ECOFUSION – A Cellular, Electron Cooled Approach to Fusion Energy Generation

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Outline

- Introduction
- Overall Goals of Fusion Production System
- Introduction of the ECOFusion Concept (Review of Electron Cooling)
- Setting Initial Parameters
- Ion Beam Physics
- Ion Beam Optics
- Electron Beam Physics
- Component Designs
- Summary Predictions on Device Operation

Introduction

- The World Energy Situation
  - Fossil Fuel – CO_2, Supply limited
  - Nuclear – accidents, waste, proliferation
  - Solar, Wind, Hydro, Renewables – limited and not truly ECOFriendly
- Promise of Fusion
  - Clean, Inexhaustible
- Frustration of Fusion
  - We're 20 years away!
    - (for the last 50 years)

Overall Goals of Fusion Energy Production System

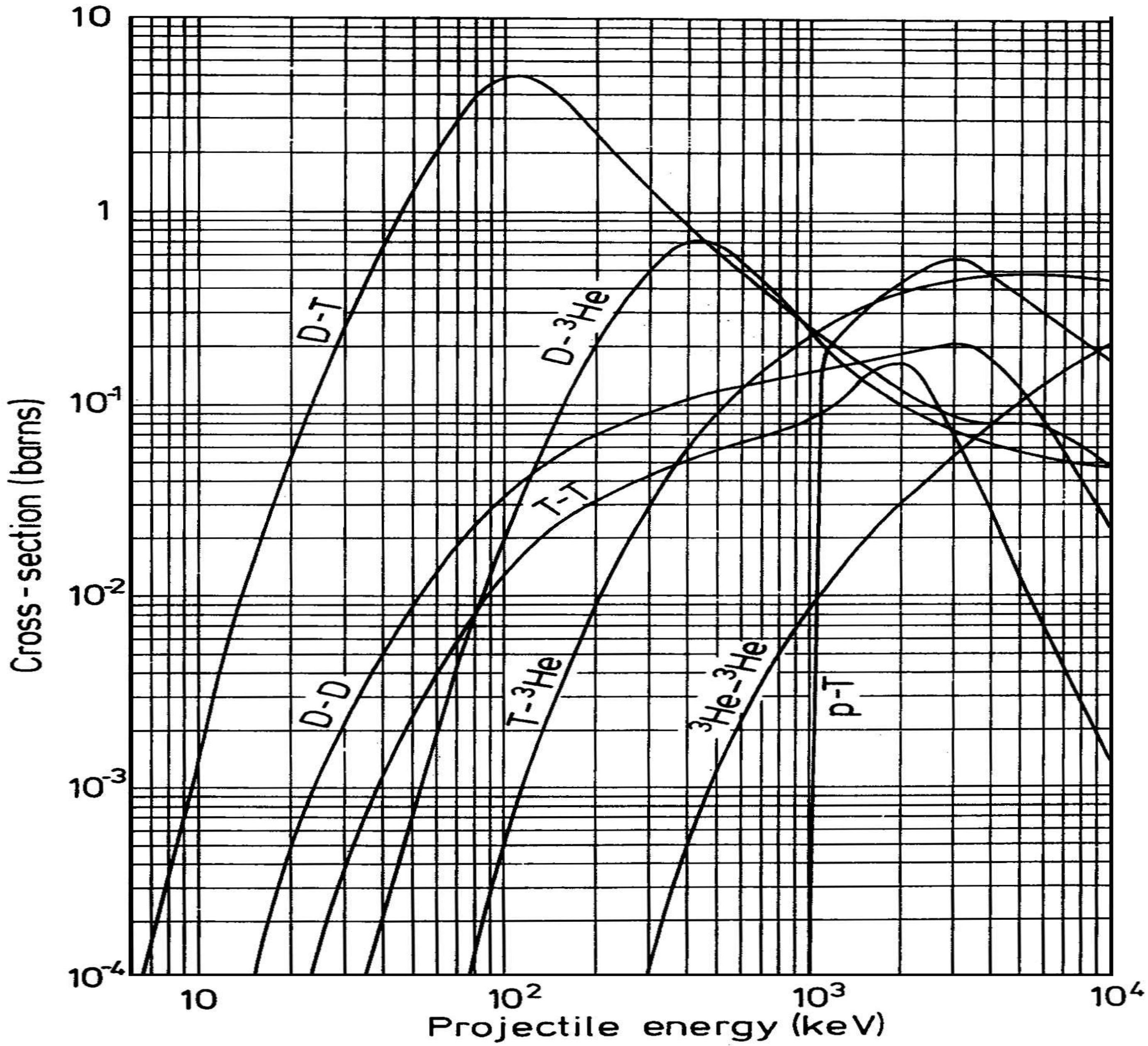
What is the Goal? (I)

- We Wish to Produce Clean, Essentially Limitless Power:
- D + T -> He4 + n + 17.6 MeV
- n + Li6 -> T + He4 + 4.8 MeV
- Seems simple enough, just bring enough D and T into collision at the right energy and fuel the world.
- However three problems exist:
  - Space Charge Repulsion
  - Appropriate Energy for Reaction to Occur
  - Most particles will not fuse, even at the right energy

What is the Goal? (II)

- We Must have a Device that achieves:
- Q = (Power Out)/(Power In) > 2-3
- To Maximize Q, Three Attributes Needed:

1. Maximize Power Out by Overcoming Space Charge Repulsion
   - Introduce electrons to neutralize space charge
2. Maximize Power Out by Getting Particles to the Appropriate Energy for Reaction to Occur
   - Try to get center of mass energy as close to the peak of the cross section as possible
3. Minimize Power In by Recycling Particles
   - Give particles many chances at fusing; supply the input power only once



10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
Cross - section (barns)
10
10²
10³
10⁴
Projectile energy (keV)
D-T
D-³He
D-D
T-T
T-³He
³He-³He
p-T

Why Not Easy Way? – dE/dx

- Easiest approach – make polymer film with high Tritium content
- Impinge Deuterium Beam on film
- Recover Energy of spent beam
- Or use electron cooling to recycle spent beam
- Problem is that much more power is lost to dE/dx than is gained by fusion
- dE/dx losses rule out controlled beam/solid, beam/liquid and beam/gas approaches
- Aside: Inertial Confinement and Bombs work by having fusion happen so fast that particle densities remain high for a short period of time – a burn

What About Beam/Plasma?

- Problem here is that beam must get into and out of plasma, and confining apparatus must be passed
- Either the holes penetrating the apparatus must be large, or single scattering losses will be large (beam particles will intercept apparatus)

What About Pure Plasma?

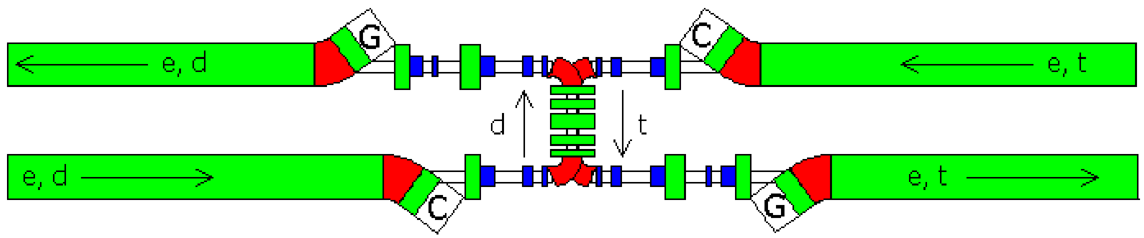
- Tokomak has held promise for decades
- To date, particles escaping the magnetic bottle have proved too problematic to achieve commercial fusion

Beam-Beam is the Remaining Choice

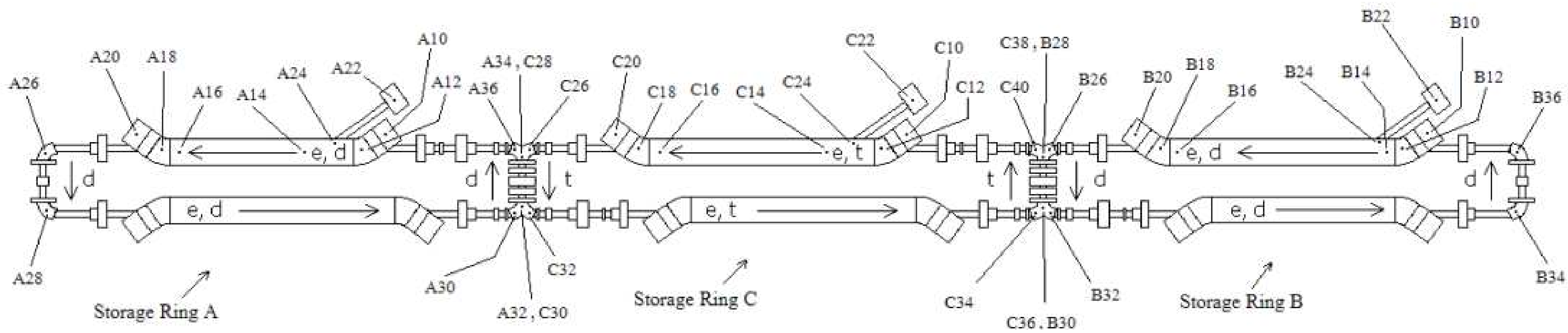
- Hence, one remaining possibility to explore is beam/beam fusion

Introduction of the ECOFusion Concept and a Review of Electron Cooling

Confinement from Magnetic Beam Focusing; Cooling Takes Away Imperfections and Allows Stacking

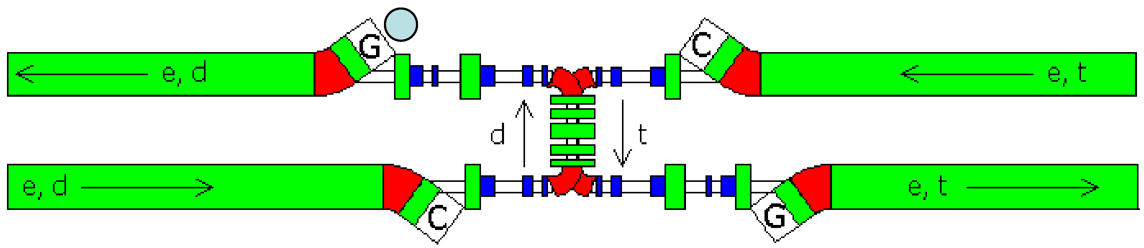


- The Interaction Region of ECOFusion Cell



- A Three Ring ECOFusion Configuration

Confinement from Magnetic Beam Focusing; Cooling Takes Away Imperfections and Allows Stacking



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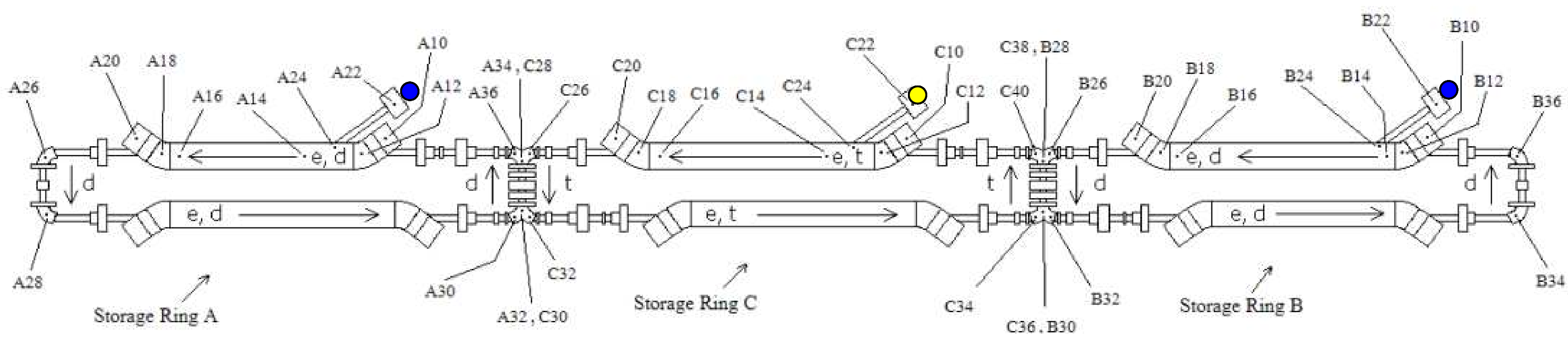


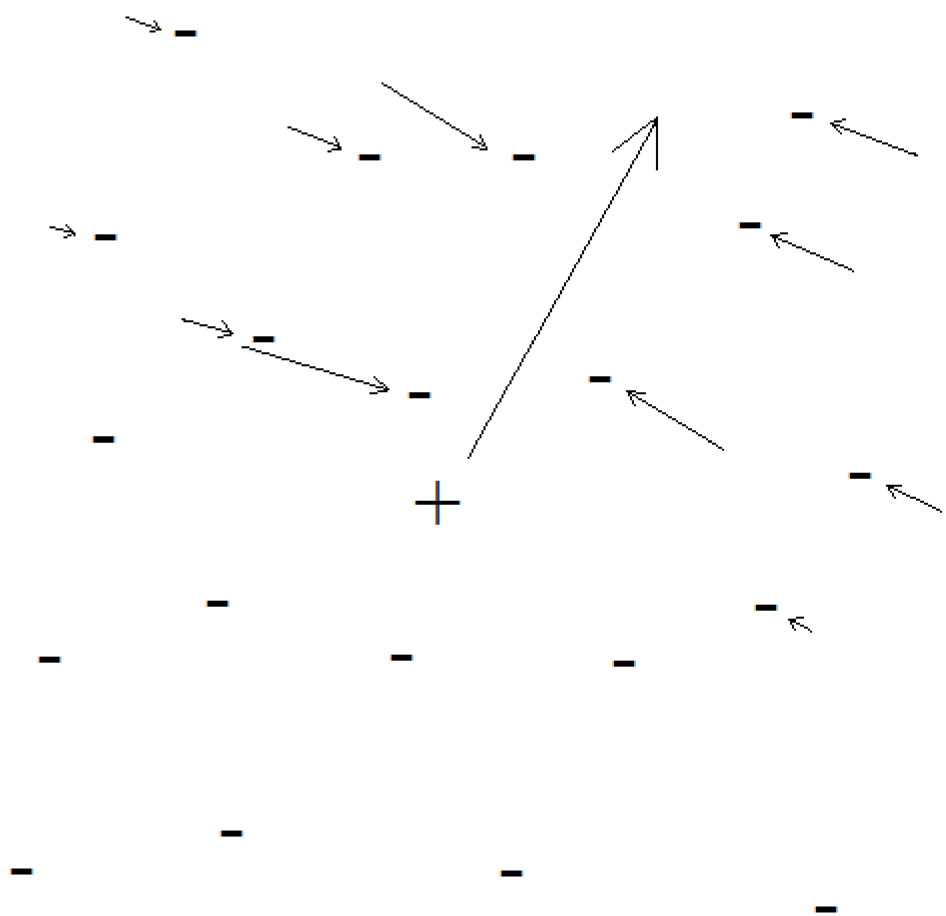
- A Three Ring ECOFusion Configuration

Meeting The Three Needs

1. Maximize Power Out by Overcoming Space Charge Repulsion
   - Tokomak – Trapped Plasma Electrons
   - ECOFusion – Electrons Trapped by Space Charge of Beams in non-cooling regions; Beam-beam overlap in cooling regions
2. Maximize Power Out by Getting Particles to the Appropriate Energy for Reaction to Occur
   - Tokomak – Thermal Distribution (10%?)
   - ECOFusion – Direct Acceleration (100%)
3. Minimize Power In by Recycling Particles
   - Tokomak – Magnetic Confinement
   - ECOFusion – Confinement Standard for Particle Beams; Electron Cooling of Strays

What Is Electron Cooling?

- Spitzer, 1956: Warm Ions Come to Equilibrium with Cooler Electrons in a Plasma



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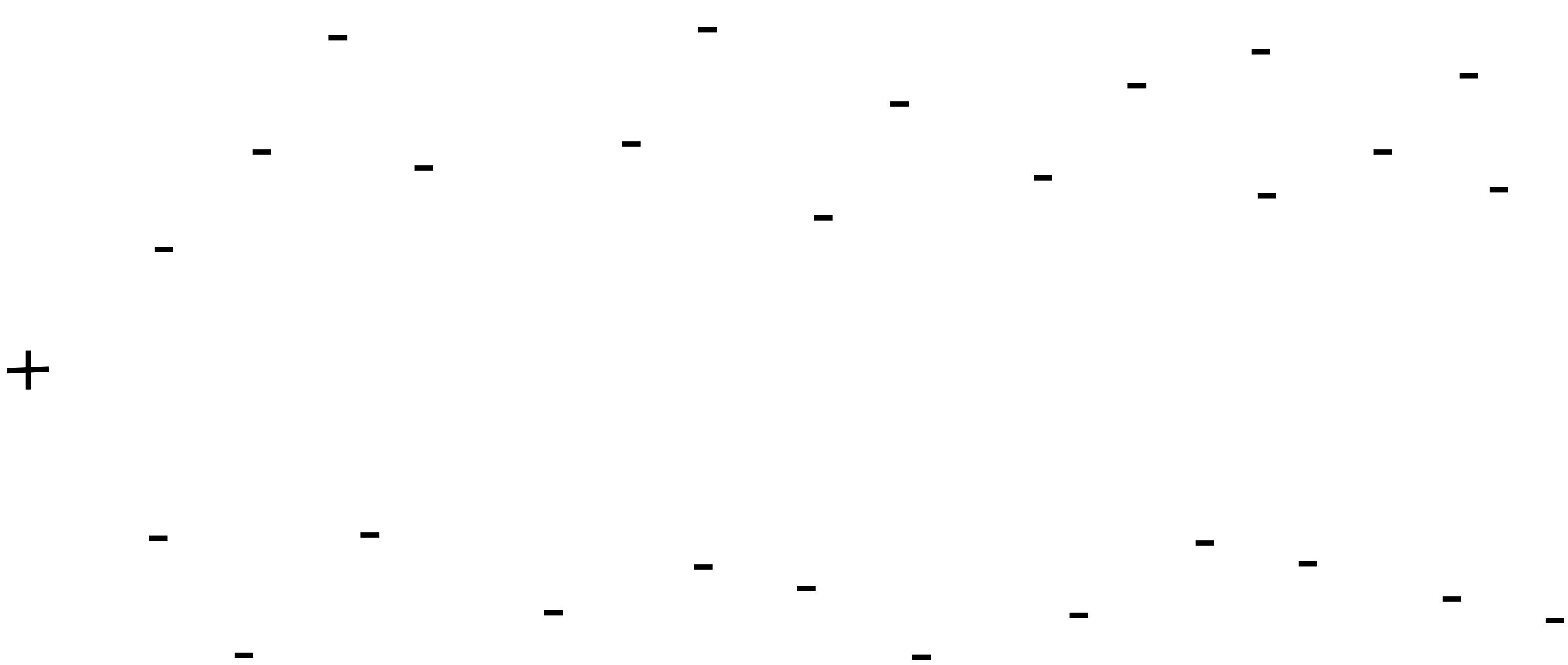
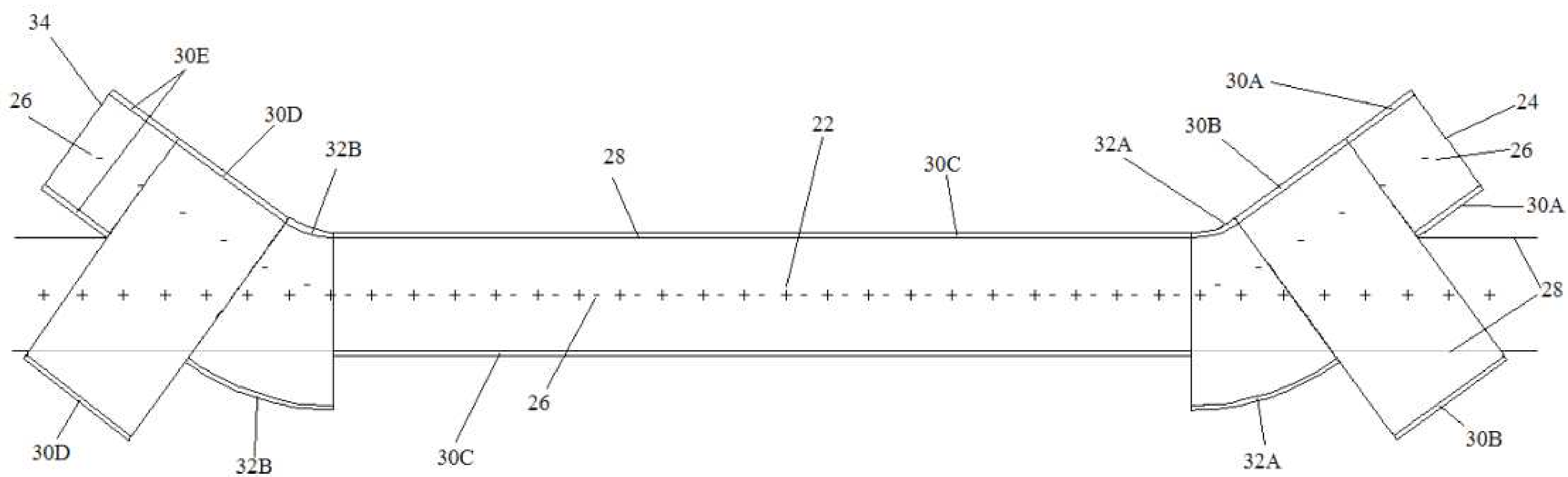


What Is Electron Cooling?

- Budker, 1966: Electron Beam is Simply a Moving Electron Plasma. Superimpose electron beam on ion beam to cool:



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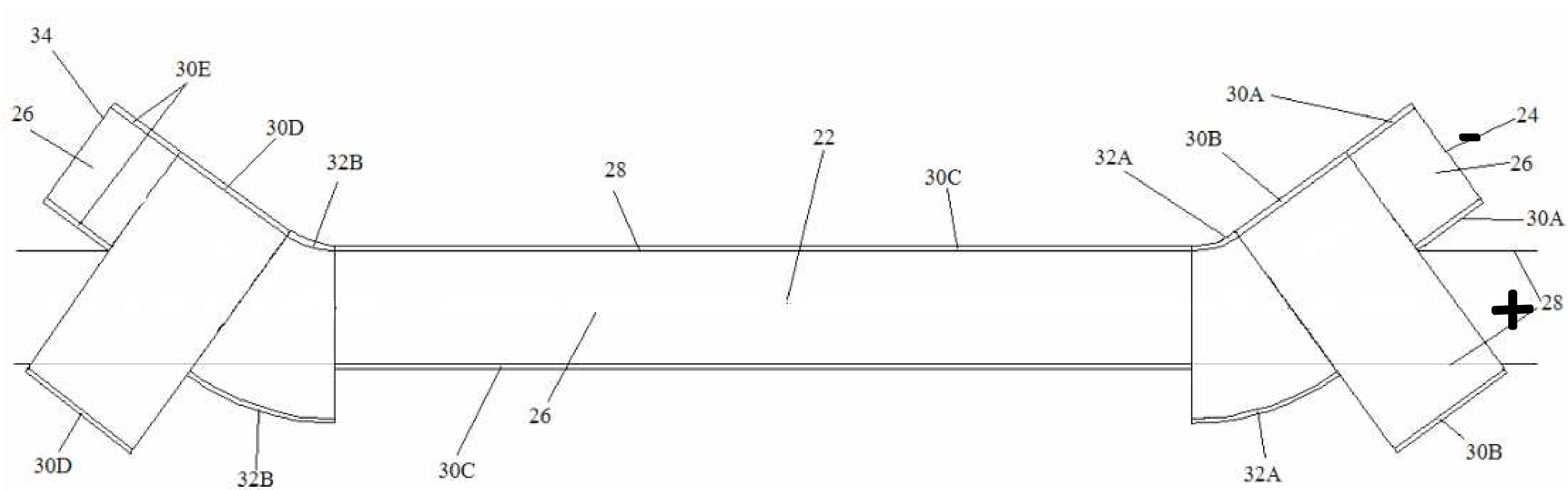


Electron Cooling Formulas

- $dv/dt = -[4\pi n c^4 r_e r_i / v^2] \ln(B)$ ->
- $d\mathbf{v}/dt=$

  $-[4ILc^3 r_e r_i \ln(B)/Ca^2 e\beta] \iiint [\mathbf{u}\, g_e(\mathbf{v_e})/(\mathbf{v}-\mathbf{v_e})^2] d\mathbf{v_e}$
- For perfectly cold electrons, $g_e(\mathbf{v_e}) \to \delta$, and integrating leaves: to

  $t_{coolcolde} = v_{initial}{}^3 a^2 eC\beta/[12ILc^3 r_e r_i \ln(B)]$
- dominant dp/p:

  $t_{coolcolde}=(dp/p)^3 a^2 eC\beta/[12ILr_e r_i \ln(B)]$
- dominant ε_n:

  $t_{coolcolde}=\varepsilon_n{}^3 a^2 eC\beta/[12ILx^3\pi^3 r_e r_i \ln(B)]$

  – (often expressed with $\varepsilon_n{}^3 = \beta^3\gamma^3\varepsilon_n{}^3$; an exaggeration.)
- dominant θ:

  $t_{coolcolde}=\theta^3 a^2 eC\beta^4/[12ILr_e r_i \ln(B)]$

An Overview of Completed Analysis and Setting Some Initial Parameters

Completed Calculations:

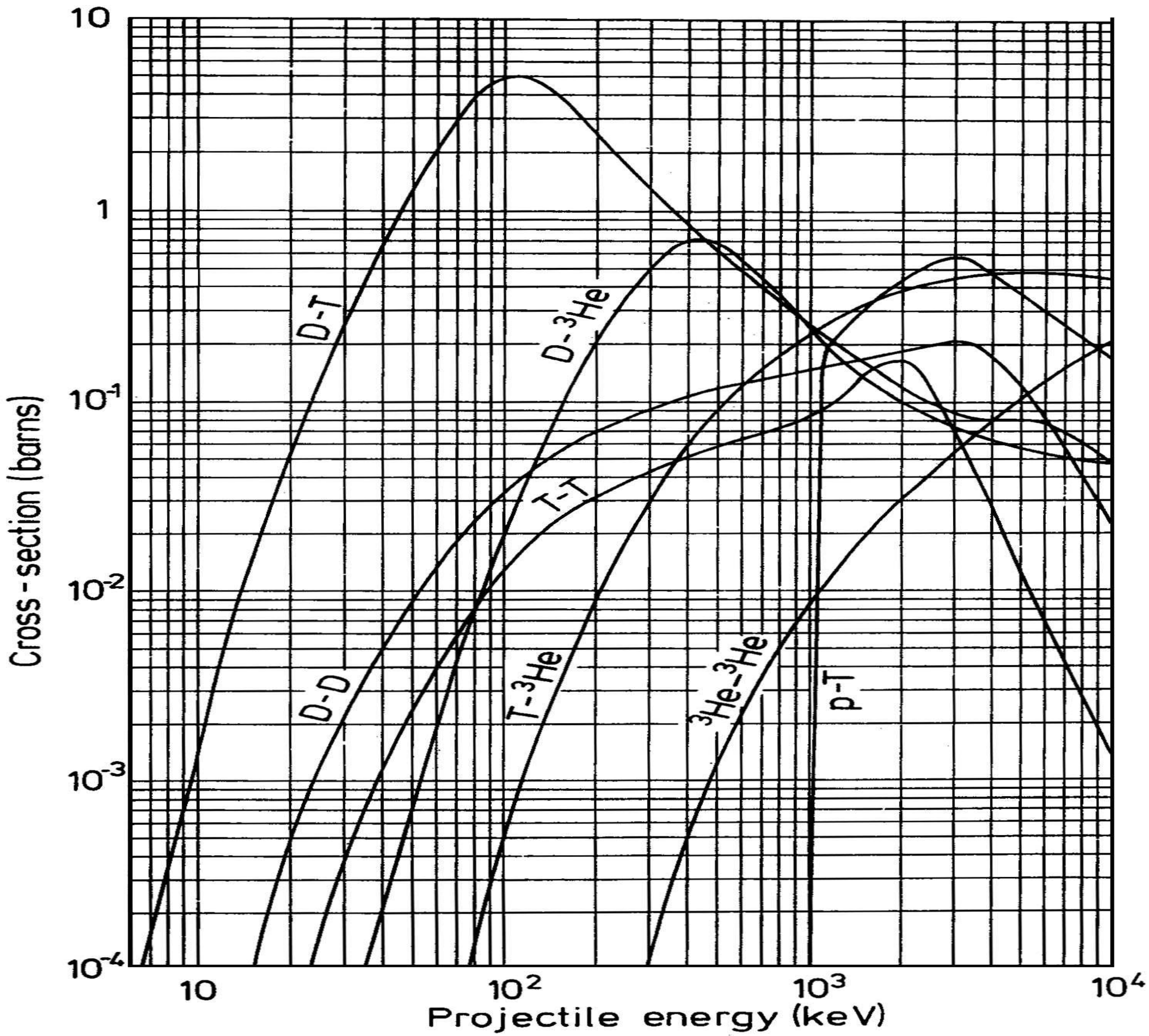
- Three Regions of Analysis: Colliding Beams; Cooling Section; Free Transport
- Many Entities: One or More Beams; Background Gas; Trapped, Charged, Neutralizing Particles; Walls; Superimposed Magnetic Fields
- Forces: Gravity (neglected); Electromagnetism; Strong and Weak (wrapped into fusion cross section)
- Electromagnetic Forces break down into Scattering and Collective Behavior Categories
- Scattering: dE/dx; Single Scattering; Multiple Scattering; Intrabeam Scattering
- Collective: Beam Steering and Focusing (Ion Optics); Space Charge; Resonances; Instabilities
- Scattering and Collective Effects have been Analyzed For All Entities in Each Region; Only Highlights will be Presented today

Some Initial Calculations

- To Keep Optics the Same: $m_D v_D = m_T v_T$
- Because of Electron Cooling Beam Single Scattering: $(1/2)m_D v_D^2 + (1/2)m_T v_T^2 = 400$ keV

- Hence, $\sigma_F = 0.85$ barn
- $E_T = (1/2)m_T v_T^2 = 160$ keV, $E_D = 240$ keV

- Possible parameters: L = 1.2 mm, $I_D = I_T =$ 10,000 A, r = 90μ -> $n_D = 5.12 \times 10^{17}$ cm^{-3}, $n_T = 7.66 \times 10^{17}$ cm^{-3}, power output = 29.2 kW per focus region



10
1
10-1
10-2
10-3
10-4
Cross-section (barns)
10
10^2
10^3
10^4
Projectile energy (keV)
D-T
D-3He
D-D
T-T
T-3He
3He-3He
p-T

A 1 GW Power Plant:

• Each ECOFusion cell one meter high, three meters wide and 22 meters long

• Each ECOFusion cell produces 58.4 kW of Power (2 IRs per cell)

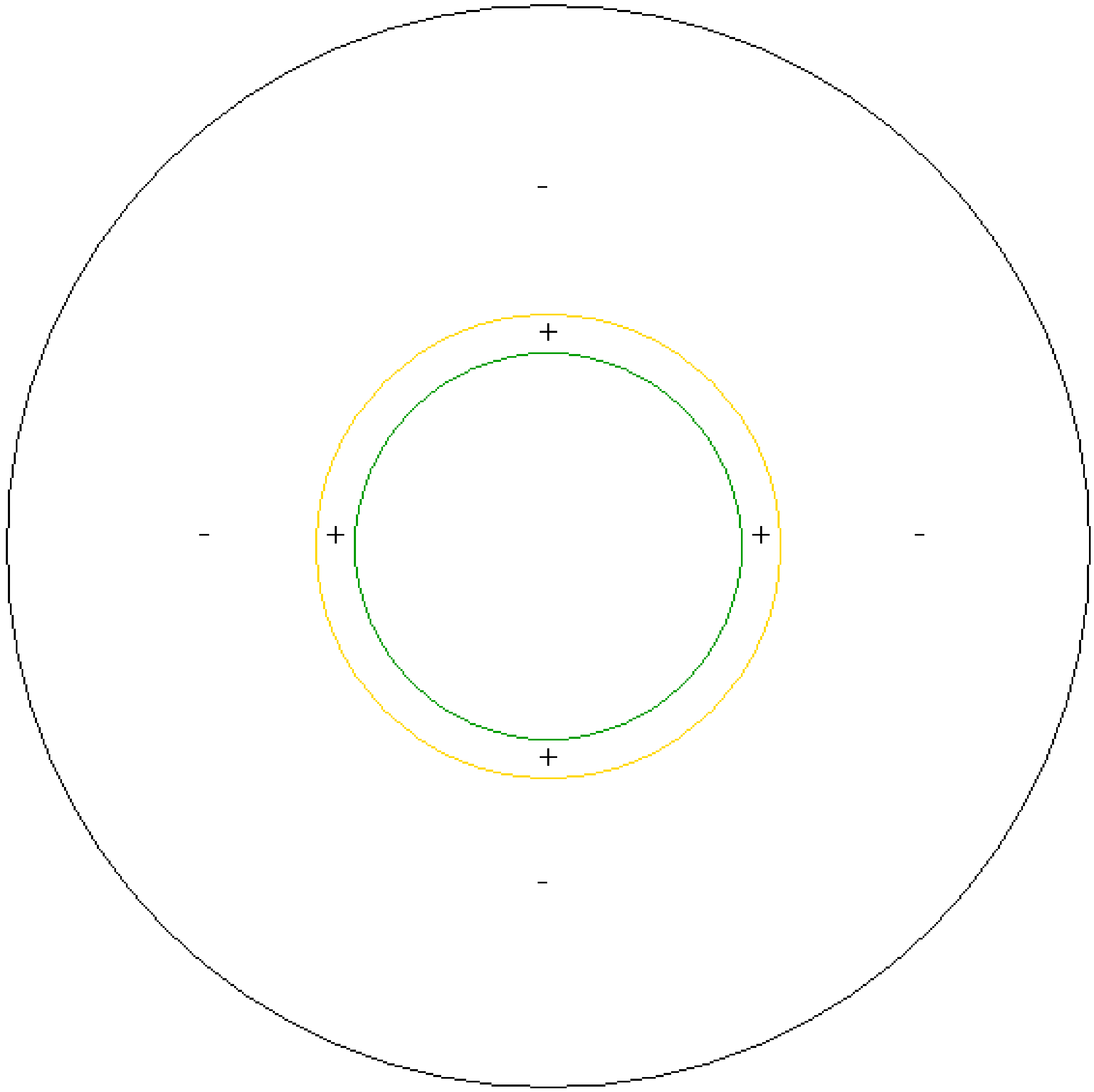
• A 1 GW Power Plant would then be 220 meters wide by 219 meters long by 24 meters high.

Ion Beam Physics

- Neutralizing Background Electrons
- dE/dx vs. Wall Power Plasma Equilibrium
- Halo Source
- Remnant Field Effects
- Single Scattering
- Multiple Scattering
- Intrabeam Scattering
- Injection
- Recombination and Charge Exchange
- Equilibrium Emittances
- Sanity Check

Ion Beam Physics (1)

- Neutralizing Self Space Charge
  - Electron Beam Neutralizes in Overlap Region
  - Trapped Neutralizing Electrons in Other Regions
- Electrons Neutralize Core of Beam
- Small Shell of Net Positive Charge Forms containing Electric Field for Electrons
- An equilibrium will exist between the dE/dx heating from beam and cooling as electrons deposit heat by hitting walls
  - Maxwellian Distribution
- This shell also produces beam halo



Ion Beam Physics (2)

- dE/dx and Wall Loss Equilibriums
  - IR Equilibrium Estimate is a 5625 V Trap
  - IR Equilibrium Estimate is a 1000 eV electron plasma
  - IR Equilibrium Estimate is 750 W dE/dx loss per IR
  - IR Halo Production 2 Amp T, 3 Amp D
  - Non–IR Equilibrium Estimate is ~300 V Trap
  - Non–IR Equilibrium Estimate is a ~100 eV electron plasma
  - Non–IR Equilibrium Estimate is ~15 W dE/dx loss per beam
  - Non–IR Halo Production 0.083 Amp T, 0.21 Amp D
- Remnant Self Field Effects
  - Need about 1 micron steering at IR
  - Focal properties of self magnetic field acceptable
  - Effects of Merge Region Acceptable

Ion Beam Physics (3)

- Single Scattering
  - 200 mRad Assumed Limit
  - Leads to 10 barn cross section for losses (~12 x fusion cross section)
- Multiple Scattering
  - Negligible in comparison to IBS
- Intrabeam Scattering
  - Leading Cause of dp/p heating:
  - Analysis shows that longitudinal growth in focal region is dp/p = 9.8×10^{-4} for Tritium case
  - Analysis shows that longitudinal growth in focal region is dp/p = 4.2×10^{-4} for Deuterium case

Ion Beam Physics (4)

- Injection
  - 20 mRad Injection Angle for D Cooled in Single Turn
  - 33 mRad Injection Angle for T Cooled in Single Turn
- Instabilities and Resonances
  - Single Turn Cooling Implies no Problems here
- Recombination and Charge Exchange (small)

Equilibrium Ion Beam Emittance

- Non-Magnetized Electron Cooling predicts Equilibrium emittances of
  - $dp/p = \beta^*/\beta_{beam}$: 4.23×10^{-3} (T) 2.93×10^{-3} (D)
  - $\varepsilon_{nx} = \varepsilon_{nz} = \beta\varepsilon_z$: 4.98×10^{-6} m-r (T) 5.68×10^{-6} m-r (D)
- Magnetized Electron Cooling predicts Equilibrium emittances of
  - $dp/p = \beta^*/\beta_{beam}$: 7.45×10^{-4} (T) 5.16×10^{-4} (D)
  - $\varepsilon_{nx} = \varepsilon_{nz} = \beta\varepsilon_z$: 5.64×10^{-9} m-r (T) 1.02×10^{-8} m-r (D)
- Optics Studies Use Equilibrium Emittances:
  - $dp/p = \beta^*/\beta_{beam}$: 7×10^{-4} (T) 7×10^{-4} (D)
  - $\varepsilon_{nx} = \varepsilon_{nz} = \beta\varepsilon_z$: 2.11×10^{-7} m-r (T) 2.11×10^{-7} m-r (D)

Sanity Check – FEL Operation

- MeV, kiloamp electron beams have been produced for free electron laser experiments
- Electrons are much more susceptible to instability (due to their light mass).
- The ECOFusion device is proposed to use 10,000 A, ~200 keV ion beams – momentum rigidity is about twice what it is for the FEL electron beams.
- The path length traveled by the ions is shorter, and the particle beam currents similar.
- Hence, there should be no instability in the short path that the ions are required to traverse in the ECOFusion cell.

Ion Beam Optics

- SCAT Optics Code
- Core Optics with Various Design Currents
- Halo Optics
- Aberrations
- Sanity Check
- Redundancy Check Against TRACE 3-D

SCAT Ion Optics Code

- Space Charge Acceleration Twiss
- SCAT First Written for Design of Ampere Intensity, 3 MV Electron Accelerator for E-Cooling of Pbars.
  - (Thesis work, 1984)
  - Device Worked
- SCAT a numerical integration of beam Twiss parameters, includes acceleration, emittance, dispersion and space charge for 2D beams.
- Used around the world
  - UCF Free electron laser
  - Israeli e-cooler (as I recall)
  - Japanese proton therapy
  - Fermilab's PET experiment
  - ECOFusion

Core Ion Optics Studies

- Deuterium Studied at Zero Current
- Deuterium Studied at Full Current (10 kA)
- Deuterium Studied at Half Current (5 kA)
- Tritium Studied at Zero Current
- Tritium Studied at Full Current (10 kA)
- All Current States Possible With Magnetic Field Adjustments
- Magnetic Changes were continuous and smooth (tuning possible)

Deuterium Core Optics

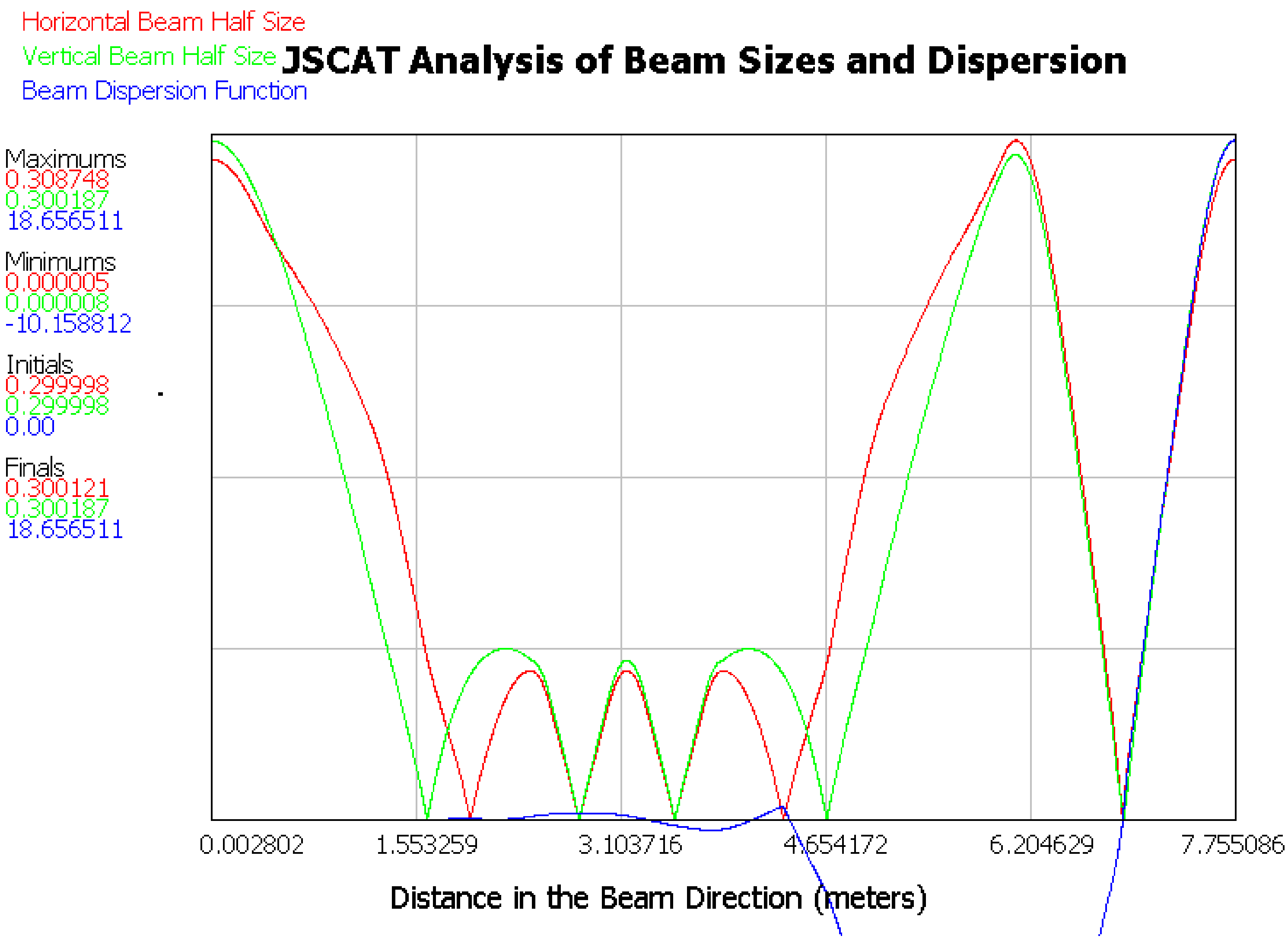


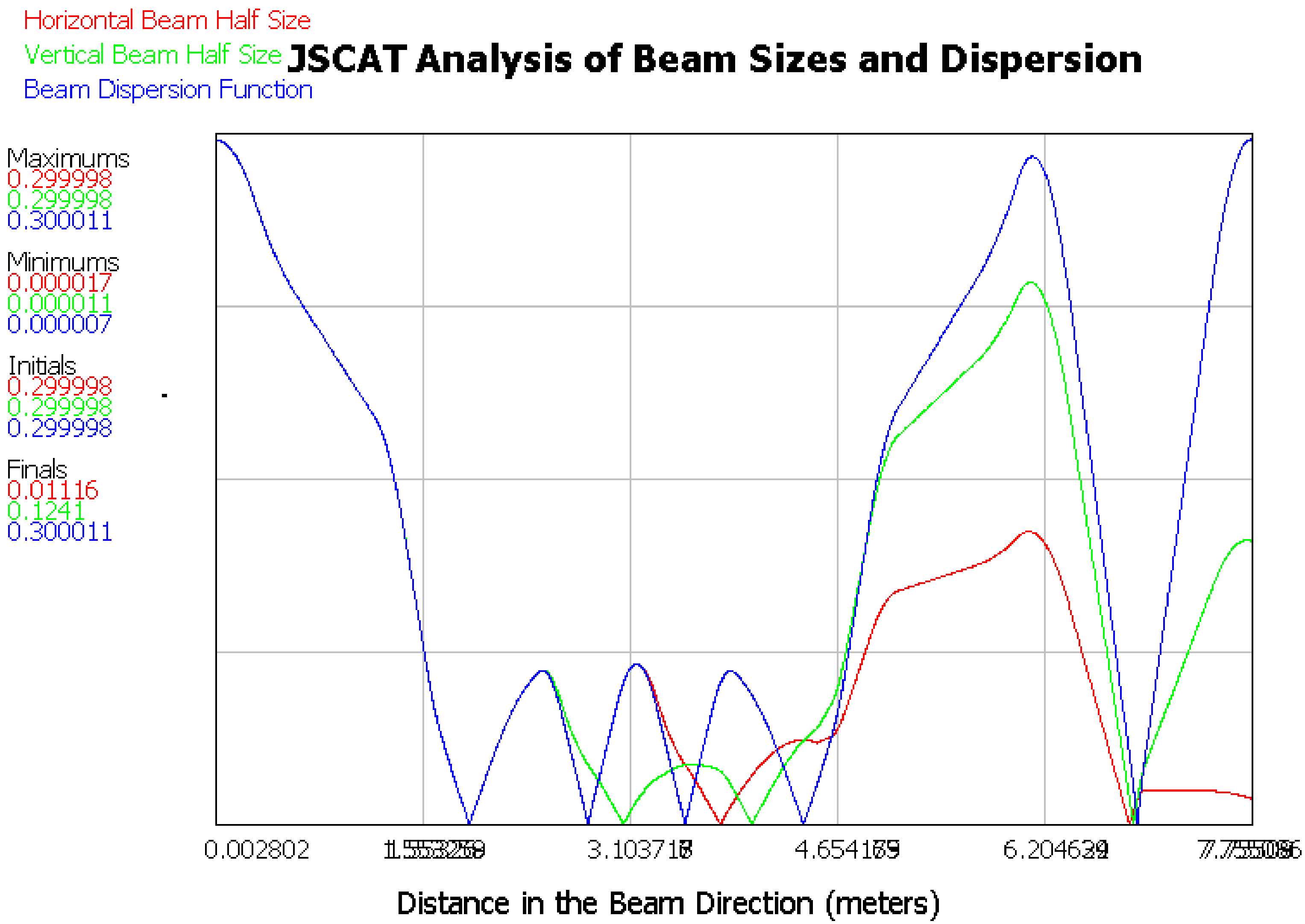
Table 14.1. Magnetic Excitations For Various Conditions.

Element	Deuterium, full current	Deuterium, half current	Deuterium, no current	Tritium, full current	Tritium no current
S1	2.19 kG	2.60 kG	2.95 kG	2.18 kG	3.00 kG
Q1	-6.40 G/cm	-9.07 G/cm	-12.2 G/cm	-6.74 G/cm	-12.1 G/cm
Q2	27.7 G/cm	45.8 G/cm	82.5 G/cm	32.4 G/cm	81.6 G/cm
Q3	-251 G/cm	-205 G/cm	-322 G/cm	-278 G/cm	-324 G/cm
S2	10 kG	10.5 kG	11 kG	10 kG	11 kG
S3	6 kG	6 kG	6 kG	6 kG	6 kG
S4	10 kG	10 kG	10 kG	10 kG	10 kG
S5	6 kG	6 kG	6 kG	6 kG	6 kG
S6	10 kG	10.5 kG	11 kG	10 kG	11 kG
Q4	-299 G/cm	-187 G/cm	-355 G/cm	-210 G/cm	-333 G/cm
Q5	29.3 G/cm	38.2 G/cm	82.9 G/cm	13.9 G/cm	80.2 G/cm
Q6	-6.35 G/cm	-9.07 G/cm	-12.2 G/cm	-6.74 G/cm	-12.1 G/cm
S7	4.45 kG	4.67 kG	4.94 kG	4.30 kG	5.02 kG
Q7	2.06 kG/cm	2.06 kG/cm	2.06 kG/cm	1.56 kG/cm	1.56 kG/cm
Q8	-2.97G/cm	-2.02 G/cm	-2.76 G/cm	0.1 G/cm	-2.02 G/cm
S8	4.36 kG	4.50 kG	4.63 kG	4.37 kG	4.69 kG

Halo Optics

- Halo Produced for IR and Non-IR regions for both Deuterium and Tritium
- Magnitude of Halo determined by dE/dx and particle loss equilibrium, which determines trap potential and trap source magnitude
- IR Currents of 2 A (Tritium) and 3 A (Deuterium) provide necessary trap in IR region
- Non-IR Currents of 0.083 A (Tritium) and 0.21 A (Deuterium) provide necessary trap in non-IR region
- Halo will be produced for incoming beam only in IR, as outgoing beam is immersed in oncoming beam's halo after the waist is passed
- All Halo must be Transported to the Cooler with Trajectories that can be Cooled, and Single Turn Cooling is Desired

Deuterium IR Horizontal Halo Optics



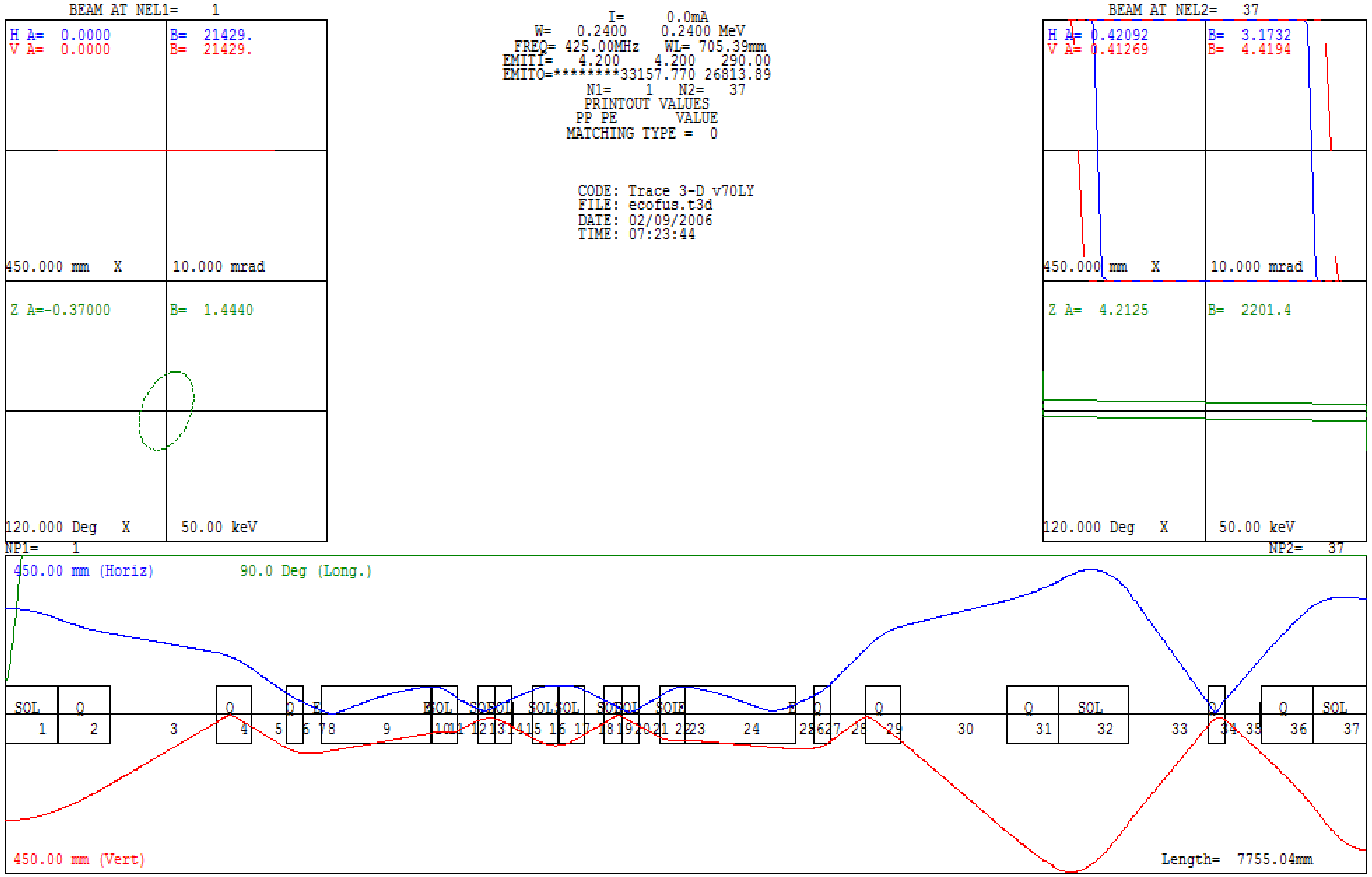
Aberrations

- Chromatic Aberrations
  - introduced by Solenoids
  - with dp/p = 0.07% -> 90 micron spot
- Spherical Aberrations
  - $dr_{min} = |dr_{si}|/4 = |M\ f\ \tan 3\gamma_o|/24$
  - $dr_{min} << 90$ microns

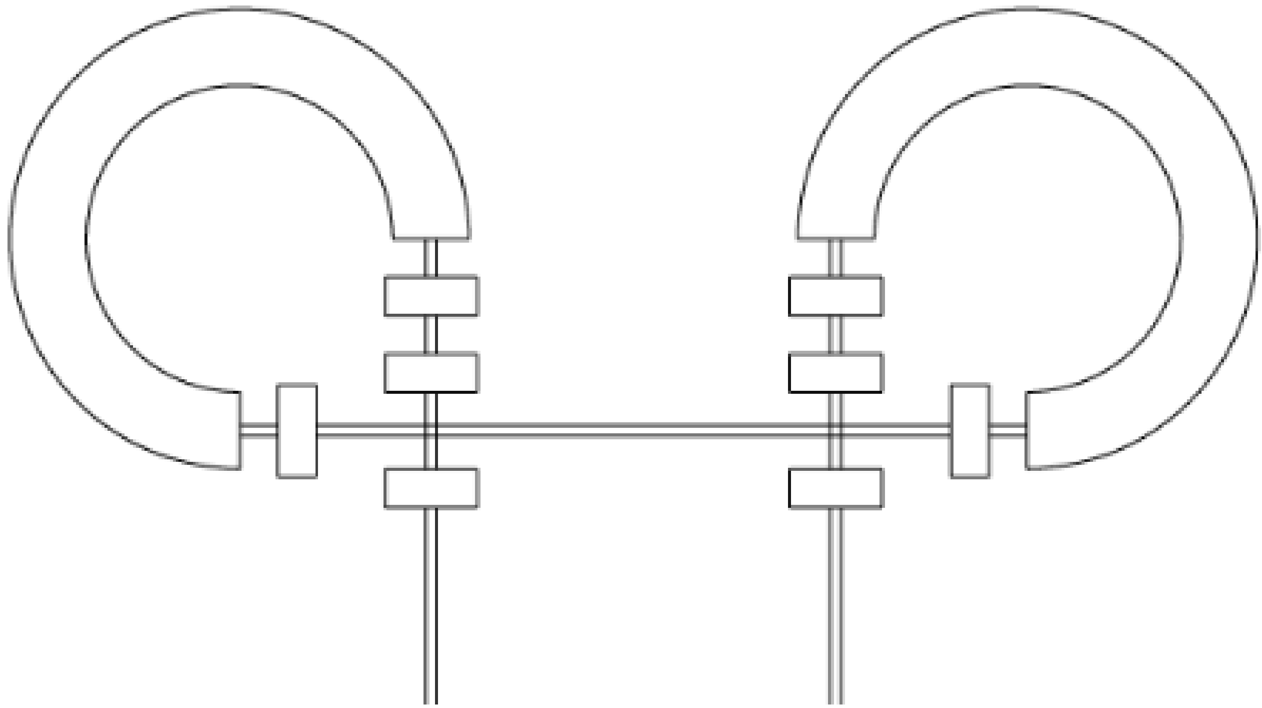
Dispersion

- Nominal Design has 40 micron contribution – could reduce this

TRACE 3-D Redundancy Check



Sanity Check – FNAL 1 MeV He-3 PET MEBT Accelerator Comparison



Sanity Check – FNAL 1 MeV He-3 PET MEBT Accelerator Comparison:

- PET 200 micron spot ; ECOFusion 90 micron spot
- PET 50 mr convergence; ECOFusion 250 mr convergence
- PET 4.25 cm max beam size; ECOFusion 30 cm max beam size
- PET 1 MeV He-3; ECOFusion 0.4 MeV Tritium & 0.6 MeV Deuterium
- PET 40 milliAmps pulsed; ECOFusion 10 kiloAmps continuous

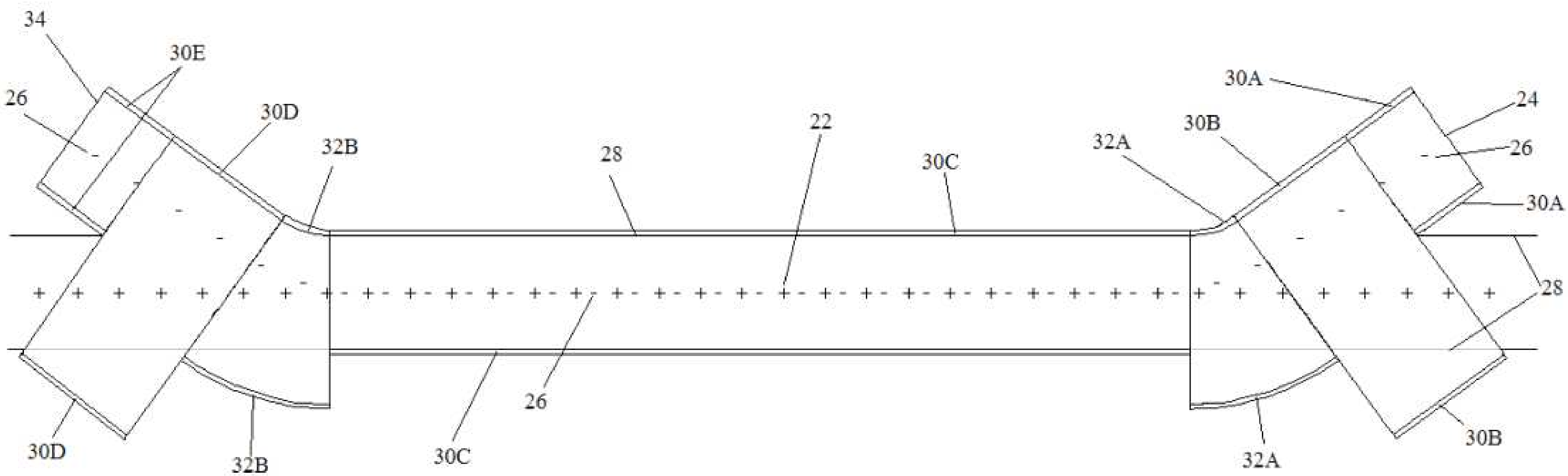
Electron Beam Physics

- Electron Beam Parameters
- Interaction with the Solenoidal Guide Field
- Interaction with the Background Gas
- Interaction with the Ion Beams
- Electron Beam Self Interactions
- Background Ion Neutralization
- Interaction with Trapped Ions

Electron Beam Parameters

- Electron Beam Current – 10,000 A
- Cathode Emission – 10 A/cm^2
- Cathode Radius – 17.8 cm
- Cathode Temperature – 0.1 eV
- Electron Beam Emittance
  - $\varepsilon_{n6\sigma} = \pi(178\text{ mm})(1.09\text{ mr}) = 193\ \pi$ mm-mr
- Electron Beam Momentum Spread
  - $(\Delta p/p)_{ed} = 1/2(0.1/67.3) = 7.42\text{x}10^{-4}$
  - $(\Delta p/p)_{et} = 1/2(0.1/30.5) = 1.64\text{x}10^{-3}$

The Electron Cooler



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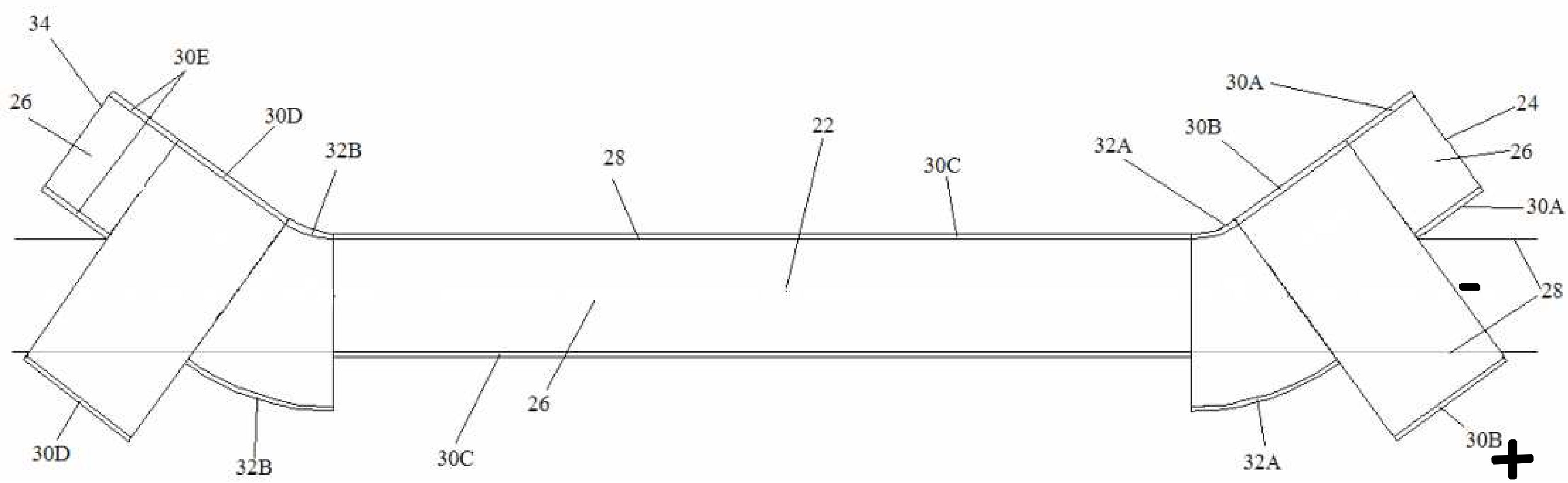


Electron Beam Interaction with the Solenoidal Guide Field

- Electron Optics – Electrons Follow Solenoidal Guide Field
- 100 Gauss Solenoidal Field in Cooler Straight Section
- Electron Gyro Radius in Solenoidal Field is 0.107 mm (both cases)
- Gyro Motion Reduces Solenoidal Guide Field by 0.003 Gauss (plasma β is < 10-4)

Electron Beam Neutralization

- Electron Beam Energy 30 eV in Tritium Cooling Case
- Electron Current 10 kA
- Need High Level of Neutralization
- Background Gas Ions Form at $1/40^{th}$ of an eV
- $1/40^{th}$ eV Ions Trapped an any Potential Greater than $1/40^{th}$ V
- Electron Cooling Sweeping Time $(1/.033)^3$ of Injection Cooling -> 27,000 turns if swept in same direction
  - But not in same direction

Electron Interaction with Trapped Ions

- Single Scattering
  - Tritium case, 4.7% of electrons scatter at > 100 mr in 1 m
  - Deuterium case, 0.7% of electrons scatter at > 100 mr in 1 m
- Multiple Scattering
  - Tritium case, 20% Emittance Growth in 10 cm
  - Deuterium case, 7.3% Emittance Growth in 10 cm
- These Values not a problem at 400 keV design, but scaling with velocity is strong and at 100 keV problems are significant

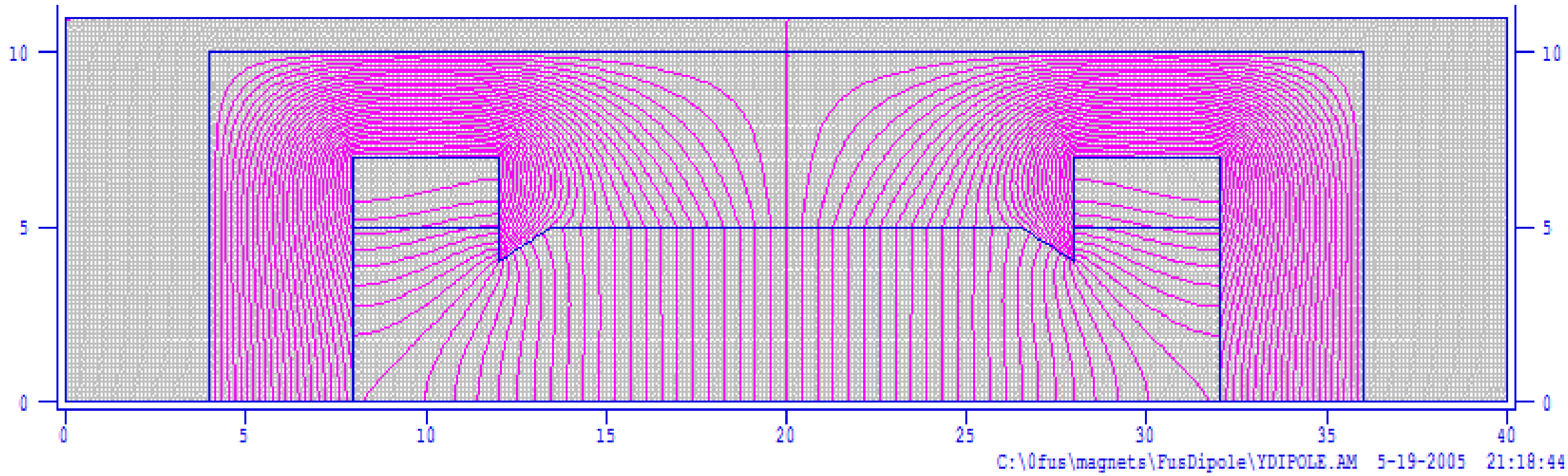
Sanity Check – Electron Cooler Collector Comparison:

- Electron Cooler Collectors work well past space charge limit
- Ions have Longitudinal trapping electric fields
- Ions have Transverse trapping magnetic fields
- FNAL cooler – 22 A, 500 V (as I recall)
- Thesis bench test – 4 A, few hundred V
- Thesis operation with 0 V with no magnetic field
- ECOFusion will need about the same current density, somewhat lower energy, much longer path
- Reversed field cooler is patent 7501640

Component Designs

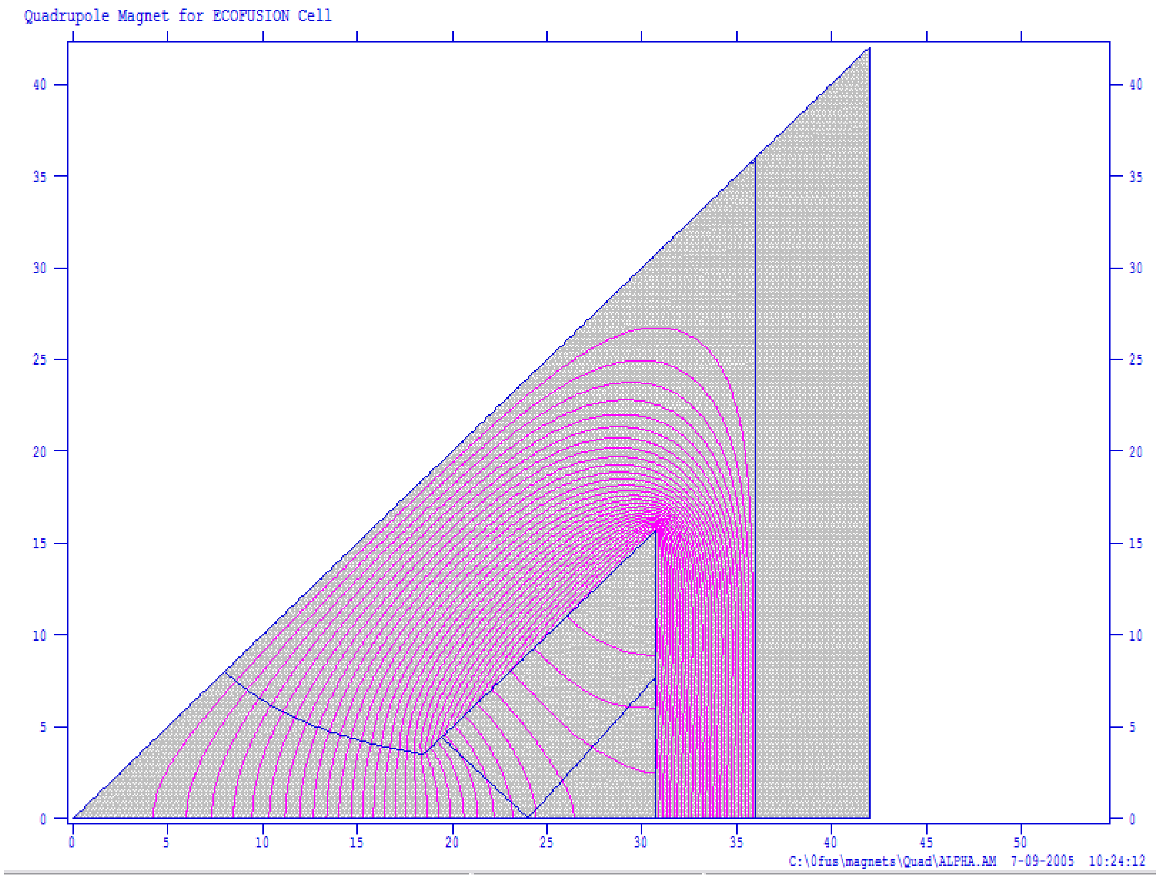
- Dipole Design
- Quadrupole Design
- Solenoid Design
- Electron Beam Components
- Power Estimates

Dipole Design



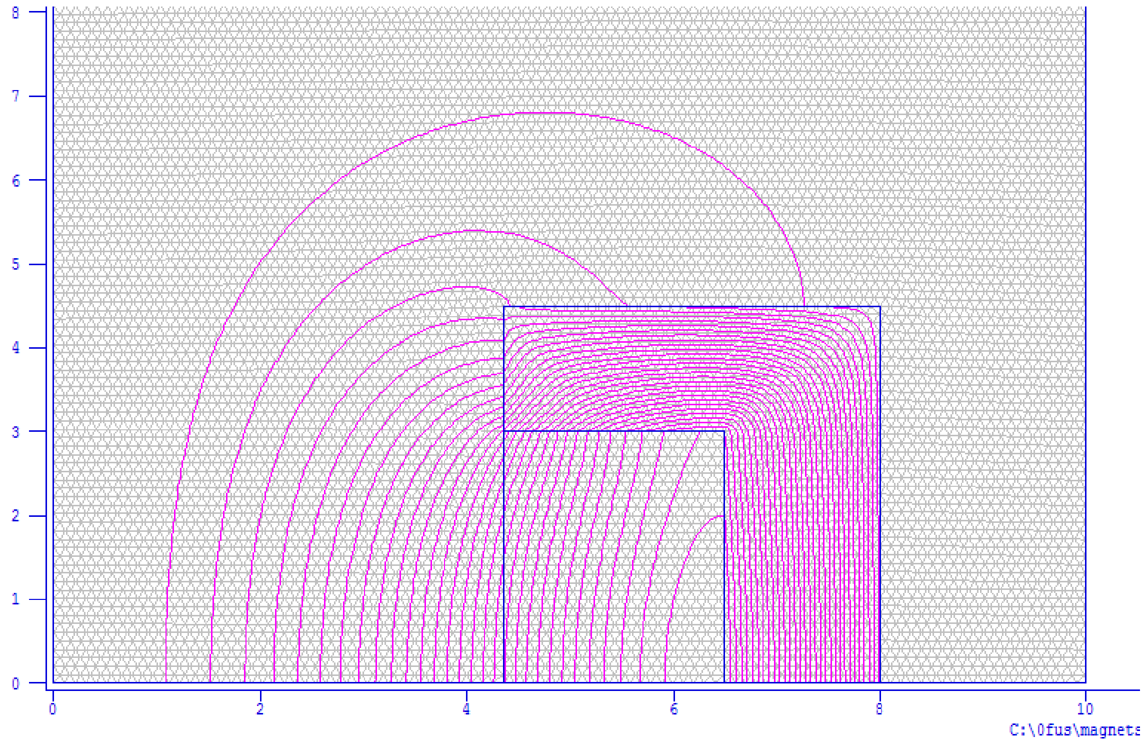
- POISSON Design Above
- power required for the coils I^2R = 15.3 kW

Quadrupole Design



• POISSON Design Above – meets Required Specs

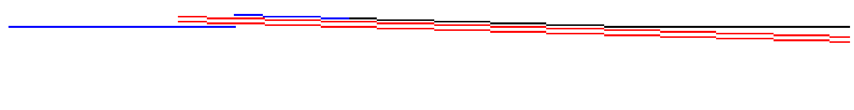
Solenoid Design



- POISSON Design Above – meets Required Specs

Electron Beam Components

- Standard Cathode Surface for Emission
- Magnetic Solenoid and Torroid have simple wire windings yielding 100 Gauss Fields
- Collector will Suppress Secondaries



- Simple Injection System Above

Table 28.17. Hardware Power Estimates.

Parameter		Value	See Section
Electromagnetic Dipole Power		15.3 kW	22.3
Electromagnetic Quadrupole Power (Medium Quads – Q2 and Q5)		0.467 kW	23.3
Electromagnetic Quadrupole Power (Large Quads – Q1, Q6 and Q8)		0.361 kW	23.4
Electromagnetic Quadrupole Power (Small Quads – Q3 and Q4)		0.245 kW	23.4
Electromagnetic Quadrupole Power (Very Small Quad – Q7)		0.169 kW	23.4
Electromagnetic Solenoid Power (8.7 Inch ID Solenoids – S2, S3, S4, S5 and S6)		143 kW	24.5
Electromagnetic Solenoid Power (32 Inch ID Solenoids – S1, S7 and S8)		166 kW	24.3
Electron Cooler Solenoid Power		18.4 kW	26.1
Electron Cooler Toroid Power		3.12 kW	26.2
ΔI/I Requirement of Power Supplies		1 part in 10^6	14.15

Summary

- Predictions on Q
- Path to Improvements
- The Dream of D-D -> He^4
- Summary Comments

Non-Optimized Predictions on Q

- Q scientific = 58.4/(12.7+4.94+2.744) +1 = 2.86 + 1 = 3.86
- Q engineering = 58.4/(12.7+4.94+2.744+5+5+4+4+2+2+10)+1 = 1.11+1 = 2.11
- 12.7 – ion beam drive power
- 4.94 – electron beam drive power (T)
  - IBS dominant contributor; power recovery assumed
- 2.744 – electron beam drive power (D)
  - IBS dominant contributor; power recovery assumed
- Remaining factors are various inefficiencies
  - 5's: Collection V; 4's: grid power; 10: recomb.
- Note that Permanent Magnet Solenoids Are Needed

Known Path to Improvements

- Electron scattering in merge regions a problem at lower velocity
- Self magnetic fields limit currents
- However, gains could be made by moving somewhat toward lower energy, higher currents
- Also, efforts at ion microscopy could increase power output by lowering the radius
- One IR instead of Two Immediately leads to 4X Smaller r, which leads to Two times output power and less halo

Unknown Path to Improvements

- Halo may not hit where modeling predicts
- Ion currents may not fully equal electron currents
- Other unforeseen issues may arise
- Main point is that once we learn about operation, we can adjust
  - Different halo correction mechanism
  - More electron current
- Can always work on P_{out} and P_{in} !

The Possibility of Achieving the Ultimate Goal: D-D -> He^4

- The design presented herein is appropriate also for a D – He^3 reactor
- Cross section about the same, but more problems with space charge, recombination and charge exchange
- D – He^3 will be good for initial testing; no neutrons; no Tritium – very, very safe
- The Ultimate Goal: D – D reactor could be used to produce T and He^3 at central location with D –T reactor providing power for the D – D reactor;

D – He^3 situated in communities due their safety

- The Ultimate Goal involves only D going eventually to He^4
  - No Lithium Limit

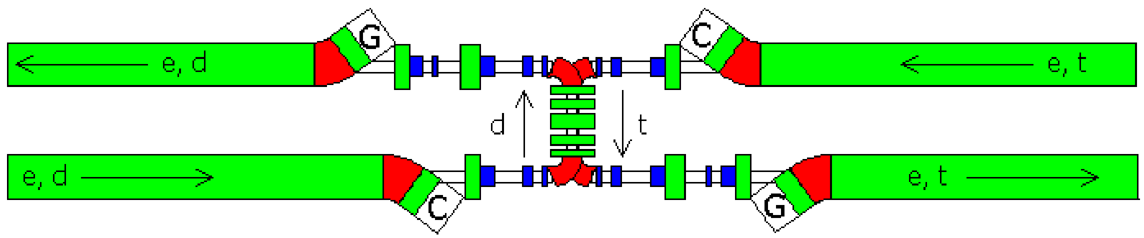
Summary Comments I

- ECOFusion, a new approach toward fusion energy generation, has been proposed to you today
- Proposal uses colliding beam devices that can be built with materials and technologies that are available today
- Output power per cell of about 50 kW is predicted from present design, but improvements in spot size (2) and lower energy (3) could increase this to 300 kW
- Calculations predict an engineering Q good enough to consider for use in a power plant

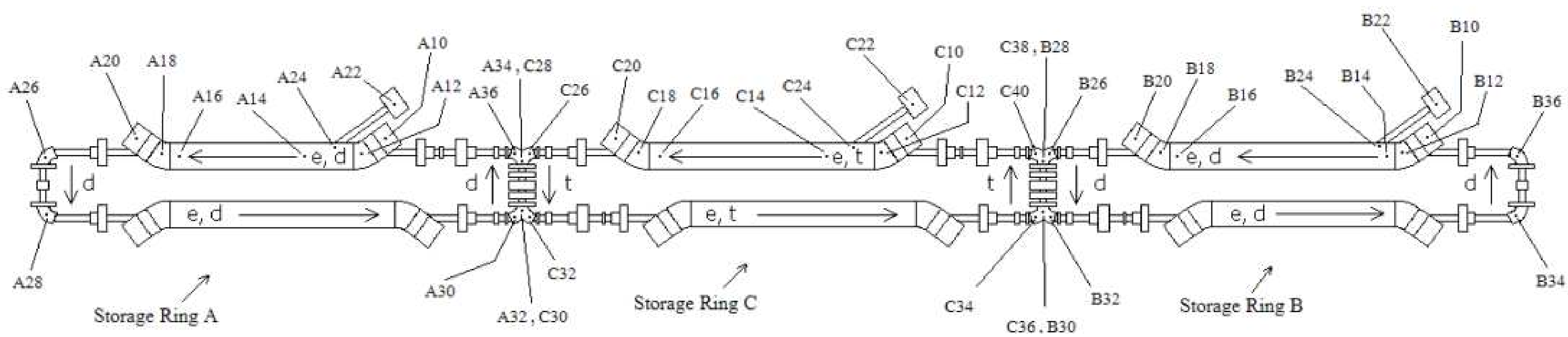
Summary Comments II

- While device may seem expensive now, $300,000 is a lot of material – cars are built for $10,000; first transistor was quite large and expensive too
- Advantageously, ECOFusion holds out the promise of using a pure Deuterium source as fuel – a limitless supply
- The theoretical analysis has been extensive, although only by one man – it is time for serious review
- It is also time to begin work on prototype construction and testing

Confinement from Magnetic Beam Focusing; Cooling Takes Away Imperfections and Allows Stacking



- The Interaction Region of ECOFusion Cell



- A Three Ring ECOFusion Configuration

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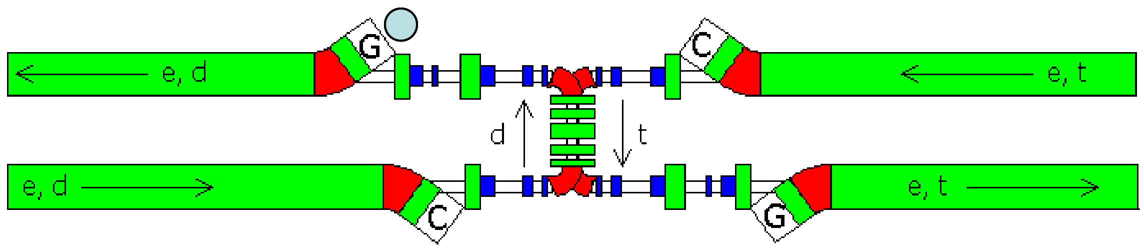

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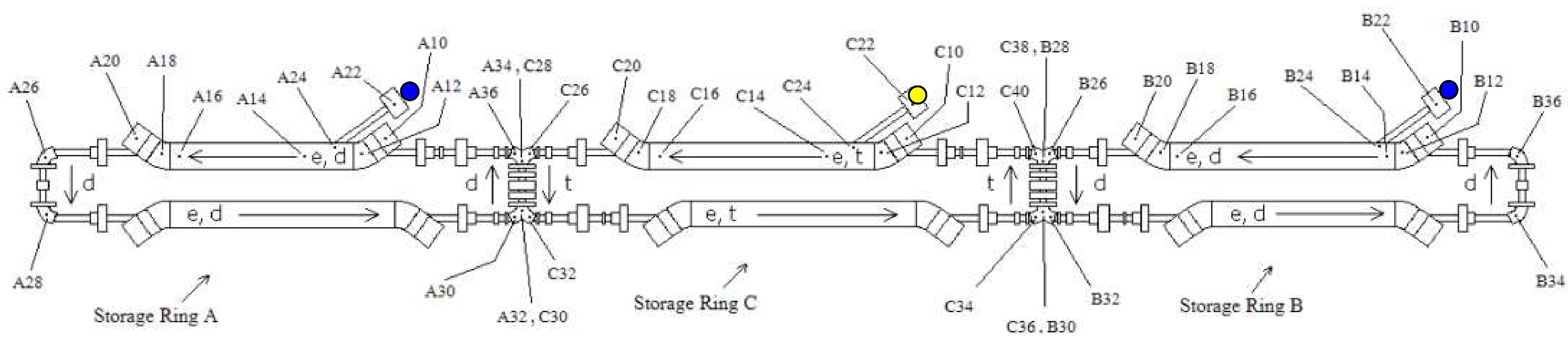

- A Three Ring ECOFusion Configuration