On the way to extreme light

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**Institute of Applied Physics,
Russian Academy of Sciences**

A Celebration of Toshiki Tajima’s 70th Birthday

26 January 2018

IAP RAS

2018

Exawatt Center for Extreme Light Studies (XCELS)

Mega Science Projects in Russia

1. Tokamak Fusion Reactor IGNITOR

/TRINITY,Troitsk,Moscow region/

2. High-Flux Neutrons Research Nuclear Reactor PIK

/Inst. Nuclear Physics,Gatchina, St-Petersburg/

3. Fourth-Generation Synchrotron-Radiation Light Source

/Kurchatov Inst./

4. Electron-Positron Collider Super C-Tau Factory /Budker Inst/

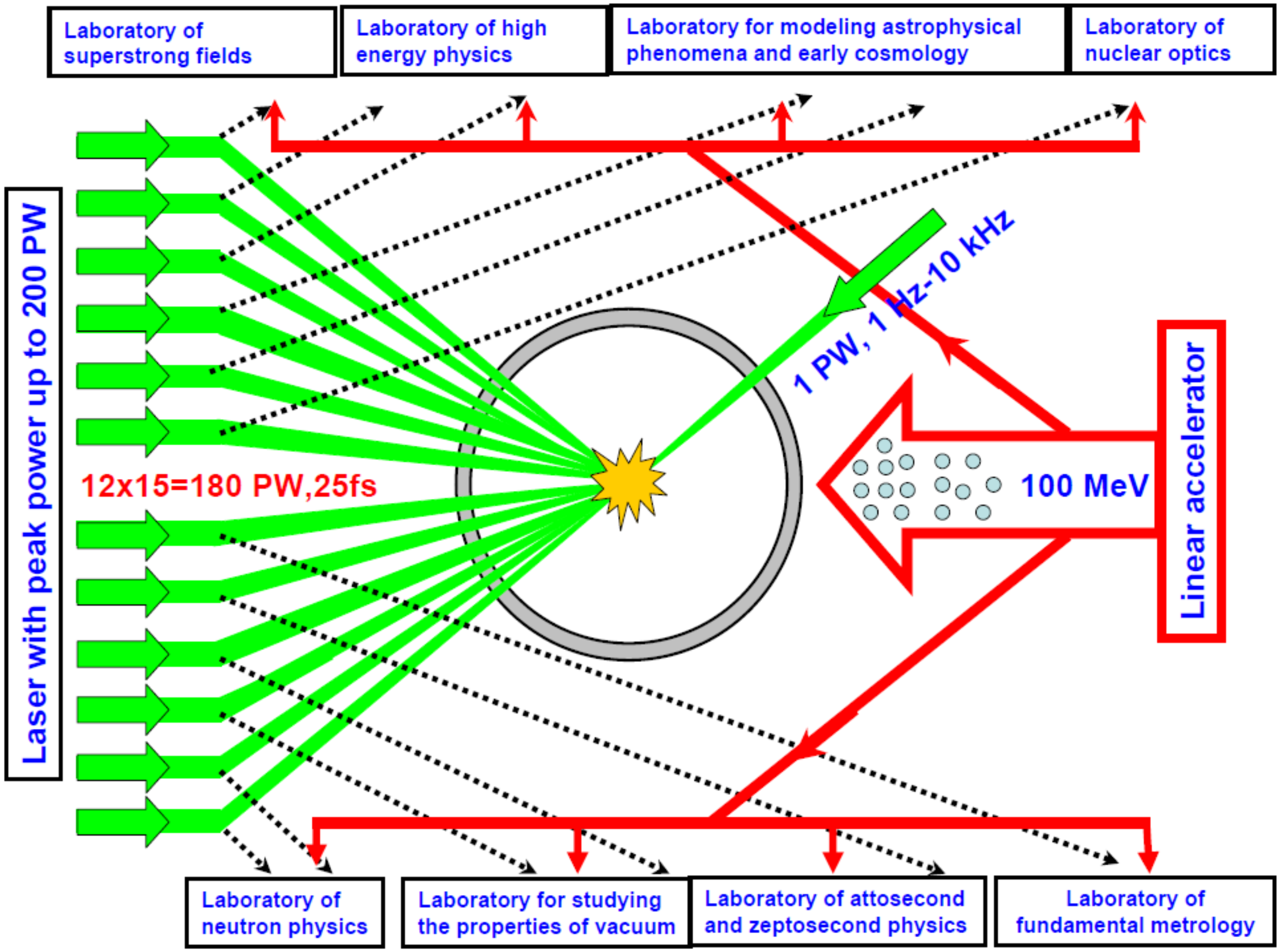
5. Nuclotron-Based Ion Collider Facility/Dubna,Moscow region/

6. Exawatt Laser Facility XCELS/IAP RAS, Nizhny Novgorod /

2018

200 Petawatt Infrastructure

12 channels, 15 PW each, 400 J, 25 fs, 910 nm, intensity 10^{25} W/cm^2



Exawatt Center for Extreme Light Studies (XCELS)

Host Institute: IAP RAS

IAP RAS is one of the largest and most successful institutions of the Russian Academy of Sciences.

Scientific studies are provided by about 1500 employees, about 580 of whom are scientists, including
6 Academicians and 10 Corresponding Members of RAS,
around 120 Doctors and 260 Candidates of Science.
About one third of the scientists are people younger than 35.

Main fields of research:

High power microwave electronics
Plasma physics and plasma technologies
Laser physics and photonics
Radiophysical methods of diagnostics and remote sensing
Wave processes in geophysics
Nonlinear dynamics
Physics of condensed matter and nanoscience
Material science

XCELS: Why in Nizhny Novgorod?

One of the biggest industrial, research, educational, and cultural centers of the Russian Federation

Pioneer works of the IAP team in laser optics:

- 3rd Russian laser and 1st based on domestic crystal
- Averaged ponderomotive force, self-focusing, beat-wave excitation of plasma oscillations, relativistic nonlinear optics, OPA, phase-conjugation, awarded by USSR State Prizes
- First petawatt OPCPA laser in the world

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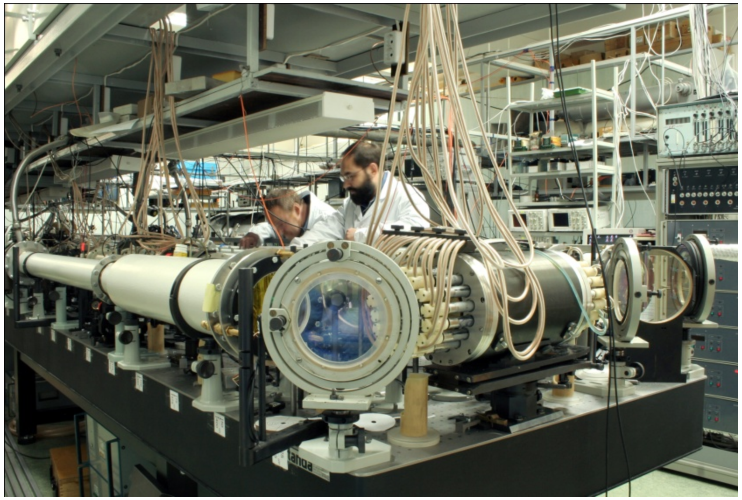
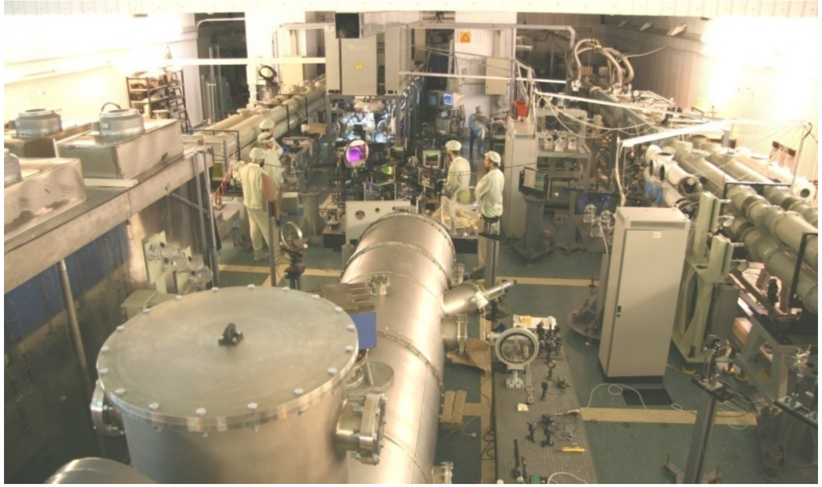
XCELS Basic Technologies


Petawatt PEARL facility at IAP: 0.56 PW 43 fs

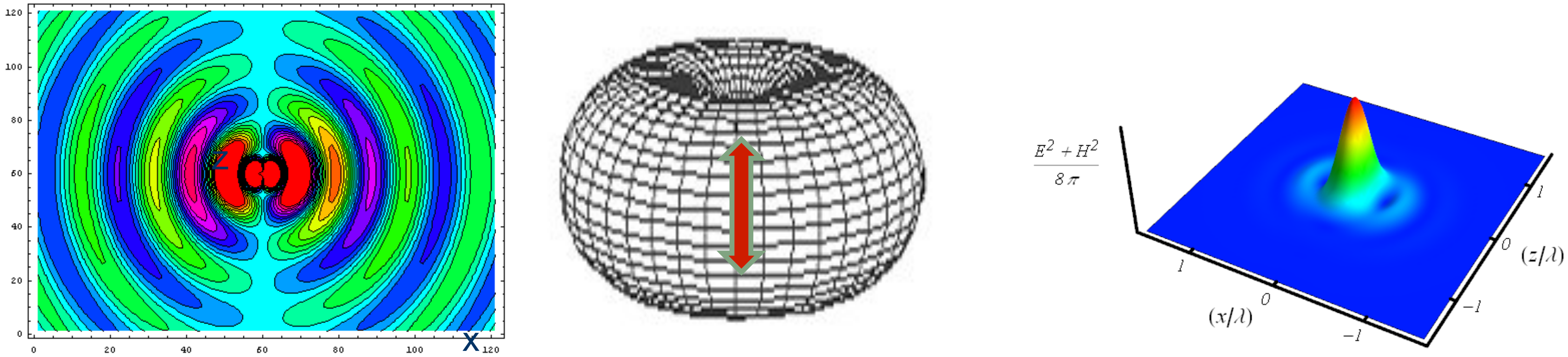
Factory of large aperture
KDP and KD*P crystals at IAP


Petawatt FEMTA-LUCH facility in Sarov

How to maximize field intensity at a given power ?

Rule of thumb for coherent combining of several beams:
To maximize the electric field at focusing point,
radiation of several combining beams should reproduce
configuration of **phase conjugated dipole radiation field**

I. Gonoskov, A. Aiello, S. Heugel, and G. Leuchs, Phys. Rev. A (2012)



Minimum focusing volume: $V_{dp} \approx 0.032\lambda^3$

Converging dipole wave as an exact solution of Maxwell equations:

$$\mathbf{E} = -\nabla\times\nabla\times\mathbf{Z}, \quad \mathbf{H} = -\frac{1}{c}\nabla\times\dot{\mathbf{Z}} \qquad \mathbf{Z} = \hat{z}\,\frac{d}{R}\left[g(t+R/c) - g(t-R/c)\right]$$

$$\mathbf{E}(0,t) = \hat{z}\,\tfrac{4d}{3c^3}\dddot{g}(t) \qquad \mathbf{H} = 0 \qquad g(\tau) = e^{-(\tau^2/D^2)\ln 4}\sin(\omega\tau)$$

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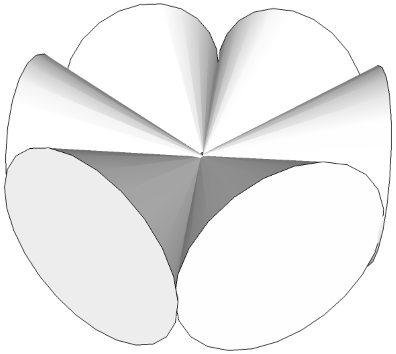
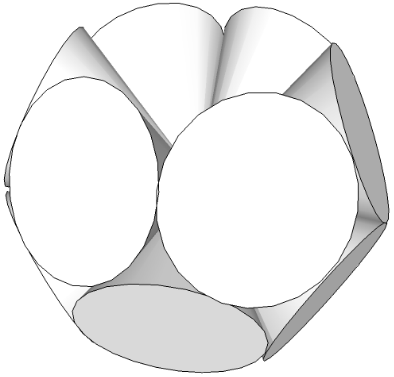
Coherent combining to mimic a converging dipole wave



Belt-6



Double-Belt-12

PHYSICAL REVIEW LETTERS

Articles published week ending 4 JULY 2014

Published by American Physical Society

Volume 113, Number 1

Geometry	Power per channel	Intensity, $\times 10^{25}$W/cm^2	I/I(f=1.2)	Equivalent power (f=1.2)
Single beam (f=1.2)	P_0=200 PW	1.2	1	200 PW
Double-Belt-12 12× (f=0.96)	P_0/12	13.4	11.2	2.2 EW
Dipole-Wave	-	16.7	13.9	2.8 EW

A. Gonoskov, A. Bashinov, I. Gonoskov,C. Harvey, A. Ilderton, A. Kim, M. Marklund, G. Mourou,,A. Sergeev, PRL (2014)

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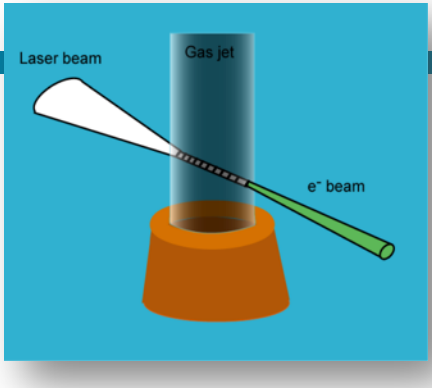
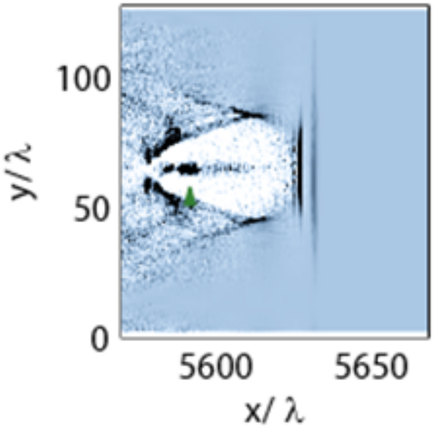
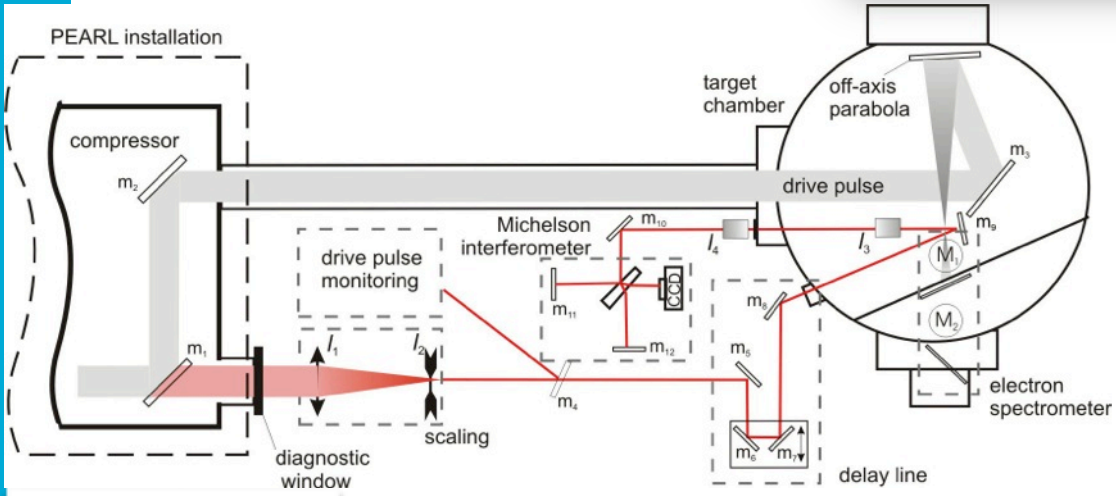
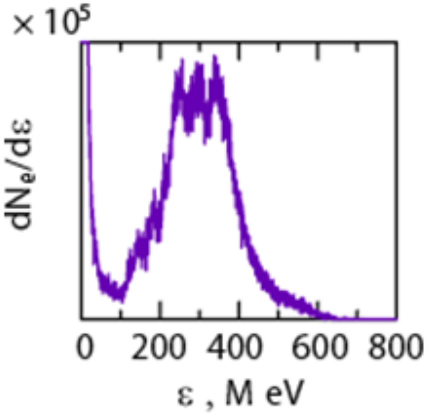
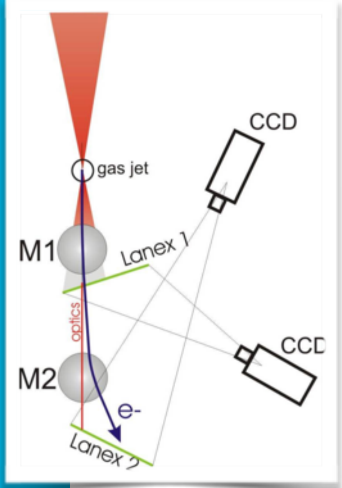
Laser wakefield acceleration

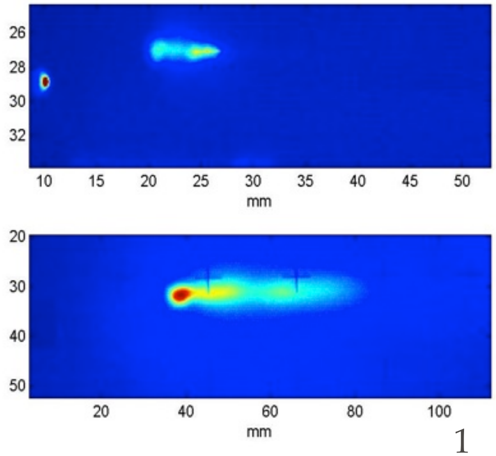












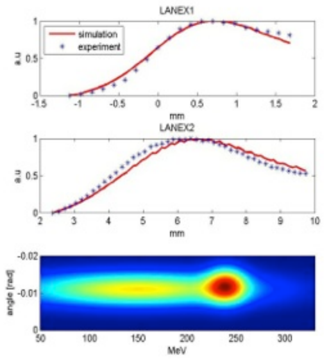
Launch angle = -0.011

Angular size = 4,6 mrad

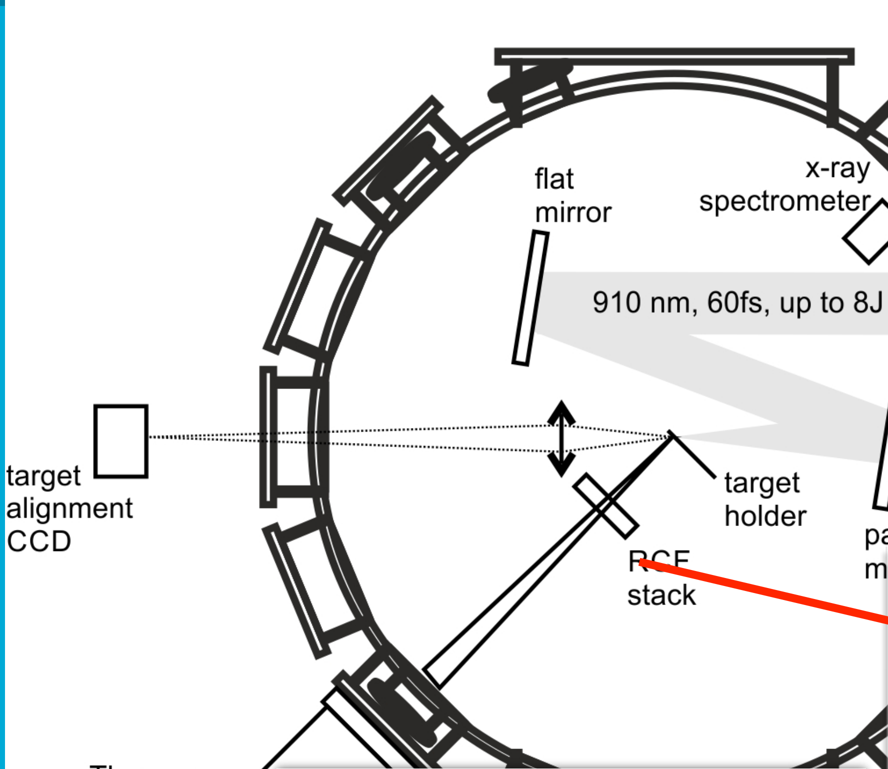
W = 260 MeV (±20 MeV)

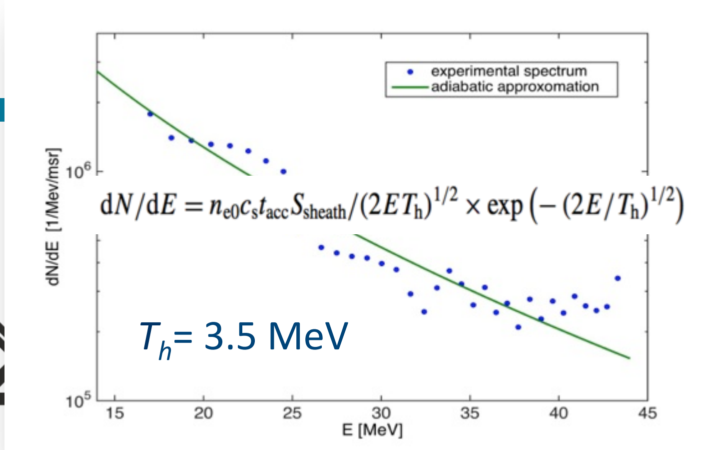
dW = 18 MeV (±10 MeV)

18 pC



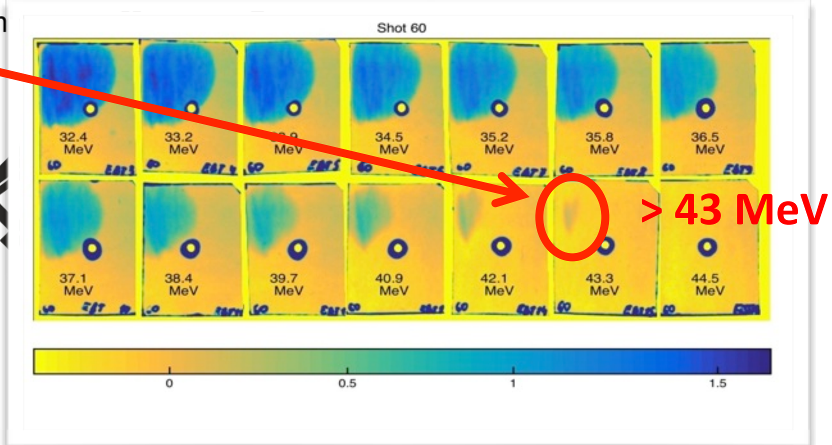
2018 TNSA ion acceleration



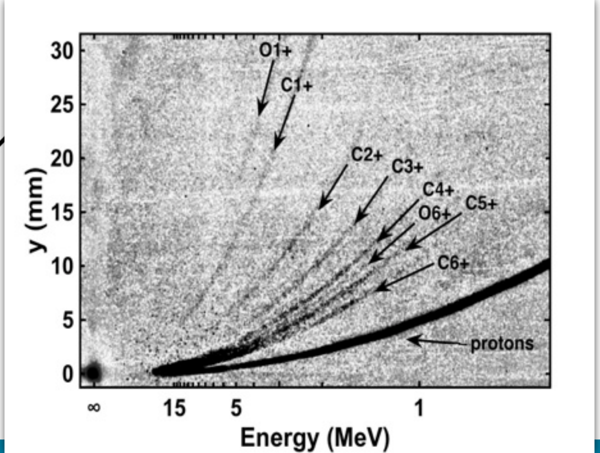


$$dN/dE = n_{e0} c_s t_{acc} S_{sheath} / (2 E T_h)^{1/2} \times \exp\left(-(2E/T_h)^{1/2}\right)$$

T_h= 3.5 MeV



> 43 MeV



43.3 MeV proton beam

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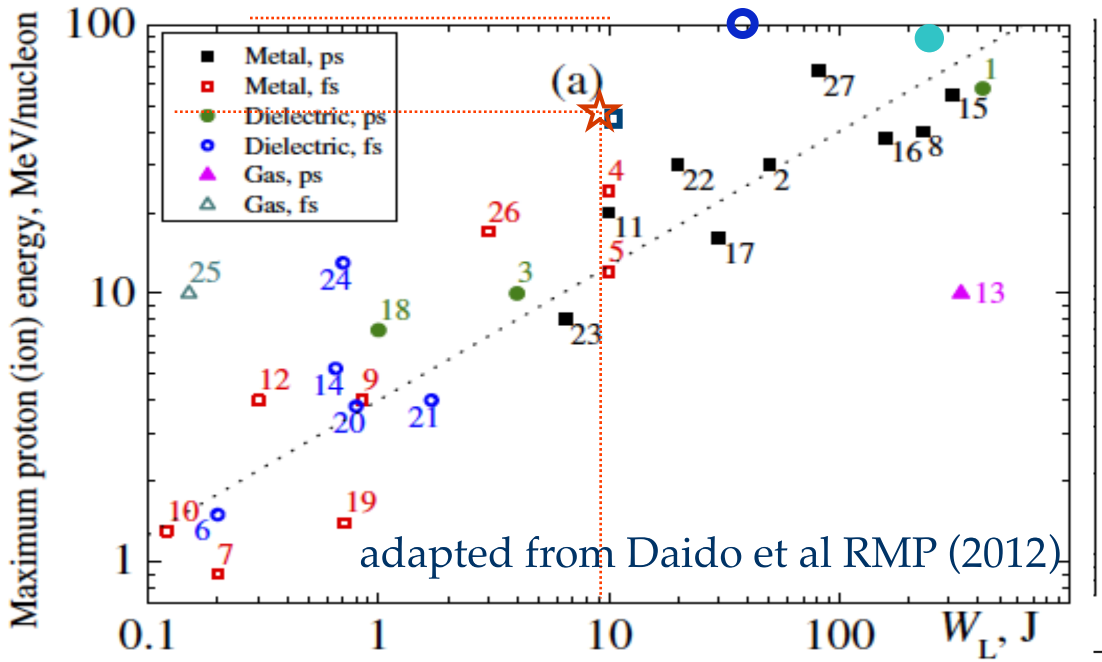


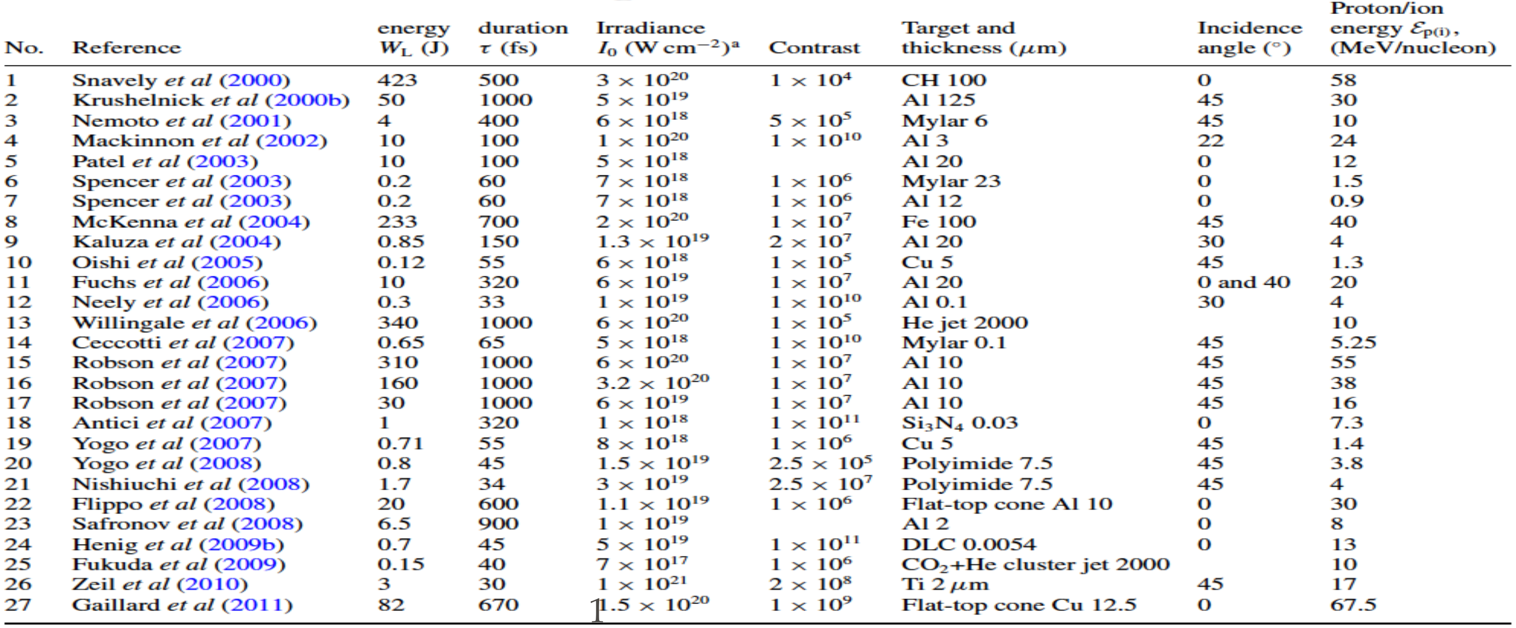
adapted from Daido et al RMP (2012)

▪ Ogura et al., Optics Letters 37 14 (2012) 41 MeV - TNSA

☆ IAP RAS summer 2015: 43 MeV – TNSA (Soloviev et al., Sci.Rer. 7, 12144 (2017))

● Wagner et al, Phys Rev Letters 116 205002 (2016); 85 MeV - TNSA

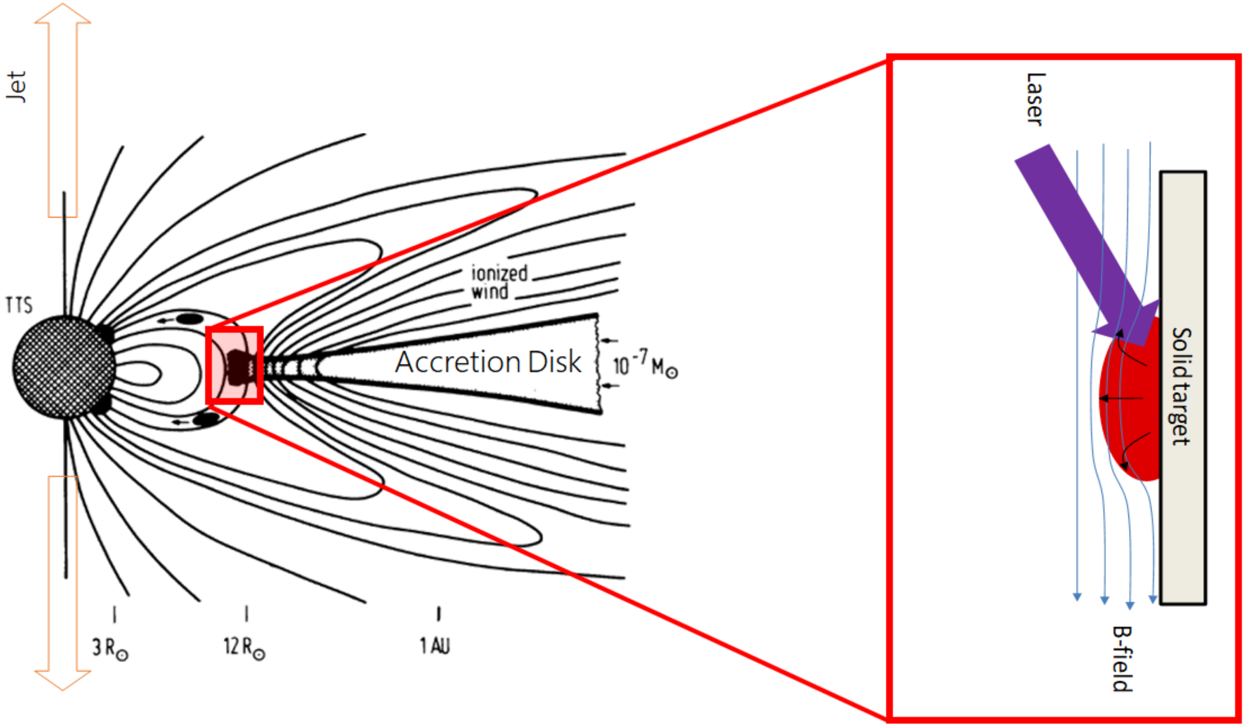
○ Jong Kim et al, Phys.Plasmas 23 070701 (2016); 93 MeV – RPA (world record)



No.	Reference	energy W_L (J)	duration τ (fs)	Irradiance I_0 (W cm^{-2})^a	Contrast	Target and thickness (μm)	Incidence angle (°)	Proton/ion energy $\mathcal{E}_{p(i)}$, (MeV/nucleon)
1	Snavely *et al* (2000)	423	500	3×10^{20}	1×10^{4}	CH 100	0	58
2	Krushelnick *et al* (2000b)	50	1000	5×10^{19}		Al 125	45	30
3	Nemoto *et al* (2001)	4	400	6×10^{18}	5×10^{5}	Mylar 6	45	10
4	Mackinnon *et al* (2002)	10	100	1×10^{20}	1×10^{10}	Al 3	22	24
5	Patel *et al* (2003)	10	100	5×10^{18}		Al 20	0	12
6	Spencer *et al* (2003)	0.2	60	7×10^{18}	1×10^{6}	Mylar 23	0	1.5
7	Spencer *et al* (2003)	0.2	60	7×10^{18}	1×10^{6}	Al 12	0	0.9
8	McKenna *et al* (2004)	233	700	2×10^{20}	1×10^{7}	Fe 100	45	40
9	Kaluza *et al* (2004)	0.85	150	1.3×10^{19}	2×10^{7}	Al 20	30	4
10	Oishi *et al* (2005)	0.12	55	6×10^{18}	1×10^{5}	Cu 5	45	1.3
11	Fuchs *et al* (2006)	10	320	6×10^{19}	1×10^{7}	Al 20	0 and 40	20
12	Neely *et al* (2006)	0.3	33	1×10^{19}	1×10^{10}	Al 0.1	30	4
13	Willingale *et al* (2006)	340	1000	6×10^{20}	1×10^{5}	He jet 2000		10
14	Ceccotti *et al* (2007)	0.65	65	5×10^{18}	1×10^{10}	Mylar 0.1	45	5.25
15	Robson *et al* (2007)	310	1000	6×10^{20}	1×10^{7}	Al 10	45	55
16	Robson *et al* (2007)	160	1000	3.2×10^{20}	1×10^{7}	Al 10	45	38
17	Robson *et al* (2007)	30	1000	6×10^{19}	1×10^{7}	Al 10	45	16
18	Antici *et al* (2007)	1	320	1×10^{18}	1×10^{11}	Si_3N_4 0.03	0	7.3
19	Yogo *et al* (2007)	0.71	55	8×10^{18}	1×10^{6}	Cu 5	45	1.4
20	Yogo *et al* (2008)	0.8	45	1.5×10^{19}	2.5×10^{5}	Polyimide 7.5	45	3.8
21	Nishiuchi *et al* (2008)	1.7	34	3×10^{19}	2.5×10^{7}	Polyimide 7.5	45	4
22	Flippo *et al* (2008)	20	600	1.1×10^{19}	1×10^{6}	Flat-top cone Al 10	0	30
23	Safronov *et al* (2008)	6.5	900	1×10^{19}		Al 2	0	8
24	Henig *et al* (2009b)	0.7	45	5×10^{19}	1×10^{11}	DLC 0.0054	0	13
25	Fukuda *et al* (2009)	0.15	40	7×10^{17}	1×10^{6}	CO_2+He cluster jet 2000		10
26	Zeil *et al* (2010)	3	30	1×10^{21}	2×10^{8}	Ti 2 μm	45	17
27	Gaillard *et al* (2011)	82	670	1.5×10^{20}	1×10^{9}	Flat-top cone Cu 12.5	0	67.5

Laboratory astrophysics: accretion processes

laser plasma expansion across B_0



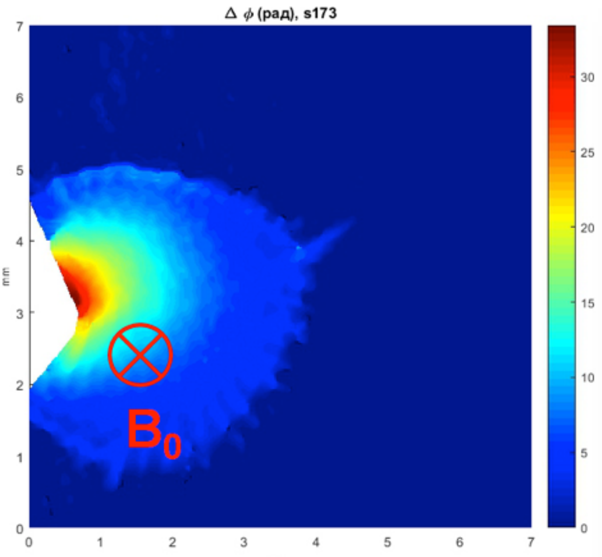
Adapted from Camenzind, (1990).

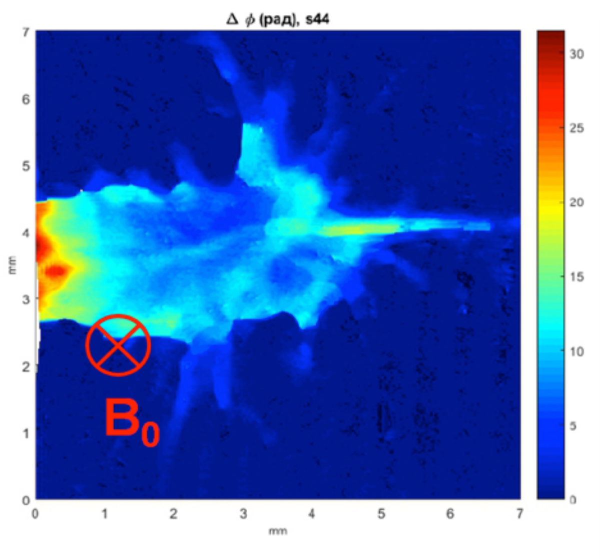
B = 10 T

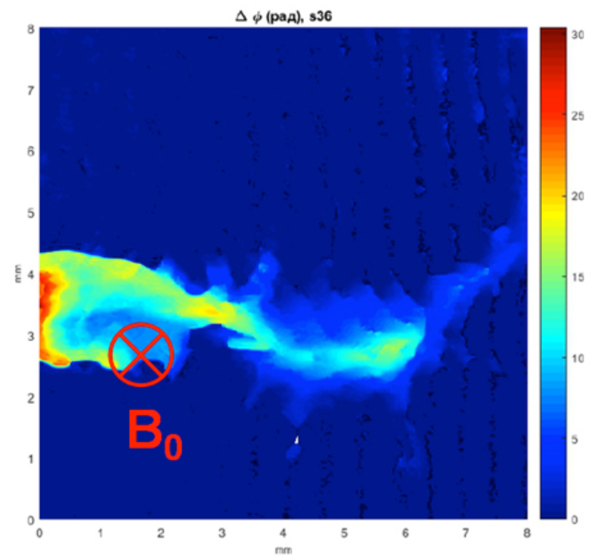
- The source of the turbulence in accretion discs (α-models)
- Plasma dynamics at the edge of accretion discs etc.

Laboratory astrophysics: accretion processes

laser plasma expansion across B_0







- Fast-growth small-scale instabilities develop at the plasma-magnetic field boundary
- Possible source of the turbulence in accretion discs (α-models)
- Modeling the topology of plasma flows in the vicinity of different astrophysical objects (hot Jupiters etc.)

Gyro-devices

Extraordinary high CW and average power at mm and submm wavelengths

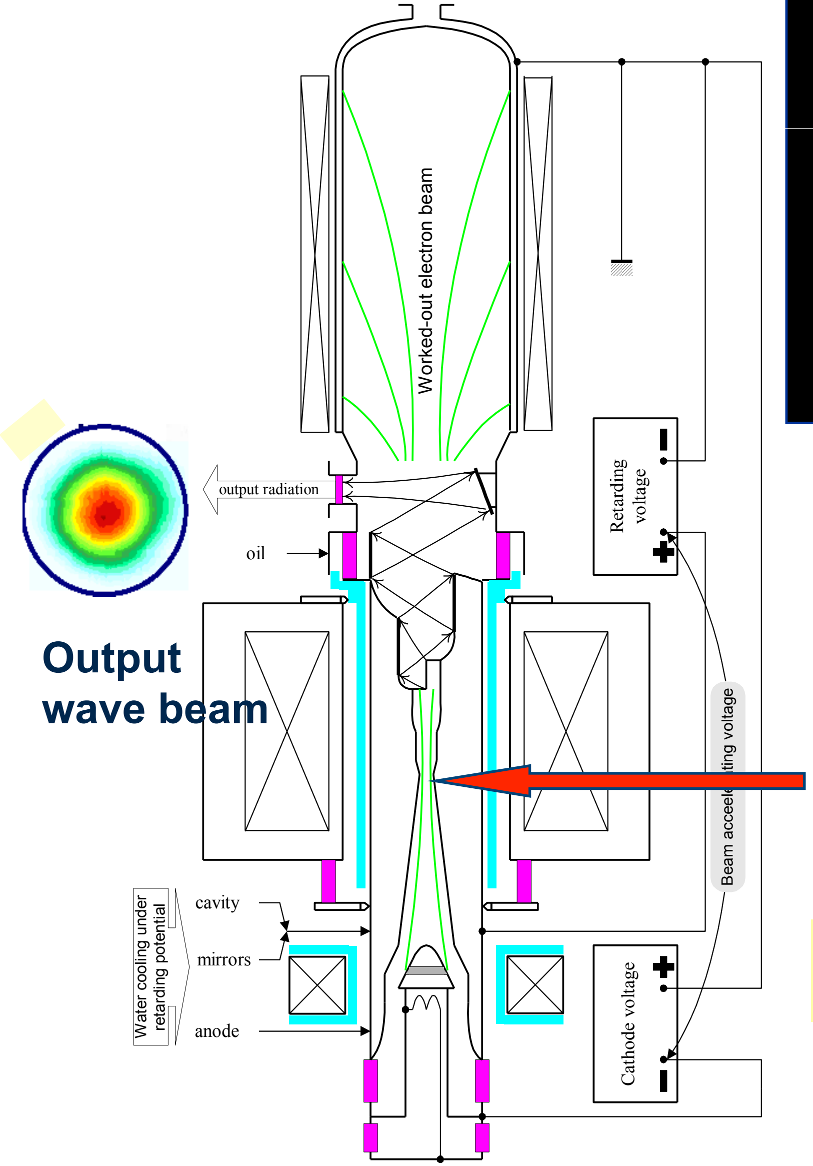
Main applications:

- **ECW systems for plasma fusion installations (50- 200GHz/1MW)**

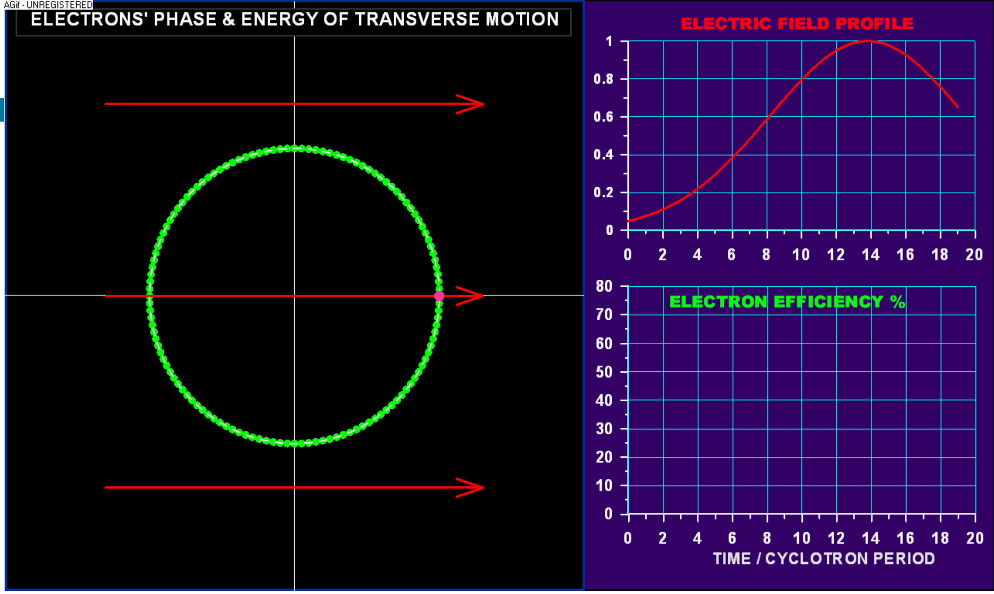
  Recent achievement – T_e = 1 keV in the mirror trap (Budker Inst.)
- Technological applications (ceramics sintering, CVD diamond films, 24-80 GHz/3-60kW)
- Plasma physics and plasma chemistry

  (ion sources, neutron sources…)
- Point- like source of EUV for nano-lithography based on THz gaseous discharge (0.3 THz/ 100 kW)

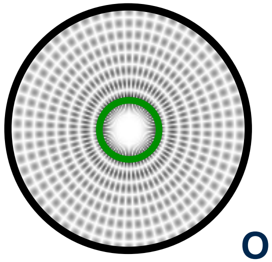
2018



Output wave beam



Gyrotrons for plasma fusion installations



Operating mode

TE$_{31.8,}$ TE$_{25.10}$

Ø ≈ 20 λ

TE$_{28.12}$

TE$_{31.12}$

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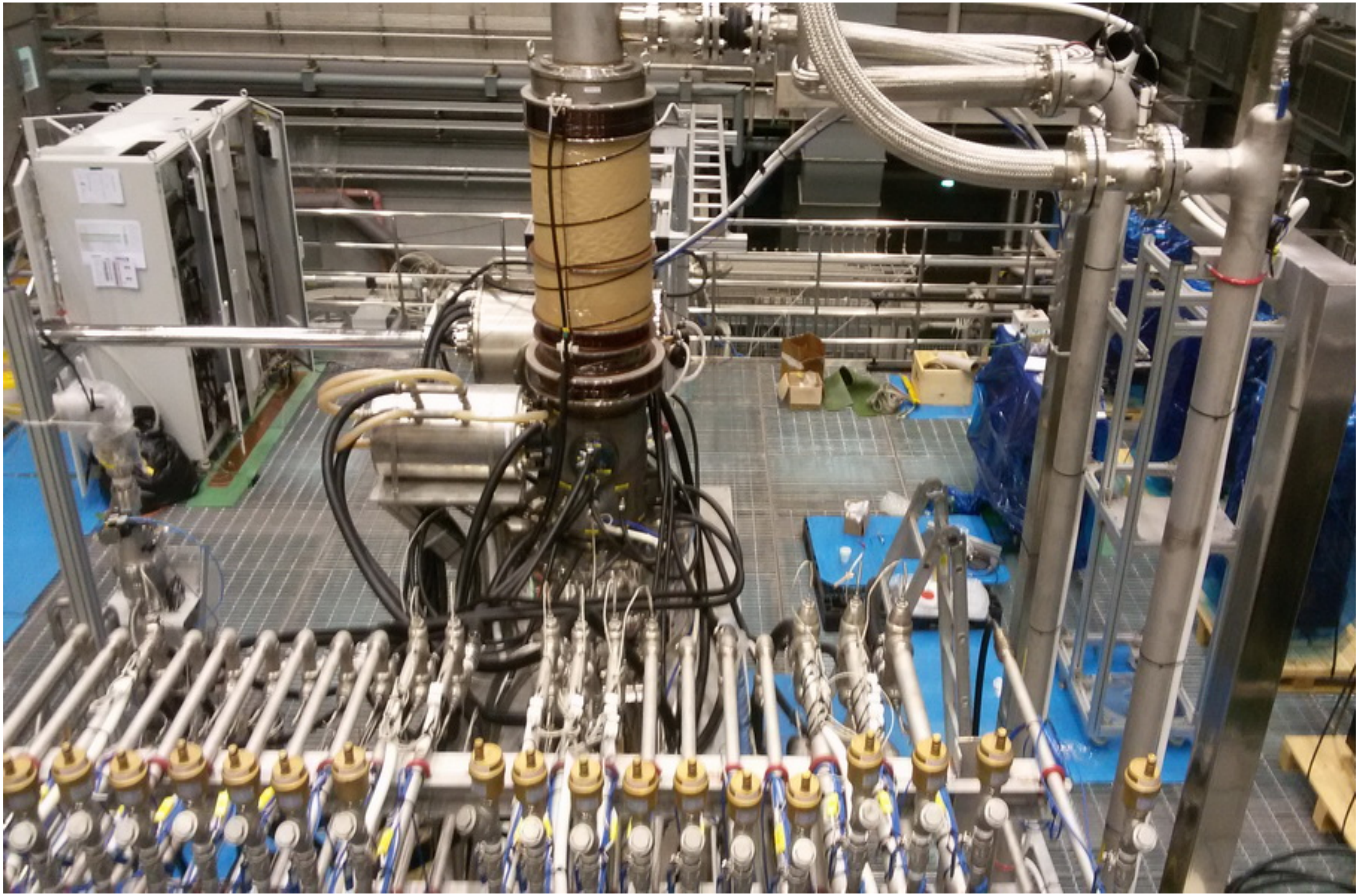
140 / 105 GHz, 1 MW, 300 s gyrotron system test at NFRI

-140 GHz: power 950 kW (855 kW at load after line)

-105 GHz: power 800 kW   (715 kW at load after line)

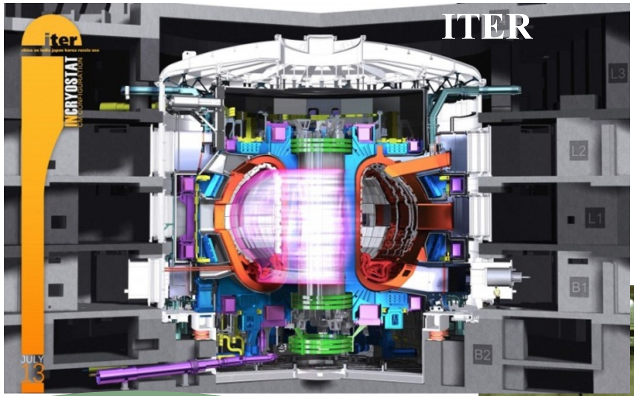


Recent requests & deliveries

140/105 GHz
2 gyrotrons – delivered
1 gyrotron – is under production
1 gyrotron – is ordered


ASDEX Upgraide

170 GHz
8 gyrotrons – to be delivered as components of self-sufficient RF sources


ITER

140/105 GHz
1 gyrotron – delivered
1 gyrotron – is under production


KSTAR

GYCOM
1MW / 3 -1000 s gyrotrons
for ECRH and current drive

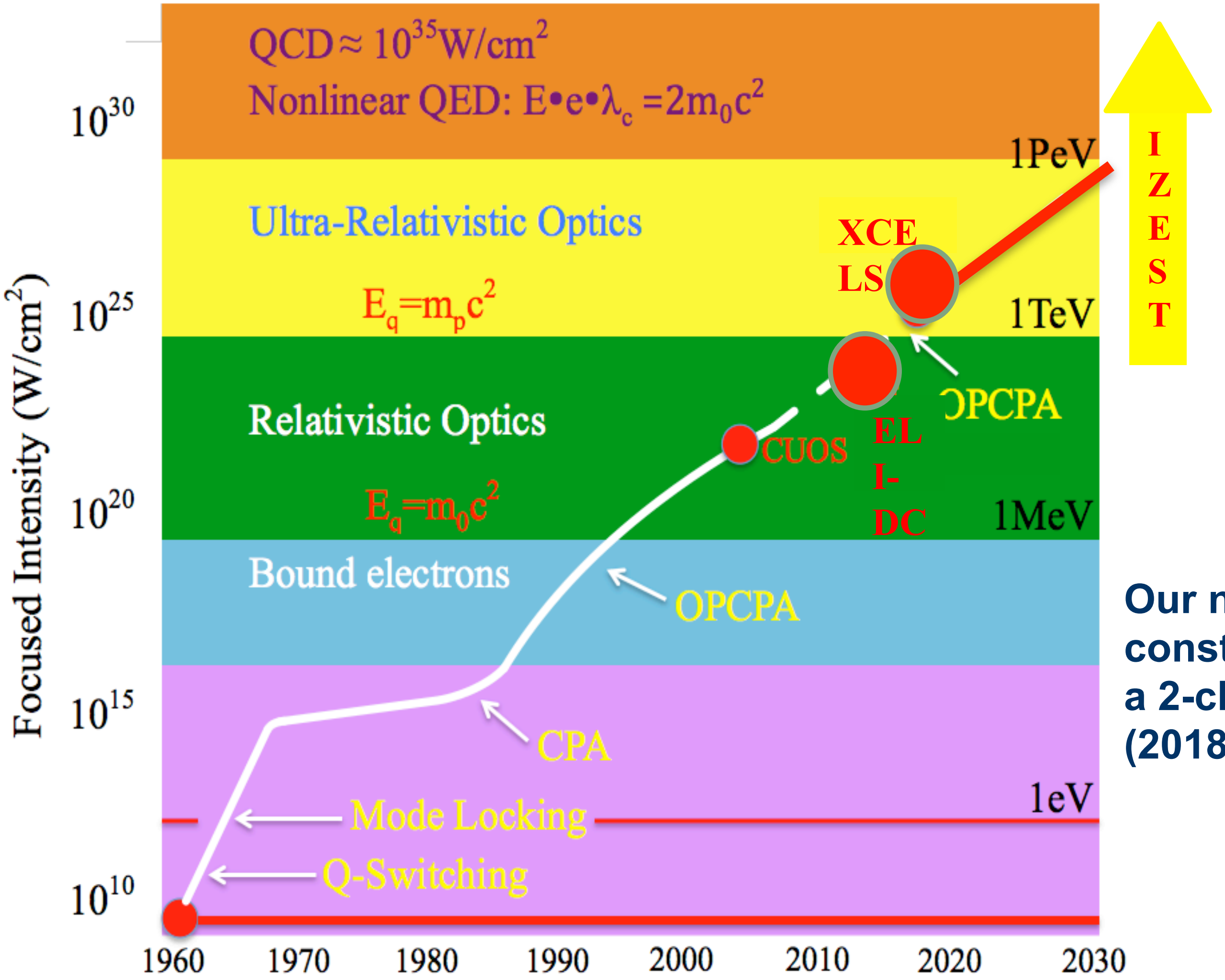
140 GHz
1 gyrotron – delivered
1 gyrotron – is under production


EAST


HL – 2A

140 GHz
2 gyrotrons – delivered
105 GHz
2 gyrotrons – delivered
2 gyrotrons – is under production
1 gyrotron – is ordered

Laser Intensity vs. Years



Our nearest plans:
construction of
a 2-channel prototype
(2018-2021)