Nuclear Physics with PERLE

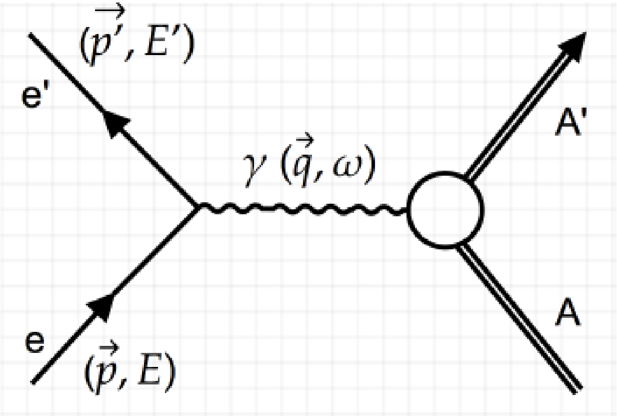
Some nuclear physics opportunities with PERLE@Orsay and the perspectives it would open

David Verney – IJCLab Orsay

The electromagnetic probes in nuclear physics

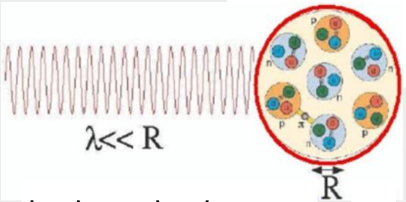
- ion manipulation with em fields: mass measurements
- interaction with the hyperfine field : laser spectroscopy, nuclear orientation→ $I^{(\pi)}, \mu, Q_s, \delta\langle r^2_c\rangle$
- γ-spectroscopy : lifetimes, $B(E\lambda)$, $B(M\lambda)$
- e- scattering

→ Precision physics, the probe is perfectly known
→ e penetrate deeply without absorption

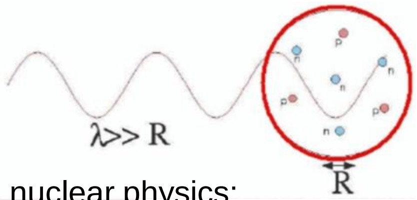


Single virtual photon exchange (good approximation)

e momentum transfer q $\approx 1/\lambda$



hadron physics:
structure of the nucleon



nuclear physics:
internal structure of the nucleus
E_e= 500 MeV → ≈0.5 fm scale

Electron scattering off nuclei

- ion manipulation with em fields: mass measurements
- interaction with the hyperfine field : laser spectroscopy, nuclear orientation$\rightarrow$ $I^{(\pi)}$,μ, Q_s, $\delta\langle r^2_c\rangle$
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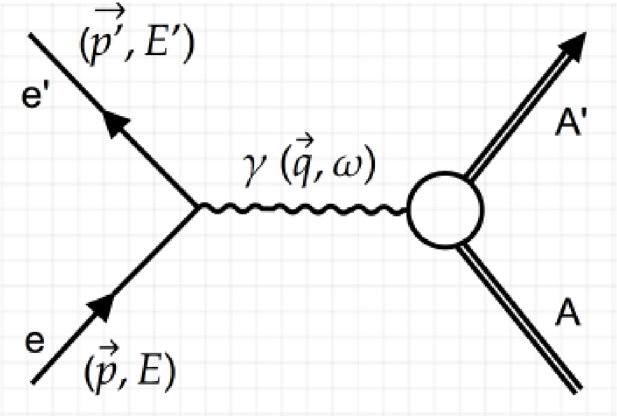


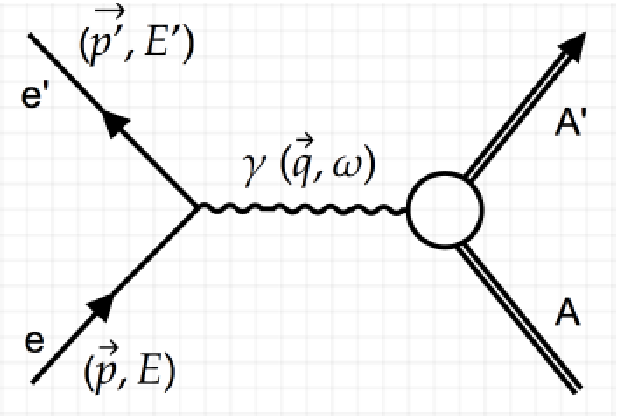
Integrated quantities → Spatially dependent quantities

Electron scattering off nuclei

→ Precision physics, the probe is perfectly known
→ e penetrate deeply without absorption

→ what we need to measure

$$\frac{d\sigma}{d\Omega\, dE} = \frac{4\pi}{M_T}\, \sigma_{Mott} \left[\left(\frac{q_\lambda^2}{q^2}\right)^2 S_L(q,\omega) + \left(\frac{1}{2}\frac{q_\lambda^2}{q^2} + tan^2\frac{\theta}{2}\right) S_T(q,\omega) \right]$$



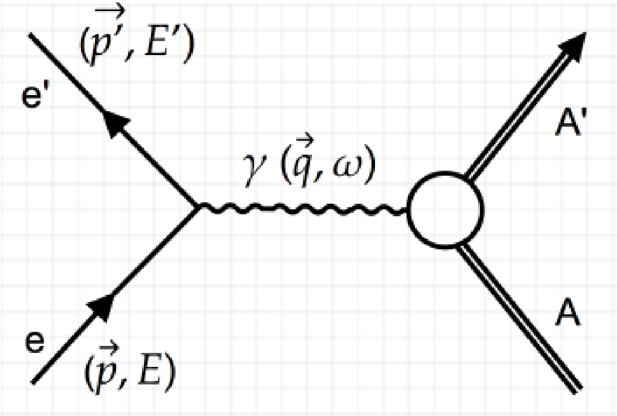
$\omega \rightarrow$ *Exc. Energy*
$q \rightarrow r$

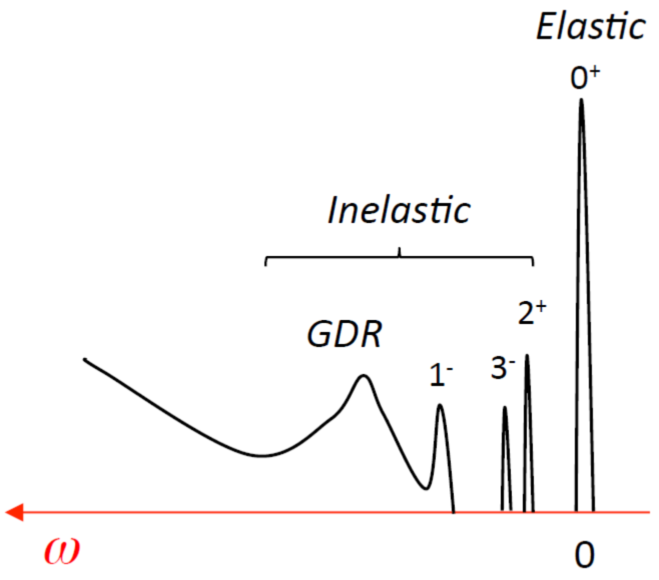
Nuclear response surfaces
or
Dynamic structure functions

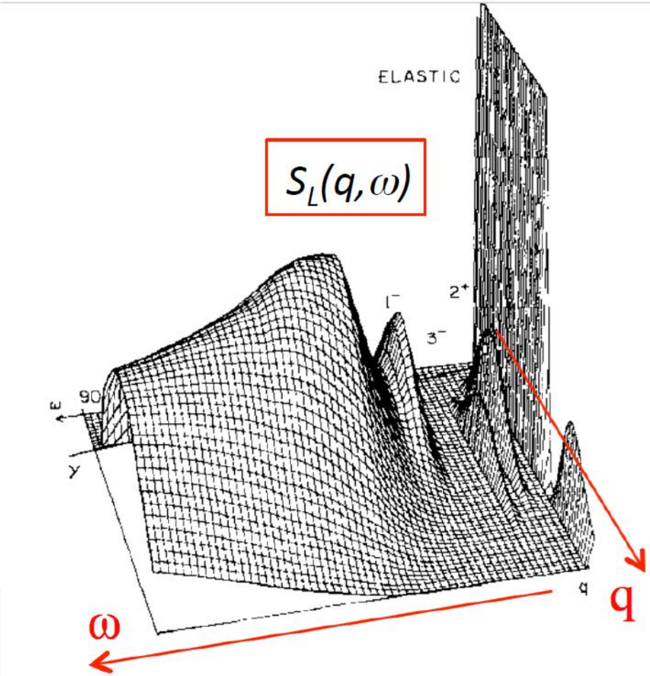
Electron scattering off nuclei

→ Precision physics, the probe is perfectly known
→ e penetrate deeply without absorption

→ what we need to measure







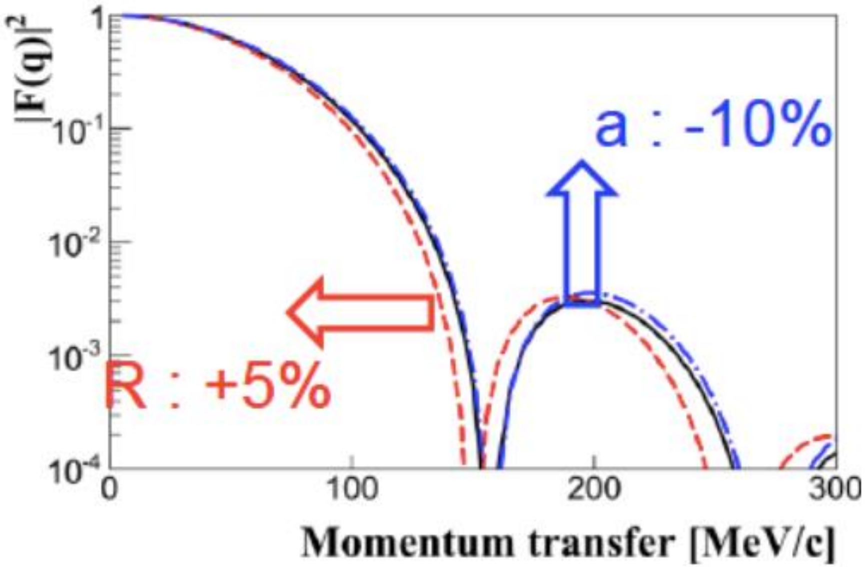
[Donelly and Walecka, ARNPS 25, 329 (1975)]

Simple example : elastic scattering

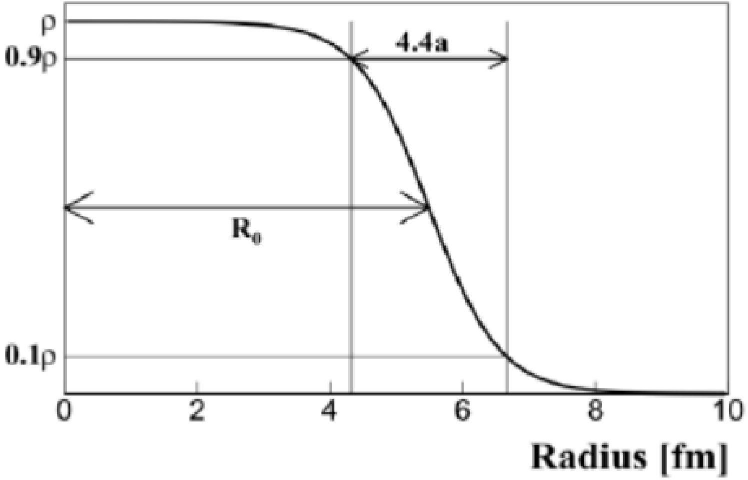
For (ω=0) and $J^\pi=0^+$ states

$$\left(\frac{d\sigma}{d\Omega}\right)_{eA\to eA} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} |F_c(\vec{q})|^2 \qquad F_c(\vec{q}) = \frac{1}{(2\pi)^{3/2}} \int \rho_c(\vec{r})\, e^{i\vec{q}.\vec{r}}\, d^3r$$

→ access to some aspects of the most fundamental properties of nuclei : saturation properties

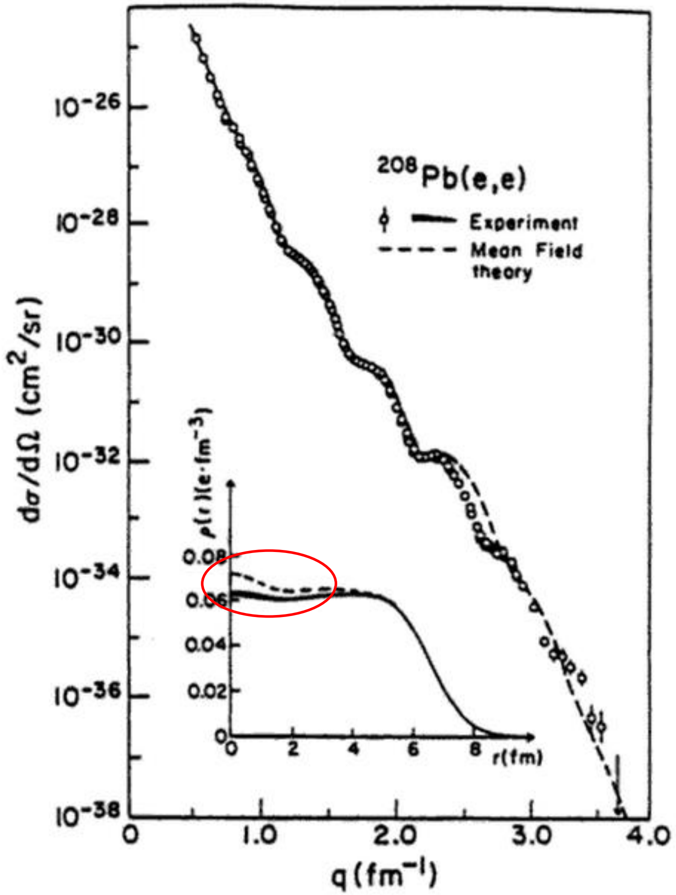


$$\rho_C = \rho/(1 + e^{(r-R)/a})$$



Simple example : elastic scattering

these measurements have had exceptional moments of glory…on **stable** nuclei



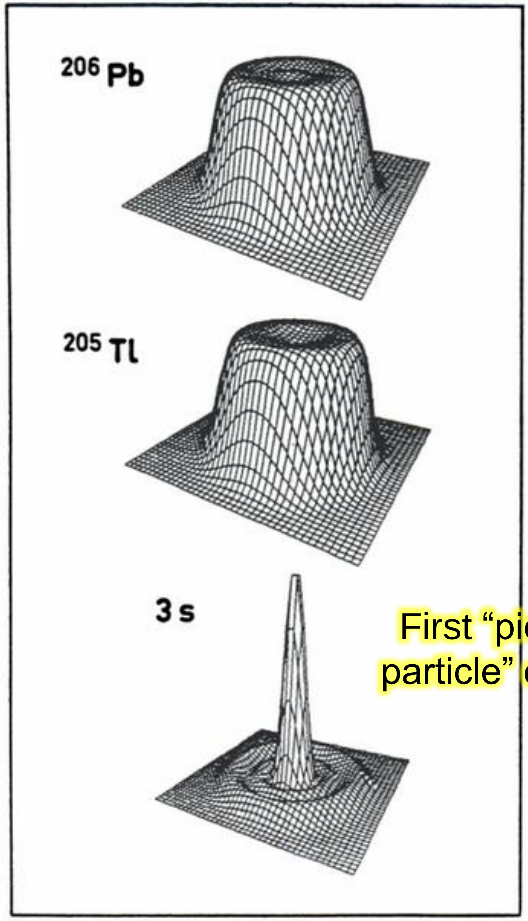
12 orders of magnitude !

B. Frois and Papanicolas
Ann. Rev. Nucl. Part. Sci 37 (1987)

Dechargé and Gogny
PRC 81 (1980)

Cavedon, Frois, Goutte et al.
PRL 49 (1982)

etc…



B. Frois et al
in Modern Topics in Electron Scattering
(World Scientific 1991)

First “picture” of a “single particle” evolving inside the nucleus

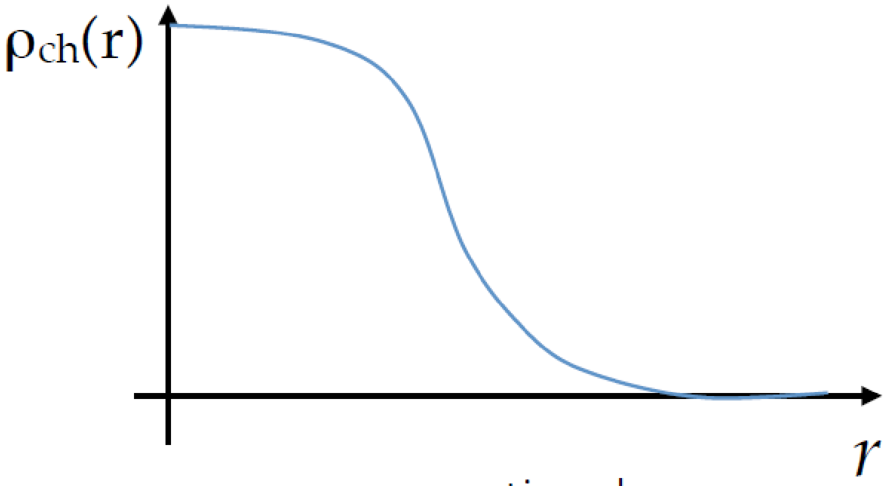
Perspectives for the XXIst century : e-scattering off unstable nuclei

Case for a “flagship" experiment on exotic nuclei : “bubble nuclei”

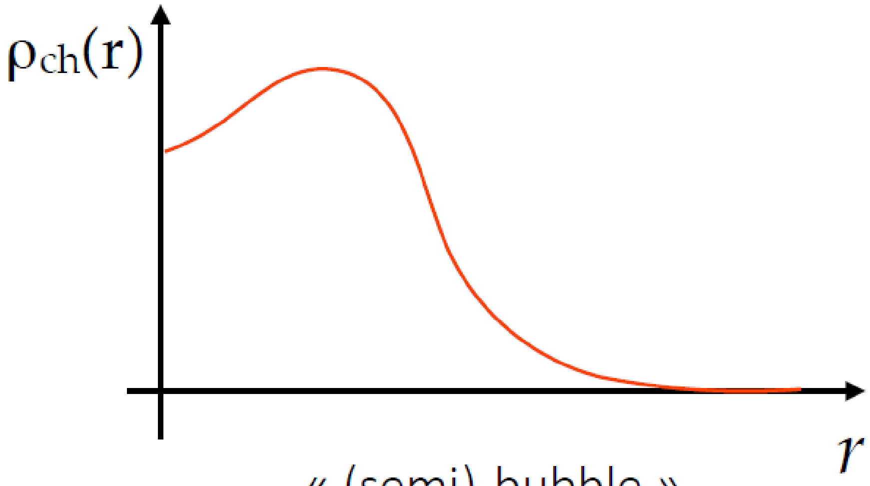
Prediction

Central depletion of $\rho_{ch}(r)$

[Dechargé et al. 2003, Bender & Heenen 2013]
[Khan et al. 2008, Grasso et al. 2009,...]



« conventional »



« (semi)-bubble »

Perspectives for the XXIst century : e-scattering off unstable nuclei

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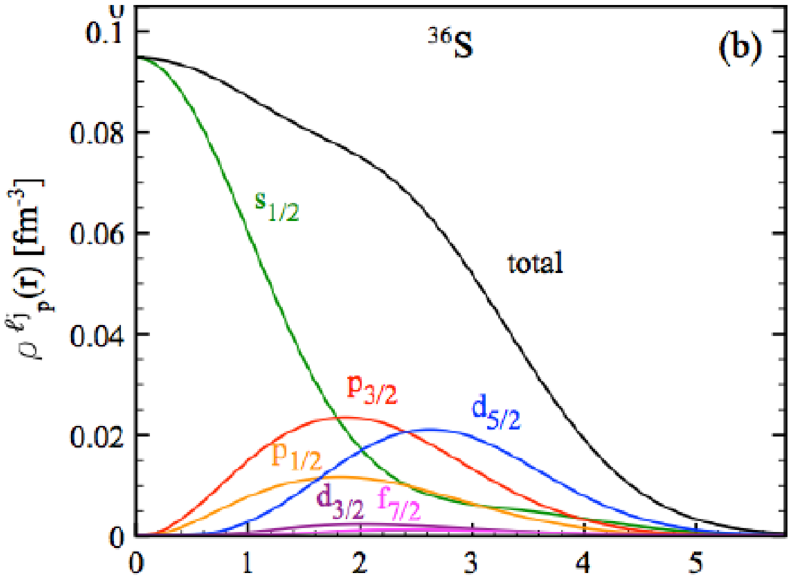
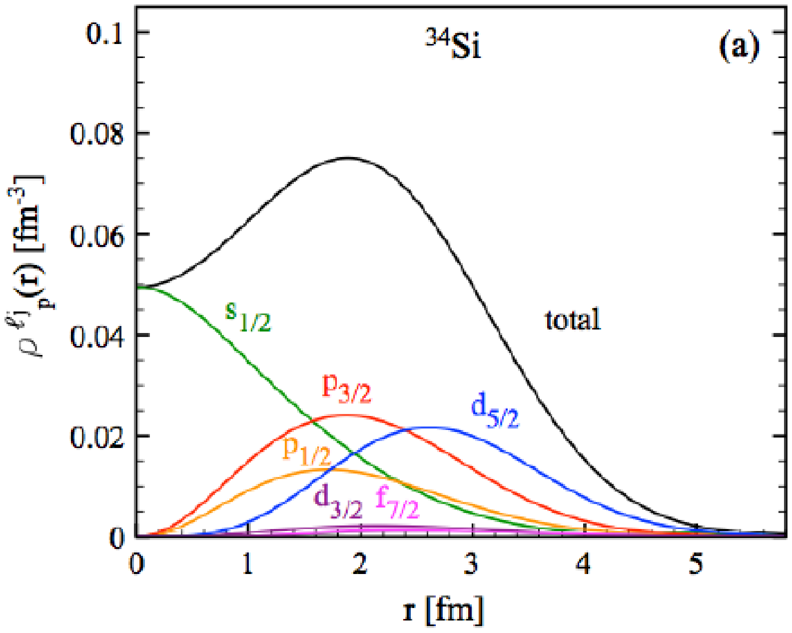
Interpretation

QM effect

$\ell = 0$ orbitals radially peaked at $r = 0$
$\ell \neq 0$ orbitals suppressed at small r



(-2p)
in $s_{1/2}$ orbital



Figures from [T. Duguet, V. Somà et al., PRC 95 (2017) 034319]

Perspectives for the XXIst century : e-scattering off unstable nuclei

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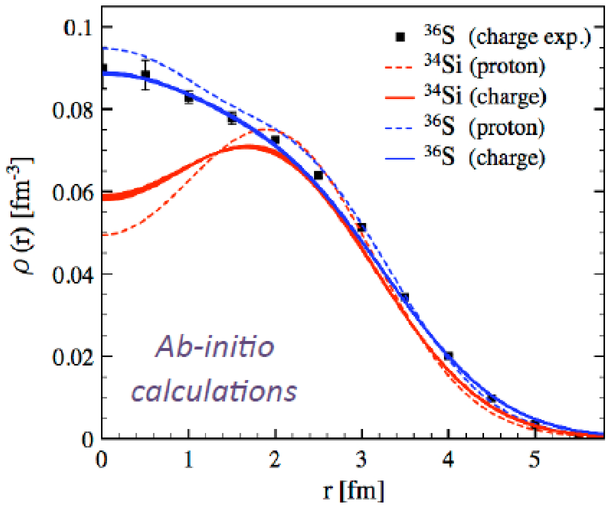
Consequence

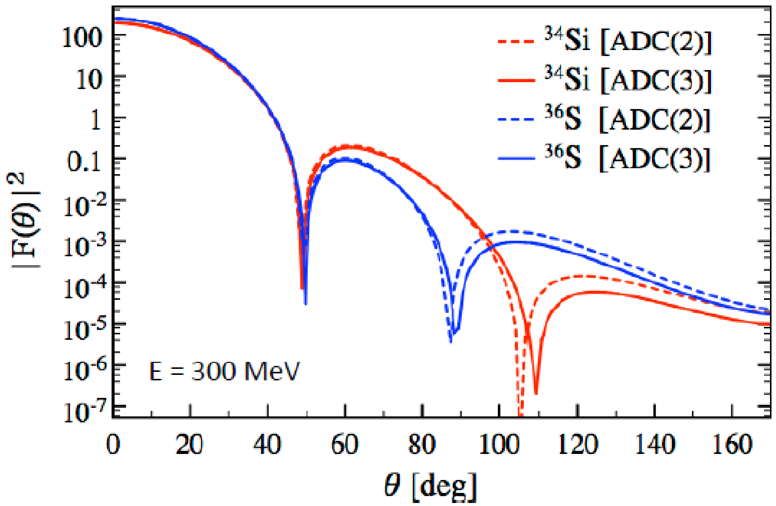
Spin-Orbit interaction

$$V_q^{so}(\vec{r},\vec{p}) = \frac{1}{2}\left[W_1 \nabla\rho_q(\vec{r}) + W_2 \nabla\rho_{\bar{q}}(\vec{r})\right]\sigma \wedge \vec{p}$$

Direct/Unambiguous signature of central depletion

[T. Duguet, V. Somà et al., PRC 95 (2017) 034319]

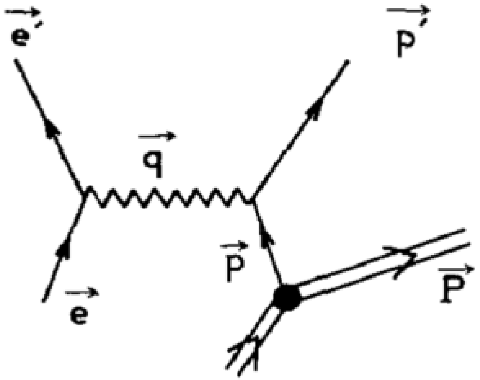




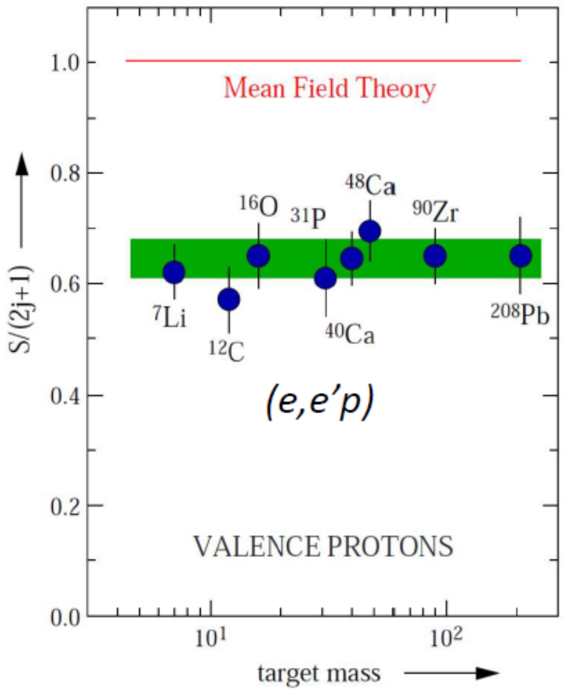
Clear differences in $|F(\theta)|^2$ for θ>50°

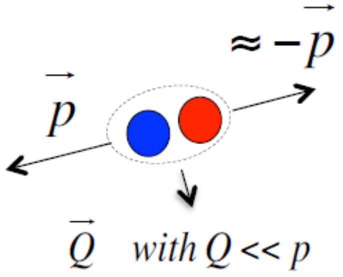
Perspectives for the XXIst century : e-scattering off unstable nuclei

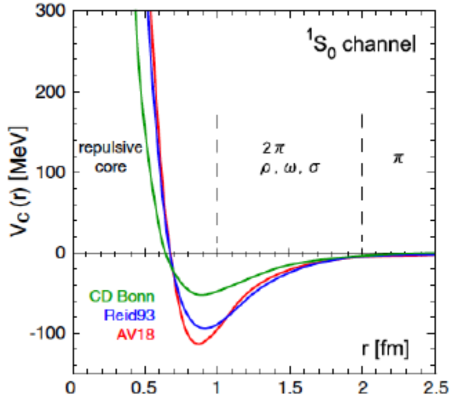
The long term horizon : (e,e'p) quasi-free scattering : short range correlations



[Dickhoff and Barbieri, PPNP **52** 377 (2004)]





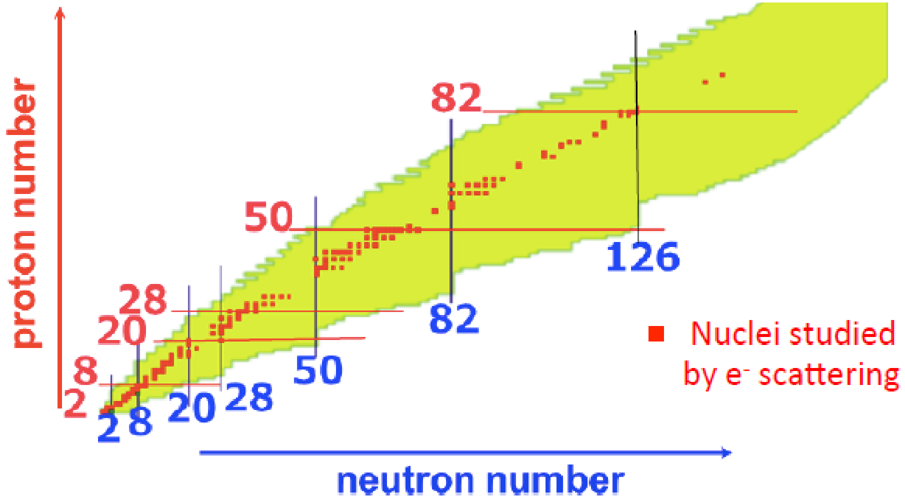


- Repulsive hard-core + tensor → **high-mom. correlations**
- Stable nuclei:
  - **20% of nucleons** are concerned
  - with **90% of neutron-proton pairs**

*[Subedi et al., Science **320** (2008)]*

How does these correlations evolve for exotic nuclei with asymetric n/p ratios?

Required luminosities



Reaction	Deduced quantity	Target Nuclei	Luminosity [$cm^{-2}s^{-1}$]
Elastic scattering at small q	r.m.s. charge radii	Light Medium	10^{24}
First minimum in elastic form factor	Density distribution with 2 parameters	Light Medium Heavy	10^{28} 10^{26} 10^{24}
Second minimum in elastic form factor	Density distribution with 3 parameters	Medium Heavy	10^{29} 10^{26}
Inelastic scattering Pygmy/Giant resonances	Position, width, strength, decays	Medium Heavy	10^{28} 10^{28}
Quasi-free scattering	SF, spectral strength	Light	10^{29}

Required luminosities for different electron scattering studies, adapted from [Antonov et al., NIMA 637, 60 (2011)]

Possible implementations

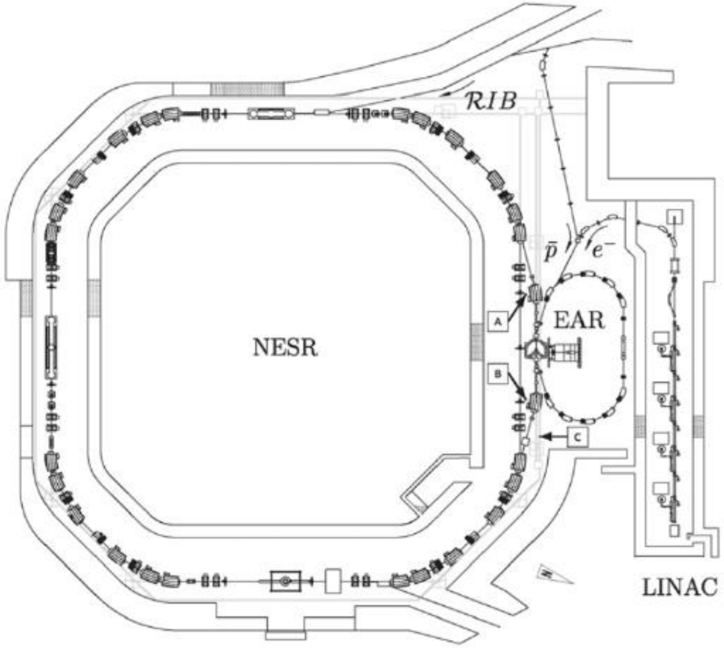
Two different strategies to address e-RIB scattering

→ double-ring collider : ELISE project at FAIR

NESR (0.74 GeV/nucleon) **+ EAR** (0.5 GeV)

→ Targeted luminosity ~ $\mathbf{10^{28}}$ **($\mathbf{cm^{-2}s^{-1}}$)**

Excluded from funded part of FAIR modularized start version (module 4)



A. Antonov et al., NIMA **637** 60 (2011)

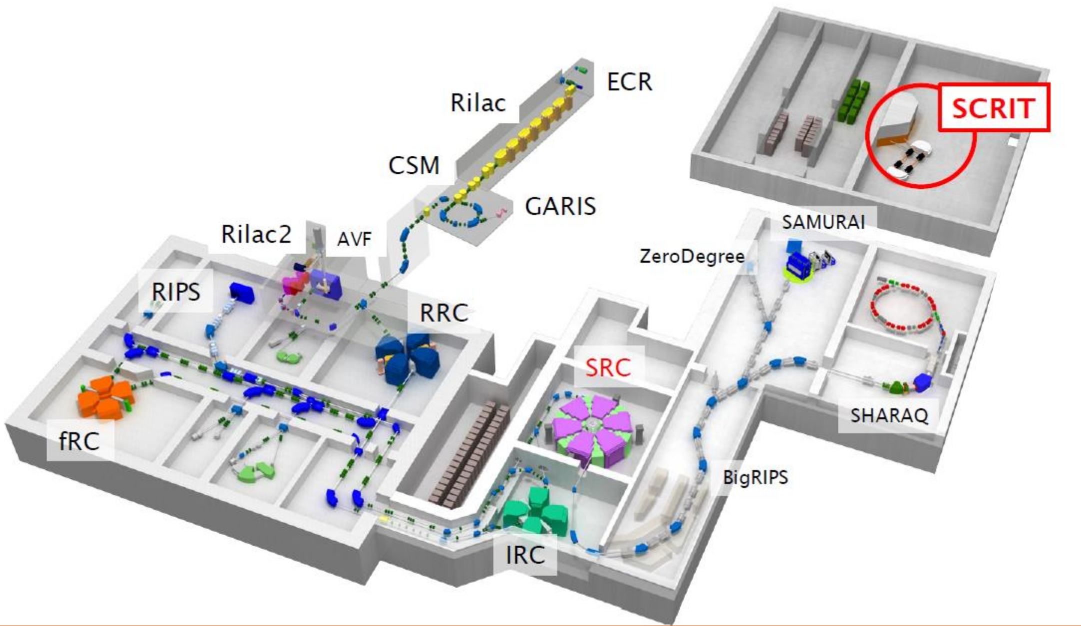
→ Self-confining fixed target : SCRIT

Possible implementations

T. Suda, M. Wakasugi, T. Emoto, K. Ishii, S. Ito, K. Kurita, A. Kuwajima, A. Noda, T. Shirai, T. Tamae, H. Tongu, S. War and Y. Yano,
"First Demonstration of Electron Scattering Using a Novel Target Developed for Short-Lived Nuclei,"
Physical Review Letters **102** (10) (2009).

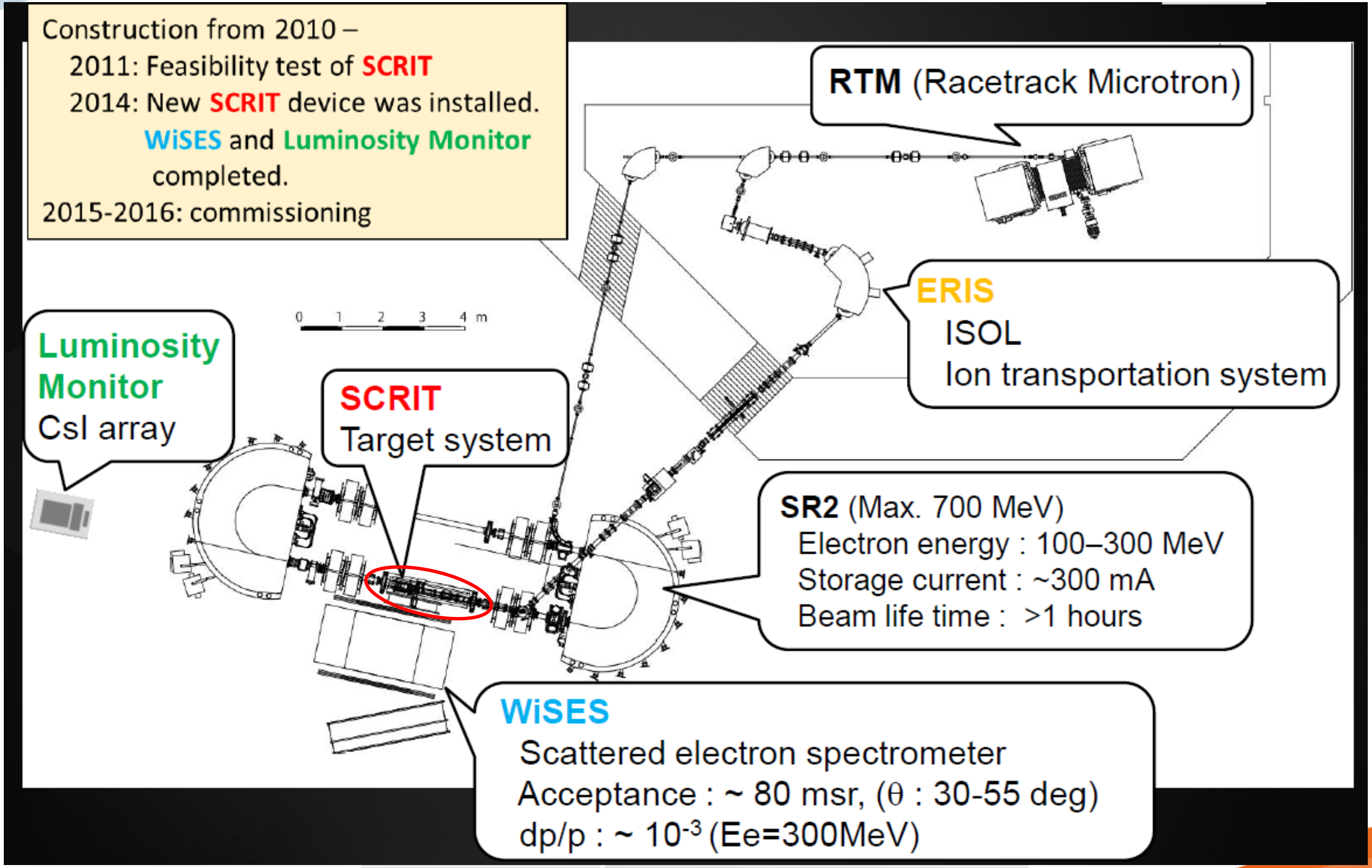
M. Wakasugi, T. Emoto, Y. Furukawa, K. Ishii, S. Ito, T. Koseki, K. Kurita, A. Kuwajima, T. Masuda, A. Morikawa, M. Nakamura, A. Noda, T. Ohnishi, T. Shirai, T. Suda, H. Takeda, T. Tamae, H. Tongu, S. Wang, and Y. Yano,
"Novel internal target for electron scattering off unstable nuclei,"
Physical Review Letters **100** (16) (2008).

Location of the SCRIT Facility in the RIKEN RI Beam Factory



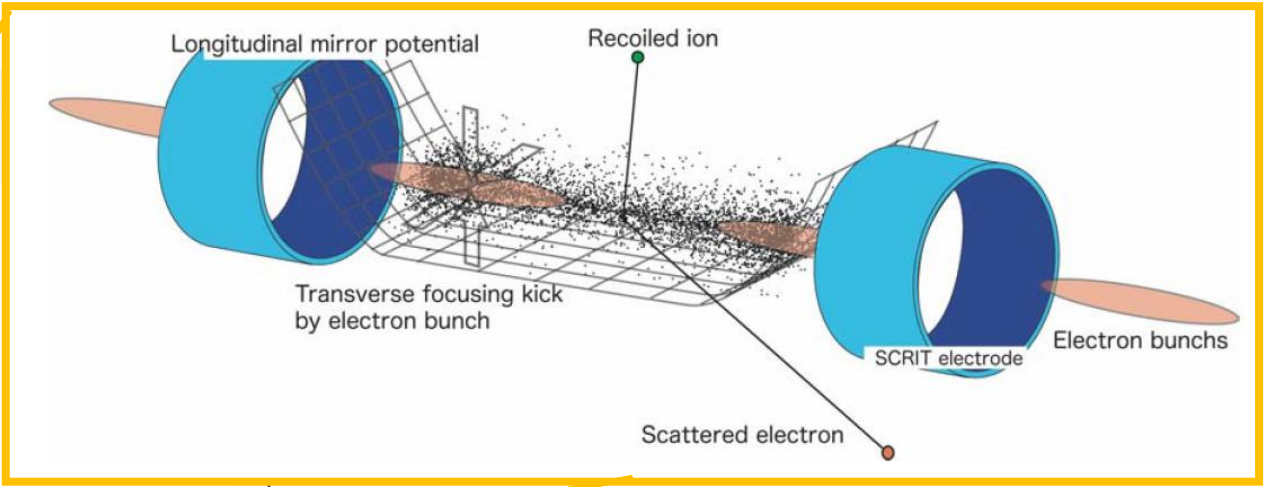
taken from : M. Wakasugi
Workshop on e-Ion collision
at CEA Saclay
(25-27 Apr. 2016)

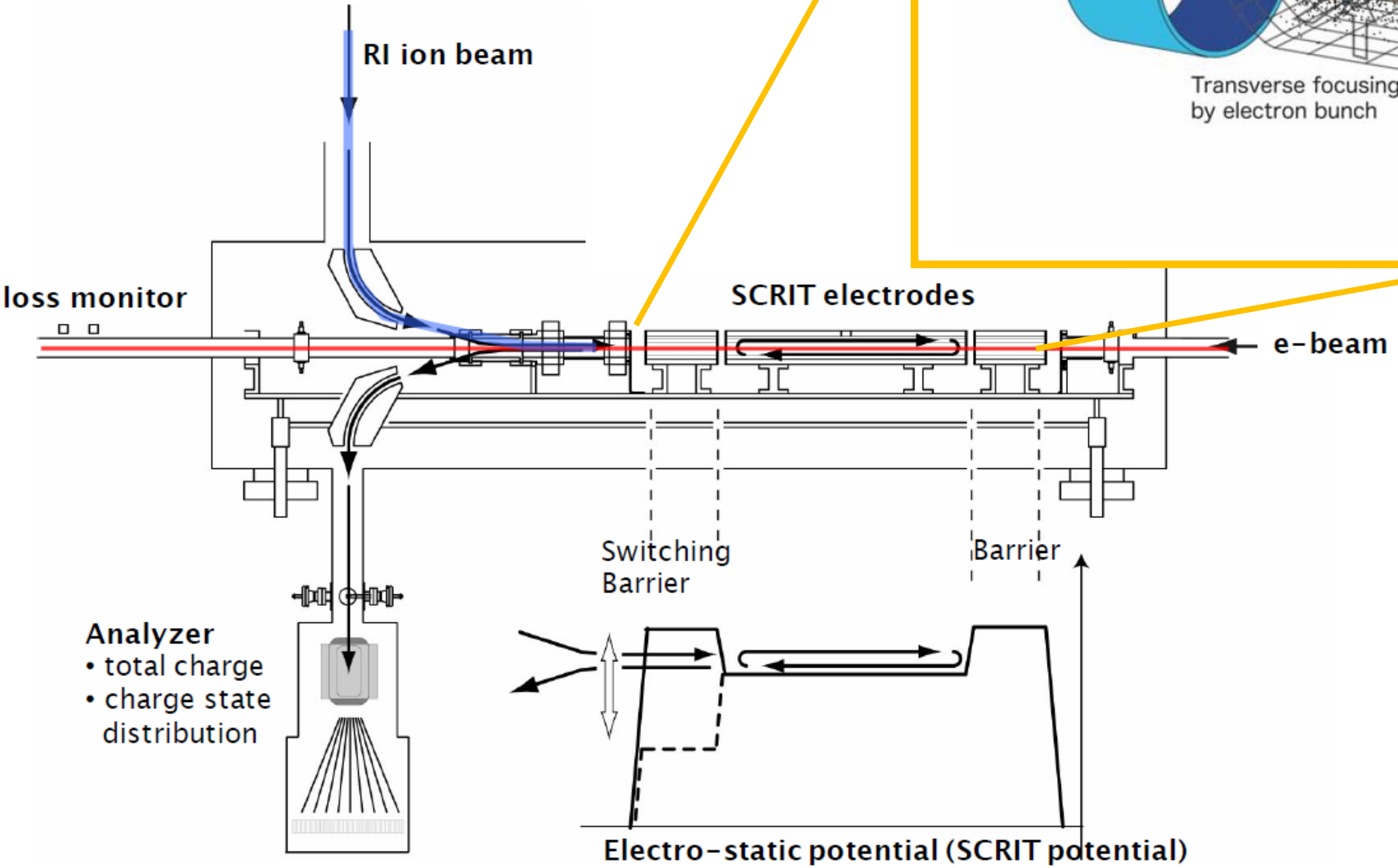
Possible implementations



taken from : T. Tsukuda Workshop on e-Ion collision at CEA Saclay (25-27 Apr. 2016)

Possible implementations





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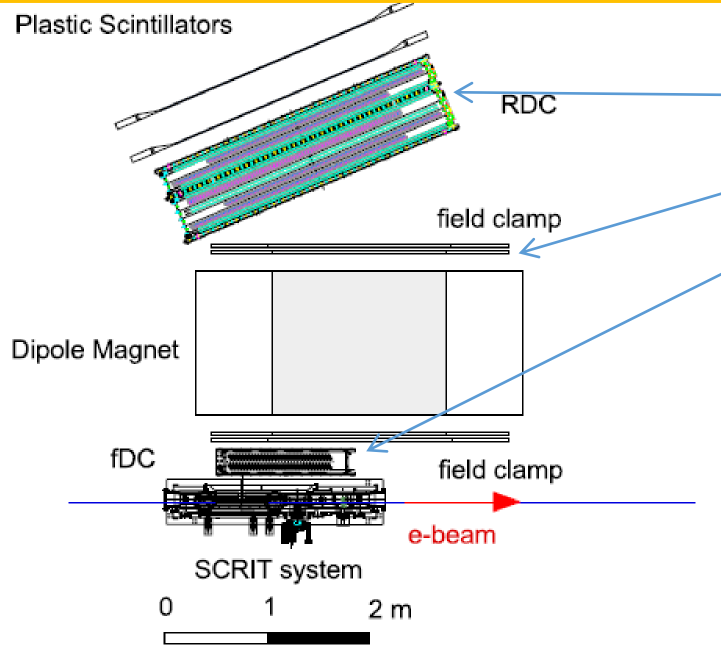
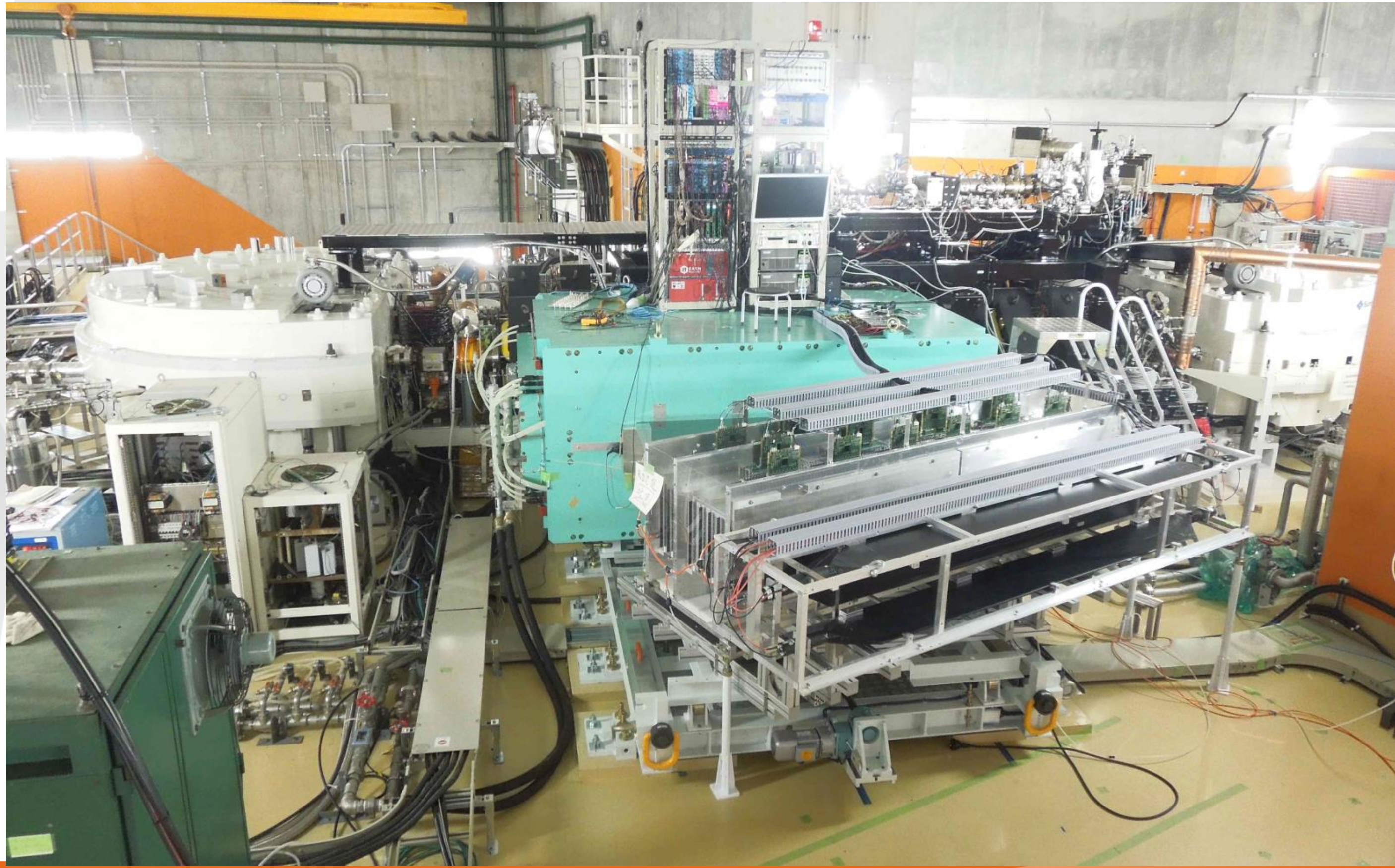


Figure 2. Schematic layout of detectors in WiSES.

Rear drift chamber

Dipole : 0.4 T for 150 MeV

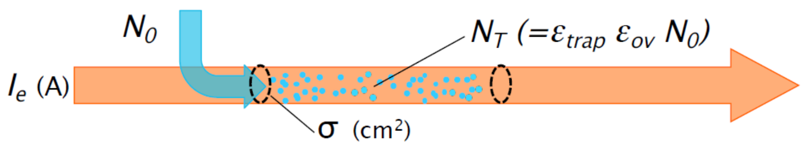
Front drift chamber



T Ohnishi et al
Phys. Scr. T166 (2015) 014071

Possible implementations

Achievable luminosity



$$L \sim \frac{I_e/e \quad N_T}{\sigma} \ /(\mathrm{cm^2 s})$$

Chancé et al (CEA Saclay) ETIC project within GANIL-2025 (2015) – calculations within ERL hypothesis **:**

I_e=200 mA N_A=10^6 trapped ions: $\mathcal{L} \simeq 10^{29}$ should be achieved

based on

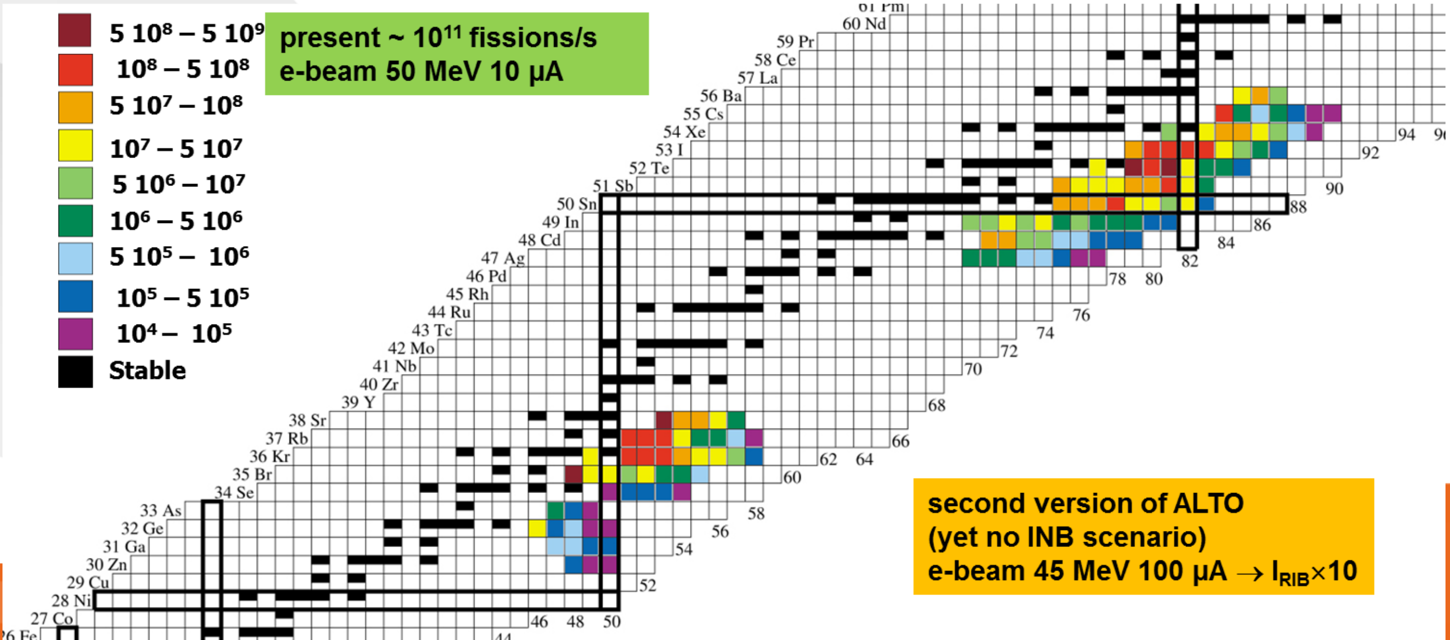
[A.N. Antonov et al., Nucl. Instr. and Meth. A **637** 60 (2011)] ELISE project GSI

PERLE@Orsay : 20 mA $\rightarrow \mathcal{L} \simeq 10^{28}$ is *probably* achievable for a **10^6** trapped RI population **on the principle**

but the dynamical e-beam-RI coupling should be investigated : first time with a ERL time structure

e-beam instabilities ? impact on ERL operation ?

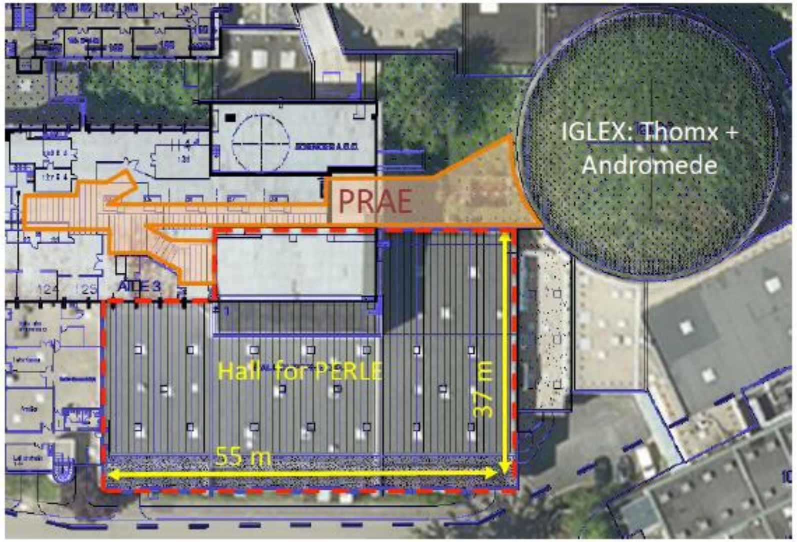
Production pps



present ~ 10^{11} fissions/s
e-beam 50 MeV 10 μA

second version of ALTO
(yet no INB scenario)
e-beam 45 MeV 100 μA $\rightarrow I_{RIB}\times 10$

Suggested strategy and perspectives



A nuclear physics project at PERLE@Orsay
DESTIN [DEep STructure Investigation of (exotic) Nuclei]
is for the time being just in idea…

Goals:

• to seize the opportunity of the construction of an ERL prototype on the Paris-Saclay University Campus to build an RI-e-scattering experimental setup (inspired by SCRIT)

• requires to build/move/adapt our existing ALTO ISOL photofission facility in Orsay

• a necessary demonstration step : fixed radioactive target in ERL for the first time
$\rightarrow$ towards a possible more ambitious ERL-based system ($\rightarrow \mathcal{L} \simeq \mathbf{10^{29}}$) at GANIL
$\rightarrow$ (presently discussed/considered within the French nuclear physics long-range plan)

• realize a sustainable, realistic physics program that would collect the interest of the low-energy nuclear physics community (local, national, international)
(extension and deepening of the existing activity based on the em probe)