Exploring in-laboratory plasmas optical properties to study the impact of compact binary ejecta opacity on kilonova transient signals

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on behalf of the PANDORA collaboration

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NAM 2021

BACKGROUND

- **Electromagnetic transient** signals known as **kilonovae** (KN) are one of the counterparts emitted by merging compact objects.
- The first unambiguous KN was recently observed as **counterpart of the gravitational-wave (GW)** event GW170817, delivering precious information on the **composition and dynamics of the ejecta** arising from the merger of **two neutron star**.
- Observational evidence ranks these astrophysical sites among the **major r-process nucleosynthesis loci**, making the study of KN a novel challenge for **nuclear astrophysics in the multi-messenger astronomy era**.

MOTIVATION

- **STATE-OF-THE-ART**: Because of a **heterogeneous composition** and r-process yields of heavy elements, **further knowledge on the opacity of ejecta** is of fundamental importance for reliable predictions on **the KN light curve from the radiative transport calculations**.
- Knowledge of **opacity helps** to **constrain r-process elements abundances**.
- **PROBLEM**: **models oversimplify opacity estimates** due to the lack of thorough atomic databases: incompatibilities with observational data.
- **PROPOSAL: experimental setup** to **measure plasma opacity in compact magnetic traps** for **astrophysical conditions typical of early-stage KN.**

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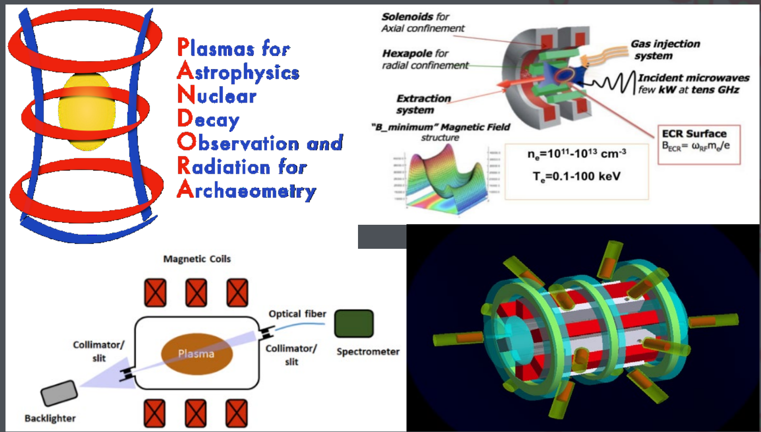
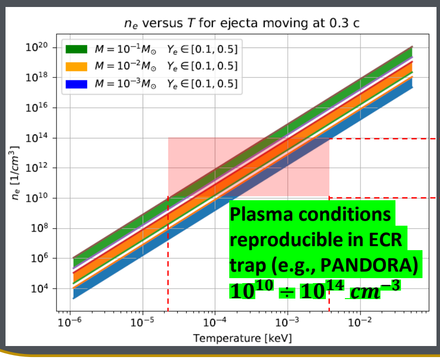
PANDORA: PLASMA TRAP FACILITY FOR MULTIDISCIPLINARY STUDIES

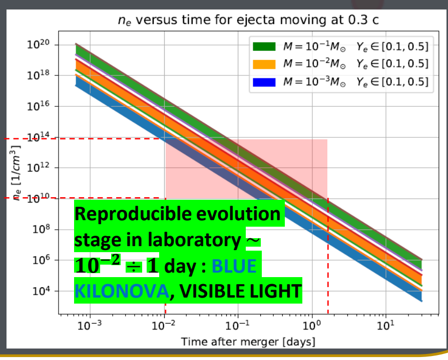


- **MAIN GOAL OF PANDORA [1]** : adopt new approach to **measure**, for the first time, **nuclear β-decay rates** in ECR plasma simulating **stellar-like conditions**.
- **HOW ?**: tuning **electron temperature** allows to establish an **ion charge state distribution** which can **mimic specific stellar environment**.
- **Plasma parameters** inferred using **diagnostic tools** and the **nuclear decay rates** as a function of **the charge state distribution** of plasma ions.
- **PANDORA FOR PLASMA OPACITY MEASUREMENTS**: re-create **KN ejecta environments** (**density, temperature, composition**) at a **specific time-stage** and perform **spectroscopic measurements** of plasma **opacity and emissivity**, controlling plasma conditions.

FEASIBILITY STUDY: DENSITY AND TEMPERATURE CONSTRAINTS FROM ASTROPHYSICAL MODEL

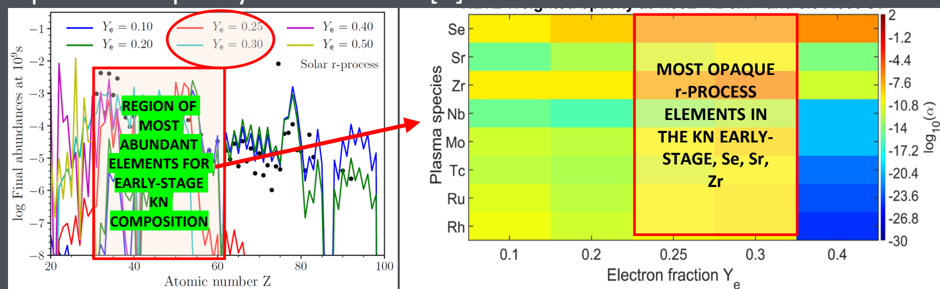
- **MODEL: time-evolving ejecta** through homologous expansion of a fluid element under adiabatic conditions (vs. mass, temperature, velocity, and electron fraction) [2,3,6].





FEASIBILITY STUDY: NUCLEAR NETWORK AND OPACITY CONTRIBUTION

- **Time-dependent r-process elements abundances from SKYNET** [4], with distribution of ejecta properties (entropy, electron fraction and expansion timescale) from astrophysical simulations.
- **MEAN OPACITY** vs. T, weighted with abundances from SKYNET: synthetic spectra of opacity from FLYCHK [5].



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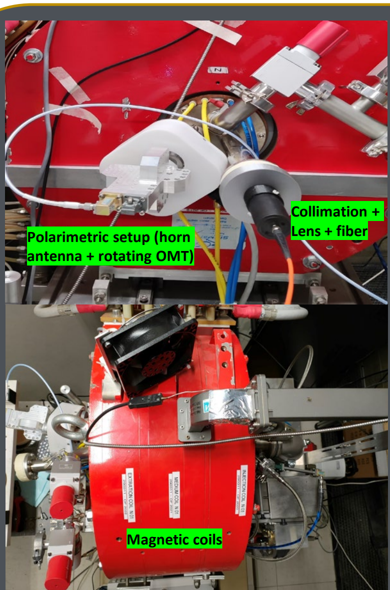
STARTING POINT FROM NUMERICAL RESULTS

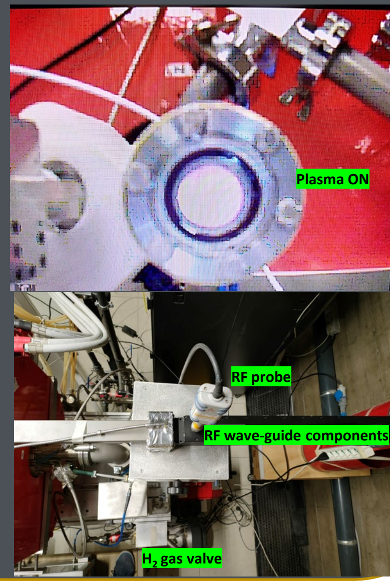
- **Simulations constrain on blue-KN ejecta density and temperature @ $10^{10} \div 10^{14}\ cm^{-3}, 1-2\ eV$**
  - **GOAL**: **finding** in ECR trap stable and reproducible **plasma having these parameters.**
- **From r-process yields distribution weighted with opacity from synthetic spectra, Se and Sr among the most interesting species**
  - **GOAL**: **measuring metallic plasma opacity** for these elements in ECR plasma trap

THE FLEXIBLE PLASMA TRAP (FPT)



- **THE FACILITY: compact plasma trap** for ECR Ion Sources, with **flexible magnetic field profiles** to change electron/ion confinement. The **chamber** is designed to **account for multiple RF waveguide** inputs, and to **host different type of diagnostics** to monitor plasma parameters [7].
- FPT used as smaller operative trap for first experiments using a multi-diagnostic system (Optical Emission Spectroscopy + microwave interfero-polarimetry), in view of measurements in PANDORA.

- **PLASMA TRAP CONFIGURATION** (**FPT** vs. **PANDORA**):
  - Simple mirror field (magnetic bottle) (PANDORA: min-B field)
  - RF power : 50 ÷ 450 W (PANDORA: up to 2.4 kW)
  - Heating RF frequency: 3 ÷ 4 GHz (PANDORA: 17 ÷ 22 GHz)



EXPERIMENTAL ACTIVITY: PLANNED VS. COMPLETED

1. Plasma **characterization** (vs. heating frequency, RF power, neutral gas pressure, magnetic field).
2. Finding **stable and reproducible plasma configurations** for optical measurements.
3. Plasma **density and temperature from multidiagnostic** setup (OES + interfero-polarimetric measurements).
4. First measurements of **transmission spectrum** from **white light source** through **gaseous plasma** (H_2), for **opacity estimates**.

COMPLETED

WORK IN PROGRESS

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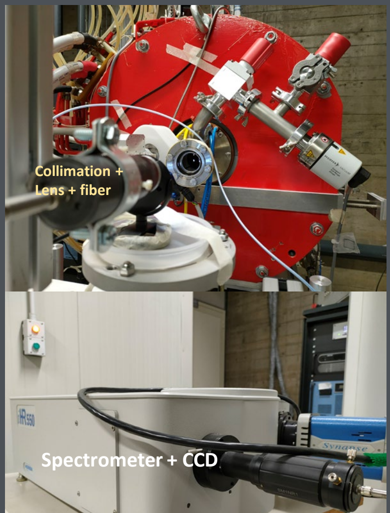
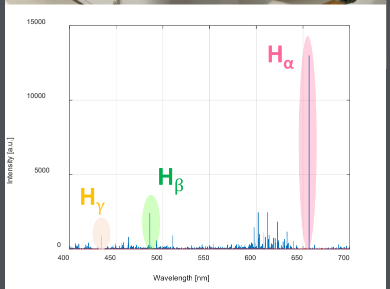
7. S. Gammino *et al* 2017 *JINST* **12** P07027

METHODOLOGY FOR OPTICAL EMISSION SPECTROSCOPY (OES)

- We extended from **previous work** [8] parameter space ***(press,P)*** **(7E-04 mbar,100 W)** trying to achieve smaller plasma temperature and larger density.
- We now explore **plasma parameters** fixing frequency and field, at different gas pressure (H_2) *press* (**7E-03÷2E-02 mbar**) and RF power *P* (**150÷450 W**).
- We collect plasma **self-emitted light in the visible range** (350-750 nm) and related spectra.
- **Balmer's lines** of hydrogen plasma spectra used in the **line ratio method** to determine both **electron density and temperature** [9].

EXPERIMENTAL SETUP: OES and PRELIMINARY RESULTS



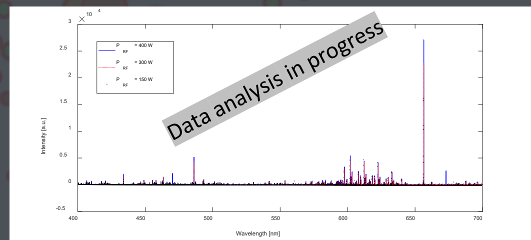


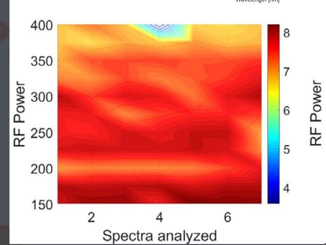
- In-fiber visible-light collection at the focal length of lens inside a long-collimator system: reduction of chamber-wall reflectance.
- Spectra obtained from spectrometer HORIBA: resolution R = 35 pm in 350-750 nm

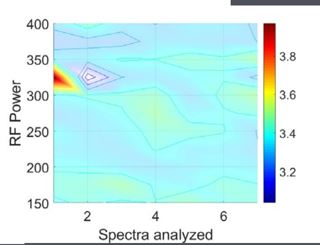
$$\frac{I_\alpha}{I_\beta} = \frac{\eta_\alpha}{\eta_\beta}\frac{\chi_\alpha(\rho,T)}{\chi_\beta(\rho,T)} \rightarrow \langle\rho\rangle, \langle T\rangle$$

- **ESITMATES : Average density and temperature** proportional to the **effective emission coefficients** χ_λ.
- Obtained by the comparison of both H_α/H_β , H_β/H_γ ratios with their theoretical trends from Yacora database [10], **solving non-linear two-variables equation system from two-lines integrated ratios**.
- **Multi-diagnostic constrain on density:** provided by **simultaneously measuring** the **Faraday rotation angle** induced by the magnetoplasma:**polarimetric measurements.**

CONCLUSION







- Spectral data from OES collected for several (pressure, Power) cfgs.
- Integrated-line ratios calculated from fitting spectral emission lines as function of cfgs paramters.
- Data analysis in progress to estimate density and temperature of plasma.
- First **rough constraint on the density** supported by polarimetric measurements: $\sim$ **$2 \cdot 10^{12}$ cm-3 @ (press = 10^{-2} mbar, 400 W)**
- Complete plasma characterization, optimization of analysis code, and further improvements of experimental setup also ongoing in view of the planned opacity measurements.

ACKNOWLEDGEMENTS

INFN LNS – INFN – INAF – Technische Universität Darmstadt – Università di Trento

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