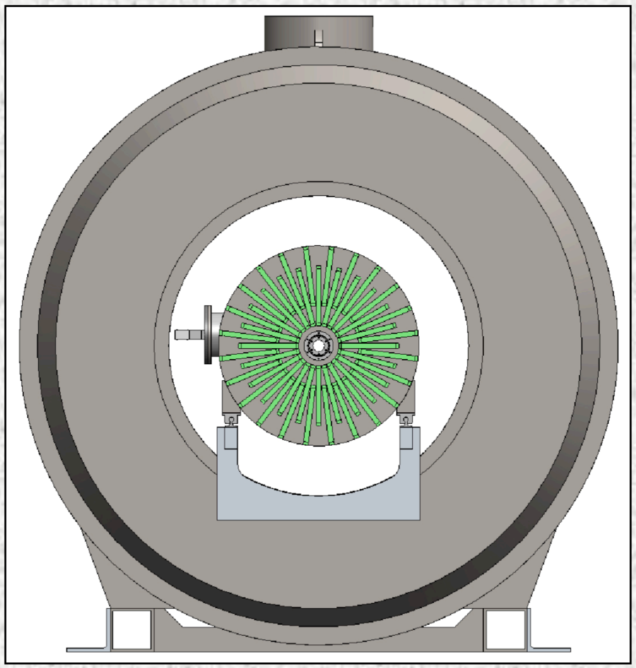
Implementing An Active Target Time Projection Chamber at NSCL



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What is the AT-TPC?

- The AT-TPC combines time projection and active target functionality allowing measurements of:
  - Rare processes that require high detection efficiency and large acceptance
  - Low energy processes that are traditionally difficult to measure due to the short range of the reaction products in matter
- Active Target Mode:
  - The chamber gas will act as both detector and target
  - Appropriate <u>gas identity</u> and <u>pressure</u> will be chosen to study the reaction of interest in inverse kinematics
  - Limitations imposed by low beam intensities will be addressed by providing a thick target while retaining high resolution and efficiency
- Fixed Target Mode:
  - A target wheel will be installed within the chamber thus the gas will serve only as a detector
  - Configuration will reflect standard TPC conditions (P10 @ 1atm)

Scientific Program Overview

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 - 150	50,000
Heavy Ion Reactions	Nuclear EOS	^{106}Sn - ^{126}Sn, ^{37}Ca - ^{49}Ca	50 - 150	50,000

- Detector will make use of the full range of beam energies and intensities available at NSCL
- Portability among vaults is essential
- High resolution and efficiency of detector allow reactions induced by low intensity beams to be completed in a reasonable running period

Active Target Experiments

- Transfer Reactions:
  - Coulomb dominated transfer reactions provide the most precise asymptotic normalisation coefficients (ANC)
  - Used to distinguish whether a state has essentially a single-particle nature
  - Angular momentum of state obtained from the cross-section energy dependence
  - Many transfer cross-sections are highest at energies of 1 – 2 AMeV due to excellent velocity matching between the initial and final states
  - Study (d,p), (^{3}He,d) and (α,t) transfer reactions in the vicinity of closed shells
  - Proton energies ~10 MeV in the case of (d,p) reactions
  - An example of interest for understanding shell closures far from stability that will be possible with the AT-TPC is the ^{32}Mg(d,p)^{33}Mg reaction
  - Beam energy ≤ 3 AMeV; Minimum beam intensity 100pps
- Resonance Reactions:
- Astrophysical Reactions:
- Fission Barriers:
- Giant Resonances:

Active Target Experiments

- Transfer Reactions:
- Resonance Reactions:
  - Study the production and decay of isobaric analog resonance states in both elastic and inelastic scattering using $^{A}Z(p,p)$, to determines the properties of the nucleus ^{A+1}Z.
  - Large cross-sections are typical for this reaction where the interference between the potential and the resonant amplitudes determines J^{π}.
  - The gas pressure of the AT-TPC will be adjusted to stop the beam in the detector, allowing continuous excitation functions to be measured between beam energy and zero energy.
  - Backward CoM angles are important => correspond to 0-45° in lab
  - Center-of-mass resolution of 35 keV expected
  - Reaction example: $^{26}Ne(p,p)^{26}Ne$
  - Beam energy $\leq$ 3 AMeV; Minimum beam intensity 100pps
- Astrophysical Reactions:
- Fission Barriers:
- Giant Resonances:

Active Target Experiments

- Transfer Reactions:
- Resonance Reactions:
- Astrophysical Reactions:
  - Study proton reaction rates relevant for hot and explosive stellar environments where nuclei are far from stability
  - Example: Origin of large galactic abundance of ^{26}Al unresolved
  - Proton capture on ^{25}Al followed by ^{26}Si beta decay could be the mechanism, but depends on the capture cross section and the structure of high lying levels in ^{26}Si
  - Use indirect ANC to measure the ^{25}Al(^{3}He,d)^{26}Si transfer reaction
  - Very good energy resolution is needed due to the high level density in ^{26}Si.
  - A 5 keV deuteron resolution $\Rightarrow$ 10 keV excitation energy resolution.
  - Due to the low deuteron energy (0.4-1.0MeV), a conventional target would need to be extremely thin
  - Beam energy $\leq$ 3 AMeV; Minimum beam intensity 100pps
- Fission Barriers:
- Giant Resonances:

Active Target Experiments

- Transfer Reactions:
- Resonance Reactions:
- Astrophysical Reactions:
- Fission Barriers:
  - Provide constraints for fission cycling, beta-delayed and neutrino-induced fission contributions to r-process yields
  - Test extrapolations of ground state and fission saddle point binding energies away from the valley of stability
  - Use H_2 or He as active target gas
  - Beam intensities of 10^4 particles/s and average fission cross-sections of 0.3 mb, give of 12 evt/h per MeV excitation energy
  - Fission barrier of ^{200}Pb from $78 \le Z \le 81$ measured in 2.5 days
  - Require beam energies of 20-60 AMeV
- Giant Resonances:

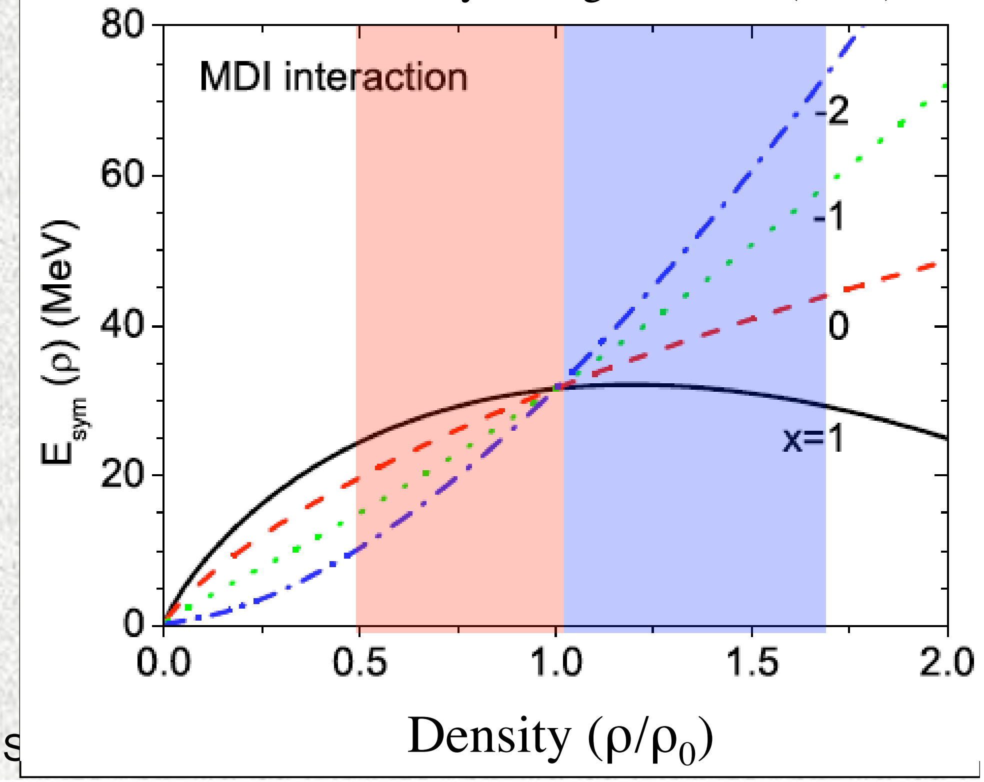
Active Target Experiments

- Transfer Reactions:
- Resonance Reactions:
- Astrophysical Reactions:
- Fission Barriers:
- Giant Resonances:
  - Measurements along isotopic chains constrain the contribution of the symmetry energy to the nuclear incompressibility
  - Extend studies to neutron-rich isotopes such as ^{54}Ni-^{70}Ni and ^{106}Sn-^{127}Sn
  - Forward center of mass (CM) angles are essential to separate the $\ell=0$ contribution from that of $\ell=2$
  - Consider inelastic scattering of deuterons instead of α's because, for pure helium gas and proportional wires, the maximum gain is low without a quencher
  - Both are T=0 probes and the kinematics of the two cases are similar
  - To collect 1000 GR counts, a beam of 50,000 particles/s for 3 days is needed, allowing GR to be studied for ^{54}Ni-^{70}Ni and ^{106}Sn-^{127}Sn
  - Requires beam energies of 50-150 AMeV

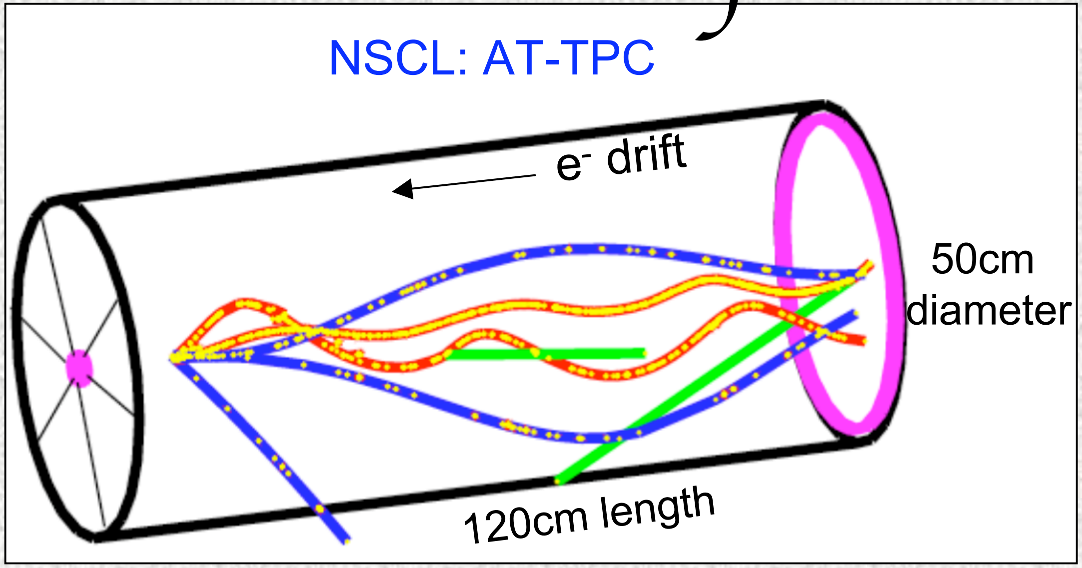
Fixed Target Experiments

- Heavy ion collisions with fast beams:
  - Study density dependence of symmetry energy
  - 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
      - Isotopic spectra
      - Isotopic flow
  - With NSCL beams, densities up to $1.7\rho_0$ are accessible
  - Beams: 50-150 MeV, 50,000pps ^{106}Sn-^{126}Sn, ^{37}Ca-^{49}Ca

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

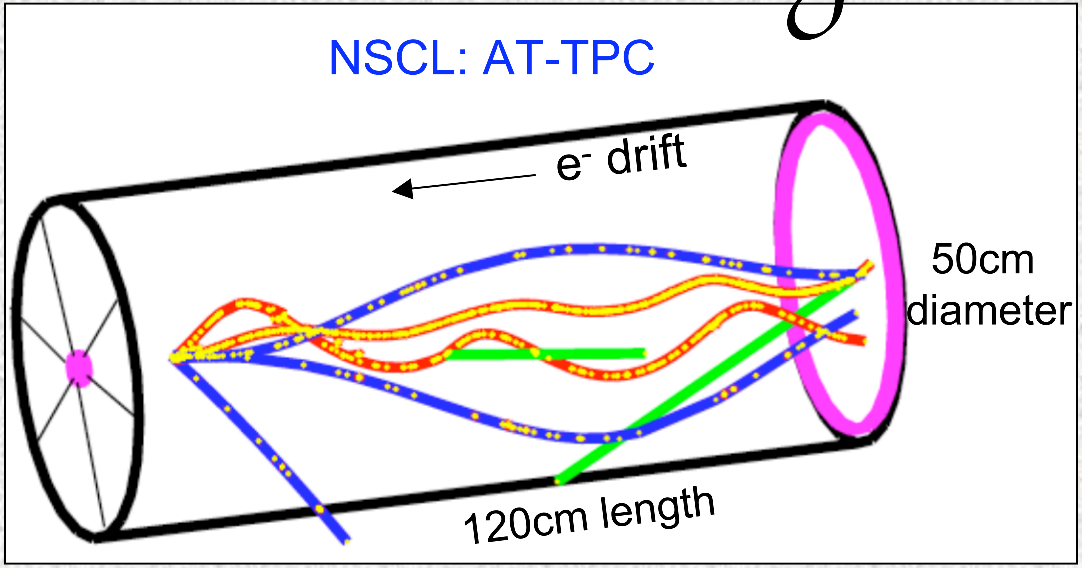


TPC Principles



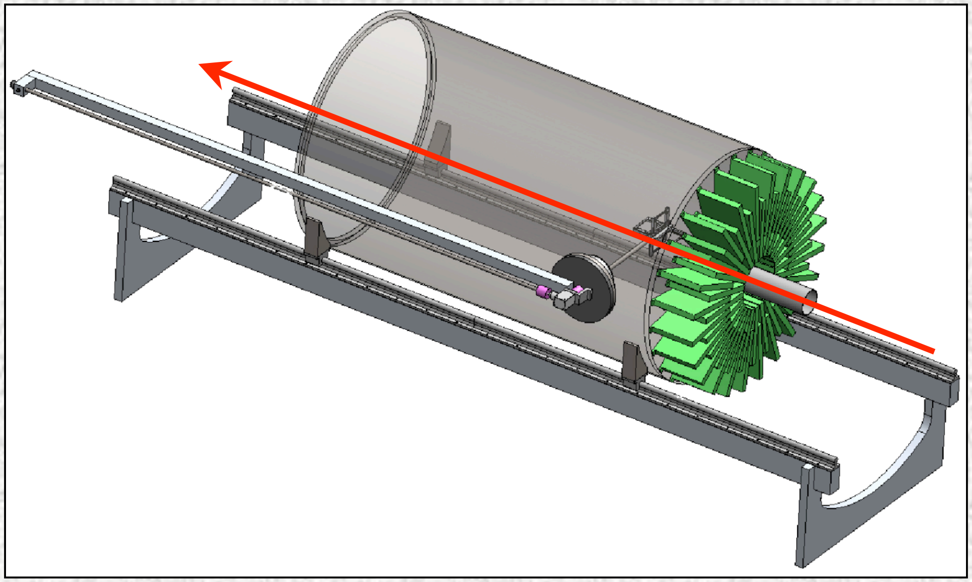
- Particle Tracking:
  - Active volume filled with ionizing gas
  - Charged particle creates e^- clusters
  - e^-'s drift in electric field to readout plane
  - Position of signal on readout plane gives 2D track coordinates
  - Signal time of arrival gives drift coordinate
  - Connect the dots to reconstruct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

TPC Advantages



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

AT-TPC Chamber Design



NSCL: AT-TPC

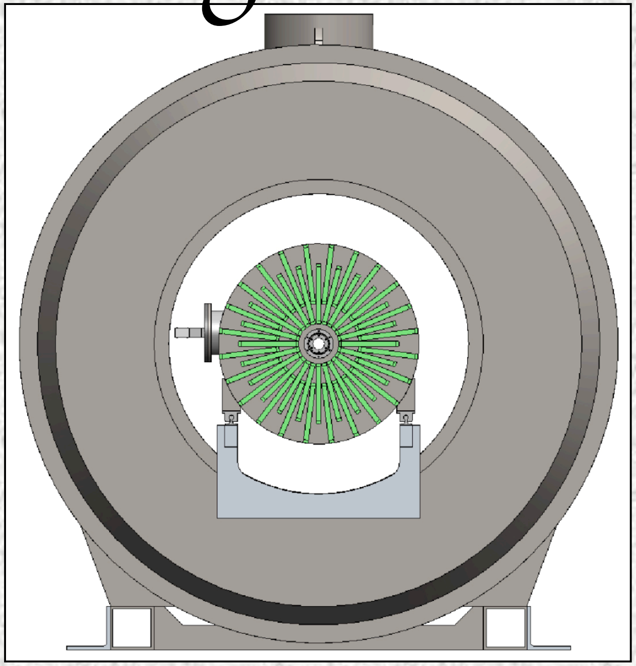
- Cylinder - length 120cm, radius 35cm
- Chamber designed to sustain vacuum
- 2cm radius entrance window
- 23cm radius exit window
- Removable target wheel
- 8000pads, 0.5cm x 0.5cm
- Testing wire planes, GEMS & Micromegas for electron amplification

Sub - Systems

- Gas Mixing System:
  - Monitors & maintains chamber pressure and gas purity
  - 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)
    - Pressures ranging from 0.2-1.0 atm

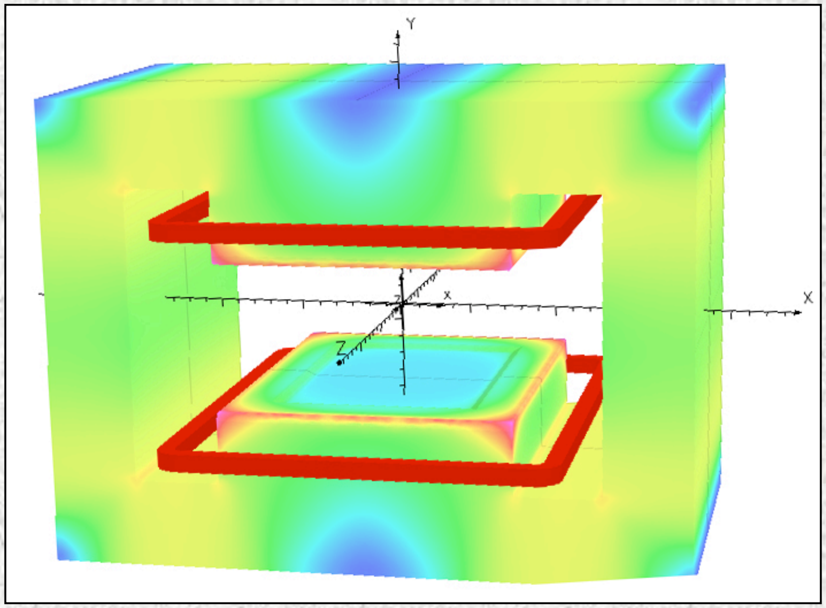
- Laser Calibration System:
  - Calibration based on drift rate of laser induced ionization
  - Compensates for changing environmental conditions and static non-uniformities in the magnetic and electric fields
  - A predefined fraction of the event rate will be laser triggered allowing the electron drift rate to be continuously sampled
  - Will be installed within detector and will require safety review

Magnetic Field Considerations



Solenoid

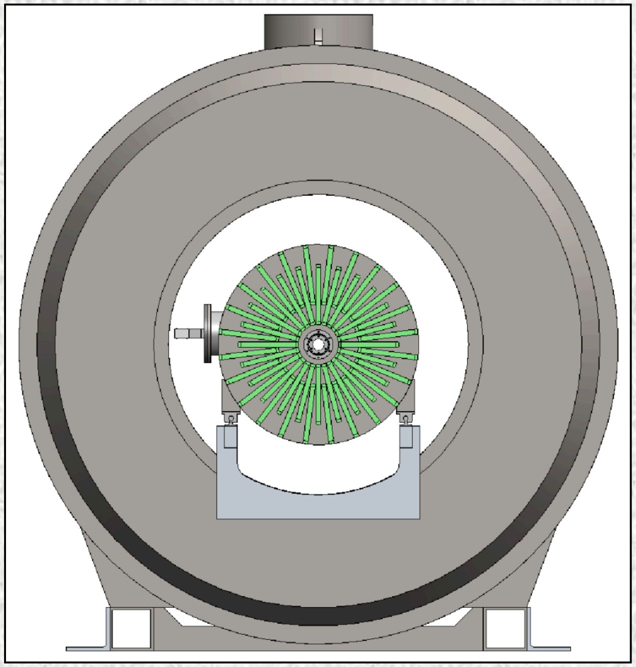
- Beam trajectory centered in magnet
- Beam path independent of beam species & energy
- Optional field cage can be used to mask beam ionization
- Narrow downstream acceptance
- Poor momentum resolution at very forward angles

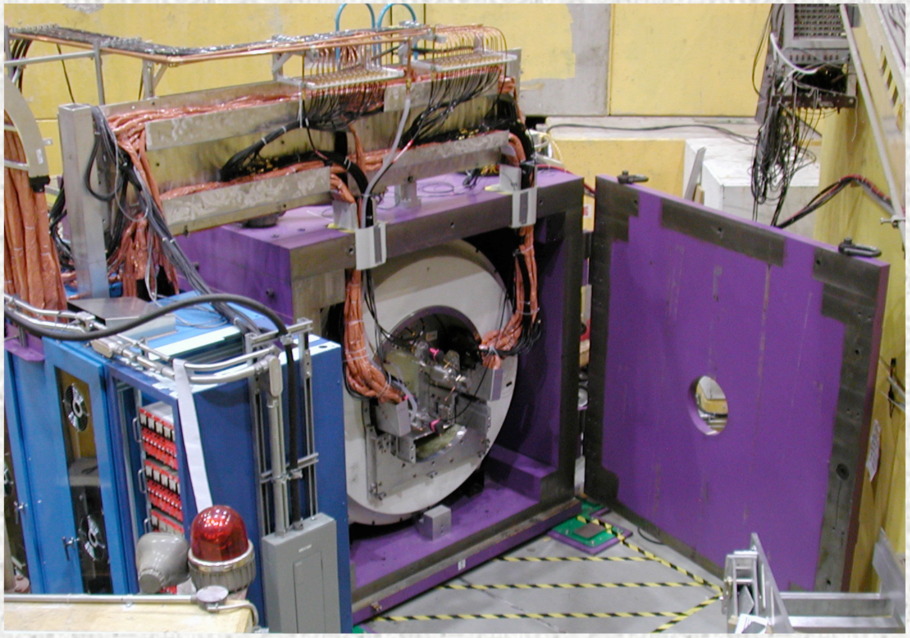


Dipole

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

TWIST Solenoid

- Superconducting solenoid
- 2 Tesla Field
- Bore Dimensions:
  - 105 cm diameter
  - 229 cm length
  - 107 cm beam height (w/o yoke)
  - 130 cm beam height (w/ yoke)
- Field Non-uniformity: < 1%

Spatial Constraints

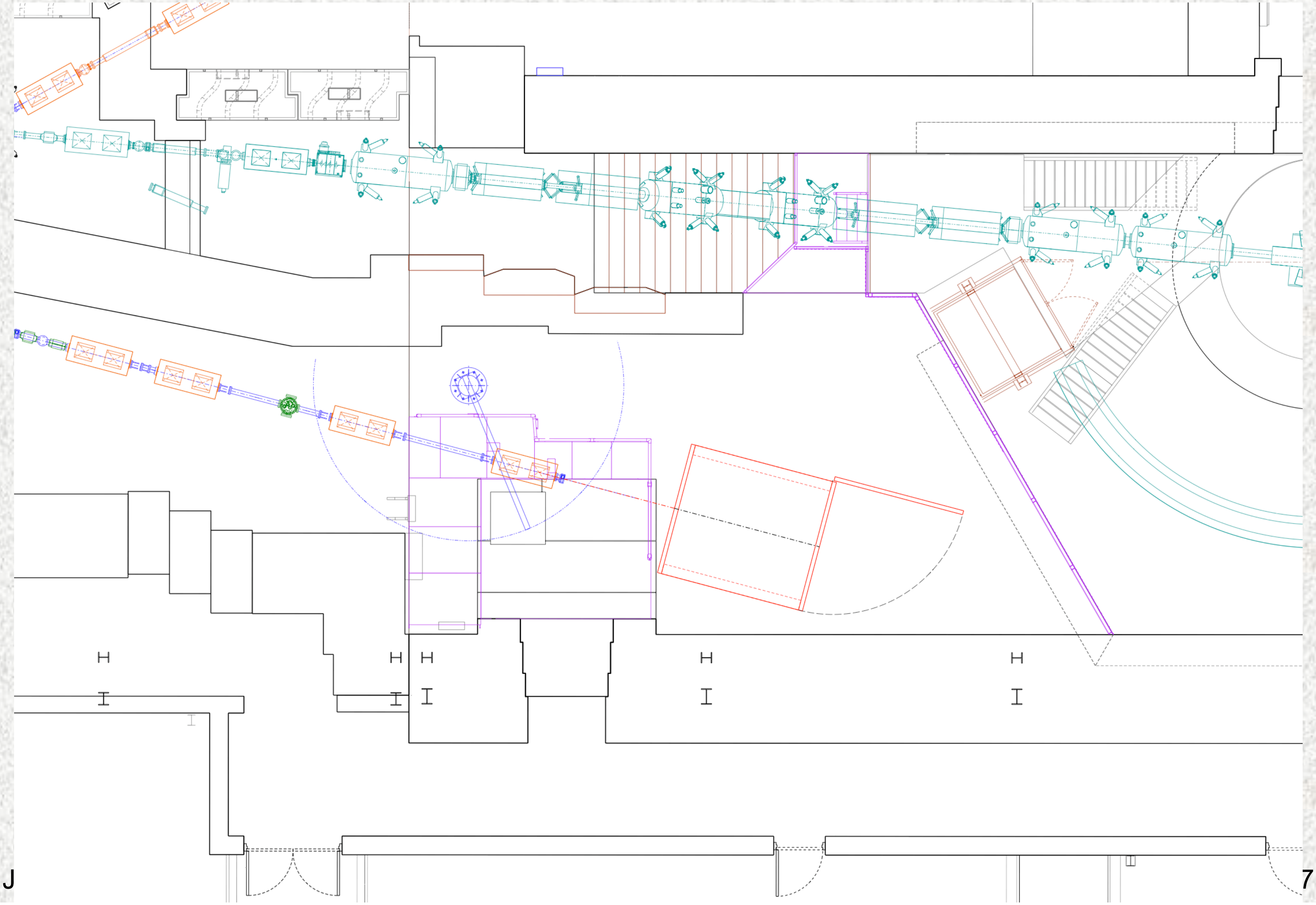
Solenoid

- External Dimensions:
  - Diameter = 195.5cm
  - Length = 229.0cm
  - Height:
    - 107.0 cm central field
    - 240.0 cm overall
    - 274.0 cm min ceiling
- Mass:
  - Dry = 7450kg
  - Filled = 7800kg

Yoke

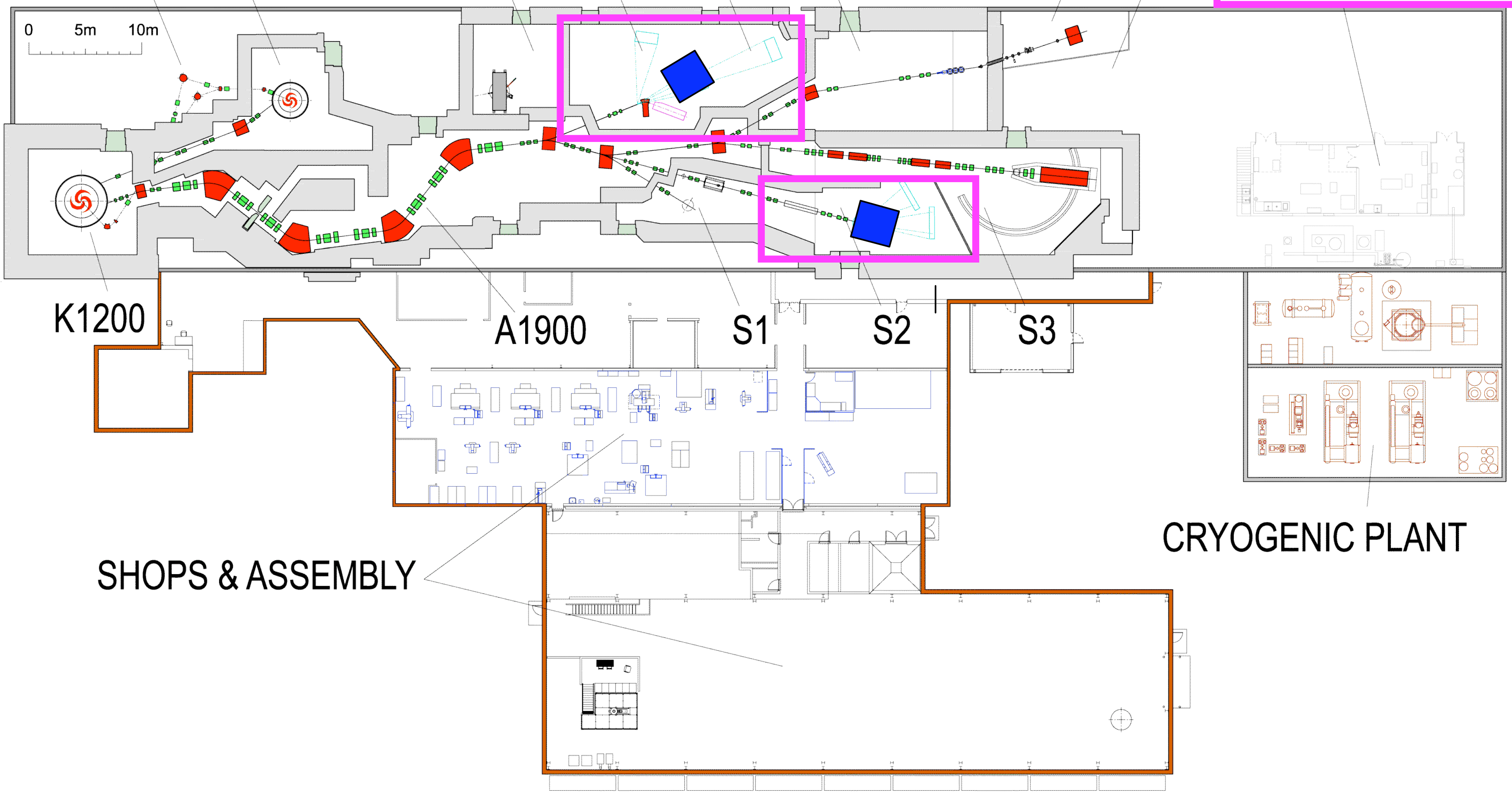
- External Dimensions:
  - Sides
    - 19.5cm thick steel
    - 221.0 x 278.4 cm
  - Endcaps
    - 8cm thick steel
    - 261.0 x 252.0 cm
    - 40cm hole diameter (will be expanded)
  - Top & Bottom
    - 19.2cm thick steel
    - 261.0 x 278.4 cm
- Mass:
  - Sides = 2 x 9.4E3kg
  - Endcaps = 2 x 4.1E3kg
  - Top & Bottom = 2 x 11.0E3kg
  - Corner pieces = 4x0.94E3kg
  - Total = 53E3kg

S2 Vault



NSCL Footprint

Future Reaccelerator area



Fringe Field

- Optimization of yoke design:
  - increase the field uniformity in the central region
  - decrease range of fringe field
  - 10G line currently sits at ?m from endcaps
- Planned yoke modifications:
  - expand exit window to maximize downstream acceptance
  - Initial estimates show 10G line extends to 12m in beam direction and 9.5m in axial direction
  - Further studies needed

Technical Considerations

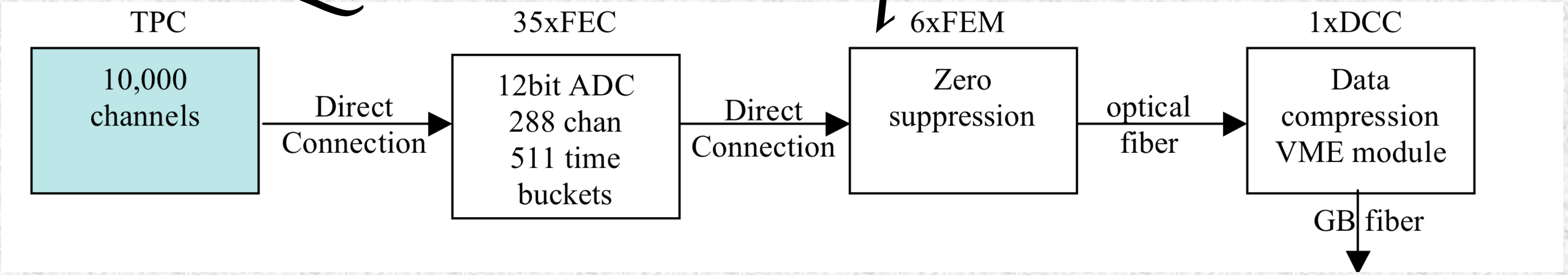
- Liquid Helium Consumption:
  - 100L He(liq) per week
  - While ramping the field up or down, with the current lead inserted, consumption of LHe is significantly higher.
  - A ramp to full current takes typically 8 hours and requires about 120L He(liq)
- Liquid Nitrogen Consumption:
  - 110L of N_2(liq) per week
- Power Supply:
  - Oxford Model 2140, see hardcopy of handbook
  - No remote operation, solenoid must be ramped by hand in the vault
  - The power supply has a voltage-limited ramp rate. Standard ramping steps: 5V to 100A, 4V to 150A, 3V to 180A, 2V to 195A, 1.5V to 210A, and 1V to the full 227A
  - If the ramp rate is too high, especially near full field, there is a quench risk

Triggering

- Active & Fixed Target Requirements:
  - 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

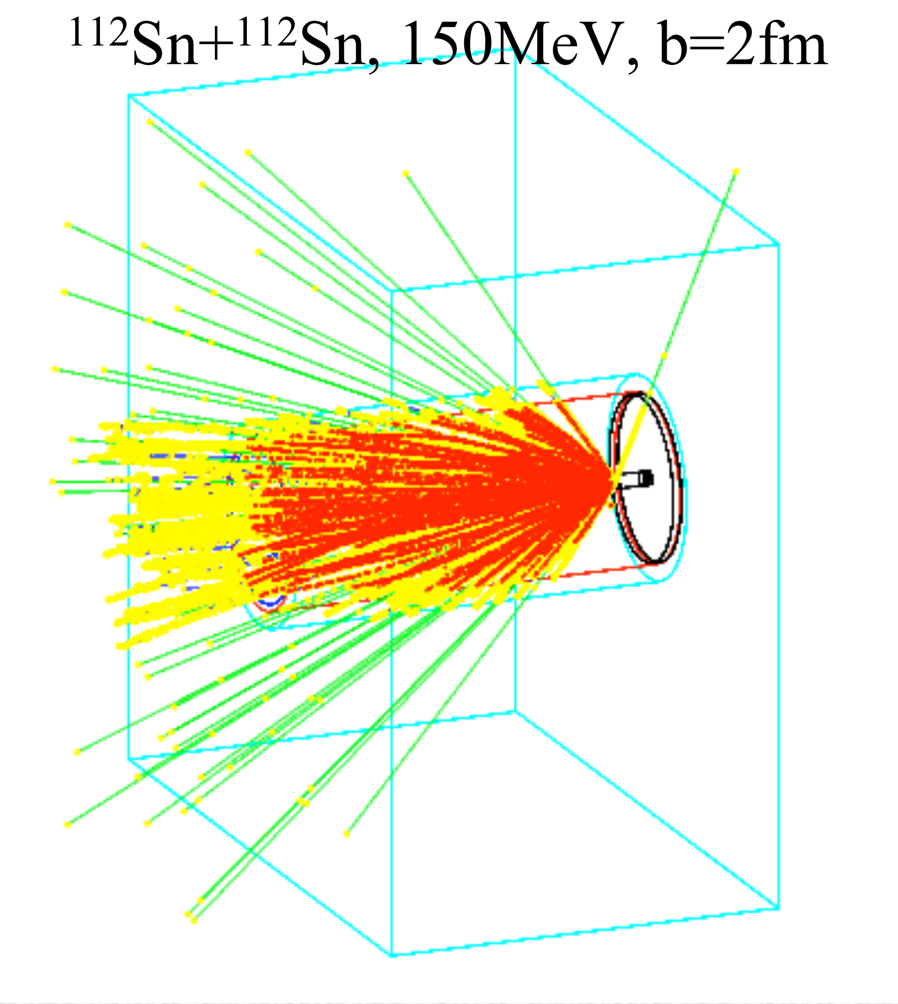
- Fixed Target Mode:
  - Downstream calorimeter to measure Z of leading particle
  - Additional floor space not required in reaccelerated beam area

Electronics Requirements

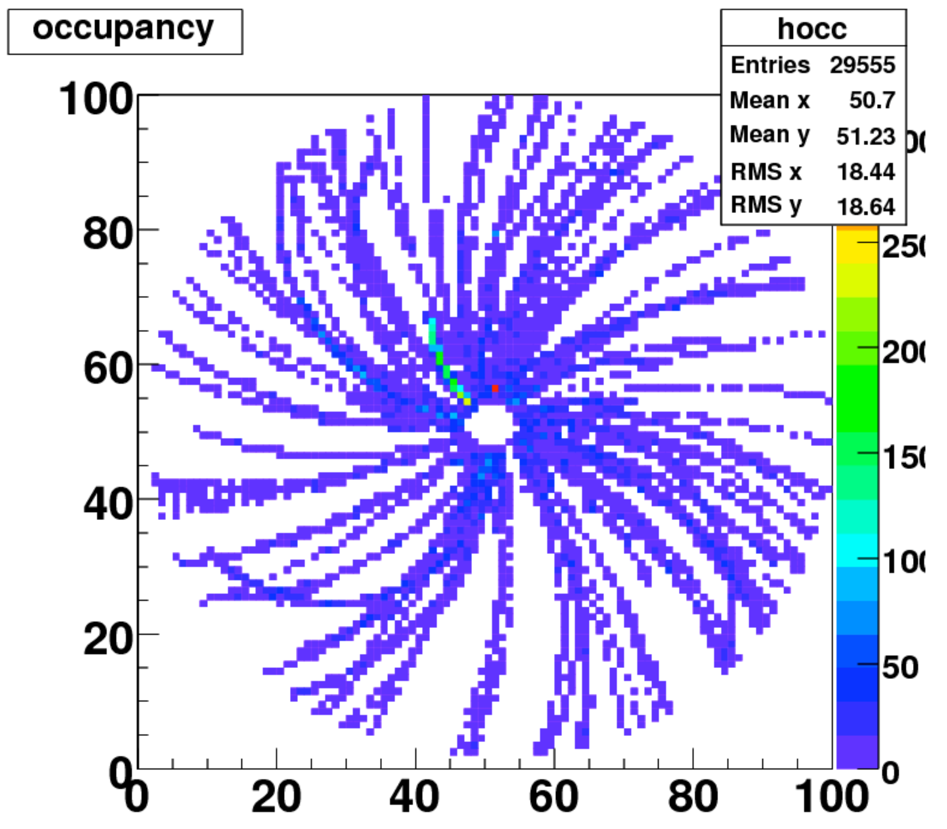


- Investigating opportunities to modify existing T2K electronics chain to accommodate our requirements
- Effort being led by ACTAR working group
- Internal triggering capability will allow low energy reactions to trigger on number of channels above threshold
- Dynamic range of ADC is key due to wide range of particle species to be simultaneously identified ∴ 12bit AFTER+ chip will be used
- Must sustain 1kHz/chan data rate

Data Volume



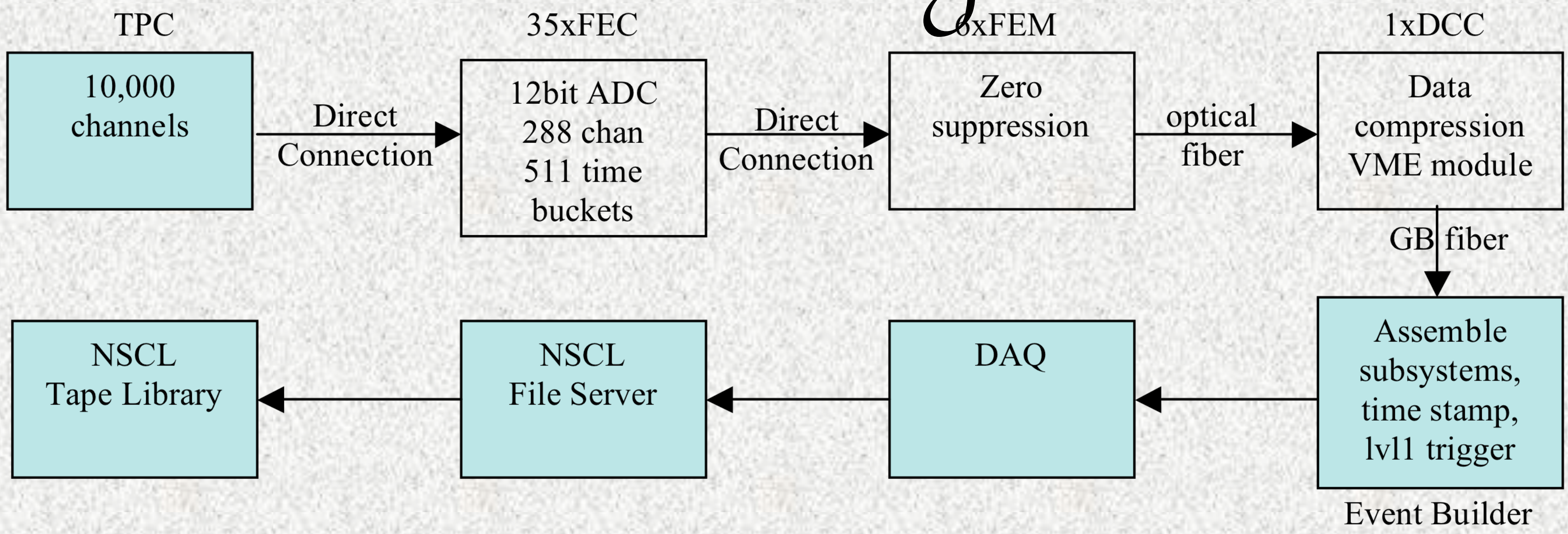
^{112}Sn+^{112}Sn, 150MeV, b=2fm



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

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

Data Management



TPC

10,000 channels

Direct Connection

35xFEC

12bit ADC 288 chan 511 time buckets

Direct Connection

6xFEM

Zero suppression

optical fiber

1xDCC

Data compression VME module

GB fiber

Assemble subsystems, time stamp, lvl1 trigger

Event Builder

DAQ

NSCL File Server

NSCL Tape Library

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.

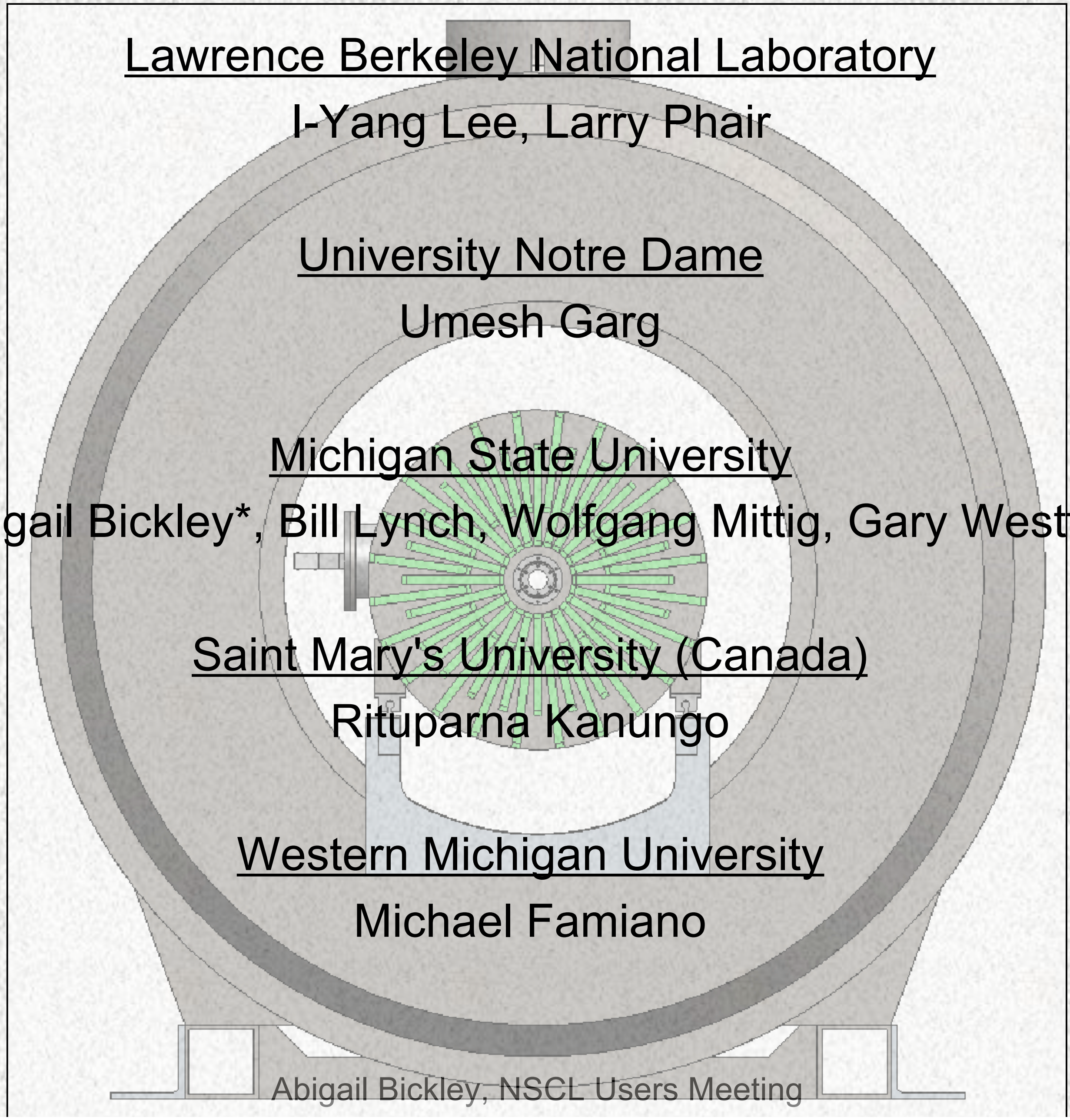
- GB fiber link to vault essential

Timeline & Funding

- Initially submitted as an NSF MRI proposal
- NSF response not expected until end of June
- In the meantime DOE preapplication submitted
- DOE proposal more inclusive of manpower and ancillary detector costs
- Total budget:
  - NSF: $429 equipment + $120k manpower + ~~$450k magnet~~
  - DOE: $660k equipment + $645k manpower + ~~$600k magnet~~

- 2008 - Prototype testing, Mechanical Design, Electronics Design
- 2009 - Electronics Design & Testing, Magnet, Laser & Gas Systems
- 2010 - System Commissioning
- 2011 - First experiments

AT-TPC Collaboration



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Summary

- The AT-TPC is a powerful tool for studying reactions induced by rare isotope beams.
- The scientific program will exploit the full extent of beam species, energies and intensities currently available with fragmentation and reaccelerated beams.
- Active target reactions will study fusion, isobaric analog states, cluster structure of light nuclei and transfer reactions.
- Scientific program can be conducted with existing rare isotope beams, but requires a high resolution AT-TPC.
- The AT-TPC will allow these measurements to be made prior to the completion of the future rare isotope beam facility.