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Fragmentation peak splitting of the light ions in $^{56}Fe + {}^{9}Be$ collisions at 0.23 GeV/nucleon



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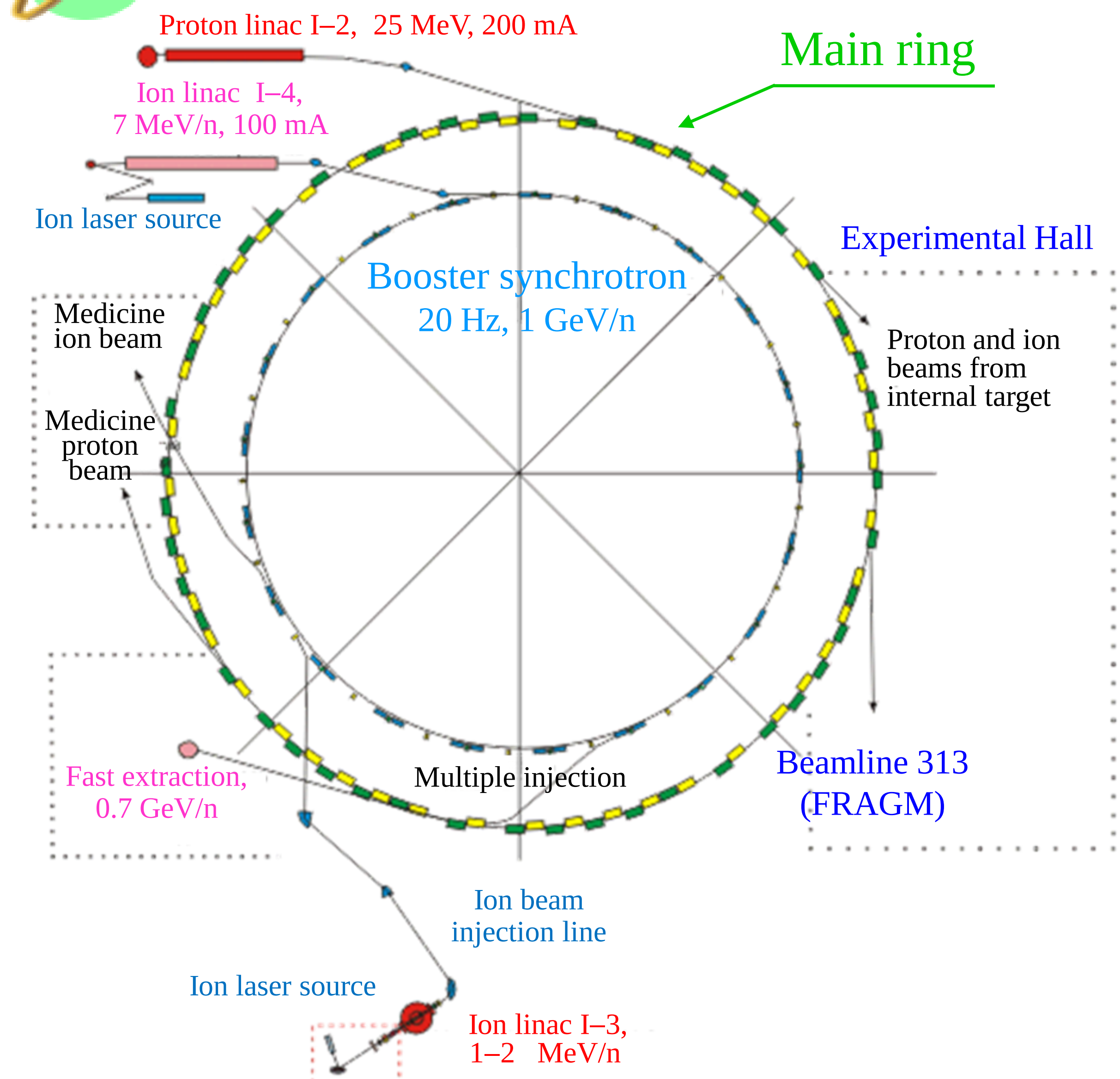
Motivations and purposes

- FRAGM detector was optimized to measure yields of nuclear fragments produced at ion–ion interactions and operated at accelerating–storage complex TWAC at ITEP (Moscow) until 2012
- Report is based on the results obtained for reaction : $^{56}Fe + ^{9}Be \rightarrow f + X$, where f – proton or nuclear fragment registered with the detector at small angle (~ 3.5^0)
- Experimental setup permits us to detect ^{56}Fe fragments (p, d, t, ^3He, ^4He …) of kinetic energy at $T_0 = 0.230$ GeV/nucleon
- Measurement of the differential cross sections for fragments :
  - ✓ Allows to test of the different models of ion–ion interactions covering large kinematic region (evaporation and cumulative)
  - ✓ Gives a possibility to calculate the physical parameters of nuclear structure used in the theoretical models, such as thermodynamical (thermal) and coalescence ones
- Data on iron fragmentation for light fragments are absent and this measurement can cover this gap. Also, current study is important as input to transport codes

TWAC – ITEP



TWAC – TeraWatt Accumulator Complex

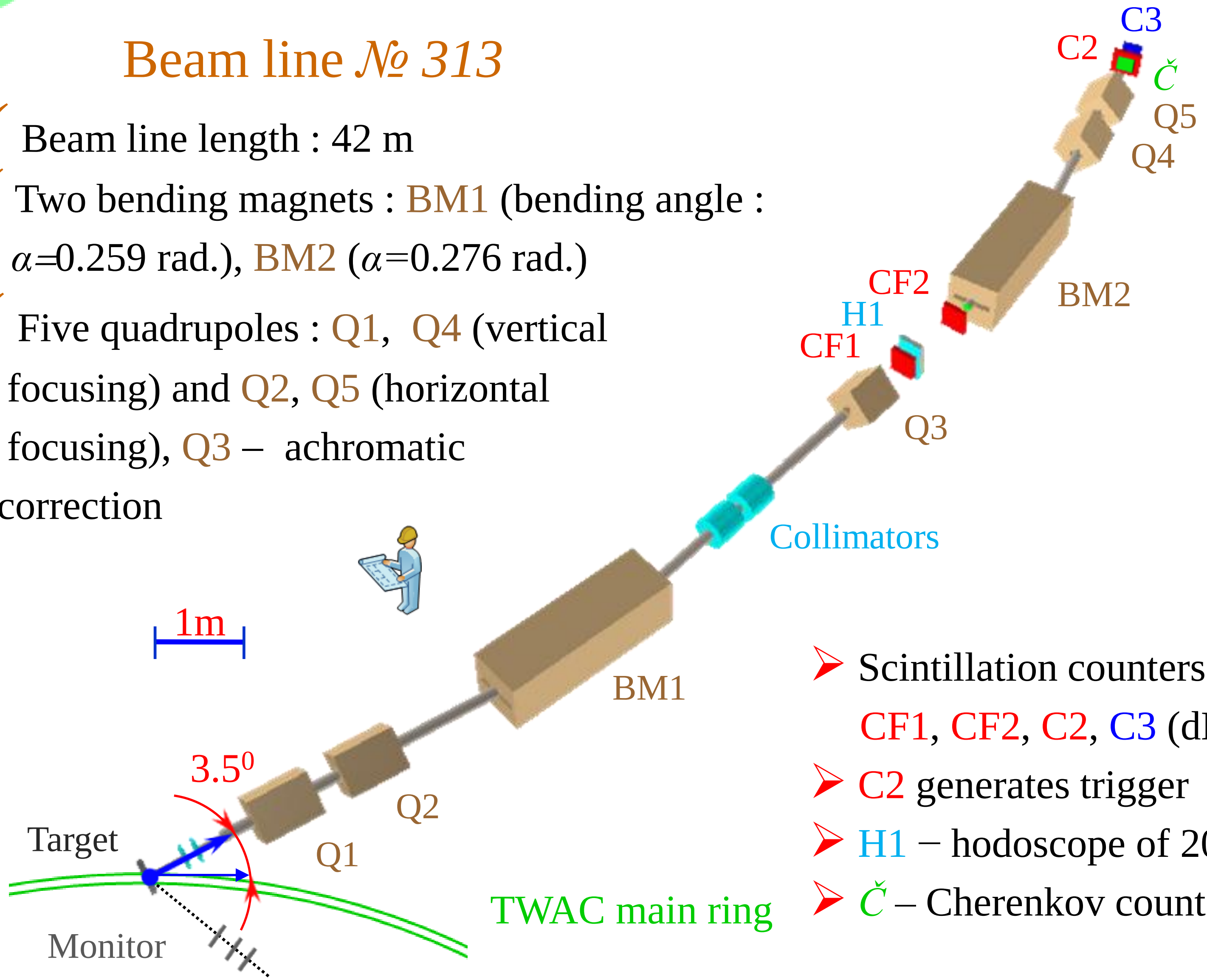
TWAC last parameters

- ✓ Proton acceleration :
  50 – 10000 MeV
- ✓ Ion acceleration :
  up to 4 GeV/nucleon
- ✓ Ion accumulation :
  up to 700 MeV/nucleon
- ✓ Accelerating ions :
  up to ^{56}Fe
- ✓ As a result of the strong fire accident in 2012, TWAC was decommissioned. The restoration / modernization of the accelerating–storage complex is a priority task of ITEP

Experiment FRAGM

Beam line № 313

- Beam line length : 42 m
- Two bending magnets : BM1 (bending angle : α=0.259 rad.), BM2 (α=0.276 rad.)
- Five quadrupoles : Q1, Q4 (vertical focusing) and Q2, Q5 (horizontal focusing), Q3 – achromatic correction

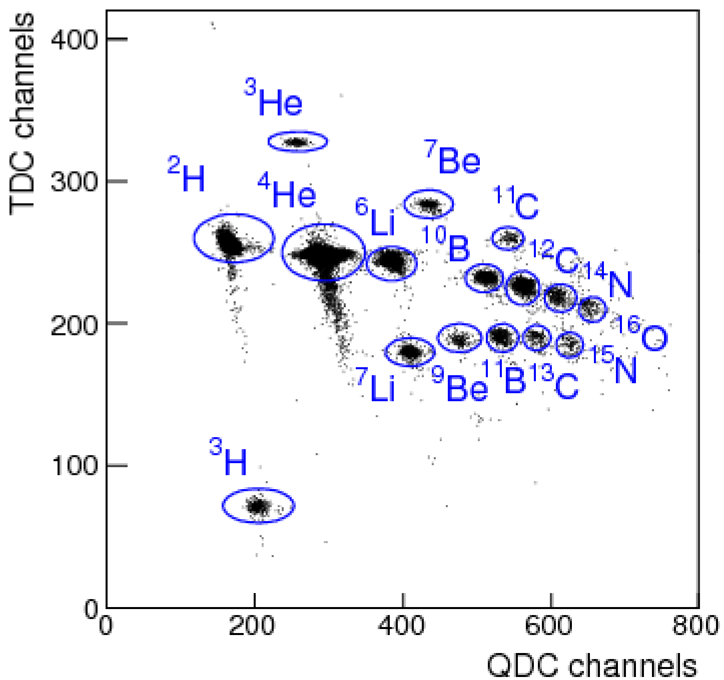


- Scintillation counters : CF1, CF2, C2, C3 (dE/dx, TOF)
- C2 generates trigger
- H1 – hodoscope of 20 elements
- Č – Cherenkov counter

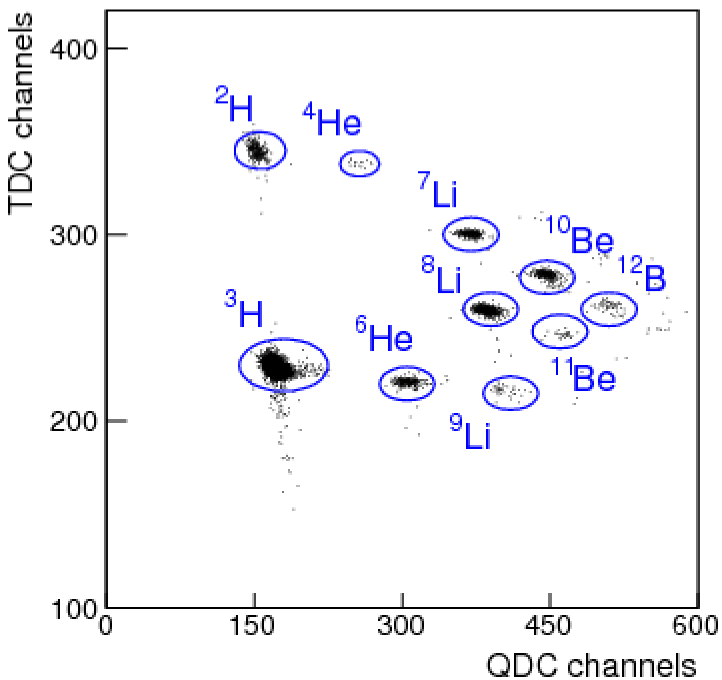
Fragment separation in FRAGM

Fe – Be collisions at T_0 = 230 MeV/c

Rigidity=p / Z = 1.3 GeV/c



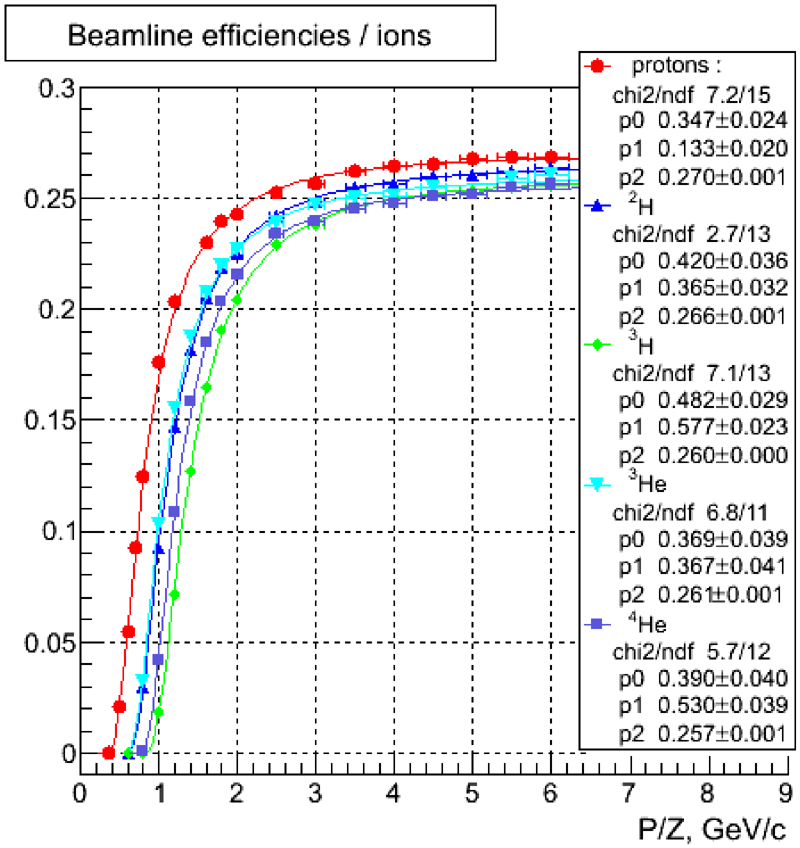
Rigidity=p / Z = 1.8 GeV/c



✓QDC (function of dE/dx and Z of fragment) (from CF1) vs TDC (TOF as a function of the atomic mass number of fragment) between CF1 and C2

✓Regions of the different fragments are well separated and can be clearly selected

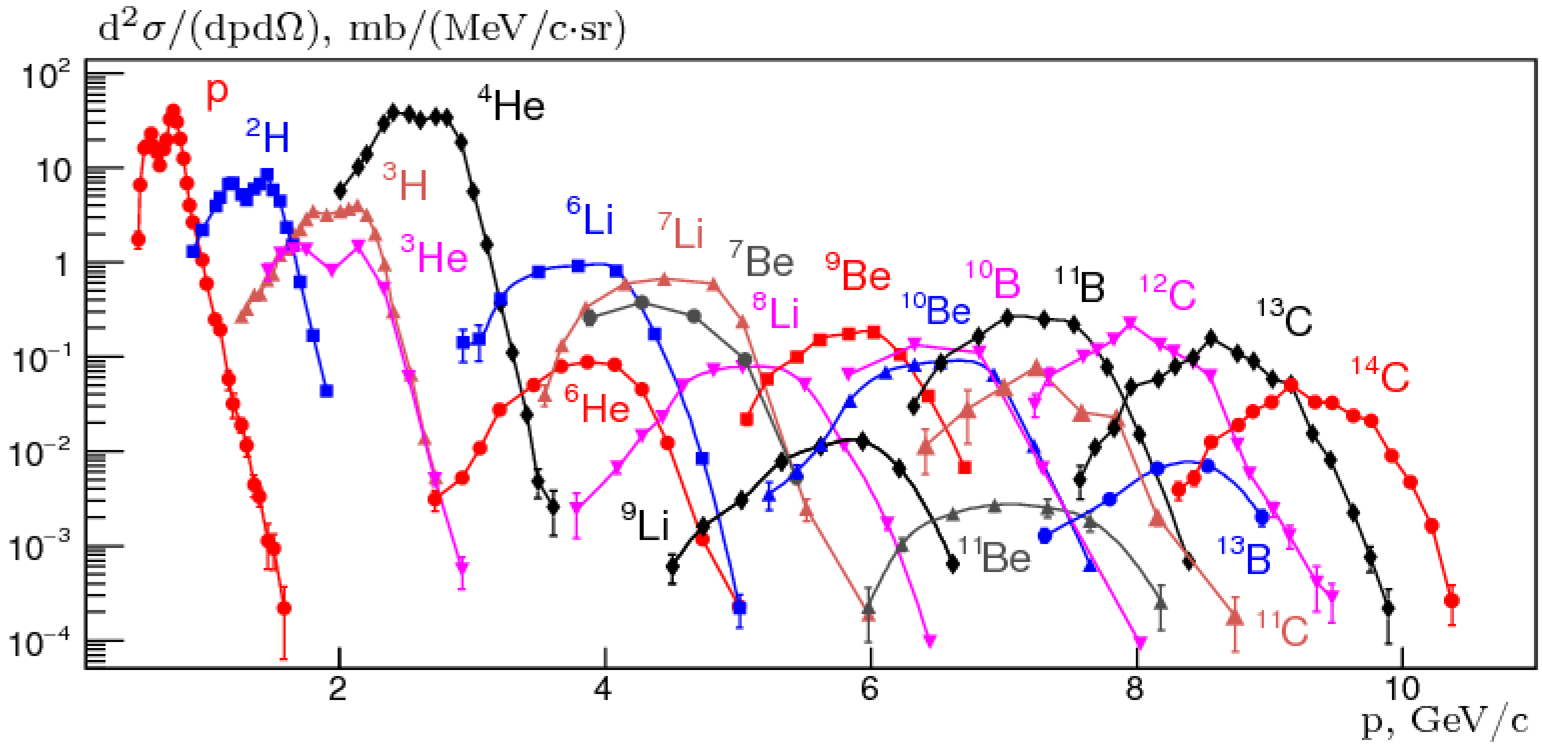
Beamline efficiencies for different ions



- Beamline has several construction features (beam pipe break ~ 3 m, stubs etc.); all counters are positioned on the beam. So, detection efficiency depends on beam momentum
- MC for FRAGM is performed with GEANT4 code (version 4.9.4)
- Protons and light ions (^{2}H, ^{3}H, ^{3}He, ^{4}He) at 0.6 < P/Z < 6 GeV/c
- Values of the magnet currents are adjusted for different momenta

- Program transports particles in the magneto – optical channel taking into account multiple scattering effects, ionization losses and absorption in the detector materials.
- Efficiency is essential for P/Z < 2 GeV/c

Measured fragment momentum spectra



- Up to 22 fragments have been measured from proton to ^{14}C
- There are many other fragments, which are not analyzed (till ^{16}O) or dropped out from the FRAGM beamline
- Data are normalized to BC model prediction for protons at fragmentation maximum (with total cross section σ_{tot} = 1759 mb)

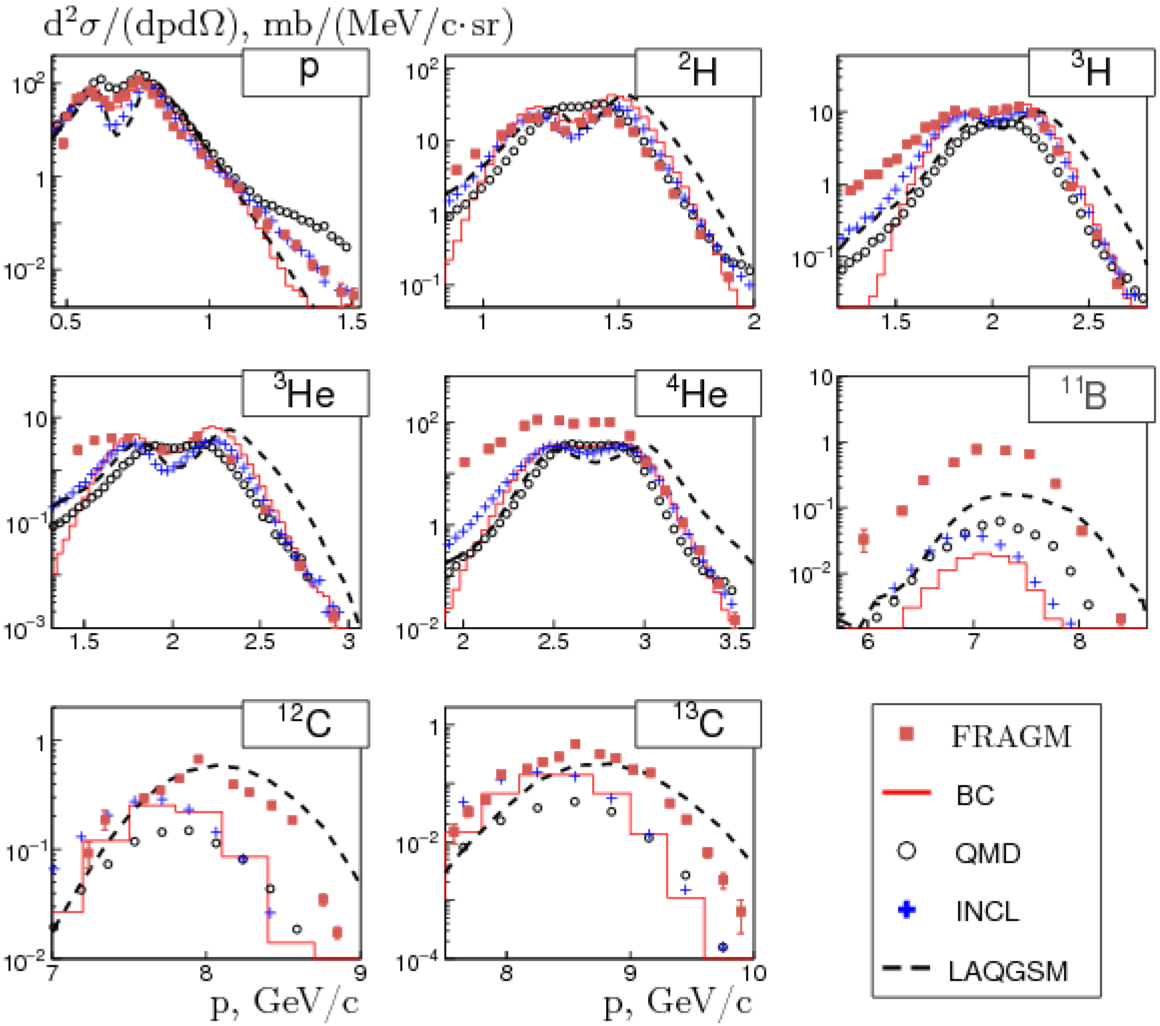
Ion – ion interaction models

- Binary Cascade (BC, GEANT4 toolkit, G. Folger *et al.*, EPJA 21 (2004) 407) :
  - Useable when either projectile or target are light ions. But, it gives a reasonable results for for higher mass ions too
  - Novel approach of the intra-nuclear cascade is implemented: nucleons distributed in space according to nuclear density; nucleon momenta are distributed assuming Fermi gas model
- Quantum Molecular Dynamics (QMD, GEANT4 toolkit)

  T. Koi *et al.*, AIP Conf. Proc. 896 (2007) 21:
  - Available for light and heavy ions
  - All nucleons are considered as participants and are propagated by means of phenomenological nucleon-nucleon potential
  - Includes a high number of different resonances
- Liege Intranuclear Cascade (INCL++, J. Dudouet *et al.*, PR **C**89 (2014) 054616) :
  - Combines best features of the BC and QMD models
  - Gives a better agreement with our data by the kinematic parameters of fragments
- Los Alamos version of Quark Gluon String Model (LAQGSM03.03)

  LA-UR-11-01887, presented by M.I. Baznat (Academy of Sciences of Moldova)
  - First stage is the intranuclear time-dependent cascade developed initially at JINR
  - It was tested in a wide energy region up to 1 TeV/nucleon and large number of ions

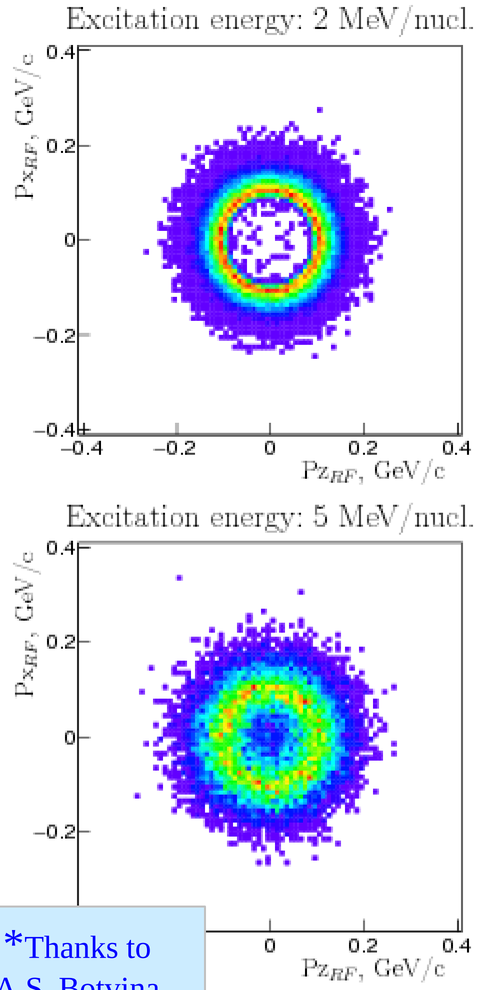
Comparison : FRAGM data vs models



- From protons to ^{4}He all models except QMD give a good description of the experimental data
- The QMD model predicts much narrower fragmentation peaks for all fragments than are observed in the experiment
- INCL++, LAQGSM and BC give similar results both by cross section and by shape of the peaks; both models demonstrate peak splitting
- Yields of fragments decrease with A grows and the accuracy of the prediction becomes worse

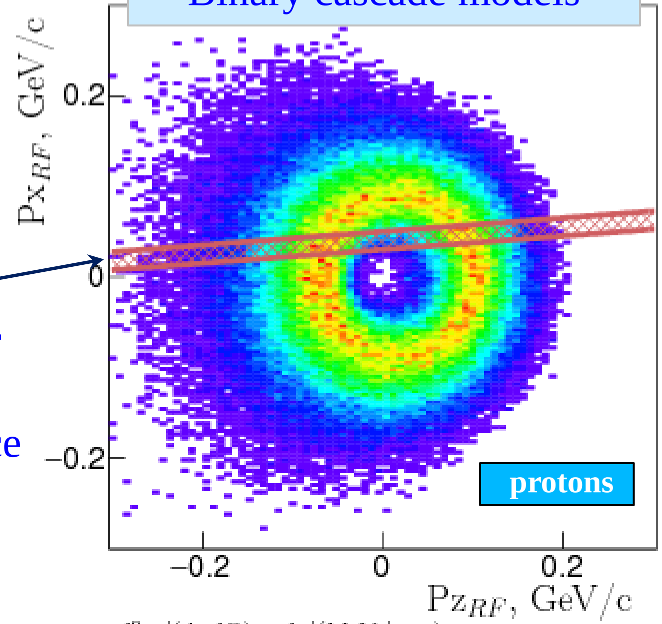
Comments to the fragmentation peak splitting

Statistical multifragmentation model (SMM) at different excitation energies*

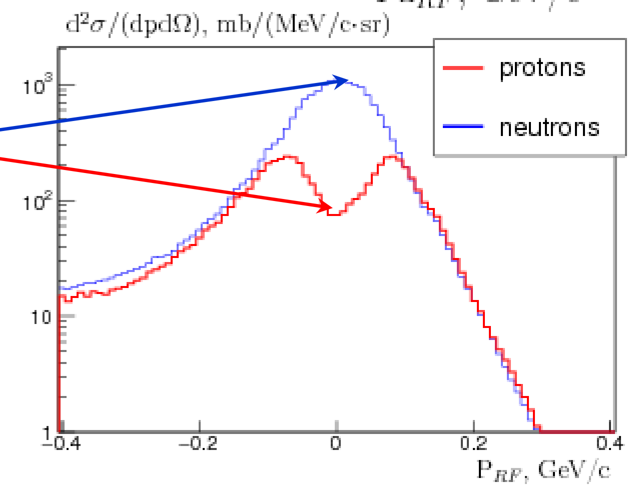


*Thanks to A.S. Botvina

Binary cascade models

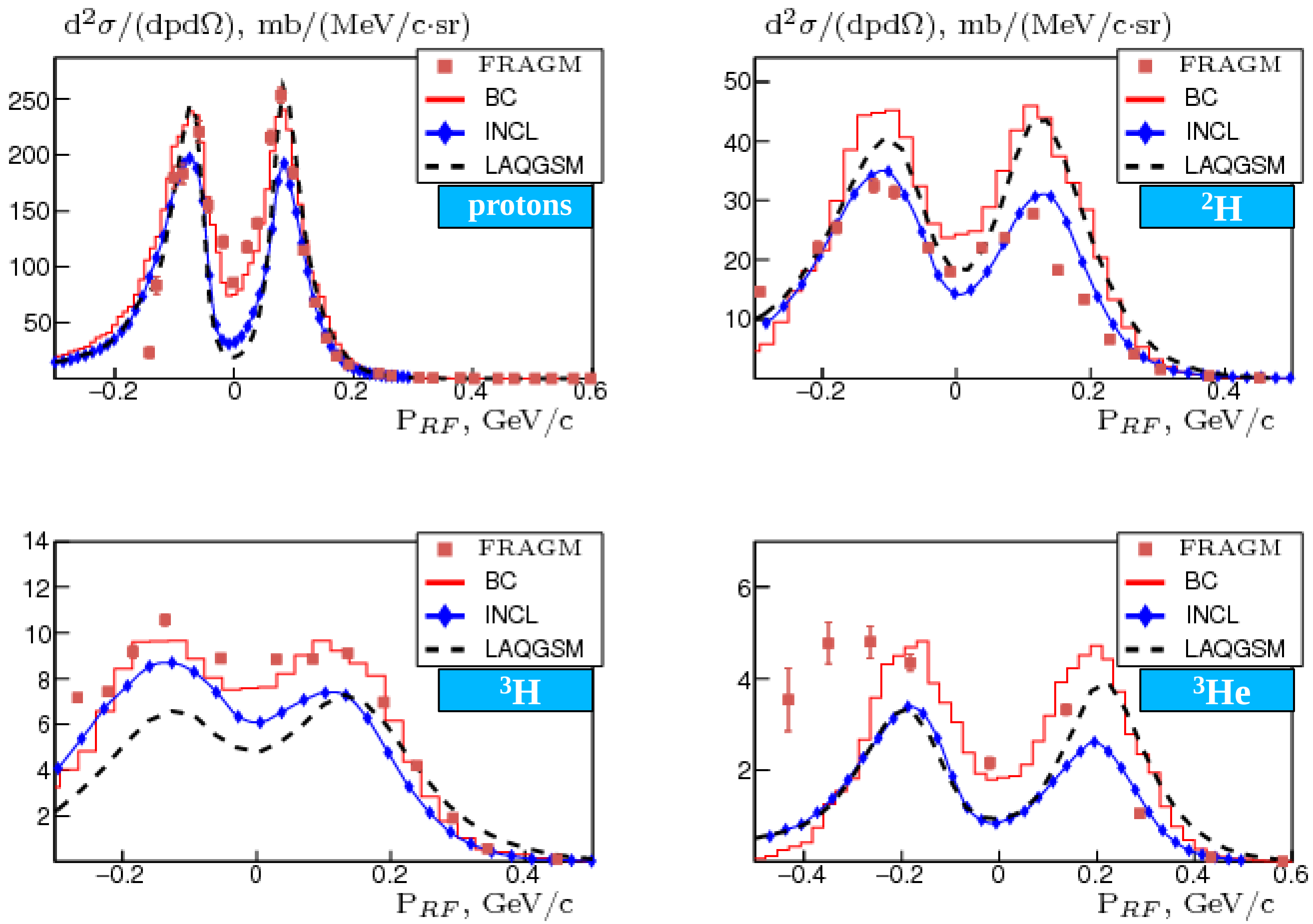


Detector angular acceptance



Effect of the Coulomb repulsion

Splitting of the rest frame peak



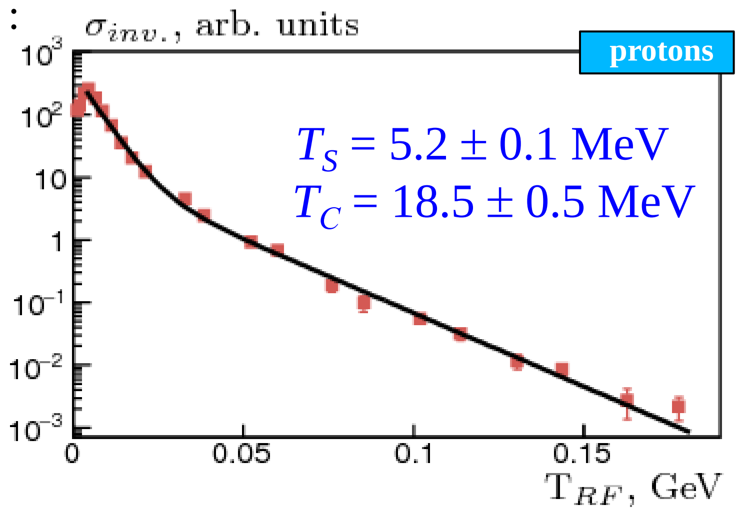
- Momentum spectra of fragment in the projectile (^{56}Fe) rest frame for light ions
- Splitting of the fragmentation peak around zero, this effect is not seen for A > 4

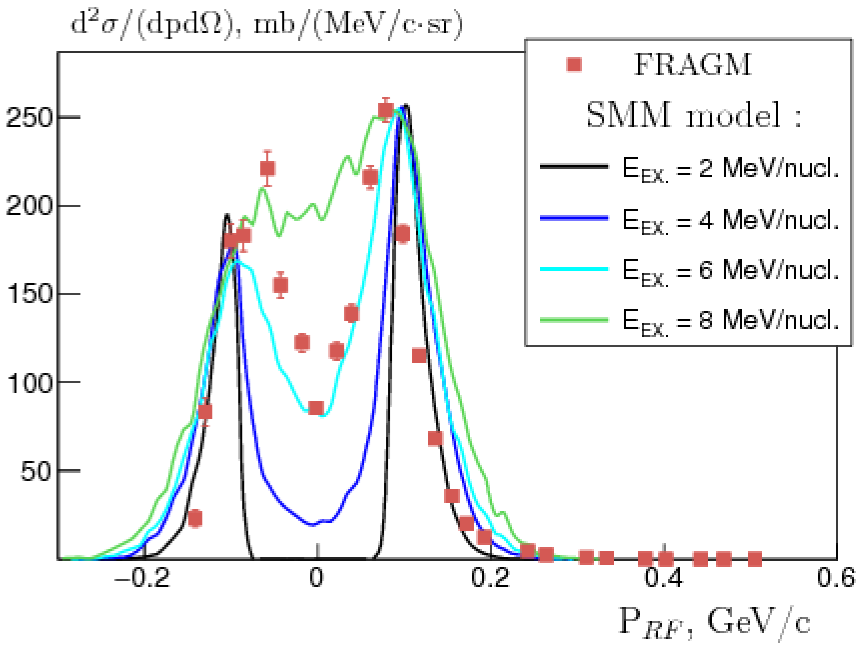
Excitation energy estimation

➢ In the thermodynamical model the projectile rest-frame kinetic energy spectra (T) can be described by a sum of two exponents with slope parameters T_S (statistical temperature) and T_C (high momentum or cumulative temperature) in the form :

$$Ed^3\sigma/d^3p = A_S e^{(-T/T_S)} + A_C e^{(-T/T_C)}$$

$\Rightarrow$



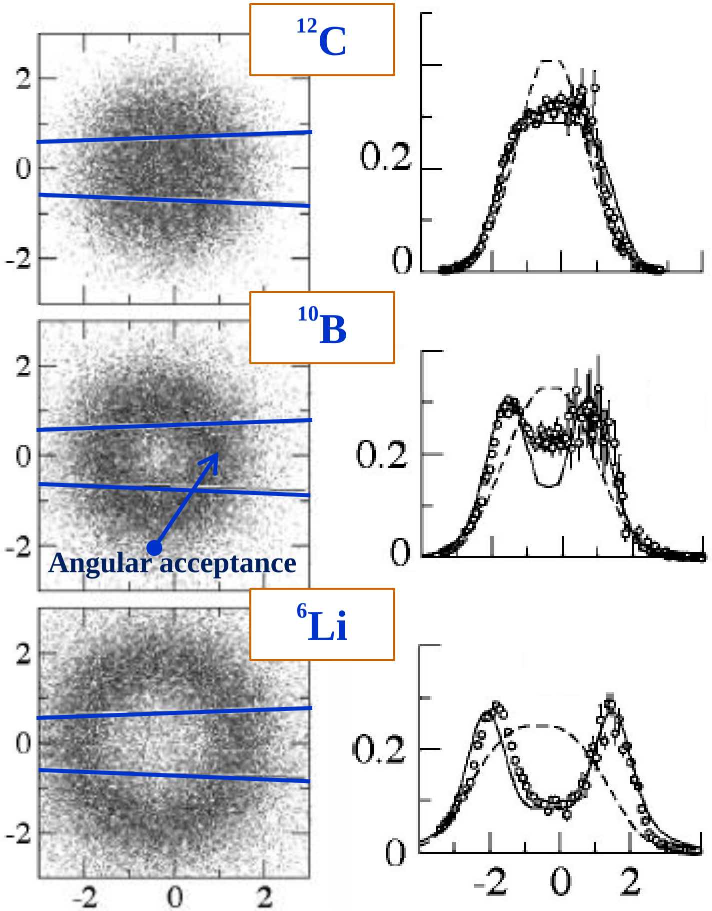


➢ SMM model has a possibility to change excitation energy (Eex.) of the projectile-like fragment (PLF) source

➢ Good agreement between data and model can be reached at Eex. ~ 6 MeV/nucleon

➢ This value is in a good agreement with the temperature T_S

GSI–FRS experimental data



^{56}**Fe** on hydrogen target
Plot : velocity in the beam frame ($\upsilon_{\parallel}$, $\upsilon_{\perp}$)

Velocity in the beam frame in cm/ns units

- Similar set of data was obtained at GSI-FRS (Darmstadt) at the heavy-ion synchrotron SIS
- Beam : ^{56}Fe at energy equal to 1 GeV / nucleon and different targets (hydrogen and titanium); detector was constructed as magnetic spectrometer to perform high-resolution velocity measurement
- Wide range of the fragments, but higher than ^{6}Li, which has most visible peak distortion
- Main mechanism of the peak splitting is claimed to be an asymmetric fission by mass of the PLF source
- Effect of the Coulomb repulsion component in the fragmentation process rather reflects the dominating influence of a very asymmetric fission
- Basic paper : P. Napolitani *et al.* Phys. Rev., C. 70, 054607 (2004)

Conclusions

✓ Fragment yields for the reaction $^{56}Fe + Be \to f + X$ were measured at ion incident energy T_0 = 0.230 GeV/nucleon with a magnetic spectrometer in the FRAGM experiment at accelerating–storage complex TWAC at ITEP (Moscow).

✓ Fragments from protons to carbon isotopes were identified by the correlation measurement TOF–ionization losses in scintillation detectors

✓ It's the first measurement of ^{56}Fe fragmentation into light fragments with $A < 6$

✓ The momentum spectra in the laboratory system were compared with the predictions of ion–ion interaction models: INCL++, LAQGSM, QMD and BC. The effect of the momentum split was found for light elements (^{1}H, ^{2}H, ^{3}H, ^{3}He and ^{4}He), which disappears on ^{6}Li

✓ Two models (INCL++ and LAQGSM) reproduce the shape of the fragment momentum spectra well including a peak split. It looks as an influence of the Coulomb field

✓ SMM model permits us to define the PLF source excitation energy as a result from the fragmentation peak splitting

✓ Similar measurements were performed on the proton target at GSI–FRS. The split of the fragmentation peaks was obtained for a set of the fragments with $Z = 3 \div 5$. Authors claimed that main source of the peak splitting is an asymmetrical fission of the PLF source

Thank You