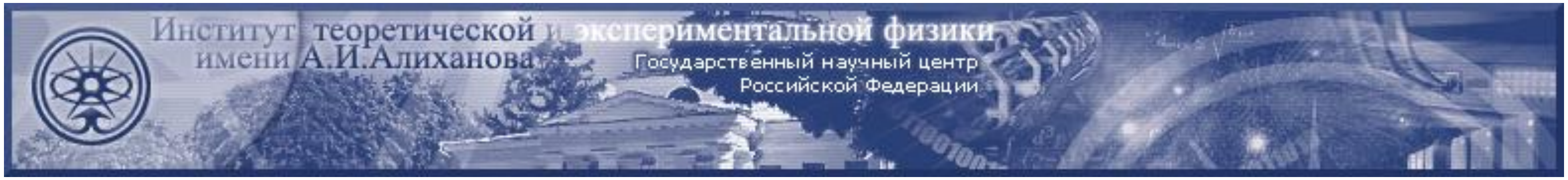

Light fragments from (C + Be) interactions at 0.6 GeV/nucleon

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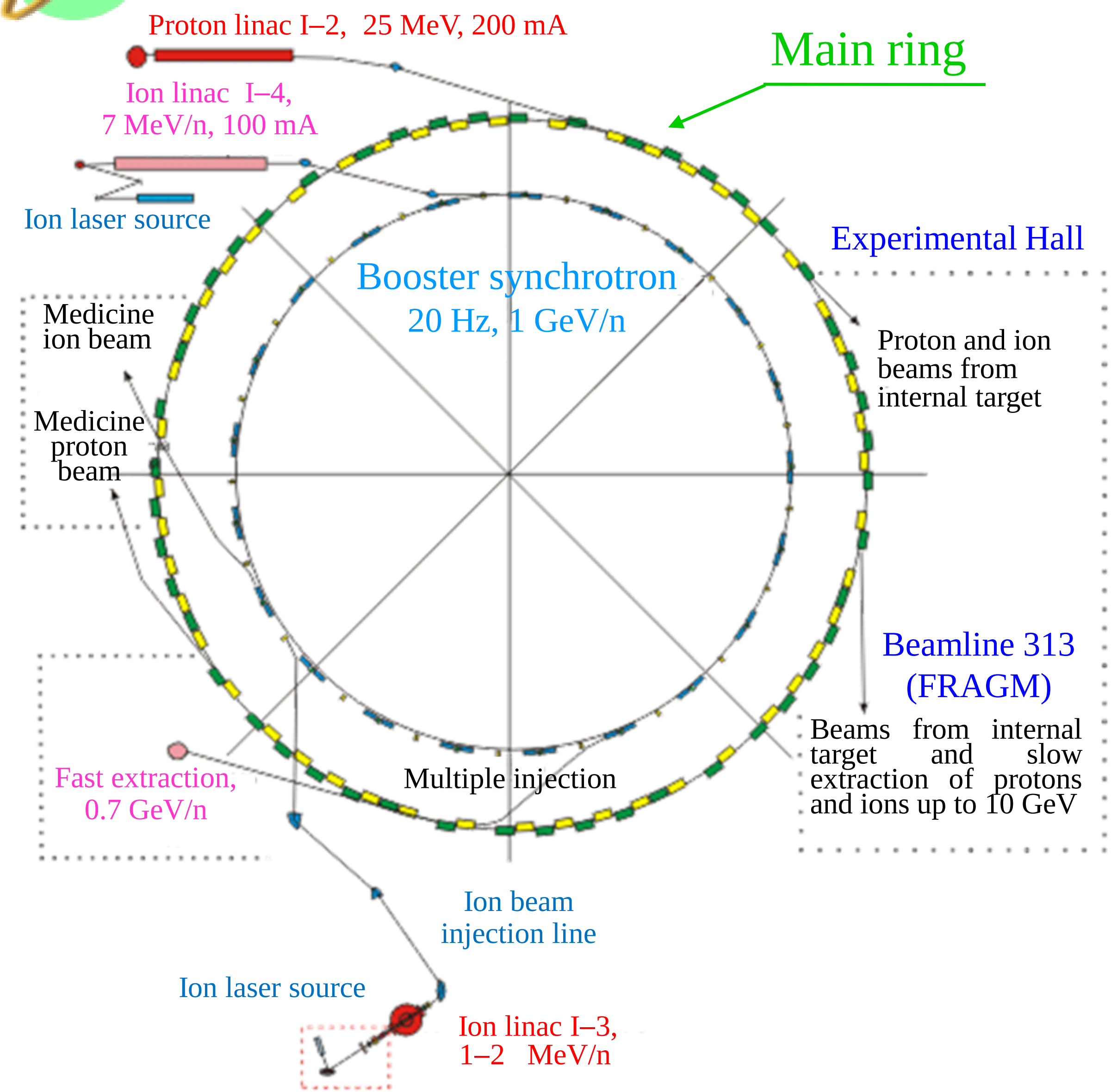
Motivation and purposes

- FRAGM detector is optimized to measure yields of nuclear fragments produced at ion–ion interactions and operated at TWAC accelerated complex at ITEP (Moscow)
- Reaction that is being studied in our experiment : $^{12}C + Be \rightarrow f + X$, where f – proton or nuclear fragment registered by detector at small angle (~ 3.5^0)
- Experimental setup permits us to detect a large set of the fragments (p, d, t, ^3He, ^4He, ^6He, ^8He, etc.) for projectile kinetic energies T_0 = 0.2 – 3.2 GeV/nucleon
- Precise measurement of high energy fragment spectra allows :
  - ✓ Study cumulative (high momentum) effect for protons produced in the kinematic region forbidden for interaction with free nucleon. Cumulative particles were discovered in 70's (JINR, Dubna), but the nature of effect is still under discussion
  - ✓ There is a lack of data on fragment emission at intermediate energies in ion–ion collisions
  - ✓ Test of the different models of ion–ion interactions covering large kinematic region (fragmentation region and cumulative part)
- This study is important as input to transportation codes for radiotherapy with ions and for radioactive ion beam design for TWAC future upgrade

ITEP accelerator complex TWAC



TWAC= TeraWatt Accumulator Complex

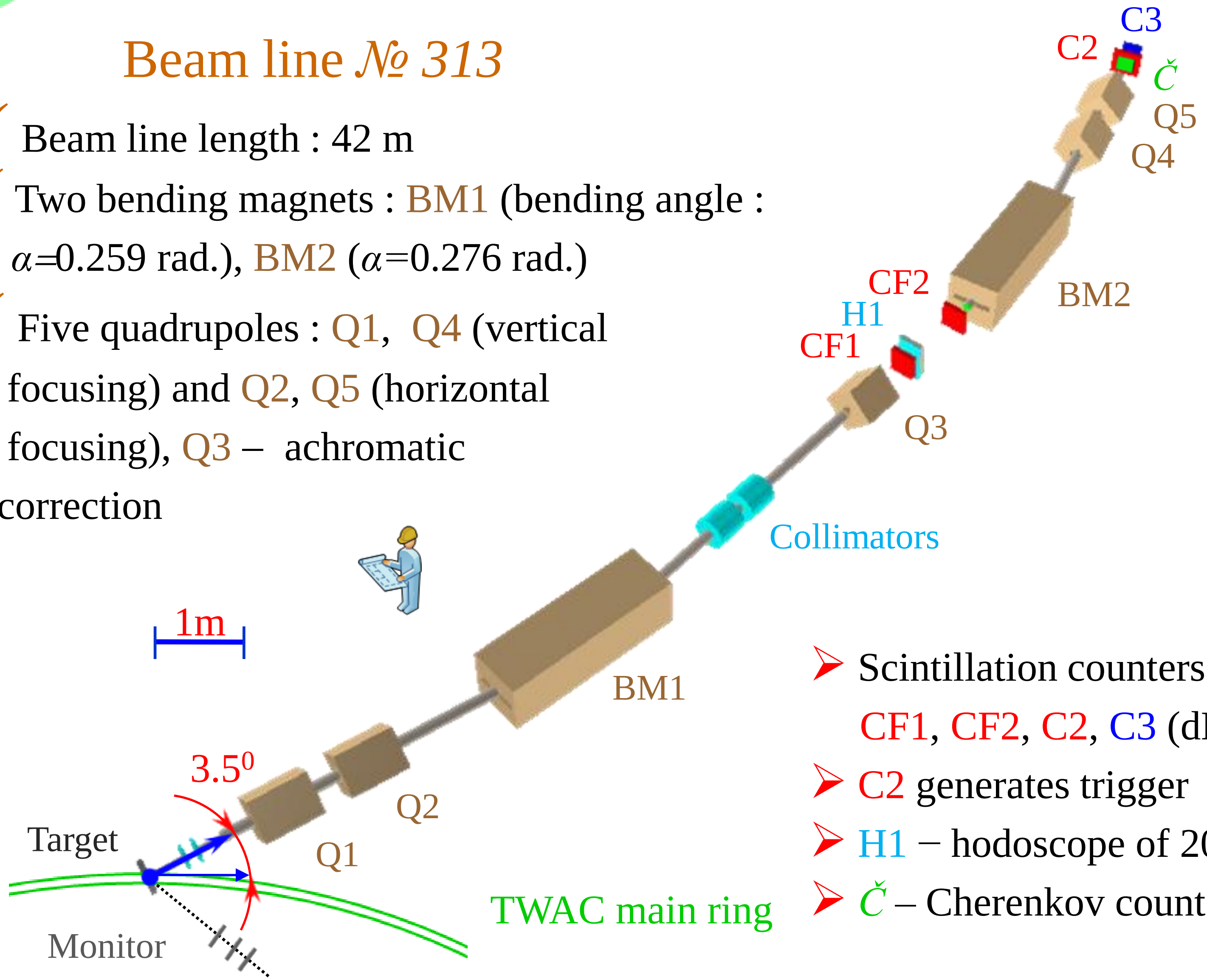
TWAC current parameters

- ✓ 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
- ✓ Typical intensity :
  10^{11} nucleons / s

Experiment FRAGM

Beam line № 313

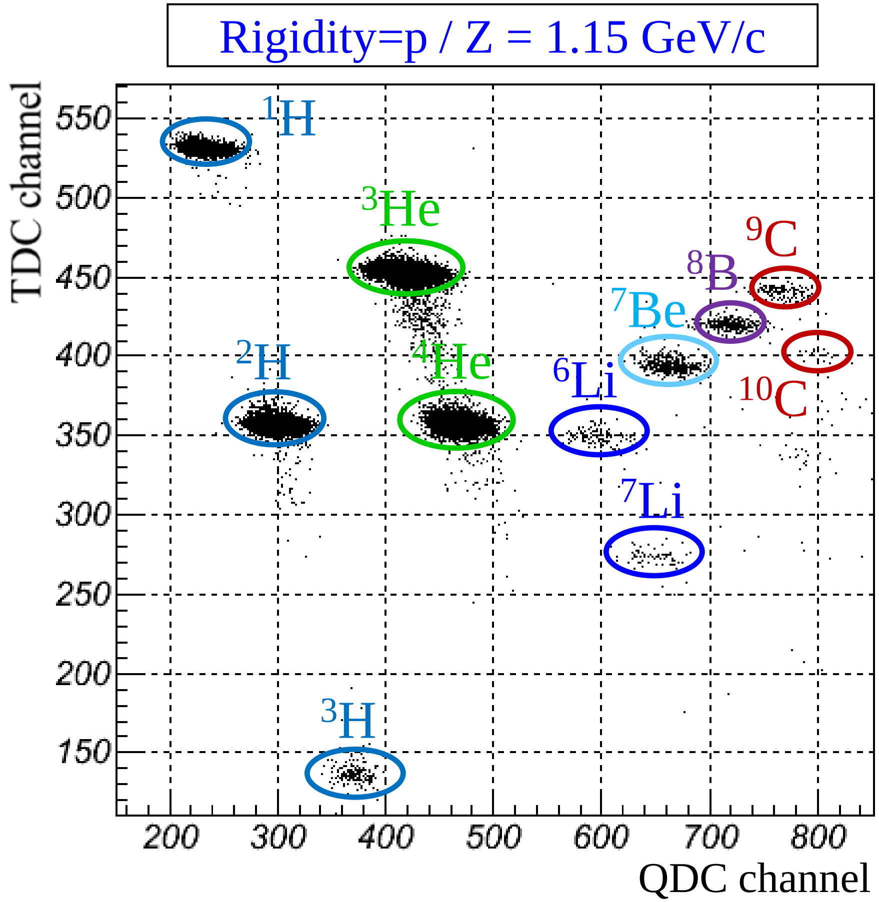
- Beam line length : 42 m
- Two bending magnets : BM1 (bending angle : α=0.259 rad.), BM2 (α=0.276 rad.)
- Five quadrupoles : Q1, Q4 (vertical focusing) and Q2, Q5 (horizontal focusing), Q3 – achromatic correction

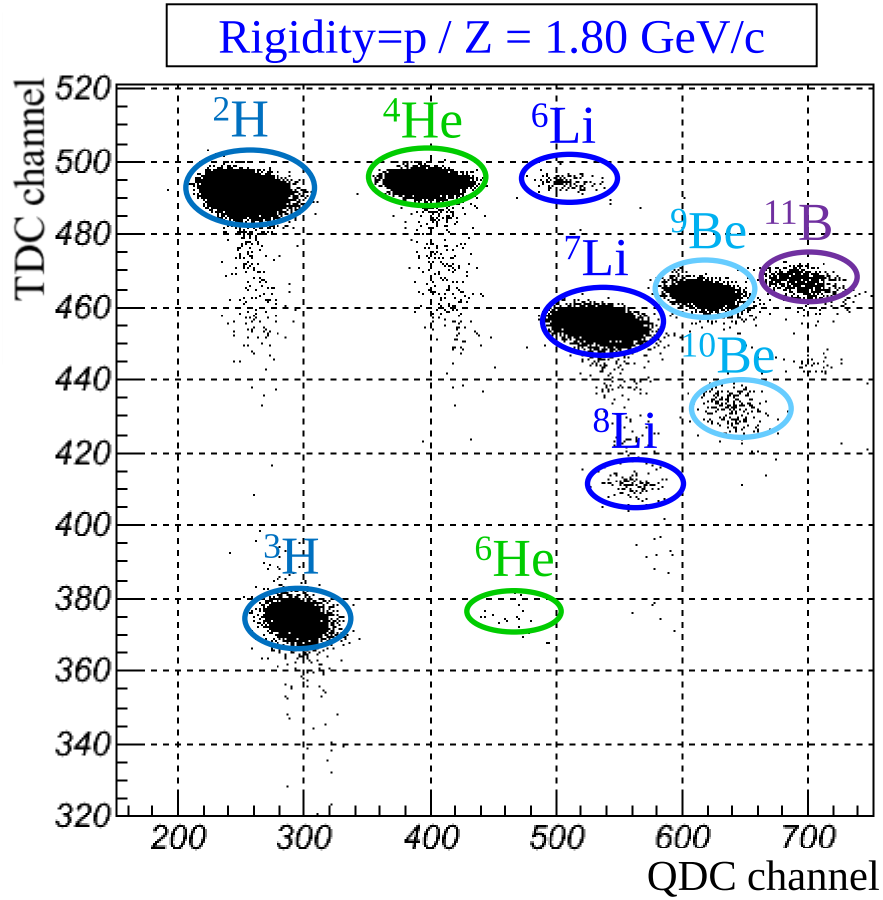


- Scintillation counters : CF1, CF2, C2, C3 (dE/dx, TOF)
- C2 generates trigger
- H1 – hodoscope of 20 elements
- Č – Cherenkov counter

Fragment production in FRAGM

Example: C – Be collisions at 0.3 GeV/nucleon





- QDC (from CF1) vs TDC between CF1 and C2
- Regions of different fragments are well separated and can be clearly selected
- TDC is a function of A, so it gives a mark for clear fragment identification

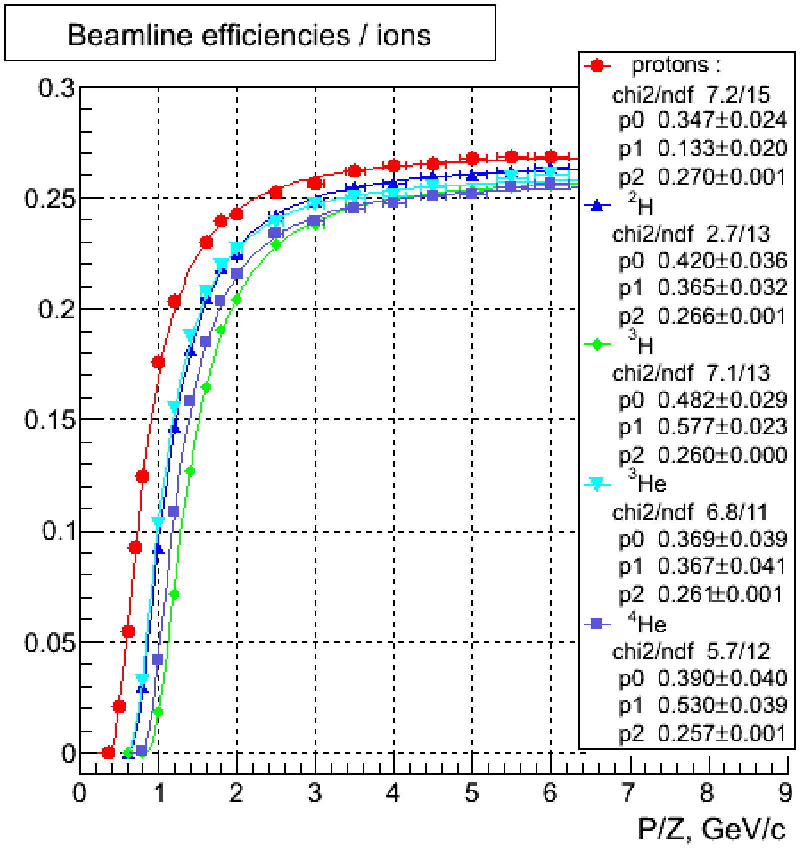
Beamline efficiencies for different ions

➢ Beamline has several construction features (beam pipe break ~ 3 m, stubs etc.); all counters are positioned through beam. Detection efficiency depends on beam momentum

➢ MC for FRAGM is performed with GEANT4-based code developed by our group

➢ Protons and light ions are used (^{2}H, ^{3}H, ^{3}He, ^{4}He and etc.) at 0.6 < P/Z < 6 GeV/c

➢ Values of the magnet currents are recomputed 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 correction is essential for P/Z < 2 GeV/c

Ion – ion interaction models: BC and QMD

➢ Our experimental data are useful to test different ion – ion interaction models. We selected four more reliable (BC, QMD, INCL and LAQGSM) to test :

✓ Binary Cascade (BC, GEANT4 toolkit) :

- ➢ Useable when either projectile or target is ^{12}C or lighter
- ➢ It uses a 3-dimensional model of the nucleus
- ➢ Model is based exclusively on binary scattering between reaction participants and nucleons within this nuclear model
- ➢ Novel approach of the intra-nuclear cascade is implemented. Cascade stops if the mean kinetic energy of the participants are below 15 MeV

(G. Folger *et al.*, EPJA 21 (2004) 407)

✓ Quantum Molecular Dynamics (QMD, GEANT4 toolkit) :

- ➢ Available for light and heavy ions
- ➢ All nucleons (target and projectile) are considered as participants and are propagated by means of a phenomenological nucleon-nucleon potential
- ➢ Time evolution of the system is stopped at 100 fm/c where it is assumed that equilibrium has been achieved

(T. Koi *et al.*, AIP Conf. Proc. 896 (2007) 21)

Ion – ion interaction models: INCL and LAQGSM

✓ Liege Intranuclear Cascade (INCL++) :

- Model is implemented in the GEANT4 toolkit
- It has recently shown promising result comparable with the BC and QMD
- INCL is not able to use projectile heavier than A = 18
- Clustering procedure is applied to nucleus and based on a coalescence model
- Cascade procedure is time-dependent and stopping time : $t = 70\times(A_{TARGET} / 208)^{0.16}$ fm/c

(J. Dudouet *et al*., PR **C**89 (2014)054616)

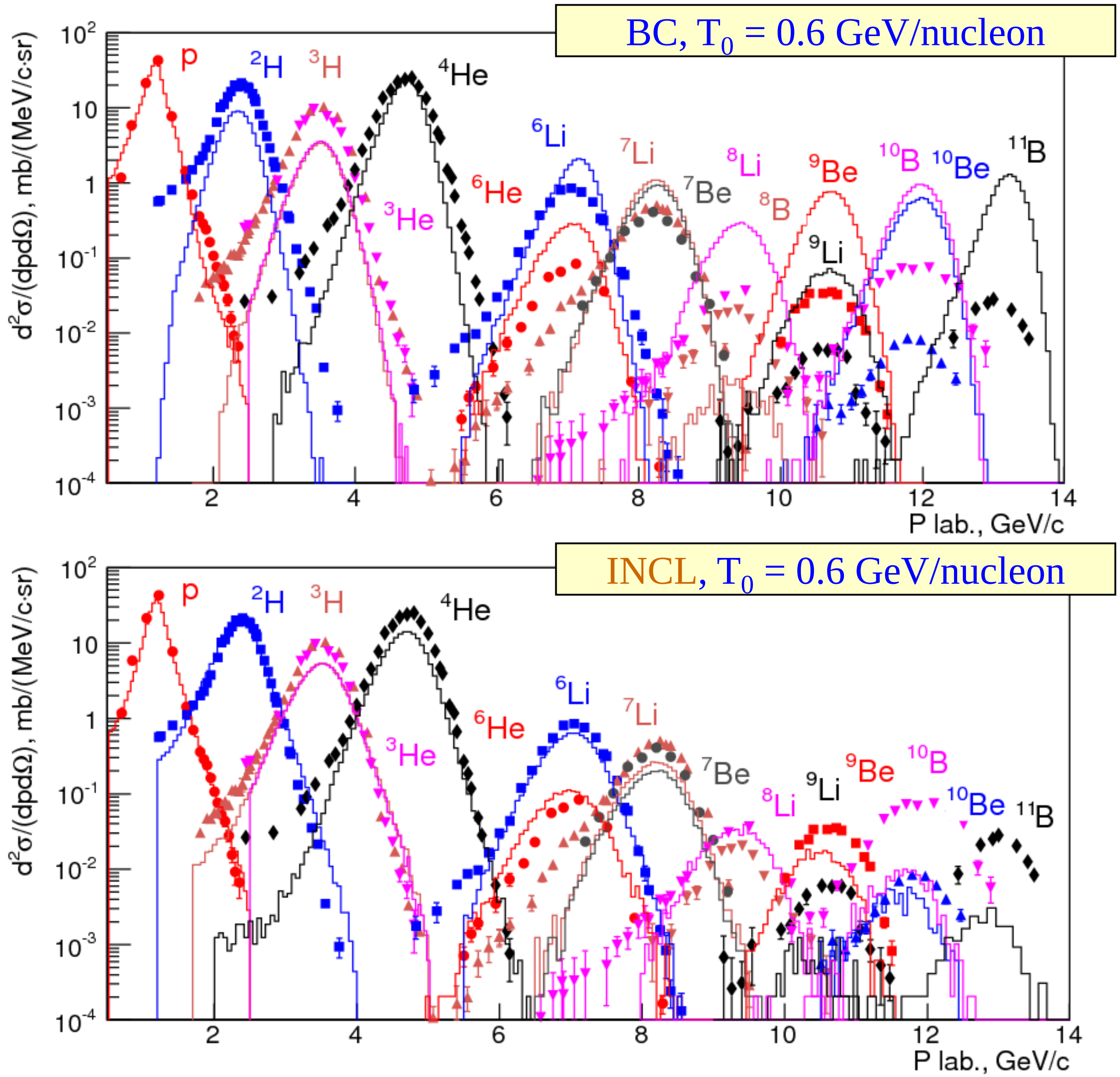
✓ Los Alamos version of the Quark Gluon String Model (LAQGSM03.03) (by courtesy of S. Mashnik) :

- First stage is the internuclear time-dependent cascade developed initially at JINR
- Second stage: Fermi breakup disintegration of light excited residual nuclei
- Model also accounts for coalescence of light fragments (complex particles) from energetic nucleons emitted during first stage
- It was tested in a wide energy region till 1 TeV/nucleon and large number of ions (LA-UR-11-01887)

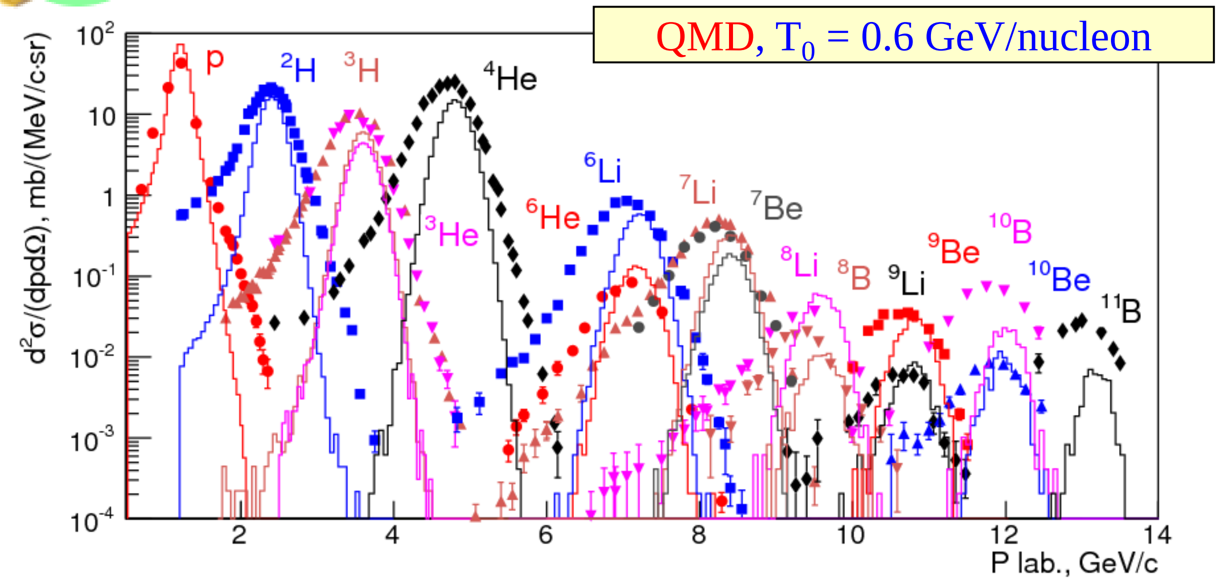
✓ It was generated 10M ion – ion interactions to have a reasonable comparison with our data

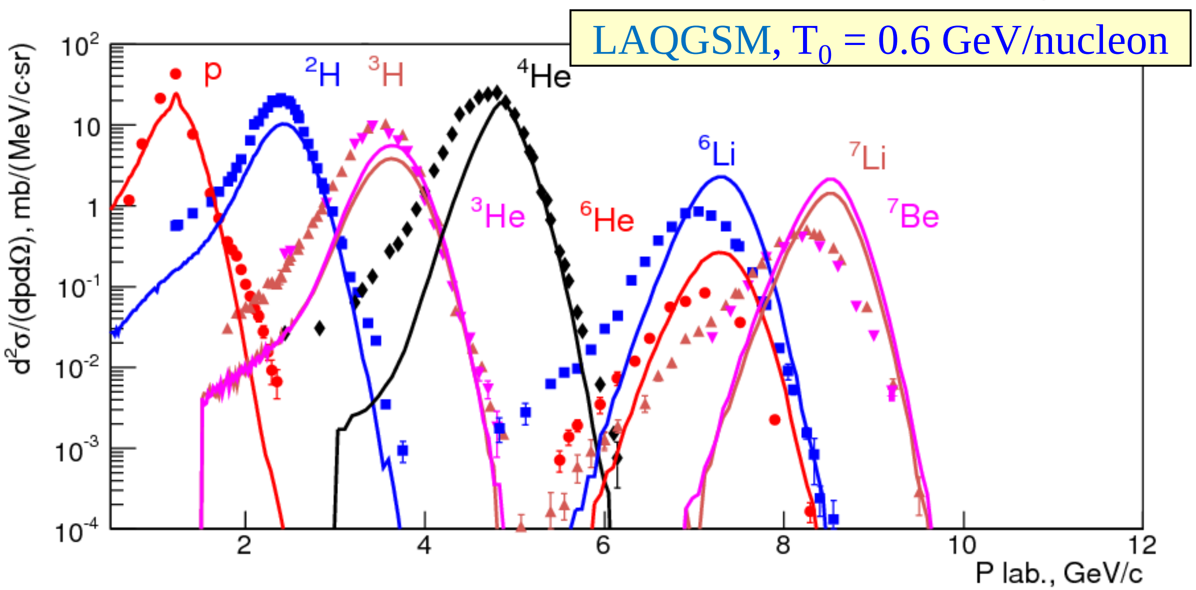
Momentum spectra :BC and INCL models

- Plots present data (points) in comparison with BC and INCL models (histrograms)
- Data are normalized to BC for protons at frag - mentation maximum
- In the region of fragmentation peaks, all models give reasonable description of the data
- In the cumulative region INCL model is in a good agreement with our data, especially for light fragments



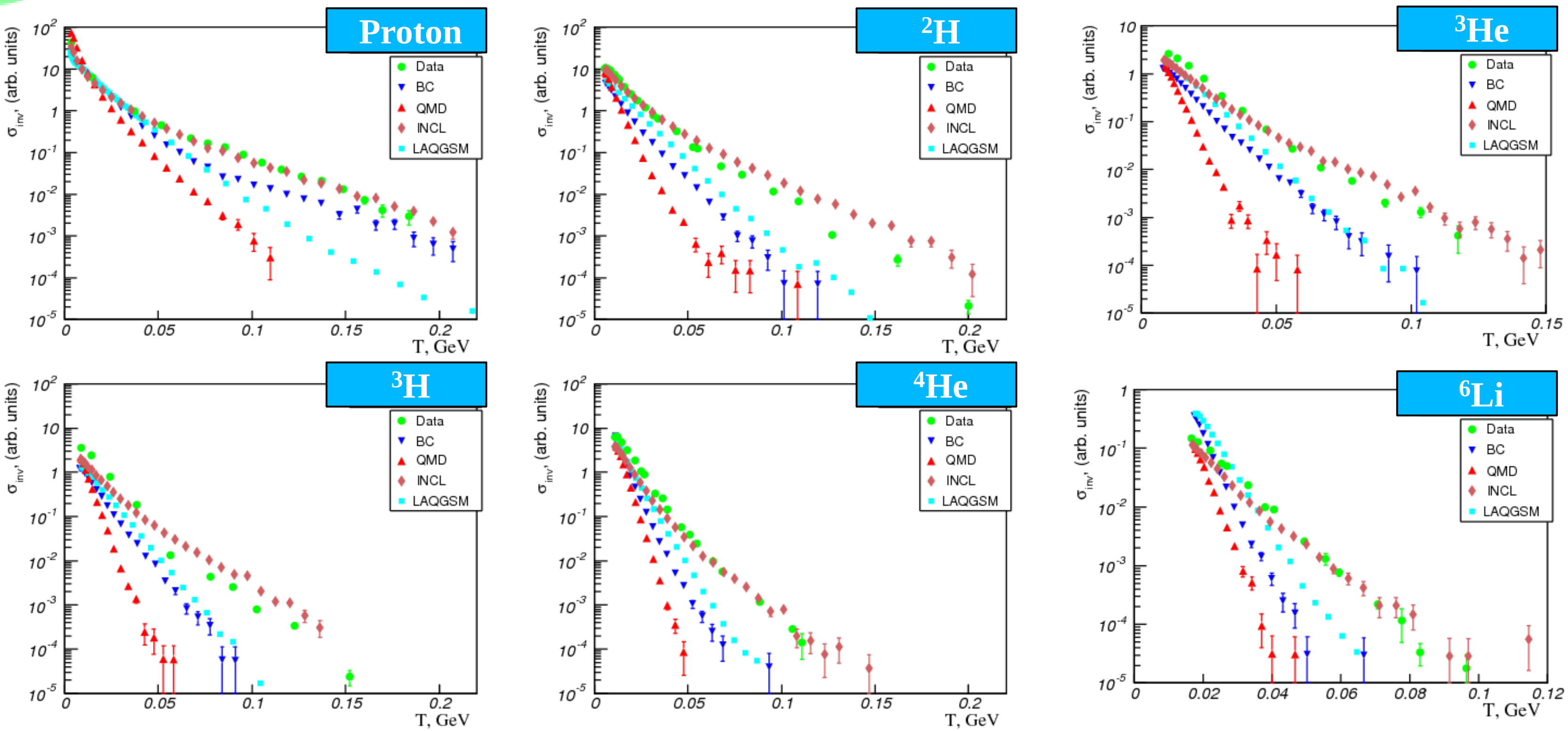
Kinetic energy spectra : QMD and LAQGSM

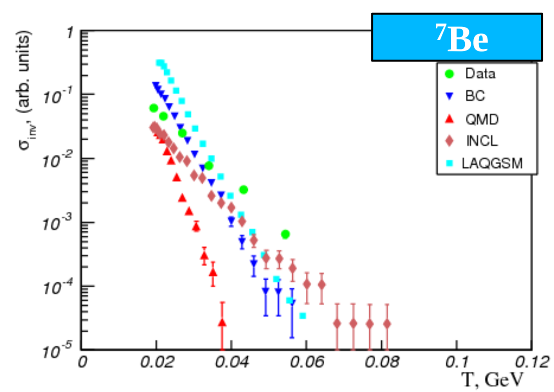




- ✓ Within the QMD model, fragmentation peaks are too narrow (apart from protons)
- ✓ High momentum region is strongly underestimated
- ✓ Shapes of fragmentation peaks for protons and deuterons are reasonably described by LAQGSM
- ✓ For ^{2}H, ^{3}He, ^{4}He the fragmentation peaks are narrower in the model than in the data
- ✓ High momentum region is in a reasonable agreement with out data

Kinetic energy spectra : data vs models





- Kinetic energy spectra (T, GeV) – fragment energy in the projectile (^{12}C) rest frame
- Plots present Data in comparison with different models : BC, QMD, INCL and LAQGSM for different fragments

Slope parameters from kinetic energy spectra

$$Ed^3\sigma/d^3p \sim A_S e^{(-T/Ts)} + A_C e^{(-T/Tc)}$$

- Two slope parameters Ts and Tc (in MeV) are obtained from fit
- Double exponential function well describes the kinetic energy spectra till ^{4}He
- Odeh: T. Odeh et al., PRL 84 (2000) 4557, ^{197}Au – ^{197}Au collisions at 1 GeV/n

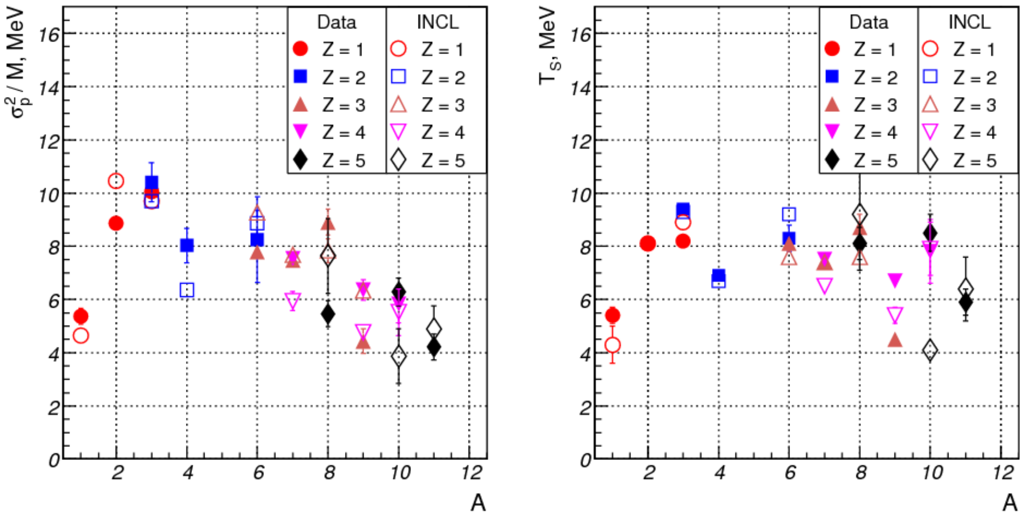
Fragment	Data		INCL model		BC model		Odeh
	Ts (MeV)	Tc (MeV)	Ts (MeV)	Tc (MeV)	Ts (MeV)	Tc (MeV)	Tc (MeV)
p	5.4 ± 0.3	26.5 ± 0.5	4.3 ± 0.7	20.5 ± 0.3	2.0 ± 0.1	11.6 ± 0.7	25.5 ± 1.0
^{2}H	8.1 ± 0.2	17.0 ± 0.4	8.1 ± 0.1	20.9 ± 0.3	6.0 ± 0.2	10.6 ± 0.4	16.0 ± 1.0
^{3}H	8.2 ± 0.2	18.6 ± 0.8	8.9 ± 0.2	21.0 ± 1.0	7.4 ± 0.1	15.8 ± 5.3	15.0 ± 1.0
^{3}He	9.4 ± 0.2	28.0 ± 6.6	9.3 ± 0.2	22.0 ± 1.0	7.7 ± 0.1	21.2 ± 6.7	19.0 ± 1.0
^{4}He	6.9 ± 0.1	14.2 ± 1.0	6.7 ± 0.1	17.0 ± 1.0	3.5 ± 0.1	6.1 ± 0.2	14.0 ± 1.0

- Slope parameters Ts in Odeh change in the range: 5 ÷ 7 MeV
- INCL model is in a reliable agreement with our data and «Odeh» data

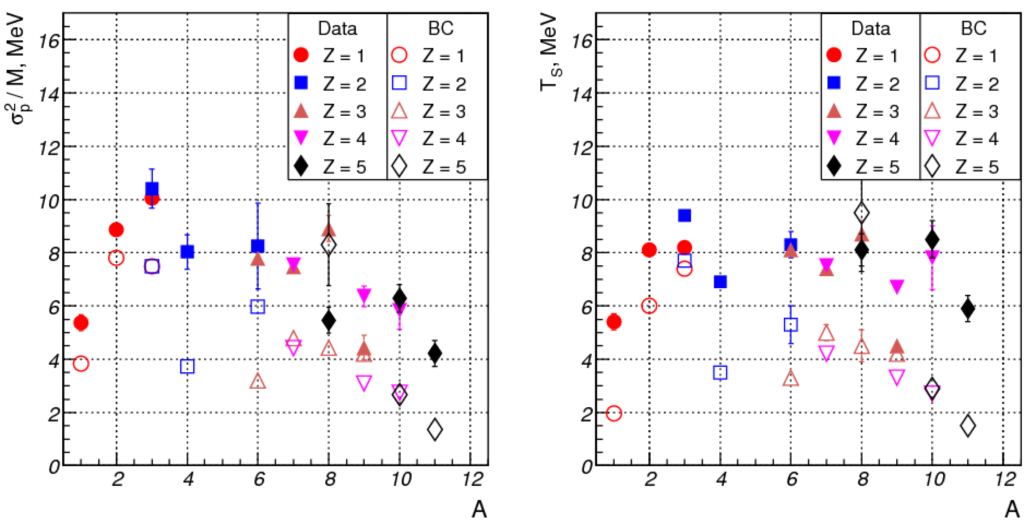
Fit parameters comparison

- Plots show a comparison of the different parameters (σ^2/M, Ts) for two models (INCL and BC)
- Analyzed fragments : p, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He, ^{6}Li, ^{7}Li, ^{8}Li, ^{9}Li, ^{7}Be, ^{9}Be, ^{10}Be, ^{8}B, ^{10}B, ^{11}B)
- σ^2/M is RMS^2 of the fragmentation peak divided by fragment mass, Ts – slope parameter
- Our experimental data are shown by the filled points, models by the open points
- Fragments with atomic number Z > 2 are well described only by one exponential component with slope parameter Ts

INCL model



BC model



Conclusion

- Fragment yields from reaction $^{12}C + Be \rightarrow f + X$ were measured at projectile kinetic energy T_0 = 0.6 GeV/nucleon at 3.5^0
- Several models (BC, QMD, INCL and LAQGSM) of the ion – ion collisions were compared to data
- In the region of the fragmentation peak all models give reasonable description of the data. INCL model is closer to our data in comparison with other models
- Kinetic energy spectra in the projectile rest frame can be parameterized as $A_S e^{(-T/T_S)} + A_C e^{(-T/T_C)}$, where Ts and Tc are slope parameters («temperatures»)
- Ts values for protons and other fragments is in a good agreement with predictions of the INCL model
- Tc can be used for a description of the kinetic energy spectra up to ^{4}He. Our data are in a reasonable agreement with INCL model and with other experimental data

Thank You