Looking forward to a Muon Collider at Fermilab

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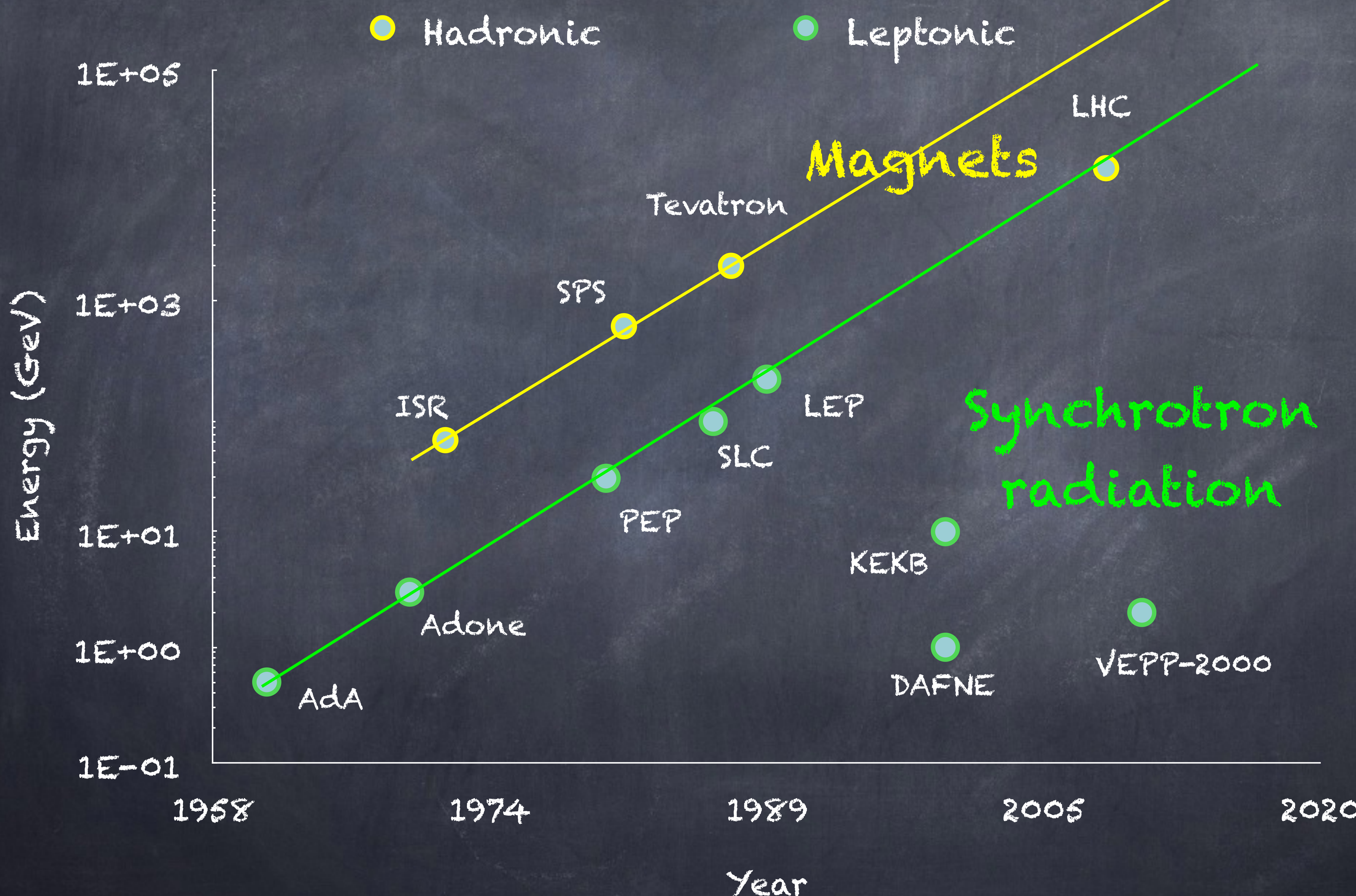
SUMMARY

We will talk about:

- Current accelerators and possible classical future options
- Possibility of muon colliders and related advantages
- Muon Collider Layout and major components
- Ionization cooling and MICE experiment
- Muon Accelerator Program
- Tuner tests for MICE cavity

ACCELERATORS EVOLUTION



WHAT NEXT?

<u>What we are interested in:</u>

- Higgs Factory:
  - Machine able to reach Higgs resonance
  - Leptonic signal cleanliness
- Possibility of multi TeV upgrade:
  - Ability to run at higher energies form the beginning or with an upgrade
  - Dependent on next years LHC results

WHAT NEXT?

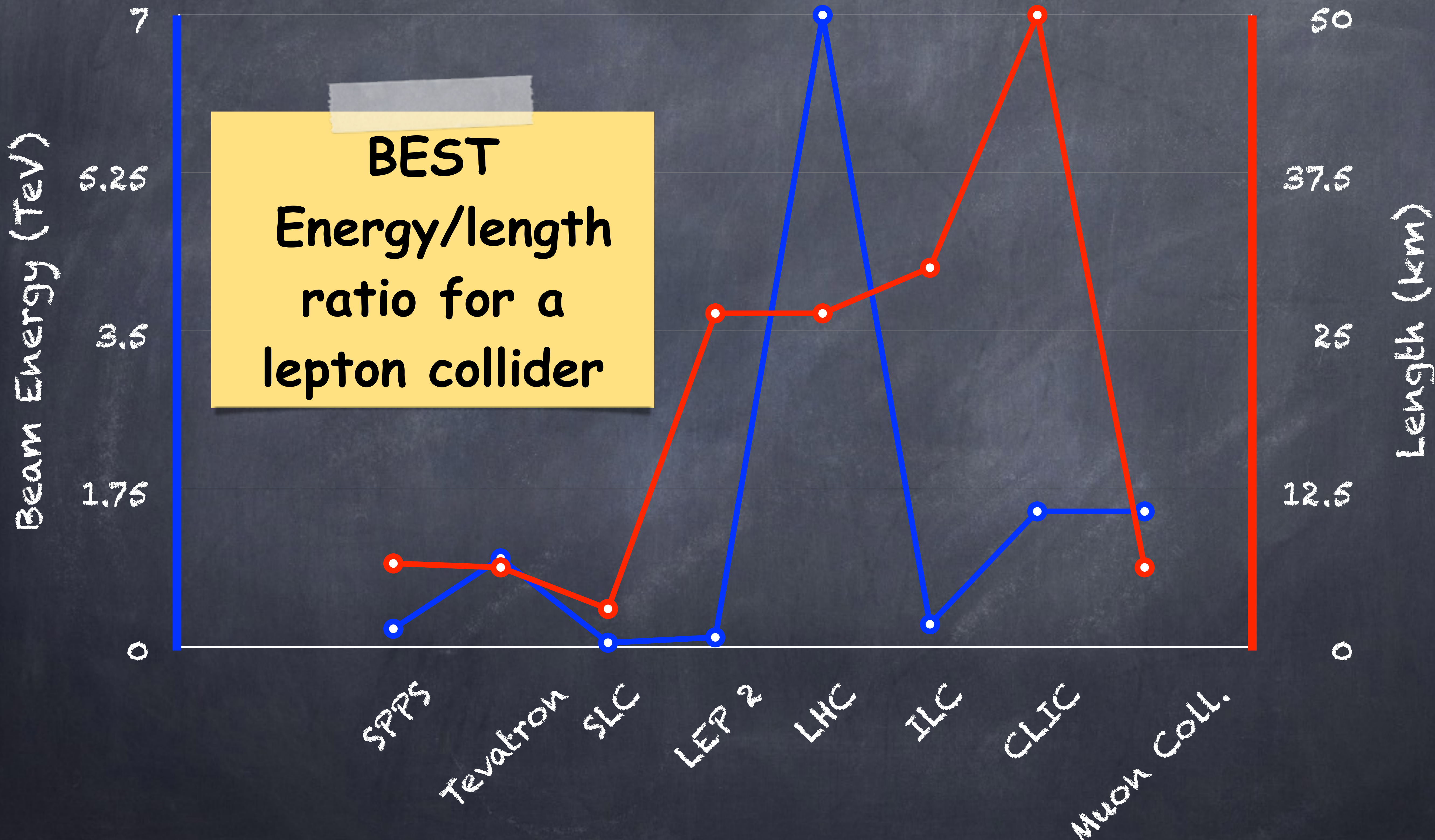
What we could (would like to) build:

- Circular e^+e^- machine:
  - LEP3, SuperTRISTAN, VLCC, TLEP (Just some of the many possible options)
  - Major constraints coming from radiated power (synchrotron radiation)
- Linear machine:
  - ILC or CLIC
  - No radiation loss
  - Complications: single pass, very long, first linear collider (will we be able to achieve proper tune?)

POSSIBLE FUTURE CIRCULAR ELECTRON COLLIDERS

	LEP2	***LEP3***	***SuperTRISTAN***	***VLCC***
Beam Energy (GeV)	*104.5*	*120*	*200*	*200*
Circumference (km)	*26.7*	*26.7*	*60*	*233*
Bunch Population (10^{10})	*57.5*	*133.3*	*249.2*	*48.5*
β_y (mm)	*50*	*1.2*	*0.32*	*10*
σ_y (μm)	*3.536*	*0.4243*	*0.0738*	*0.56*
σ_z (μm)	*16.1*	*3*	*1.4*	*6.67*
Crossing Angle ($mrad$)	*0*	*0*	*35*	*0*
Radiation Loss per turn (GeV)	*3.408*	*6.99*	*18.5*	*4.42*
Radiation Power (MW)	*22*	*100*	*74*	*100.7*
Equilibrium energy spread (%)	*0.22*	*0.232*	*0.196*	*0.096*
Luminosity per IP (10^{34})	*0.0125*	*1.33*	*5.2*	*0.88*

COLLIDERS COMPARISON



MUON COLLIDER!!!

A different path could be taken:

- A muon collider removes most of linear and circular constraints
- Easy upgrade from Higgs factory to multi TeV collider
- Possible cost saving (mainly from infrastructures and site power but related to the final technology which is still unknown)

- HOWEVER: many other complications are introduced

MC: ADVANTAGES

<u>Radiation loss:</u>

- Radiation loss in a circular machine is expressed by:

$$\boxed{P_\gamma = \frac{q^2 c}{6\pi\varepsilon_0 c^2}\frac{E^4}{\rho^2 m^4}}$$

- Muons (105 MeV) are $\sim$ 207 times heavier than electrons (510 KeV):
    - Radiation loss becomes negligible (10^9 times smaller than electrons)
    - Smaller radius and less RF power for fixed energy

MC: ADVANTAGES

Luminosity:

- A simplified expression for luminosity is:

$$\mathcal{L} = \frac{N_1 N_2 n_b f}{4\pi\sigma_x\sigma_y}$$

- Emittance is related to β function and therefore to beam size:

$$\sigma_x = \sqrt{\varepsilon\beta_x}$$

- Beams collide many times (∼1000 turns):
  - A less demanding (bigger) emittance is allowed for fixed luminosity

MC: ADVANTAGES

Beamstrahlung:

- Bunch particles are deflected by EM field of bunches of the other beam:
- Deflection depends on:
  - Particle position inside bunch
  - Opposite-Bunch charge distribution
- Each particle radiates a different energy
  - Energy spread is created
- It's proportional to:

$$\boxed{U \propto \gamma^4 = \frac{E^4}{m_0^4 c^8}}$$

- It is heavily dumped with respect to electrons because of higher mass.

MC: ADVANTAGES

Physics advantages:

- S-channel Higgs boson production related to the square of colliding particles mass:

$$\boxed{\left(\frac{m_\mu}{m_e}\right)^2 \approx 40 \cdot 10^3}$$

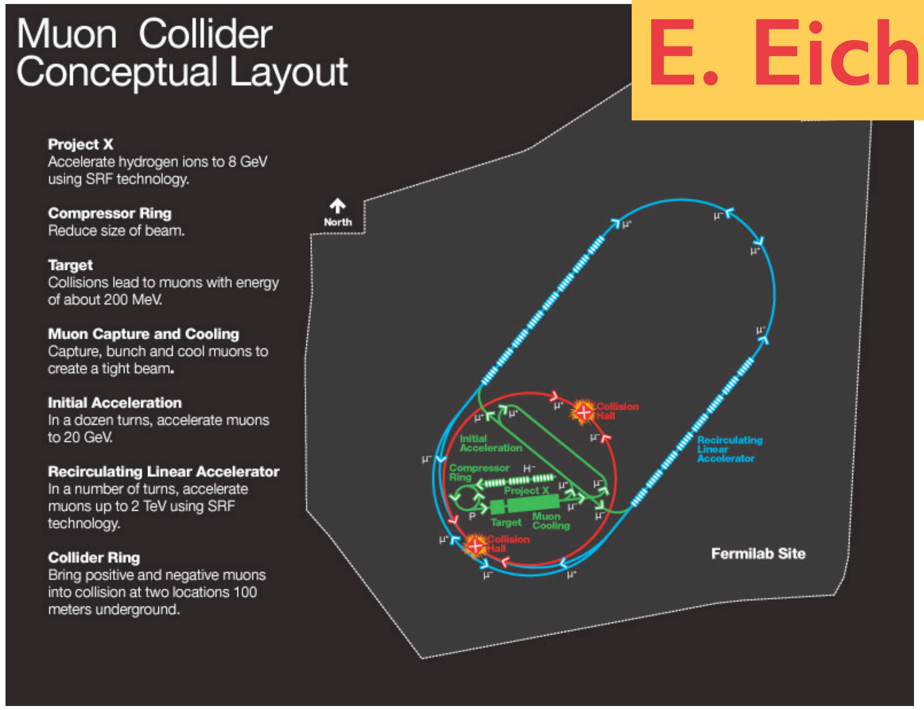
- Precision probe of fundamental interactions, as with an e^+e^- collider, in contrast to hadron colliders

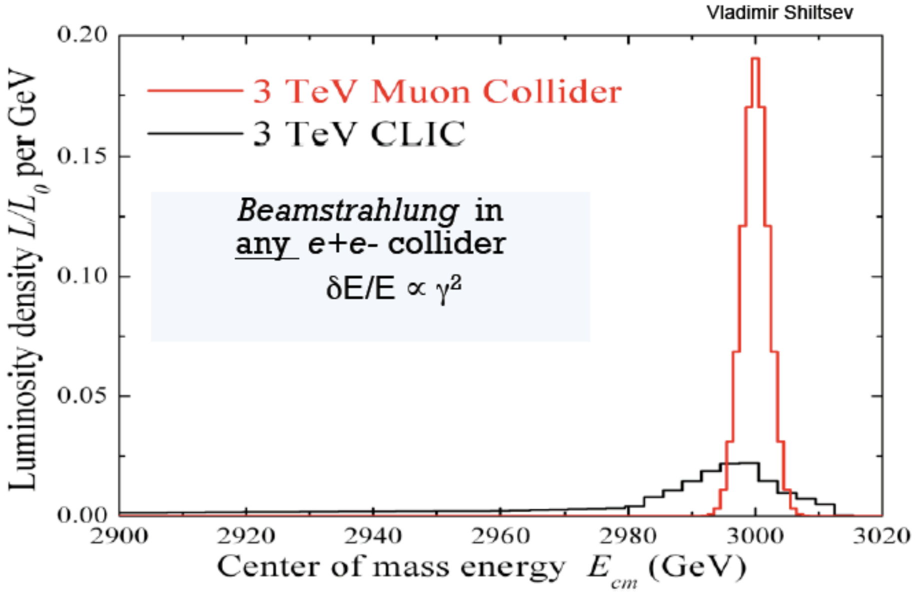
- Exquisite energy resolution (100 times better that at the LHC and LEP2 for Higgs energy) with 95% luminosity in dE/E ~ 0.1%

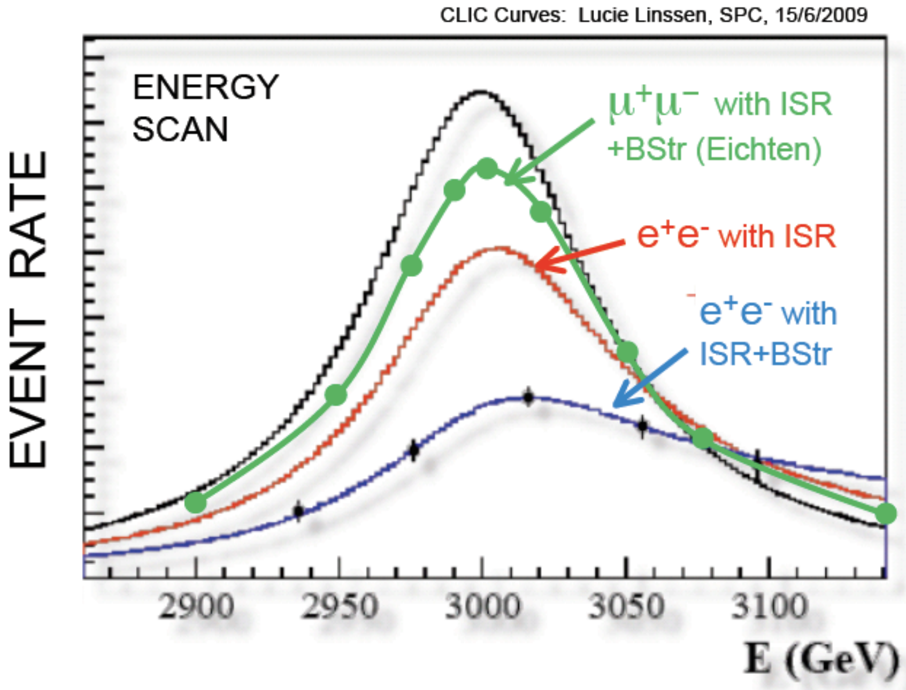
MC: ADVANTAGES

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 6 TeV (3 Tev)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (440 fb^{-1}/yr)
  - Compact facility
    - 3 TeV - ring circumference 3.8 km
    - 2 Detectors
  - Superb Energy Resolution
    - MC: 95% luminosity in dE/E ~ 0.1%
    - CLIC: 35% luminosity in dE/E ~ 1%

E. Eichten





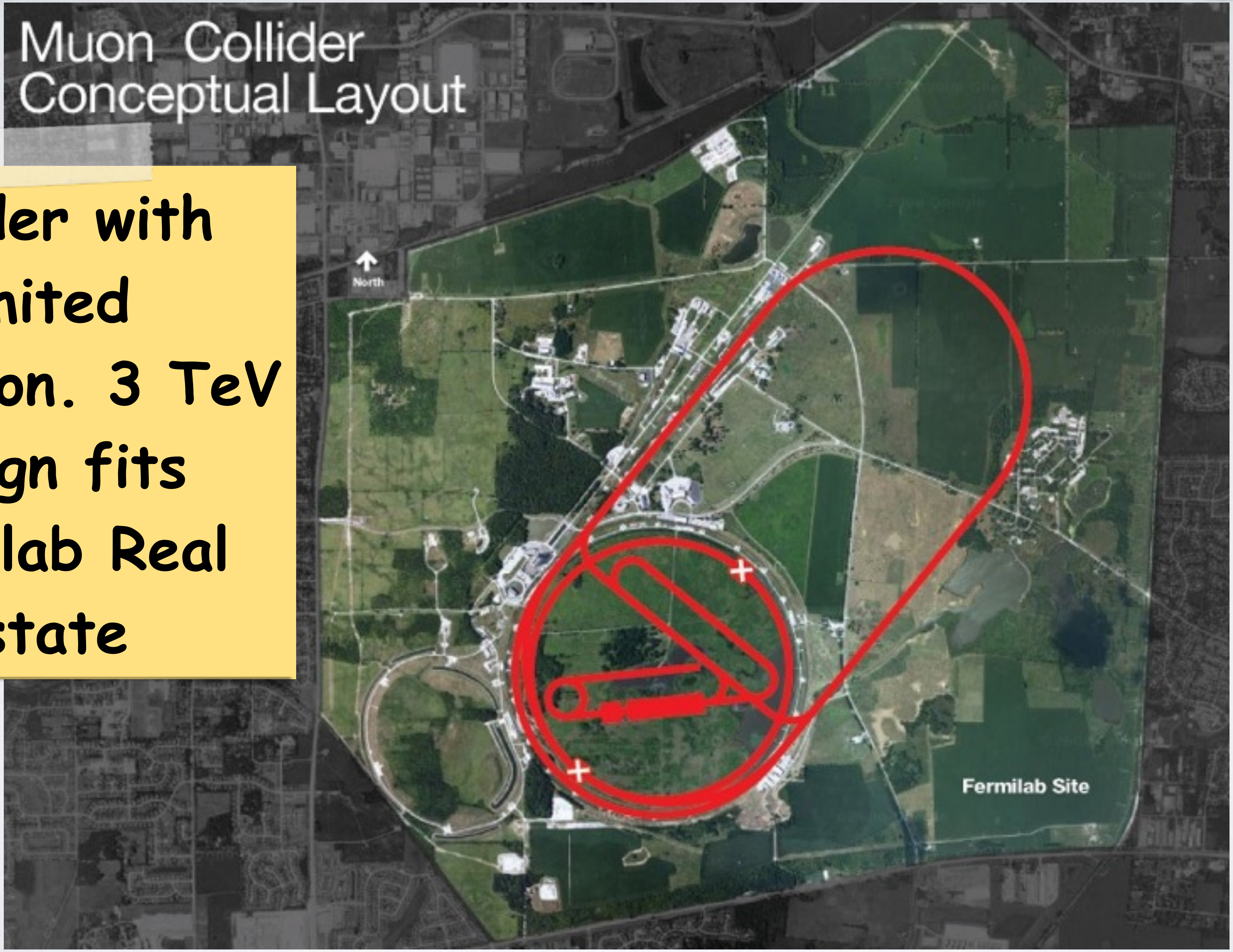


MC: DISADVANTAGES

Few but relevant disadvantages:

- Short muons lifetime (τ_0 of only 2.2 *us*): acceleration and manipulation have to be fast!
- Significant radiation to equipment
  - Coming from decay, not synchrotron radiation
- High initial emittance, because produced as tertiary particles ($\boldsymbol{p} \rightarrow \pi \rightarrow \boldsymbol{u}$)
- Low production efficiency (12 muons in the interaction region every 1000 protons on the target with current design)→ High driver power

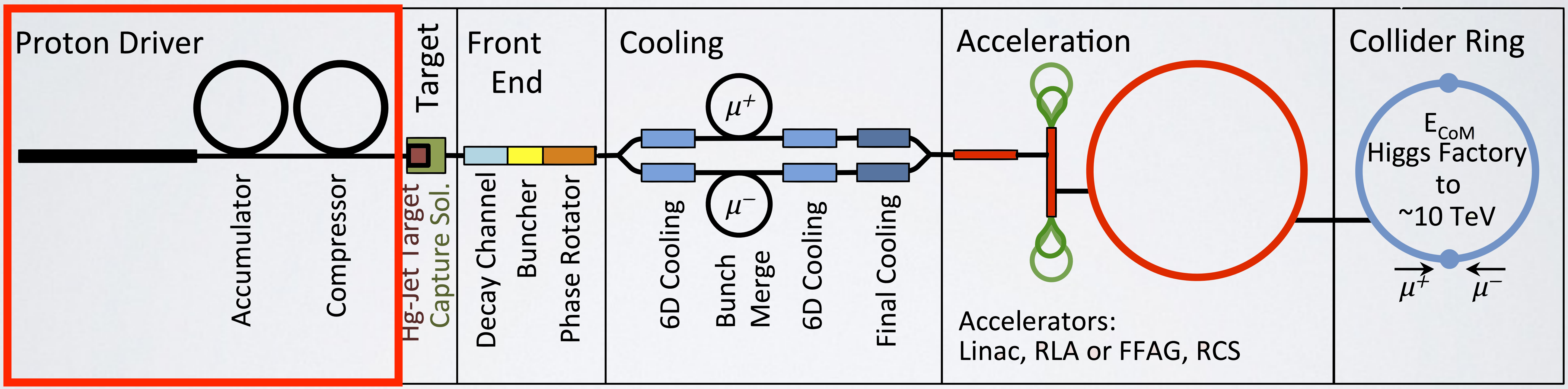
MUON COLLIDER!!!



Collider with limited dimension. 3 TeV design fits Fermilab Real Estate

MUON COLLIDER LAYOUT

Technical challenges have brought to this proposed layout



MC: PROTON DRIVER

Driver Power:

$$P = E \cdot f \cdot n \cdot e = 3.2\, MW$$

Low muons production rate and decay before collision imply high proton power :

- *12 colliding muons every 1000 protons*
- *$2 \cdot 10^{12}$ muons per beam -> $1.67\ 10^{4}$ protons on the target per driver macro-pulse*
- *The MC is filled with a single proton driver burst! All machines are pulsing at the same frequency*

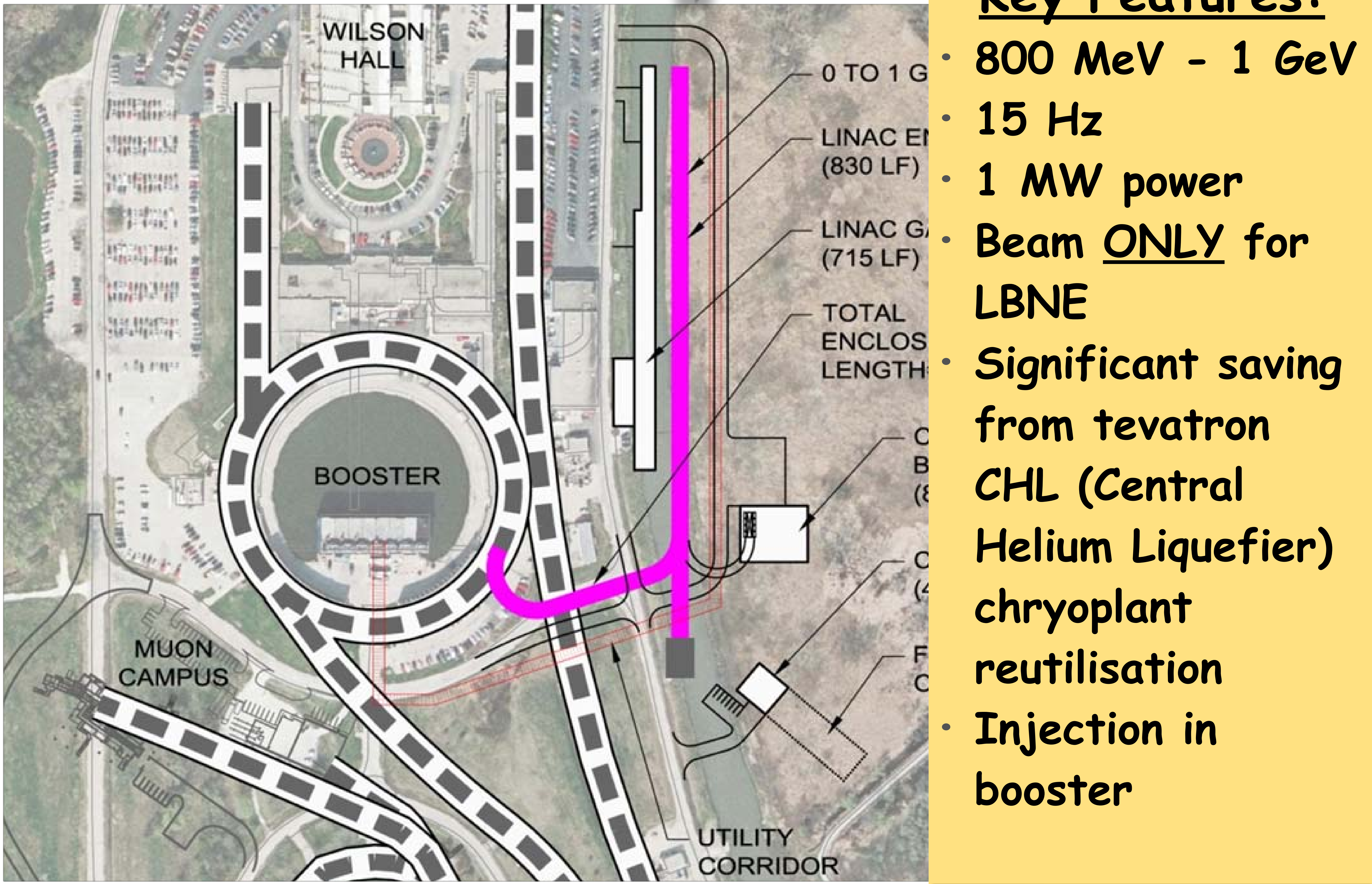
E: Energy of proton beam on the target (8 GeV) :

- *At this stage it would be easy to increase energy in order to increase power*
- *Energy is limited by target ability to sustain high energy beam*
- *It is related to outcoming muons energy*

f: Operational frequency of 15 Hz :

- *Determines the frequency of all following machines*
- *Forces the proton driver to high performances. it's very hard to achieve high repetition rates!*

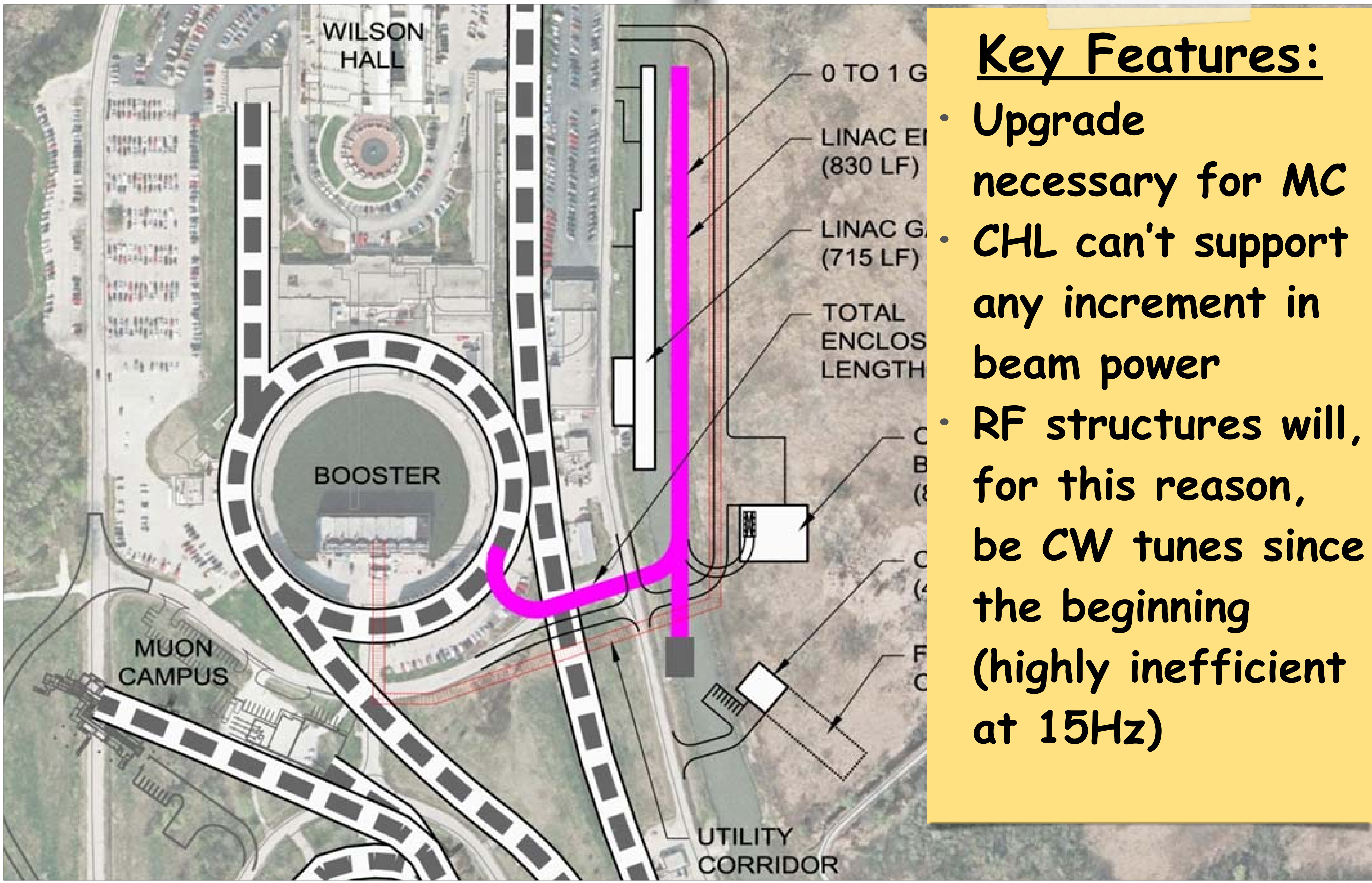
Proton Driver at FNAL



Key Features:

- 800 MeV - 1 GeV
- 15 Hz
- 1 MW power
- Beam <u>ONLY</u> for LBNE
- Significant saving from tevatron CHL (Central Helium Liquefier) chryoplant reutilisation
- Injection in booster

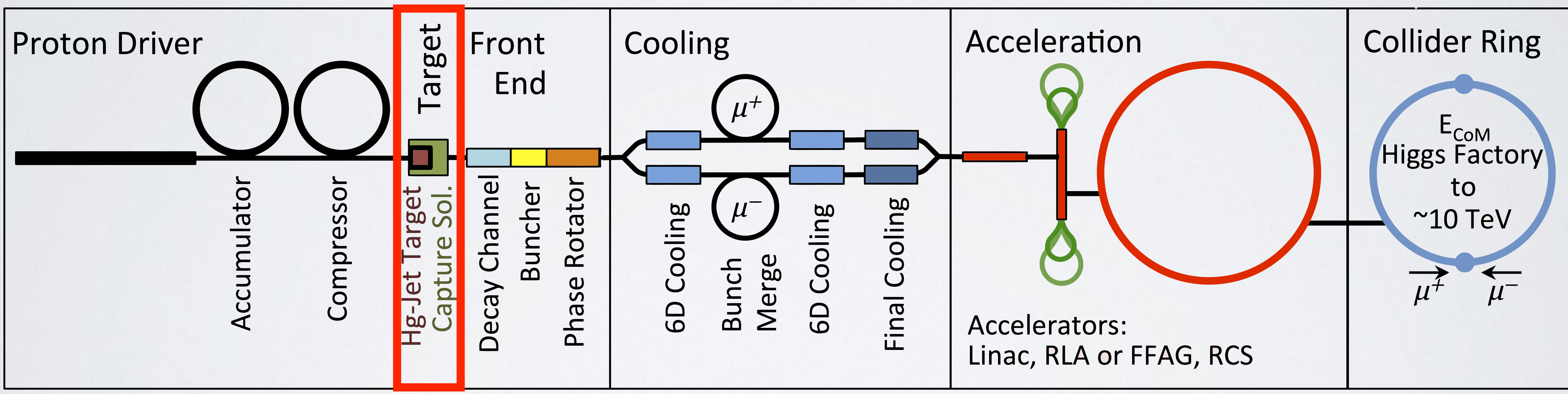
Proton Driver at FNAL



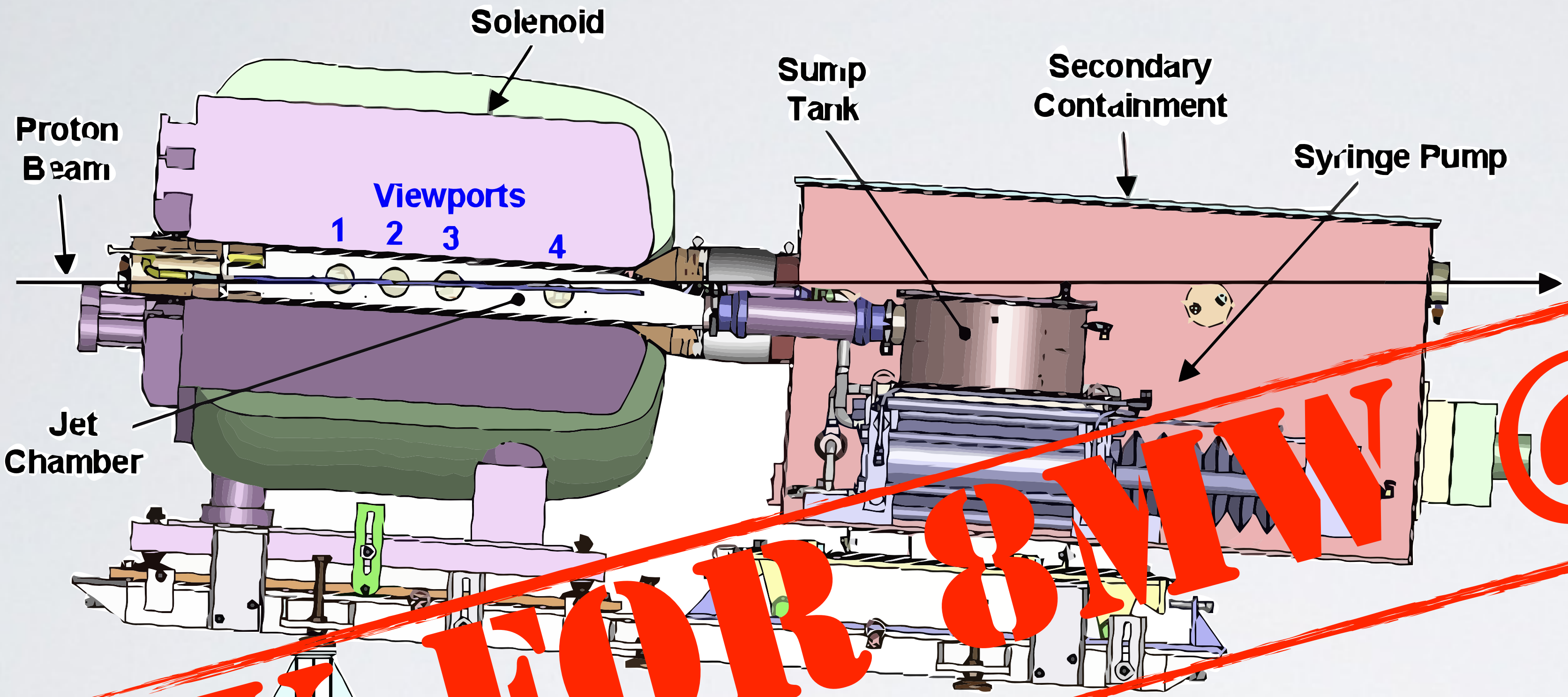
Key Features:

- Upgrade necessary for MC
- CHL can't support any increment in beam power
- RF structures will, for this reason, be CW tunes since the beginning (highly inefficient at 15Hz)

MUON COLLIDER LAYOUT



MC: TARGET



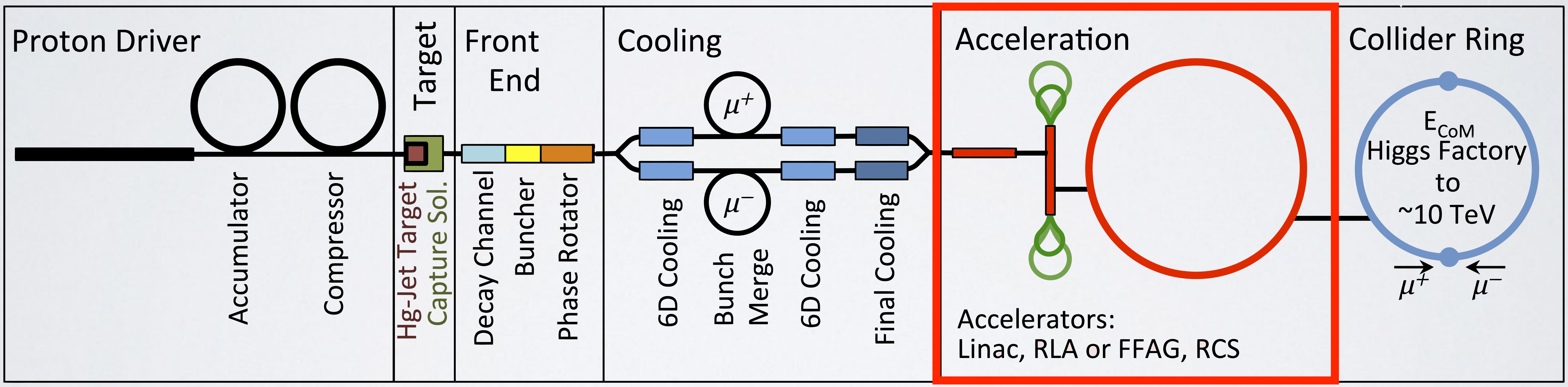
OK FOR 8MW @ 70HZ

MERIT @ CERN:

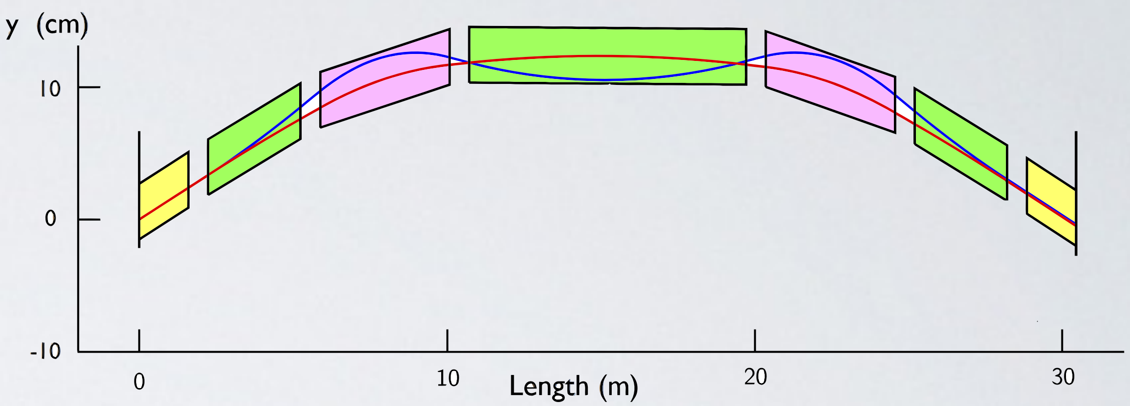
- 20 m/s mercury jet
- 15 T solenoid
- 115 KJ/pulse

- E_{Max}: 24 GeV
- 8 MW
- 70 Hz

MUON COLLIDER LAYOUT



MC: ACCELERATION



RLA:

- Recirculating Linear Accelerators
- Fast Kickers select the proper trajectory at the ends
- Minimisation of arch length at low energies

RCS:

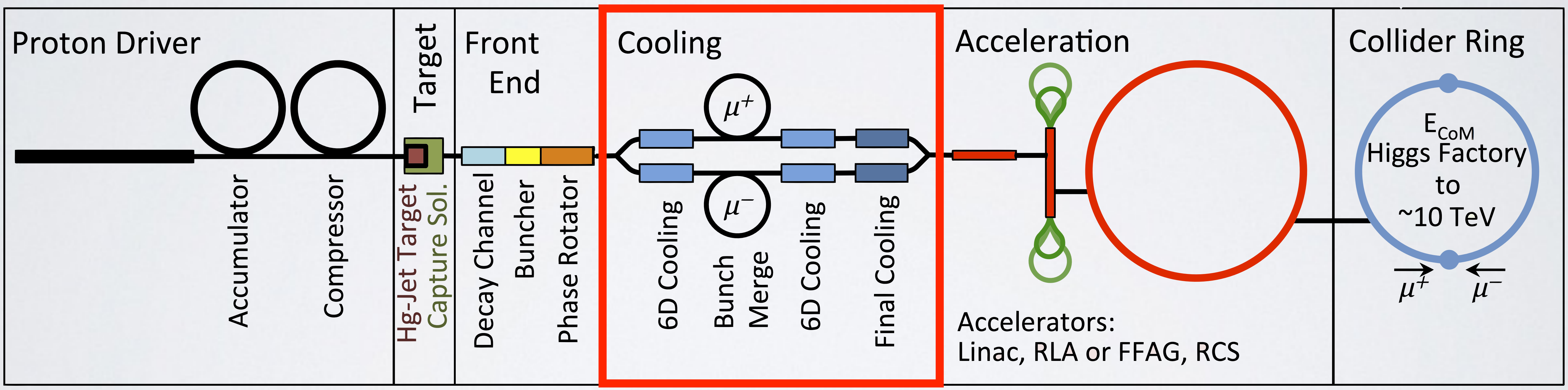
- Rapid Cycling Synchrotrons
- More economic that RLAs
- Particular technology to be FAST
- 8T SC + 1.8T NC

MC: PARAMETERS

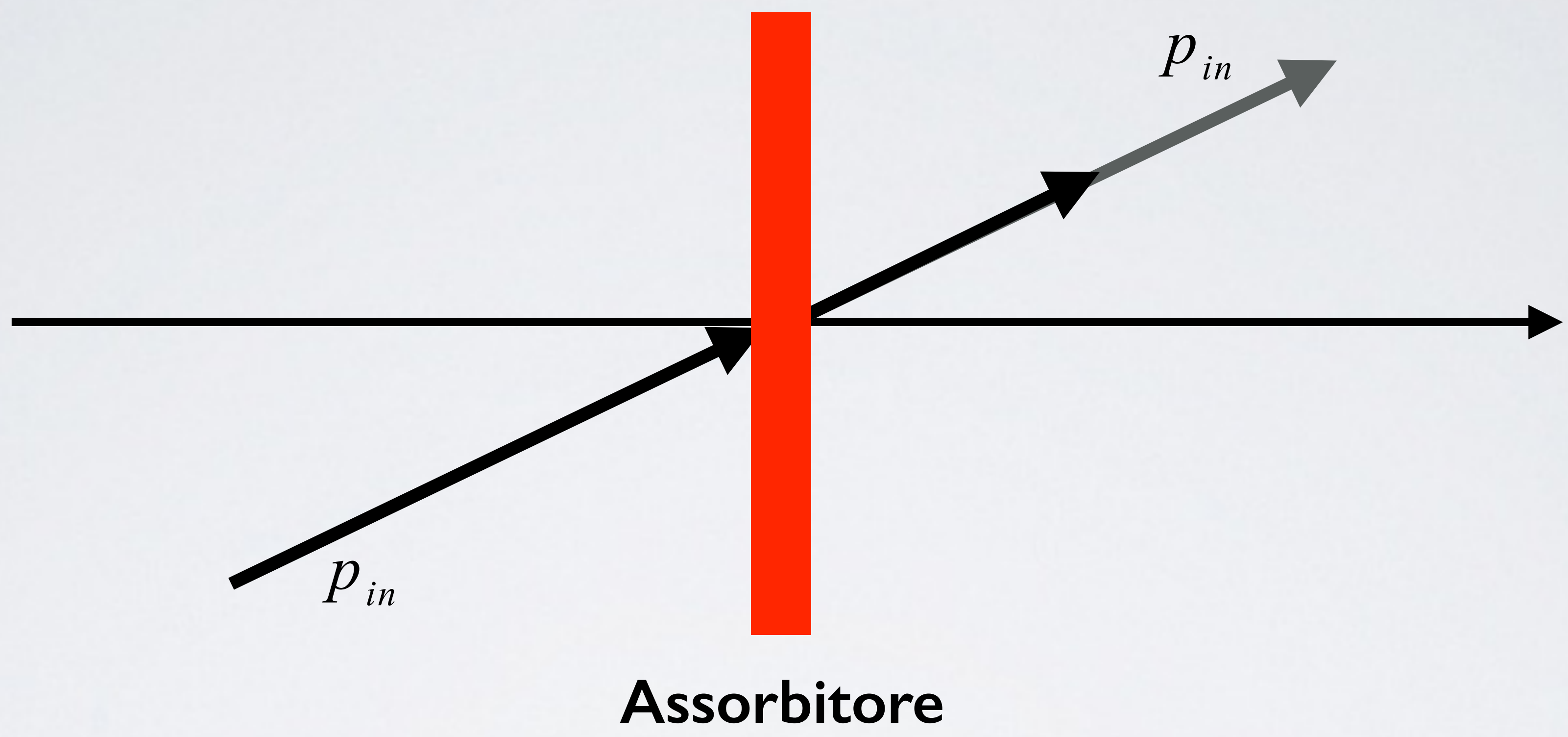
Parameter	Higgs Factory	1.5 TeV	3.0 TeV
Ecom (TeV)	0.126	1.5	3.0
Avg. Luminosity (10	0.008	1.25	4.4
Beam energy spread (%)	0.004	0.1	0.1
Circumference (Km)	0.3	2.5	4.5
# of IPs	1	2	2
Repetition Rate (Hz)	15	15	12
BetaFunction @ IPs	1.7	1	0.5
# Muons/Bunch (10	4	2	2
# Bunches/Beam	1	1	1
Norm. Transverse Emittance (mm-rad)	0.2	0.025	0.025
Norm. Longitudinal Emittance (mm-rad)	1.5	70	70
Proton Driver Power (MW)	4	4	4

MUON COLLIDER LAYOUT

A new FAST cooling technique is necessary

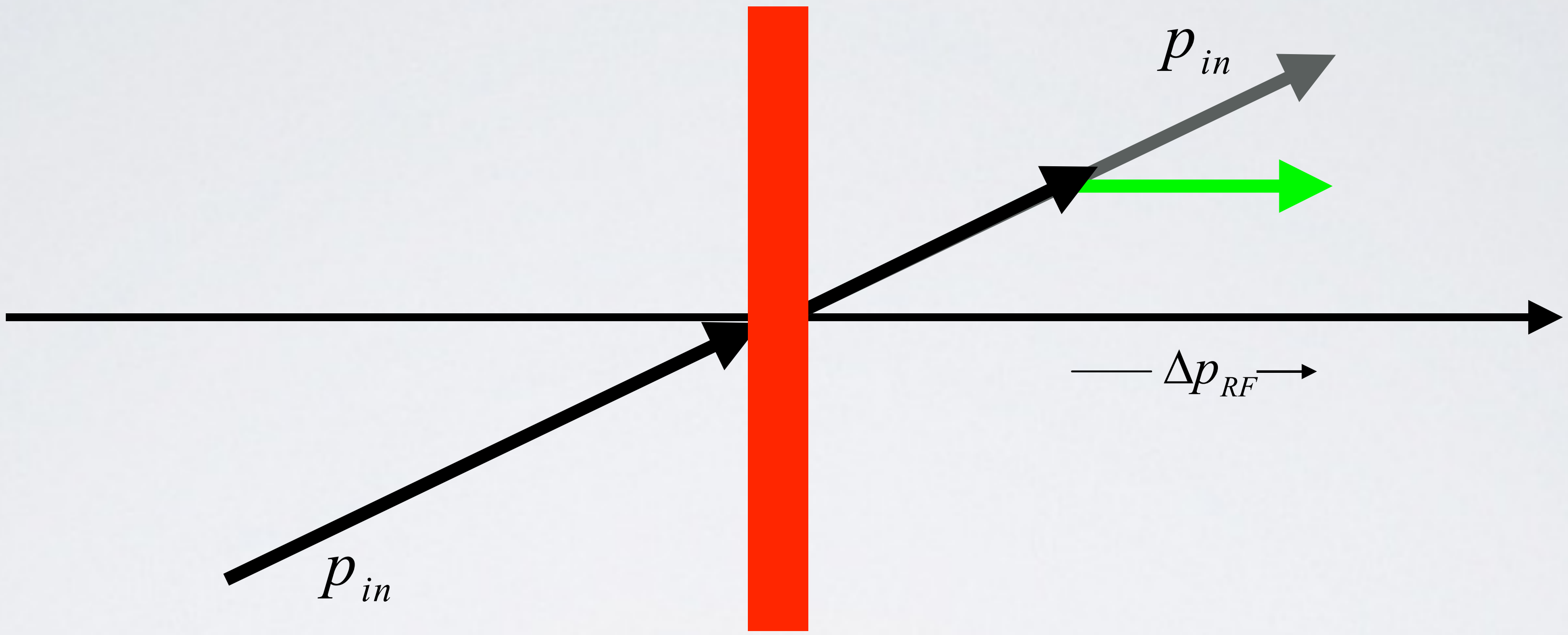


TRANSVERSE IONIZATION COOLING



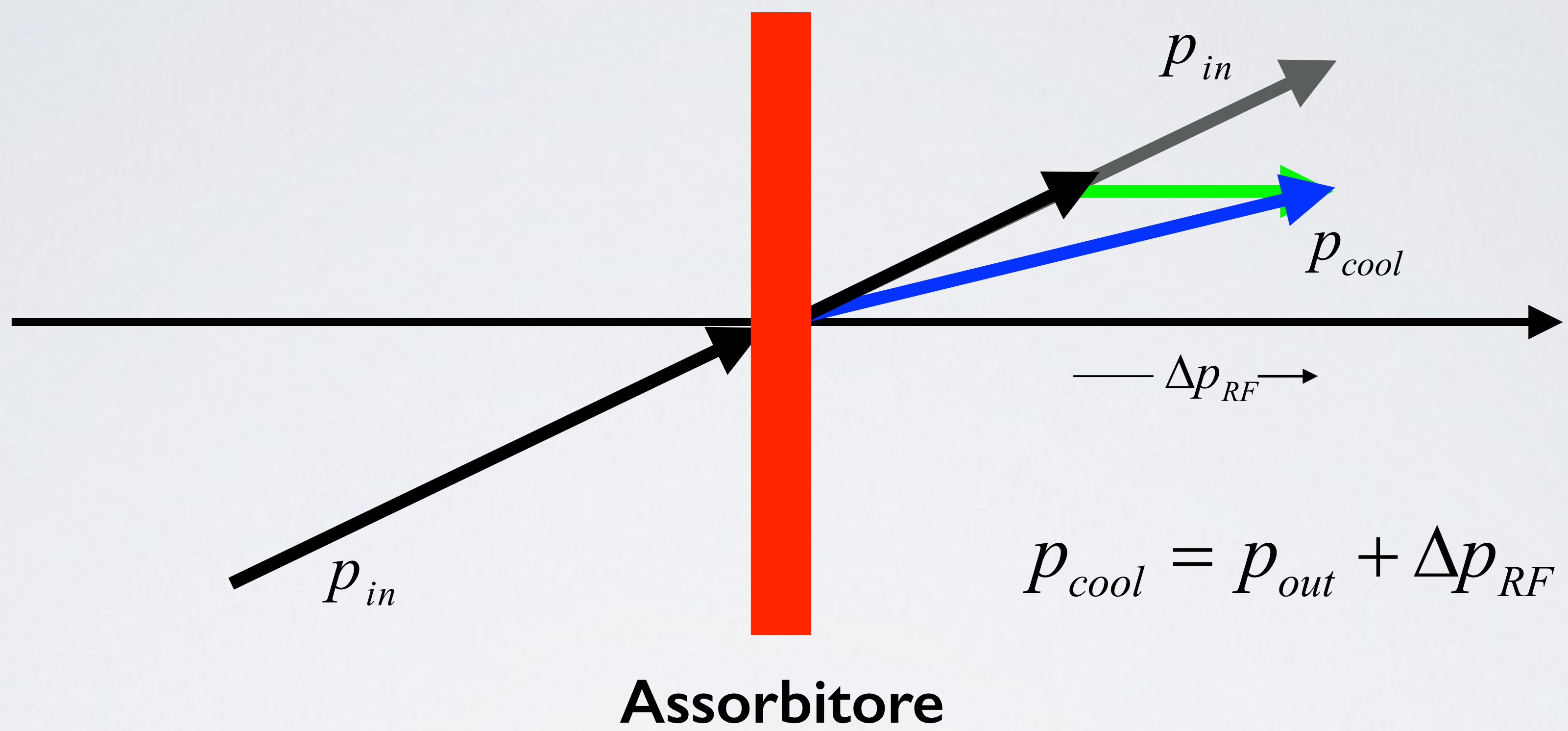
1. An absorber reduces each momentum component
2.

TRANSVERSE IONIZATION COOLING



1. An absorber reduces each momentum component
2. RF cavities reintegrates longitudinal momentum

TRANSVERSE IONIZATION COOLING



1. An absorber reduces each momentum component
2. RF cavities reintegrates longitudinal momentum
3. The result is a reduction in transverse emittance

TRANSVERSE COOLING

According to this simple explanation it looks like we can reach point-like beams in transverse plane:

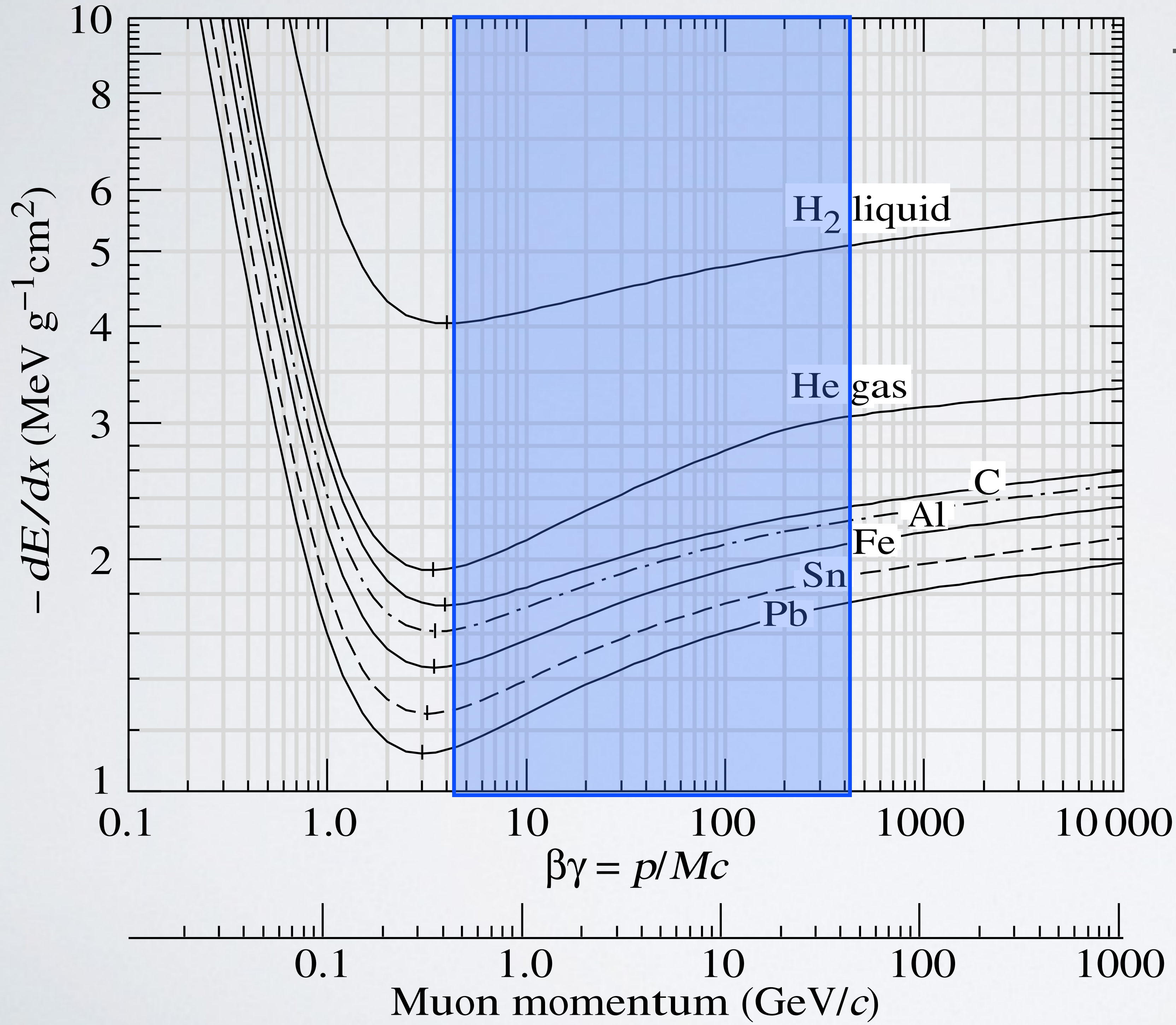
However: Cooling from contribution of two factors

Emittance Variation **=** **Ionization Cooling** **+** **Scattering Heating**

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

$$\varepsilon_n^{equ} = \frac{\beta_\perp (0.014)^2}{2\beta m_\mu \frac{dE_\mu}{ds} X_0}$$

LONGITUDIONAL COOLING

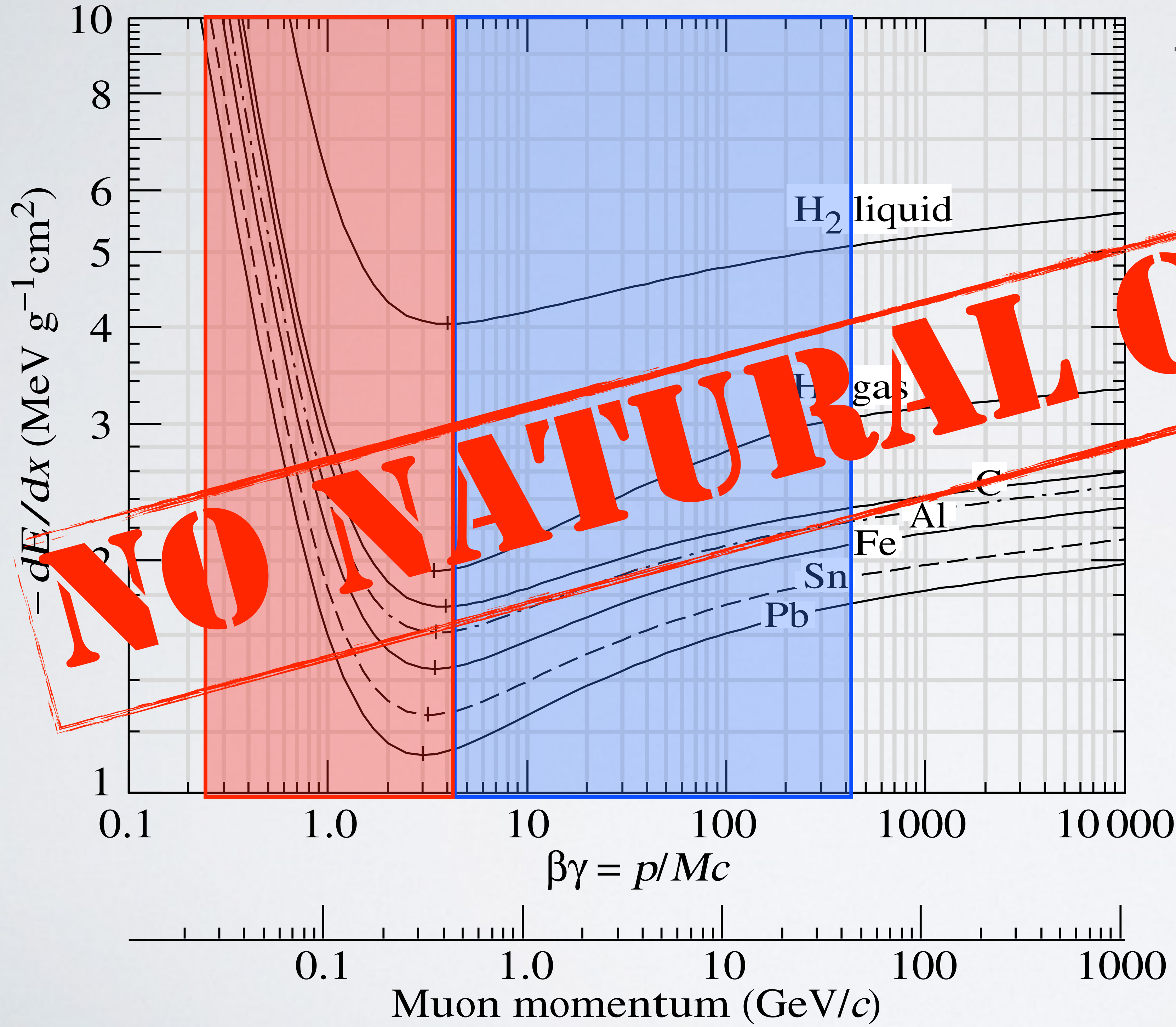


In principle

Natural cooling:

- Faster muons are slowed down the most
- BUT dE/dx is not steep enough!!

LONGITUDIONAL COOLING



In principle

Natural cooling?

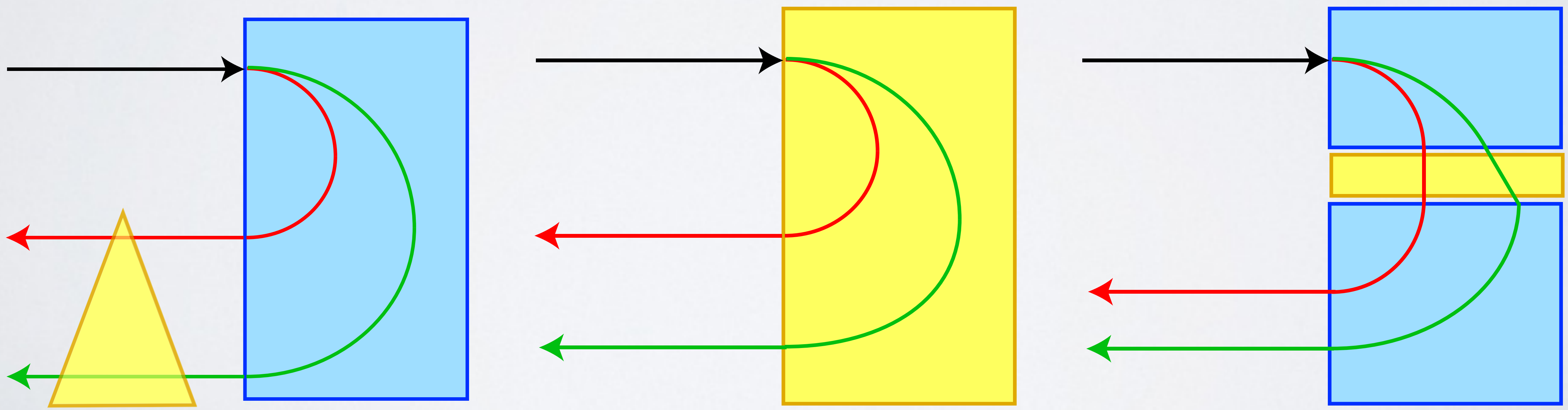
- Where slope is steep, it provides HEATING!!

LONGITUDINAL COOLING

We are smart!

Here is the idea:

- Create dispersion with magnets (dipole)
- Different trajectory for different momentum
- More absorbers on higher energy trajectories



Wedge Absorbers   Gas-Filled Magnet   Slab and Magnet

MICE

Muon Ionization Cooling Experiment:

- No experimental proof of Ionization Cooling
- MICE experiment built on purpose with following goals:
    - 200 MeV/c muons with a 25% momentum spread
    - Initial transverse emittance of 3-10 π mm rad
    - Produce a 10% emittance reduction
    - Measure it with absolute precision of 0.1%

MICE

ISIS:

- Protons at 800 MeV
- 50 Hz

Target

- Titanium
- 1 Hz
- 80g
- 1 ms spill

Selection dipoles and decay channel:

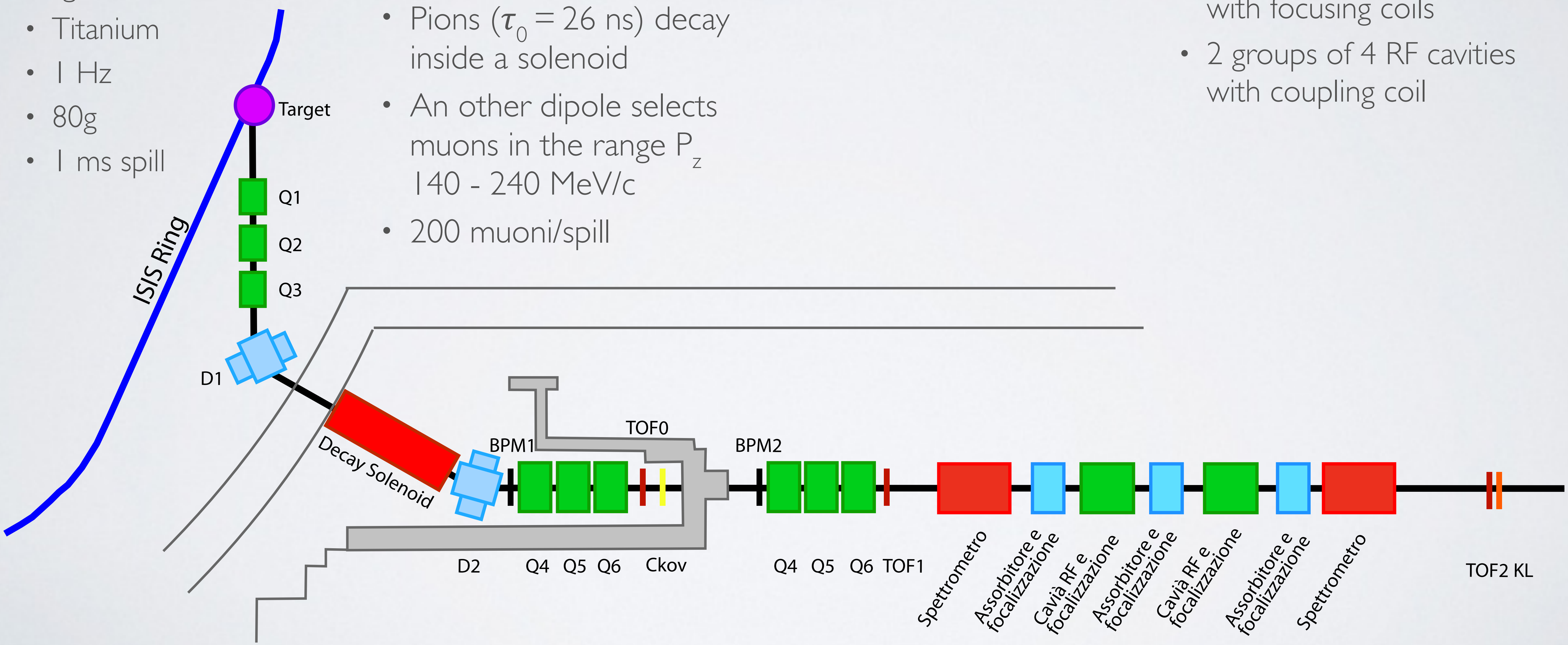
- Pions selected in the range P_z 140 - 450 MeV/c with a 5%spread.
- Pions ($\tau_0 = 26$ ns) decay inside a solenoid
- An other dipole selects muons in the range P_z 140 - 240 MeV/c
- 200 muoni/spill

Particles identification:

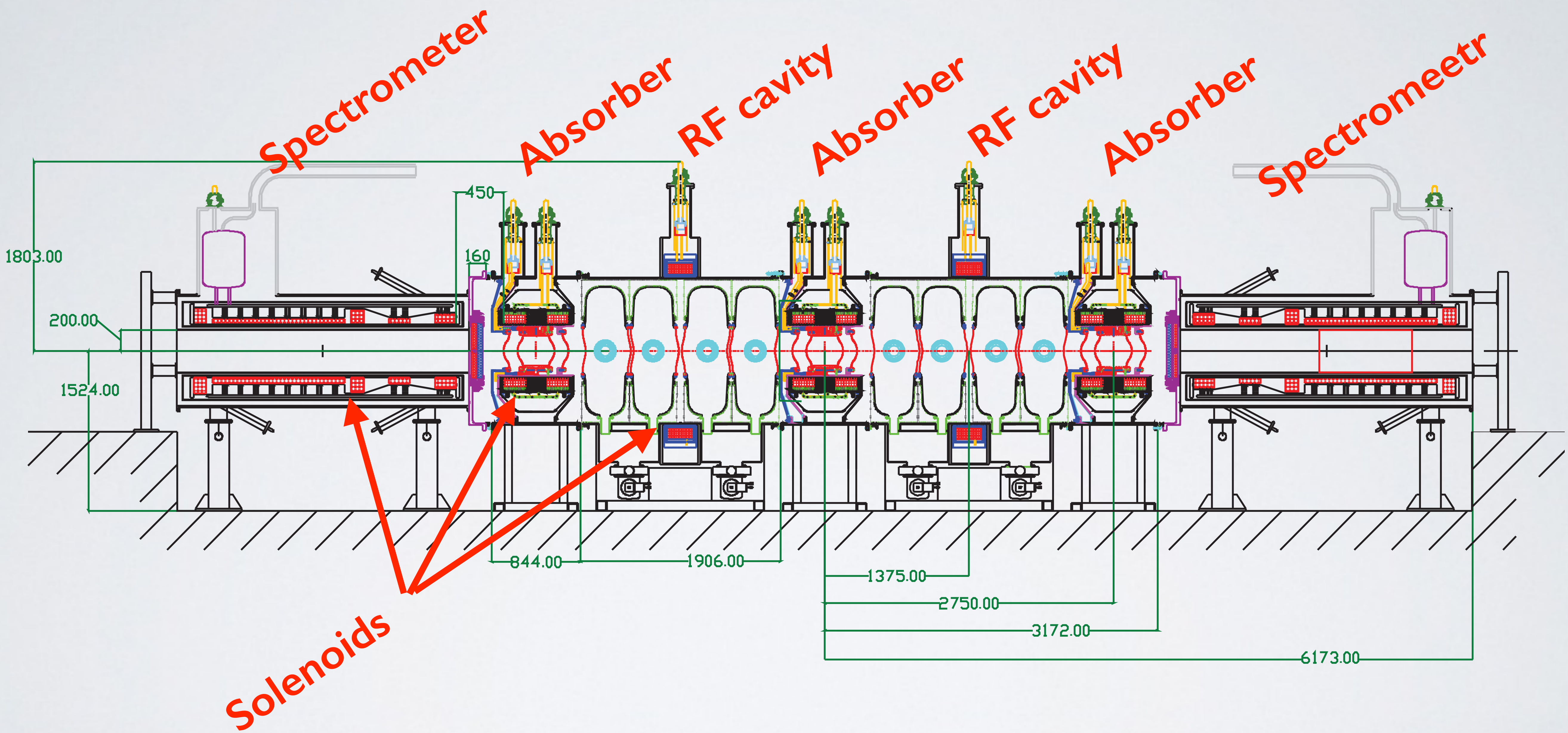
- 3 TOF
- 2 Cherenkov
- 1 Calorimeter

Emittance reduction (final configuration - 2019):

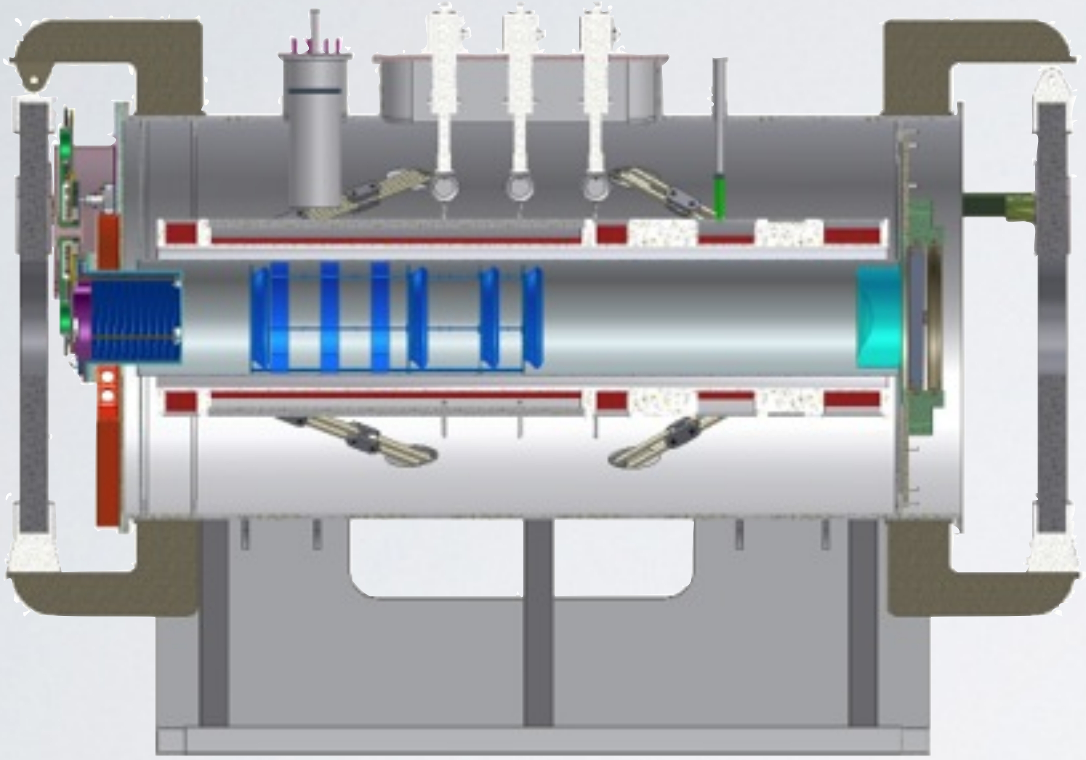
- 2 Spectrometers to measure emittance reduction
- 3 liquid hydrogen absorbers with focusing coils
- 2 groups of 4 RF cavities with coupling coil



MICE

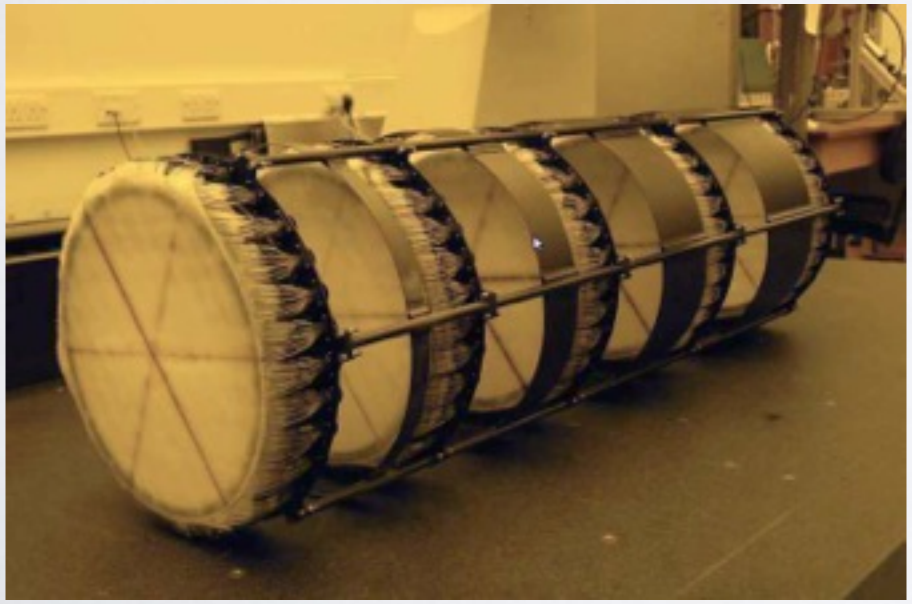

Spectrometer
Absorber
RF cavity
Absorber
RF cavity
Absorber
Spectromeetr
1803.00
450
160
200.00
1524.00
844.00
1906.00
1375.00
2750.00
3172.00
6173.00
Solenoids

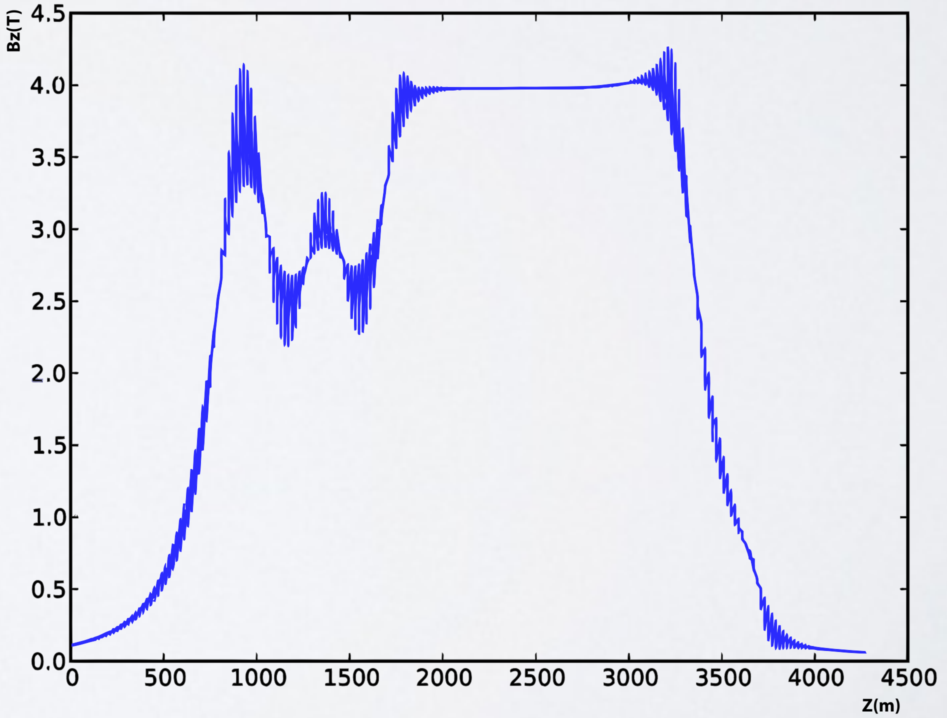
MICE: TRACKER



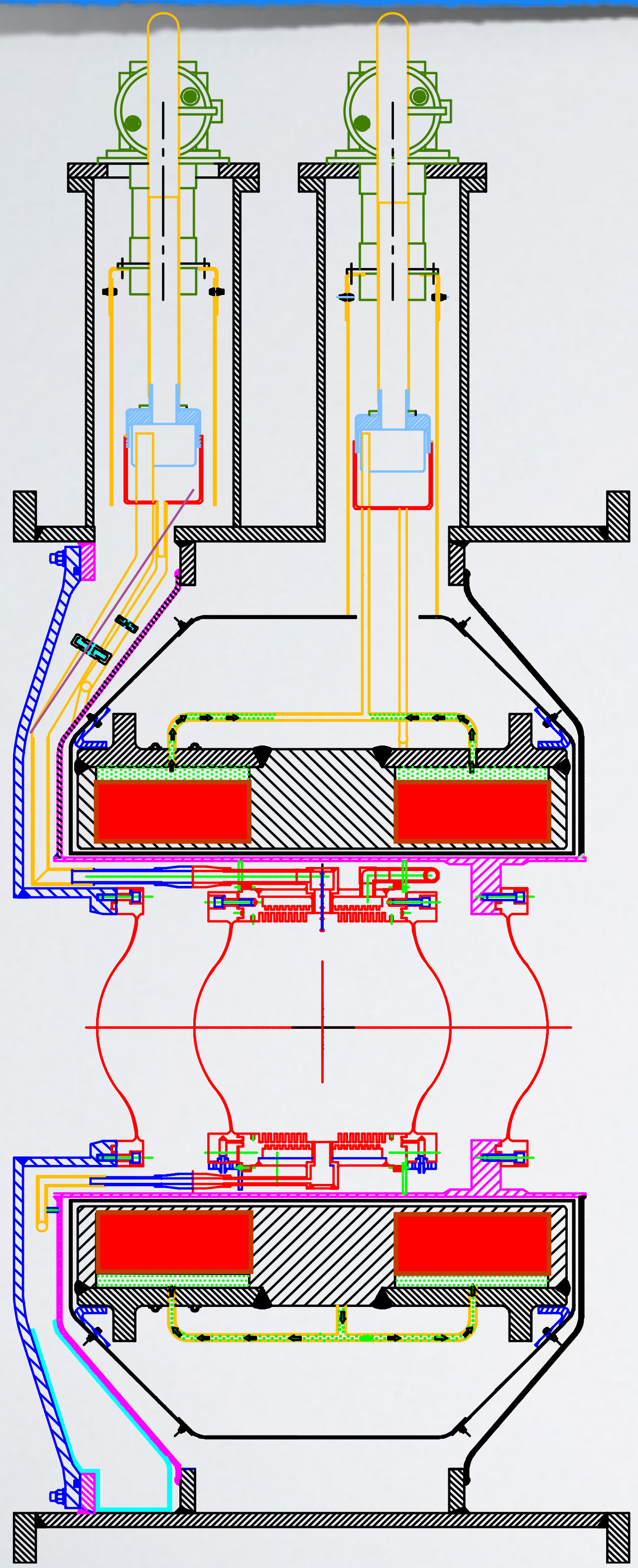
Tracking system

- 5 layers of scintillating fibers (1.6 mm resolution, 30 cm diameter)
- 5 solenoidal coils
- Emittance measurement from trajectory of each single muon



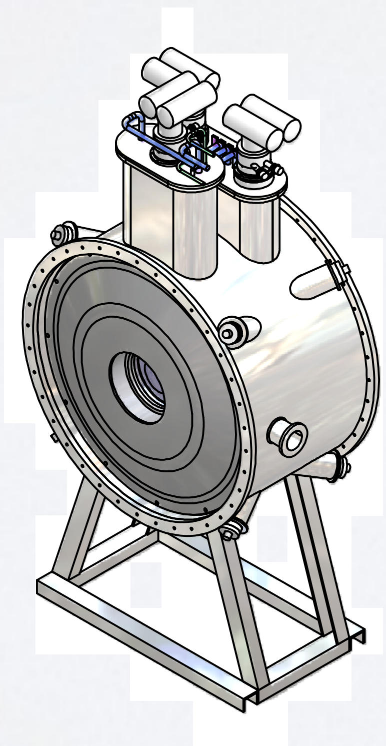


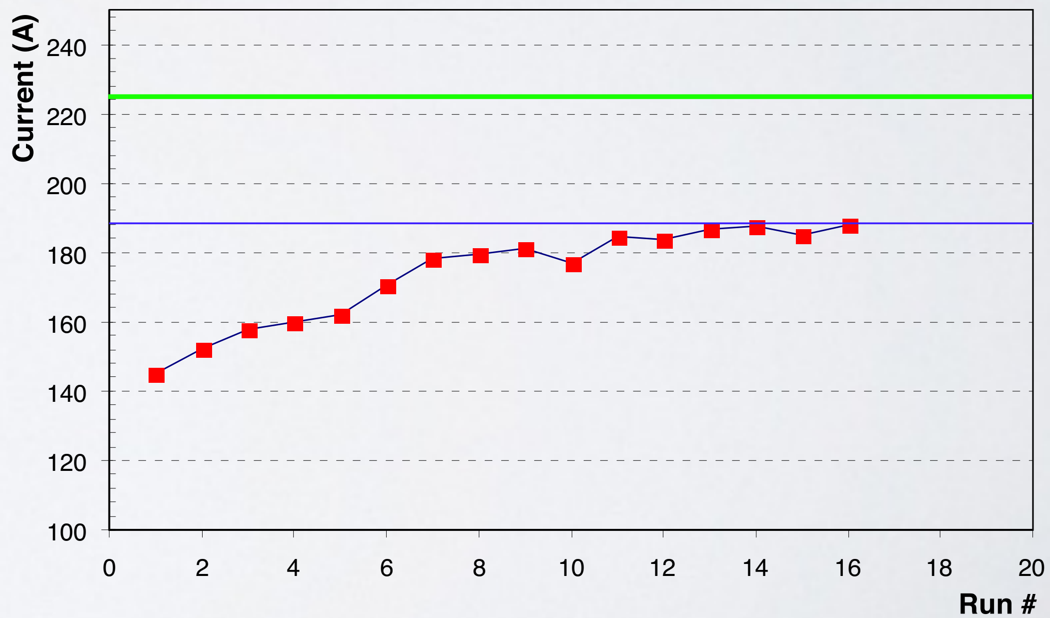
MICE: AFC



Absorber and Focusing Coil

- 21 liters of liquid argon @ 15K
- 17000 liters @ Room Temperature
- Safety issues: containment vessel
- Couple of focusing coil to reduce beam size
- Troubles to reach design field in flip mode. Tests on second absorber will clarify the problem

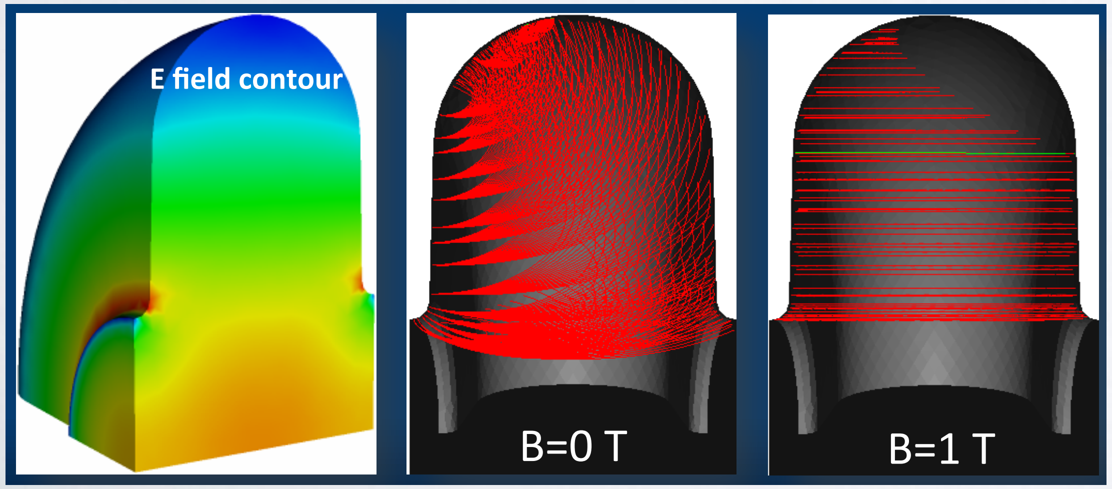


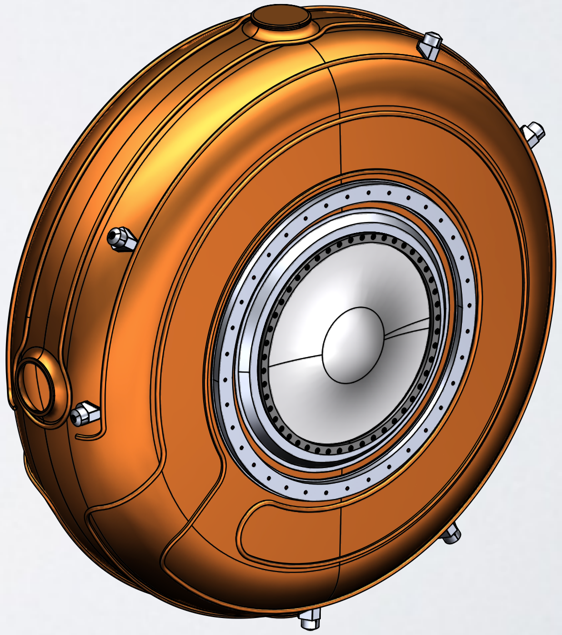


MICE: RFCC

Radio Frequency and Coupling Coil

- 4 cavities @ 201.25 MHz
- 1 huge focusing solenoid (5 T)
- Vacuum environment (10^{-8} torr)
- Baking at 100 C
- Cavity sealed with thin beryllium windows to increase Q
- Several issues with multipacting in B field





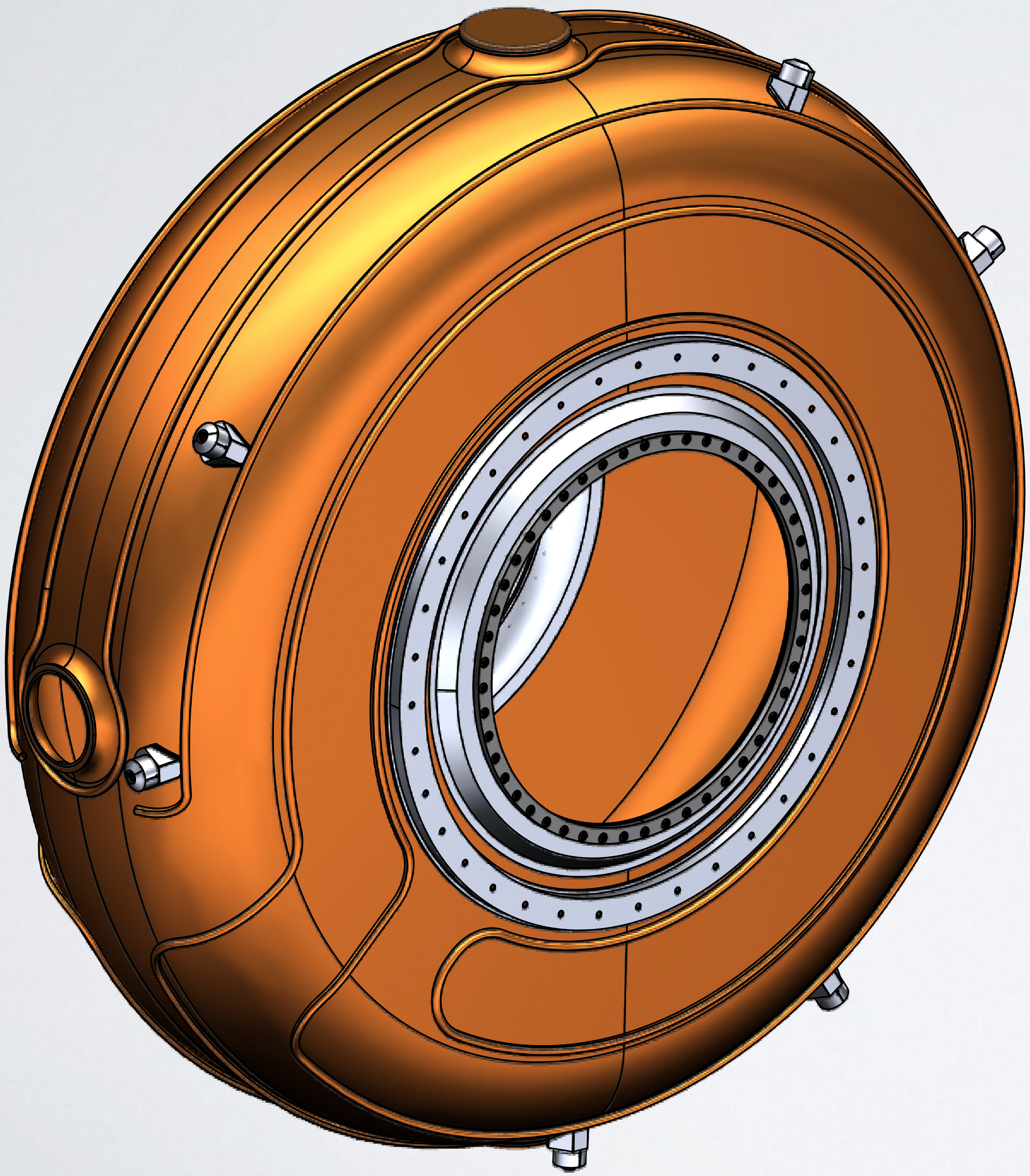
MICE OPERATIONS

- 200 muons/spill
- Selection of 30 muons/spill in 3 ms spills
- Repetition at 1 Hz
- Total statistics per configuration $100 \cdot 10^3$ muons

Major limitations coming from:

- Radiation in the ISIS
- Limited RF power and repeatability
- Detector saturation

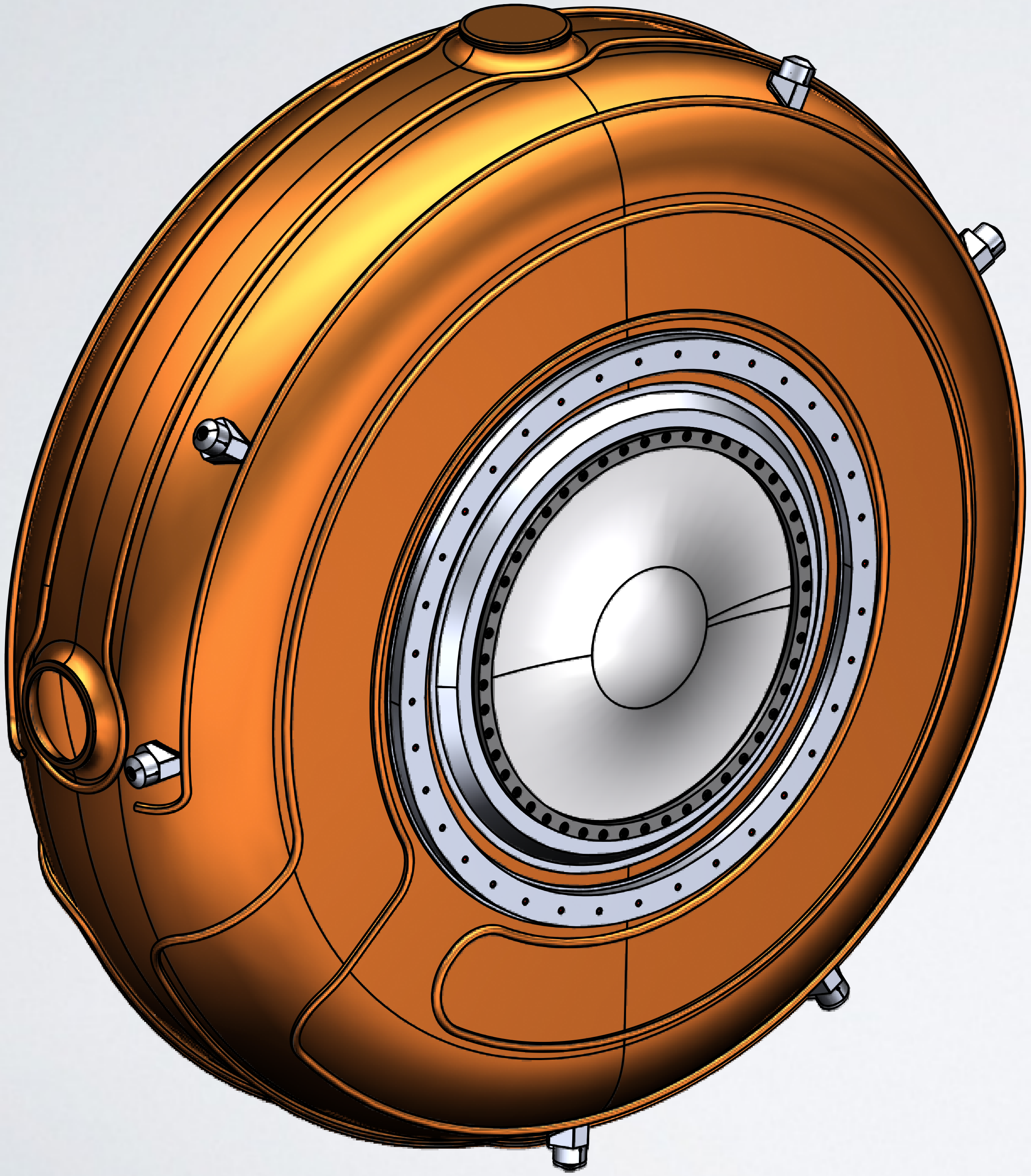
RF CAVITY



Caratteristiche:

- 201.25 MHz
- Q= 53500
- 3ms RF pulses every 1Hz
- RF: 8 MV/m, 1MW
- Huge beam openings for high emittance beam (d = 42cm)
- Gap 42cm
- Diameter 1m
- 2 coupling ports and 2 instrumentation ones
- Copper cooling lines

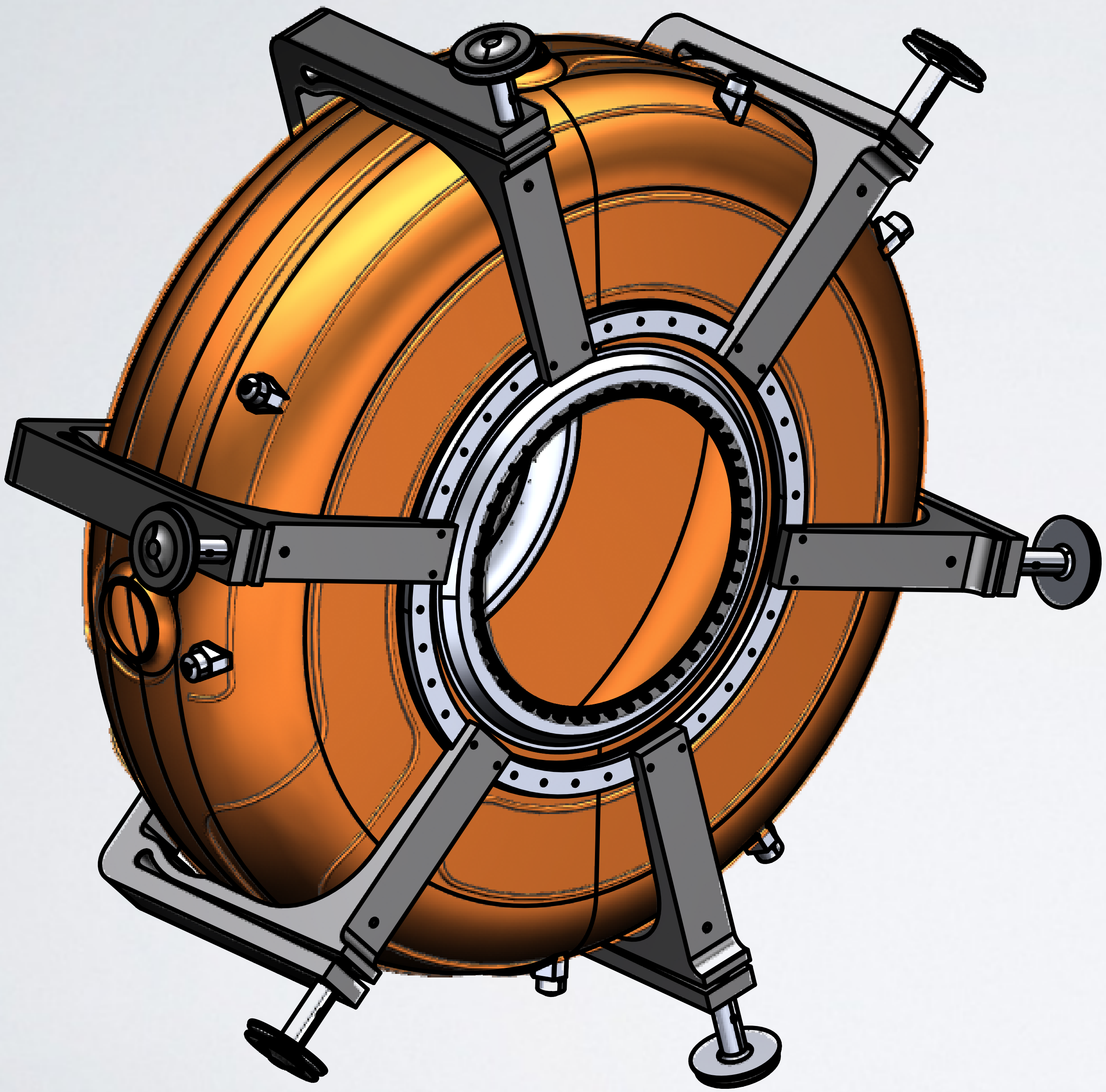
RF CAVITY



Beryllium windows:

- Thin (0.38 mm) to avoid beam perturbation
- Each cavity is independent
- Doubling od shunt impedance (22 MΩ/m)
- Fragile: unable to sustain any differential pressure
- Need for a vacuum vessel

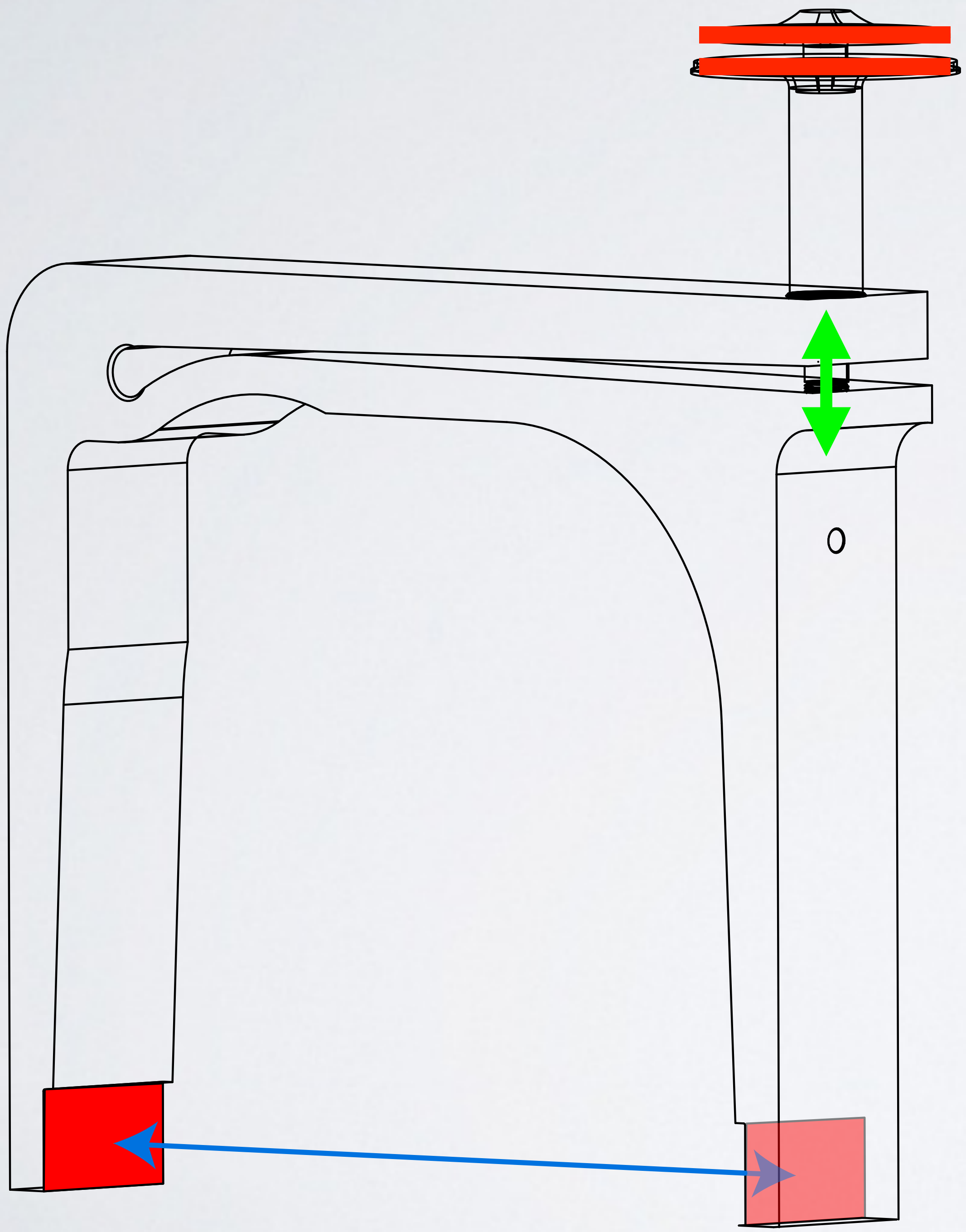
TUNING SYSTEM



Tuning system:

- 6 stainless steel forks
- Actuated by 6 pistons connected in parallel
- Operational interval: 0-100 PSI in compression and expansion

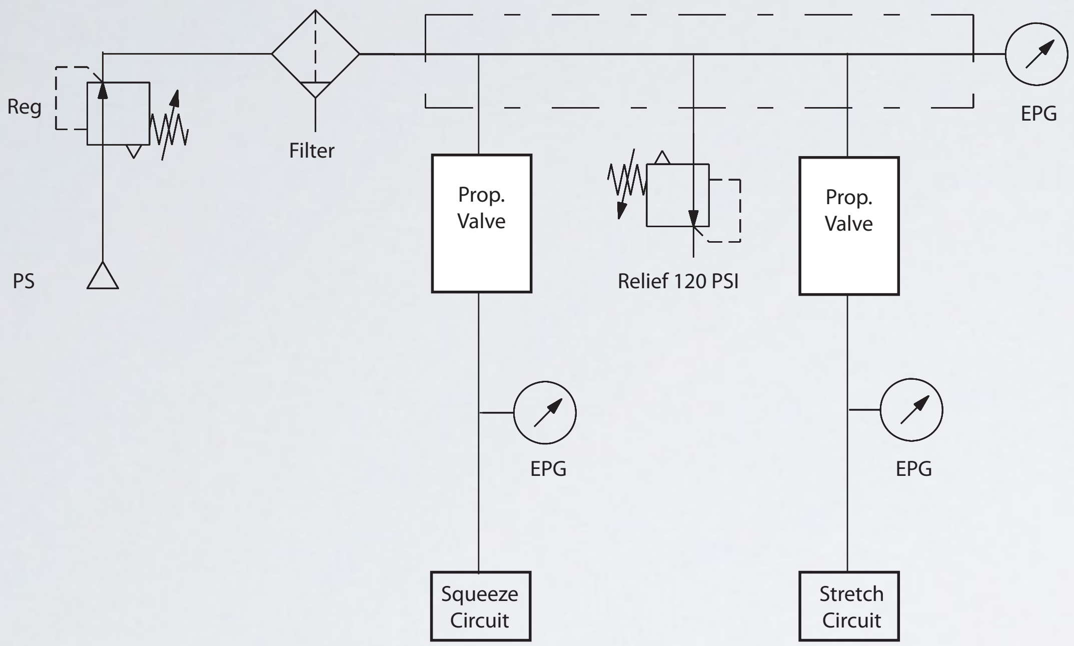
TUNING SYSTEM

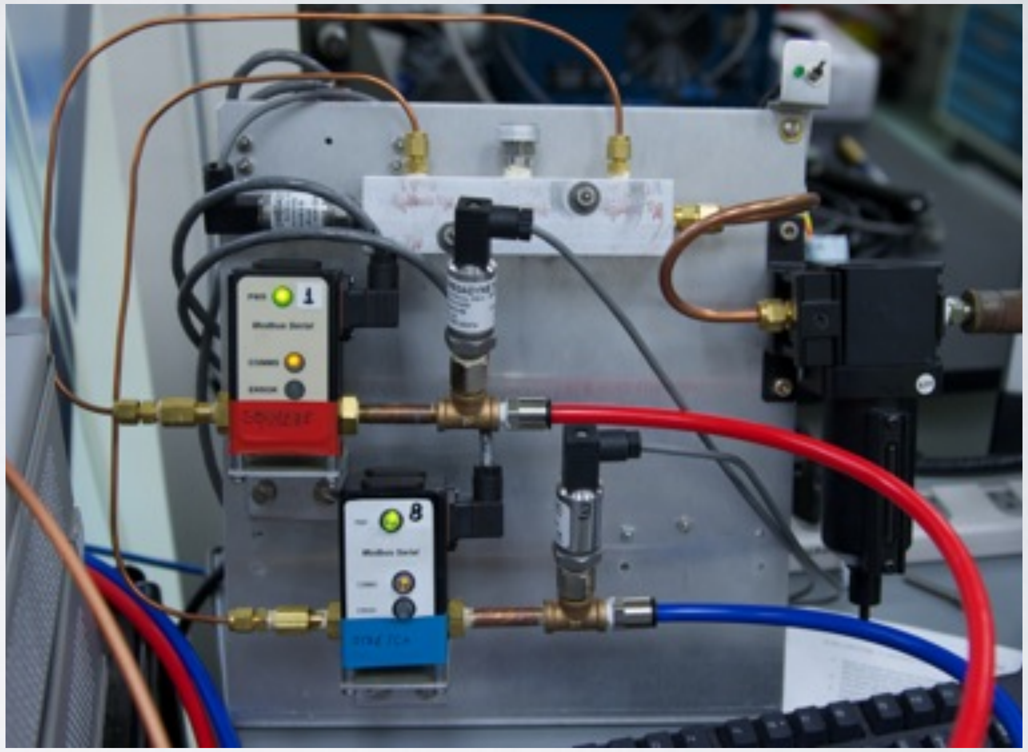


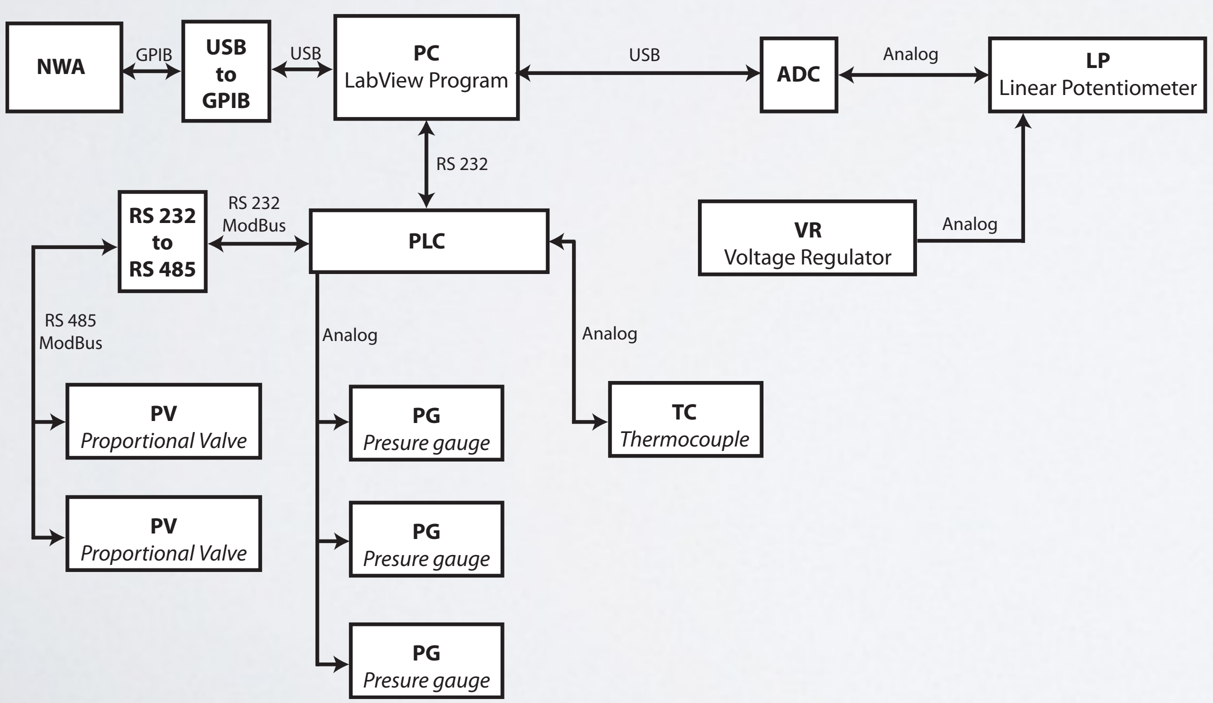
How it works:

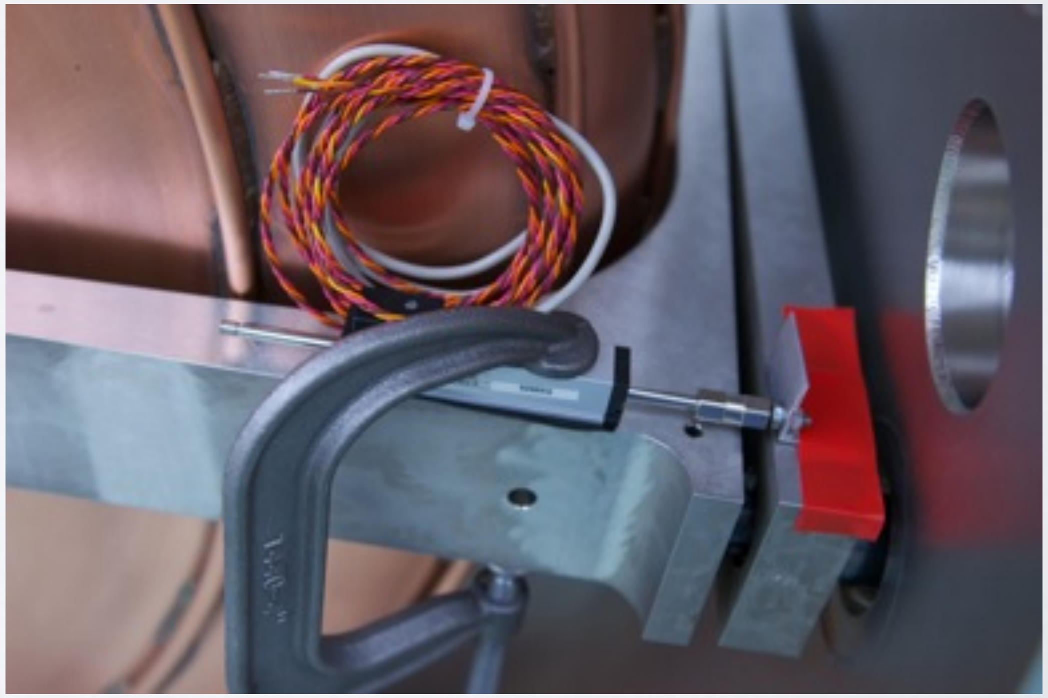
- Pressurisation of 2 pistons
- Variation of fork gap (green)
- Cavity compression or expansion (blu)

PNEUMATIC AND ELECTRONIC CONTROLS

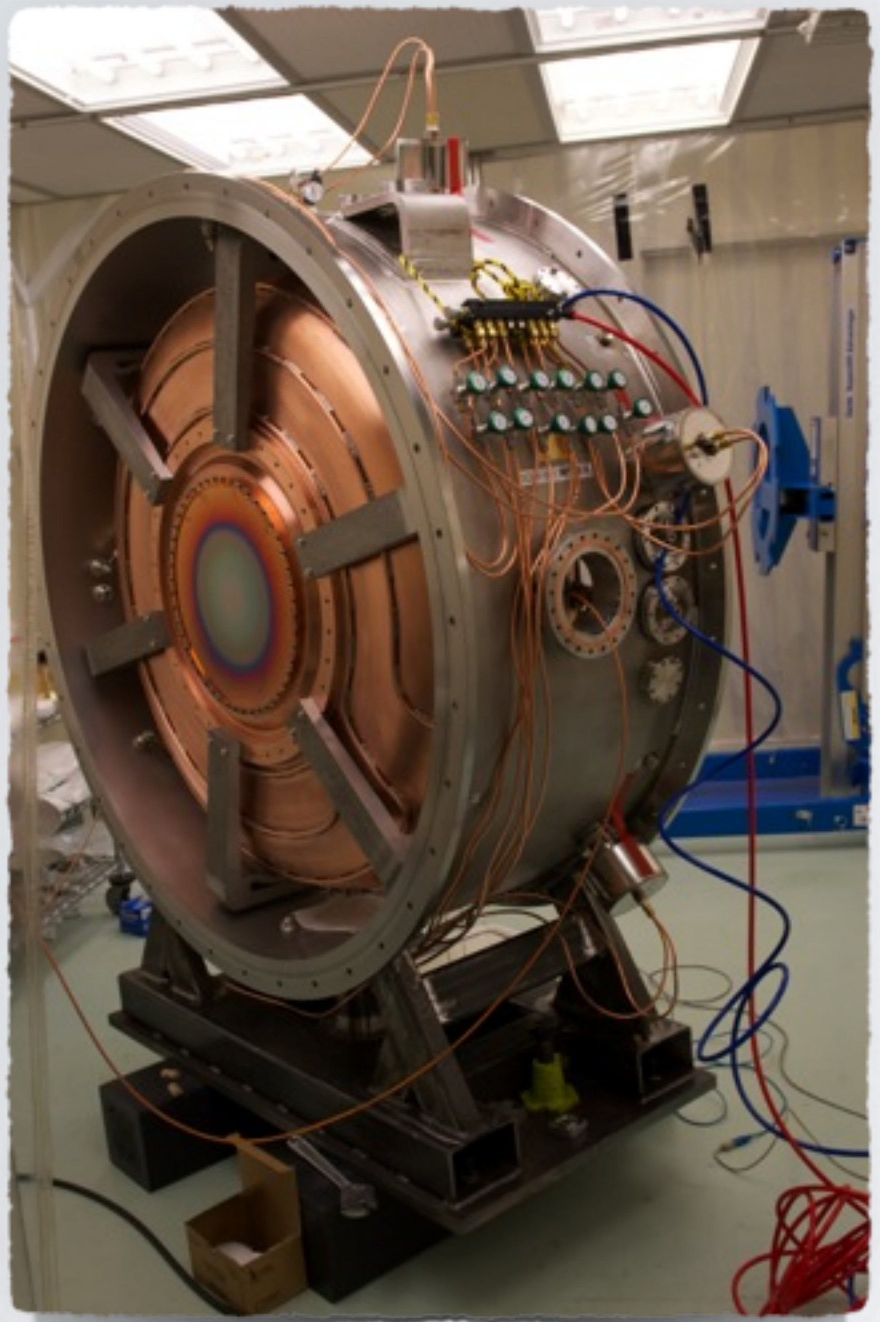




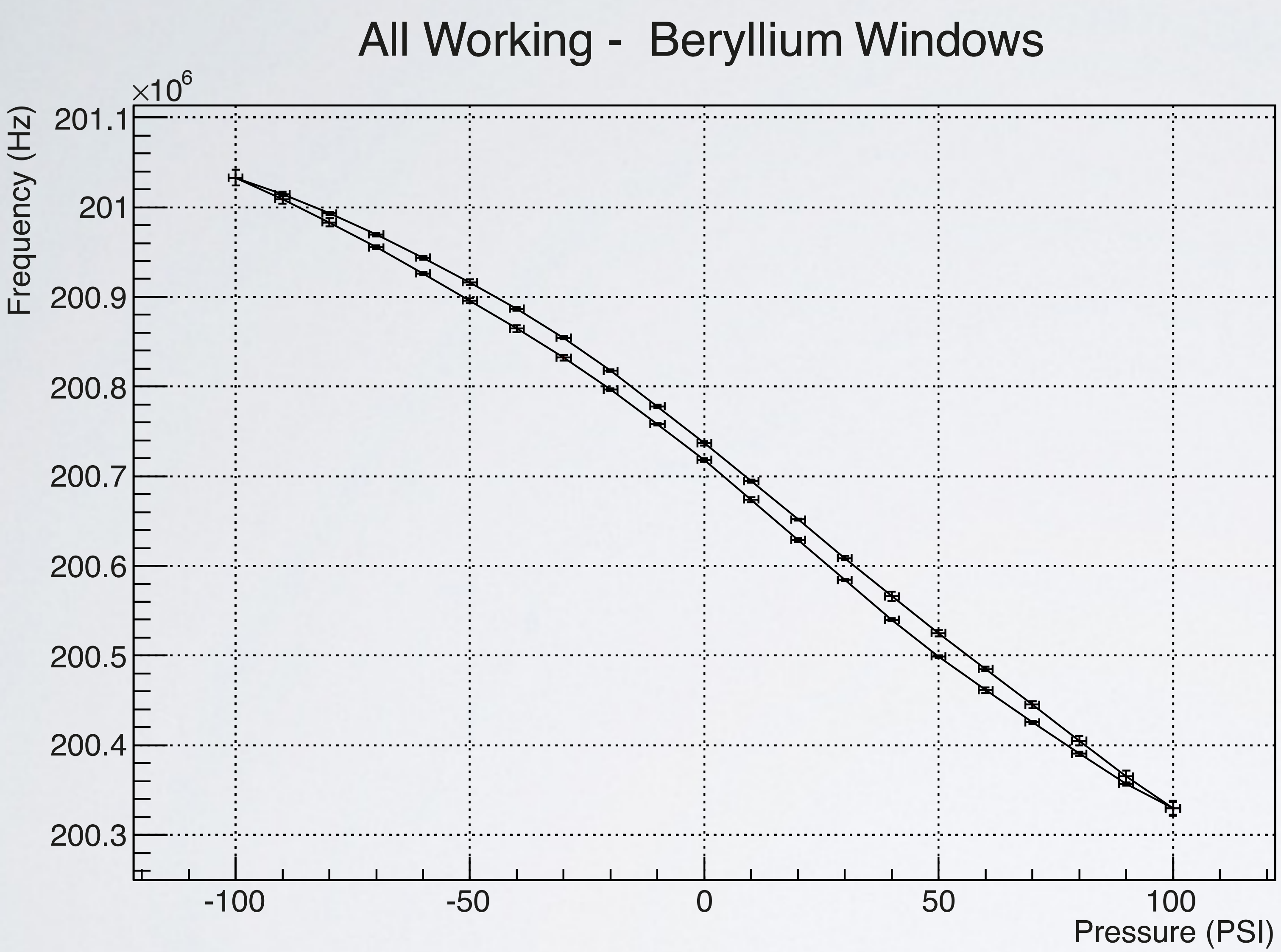




ASSEMBLED SYSTEM



TUNER TRANSFER FUNCTION

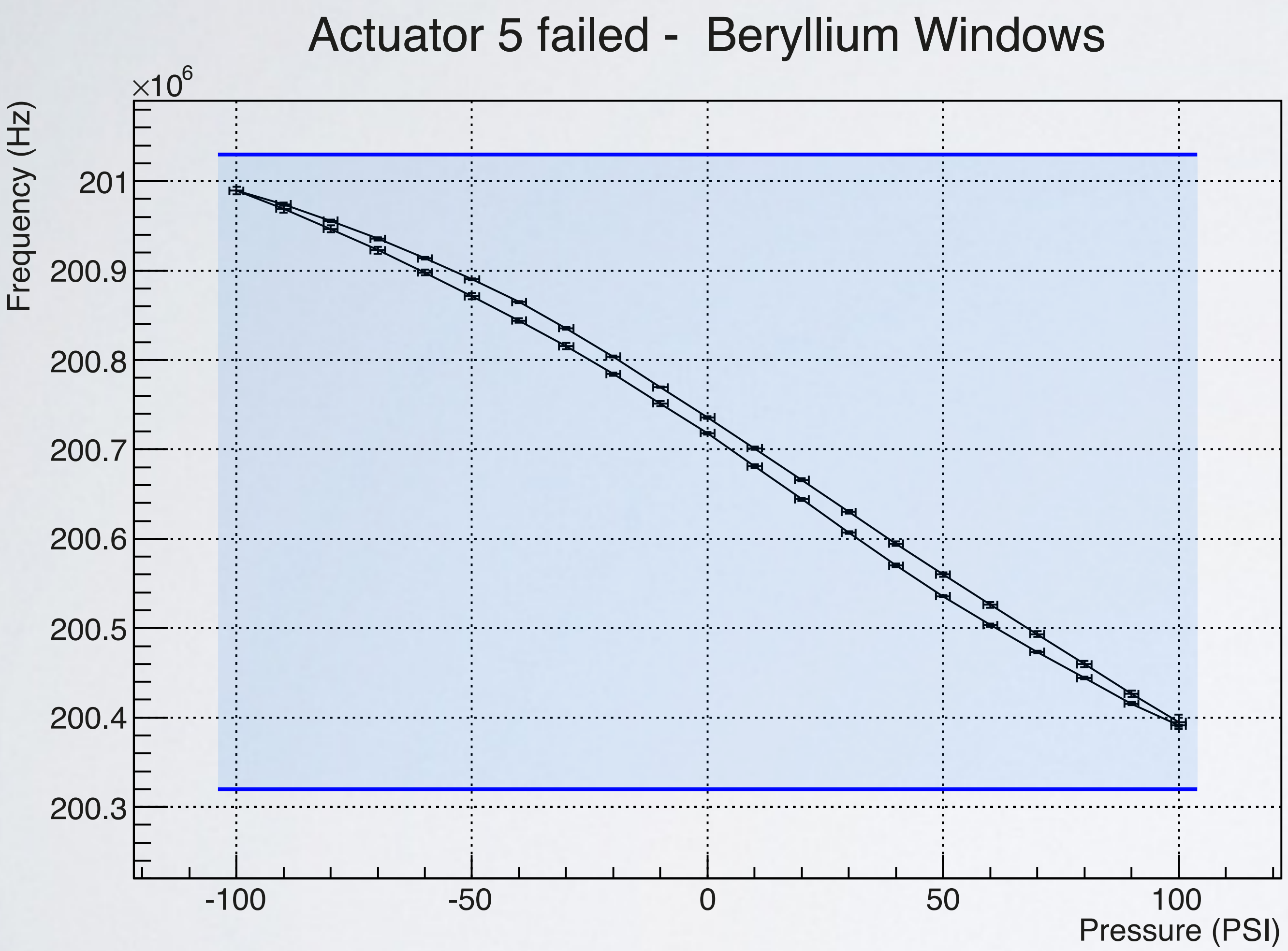


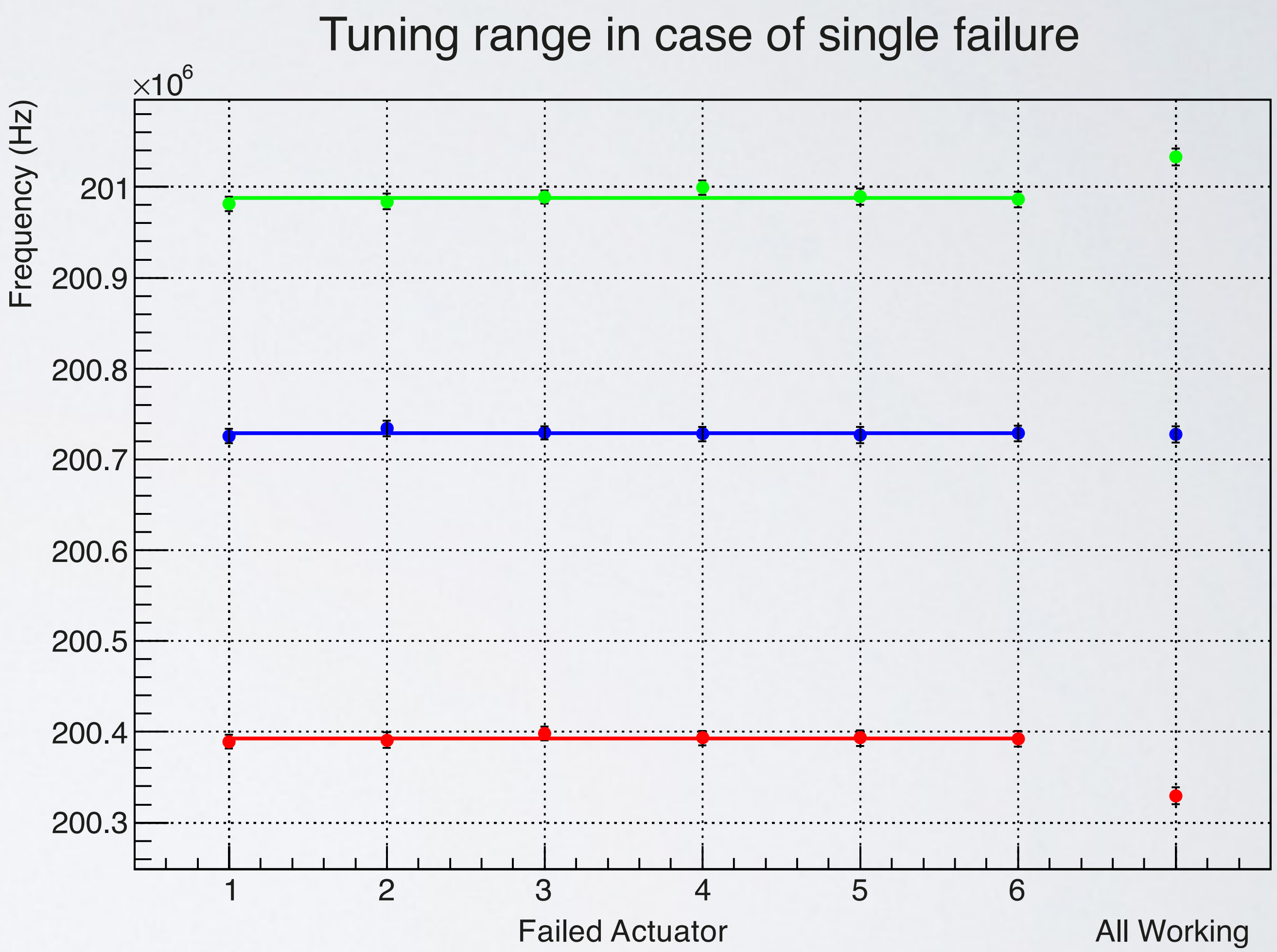
Resonant Frequency	200.727±0.009MHz
Maximum Frequency (@-100PSI)	201.033±0.003MHz
Minimum Frequency (@100PSI)	200.329±0.002MHz
Q	41820 ± 1045

- Q is lower that design one, but similar to prototype cavity
- remarkable hysteresis cycle: (20 KHz)
- Saturation at negative pressures

IN CASE OF FAILURE

Tuning with a failed actuator





Cavity is still operable but with a tuning range reduced of 100 KHz

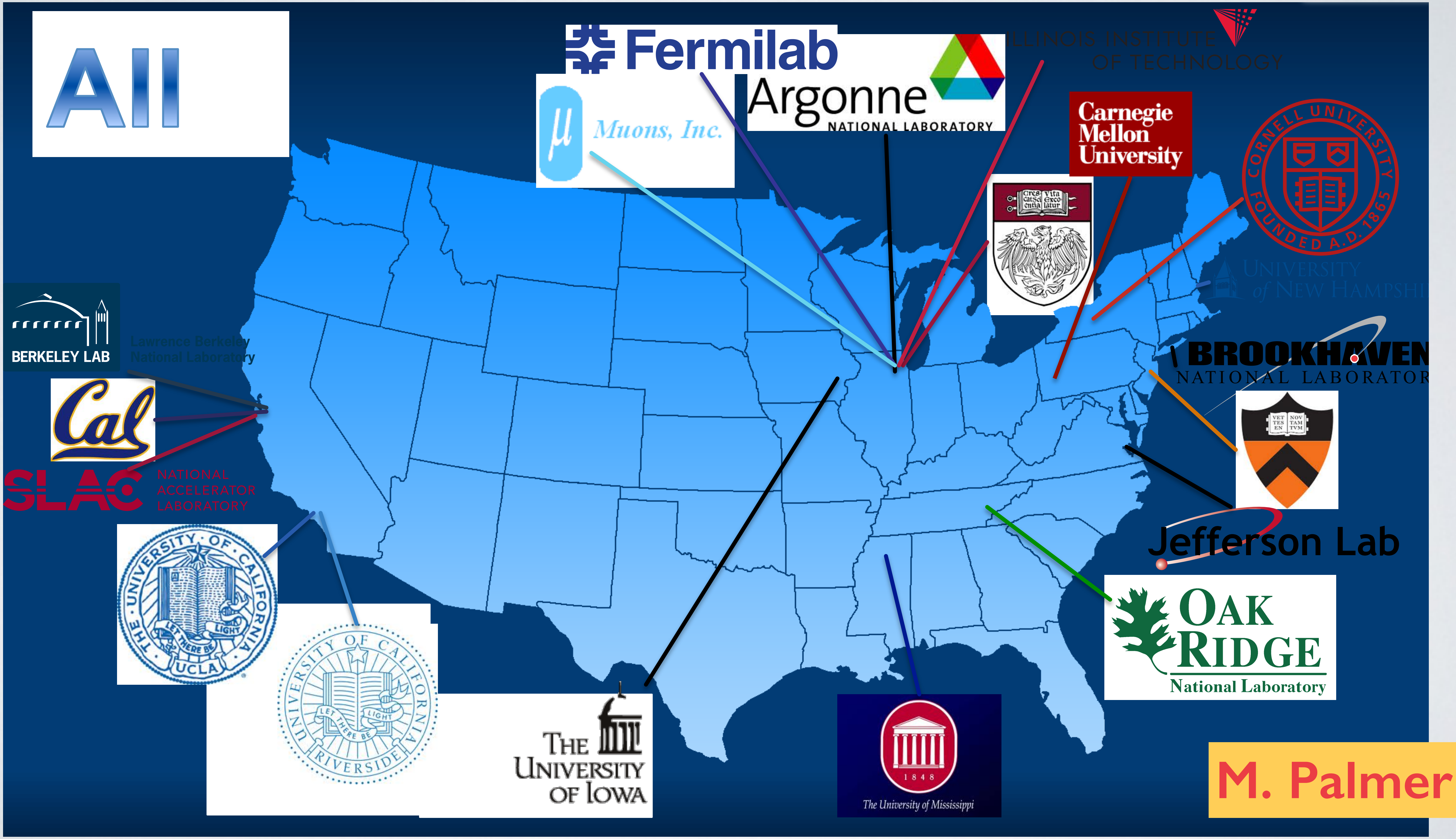
MAP

Who is taking care of the R&D effort?

Muon Accelerator Program

- Created in 2010 to support DOE MC R&D
- Target: development of MC design
- Centred at Fermilab, participation of many institutions
- Strict collaboration with MICE

MAP COLLABORATORS



MAP TIMEFRAME

M. Palmer

Feasibility Assessment: Phase I

FY13 – FY15:
- Identify ***baseline*** design concepts
- Identify high leverage ***alternative*** concepts
- Identify key engineering paths to pursue:
  - RF
  - High Field Magnets
- Develop critical engineering concepts (eg, 6D Cooling Cell)
- Support major systems tests
  - MICE Step IV
  - MICE RFCC construction & testing

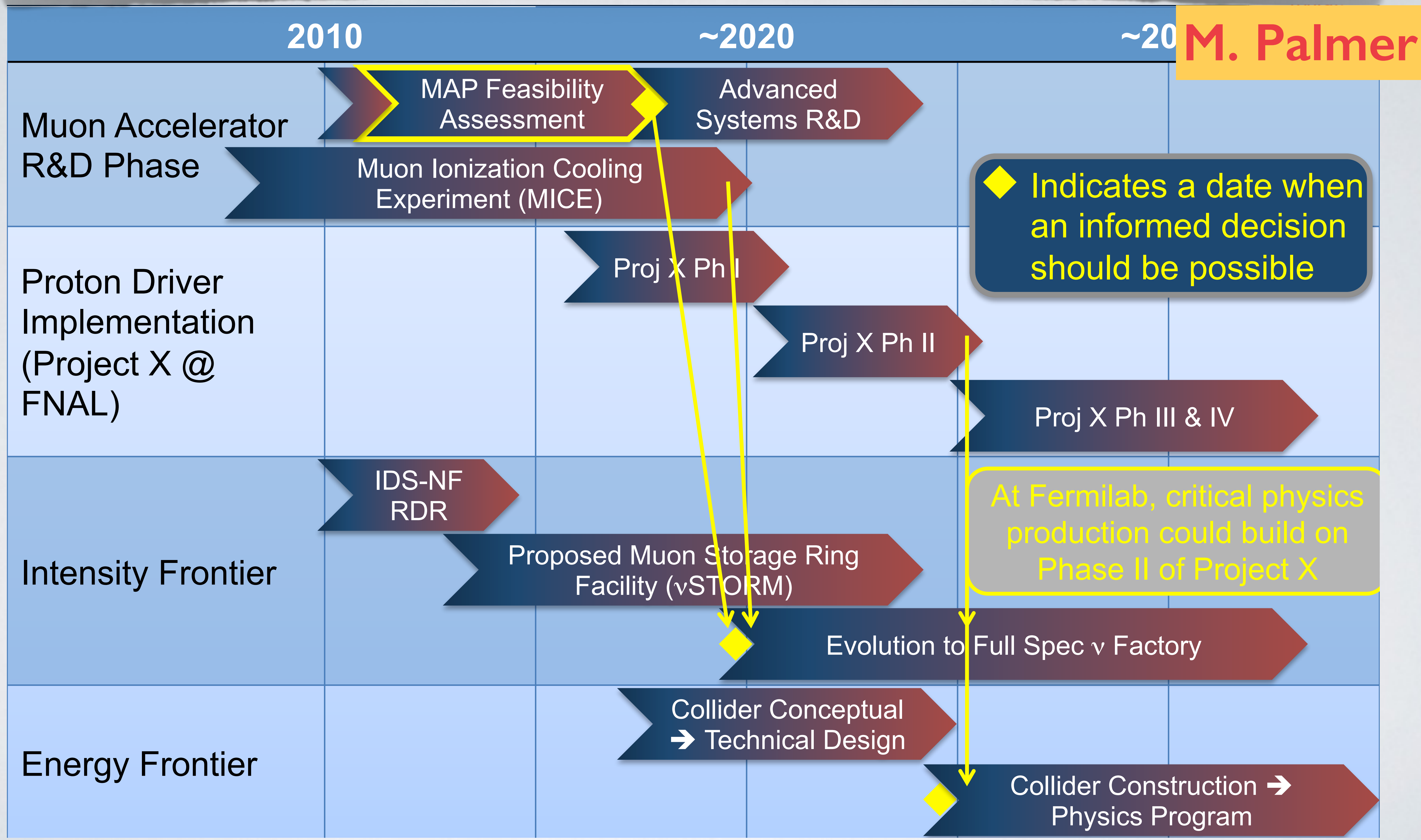
Feasibility Assessment: Phase II

FY16 – FY18:
- Technical demonstration of critical ***baseline*** concepts
  - eg, 6D Cooling cell
- Pursue high leverage ***alternative*** concepts
- Assess technical and cost feasibility of ***baseline*** concepts
- Support major systems tests
  - MICE Step V/VI
  - 6DICE planning

Beyond the Feasibility Assessment

FY19 →
- Plan contingent on the feasibility assessment!
- Can we launch the design effort towards a staged implementation of a NF & MC?
- Advanced systems tests
  - 6DICE?
  - Support physics?

MAP TIMEFRAME



IN MY OPINION …

DISCLAIMER:

Following slides express speaker's very personal point of view!

IN MY OPINION ...

PROs:

Many good aspect in MC, MAP and MICE:

- Thrilling search for new technology
- New and unexplored regions of physics colliding particles never collided before
- Considerable development in accelerators technology
- Related industrial/technical benefit from new technologies (Pressurised RF, absorbers, 20T magnets)
- Good DOE support compared to other projects (still small support but with steady increases)
- Young environment with LOT of space for young and motivated people. You CAN take your space!

IN MY OPINION ...

CONs:

Other less motivating aspects in MC, MAP and MICE:

- Low priority projects for every lab (RAL, Fermilab AD etc.)
    - Frequent delays for simple reasons like absence of mechanical support
    - Confused and inefficient technical crew sharing among tons of projects
    - Unbalance between technical (shared) people and physics (100% MC) resulting in considerable dead time for the first

IN MY OPINION ...

<u>CONs:</u>

Other less motivating aspects in MC, MAP and MICE:

- Fragmentation between many minors institutions
  - Remarkable errors caused by miscommunications and lack of global hierarchy
- Lack of motivation due to slow response of the program to stimuluses:
  - Departure of "good cookies"
  - Gathering of less motivated physicist

IN MY OPINION ...

POSSIBLE SOLUTION:

Extreme need for a motivated institution or group:

- Muons need to be it’s main concern
- It has to trail and coordinate the whole muons effort whether it’s the realisation of a MC or simply the proof of principle of ionisation cooling

The Muon Collider looks so cumbersome. Will we be really able to build it?

What would Ernest Lawrence Berkeley have said about the LHC?

THANK YOU!