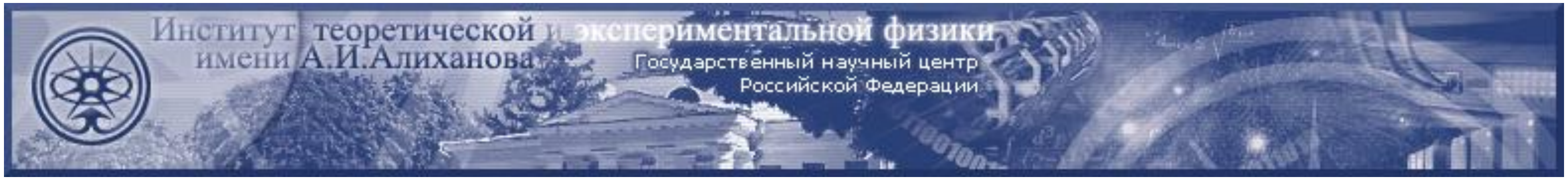

Испарительные и кумулятивные протоны при фрагментации ионов углерода при промежуточных энергиях

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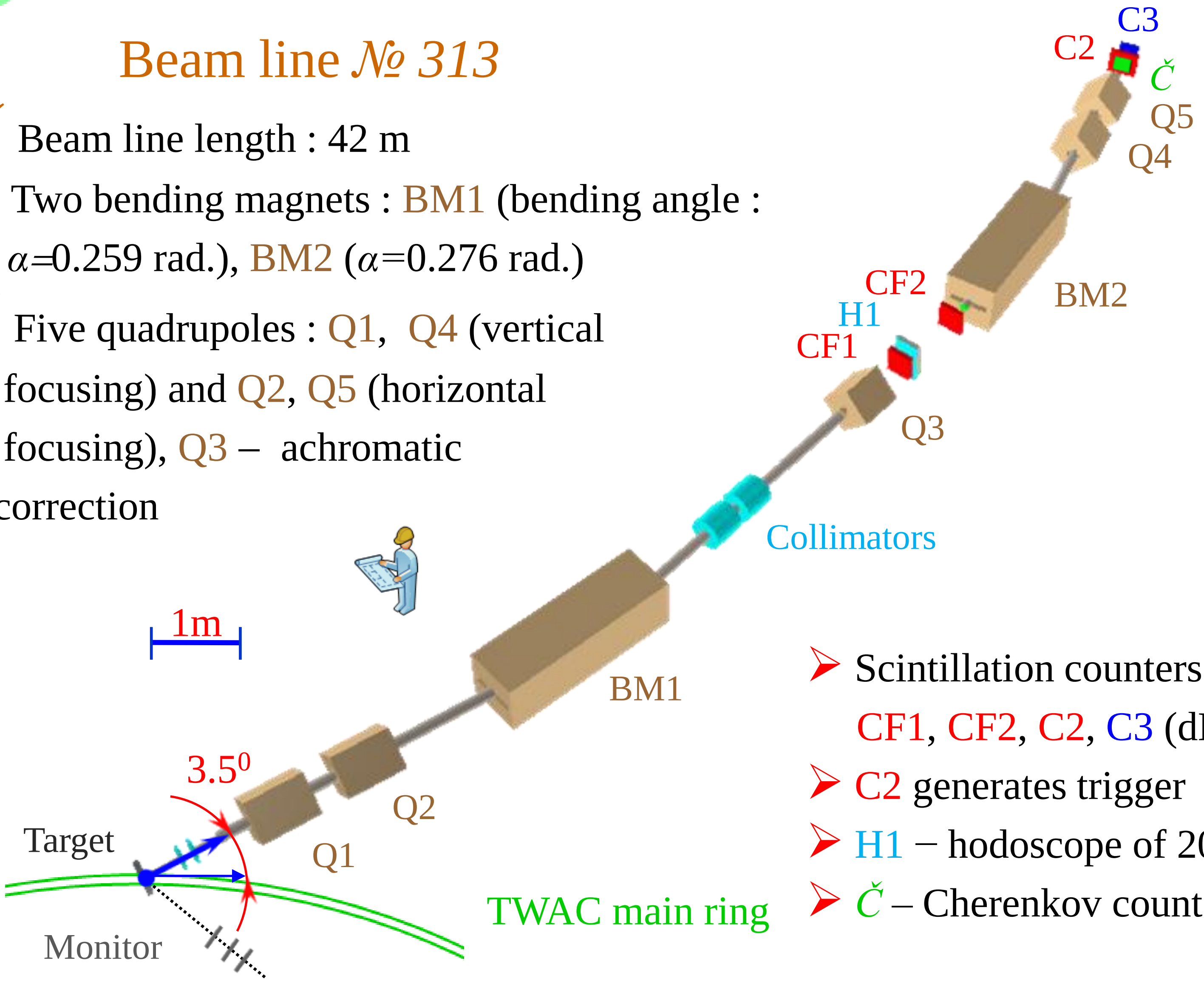
Experiment FRAGM

Beam line *№ 313*

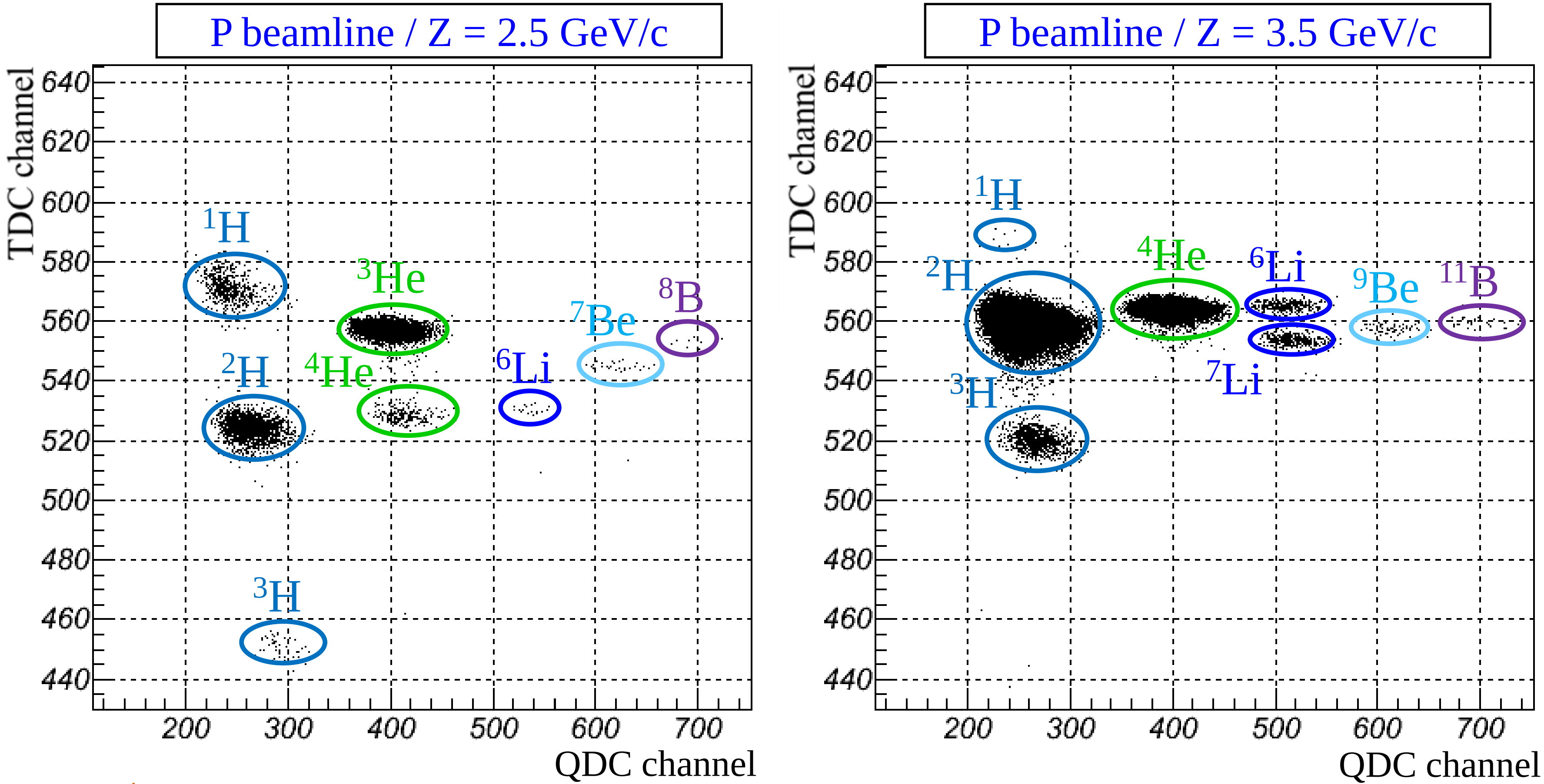
- Beam line length : 42 m
- Two bending magnets : BM1 (bending angle : α=0.259 rad.), BM2 (α=0.276 rad.)
- Five quadrupoles : Q1, Q4 (vertical focusing) and Q2, Q5 (horizontal focusing), Q3 – achromatic correction



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

Fragment production in FRAGM

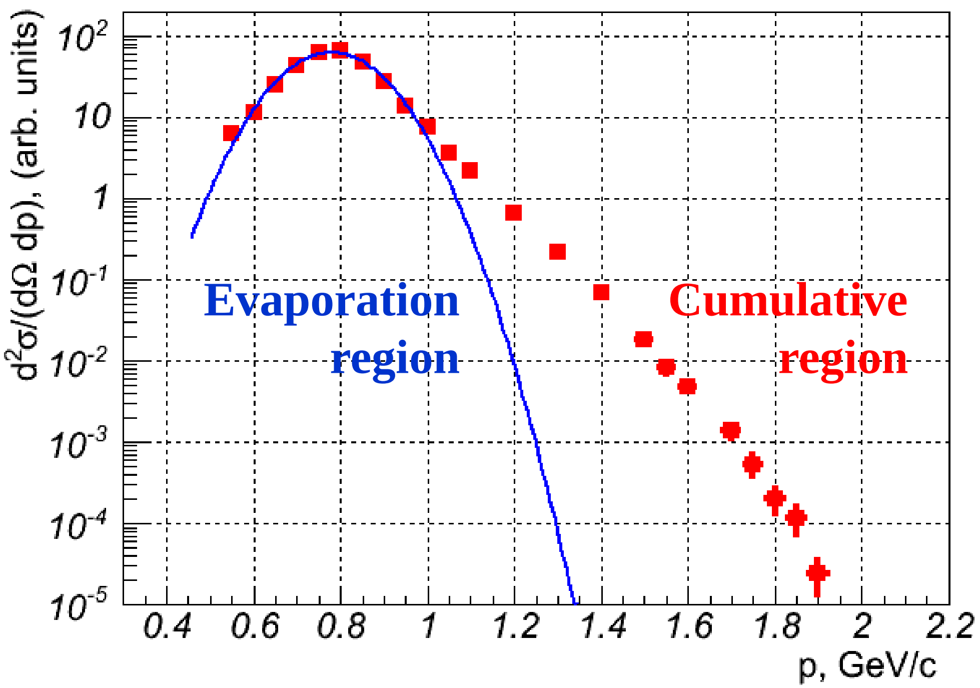
C – Be collisions at 0.95 GeV/nucleon



- ✓ Regions of the different fragments are well separated and can be clearly selected
- ✓ Increase of the projectile momentum leads to smaller cross section for light fragment production at 3.5^{0}

Cumulative effect

C – Be collisions at 0.3 GeV/nucleon



✓ Nature of the **cumulative protons** is under discussion up to now. Possible sources of this effect can come from :

- Highly excited nuclear prefragments
- Intranuclear multiple scattering
- Fluctuations of nuclear matter density
- Short – range correlations of the nucleons
- Multiquark cluster

✓ Most successful approach to the problem of cumulative particle production is the quark cluster model proposed by A. Efremov and A. Kaidalov in the framework of quark–gluon string model (QGSM) [A. Efremov, A.B. Kaidalov *et al*. Phys. Atom. Nucl. 57, (1994) 874]

✓ This model was used to describe yields of cumulative pions, kaons and antiprotons. However, for protons such analysis was not performed

Quark cluster model and cumulative effect

In the framework of this model cumulative process was performed by quark clusters existing in a nucleus. Clusters have quark multiplicity 3k (k= 1, 2, 3) and corresponding probabilities w_k ; invariant cross section can be described as a sum of three components :

$$E\frac{d^3\sigma}{d^3p} = G_0\left[w_1 g(x, p_\perp^2) + w_2 b_2(x, p_\perp^2) + w_3 b_3(x, p_\perp^2)\right]$$

$$g(x, p_\perp^2) = G \times exp\left(-0.5(1-\Delta-x)^2/\sigma_x^2\right) exp\left(-0.5\, p_\perp^2/\sigma_P^2\right)$$

$$b_2(x, p_\perp^2) = \begin{cases} B_2(x/2)^3(1-x/2)^3 exp\left(-\alpha_1 p_\perp^2\right) \\ 0, \quad x \notin [0,\ 2] \end{cases} \qquad b_3(x, p_\perp^2) = \begin{cases} B_3(x/3)^3(1-x/3)^6 exp\left(-\alpha_2 p_\perp^2\right) \\ 0, \quad x \notin [0,\ 3] \end{cases}$$

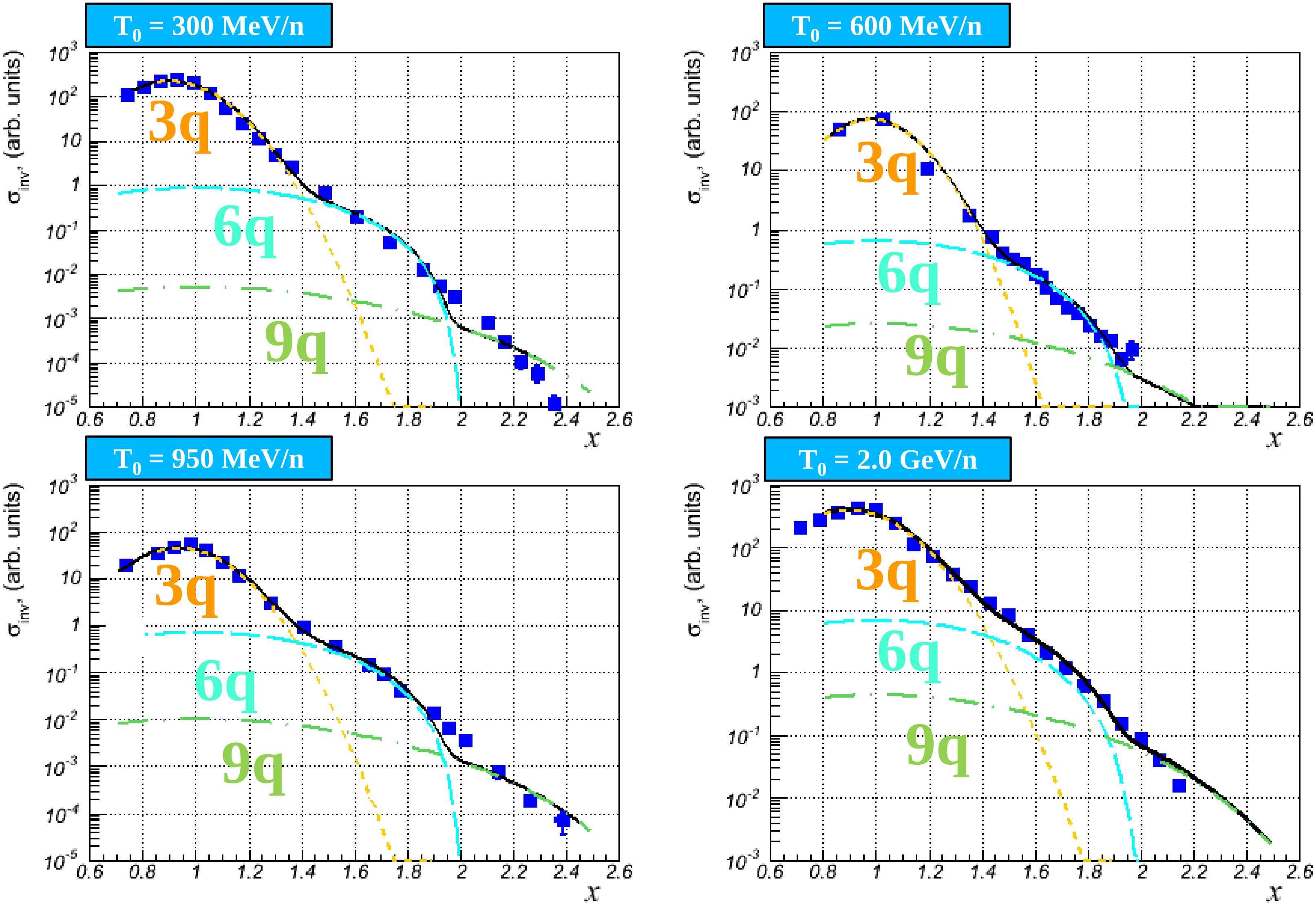
$$\int_0^\infty\int_0^\infty b_i(x, p_\perp^2)dxdp_\perp^2 = i/2, i = 2,\ 3$$

where x = p/p0 – cumulative variable; g, b_2 and b_3 – known fragmentation function (QGSM); transverse parameters α_1 = 5 GeV $^{-2}$ and α_2 = 3 GeV $^{-2}$ [L. Anderson *et al*. Phys.Rev. C 28 (1983) 1224]; G, B2, B3 – known normalization constants [JETP Lett. 97 (2013) 439]

- Fit parameters are mean value (1–Δ), corresponding r.m.s. σ_x , scale coefficient G_0, two probabilities w_2 and w_3 connected to w_1 with relation $w_1 + w_2 + w_3 = 1$ (see next slide)

x spectra at different energies

C – Be collisions



Fit result and comparison to other data

T_0, GeV/nucleon	p_0, GeV/nucleon	x_{max}	w_2	w_3
0.6	1.22	1.95	0.077 ± 0.010	0.004 ± 0.002
0.95	1.6	2.4	0.119 ± 0.017	0.002 ± 0.001
2.0	2.72	2.15	0.098 ± 0.018	0.006 ± 0.001

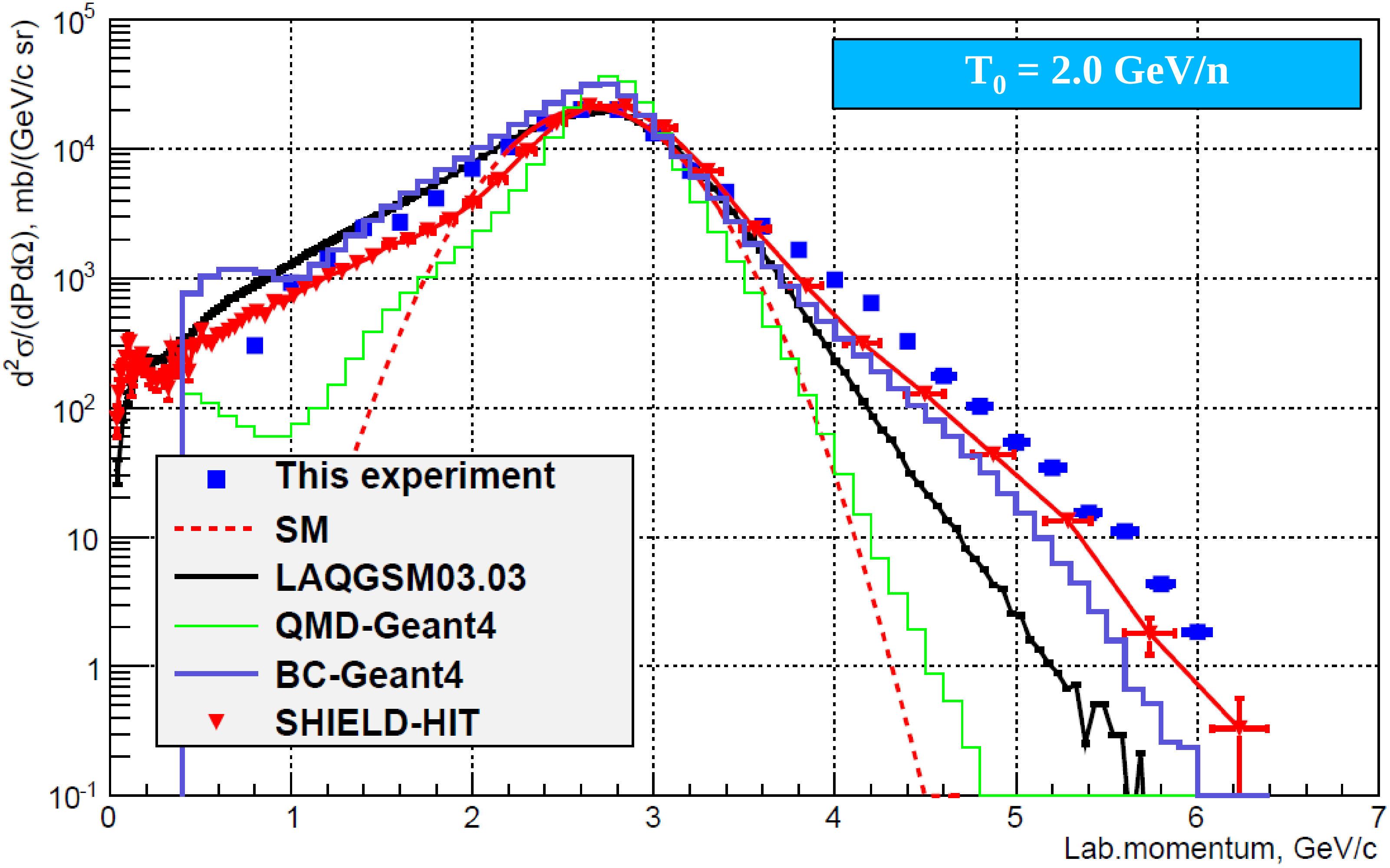
- Two – nucleon cluster probability (***w_2***), estimated at different projectile energies varies within 7.7 – 11.9 %, while the three – nucleon (***w_3***) is within 0.2 – 0.6 %. They are compatible both with given statistical errors of the fit and with expected independence of these probabilities on projectile energy
- Obtained value of ***w_2*** is close to the value of 6 % reported in [V. Burov *et al*. Phys.Lett. B 28 (1977) 46] and to theoretical prediction of 12.5% in [M. Sato *et al*. Phys. Rev. C 33 (1986) 1062]
- However, the value of ***w_3*** is smaller than 2.6% predicted in last paper. The values ***w_2*** (***w_3***) are not far from corresponding probabilities obtained in the TJNAF experiment [K. S. Egiyan *et al*. Phys. Rev. Lett. 96, (2006) 082501] and wich are equal to (19.3 ± 4.1) % and (0.55 ±0.17) % for carbon nucleus
- Reasonable agreement of the results of these experiments can be considered as evidence for unique nature of quark clusters and short range nucleon correlations in nuclei

Models of the ion–ion interaction

- A few standard models, used as part of GEANT4 code, were tested (QMD and BC)
- Also we investigated two specific models : SHIELD – HIT (by courtesy of N.Sobolevsky) and LAQGSM(by courtesy of S.Mashnik)
- Generally, nuclear interaction reactions occur in three main stages :
  - Fast stage which presents ion – ion interaction as series of binary collisions between nuclear constituents and production of the secondary particles
  - Next, coalescence stage, is performed by the cascade when baryons, which are close each to other in the momentum space, produce complex particle some particles is getting stable and can be emitted during this pre – equilibrium process
  - Further evolution of the nucleus towards equilibrium stage is realized via different and well known processes : particle – fragment evaporation, nuclear fission, multifragmentation and Fermi breakup

Comparison data and models

^{12}C – Be collisions



Conclusions

- Spectra of high momentum protons from ^{12}C fragmentation have been analyzed in two approaches :

- Multi−quark cluster model with fragmentation functions calculated in QGSM gives reasonable description of the data. Parameters of the model – quark cluster probabilities have been estimated. They are near 10% for 6q- and 0.5% for 9q-clusters in agreement with estimations from other processes. Our results were published in B. Abramov *et al*. JETP Lett. 97 (2013) 439.

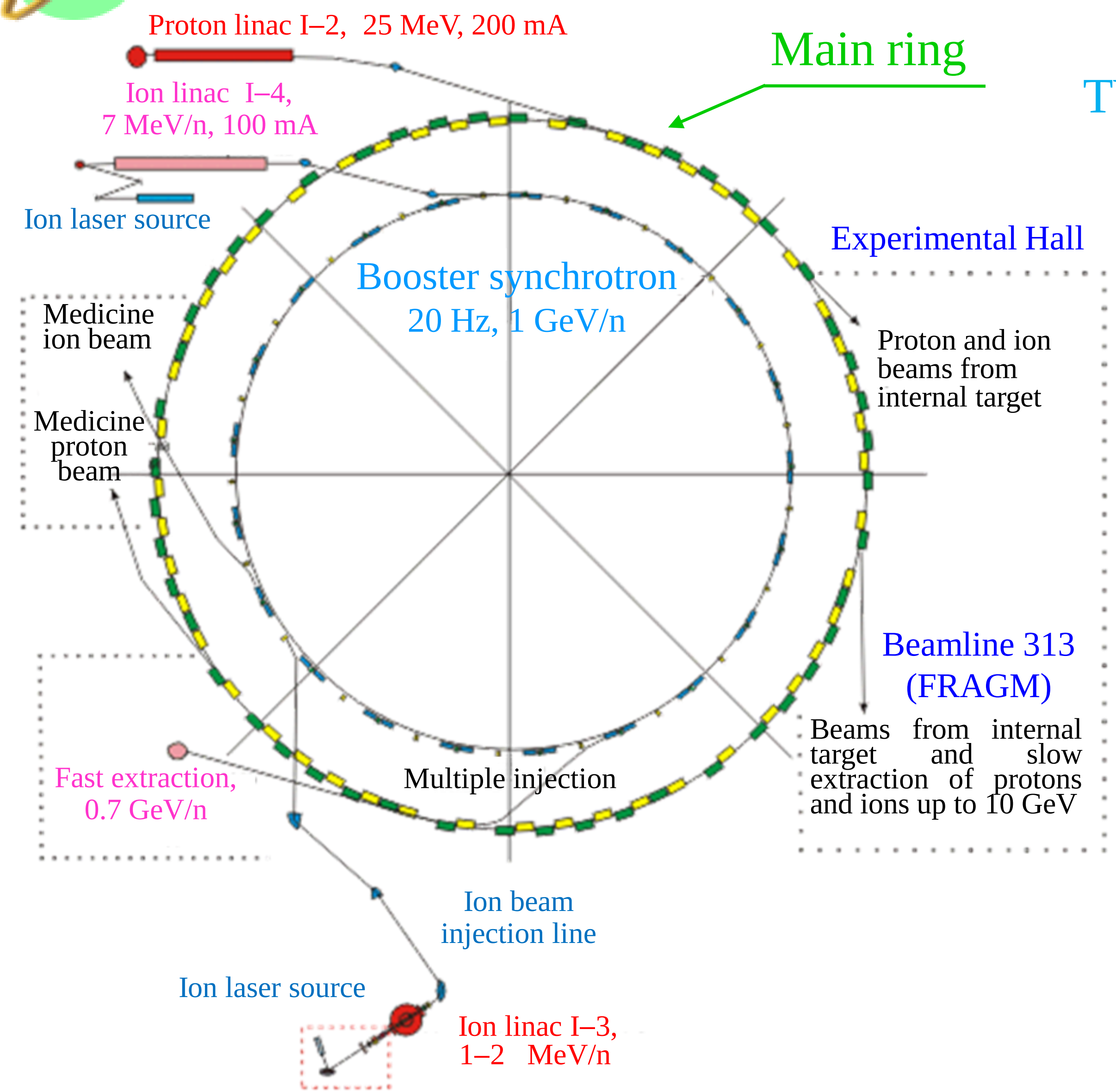
- Predictions of four models of ion-ion interactions (Binary Cascade, QMD, LAQGSM and SHIELD – HIT) have been compared to the data. It was shown, that experimental data in the cumulative region is a critical test for models of ion-ion interactions.

Thank You

Motivations 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)
- Report is based on results obtained for reaction : $^{12}C + Be \rightarrow f + X$, where f – proton or nuclear fragment registered by detector at small angle (~ 3.5^0)
- Experimental setup permits us to detect ^{12}C fragmenation (p, d, t, ^3He, ^4He, ^6He, ^8He, etc.) for high 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
  - ✓ Test of the different models of ion–ion interactions covering large kinematic region (evaporation and cumulative parts)
- This study is important as input to transportation codes for radiotherapy with ions and also for ion beam design for TWAC future upgrade

ITEP accelerator complex TWAC



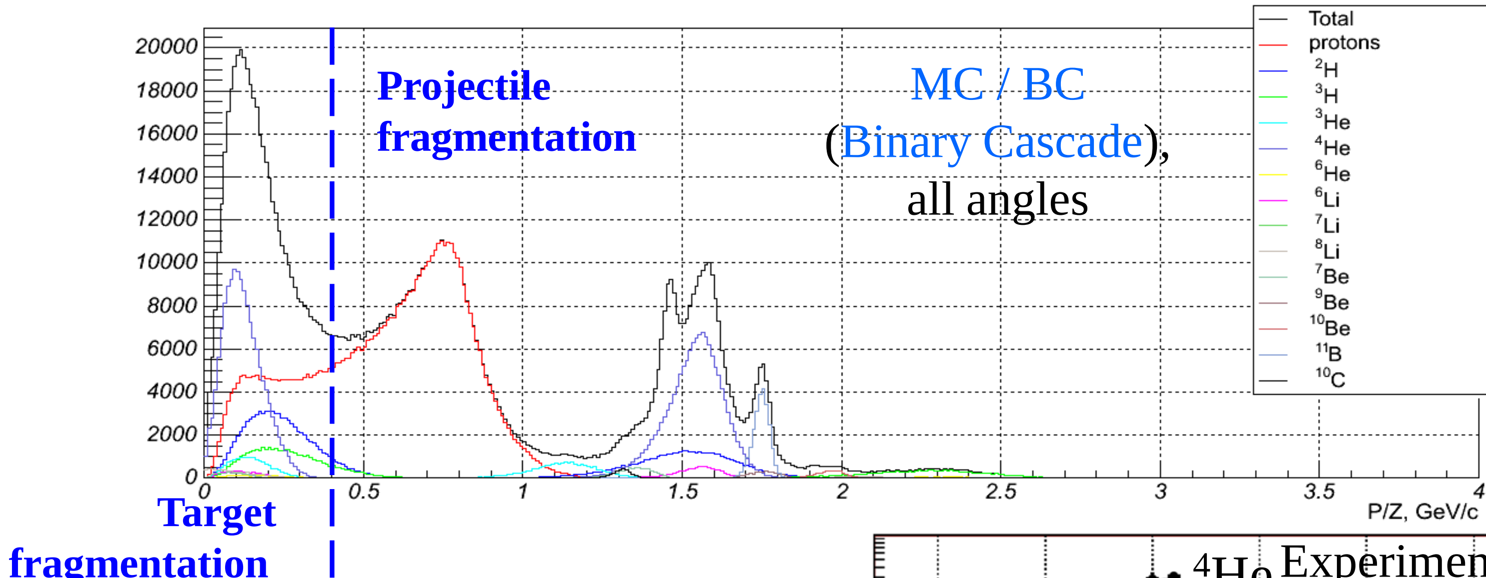
TWAC TeraWatt Accumulator Complex

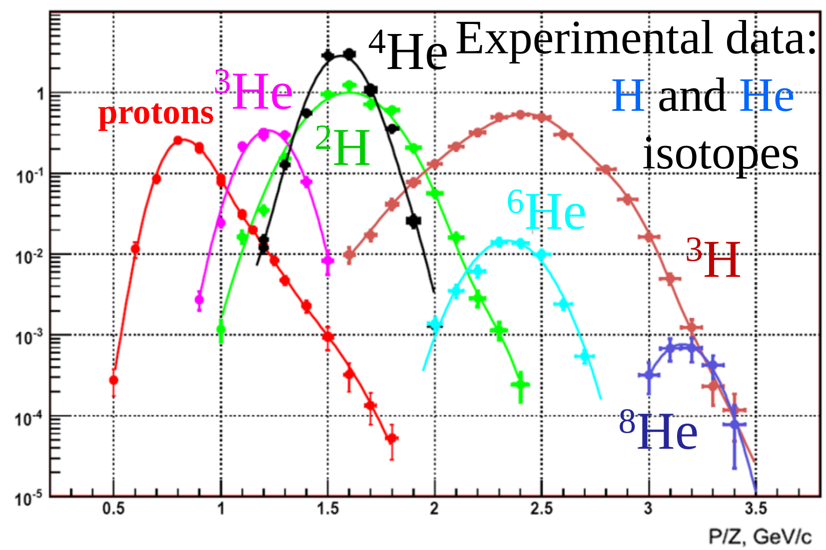
TWAC current parameters

- ✓ 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

Registered yields of the different fragments

C – Be collisions at 300 MeV/nucleon

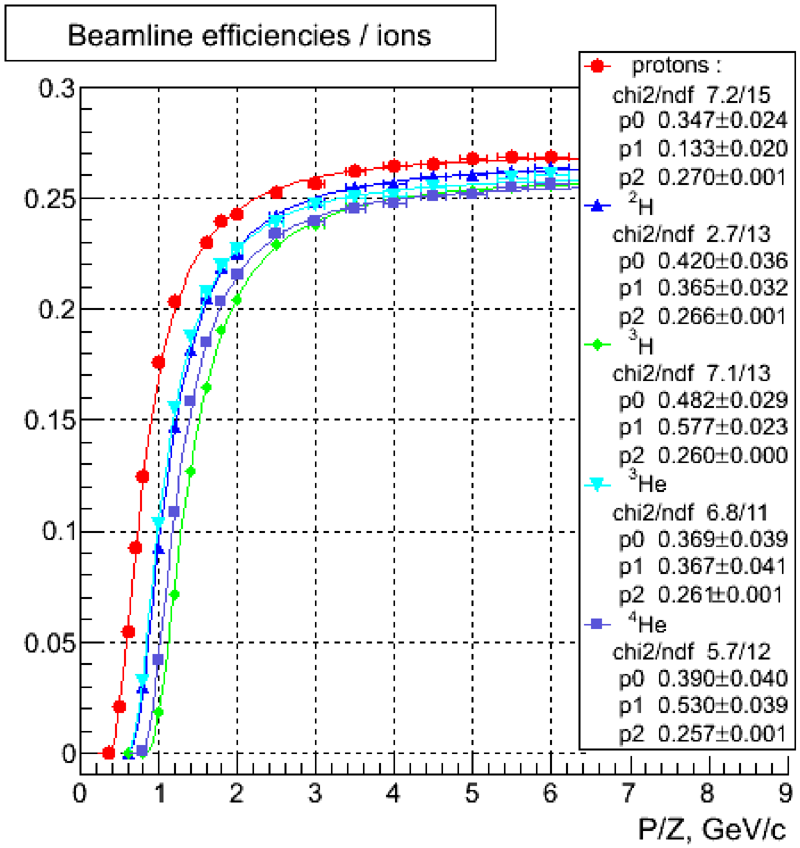




- FRAGM detector is able to registrate projectile fragmentation region and influence of target isn't sufficient
- Experiment and MC simulation are slightly different by shapes at low momenta region. It should be corrected by registration efficiency

Beamline efficiencies for different ions

- Beamline has several construction features (beam pipe break ~ 3 m, stubs etc.); all counters are positioned through 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 trasnports 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

Models of the ion–ion interaction / II

- Binary Cascade (BC) model :
  - Recommended for use when either projectile or target is ^{12}C or lighter
  - Model is useable for energy range less than 10 GeV / nucleon
  - Detailed model of ions : nucleons distributed in space according to nuclear density; nucleon momenta are sampled assuming Fermi gas model
- Quantum Molecular Dynamics (QMD) model :
  - Used to analyze light and heavy ion reactions
  - Recommended energy range less than 5 GeV / nucleon
  - Includes participant – participant scattering and large number of different resonances
  - This model is under construction, but one of the useable version is in a standard GEANT4.9.4 package
- SHIELD – HIT transport code (N. Sobolevsky) :
  - Based on the Dubna Cascade Model (< 1 GeV / nucleon) and QGSM
  - Recommended to use for energies from 15 MeV to 100 GeV for light and heavy ions
  - Tested on a large variety of hadron – ion and ion – ion interactions
- Los Alamos QGSM (LAQGSM) event generator (S. Mashnik) :
  - High energy generator works up to 1 TeV / nucleon, but also for low region (100 MeV – 1 GeV) is well useable and tested
  - Recommended for use for light and heavy ion till ^{238}U and fragments till ^{28}Mg