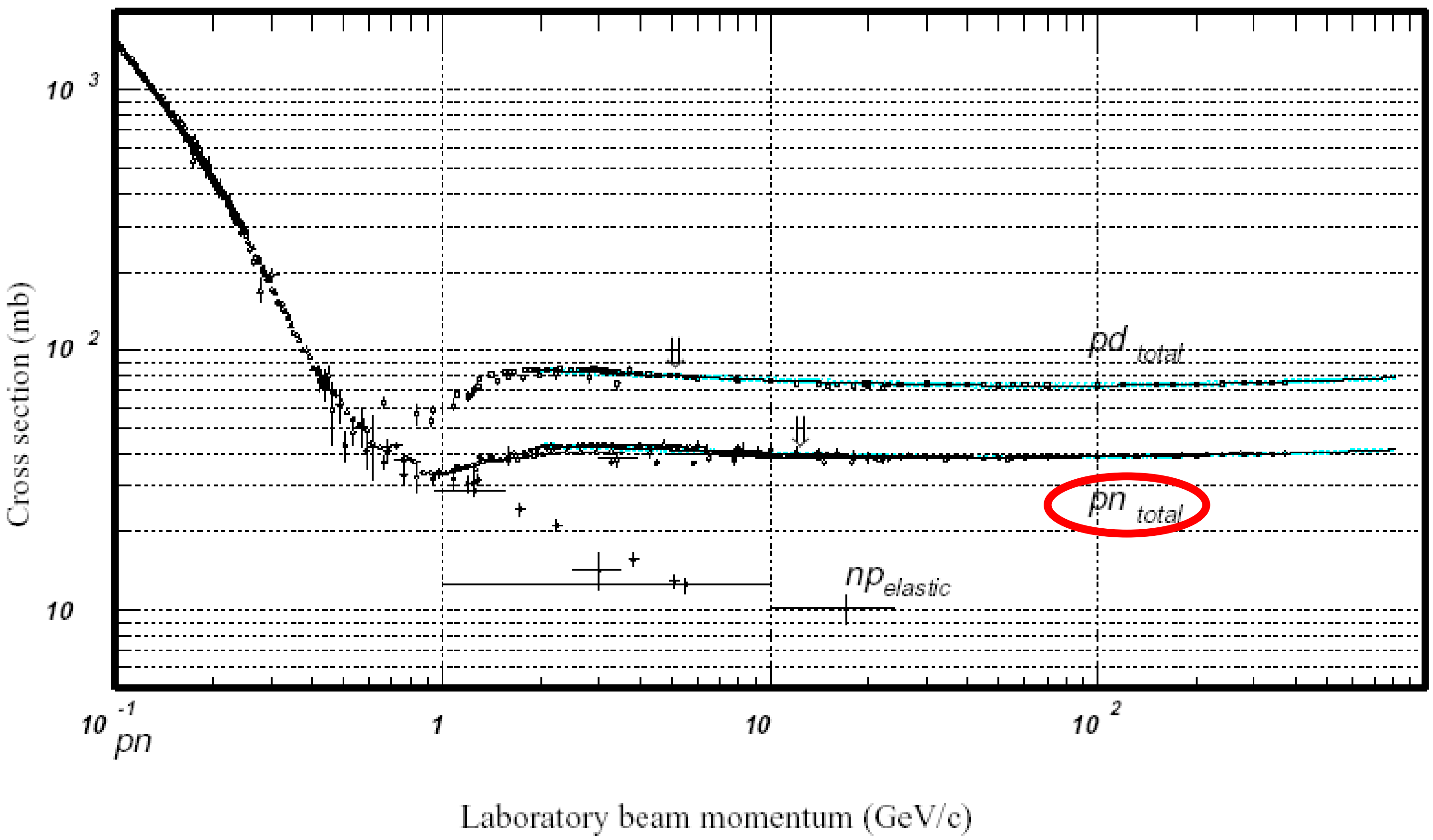
$\delta p \sim 10$ MeV/c

$\delta E_s \sim 1$ MeV

fixed (thick) target: energy degradation of ion beam
energy / angular straggling

NESR

Energy range (A/Z=2.7) (Ramp Rate 1 T/s)	4 - 740 MeV/u
Cooling time constant (for 10^7 U^{92+}-ions)	0.3 - 0.5 s
Transverse emittance after cooling	0.1 (h) / 0.1 (v) mm mrad
Momentum spread after cooling	$\pm 1 \times 10^{-4}$
Luminosity at internal gas target for ^{132}Sn	6×10^{28} cm^{-2} s^{-1}



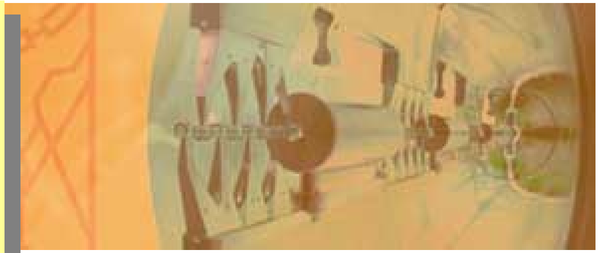
Cross section (mb)
10 3
10 2
10
10 -1
1
10
10 2
pd total
pn total
np elastic
pn
Laboratory beam momentum (GeV/c)

Light Ion Scattering

Experimental method (typical reactions)	Physical observables	Related specific effects †in EXOTIC Nuclei
elastic scattering (p,p); (^{4}He,^{4}He);	nuclear matter radii and their higher moments	halo; neutron skin; central density; optical-potential parameters
inelastic scattering (p,pÅ); (p,pÅ); (^{4}He,^{4}HeÅ)	surface collective states; electric giant resonances; isovector magnetic excitation for (p,pÅ); analyzing powers	bulk properties in N-Z asymmetric matter;isoscalar vs. isovector excitations; spin-orbit; proton/neutron deformation; nuclear compressibility; threshold multipole strength; soft modes
charge exchange (d,^{2}He); (^{3}He,t)	spin-isospin excitations; Gamow-Teller; spin-dipole resonance	(stellar) weak interaction rates; spin excitations; neutron skin
transfer reaction (p,d); (d,^{3}He); (p,t)	spectroscopic factors; stretched high-spin states;	single-particle structure; spin-orbit; shell effects; pairing interaction
quasi-free scattering (p,2p); (p,np); (p, p ^{4}He)	single-particle spectral function; cluster knockout	(inner-shell) single-particle structure; momentum-energy distribution; nucleon-

Hadron scattering:

Elastic (p,p) …
Inelastic (p,p'), (α,α') ...
Charge exchange: (p,n), (^{3}He,t), (d,^{2}He) …
Quasifree (p,pn), (p,2p), (p, pα) …



Reversed kinematics:

Excitation energy and

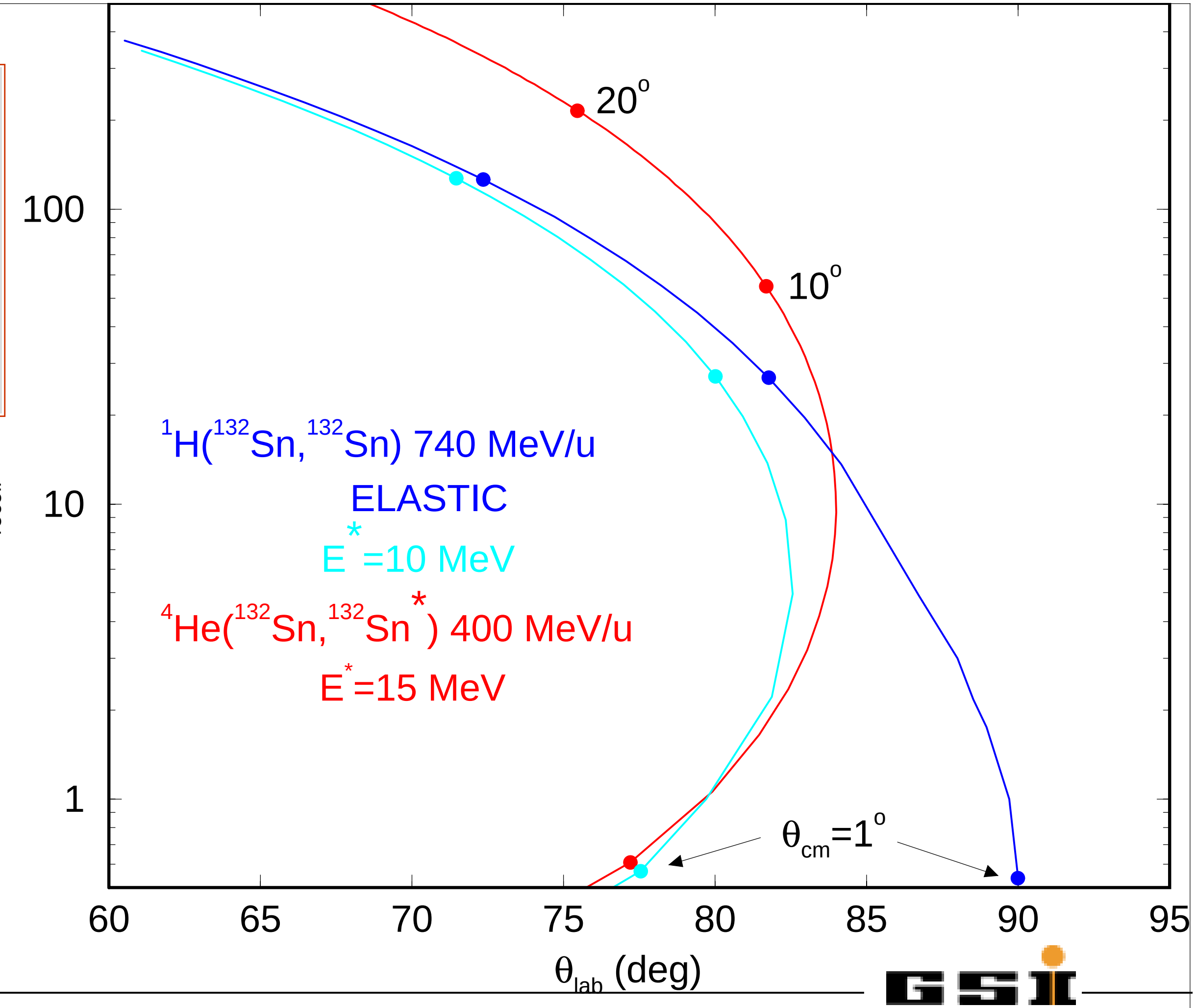
Form factors from low energy/momentum recoils

Thin (gaseous) targets,

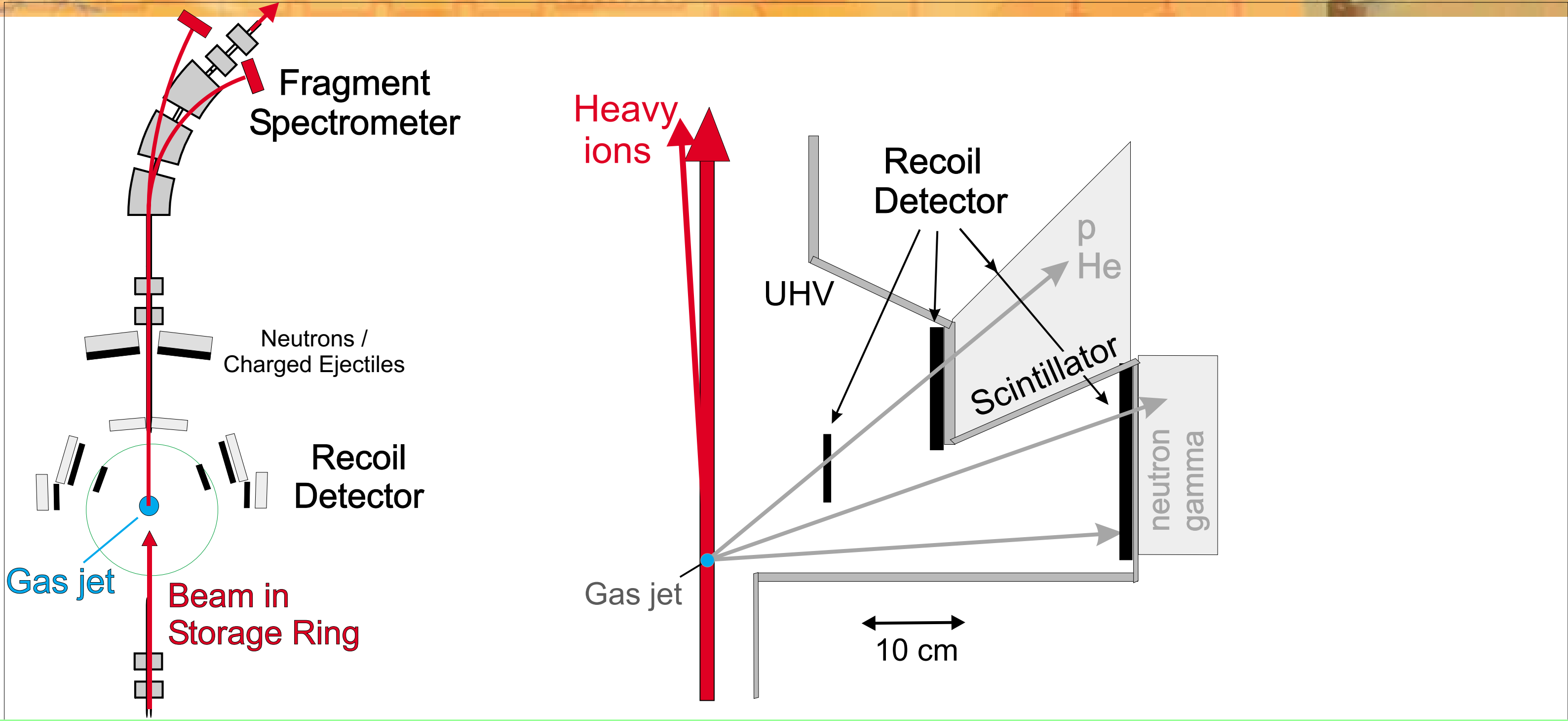
→ STORAGE RING

→ new detector concepts, e.g. UHV in-ring det.

…… ……. ….



Storage Ring Experiments

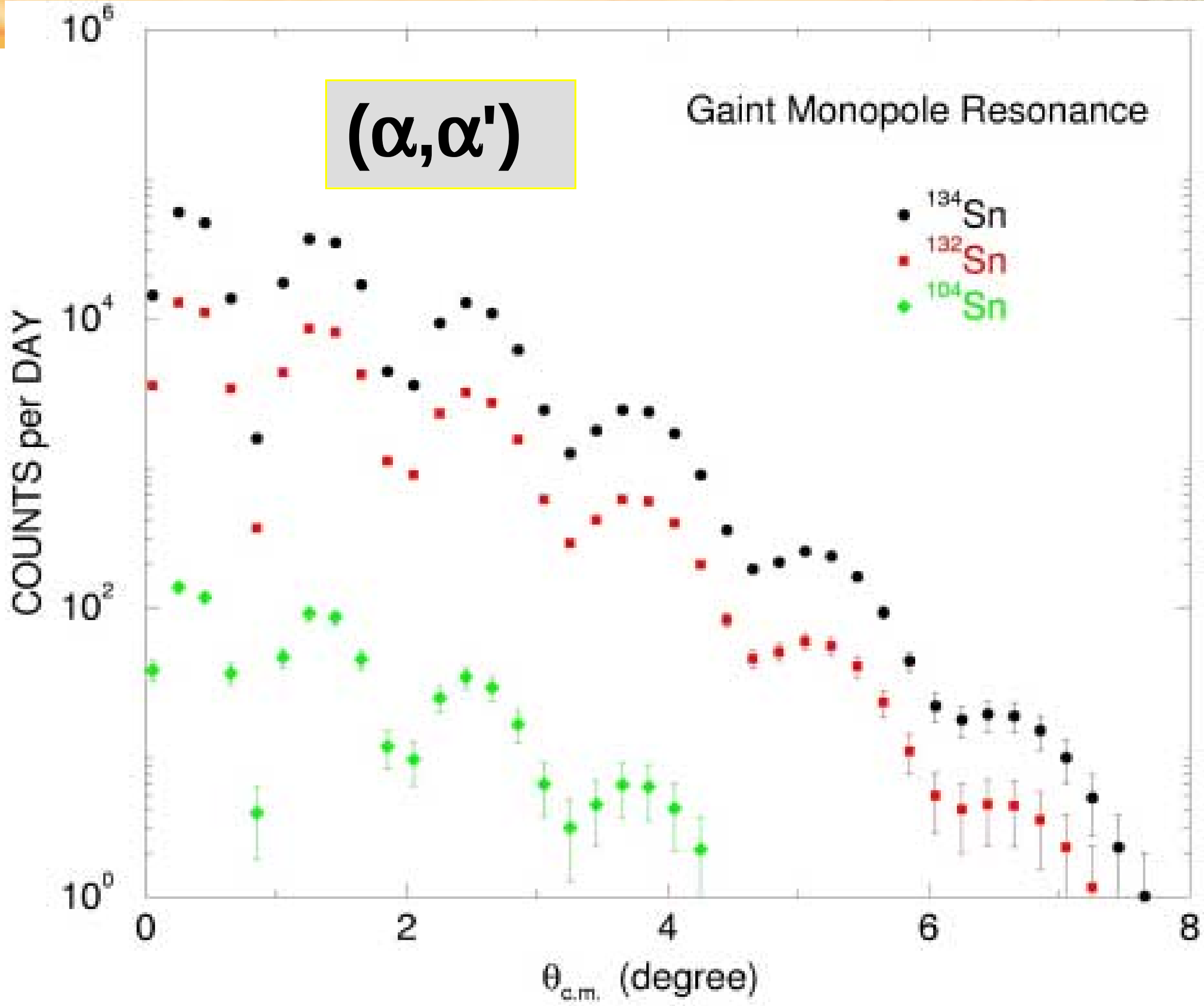


target recoil – heavy fragment – light ejectiles - (γ) - concidence

→ **full event characterization**

→ **final state identification**

→ **suppression of physical background ?**



(α,α')
Gaint Monopole Resonance
134Sn
132Sn
104Sn
COUNTS per DAY
10^6
10^4
10^2
10^0
0
2
4
6
8
θc.m. (degree)

Electron Scattering

Electron-Ion (eA) collider

• Point like particle

• Pure electromagnetic probe

F(q) transition formfactors
⇒ high selectivity to certain multipolarities

• Unstable nuclei

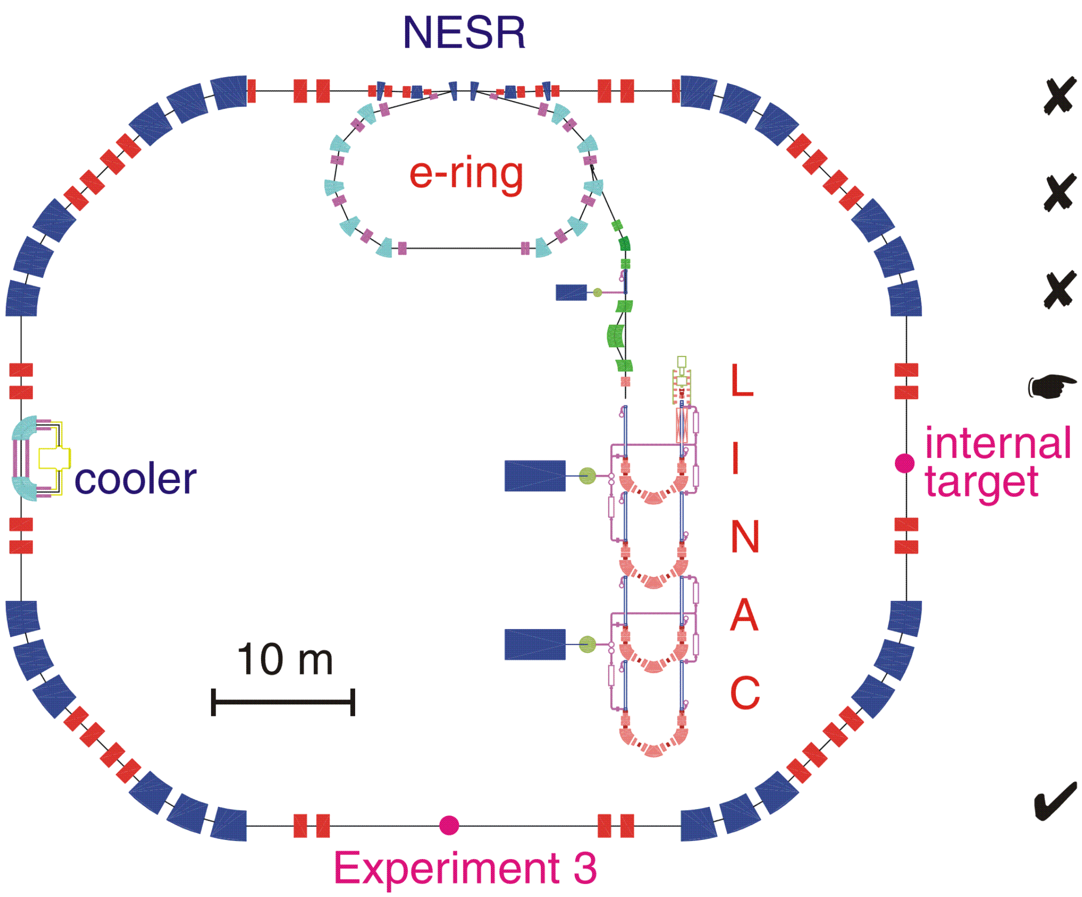
• Large recoil velocities
⇒ full identification (Z,A)

• Kinematics
⇒ eff. 4π - geometry, small angles
complete kinematics

• Bare ions
⇒ reduced atomic background

LUMINOSITY : up to 10^{28} $s^{-1}cm^{-2}$

The eA Collider



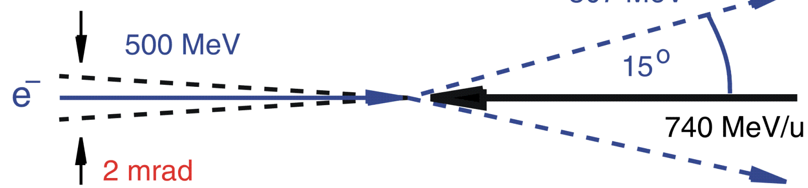
- ✘ E_e = 125,250,375,500 MeV
- ✘ E_I = 200-740 MeV/u
- ✘ $\mathcal{L} = f_e n_e \frac{N_e N_I}{4\pi\sigma_x\sigma_z}$
- ☛ $\sigma_{x,z} \approx 100\ \mu m$
  - n_e= 5 - 8, f_e=6.6 Mhz
  - $N_e = 5 \cdot 10^{10}$
  - $N_I = 10^5 \ldots 10^{10}$
- ✔ $\mathcal{L} \approx 10^{26}$ - 10^{31} $cm^{-2}s^{-1}$

Kinematics

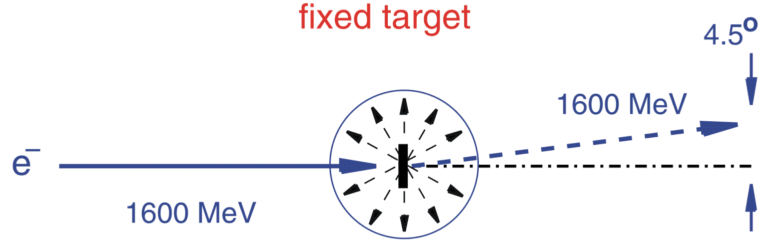
$q = 80\text{MeV/c} - 180\text{MeV/c}$

$\Theta_{lab} = 10^o \quad - 20^o$

collider



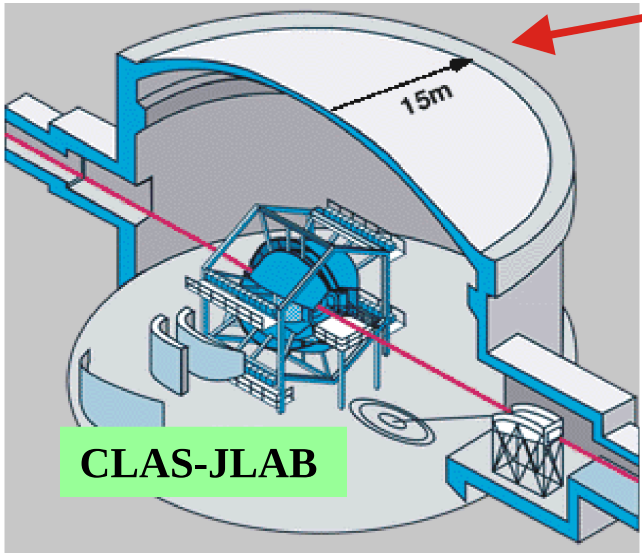
fixed target

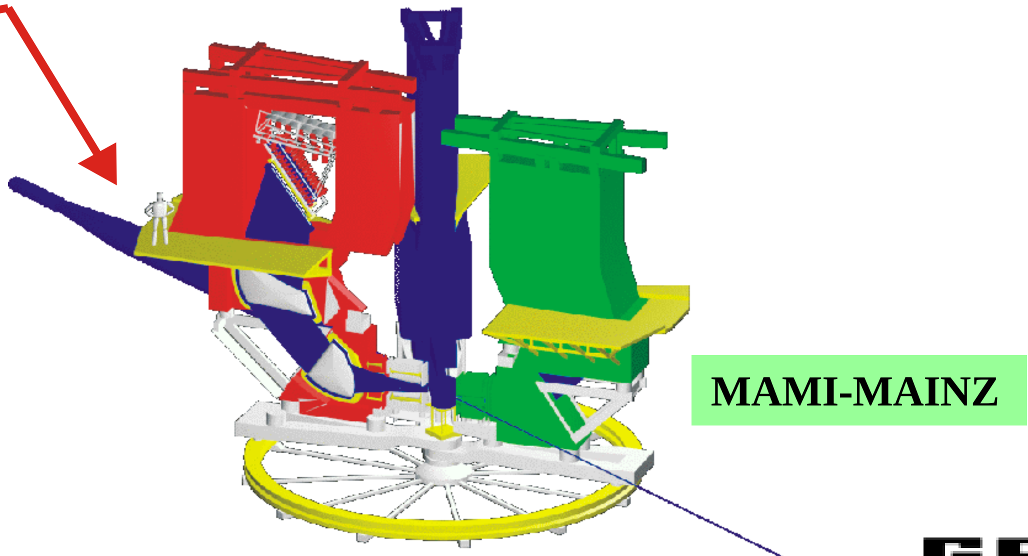


E_{ion}	Θ	E_e(fixed target)
740 MeV/u	$2.5^o - 6.5^o$	1600 MeV
100 MeV/u	$6.3^o - 12.4^o$	785 MeV

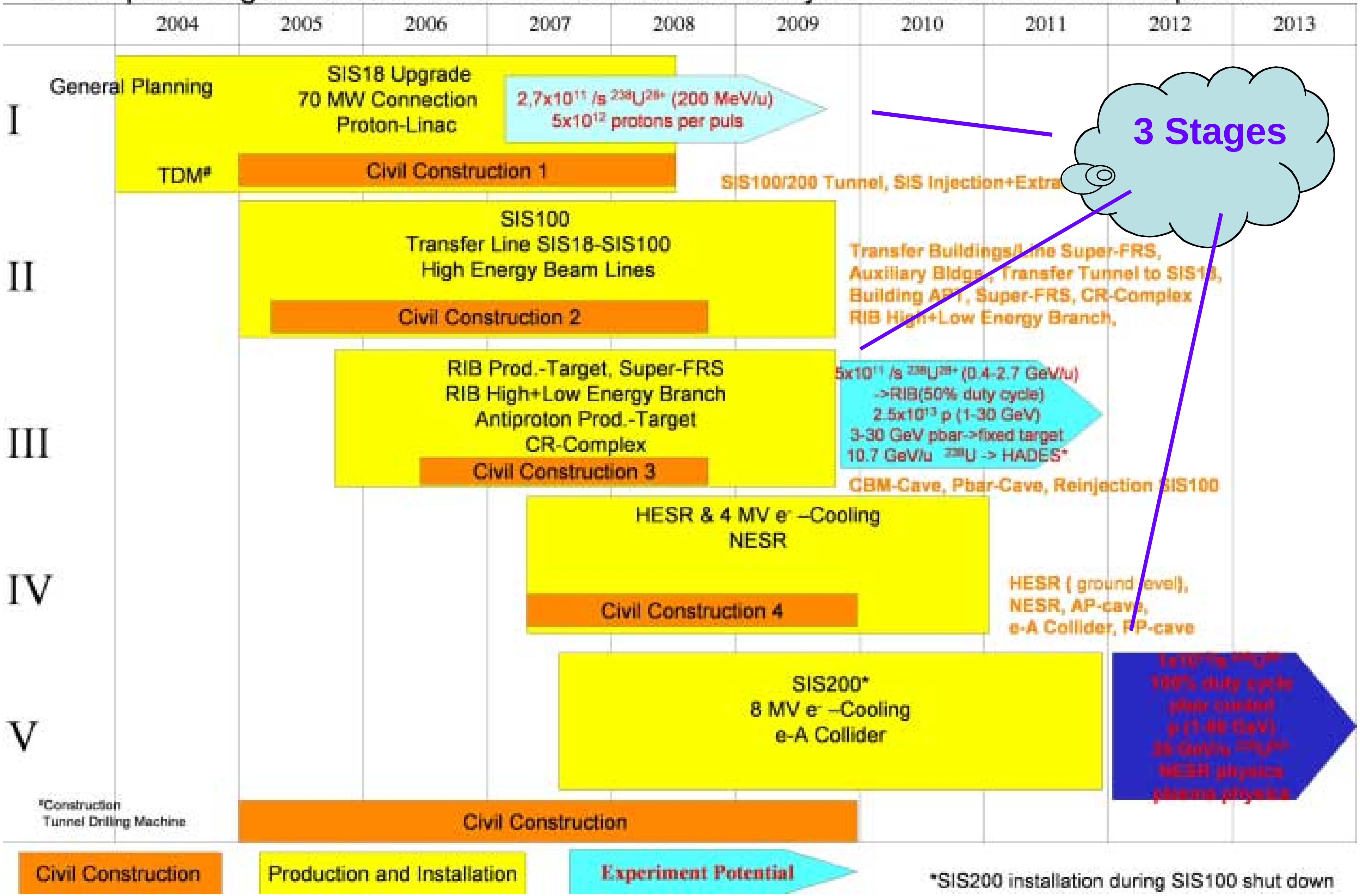
Electron - Ion Collider ---- Electron spectrometer ?

Large Acceptance	+	High Resolution
8-142 degree		28 msr
0.2-4 GeV/c		20 %
$\Delta p/p$: 0.5 %		0.01 %
2 mrad		1 mrad





Concept for staged Construction of the International Facility for Beams of Ions and Antiprotons



…. and **10** years after ……