State Machine Operation of the MICE Cooling Channel

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CHEP'13

Outline

I Motivation

II Procedure for cooling muons

III MICE description

IV State Machine operation

V Future

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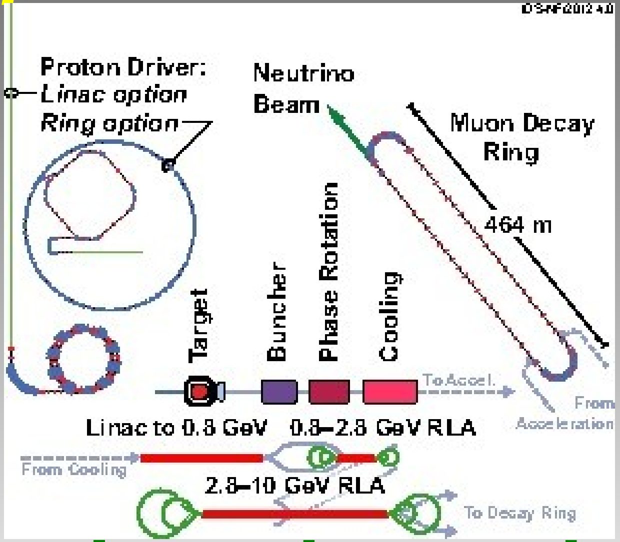
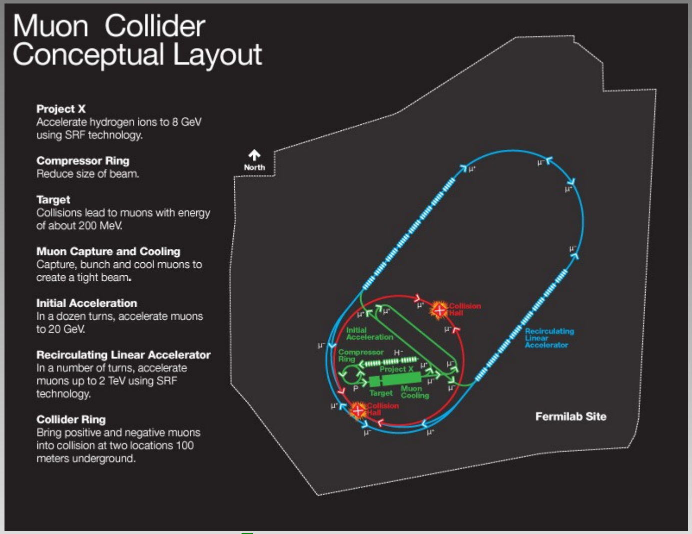
Motivation

The goal of MICE is:

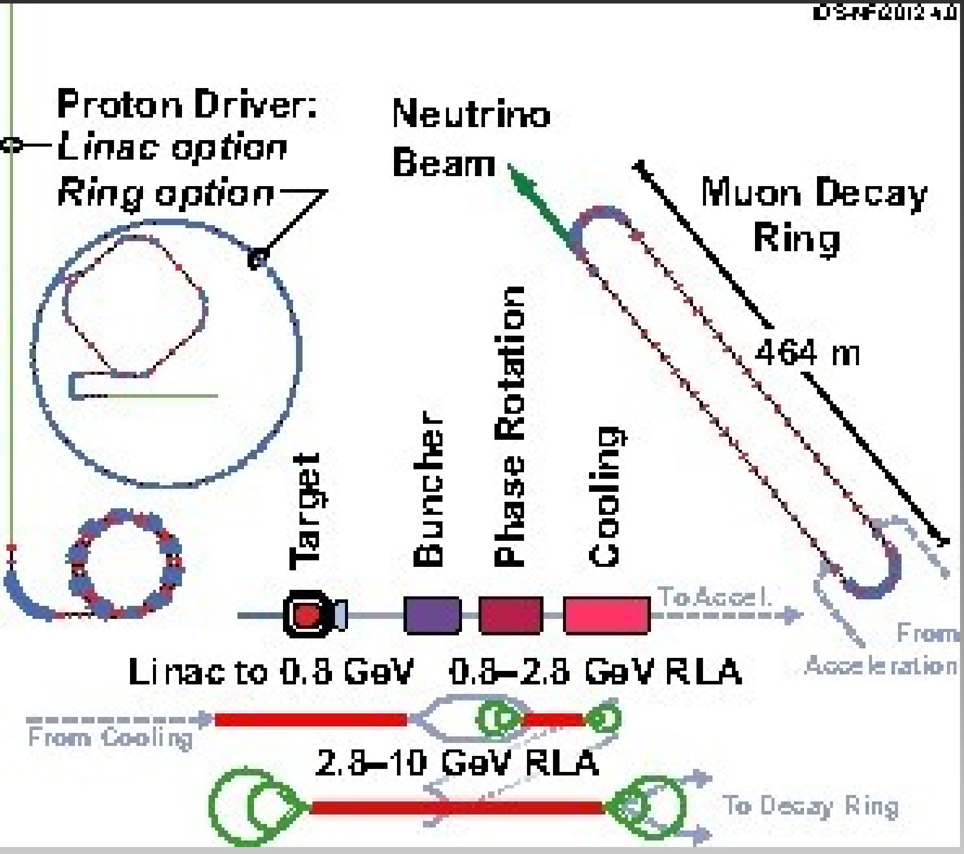
- ***Design, build, commission and operate a realistic section of muon cooling channel***
- ***Measure its performance in a variety of modes of operation and beam conditions***





Results to be used to optimize Neutrino Factory and Muon Collider designs.

Motivation: Neutrino Factory



IDS-NF baseline design

Neutrino Factory: accelerate and store muons to produce neutrinos

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

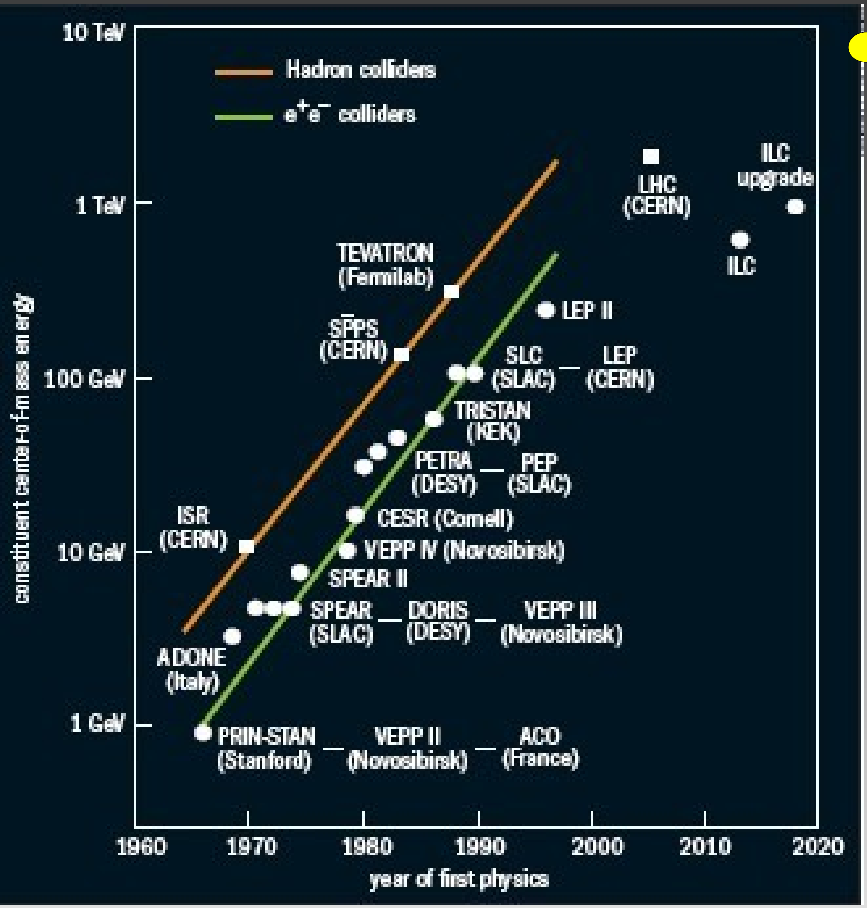
High energy ν_e are *unique* among future facilities.

Golden channel: $\nu_e \rightarrow \nu_\mu$ long baseline oscillations manifested by wrong sign muons:

$$\nu_\mu + N \rightarrow \mu^- + X$$

Motivation
Muon Collider

Historically, we've fallen off the curve:



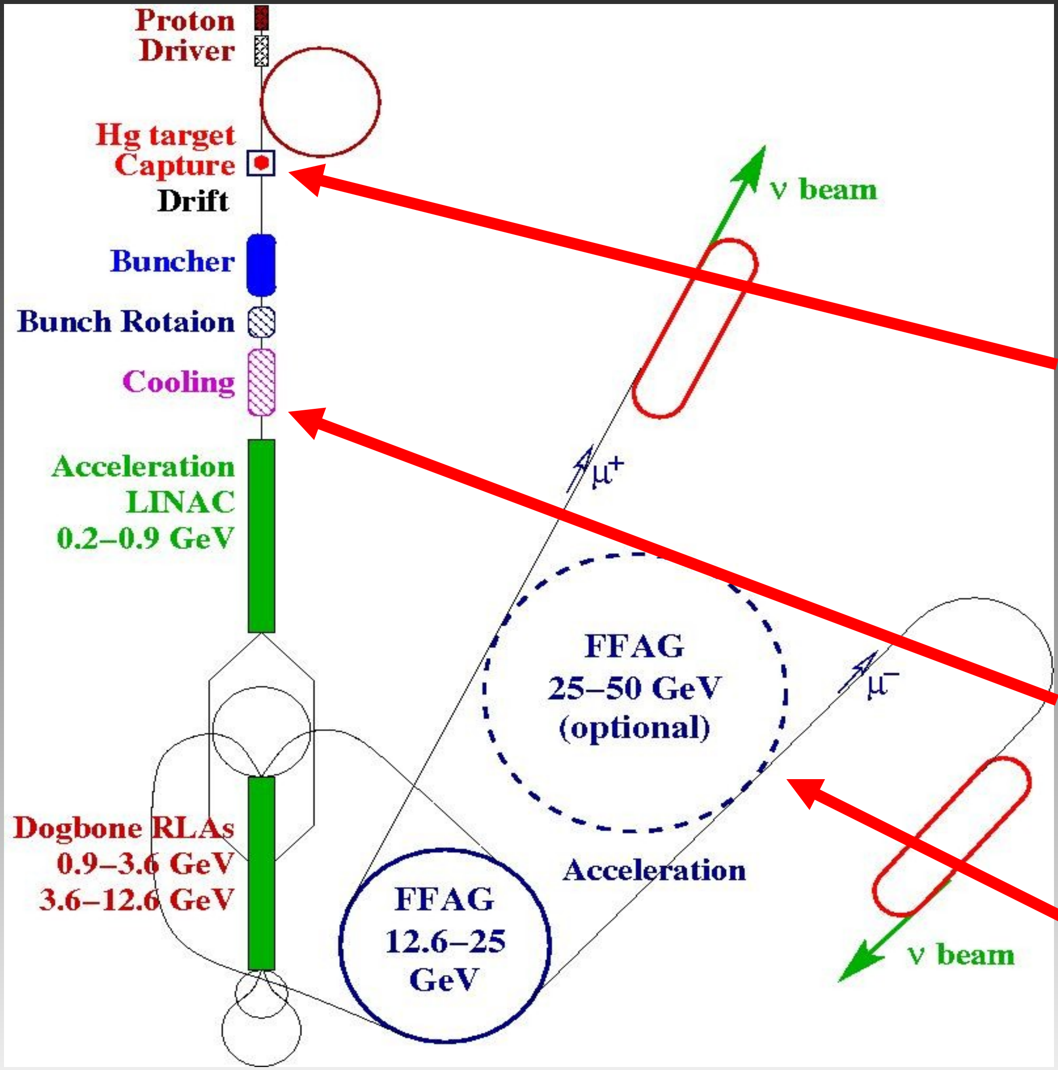
Livingston Plot

- μ accelerator solution
  - fundamental particles
  - cleaner interactions
  - tunable interaction energy
  - $m_\mu = 205 m_e$ reducing synchrotron radiation
- μ ***lifetime: 2.2μs (rest frame)***

Technological challenge, but not impossible

Intermediate Higgs factory

Motivation:
Muon Accelerator



International R&D efforts to meet the challenges

High-power target:
4MW proof of principle
- ***MERIT (CERN)***

Fast muon cooling:
- ***MICE (RAL)***

Fast, large aperture accelerator (FFAG)
- ***EMMA (Daresbury)***

Motivation

MICE is the

Muon

Ionization

Cooling

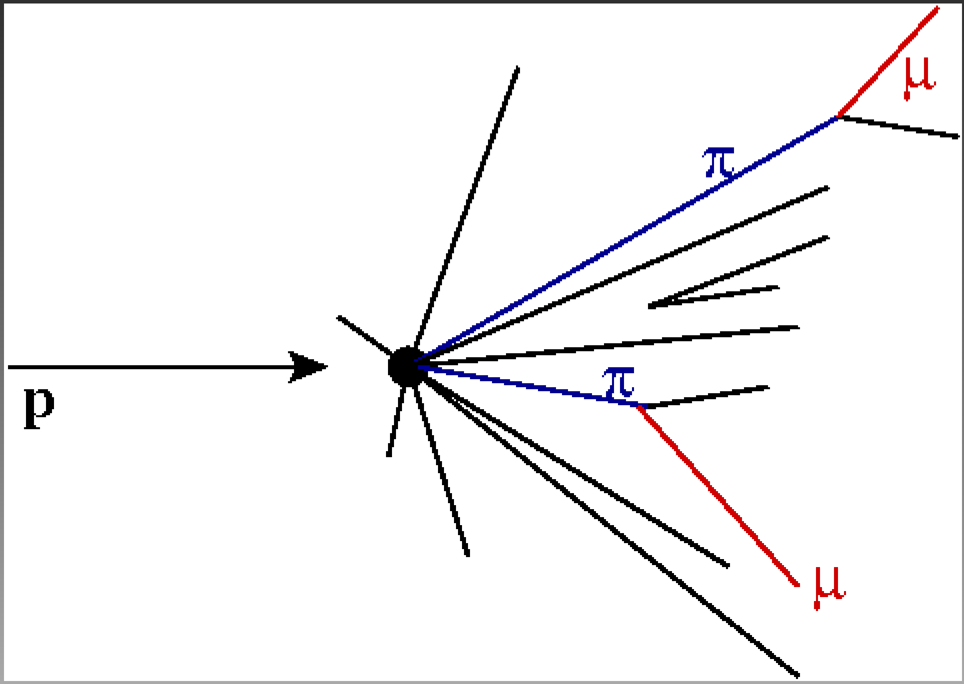
Experiment

MICE **is a proof of principle experiment to demonstrate that we can "cool" a beam of muons.**

Motivation

Why cool muons?

- muons are created as tertiary particles
- created with large inherent emittance – beam spread in 6D phase space:
  - x, y, z
  - p_x, p_y, p_z



- accelerators require particles in tight bunches
- must “cool” muons – reduce emittance of beam
  – “smaller beam” reduces cost of accelerator
  – “smaller beam” increases luminosity

Outline

✔ I Motivation

II **Procedure for cooling muons**

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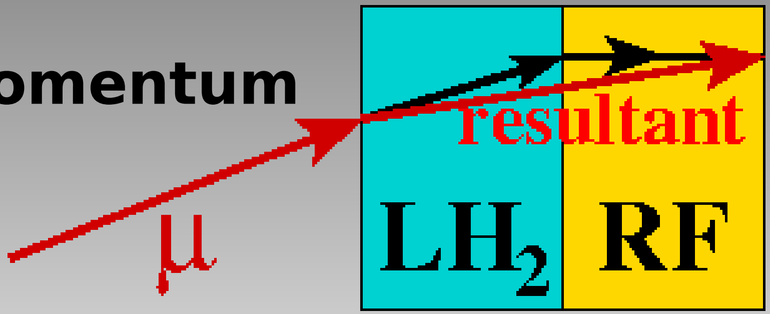
Procedure: Ionization Cooling

- Recall: μ's are created with large emittance
- "Cooling" muons refers to reducing the emittance of the muon beam.
- Conventional techniques won't work (too slow)
- Due to short muon lifetime, the only viable option is ionization cooling. Must cool ***AND*** accelerate muons rapidly:
  - diagram vectors represent momentum
  - lose momentum in p_T and p_L
  - restore p_L



- Magnetic fields focus muons at absorber to reduce x & y where they lose momentum

Procedure: Ionization Cooling

- Strong focusing at absorber yields small β ⊥

$$\frac{d\,\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle \frac{d\,E_\mu}{ds}\right\rangle \frac{\varepsilon_N}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014\,GeV)^2}{2\,E_\mu m_\mu X_0}$$

cooling heating

Low Z absorbers yields large X_0

Cooling is:

- **Momentum loss in all dimensions via dE/dx**
- **Replace longitudinal momentum with RF**

MICE Procedure

MICE will measure a 10% cooling effect with 1% accuracy => a 0.1% relative emittance measurement

1. create beam of muons
2. identify muons and reject background
3. measure muon emittance
4. “cool” muons in low-Z absorber
5. restore longitudinal momentum
6. re-measure muon emittance
7. identify muons to reject e's from μ decay

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✔ II Procedure for cooling muons

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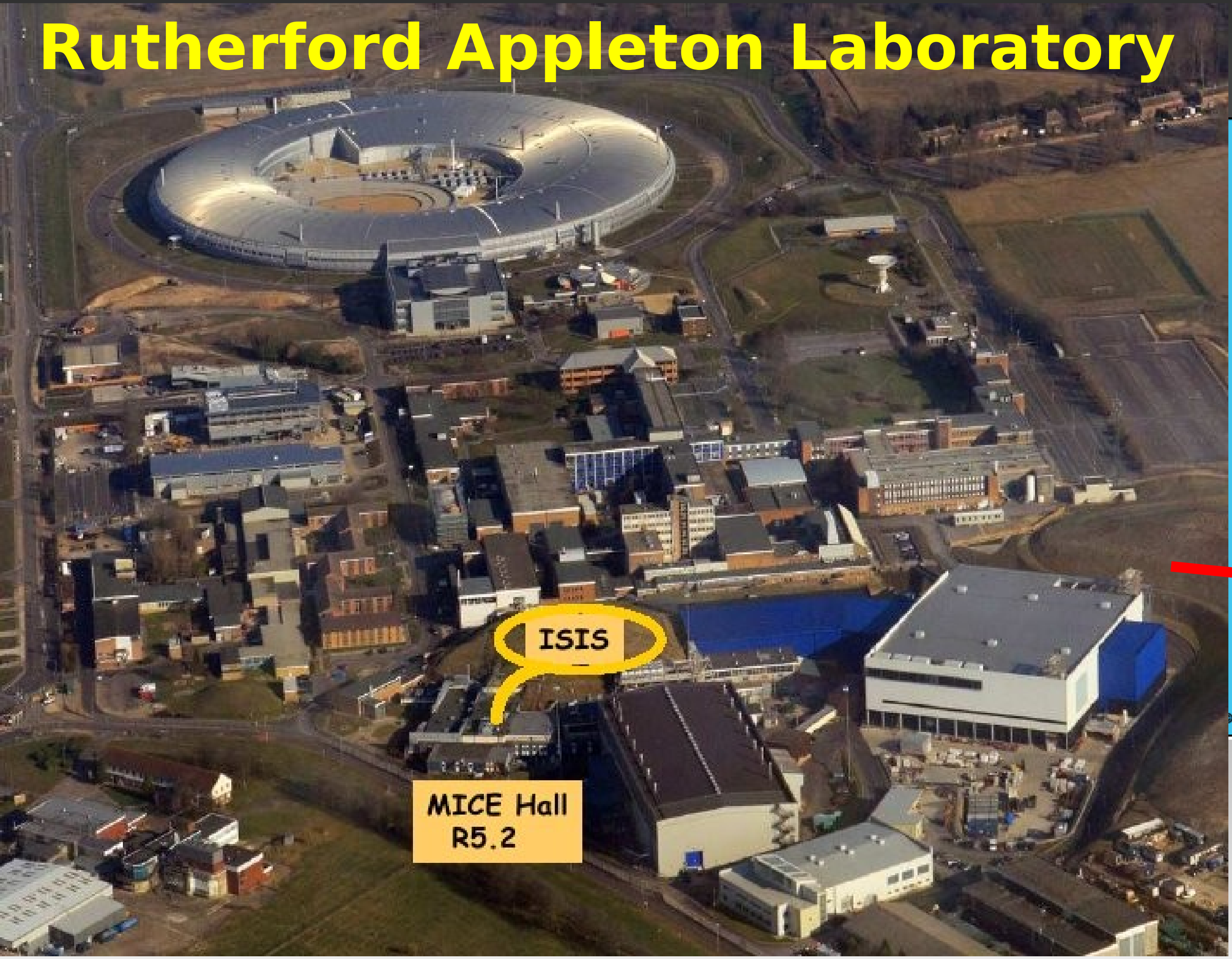
Description: The Lab

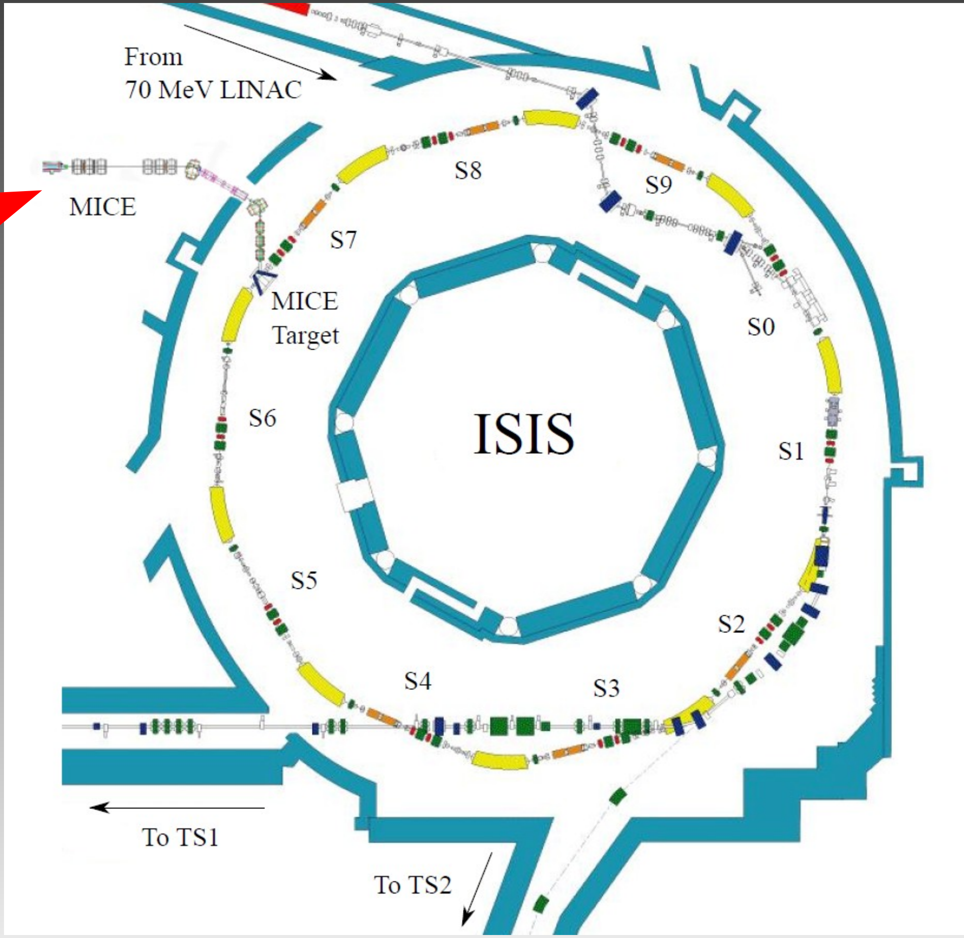


United Kingdom

ISIS Accelerator

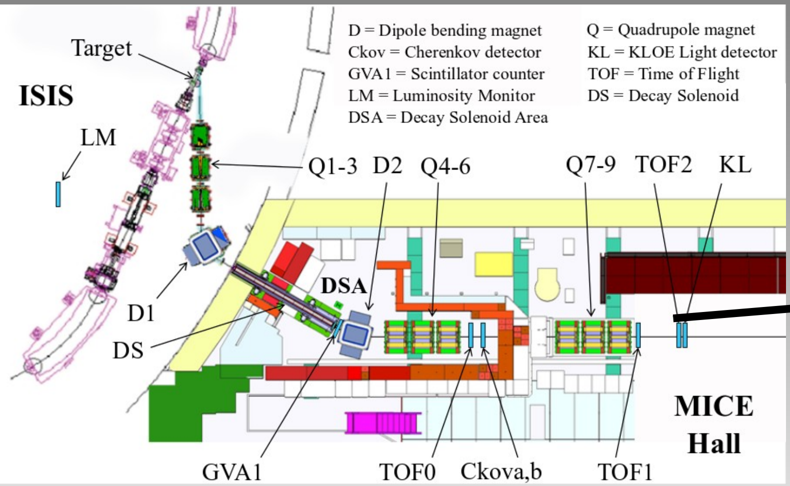
ISIS Accelerator at RAL

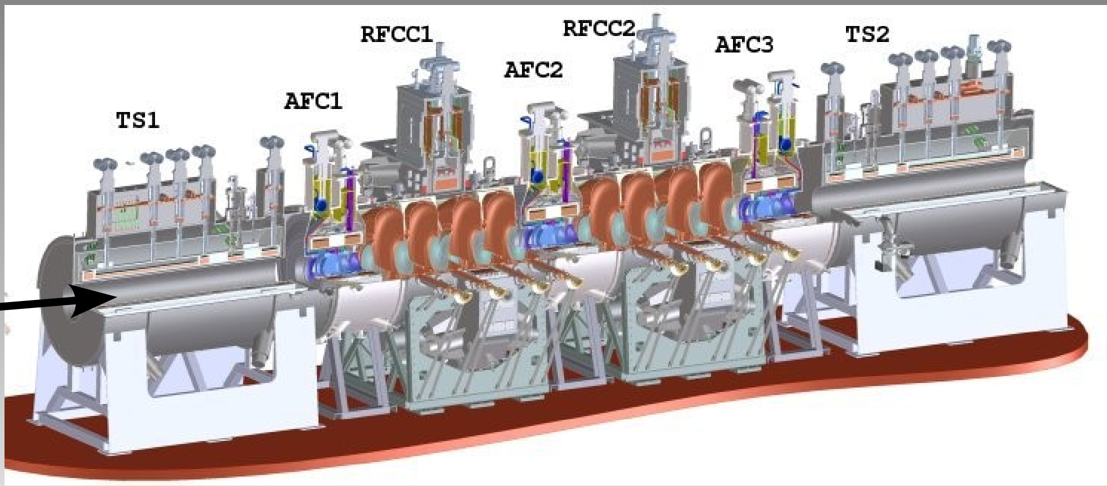
MICE beamline



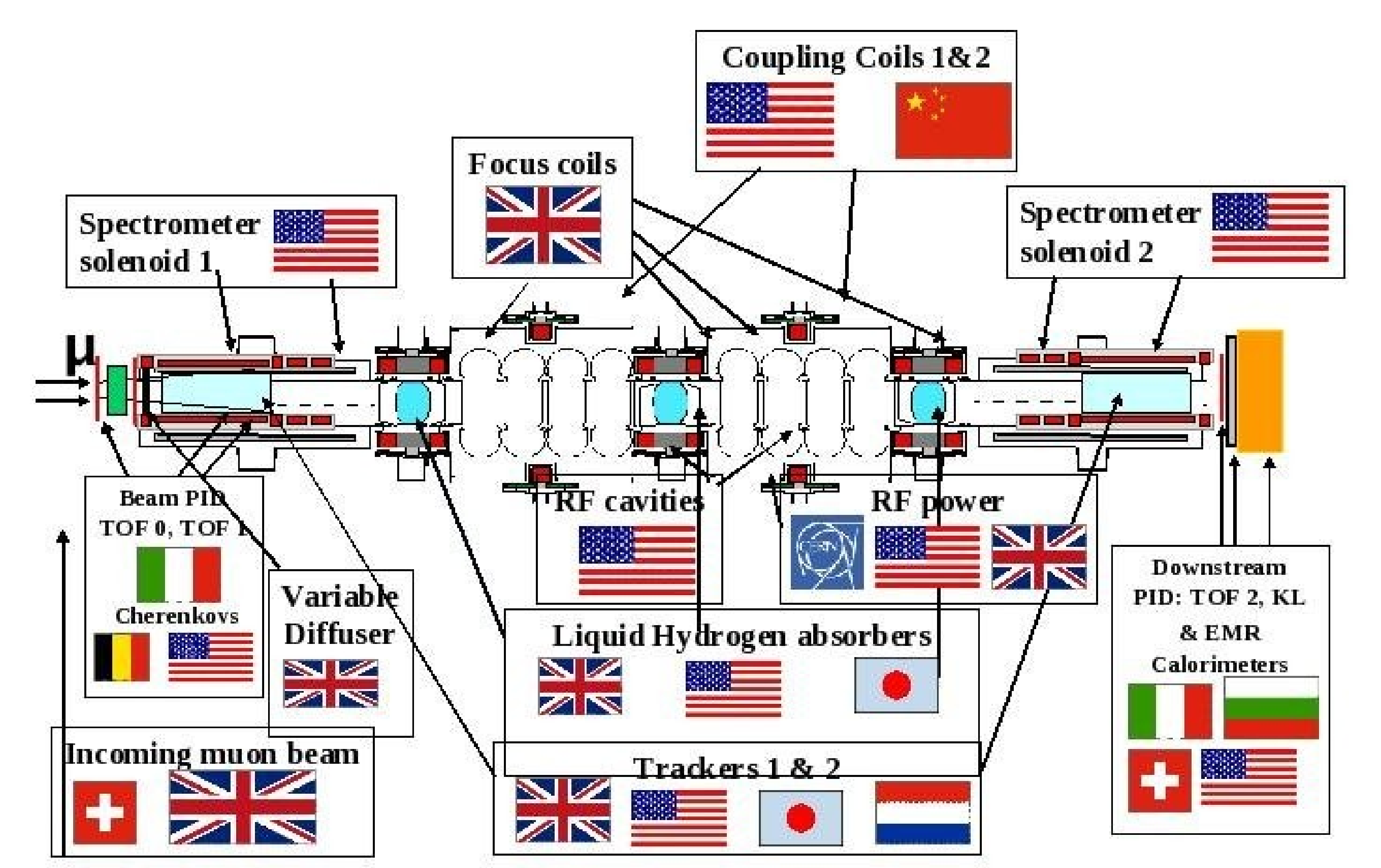
Description: Experiment

- **Beamline – create beam of muons**
- **Particle ID – verify/tag muons (before/after)**
- **Trackers – measure emittance (before/after)**
- **Absorber (LH_2 or LiH) – cooling**
- **RF – re-establish longitudinal momentum**





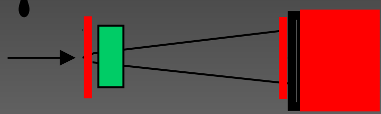
Description: Who are MICE?



MICE Schedule

Provisional MICE SCHEDULE
update: June 2013

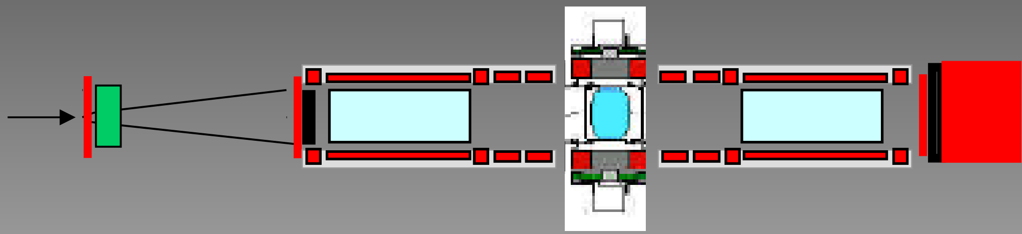
μ



STEP I

Run date:

EMR run Oct 2013

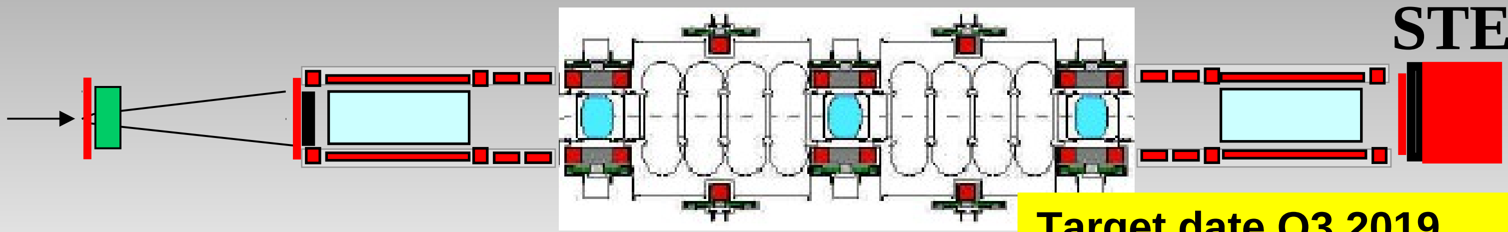


STEP IV

(possibly
w/o field:
Q2 2014)

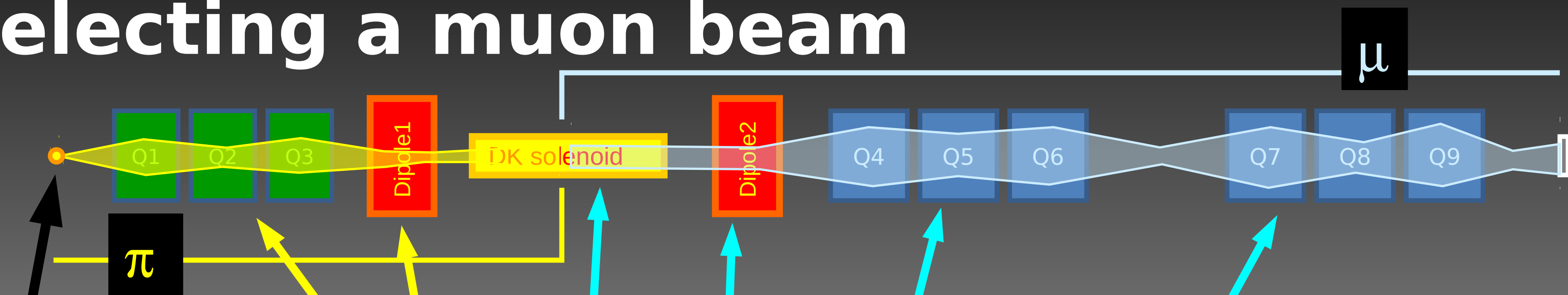
Q1 2015
to Q1 2016

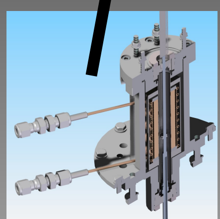
STEP VI



Target date Q3 2019
Step V run possible 2018

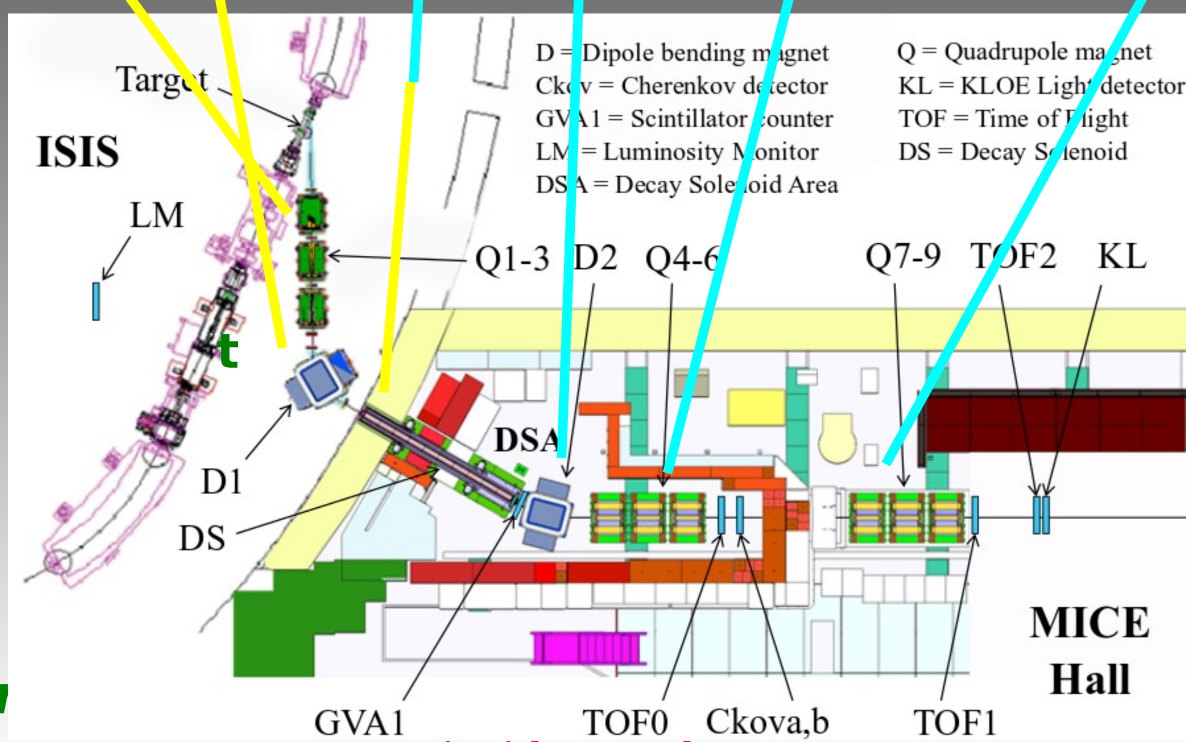
Selecting a muon beam





target

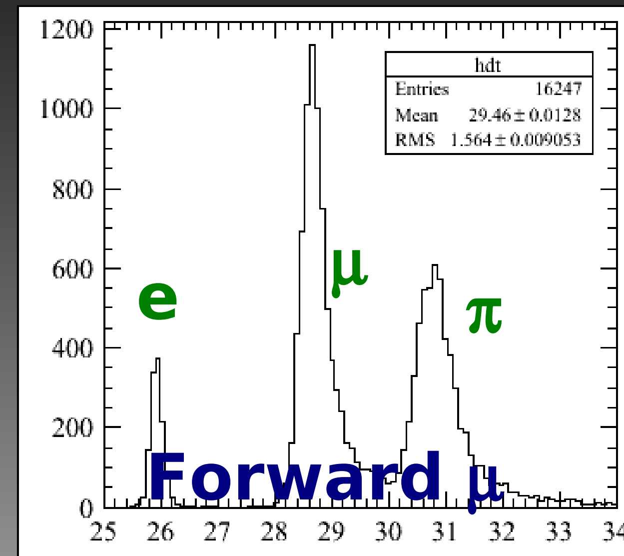
~90g acceleratio

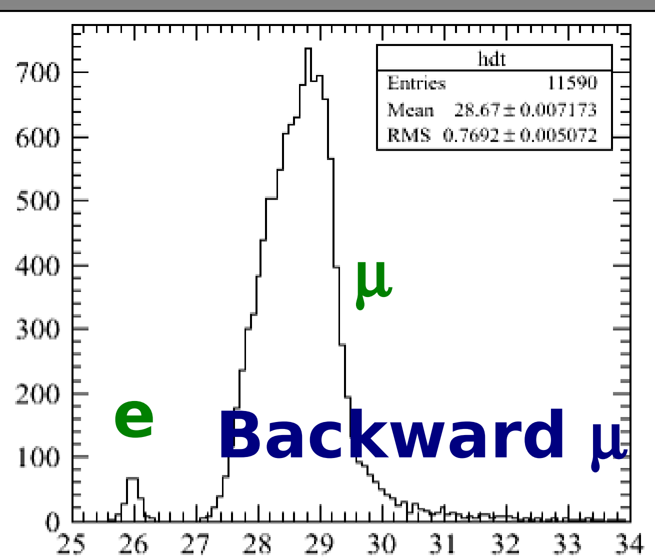


Beam Selection

μ direction in π rest frame

$p_{D1} \simeq p_{D2}$:
beamline optimized for calibration studies and rate





$p_{D1} \simeq 2p_{D2}$:
beamline optimized for
$\pi \rightarrow \mu$ transmission

Beam Preparation

Muon beam preparation for MICE measurements

vary p_{D1}/p_{D2} to select beam

p_{tgt}: p at target

p_{sol}: p at DS

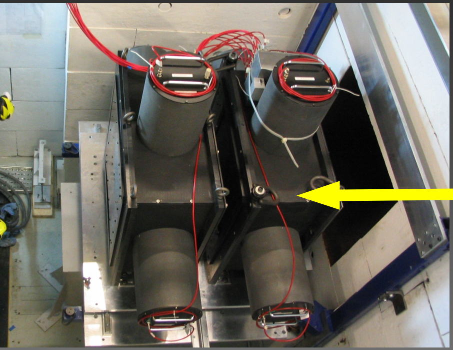
p_{dif}: p at diffuser

momentum (MeV/c) →

emittance (mm) ↓

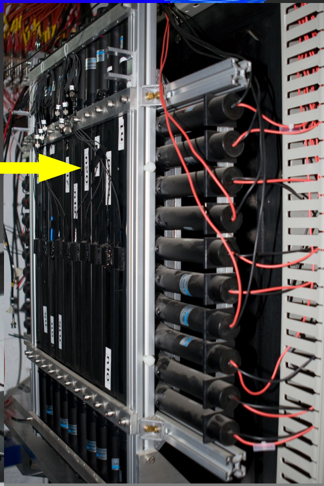
emittance (mm)	140	200	240
3	p_{tgt}=321 p_{sol}=185 p_{dif}=151	p_{tgt}=390 p_{sol}=231 p_{dif}=207	p_{tgt}=453 p_{sol}=265 p_{dif}=245
6	p_{tgt}=328 p_{sol}=189 p_{dif}=148	p_{tgt}=409 p_{sol}=238 p_{dif}=215	p_{tgt}=472 p_{sol}=276 p_{dif}=256
10	p_{tgt}=338 p_{sol}=195 p_{dif}=164	p_{tgt}=429 p_{sol}=251 p_{dif}=229	p_{tgt}=486 p_{sol}=285 p_{dif}=267

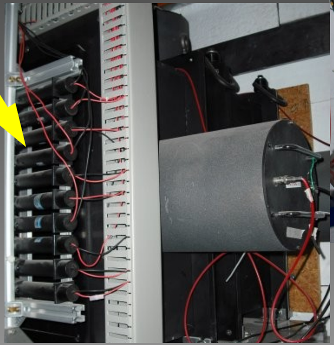
MICE PID: Detectors



Upstream PID:
discriminate p, π, μ

- ***Time of Flight – ToF0 & ToF1***
- ***Threshold Cerenkov***

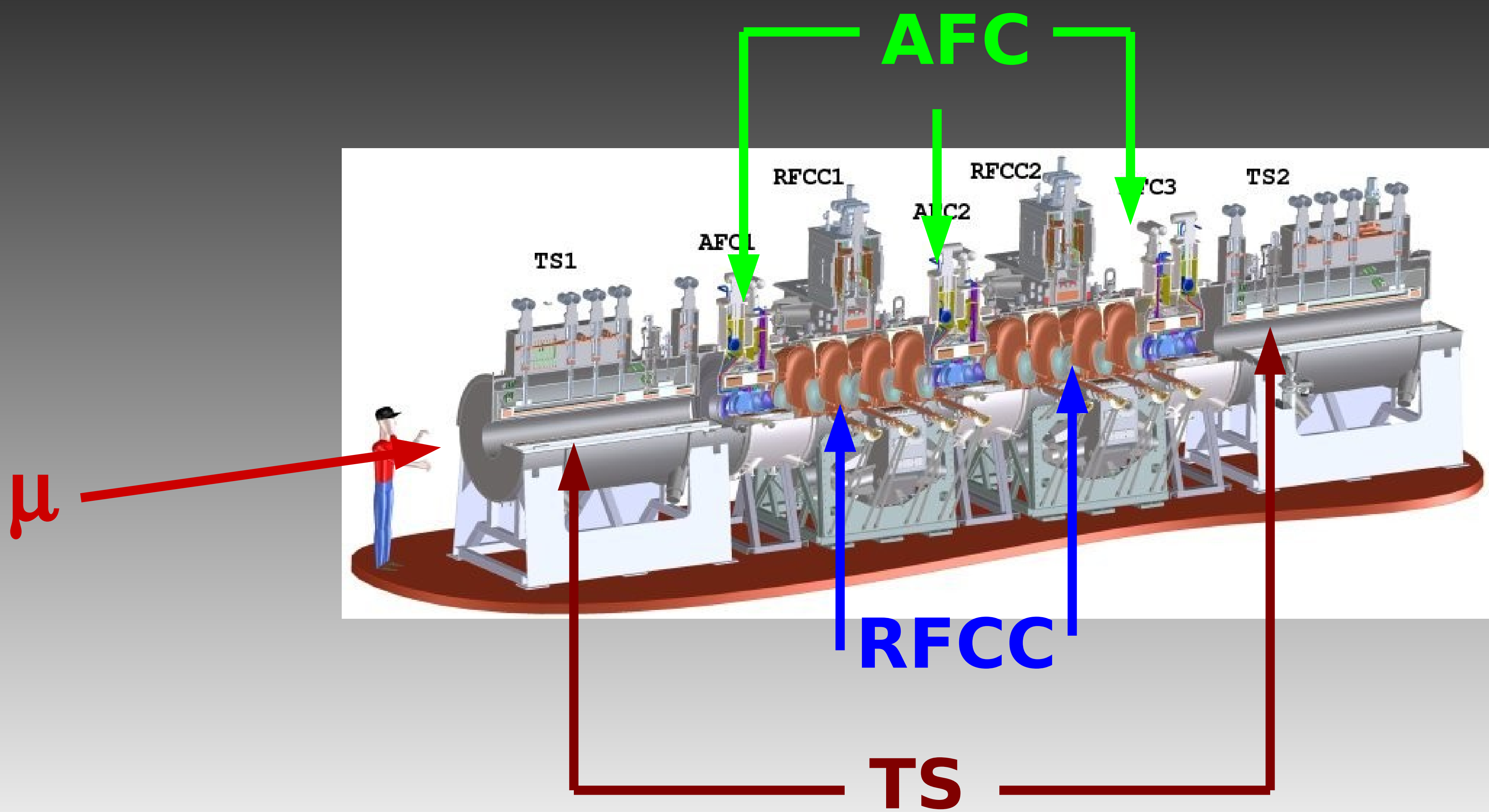




Downstream PID:
reject decay electrons

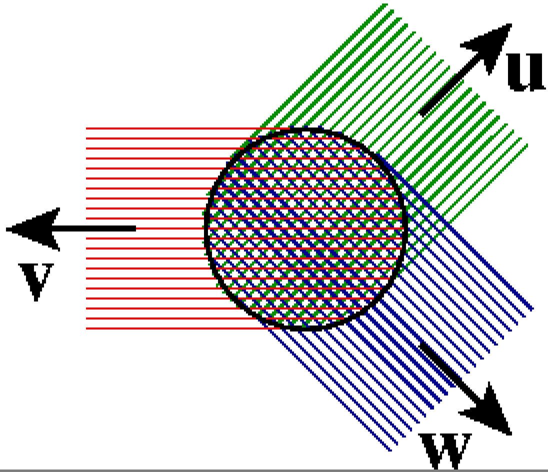
- ***Time of Flight - ToF2***
- ***Kloe-light Calorimeter - KL***
- ***Electron-Muon Ranger -EMR***

MICE Cooling Channel



MICE Tracking

- Two trackers – before/after
- Measures x, y, x', y', z
- 5 stations/tracker
- 3 stereo planes/station – U/V/W
- 1400 350μm fibers/plane
- double layer, 7 fibers/group
- <0.2% dead channels
- >10.5 photoelectrons/MIP
- 470μm RMS position resolution



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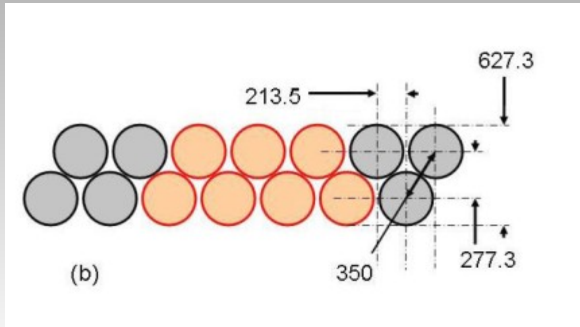
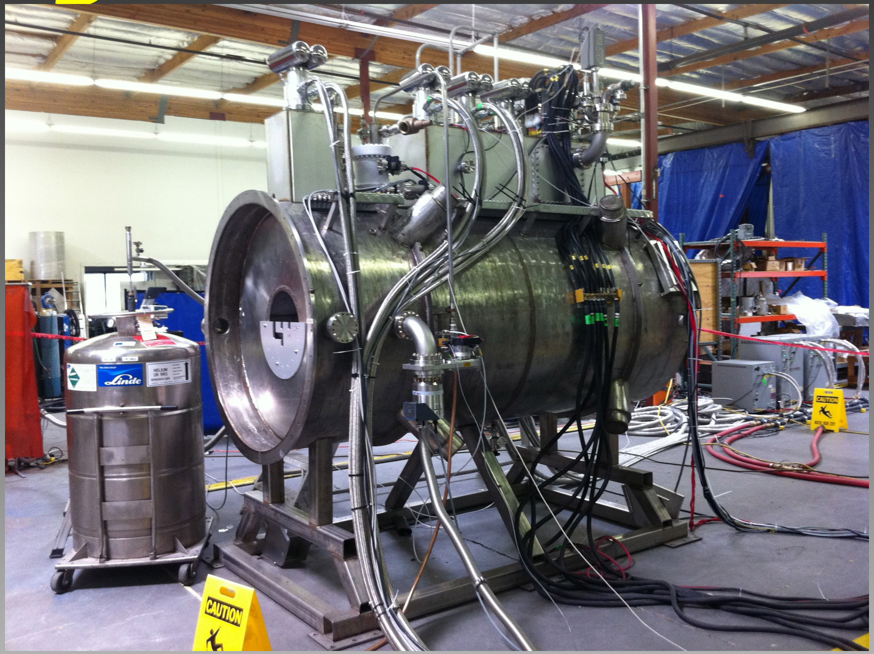
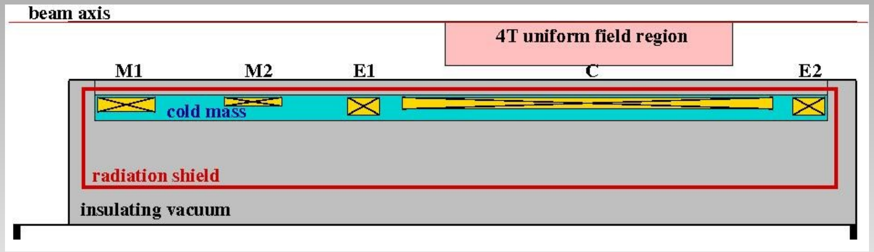


Spectrometer Solenoids

- 4 T superconducting solenoids
- 20 cm warm bore
- 2.9 m long

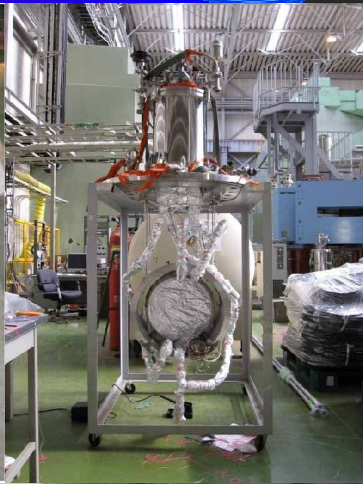


- 5 coils:
  - 1 tracker coil
  - 2 end coils
  - 2 matching coils



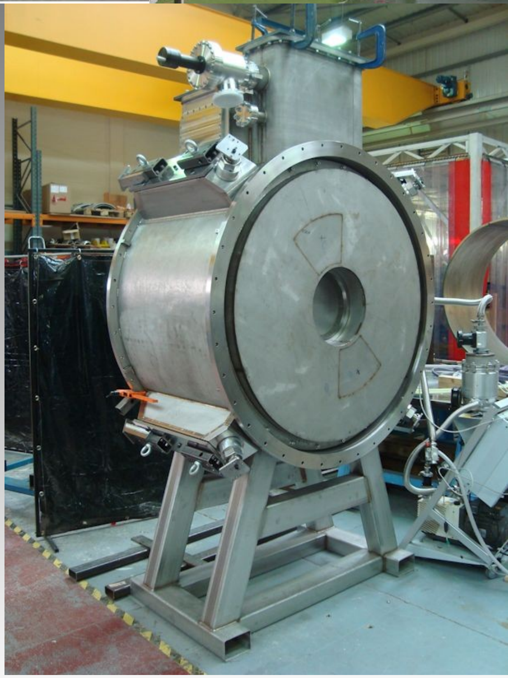
Absorber/Focus Coils

LH_2 Absorbers



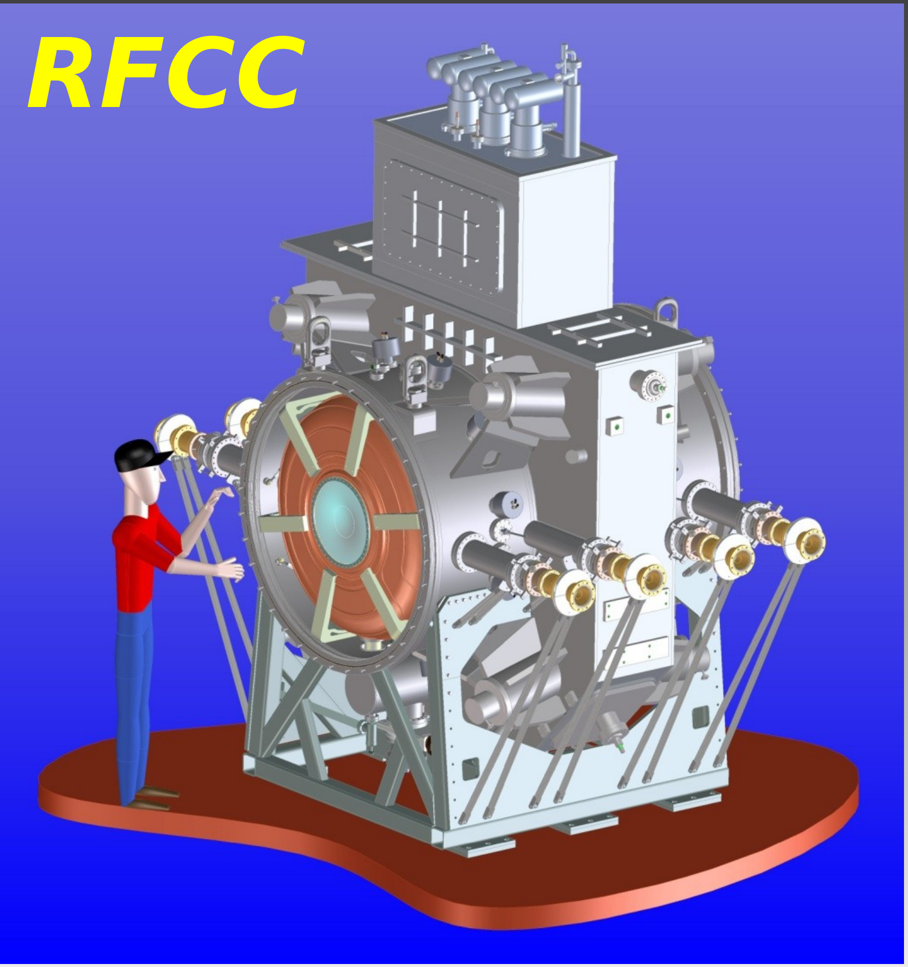
Focus Coil

2 coils operated:
- **solenoid mode**
- **flip mode**



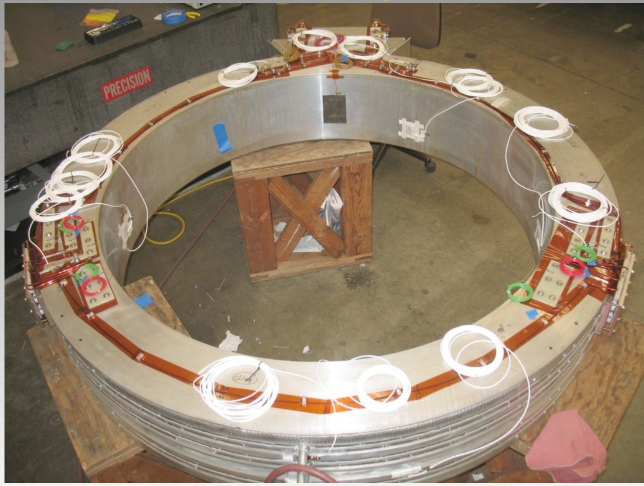
RF/Coupling Coils

RFCC



201 MHz RF Cavity
1 of 4

Coupling Coil



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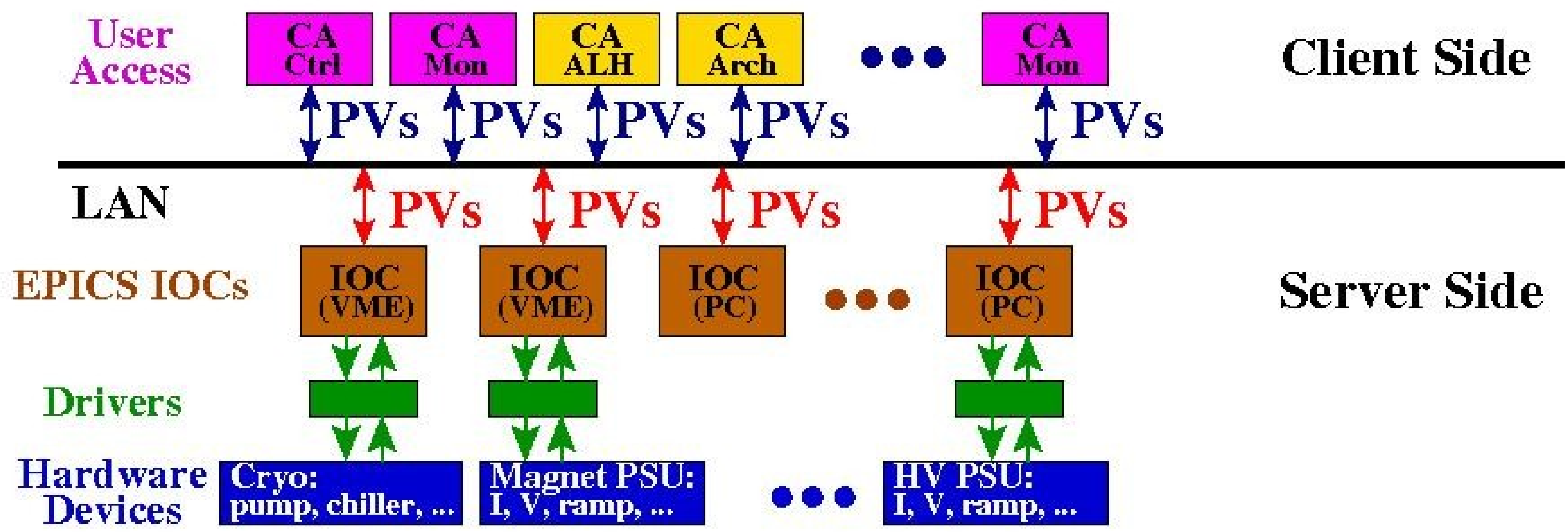
- IV <u>State Machine operation</u>
- V Future

Framework: EPICS

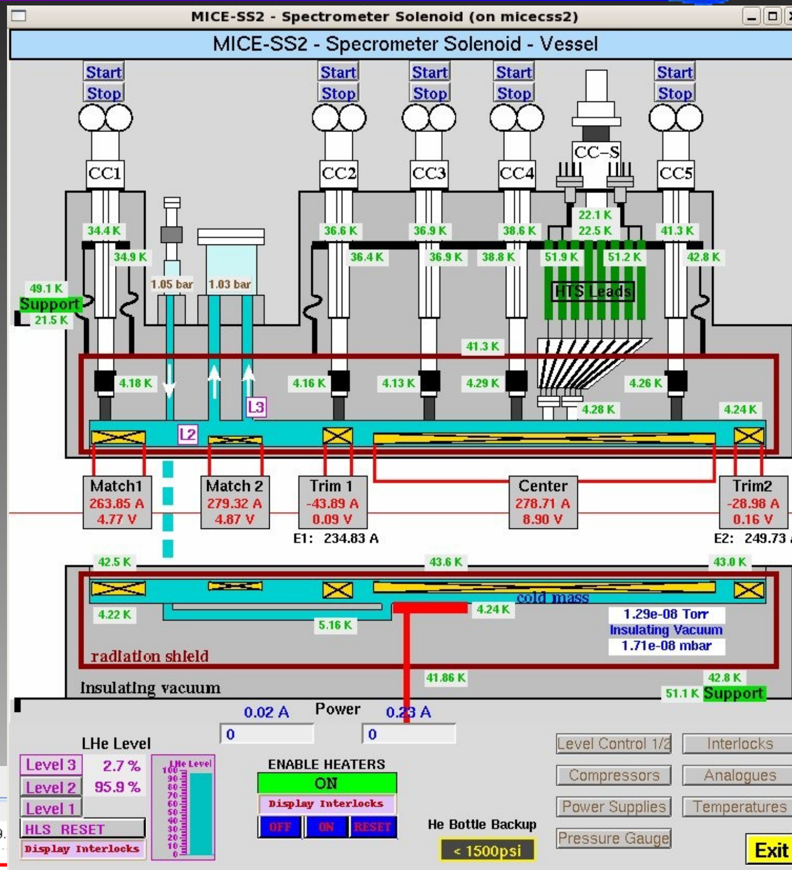
Experimental Physics & Industrial Control Systems

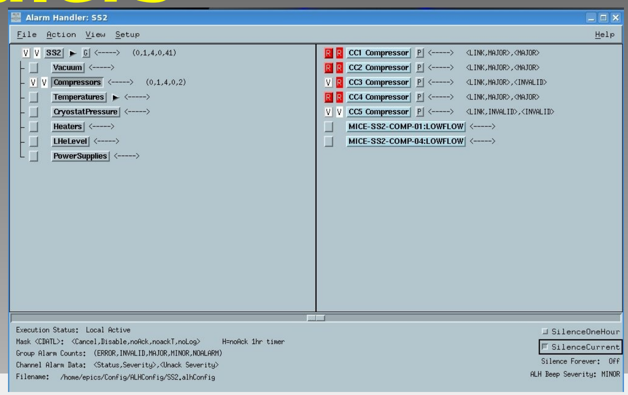
- **HW+Drivers connect to IOCs** (Input/Output Controllers)
- **IOCs create PVs** (process variables) **to represent params**
- **PVs further described with native fields**
- **PVs available on LAN to other IOCs or clients**

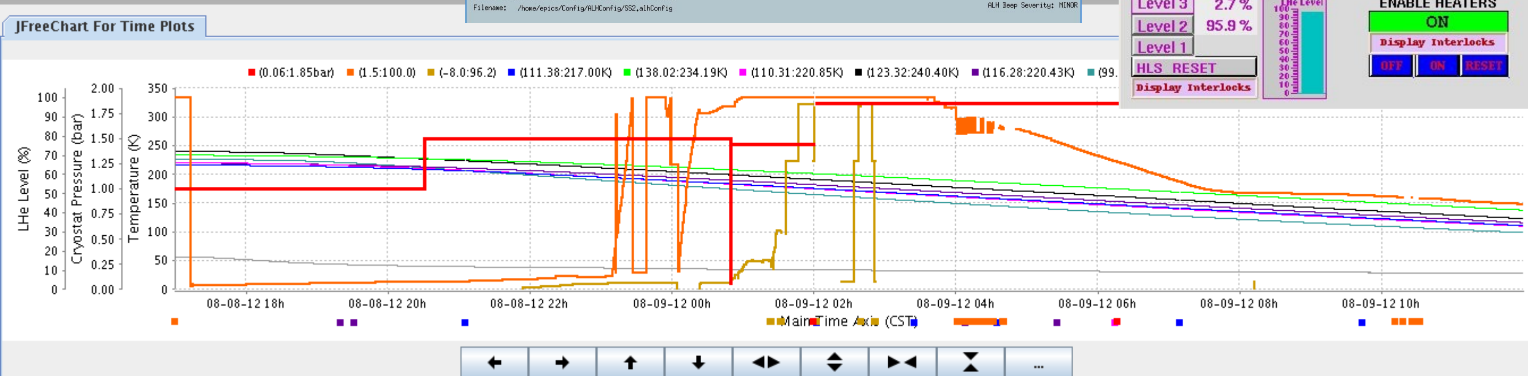


Framework: EPICS

PVs are used for:
- controlling the hardware
- interacting with other IOCs
- graphical displays – GUIs
- alarm handlers
- archiving







Controls & Monitoring

- **Beamline**
  - target
  - decay solenoid
  - conventional magnets
  - proton absorber
  - beam stop
  - diffuser
- **Particle ID (PID)**
  - GVa1
  - ToF 1/2/3
  - CKOV A/B
  - KL
  - EMR
- **Environment**
  - temp./humidity..
- **Facilities/Computing**
- **Tracking Spectrometers**
  - spectrometer solenoids
  - trackers
- **AFC**
  - absorbers
  - focusing coils
- **RFCC**
  - RF (acceleration)
  - coupling coils

These magnets require:

- vacuum
- cryogenics
- power supplies

Problem …

- Different sub-systems have different needs
- Each sub-system has 10^1–10^3 PVs
- Many PVs have up to 4 alarm limits
- Each PV has different archiving needs
- For different operational states:
  - the PVs of interest change
  - the alarm limits change
  - the archiving needs change
  - the list of critical PVs change

Too much room for human error!

e.g. Powering a superconducting magnet

Problem?
… No problem

EPICS state notation language employed:

- define equipment operational states
- for each state:
  - define transitions out of state
  - set alarm limits
  - set archiving features
  - define critical variables
- check for software interlocks; e.g. quench
- check for errors
- check for transition

All parameters come from configuration database (CDB) – ensures correct settings

State Machine Requirements

Subsystem Owners must enumerate the states and provide:

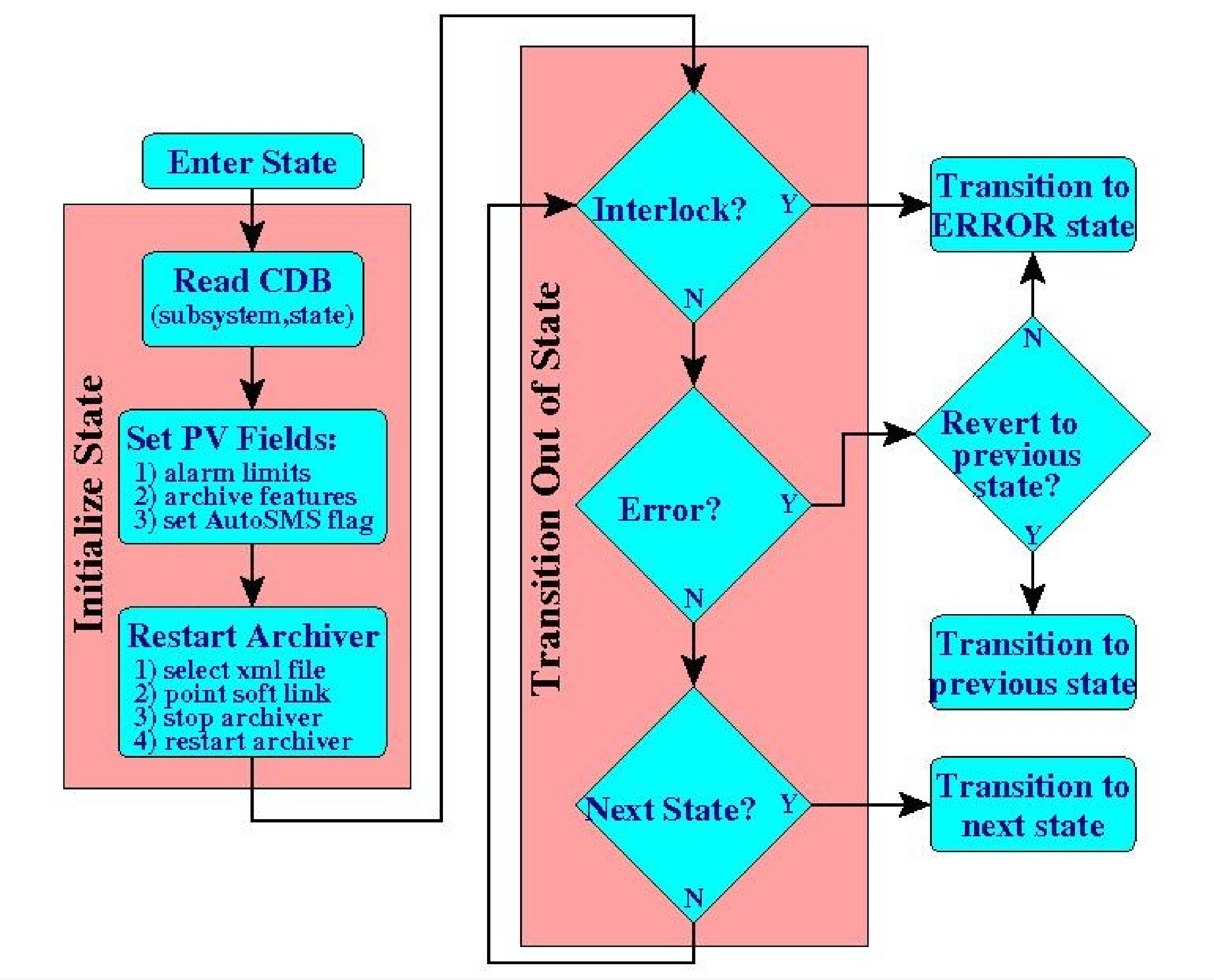
1) Description of state
2) Transition into state
3) PVs of interest
4) Alarm limits for PVs
5) Archiving features for PVs
6) AutoSMS (auto dialer) flag
7) Hardware interlocks
8) Software “interlocks” (enables)

- Required for each state
- Loaded into the CDB

State Machine Procedures

For each subsystem & state, the algorithm:

- **Transitions:**
- **manual**
- **automatic**



State Machine: SS Example

Spectrometer Solenoid Magnets:

1)Offline
2)Pumping: establish insulating vacuum
3)Pumped_Warm: insulating vacuum established
4)Pre_Cooling: N_2 pre-cooling (T>100K)
5)Cooling: cryo-coolers lower shield/cold mass T
6)LHe_Filling: add liquid He
7)Cold_Ready: cold and stable
8)Ramping: applying current
9)Powered: stable operation
10)Quenched: quench detected
11)Error: error requires operator intervention
12)Testing: interlocks disabled for manual testing

Presently used in training/mapping SS magnets

State Machine: Target Example

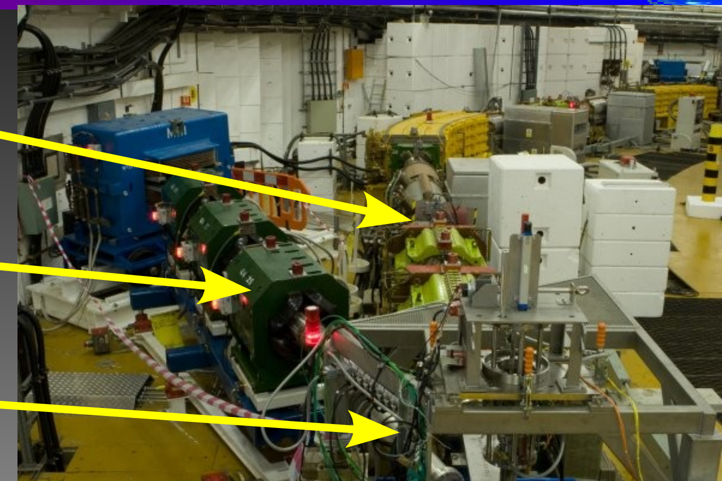
Target Example:

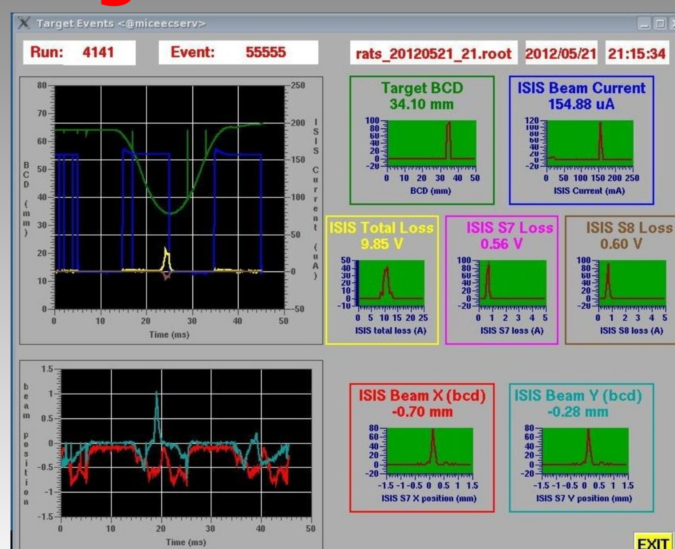
1)Offline
2)Parked_Powered
3)Raised_Holding
4)Raised_Actuating
5)Moving_Holding
6)Lowered_Holding
7)Lowered_Actuating
8)Error
9)Unknown

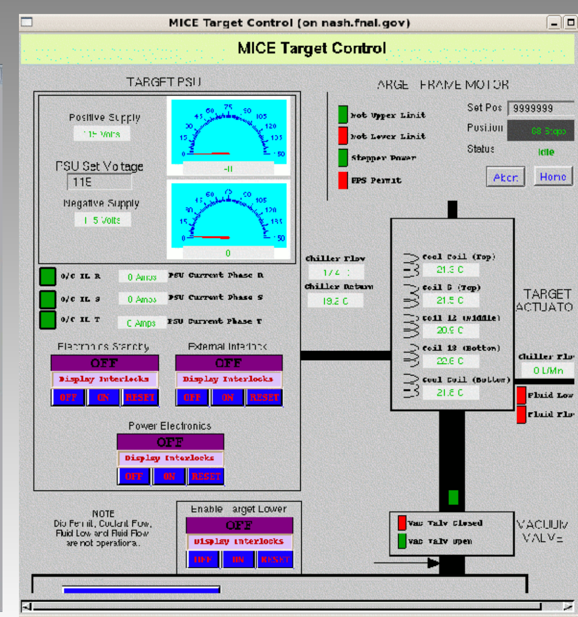
ISIS

MICE

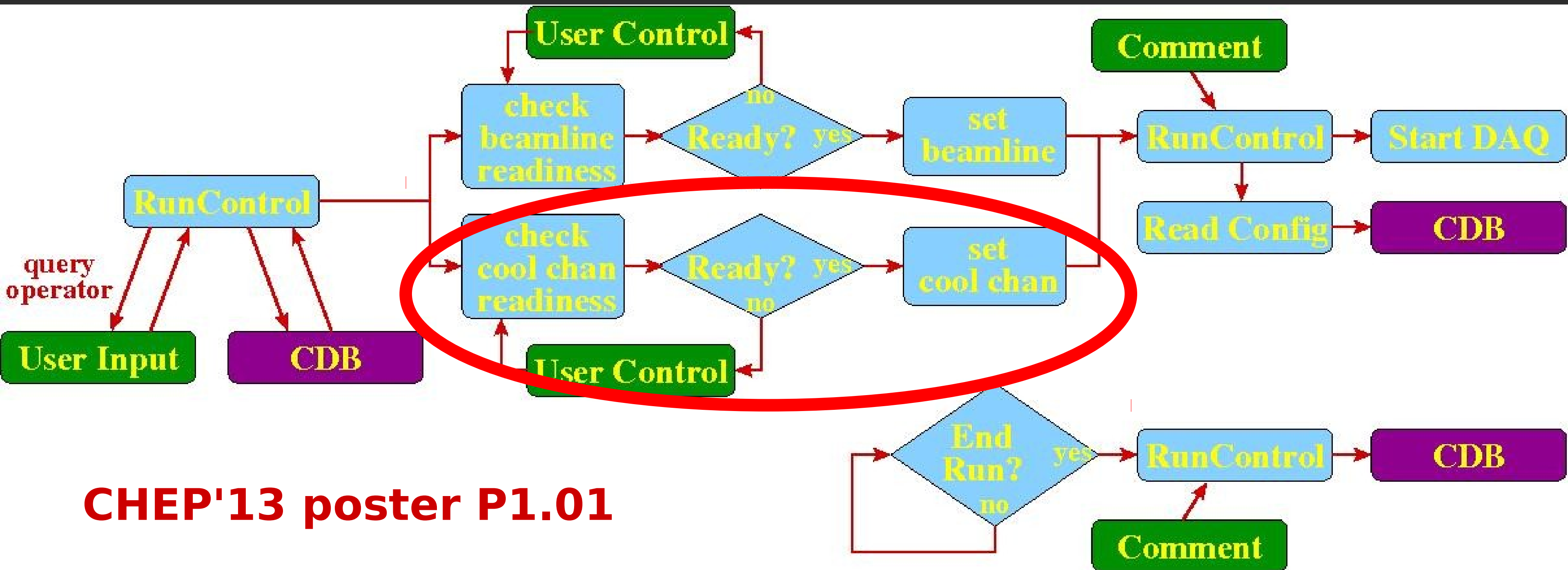
target







State Machine Effect on RunControl



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State machines for magnet control greatly reduces complexity of RunControl. RC need only check state of each magnet.

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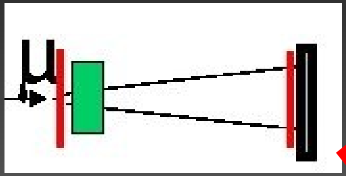
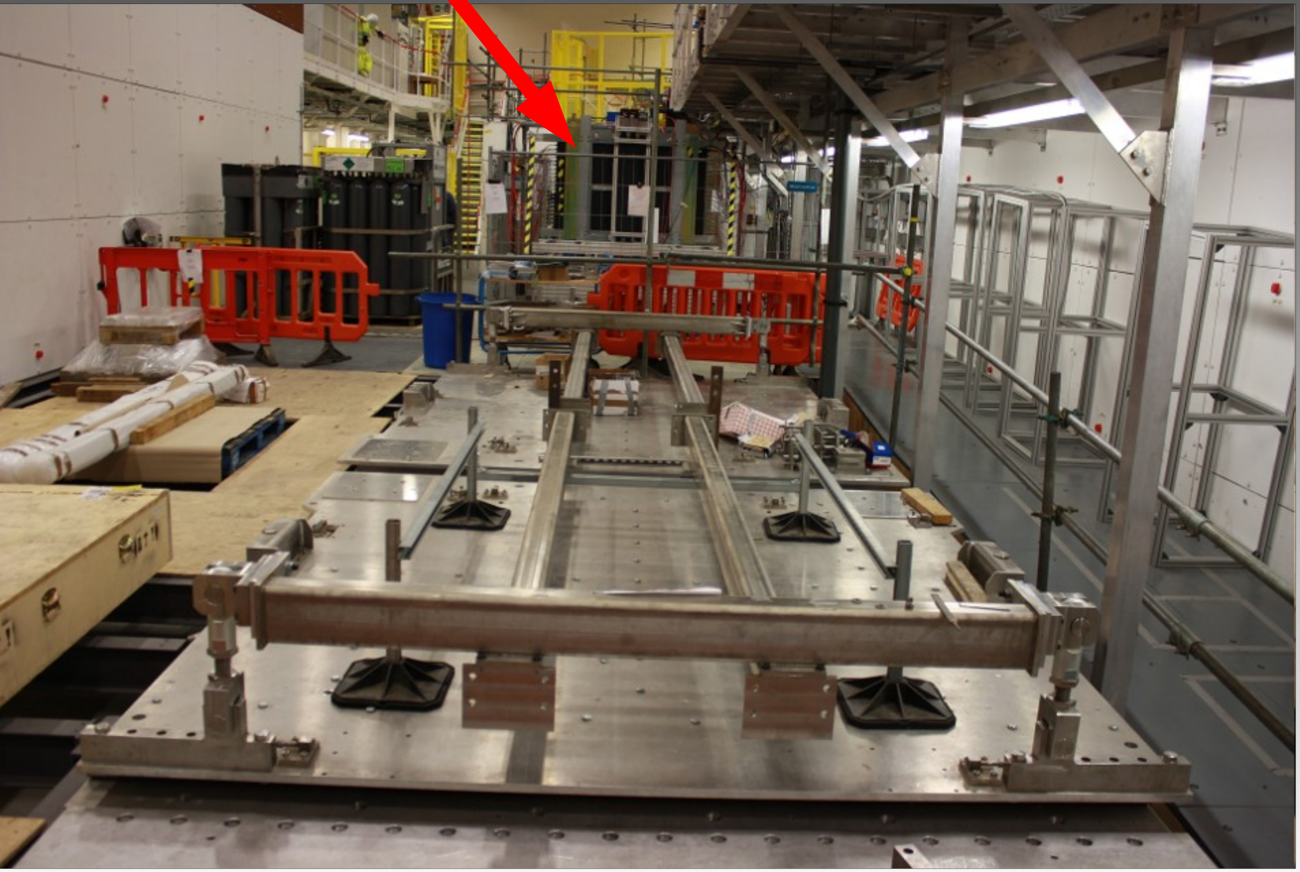
MICE Next Steps



Now that Step I is complete:



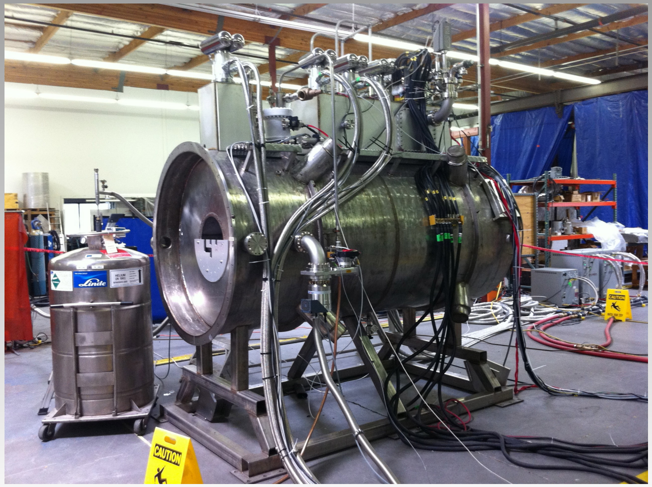
Fill up this hall!!!

Prepare for Step IV

Equipment is arriving:

More under test:

- SS1
- FC for AFC
- EMR



Conclusions

- MICE is a precision experiment: 0.1%
- MICE is preparing for Step IV
- C&M challenge to provide systematic operational settings
- State machine operation of major sub-systems meets this challenge