What Interferometry May Bring to the Study of High Density Symmetry Energy?

- The history of interferometry
- nn, np and pp correlations measured simultaneously
- Heavier particles
- What did we learn about the symmety term in experiments at energy < 100A MeV?
- Theory – at these energies ,,,,,,and higher.
- A comment about chronology
- Perspectives for ASY-EOS

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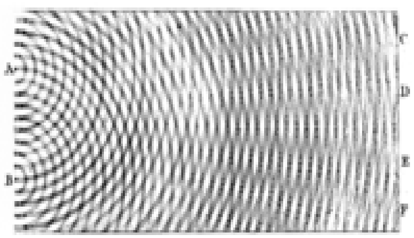
Interferometry has a long history ....

in optics ...., in astrophysics ..., in particle .. and nuclear physics .....

Newtons rings

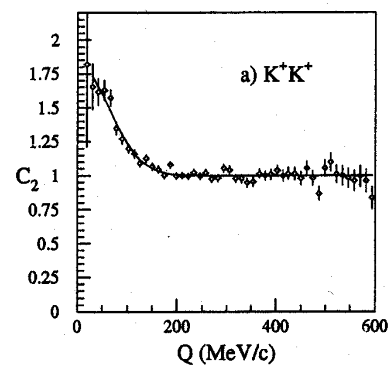


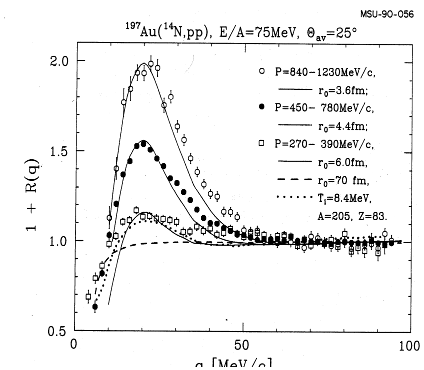
Double-slit exp. (original drawing)

Light interfero-meter

Speed of light

HBT





Measurement of diameter of Cygnus A ....

Bose-Einstein

Fermi-Dirac corr.

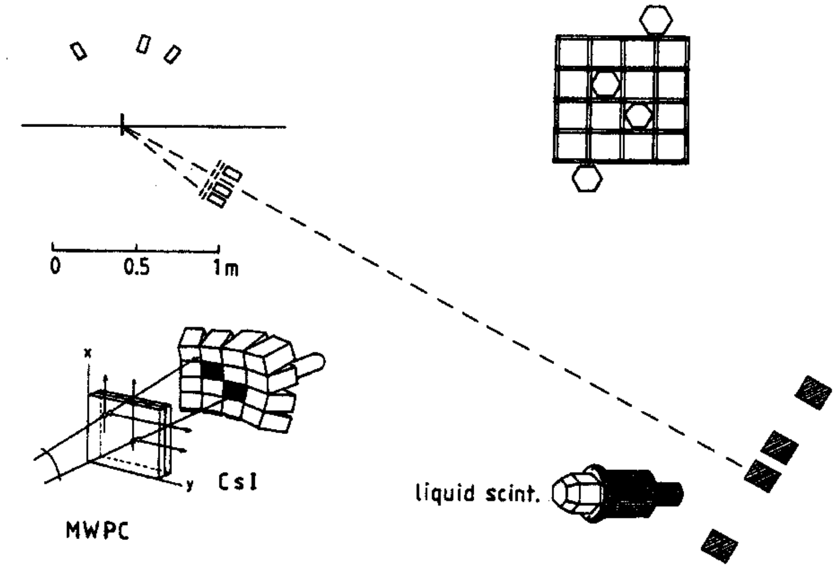
1680	1809	1887	1924	1954	1977	1980	1991
Robert Hooke	Th, Young	Michelson and Moreley	de Broglie	R. Hanbury-Brown	S. Koonin, Kopylov and Podgoretzky,... G. Goldhaber et al.	W. Lynch et al.	

over

Bo Jakobssn, Zagreb, Oct. 2009

..... and then came simultaneous pp, np and nn correlation experiments

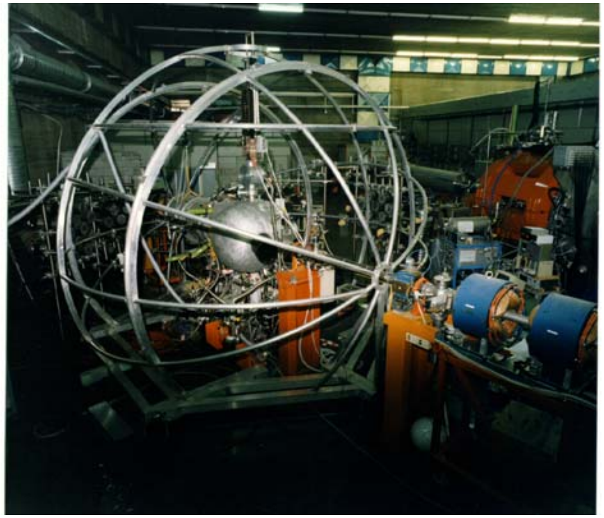
This experiment was outlined at the Jackson Hole meeting 1992 ....



... and proposed to the SARA PAC at ISN Grenoble, that rejected it with the argument that it should be more "safe to focus on pp correlations"!

After a convincing per-formance by Ö. Skeppstedt about our ability to handle liquid scintillators, the next PAC accepted it

and he size of these expeiments changed...



p: 20 CsI(Tl) [EMRIC]

n: 48 liq. scint [EDEN]

PF: 36 phoswich [ARGOS]

experiments perfrormed @ SARA, RIKEN, AGOR, LNS

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and the result was ......

.... where we plot

$$C(q) = \frac{N_c(q)}{N_{nc}(q)}, \quad where \quad q = \mu \cdot \left| \overrightarrow{p_1} - \overrightarrow{p_2} \right|$$

and compare it to the two-particle correlation formalism of Koonin/Pratt including (anti)symmetrization of the two-particle wave function and final state interactions (attractve strong interaction and for pp Coulomb int.)

$$C(\vec{q}, \vec{P}) = \int d^3 r \cdot \frac{\int d^3\vec{R} \cdot f(\vec{P}, \vec{r_1}, t_e) \cdot f(\vec{P}, \vec{r_2}, t_e)}{\left| d^3 r_1 \cdot f(\vec{P}, \vec{r}, t_e) \right|^2} \cdot \left| \Psi_{12}(\vec{q}, \vec{R}) \right|^2$$

$where\ \vec{P} = \frac{1}{2} \cdot (\overrightarrow{p_1} + \overrightarrow{p_2}),\ \vec{r} = \vec{r_1} + \vec{r_2},\ \vec{R} = \frac{\vec{r}}{2}\ and\ t_e\ is\ the$ $emission\ time\ for\ both\ particles\ at\ which\ the\ Wigner$ $functions\ in\ space\ and\ phase-space\ are\ introduced$

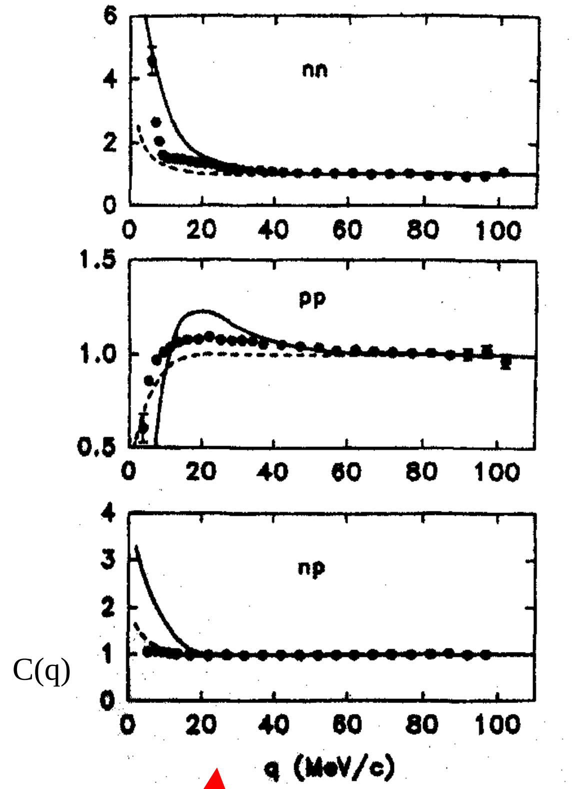
$$f(\vec{P}, \vec{R}, t_e) = \int_{-\infty}^{t_e} dt \cdot g(\vec{P}, \vec{R} - \overrightarrow{v_p}(t_e - t), t)$$

g is now the emission model of your choice

curves right: Δt = 0, Gaussian in r and p (- - - -)

Evaporative (——)

$^{40}Ar + {}^{197}Au$, 30A MeV , Θ ~30°

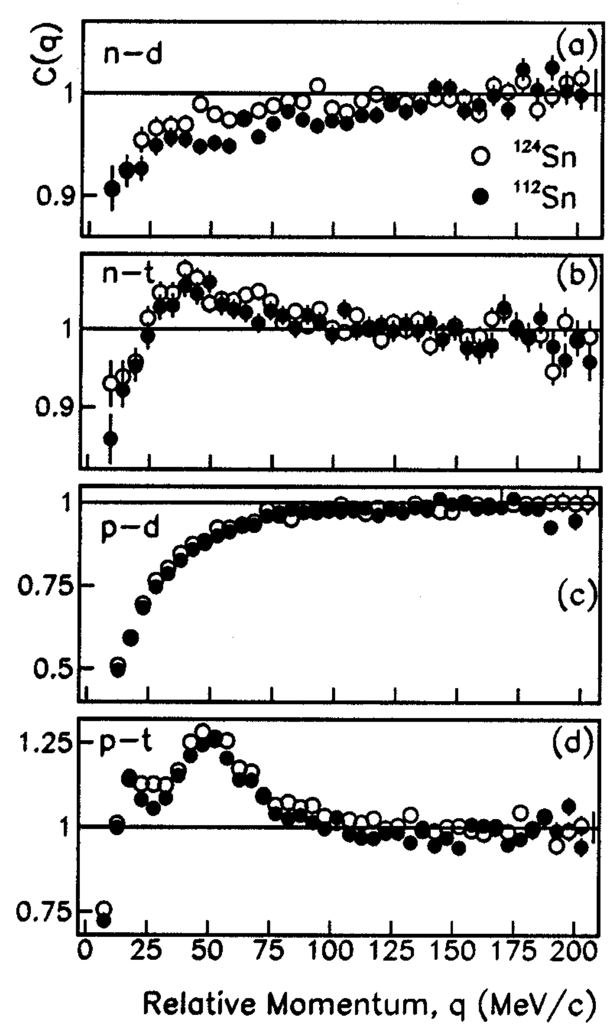


The weak np correlation due to:
i) supression of the S = 0 np state
ii) p interaction with Coulomb field

isospin effects - easier to observe for heavier particles?

61A MeV ^{36}Ar + ^{112,124} Sn

Data: CHIC Collaboration + S. Kopecky, V. Kravchuk, H. Wilschut, KVI, Groningen



30 - 45°

60 - 120°

- **anticorrelations in nd due to t formation**
- **nt function contains ^{4}H unbound states**
- **pd (and pt) are dominated by Coulomb**
- **and pt shows also decay of exc. ^{4}He**
- **isospin effects obvious for nd, nt, pt**

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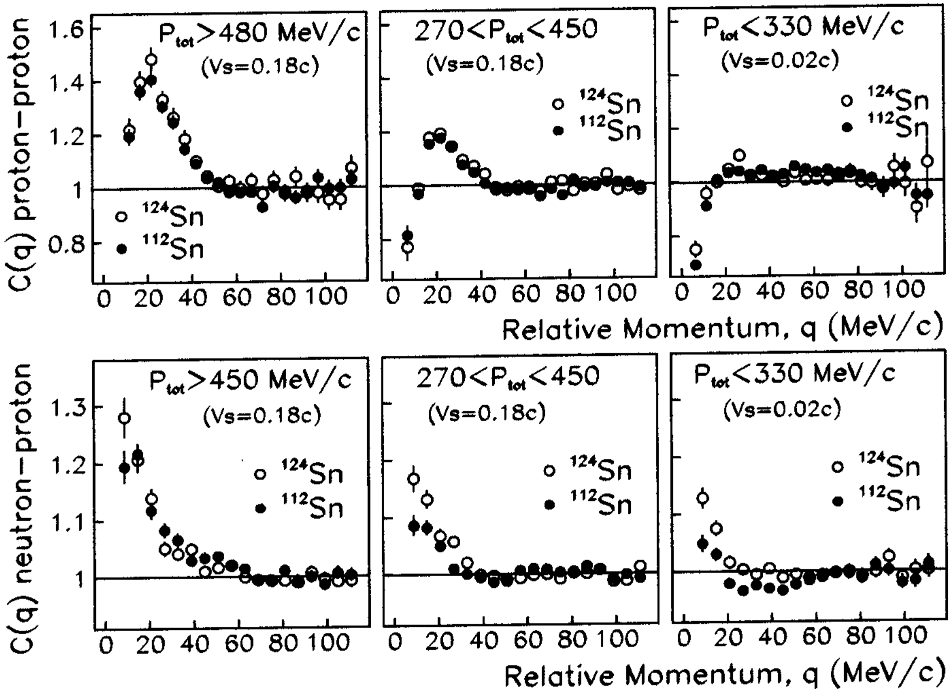
Isospin effects ....in $\overrightarrow{p_{tot}} = \overrightarrow{p_1'} + \overrightarrow{p_2'}$ *gated correlations*



in the source rest frame?

Source analysis gives velocity 0.02c for TLS and 0.18c for IS

Gates to probe IS are:

- **Θ = 30 - 42°**
- **high P_{tot} (early emission)**
- **interm. P_{tot} (late emission)**

TLS:

- **low P_{tot}**
- **Θ = 54 - 120°**

Observations

- **progressively weaker correlations from left to right –> longer emission times**
- **higher correlation peaks for the n-rich isotope**

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Interferometry - calculations

1. **Comb. of Evaporation and $\Delta t = 0$ Gaussian in r and p (old data) [Jakobsson, Pratt]**
2. **Expanding fireball + Evaporation, Gaussian in space, Boltzmann in energy, succesive cooling (LNS and KVI data, see figure to the right) [Czörgö, Helgesson]**
3. **BUU (Bao-An Li), isospin dependent and momentum-independent, Skyrme potential $U = Au + Bu^{\sigma} + C_z u^{\gamma} \delta^2$ NN collisions with Pauli blocking. Freeze-out density $\rho_o/8$ (so farKVI pp and np data) [Helgesson]**

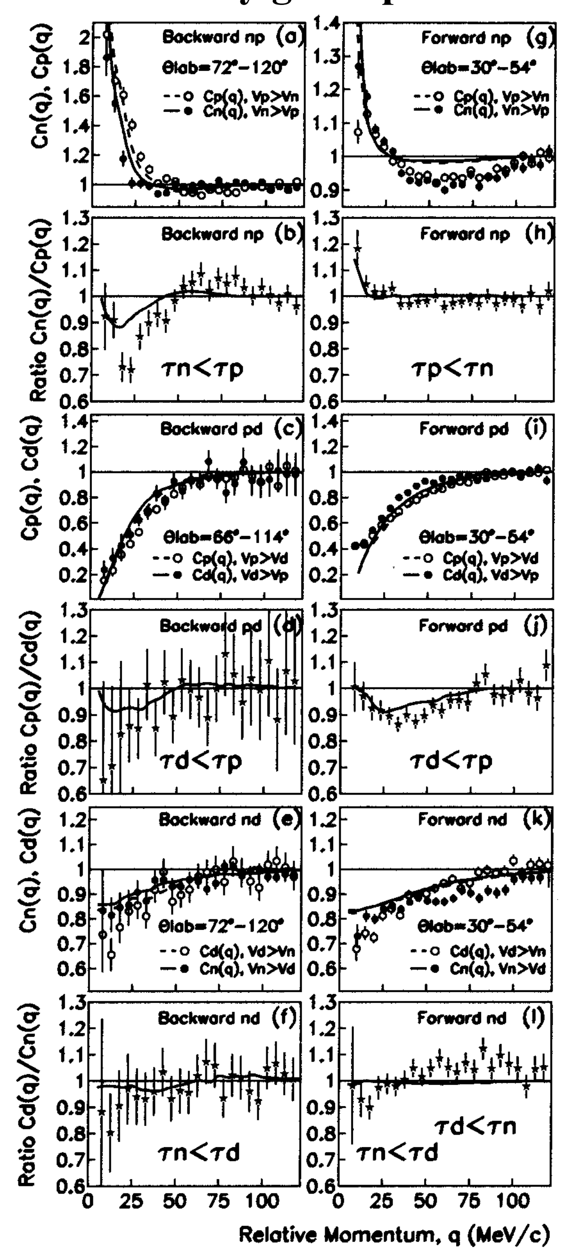
....all convoluted to the Koonin-Pratt two-particle relative wave functions

Data where singles spectra are used to set source velocities and version 2 then is introduced in the correlation plots are from:

LNS Catania, 45A MeV ^{58}Ni + ^{27}Al, ^{nat}Ni, ^{197}Au [xxx]

KVI Groningen, 61A MeV ^{36}Ar + ^{27}Al (see right), ^{112,124}Sn

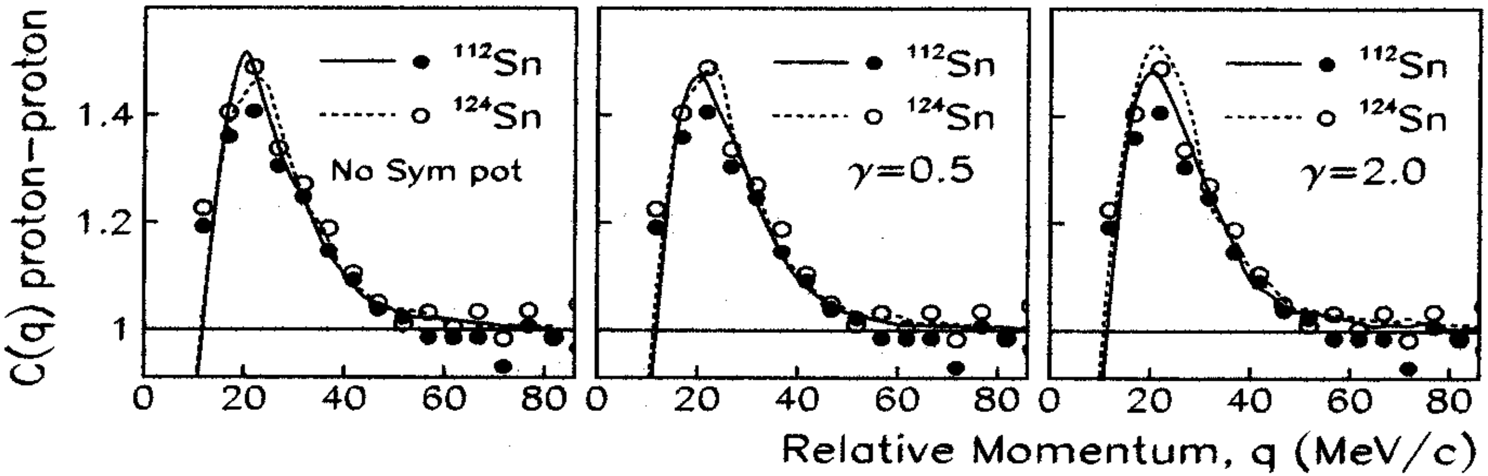
Velocity gated pairs



Isospin effects ....calculations vs data

Calculations, model 3, (J Helgesson, BUU – Bao-an Li)

no isospin soft stiff e.o.s



The overall agreement is quite good (BUU stopped at 110 fm/c)
Isospin dependent potential gives better agreement
The stiff eos describes the differences better

pn data does not fit into this scheme!

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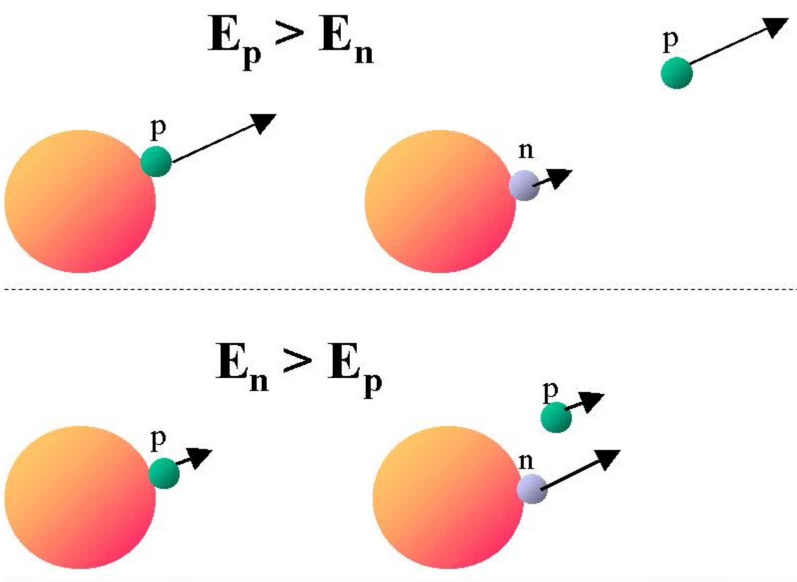
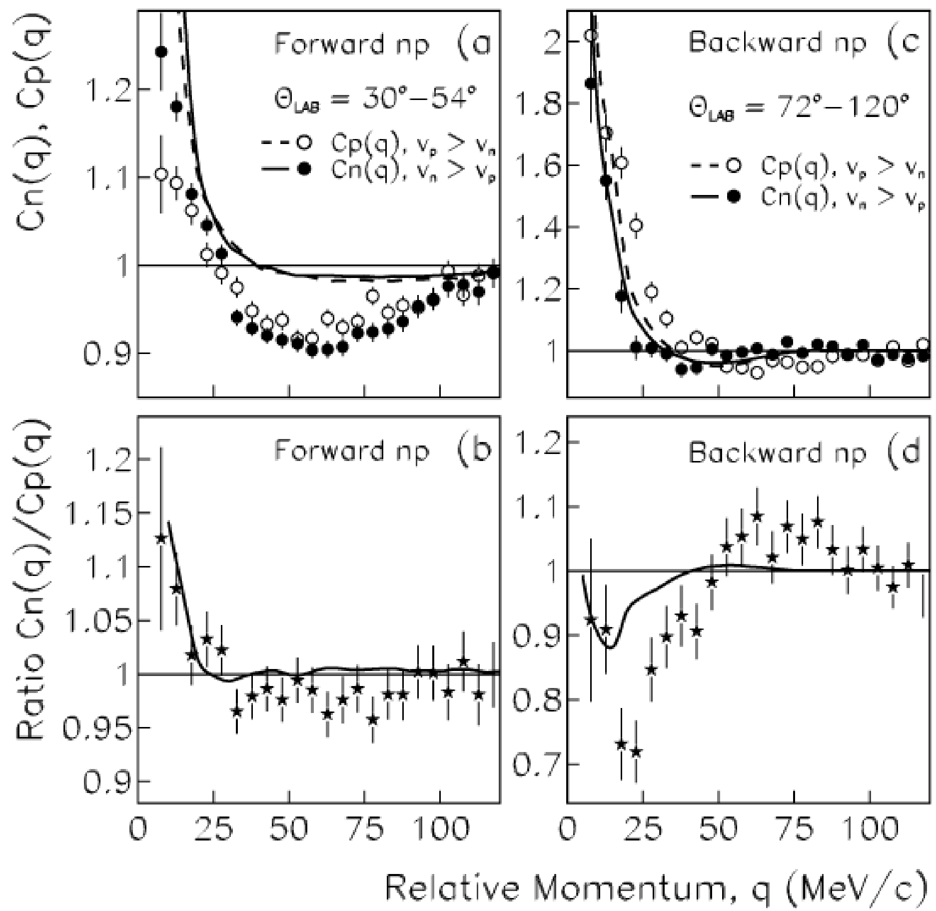
As chronometer...........

Ar + Al, 61A MeV, velocity gated correlations

Classical picture of ....





.... The Lednicky prescription on how to utilize the asymmetry of the unlkie-particle wavefunction

For beam/target residues : $t_d < t_p < t_n$

For dynamic (IE) sources : $t_n < t_d < t_p$

But IE source at 45A MeV : $t_p < t_d < t_n$

Neck formation →

Perspectives for ASY-EOS

Detectors:

Some of those detector systems that are proposed for ASY-EOS are well suited as c.p. Interferometers (see next slides)

Neutron detectors (LAND, NEULAND, Liq. scint. Walls) must be carefully evaluated as nn and part of np intterferometers

Parts of CHIMERA well suited for PFs. What about time and energy resolution now for the use as interferometer?

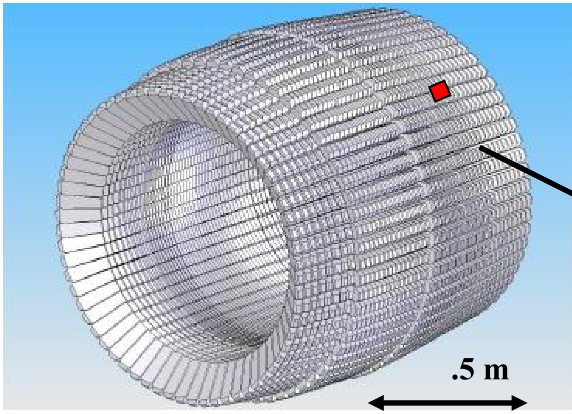
Electronics: Trigger electronics well known (see last slide).

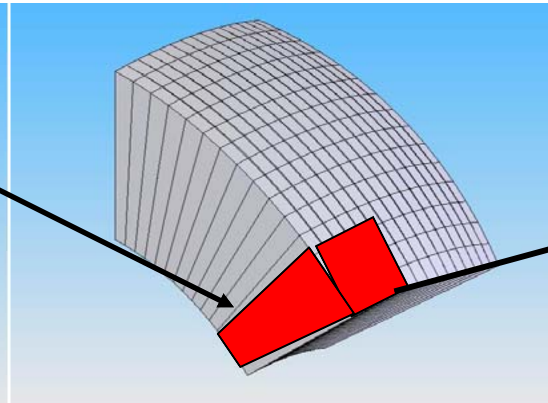
DAQ: No extreme requirements (slow count rates)

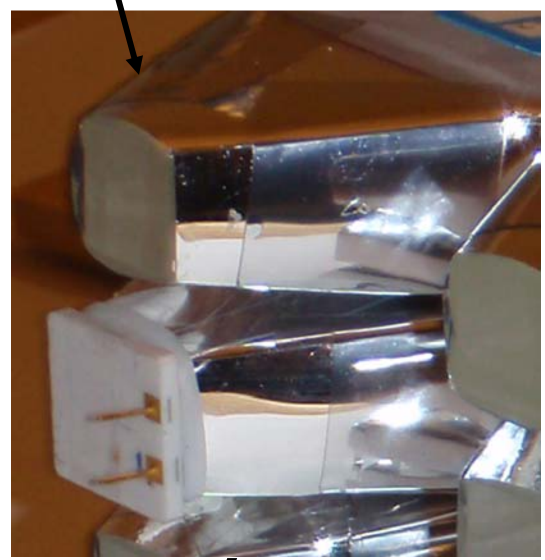
Physics: Extrapolations of BUU + evaporation

and QMD + evaporation to 400 – 800A MeV needed

Calorimeter part of Demonstrator(s)
- 3*5 CsI(Tl) detectors of CALIFA/barrel type -







5 mm

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V. Avdeichikov
J. Cederkäll
K. Fissum
P Golubev
L. Isaksson
D. di Julio

Produced by Monocrystal, Kharkov

Assembled and bench tested in Lund and Santiago de C.

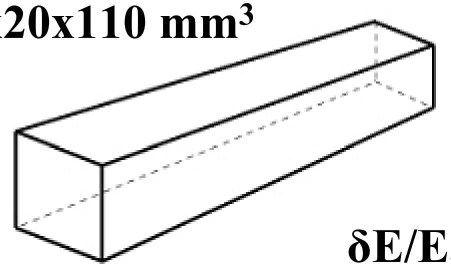
Tested in 180 MeV proton beams at TSL, Uppsala

final choice of readout device to be made soon (normal PDs work very well for protons and light fragments but unfortunately not for photons at 100 keV, noise level too high)

*) USC design

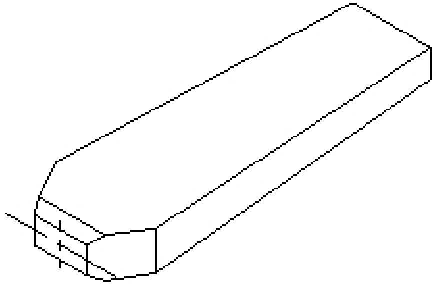
TSL test with 179 MeV protons show small differences in the energy resolution between,

20x20x110 mm³

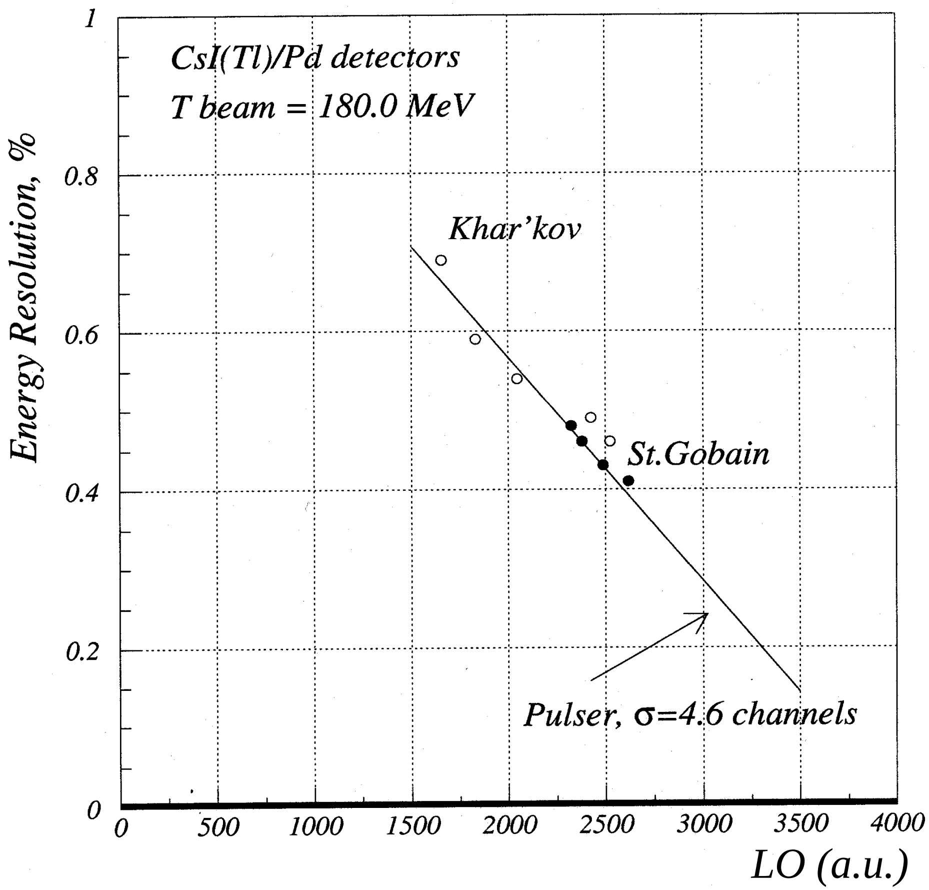


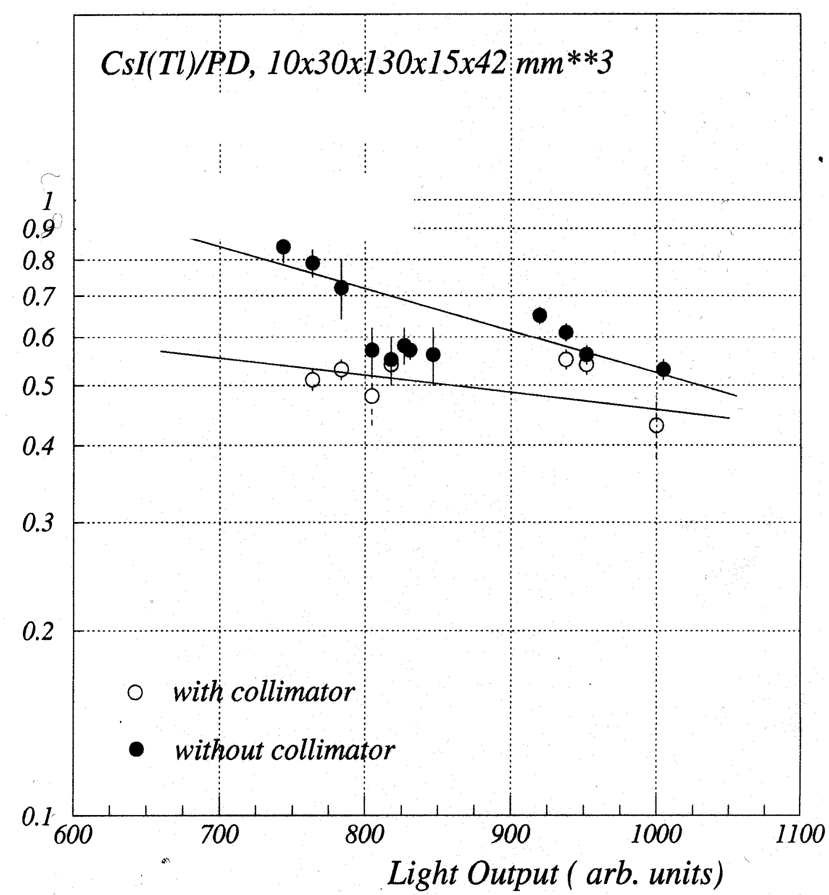
δE/E, 0.4 – 0.7 %

10x30x100/130 mm³
two-truncated
pyramide (USC) type



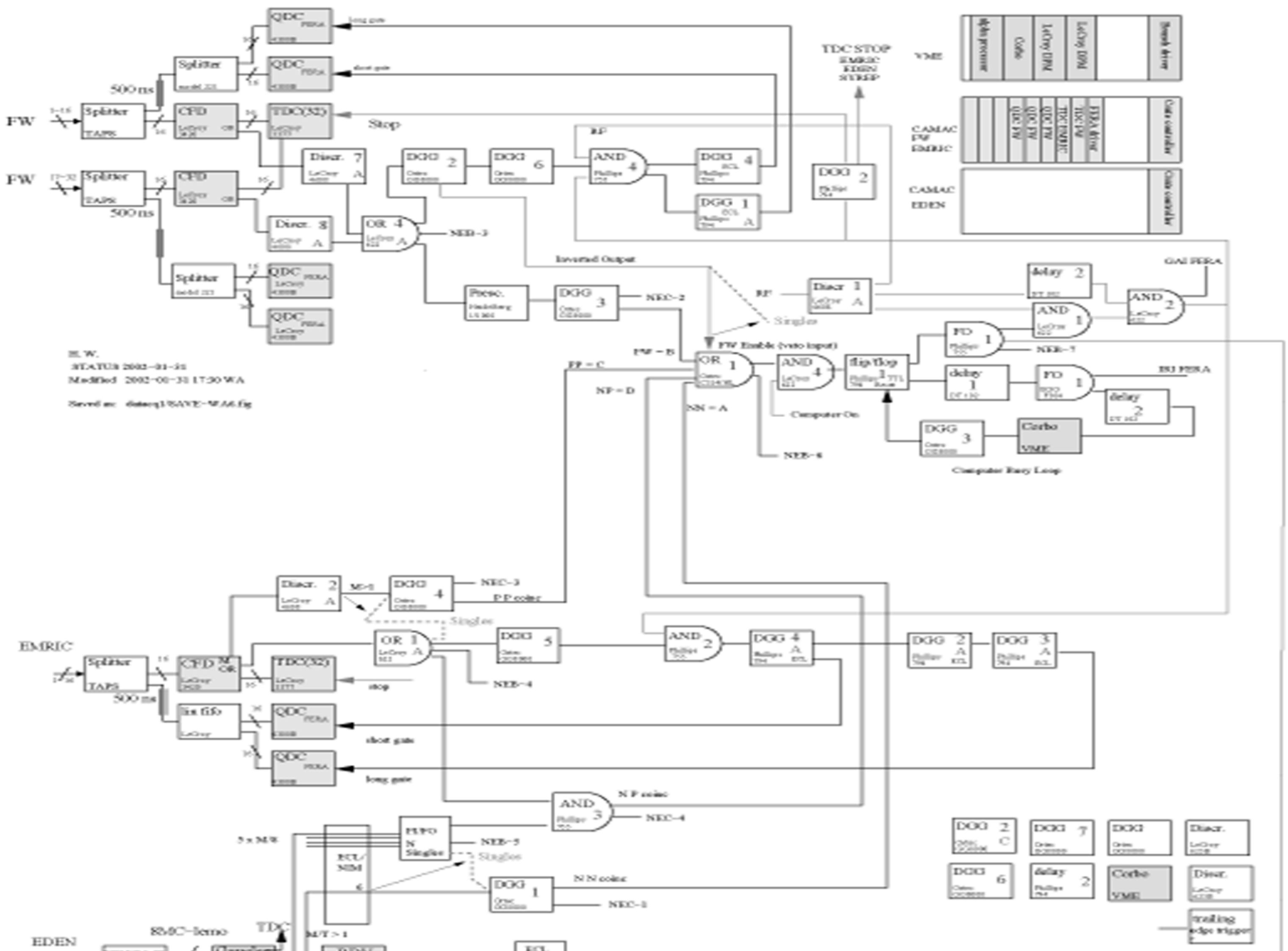
δE/E, 0.5 – 0.9%





Trigger electronics in NIM/CAMAC standard

for typical nn-np-pp interferometer



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