Lawrence Livermore National Laboratory

Flux Concentrator Magnet R&D

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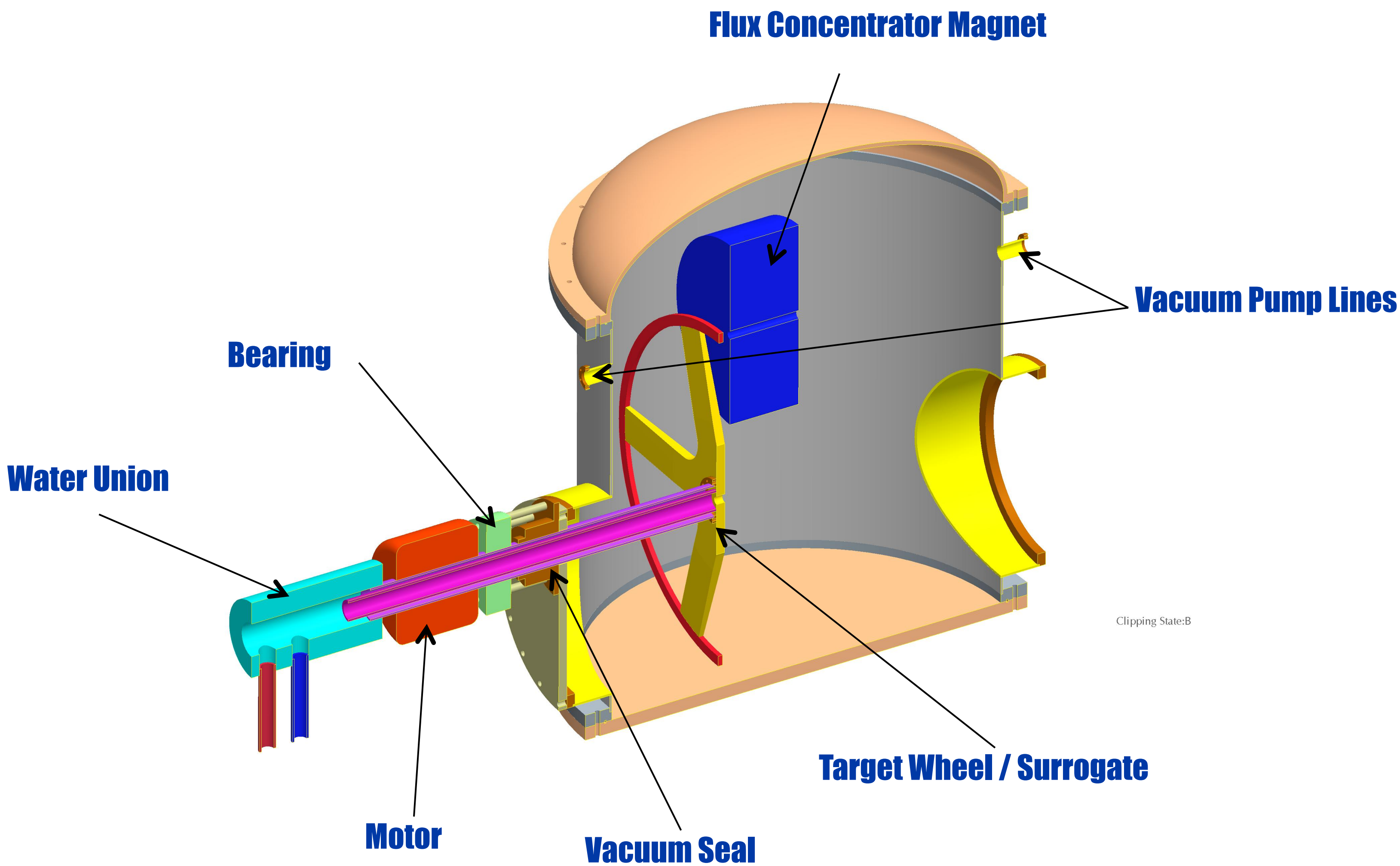
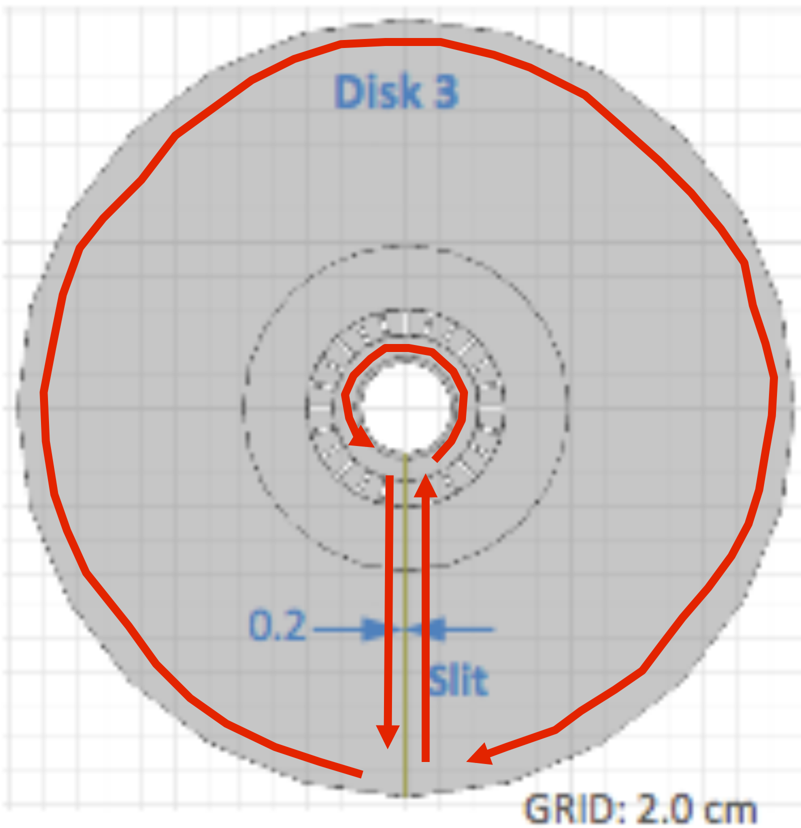
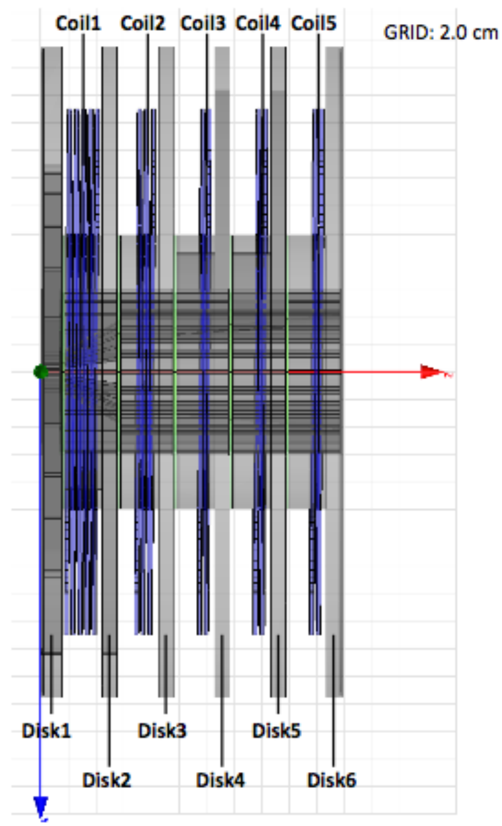
The pulsed flux concentrating magnet sits after the target and increases the capture efficiency



Flux Concentrators are a known technology, we started with a 40 year old design from Brechna



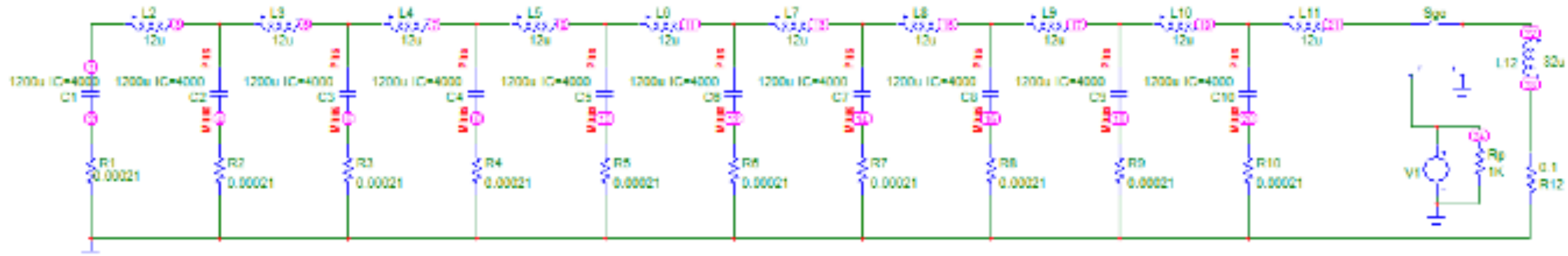
Current induced in a copper disk is forced by a non-conductive slit to flow around the bore



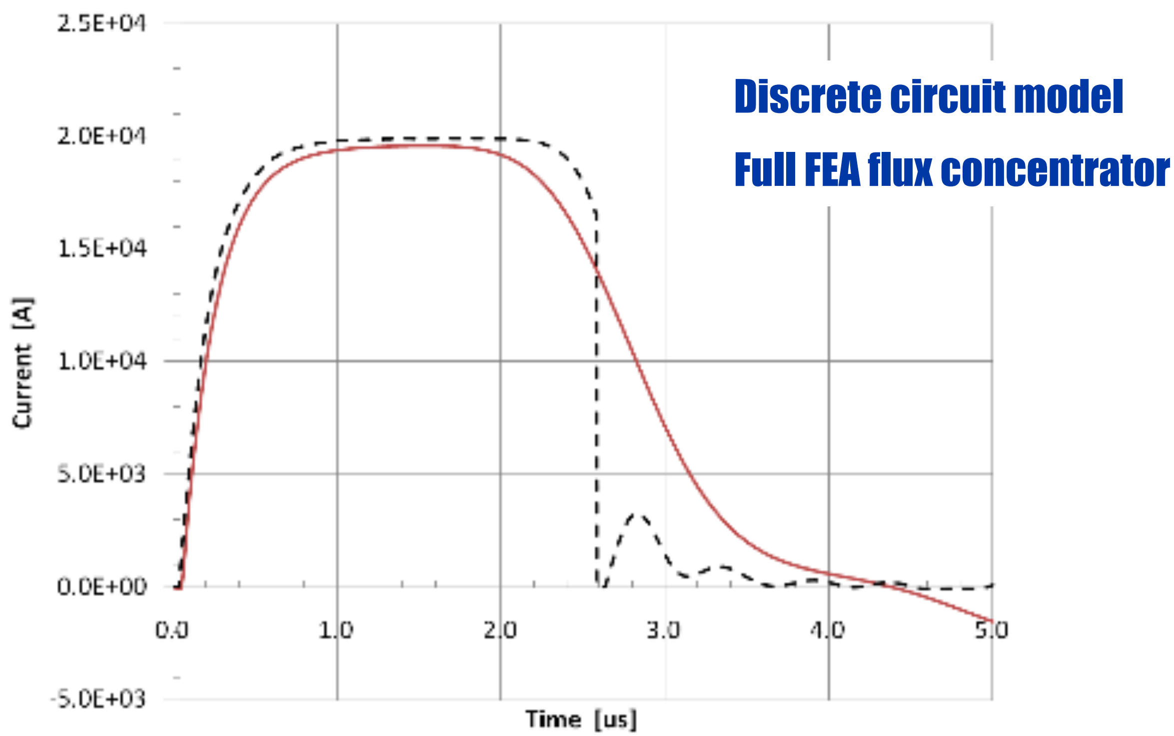
A set of disk with varying bore size are energized by current in copper coils to produce the desired field

First PFN design was 20kA – 2ms flat top pulser, Flux concentrator with minimum number of turns

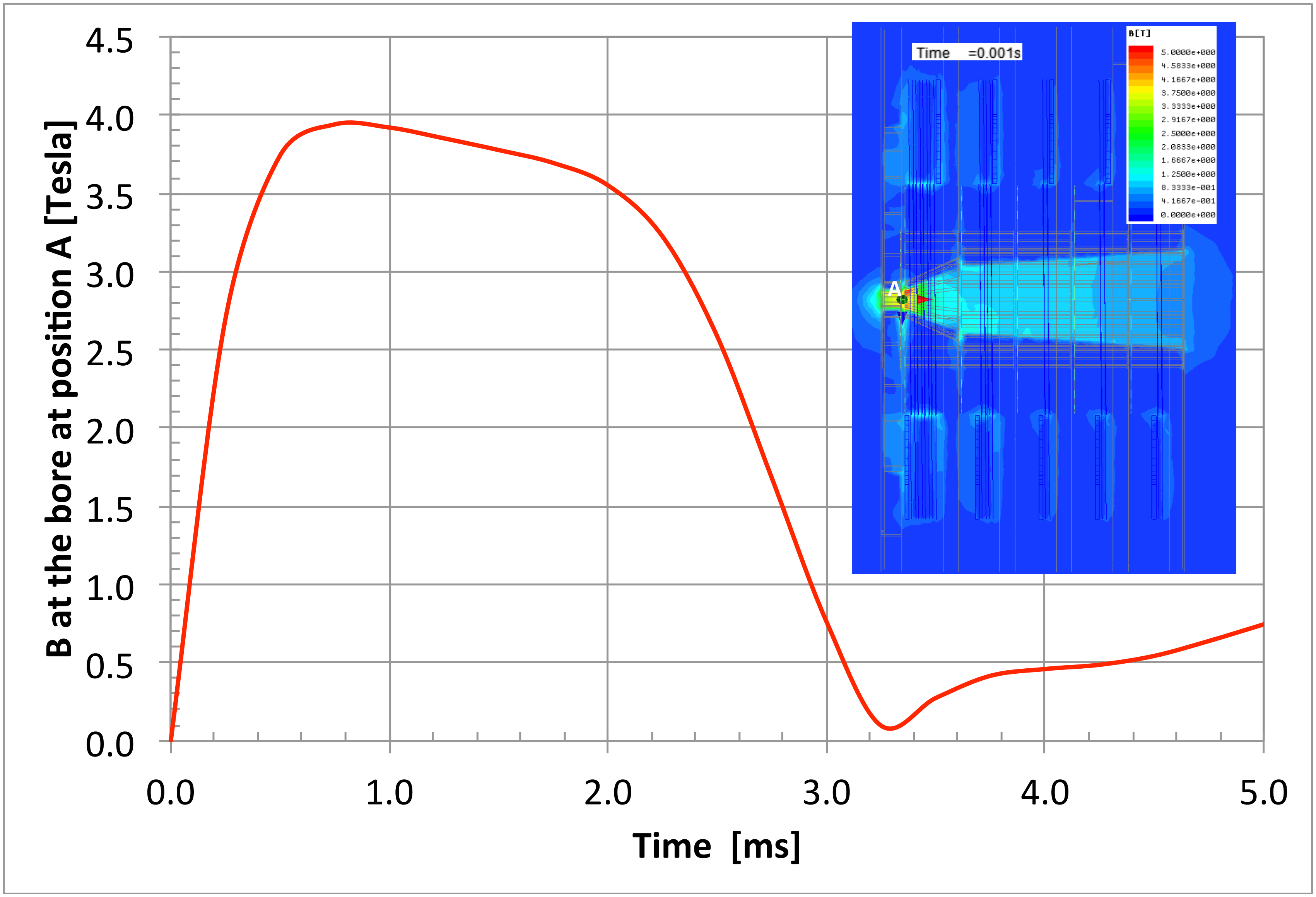
Verification of Current from Maxwell with Equivalent Microcap Circuit



- 96kJ/pulse
  - 480kW at 5Hz
- 12,000 microFarads of capacitors at 4000V
  - 48 C/pulse



The current is constant but the magnetic field droops over time as expected



Technical Challenges

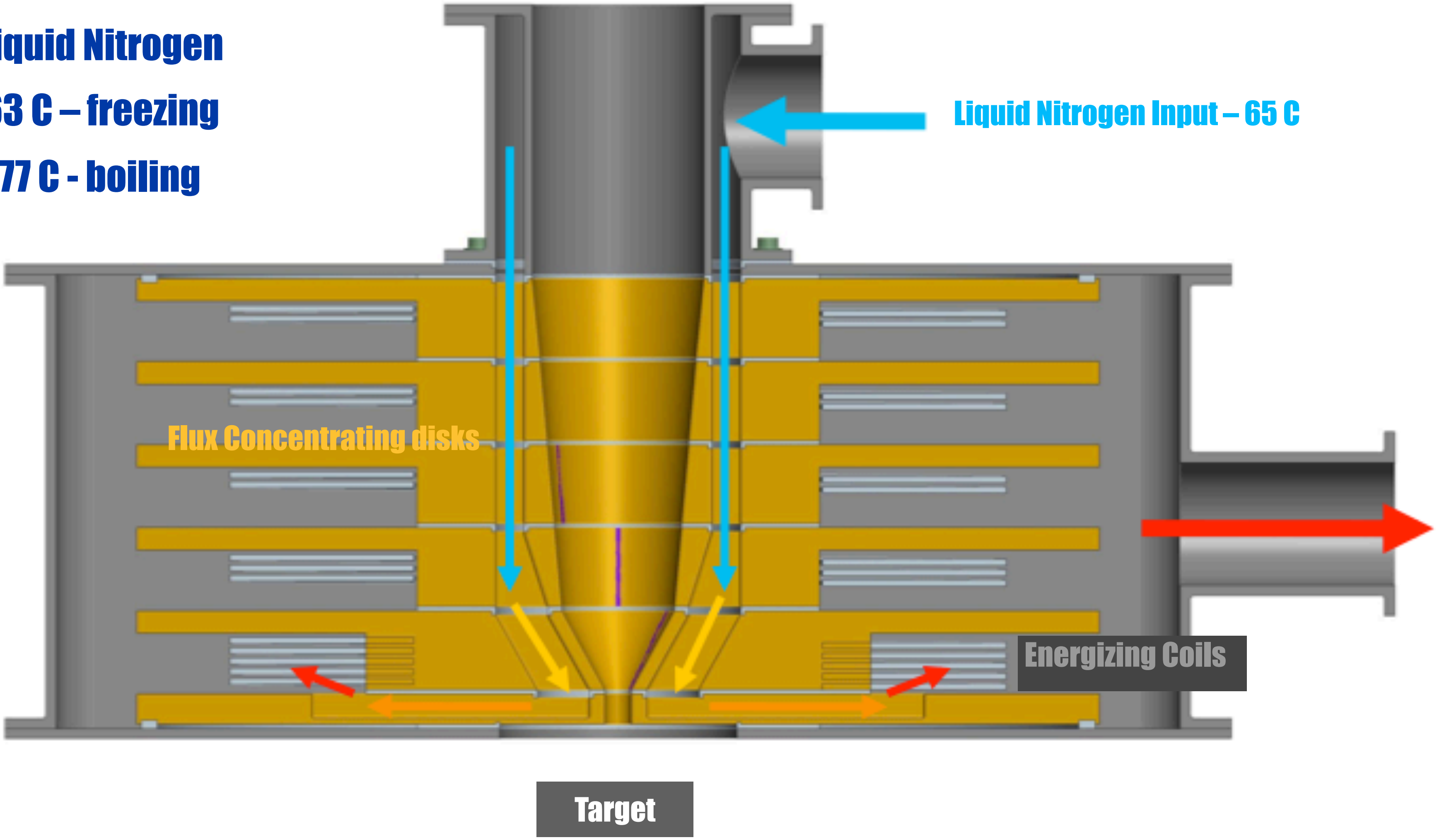
- Near the target - high radiation environment
- Pulsed device 5 Hz, 24/7 for 1 year
  - Must survive cyclic stresses
- Cooling flow is needed near the bore
  - location of maximum power dissipation

The current concept of the device

Liquid Nitrogen

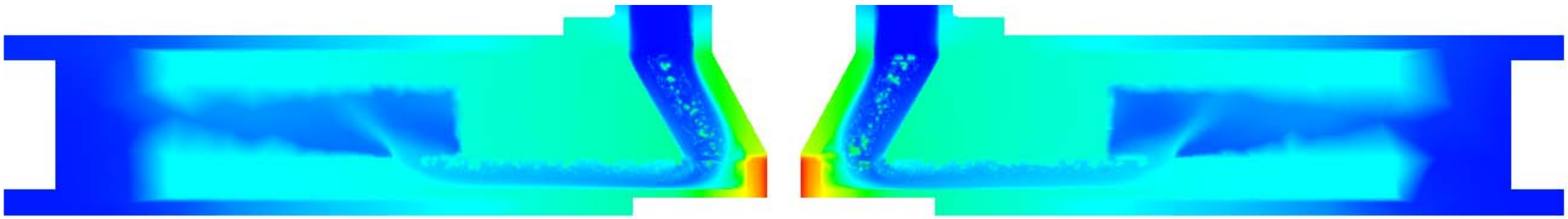
63 C – freezing

77 C - boiling



Energy deposition is max at the bore

Reduced fea model of heat and coolant flow

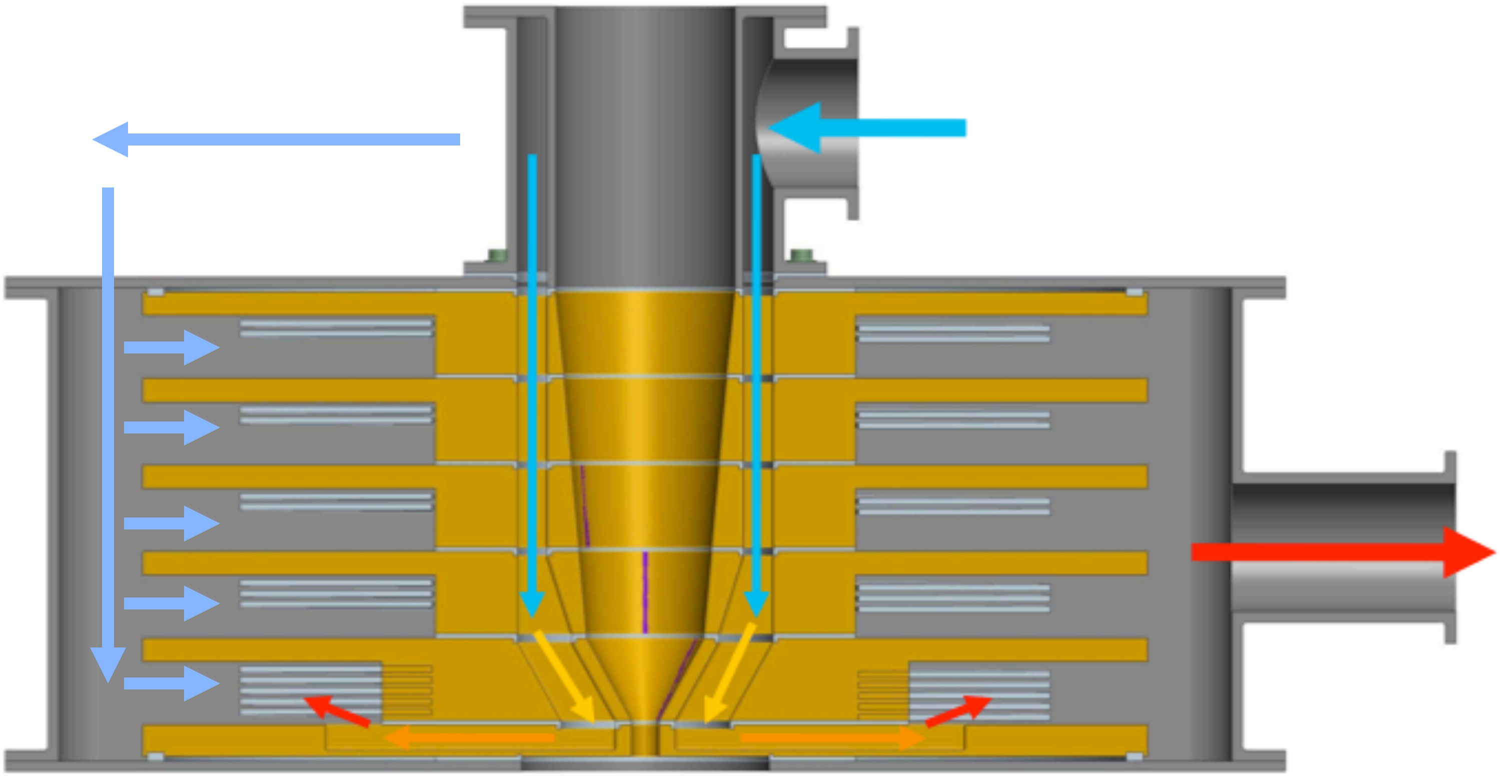


- Average power 800 W
- Desired coolant ΔT of 5 K gives 10 J/gm IN_2 cooling
- Required flow 80 gm/s = 100 cc/s = 6 lpm
- Bore Temp 97 K

- Max radiation is at bore 10^12 Gray/9 months = 8 J/gm/train
- ΔT = 4K from de/dx during the train
- Ok for boiling but prefer reduced depo for repetitive shock

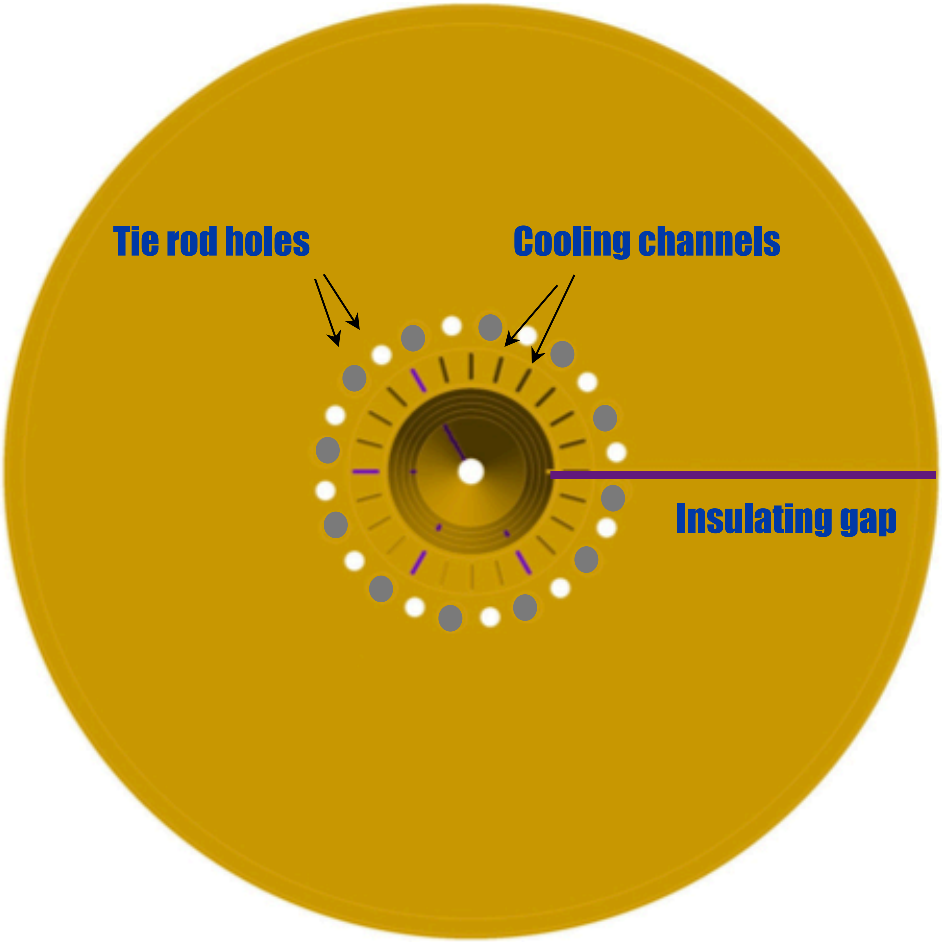
Equivalent average power in the coils

Final design will require additional cooling channel



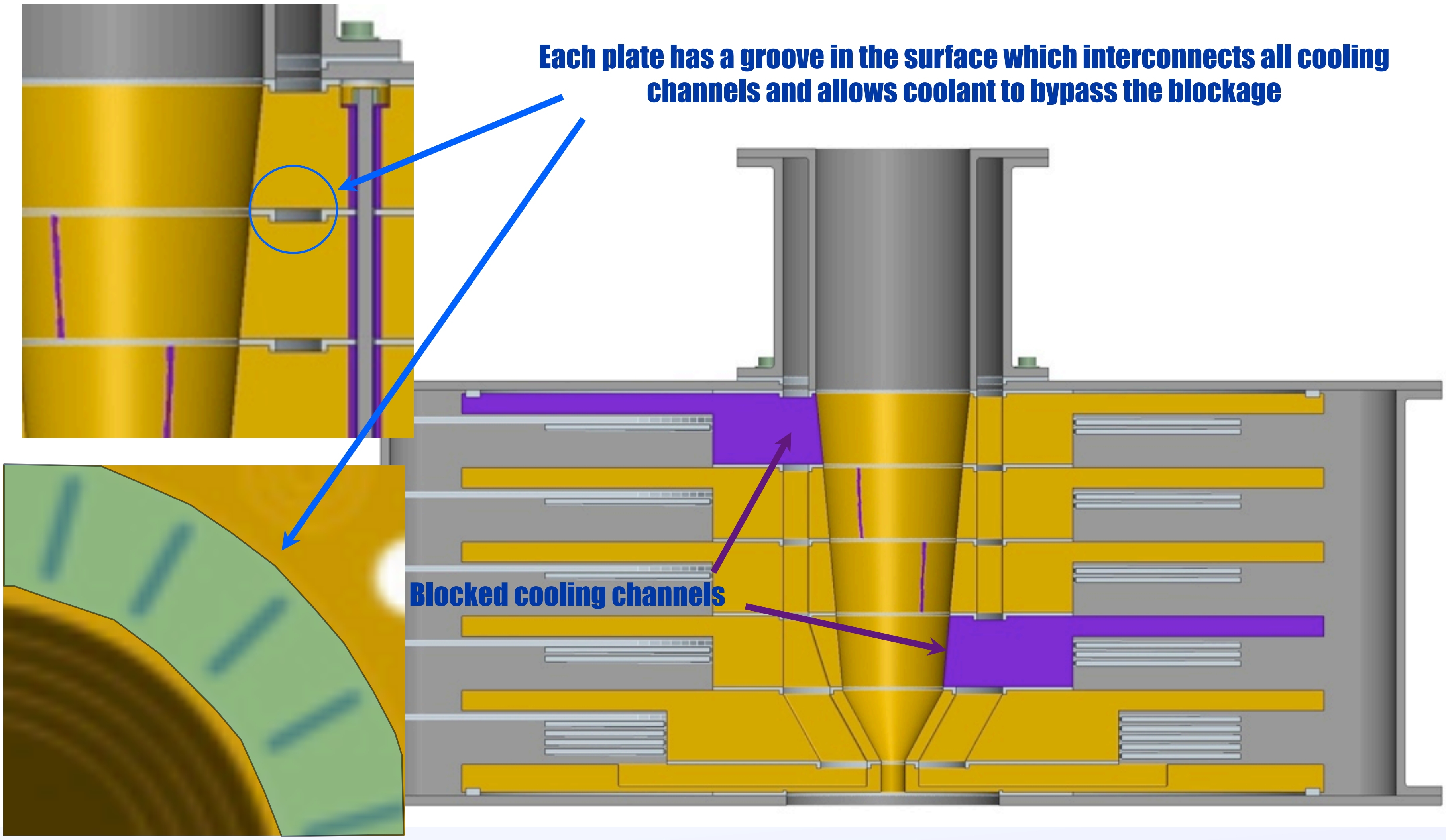
Another 6 lpm of coolant flow to keep the outlet at 70K

Real Estate around the bore is crowded and is needed for a variety of task



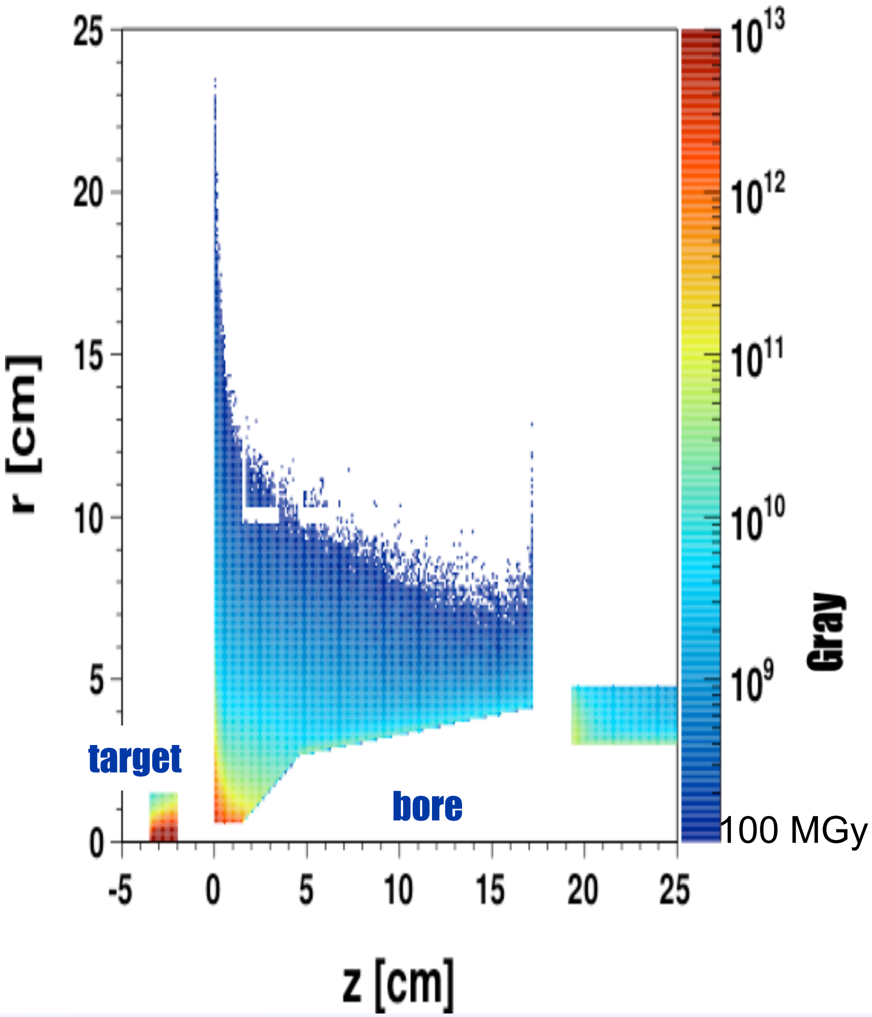
- Cooling channels for liquid nitrogen flow need to be around the bore since that is where the heat is deposited
- Holes for threaded rods to tie the assembly together are needed
- These regions should not interfere with the current flow around the concentrating disk

Some of the gap fillers block a single cooling channel

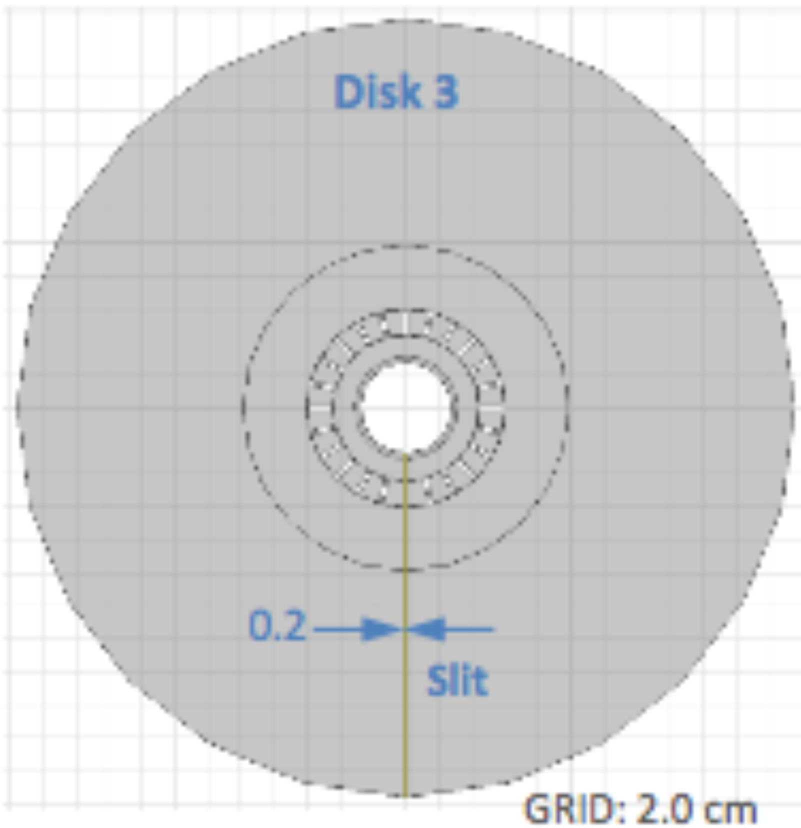


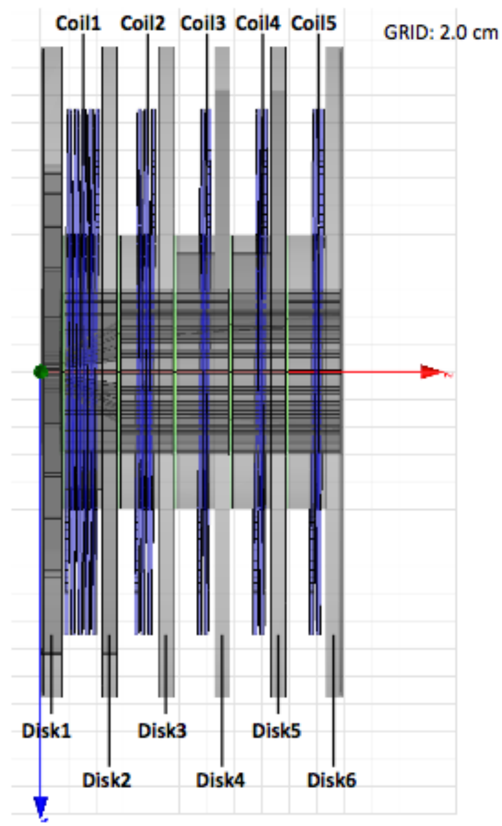
Radiation levels preclude organic insulators near the magnet bore

- 100 Mgy is Kapton radiation limit based on work from CERN
- Calculation from Ushakov shows area where inorganic insulators will be needed
- Energizing coils will use Kapton
  - First and second coil will be moved out in radius for greater shielding



Zirconia Toughened Alumina (ZTA) will be used as an inorganic insulator

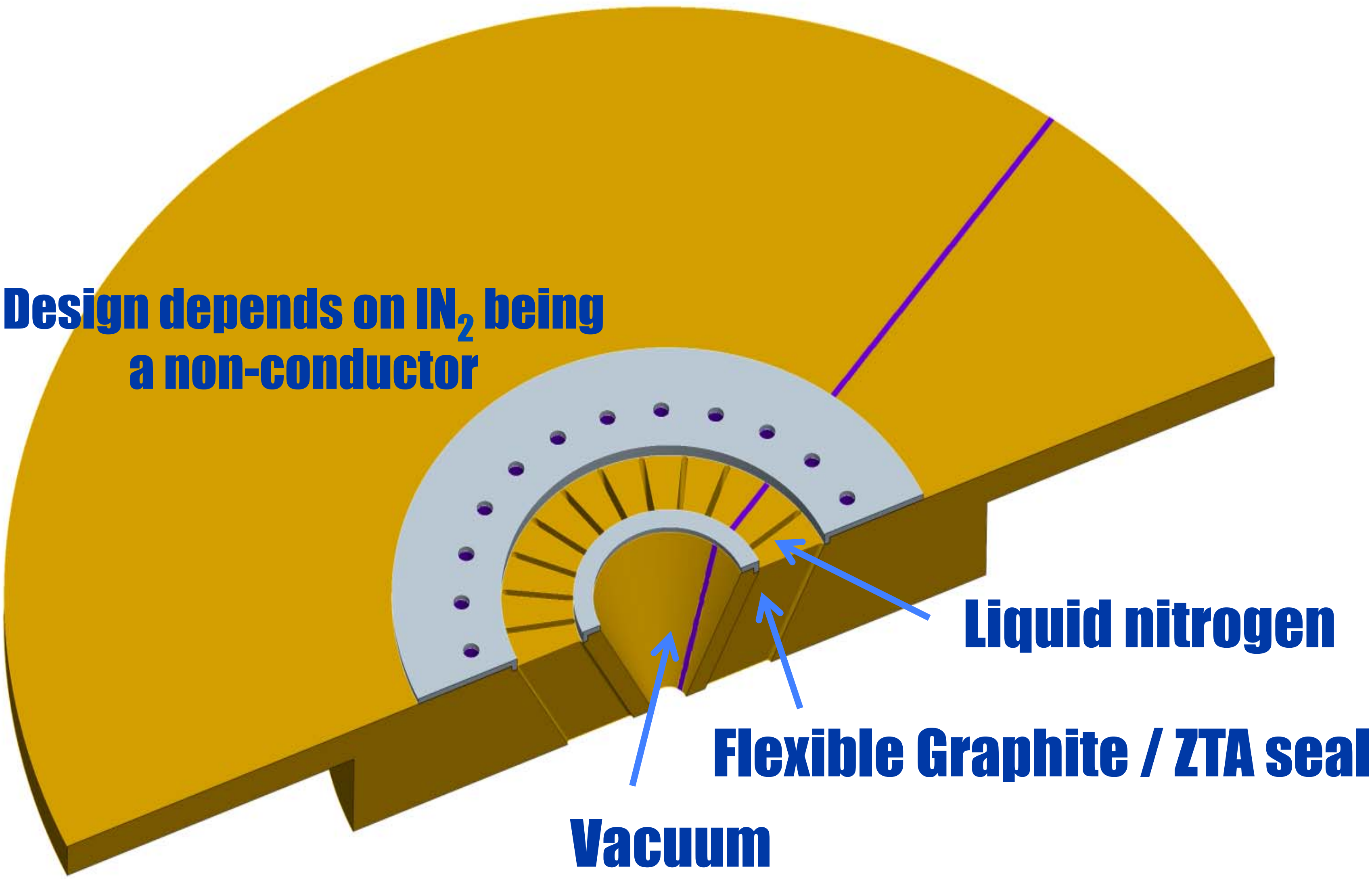




ZTA will be bonded into the gaps in the concentrating plates

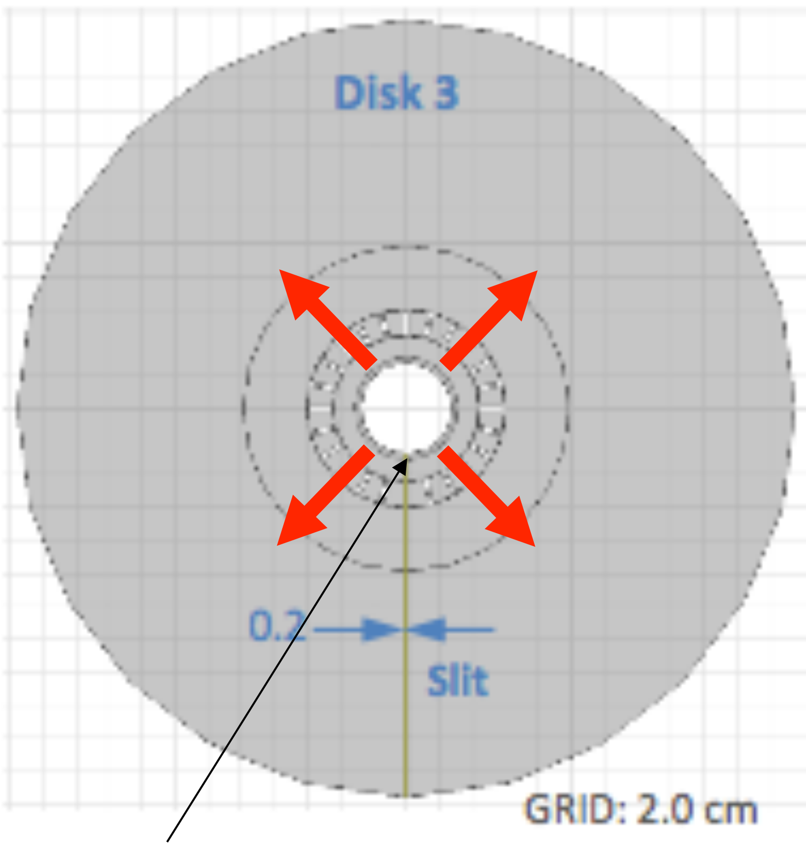
ZTA disks will separate the concentrating plates with Flexible Graphite disks to form the vacuum seal

Non-conductive, non-organic vacuum seal achieved with flexible graphite gaskets and ZTA



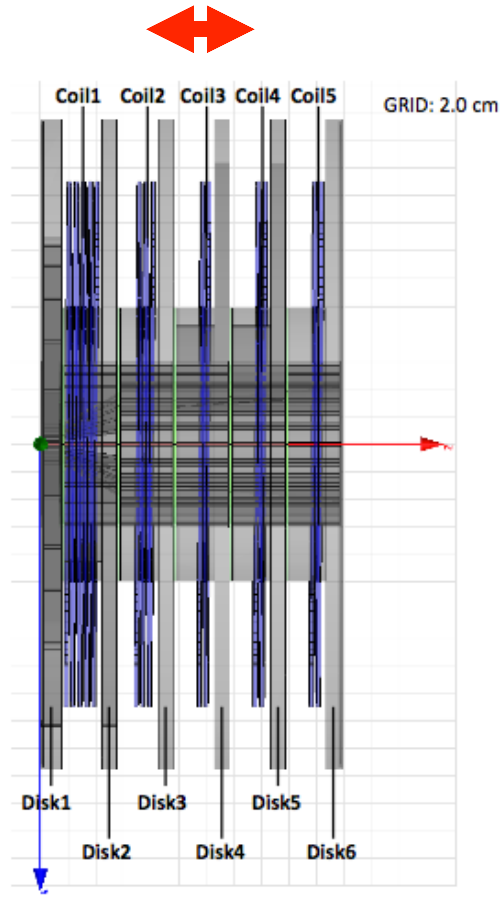
The device must survive repetitive stresses at 5Hz

Radial E x B Forces



ZTA spacer is point of maximum stress

Axial Interplate forces



Achievable fields is limited by ZTA filler stress

B_0	4.2	T
σ_0	1.40E+08	Pa
s_f	7.60E+08	Pa
a	2.00E-04	m
F	1.12	-

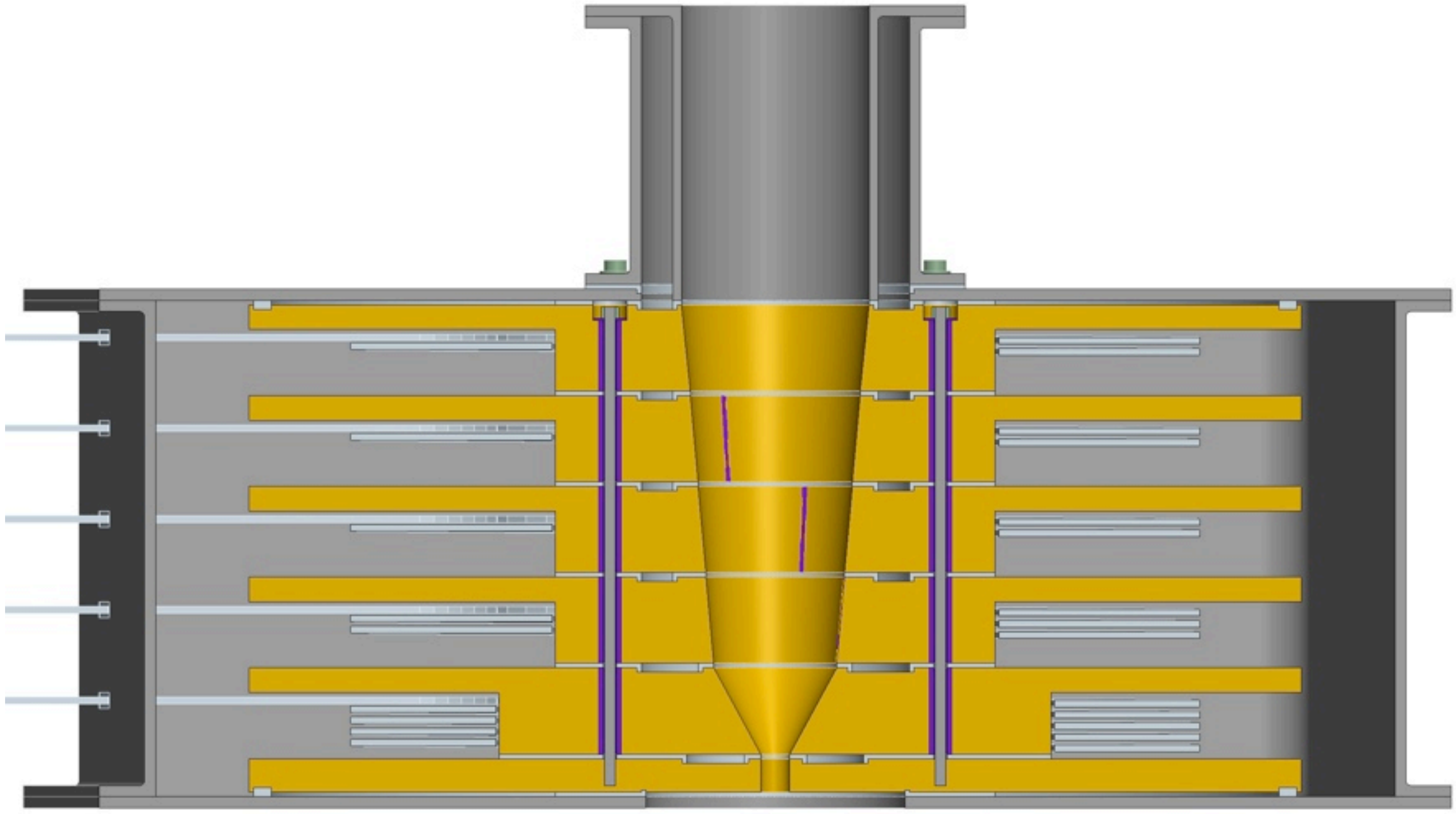
	FS	K_{Ic}	a_t	s_{cg}	s_{ag}	B
	-	Pa·√m	m	Pa	Pa	T
Case 1	1.5	6.00E+06	1.98E-05	2.14E+08	1.42E+08	4.3
Case 2	2	6.00E+06	1.98E-05	2.14E+08	1.07E+08	3.2
Case 3	3	6.00E+06	1.98E-05	2.14E+08	7.12E+07	2.1
Case 4	1.5	1.00E+07	5.51E-05	3.56E+08	2.37E+08	7.1
Case 5	2	1.00E+07	5.51E-05	3.56E+08	1.78E+08	5.3
Case 6	3	1.00E+07	5.51E-05	3.56E+08	1.19E+08	3.6

Key:

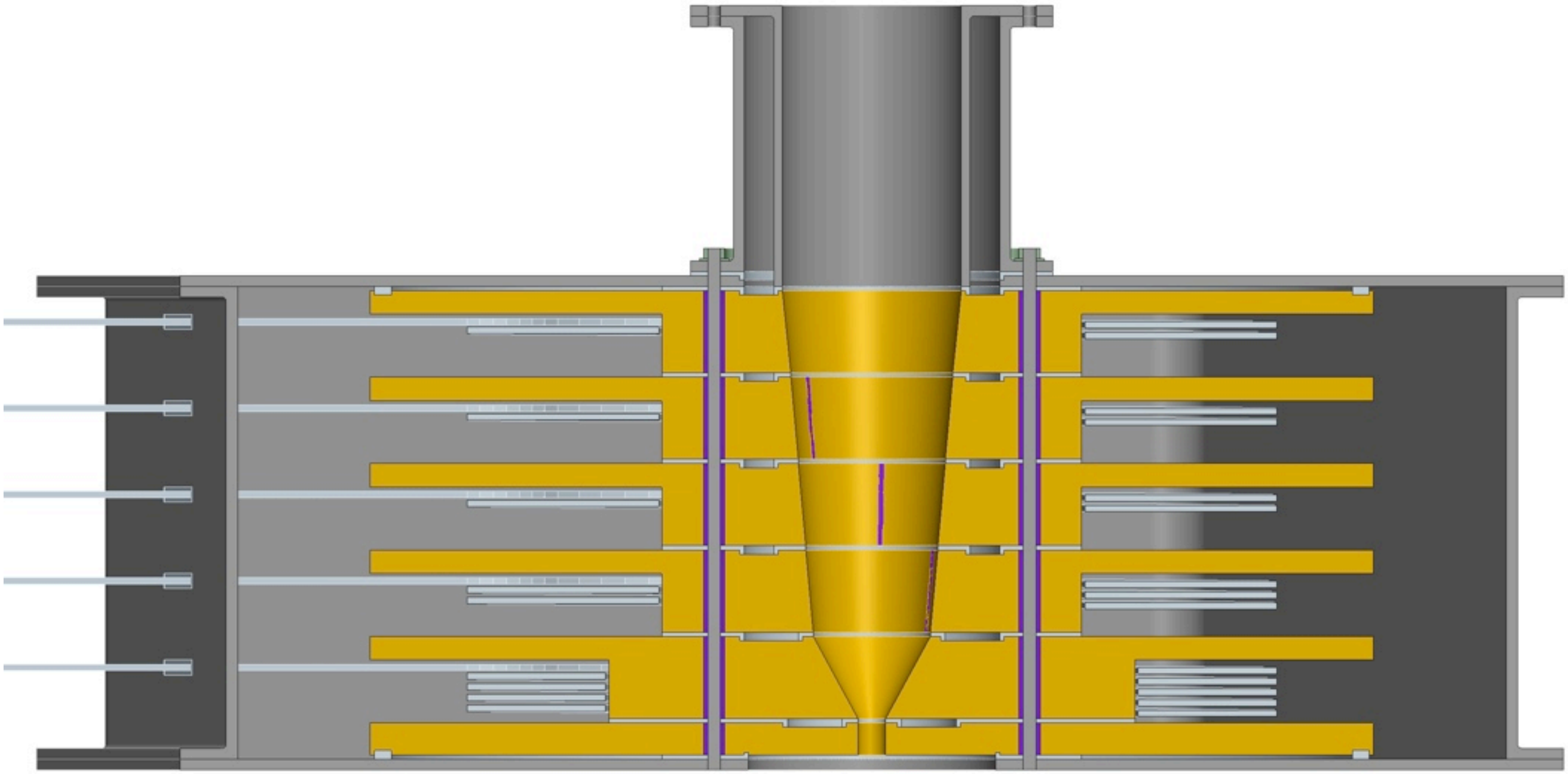
- B_0 Reference peak magnetic flux density
- σ_0 Reference ZTA stress
- s_f ZTA flexural strength
- a Assumed flaw (crack) size
- F Flaw stress multiplier
- FS Factor of Safety
- K_{Ic} ZTA fracture toughness (Mode I)
- a_t Transition flaw size (use LEFM for flaws larger than this)
- s_{cg} Critical gross section stress (max principal?)
- s_{cg} Allowable gross section stress with FS (max principal stress from FEA?)
- B Peak allowable magnetic field (flux density)

- Mechanical stresses in the ZTA gap filler become the limiting factor in the achievable field
- Stress is proportional to B^2
- Safety factor of 2 with conservative assumptions gives 3.2 T B-field

One set of tie rods provides the compressive force to seal the concentrating plates together

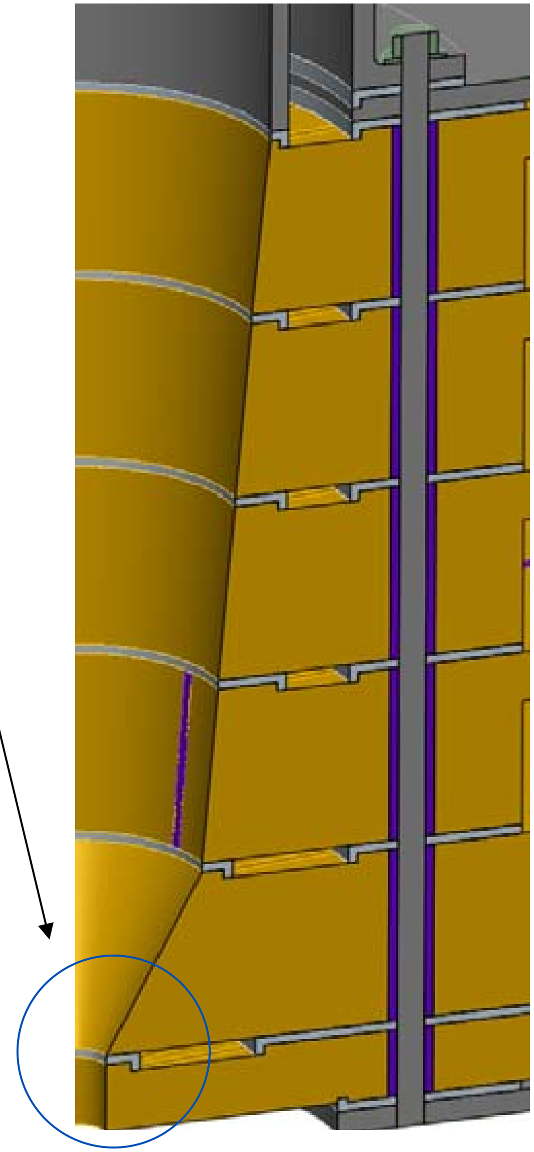


The other connects to the outer casing



The vacuum seal is located where the repetitive stresses are highest

- All of the action is in plates 1 and 2
- ~ 25K ΔT per pulse around the bore
- 40K steady state gradient from bore surface to cooling channels
- Plates are flexing during the pulse due to radial forces
- Plates are flexing axially



The device should survive for 9 months of 5 Hz operation

- Need to back off the peak field to 3.2 T to get a factor of two safety margin in the fracture propagation in ZTA using conservative assumptions
  - Acceptable capture efficiency

- Remaining design choice is the energizing coils
  - Number of amp-turns per coil is set
  - But how many turns?
  - Depends on choice of pulse forming network

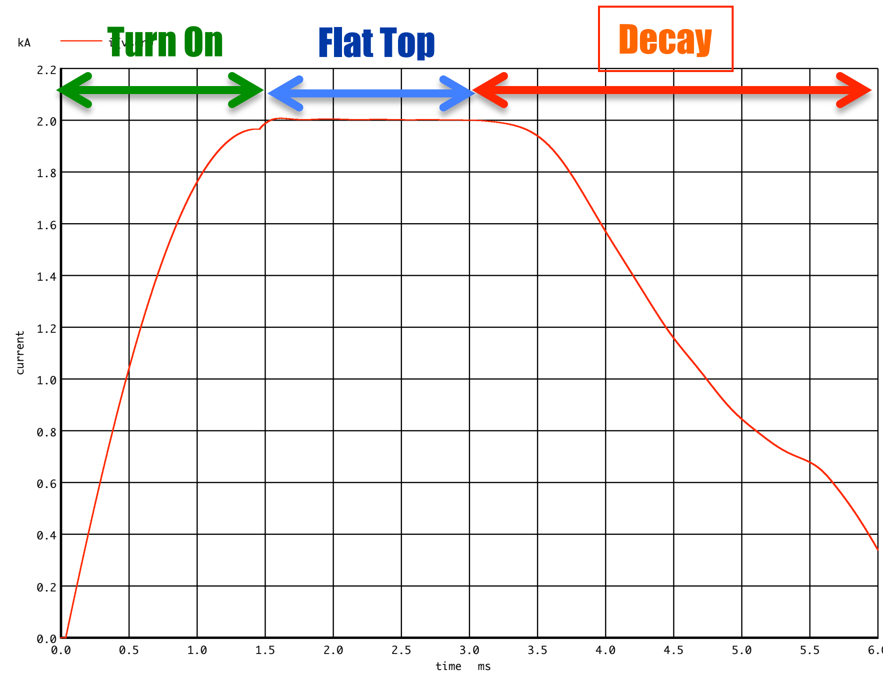
The Pulse Forming Network for the Flux Concentrator is a challenge to optimize

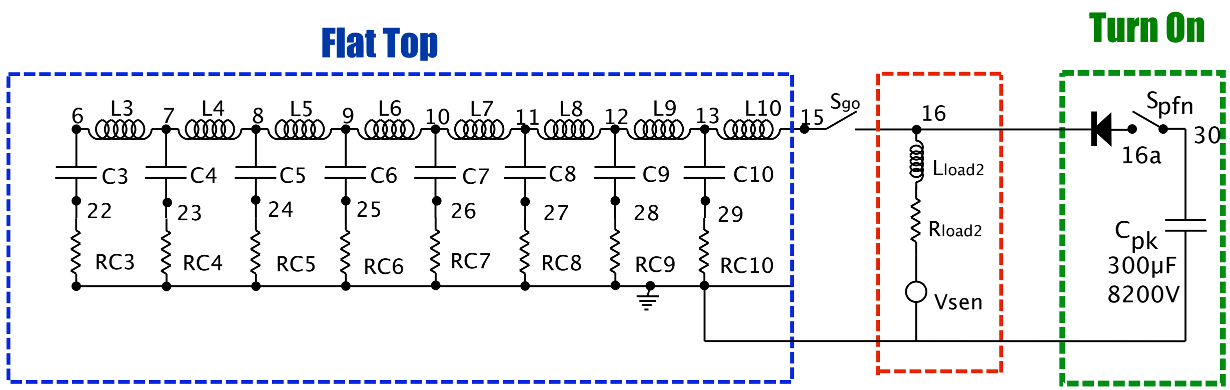
- We want:
  - One milllisecond flat top
  - Fast turn on
  - Minimize capital cost of the pulser (capacitors)
  - Minimize operating cost (Joules / pulse)

- We need power during the initial turn on
- At the flat top we need current but little power

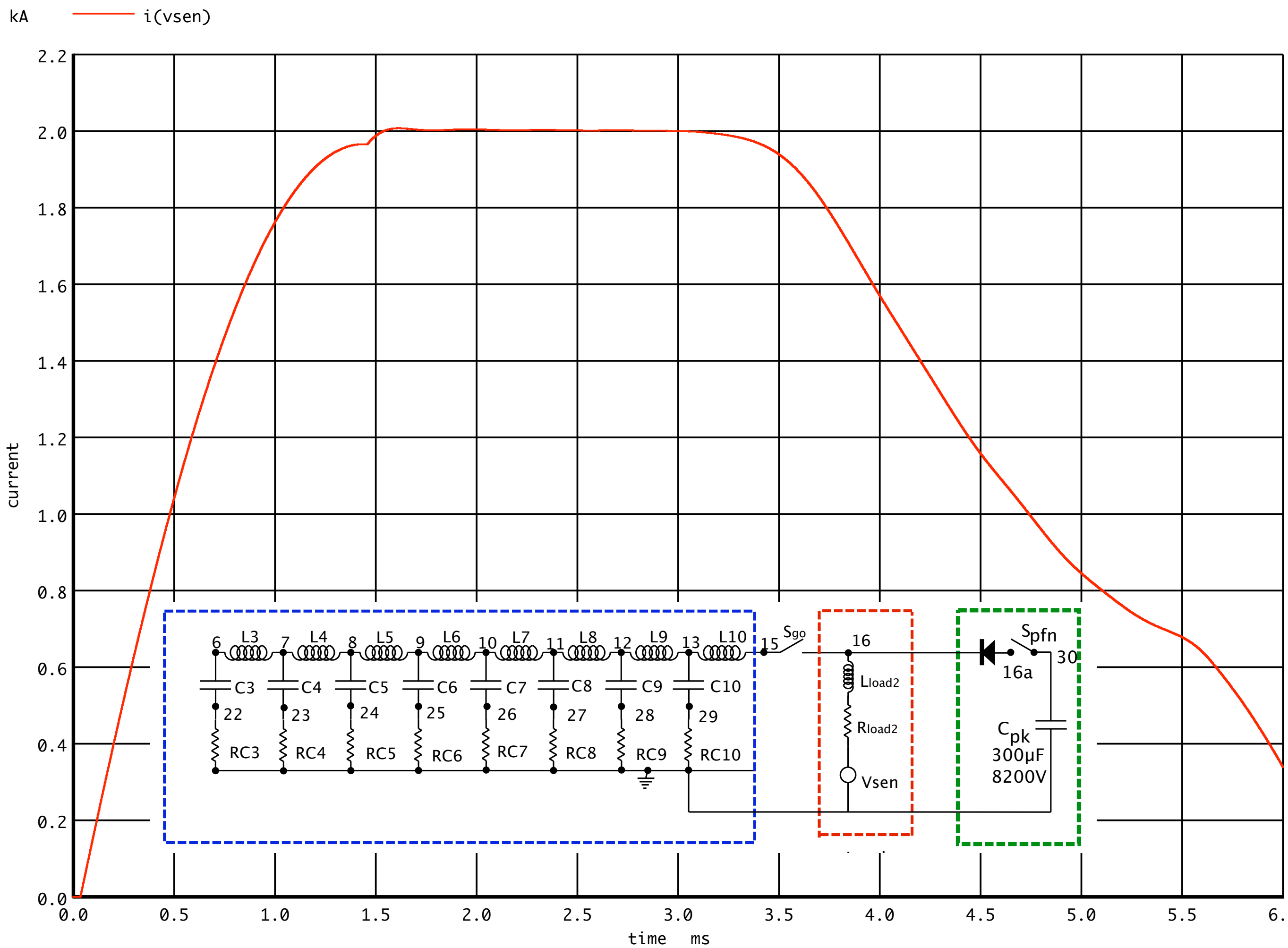
Separate turn-on phase from flat top in the pulse forming network

- Turn-on circuit fires first
- At peak, flat top circuit fires
- Allows to have higher number of turns – lower peak current





Design for 10x turns – 2kA peak current reduces capital and operational cost in pulser



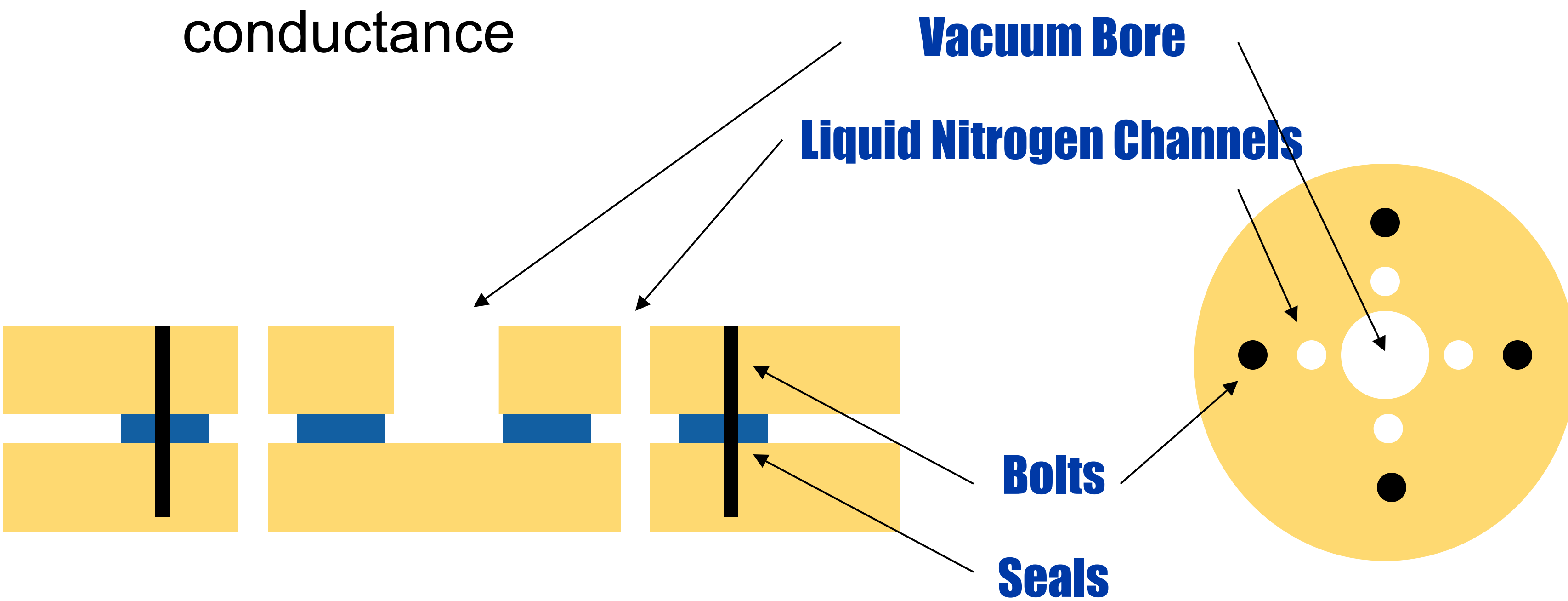
- 17kJ/pulse
  - 85kW at 5Hz
- 2,200 microF at 4000V

Design phase is coming to a close

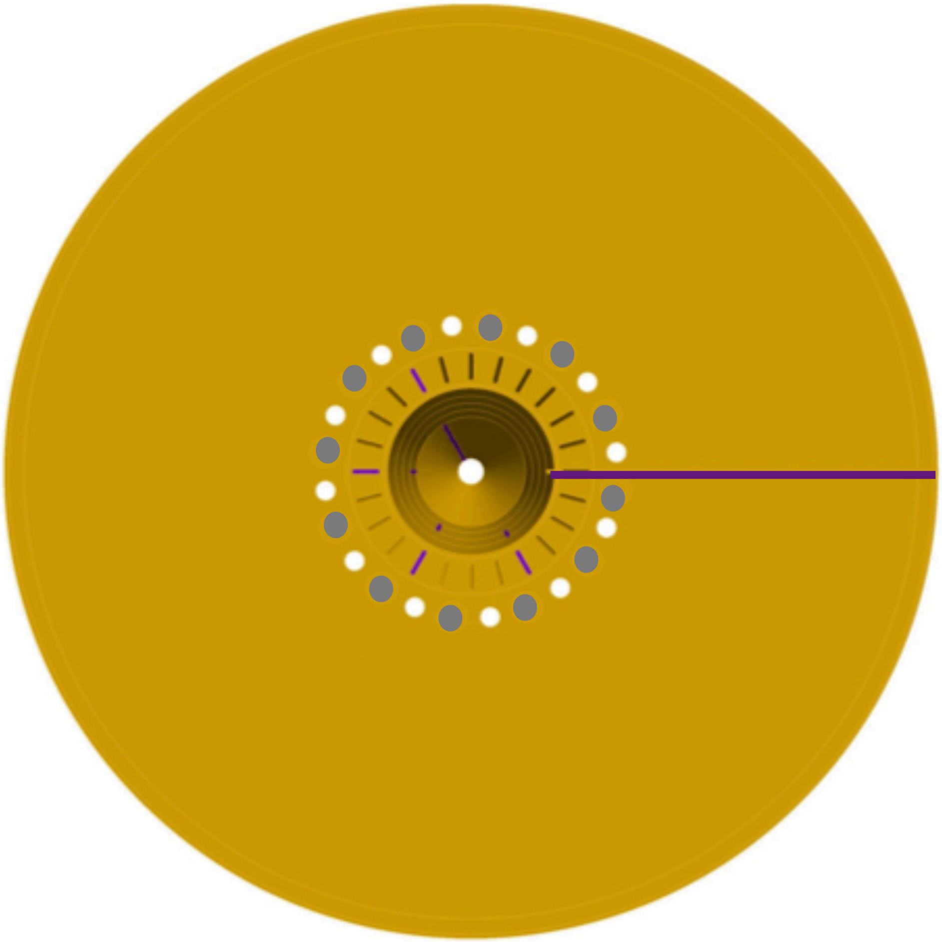
- A document on the design is in preparation
  - There have been many simulations with many assumptions over the years
  - We're insuring we have a fully self-consistent set of numbers and simulations
- Preparation of drawings for manufacture has begun
- We will begin constructing simplified test pieces to confirm various parts of the design

We will test the vacuum seal concept

- We need to test the ZTA / flexible graphite seal concept and gain manufacturing experience with vendors
  - The test piece can be thermally cycled in liquid nitrogen
  - Can apply voltage to measure liquid nitrogen conductance



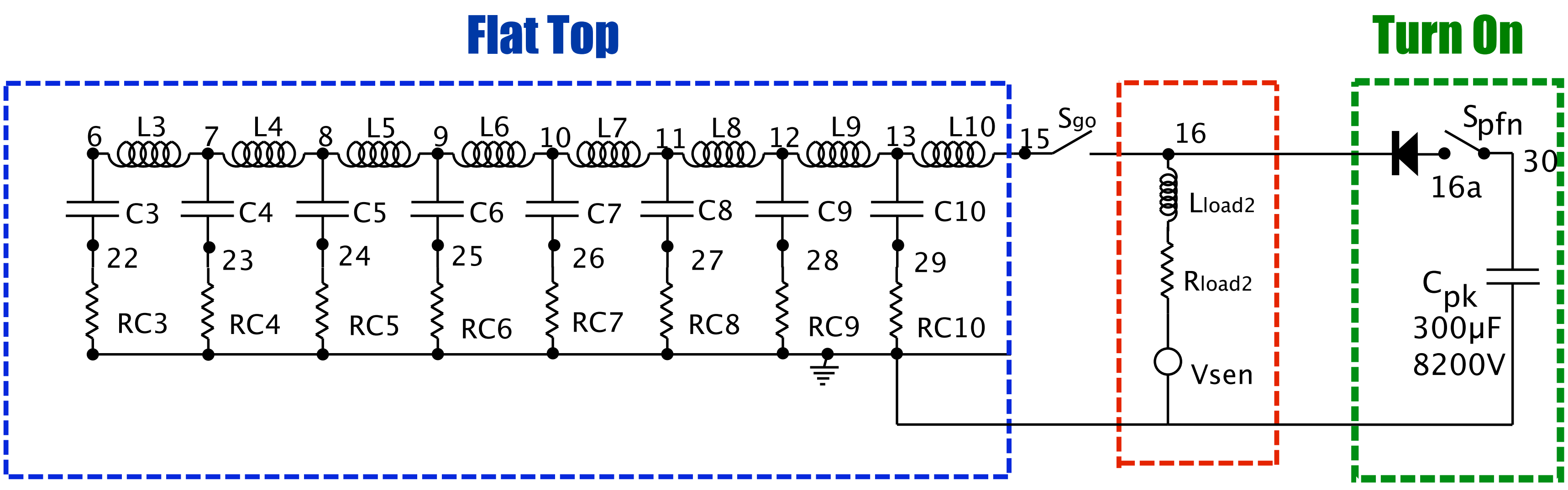
Create a simplified disk to test bonding of ZTA in the gap



- Only include:
  - Slit
  - Bore hole
  - Bolt holes
- Eliminate
  - Cooling channels
  - Seal
- Thermally cycle to look for bond failure

Construction will begin on the pulser

- First the turn-on section
  - Lets us get to full current at peak
  - near full current for 1 ms
- Add flat-top section as needed for testing



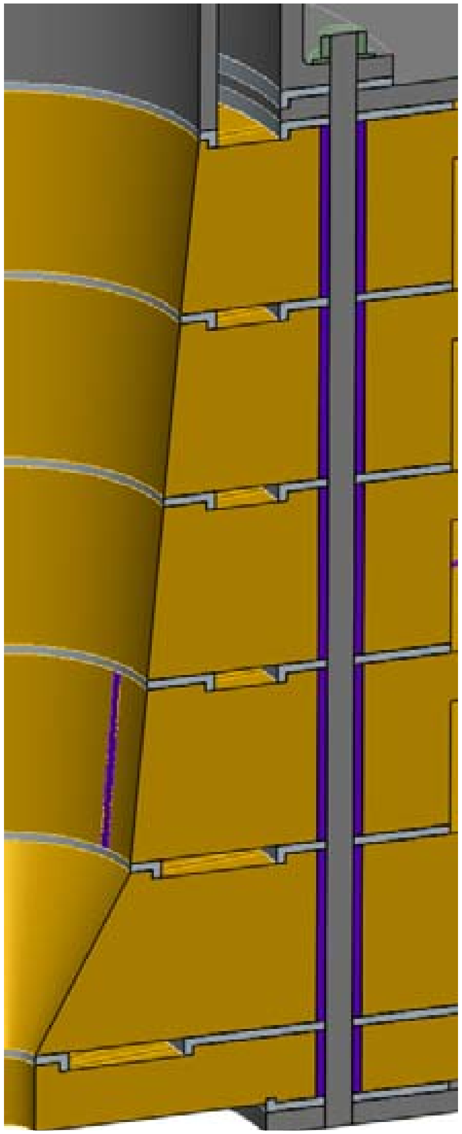
Commission the pulser with simplified-plate test stack with plates 1 and 2

- Air cooled – low rep rate
- Insulated with Kapton sheets
- Hand wound with cable

- Measure B field
- Stress the ZTA filler

Create a full six-plate stack

- If the results from the test pieces are good we proceed to make a full six-plate assembly without the housing
  - Add pieces to seal off the bore so we can apply vacuum and have a magnetic field measurement
  - Low rep rate but full current
- Run at room temperature
- Immerse in liquid nitrogen and run



Summary

- Thermal cooling is workable
- Energy deposition from beam particles is acceptable
- Stresses in the device are within acceptable limits for repetitive cycling (now that we have backed off to a 3.2 T field)

- A test of the vacuum seal concept under design stresses will greatly increase confidence in the design

- Should work