# Routes to improved cooling performance

Diktys Stratakis
Fermi National Accelerator Laboratory

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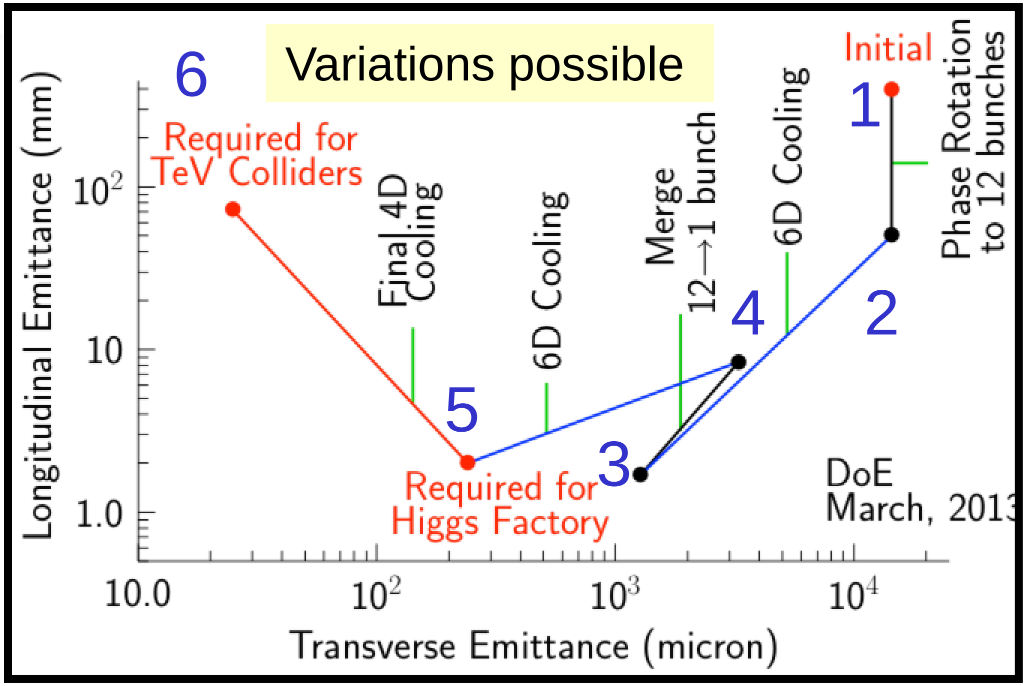
# Ionization cooling

- Muon Colliders require significant reduction of the 6D phase-space. Ionization cooling method is the only technique that can achieve that
- Cooling has a HUGE leverage on the overall machine design
  - It will determine the proton driver and target station specifications
  - It will have a tremendous impact on the overall luminosities envisioned
- Using recent theoretical and technology improvements its critical to develop designs that could give us the lowest possible 6D emittance

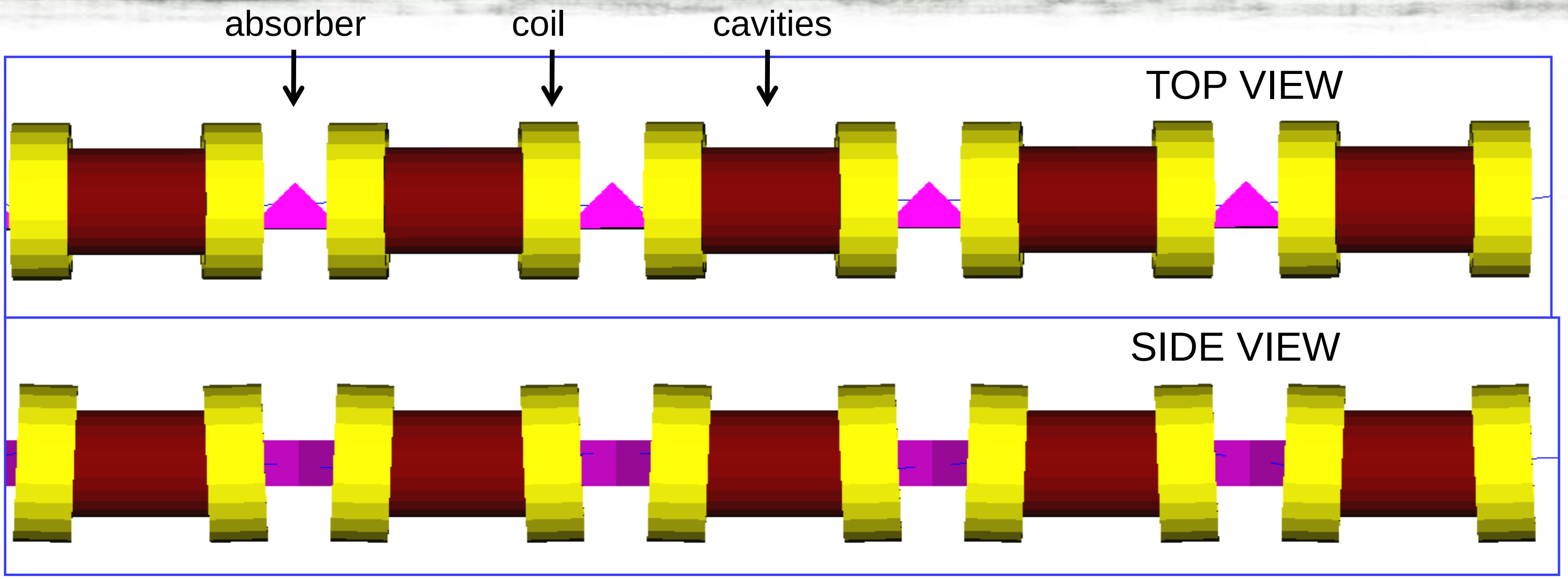
# Cooling baseline



# Questions we like to address

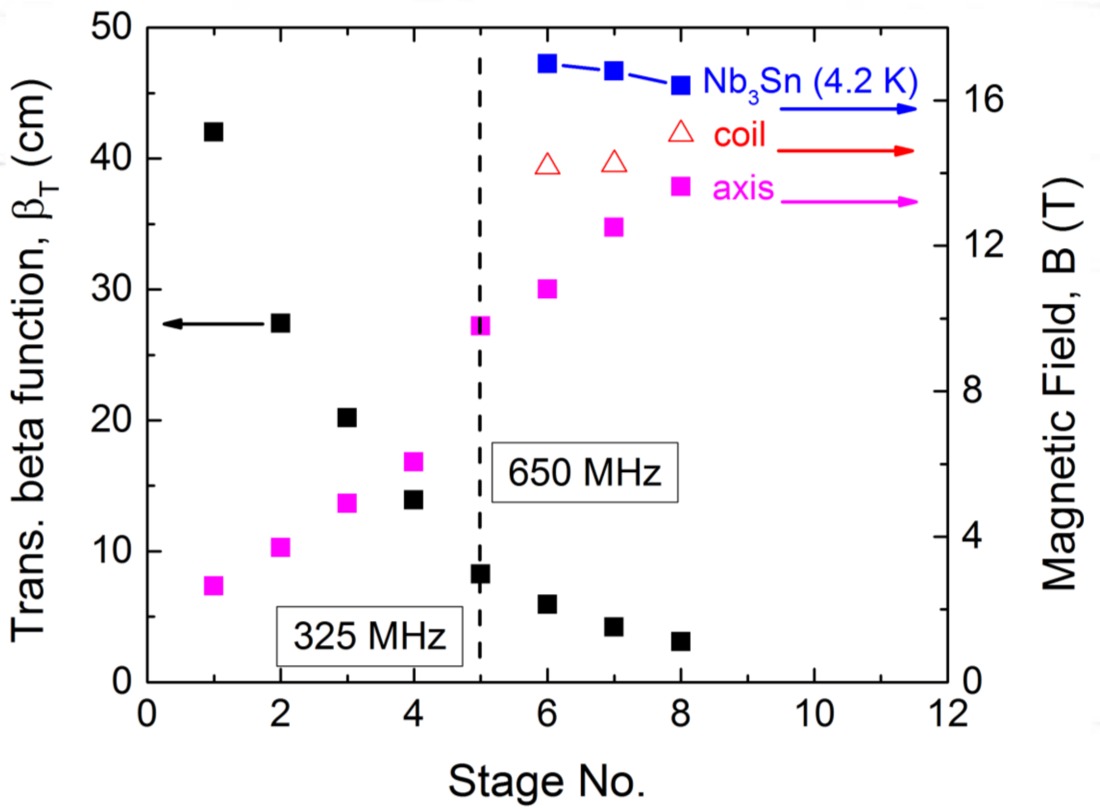
- What are the limitations of 6D cooling? By taking into account recent technology advancements and the newest optimization methods how far can we cool the beam?
- How low (in terms of emittance) can we go with final cooling?
- Could some alternatives options, aid the final cooling process so that we can reach emittances beyond existing designs?

# Rectilinear channel for 6D cooling




- Straight geometry simplifies construction and relaxes several technological challenges
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling
- **Very promising solution for 6D cooling**. BUT…(see next slides)

# Past constrains from technology (1)




- Peak fields on coils should not exceed $Nb_3Sn$ limits

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# Past constrains from technology (2)

- Need consistent value for comparison
- Cavity lengths also matter
- Propose consistent values
  - consistent with 17 MV/m at 201.25 MHz

| Freq. MHz | Length cm | Grad MV/m | $\Delta E$ $v = c$ MeV | $\Delta E$ 200 MeV/c MeV |
|---|---|---|---|---|
| 325 | 30 | 22 | 5.51 | 5.23 |
| 650 | 15 | 31 | 3.88 | 3.68 |
| 975 | 10 | 38 | 3.17 | 3.01 |

8 October 2013 J. S. Berg | Analysis of Cooling Lattices | Vacuum RF

- Normal conducting rf cavities within > 1 T operate ~ 30-50% of the achievable gradient at 0 T

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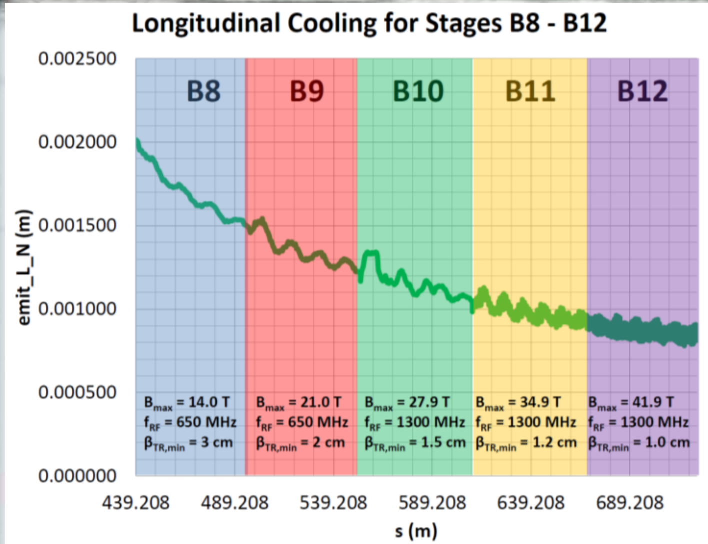
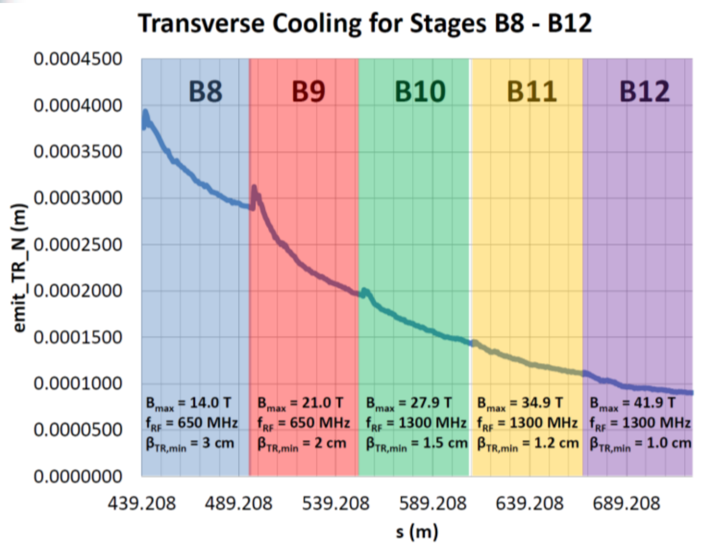
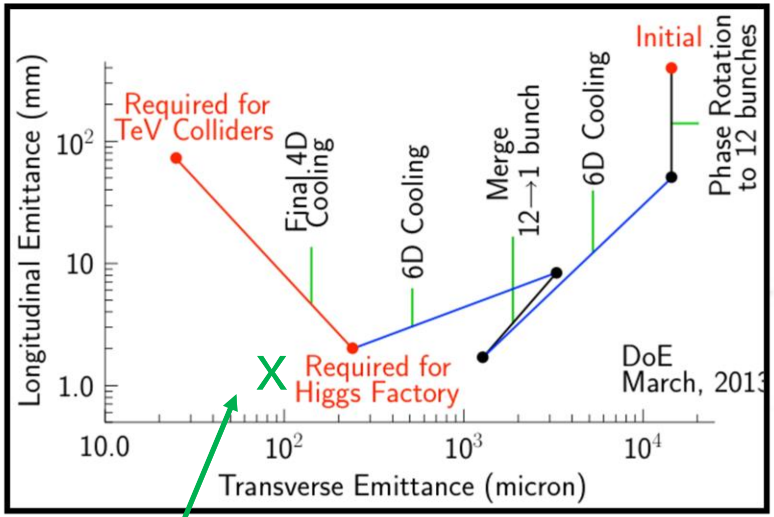
# Pushing the limits of 6D cooling




- If HTS magnet technology is considered, rectilinear channel can reduce the 6D emittance even more

Don Summers, University of Mississippi




Emittances achieved

# Optimization algorithms

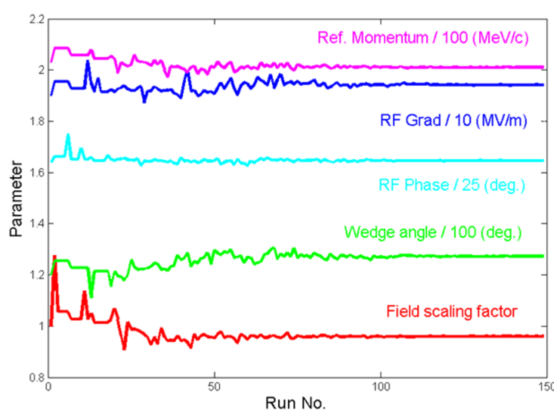
- Cooling channel design is a challenging problem with many knobs and multiple design objectives. Simulations using G4Beamline are moderately expensive in time
- Using recent advances in efficient optimization algorithms, we could find optimal settings for muon cooling design.

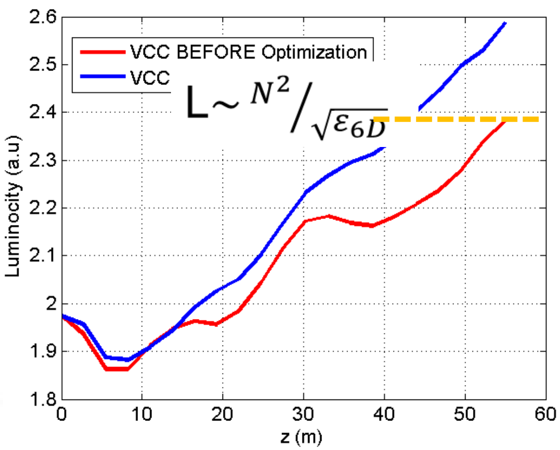
**SURROGATE ASSISTED ALGORITHMS**

Evolutionary algorithms take many evaluations to converge. This is a problem when running on expensive (up to 1hr per simulation) accelerator codes. Modern methods build a "surrogate model" from data as optimization is performed to inform the suggestion of future candidate solutions

**A COMPARISON SURROGATE**

Instead of modeling objective functions (IE emittance, bunch length, etc) directly, model the comparison relationship (f(x1) < f(x2)). The classification problem may be simpler and is invariant under monotonous transformations of f(x).




University of Chicago + Fermilab collaboration started

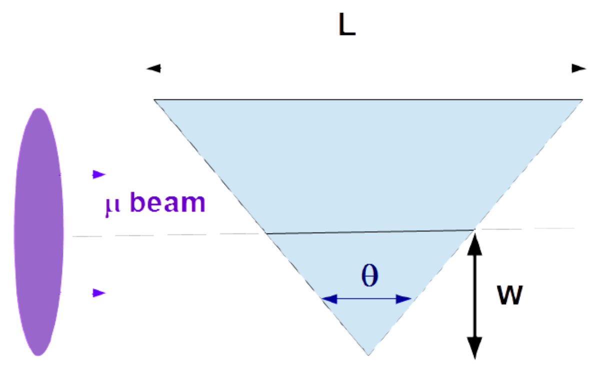
# Final cooling with thick wedges

- The idea is to use a thick wedge for aggressive transverse cooling through the emittance exchange process
- When passing the beam through a wedge absorber, the bunch width is transformed into an energy width
- This process has shown to be very promising although at this moment, a conceptual design is available, only.

**Final Cooling for a High-Energy High-Luminosity Lepton Collider**

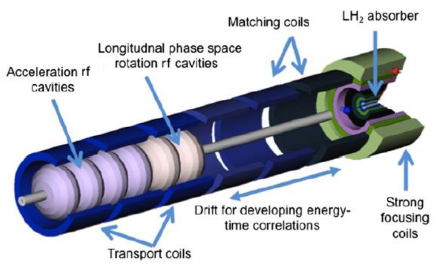
**David Neuffer,[a*] Hisham Sayed,[b] Terry Hart and Don Summers[c]**

[a] *Fermilab,*
*PO Box 500, Batavia IL 60510, USA*
[b] *BNL,*
*Upton, NY 11973, USA*
[c] *University of Mississippi*
*Oxford, MS 38655, USA*



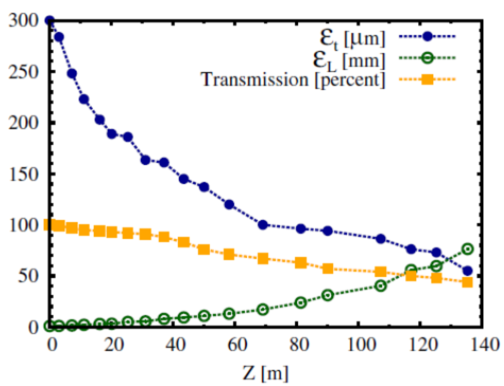
# Final cooling example

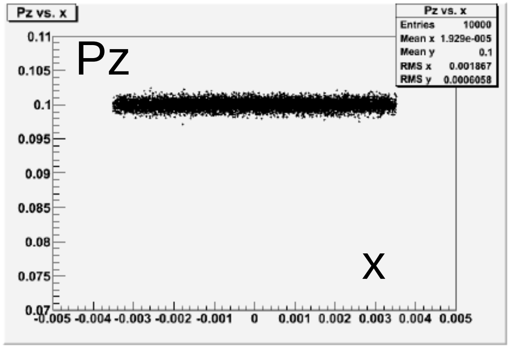
- The performance of this system has been simulated by David Neuffer. The starting point is the beam coming out at stage ~9 of Palmer's high-field solenoidal channel

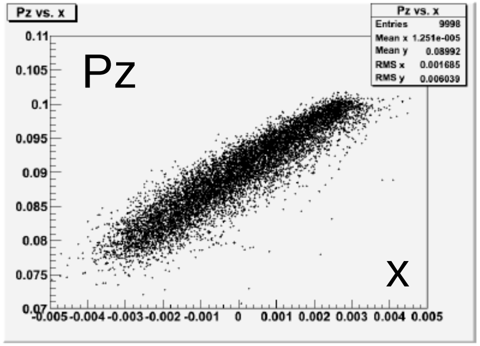



| $z(cm)$ | $P_z(MeV/c)$ | $\varepsilon_x(\mu m)$ | $\varepsilon_y(\mu m)$ | $\varepsilon_L(mm)$ | $\sigma_E(MeV)$ | 6-D $\varepsilon$ increase |
|---|---|---|---|---|---|---|
| 0 | 100 | **129** | 127 | 1.0 | 0.50 | 1.0 |
| 0.6 | 95.2 | **40.4** | 130 | 4.03 | 1.95 | 1.29 |
| 1.2 | 90.0 | **25.0** | 127 | 7.9 | 3.87 | 1.54 |

MuC emittance goal achieved



# Optimization steps

- Step 1: Bring down transverse emittance to ~130-150 micron range
  - Rectilinear channel is preferred for the hand-off as it will keep longitudinal emittance low
- Step 2: Match into the first wedge: Phase-rotate to reduce momentum spread. Typical ranges are ~120 MeV/c at (0.8-1) MeV/c momentum spread. Focus into first wedge causes an emittance exchange to 25-30 μm (x), 130-150 μm (y), 15 mm (z).
- Step 3: Match into the second wedge: Beam is stretched in time to enable phase energy rotation and reduce energy spread. Dispersion suppression may required. Focus on the second wedge for emittance 30 μm (x), 25-30 μm (y), 75 mm (z)
- Preliminary studies indicate that no very high magnetic fields are needed but more work is needed.

# Path forward

- Funding is very limited to explore any of the ideas discussed here
- We have established a collaboration with U. Chicago to work on some of the 6D cooling channel optimizations
  - Our interest is to find out how far we can push this channel using newest advancements (continue Don Summers work)
- We have a Fermilab summer intern who works on optimizing the emittance exchange wedge for final cooling
  - We anticipate to have more results within the next 4-6 weeks
- A proposal for further funding submitted through Fermilab's Laboratory Directed Research program
  - This will gives us resources to bring-in more experts on the final cooling design and simulation work