Design Update of MOMENT

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Outline

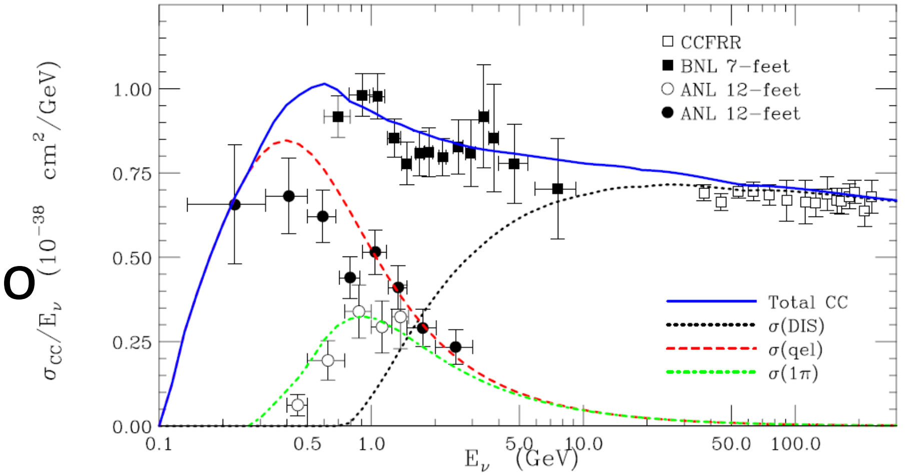
- Introduction
- Proton driver: some news from ADS linac
- Target station
- Pion/muon transport and decay channel
- Neutrino flux and possible detector
- Additional pion-decay beam
- Summary

Introduction

- MOMENT was launched in 2013 (IPAC13/Nufact2013) as the third phase of neutrino experiments in China
  - Neutrino experiments at Daya Bay continues data-taking
  - Jiangmen (JUNO, or DYB-II) will start civil construction end year
- A dedicated machine to measure CP phase, if other experiments (such as LBNF, HyperK) will have not completed the task in 10 years
- As a driving force to attract researchers from China to work on neutrino experiments based on accelerators

Introduction

- Main concepts



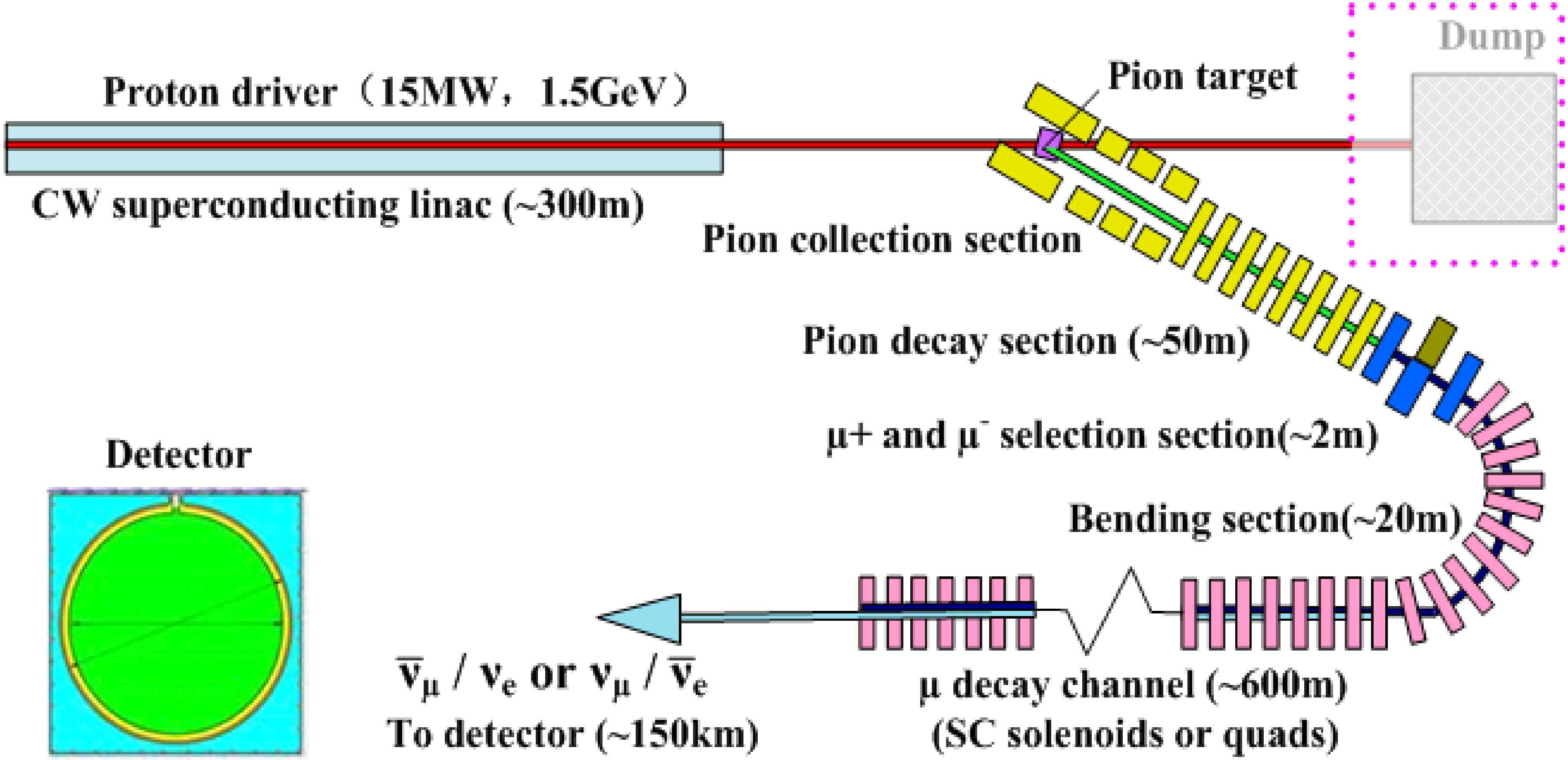
- Medium baseline with neutrino energy of about 300 MeV
  - Eliminate $\pi0$ background
- Muon-decay neutrinos instead of pion-decay ones
- Using a CW proton linac as the proton driver
  - Simplified design from the China-ADS linac
  - 1.5 GeV, 10 mA ➔ 15 MW in beam power
- A fluidized target in high-field SC solenoid
  - Collection of pions and muons
- Muon transport and decay channel
  - Pure μ+ or μ- decay
- High neutrino flux at a detector of >50 km

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{-} \to e^{-} + \nu_{\mu} + \bar{\nu}_{e}$$

$$\mu^{+} \to e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

Schematic for MOMENT

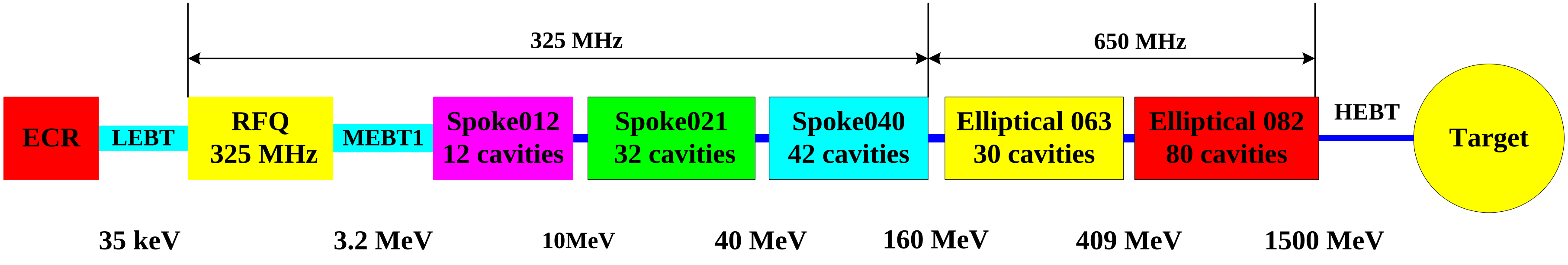


A CW linac as proton driver

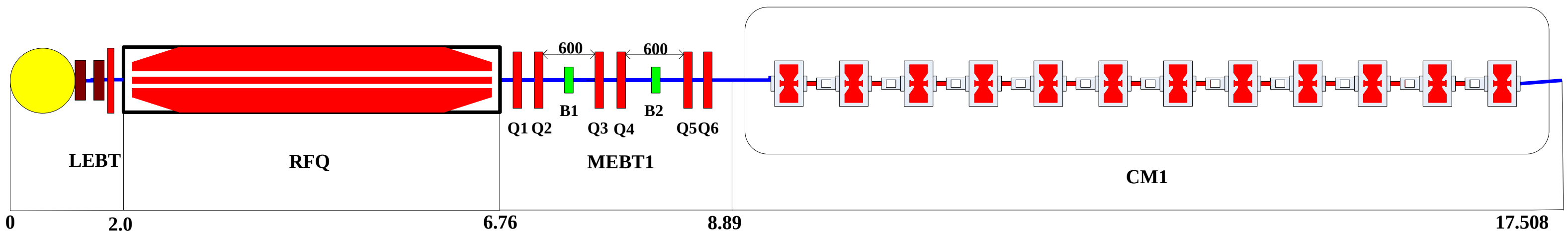
- A CW proton SC linac can provide the highest beam power, and selected as the proton driver for MOMENT
- China-ADS project was launched in beginning 2011, with a long-term goal to drive a subcritical reactor with 12-15 MW proton beam; MYRRHA is also developing a CW proton linac.
- One of the main goals in the China-ADS R&D phase is to solve the technical problems with the SC proton linac working in CW mode
- If C-ADS R&D successful in CW linac, in early 2020 (DEMO phase to about 2040), the accumulated experience will allow us to build a proton driver based on the similar CW linac in GeV but with much lower requirement on reliability

Design scheme for the proton driver

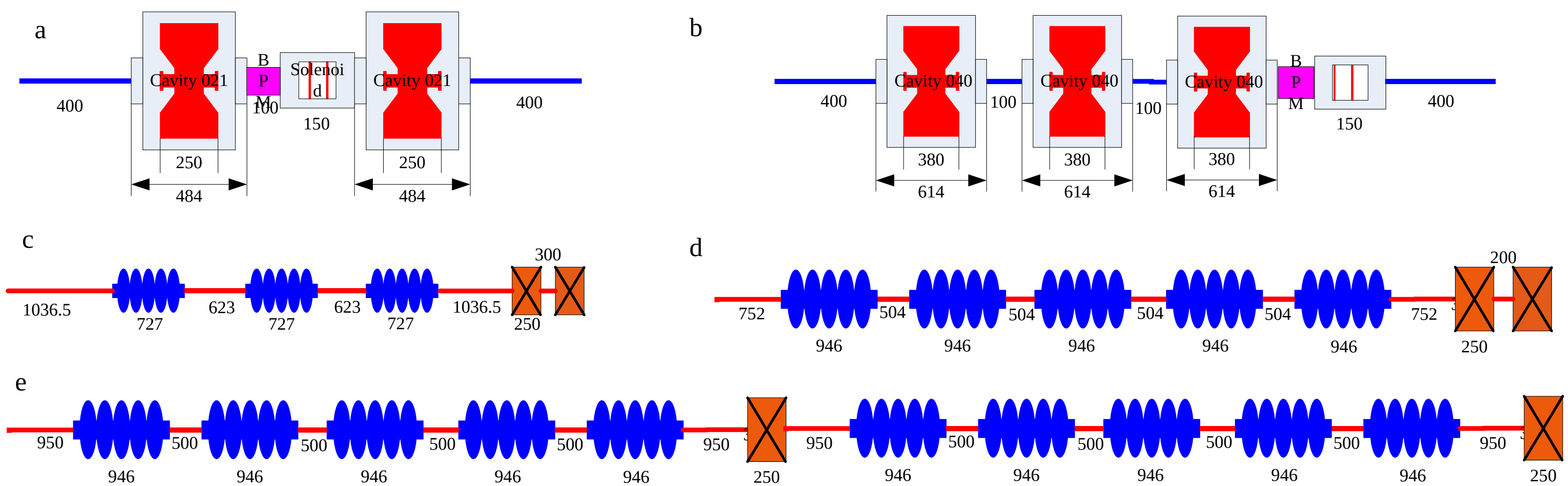
- Design goal:
  - Beam power: 15 MW
  - Beam energy: 1.5 GeV (alternate design: 2.0 or 2.5 GeV)
  - Beam current: 10 mA (lower with higher energy)
- Simplified design scheme from the China-ADS design
  - Much less redundancy wrt China-ADS
  - 3.2-MeV RFQ (room-temperature)
  - Three sections SC spoke cavities (160 MeV)
  - Two sections SC elliptical cavities (1.5 GeV)
  - In total, 196 SC cavities in 42 cryostats, linac length: ~ 300 m



Basic lattice design for MOMENT

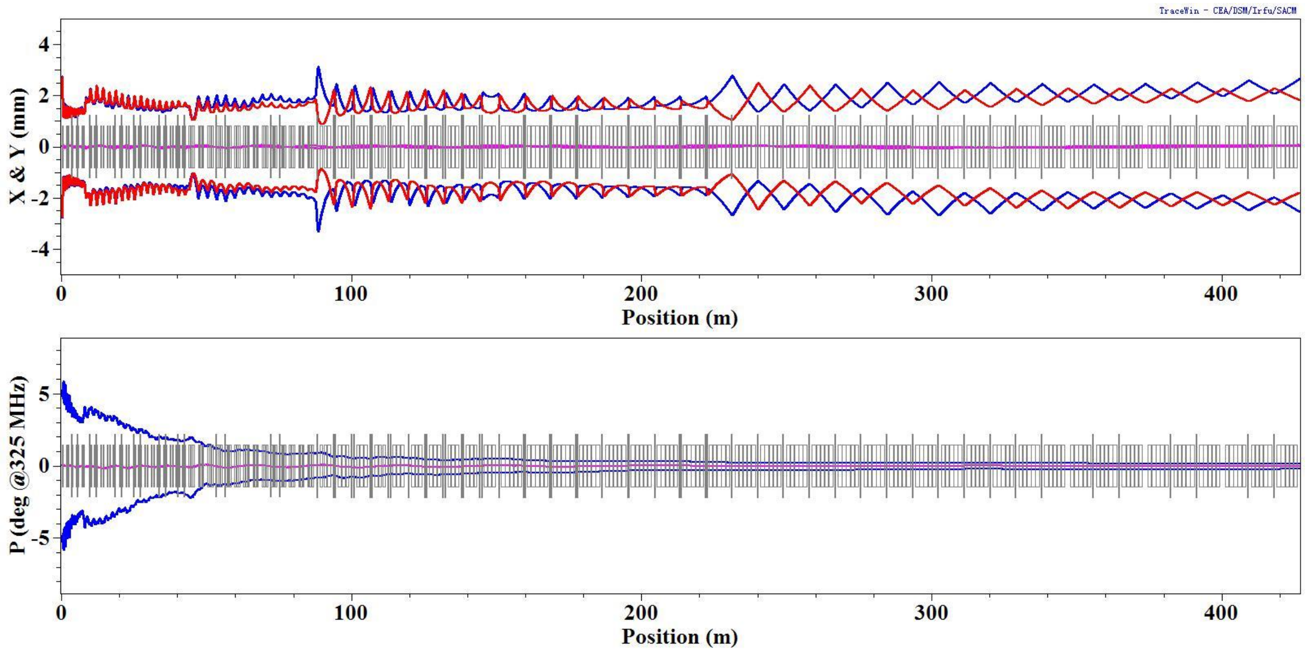


10 MeV

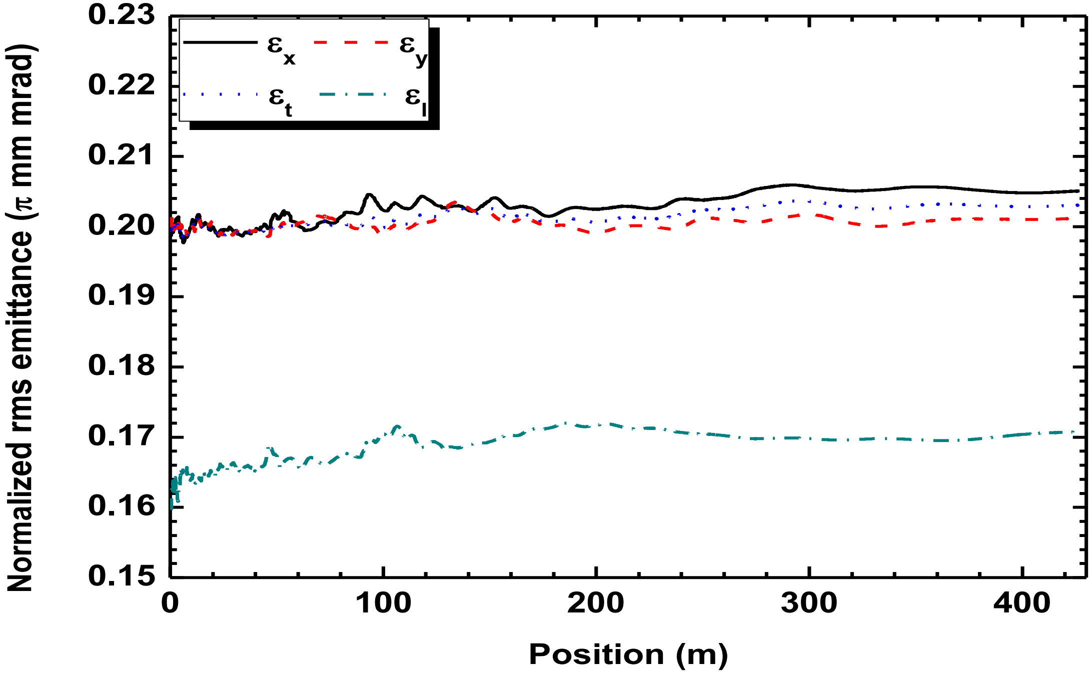


a: Spoke021 section, b: Spoke040 section, c: Ellip063 section, d: Ellip082 section (<1 GeV), e: Ellip082 section (> 1 GeV)

Envelopes along the linac

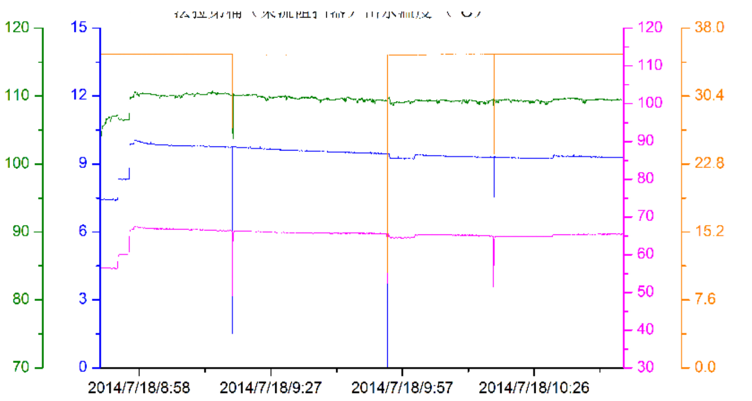


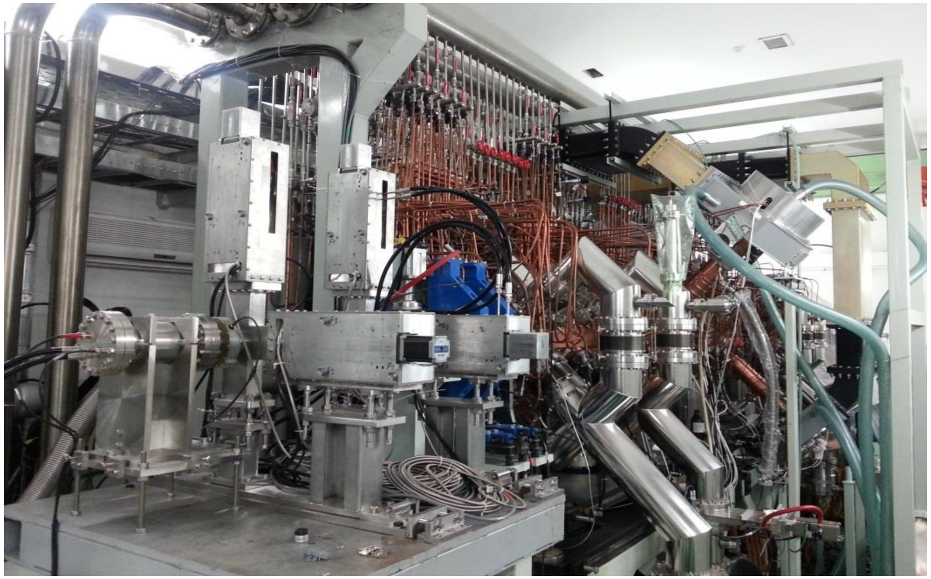
rms emittance along the linac



R&D efforts on ADS linac front-end at IHEP and IMP

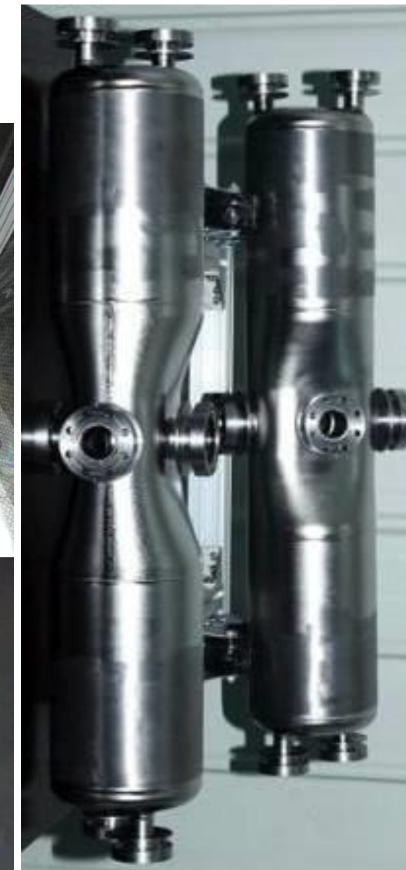
- RFQs:
  - IMP completed the commissioning test of a 2.1 MeV-10 mA-162.5 MHz RFQ in CW mode
  - IHEP is testing a 3.2 MeV-10 mA-325 MHz (now 10% beam and 50% RF duty factors)





- Low-beta superconducting cavities
  - 325 MHz beta=0.12 Spoke cavities: 2 prototypes finished, both vertical and horizontal tests completed and meeting specifications; more under fabrication
  - 325 MHz beta=0.21 spoke cavities: one tested, meeting specifications
  - 162.5 MHz beta=0.09 HWR cavities: several tested and meeting specifications
- Elliptical cavities: two finished waiting for test.

Spoke-0.12 (upper)
Spoke-0.21 (lower)



HWR

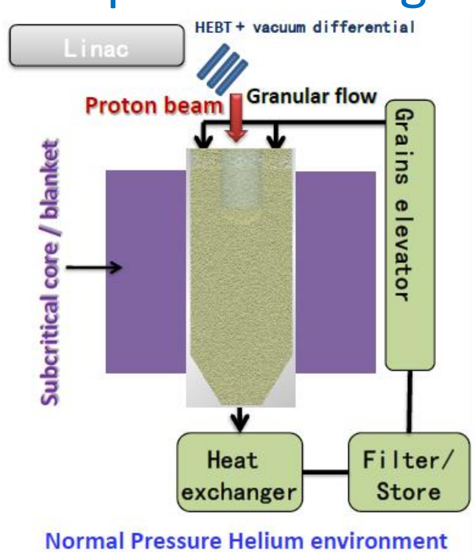
Elliptical (beta=0.63)

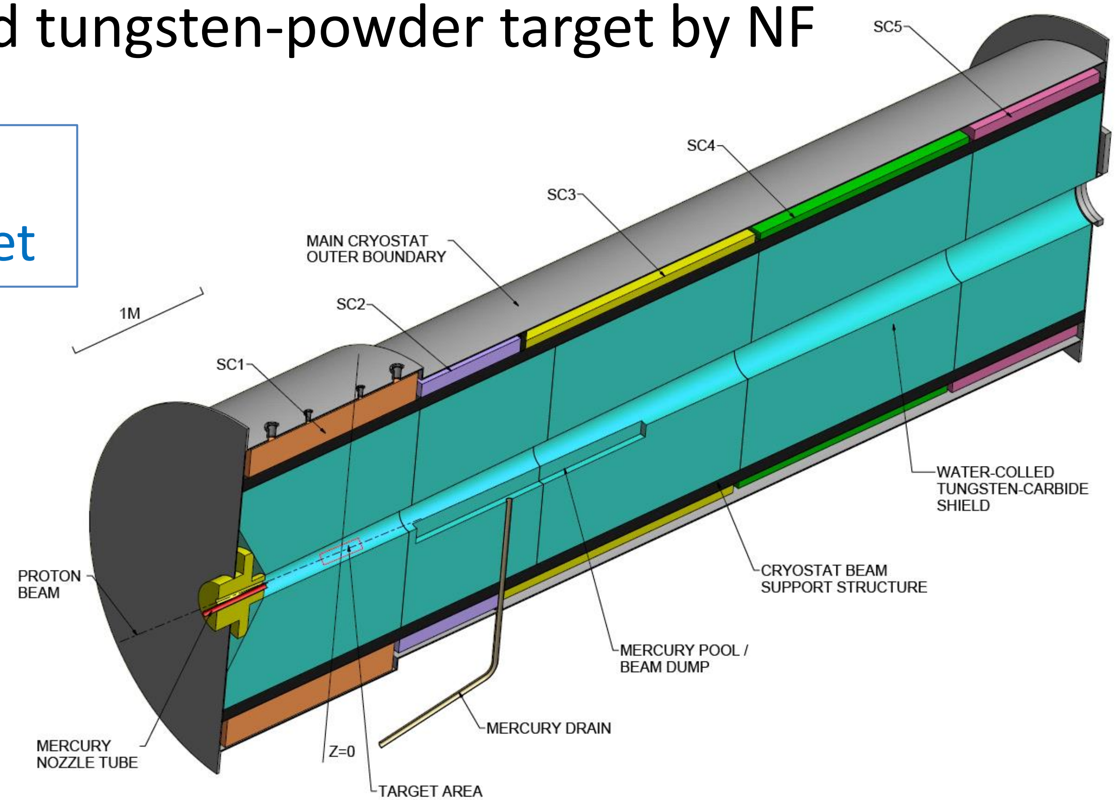
- Near-term goal for ADS linac
  - By 2015, two injector schemes reach 5 MeV, CW operation
  - By 2016, two injector schemes reach 10 MeV-10 mA-CW operation

Target Station

- Baseline design: Mercury jet target (similar to NF design, MERIT) and high-field superconducting solenoids
  - Higher beam power: heat load, radioactivity
  - On the other hand, easier to some extent due to CW proton beam (no shock-wave problem)
- More interests in developing fluidized granular target in collaborating with the C-ADS target team, and also waiting for study result with fluidized tungsten-powder target by NF collaboration

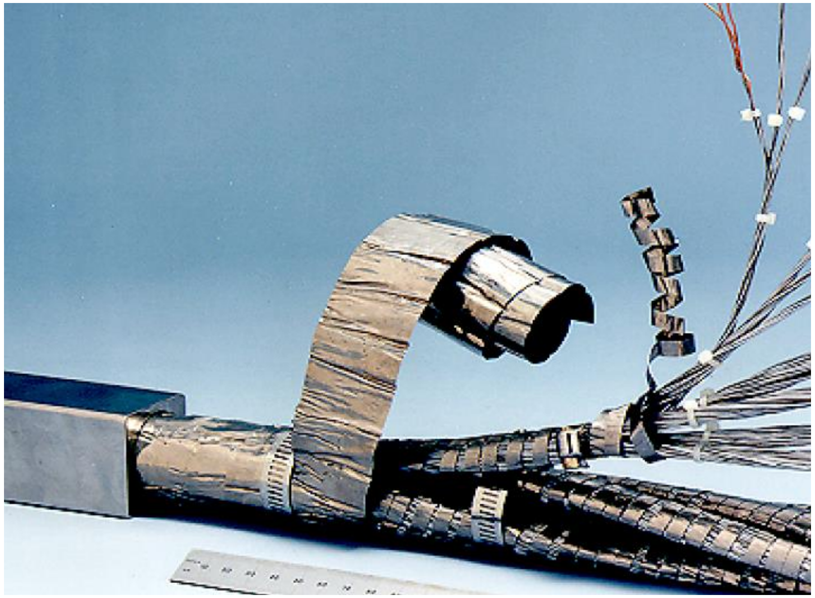
Trying to work out a feasible concept based on granular target

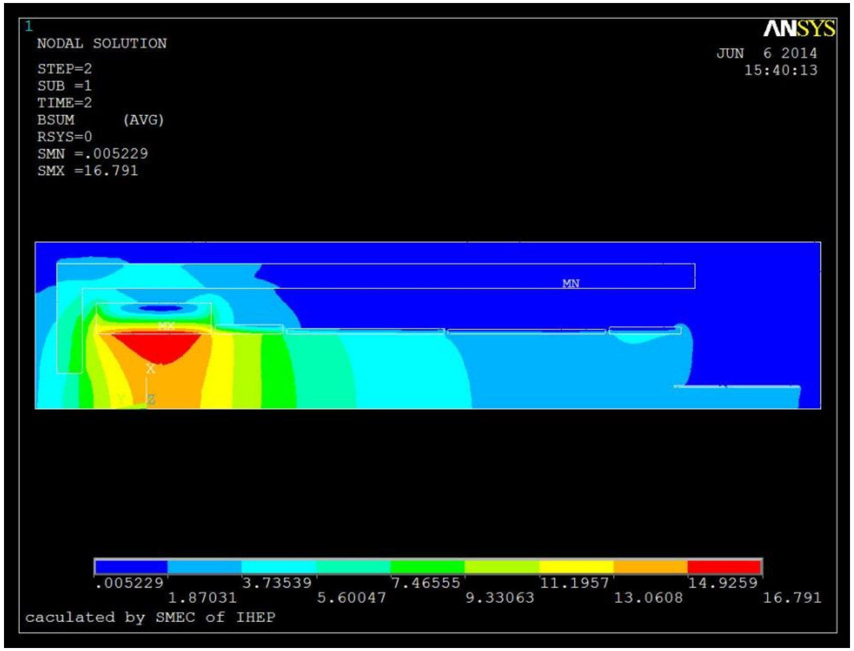




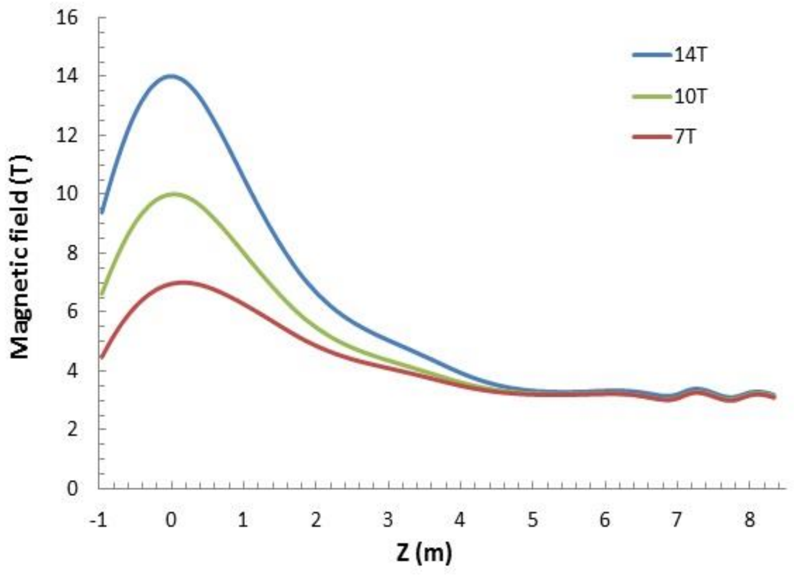
High-field superconducting solenoids

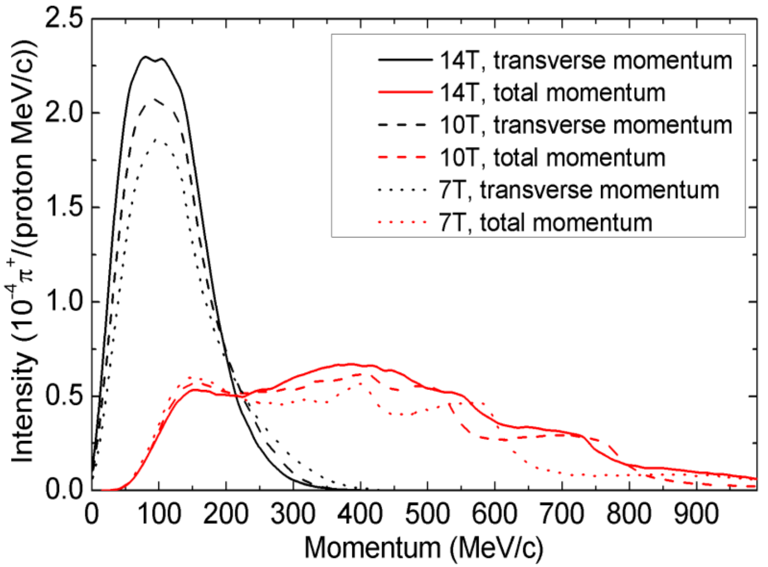
- Very large apertures due to collection of secondary /tertiary beams and space for inner shielding
  - Based on Nb_3Sn superconducting conductors, CICC (Cable-in-Conduit Conductor) coil (ITER)
  - HTS coils are also under consideration
  - High-field magnet R&D efforts at IHEP (incorporated with SppC)



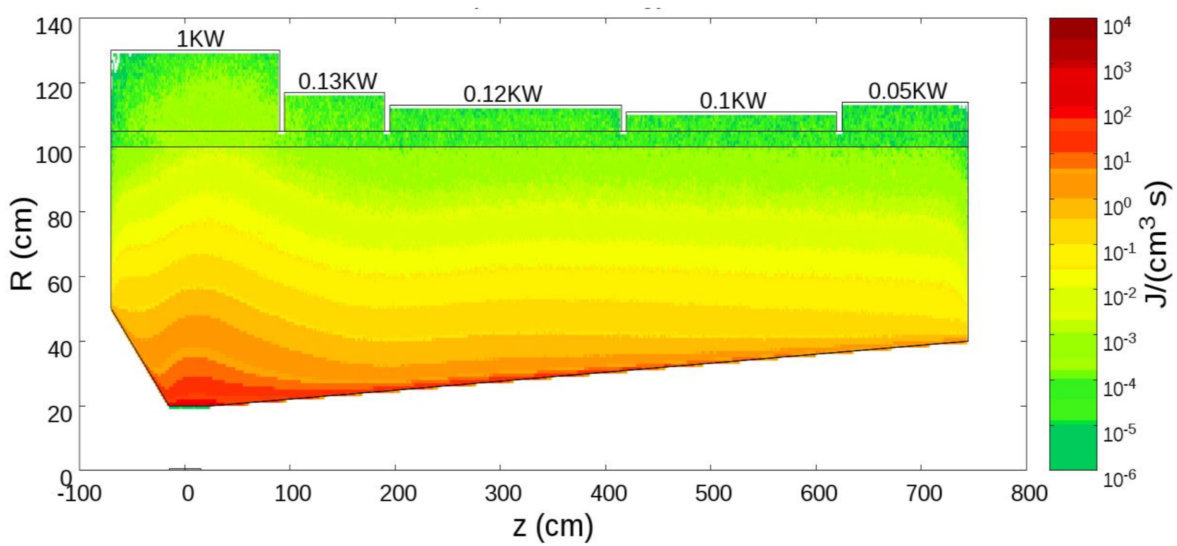


- Different field levels have been studied: 7/10/14 T
  - Evident advantage on pion collection with higher field
- Relatively short tapering section: <5 m
- High radiation dose level is considered not a big issue here (compared with ITER case)(both Nb_3Sn and HTS conductors are radiation resistant, problems are with electrical insulation)





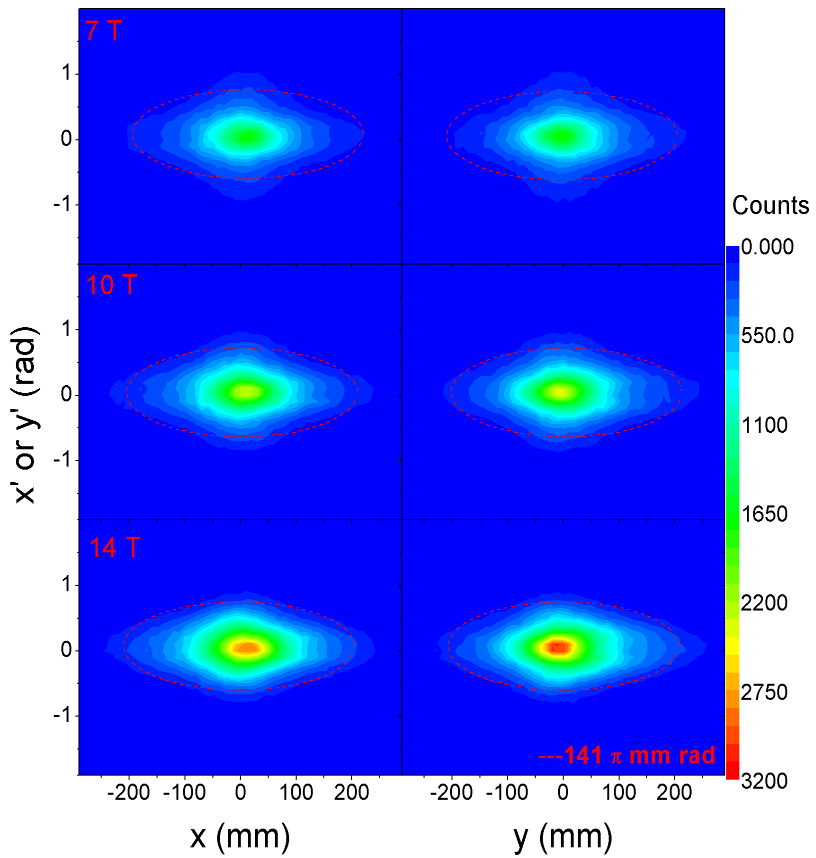
- Very high heat load from beam-target interaction (neutrons, gammas) , strong shielding needed to reduce heat load in cryostat and radiation level in coils
  - Shielding block thickness: 800 mm (~10 MW, also tough)
  - Heat load in cryostat: ≤1 kW
  - Dose rate in coils: 6×10^{13} /(m^2 s), which means a fluence of 6×10^{21} /m^2 for 10 years (10^7 s per year)



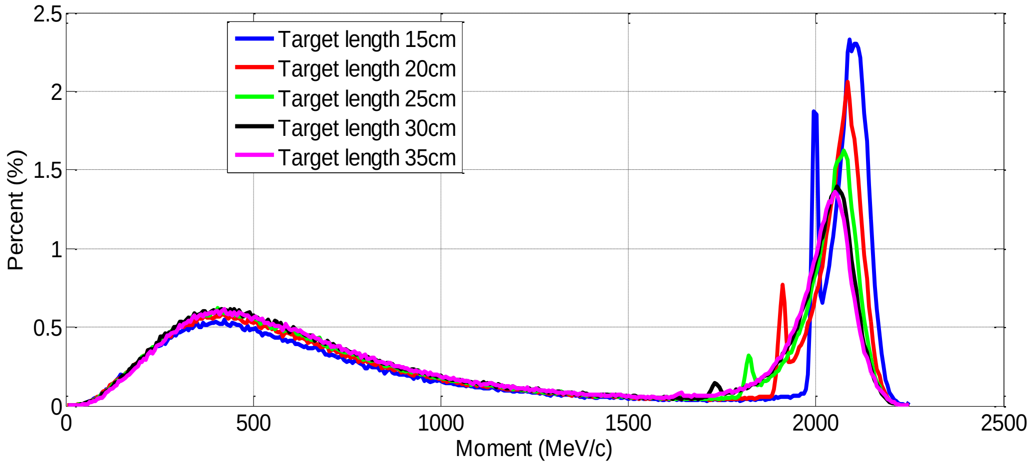
Pion production and collection

- Pion production rate: 0.10 pion/proton (1.5 GeV, 300 mm Hg)
- Collection efficiencies of forward/total pions: 82% / 58% (@14 T)

- Distributions in (X-X')/(Y-Y') at end of pion decay channel (from upper down: 7/10/14T)
- Higher field increases the core density significantly



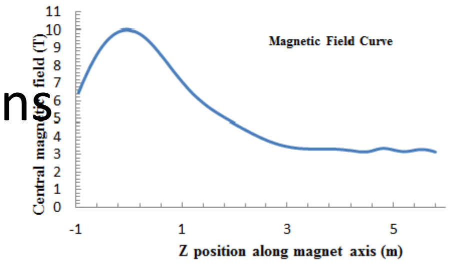
Spent protons



- There are two parts in the spent protons (3 peaks!):
  - one is the scattered protons from the side of the thin mercury jet and the pass-thru protons from the jet which have higher energy (4.7 MW with 30 cm target)
  - the other is from nuclear reactions which have lower energy (1.8 MW with 30 cm target)
- It is advantageous to guide spent proton out of the target station to a dedicated dump, to reduce heat load, dose rate level in the target station or make troubles to the decay channel
- It looks that we can only do something on energetic protons (well confined), as low-energy protons are difficult to separate from pions/muons
- Work to do:
  - Optimize beam-target intersection for better proton spectrum
  - Find out method to separate energetic protons from pions/muons, such as bent solenoids; collimation

Pion decay section

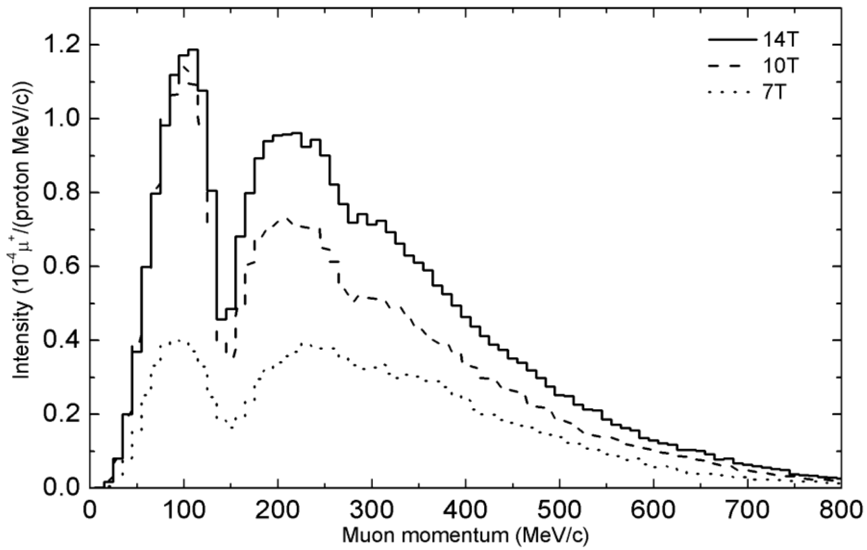
- A straight section in SC solenoids of about 100 m to match the SC solenoids at the target, and for the pions to decay into muons
  - Adiabatic field transition (tapering section) from the high capture field to the lower focusing field to convert transverse momentum into longitudinal
  - Chicane in the beginning to collect scattered protons
  - Very large emittance and momentum spread
  - Longer section for energetic pions to decay



- Similar beam rigidity assures that pions and muons can be transported in the same focusing channel
  - Momentum and emittance of pions most preserved in muons

More about the pion decay channel

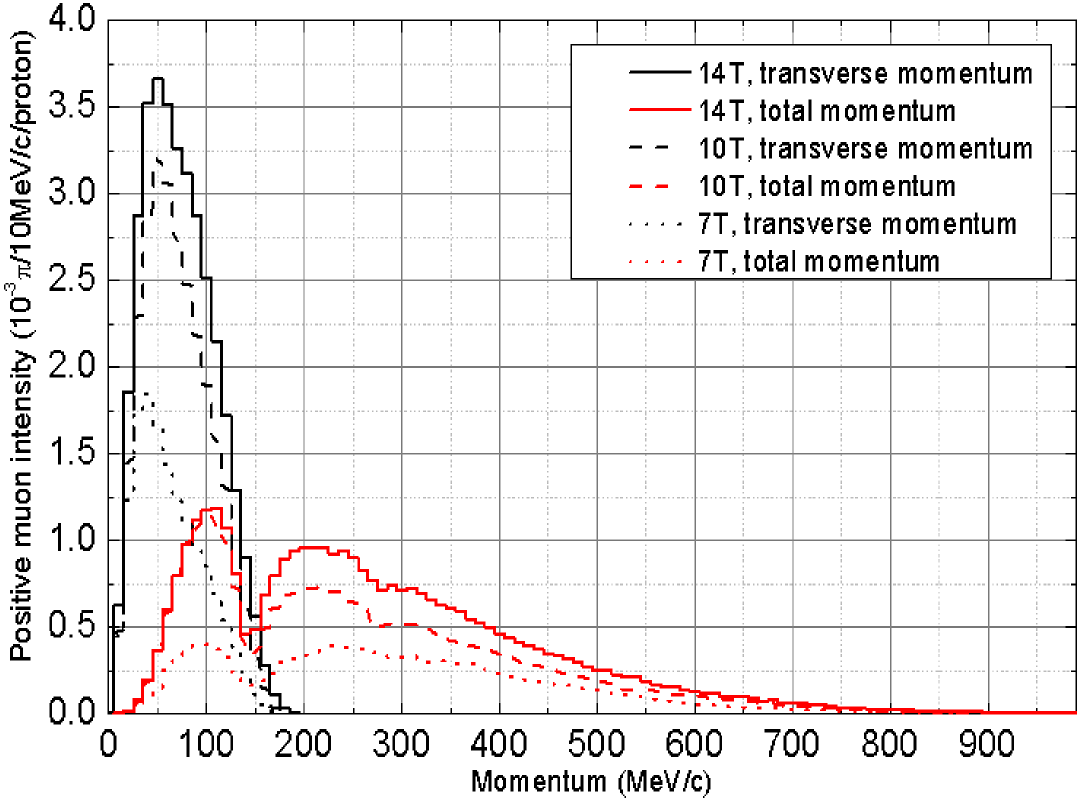
- SC solenoids form FOFO lattice (stop-band at certain energy)
- Very large acceptance for channels
- About 0.0052 μ+/proton for about 50 πmm-rad at entrance of muon decay channel



	muon/proton	Portion （%）
No limit on emittance	9.48E-03	100
Emittance: 100 πmm-rad	8.04E-03	85
Emittance: 80 πmm-rad	7.31E-03	77
Emittance: 50 πmm-rad	5.22E-03	55

Emittance limit in both (X-X') and (Y-Y')

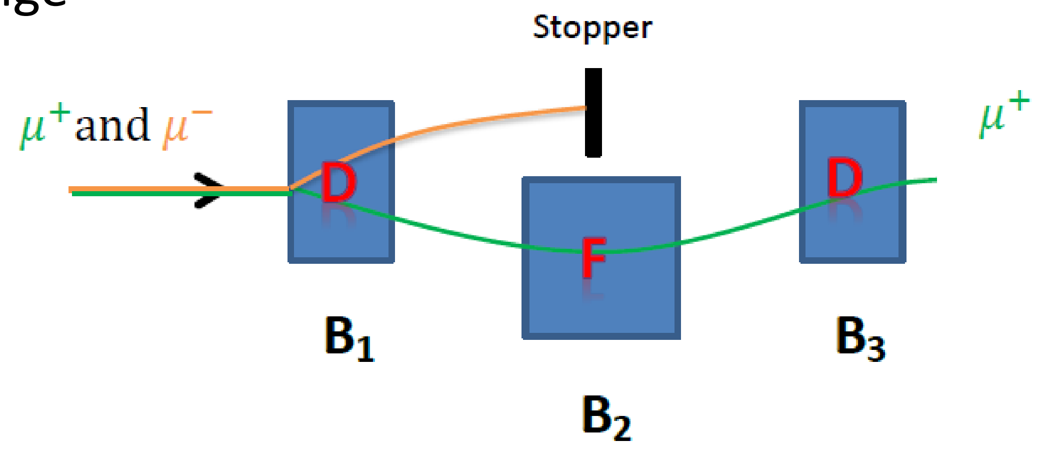
- Try to transport large momentum range π/μ
- Expected: >±50% centered at 300 MeV/c



Muon momentum spectrum at the entrance of the bending section

Charge selection

- A selection section to select π+/μ+ from π-/μ-, as either μ+ beam or μ- beam is used for producing the required neutrinos
  - Reverse the fields when changing from μ+ to μ-
  - Also for removing very energetic pions who still survive
  - Very difficult due to extremely large beam emittance (T/L)
- Scheme 1: based on 3 SC dipoles with strong gradient (DFD triplet focusing, a few meters). For very large emittance, large bending angles (40 ° /-80 ° /40 °)
  - FFAG magnets are under consideration to compensate focusing of large moment range



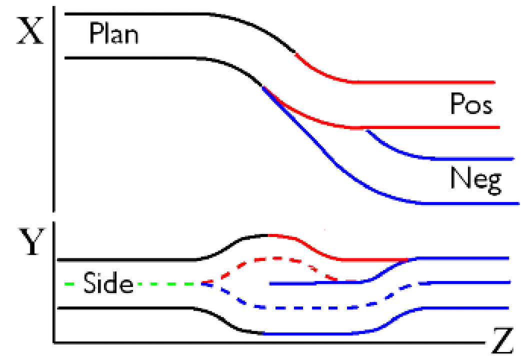


Figure 1: Schematic of charge separation method.

- Scheme II: by bent solenoids
  - Mixed μ+ and μ- beams have different rotation directions in a bent solenoid. With a large aperture, the two beams can be separated each other at certain phase advances

	Advantage	Disadvantage
Scheme-I	1) Second beam extracted 2) Short section 3) Smaller emittance growth	1) effectiveness influenced by large emittance 2) Lower transmission 3) Very large aperture magnets
Scheme-II	1) Higher transmission 2) More effective separation	1) effectiveness influenced by large emittance 2) Second beam stopped 3) Very large aperture solenoids and long section

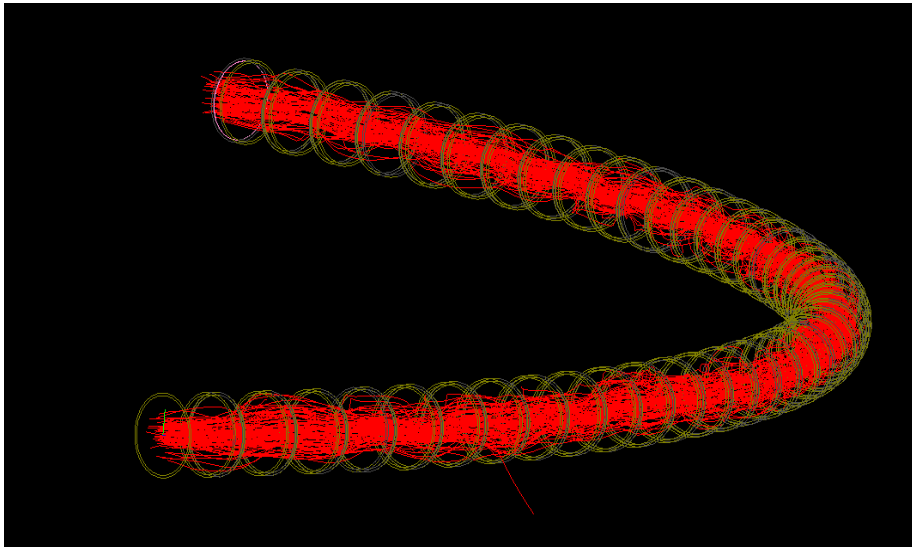
Muon transport and decay

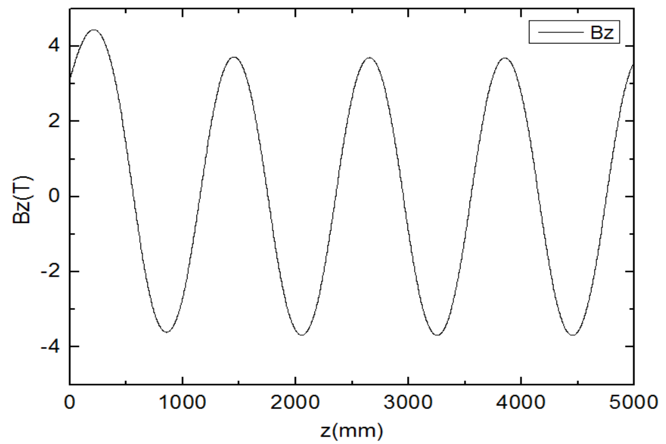
- Muon bending section

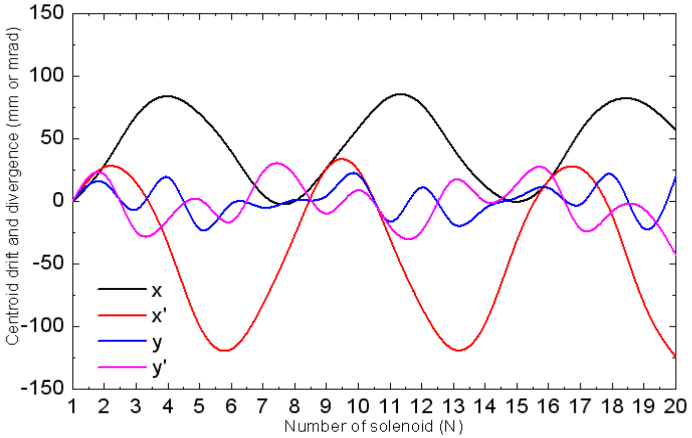
- A bending section is required before the muon decay channel, to suppress the background of pion-decayed neutrinos at the detector by limiting the momentum acceptance when needed
  - Bending angle is adaptable according to the general layout
  - More energetic pions continue to decay in the section
- Many short SC solenoids aligned with increased angle displacement to bend and focus the beam simultaneously
  - Short solenoids helps reduce beam centroid excursion (aperture, beam loss)
  - Alternate reverse SC field also helps reduce the excursion, and emittance coupling
  - A small vertical field component is also helpful to reduce the excursion and for momentum selection

- Beam tracking simulated by G4beamline

- Bending section by slanted solenoids (39*2°=78°) has very good momentum acceptance, Δp/p>±50%
- Small vertical component (~0.055 T) helps







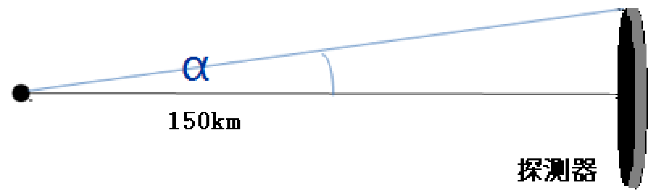
Field distribution (left) and beam centroid evolution (right)

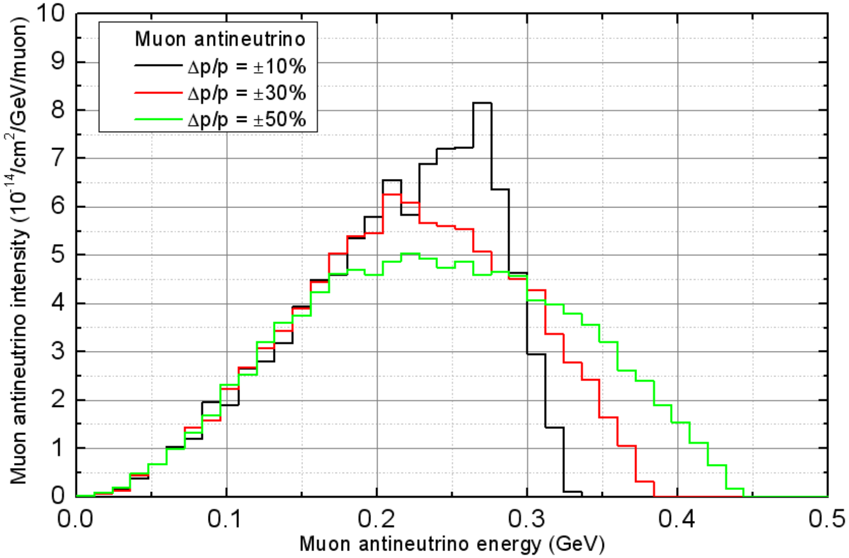
Muon transport and decay
- Muon decay channel

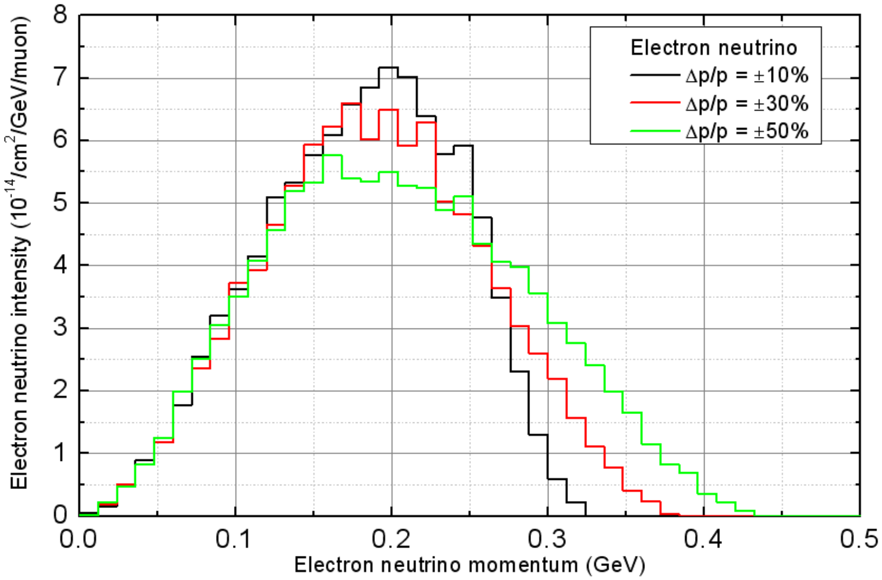
- A long decay channel of about 600 m is designed for production of neutrinos
  - About 35% (centered momentum: ~300 MeV/c)
- Important to have smaller divergent angle
  - Neutrino energy spectrum at detector related to the angle
  - Modest beam emittance and large aperture
  - Adiabatic matching from 3.7 T in the bending section to 1.0 T in the decay section

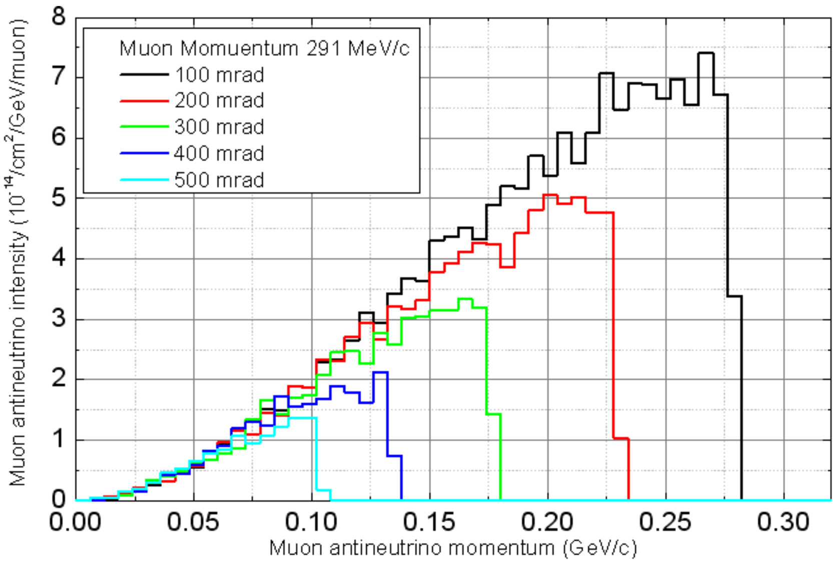
Aperture/Field	Acceptance (πmm-rad) X: in mm; X': in mrad
ϕ600, 3.7 T	100 (x: 280, x': 357)
ϕ800, 1.0 T	65 (x: 380, x': 171)

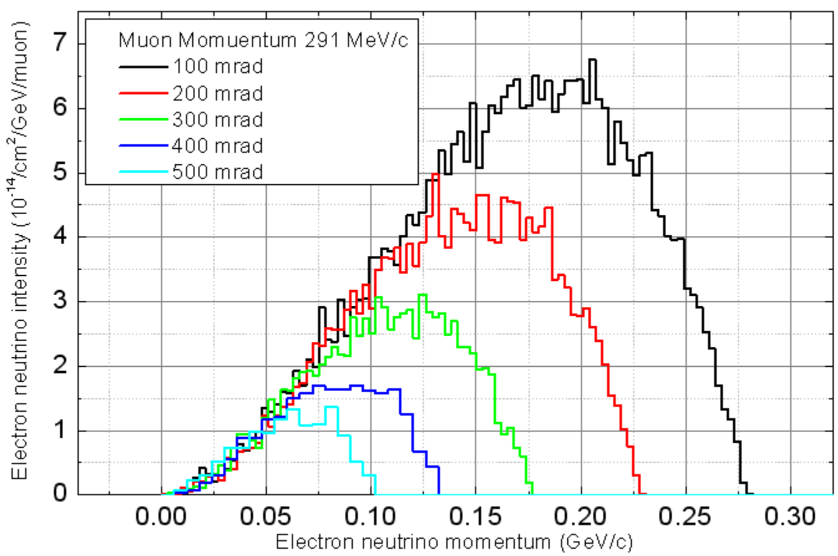
Neutrino energy spectra dependent on muon momentum and divergent angle





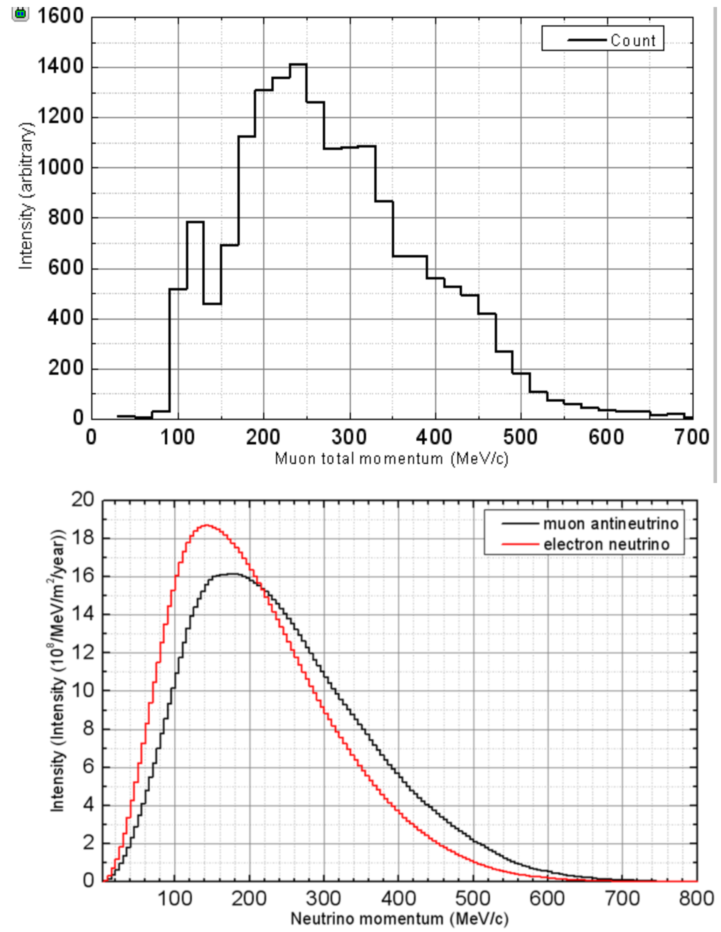






Neutrino flux and possible detector

- Suitable detector for MOMENT is still under study
  - 100-150 km from the target/source
  - Mass: 0.1-1 Mton
  - Simultaneous detection of all four neutrino types: $\bar{\nu}_\mu, \nu_e/\nu_\mu, \bar{\nu}_e$
- Neutrino spectra at the detector centered at about 250 MeV



Energy spectra of decayed muons and neutrino at detector

Estimate of neutrino flux

- Proton on target (operation 5000 h): 1.125×10^{24} proton/year
- Muon yield: 1.62×10^{-2} μ/proton
- Muon decay probability: 0.35
- Total neutrino yield: 4.8×10^{-3} ν/proton (in pair)

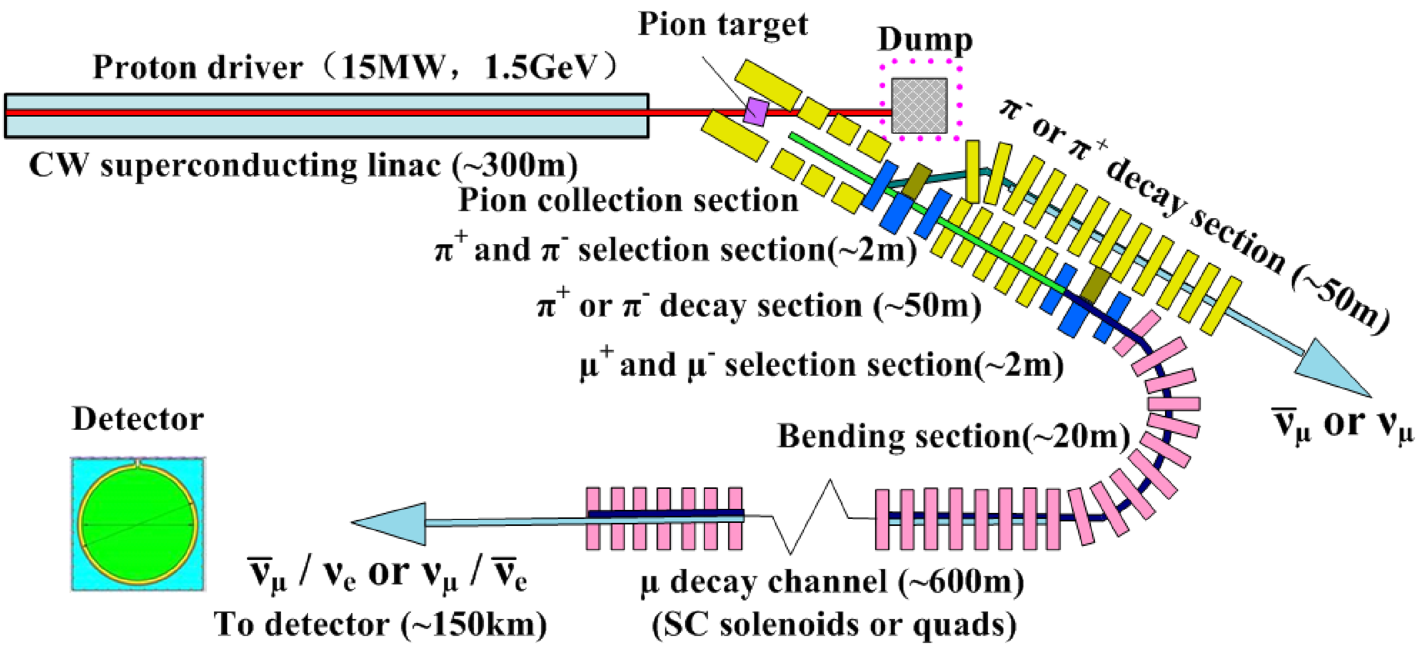
  5.4×10^{21} ν/year (in pair)

  (NF: 1.1×10^{21} ν/year)
- Neutrino flux at detector: dependent on the distance

  4.7×10^{11} ν/m^2/year (@150 km)

Additional pion-decay neutrino beam

- We are also investigating the possibility to extract a pion beam of narrowly-selected energy range for producing pion-decay neutrinos (Alan Bross)
  - Add a charge separation section close to target to extract energetic pions (eliminating low-energy muons)



Summary

- MOMENT becomes a driving force to attract Chinese researchers to collaborate on neutrino experiment based on accelerator-based neutrino beams
  - Until today, 6 institutions and about 40 people are involved in the joint study
- Not a facility project yet, just concept study, future uncertain
- Following studies will focus on
  - Suitable detector
  - Granular target and treatment of used protons
  - Optimization of transport/decay channels
- Technical difficulties
  - Proton driver: to be solved by China-ADS and others
  - Target and very high field SC solenoids: collaboration and R&D
  - Detector: to be identified
- Collaboration
  - Seek international collaborations: already established with LBNE, interests with IDS/MICE-Neutrino Factory and ESSnuSB

Thank you for attention!