Bright Muon Beams for Colliders, Neutrino Factories, and Muon Physics

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

New inventions are improving the prospects for high luminosity muon colliders for Higgs factories and at the energy frontier. Recent 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. A strategy is being developed for achieving an almost unlimited program of experimental physics based on the cooling and acceleration of muon beams. The challenge of doing cutting-edge accelerator R&D as a growing small for-profit company has required other initiatives that include new ideas for accelerator-driven subcritical reactors.

Please visit "Papers and Reports" and "LEMC Workshop" at http://www.muonsinc.com/

outline

- A top-down presentation of what we are up to with muons: New machines for Fermilab, each separately fundable with worthy physics goals ending up with an energy frontier muon collider
- New techniques for muon cooling to enable intense stopping muon beams, neutrino factories, Higgs factories, Z’ factories, and muon colliders (more than 1 scenario-see Palmer, Alexahin)
- New technology to support the new techniques, e.g. Hydrogen-pressurized RF cavities and superconducting high-field magnets
- Expanding Project-X to develop SRF capability for a prototype for an Accelerator-Driven Subcritical Molten Salt Reactor

Muons, Inc. Project History

Year	Project	Expected Funds	Research Partner
2002	Company founded		
2002-5	High Pressure RF Cavity	$600,000	IIT (Kaplan)
2003-7	Helical Cooling Channel	$850,000	JLab (Derbenev)
2004-5†	MANX demo experiment	$ 95,000	FNAL (Yarba)
2004-7	Parametric Ionization C.	$745,000	JLab (Derbenev)
2004-7	HTS Magnets	$795,000	FNAL (Yarba)
2005-8	Reverse Emittance Exch.	$850,000	JLab (Derbenev)
2005-8	Capture, ph. rotation	$850,000	FNAL (Neuffer)
2006-9	G4BL Sim. Program	$850,000	IIT (Kaplan)
2006-9	MANX 6D Cooling Demo	$850,000	FNAL (Lamm)
2007-10	Stopping Muon Beams	$750,000	FNAL (Ankenbrandt)
2007-10	HCC Magnets	$750,000	FNAL (Zlobin)
2007-8	Compact, Tunable RF	$100,000	FNAL (Popovic)
2008-9	RF Breakdown Studies	$100,000	LBNL (Li) ANL (Gai)
2008-9	Rugged RF Windows	$100,000	Jlab (Rimmer)
2008-9	H2-filled RF Cavities	$100,000	FNAL (Yonehara)

(these projects are finished)

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Project History (cont.)

Year	Project	Expected Funds	Research Partner
2008-11	Pulsed Quad RLAs	$850,000	JLab (Bogacz)
2008-11	Fiber Optics for HTS	$800,000	NCSU (Schwartz)
2009-12	HOM Absorbers	$850,000	Cornell(Hoffstaetter)
2009-12	Quasi Isochronous HCC	$850,000	FNAL (Neuffer)
2009-10	DC Gun Insulator	$100,000	JLab (Poelker)
2009-12	H-minus Sources	$850,000	ORNL/SNS (Stockli)
2009-12	Hi Power Coax Coupler	$850,000	JLab (Rimmer)
2009-10	Hi Field YBCO Magnets	$100,000	NCSU (Schwartz)
2009-12	ϕ & f –locked Magnetrons	$850,000	FNAL (Popovic)
2009-11	Mono-E Photons	$172,588	3 contracts w PNNL
2009-10	Project-X and MC/NF	$260,000	contract w FNAL
2009-10	MCP and ps timers	$108,338	contract w ANL
2010-11	MAP	$ 55,739	2 contracts w FNAL
2010-11	805 MHz RF Cavity	$230,000	contract w LANL
2010-11	ps detectors for MCDE	$100,000	U Chicago (Frisch)
2010-11	Crab Cavities	$100,000	JLab (Rimmer)
2010-11	Epicyclic PIC	$100,000	JLab (Derbenev)
2010-11	MC detector bkgnds	$100,000	NIU (Hedin)

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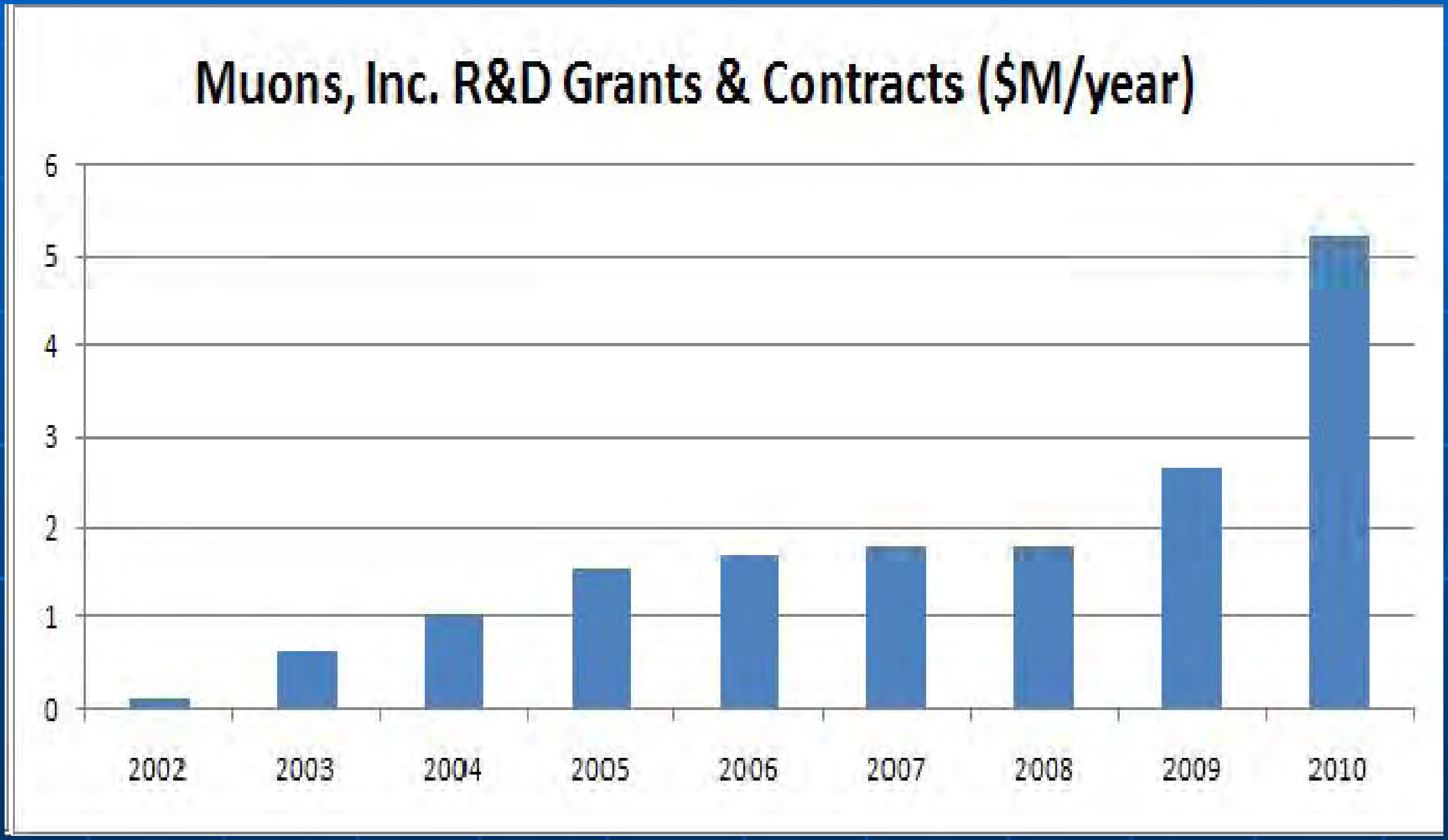
Growth requires diversification



And a new company to raise funds for Muons, Inc. :
Accelerator Technologies Inc, see http://acceltech.us

Muon Colliders: Back to the Livingston Plot
A lepton collider at the energy frontier!

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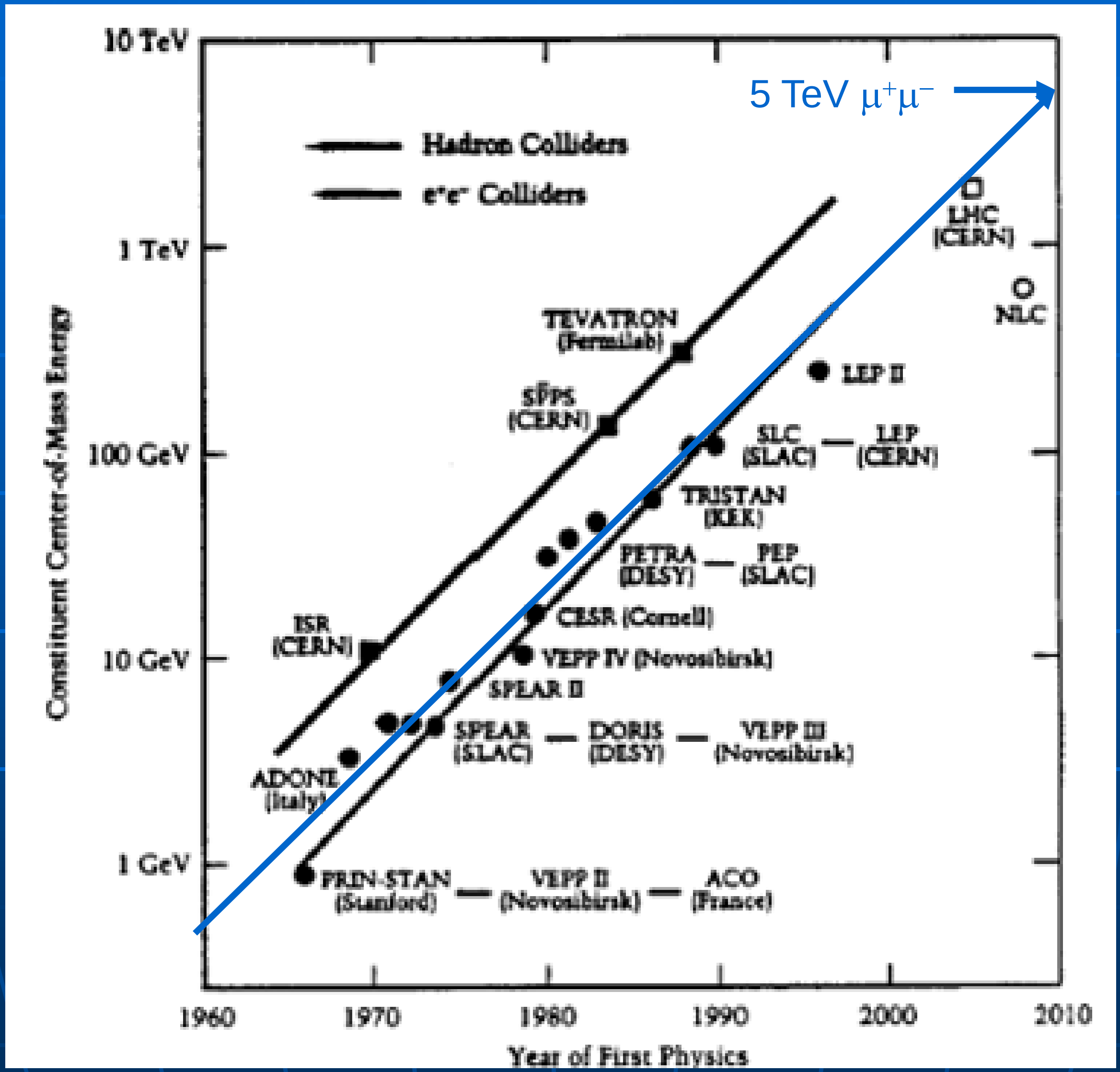


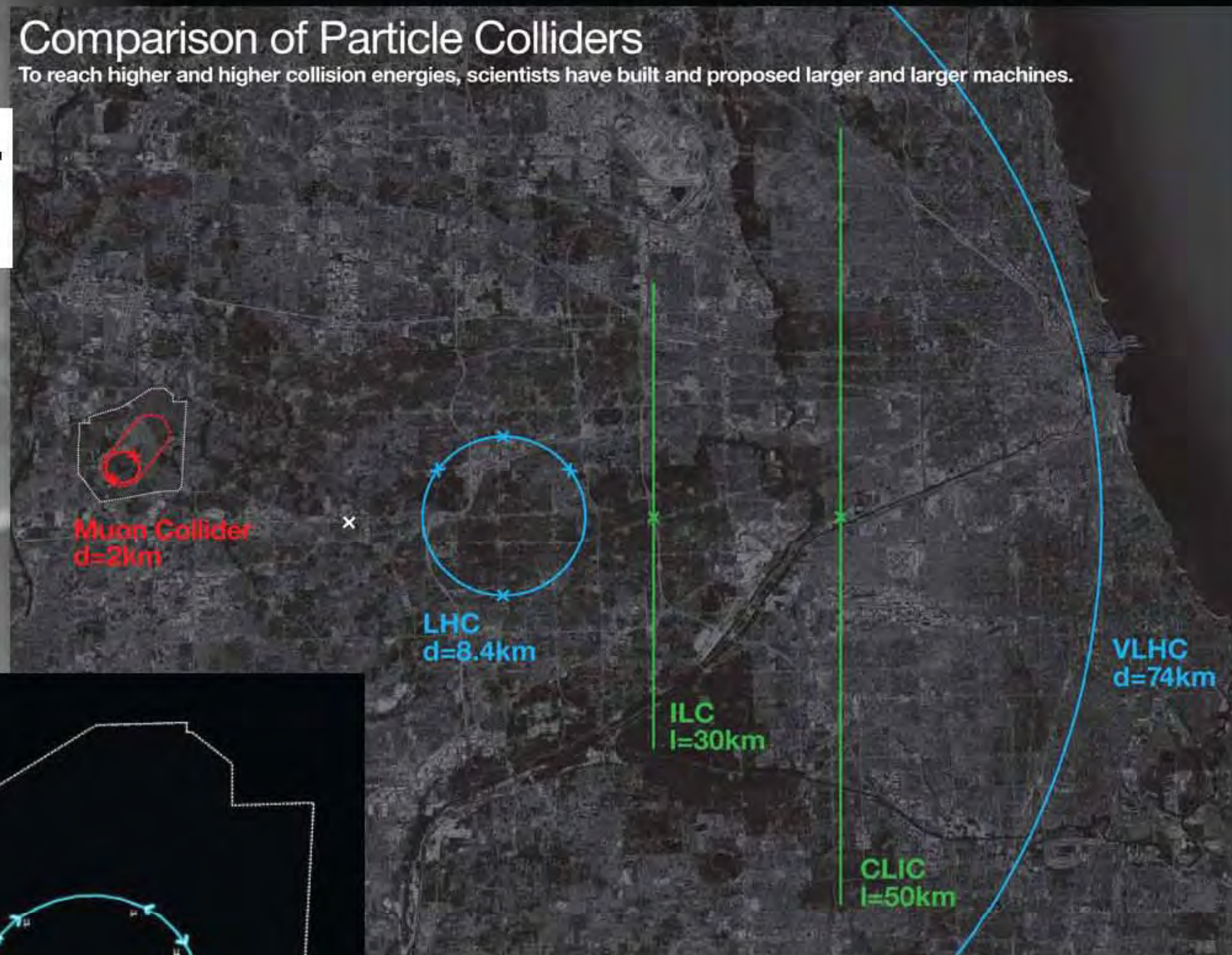
Modified Livingston Plot taken from: W. K. H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, s121-s132 (1999)

Compact Muon Collider

Fit in Fermilab campus

Muon Collider: 20??
Cost: Unknown
Energy: 0.5 ~ 4 TeV
Components: 10,000

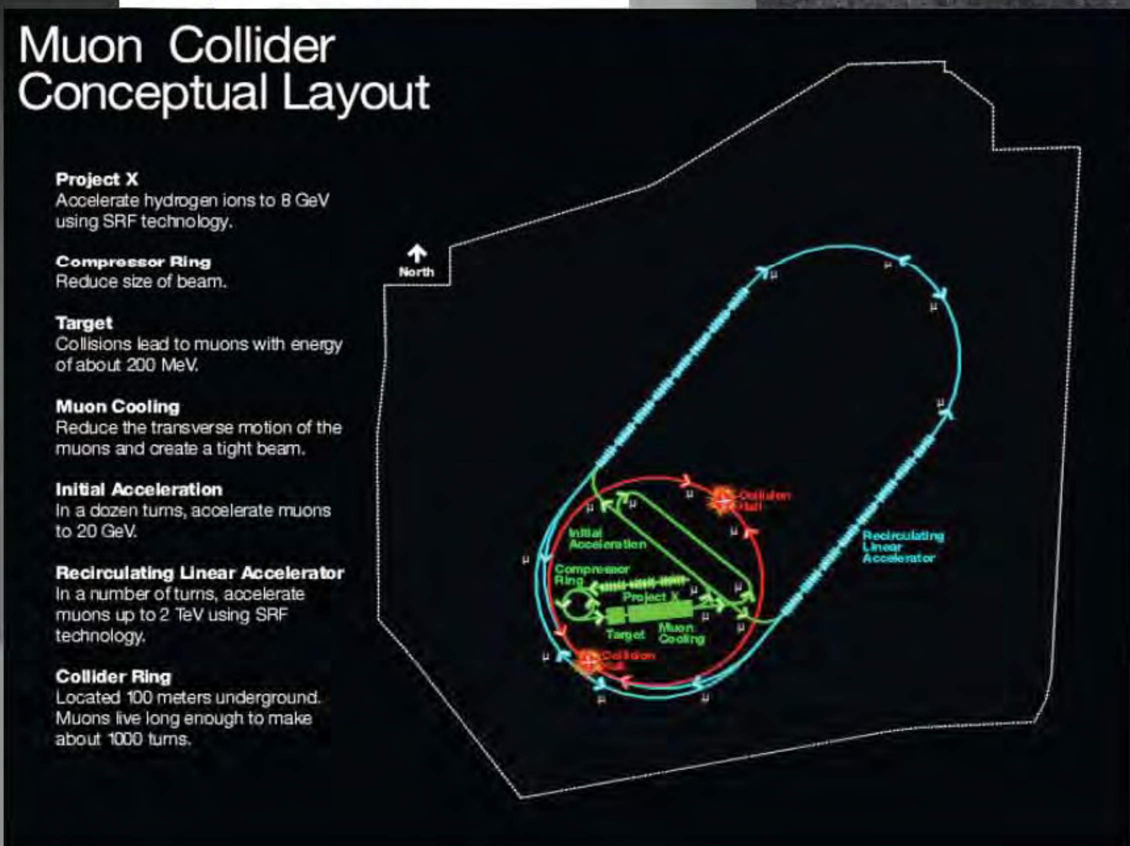
CLIC: 20??
Cost: Estimate due in 2010
Energy: 0.5 ~ 3 TeV
Components: 260,000



LHC: 2009-present
Cost: US $4.6 billion
Energy: 14 TeV
Components: 11,000

ILC: 20??
Cost: US $8 billion in 2007
Energy: 0.5 TeV
Components: 38,000

VLHC: 2???
Cost: Unknown
Energy: 40 ~ 200 TeV



Numbers are taken from
Nature **462**, 260-261 (2009)

5 TeV ~ SSC energy reach

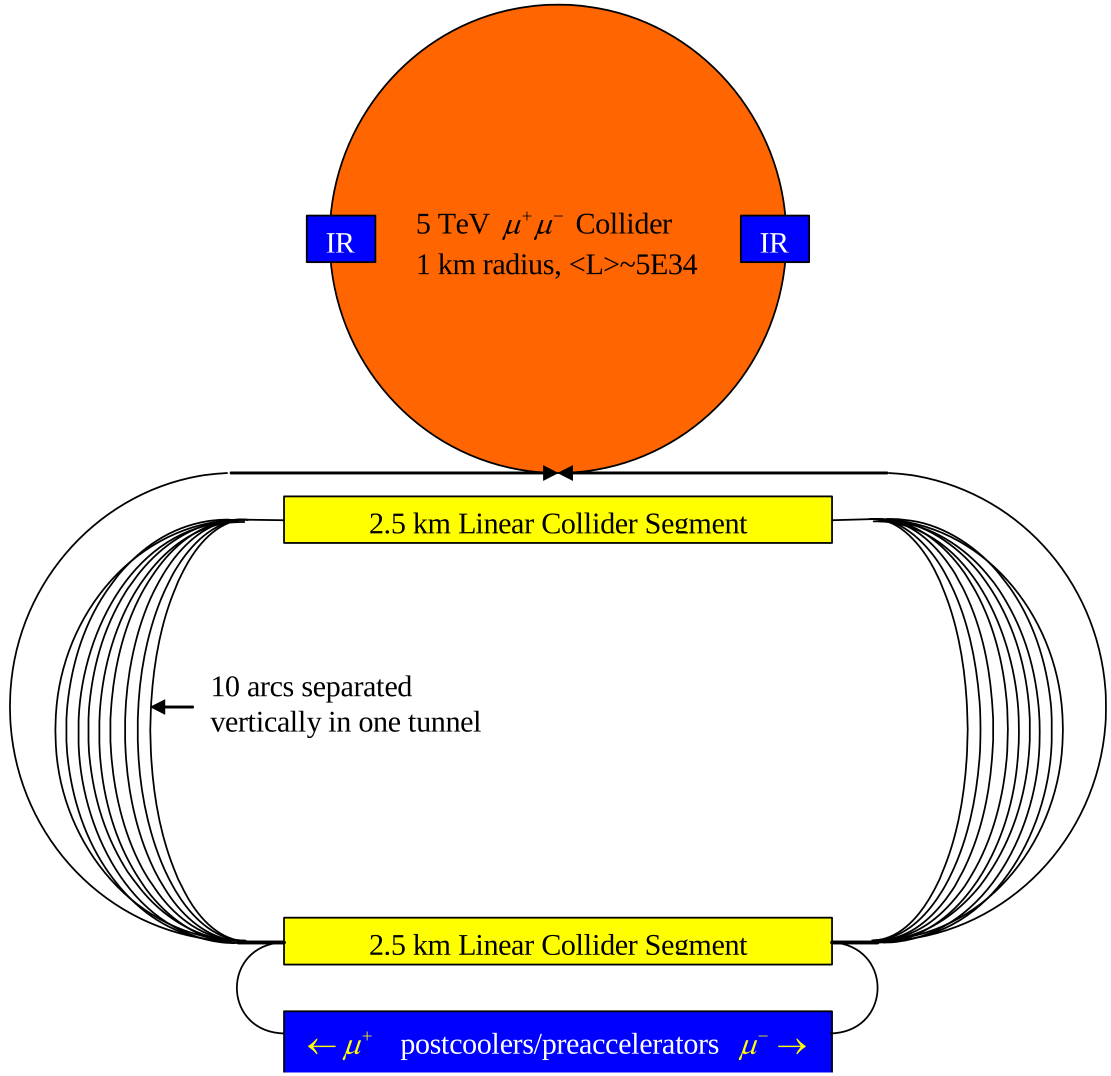
~5 X 2.5 km footprint

Affordable LC length (5 km), includes ILC people, ideas

More efficient use of RF: recirculation and both signs

High L from small emittance!

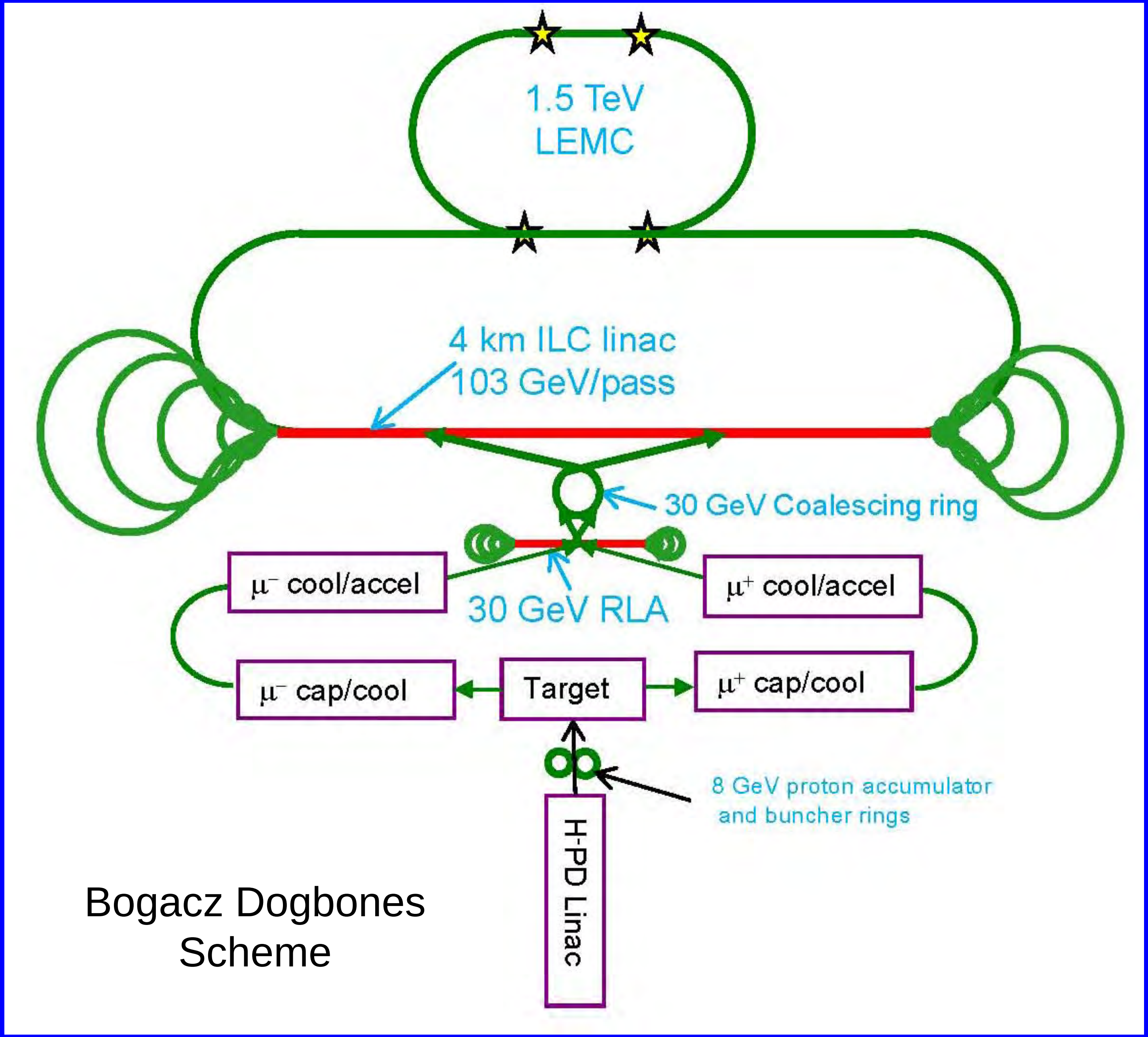
with fewer muons than originally imagined:
a) easier p driver, targetry
b) less detector background
c) less site boundary radiation



Beams from 23 GeV Coalescing Ring

This recirculating linac approach is much like CEBAF at Jlab. However a single linac with teardrop return arcs looks better and is a subject of a new SBIR proposal.

LEMC Scenario (2008)



Ultimate Goal: High-Energy High-Luminosity Muon Colliders

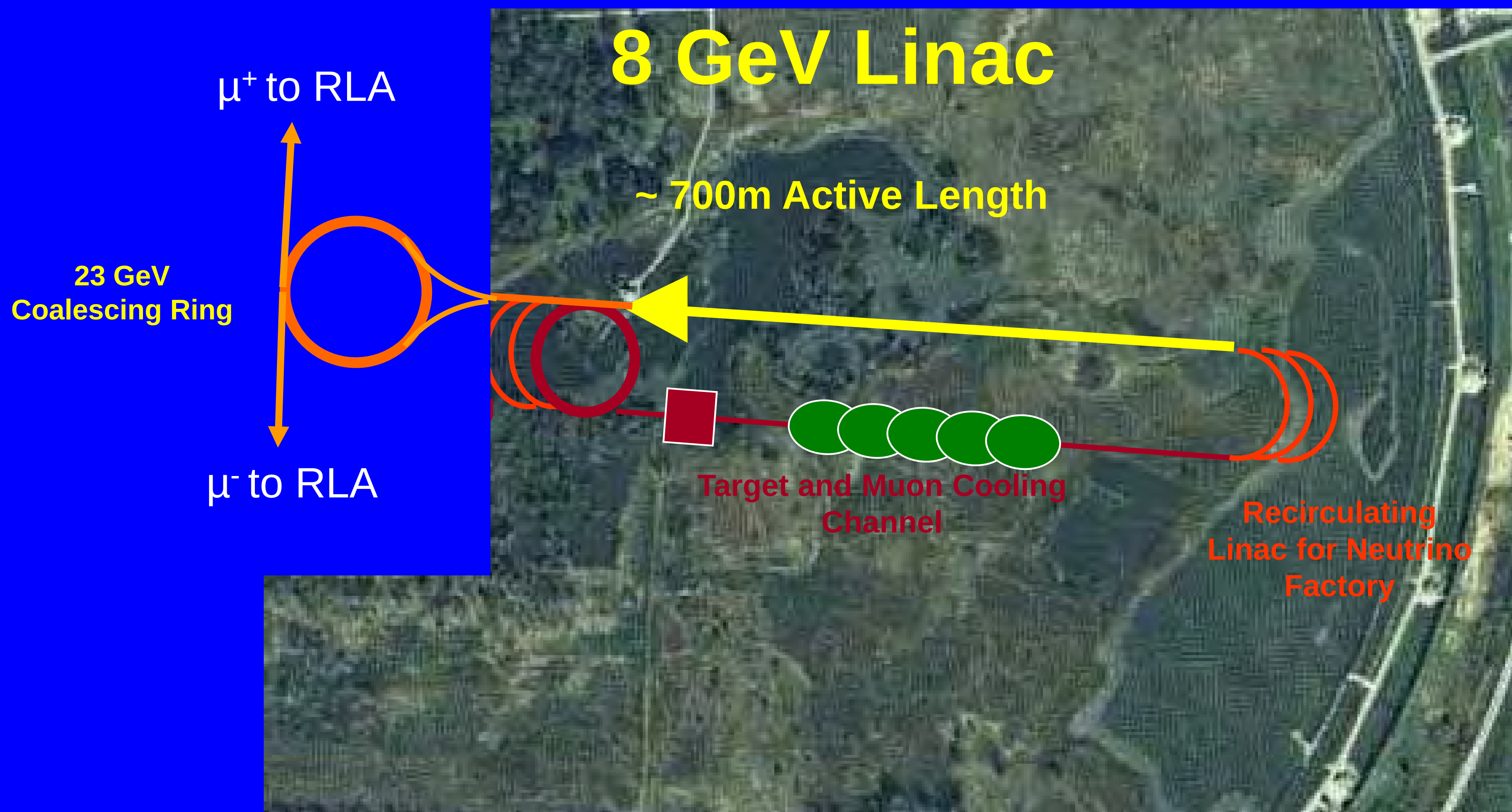
- precision lepton machines at the energy frontier
- achieved in physics-motivated stages that require developing inventions and technology, e.g.
  - high-power 8-GeV H^- Linac (CW with AR & BRs, ADSR)
  - stopping muon beams (HCC, EEXwHomogeneous absorber)
  - neutrino factory (HCC with HPRF, RLA in 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)

Neutrino Factory use of 8 GeV SC Linac

Beam cooling allows muons to be recirculated in the same linac that accelerated protons for their creation,
Running the Linac CW can put a lot of cold muons into a small aperture neutrino factory storage ring.

Muon Collider use of 8 GeV SC Linac

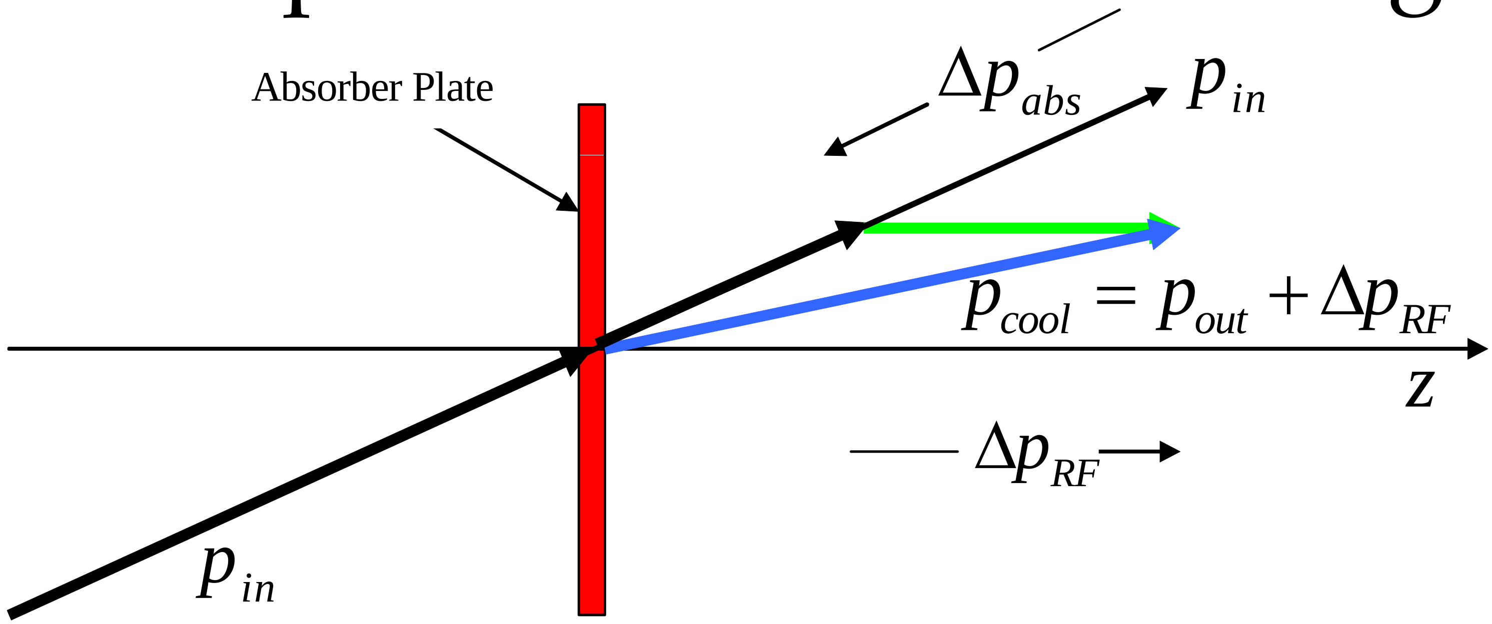
Or a coalescing ring (also new for COOL07) can prepare more intense bunches for a muon collider



Recent Inventions and Developments

- **New Ionization Cooling Techniques**
  - Emittance exchange with continuous absorber for longitudinal cooling
  - Helical Cooling Channel
    - Effective 6D cooling (simulations: cooling factor $>10^5$ in 300 m)
  - Momentum-dependent Helical Cooling Channel
    - 6D Precooling device
    - 6D cooling demonstration experiment (>500% 6 D cooling in 4 m)
    - 6D cooling segments between RF sections
  - Ionization cooling using a parametric resonance, (Epicyclic CC)
- **Methods to manipulate phase space partitions**
  - Reverse emittance exchange using absorbers
  - Bunch coalescing (neutrino factory and muon collider share injector)
- **Technology for better cooling**
  - Pressurized RF cavities
    - simultaneous energy absorption and acceleration and
    - phase rotation, bunching, cooling to increase initial muon capture
    - Higher Gradient in magnetic fields than in vacuum cavities
  - High Temperature Superconductor for up to 50 T magnets
    - Faster cooling, smaller equilibrium emittance

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

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

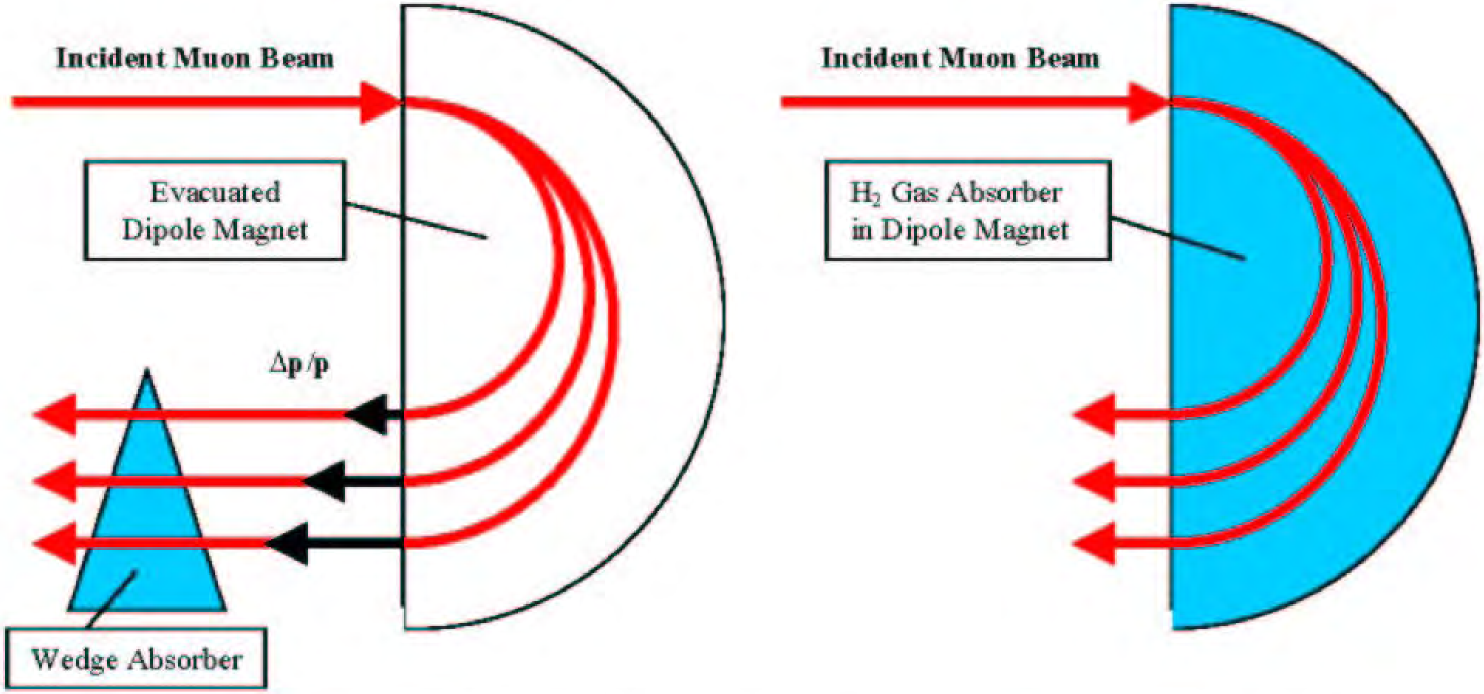


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

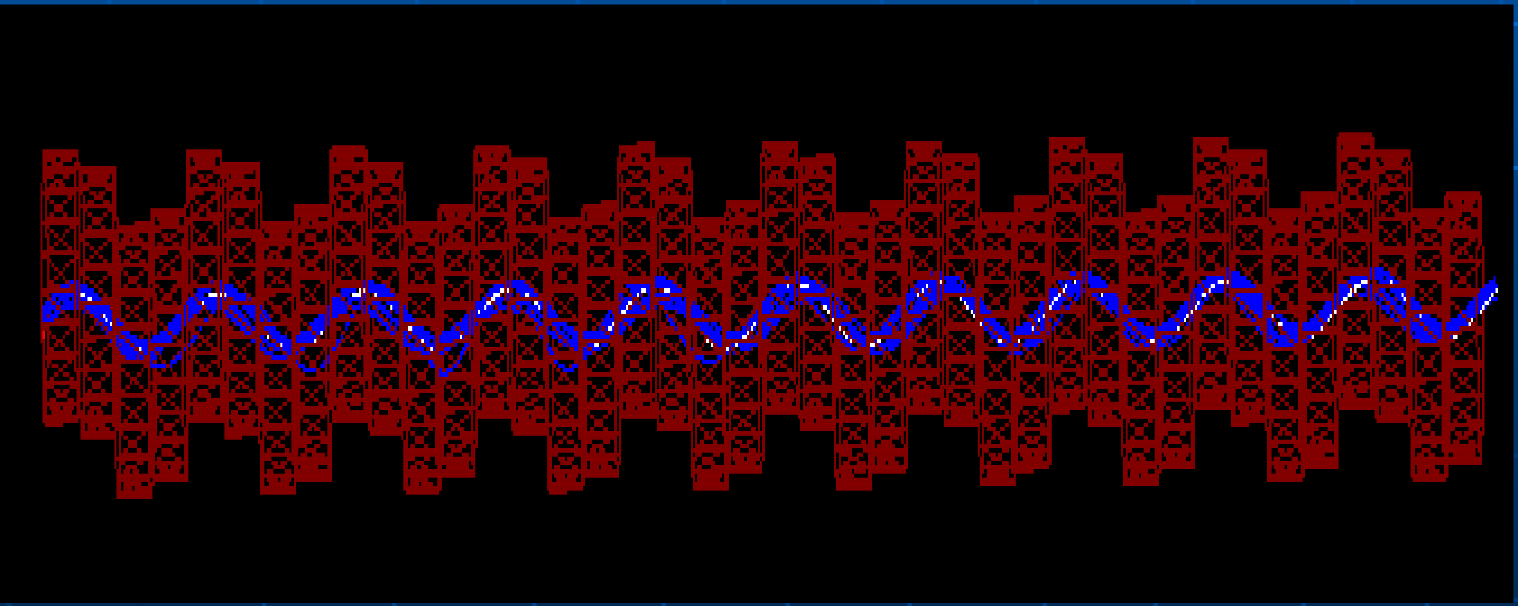
Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

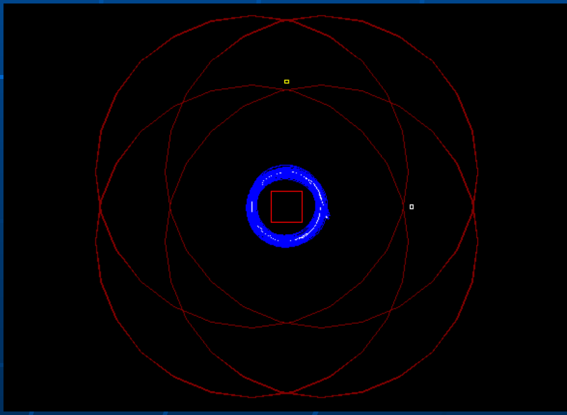
Personal excitement over recent progress

- Simulations, Models, and Inventions
  - New HCC simulations show impressive 6-D cooling
    - More conservative frequencies and apertures – 10^{34} still looking good
  - Parametric-resonance Ionization Cooling – key to LEMC!
    - Epicyclic PIC invention seems to overcome fringe field and D problems
    - G4Beamline model working, ready for development
    - New person (Vasiliy Morozov) dedicated to solving this problem
  - Ramping RLA Magnets to enable more RF cavity traversals
    - variations on and extensions to U Miss concept

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





See Katsuya Yonehara's Talk

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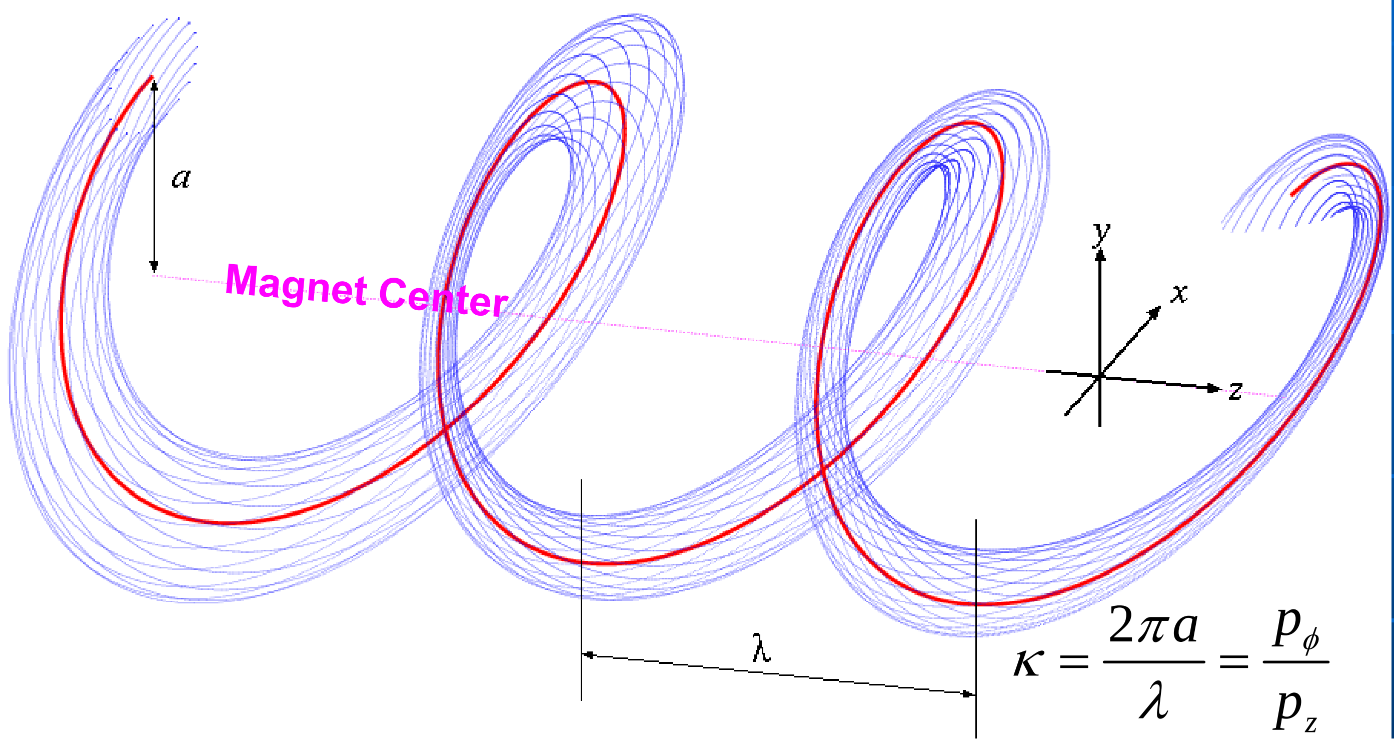
Particle Motion in a Helical Magnet

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

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

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

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

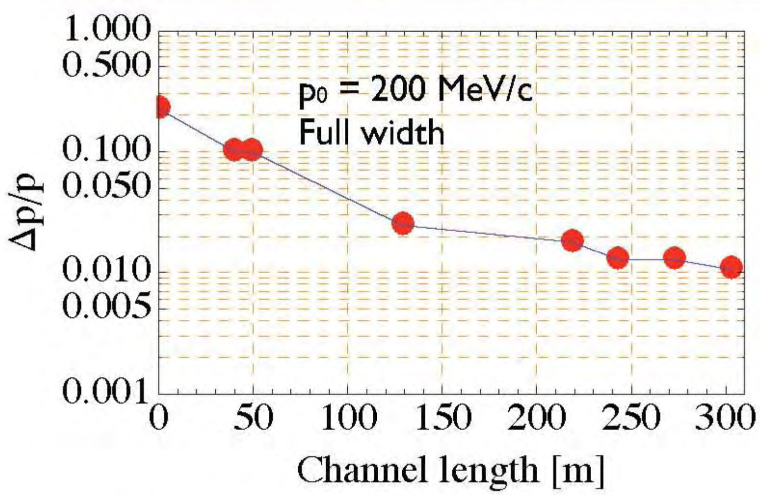
Longitudinal cooling only
$$\hat{D} \equiv \frac{p}{a}\frac{da}{dp} = 2\frac{1+\kappa^2}{\kappa^2} \qquad q = 0$$

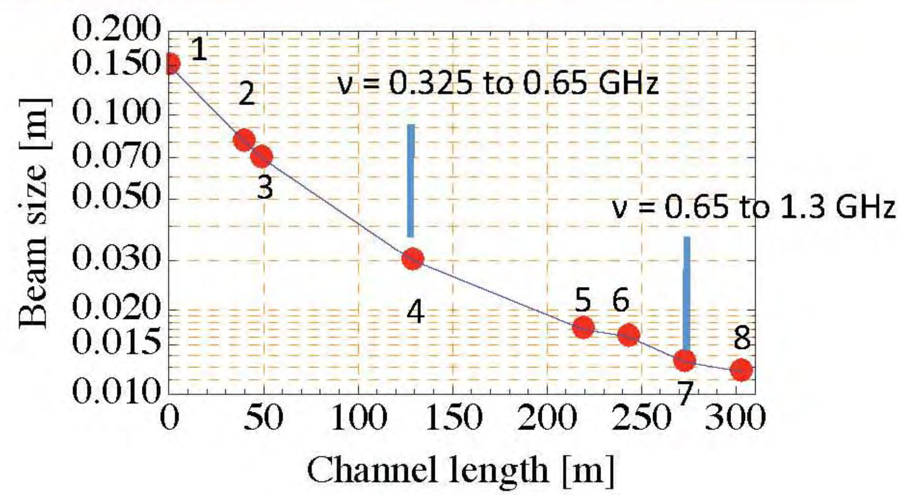
~Momentum slip factor
$$\eta = \frac{d}{d\gamma}\frac{\sqrt{1+\kappa^2}}{\beta} = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right) \qquad \frac{\kappa^2}{1+\kappa^2}\hat{D} \sim \frac{1}{\gamma^2_{transition}}$$

Simulation parameters & results

Simulation has been made with analytical EM field expression in G4beamline

	z	b	b'	bz	λ	N	ε_T	ε_L	ε_{6D}	ε
unit	m	T	T/m	T	m	GHz	mm rad	mm	mm^3	Transmission
1	0						20.4	42.8	12900	
2	40	1.3	-0.5	-4.2	1.0	0.325	5.97	19.7	415.9	0.92
3	49	1.4	-0.6	-4.8	0.9	0.325	4.01	15.0	10.8	0.86
4	129	1.7	-0.8	-5.2	0.8	0.325	1.02	4.8	3.2	0.73
5	219	2.6	-2.0	-8.5	0.5	0.65	0.58	2.1	2.0	0.66
6	243	3.2	-3.1	-9.8	0.4	0.65	0.42	1.3	0.14	0.64
7	273	4.3	-5.6	-14.1	0.3	0.65	0.32	1.0	0.08	0.62
8	303	4.3	-5.6	-14.1	0.3	1.3	0.34	1.1	0.07	0.60





Other important parameters:

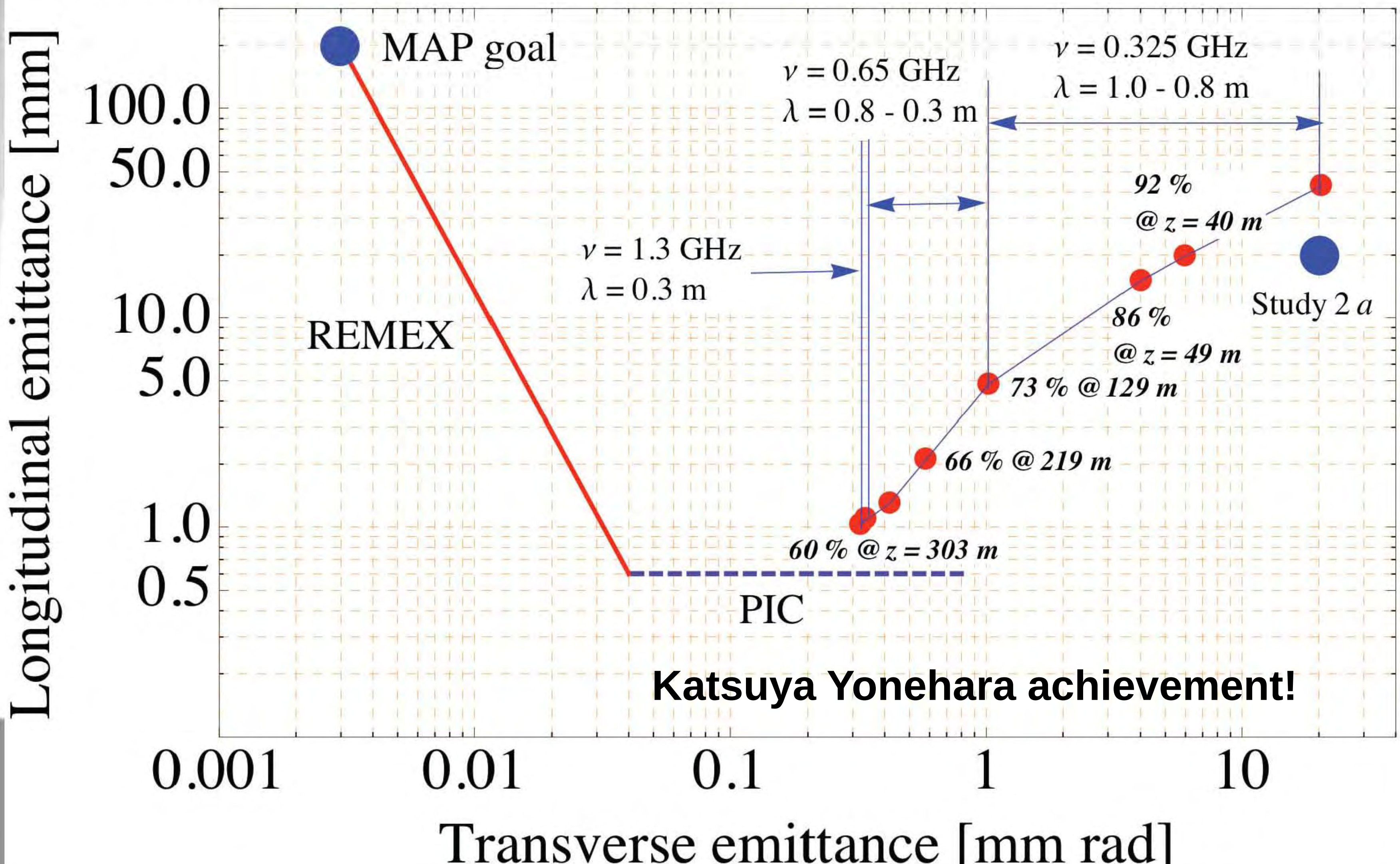
RF E_{peak} = 27 MV / m ⇒ Peak RF power = 10 to less than 0.2 MW / m

60 μm Be window at RF entrance (optimization is on going,

GH2 pressure = 160 atm at 300 K not covered in this talk)

Emittance Evolution in Homogeneous GH2 Filled HCC

- 10^6 of 6D cooling factor is needed for MC
- HCC demonstrated 6D cooling factor > 10^5 with 60 % transmission efficiency
- Additional cooling is needed (Parametric Ionization Cooling etc.)

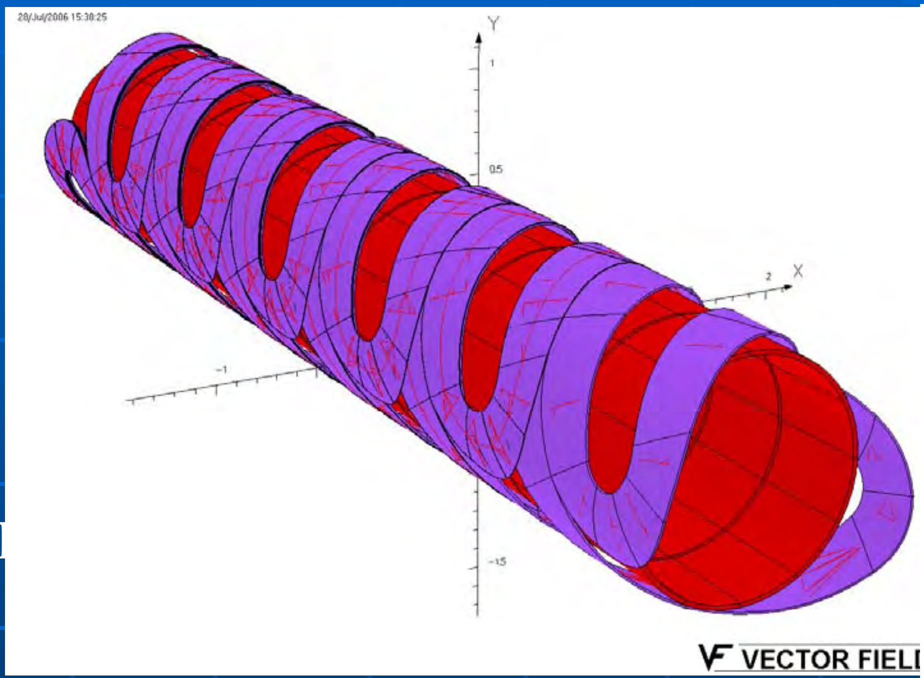


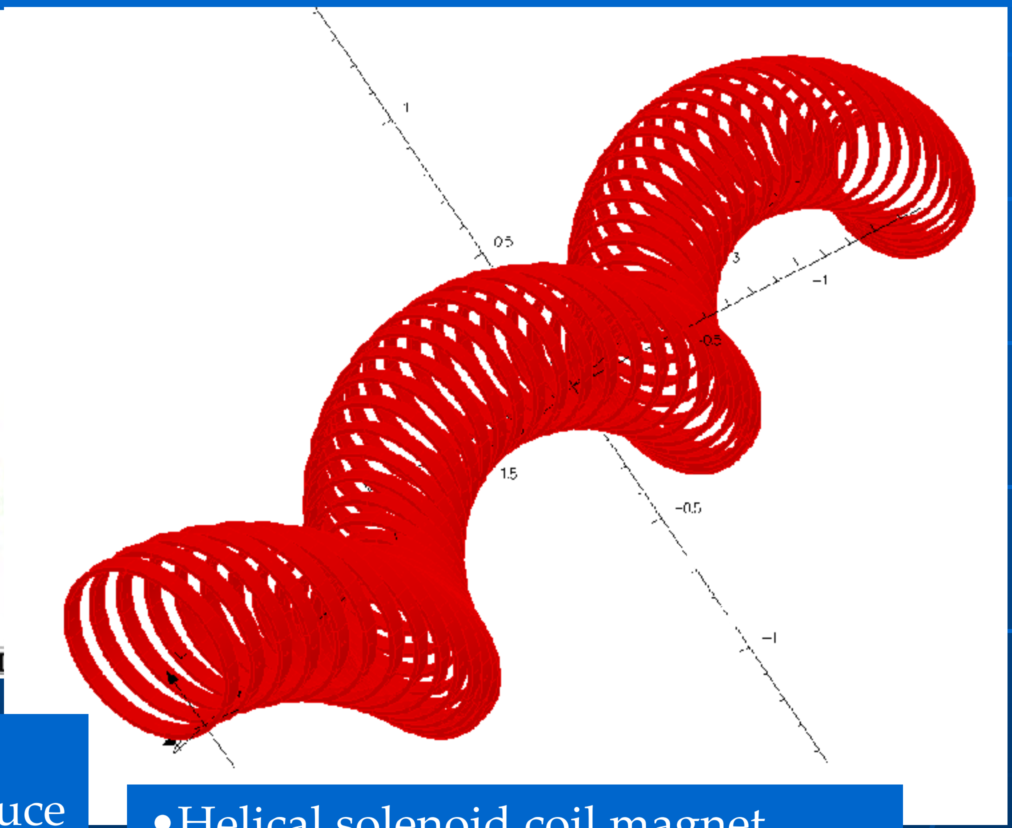
Personal excitement over recent progress

- Technology Development
  - Magnets
    - Helical Solenoid (HS) invention achieves HCC field parameters
    - 1st HS magnets with NbTi built, iterations underway
    - Final HCC magnets using HTS engineered based on HS
    - Two-coil YBCO HS was tested
    - Fiber optic quench protection to be experimentally developed
    - High field magnet development funded by SBIR-STTR
  - RF Cavities
    - First SF6 doping studies support models (which imply beam capability)
    - Beam to the MTA soon
    - Dielectric loaded RF to be tested
    - Engineering solutions for HTS HS with integrated RF proposal submitted
  - RF power
    - Phase and frequency locked magnetron prototype being built

Two Different Designs of Helical Cooling Magnet

Great new for COOL07 innovation!



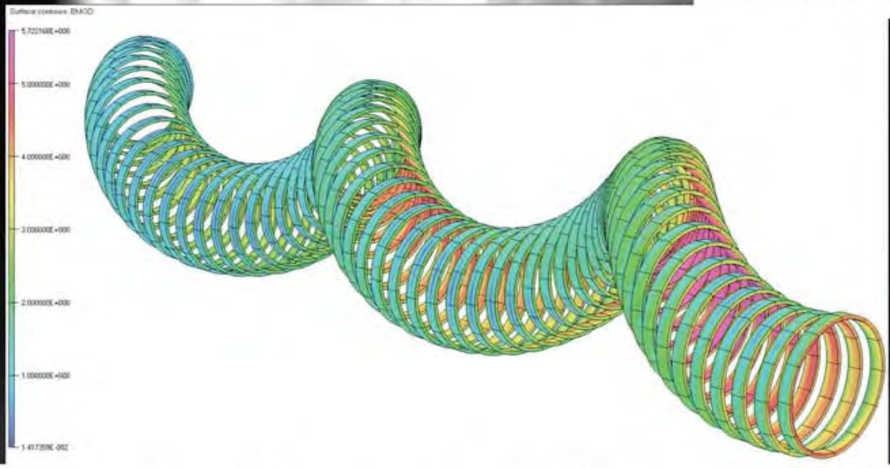


- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.

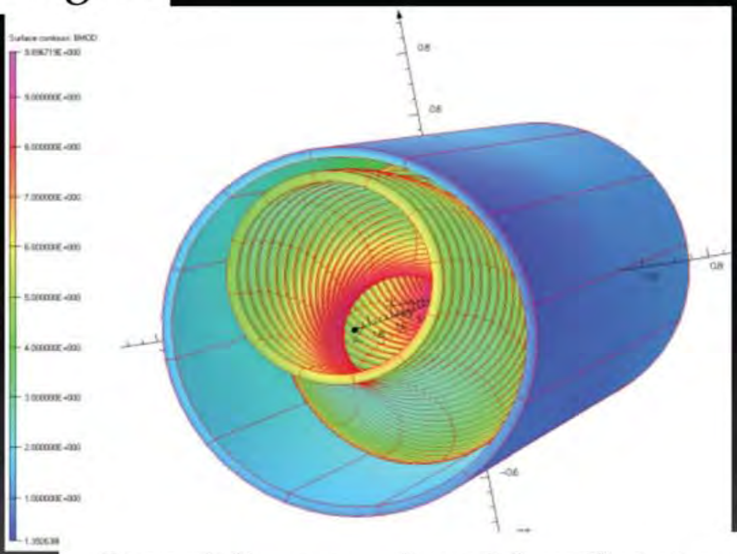
- Helical solenoid coil magnet
- Consists of 73 single coils (no tilt).
- Maximum field is 5 T
- Coil diameter is 0.5 m.

Helical Magnet

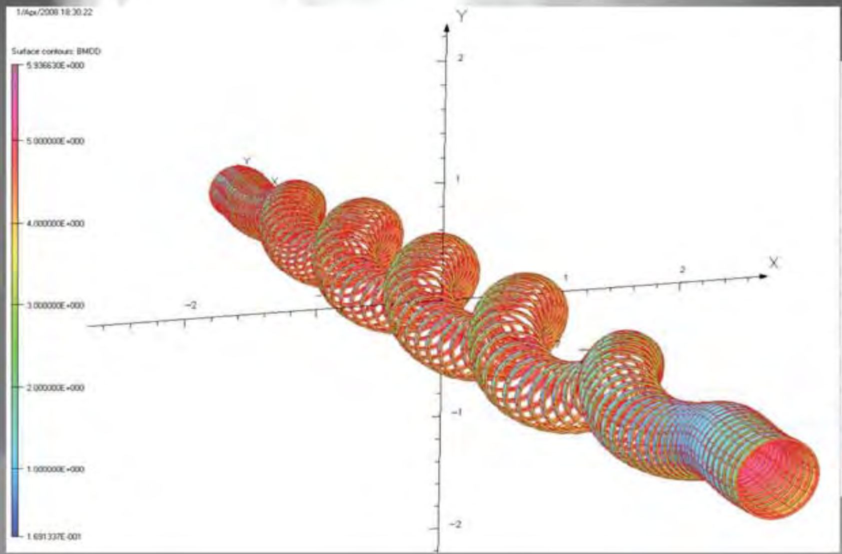
Helical solenoid magnet



- Coil center follows on the helical reference track
- It generates proper helical dipole + field gradient

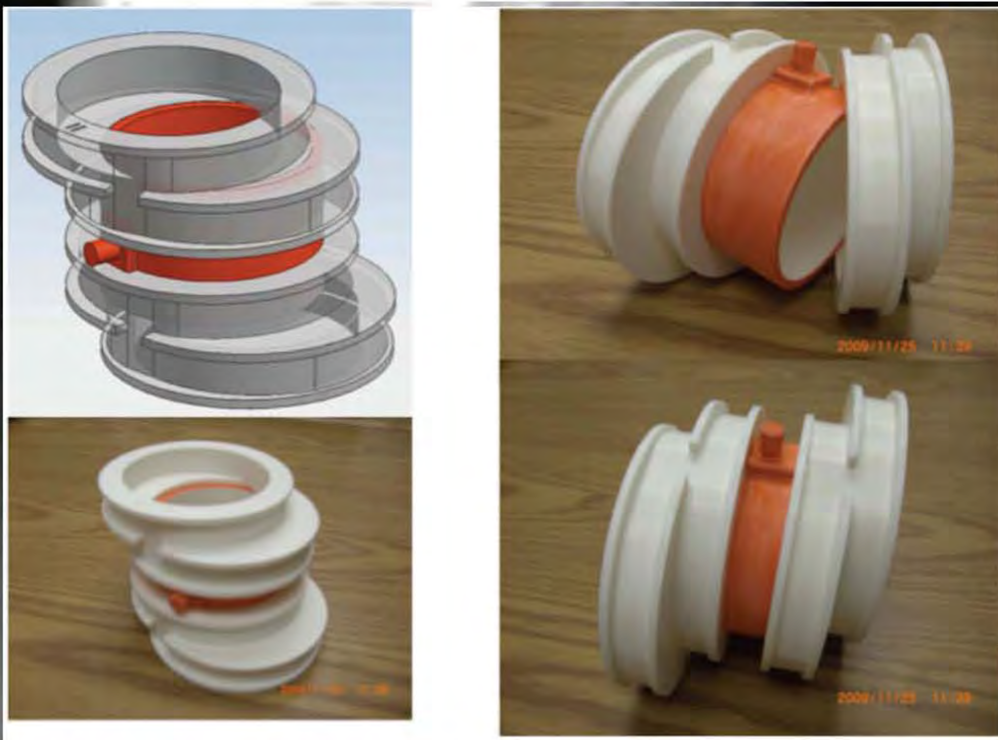


- By adding a solenoid coil, it tunes all three field components (b, b', bz)

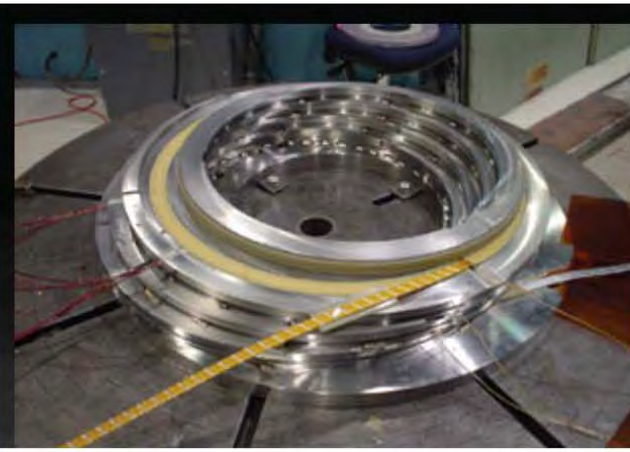


- By modulating the coil position, it can make a beam adapter to connect between straight and helical magnet sections.
- Helical solenoid magnet generates more uniform field than analytical field.
- It means that helical solenoid magnet has larger acceptance than analytical one.

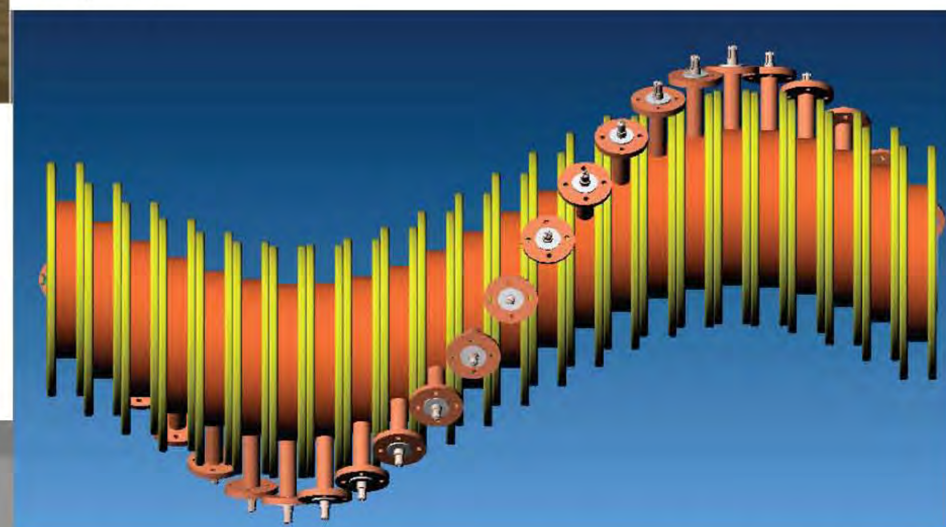
Incorporate RF Cavity into Helical Magnet



- Plastic model to demonstrate integrating RF into helical magnet
- Segment RF cavity and helical solenoid coil
- Red: RF cavity
- White: Helical magnet



- 4-coil helical solenoid magnet to study support structure, splice ground insulation, field quality test, etc...

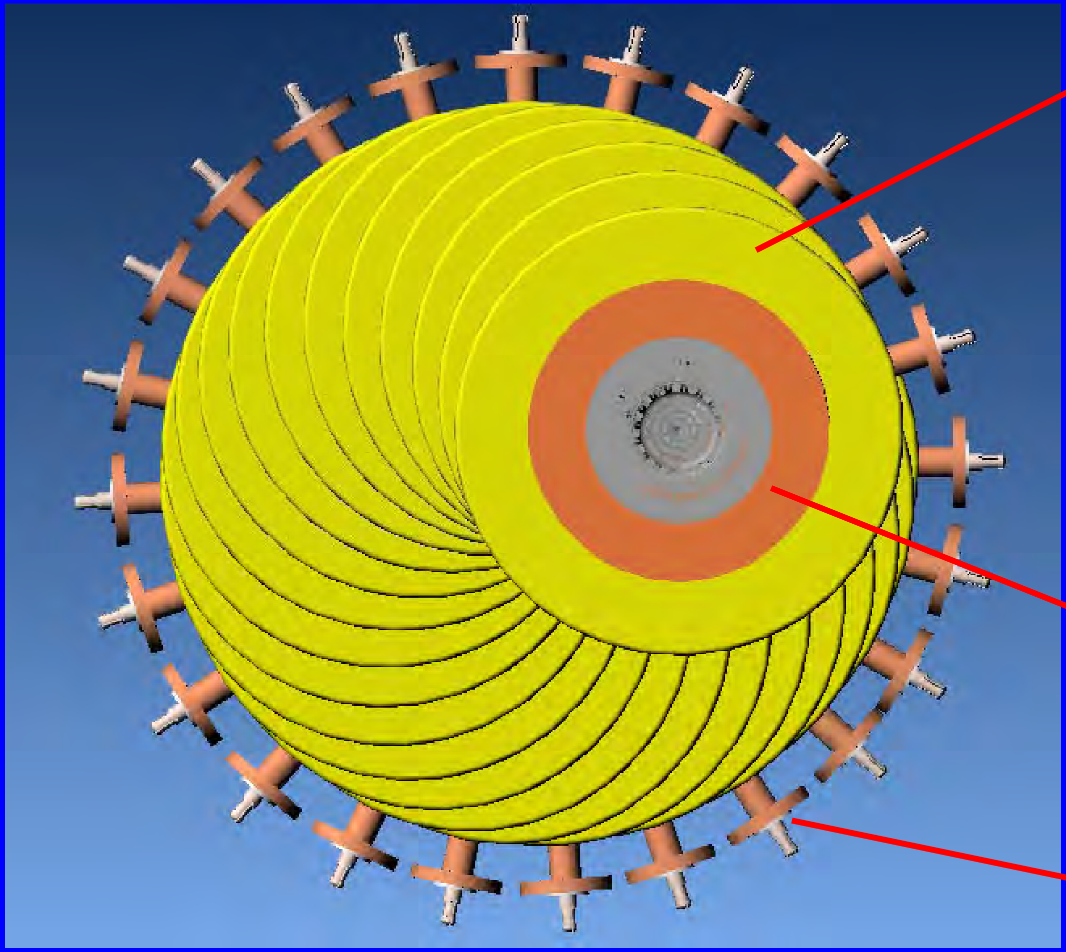


- CAD drawing to show one helical period

See John Tompkins' Talk


BROOMFIELD
S-50 Winder Control
BROOMFIELD
350
See John Tompkins’ Talk

This is a 24 cavity per period 400 MHz design



- Approximate Diameter at the coax flange is 40”

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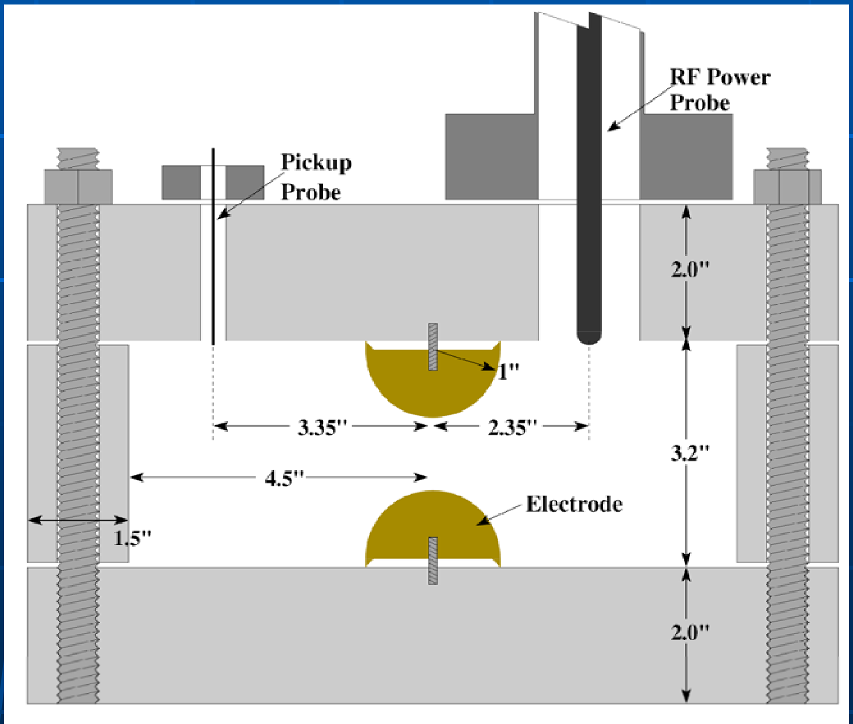
Pressurized High Gradient RF Cavities (IIT, Dan Kaplan)

- 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



MuCool Test Area (MTA)

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Pressure barrier

Mark II Test Cell

Wave guide to coax adapter

5T Solenoid

HPRF Test Cell Measurements in MTA

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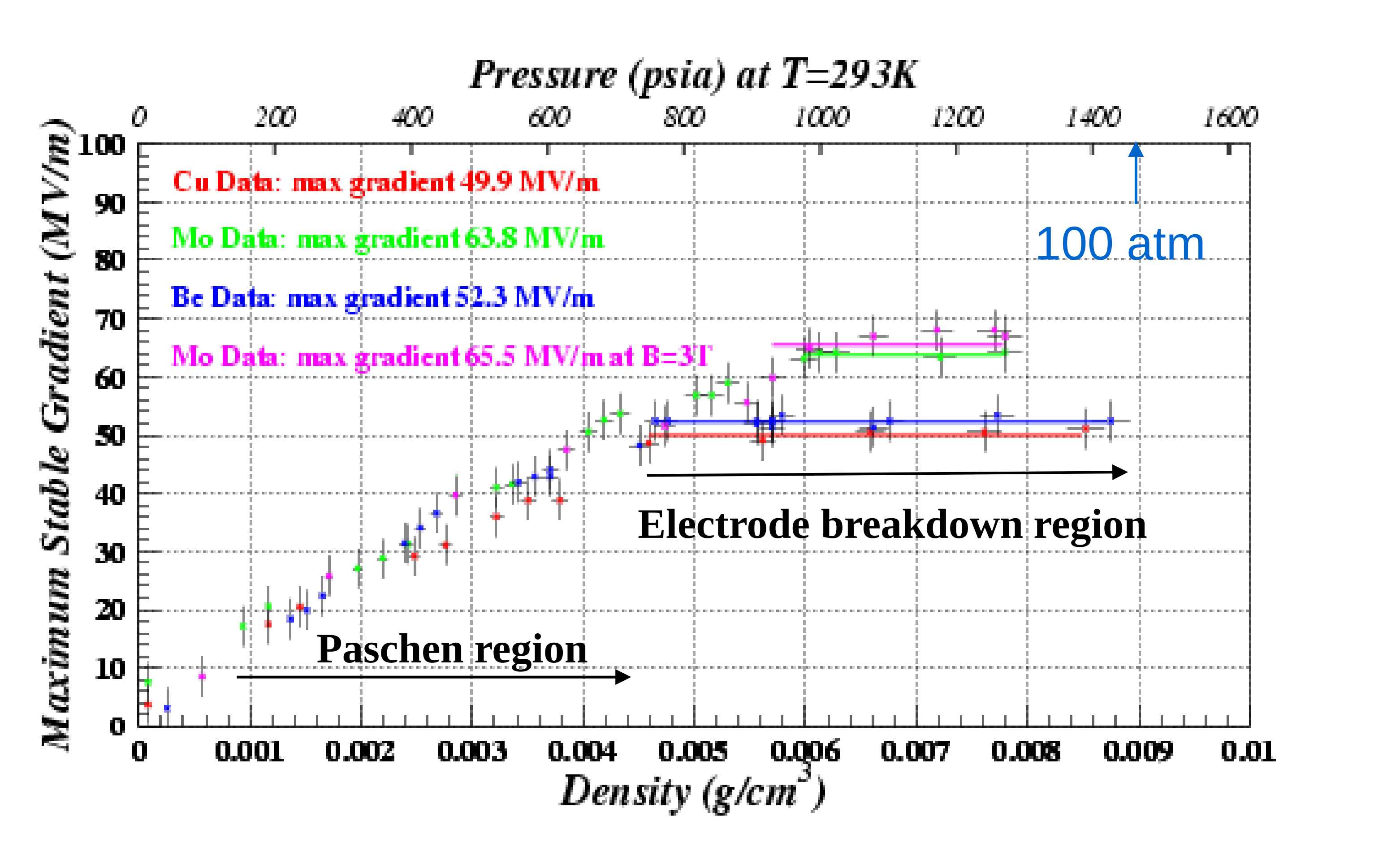
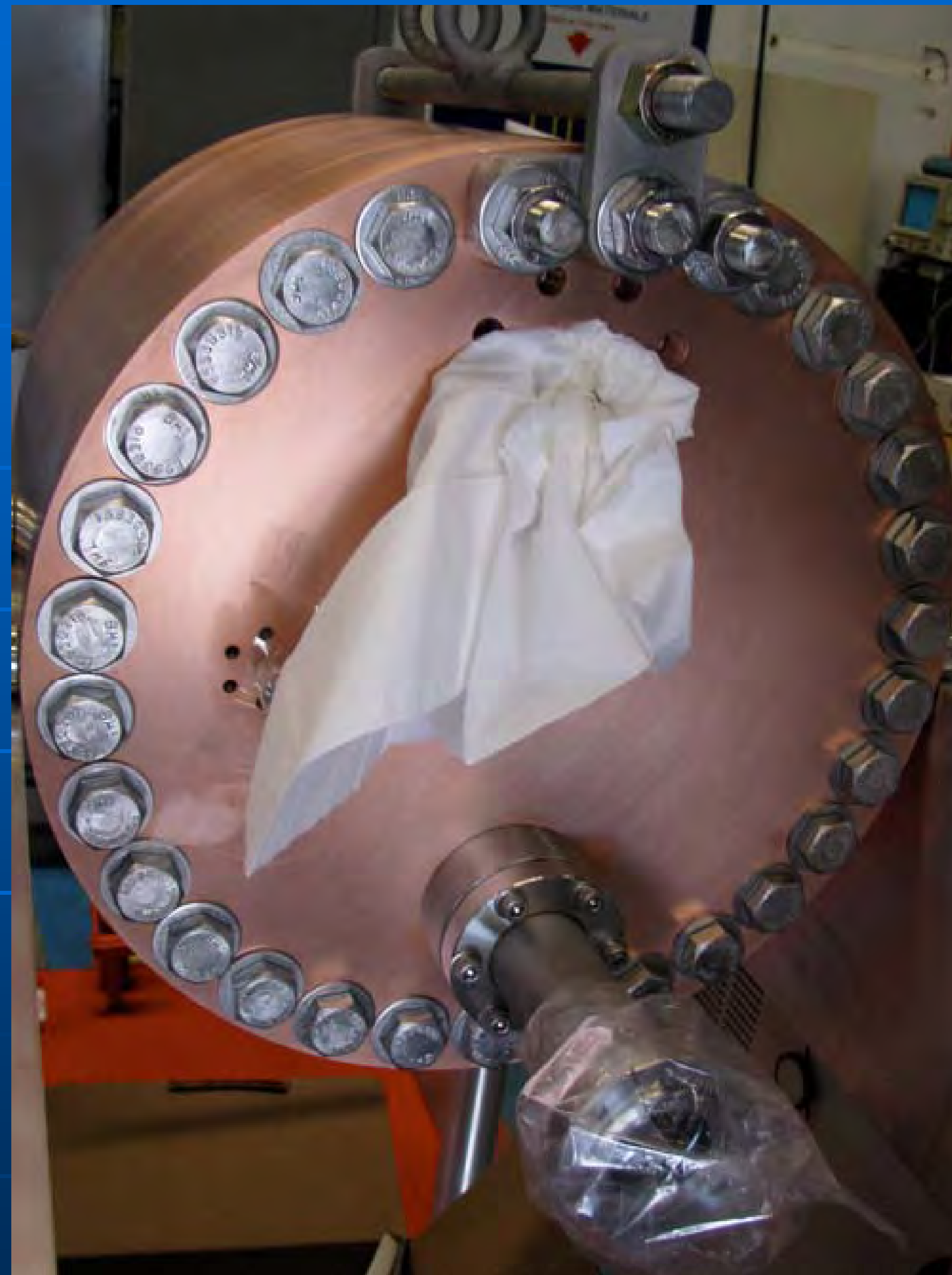


- Paschen curve verified
- Maximum gradient limited by breakdown of metal.
- Cu and Be have same breakdown limits (~50 MV/m), Mo(~63MV/m), W(~75MV/m).
- Results show no B dependence, much different metallic breakdown than for vacuum cavities.
- **Need beam tests to prove HPRF works.**

See Alvin's Talk

All seasons pillbox cavity
New contract with LANL



End plates can be of different shapes (grids,windows..), materials (Cu, Be..), or treatments (EP, ALD…)

Bolted cavity achieved <3E-8 Torr

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See Vasiliy Morozov'sTalk!

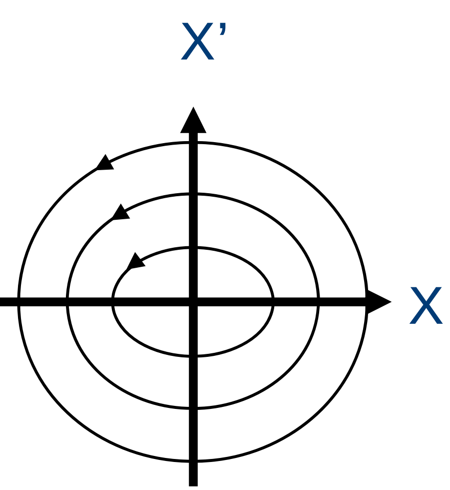
Parametric-resonance Ionization Cooling

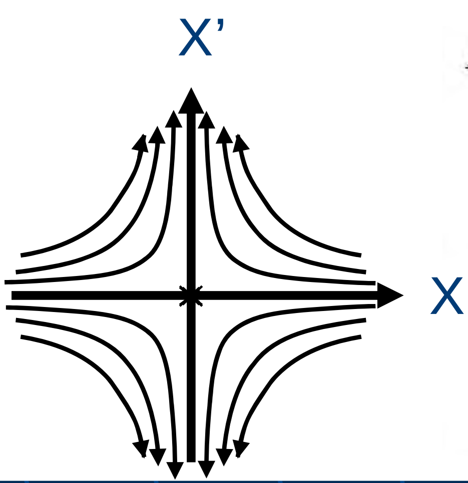
Excite ½ integer parametric resonance (in Linac or ring)

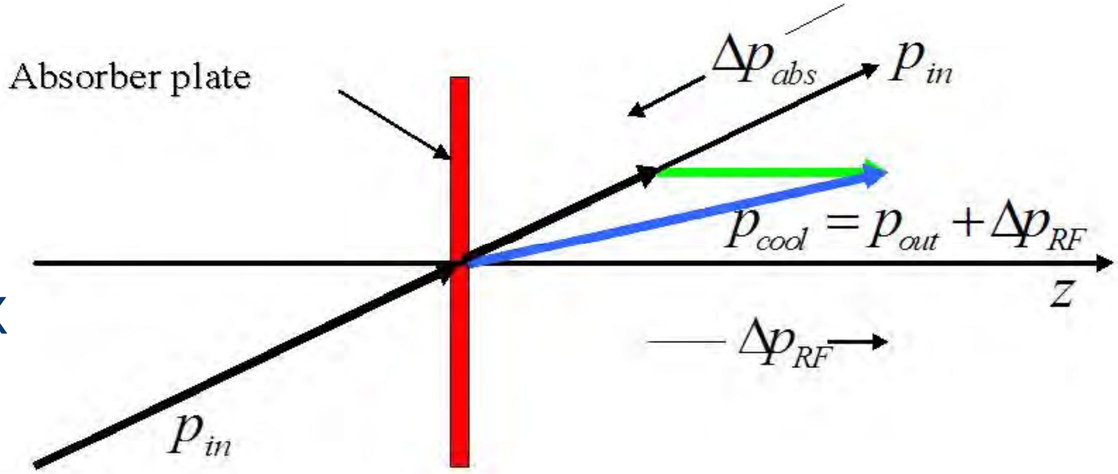
- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx'=const to reduce x, increase x'
- Use IC to reduce x'

Detuning issues being addressed (chromatic and spherical aberrations, space-charge tune spread). Simulations underway.

Smaller beams from 6D HCC cooling essential for this to work!

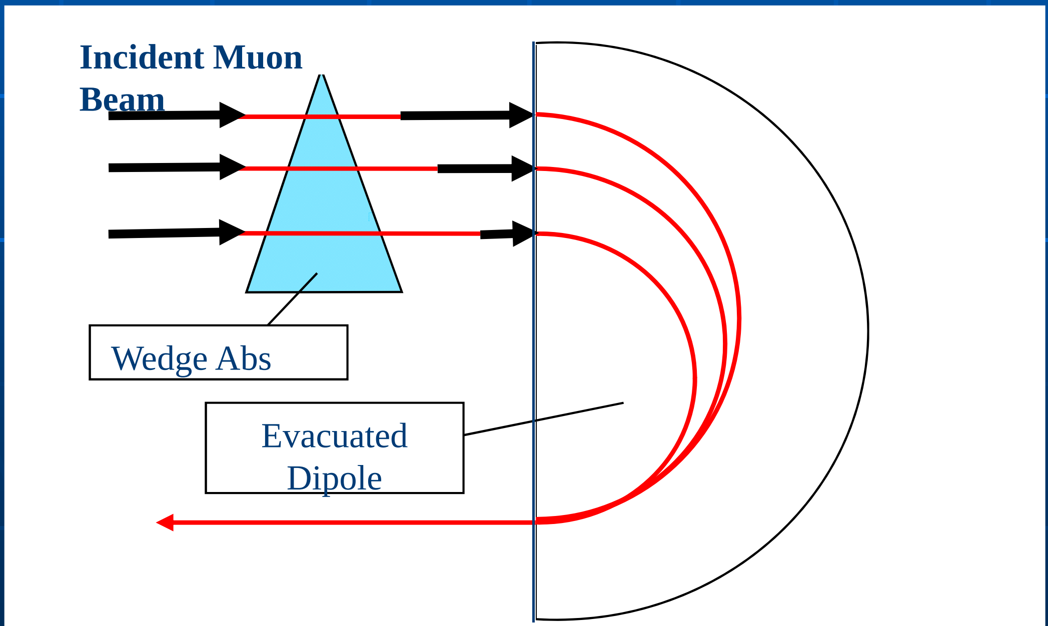




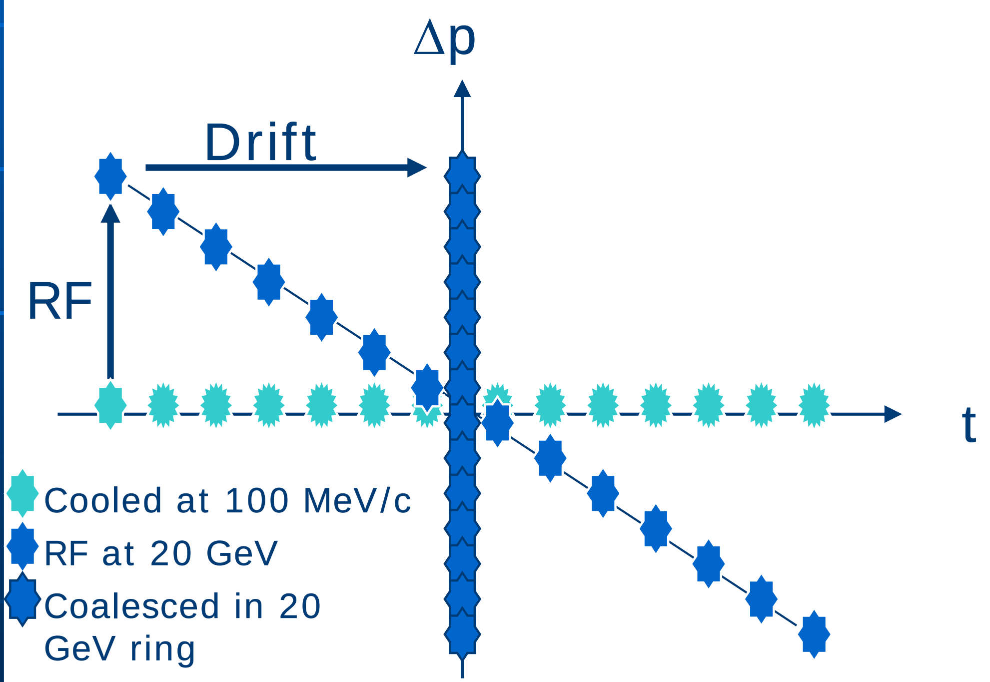


Reverse Emittance Exchange, Coalescing

- p(cooling)=100MeV/c, p(colliding)=2.5 TeV/c => room in Δp/p space
- Shrink the transverse dimensions of a muon beam to increase the luminosity of a muon collider using wedge absorbers
- Allow bunch length to increase to size of low beta
- Low energy space charge, beam loading, wake fields problems avoided
- 20 GeV Bunch coalescing in a ring Neutrino factory and muon collider now have a common path



Concept of Reverse Emittance Exch.



1.3 GHz Bunch Coalescing at 20 GeV

Updated Letter of Intent to Propose

MANX, A 6D MUON BEAM COOLING EXPERIMENT

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], Stephen Geer[2], 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], Vladimir Shiltsev[2], Linda Spentzouris[6], Alvin Tollestrup[2], Daniele Turrioni[2], Victor Yarba[2], Katsuya Yonehara[2], Cary Yoshikawa[2], Alexander Zlobin[2]

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[2] *Fermi National Accelerator Laboratory*
[3] *Thomas Jefferson National Accelerator Facility*
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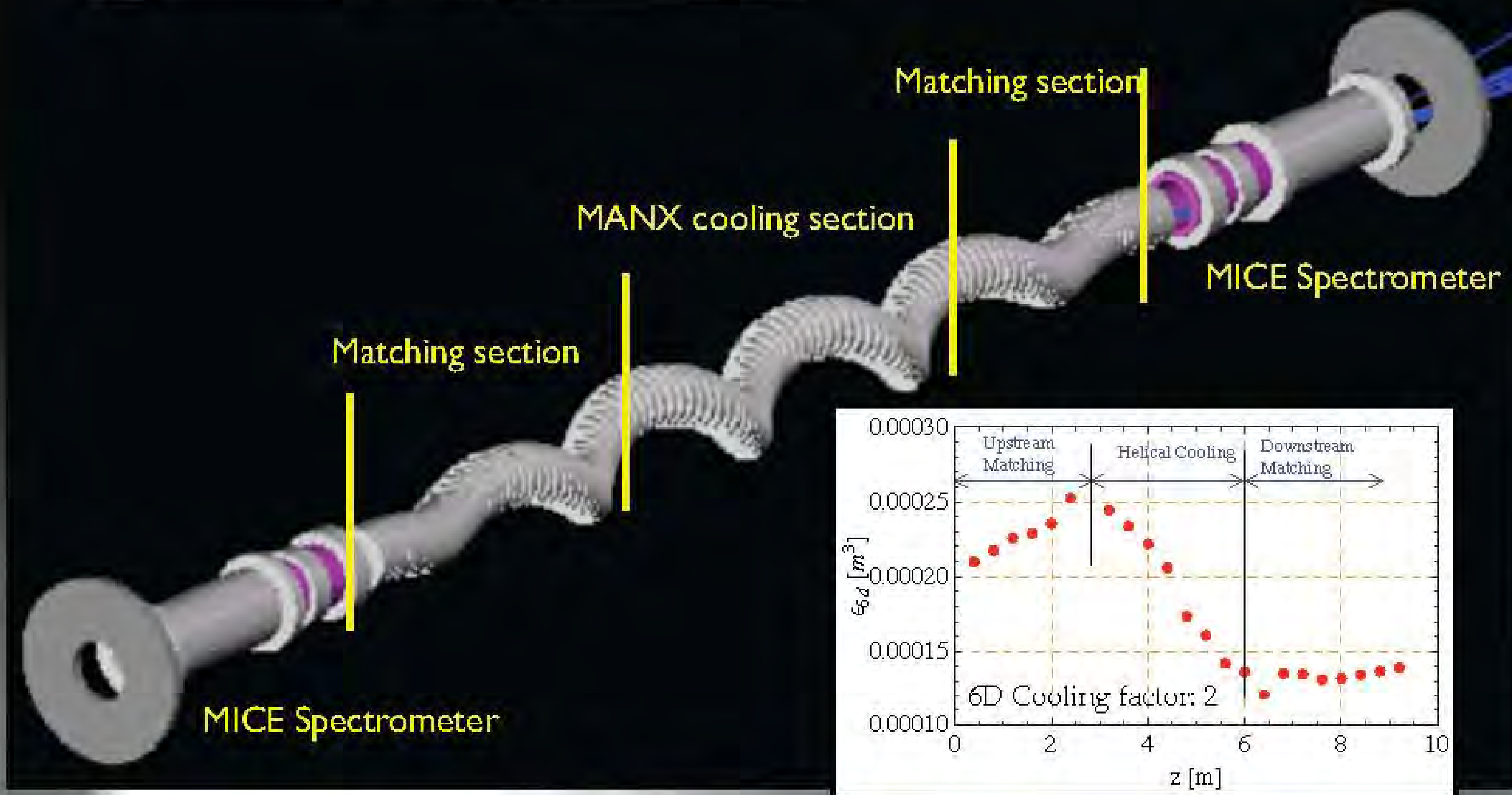
Helical 6D cooling demo experiment

Muons, Inc.
Innovation in Research



- LHe is contained as cooling absorber
- No RF in original design for simplicity and cost saving
- RF can be loaded in later
- Beam element is re-usable for real MC complex

Personal excitement over recent progress (cntd)

•New Synergies

•Project-X heeding MC and NF needs
- •Contributing to: H^- Source, laser stripping, magnetron, couplers,

•Mu2e experiment P-X upgrade uses muon cooling techniques,
- •Favorable reviews, but still awaiting Fermilab response to “MANX following MICE” and “Mu2e Upgrade” proposals
- •My lesson – need to have at least two competitors

•Homeland Security
- •Muons for Special Nuclear Material (SNM) detection (LANL)

•Advanced Research Project Administration – Energy (ARPA-E)
- •Accelerator-Driven Subcritical (ADS) Power Generation, and Nuclear Waste Disposal (ATW)
- •Can ARPA-E help fund and expedite more powerful Project-X, to make sure MC and NF needs are met?

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.

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.

Energy Independence, Climate Change, High-Tech National Goals

P-X and ADS

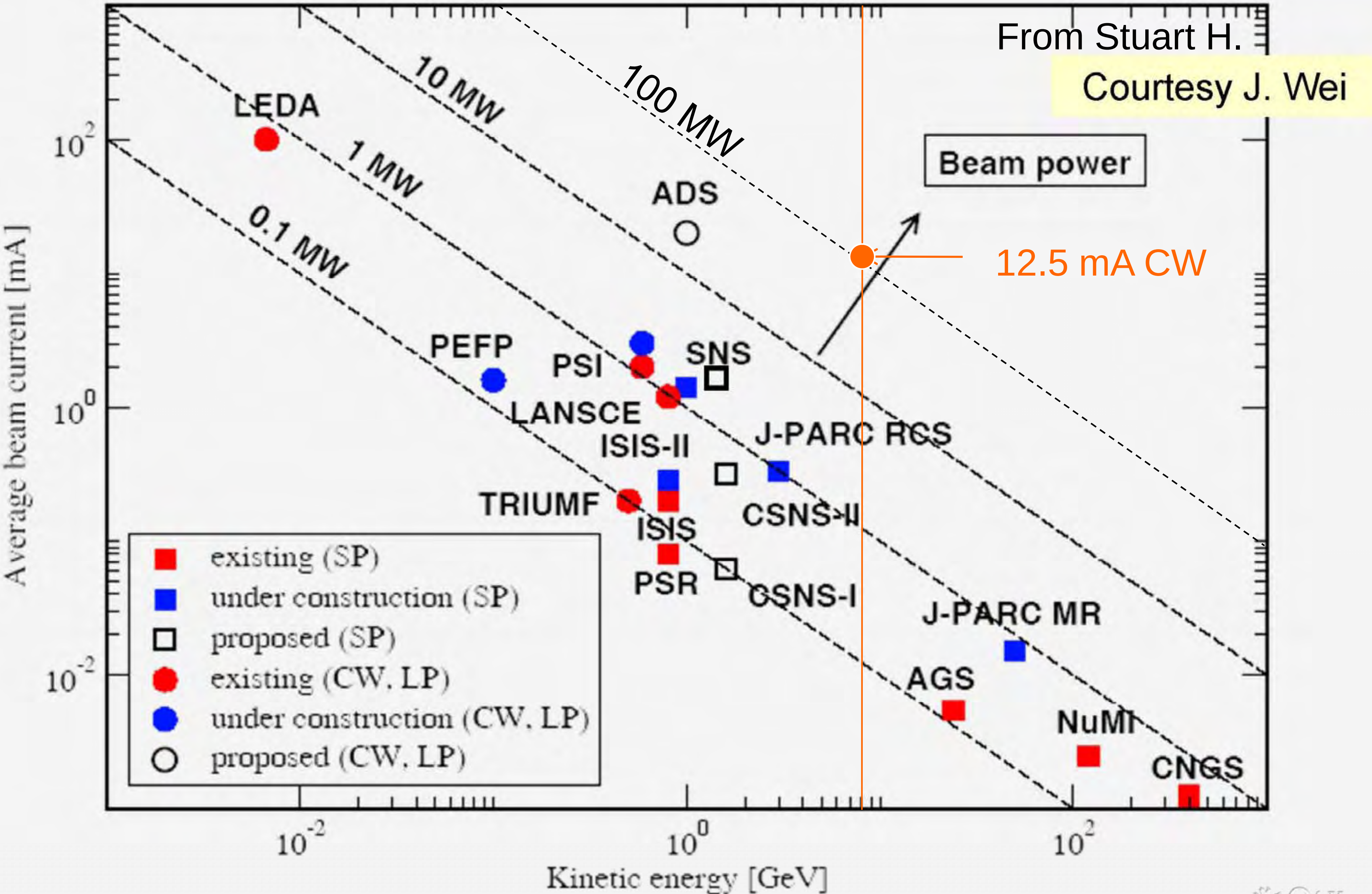
P-X can be the prototype for an ADS ATW machine to develop accelerator and reactor techniques and test materials (>>10 MW)

Since most P-X physics uses require accumulator and buncher rings, the linac design can be flexible. High current capability makes HEP easier.

Let's get the US Government (for national environmental goals) and US Industry (for fun and profit) interested to support ADS R&D using our unique accelerator expertise.

We imagine a Project-X which would supply the required power for ADS & ATW development and also replace the Fermilab Booster for the next 40 years of exciting fundamental science at the intensity and energy frontiers while addressing National Goals: Energy Independence, Climate Change, High-Tech Work Force.

An Intensity Frontier Machine to also feed an Energy Frontier Machine



Comparing alternatives

AkerSolutions

To continuously generate a power output of 1GW for a year requires:

3,500,000 tonnes of coal

Significant impact upon the Environment

especially CO_2 emissions

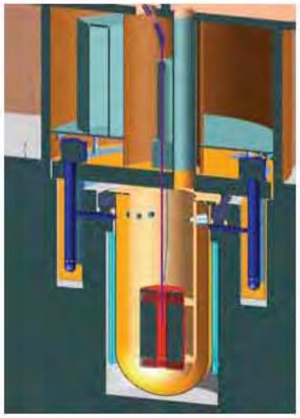
200 tonnes of Uranium

Low CO_2 impact

but challenges with reprocessing

and very long-term storage of hazardous wastes

Proliferation



1 tonne of Thorium

Low CO_2 impact

Can consume Plutonium and radioactive waste

Reduced quantity and much shorter duration for storage of hazardous wastes

No proliferation

C.Rubbia2, Energy 2050, Stockholm

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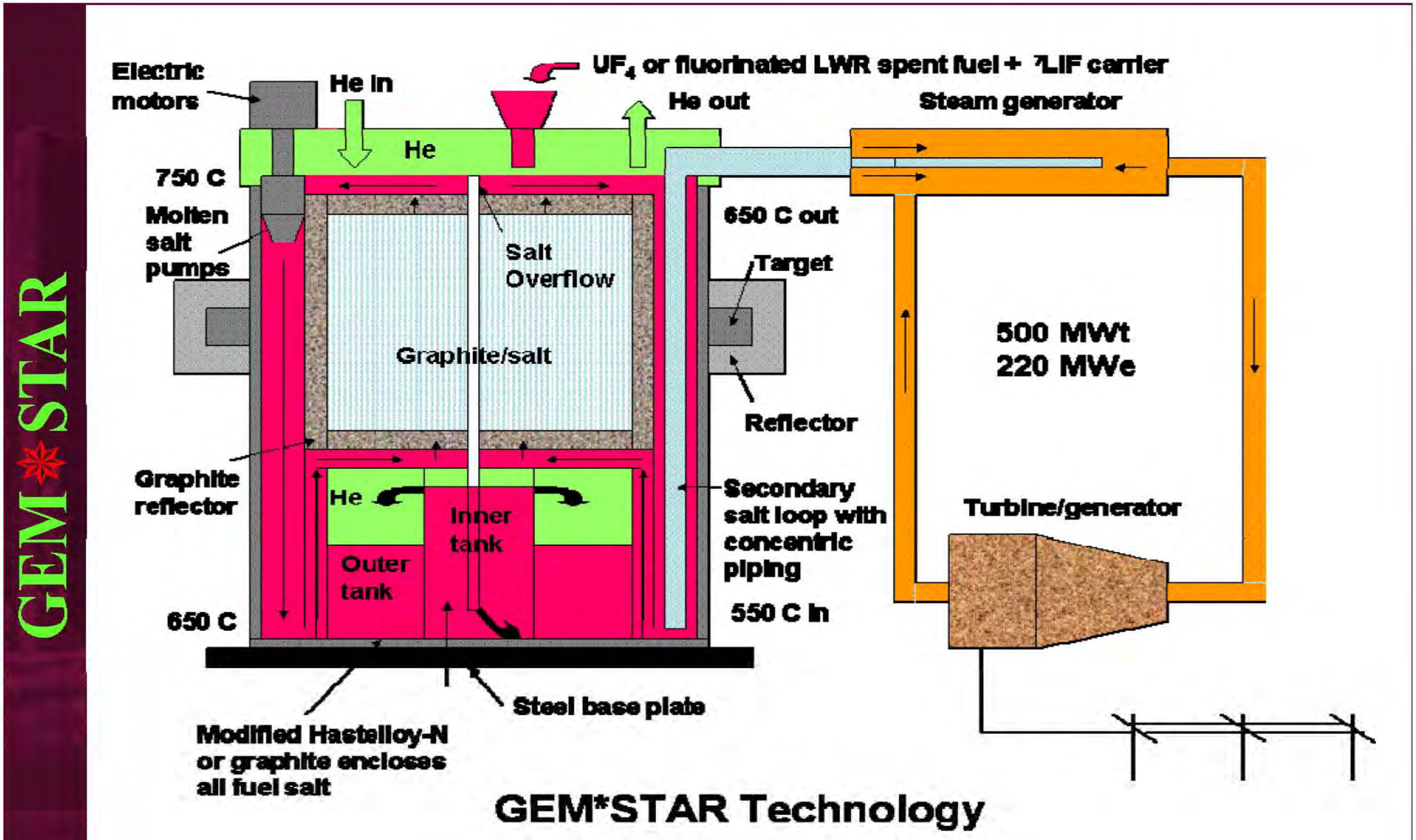

Functional Components

Conclusions

It is possible to get the US back to the energy frontier!

And along the way, we can provide the world with an abundance of power for 1,000 years with minimal impact on the environment!

Anyone who believes these goals are exciting is invited to join in.