A TriForce Module for Performing Hydrogen Spectroscopy on the Princeton Field Reversed Configuration.

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Outline

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- Motivation / Background
- Goals
- Simulation Setup
- Results
- Conclusion / Future Work

https://en.wikipedia.org/wiki/File:PFRC-2_discharge.gif

Motivation / Background

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- The PFRC-2 is a rotating magnetic field-heated (RMF-heated) field reversed configuration (FRC) with the primary goal of reaching average ion temperatures of > 500 eV

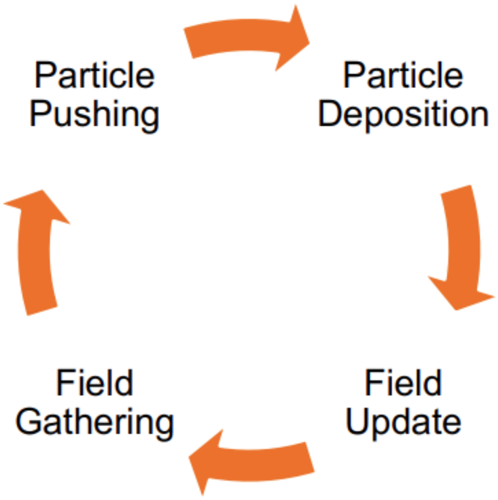
- To heat ions, their energy loss to electrons must be reduced.

- Experimental measurement of electron temperatures via visible line emission has been performed on the PFRC-2, but the interpretation methods used result in variations of up to 50%.

Motivation / Background

- Particle-in-cell (PIC) codes are used to simulate plasmas
  - In certain cases, the general PIC model is not viable
- Tri-Force provides better predictive capability
  - Consists of a PIC and meshless hydrodynamic model
- TFFate
  - Quick implementation and evaluation of algorithms

There are 4 basic steps to the PIC algorithm:



Particle_Pushing_for_Dummies_v1.0%20(5).pdf

Goals

Goals

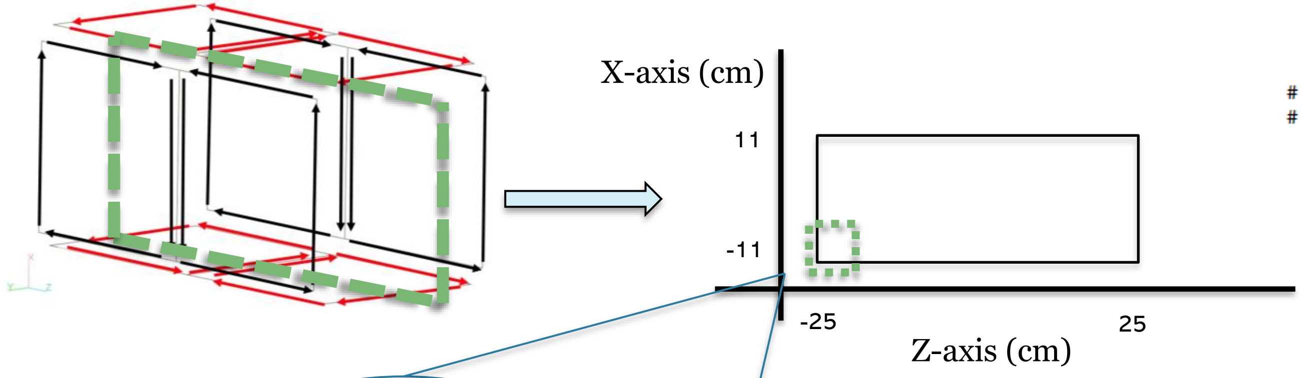
- Read from PFRC-1 simulation data files for ion density, electron density, temperature, and volume
- Use PIC data to simulate the expected radiation in the plasma
  - Focusing on Bremsstrahlung x-ray spectra
- Will allow synthetic spectra to be compared to detector measurements to check uncertainties/calibration issues etc

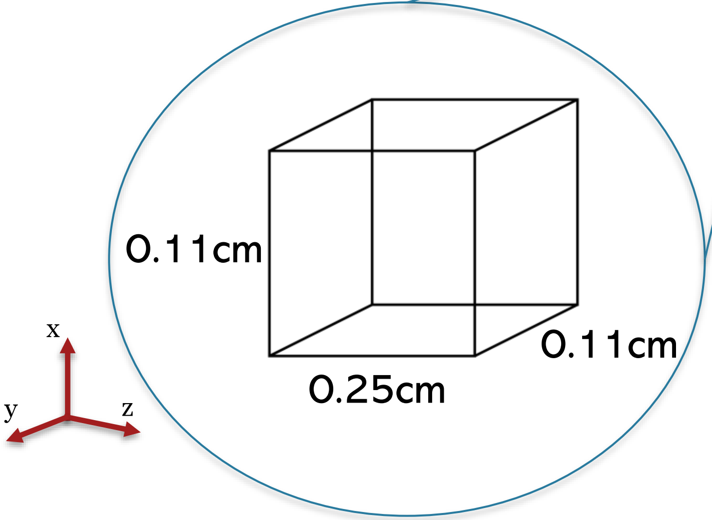
Simulation Setup

Simulation Setup

- Assumptions:
  - Free-Free Bremsstrahlung x-ray emission occurring in an optically thin plasma
    - Optically thin plasma – no absorption of photons
    - Radiation from electron–electron collisions and from ions can be ignored
  - Ion & Electron density, temperature, and volume come from each “cell”
  - Spectra is simulated over a set range of frequencies
    - Emissivity is calculated over the photon energy range of interest for each cell

Simulation Setup





Example cell

x = Z (cm), y = X (cm), z = e- density (#/cm^-3)

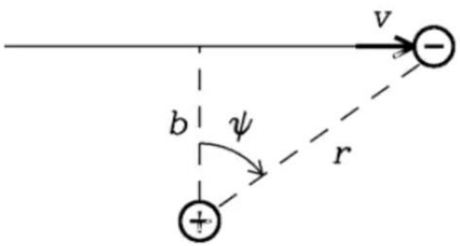
x	y	z
-25.0000000	3.96000004	28961112.0
-25.0000000	4.06999969	22457130.0
-25.0000000	4.18000031	14716490.0
-25.0000000	4.28999996	8518239.00
-25.0000000	4.39999962	5015599.00
-25.0000000	4.51000023	1675011.88
-25.0000000	4.61999989	940293.750
-25.0000000	4.72999954	205575.703
-25.0000000	4.84000015	0.00000000
-25.0000000	4.94999981	0.00000000
-25.0000000	5.05999947	0.00000000
-25.0000000	5.17000008	0.00000000
-24.7500000	-4.73000002	1644259.38
-24.7500000	-4.61999989	7486105.00
-24.7500000	-4.51000023	13327898.0
-24.7500000	-4.40000010	22743964.0
-24.7500000	-4.28999996	32377636.0
-24.7500000	-4.17999983	70371480.0
-24.7500000	-4.07000017	124549920.
-24.7500000	-3.96000004	193581872.
-24.7500000	-3.84999990	288607456.
-24.7500000	-3.74000025	381590784.
-24.7500000	-3.63000011	454081344.
-24.7500000	-3.51999998	526571584.
-24.7500000	-3.40999985	648586496.
-24.7500000	-3.30000019	781649408.
-24.7500000	-3.19000006	868099136.

Example of PFRC-1 raw data

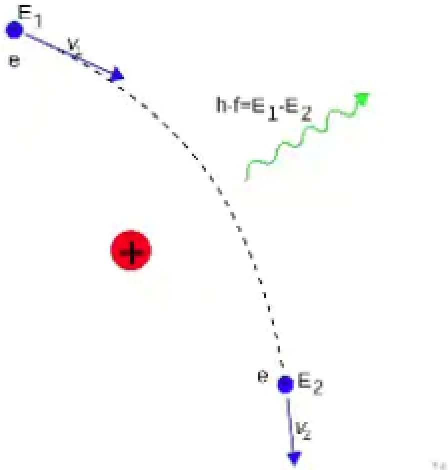
Free-Free Emission - Bremsstrahlung Radiation

- Total radiated spectrum that one electron, at velocity v, sees per second at impact parameter b

$$P(\omega, v) = \frac{16}{3}\frac{e^6 n_i}{m_e^2 v c^3}\ln(\frac{b_{max}}{b_{min}}) \tag{1}$$



https://www.slideshare.net/KhaledEdris/radio-astronomy-emission-mechanisms



Bremsstrahlung Wiki

Spectrum Eqns. Continued

$$j_{ff}(\nu) = \frac{1}{4\pi}\int_0^\infty P(\omega, v) f(v) dv \quad (2)$$

- Where $j_{ff}(\nu)$ is the free-free emissivity as a function of frequency, and f(v) is a Maxwellian distribution of electron speeds

$$j_{ff}(\nu) = 5.44 \times 10^{-39}\, g_{ff}(\nu,\mathrm{T}) \frac{n_e n_i}{T^{1/2}} e^{-h\nu/k_B T} \quad (3)$$

- Where $g_{ff}(\nu,T)$ is the gaunt factor defined in the x-ray range (below), n_e is the electron density, n_i is the ion density, T is temperature, h is Planck's constant, and k_B is Boltzmann's constant.

For $h\nu \lesssim k_B T$

$$g_{ff}(\nu,\mathrm{T}) \cong \frac{\sqrt{3}}{\pi} \ln\left(\frac{h\nu}{k_B T}\right) \quad (4)$$

Simulation Setup

- Python Spectrum function

```
#Emissivity— Photon count rate vs Energy at a specific temperature, ion & electron density, and volume
#Each cell in the simulation code provides the temperature, density, and volume in that cell
#Gaunt factor defined for x-ray range h*nu ≲  kB*T
def spectrum(ni,ne,T,nu,volume):
    new = np.array([])
    for i in nu:
        const = (4*np.pi*((3**(0.5))/np.pi)*((5.44*10**(-39))*10**(-1)))/(h*i)
        spec = (const*(np.log((q_e*T)/(h*i)))*(ne*ni)/((q_e*T)**(0.5))*np.exp((-h*i)/(q_e*T)))*volume
        sumspec = np.sum(spec)
        new = np.append(new,sumspec)
    return new
```

Results

- Comparison of test data and raw PFRC-1 data

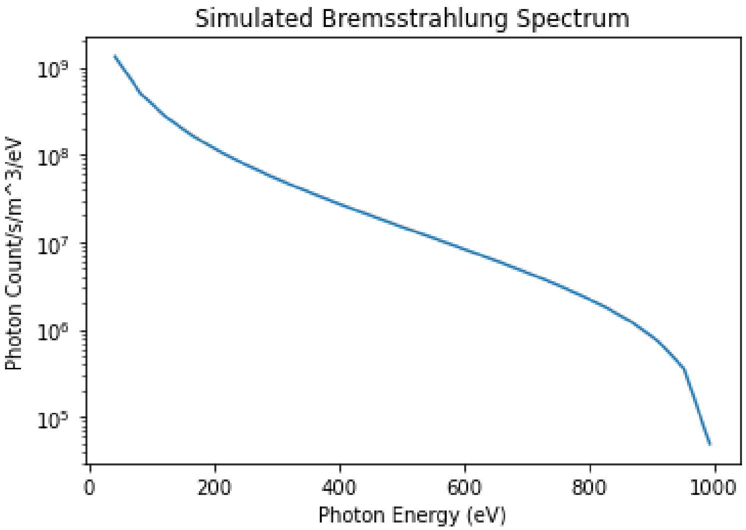


Fig1. Plot of Spectrum using constant arrays chosen plasma parameter values

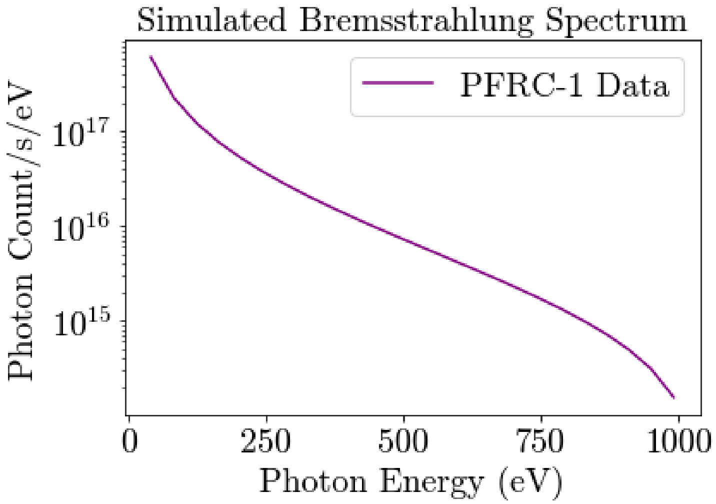
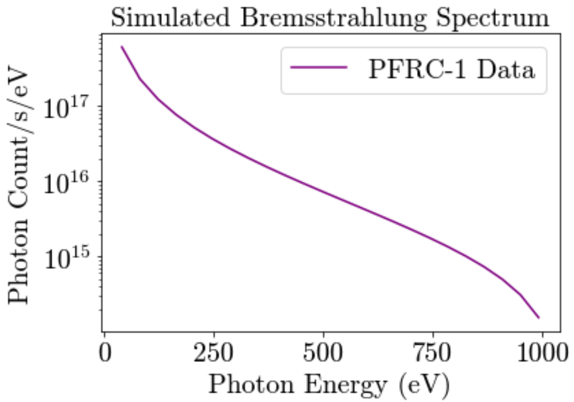


Fig2. Plot of PFRC-1 particle-in-cell Raw Data

Results



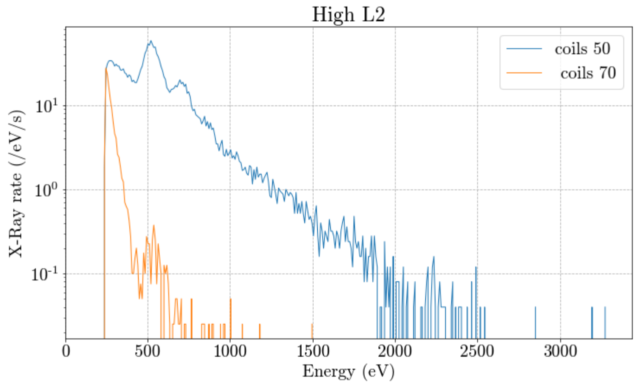


Fig3. Plot of measured x-ray data gathered by silicon drift detector.

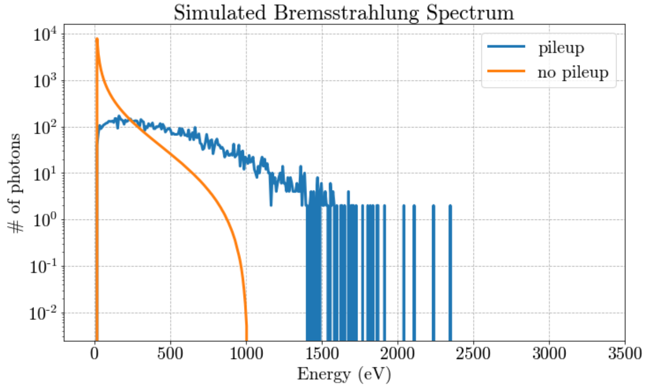


Fig4. Plot of 1keV Monte Carlo simulation demonstrating correction to Fig3 plot.

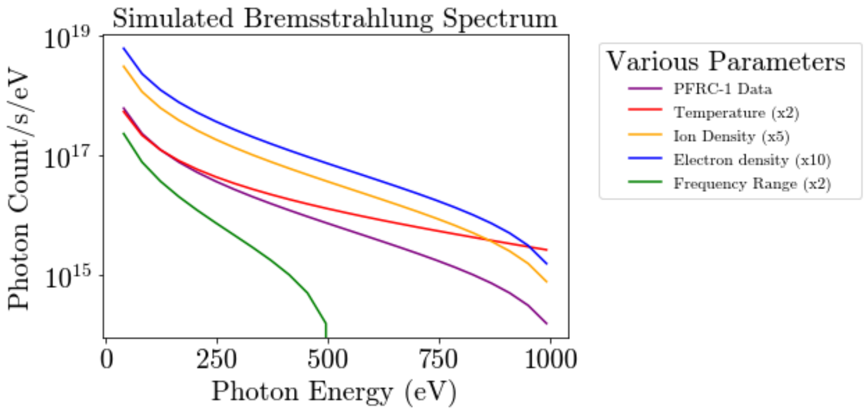


Fig5. The effect that varying plasma parameters has on bremsstrahlung spectrum

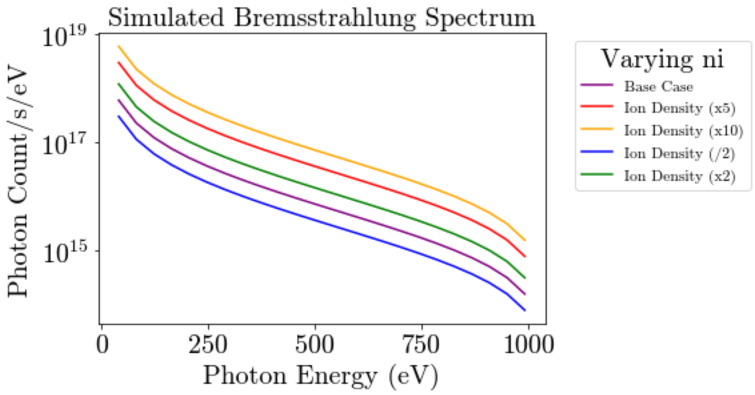


Fig6. The effect of varying ion density on bremsstrahlung spectrum

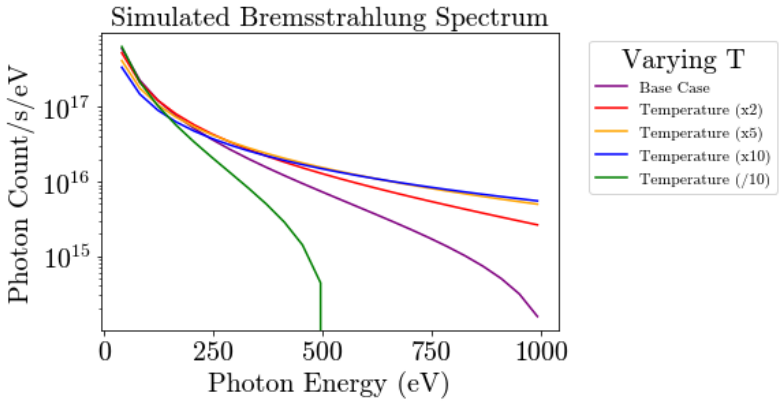


Fig7. The effect of varying electron temperature on bremsstrahlung spectrum

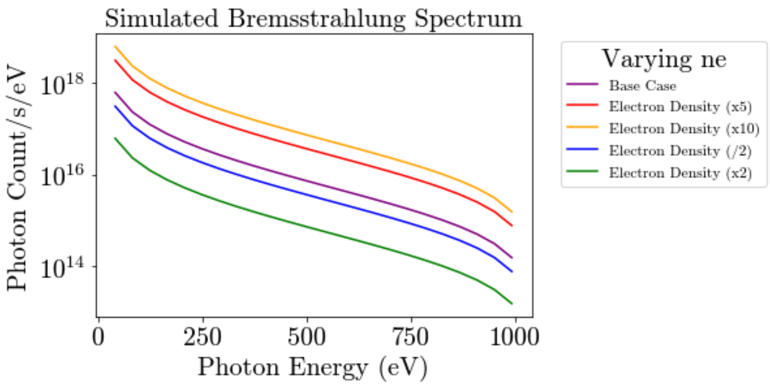


Fig8. The effect of varying electron density on bremsstrahlung spectrum

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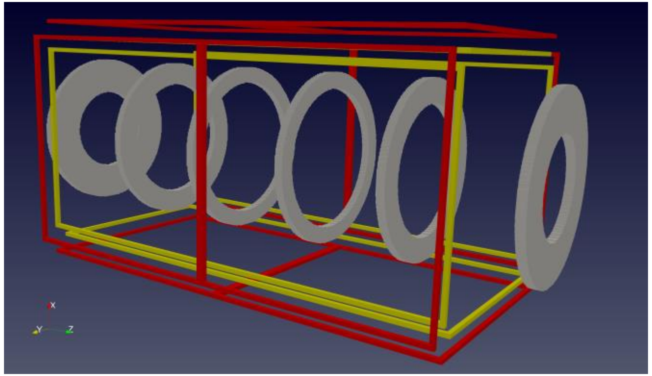
Conclusion / Future Work

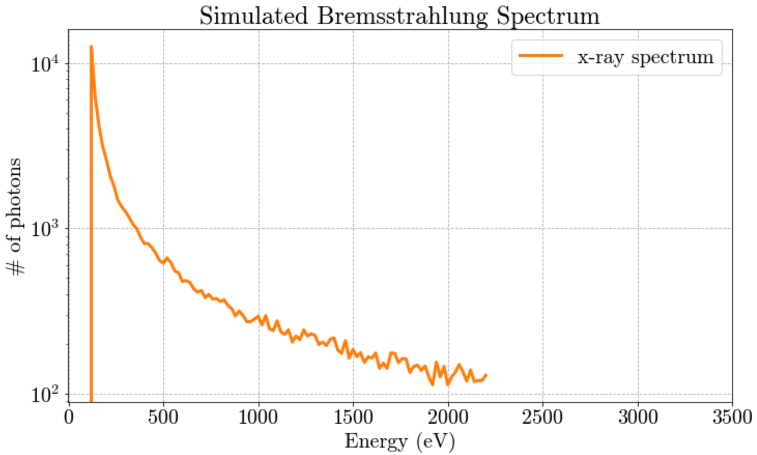
Conclusion / Future Work

- **Conclusion:**
- A Python module has been developed for TriForce that reads particle-in-cell data and graphs the expected bremsstrahlung radiation spectrum over a photon energy range of interest.

- **Future Work:**
- Simulate detector window geometry and film material to more closely compare with detector data
- Incorporate other radiation of interest
  - Line radiation and synchrotron/cyclotron radiation
- Resolve certain assumptions
  - Gaunt factor will ideally vary over certain intervals depending on plasma parameters
- Use simulations to accurately infer electron temperature

RF antenna (red)
Faraday cage (yellow)
Flux-conserving rings (silver)





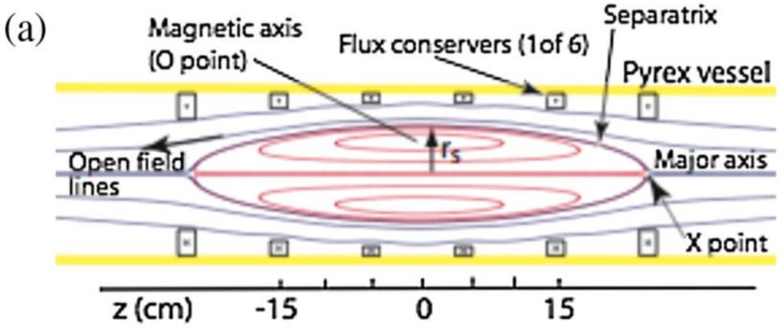


FIG. 1 (color online). (a) Midplane of the PFRC device with magnetic-field lines shown. Closed field lines are red.

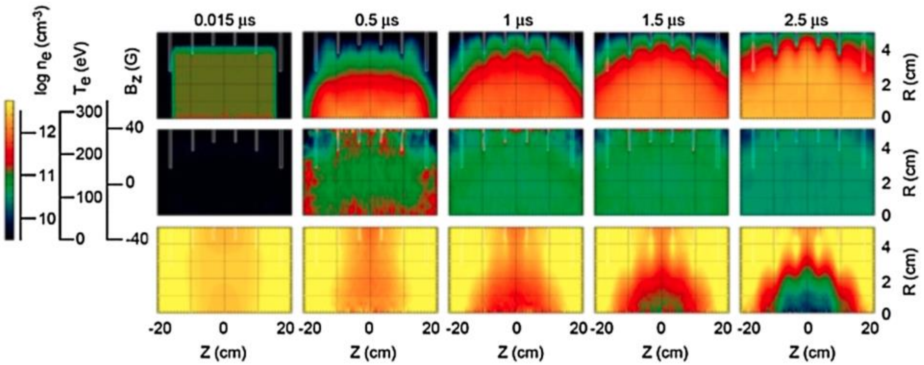


FIG. 3 (color online). Top row: $\log_{10} n_e(\mathrm{cm}^{-3})$. Middle row: T_e (eV). Bottom row: B_z (G). The five columns are snapshots at the following times, from left to right: 0.015, 0.5, 1, 1.5, and 2.5 μs. Color-contour scales are to the left. The plasma shape is modulated by the flux conservers.