Simulations of Omega shock ignition experiments

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Goal : Compare CHIC simulations to experimental Data (Omega laser facility)

• **First step 1D and 2D simulations of**

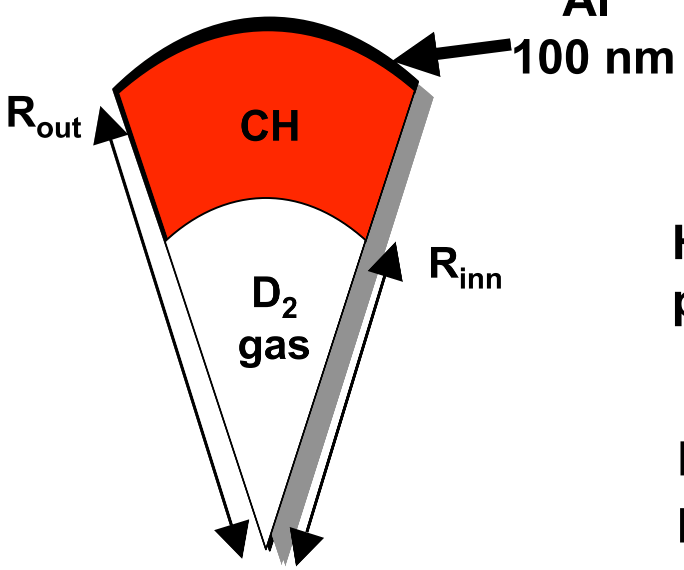
Reference experiment : W. Theobald, et al. PoP 15, 056306 (2008)

Initial experiment on shock-ignition inertial confinement fusion concept

- **Irradiation 60 Omega beams**
- **Targets : Warm plastic shell : CH + D_2 + Al coating**
- **Shot number:**
  - **#46073 : Picket Without spike**
  - **#46078 : Picket With spike (Shock-ignition)**
  - **#48674 : Optimized picket with spike (Shock-ignition)**
- **1D + 2D CHIC simulations**

Targets description

Warm plastic shell



	Shot#	Pressure D_2 (atm)	R_{inn} (μm)	R_{out} (μm)	CH thickness (μm)
High D_2 pressure	46073 With out SI	25	395	436.5	41.5
High D_2 pressure	46078 With SI	25	392.5	432.5	40.0
Low D_2 pressure	48674 With SI	8.3	393.5	433.9	40.4

SI : Shock ignition

Initial temperature : 300 K

CHIC 1D simulations

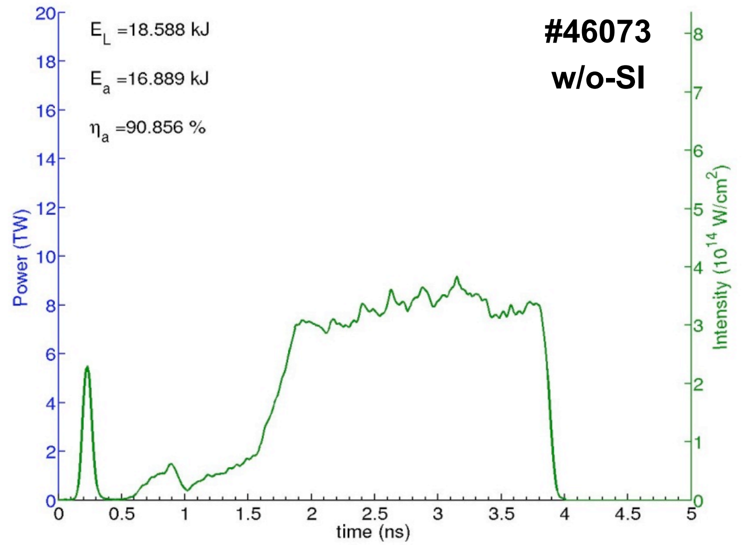
CHIC simulation parameters (1D and 2D)

- Lagrangian scheme, Godunov acoustic solver
- ALE :Winslow-Crowley + 2nd order remapping
- 3D raytracing + refraction + Caustic (f/D)

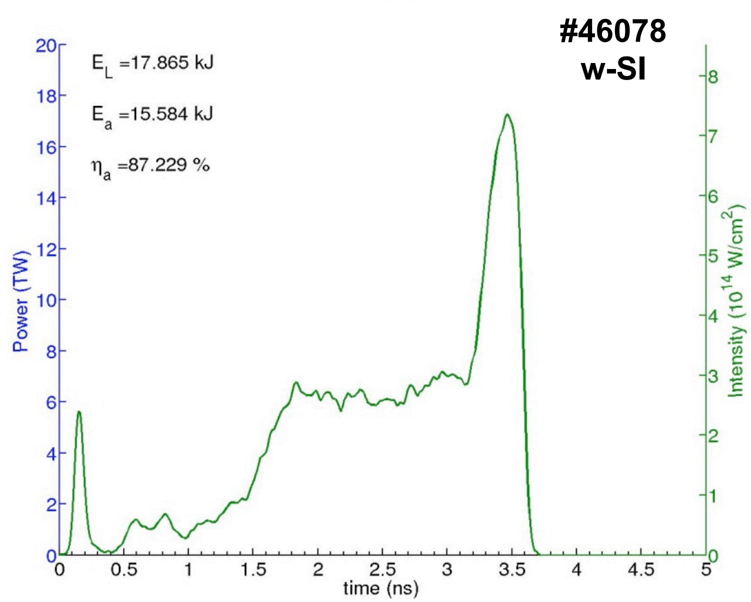
+ non linear collisional absorption (Langdon)

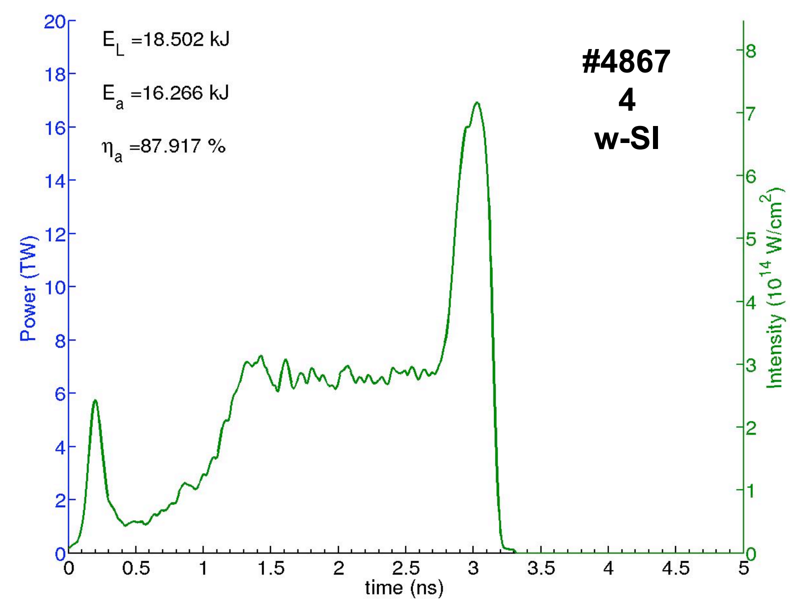
- EOS : Sesame (D2) , Thomas Fermi (CH, Al)
- Ionisation : Thomas Fermi
- Heat conduction : Flux limited Spitzer f=0.06% (Sharp Cutt-off)
- Radiative diffusion model 30 groups:
  - LTE opacities model: screened hydrogenic average atom
- Fusion reactions: D+D -> ^{3}He+n; ^{3}He +D -> p + ^{4}He,
  D+D -> p+T, D+T -> ^{4}He+n

Laser pulses used in simulations*



Shot#	Pulse at 3ω	SSD	Energy (kJ)
46073	LA37090	OFF	18.6
46078	FIS3601P	OFF	17.9
48674	FIS3601P	OFF	18.5

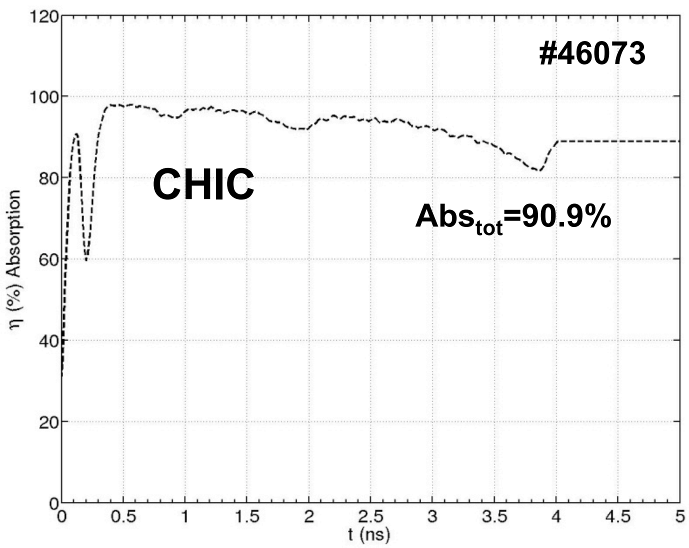


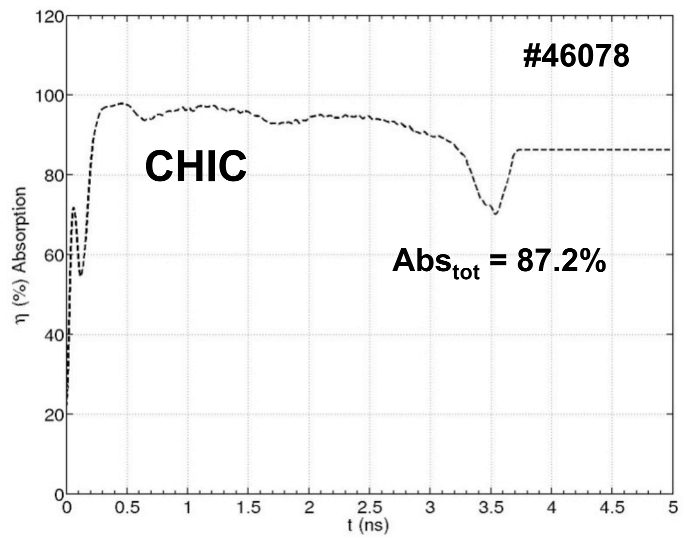


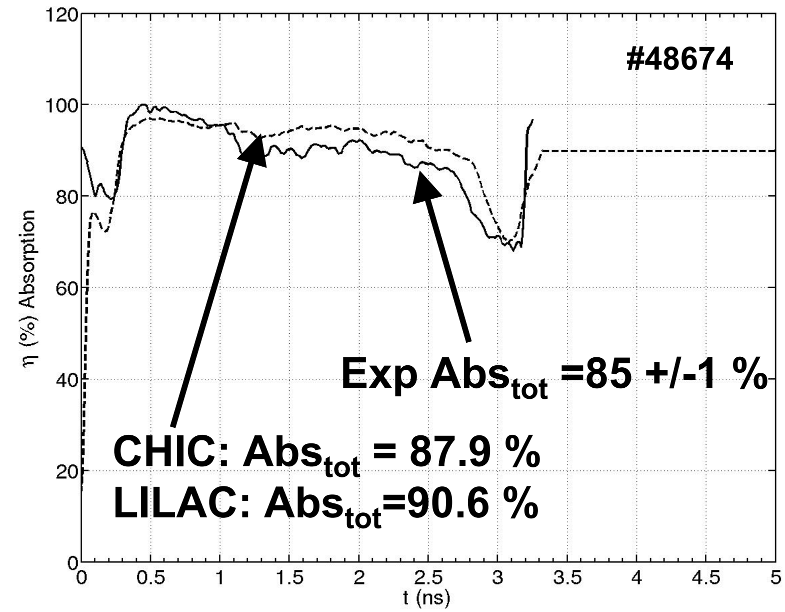
* W. Theobald PoP 15 056306 (2008)

In CHIC no smoothing SSD

Laser pulses absorption





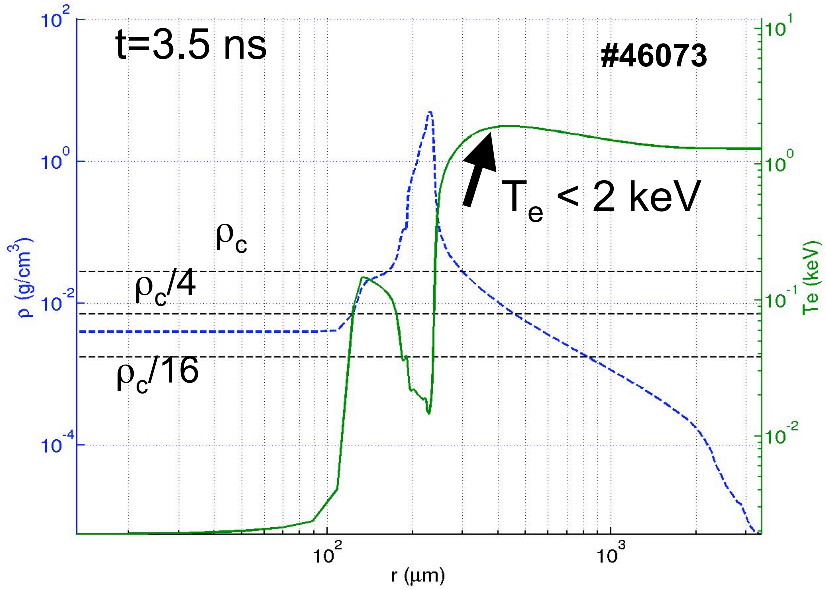


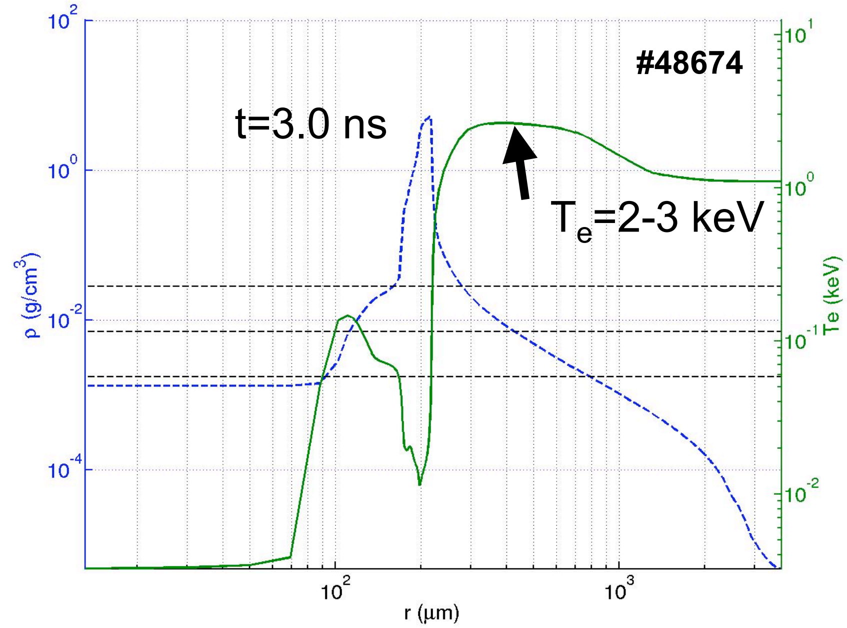
- **Good agreement between CHIC simulations and experiment**

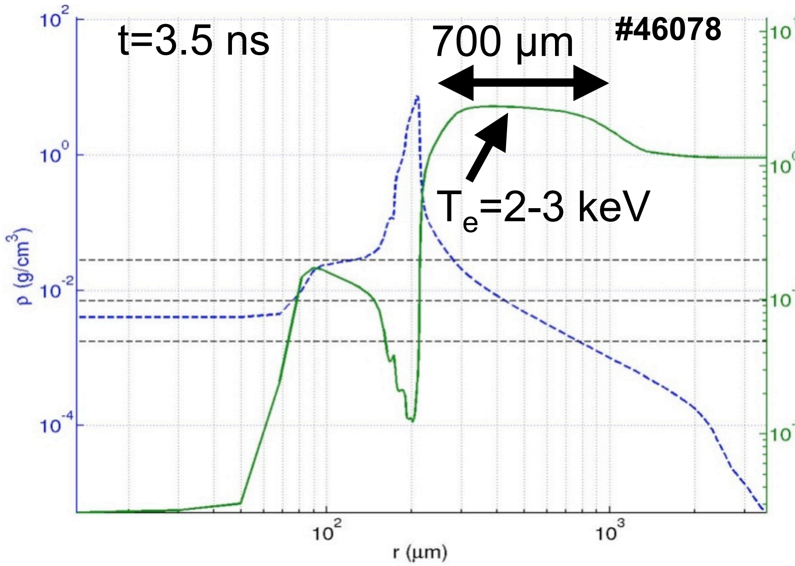
- In CHIC Inverse Bremsstrahlung with Langdon effect

Coronal plasma at spike launch time

Corona temperature during the spike





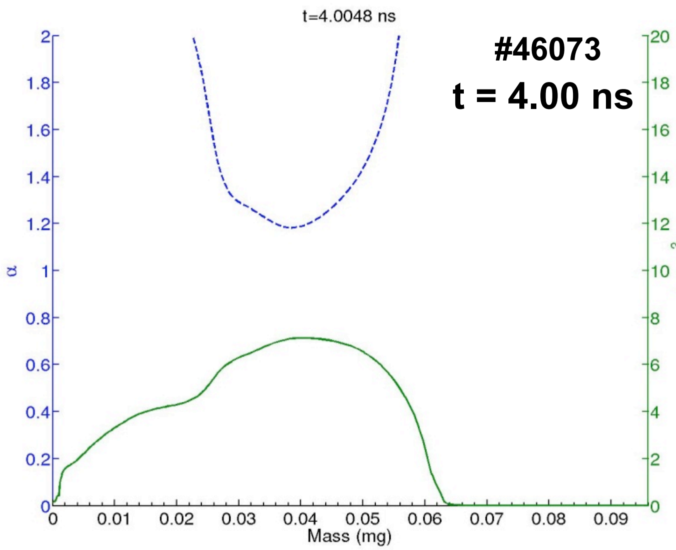


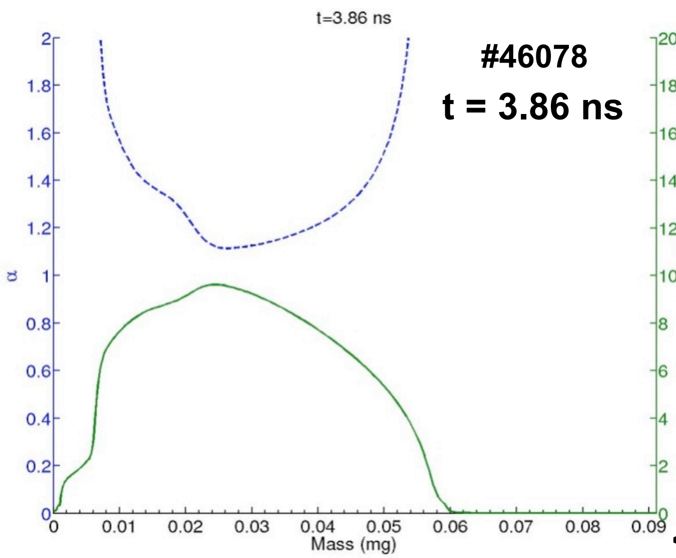
- **Long plasmas: ~mm between ρ_c and $\rho_c/16$**

- **High temperature: below 3 keV**

Coasting phase

Adiabat and density profile at the beginning of deceleration



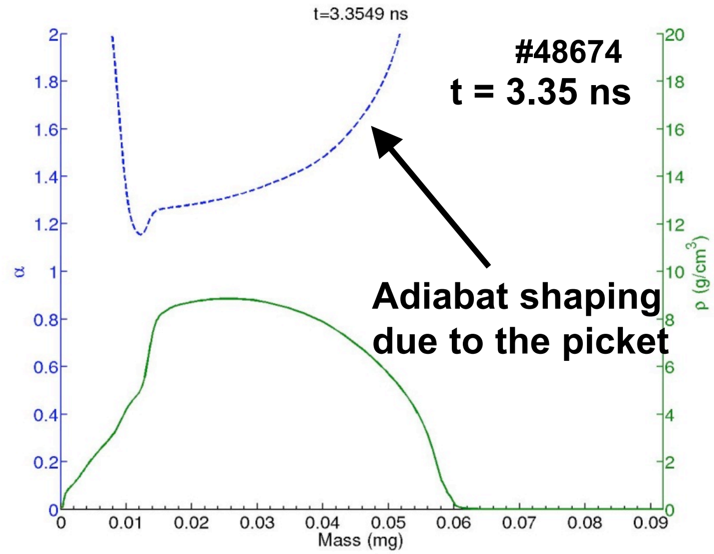


Adiabat like in DT

$$á = \frac{P(Mbar)}{2.25\ ñ^{5/3}(g/cm^3)}$$

$$\langle á \rangle ; \frac{\int_0^{R_a} á(r)ñ(r)dr}{\int_0^{R_a} ñ(r)dr}$$

R_a: Ablation front

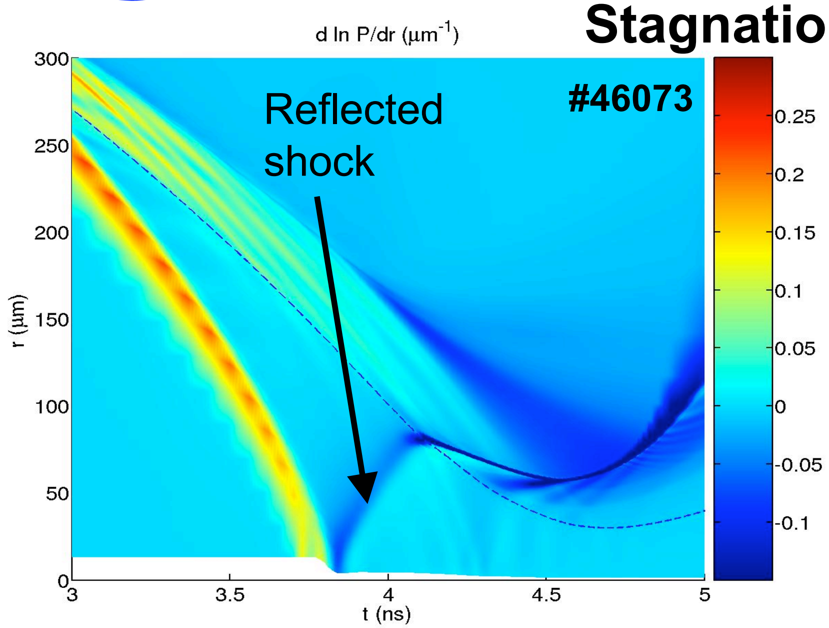


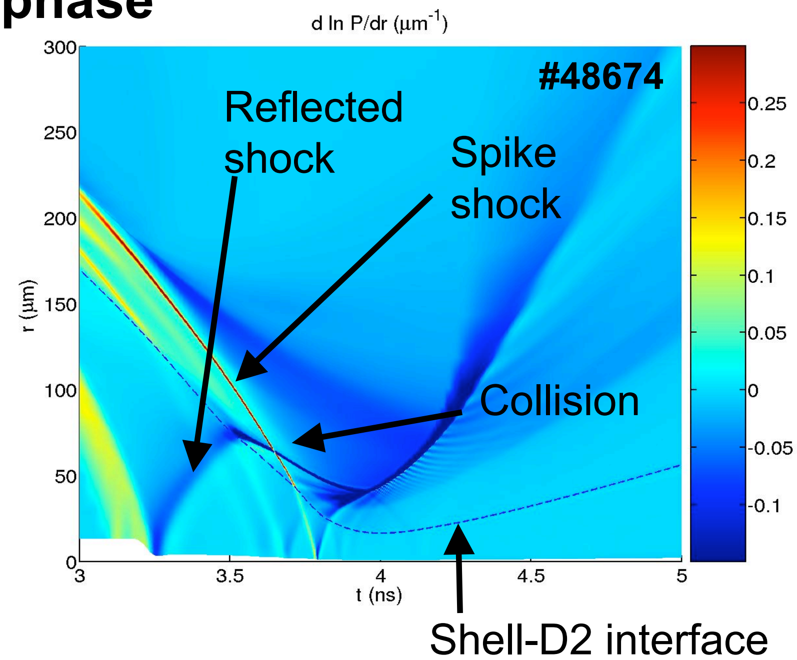
Shot#	<_>	M_{imp} (µg)	$\langle E_k \rangle$ (J)	$\langle V_{imp} \rangle$ (km/s)
46073 t = 4.00 ns	1.65	59	831	168
46078 t = 3.86 ns	1.30	55	826	173
48674 t = 3.35 ns	1.45	56	877	177

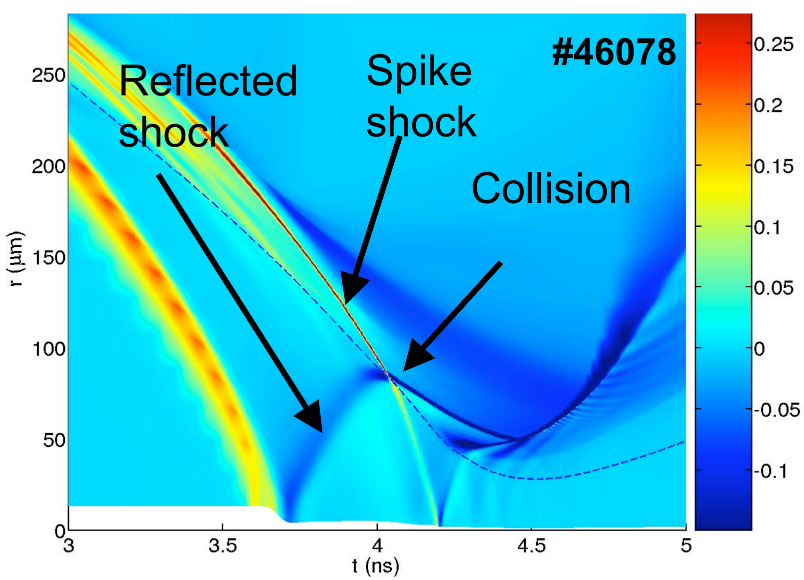
$\langle V_{imp} \rangle$ is obtained from the shell kinetic energy $\langle E_k \rangle$ and imploded mass M_{imp}.

Collision between the ignitor shock and the reflected shock

Stagnation phase



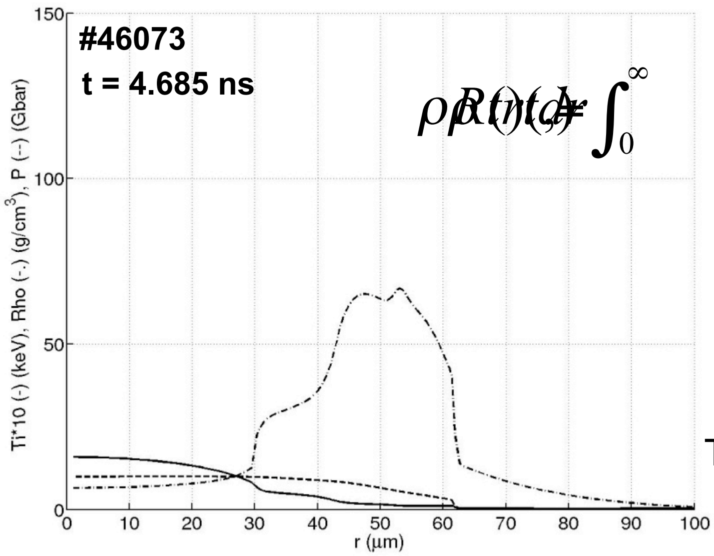




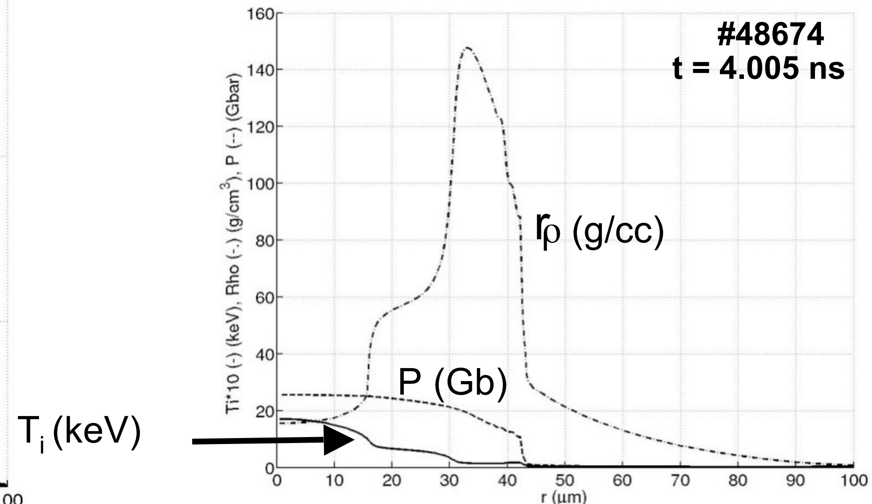
- **#46078: Collision near the D_2-CH inner interface**
- **#48684 : Collision inside the CH shell**

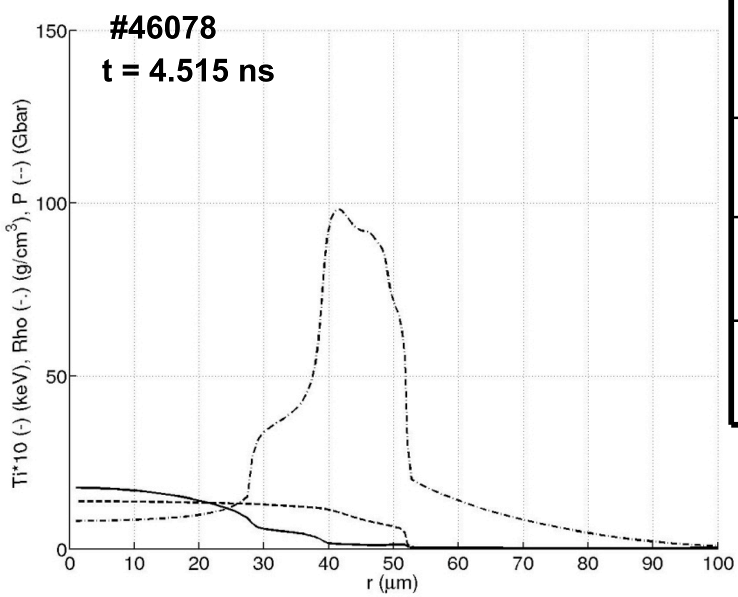
Stagnation parameters

Density, pressure, temperature profiles at ρR_{max}



$$\rho R(t) = \int_0^\infty \rho(r,t)\,dr$$





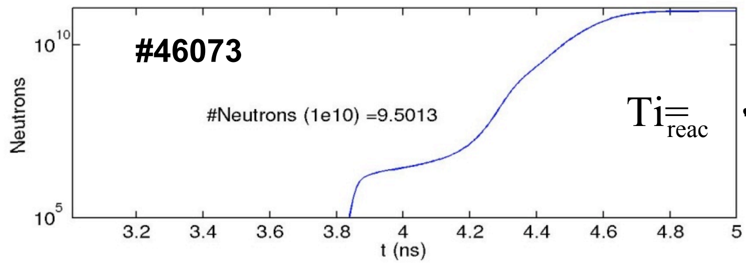
Shot#	ρR_{max} (g/cm^2)	ρ_{max} (g/cm^3)	R_{pc} (μm)	Hot spot CR
#46073 (t=4.685ns)	0.204	73	29.8	14.6
#46078 (t=4.515 ns)	0.226	101	27.7	15.6
#48674 (t=4.005 ns)	0.314	140	16.3	26.6

- Hot spot CR = D2--CH interface at ρR_{max} / initial inner CH shell radius

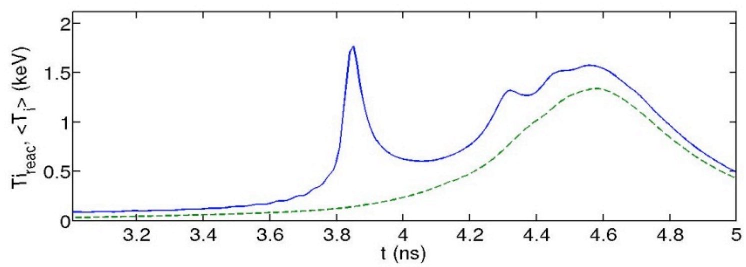
The Spike compresses the fuel assembly

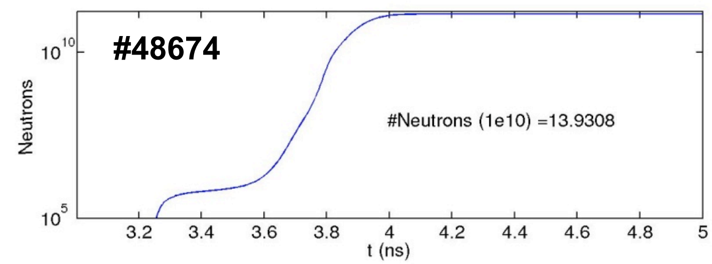
Fusion yield

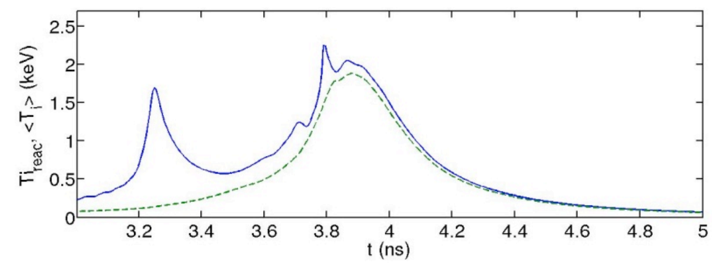
Neutron production, temperature and ρR time evolution

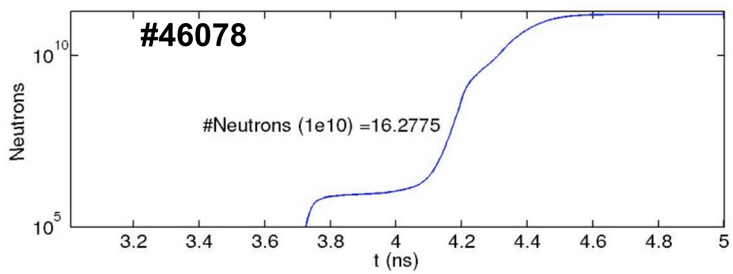


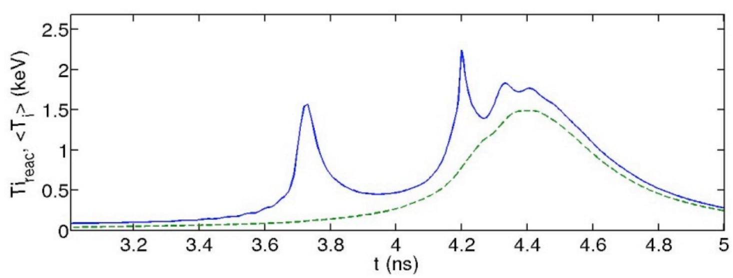
$$Ti_{reac} = \frac{\int T \langle\sigma\rangle n_{\alpha} n_{\beta} dr^3}{\int \langle\sigma\rangle n_{\alpha} n_{\beta} dr^3}$$











Shot#	#Neutron $x10^{10}$	Ti_{reac} (keV)	Neutron rate max (1/s)($x10^{20}$)
#46073	9.5	1.58	3.5 (t=4.60 ns)
#46078	16.3	1.77	8.5 (t=4.40 ns)
#48674	14.0	2.04	9.0 (t=3.90 ns)

Fusion reactions for D_2 in CHIC

D+D -> ^{3}He+n; ^{3}He +D -> p + ^{4}He,

D+D -> p+T, D+T -> ^{4}He+n

CHIC 1D Simulations and comparison to measurements (1)

Omega data : blue   black : CHIC   Green : LILAC

Shot#	Energy inc (kJ)	Energy inc (kJ)	Total Absorption	Total Absorption	Hot spot CR at ρR_{max}	Hot spot CR	Inflight <Adiabat>	<Adiabat>
#46073	18.6	19.41	90.9 %		14.6 (t=4.685ns)	13.7	1.75 (SC) (t = 4.0 ns)	1.22
#46078	17.9	18.63	87.2 %		15.7 (t=4.515 ns)	14.8	1.38 (SC) (t = 3.85 ns)	1.30
#48674	18.5	17.97	87.9 %	85 +/-1 % (Exp) 90.6 % (LILAC=SC) 89.8% (DFL)	26.6 (t=4.005 ns)	22.4	1.51(SC) (t = 3.35 ns)	1.87

CHIC: Sharp Cuttoff f = 0.06 %
LILAC f=0.06 % Sharp Cuttoff
DFL: Time Dependant Flux Limiter

Good agreement between CHIC, LILAC and experiment for absorption

CHIC 1D simulations and comparison to measurements (2)

Omega data in blue : black : CHIC simulation

Shot#	$<V_{imp}>$ (km/s) (Inflight)	$<V_{imp}>$ (km/s)	ρR_{max} (g/cm^2)	<RhoR> (g/cm^2)	$<T_{ireac}>$ (keV)	$<T_i>$ (keV)
#46073	168	168	0.204	0.162+/-0.02	1. 54	1.49
#46078	173	177	0.226	0.171+/-0.02	1.74	1.87
#48674	177	175	0.314	0.220+/-0.02 0.345 (LILAC)	1.90	2.7

$$YOC = \#Neutron_{Exp}/\#Neutron_{1D}*100$$

Shot#	Neutron (x10^{10})	Neutron (x10^{10}) LILAC	Neutron (x10^{10})	YOC (%)	YOC (%)	Neutron rate $_{max}$ (1/s) (x10^{20})
#46073	9.5	8	0.227	2.4	2.8	3.5 (t=4.60 ns)
#46078	16.5	10	0.803	5.0	8	8.5 (t=4.40 ns)
#48674	14.0	6.5	0.642	4.6	~10	9 (t=3.90 ns)

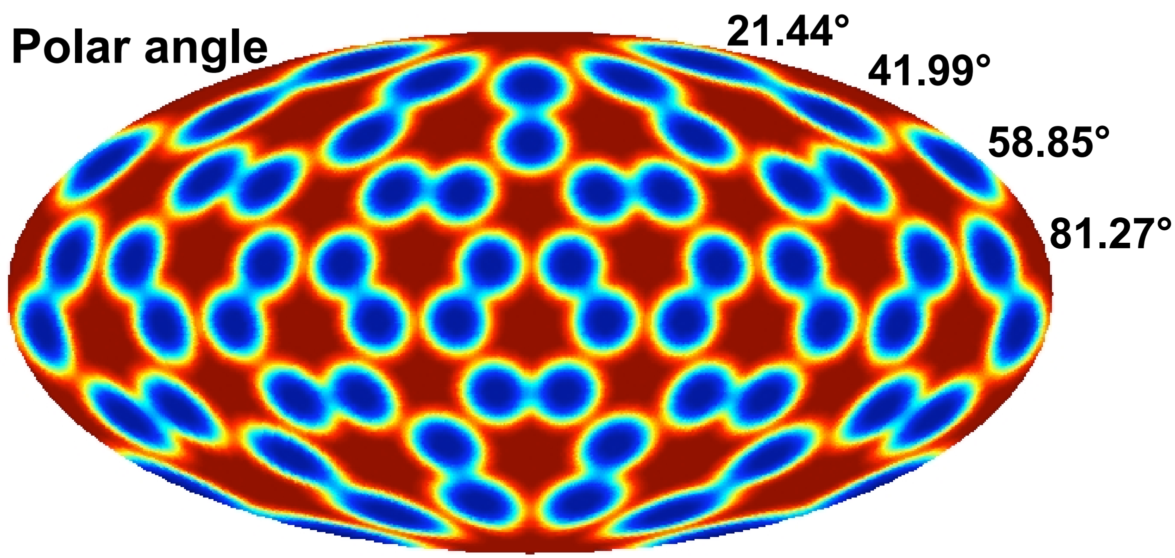
Spike increased by factor 2 the neutrons in simulation and by 3-4 in experiment

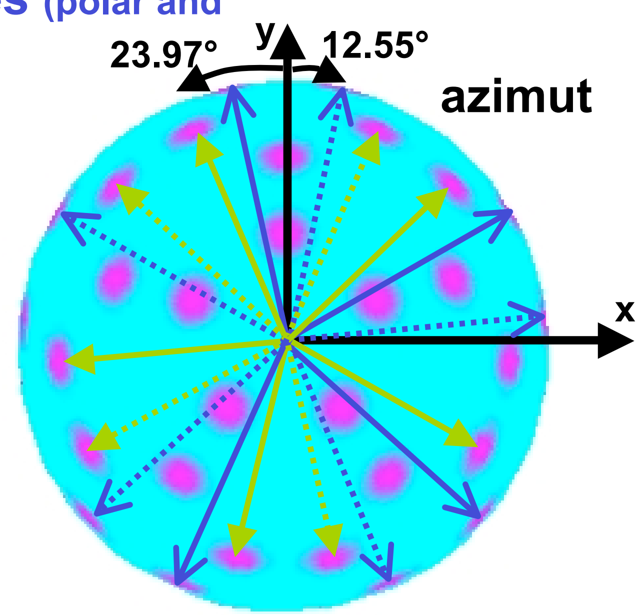
CHIC 2D SIMULATIONS
Omega irradiation conditions

Geometry

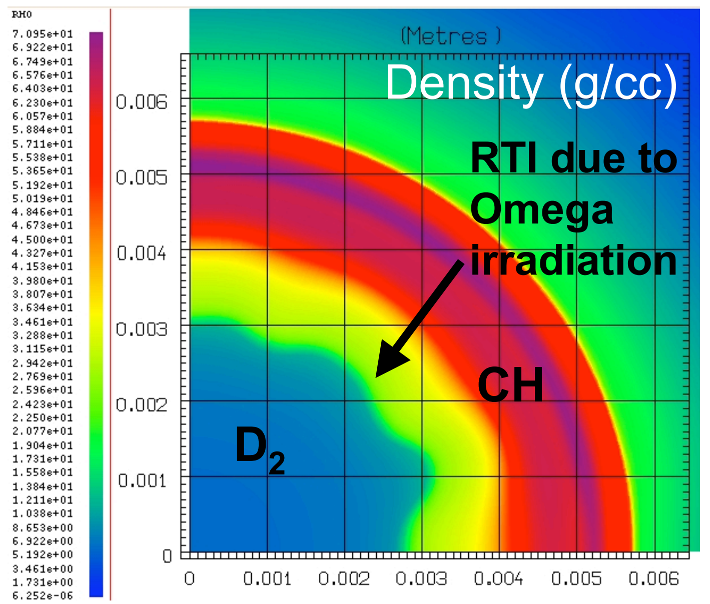
- 60 Beams
  - North hemisphere 30 Beams

    Position : (Θ,Φ) -- n=[1,2,3,4,5]
    - 5 beams at (21.44°,n*360°/5)
    - 5 beams at (41.99 °, n*360°/5)
    - 10 : 5 beams at (58.85°, n*360°/5+23.97°)
      5 beams at (58.85°, n*360°/5-23.97°)
    - 10 : 5 beams at (81.27°, n*360°/5+12.55°)
      5 beams at (81.27°, n*360°/5-12.55°)
  - South hemisphere obtained 2 symmetries (polar and equatorial : Θ= 180°- Θ and Φ= 180°+ Φ)



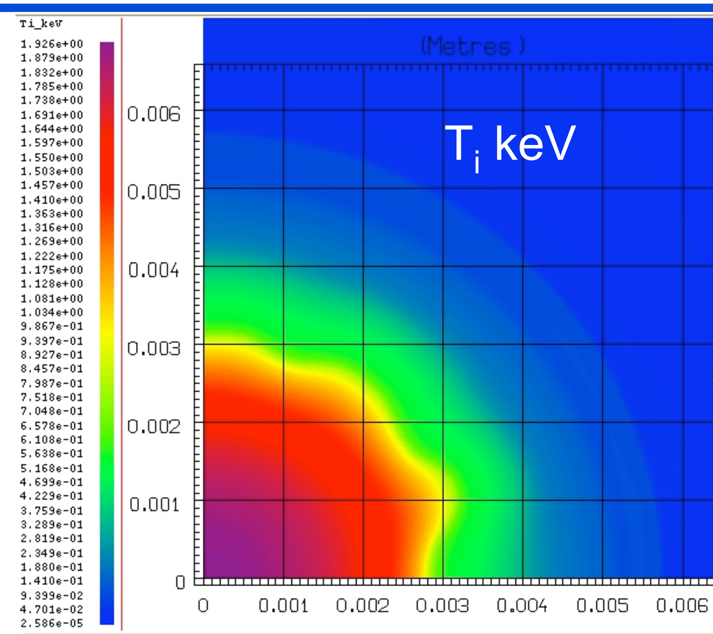


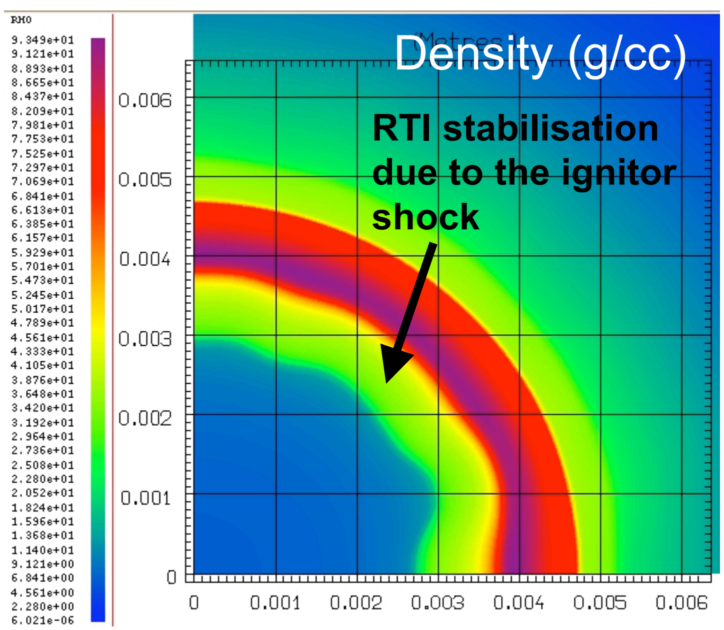
CHIC 2D ALE Simulations (1)



Without Spike

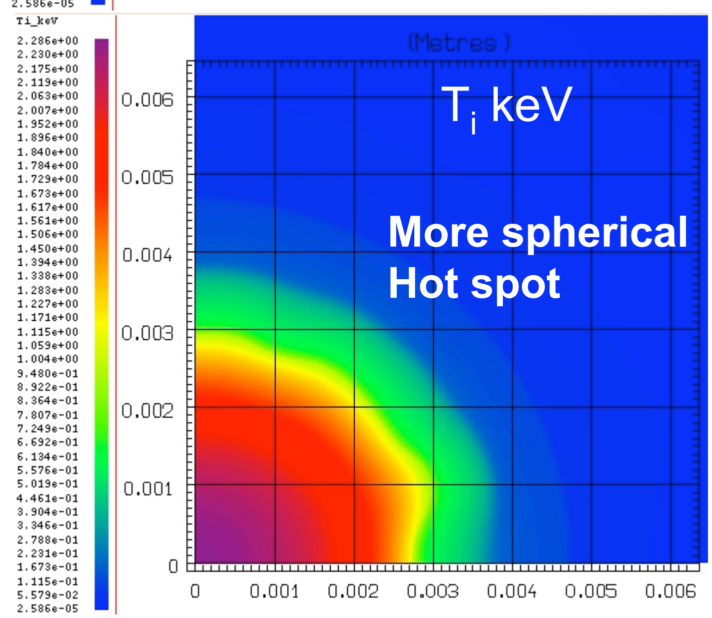
#46073 (t=4.56 ns)
Neutron rate max





With Spike

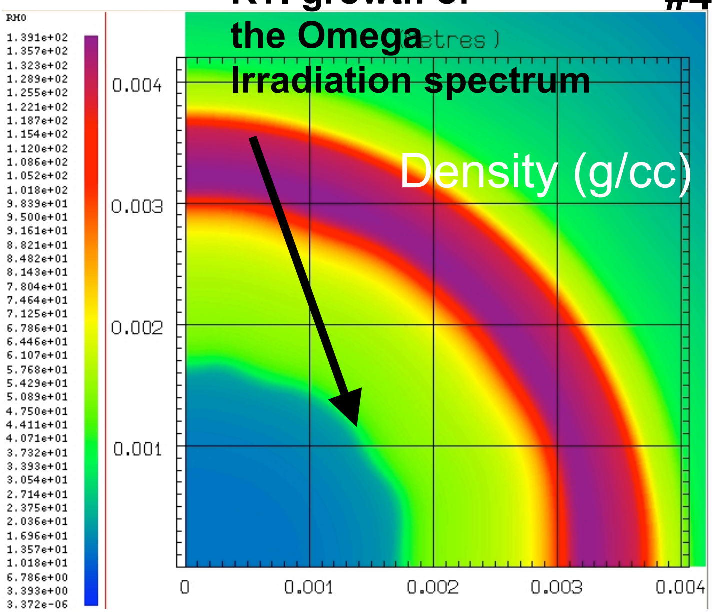
#46078 (t=4.37 ns)
Neutron rate max



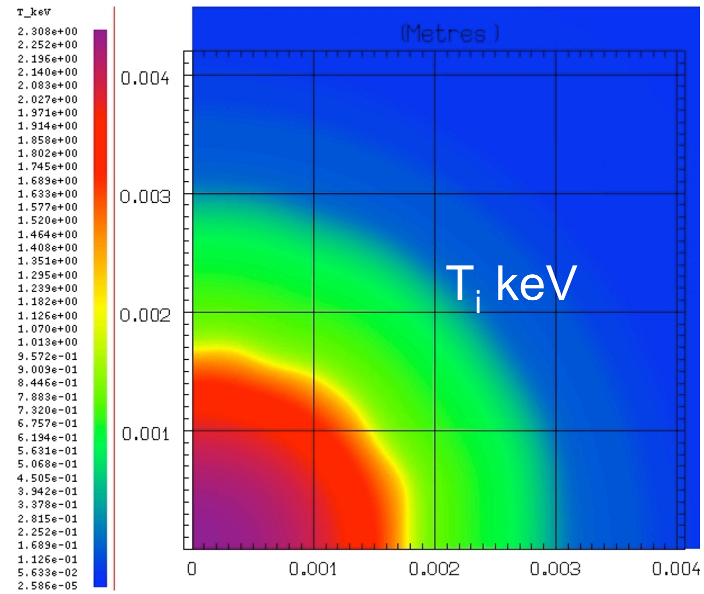
CHIC 2D ALE Simulations (2)

#48674 (t=3.90 ns) Neutron rate max

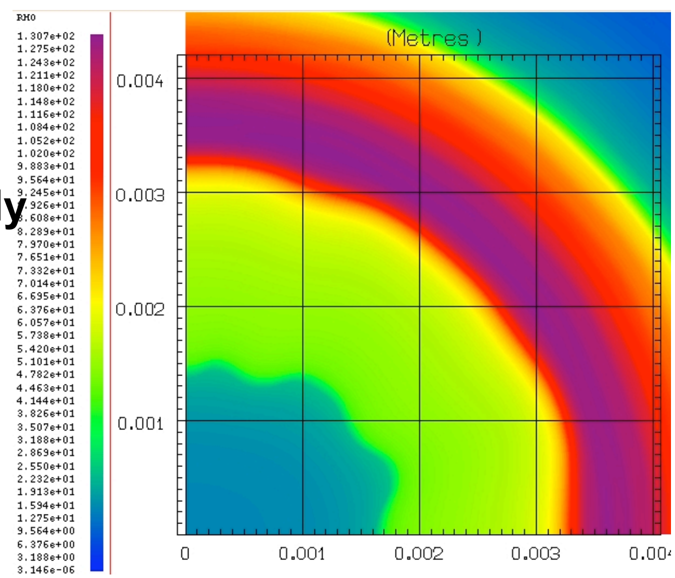
RTI growth of the Omega Irradiation spectrum



The D_2-CH interface implosion is weakly perturbed by RTI at maximum of neutrons production

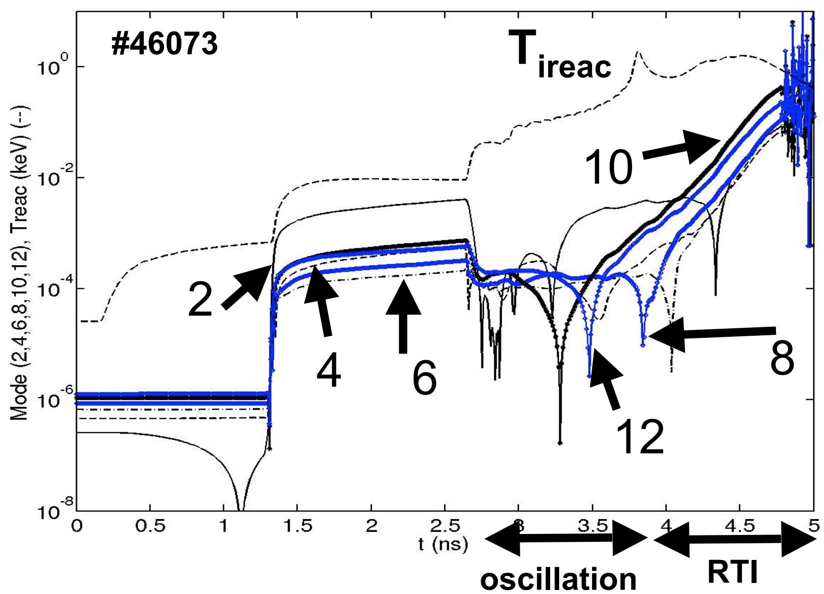


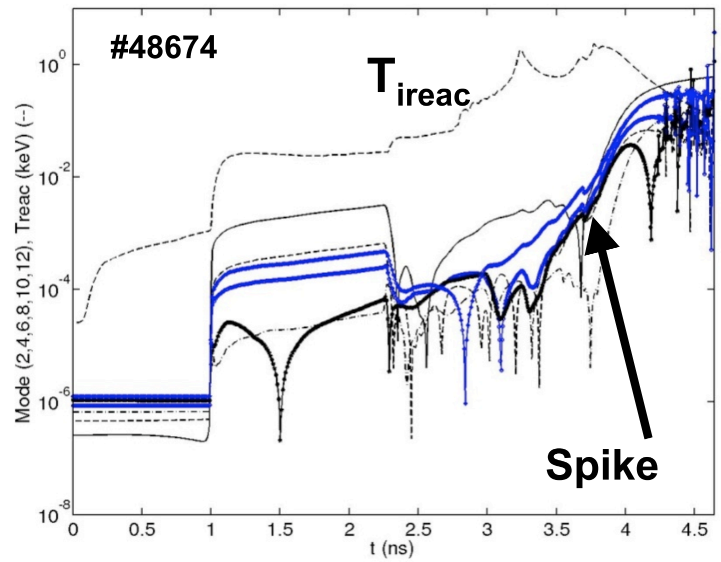
modes 2 and 12 clearly appear 100 ps later

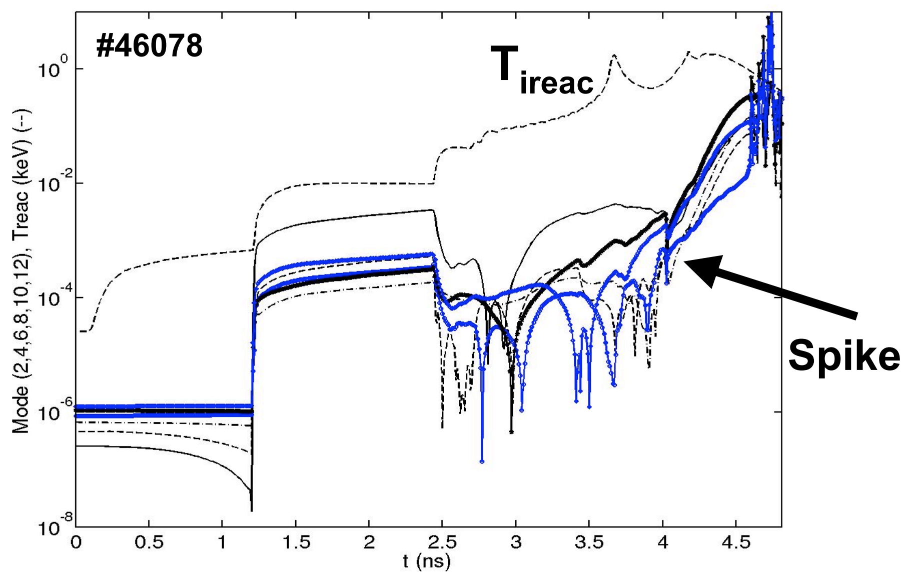


Legendre mode evolution of the CH-D_2 interface

Low modes: 2 - 4 - 6 - 8 - 10 - 12





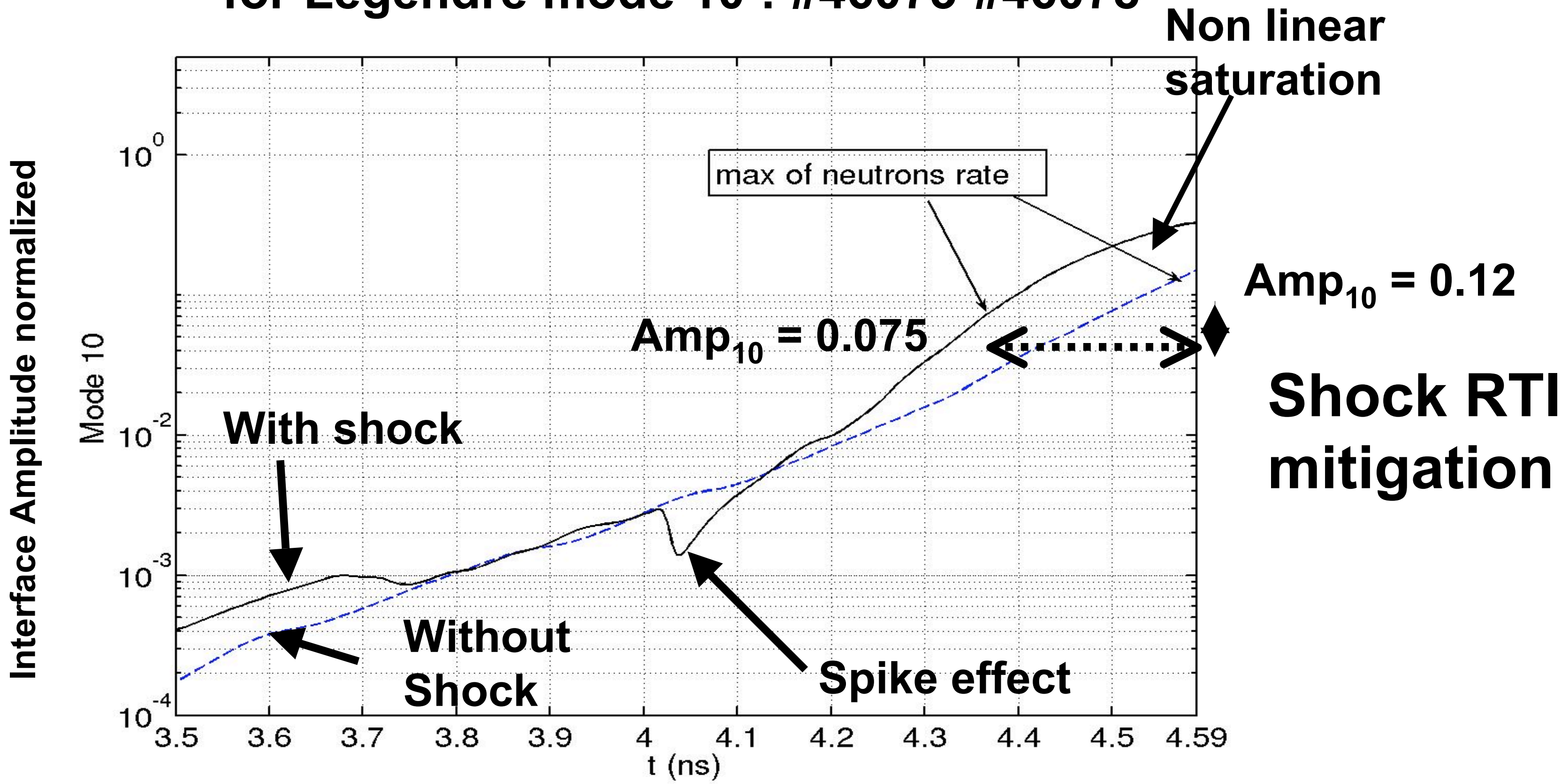


Shot#	Mode l=	Amplitude Normalized by radius
#46073	10	0.120 (t=4.56 ns)
#46078	10	0.075 (t=4.37 ns)
#48674	2-12	0.046-0.034 (t=3.90 ns)

Mode 2 can be controlled with Laser power balance

CHIC 2D ALE Simulations
Spike effect on RTI

Comparison of RTI amplification for Legendre mode 10 : #46073-#46078



Although the RTI growth rate with spike is greater at the maximum of neutrons rate, the interface D_2-CH amplitude is smaller.

RTI mitigation observed by W. Theobald, et al. PoP 15, 056306 (2008) and by Ribeyre et al. PPCF 51, 015013 (2009)

Conclusion

CHIC simulations are in good agreement with LILAC and relatively good agreement with Omega experimental data

- For the laser absorption
- Final central temperature, Areal density
- #Neutrons increased by the shock spike X2 in X4
- 2D simulations show an effect on RTI development

Mitigation is observed, as in experiment

Future

- Participation to: 40 compression + 20 beams ignition experiment optimisation