Muon Collider Progress and Prospects

Rolland P. Johnson
Muons, Inc. (http://www.muonsinc.com/)

Analytical calculations, numerical simulations, and experimental measurements are coming together to make a strong case for a series of machines to be built, where each one is a precursor to the next, with its own unique experimental and accelerator physics programs.

In less than 5 years we can know how to design an energy-frontier muon collider with $E_{com} > 4$ TeV and $L > 10^{34}$ and we can be building the Project-X proton driver as its first essential component.

Muons do not radiate like electrons so beams pass many times through each RF cavity. 4-km of linac can accelerate both signs of muon to achieve these parameters. This collider can fit on the Fermilab site!

A Scenario for: High-Energy High-Luminosity Muon Colliders

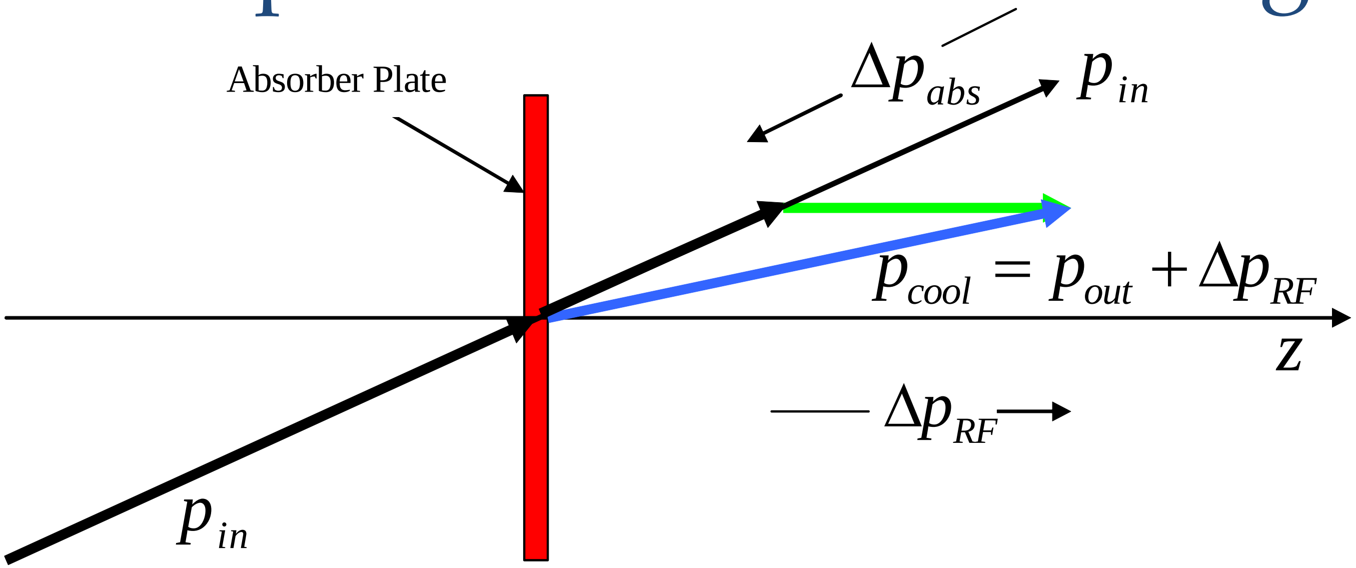
- precision lepton machines at the energy frontier
- achieved in physics-motivated stages that require developing inventions and technology, e.g.
  - intense proton driver (CW Linac, H- Source, Laser Stripping)
  - stopping muon beams (HCC, EEX w Homogeneous absorber)
  - neutrino factory (HCC with HPRF, RLA in CW Proj-X)
  - Z' factory (low Luminosity collider, HE RLA)
  - Higgs factory (extreme cooling, low beta, super-detectors)
  - Energy-frontier muon collider (more cooling, lower beta)

Progress on all MC Components

- Ionization Cooling is critical. Some recent advances:
  - RF cavities pressurized with hydrogen – experiments verify models
  - Helical Cooling Channel (HCC) for 6D emittance reduction- theory
  - Helical solenoid (HS) invention,
  - NbTi and YBCO HTS HS magnet prototypes
  - HCC simulations show 6D $\varepsilon_{initial}/\varepsilon_{final}\sim 3\text{x}10^5$ cooling, with realistic B and RF
  - MANX- 6D HS muon cooling demo experiment was proposed to Fermilab
    - MANX HS can be used for mu2e experiment upgrade
- Muon Acceleration advances.
  - Recirculating Linear Accelerator (RLA) 4-km linac with multi-turn arcs
    - New lattices for linac and arcs, new pulsed magnet schemes for each
- Lower Emittances imply less detector background
  - Ability to instrument forward cones looks promising
- Project-X Proton Driver will include MC and NF capability
  - Initial Configuration Document (ICD-2) will use CW SRF for > 4 MW
  - Greater potential if ADS and ATW study capability added

    see concept paper for ARPA-E study (papers & reports on Muonsinc.com)

Principle of Ionization Cooling



- Each particle loses momentum by ionizing a low-Z absorber
- Only the longitudinal momentum is restored by RF cavities
- The angular divergence is reduced until limited by multiple scattering
- Successive applications of this principle with clever variations leads to small emittances for many applications
- Early work: Budker, Ado & Balbekov, Skrinsky & Parkhomchuk, Neuffer
- The only cooling technique that is fast enough for the 2.2 μs muon lifetime

Transverse Emittance IC

- The equation describing the rate of cooling is a balance between cooling (first term) and heating (second term):

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

Bethe-Bloch

Moliere (with low Z mods)

- Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity.

- See related talks by Coney, Kaplan, Torun on MICE and MuCool

Wedges or Continuous Energy Absorber for Emittance Exchange and 6d Cooling

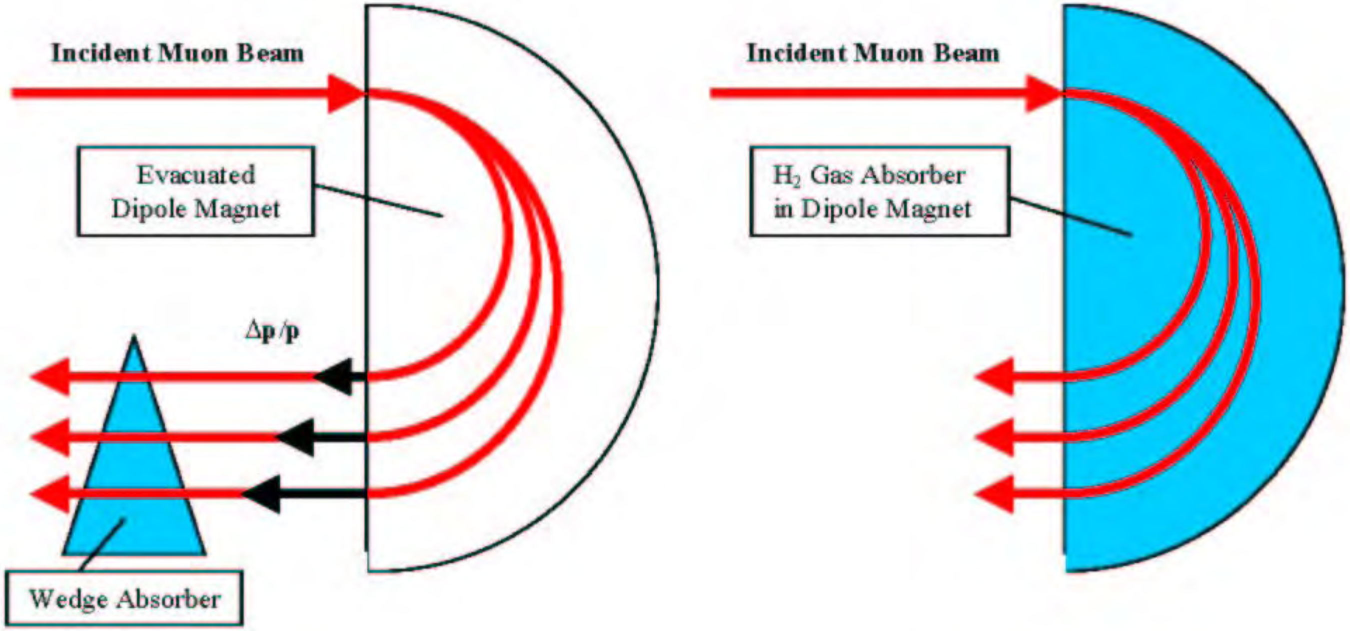


Figure 1. Use of a Wedge Absorber for Emittance Exchange

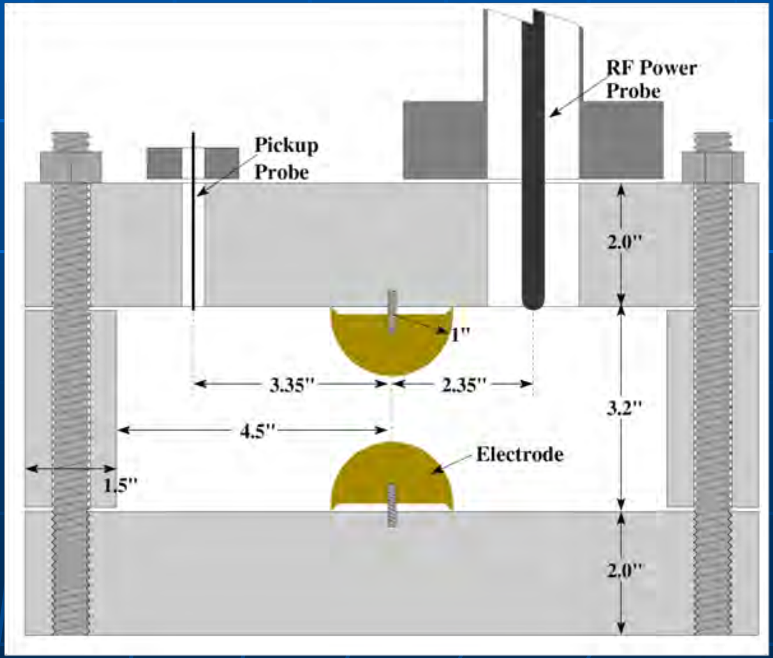
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

THIS RH CONCEPTUAL PICTURE BE REALIZED? A MANX GOAL!

Pressurized High Gradient RF Cavities

- Copper plated, stainless-steel, 800 MHz test cell with GH2 to 1600 psi and 77 K in Lab G, MTA
- Paschen curve verified
- Maximum gradient limited by breakdown of metal
  - fast conditioning seen, no limitation by external magnetic field!
- Cu and Be have same breakdown limits (~50 MV/m), Mo ~28% better



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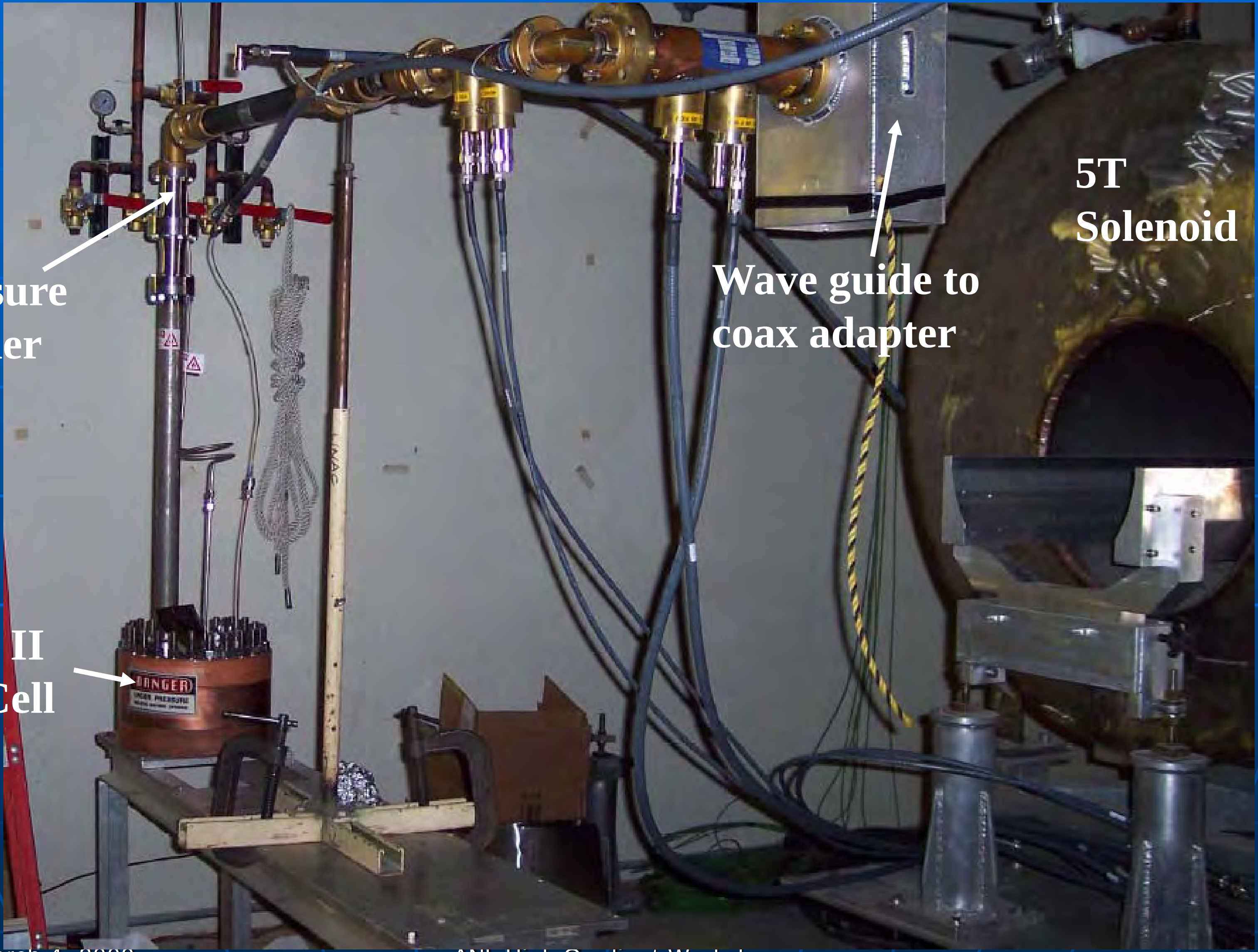
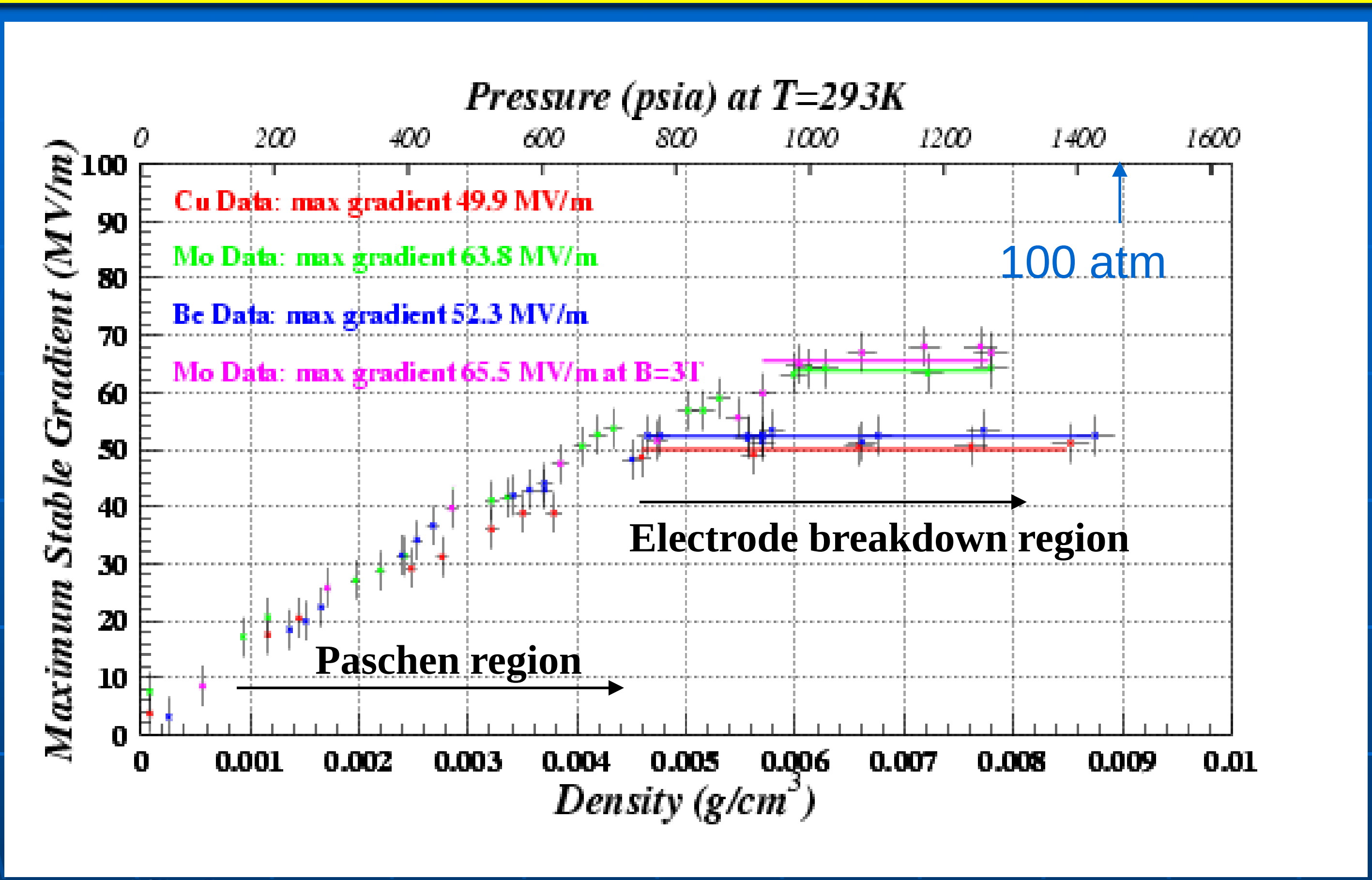
MuCool Test Area (MTA)



HPRF Test Cell Measurements in MTA



100 atm

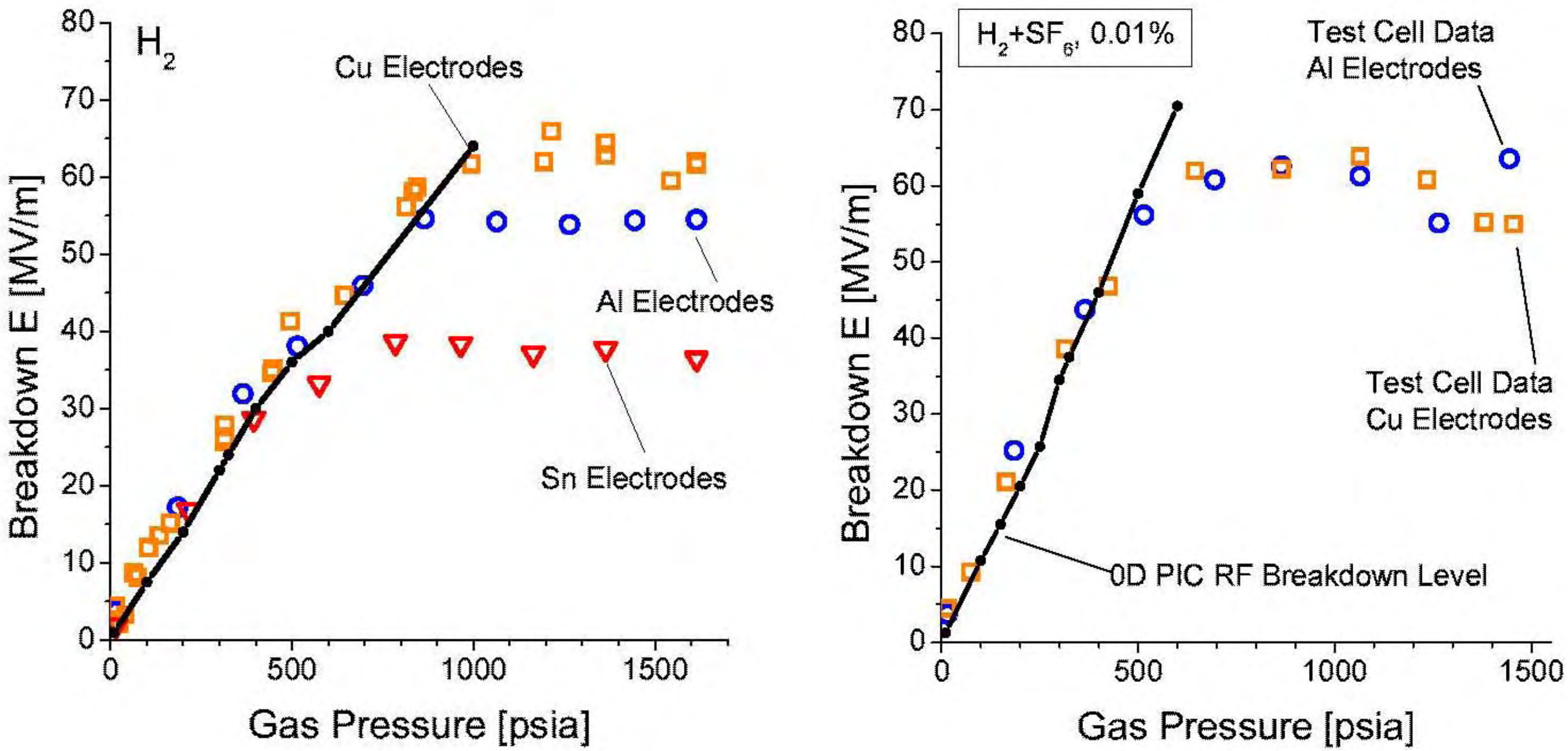
Electrode breakdown region

Paschen region

- Paschen curve verified
- Maximum gradient limited by breakdown of metal.
- Cu and Be have same breakdown limits (~50 MV/m), Mo(~63MV/m), W(~75MV/m).
- Results show no B dependence, much different metallic breakdown than for vacuum cavities.
- **Need beam tests to prove HPRF works.**

Simulations of breakdown in H_2 w & w/o 0.01% SF_6 doping.

Agreement with data gives confidence that pressurized RF cavities
can be made to operate in an intense muon beam.



Time-Dependent Zero-Dimensional Kinetic Simulations of RF Breakdown in High Pressure H2 with Small Admixtures of SF6 D. V. Rose, C. Thoma and D. R. Welch *Voss Scientific, LLC,* K. Yonehara *Fermilab,* R. P. Johnson *Muons Inc.*

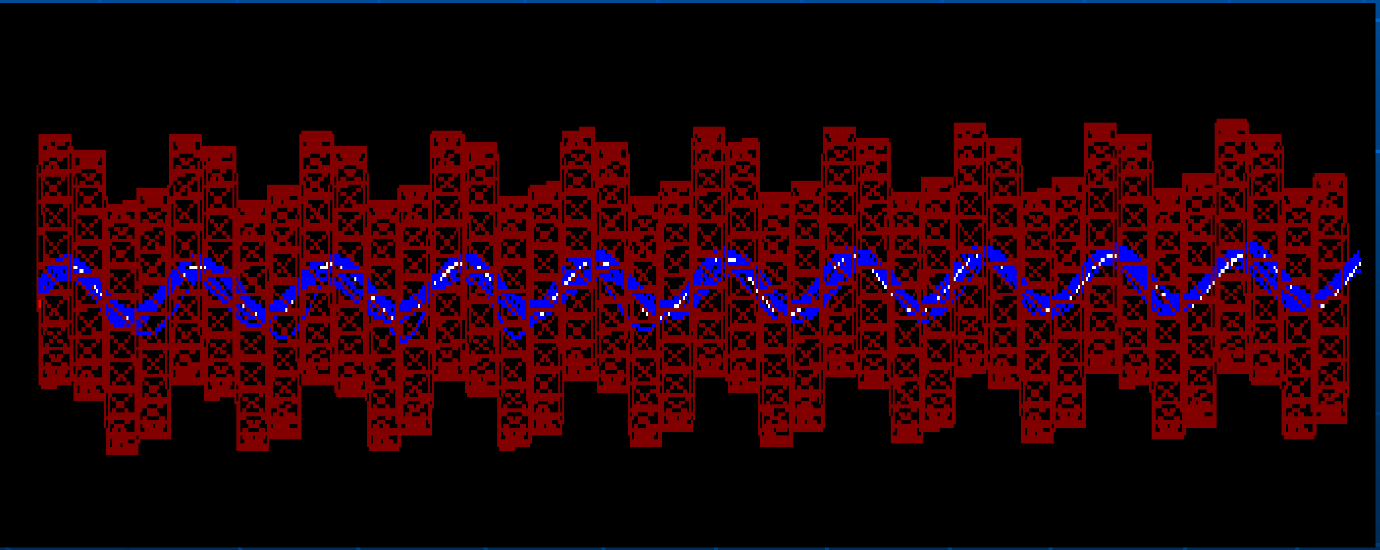
Helical Cooling Channel

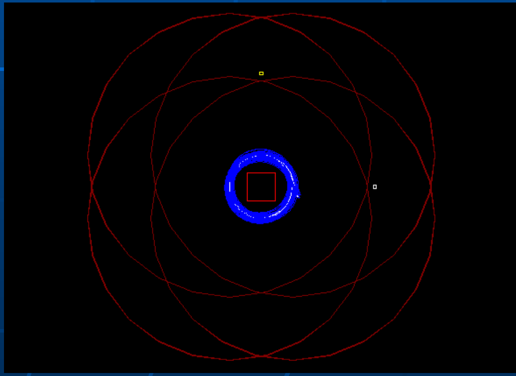
(Pavel Snopok will talk about another scheme later)

- First simulations showed factor of ~150,000 reduction in 6d emittance in less than 100 m of HCC.
- ~40,000 microns normalized transverse acceptance
- Used 200 MHz H2-pressurized cavities inside magnet coils. (absorber and RF occupy same space)
- Engineering Implementation requires creativity
  - Coils outside of such large RF Cavities are difficult. Solutions?
    - bigger coils: Helical Solenoid with/without correction coils
    - smaller cavities: 1) dielectric-loaded or 2) traveling wave solutions
    - smaller pitch angle (weaker helical dipole) eases field at conductor
  - H2-Pressurized RF cavities are undeveloped/unproven
    - Max RF gradient shown to be insensitive to external B field.
    - MTA proton beam tests soon. (SF6 dopant calcs/tests encouraging)

6-Dimensional Cooling in a Continuous Absorber

- Helical cooling channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z- and time-independent Hamiltonian
  - Derbenev & Johnson, Theory of HCC, April/05 PRST-AB
    - http://www.muonsinc.com/reports/PRSTAB-HCCtheory.pdf

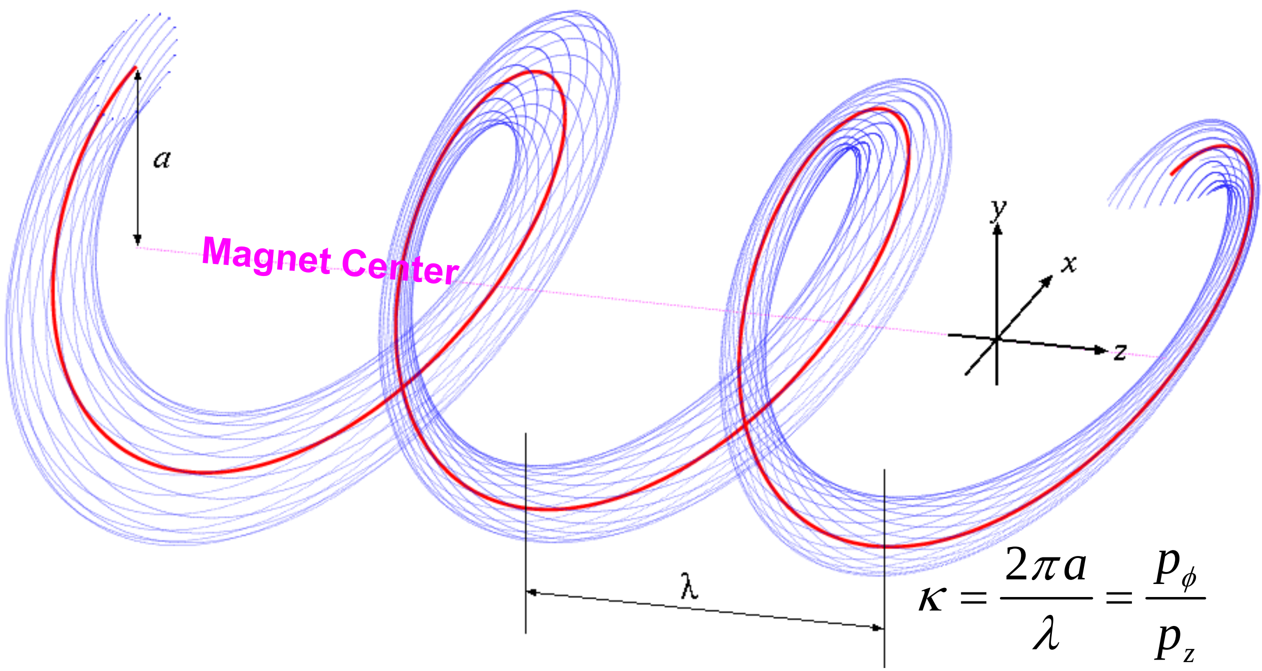




Particle Motion in an HCC Magnet

Combined function magnet (invisible in this picture)

Solenoid + Helical dipole + Helical Quadrupole



$$\kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

Red: Reference orbit

Blue: Beam envelope

Dispersive component makes longer path length for higher momentum particles and shorter path length for lower momentum particles.

Opposing radial forces

$$F_{h-dipole} \approx p_z \times B_\perp; \quad b \equiv B_\perp$$

$$F_{solenoid} \approx -p_\perp \times B_z; \quad B \equiv B_z$$

Transforming to the frame of the rotating helical dipole leads to a time and z – independent Hamiltonian

b' added for stability and acceptance

Some Important Relationships

Hamiltonian Solution

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{\kappa} b\right] \qquad k = 2\pi/\lambda \qquad \kappa = ka$$

Equal cooling decrements

$$q \equiv \frac{k_c}{k} - 1 = \beta\sqrt{\frac{1+\kappa^2}{3-\beta^2}} \qquad k_c = B\sqrt{1+\kappa^2}/p$$

Longitudinal cooling only

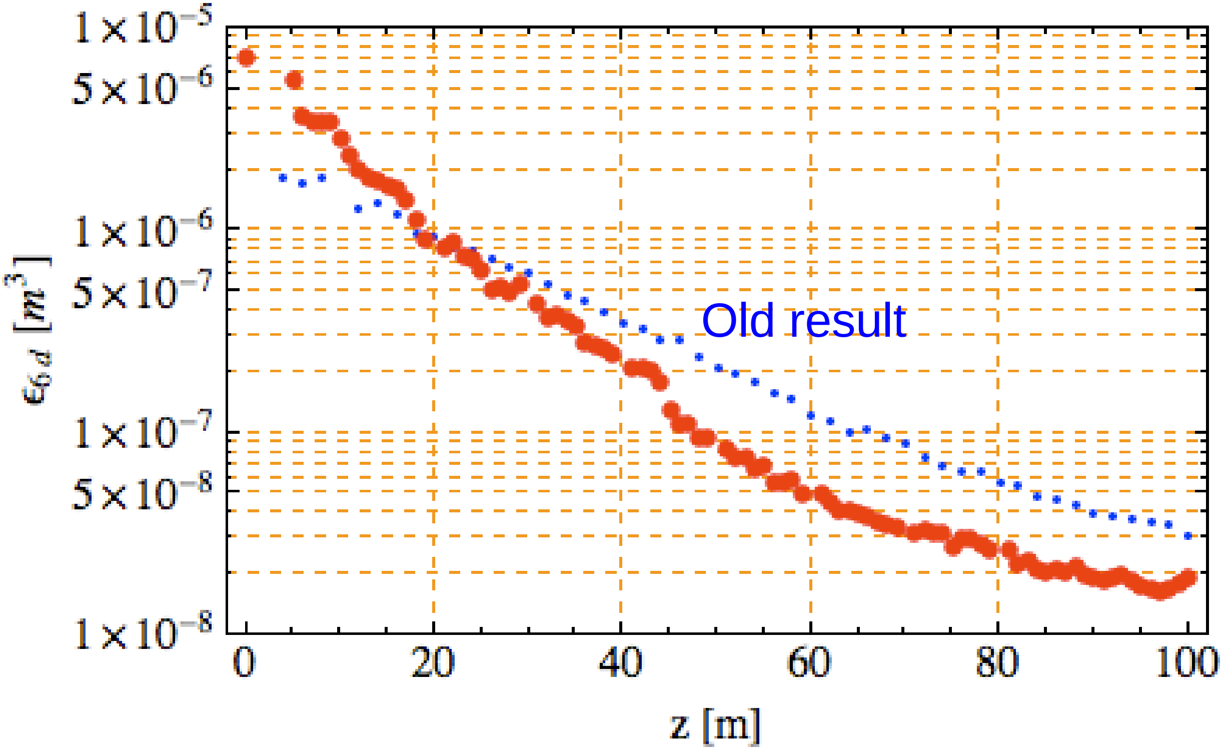
$$\hat{D} \equiv \frac{p}{a}\frac{da}{dp} = 2\frac{1+\kappa^2}{\kappa^2} \qquad q = 0$$

~Momentum slip factor

$$\eta = \frac{d}{d\gamma}\frac{\sqrt{1+\kappa^2}}{\beta} = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right) \qquad \frac{\kappa^2}{1+\kappa^2}\hat{D} \sim \frac{1}{\gamma^2_{transition}}$$

Six-Dimensional emittance evolution in new HCC (using RF and magnets we think we can build)

ν = 400 MHz, κ=1.0, λ=1.0 m
GH2 pressure = 200 atm (at room temp)



Cooling factor > 500 ~ 2^9 @ z = 100 m

Parameter list

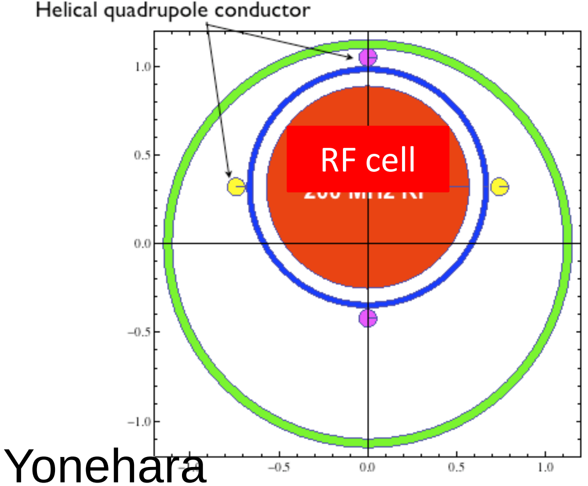
Field parameter

	λ (m)	κ	b (T)	b' (T/m)	bz (T)	E_{rf} (MV/m)	ϕ_{rf}	L_{rf} (mm)
400 MHz HCC	1.0	1.0	1.60	-0.55	-5.30	31.46	160	100
800 MHz HCC	0.6	1.0	2.67	-1.53	-8.84	32.58	160	60
1600 MHz HCC	0.3	1.0	5.33	-6.10	-17.7	32.53	160	30

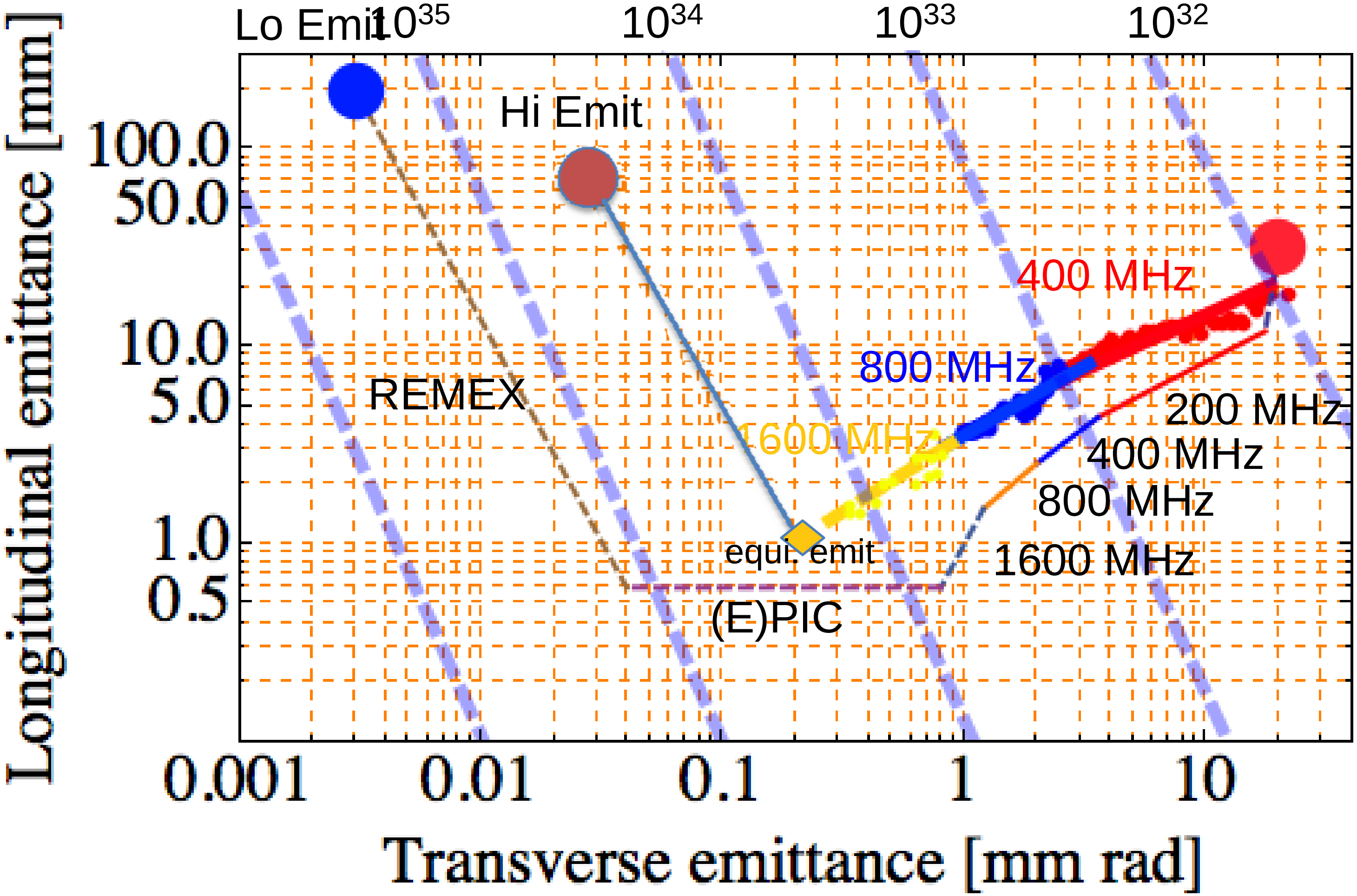
Average momentum = 0.25 GeV/c
GH2 pressure = 200 atm @ room temp
Dispersion factor = D/ρ = 1.83
Length of each channel = 100 m

RF length will be double to save RF power
For instance,
400 MHz HCC, L_{rf} = 200 mm, E_{rf} = 40 MV/m

HCC field can be produced with correction magnets (although it is not a final design)



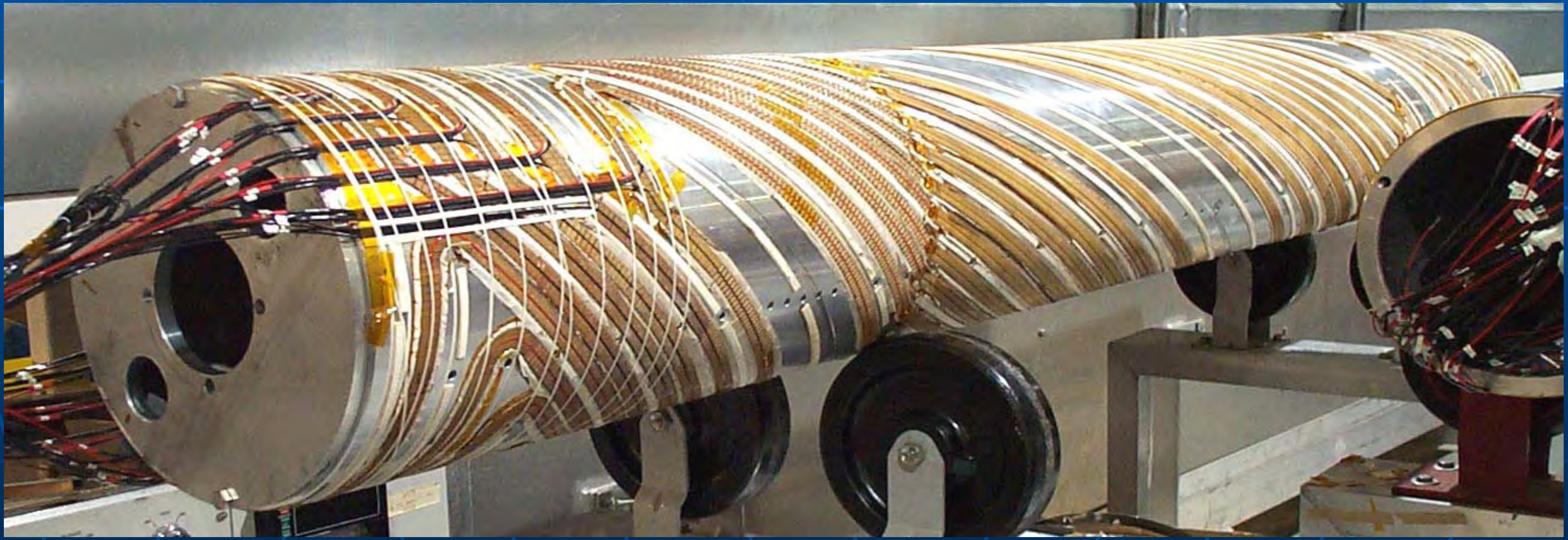
Transverse vs Longitudinal phase space



- A 400 MHz HCC may be sufficient to accept the beam phase space after conventional frontend channel
- If Luminosity estimation is correct we can reach 10^{34} even only HCC section (but reverse emittance exchange is still needed)

Helical Cooling Channel

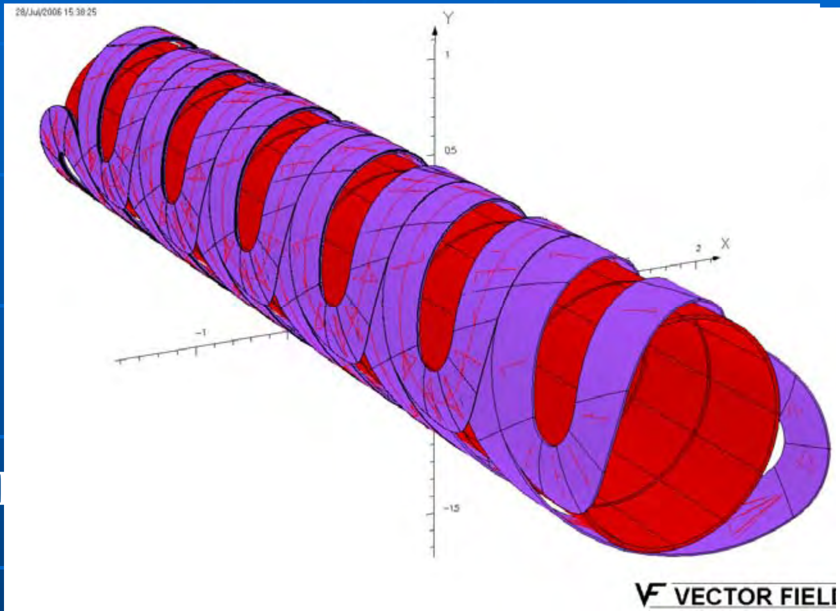
Continuous, homogeneous energy absorber for longitudinal cooling
Helical Dipole magnet component for dispersion
Solenoidal component for focusing
Helical Quadrupole for stability and increased acceptance

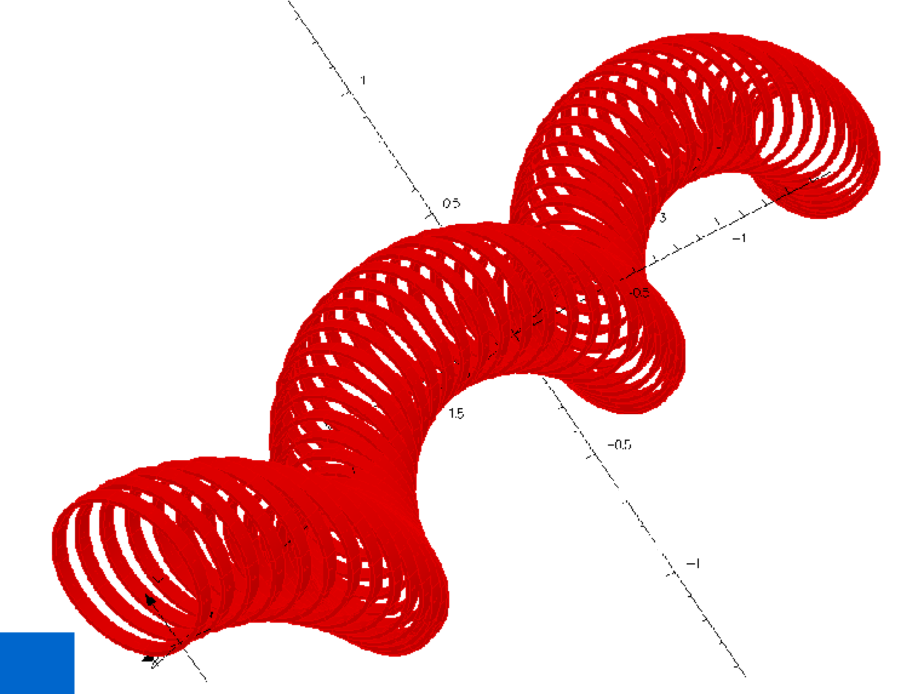


BNL Helical Dipole magnet for AGS spin control

Two Different Designs of Helical Cooling Magnet

Great new innovation!





- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.

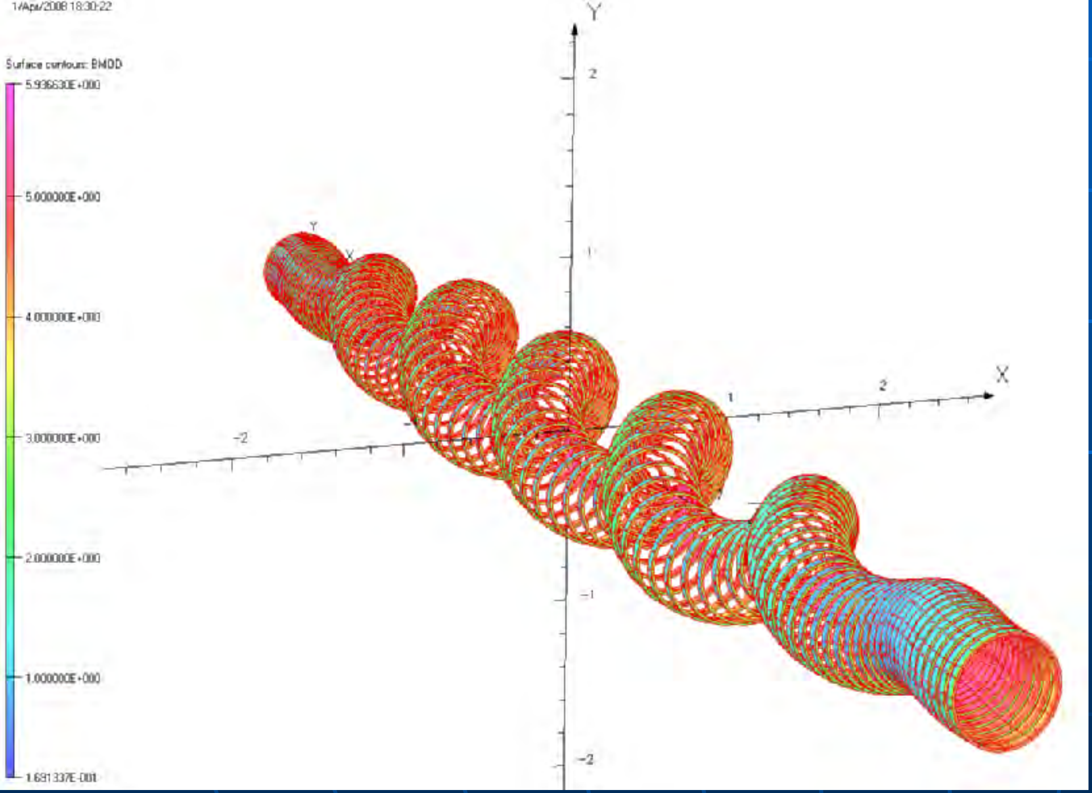
- Helical solenoid coil magnet
- Consists of 73 single coils (no tilt).
- Maximum field is 5 T
- Coil diameter is 0.5 m.

HS for Cooling Demonstration Experiment

V. Kashikhin, A. Zlobin, M. Lamm, S. Kahn, M. Lopes

Goals: cooling demonstration, HS technology development

Features: SSC NbTi cable, B_{max}~6 T, coil ID ~0.5m, length ~10m



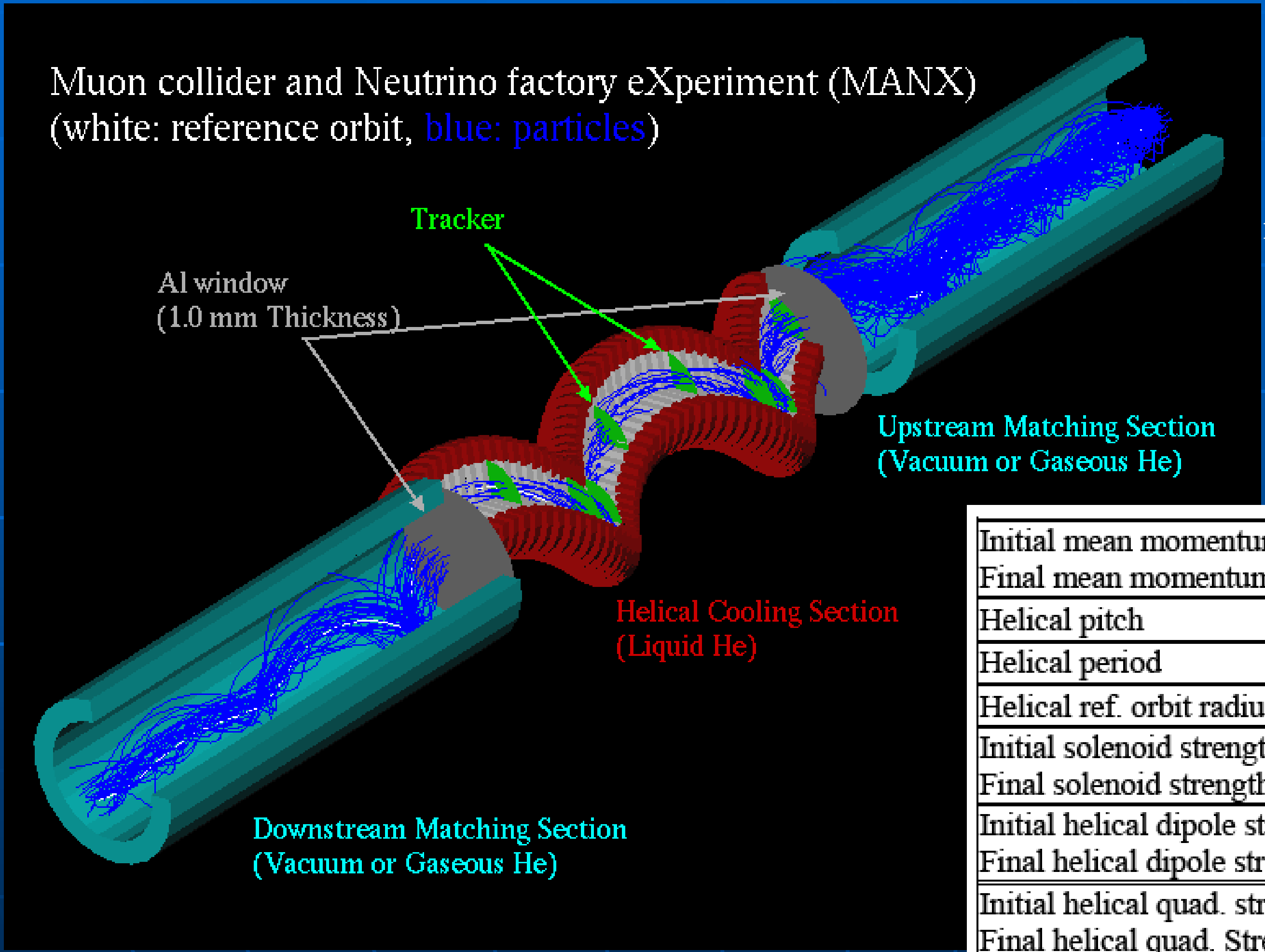
Status: conceptual design complete

- solenoid
- matching sections

Next: engineering design

- mechanical structure
- field quality, construction tolerances
- cryostat
- powering and quench protection

Overview of original MANX



Muon collider and Neutrino factory eXperiment (MANX)
(white: reference orbit, blue: particles)

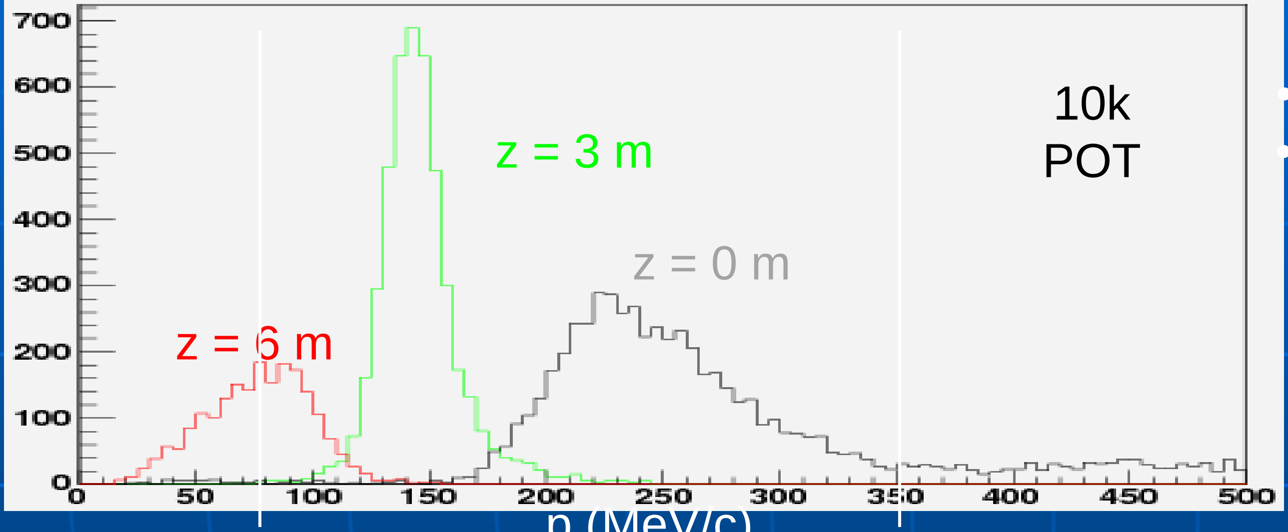
- Use Liquid He absorber
- No RF cavity
- L of cooling channel: 3.2 m
- L of matching section: 2.4 m
- Helical pitch κ: 1.0
- Helical orbit radius: 25 cm
- Helical period: 1.6 m
- Transverse cooling: ~1.3
- Longitudinal cooling: ~1.3
- 6D cooling: ~2

Initial mean momentum Final mean momentum	**P**	300 MeV/c 170 MeV/c
Helical pitch	κ	1
Helical period	λ	1.6 m
Helical ref. orbit radius	*A*	0.255 m
Initial solenoid strength Final solenoid strength	**B**	-3.8 T -1.7 T
Initial helical dipole strength Final helical dipole strength	**B**	1.2 T 0.8 T
Initial helical quad. strength Final helical quad. Strength	**b'**	-0.9 T/m -0.5 T/m

MANX as a Pre-cooler

(related talk by Mike Syphers later)

D. Neuffer, C. Yoshikawa



- Use LiH plate in this design
- Good transmission (> 90%)

Distance in HCC, z(m) & Momentum Cut	*N(π^-&μ^-) per POT*	*N(π^-) per POT*	*N(μ^-) per POT*
0	*0.3302*	*0.0016*	*0.3139 (95.1%)*
z = 0; p < 350 MeV/c	*0.1954*	*0.0004*	*0.1949 (99.8%)*
3	*0.1734*	*0.0002*	*0.1733 (~100%)*
6	*0.0780*	*0.0000*	*0.0780 (100%)*
z = 6; p < 75 MeV/c	*0.0348*	*0.0000*	*0.0348 (100%)*

In Feb. 2009 we presented a proposal to the FNAL AAC

(See talk by Mary Anne Cummings yesterday)

MANX, A 6D MUON BEAM COOLING EXPERIMENT TO FOLLOW MICE

Robert Abrams[1], Mohammad Alsharo'a[1], Charles Ankenbrandt[2], Emanuela Barzi[2],
Kevin Beard[3], Alex Bogacz[3], Daniel Broemmelsiek[2], Alan Bross[2], Yu-Chiu Chao[3],
Mary Anne Cummings[1], Yaroslav Derbenev[3], Henry Frisch[4],
Ivan Gonin[2], Gail Hanson[5], Martin Hu[2], Andreas Jansson[2], Rolland Johnson[1]
Stephen Kahn[1], Daniel Kaplan[6], Vladimir Kashikhin[2], Sergey Korenev[1],
Moyses Kuchnir[1], Mike Lamm[2], Valeri Lebedev[2], David Neuffer[2], David Newsham[1],
Milorad Popovic[2], Robert Rimmer[3], Thomas Roberts[1], Richard Sah[1],
Linda Spentzouris[6], Alvin Tollestrup[2], Daniele Turrioni[2], Victor Yarba[2],
Katsuya Yonehara[2], Cary Yoshikawa[2], Alexander Zlobin[2]

[1]*Muons, Inc.*
[2]*Fermi National Accelerator Laboratory*
[3]*Thomas Jefferson National Accelerator Facility*
[4]*University of Chicago*
[5]*University of California at Riverside*
[6]*Illinois Institute of Technology*

We need the MICE Collaboration support to do this !!!!
(Fermilab would be asked to build the magnet to be used at RAL)

Key MANX features

- Will Test:
  - Theory of Helical Cooling Channel (HCC)
    - p-dependent HCC with continuous absorber
    - modify currents to change cooling decrements, γ_t
  - Helical Solenoid Magnet (HS)
  - Simulation programs (G4BL, ICOOL)
- Minimizes costs and time
  - no RF, uses normalized emittance, ~5 m LHe E absorber
  - RF is developed in parallel with new concepts
  - builds on MICE, adds 6-d capability, ~ps detectors
- Synergies in funding for uses w/o RF:
  - HS for stopping muons, especially mu2e upgrade
  - Isochronous pion decay channel
  - Precooler

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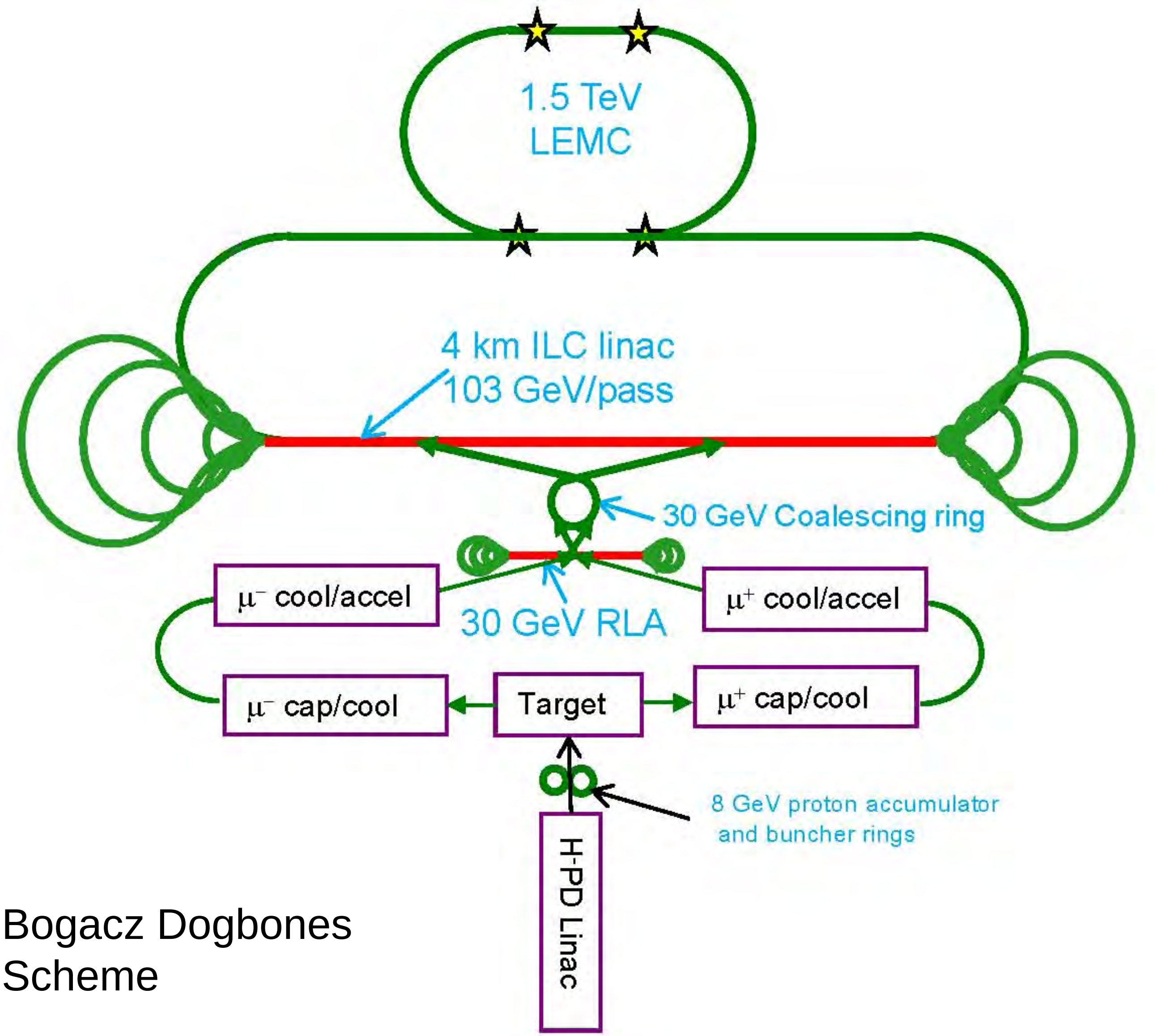
LEMC Scenario



Bogacz Dogbones Scheme

How to Fund a Muon Collider (by Solving Important Problems Along the Way)

Rolland Johnson
Muons, Inc.

"ask not what your country can do for you - ask what you can do for your country"

J. F. Kennedy, Jan 20, 1961

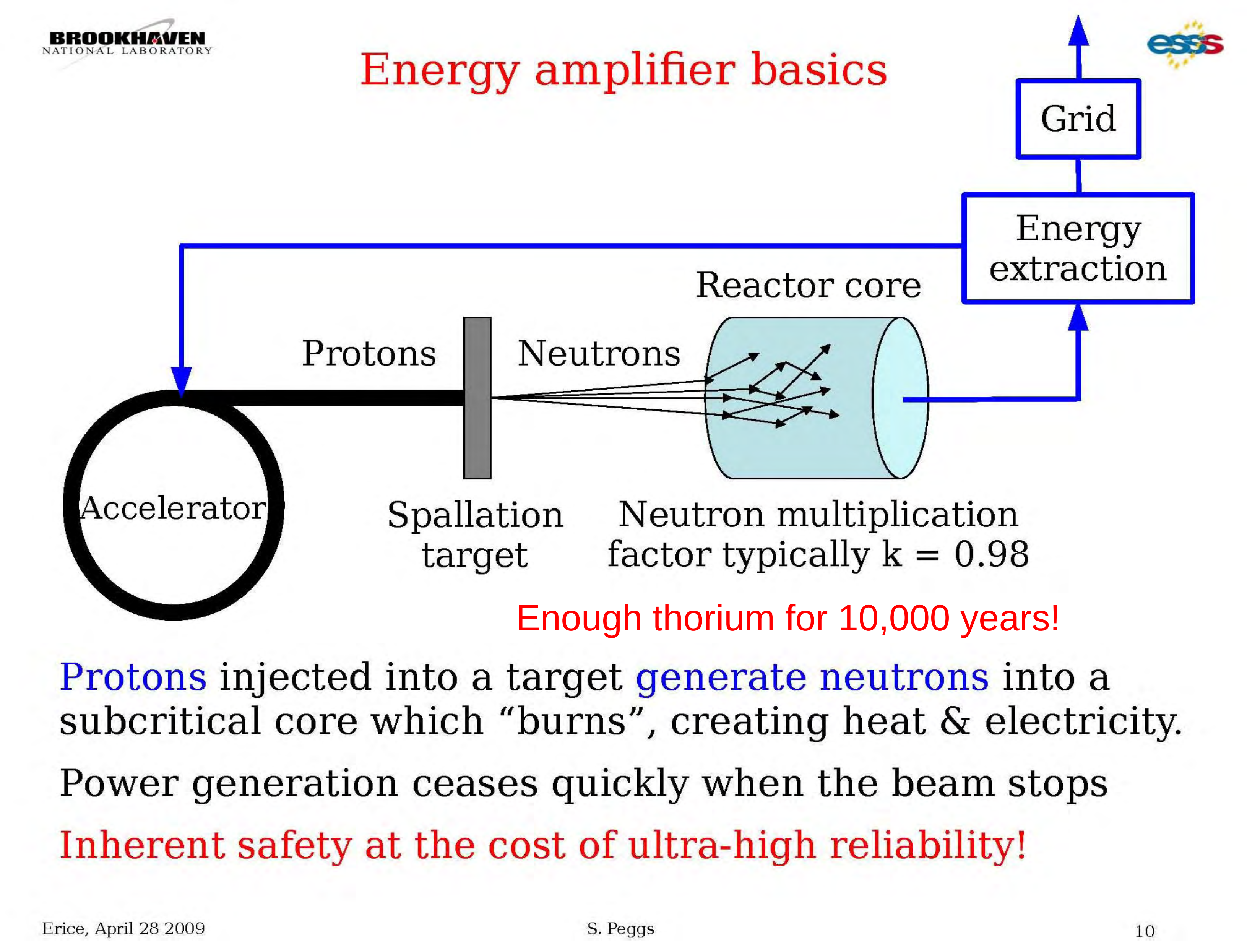
CONCEPT: SRF Linear Accelerators for Transformational Energy Technologies

Lead proponent: Muons, Inc. (http://muonsinc.com/)

Proposed partners: Fermi National Accelerator Laboratory (Fermilab),
Thomas Jefferson National Accelerator Facility (JLab), and
Oak Ridge National Laboratory (SNS)
Interest also from BNL, LBNL, PNNL

GOALS: accelerator-driven subcritical (ADS) nuclear power stations

- operating at 5 to 10 GW,
- in an inherently safe region below criticality,
- without generation of greenhouse gases,
- producing minimal nuclear waste,
- no byproducts that are useful to rogue nations or terrorists,
- incinerating waste from conventional nuclear reactors (ATW),
- efficiently using abundant thorium fuel,
- which does not need enrichment.



BROOKHAVEN NATIONAL LABORATORY

Energy amplifier basics

Enough thorium for 10,000 years!

Protons injected into a target generate neutrons into a subcritical core which “burns”, creating heat & electricity.

Power generation ceases quickly when the beam stops

Inherent safety at the cost of ultra-high reliability!

Muons, Inc.

Why 8 GeV and not 1 GeV? To supply 8 GW.

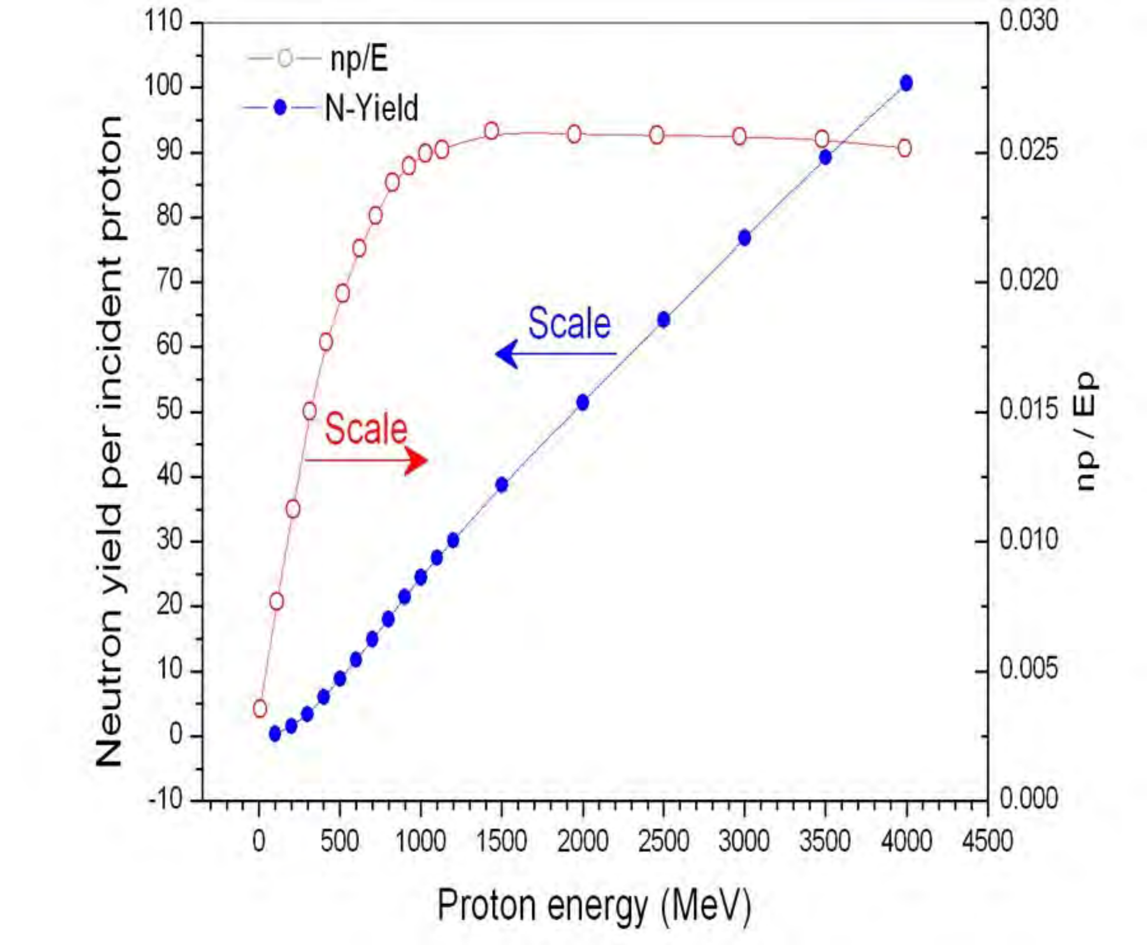


Figure 1: Neutron yield as a function of proton energy for one set of target and moderator conditions. Above about 1 GeV the useful neutron flux is proportional to beam power. (Peggs Erice lecture.)

CONCEPT: SRF Linear Accelerators for Transformational Energy Technologies

First, the feasibility of the accelerator technology must be demonstrated.

Fermilab has already proposed a $1B to $1.5B 8-GeV super-conducting RF (SRF) linear accelerator called Project-X for particle physics at the intensity and energy frontiers.

Muons, Inc. proposes to work with its SBIR-STTR partners Fermilab, JLab, and SNS (also ANL, BNL, LBNL, and PNNL) to extend this linac design to become also a prototype for a practical accelerator for ADS reactors and to provide beams for reactor development.

The first major milestone of the project to be proposed here is to produce an enhanced or alternative design for the Project-X CD1 document that includes ADS and ATW development needs.

Concept paper is posted on Papers and Reports of Muons, Inc. web site.

(Related talk by Camille Ginsburg later today)

Progress seen in many new ideas under development:

- H_2-Pressurized RF Cavities
- Continuous Absorber for Emittance Exchange
- Helical Cooling Channel
- Epicyclic HCC
  - Parametric-resonance Ionization Cooling
  - Reverse Emittance Exchange
- RF capture, phase rotation, cooling in HP RF Cavities
- Bunch coalescing
- Very High Field Solenoid magnets for better cooling
- p-dependent HCC
  - precooler
  - HTS for extreme transverse cooling and higher B collider ring
  - MANX 6d Cooling Demo
  - improved mu2e design
- Instrumenting forward cones of detectors
- New low beta schemes for MC ring
- ADS and ATW to push for a proton driver suitable for MCs

Conclusions

Progress? Amazing and Inspiring (and I only talked about our projects)

Prospects? Pier Oddone and Dennis Kovar now talk about muon colliders in our future!

How soon? Depends on the enthusiasm and endeavor of the HEP community. Help is needed!

I have assumed a steady progression of machines toward a MC, but things could change if we can create a tipping point. E.g. What happens if there is a Z’ at 1.5 TeV? Or what if people understand that HEP accelerator expertise can help solve the world energy crisis and prevent unwanted climate change? Or that a muon collider is a national goal?