Thoughts on Incorporating HPRF in a Linear Cooling Channel

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Outline

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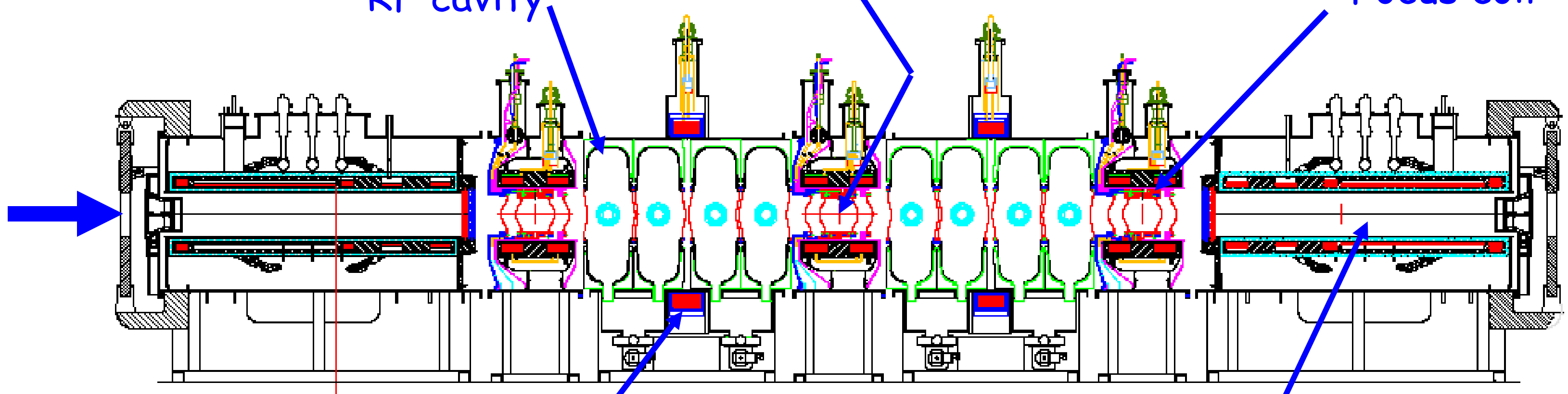
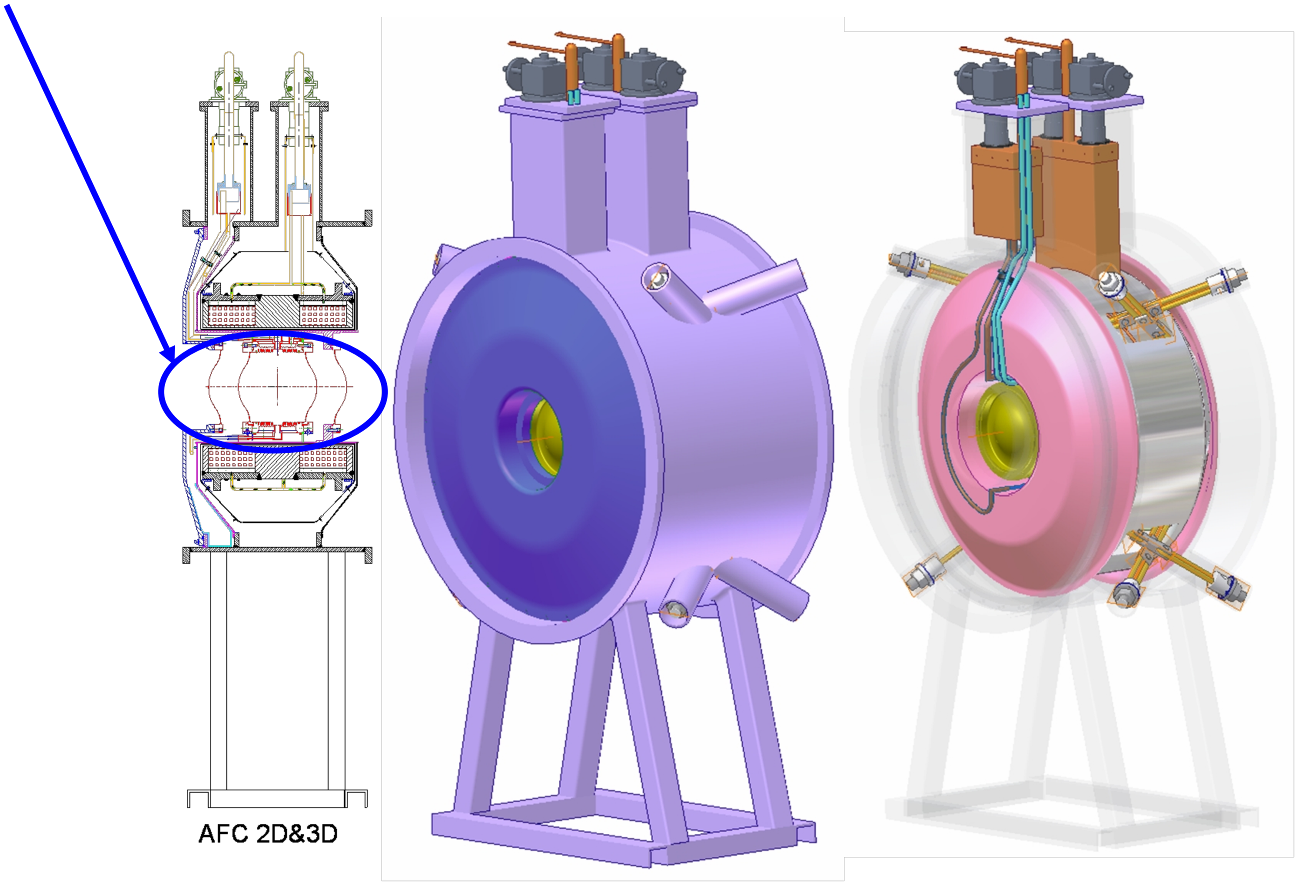
Introduction (1)

- Present layout of MICE illustrates use of LH_2 for ionization cooling
  - makes use of vacuum RF cavities to provide reacceleration
- Absorber is most significant safety issue
  - RF cavities and SC magnets are standard fare in HEP experiments
    - safety issues well understood
  - compact layout means absorber cannot be considered in isolation ⇒ holistic approach to safety



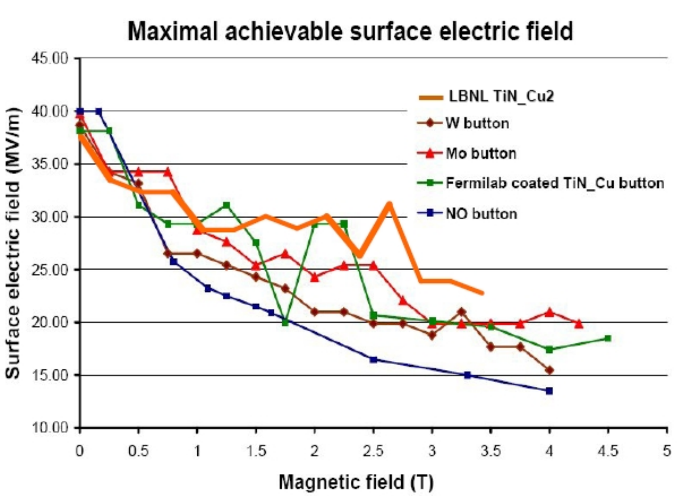
Introduction (2)

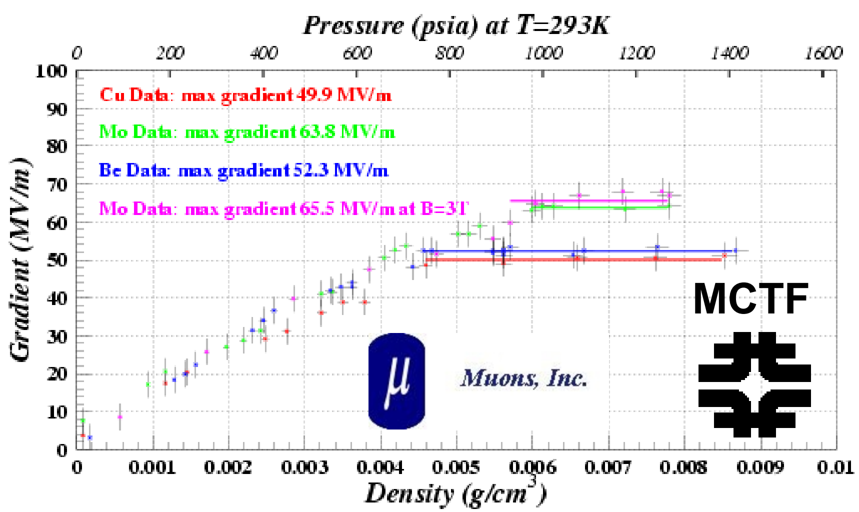
- **Absorber is isolated from remainder of MICE by buffer vacuum volume**
  - H_2 zone comprises only absorber + buffer vacuum



Introduction (3)

- We have evidence that vacuum RF cavity gradient performance degrades in a strong magnetic field
  - alternative approach of HPRF does not
    - though it has other potential issues
- It seems prudent to begin investigating the technical aspects of implementing HPRF in a linear cooling channel





MICE Safety Approach (1)

- Primary objective: to have a safe, but *usable* system
  - meeting either requirement by itself is relatively easy!
- Hydrogen safety design approach to follow
  - maintain separation of hydrogen and oxygen atmospheres
  - avoid ignition sources in contact with hydrogen
- These are redundant requirements
  - either suffices to prevent an unsafe condition
- Our definition of "safe"
  - system must tolerate *two things going wrong simultaneously*

MICE Safety Approach (2)

- Principal RAL regulations to address
  - explosive gas (ATEX)
    - ATmosphere EXplosible

      http://europa.eu.int/comm./enterprise/atex/

      - requires document outlining explosion protection techniques
  - pressure vessel code (BS5500 or equivalent)
    - vacuum vessels defined as pressure vessels and must meet code
  - RAL codes of Practice and Safety Policy
    - Health and Safety Executive

      http://www.hse.gov.uk
    - Control of Substances Hazardous to Health

      http://www.hse.gov.uk/hthdir/noframes/coshh/index.htm
  - work must be carried out to recognized QA system standards

MICE Safety Approach (3)

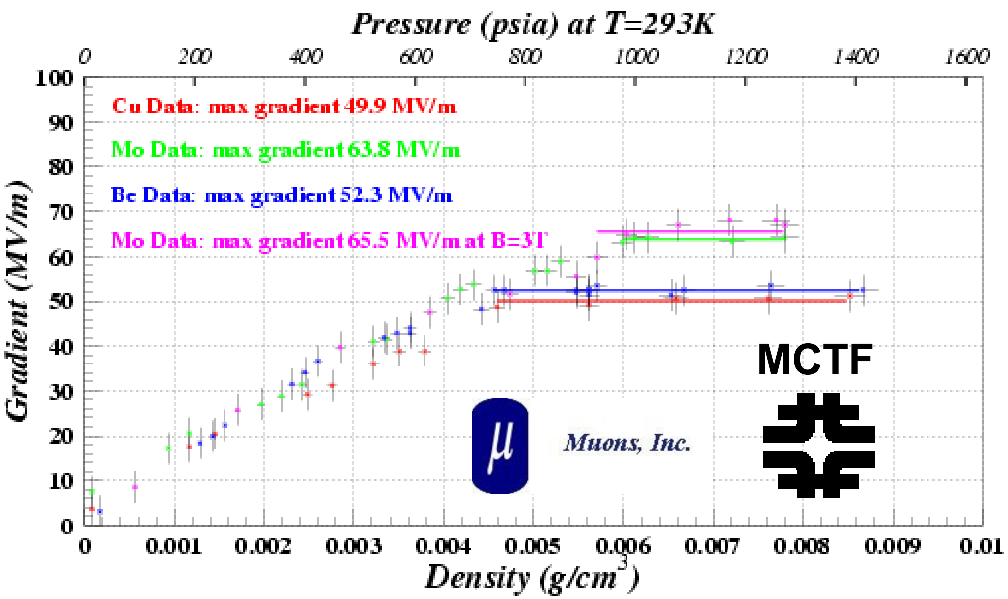
- Hydrogen safety issues
  - flammability (4–75% in air)
  - detonation (18–59% in air)
  - low temperature
    - cold surfaces can cryo-pump O_2
    - large liquid-to-gas expansion ratio plus gas warm-up could lead to overpressure in containment vessel
- In general, the same considerations will apply to a linear HPRF channel

MICE Safety Approach (4)

- We adopted the following criteria for our design:
  - all vacuum vessels designed as "pressure vessels" per BS or ASME code
    - implies testing to 1.25x "design pressure" (pressure where relief valve is set, 1.6 bar)
  - absorber and vacuum safety windows designed for 4x design pressure (internal) and 1.7 bar (external) without buckling
  - two barriers between LH_2 and possible contact with oxygen
    - barrier is either window or Ar jacket
  - separate vacuum volumes for RF, magnets, and detectors
  - hydrogen evacuation paths for absorber (vent pipe) and storage system (vent hood)
- R&D program, including rigorous testing procedures, serves to validate design
- Corresponding requirements must be implemented for linear channel

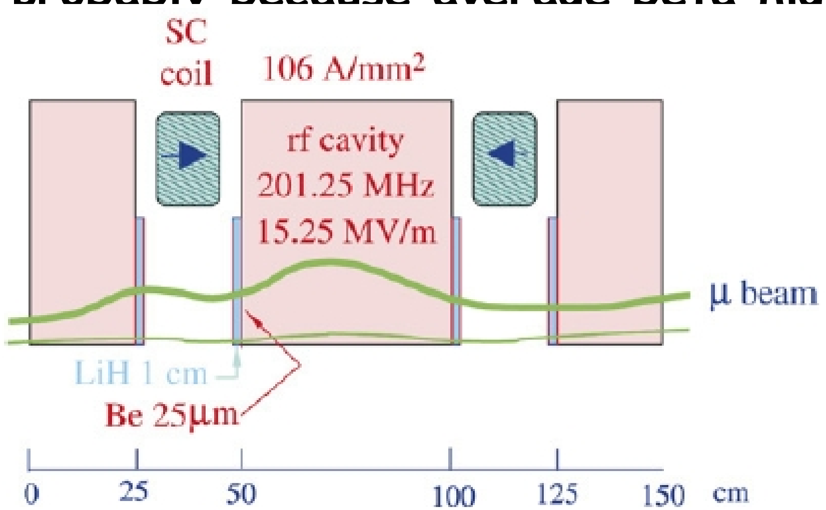
HPRF Issues

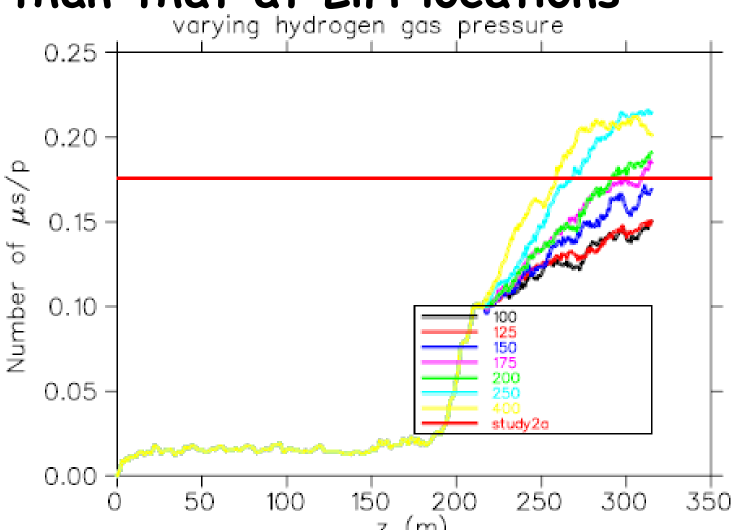
- Many differences between HPRF and "standard" linear cooling channel
  - energy loss distributed rather than limited to discrete absorbers
  - loss medium gaseous rather than liquid hydrogen or LiH
    - likely requires some modularity for safety reasons
  - must match gradient to energy loss, even if max. gradient higher
    - cannot take full advantage of high maximum gradient



Study 2a with GH_2

- **Study 2a cooling cell layout**
  - 1.5 m long, four 1-cm LiH windows, one 201-MHz cavity, 53 cells
- **Version studied by Fernow and Gallardo (MuCool Note 311) had more cells (66)**
  - initial try used 124 atm of H_2 to match ΔE of LiH absorbers
  - full simulations (*without isolation windows*) showed 200 atm needed to match (really, somewhat improve upon) Study 2a performance
    - probably because average beta higher than that at LiH locations





Comments on GH_2 Study

- Not obvious that replacing *all* the LiH is the best idea
  - requires very high pressure (124-200 atm at room temperature)
    - cooling to LN temperature lowers *P* by a factor of ~4, but still high
    - need thick isolation windows
      - not clear one can (or should) plan for only one set of windows
  - high *P* would permit operation of cavities at much higher gradients, but
    - hard to increase ΔE of channel correspondingly with gaseous absorber
      - reducing number of cavities mitigates this
        - e.g., halving number of cavities at 2x gradient
    - impractical to feed required power into the cavity
      - if gradient limited by surface breakdown, might get E_{acc} of

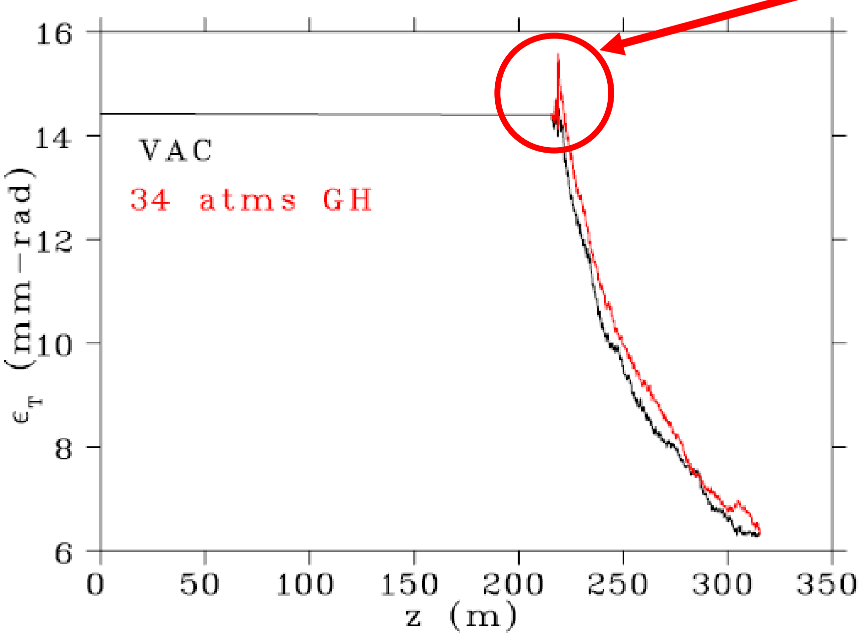
        ~50 MV/m
        - would require ~10x higher power than 16 MV/m, or ~ 40 MW per cavity
      - even halving the number of cavities would require 4x more power, or 16 MW per cavity

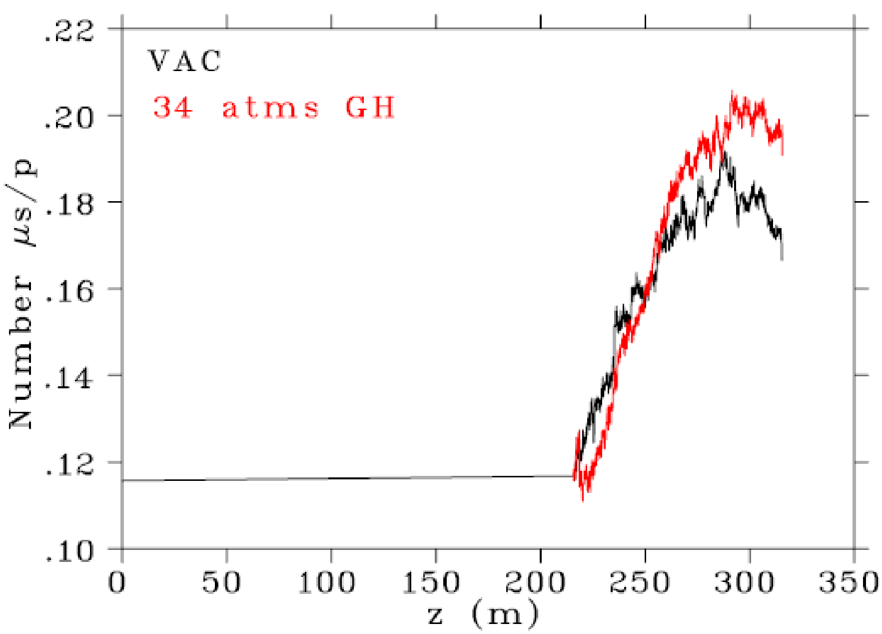
Alternative Strategy

- Primary purpose of HPRF is to avoid degradation from magnetic field
  - use gas only to deal with this task
    - requires much lower pressure than to reach material limit
- For the Study 2a case, we need gradient of ~15 MV/m
  - from HPRF test cavity, expect this to require only ~34 atm at room temperature
    - or ~9 atm at 77 K
  - need eventually to confirm with 201-MHz cavity
- At this pressure, GH_2 ΔE is ¼ of LiH ΔE
  - reduce LiH thickness by 25% to maintain same overall ΔE
    - this will not be exactly right due to different beta weighting
      - should be a reasonable starting point for re-optimizing channel performance
    - looking into this now

Preliminary Evaluation (1)

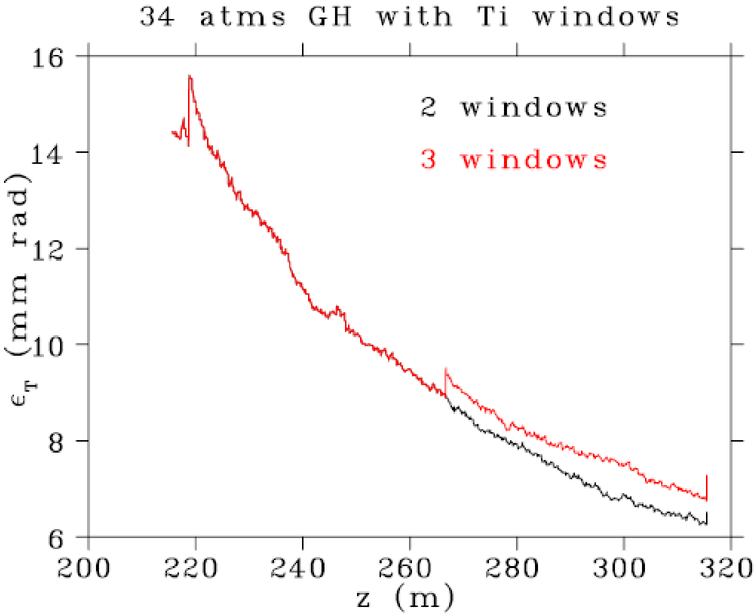
- Took a quick look at performance of proposed "hybrid" channel (Gallardo)
  - results encouraging, but not yet optimized
    - not much change in performance between gas-filled hybrid (red line) and vacuum (black line) channels
      - isolation window does have a substantial effect ☹

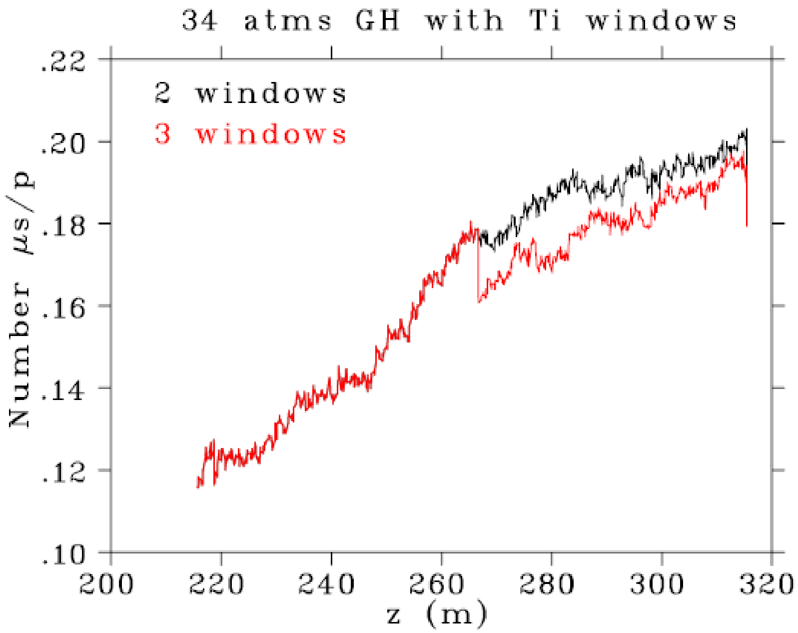




Preliminary Evaluation (2)

- Took quick look at effect of adding even one more isolation window (Gallardo)
  - it hurts!
  - maintenance can be accommodated with gate valves
    - safety considerations may dictate more subdivisions
      - using lower *Z* window material may help
        - hydrogen embrittlement must be evaluated for each choice



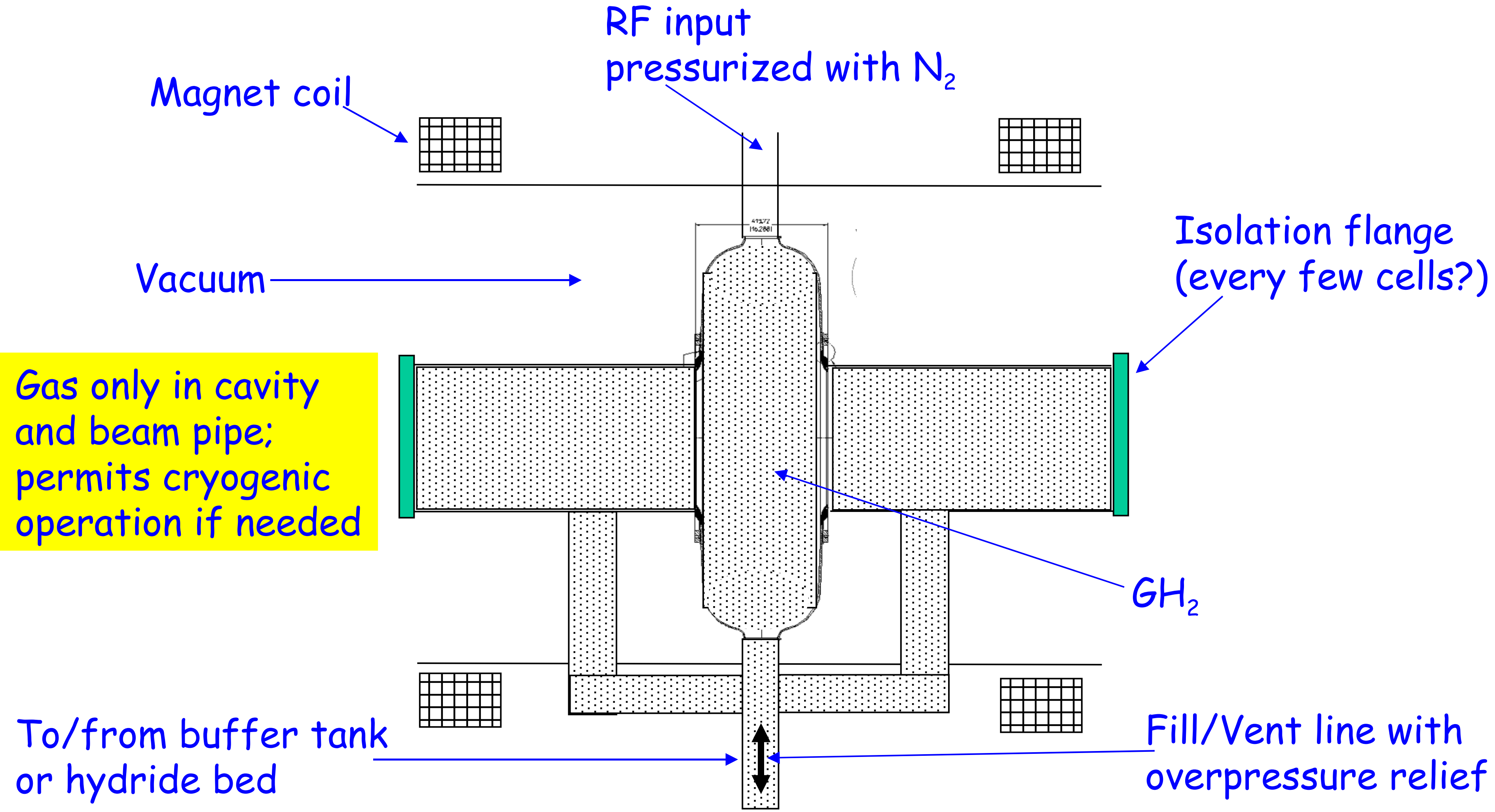


Comments on Implementation

- Implementation of gas-filled channel likely to be tricky
  - continuous 80-100 m pipe with high-pressure hydrogen does not seem prudent in today's safety culture
    - *any* problem would then involve the entire hydrogen inventory
    - storage or removal of entire gas inventory means providing large volumes
    - vent pipes would be distributed along the channel in any case to give adequate conductance
  - modular system, with independent gas supplies, seems more desirable
    - but comes with the obvious drawback of more thick isolation windows
      - maybe simply using gate valves will suffice
  - materials issues must be carefully considered
    - hydrogen embrittlement must be evaluated for all structural materials
      - also Cu, Be, and LiH; Al and Be-Cu alloys are particularly resistant
  - operating at LN temperature reduces *P* by factor of ~4
    - but complicates engineering of channel
      - insulating vacuum, cooling of RF cavities, differential expansion,...

Possible Implementation (A)

- Took a preliminary look at layout to get an idea of issues



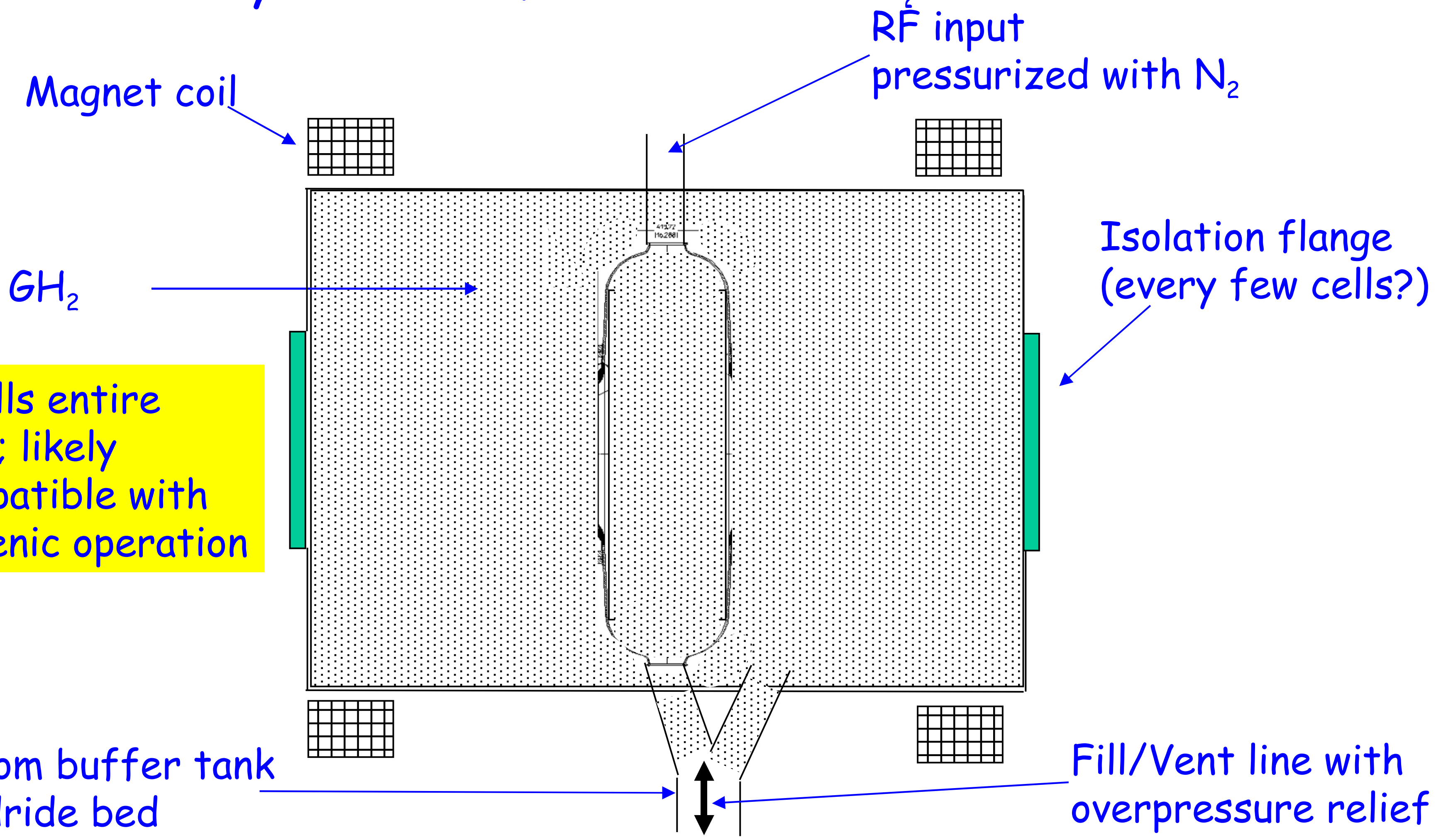
Issues to Consider (A)

- Cavity walls must be thick enough to withstand pressure
- RF window must be pressurized on both sides to 34 atm
- Vent/fill line must avoid ΔP on LiH windows
- Cryogenic operation probably possible
  - need to insulate fill/vent lines outside vacuum area
  - need to accommodate differential contraction (e.g., between sections)
    - usually use bellows for this, but may not be possible with 34 atm of gas
- Choice of buffer volume *vs.* hydride bed for storage
- Many pressure-vessel code issues to deal with

- On the plus side, can likely keep hydrogen zone contained within apparatus

Possible Implementation (B)

- Could consider a more "MICE-like" implementation
  - fill both cavity and containment vessel with GH_2



Gas fills entire vessel; likely incompatible with cryogenic operation

Issues to Consider (B)

- Cavity and tuners could be similar to MICE implementation
- Bellows connections between sections may not be permitted
- RF window must be pressurized on both sides to 34 atm
- Vent/fill line must avoid ΔP on LiH windows
- Choice of buffer volume *vs.* hydride bed for storage
- Cryogenic operation more difficult
  - would require a vacuum-insulated outer layer
  - warming individual sections would be problematical unless bellows are permissible
- Outer vessel is a (substantial) pressure vessel
- Area outside containment vessel probably a hydrogen zone
  - special requirements for electrical equipment, lights and switches, hydrogen sensors,...

Summary

- Took initial look at implications of using HPRF in linear cooling channel
- Proposed new "hybrid" approach (GH_2 and LiH)
  - initial evaluation looks encouraging
- Looked briefly at pros and cons of two alternative implementation schemes
  - both would be challenging
  - isolation flanges have substantial performance impact
    - can we live with only two, or mitigate effects with low beta sections?
- Cryogenic operation would reduce *P* by a factor of ~4, but at the expense of many engineering challenges
  - probably not cost effective for hybrid approach
    - and less necessary

Acknowledgments

Thanks to:

Juan Gallardo (BNL) for help with initial performance evaluation of hybrid channel

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*but not very good at it!