The Pinch Plasma of the Philips Extreme UV Source

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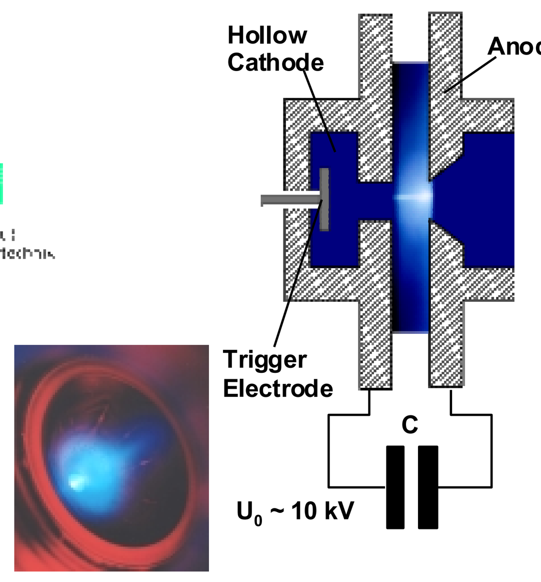
Philips Extreme UV: HCT Pinch as source

"Hollow Cathode Triggered Pinch"

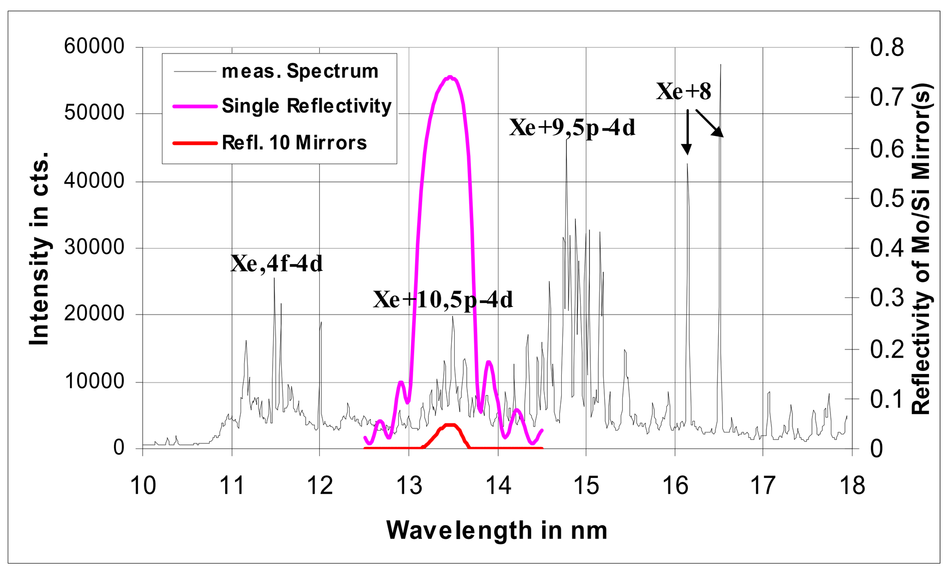
Joint Venture of

Philips Extreme UV & Fraunhofer ILT



- Hollow Cathode
  - defined ignition & triggering
  - ignition at "left hand side" of Paschen curve
- High current pinch discharge
  - "pseudo spark discharge"
  - production of hot plasma by magnetic (self-)compression
  - intense EUV radiation

EUV Spectrum of Xe and reflectivity of Mo/Si Mirrors



Modeling of

- Electrical circuit
- Pinch dynamics
- Ionisation/Recombination
- Radiation

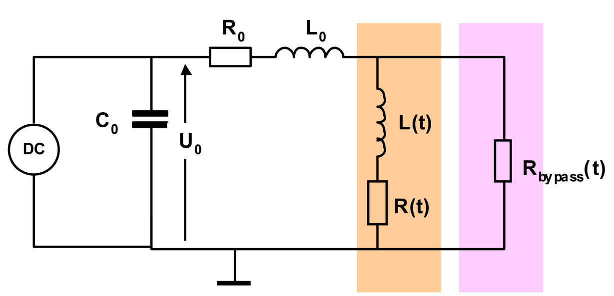
Plasma Material Function from ADAS (Univ. of Strathclyde, Glasgow), calculated from first principles:

- Power radiated from each ion $U_{rad,ionstage}(N,T_e,n_e)$
- Ionisation Rates for each ion $IR_{ionstage}(T_e,n_e)$,
- Recombination Rates for each ion $RR_{ionstage}(T_e,n_e)$
- Spectra of each ion

Zero Dimensional Dynamic Pinch Model (1)

Zero dimensional dynamic pinch model, coupled to circuit equations, L_0, R_0, C_0 circuit, pinch with L(t), R(t):

Total Energy per pulse: $E=\frac{1}{2}C_0U_0^2$



$$\frac{dU_0}{dt}=-I_{tot}/C_0$$

$$U_0=L_0\frac{dI_{tot}}{dt}+R_0I_{tot}+L\frac{dI}{dt}+\left(R+\frac{dL}{dt}\right)\cdot I$$

$$\tau_{Period}\sim 2\pi\sqrt{L_0C_0}$$

$$R_{Bypass}(I_{tot}-I)=L\frac{dI}{dt}+\left(R+\frac{dL}{dt}\right)\cdot I$$

Bypass caused by Photoionisation of outer gas

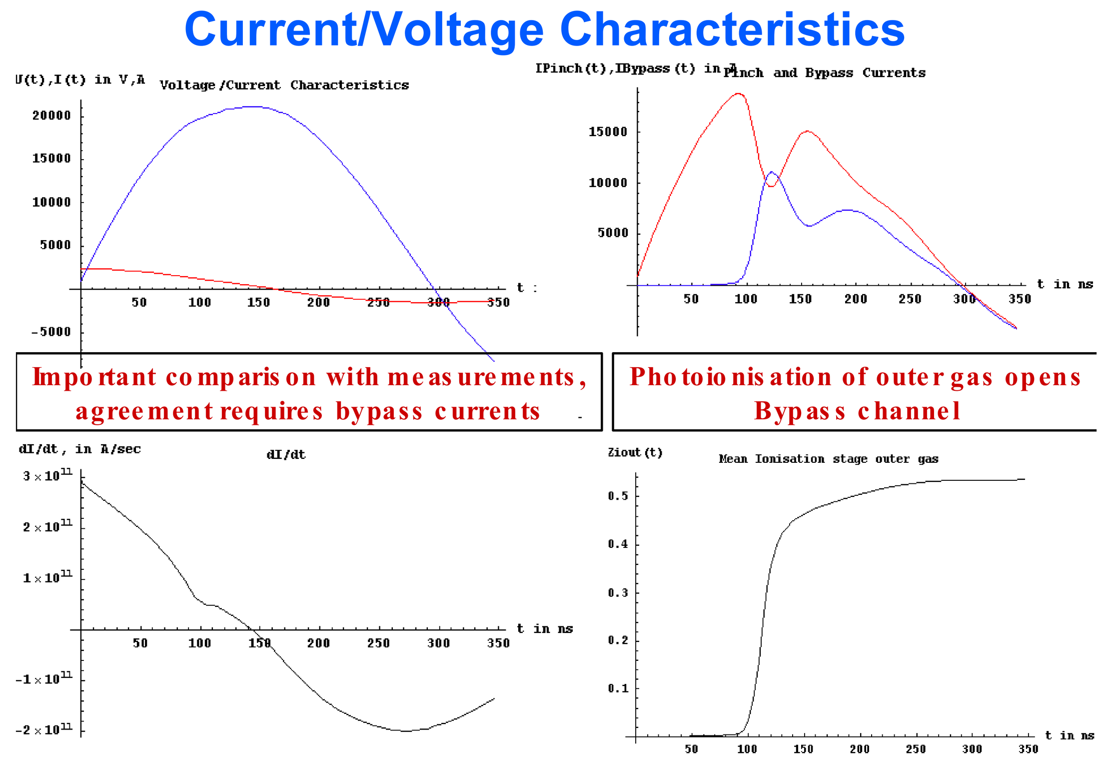
Dynamic ionisation of outer gas

$$\frac{dZ_{out}}{dt}=\sigma_{PhotoIonisation}\cdot PhotonFlux\cdot\theta(h\nu-E_{ion}(Z_{out}))$$

Bypass Resistance:
electrode fall + collisionless, quasineutral plasma

$$R_{Bypass}\cdot I_{Bypass}=V_{Bypass}=V_{Fall,By}+\frac{m_e}{2e}\left(\frac{j_{Bypass}}{e\cdot Z_{out}\cdot n_0}\right)^2$$

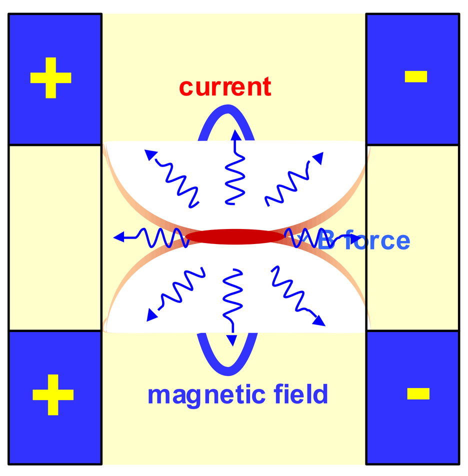
Current/Voltage Characteristics



Important comparison with measurements, agreement requires bypass currents

Photoionisation of outer gas opens Bypass channel

Pinch Phase after ignition



- Magnetic compression (pinching) of Xe plasma
- Current several ten kA during pinch phase
- Pinch time ~ 100ns
- T_e ~ 50eV
- EUV radiated by highly ionized Xe: Xe^{+8} ... Xe^{+12}
- EUV in 13.5 nm band mainly radiated by Xe^{+10}

Zero Dimensional Dynamic Pinch Model (2)

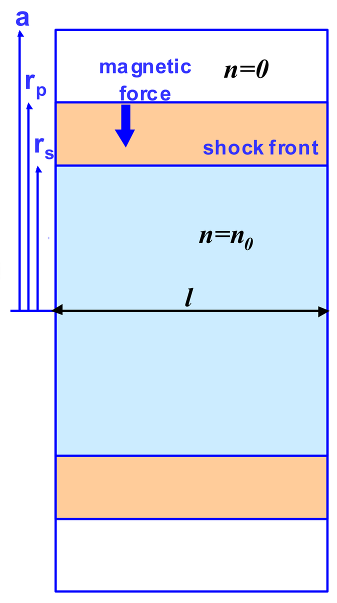
Supersonic implosion phase, snowplough with shock front preceding magnetic piston:

Momentum equation, piston radius, starting at a:

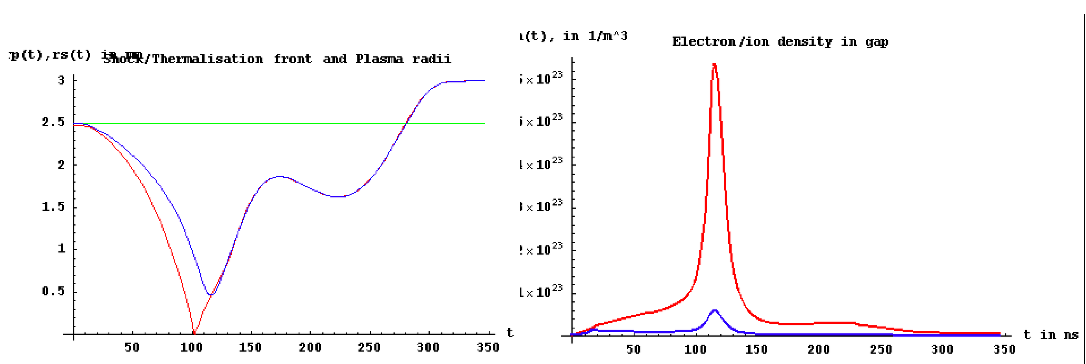
$$N\frac{d}{dt}\left(M_{atom}\left(1-\frac{r_s^2}{a^2}\right)v_p\right)=2\pi lr_p\cdot(p_{therm}-p_{mag})$$

Equation for shock front
(equilibrium of thermal and shock pressures):

$$v_s=\dot{r}_s=-\sqrt{\frac{k(ZT_e+T_i)}{M_{atom}}\frac{(a^2-r_p^2)}{(r_p^2-r_s^2)}}$$



Pinch Radii and Electron density



Velocities of order ~20000 m/sec

Electron density changes very fast

Zero Dimensional Dynamic Pinch Model (3)

Energy equations for electron Temperature:

$$N\frac{d}{dt}\left[\frac{3}{2}kZT_e+E_{ion}(Z)\right]=R\cdot I(t)^2-p_edV-Q_{ei}$$
$$-\sum_i A_{ionstage}\cdot U_{rad,ionstage}(N,T_e,n_e)$$

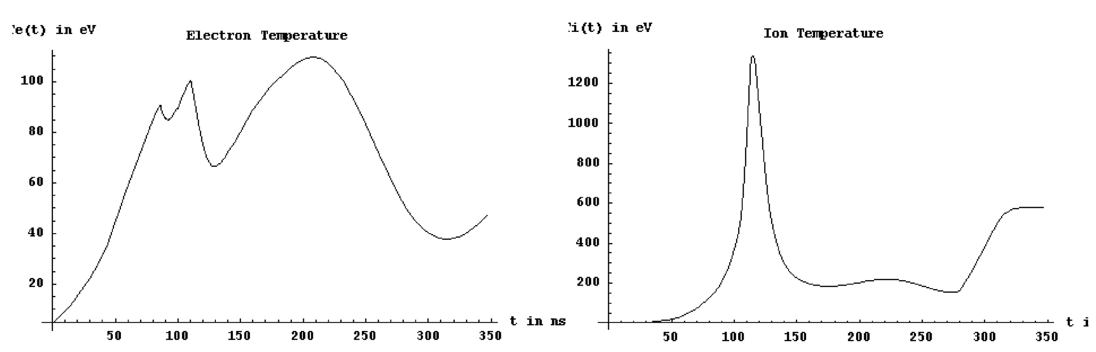
$U_{rad,ionstage}(N,T_e,n_e)$ Radiation Power, tabulated from ADAS, based on CR population of excited states of each ionisation stage + escape factors

R: Spitzer Resistivity; Q_{ei}: Energy exchange electrons-ions

Energy equations for ion Temperature:

$$N\frac{d}{dt}\left[\frac{3}{2}kT_i\right]=-NM_{atom}\frac{r_sv_s}{a^2}v_p^2-p_idV+Q_{ei}$$

Temperatures of Electrons/Ions

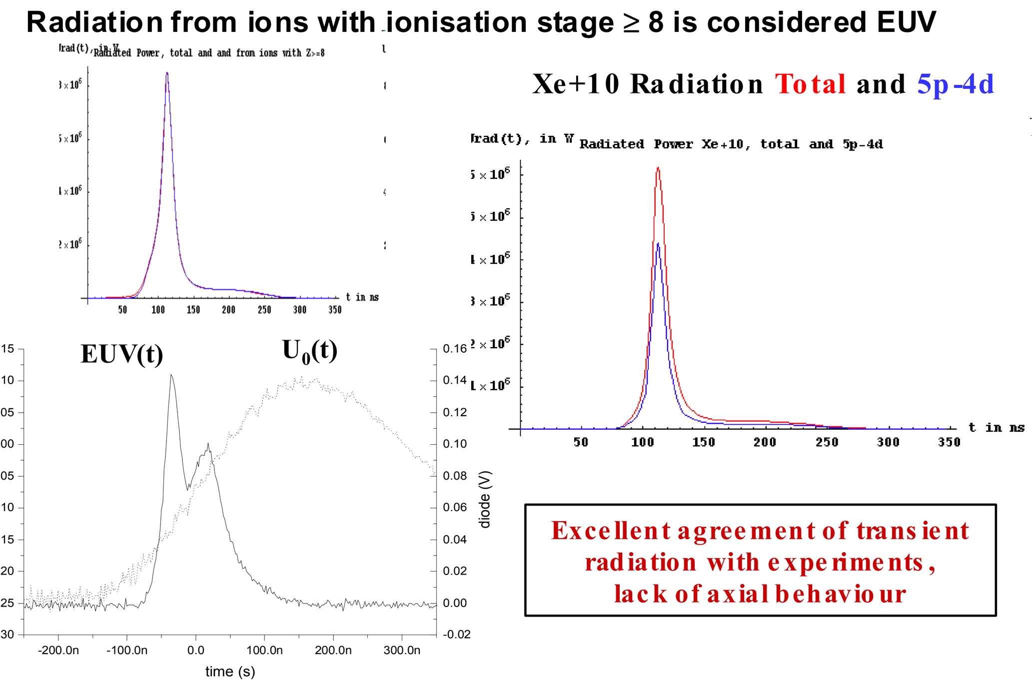


Electrons mostly heated ohmically, loose energy via ionisation, radiation

Ions heated by magnetic compression/shock heating energy transferred to electrons at high densities

Radiation

Radiation from ions with ionisation stage ≥ 8 is considered EUV



Excellent agreement of transient radiation with experiments, lack of axial behaviour

Zero Dimensional Dynamic Pinch Model (4)

Ionisation dynamics to compute abundances $A_{ionstage}$ of all ion stages:

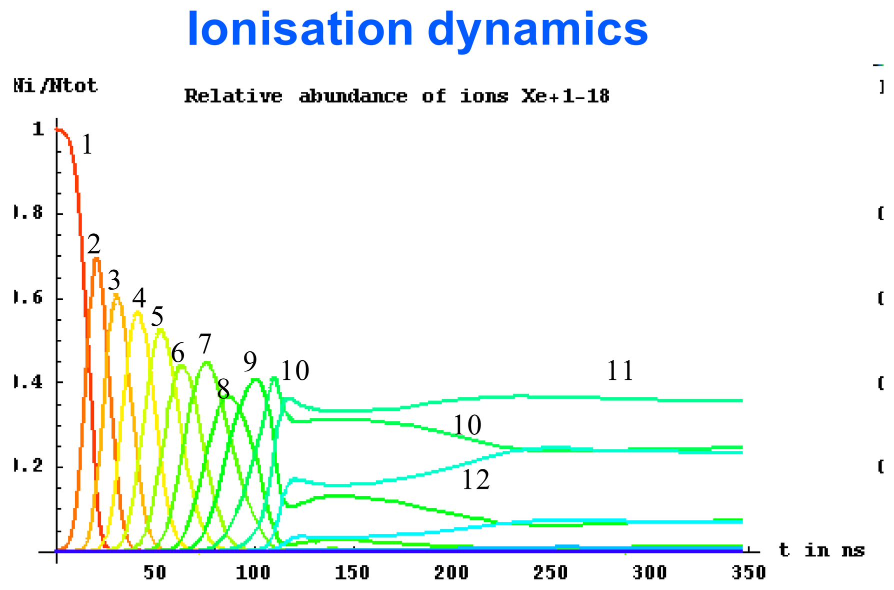
$$\frac{dA_{ionstage}}{dt}=n_e\cdot\begin{pmatrix}A_{ionstage-1}\cdot IR_{ionstage-1}(T_e)-A_{ionstage}\cdot IR_{ionstage}(T_e)\\+A_{ionstage+1}\cdot RR_{ionstage+1}(T_e)-A_{ionstage}\cdot RR_{ionstage}(T_e)\end{pmatrix}$$

$IR_{ionstage}, RR_{ionstage}$:

Ionisation and Recombination rates of each ionisation stage, including dielectronic processes, tabulated from ADAS

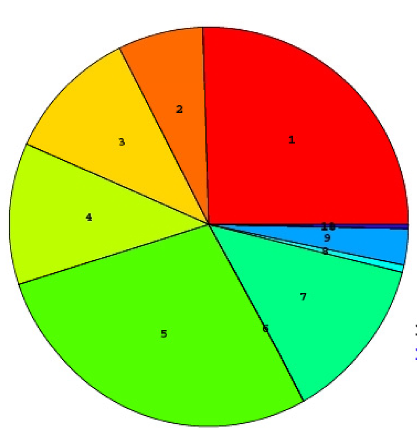
Axial Particle Losses: $\frac{dN}{dt}=-2N\frac{v_{th,i}(T_i)}{l}$

Ionisation dynamics



Ionisation/recombination must be treated dynamically

Energy Balance of Plasma/Circuit



1: Electric Energy left in Capacitors, = 0.774465 J
2: Magnetic Energy left in Circuit, = 0.209735 J
3: Ohmic heating of Device, = 0.331863 J
4: Ohmic heating of Bypass, = 0.353318 J
5: Heating of Cathode, = 0.849254 J
6: Magnetic energy left in gap, = 0.0000963268 J
7: Total radiation, = 0.400999 J, including 0.256357 J EUV
8: Internal plasma energy left, = 0.0184228 J
9: Axial Loss of internal plasma energy, = 0.0904373 J
10: Kinetic energy of plasma, = 0.0000189438 J
11: Axial Loss of kinetic plasma energy, = 0.0104045 J

Summary and Outlook

- Excellent agreement with all experiments with respect to different parameter variations
- Model has been successfully applied to maximise inband radiation at 13.5 eV (from Xe XI)
- 2d-model to calculate axial pinch/radiation geometry
- Calculate atomic data for other elements

Reference (ADAS):
H. Summers et al., Atomic Data and its Utilisation at the Jet experiment,
Plenum Press Series Physics of Photons and Molecules,
Photon and electron collisions with atoms and molecules,
edited by P.G. Burke, C.J. Joachain (1997), page 265 .