Probing the Symmetry Energy using Time Projection Chambers at NSCL and RIKEN

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May 29, 2008

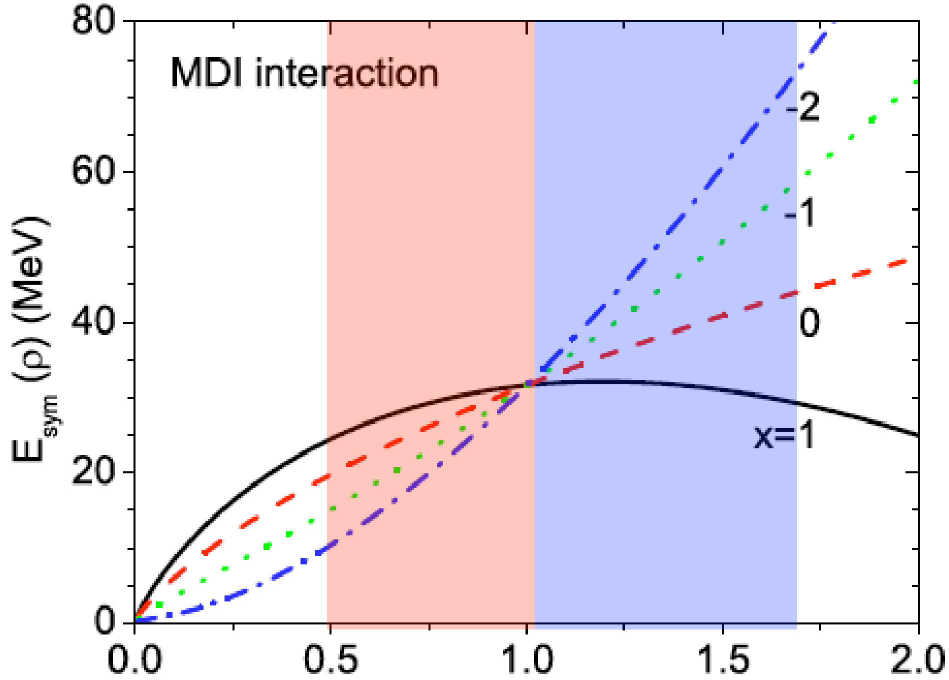
Isospin Dependent Observables

As a function of isospin, centrality, and incident energy:

- Neutron/proton energy spectra
- Neutron and proton flow
  - p_x vs. y (v_1)
  - Elliptic flow (v_2)
    - As a function of p_t
  - Disappearance of flow (balance energy)
- π^+/π^- spectra
- π^+/π^- flow
  - p_x vs. y (v_1) and elliptic flow (v_2)
    - As a function of p_t
- Isotope energy spectra
  - t/^{3}He ratio, ^{3}He/^{4}He ratios, ^{6}Li/^{7}Li ratios, ^{6}He/^{6}Li
- Isotope flow, p, d, t, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li
  - p_x vs. y
  - Elliptic flow
    - As a function of p_t

Density Dependence of Symmetry Energy

Li *et al.*, Acta Phys.Hung.A25, 219 (2006).

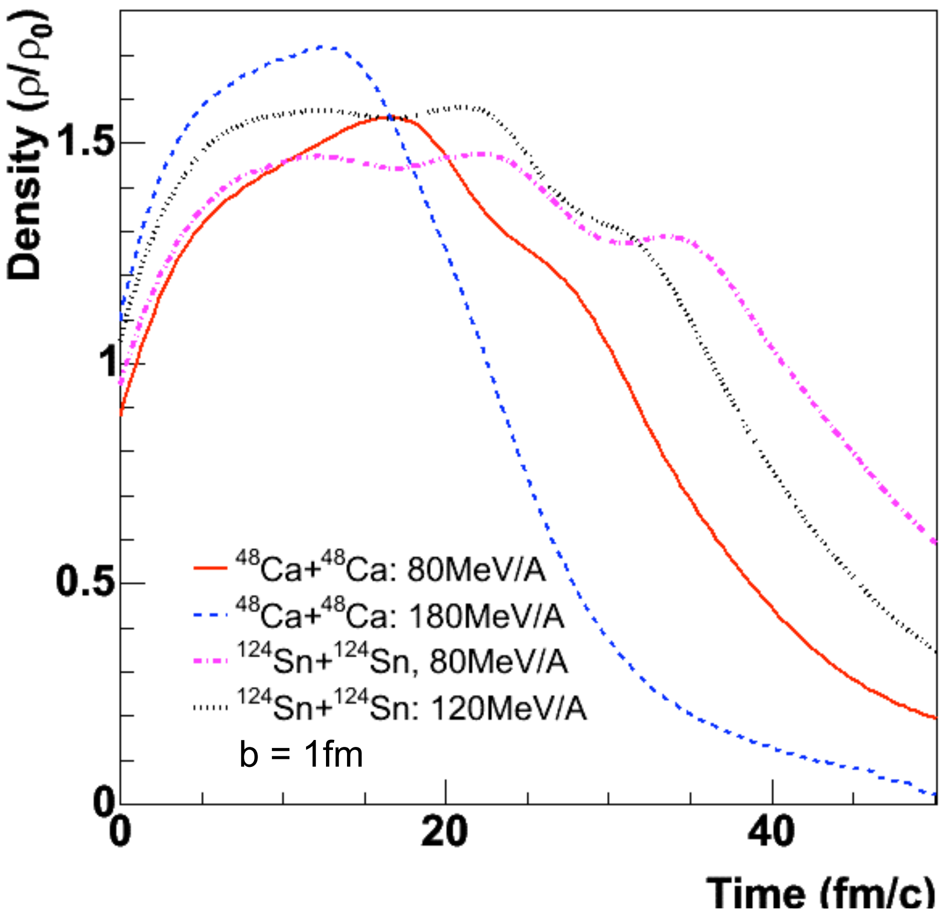


Density (ρ/ρ_0)

- Density region sampled depends on collision observable & beam energy
- $\rho<\rho_0$ examples:
  - Isospin diffusion
  - n/p ratios
- $\rho>\rho_0$ examples
  - Pion energy spectra
  - Pion production ratios

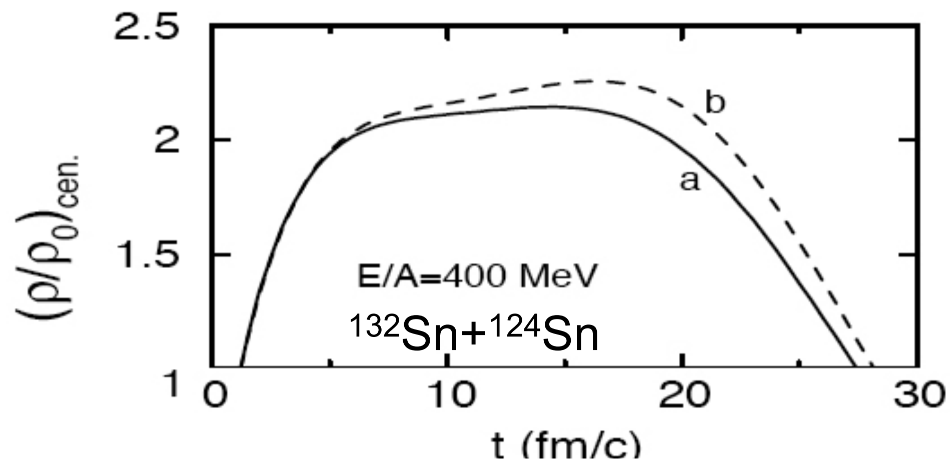
Can sufficiently high densities be obtained?

NSCL



BUU from: Danielewicz, NPA**673**, 375 (2000).

RIKEN

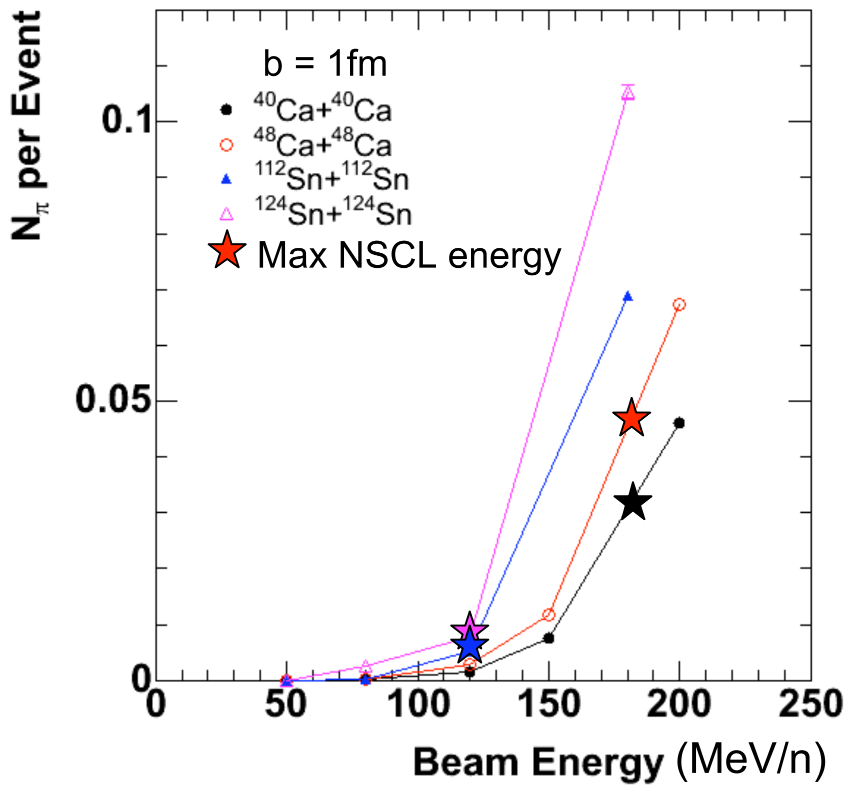


Li, nucl-th/0206053

- High densities are achieved even in collisions at 80 MeV/A
- Delta resonances formed early
- Pions evolve later (shaded regions)
- Memory of dense region of formation depends on reinteractions

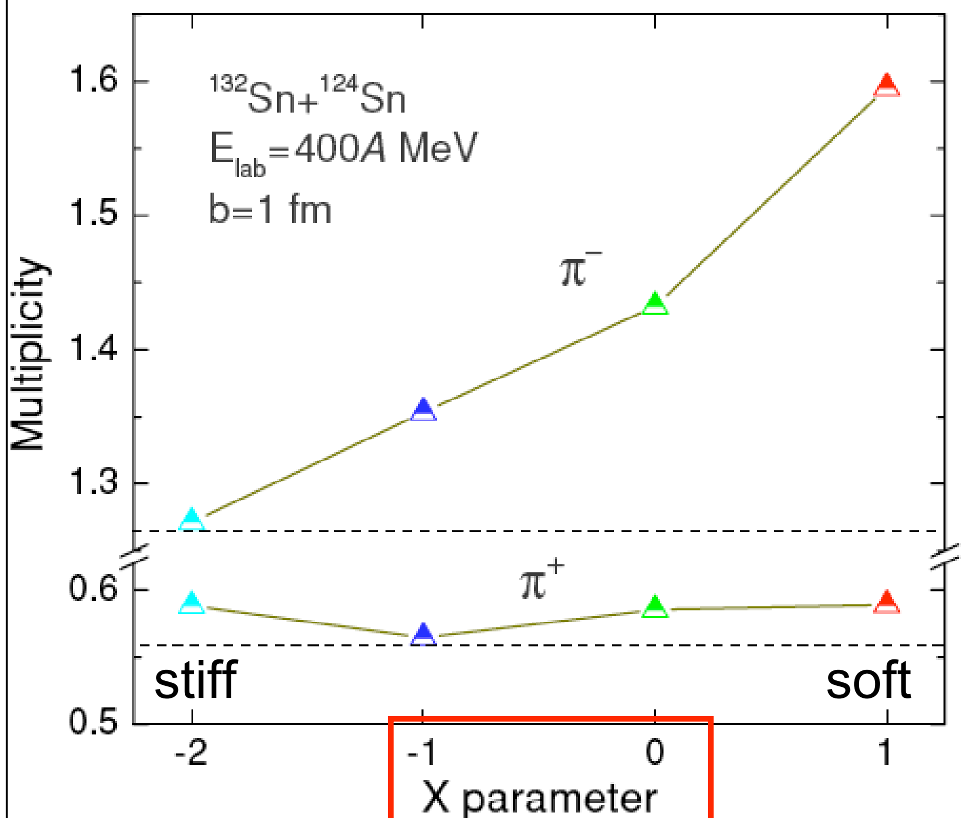
Can a sufficient number of pions be produced?

NSCL



BUU from: Danielewicz, NPA**673**, 375 (2000).

RIKEN

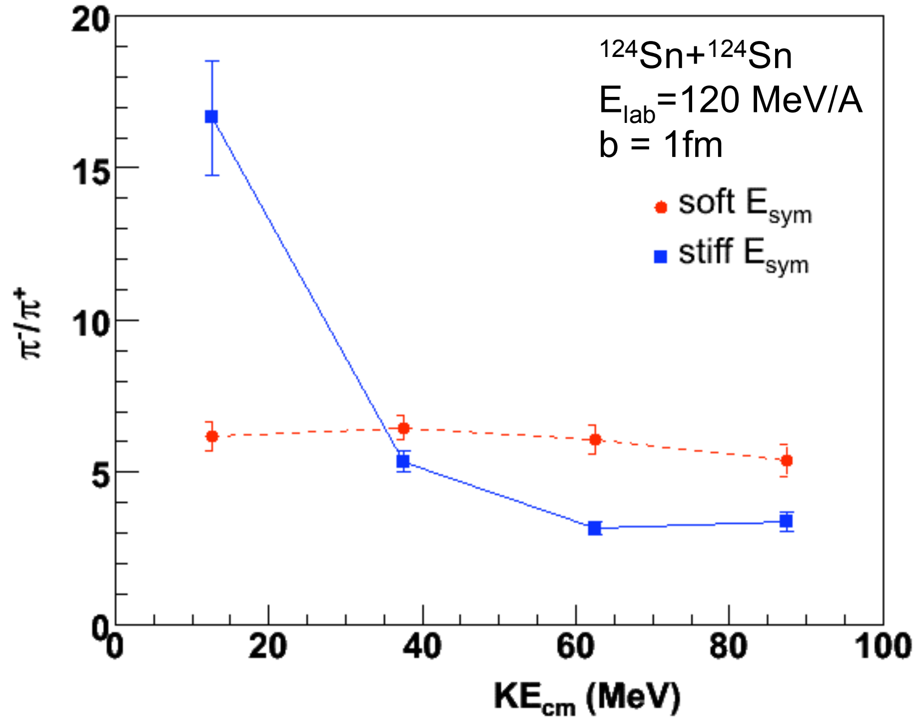


Li, et al. PRC71, 014608 (2005).

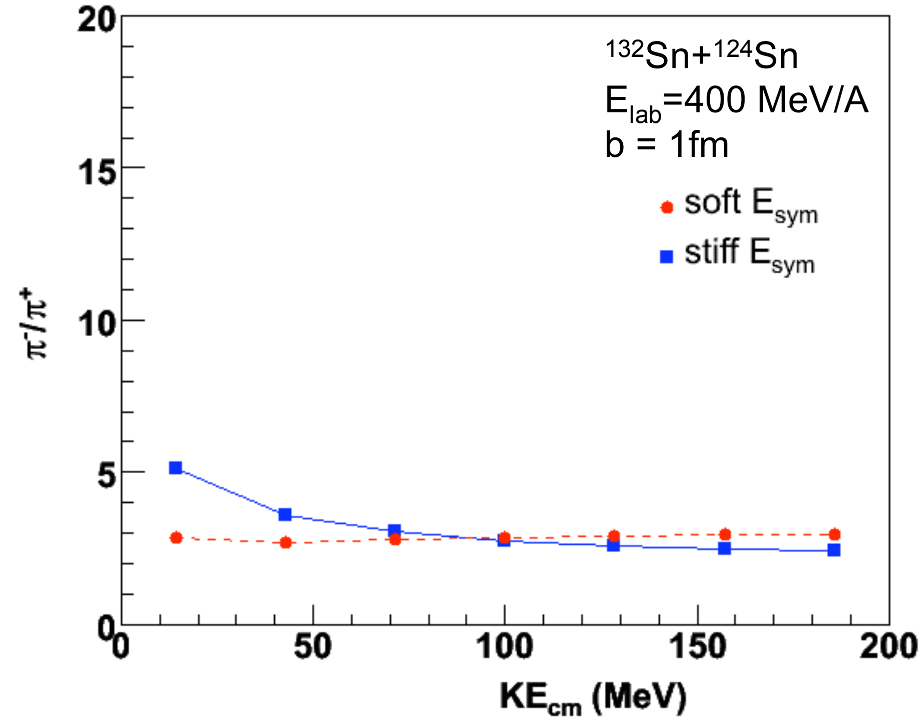
Pion production sub-threshold @ NSCL

Collision Energy Dependence

NSCL



RIKEN



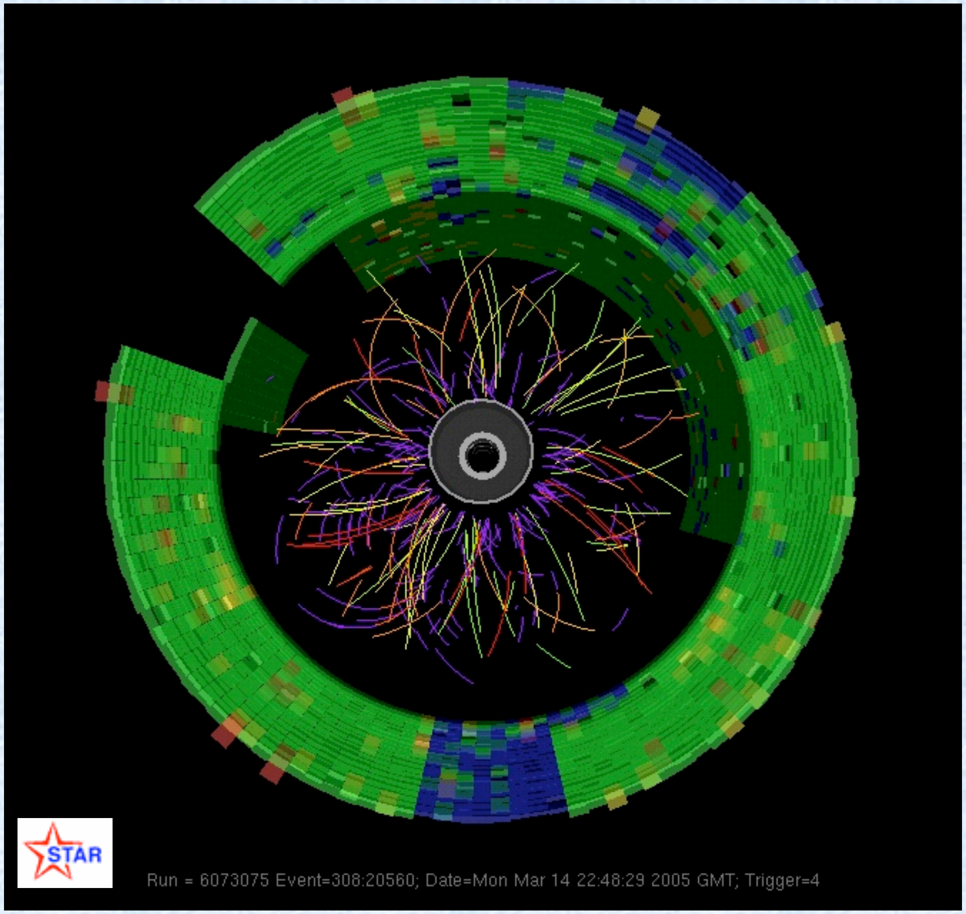
- Pion ratio retains dependence on EOS @ low energy
- Pion ratio lower at high energy because increased second-chance collisions wash out charge ratio
- Attention: x-axis scales are different!
- Effect previously noted at higher energies (B.A. Li, PRC67, 017601 (2003).

BUU from: Danielewicz, NPA**673**, 375 (2000).

Detector Requirements

- Current NSCL & RIKEN detectors not designed to detect pions.
- Need ability to distinguish particles by mass and charge state from pions to light fragments
- Able to resolve many different species of produced particles ⇒ useful for a wide range of experimental programs
- Large acceptance needed for reaction plane reconstruction
- High efficiency to distinguish pions

Detector Requirements



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- High efficiency to distinguish pions
- TPC provides large acceptance coverage of particle tracking in an applied magnetic field

AT-TPC Scientific Program

Table 1: Overview of AT-TPC scientific breadth.

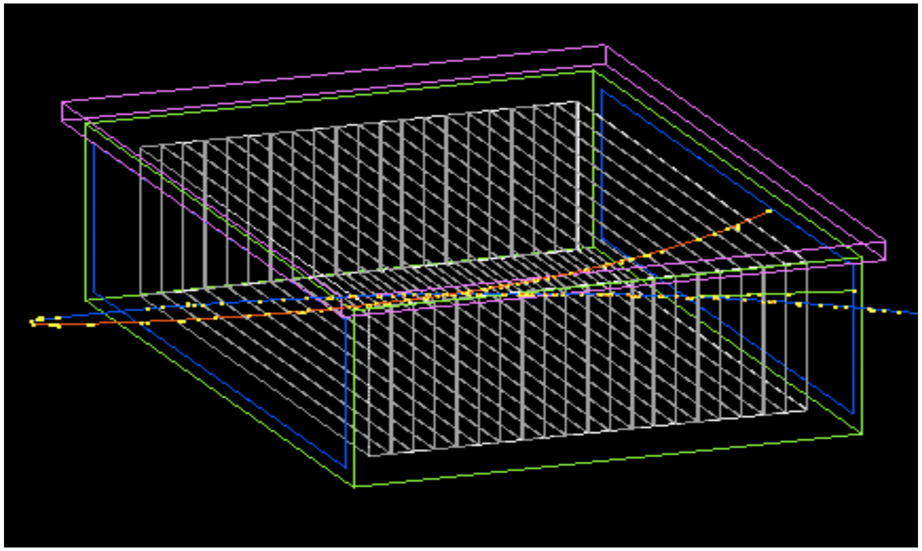
Measurement	Physics	Beam Examples	Beam Energy	Min Beam Intensity
Transfer Reactions	Nuclear Structure	$^{32}Mg(d,p)^{33}Mg$	3 (A MeV)	100 (pps)
Resonant Reactions	Nuclear Structure	$^{26}Ne(p,p)^{26}Ne$	3	100
Astrophysical Reactions	Nucleosynthesis	$^{25}Al(^{3}He,d)^{26}Si$	3	100
Fission Barriers	Nuclear Structure	^{199}Tl, ^{192}Pt	20 - 60	10,000
Giant Resonances	Nuclear EOS, Nuclear Astro.	^{54}Ni-^{70}Ni, ^{106}Sn-^{127}Sn	50 - 200	50,000
Heavy Ion Reactions	Nuclear EOS	^{106}Sn - ^{126}Sn, ^{37}Ca - ^{49}Ca	50 - 200	50,000

* GMR measurements to be made in inverse kinematics with D_2 active target

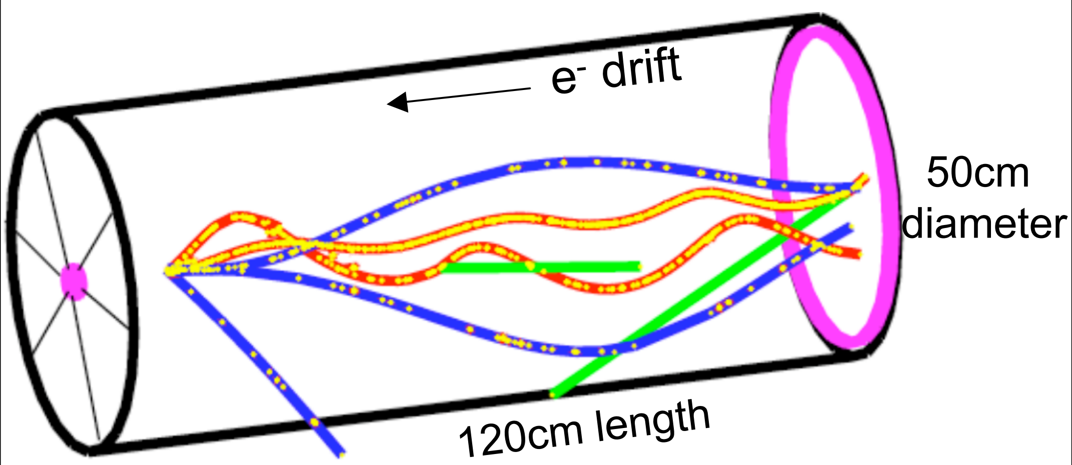
TPC Principles

RIKEN: SAMURAI (based on EOS)

Rai et al, IEEE Trans. Nucl. Sc. 37, 56 (1990).



NSCL: AT-TPC

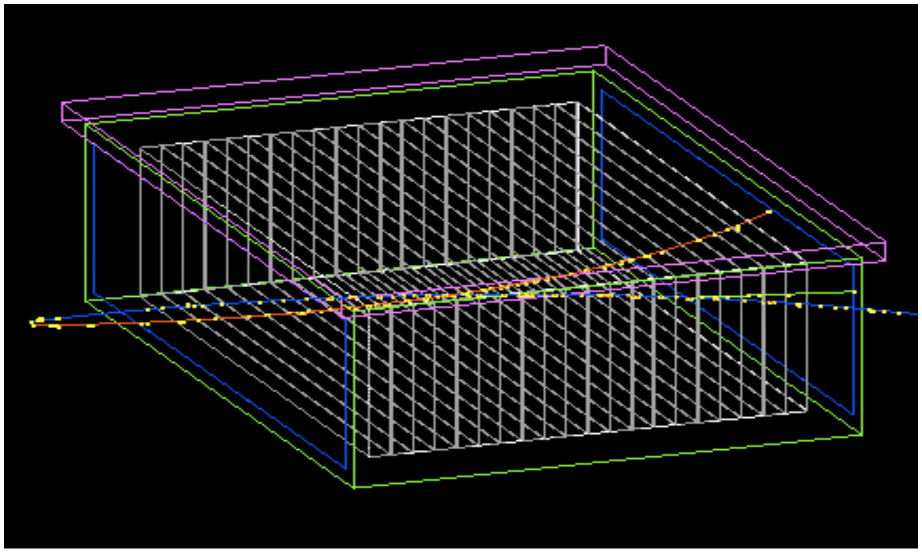


- Particle Tracking:
  - Active volume filled with ionizing gas
  - Charged particle creates e^- clusters
  - e^-'s drift in electric field to readout plane
  - Position of signal on readout plane gives 2D track coordinates
  - Signal time of arrival gives drift coordinate
  - Connect the dots to reconstruct particle path

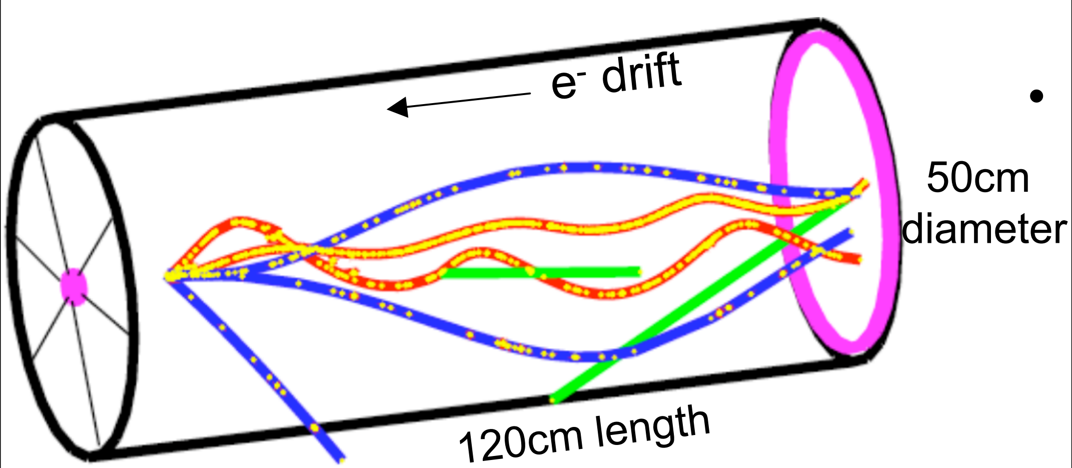
TPC Advantages

RIKEN: SAMURAI (based on EOS)

Rai et al, IEEE Trans. Nucl. Sc. 37, 56 (1990).



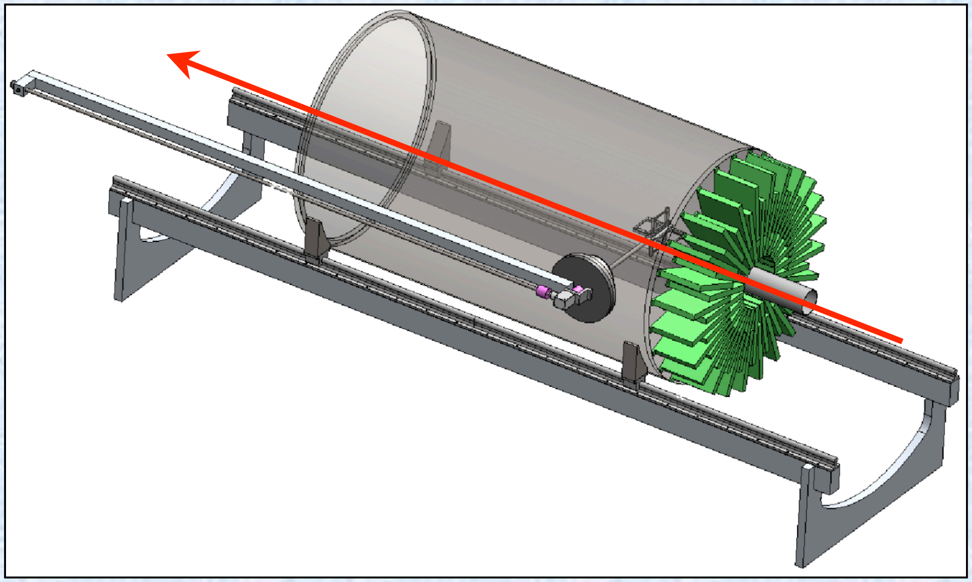
NSCL: AT-TPC

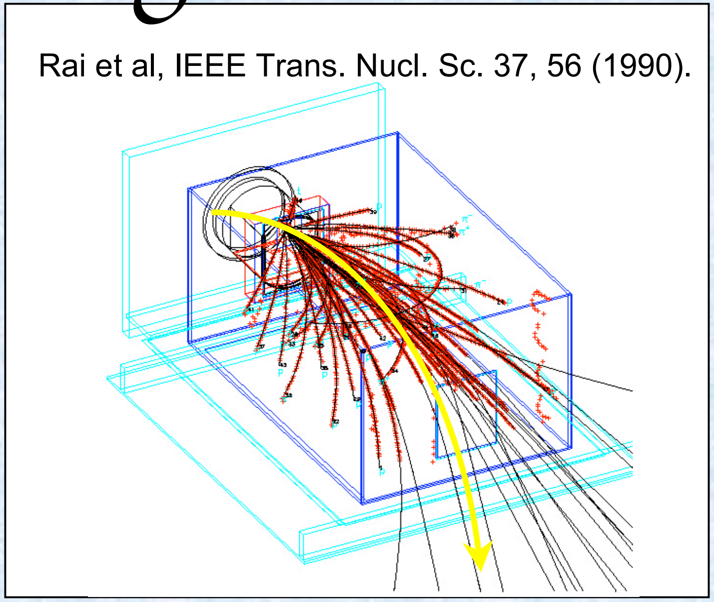


- 4π geometrical acceptance
- High resolution and efficiency tracking
- Sufficient magnetic field to resolve light fragments in heavy ion reactions
- Multiplicity triggering for intermediate energy heavy ion reactions
- Internal triggering for low energy particles that stop in the detector gas
- Large dynamic range for particle detection
- Electronics that can accommodate large data volumes and rates

Dual functionality as active target:
  - Variable pressure and identity of gas
  - Measure active target reactions with beam intensities down to 100pps

Chamber Design





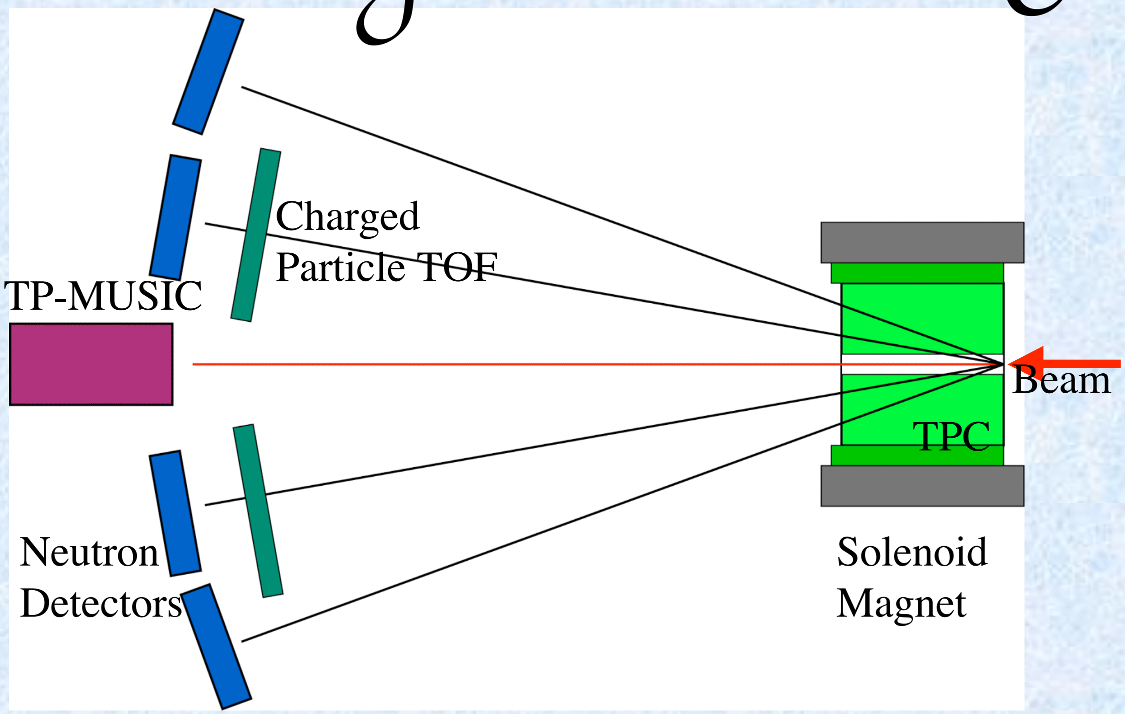
NSCL: AT-TPC

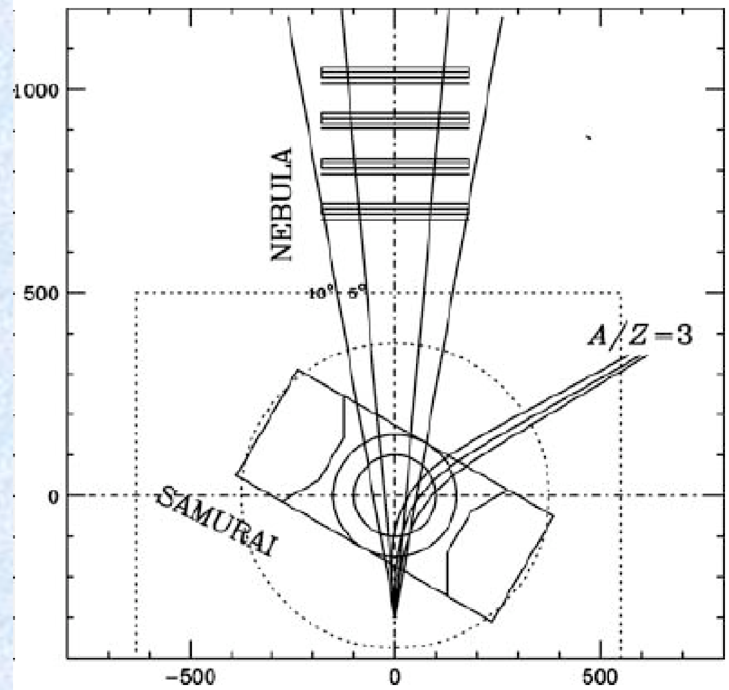
- Cylinder - length 120cm, radius 25cm
- Chamber designed to sustain vacuum
- 2cm radius entrance window
- 23cm radius exit window
- Removable target wheel
- 8000pads, 0.5cm x 0.5cm

RIKEN: SAMURAI

- Box - length 150cm, width 100cm, height 55cm
- Operates at atmospheric pressure
- Target sits outside entrance window
- 11760pads, 1.2cm x 0.8cm

Magnetic Field Considerations





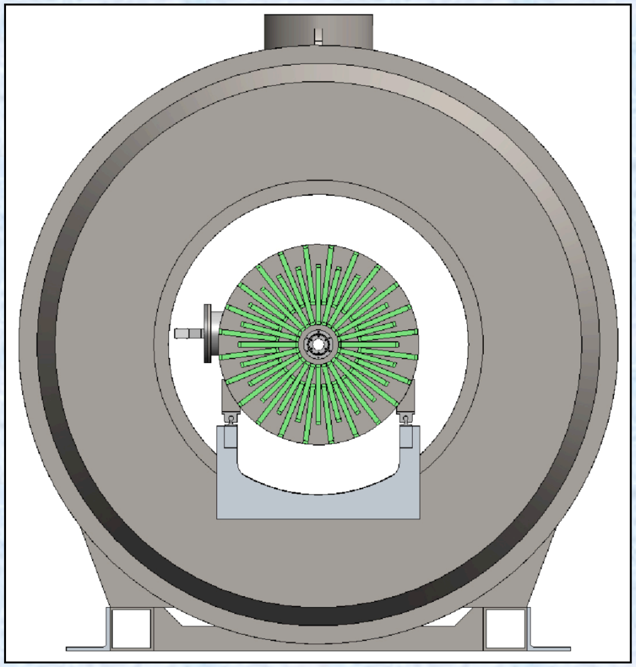
<u>Solenoid</u>

- Narrow downstream acceptance
- Poor momentum resolution at very forward angles
- Beam trajectory centered in magnet
- Beam path independent of beam species & energy
- Field cage can be used to mask beam ionization

<u>Dipole</u>

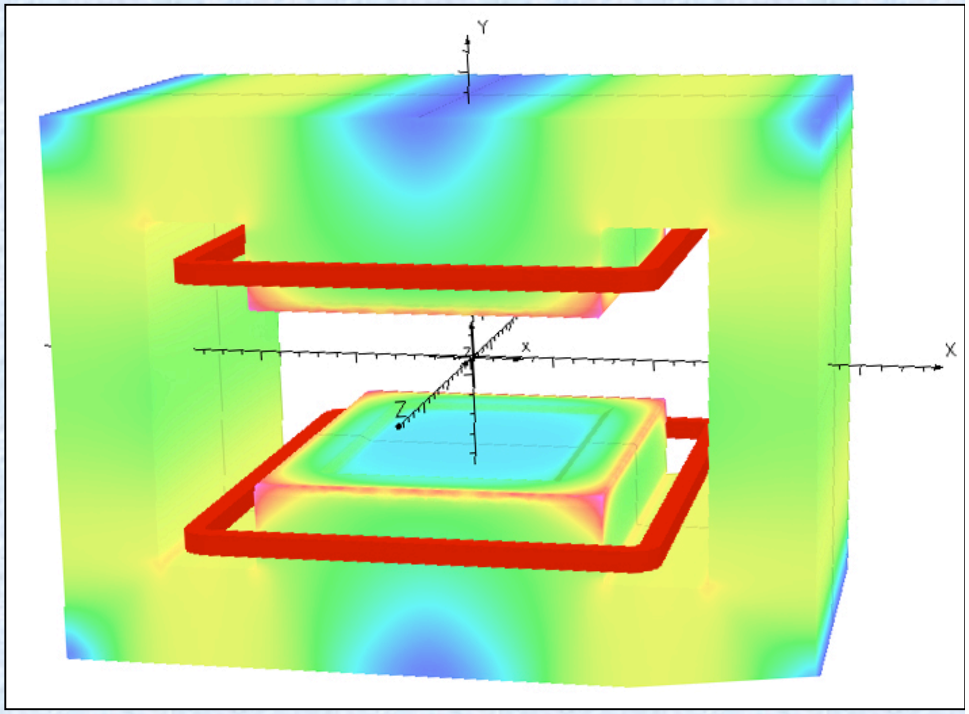
- Wide downstream acceptance
- Good momentum resolution in forward direction
- Beam trajectory influenced by Bfield
- Beam path dependent upon beam species & energy
- Difficult to mask beam ionization
- Difficult to distinguish π^+ from beam

Magnetic Field



NSCL: AT-TPC

- Superconducting solenoid
- 2 Tesla Field
- Bore Dimensions:
  - ≥ 70 cm diameter
  - ≥ 120 cm length
  - ≤ 125 cm beam height
- Field Non-uniformity: ≤ 10%
- Consistent with a medical MRI solenoid



RIKEN: SAMURAI

- Superconducting dipole
- 3 Tesla Field
- Gap Dimensions:
  - 200 cm pole diameter
  - 80 cm height
- 180deg rotating base
- 650Ton weight

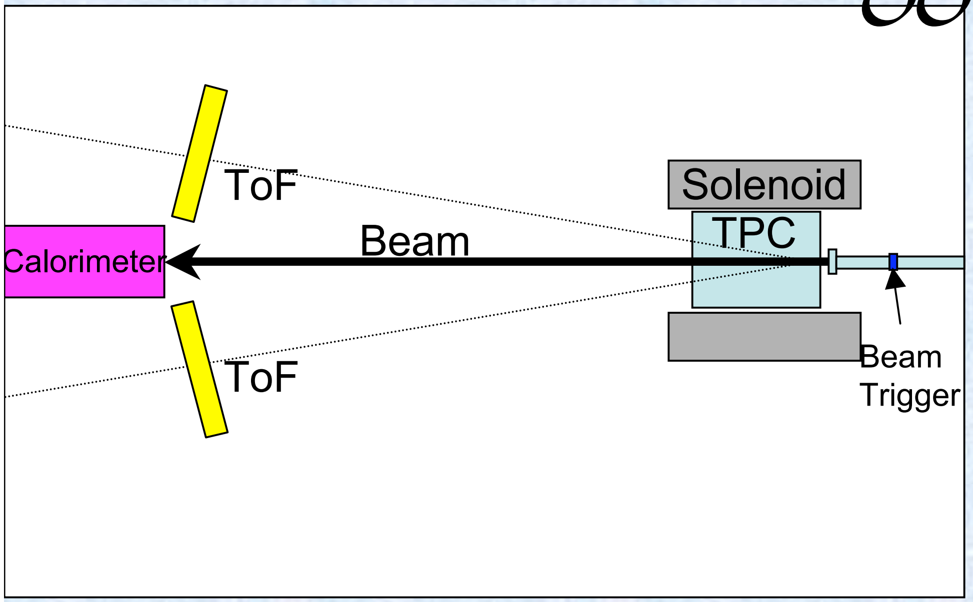
Historical Perspective

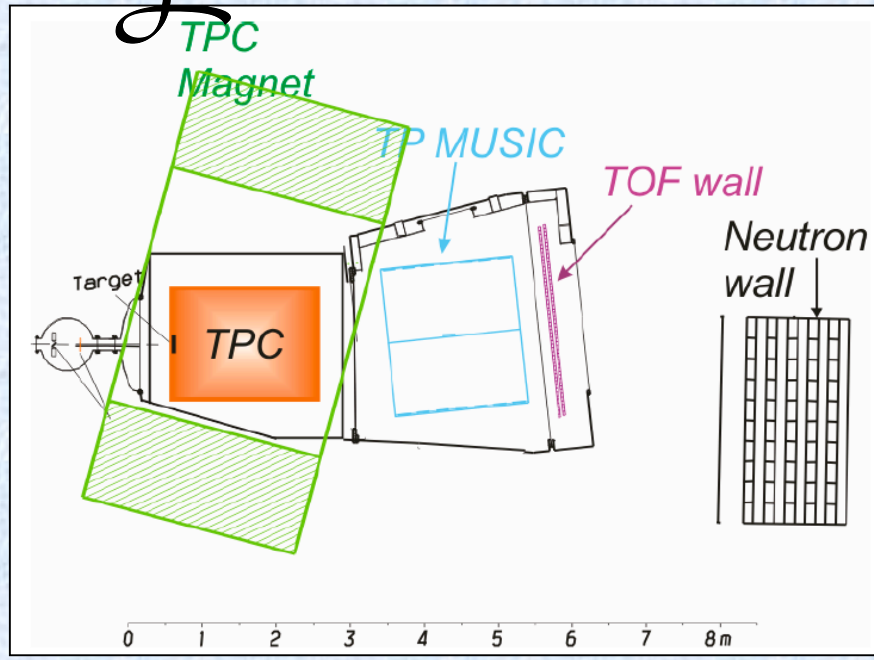
Table 1: Summary of TPC experiments [EOS1990, STA2003, ALI2007, T2K2007].

System	*Pads*	*Pad Size (cm)*	*Magnet*	*Field (T)*	*Drift(cm)*
EOS	15360	1.2 x 0.8	Dipole	1.3	75
STAR	136608	0.3x1.2, 0.6x2.0	Solenoid	0.5	210
ALICE	557568	0.6x1.0, 0.6x1.5	Solenoid	0.4	250
T2K	124000	0.7x1.0	Dipole	0.2	500
AT-TPC	10000	0.5x0.5	Solenoid	2.0	120
SAMURAI	11760	1.2 x 0.8	Dipole	3.0	55

- Scale of both detectors consistent with EOS experiment
- NSCL: AT-TPC
  - Pad plane design will allow improved resolution over both EOS & STAR
  - Solenoid field constrains beam path to center of detector independently of beam identity
  - Increased field strength suitable for identifying high mass species
  - Drift distance coupled with readout allows for <2.5mm resolution
- RIKEN: SAMURAI
  - Identical to EOS with exception of reduced drift distance

Triggering





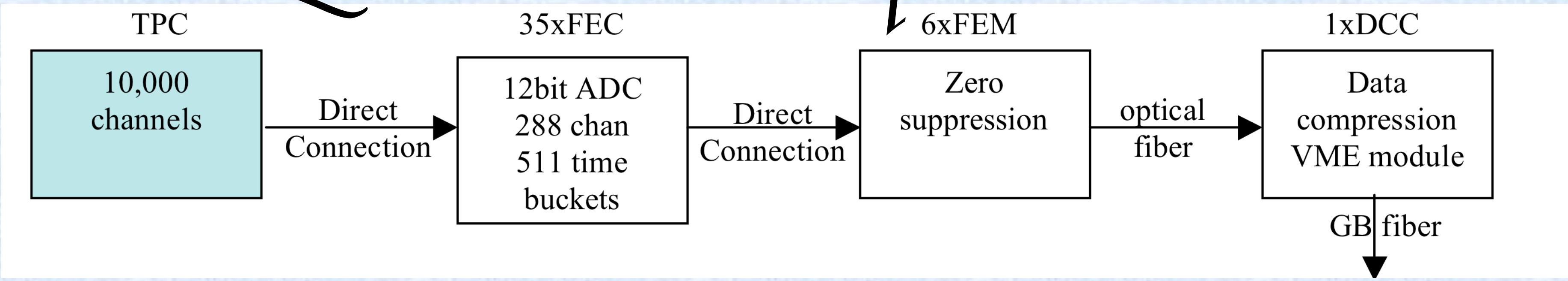
NSCL: AT-TPC

- Beam trigger - provided by PPAC & RF-ToF before beam enters chamber
- Internal trigger - discriminator incorporated in TPC electronics to be used as a threshold trigger
- Downstream calorimeter to measure Z of leading particle

RIKEN: SAMURAI

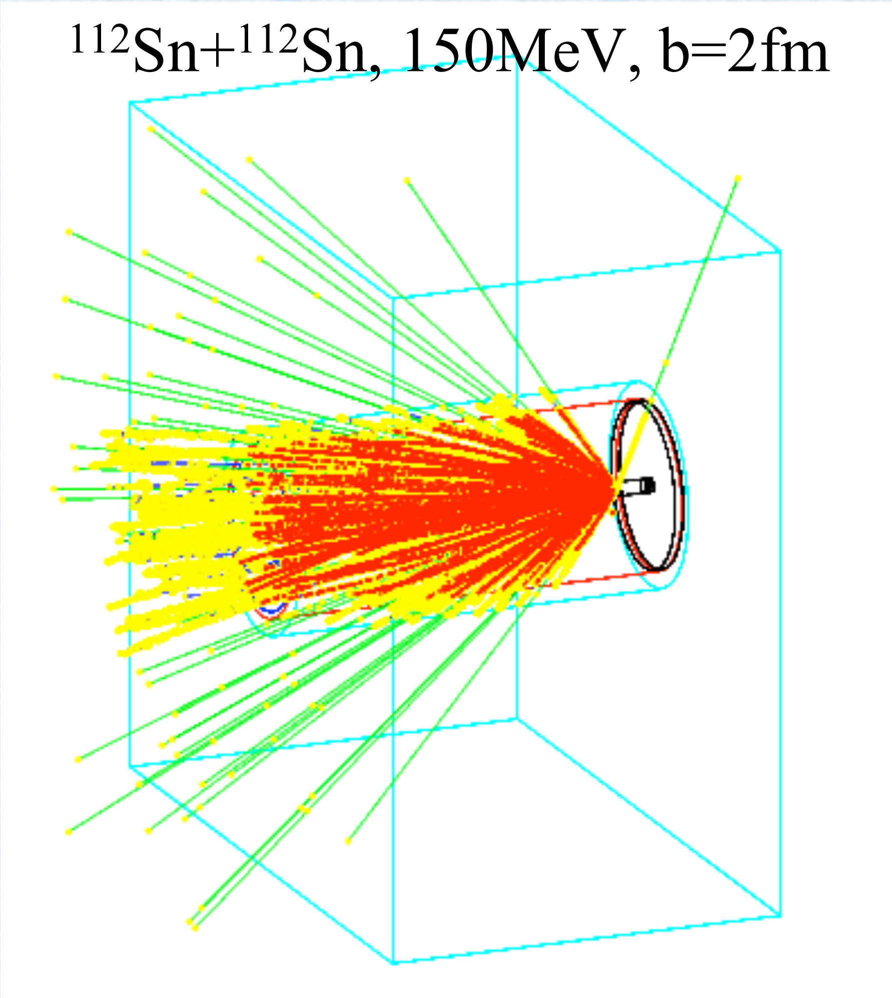
- Beam tracking detector
- Fast scintillator array, $\theta<60°$
- Diamond detector as ToF start

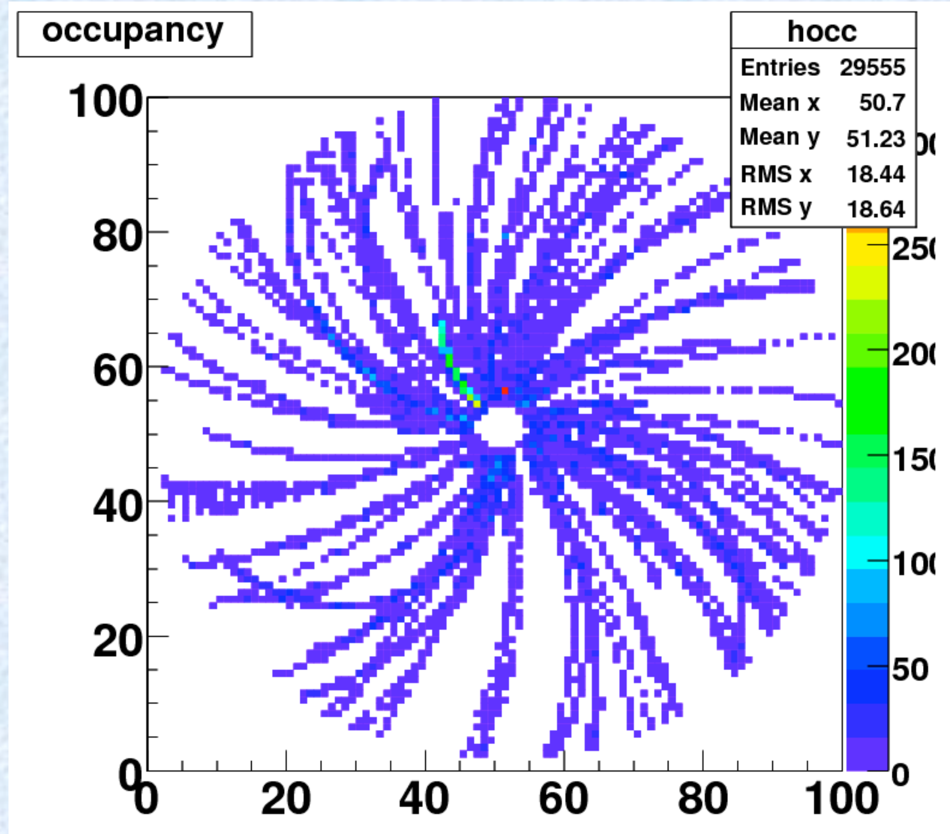
Electronics Requirements



- Investigating opportunities to modify existing T2K electronics chain to accommodate our requirements
- Effort being led by ACTAR working group
- Dynamic range of ADC is key due to wide range of particle species to be simultaneously identified ∴ 12bit AFTER+ chip will be used
- Must sustain 1kHz/chan data rate
- Internal triggering capability will accommodate active target requirements of AT-TPC

Data Volume





- High collision multiplicity expected
- ~2% channels & time buckets filled
- Results in data volume of :

5 kB/s*chan
50MB/s
} Zero suppressed

Data Management

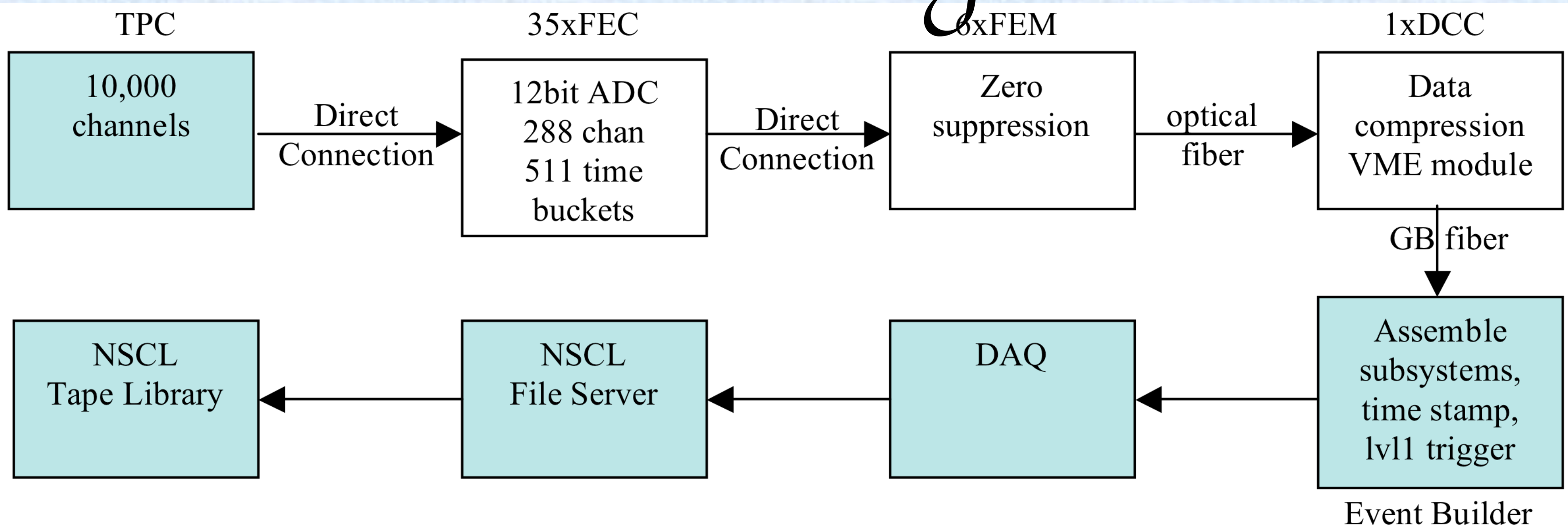


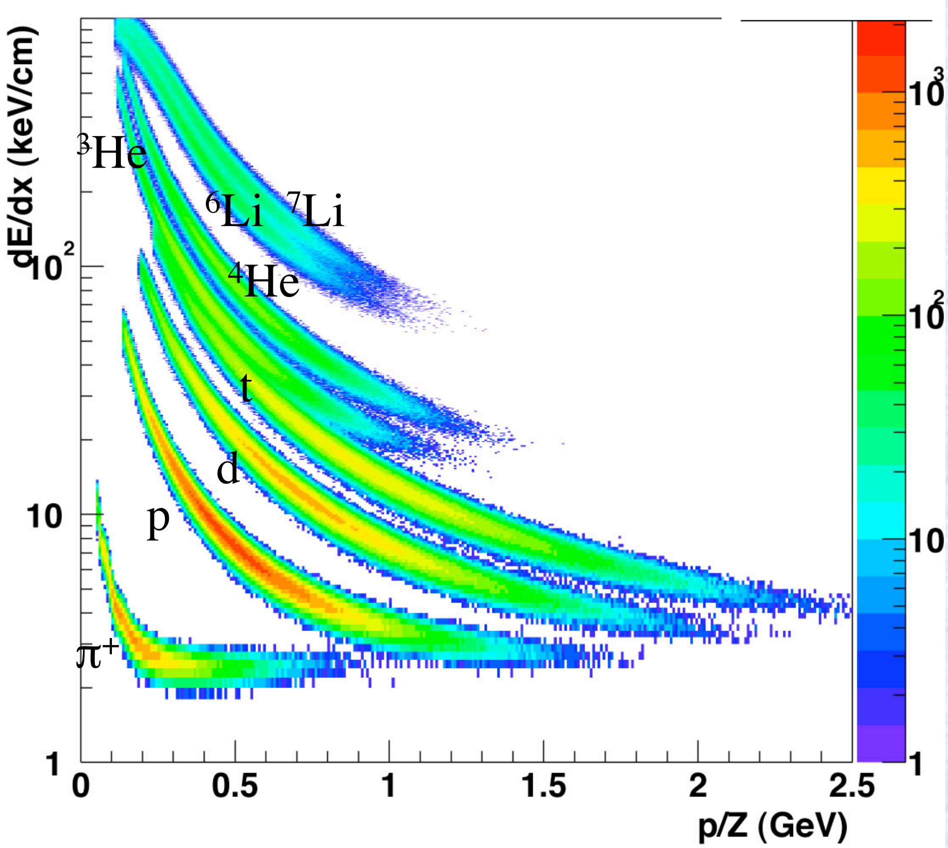
Figure 1: Overview of data flow. The shaded items will be developed at NSCL while the FEC, FEM, and DCC will be adapted from the T2K experiment.

Sub - Systems

- Gas Mixing System:
  - Monitors & maintains chamber pressure and gas purity
  - NSCL: AT-TPC
    - identity and pressure of the gas used to fill the detector will be dependent upon the experimental requirements.
    - H_2, D_2, ^3He, Ne, Ar, isobutane and P10(90% Ar + 10% CH_4)
  - RIKEN: SAMURAI
    - P10(90% Ar + 10% CH_4)
- Laser Calibration System:
  - Calibration based on drift rate of laser induced ionization
  - Compensates for changing environmental conditions and static non-uniformities in the magnetic and electric fields

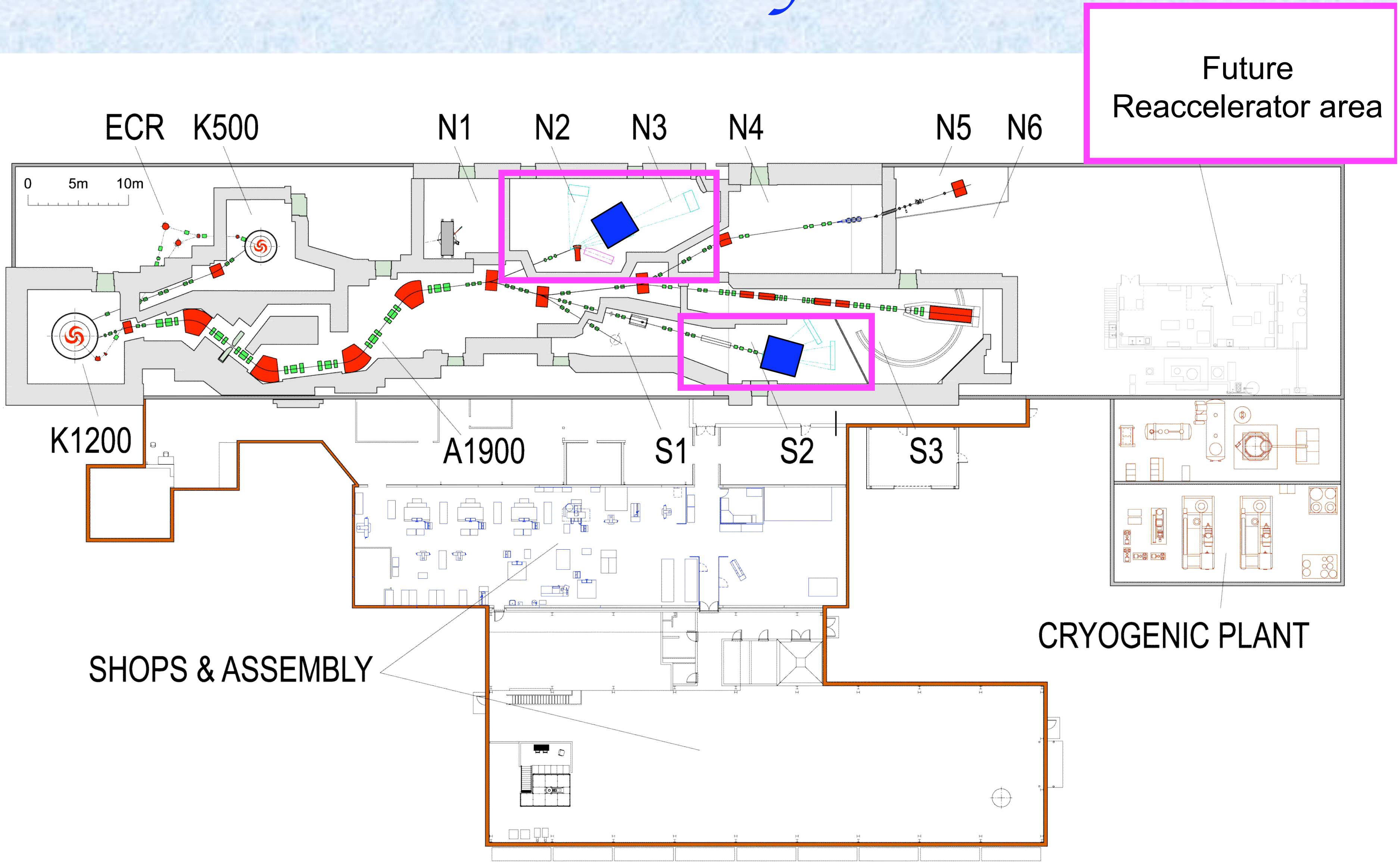
Principles of Particle Identification

Simulation w/ STAR resolution, scaled to EOS

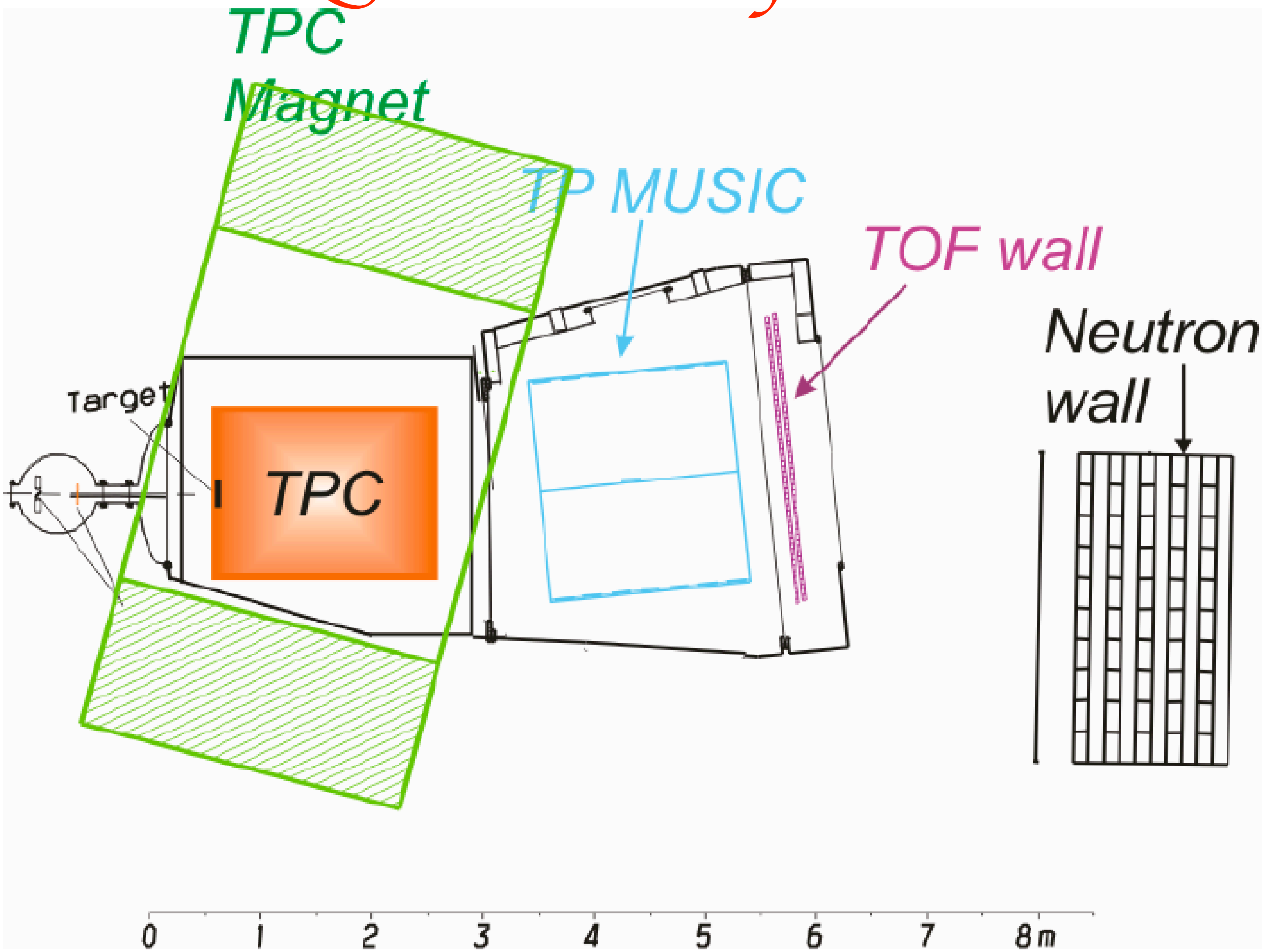


- Energy deposition and radius of curvature of each particle species is unique
- Allows identification of particle species and charge state
- Dynamic range sufficient to simultaneously measure pions → light isotopes

NSCL Footprint



RIKEN Footprint



Timeline & Funding

NSCL: AT-TPC

- Proposals submitted to both NSF and DOE
- Total budget: $1-2M
- 2008 - Prototype testing, Mechanical Design
- 2009 - Electronics, Magnet, Laser System, Gas Mixing
- 2010 - System Commissioning
- 2011 - First experiments

RIKEN: SAMURAI

- Magnet and supporting subsystems included in SAMURAI budget
- Proposal submitted to DOE for chamber construction at NSCL
- Chamber budget - $800k
- 2010 - Chamber construction begins
- 2011 - Dipole completed
- 2013 - First experiments

Collaboration

NSCL: AT-TPC

- LBNL - Lee, Phair
- University Notre Dame - Garg
- NSCL - Bickley*, Lynch, Mittig, Westfall
- Western Michigan University - Famiano

RIKEN: SAMURAI

- Daresbury Laboratory - Lemmon
- GANIL - Chbihi
- GSI - Lukasik, Stoecker, Trautman
- Kyoto Univ. - Murakami*
- LNS-INFN - Colona, Di Toro, Verde
- NSCL - Bickley, Brown, Danielewicz, Lynch, Tsang, Westfall
- Riken - Nakai, Nishimura, Sakurai
- Rikkyo University - Ieki, Murata
- SUBATECH - Hartnack
- Smith College - Pfabe
- Texas A&M University - Yennello
- Texas A&M University Commerce - Li
- Tohoku University - Ono
- Western Michigan Univ. - Famiano
- Universidade Federal do Rio Grande do Sul - Souza
- Universidade Federal do Rio de Janeiro Cidade Universit´aria - Donangelo

Thank you