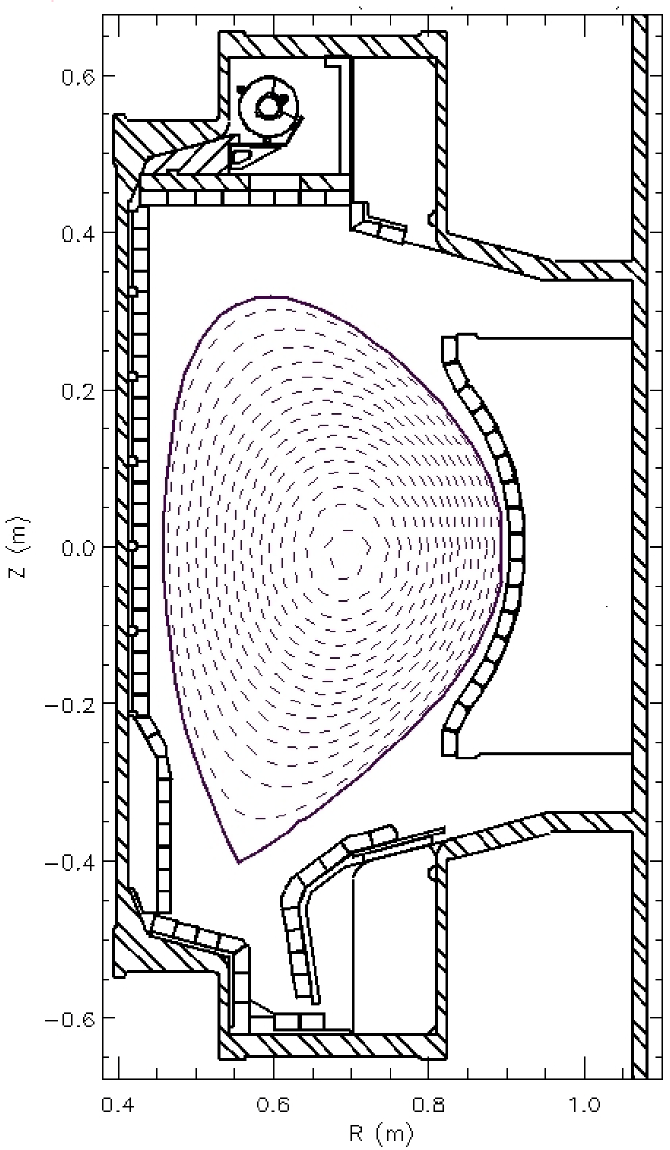
Core-CXRS system on Alcator C-Mod and DNB simulation by ALCBEAM code

I. O. Bespamyatnov[a*], W. L. Rowan[a], K. T. Liao[a], M. Brookman[a] and Alcator C-Mod team[b]

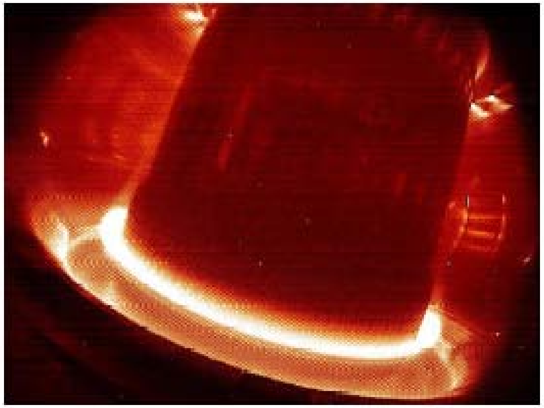
[a] *Institute for Fusion Studies, The University of Texas, Austin, TX*
[b] *MIT Plasma Science and Fusion Center, Cambridge, MA*

**bespam@physics.utexas.edu*

The Alcator C-Mod tokamak



Alcator C-Mod is a compact, high density, high field tokamak[1]

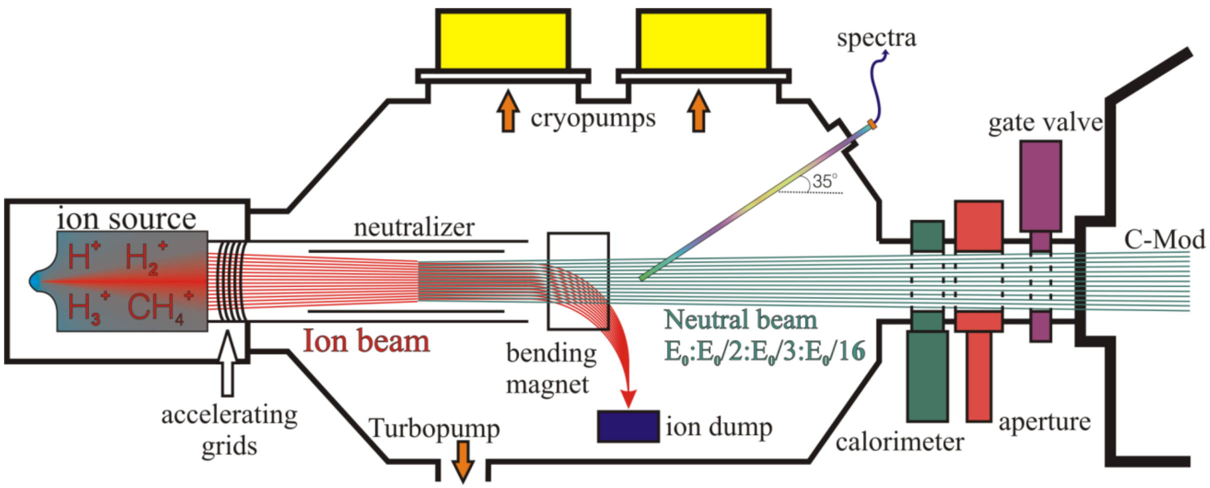


- R_0= 0.67m, a=0.22 m
- V_{plasma}~1 m^3,
- B_T =3-8T
- I_p = 0.3-1.5MA
- n_e=1-5x10^{14} cm^{-3}, T_e – 1-6 keV
- Length of plasma pulse ~ 2 sec
- Plasma facing components Mo/W
- Boronization is used to improve plasma purity.
- Heating methods:
  ICRF (up to 6MW), LH (900kW)
- Large diversity of intrinsic (B, F, Fe, Mo, W) and seeded impurities:
  gas puff (He, N, Ne, Ar)
  laser blow-off (Al, Ca, Ni)

Base diagnostic capabilities and DNBI

Base diagnostics:

- Thompson scattering: T_e, n_e
  1mm (edge), 2mm (core), 60Hz
- ECE: T_e (4 mm, 1MHz)
- DNB (Diagnostic neutral beam)[2]
- CXRS: v_φ, v_θ, T_z and n_z
  1cm (core), 20 msec [3]
  2mm (edge),5-10 msec
- MSE : I_p profile, pitch angle
- X-ray imaging: v_φ, T_z
- Scanning probes: T_e, n_e (SOL)
- Interferometry: $\langle n_e \rangle$
- Bolometry: P_{loss}
- PCI (fluctuations)
- Magnetics (fluctuations)



Beam parameters: E ~ up to 50 keV, I ~ up to 7.5 A
τ ~ up to 1.5 sec (modulated)

- Beam energy fractions %:
  E,E/2, E/3, E/16=[70,6,18,6]
- Fueling ions: H
- Manufactured by Budker Institute (Russia)

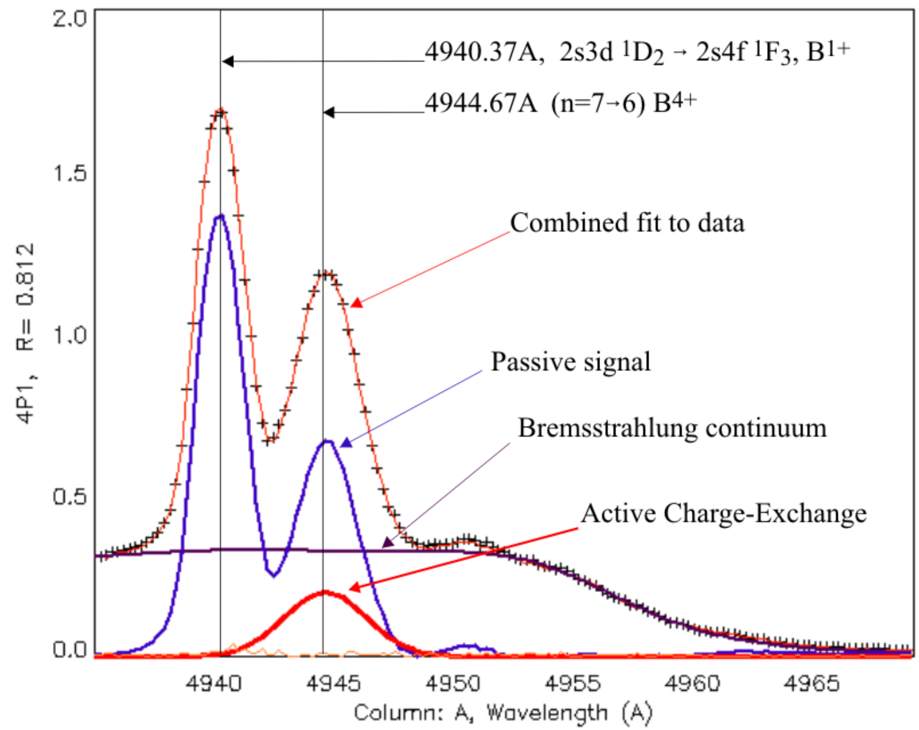
Charge Exchange Recombination Spectroscopy

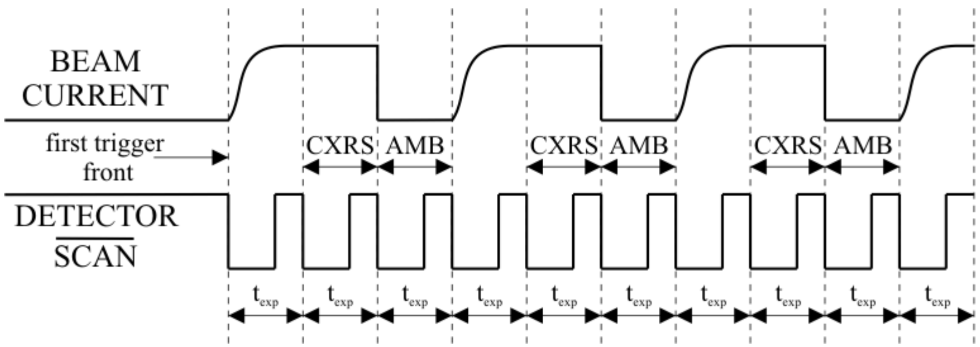
$$H^0(n=1,2,3)+B^{5+} \rightarrow B^{4+}(n=7)+H^+$$

$$B^{4+}(7) \rightarrow B^{4+}(6)+h\nu(n=7\rightarrow 6)$$

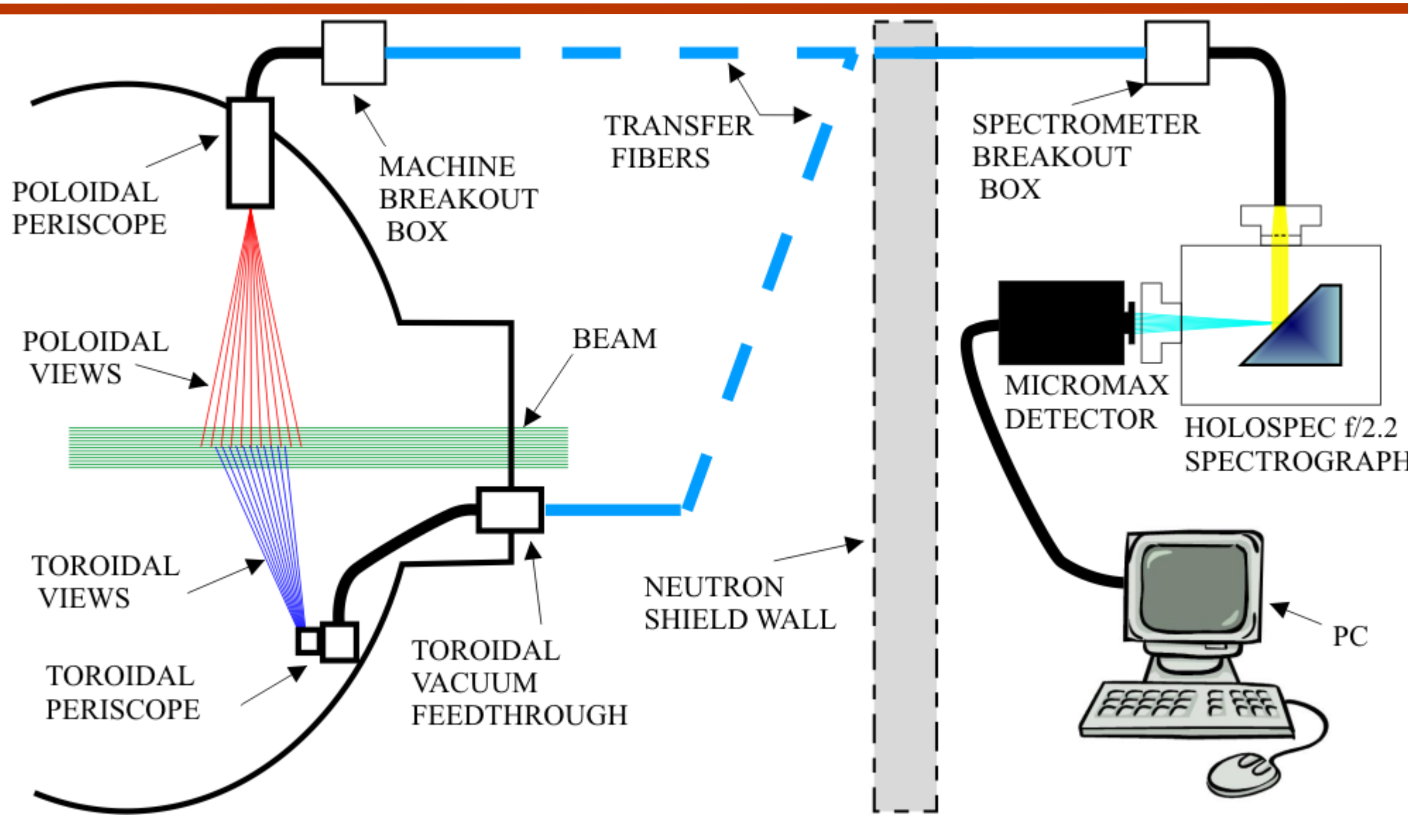
- CXRS - 4944.6 B^{4+} (n=7→6)
- Orange spectrum: acquired during DNB pulse
- Blue spectrum: B^{4+} background emission
- Brown: bremsstrahlung
- Red :CXRS enhancement

- This intensity proportional to the density of boron ions. The Doppler broadening and Doppler shift of the spectral lines yields information on the ion temperature and plasma rotation.
- Both ground (n=1) and excited states (n=2, 3) of beam atoms are important for CXRS analysis[4,5].





Poloidaly and toroidaly core-CXRS periscopes

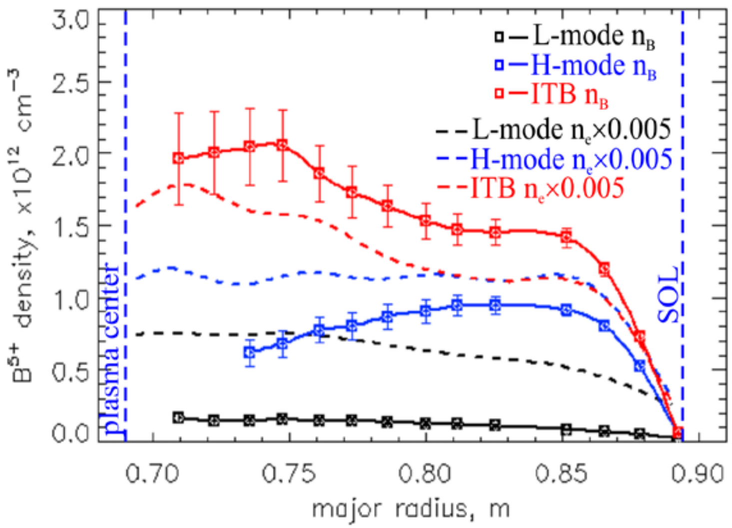


[3]

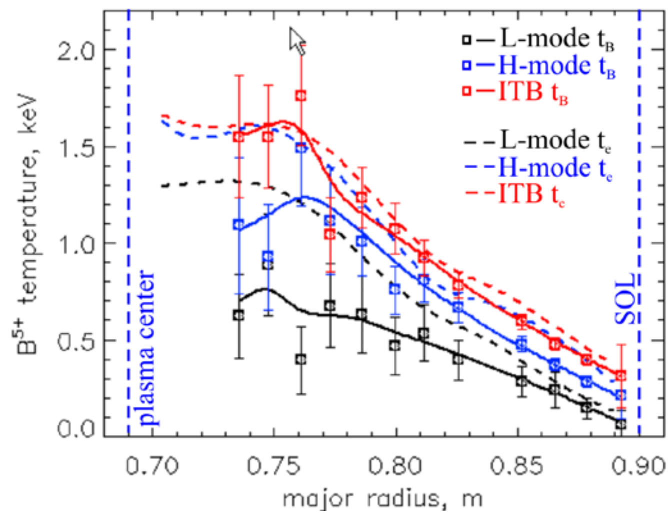
- Two optical periscopes: 20-channels poloidal periscope and 20-channels toroidal periscope
- Holographic imaging spectrograph (Kaiser f/1.8 Holospec).
- Princeton Instruments Micromax high-speed CCD camera.
- Both optical systems: spatial resolution -1 cm, temporal resolution - 20 msec.

Examples of the B^{5+} profiles

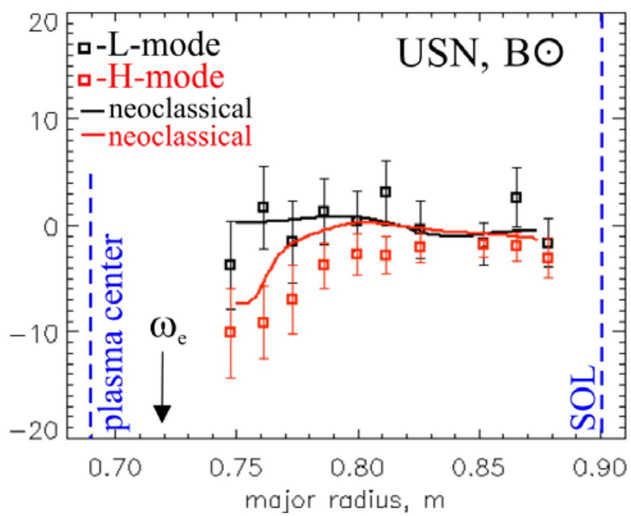
B^{5+} density, $x10^{12}$ cm^{-3}



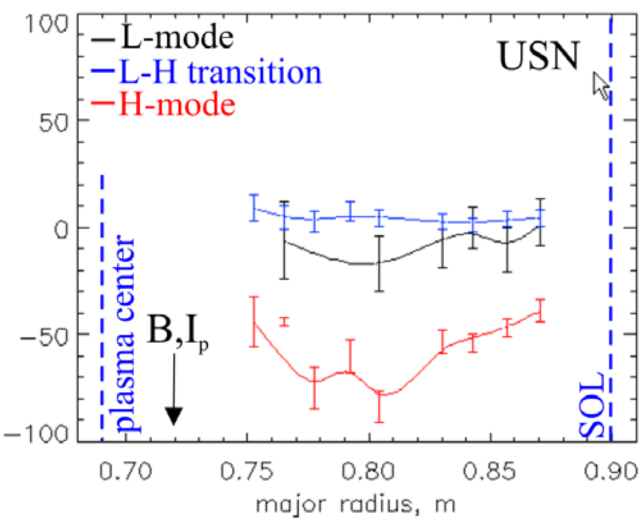
B^{5+} temperature, keV



B^{5+} poloidal velocity, km/sec

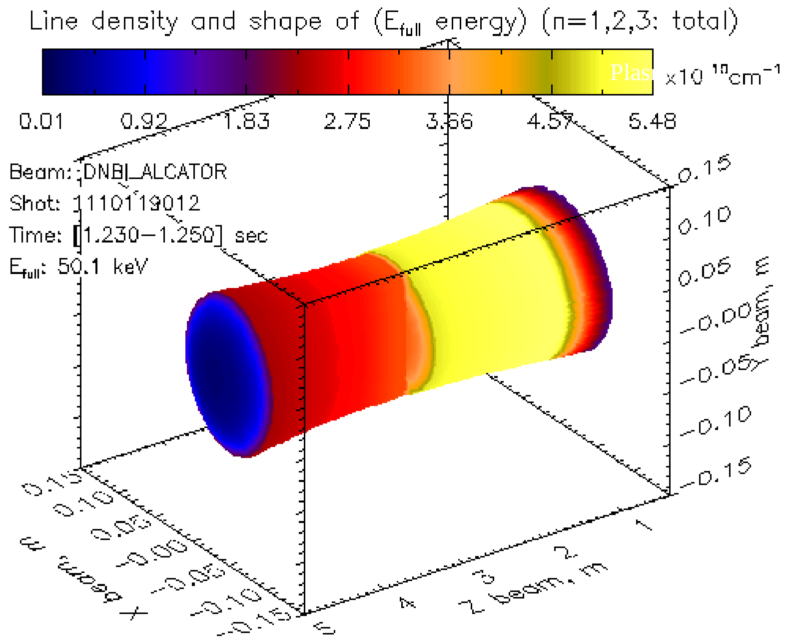


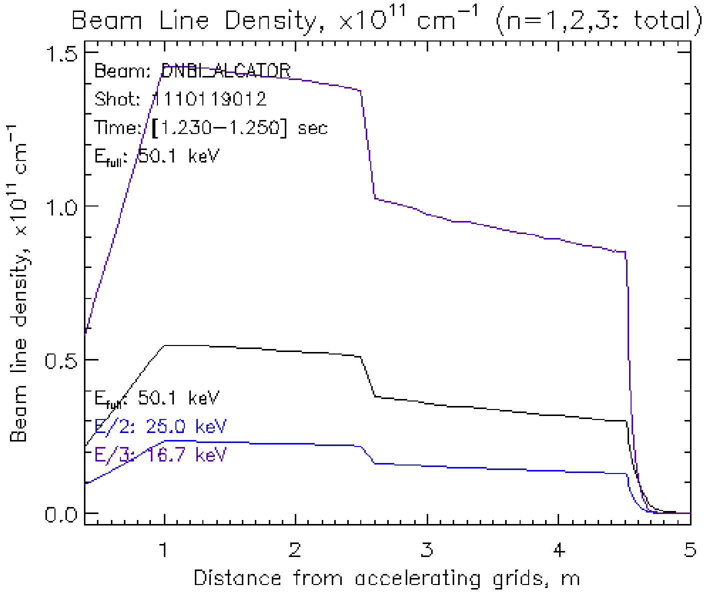
B^{5+} toroidal velocity, km/sec



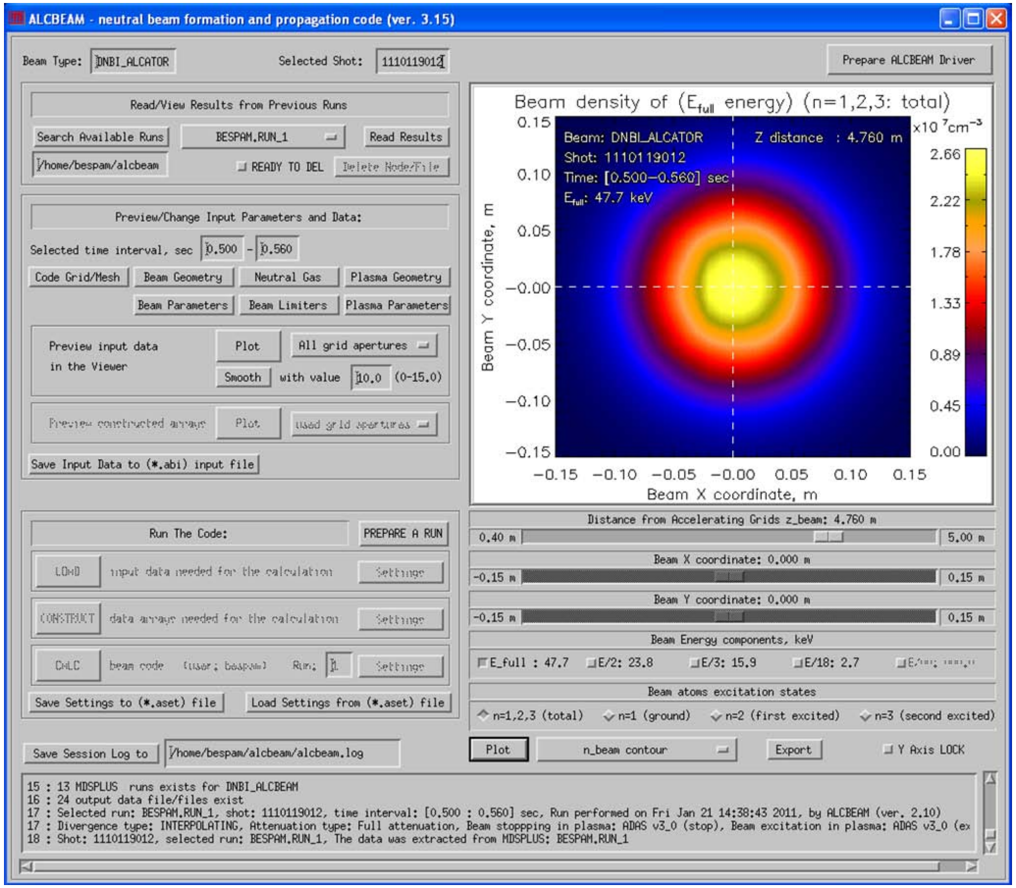
ALCBEAM- neutral beam formation and propagation code

- Unlike NUBEAM[6] , NBEAMS[7] or other beam deposition codes, ALCBEAM focuses not on beam ion deposition physics, but on accurate characterization of the beam itself.
- ALCBEAM unifies:
  ion beam formation, extraction and neutralization processes with beam attenuation and excitation in plasma and neutral gas and beam stopping by the beam apertures.
- Used for simulation of the C-Mod DNBI
- DNB and HNB on EAST tokamak
- Submitted to CPC journal and CPiP library[8]





ALCBEAM v3.15 features



Three choices of simulation methods:

1. Analytical[9] (fast, 1D attenuation)
2. Interpolative(2-½ D attenuation, more accurate)
3. Precise (full 3D attenuation, most accurate)

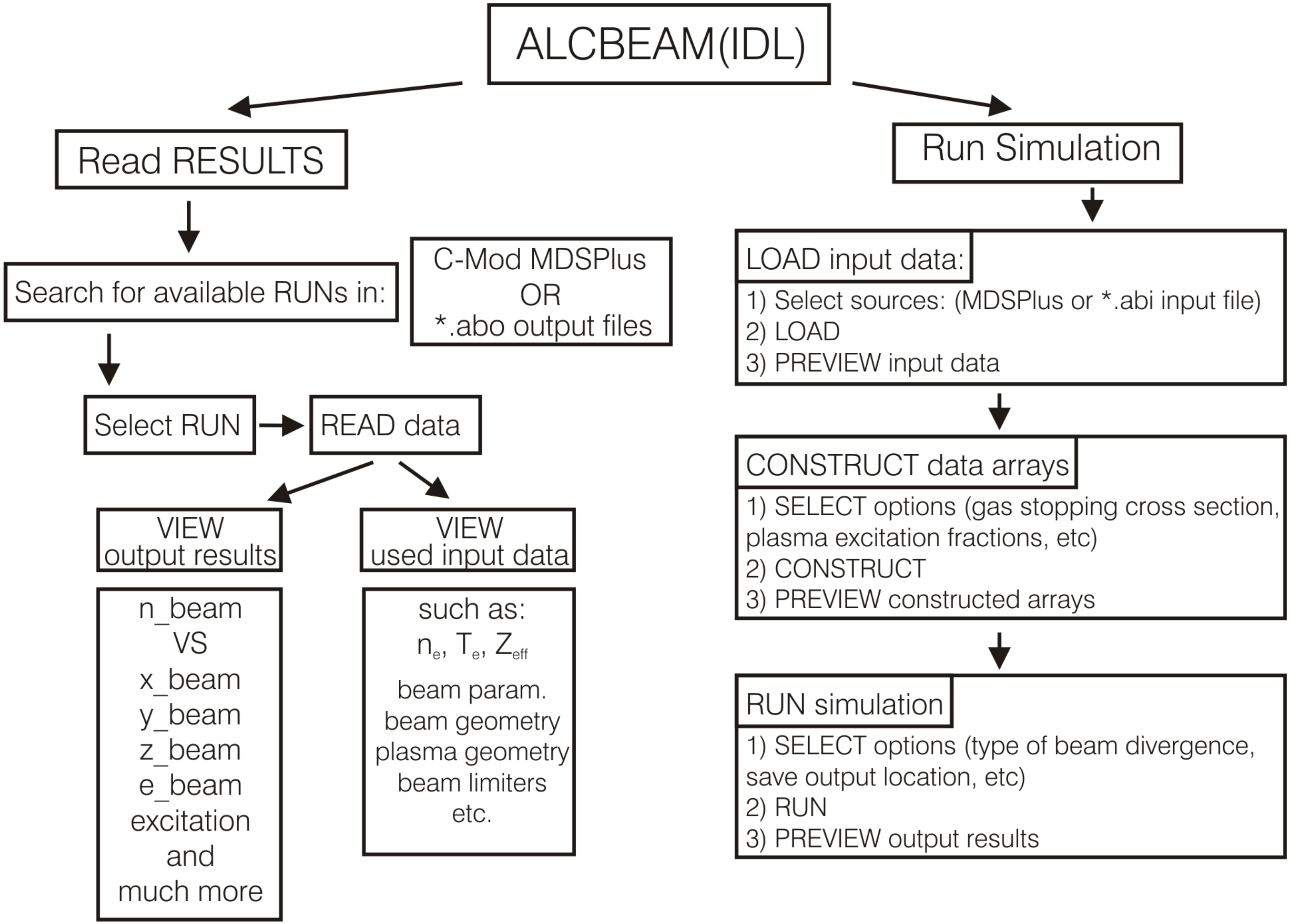
Ion formation concept

1. Set of grid apertures/pores
2. Each pore emits beamlet toward the focal point
3. Radial profile of the current density is parabolic[10]
4. Divergence of each beamlet depends on the local current density[8]

Atomic physics

1. Attenuation in gas
   Red-Book-ORNL[11]
2. Attenuation in plasma:
   ADAS(3.0 or 3.1)[12],
   Delabie[13], Suzuki[14]
3. Excitation in the plasma:
   ADAS(3.0 or 3.1),
   Delabie[13]
   Hutchinson[15]

ALCBEAM IDL widget



ALCBEAM and NUBEAM (3D comparison)

NUBEAM (available through TRANSP)

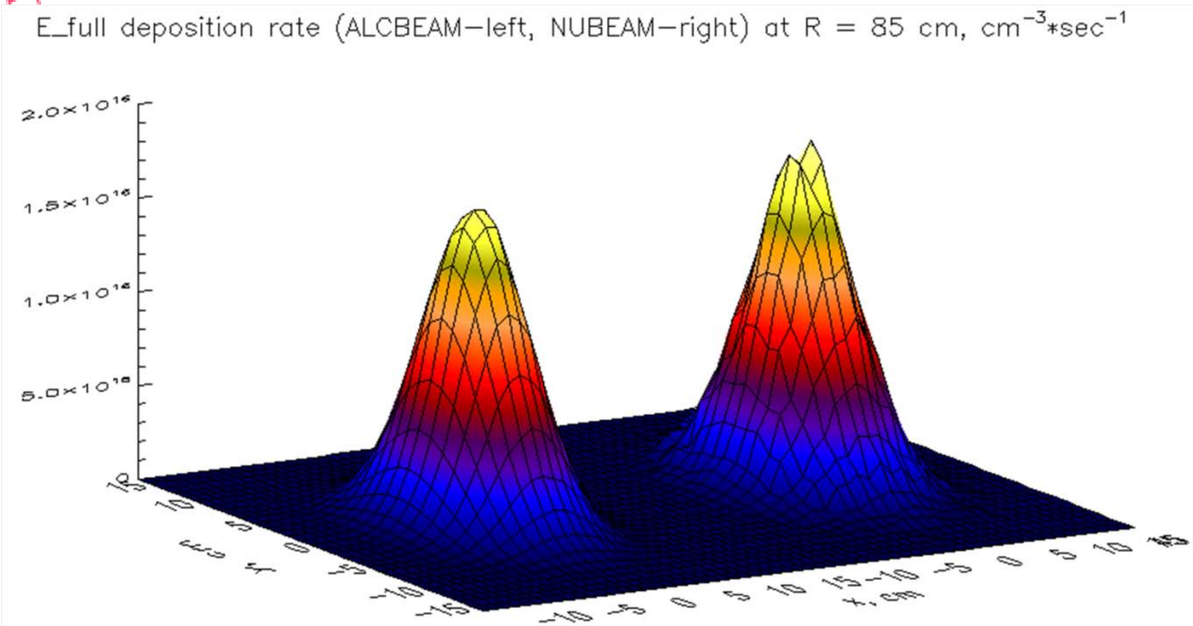
- Monte Carlo code
- Recently incorporated ADAS3.0 cross-section[9]
- Most of the output data is flux averaged.
- 3D beam deposition output only available as an optional output.
- NUBEAM was run for one of the C-Mod real shots (with help from Marina Gorelenkova TRANSP-team, PPPL)
- Max possible number of neutral tracks:100,000 (run time: 10 hours).
- 3.3Gb output data file was fetched from PPPL server.
- 3D beam deposition was extracted using the PPPL tools

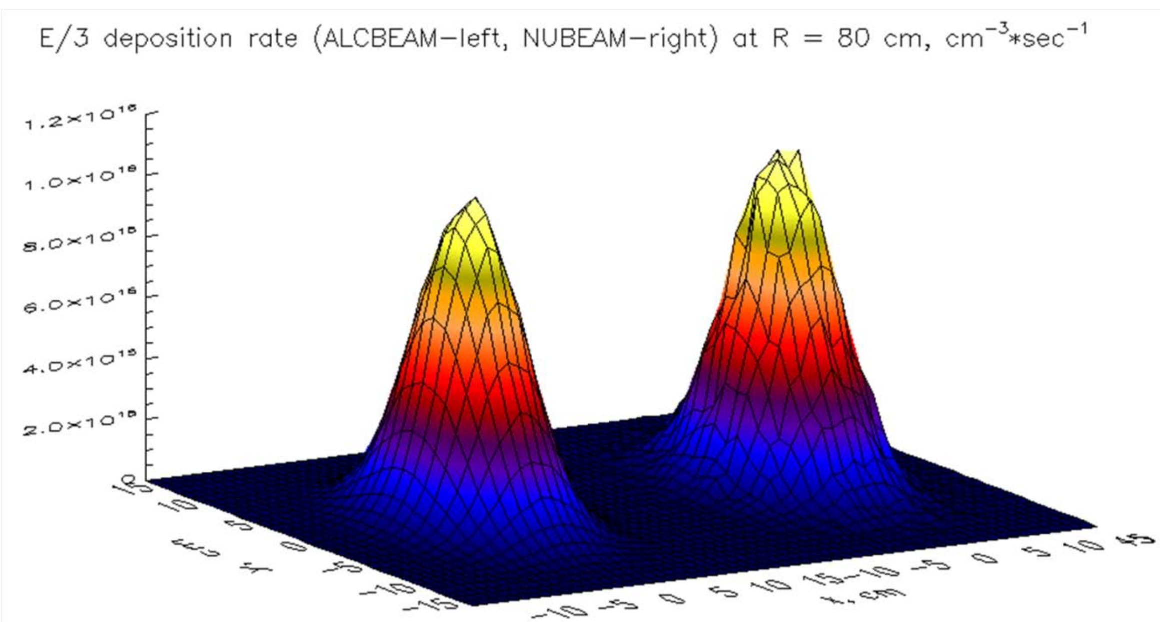
ALCBEAM

- Inputs are adjusted to match the NUBEAM inputs

1. Non-uniform source density (OFF)
2. Gas attenuation (OFF)
3. Plasma attenuation (ADAS3.0)
4. Energy components (E,E/2,E/3)
5. Z_{eff}=1.2 (Single boron impurity)
6. Comparison of beam depositions
7. Run time: 5 minutes.

Comparison of the results (deposition shape)



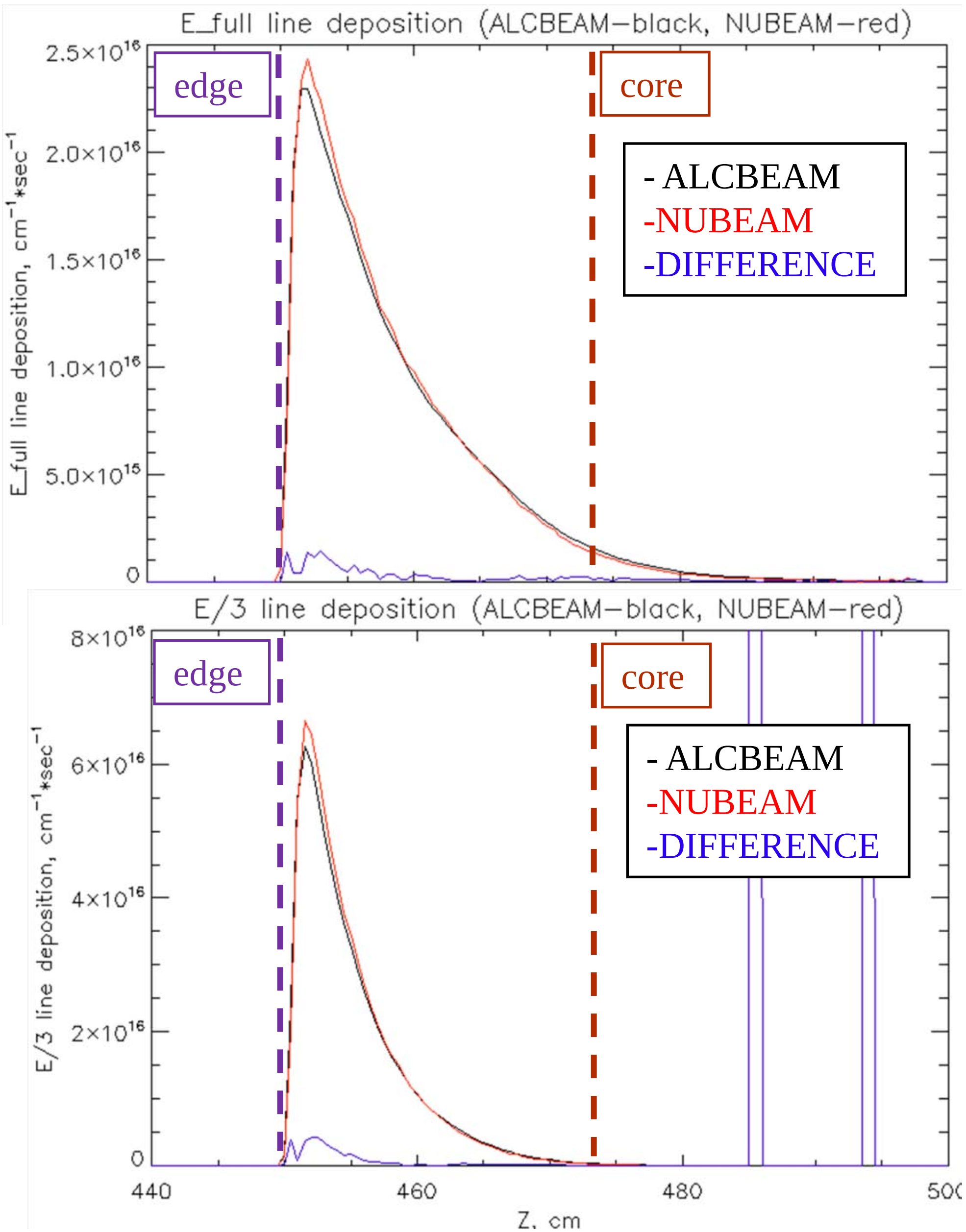


- Comparison of deposition rate profiles at:

  (top) Z=455cm (R=85 cm, rho~0.8)

  (bottom) Z=460cm (R=80 cm, rho~0.54)
- NUBEAM profiles are still a bit noisy.
- Results are in a very good agreement, given the radical difference of the methods used by both codes.

Comparison of the results (integrated deposition)



- Comparison of deposition rates

  (deposition is integrated over the beam cross-section)

  (top) E_{full} component

  (bottom) E/3 component

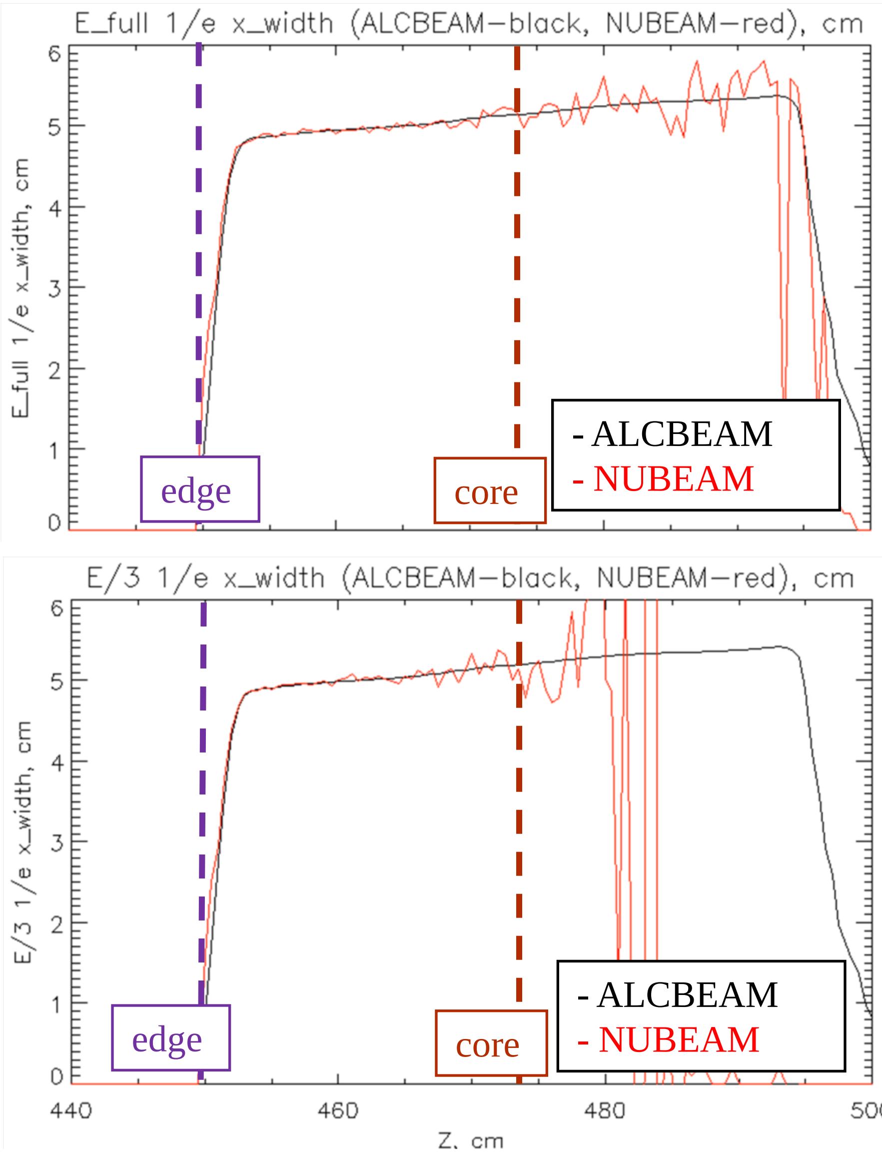
- Maximum difference is on the plasma edge (about 7%).

- Most probable reason for difference is the difference in plasma equilibrium.

  ALCBEAM –EFIT

  NUBEAM – TRANSP

Comparison of the results (beam width)



- Comparison of horizontal 1/e widths (top) E_{full} component (bottom) E/3 component
- Very good agreement.
- NUBEAM profiles gets very noisy for regions where beam is strongly attenuated (where Monte-Carlo statistics is low)
- ALCBEAM calculated beam density and width properly within the full plasma volume.

Some conclusions

1. Alcator C-Mod is a world-class tokamak to generate and study the plasma in unique parameter range.
2. C-Mod's plasma contains a variety of impurities and has demonstrated to be tolerant to high impurity levels. This makes C-Mod an instrumental facility for study of atomic processes in plasmas.
3. Neutral beam is a useful diagnostic tool for tokamak plasmas. C-Mod's DNB is strongly attenuated and excited by the C-Mod's high density plasmas.
4. It is critical for most of the DNB-based diagnostics to properly characterize the beam in plasma (3D density profile, energy components, beam excitation).
5. To achieve that an accurate 3D DNB simulation is required, which should include all of the important aspects of beam formation and propagation.
6. ALCBEAM was developed for this purpose and proved to be instrumental for DNB simulation for C-Mod and some other beams.
7. Core-CXRS diagnostic has an unique place among a variety of other diagnostics on C-Mod. It proves to be a great tool to measure T_i profiles and study light impurity transport.

References

1. E. S. Marmar, Fusion Science and Technology, 51 (2007)
2. I. O. Bespamyatnov *et al*., Review of Scientific Instruments 79, 10F315 (2008)
3. W. L. Rowan *et al*., Review of Scientific Instruments 79, 10F529 (2008)
4. I. O. Bespamyatnov *et al*., Review of Scientific Instruments 77, 10F123 (2006)
5. F. Guzman *et al*, Journal of Physics B, 43,144007 (2010)
6. A. Pankin *et al*, Computer Physics Communications 159, 157-184 (2004)
7. J. Mandrekas (http://w3.pppl.gov/ntcc/NBEAMS/)
8. I. O. Bespamyatnov *et al*, Computer Physics Communications and CPiP library (submitted)
9. T. D. Akhmetov *et al*, IEEE Transaction on Plasma Science 36, 4, 1545 (2008)
10. V. I. Davydenko *et al*, Rev. Sci. Instrum. 77, 03B902 (2006)
11. C. F. Barnett, Atomic Data for Fusion. Volume 1, Oak Ridge, TN, (1990) p. E6-E7
12. H. Summers. Atomic Data and Analysis Structure (http://adas.phys.strath.ac.uk)
13. E. Delabie et al, Plasma Phys. Control. Fusion 52 125008 (2010)
14. S. Suzuki el at, Plasma Phys. Control. Fusion 40 2097-2111 (2000)
15. I.H. Hutchinson, Plasma Phys. Control. Fusion 44 71-82 (2002)
16. M. Kraus, ADAS workshop 2009