Muon Collider Design Workshop - Summary

Alex Bogacz

Muon Collider Design Workshop

Muons, Inc. Innovation in Research

Muon Collider Task Force

Sponsorship support provided by Muons, Inc.

Motivation & Goals

The annual Muon Collider Design Workshop (previously hosted at BNL) is aimed at bringing together all the groups working on various designs for Muon Colliders. The goal is to **review and assess the current state of the concepts, simulation work and experiments**. We shall examine practical limits on the performance of required technologies in attempt to focus future efforts towards a baseline collider scenario. The workshops will cover topics such as:

- Proton drivers
- Muon cooling and demonstration experiments
- Bunch recombination
- Muon acceleration schemes
- Collider Ring and Interaction region design
- Site boundary radiation
- Detector concepts for energy frontier

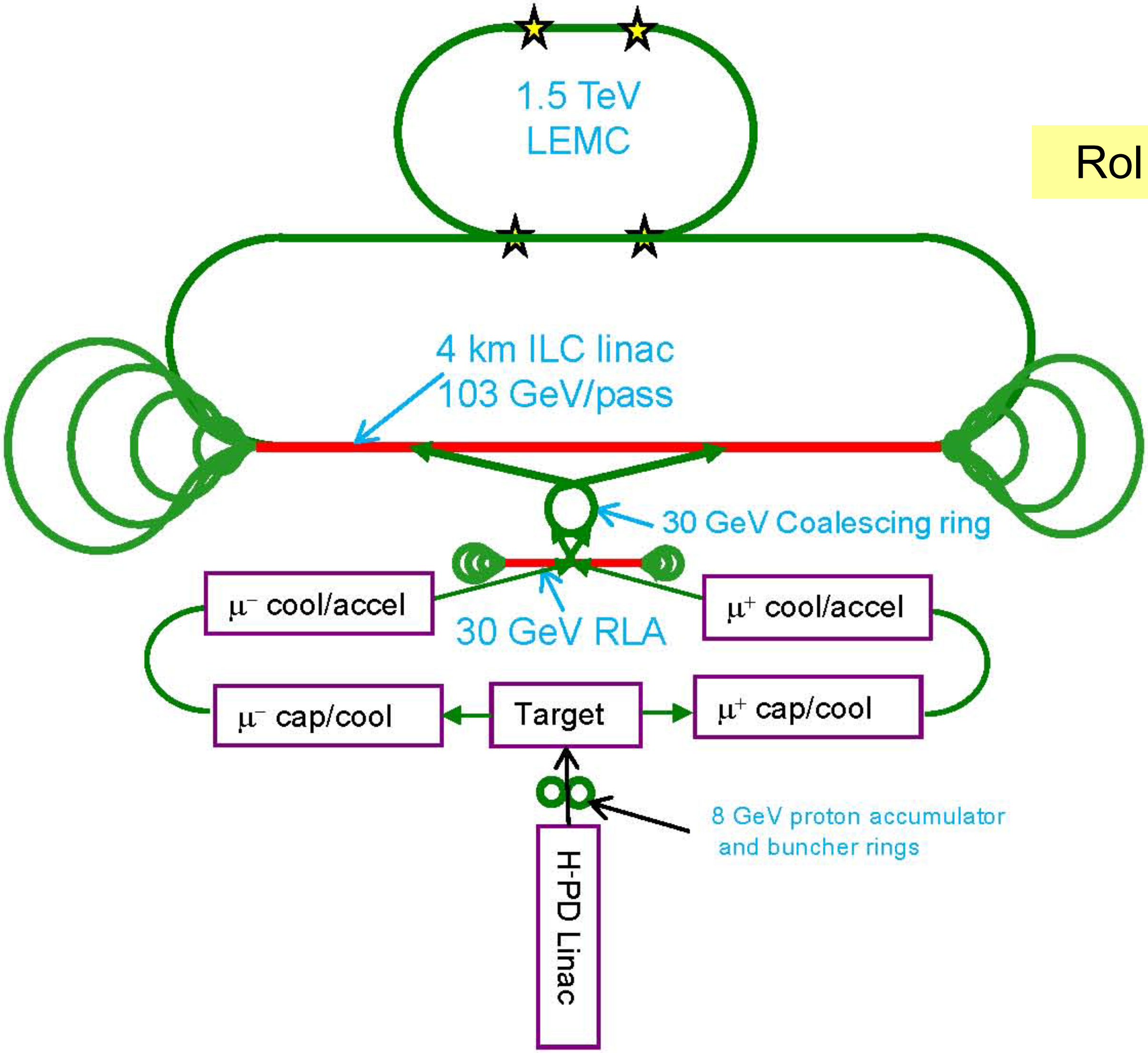
Program - Sessions

- COLLIDER SCENARIOS
- PROTON DRIVER & RF
- COOLING SIMULATIONS
- FINAL COOLING
- ACCELERATION
- INTERACTION REGION
- EXPERIMENTS & PLANS
- SUMMARIES

Participants

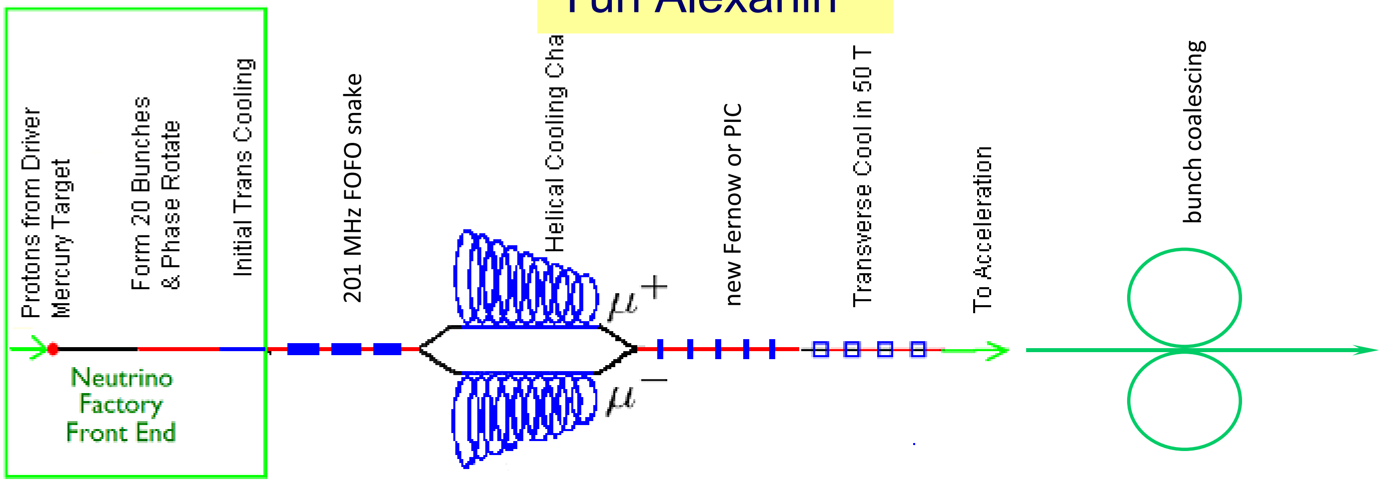
LEMC Scenario

Rol Johnson



Medium Emittance scheme of 2007

Yuri Alexahin



Bob Palmer found a number of weak points with this scheme:

- bunch length grows >1m during REMEX in 50T solenoids ⇒ bunch frequency of 200MHz can not be sustained ⇒ merging should be done before REMEX with all the losses due to merging and recooling;
- "super-Fernow" (aka bucked coil) lattice has poor transmission (<50%) making the overall survival a dismal 4% (if Guggenheims are used for 6D cooling).

Still I think that the idea is not hopeless, though modifications are necessary

Parameters of Different MC options

	Low Emit.	High Emit.	MCTF07		MCTF08
$\sqrt{s}$ (TeV)		1.5			
Av. Luminosity (10^{34}/cm^2/s) *	2.7	1	1.33-2		
Av. Bending field (T)	10	6	6		
Mean radius (m)	361.4	500	500	$\Rightarrow$	495
No. of IPs	4	2	2		
Proton Driver Rep Rate (Hz)	65	13	40-60		
Beam-beam parameter/IP	0.052	0.087	0.1		
β^* (cm)	0.5	1	1		
Bunch length (cm)	0.5	1	1		
No. bunches / beam	10	1	1		
No. muons/bunch (10^{11})	1	20	11.3		
Norm. Trans. Emit. (μm)	2.1	25	12.3		
Energy spread (%)	1	0.1	0.2		
Norm. long. Emit. (m)	0.35	0.07	0.14		
Total RF voltage (GV) at 800MHz	$407\times10^3\alpha_c$	0.21**	0.84**	$\Rightarrow$	0.3†
Muon survival $N\mu/N\mu0$	0.31	0.07	0.2		?
μ+ in collision / proton	0.047	0.01	0.03		?
8 GeV proton beam power	3.62***	3.2	1.9-2.8		?

HEMC Scenario

Collider Parameters

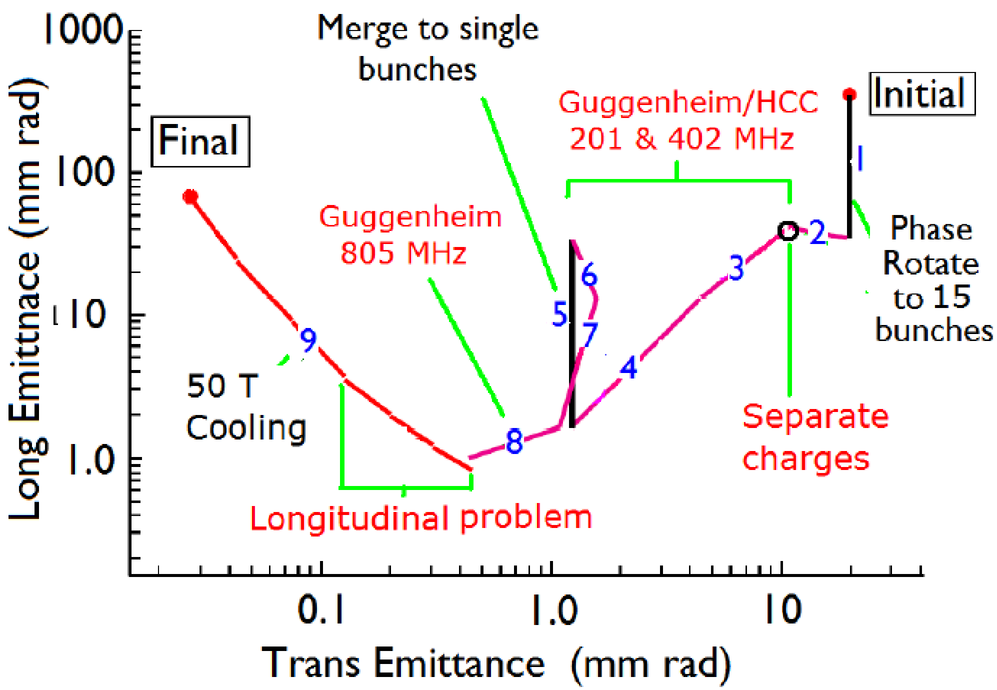
Bob Palmer

Same as last year included for reference

C of m Energy	1.5	4	TeV
Luminosity	1	4	10^{34} cm^{2}sec^{-1}
Muons/bunch	2	2	10^{12}
Ring circumference	3	8.1	km
Beta at IP $= \sigma_z$	10	3	mm
rms momentum spread	0.1	0.12	%
Required depth for ν rad	13	135	m
Repetition Rate	12	6	Hz
Proton Driver power	$\approx$4	$\approx$ 1.8	MW
Muon Trans Emittance	25	25	pi mm mrad
Muon Long Emittance	72,000	72,000	pi mm mrad

- Based on real Collider Ring designs, though both have problems
- Emittance and bunch intensity requirement same for all examples
- Luminosities are comparable to CLIC's
- Depth for ν radiation keeps off site dose < 1 mrem/year

HEMC Scenario



Most Serious Questions

1. Transmission
2. Breakdown in Cooling rf and effect on #1 Discussed here
3. Separation of charges and effect on #1 Fernow
4. Early 50 T cooling and effect on #1 Next

Proton Driver

	PROTON DRIVER & RF	Chair, Bill Weng
1:00-1:40	Project X: the Initial Configuration	Paul Derwent
1:40-2:05	Project X as a Proton Driver	Chuck Ankenbrandt
2:05-2:30	Physics Issues of 8-GeV Accumulator/Buncher Ring	Valeri Lebedev
2:30-2:55	CW Linac Version of Project X [Part 1 | Part 2]	Rol Johnson
2:55-3:25	Coffee Break & Group Photo	
3:25-3:50	Overview of Proton Driver Studies in UK	Chris Prior
3:50-4:15	IDS Proton Driver to Drive a Muon Collider	Scott Berg
4:15-4:40	Recent RF Ideas	Diktys Stratakis
4:40-5:05	Dielectric Loaded RF Cavities	Milorad Popovic
5:15-6:45	Welcome Reception	

IDS Proton Driver Specifications

Scott Berg

- Proton driver power: 4 MW
- Proton driver repetition rate: 50 Hz
- Proton driver energy: around 10 GeV
- 3 proton bunches in train
  - 1.7×10^{13} protons per bunch at 10 GeV
- Bunch length: 1–3 ns
- Train length at least 200 μs

Conclusions

Scott Berg

- Gap to bridge between NF and MC
- Get a little from everyone
  - Squeeze as much current into PD as we can
    - Easy to say. . .
    - Multiple-beamline systems? Duplication
  - Higher energy PD
  - Maximize cooling for more rep rate
    - Easy to say. . .

Boundary conditions

Valeri Lebedev

- Linac
  - Beam current ≤ 40 mA
  - Pulse length ≤ 1 ms
  - Repetition rate = 15 Hz
- RMS bunch length after compressed < 60 cm
- Beam is focused on the mercury target of 5 mm radius
- Rms beam size = 2 mm
- Beta-function on the target ≥ target length (~20 cm)
- Maximize beam power on the target

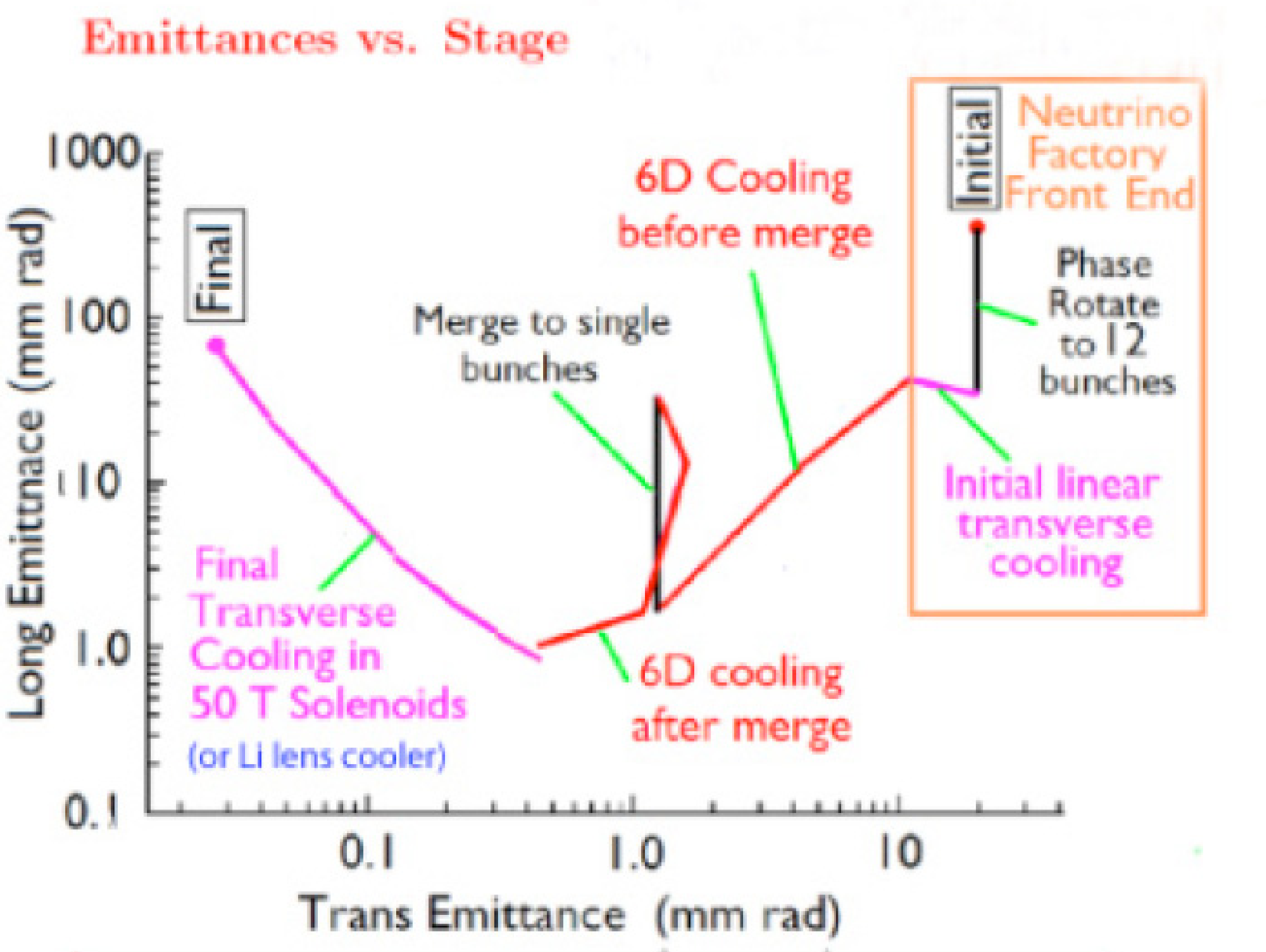
More or about 1 MW is desirable

Main beam physics limitations

- Consistency of beam parameters through entire chain of the planned proton accelerators
- Beam focusing on the target
- Longitudinal beam stability
- Transverse beam stability
- Particle loss due to non-linear forces of the beam space charge

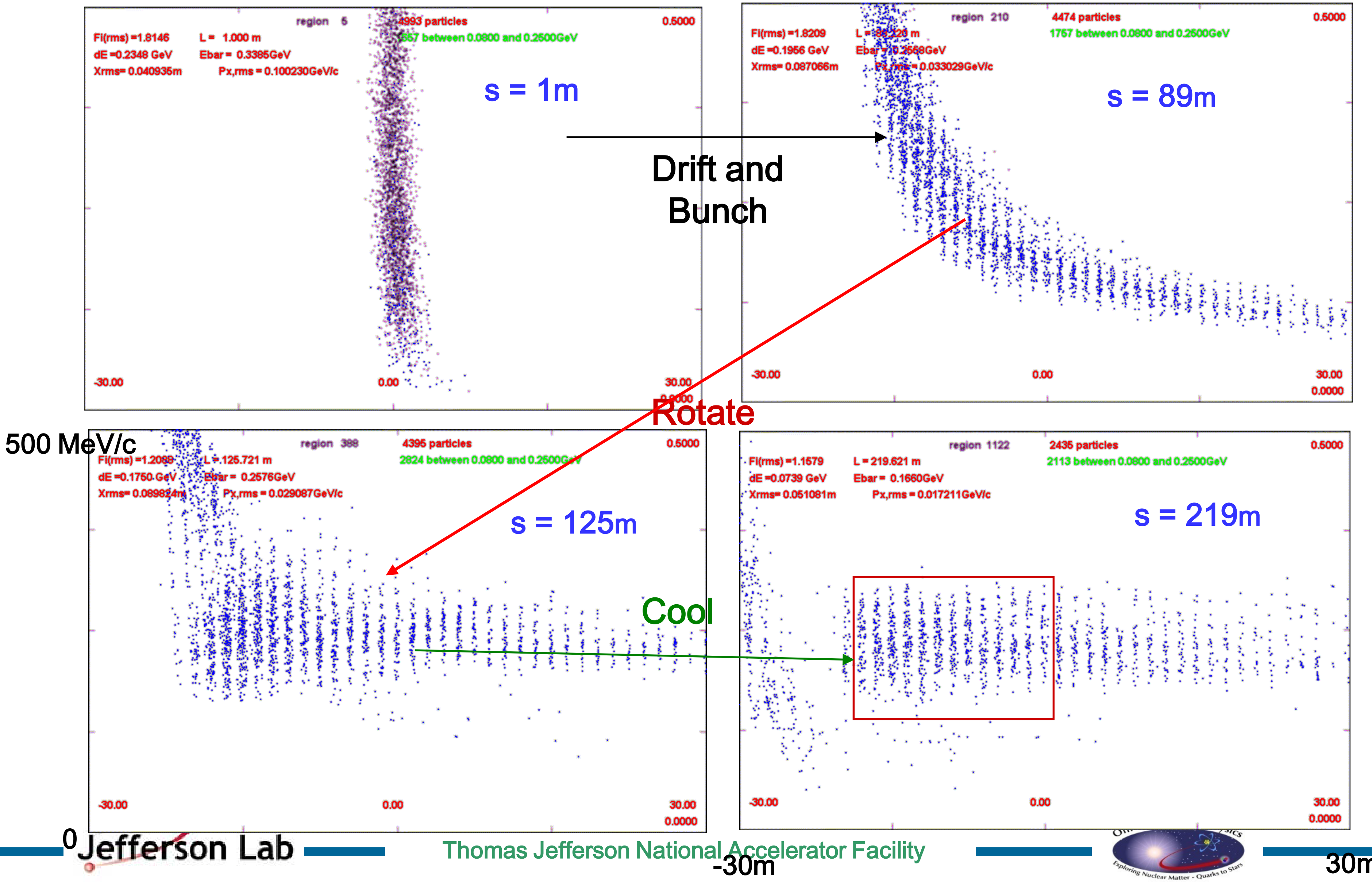
	COOLING SIMULATIONS	Chair, Rick Fernow
9:00-9:25	Front End Simulations	Dave Neuffer
9:25-9:50	Overview of Cooling Studies in UK	Chris Rogers
9:50-10:15	Guggenheim Simulations	Pavel Snopok
10:15-10:45	Coffee Break	
10:45-11:10	TM110 Cavity for Emittance Exchange	Bob Rimmer
11:10-11:35	HCC Simulations with Wedge Absorbers	Valeri Balbekov
11:35-1:00	Lunch - On Your Own	
	FINAL COOLING	**Chair, Juan Gallardo**
1:00-1:25	Status of HCC optimization with new RF structure	Katsuya Yonehara
1:25-1:50	Lithium Lens for Final Cooling	David Cline
1:50-2:15	Lithium Lens Simulations	Kevin Lee
2:15-2:40	Helical FOFO Snake Simulations	Yuri Alexahin
2:40-3:10	Coffee Break	
3:10-3:35	Epicyclic channels for PIC	Andrei Afanasev
3:35-4:00	Particle Refrigerator	Tom Roberts
4:00-4:25	Inverse Cyclotron Simulations with G4beamline and ICOOL	Terry Hart
4:25-4:50	Inverse Cyclotron Simulations with Space-charge	Kevin Paul

Big View of Muon Cooling….



Front End Capture/Phase Rotation & Cooling Studies

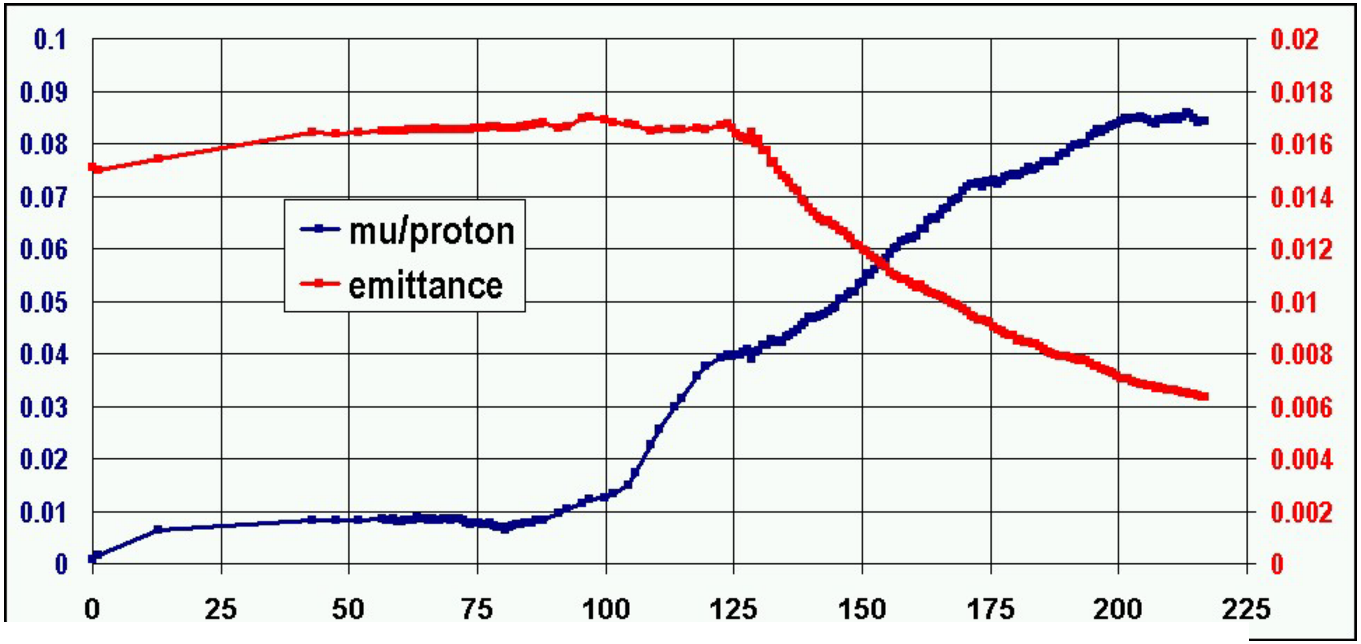
Dave Neuffer

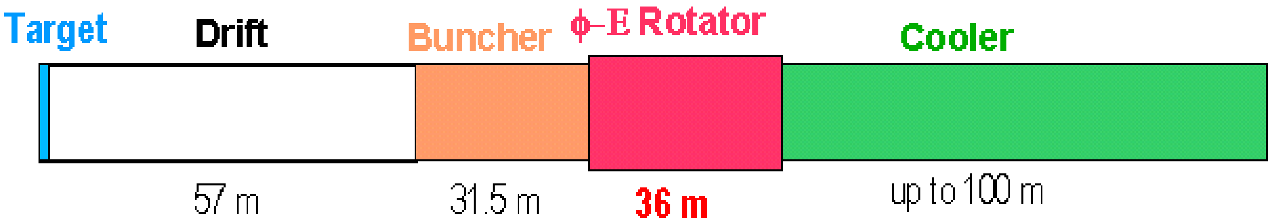


Front end simulations

Dave Neuffer

- Initial beam is 8GeV protons, 1ns bunch length



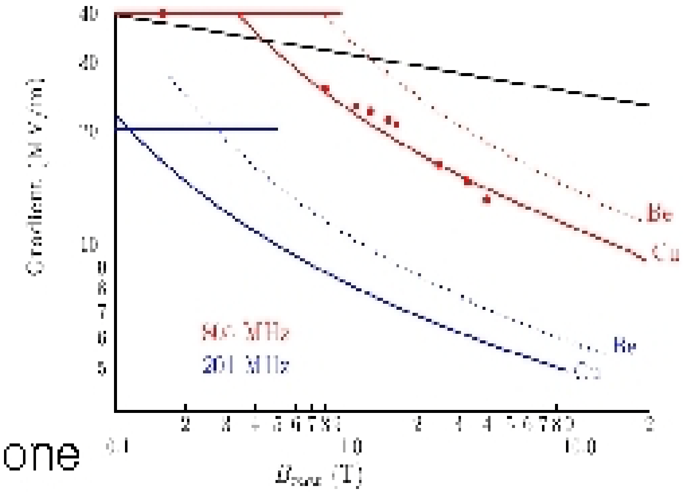


Overview of Cooling Studies in the UK

Chris Rogers

Cooling with Reduced Gradient

- NF cooling channel RF is
  - 15.25 MV/m @ 200 MHz
  - Sitting in ~2.4 T field
- It looks like this is tough to achieve
  - Kilpatrick Limit is at 17 MV/m
  - But 2.4T field limits what can really be done
  - Palmer's simulations indicate might only get ~7 MV/m
    - Many caveats, esp that FS2A coils sit on a field flip



Helical FOFO Snake Simulations

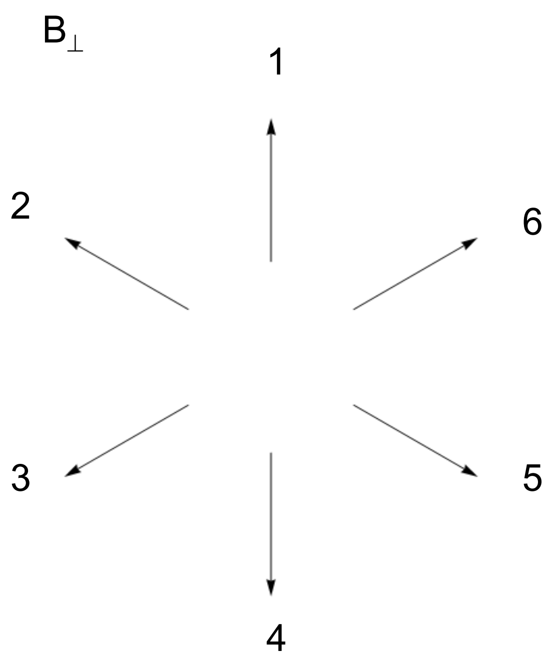
Create rotating $B_\perp$ field by tilting (or displacing) solenoids in rotating planes

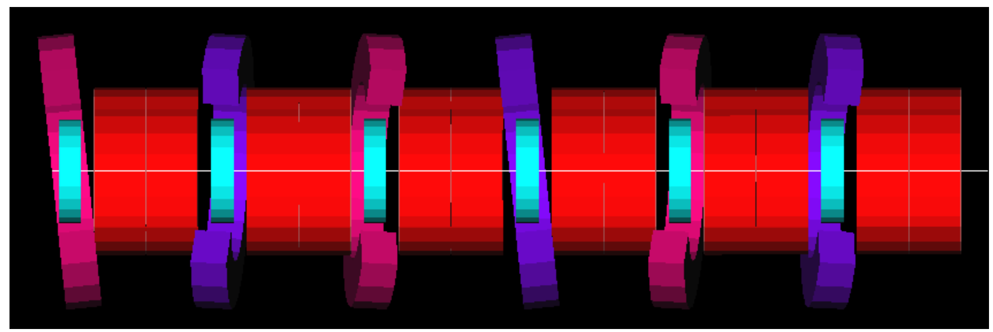
$$x*\cos(\phi_k)+y*\sin(\phi_k)=0,\ k=1,2,\ldots$$

Yuri Alexahin

Example for 6-cell period:

Solenoid #	1	2	3	4	5	6
Polarity	+	-	+	-	+	-
Roll angle ϕ_k	0	$2\pi/3$	$4\ \pi/3$	0	$2\ \pi/3$	$4\ \pi/3$





Channel parameters:

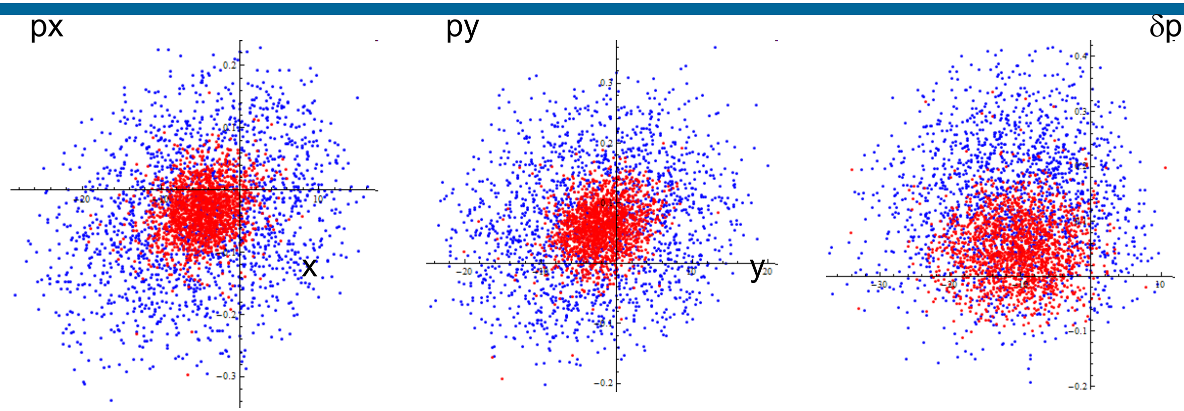
200 MHz pillbox RF 2x36cm, Emax=16MV/m

Solenoids: L=24cm, Rin=60cm, Rout=92cm,

Absorbers: LH2, total width (on-axis) 6x15cm,

Total length of 6-cell period 6.12m

Phase space distributions



blue - initial, red - final

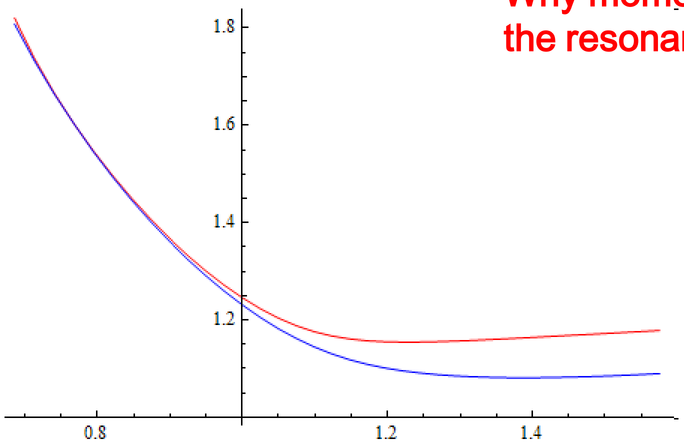
z-v0*t

"Emittances" (cm)	initial	final
6D	10.3	0.07
Trans. average	1.99	0.29
Longitudinal	3.75	1.46

$$\delta_p = \frac{\gamma - \gamma_0}{\beta_0^2 \gamma_0},$$

$$\frac{p}{p_0} = 1 + \delta_p - \frac{\delta_p^2}{2\gamma_0^2} + \dots$$

Why momentum acceptance is so large (>60%) in the resonance case?

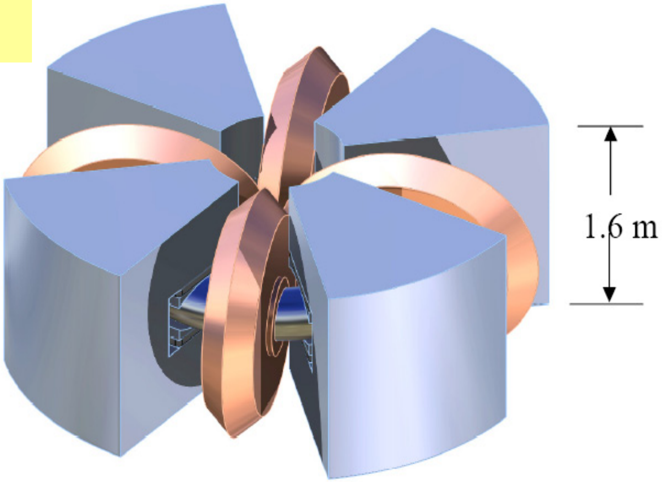


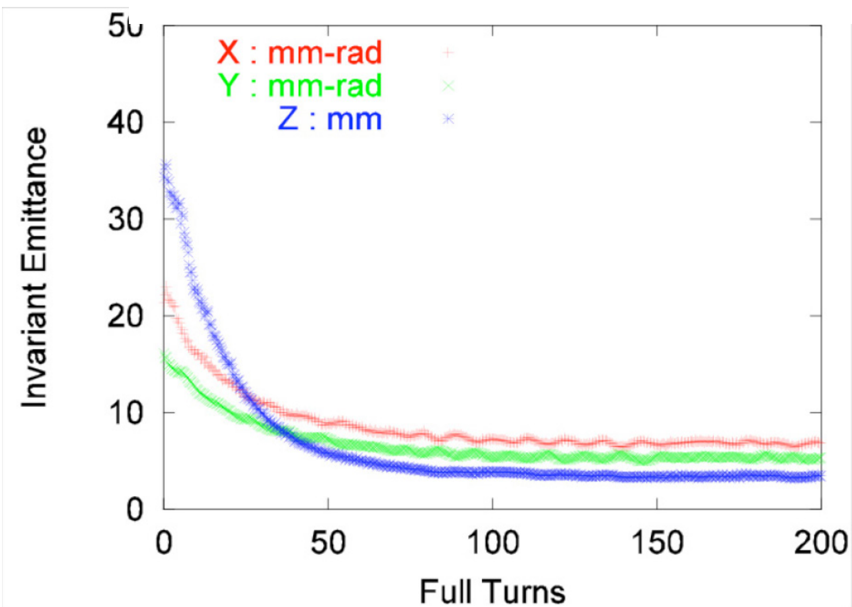
Nice surprise:

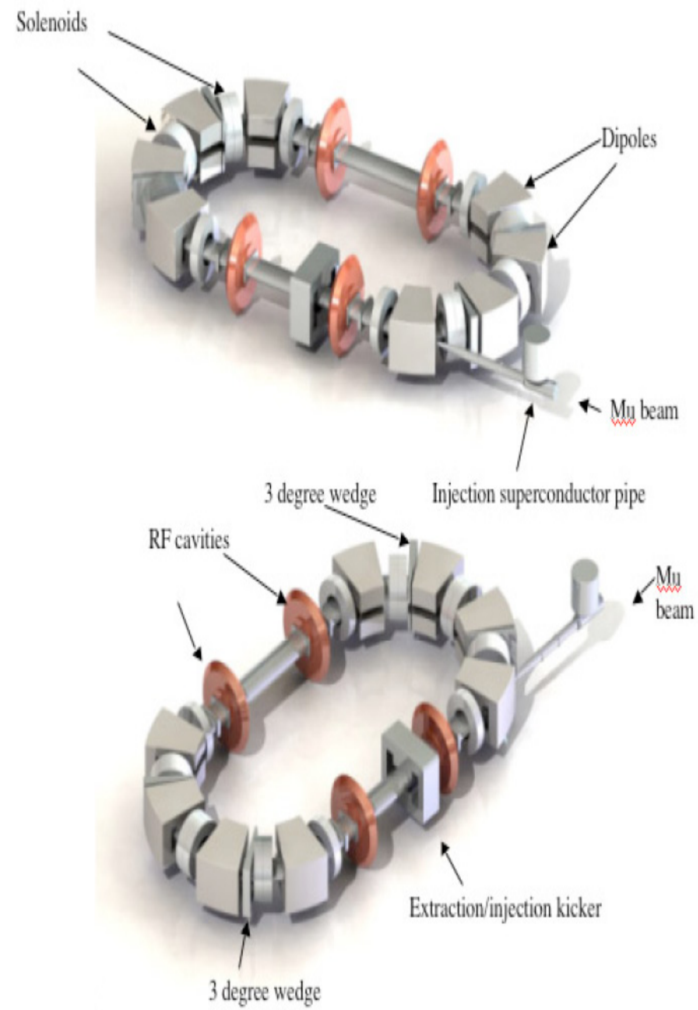
Large 2nd order chromaticity due to nonlinear field components keeps both tunes from crossing the integer !

Study of Ring Coolers for μ+ μ- Colliders

David Cline



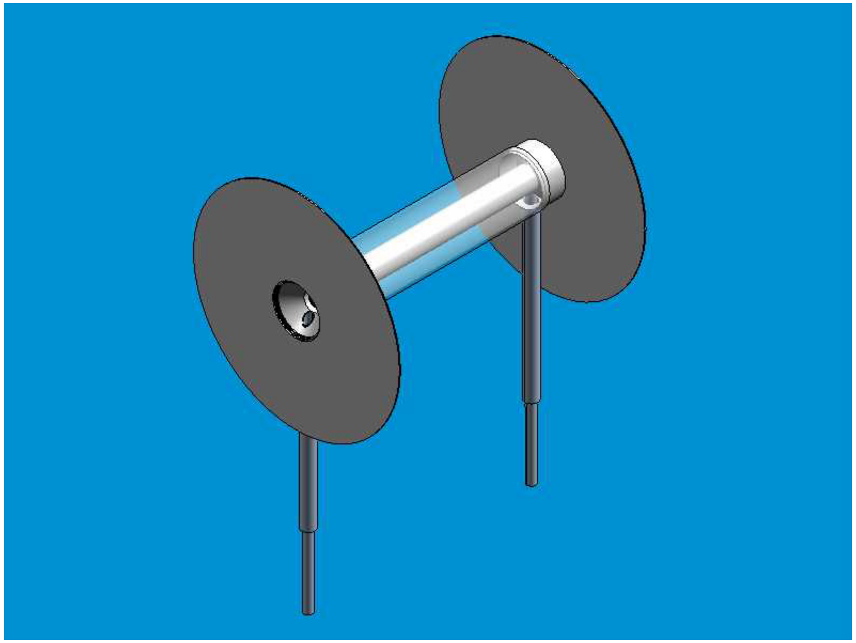


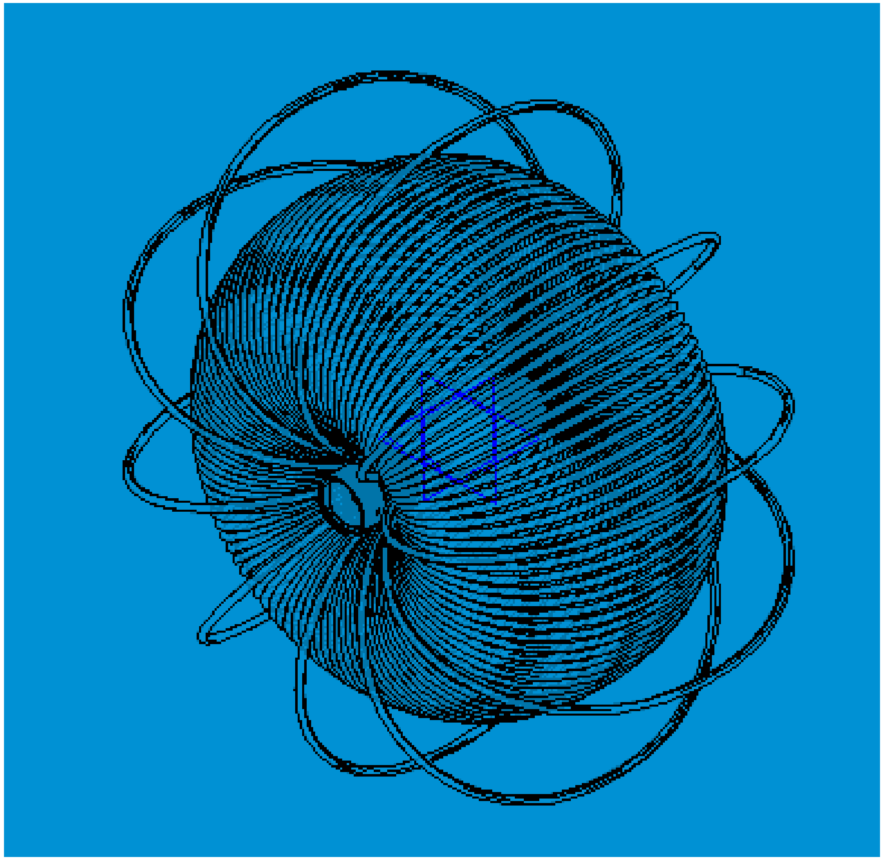


Lithium Lens for Muon Final Cooling

Initial Design of Liquid Li Lens

Kevin Lee



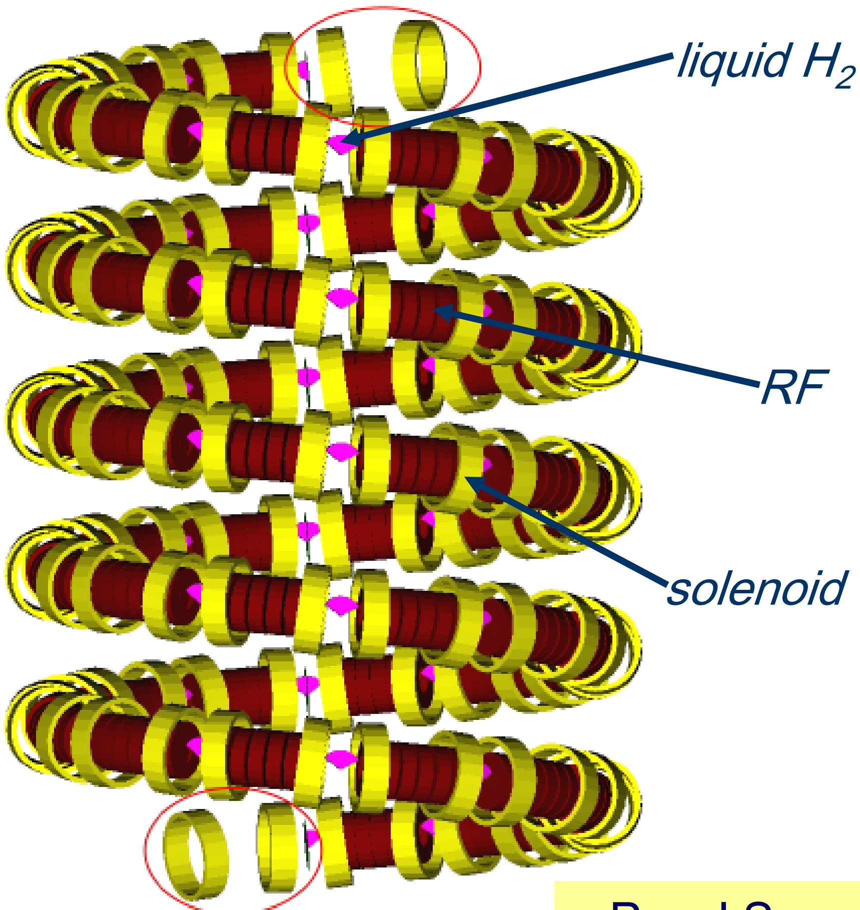


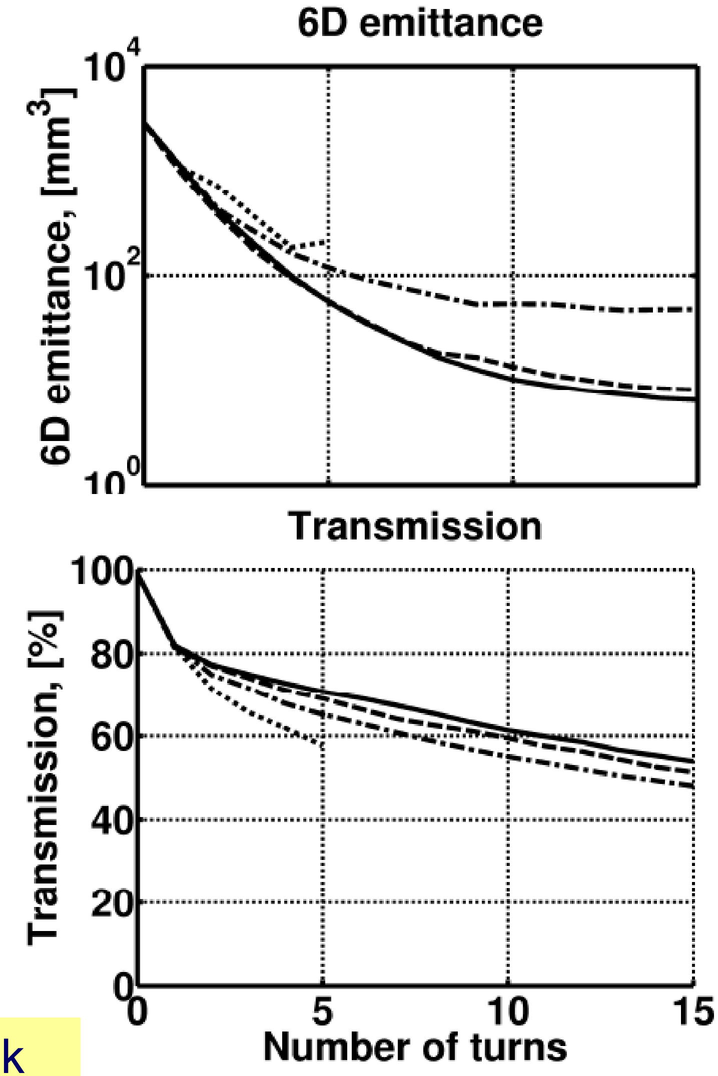
Lens assembly w/ current discs and the primary and secondary coils

Li D = 2.54 cm; L = 30.0 cm

Progress on Guggenheim RFOFO - Simulations

Multilayer scheme



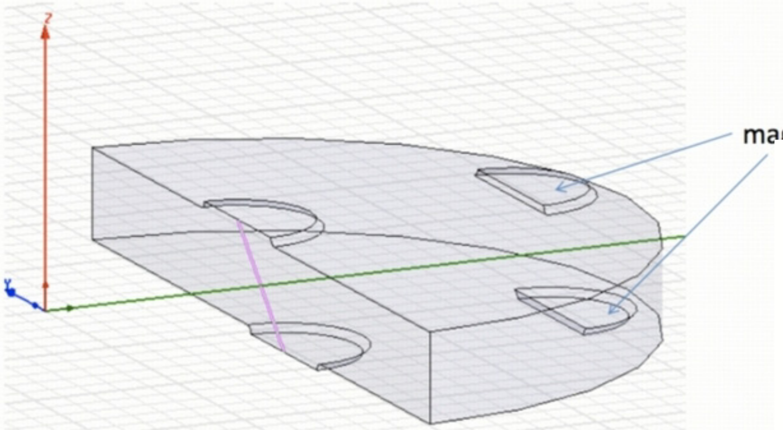


Pavel Snopok

Progress on Design of Helical Cooling Channel

Traveling wave RF structure in HCC (II)

Additional coupling ports for backward wave: a handle to reduce the group velocity

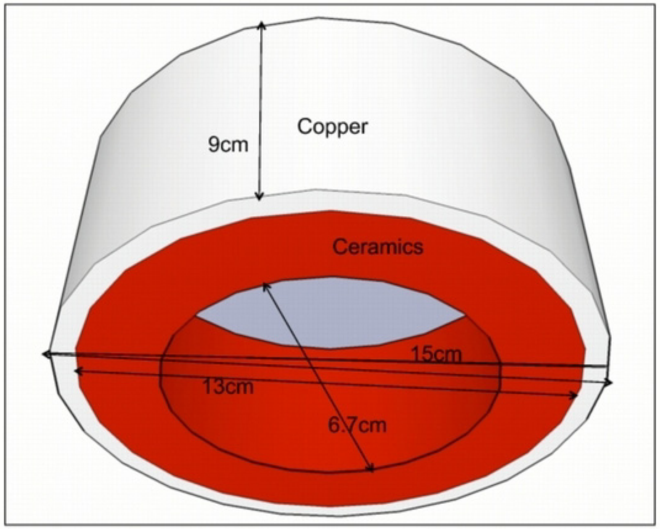


betagroup =0.00023 , 4.67 MW, grad. = 12MV/m, W = 4.6 J/cell,
Enhancement = 2.3, f= 0.393 GHz

Katsuya Yonehara

Compact dielectric RF for HCC

- Reduce transverse size of RF cell
- Milorad will present this idea more detail

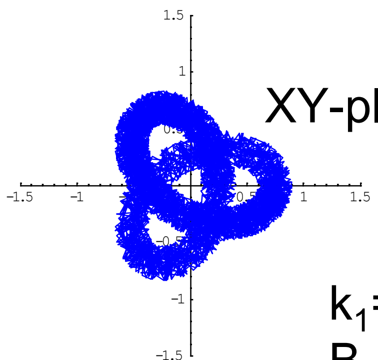


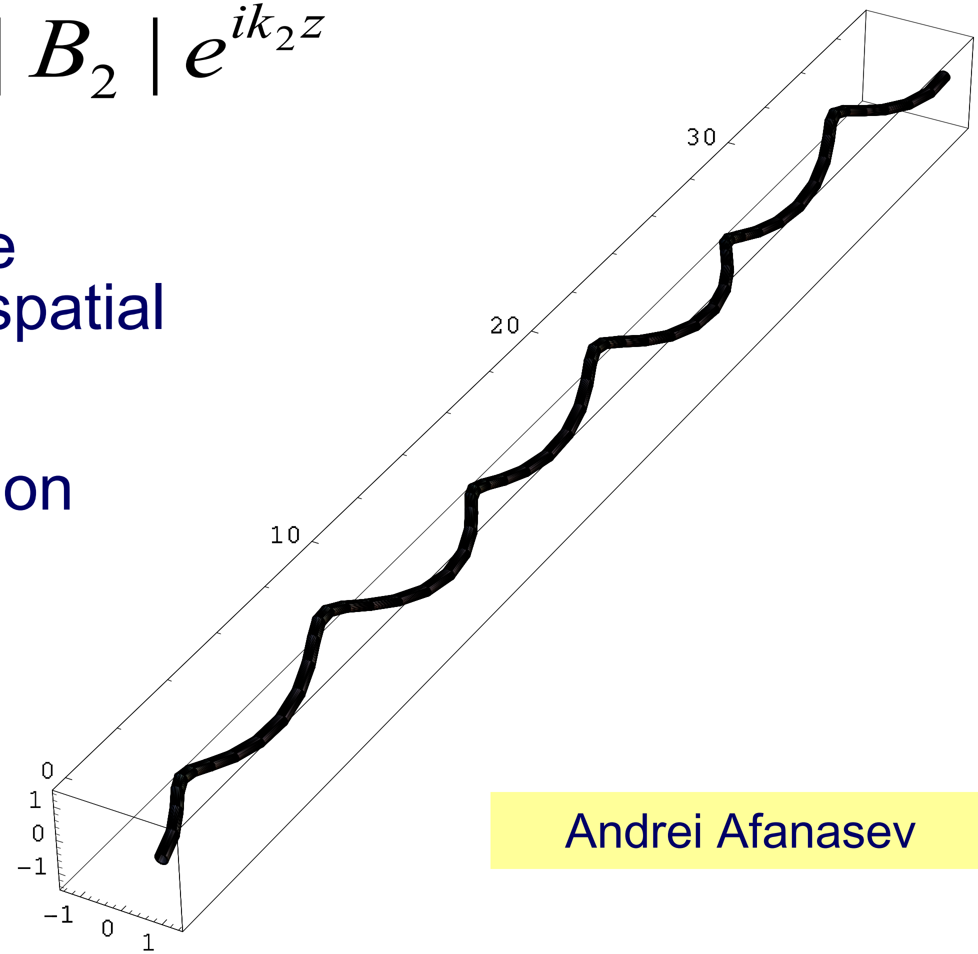
Milorad Popovic

Epicyclic Helical Solenoid

$$B_T = |B_1| e^{ik_1 z} + |B_2| e^{ik_2 z}$$

- Superimposed transverse magnetic fields with two spatial periods
- Variable dispersion function

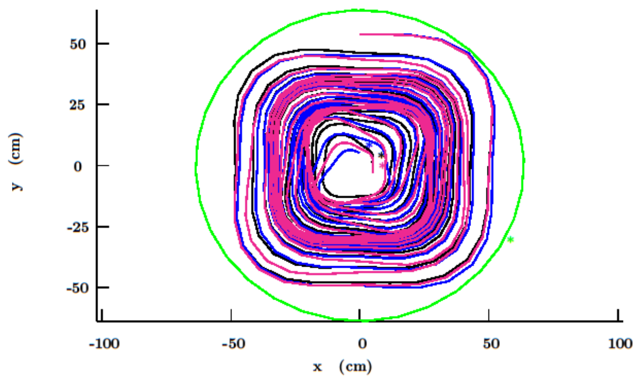




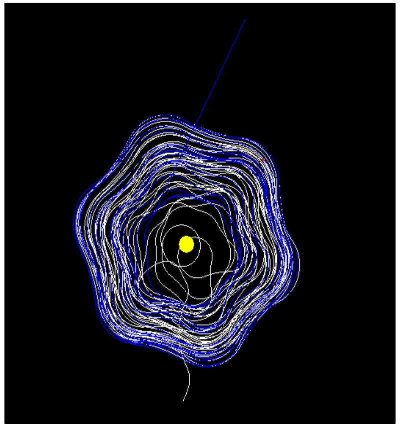
Andrei Afanasev

Simulations of Muon Cooling With an Inverse Cyclotron

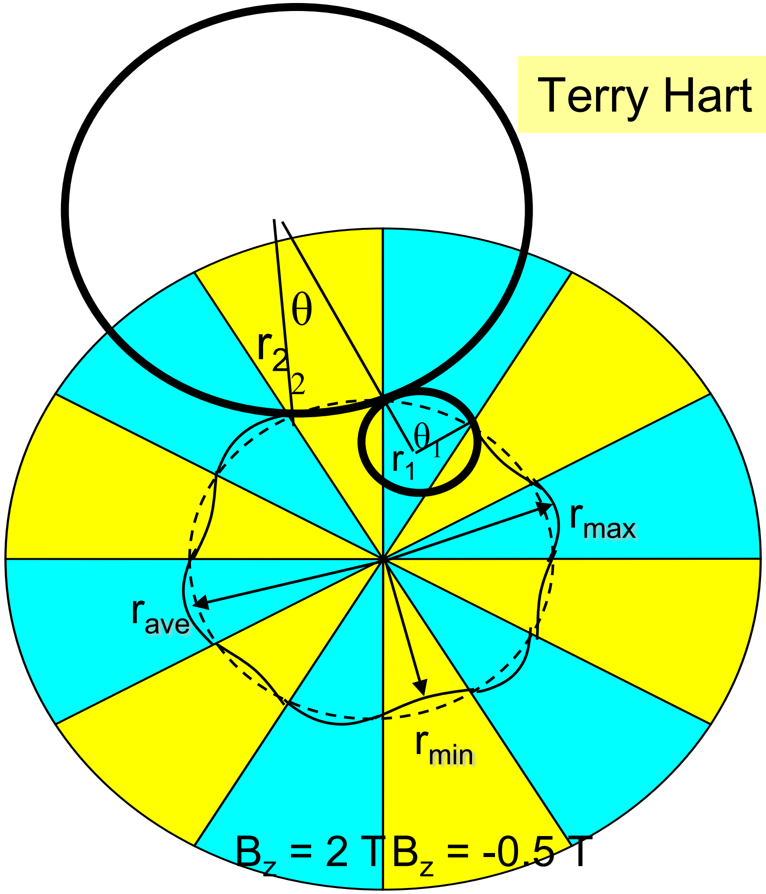
R. Palmer's ICOOL model



G4beamline model



Terry Hart

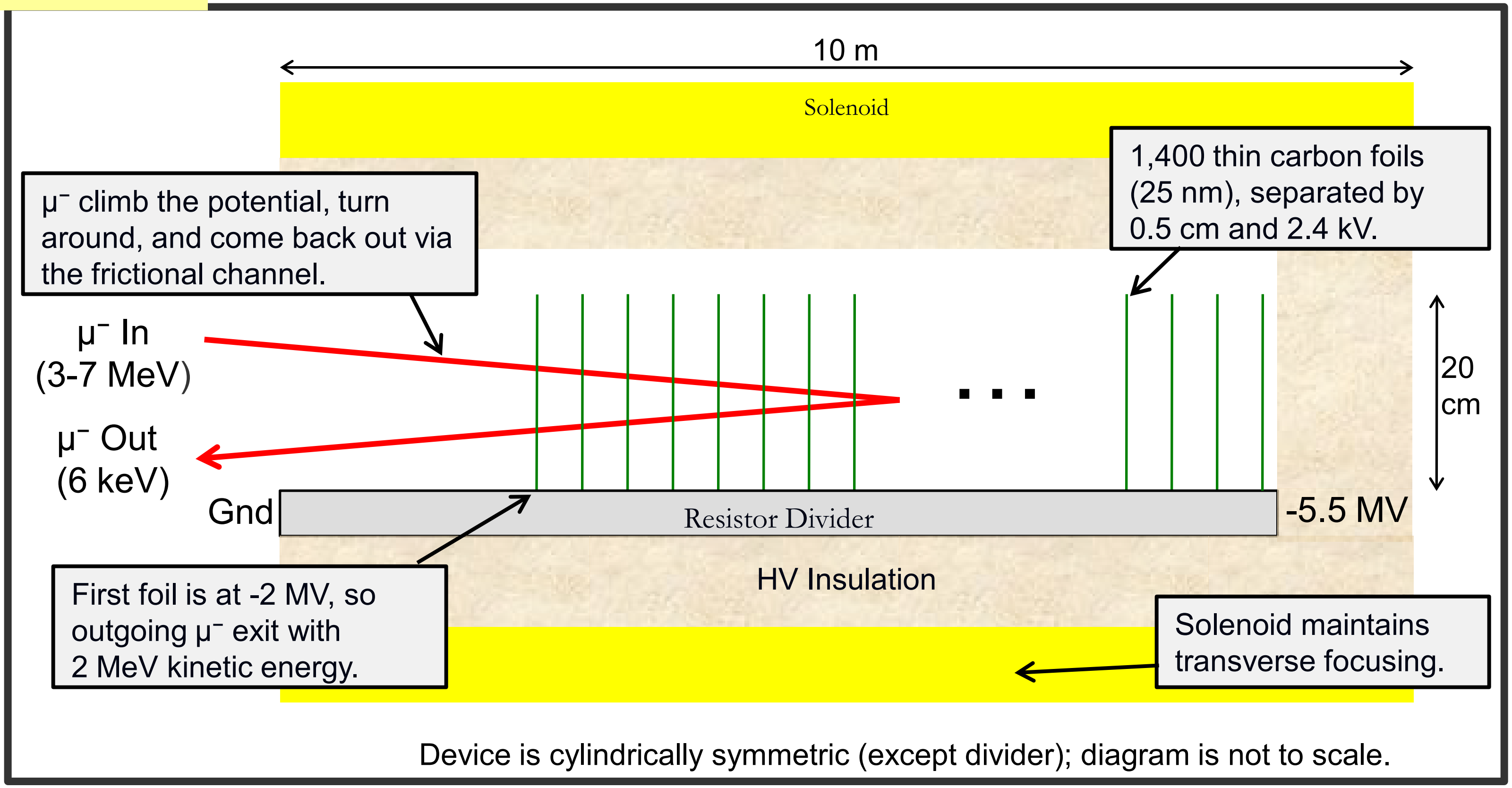


VORPAL 3D Simulations with space-charge

Kevin Paul

Frictional Cooling

Tom Roberts



Remember that 1/e transverse cooling occurs by losing and re-gaining the particle energy. That occurs every 2 or 3 foils in the frictional channel.

DRAFT MANX following MICE at RAL DRAFT

Robert Abrams[1], Mohammad Alsharo'a[1], Charles Ankenbrandt[1], Emanuela Barzi[2], Kevin Beard[1], Alex Bogacz[3], Daniel Broemmelsiek[2], Yu-Chiu Chao[3], Mary Anne Cummings[1], Yaroslav Derbenev[3], Henry Frisch[4], Ivan Gonin[2], Gail Hanson[5], David Hedin[7], Martin Hu[2], Rolland Johnson[1], Stephen Kahn[1], Daniel Kaplan[6], Vladimir Kashikhin[2], Moyses Kuchnir[1], Michael Lamm[2], Valeri Lebedev[2], David Neuffer[2], Milord 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*

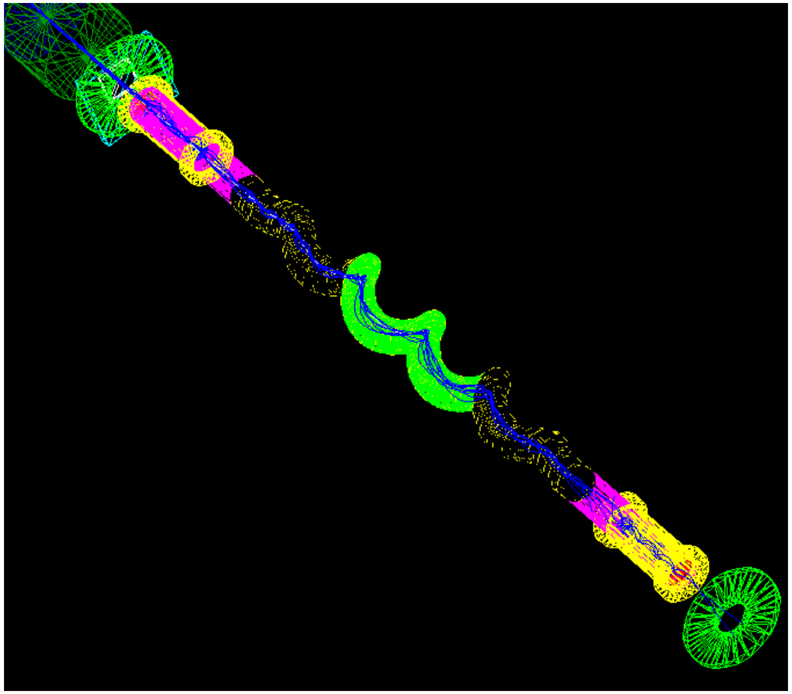
[5] *University of California at Riverside*

[6] *Illinois Institute of Technology*

[7] *Northern Illinois University*

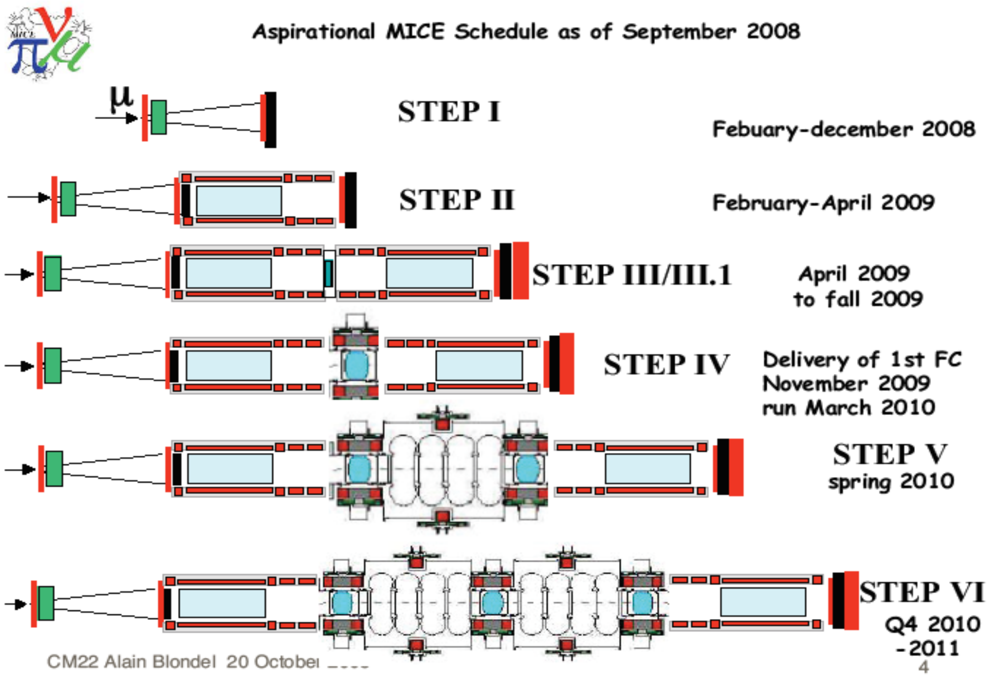
If MANX isn't a prototype for NF or MC cooling, could it be?

- For example, if HPRF can't be made to work, then you could
- match 6d MANX output to ~150 MeV vacuum RF section, (a la Fernow)
- accelerate 150 MeV, which would improve 6d emittance by factor of ~5.
- Inject into another MANX section, and iterate 9 times to reduce 6d emittance by a factor of a million in 10X30 = 300 m.

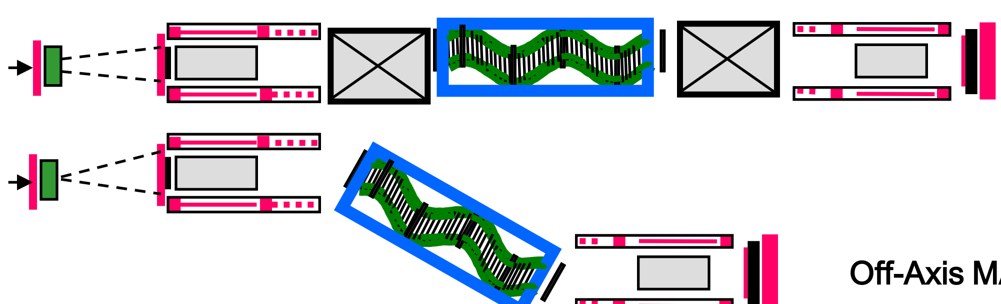


Rol Johnson

MICE Phases + MANX



MANX in MICE (Conceptual)



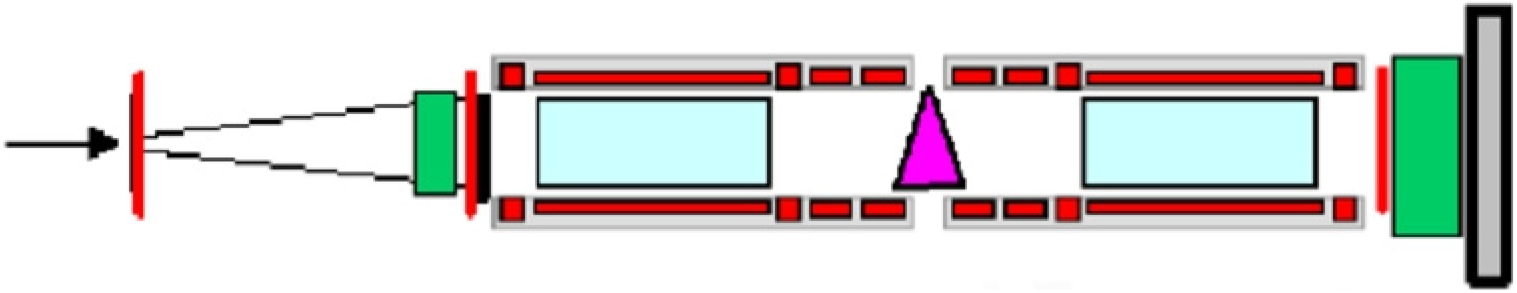
MANX Objectives

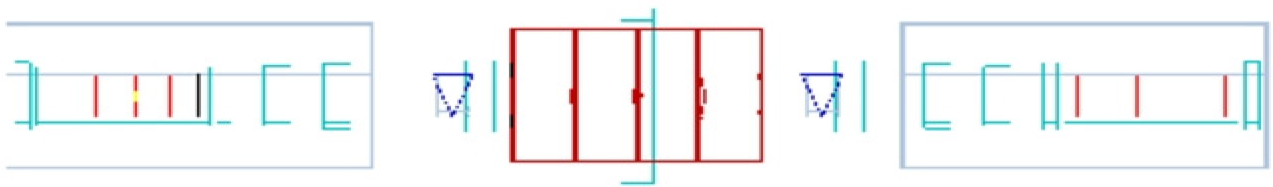
- Measure 6D cooling in a channel long enough for significant reduction of emittance
- Study the evolution of the emittance along the channel by making measurements inside the channel as well as before and after
- **Test the Derbenev-Johnson theory of the HCC**
- Advance muon cooling technology

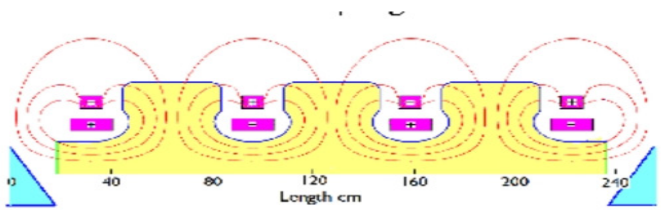
Much discussion!

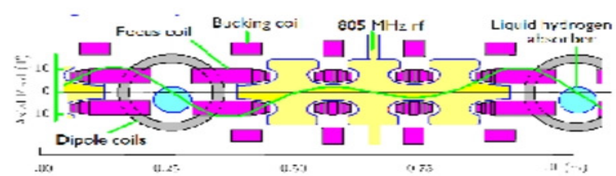
Further Cooling Experiments

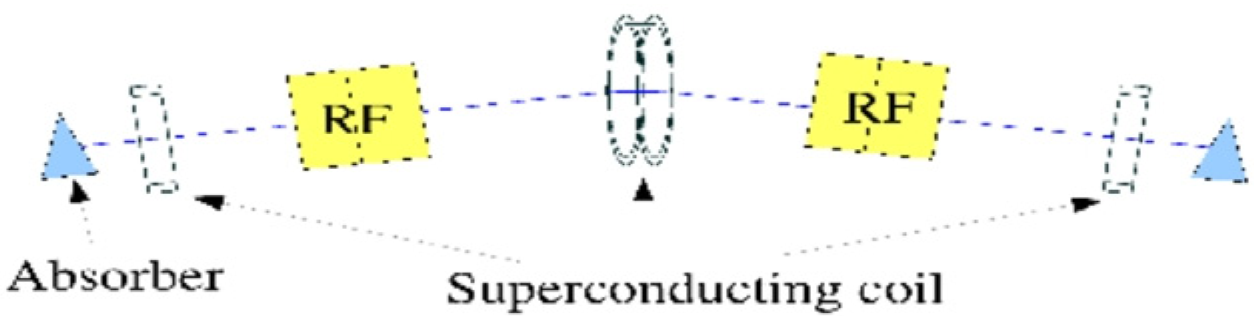
Chris Rogers







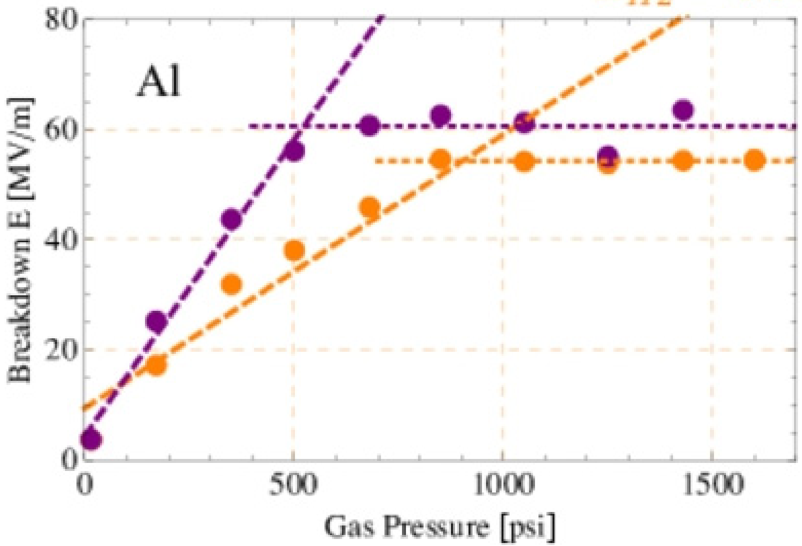




Study high pressure hydrogen gas filled RF cell

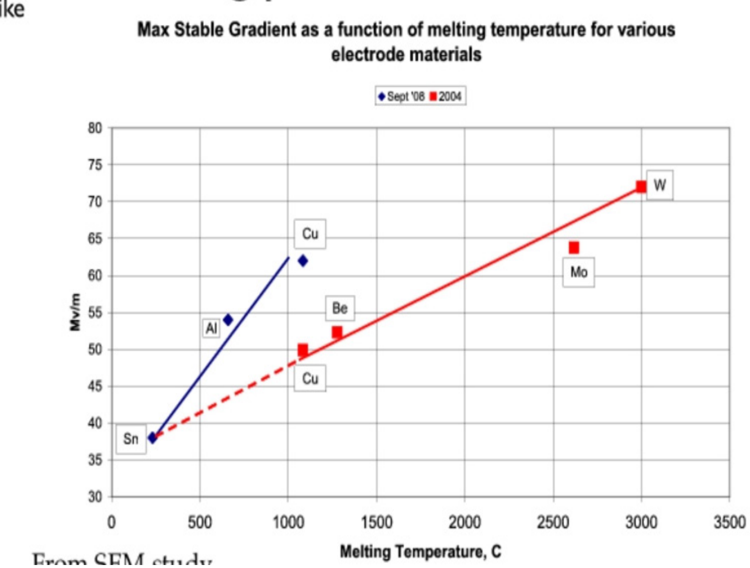
$$E_{SF6} = 0.1076 \times Pressure + 4.378$$

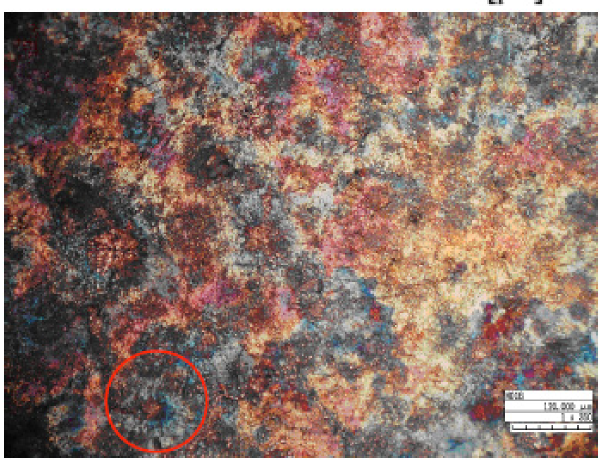
$$E_{H2} = 0.0497 \times Pressure + 9.406$$



Mike

Melting point vs Breakdown field





Katsuya Yonehara

	ACCELERATION	**Chair, Harold Kirk**
9:00-9:25	FFAG - Type Multipass Arcs for RLA's	Dejan Trbojevic
9:25-9:50	Multi-pass Droplet Arc Design	Guimei Wang
9:50 - 10:15	High-Gradient Induction Linacs for Protons and Muons	Yu-Jiuan Chen
10:15-10:45	Coffee Break	
10:45-11:10	Rapid Cycling Synchrotrons	Don Summers
11:10-11:35	Summary of Recent One-Day RF Workshop	Andreas Jansson
11:35-1:00	Lunch - On Your Own	
	INTERACTION REGION	**Chair, Al Garren**
1:00-1:25	Update on the 'Dipole first' Muon Collider optics	Yuri Alexahin
1:25-1:50	Studies for a Muon Collider Optics with non-interleaved sextupole scheme	Eliana Gianfelice-Wendt
1:50-2:15	Considerations on Optimized IR Design	Yaroslav Derbenev
2:15-2:45	Coffee Break	
2:45-3:10	Beam Induced Detector Backgrounds for a Muon Collider	Steve Kahn
3:10-3:35	Low-beta Region Muon Collider Detector	Mary Anne Cummings
	EXPERIMENTS& PLANS	**Chair, Richard Sah**
3:40-4:10	The MANX Proposal	Bob Abrams
4:10-4:40	Recent RF Results from MTA	Katsuya Yonehara

Magnet Steel Lamination Properties

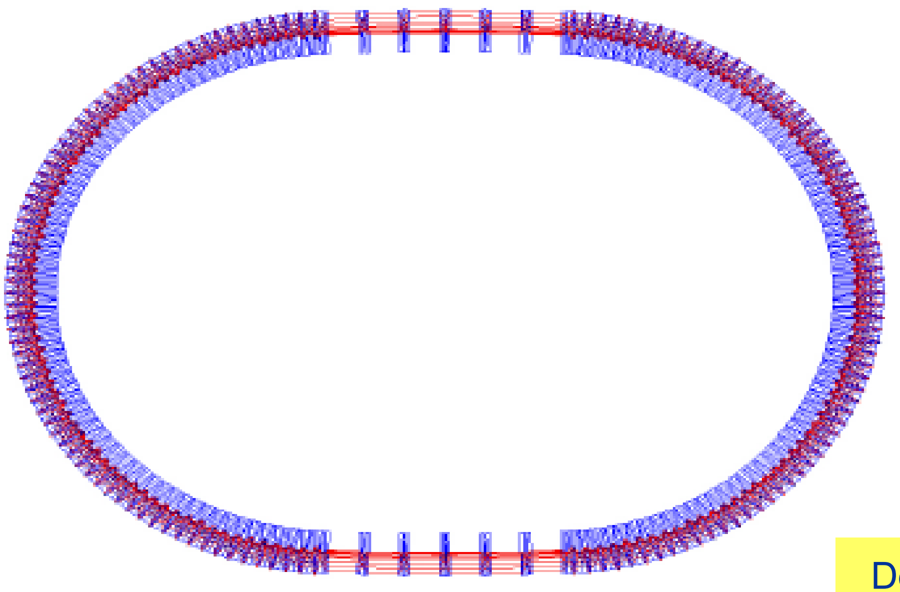
Material	Composition (%)	ρ ($\mu\Omega$-cm)	H_c (Oersteds)
Low Carbon Steel	Fe, C .0025	10	1.0
3% Silicon Steel	Fe 97, Si 3	47	0.7
Grain Oriented Steel	Fe 97, Si 3	47	0.1
JFE Super Core	Fe 93.5, Si 6.5	82	0.2
Metglas 2605A1	Fe 81, B 14, Si 3, C 2	135	.03

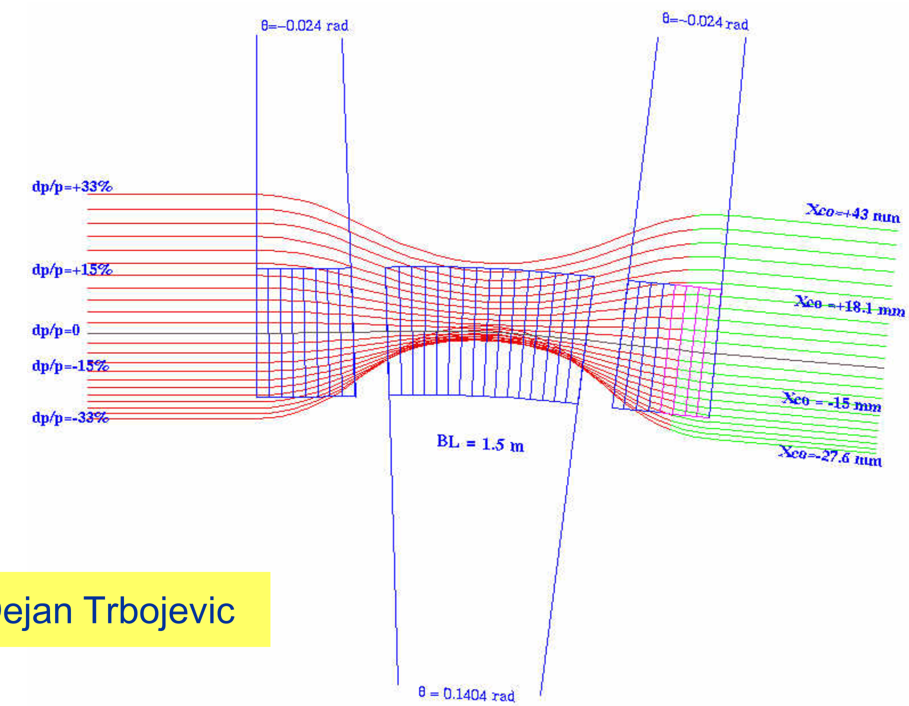
- Eddy Current Loss = [Volume]$(2\pi\, f\, B\, t)^2/(24\rho)$
  High ρ is good. t = lamination thickness.
- Hysteresis Loss = $\int H\, dB$. Low coercivity (H_c) is good.
- Vendor: TC Metal Company Slitting and Shearing
  $3/lb for slit and sheared .23mm grain oriented silicon steel
- Magnet Measurement: F. W. Bell Model 4048 Hall Probe.
  Measure to 2T with an accuracy of 2% from 100 to 3000Hz.

Prototype Arc design NS-FFAG

NS-FFAG (Non-Scaling Fixed Field Alternating Gradient)

- 'Racetrack' RLA to accommodate large momentum range (~60%)





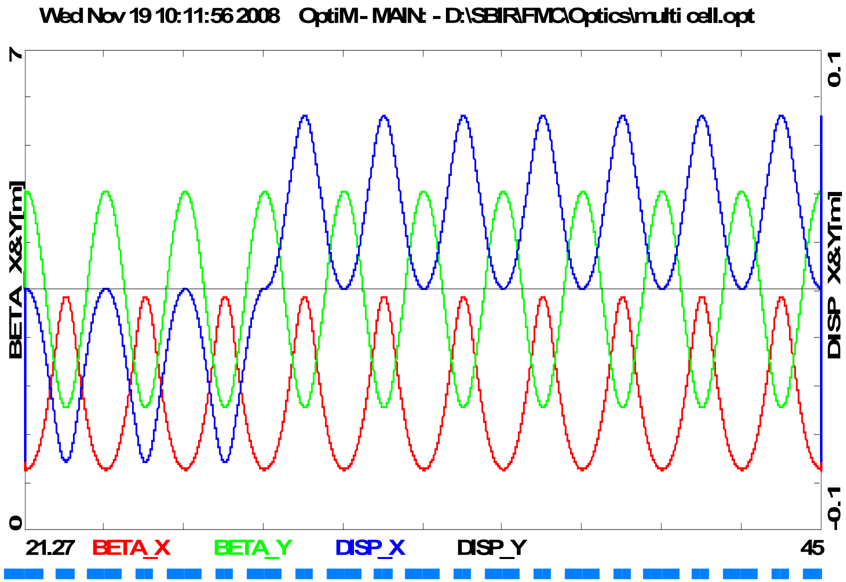
Dejan Trbojevic

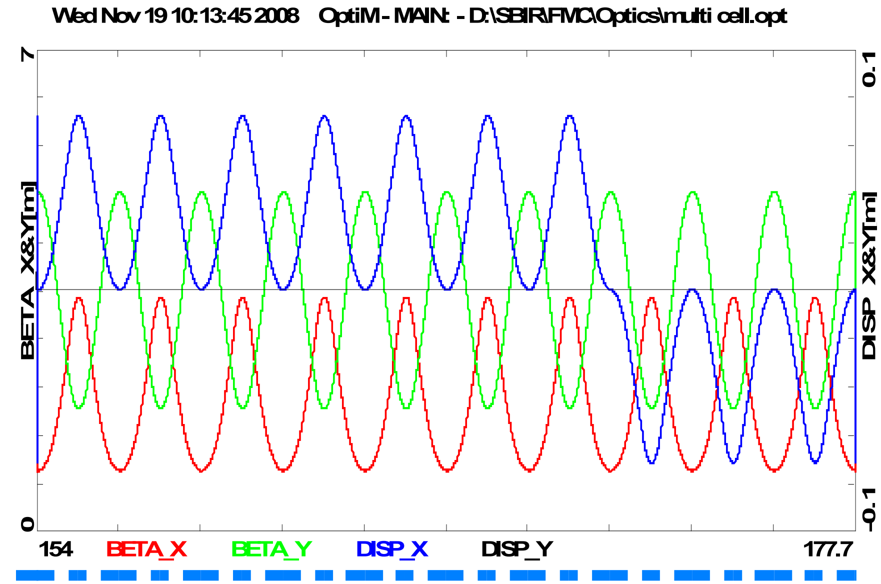
1. Large energy acceptance
2. Very small orbit offsets
3. Reduce number of arcs
4. Very compact structure

Basic cell structure in ARC (combined function magnet with extremely strong focusing)

Reference: Flexible Momentum Compaction Return Arcs for RLAs, D. Trbojevic, R.P. Johnson, EPAC, 2578-2580

NS-FFAG multi-pass 'Droplet' Arc

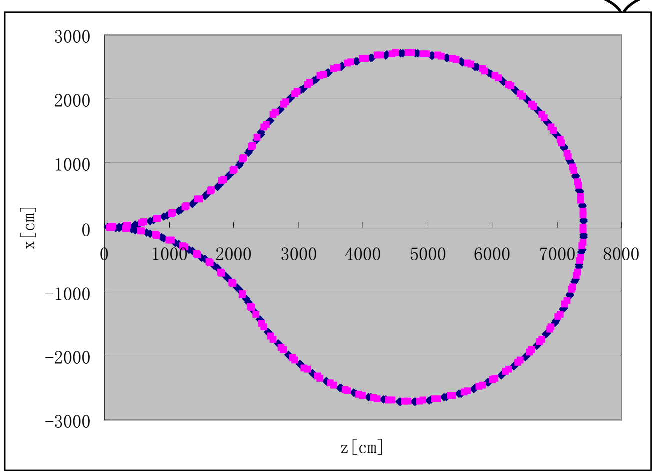


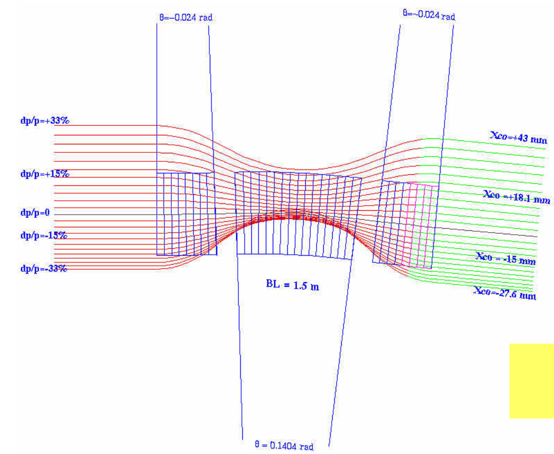


60^0 outward

300^0 inward

60^0 outward



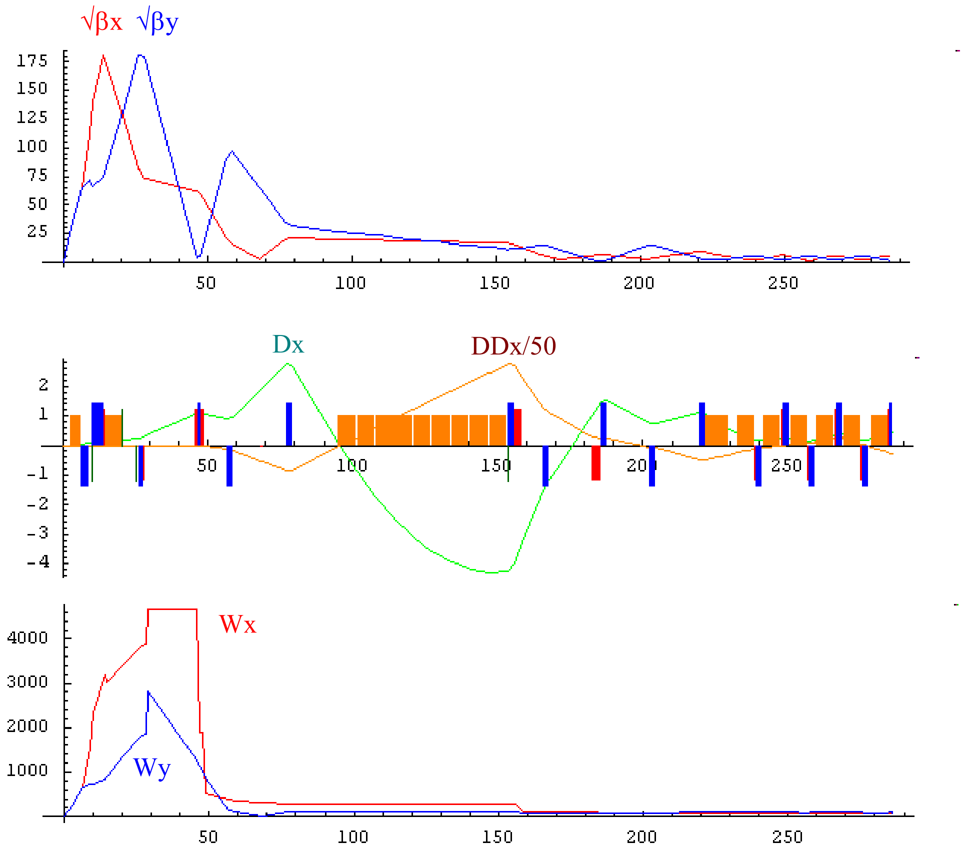


Guimei Wang

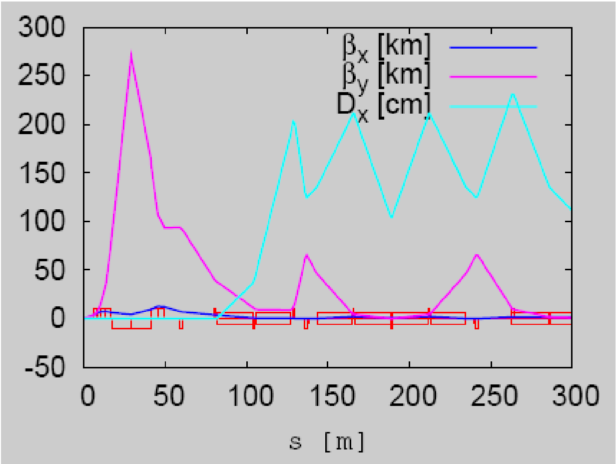
IR Optics

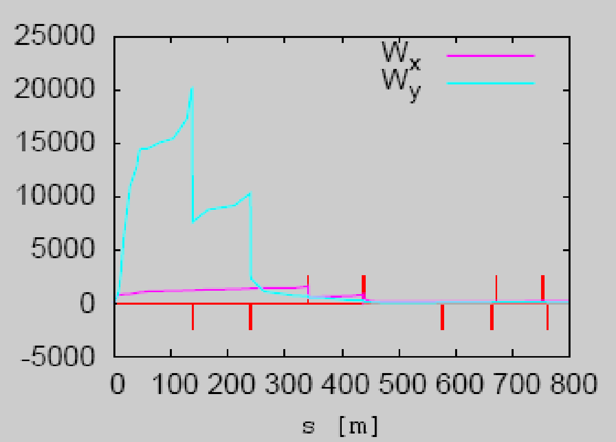
Yuri Alexahin

"Dipole first"



modified Oide





Nonlinear Detuning and Dynamic Aperture

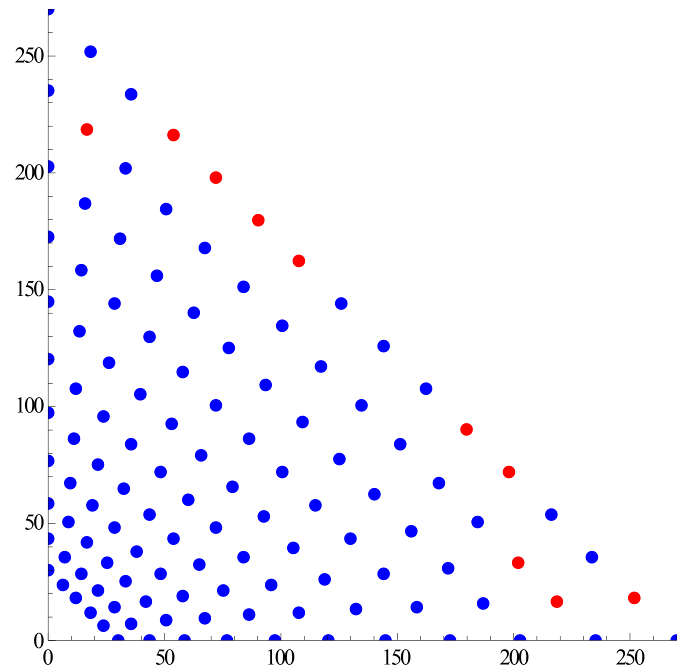
"Dipole first"

Eliana Gianfelice

modified Oide

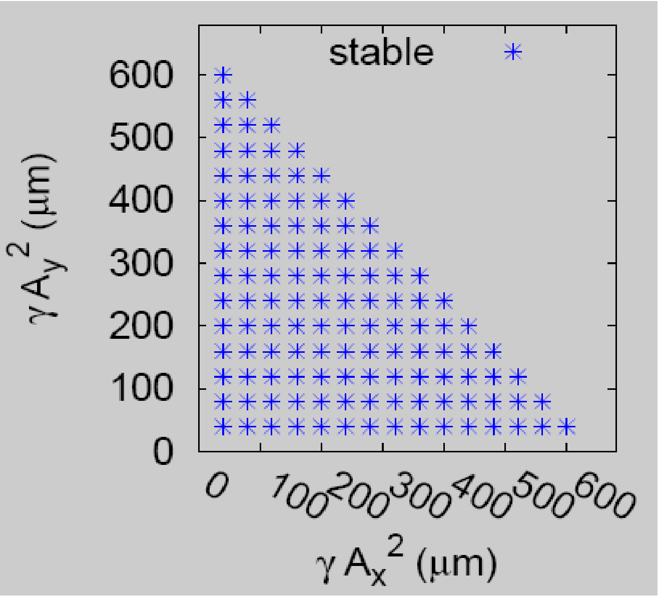
```
Normalized anharmonicities:
dQ1/dE1 =  0.25242152E+08
dQ1/dE2 =  0.19616977E+08
dQ2/dE2 =  0.18515914E+08
```

γ CSIy [μm]



γ CSIx [μm]

Tune Dependence on Amplitude (no octupoles) (MAD8 STATIC)	
dQ_1/dE_1	0.50×10^3
dQ_1/dE_2	0.30×10^4
dQ_2/dE_2	-0.16×10^7



Status of the Collider-IR design

Yuri Alexahin

With the present level of understanding it seems possible:

- $\beta^* = 1\text{cm}$
- $\alpha_c \sim 10^{-5} - 10^{-4}$
- momentum acceptance ±1%
- Dynamic aperture ~ 5σ for $\varepsilon_{\perp N} = 25\ \mu\text{m}$ (HE option)
- Circumference ~ 3km

(all at the same time)

To proceed further to a realistic design a close collaboration between lattice designers and detector, energy deposition and magnet technology groups is a must.

Muon Collider Detector Revision

- Prepare G4Beamline to simulate beam-induced backgrounds in sensor arrays of a large detector in the low-beta region of a muon collider.
- Verify the simulations by comparing distributions and rates to other codes, such as MARS, and to analytic calculations.
- Consolidate existing NIU and other photon sensor performance data and extend them as needed with new measurements.
- Compare the apparent requirements from the preliminary G4beamline simulations for at least one muon collider scenario with the performance data to identify inconsistencies or areas where improvement is needed in the devices, electronics, IP design, or machine parameters.

Mary-Anne Cummings

Proton Driver & RF, Acceleration – Discussion

- How to transform Project X into a Proton Driver?
- Should linac be CW or pulsed?
- How many IR's?
- How promising are new Induction Accel. ideas?
- MANX, MICE, & the 5-year plan
- Will MC be low, med, or high emittance?
- What were the highlights of this workshop?
- Questions about particular talks

Chuck Ankenbrandt